LTP/PSI Thursday Colloquia, PSI, Switzerland 15th October 2026

The Hitchhiker's Guide to the Higgs: From Discovery to the Precision Era

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Durham University

THE ROYAL SOCIETY

Photo Credit: ATLAS

Outline

Goal of this Talk

Overview of Discovery → Current Era

Motivation

Why study the Higgs sector?

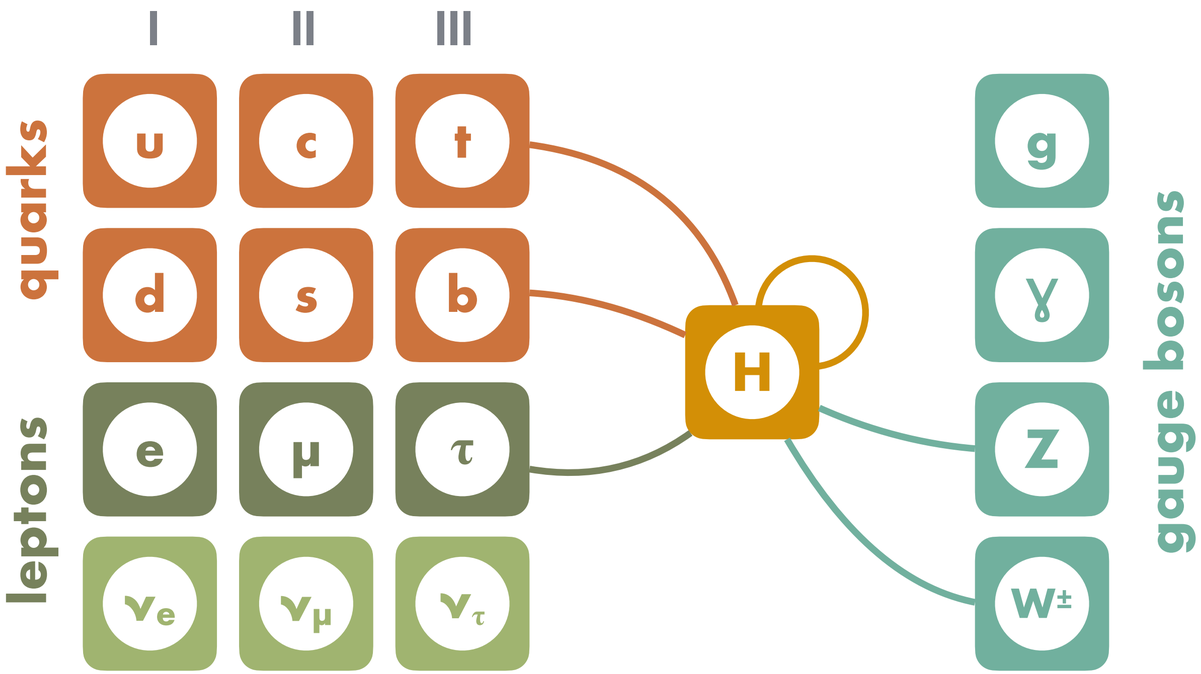
Higgs Production & Higgs Decay

What have we learned so far?

Selected Highlights

Challenges

Future Directions



Why Study the Higgs Sector?

Setting the Stage

The story of the Higgs long predates the Standard Model of particle physics…

Spontaneous symmetry breaking had already attracted significant attention in the context of superconductivity

(A Historical Profile of the Higgs Boson) Ellis, Gaillard, Nanopoulos 16

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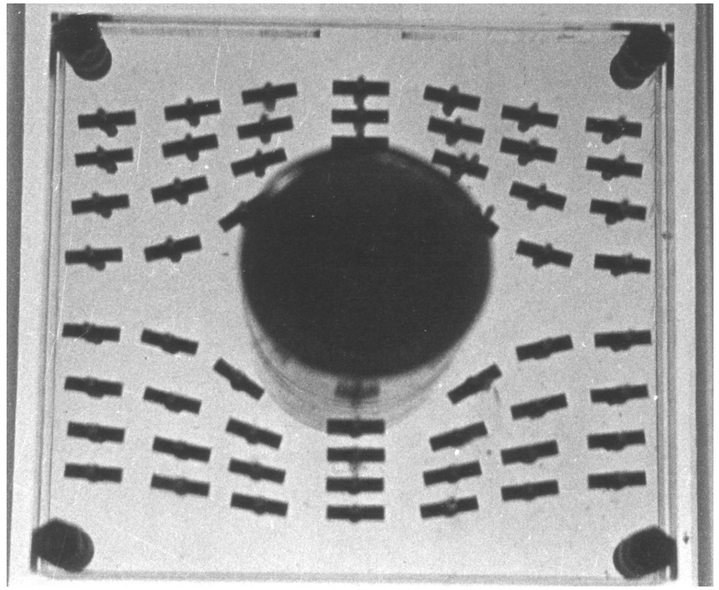
Bardeen-Cooper-Schrieffer Theory

In free space, Lorentz invariance and $U(1)$ gauge symmetry forbid a photon mass. But, a photon can gain an **effective mass** when it propagates through a superconductor.

The superconductor defines a rest-frame, breaking Lorentz invariance. The gauge symmetry remains but is hidden by the condensation of electrons into Cooper pairs in the ground state. Interactions between the photon the Cooper pairs cause the photon to acquire an effective mass.

Ginzburg, Landau 50, 57; Cooper 56; Bardeen, Cooper, Schrieffer 57; Nambu 60; Goldstone 61; Anderson 63



(Meissner Effect) Image: Alfred Leitner via Wikipedia

It was debated whether this mechanism could exist in a fully relativistic field theory…

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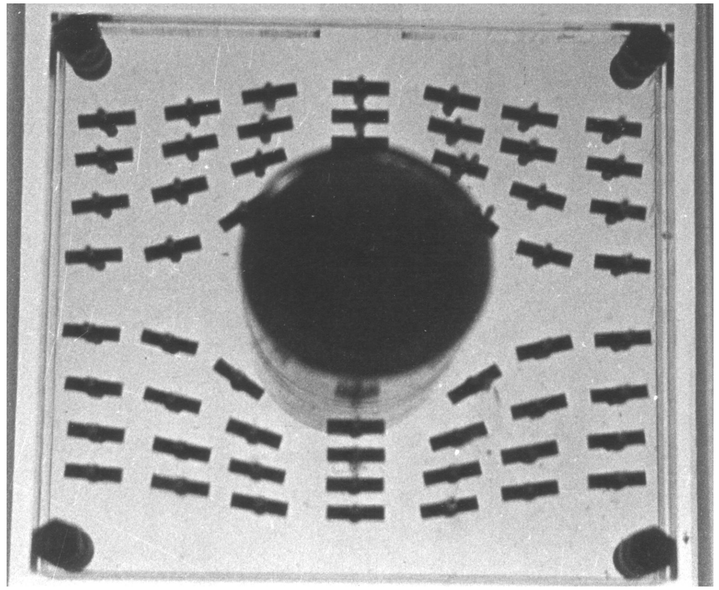

(Meissner Effect) Image: Alfred Leitner via Wikipedia

It was debated whether this mechanism could exist in a fully relativistic field theory

Yes! It can be realised using a scalar field (which has an associated massive scalar particle)

Englert, Brout 64; Higgs 64, 66; Guralnik, Hagen, Kibble 64

(A Historical Profile of the Higgs Boson) Ellis, Gaillard, Nanopoulos 16

The Role of the Higgs Field in the Standard Model

$$\mathscr{L}_{\text{SM}} = \mathscr{L}_{\text{gauge}} + \mathscr{L}_{\text{Fermion}} + \mathscr{L}_{\text{Higgs}} + \mathscr{L}_{\text{Yukawa}} + \mathscr{L}_{\text{GF}} + \mathscr{L}_{\text{Ghost}}$$

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The Higgs field plays a central role in the SM

It provides mass to $W^{\pm}/Z$ bosons via Electroweak symmetry breaking and leptons via Yukawa couplings

$$\mathscr{L}_{\text{Higgs}} = \left(D_\mu \Phi\right)^\dagger D_\mu \Phi + \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2$$

$$\Phi = \begin{bmatrix} \varphi^+ \\ \dfrac{v + H + i\varphi_Z}{\sqrt{2}} \end{bmatrix}.$$

$$\mathscr{L}_{\text{Yukawa}} = -\overline{L}_L Y_l \Phi \; \ell_R - \overline{Q}'_L Y_d \Phi \; d'_R - \overline{Q}'_L Y_u \widetilde{\Phi} \; u'_R + \text{h.c.}$$

$$\widetilde{\Phi} = i\sigma_2 \Phi^*$$

Complex SU(2) doublet

Left-handed SU(2) doublets

Right-handed singlets

Complex 3x3 matrices in flavour

The Higgs field talks to a lot (17/19 parameters): Higgs sector (2/2), Gauge (2/4), Yukawa/Flavour (13/13)

Higgs Couplings

Let's consider what freedom we have in the Higgs sector of the Standard Model

$$D_\mu\Phi = \left[\partial_\mu + i\eta\frac{g}{\sqrt{2}}\left(\tau^+W_\mu^+ + \tau^-W_\mu^-\right) + i\eta\frac{g}{2}\tau_3 W_\mu^3 + i\eta'\frac{g'}{2}B_\mu\right]\Phi$$

$$\mathscr{L}_{\text{Higgs}} = \left(D_\mu\Phi\right)^\dagger D_\mu\Phi - V(\Phi)$$

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda\left(\Phi^\dagger\Phi\right)^2$$

EW symmetry breaking

$$\mu^2 = \frac{m_h^2}{2}, \quad \lambda = \frac{1}{2}\frac{m_h^2}{v^2}$$

Higgs self-coupling is not a free parameter!

$$V(\Phi) = -\frac{m_h^2}{2}H^2 + \frac{m_h^2}{2v}H^3 + \frac{m_h^2}{8v^2}H^4$$

Couplings fixed by gauge invariance $(g, g') \leftrightarrow (m_W, m_Z)$

$$\left(D_\mu\Phi\right)^\dagger D_\mu\Phi \longrightarrow \frac{1}{8}g^2v^2W_\mu^3W^{\mu 3} + \frac{1}{8}g'^2v^2B_\mu B^\mu - \frac{1}{4}\eta\eta' g g' v^2 W_\mu^3 B^\mu + \ldots$$

$$\sim g m_W W^{+\mu}W_\mu^- H + g\frac{m_Z}{\cos\theta_W}Z^\mu Z_\mu H$$

No extra free parameters!

In the SM the Higgs/Electroweak sector is quite highly constrained, this has severe ramifications when trying to adjust HVV or $HHVV$ couplings (e.g. in the κ framework), modifying them can easily cause higher-order Electroweak corrections to violate gauge invariance

Thinking about Phenomenology

The Higgs mechanism seemed to work on paper, but was it realised in reality?

People started to think about how to detect the scalar boson…

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

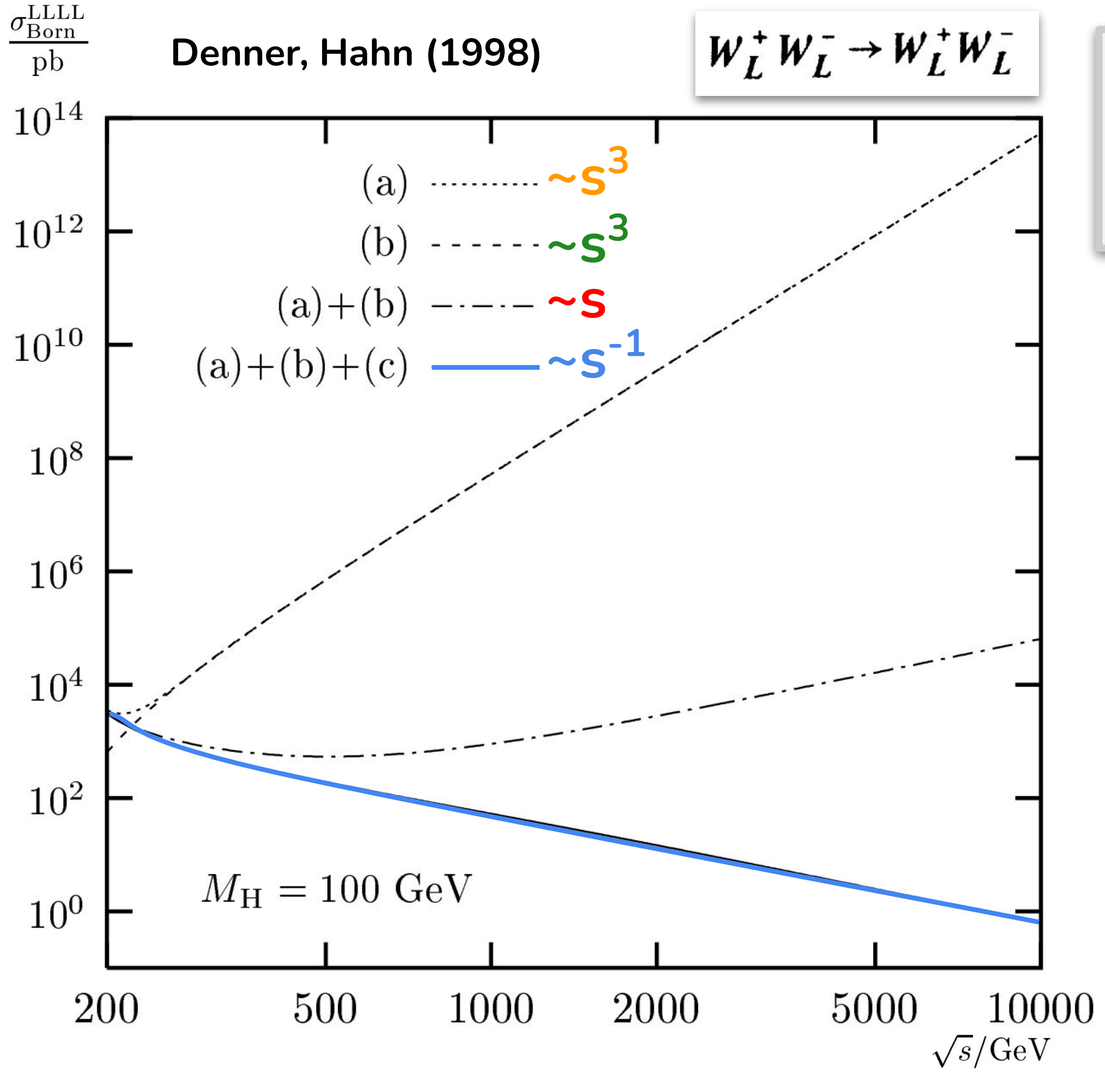
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3,4] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

*statement was made ``rather tongue-in-cheek''

This was not what happened…

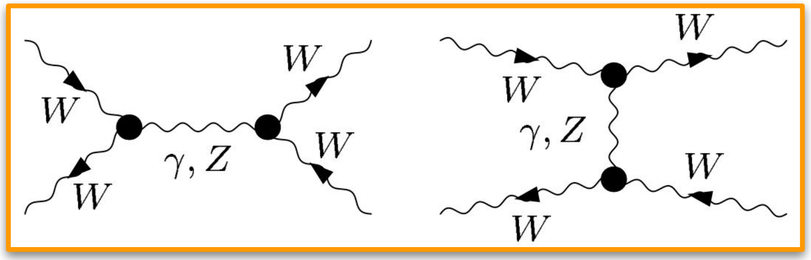
Lesson: never tell an experimentalist they can’t measure something

The No-Lose Theorem



The SM Higgs boson (4.5 GeV < m_h < ~2m_W) cancels the energy growth of purely-bosonic $V_L V_L \to V_L V_L$ scattering, preserving unitarity.

(a)



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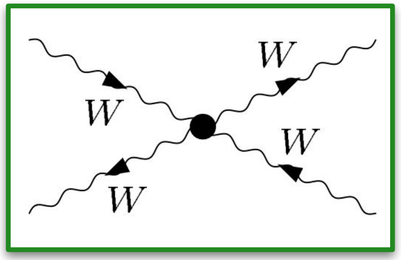

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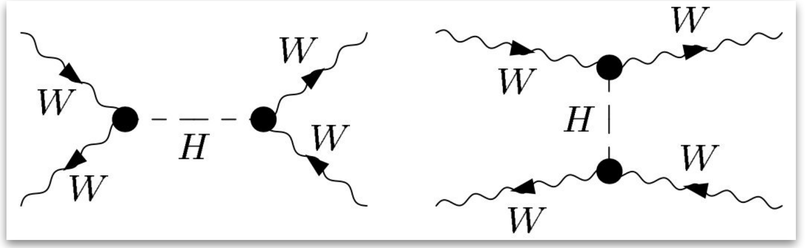


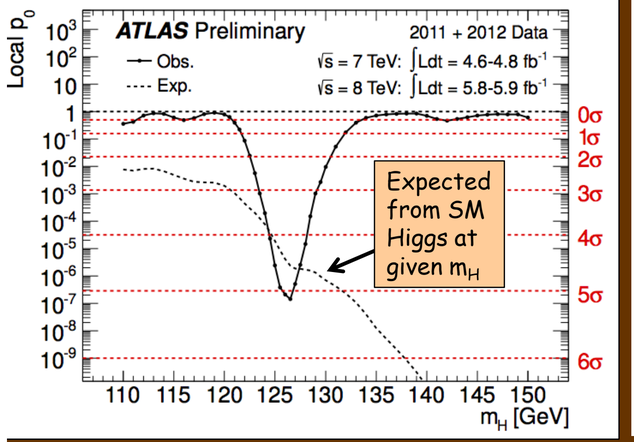
Slide: Giacomo Boldrini LLR Seminar (May 2025)

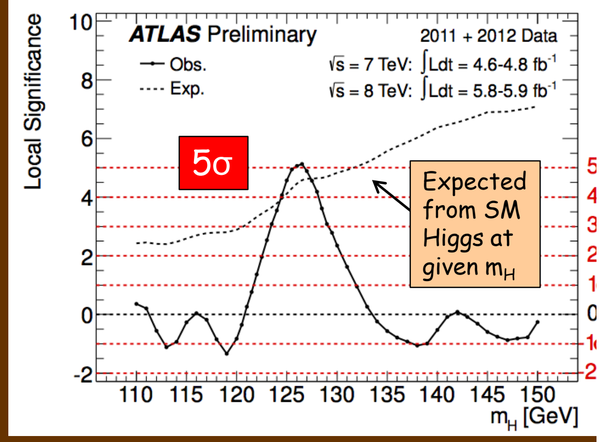
Higgs Announcement

4th July 2012



Combined results: the excess





Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	5.0 σ
Probability of background up-fluctuation	3 x 10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

Discovery of a resonance compatible with the SM Higgs, driven by $H \to \gamma\gamma$ and $H \to ZZ^* \to 4l$ analyses

Rocked the world… due to the importance of the announcement… and the use of Comic Sans

Announcement: https://indico.cern.ch/event/197461/

Announcement 2: https://cds.cern.ch/record/1998699

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The next steps …

ATLAS plans to submit a paper based on the data presented today at the end of July, at the same time as CMS and to the same journal

H→ WW(*) → lνlν channel: plan is to include results in the July paper
H→ ττ , W/ZH → W/Z bb: first results with 2012 data expected later in the Summer

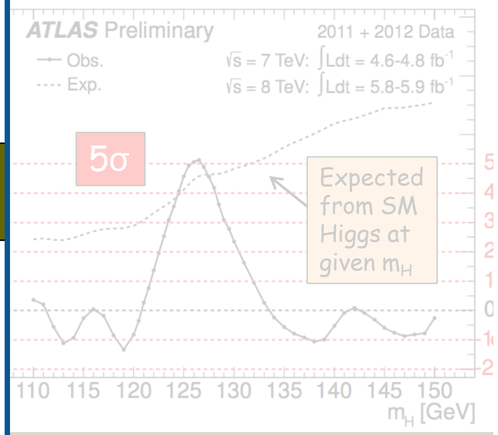
MORE DATA will be essential to:
- ❑ Establish the observation in more channels, look at more exclusive topologies
- ❑ start to understand the nature and properties of the new particle

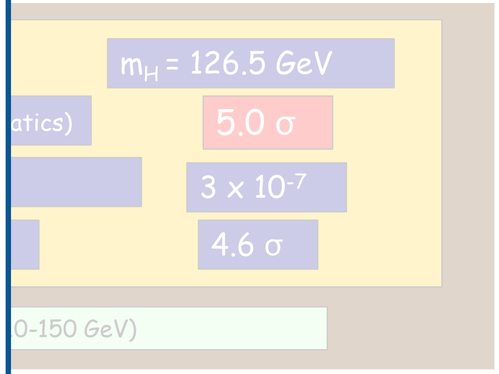
This is just the BEGINNING !

We are entering the era of "Higgs" measurements
First question: is the observed excess due to the production of a SM Higgs boson ?

Note:
- ❑ we have only recorded ~ 1/3 of the data expected in 2012
- ❑ the LHC and experiments have already accomplished a lot and much faster than expected

ATLAS: Status of SM Higgs searches, 4/7/2012 49





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And yet… almost every problem of the Standard Model originates from Higgs interactions!

naturalness stability cosmological constant

$$\mathscr{L}_{\text{Higgs}} = \left(D_\mu \Phi\right)^\dagger D_\mu \Phi + \mu^2 \Phi^\dagger \Phi - \lambda \left(\Phi^\dagger \Phi\right)^2 - V_0$$

$$\mathscr{L}_{\text{Yukawa}} = -\overline{L}_L Y_l \Phi \; \ell_R - \overline{Q}'_L Y_d \Phi \; d'_R - \overline{Q}'_L Y_u \widetilde{\Phi} \; u'_R + \text{h.c.},$$

flavour

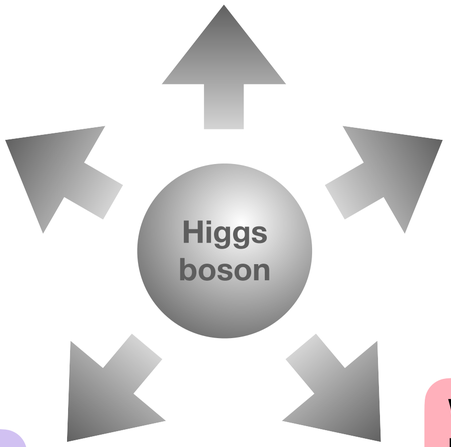
Open Questions

What is the origin of the early-universe inflation?

- Is the Higgs connected to the mechanism that drives inflation?
- Are there any imprints in cosmological observations?

What is the origin of the vast range of quark and lepton masses in the Standard Model?

- Are there modified interactions to the Higgs boson and known particles?
- Does the Higgs decay into pairs of quarks and leptons with distinct flavours (for example, $H \to \mu^+\tau^-$)?



Why is the electroweak interaction so much stronger than gravity?

- Are there new particles close to the mass of the Higgs boson?
- Is the Higgs boson elementary or made of other particles?
- Are there anomalies in the interactions of the Higgs with the W and Z?

What is dark matter?

- Can the Higgs provide a portal to dark matter or a dark sector?
- Is the Higgs lifetime consistent with the Standard Model?
- Are there new decay modes of the Higgs?

Why is there more matter than antimatter in the universe?

- Are there charge-parity violating Higgs decays?
- Are there anomalies in the Higgs self-coupling that would imply a strong first-order early-universe electroweak phase transition?
- Are there multiple Higgs sectors?

Salam, Wang, Zanderighi 22

The Higgs as a candle in the dark…

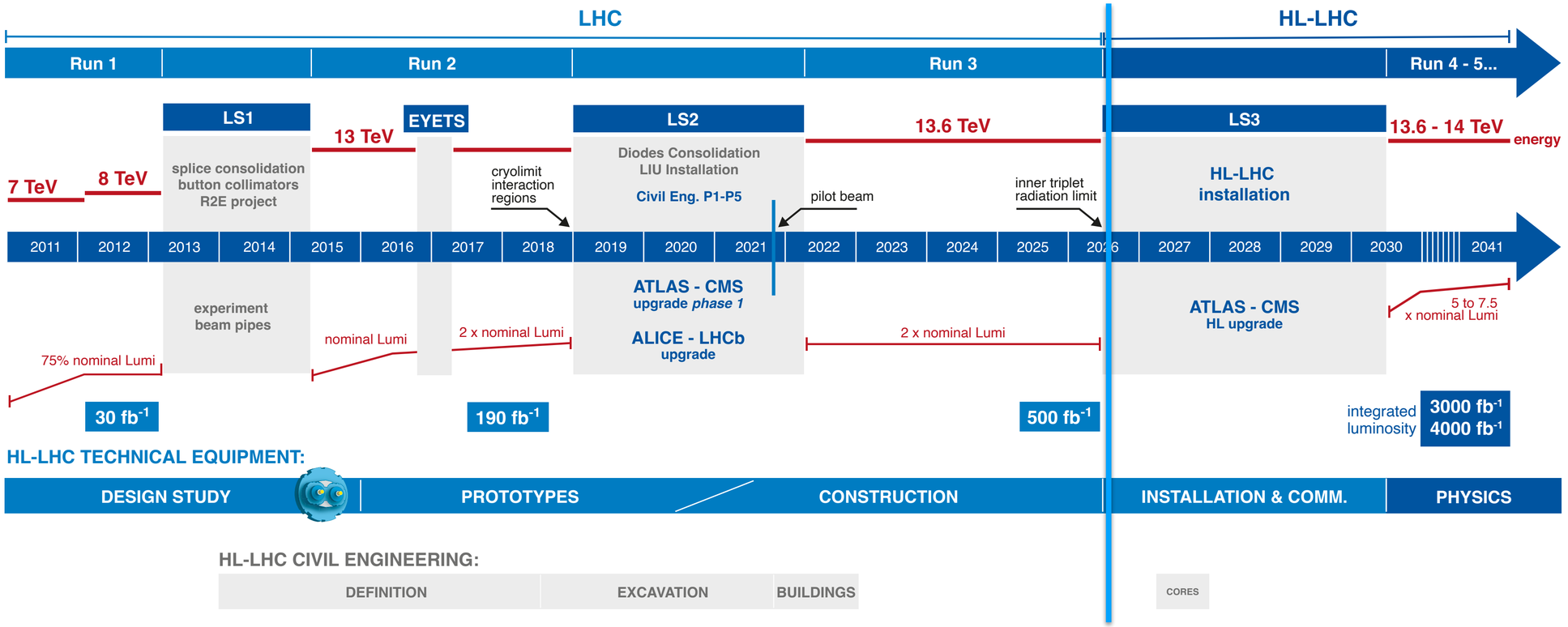
- Does the Higgs couple to the 2nd/3rd generation fermions as the SM predicts?
- What else does the Higgs couple to? E.g. what is hiding in the tails of boosted Higgs production?
- Is the Higgs potential as the SM predicts?

Suddenly we are able to explore a new sector of the SM Lagrangian, there is much left to measure and surprises are not ruled out!

What Have We Learned So Far?

LHC & HL-LHC

At 05:52am on 27 June 2026, the final protons of the Large Hadron Collider's 3rd data-taking period circulated…



ATLAS

Run 3: 332 fb^{-1}

Total: 505 fb^{-1}

CMS

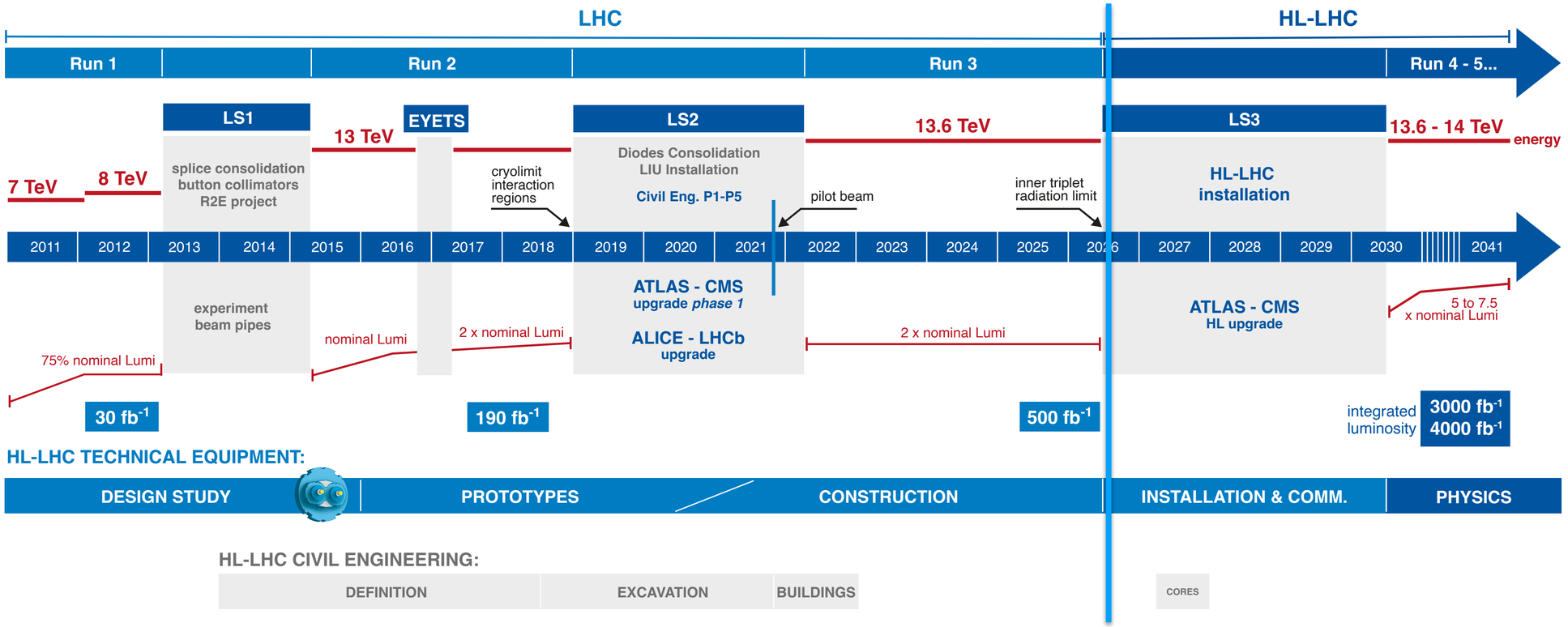
Run 3: 355 fb^{-1}

Total: 504 fb^{-1}

So long LHC, and thanks for all the Higgs!

LHC & HL-LHC

Fortunately, every end brings a new beginning, work is already underway on the construction of the High-Luminosity LHC



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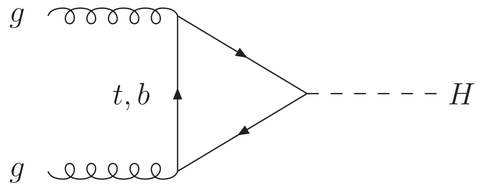
Luminosity



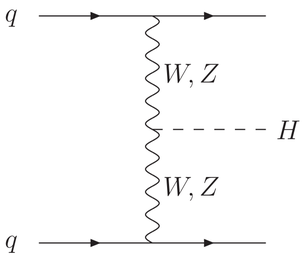
Figure adapted from Monica Dunford (HP2 2026)

Higgs Production

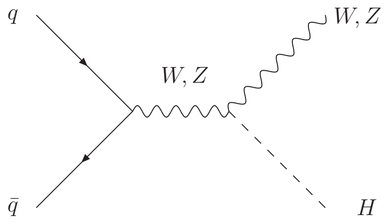
σ [pb] @ 13 TeV / # Higgs in $140\ \mathrm{fb}^{-1}$



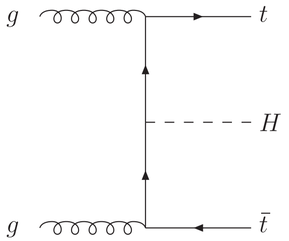
49 pb / 6.9M



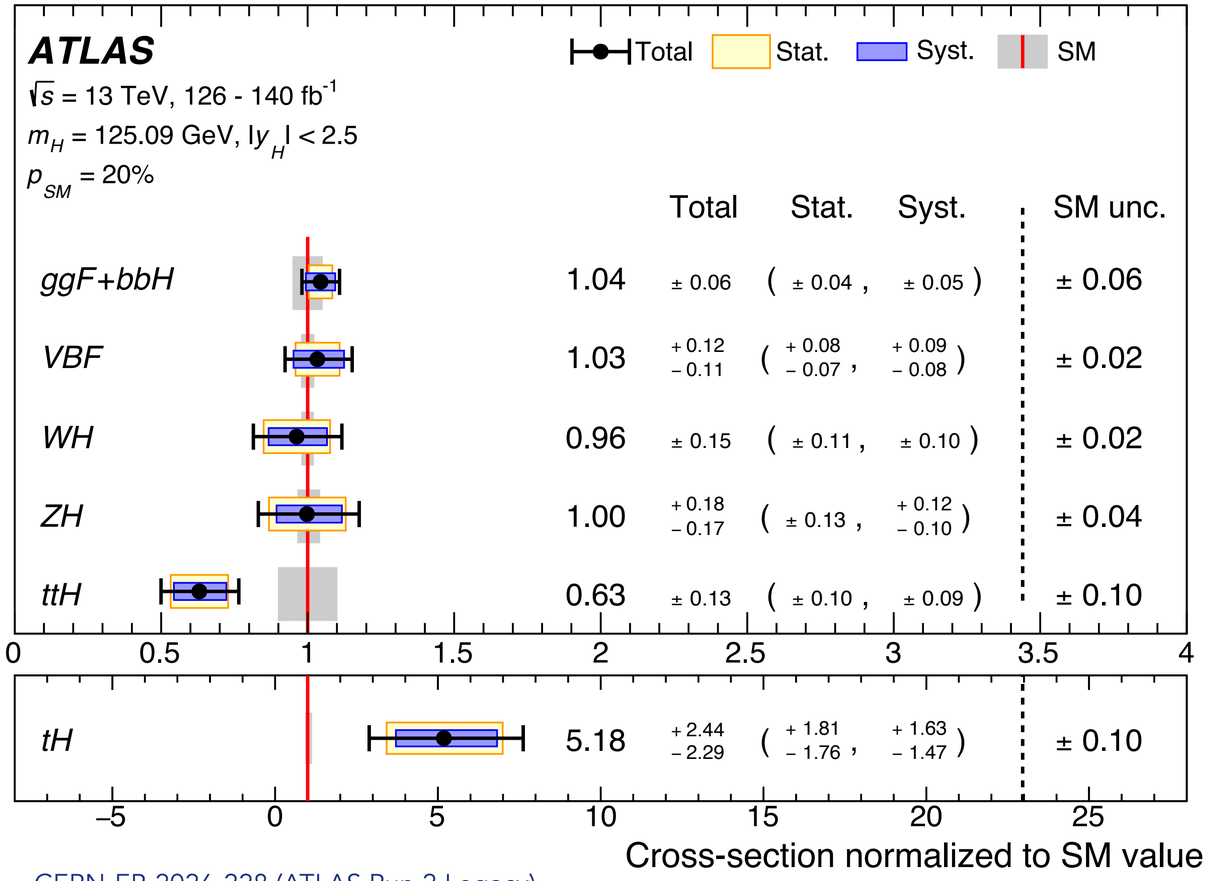
3.8 pb / 520k



2.3 pb / 320k



0.5 pb / 70k



CERN-EP-2026-228 (ATLAS Run 2 Legacy)

Experimental Measurement of Higgs Production

$$R_{if} = \sigma_i \times B_f$$

R_{if} - rate of production via process i with decay info final state f

σ_i - cross section for production process i

B_f - branching ratio into final state f

Signal Strength

$$\mu_{if} = (\sigma_i \times B_f)/(\sigma_i^{\mathrm{SM}} \times B_f^{\mathrm{SM}})$$

μ_{if} - signal strength for production via i and decay into f

Global Signal Strength

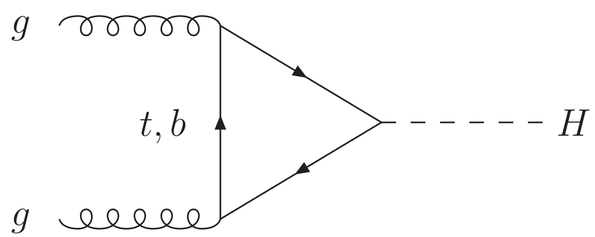
Global fit of all production and decay processes

Theory errors are already dominating with Run 2 data!

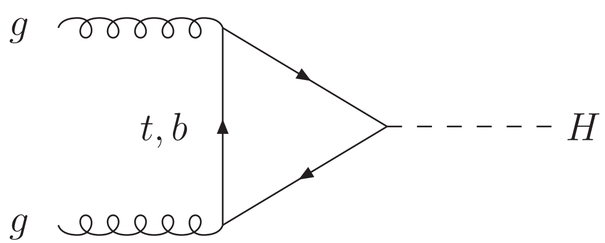
$$\mu = 0.990 \pm 0.027\ (\mathrm{stat.}) \pm 0.024\ (\mathrm{exp.})\ ^{+0.037}_{-0.035}\ (\mathrm{sig\ .\ th.})\ ^{+0.016}_{-0.015}(\mathrm{bkg\ .\ th.})$$

CERN-EP-2026-228 (ATLAS Run 2 Legacy)

Higgs Production: Gluon Fusion



Gluon Fusion



Factorisation formula

$$\sigma(H+X) = \Sigma_{i,j} \int \mathrm{d}x_1 f_i(x_1,\mu_F) \int \mathrm{d}x_2 f_j(x_2,\mu_F) \times \hat{\sigma}_{ij\to H+X}(s, m_H, \mu_F, \mu_R)$$

Total Cross Section

$$\sigma_{LO}(pp \to H) = \sigma_0 \tau_H \frac{d\mathscr{L}^{gg}}{d\tau_H}$$

Gluon luminosity

$$\frac{d\mathscr{L}^{gg}}{d\tau} = \int_\tau^1 \frac{dx}{x}\, g(x,\mu_F^2) g(\tau/x,\mu_F^2)$$

Coefficient Function / Squared Matrix Element

$$\sigma_0 = \frac{\pi^2}{8M_H^3}\Gamma_{LO}(H\to gg) = \frac{G_F \alpha_s^2(\mu_R)}{288\sqrt{2}\pi} \left| \sum_Q A_Q^H(\tau_Q) \right|^2$$

$$\tau_H = M_H^2/s$$

$$\tau_Q = 4M_Q^2/M_H^2$$

$$A_Q^H(\tau) = \frac{3}{2}\tau\left[1+(1-\tau)f(\tau)\right]$$

$$f(\tau) = \arcsin^2\frac{1}{\sqrt{\tau}} \qquad \tau \geq 1$$

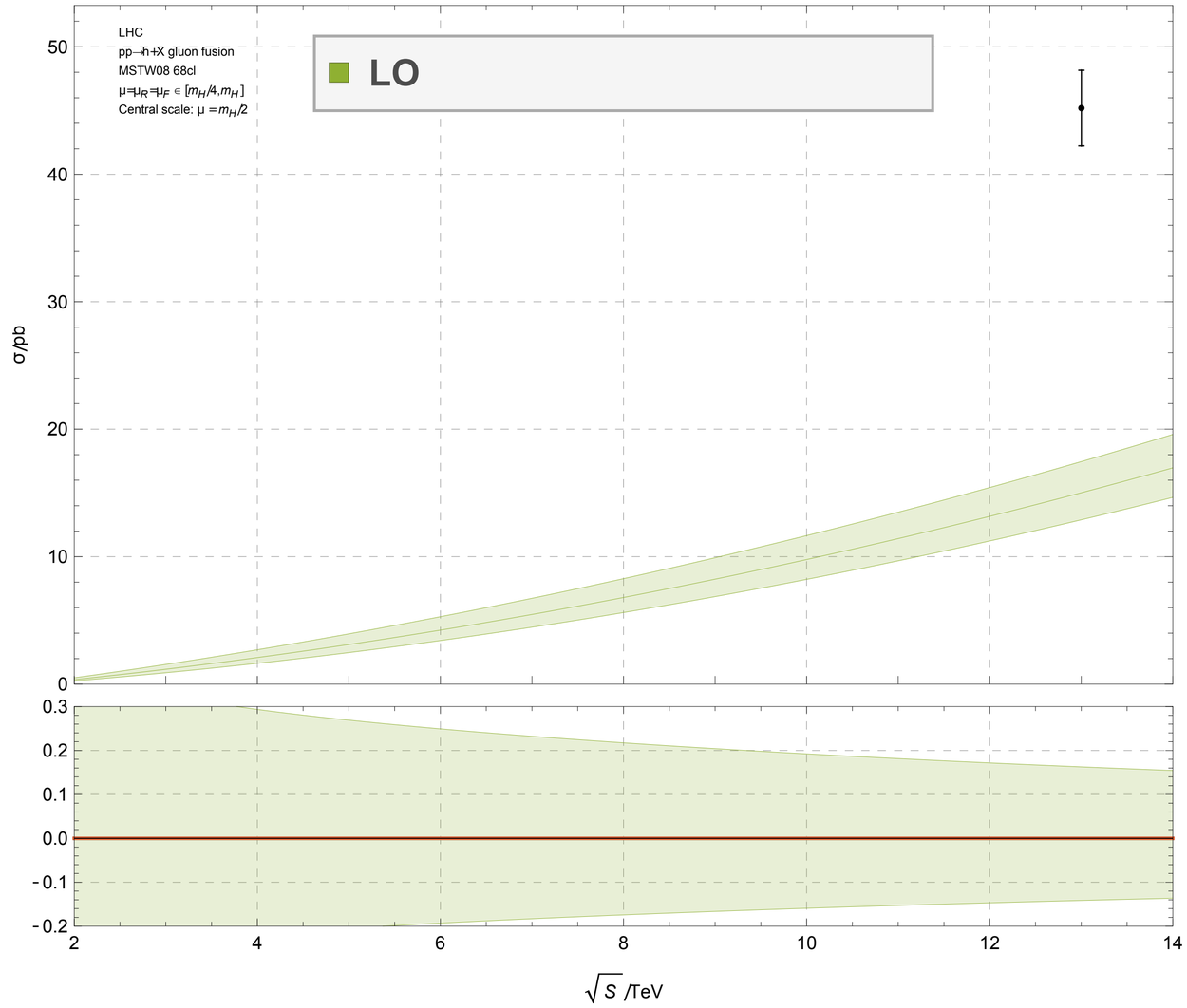
$$f(\tau) = -\frac{1}{4}\left[\log\frac{1+\sqrt{1-\tau}}{1-\sqrt{1-\tau}} - i\pi\right]^2 \qquad \tau < 1$$

Graudenz, Spira, Zerwas 93;

Spira, Djouadi, Graudenz, Zerwas 95;

How Important is Precision?

Let's take ~current experimental results for $gg \to H$ and compare it to this theory prediction



``ATLAS-CONF-2021-053''

Did we just find BSM physics?

Don't panic

*Warning: just a cartoon, don't trust data/theory from this plot!

NLO Corrections

How do we improve the perturbative precision?

$$\sigma(H+X) = \Sigma_{i,j} \int \mathrm{d}x_1 f_i(x_1,\mu_F) \int \mathrm{d}x_2 f_j(x_2,\mu_F) \times \hat{\sigma}_{ij\to H+X}(s, m_H, \mu_F, \mu_R)$$

$$\hat{\sigma}(ij \to H+X) = \hat{\sigma}^{(0)}(ij \to H) + \hat{\sigma}^{(1)}(ij \to H + 0/1 \text{ partons}) + \hat{\sigma}^{(2)}(ij \to H + 0/1/2 \text{ partons}) + \cdots$$

Born α_s^2

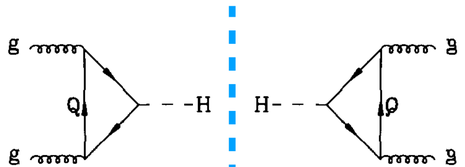
$\hat{\sigma}^{(0)}(ij \to H)$

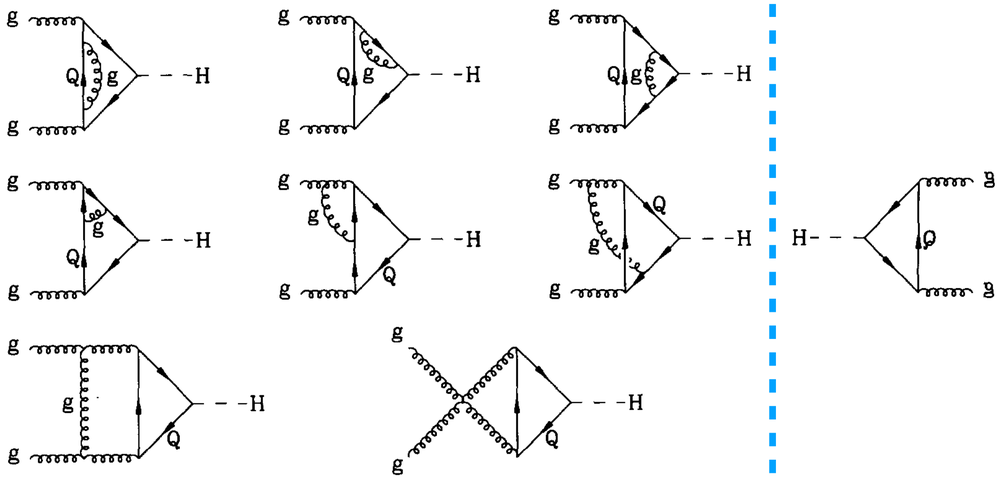
Virtual α_s^3

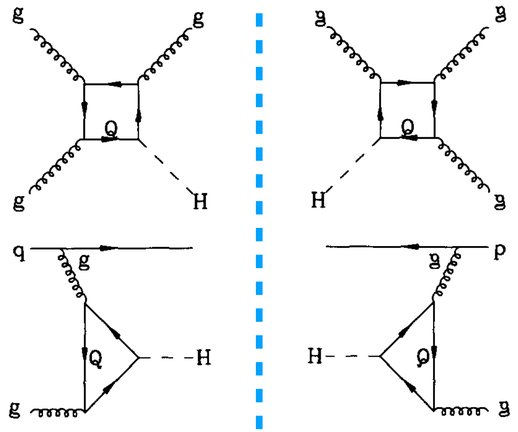
$\hat{\sigma}^{(1)}(ij \to H + 0 \text{ partons})$

Real α_s^3

$\hat{\sigma}^{(1)}(ij \to H + 1 \text{ partons})$





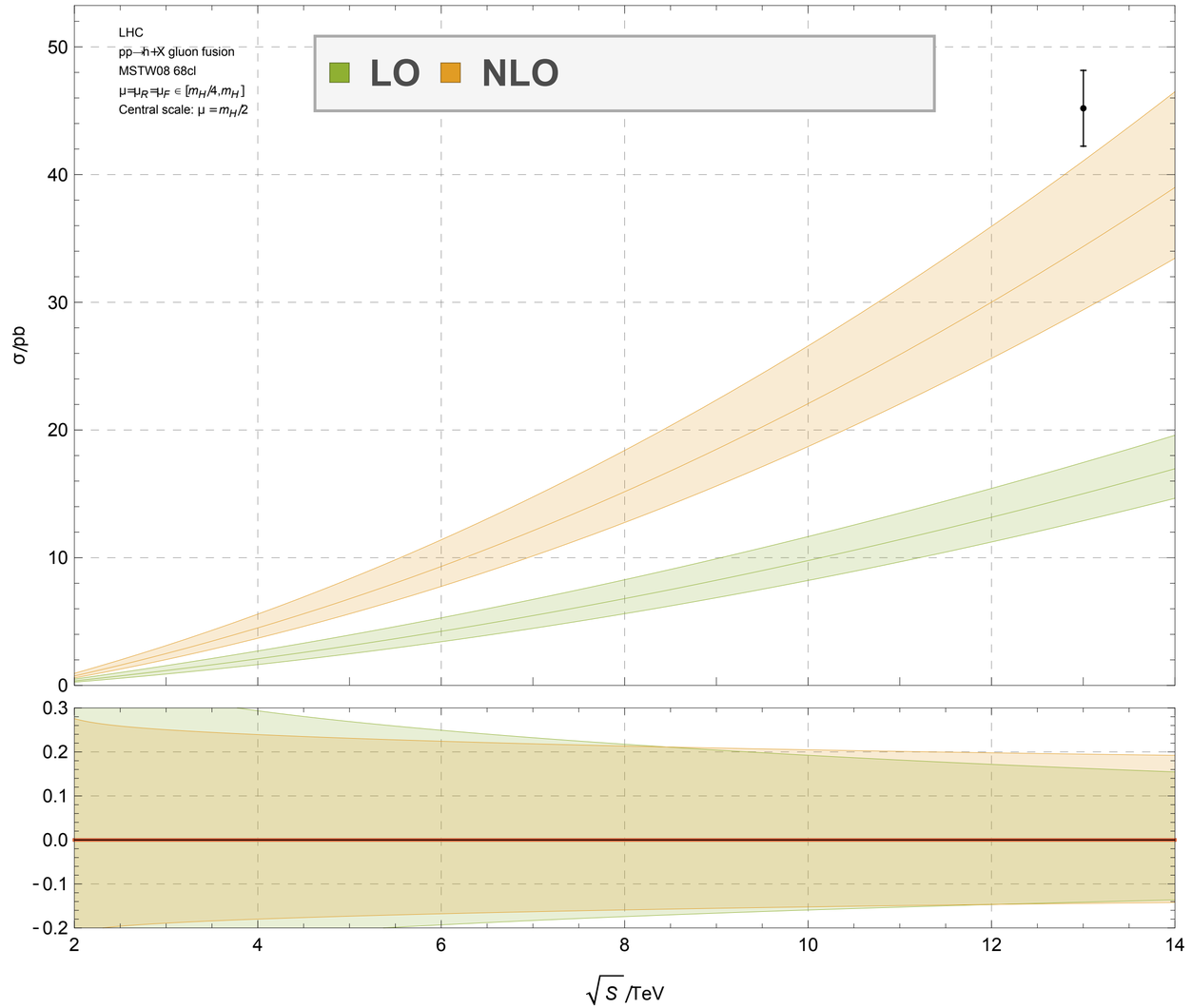


New production channels!

Spira, Djouadi, Graudenz, Zerwas 95;

How Important is Precision?

Imagine we had ~current experimental results for $gg \to H$, but only NLO theory…



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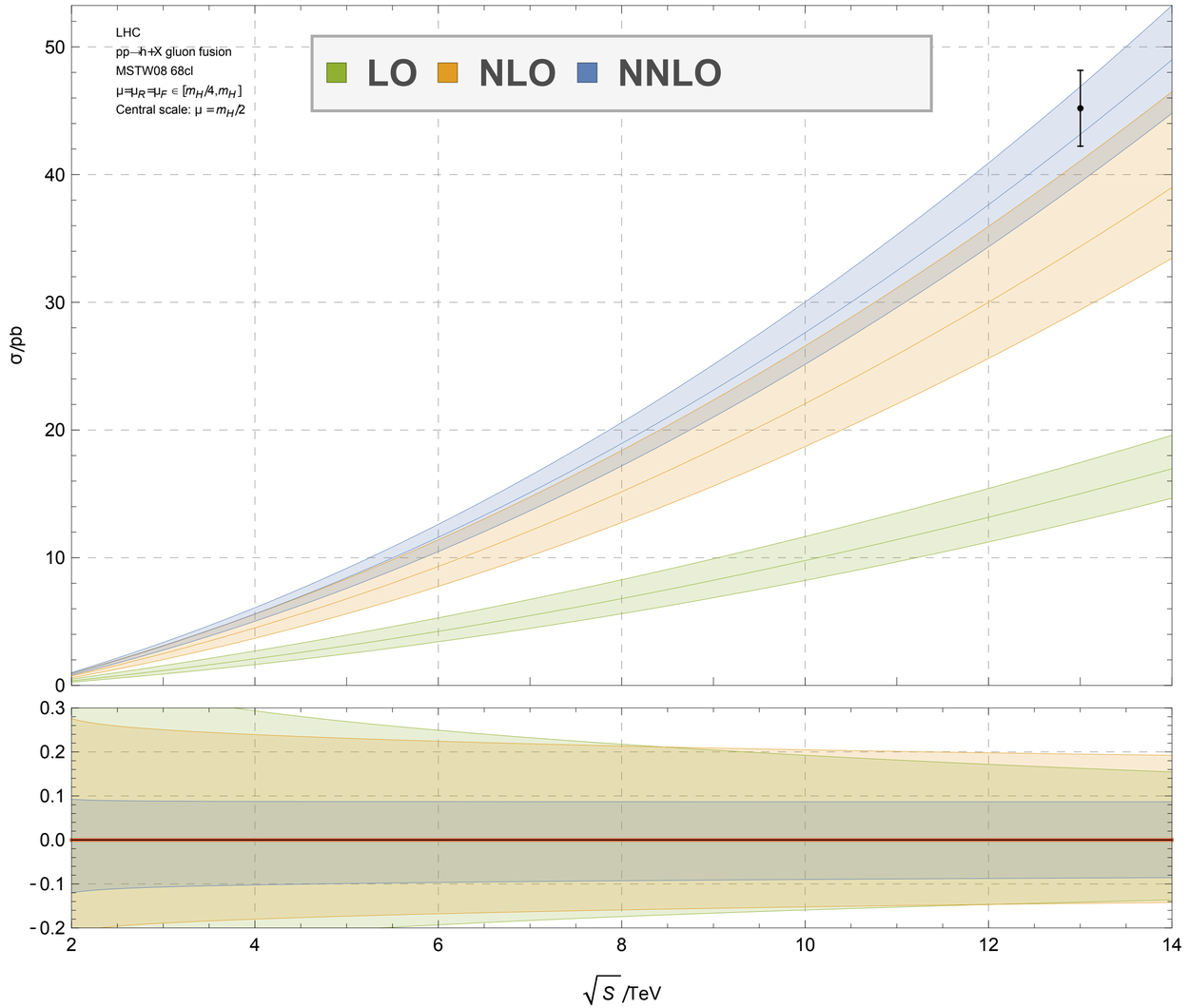
How Important is Precision?

Imagine we had ~current experimental results for $gg \to H$, but only NNLO theory…

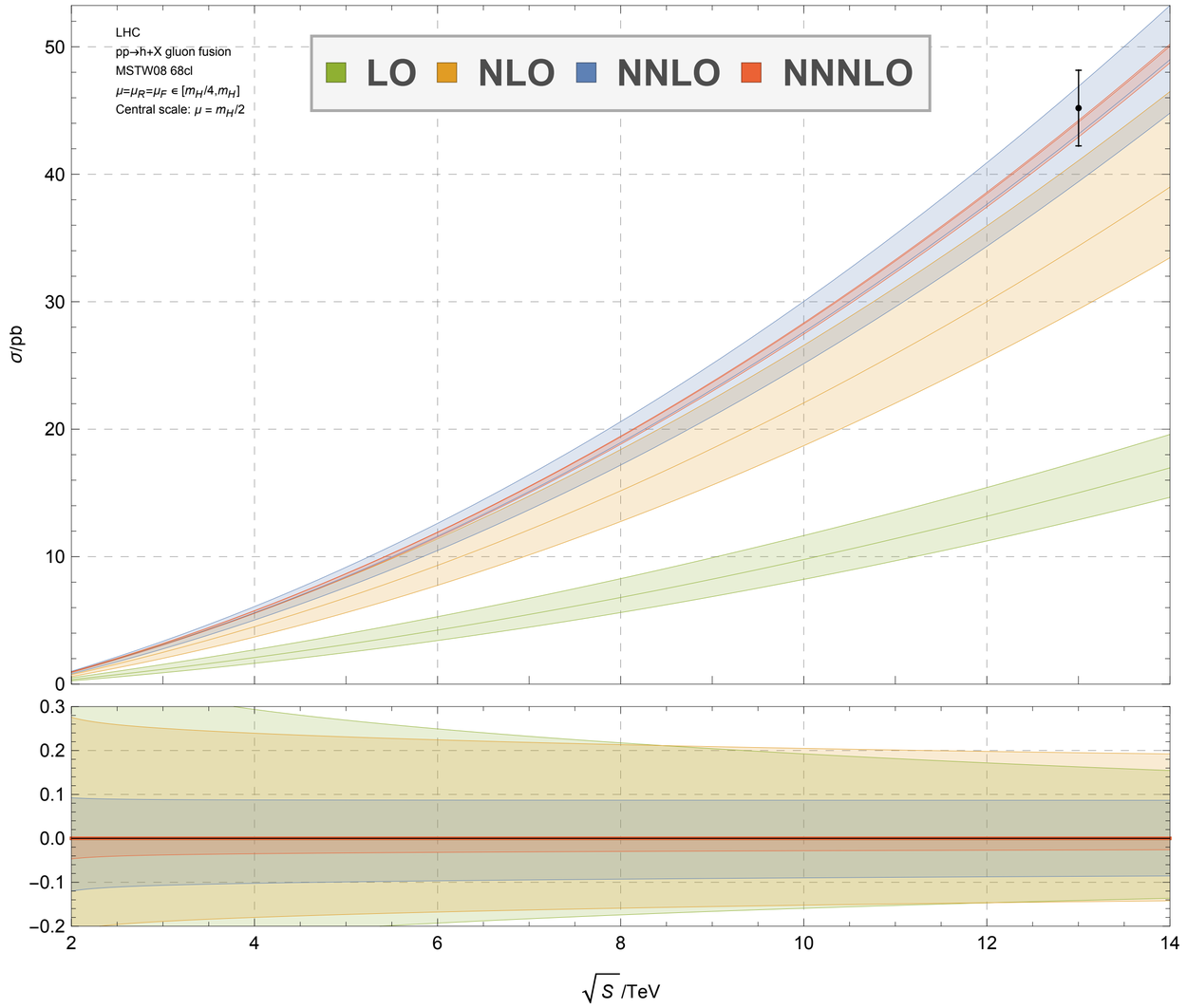


Anastasiou, Melnikov 02;
Harlander, Kilgore 02;
Ravindran, Smith, van Neerven 03;

*Warning: just a cartoon, don't trust data/theory from this plot!

How Important is Precision?

Imagine we had ~current experimental results for $gg \to H$, but only N3LO theory…



Anastasiou, Duhr, Dulat, (Furlan), (Gehrmann), Herzog, Mistlberger 16; Mistlberger 18;

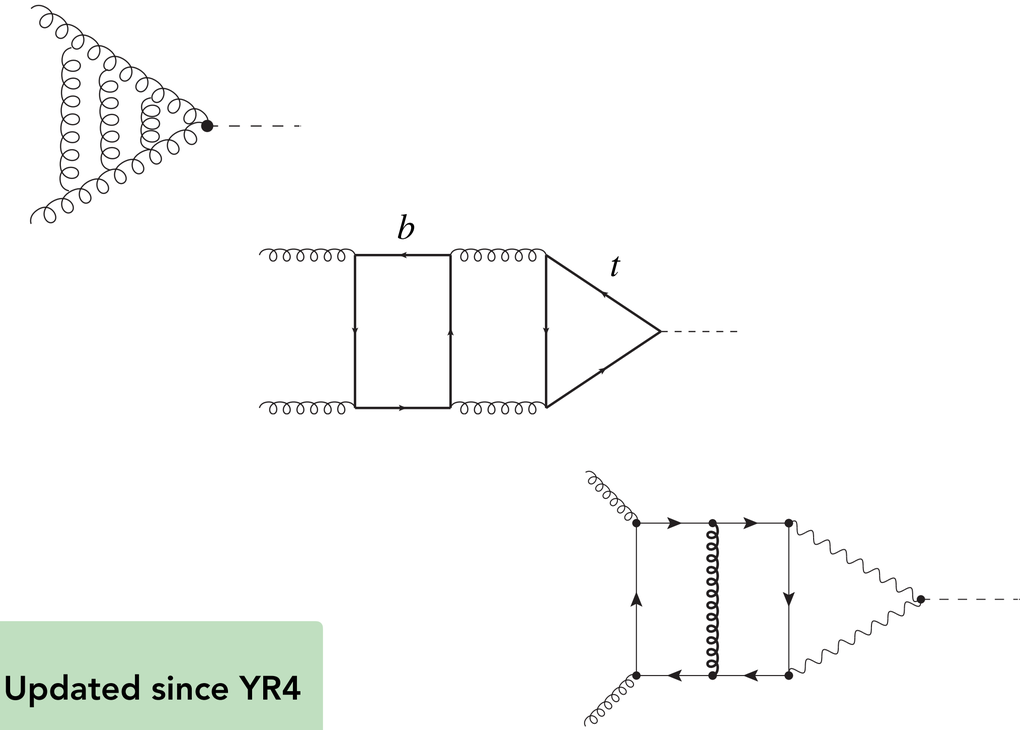
*Warning: just a cartoon, don't trust data/theory from this plot!

Overview of Theory Inputs

Theory uncertainties are much more than just ``scale uncertainties''

LHCHWG ggF (Report 5 Preparation)

Calculations	References
Approximate N^4LO HTL QCD	[1]
N^3LO HTL QCD	[2,3,4]
NNLO HTL QCD	[5,6,7]
NLO HTL QCD	[8,9]
NNLO QCD	[10,11,12,13]
NLO QCD	[14,15]
EW & Mixed QCD-EW Corrections	[16,17,18,19]
N^3LL Threshold Resummation	[20,21]
PDFs	**References**
Approximate N^3LO PDFs	[22,23,24,25]
QED Evolution PDFs	[26,27,28,29,30,31,32]
NNLO PDFs	[33,34,35,36,37]
Codes	**References**
N^3LO QCD	[38]



Updated since YR4

[1] Das, Moch, Vogt 20; [2,3] Anastasiou, Duhr, Dulat, (Furlan, Gehrmann), Herzog, (Lazopoulos), Mistlberger 15, (16); [4] Mistlberger 18; [5] Anastasiou, Melnikov 02; [6] Harlander, Kilgore 02; [7] Ravindran, Smith, van Neerven 03; [8] Dawson 91; [9] Djouadi, Spira, Zerwas 91; [10] Czakon, Niggetiedt 20; [11] Czakon, Harlander, Klappert, Niggetiedt 21; [12,13] Czakon Eschment, Niggetiedt (Poncelet, Schellenberger) 24 (24);[14] Graudenz, Spira, Zerwas 93; [15] Spira Djouadi, Graudenz, Zerwas 95; [16,17] Actis, Passarino, Sturm, Uccirati 08, 09; [18] Aglietti, Bonciani, Degrassi, Vicini 04; [19] Becchetti, Bonciani, Del Duca, Hirschi, Moriello, Schweitzer 21; [20] Bonvini, Marzani 14; [21] Catani, Cieri, de Florian, Ferrera, Grazzini 14; [22] MSHT 22; [23] NNPDF 24; [24] Benchmarking 24; [25] MSHT+NNPDF 25; [26,27] Manohar, Nason, Salam Zanderighi 16, 17; [28,29] NNPDF 18, 24; [30,31] MSHT 19, 22, 24; [32] CTEQ 22; [33] PDF4LHC21; [34] CTEQ 21; [35] MSHT 21; [36] ABM 17; [37] NNPDF 17; [38] iHixs 2 18

Quark Mass Corrections Overview

Main Formula

$$\sigma_{ij} = \mathrm{R}_{\mathrm{LO}} C^2 \left(\sigma_{ij}^{\mathrm{LO,HTL}} + \sigma_{ij}^{\mathrm{NLO,HTL}} + \sigma_{ij}^{\mathrm{NNLO,HTL}} + \sigma_{ij}^{\mathrm{N^3LO,HTL}} \right) + \delta\sigma_{ij}^{\mathrm{LO},(t,b,c)} + \delta\sigma_{ij}^{\mathrm{NLO},(t,b,c)} + \delta\sigma_{ij}^{\mathrm{NNLO},(t,b,c)}$$

Mass Corrections

$$\delta\sigma_{ij}^{\mathrm{N^nLO},(t,b,c)} = \delta\sigma_{ij}^{\mathrm{N^nLO},(t)} + \sigma_{ij}^{\mathrm{N^nLO},(b)} + \sigma_{ij}^{\mathrm{N^nLO},(c)} + \sigma_{ij}^{\mathrm{N^nLO},(t\times b)} + \sigma_{ij}^{\mathrm{N^nLO},(t\times c)} + \sigma_{ij}^{\mathrm{N^nLO},(b\times c)}$$

Dominant Contributions

$$\delta\sigma_{ij}^{\mathrm{N^nLO},(t)} = \sigma_{ij}^{\mathrm{N^nLO},(t)} - \left[C_{\mathrm{QCD}}^2 R_{\mathrm{LO}} \sigma_{ij}^{\mathrm{HTL}} \right]_{\alpha_s^{n+2}},$$

$M_t^{\mathrm{OS}} = 172.5\ \mathrm{GeV}$, $M_b^{\overline{\mathrm{MS}}}(M_b^{\overline{\mathrm{MS}}}) = 4.18\ \mathrm{GeV}$, $M_c^{\overline{\mathrm{MS}}}(3\mathrm{GeV}) = 0.986\ \mathrm{GeV}$

$\sqrt{s} = 13.6\,\mathrm{TeV}$							
	$\sigma^{(t,b,c)}$ [pb]	$\sigma^{(t)}$ [pb]	$\sigma^{(b)}$ [pb]	$\sigma^{(c)}$ [pb]	$\sigma^{(t\times b)}$ [pb]	$\sigma^{(t\times c)}$ [pb]	$\sigma^{(b\times c)}$ [pb]
σ^{LO}	+15.865	+17.115	+0.045	+0.000	−1.172	−0.131	+0.008
σ^{NLO}	+21.358	+22.036	+0.063	+0.001	−0.663	−0.089	+0.012
σ^{NNLO}	—	+10.103	—	—	+0.04	—	—
Total	—	+49.254	—	—	−1.795	—	—

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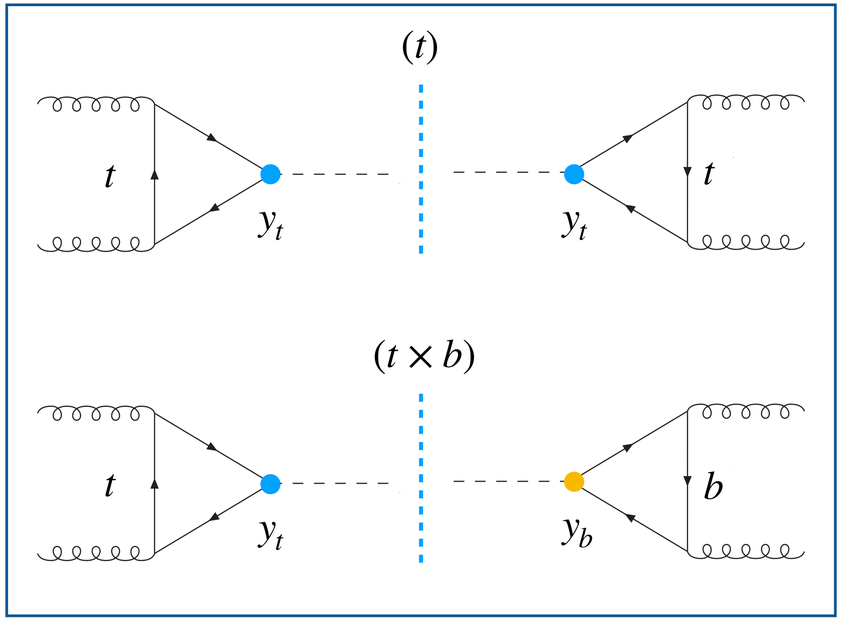
NNLO Numbers: Czakon, Niggetiedt, Harlander, Klappert, Eschment, Poncelet, Schellenberger
Based on: Czakon, Niggetiedt 20; Czakon, Harlander, Klappert, Niggetiedt 21; Czakon Eschment, Niggetiedt (Poncelet, Schellenberger) 24 (24);



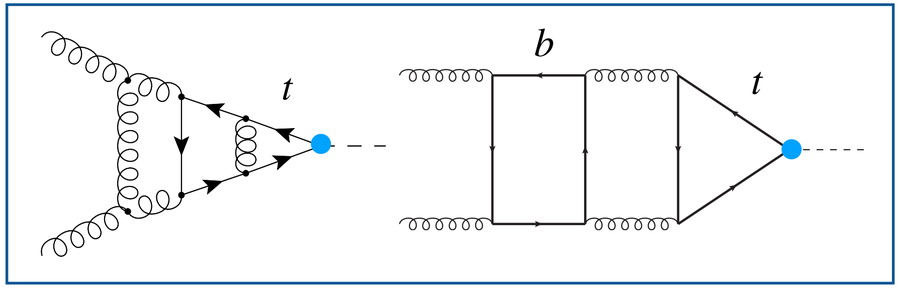
We now estimate missing higher order effects for **all** mass corrections via **scale variations** and **scheme uncertainties**

Top Mass Corrections

$$\delta\sigma_{ij}^{\mathrm{N}^n\mathrm{LO},(t)} = \sigma_{ij}^{\mathrm{N}^n\mathrm{LO},(t)} - \left[C_{\mathrm{QCD}}^2 R_{\mathrm{LO}} \sigma_{ij}^{\mathrm{HTL}}\right]_{\alpha_s^{n+2}},$$

	7 TeV [pb]	8 TeV [pb]	13 TeV [pb]	13.6 TeV [pb]	14 TeV [pb]
$\delta\sigma^{\mathrm{NLO},(t)}$	−0.0630	−0.0907	−0.3108	−0.346	−0.3707
$\delta\sigma^{\mathrm{NNLO},(t)}$	+0.0395(2)	+0.0538(3)	+0.1488(9)	+0.1634(8)	+0.173(1)

LHCHWG Summary Report 26
NNLO Numbers: Czakon, Niggetiedt, Harlander, Klappert, Eschment, Poncelet, Schellenberger



Estimating Residual Uncertainties

Extrapolate NNLO numbers provided from $m_H^{\mathrm{ref}} = 125.09\ \mathrm{GeV}$ to other m_H values using HTL, assign 100% of shift as uncertainty

$$\delta\sigma^{\mathrm{NNLO},(t),\mathrm{ext}}(M_H) = R_4^H(M_H)\ \delta\sigma^{\mathrm{NNLO},(t)}(M_H^{\mathrm{ref}}), \qquad R_n^H(M_H) = \frac{\left[C_{\mathrm{QCD}}^2 \mathrm{R}_{\mathrm{LO}} \sigma_{ij}^{\mathrm{HTL}}\right]_{\alpha_s^n}(M_H)}{\left[C_{\mathrm{QCD}}^2 \mathrm{R}_{\mathrm{LO}} \sigma_{ij}^{\mathrm{HTL}}\right]_{\alpha_s^n}(M_H^{\mathrm{ref}})}$$

$$\delta^{\mathrm{ext}}(t) = \delta\sigma^{\mathrm{NNLO},(t),\mathrm{ext}}(M_H) - \delta\sigma^{\mathrm{NNLO},(t)}(M_H^{\mathrm{ref}}) < 0.07\,\%$$

Estimate MHOU via 7-point scale variation about $\mu_{R,F} = m_H/2$

$$\delta^{\mathrm{MHOU}}(t) = \pm\, 0.17\,\%$$

Estimate Mass Scheme uncertainty by comparing $\overline{\mathrm{MS}}$ and OS for top quark $\delta^{\mathrm{scheme}}(t) = \pm\, 0.01\,\%$

Order	$(\sigma_t^{\overline{\mathrm{MS}}} - \sigma_t^{\mathrm{OS}})$ [pb]
$\sqrt{s} = 13$ TeV	
$\mathcal{O}(\alpha_s^2)$	-0.04
LO	$-0.04^{+0.12}_{-0.17}$
$\mathcal{O}(\alpha_s^3)$	$+0.02$
NLO	$-0.02^{+0.14}_{-0.30}$
$\mathcal{O}(\alpha_s^4)$	$+0.01$
NNLO	$-0.01^{+0.12}_{-0.24}$

Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 23, 24

Top-Bottom Interference

NNLO corrections for top-bottom interference contribution are small for $M_b^{\overline{\text{MS}}}$

	7 TeV [pb]	8 TeV [pb]	13 TeV [pb]	13.6 TeV [pb]	14 TeV [pb]
$\sigma^{\text{LO},(t\times b)}$	−0.39	−0.50	−1.09	−1.17	−1.22
$\sigma^{\text{NLO},(t\times b)}$	−0.27	−0.32	−0.63	−0.66	−0.69
$\sigma^{\text{NNLO},(t\times b)}$	−0.02	−0.02	+0.02	+0.04	+0.03
Total	−0.68	−0.84	−1.70	−1.80	−1.88

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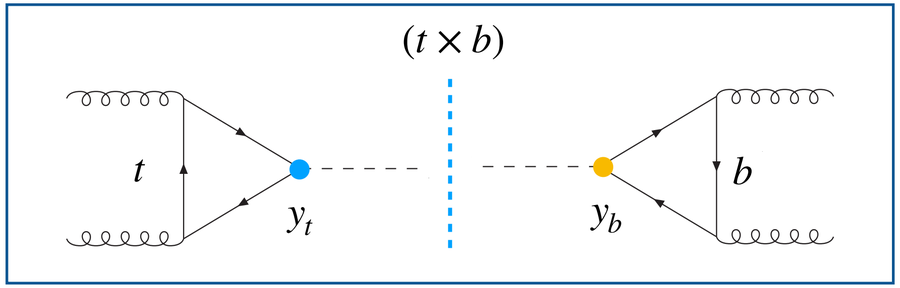
NNLO Numbers: Czakon, Niggetiedt, Harlander, Klappert, Eschment, Poncelet, Schellenberger



Estimating Residual Uncertainties

Extrapolation to different values of M_H gives negligible uncertainty

$$\delta\sigma^{\text{NNLO},(t\times b),\text{ext}}(M_H) = R_4^H(M_H)\ \delta\sigma^{\text{NNLO},(t\times b)}(M_H^{\text{ref}}) < 0.06\,\%$$

Estimate MHOU via 7-point scale variation about $\mu_{R,F} = m_H/2$

$$\delta^{\text{MHOU}}(t\times b) = \pm 0.17\,\%$$

Perturbative corrections for M_b^{OS} appear to converge poorly

We estimate **scheme uncertainty** using 5FS vs 4FS with $M_b^{\overline{\text{MS}}}$

$$\delta^{\text{scheme}}(t\times b) = \pm 0.09\,\% \quad (\delta^{\text{scheme}}(t\times b) = \pm 0.26\,\% \text{ for } \overline{\text{MS}}/OS)$$

Order	$\sigma_{t\times b}$ [pb]			
	$\sqrt{s} = 13$ TeV			
	5FS $m_t = 173.06$ GeV $\overline{m}_b(\overline{m}_b) = 4.18$ GeV	5FS $m_t = 173.06$ GeV $m_b = 4.78$ GeV	5FS $m_t(m_t) = 162.7$ GeV $\overline{m}_b(\overline{m}_b) = 4.18$ GeV	4FS $m_t = 173.06$ GeV $\overline{m}_b(\overline{m}_b) = 4.18$ GeV
$\mathcal{O}(\alpha_s^2)$	-1.11	-1.98	-1.12	-1.15
LO	$-1.11^{+0.28}_{-0.43}$	$-1.98^{+0.38}_{-0.53}$	$-1.12^{+0.28}_{-0.42}$	$-1.15^{+0.29}_{-0.45}$
$\mathcal{O}(\alpha_s^3)$	-0.65	-0.44	-0.64	-0.66
NLO	$-1.76^{+0.27}_{-0.28}$	$-2.42^{+0.19}_{-0.12}$	$-1.76^{+0.27}_{-0.28}$	$-1.81^{+0.28}_{-0.30}$
$\mathcal{O}(\alpha_s^4)$	$+0.02$	$+0.43$	-0.02	-0.02
NNLO	$-1.74(2)^{+0.13}_{-0.03}$	$-1.99(2)^{+0.29}_{-0.15}$	$-1.78(1)^{+0.15}_{-0.03}$	$-1.83(2)^{+0.14}_{-0.03}$

Czakon, Eschment, Niggetiedt, Poncelet, Schellenberger 23, 24

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Final result receives contributions from many sources, uncertainties related to finite masses greatly reduced from ~2% -> 0.3%

$$\delta(\text{theory}) = \delta(\text{scale}) + \delta(\text{EWK}) + \delta(t,b,c)$$
$$\delta(t,b,c) = \delta^{\text{scheme}}(t) + \delta^{\text{MHOU}}(t) + \delta^{\text{scheme}}(t\times b) + \delta^{\text{MHOU}}(t\times b) + \delta^{\text{MHOU}}(b,c,t\times c, b\times c)$$

$\pm 0.01\,\%$ $\pm 0.17\,\%$ $\pm 0.09\,\%$ $\pm 0.17\,\%$ $\pm 0.06\,\%$

$$\delta(\text{PDF}+\alpha_s) = \sqrt{\delta(\text{PDF})^2 + \delta(\alpha_s)^2}$$

$$\delta(\text{PDF}-\text{TH}) = \pm\,|\,\sigma^{(2),\text{HTL,NNLO}} - \sigma^{(2),\text{HTL,NLO}}\,|$$

NNLO PDF: PDF4LHC21
aN^{3}LO PDF: MSHT20xNNPDF40

Table 4: Total ggH cross sections in the SM for a LHC CM energy of $\sqrt{s} = 13.6\,\text{TeV}$.

$\sqrt{s} = 13.6\,\text{TeV}$						NNLO PDF				aN^{3}LO PDF				
M_H [GeV]	σ [pb]	δ(theory)	δ(scale)	δ(EWK)	δ(t, b, c)	$\delta(\text{PDF}+\alpha_s)$	δ(PDF)	$\delta(\alpha_s)$	δ(PDF–TH)	Δ [pb]	$\delta(\text{PDF}+\alpha_s)$	δ(Gauss)	δ(Total)	δ(Total(Gauss))
120.00	55.54	$^{+1.65}_{-4.66}\,\%$	$^{+0.31}_{-3.32}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.48\%$	$^{+1.65}_{-1.65}\,\%$	$\pm 1.85\%$	$\pm 2.42\%$	-2.56	$^{+1.73}_{-1.73}\,\%$	$\pm 4.09\%$	$^{+4.76}_{-7.50}\,\%$	$\pm 4.78\%$
122.00	53.97	$^{+1.66}_{-4.65}\,\%$	$^{+0.32}_{-3.31}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.47\%$	$^{+1.65}_{-1.65}\,\%$	$\pm 1.84\%$	$\pm 2.40\%$	-2.49	$^{+1.73}_{-1.73}\,\%$	$\pm 4.07\%$	$^{+4.75}_{-7.47}\,\%$	$\pm 4.76\%$
124.00	52.46	$^{+1.65}_{-4.65}\,\%$	$^{+0.31}_{-3.31}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.84\%$	$\pm 2.37\%$	-2.43	$^{+1.74}_{-1.74}\,\%$	$\pm 4.05\%$	$^{+4.71}_{-7.44}\,\%$	$\pm 4.74\%$
124.60	52.02	$^{+1.65}_{-4.65}\,\%$	$^{+0.31}_{-3.31}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.84\%$	$\pm 2.36\%$	-2.41	$^{+1.74}_{-1.74}\,\%$	$\pm 4.05\%$	$^{+4.70}_{-7.43}\,\%$	$\pm 4.74\%$
124.80	51.87	$^{+1.65}_{-4.65}\,\%$	$^{+0.31}_{-3.31}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.83\%$	$\pm 2.36\%$	-2.41	$^{+1.74}_{-1.74}\,\%$	$\pm 4.05\%$	$^{+4.70}_{-7.43}\,\%$	$\pm 4.73\%$
125.00	51.72	$^{+1.65}_{-4.65}\,\%$	$^{+0.31}_{-3.31}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.83\%$	$\pm 2.36\%$	-2.40	$^{+1.74}_{-1.74}\,\%$	$\pm 4.05\%$	$^{+4.70}_{-7.43}\,\%$	$\pm 4.73\%$
125.09	51.66	$^{+1.65}_{-4.65}\,\%$	$^{+0.31}_{-3.31}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.83\%$	$\pm 2.36\%$	-2.40	$^{+1.74}_{-1.74}\,\%$	$\pm 4.05\%$	$^{+4.70}_{-7.43}\,\%$	$\pm 4.73\%$
125.20	51.58	$^{+1.65}_{-4.65}\,\%$	$^{+0.31}_{-3.31}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.83\%$	$\pm 2.35\%$	-2.39	$^{+1.74}_{-1.74}\,\%$	$\pm 4.04\%$	$^{+4.69}_{-7.42}\,\%$	$\pm 4.73\%$
125.30	51.51	$^{+1.65}_{-4.64}\,\%$	$^{+0.31}_{-3.30}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.83\%$	$\pm 2.35\%$	-2.39	$^{+1.74}_{-1.74}\,\%$	$\pm 4.04\%$	$^{+4.69}_{-7.41}\,\%$	$\pm 4.72\%$
125.38	51.45	$^{+1.65}_{-4.64}\,\%$	$^{+0.31}_{-3.30}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.83\%$	$\pm 2.35\%$	-2.39	$^{+1.74}_{-1.74}\,\%$	$\pm 4.04\%$	$^{+4.69}_{-7.41}\,\%$	$\pm 4.72\%$
125.60	51.29	$^{+1.65}_{-4.64}\,\%$	$^{+0.31}_{-3.30}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.83\%$	$\pm 2.35\%$	-2.38	$^{+1.74}_{-1.74}\,\%$	$\pm 4.04\%$	$^{+4.69}_{-7.41}\,\%$	$\pm 4.72\%$
126.00	51.01	$^{+1.65}_{-4.64}\,\%$	$^{+0.31}_{-3.30}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.46\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.83\%$	$\pm 2.34\%$	-2.37	$^{+1.74}_{-1.74}\,\%$	$\pm 4.03\%$	$^{+4.69}_{-7.40}\,\%$	$\pm 4.72\%$
128.00	49.62	$^{+1.64}_{-4.63}\,\%$	$^{+0.30}_{-3.29}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.45\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.83\%$	$\pm 2.32\%$	-2.31	$^{+1.74}_{-1.74}\,\%$	$\pm 4.01\%$	$^{+4.66}_{-7.37}\,\%$	$\pm 4.70\%$
130.00	48.28	$^{+1.64}_{-4.62}\,\%$	$^{+0.30}_{-3.28}\,\%$	$\pm 1.00\%$	$\pm 0.34\%$	$\pm 2.45\%$	$^{+1.64}_{-1.64}\,\%$	$\pm 1.82\%$	$\pm 2.30\%$	-2.25	$^{+1.74}_{-1.74}\,\%$	$\pm 4.00\%$	$^{+4.64}_{-7.34}\,\%$	$\pm 4.69\%$

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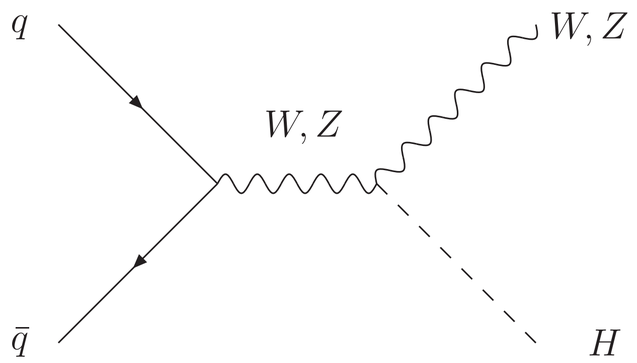
$$\delta(\text{Gauss}) = \left(\max[\,|\,\delta(\text{theory})\,|\,] + \delta(+\text{PDF}-\text{TH})\right]/\sqrt{3}, \quad \delta(\text{Total}) = \sqrt{(\delta(\text{theory}) + \delta(\text{PDF}-\text{TH}))^2 + \delta(\text{PDF}+\alpha_s)^2}, \quad \delta(\text{Total(Gauss)}) = \sqrt{\delta(\text{Gauss})^2 + \delta(\text{PDF}+\alpha_s)^2}$$

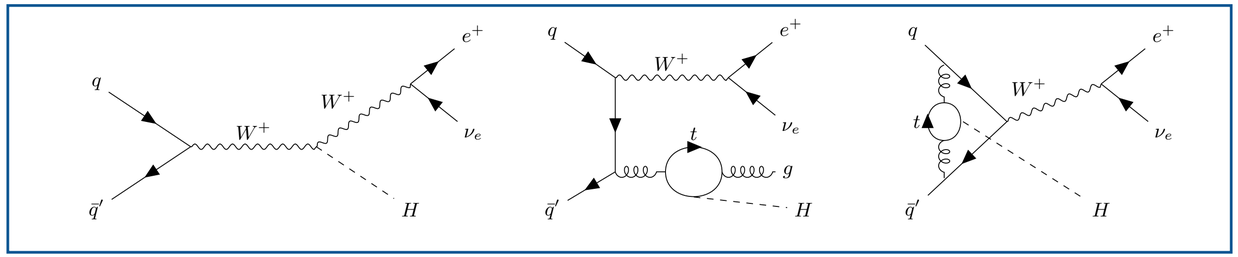
Higgs Production: W/Z Associated Production



HW Associated Production

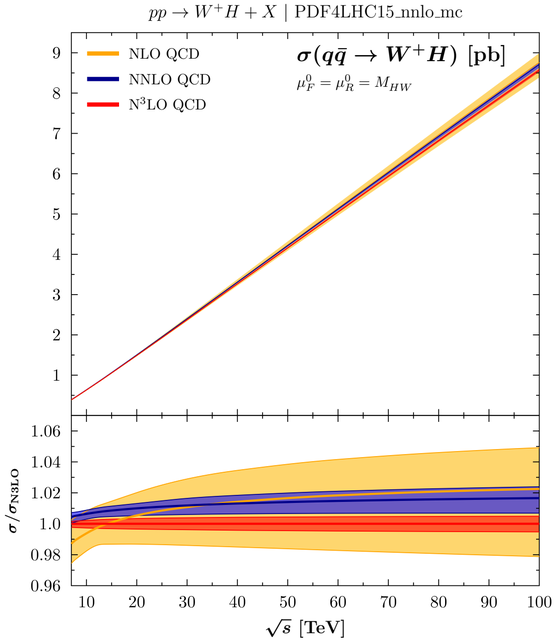
Fully differentially at N3LO were recently computed

(Inclusive) Baglio, Duhr, Mistlberger, Szafron 22
Gehrmann-De Ridder, Huss, Marcoli, Monni, Re, Rottoli, Silvetti, Torrielli 26;



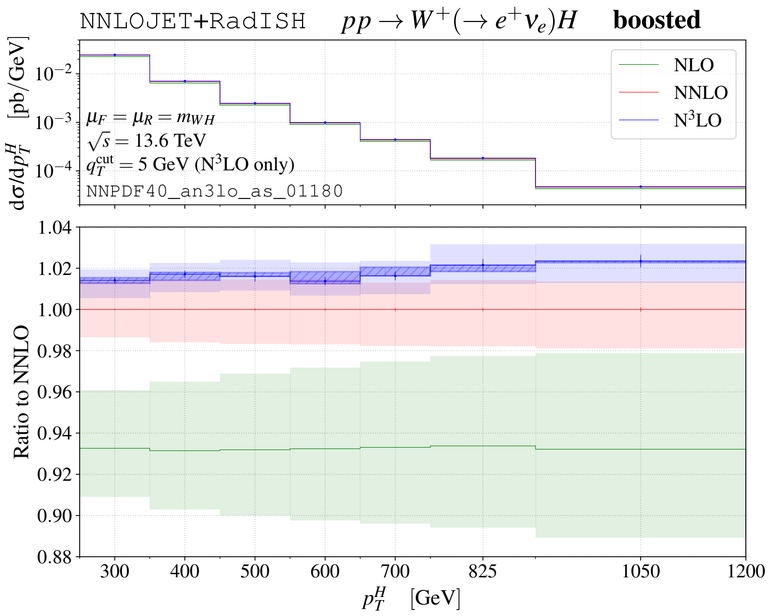
Inclusive

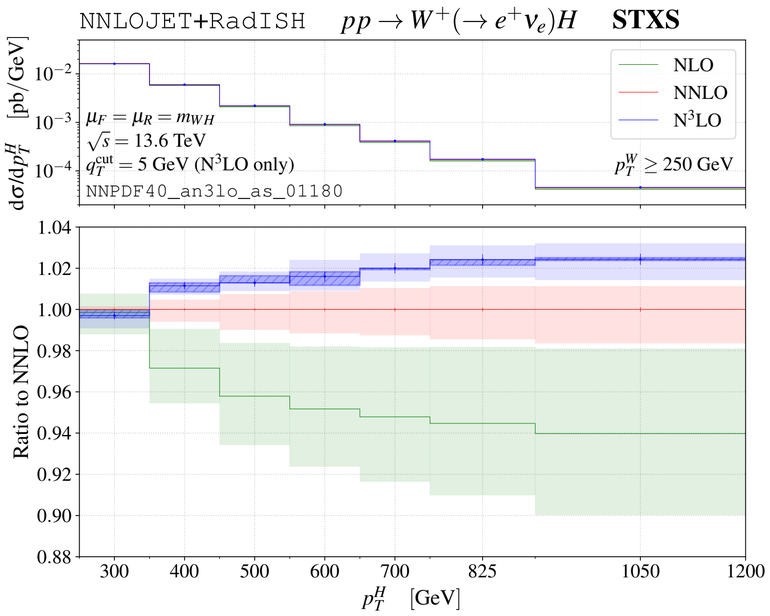
-0.9 % for W^+H total cross section



Fiducial Cuts

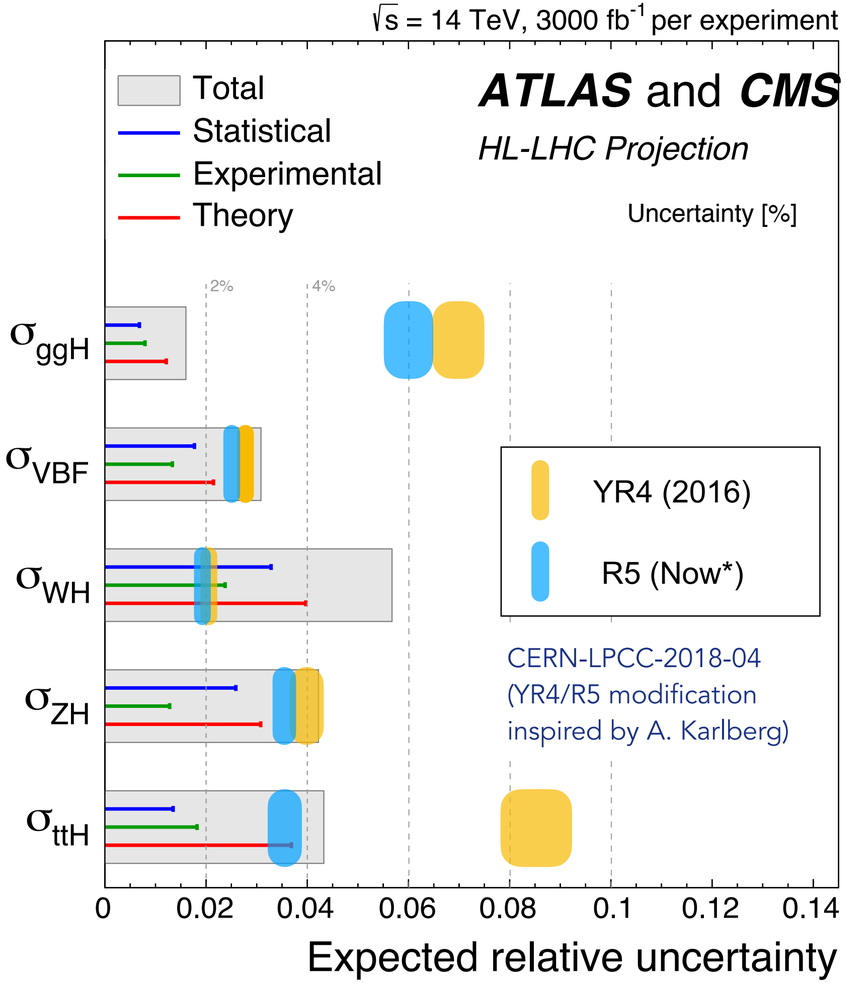
+1-2% in the boosted setup, not a flat correction with respect to NNLO





Highlights the importance of having fiducial measurements and fully differential predictions

Higgs Working Group



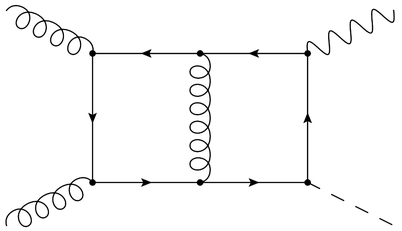
Community effort to stimulate TH and encourage EXP/TH communication

ggH: heavy-top @ $\mathrm{N^3LO}$ + finite quark mass effects @ NNLO

Mistlberger 18; Czakon, Niggetiedt 20; Czakon, Harlander, Klappert, Niggetiedt 21; Czakon Eschment, Niggetiedt (Poncelet, Schellenberger) 24 (24);

ZH: $gg \to ZH$ @ NLO

Aveleira, Chen, Davies, Degrassi, Giardino, Gröber, Heinrich, SPJ, Kerner, Schlenk, Steinhauser, Vitti 25



$t\bar{t}H$: approximate $t\bar{t}H$ @ NNLO

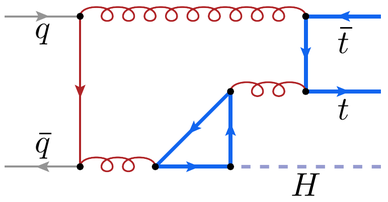
Catani, Devoto, Grazzini, Kallweit, Mazzitelli, Savoini 22; Wang, Xia, Lin Yang, Ye 24

Ongoing efforts to compute missing corrections

Febres Cordero, Figueiredo, Kraus, Page, Reina 23

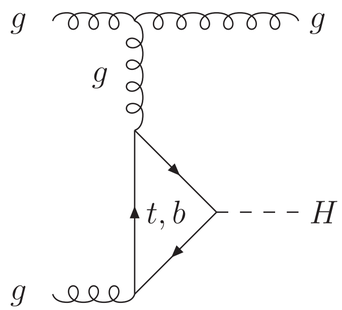
Agarwal, Heinrich, SPJ, Kerner, Klein, Lang, Magerya, Olsson 24

Chen, Grazzini, Kallweit (HP2 2026 Talk)



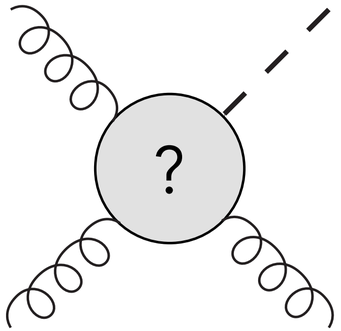
This glosses over the (perhaps) more interesting differential measurements which allow us to probe higher energies

Boosted Higgs



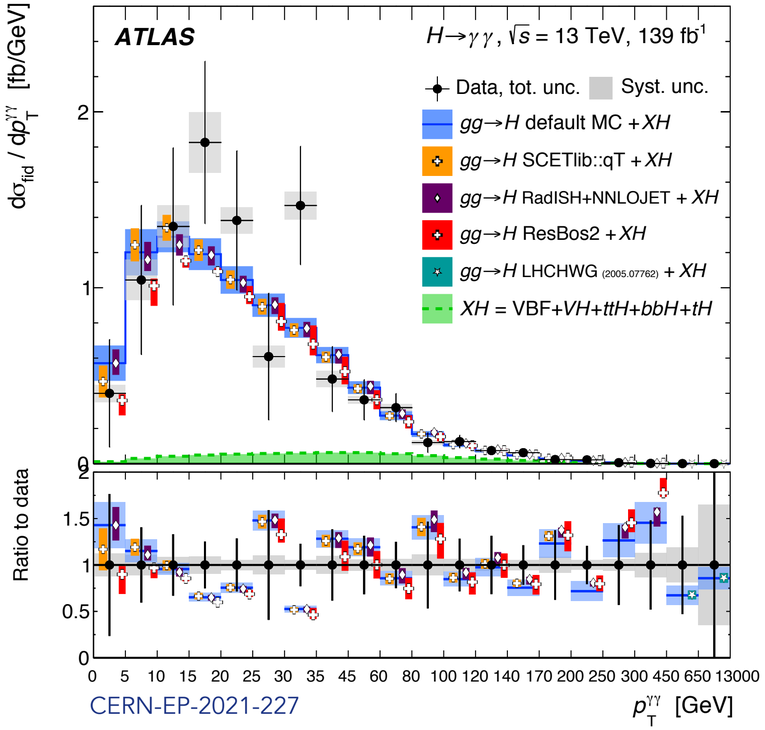
Boosted Higgs

Why might we want to study boosted (high-p_T) Higgs production?

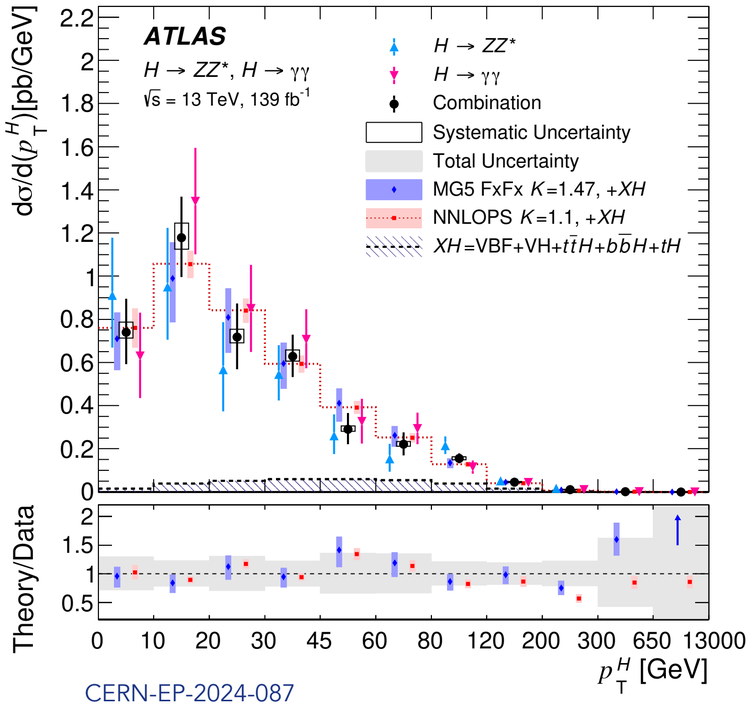


At moderate/large pT:

- Particles in the loop can be resolved
- May disentangle modified top quark Yukawa coupling from (BSM) point-like ggH coupling
- As we cross the top threshold, top mass becomes important!



CERN-EP-2021-227



CERN-EP-2024-087

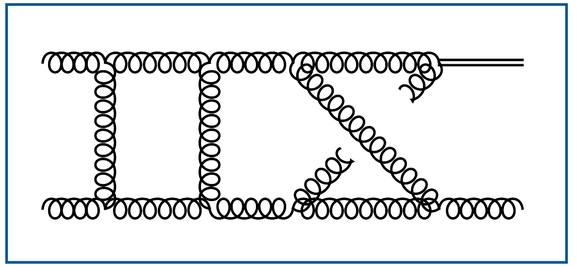
Higgs + Jet @ $\mathrm{N^3LO_{HTL}}$

For $p_{T,H} \lesssim m_T$, work in the Heavy Top Limit (HTL)

$$\mathcal{L}_{eff} = \mathcal{L}_{SM,5} - \frac{C^0}{4} H G_a^{\mu\nu} G_{a,\mu\nu}$$



HTL valid for $\sqrt{s_{12}} \ll 2m_T$



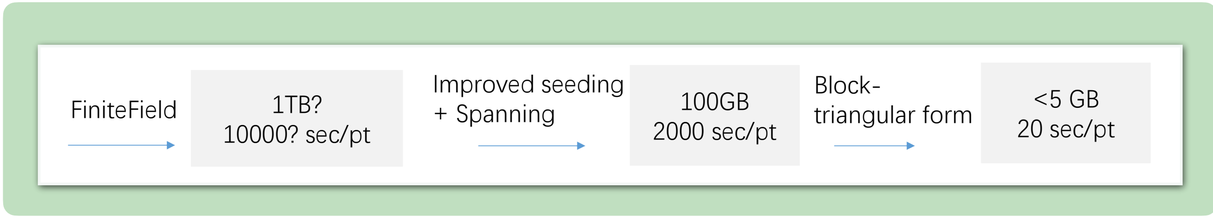
Chen, Guan, Mistlberger 25

Guan, Mistlberger, Ruf 26

Mistlberger, Suresh 25

Virtual amplitudes for Higgs + Jet @ 3 Loop

Generalised leading colour $\{N_c^6, N_c^5 n_f, N_c^4 n_f^2, N_c^3 n_f^3\}$



Guan (QCD@LHC 2025)

Reduction

Very challenging calculation involving difficult IBP reduction

Blade (+improved seeding → seed with different ranks in different sectors)

Guan, Liu, Ma, Wu 24; Liu, Ma 18; Guan, Liu, Ma 20; Driesse, Jakobsen, Mogull, Plefka, Sauer, Usovitsch 24

Master Integrals

3-loop massless + one off-shell leg

Planar + non-planar result expressed in terms of GPLs

Vita, Mastrolia, Schubert, Yundin 14
Canko, Syrrakos 21, 23
Henn, Lim, Torres Bobadilla 23
Gehrmann, Henn, Jakubcik, Lim, Mella, Syrrakos, Tancredi, Torres Bobadilla 24

Higgs + 2 Jets @ $\mathrm{NNLO_{HTL}}$

Relevant ingredient for full H + Jet @ $\mathrm{N^3LO_{HTL}}$

Irreducible background to Higgs VBF process

Sensitive probe of CP nature of the top Yukawa coupling

Background to $HH(\to b\bar{b})$

Virtual amplitudes for Higgs + 2 Jets @ 2 Loop

Generalised leading colour ($N_f \sim N_c$)

Reduction

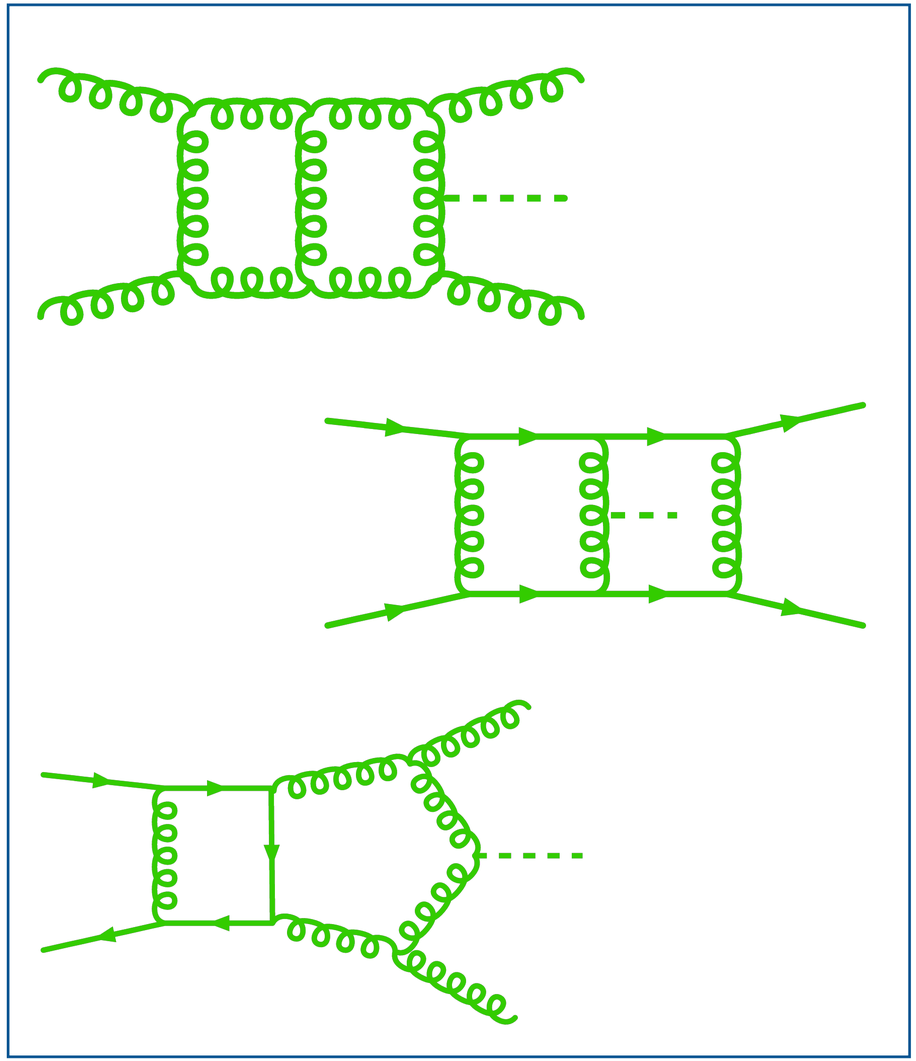
Cutting edge calculation: 6 scales, non-planar, high-rank integrals

Clever use of integrand ansatz to reconstruct result

Ita 15; Abreu, Dormans, Febres Cordero, Ita, Page 18; Abreu, Dormans, Febres Cordero, Ita, Kraus, Page, Pascual, Ruf, Sotnikov 20;

Incredibly compact result → much easier to understand structure

De Laurentis, Page 22; Abreu, De Laurentis, Ita, Klinkert, Page, Sotnikov 23; De Laurentis, Ita, Page, Sotnikov 25;

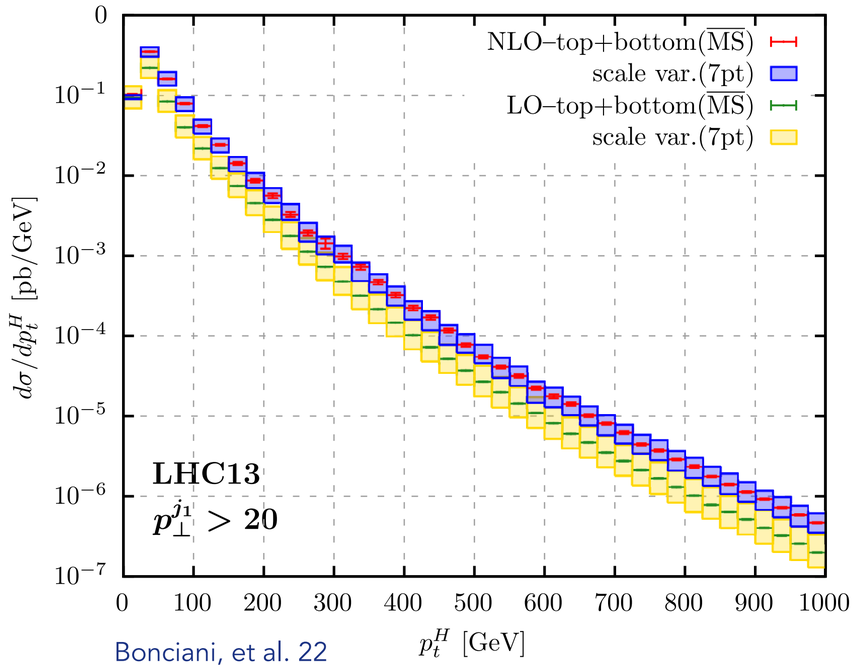


De Laurentis, Ita, Kuschke, Ruf, Sotnikov 26; Figure: Viktor Kuschke (HP2 2026)

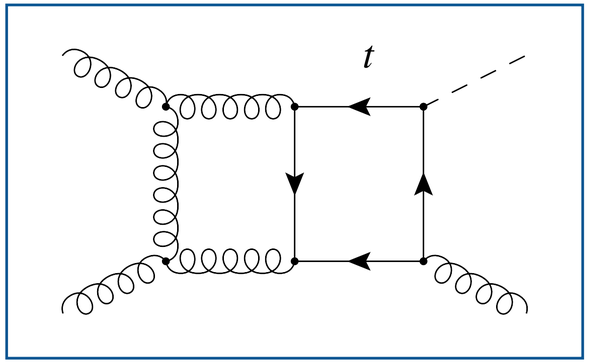
Boosted Higgs: NLO H+j

HTL not valid for $p_T \gtrsim m_t$: (b,t)-quark mass effects known for H+j at NLO

Bonciani, Del Duca, Frellesvig, Hidding, Hirschi, Moriello, Salvatori, Somogyi, Tramontano 22; Kudashkin, Melnikov, Wever, Lindert/ Neumann/ Chen, Huss, SPJ, Kerner, Lang, Luisoni, Zhang 18-21



Bonciani, et al. 22



renormalisation of internal masses	$\sigma_{\rm LO}$ [pb]	$\sigma_{\rm NLO}$ [pb]
top+bottom–($\overline{\rm MS}$)	$12.318^{+4.711}_{-3.117}$	$19.89(8)^{+2.84}_{-3.19}$
top–($\overline{\rm MS}$)	$12.538^{+4.822}_{-3.183}$	$19.90(8)^{+2.66}_{-2.85}$
top–(OS)	$12.551^{+4.933}_{-3.244}$	$20.22(8)^{+3.06}_{-3.09}$

Full NLO Result

Enhances cross-section by ~1.6x

Significantly reduces scale uncertainty

Top quark mass scheme uncertainty reduced but comparable to scale uncertainty

Higgs + Jet @ $\mathrm{NLO_{EW}}$

Two independent calculations of EW corrections to HJ

Kira + Fire + Blade → 3600 Master Integrals

Klappert, Lange, Maierhöfer, Usovitsch 08; Smirnov 15; Guan, Liu, Ma, Wu 24;

Find basis with d and invariants factorising & at most linear in d

Boundary conditions for master integrals using AMFlow — Liu, Ma, Wang 18; Liu, Ma 23;

Solve differential equations numerically

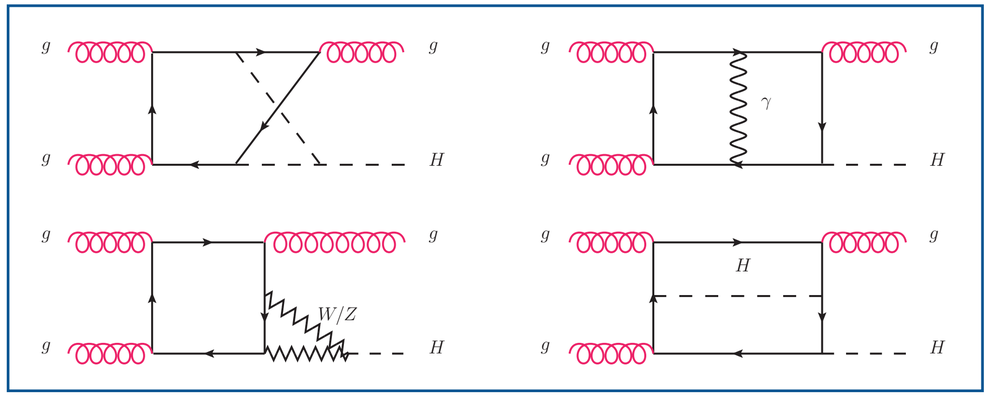
Chen, Li, Sang 25

Blade + FiniteFlow fixing ϵ numerically Peraro 19

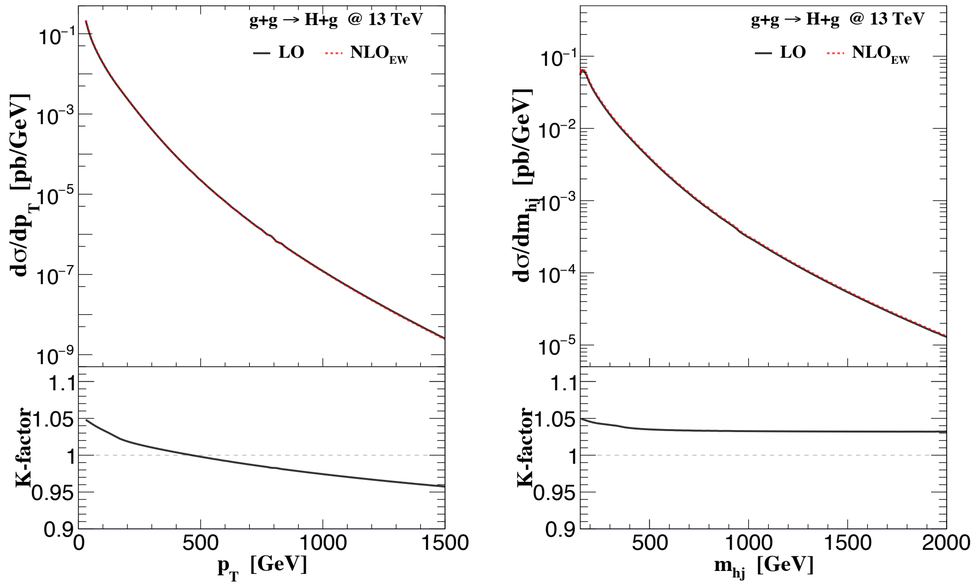
Compute master integrals using AMFlow

Bi, Ma, Mu 25

Both groups find that the EW corrections enhance the cross-section by around 4-5%, K-factor depends on p_T



Bi, Ma, Mu 25; Chen, Li, Sang 25;

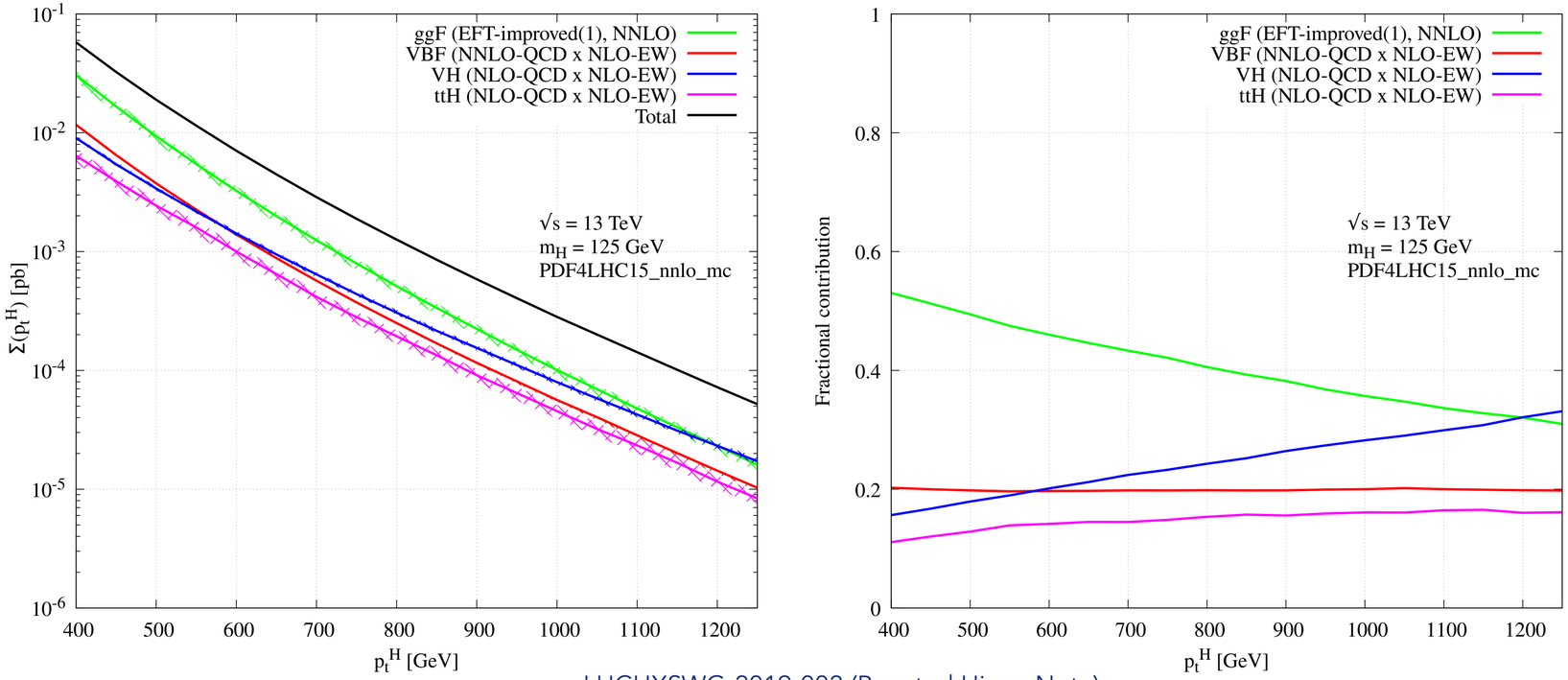


Chen, Li, Sang 25;

Boosted Higgs Contamination

Complicated interplay of channels relevant for high-p_T^H predictions

Fractional contribution of VBF approximately constant with p_T^H
+ ggF contamination decreases for boosted H
+ VH contamination increases for boosted H



LHCHXSWG-2019-002 (Boosted Higgs Note)

Future update on boosted Higgs requires input from several working groups

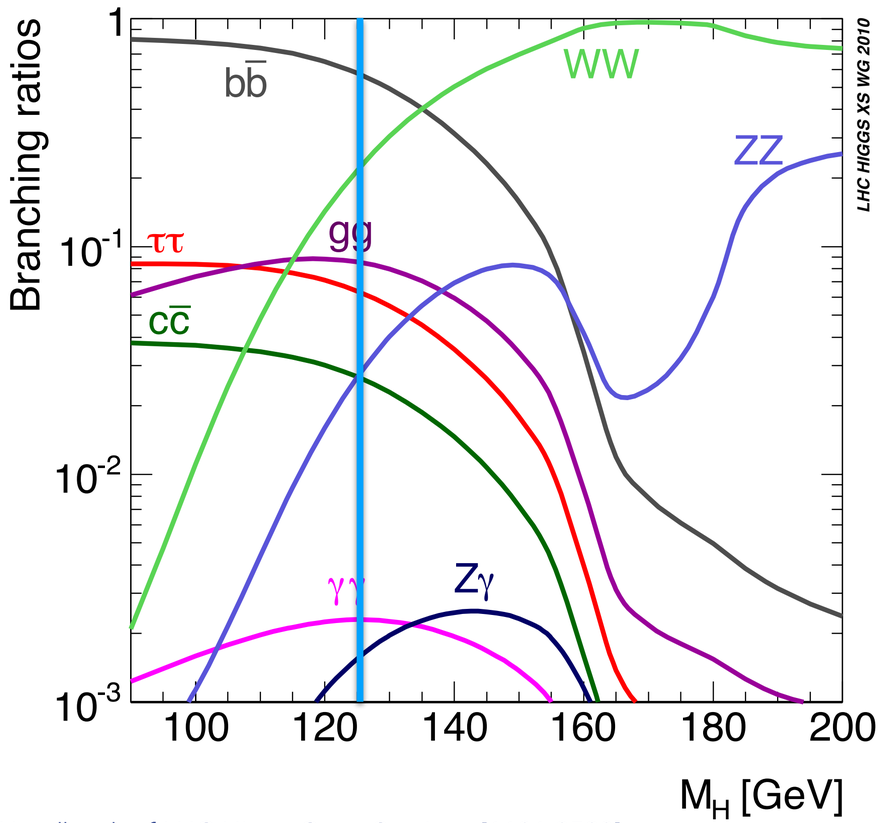
Kick-off Meeting (24.09.26): https://indico.cern.ch/event/1728760/

Higgs Decays & Couplings

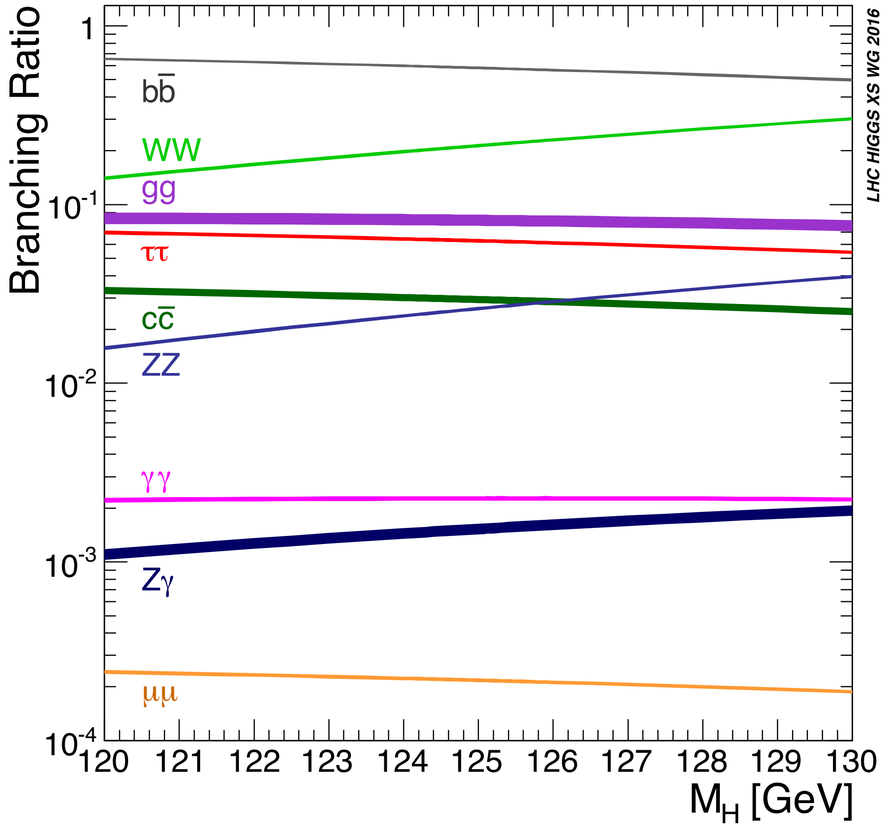
Higgs Decay

The value of the Higgs boson mass means that many decays are possible in the SM

This makes the study of Higgs decays very rich!



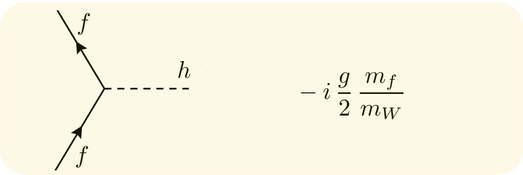
Handbook of LHC Higgs Cross Sections [1101.0593]



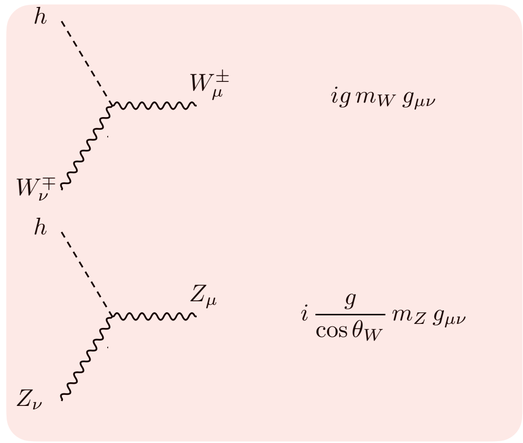
Feynman Rules



$$\frac{i}{p^2 - m_h^2 + i\epsilon}$$

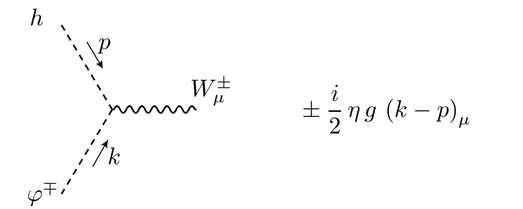


$$-\,i\,\frac{g}{2}\,\frac{m_f}{m_W}$$

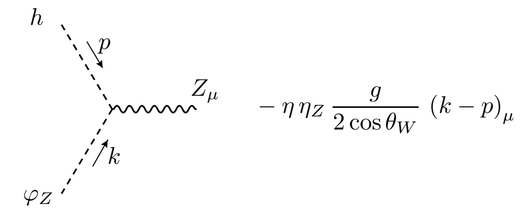


$$ig\,m_W\,g_{\mu\nu}$$

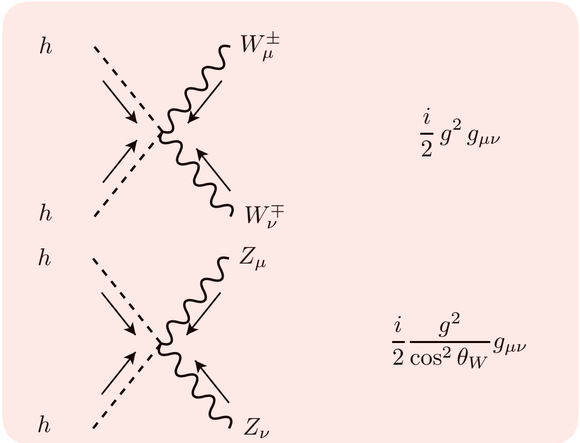
$$i\,\frac{g}{\cos\theta_W}\,m_Z\,g_{\mu\nu}$$



$$\pm\,\frac{i}{2}\,\eta\,g\,(k-p)_\mu$$

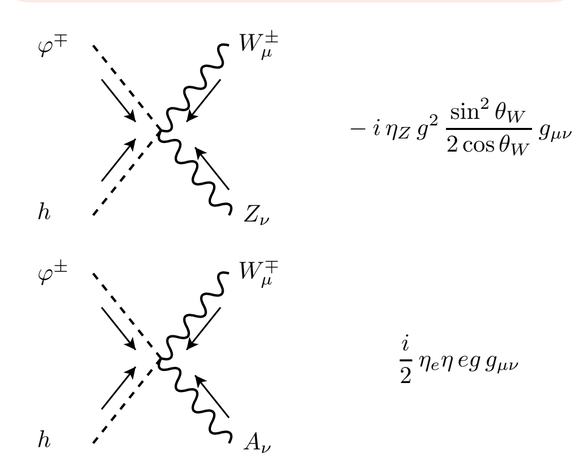


$$-\,\eta\,\eta_Z\,\frac{g}{2\cos\theta_W}\,(k-p)_\mu$$



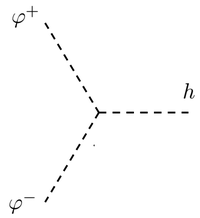
$$\frac{i}{2}\,g^2\,g_{\mu\nu}$$

$$\frac{i}{2}\,\frac{g^2}{\cos^2\theta_W}\,g_{\mu\nu}$$



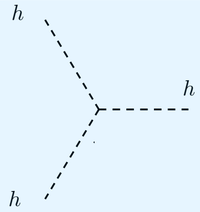
$$-\,i\,\eta_Z\,g^2\,\frac{\sin^2\theta_W}{2\cos\theta_W}\,g_{\mu\nu}$$

$$\frac{i}{2}\,\eta_e\eta\,eg\,g_{\mu\nu}$$

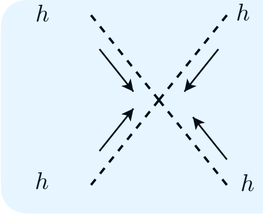


$$-\,\frac{i}{2}\,g\,\frac{m_h^2}{m_W}$$

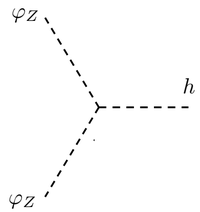
$$g = 2\frac{m_W}{v}$$



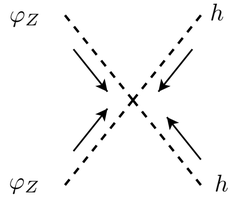
$$-\,\frac{3}{2}\,i\,g\frac{m_h^2}{m_W}$$



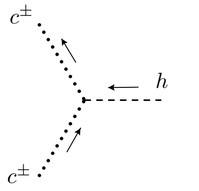
$$-\,\frac{3}{4}\,i\,g^2\frac{m_h^2}{m_W^2}$$



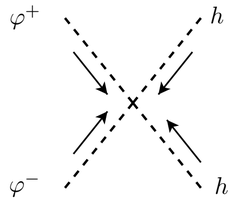
$$-\,\frac{i}{2}\,g\frac{m_h^2}{m_W}$$



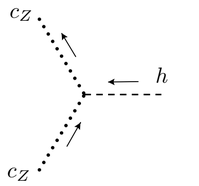
$$-\,\frac{i}{4}\,g^2\frac{m_h^2}{m_W^2}$$



$$-\,\frac{i}{2}\,\eta_G\,g\,\xi_W\,m_W$$



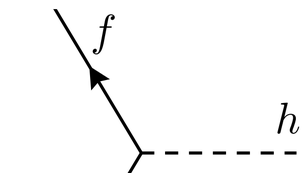
$$-\,\frac{i}{4}\,g^2\,\frac{m_h^2}{m_W^2}$$



$$-\,\eta_G\,\frac{ig}{2\cos\theta_W}\,\xi_Z\,m_Z$$

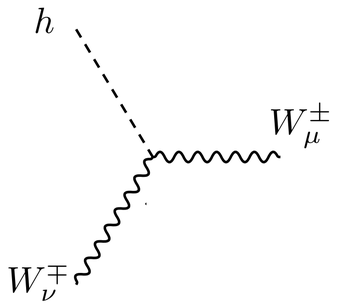
Transcribed from: Romao, Silva [1209.6213]

Feynman Rules



$$-i\frac{g}{2}\frac{m_f}{m_W} = -i\frac{m_f}{v}$$

Proportional to quark mass !

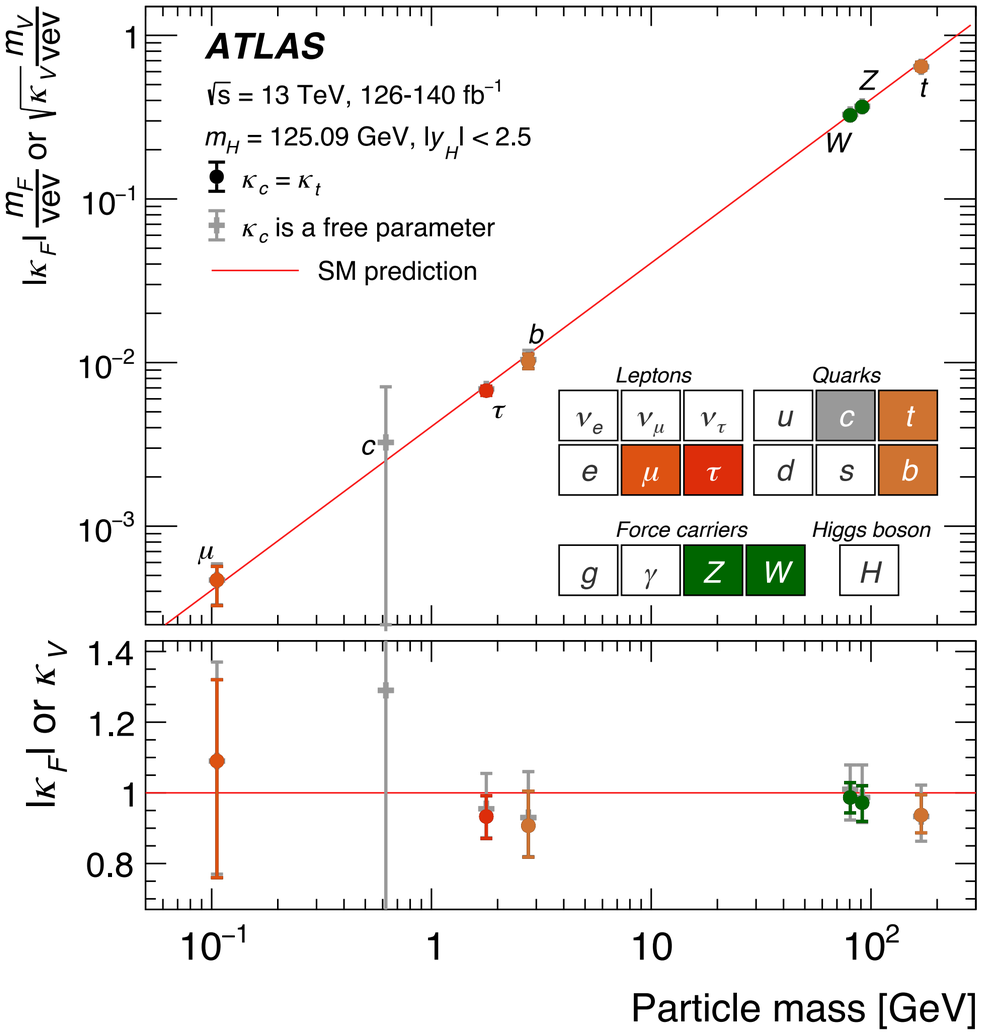


$$igm_W\, g_{\mu\nu} = i2\frac{m_W^2}{v}\, g_{\mu\nu}$$

Proportional to boson mass² !

Transcribed from: Romao, Silva [1209.6213]

Higgs Couplings



Incredible experimental (and theoretical) work has enabled observation and/or evidence for several of the Higgs couplings

Observation of $t\bar{t}H$ CMS 1804.02610/ ATLAS 1806.00425

Observation of $H \to b\bar{b}$ CMS 1808.08242/ ATLAS 1808.08238

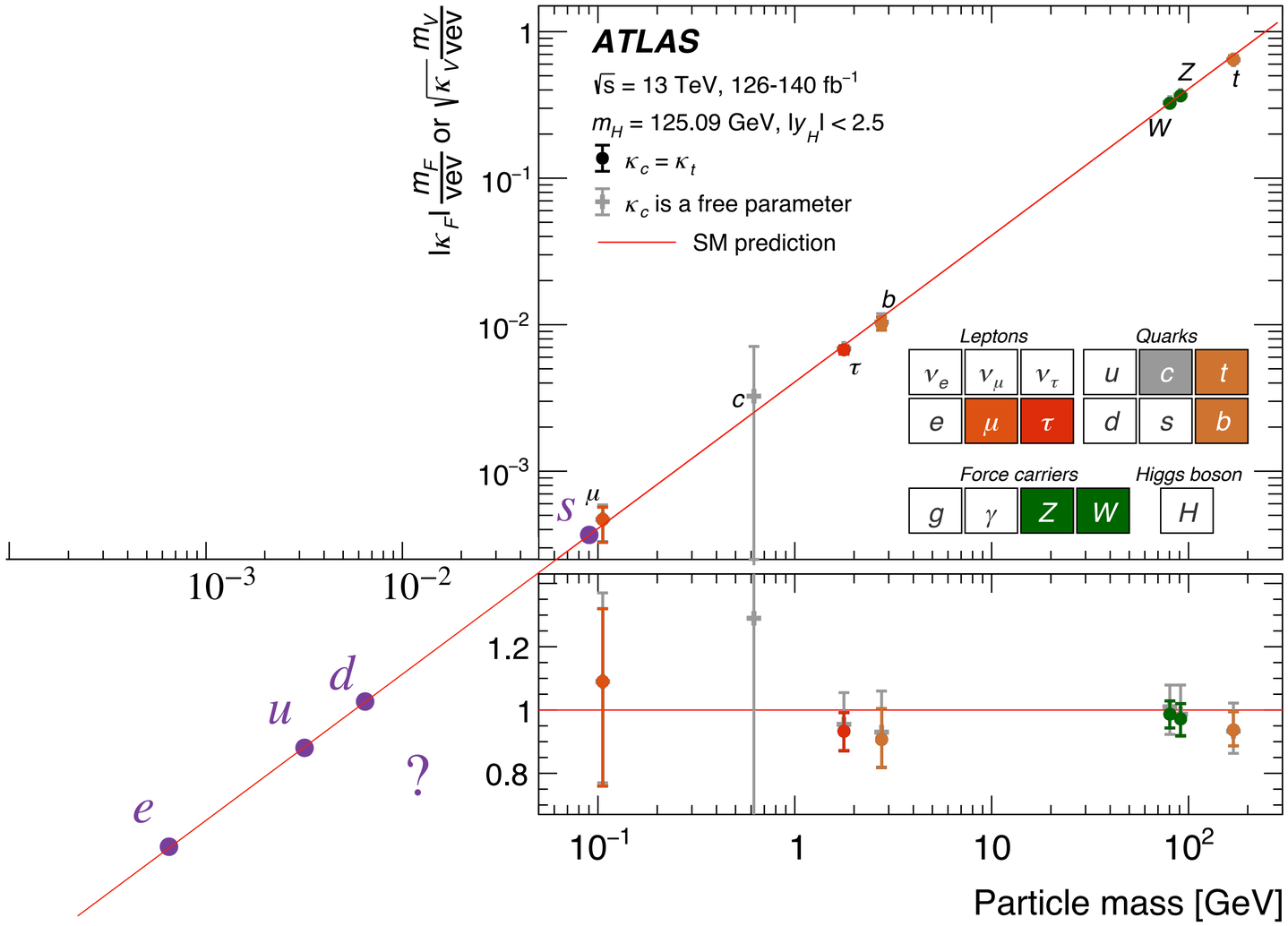
Observation of $H \to \tau^+\tau^-$ CMS 1708.00373/ ATLAS 1811.08856

The mass of the 3rd generation quarks & leptons is generated by interacting with the Higgs field!

(Not part of the LHC design)

Tempting to think that we have confirmed the SM but we are only just beginning to scratch the surface

Higgs Couplings



What about the 2nd and 1st generations?

(Also… what about neutrinos?)

HL-LHC

Observation of μ coupling

Probe Higgs potential (later in talk)

FCC-ee

Major increase in precision

Many couplings measured to per mil

Evidence/Observation s coupling?

Observation of e coupling? (smart techniques)

Constrain $H \rightarrow$ invisible

$H \to \mu\mu$

A direct probe of Higgs coupling to 2nd generation fermions!

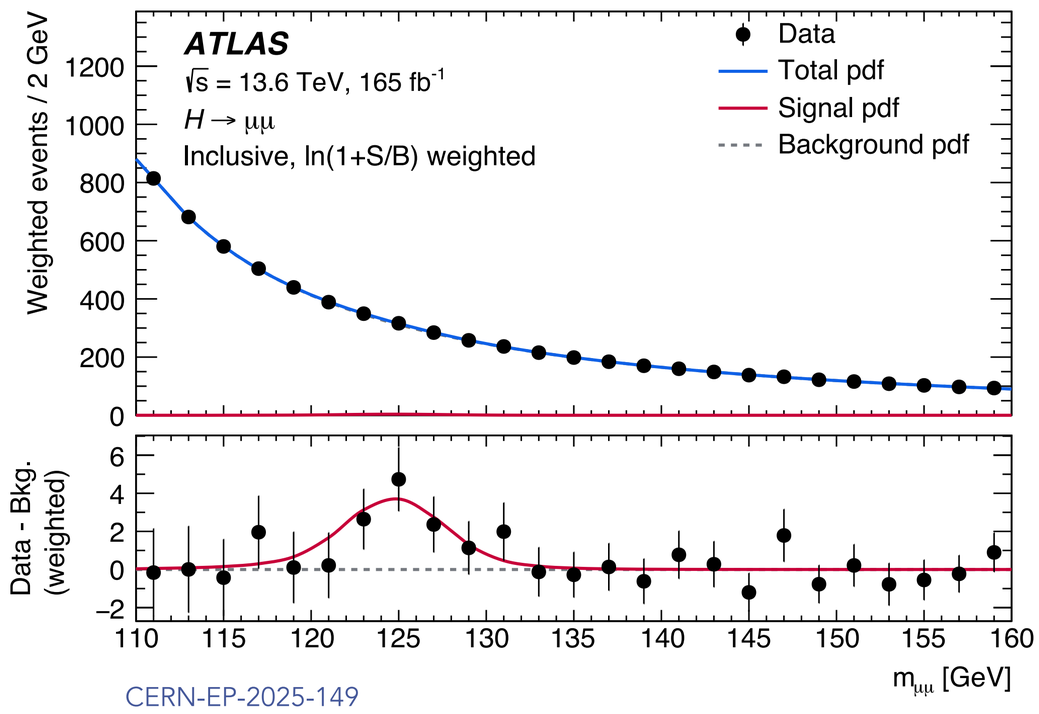
Run 2 $140\ \text{fb}^{-1} @ \sqrt{s} = 13\ \text{TeV}$
+ **Run 3** $165\ \text{fb}^{-1} @ \sqrt{s} = 13.6\ \text{TeV}$

Signal Strength

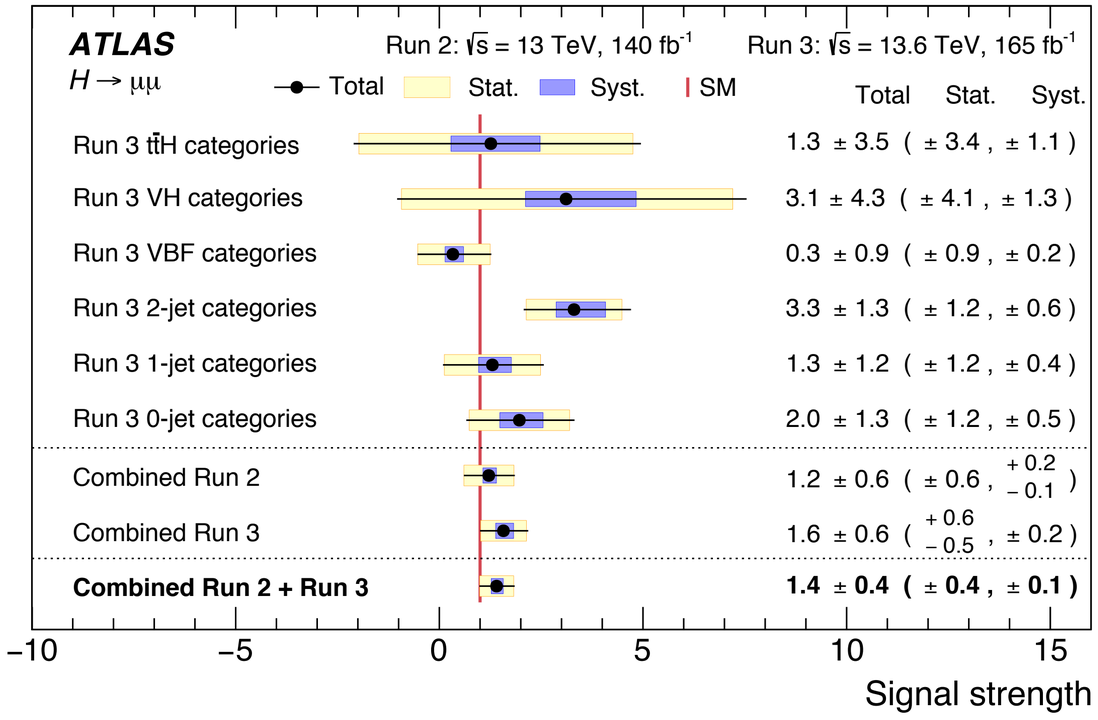
$\mu = 1.4 \pm 0.4 \qquad 3.4\sigma\ (2.5\sigma)$

Statistically limited
(systematic uncertainties 5% of total)

Incredibly close to discovery…



CERN-EP-2025-149



Higgs Production: HH Production

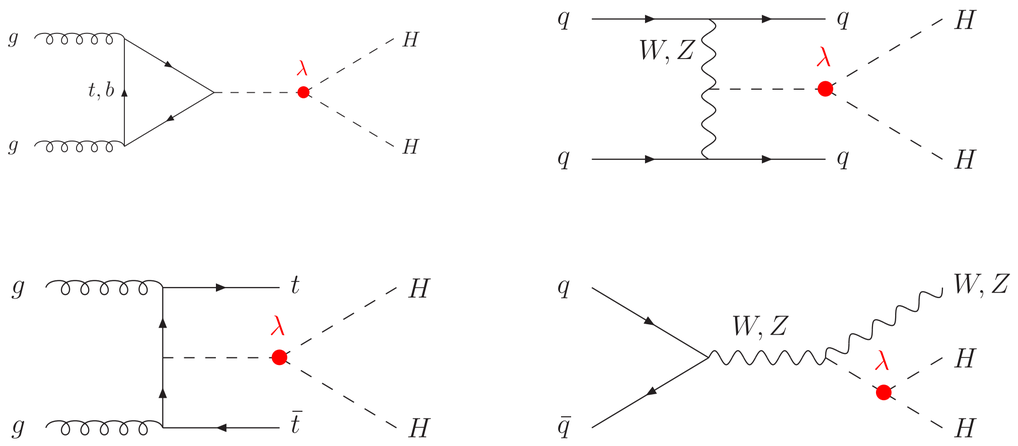


Figure: Spira 16

Higgs Boson Pair Production

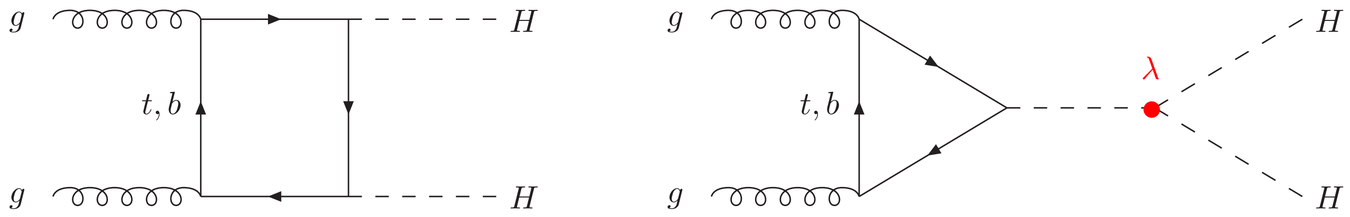
Standard model: trilinear and quartic self-couplings determined by m_H, v

$$V(\Phi) = -\mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2 \longrightarrow V(H) = \frac{1}{2}m_H^2H^2 + \lambda v H^3 + \frac{\lambda}{4}H^4$$

EW symmetry breaking

$$\mu^2 = \lambda v^2$$
$$m_H^2 = 2\lambda v^2$$

Experimentally: Need measurements to test this!



HH Production channels similar to H

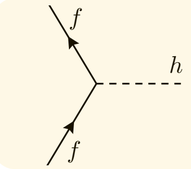
Important difference:

$$\sigma(pp \to HH) \sim \frac{\sigma(pp \to H)}{1000}$$

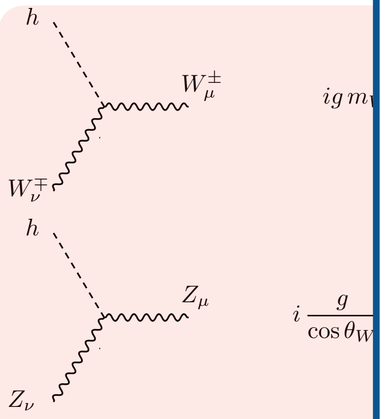
Feynman Rules



$$\frac{i}{p^2 - m^2 + i\epsilon}$$

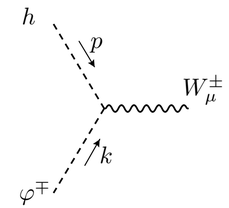


$$-i\frac{g}{2}\frac{m}{m}$$

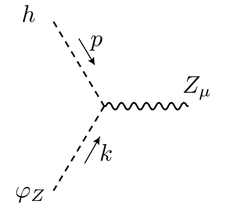


$$ig\,m_{W}$$

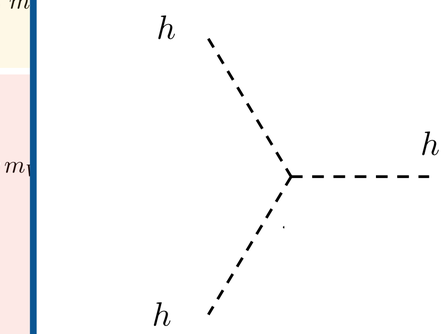
$$i\frac{g}{\cos\theta_W}$$



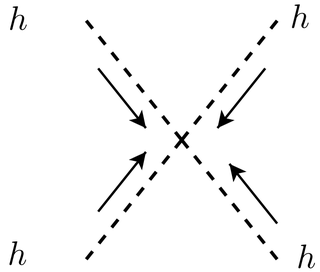
$$\pm\frac{i}{2}\eta\,g$$



$$-\eta\eta_Z\frac{g}{2\cos}$$



$$-\frac{3}{2}ig\frac{m_h^2}{m_W} = -3i\frac{m_h^2}{v}$$



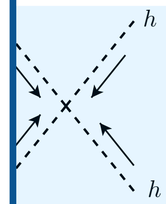
$$-\frac{3}{4}ig^2\frac{m_h^2}{m_W^2} = -3i\frac{m_h^2}{v^2}$$

In the SM: determined by Higgs mass and vev!

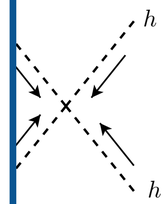




$$g = 2\frac{m_W}{v}$$



$$-\frac{3}{4}ig^2\frac{m_h^2}{m_W^2}$$



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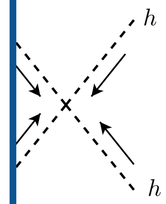


$$-\frac{i}{4}g^2\frac{m_h^2}{m_W^2}$$

Transcribed from: Romao, Silva [1209.6213]

Experimental Progress

Experimental Limits (Run 2) @ 95% CL

ATLAS: $-1.2(-1.6) < \kappa_3 < 7.2(7.2)$ $\quad \sigma \leq 2.9\ (2.4) \times \sigma_{SM}$

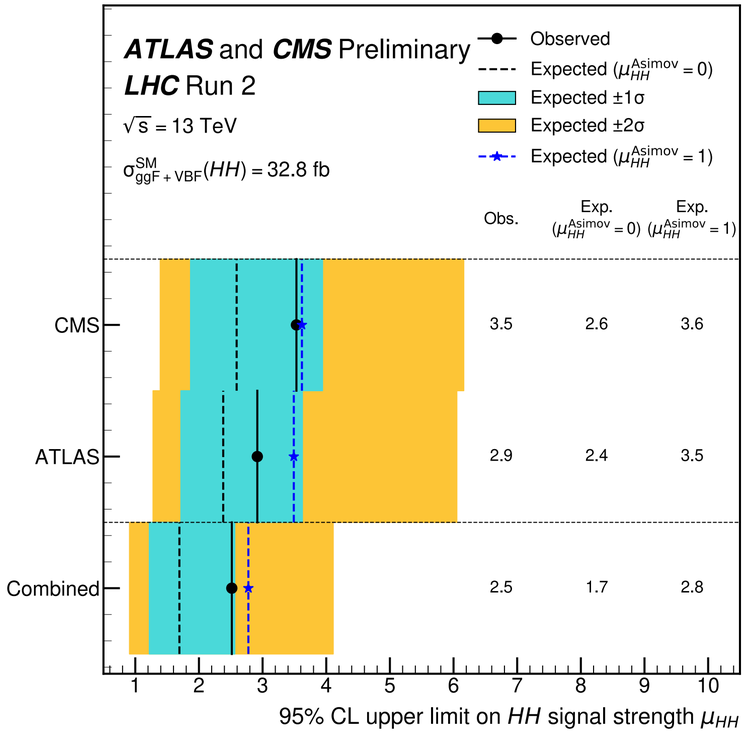
ATLAS CERN-EP-2024-160

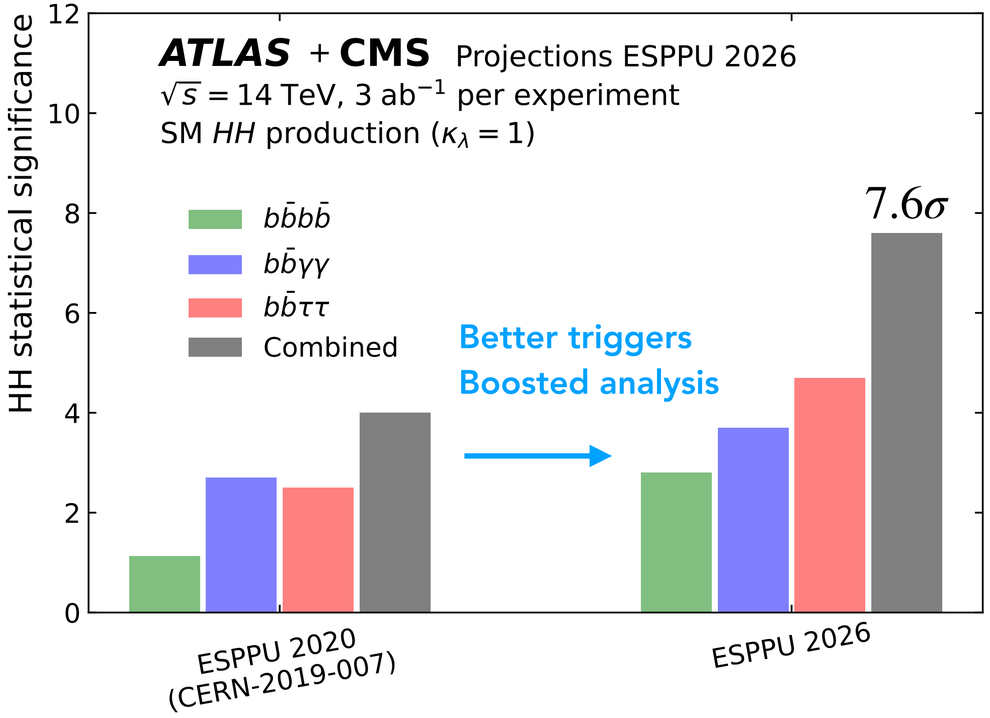
CMS: $-1.39(-1.02) < \kappa_3 < 7.02(7.19)$ $\quad \sigma \leq 3.5\ (2.5) \times \sigma_{SM}$

CMS-PAS-HIG-20-011

A+C: $-0.71(-1.3) < \kappa_3 < 6.1(6.7)$ $\quad \sigma \leq 2.5\ (1.7) \times \sigma_{SM}$

CERN-EP-2026-011





ATL-PHYS-PUB-2025-018 / CMS-HIG-25-002

Projections for HL-LHC (European Strategy 2026)

Expected measurement of κ_3 with uncertainty $< 30\,\%$

TH systematics approximately halved in projections

Theory Progress

(Slide design shamelessly stolen from G. Salam)

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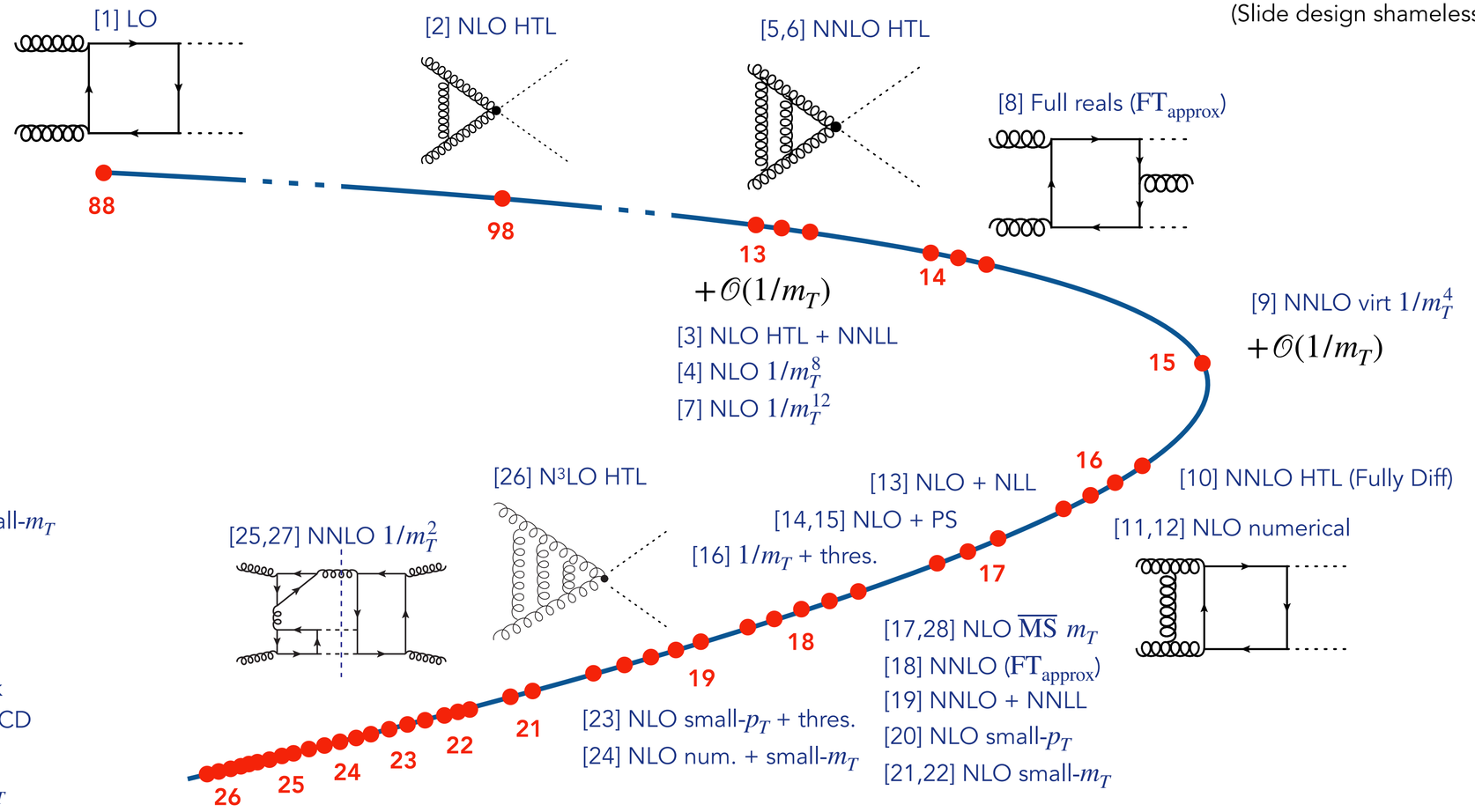

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Theory Progress

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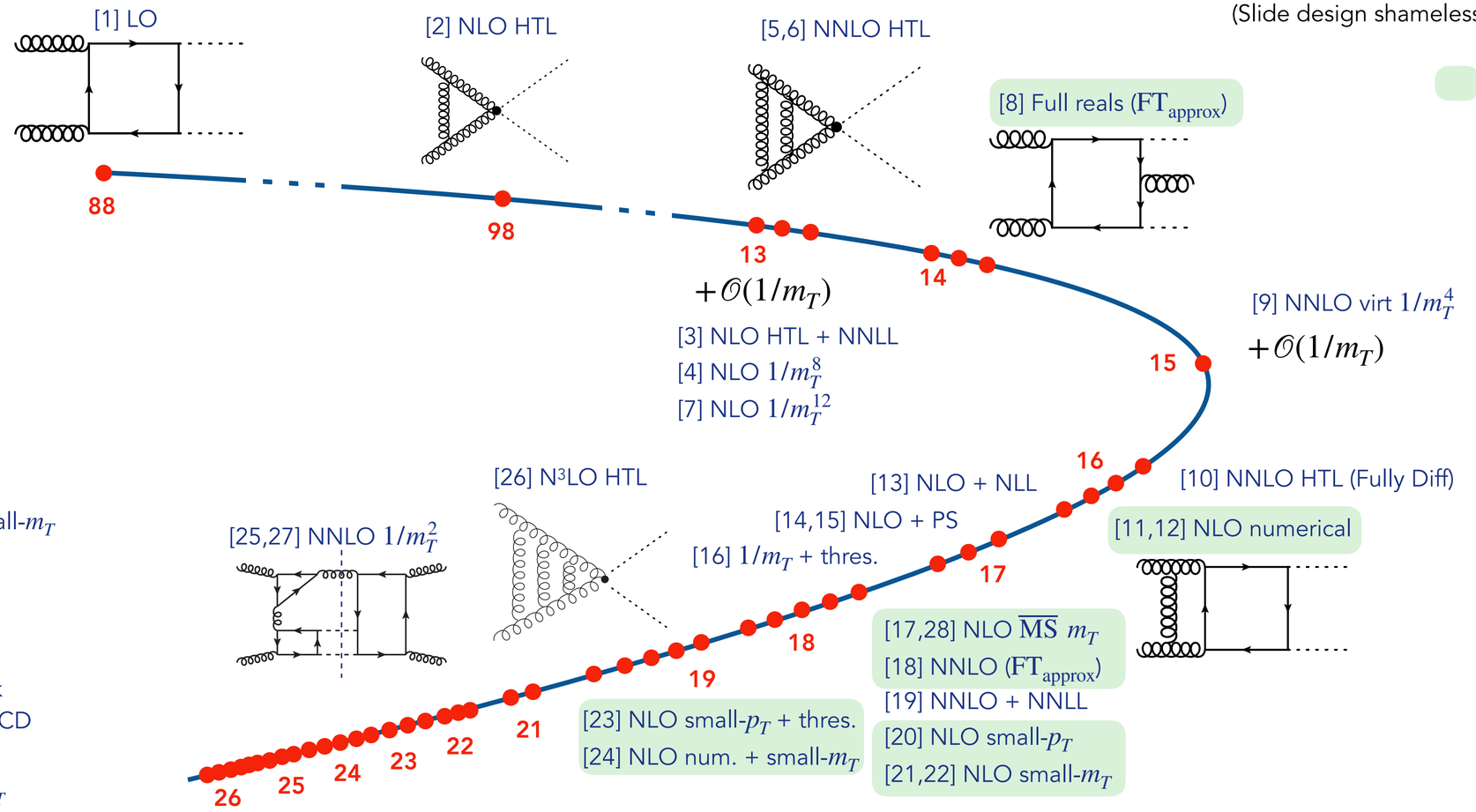

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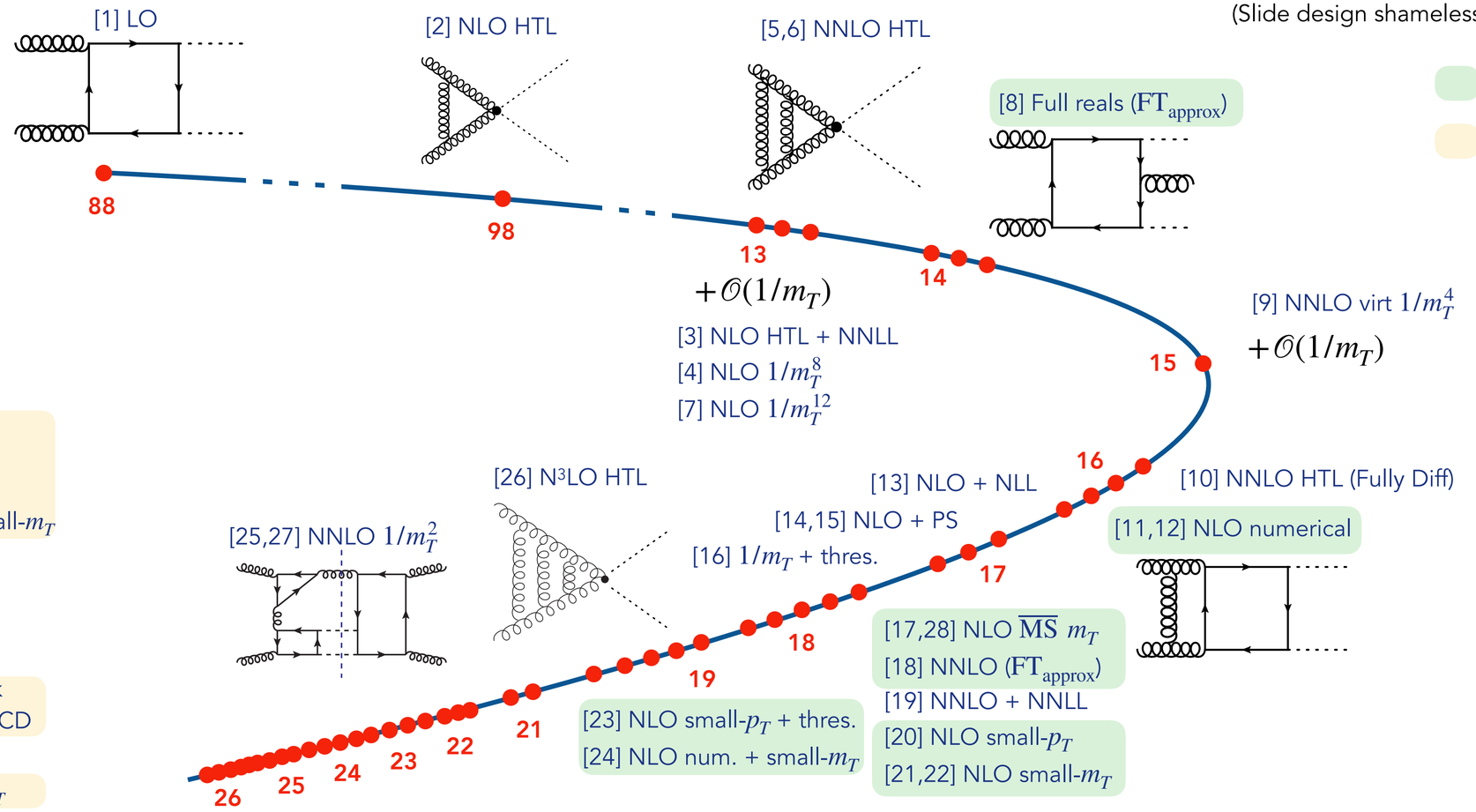

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Report 5 2025/2026

Efforts to update the recommendation recently concluded!

Recommendation

$$\sigma(\sqrt{s}) = \sigma_2(\sqrt{s}) \times K_3(\sqrt{s}) \times K_{\text{EW}}(\sqrt{s}) \qquad \sigma_2 = \text{NNLO FT}_{\text{approx}} \qquad K_3 = \left(\frac{\text{N}^3\text{LO} + \text{N}^3\text{LL HTL}}{\text{NNLO HTL}} \right) \sim 1.03 \qquad K_{\text{EW}} = \frac{\sigma_{\text{NLO EW}}}{\sigma_{\text{LO}}} \sim 0.96$$

Uncertainties

$$\delta_{\text{scale}}(\sqrt{s}) = \delta_{\sigma_2\ \text{scale}}(\sqrt{s}) \qquad \delta_{\text{PDF}}(\sqrt{s}) = \delta_{\sigma_2\ \text{PDF}}(\sqrt{s})$$

$$\delta_{\text{MHOU}} = \left| \frac{\sigma^{\text{N}^3\text{LO}}_{\text{N}^3\text{LO–PDF}} - \sigma^{\text{N}^3\text{LO}}_{\text{NNLO–PDF}}}{\sigma^{\text{N}^3\text{LO}}_{\text{N}^3\text{LO–PDF}}} \right| \sim 2.18\,\%$$

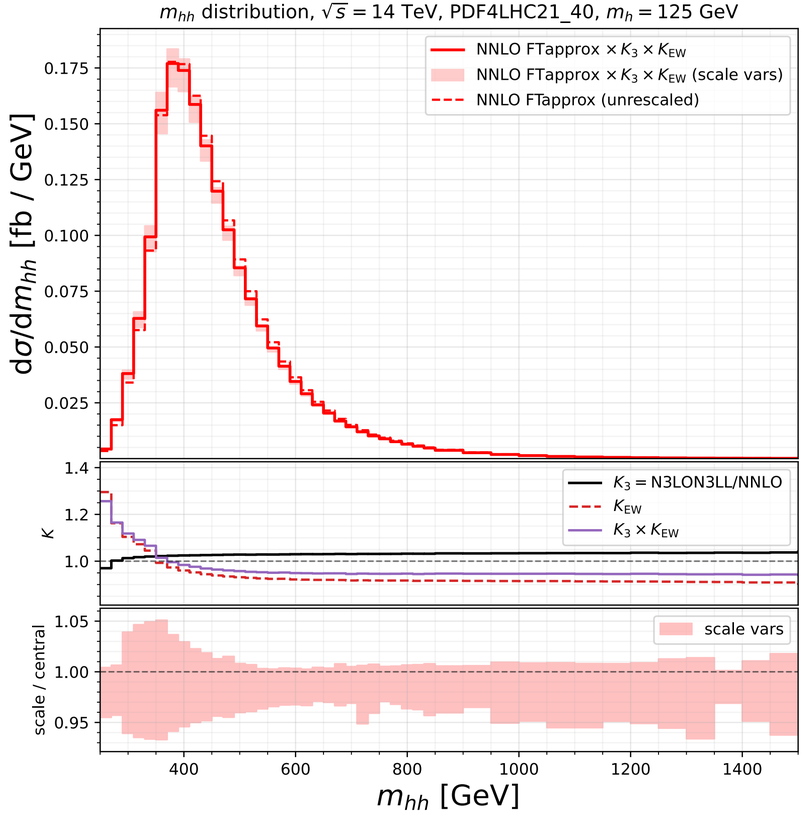
Not in final uncertainties

$$\delta_{m_t} = {}^{+5\%}_{-16\%}$$ ← NLO

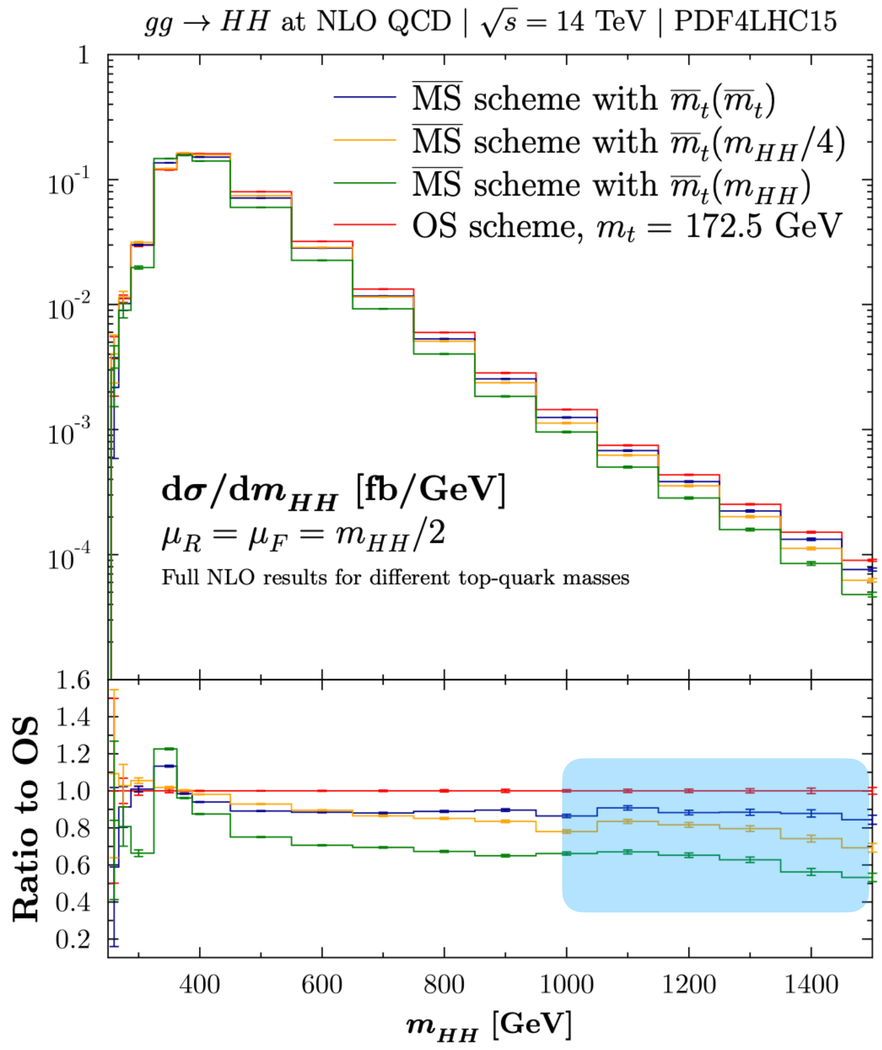
$\sqrt{s}$ [TeV]	**13**	**13.6**	**14**
$\sigma_{\text{rec.}}$ [fb]	30.40	33.62	35.81
± PDF unc. [%]	1.96	1.92	1.89
$\pm\alpha_s$ unc. [%]	1.51	1.49	1.47
± PDF + α_s unc. [%]	**2.47**	**2.43**	**2.39**
QCD scale unc. [%]	$^{+2.11}_{-4.98}$	$^{+2.07}_{-4.85}$	$^{+2.01}_{-4.78}$
m_t scheme unc. [%]	$^{+5}_{-16}$	$^{+5}_{-16}$	$^{+5}_{-16}$
± THU [%]	0.14	0.19	0.21
Scale + THU + m_t scheme unc. [%]	$^{\mathbf{+7.25}}_{\mathbf{-21.12}}$	$^{\mathbf{+7.26}}_{\mathbf{-21.04}}$	$^{\mathbf{+7.22}}_{\mathbf{-20.99}}$

← Numerics & $r_{\text{cut}} \to 0$

LHCHWG-2026-010



Theory Uncertainties $gg \to HH$



Trusting the NLO + NNLO HTL combinations

Scale: $+2.1\,\% / -4.8\,\%$ PDF+α_s: $\pm 2.4\,\%$

m_T scheme: $+5.0\,\% / -16.0\,\%$

Physical predictions should not depend on a scheme choice!

But, truncating our perturbative series at NLO the **dominant theoretical uncertainty** comes from the definition/value of the top-quark mass (mass scheme choice)

Why?

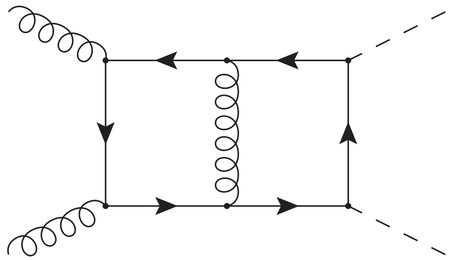
Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira, Streicher 18, 20, 20

High-energy limit

Expanding amplitude perturbatively $A_i^{\text{fin}} = \frac{\alpha_s}{2\pi} A_i^{(0),\text{fin}} + \left(\frac{\alpha_s}{2\pi}\right)^2 A_i^{(1),\text{fin}} + \mathcal{O}(\alpha_s^3)$ and around $m_t \sim 0$

$gg \to HH$

Davies, Mishima, Steinhauser, Wellmann 18; Baglio, Campanario, Glaus, Mühlleitner, Ronca, Spira, Streicher 20



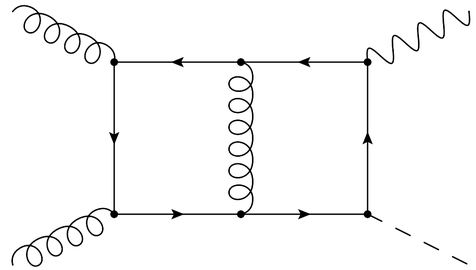
$$A^{(0)}_{i,y_t^2} \sim y_t^2 f_i(s,t) + y_t^2 \mathcal{O}(m_t^2)$$

$$A^{(1)}_{i,y_t^2} \sim 3 C_F A_i^{(0)} \log\left[\frac{m_t^2}{s}\right] + y_t^2 \mathcal{O}(m_t^2)$$

Leading $\log(m_t^2)$ from mass counter term, converting to $\overline{\text{MS}}$ gives $\log\left[\mu_t^2/s\right] \to$ scale choice of $\mu_t^2 \sim s$

$gg \to ZH$

Davies, Mishima, Steinhauser 20; Chen, Davies, Heinrich,SPJ, Kerner, Mishima, Schlenk, Steinhauser 22



$$A_i^{(0)} \sim y_t\, m_t\, f_i(s,t)\ \log^2\left[\frac{m_t^2}{s}\right]$$

$$A_i^{(1)} \sim \frac{(C_A - C_F)}{12} A_i^{(0)}\ \log^2\left[\frac{m_t^2}{s}\right]$$

Leading $\log(m_t^2)$ not coming from mass counter term ($C_A - C_F$ structure)

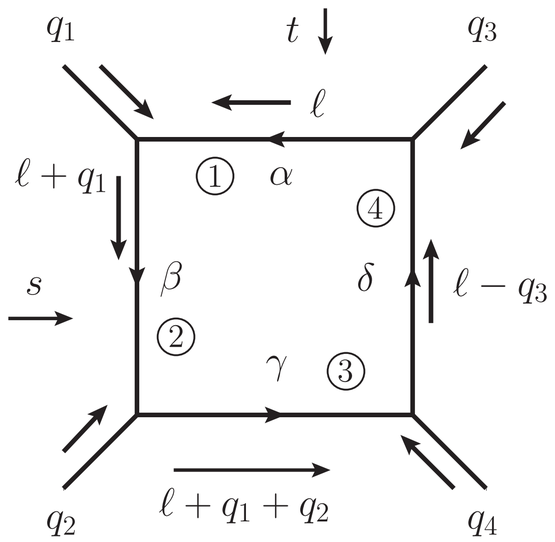
How does this simple structure arise? Does it generalise to all orders?

Expansion of $gg \to HH$ @ 1-loop

Jaskiewicz, SPJ, Szafron, Ulrich 25

Limit: $s, |t|, |u| \gg m_t^2 \gg m_H^2\,, \quad m_H^2 \to 0$ and $\lambda \sim m_t/Q$

Kinematics: $s + t + u = 0, \quad m_H = 0$



Expand integrals in parameter space (Method of Regions)

$\mathbf{u}^R$	**order**	**interpretation**	**routing**
(-2, -2, 0, 0)	$4 - 2(\epsilon + \alpha + \beta)$	c_1	ℓ
(0, -2, -2, 0)	$4 - 2(\epsilon + \beta + \gamma)$	c_2	$\ell - q_1$
(-2, 0, 0, -2)	$4 - 2(\epsilon + \alpha + \delta)$	c_3	$\ell + q_3$
(0, 0, -2, -2)	$4 - 2(\epsilon + \gamma + \delta)$	c_4	$\ell - q_1 - q_2$
(0, 0, 0, 0)	0	h	n/a

Using a set of possible loop momenta modes can **systematically search** for momentum routing to give a momentum space interpretation

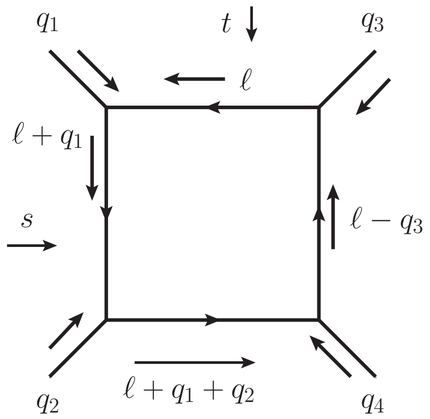
Implemented in pySecDec by Y. Ulrich (TBA)

Amplitude Level Results @ 1-loop

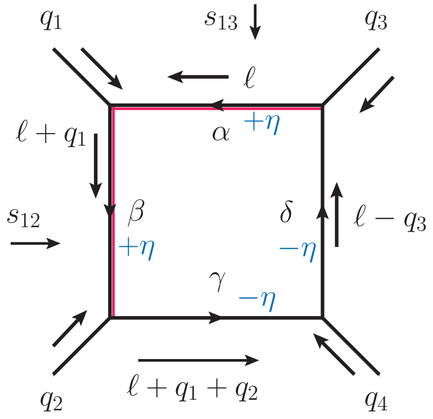
Jaskiewicz, SPJ, Szafron, Ulrich 25

Can compute amplitude level results for each region, at the 1-loop level:

Hard region



Collinear q_1 region



Leading Power (LP)

$$A^{(h)}_{1,y_t^2} = \frac{4y_t^2}{s}\left\{2 - 2m_t^2\left[-\frac{2}{\epsilon^2 s} - \frac{1}{\epsilon}\left(\frac{s^2+2tu}{stu}\,l_s + \frac{l_t}{u} + \frac{l_u}{t}\right)\right.\right.$$
$$+\frac{-l_s^2+2l_t^2+2l_u^2}{s} + \frac{l_s\,l_t}{t} + \frac{l_s\,l_u}{u} + \frac{(t-u)^2\,l_t\,l_u}{stu}$$
$$\left.\left. - \left(\frac{2}{s}+\frac{1}{t}+\frac{1}{u}\right)l_s - \frac{t\,l_t}{su} - \frac{u\,l_u}{st} + \frac{60+13\pi^2}{6s}\right] + \mathcal{O}(m_t^4)\right\}$$

Next-to-Leading Power (NLP)

$$A^{(c_1)}_{1,y_t^2} = \frac{-4y_t^2 m_t^2\,\mu^{2\epsilon}e^{\gamma_E\epsilon}\Gamma(2\eta)^2\Gamma(\epsilon+2\eta)}{s(stu)(1-2\eta-\epsilon)\Gamma(4\eta)\Gamma(1+\eta)^2}\left(\frac{1}{m_t^2}\right)^{2\eta+\epsilon}$$
$$\times\left\{(-t)^\eta(-u)^\eta\left[s^2\left(1+2\epsilon^2-(2+\eta)\epsilon\right)-2\eta\,tu\right]\right.$$
$$+(-s)^\eta(-t)^\eta\left[su\left(1+2\epsilon^2-(2+\eta)\epsilon\right)-tu(1-3\eta-(2-5\eta)\epsilon)\right]$$
$$\left.+(-s)^\eta(-u)^\eta\left[st\left(1+2\epsilon^2-(2+\eta)\epsilon\right)-tu(1-3\eta-(2-5\eta)\epsilon)\right]\right\}$$

Generates $\log(m_t^2)$ at NLP

Overview of Structure

Jaskiewicz, SPJ, Szafron, Ulrich 25

The $gg \to HH$ virtual amplitude in $\overline{\text{MS}}$ scheme has the following leading power structure (obtained to all orders using the tools of Soft Collinear Effective Theory)

$$l_\mu = \log(\mu_t^2/s)$$

$$l_m = \log(\mu_t^2/s), \log(m_t^2/s)$$

$$\text{LO} : \alpha_s y_t^2 (c_0 + m_t n_0),$$

$$\text{NLO} : \alpha_s^2 y_t^2 (a_1 l_\mu + c_1 + m_t n_1),$$

$$\text{NNLO} : \alpha_s^3 y_t^2 (a_2 l_\mu^2 + b_2 l_m + c_2 + m_t n_2),$$

$$\text{N}^3\text{LO} : \alpha_s^4 y_t^2 (a_3 l_\mu^3 + b_3 l_m^2 + d_3 l_m + c_3 + m_t n_3),$$

$$\text{N}^i\text{LO} : \alpha_s^{i-1} y_t^2 (a_i l_\mu^i + b_i l_m^{i-1} + d_i l_m^{i-2} + \ldots + c_i + m_t n_i)\,.$$

Integrals are known

Henn, Mistlberger, Smirnov, Wasser 20
Caola, von Manteuffel, Tancredi 20;
Bargiela, Caola, von Manteuffel, Tancredi 22;

Leading log structure generated to all orders by RG running

$$m^{\text{LL}}(\mu) = M \exp\left[a_{\gamma_m}^{\text{LL}}(\mu)\right] z_m(M)$$

$$a_{\gamma_m}^{\text{LL}}(\mu) = \frac{3C_F}{2\beta_0} \ln\left(1 - \frac{\alpha_s(\mu)}{2\pi}\beta_0 \ln\left(\frac{\mu^2}{M^2}\right)\right)$$

LP LL
Known from RG running of top-quark mass

LP NLL
RG running + massification

Penin 06; Moch, Mitov 07; Becher, Melnikov 07; Engel et al 19; Wang, Xia, Yang, Ye 23;

LP Constant
Hard region ($m_t = 0$) contribution only, known to NLO

Partial Results

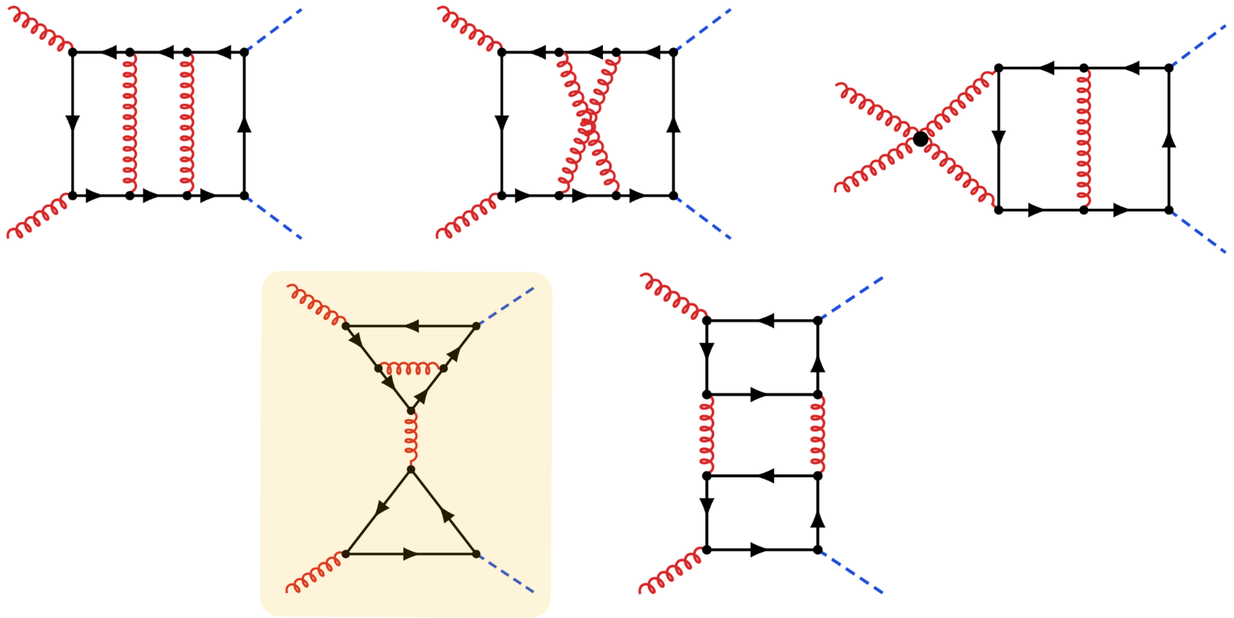
Hard region ($m_H = 0, m_T = 0$) Box (y_t^2) Amplitudes

Ajjath, SPJ, Magerya (WIP)

3728 Feynman diagrams

3 integral families + crossings

Integrals in terms of GPLs



Several pieces known

Reducible contributions with exact m_t $\propto$ (Higgs production with off-shell gluon leg)^2

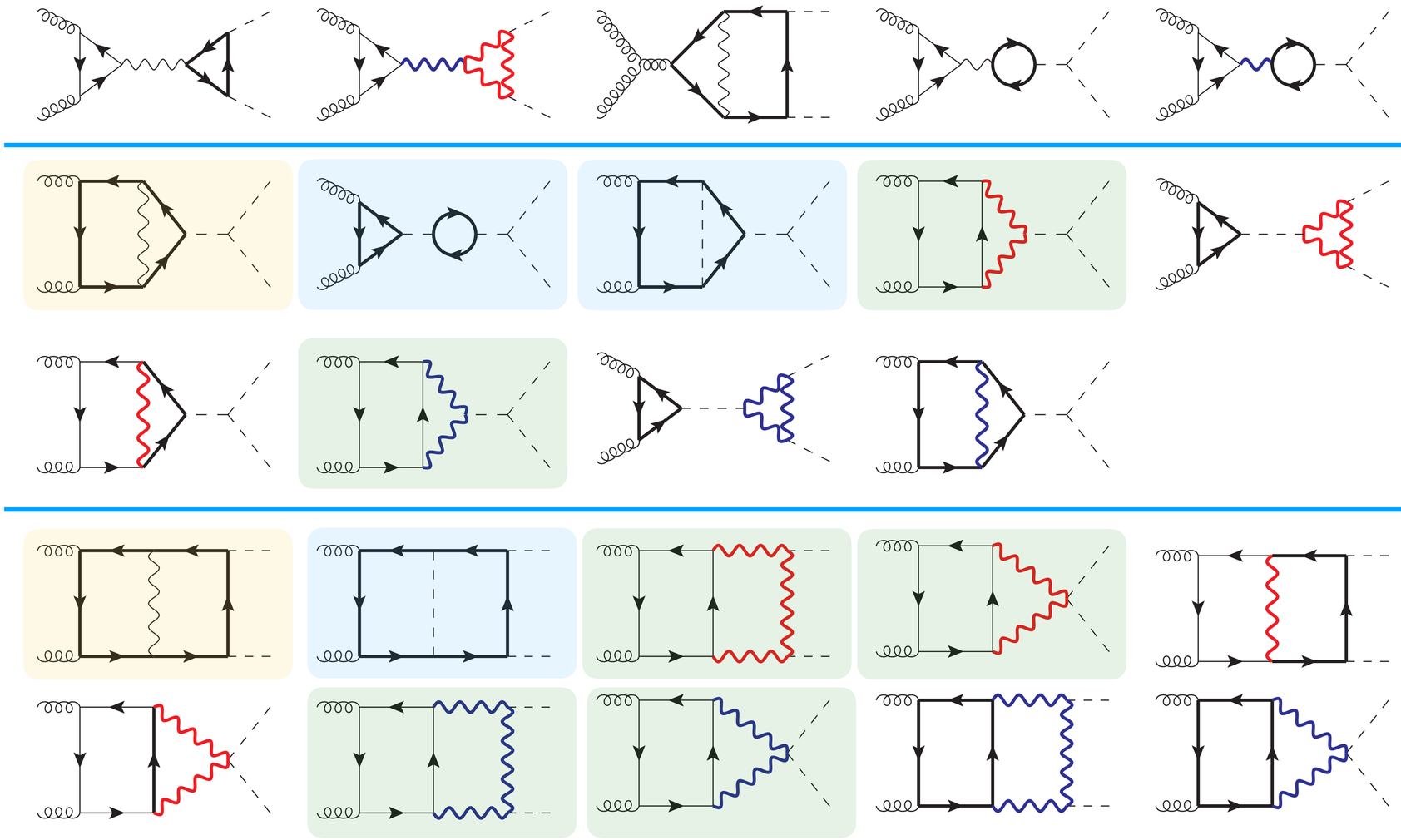
Davies, Schönwald, Steinhauser, Vitti 24

Large-n_f and large-N_c in the forward limit ($t = 0$, $m_H = 0$)

Davies, Schönwald, Steinhauser 23, 25

Need $gg \to HH$ at NNLO QCD with the full mass dependence

$gg \to HH$: NLO EW



Block 1 (= 0)
Furry/Colour/Anomaly cancellation

Block 2
1PR through H

Block 3
1PI

Complete Result
Bi, Huang, Huang, Ma, Yu 23

Photon contrib.

Light-quark

Yukawa/Self-Coup.

Davies, (Mishima), Schönwald, Steinhauser, Zhang (22), 23, 24, 25, 26; Mühlleitner, Schlenk, Spira 22; Heinrich, SPJ, Kerner, Stone, Vestner 24; Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, Spira 25; Bonetti, (Heinrich), Rendler, Bobadilla 25, (26);

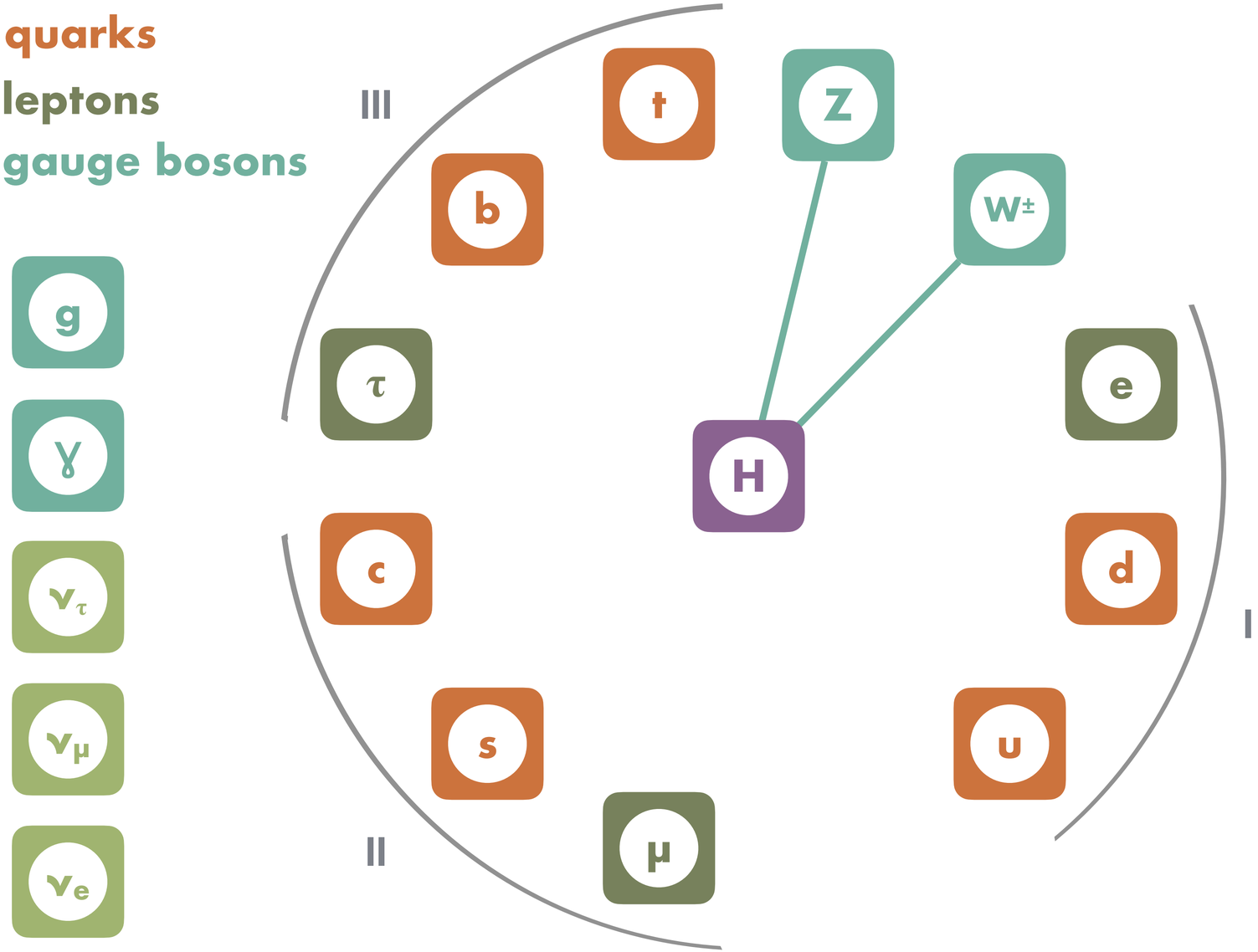
Extremely important to have extensively cross-checked results and flexible calculations (for EFTs and BSM)

Summary

quarks

leptons

gauge bosons



$$\mathscr{L} =$$

$$+ |D_\mu \phi|^2$$ **Gauge Interactions**

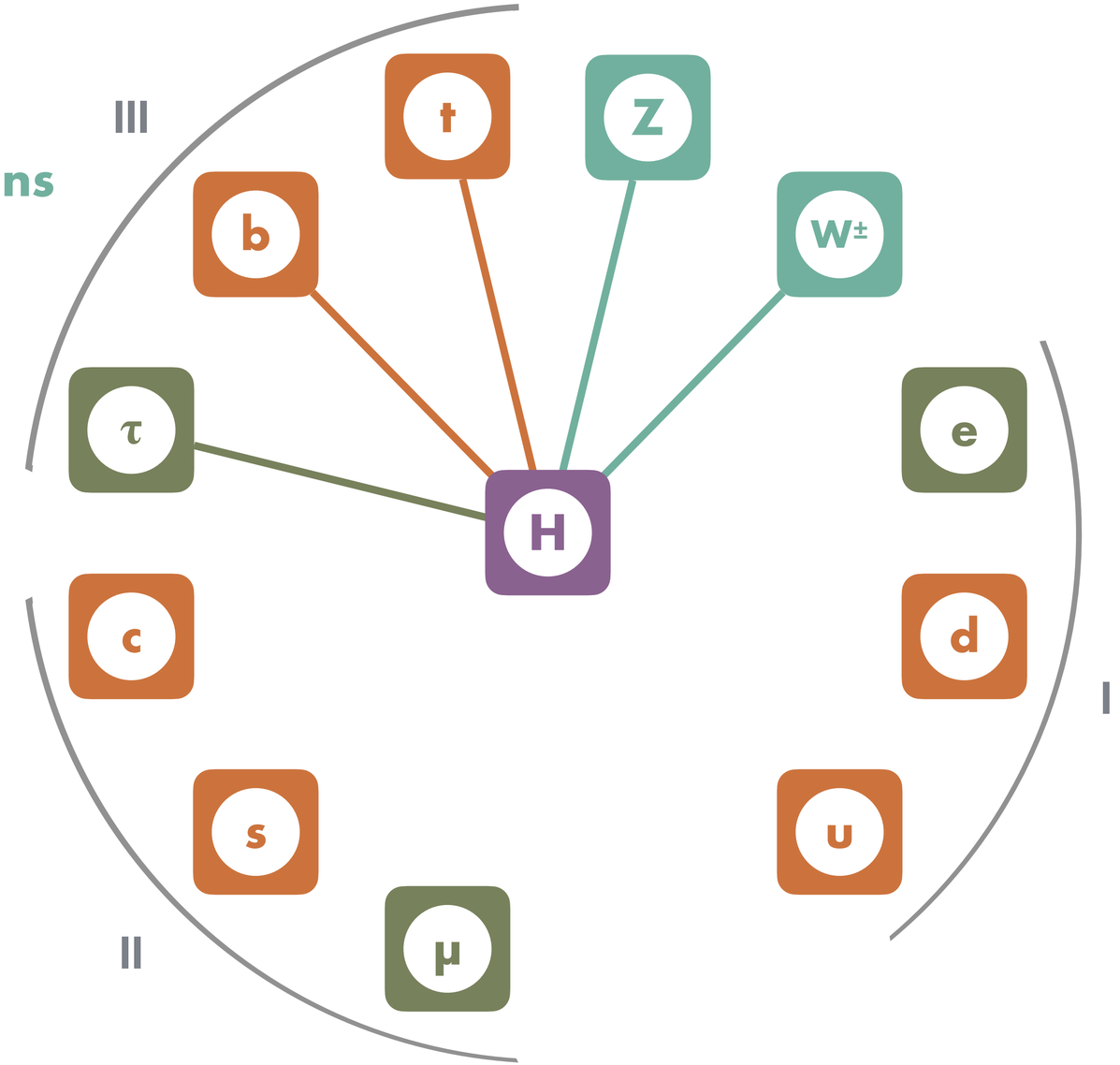
~5-10% @ Run 2 LHC

quarks

leptons

gauge bosons





$$\mathscr{L} =$$

$$+ |D_\mu \phi|^2$$ **Gauge Interactions**

$$+ \psi_i y_{ij} \psi_j \phi$$ **Yukawa Interactions**

fermion masses ↔ flavour

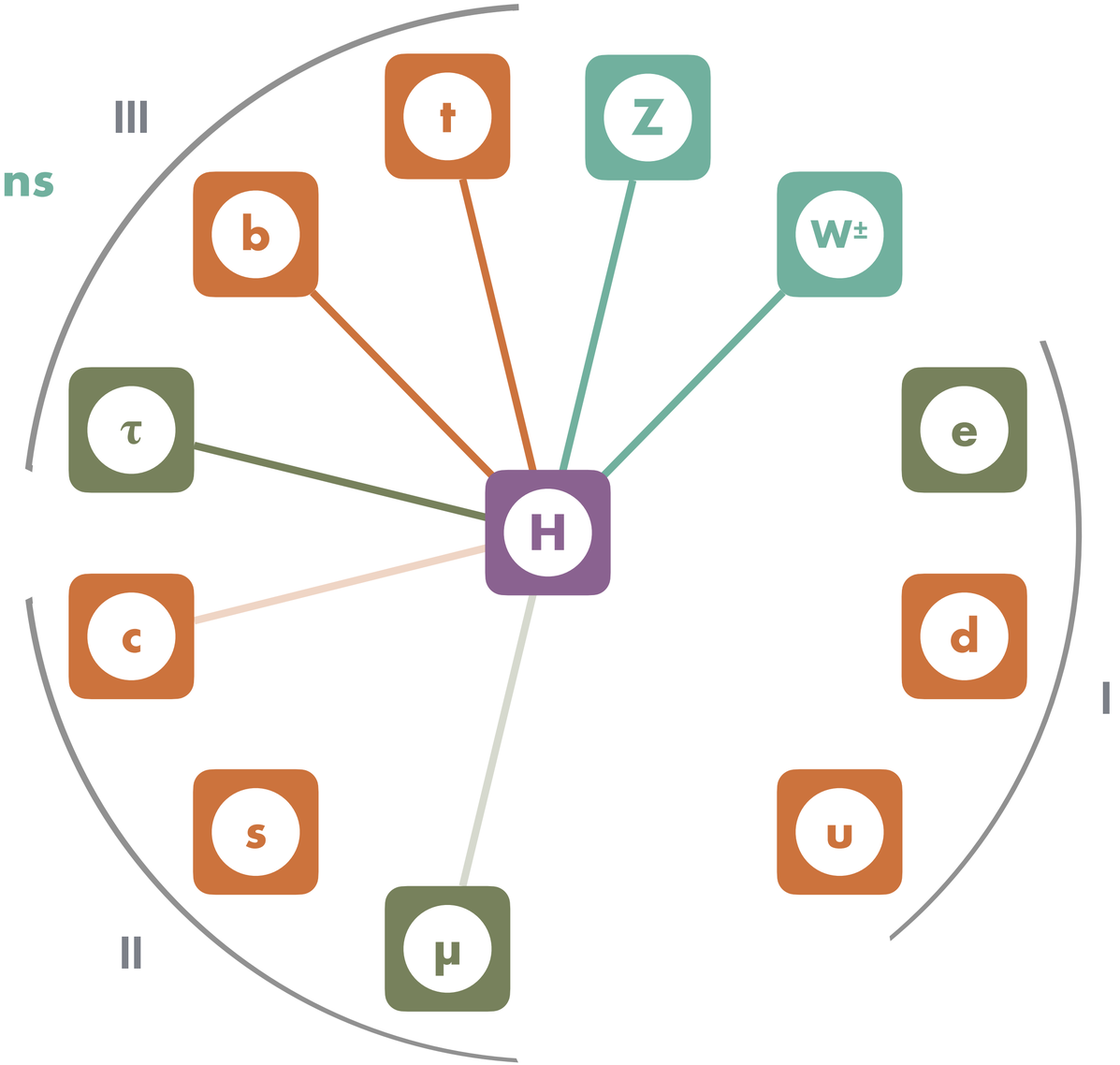
III ~10-20% @ Run 2 LHC

quarks

leptons

gauge bosons





$$\mathscr{L} =$$

$$+ |D_\mu \phi|^2$$ **Gauge Interactions**

$$+ \psi_i y_{ij} \psi_j \phi$$ **Yukawa Interactions**

fermion masses ↔ flavour

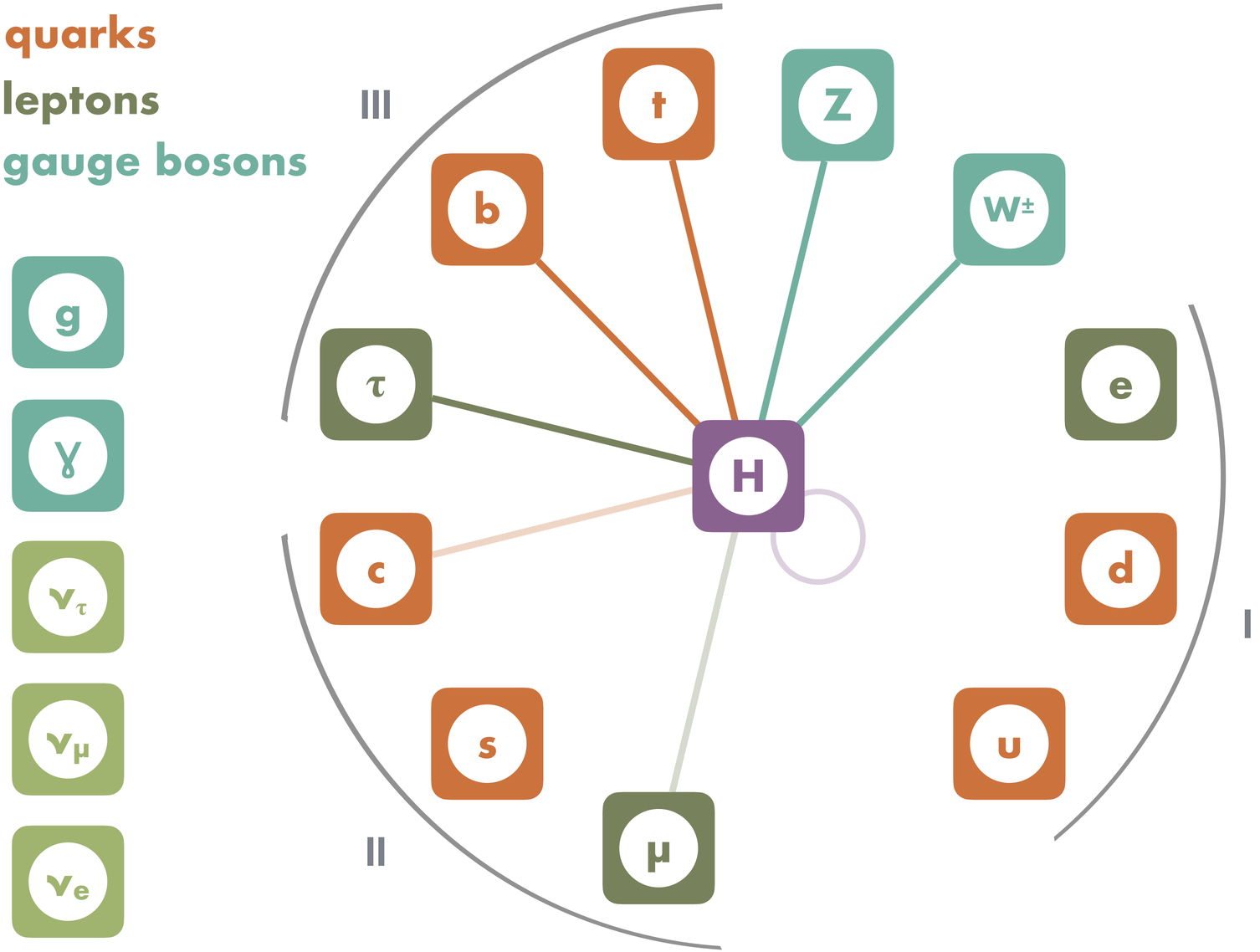
III ~10-20% @ Run 2 LHC

II ~60% / first hints

quarks

leptons

gauge bosons



$$\mathscr{L} =$$

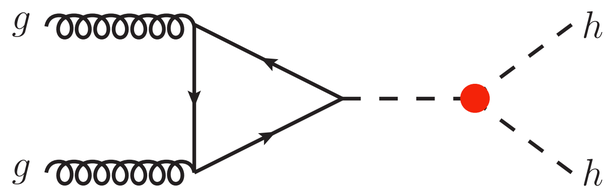
$$+ |D_\mu \phi|^2$$ **Gauge Interactions**

$$+ \psi_i y_{ij} \psi_j \phi$$ **Yukawa Interactions**

fermion masses ↔ flavour

$$- V(\phi)$$ **Higgs Potential**

self-coupling ↔ vacuum stability



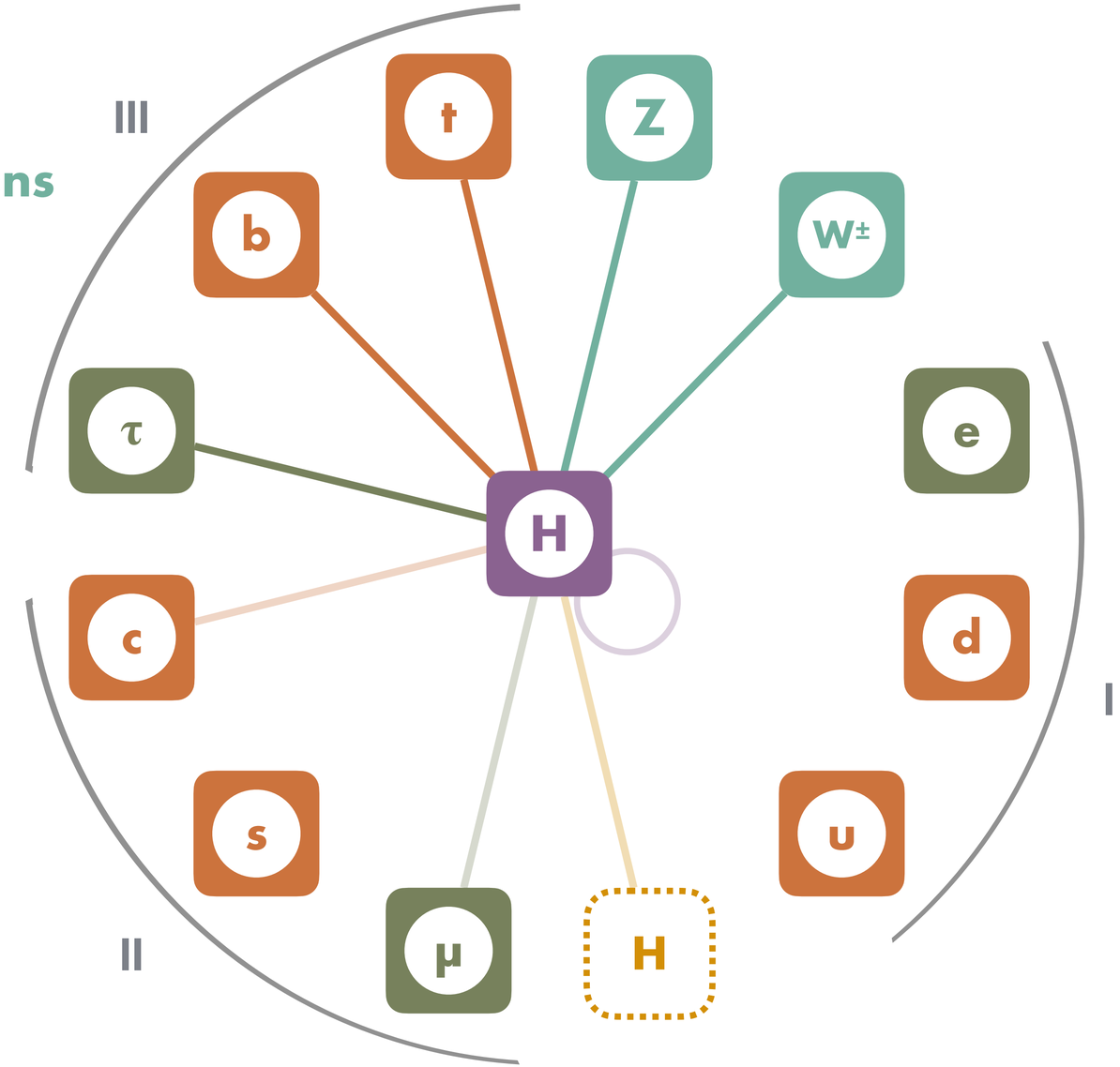
Direct measurement of the Higgs self-coupling would be a fundamental discovery!

quarks

leptons

gauge bosons





$$\mathscr{L} =$$

$$+ |D_\mu \phi|^2$$ **Gauge Interactions**

$$+ \psi_i y_{ij} \psi_j \phi$$ **Yukawa Interactions**

fermion masses ↔ flavour

$$- V(\phi)$$ **Higgs Potential**

self-coupling ↔ vacuum stability

$$+ \ldots$$ **Surprises**

BSM

Higgs Discoveries

The LHC has delivered incredible discoveries in the Higgs sector beyond discovering the Higgs boson

2014 ($H \to WW^*$): Observation of Higgs coupling to W bosons

ATLAS 1412.2641

2018 ($t\bar{t}H$): Direct observation of the top Yukawa coupling

CMS 1804.02610/ ATLAS 1806.00425

2018 ($H \to b\bar{b}$): Observation Higgs field is responsible for mass of 3rd gen. quarks

CMS 1808.08242/ ATLAS 1808.08238

2018 ($H \to \tau^+\tau^-$): Observation Higgs field is responsible for mass of 3rd gen. leptons

CMS 1708.00373/ ATLAS 1811.08856

2020 ($H \to \mu^+\mu^-$): Direct evidence Higgs field is responsible for mass of 2nd gen. leptons

CMS 2009.04363 / ATLAS 2007.07830

2022 ($H \to c\bar{c}$): Hints Higgs field is responsible for mass of 2nd gen. quarks

2205.05550 / ATLAS 2201.11428

2023 ($H \to Z\gamma$): Evidence of a rare decay

CERN-EP-2023-157

I believe that we can and should celebrate this more than we do!

Precision Progress

Higgs is just one example, in reality the success of the HL-LHC programme requires many accurate predictions

Higgs

process	known	desired
$pp \to H$	$\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}^{(t,t\times b)}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}^{(HTL)}}$ $\mathrm{NLO_{QCD}}$	$\mathrm{N^4LO_{HTL}}$ (incl.)
$pp \to H + j$	$\mathrm{NNLO_{HTL}}$ $\mathrm{NLO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO_{HTL}}$ $\mathrm{NNLO_{QCD}}$
$pp \to H + 2j$	$\mathrm{NLO_{HTL}} \otimes \mathrm{LO_{QCD}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NNLO_{HTL}} \otimes \mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ $\mathrm{NNLO_{QCD}^{(VBF)}}$ $\mathrm{NLO_{QCD}}$
$pp \to H + 3j$	$\mathrm{NLO_{HTL}}$ $\mathrm{NLO_{QCD}^{(VBF)}}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO_{QCD}^{(VBF^*)}}$
$pp \to VH$	$\mathrm{N^3LO_{QCD}}$ (incl.)$+ \mathrm{NLO_{EW}}$ $\mathrm{NLO_{gg\to HZ}^{(t,b)}}$	$\mathrm{N^3LO_{QCD}}$ $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to VH + j$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to HH$	$\mathrm{N^3LO_{HTL}} \otimes \mathrm{NLO_{QCD}}$ $\mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to HH + 2j$	$\mathrm{N^3LO_{QCD}^{(VBF^*)}}$ (incl.) $\mathrm{NNLO_{QCD}^{(VBF^*)}}$ $\mathrm{NLO_{EW}^{(VBF)}}$	$\mathrm{NLO_{QCD}}$
$pp \to HHH$	$\mathrm{NNLO_{HTL}}$	$\mathrm{NLO_{QCD}}$
$pp \to H + t\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ $\mathrm{NNLO_{QCD}}$ (approx.)	$\mathrm{NNLO_{QCD}}$
$pp \to H + t/\bar{t}$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$

Vector Bosons

process	known	desired
$pp \to V$	$\mathrm{N^3LO_{QCD}} + \mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$ $\mathrm{NLO_{EW}}$	$\mathrm{N^2LO_{EW}}$
$pp \to VV'$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ + Full $\mathrm{NLO_{QCD}}$ $(gg \to ZZ)$, approx. $\mathrm{NLO_{QCD}}$ $(gg \to WW)$	Full $\mathrm{NLO_{QCD}}$ (gg channel, w/ massive loops) $\mathrm{N^{(1,1)}LO_{QCD\otimes EW}}$
$pp \to V + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	hadronic decays
$pp \to V + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	$\mathrm{NNLO_{QCD}}$
$pp \to V + b\bar{b}$	$\mathrm{NLO_{QCD}}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W + b\bar{b}$	$\mathrm{NNLO_{QCD}}$	
$pp \to VV' + 1j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{NNLO_{QCD}}$
$pp \to VV' + 2j$	$\mathrm{NLO_{QCD}}$ (QCD component) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to W^+W^+ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to W^+W^- + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to W^+Z + 2j$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (EW component)	
$pp \to ZZ + 2j$	Full $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	
$pp \to VV'V''$	$\mathrm{NLO_{QCD}}$ $+\mathrm{NLO_{EW}}$ (w/ decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off-shell)
$pp \to WWW$	$\mathrm{NLO_{QCD}}$ + $\mathrm{NLO_{EW}}$ (off-shell)	
$pp \to W^+W^+(V \to jj)$	$\mathrm{NLO_{QCD}}$ + $\mathrm{NLO_{EW}}$ (off-shell)	
$pp \to WZ(V \to jj)$	$\mathrm{NLO_{QCD}}$ + $\mathrm{NLO_{EW}}$ (off-shell)	
$pp \to \gamma\gamma$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}}$
$pp \to \gamma\gamma + j$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ $+ \mathrm{NLO_{QCD}}$ (gg channel)	
$pp \to \gamma\gamma\gamma$	$\mathrm{NNLO_{QCD}}$	$\mathrm{NLO_{EW}}$

Top

process	known	desired
$pp \to t\bar{t}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays) $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off-shell) $\mathrm{NNLO_{QCD}}$ (w/ decays)	$\mathrm{N^3LO_{QCD}}$
$pp \to t\bar{t} + j$	$\mathrm{NLO_{QCD}}$ (off-shell effects) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w decays)
$pp \to t\bar{t} + 2j$	$\mathrm{NLO_{QCD}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w decays)
$pp \to t\bar{t} + V'$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (w decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w decays)
$pp \to t\bar{t} + \gamma$	$\mathrm{NLO_{QCD}}$ (off-shell)	
$pp \to t\bar{t} + Z$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off-shell)	
$pp \to t\bar{t} + W$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off-shell)	
$pp \to t/\bar{t}$	$\mathrm{NNLO_{QCD}}^*$(w decays) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w decays)
$pp \to tZj$	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off shell)	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$ (w/o decays)
$pp \to t\bar{t}t\bar{t}$	$\mathrm{NLO_{QCD}}$ (w decay) $\mathrm{NLO_{EW}}$ (w/o decays)	$\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$ (off-shell) $\mathrm{NNLO_{QCD}}$

Jets

process	known	desired
$pp \to 2\,\mathrm{jets}$	$\mathrm{NNLO_{QCD}}$ $\mathrm{NLO_{QCD}} + \mathrm{NLO_{EW}}$	$\mathrm{N^3LO_{QCD}} + \mathrm{NLO_{EW}}$
$pp \to 3\,\mathrm{jets}$	$\mathrm{NNLO_{QCD}} + \mathrm{NLO_{EW}}$	

- completed since 2021
- progress since 2021

Huss, Huston, SPJ, Pellen, Röntsch 25 (Les Houches Wishlist)

Future Directions

Current Status

Incredible performance by the LHC: discovery → precision era of Higgs physics

Theory uncertainties limit our ability to explore the Higgs sector

It is critically important to have a robust fixed-order programme alongside precision developments in parton showers and analysis techniques

Future Community Goals

Extremely exciting times ahead… (can we claim discovery of $H\mu\mu$ coupling? obtain evidence of HHH?)

Lift standard candle processes and interesting final states to $\mathrm{N^3LO}$ making this the new standard

Refine tools/techniques for multi-loop electroweak corrections, with two-loop electroweak becoming a new standard (also for design/preparation of FCC-ee)

Thank you for your attention!

Backup

The Pressing Challenges

As the HL-LHC programme progresses, can expect our experimental colleagues to continue to devise improved analysis strategies and likely even to **outperform their conservative projections**

As theorists we must…

1. Continue to improve the accuracy of our calculations as luminosity/energy increases

   Requires development of techniques for at least 2- and in many cases 3-loop fixed-order QCD and EW

2. Understand the structure of these corrections

   Develop and utilise general methods to uncover the all-order behaviour of our corrections

3. Build predictions that combine fixed-order, parton showers, resummation and advances in Parton Distribution Function extraction and evolution

   Collaborate and communicate!

4. Communicate these advances within the theory and experimental communities

QCD to Standard Model

Working with the full SM is significantly more cumbersome (and error prone) than we are used to in the QCD community

QCD Vertices

```
[ g , g , g           ; gs='1', gw='0']
[ g , g , g , g       ; gs='2', gw='0']
[ ghGbar , ghG , g    ; gs='1', gw='0']
[ ubar , u , g        ; gs='1', gw='0']
[ cbar , c , g        ; gs='1', gw='0']
[ tbar , t , g        ; gs='1', gw='0']
[ dbar , d , g        ; gs='1', gw='0']
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[ bbar , b , g        ; gs='1', gw='0']
```



SM Vertices

```
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[ a , Wp , Gm , H     ; gs='0', gw='2']
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[ bbar , b , Z        ; gs='0', gw='1']
```

Technical Challenges

Many new topologies

Many mass scales

QCD/EW effects potentially relevant

Wider Conceptual Challenges

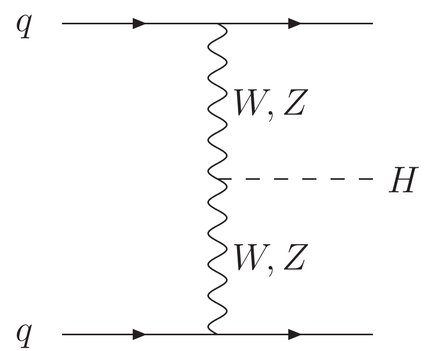
γ_5 with higher-order EW corrections

E.G: von Manteuffel, Stöckinger, Weißwange 25; Stöckinger, Weißwange 23

EW Input Schemes

Tadpole Schemes

Higgs Production: Vector Boson Fusion (VBF)

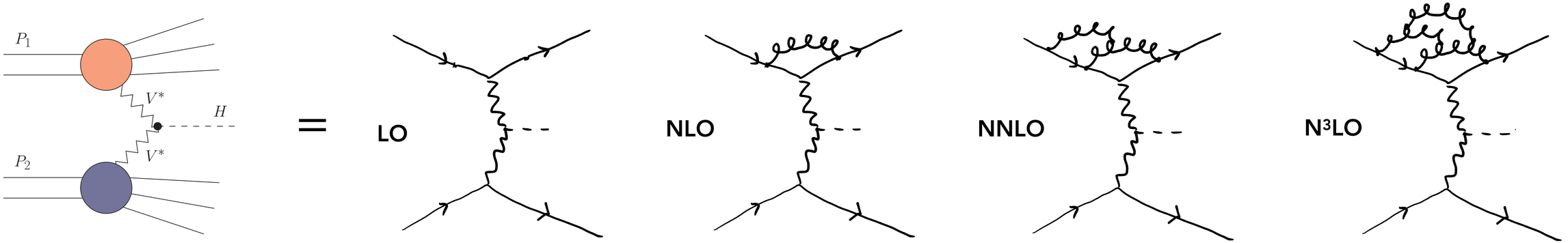


Vector Boson Fusion (VBF)

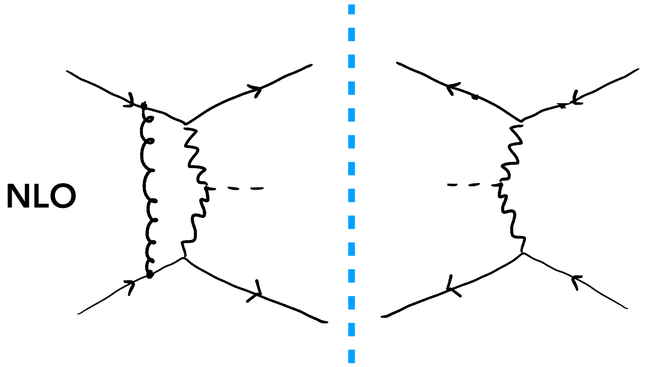
$pp \to Hjj$ with **fiducial** cuts to enhance VBF component: 2 jets, $p_{T,j} > 30\ \text{GeV}$, $m_{jj} > 300\ \text{GeV}$, $|\Delta y_{jj}| > 2$

Known to exclusively (inclusively) to NNLO (N3LO) in the **structure function / DIS approximation**

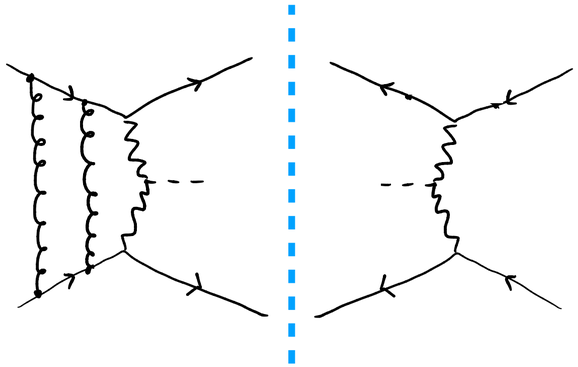
Dreyer, Karlberg 16; Cacciari, Dreyer, Karlberg, Salam, Zanderighi 15,18; Cruz-Martinez, Gehrmann, Glover, Huss 18



NLO: **non-factorisable** virtual contribution vanishes due to colour conservation



NNLO: get colour suppressed **non-factorisable** contribution



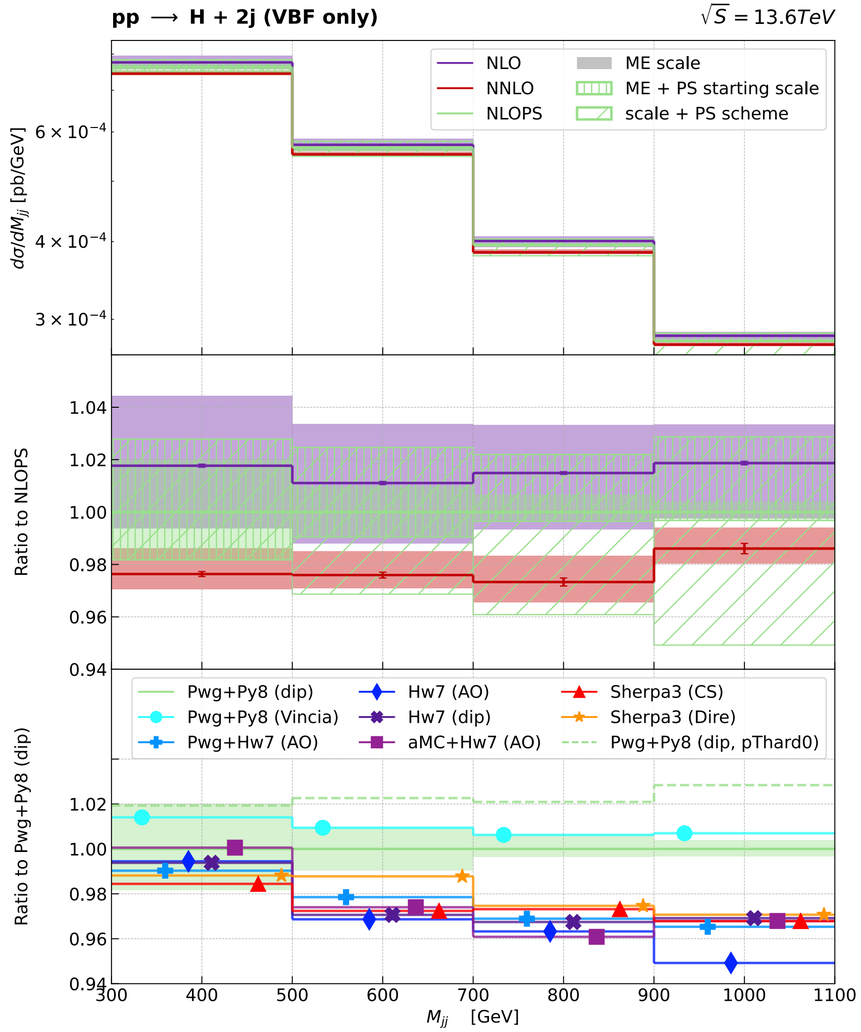
Vector Boson Fusion (VBF)

Significant theoretical effort to produce state-of-the-art predictions for this channel

Need fiducial predictions combining many different pieces and approximations

A. Buckley, et al 21; LHCHWG-2025-003

Order	σ[pb]	δ[%]
VBF approx.		
LO $[\alpha^3]$	2.479(1)	-
NLO QCD $[\alpha^3\alpha_s]$	-0.300(3)	-12.1
NNLO QCD $[\alpha^3\alpha_s^2]$	-0.088(7)	-3.55
NNLO QCD non-fact. $[\alpha^3\alpha_s^2]$	-0.0053766(7)	-0.22
Full		
LO $[\alpha^3]$	2.4772(1)	-
NLO QCD $[\alpha^3\alpha_s]$	-0.2648(10)	-10.7
NLO EW $[\alpha^4]$	-0.14759(5)	-5.95
Photon induced $[\alpha^4]$	0.021286(2)	+0.86
Loop induced int. $[\alpha^2\alpha_s^2]$	-0.003301(1)	-0.01
Loop induced squ. $[\alpha\alpha_s^4]$	0.136403(9)	5.5
LO ggF $[\alpha\alpha_s^4]$	1.7751(6)	71.5
$g\gamma \to$ ggH $[\alpha^2\alpha_s^3]$	$4.3(1) \times 10^{-6}$	0.0
Best prediction		
pp $\to$ Hjj	2.041(9)	-17.6



(b) 120 GeV < $p_{T,H}$ <260 GeV

Treatment of irreducible backgrounds (e.g. gluon-fusion) also involved

X. Chen, S. Ferrario Ravasio, Y. Haddad, S. Höche, J. Huston, T. Jezo, J. Liu, C. T. Preuss, A. Tarek, J. Winter 25

HH Uncertainties

YR4: Total Cross Section & Scale Uncertainty @ 14 TeV

Review of the status of HH shortly after the Yellow Report 4 (~2016-2018)

	$\sigma_{\rm LO}$ (fb)	$\sigma_{\rm NLO}$ (fb)	$\sigma_{\rm NNLO}$ (fb)	$\sigma_{\rm N3LO}$ (fb)
Basic HTL	$17.07^{+30.9\%}_{-22.2\%}$	$31.93^{+17.6\%}_{-15.2\%}$	$37.52^{+5.2\%}_{-7.6\%}$	$38.65^{+0.65\%}_{-2.7\%}$
B-i/proj HTL	$19.85^{+27.6\%}_{-20.5\%}$	$38.32^{+18.1\%}_{-14.9\%}$	$39.58^{+1.4\%}_{-4.7\%}$	$40.44^{+1.9\%}_{-4.7\%}$
FTapprox	$19.85^{+27.6\%}_{-20.5\%}$	$34.25^{+14.7\%}_{-13.2\%}$	$36.69^{+2.1\%}_{-4.9\%}$	–
Full Theory	$19.85^{+27.6\%}_{-20.5\%}$	$32.88^{+13.5\%}_{-12.5\%}$	–	–
NLO-i. HTL	–	$32.88^{+13.5\%}_{-12.5\%}$	$38.66^{+5.3\%}_{-7.7\%}$	$39.56^{+0.64\%}_{-2.7\%}$

$\sqrt{s} = 14$ TeV

PDF4LHC15_nlo/nnlo

$m_H = 125$ GeV $\quad m_T = 173$ GeV

$\mu_R = \mu_F = \dfrac{m_{HH}}{2}$

$\mu \in \left[\dfrac{\mu_0}{2}, 2\mu_0\right] \quad (7-\text{point})$

Chen, Li, Shao, Wang 19, 19; Grazzini, Heinrich, SPJ, Kallweit, Kerner, Lindert, Mazzitelli 18;
de Florian, Grazzini, Hanga, Kallweit, Lindert, Maierhöfer, Mazzitelli, Rathlev 16; Maltoni, Vryonidou, Zaro 14;
Borowka, Greiner, Heinrich, SPJ, Kerner, Schlenk, Schubert, Zirke 16; Dawson, Dittmaier, Spira 98; Glover, van der Bij 88

If we trust the NLO + N^{m}LO HTL combinations

Scale: $+2.1\,\% / -4.9\,\%$ PDF+α_s: $\pm 2.2\,\%$ m_T approx: $\pm 2.7\,\%$ m_T scheme: $+4.0\,\% / -18.0\,\%$

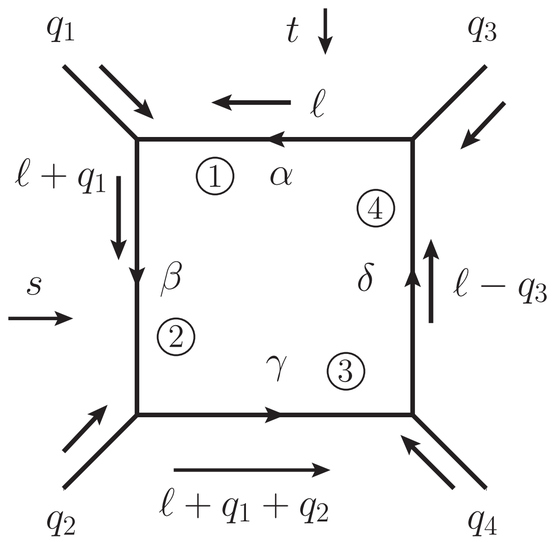
LHC HWG HH Twiki

Expansion of $gg \to HH$ @ 1-loop

Jaskiewicz, SPJ, Szafron, Ulrich 25

Limit: $s, |t|, |u| \gg m_t^2 \gg m_H^2\,, \quad m_H^2 \to 0$ and $\lambda \sim m_t/Q$

Kinematics: $s + t + u = 0, \quad m_H = 0$



$$\int \frac{d^d\ell}{(2\pi)^d} \frac{1}{\ell^2 - m_t^2} \frac{1}{(\ell + q_1)^2 - m_t^2} \frac{1}{(\ell + q_1 + q_2)^2 - m_t^2} \frac{1}{(\ell - q_3)^2 - m_t^2}$$

↓

Hard region $\mathbf{u}^{(0)} = (0,0,0,0)$

↓

Every propagator scales as λ^0

Achieved by **hard scaling** of the loop momenta $\ell^\mu = Q(1,1,1)$

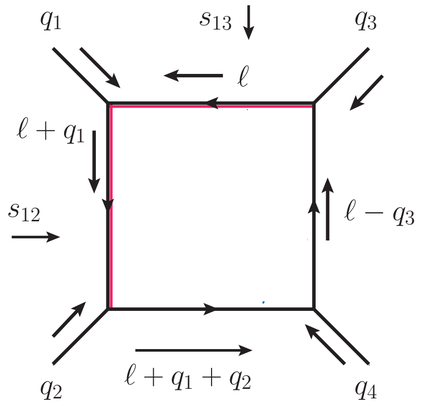
↓

$$\int \frac{d^d\ell}{(2\pi)^d} \frac{1}{\ell^2} \frac{1}{(\ell + q_1)^2} \frac{1}{(\ell + q_1 + q_2)^2} \frac{1}{(\ell - q_3)^2} \sim \lambda^0$$

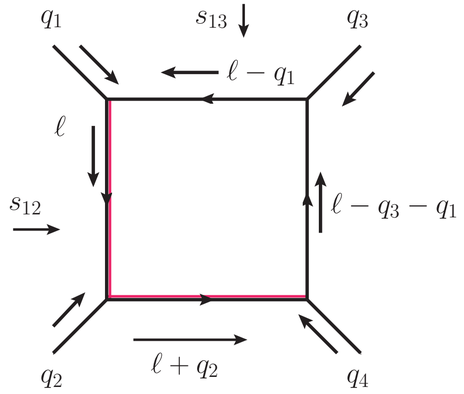
Expansion of $gg \to HH$ @ 1-loop

Jaskiewicz, SPJ, Szafron, Ulrich 25

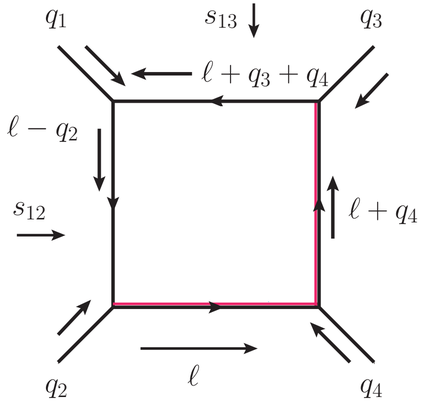
Collinear Regions



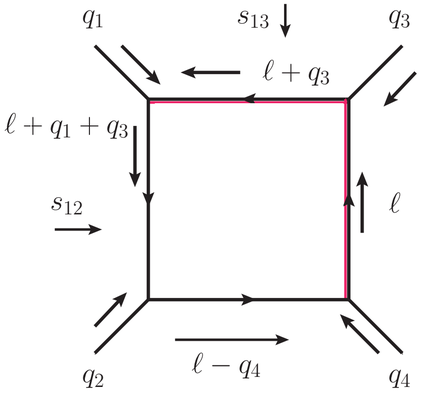
$\mathbf{u}^{(1)} = (-2,-2,0,0)$



$\mathbf{u}^{(2)} = (0,-2,-2,0)$



$\mathbf{u}^{(4)} = (0,0,-2,-2)$



$\mathbf{u}^{(3)} = (-2,0,0,-2)$

Collinear q_1 region $\ell^\mu = Q(1,\lambda^2,\lambda)$

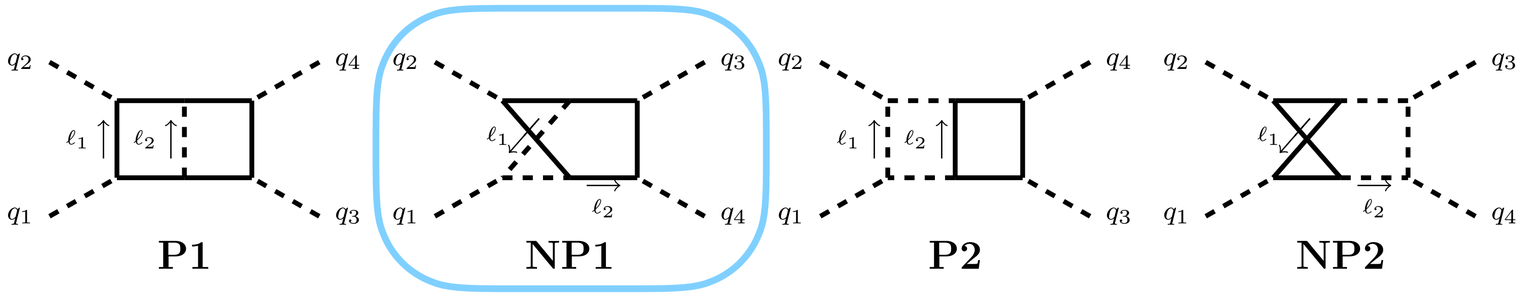
$$\int \underbrace{\frac{d^d\ell}{(2\pi)^d}}_{\lambda^4} \underbrace{\frac{1}{\ell^2 - m_t^2}}_{\frac{1}{\lambda^2}} \underbrace{\frac{1}{(\ell+q_1)^2 - m_t^2}}_{\frac{1}{\lambda^2}} \frac{1}{2(\ell+q_1)\cdot q_2} \frac{1}{-2\ell\cdot q_3}$$

Collinear regions are also leading power at the level of scalar integrals!

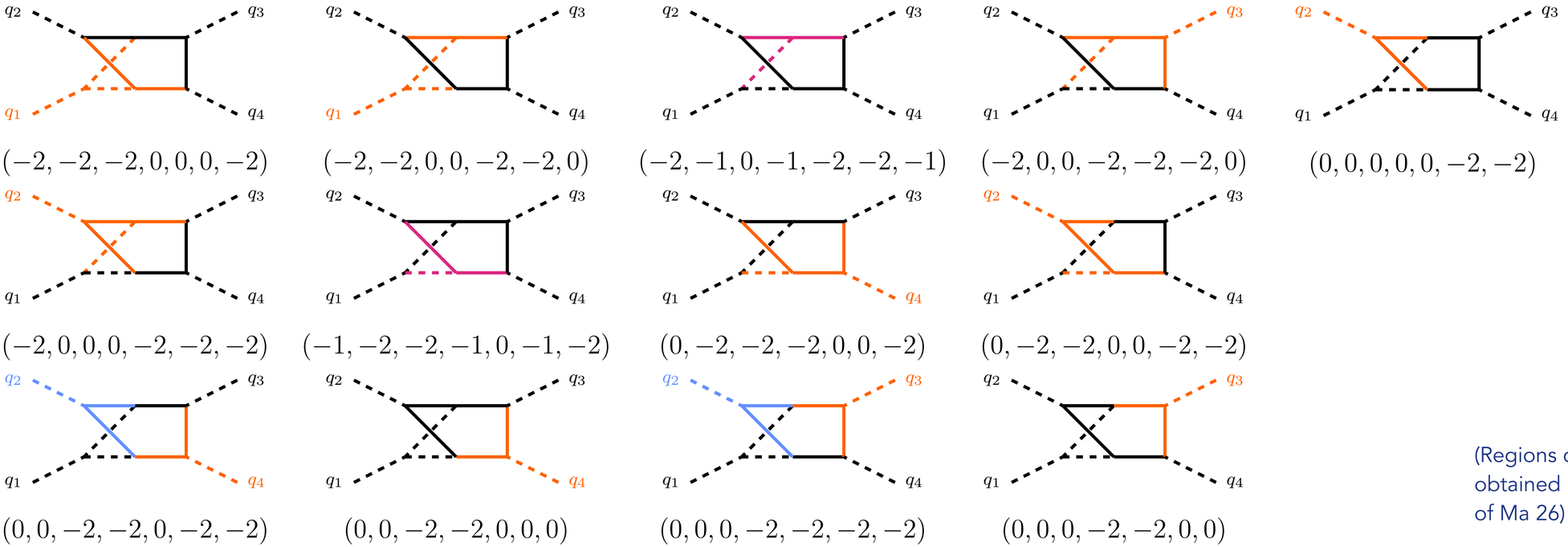
High-Energy Expansion of $gg \to HH$ @ 2-loops

Jaskiewicz, SPJ, Szafron, Ulrich 25

Topologies



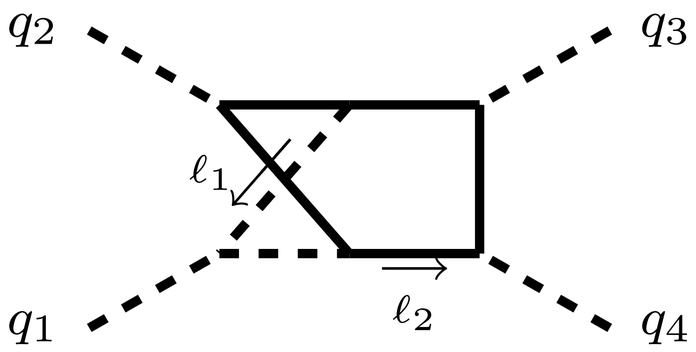
Regions (Parameter Space)



(Regions can also be obtained using analysis of Ma 26)

High-Energy Expansion of $gg \to HH$ @ 2-loops

Jaskiewicz, SPJ, Szafron, Ulrich 25



New features:

1. Soft modes appear $l_S^\mu = Q(\lambda, \lambda, \lambda)$
2. Soft regions are power enhanced at level of scalar integral

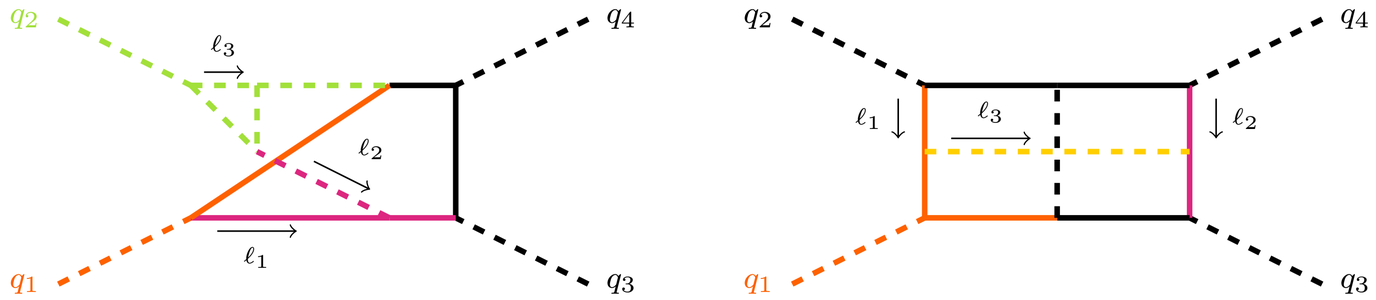
$\mathbf{u}^R$	order	interpretation	routing
(-2, -2, -2, 0, 0, 0, -2)	-4ϵ	$c_1 c_1$	ℓ_1, ℓ_2
(-2, -2, 0, 0, -2, -2, 0)	-4ϵ	$c_1 c_1$	$\ell_1, \ell_2 - q_3 - q_4$
(-2, -1, 0, -1, -2, -2, -1)	$-1-4\epsilon$	ss	$\ell_1, \ell_2 - q_3 - q_4$
(-2, 0, 0, -2, -2, -2, 0)	-4ϵ	$c_3 c_3$	$\ell_1, \ell_2 - q_4$
(-2, 0, 0, 0, -2, -2, -2)	-4ϵ	$c_2 c_2$	$\ell_1, \ell_2 - q_3 - q_4$
(-1, -2, -2, -1, 0, -1, -2)	$-1-4\epsilon$	ss	$\ell_1 - q_1, \ell_2$
(0, -2, -2, -2, 0, 0, -2)	-4ϵ	$c_4 c_4$	$\ell_1 - q_1, \ell_2$
(0, -2, -2, 0, 0, -2, -2)	-4ϵ	$c_2 c_2$	$\ell_1 - q_1, \ell_2$
(0, 0, -2, -2, 0, -2, -2)	-4ϵ	$c_4 \bar{c}_2$	$\ell_1 - \ell_2 + q_3 + q_4, \ell_1$
(0, 0, -2, -2, 0, 0, 0)	-2ϵ	$c_4 h$	$\ell_1 - \ell_2 + q_3 + q_4, \ell_1$
(0, 0, 0, -2, -2, -2, -2)	-4ϵ	$c_3 \bar{c}_2$	$\ell_1 - \ell_2 + q_3, \ell_1 - q_4$
(0, 0, 0, -2, -2, 0, 0)	-2ϵ	$c_3 h$	$\ell_1 - \ell_2 + q_3, \ell_1 - q_4$
(0, 0, 0, 0, 0, -2, -2)	-2ϵ	$h c_2$	$\ell_1, \ell_1 + \ell_2 - q_3 - q_4$
(0, 0, 0, 0, 0, 0, 0)	0	hh	n/a

Can again find momentum space interpretation

High-Energy Expansion of $gg \to HH$ @ 3-loops

Jaskiewicz, SPJ, Szafron, Ulrich 25

Considering $gg \to HH$ diagrams at 3-loops we systematically checked for new loop momenta modes



Indeed find new modes entering

Hard-collinear $l^\mu_{HC_i} = Q(1, \lambda, \lambda^{\frac{1}{2}})$

Soft-collinear $l^\mu_{SC_i} = Q(\lambda, \lambda^2, \lambda^{\frac{3}{2}})$

Ultra-soft $l^\mu_{US} = Q(\lambda^2, \lambda^2, \lambda^2)$

Expect new modes entering at each loop order, consistent with results in the literature

Ma 23

Amplitude Level Results @ 2-loop

Jaskiewicz, SPJ, Szafron, Ulrich 25

Could compute each region at 2-loops (tedious), can instead examine numerator prior to reduction

Region $c_1 c_1$

$$\ell_1^\mu \sim \ell_2^\mu \sim Q(1, \lambda^2, \lambda)$$

$$l_1^2 \sim \lambda^2 Q^2, \qquad l_2^2 \sim \lambda^2 Q^2, \qquad l_1 \cdot l_2 \sim \lambda^2 Q^2,$$
$$l_1 \cdot q_1 \sim \lambda^2 Q^2, \qquad l_2 \cdot q_1 \sim \lambda^2 Q^2,$$
$$l_1 \propto q_1, \qquad l_2 \propto q_1 .$$

Inserting into amplitude, projecting form factors and computing traces

Numerator gives a λ^2 suppression for all soft/collinear regions

Region ss

$$\ell_1^\mu \sim \ell_2^\mu \sim Q(\lambda, \lambda, \lambda)$$

$$l_1^2 \sim \lambda^2 Q^2, \qquad l_2^2 \sim \lambda^2 Q^2, \qquad l_1 \cdot l_2 \sim \lambda^2 Q^2,$$
$$l_1 \cdot q_2 \sim \lambda^2 Q^2, \qquad l_1 \cdot q_3 \sim \lambda^2 Q^2, \qquad l_1 \cdot q_4 \sim \lambda^2 Q^2,$$
$$l_2 \cdot q_2 \sim \lambda^2 Q^2, \qquad l_2 \cdot q_3 \sim \lambda^2 Q^2, \qquad l_2 \cdot q_4 \sim \lambda^2 Q^2,$$

Consistent with the result of Steinhauser et al. for the $m_t \to 0$ limit

Davies, Mishima, Steinhauser, Wellmann 18;

Suggests that regions other than the hard region are **helicity suppressed** by at least $\lambda \sim m_t$

Effective field theory Analysis

Jaskiewicz, SPJ, Szafron, Ulrich 25

Study amplitude using Soft Collinear Effective Theory (SCET)

Bauer, Fleming, Pirjol, Stewart 00; Bauer, Pirjol, Stewart 01;
Beneke, Chapovsky, Diehl, Feldmann 02; Beneke, Feldmann 02

$$\psi(x) \to \underbrace{\psi_1(x)+\ldots+\psi_N(x)}_{N\,\text{collinear fermion fields}} + q(x) \qquad \mathscr{L}_{\text{SCET}} = \sum_{i=1}^{N} \mathscr{L}_{c_i} + \mathscr{L}_{\text{soft}}$$

Lagrangians belong to a specific collinear direction
Can be expanded in powers of the small parameter

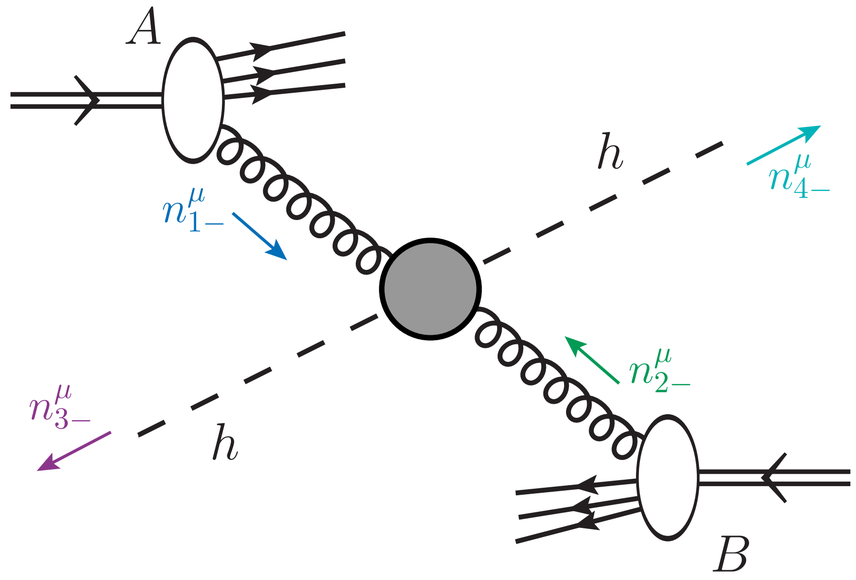
$$\mathscr{L}_{c_i} = \underbrace{\mathscr{L}^{(0)}_{c_i}}_{\text{LP}} + \underbrace{\mathscr{L}^{(1)}_{c_i}}_{\mathcal{O}(\lambda^1)} + \underbrace{\mathscr{L}^{(2)}_{c_i}}_{\mathcal{O}(\lambda^2)} + \ldots$$

Keep collinear, anti-collinear, and soft degrees of freedom
Hard modes are integrated out

Generic N-jet operator has the form:

Beneke, Garny, Szafron,
Wang 17, 17, 18, 19

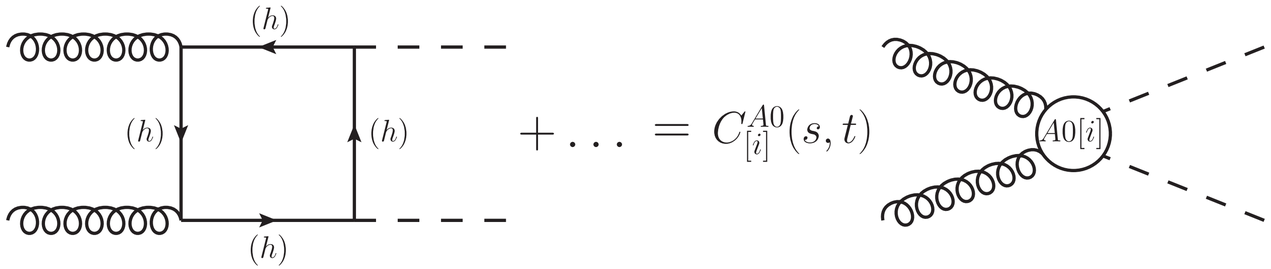
$$J = \int \left[\prod_{ik} dt_{i_k}\right] C(\{t_{i_k}\}) \prod_{i=1}^{N} J_{c_i}(t_{i_1}, t_{i_2} \ldots)$$



Leading Power Analysis

Jaskiewicz, SPJ, Szafron, Ulrich 25

Leading power matching $J^{[i]}_{\rm LP}(t_1,t_2,t_3,t_4) = y_t^2\, P_i^{\mu\nu}\; \mathscr{A}_{c_1\perp_1\,\mu}(t_1 n_{1+})\, \mathscr{A}_{c_2\perp_2\,\nu}(t_2 n_{2+})\; h_{c_3}(t_3 n_{3+})\; h_{c_4}(t_4 n_{4+})$



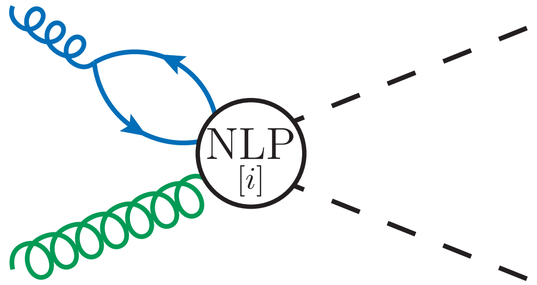
Collinear Regions c_1, c_2 $\mathcal{M}^{\rm QCD}_{\rm LP} \propto \left(\bar v_{c_1}(\bar r q_1)\frac{\not n_{1+}}{2} u_{c_1}(r q_1) n_{3-\nu}\varepsilon^{\nu}_{\perp_1}(q_2) + \bar v_{c_1}(\bar r q_1)\frac{\not n_{1+}}{2}\gamma_5 u_{c_1}(r q_1) n^{\mu}_{3-} i\epsilon^{\perp_1}_{\mu\nu}\varepsilon^{\nu}_{\perp_1}(q_2)\right)$

Relevant operator structures are scalar/pseudoscalar

$$J_{S_i}(\{t_{i_1},t_{i_2}\}) = \bar\chi_{c_i}(t_{i_2} n_{i+})\frac{\not n_{i+}}{2}\,\chi_{c_i}(t_{i_1} n_{i+}),$$

$$J_{P_i}(\{t_{i_1},t_{i_2}\}) = \bar\chi_{c_i}(t_{i_2} n_{i+})\frac{\not n_{i+}}{2}\,\gamma_5\,\chi_{c_i}(t_{i_1} n_{i+}),$$

Mixing with the external gluon is forbidden at LP



Leading Power Analysis

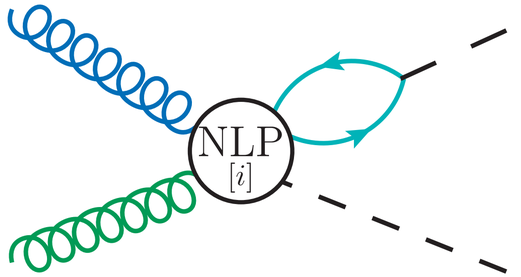
Jaskiewicz, SPJ, Szafron, Ulrich 25

Collinear Regions c_3, c_4

$$\mathcal{M}_{\rm LP}^{\rm QCD} \sim i g_s^2 \mathbf{T}^B \mathbf{T}^A \left[\frac{g_W y_t}{2}\right] \bar{v}_{c_3}(q') \frac{1}{\bar{r}(n_{3+}q_3)} \left[\frac{2 n_{3-\mu}}{(n_{1+}q_1) n_{3-}\cdot n_{1-}} \frac{\not{n}_{3+}}{2} \gamma_{\nu\perp_3} u_{c_3}(q) + \frac{1}{r(n_{3+}q_3)} n_{3+\nu} \frac{\not{n}_{3+}}{2} \gamma_{\mu\perp_3} u_{c_3}(q)\right] \varepsilon^{\nu}_{\perp_2}(q_2)\ \varepsilon^{\mu}_{\perp_1}(q_1)$$

Situation reversed, structures appearing at LP are vector-like

Mixing with the external Higgs is forbidden at LP

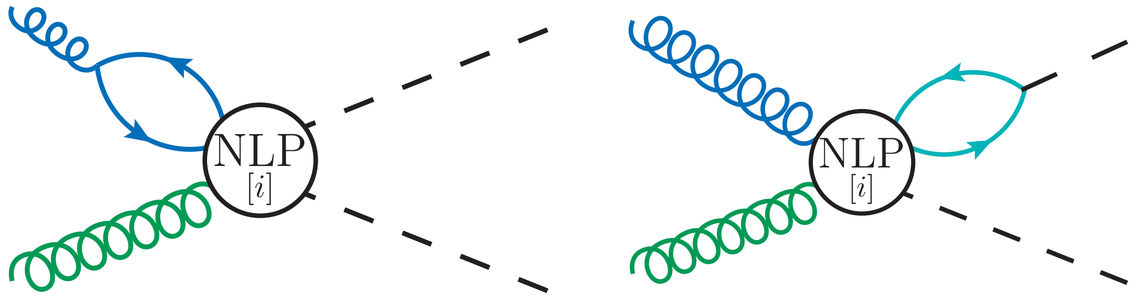


Result holds to all orders in α_s due to helicity conservation for $m_t \to 0$

Next-to-Leading Power

Structure of the amplitude allows mixing with external gluon/Higgs

Expect contributions from collinear/soft regions



Leading Power Analysis

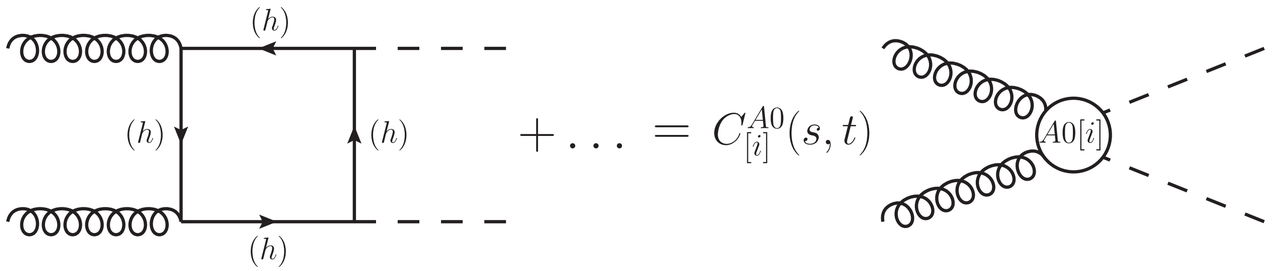
Jaskiewicz, SPJ, Szafron, Ulrich 25

Soft Collinear Effective Theory (SCET) an approximation of QCD based on soft/collinear expansion Bauer, Fleming, Pirjol, Stewart, Beneke, Chapovsky, Diehl, Feldmann, …

$$\psi(x) \to \underbrace{\psi_1(x) + \ldots + \psi_N(x)}_{N \text{ collinear fermion fields}} + q(x)$$

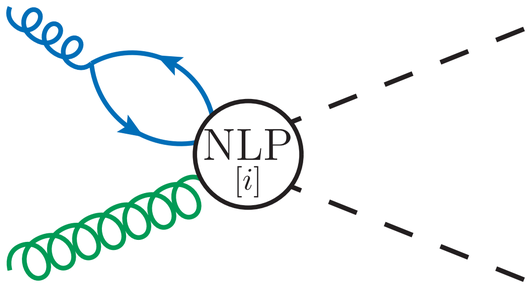
Leading power matching

$$J^{[i]}_{\rm LP}(t_1,t_2,t_3,t_4) = y_t^2\, P_i^{\mu\nu}\; \mathscr{A}_{c_1\perp_1\,\mu}(t_1 n_{1+})\, \mathscr{A}_{c_2\perp_2\,\nu}(t_2 n_{2+})\; h_{c_3}(t_3 n_{3+})\; h_{c_4}(t_4 n_{4+})$$



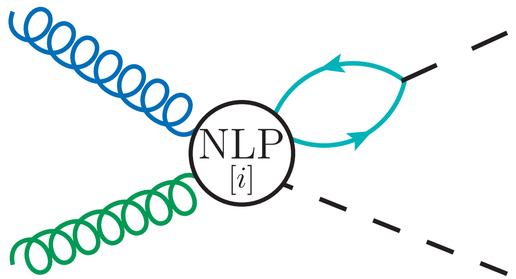
Collinear Regions c_1, c_2

Mixing with the external gluon is forbidden at LP



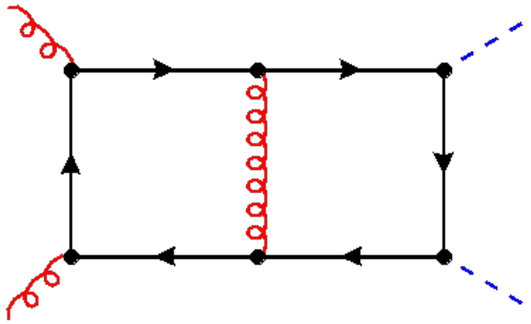
Collinear Regions c_3, c_4

Mixing with the external Higgs is forbidden at LP



Result holds to all orders in α_s due to helicity conservation for $m_t \to 0$

QCD Corrections



Parton Showers: NNLO + PS

Alioli, Billis, Broggio, Gavardi, Kallweit et al 22
Alioli, Marinelli, Napoletano 25

Several NLO+PS results available for some time

↪ MadGraph & POWHEG

↪ Sherpa

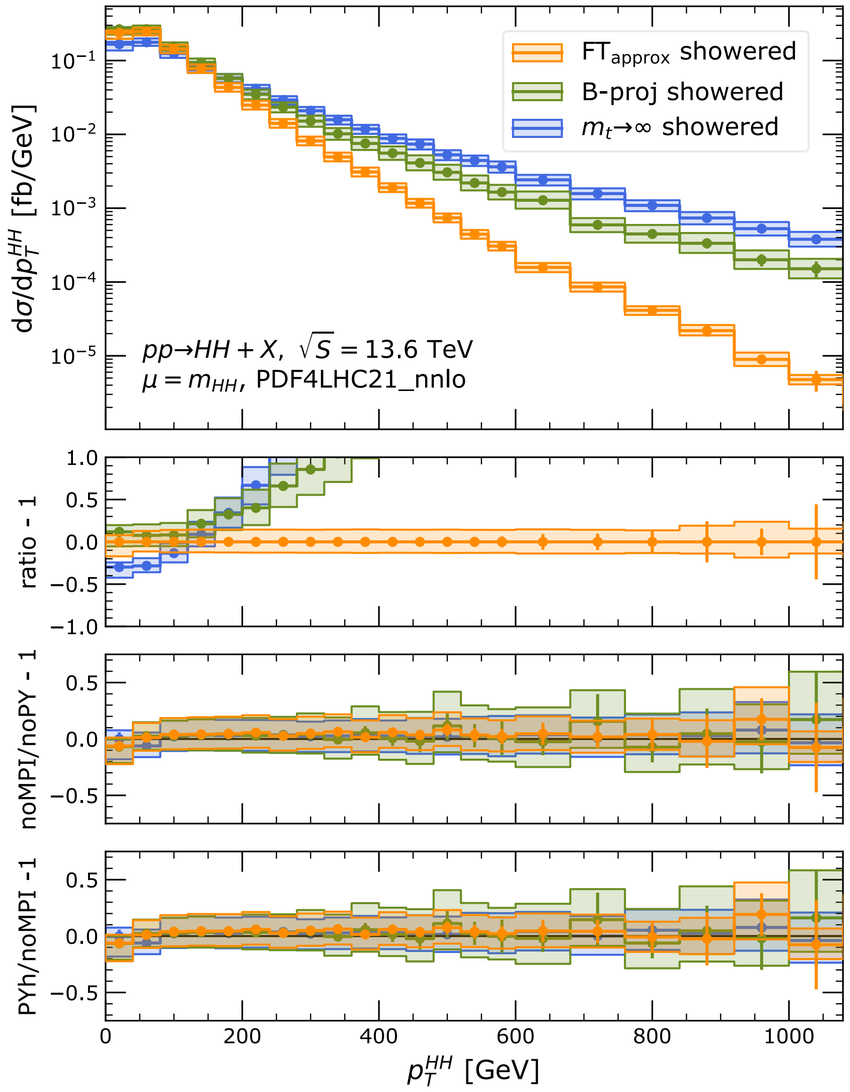
Heinrich, SPJ, Kerner, Luisoni, Vryonidou 17; SPJ, Kuttimalai 17;
+κ_3, y_t variations: Heinrich, SPJ, Kerner, Luisoni, Scyboz 19;
Bagnaschi, Degrassi, Gröber 23;
+HEFT: Heinrich, SPJ, Kerner, Scyboz 20
+SMEFT: Heinrich, Lang, Scyboz 22; Heinrich, Lang 23, 24;

Can suffer from very large shower scale uncertainties, especially for LO accurate distributions such as p_T^{HH}

NNLO+PS results including top-mass corrections

↪ Reproduces $\mathrm{FT}_{\mathrm{approx}}$ result of MATRIX, adds PYTHIA shower

↪ Uses GENEVA framework, adds resummation of τ_0 to NNLL'



NLO QCD Corrections: ggxy

Davies, Mishima, Schönwald, Steinhauser 23
Davies, Schönwald, Steinhauser, Stremmer 25

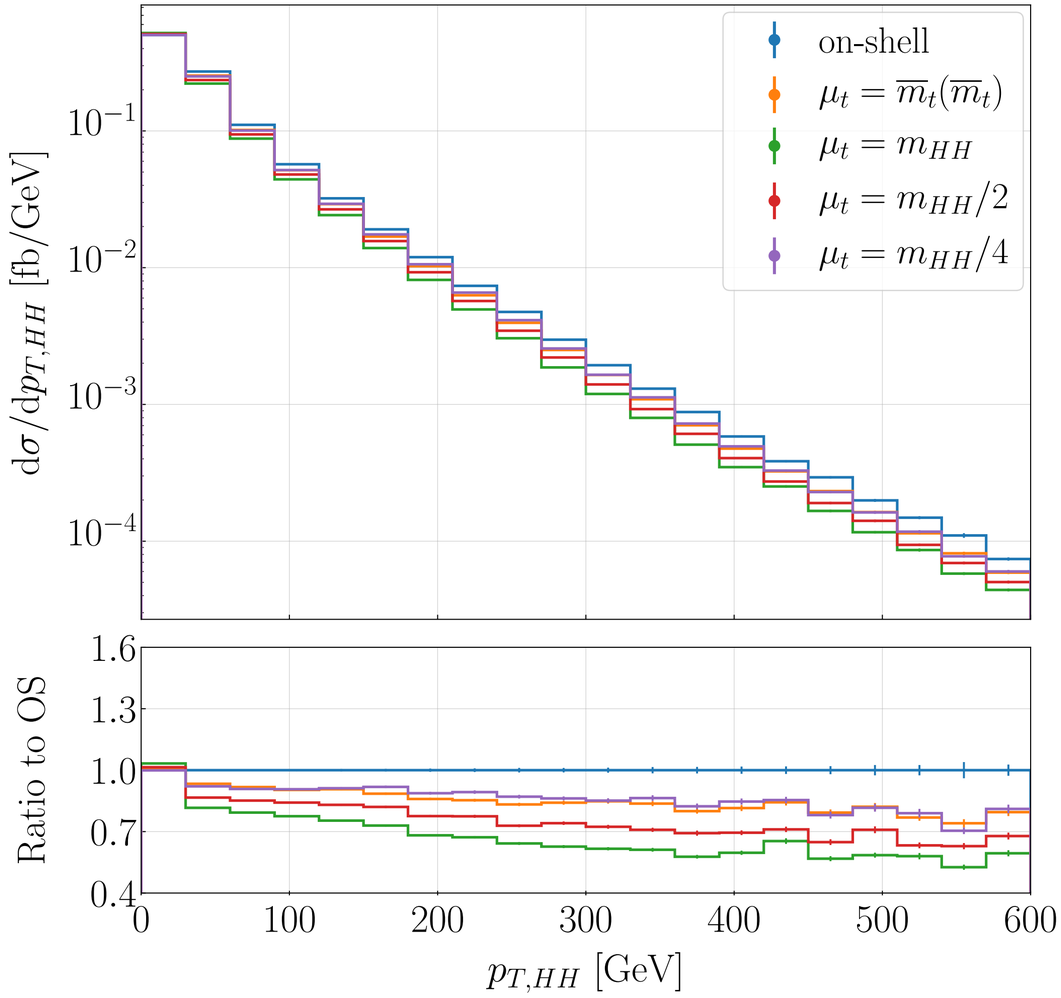
Fast C++ library with NLO QCD results for $gg \to HH$

↪ Combines expansions to cover phase-space: forward limit (to m_H^4 and t^5) + high-energy (to m_H^4 and m_t^{120})

↪ Easily vary m_H, m_t and κ_3 for mass-scheme uncertainties/ BSM scans

↪ Linked to Powheg (ggxy_ggHH), around 4-5x faster than existing code (ggHH) Heinrich, SPJ, Kerner, Luisoni, Vryonidou, (Scyboz) 17, 19;

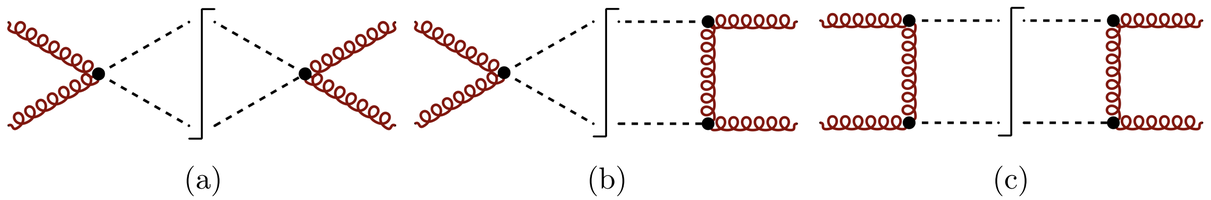
↪ Validated against fully numeric calculations, yields excellent agreement



N³LO HTL + NLO QCD: Fully Differential

Chen, Dai, Tao Li, Li, Shao, Wang 26

Fully differential predictions at N³LO HTL + NLO QCD, can apply experimental fiducial cuts and produce any distribution



Consider various scheme for including NLO m_t effects

$$\mathrm{N}^k\mathrm{LO} \oplus \mathrm{NLO}_{m_t} \quad : \quad d\sigma_{hh}^{\mathrm{N}^k\mathrm{LO}\oplus\mathrm{NLO}_{m_t}} = d\sigma_{hh}^{\mathrm{NLO}_{m_t}} + d\sigma_{hh}^{\mathrm{N}^k\mathrm{LO}} - d\sigma_{hh}^{\mathrm{NLO}} \,,$$

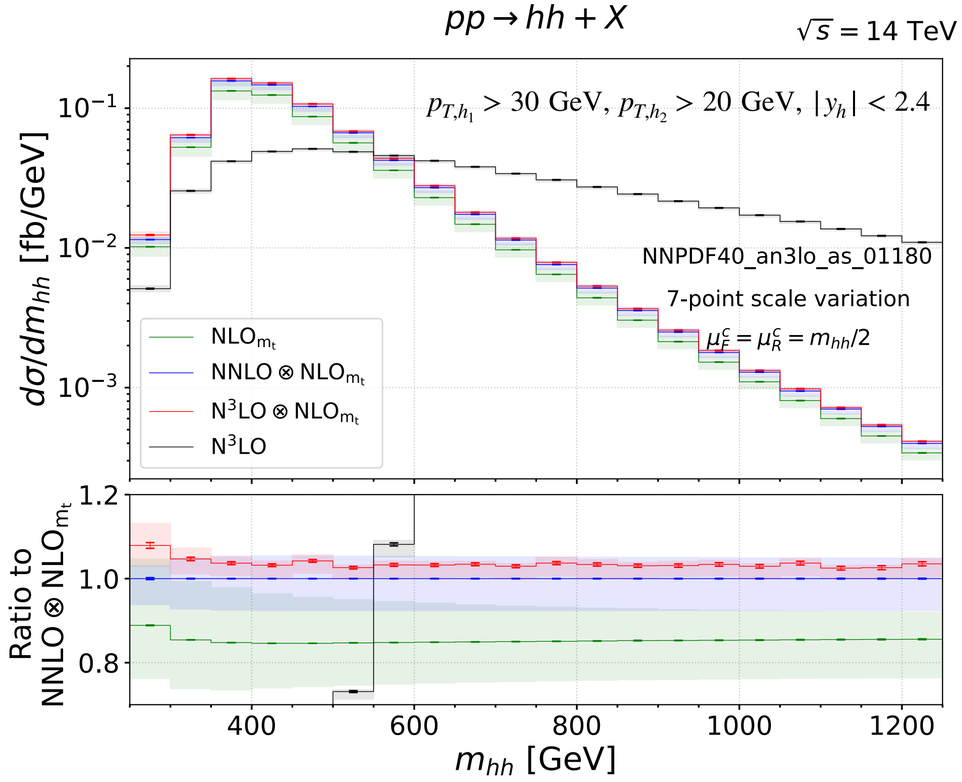
$$\mathrm{N}^k\mathrm{LO}_{\mathrm{B-i}} \oplus \mathrm{NLO}_{m_t} \quad : \quad d\sigma_{hh}^{\mathrm{N}^k\mathrm{LO}_{\mathrm{B-i}}\oplus\mathrm{NLO}_{m_t}} = d\sigma_{hh}^{\mathrm{NLO}_{m_t}} + \left(d\sigma_{hh}^{\mathrm{N}^k\mathrm{LO}} - d\sigma_{hh}^{\mathrm{NLO}}\right)\frac{d\sigma_{hh}^{\mathrm{LO}_{m_t}}}{d\sigma_{hh}^{\mathrm{LO}}} \,,$$

$$\mathrm{N}^k\mathrm{LO} \otimes \mathrm{NLO}_{m_t} \quad : \quad d\sigma_{hh}^{\mathrm{N}^k\mathrm{LO}\otimes\mathrm{NLO}_{m_t}} = d\sigma_{hh}^{\mathrm{N}^k\mathrm{LO}}\frac{d\sigma_{hh}^{\mathrm{NLO}_{m_t}}}{d\sigma_{hh}^{\mathrm{NLO}}} \,,$$

↪ NNLO HTL enhance by 17-20% (depending on comb.)

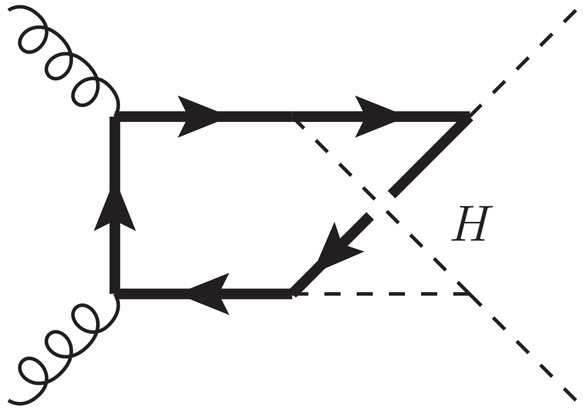
↪ N3LO HTL enhance by 4% (less dependent on comb.)

Scale uncertainties strongly depend on comb. scheme



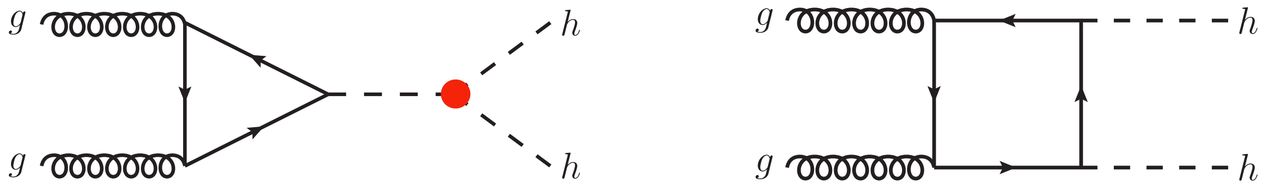
	$\sigma_{hh}^{\mathrm{N}^k\mathrm{LO}\oplus\mathrm{NLO}_{m_t}}$ [fb]	$\sigma_{hh}^{\mathrm{N}^k\mathrm{LO}_{\mathrm{B-i}}\oplus\mathrm{NLO}_{m_t}}$ [fb]	$\sigma_{hh}^{\mathrm{N}^k\mathrm{LO}\otimes\mathrm{NLO}_{m_t}}$ [fb]
$k=1$	$28.44^{+14\%}_{-12\%}$	$28.44^{+14\%}_{-12\%}$	$28.44^{+14\%}_{-12\%}$
$k=2$	$33.30^{+8.1\%}_{-7.2\%}$	$34.03^{+7.6\%}_{-6.8\%}$	$33.40^{+5.2\%}_{-7.3\%}$
$k=3$	$34.56(4)^{+6.8\%}_{-8.0\%}$	$35.47(4)^{+6.6\%}_{-9.2\%}$	$34.68(4)^{+1.4\%}_{-2.9\%}$

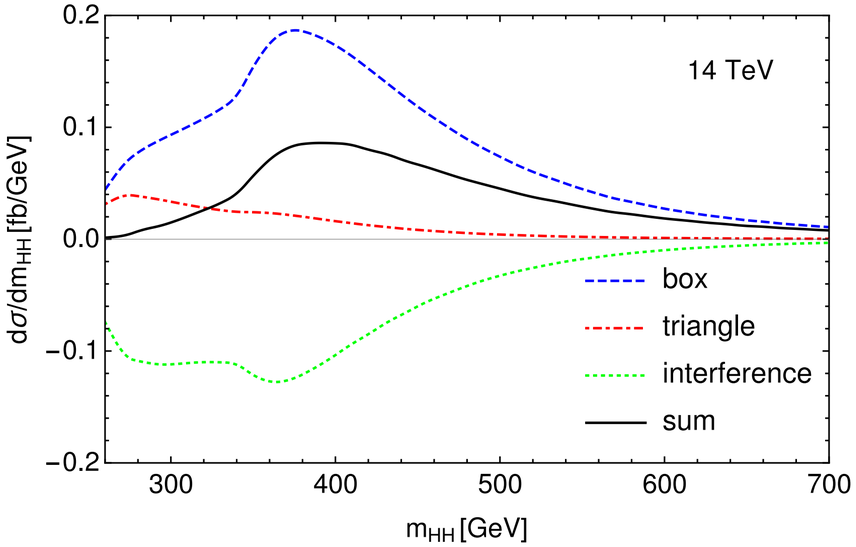
Electroweak Corrections



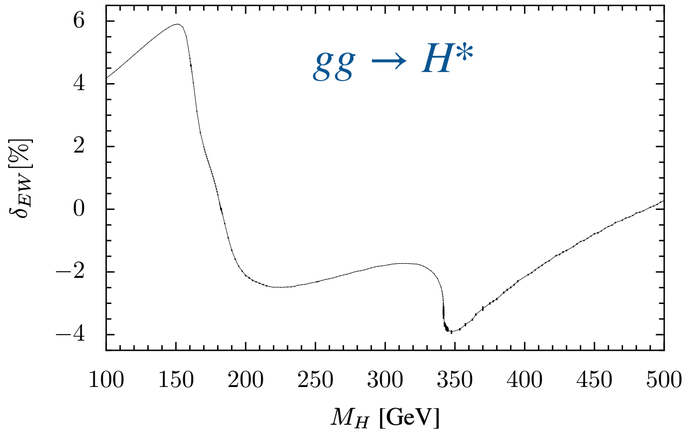
Electroweak Corrections to $gg \to HH$

$pp \to HH$ has a strong interference between the 2 possible LO topologies





Different m_{HH} behaviour of triangle/box heavily exploited by experiments for extracting λ



Electroweak Corrections to $gg \to H^*$ are $\pm 5\,\%$ and **very dependent on** m_H

Actis, Passarino, Sturm, Uccirati 08

Interesting to explore the impact of EW corrections on HH where they can spoil the delicate cancellations happening at LO

NLO Electroweak Corrections to $pp \to HH$

Bonetti, Heinrich, SPJ, Kerner, Rendler, Stone, Vestner (WIP)

We aim to compute all $gg \to HH$ diagrams (retaining control of all couplings) + combine with $q\bar{q} \to HH$ + QCD corrections

Amplitude Structure

$$\mathcal{A}^{c_1 c_2}_{\lambda_1 \lambda_2} = \delta^{c_1 c_2} \epsilon_{\lambda_1,\mu} \epsilon_{\lambda_2,\nu} \left[\mathcal{F}_1 \mathbb{T}^{\mu\nu}_1 + \mathcal{F}_2 \mathbb{T}^{\mu\nu}_2 + \mathcal{F}_3 \mathbb{T}^{\mu\nu}_3 + \mathcal{F}_4 \mathbb{T}^{\mu\nu}_4 \right],$$

$$\mathbb{T}^{\mu\nu}_1 = g^{\mu\nu} - \frac{1}{p_{12}} p_2^\mu p_1^\nu ,$$

$$\mathbb{T}^{\mu\nu}_2 = g^{\mu\nu} + \frac{1}{p_{12} p_T^2} \left(m_h^2 p_2^\mu p_1^\nu - 2 p_{23} p_3^\mu p_1^\nu - 2 p_{13} p_2^\mu p_3^\nu + 2 p_{12} p_3^\mu p_3^\nu \right),$$

← Present at LO/QCD

$$\mathbb{T}^{\mu\nu}_3 = \frac{1}{p_{12}} E^{\mu\nu\alpha\beta} p_{1\alpha} p_{2\beta} ,$$

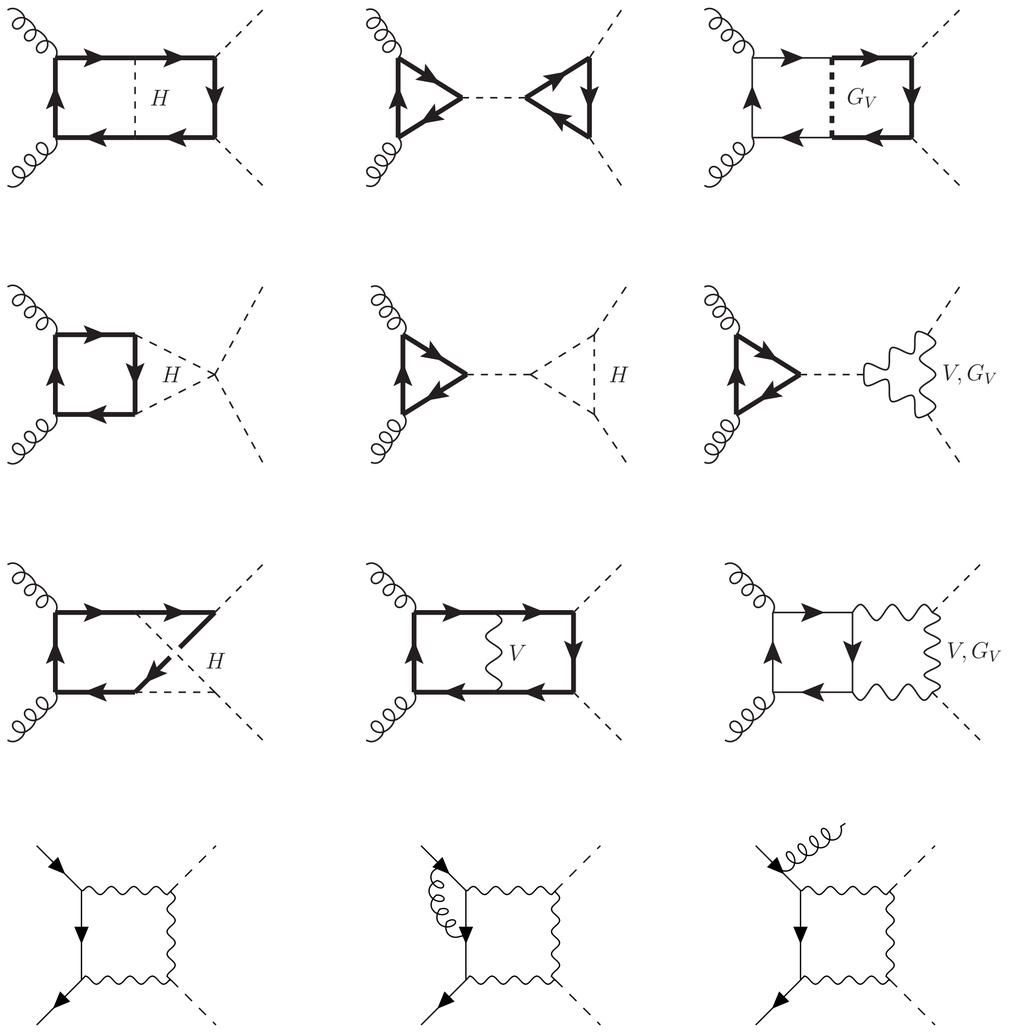
$$\mathbb{T}^{\mu\nu}_4 = \frac{1}{p_{12} p_T^2} \left(p_3^\mu E^{\nu\alpha\beta\omega} p_{1\alpha} p_{2\beta} p_{3\omega} + p_3^\nu E^{\mu\alpha\beta\omega} p_{1\alpha} p_{2\beta} p_{3\omega} + p_{23} E^{\mu\nu\alpha\beta} p_{1\alpha} p_{3\beta} + p_{13} E^{\mu\nu\alpha\beta} p_{2\alpha} p_{3\beta} \right) ,$$

← Parity-violating terms

$\mathbb{T}^{\mu\nu}_3$, $\mathbb{T}^{\mu\nu}_4$ not relevant to NLO EW, nevertheless useful to consider them for safety

General ξ_G, ξ_A gauge for gluons/photons, but general ξ_W, ξ_Z too cumbersome
Perform one calculation in Feynman gauge ($\xi_W = \xi_Z = 1$) and one in unitary gauge ($\xi_W = \xi_Z \to \infty$)
Perform all calculations twice with different tool chains based on FORM and Mathematica/alibrary

Bestiary



Difficult due to the many masses present

$$m_T, m_H, m_W, m_Z$$
$$+s, t$$

Tackled by several groups using an array of techniques!

Figure adapted from Marco Bonetti (LHCHWG R5) + Philip Rendler (LHCHWG 25)

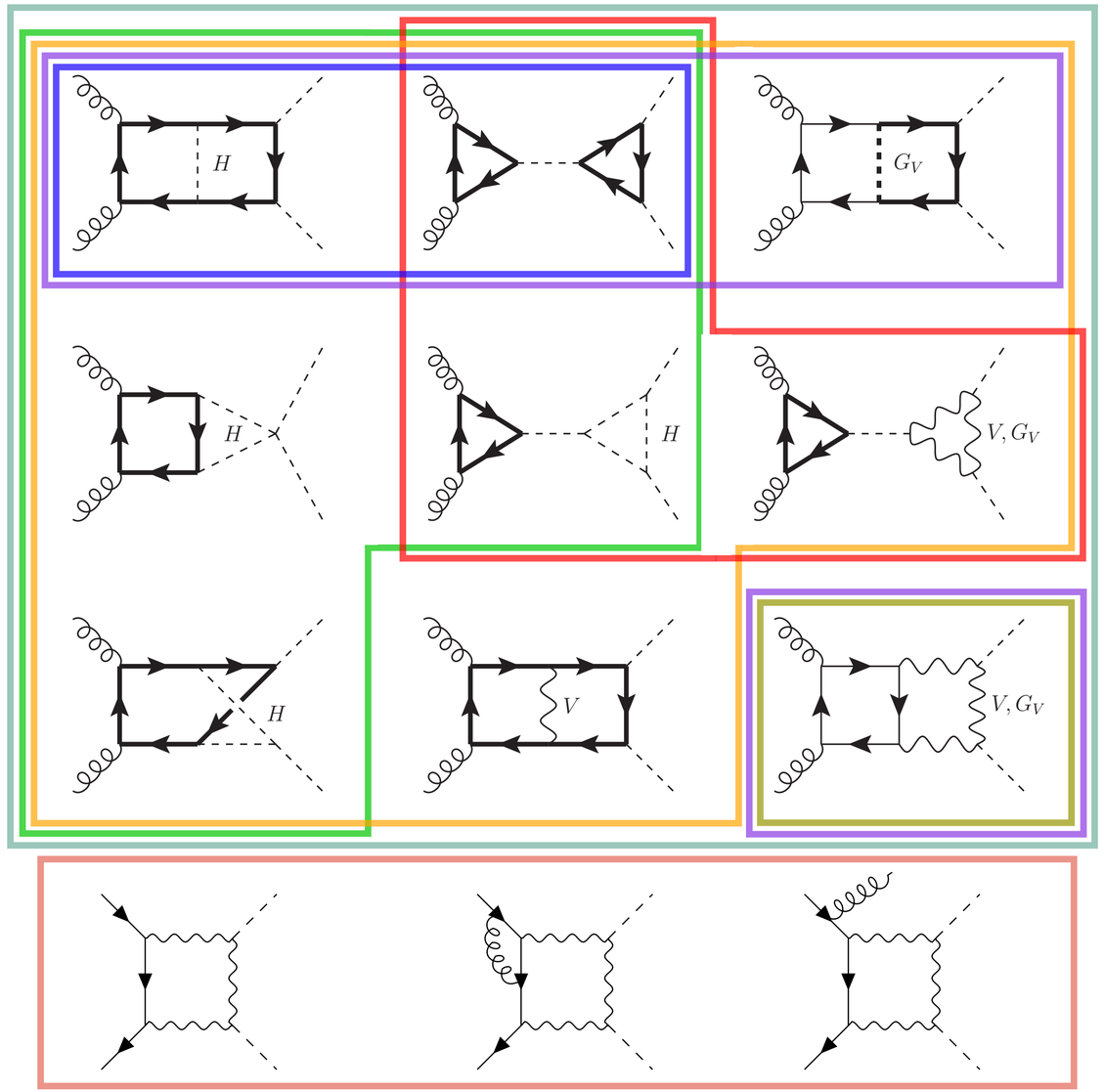


Figure adapted from Marco Bonetti (LHCHWG R5) + Philip Rendler (LHCHWG 25)

Small m_T limit, $m_T \to \infty$, full m_T via numerical integration

Davies, Mishima, Schönwald, Steinhauser, Zhang 22; Mühlleitner, Schlenk, Spira 22; Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, Spira 25

Full m_T by numerically solving DEQs, boundary AMFlow

Bi, Huang, Huang, Ma, Yu 23

Large-m_T expansion

Davies, Schönwald, Steinhauser, Zhang 23

Analytic (factorisable contribution)

Mühlleitner, Schlenk, Spira 22; Davies, Schönwald, Steinhauser, Zhang 24

Full m_T via sector decomposition, Small-m_T expansion

Heinrich, SPJ, Kerner, Stone, Vestner 24; Davies, Schönwald, Steinhauser, Zhang 25;

Analytic + series expansion of DEQs, numerical integration

Bonetti, Rendler, Bobadilla 25; Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, Spira 25;

Analytic + series expansion of DEQs

Bonetti, Heinrich, Rendler, Bobadilla 26

Gluon-Induced Corrections

Bi, Huang, Huang, Ma, Yu 23

Complete NLO EW corrections to $gg \to HH$

Extremely Challenging Calculation

Fully analytic result beyond reach

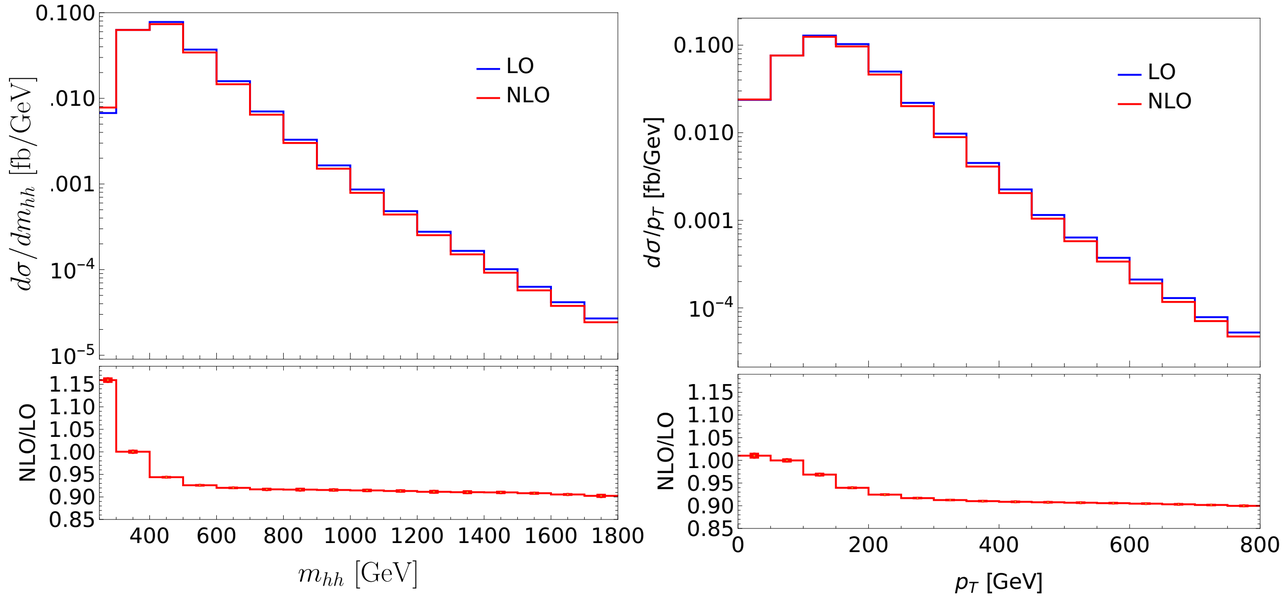
$$\frac{m_H^2}{m_t^2} = \frac{12}{23}, \quad \frac{m_Z^2}{m_t^2} = \frac{23}{83}, \quad \frac{m_W^2}{m_t^2} = \frac{14}{65}, \quad \epsilon = \pm\frac{1}{1000}$$

Renormalise all masses on-shell

Reduce integrals with Blade + FiniteFlow — Guan, Liu, Ma, Wu 25; Peraro 19;

Compute boundary conditions with AMFlow — Liu, Ma, (Wang) (17), 22, 22

Evolve using series solutions of DEQs



Results

K-factor ~ 0.96, very stable with respect to μ_R, μ_F variations

Significant ($\pm 10\,\%$) distortions to m_{HH} and p_T

Corrections reduce dependence on EW input scheme

μ	$m_{hh}/2$	$\sqrt{p_T^2 + m_h^2}$	m_h
LO	19.96(6)	21.11(7)	25.09(8)
NLO	19.12(6)	20.21(6)	23.94(8)
$\mathcal{K}$-factor	0.958(1)	0.957(1)	0.954(1)

schemes	G_μ	α_0	α_{m_Z}
LO	19.96	18.84	21.28
NLO	19.12	19.19	19.03
$\mathcal{K}$-factor	0.958	1.019	0.894

Gluon-Induced Corrections

Davies, Schönwald, Steinhauser, Zhang 25, 26

Complete NLO EW corrections to $gg \to HH$ in the high-energy limit

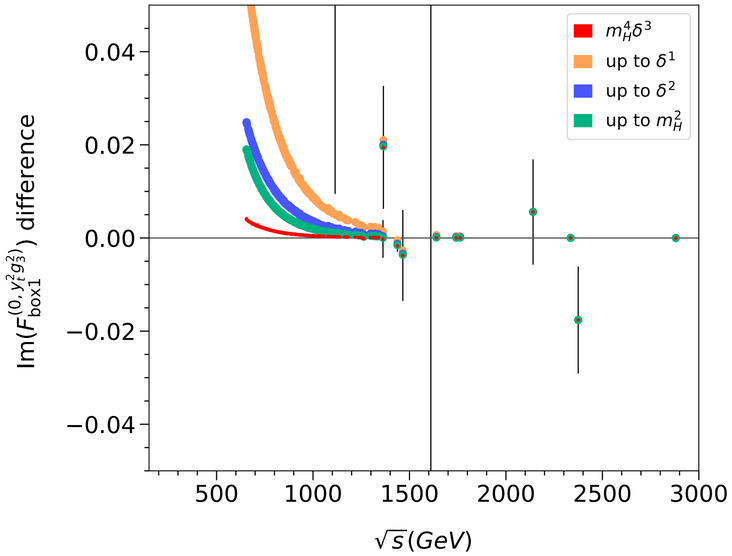
Expansion procedure

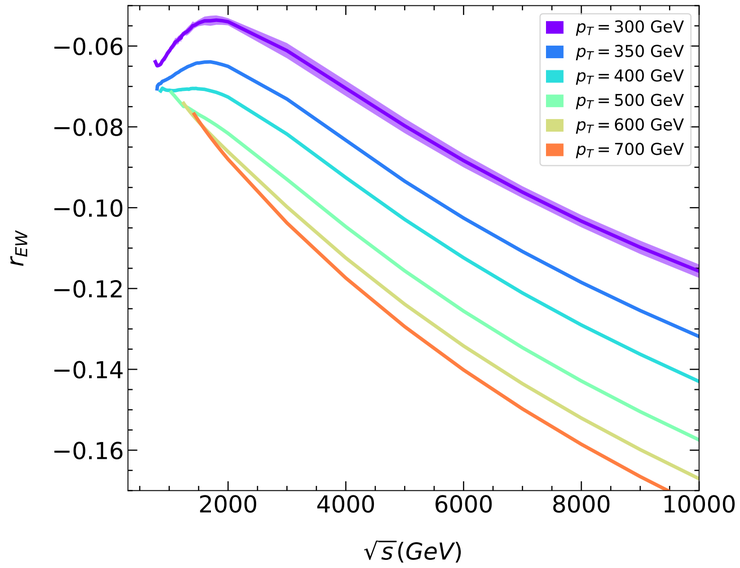
↪ Taylor expand in m_H^{ext} and $\delta = 1 - m_X/m_t$ $(m_X = m_W, m_Z, m_H^{\text{int}})$

↪ Asymptotic expansion $m_t \ll s, t$

Provides analytic expressions for studying structure of EW corrections

Can perform detailed comparison/validation of existing results





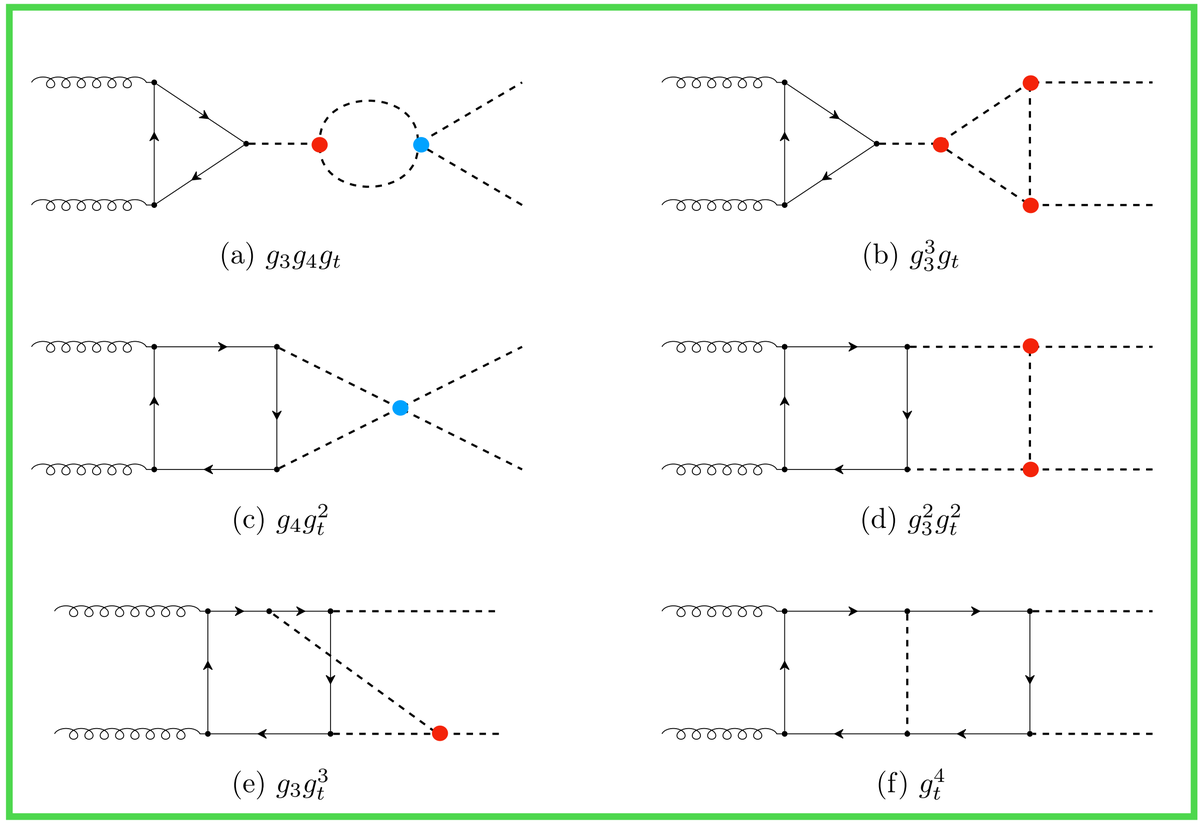
Covers $p_T \gtrsim 350$ GeV with small expansion uncertainty

Reproduce -10%(+) corrections observed at high-energy seen in first calculation of the NLO EW corrections to $gg \to HH$

Results will be made available in ggxy

Yukawa and Self-Coupling Corrections

Heinrich, SPJ, Kerner, Stone, Vestner 24



Calculation neglects diagrams containing vector bosons or Goldstone bosons (i.e. fixed to unitary gauge)

Retain **complete control and generality** in all couplings and diagram types (1PI/1PR)

$$g_{t,0} \equiv \frac{m_{T,0}}{v_0}\,, \qquad g_{3,0} \equiv \frac{3m_{H,0}^2}{v_0}\,, \qquad g_{4,0} \equiv \frac{3m_{H,0}^2}{v_0^2}\,.$$

↪ Couplings can be varied for experimental limit setting

↪ Can adapt calculation for EFTs/BSM scenarios

Adopt G_μ input scheme $\{M_Z = 0, M_W = 0,\ G_F\} + \{m_T, m_H\}$

↪ Can vary the input scheme

Result

Fully symbolic (s, t, m_T, m_H) reduction to basis of 494 finite d-factorising master integrals

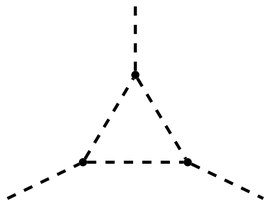
Up to 11 coupled master integrals within a single sector

Keep exact m_T, m_H dependence, evaluate master integrals numerically using pySecDec Heinrich, SPJ, Kerner, Magerya, Olsson, Schlenk 23

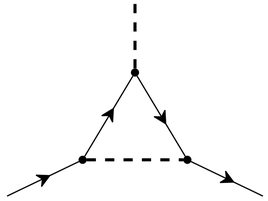
Interpretation

Heinrich, SPJ, Kerner, Stone, Vestner 24

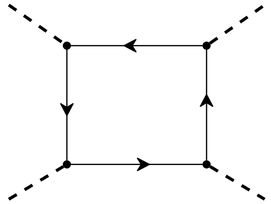
Can fix vev counterterm using any vertex…



$$\delta_v^{g_3}(g_t,g_3,g_4)|_{\rm UV} = -\frac{1}{32\pi^2 g_3 m_H^4\epsilon}\left[g_3 g_4 m_H^4 + 8 g_4 g_t m_H^2 m_T^3 N_c - 8 g_3^2 g_t m_T^3 N_c + 2 g_3 g_t^2 m_H^2\left(m_H^2+12m_T^2\right)N_c - 48 g_t^3 m_H^4 m_T N_c\right]$$



$$\delta_v^{g_t}(g_t,g_3,g_4)|_{\rm UV} = -\frac{g_3 g_t m_H^2 + 2 g_t^2 m_T\left(m_H^2-4m_T^2\right)N_c}{32\pi^2 m_H^2 m_T\epsilon}$$



$$\delta_v^{g_4}(g_t,g_3,g_4)|_{\rm UV} = -\frac{2 g_t g_4 N_c(g_t(m_H^4+6m_H^2m_T^2)-2g_3m_T^3)+g_4^2m_H^4-24g_t^4m_H^4N_c}{32\pi^2 g_4 m_H^4\epsilon}$$

Get different $1/\epsilon$ in renormalisation constants depending on the vertex!

SM limit →

$$\delta_v^{g_t}\left(\frac{m_T}{v},\frac{3m_H^2}{v},\frac{3m_H^2}{v^2}\right)\Big|_{\rm UV} = \delta_v^{g_3}\left(\frac{m_T}{v},\frac{3m_H^2}{v},\frac{3m_H^2}{v^2}\right)\Big|_{\rm UV} = \delta_v^{g_4}\left(\frac{m_T}{v},\frac{3m_H^2}{v},\frac{3m_H^2}{v^2}\right)\Big|_{\rm UV} \overset{!}{=} \delta_v|_{\rm UV}$$

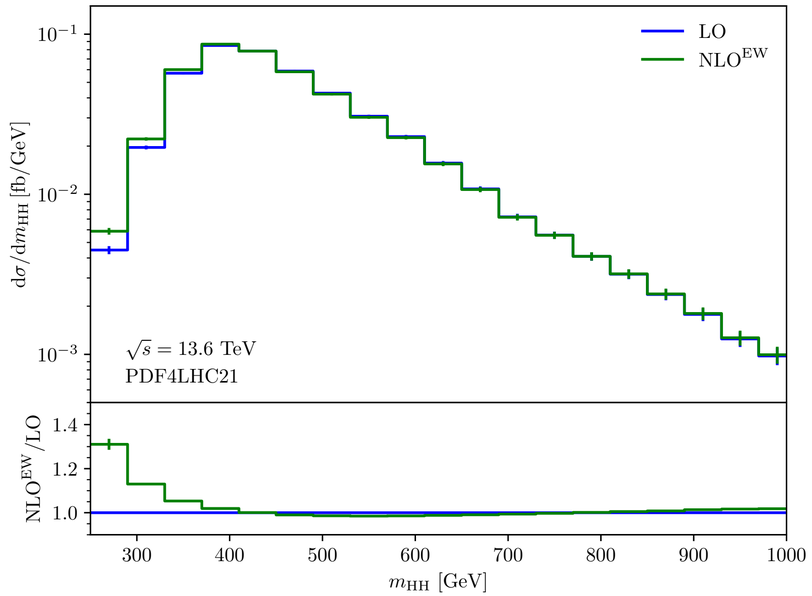
All OK

Ok to talk about κ_3, κ_4 when considering QCD corrections, EW corrections make this much more delicate

Bizoń, Ulrich Haisch, Luca Rottoli 18; Bizoń, Haisch, Rottoli, Gillis, Moser, Windischhofer 24; Tao Li, Si, Wang, Zhang, Zhao 24

NLO Electroweak Corrections to $gg \to HH$

Yukawa/ Self-coupling Corrections



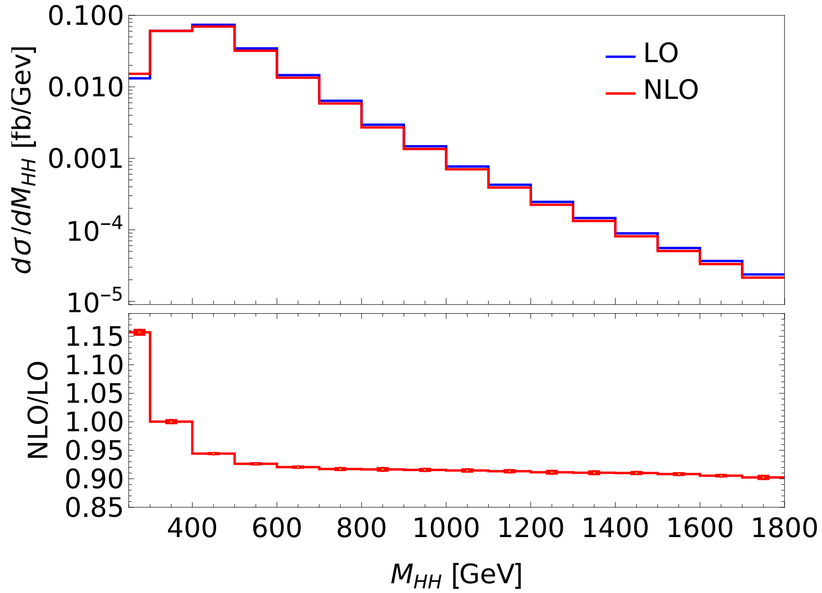
↪ +1% on total cross section

↪ +30% near production threshold*

Can be adapted for EFT analyses

Heinrich, SPJ, Kerner, Stone, Vestner 24

Full Electroweak Corrections



↪ -4% on total cross section

↪ +15% near production threshold*

↪ -10% at high energy (Sudakov-like)

Bi, Huang, Huang, Ma, Yu 23

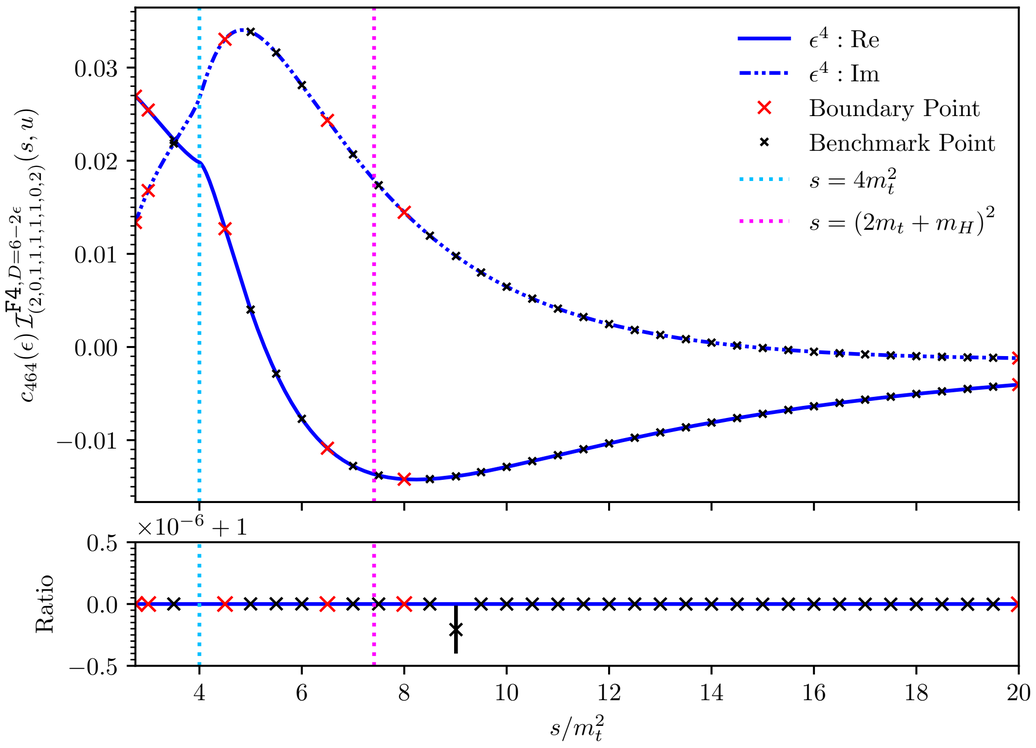
Partial results suggest that full result made up by a delicate interplay of different contributions

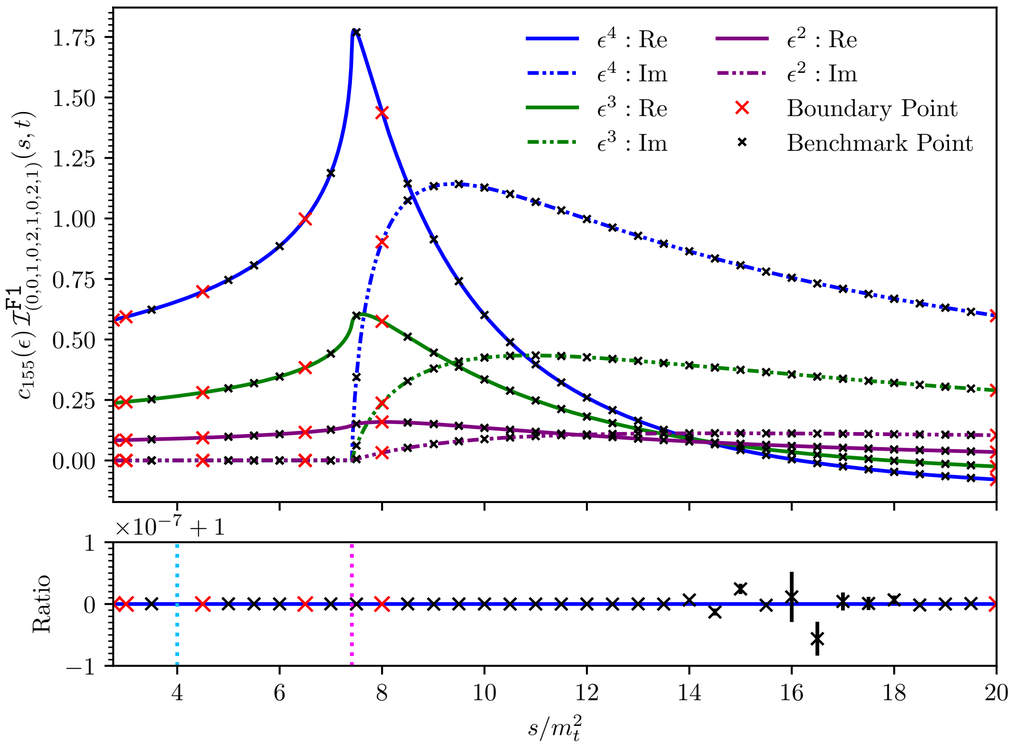
↪ Yukawa/Self-coupling corrections play an important role near to HH production threshold

↪ Vector boson corrections dominate in at high invariant mass

Master Integrals

Heinrich, SPJ, Kerner, Stone, Vestner 24





Compute integrals numerically using GPUs with pySecDec, captures full dependence on all kinematic scales and masses

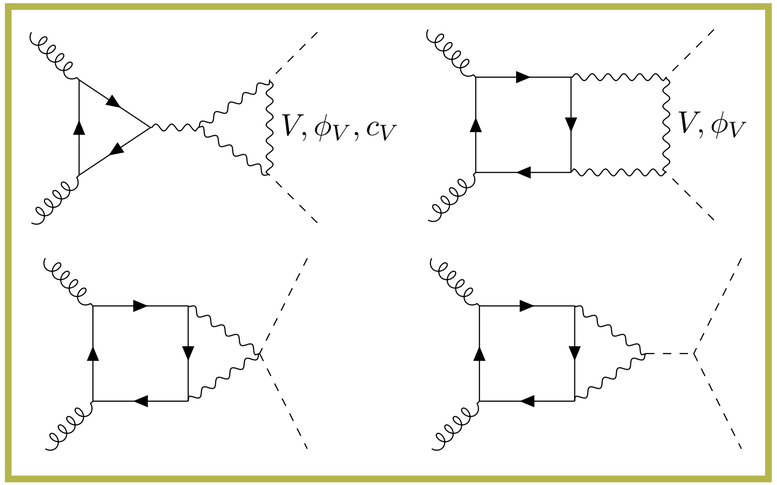
Heinrich, SPJ, Kerner, Magerya, Olsson, Schlenk 24

All 494 integrals cross-checked with DiffExp

Hidding 21

Light-Quark Mediated

Bonetti, Rendler, Torres Bobadilla 25
Bonetti, Heinrich, SPJ, Kerner, Rendler, Stone, Vestner 25



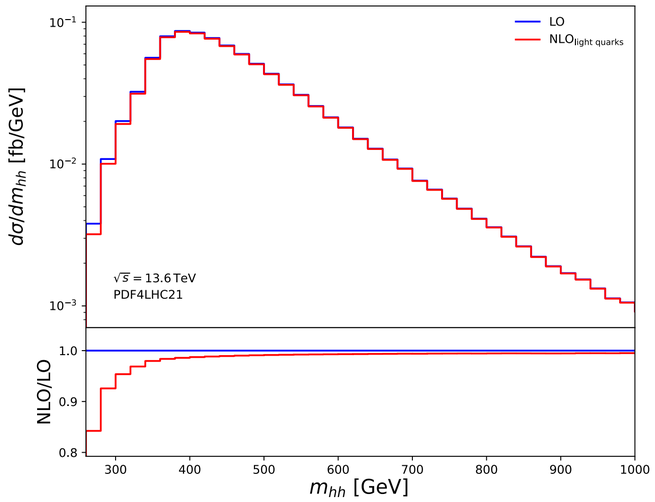
Light-Quark mediated corrections to $gg \to HH$

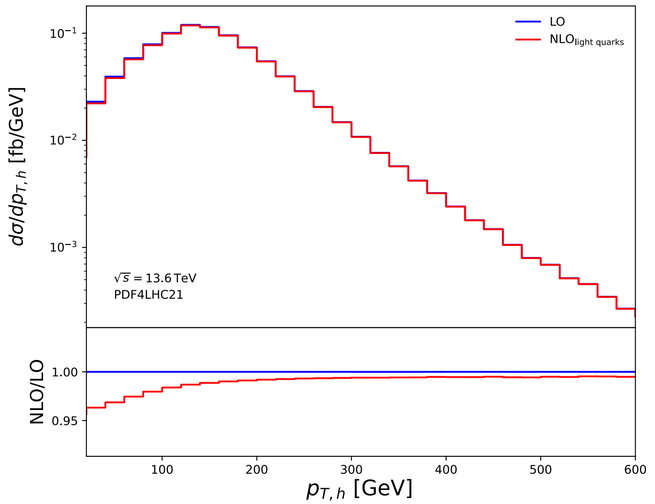
Canonical differential equations obtained (boundary values @ $s, t, u \ll m_V^2$) evolve boundary values using series-solution via DiffExp Moriello 19; Hidding 20;

Grids produced and implemented in Powheg

Small effect at total cross-section level

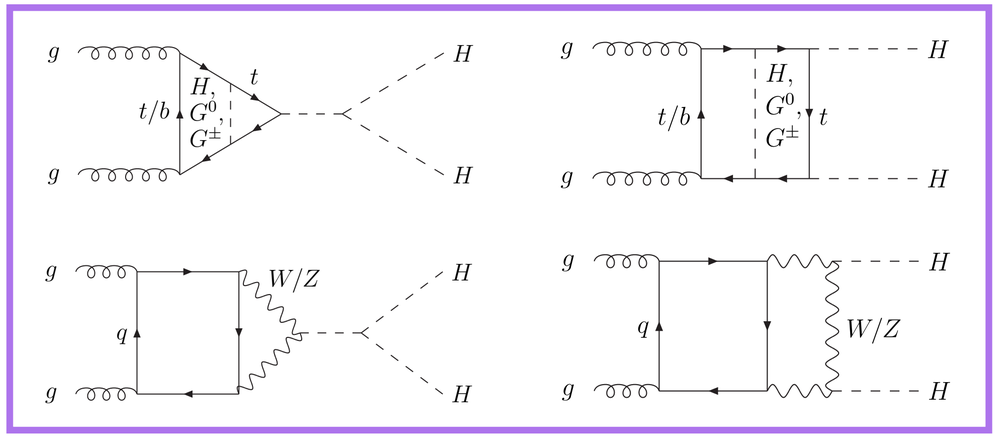
Suppresses m_{HH} and p_T significantly close to production threshold (depends on binning)

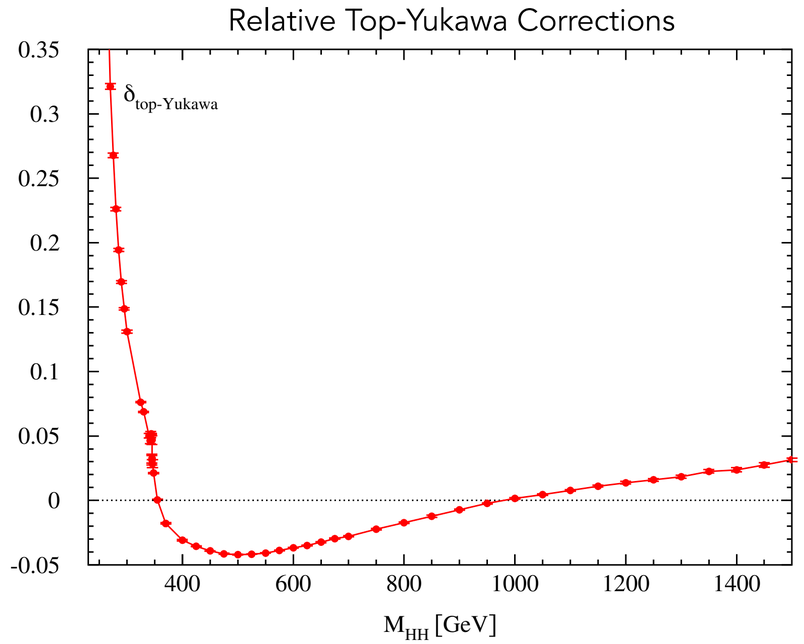




Yukawa and Light-Quark Mediated

Bhattacharya, Campanario, Carlotti, Chang, Mazzitelli, Mühlleitner, Ronca, Spira 25





Light-quark Mediated Corrections

Computed generally using numerical integration

Yukawa Corrections

Calculated in gaugeless limit i.e. neglecting vector bosons but including massless Goldstone bosons

Includes corrections to 1PR ``triangle'' diagrams and 1PI ``box'' diagrams, neglects new $y_t^2\lambda$ topologies arising at NLO EW

Calculation

Numerical integration in Feynman parameter space

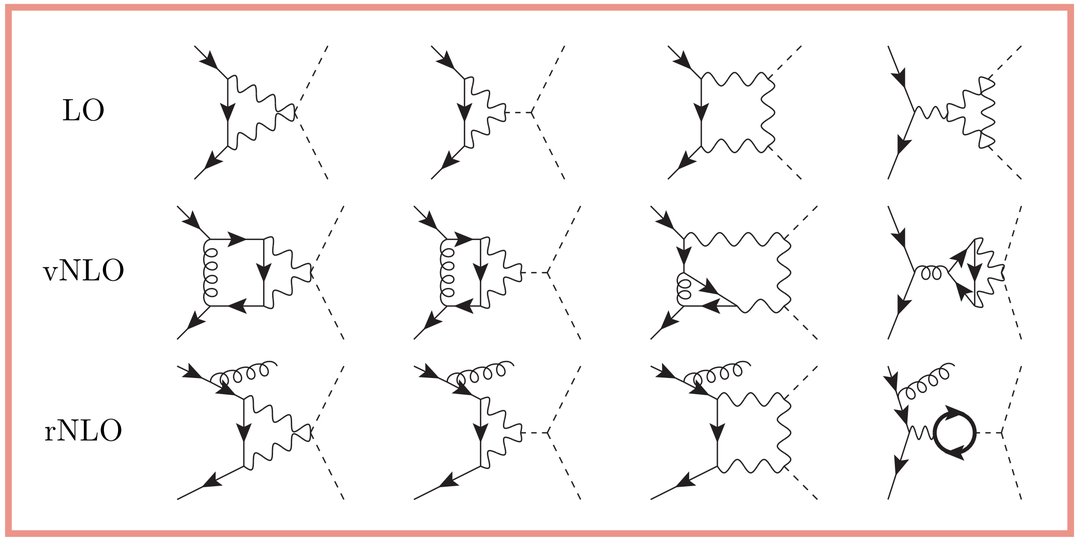
Regularise the virtual thresholds by introducing small imaginary parts

$$m_{t/b}^2 \to m_{t/b}^2(1-i\delta), \quad m_H^2 \to m_H^2(1-i\delta)$$

Extrapolate $\delta \to 0$ using Richardson extrapolation

Light-Quark Induced

Bonetti, Heinrich, Rendler, Torres Bobadilla 26



Quark-induced contribution from EW topologies + NLO QCD corrections

Canonical differential equations obtained (boundary values @ $s, t, u \ll m_V^2$) evolve boundary values using series-solution via DiffExp Moriello 19; Hidding 20;

Total cross-section effects are quite small (<1%)

Very large NLO corrections (mainly due to opening gq channel)

Can significantly modify distributions +10% in first m_{HH} bin, p_T at 1-2%

Initial state bottom quarks can lead to further modifications at 1-2% level

$\sqrt{S}$ [TeV]	$q\bar{q}_{\mathrm{LO}}$ [fb]	$q\bar{q}_{\mathrm{NLO}}$ [fb]	gg_{LO} [fb]	$q\bar{q}_{\mathrm{NLO}}/q\bar{q}_{\mathrm{LO}}$	$q\bar{q}_{\mathrm{NLO}}/gg_{\mathrm{LO}}$
13.0	0.039	0.061	16.45	+59%	+0.37%
13.6	0.041	0.066	18.26	+60%	+0.36%
14.0	0.043	0.069	19.52	+60%	+0.35%

