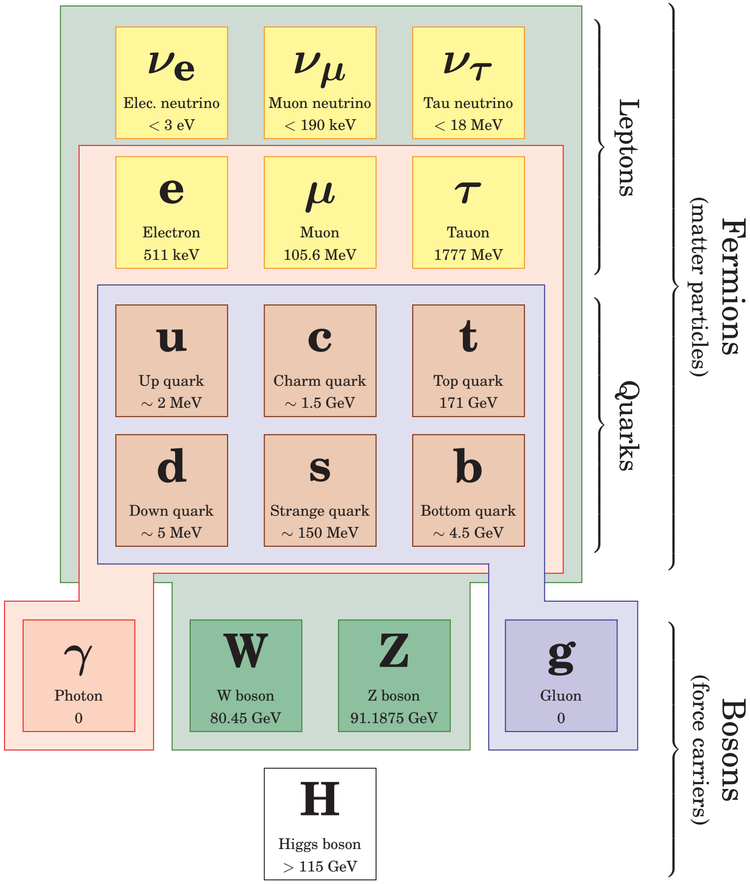
Predictions for Higgs signal and background processes at the LHC

Stefan Dittmaier
Albert-Ludwigs-Universität Freiburg

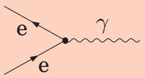
Contents

Introduction

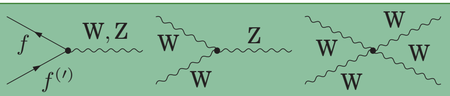
Elementary particles and their interactions



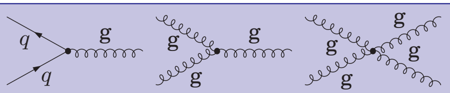
Electromagnetic force
force carrier: photon
couples to: (electric) charge
theory: quantum electrodynamics (QED) *symmetry group:* U(1)
phenomena: electricity, magnetism, atoms, molecules . . .



Weak force
force carriers: W, Z boson
couple to: weak charge
theory: electroweak interaction *symmetry group:* SU(2)
phenomena: β decay, radioactivity



Stong force
force carrier: gluon
couples to: colour charge
theory: quantum chromodynamics (QCD) *symmetry group:* SU(3)
phenomena: hadrons (e.g. proton, neutron)



Gravity ? no consistent quantum theory yet ?
force carrier: graviton
couples to: mass, energy
theory: general relativity *symmetry group:* Poincaré group
phenomena: force of gravity, stars, planets, . . .

"'Elementary"' means:

- point-like: no substructure, locally interacting
- but not necessarily: stable or observable as free particles

Theoretical description of particle interactions and processes

Starting point: quantum field theory defines model

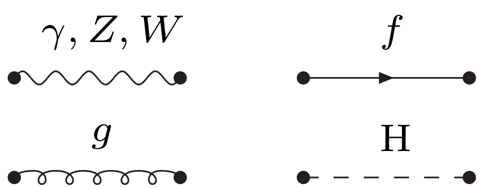
- each particle corresponds to a field ϕ_i
- Lagrangian $\mathcal{L}(\phi_i)$ for free motion & interactions

Perturbative evaluation of quantum field theories

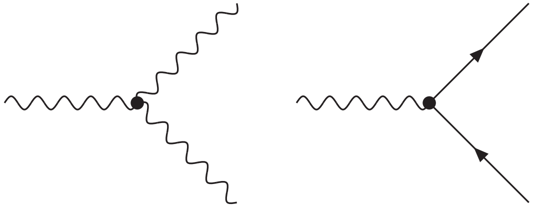
Transition amplitude $\langle f|S|i\rangle = \sum$ Feynman graphs for $|i\rangle \to |f\rangle$

Form graphs following Feynman rules:

free propagators:



vertices = elementary interactions:



etc.

propagators & vertices $\longleftrightarrow$ terms in $\mathcal{L}(\phi_i)$

Perturbative series for $g \to 0$

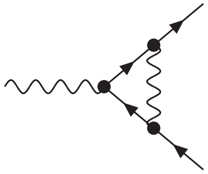
= power series in g^n

= power series in $\hbar^m$

= expansion in # loops in diagrams

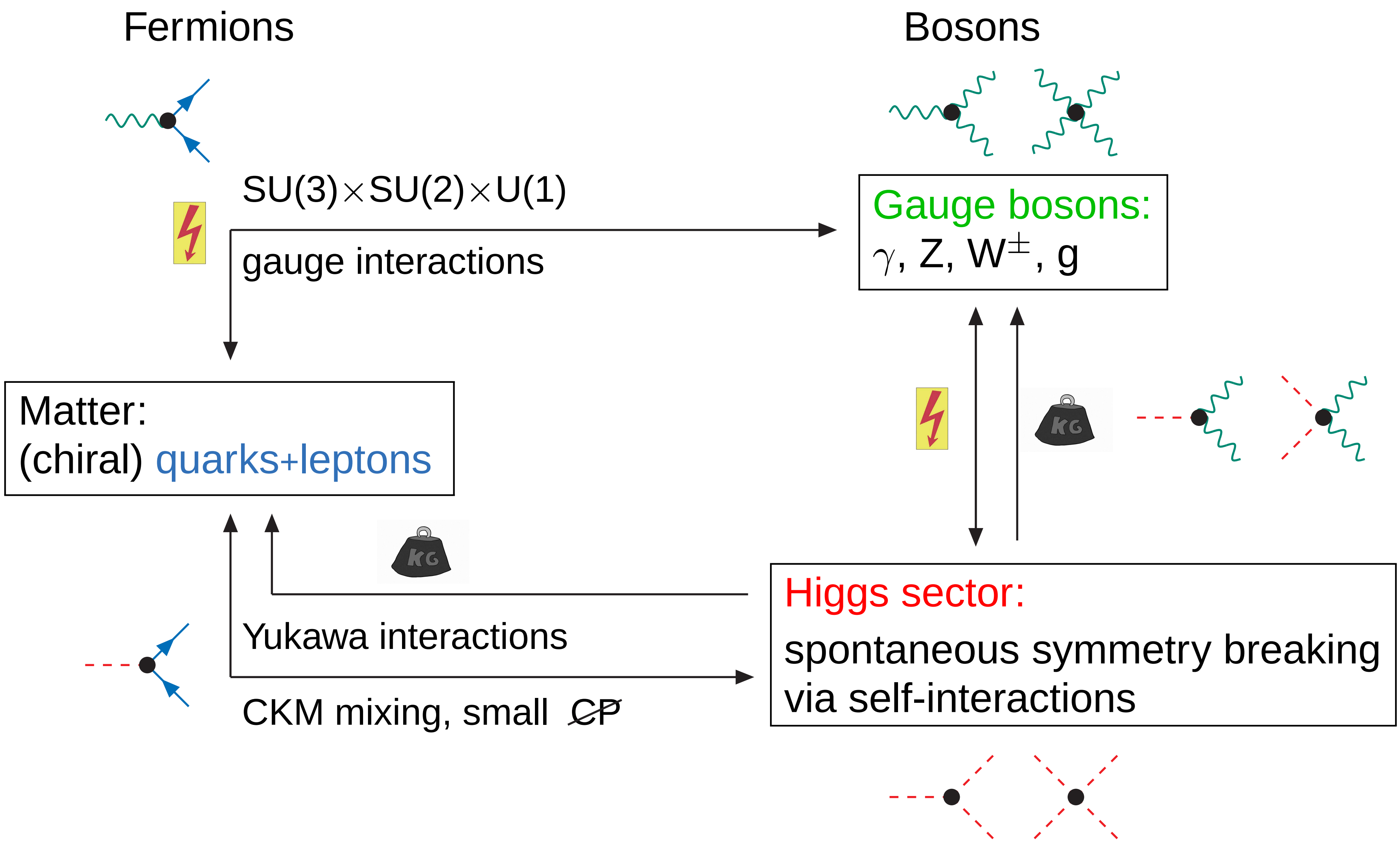
$\Rightarrow$ loop diagrams

= quantum corrections



etc.

Structure and elementary interactions of the SM



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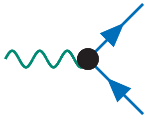
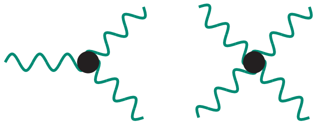
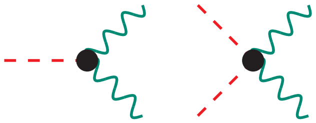
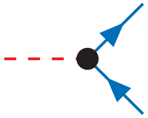




Test of the model

$\Leftrightarrow$ Exp. reconstruction of the $\underbrace{\text{elementary couplings}}_{\text{Feynman rules}}$





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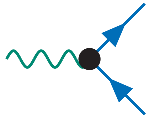
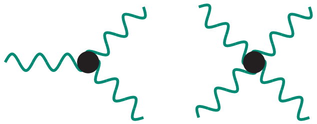


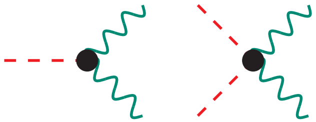


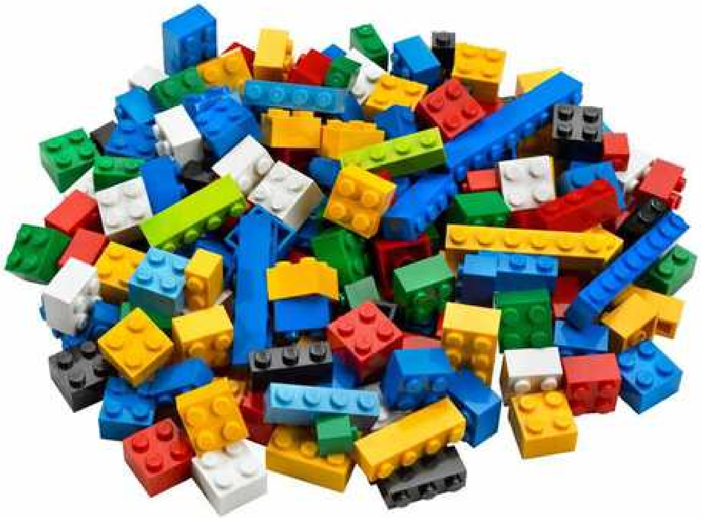
Test of the model

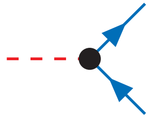
$\Leftrightarrow$ Exp. reconstruction of the elementary couplings

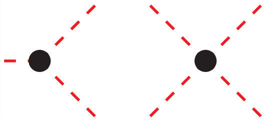
Feynman rules

Building blocks for particle reactions

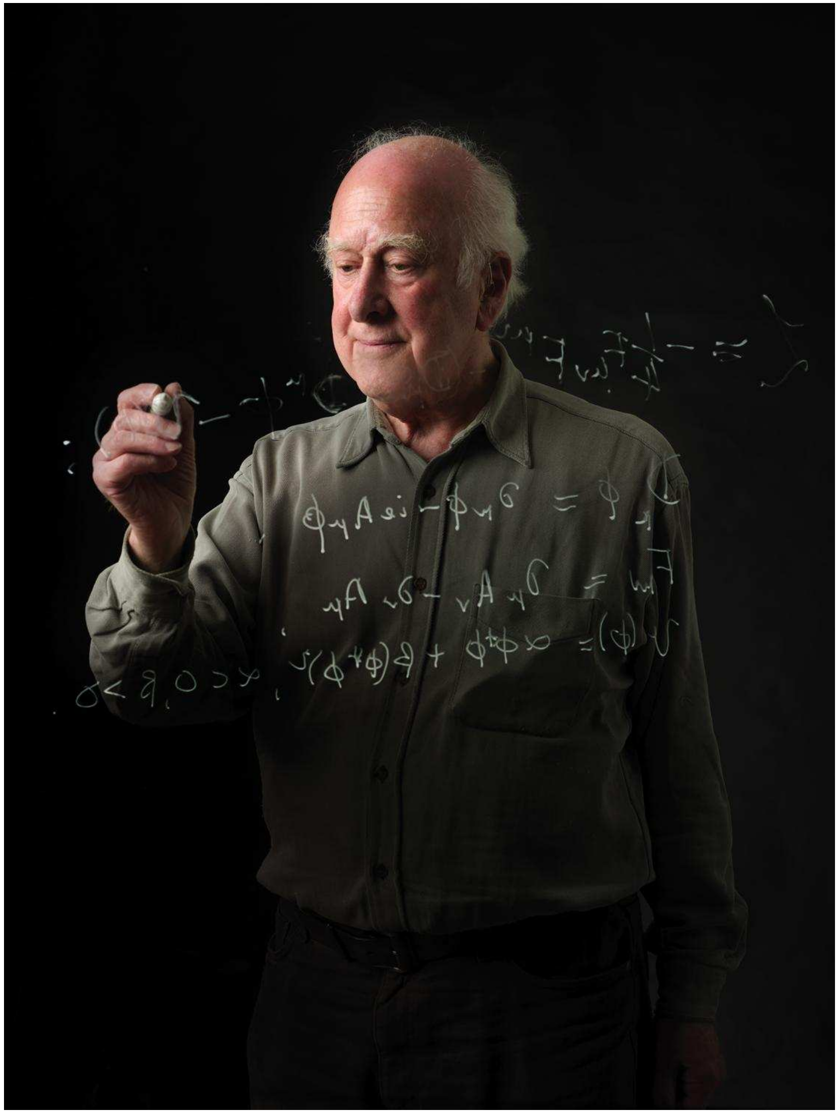








The Higgs mechanism – how do particles get their mass ?



Peter Higgs

... describing the Abelian Higgs model

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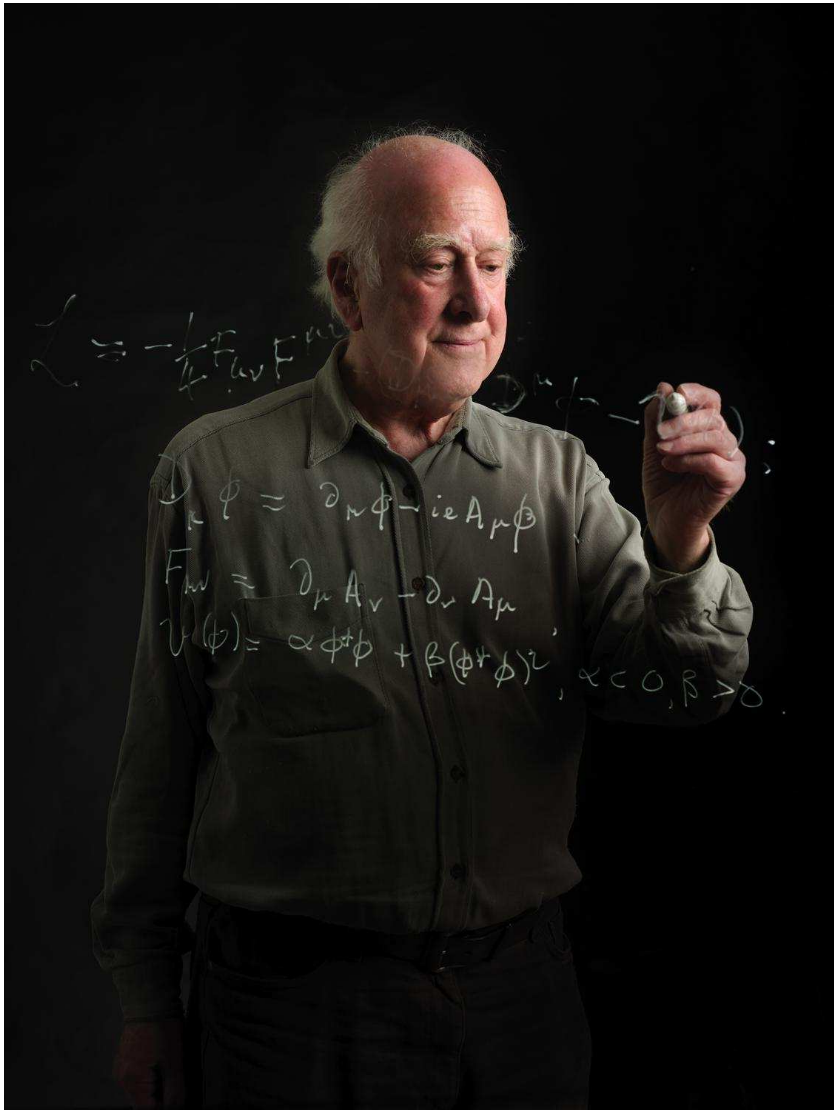

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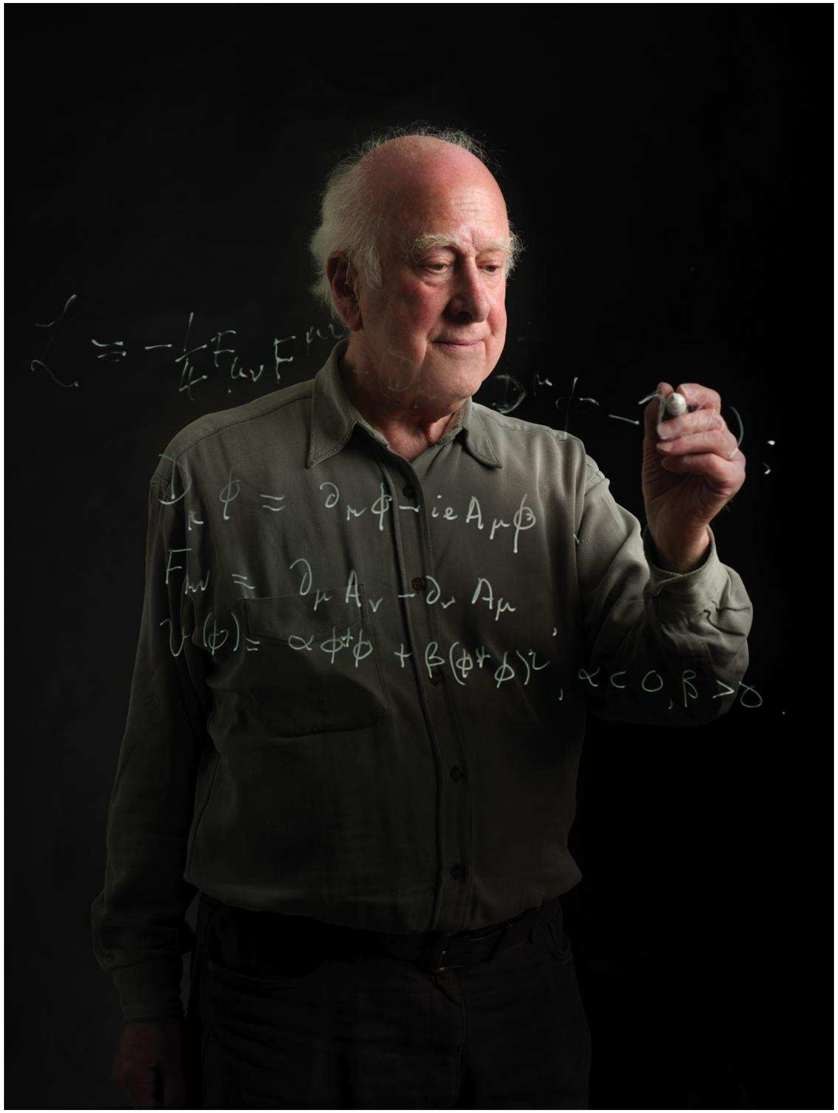

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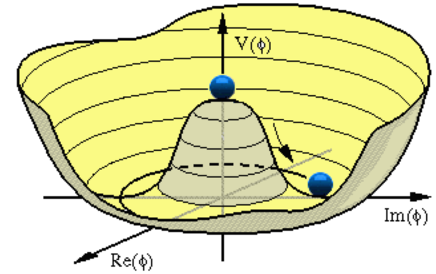


- Vacuum configuration $\langle 0|\phi(x)|0\rangle \neq 0$
  determined by minimum of potential
  $\hookrightarrow$ $\langle 0|\phi(x)|0\rangle = v$ not invariant,
  i.e. spontaneous symmetry breaking
- field excitation: H = Higgs boson
  $\phi(x) = v + H(x) + \mathrm{i}\chi(x)$
- coupling of field ψ to ϕ:
  $$g\phi(x)\psi(x)^2 = \underbrace{gv}_{=m}\,\psi(x)^2 + gH(x)\psi(x)^2 + \ldots$$

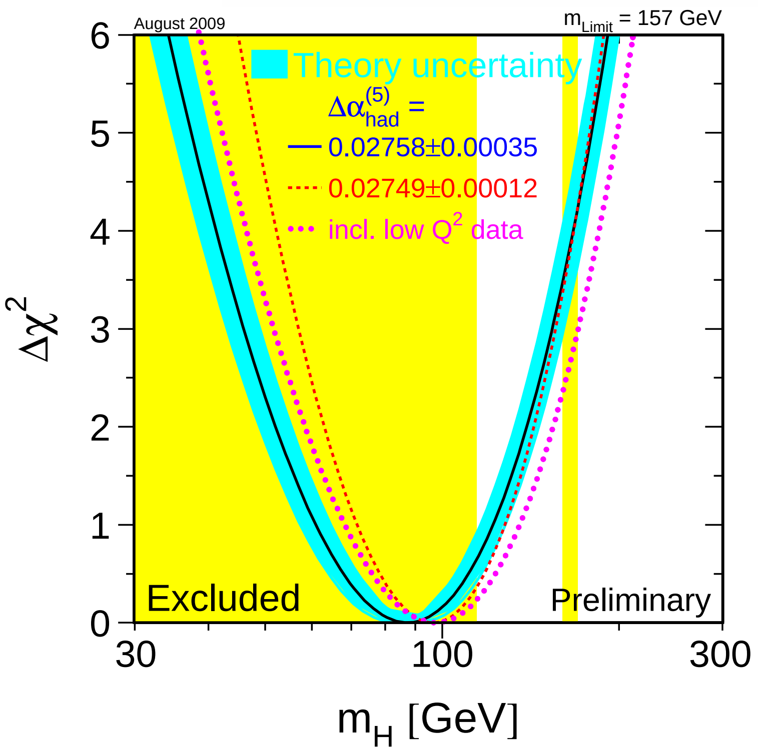
$\hookrightarrow$ ψ gets mass $m = vg$

Central results from LEP/SLC/Tevatron

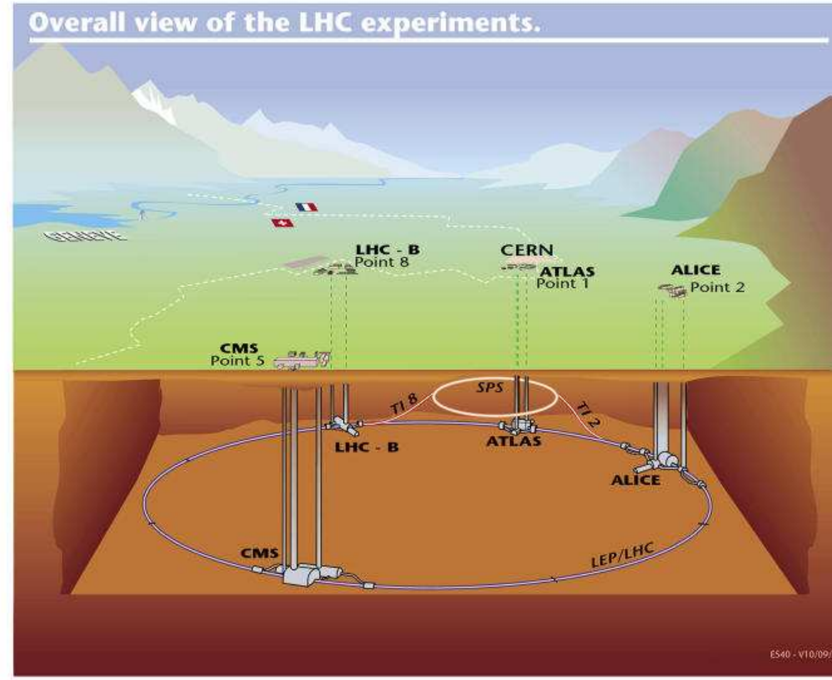
- Confirmation of the Standard Model as quantum field theory (quantum corrections significant)
- Particle content completely discovered apart from Higgs boson
- Higgs mass M_{H} indirectly constrained
  $\hookrightarrow$ impact on Higgs search

Great success of electroweak precision physics

- $M_{\mathrm{H}} > 114.4\,\mathrm{GeV}$ (LEPHIGGS '02)
  $\mathrm{e^+e^-} \not\rightarrow \mathrm{ZH}$ at LEP2
- $M_{\mathrm{H}} < 160\,\mathrm{GeV}$ and $M_{\mathrm{H}} > 170\,\mathrm{GeV}$
  $\mathrm{p\bar{p}} \not\rightarrow \mathrm{H} \rightarrow \mathrm{WW}$ at Tevatron (CDF/D0 '09)
- $M_{\mathrm{H}} < 157\,\mathrm{GeV}$ (LEPEWWG '09)
  fit to precision data
  i.e. via quantum corrections



Large Hadron Collider – the world largest particle accelerator

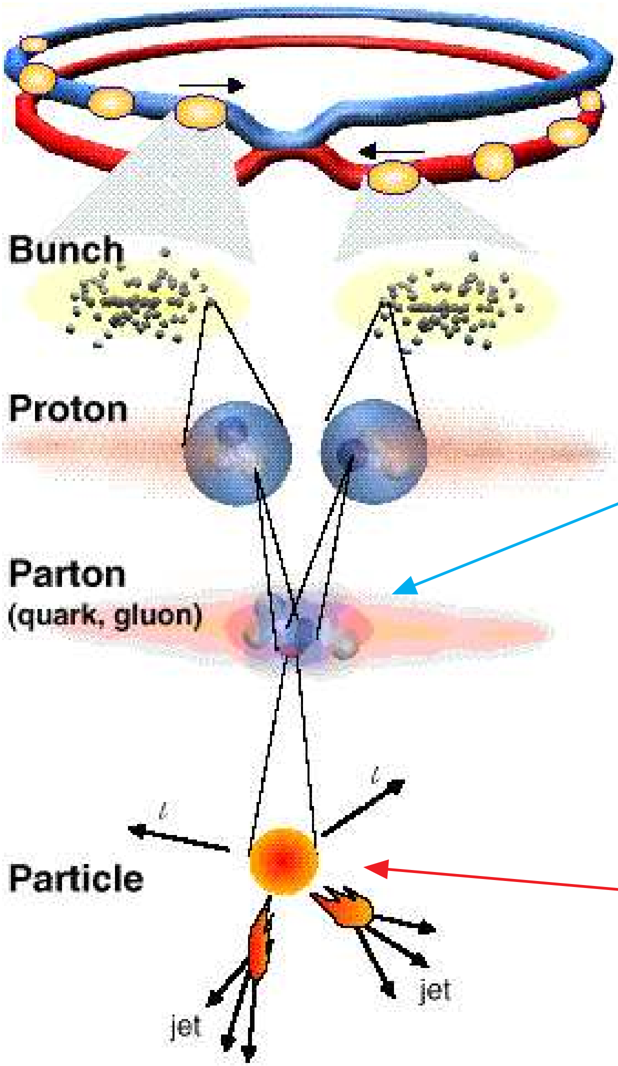


LHC back to live !

- 20.11.09: first proton beams in accelerator
- 23.11.09: first collisions with beam energy $E_{\mathrm{beam}} = 450\,\mathrm{GeV}$
- 30.11.09: $E_{\mathrm{beam}} = 1.18\,\mathrm{TeV}$ $\quad\rightarrow\quad$ new world record!
- 16.12.09: LHC turned off $\rightarrow$ ca. 1 Million collisions on tape
- 30.03.10: LHC turned on again at $E_{\mathrm{beam}} = 3.5\,\mathrm{TeV}$

  $\hookrightarrow$ ca. 500 Million events recorded (first W's, charm, bottom)

Predicting pp collisions



Parton content of the proton:

valence quarks uud

sea quarks $\mathrm{u, d, c, s, b}$

gluons g (+photons γ)

"Parton distribution functions" (PDF) $f_{i/\mathrm{p}}(x, Q)$

determine fraction x of the p momentum

carried by parton i at "factorization scale" Q

= non-perturbative input (from exp.),

but process independent

Hard interaction of partons

$\hookrightarrow$ perturbative QFT applicable

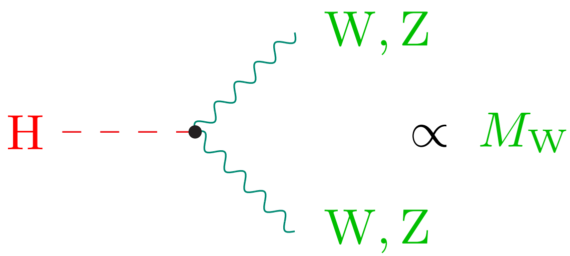
Model for hard interactions

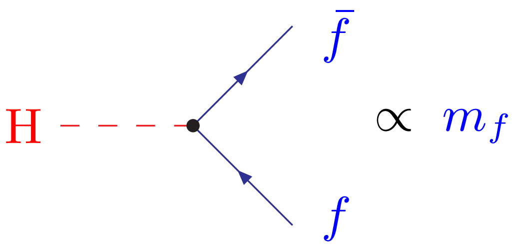
(apart from QCD/QED) enters only here

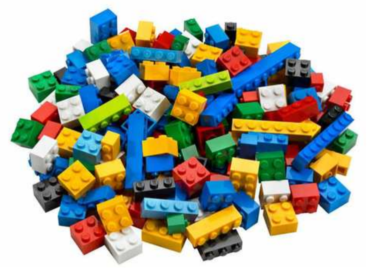
$$\sigma_{\mathrm{pp}\to F+X}(p_1, p_2) = \int_0^1 \mathrm{d}x_a \int_0^1 \mathrm{d}x_b \sum_{a,b} f_{a/\mathrm{p}}(x_a, Q)\, f_{b/\mathrm{p}}(x_b, Q)\, \hat{\sigma}_{ab\to F}(x_a p_1, x_b p_2, Q)$$

Higgs search at the LHC

Higgs bosons couple proportional to particle masses:







$\Rightarrow$ Higgs production via couplings to W/Z bosons or top-quarks

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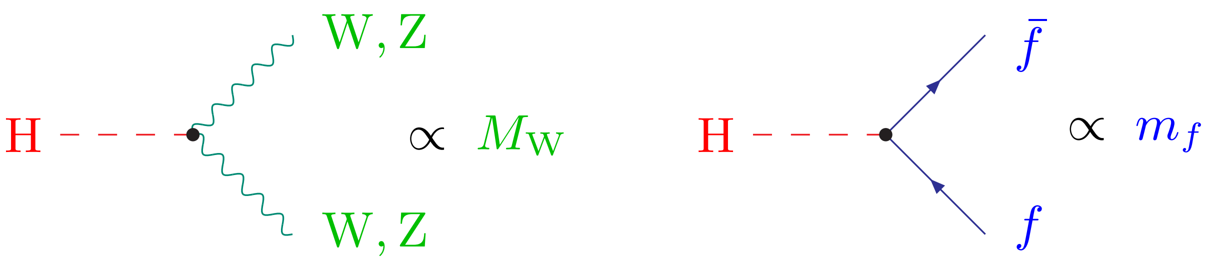
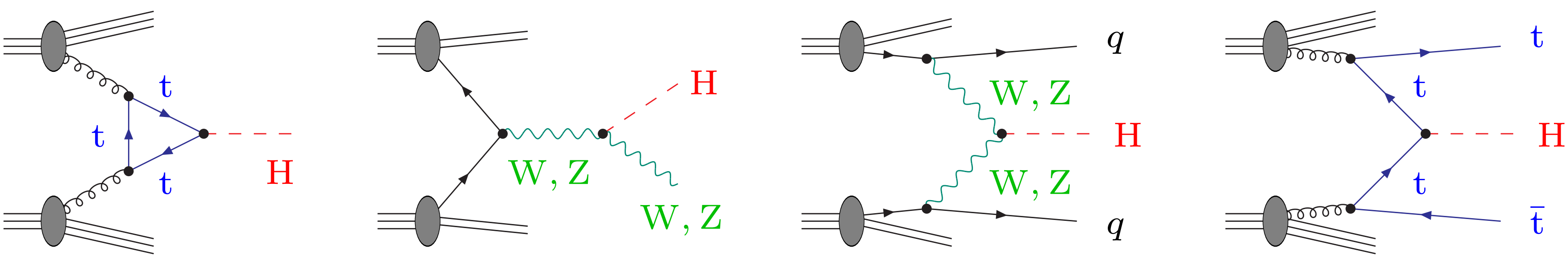


⇒ Higgs production via couplings to W/Z bosons or top-quarks

Processes at hadron colliders ($p\bar{p}/pp$):



Higgs search at the LHC

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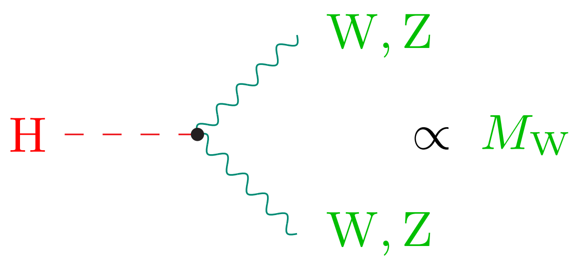

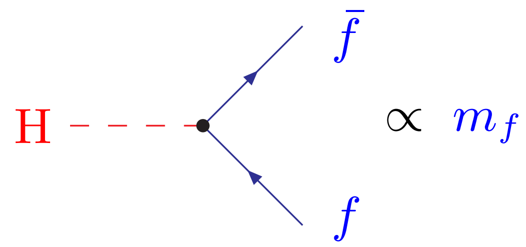

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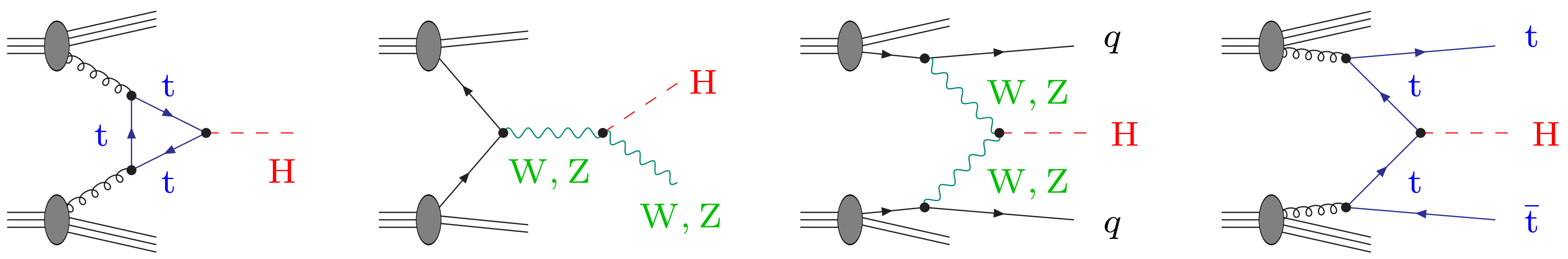
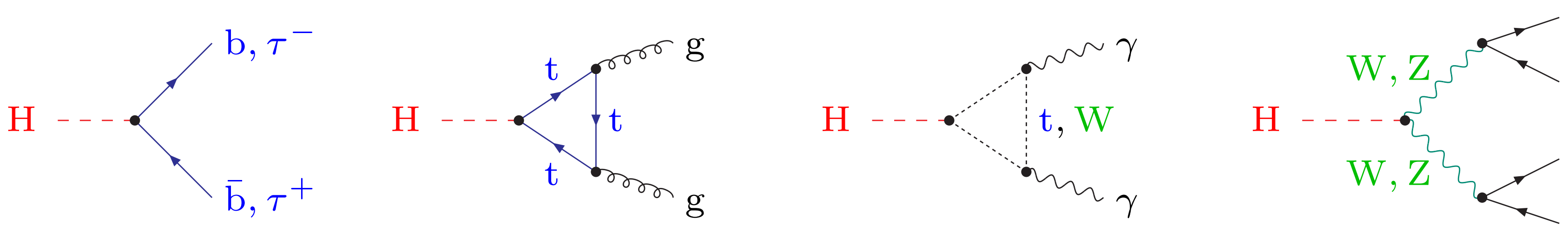
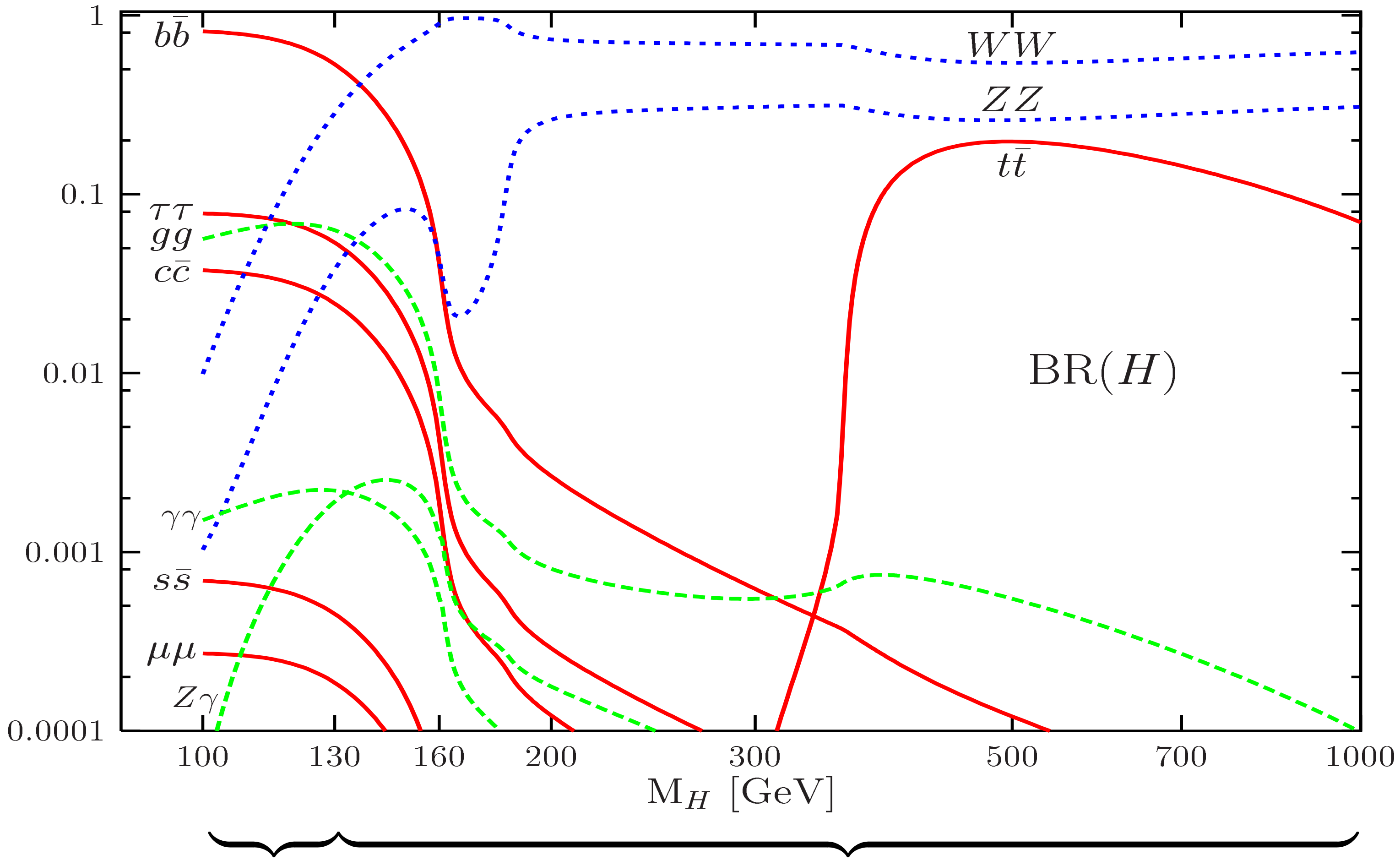


Decay channels for Higgs bosons of moderate mass ($M_H \lesssim 300\,\mathrm{GeV}$):



Branching ratios of the SM Higgs boson

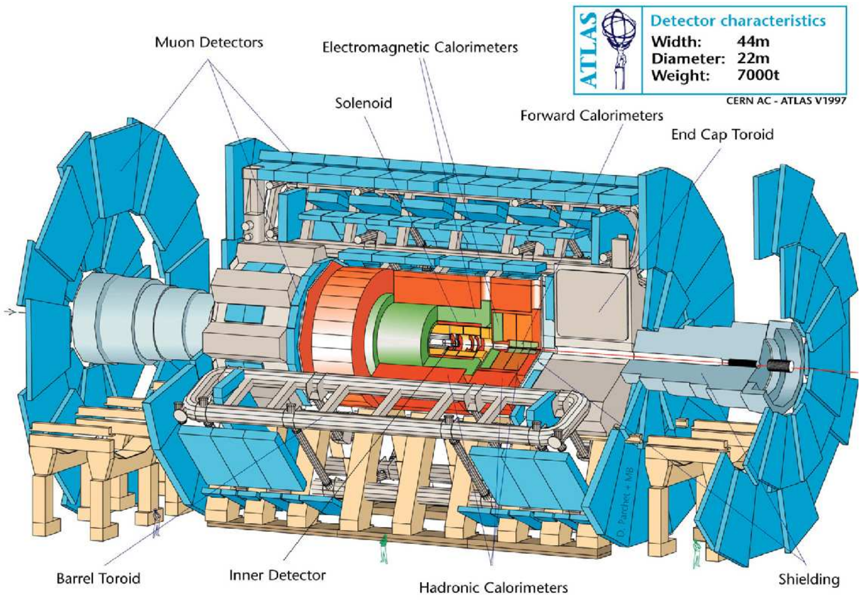
HDECAY (Djouadi, Kalinoswki, Spira)

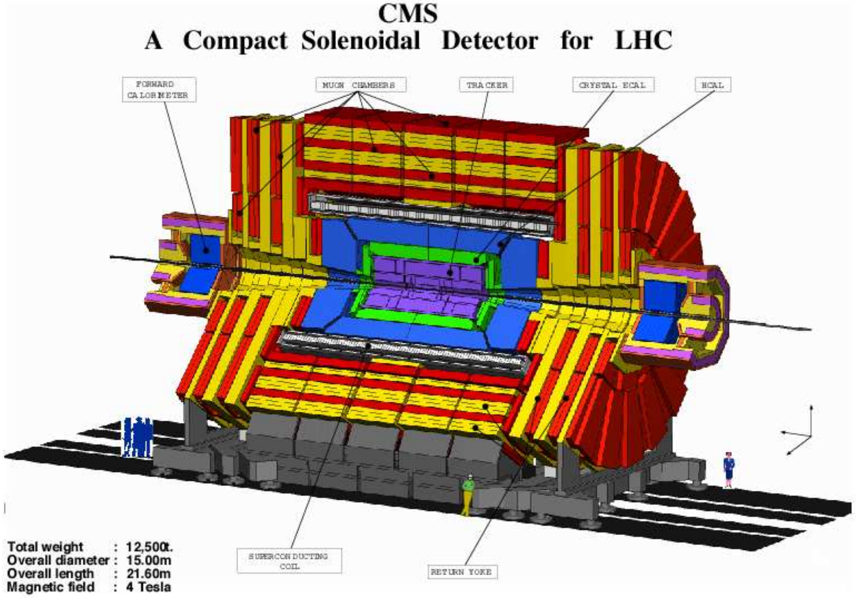


experimentally difficult:
$\mathrm{b\bar{b}}$ with large background,
decays into $\gamma\gamma$, $\tau\tau$ rare

experimentally clear signals by
$\mathrm{H \to WW \to 2}$ leptons $+ 2$ neutrinos or
$\mathrm{H \to ZZ \to 4}$ leptons

Higgs event reconstruction with detectors ATLAS and CMS





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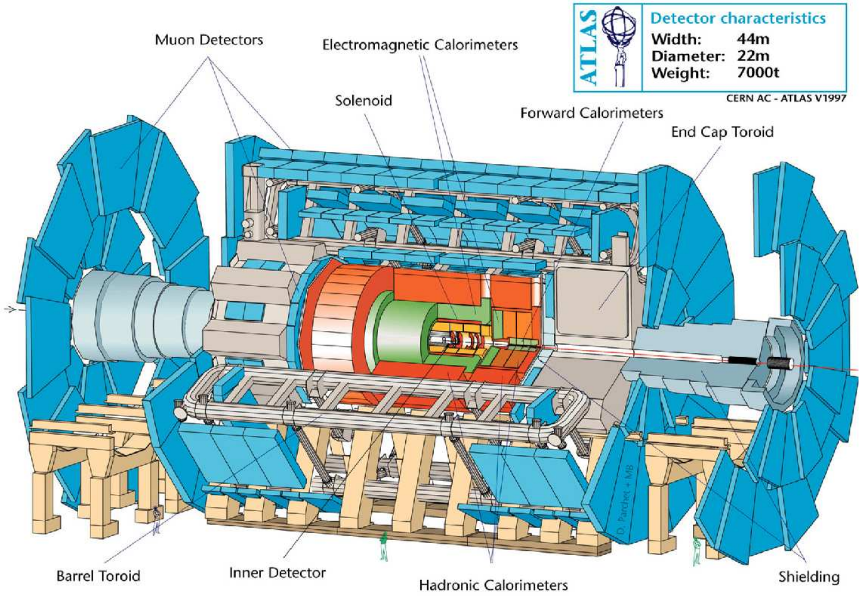
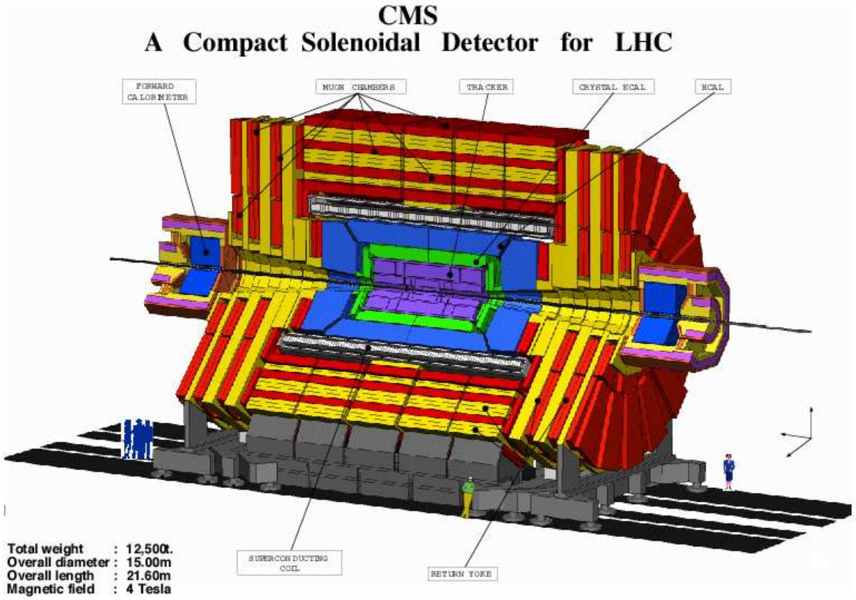
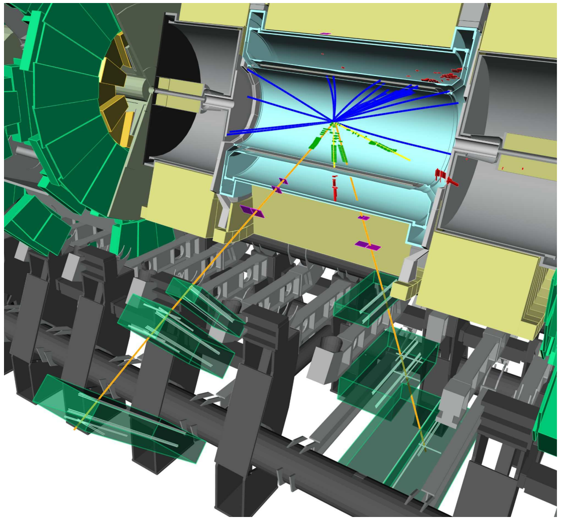
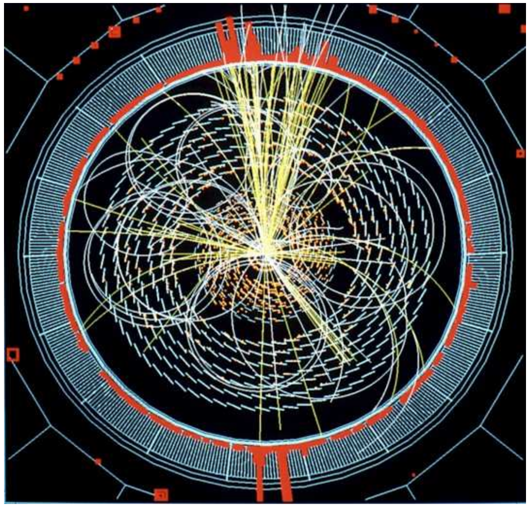




Simulation of Higgs events ("'simple"' signatures $\mathrm{H} \to \mathrm{ZZ} \to 2\mathrm{e}2\mu/2\mathrm{e}2q$)





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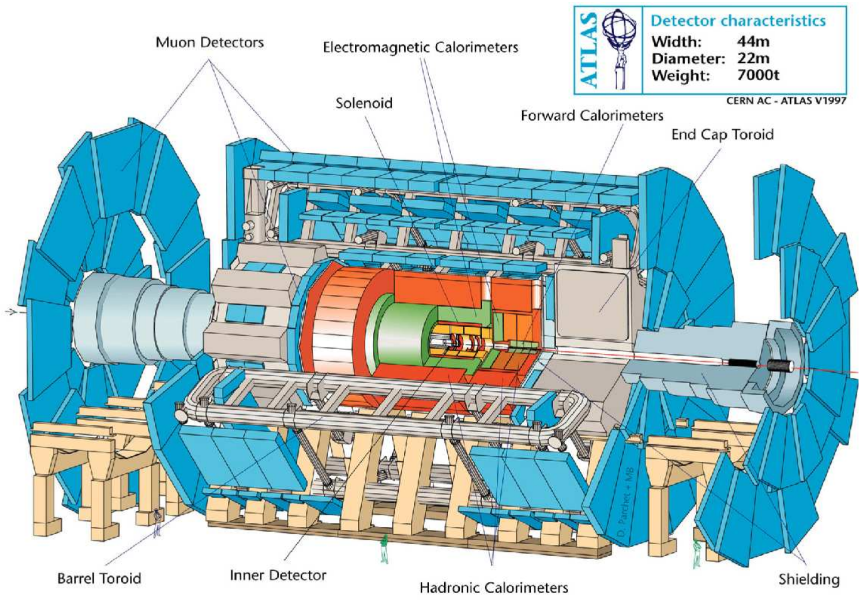

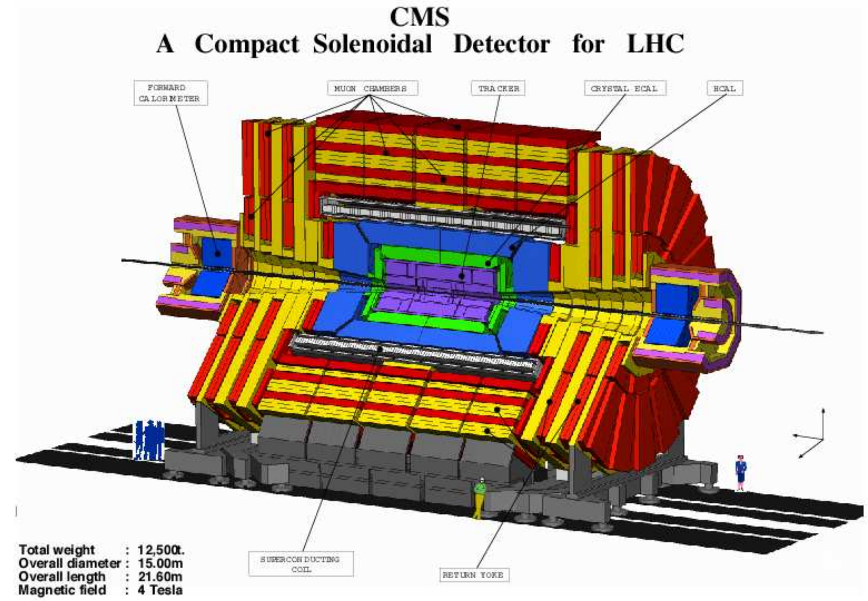

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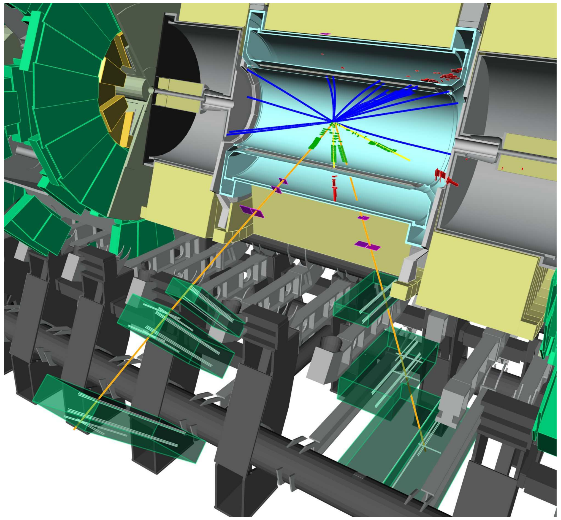
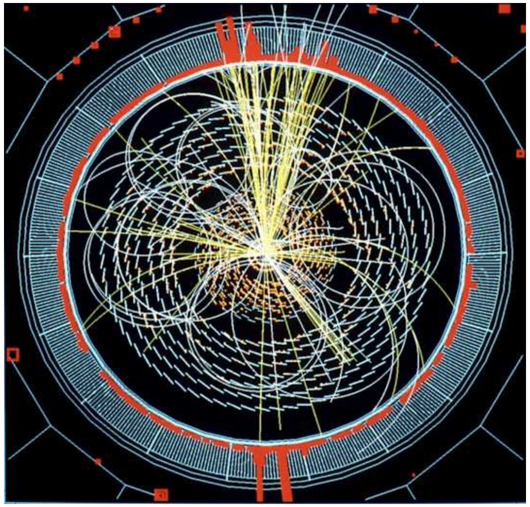
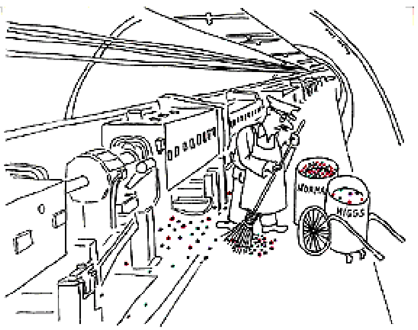
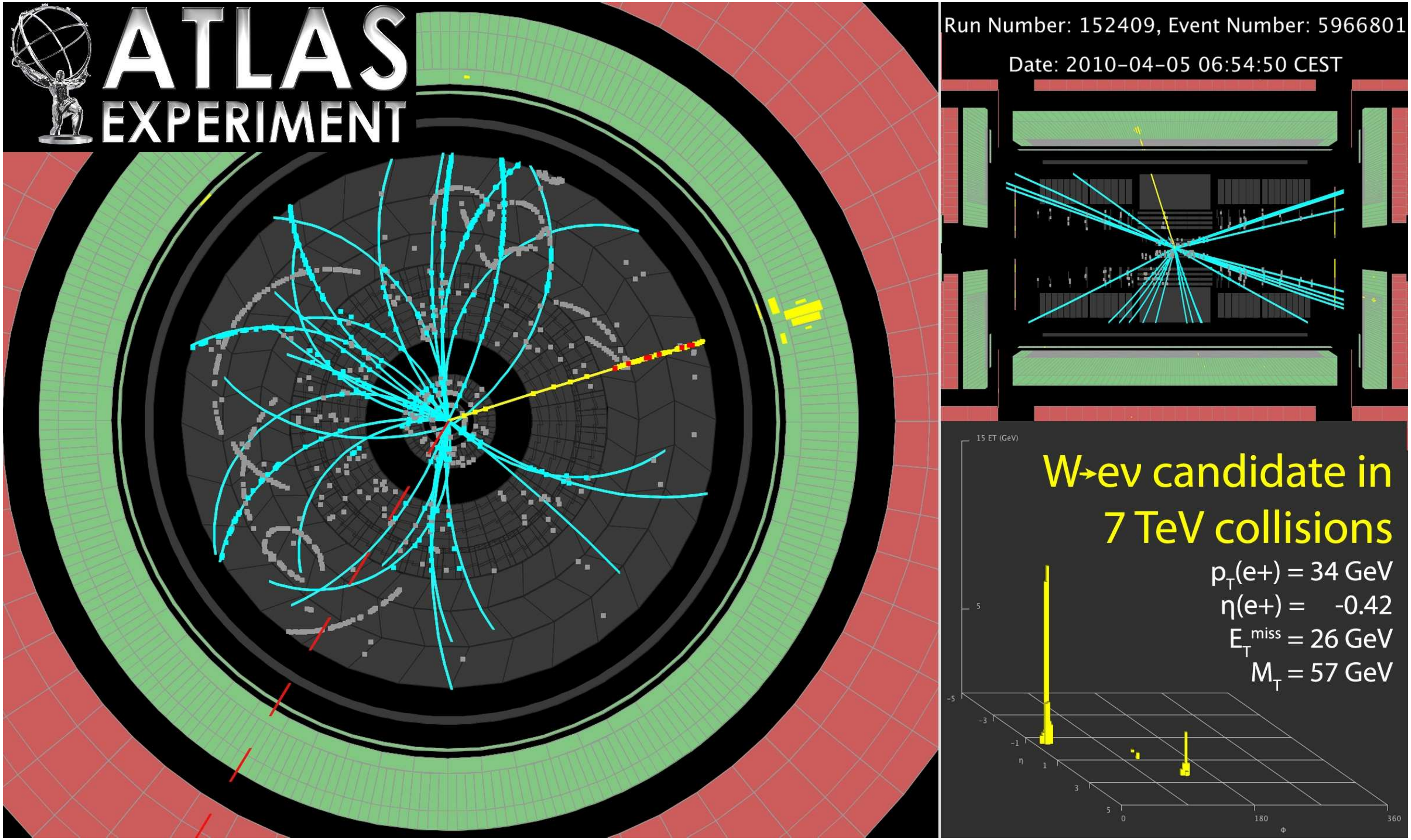




Precise predictions necessary, otherwise . . .

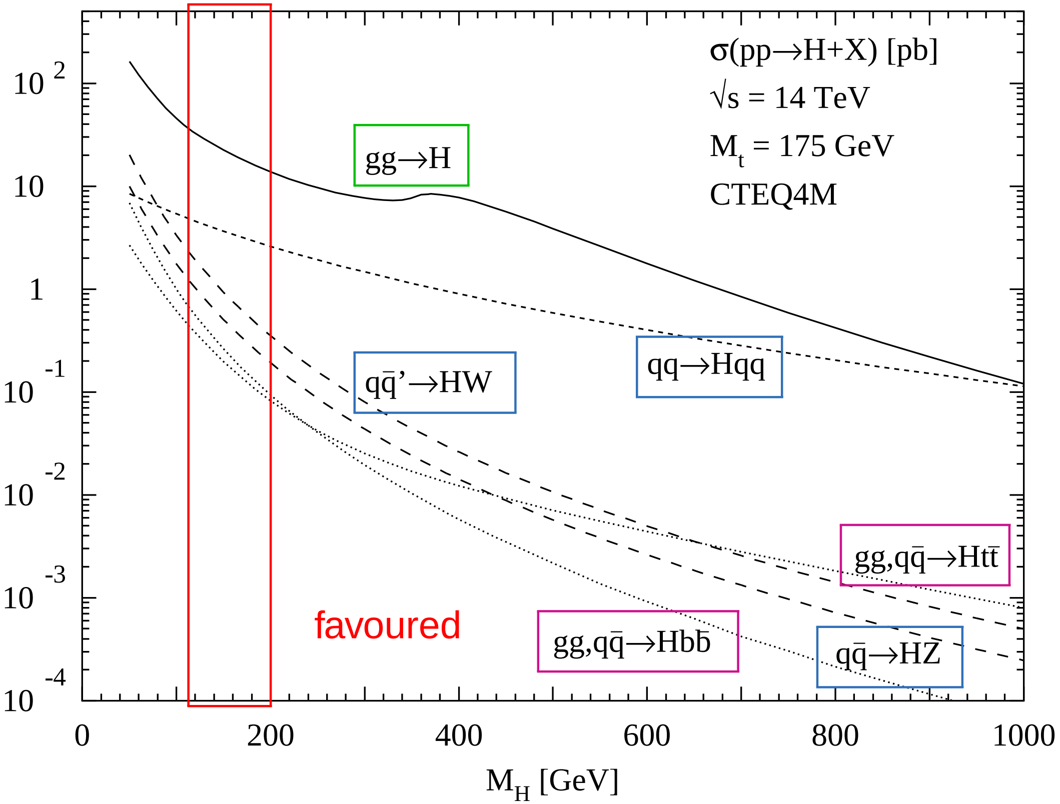


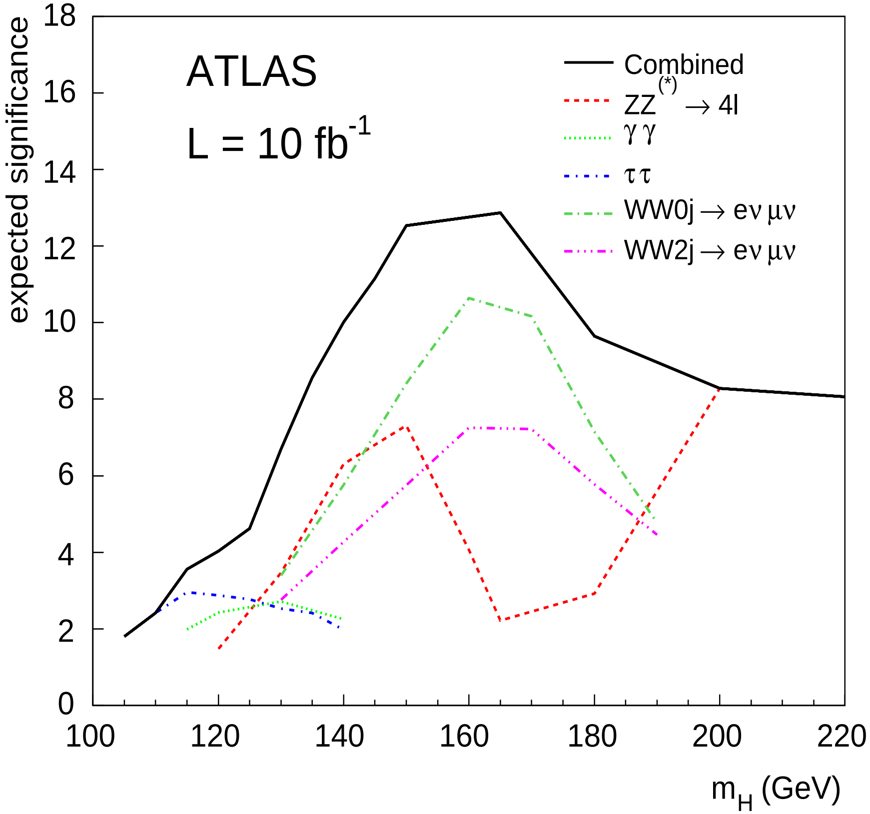
A real event at ATLAS



Cross sections and significance of the Higgs signal at the LHC

(not only) Spira et al.





Typical size of perturbative corrections at next-to-leading order (NLO):

QCD: $\mathcal{O}(\alpha_s) \sim 10{-}100\%$ Electroweak: $\mathcal{O}(\alpha) \sim 10\%$

$\hookrightarrow$ calculate / control higher orders to reduce theoretical uncertainty down to the level of PDF ($q\bar{q} \sim 5\%$, $gg \sim 5{-}10\%$) and experimental uncertainties

Complication: task requires "multi-loop" or "multi-leg" computations

LHC-Higgs cross section group → mandate for theory update

CrossSections < LHCPhysics < TWiki - Mozilla Firefox

Datei Bearbeiten Ansicht Chronik Lesezeichen Extras Hilfe

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/CrossSections

Meistbesuchte Se... Getting Started Latest Headlines

(22-28 July 2010) | Indico - Management area | CrossSections < LHCPhysics...

Organization

Overall Contacts

ATLAS	CMS	THEORY	
Reisaburo Tanaka (LAL)	Chiara Mariotti (Torino)	Stefan Dittmaier (Freiburg)	Giampiero Passarino (Torino)

Subgroup Contacts and Link for Subgroup Wiki

* We are organized in 10 subgroups, with 2 experimental contacts (one from ATLAS and one from CMS) and 2 theoretical contacts.

* LHCb collaboration participates in WH/ZH group.

Group	ATLAS	CMS	LHCb	THEORY	
1. ggF	Jianming Qian (Michigan)	Fabian Stöckli (CERN)		Massimiliano Grazzini (Firenze)	Frank Petriello (Wisconsin)
2. VBF	Daniela Rebuzzi (Pavia) Sinead Farrington (Oxford)	Christoph Hackstein (Karlsruhe)		Ansgar Denner (PSI)	Carlo Oleari (Milano-Bicocca)
3. WH/ZH	Giacinto Piacquadio (CERN)	Jim Olsen (Princeton)	Clara Matteuzzi (Milano-Bicocca)	Stefan Dittmaier (Freiburg)	Robert Harlander (Wuppertal)
4. ttH	Simon Dean (UCL)	Chris Neu (Virginia)		Laura Reina (Florida)	Michael Spira (PSI)
5. MSSM neutral	Markus Warsinsky (Freiburg)	Monica Vazquez Acosta (IC)		Michael Spira (PSI)	Georg Weiglein (DESY)
6. MSSM charged	Martin Flechl (Freiburg)	Sami Lehti (Helsinki)		Michael Krämer (Aachen)	Tilman Plehn (Heidelberg)
7. PDF	Joey Huston (Michigan State)	Kajari Mazumdar (TIFR)		Stefano Forte (Milano)	Robert Thorne (UCL)
8. Branching ratios	Daniela Rebuzzi (Pavia)	Ivica Puljak (Split)		Ansgar Denner (PSI)	Sven Heinemeyer (IFCA)
9. NLO MC	Jae Yu (Texas)	Marta Felcini (UCD)		Fabio Maltoni (Louvain)	Paolo Nason (Milano-Bicocca)
10. Pseudo-observables	Michael Dührssen (CERN)	Martin Grünewald (Ghent)		Sven Heinemeyer (IFCA)	Giampiero Passarino (Torino)

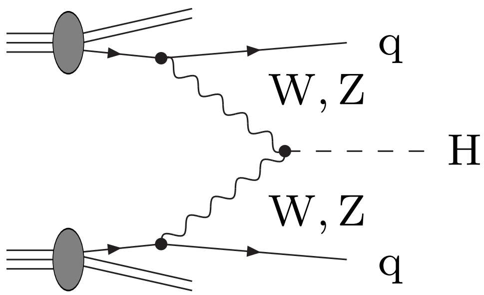
Fertig twiki.cern.ch

Higgs production

via

vector-boson fusion

Higgs production via weak vector-boson fusion (VBF)



colour exchange between quark lines suppressed

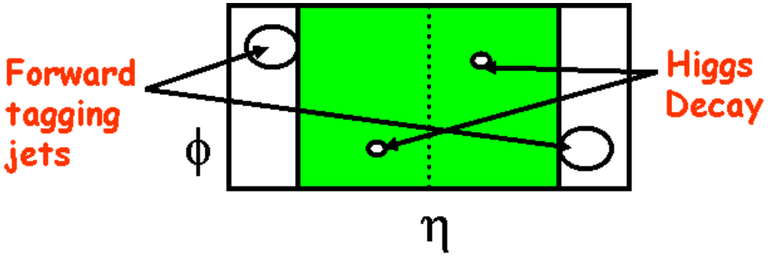
$\Rightarrow$ small QCD corrections

Han, Valencia, Willenbrock '92; Spira '98;
Djouadi, Spira '00; Figy, Oleari, Zeppenfeld '03

$\hookrightarrow$ t-channel approximation (vertex corrections)

VBF cuts and background suppression:

signature $=$ Higgs + 2jets



- 2 hard "tagging" jets demanded:
  $p_{\mathrm{Tj}} > 20\,\mathrm{GeV}, \quad |y_{\mathrm{j}}| < 4.5$
- tagging jets forward–backward directed:
  $\Delta y_{\mathrm{jj}} > 4, \quad y_{\mathrm{j1}} \cdot y_{\mathrm{j2}} < 0.$

$\hookrightarrow$ Suppression of background

- from other (non-Higgs) processes,
  such as $\mathrm{t\bar{t}}$ or WW production Zeppenfeld et al. '94-'99
- induced by Higgs production via gluon fusion,
  such as $gg \to gg\mathrm{H}$ Del Duca et al. '06; Campbell et al. '06

Work on radiative corrections to the production of Higgs+2jets

- NLO QCD corrections to VBF in "t-channel approximation" (vertex corrections)
  $\hookrightarrow$ impact $\sim$ 5–10% — Han, Valencia, Willenbrock '92; Spira '98; Djouadi, Spira '00; Figy, Oleari, Zeppenfeld '03; Berger, Campbell '04

- NLO QCD corrections to gluon-initiated channels (effective $\mathrm{H}gg$ coupling) — Campbell, R.K.Ellis, Zanderighi '06
  $\hookrightarrow$ contribution to VBF $\sim$ 5% — Nikitenko, Vazquez '07 — (NLO scale uncertainty $\sim 35\%$)

- (full) NLO QCD+EW corrections to VBF — Ciccolini, Denner, S.D. '07
  $\hookrightarrow$ NLO QCD $\sim$ NLO EW $\sim$ 5–10% $\rightarrow$ included in HAWK

- QCD loop-induced interferences between VBF and gluon-initiated channels
  $\hookrightarrow$ impact $\lesssim 10^{-3}\,\%$ (negligible!) — Andersen, Binoth, Heinrich, Smillie '07; Bredenstein, Hagiwara, Jäger '08

- SUSY QCD+EW corrections — Hollik, Plehn, Rauch, Rzehak '08
  $\hookrightarrow$ $|\mathrm{MSSM}-\mathrm{SM}| \lesssim 1\%$ for SPS points (2–4% for low SUSY scales)

- Parton-shower–matrix-element matching at NLO QCD via POWHEG
  $\hookrightarrow$ needed for full simulations at NLO — Nason, Oleari '09

- NNLO QCD corrections — Bolzoni, Maltoni, Moch, Zaro '10
  $\hookrightarrow$ corrections / remaining QCD uncertainty $\lesssim 2\%$

The program HAWK released Jan 2010

Denner, S.D., Mück

HAWK Homepage - Mozilla Firefox

http://omnibus.uni-freiburg.de/~sd565/programs/hawk/hawk.html

HAWK

A Monte Carlo generator for the production of Higgs bosons Attached to WeaK bosons at hadron colliders

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HAWK is a Monte Carlo integrator for pp -> H + 2jets.
It includes

- NLO QCD and electroweak corrections
- all weak-boson fusion and quark-antiquark annihilation diagrams
- all interferences at LO and NLO
- contributions from incoming photons
- leading heavy-Higgs-boson effects at two-loop order
- contributions of b-quark pdfs at LO
- an interface to LHApdf (default = standalone with MRST2004QED and CTEQ6 pdf tables)

What is not included / planned upgrades:

- Higgs-boson decays
- production of unweighted events
- p pbar collisions
- interface to parton showers
- contributions from gg initial states with effective Hgg couplings
- anomalous HWW and HZZ couplings

Downloads:

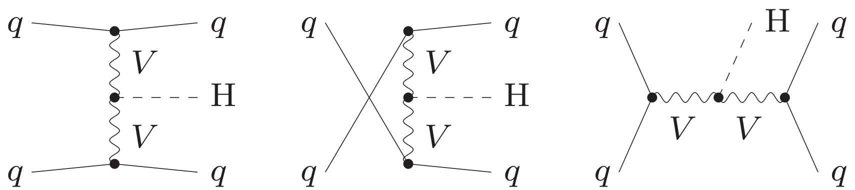
- README
- source code of HAWK 1.0 (released on Jan 26, 2010, updated on Feb 24, 2010)

Details of the full NLO QCD $\oplus$ EW calculation

Ciccolini, Denner, S.D. '07

EW production of Higgs+2jets in LO:

- many subcontributions from qq, $q\bar{q}$, and $\bar{q}\bar{q}$ channels
- each channel receives contributions from one or two topologies ("t, u, s"):



$\hookrightarrow$ all contributions and interferences taken into account in LO and NLO

EW production of Higgs+2jets in NLO:

- partonic channels for
  - ◇ one-loop diagrams: qq, $q\bar{q}$, $\bar{q}\bar{q}$
  - ◇ real QCD corrections qq, $q\bar{q}$, $\bar{q}\bar{q}$ (gluon emission), qg, $\bar{q}g$ (gluon induced)
  - ◇ real QED corrections qq, $q\bar{q}$, $\bar{q}\bar{q}$ (photon emission), $q\gamma$, $\bar{q}\gamma$ (photon induced)
- collinear initial-state singularities from QCD and QED splittings

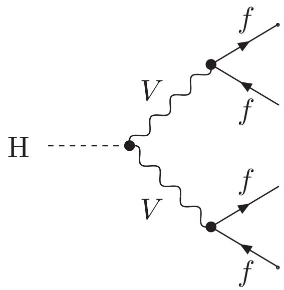
$\hookrightarrow$ factorization and PDF redefinition for QCD and QED singularities

Recycling strategy:

obtain all LO and NLO amplitudes via crossing
from NLO EW and QCD corrections to $\mathrm{H} \to \mathrm{WW/ZZ} \to 4f$ Bredenstein, Denner, S.D., Weber '06

Survey of Feynman diagrams for NLO EW and QCD corrections

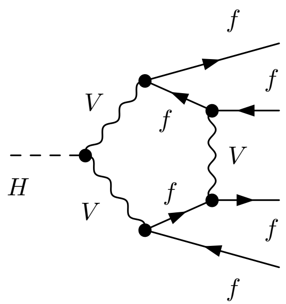
Lowest order:



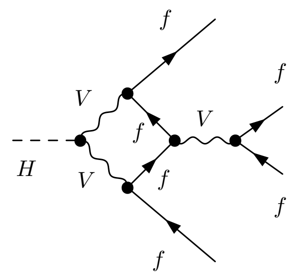
(one or two diagrams per flavour channel)

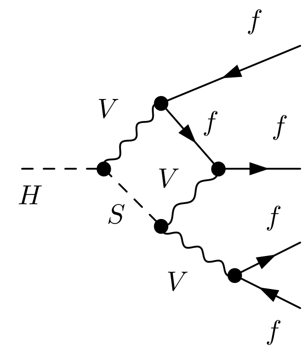
Typical one-loop diagrams: # diagrams = $\mathcal{O}(200{-}400)$

pentagons

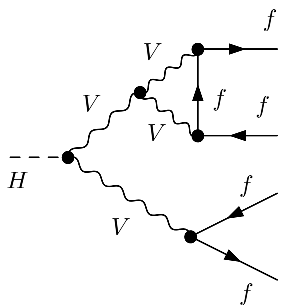


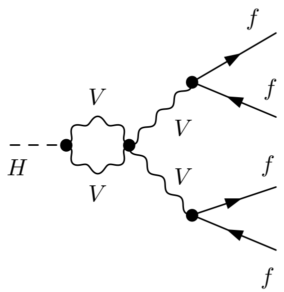
boxes



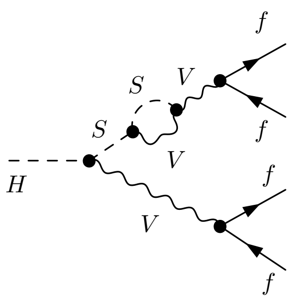


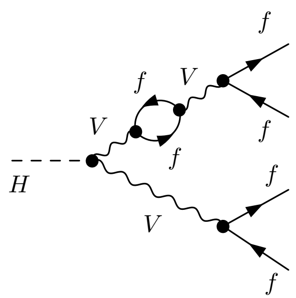
vertices





self-energies



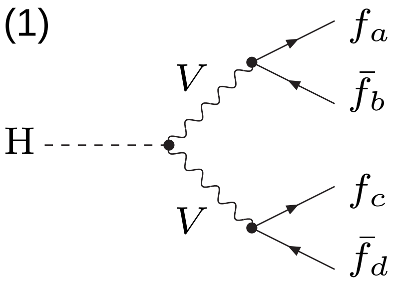


$+$ tree graphs with real photons or gluons

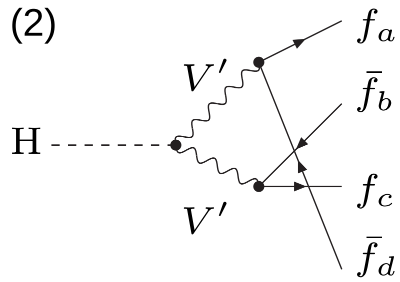
Classification of NLO QCD corrections

Possible Born diagrams:

(1)



(2)



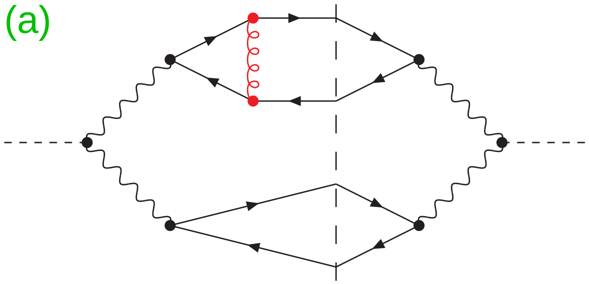
diagrams (2) only for

$q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$ channels

(q' = weak-isospin partner of q)

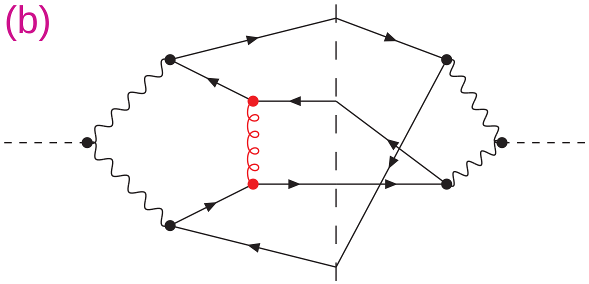
Classification of NLO QCD corrections into four categories: (typical diagrams shown)

(a)

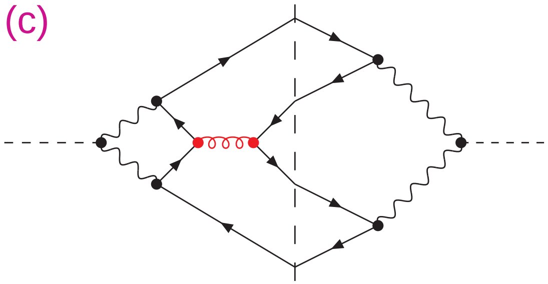


(a) contains previously known "t-channel approximation"

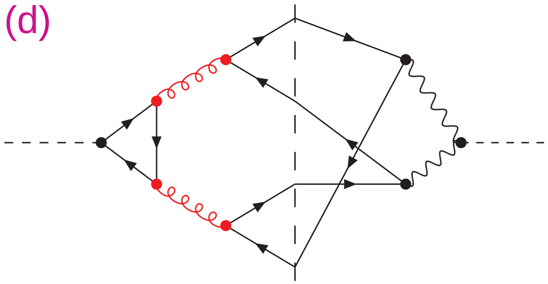
(b)



(c)



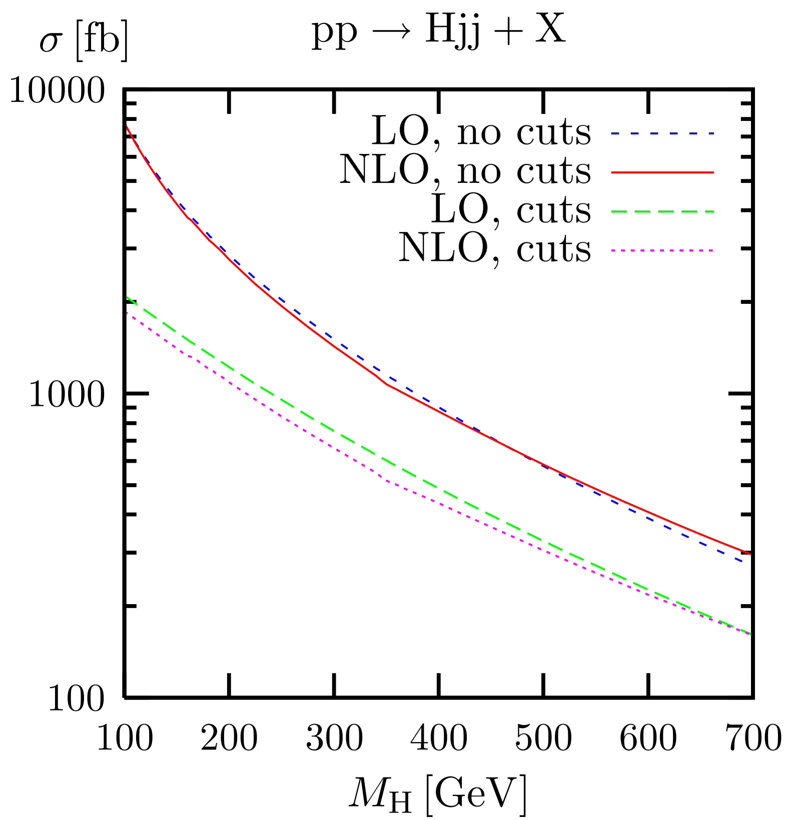
(d)

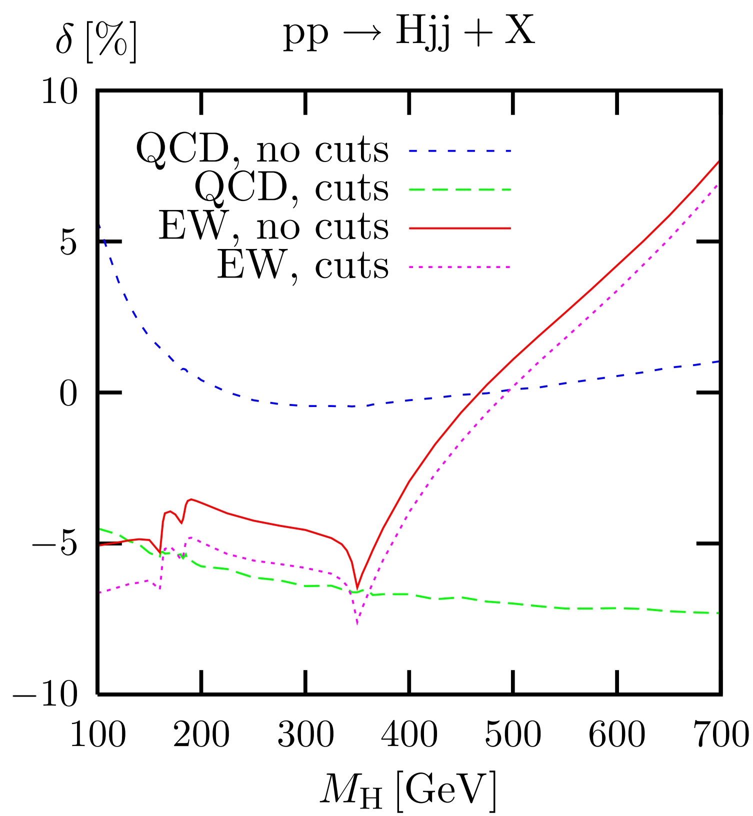


(b,c,d) = corrections to interferences (for $q\bar{q}q\bar{q}$ and $q\bar{q}q'\bar{q}'$) $\rightarrow$ turn out to be negligible

Results on integrated cross sections

Ciccolini, Denner, S.D. '07





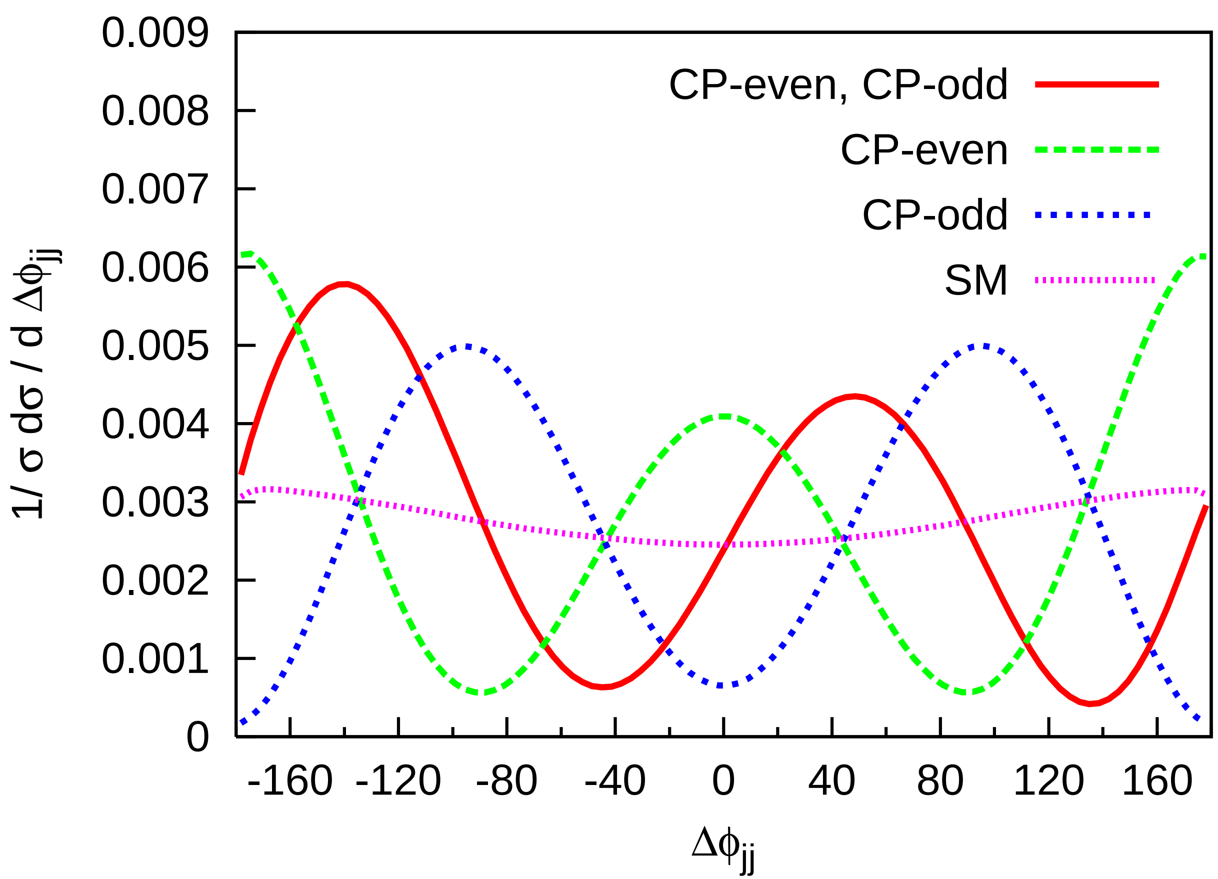
- QCD and EW corrections are of same generic size
- scale uncertainty $\sim 3\%$ within $M_W/2 < \mu_{ren/fact} < 2M_W$ in NLO ($\sim 10\%$ in LO)
- sensitivity to cuts: large for QCD, small for EW corrections
- heavy-Higgs corrections at $M_H \sim 700\,\text{GeV}$: $\underbrace{G_\mu M_H^2}_{\text{1-loop}} \sim \underbrace{(G_\mu M_H^2)^2}_{\text{2-loop}} \sim 4\%$

  $\hookrightarrow$ breakdown of perturbation theory

Distribution in the azimuthal angle difference $\Delta\phi_{\rm jj}$ of the tagging jets

Sensitivity to non-standard effects:

Hankele, Klämke, Zeppenfeld, Figy ’06



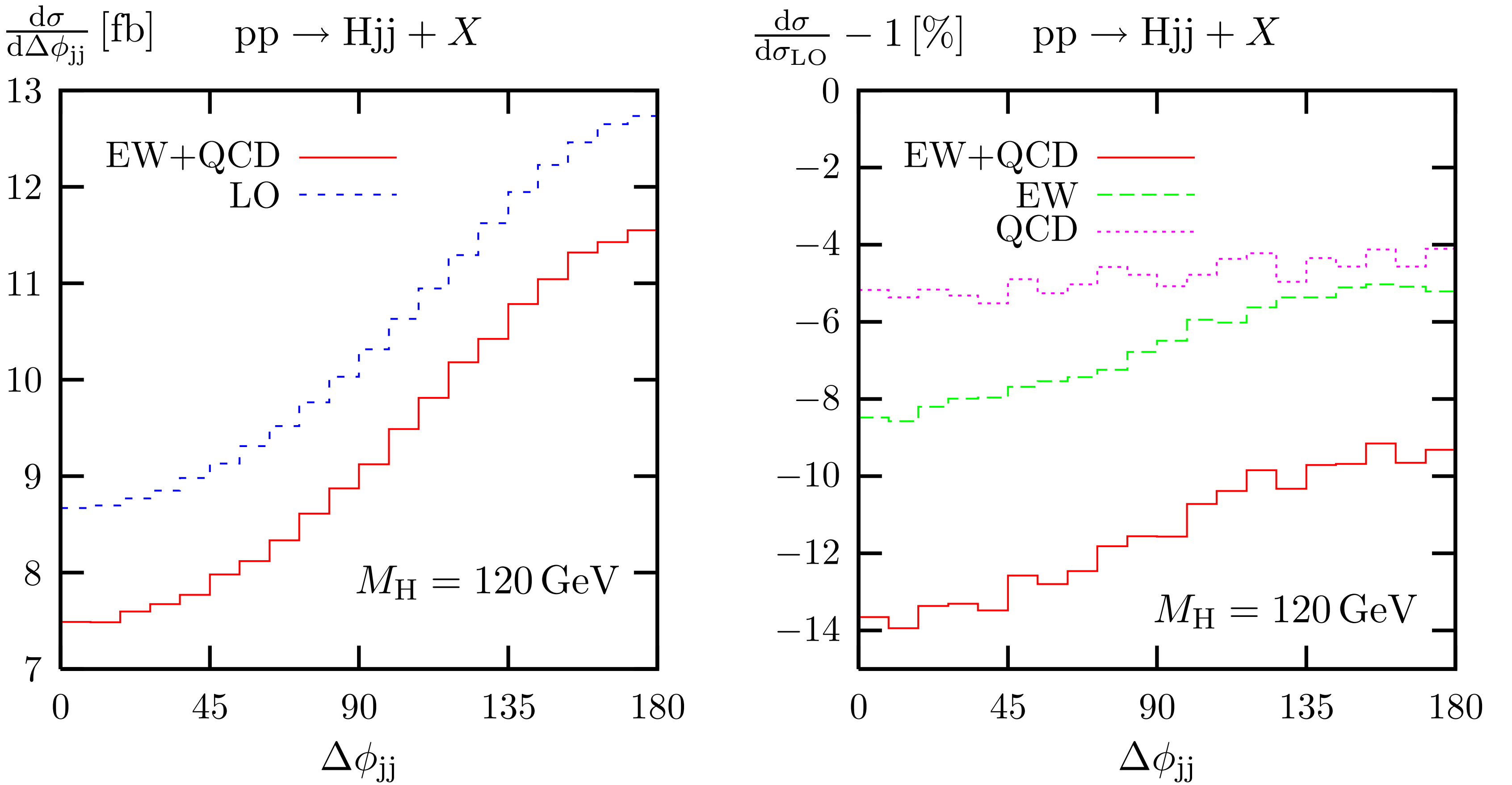
(Individual contributions without SM)

CP-even: $\mathcal{L} \propto HW^+_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto g_{\mu\nu}(k_+k_-) - k_{+,\nu}k_{-,\mu}$

CP-odd: $\mathcal{L} \propto H\tilde{W}^+_{\mu\nu}W^{-,\mu\nu}, \qquad \Gamma^{HW^+W^-}_{\mu\nu} \propto \epsilon_{\mu\nu\rho\sigma}k^\rho_+k^\sigma_-$

Corrections to the $\Delta\phi_{jj}$ distribution:

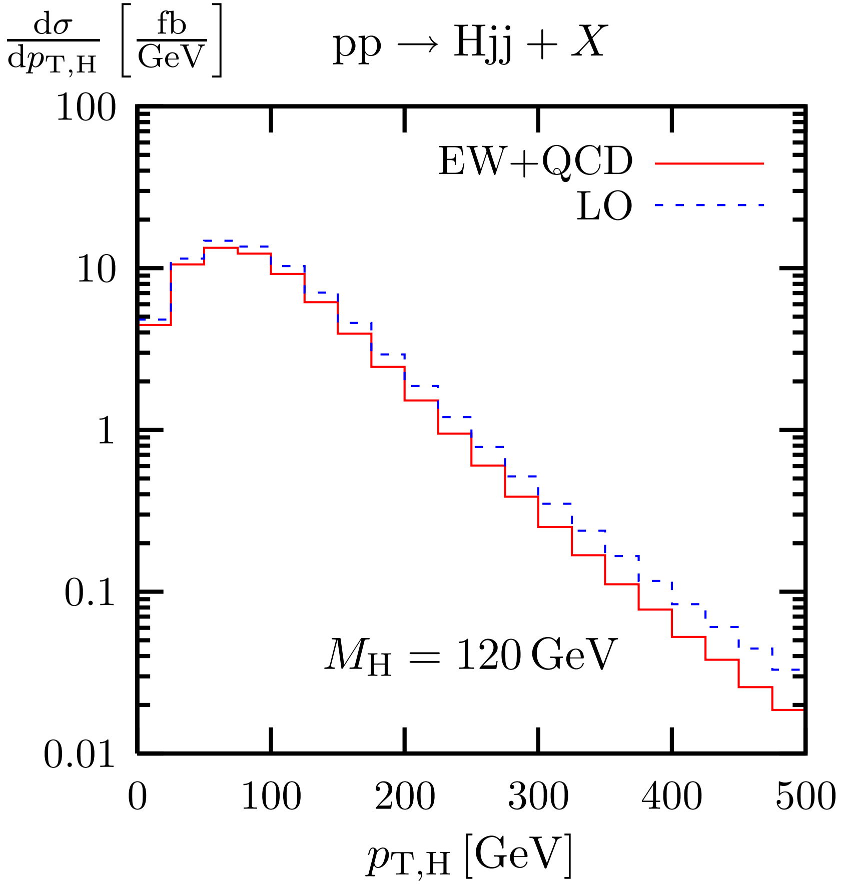
Ciccolini, Denner, S.D. ’07

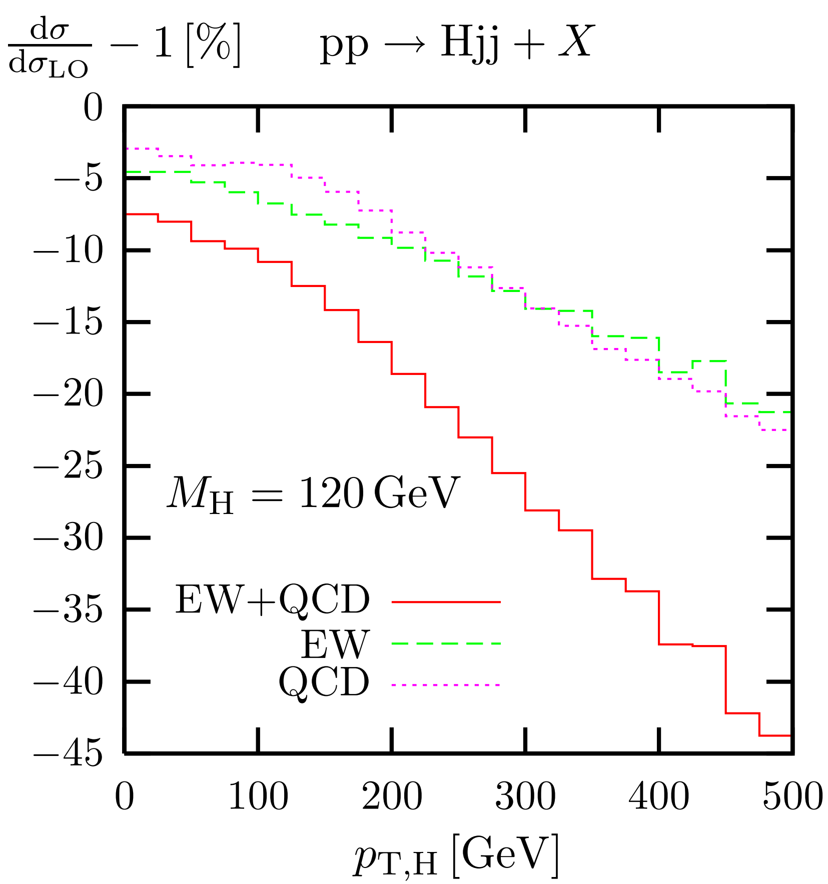


Corrections induce small distortions (which are larger for p_T and y distributions).

Distribution in the Higgs transverse momentum $p_{\mathrm{T,H}}$

Ciccolini, Denner, S.D. '07





$\hookrightarrow$ QCD and EW corrections distort shapes

QCD+EW $\sim$ $20\%(40\%)$ at $p_{\mathrm{T,H}} = 200\,\mathrm{GeV}(500\,\mathrm{GeV})$

Predictions for background processes

$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$ at NLO QCD

At the LHC the background to some signals probably cannot be measured !

"Les Houches wishlist '05" of missing NLO predictions for 'multi-leg" background:

	background for
$\mathrm{pp} \to \mathrm{VV} + \mathrm{jet}$	$\mathrm{t\bar{t}H}$, new physics

WW+jet: S.D., Kallweit, Uwer '07,'09; Campbell, R.K.Ellis, Zanderighi '07
Wγ+jet: Campanario, Englert, Spannowsky, Zeppenfeld '09; ZZ+jet: Binoth et al. '09

$\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$	$\mathrm{t\bar{t}H}$

Bredenstein, Denner, S.D., Pozzorini '08,'09; Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09

$\mathrm{pp} \to \mathrm{t\bar{t}} + 2\mathrm{jets}$	$\mathrm{t\bar{t}H}$

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '10

$\mathrm{pp} \to \mathrm{VVb\bar{b}}$	VBF $\to \mathrm{H} \to \mathrm{VV}$, $\mathrm{t\bar{t}H}$, new physics
$\mathrm{pp} \to \mathrm{VV} + 2\mathrm{jets}$	VBF $\to \mathrm{H} \to \mathrm{VV}$

VBF: Jäger et al. '06,'09; Bozzi et al. '07

$\mathrm{pp} \to \mathrm{V} + 3\mathrm{jets}$	$\mathrm{t\bar{t}}$, new physics

W+3jets: R.K.Ellis, Melnikov, Zanderighi '09; Berger et al. '09
Z+3jets: Berger et al. '10

$\mathrm{pp} \to \mathrm{VVV}$	SUSY tri-lepton

Lazopoulos et al. '07; Binoth, Ossola, Papadopoulos, Pittau '08; Hankele, Zeppenfeld '08

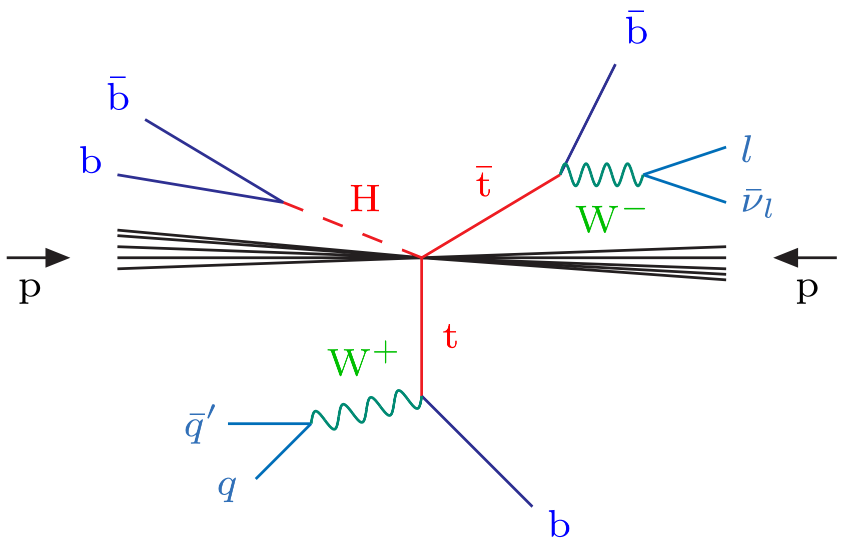
$\mathrm{pp} \to \mathrm{b\bar{b}b\bar{b}}$	Higgs and new physics (added 2007)

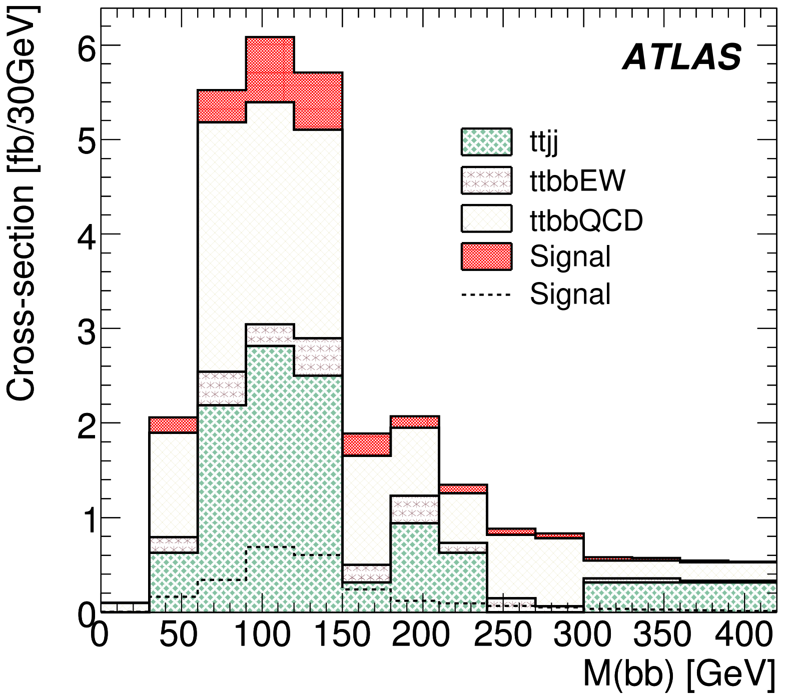
$q\bar{q}$: Binoth, Greiner, Guffanti, Guillet, Reiter, Reuter '09

$\hookrightarrow$ Many long-termed NLO calculations for theorists !
(several 10^4 diagrams, many "(wo)men-decades")

$t\bar{t}H(\to b\bar{b})$ production – a problematic channel

“CSC book”,CERN-OPEN-2008-020





- Relevance: direct experimental access to $t\bar{t}H$ Yukawa coupling
- Problem: control background by $pp \to t\bar{t}b\bar{b}, t\bar{t} + \text{jets}$

  status 2008: signal not significant due to background contamination

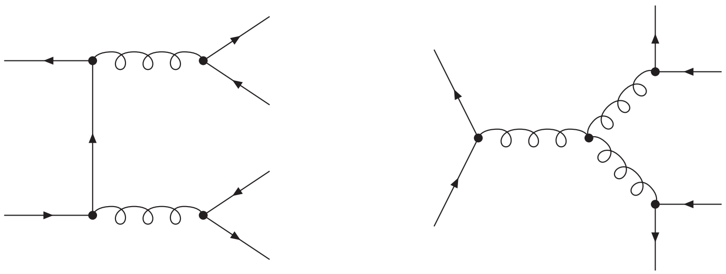
  $\hookrightarrow$ activities:
  - ⋄ more sophisticated tricks in analysis
  - ⋄ NLO QCD prediction also for background

The process $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}}$ in NLO QCD

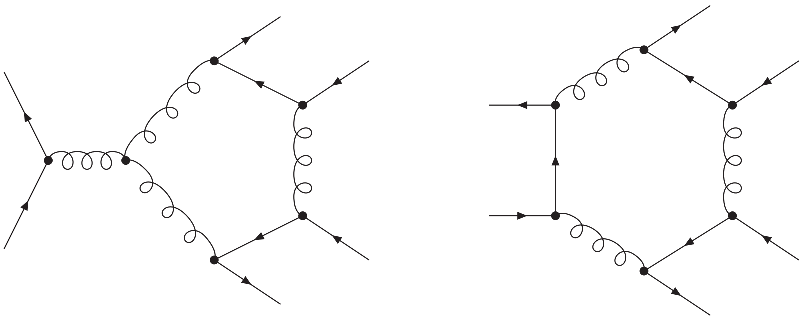
Bredenstein, Denner, S.D., Pozzorini ’08,’09;   Bevilacqua, Czakon, Papadopoulos, Pittau, Worek ’09

$q\bar{q} \to \mathrm{t\bar{t}b\bar{b}}$

LO: 7 tree graphs

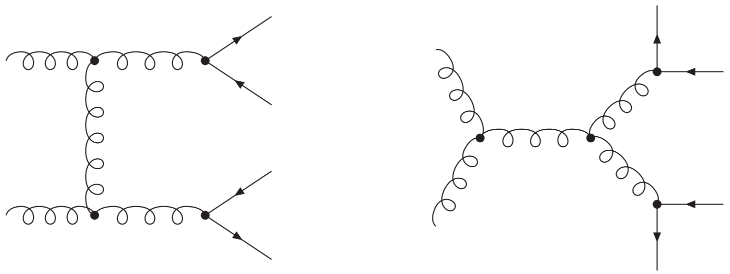


NLO: $\mathcal{O}(200)$ 1-loop diagrams
(24 pentagons, 8 hexagons)

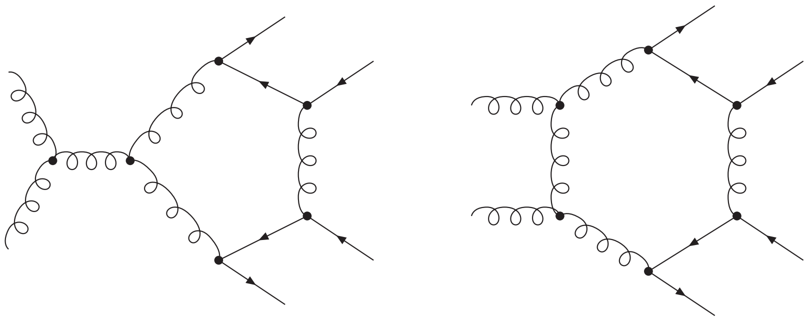


$\mathrm{gg} \to \mathrm{t\bar{t}b\bar{b}}$

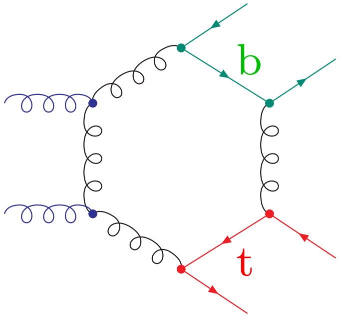
LO: 36 tree graphs



NLO: $\mathcal{O}(\gtrsim 1000)$ 1-loop diagrams
(> 100 pentagons, 40 hexagons)



Complexity defines present “NLO multi-leg frontier"’.



$$= \frac{g_s^6}{2^4} f^{afc} f^{bfd} \mu^{2(4-D)} \int \frac{\mathrm{d}^D q}{(2\pi)^D} \varepsilon^{\alpha,a}(p_1)\, \varepsilon^{\beta,b}(p_2)$$

$$\times\, \overline{u}_{\mathrm{b},k}(k_3)\, (\lambda^e \lambda^c)_{kl}\, \gamma^\mu \frac{m_\mathrm{b} - \not{q}}{q^2 - m_\mathrm{b}^2} \gamma^\nu\, v_{\bar{\mathrm{b}},l}(k_4)$$

$$\times\, \overline{u}_{\mathrm{t},i}(k_1)\, (\lambda^d \lambda^e)_{ij}\, \gamma^\rho \frac{m_\mathrm{t} - \not{k}_2 - \not{k}_3 - \not{q}}{(q + k_2 + k_3)^2 - m_\mathrm{t}^2} \gamma_\mu\, v_{\bar{\mathrm{t}},j}(k_2)$$

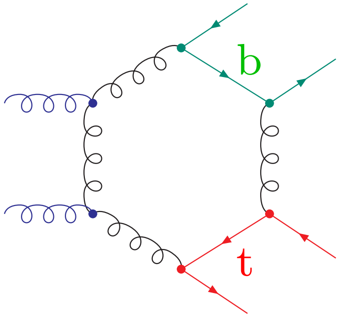
$$\times \frac{\Big[(q + 2p_1 - k_4)_\nu g_{\alpha\sigma} + (q - p_1 - k_4)_\sigma g_{\nu\alpha} - (2q + p_1 - 2k_4)_\alpha g_{\nu\sigma}\Big]}{(q + k_3)^2\, (q + p_1 + p_2 - k_4)^2\, (q + p_1 - k_4)^2\, (q - k_4)^2}$$

$$\times \Big[(2q + 2p_1 + p_2 - 2k_4)_\beta g_{\rho\sigma} - (q + p_1 - p_2 - k_4)_\rho g_{\beta\sigma} - (q + p_1 + 2p_2 - k_4)_\sigma g_{\beta\rho}\Big]$$

D-dim. integral over Minkowski momentum space contains

- various “soft” divergences
- various “collinear” divergences

$\hookrightarrow$ dimensional regularization turns divergences into poles $(D-4)^{-1}$ and $(D-4)^{-2}$



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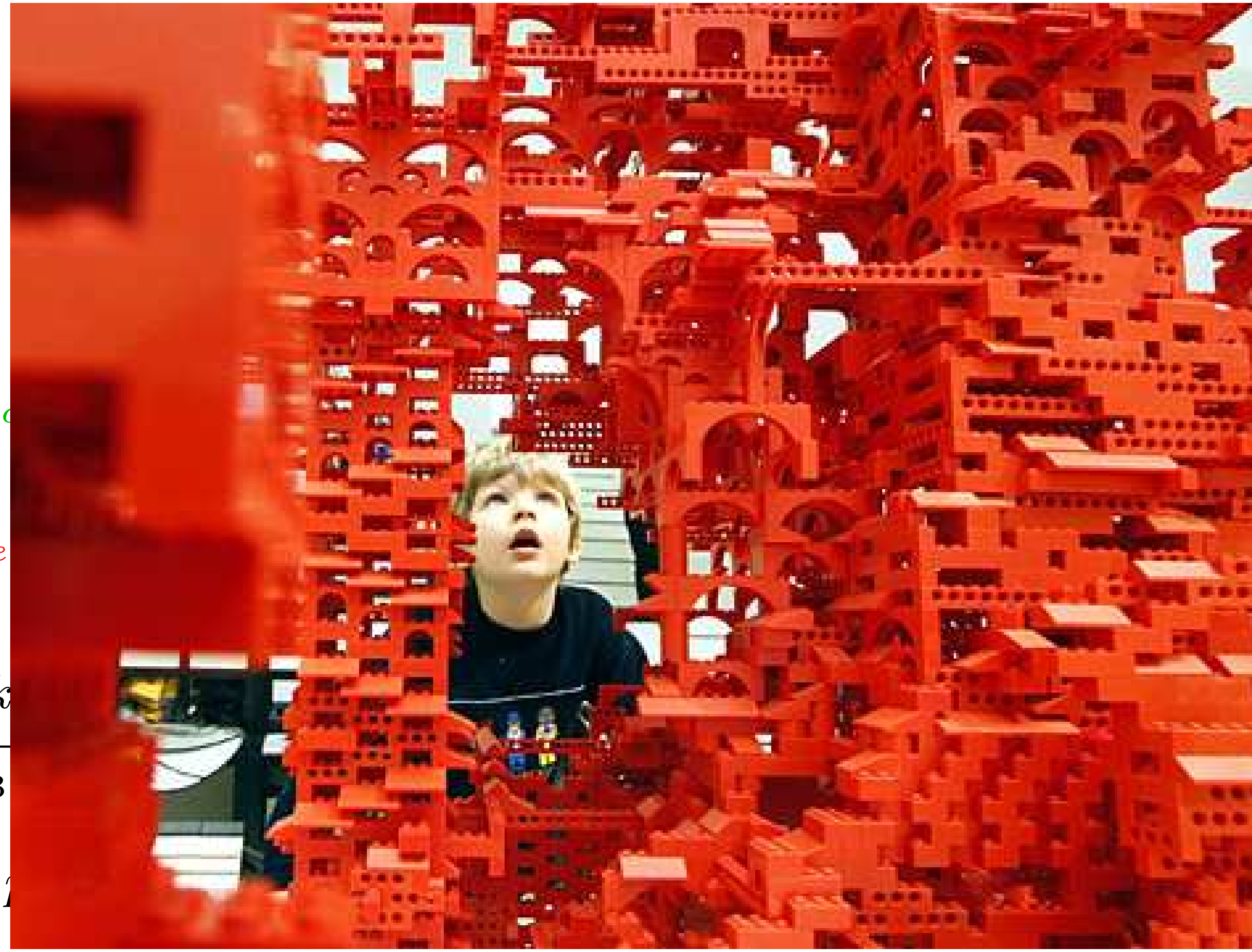


$\times\ \overline{u}_{\mathrm{b},k}(k_3)\,(\lambda^e\lambda^{\ldots}$

$\times\ \overline{u}_{\mathrm{t},i}(k_1)\,(\lambda^d\lambda^e\ldots$

$\times\ \dfrac{\Big[(q+2p_1-k\ldots}{(q+k_3\ldots}$

$\times\ \Big[(2q+2p_1+p\ldots \quad \ldots k_4)_\sigma\, g_{\beta\rho}\Big]$

D-dim. integral over Minkowski momentum space contains

- various “soft” divergences
- various “collinear” divergences

$\hookrightarrow$ dimensional regularization turns divergences into poles $(D-4)^{-1}$ and $(D-4)^{-2}$

Main difficulties in the loop calculation:

- **Algebraic complexity**

  Generation of graphs / amplitudes via computer algebra (MATHEMATICA)

  $\hookrightarrow$ computer-algebraic reduction to standard form

  $\hookrightarrow$ $\sim$ 1.4 Mio automatically generated lines of code

- **Analytic structure**

  Difficult loop integrals with UV and IR divergences

  $\hookrightarrow$ regularization in $D \neq 4$ space-time dimensions

  $\hookrightarrow$ elimination of UV divergences via renormalization

- **Numerical stability**

  Strong cancellation between contributions to loop integrals

  $\hookrightarrow$ dedicated methods for dangerous phase-space regions

- **Efficient numerical evaluation**

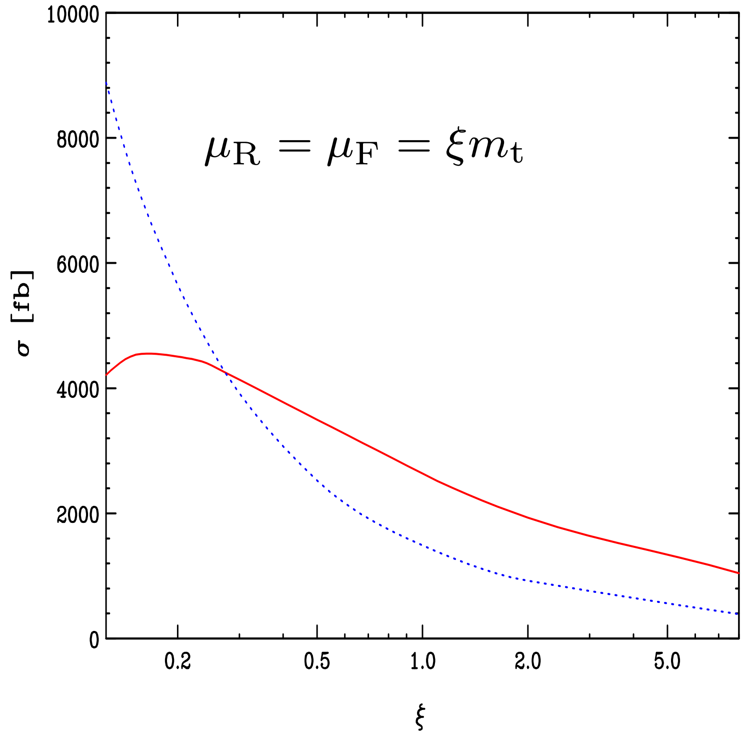
  Goal: fast, numerically stable evaluation in $\lesssim 1\mathrm{sec/event}$

  $\hookrightarrow$ appropriate algorithms, optimizations, cache systems, etc.

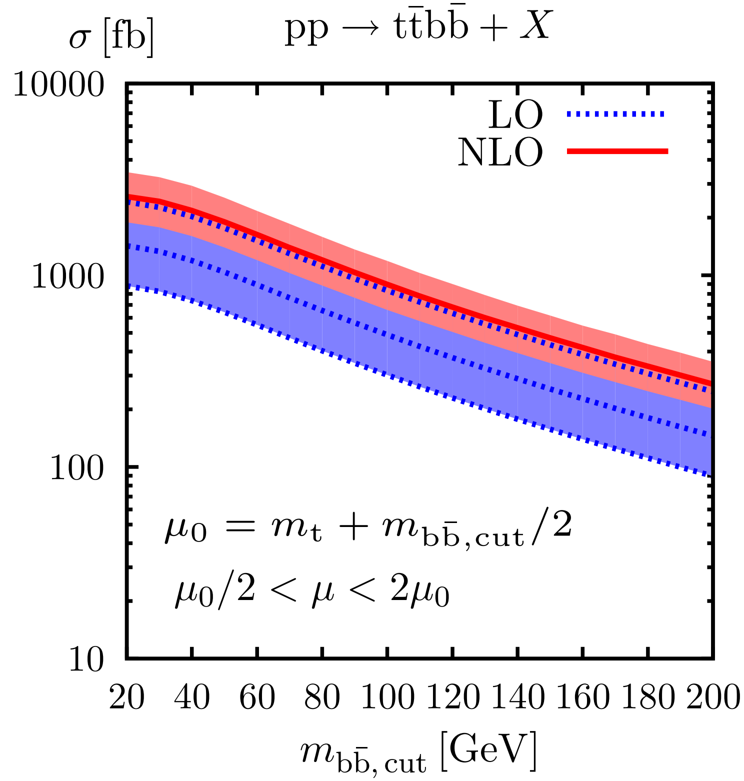
  our result: $\mathcal{M}_{1-\mathrm{loop}}^{q\bar{q}/\mathrm{gg}\to\mathrm{t\bar{t}b\bar{b}}}$ in $\mathcal{O}(0.2\mathrm{sec/event})$

NLO QCD corrections to integrated cross sections

Bevilacqua, Czakon, Papadopoulos, Pittau, Worek '09



Bredenstein, Denner, S.D., Pozzorini '09



Main results:

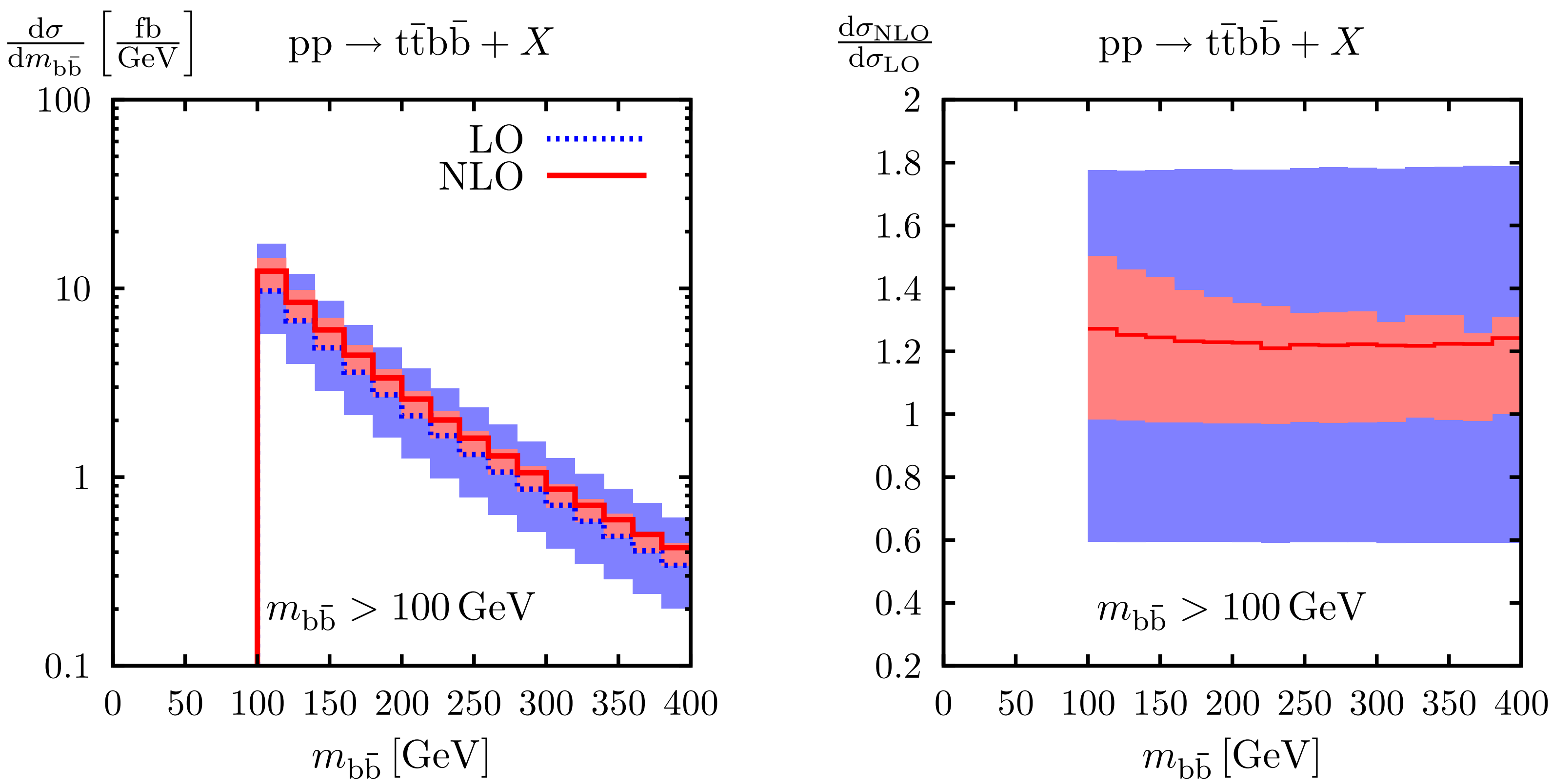
- results of the two groups agree
- correction very large at central scale $\mu_{R/F} = m_t$: $K = 1.77$
- NLO scale dependence still large: $\sim 33\%$ for $\mu_0/2 < \mu_{R/F} < 2\mu_0$ ($\sim 70\%$ at LO)

$\hookrightarrow$ further theoretical and/or phenomenological tricks necessary to stabilize analysis

More results on $\mathrm{pp} \to \mathrm{t\bar{t}b\bar{b}} + X$

- Improvements on scale choice and selection cuts:

Bredenstein, Denner, S.D., Pozzorini ’09



$\hookrightarrow$ reduced K factor ~ 1.2 and NLO scale dependence $\sim 21\%$ for new central scale $\mu_0^2 = m_{\mathrm{t}}\sqrt{p_{\mathrm{T,b}}\,p_{\mathrm{T,\bar{b}}}}$

- Another idea under discussion:

Butterworth et al. ’08; ATL-PHYS-PUB-2009-088

fat jets containing $\mathrm{b\bar{b}}$ pairs from high-p_{T} Higgs (successful in WH/ZH revival!)

$\hookrightarrow$ better background suppression

Plehn, Salam, Spannowsky ’09

Conclusions

Conclusions

The search for the Higgs boson

- Bounds on the Higgs mass from LEP2 search and precision physics:
  $114\,\mathrm{GeV} < M_\mathrm{H} \lesssim 200\,\mathrm{GeV}$

- LHC has sensitivity to SM-like Higgs up to $M_\mathrm{H} \lesssim 1\,\mathrm{TeV}$
  radiative corrections = substantial part of predictions
  - ◇ signal processes up to $\mathcal{O}(5{-}20\%)$ known in SM
    $\hookrightarrow$ continuous refinements (e.g. QCD resummations, EW corrections)
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But for sure: $\sim 10{-}20$ years of exciting particle physics !