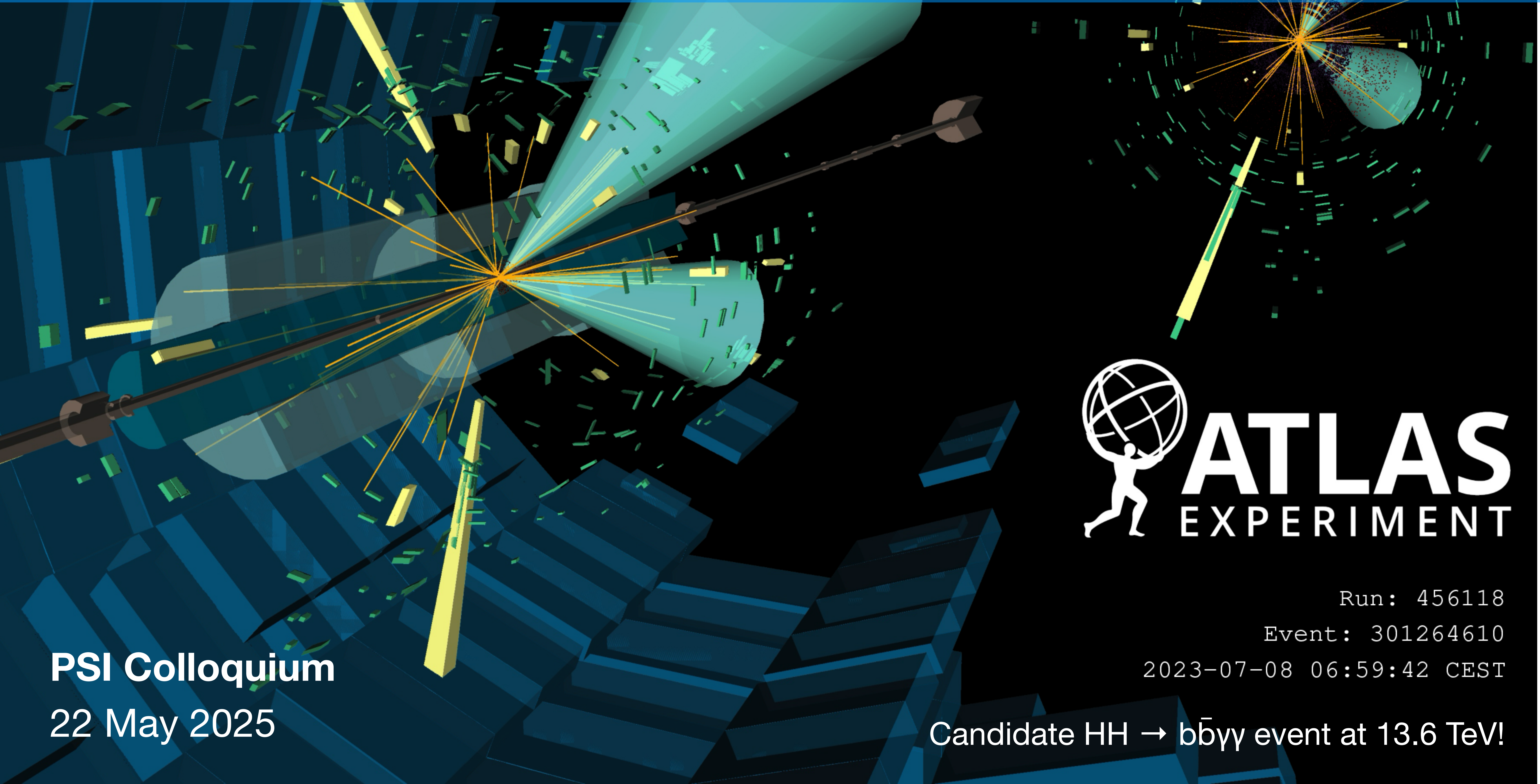
Perspectives in Higgs Physics



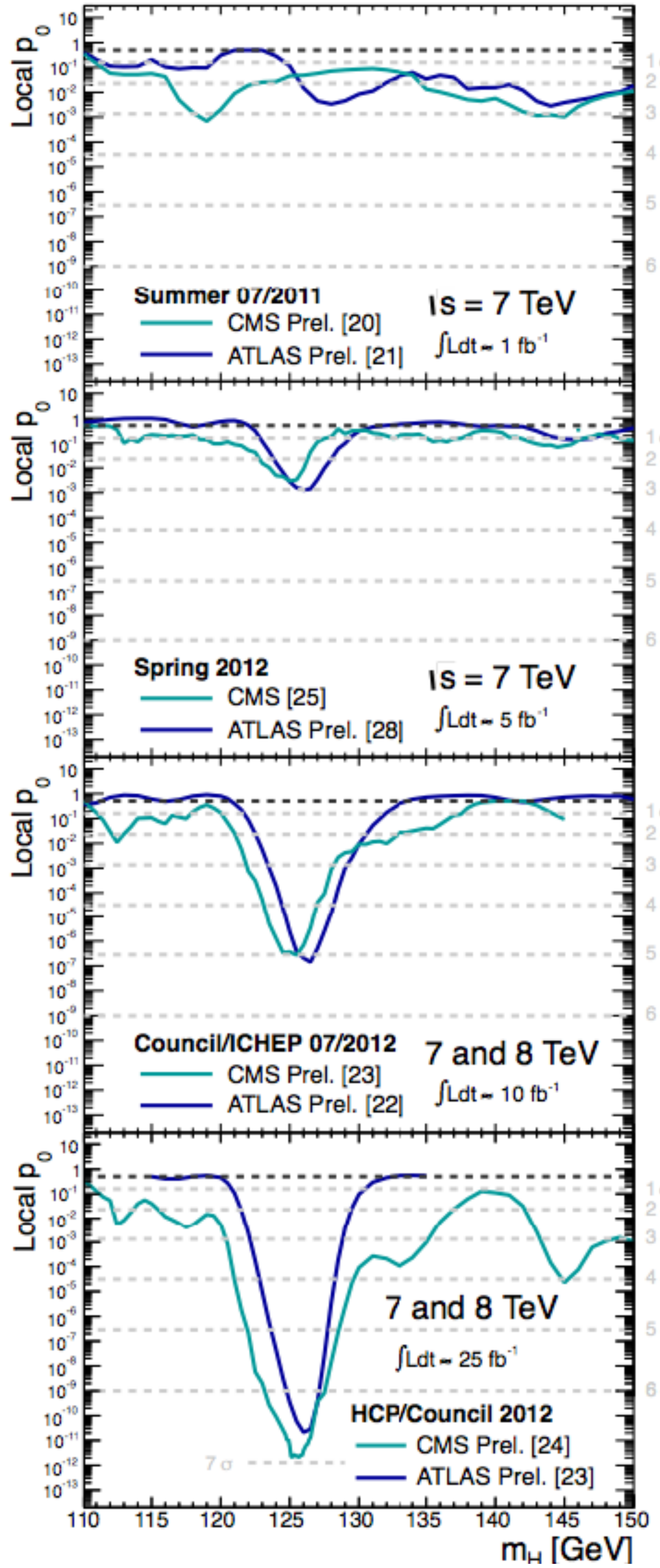
PSI Colloquium

22 May 2025

Marumi Kado

MAX-PLANCK-INSTITUT FÜR PHYSIK

The Higgs Particle : a Gift of Nature



Higgs triumph opens up field of dreams

Nature **487**, 147–148 (2012)

At the time of the discovery the Higgs boson mass was already known to be 125 GeV at 0.5% precision (now it is known at less than one permil).

Its mass is **gift of nature** (a Higgs boson mass maximising the number of channels in which to measure its coupling properties)

''It is the first example we've seen of the simplest possible type of elementary particle. It has no spin, no charge, only mass, and **this extreme simplicity makes it theoretically perplexing.**''

Nima Arkani Hamed

2013

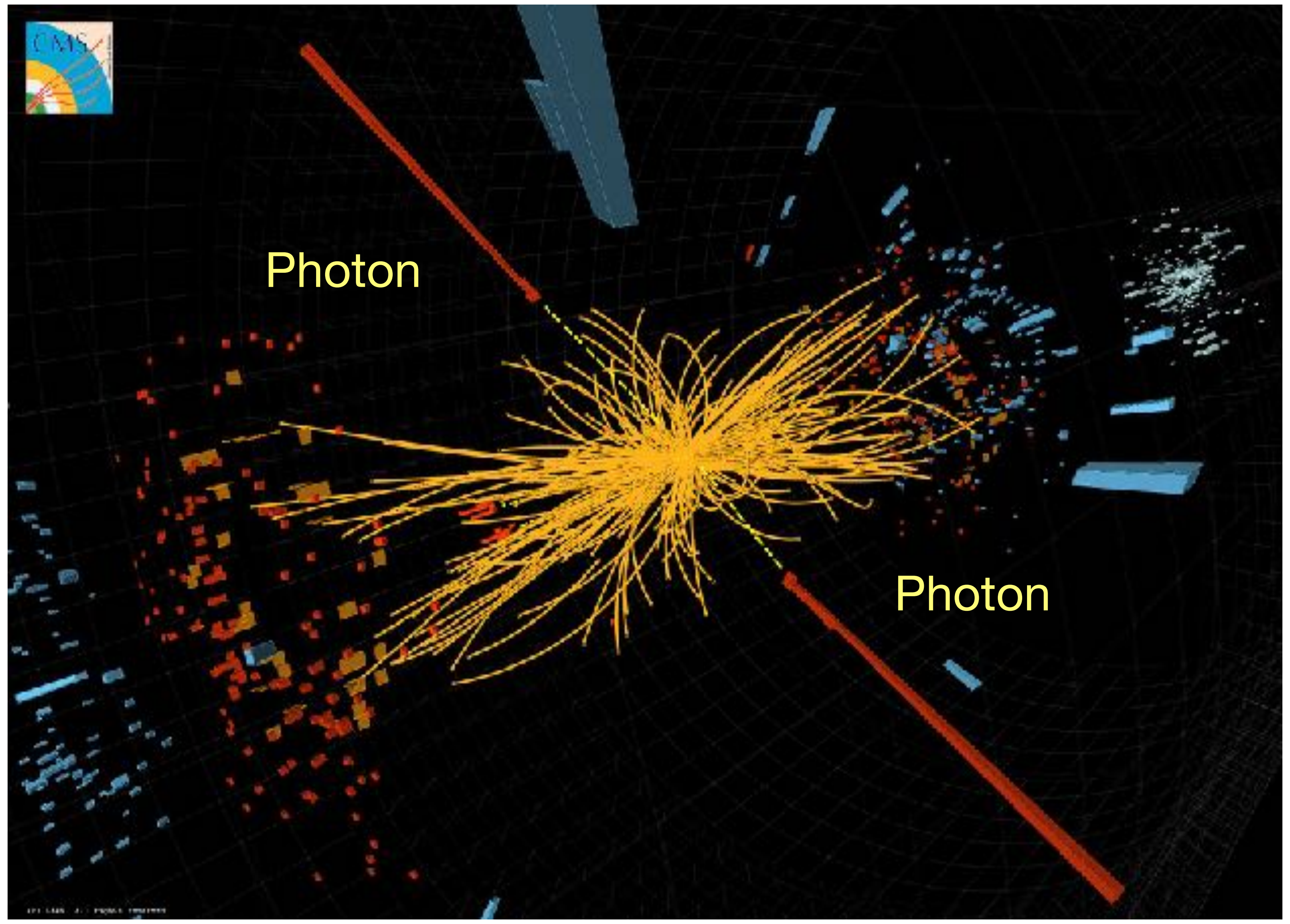
Francois Englert and Peter Higgs

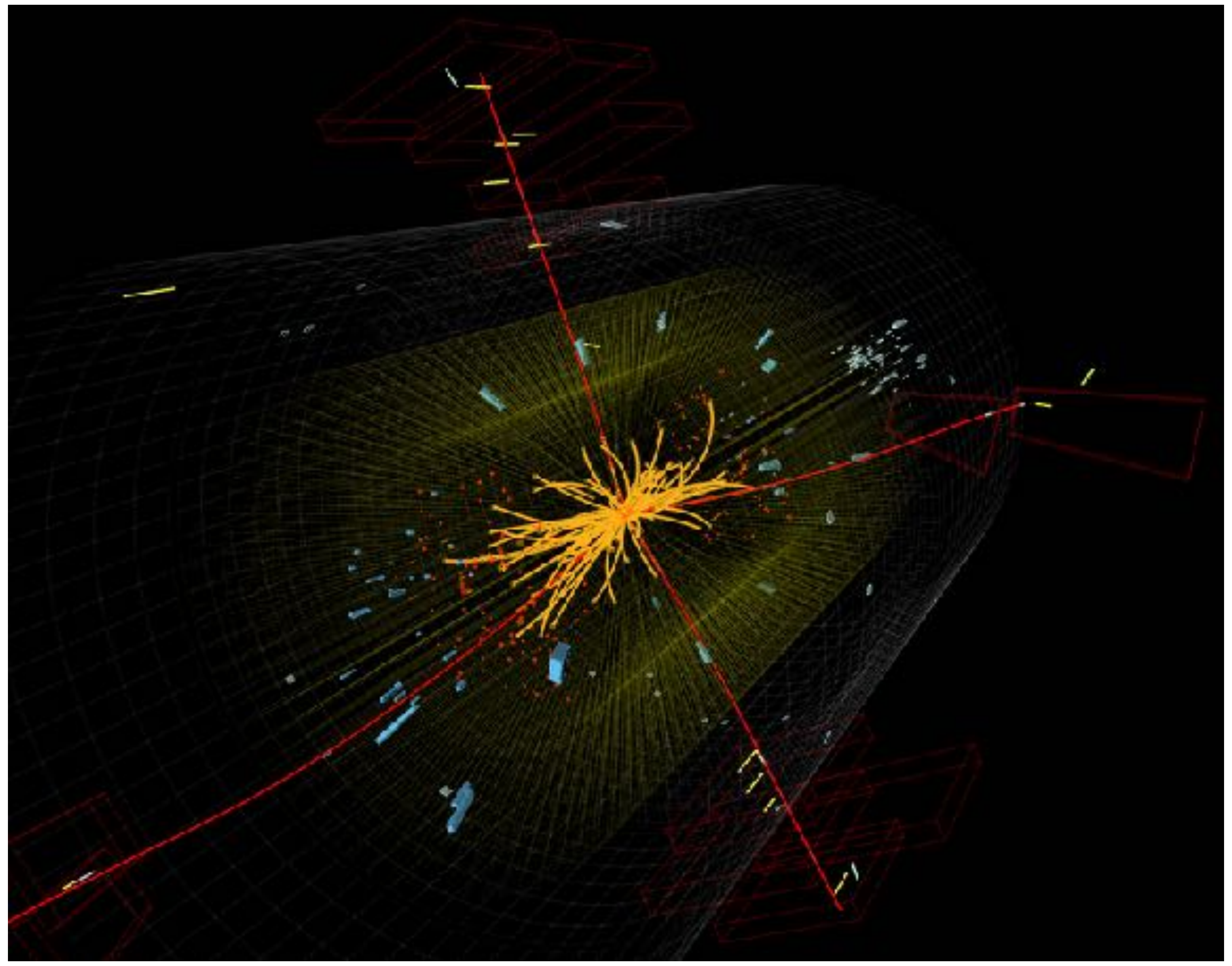
"Interactions with short range forces and scalar particles" [Announcement changed]

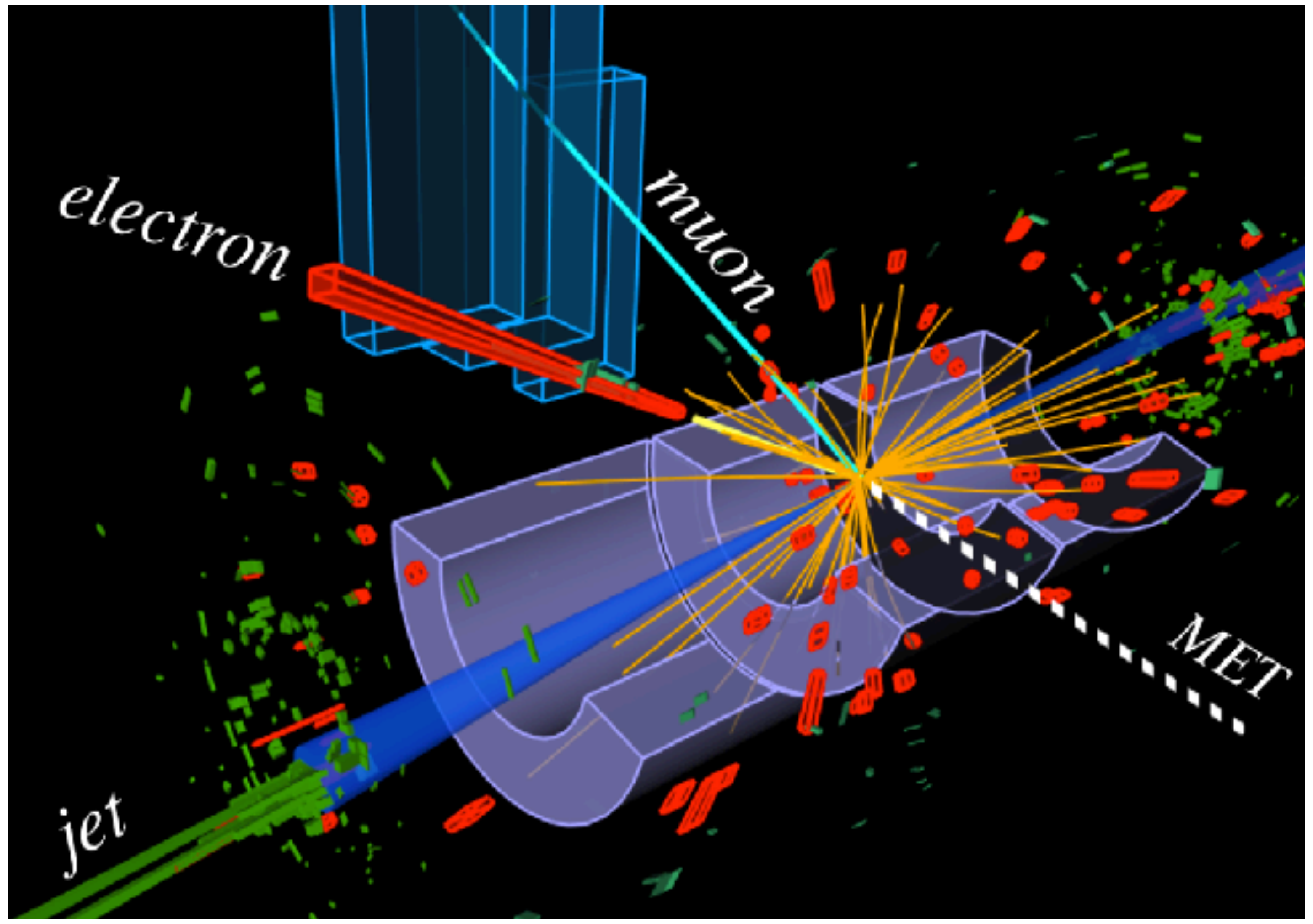
Signatures of the discovery

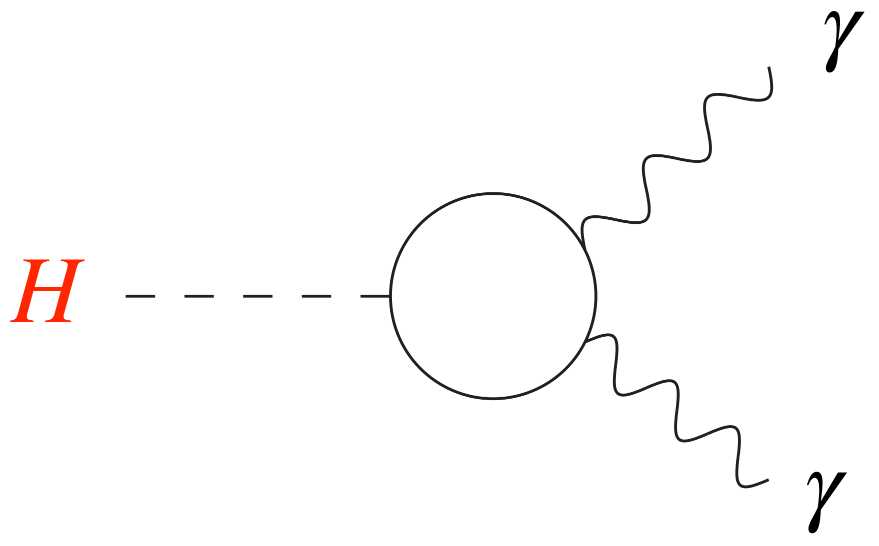
Channels of the Discovery

Higgs boson decays to vector bosons (photons, Z and W)

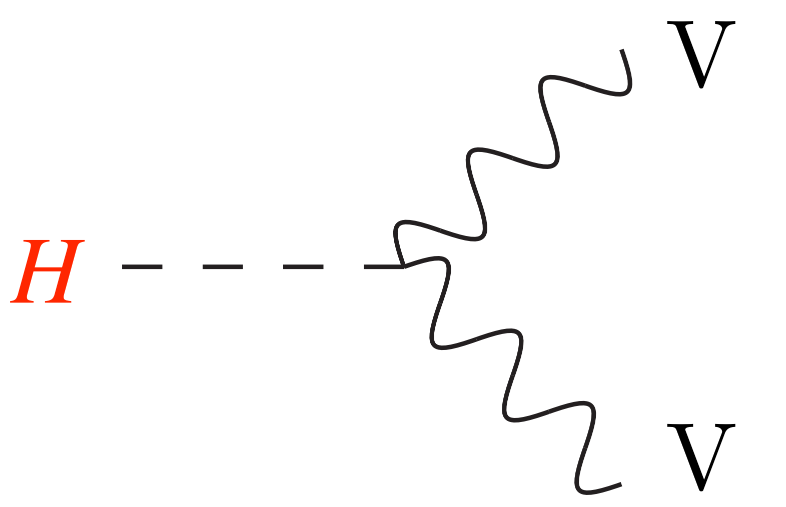








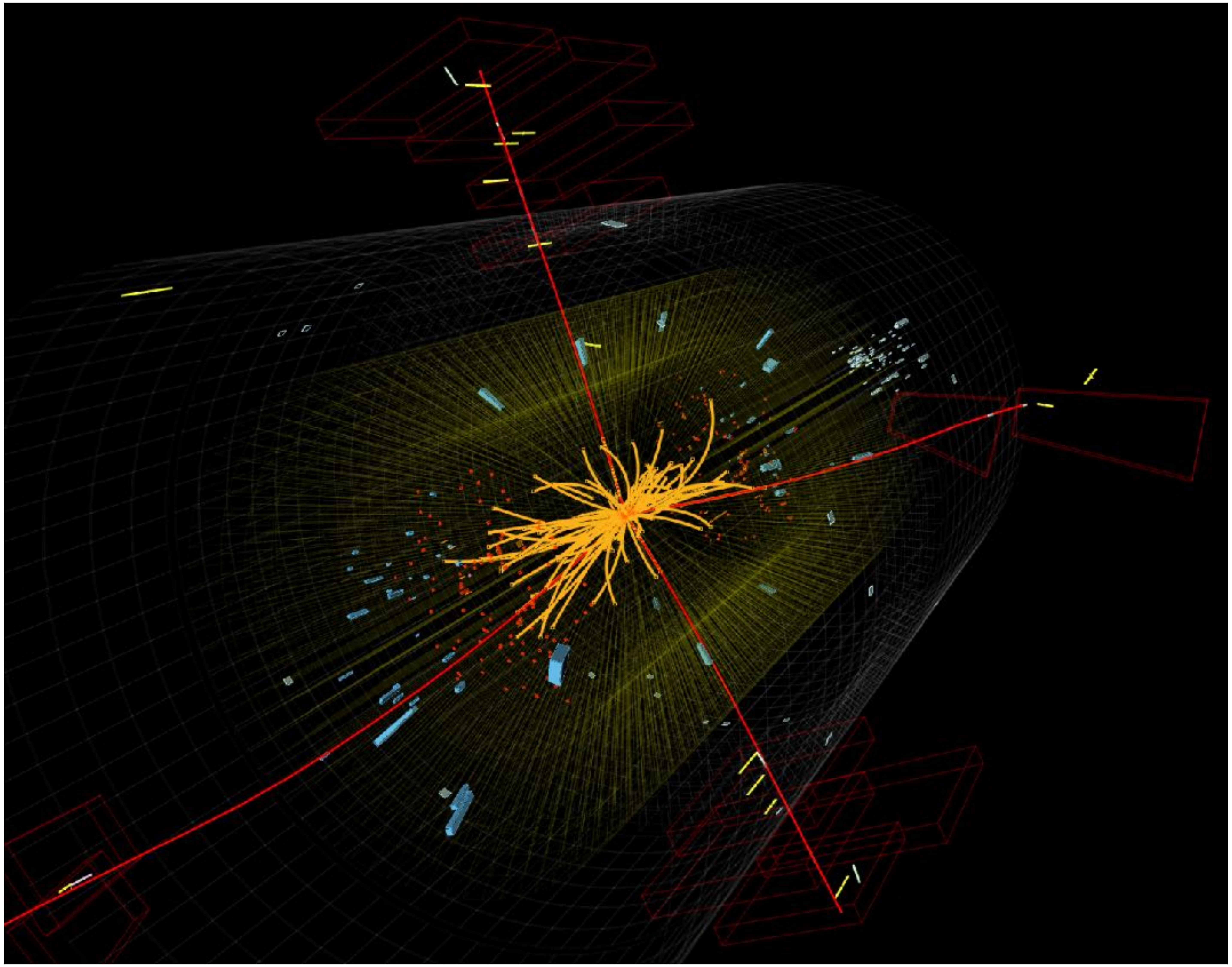
THE BEH-MECHANISM,
INTERACTIONS WITH SHORT RANGE FORCES
AND
SCALAR PARTICLES



Massless gauge bosons (indirectly)

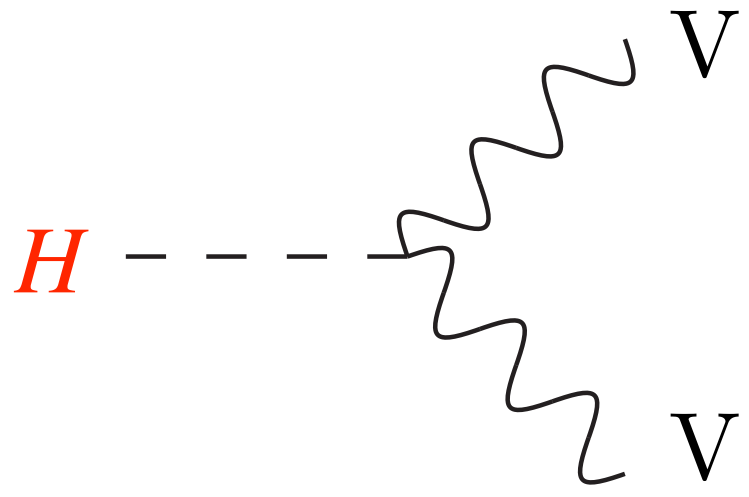
Higgs Boson decays to massive gauge bosons

Higgs Condensate in the Universe

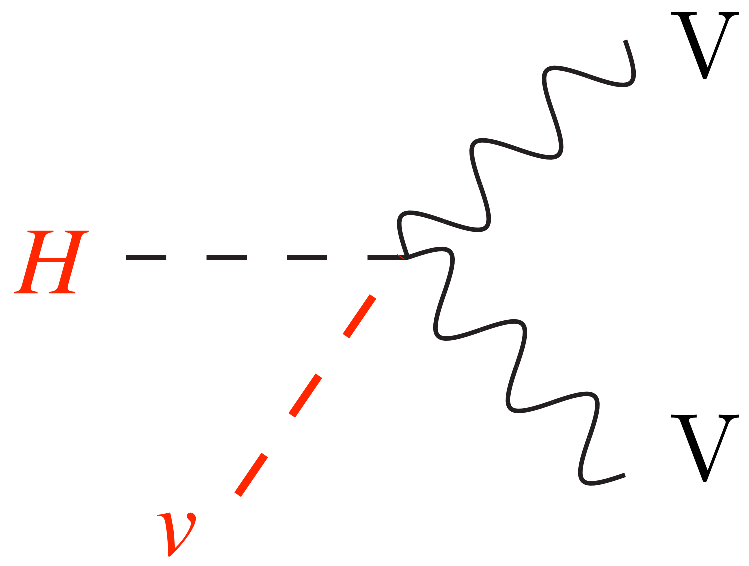


$$H \to ZZ^* \to \ell^+\ell^-\ell^+\ell^-$$

Unambiguous observation of a coupling to vector bosons



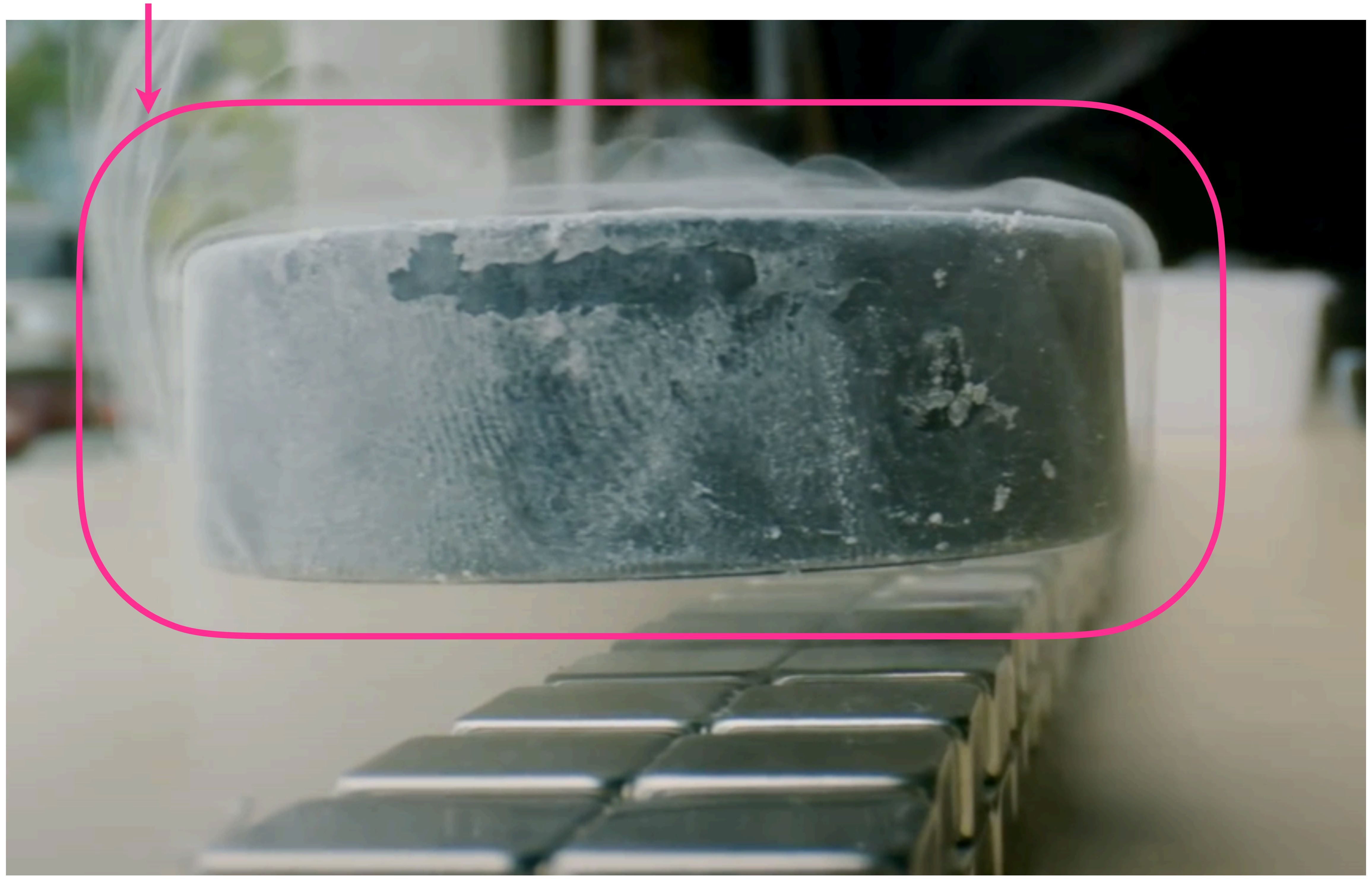
Dimensionally inconsistent requires an additional components usually not shown



Proof of the existence of a condensate!

An Accurate Analogy

The universe



Superconductivity

SC (BCS) Theory	Higgs Mechanism
Cooper pair condensate	Higgs field (No dynamic explanation)
Electrically charged (2e)	Weak charge
Mass of the photon	Mass of the W and Z bosons

1950 – Landau and Ginzburg
JETP 20 (1950) 1064

1957 – Bardeen, Cooper and Schrieffer
Phys. Rev. 108 (1957) 1175

Further reading : L. Dixon, "From superconductors to supercolliders"
(http://www.slac.stanford.edu/pubs/beamline/26/1/26-1-dixon.pdf)

Is the Higgs boson composite?

The Coronation of the Standard Model

Two main outcomes of the LHC: The discovery of the Higgs boson and nothing else (so far)!

Standard Model: formidably simple (gauge) fundamental theory for phenomena at microscopic, astronomical, and cosmic scales!

The dynamics governed by gauge symmetries!

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\psi} \not{D} \psi + h.c.$$

Beauty: simplicity of these expressions, and interactions only 2 (EW) and 2 (QCD) parameters!

The Higgs Mechanism… postulates the **Higgs field**!

Particle masses emerge from their interactions with the Higgs field condensate.

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c. \quad + \frac{c_{ij}}{\Lambda} L_i L_j H H \ ?$$

$$+ |D_\mu \phi|^2 - V(\phi) \quad + \Lambda^4 \ ? \quad + \mathrm{DM} \ ?$$

Ugliness: number of free parameters (26 altogether) not governed by symmetries

Open Questions

The strong CP problem

$$\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu}$$

$\theta < 10^{-10}$ From neutron electric dipole moment measurements

Hierarchies

- Gauge Hierarchy (and Naturalness)
- Flavour hierarchy (includes neutrino masses)

Why are masses so different? Yukawa couplings are set by hand!

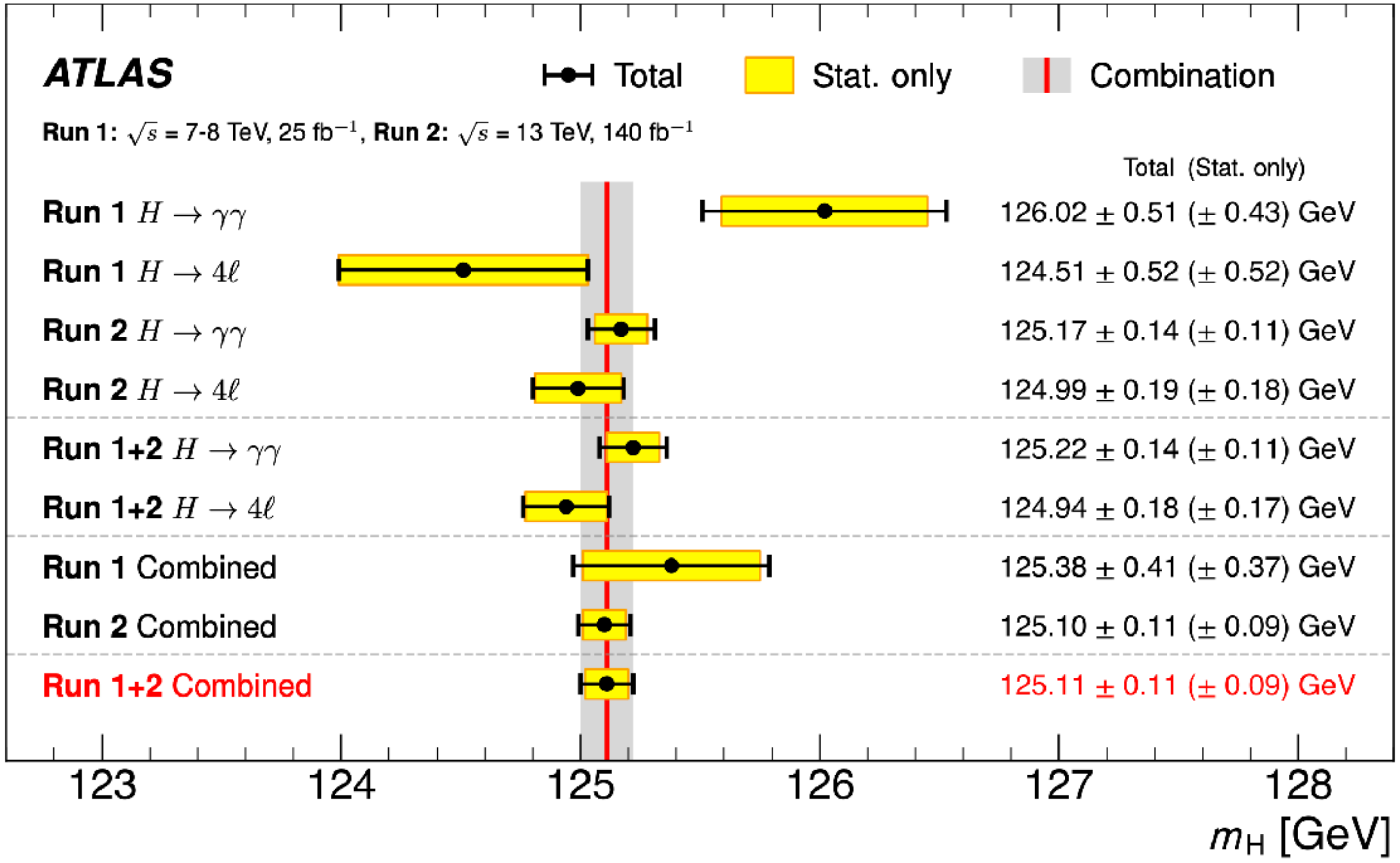
Dark Sector ?

What is the nature of **DM** and **DE**, is there a Dark Sector?

First Precision Measurement at the LHC!

Higgs boson mass measurement

- Measurement done exclusively in the diphoton and 4-leptons channel.
- Systematics dominated by experimental uncertainties.
- Reached at Run 1 a precision of 0.2%.
- Precision reached **0.09%** (below permil!)



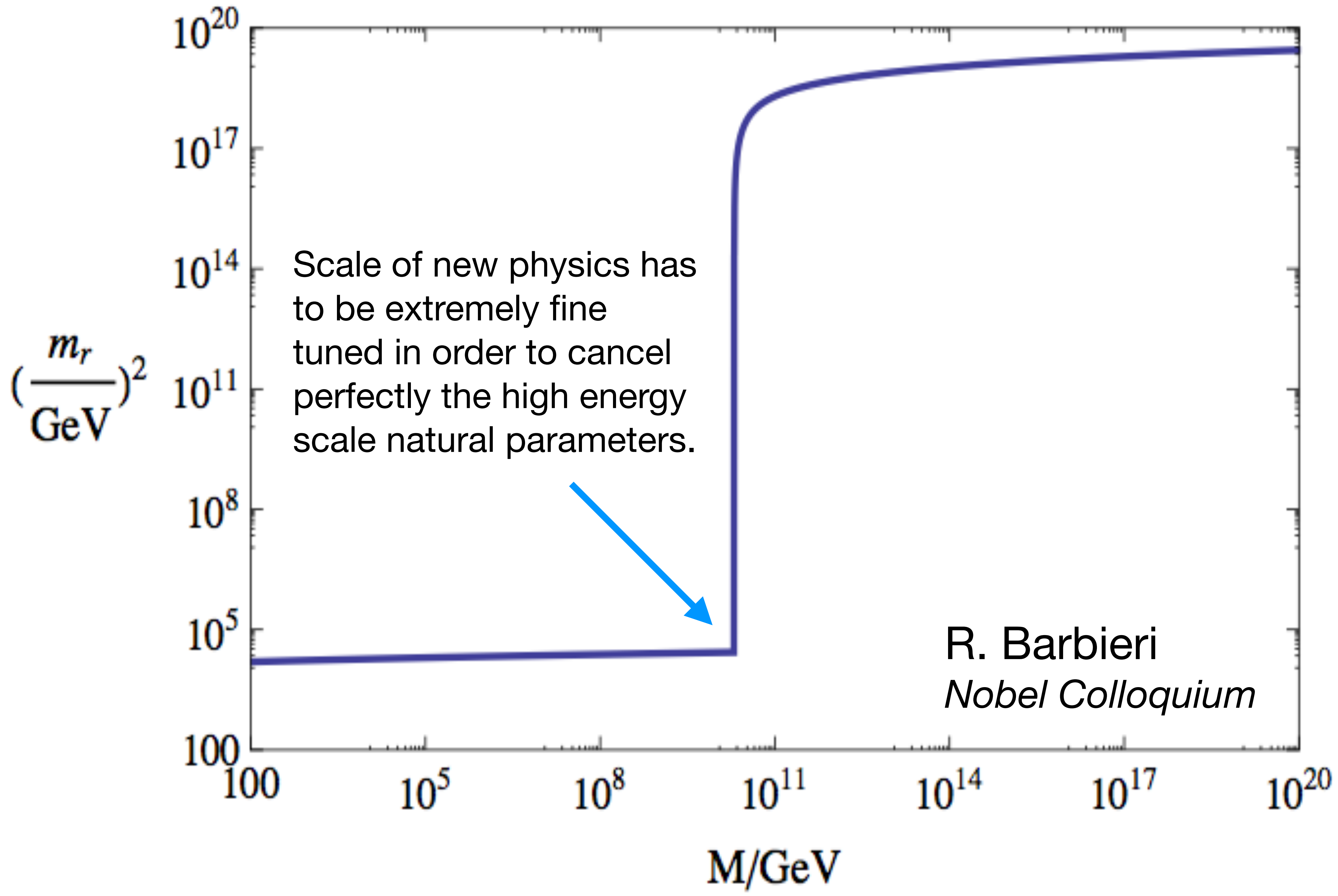
Precision foreseen at HL-LHC 10-20 MeV

Similar precision by CMS

The (running) Higgs mass and the Naturalness Problem

Naturalness cannot be dismissed!

If the Higgs boson is an elementary scalar, loop corrections to its mass are quadratically divergent, not an issue per se (renormalisation) but if there is new physics at a high scale a **threshold in the running Higgs mass** will appear **implying a fine tuning of the mass at the high scale!**



Solutions explored:

- **Weakly coupled** (SUSY)
- **Strongly coupled** (Composite)
- **Warped extra dimensions**

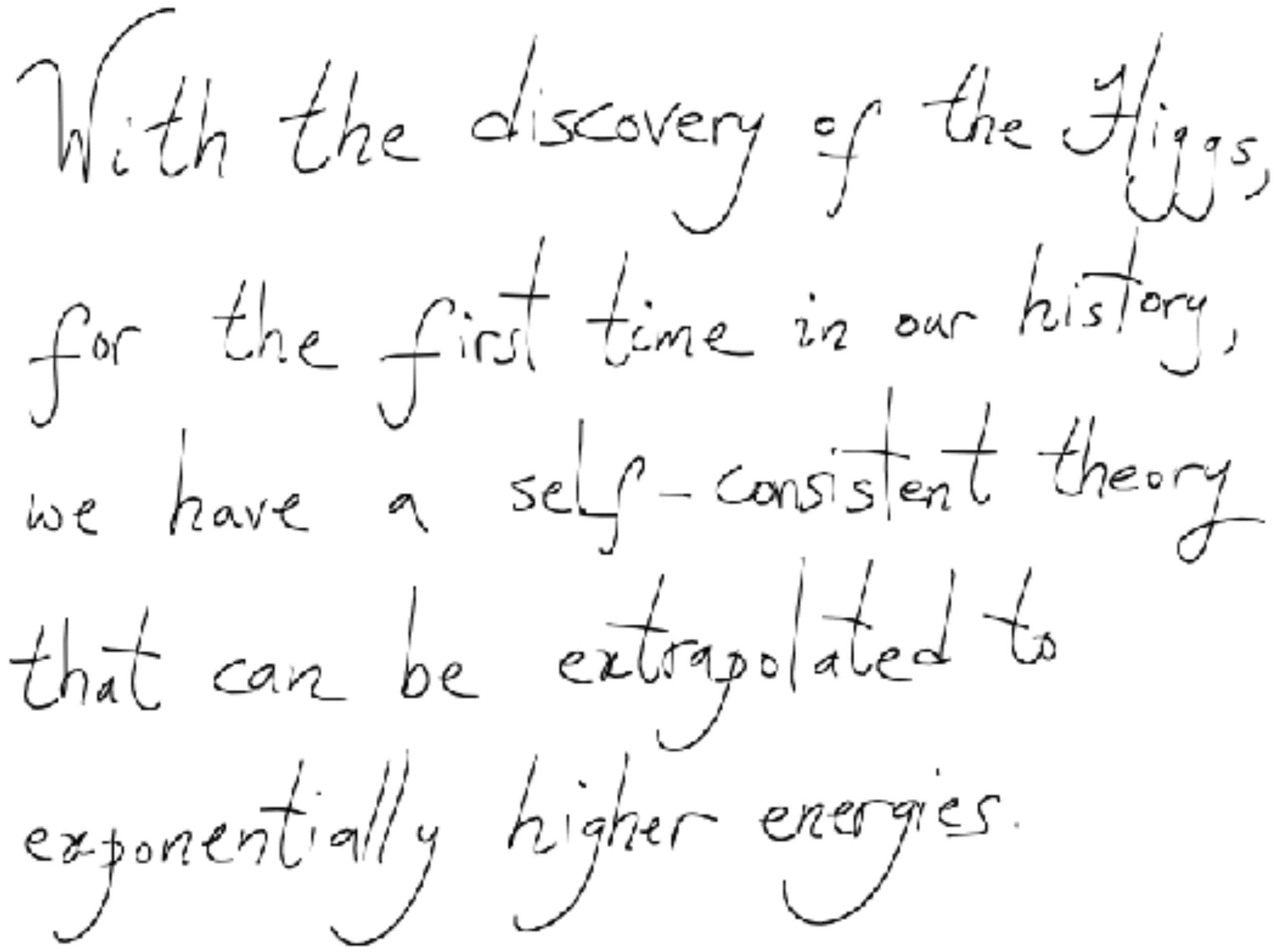
To be natural, solutions involve new physics at close-by energy scales! Or invoke the **Anthropic principle**…

Having discovered the Higgs boson and nothing else remains a paradox and further **investigating the O(10 TeV) scale is more not less important** (after LHC 13 TeV results)!

One of the three naturalness problems mentioned earlier (with Cosmological Constant and Strong CP)

Stability of the Universe

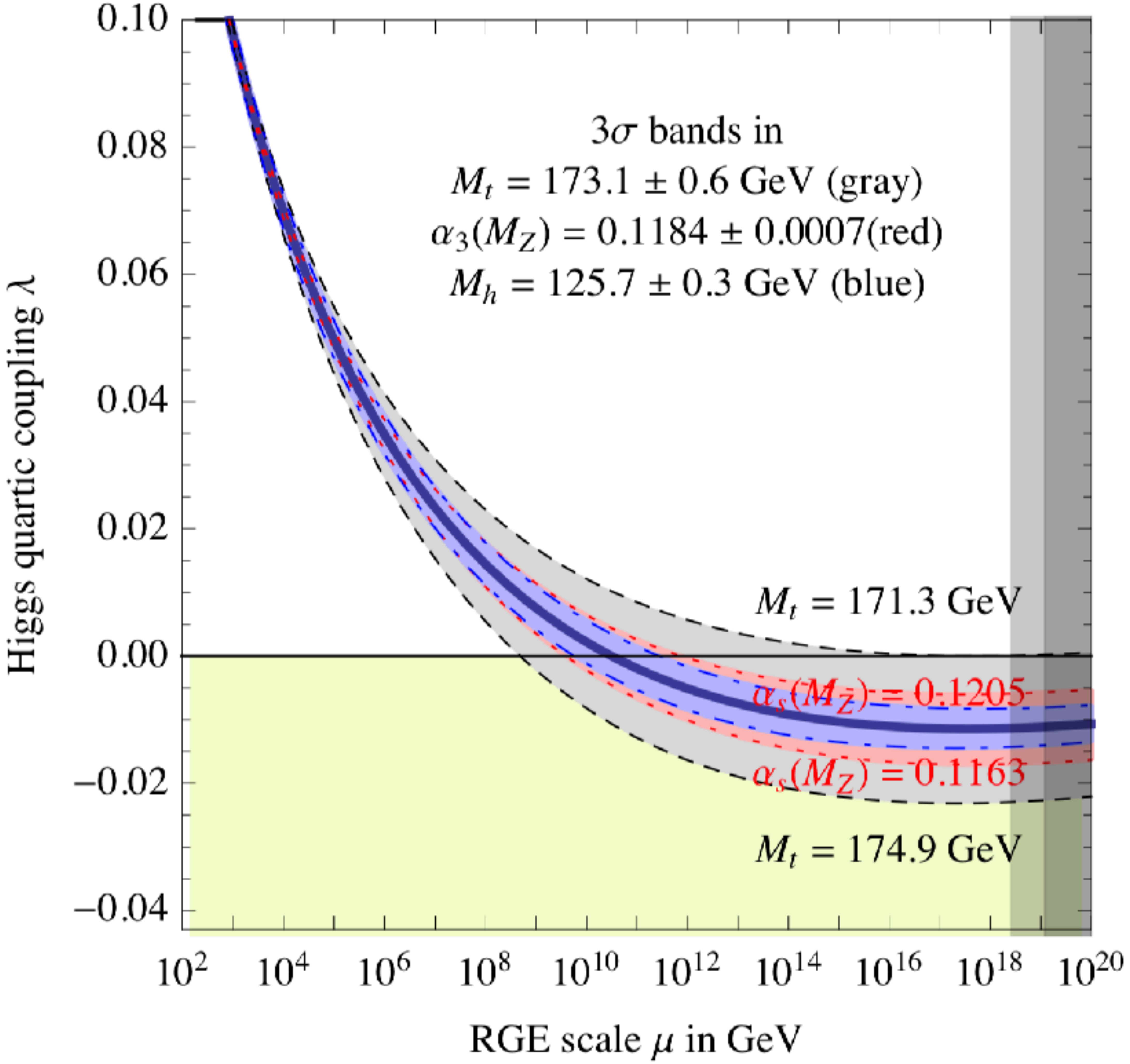
Running of the Higgs self coupling, **assuming SM only** up to high energy scale



Nima Arkani Hamed

Near vanishing coupling at the Planck scale is a striking fact!

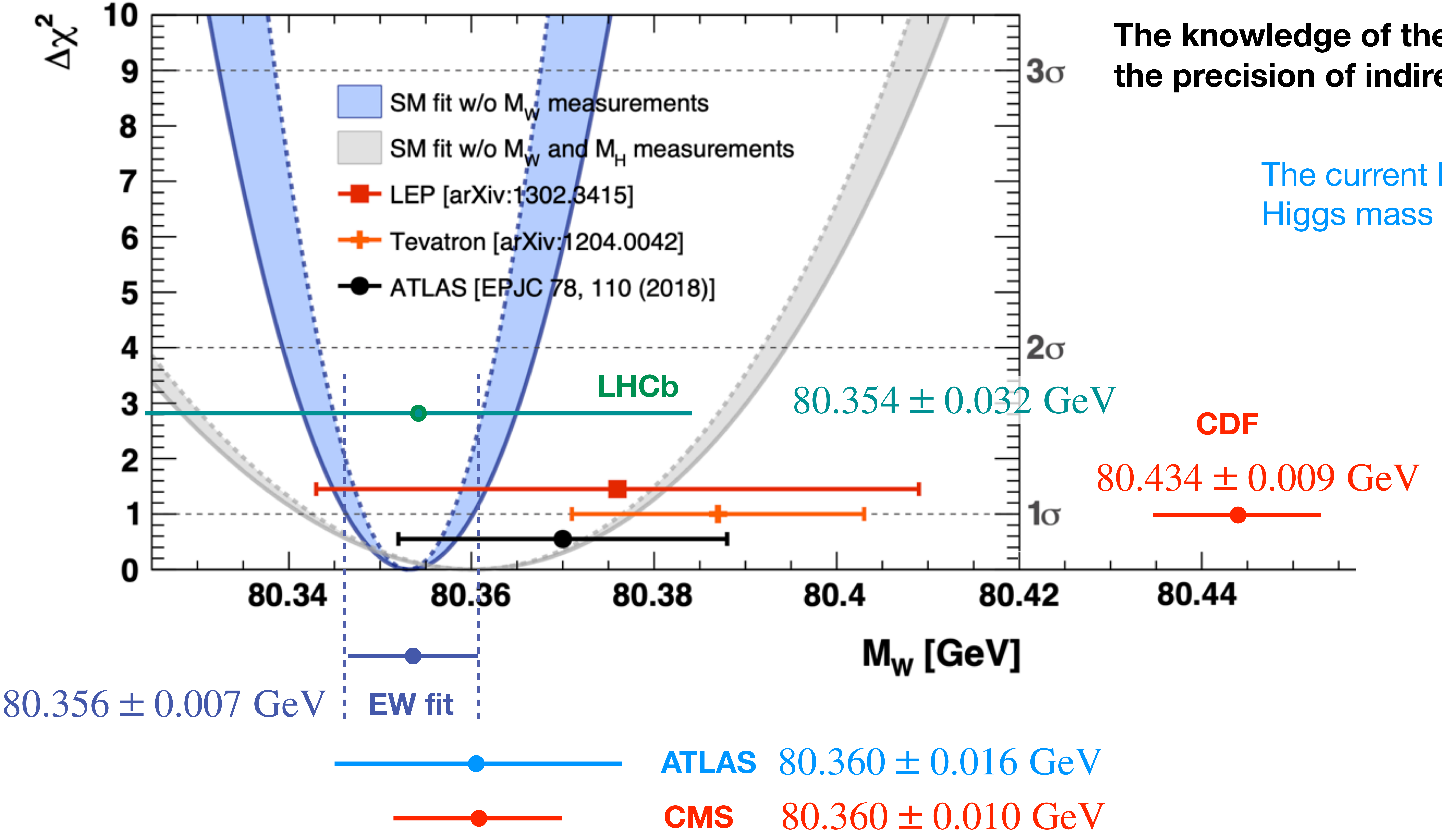
Vacuum (meta) stability



Higgs and Precision EW Measurements

Precision measurements allow to make predictions!!

Assuming the SM

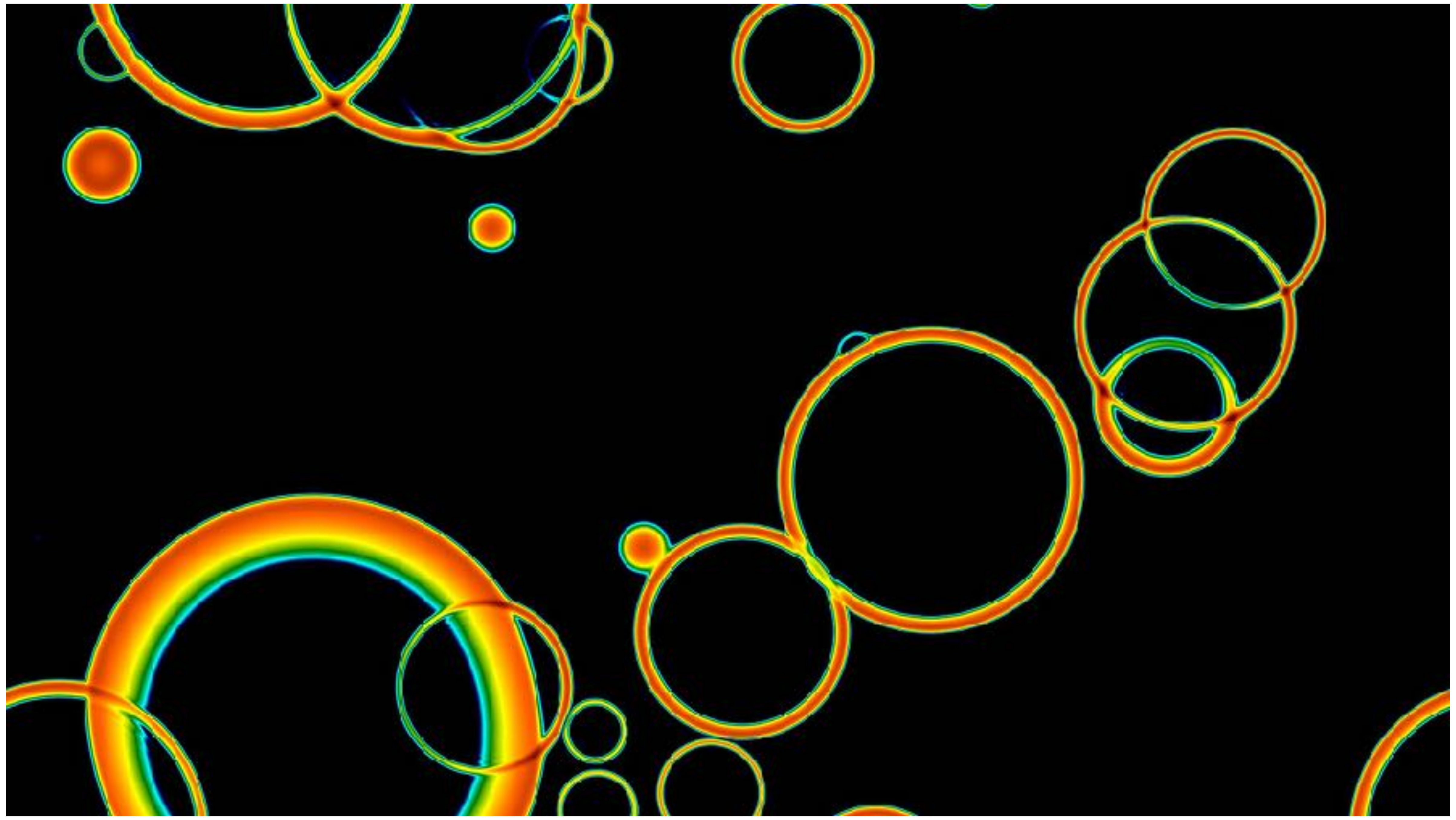


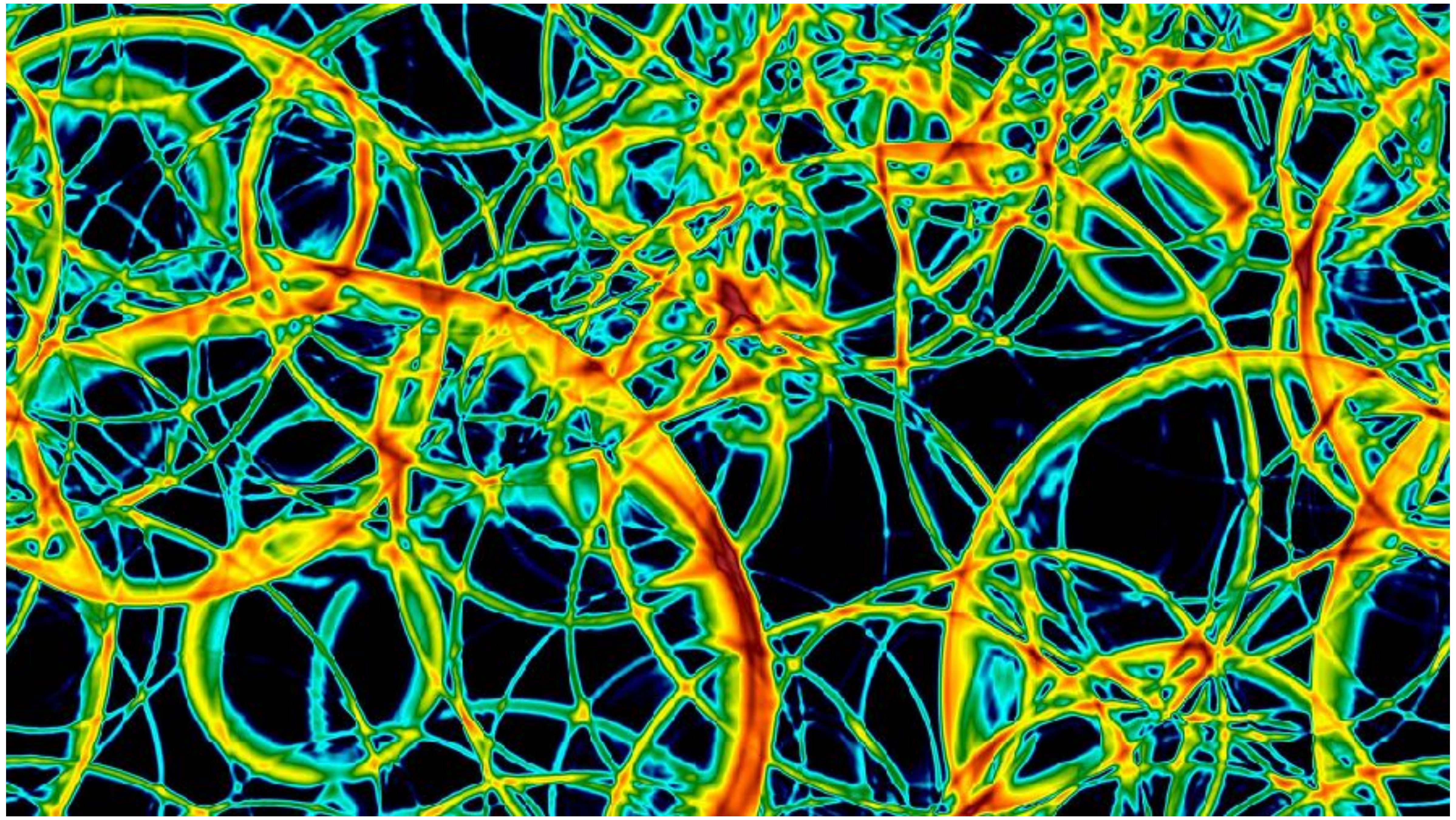
The knowledge of the Higgs mass has large impact on the precision of indirect measurements!

The current level of precision on the Higgs mass has little impact on this.

Significant evidence of measurement systematic bias!

Matter-anti-matter Asymmetry and the Higgs





Generation of stochastic background of gravitational waves

The origin of the matter-antimatter asymmetry in the Universe remains one of the outstanding open problems in particle physics.

Sakharov conditions for baryogengesis: baryon number non-conservation, charge and charge-parity violation, and **non-equilibrium dynamics** e.g. phase transition.

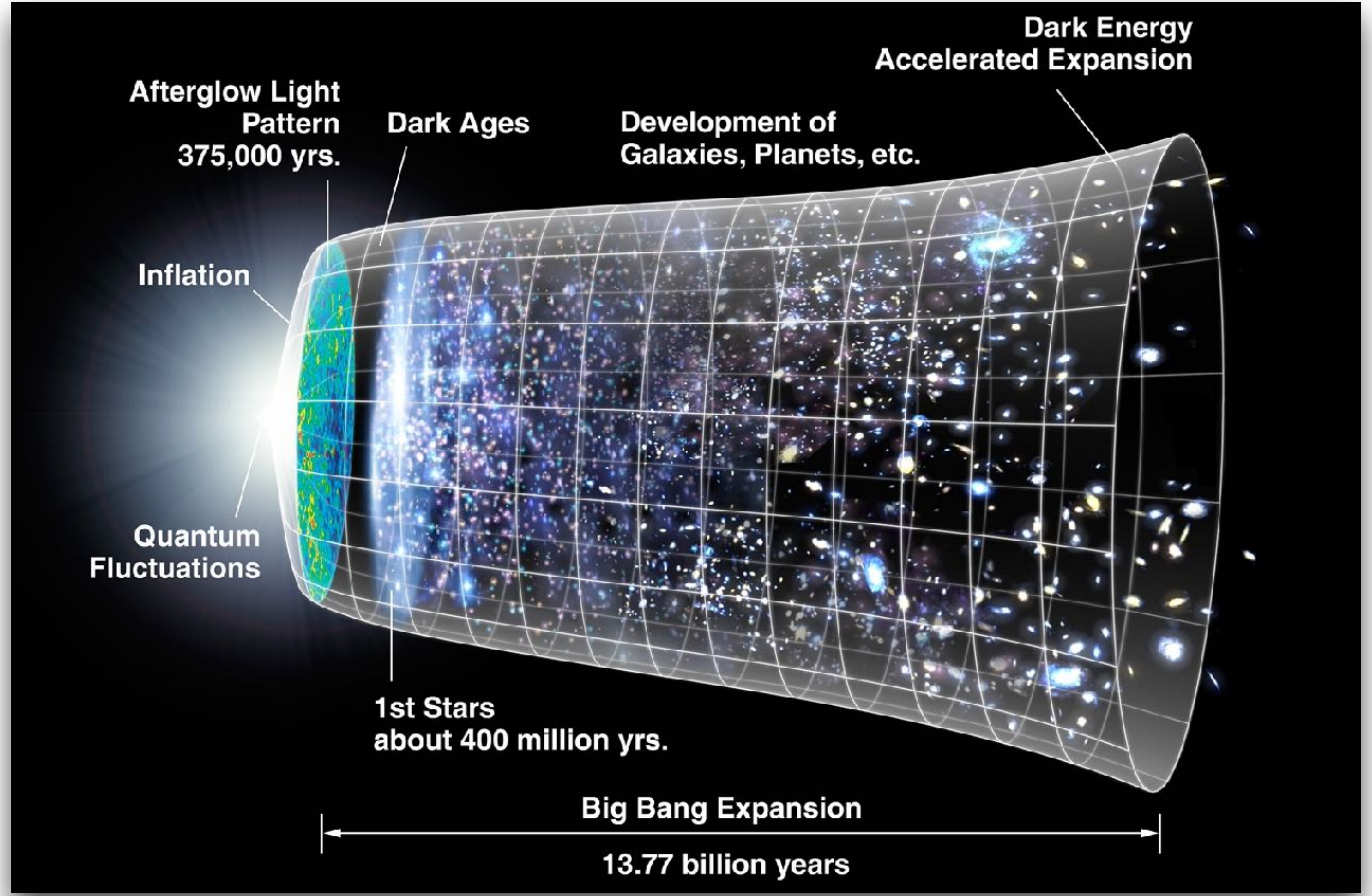
The electroweak transition (cross over in the Standard Model) takes place at the start or during inflation at 10^{-36} to 10^{-32}s after the big bang!

Higgs and the Early Universe

The mechanism responsible for inflation is not known.

The Higgs could in principle act as the inflaton.

Not favoured scenario as it requires a strong non-minimal coupling to gravity.



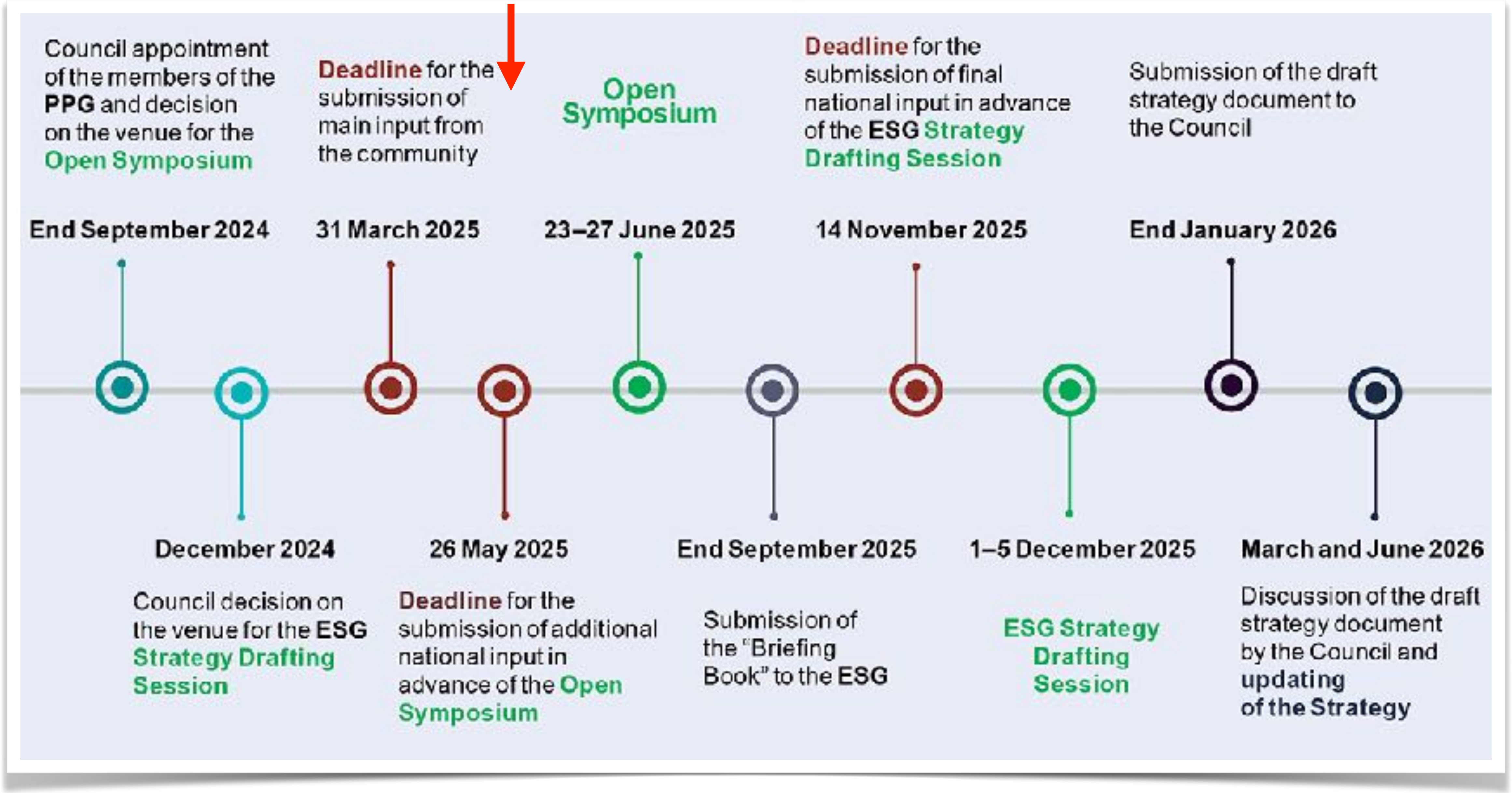
A Scientific Mission for the 21st Century

A Pivotal Moment for Particle Physics

Physics community called to make a strategic decision.

European Strategy Process well underway with principal goal to decide on the next flagship CERN project.

We are here!



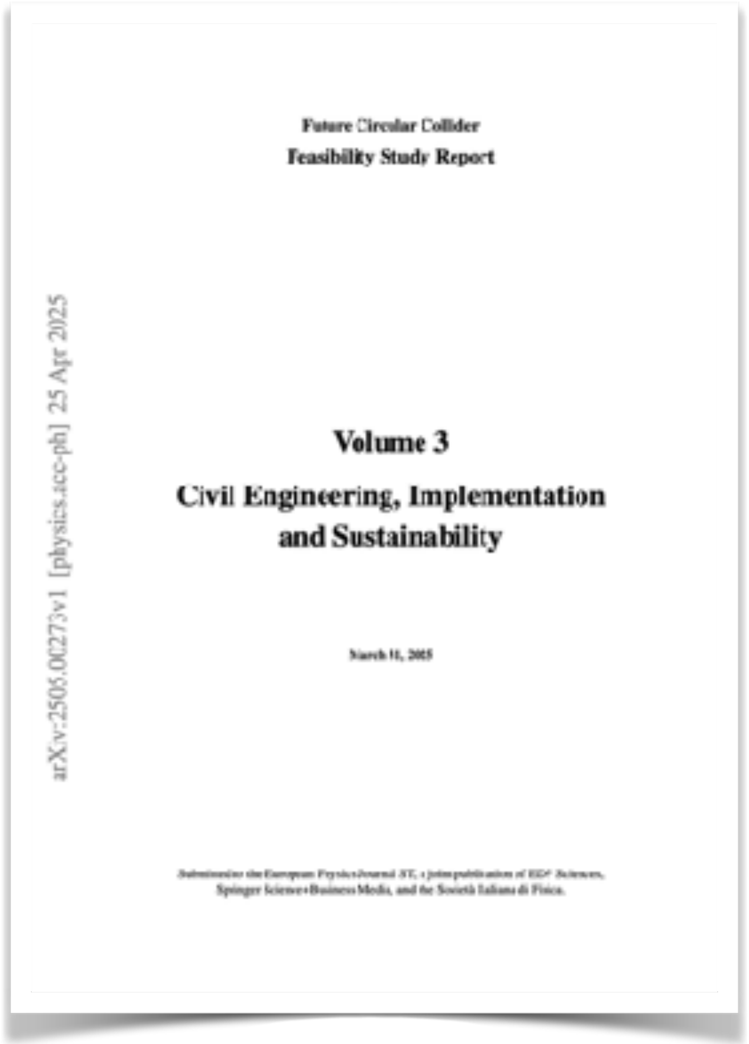
European Strategy Update

263 inputs received!

Strategy Documents Link

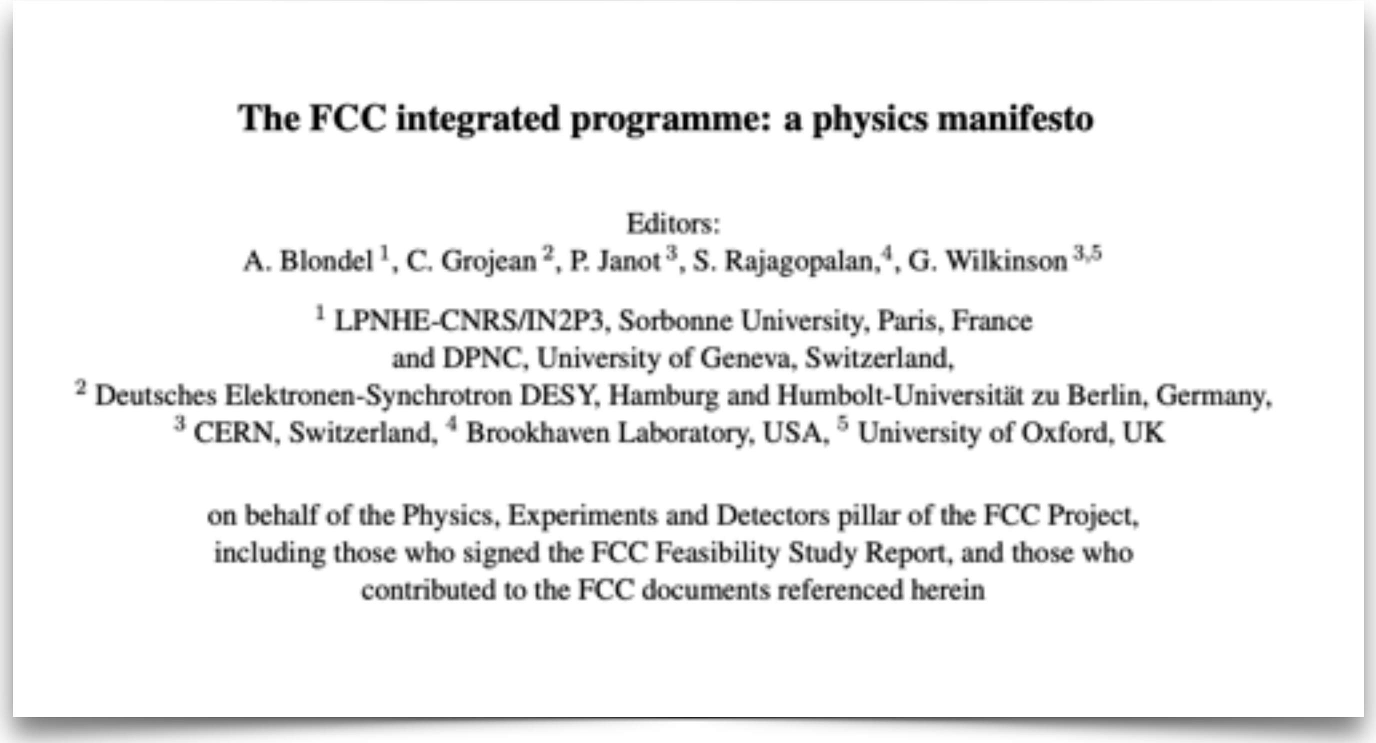
Feasibility study report Link


Future Circular Collider
Feasibility Study Report
Volume 1
Physics, Experiments, Detectors


Future Circular Collider
Feasibility Study Report
Volume 3
Civil Engineering, Implementation and Sustainability


Future Circular Collider
Feasibility Study Report
Volume 2
Accelerators, Technical Infrastructure and Safety

Altogether 1,200 pages opus!


The FCC integrated programme: a physics manifesto

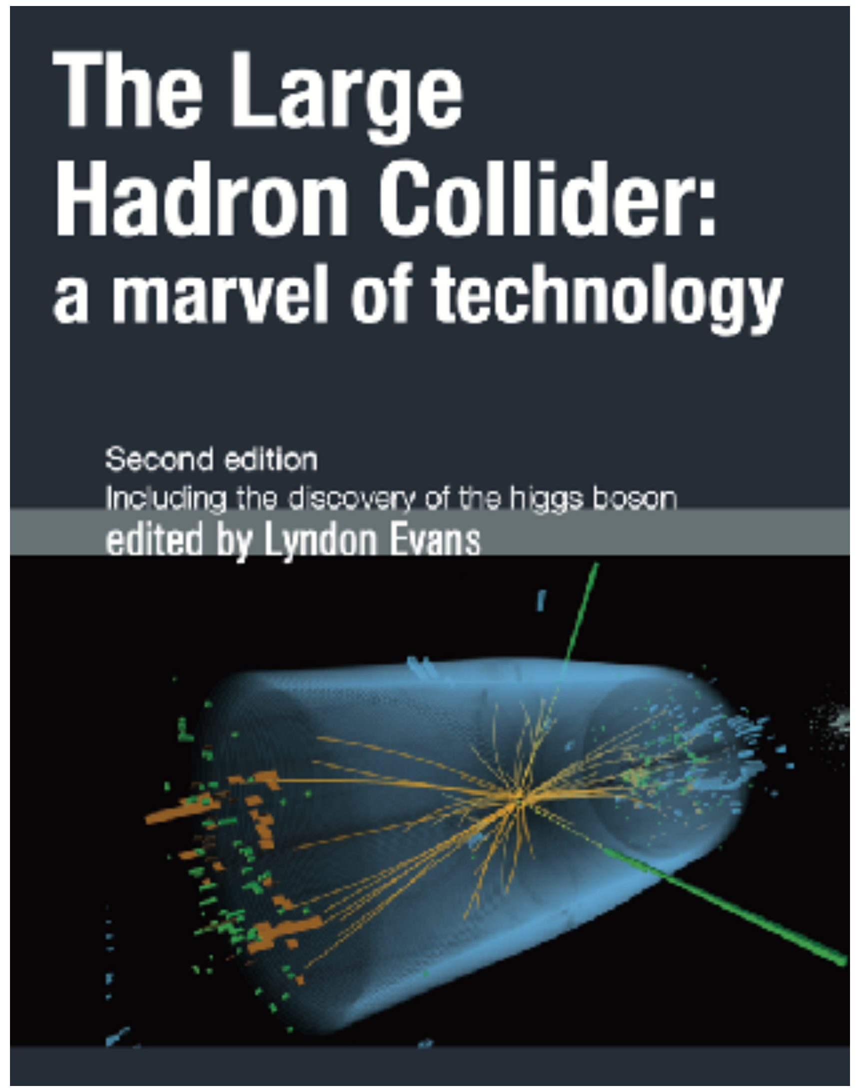
Editors:
A. Blondel [1], C. Grojean [2], P. Janot [3], S. Rajagopalan, [4], G. Wilkinson [3,5]

[1] LPNHE-CNRS/IN2P3, Sorbonne University, Paris, France and DPNC, University of Geneva, Switzerland,
[2] Deutsches Elektronen-Synchrotron DESY, Hamburg and Humbolt-Universität zu Berlin, Germany,
[3] CERN, Switzerland, [4] Brookhaven Laboratory, USA, [5] University of Oxford, UK

on behalf of the Physics, Experiments and Detectors pillar of the FCC Project, including those who signed the FCC Feasibility Study Report, and those who contributed to the FCC documents referenced herein

Physics manifesto!
Link

The LHC a Marvel of Technology



Link

Unrivalled at Energy Frontier

13.6 TeV (COM energy)

Outstanding at Intensity Frontier

Record Luminosity* $2.26 \times 10^{34}\ cm^{-2}s^{-1}$

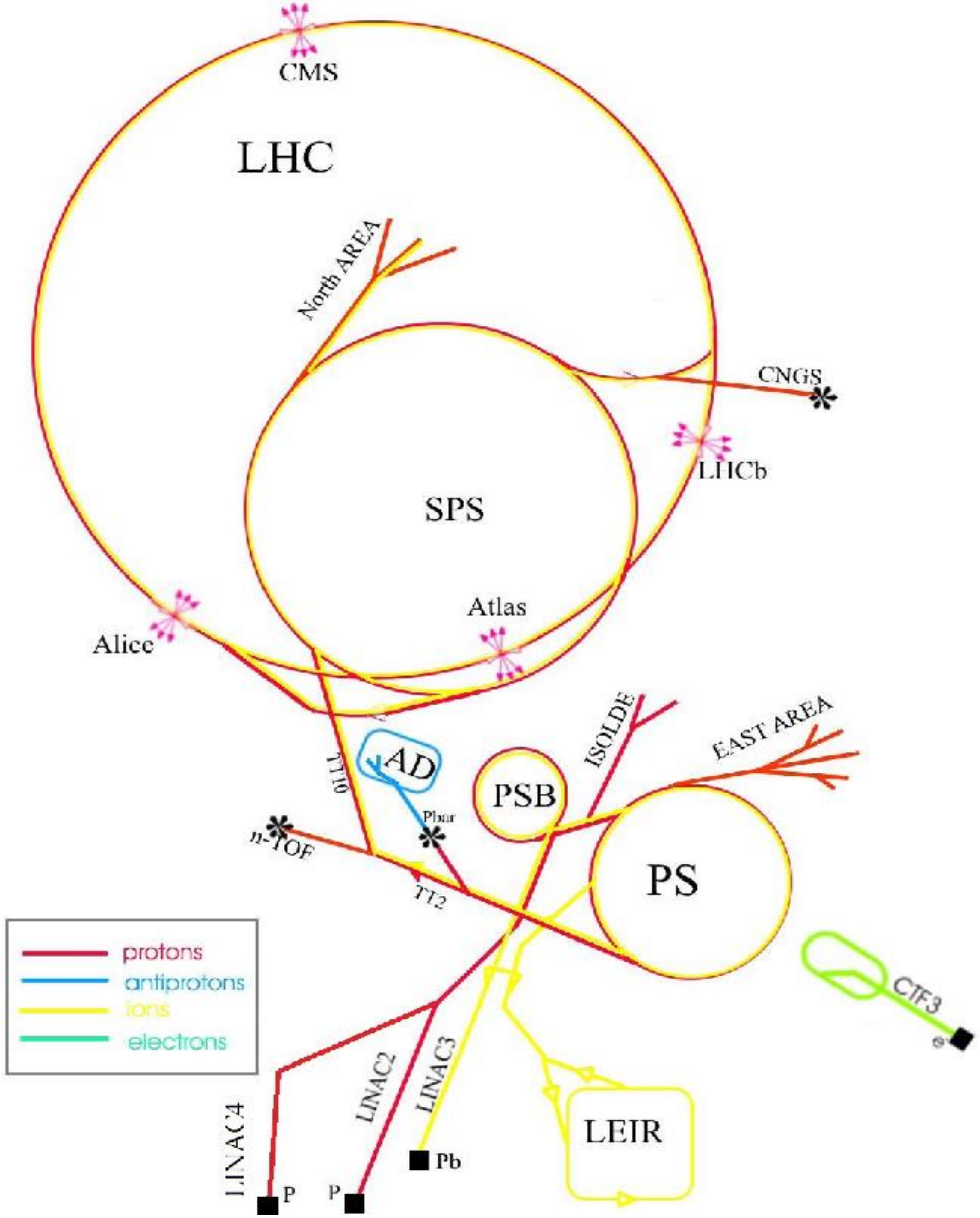
*Close to SuperKEKB at $5.1 \times 10^{34}\ cm^{-2}s^{-1}$

So far the LHC has delivered:

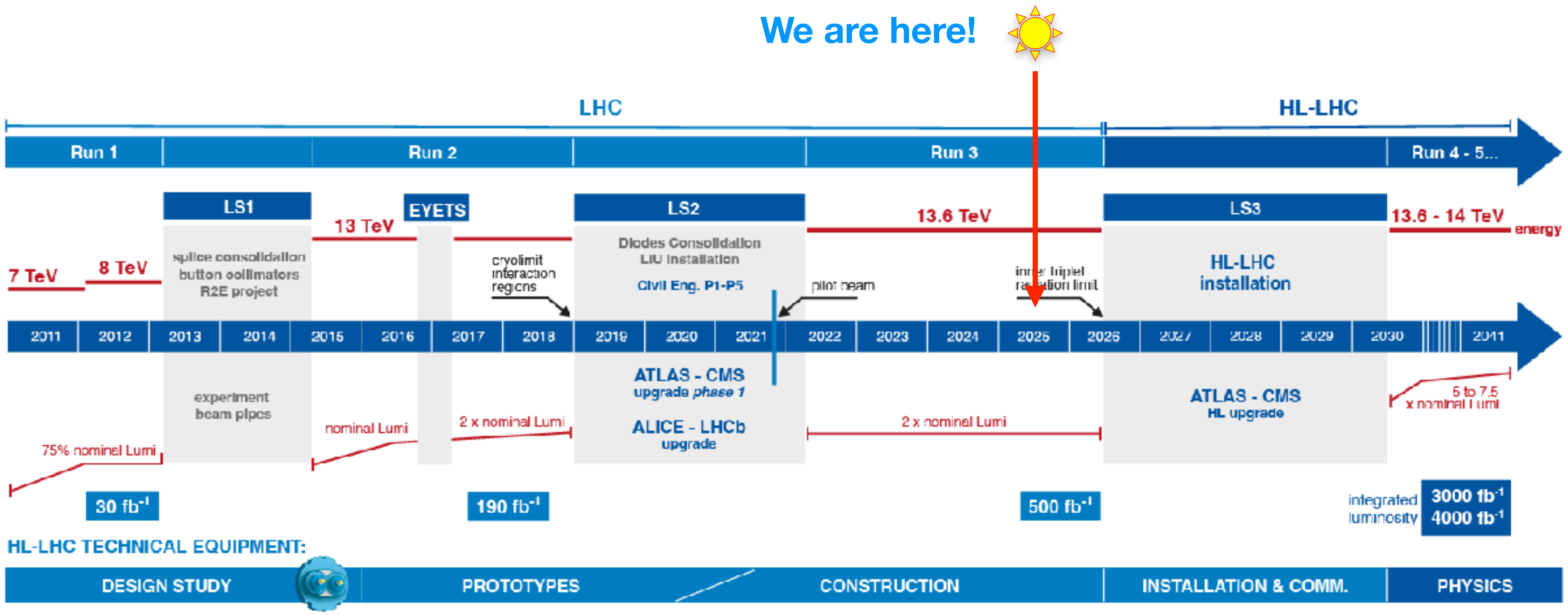
- 15 Million Higgs bosons produced
- 600 Million top quarks produced
- 15 Billion Z bosons with 300 Million per lepton flavour
- 60 Billion W bosons (3 billion per lepton flavour)
- 300 Trillion b quarks (approximately 2 Trillion for LHCb)

Still 10 times more statistics expected at HL-LHC!

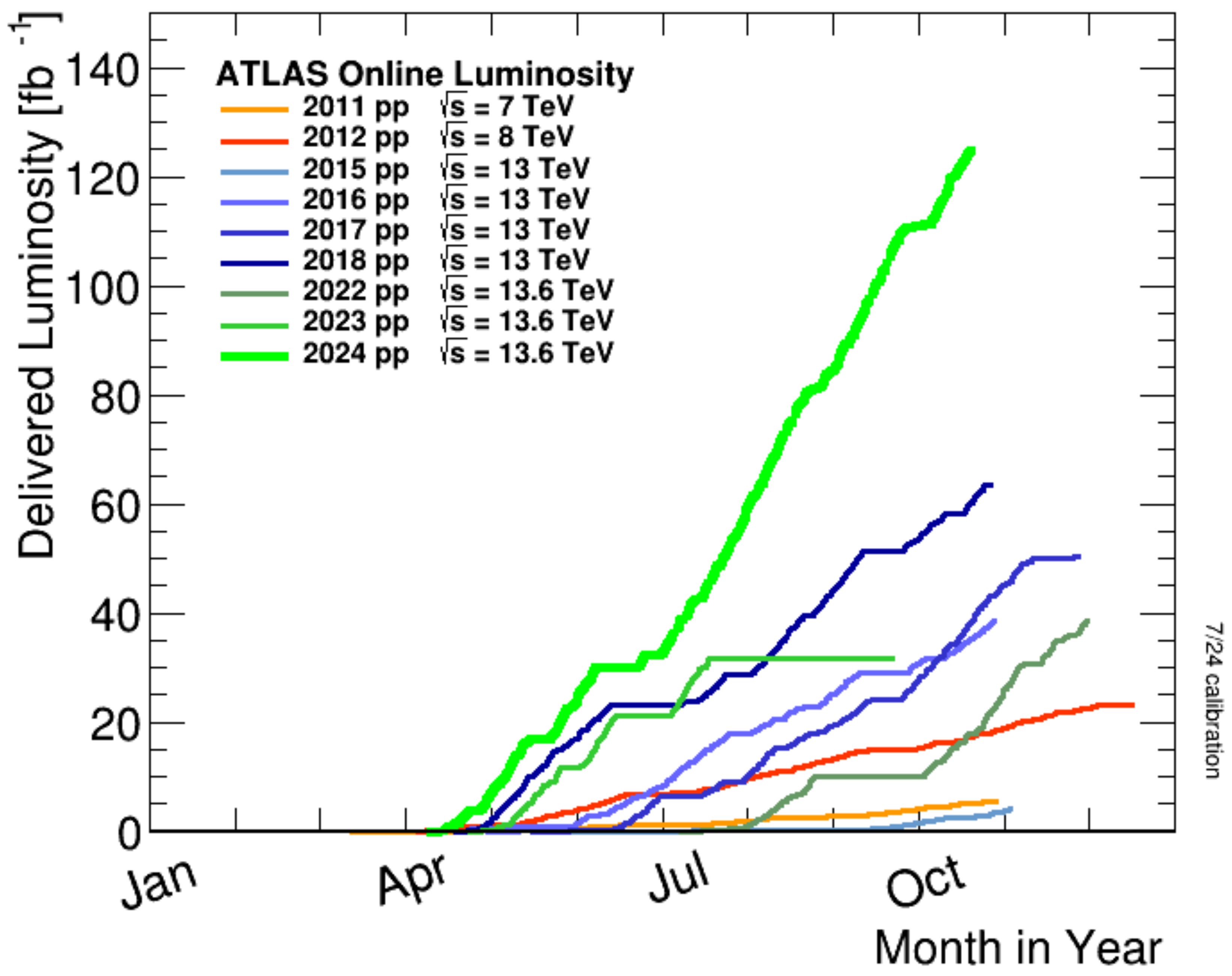
More than 20 times more luminosity with the LHCb upgrade II



LHC Operations



2024 - High availability operation, Full mastery of considerable inherent operational risks



- The Run 2 dataset surpassed the initial goal (in luminosity) of the LHC project and is a **clean and well calibrated dataset of ~140** fb^{-1} at 13 TeV

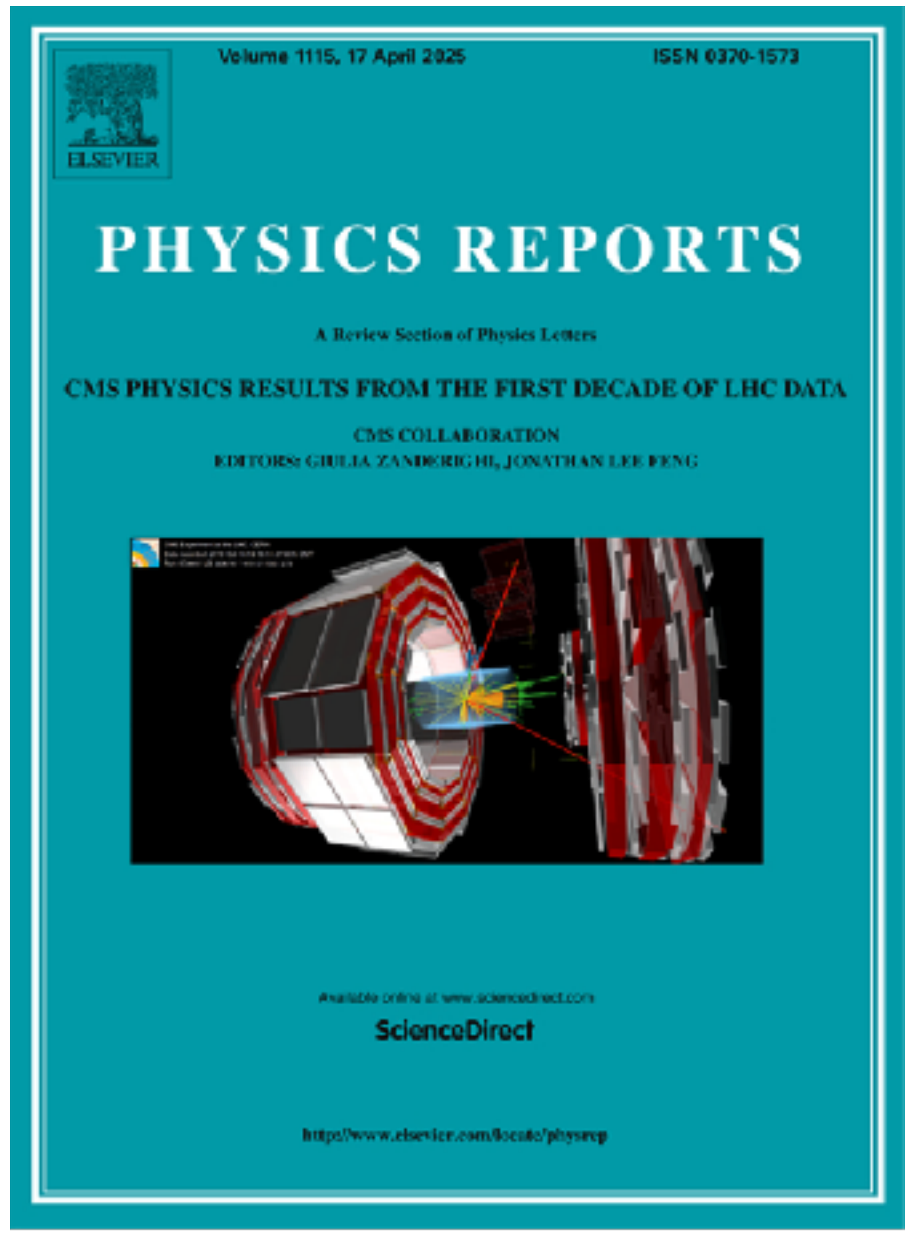
Most LHC results presented here are based on Run 2 data

- The Run 3 has now surpassed the Run 2 dataset ~180 fb^{-1} at 13.6 TeV

- Approximately x10 Luminosity **at HL-LHC** (in terms of results x20). **Requires major upgrades leading** to the High Luminosity during LS3 now on the horizon!

Even with the record luminosity in 2024 need more than 20 running years to achieve HL-LHC luminosity!

The LHC Run 2 Physics Program



ATLAS Phys. Rep. Link

1. Forward to the collection
2. Climbing to the Top
3. Electroweak, QCD and flavour physics
4. Characterising the Hihggs boson
5. Exotic Jungle Beyond the Standard Model
6. Additional scalars and exotic decays
7. The quest to discover supersymmetry

CMS Phys. Rep. Link

1. The Stairway to heaven
2. Stairway to discovery: cross section measurements
3. Review of top quark mass measurements
4. High density QCD
5. Searches for Higgs decays of heavy resonances
6. Dark sector searches
7. Vector like quarks, leptons and heavy neutral leptons
8. Searches through data scouting

A collection of 14 Physics Reports - an overview of the LHC Run 2 results

FUNDAMENTAL PHYSICS
BREAKTHROUGH
PRIZE

ALICE Collaboration

ATLAS Collaboration

CMS Collaboration

LHCb Collaboration

The FCC in a nutshell

FCC-ee

Ultimate Precision Frontier

Goal Luminosity $144 \times 10^{34}\ cm^{-2}s^{-1}$

One LEP every few minutes !!!

At the Z peak (per IP) - 4 IPs

Z, WW, ZH and $t\bar{t}$ COM energies

Continuous beams

No Pile Up

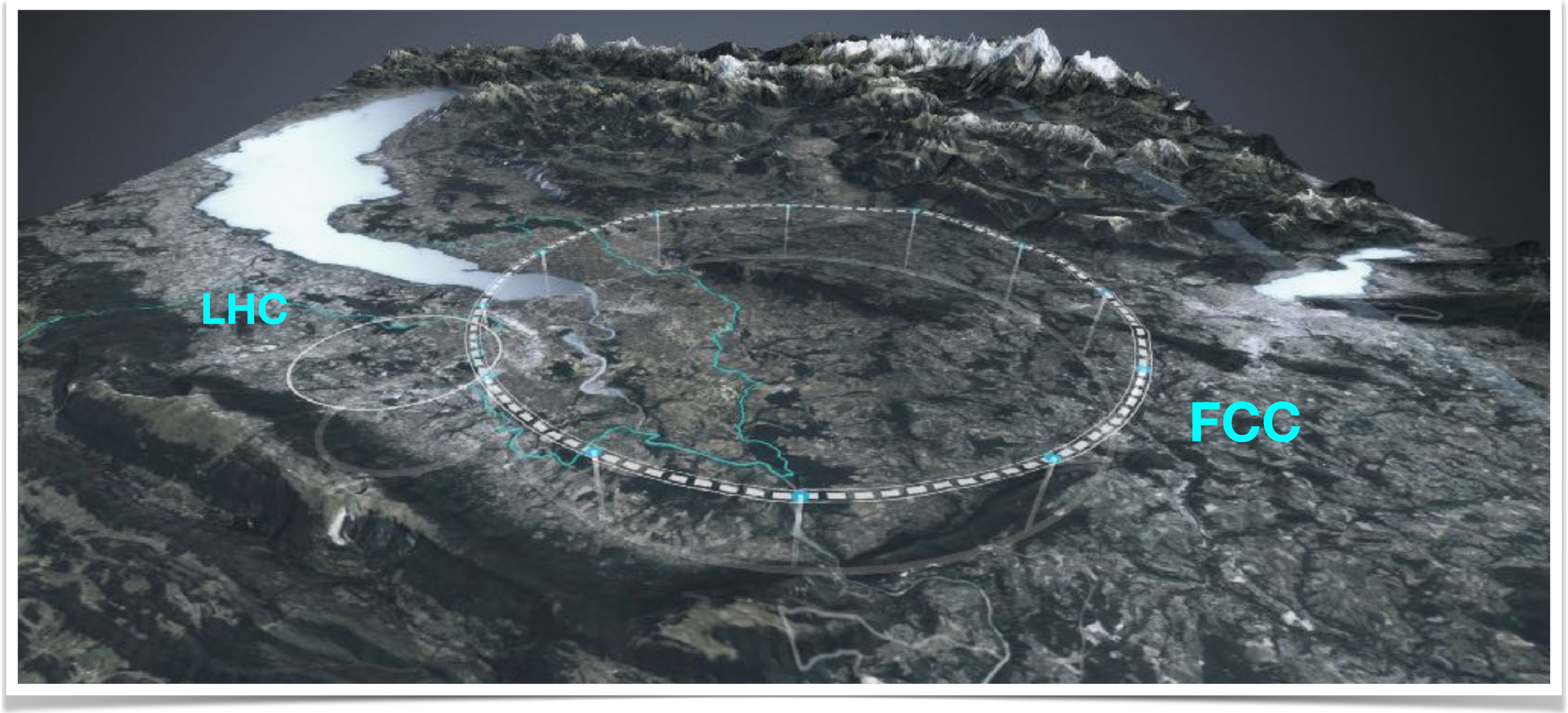
15 Years of running

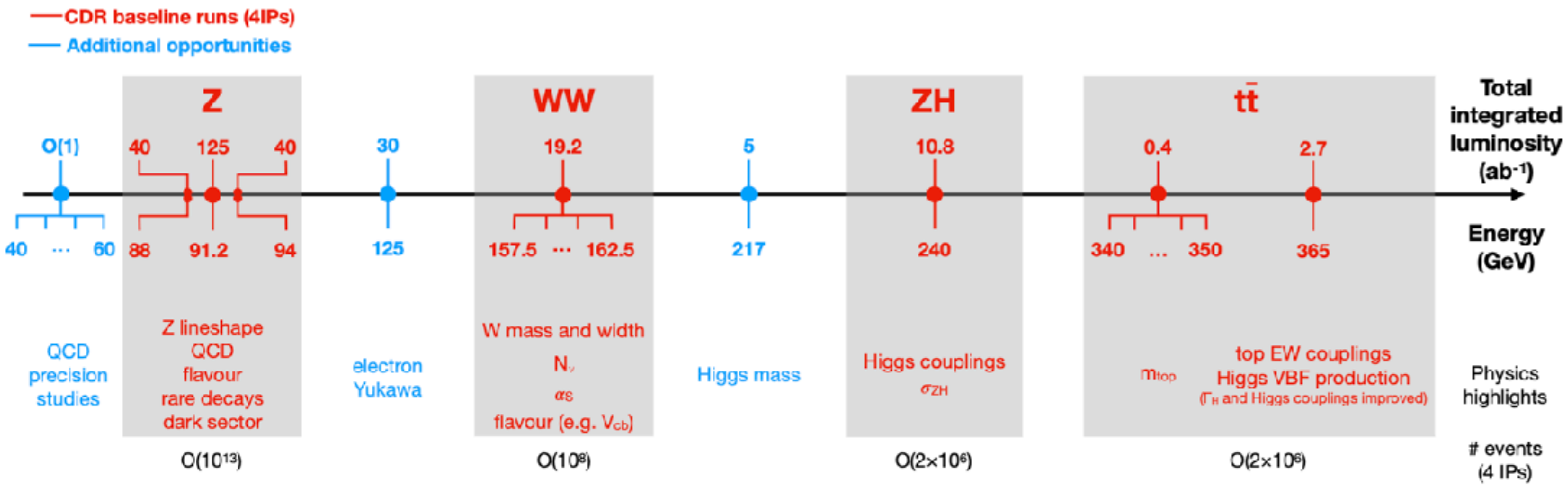
Targets to deliver

- 3 Million Higgs bosons
- 2 Million top quarks
- 240 Million WW events
- 6 $\times 10^{12}$ Z bosons

In terms of B hadrons ~current LHCb statistic also 10 times the Belle II design statistics

All these events in a much cleaner environment!





"Quasi-total flexibility in the order of operation for all running points" !

The FCC in a nutshell

FCC-ee

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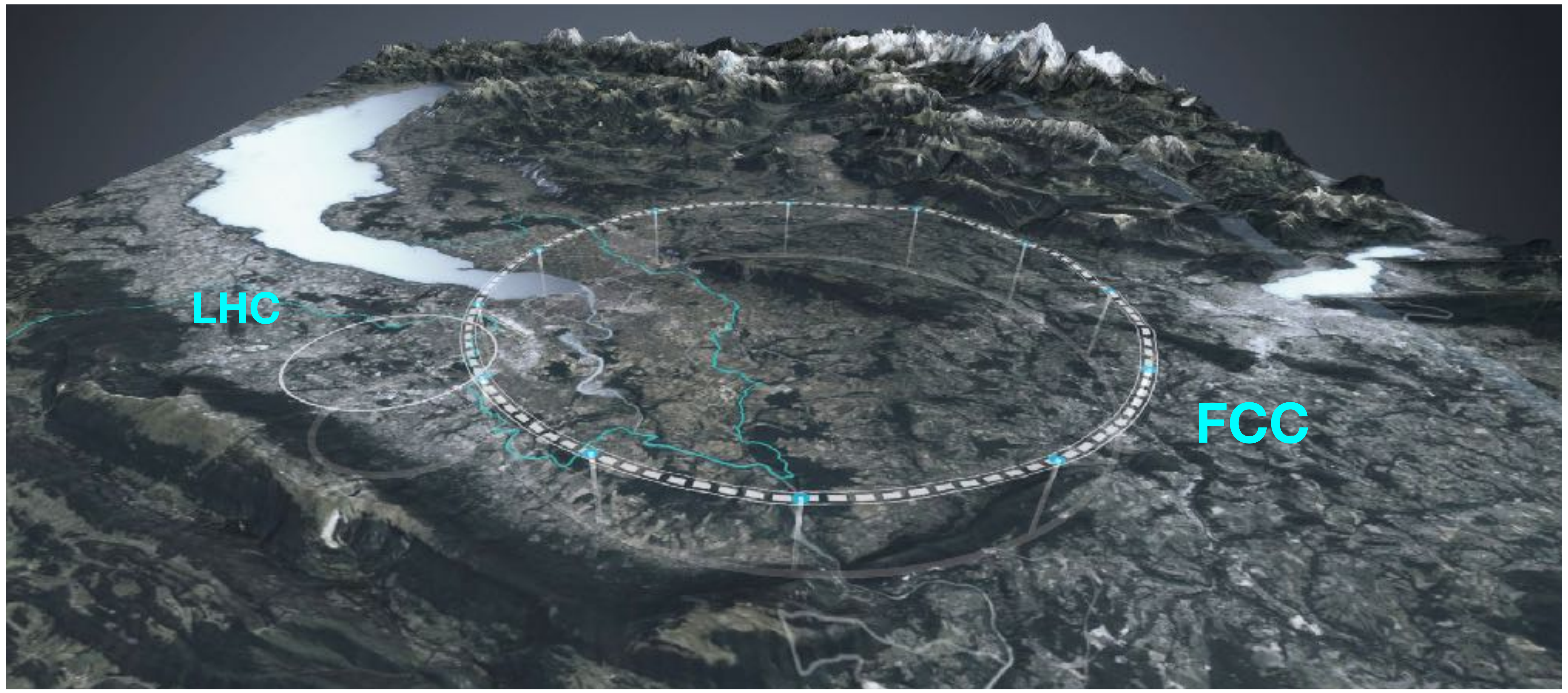


FCC-hh

Ultimate Energy Frontier

85 TeV (baseline COM energy)

Target luminosity 20ab^{-1}

14 T Nb_3Sn magnets

Luminosity $30 \times 10^{34}\ cm^{-2}s^{-1}$ - 4 IPs

PU / bunch crossing up to 1000!

25 Years of running

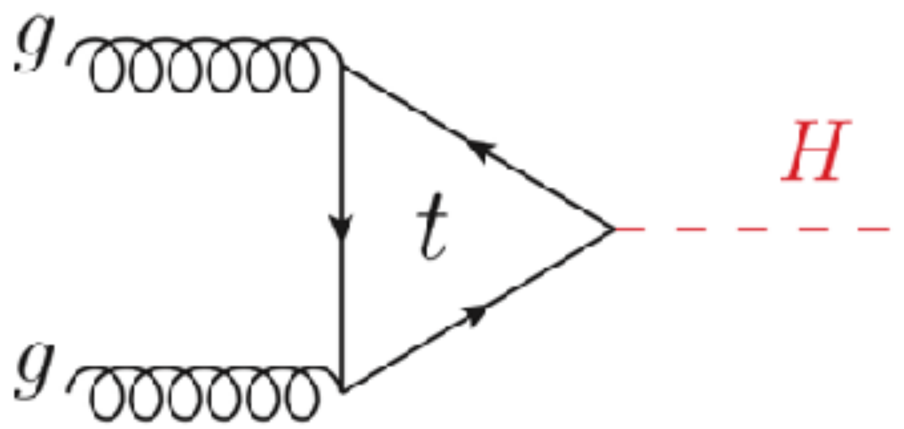
Targets to deliver extraordinary statistics

- Over 25 Bilion Higgs bosons
- 1 Billion ttH
- 36 Million HH

Except for very specific cases the FCC-hh 85 TeV with more luminosity has a similar reach as the 100 TeV

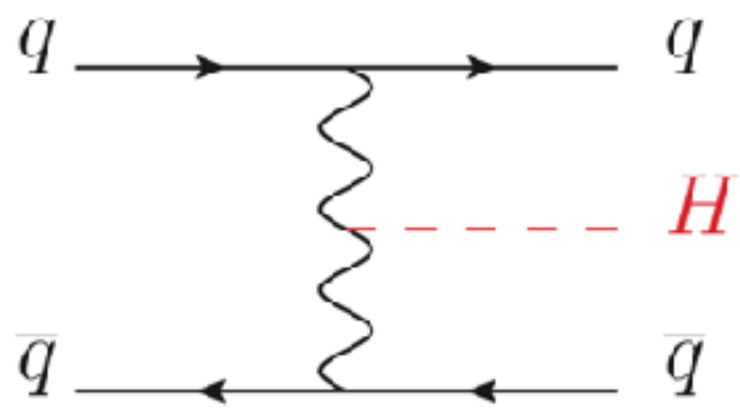
Signatures of the Higgs Boson

Production rates so far



Gluon fusion process

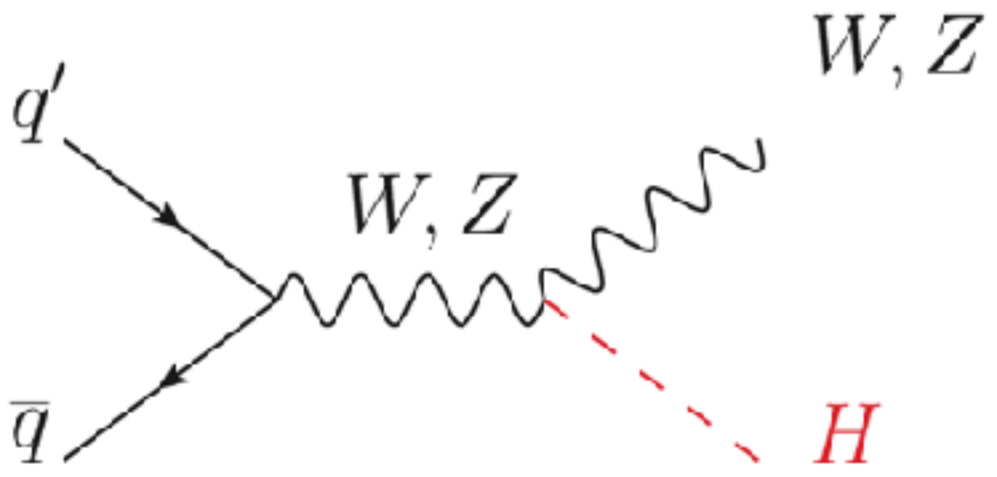
~13 M events produced



Vector Boson Fusion

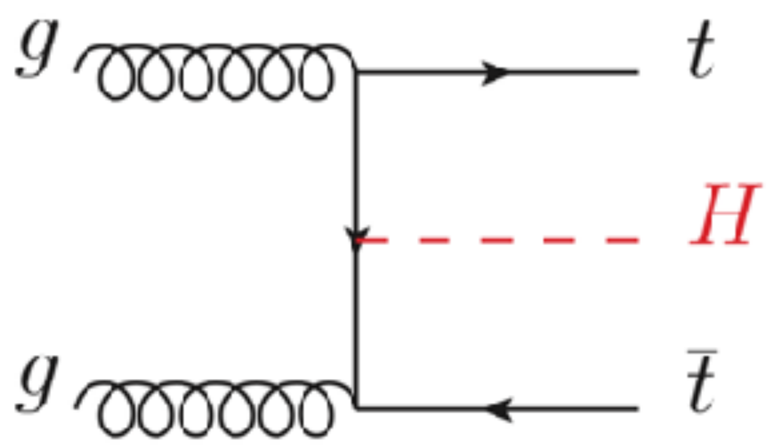
Two forward jets and a large rapidity gap

~1 M events produced



W and Z Associated Production

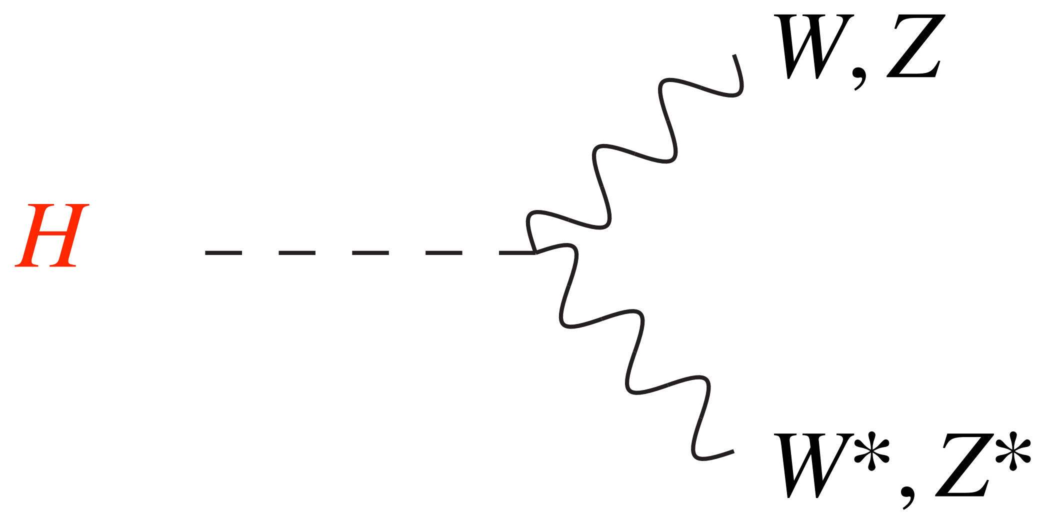
~650 k events produced



Top Assoc. Prod.

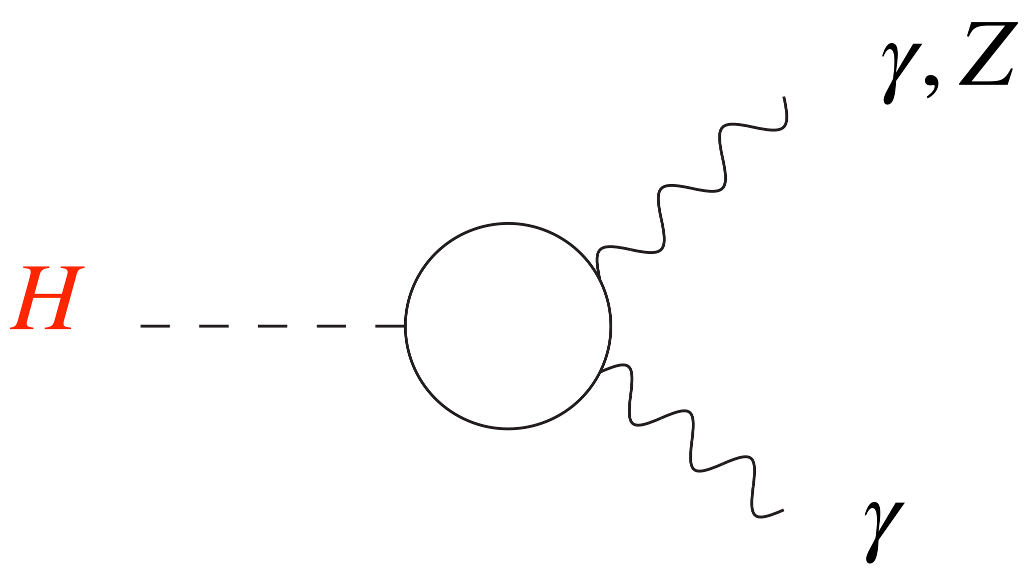
~130 k evts produced

Decay branching fractions



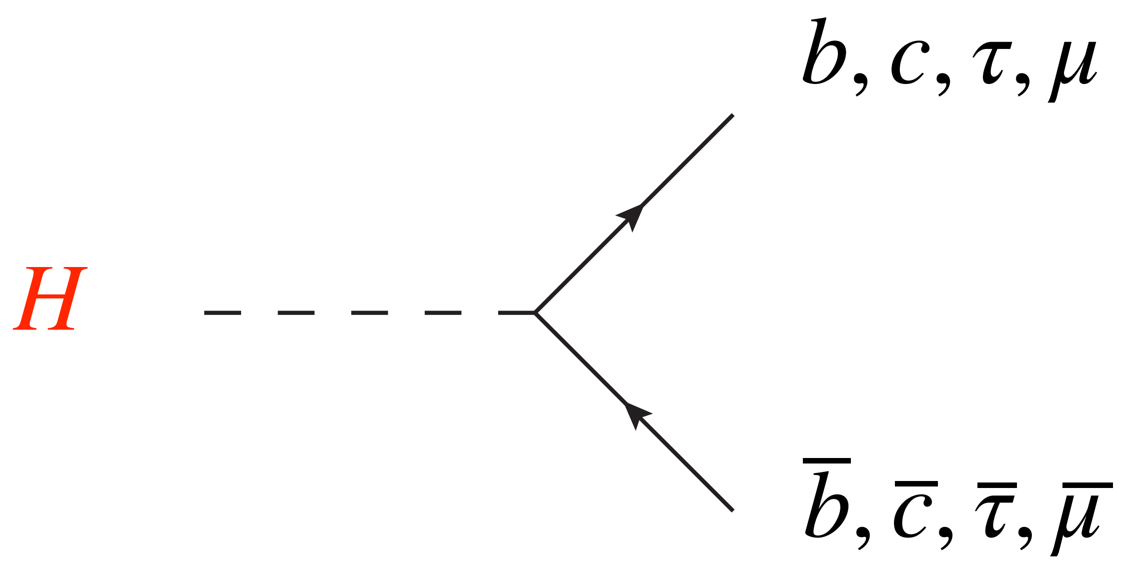
$\mathrm{Br}(H \to WW^*) = 22\,\%$

$\mathrm{Br}(H \to ZZ^*) = 3\,\%$



$\mathrm{Br}(H \to \gamma\gamma) = 0.2\,\%$

$\mathrm{Br}(H \to Z\gamma) = 0.2\,\%$



$\mathrm{Br}(H \to b\bar{b}) = 57\,\%$

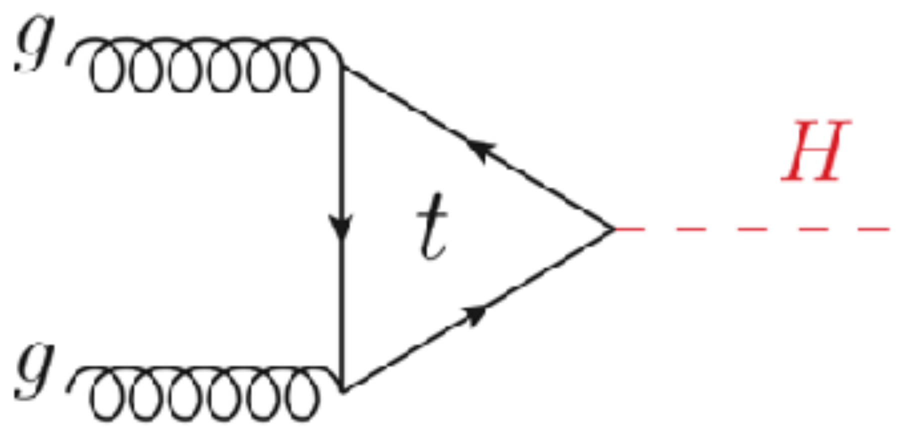
$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

$\mathrm{Br}(H \to c\bar{c}) = 3\,\%$

$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

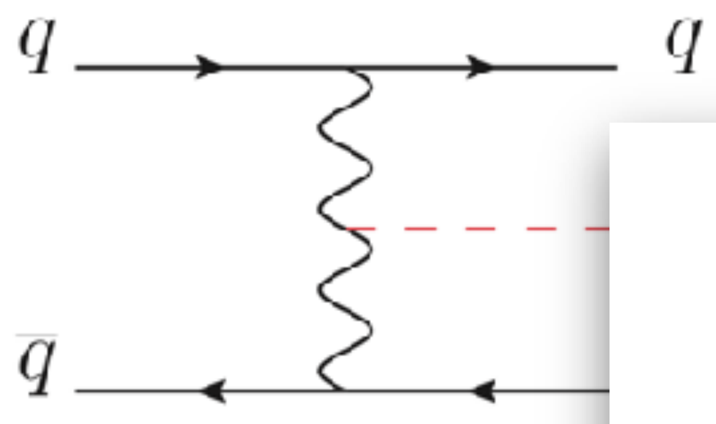
Signatures of the Higgs Boson

Production rates so far

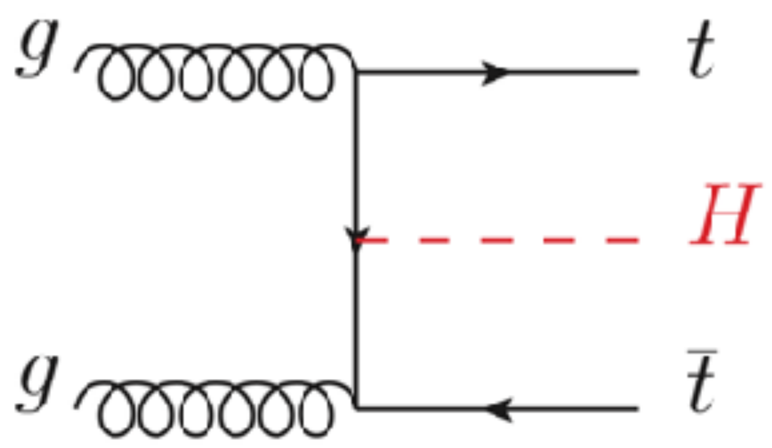


Gluon fusion process

~13 M events produced



Vector Boson Fusion

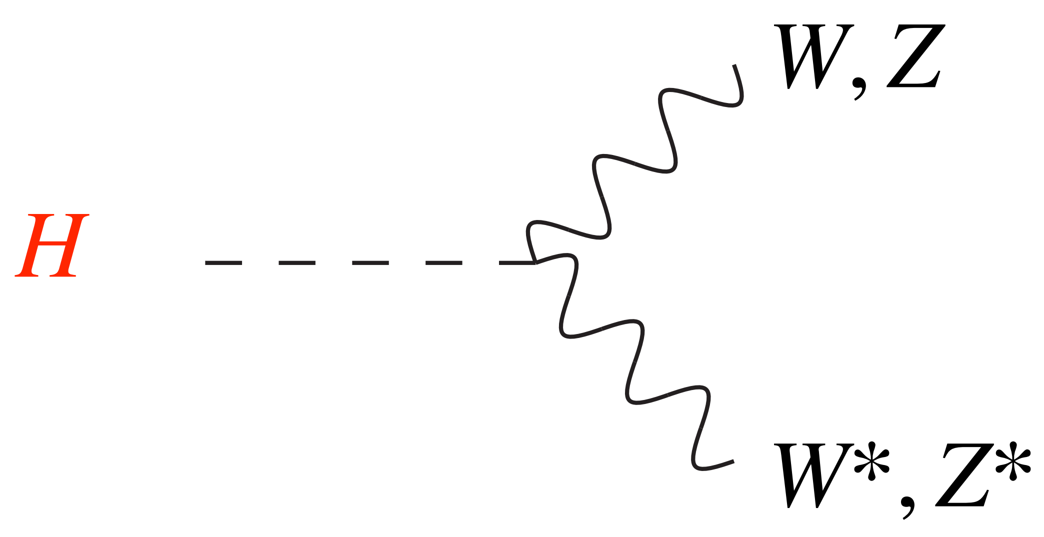


Top Assoc. Prod.

~130 k evts produced

Process	ggF	HH	ttH
13 TeV / 8 TeV	2.3	2.4	3.9
13.6 TeV / 13 TeV	7%	11%	13%
14 TeV / 13.6 TeV	6%	7%	7%

Decay branching fractions



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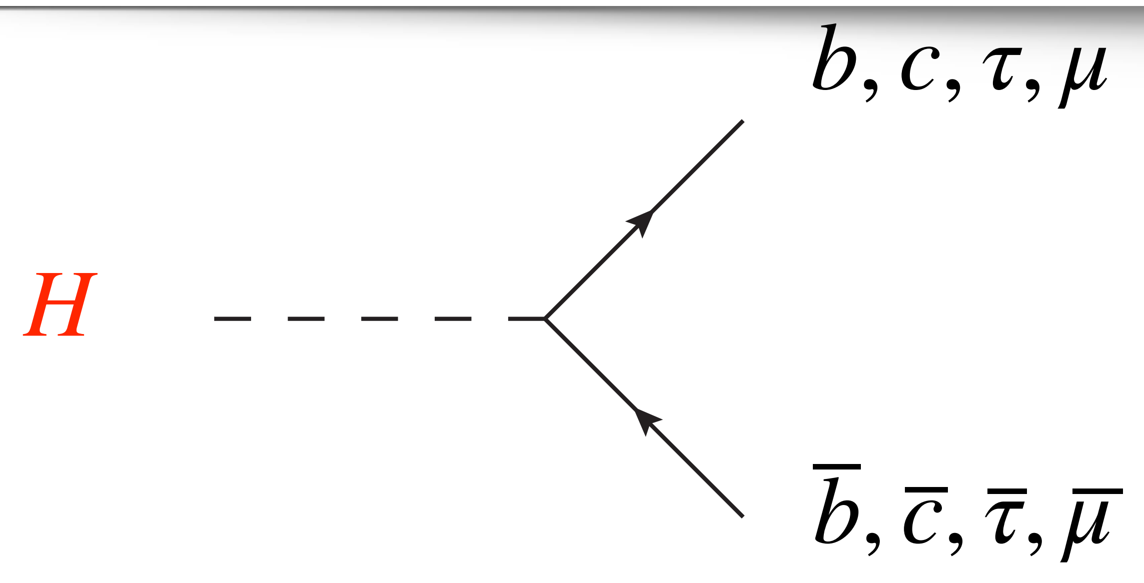

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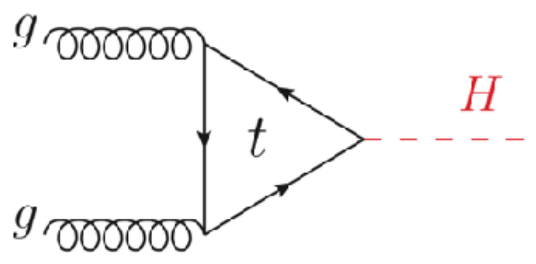
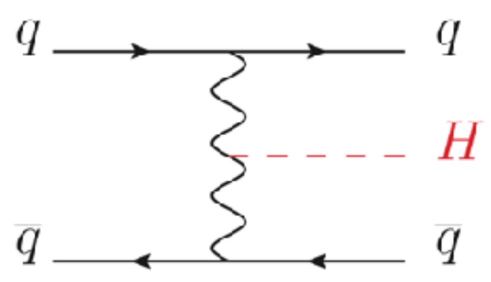
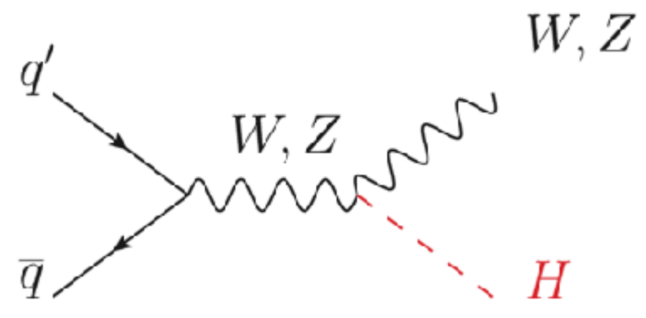
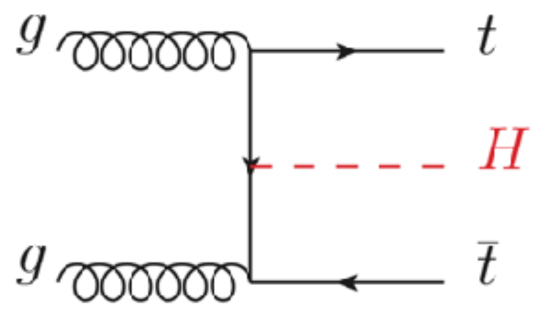
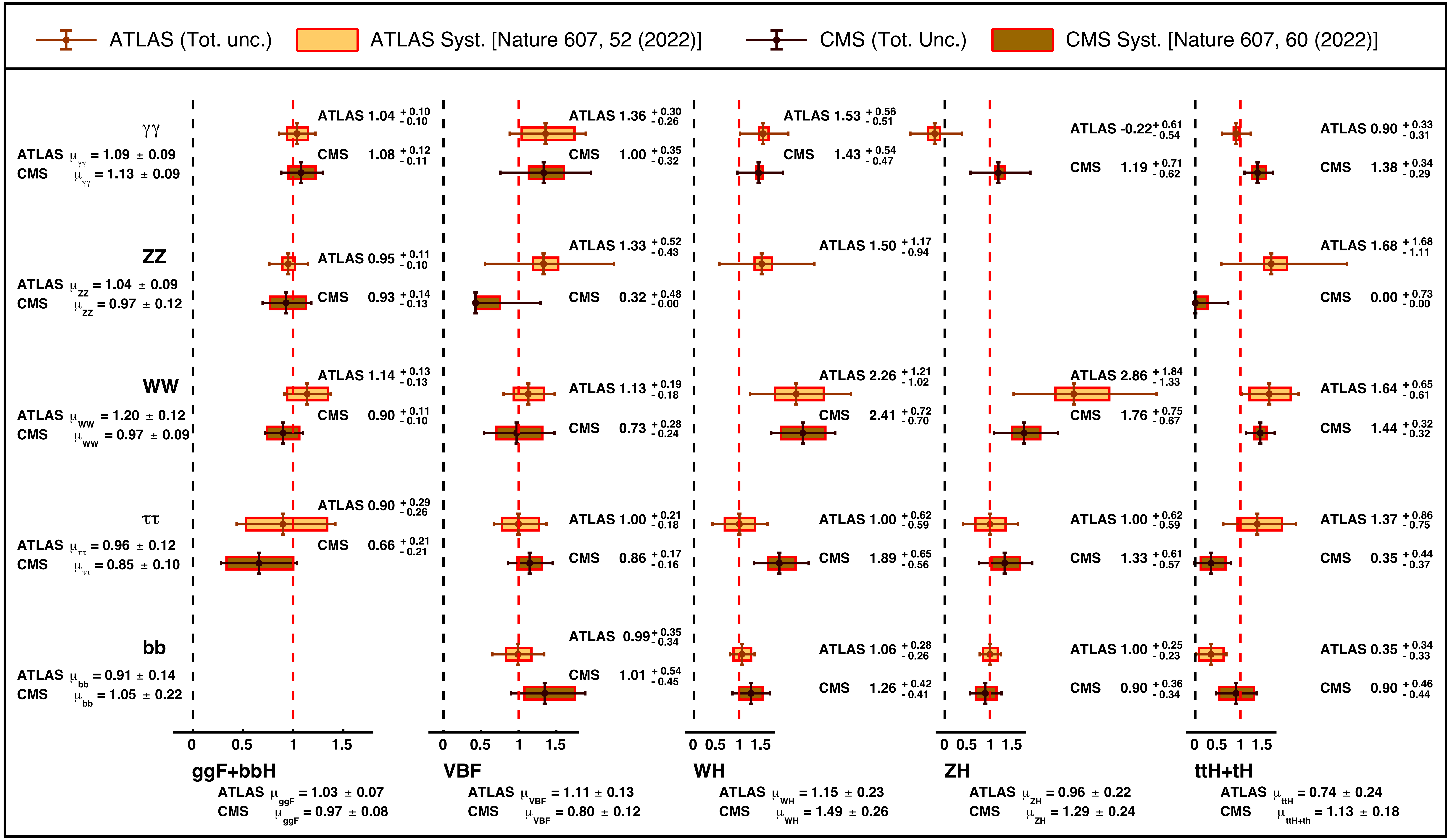
$\mathrm{Br}(H \to \mu^+\mu^-) = 0.02\,\%$

Main Higgs Analyses Channels at LHC

	Channel categories	Br	ggF  ~8 M vets produced	VBF  ~600 k vets produced	VH  ~400 k vets produced	ttH  ~80 k evts produced
	Cross Section 13 TeV (8 TeV)		48.6 (21.4) pb*	3.8 (1.6) pb	2.3 (1.1) pb	0.5 (0.1) pb
Observed modes	γγ	0.2 %	✓	✓	✓	✓
Observed modes	ZZ	3%	✓	✓	✓	✓
Observed modes	WW	22%	✓	✓	✓	✓
Observed modes	ττ	6.3 %	✓	✓	✓	✓
Observed modes	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
Remaining to be observed	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

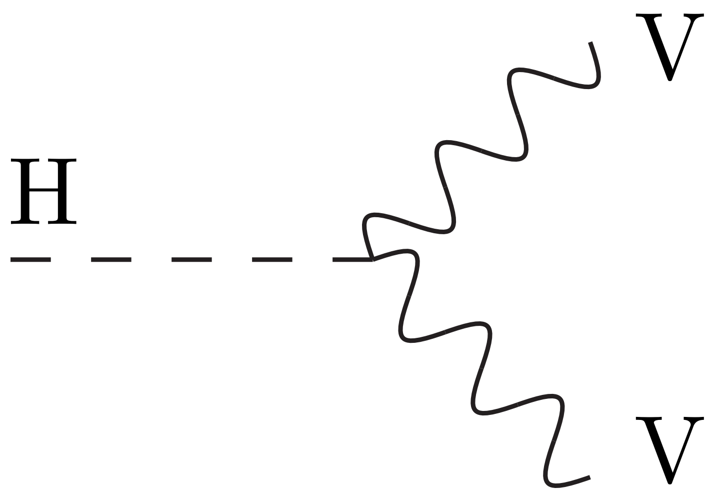
*N3LO

Very broad overview!



Pillars of Higgs Physics at Colliders

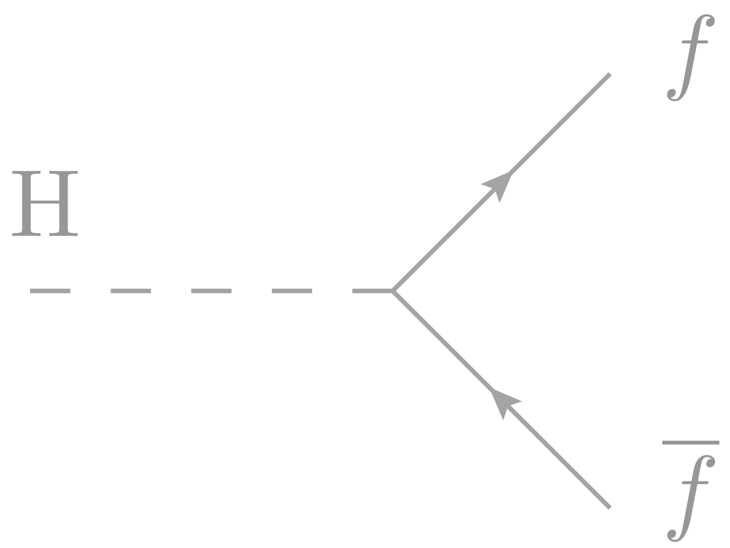
All the couplings of the Higgs boson to Standard Model particles (except itself) were known before the discovery of the Higgs boson! A very predictive model!



$$\frac{2m_V^2}{v}$$

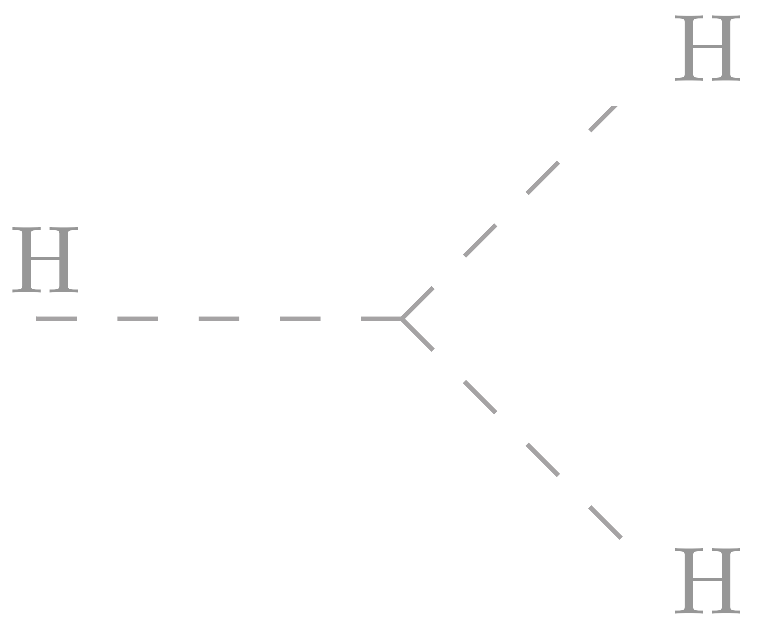
$|D_\mu \phi|^2$

This term indicates existence a vev

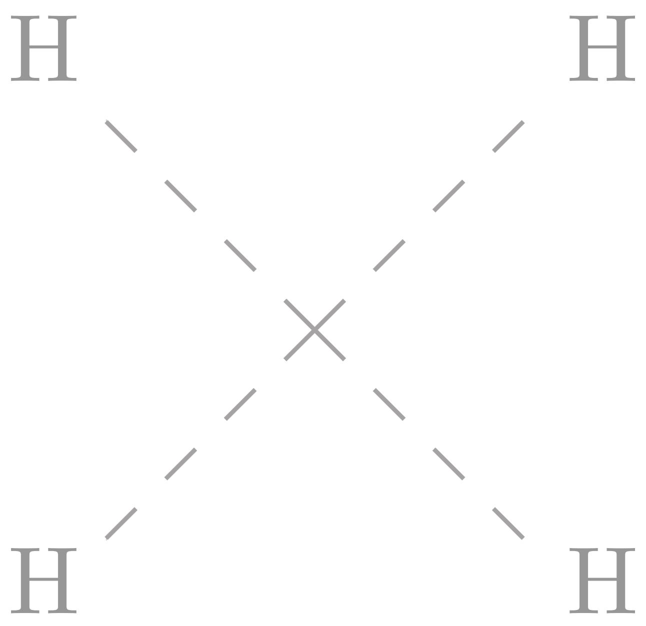


$$\frac{m_f}{v}$$

$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$



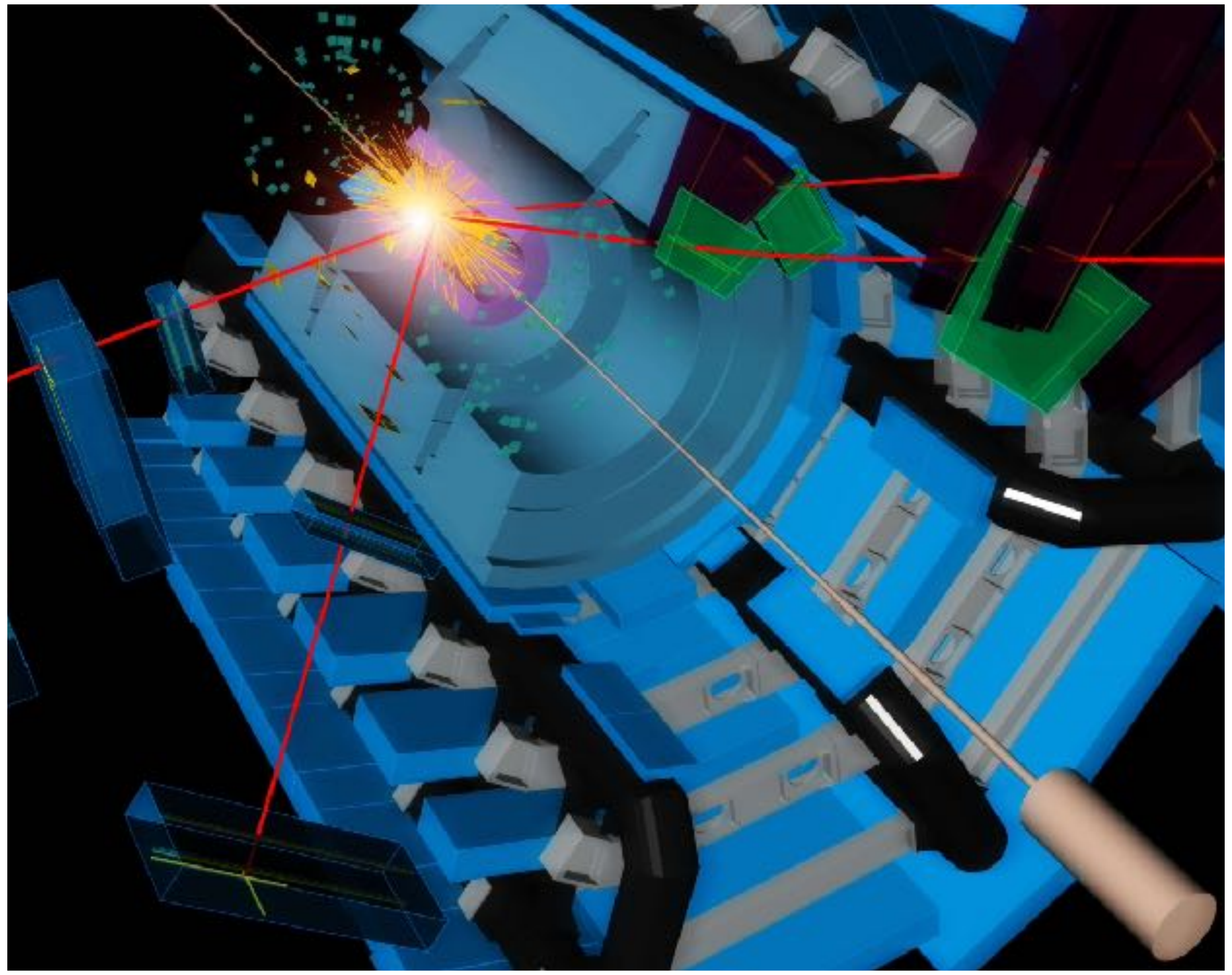
$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$V(\phi)$

Four lepton events can have s/b of up to ~30!



Proof of the existence of a condensate!

$\kappa_{W,Z}$

Current
6%

Pillars of Higgs Physics at Colliders

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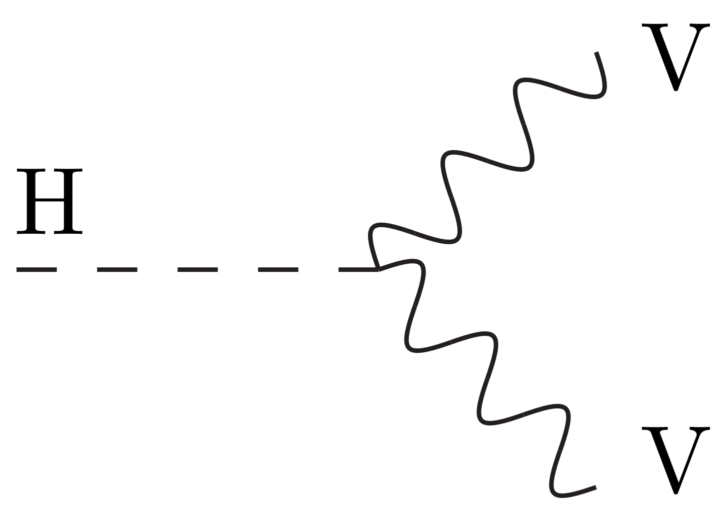

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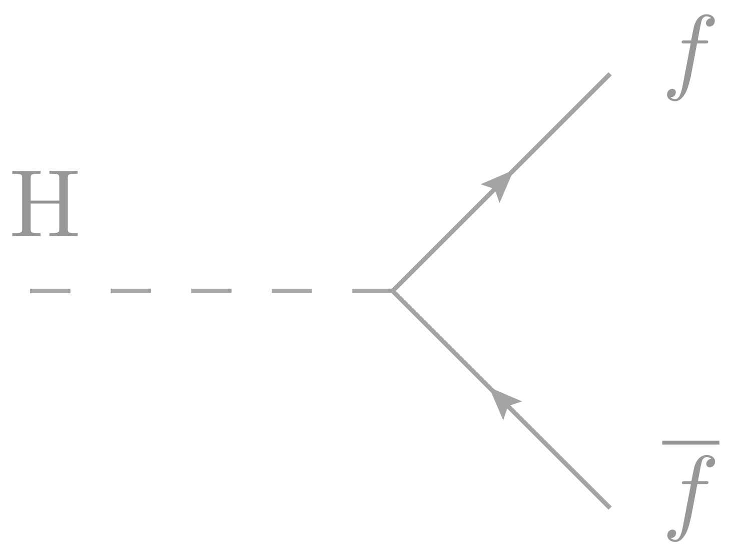
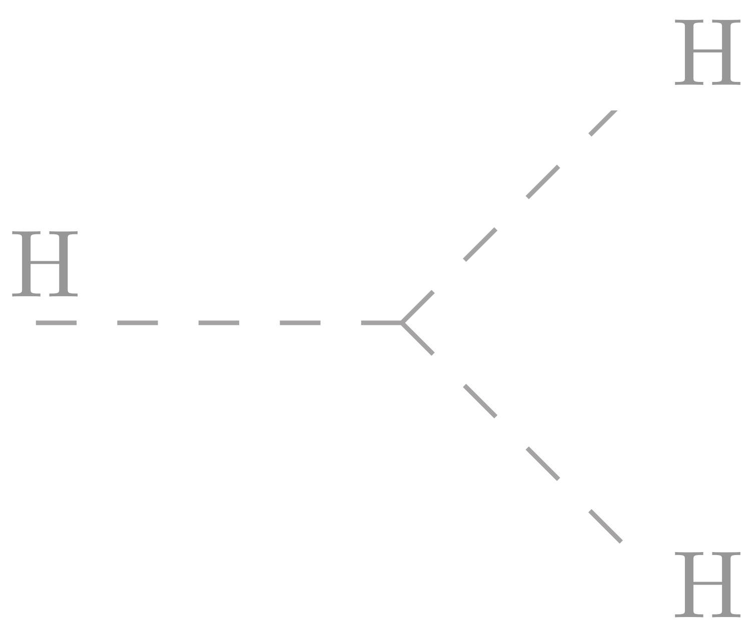
$$|D_\mu \phi|^2$$

This term indicates existence a vev

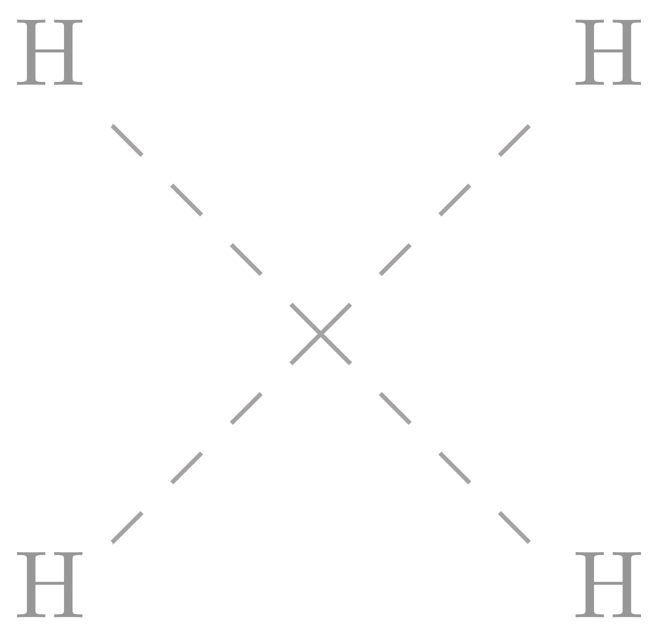


$$\frac{m_f}{v}$$

$$\bar{\Psi}_i y_{ij} \Psi_j \phi + h.c.$$

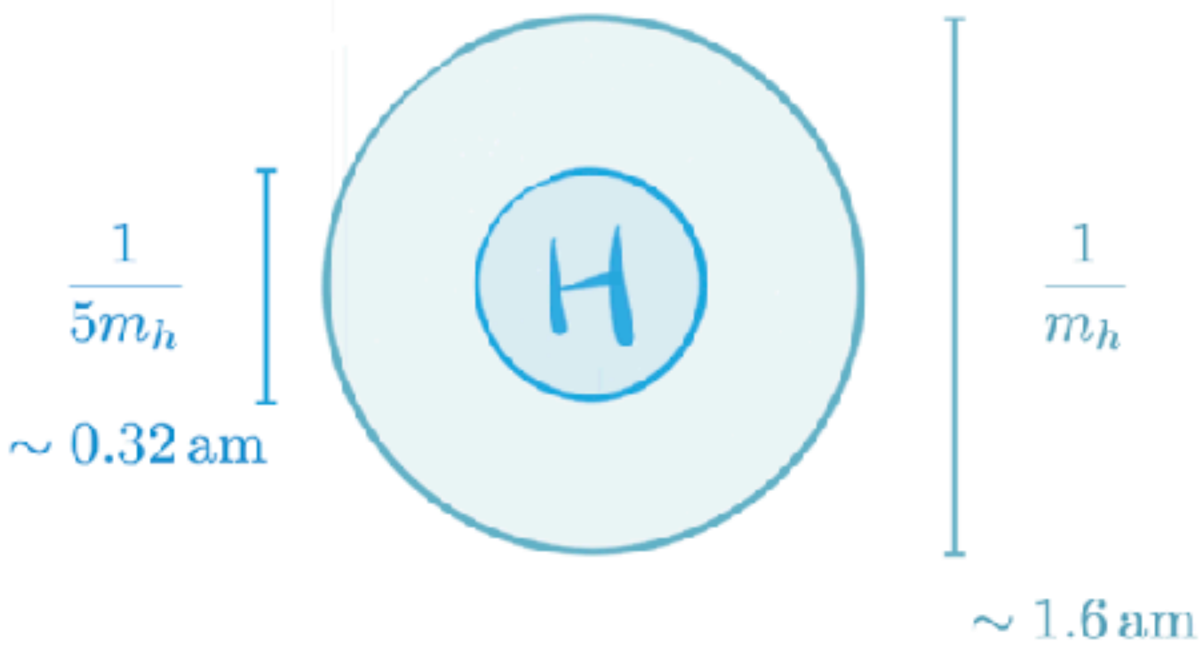


$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$



Most precisely known Higgs coupling tells us how elementary the Higgs boson is!

...or what its effective size is!

Comparing the **Compton radius** of the Higgs $1/m_H$ to its **effective radius** $1/f_H$ through the higher order operator:

$$\frac{c_H}{f_H^2} \cdot \frac{1}{2} \left(\partial_\mu |H|^2\right)^2 \rightarrow \left(\frac{2c_H v^2}{f_H^2}\right) \cdot \frac{1}{2} \left(\partial_\mu h\right)^2$$

(as comparing the mass of the pion to that of the ρ meson)

Current precision $f_H > 1$ TeV

The Higgs could well be a pNGB as the pion!

SILH Giudice, Grojean, Pomarol, Rattazzi (See paper)

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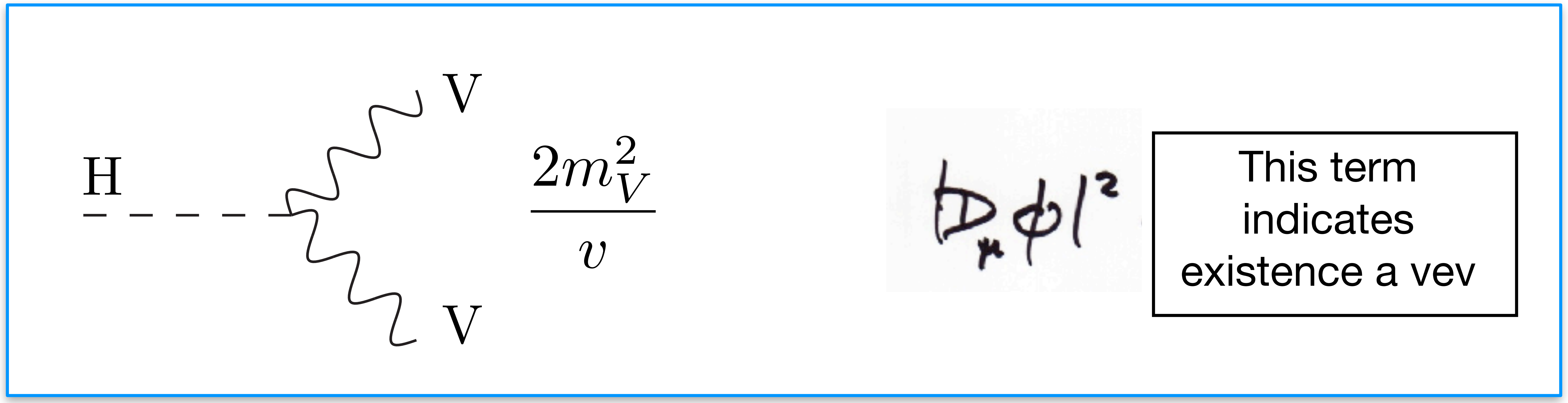

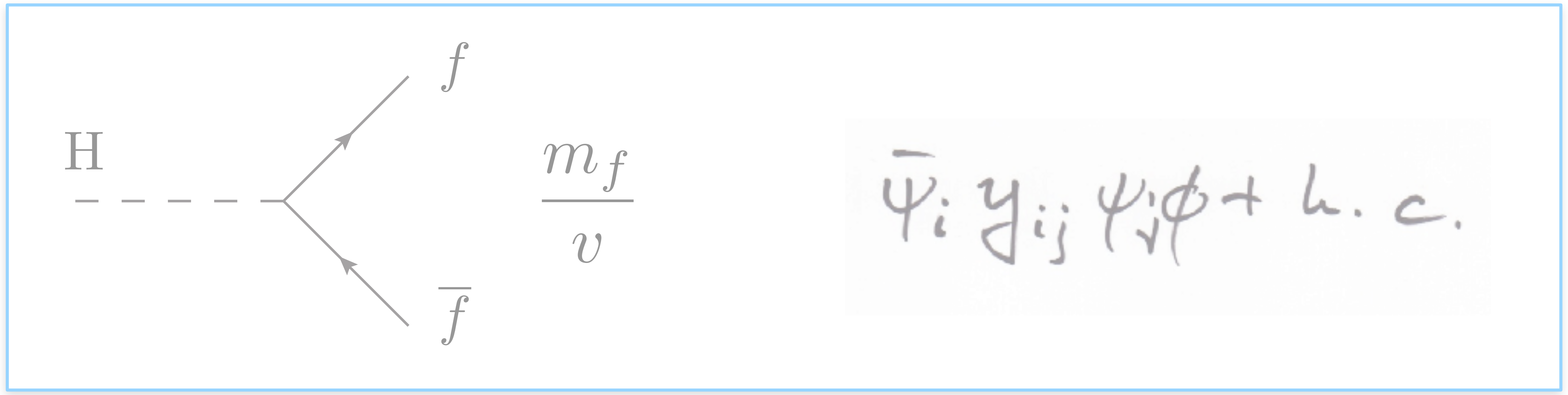

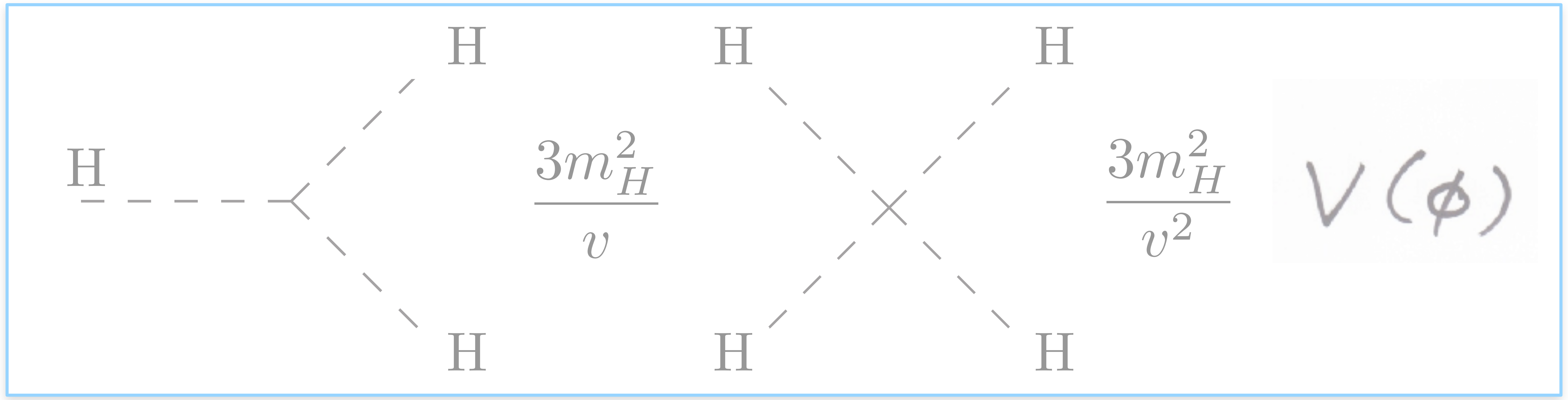

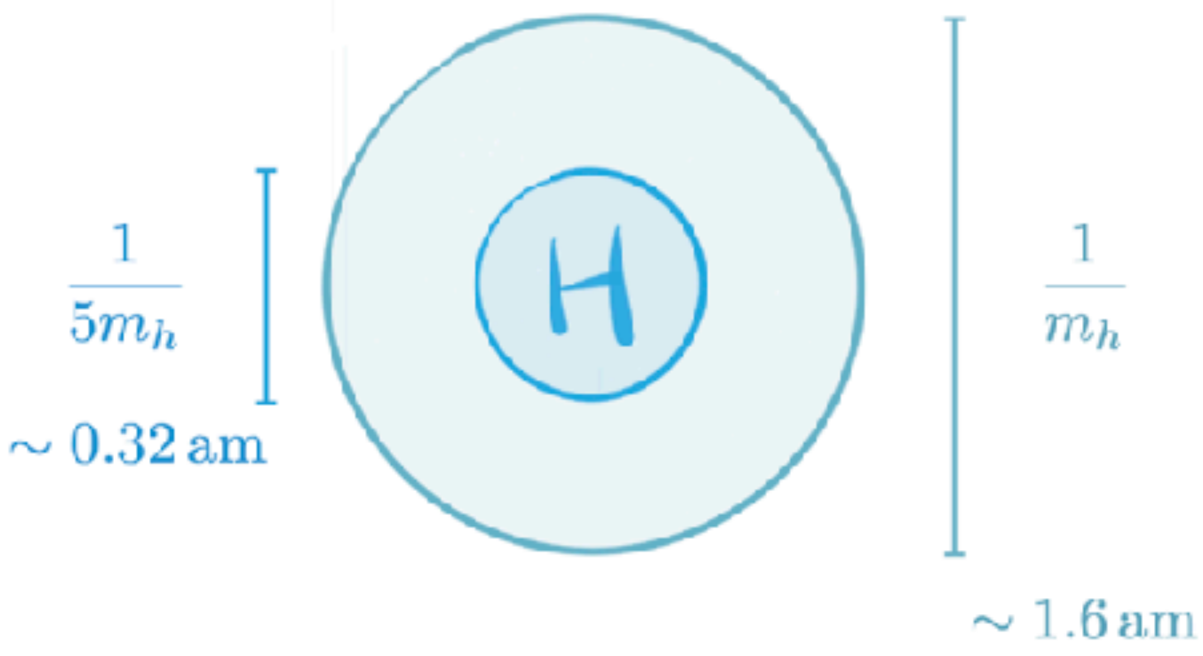

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	Current*	HL-LHC*	FCC (ee)
$\kappa_{W,Z}$	6%	1.6%	0.1%

***No BSM Br**

x30 improvement on the most precise Higgs coupling (under same hypotheses no BSM in branchings)

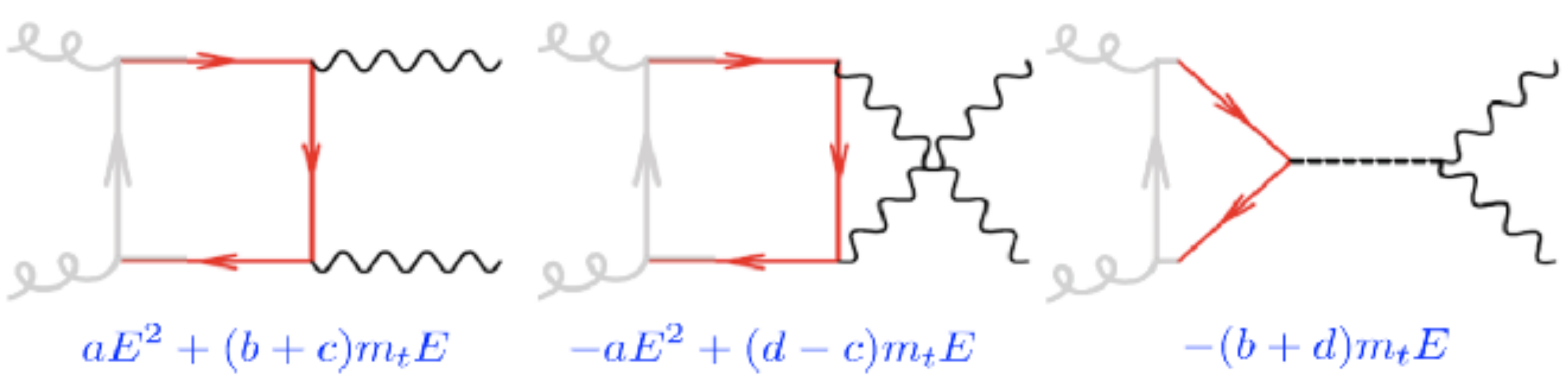
Will yield $f_H > 8$ TeV

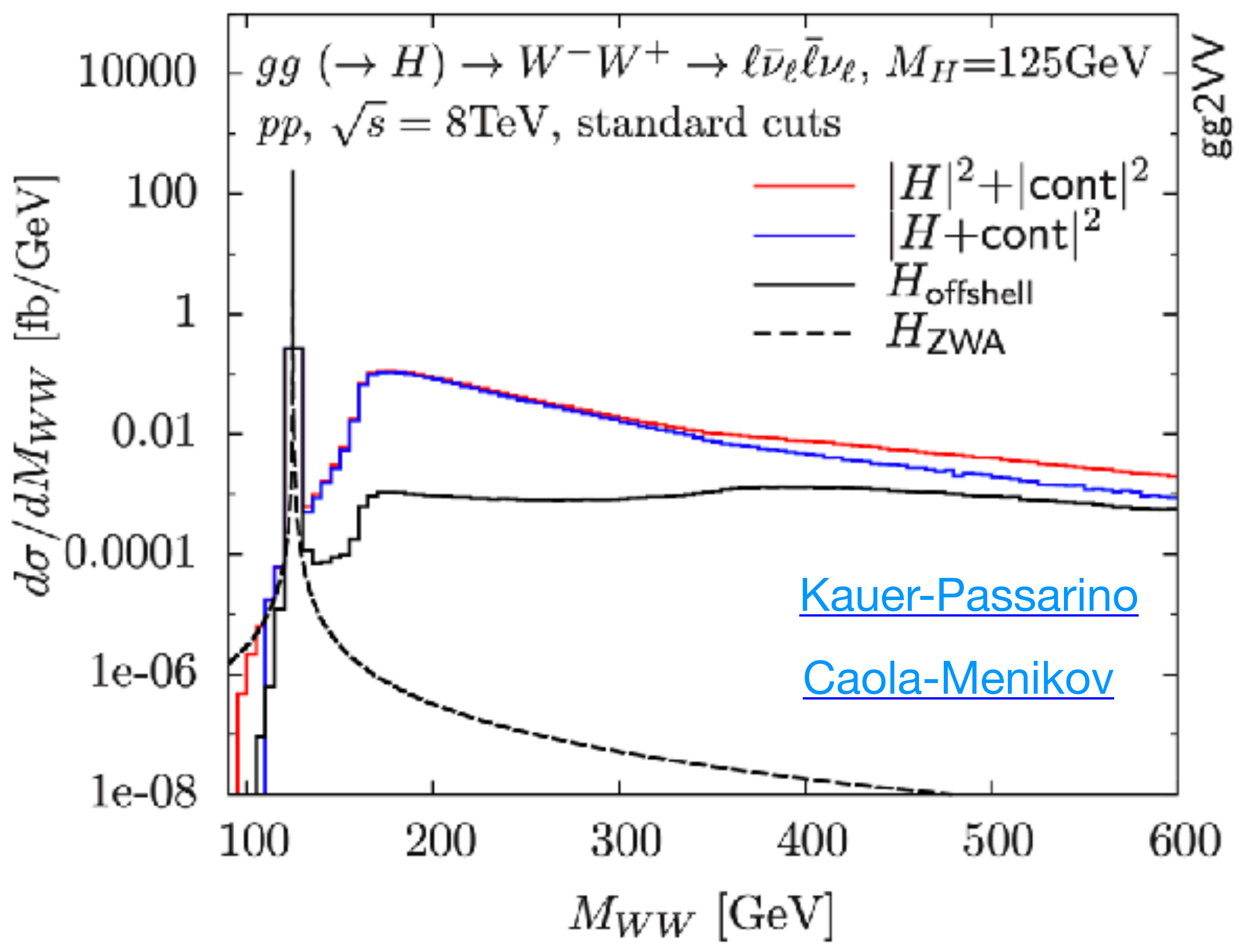
Nearly 50 x Higgs Compton radius!

Making the Impossible - the Higgs Width

Measuring the Higgs width with the Higgs as a propagator!

From J. Campbell





CMS Result

$\Gamma_H = 3.2^{+2.4}_{-1.7}$ MeV

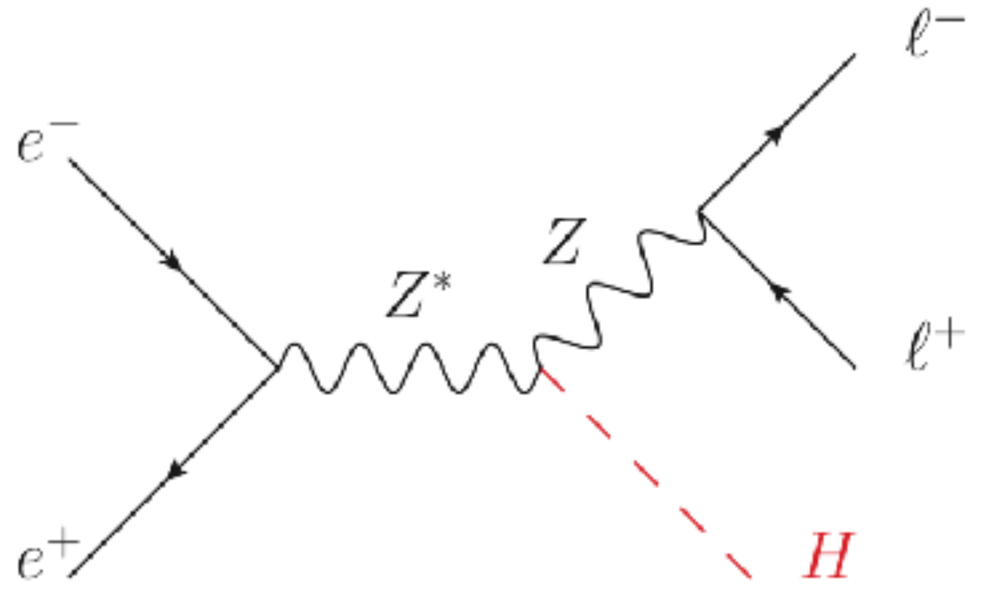
ATLAS Result

$\Gamma_H = 4.5^{+3.3}_{-2.5}$ MeV

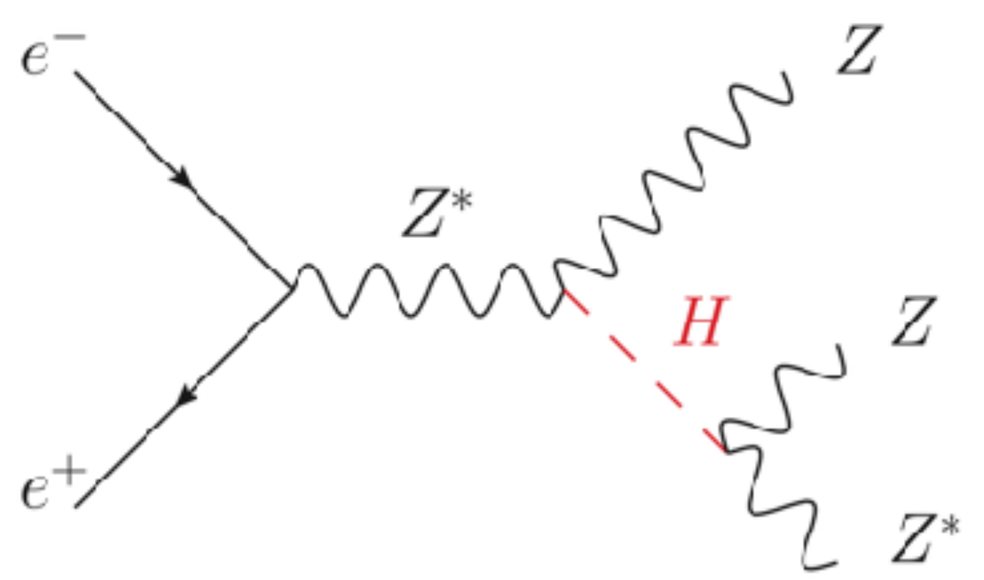
Evidence for Off-Shell production at more than 3σ both experiments

at HL-LHC $\Gamma_H = 4.1^{+1.0}_{-1.1}$ $\Delta\Gamma_H = 25\,\%$

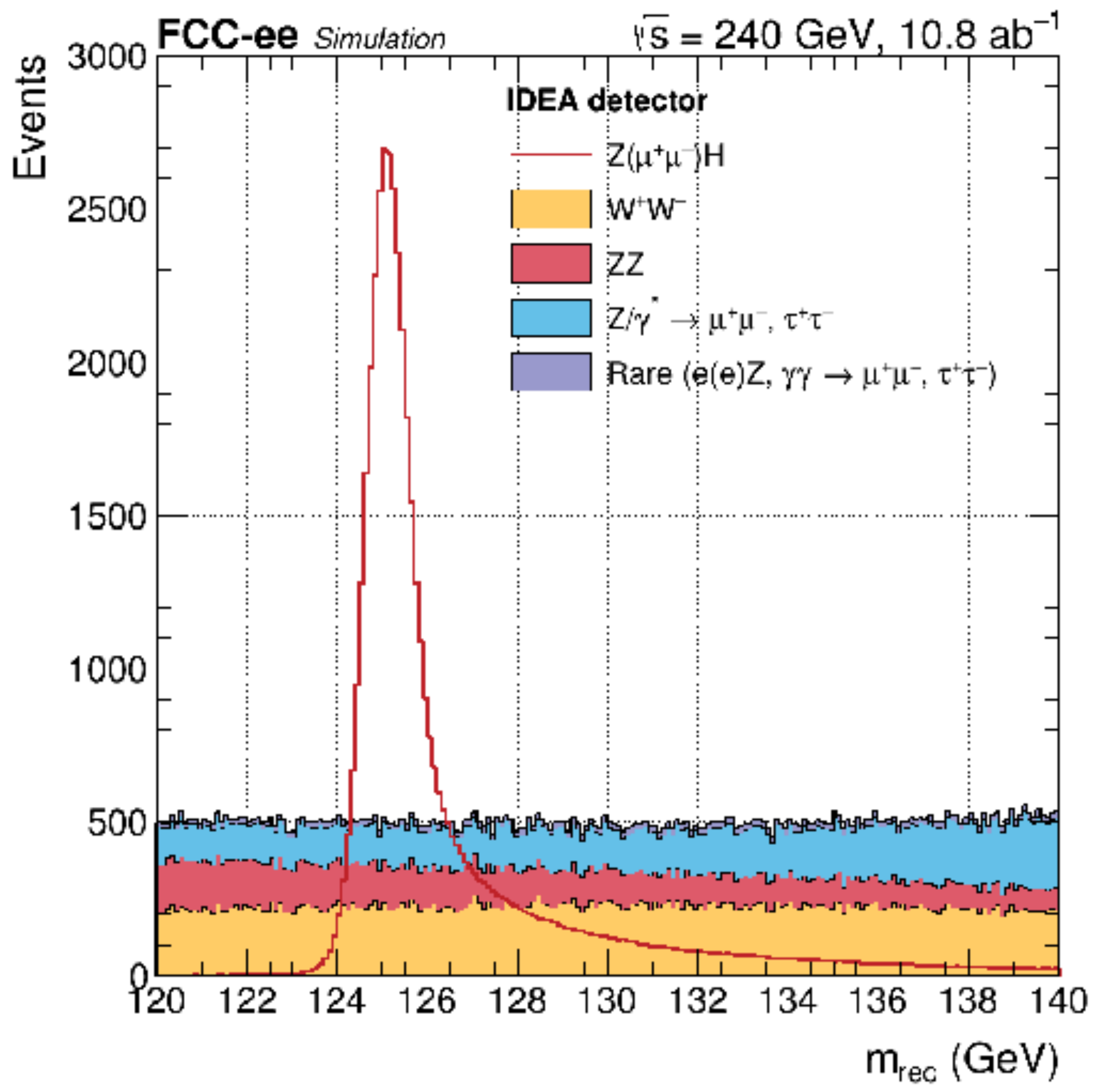
at FCC-ee



$\sigma(e^+e^- \to HZ) \propto \kappa_Z^2$



$\sigma(e^+e^- \to HZ) \times B(H \to ZZ^*) \propto \frac{\kappa_Z^4}{\Gamma_H}$



Access to the ZH total cross section through the recoil mass!

Also possible using the W fusion Higgs production process to reach outstanding precision!

$\Delta\Gamma_H = 0.78\,\%$

30 times more precise!

Very important precise estimate to access absolute couplings!

Pillars of Higgs Physics at Colliders

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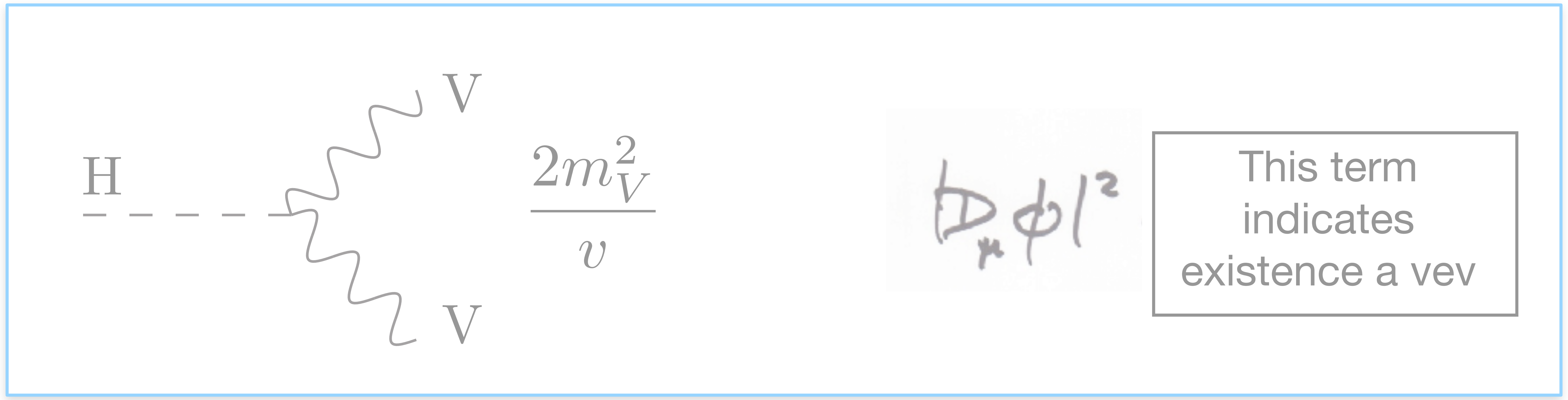
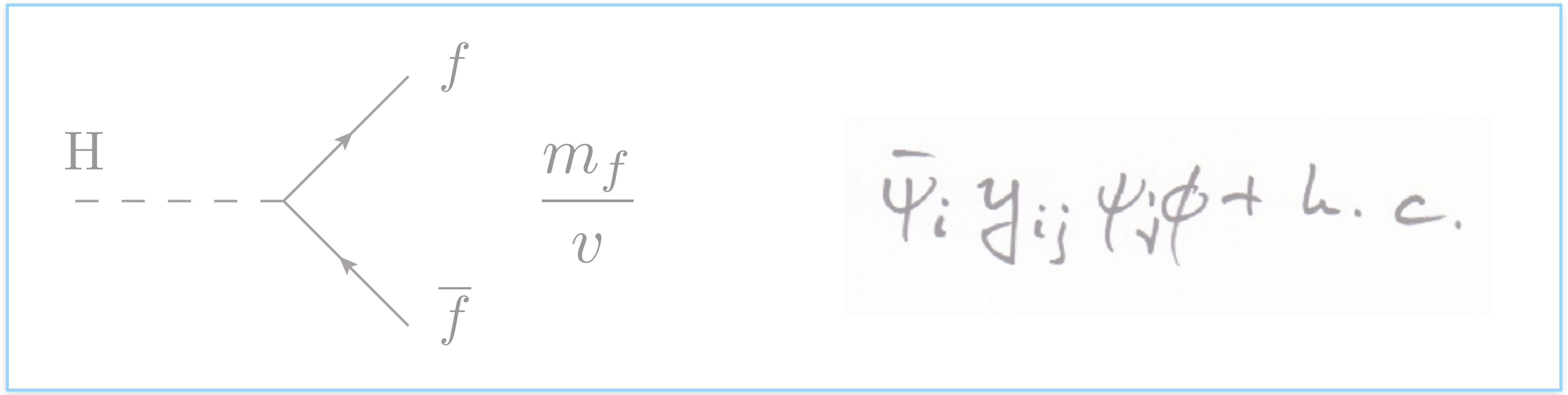
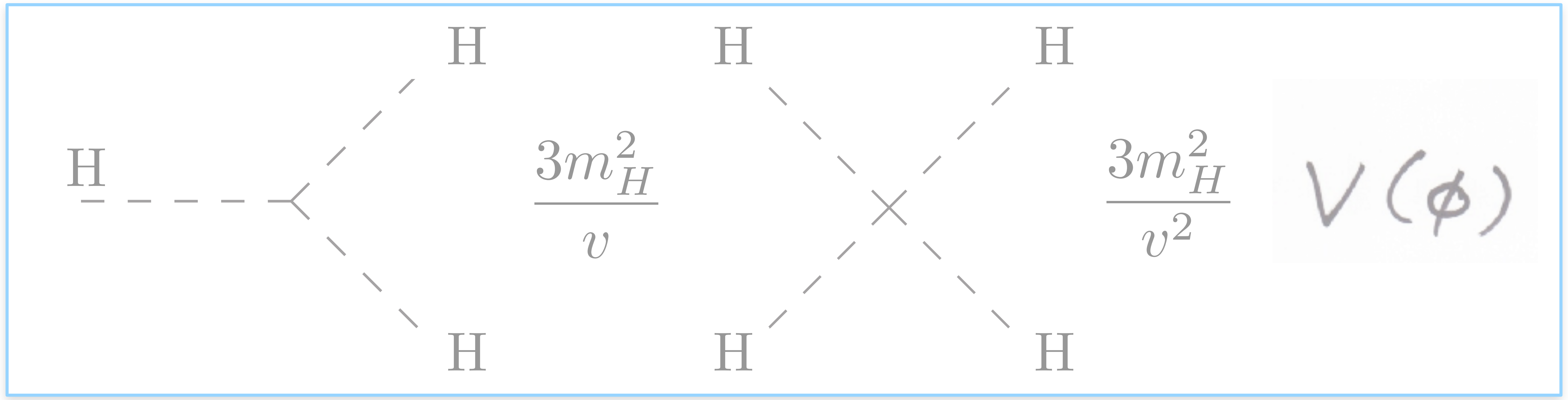
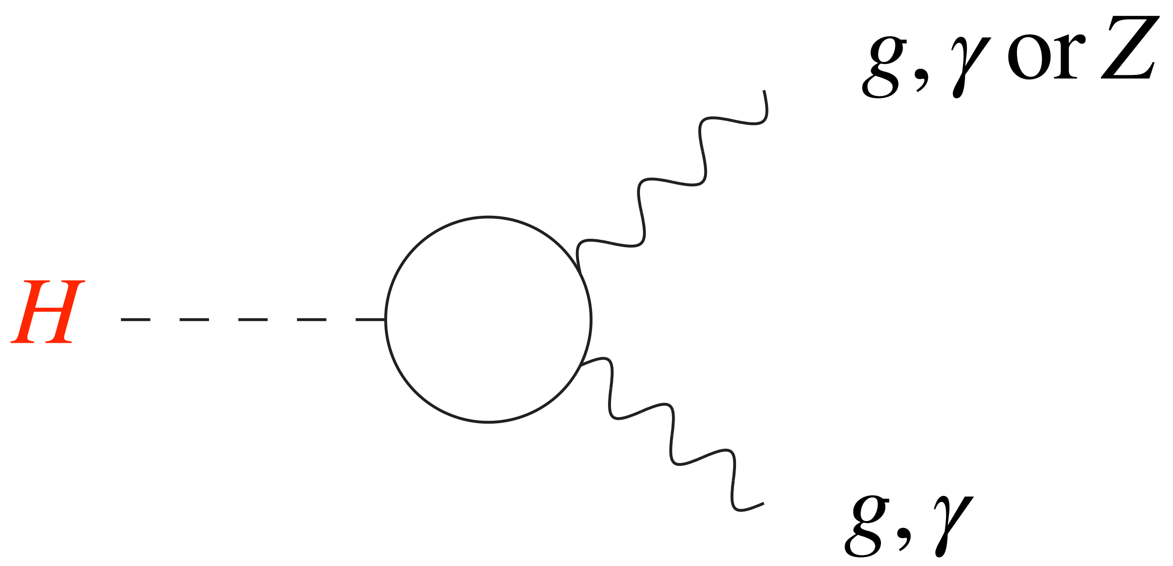






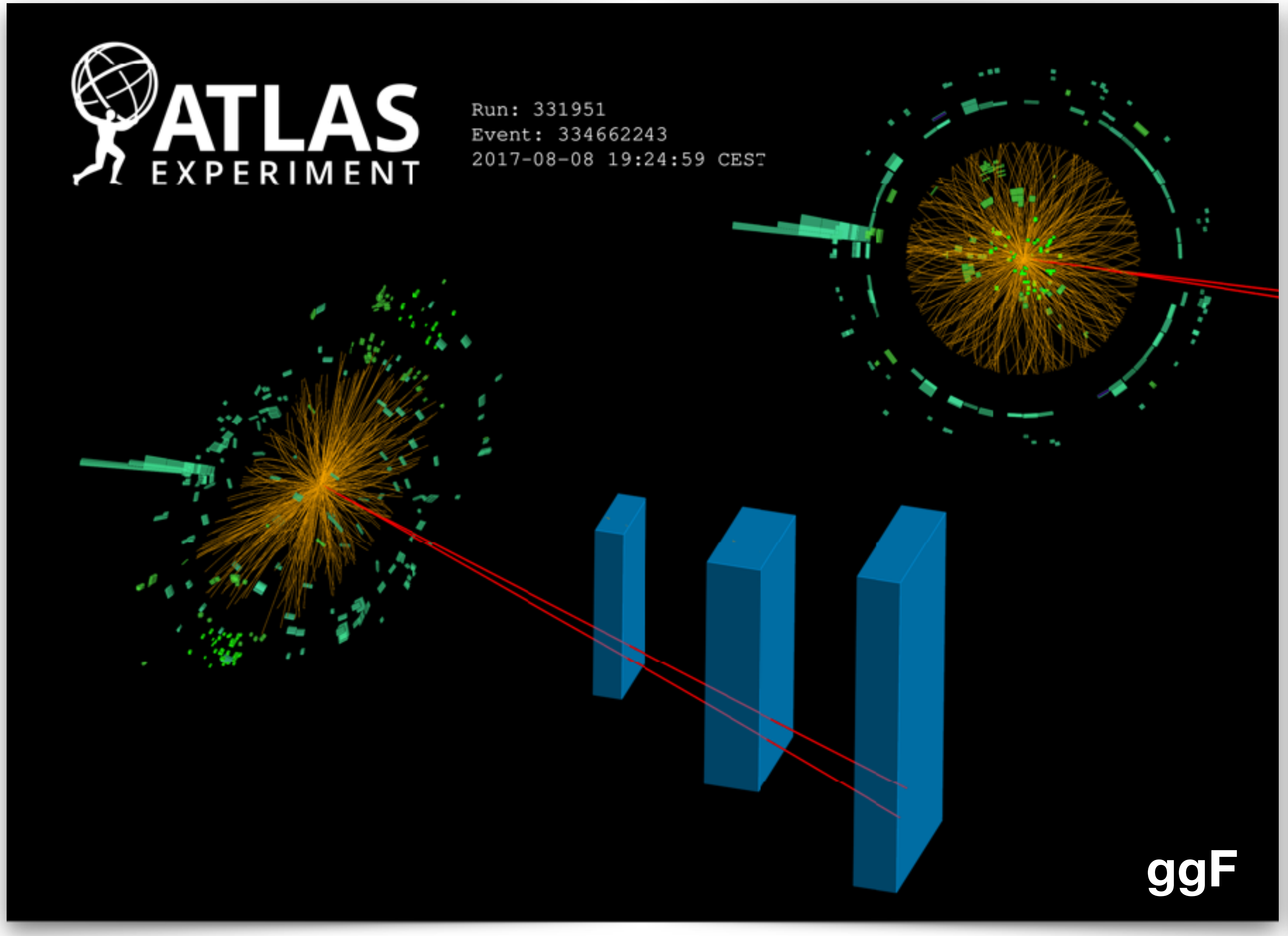
Probing new particles through loops in production and decays!

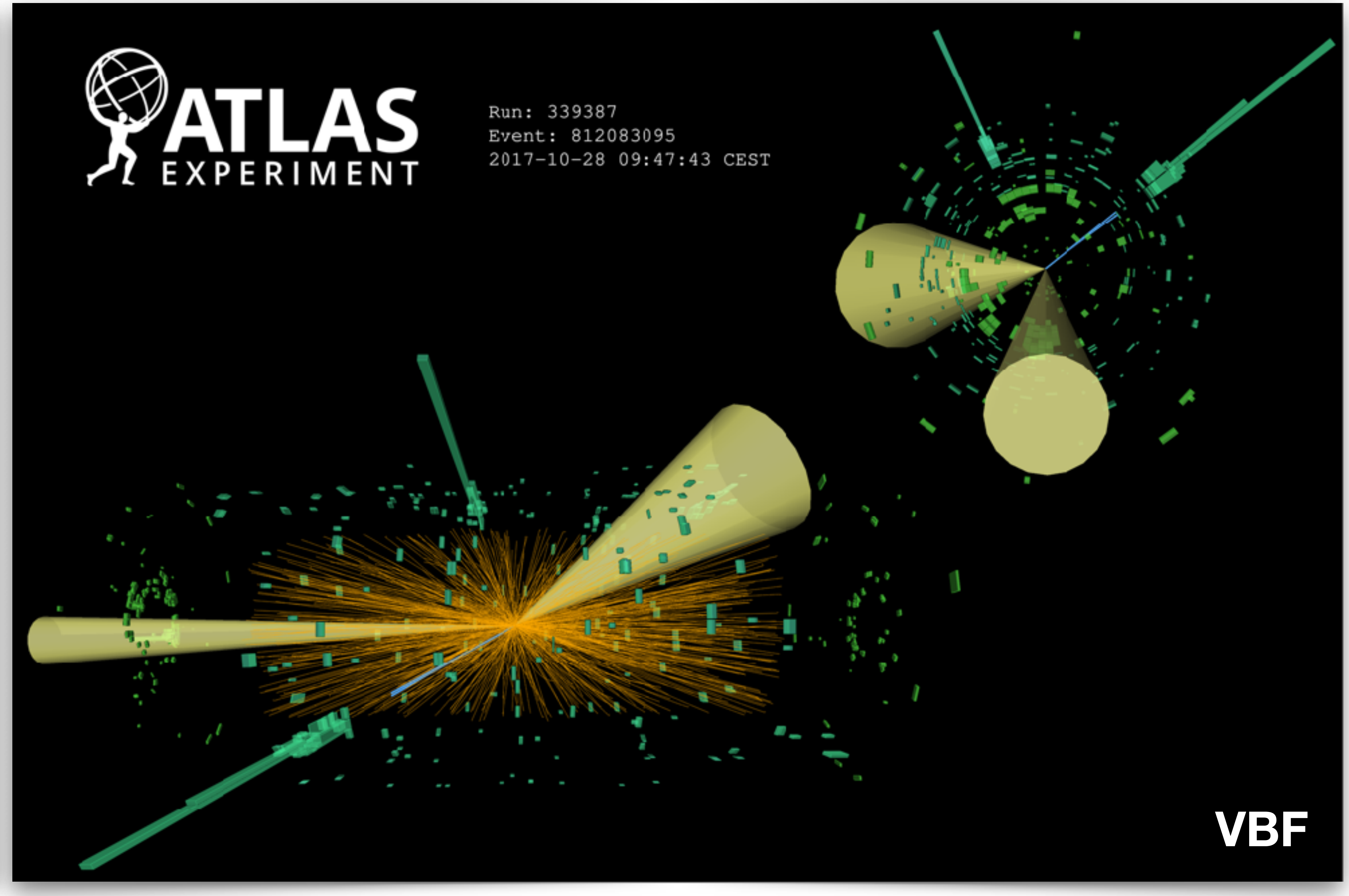


	Current*	HL-LHC*	FCC (ee)	FCC (ee/hh)
κ_γ	6%	1.8%	1.1%	0.3%
κ_g	7%	2.4%	0.5%	0.4%
$\kappa_{Z\gamma}$	30%	6.8%	4.3%	0.7%

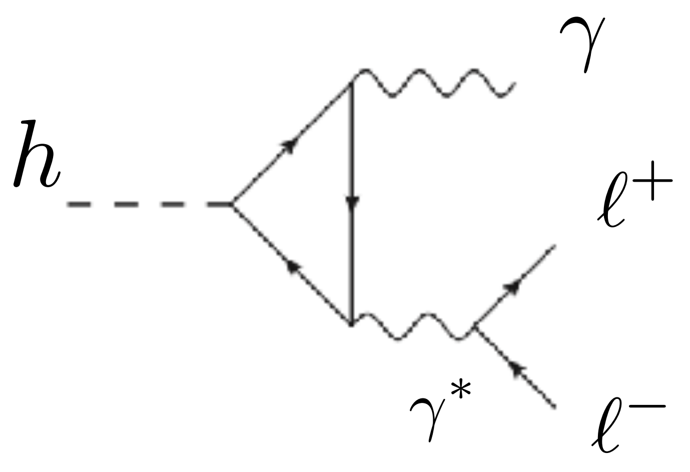
***No BSM Br**

Evidence for $H \to \gamma^* \ell^+ \ell^-$





Evidence for $H \to \gamma^* \ell^+ \ell^-$



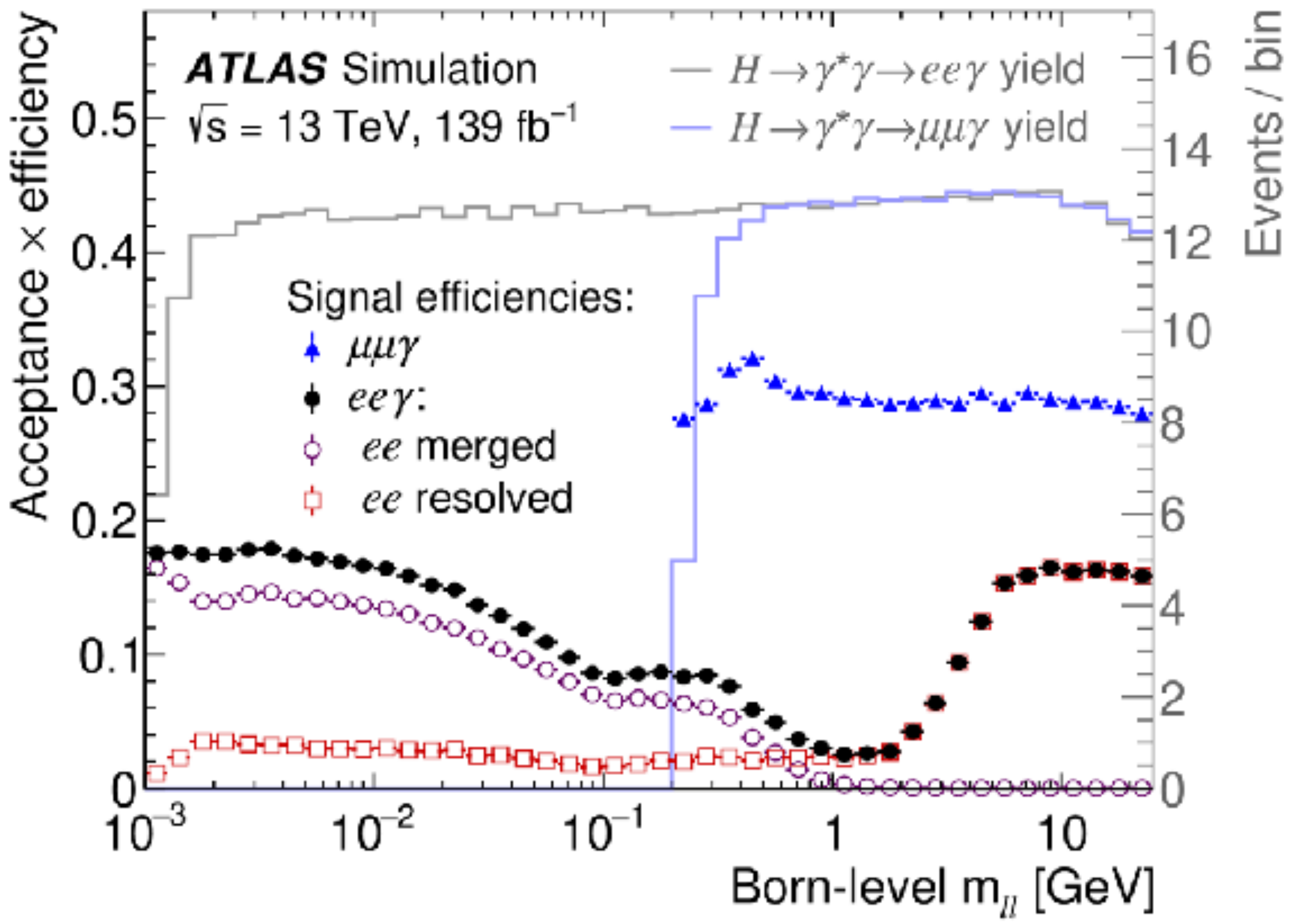
Search initially made in this case in the dimuon channel only (in the low di-lepton mass limit the shower of electrons merge).

~ 1.7% of $Br(\gamma\gamma)$

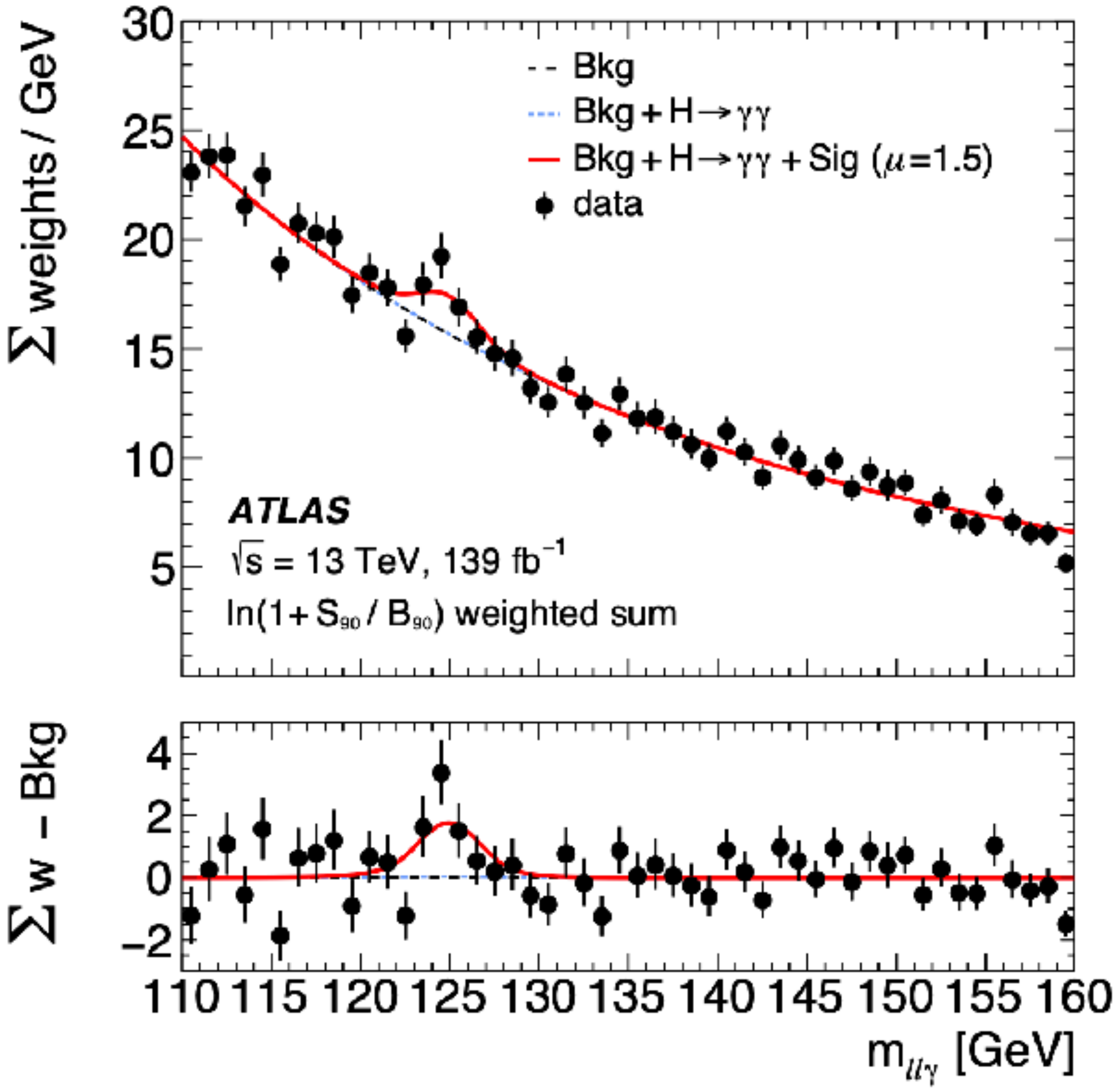
$$m_{\ell^+\ell^-} < 50 \text{ GeV}$$

Key experimental challenge is to go to low dilepton mass this required a **new reconstruction technique**:

Merged electron reconstruction where a calorimeter (electron-like) cluster is associated to two tracks and conversions are carefully rejected!



[Phys. Lett. B 819 (2021) 136412]



- 3 x 3 categories (VBF, high pT ggF, low pT ggF) $\otimes$ (ee resolved, ee merged, $\mu\mu$)
- Contributions from J/ψ are removed with a mass cut

$$\mu = 1.5 \pm 0.5 = 1.5 \pm 0.5 \text{ (stat.)} ^{+0.2}_{-0.1} \text{ (syst.)}$$

$$\mu_{\text{exp}} = 1.0 \pm 0.5 = 1.0 \pm 0.5 \text{ (stat.)} ^{+0.2}_{-0.1} \text{ (syst.)}$$

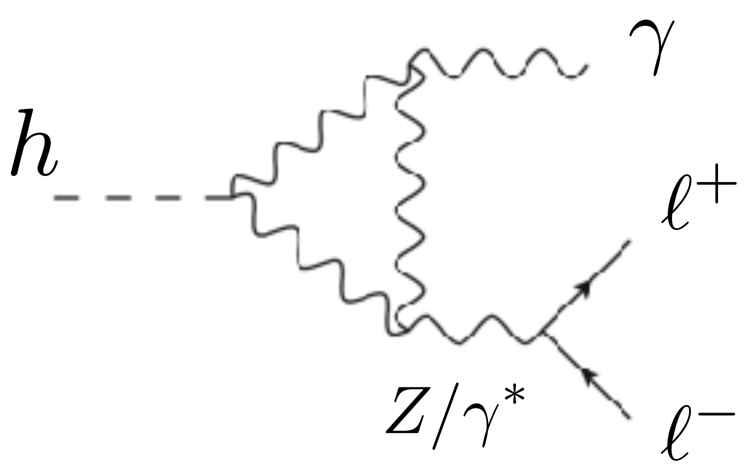
Expected 2.1σ

Observed 3.2σ

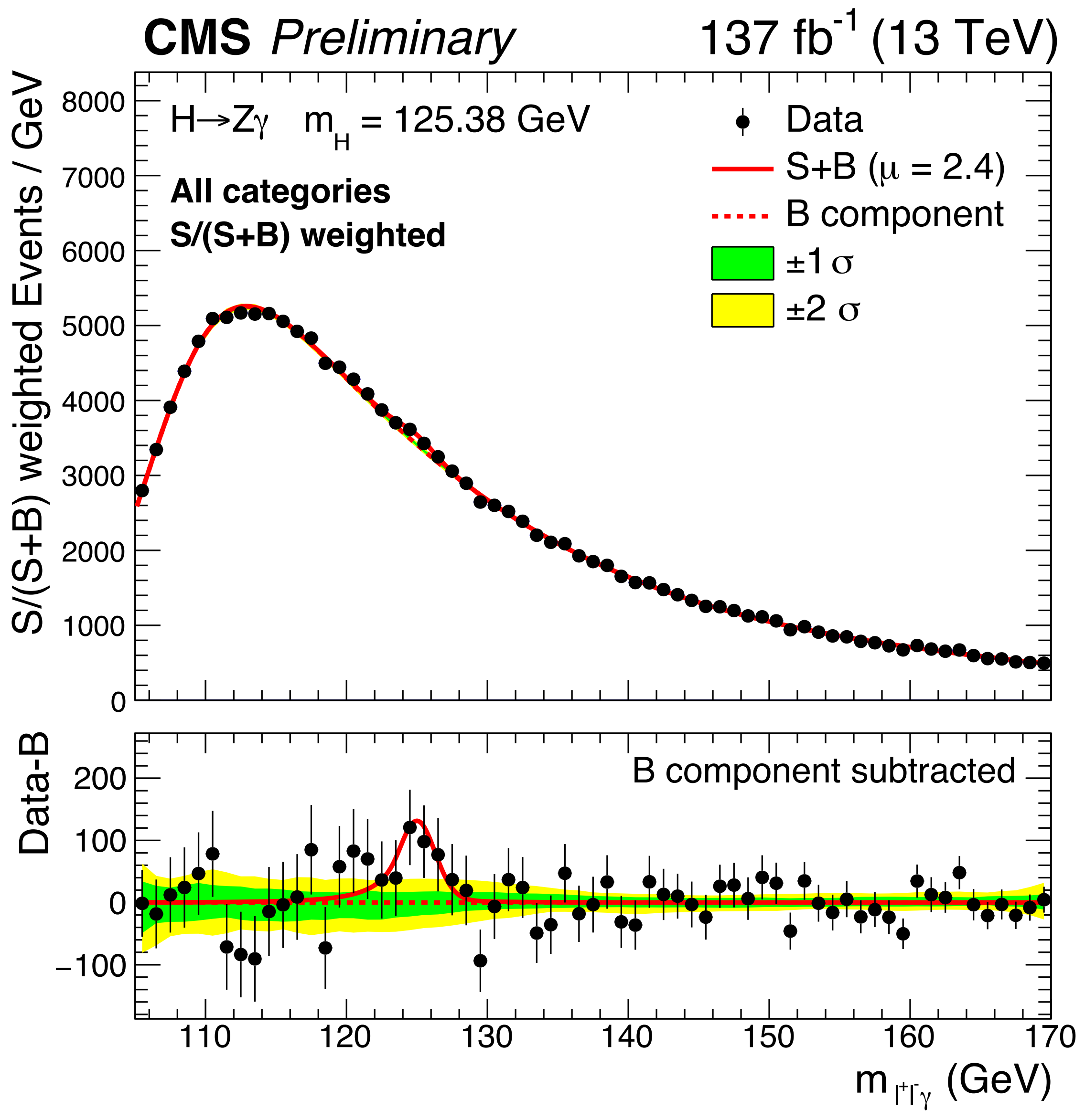
Searches for the $H \to Z\gamma$ Decay Mode

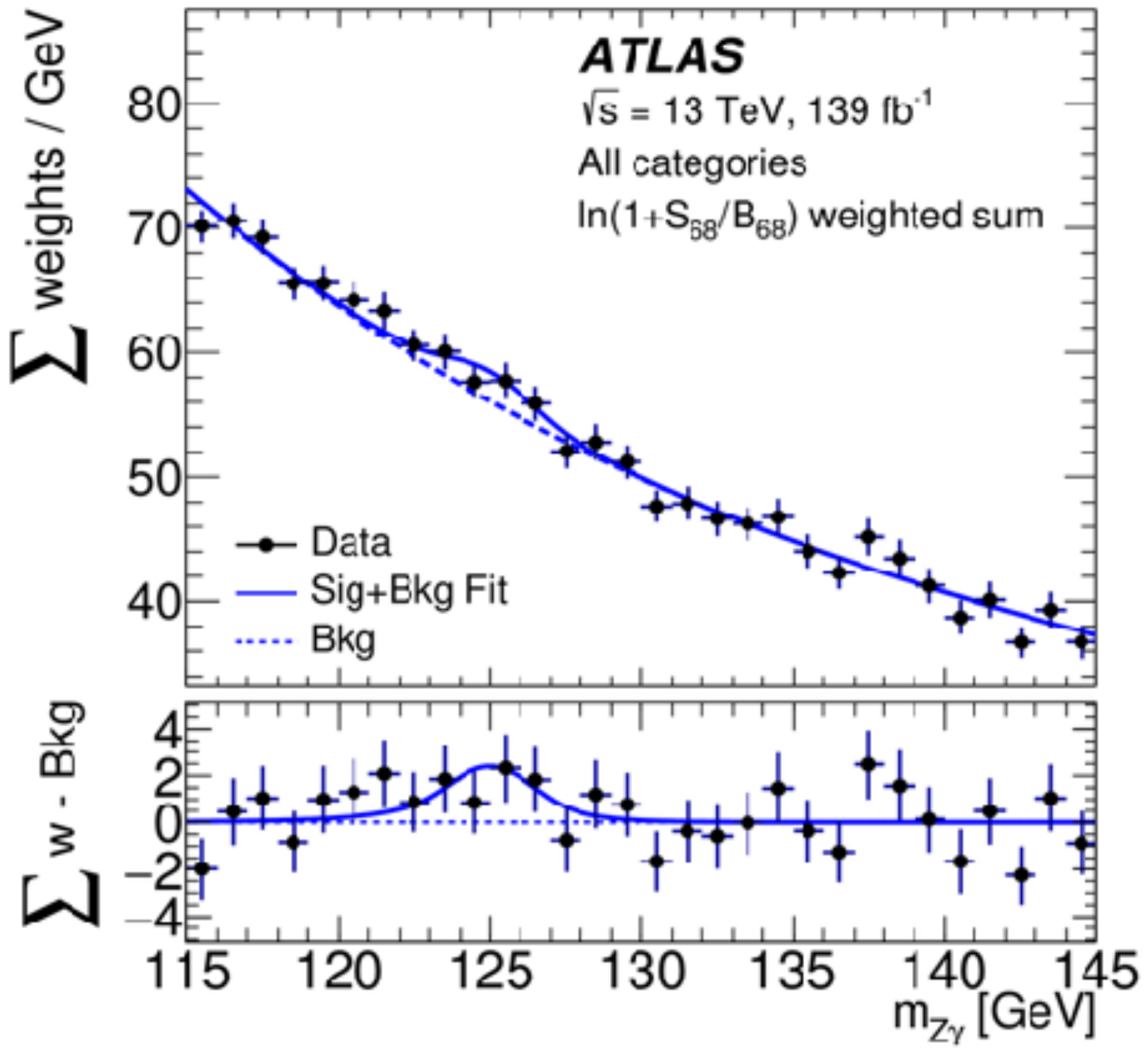
Z-photon $|H^2|W^a_{\mu\nu}W^{\mu\nu a}$

Field tensor coupling not measured yet!

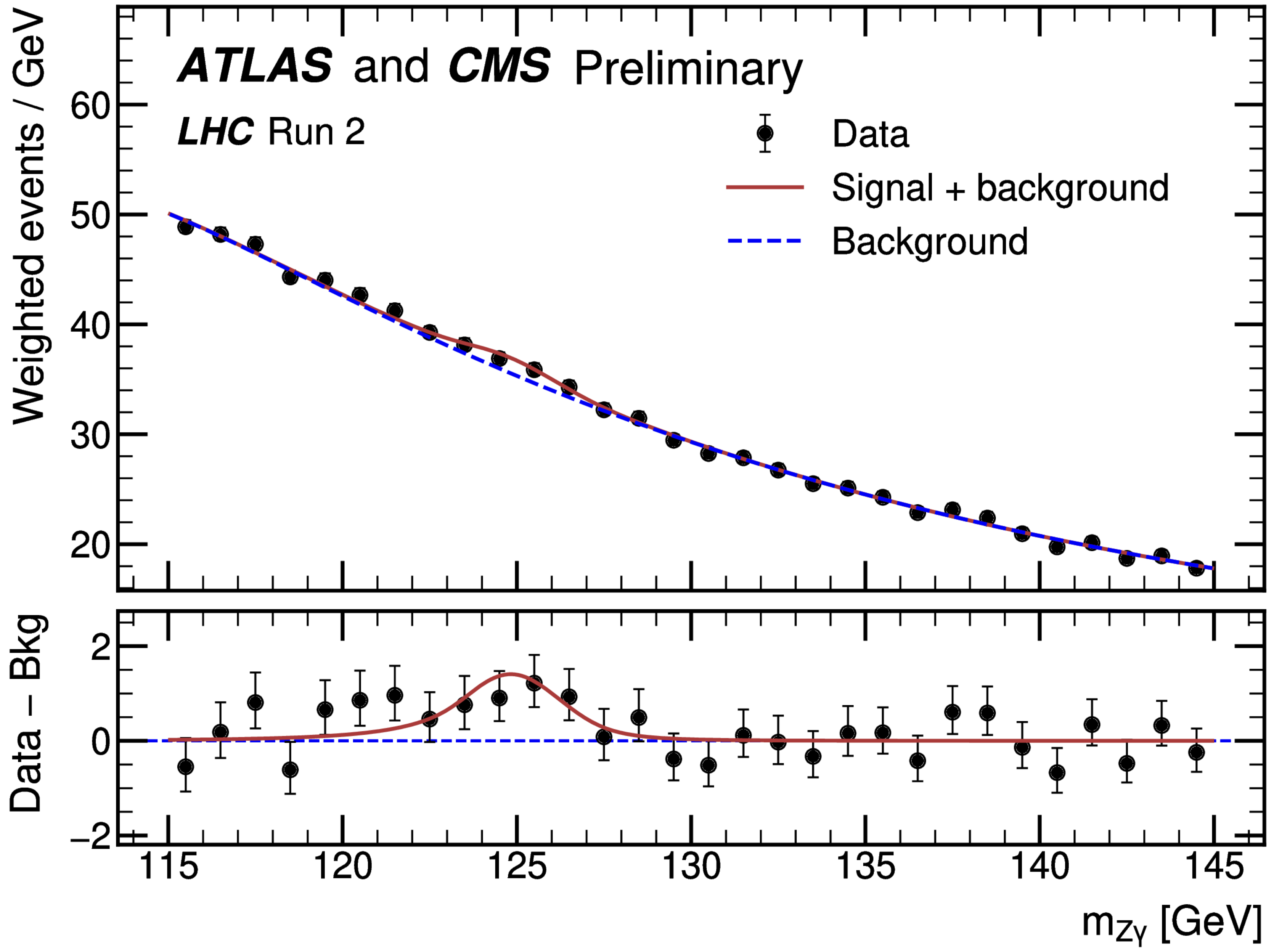


~ 2.3% of $Br(\gamma\gamma)$





Combined ATLAS and CMS mass spectrum!



CMS Result

ggF, VBF, VH and ttH enriched

Expected 1.2σ

Observed 2.7σ

ATLAS Result

ggF and VBF enriched

Expected 1.2σ

Observed 2.2σ

Combined search yields 3.4σ observed and 1.6σ expected (consistent with the SM expectation at the 1.9σ): First evidence!

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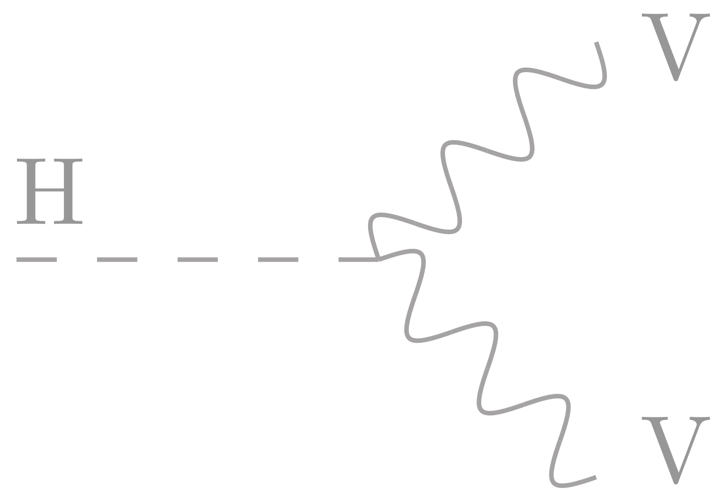
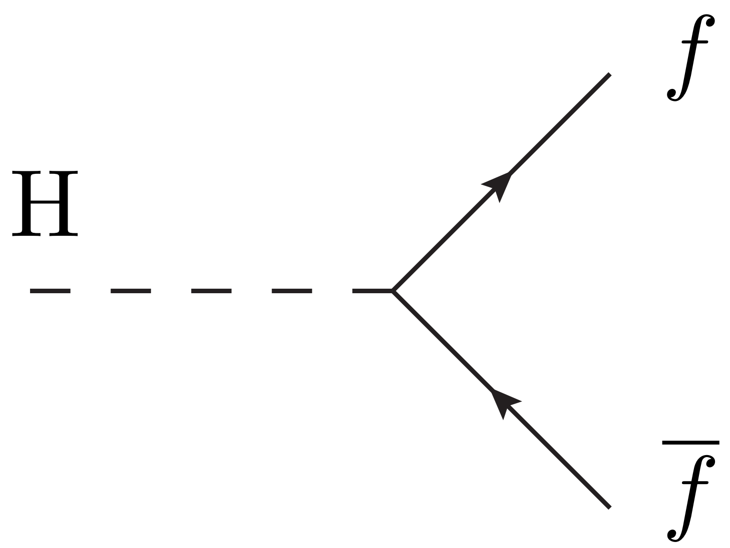


$$\frac{2m_V^2}{v}$$

$|D_\mu \phi|^2$

This term indicates existence a vev



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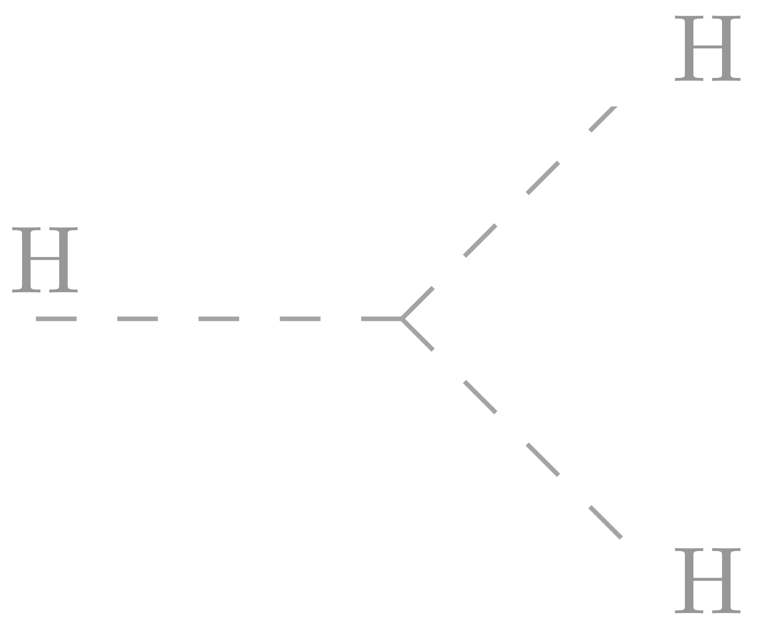
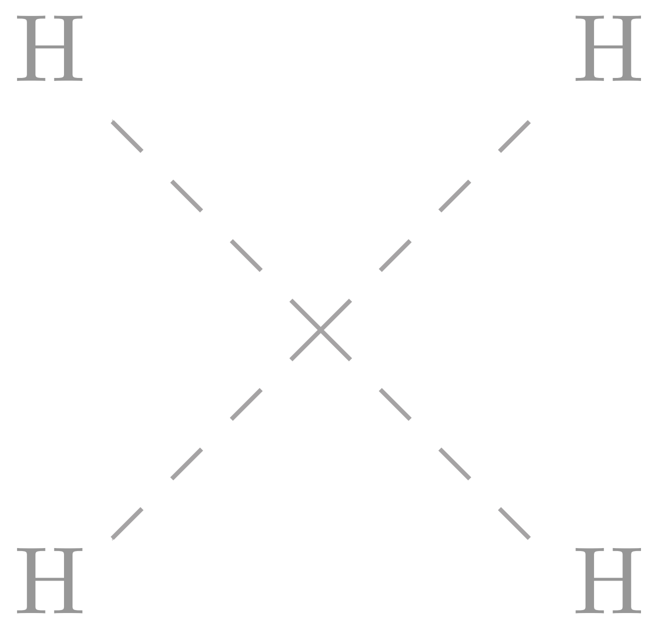


$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$V(\phi)$

	Current*	HL-LHC*	FCC (ee)	FCC (ee-hh)
κ_t				
κ_b	11%	3.6%	0.5%	0.5%
κ_τ	8%	1.9%	0.5%	
κ_μ	20%	3.0%	3.3%	0.4%

***No BSM Br**

"We would not consider the theory of electromagnetism established if we had only verified […] to within 10% accuracy." (Salam et al., Nature)

Much came our of LEP: "LEP changed high-energy physics from a 10% to a 1% science." It was a major achievement! (H. Schopper CERN Courier)

What about the other fermion generations?

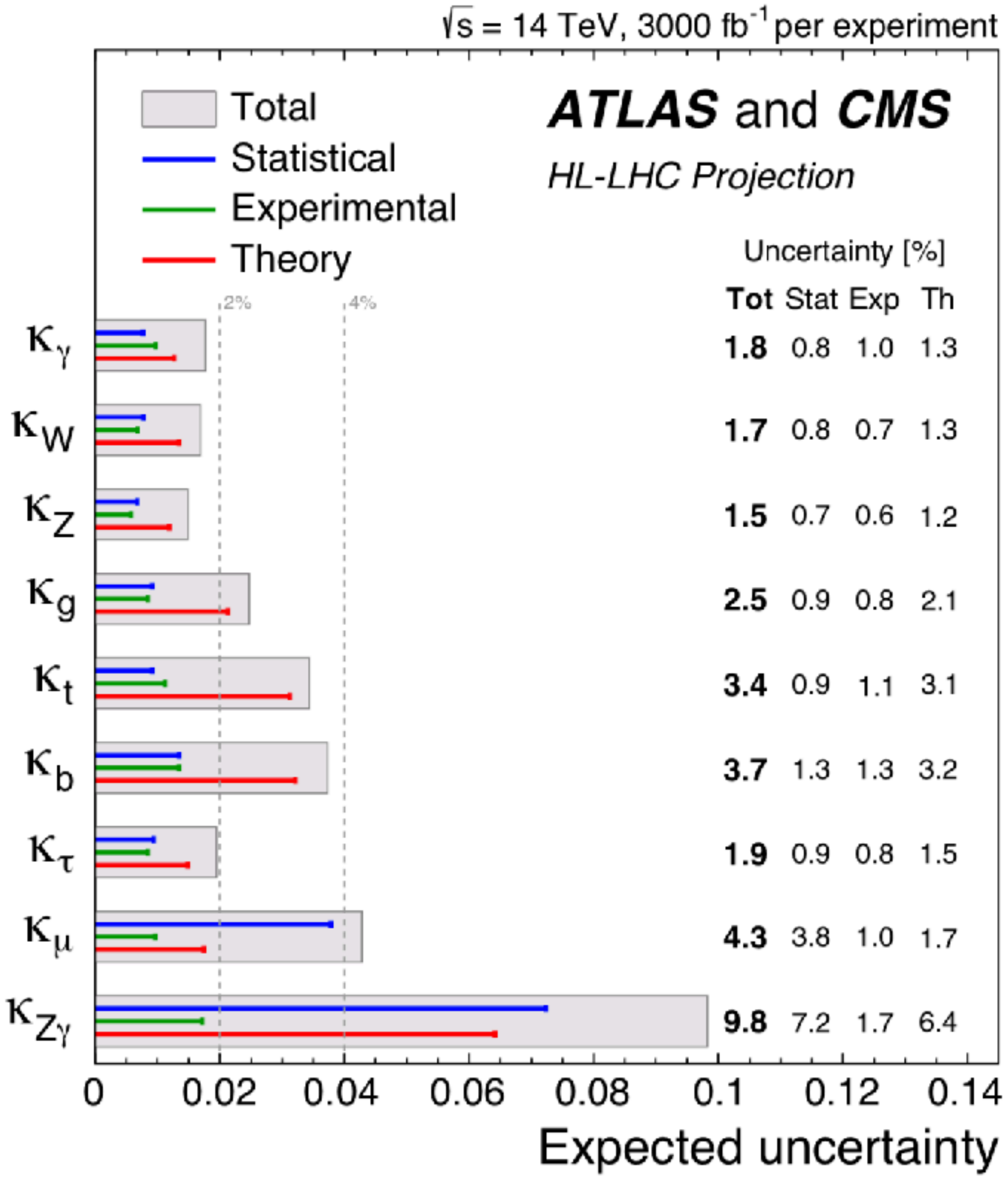
Crucial to further improve ttH measurements at the LHC - inaccessible until FCC-hh!

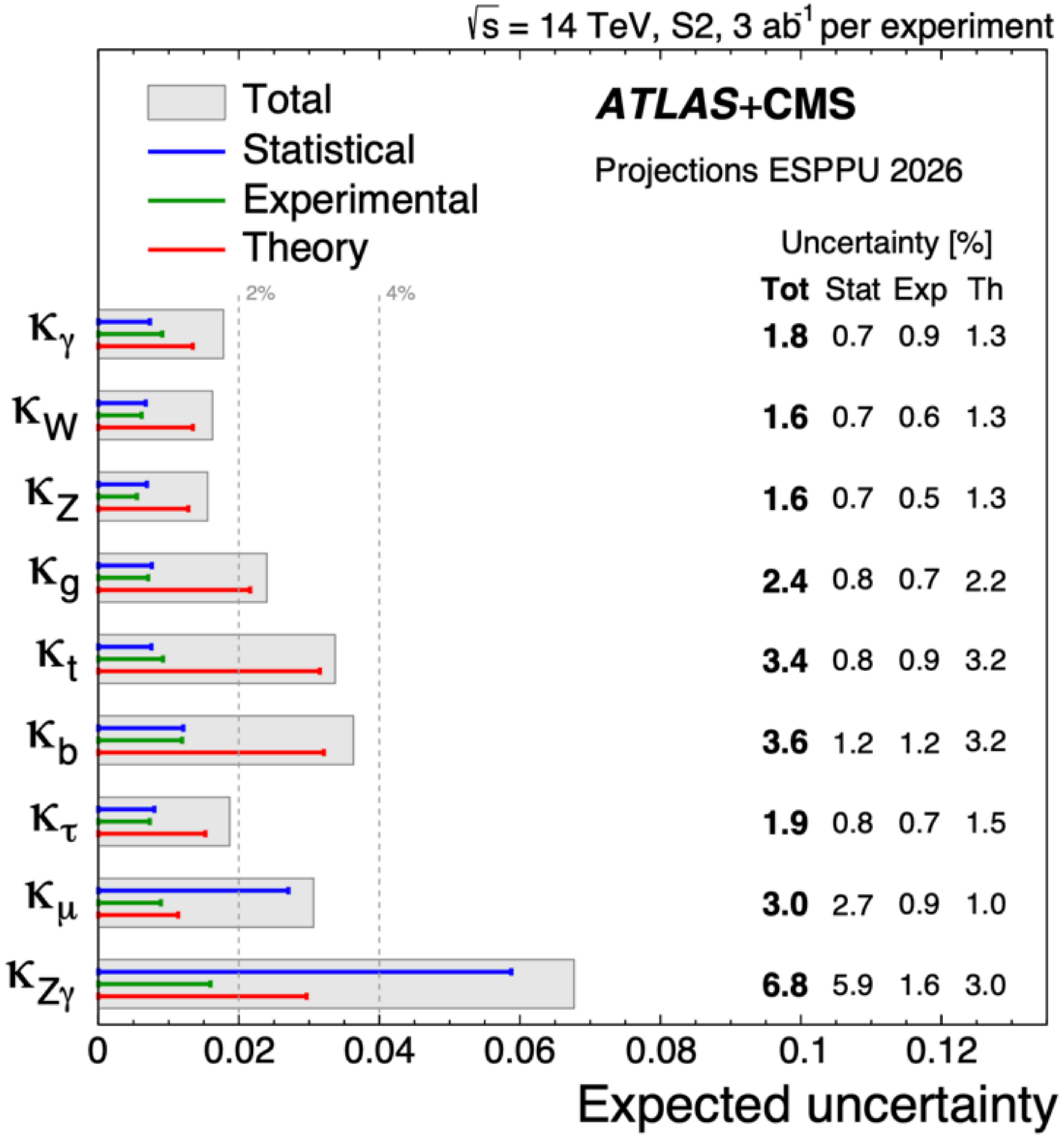
Also indirectly at FCC-ee!

The Importance of Theory and Modelling

Update on Higgs couplings!

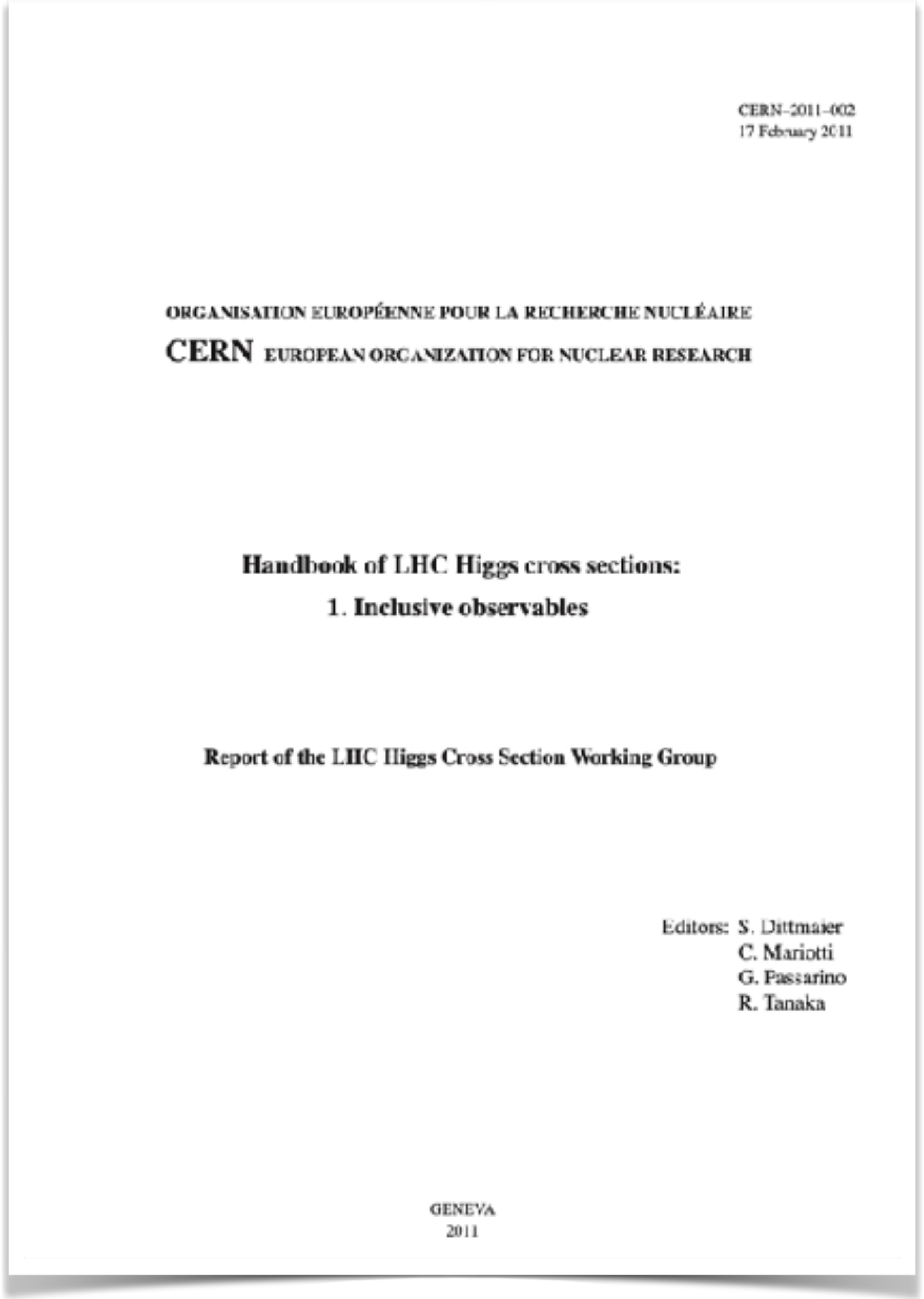
Numbers are mostly unchanged (already previously dominated by TH uncertainties) with two exceptions.





The Importance of Theory and Modelling

The LHC Higgs (Cross Section) Working Group
Played an essential role in the success of the entire Higgs physics program of the LHC, uniting TH efforts and facilitating the communication between TH and EXP.


CERN-2011-002
17 February 2011

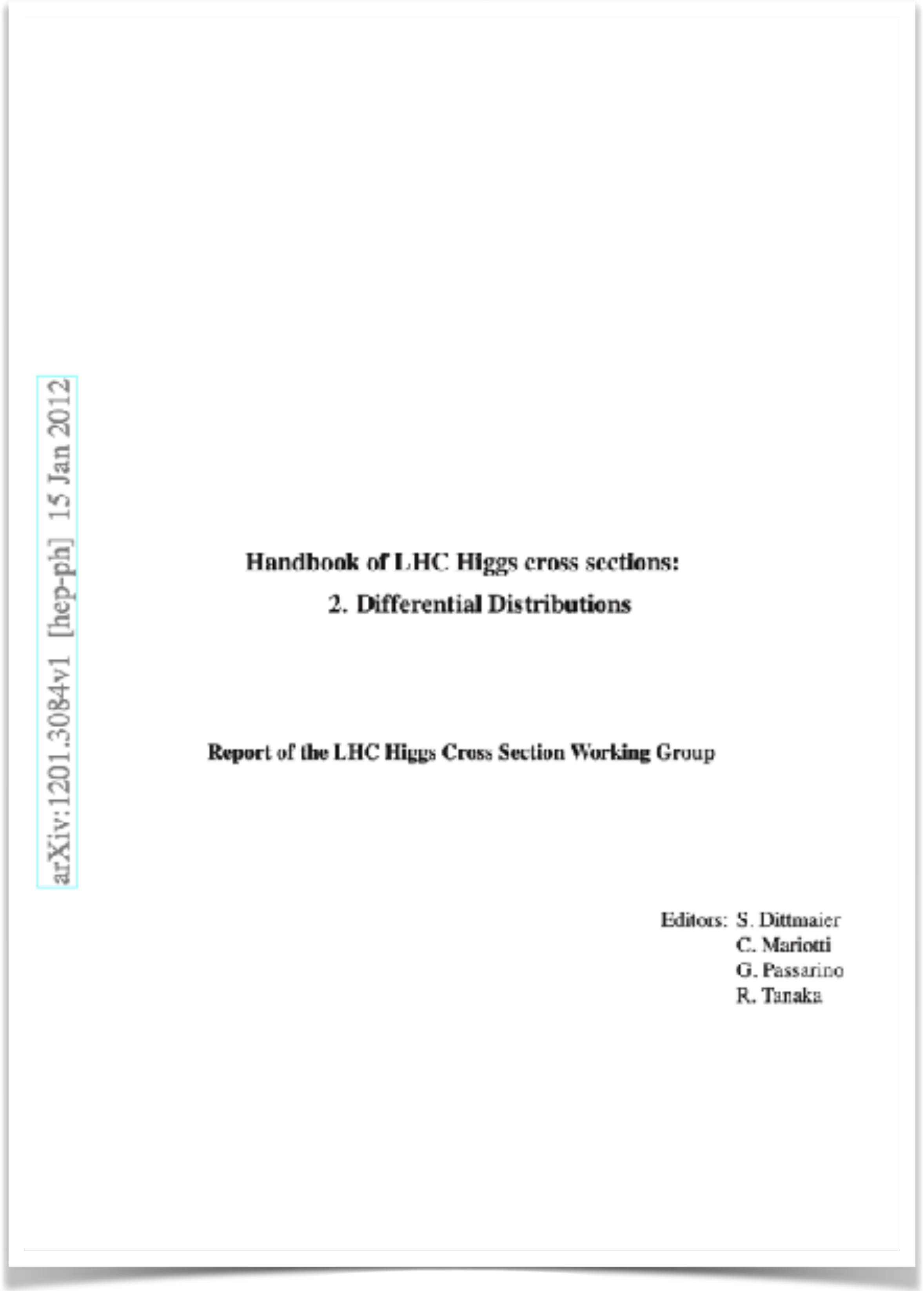
ORGANISATION EUROPÉENNE POUR LA RECHERCHE NUCLÉAIRE
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
1. Inclusive observables

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka

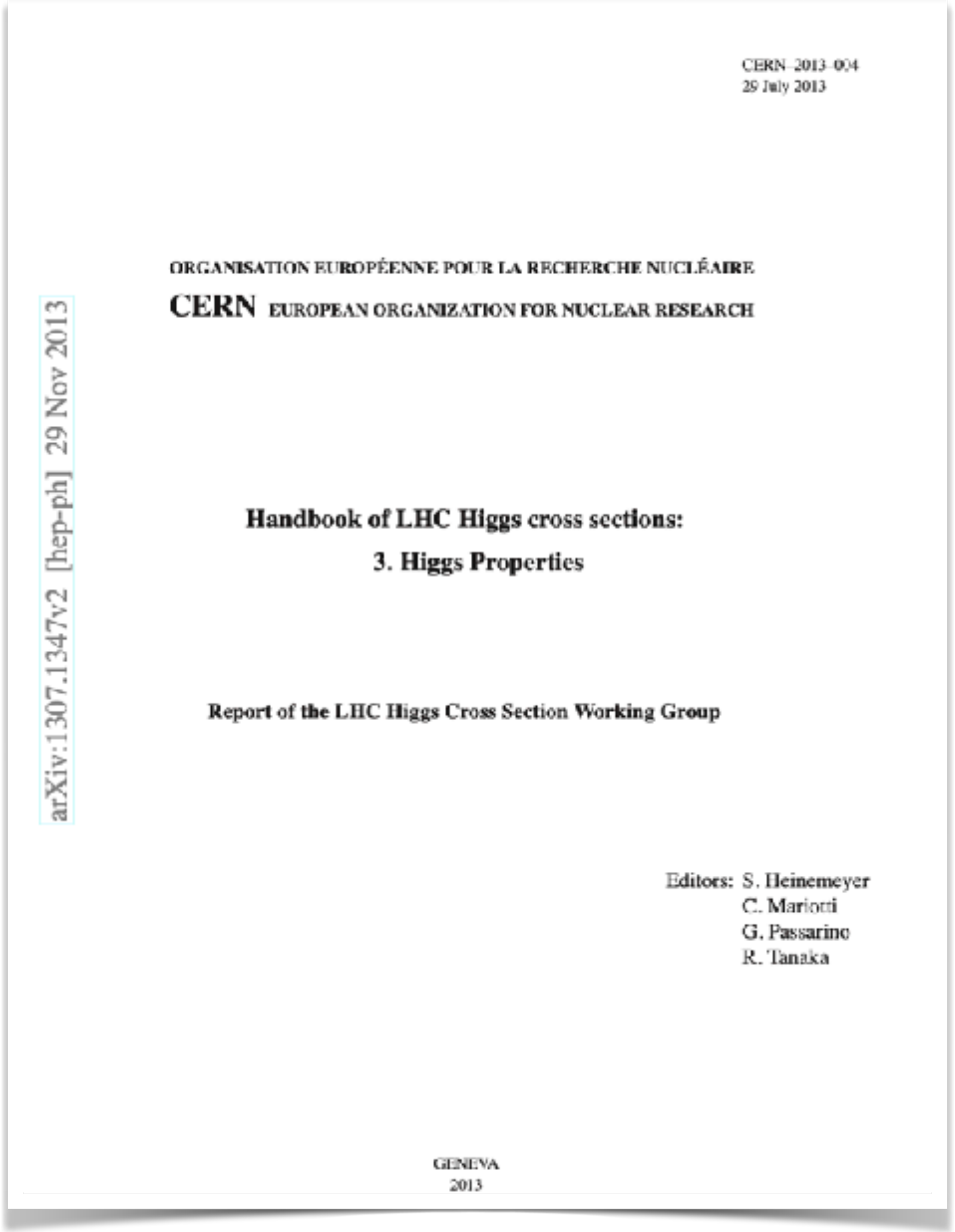
GENEVA
2011


arXiv:1201.3084v1 [hep-ph] 15 Jan 2012

Handbook of LHC Higgs cross sections:
2. Differential Distributions

Report of the LHC Higgs Cross Section Working Group

Editors: S. Dittmaier
C. Mariotti
G. Passarino
R. Tanaka


CERN-2013-004
26 July 2013

arXiv:1307.1347v2 [hep-ph] 29 Nov 2013

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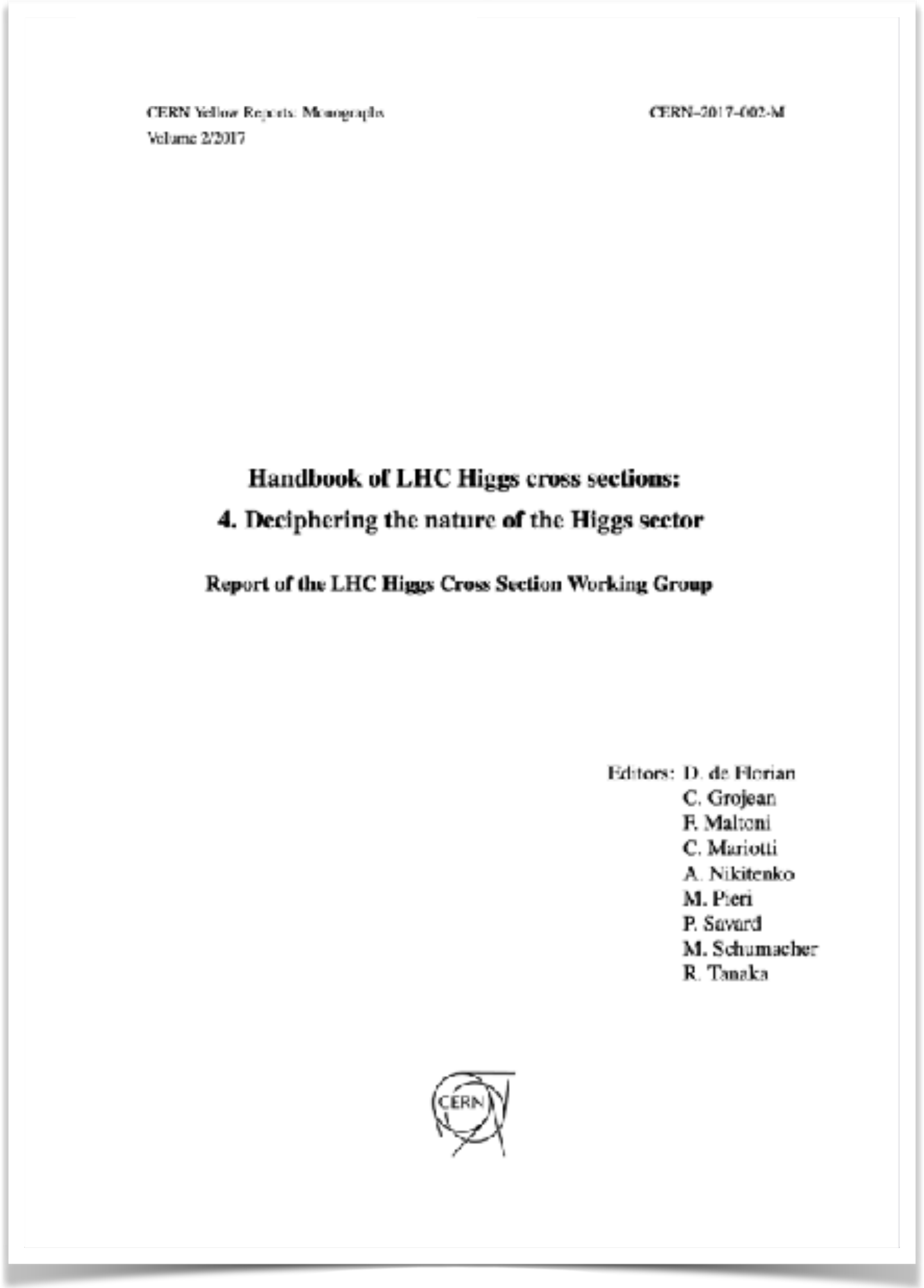
CERN EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

Handbook of LHC Higgs cross sections:
3. Higgs Properties

Report of the LHC Higgs Cross Section Working Group

Editors: S. Heinemeyer
C. Mariotti
G. Passarino
R. Tanaka

GENEVA
2013


CERN Yellow Reports: Monographs
Volume 2/2017
CERN-2017-002-M

Handbook of LHC Higgs cross sections:
4. Deciphering the nature of the Higgs sector

Report of the LHC Higgs Cross Section Working Group

Editors: D. de Florian
C. Grojean
F. Maltoni
C. Mariotti
A. Nikitenko
M. Pieri
P. Savard
M. Schumacher
R. Tanaka

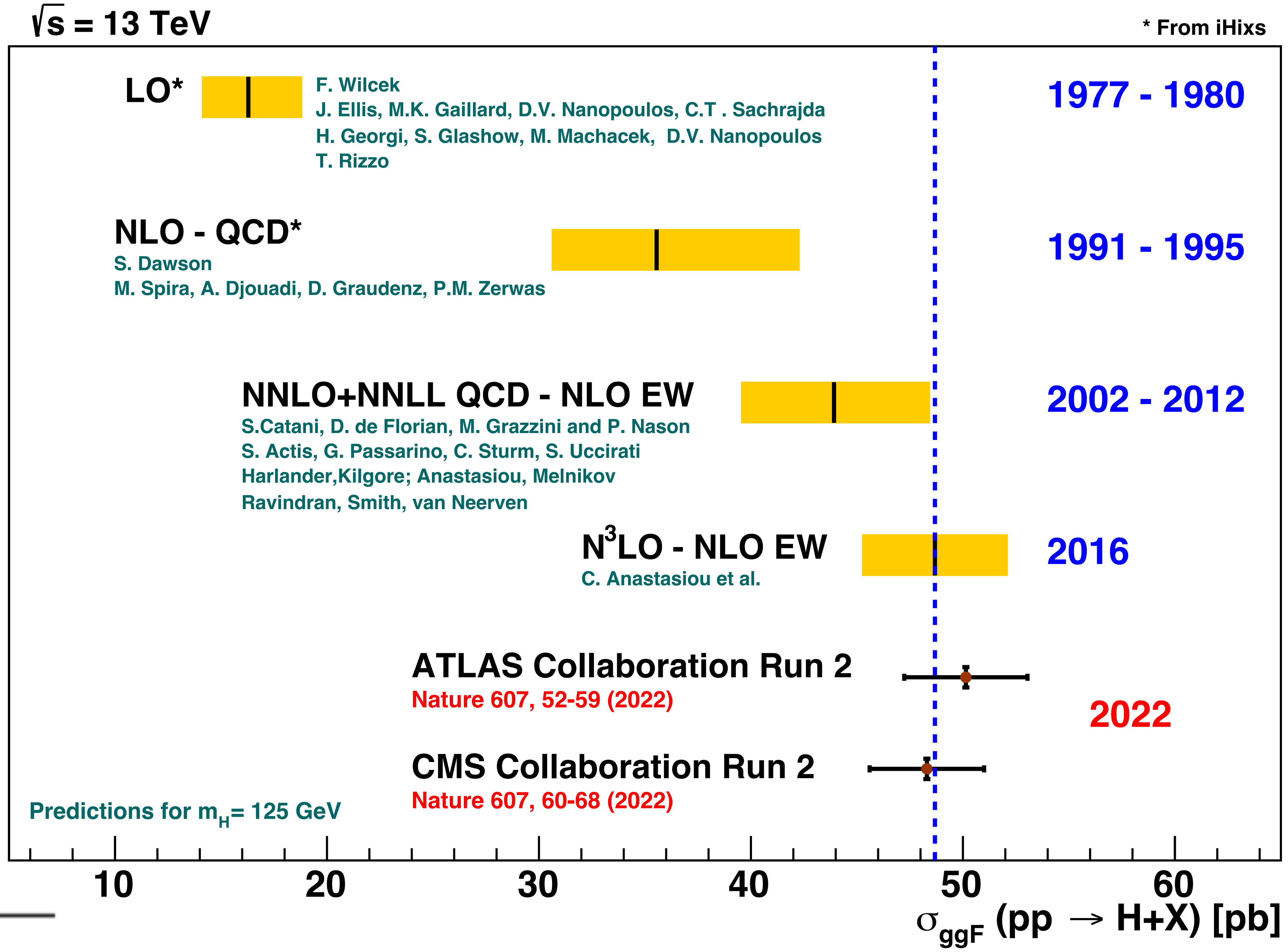
The Importance of Theory and Modelling

Predictions at hadron colliders are complex require higher order hard processes, parton fragmentation, hadronization, parton distribution functions, etc…

The interpretability of our results relies on our ability to compute accurate and precise predictions!

Precision at the LHC would not be possible without the efforts of precise TH and modelling.

Half a century of progress in Higgs production predictions



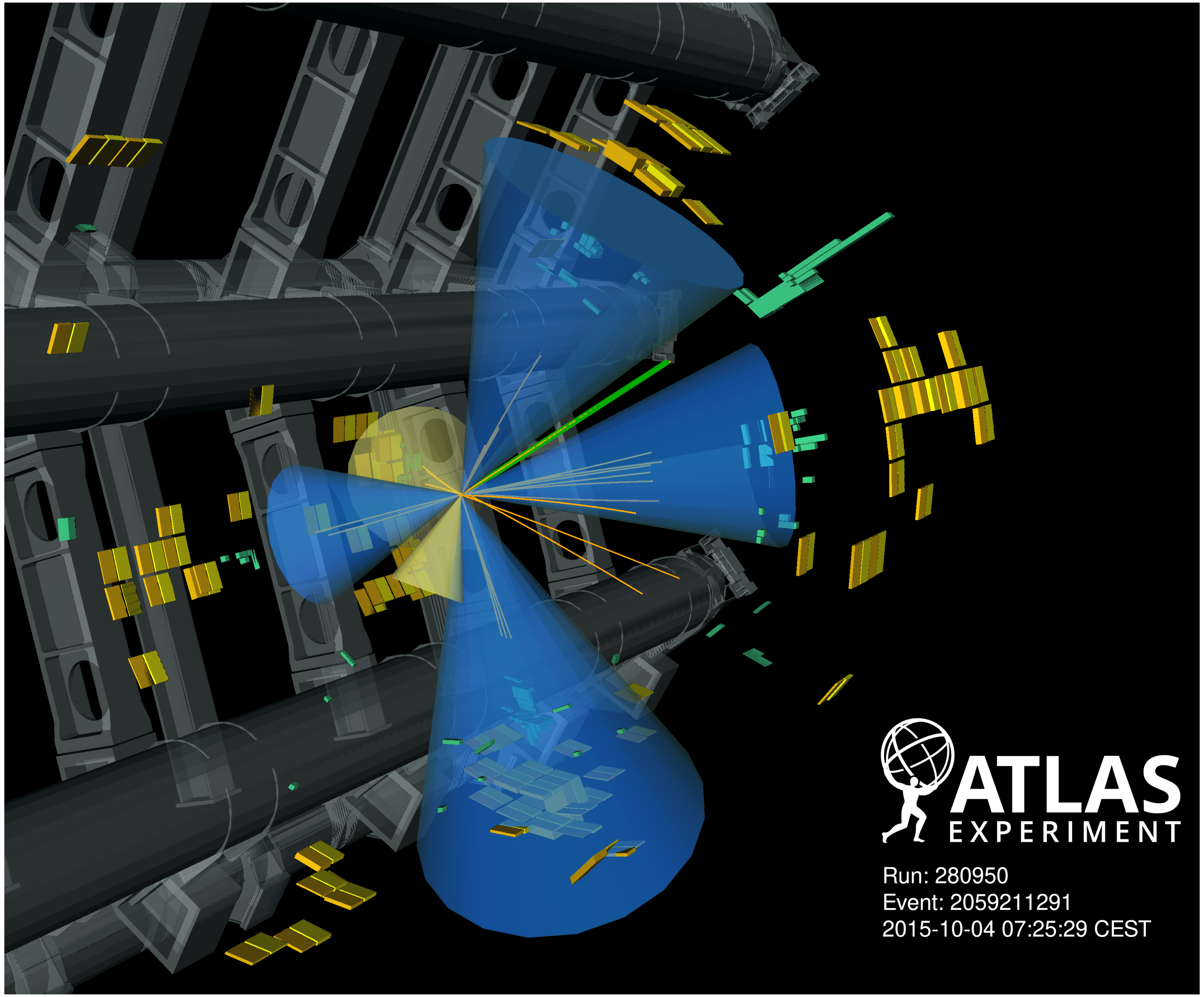
Current state-of-the-art $(pp \to H + X)$

E_{CM}	σ	δ(theory)	δ(PDF)	$\delta(\alpha_s)$
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}}$ $\left(^{+4.27\%}_{-6.49\%}\right)$	± 0.89 pb ($\pm 1.85\%$)	$^{+1.24\text{pb}}_{-1.26\text{pb}}$ $\left(^{+2.59\%}_{-2.62\%}\right)$

Stil linear sum of:
Missing beyond N3LO and EW; finite quark masses beyond NLO; mismatch in perturbative order of PDFs.

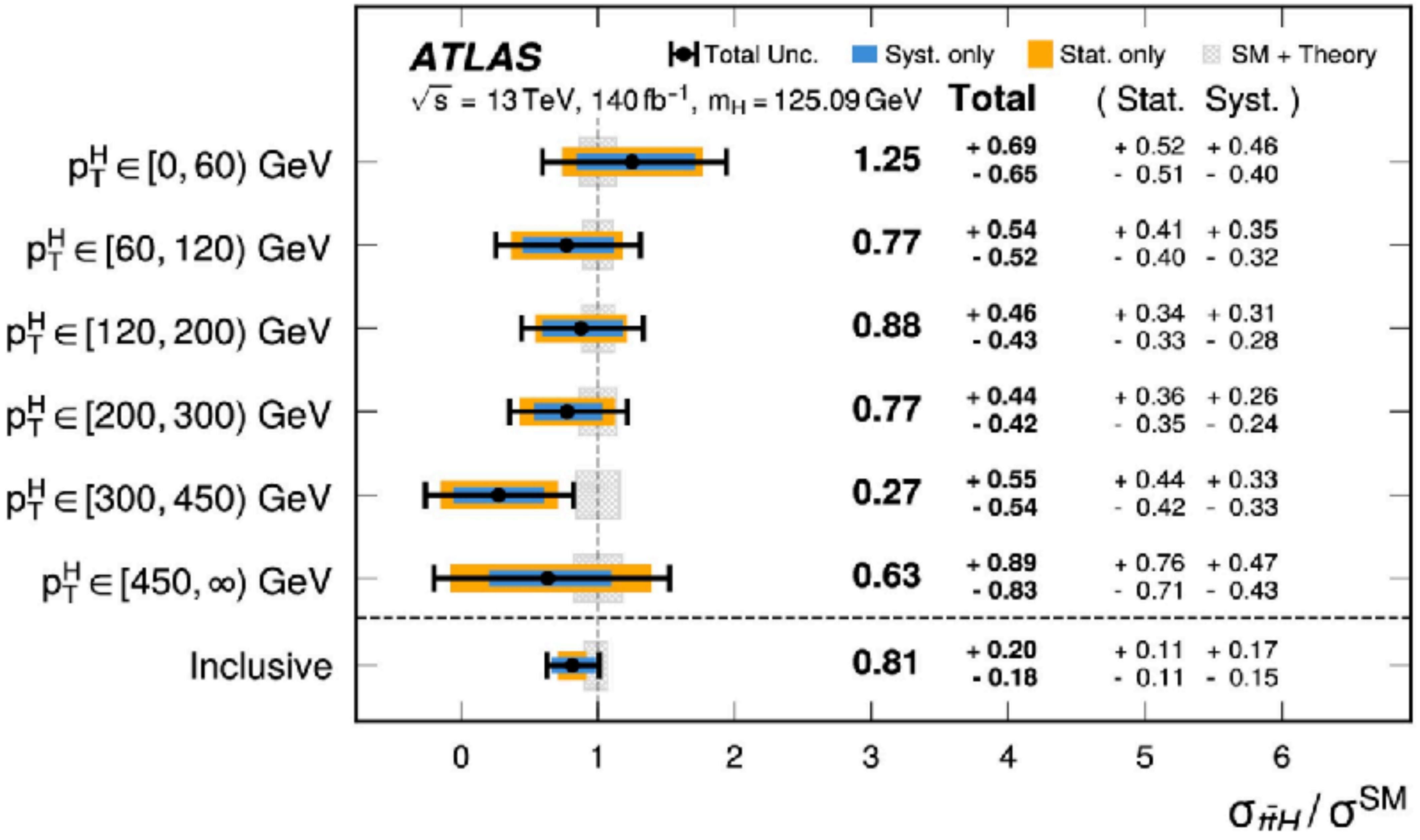
Room for improvement also in PDFs and α_s using LHC data and/or future ep collider.

Top Yukawa Coupling at the LHC



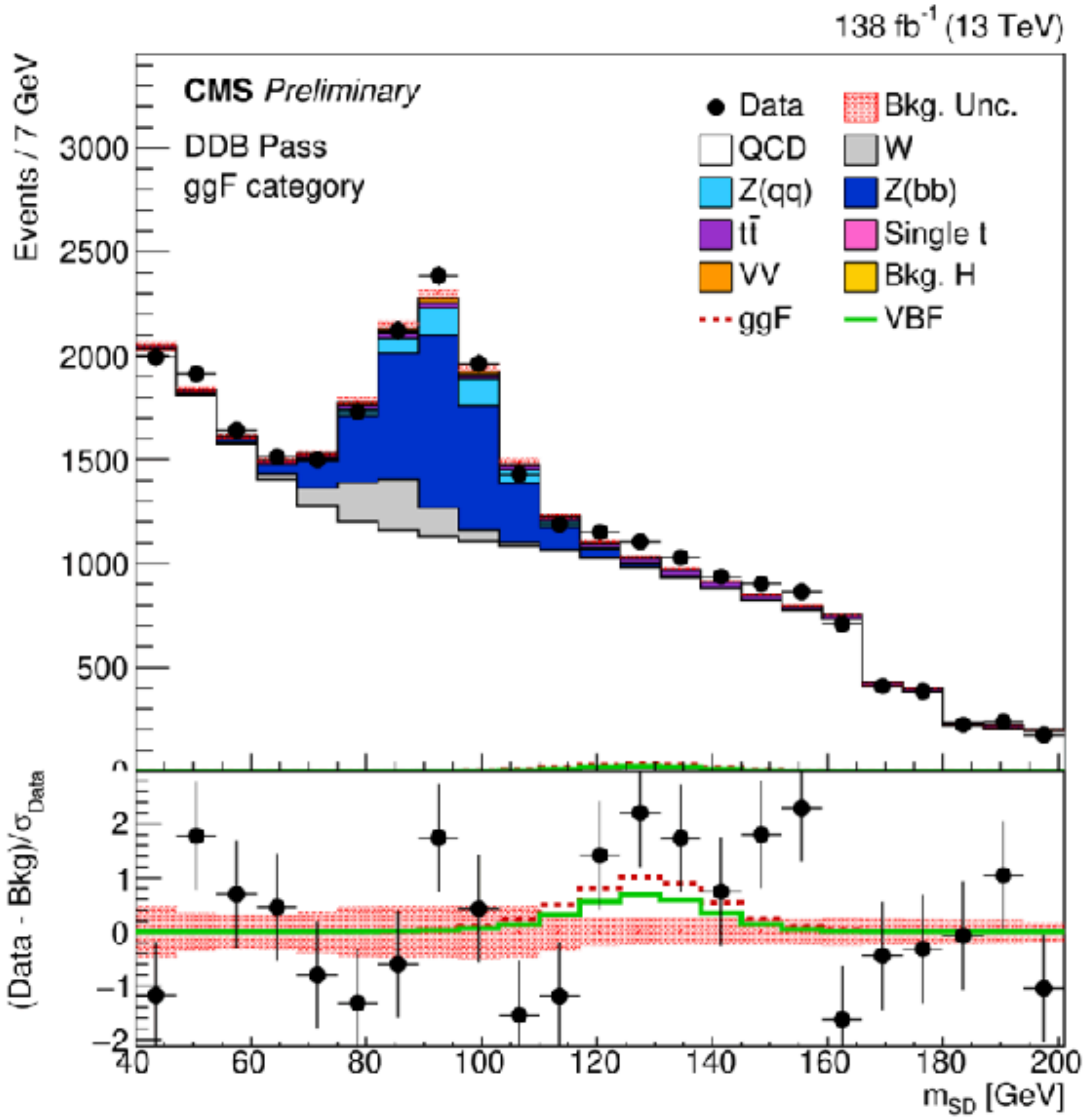
ttH news from ATLAS!

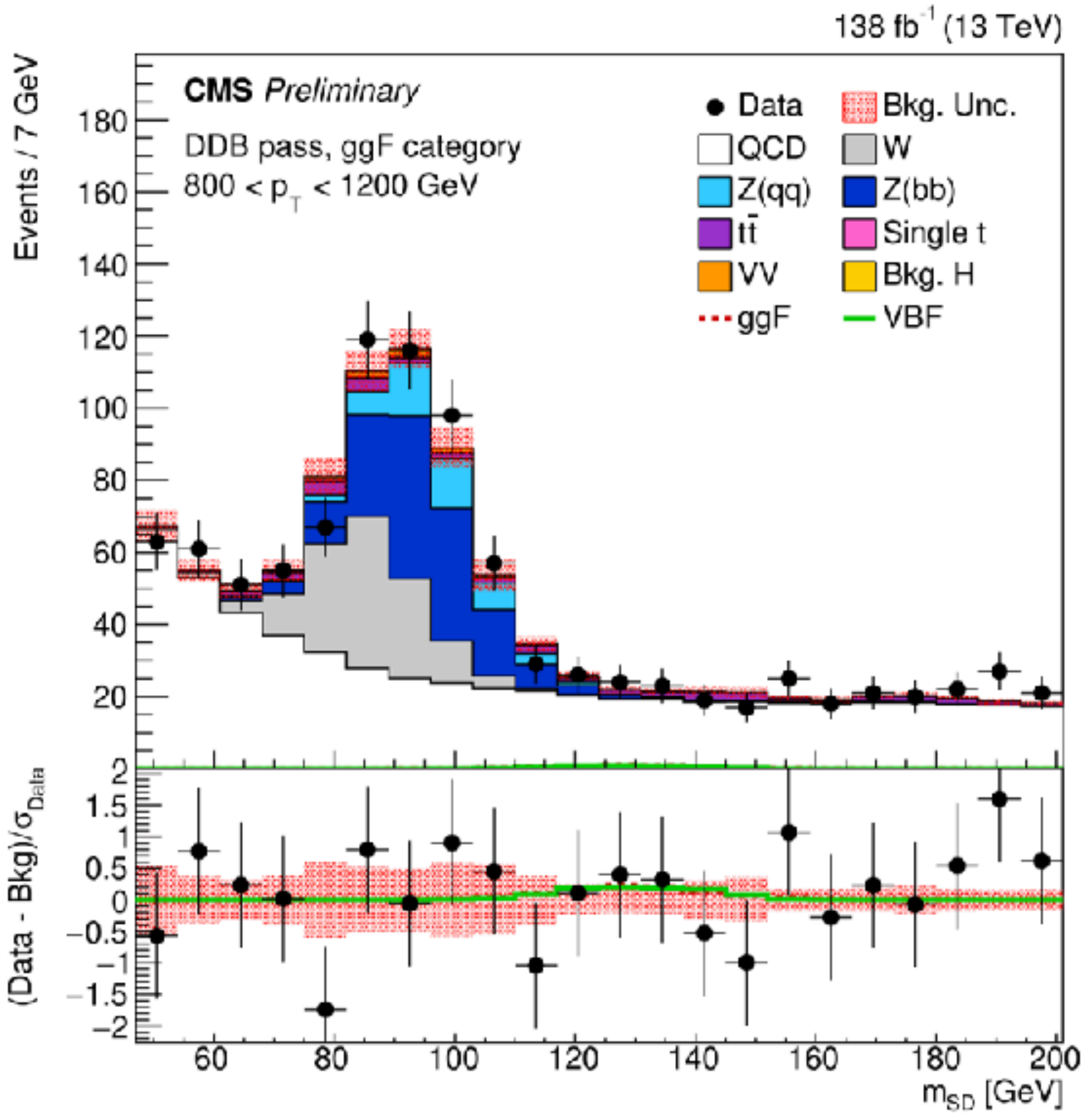
Very complex final state Main challenge: tt+bb background

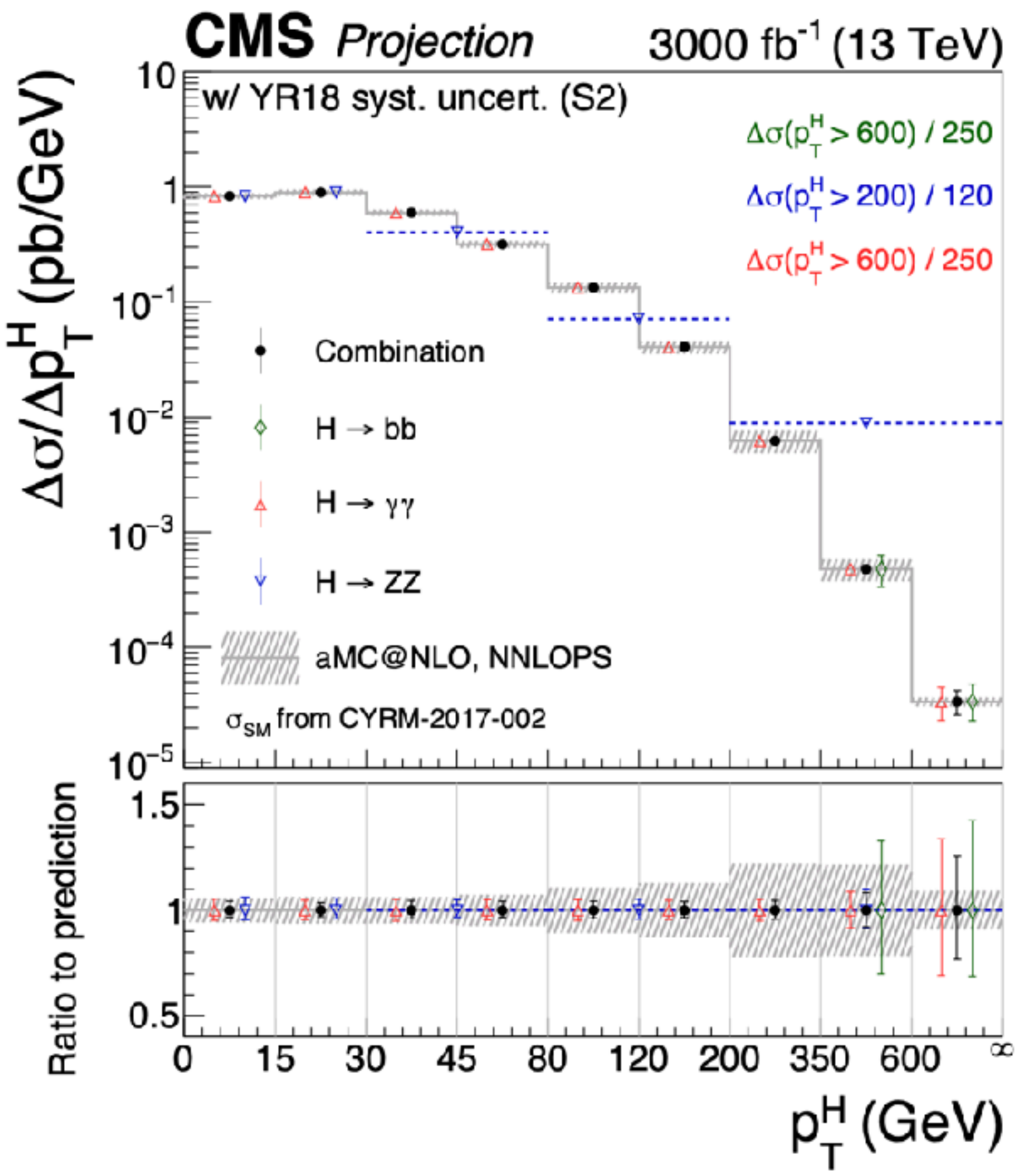


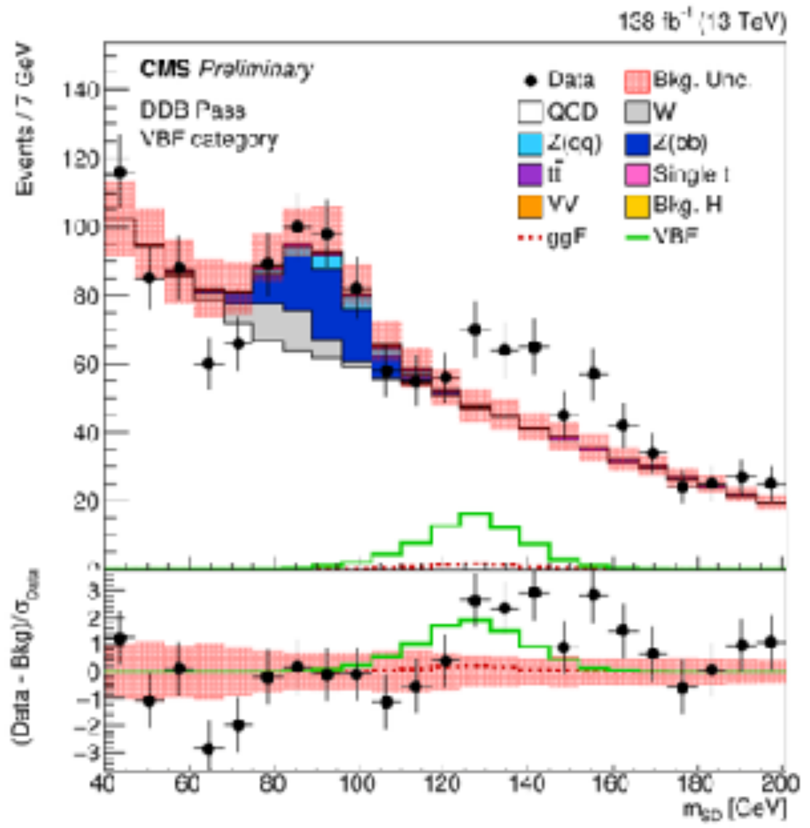
Best single ttH measurement!
Overall uncertainty improved by factor 1.8, 4.6σ

Boosting the Higgs Boson!









$$pp \to H(\to b\bar{b}) + \text{jets}$$

Was thought to be completely impossible!

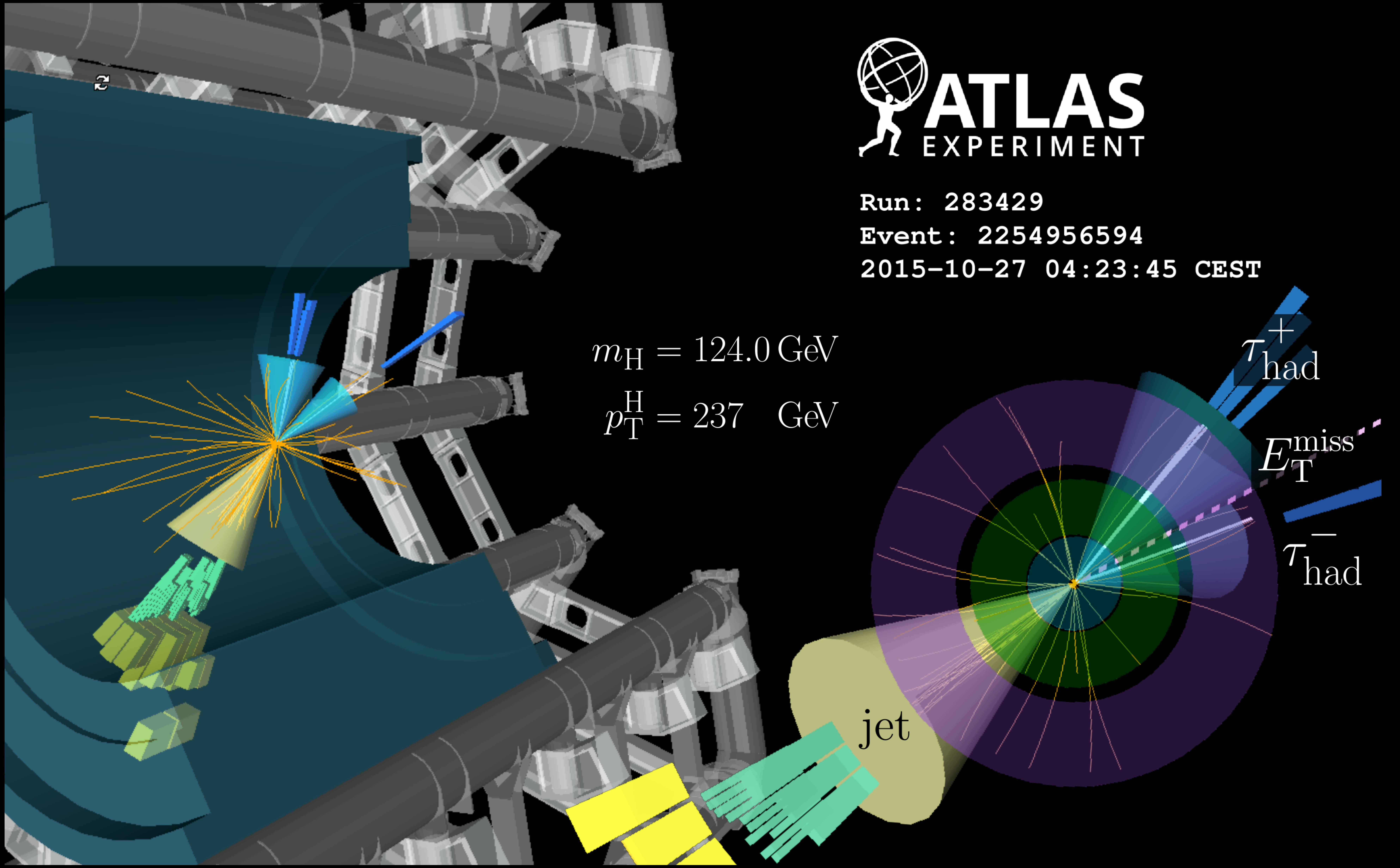
VBF significance is 3.0 σ (0.9 σ)

ggF significance of 1.2 σ (0.9 σ)

It can play an important role in the measurements of the inclusive production at high transverse momentum!

Extremely interesting for indirect NP constraints!

Higgs Yukawa to taus CP Properties



CP properties of the tau Yukawa through polarisation correlations in $H \to \tau^+\tau^-$ decay

Boosted $H \to \tau^+\tau^-$ candidate event

Higgs Yukawa to taus CP Properties

The CKM sector CP violation is insufficient for baryogenesis, pseudoscalar coupling of the Higgs boson to fermions could be an important source of CP violation!

$$\frac{\lambda_f}{\sqrt{2}}\left(\kappa_f h\overline{\psi}_f\psi_f + i\tilde{\kappa}_f h\overline{\psi}_f\gamma_5\psi_f\right)$$

Non zero $\tilde{\kappa}_f$ implies CP violation in the Yukawa interaction

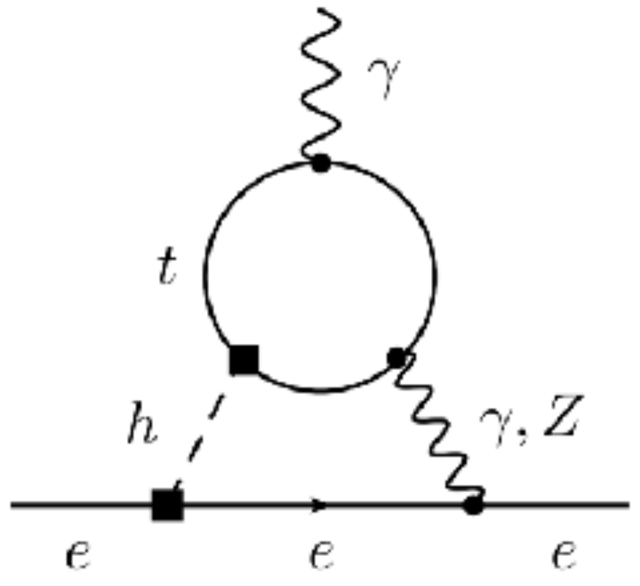
However indirect probes through electron (and neutron) EDM
Very suppressed in the SM (where it arises at four loops)

$$d_e/e < 10^{-38}\ \mathrm{cm}$$

Larger if neutrinos are Majorana

A good probe for NP BSM!

Careful, constraints from eEDM are already strong! From J. Brod., U. Haisch and J. Zupan 2013



$$\frac{d_e}{e} \propto G_F m_e\left[C_1\kappa_e\tilde{\kappa}_t + C_2\tilde{\kappa}_e\kappa_t\right]$$

$$f\left(\frac{m_t^2}{m_h^2}\right)$$

JILA limit: $\left|\frac{d_e}{e}\right| < 4.1\times10^{-30}\mathrm{cm}$

Assuming electron Yukawa SM $\tilde{\kappa}_t < 0.001$

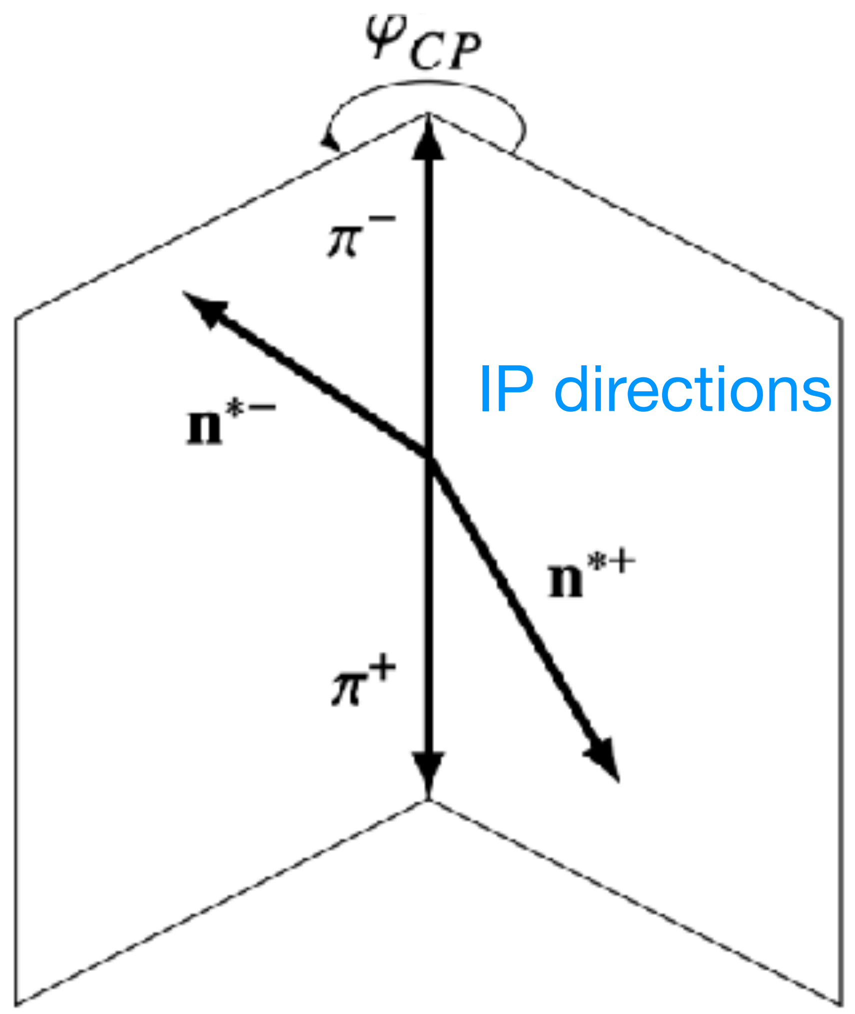
The electron EDM constraint is weaker for taus $\tilde{\kappa}_\tau < 0.3$

First attempts to constrain this coupling using tau polarisation observables

Higgs Yukawa to taus CP Properties

Use tau polarisation variables in tau decays of the Higgs boson!

$$H \to \tau^+\tau^- \to \pi^+\pi^- + 2\nu$$



Zero Momentum Frame

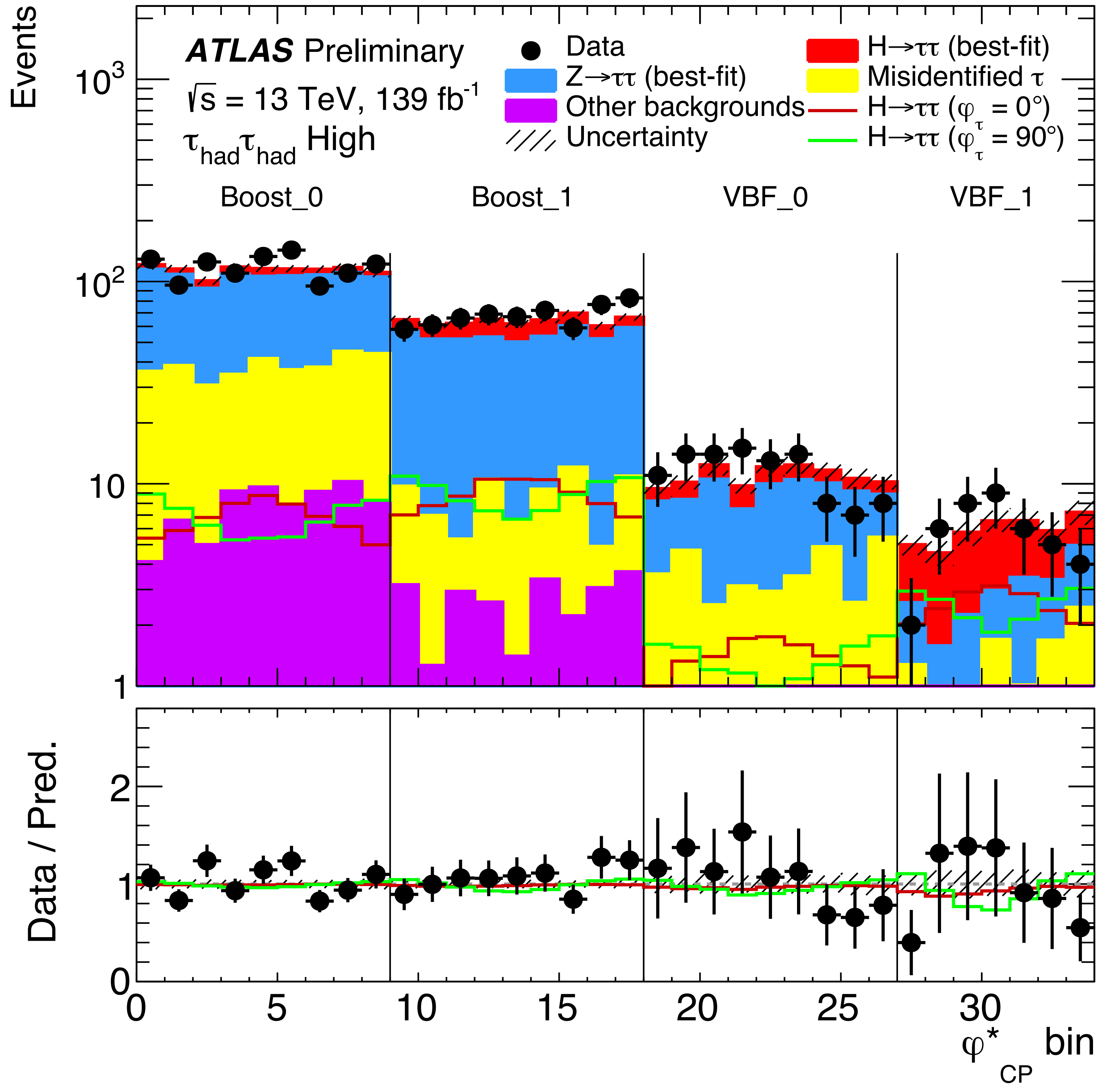
Tau transverse spin correlation sensitive variable

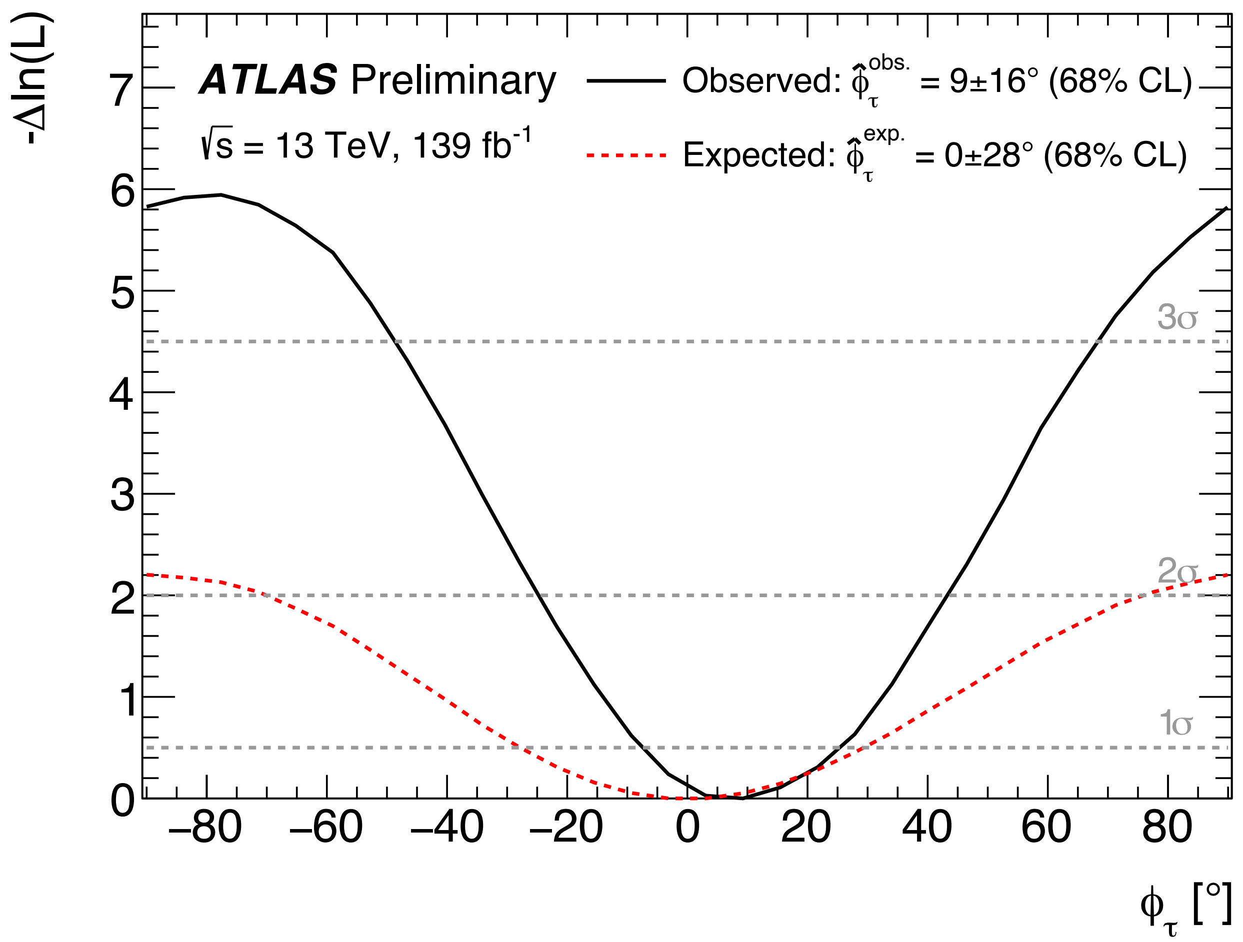
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

Fit the ϕ_τ parameter to the ϕ^*_{CP}

Using several decay modes of the taus

Boosted and VBF (using a BDT) categories

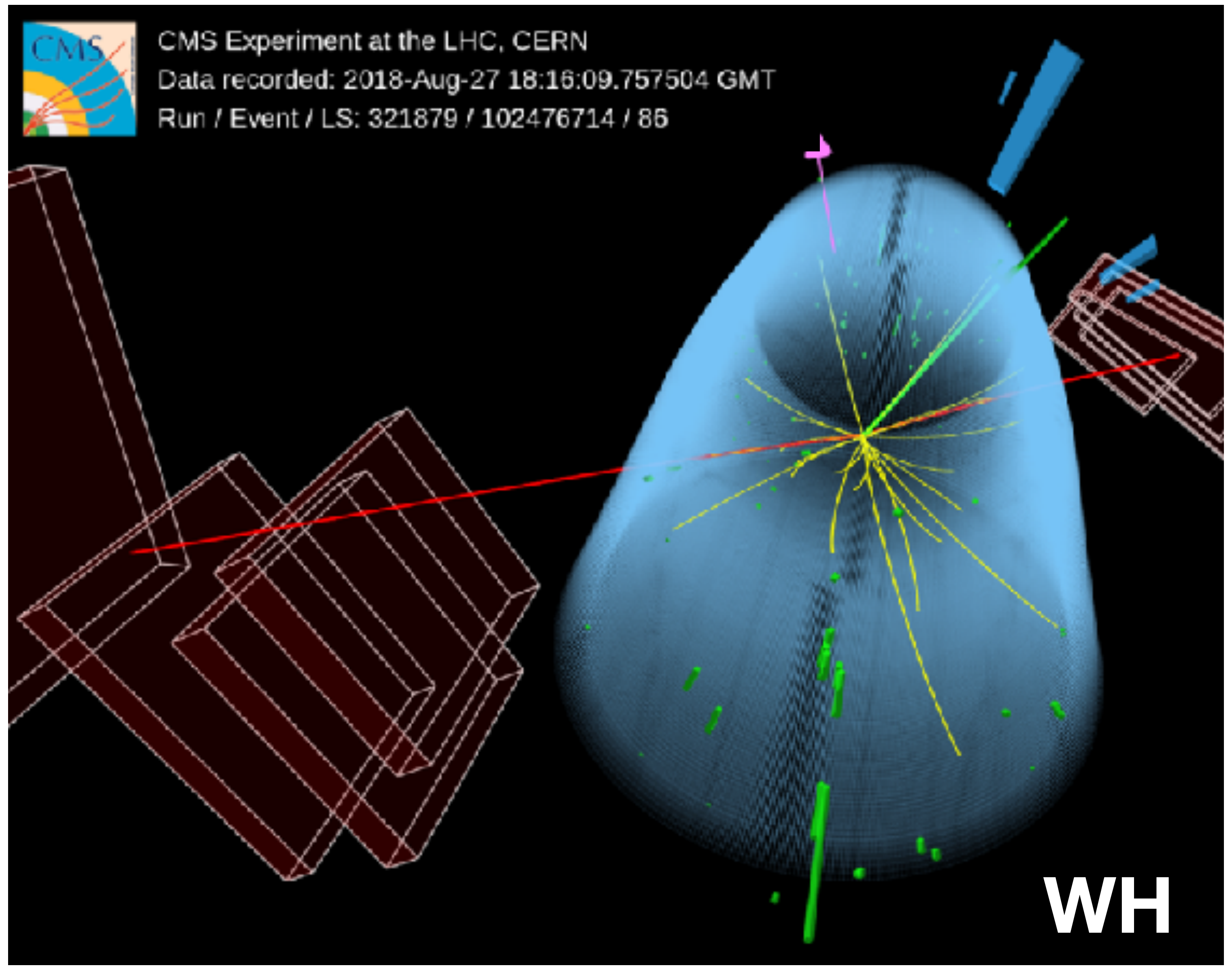


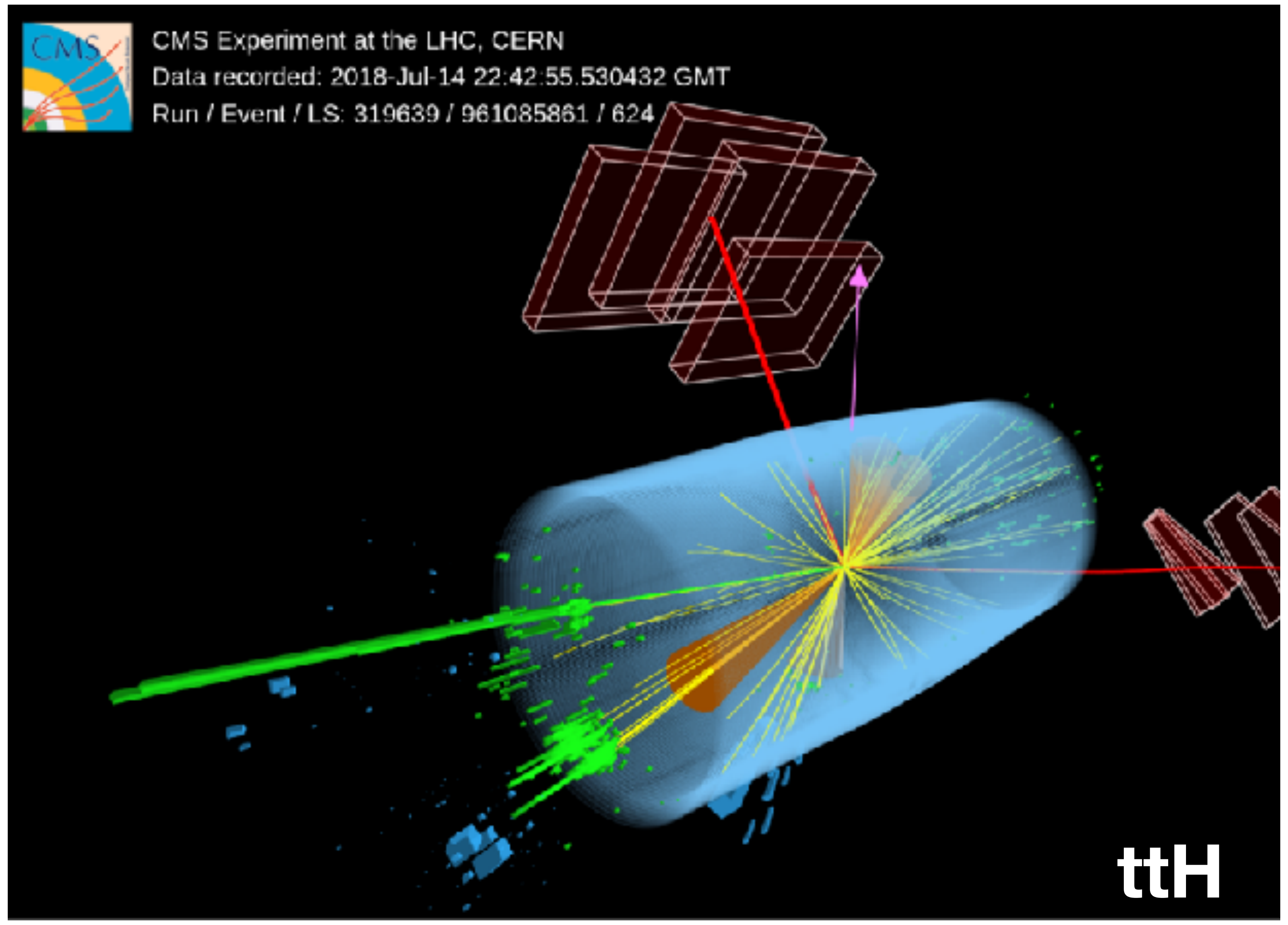


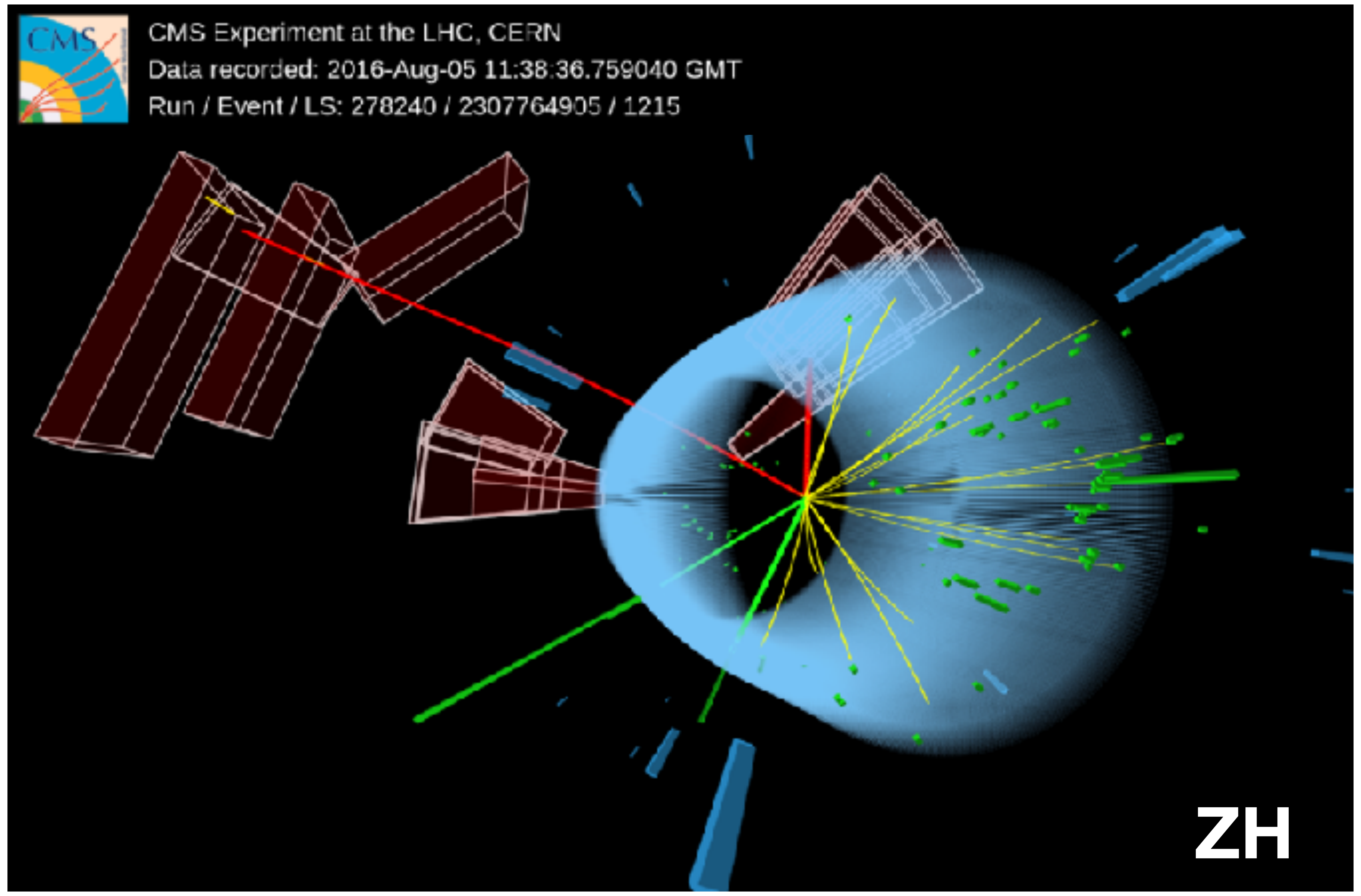
Pure CP-Odd hypothesis excluded at 3.4σ

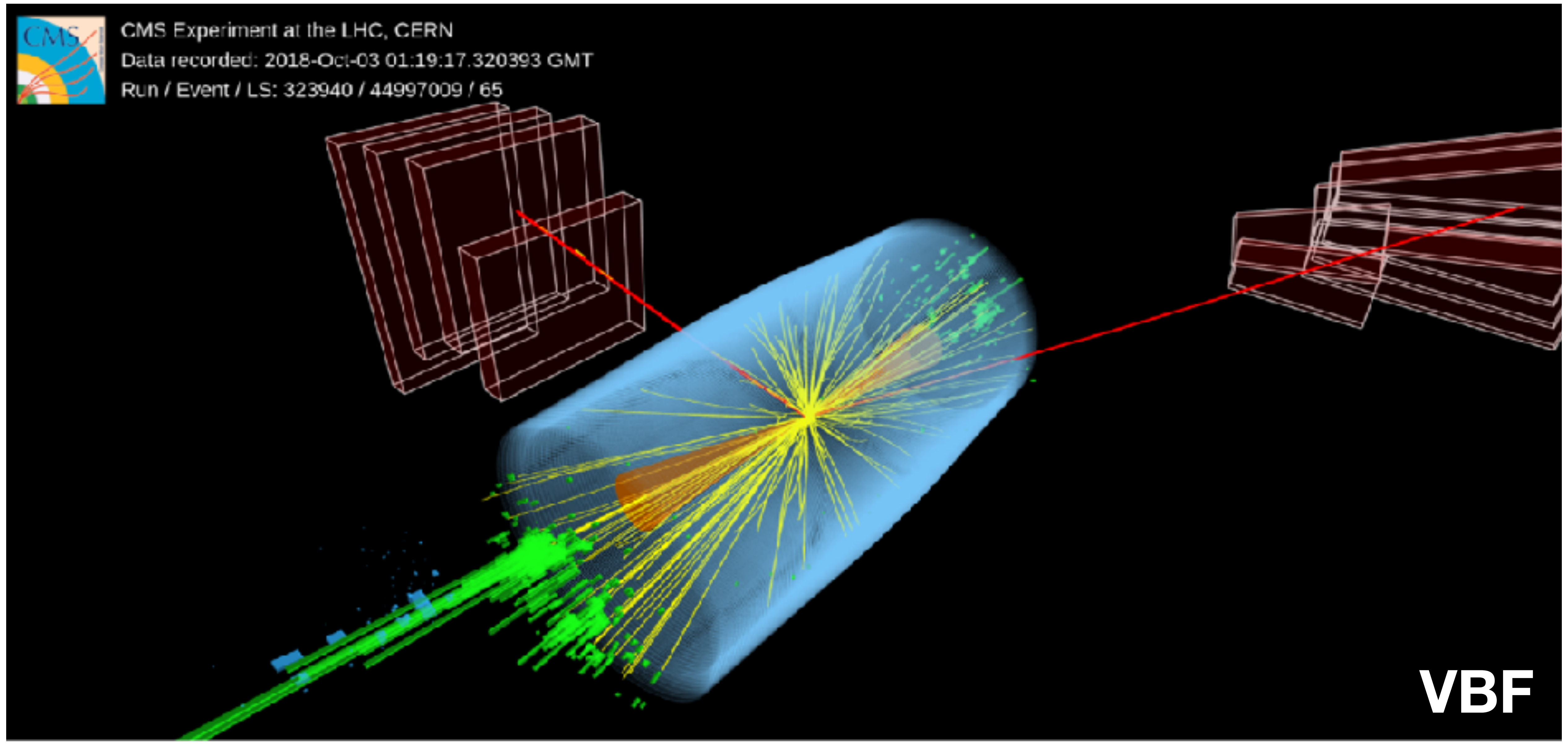
$$\phi_\tau = 9^o \pm 5^o(\text{sys}) \pm 16^o(\text{stat})$$

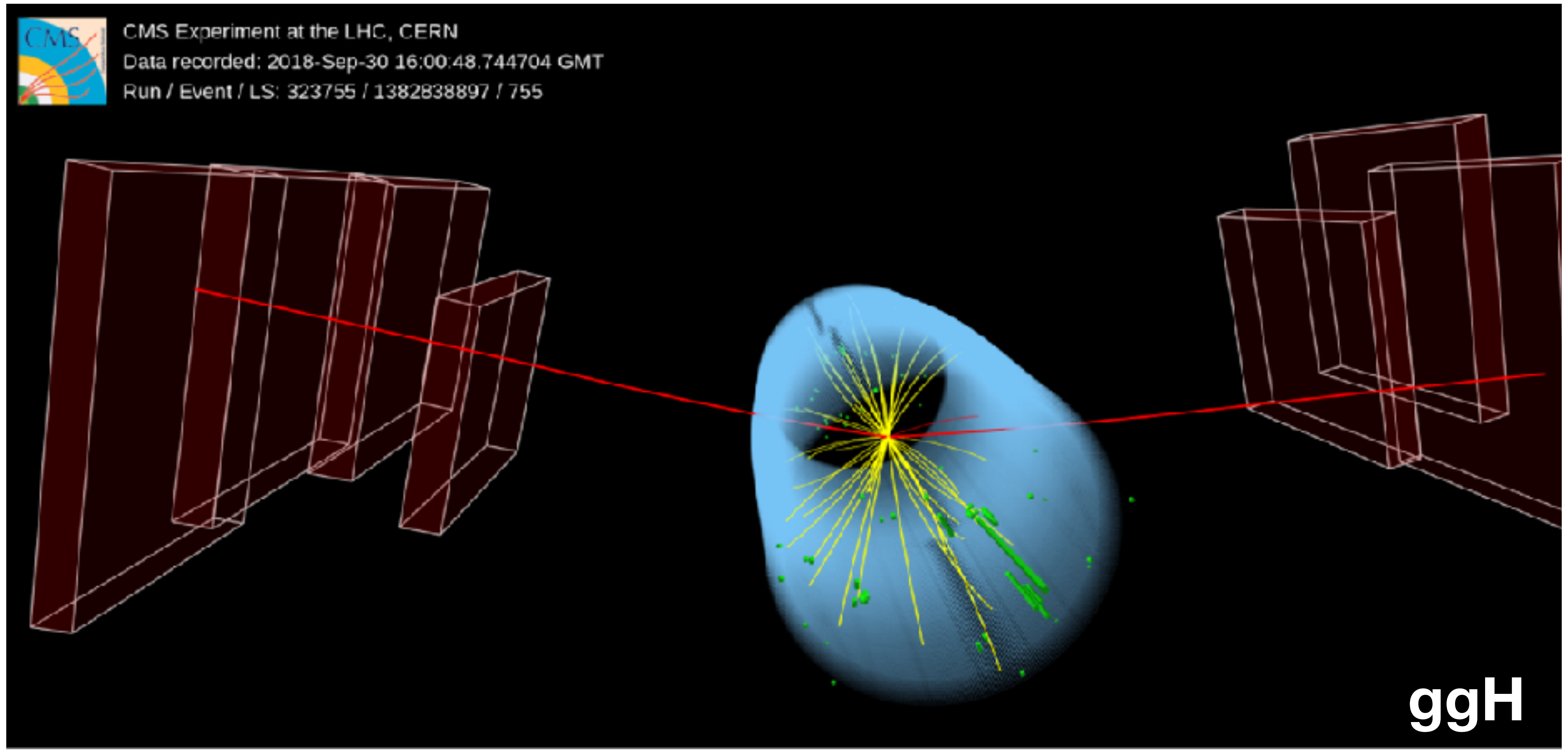
Evidence for $H \to \mu^+\mu^-$









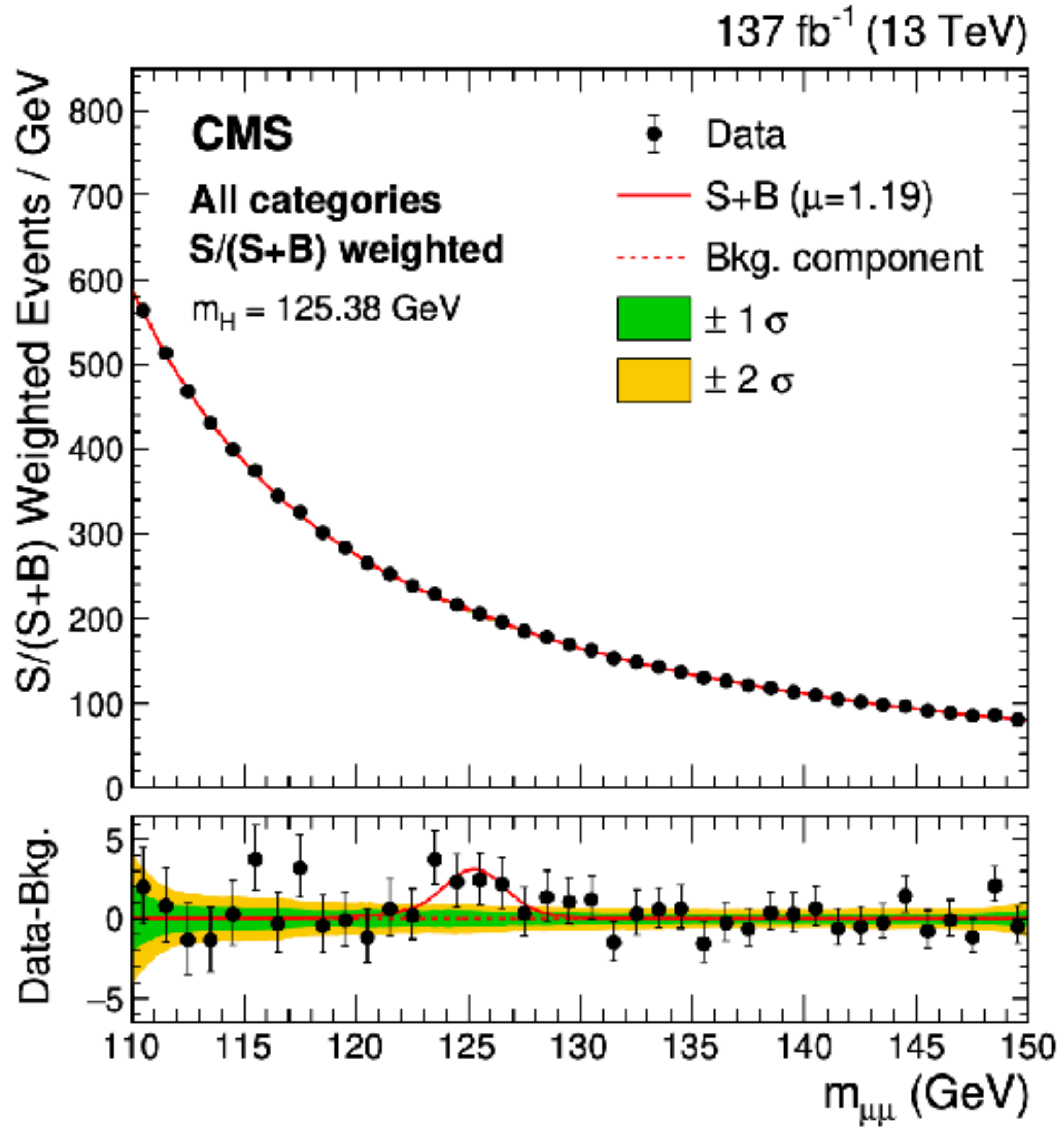


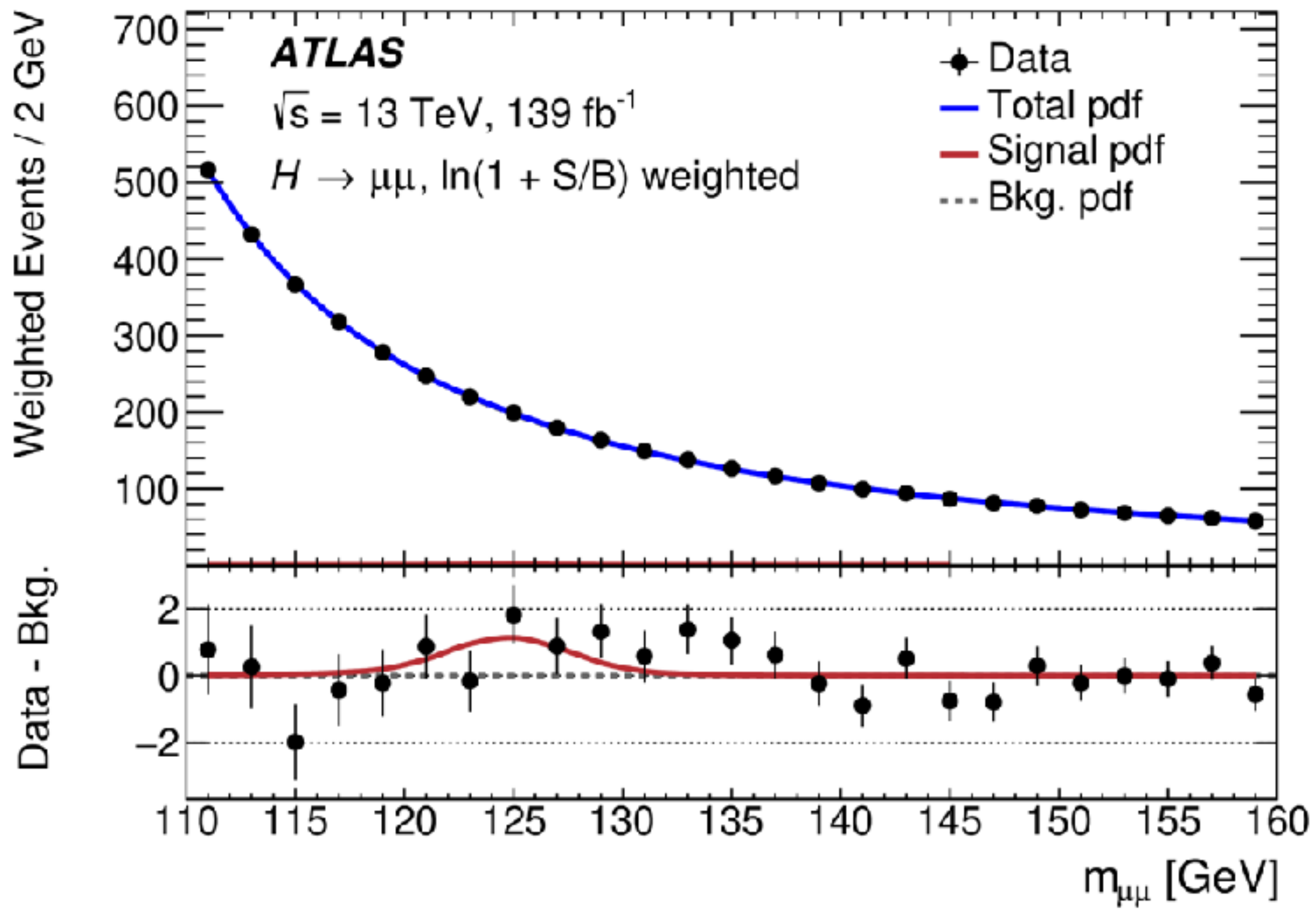
Evidence for Second Generation Yukawa Coupling

Very challenging channel!

- Approximately 2k events produced but very small signal-to-noise
- Requires a very accurate description of the backgrounds.
- Gain in sensitivity: ggF, VBF, VH, ttH; mass resolution through Brem recovery!

Summary of all categories Estimate the background parameters through a fit of an analytical form!





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- Requires a very accurate description of the backgrounds.
- Gain in sensitivity: ggF, VBF, VH, ttH; mass resolution through Brem recovery!

Summary of all categories Estimate the background parameters through a fit of an analytical form!

CMS Result

Expected 2.5σ

Observed 3.0σ

$$\mu = 1.19 \pm 0.43$$

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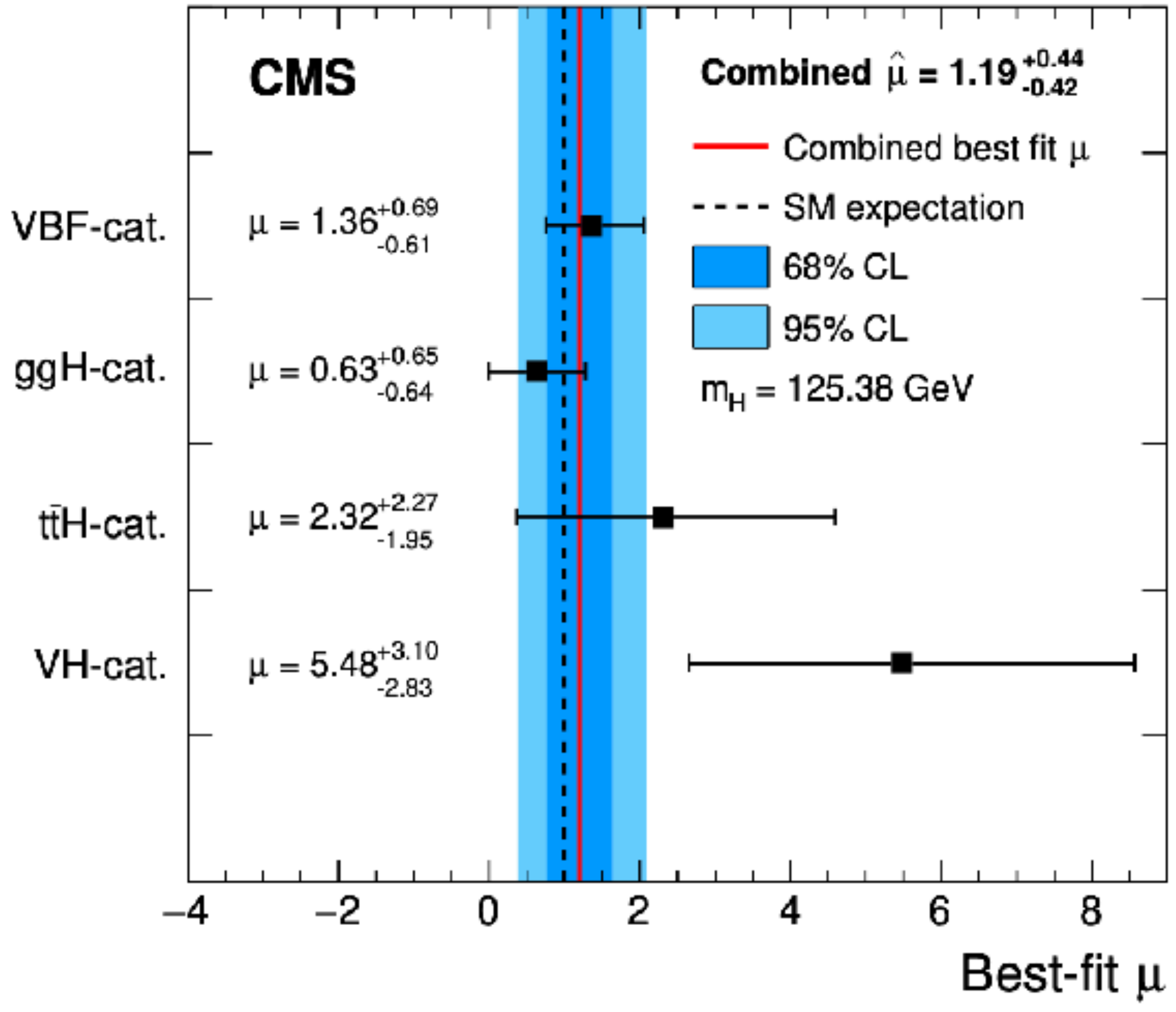
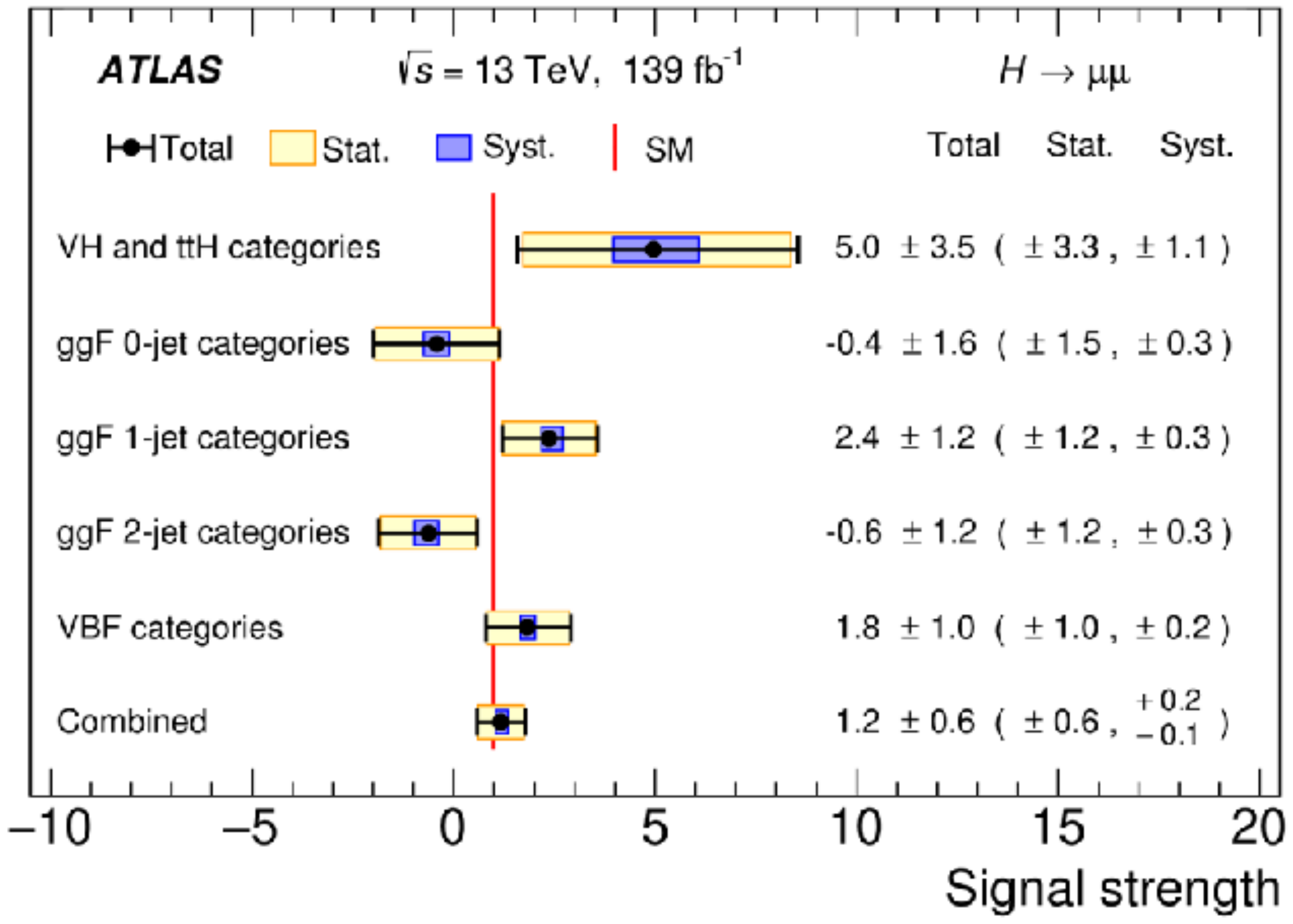


PLB 812



ATLAS Result

Expected 1.7σ

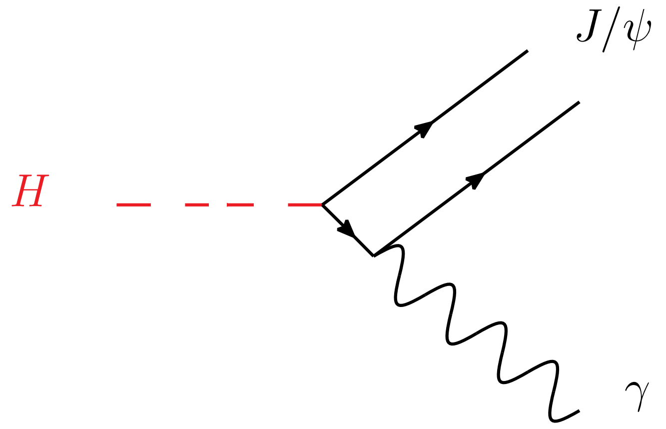
Observed 2.0σ

$$\mu = 1.2 \pm 0.6$$

Result dominated by statistical uncertainty, but watch systematics!

More Rare Decays and Production

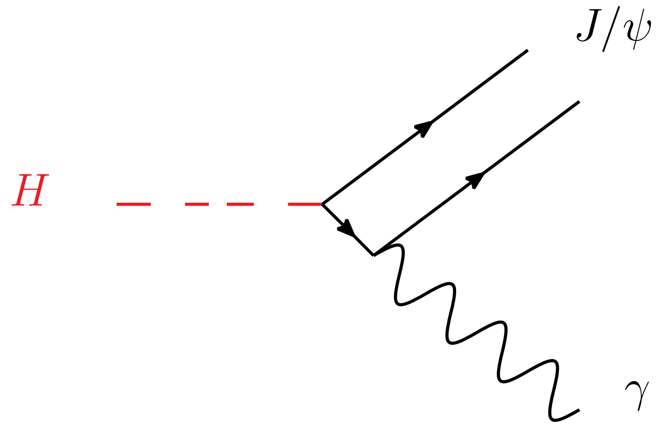
Quarkonia-photon



Potentially sensitive to charm Yukawa

$\mu^+\mu^-\gamma$

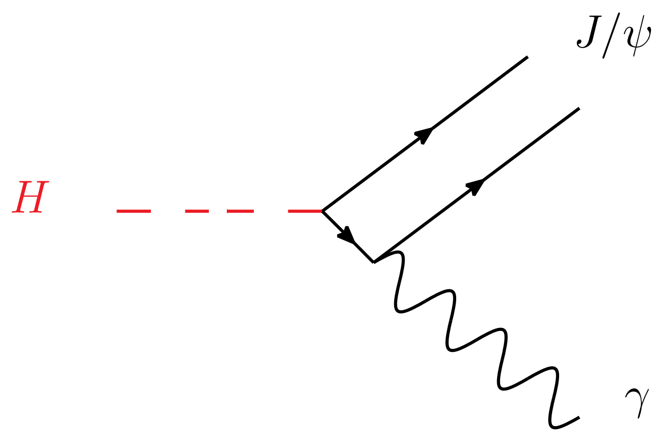
~100 x SM



Potentially sensitive to strange Yukawa

$K^+K^-\gamma$

~200 x SM

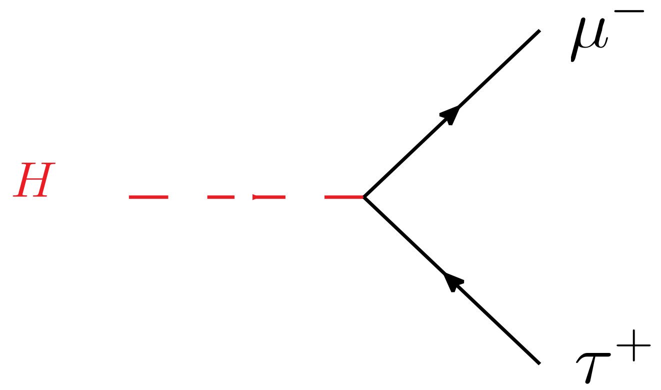


Potentially sensitive to light Yukawa

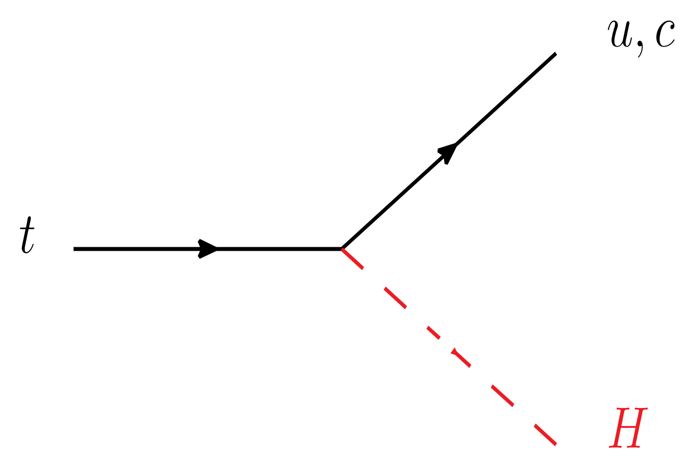
$\pi^+\pi^-\gamma$

~50 x SM

Lepton flavor violating decays

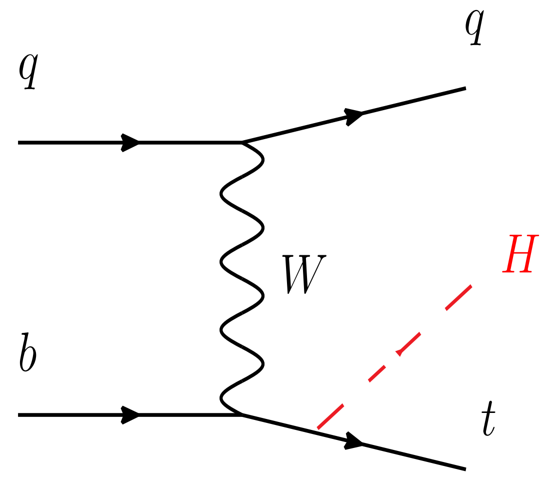


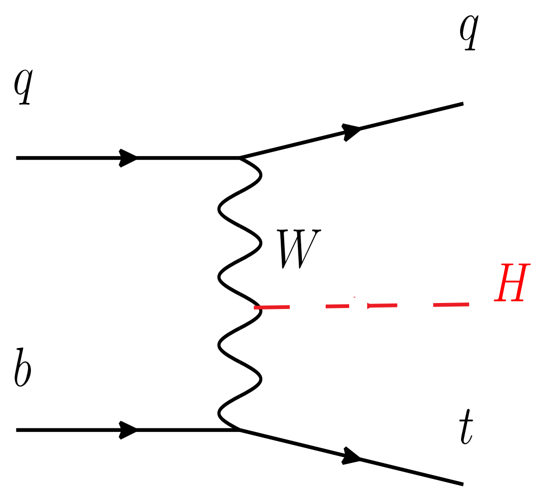
FCNC decays of the top quark



Various decay channels of the Higgs boson (diphoton, bb)

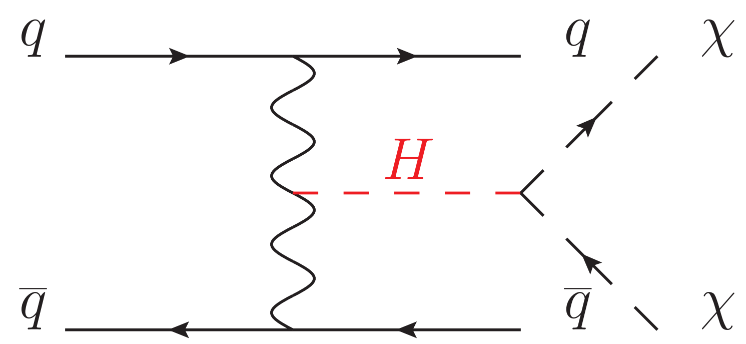
Single top associated production

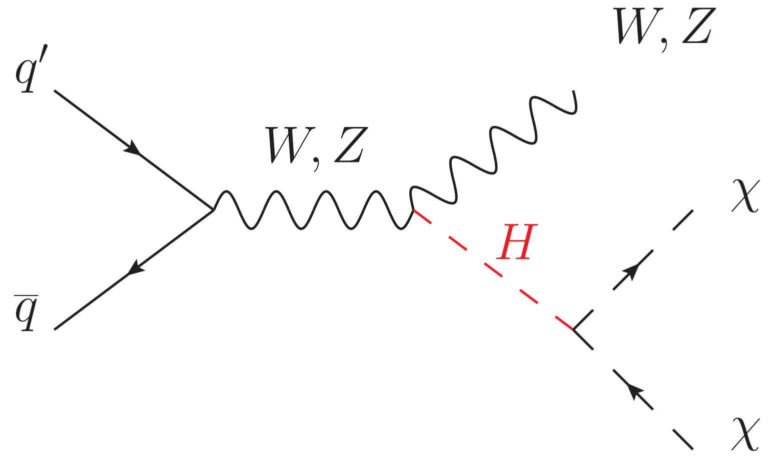


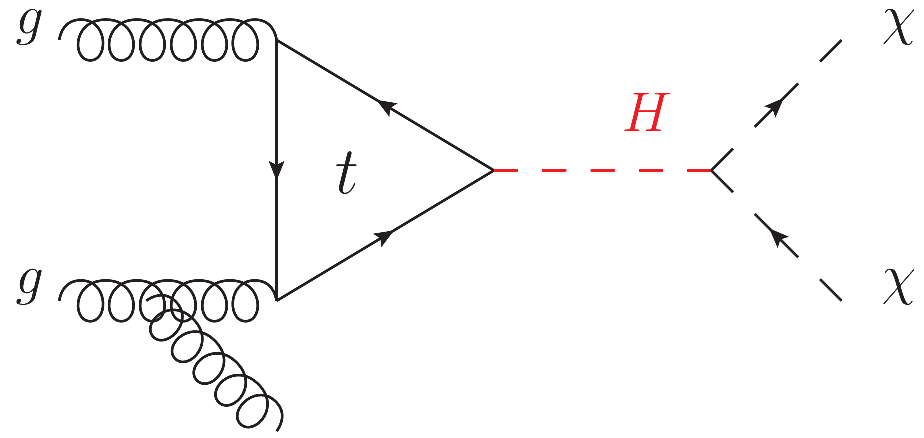


Tree level interference between W and top

Invisible decays







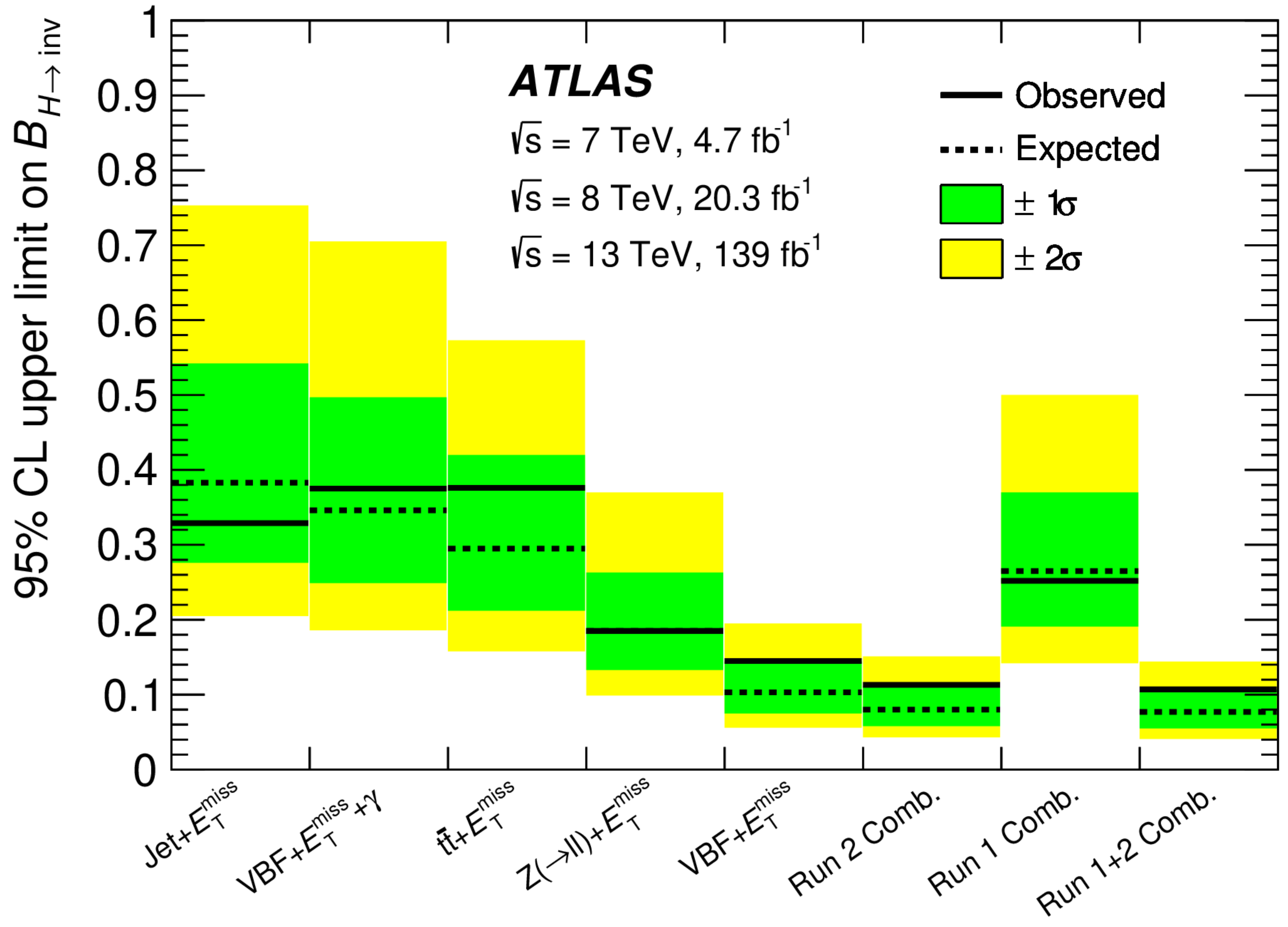
<11% @ 95% CL

HL-LHC 2.5%

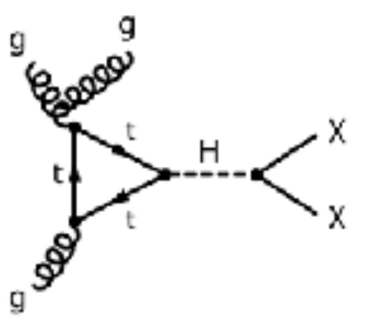
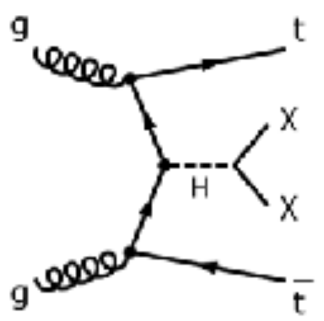
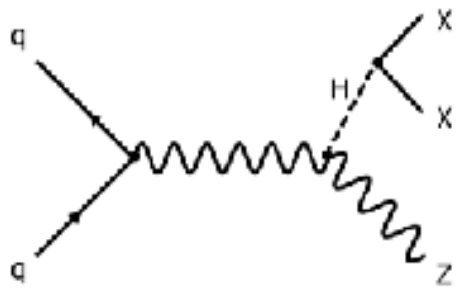
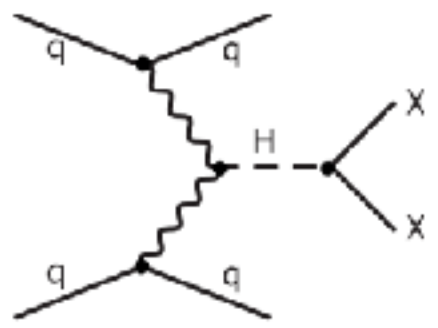
The Higgs portal and Invisible Higgs Decays

Searches for invisible decays of the Higgs boson in several channels!

To be precise: upper limit on the H→invisible branching of **0.107** (0.077) at the 95% CL



Monojet **ttH** **ZH** **VBF**

In the SM the H→invisible branching of **0.1%**

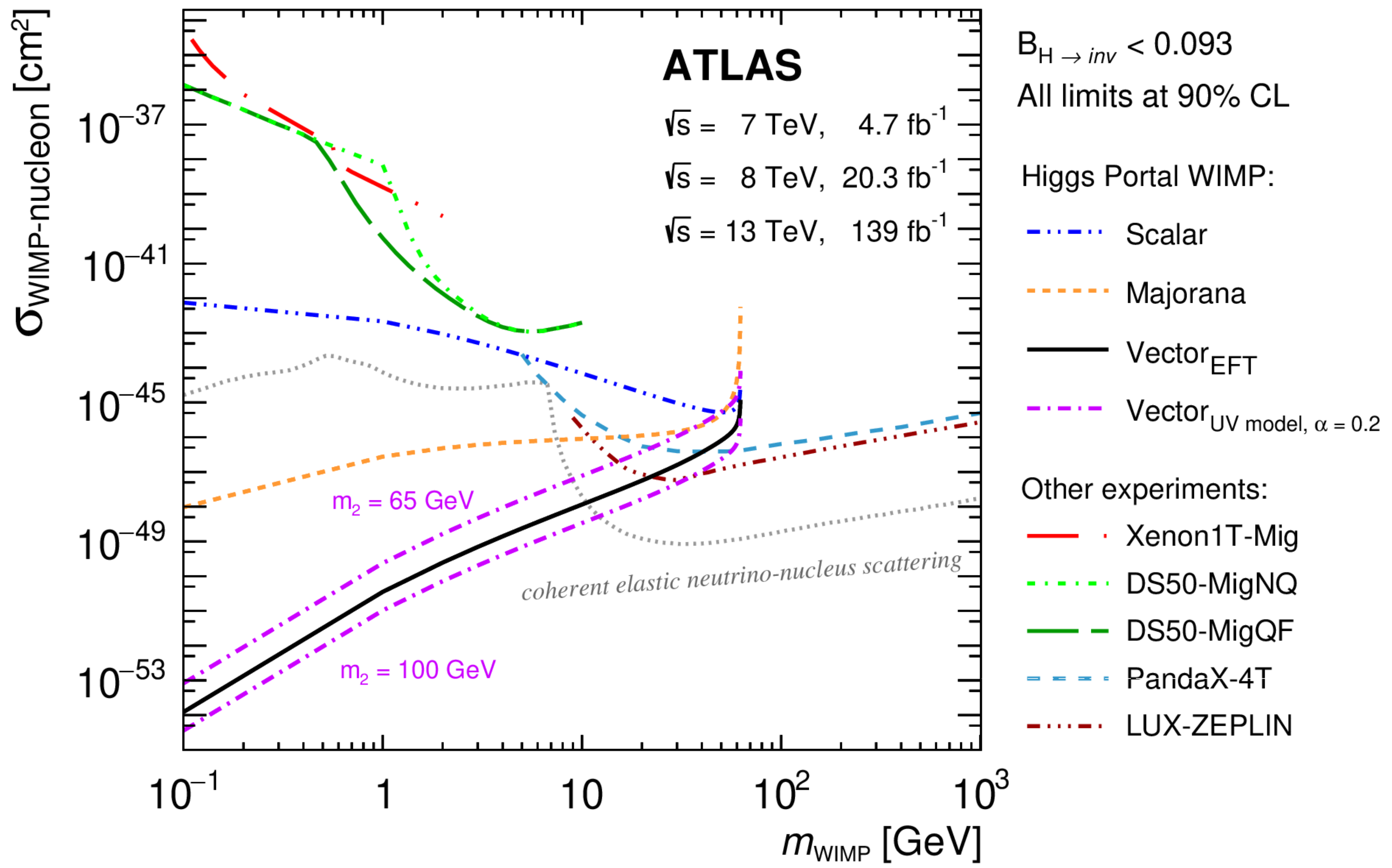
Higgs portal interpretation

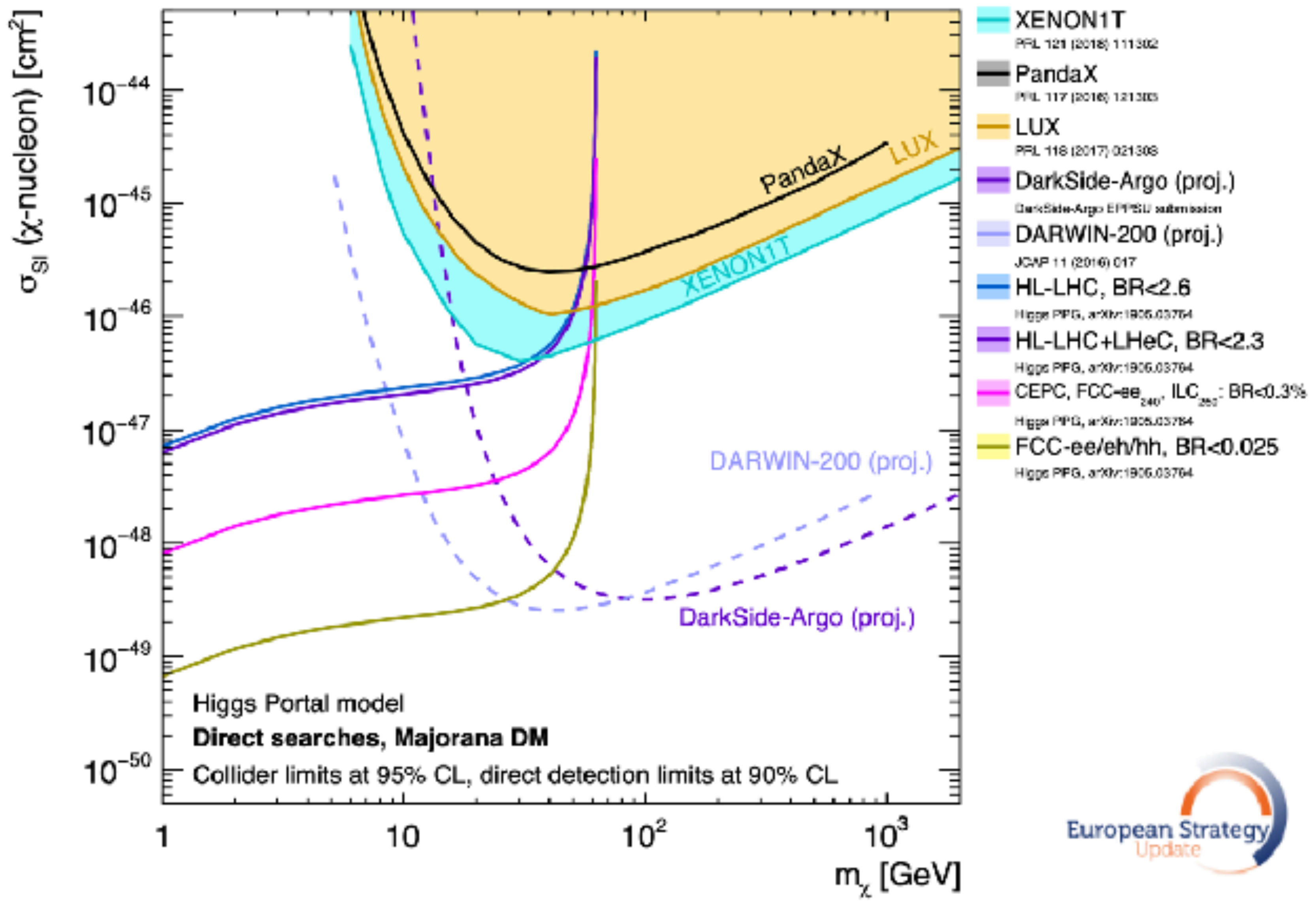
Should reach 2% level at HL-LHC!

FCC-ee will reach 0.05%

level and

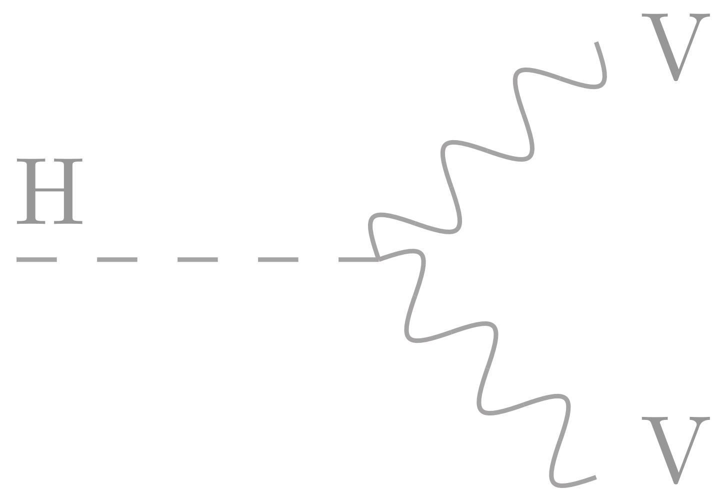
0.02% with FCC-hh





Pillars of Higgs Physics at Colliders

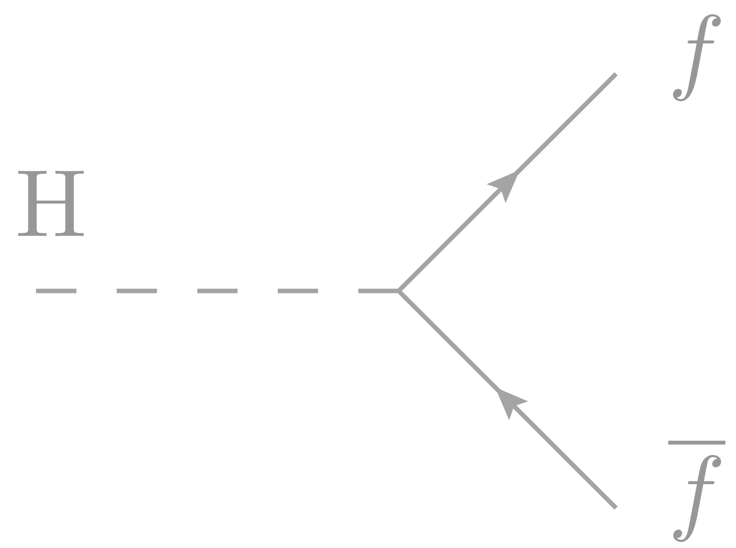
All the couplings of the Higgs boson to Standard Model particles (except itself) were known before the discovery of the Higgs boson! A very predictive model!



$$\frac{2m_V^2}{v}$$

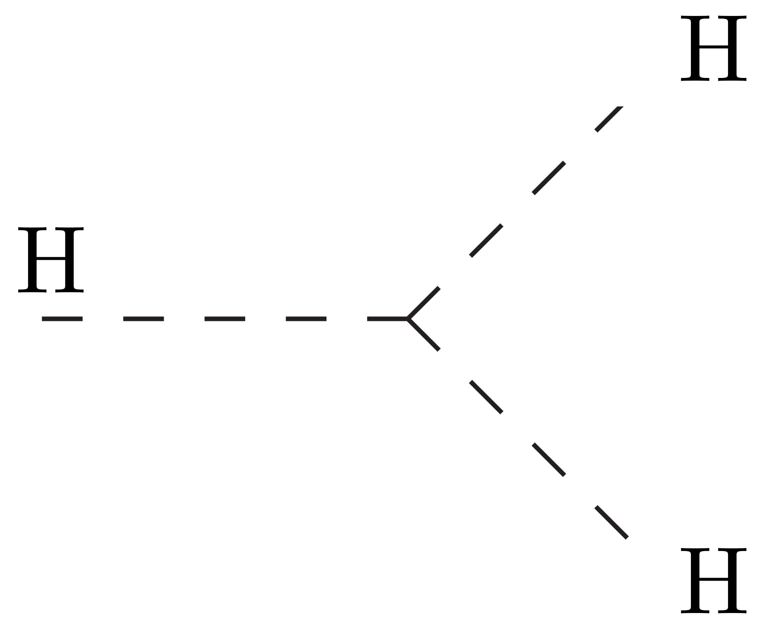
$$|D_\mu \phi|^2$$

This term could not exist without a vev

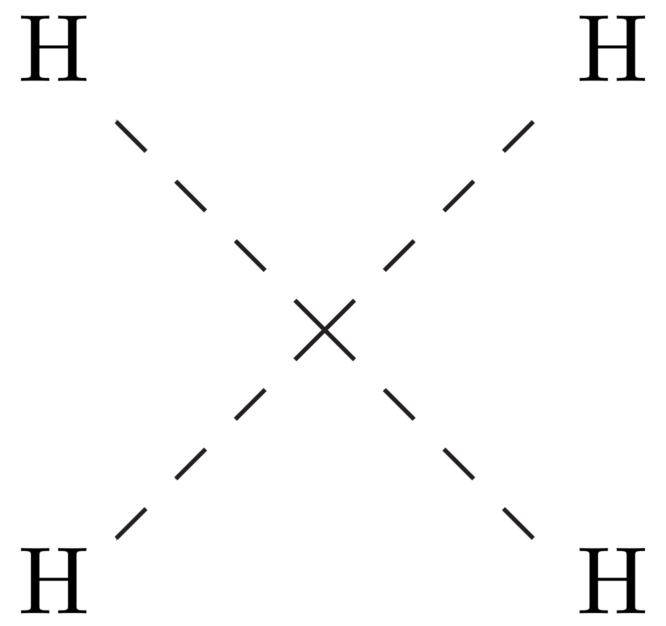


$$\frac{m_f}{v}$$

$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



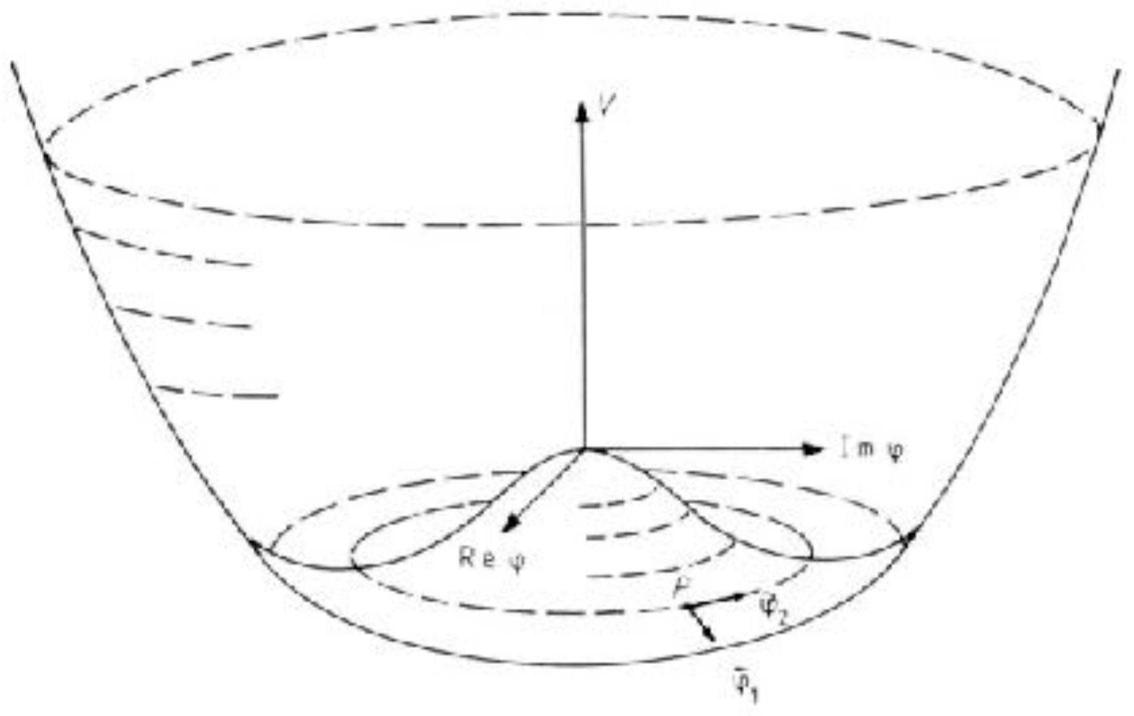
$$\frac{3m_H^2}{v}$$



$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

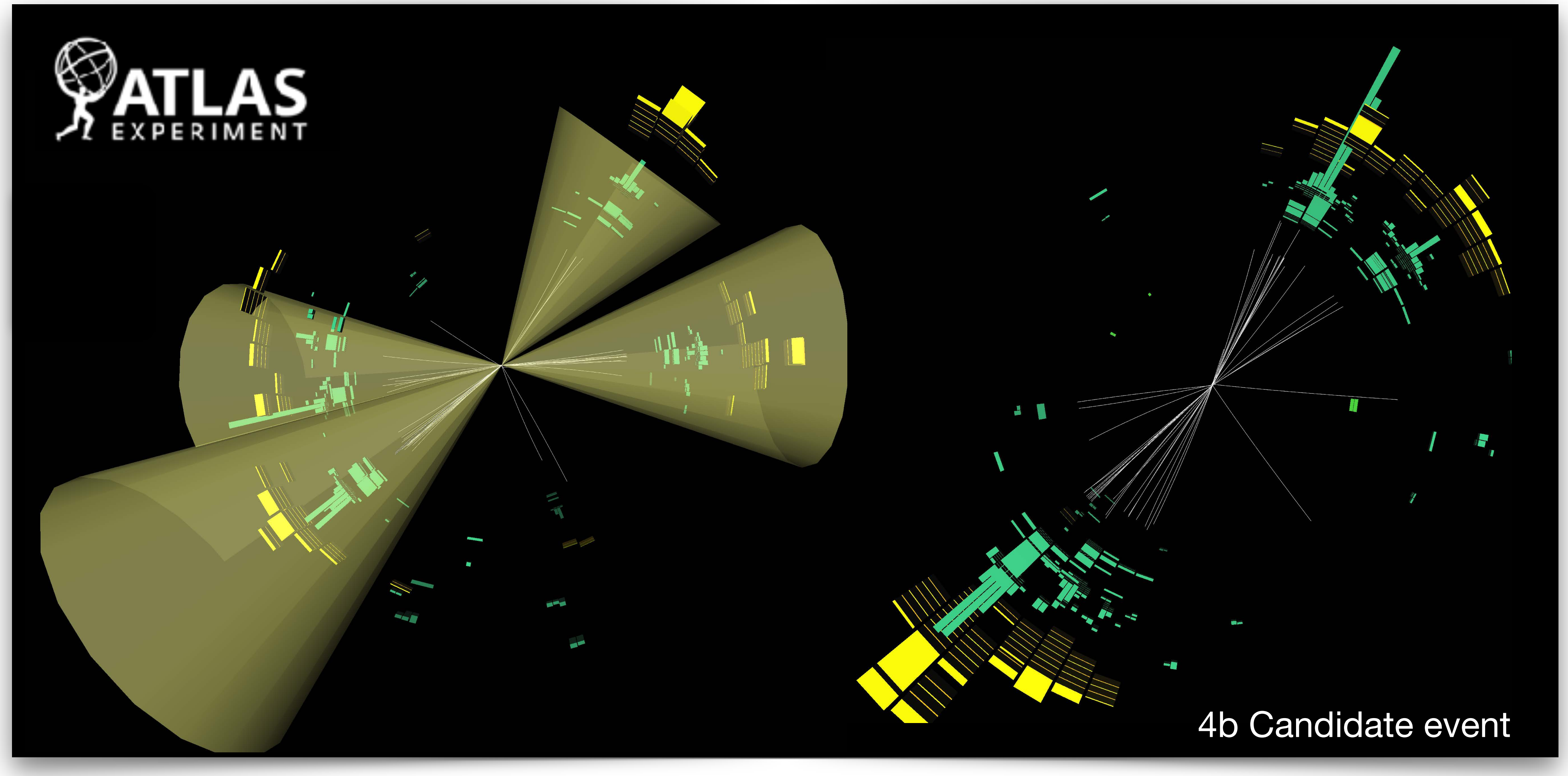
Spontaneous Symmetry Breaking

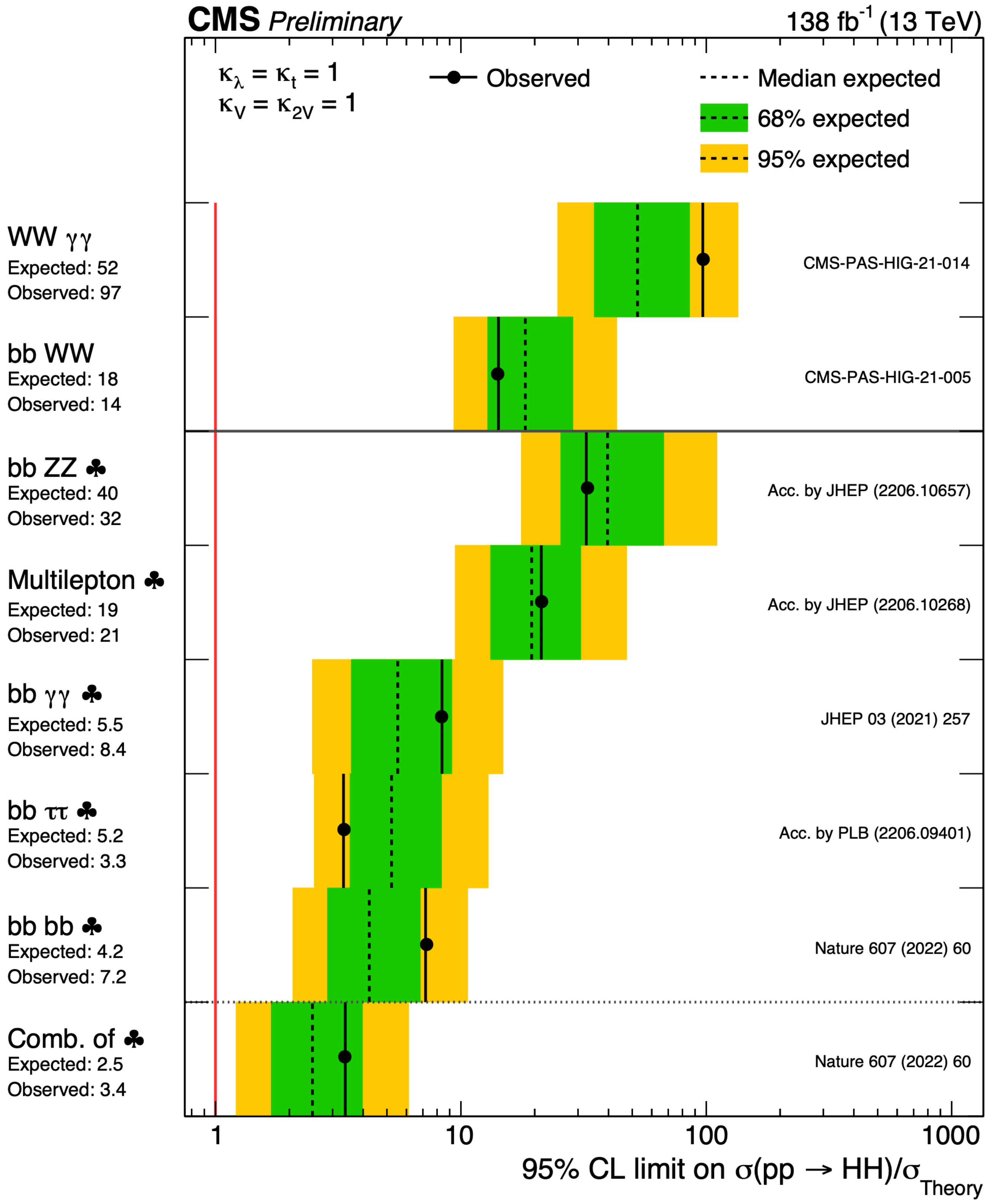


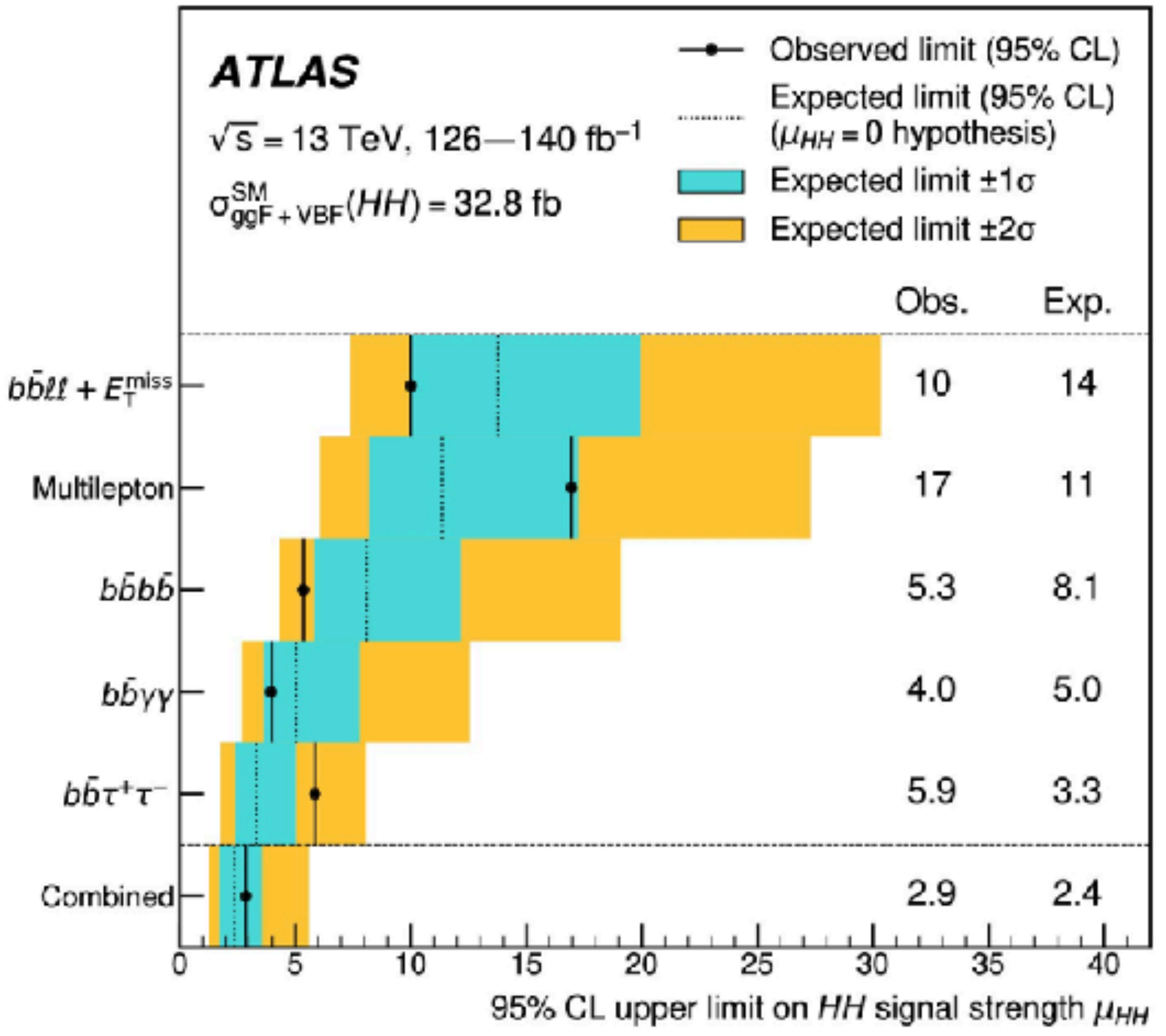
$$V(\phi) = \mu^2 \phi^* \phi + \lambda(\phi^* \phi)^2$$

Making the Impossible - the Higgs Self Coupling

Di-Higgs production and Higgs (trilinear) self-coupling!







Incredibly small cross section ~1000 times smaller than Higgs production!

Huge challenge! but still more than 100k event will be produced at HL-LHC!

Multiple channels investigated: depending on the both Higgs decays considering (bb, $\gamma\gamma$, $\tau^+\tau^-$, WW)

More channels and more performant analyses!

Observed limits start deviating from bkg. only expectation.

Both experiments have ~1σ sensitivity to a signal (Obs. ATLAS 0.4σ and CMS ~1σ) with Run 2!!

Naive comb. ATLAS-CMS sensitivity with Run 3 close 2.5 σ with improvements (and as much data as possible) **aim at 3σ**

Making the Impossible - the Higgs Self Coupling

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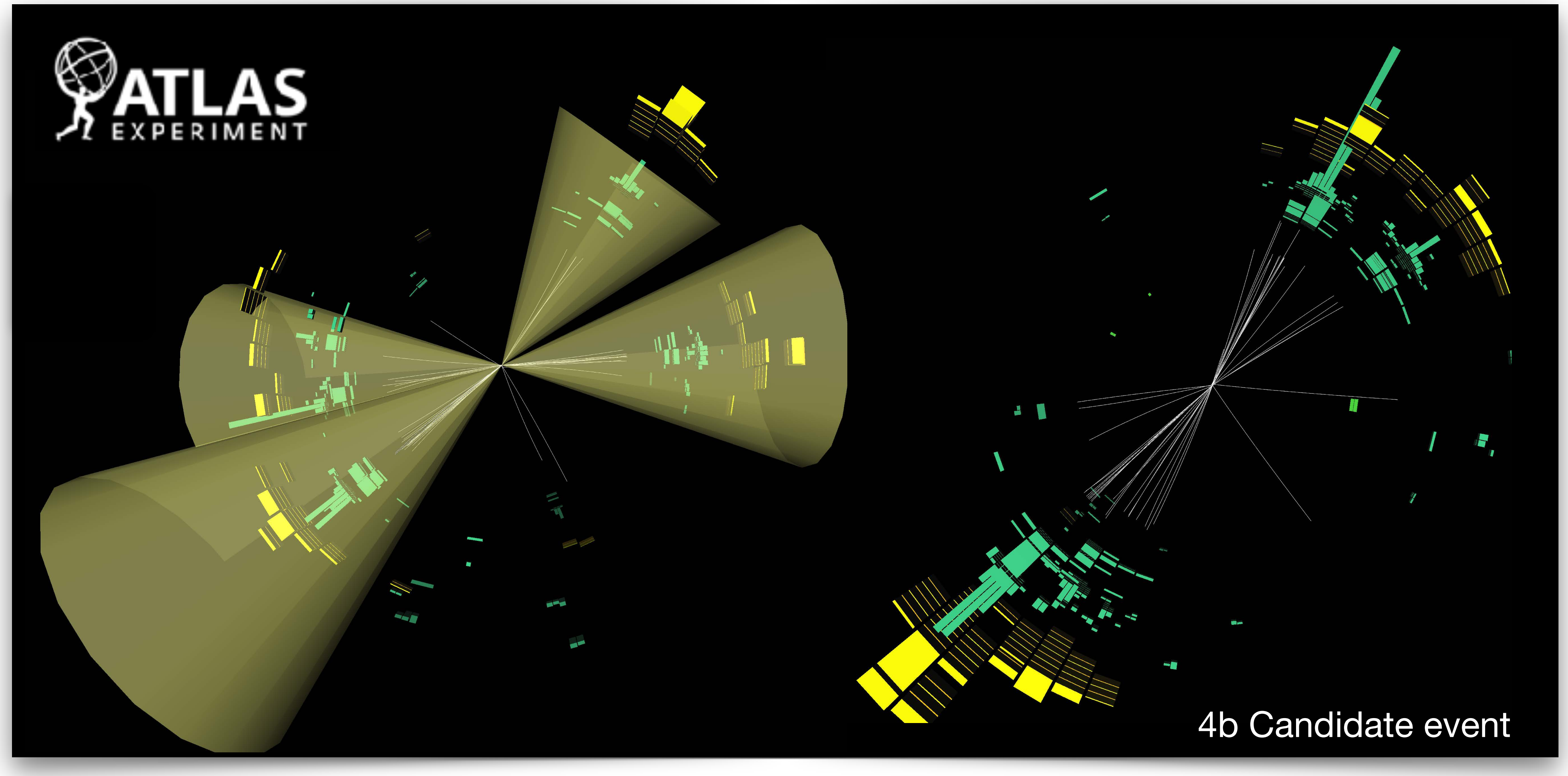

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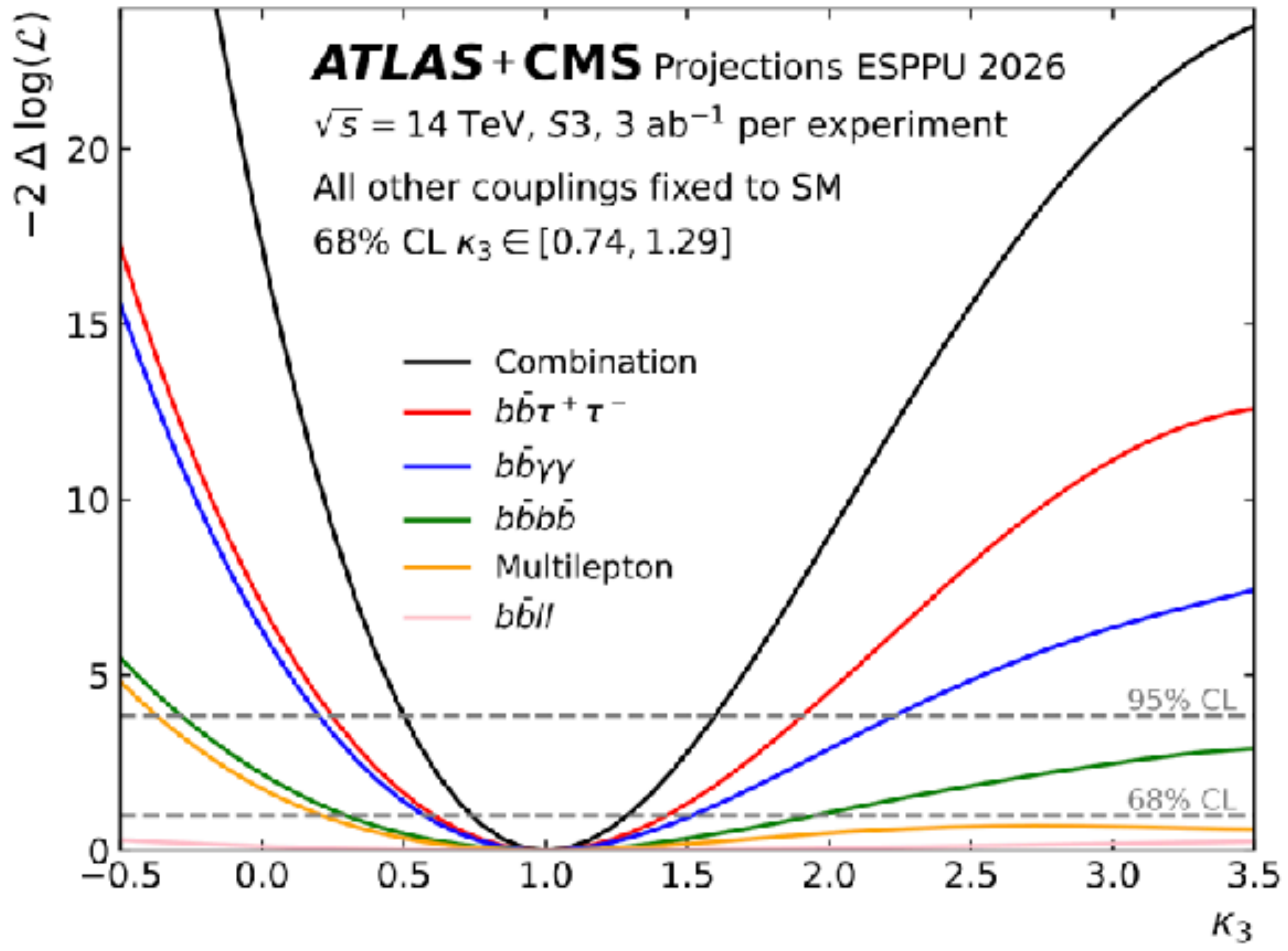
HL-LHC Projections

Include some already known performance improvements (S3)!



Both experiments reach ~4.5σ sensitivity at HL-LHC

7.6σ in combination!

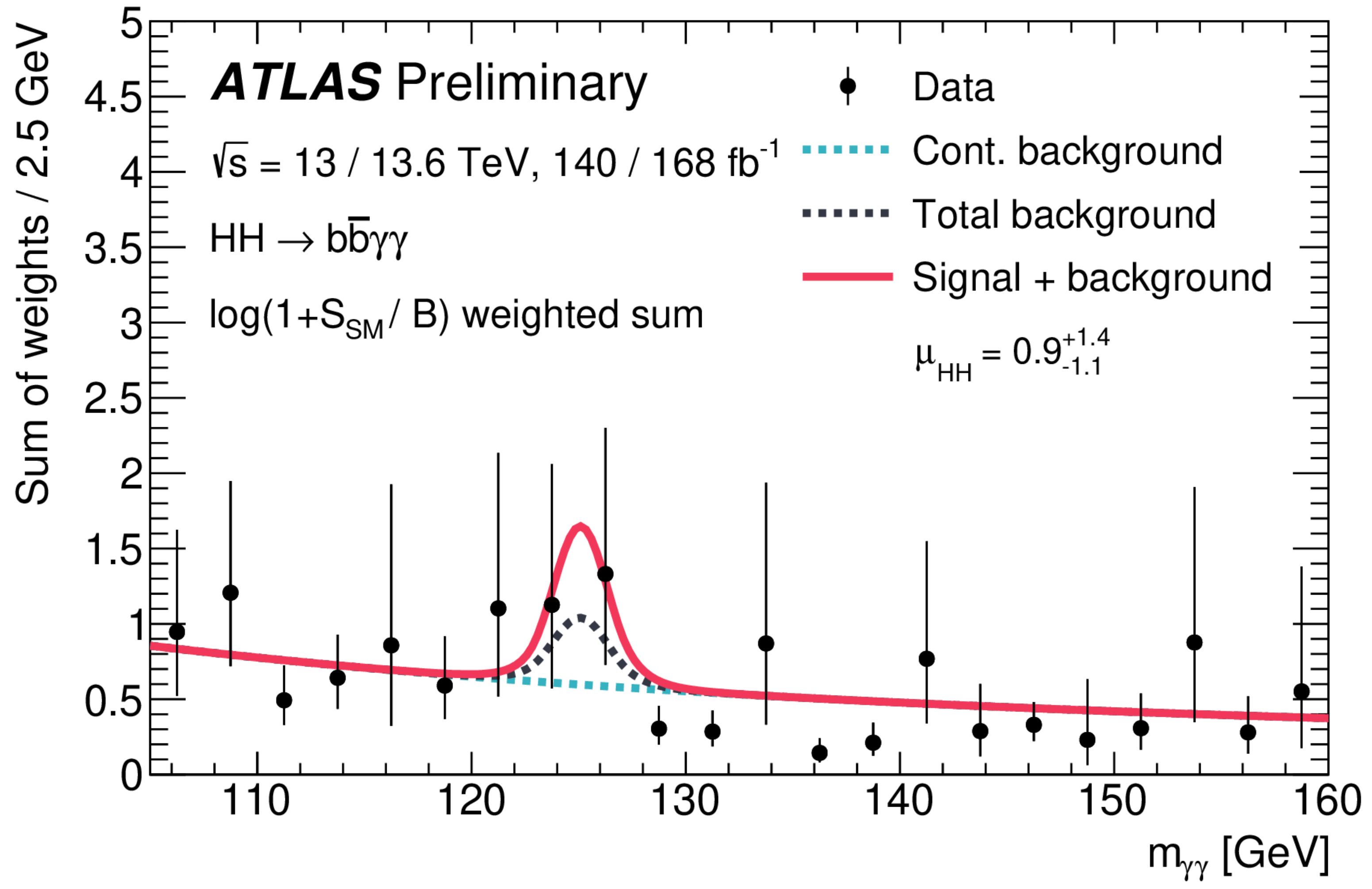
A combined measurements precision of κ_λ of $^{+29\%}_{-26\%}$

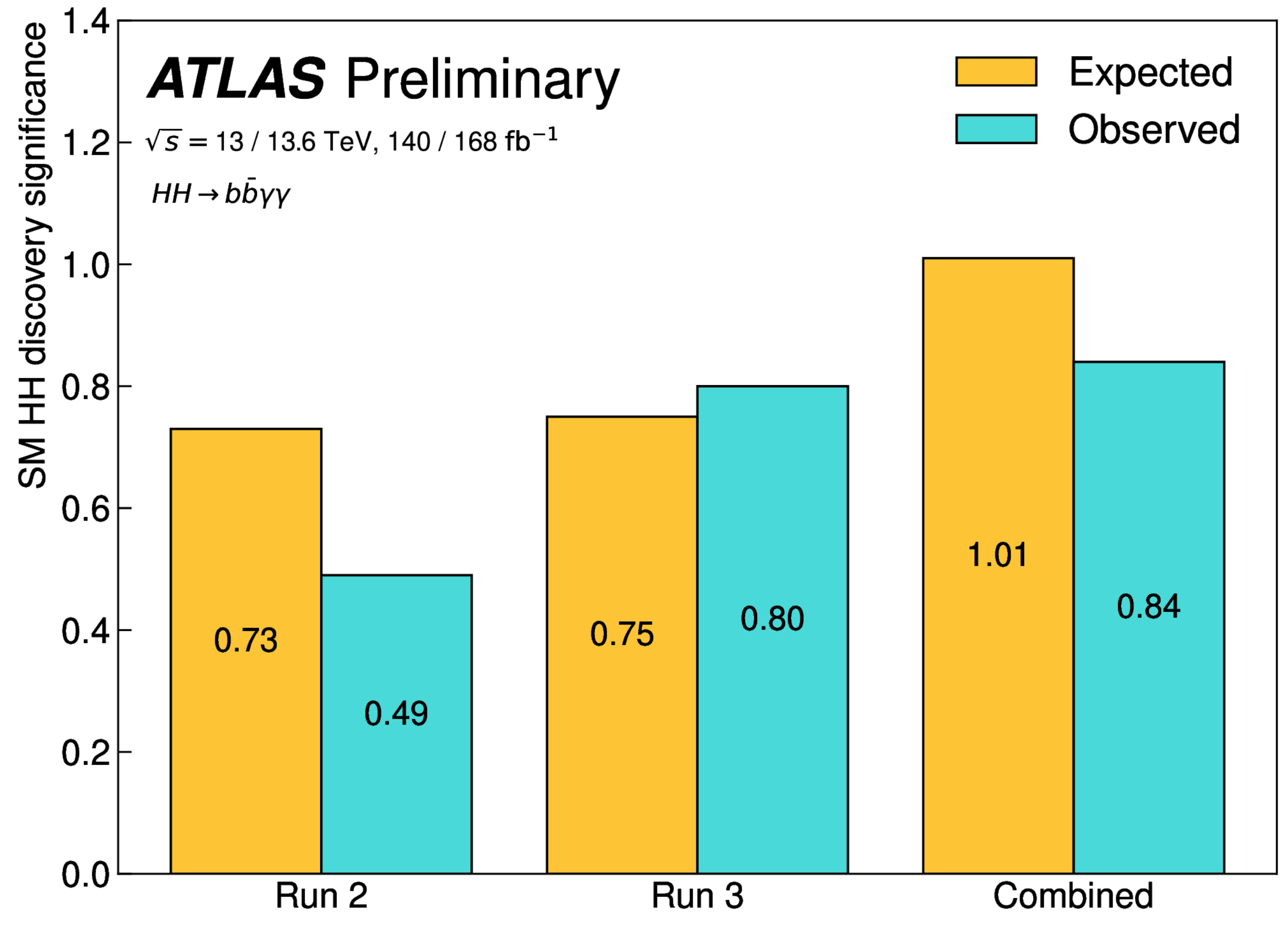
FCC-hh direct : **2-3%**

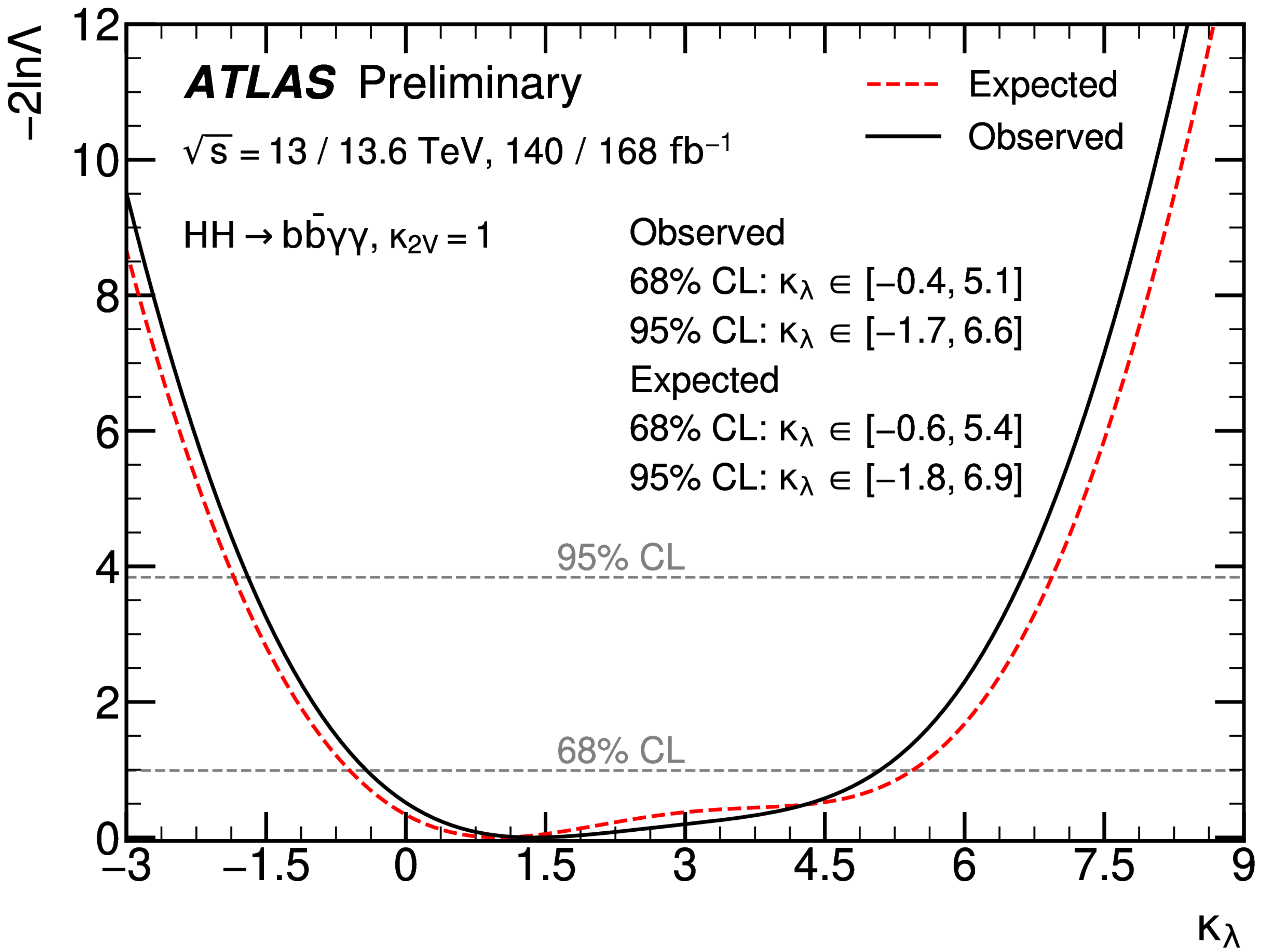
Making the Impossible - the Higgs Self Coupling

Presented this month at the LHCP conference in Taiwan

New ATLAS result in the $b\bar{b}\gamma\gamma$ with Run 3 data at 13.6 TeV !!







Sensitivity already at level of ATLAS Run 2 combination!

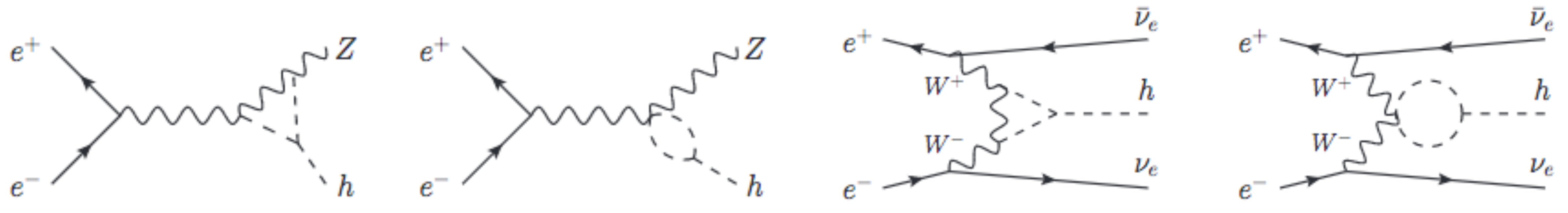
Expected sensitivity: $\mu_{HH} = 1.0^{+1.3}_{-1.0}$

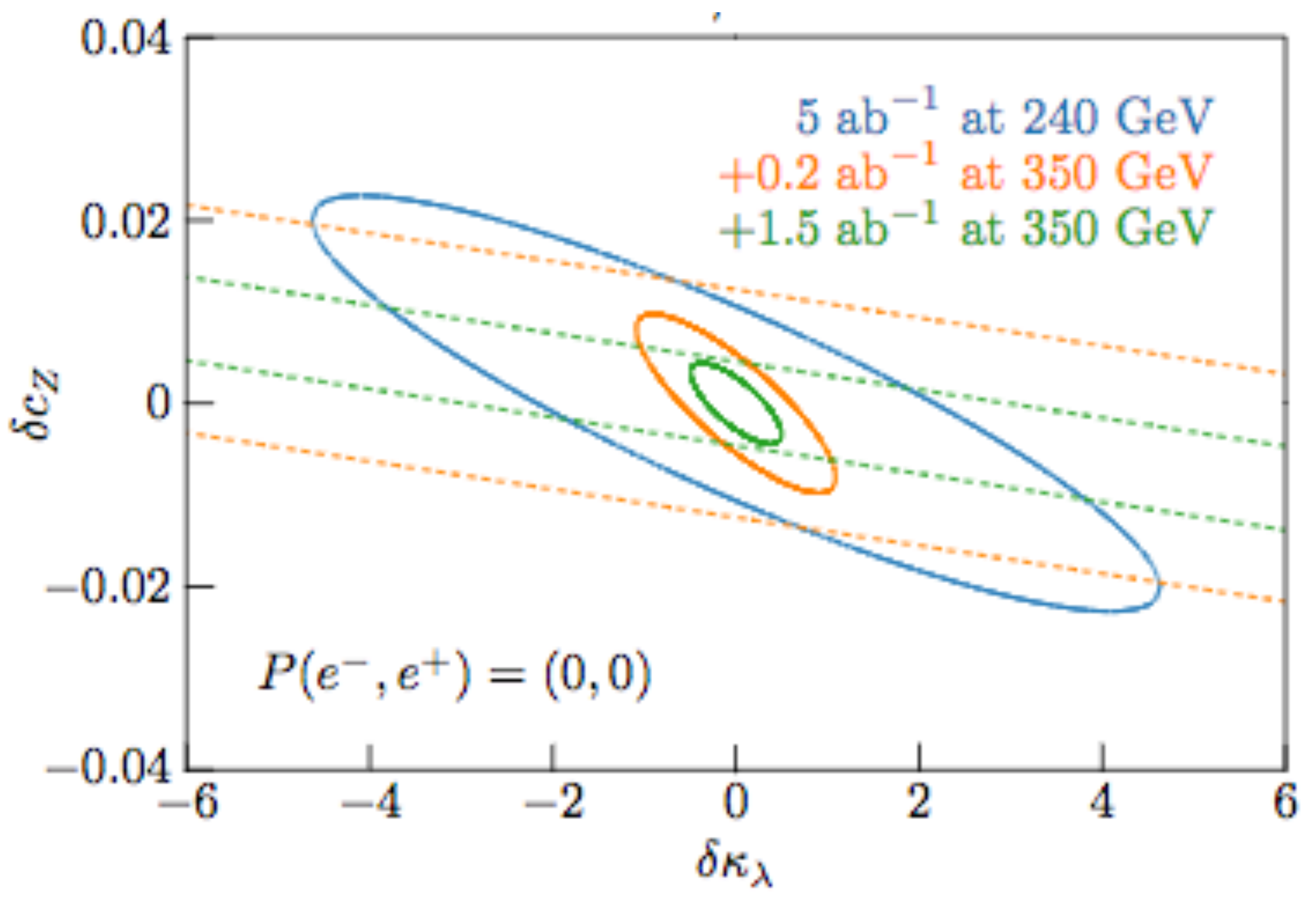
Observed: $\mu_{HH} = 0.9^{+1.3}_{-1.0}\,\text{(stat)}\,^{+0.6}_{-0.5}\,\text{(syst)}$

Making the Impossible - the Higgs Self Coupling

Loop level constraint on Higgs self coupling (assuming no BSM physics in the loops)

Higgs cross section at 240, 350, at 365 GeV





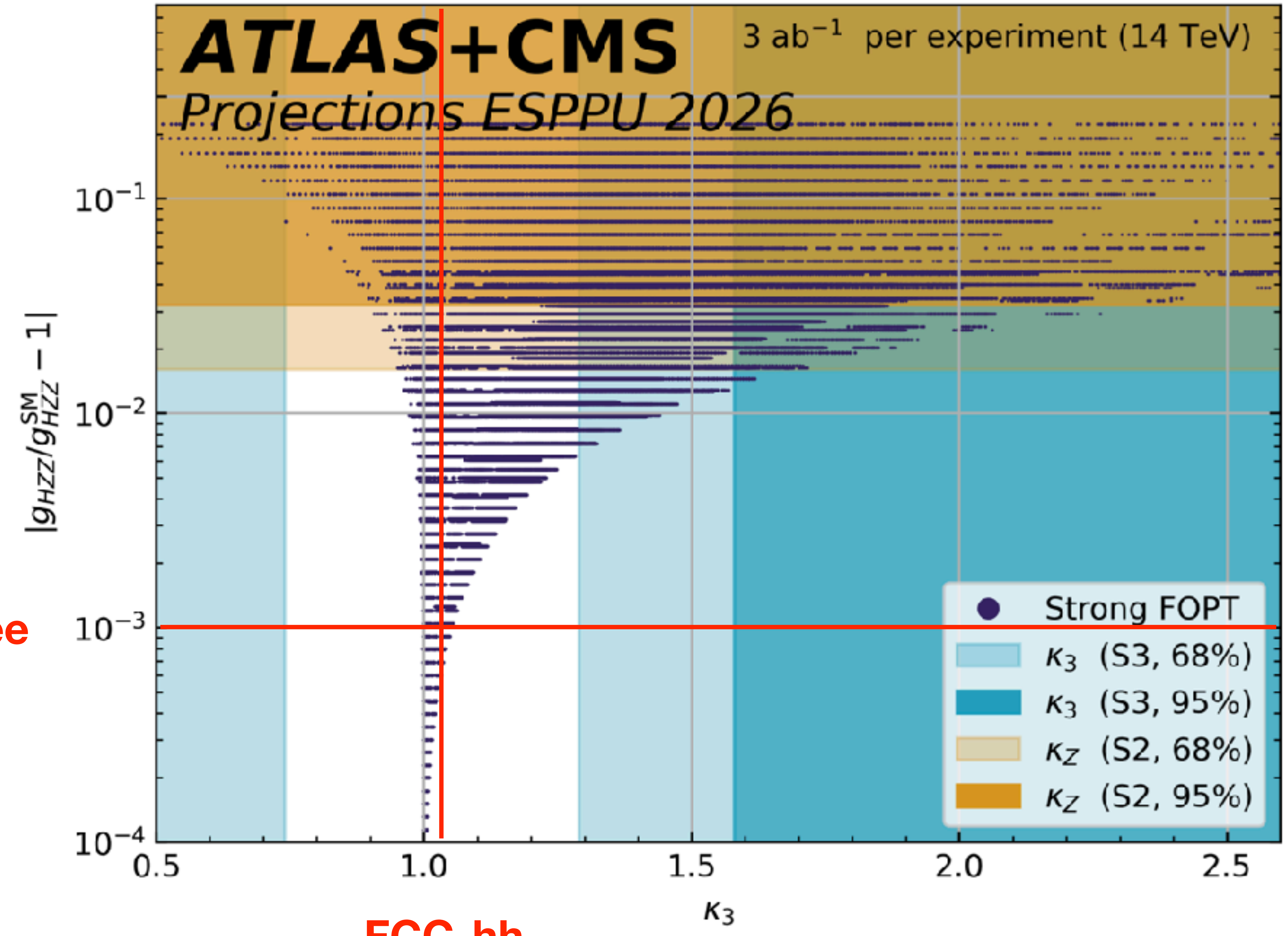
Higgs self coupling precision **~30%** - reduced to **~20%** with kappaZ = 1 from SM

Measurements at different energies will be very important.

In the case of of a specific BSM model

points correspond to strong first-order phase transition in the early universe is possible within the scalar singlet model

FCC-ee



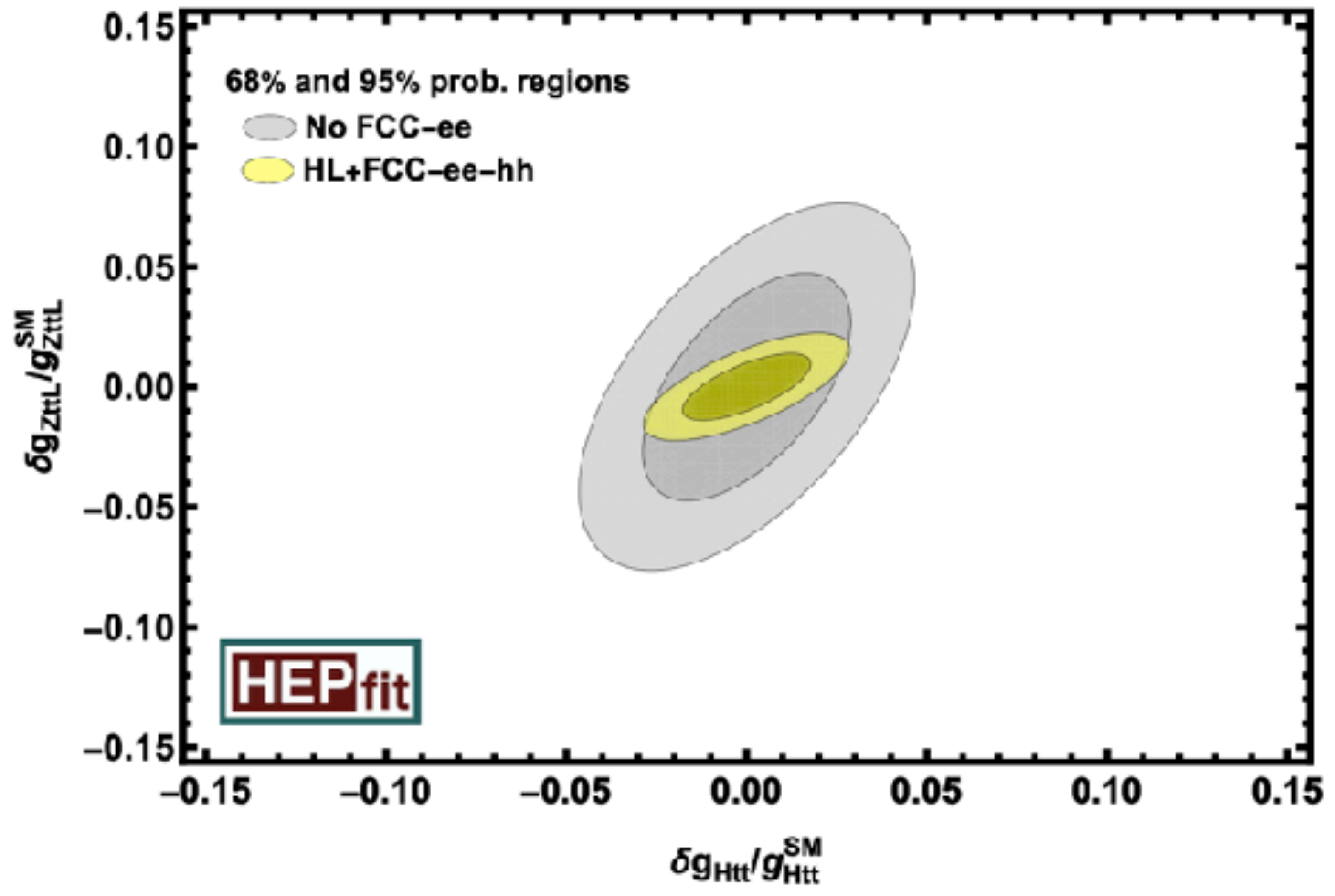
FCC-hh

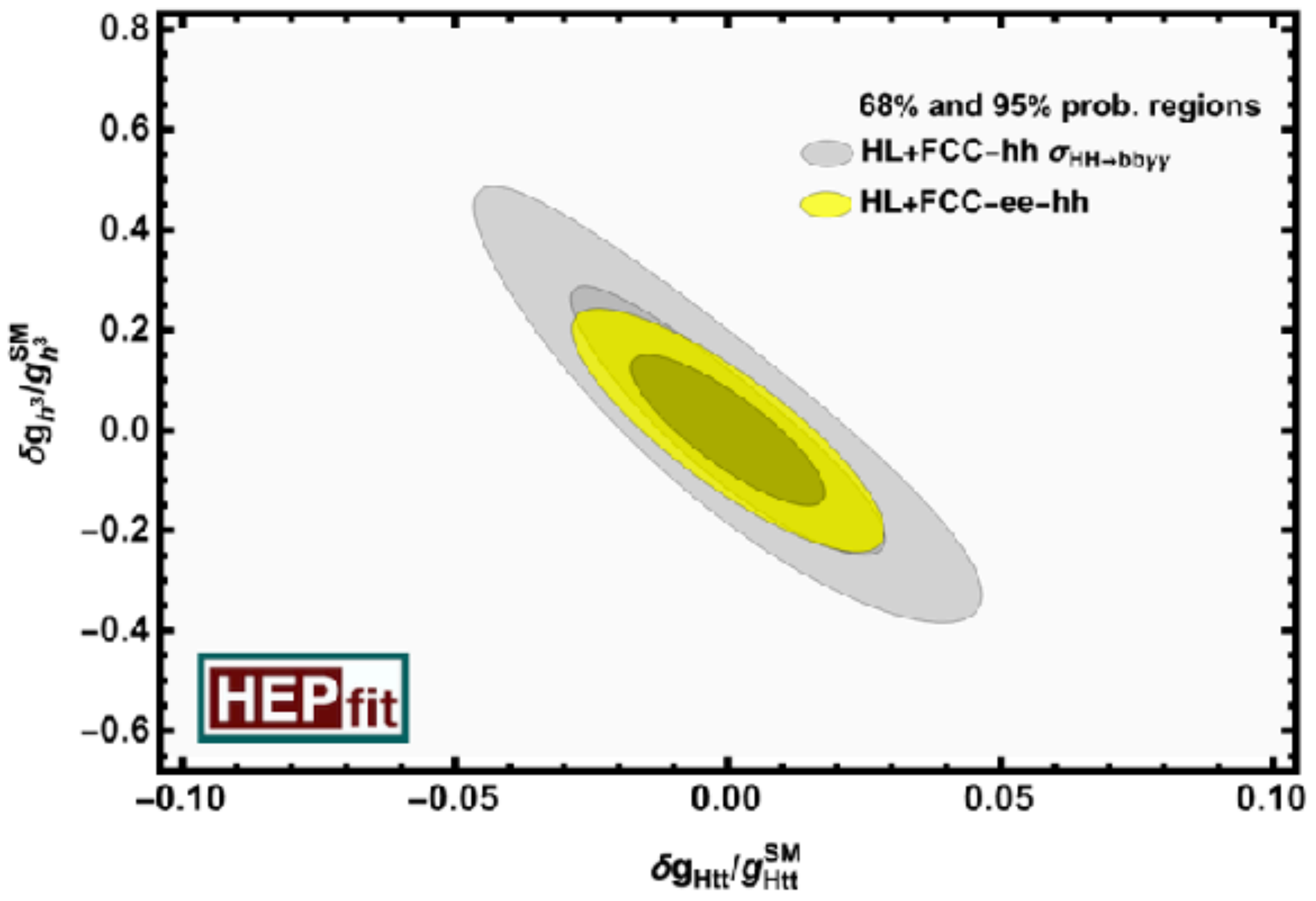
FCC will be decisive (also see that the most precisely known coupling is setting stringent limits)

Improving Higgs Couplings at FCC-hh (and HL-LHC)

The precise measurement of the most precise coupling is also important to measure more precisely other couplings.

$e^+e^- \to hZ$ Allows for a model independent measurement of the top Yukawa





$e^+e^- \to t\bar{t}$ **FCC-ee at 365 GeV**

$pp \to HH$ **FCC-hh (and HL-LHC)**

The Ztt coupling can be used from 365 GeV FCC-ee data to normalise the ttH to the ttZ reduce the systematic uncertainties.

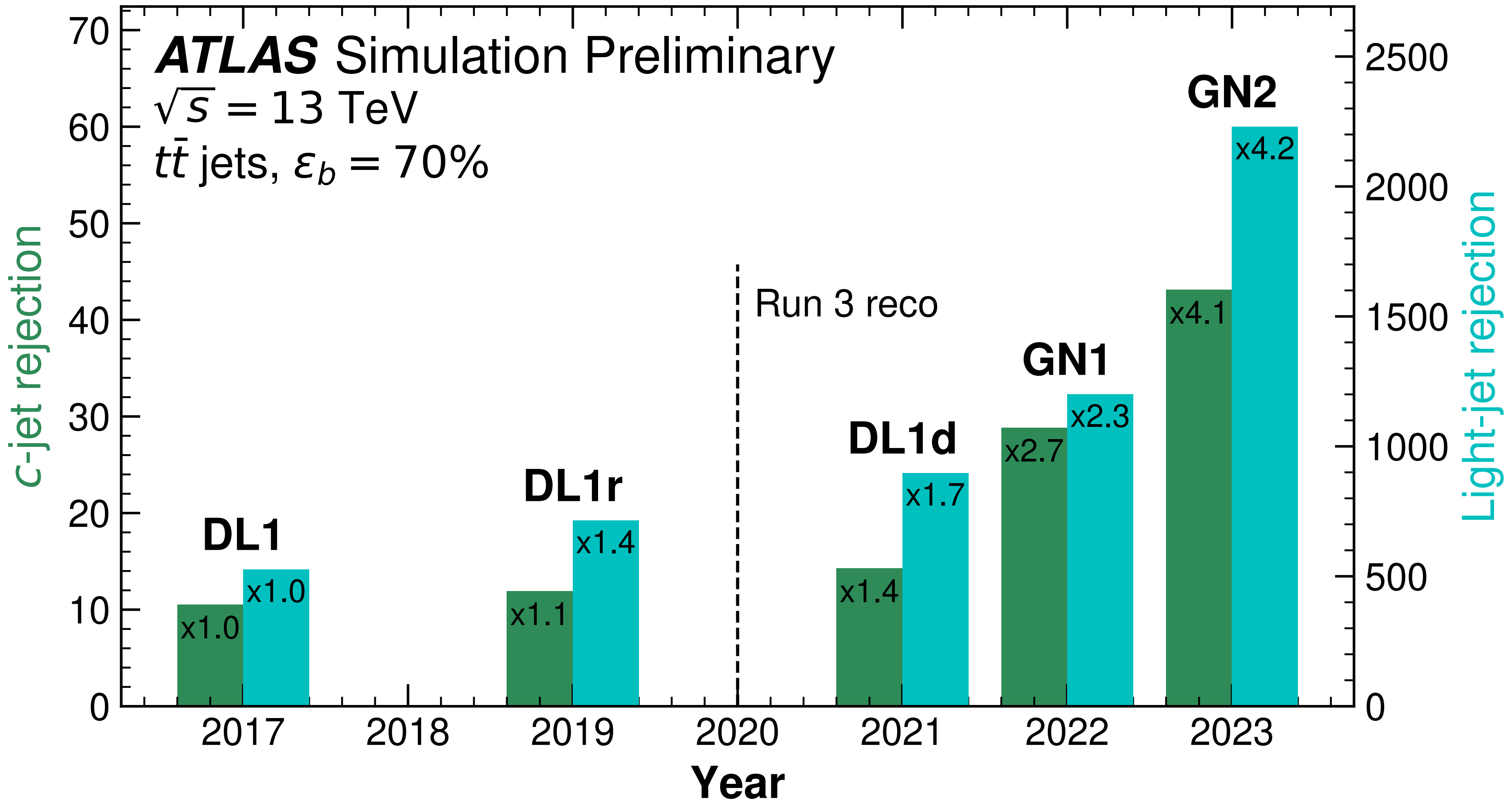
Can then be normalised to ttH to further gain in sensitivity.

AI Achievements in HEP

Progress with Deep Learning Techniques

Array of ML opportunities beyond classification and regression, in simulation, unfolding, anomaly detection, etc.

Particular success in flavour tagging



Similar trend for CMS Still **more improvements expected in flavour tagging techniques!**

Huge success in jet tagging (H, W, Z, top,...)

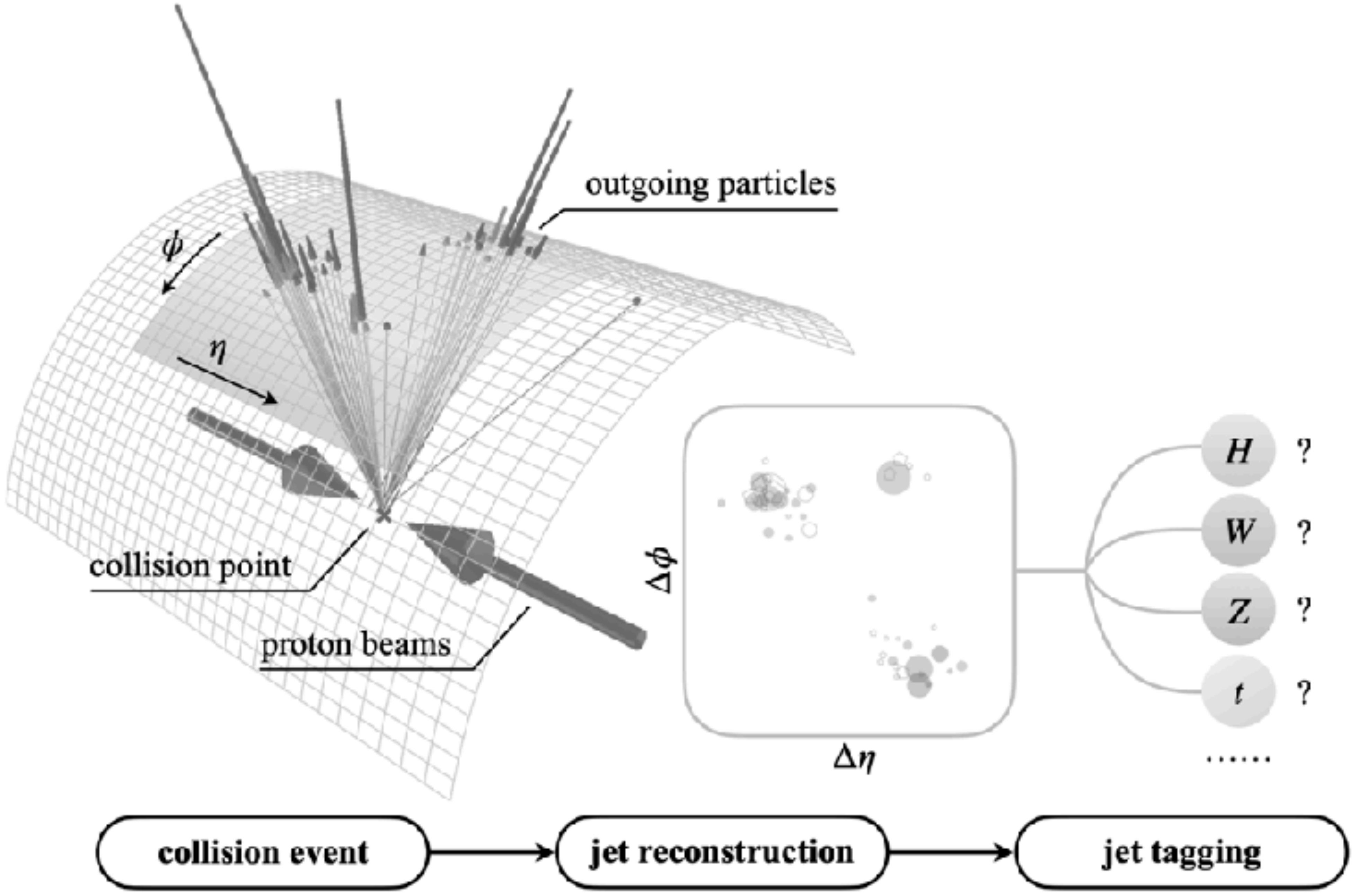
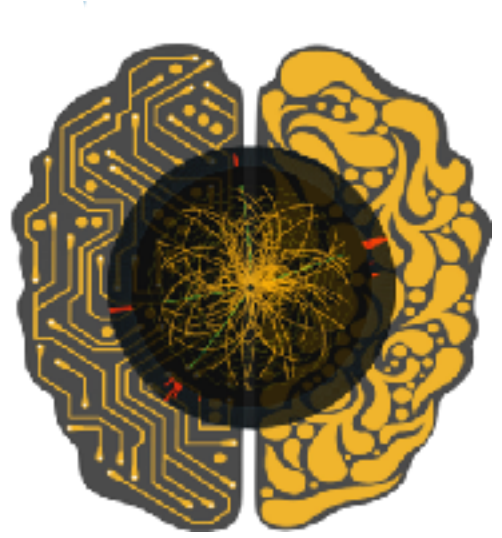


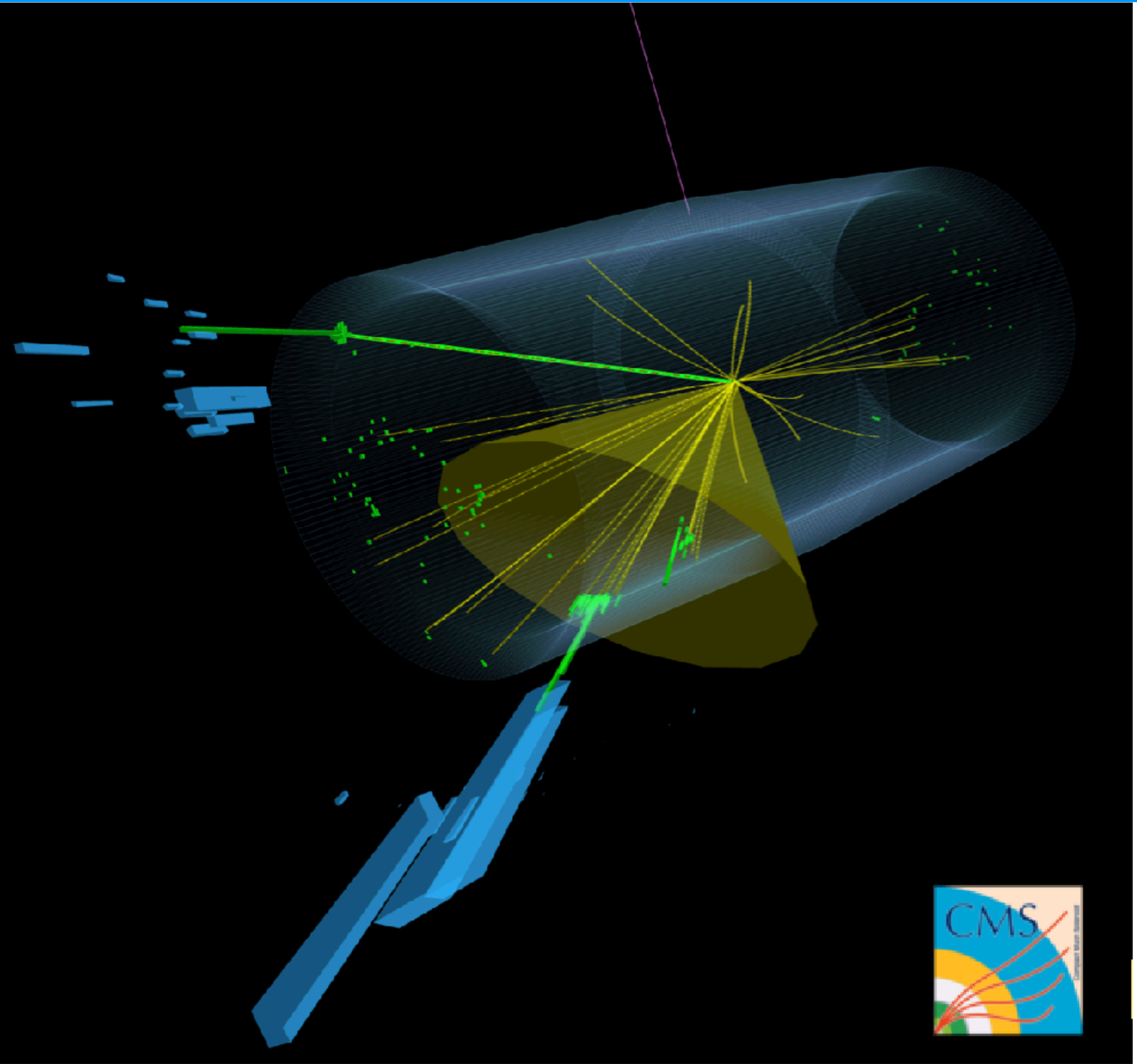
Illustration from [Particle Transformer]()



Use “particle clouds” (with more info than only 3D coordinates - 2D eta-phi, pT, charge, particle

[Particle Net]() uses Dynamic Graph CNN

Making the Impossible - the Charm Yukawa



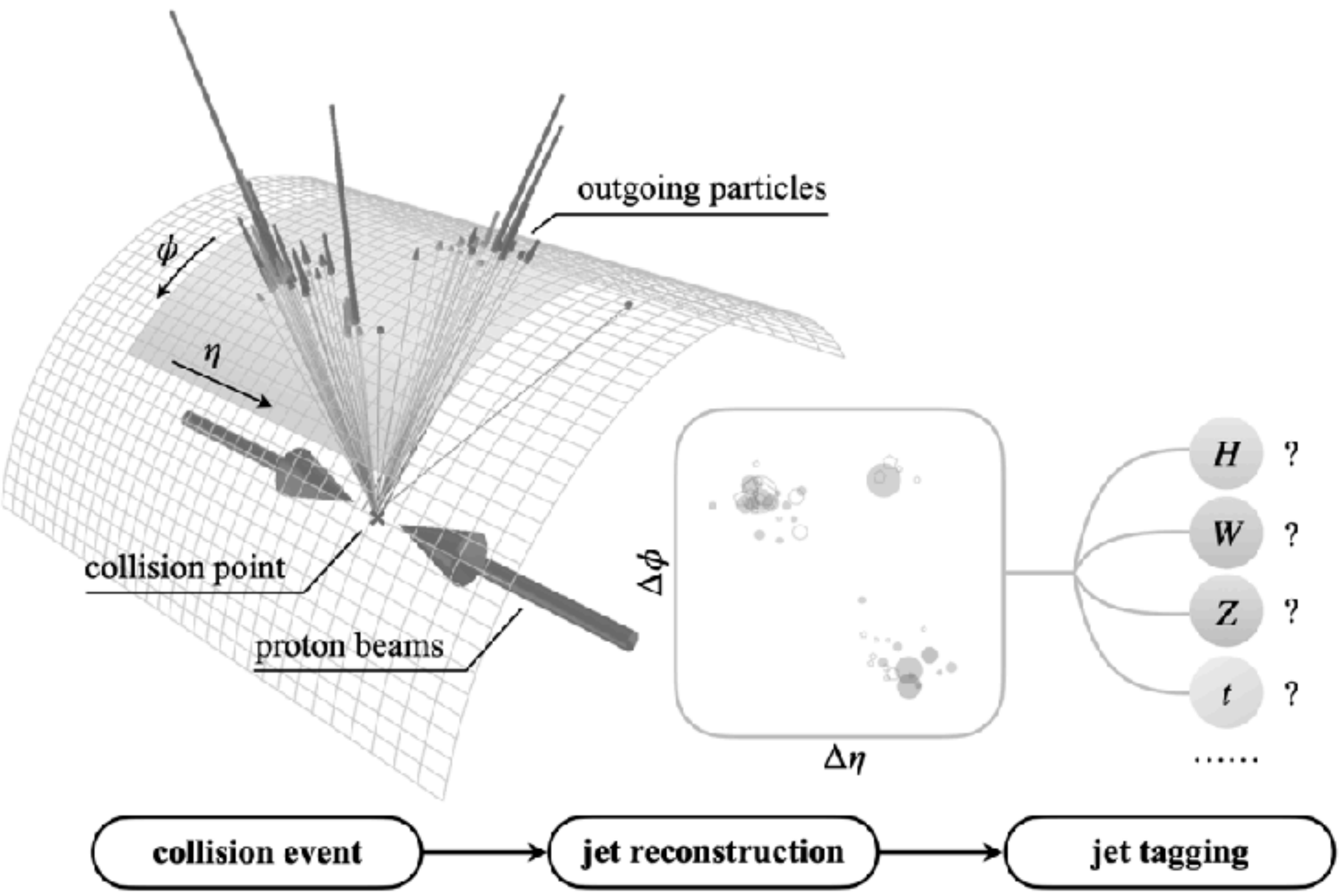
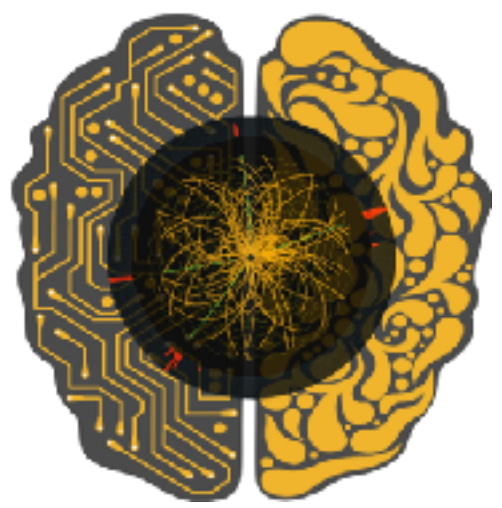


Illustration from Particle Transformer



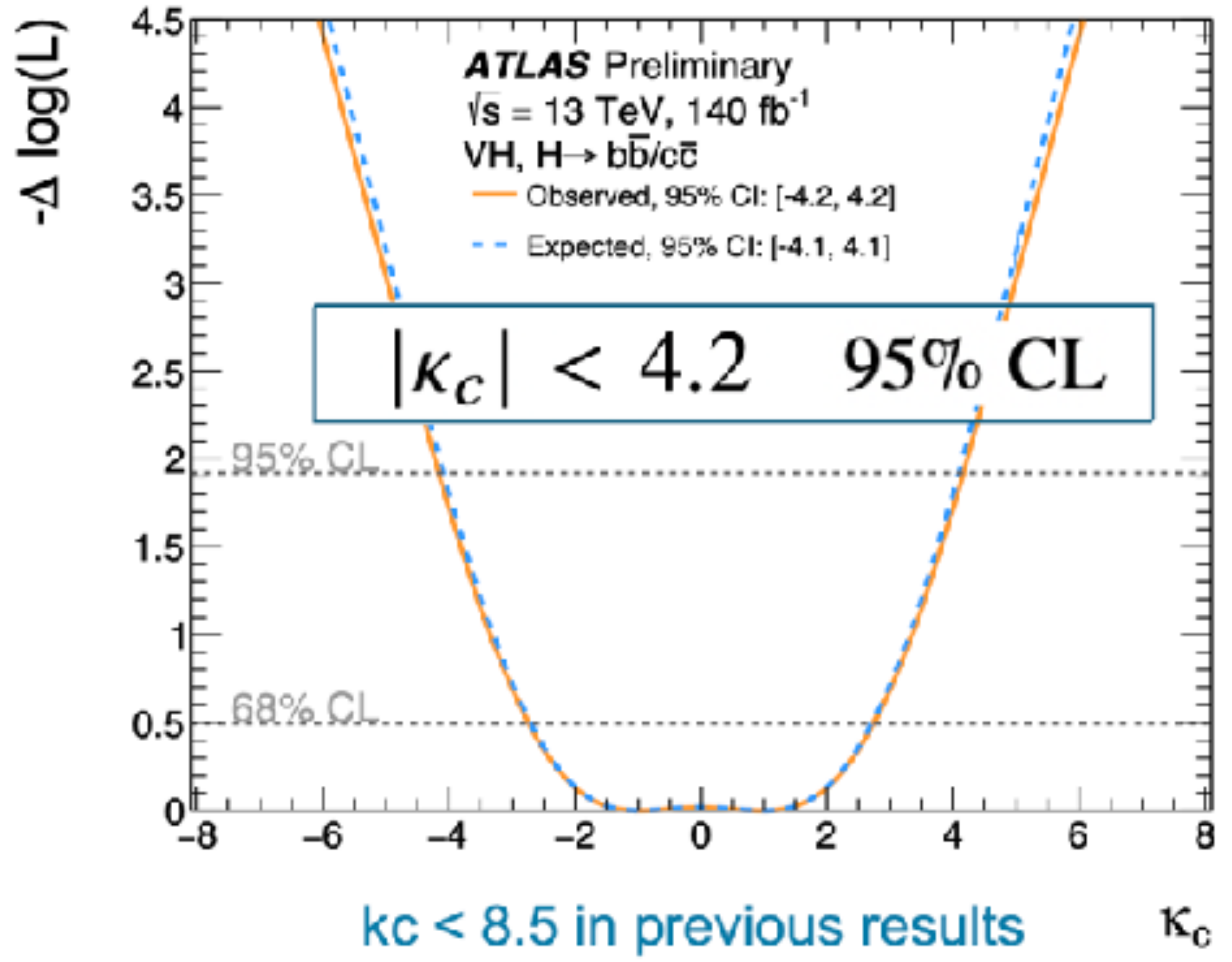
Use “particle clouds” (with more info than only 3D coordinates - 2D eta-phi, pT, charge, particle

Particle Net uses Dynamic Graph CNN

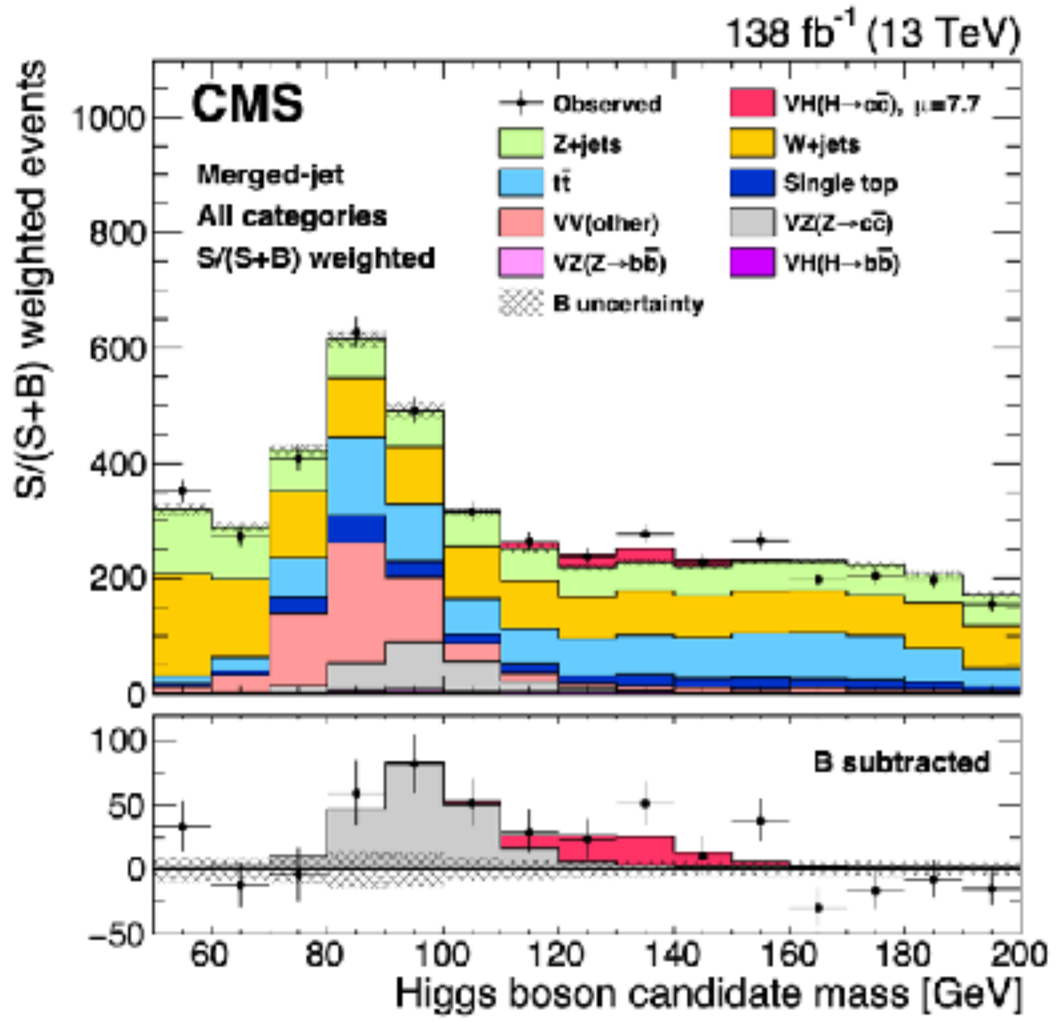
Making the Impossible - the Charm Yukawa

Charming the Higgs at the LHC?

Using new Flavour tagging in ATLAS and state-of-the-art ML techniques [Particle Net] uses Dynamic Graph CNN



kc < 8.5 in previous results



Led to hugely improved performance of VH(cc) analyses

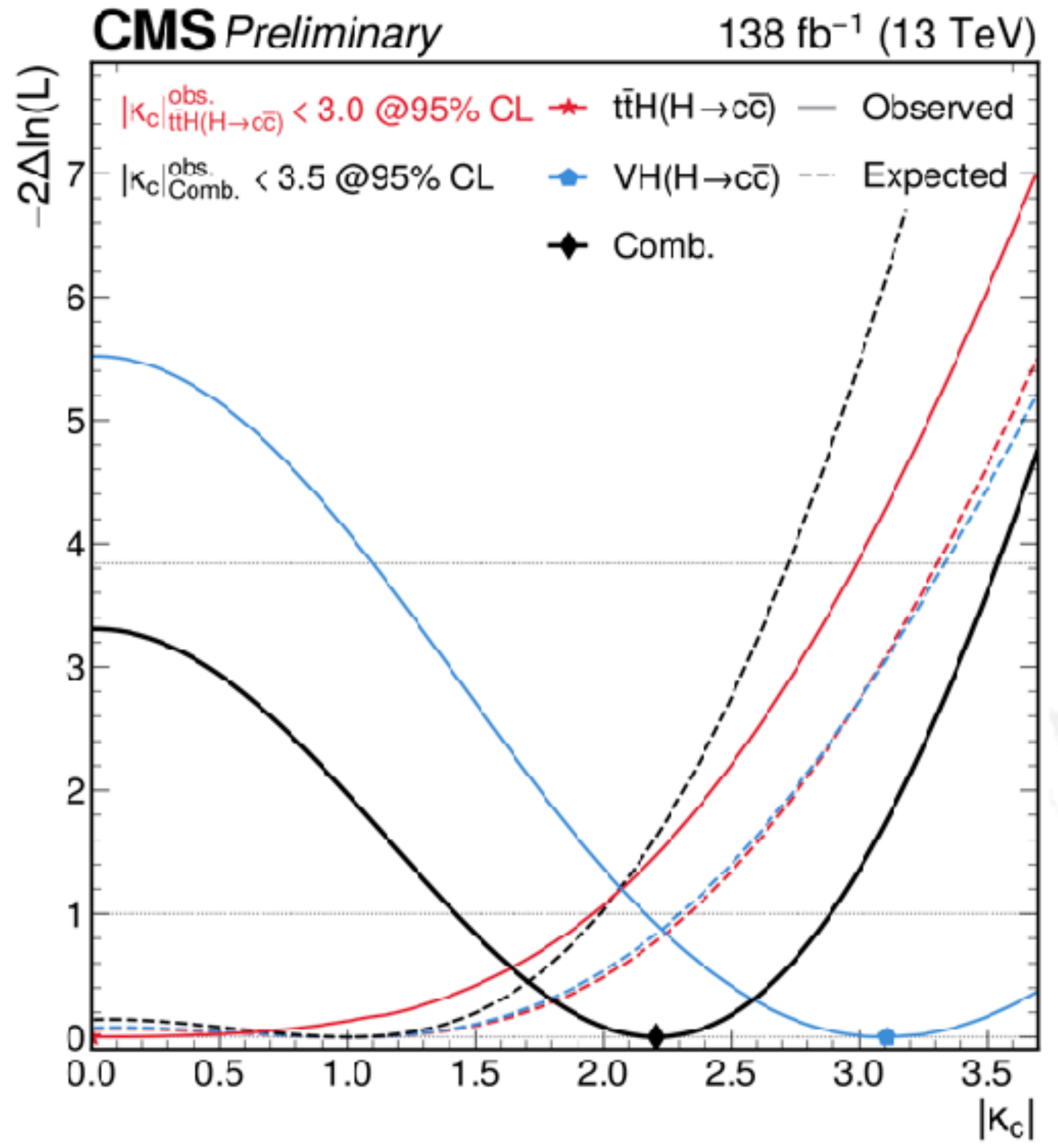
$$1.1 < \kappa_c < 5.5$$

Yields a precision on κ_c of ~40% per experiment at HL-LHC

New perspective at the LHC!

Impressive new result fresh of the oven!

[CERN Seminar] last week!



At the FCC-ee κ_c ~0.9%

X40 improvement, will also benefit from improvements in taggers

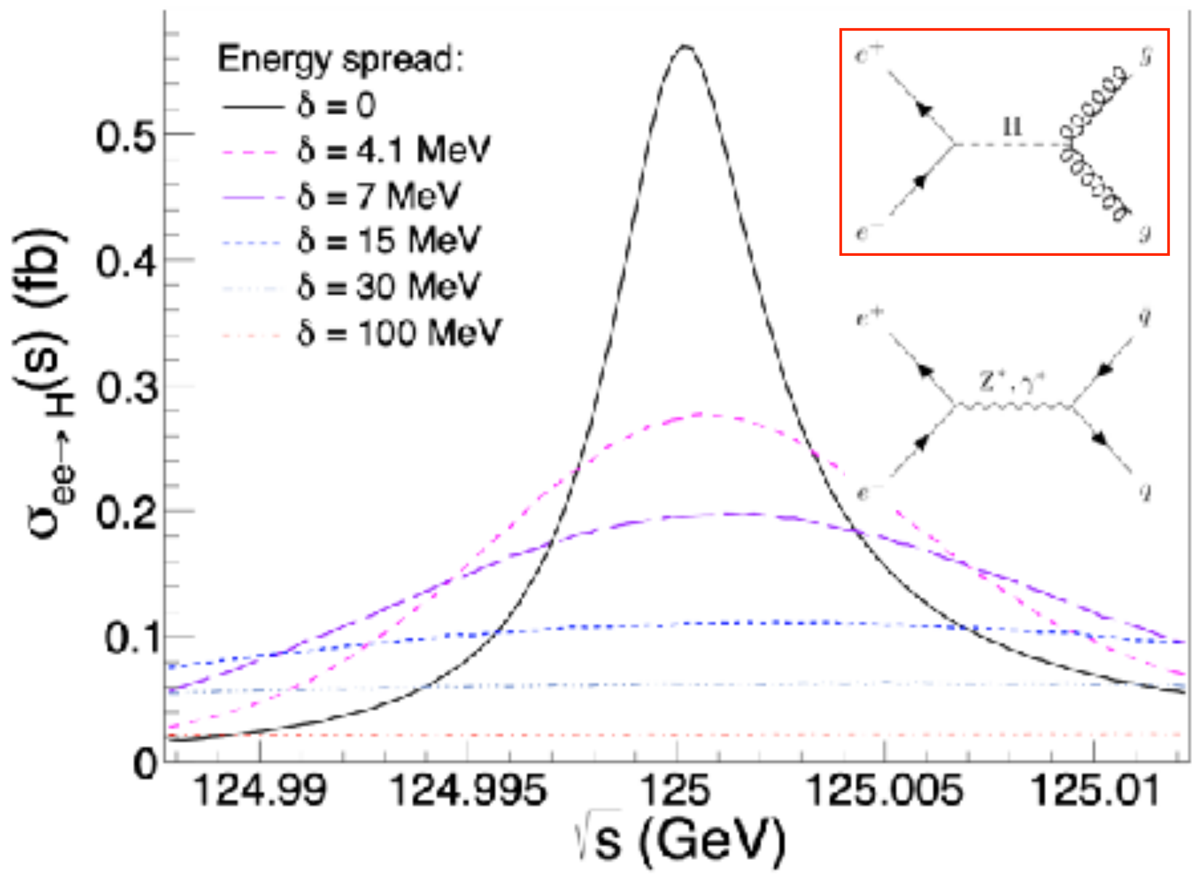
Beyond the Impossible

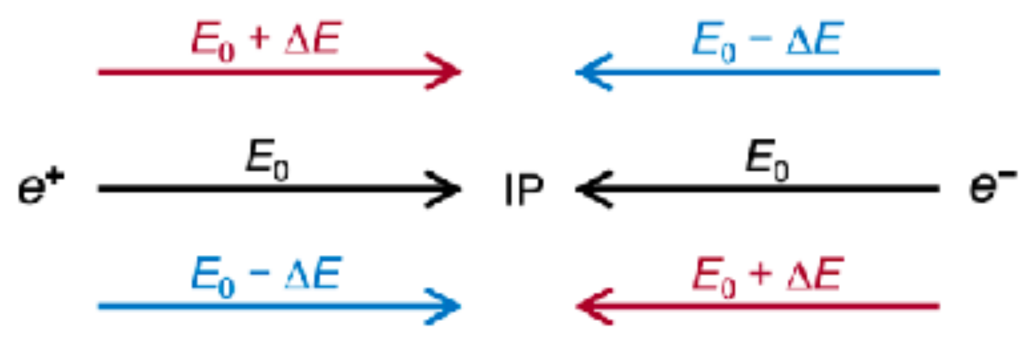
Extremely challenging s-Channel Higgs and e-Yukawa

1.- The production cross section is $\sigma(ee \to H) = 1.6 \text{ fb}$ require extremely large luminosities

2.- Given the Higgs width of 4.2 MeV, an extremely small $\sqrt{s}$ spread is an advantage - **monochromatization**.

- Beam spread ~ 100 MeV (no visible resonance) requires beam monochromatisation
- Requires a prior knowledge of the Higgs boson mass of ~couple of MeV at most!





Monochromatization considered but never used

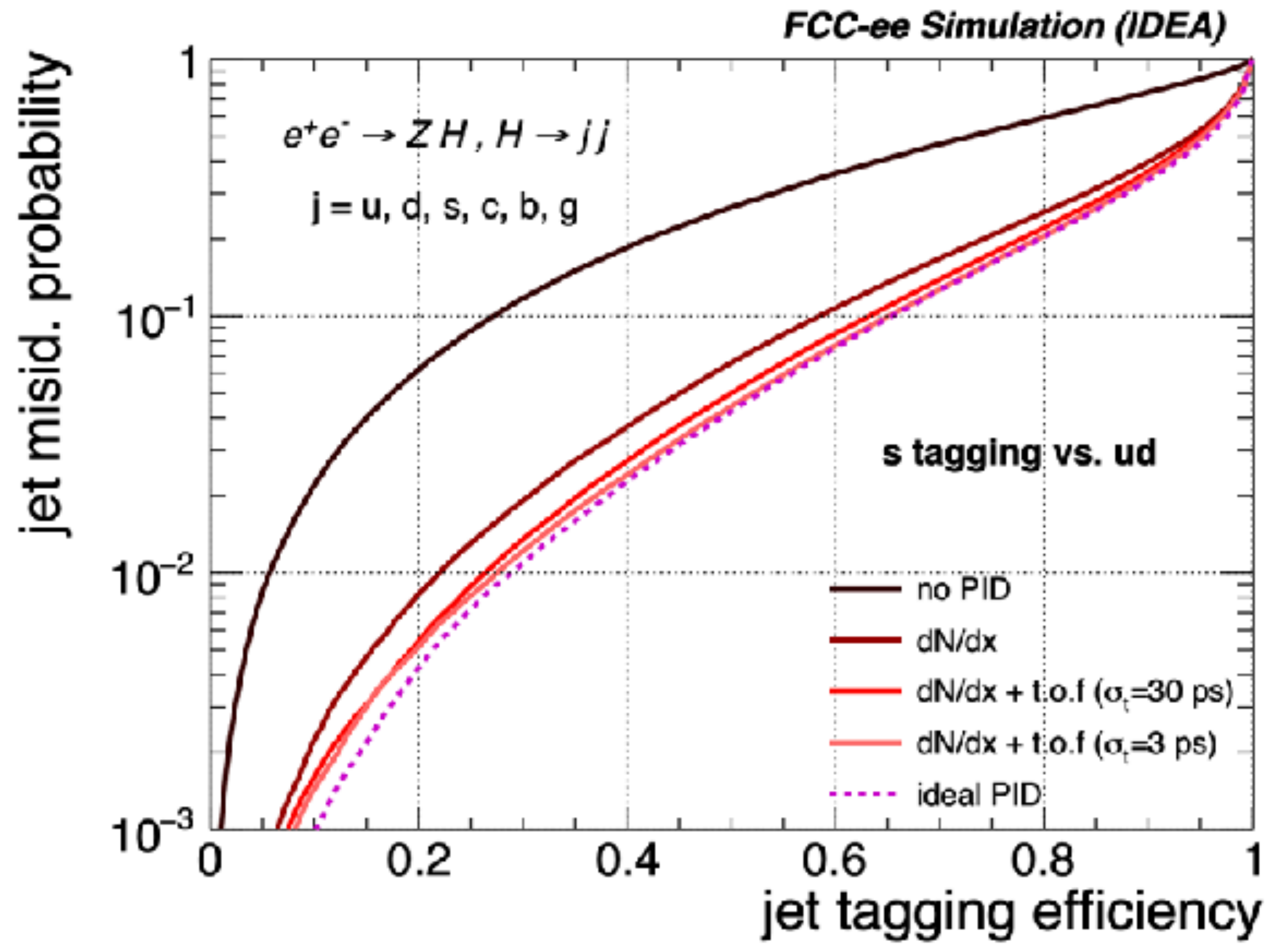
Opposite correlation between spatial position and energy.

First studies indicate a sensitivity of 0.4σ for a year in one detector

Strange Yukawa coupling

- DL tagging algorithm

- Charged hadron particle identification (PID) is essential (using number of ionisation clusters per unit length (dN/dx) in IDEA drift chamber or TOF)



First studies indicate a sensitivity of ~100% on strange Yukawa

Kaon PID and Strange tagging can also be used for HF measurements or top e.g. V_{ts} from rare $t \to Ws$ decay

Conclusions

The Higgs boson is at the heart of a large number of fundamental questions, and its detailed study is key to answer these questions.

Higgs physics has now become a field on its own, with outstanding TH predictions and measurements that were thought to be inaccessible at the LHC.

Higgs physics also has center stage in shaping the future of the field and in determining what the net flagship project for CERN will be, as it provides among the principal **guaranteed deliverables** for the possible projects.

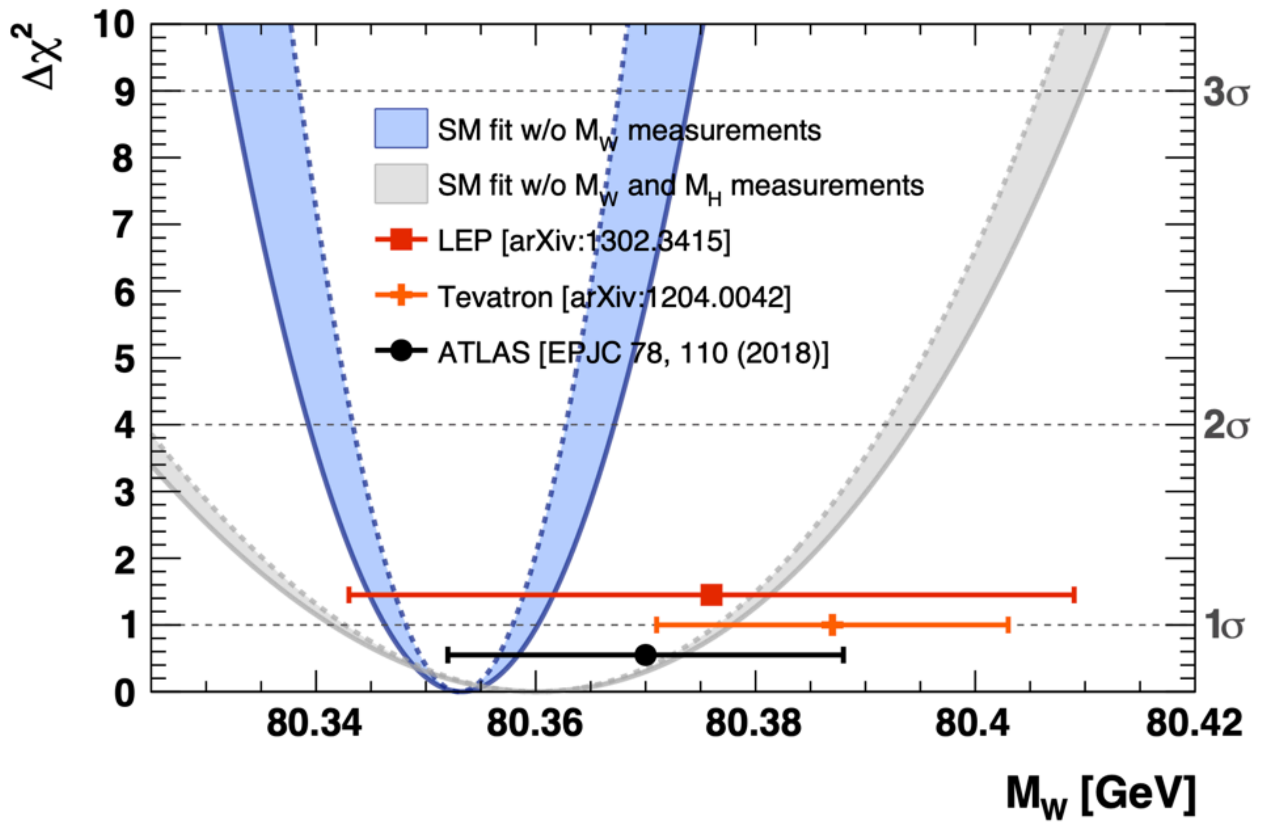
Collider projects from the HL-LHC to Multi-TeV machines offer a physics program for the 21st century with immense opportunities in particular in Higgs physics.

Now is a pivotal moment for the future of High Energy Collider Physics!

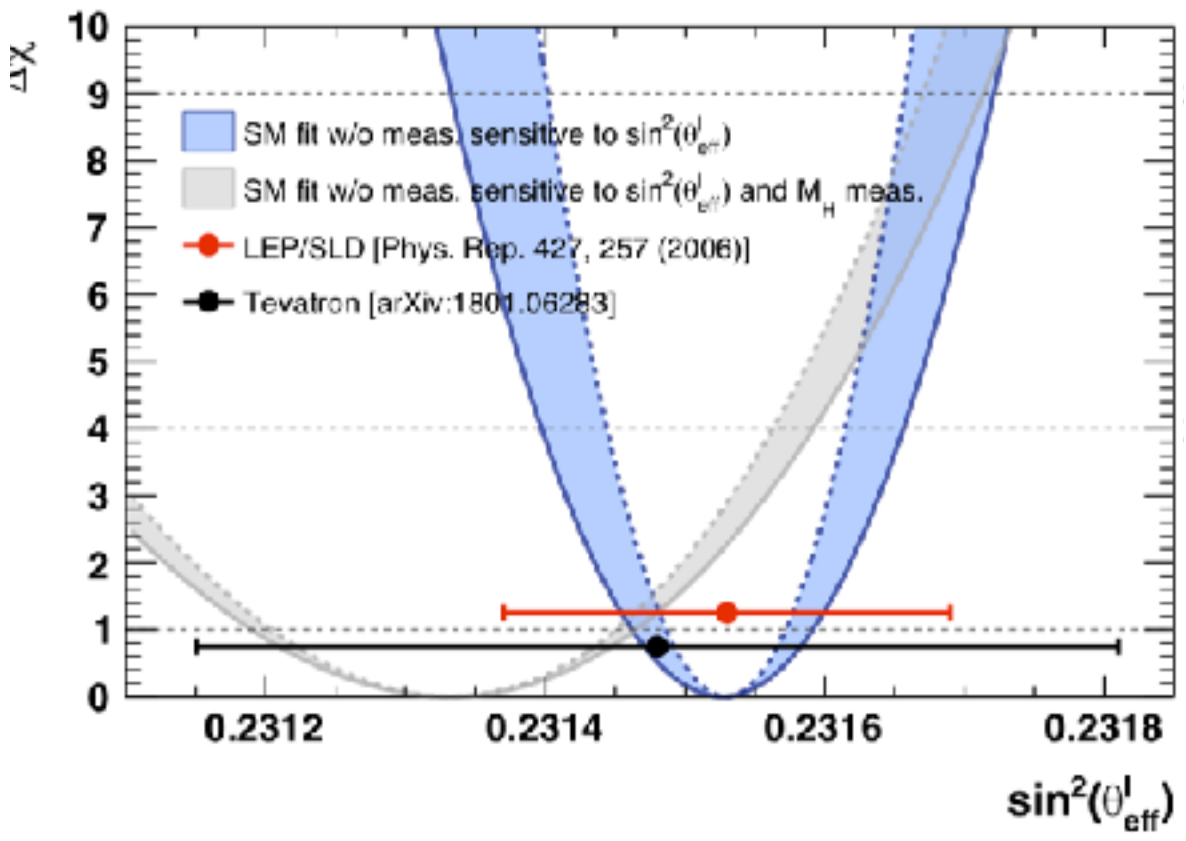
After the LHC, the FCC is the most ambitious and **the perfect flagship project for CERN!**

Backup

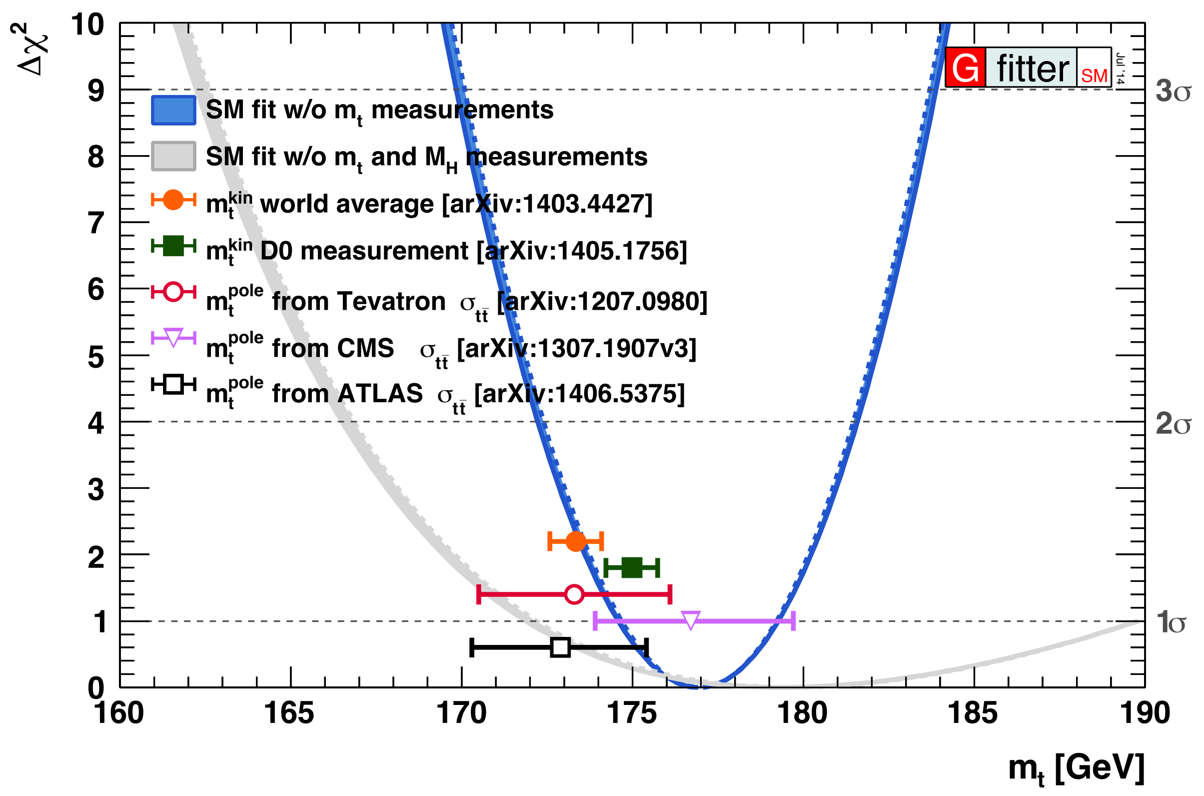
ΔPred. ~ 7 MeV ΔMeas. ~ 10 MeV



ΔPred. ~ 1.5×10^{-4} ΔMeas. ~ 7×10^{-4}



ΔPred. ~ 1.3% ΔMeas. ~0.2%

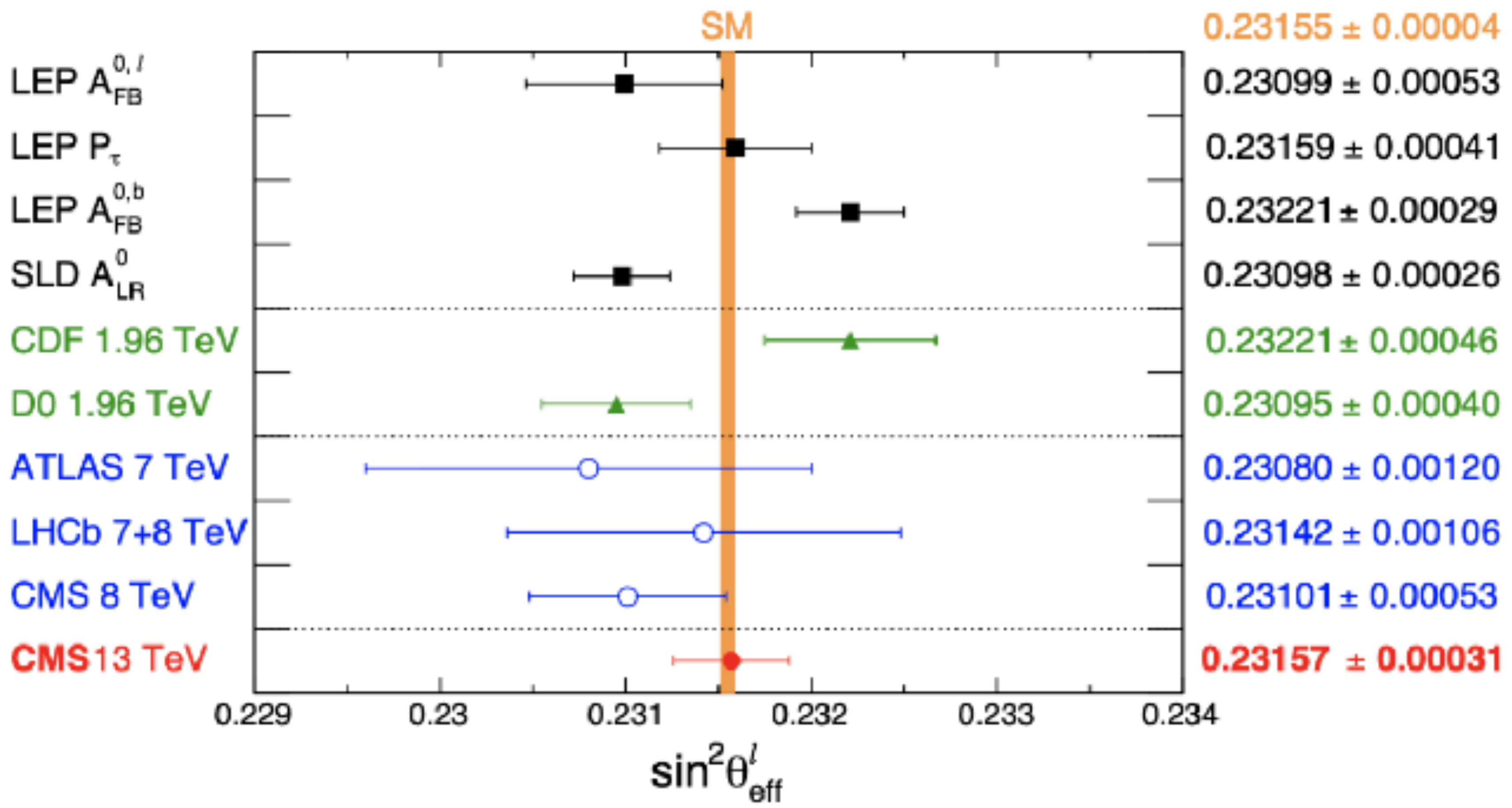


Precision EW fits have (and have had) a **huge predictive power**: top mass, the Higgs boson mass, as well as to some extent the absence of BSM physics at the LHC!

LHC Outstanding Achievements in Precision

Measurements of $\sin^2\theta_W$

Measuring the fully differential $pp \to Z \to \mu^+\mu^-$ cross section yields the weak mixing angle (mainly through A_{FB})



	ATLAS	CMS	LHCb	W.A. (w/o LHC)
Precision	0.16%	0.13%	0.21%	0.07%

Precision approaching that of LEP A^b_{FB} and SLD A_{LR}

At FCC-ee

Precision 0.0007% (7×10^{-6})

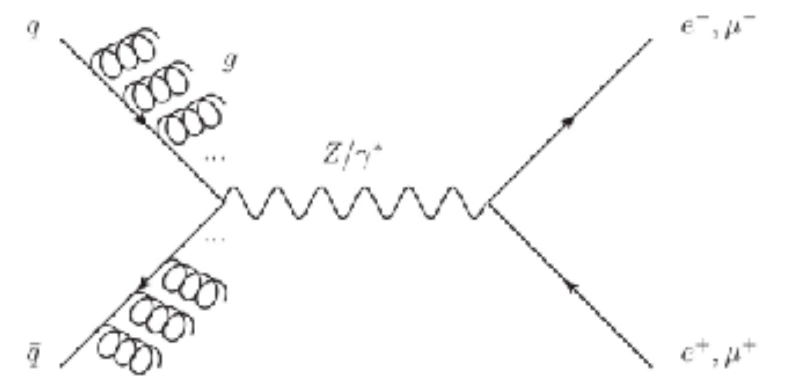
200x improvement

From $A^{\mu\mu}_{FB}$ stat nd syst (Dominated by beam energy calibration) on par.

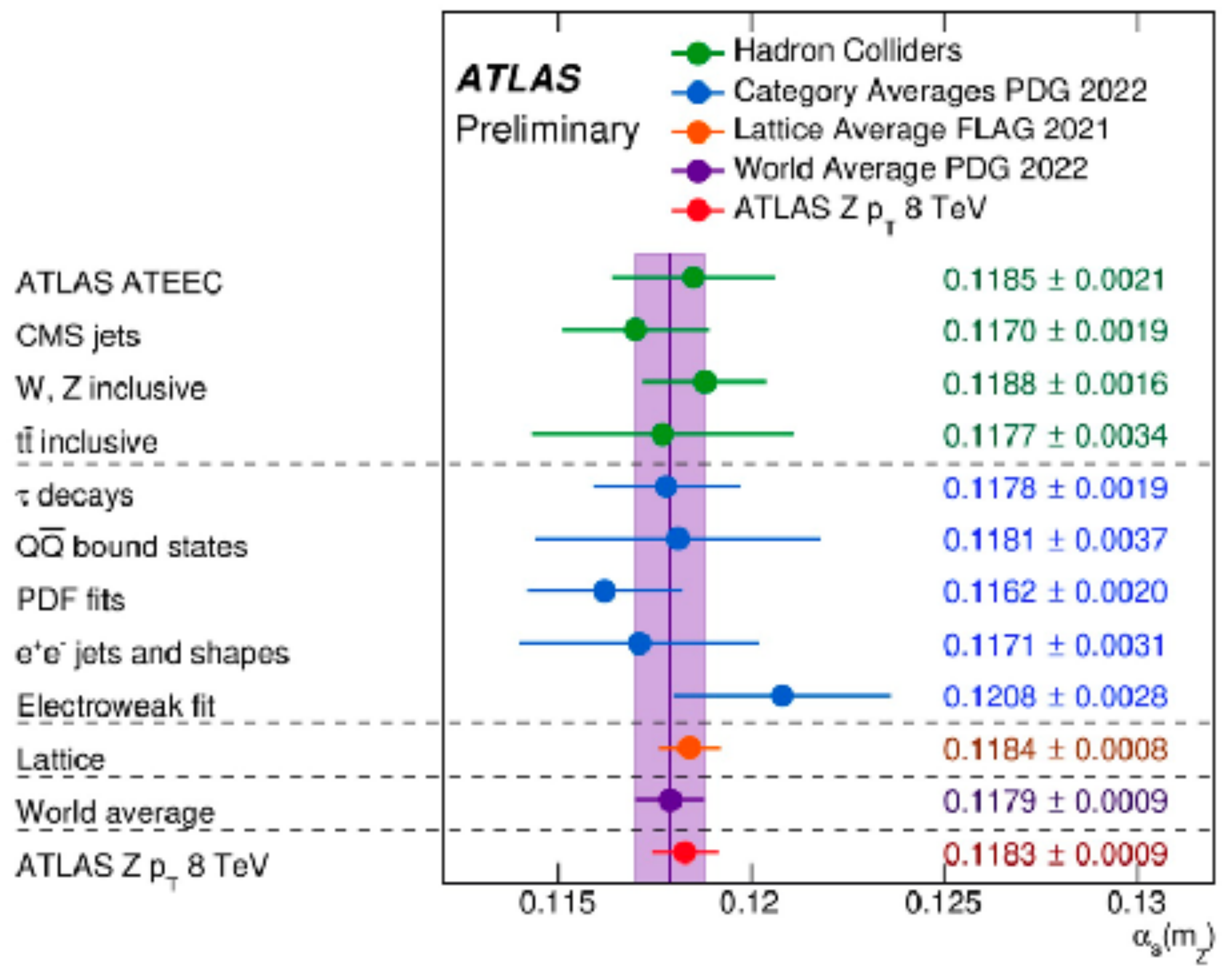
The least know coupling in the SM α_S

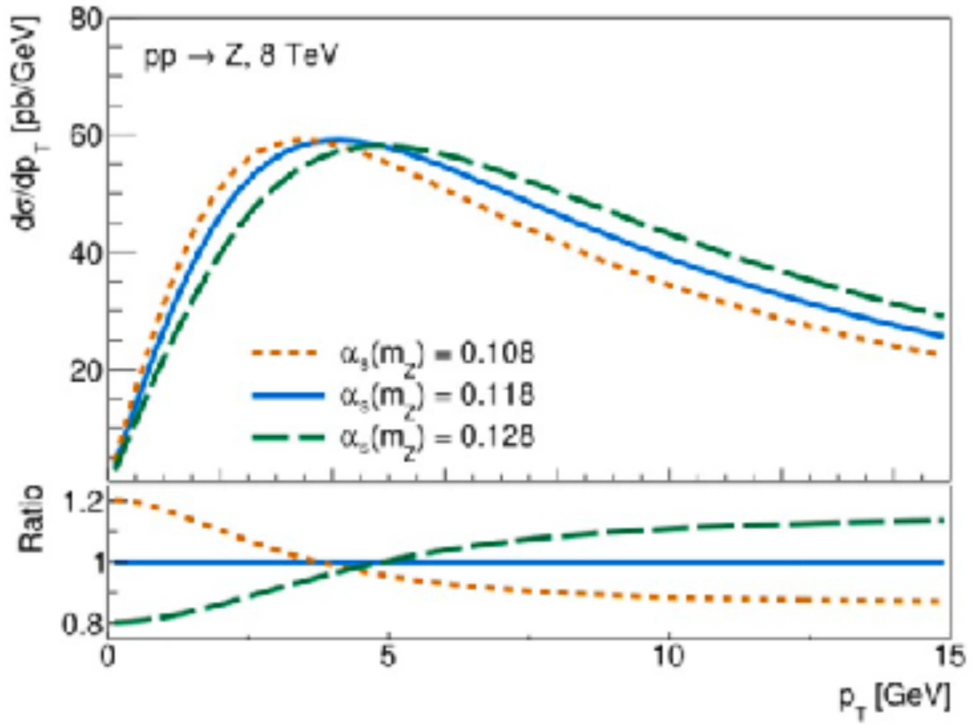
Inclusive Z transverse momentum

$$\frac{d\sigma_Z}{\sigma_z dp_\perp} \sim \frac{\alpha_s(p_\perp)}{2\pi p_\perp} \ln \frac{M_Z}{p_\perp}$$



Using **Sudakof peak in pT**, based on **resummed calculations**





0.9% Precision on par with lattice QCD and world average!

At FCC-ee

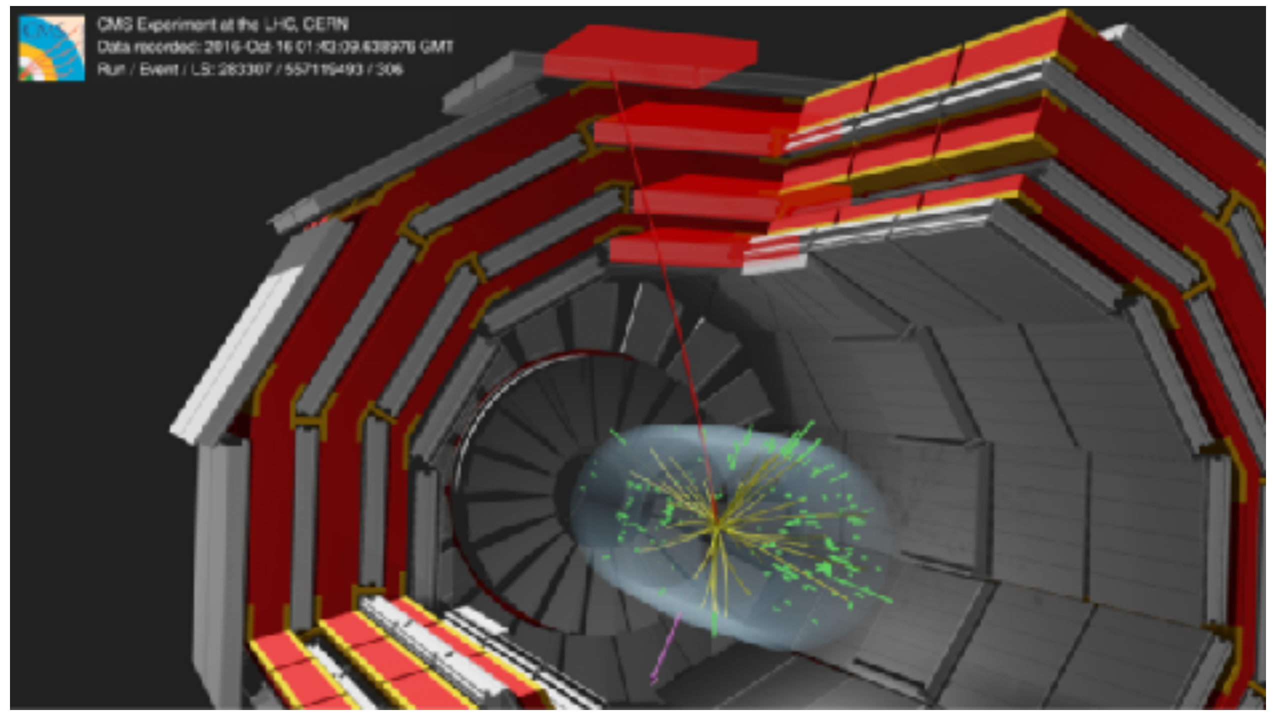
Precision 0.1% (0.01% stat)

10x improvement

From $R^Z_\ell, \Gamma^Z, \sigma^0_{had}$ syst dominated by TH

$$\Gamma_{had} = \Gamma_{had,\, no\, QCD}\left(1 + \frac{\alpha_s}{\pi} + \ldots\right)$$

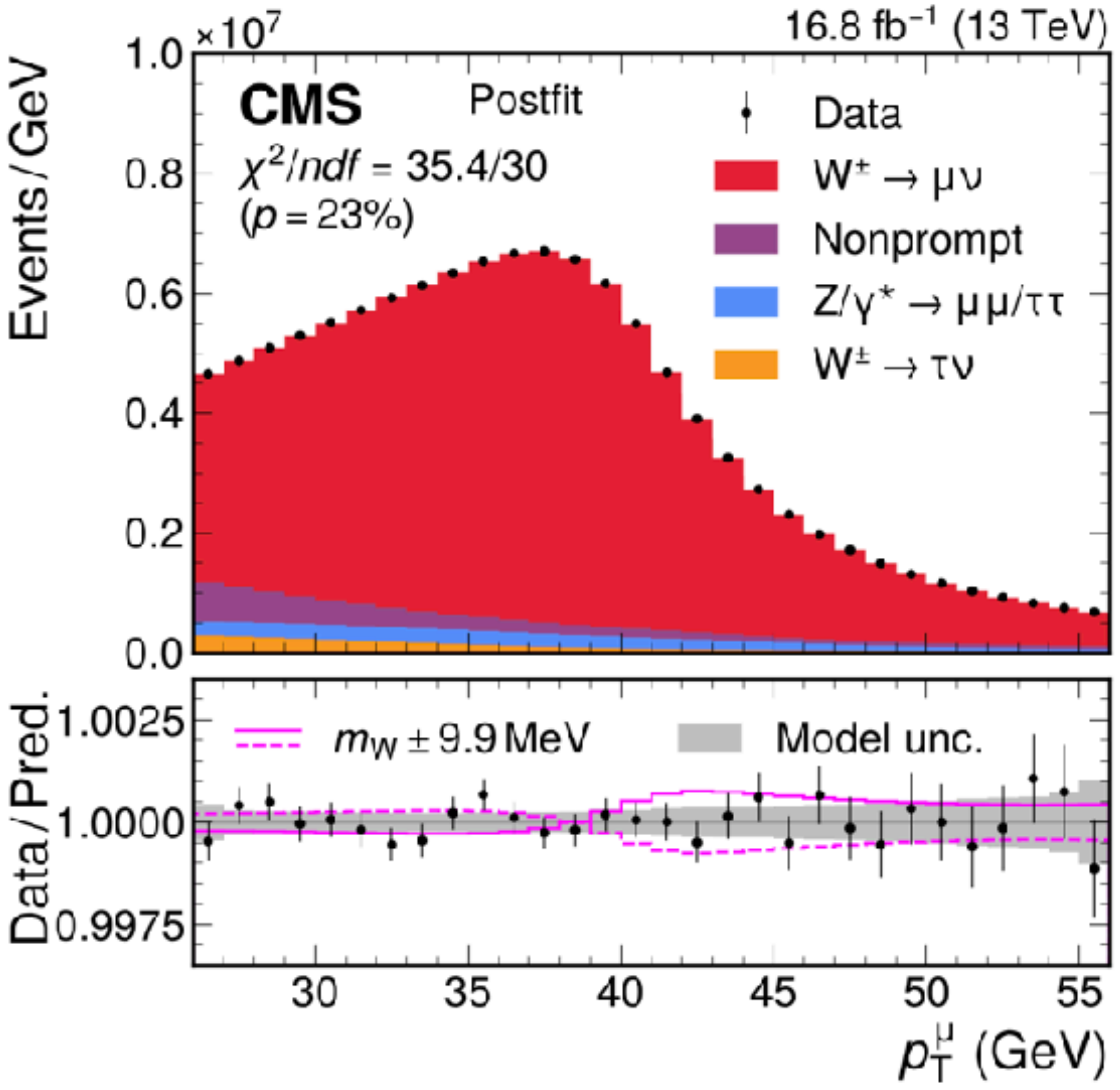
W Mass - Measurements and Puzzle

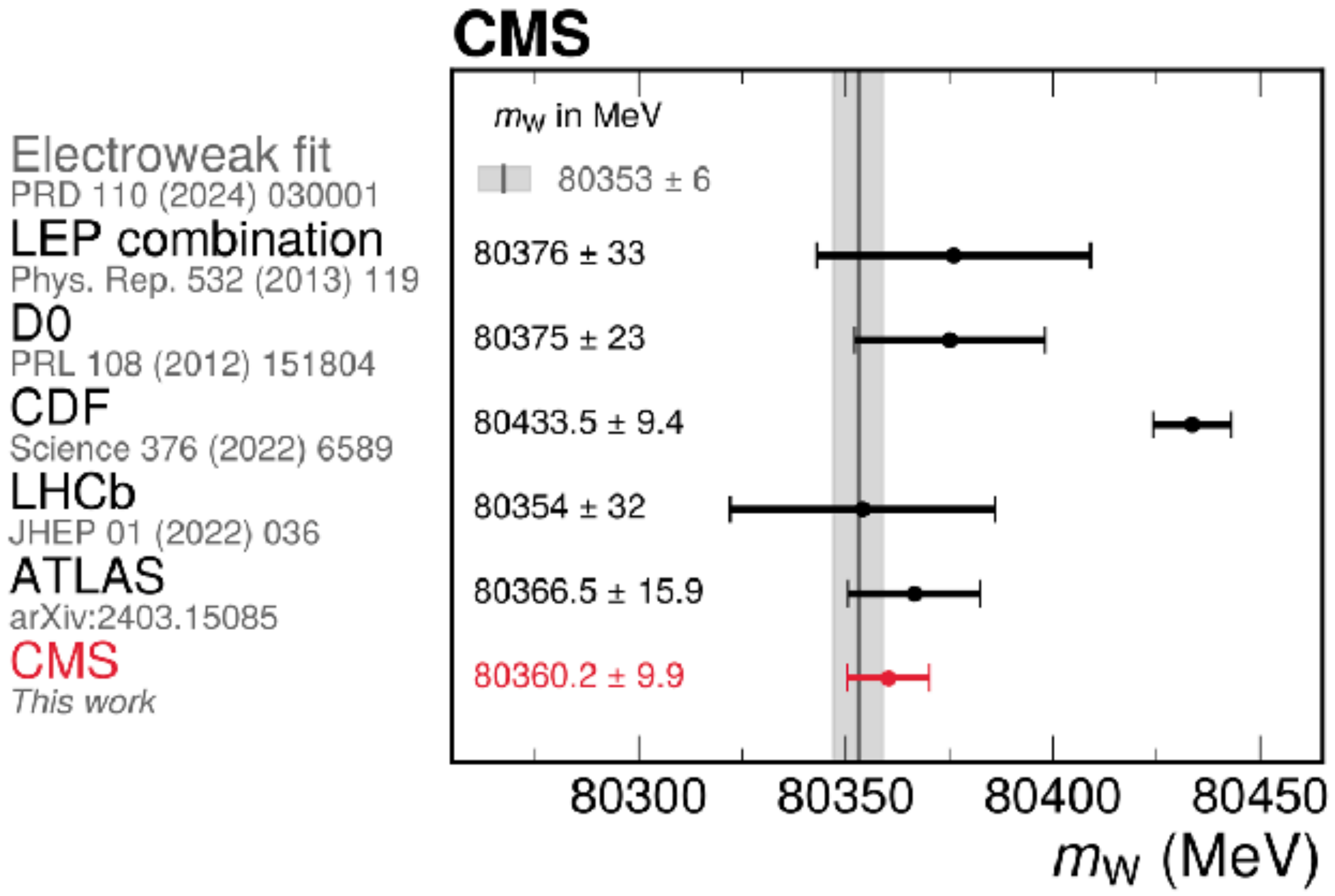


CMS Measurements of W mass

CMS briefing

Also in ATLAS and LHCb





At FCC-ee

Precision 240 keV

40x improvement

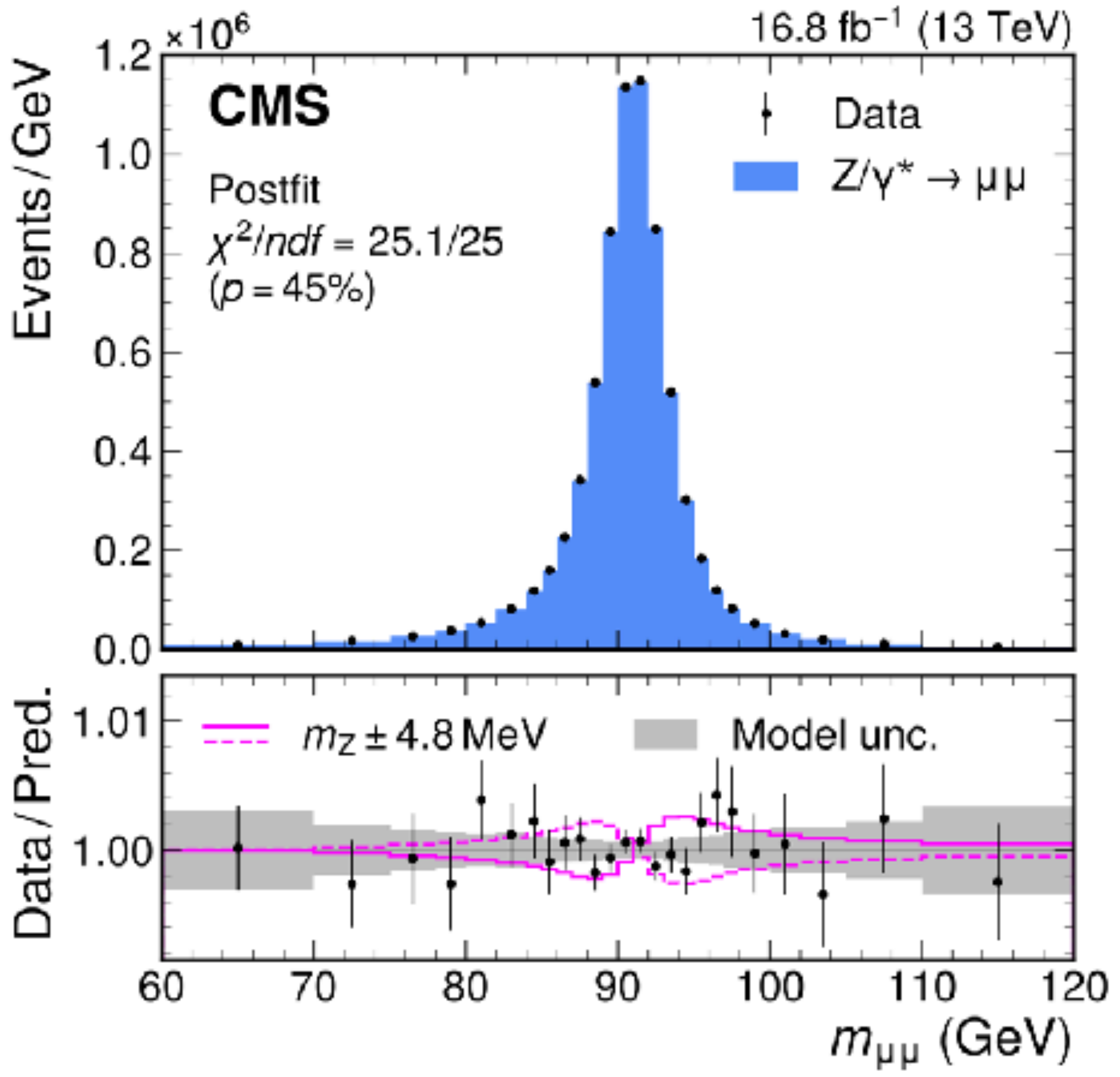
From WW threshold stat and syst on par (syst dominated by beam energy)

See slide 35 for impact on new physics!

Z Mass Measurements at the LHC

Z mass from di-muon mass by CMS

$Z \to \mu^+\mu^-$ events are not used to determine the muon momentum calibration can then be used to measure the Z mass!



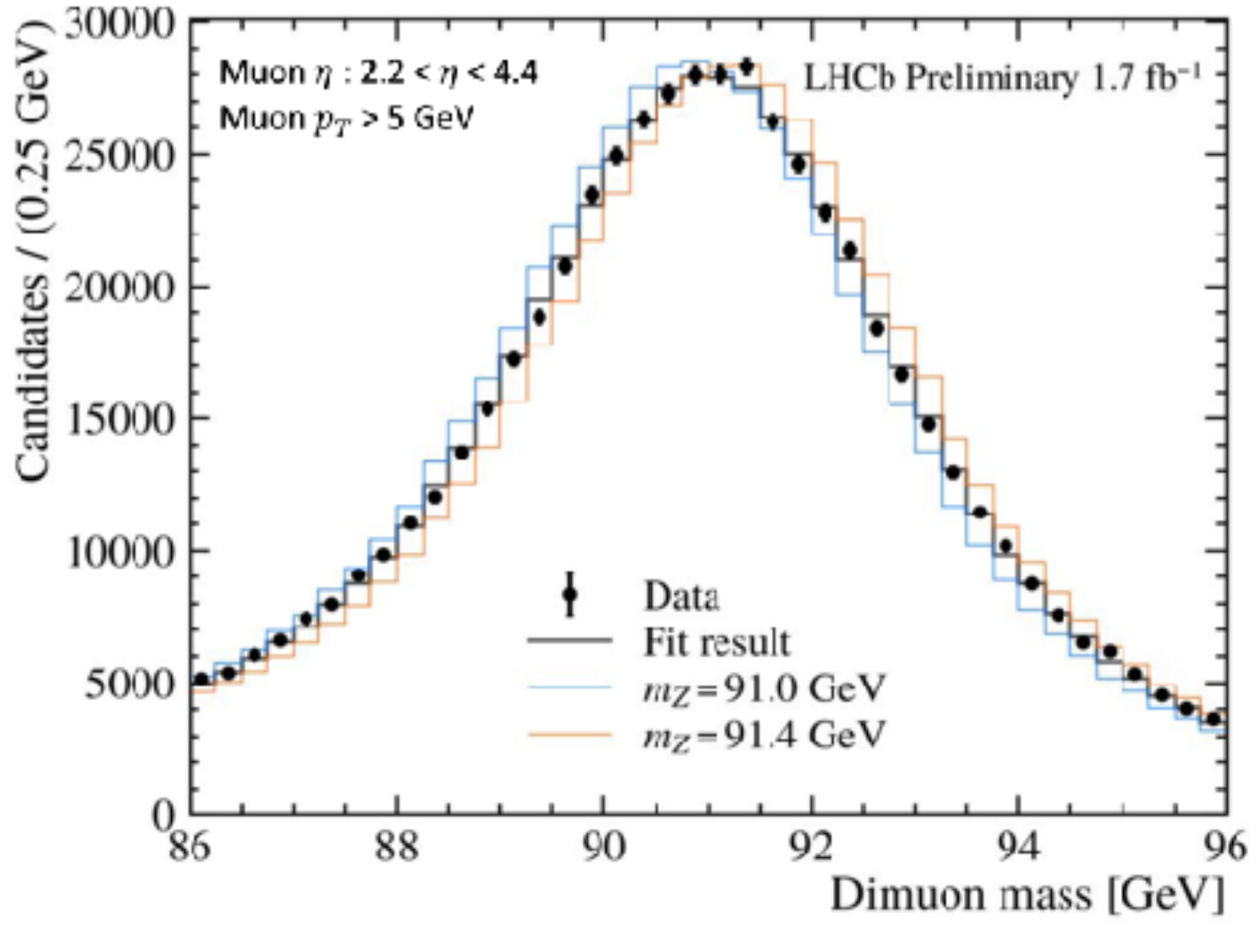
Powerful validation of the muon momentum scale and thus the W mass measurement.

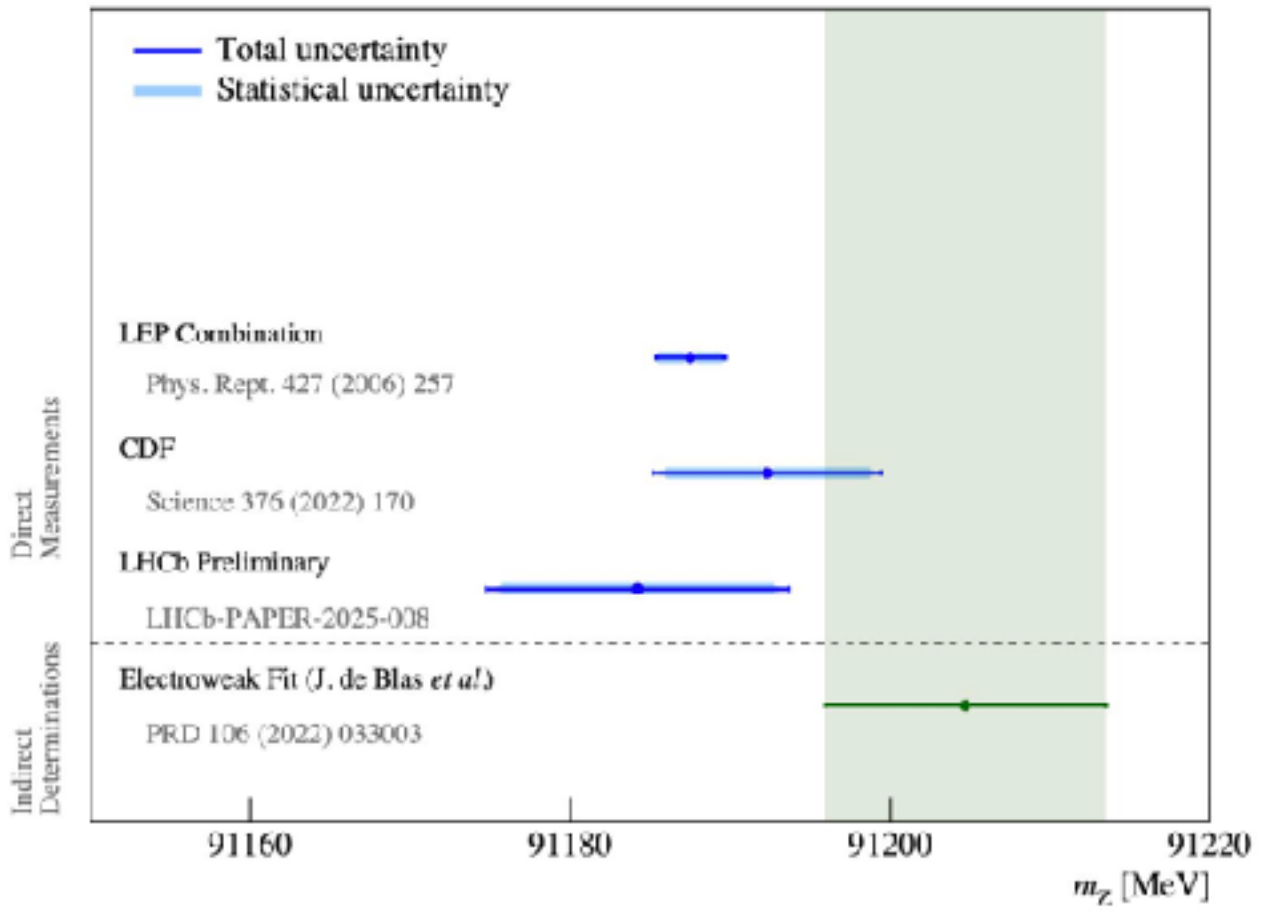
$$m_Z^{\mu\mu} - m_Z^{\text{PDG}} = -2.2 \pm 4.8\,\text{MeV}$$

Z mass measurement by LHCb

$Z \to \mu^+\mu^-$ events are not used to determine the muon momentum calibration can then be used to measure the Z mass!

$J/\psi \to \mu\mu$ (cross check) $\Upsilon(1S) \to \mu\mu$ (calibration)





First measurement at LHC!
Soon challenge LEP measurements.

$$m_Z = 91184.2 \pm 9.5\ \text{MeV}$$

At FCC-ee

Precision 100 keV (4 keV stat)

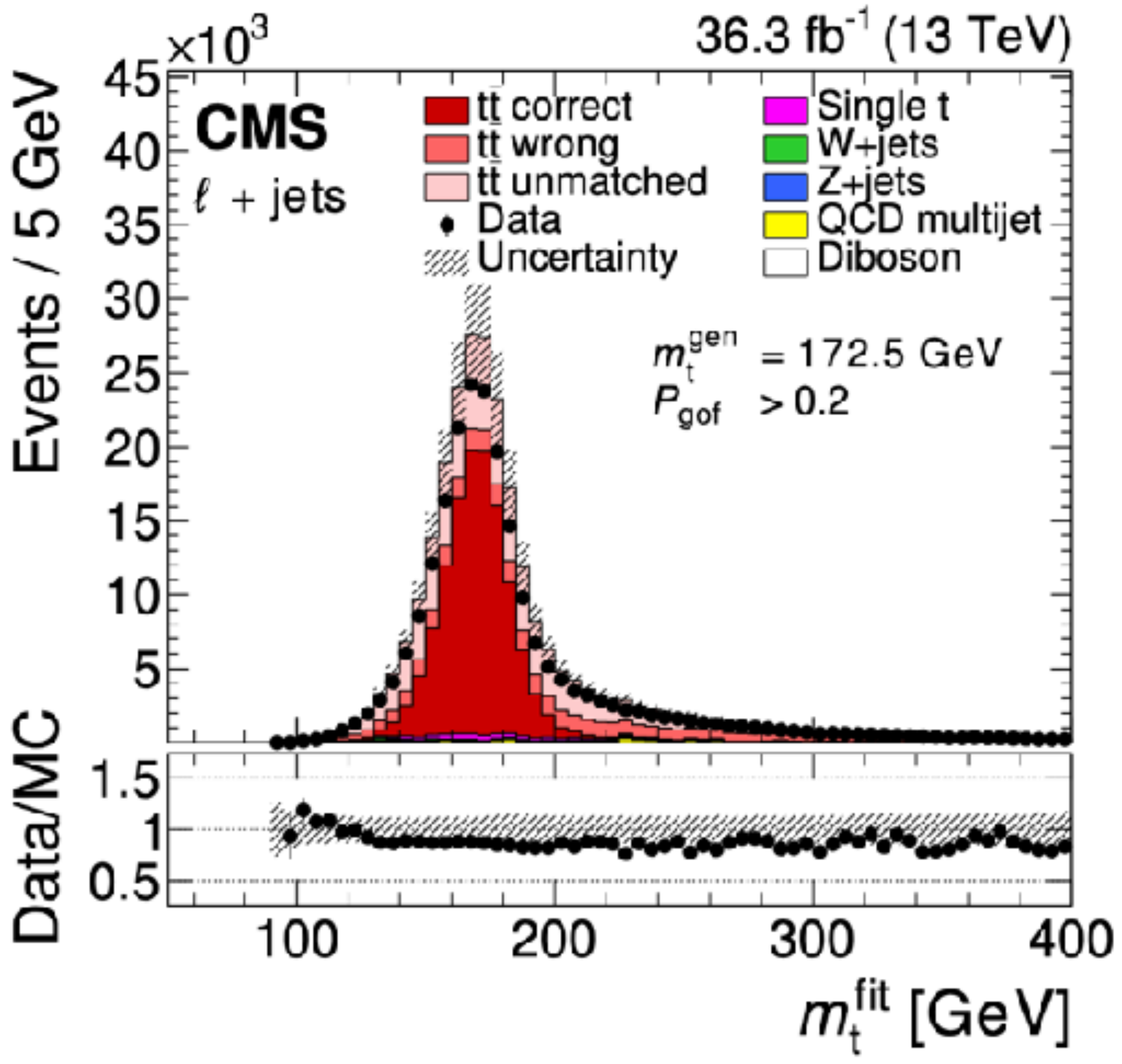
20x improvement w.r.t. LEP

From Z line shape entirely dominated by beam energy syst.

Beam energy measurement with resonant depolarisation is key!

Flavour - The Quark Sector

Most precise individual direct top mass measurement



Measurement on partial Run 2 dataset in the lepton-jets topology.

$$m_{\text{top}} = 171.77 \pm 0.37\,\text{GeV}$$

Many more top mass measurements

LHC combination

$$m_{\text{top}} = 172.52 \pm 0.14\,(\text{stat}) \pm 0.30\,(\text{syst})\,\text{GeV}$$

Still slight tension with Tevatron measurements

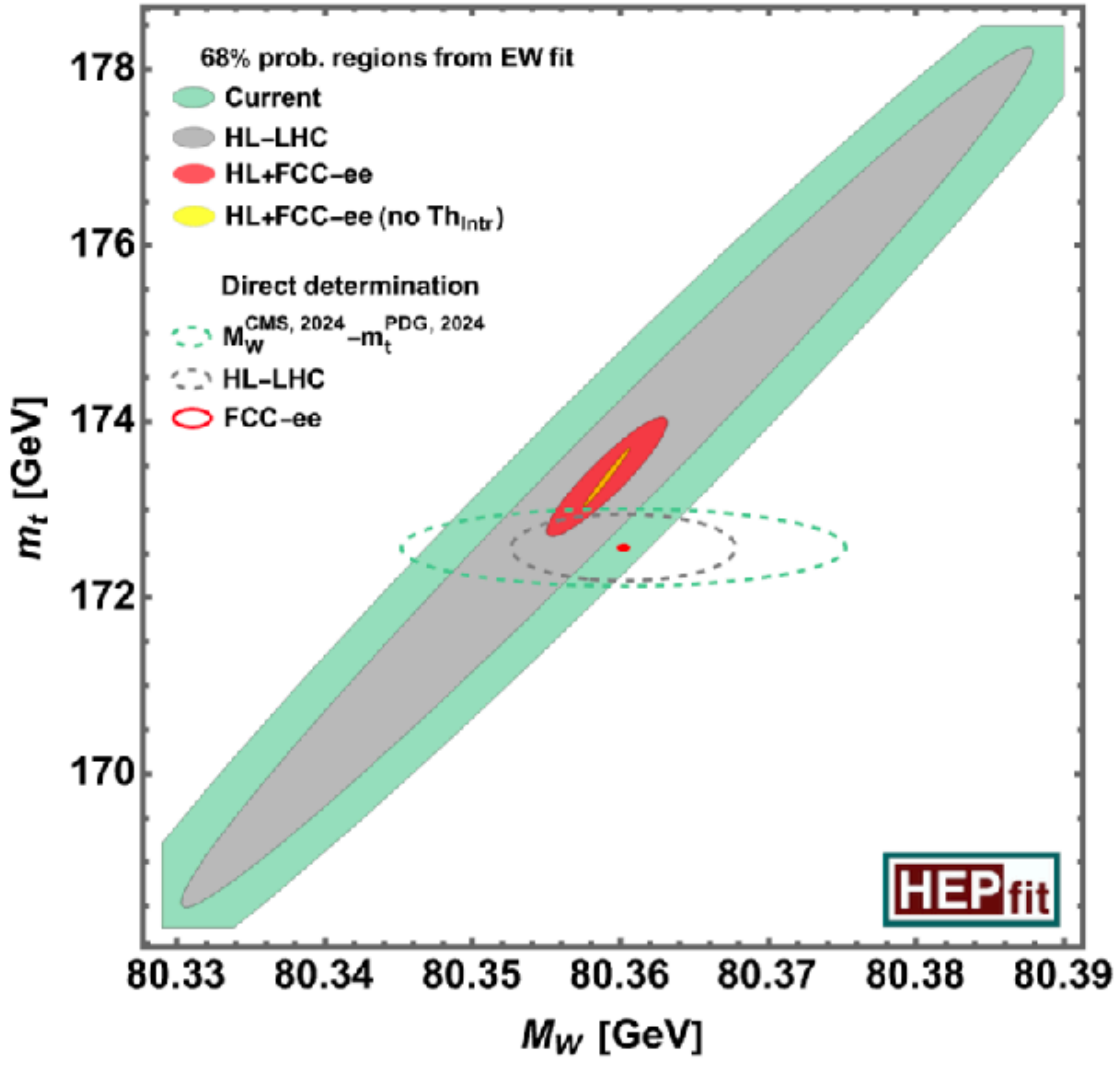
Tevatron combination: $174.34 \pm 0.37\,(stat) \pm 0.52\,(syst)$

At FCC-ee

Precision 4.2 MeV (stat) and 4.9 MeV (syst) !!

50x improvement w.r.t. LHC

From Ztt threshold, QCD uncertainties are dominant



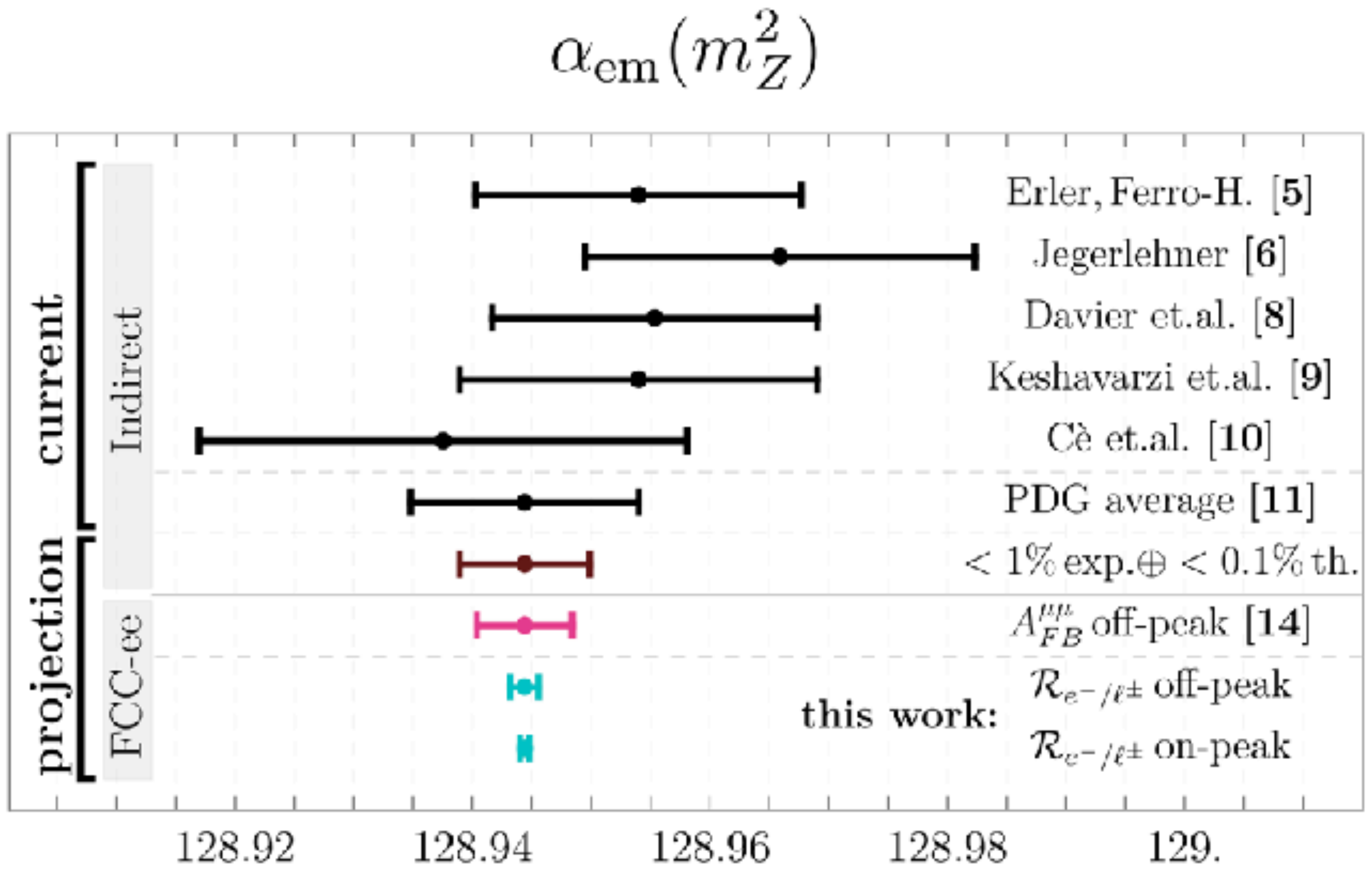
$\alpha_{em}(m_Z)$

α_{em} **at low energy is very precisely known:**

$$\alpha = 1/137.035999679(94) \quad 10^{-9}$$

Determined at low energy by electron anomalous magnetic moment and quantum Hall effect

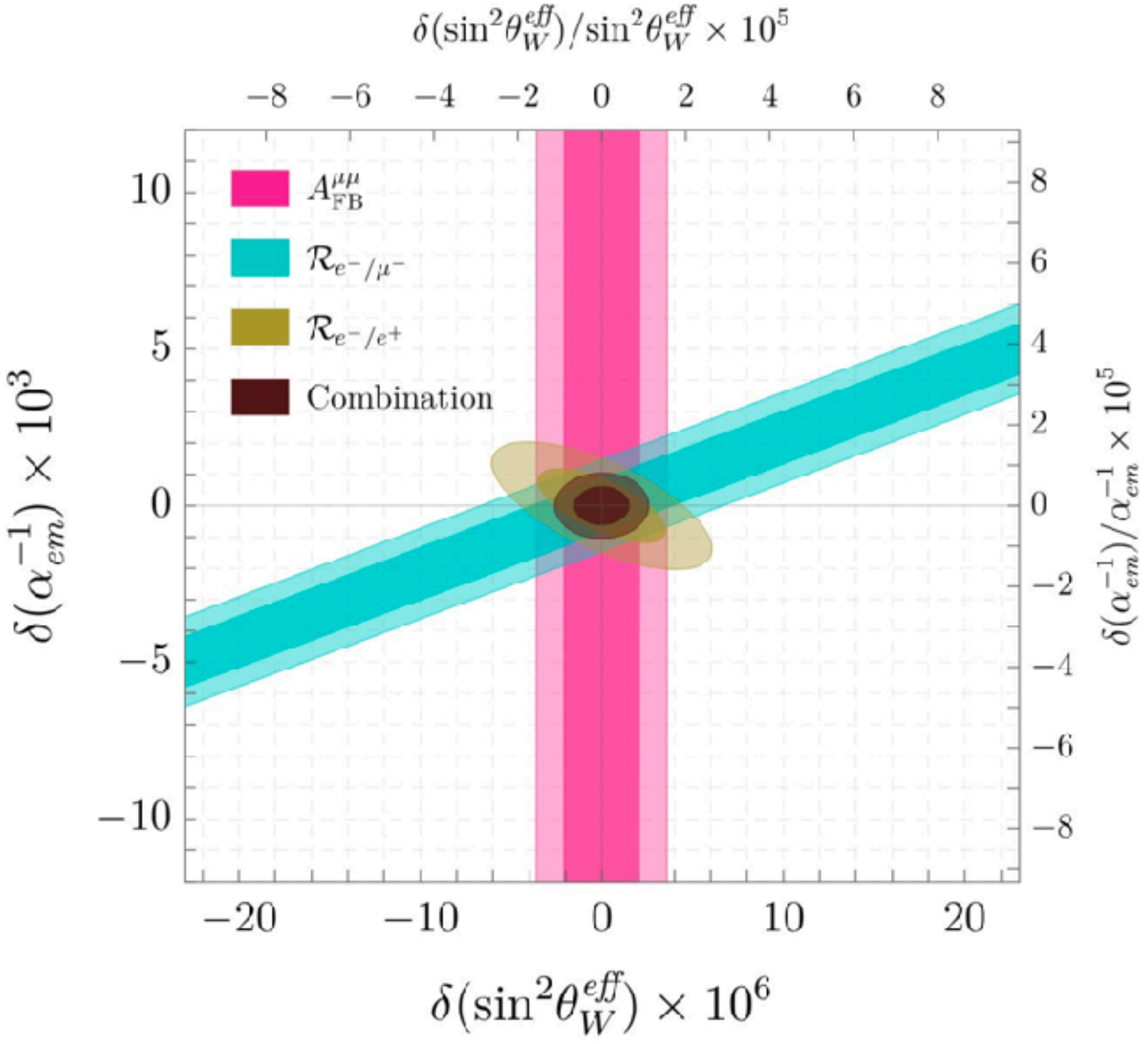
When taken at mZ, the extrapolation degrades the precision to 10^{-4}. To take full advantage of the Tera Z program a more measurement is necessary!



First idea to take $A_{FB}^{\mu\mu}$ off peak (P. Janot, 2016)

M. Riembau (link)

$$\mathcal{R}_{e^-/e^+}(\theta) = \frac{\sigma(e^-e^+ \to e^-(\theta) + X)}{\sigma(e^-e^+ \to e^+(\theta) + X)}$$



Provides a precision of below 10^{-5} statistical precision!

e^+e^- Ultimate Precision Machine!!

Observable	present value	±	present uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
m_Z (keV)	91 187 600	±	2000	**4**	100	From Z line shape scan Beam energy calibration
Γ_Z (keV)	2 495 500	±	2300	**4**	12	From Z line shape scan Beam energy calibration
$\sin^2\theta_W^{eff}$ ($\times 10^6$)	231,480	±	160	**1.2**	1.2	From $A_{FB}^{\mu\mu}$ at Z peak Beam energy calibration
$1/\alpha_{QED}(m_Z^2)$ ($\times 10^3$)	128 952	±	14	**3.9** **0.8**	small tbc	From $A_{FB}^{\mu\mu}$ off peak From $A_{FB}^{\mu\mu}$ on peak QED&EW uncert. dominate
R_ℓ^Z ($\times 10^3$)	20 767	±	25	**0.05**	0.05	Ratio of hadrons to leptons Acceptance for leptons
$\alpha_S(m_Z^2)$ ($\times 10^4$)	1 196	±	30	**0.1**	1	Combined R_ℓ^Z, Γ_{tot}^Z, σ_{had}^0 fit
σ_{had}^0 ($\times 10^3$) (nb)	41 480.2	±	32.5	**0.03**	0.8	Peak hadronic cross section Luminosity measurement
N_ν($\times 10^3$)	2 996.3	±	7.4	**0.09**	0.12	Z peak cross sections Luminosity measurement
R_b ($\times 10^6$)	216 290	±	660	**0.25**	0.3	Ratio of $b\bar{b}$ to hadrons
$A_{FB}^{b,0}$ ($\times 10^4$)	992	±	16	**0.04**	0.04	b-quark asymmetry at Z pole From jet charge
$A_{FB}^{pol,\tau}$ ($\times 10^4$)	1 498	±	49	**0.07**	0.2	τ polarisation asymmetry τ decay physics

Observable	present value	±	present uncertainty	FCC-ee Stat.	FCC-ee Syst.	Comment and leading uncertainty
τ lifetime (fs)	290.3	±	0.5	**0.001**	0.005	ISR, τ mass
τ mass (MeV)	1 776.93	±	0.09	**0.002**	0.02	estimator bias, ISR, FSR
τ leptonic ($\mu\nu_\mu\nu_\tau$) BR (%)	17.38	±	0.04	**0.00007**	0.003	PID, π^0 efficiency
m_W (MeV)	80 360.2	±	9.9	**0.18**	0.16	From WW threshold scan Beam energy calibration
Γ_W (MeV)	2 085	±	42	**0.27**	0.2	From WW threshold scan Beam energy calibration
$\alpha_S(m_W^2)$ ($\times 10^4$)	1 010	±	270	**2**	2	Combined R_ℓ^W, Γ_{tot}^W fit
N_ν ($\times 10^3$)	2 920	±	50	**0.5**	small	Ratio of invis. to leptonic in radiative Z returns
m_{top} (MeV)	172 570	±	290	**4.2**	4.9	From $t\bar{t}$ threshold scan QCD uncert. dominate
Γ_{top} (MeV)	1 420	±	190	**10**	6	From $t\bar{t}$ threshold scan QCD uncert. dominate
$\lambda_{top}/\lambda_{top}^{SM}$	1.2	±	0.3	**0.015**	0.015	From $t\bar{t}$ threshold scan QCD uncert. dominate
ttZ couplings		±	30%	**0.5–1.5 %**	small	From $\sqrt{s} = 365$ GeV run

FCC-ee is much, much more than a Higgs factory!

Superb precision achieved and uncertainties are dominated by systematic uncertainties!

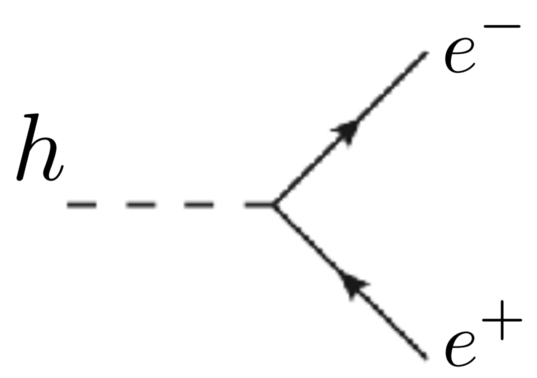
- **x50-2000*** Improvement on all EW observables
- Up to x30-100 improvement on Higgs observables

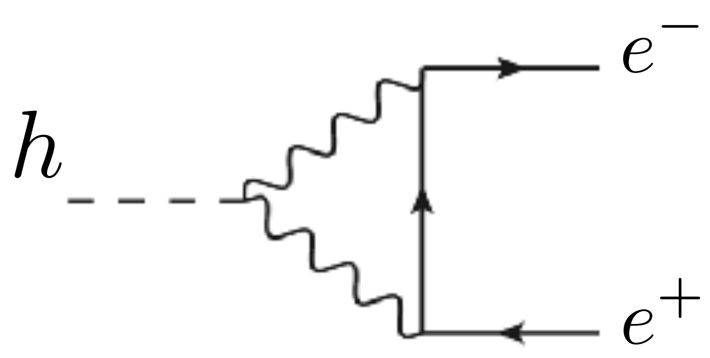
*In the case of Rb!

What about the electron Yukawa?

The soft limit of the photon is covered by the $H \to e^+e^-$ decay channel, sensitive to the electron Yukawa. The Branching fraction in the SM:

$$\mathrm{Br}(H \to e^+e^-) \sim 5\ 10^{-9}$$





Though one could hope that this would be large, it is suppressed by m_e^2

The limits obtained with a dimuon-like analysis yields a

$$\mathrm{Br}(H \to e^+e^-) < 3.4\, 10^{-4}$$

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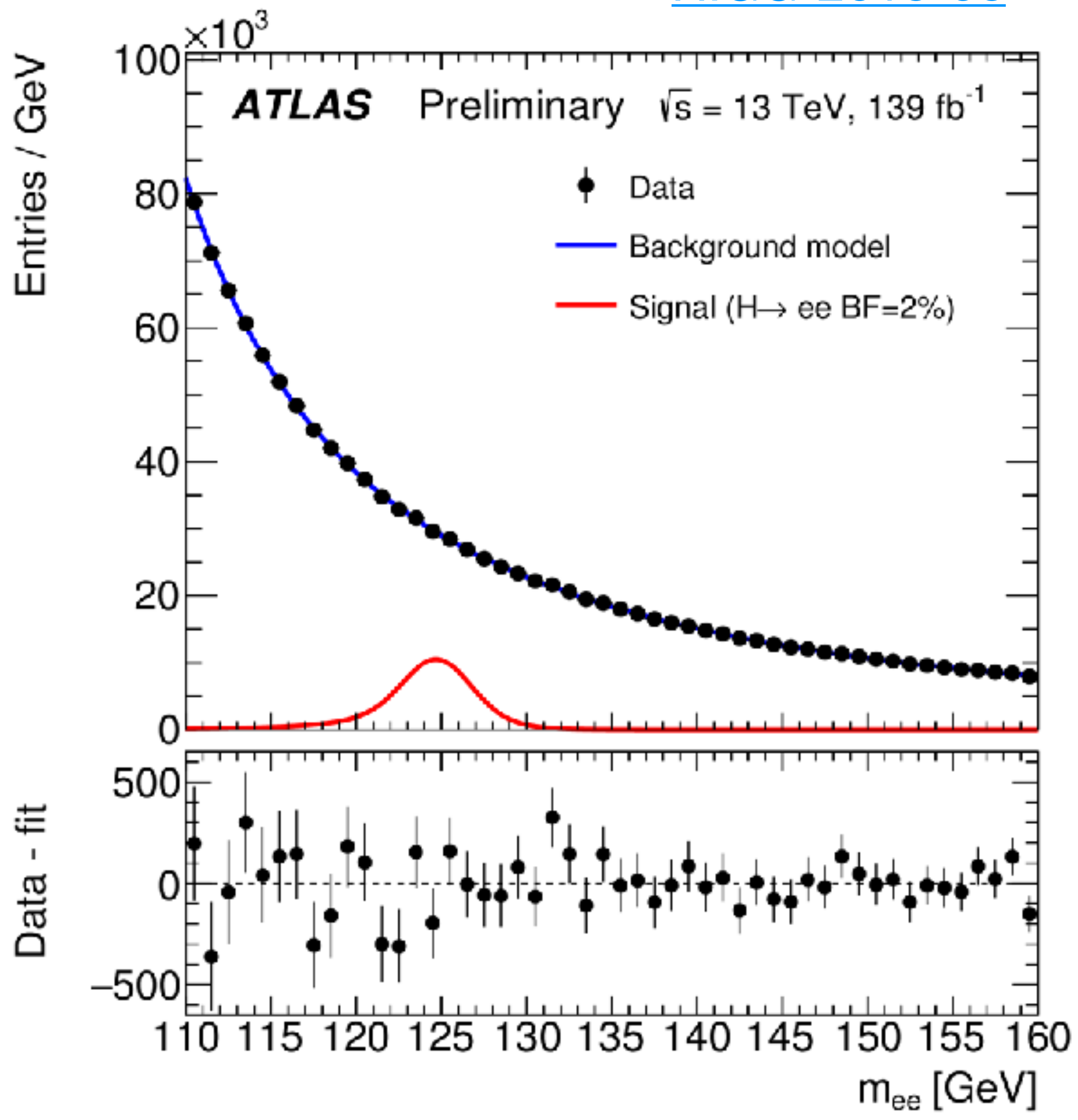


Probe large electron e-Yukawa coupling from $B \to e^+e^-$ (where B is a pseudo-scalar) which is helicity suppressed from other contributions than the Higgs exchange (potentially sensitive to large Higgs contributions)

Perhaps possible at e^+e^- collider in the s-channel $e^+e^- \to h$ (requires special run and monochromatization of beams to compensate for horizontal blow up from Bremstrahlung)

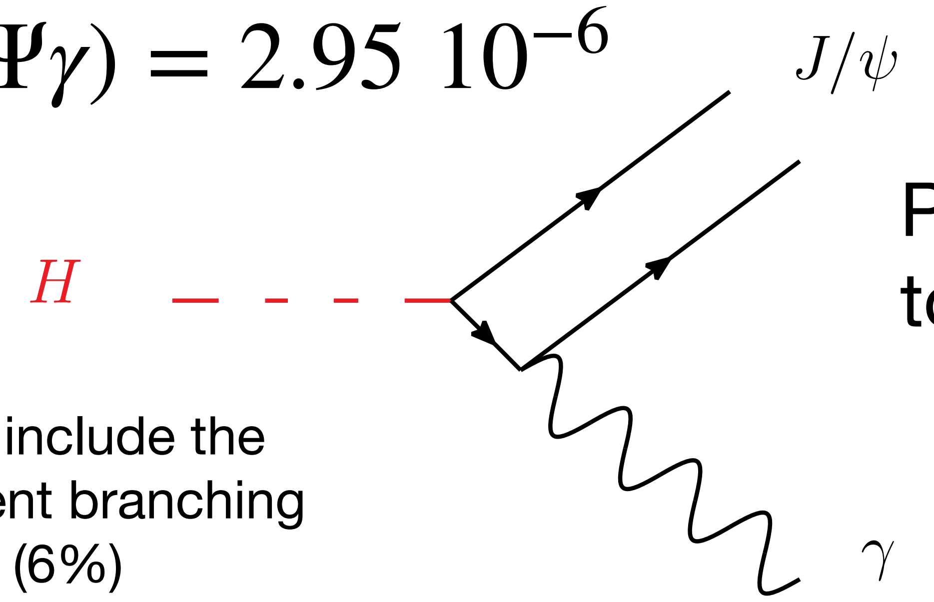
Probes of light quark and electron Yukawas in atomic physics (through isotopic shift spectroscopy in atomic clock transitions, which are the most precise frequency measurements!)

More Decays with to Quarkonia and a Photon

Current limits

Neubert et al., 2015

$$\mathrm{Br}(J/\Psi\gamma) = 2.95\ 10^{-6}$$

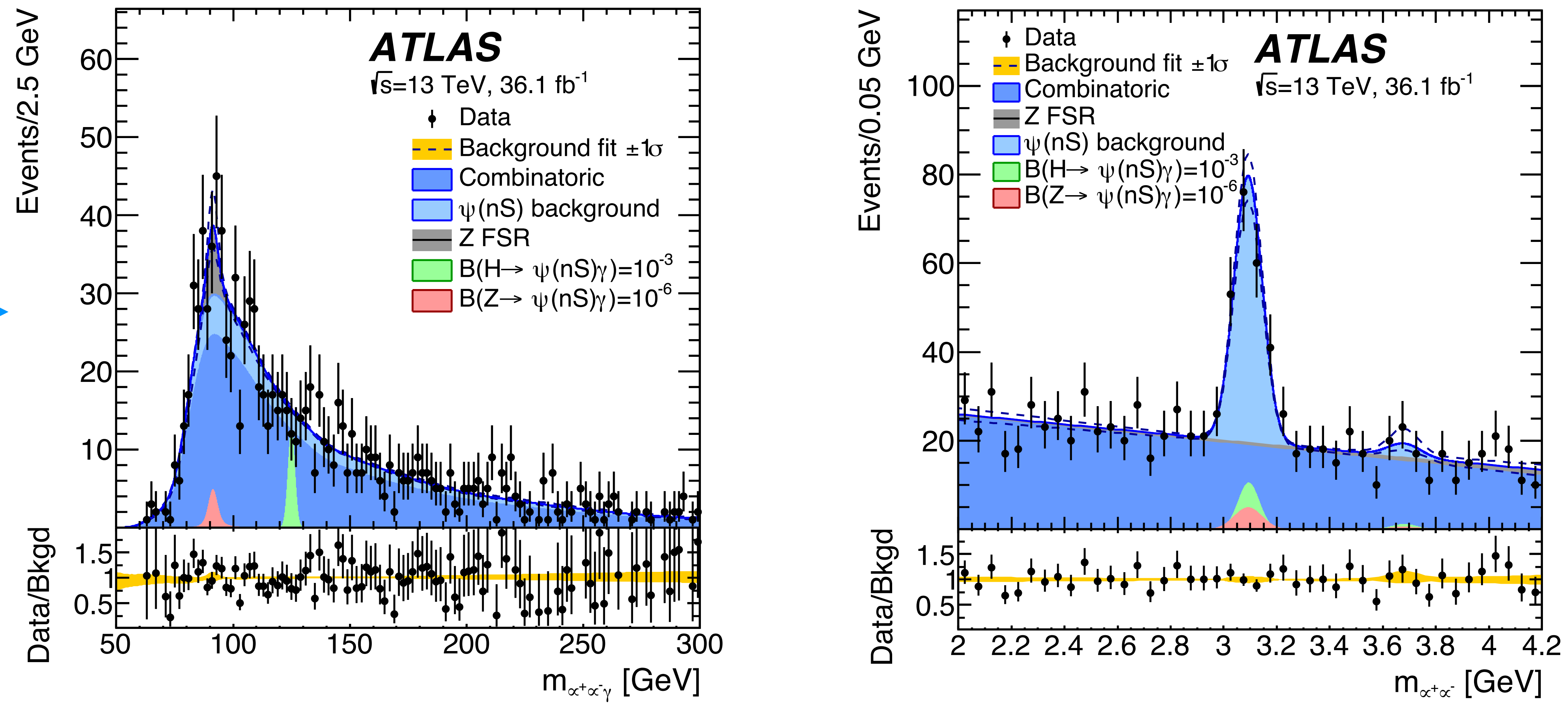


Does not include the subsequent branching to muons (6%)

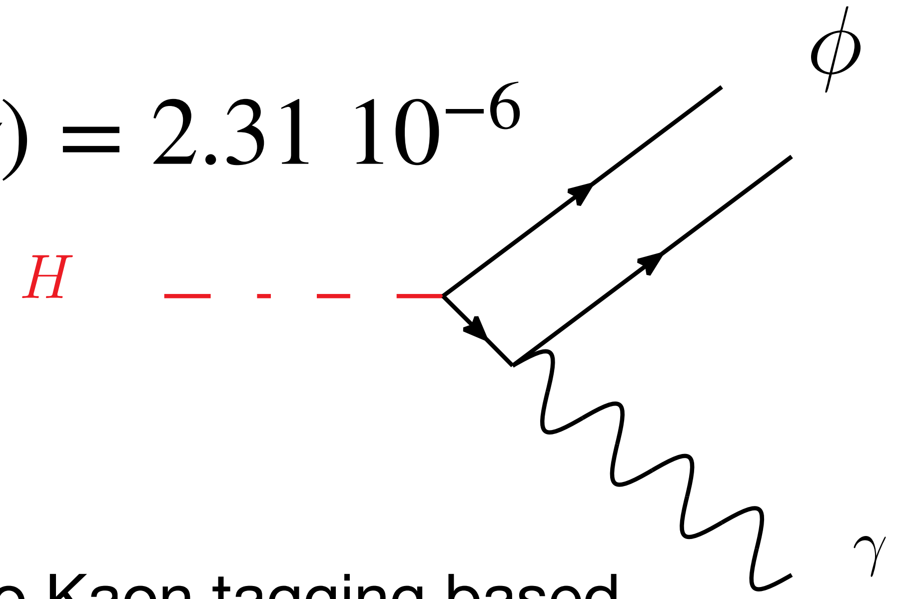
Potentially sensitive to charm Yukawa

$$\mu^+\mu^-\gamma$$

~100 x SM



$$\mathrm{Br}(\phi\gamma) = 2.31\ 10^{-6}$$



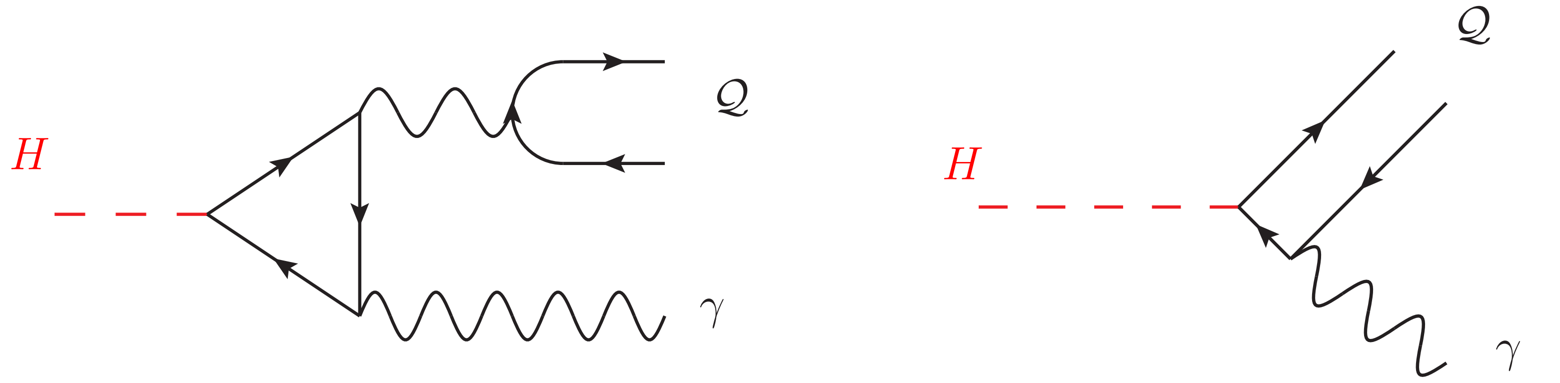
Potentially sensitive to strange Yukawa

$$K^+K^-\gamma$$

~200 x SM

No Kaon tagging based on the ϕ mass only

Measuring the Higgs decays to quarkonia and a photon do not give exclusive access to the Yukawa



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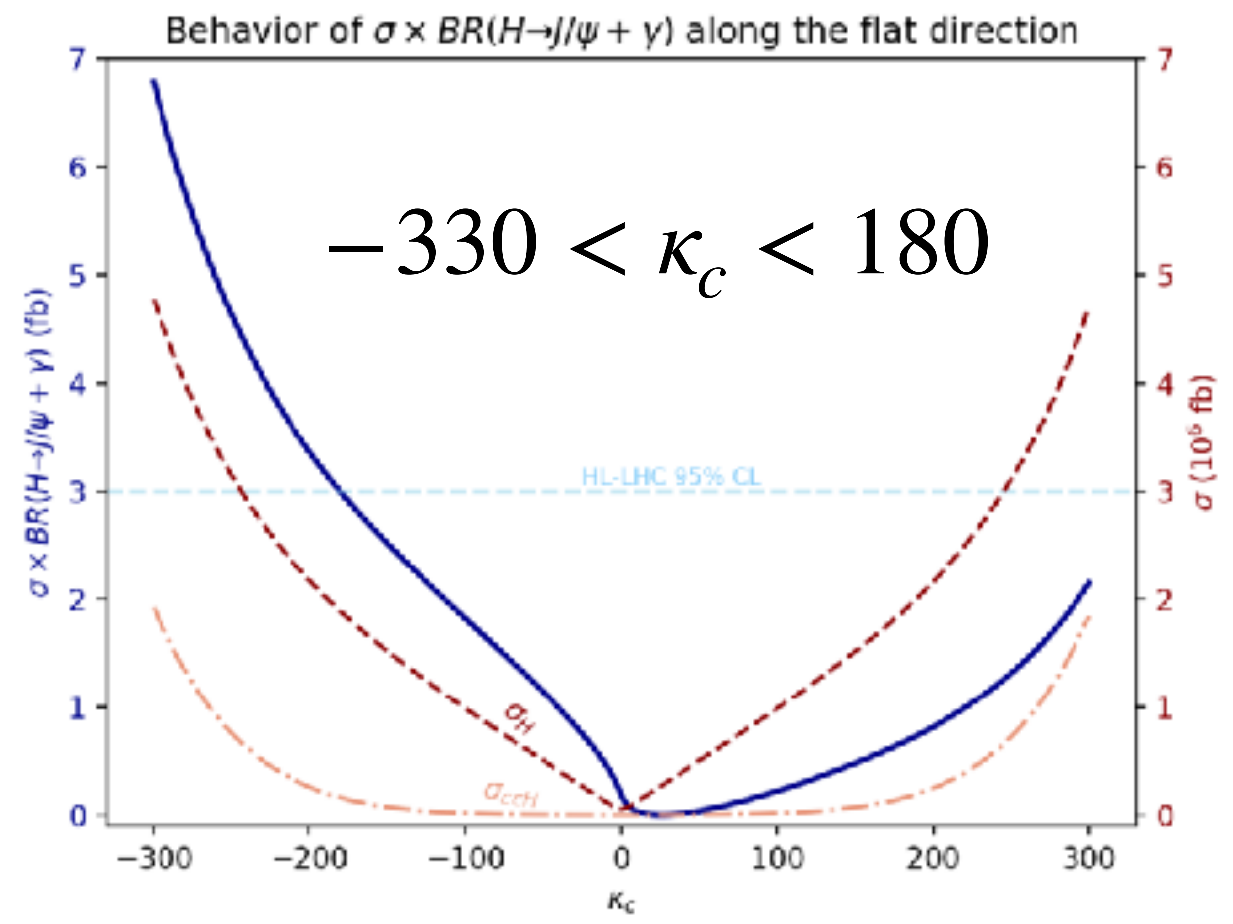
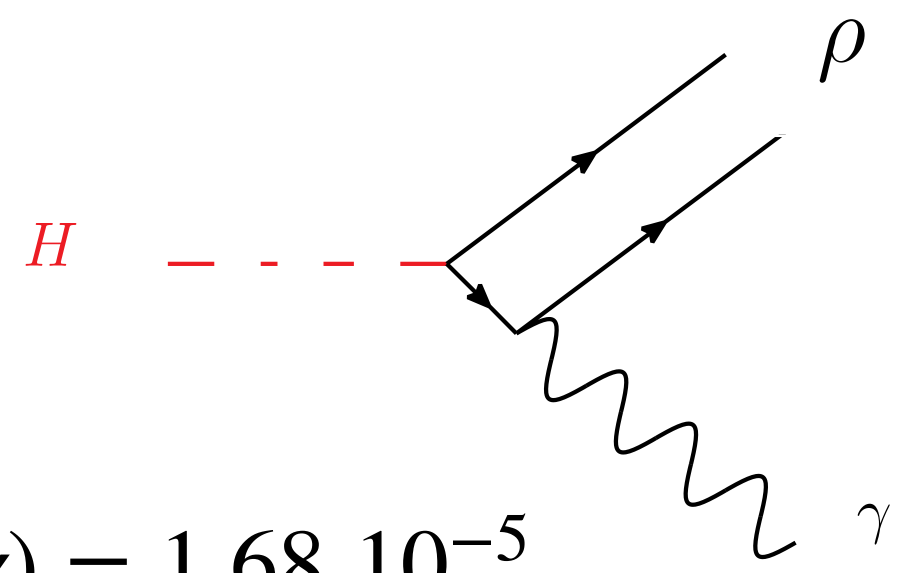




Potentially sensitive to light Yukawa

$$\pi^+\pi^-\gamma$$

~50 x SM

$$BR(H \to J/\psi + \gamma) \approx \frac{(5|\kappa_c|^{1/2} - 1.04\kappa_c)^2 \times 10^{-10}\ \mathrm{GeV}}{(0.16|\kappa_c| + 0.03\kappa_c^2) \times \Gamma_H^{SM}}$$

Highly non trivial interpretation as a value of κ_c of ~100 requires a $\kappa_t \sim 20$ i.e. a non perturbative top Yukawa!

$$\mathrm{Br}(\rho\gamma) = 1.68\ 10^{-5}$$

Paradoxically closest limit to SM sensitivity

More on the 2d Generation (charm) Yukawa Couplings

Very challenging, various ways to constrain

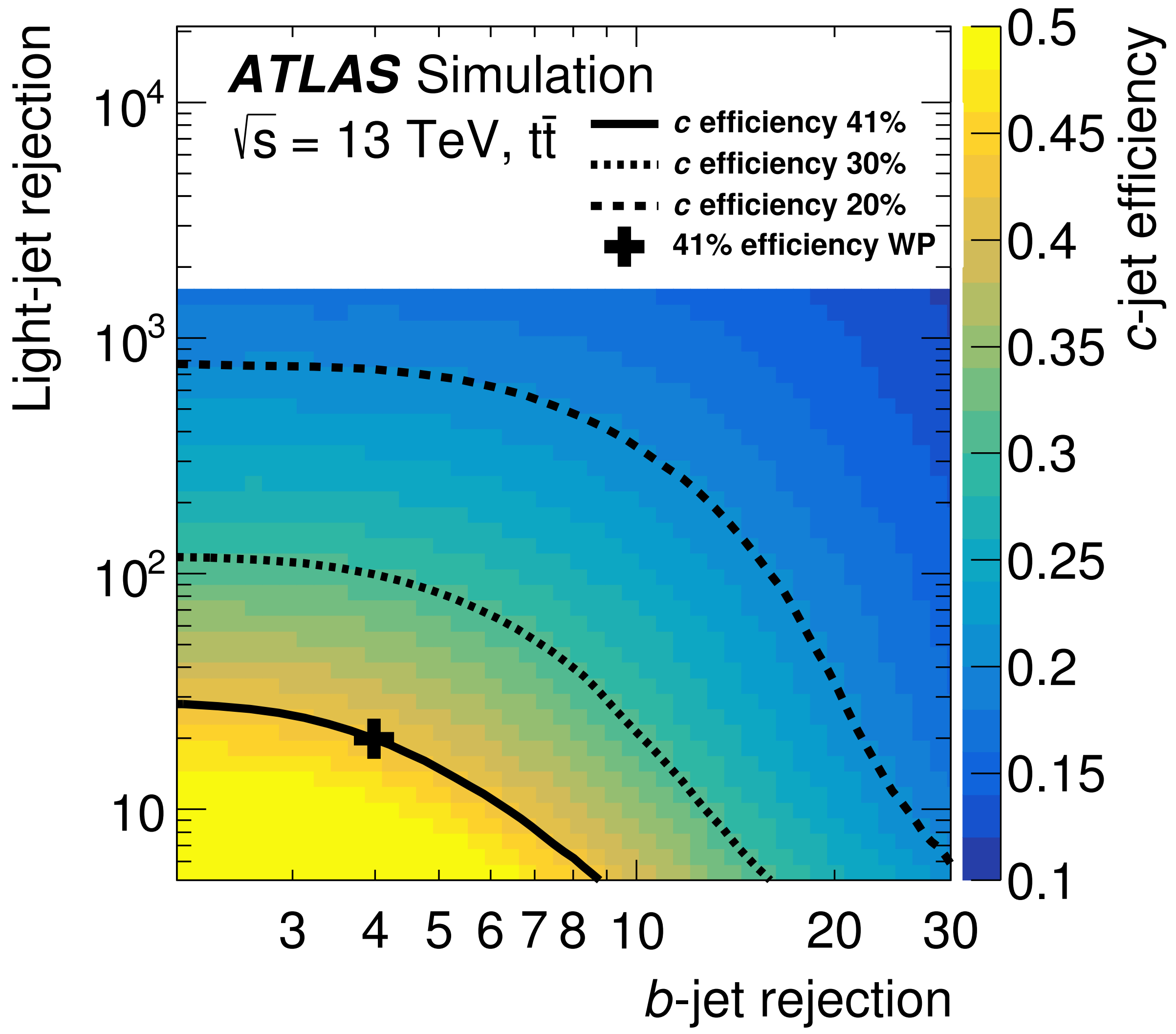
- VH(cc) direct detection, relies on ability to distinguish b and c jets, using charm tagging (based on the charm decay length comprised between b jets and light jets) - based on deep neural network techniques.

- Differential cross sections (as discussed previously in lecture 1)

- Charmonium-photon exclusive decays

- WH production charge asymmetry (PDFs)

- Search for Hc production



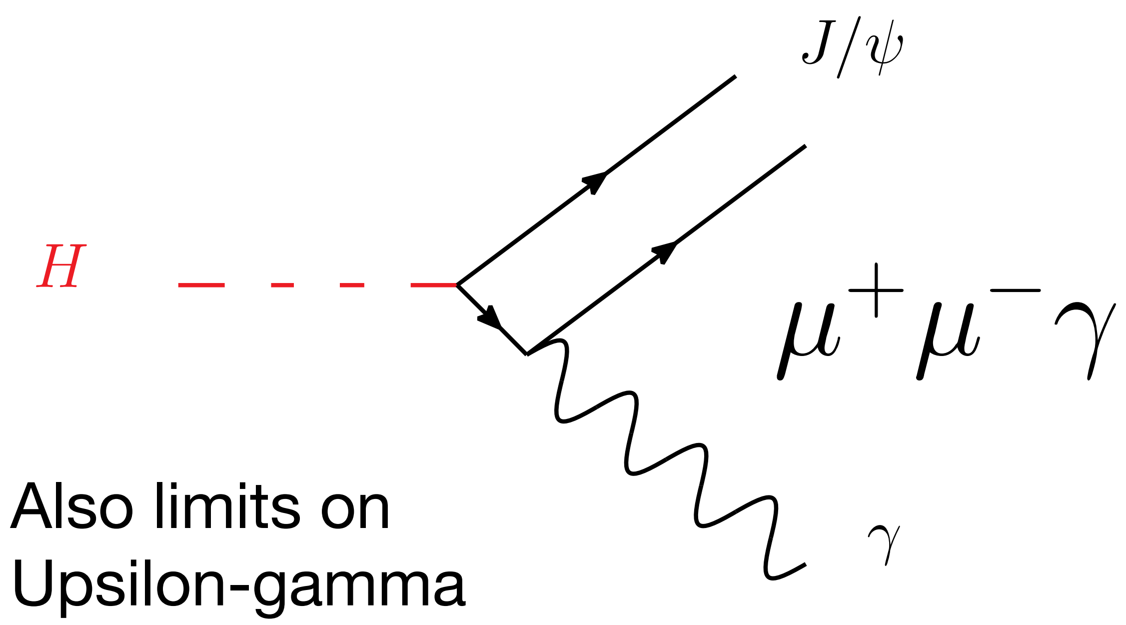
Run 2 (ATLAS and CMS)

<26xSM

HL-LHC

<6xSM

Potentially sensitive to charm Yukawa

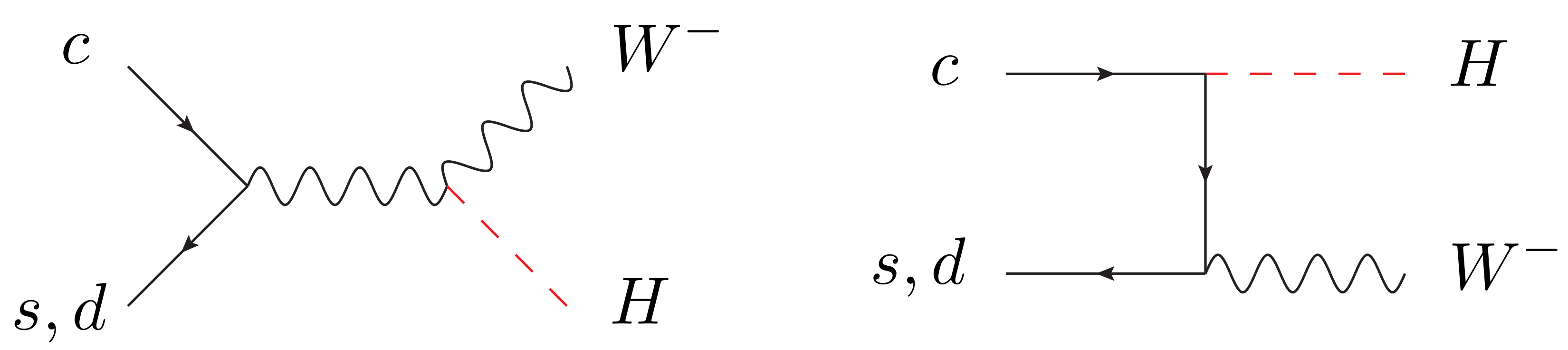


Also limits on Upsilon-gamma

Sensitivity to gamma-gamma* (top loop) and interference

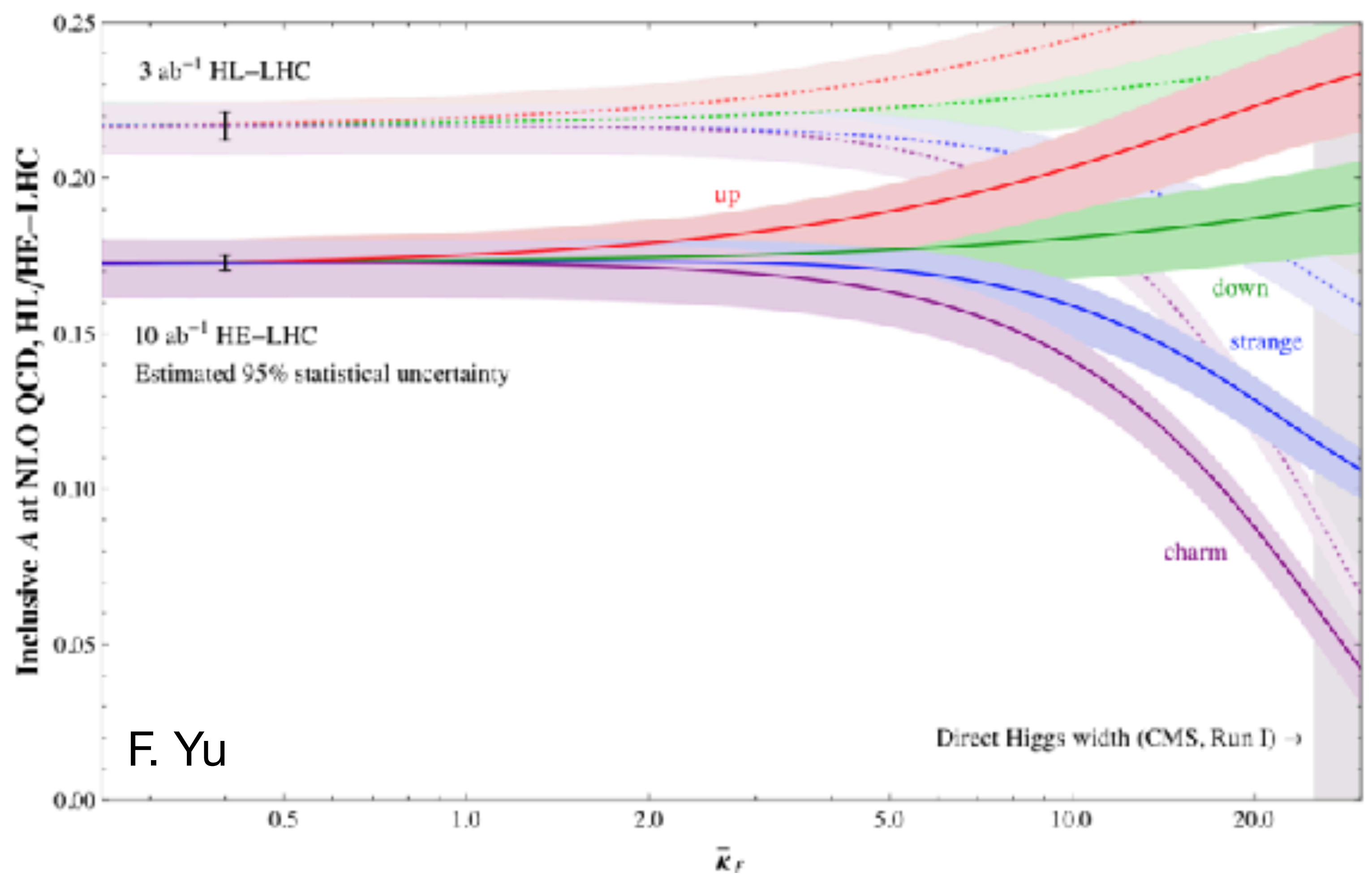
HL-LHC

<15xSM



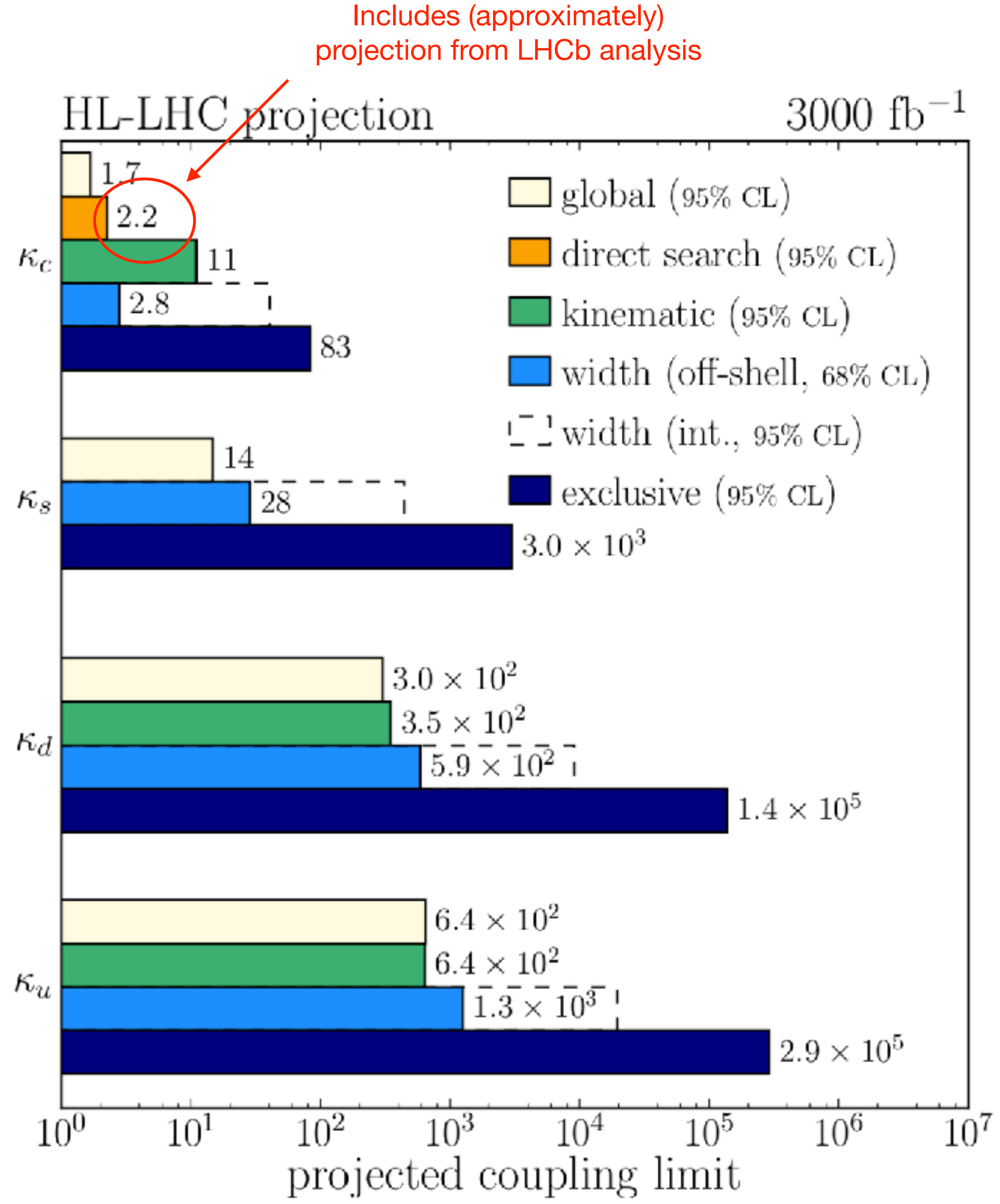
Based on d anti-d asymmetry in the PDFs

$$A = \frac{\sigma(W^+h) - \sigma(W^-h)}{\sigma(W^+h) + \sigma(W^-h)}$$



Example of new idea in ratios where many TH uncertainties will cancel, of course in this case sensitive to PDFs.

Summary on Flavors
(at HL-LHC with comments on HE-LHC)



First and Second generation Yukawas

- Extremely challenging at HL-LHC (most stringent constraint coming from the couplings fit assuming no BSM width).

- For the charm Yukawa direct search (using charm tagging) is not far behind!

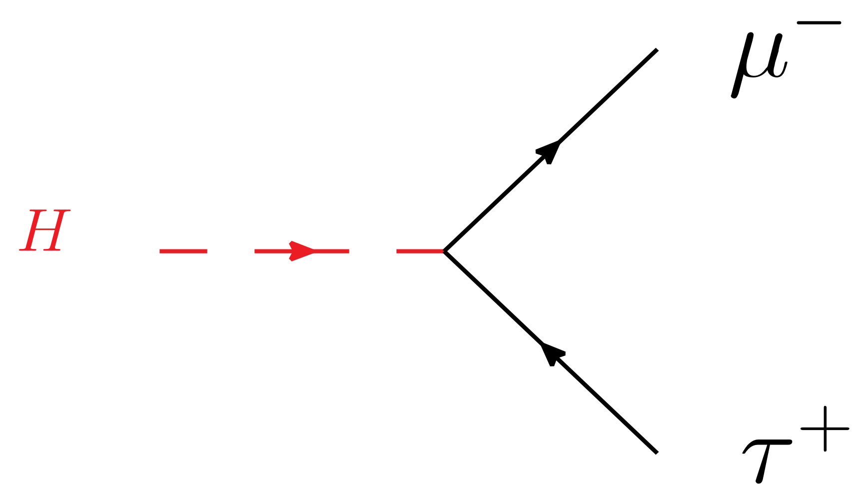
- Then comes sensitivity to coupling combination through width offshell.

- Exclusive searches still only marginally sensitive.

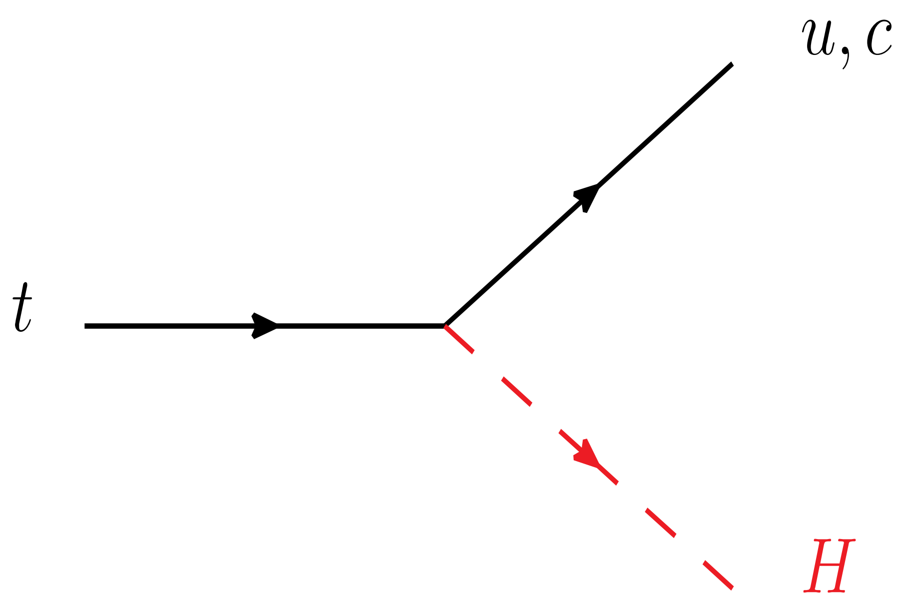
- New emerging ideas to be explored with such large datasets.

More rare decays and production Modes

Lepton flavor violating decays



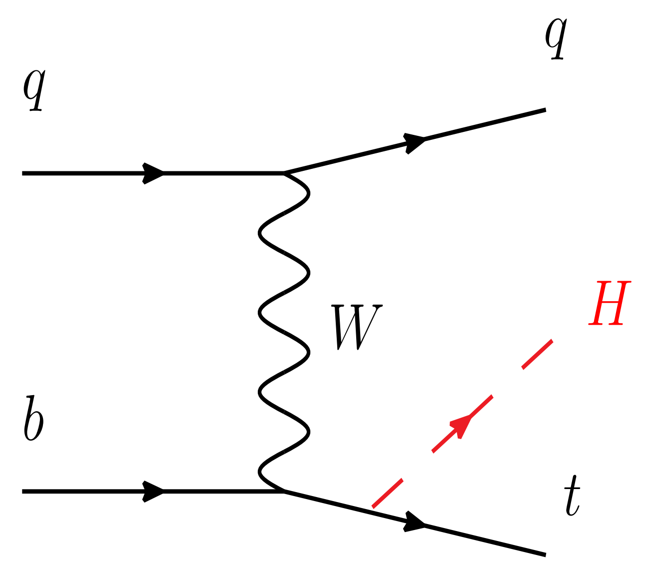
Flavor changing neutral curent decays of the top quark

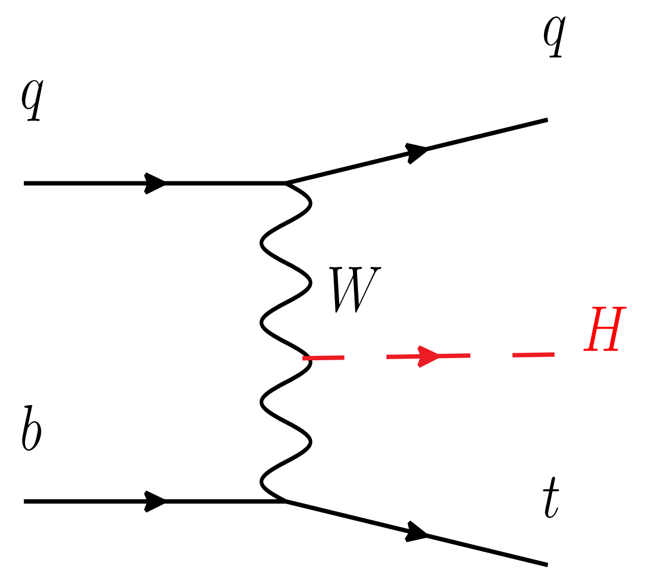


Various decay channels of the Higgs boson (diphoton, bb)

Single top associated production

Tree level interference between W and top





Flavour Changing Neutral Currents

In the **Standard Model** the Yukawa couplings are diagonalised as the mass matrix: **no flavour non-diagonal terms**.

Non diagonal terms can arise in dimension 6 operators in a SM EFT

$$\frac{\phi^\dagger \phi}{\Lambda^2}\left(\lambda_{ij} F_L^i \phi \overline{f^j_d}_R + \lambda_{ij} F_L^i \phi^c \overline{f^j_u}_R\right)$$

In this case the Yukawa-masses relation is broken, and di- and tri-Higgs terms will be generated!

$$Y_{ij} \sim \frac{m_{ij}}{v} + \frac{v^2}{\Lambda^2} c_{ij}$$

As in 2HDMs unless carefully assuming that one Higgs doublet couples to a type of fermion at a time (Natural Flavour Conservation rule - yielding types I - IV 2HDMs)!

Not a necessary condition to match the Kaon, B and muon decays data

Cheng and Sher Ansatz

$$\lambda_{ij} \sim \frac{\sqrt{m_i m_j}}{v}$$

This Ansatz works well with most constraints (light quarks and leptons), but for higher masses the Higgs data can be of interest (experimental goal).

Going beyond this Ansatz requires fine tuning and this is thus called the « Naturalness Limit »

Defines a good experimental goal!

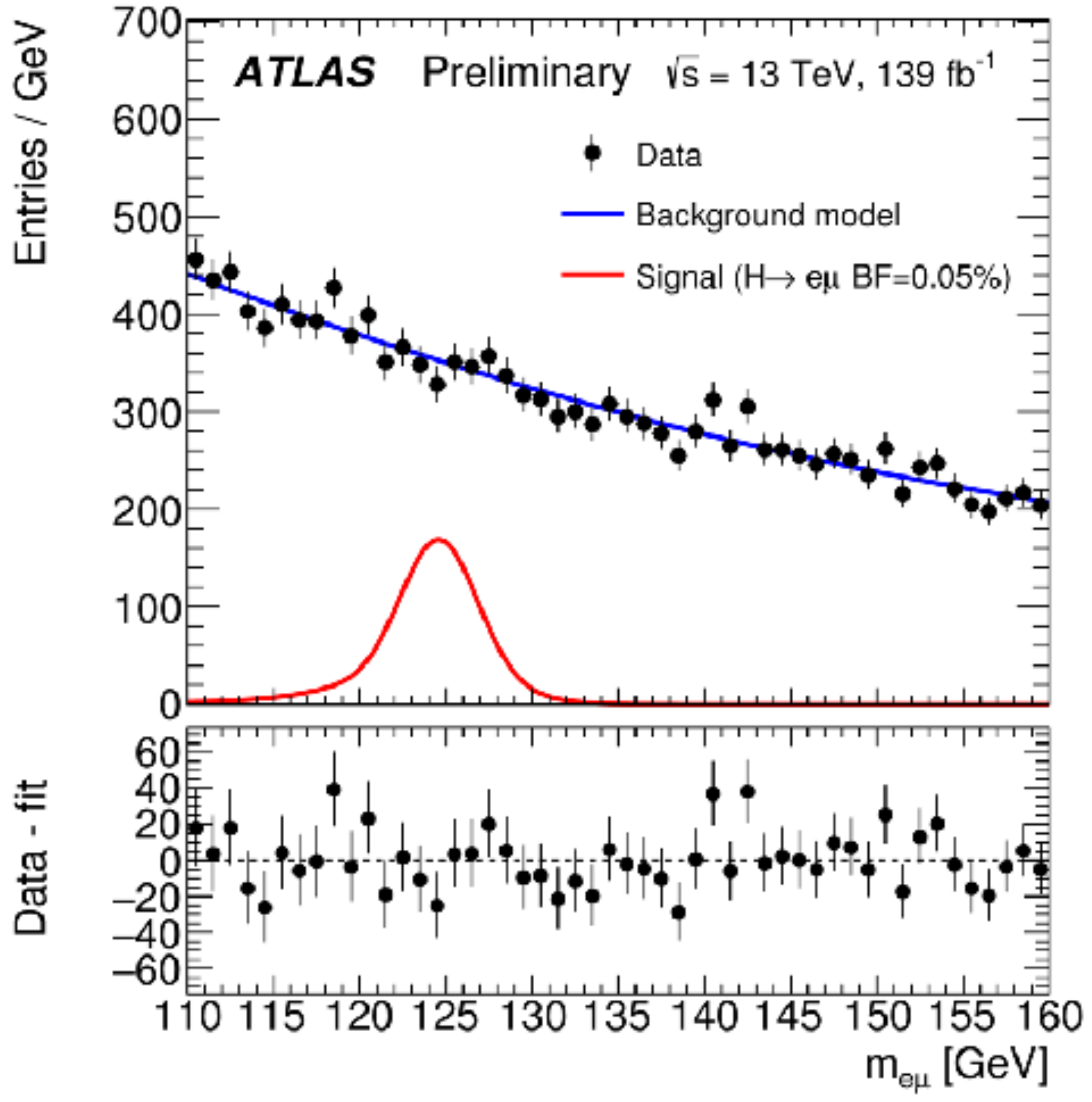
Lepton Flavor Violating Couplings

Simplest channel at the LHC is the $e\mu$ but it is way more constrained by $\mu \to e\gamma$ experiment (MEG)

$$\mathrm{Br}(\mu^+ \to e^+\gamma) < 4.2\ 10^{-13}$$

$$\mathrm{Br}(H \to e\mu) < O(10^{-8})$$

Depending on assumptions on the diagonal e and μ Yukawa

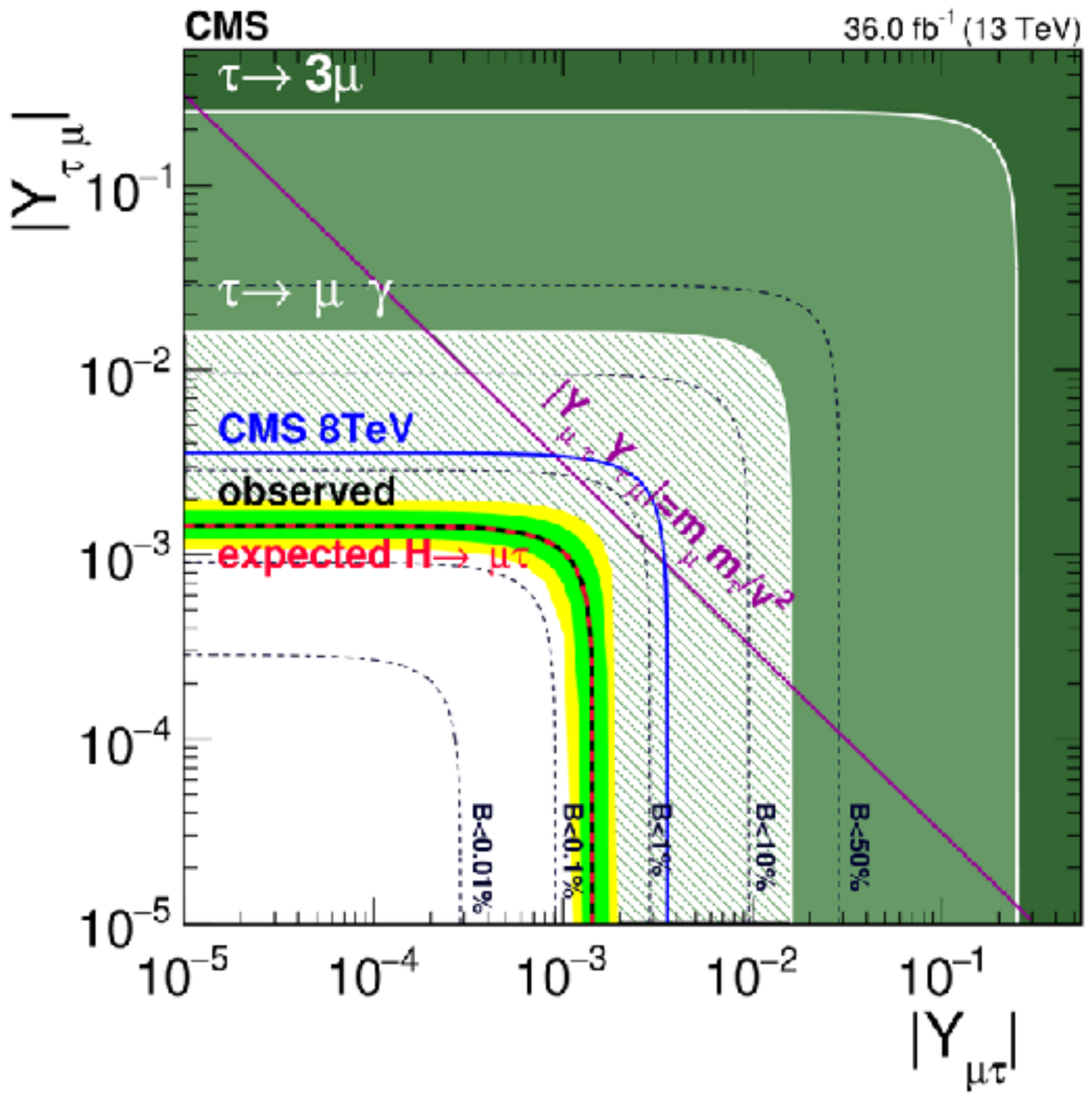


Limit on $e\mu$ LFV Branching at 95%CL:

$\mathrm{Br} < 6.1\ 10^{-5}$ Only factor ~10 from « naturalness » limit

The **Naturalness Limit** in the case of the tau and mu couplings is much larger corresponding to $\mathrm{Br} \sim 0.4\,\%$

τμ channel studied at Run 1 and Run 2 by ATLAS and CMS, with analyses in both the hadronic and leptonic decay channels of the tau (with analyses similar to the $H \to \tau^+\tau^-$ channels).



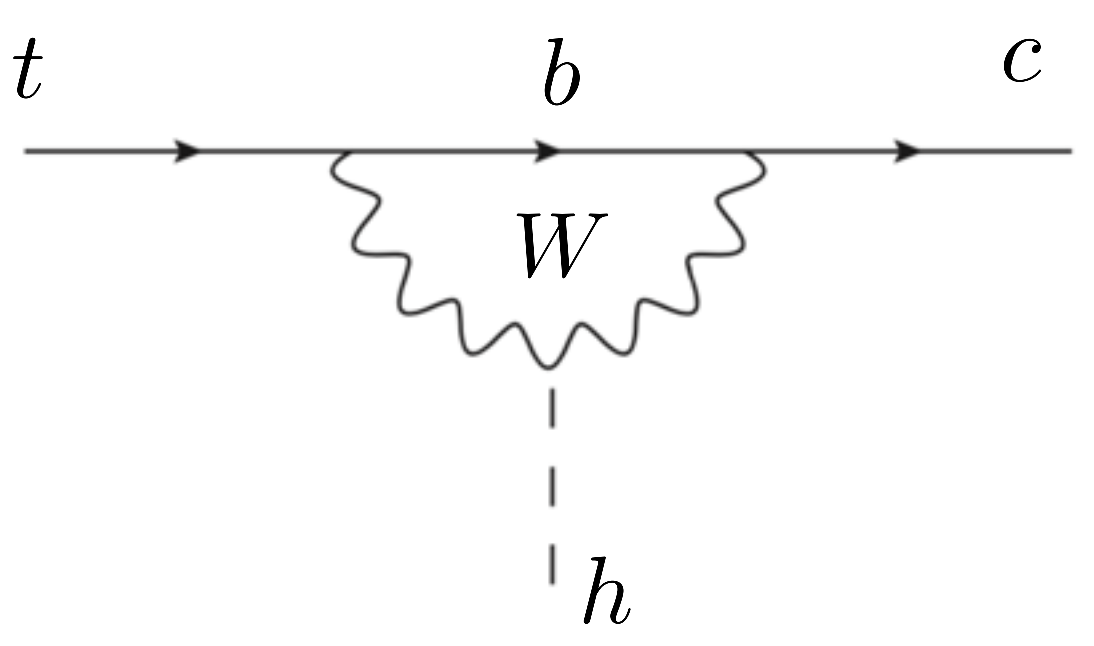
CMS result with 36 fb^{-1}

$$\mathrm{Br}(H \to \tau\mu) < 0.25\%$$

« The raise and fall » of the Cheng and Sher ansatz (see slides)

Rare modes involving top quark

Flavor changing neutral current decays of the top quark is strongly suppressed (by the GIM mechanism)

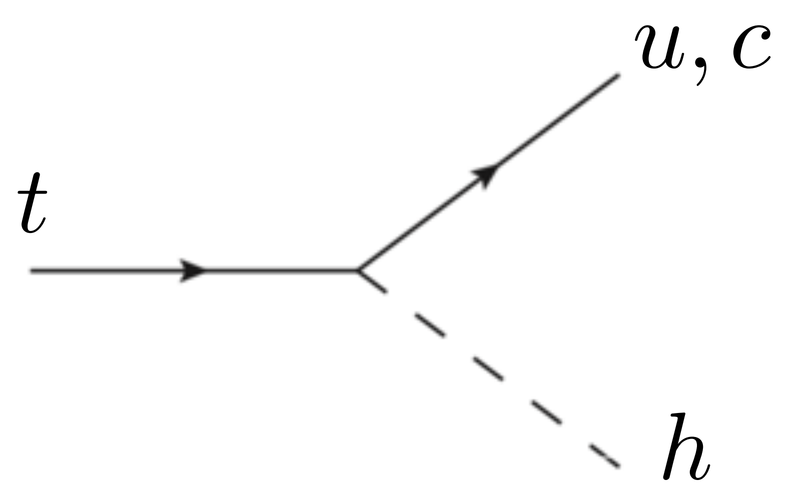


$$\propto m_t \left(\frac{m_b}{m_W}\right)^2$$

$B(t \to Hq)$

SM Branching ~10^{-15}

Therefore an excellent channel to look for New Physics!

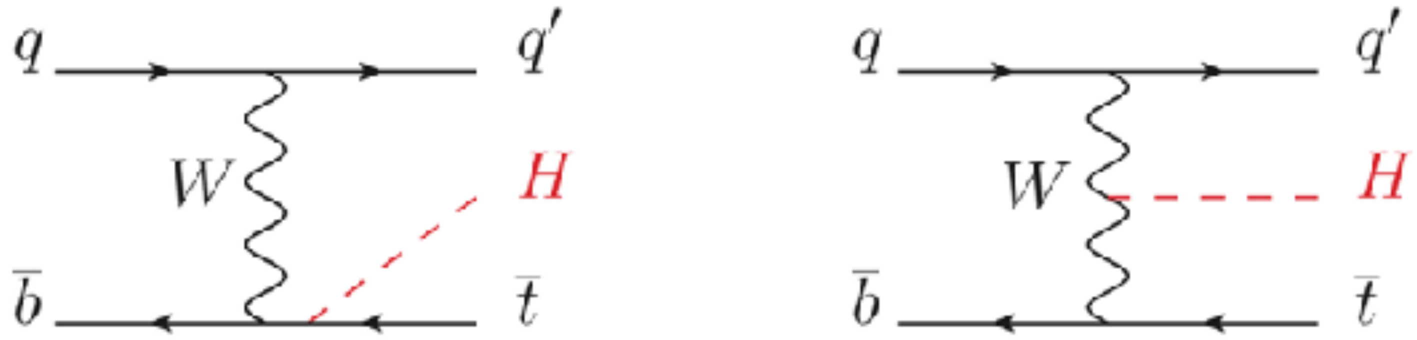


Various decay channels of the Higgs boson ($\gamma\gamma$, bb, WW)

Limits reached with $36\,\mathrm{fb}^{-1}$ at 95% CL (without charm tagging):

$$\mathrm{Br}(t \to Hc) < 0.11\%$$

Tree level interference between top Yukawa and VVH production: single-top and Higgs associated production:

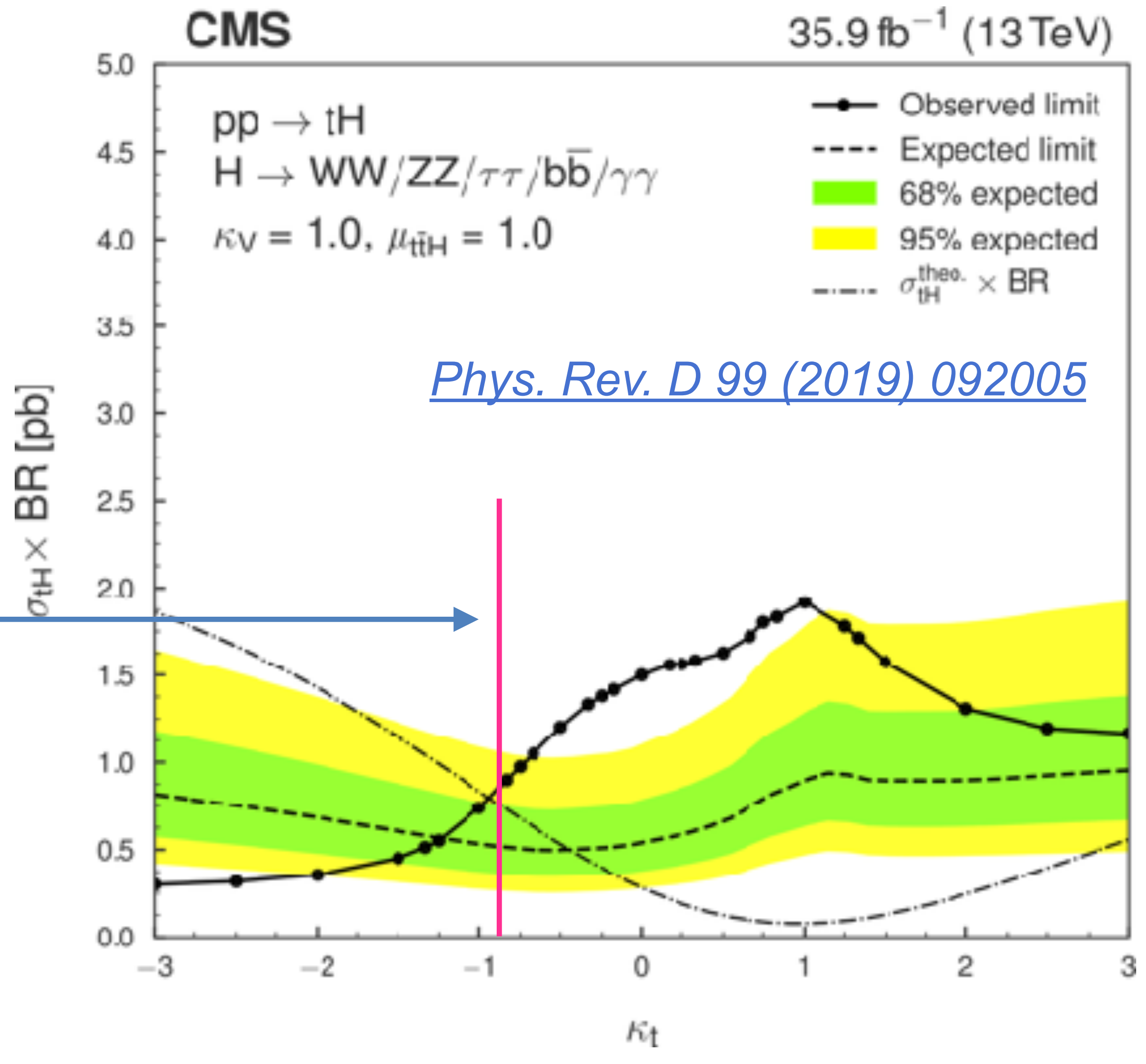


$$\propto 3.3 \times \kappa_W^2 - 5.1\kappa_W\kappa_t + 2.8\kappa_t^2$$

Allows to further constrain the relative sign of the top Yukawa coupling w.r.t. hVV

CMS analysis in combination between the multi lepton, bb and $\gamma\gamma$) channels

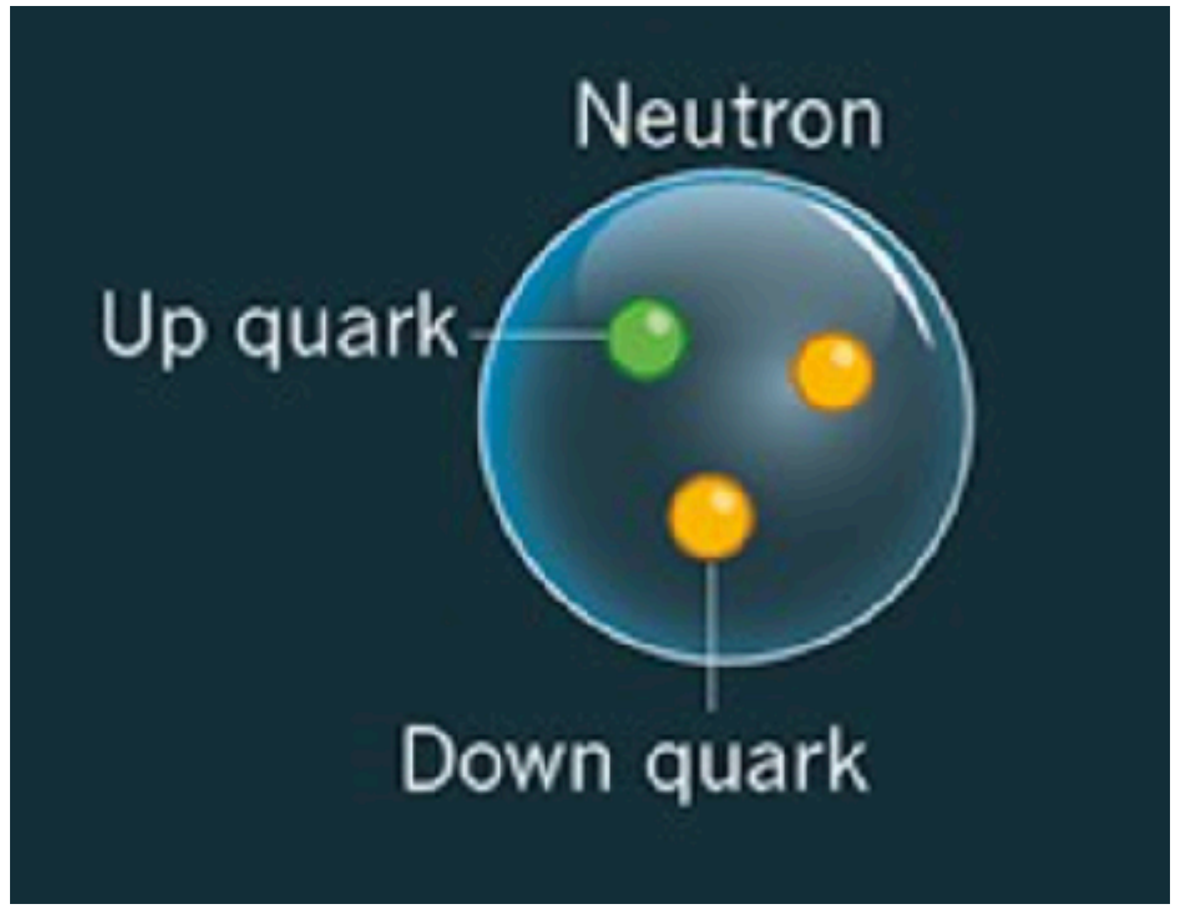
Excludes values of $\kappa_t < -0.9$ at 95% CL



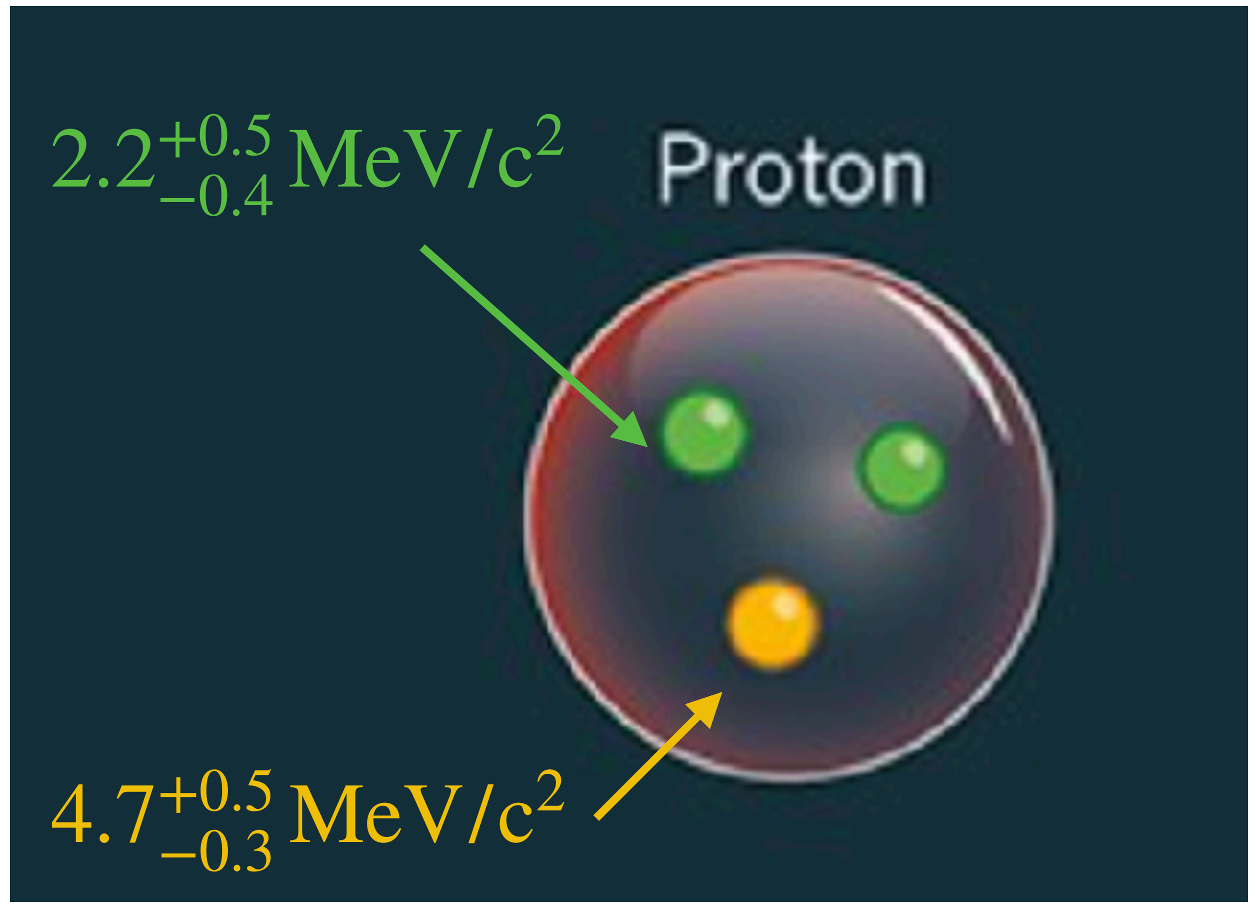
The discrepancy between observed and expected limits around is caused by the fact that the predicted ttH cross section vanishes while the data favors larger than expected yields for ttH.

Similar result from yesterday's multi lepton analysis!

The Higgs and the Nucleon Masses



939.56542052(54) MeV/c^2



938.27208816(29) MeV/c^2

The proton and the neutron are the same particle (same strong isospin double)…

The neutron-proton with a mass difference of ~0.1%

95% of the mass of nucleons from quark condensates and confined quark and gluon kinetic energies.

1% from electromagnetic effects (slightly larger for proton)

4% from its constituent quarks

With even just slightly different masses, nuclei as we know them would not be stable…

This tiny difference is due to the Higgs coupling to quarks!

Other important fundamental concepts borrowed from quark condensates and the strong interaction…