Experimental Physics at Hadron Collider

Lecture 3

The Discovery of the Higgs boson and Higgs physics

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CERN Summer Students Lectures

July 22-25, 2019

ATLAS four lepton event

Outline

***Lecture 1**: Basic concepts, cross sections and QCD results*

- Preamble
- Context and mission of the LHC
- Fundamentals of hadron collisions
- Luminosity and total cross section
- Cross sections measurements
- Jet production measurements
- Measurement of the strong coupling constant

***Lecture 2**: SM Measurements*

- The electroweak sector in a tiny nutshell
- Measurement of the weak mixing angle
- W mass measurement
- Top mass measurement
- Diboson production
- Global fit of the Standard Model

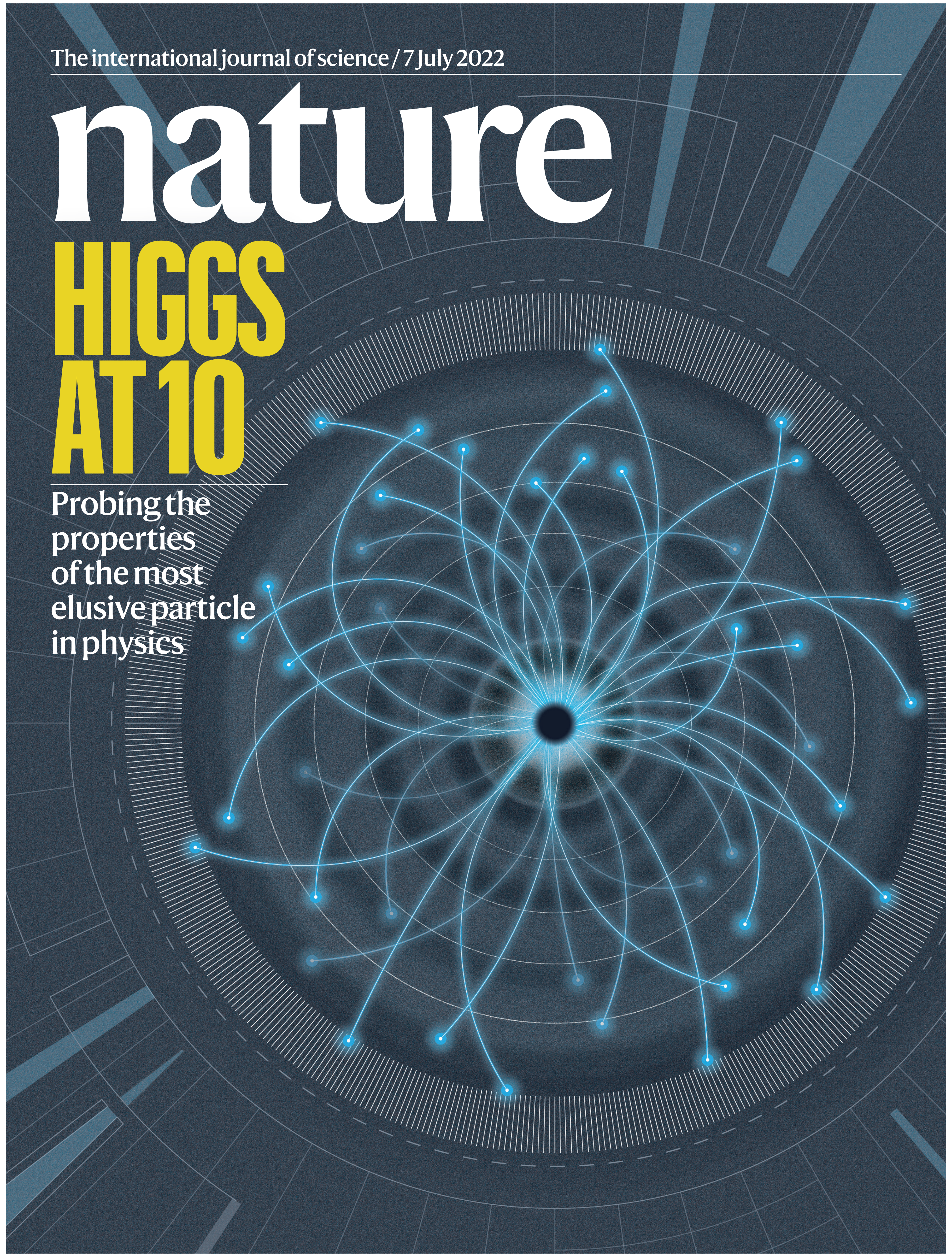
***Lecture 3**: Higgs physics*

- The Higgs mechanism and Higgs production
- The discovery of the Higgs boson
- Precision Higgs physics with diboson channels
- Measuring the Yukawa couplings
- Measurement of Higgs properties
- Rare production and decays
- Global fit of the Standard Model (revisited)

***Lecture 4**: Searching for new physics BSM and future Hadron Colliders*

- Introduction
- Searches for supersymmetry and Dark Matter
- Searches in non SUSY theories
- Searches for unconventional signatures
- EFT and high energy observables
- Outlook on future colliders
- Conclusions

Nature Higgs Anniversary Edition



NATURE PODCAST | 11 July 2022

Higgs boson at 10: a deep dive into the mysterious, mass-giving particle

We discuss the discovery of the Higgs boson and the impact it's had on physics.

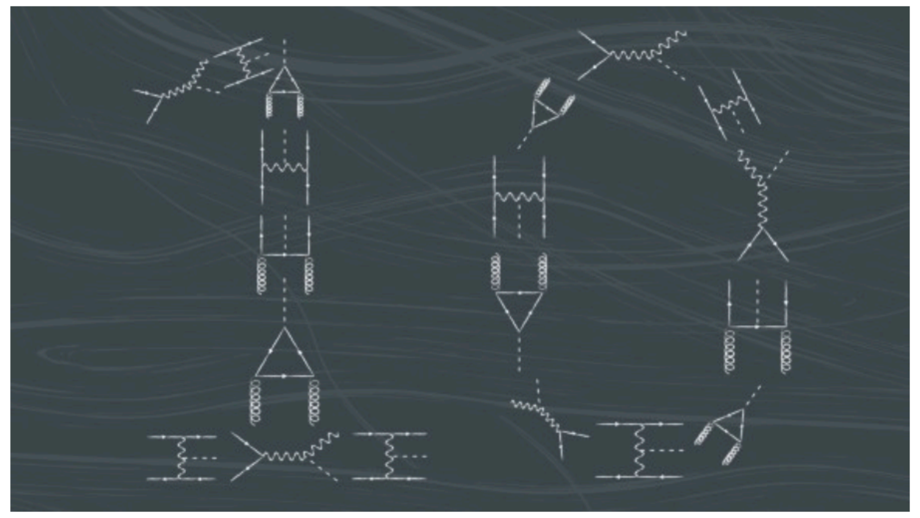
nature portfolio

nature > collection

Collection | **04 July 2022**

The Higgs boson discovery turns ten

The discovery of the Higgs boson was announced ten years ago on the 4th of July 2012 — an event that substantially advanced our understanding of the origin of elementary particles' masses. In this collection of articles from *Nature, Nature Physics* and *Nature Reviews Physics* we celebrate this groundbreaking discovery and reflect on what we have learned about the Higgs boson over the intervening years.

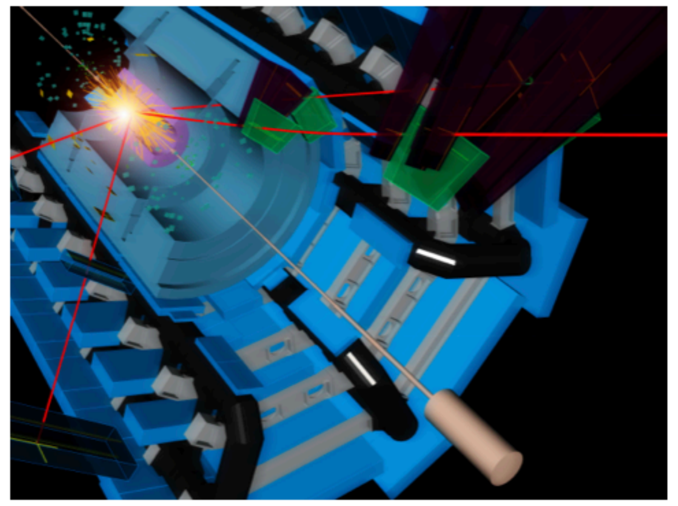


Happy Birthday Higgs Boson!

Higgs 10 symposium at CERN

CERN 10 years HIGGS boson discovery

ATLAS news

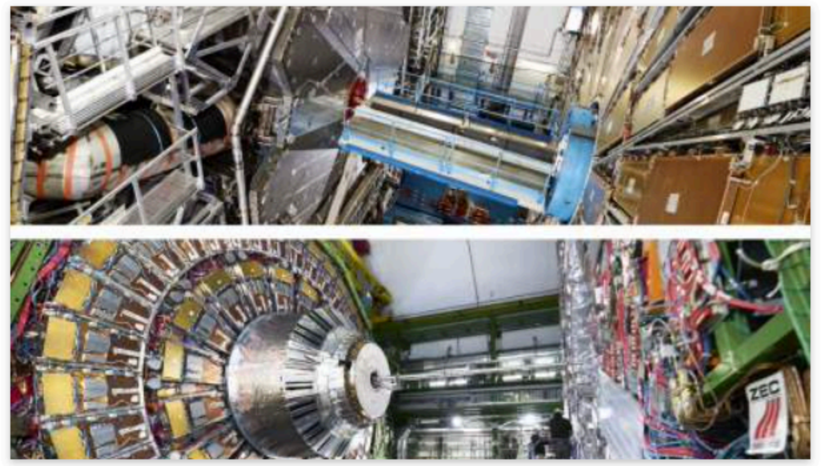


10 years of Higgs research

The ATLAS Collaboration at CERN has released its most comprehensive overview of the Higgs boson. The new paper, published in the journal Nature, comes exactly ten years after ATLAS announced the discovery of the Higgs boson. In celebration of this anniversary, a special all-day symposium on the Higgs boson is currently underway at CERN.

Press Statement I 4 July 2022

CERN news



ATLAS and CMS release results of most comprehensive studies yet of Higgs boson's properties

The collaborations have used the largest samples of proton–proton collision data recorded so far by the experiments to study the unique particle in unprecedented detail

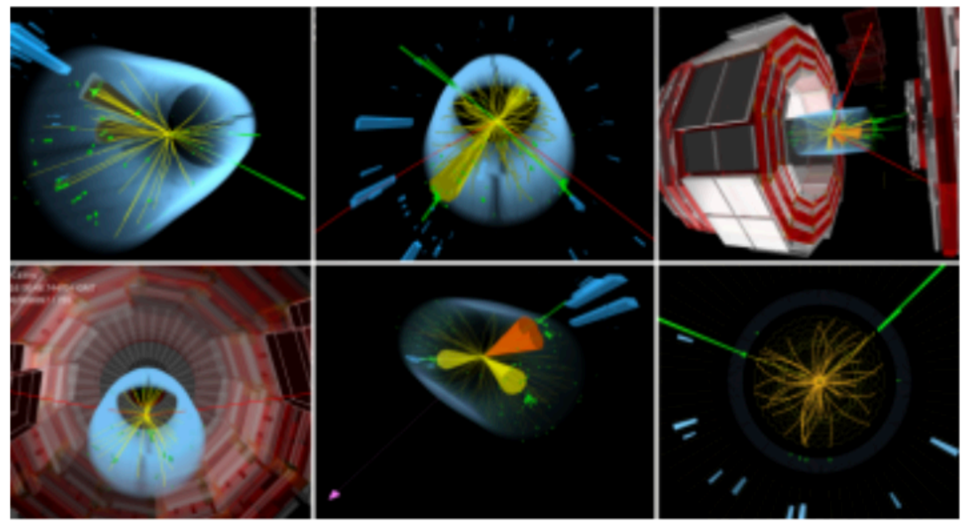
News | Physics | 04 July, 2022

Higgs10: When spring 2012 turned to summer

It was just a few short weeks in mid-2012, but they were so intense that it felt like years. As 4 July drew near, the ATLAS and CMS experiments could sense that they were homing in on something big.

News | At CERN | 04 July, 2022

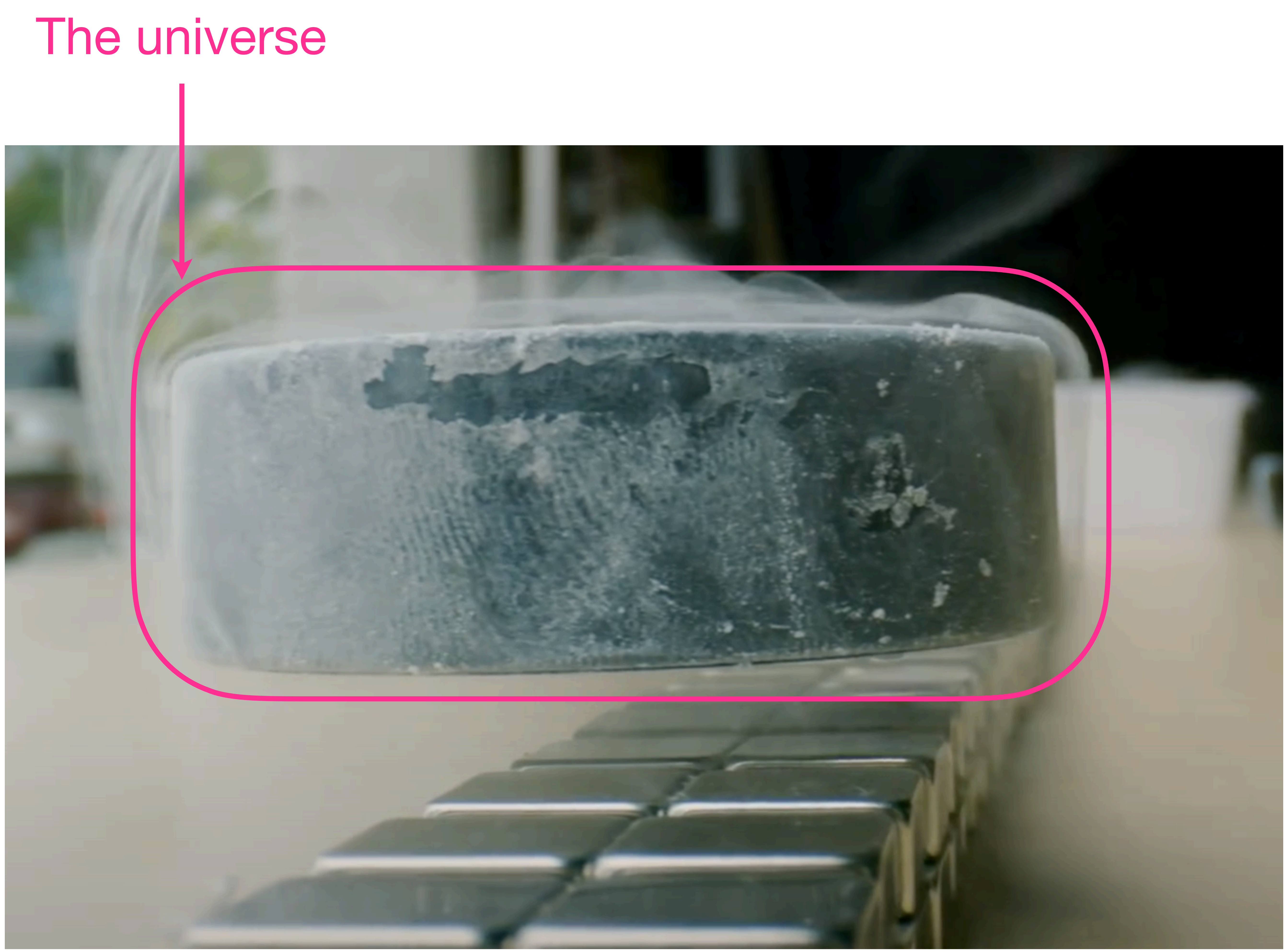
CMS news



THE HIGGS BOSON TURNS 10: RESULTS FROM THE CMS EXPERIMENT

04 JUL 2022 | AJAFARI | PHYSICS

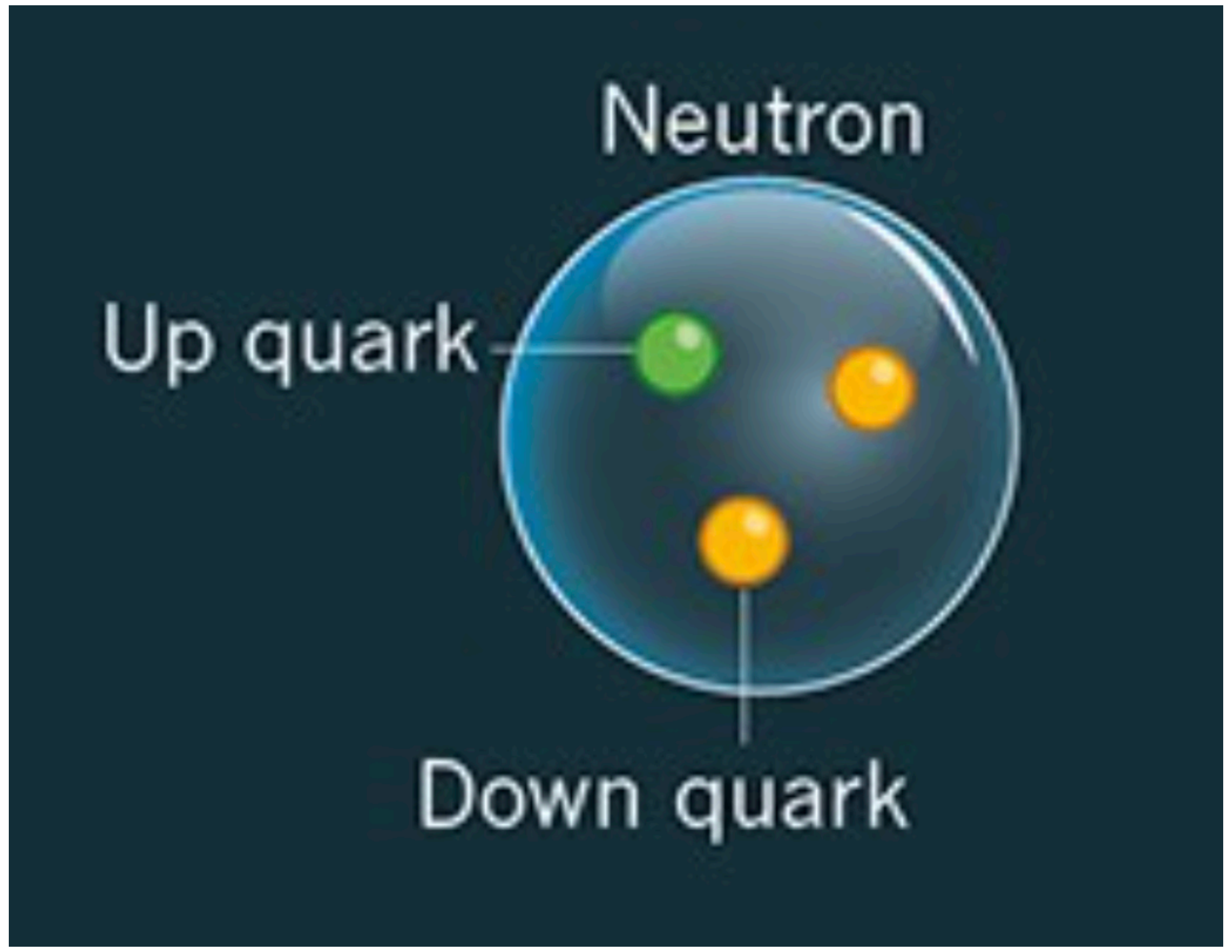
The Superconductor Analogy

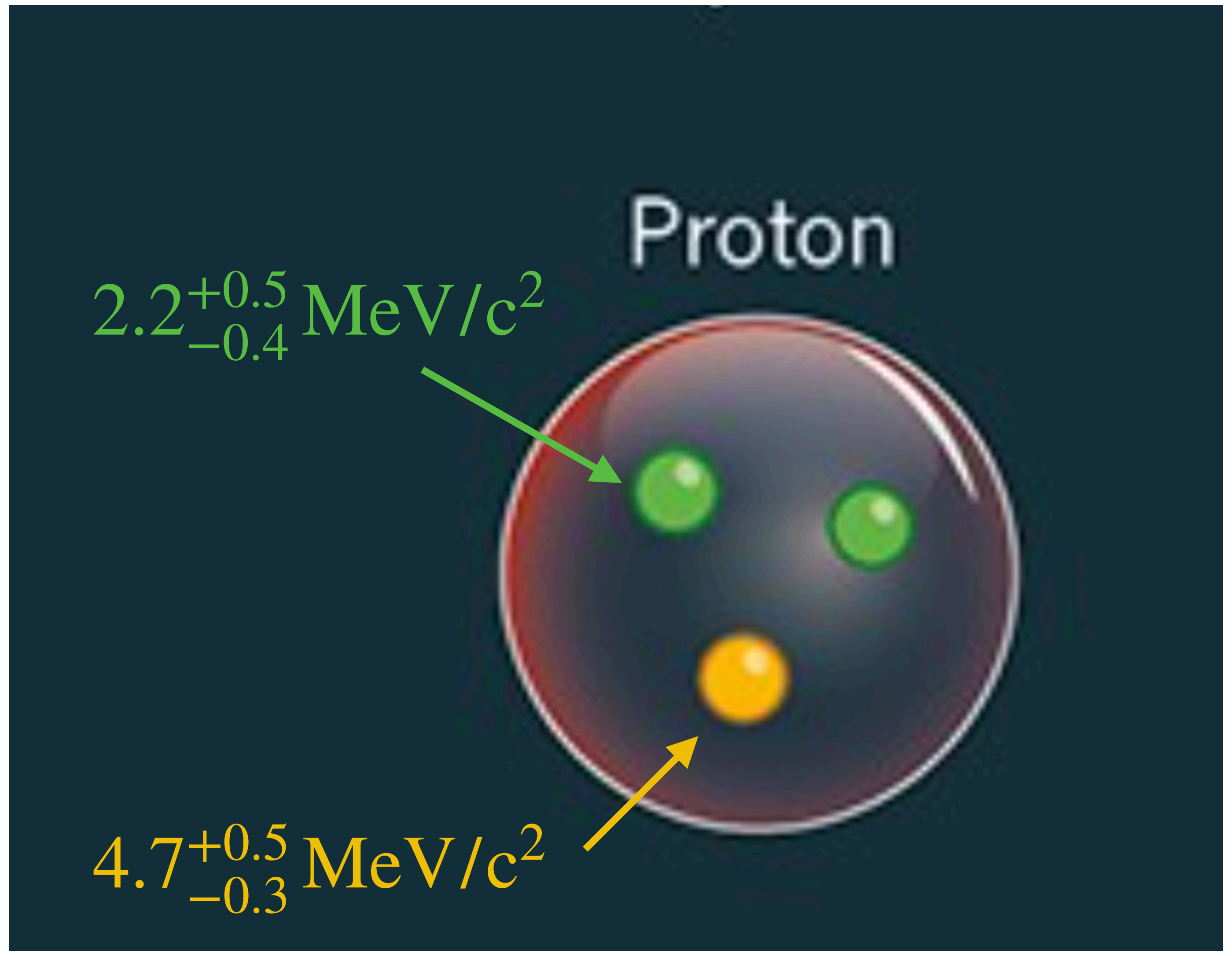


Superconductivity	Higgs Mechanism
1950 – Landau and Ginzburg JETP 20 (1950) 1064	
Cooper pairs	**Higgs field**
1957 – Bardeen, Cooper and Schrieffer Phys. Rev. 108 (1957) 1175	Introduced "by hand"
Electric charge (2e)	**Weak charge**
Photon mass	**W and Z bosons masses**
Not a "true mass" for this non relativistic system and coming from the exponential falling penetration of magnetic field in the SC…	

L. Dixon, "From superconductors to supercolliders" (link)

Matière Ordinaire





From certain point of view the neutron and the proton are the same particle!

98% of the proton and neutron mass NOT due to Higgs Boson

But…

Slightly different mass!

$1.67492749804(95)\times10^{-27}$ kg

939.56542052(54) MeV/c^2

$1.67262192369(51)\times10^{-27}$ kg

938.27208816(29) MeV/c^2

Mass difference ~0.1%

95% of its mass is due to strong interaction binding energy (which is the same between neutrons and protons)! de sa masse vient énergie de liaison forte (équivalente entre neutron et proton)! **~1%** is due to electromagnetic effects (different between proton and neutron) and **~4% is due to the mass of its main constituents (valence quarks).**

Main difference between neutron and proton mass is due to the Higgs!

The Higgs Particle

The Higgs particle is related to most of the fundamental questions we have about nature

The Higgs particle completes the Standard Model (SM) a theory that now explains all our observations at colliders.

However the SM is very far from explaining everything!

- The (origin of) Higgs mass is one of the greatest mysteries of fundamental physics! The Naturalness problem
- The nature of Dark Matter , is the Higgs responsible for its mass?
- The origin of the asymmetry between matter and anti-matter in the universe?
- The nature of neutrinos, their masses and the widely different masses between fermions. Flavour Hierarchy problem
- Why do electrons have precisely the same charge as the protons? Grand Unification
- Why is the electric dipole moment of the neutron so small? Answers involve a pseudoscalar field the axion Strong CP problem

Involve fundamental scalars {

- What fuels inflation - involves the existence of a fundamental scalar, the **inflaton**?
- Gravity at small distance scales - attempted descriptions also often imply a fundamental scalar field the **Dilaton**

The Standard Model (again)

The less elegant Higgs sector:

- Carries the largest number of parameters of the theory
- Not governed by symmetries

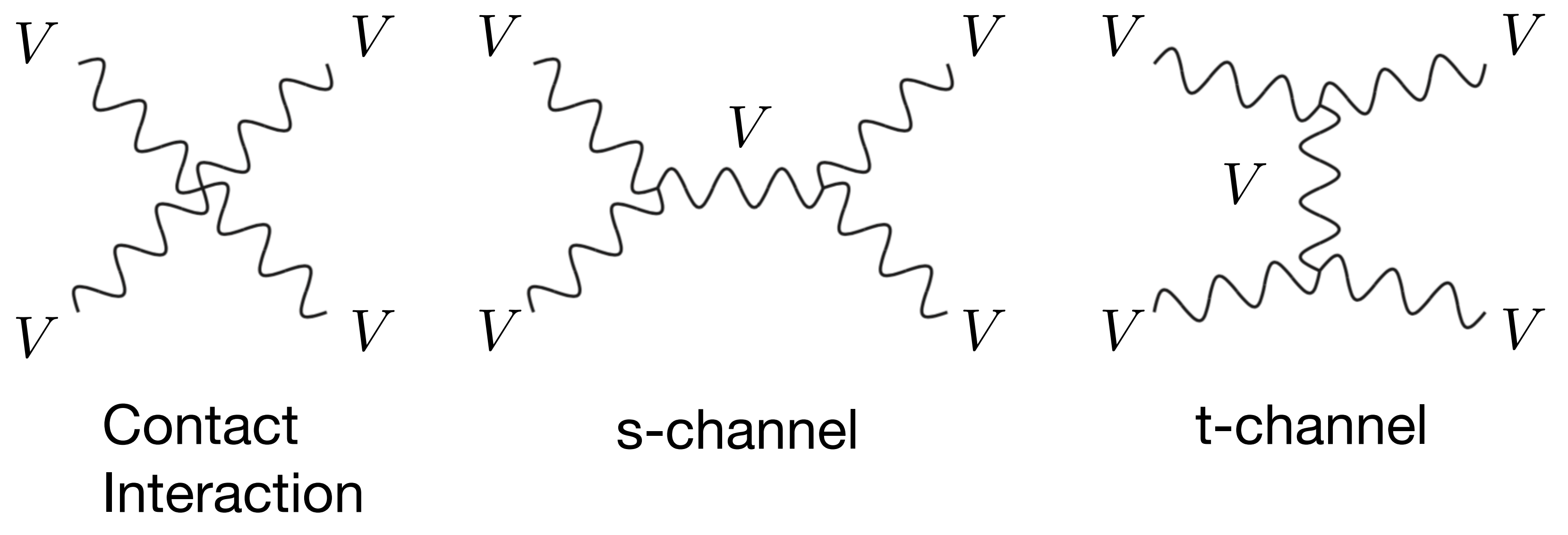
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

However: Higgs mechanism is absolutely necessary both for gauge boson and fermion masses!

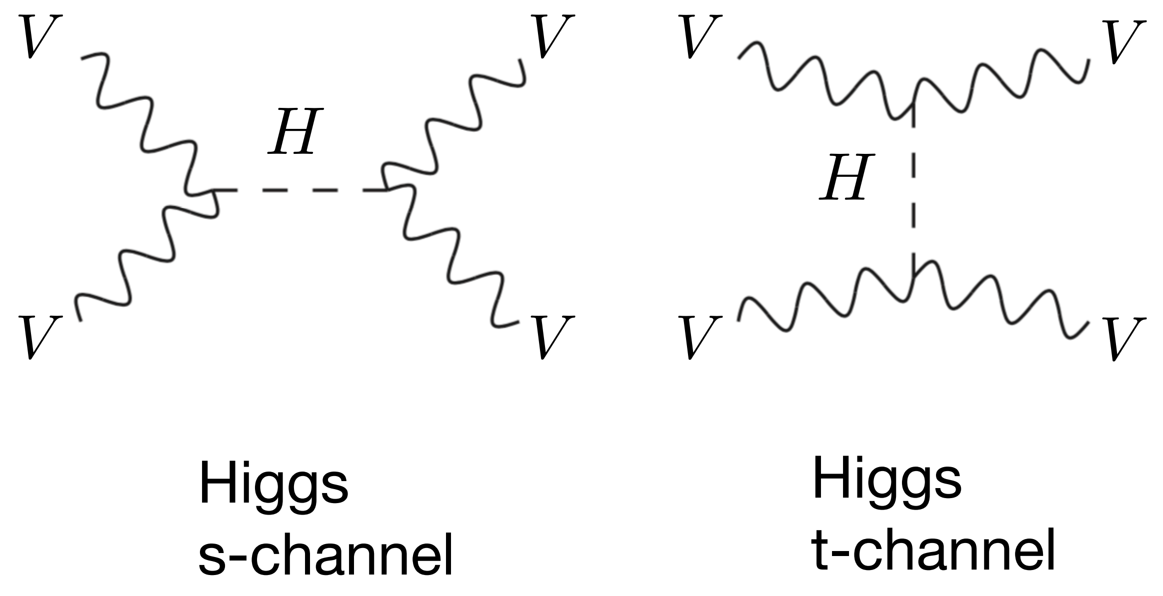
- The Higgs mechanism also predicts the relation between the gauge boson masses and their couplings.

- The Higgs mechanism also predicts the existence of a Higgs boson.

The presence of a Higgs boson also solves another important issue, the unitarity of the longitudinal vector boson scattering **(no loose theorem)**:



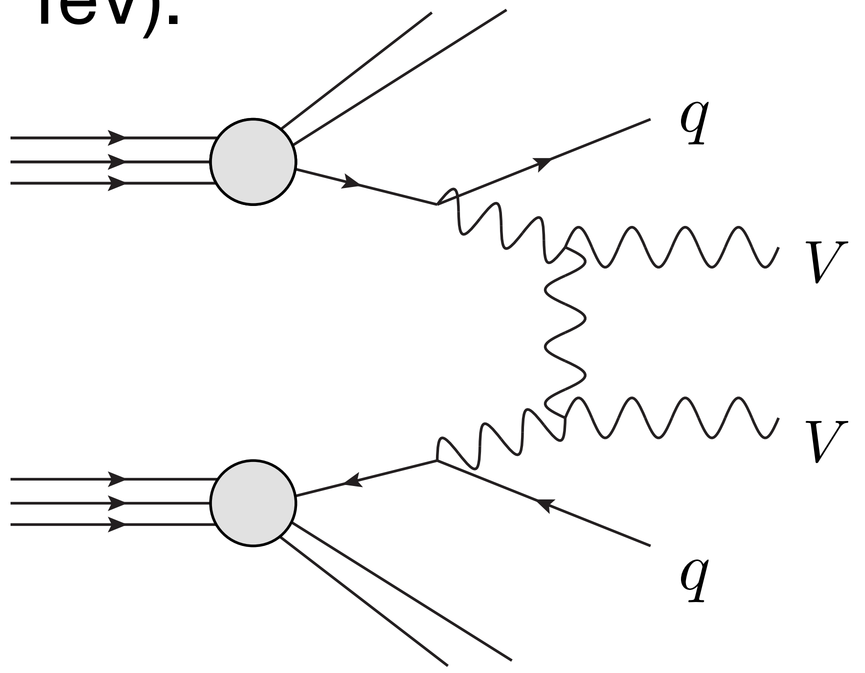
$$\mathcal{M} = g^2 \left(\frac{E}{M_W}\right)^2$$



$$\mathcal{M} = -g^2 \left(\frac{E}{M_W}\right)^2$$

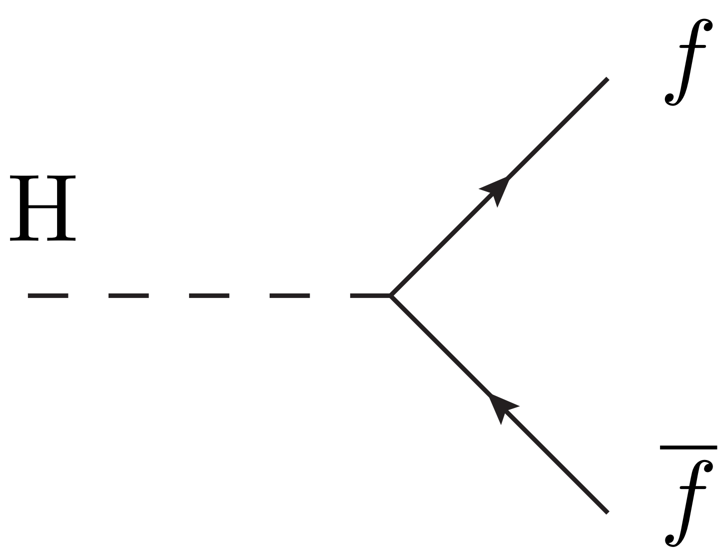
The preservation of the perturbative unitarity of the WW scattering, imposes an upper limit on the Higgs boson of ~O(1 TeV).

In the absence of a Higgs boson within this mass range, would imply the existence of strong dynamics which could be probed by the WW process (discussed in Lecture 2).

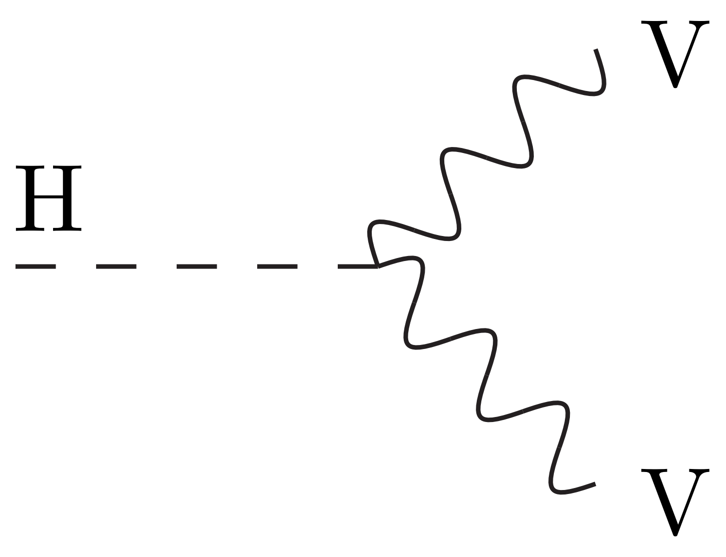


Higgs boson couplings (within the Standard Model)

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

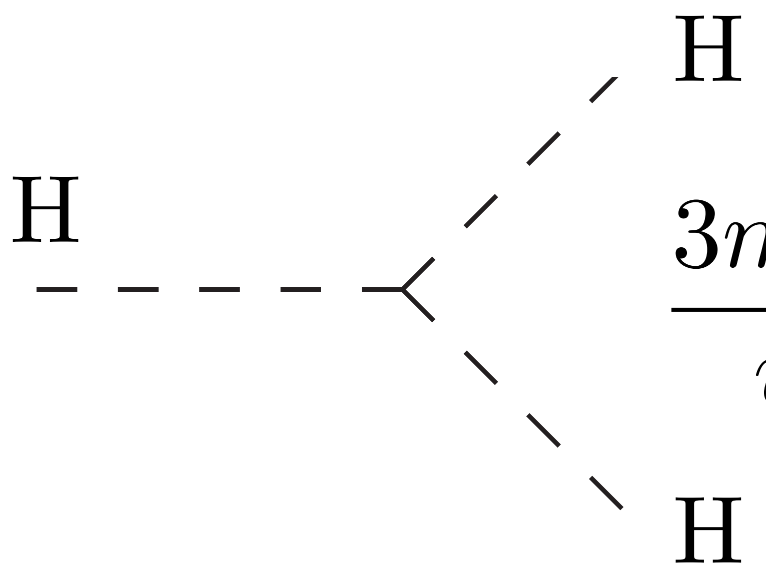


$\frac{m_f}{v}$ $\quad + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$

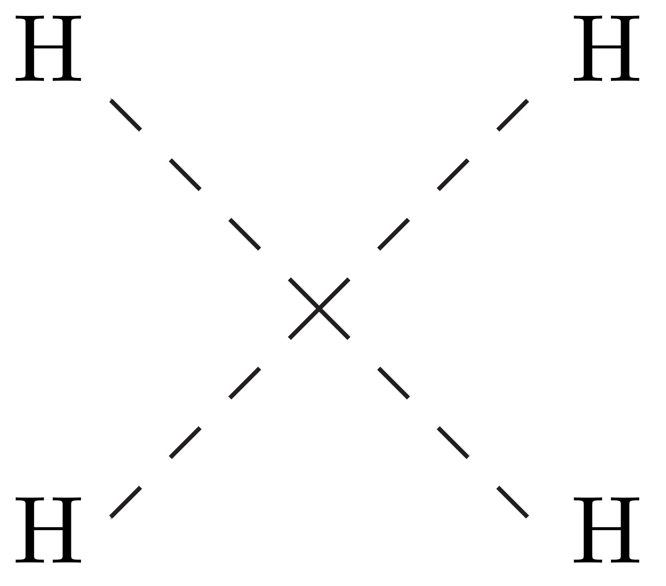


$\frac{2m_V^2}{v}$ $\quad + |D_\mu \phi|^2$

This term could not exist without a vev



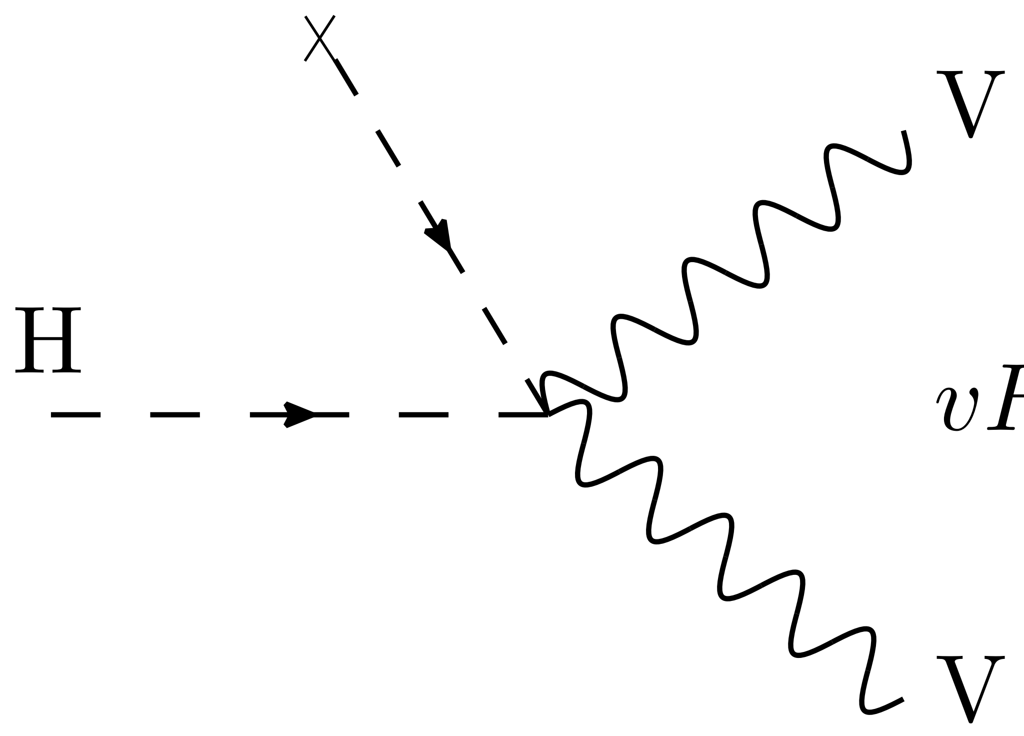
$\frac{3m_H^2}{v}$



$\frac{3m_H^2}{v^2}$ $\quad V(\phi)$

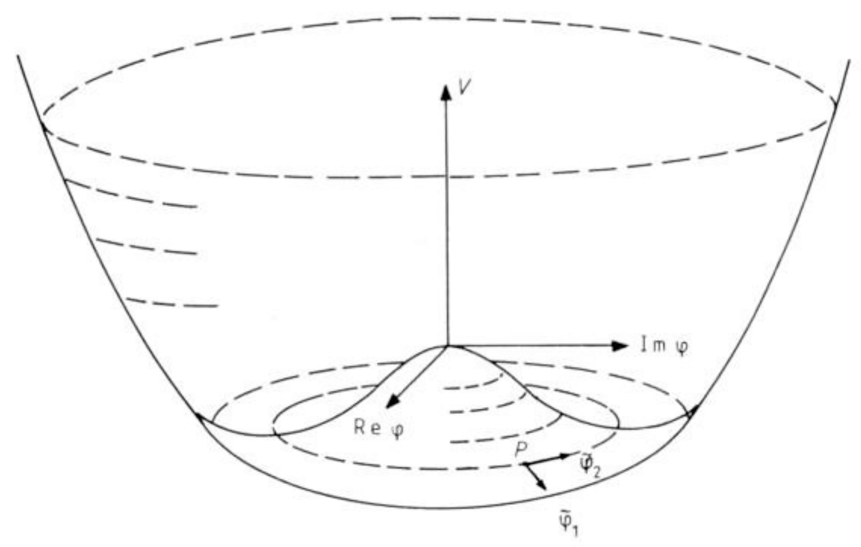
Is the Higgs boson responsible for the EW symmetry breaking also responsible for the masses of fermions?

Is the Higgs boson responsible for the masses of all fermions?



$vHV^\mu V_\mu$

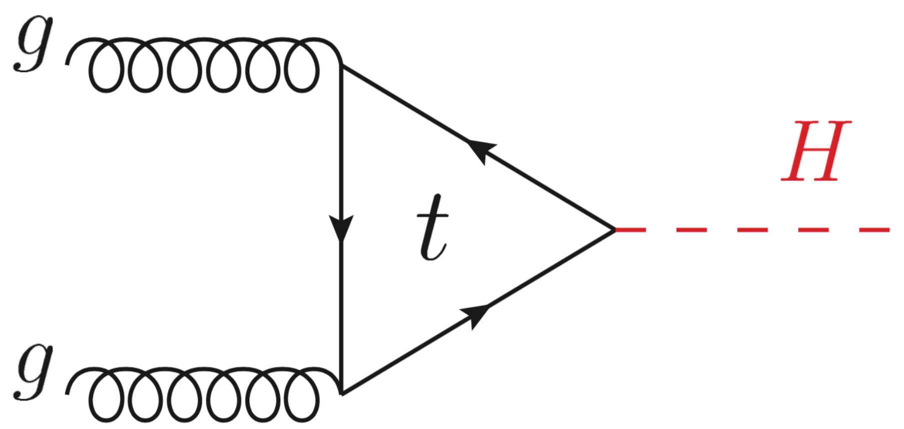
Proof of condensate !



Is the shape of the Higgs potential that predicted by the Standard Model?

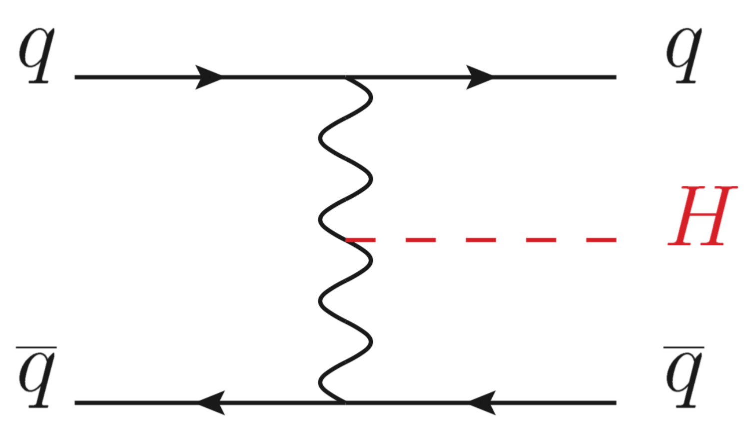
Higgs boson (main) Production and Decay Modes

Production rates at Run 2 (13 TeV) for ~150 fb^{-1}



Gluon fusion process

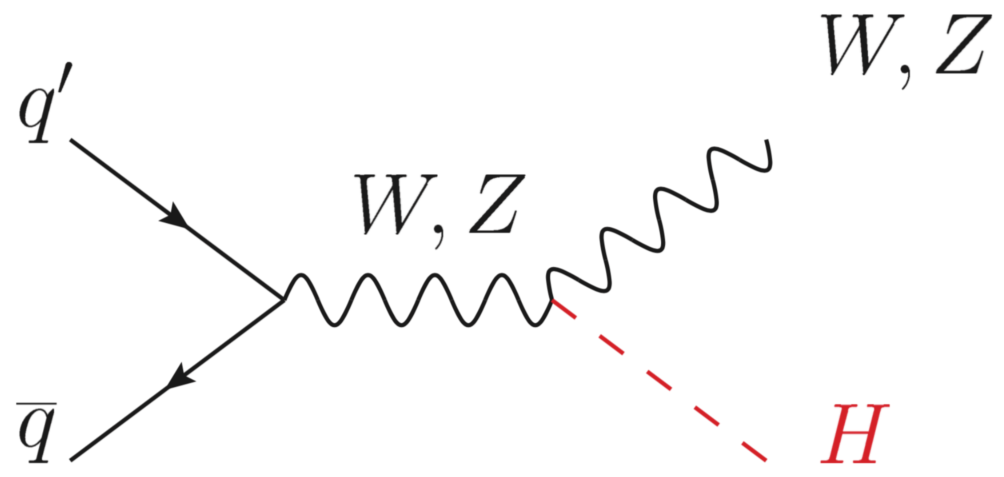
~8 M events produced



Vector Boson Fusion

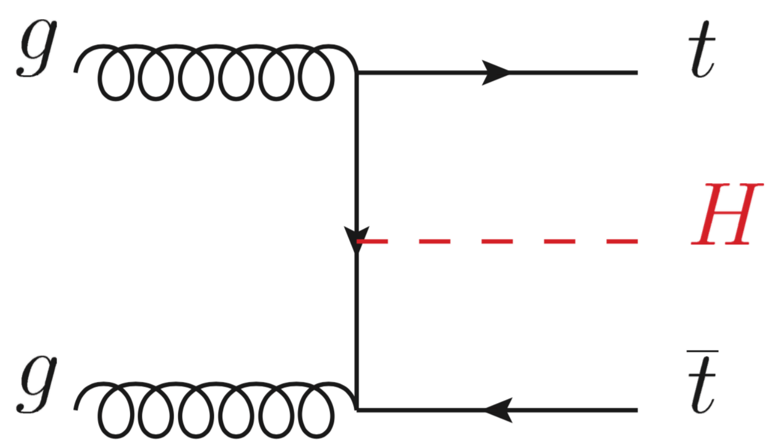
Two forward jets and a large rapidity gap

~600 k events produced



W and Z Associated Production

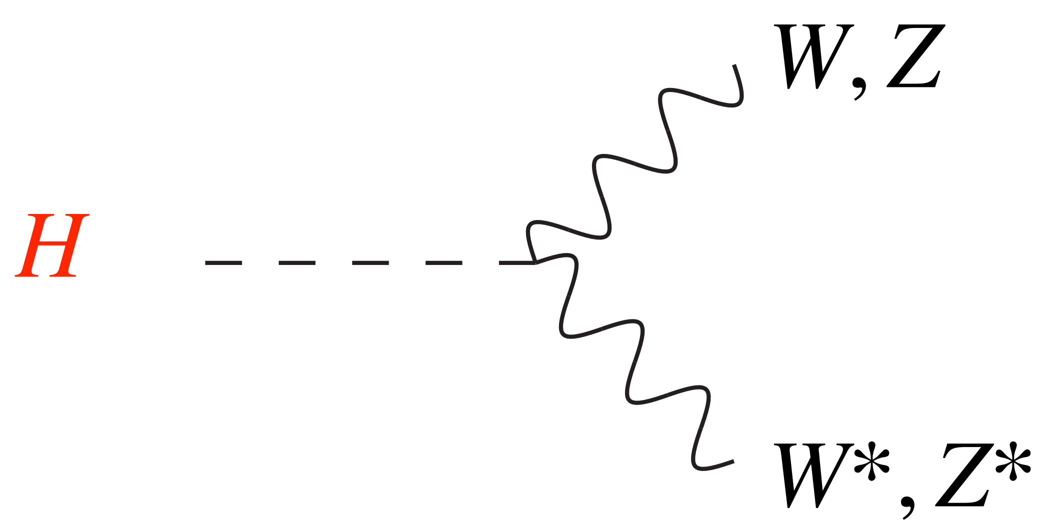
~400 k events produced



Top Assoc. Prod.

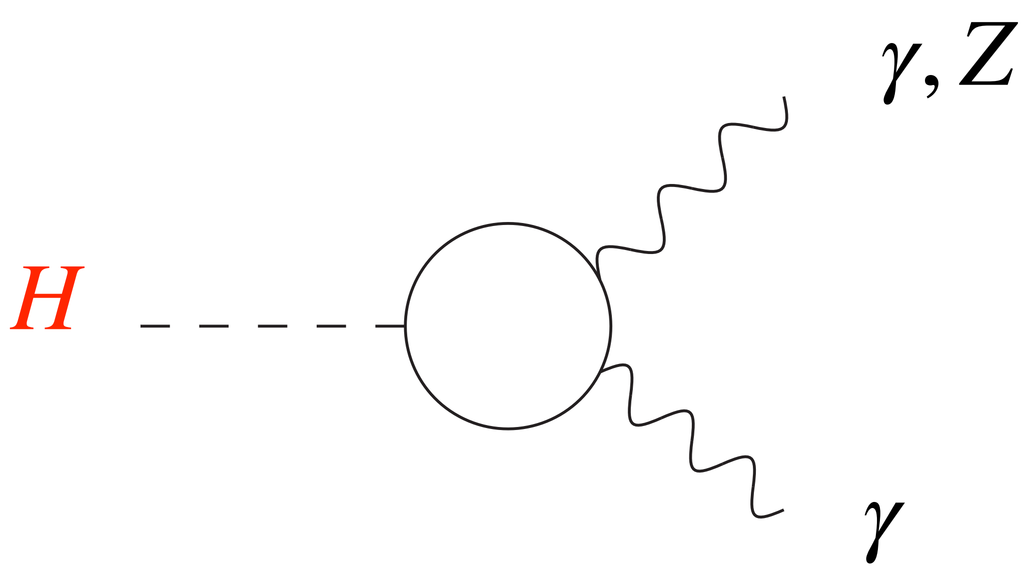
~80 k evts produced

Decay branching fractions



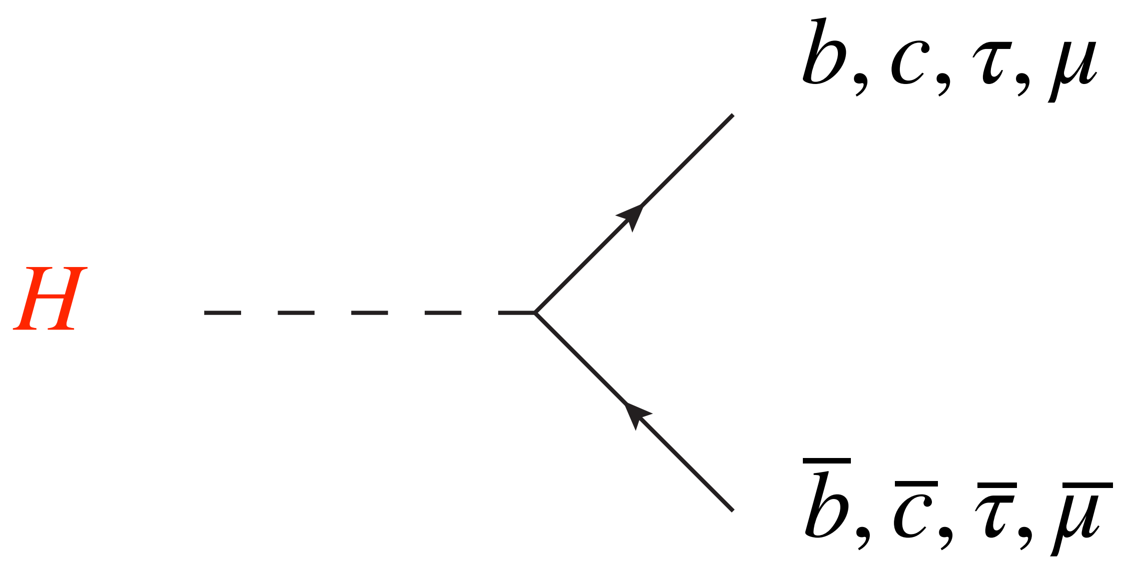
$\mathrm{Br}(H \to WW^*) = 22\,\%$

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



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

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



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

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

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

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

HL-LHC is a Higgs Factory

Outcome of the 2013 European Strategy: HL-LHC!

European Strategy 2012-2013 Recommendations

HL-LHC is a **Higgs factory** ~160 M Higgs events

In comparison Future ee up to ~1.3 M Higgs Events, but much cleaner and « usable » events

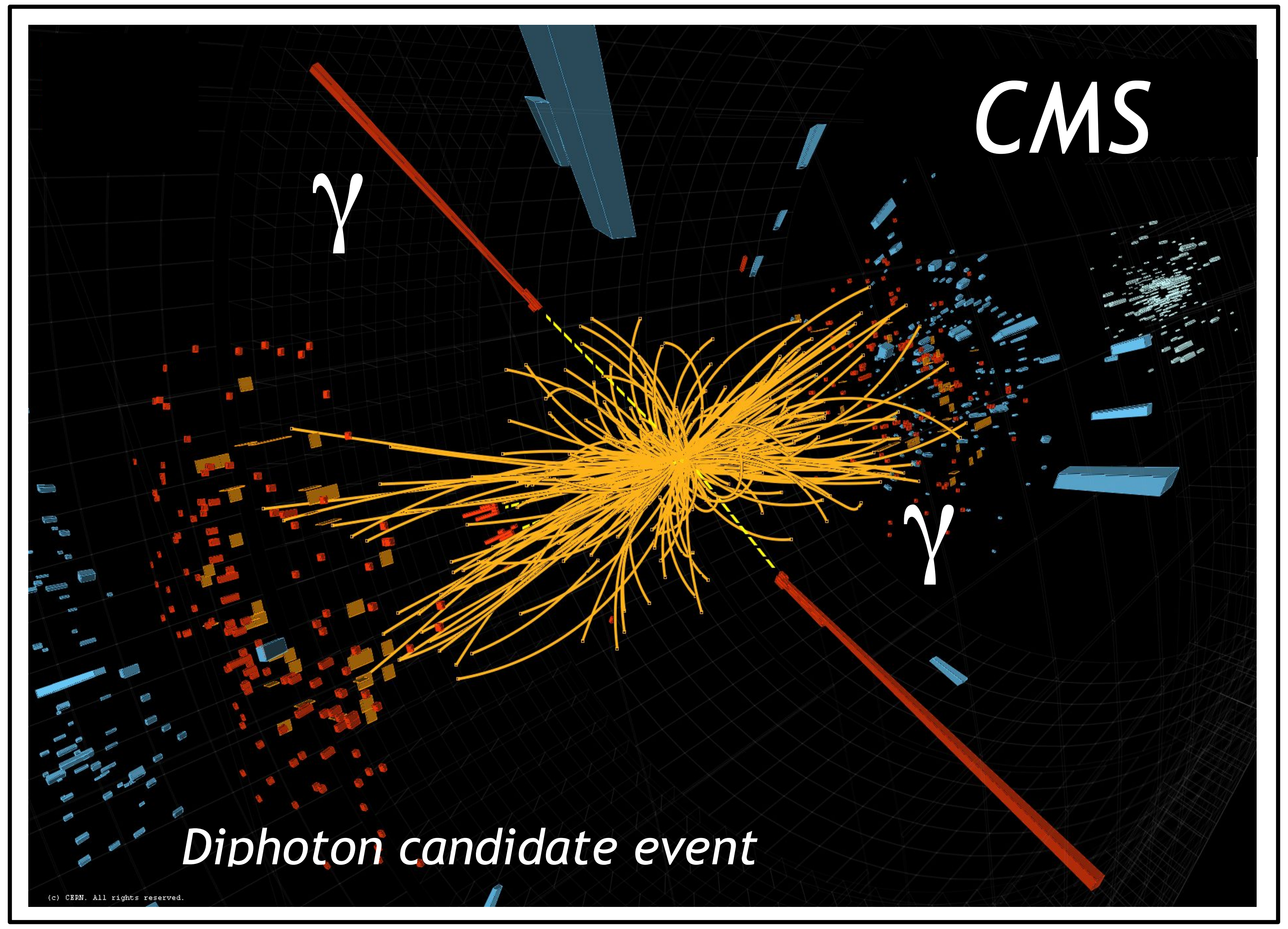
Process	ggF	HH	ttH
13 TeV / 8 TeV	**2.3**	**2.4**	**3.9**
13.6 TeV / 13 TeV	**7%**	**11%**	**13%**
14 TeV / 13.6 TeV	6%	7%	7%

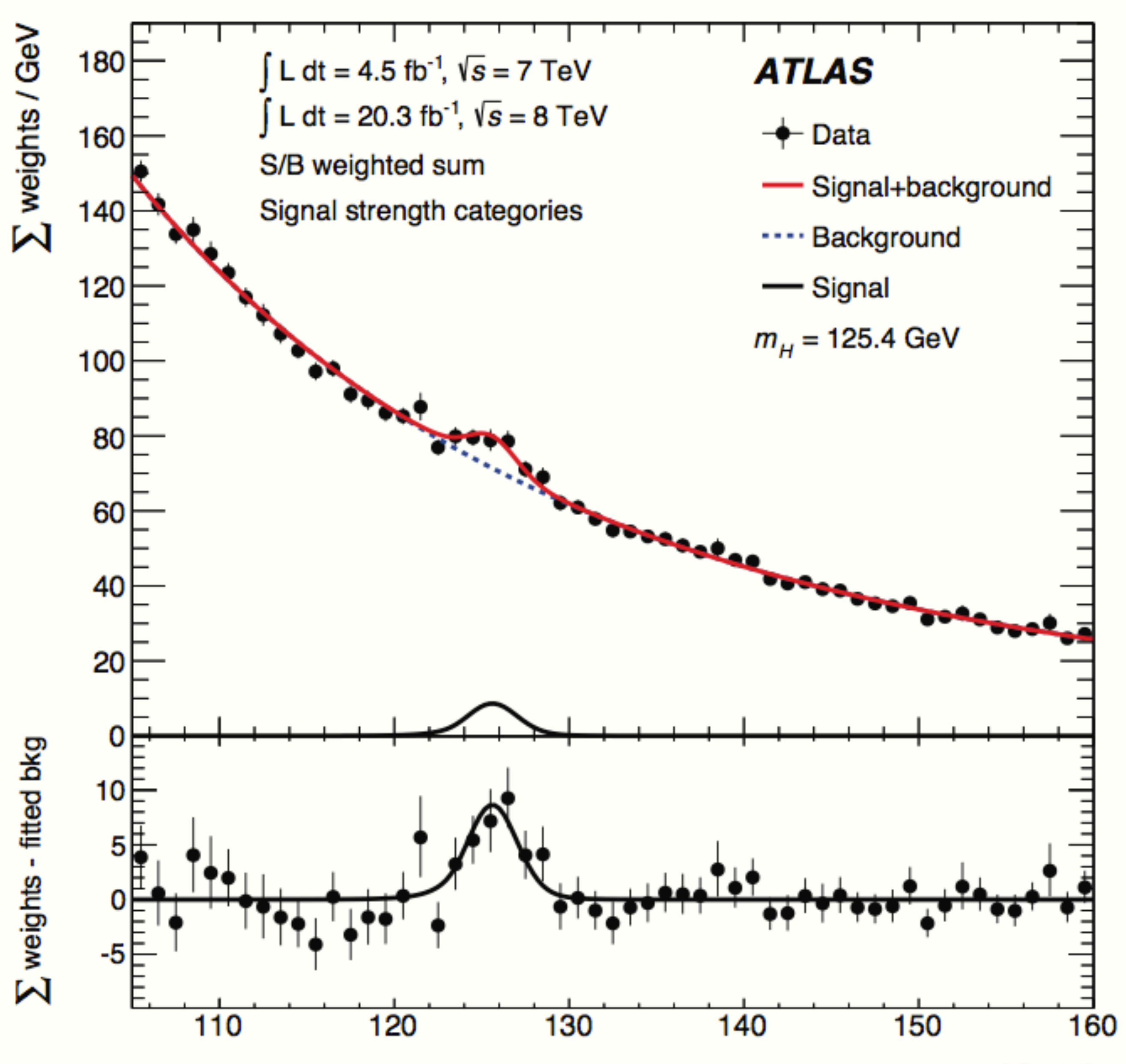
Run 1 Landmark Result

The Discovery of the Higgs Boson

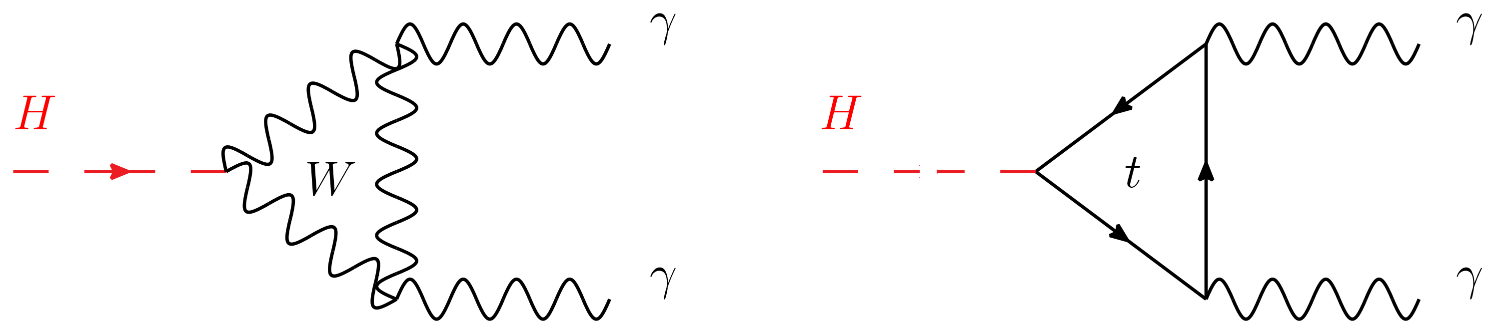
The Discovery Channels

« Bread and Butter » Mass peak signals: the diphoton channel





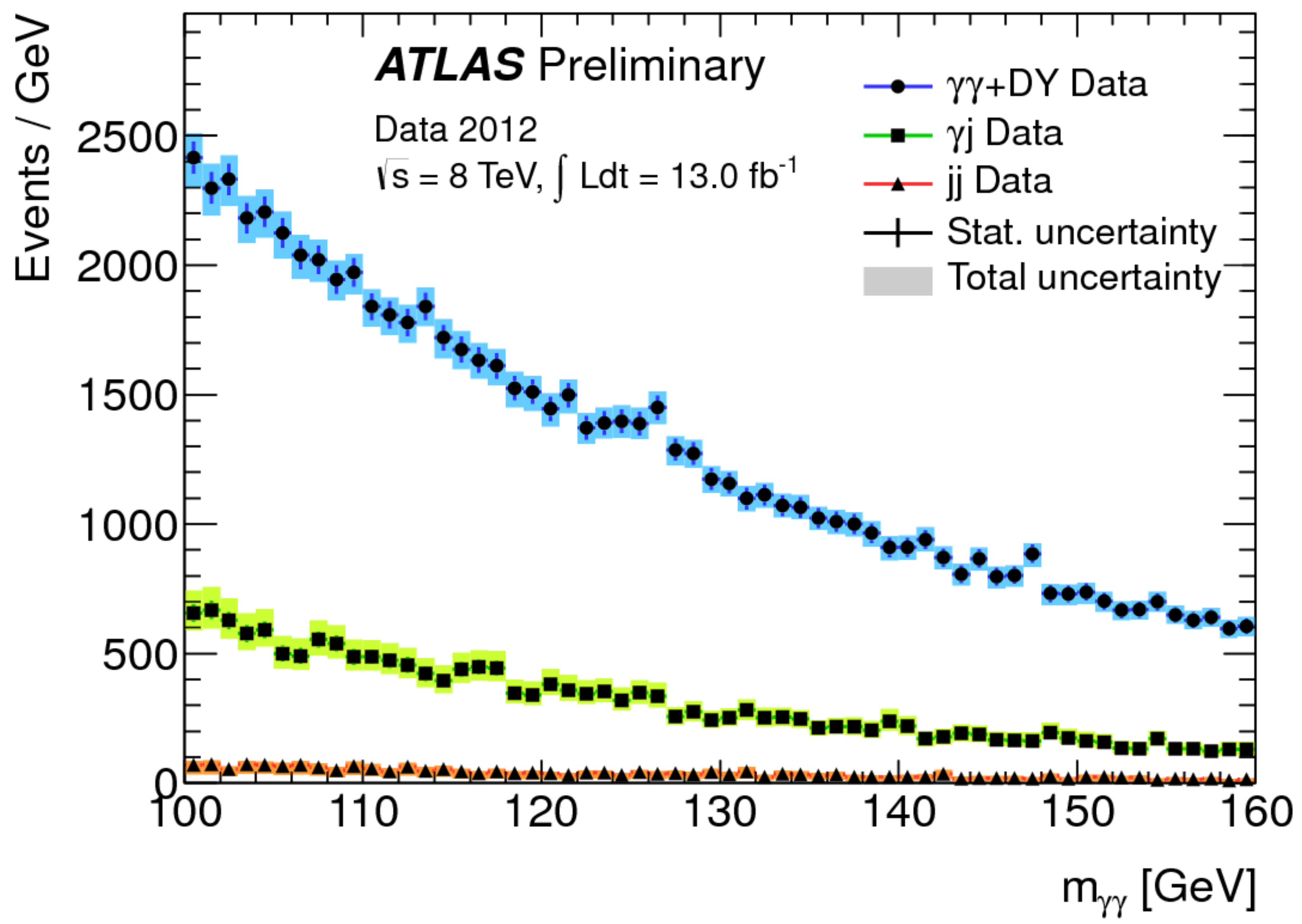
- Main production and decay processes occur through loops :

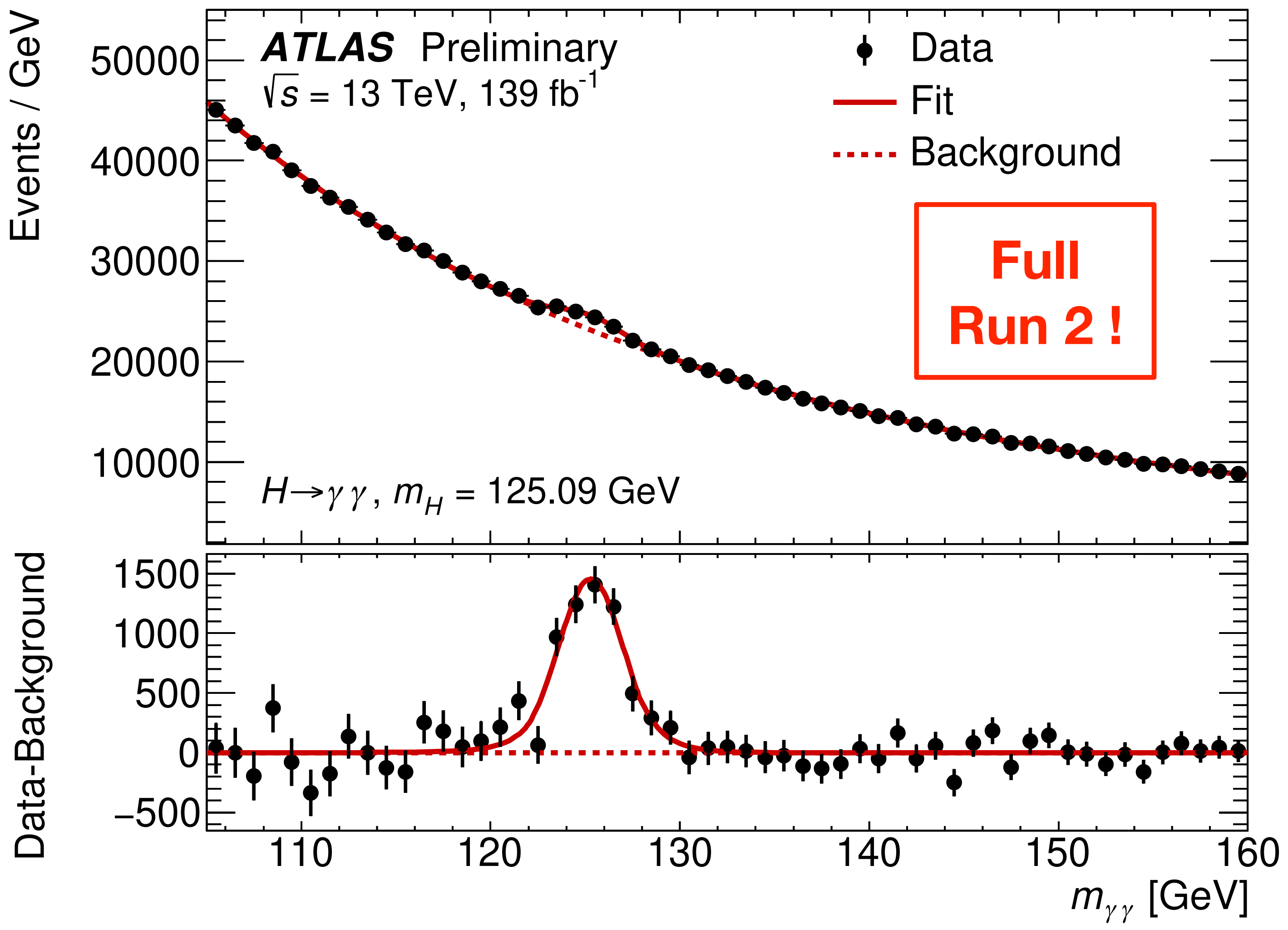


Excellent probe for new physics !

- High mass resolution channel O(1%) allowing data driven estimate of background in the sidebands.
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem

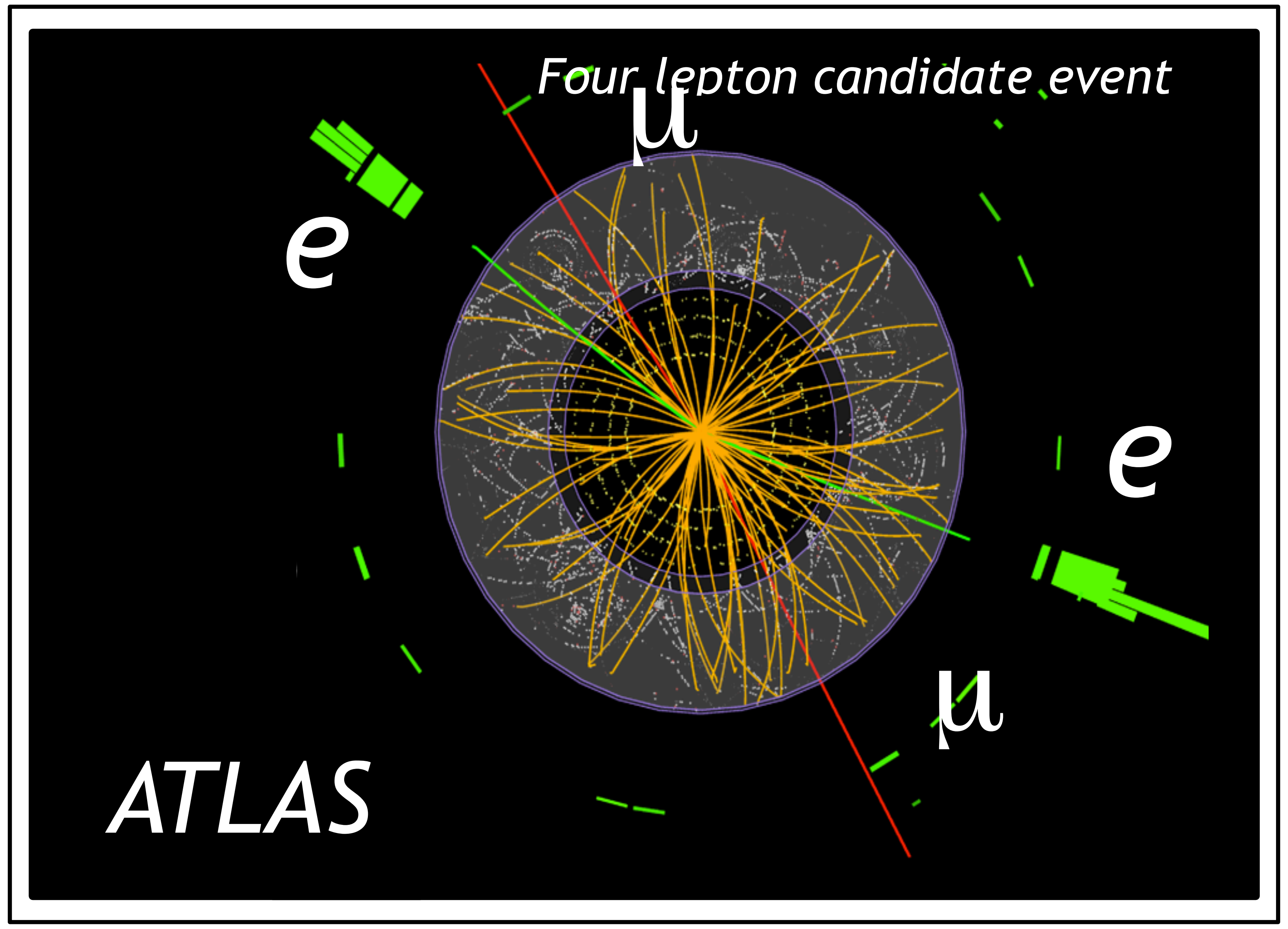
- Low signal over background but overall relatively high statistics of signal (O(300) at Run 1)
- Very simple selection cuts. The essence of the channel relies on the **quality of the detector response** and the **reconstruction**.
- Largest reducible background comes from jets! With another spin-0 particle decaying to a pair of photons: the pi0.

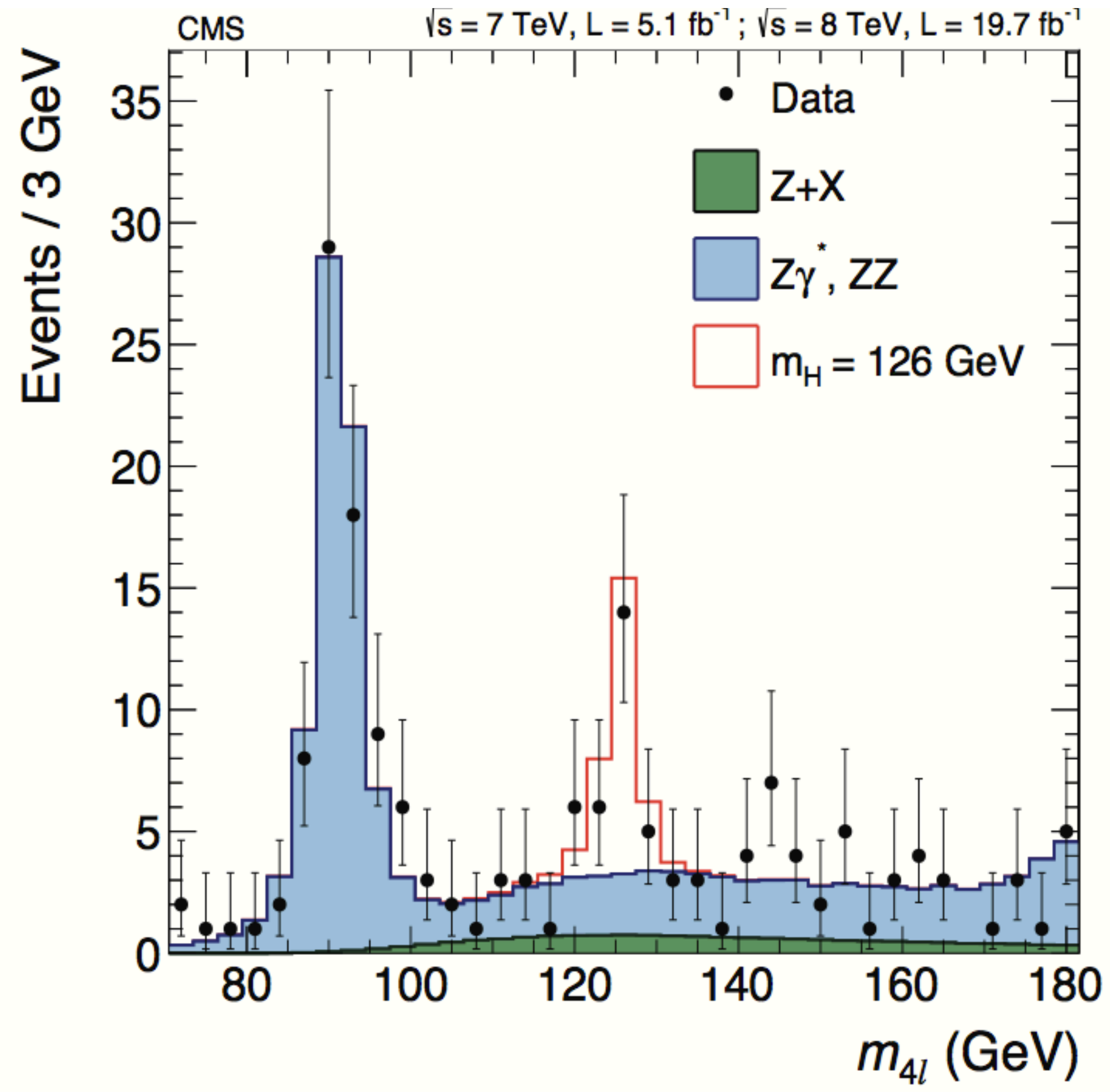




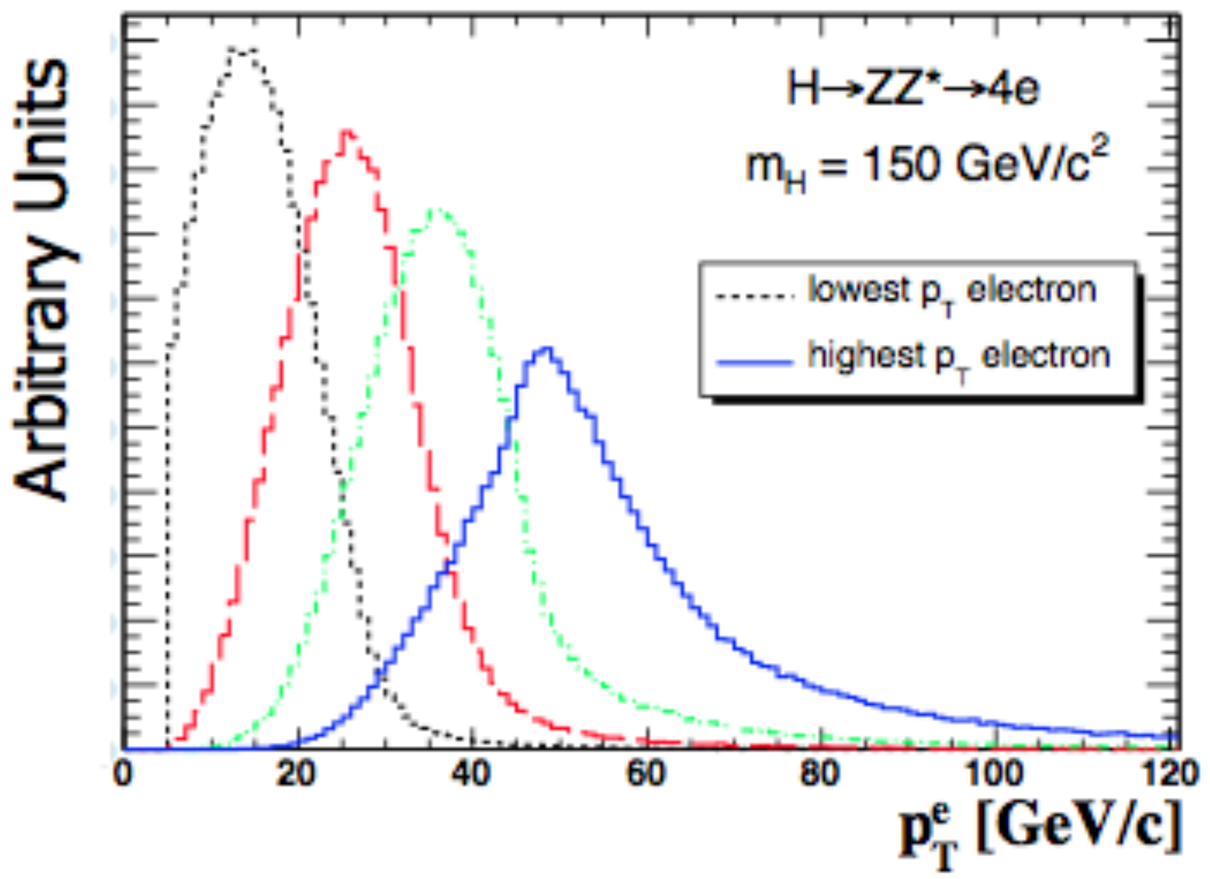
The Discovery Channels

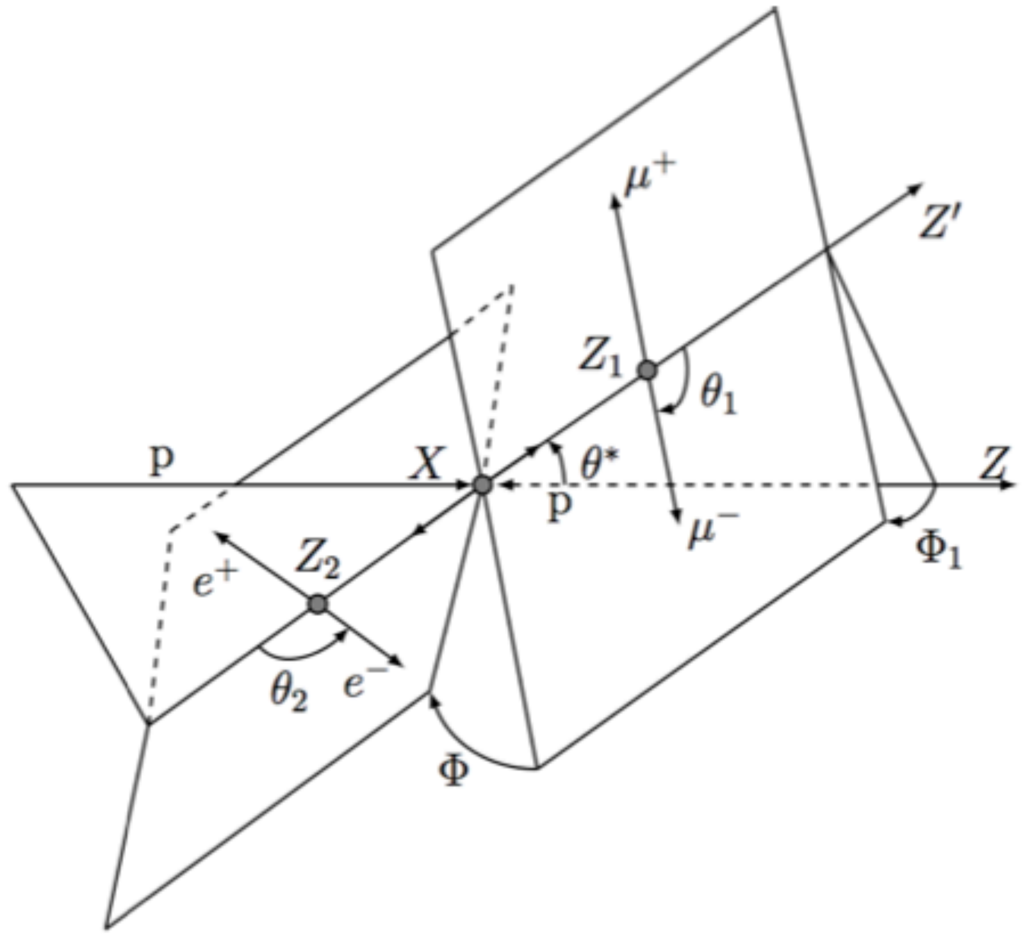
« Bread and Butter » Mass peak signals: the four leptons channel

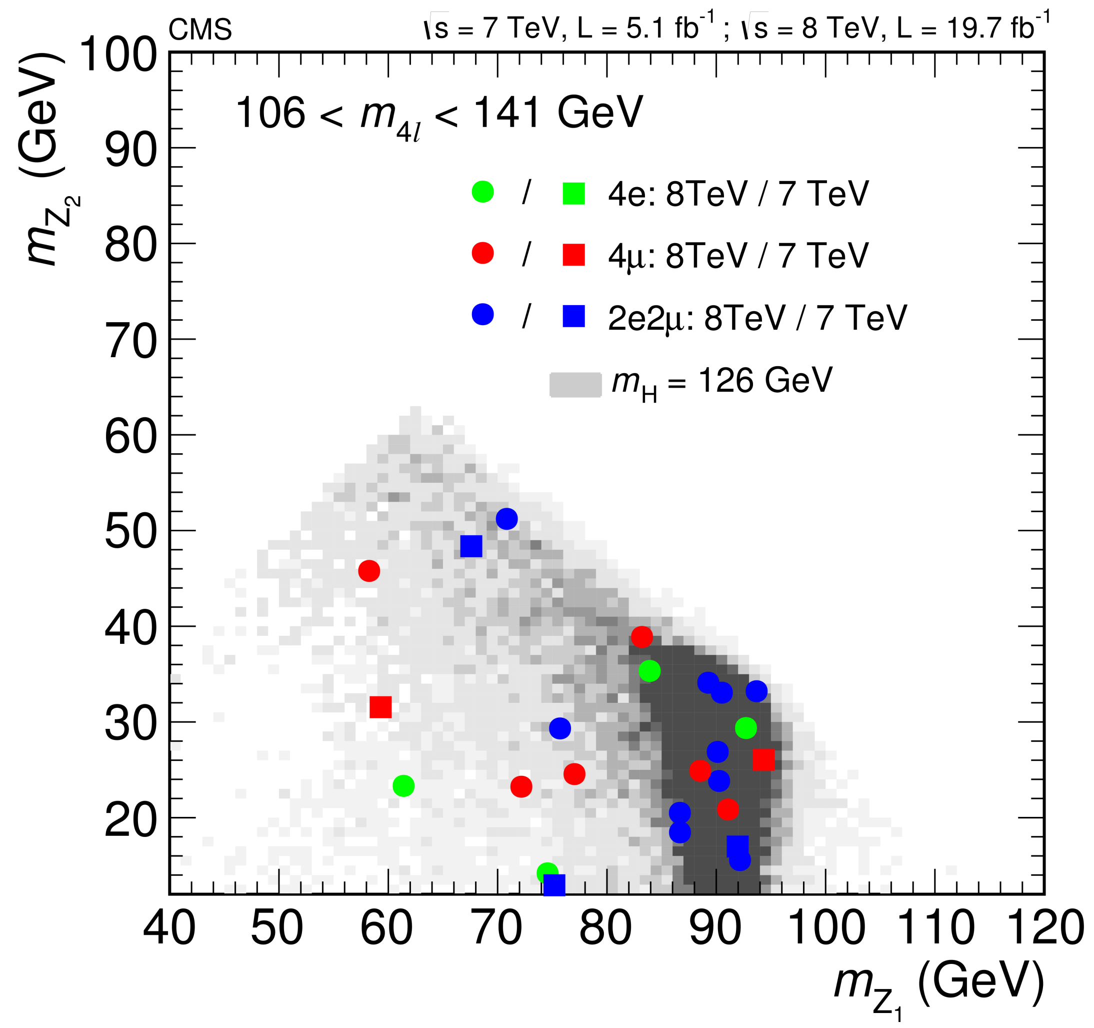


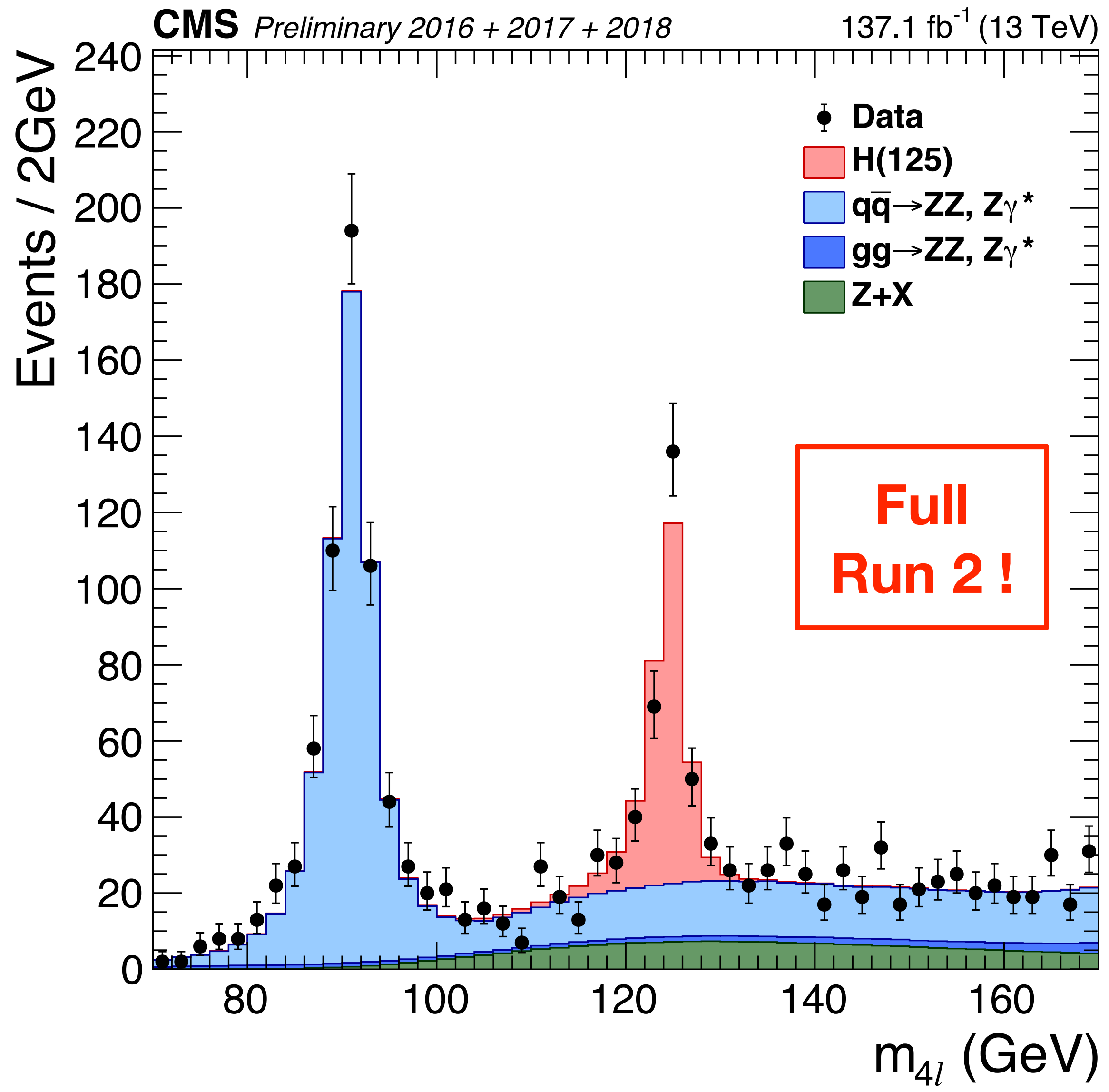


- Channel with High s/b ratio from approximately 2 up to more than 10!
- Backgrounds can be estimated from MC.
- Other important features:
  - Very low rate due to branchings of ZZ and Z to leptons! Efficiency is key!
  - The trailing lepton is at low pT.
  - The polarisation of the two Z can be reconstructed.
  - Typically one Z is on-mass shell



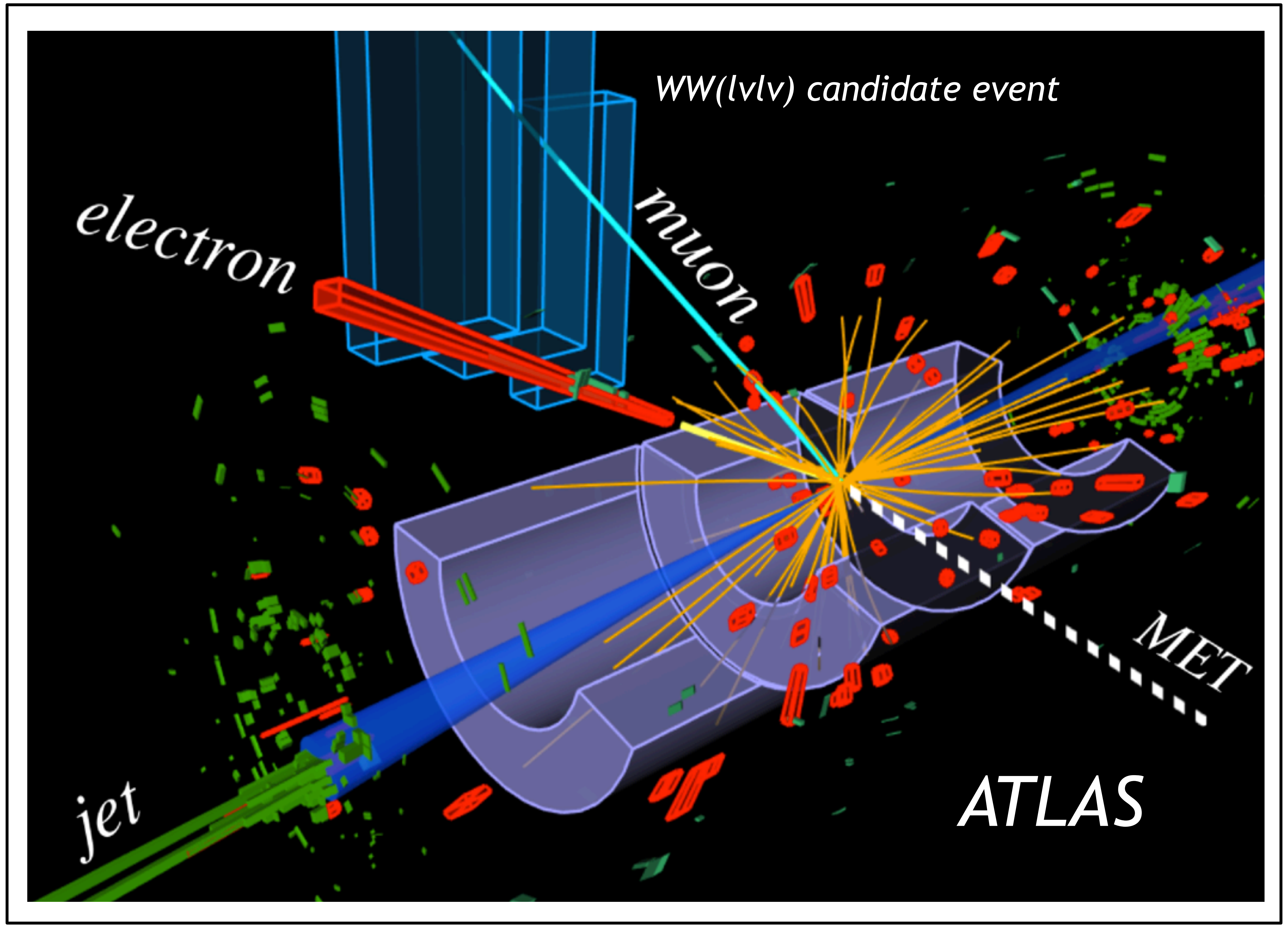






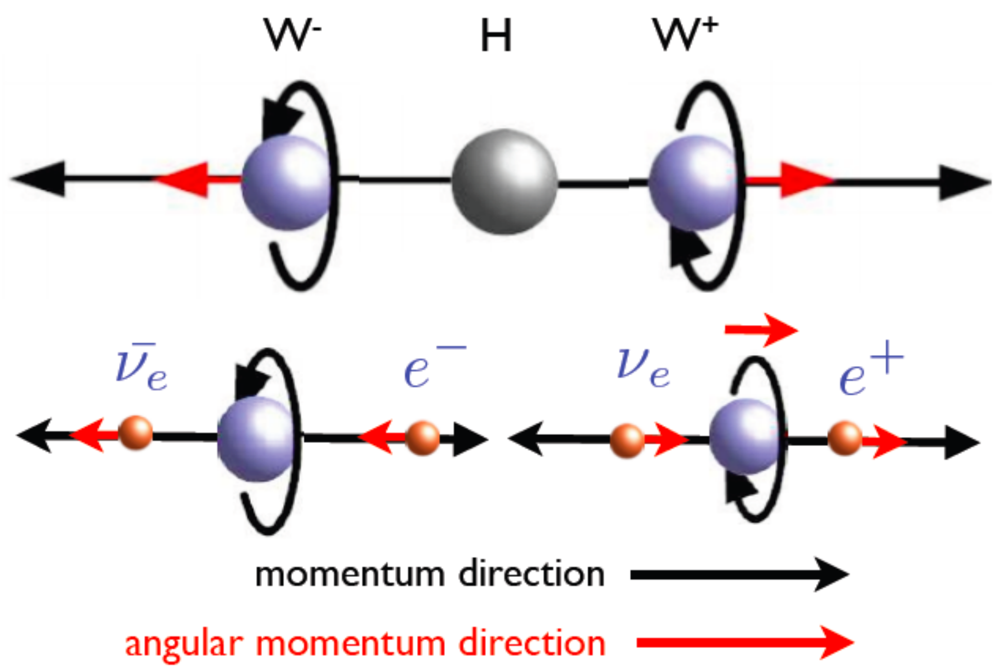
The Discovery Channels

A discovery channel of a different kind: the WW



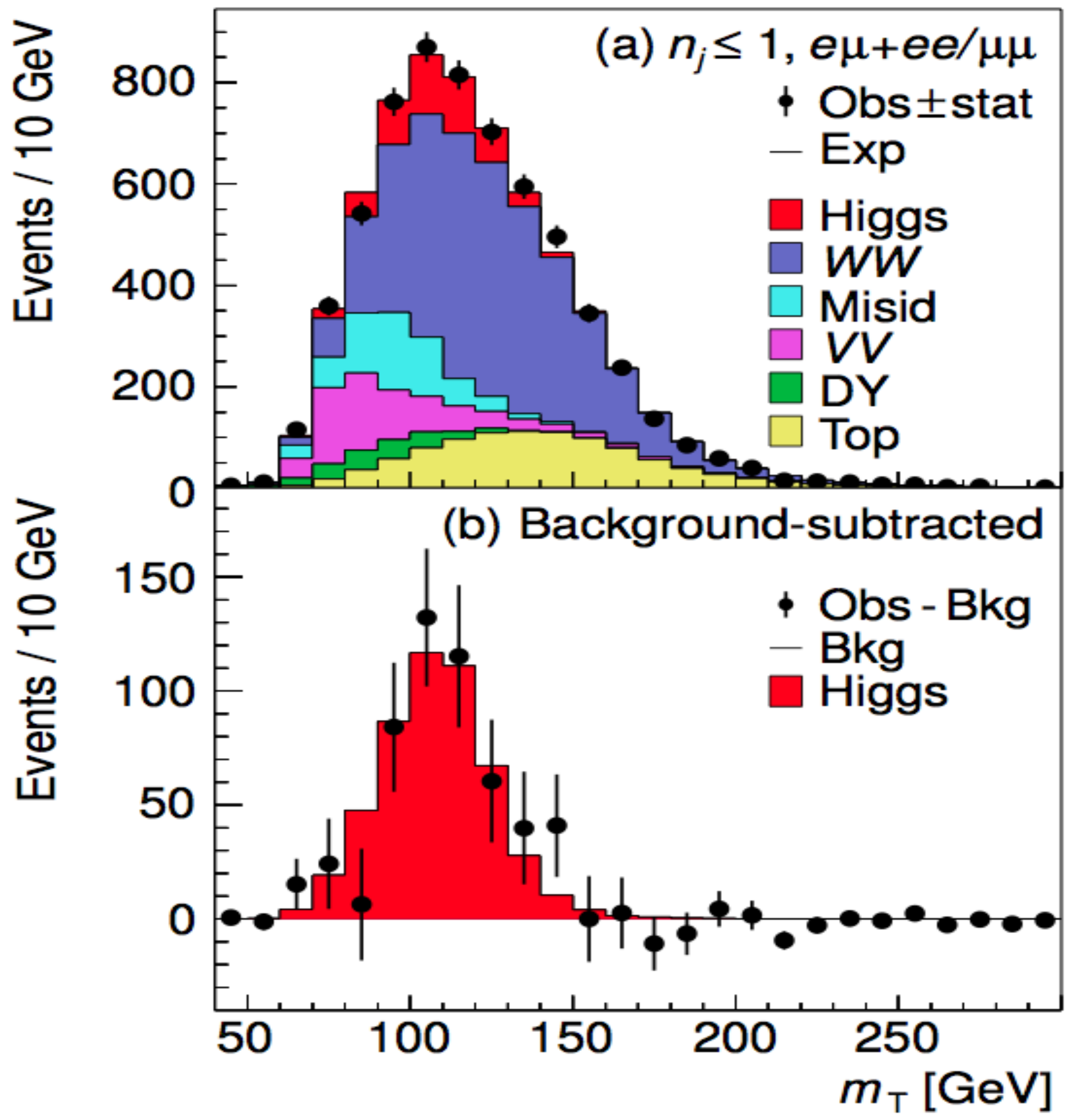
Requires good simulation of backgrounds and control regions in the data.

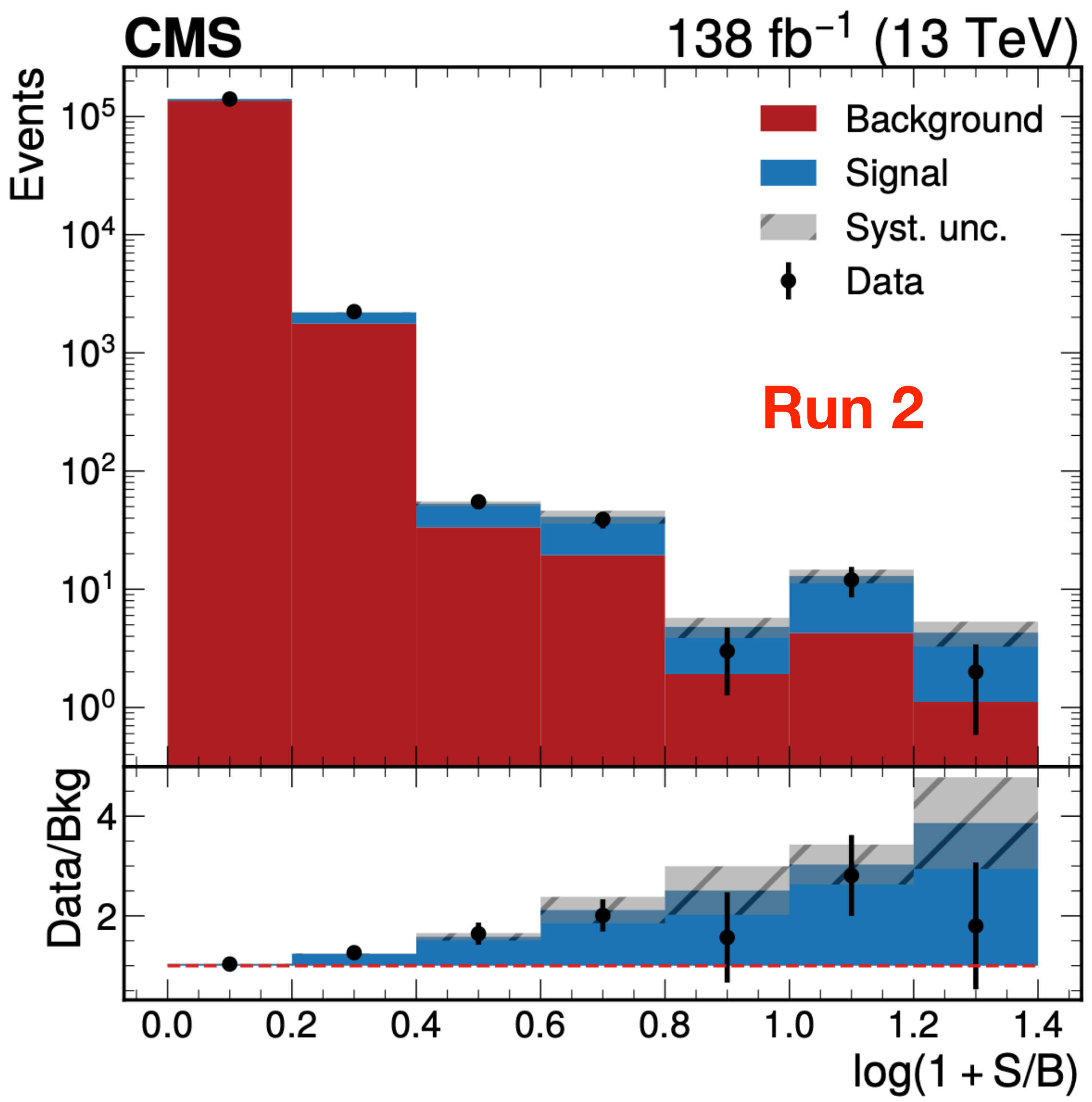
Uses the **V-A** nature of the W coupling that transfers the W **spin correlation to the electrons**.



Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

Large event rate, but also large backgrounds from the WW and top production.





A Landmark and Textbook Discovery

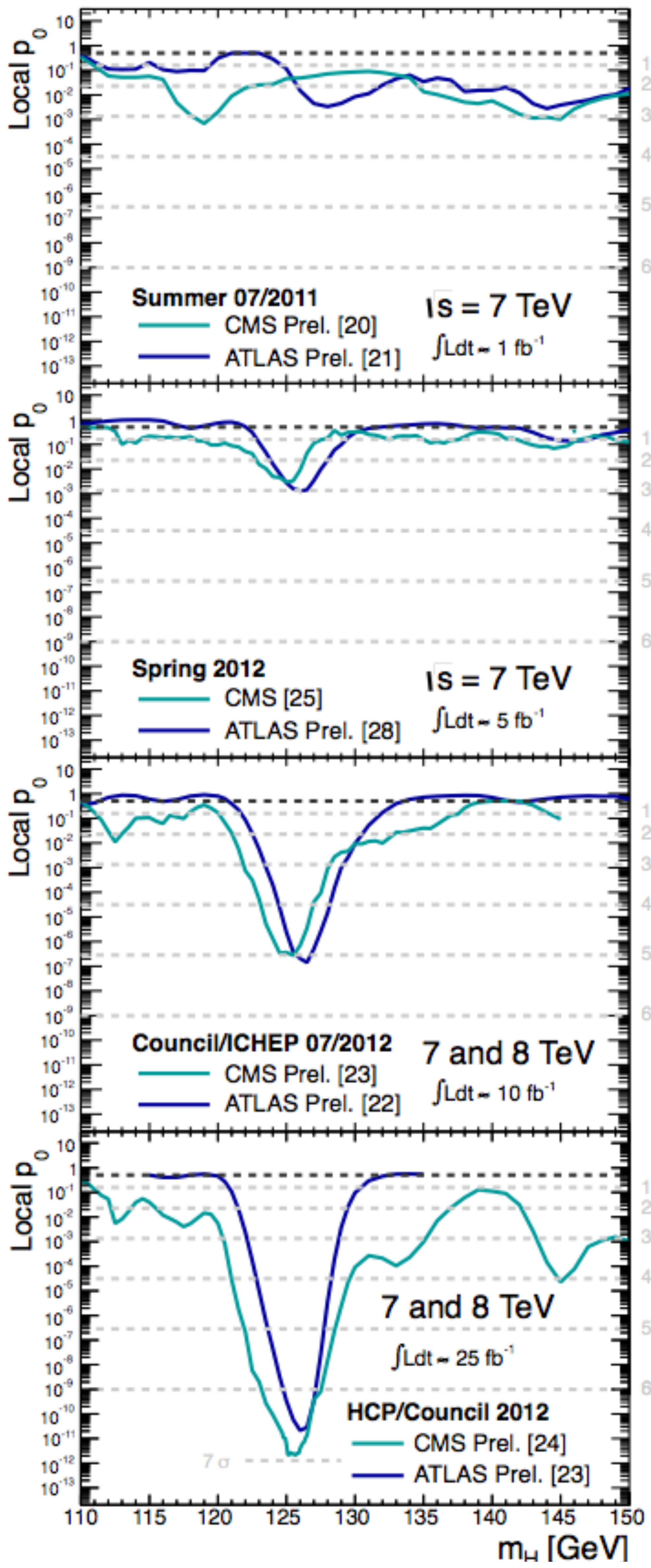
- Summer 2011 EPS and Lepton-Photon: **Still focused on limits**.
- December 2011 CERN Council: **First hints**.
- Summer 2012 CERN Council and ICHEP: **Discovery!**
- December 2012 CERN Council: **Beginning of a new era!**

✓ Strongly Motivated

✓ Significance increased with luminosity to reach unambiguous levels

✓ Two experiments

✓ Several channels



*"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

Higgs Discovery announcement July 4, 2012

2013

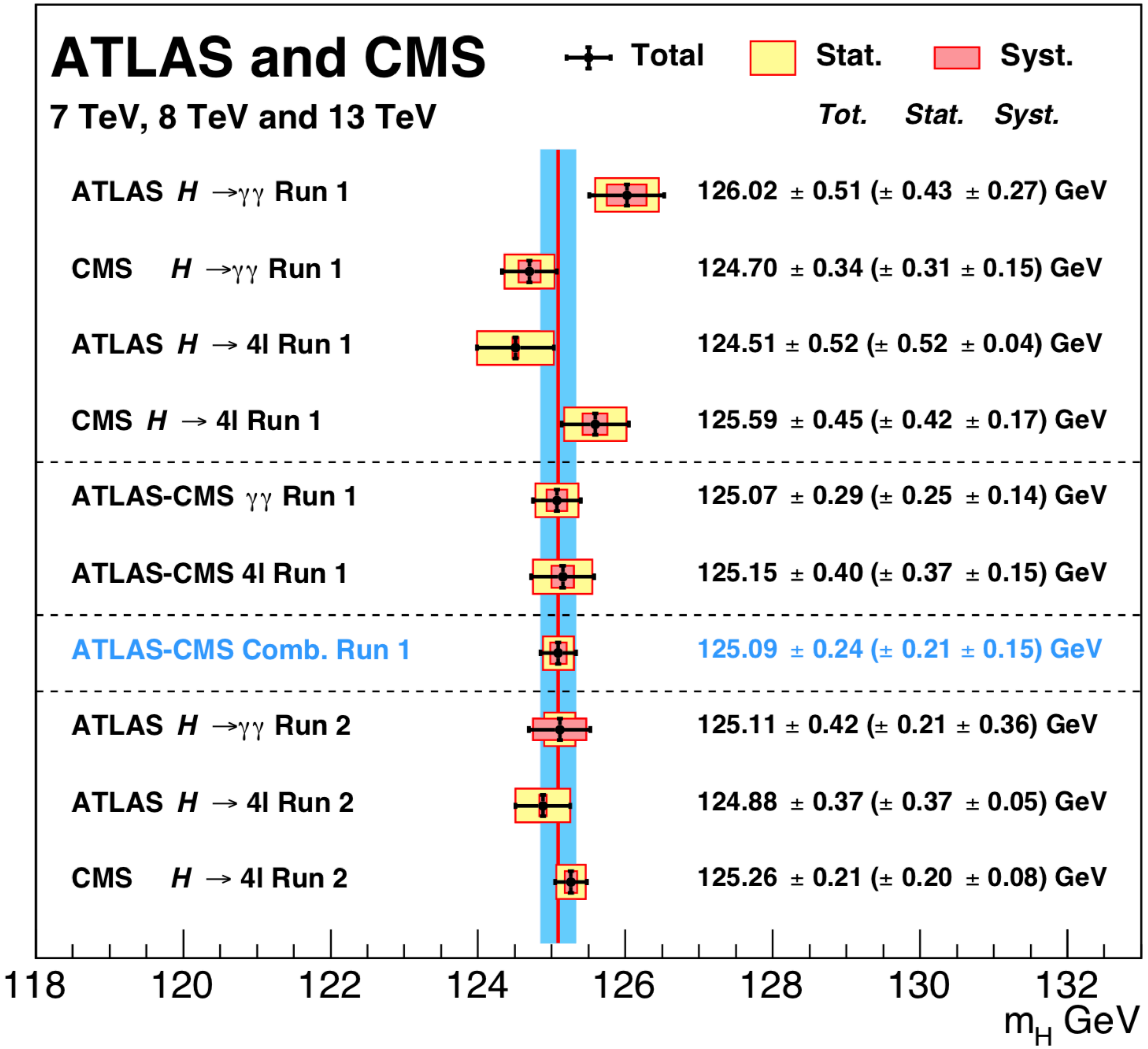
Mechanism contributing to… [full]

Francois Englert and Peter Higgs

First Precision Measurement at the LHC?

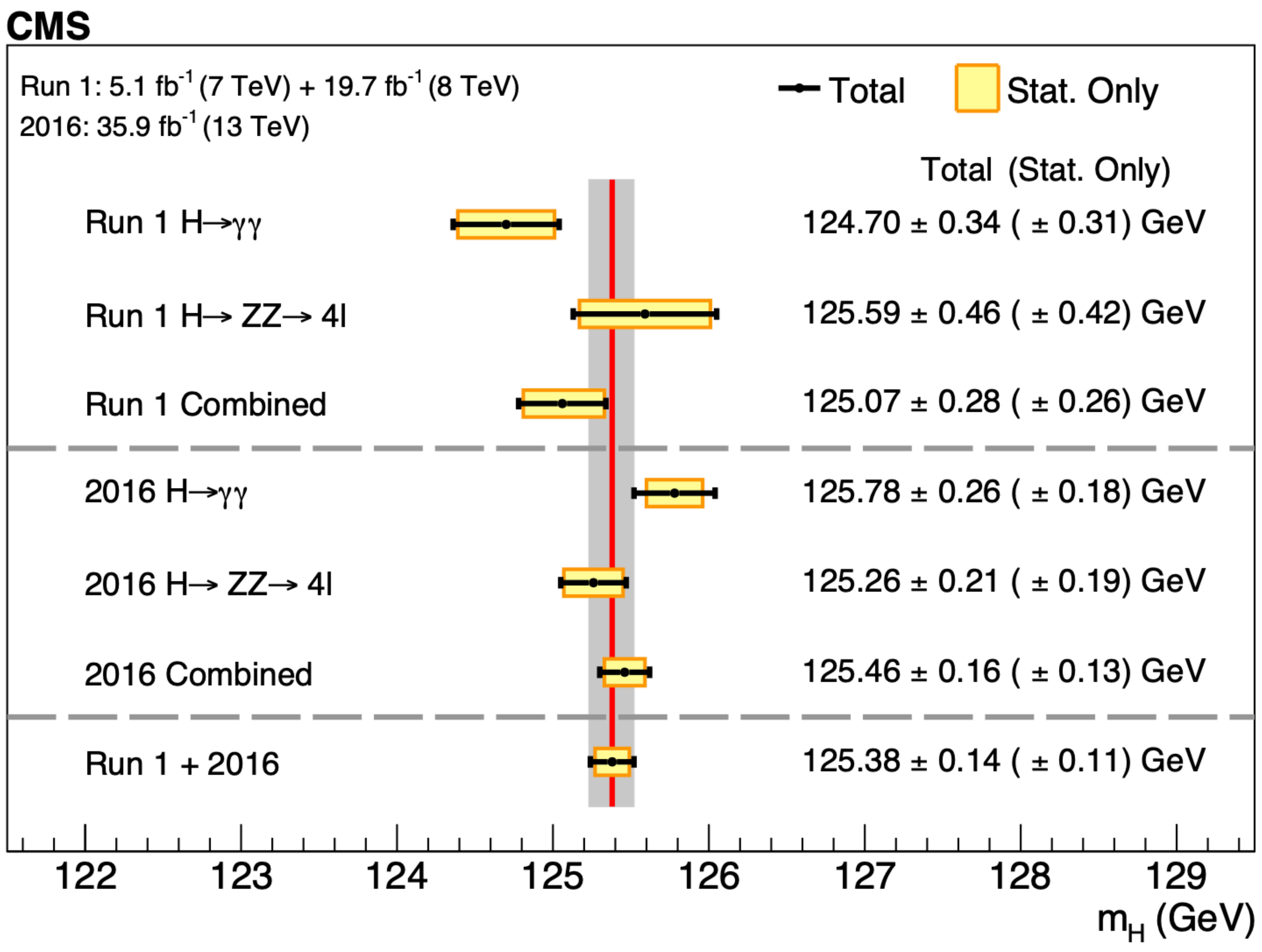
Higgs boson mass measurement

- Measurement done exclusively in the diphoton and 4-leptons channel.
- Optimizing the analysis in categories with best mass resolution (photon, electron and muons energy response).
- Reached at Run 1 a precision of 0.2%.
- Among (if not the) most precise measurement done at the LHC in 2013.

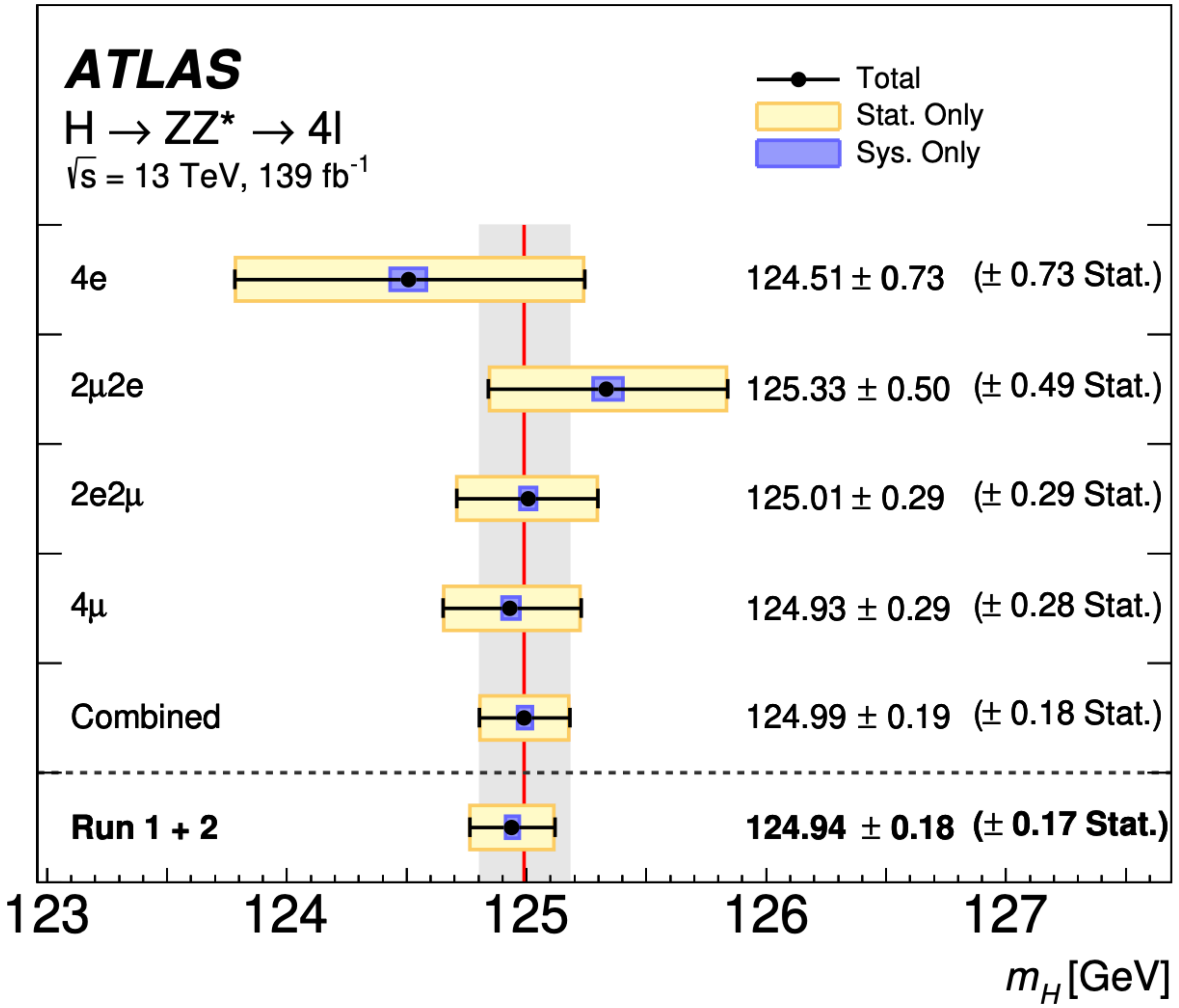


Measurement of the Higgs Boson Mass

Most precise measurement from CMS:



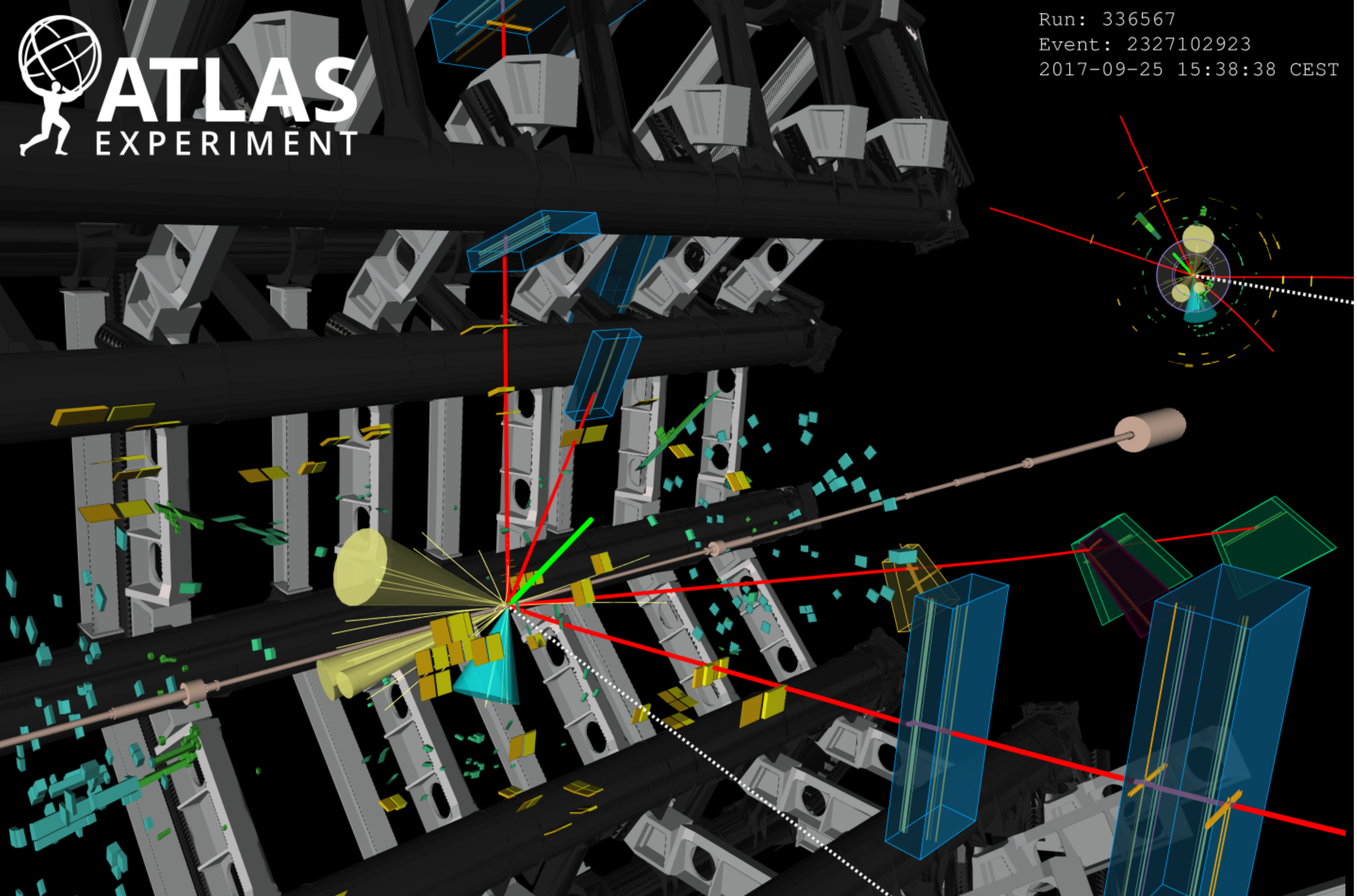
Latest measurement from ATLAS:



Systematic uncertainty (dominated by muon momentum calibration) of **30 MeV**!

The Run 2 Landmark Results

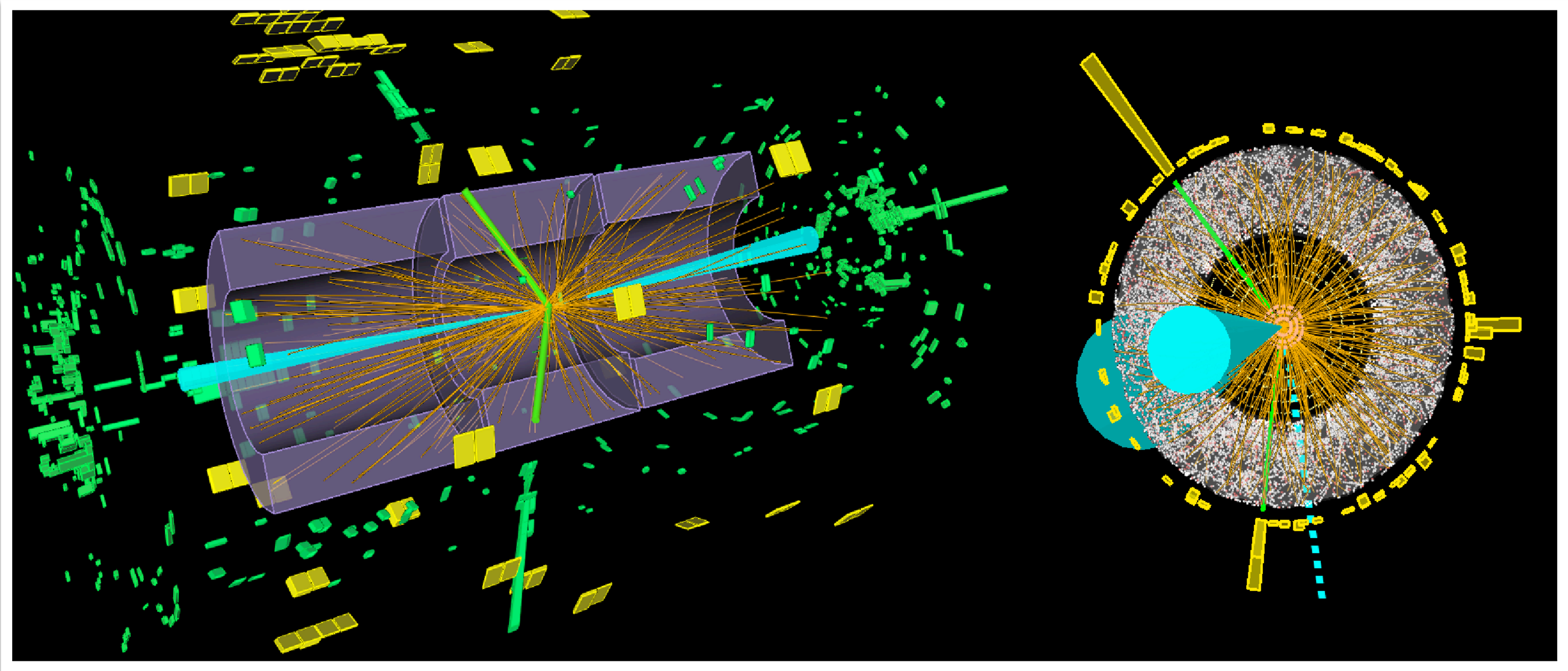
Observation and Measurement of 3^{d} generation Yukawa Couplings

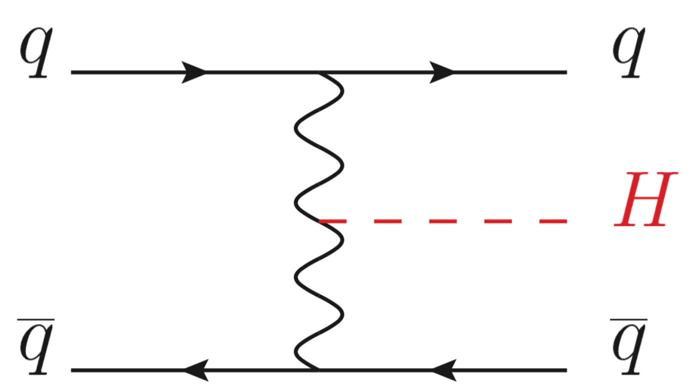


4 muon event with mass 124.4 GeV, one Z mass of 89,3 GeV and the lower mass of 33 GeV, one electron, four jets, lowest pT has tighest b-tagging.

$$s/b \sim 30$$

Higgs boson decays to Taus

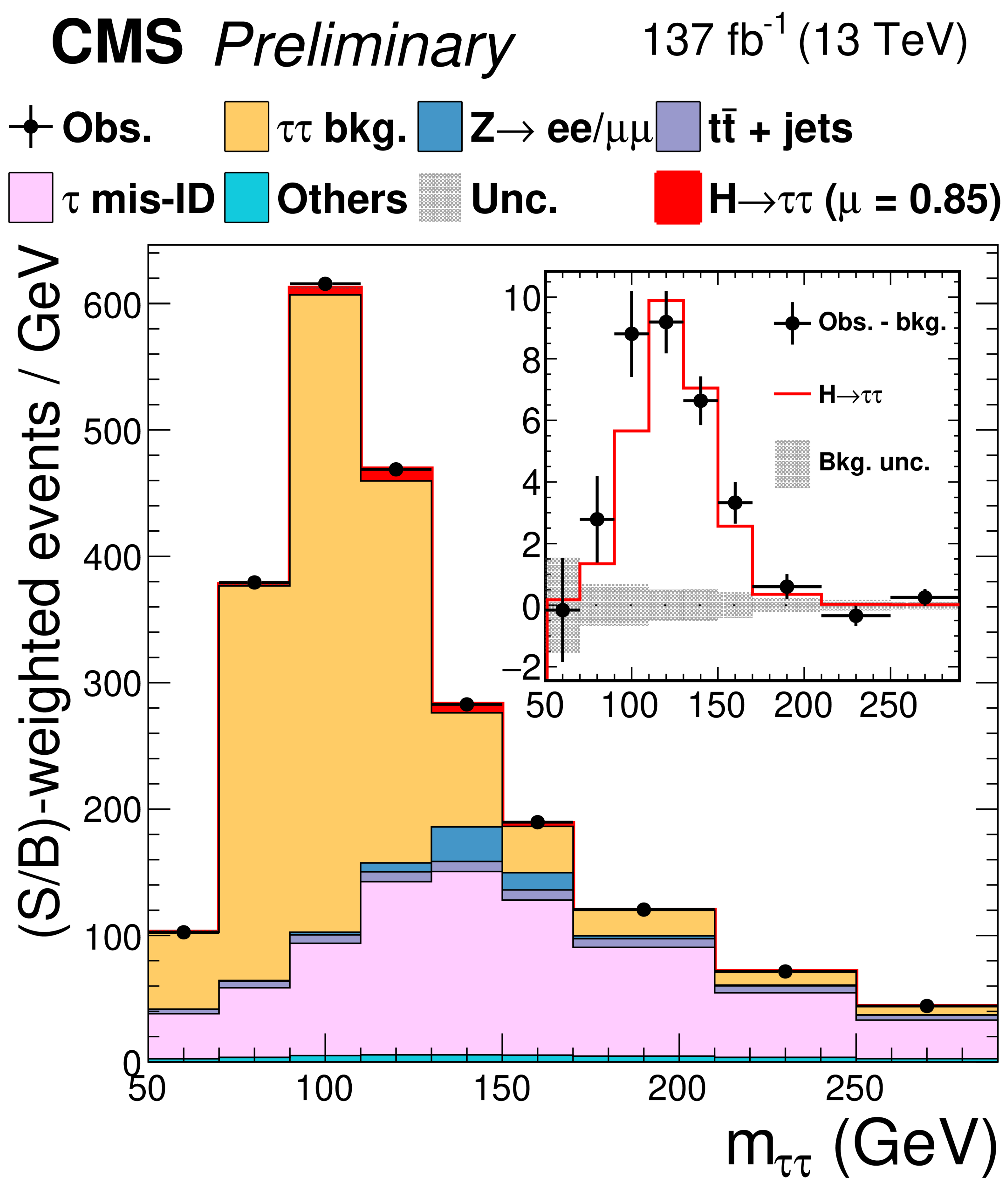




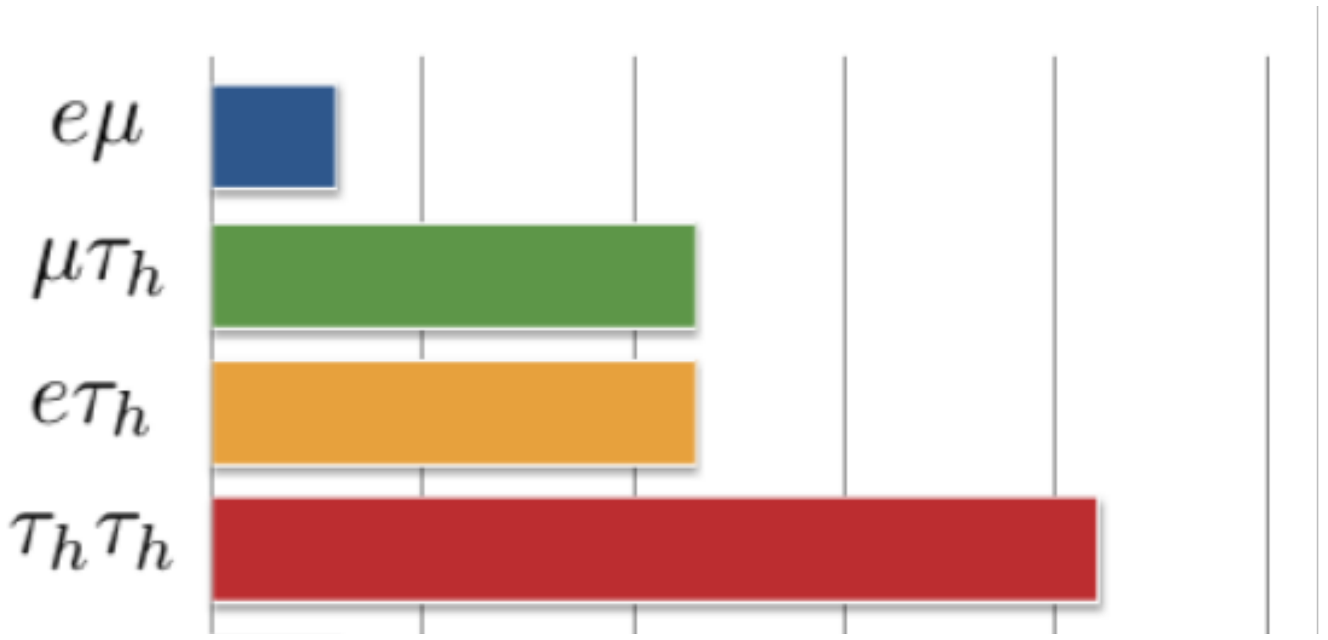
Special VBF process

With two forward jets and a large rapidity gap between the jets (due to the color singlet exchange in the t-channel

Background is Z production with two jets, in this region of phase space it is difficult to predict!



Analysis based on several channels depending on the decay mode of the tau.

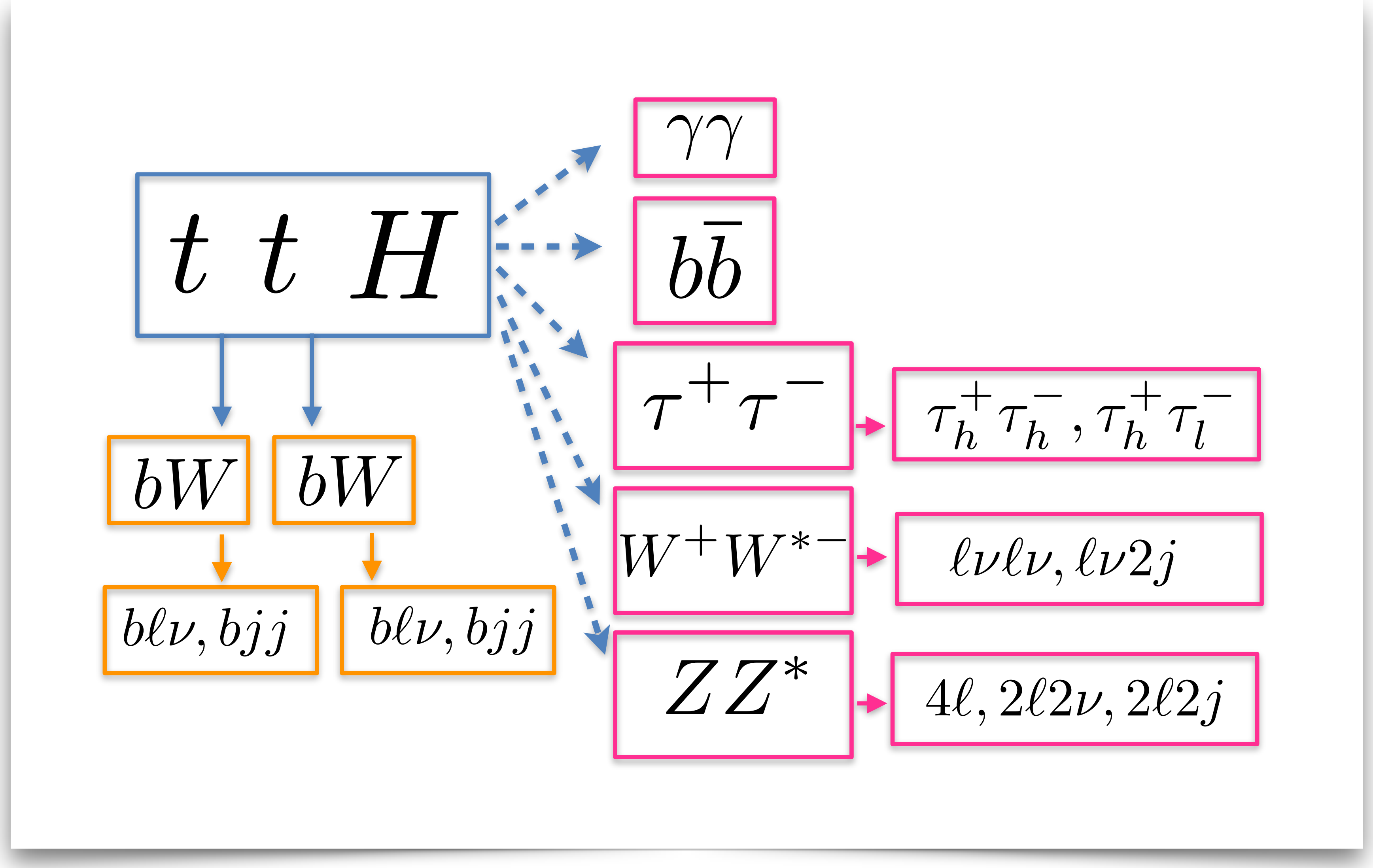


Analysis requires data driven methods to do so: e.g. the embedding of taus in Z to di-muon events.

The tau polarisation can in principle be reconstructed, but this is very difficult and was not done yet.

Direct probe of the top Yukawa coupling

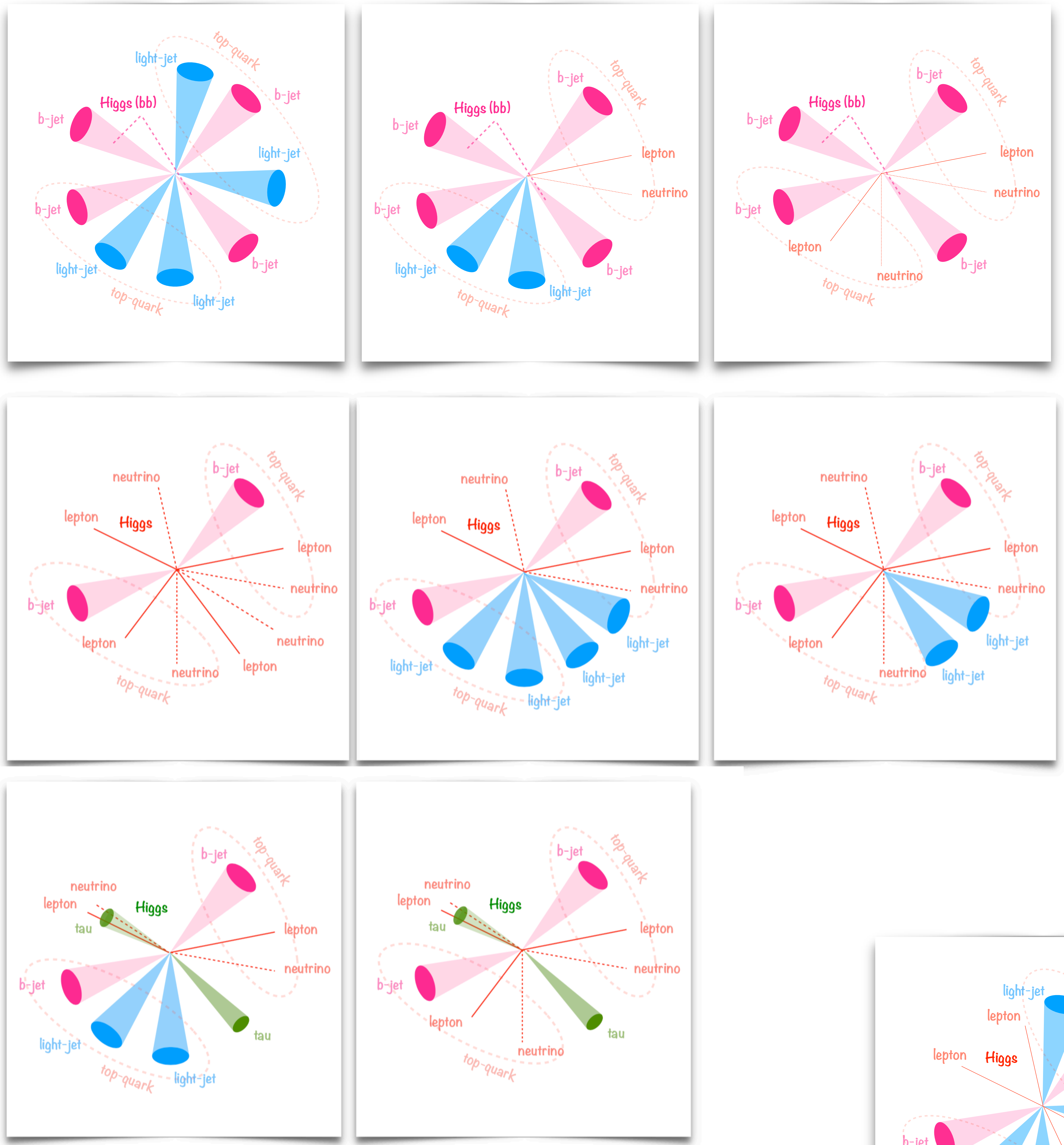
ttH Analyses at LHC: Massively Complex!



- Large number of final states which are typically very complex (mixture of b-jets, leptons, taus and photons)

- But, many different channels, also means different backgrounds and different systematic uncertainties and therefore also a strength!

- With the new Run at close to double centre-of-mass energy and increased statistics, changes in leading channels.



ttH(bb)

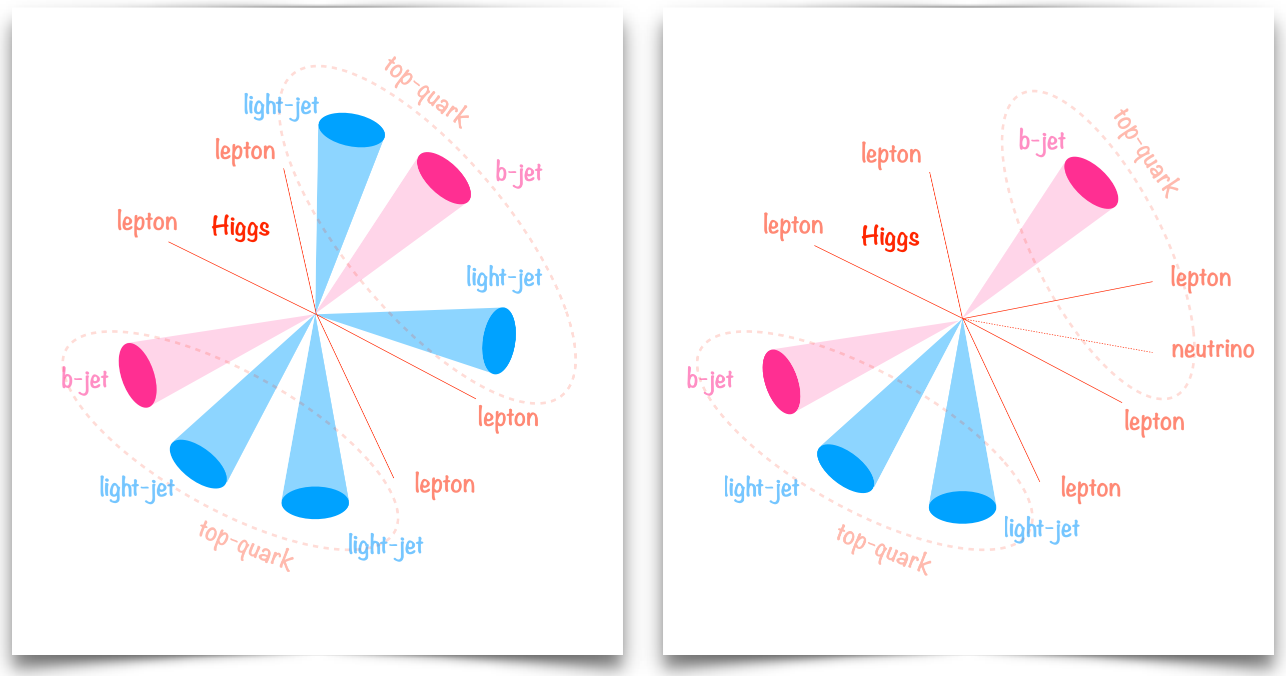
Very large backgrounds of top pair production associated with b jets

Dominated by background modelling uncertainties

ttH(WW, ZZ and tau tau)

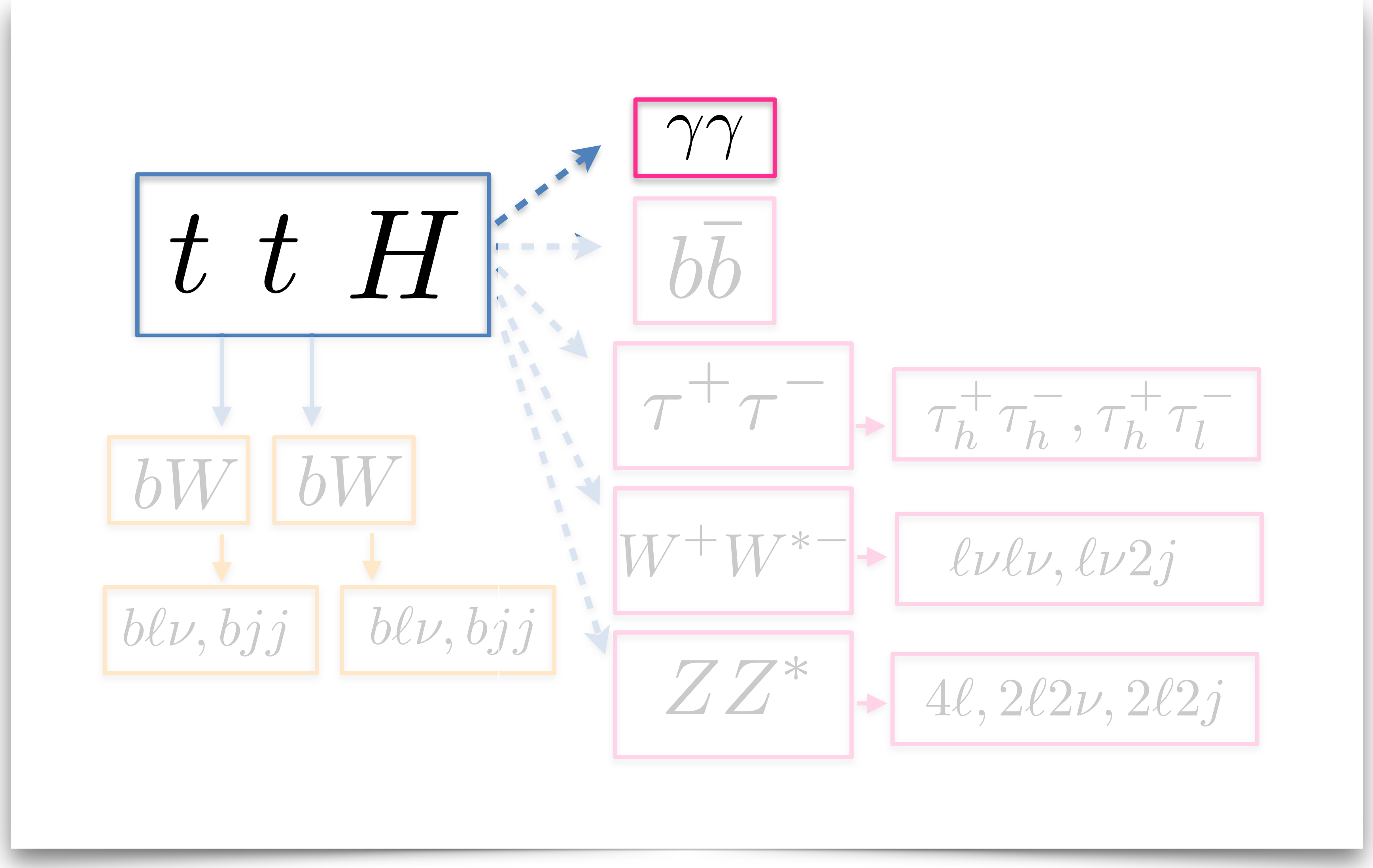
So-called multi-lepton channel

Large number of topologies intricate reducible backgrounds of jets faking leptons.

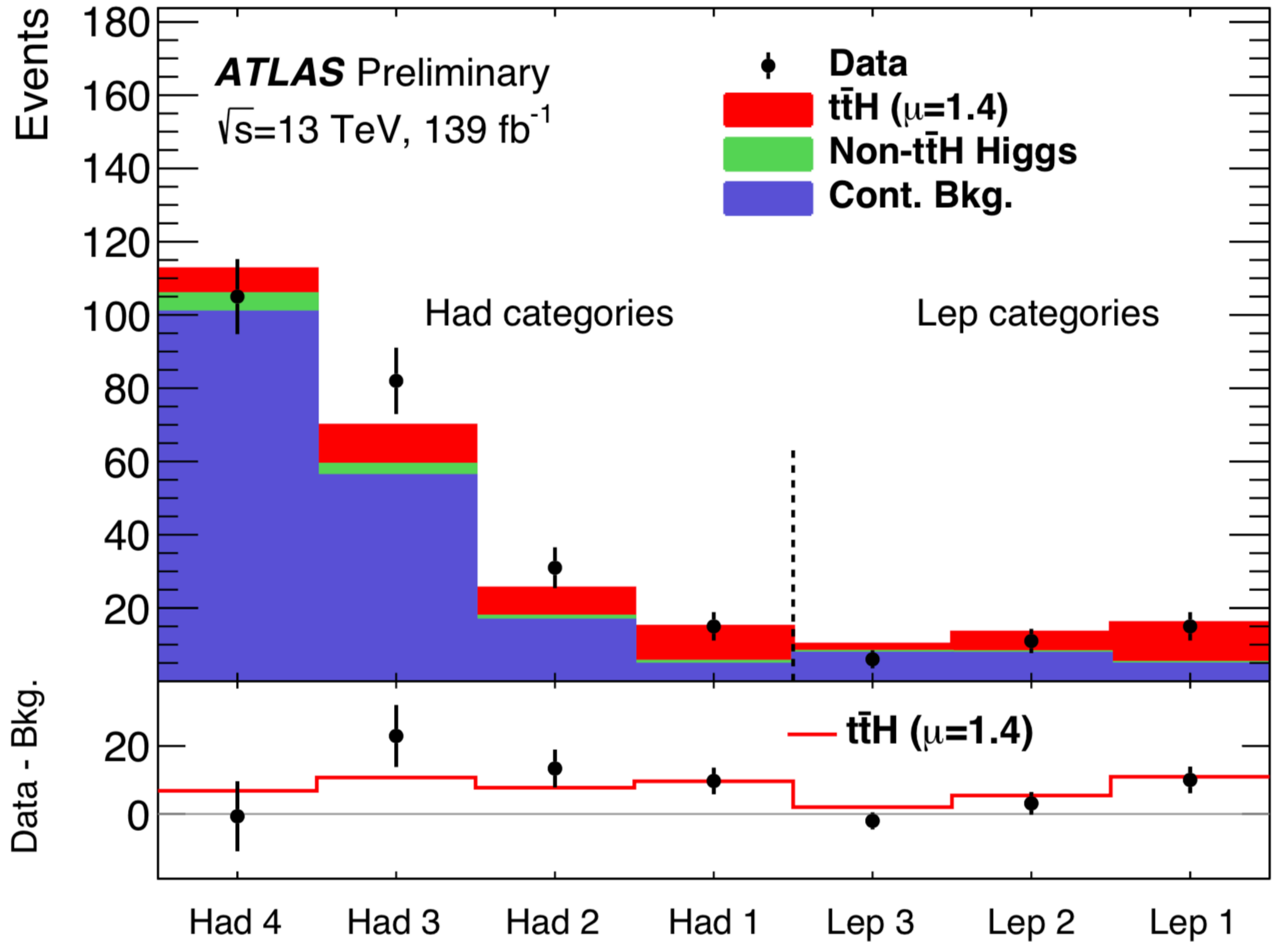


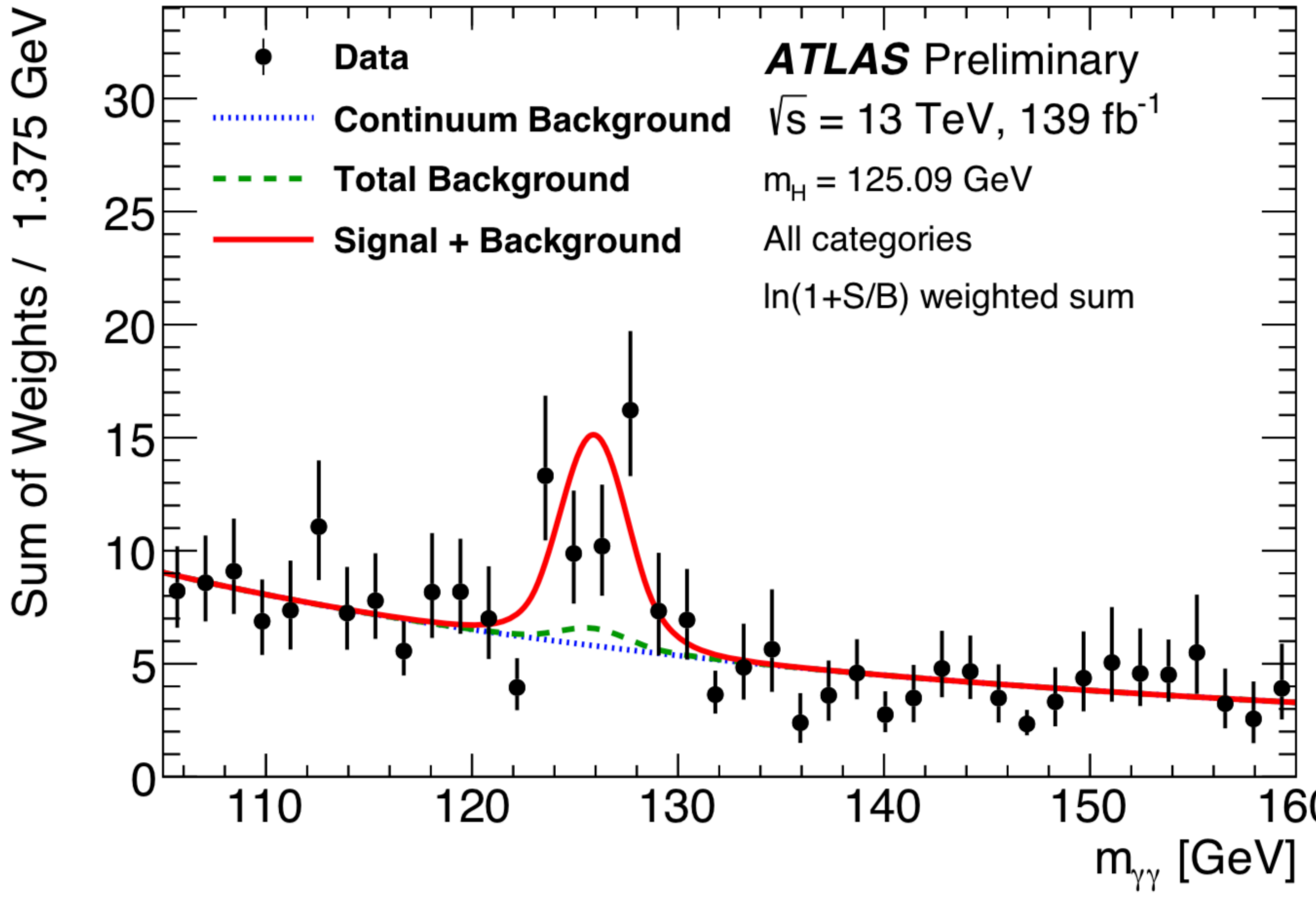
Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!



Background and signal modelled using analytic functions.

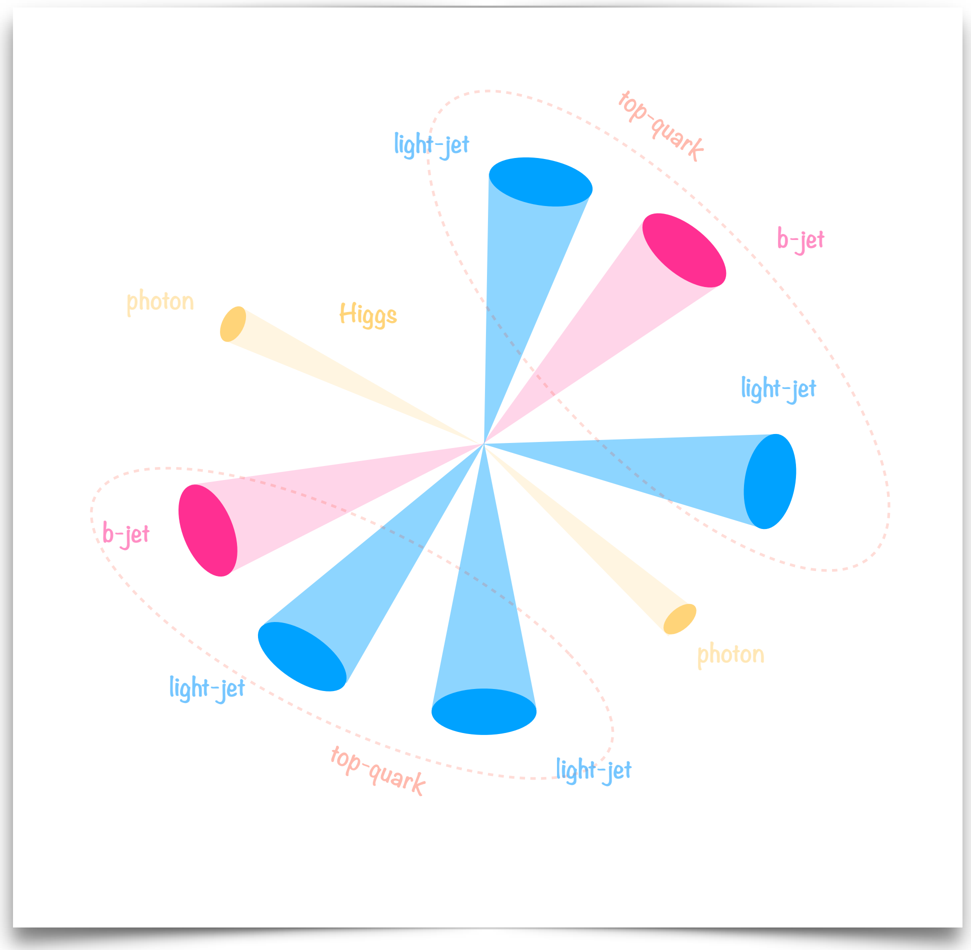


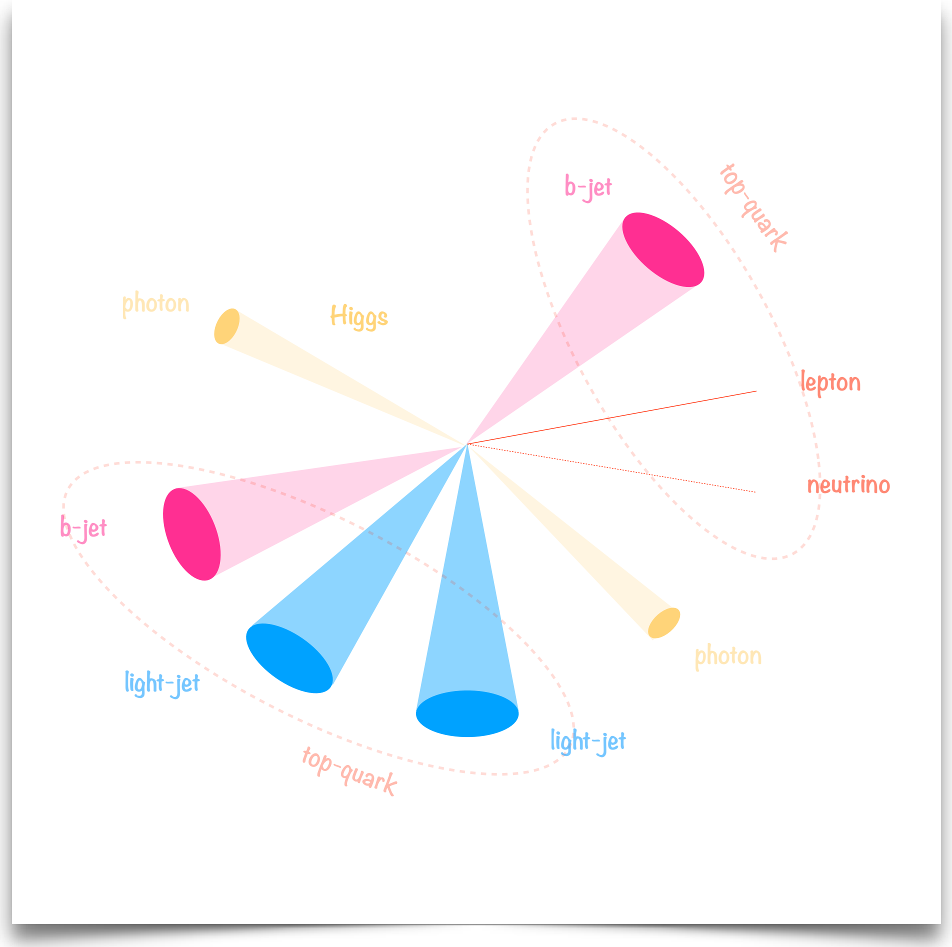


Cross section dominated by statistical uncertainties:

$$1.59^{+0.38}_{-0.36}\,(\text{stat.})\,^{+0.15}_{-0.12}\,(\text{exp.})\,^{+0.15}_{-0.11}\,(\text{theo.})\ \text{fb}$$

Currently most sensitive channel





Expected (4.2σ)

Observed 4.9σ

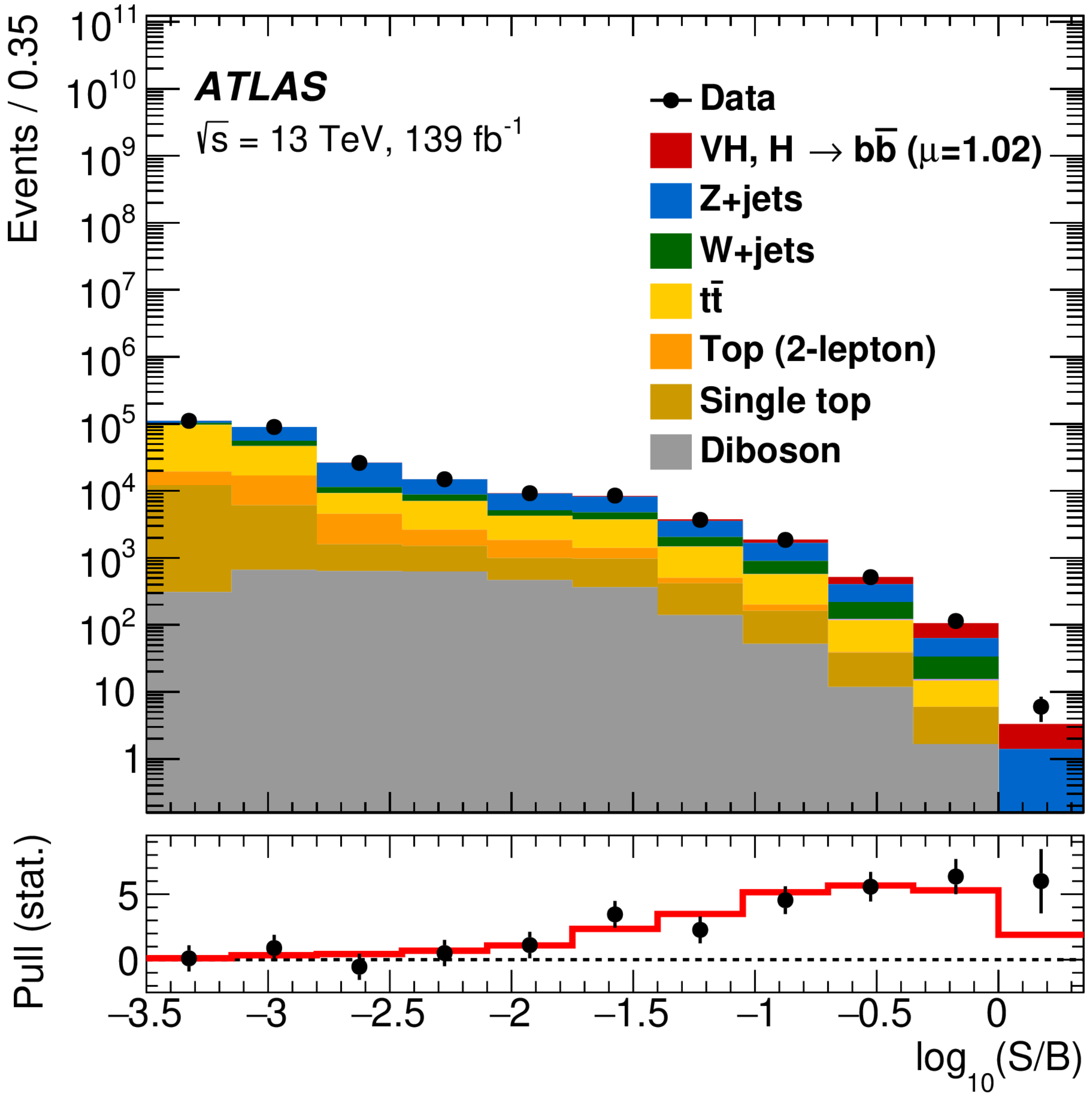
In combination with the other channels:

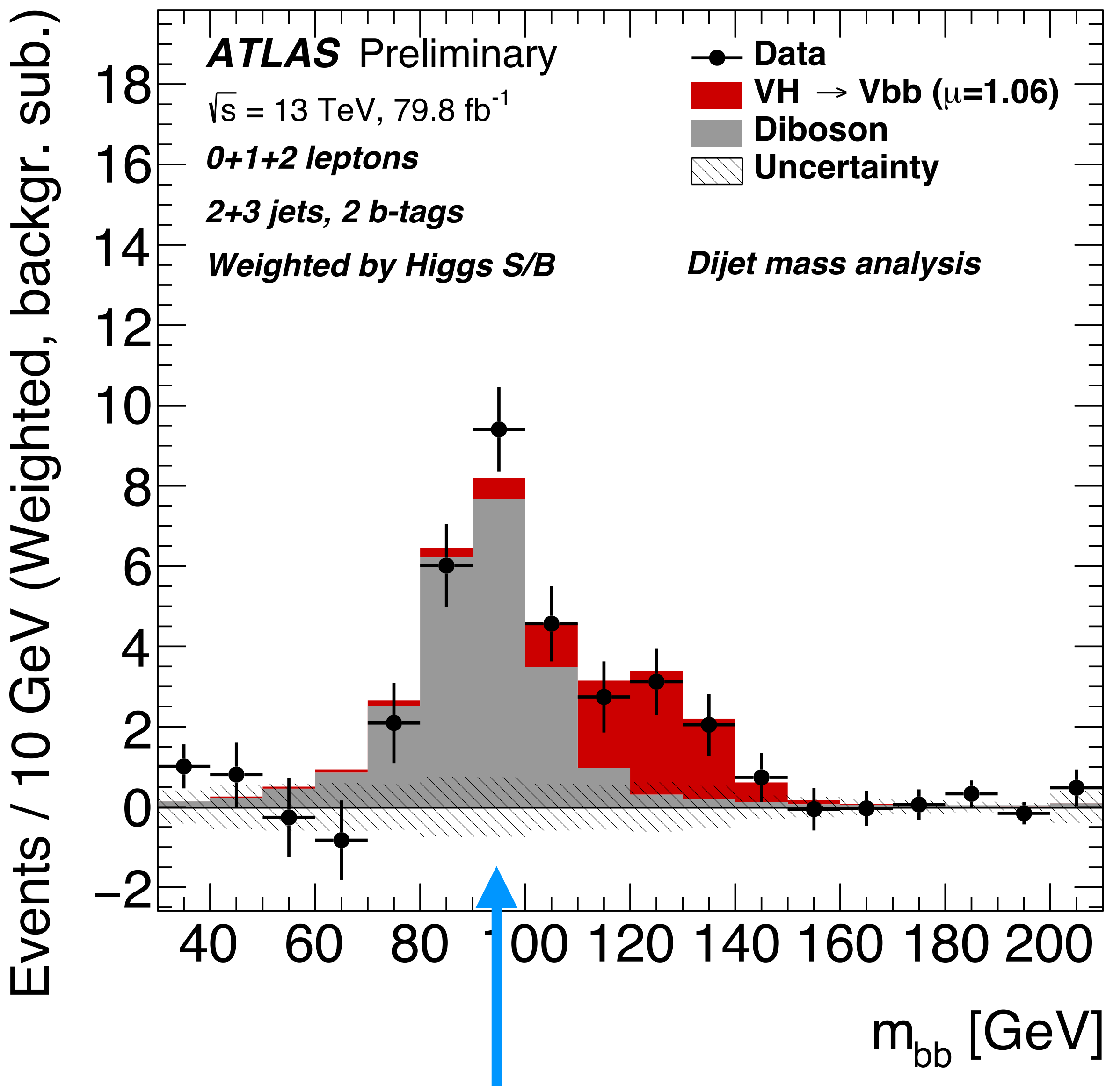
Expected 5.1σ

Observed 6.3σ

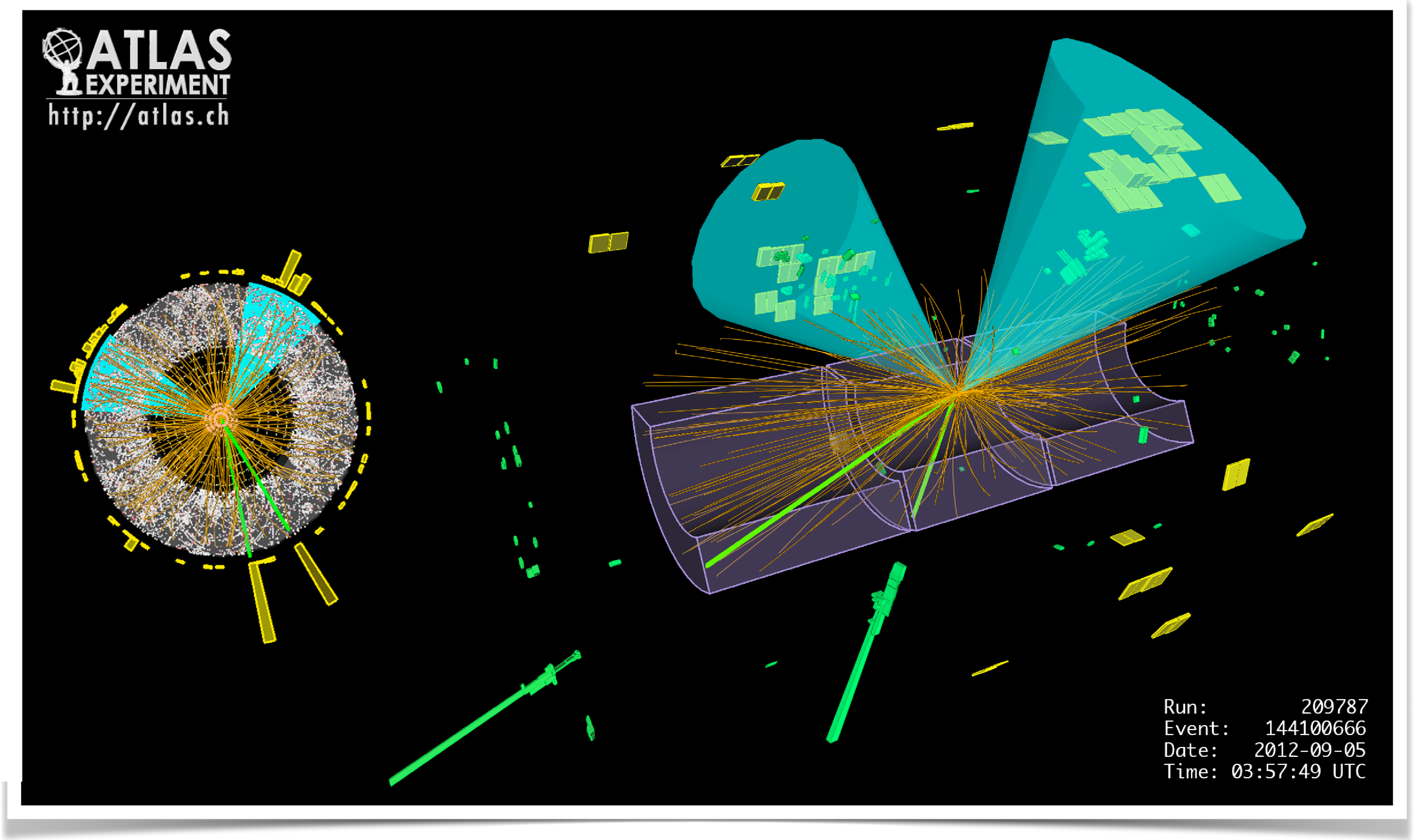
Observation!!

Higgs boson decays to b-quarks





Analysis is sensitive to Z decays to b-quarks, provide an important check.



Main background is V+jets (in particular b-jets), relies on a good simulation, but is controlled in the mass side-bands!

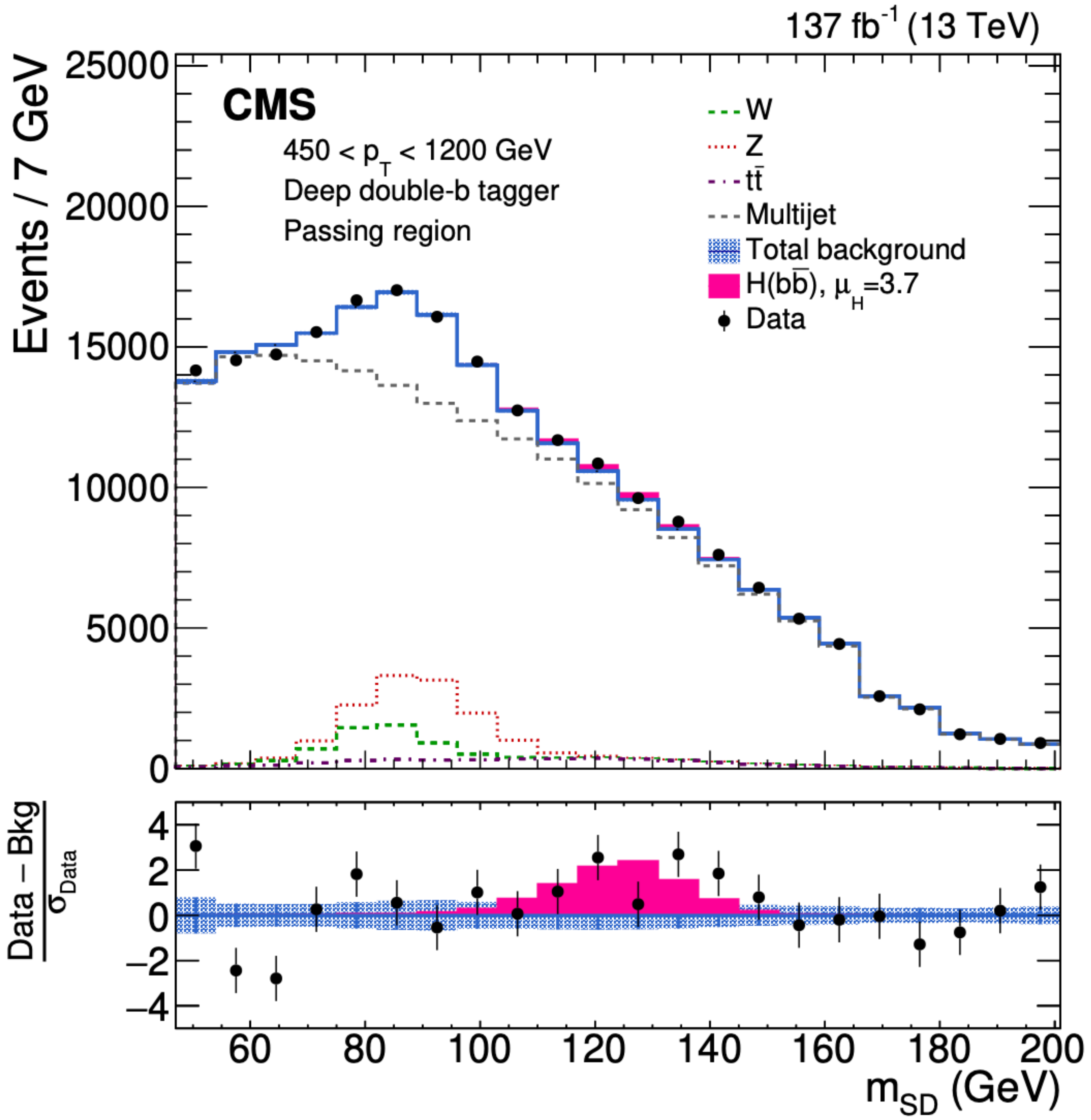
Analysis based on three main channels targeting WH and ZH production, based on the W or Z decays:

- 0 « leptons » (for neutrino decays of the Z)
- 1-lepton (W decaying to an electron or a muon)
- 2-leptons (Z decaying to electrons or muons)

Very important measurement of VZ process with Z to b quarks as a check.

Unambiguous Observation!!

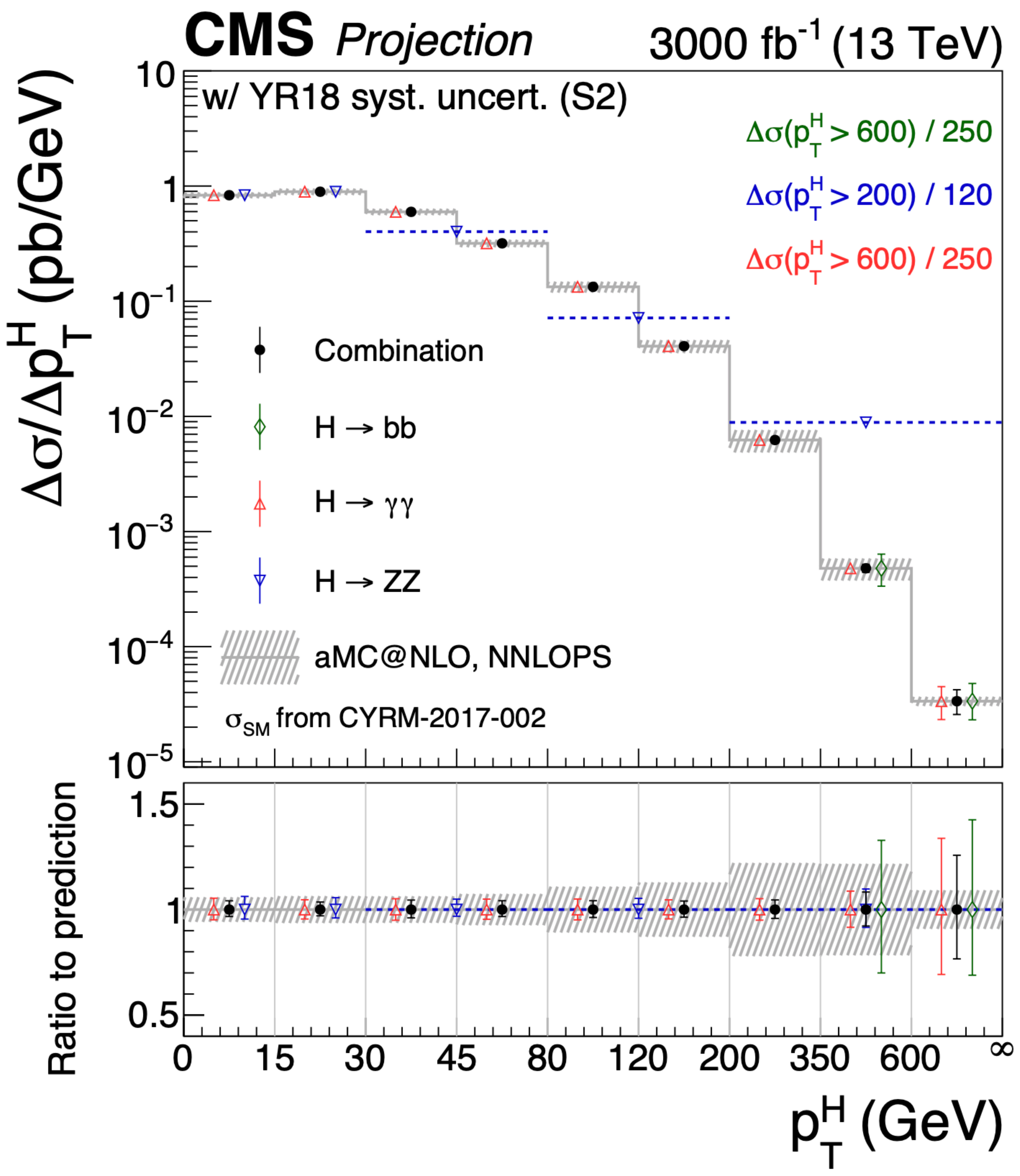
Boosting the Higgs Boson!



Thought to be completely impossible!

Expected H significance ($\mu_H = 1$) $0.7\,\sigma$

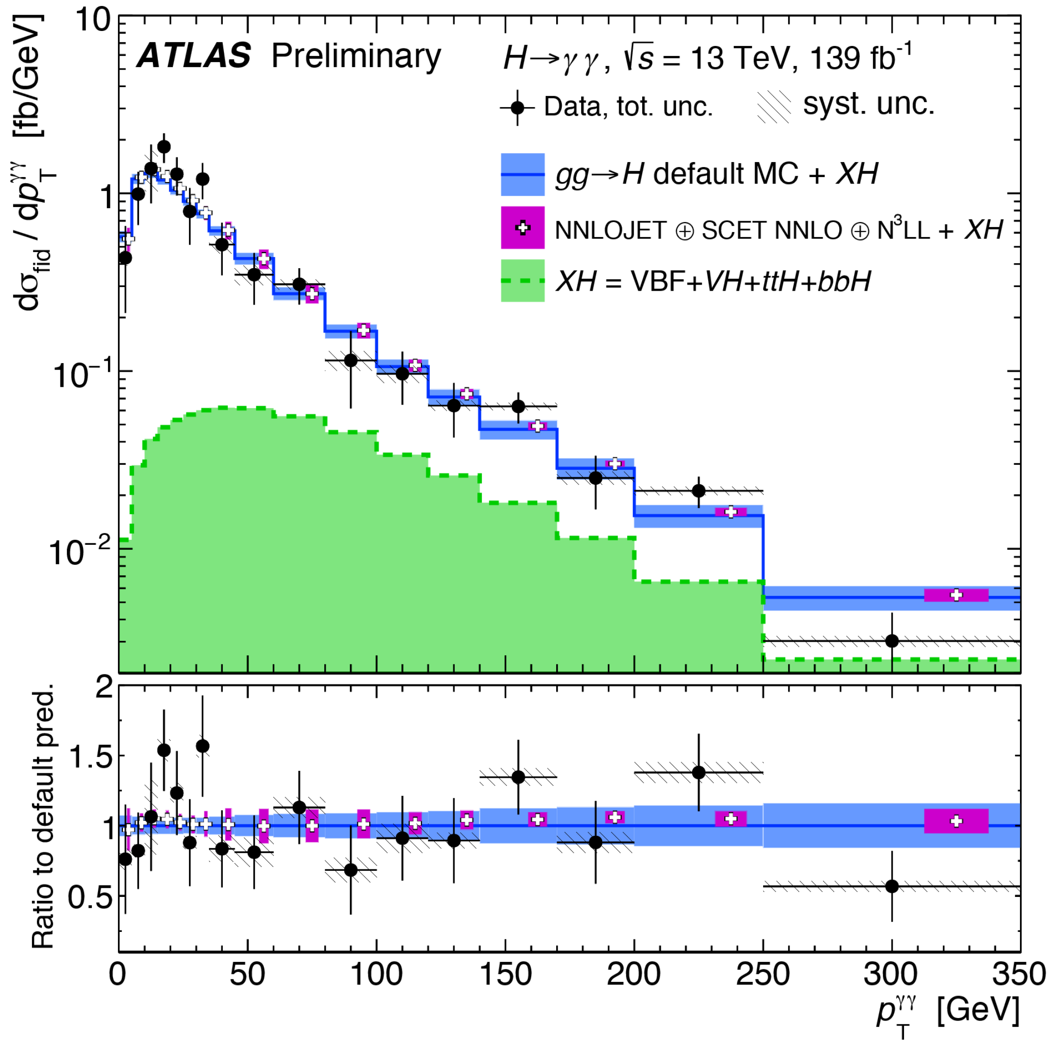
Observed H significance $2.5\,\sigma$

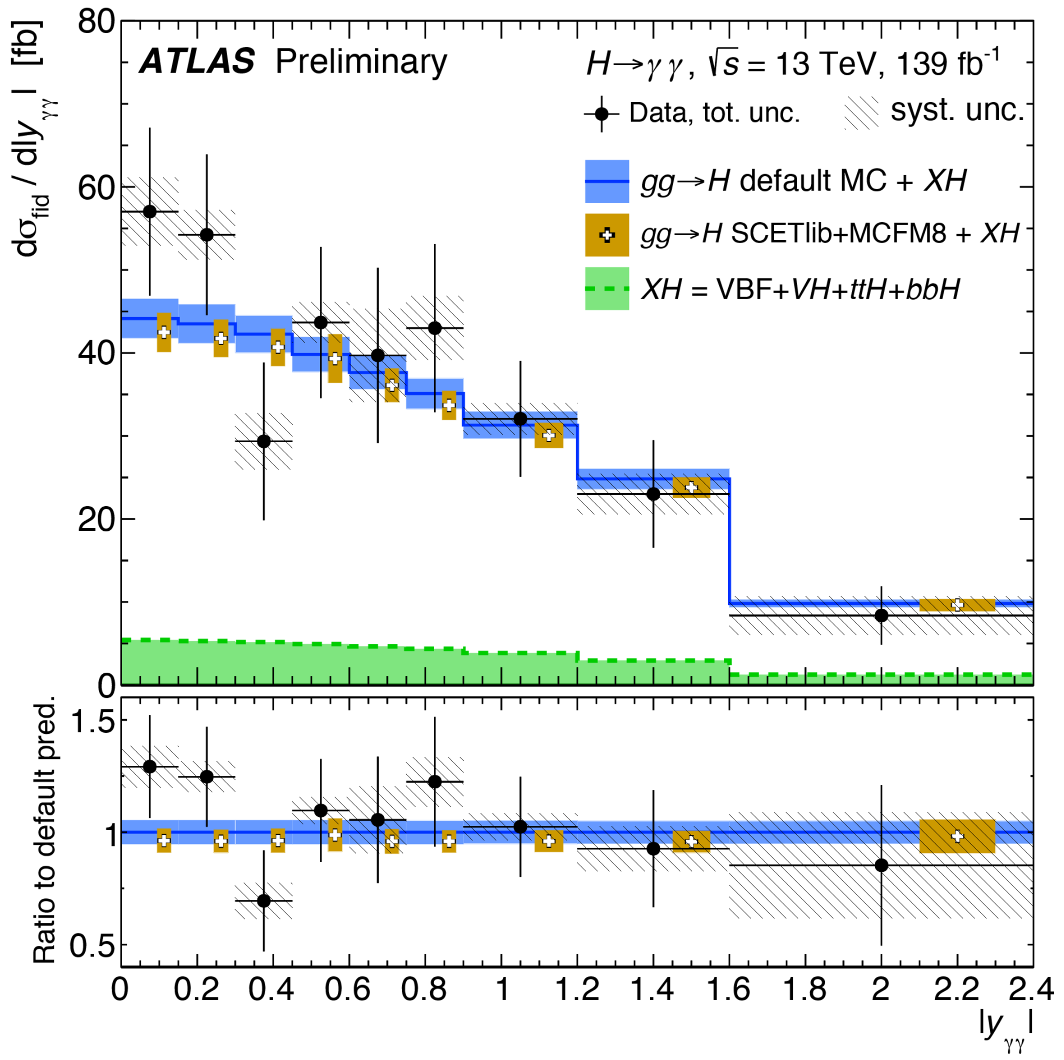


Yet can play an important role in the measurements of the inclusive production at high transverse momentum!

Extremely interesting to for indirect NP constraints!

Differential Cross Section Measurements



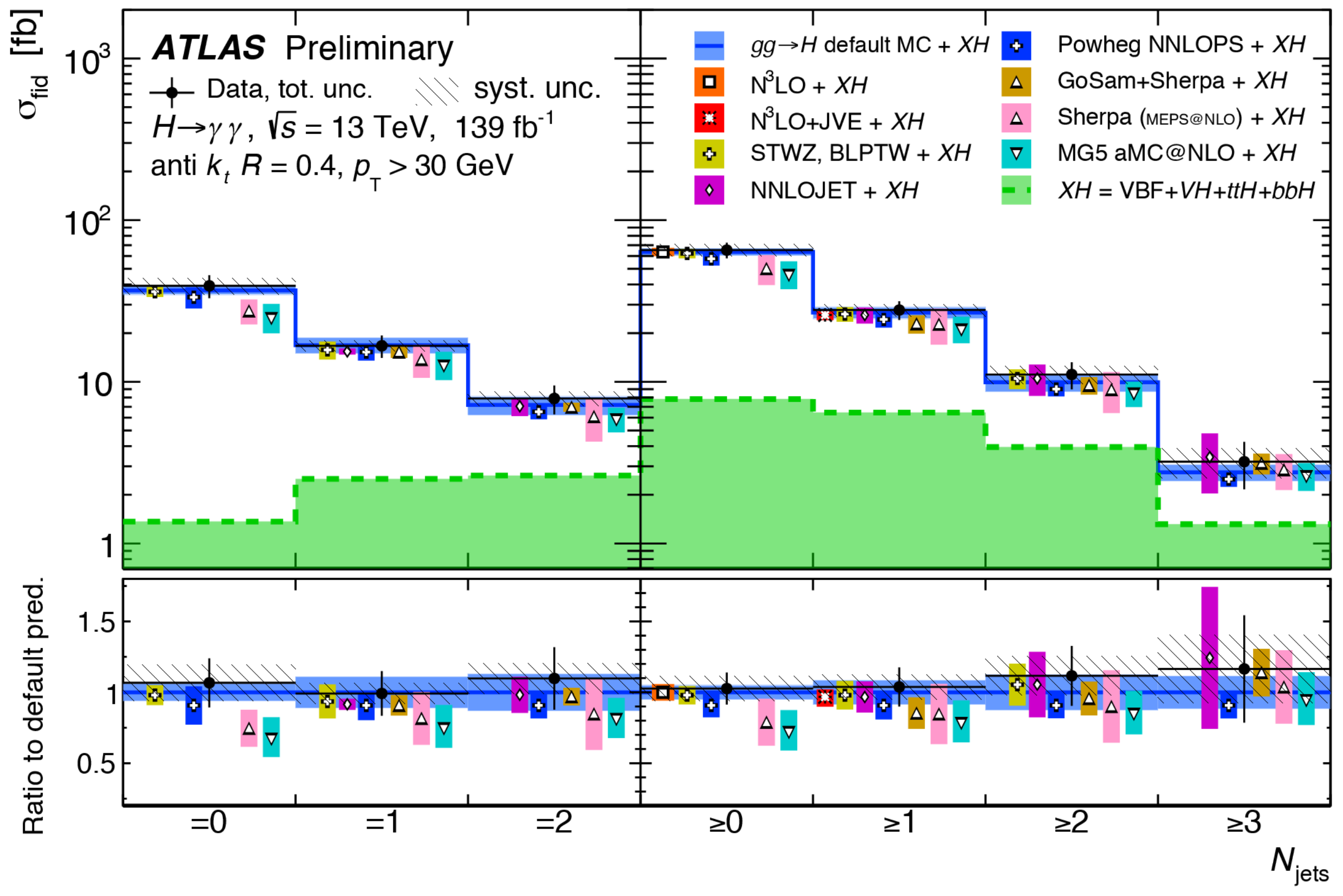


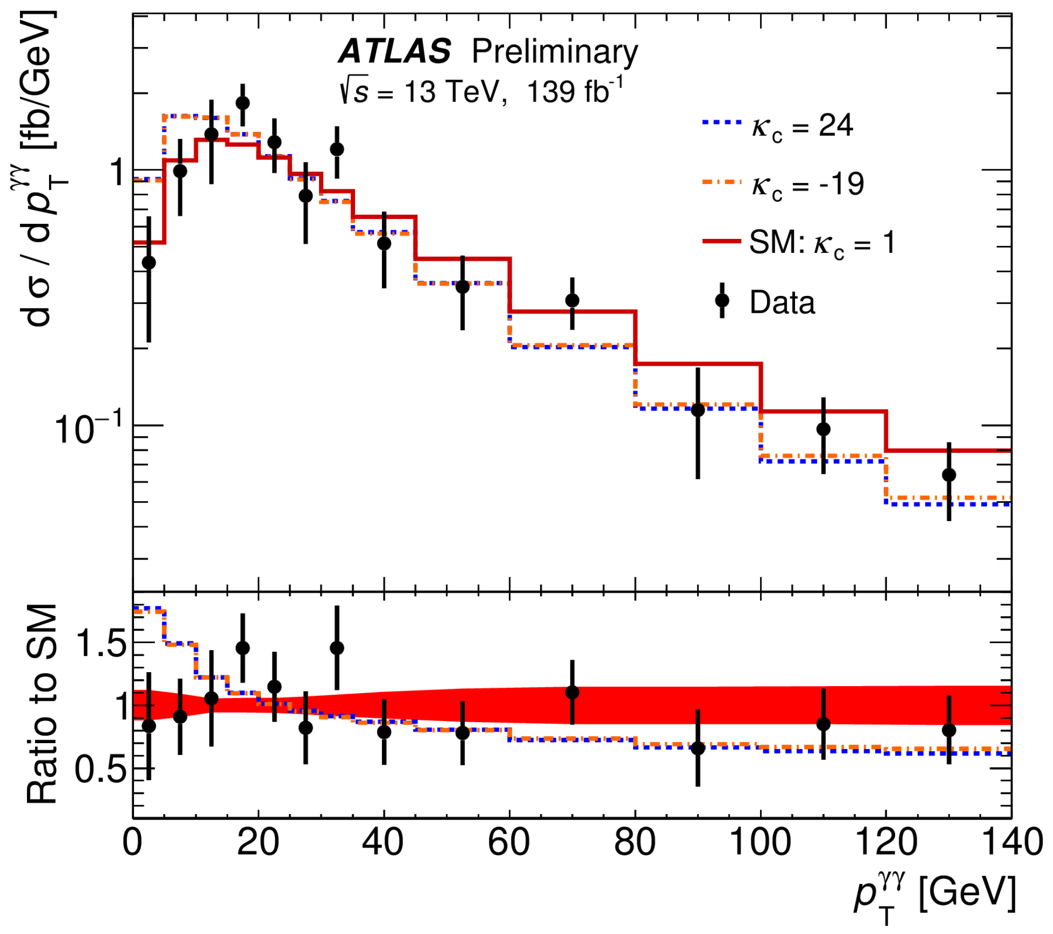
Measurement of fiducial and differential cross sections for Higgs production.

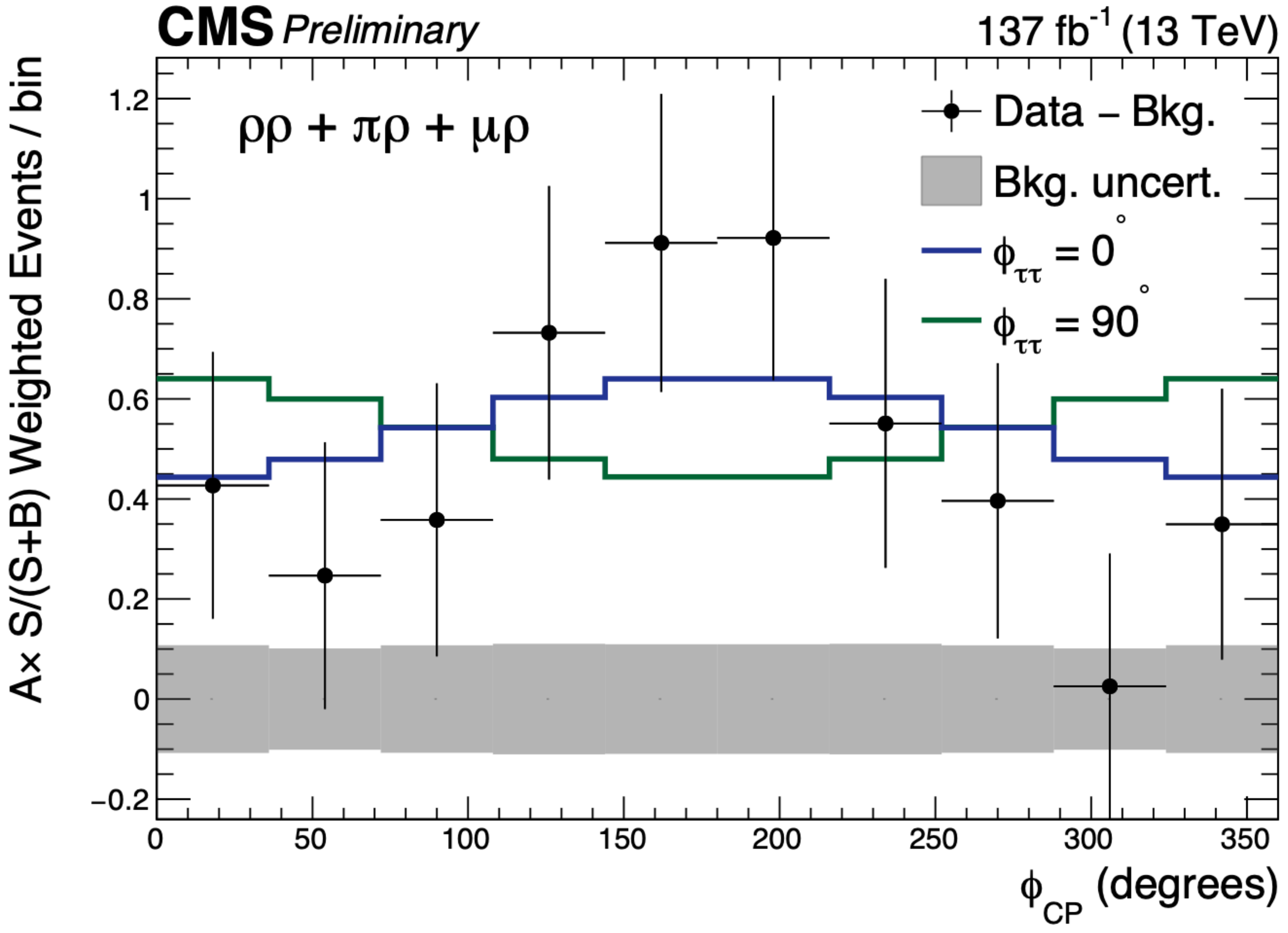
Measuring differential cross section open a vast number of interpretations in terms of properties of the Higgs boson:

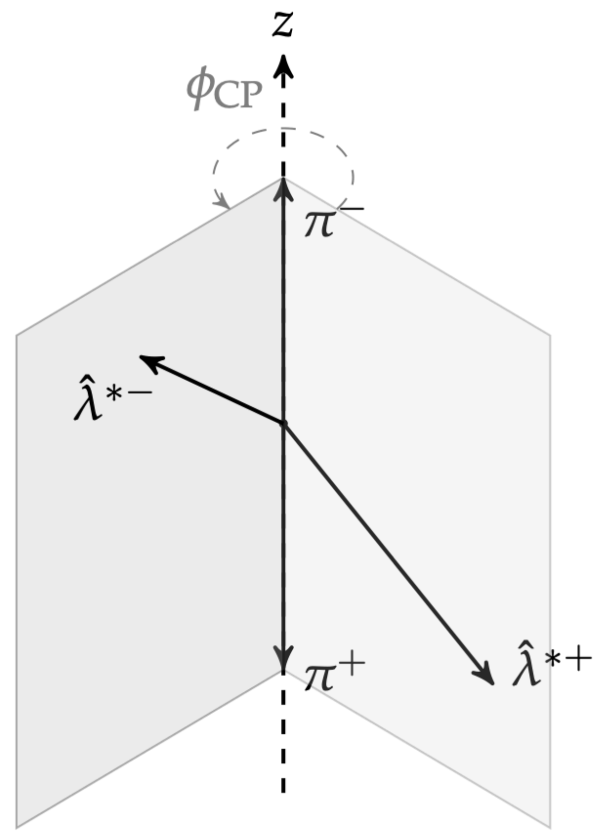
- The content of the loops involved in the production, potential to constrain any additional coupling modifying differential distributions (Yukawas, trilinear, etc…)

- Measure its spin/CP properties.

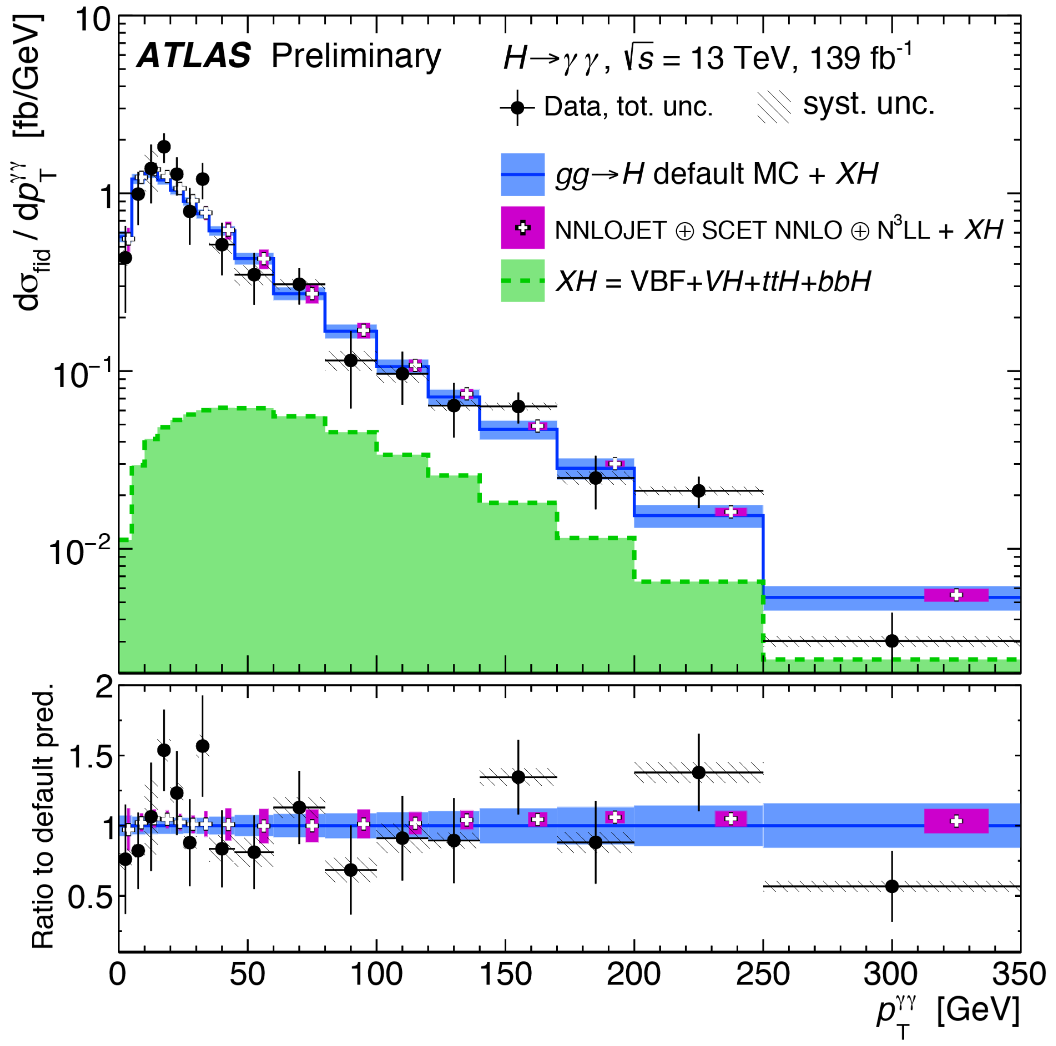


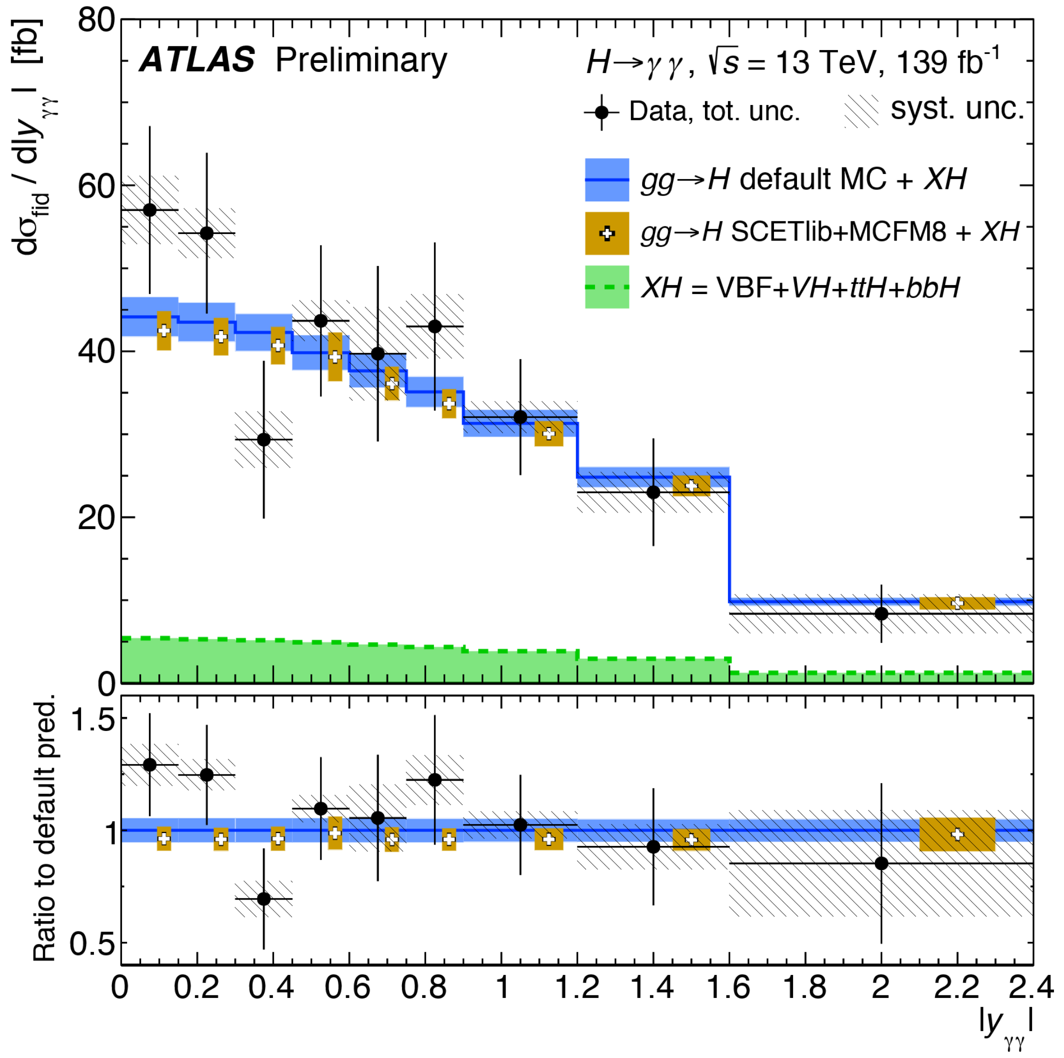






Differential Cross Section Measurements





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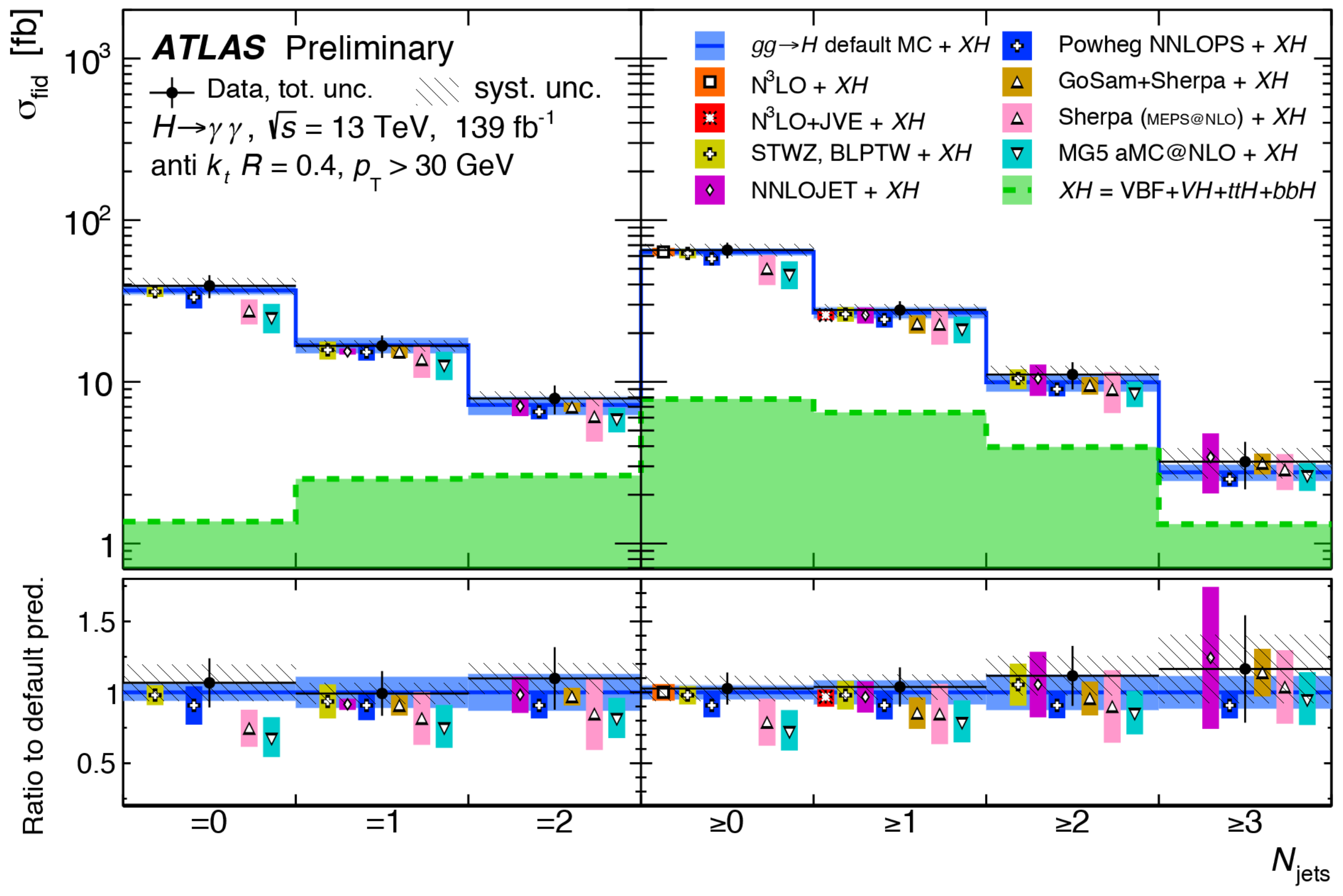
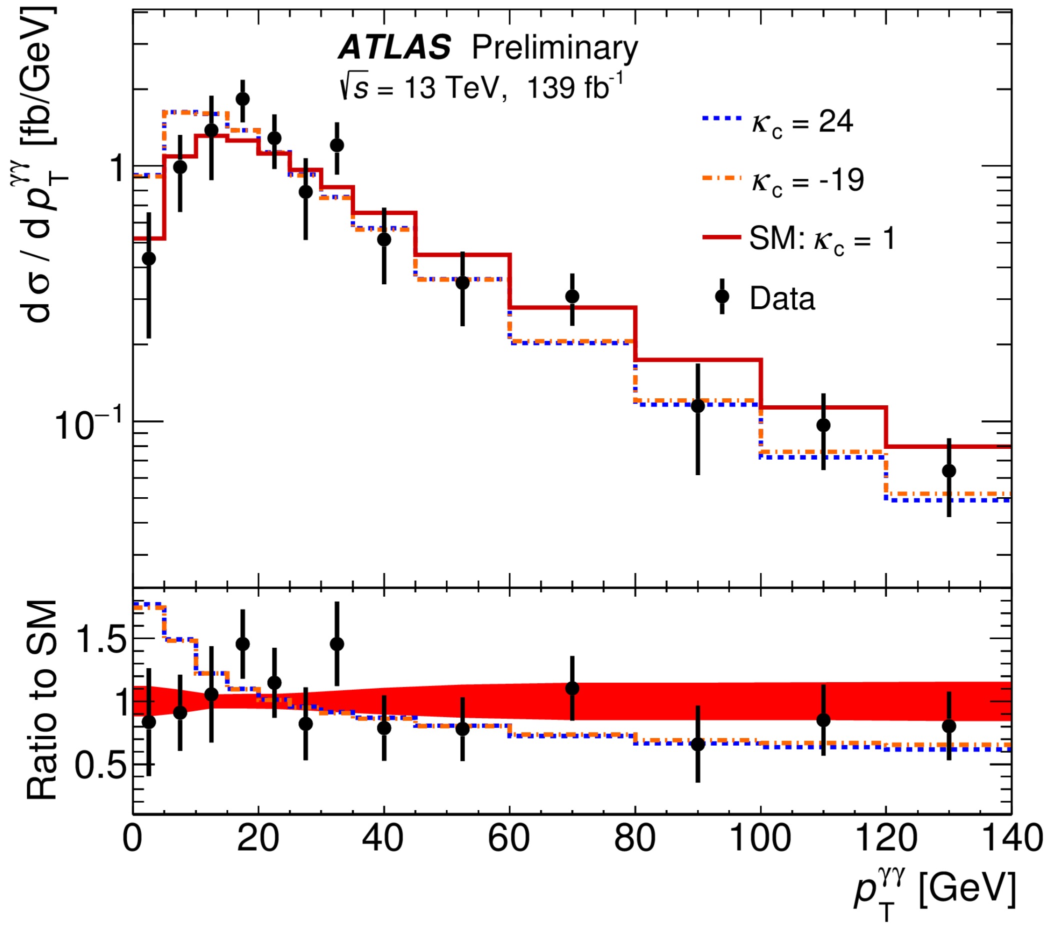
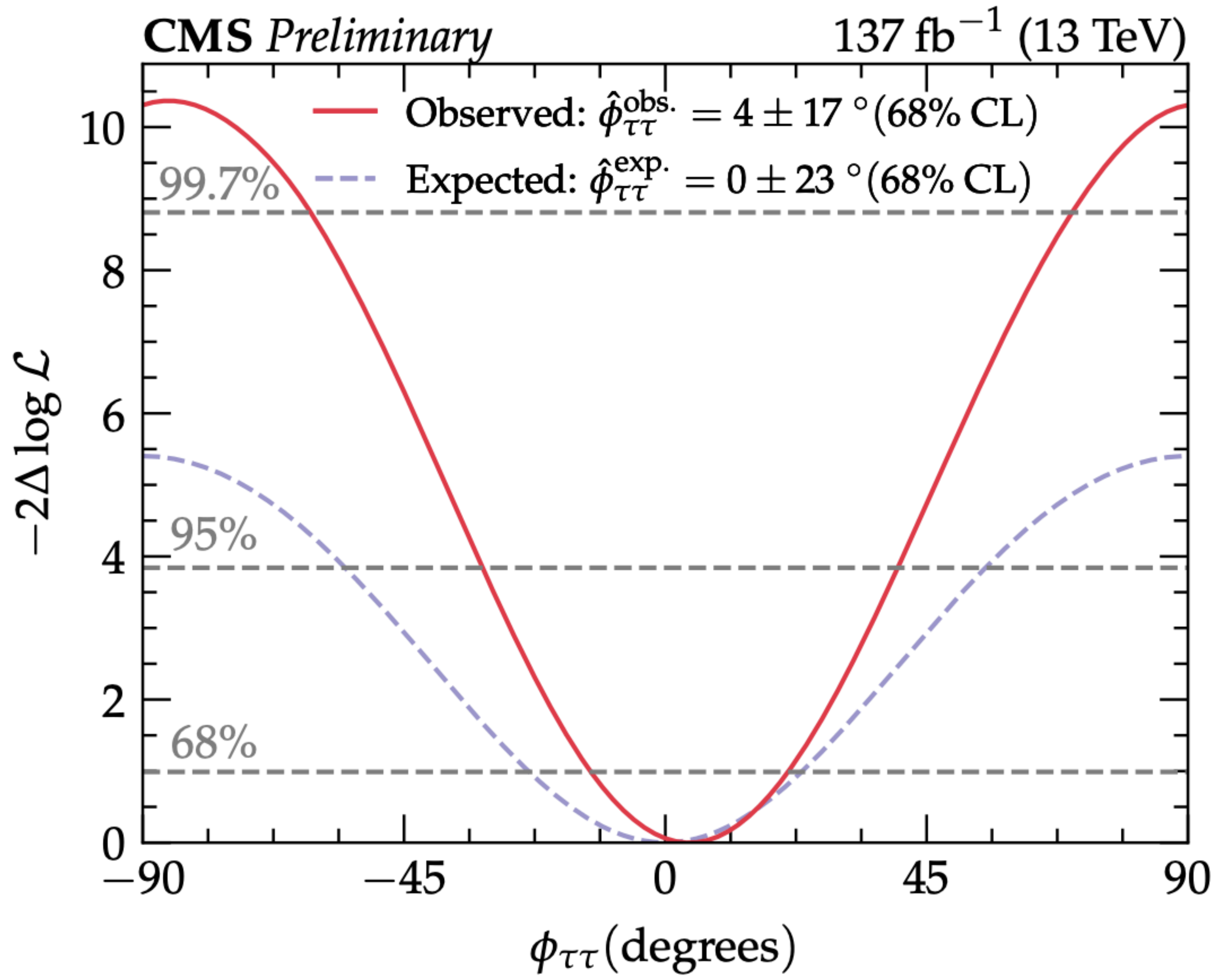






$$\mathcal{L}_Y = -\frac{m_\tau H}{v}(\kappa_\tau \bar{\tau}\tau + \tilde{\kappa}_\tau \bar{\tau} i \gamma_5 \tau)$$

$$\tan(\phi_{\tau\tau}) = \frac{\tilde{\kappa}_\tau}{\kappa_\tau}$$

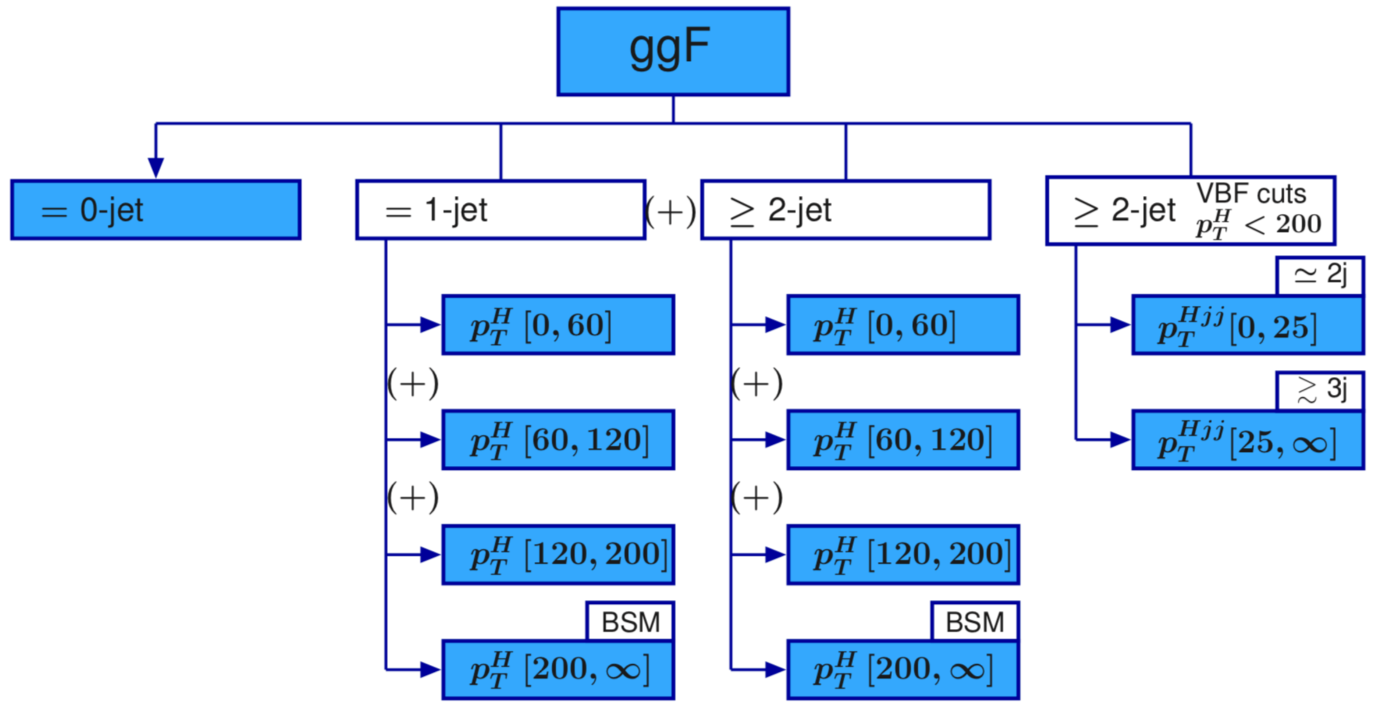
$$\phi_{\tau\tau} = 4 \pm 17^o \ (23^o \text{ exp.})$$

CP-even preferred vs CP-Odd at ~3σ level

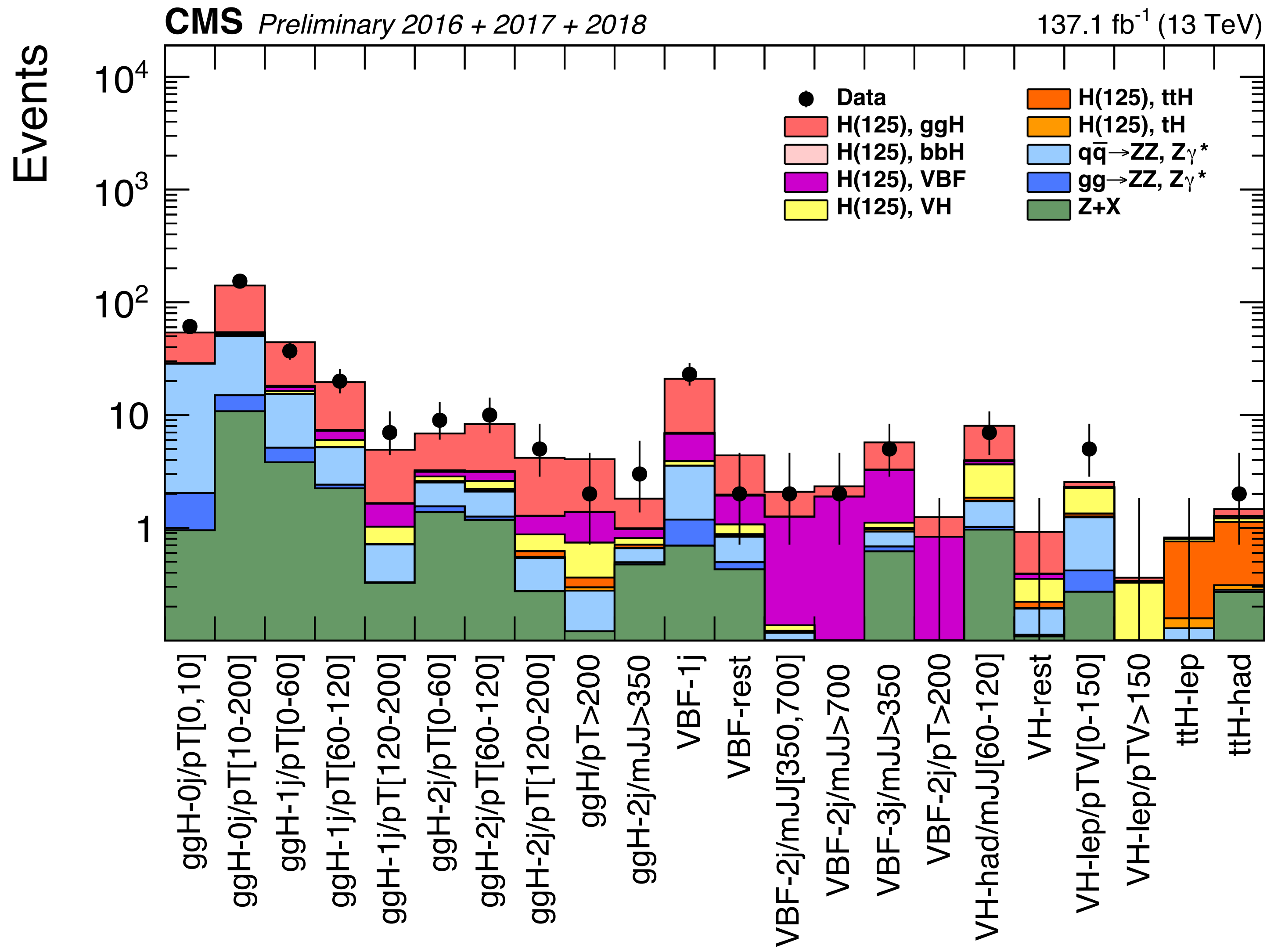
Hybrid Fiducial Approach: Simplified Template Cross Sections

w.r.t. purely fiducial: allows to **combine decay channels** and use **multivariate techniques** in specific channels. **Compromise** as both aspects increase the extrapolation.

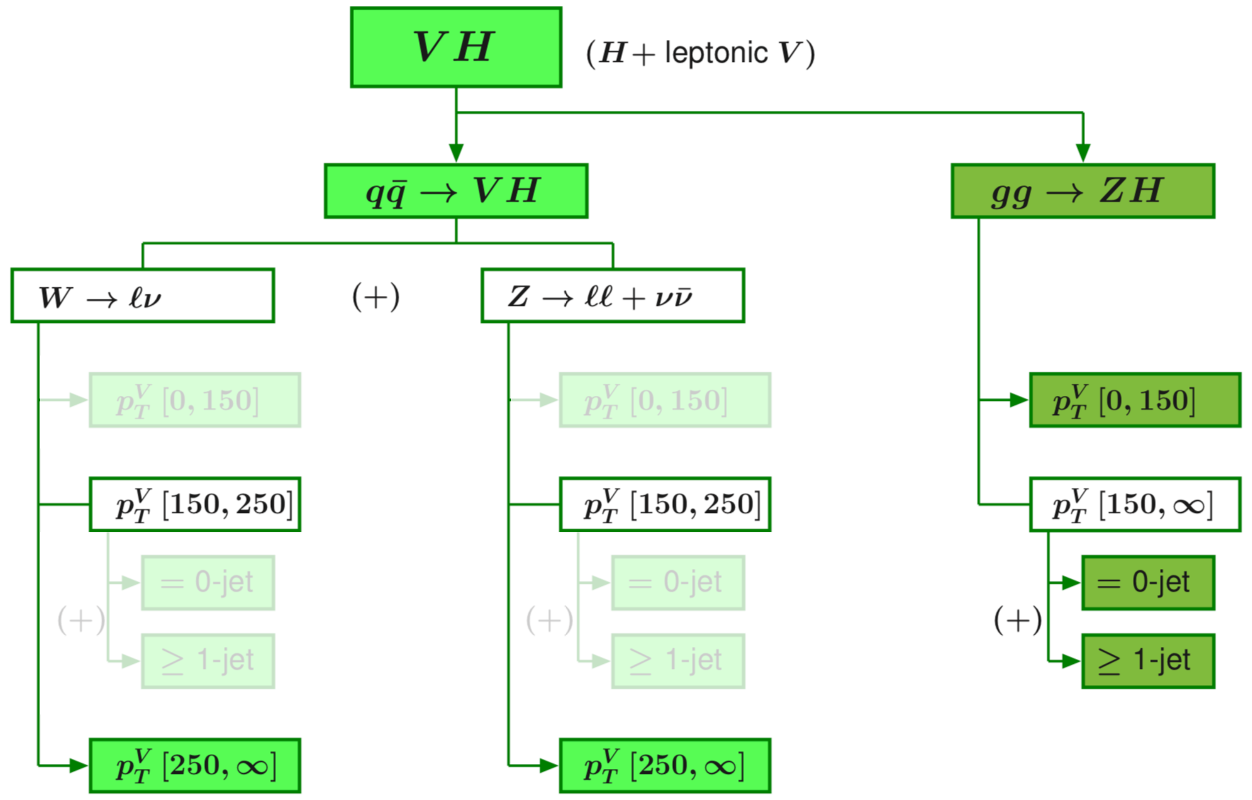
Inclusive (and most other channels) covered by discovery channels

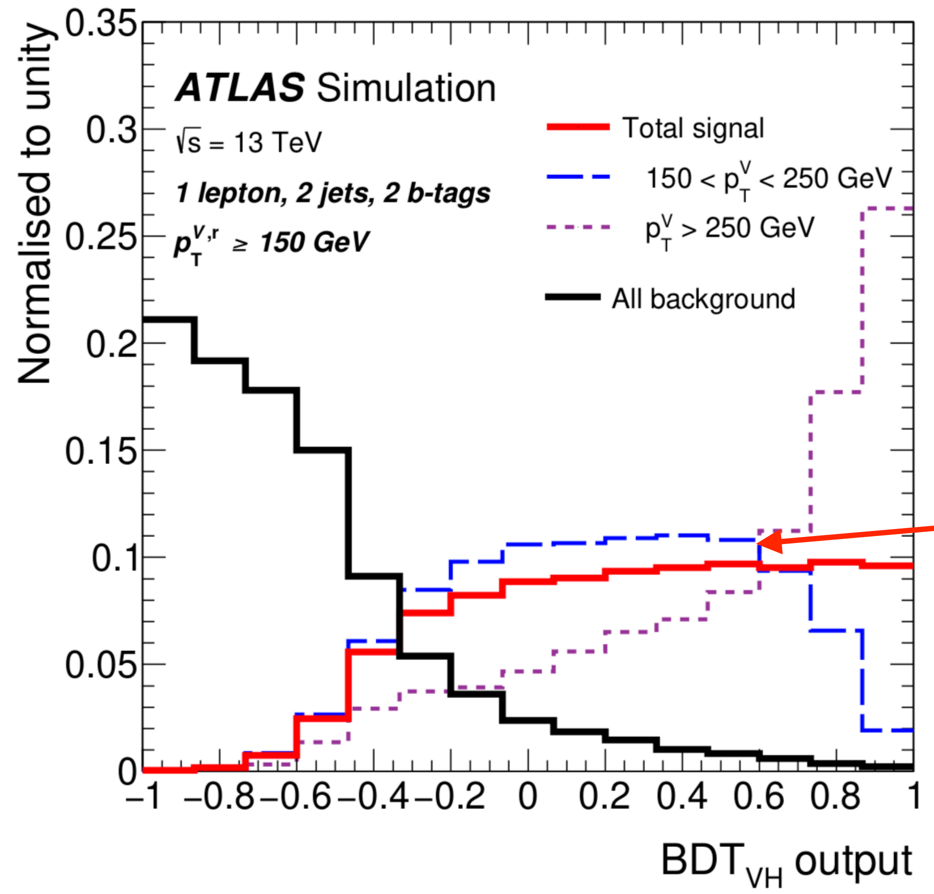


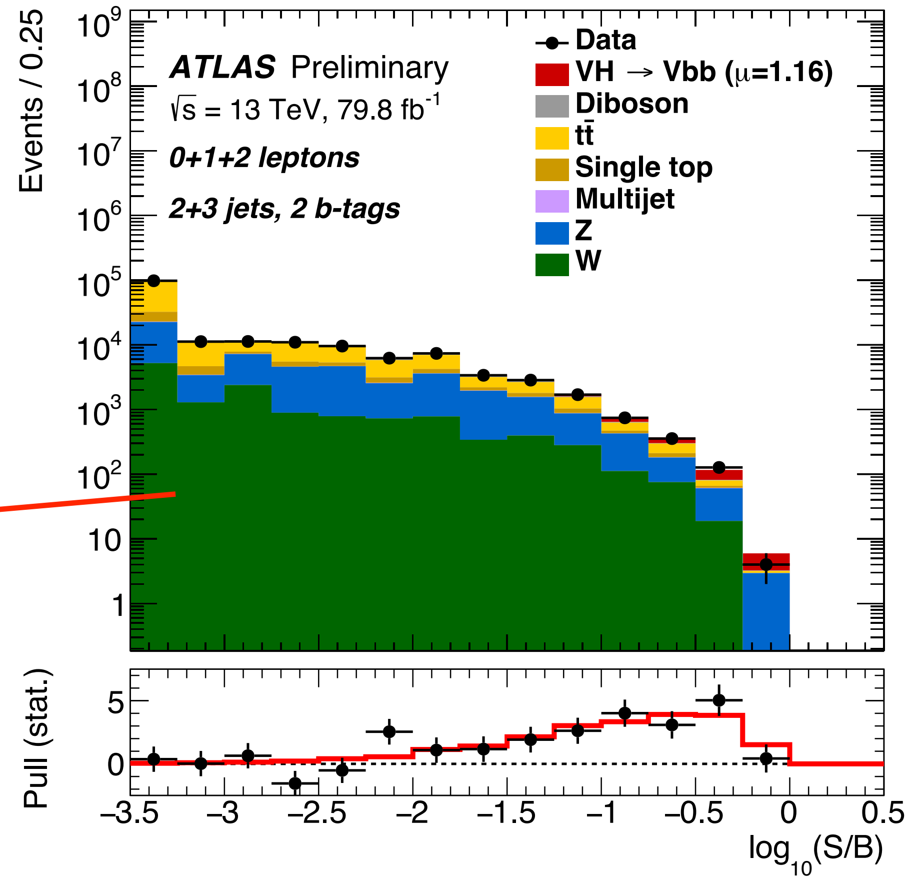
CMS-PAS-HIG-19-001



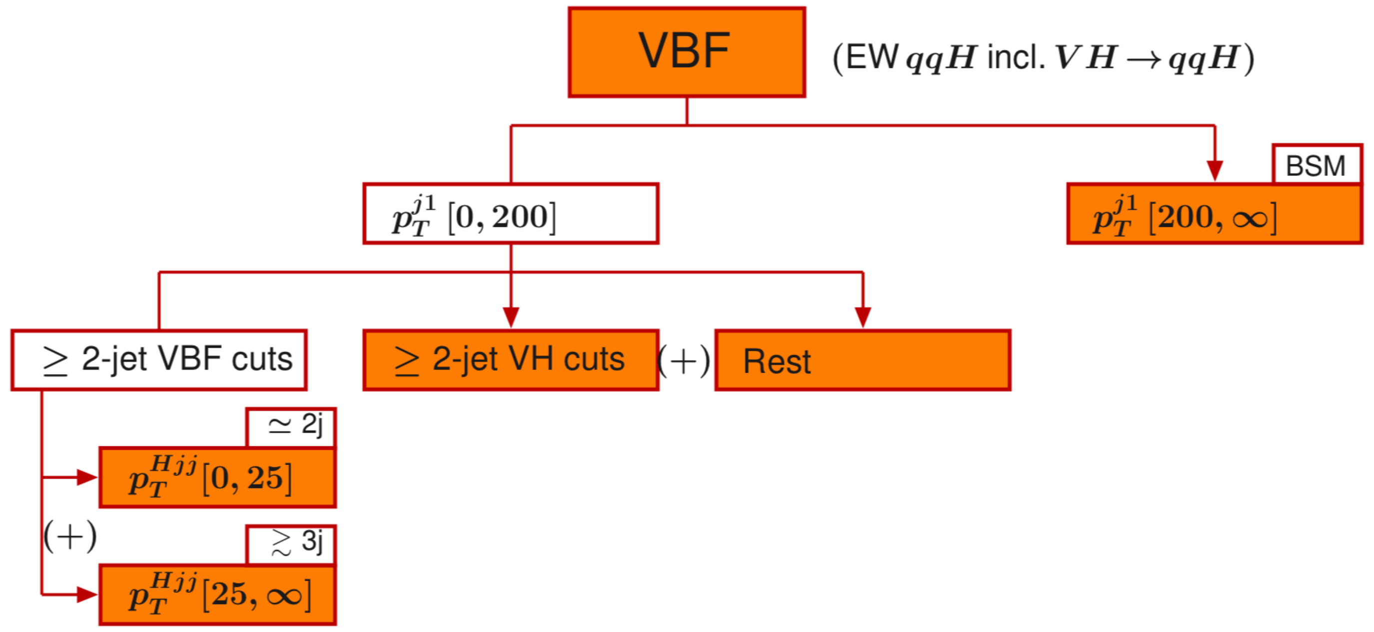
VH covered at high pT also by VH(bb)

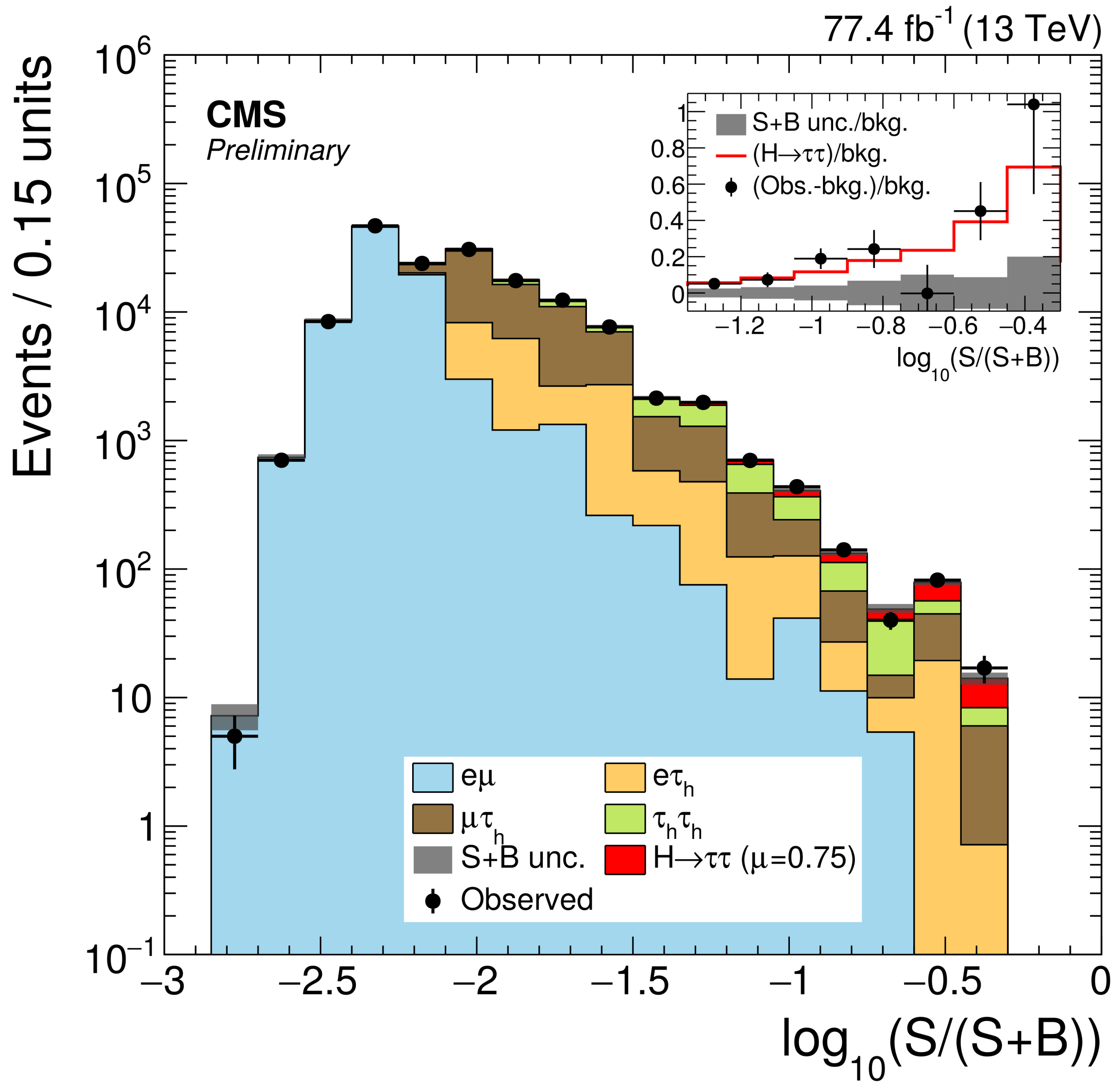






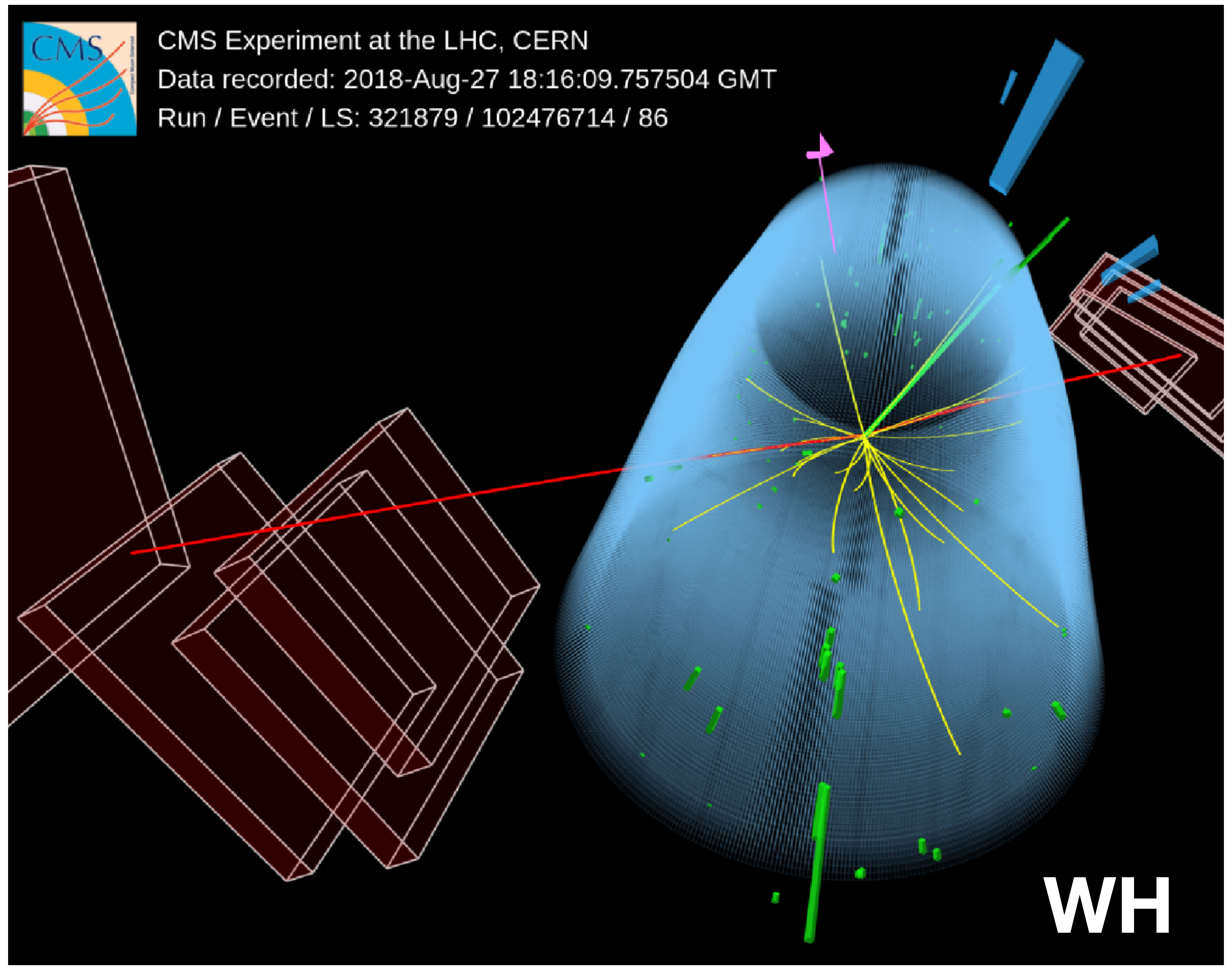
VBF covered at high pT also by VH(tau-tau)

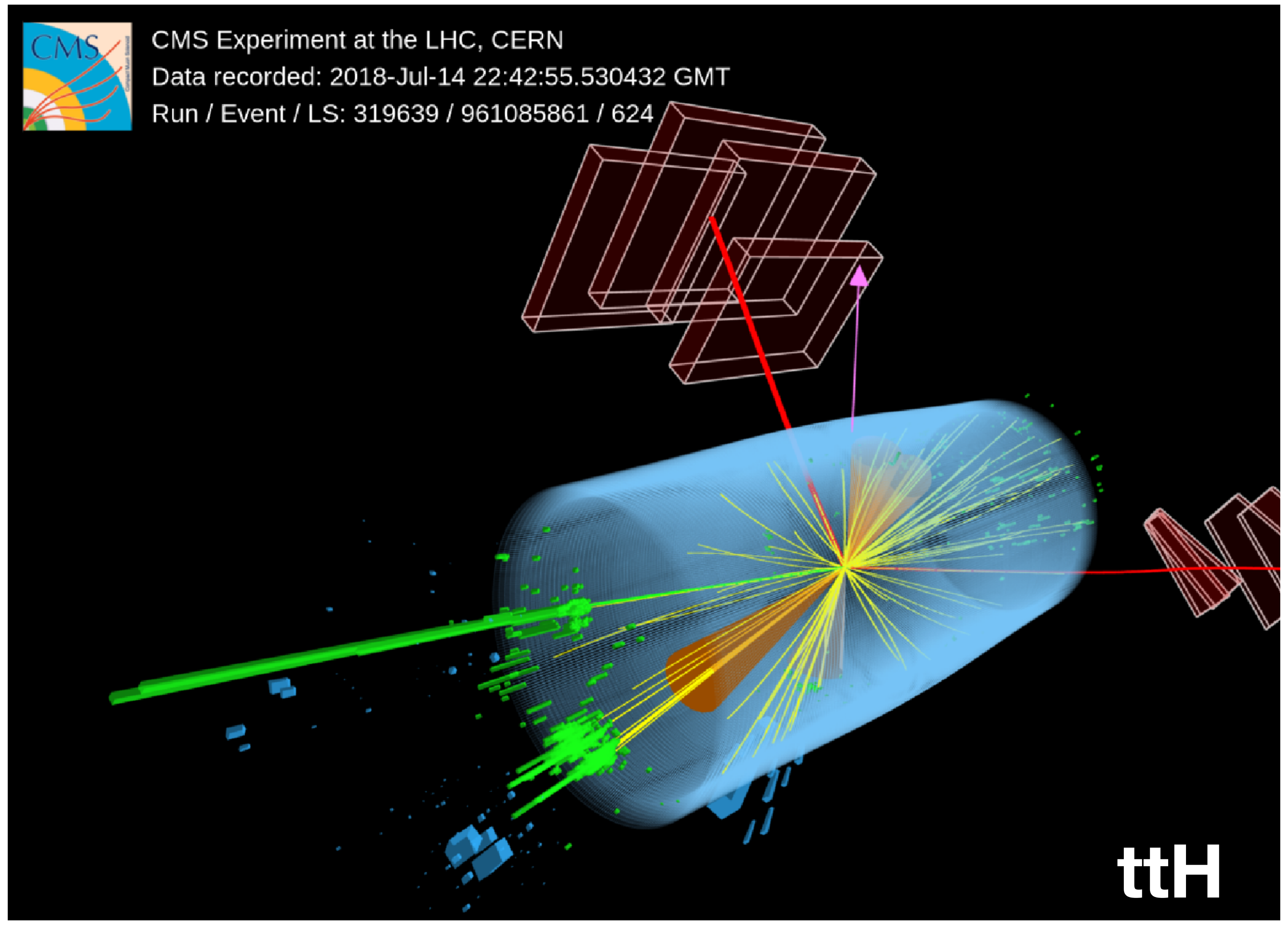


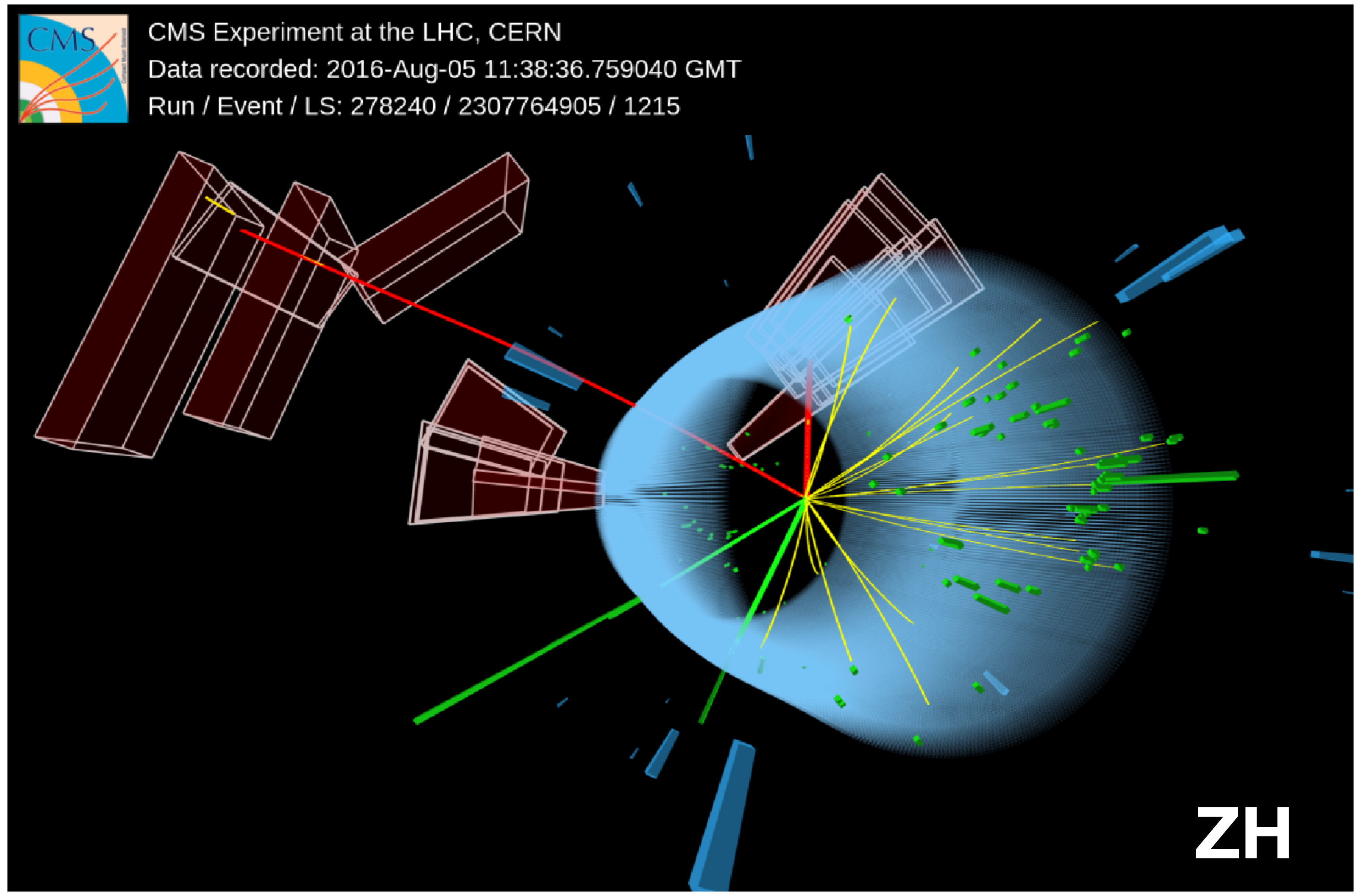


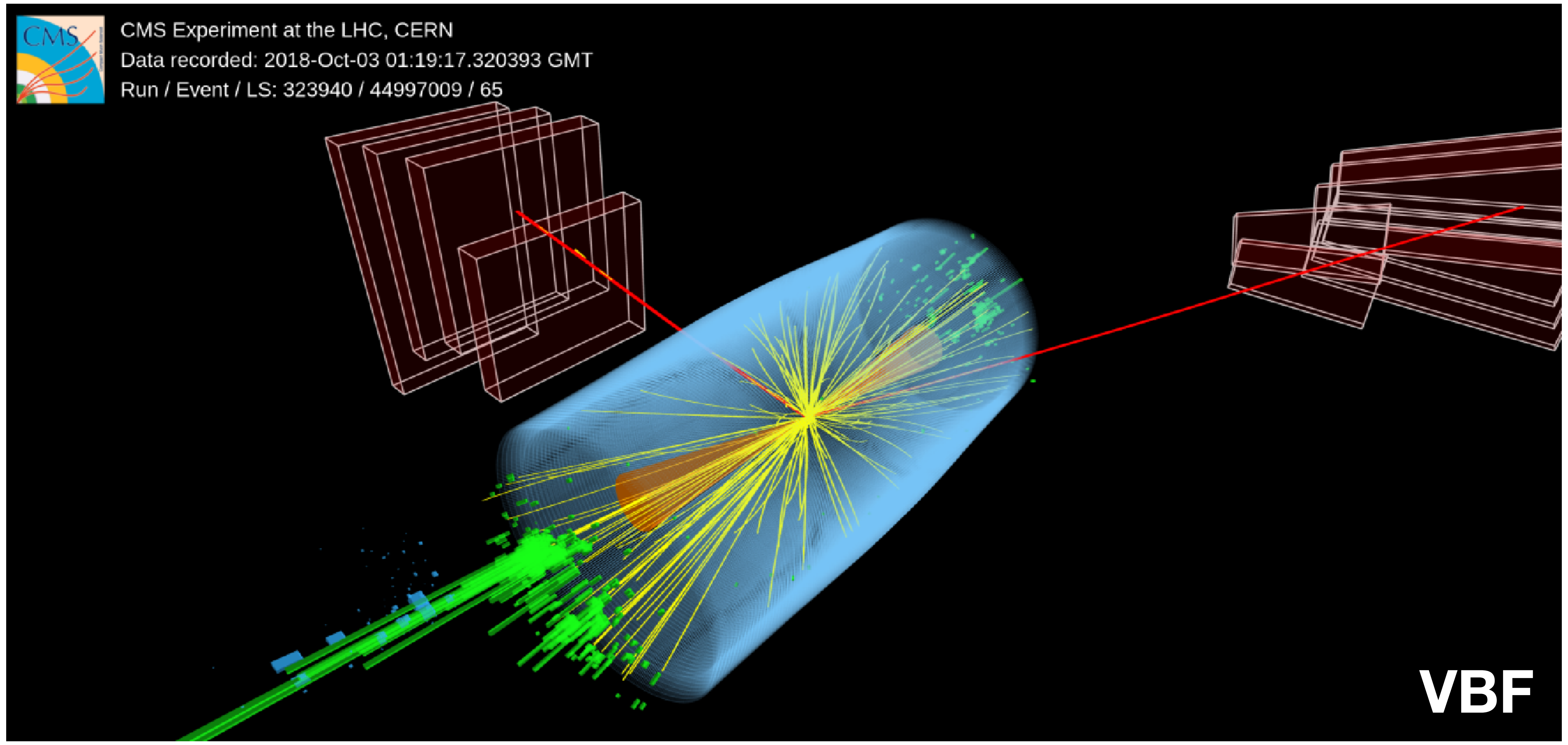
Early evidences for Rare processes

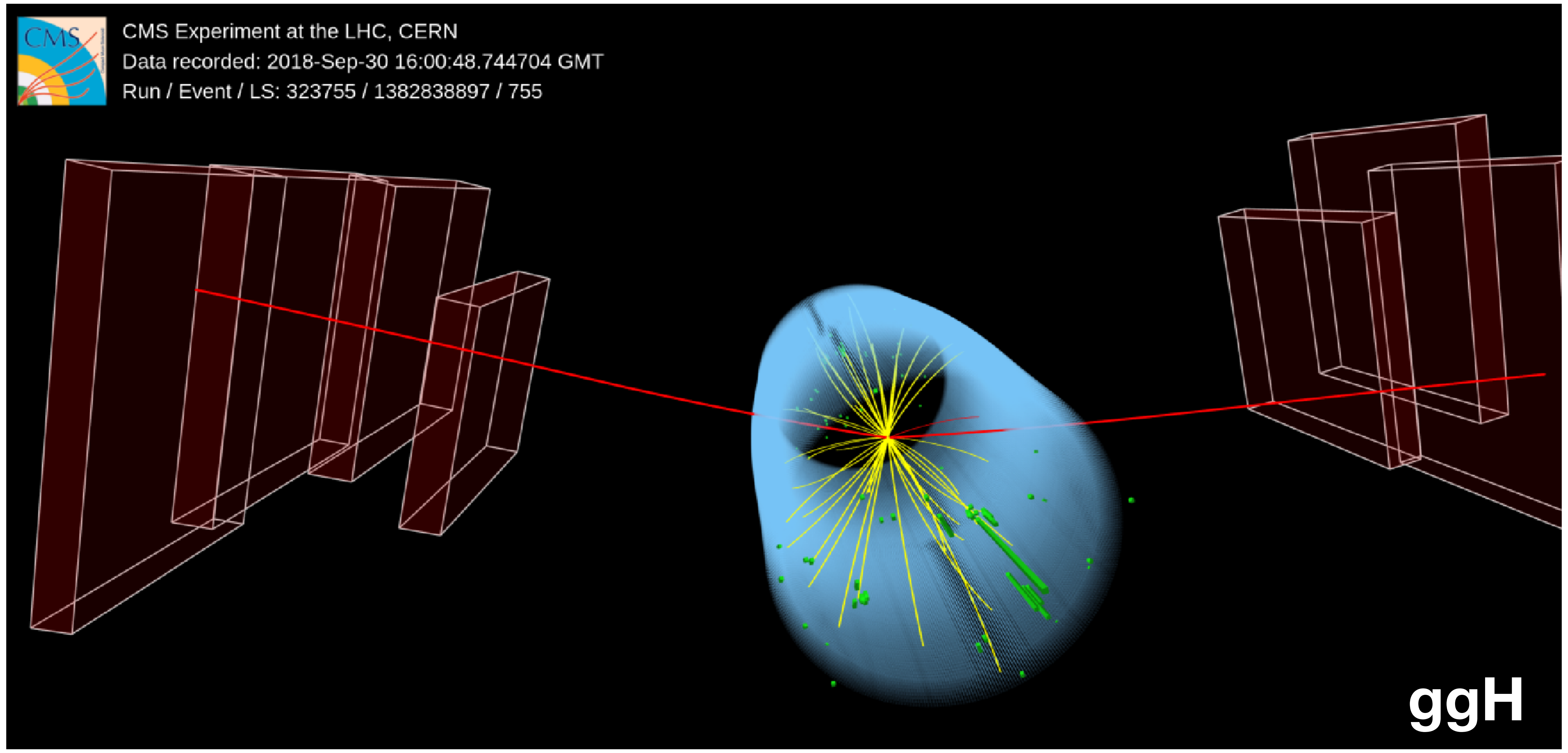
Evidence for $H \rightarrow \mu^+\mu^-$









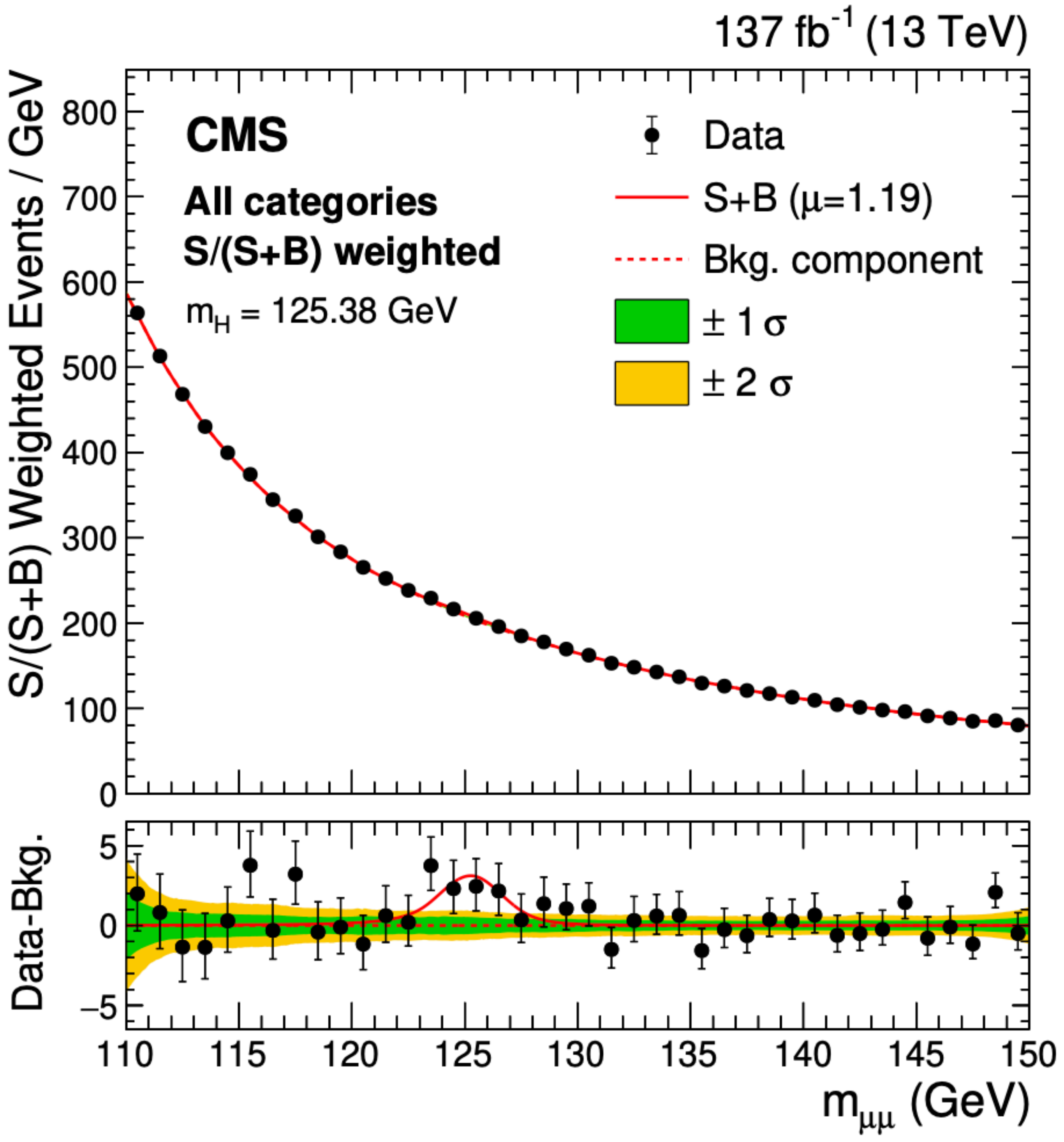


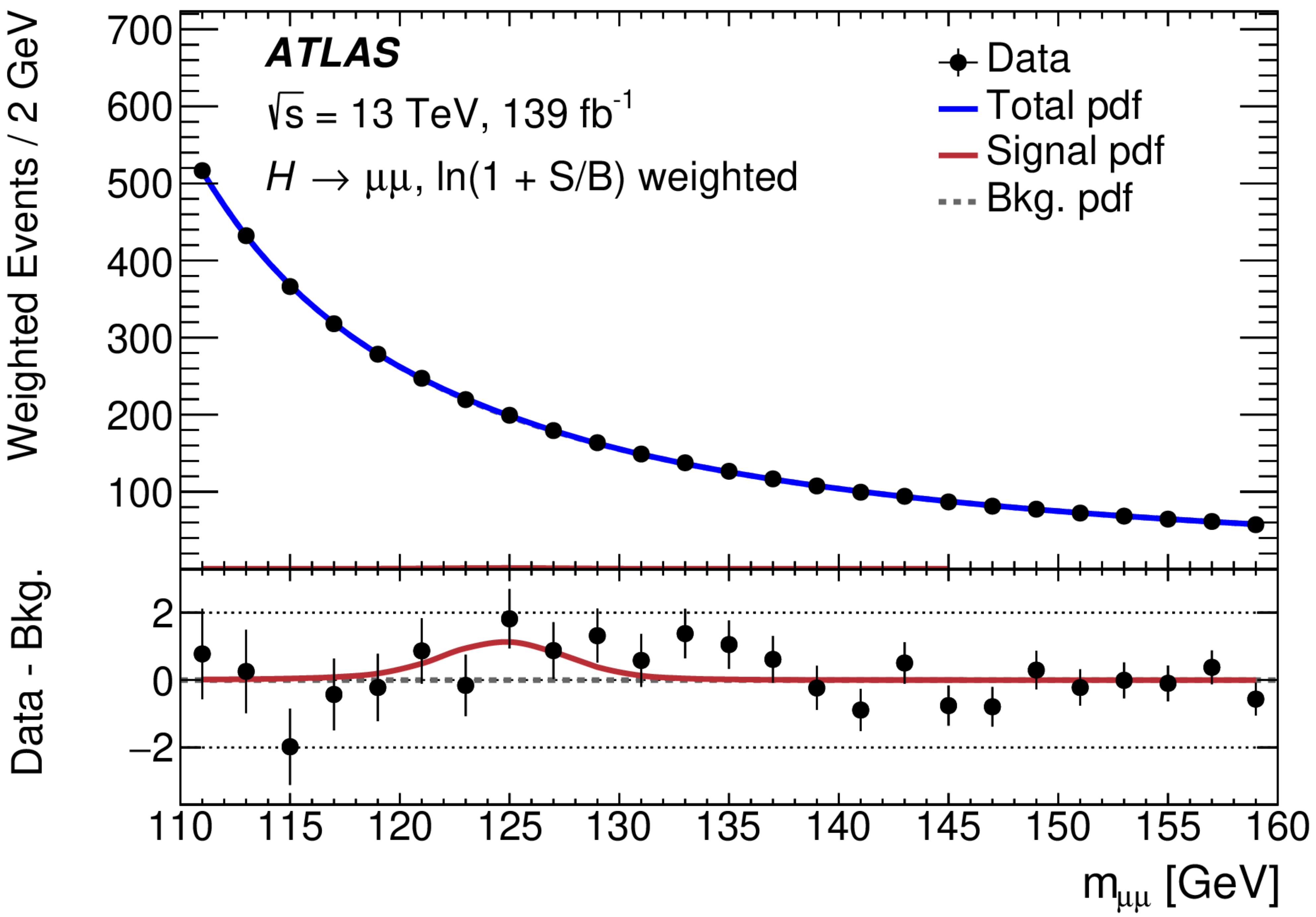
Evidence for Second Generation Yukawa Coupling

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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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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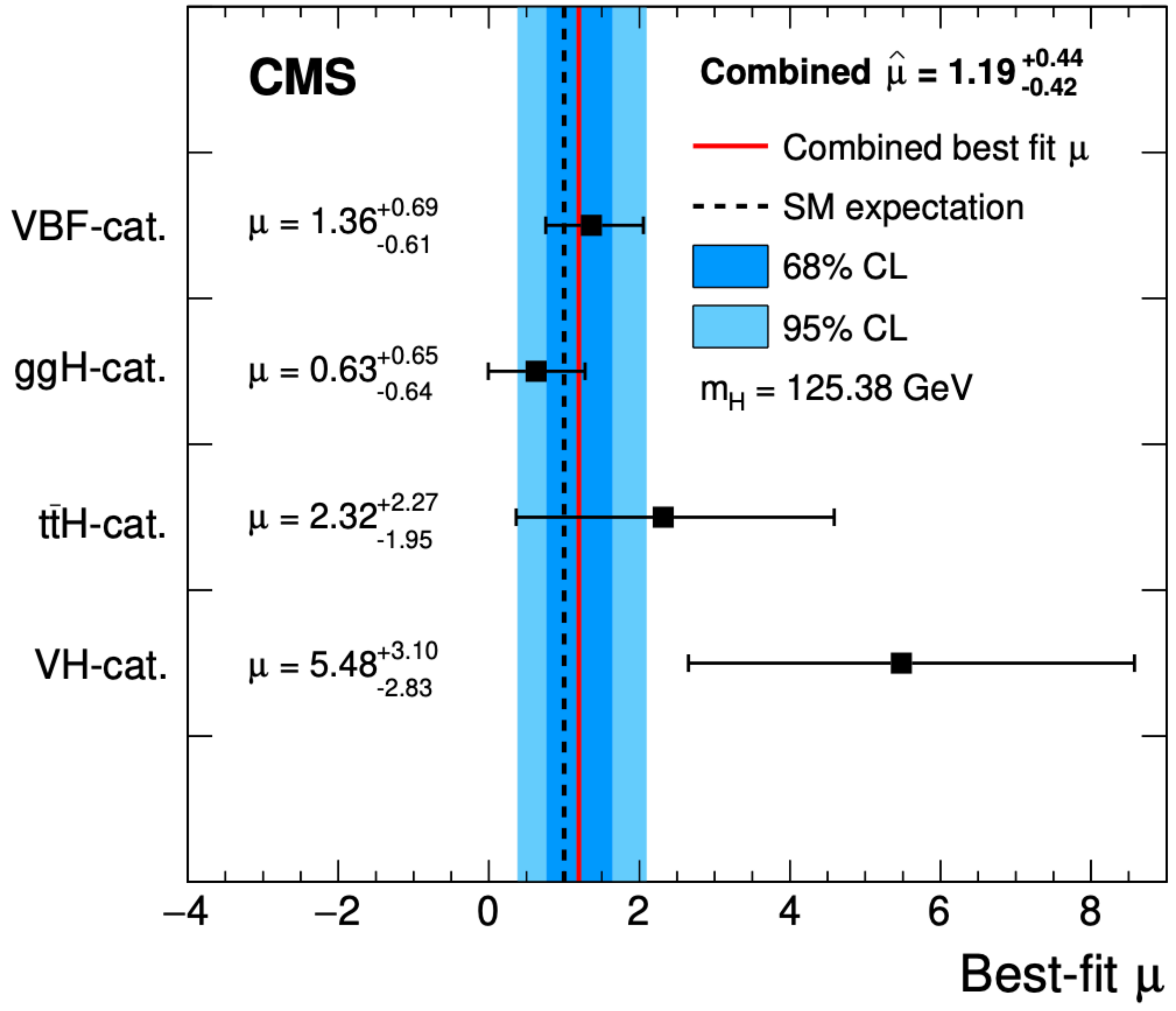
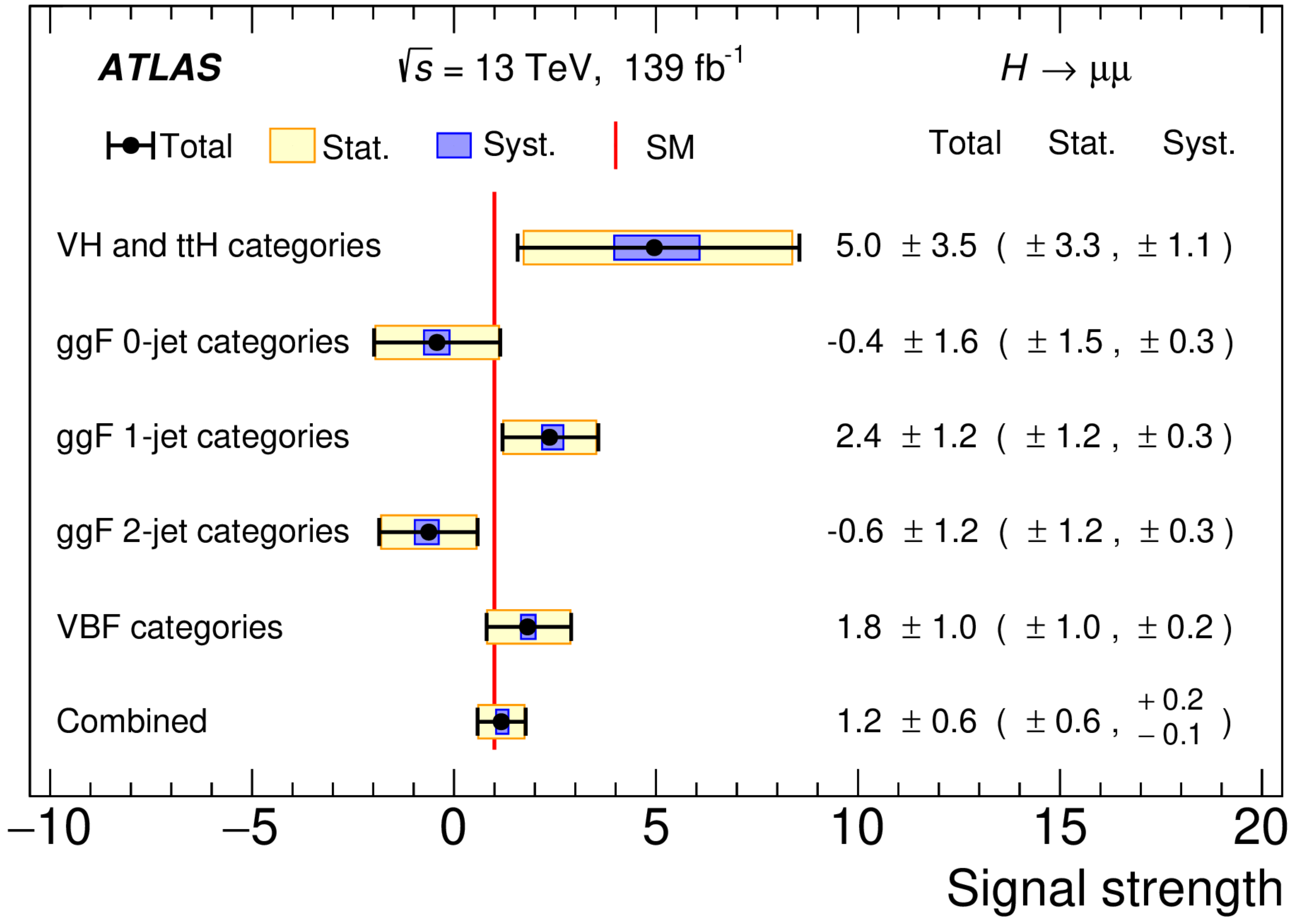


PLB 812



ATLAS Result

Expected 1.7σ

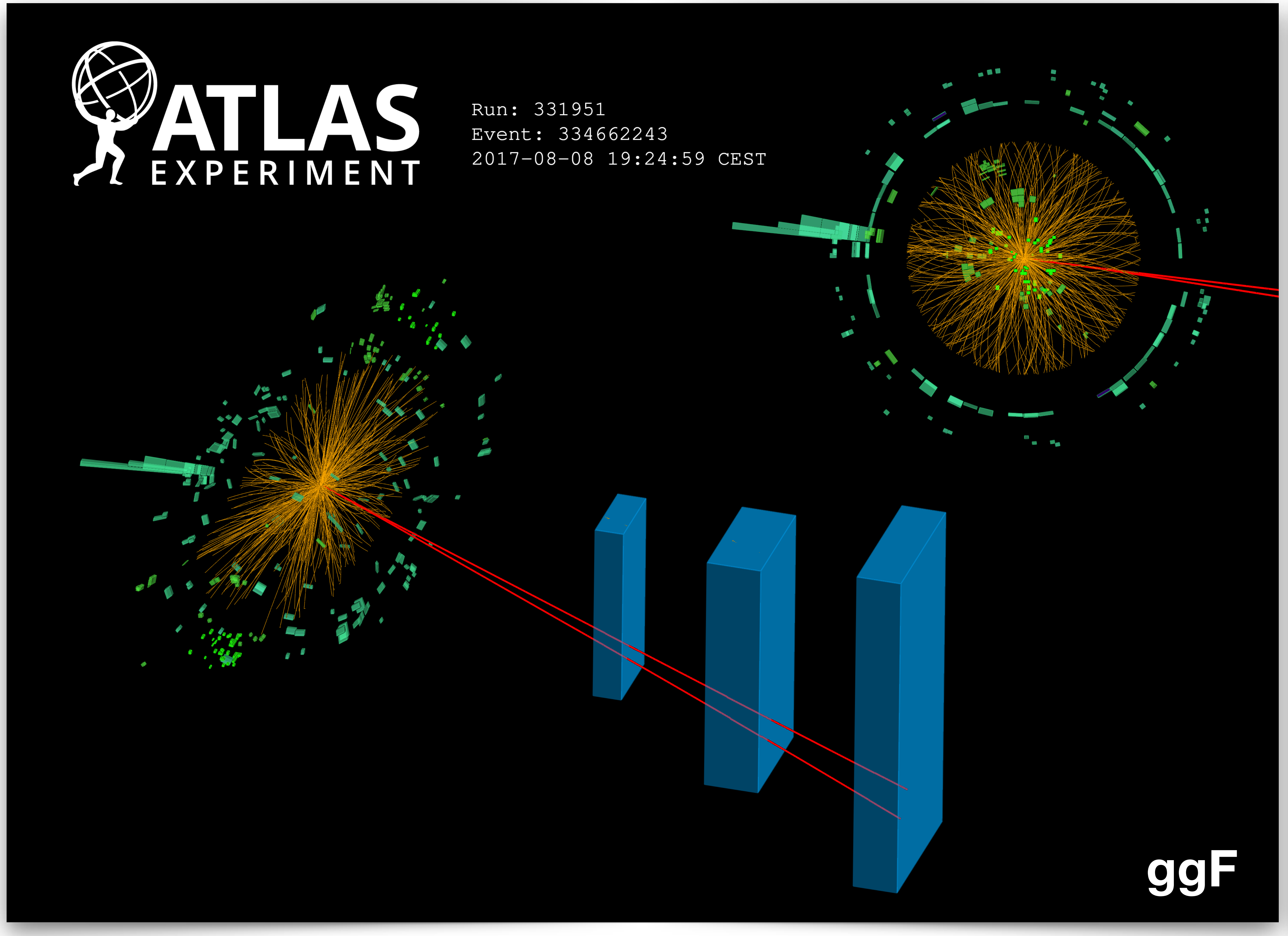
Observed 2.0σ

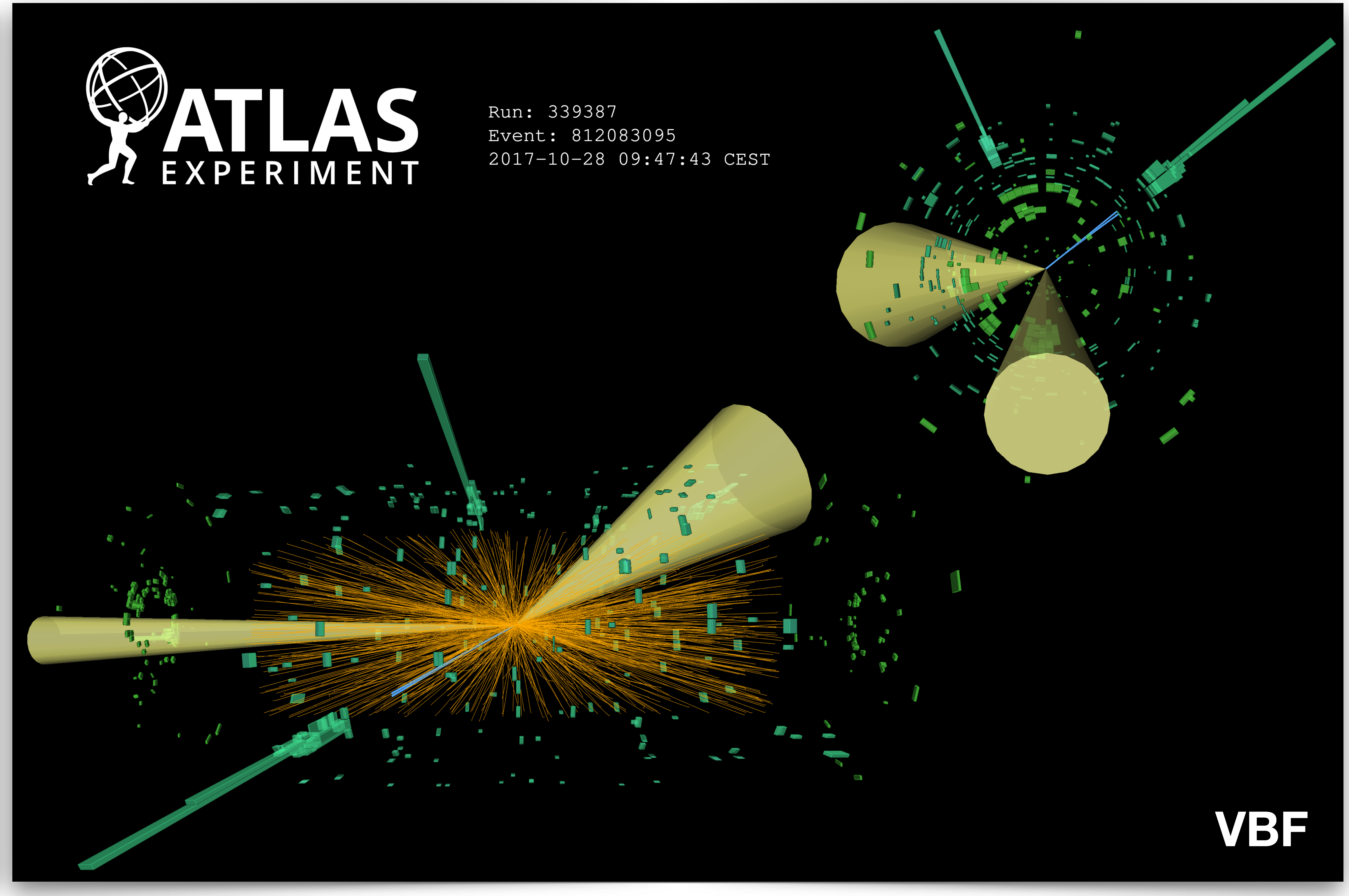
$$\mu = 1.2 \pm 0.6$$

HL-LHC **~5%**

Result dominated by statistical uncertainty, but watch systematics!

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





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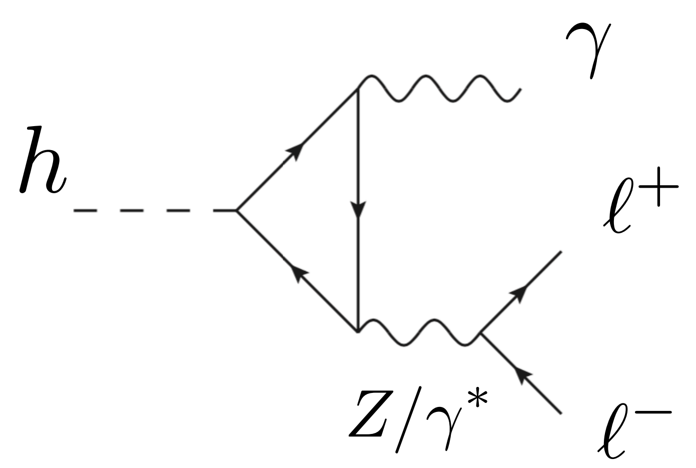


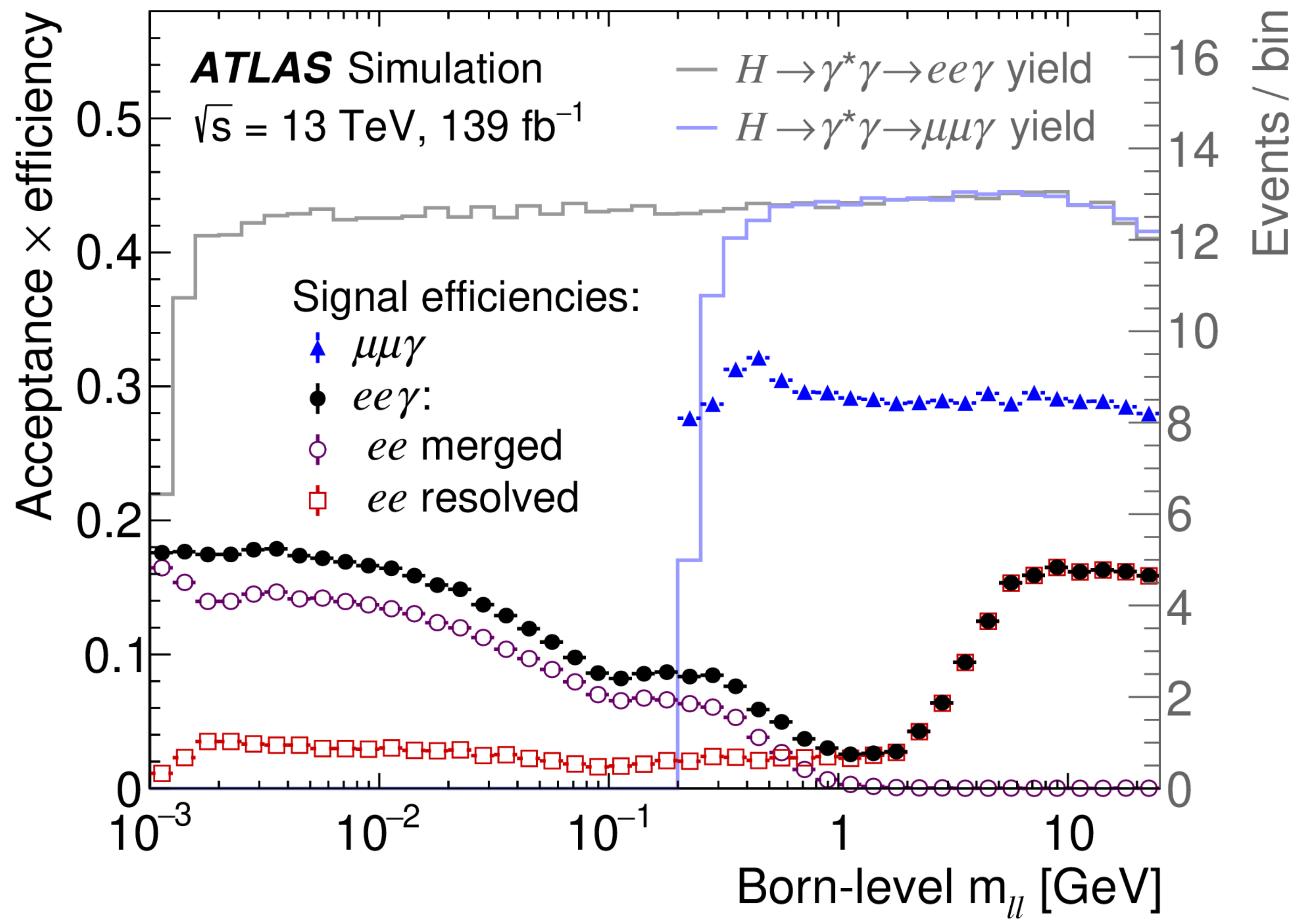
Search initially made in this case in the dimuon channel only (in the low di-lepton mass limit the shower of electrons merge).

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

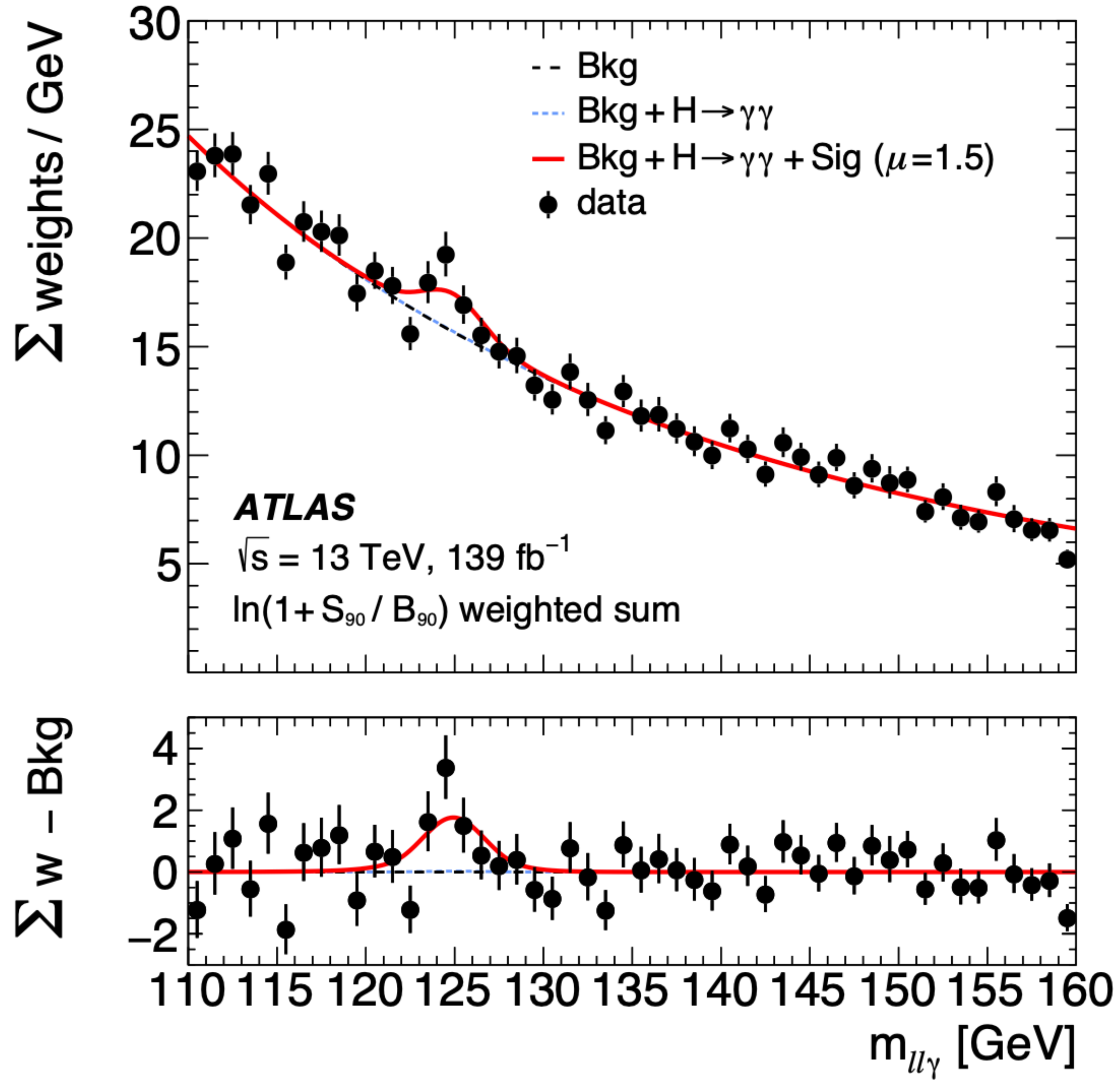
$m_{\ell^+\ell^-} < 50$ GeV

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) ⊗ (ee resolved, ee merged, $\mu\mu$)
- Contributions from J/ψ are removed with a mass cut

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

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

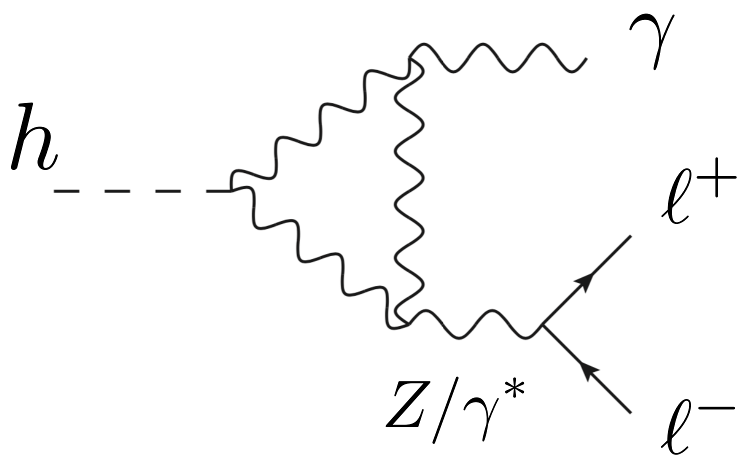
Expected 2.1σ

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 $Br(\gamma\gamma)$

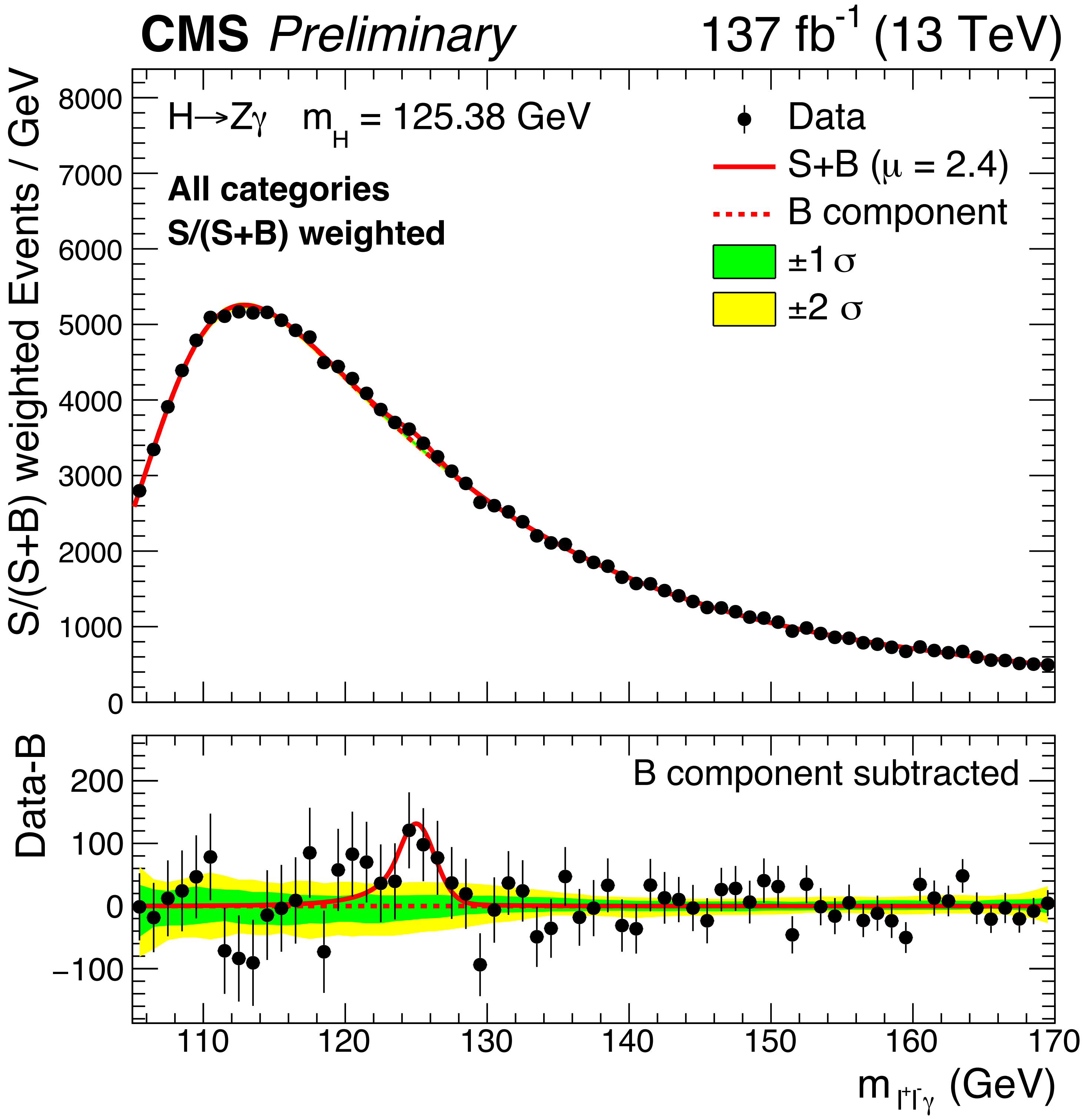
CMS Result

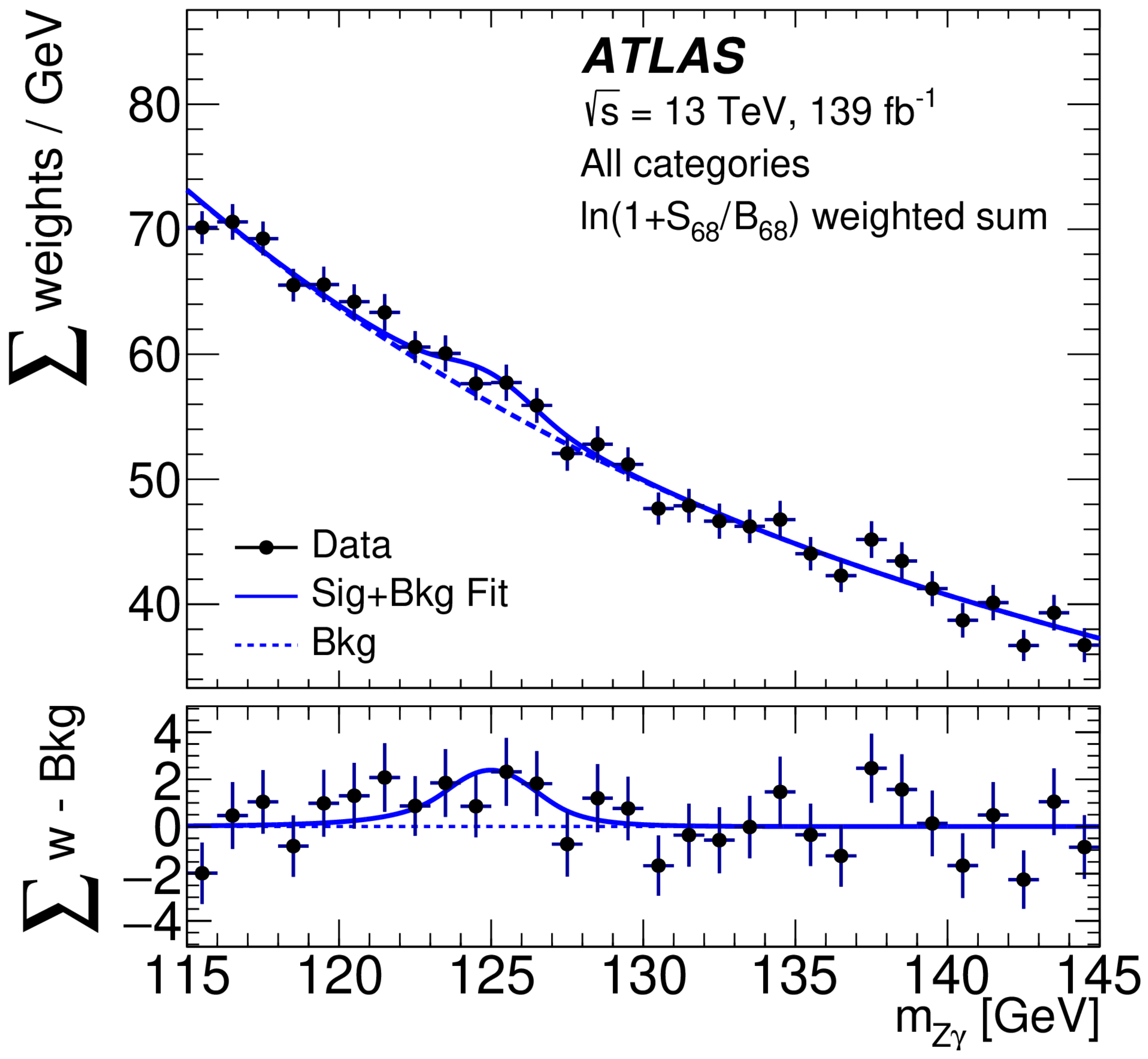
ggF, VBF, VH and ttH enriched channels

$\mu_{Z\gamma} = 2.4 \pm 0.9$

Expected 1.2σ

Observed 2.7σ





ATLAS Result

ggF and VBF enriched channels

$\mu_{Z\gamma} = 2.0 \pm 0.9$

Expected 1.2σ

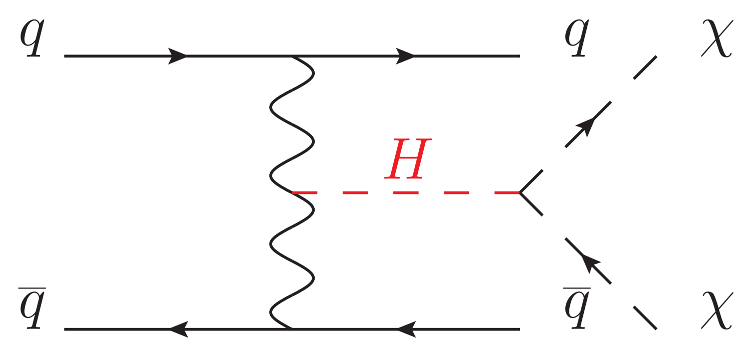
Observed 2.2σ

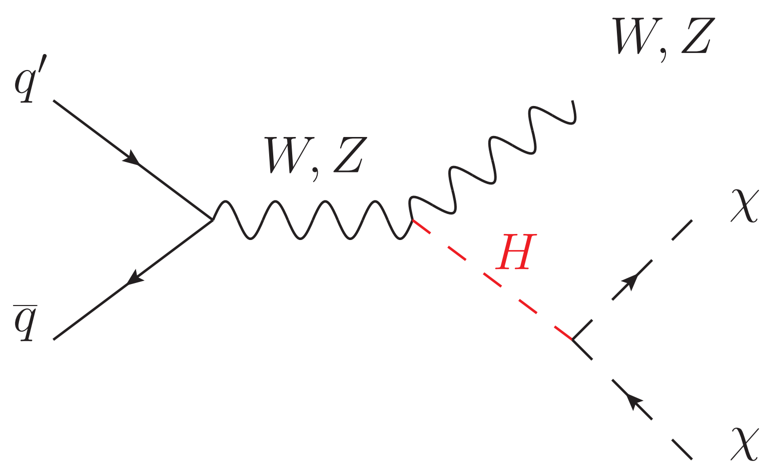
To follow closely at Run 3 for first evidence!

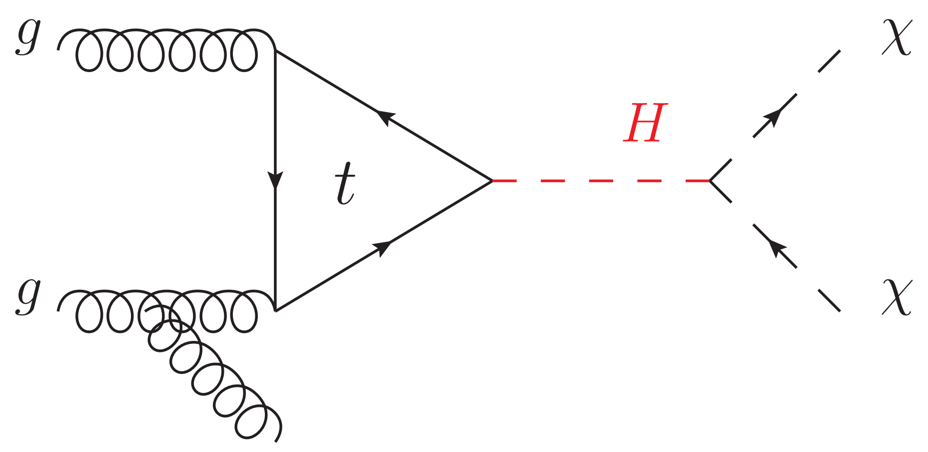
HL-LHC **~10%**

More Rare Decays and Production

Invisible decays



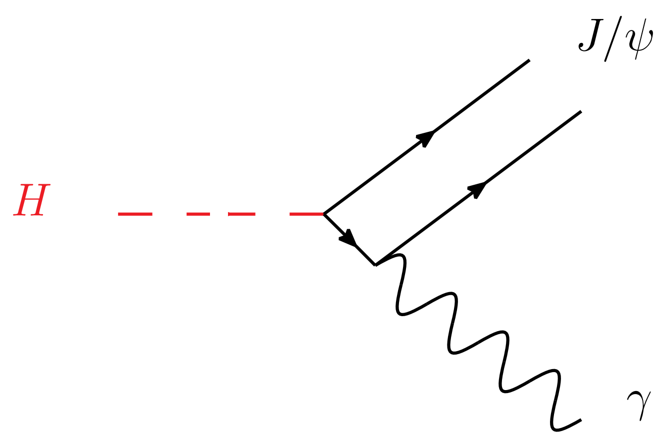




<11% @ 95% CL

HL-LHC 2.5%

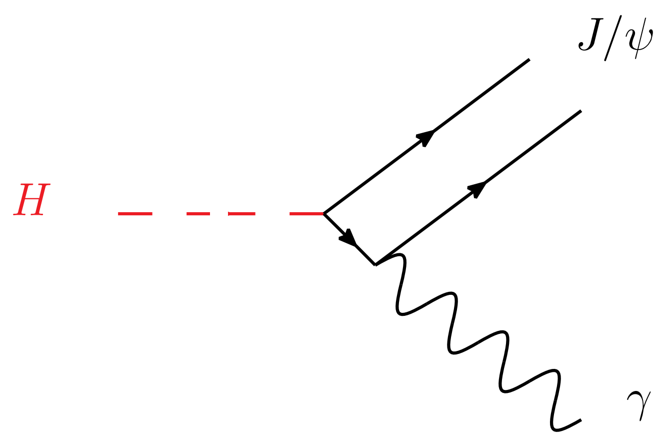
Quarkonia-photon



Potentially sensitive to charm Yukawa

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

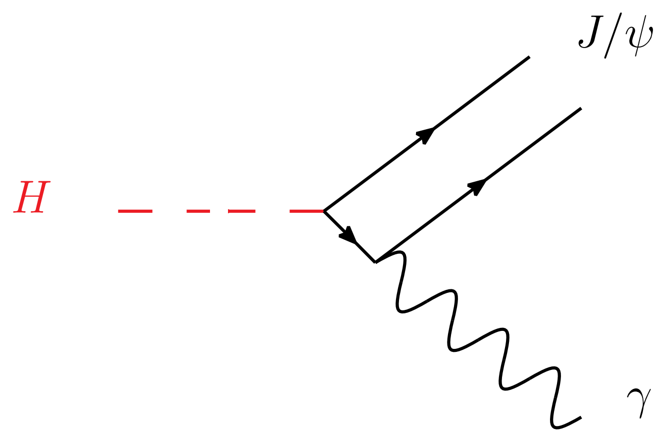
~100 x SM



Potentially sensitive to strange Yukawa

$K^+K^-\gamma$

~200 x SM

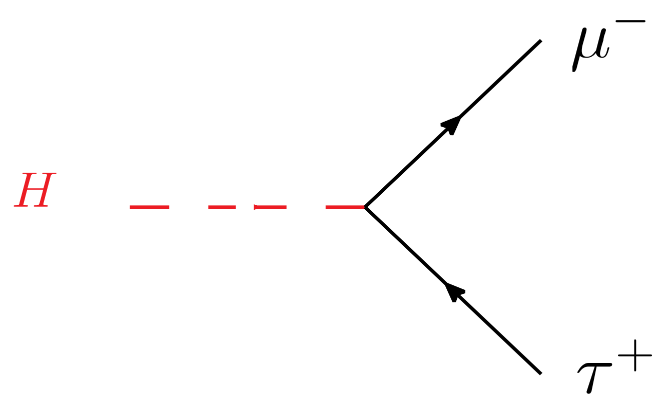


otentially sensitive to ght Yukawa

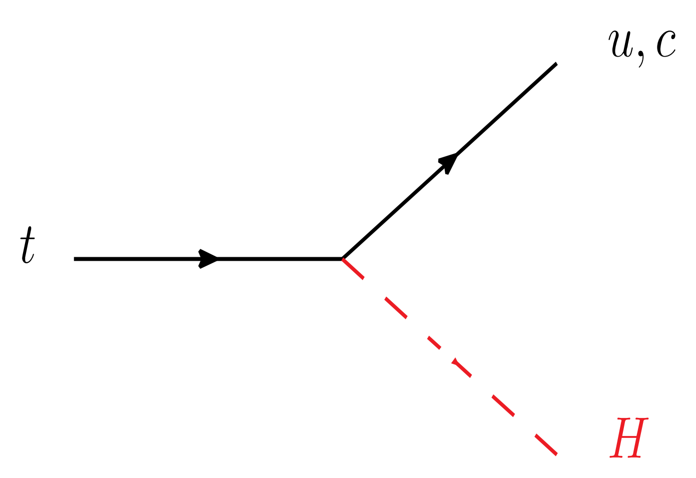
$\pi^+\pi^-\gamma$

~50 x SM

Lepton flavor violating decays

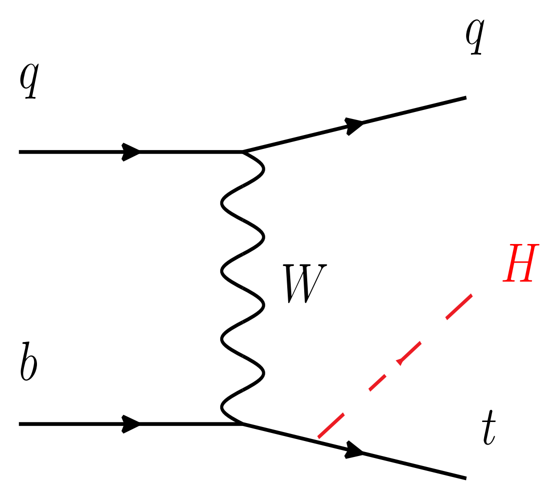


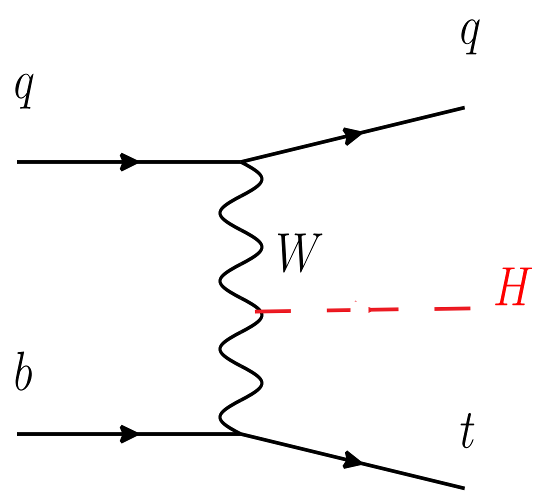
FCNC decays of the top quark



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

Single top associated production





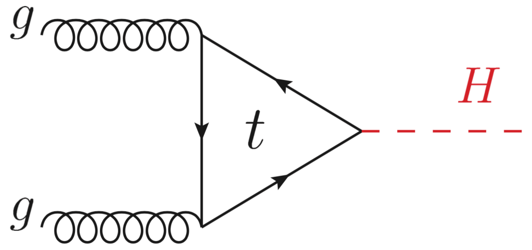
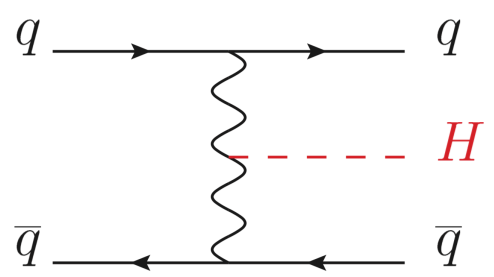
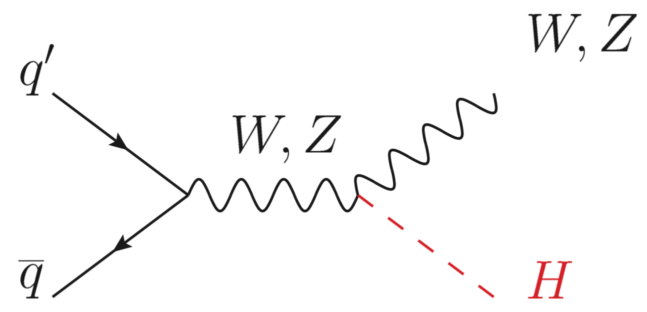
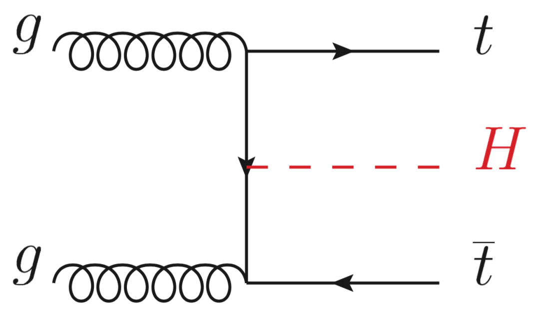
Tree level interference between W and top

Review see latest PDG review

Portrait of the Higgs Boson 10 Years after its Discovery

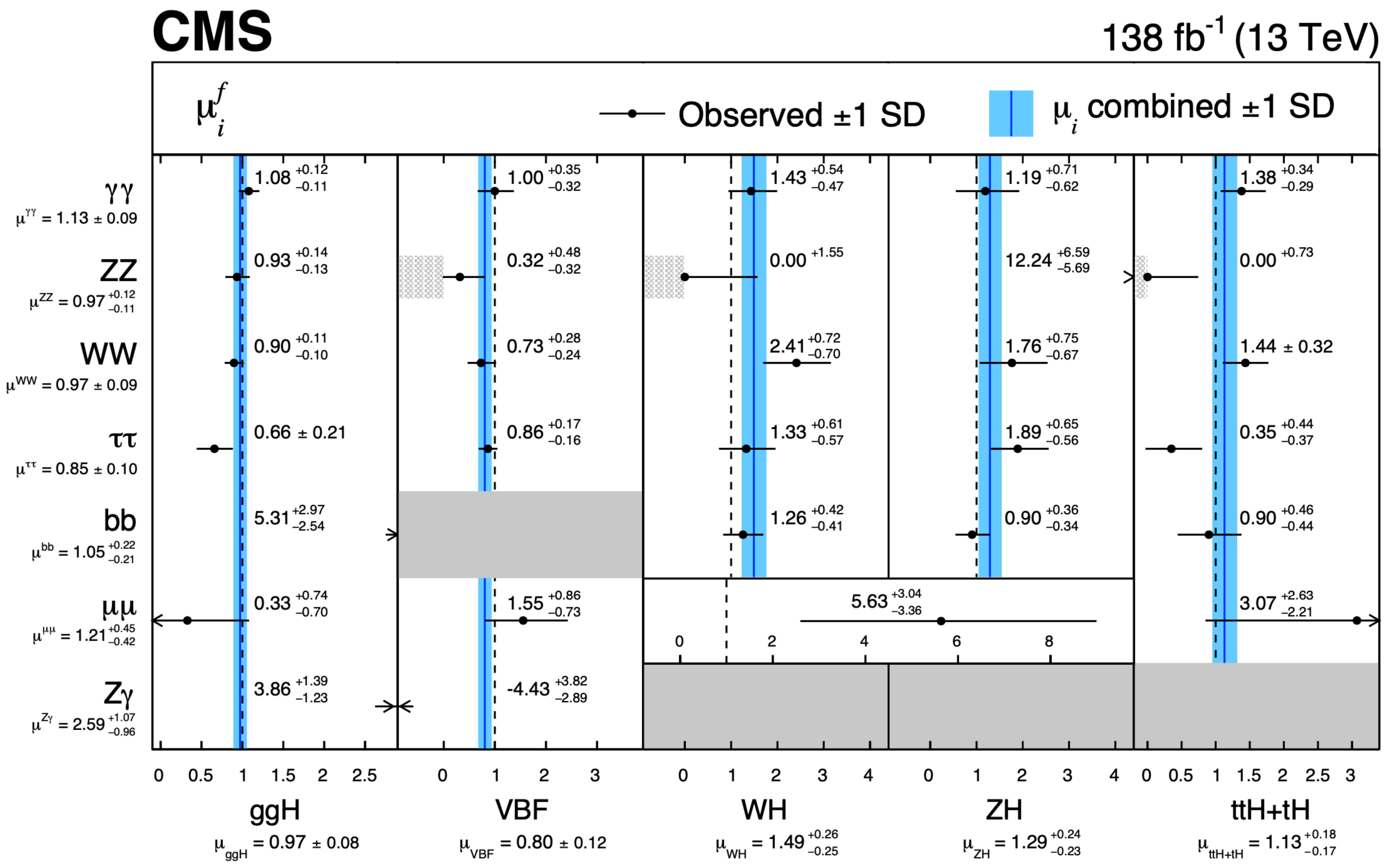
Nano Overview of Main Higgs Analyses at (HL) LHC

Most channels already covered at the Run 2 with only 3% (80 fb-1) of full HL-LHC dataset!

	Channel categories	Br	ggF	VBF	VH	ttH
			 ~4 M vets produced	 ~300 k vets produced	 ~200 k vets produced	 ~40 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 %	✓	✓	✓	✓
	ZZ	3%	✓	✓	✓	✓
	WW	22%	✓	✓	✓	✓
	ττ	6.3 %	✓	✓	✓	✓
	bb	55%	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	0.2 %	✓	✓	✓	✓
	μμ	0.02 %	✓	✓	✓	✓
Limits	Invisible	0.1 %	✓ (monojet)	✓	✓	✓

*N3LO

Portrait of the Higgs Boson 10 Years after its Discovery



Precision Higgs Couplings Measurements

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%
B_{inv}		$< 11\,\%$	$< 16\,\%$	
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)	

How elementary is the Higgs Boson?

Minimal Composite Higgs scenarios

$$g_{HVV} = \frac{2m_V^2}{v}\sqrt{1 - v^2/f^2}$$

$$4\pi f \gtrsim 9\,\mathrm{TeV}$$

Portrait of the Higgs Boson 10 Years after its Discovery

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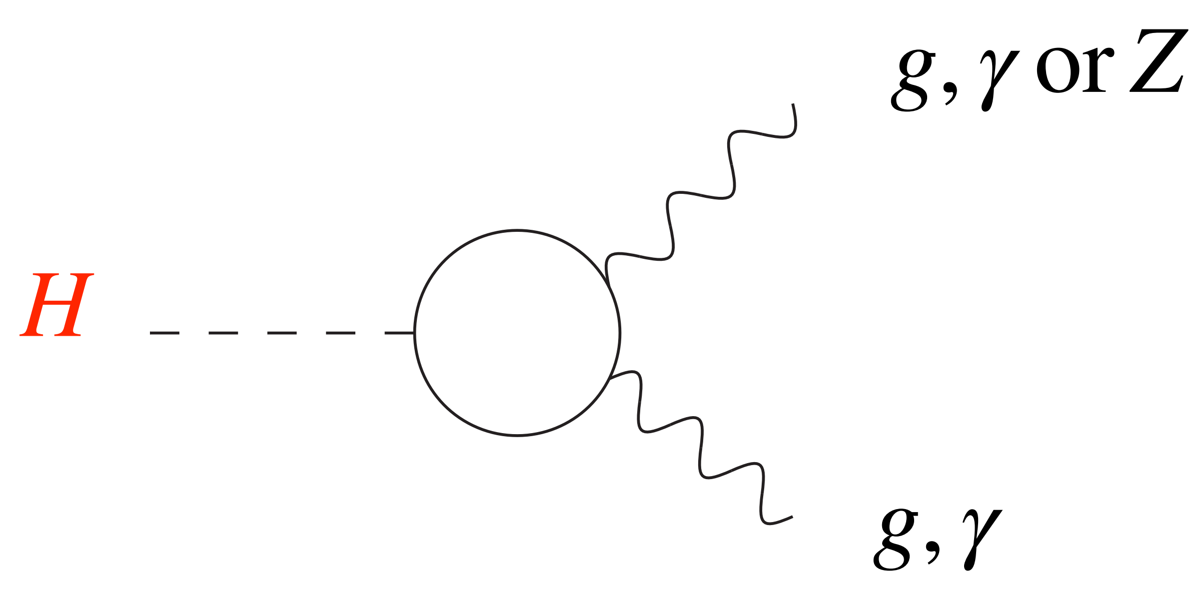
Probing new particles through loops



Portrait of the Higgs Boson 10 Years after its Discovery

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Minimal Composite Higgs scenarios

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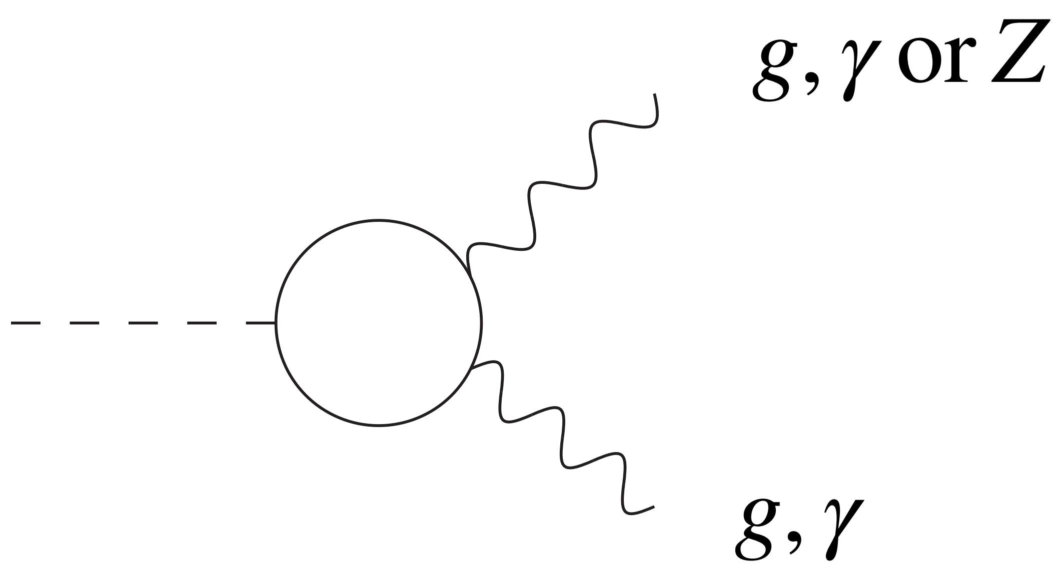
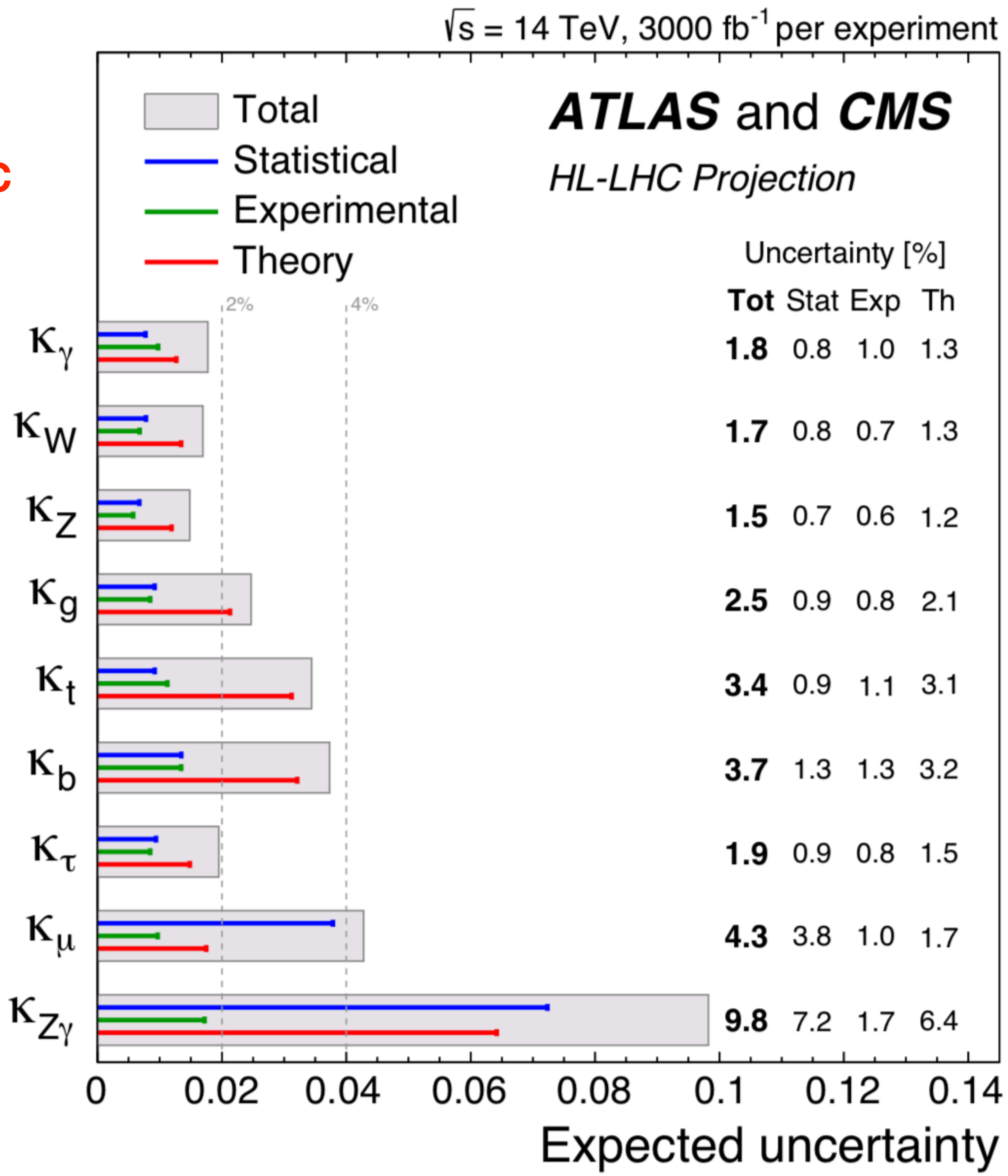
Probing new particles through loops



Probing the **Flavour Hierarchy** through the Yukawa couplings!

Portrait of the Higgs Boson 10 Years after its Discovery

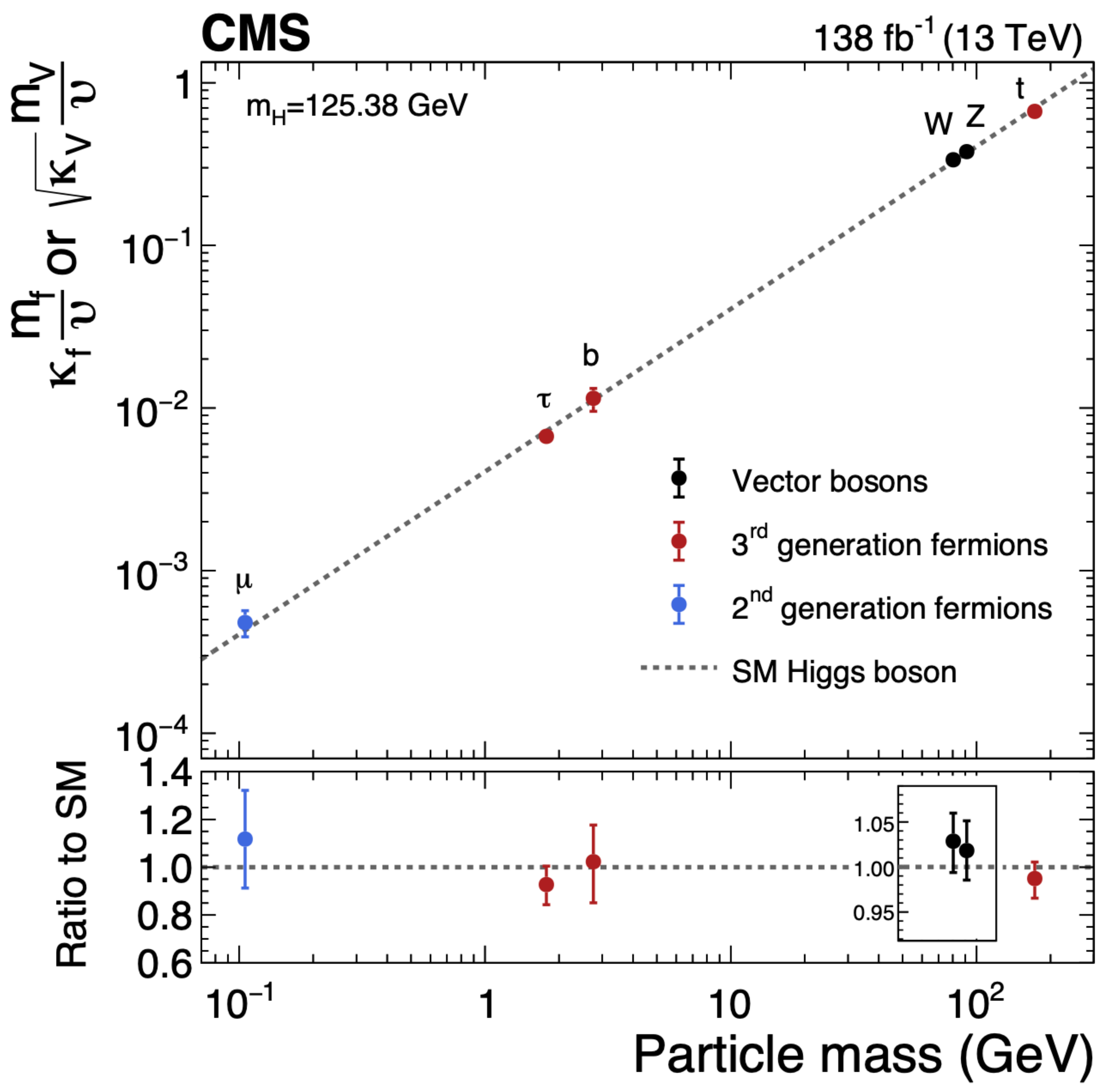
	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision	HL-LHC
κ_γ	13%	1.04 ± 0.06	1.10 ± 0.08	6%	1.8%
κ_W	11%	1.05 ± 0.06	1.02 ± 0.08	6%	1.7%
κ_Z	11%	0.99 ± 0.06	1.04 ± 0.07	6%	1.5%
κ_g	14%	0.95 ± 0.07	0.92 ± 0.08	7%	2.5%
κ_t	30%	0.94 ± 0.11	1.01 ± 0.11	11%	3.4%
κ_b	26%	0.89 ± 0.11	0.99 ± 0.16	11%	3.7%
κ_τ	15%	0.93 ± 0.07	0.92 ± 0.08	8%	1.9%
κ_μ	-	$1.06^{+0.25}_{-0.30}$	1.12 ± 0.21	20%	4.3%
$\kappa_{Z\gamma}$	-	$1.38^{0.31}_{-0.36}$	1.65 ± 0.34	30%	9.8%
B_{inv}		$< 11\,\%$	$< 16\,\%$	11%	2.5%
		Nature 607, 52-59 (2022)	Nature 607, 60-68 (2022)		



TH Uncertainties dominant (assumed to be 1/2 of Run 2)

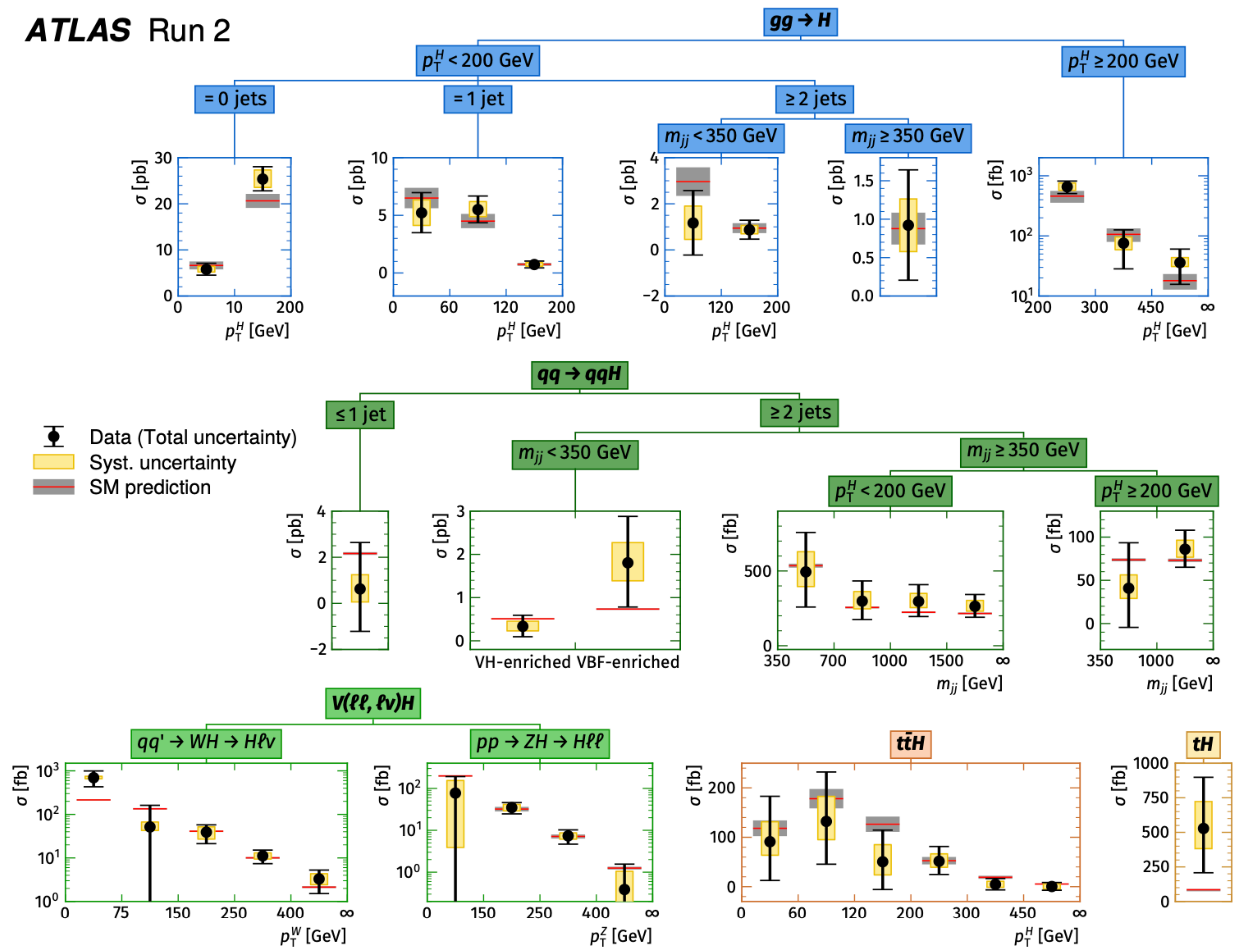
Portrait of the Higgs Boson 10 Years after its Discovery

Main coupling measurements



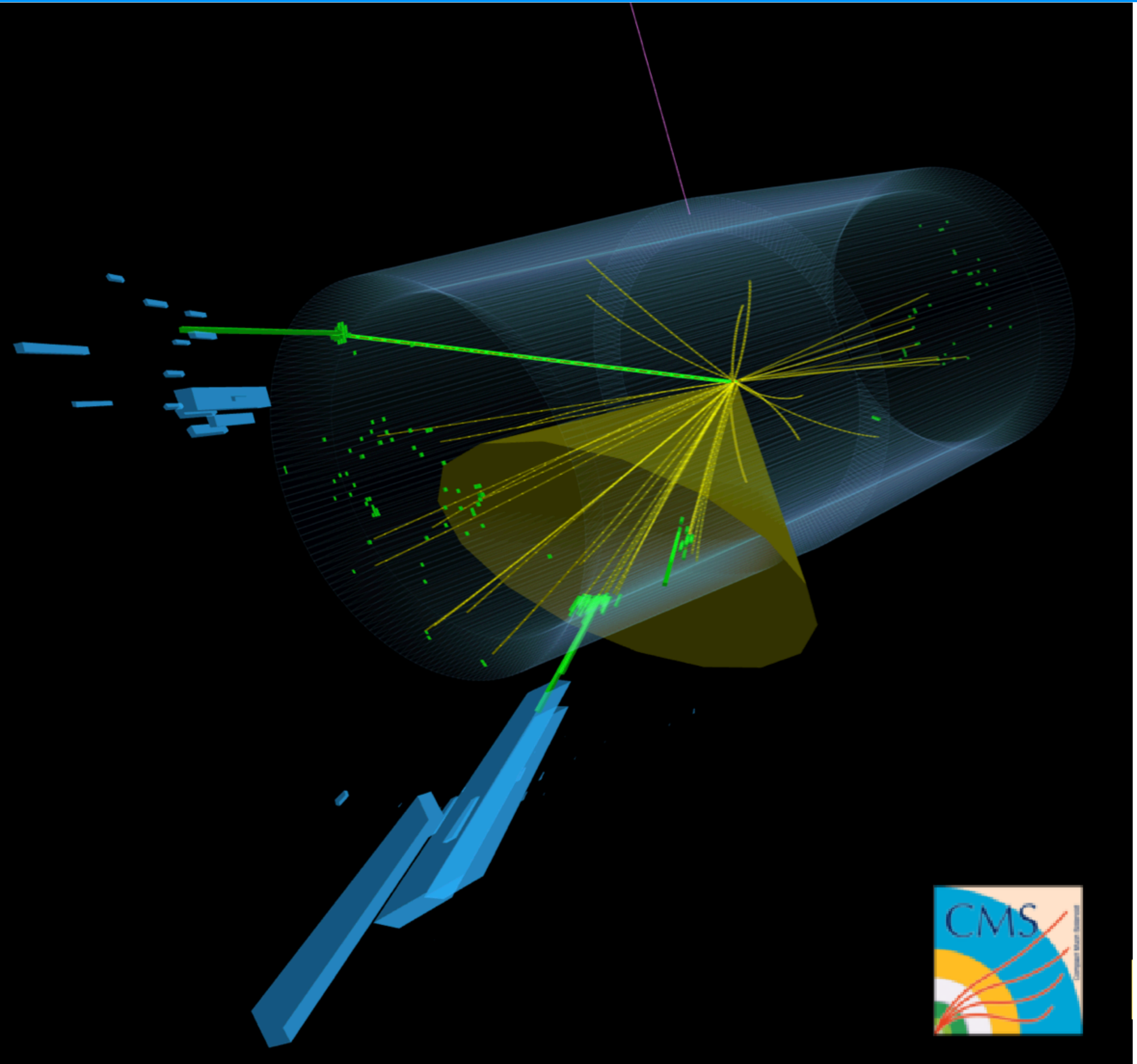
Caution not the same scale for gauge bosons and fermions

STXS measurement



Making the Impossible Possible

The Yukawa coupling to charm



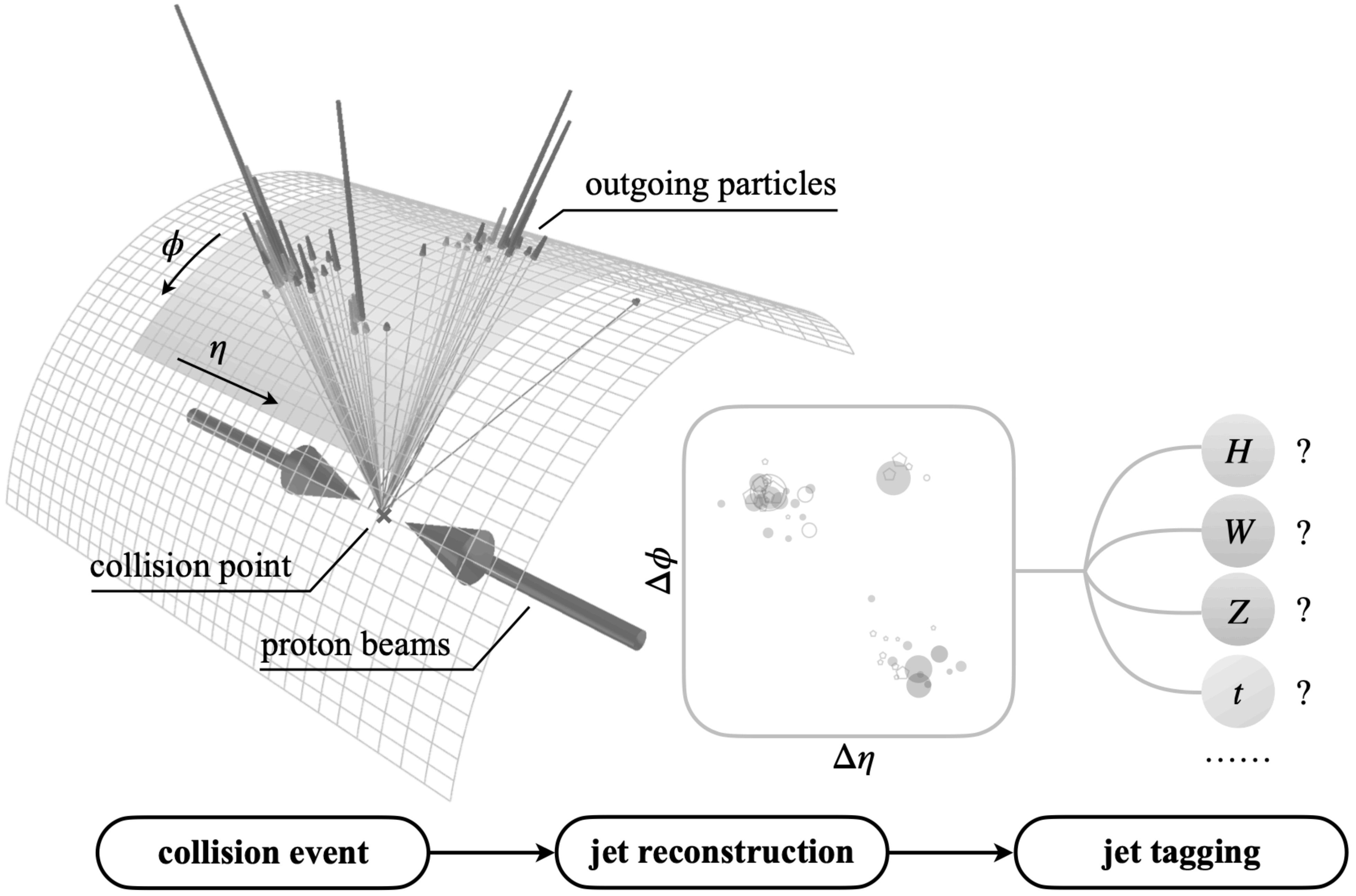


Illustration from [Particle Transformer]

Use of state-of-the-art ML techniques

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

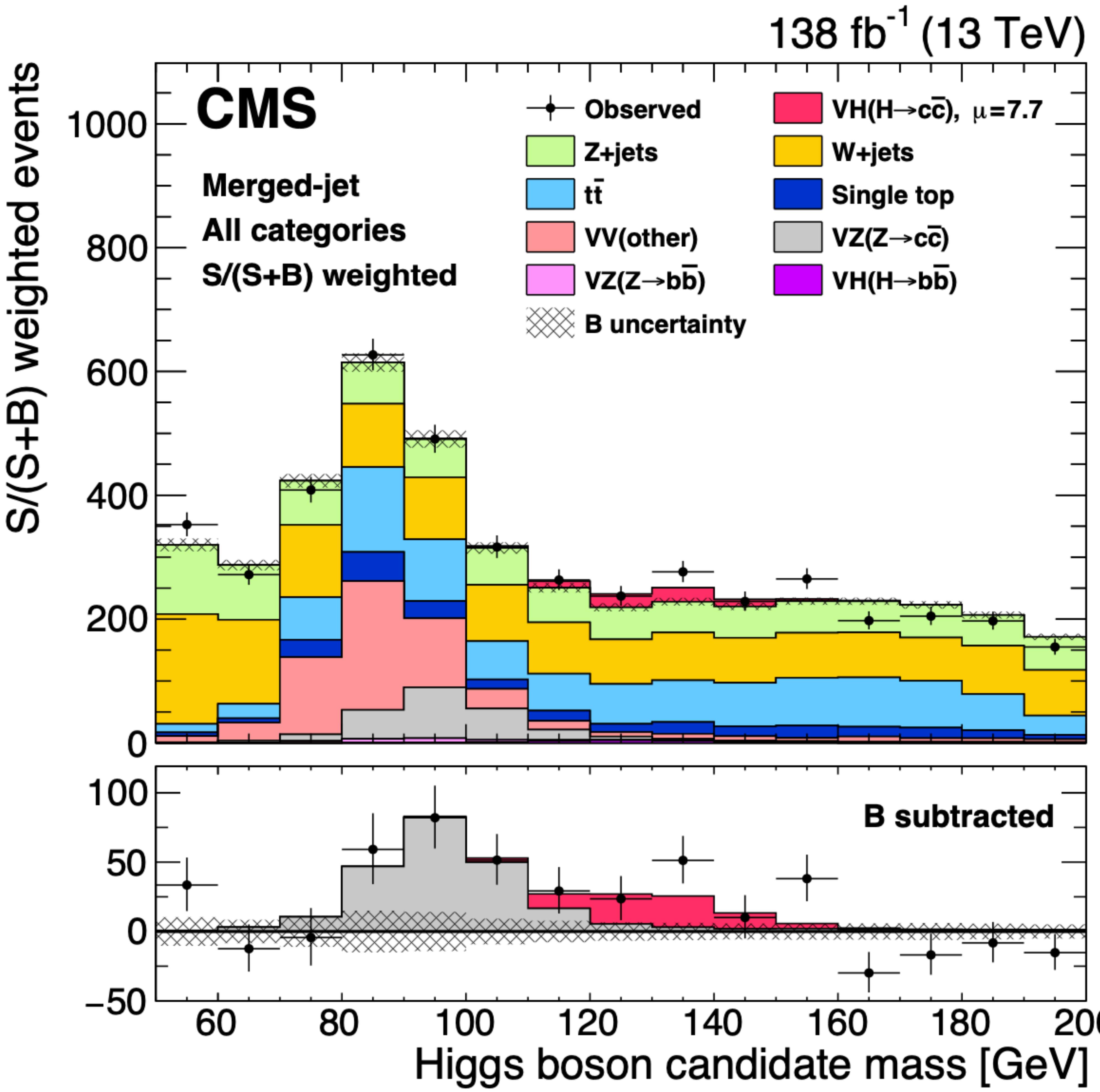
[Particle Net] uses Dynamic Graph CNN

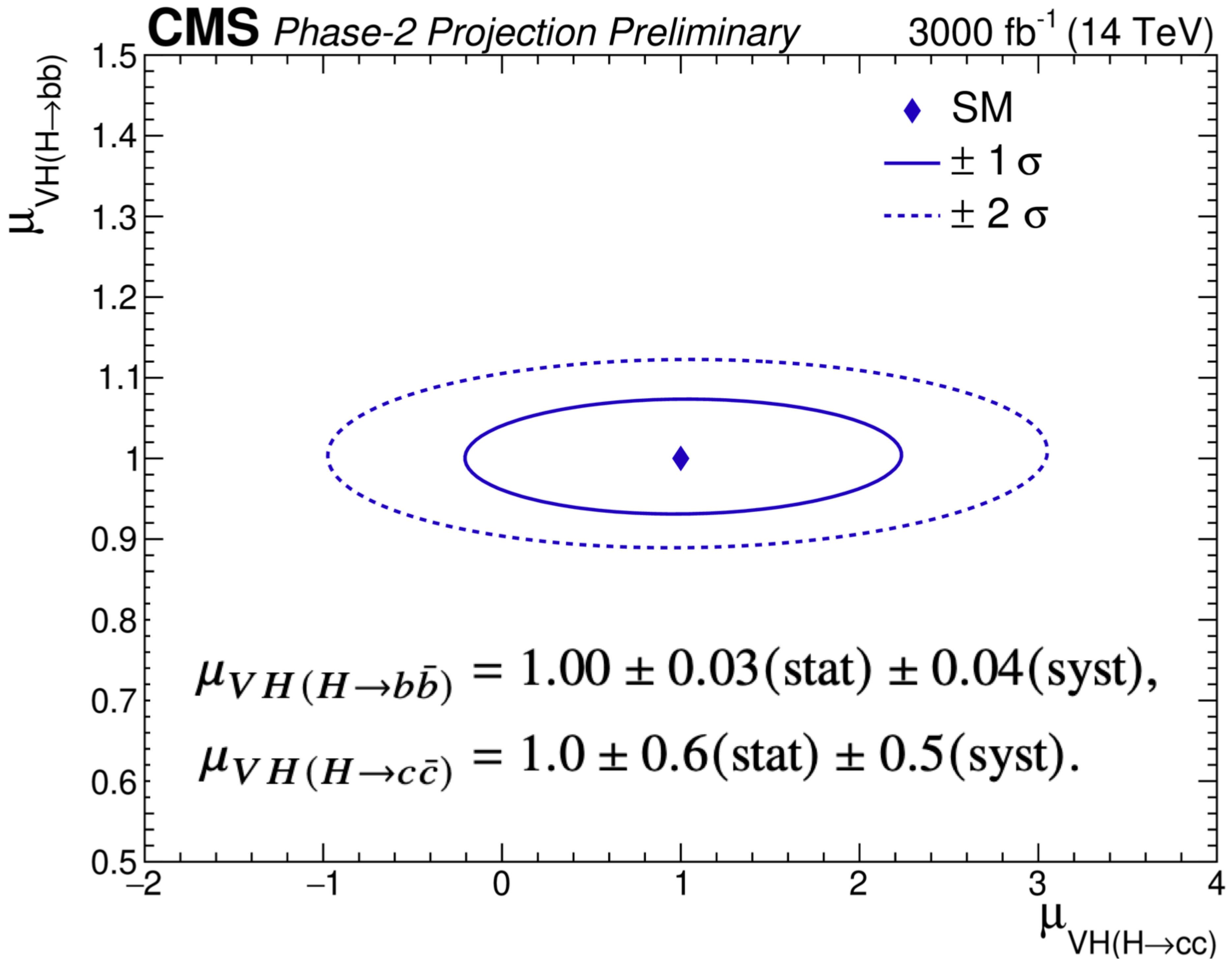
The challenging Yukawa coupling to charm

Signal strength:
$\mu < 14.4$

Impact of boosted
Resolved: 19.0 (exp)
Boosted: 8.8 (exp)
Combined: 7.6 (exp)

Constraints on charm Yukawa
$1.1 < \kappa_c < 5.5$

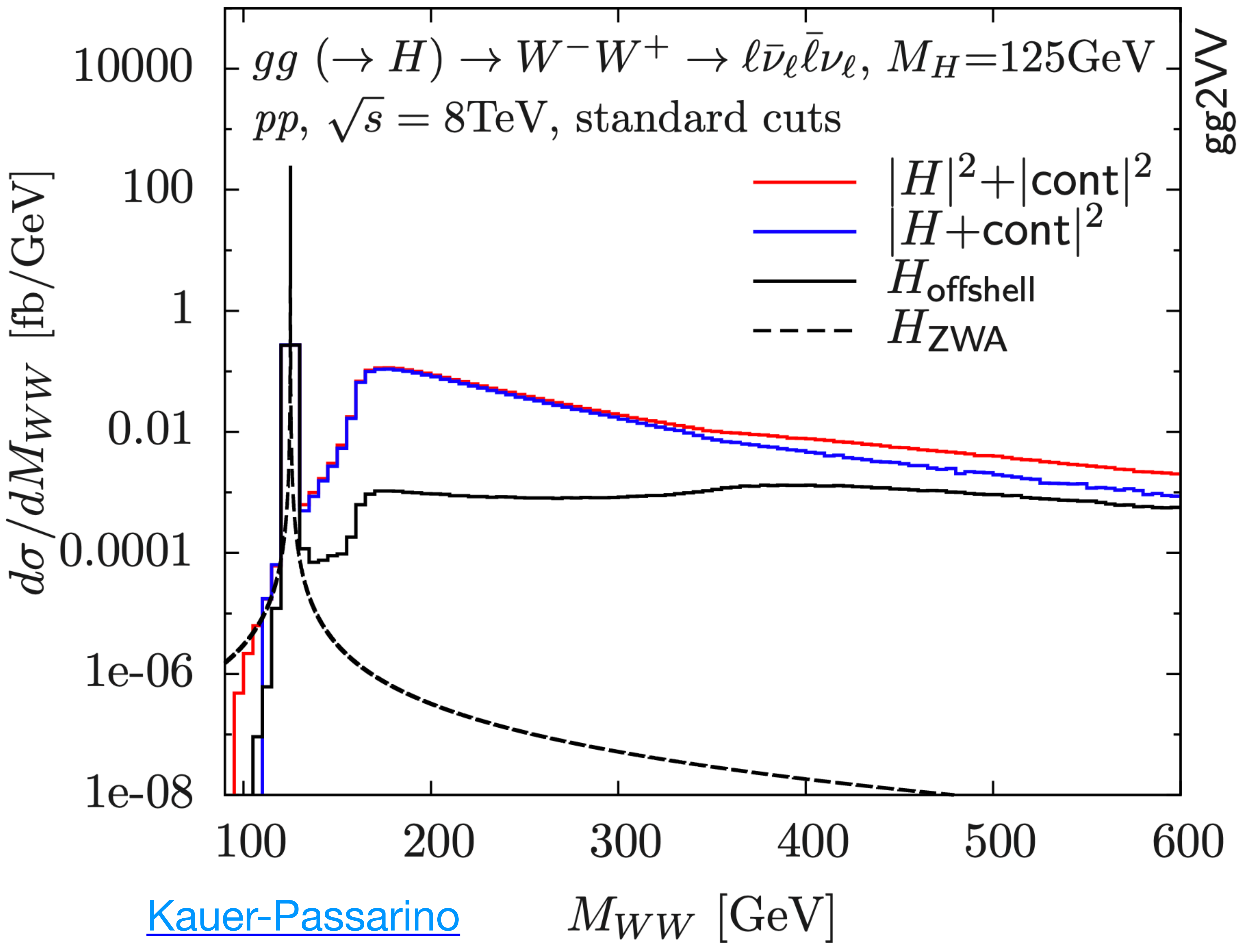




This result is very encouraging on the possibility of being sensitivity to this process at the LHC

Off Shell HVV Couplings and Width

Off Shell couplings



Kauer-Passarino

Higgs Boson width

Assumption of Standard Model and comparison to on shell allows for a measurement of the width of the Higgs boson!

$$\sigma = \int \frac{g_i^2 g_f^2}{(s - m_H^2)^2 + \Gamma_H^2 m_H^2} ds$$

Current measurement (CMS) PRD 99 (2019):

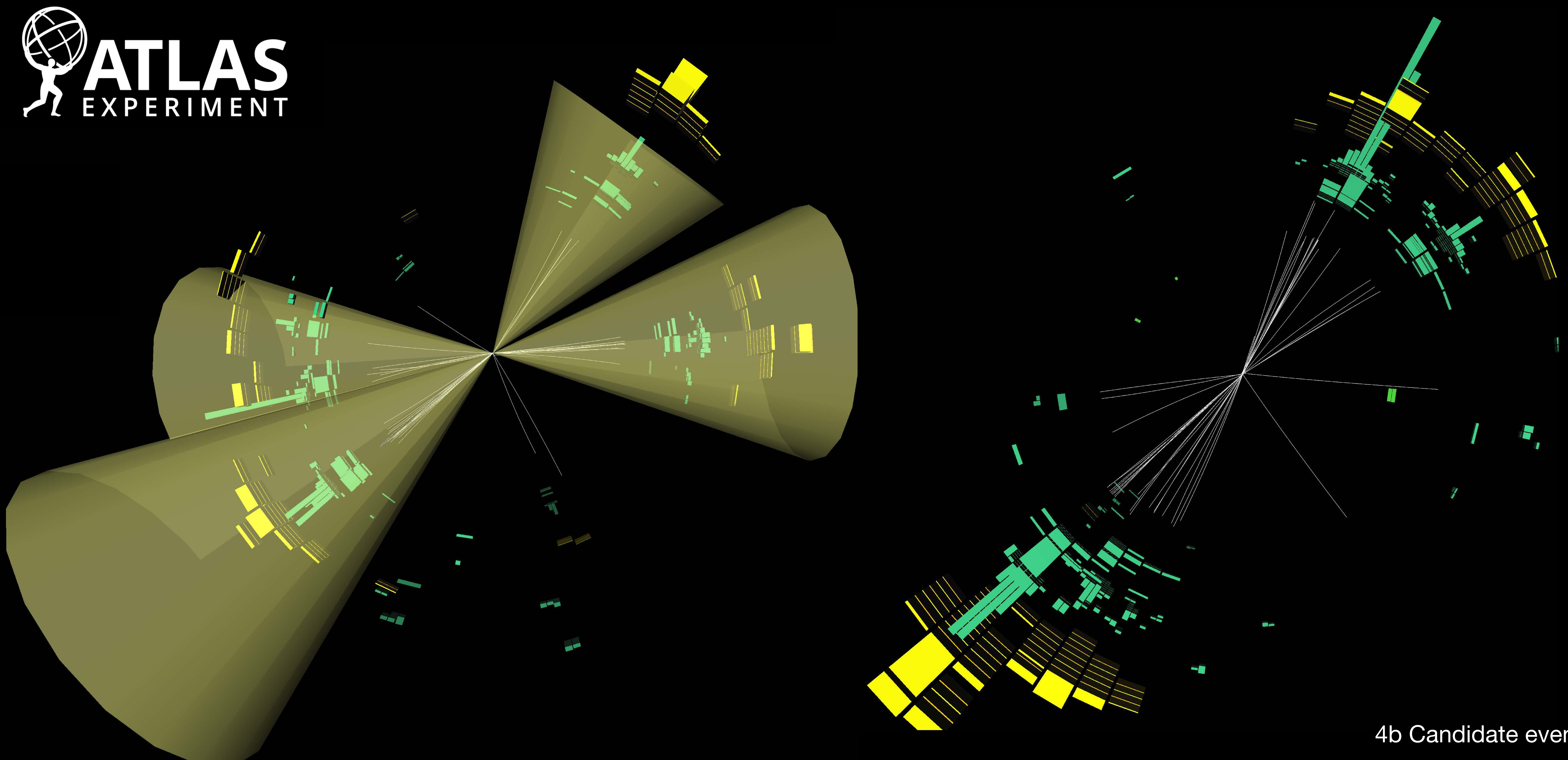
$$\Gamma_H = 3.2^{+2.4}_{-1.7}\ \text{MeV}$$

Evidence for Off-Shell production at 3.6σ

at HL-LHC: $\Gamma_H = 4.1^{+1.0}_{-1.1}$ Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab^{-1}

Remarkable result to follow closely at Run 3!
How much better can be done at HL-LHC?

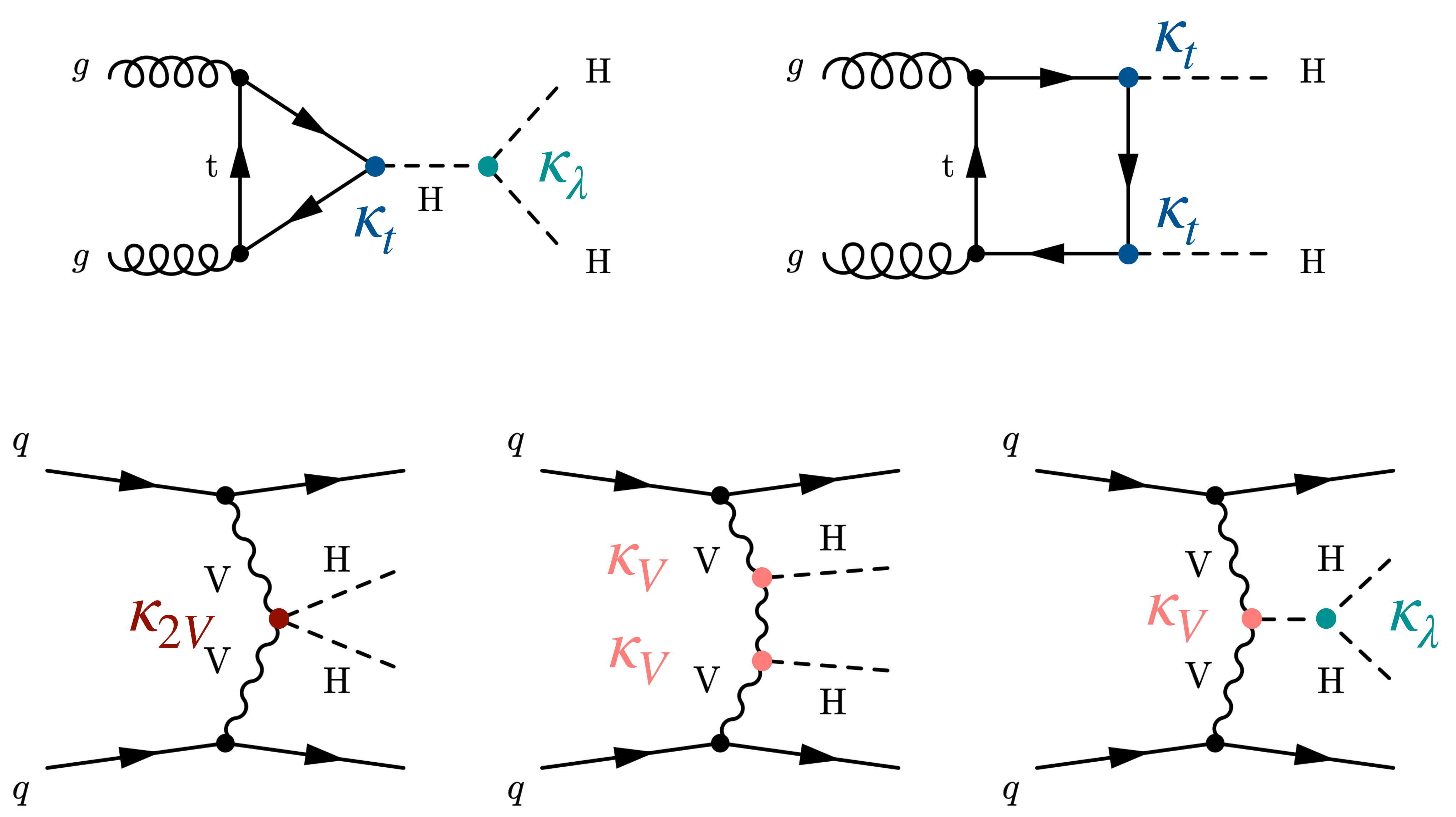
Hot off the press! Non resonant $HH \to b\bar{b}b\bar{b}$



4b Candidate event

HH Production and Higgs Self coupling

Higgs pair production through gluon fusion (and VBF)



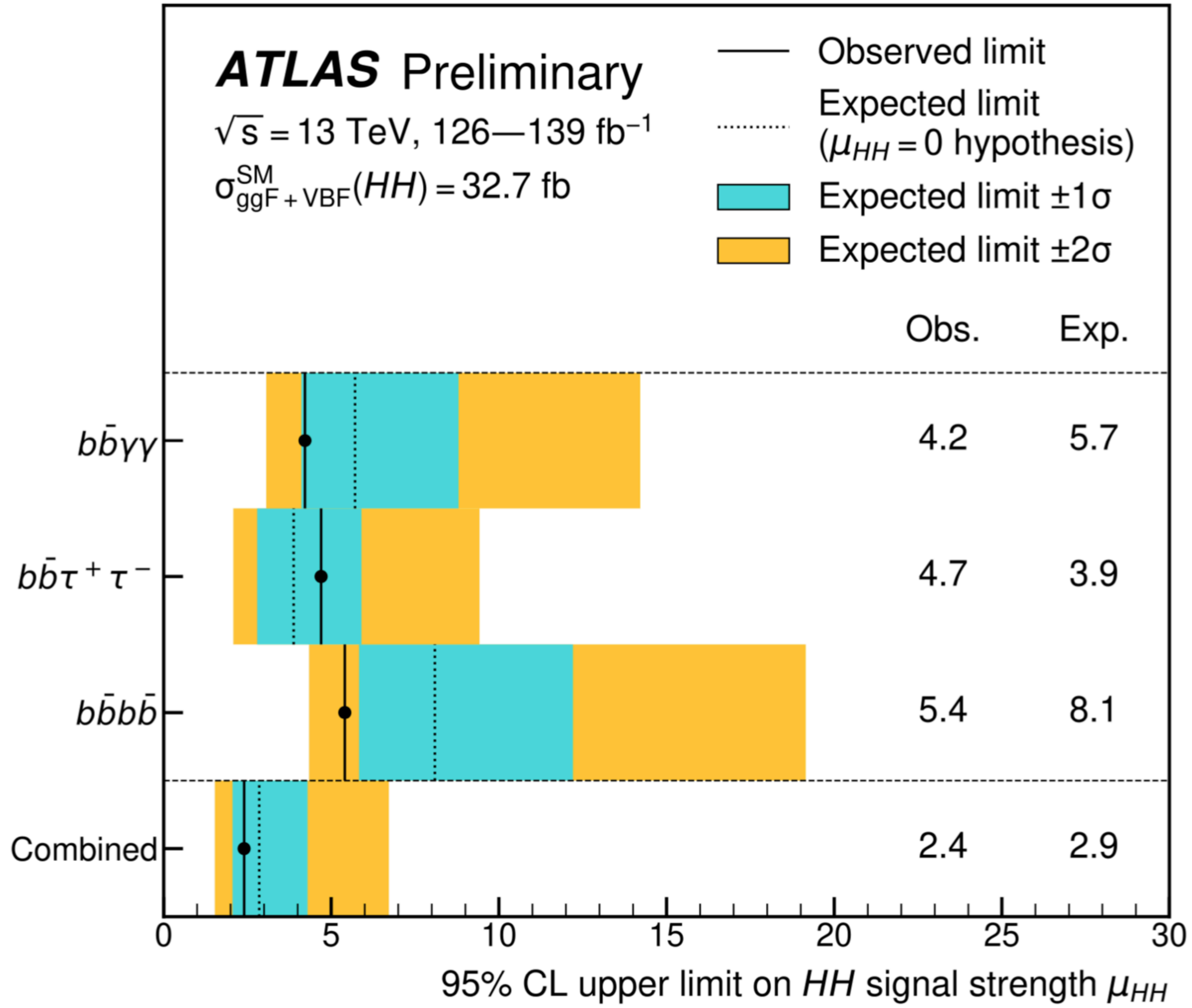
With the VBF production mode not only limits on κ_λ also on κ_{2V}

[Bishara, Contino, Rojo]

Very similar analysis as the Off-shell Higgs couplings!

Incredibly small cross section ~1000 times smaller than Higgs production! but still more than 100k event will be produced at HL-LHC!

Multiple channels investigated: depending on the both Higgs decays considering (bb, yy, tautau, WW) - All complex topologies!!



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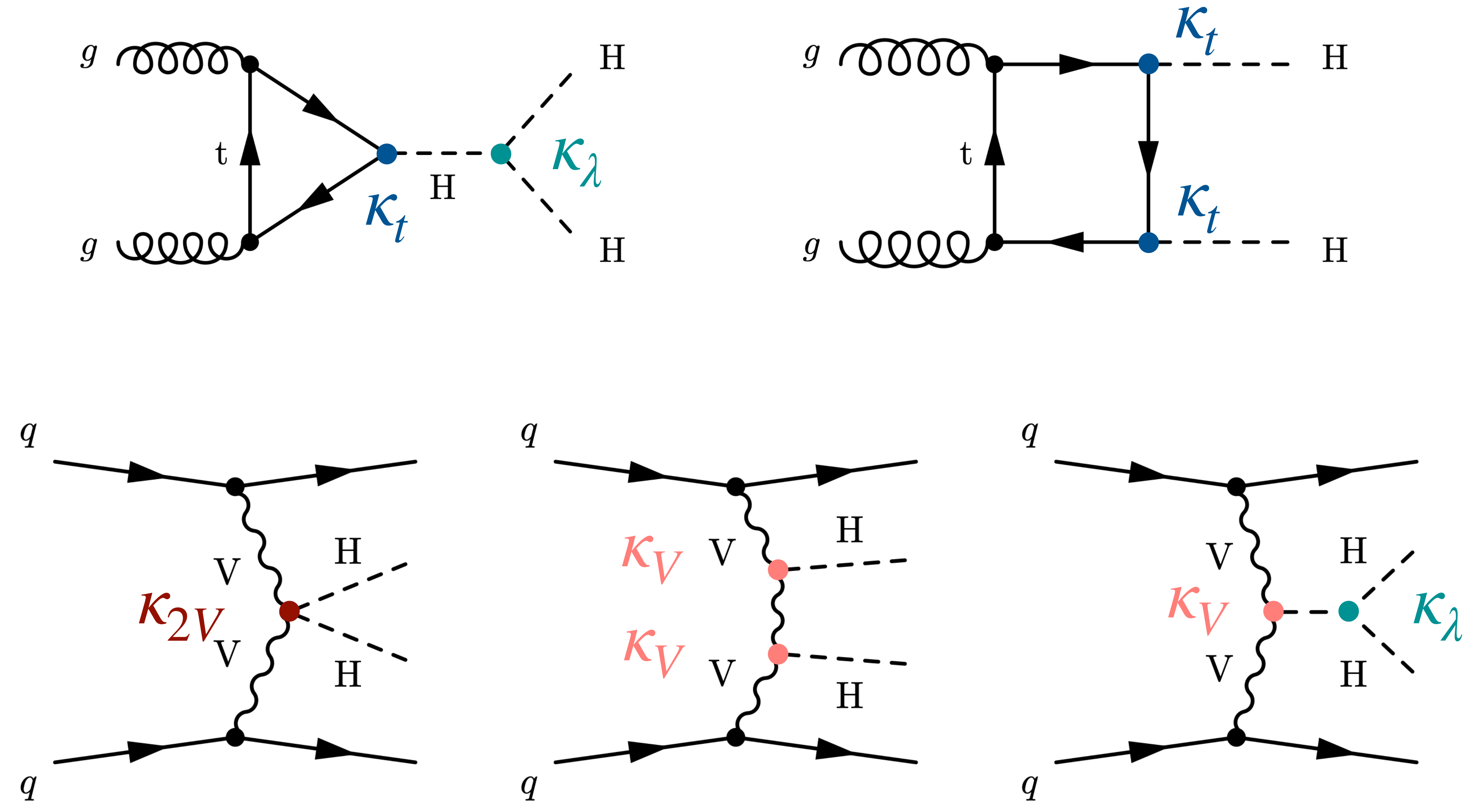

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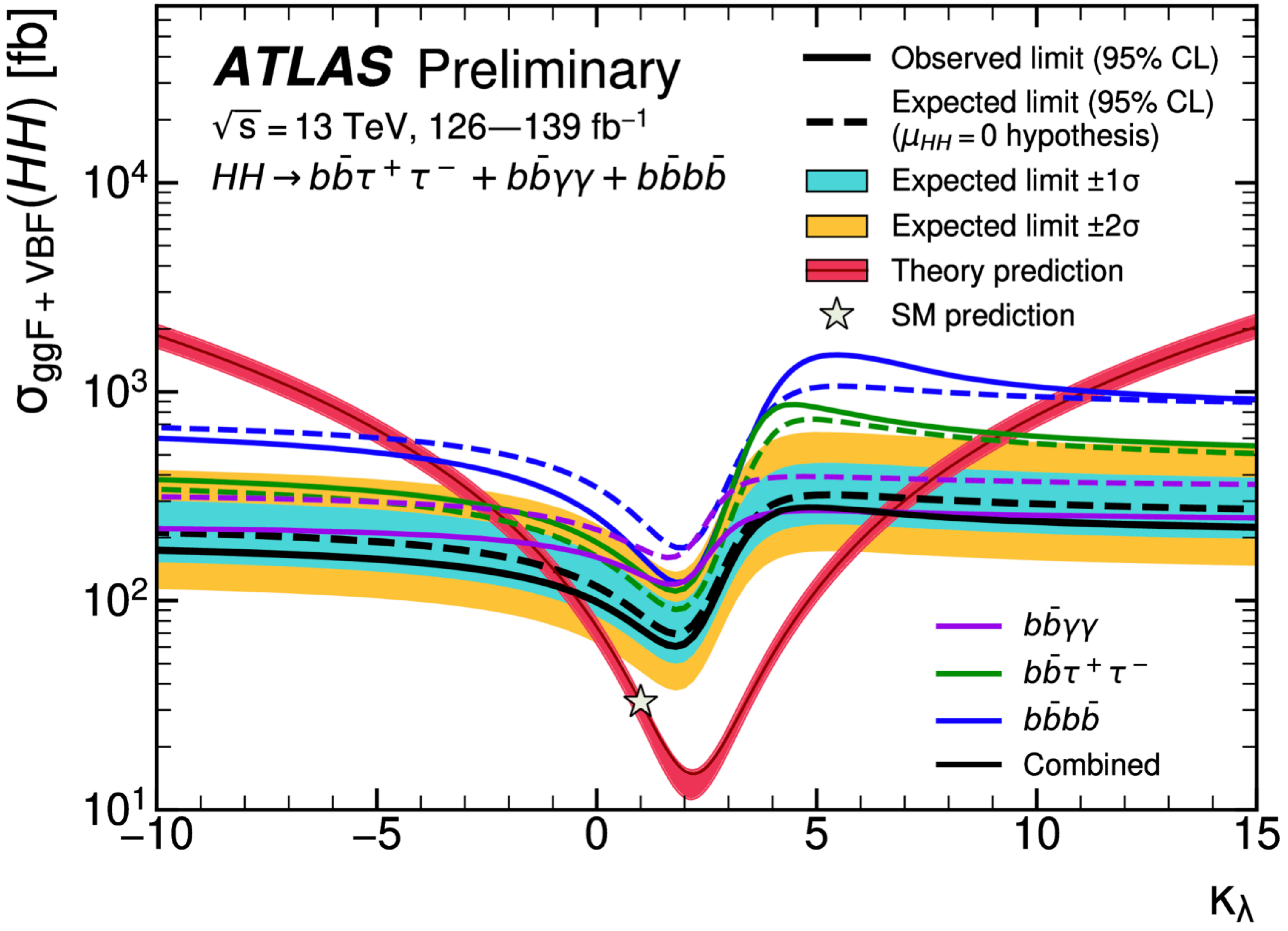


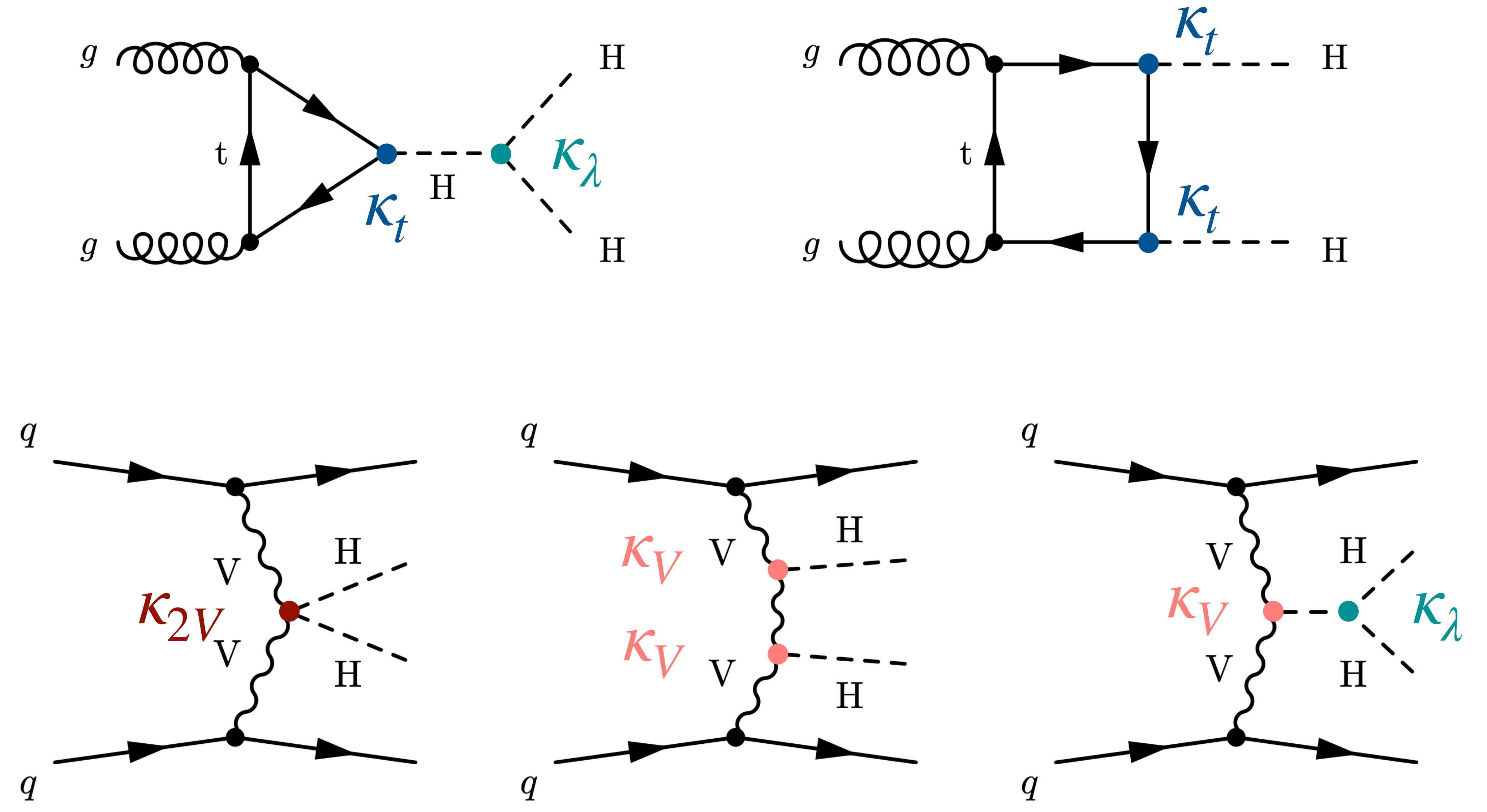
ATLAS

Observed $-0.4 < \kappa_\lambda < 6.3$

Expected $-1.9 < \kappa_\lambda < 7.5$

HH Production and Higgs Self coupling

Higgs pair production through gluon fusion (and VBF)



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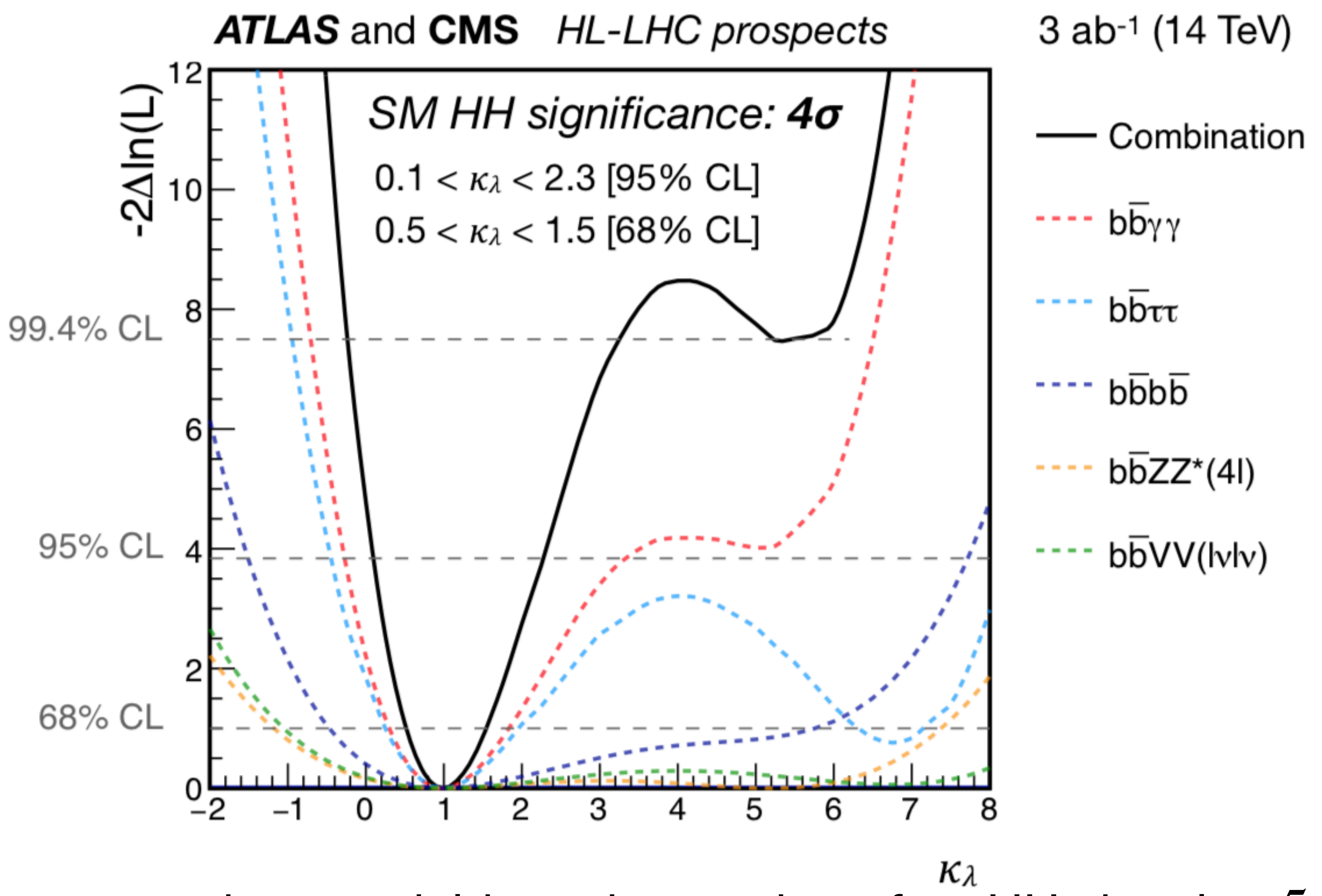
At HL-LHC



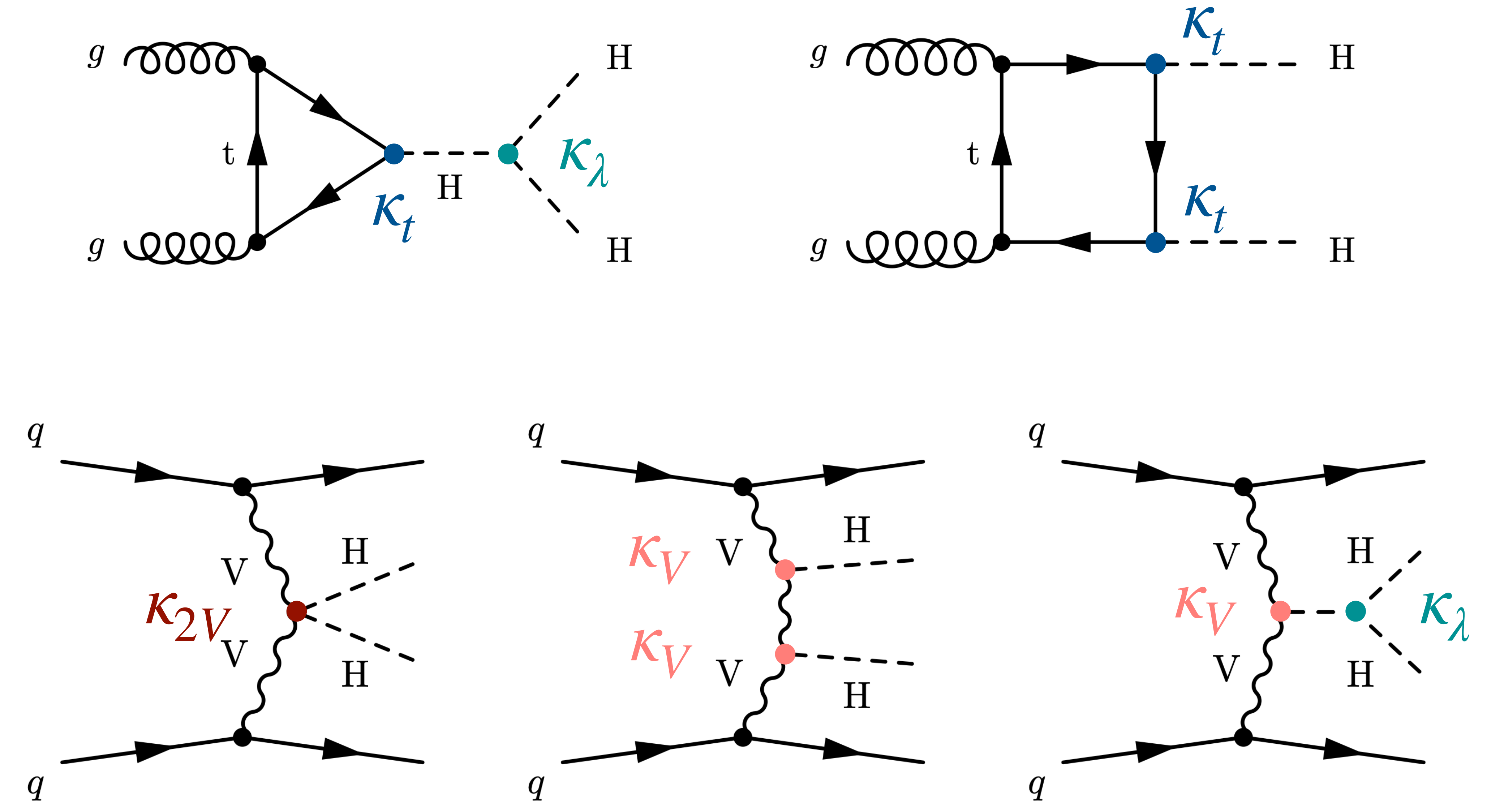
Current estimates yield an observation of an HH signal at 5σ

50% level constraints on the Higgs boson self coupling!

$$0.5 < \kappa_\lambda < 1.5$$

HH Production and Higgs Self coupling

Higgs pair production through gluon fusion (and VBF)



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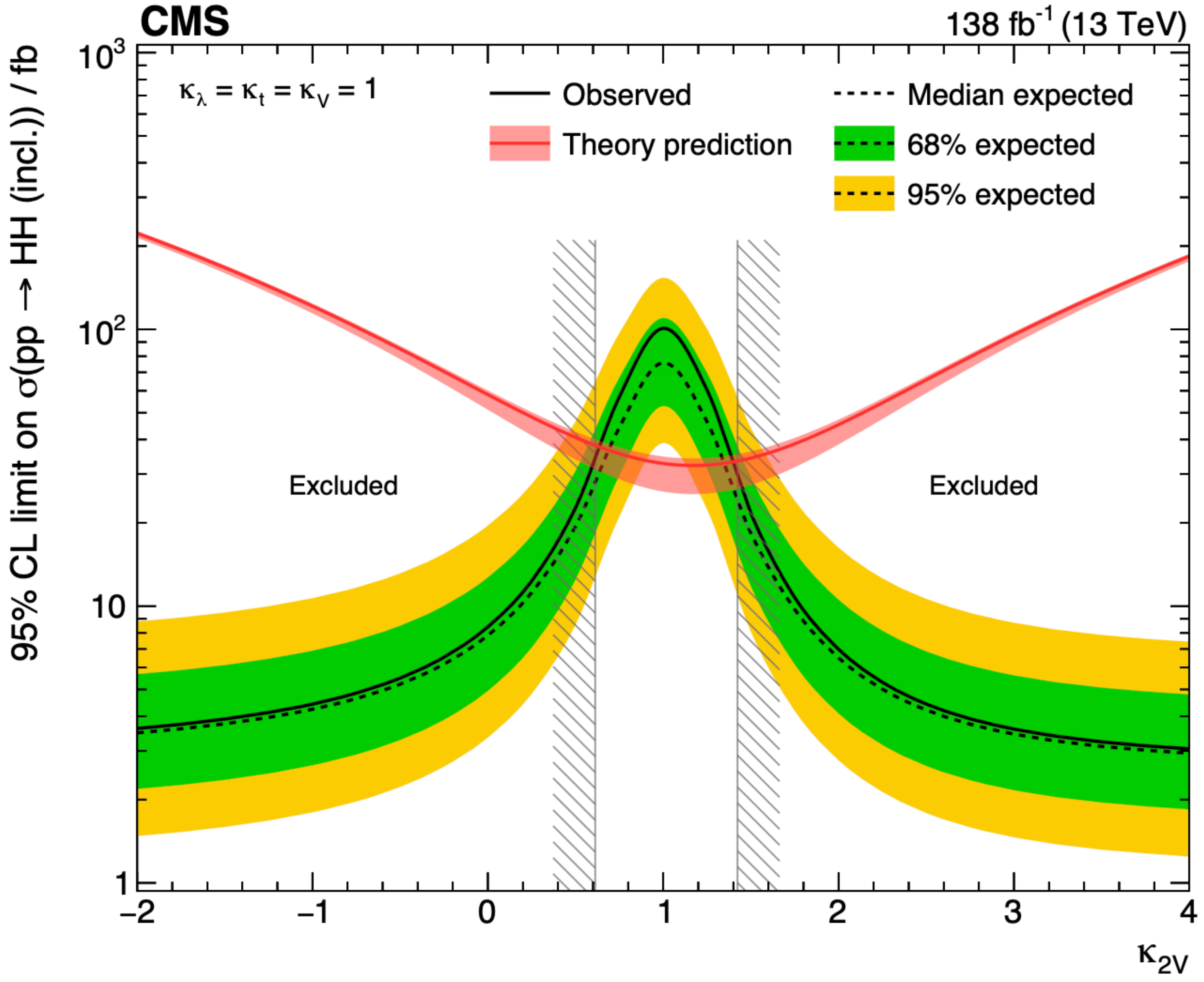


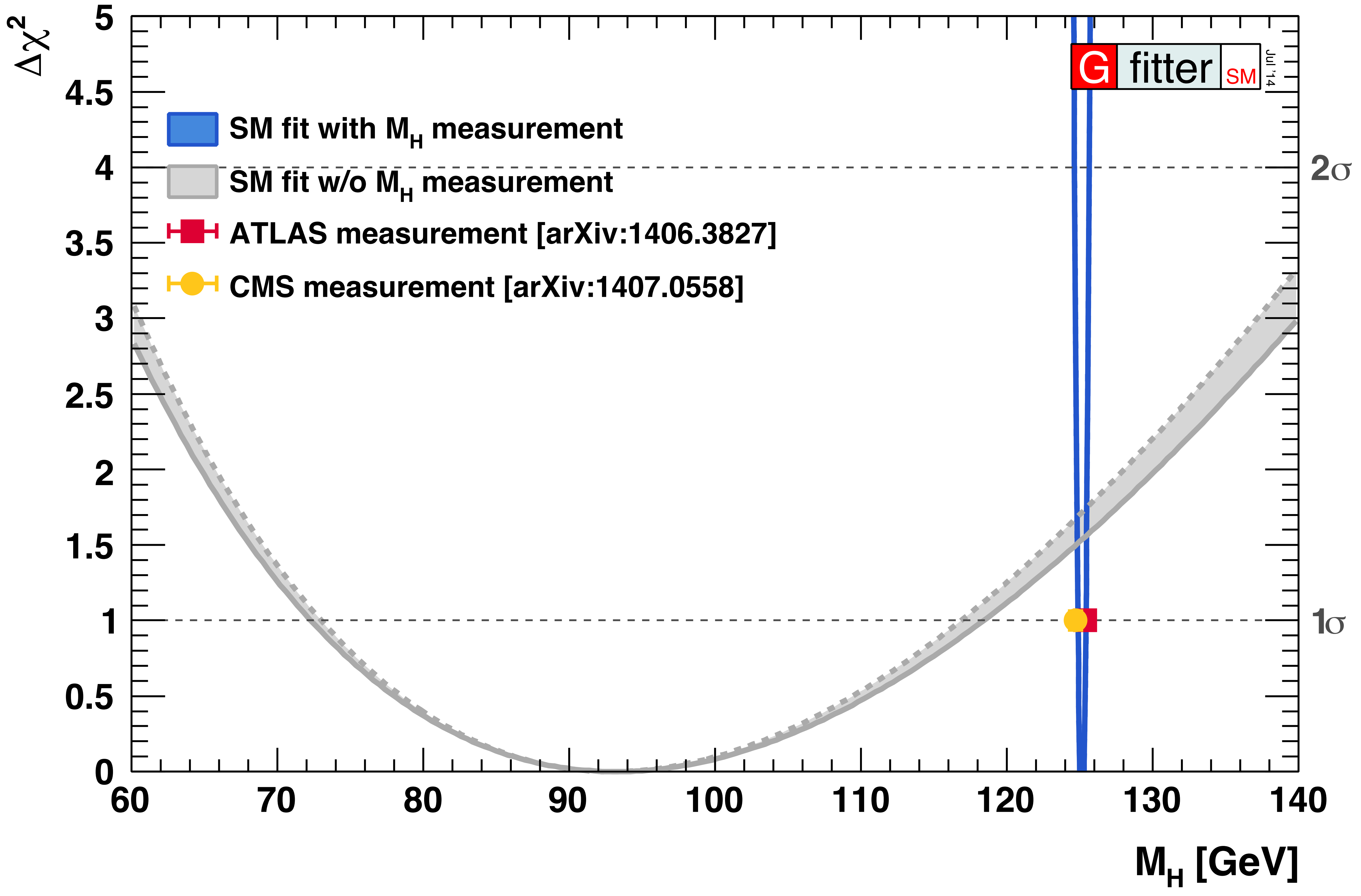
CMS $0.67 < \kappa_{2V} < 1.38$

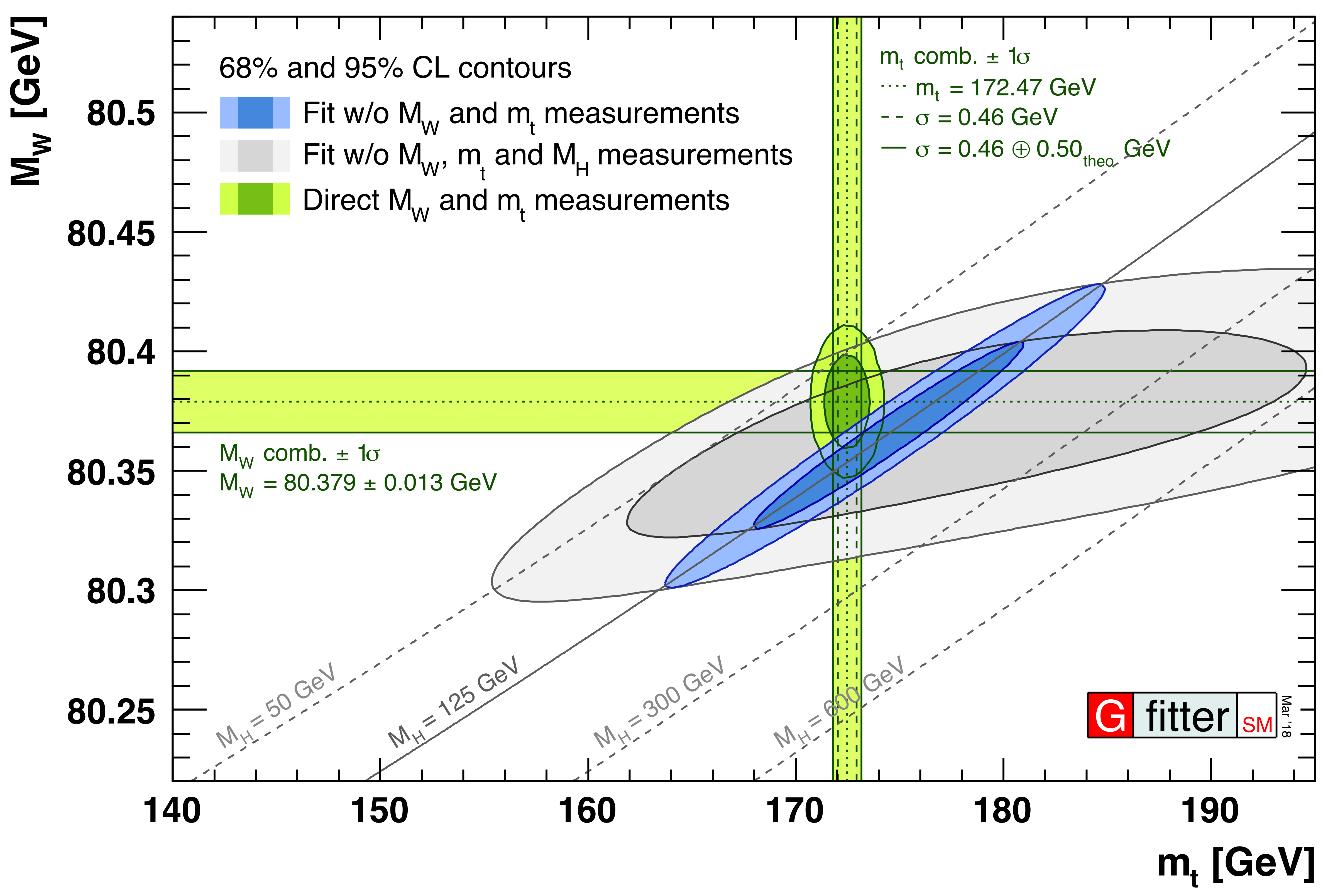
$$g_{HHVV} = \frac{2m_V^2}{v^2}(1 - 2v^2/f^2)$$

Excludes $\kappa_{2V} = 0$ at 6.6 standard deviations!!

Implications

Implications (I) – Global fit of the Standard Model





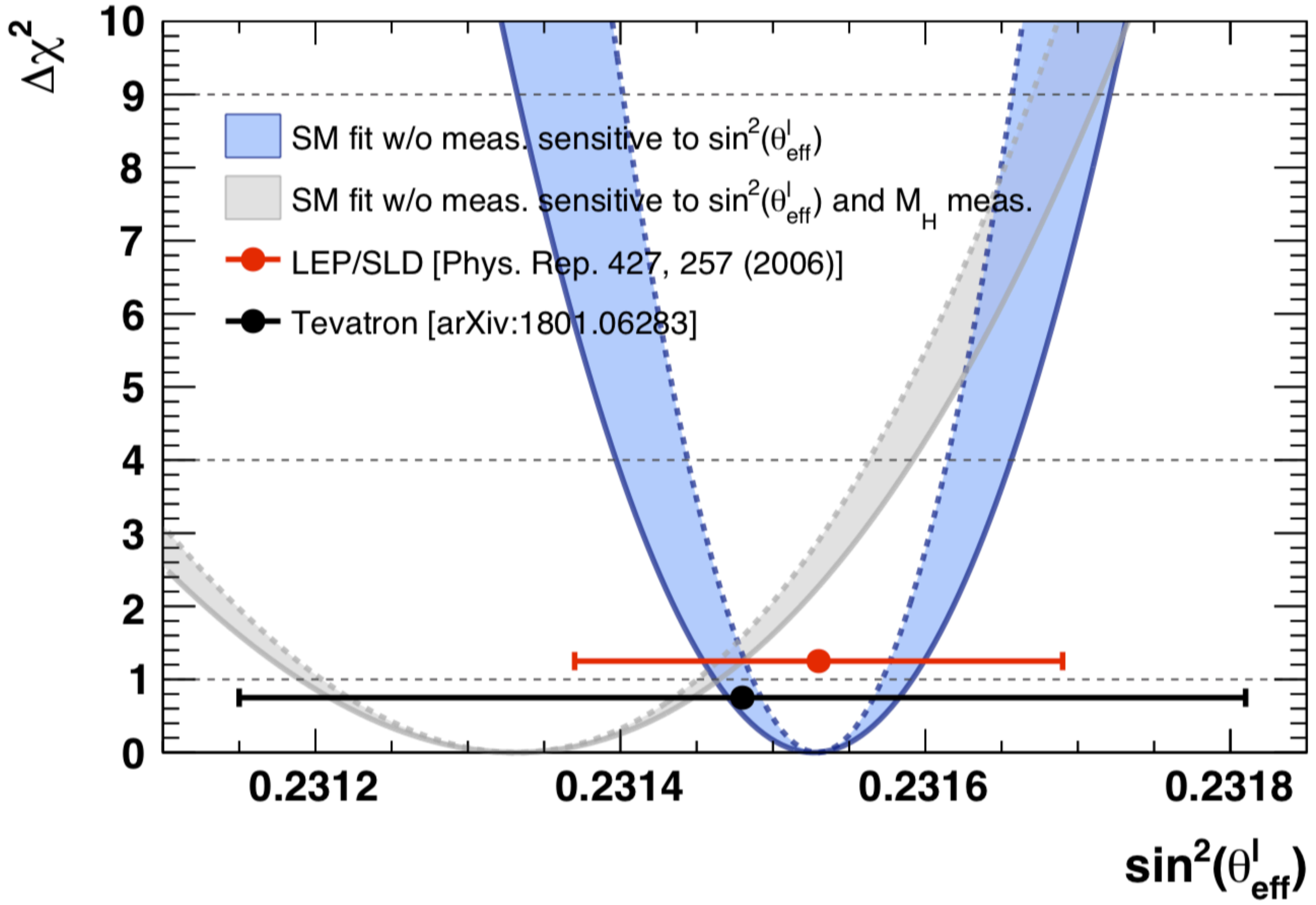
Starting from the indirect measurement of the mass of the Higgs boson discussed in Lecture 2.

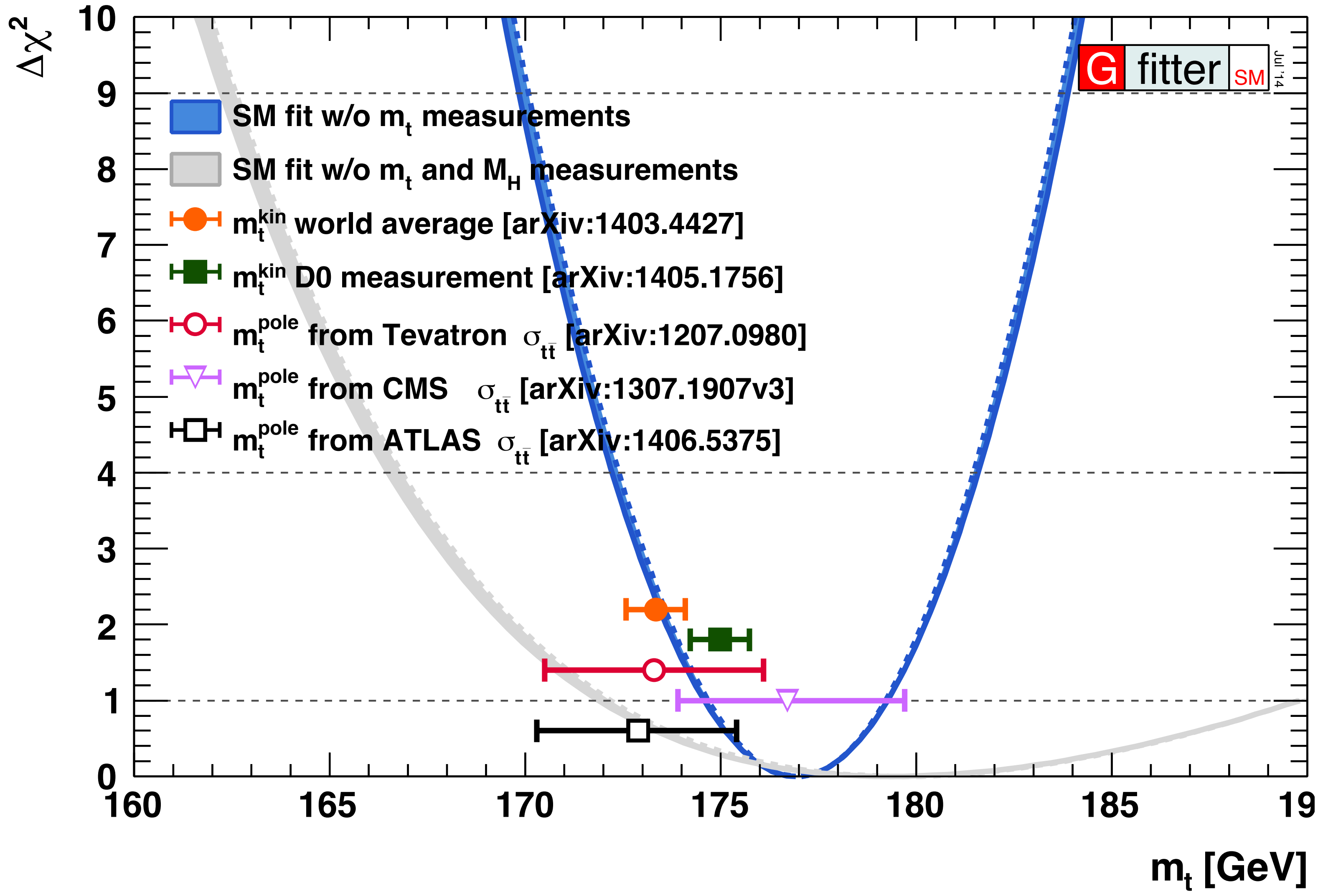
Direct measurement of the Higgs boson mass is much more precise than the indirect one.

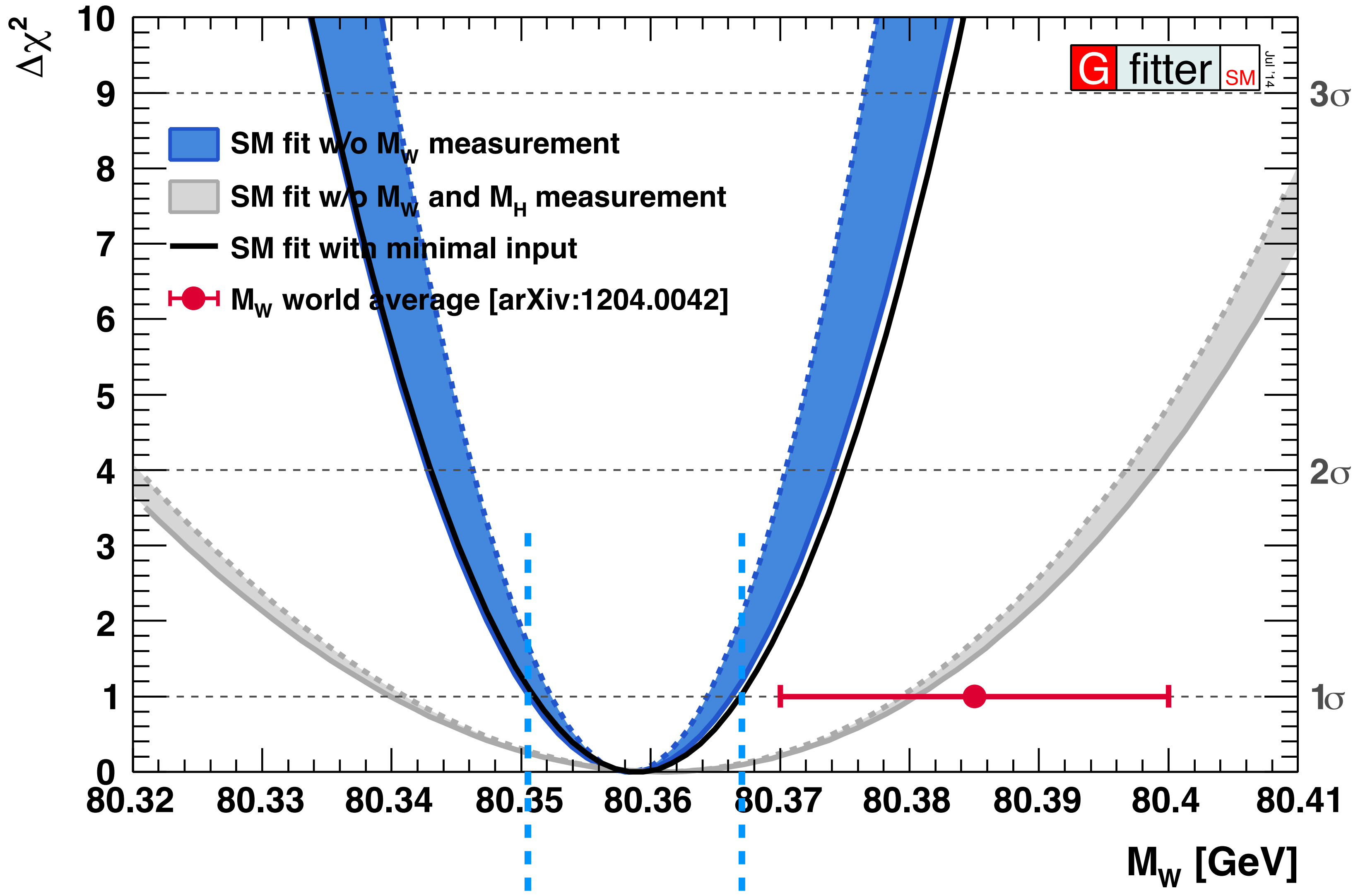
Knowing the Higgs boson mass has a large impact on global analysis.

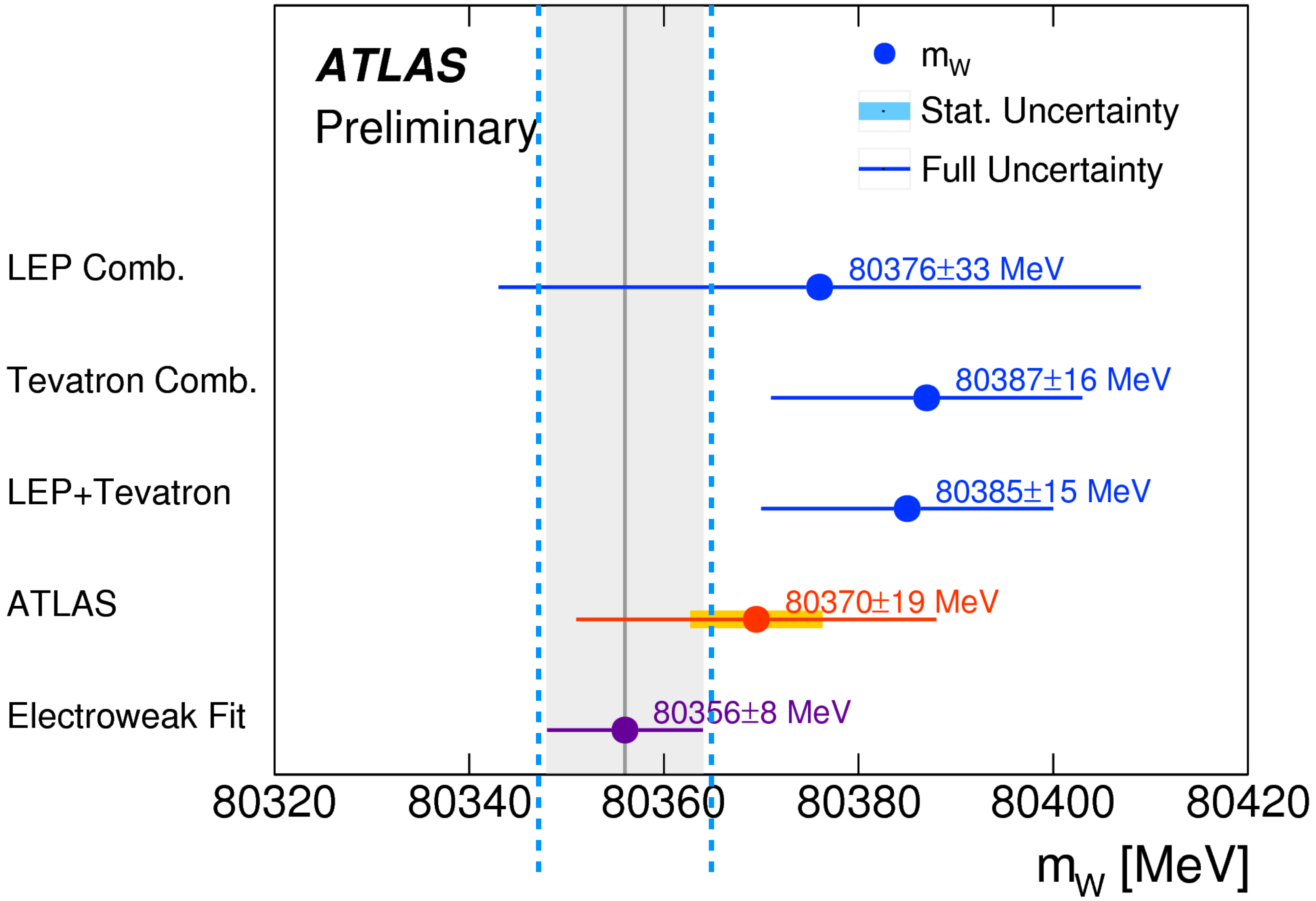
Knowing the Higgs boson mass precisely has little impact.

Implications (I) – Global fit of the Standard Model









Check the impact on the precision observables discussed in Lecture 2

Important to compare the relative precisions of the direct and indirect measurements.

The Standard Model is consistent between direct and indirect measurements!!

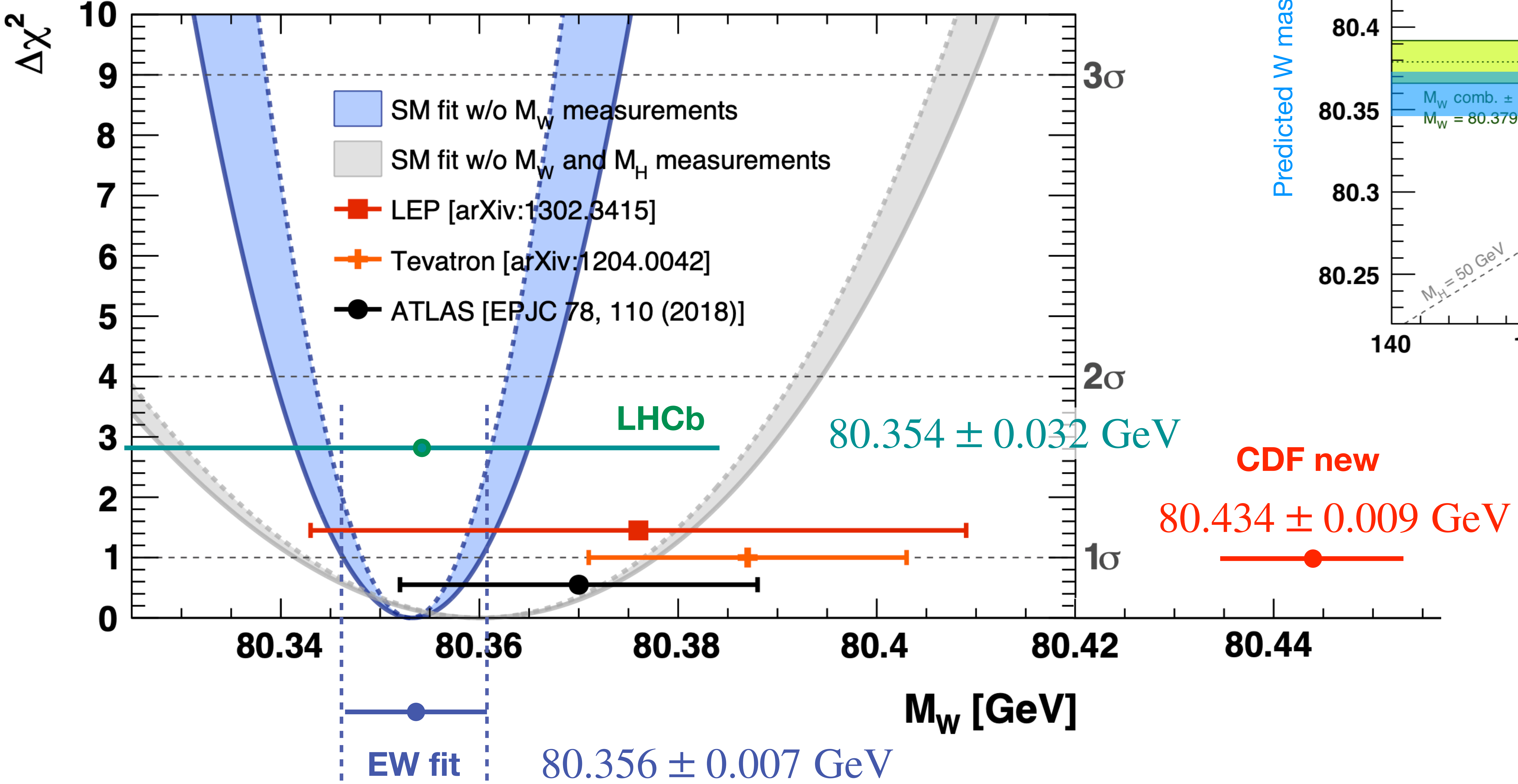
If there is new physics, it does not seem to be affecting the Standard Model through quantum corrections.

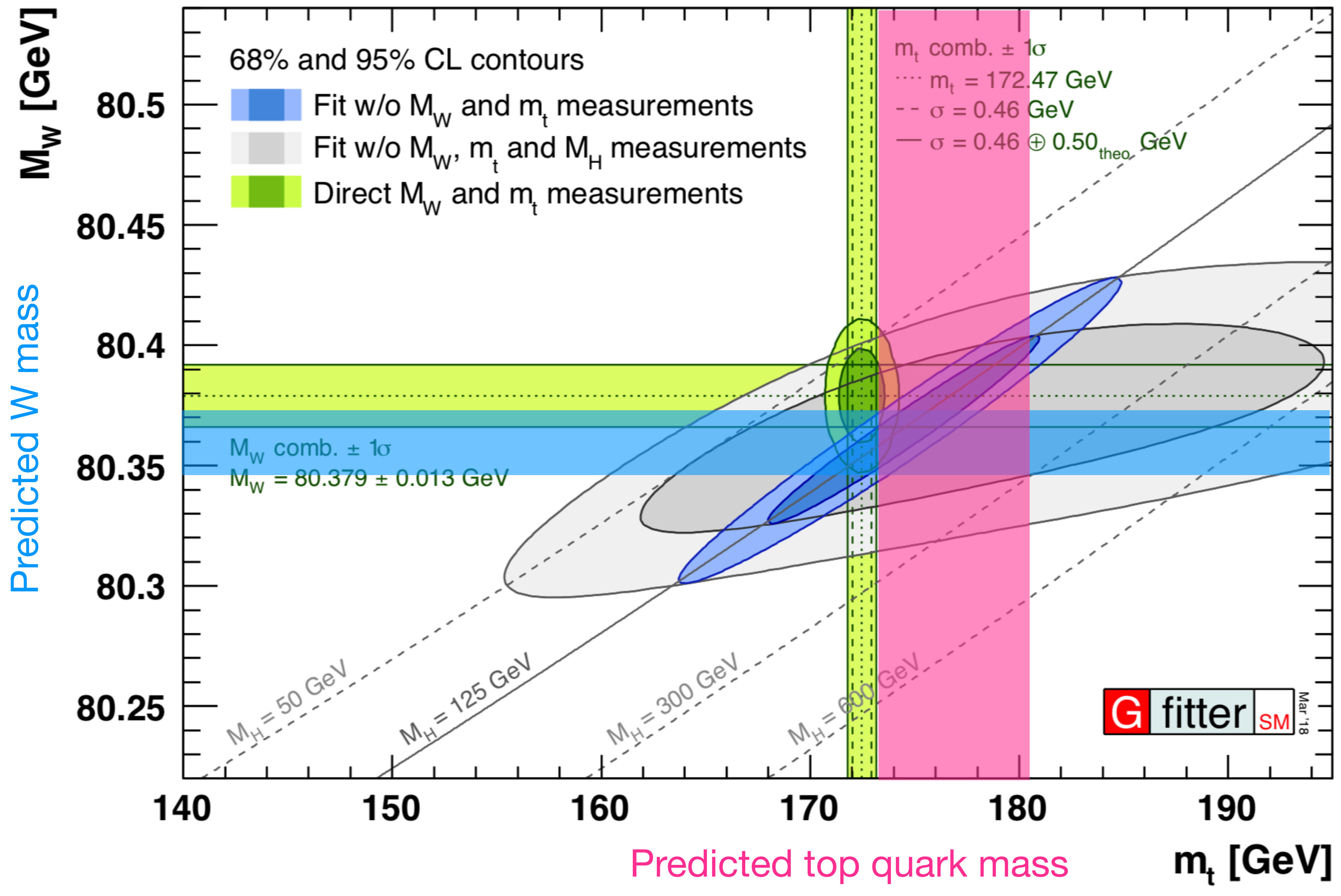
With the recent W mass measurement, the Standard Model is even more consistent!

What have we Learned from Knowing its Mass?

Precision measurements allow to make predictions!!

Assuming the SM, the top quark mass and Higgs boson mass were (approximately) known before being discovered!





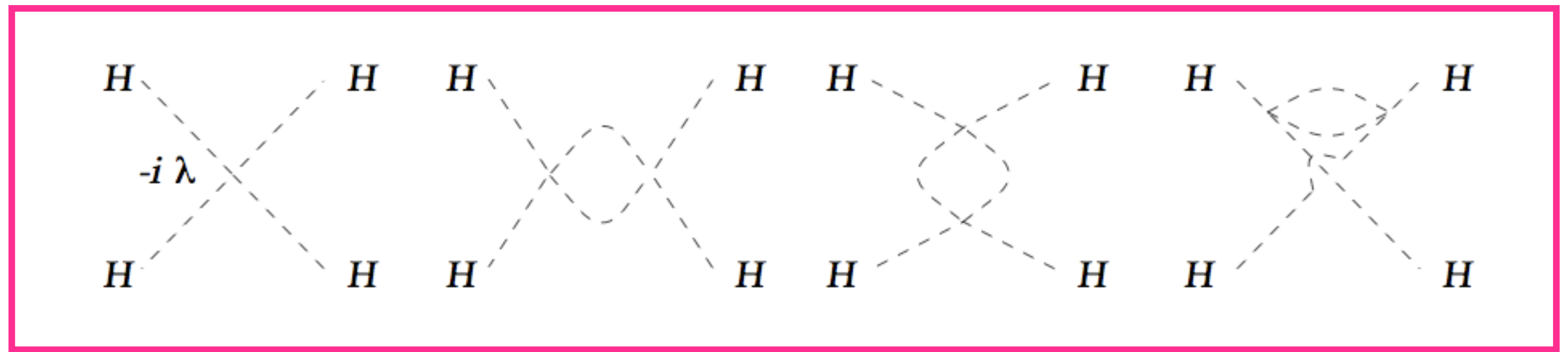
The knowledge of the Higgs mass has large impact on the precision of indirect measurements!

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

Implications (II) – Global fit of the Standard Model

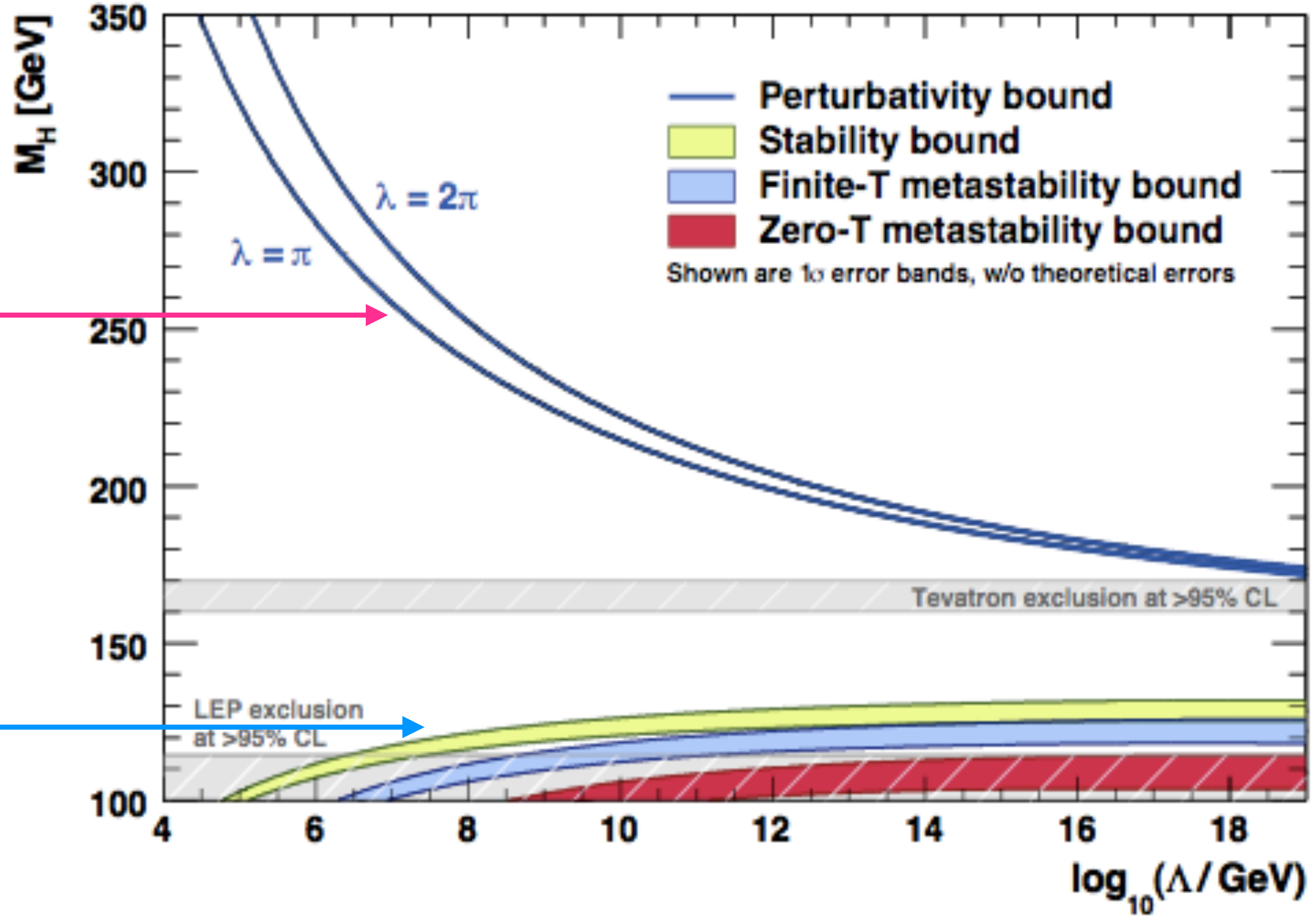
Running of the Higgs self coupling:

$$32\pi^2 \frac{\partial\lambda}{\partial\mu} = 24\lambda^2 - 6y_t^4 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4$$

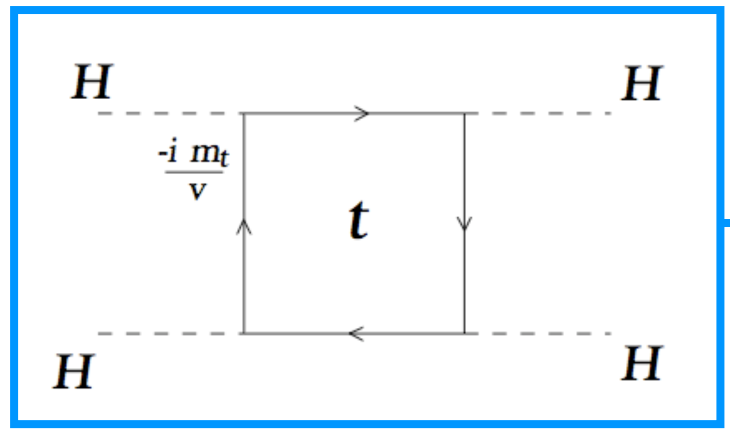


Dominant term for large values of the Higgs boson quartic coupling

The simplified differential equation can be solved and derive a so-called « triviality » bound.



Dominant term for small values of the Higgs boson quartic coupling



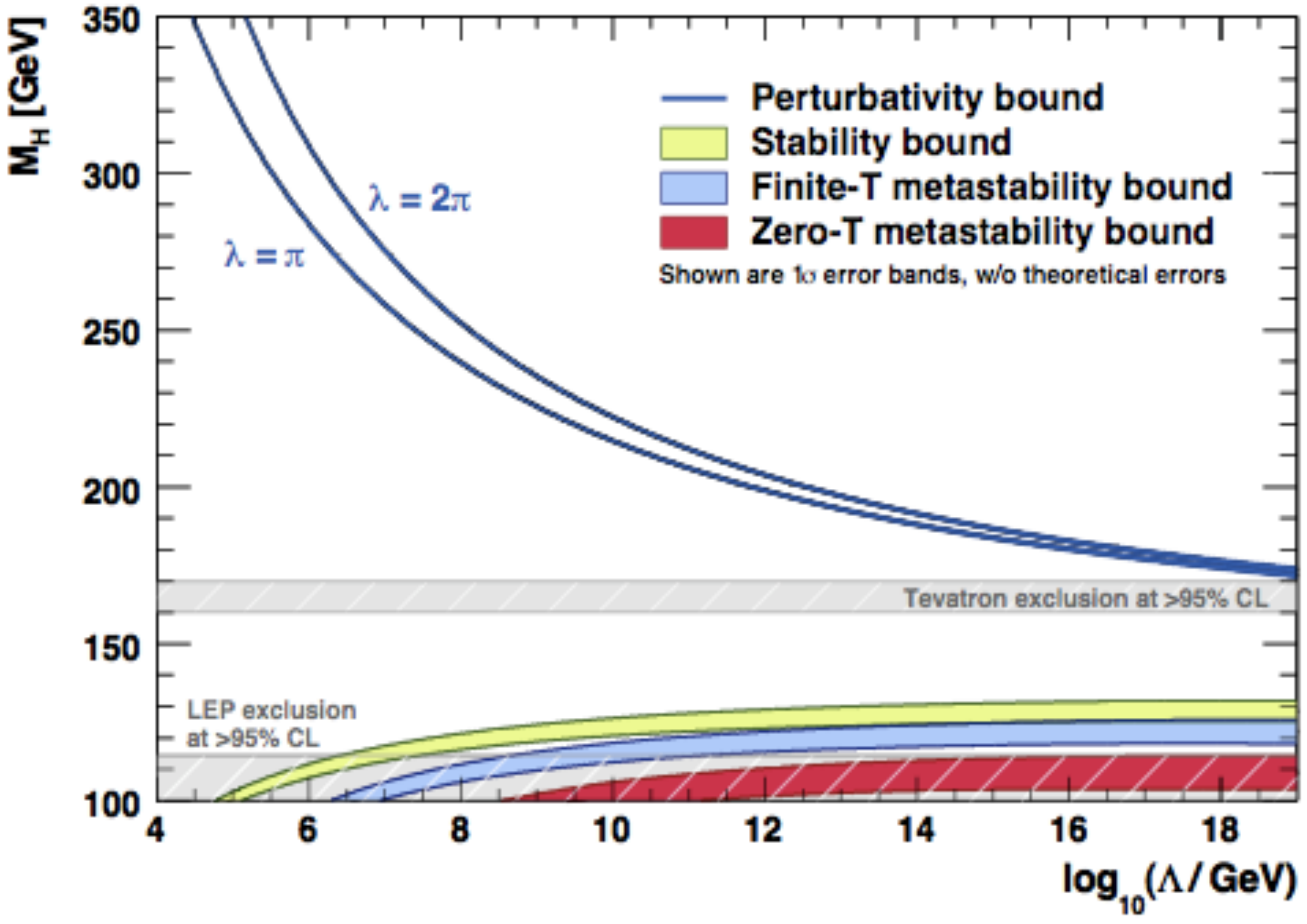
The simplified differential equation can be solved and derive a so-called « vacuum stability » bound.

Implications (II) – Global fit of the Standard Model

Running of the Higgs self coupling:

$$32\pi^2 \frac{\partial \lambda}{\partial \mu} = 24\lambda^2 - 6y_t^4 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4$$

With the discovery of the Higgs, for the first time in our history, we have a self-consistent theory that can be extrapolated to exponentially higher energies.



Here as well, knowing the Higgs boson mass is very important, but knowing it precisely has small impact, the measurement and precision of the top mass is more important!

Exercise

Running of the Quartic Coupling - Exercise

Exercise

1.- Solve the RGE of the quartic coupling in the limit of low Higgs boson mass (dominated by corrections from the top quark), derive a vacuum stability limit as a function of the mass of the Higgs boson.

2.- Solve the RGE of the quartic coupling in the limit of high Higgs boson mass (dominated by corrections from the Higgs), given the measured mass of the Higgs boson at what energy scale does a Landau pole appear?

Further Reading

Combination Procedure and Master Formula

What is done in Higgs boson couplings analyses is to count number of signal events in specific production and decay channels.

$$n_s^c = \mu \sum_{i \subset \{\text{prod}\}} \sum_{f \subset \{\text{decay}\}} \mu^i \sigma_{SM}^i \times \mu^f Br^f \times \mathcal{A}^{ifc} \times \varepsilon^{ifs} \times \mathcal{L}$$

Same formula as the total cross section measurement formula

These « mu » or signal strength factors cannot be fitted simultaneously, typical fit models include:

μ	$\mu_{if} = \mu_i \mu_f$	$\mu_i \; (\mu_f = 1)$	$\mu_f \; (\mu_i = 1)$
Extrapolated total cross section	Cross section times branching	Cross sections	Branching fractions

Manifest in this formula why absolute couplings cannot be measured with this procedure: μ_i, μ_f cannot be fitted simultaneously.

For a complete description see (link) - Chapter 10

Combination Procedure and Master Formula

These measurement correspond to cross sections times branching fractions

$$\mu \ (\text{fit}) \quad \mu_i = 1 \quad \mu_f = 1$$

$$\begin{aligned} \mu = 1.09 \quad & \pm 0.11 \\ & (\pm 0.07\,(Stat) \\ & \pm 0.04\,(Exp) \\ & \pm 0.03\,(Th.\,bkg) \\ & \pm 0.07\,(Th.\,sig)\,) \end{aligned}$$

Signal strength illustrates the agreement of measurements with the SM and the importance of the TH input.

At Run 2 TH uncertainties have evolved already and improved significantly.

A quick word on the kappa formalism

Introducing simple scale factors of the Standard Model couplings in a « naive » effective Lagrangian (assumes that the tensor structure of is that of the SM).

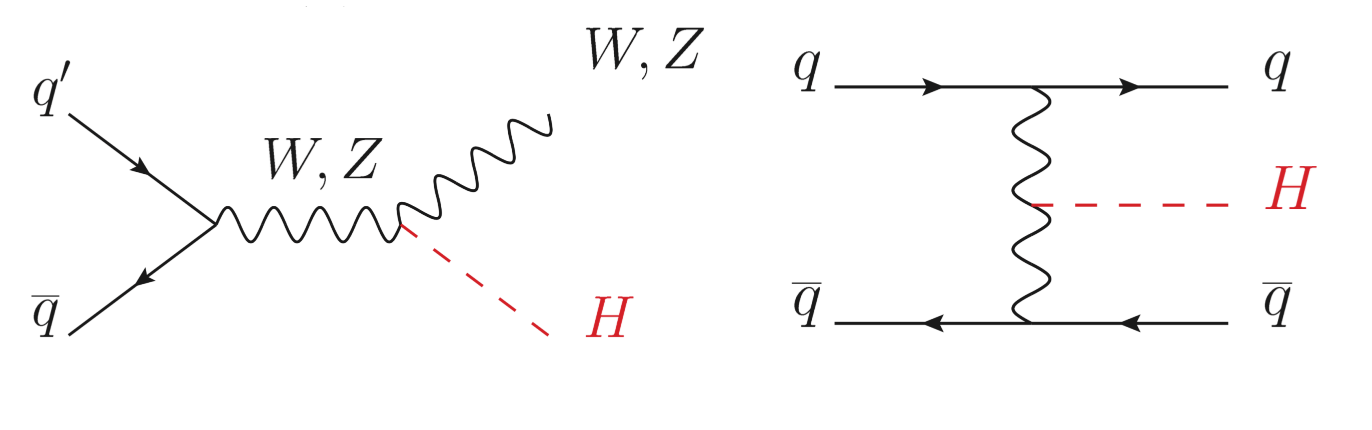
$$\mathcal{L} \supset \kappa_Z \frac{\mathrm{m}_\mathrm{Z}^2}{v} Z_\mu Z^\mu + \kappa_W \frac{\mathrm{m}_\mathrm{W}^2}{v} W_\mu W^\mu + \kappa_\gamma \frac{\alpha}{2\pi v} A_{\mu\nu} A^{\mu\nu} + \sum_f \kappa_f \frac{\mathrm{m}_f}{v} f \bar{f}$$

Not gauge invariant and partial but very useful to illustrate coupling measurement concepts.

More complete EFT and rigorous framework will be discussed later…

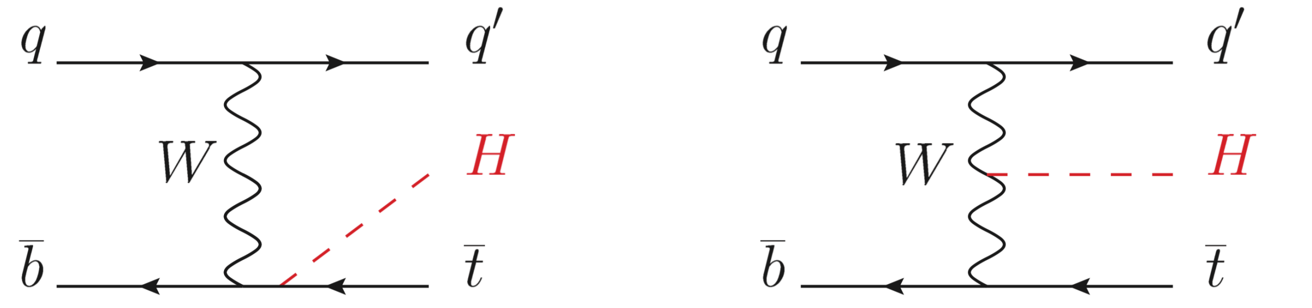
The Kappa Formalism

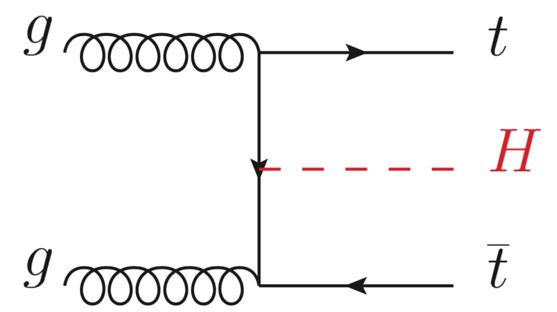
Then parametrise the production and decays at tree level



$\propto \kappa_V^2$

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

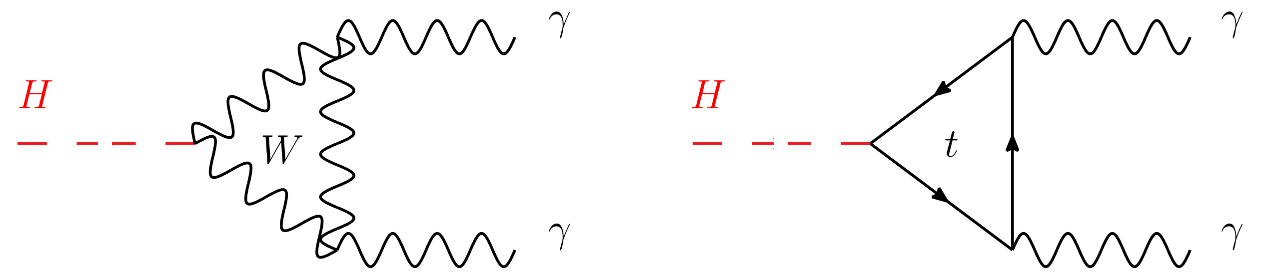




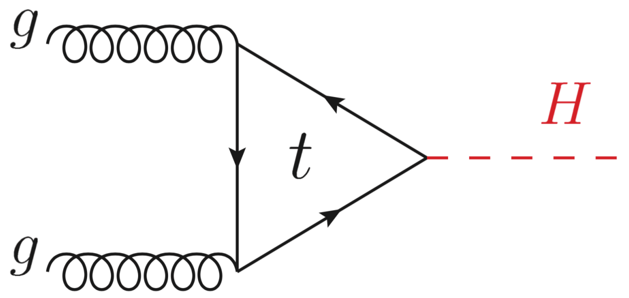
$\propto \kappa_t^2$

… and in loops (as a function of the know SM field content)

$\propto 1.6 \times \kappa_W^2 - 0.7\kappa_W\kappa_t + 0.1\kappa_t^2$



$\propto 1.06 \times \kappa_t^2 - 0.07\kappa_t\kappa_b + 0.01\kappa_b^2$



In order to measure the coupling modifiers (kappas) the signal strengths are re-parametrised as follows:

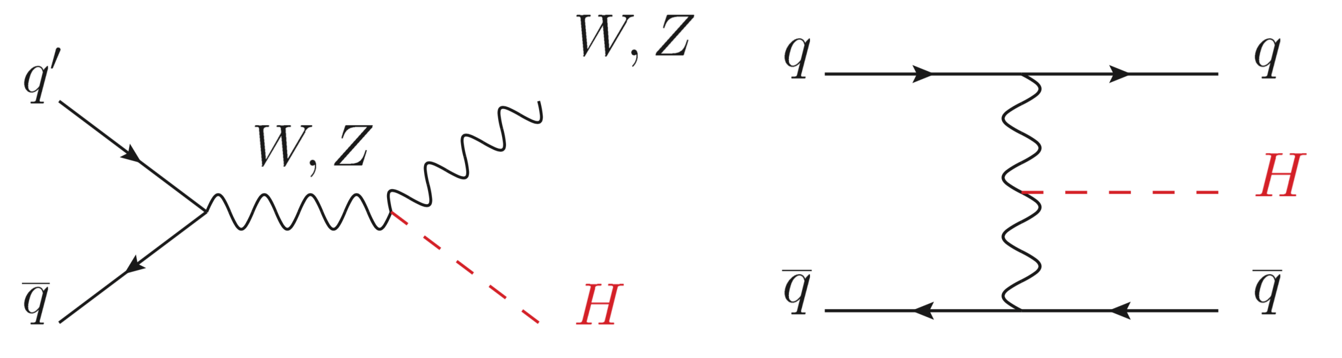
$$\mu_i = \frac{\sigma_i}{\sigma_i^{SM}}$$

$$\mu_f = \frac{\Gamma_f}{\Gamma_H} \quad \text{so} \quad \mu_f = \frac{\kappa_f^2}{\kappa_H^2} \quad \text{where} \quad \kappa_H^2 = \frac{\sum_f \Gamma_f}{\Gamma_H^{SM}}$$

κ_H can be parametrised as a function of other couplings assuming no new BSM decays of the Higgs

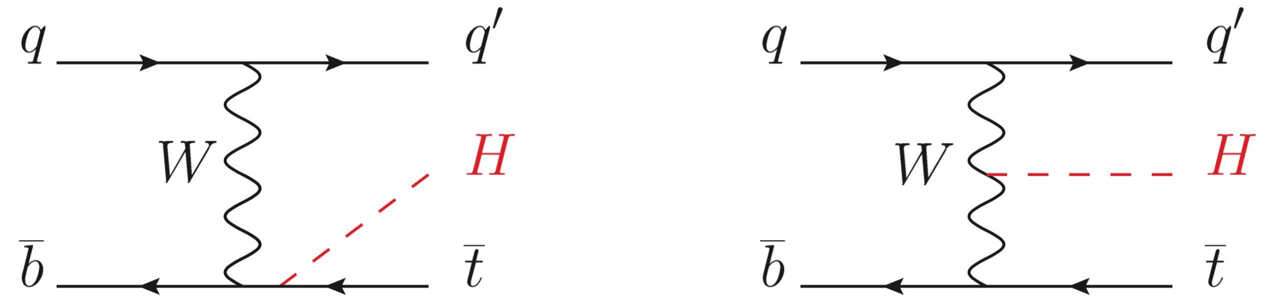
The Kappa Formalism

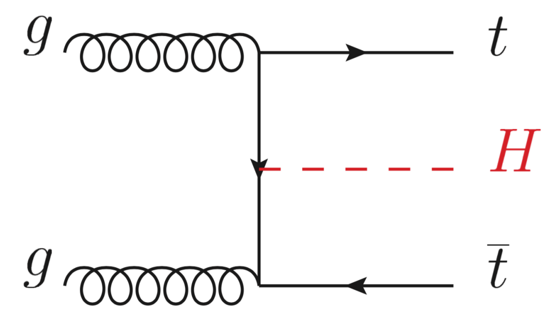
Then parametrise the production and decays at tree level



$\propto \kappa_V^2$

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





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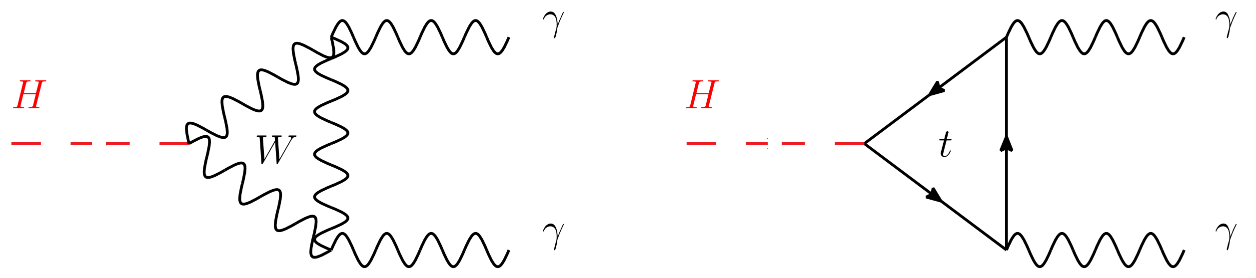
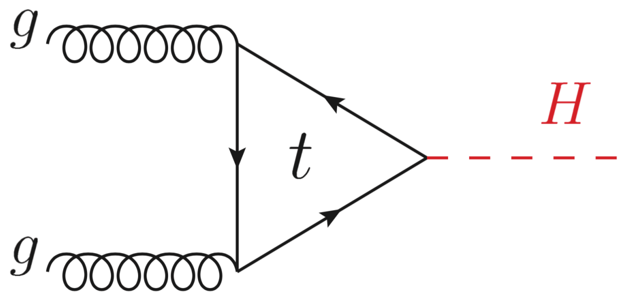


$\propto 1.06 \times \kappa_t^2 - 0.07 \kappa_t \kappa_b + 0.01 \kappa_b^2$



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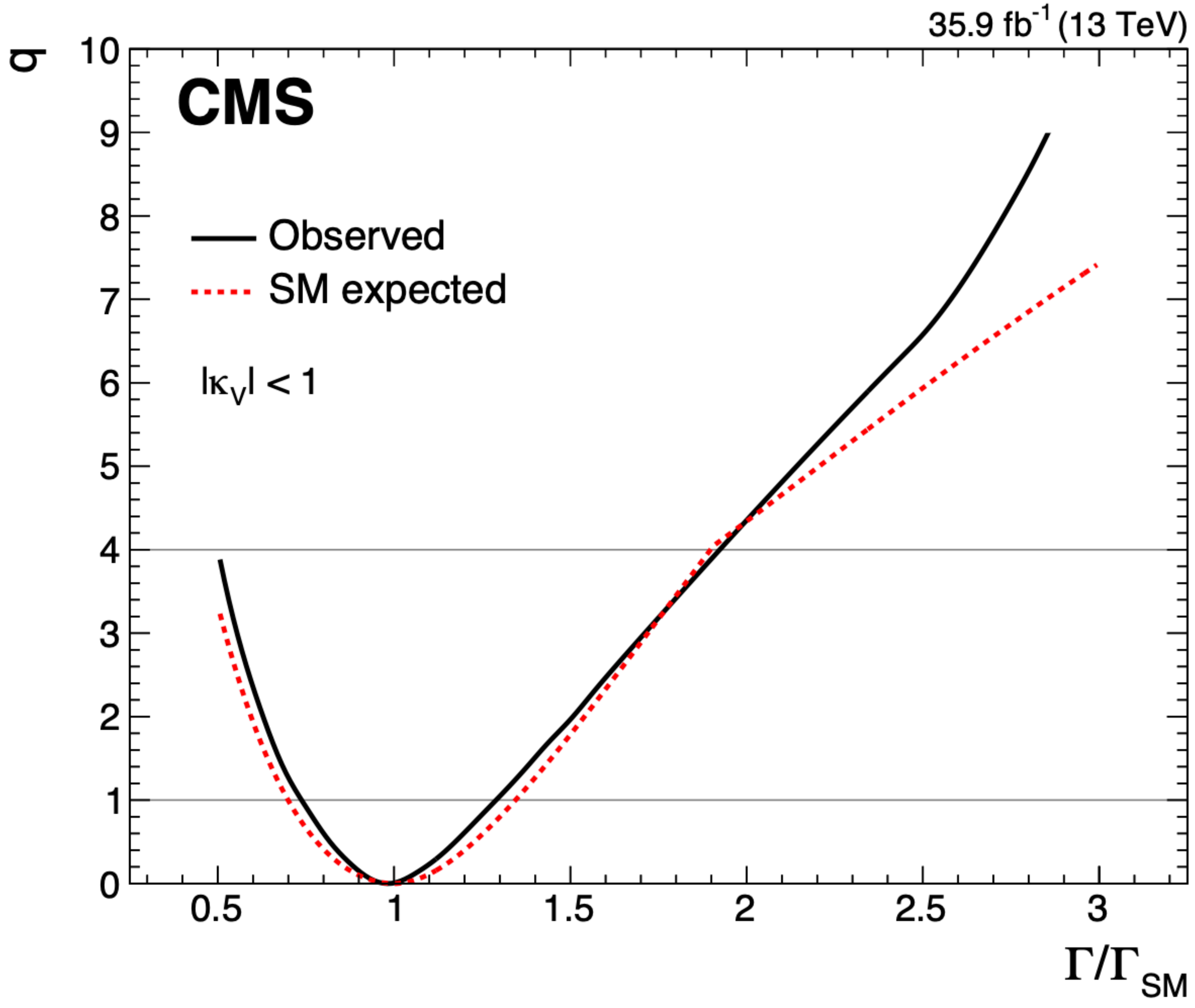
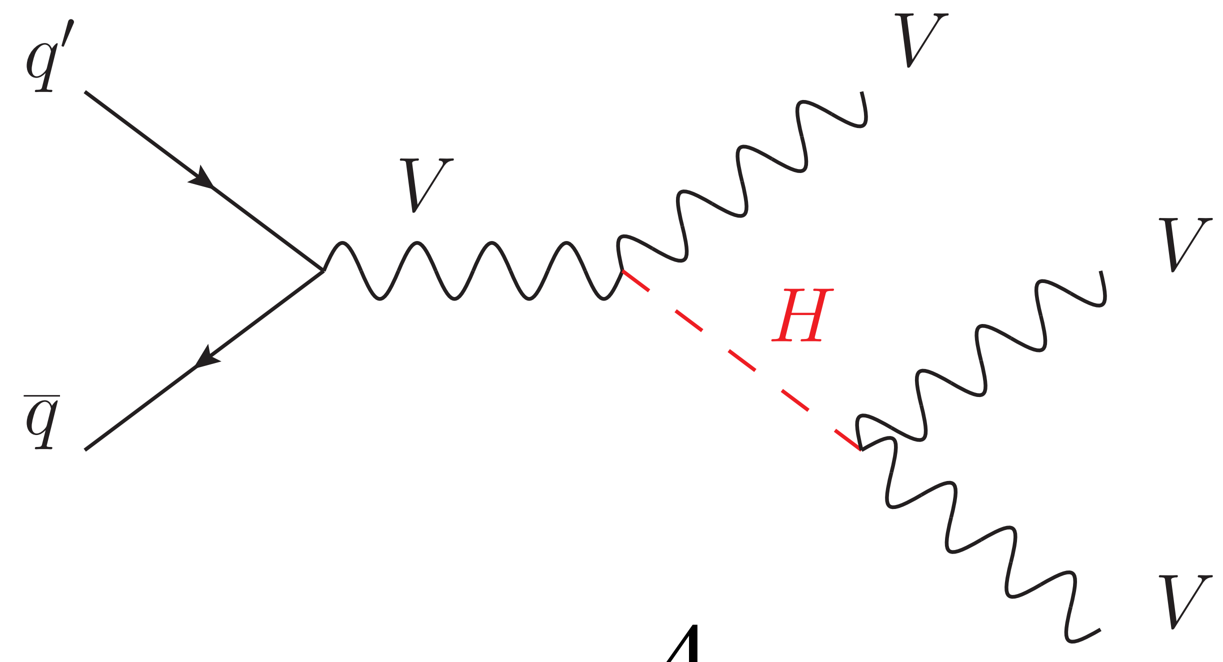
$$\kappa_H^2 \sim 0.57\kappa_b^2 + 0.22\kappa_W^2 + 0.09\kappa_g^2 + 0.06\kappa_\tau^2 + 0.03\kappa_Z^2 + 0.03\kappa_c^2 + 0.0023\kappa_\gamma^2 + 0.0016\kappa_{Z\gamma}^2 + 0.00022\kappa_\mu^2$$

Why is kV < 1 sufficient to constrain the Higgs width?





$$\mu \propto \frac{\kappa_V^4}{\kappa_H^2}$$

A measurement of μ implies that $\mu \in [\mu_{min}, \mu_{max}]$ imposing $\kappa_V < 1$

$$\mu > \mu_{min} \Rightarrow \frac{\kappa_V^4}{\kappa_H^2} > \mu_{min} \Rightarrow \kappa_H^2 < 1/\mu_{min}$$

Lower limit is more intuitive as $\kappa_H \to 0$ would require all other couplings to be very large to get SM rates (impossible with the different dependencies of couplings)!

Comments on Yukawa Couplings

The running of the top Yukawa coupling

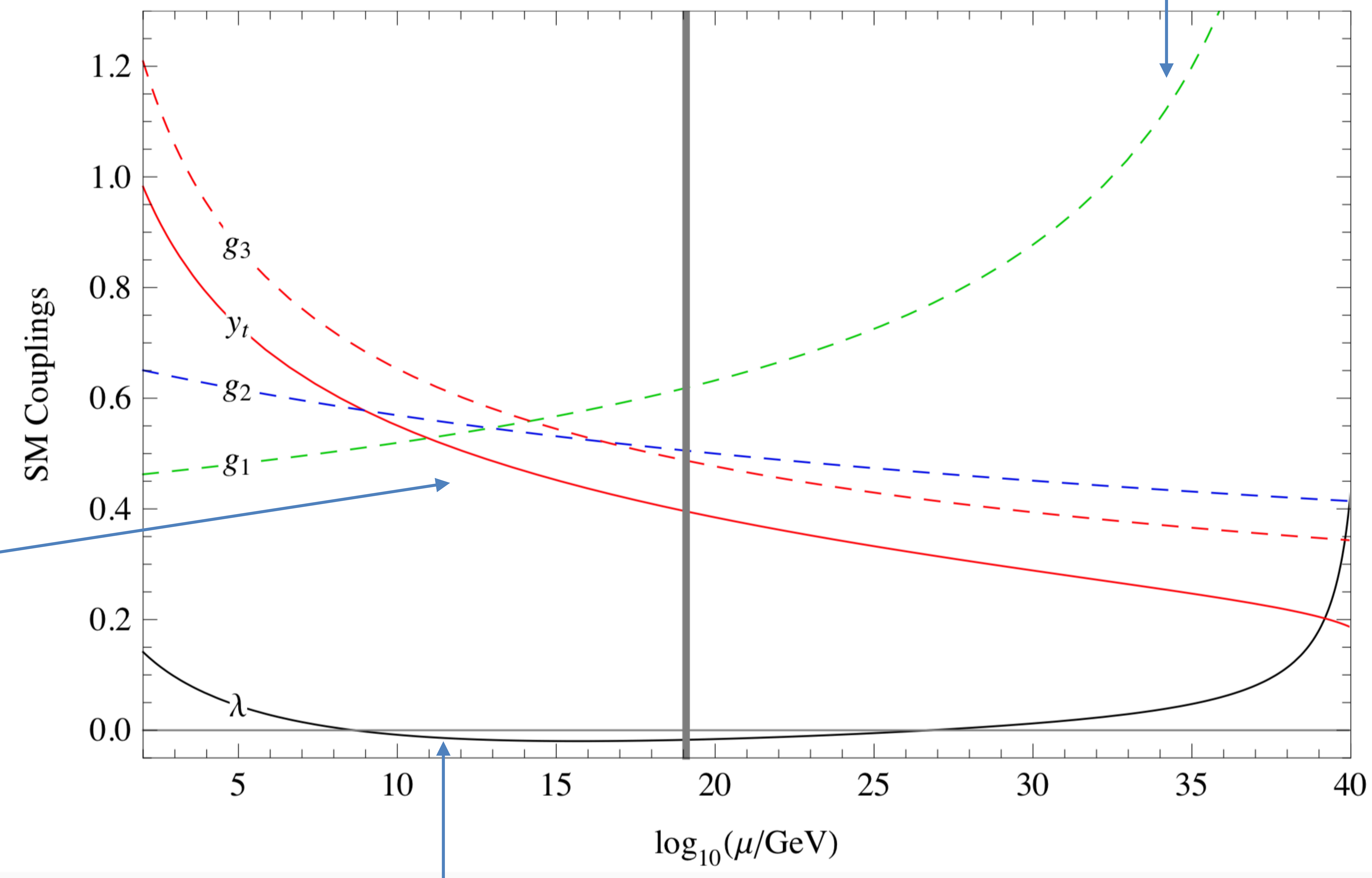
The Yukawa coupling is ~1, but perturbative because it is still small compared to 4π (very similar to QCD*)

$$\mu \frac{\partial y_t}{\partial \mu} \approx \frac{y_t}{16\pi^2}\left(\frac{9}{2}y_t^2 - 8g_3\right)$$

Two very important aspects in this RGE simple equation:

- With the observed top mass (and all the terms entering the RGE, including the Higgs quartic) the top mass smoothly decreases with energy.
- If the Yukawa is small w.r.t. strong coupling (and in general) at the high scale, it will stay small.
- If the Yukawa is large in the high scale, then there is a fixed point (which yields a top mass slightly larger than the observed mass ~230 GeV).

Landau Pole



Running of the quartic coupling will be discussed today!

$$^*\left(\alpha_S \equiv \frac{g_3^2}{4\pi}\right)$$