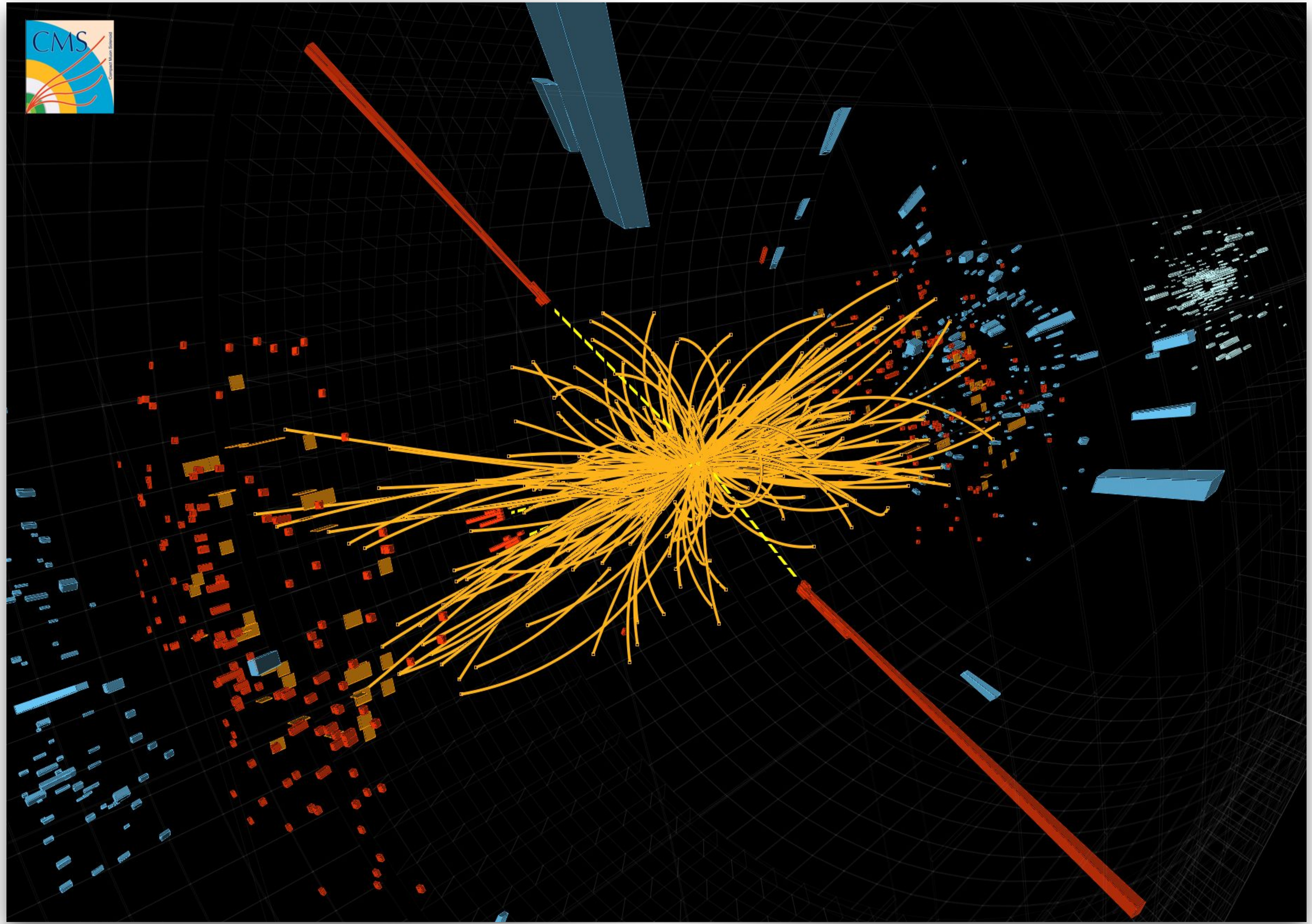
Experimental Physics at Hadron Collider



Lecture 3

The Discovery of the Higgs boson and Higgs physics

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Sapienza, Roma and LAL, Orsay

CERN Summer Students Lectures

July 22-25, 2019

CMS diphoton 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

Preamble on Yukawa Couplings

The running of the top Yukawa coupling

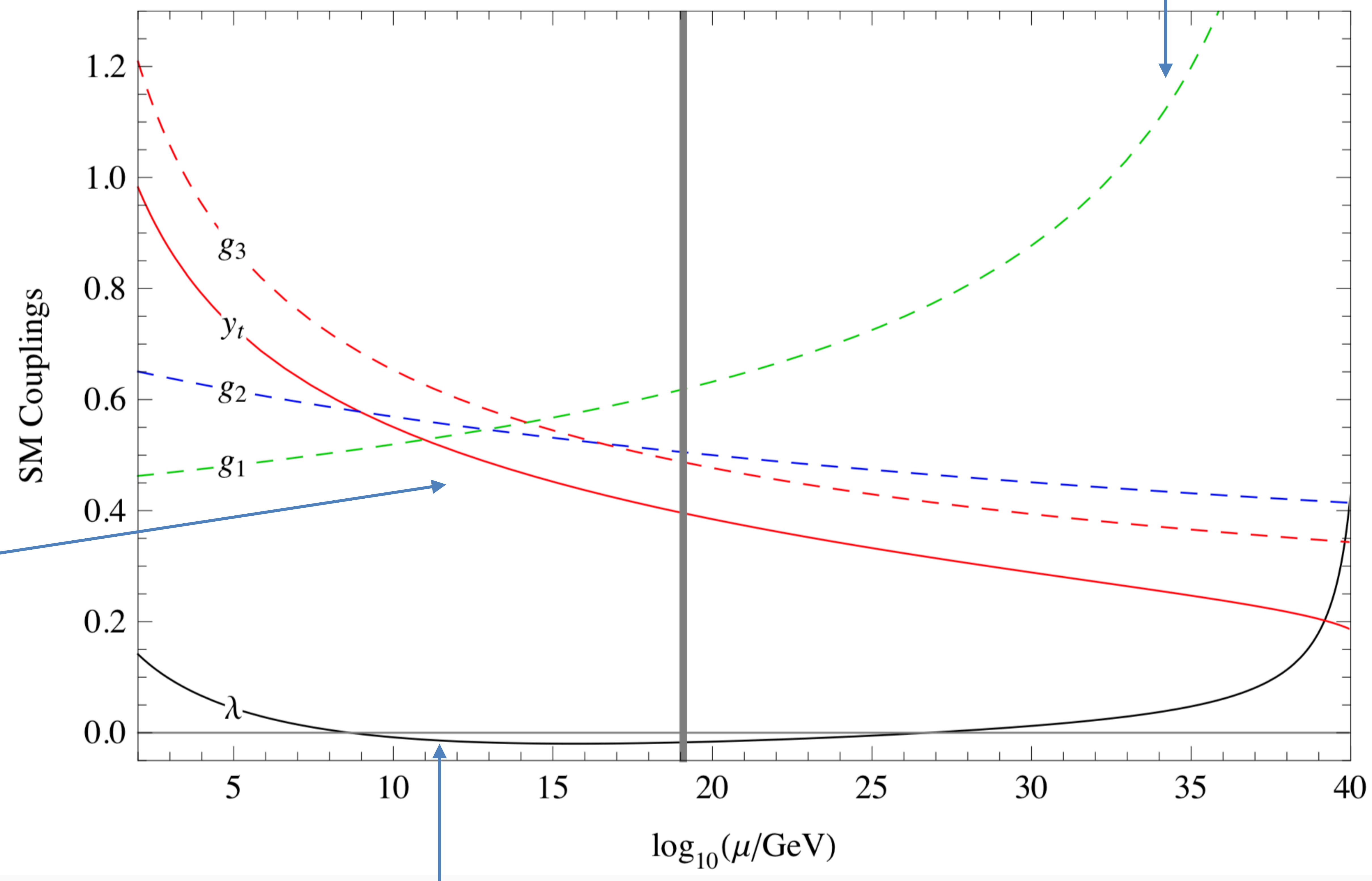
The Yukawa coupling is ~1, but perturbative because it is still small compared to 4π (very similar to QCD*)

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

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!

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

The Standard Model (again)

The less elegant Higgs sector:

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

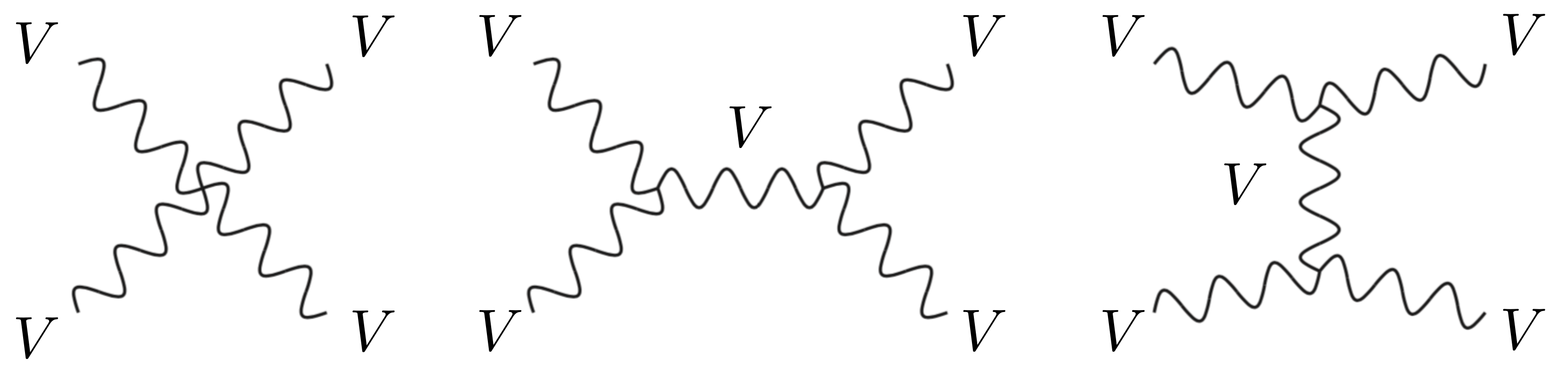
$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

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)**:

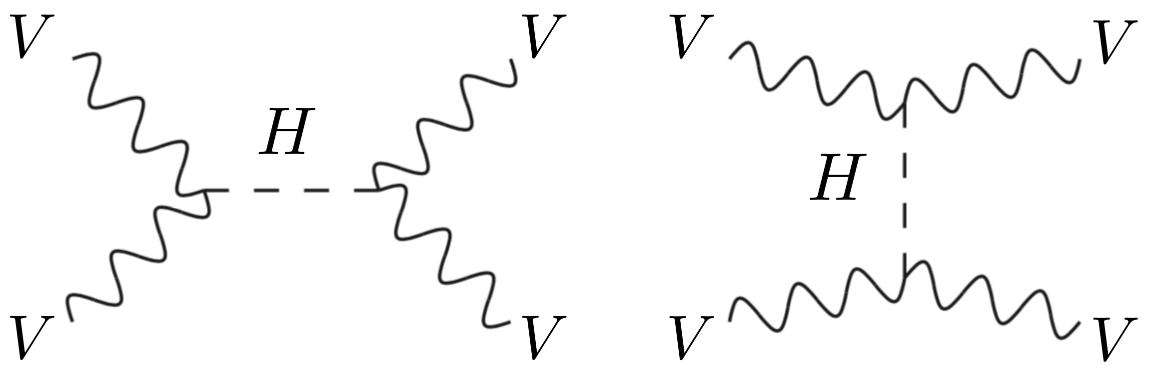


Contact Interaction

s-channel

t-channel

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



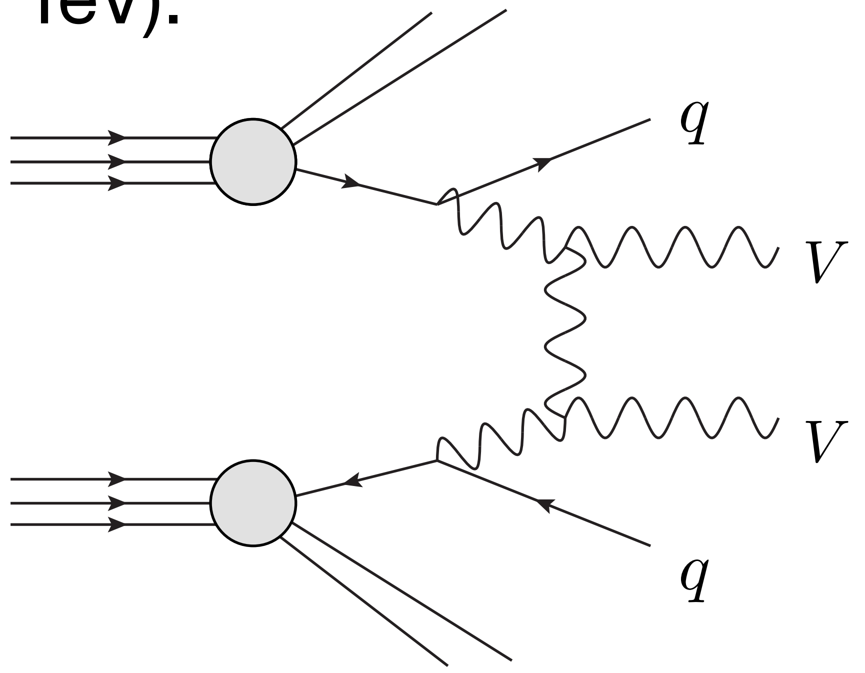
Higgs s-channel

Higgs t-channel

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

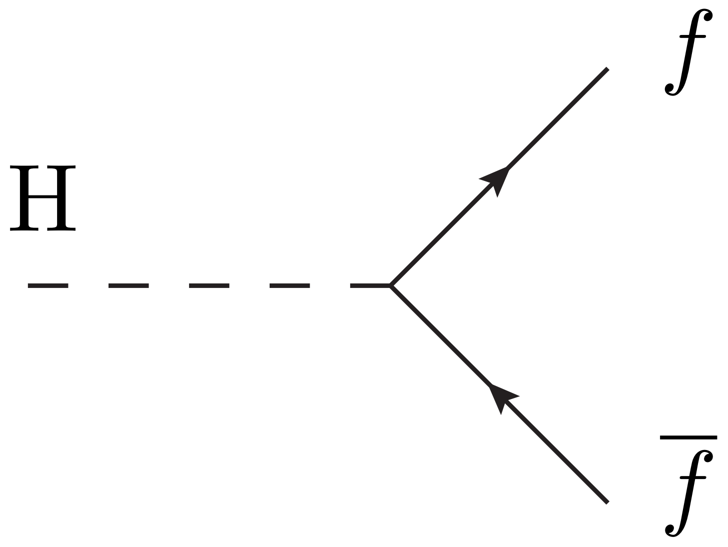
The preservation of the perturbative unitarity of the WW scattering, imposes an upper limit on the Higgs boson of ~O(1 TeV).

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).

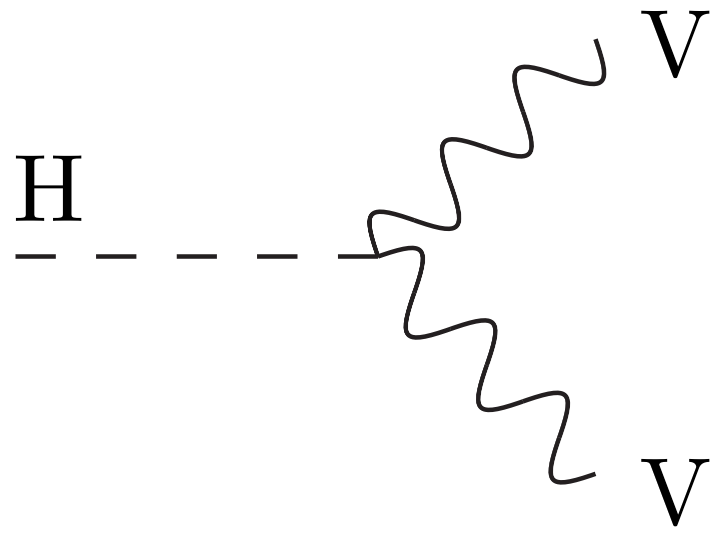


Higgs boson couplings (within the Standard Model)

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

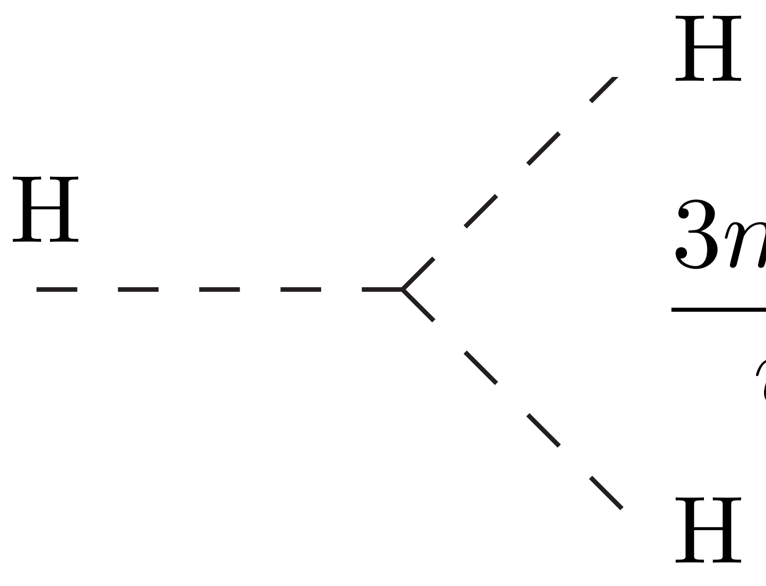


$$\frac{m_f}{v} \qquad + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

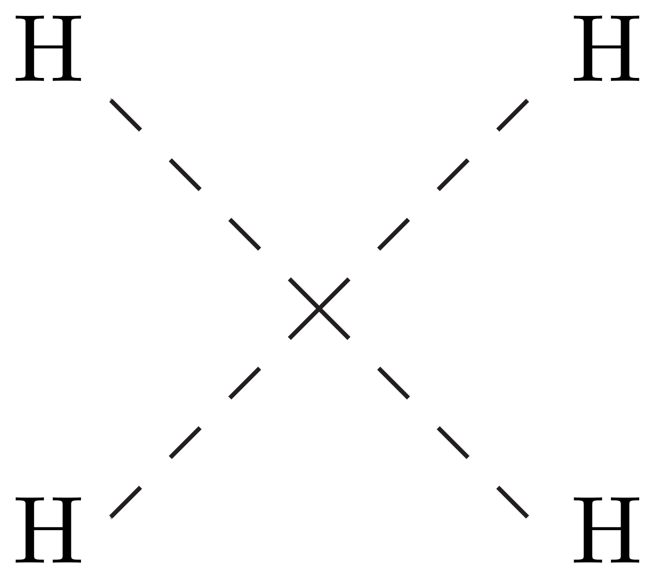


$$\frac{2m_V^2}{v} \qquad + |D_\mu \phi|^2$$

This term could not exist without a vev



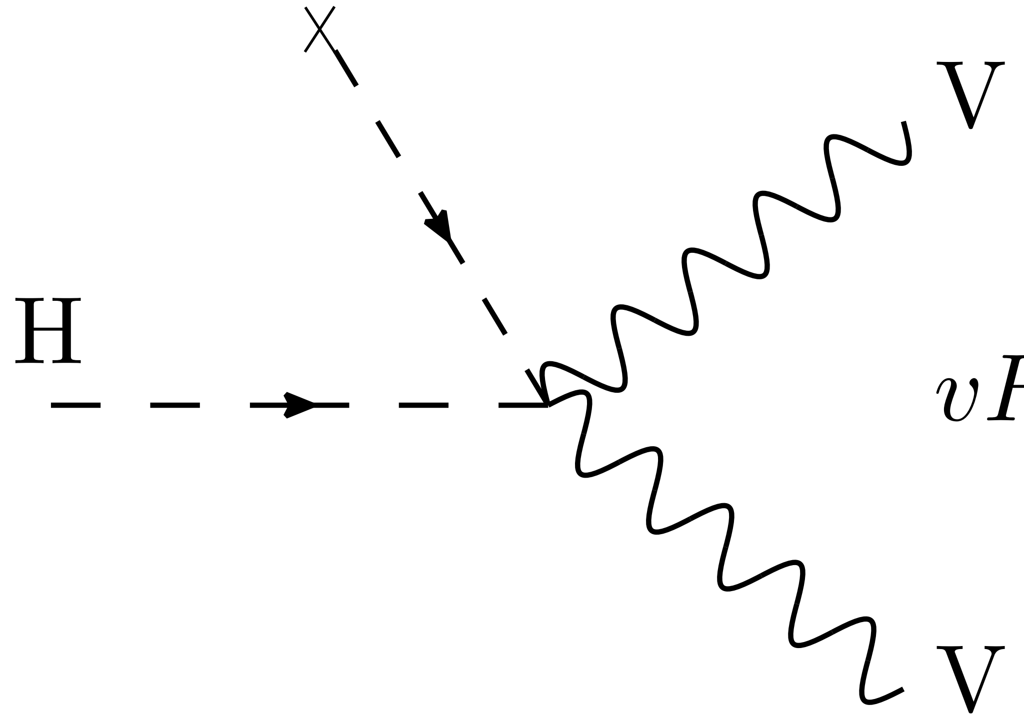
$$\frac{3m_H^2}{v}$$



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

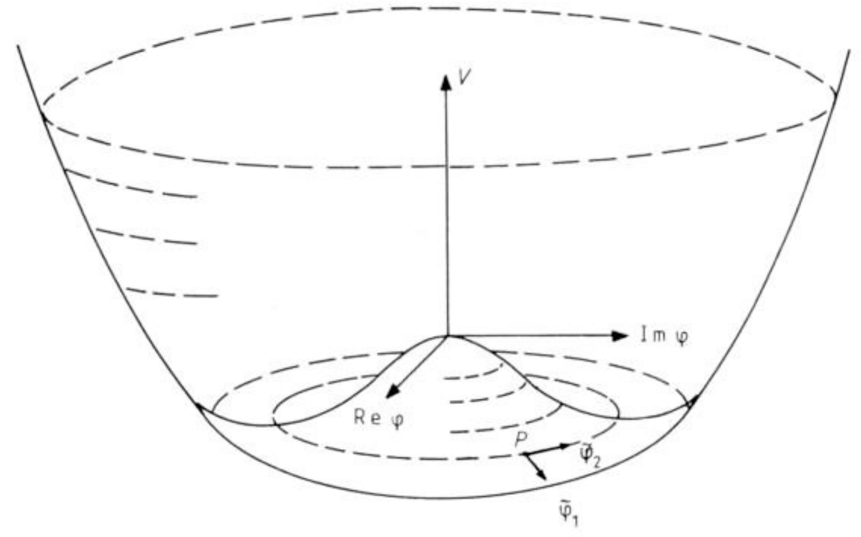
Is the Higgs boson responsible for the EW symmetry breaking also responsible for the masses of fermions?

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



$$vHV^\mu V_\mu$$

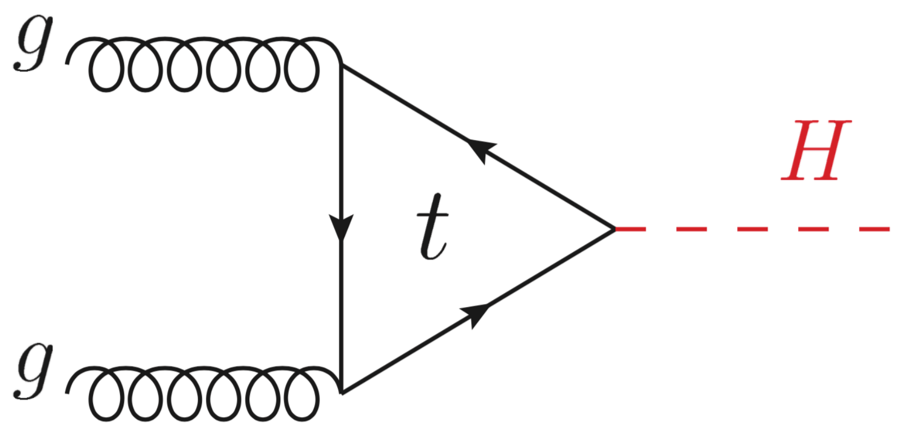
Proof of condensate !



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

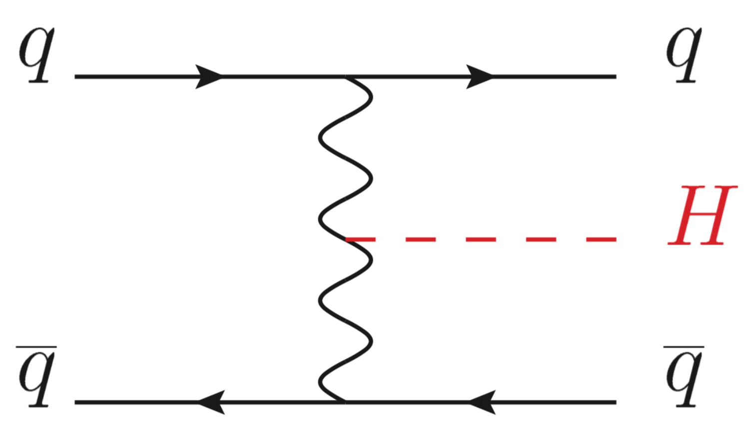
Higgs boson (main) Production Modes

Production rates at Run 2 for ~150 fb^{-1}



Gluon fusion process

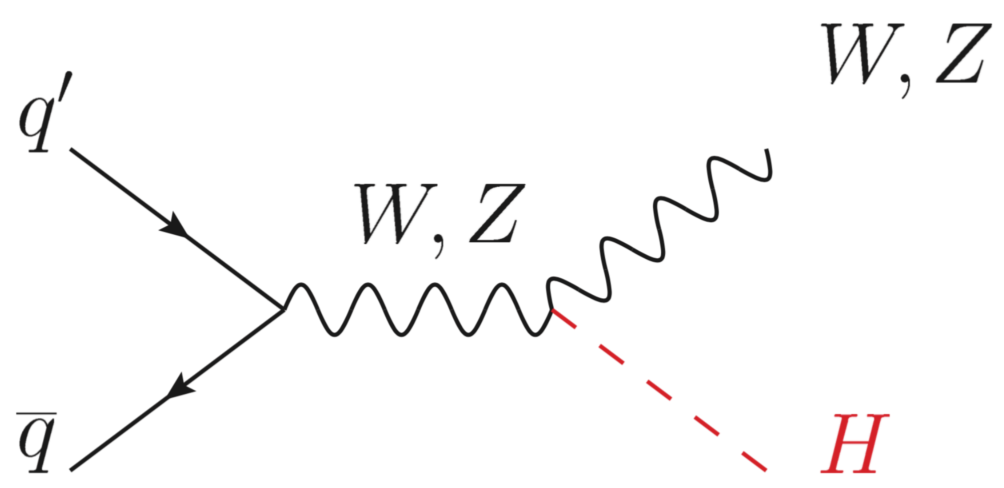
~8 M events produced



Vector Boson Fusion

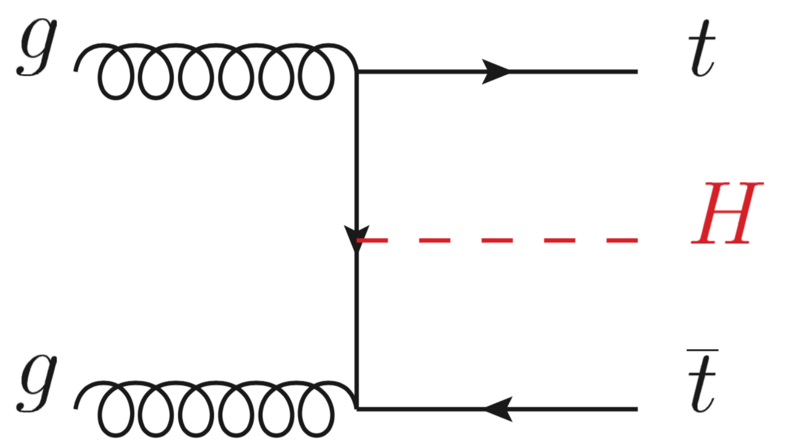
Two forward jets and a large rapidity gap

~600 k events produced



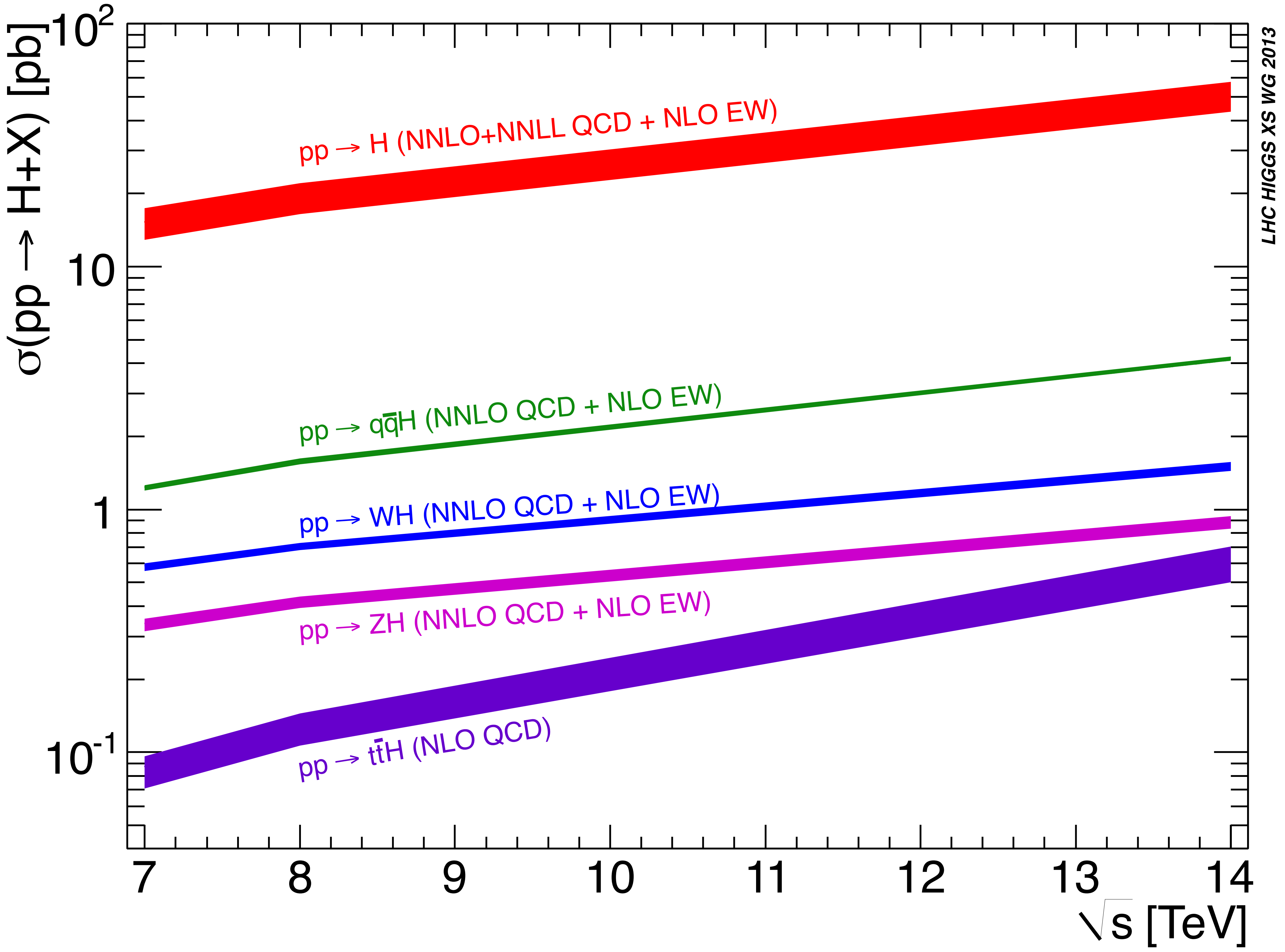
W and Z Associated Production

~400 k events produced



Top Assoc. Prod.

~80 k evts produced

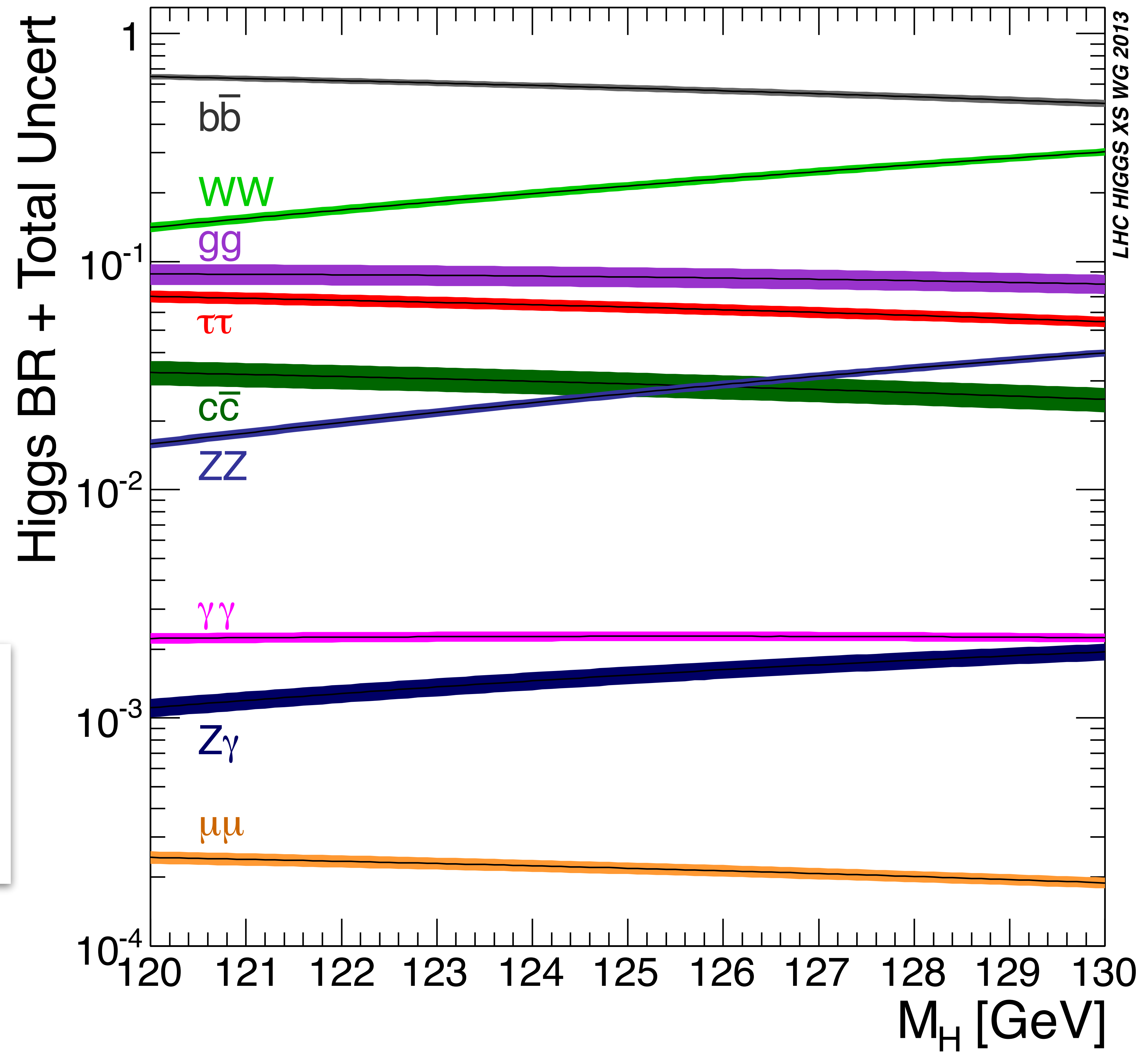


Cross section dependence on the centre-of-mass energy favours higher mass systems in the final state (i.e. the ttH production process)

The Gift of Nature

Higgs Decay Channels

Expected Standard Model Branching Fractions (for a mass of 125 GeV)



- Dominant: bb (57%)
- WW channel (22%)
- ττ channel (6.3%)
- ZZ channel (3%)
- cc channel (3%)
- The γγ channel (0.2%)
- The Zγ (0.2%)
- The μμ channel (0.02%)

SM width (small i.e. potentially large relative variations from BSM couplings)

$$\Gamma^H_{SM} = 4.07 \pm 0.16 \text{ MeV}$$

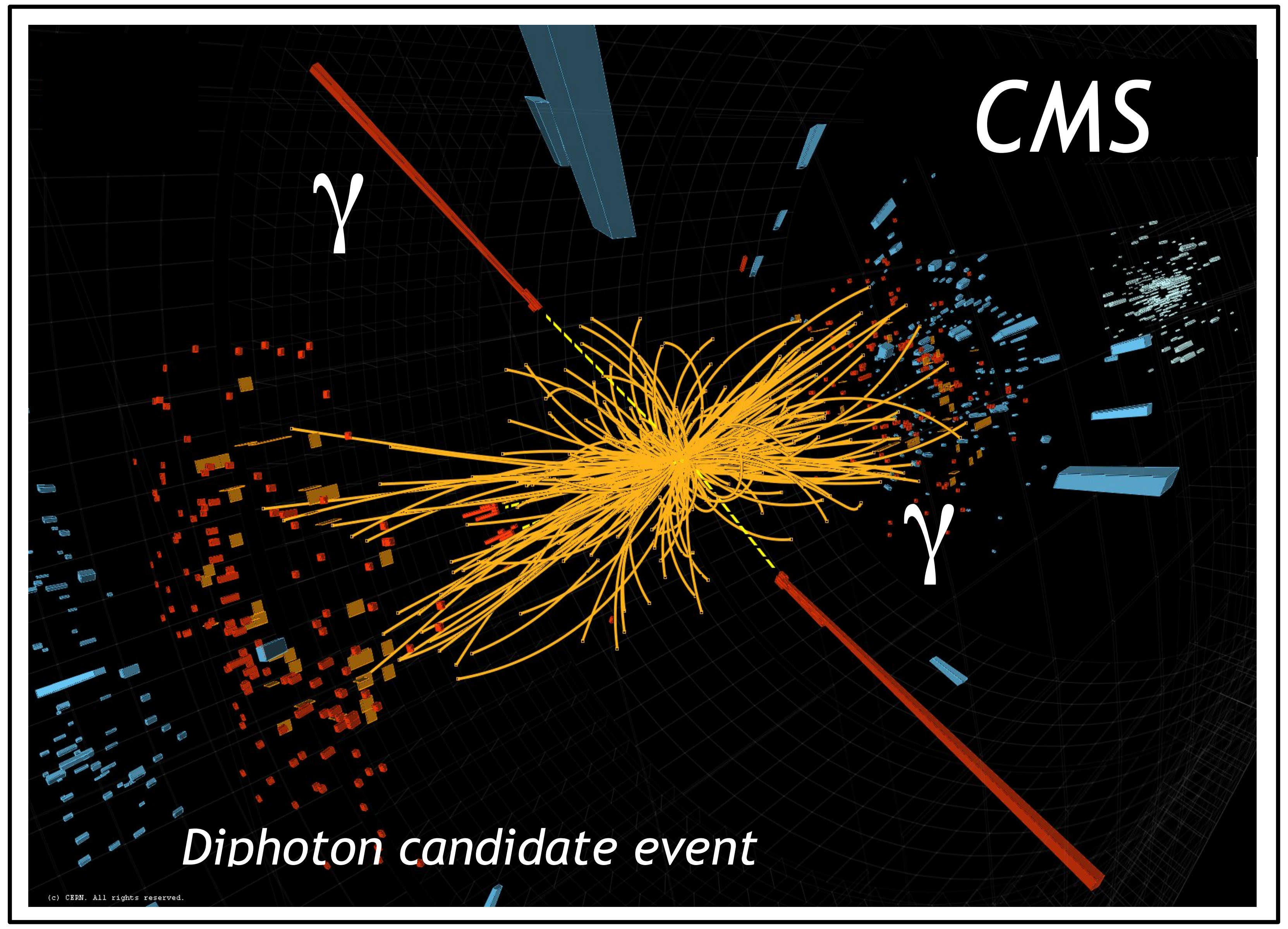
The Higgs mass is precisely at a value that approximately maximises the number of observable decay channels

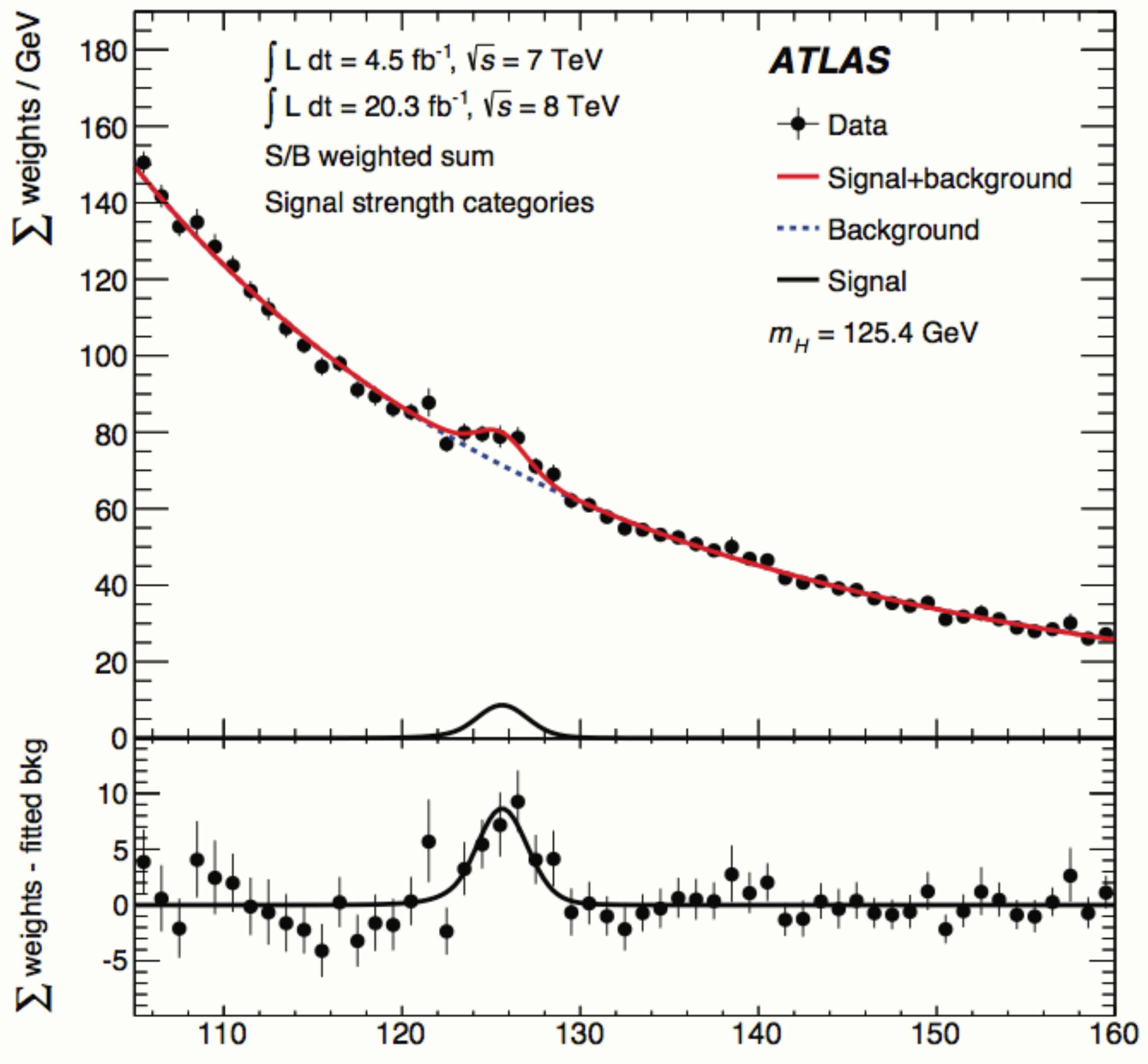
The Run 1 Landmark Result

The Discovery of the Higgs Boson

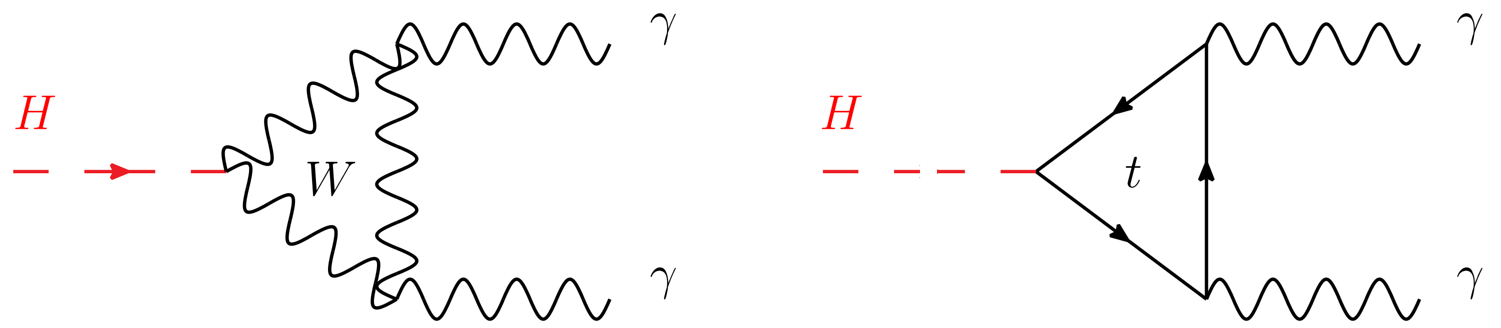
The Discovery Channels

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





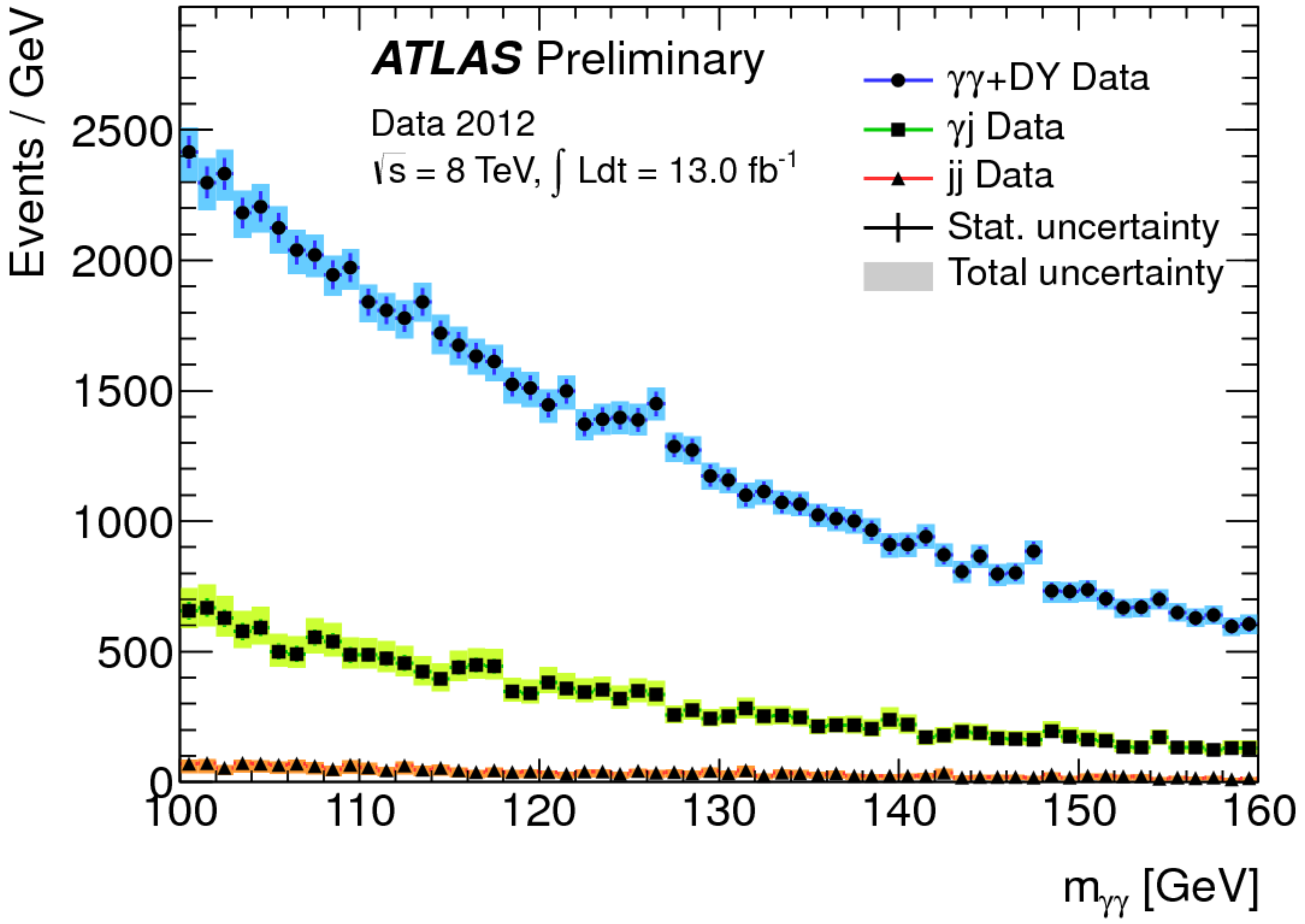
- Main production and decay processes occur through loops :

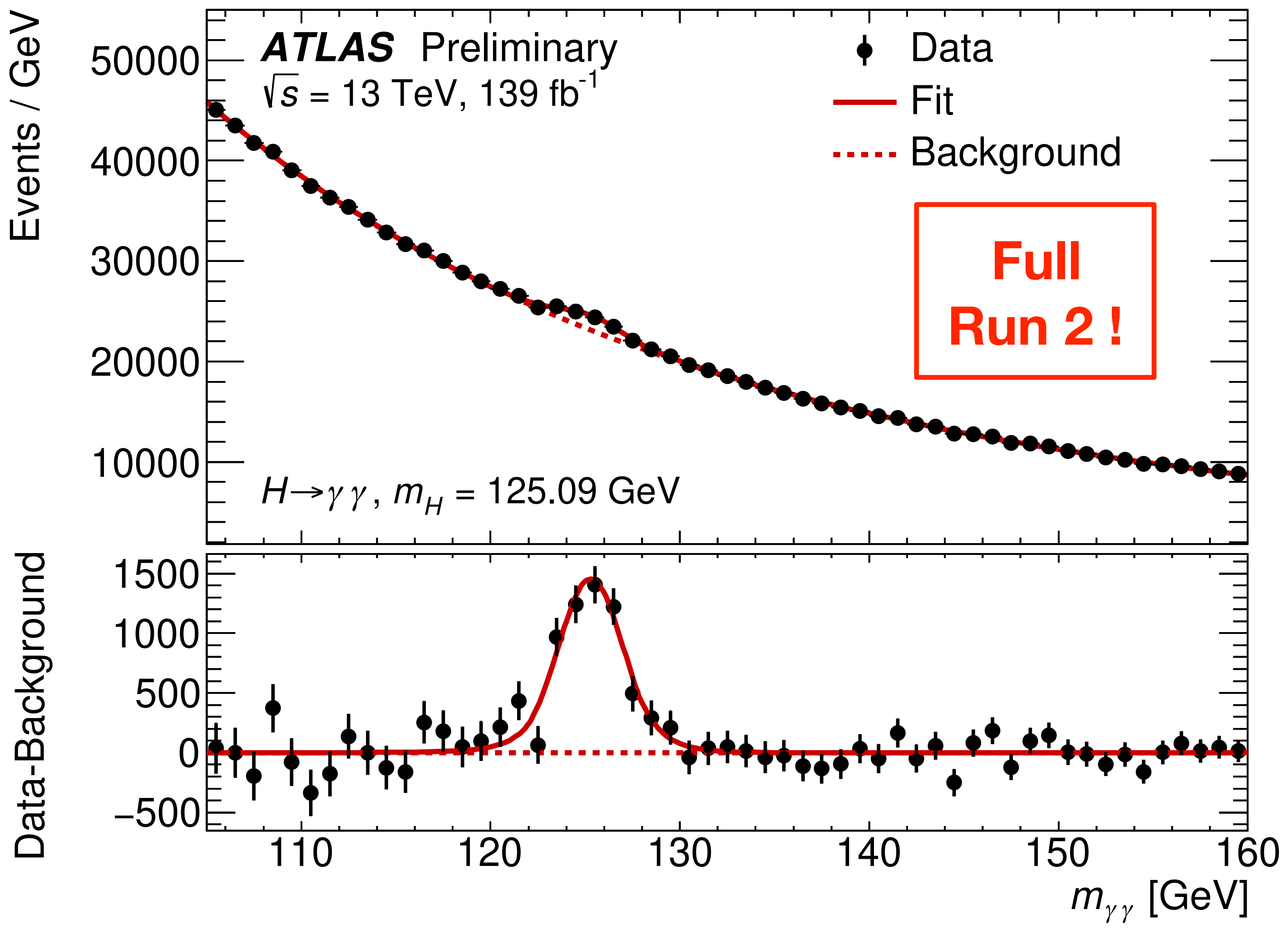


Excellent probe for new physics !

- 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

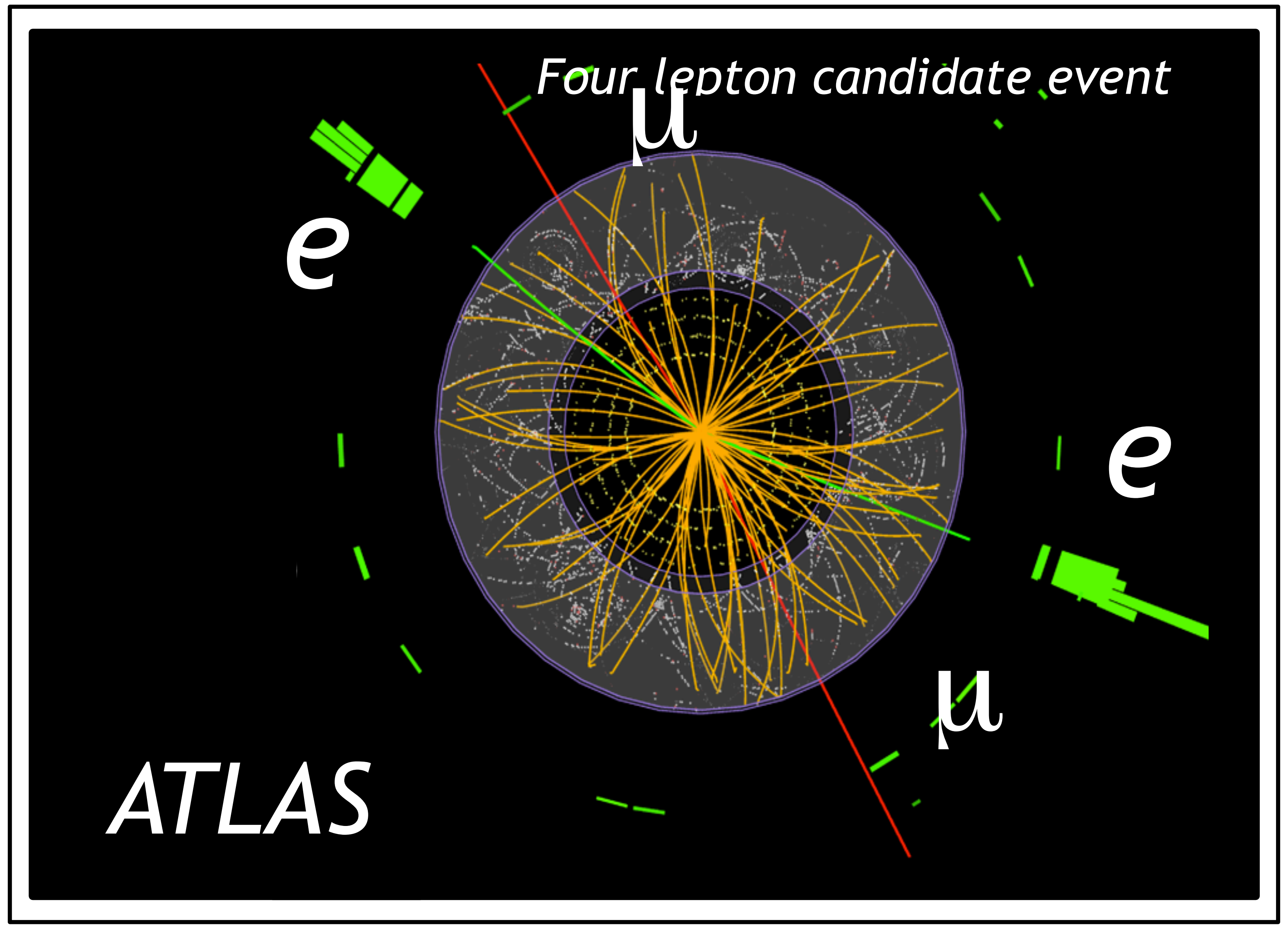
- Low signal over background but overall relatively high statistics of signal (O(300) at Run 1)
- Very simple selection cuts. The essence of the channel relies on the **quality of the detector response** and the **reconstruction**.
- Largest reducible background comes from jets! With another spin-0 particle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

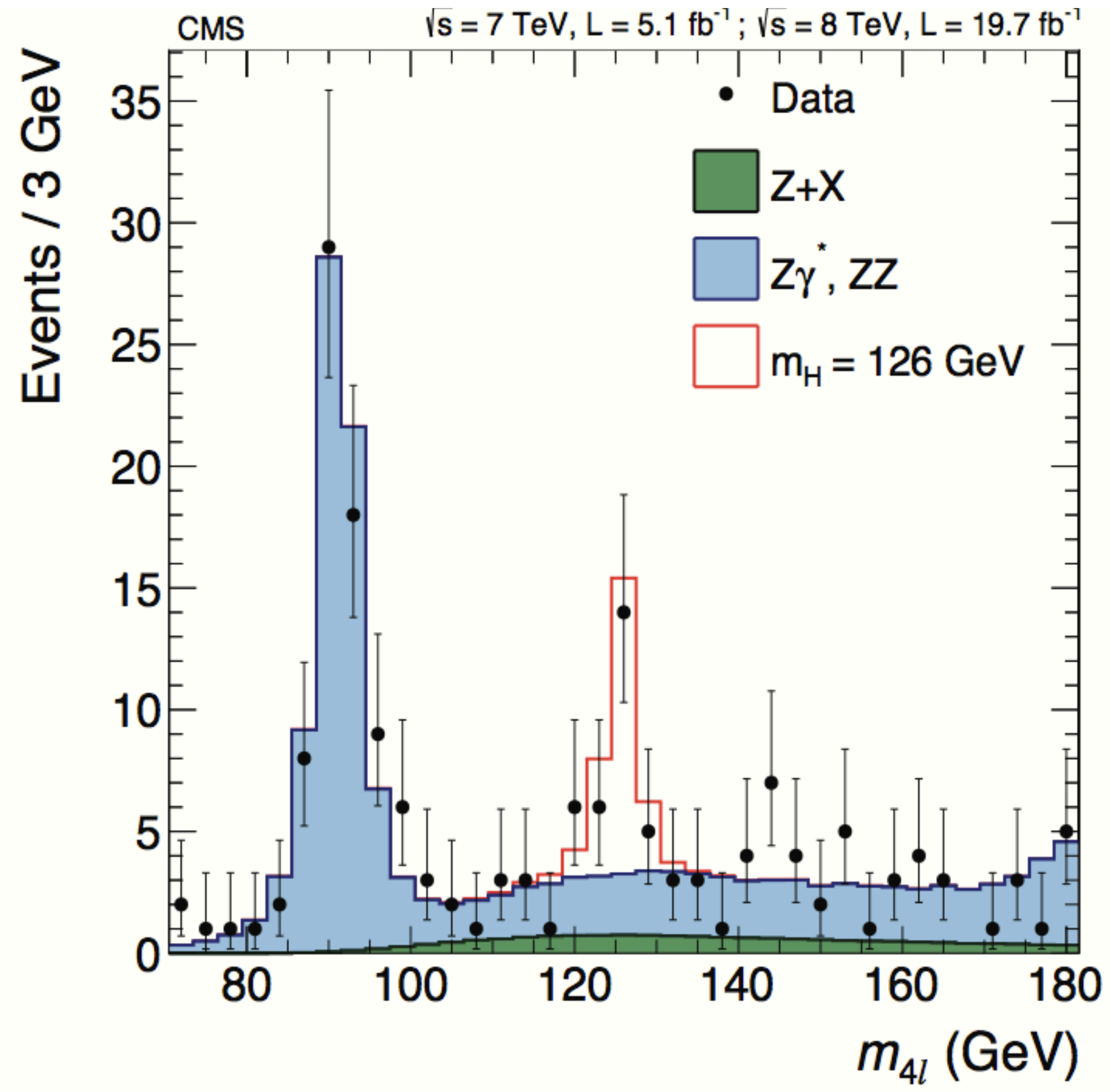




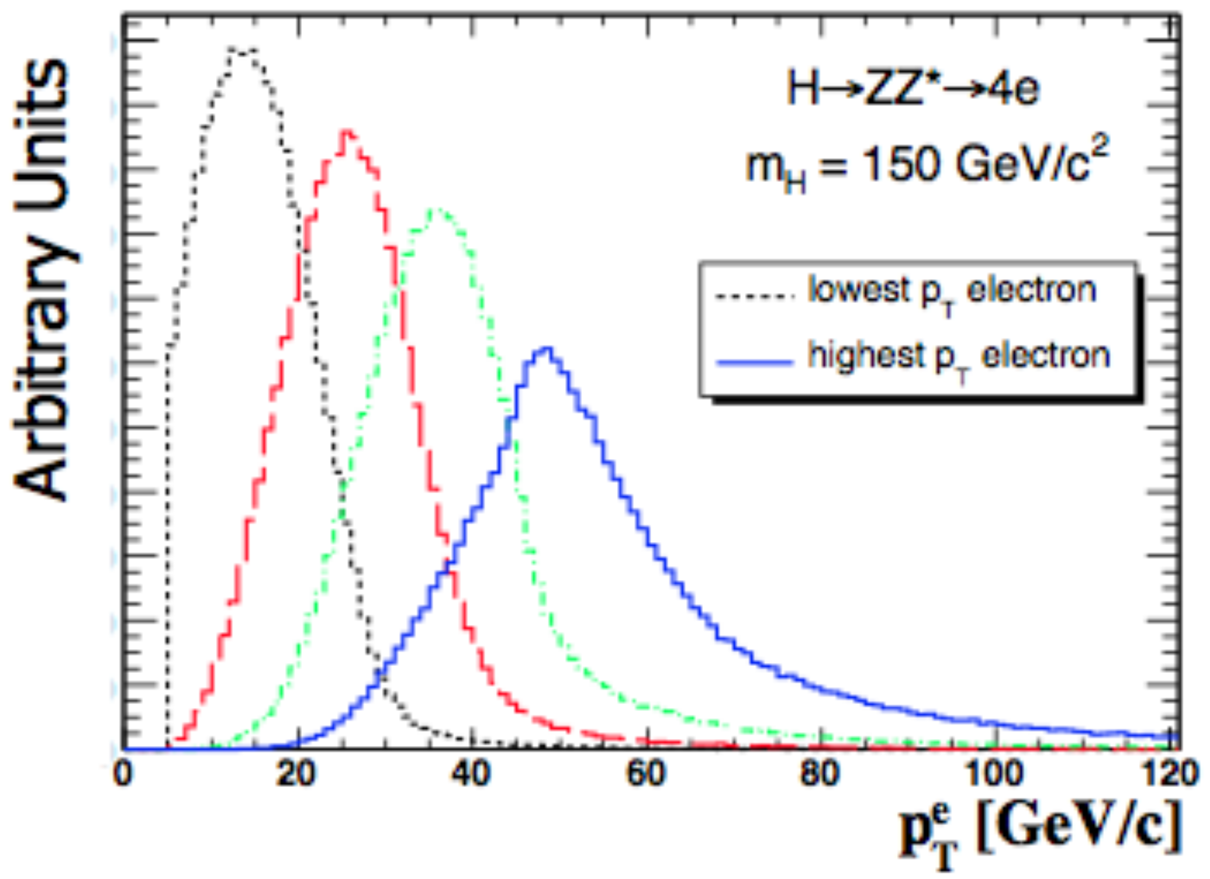
The Discovery Channels

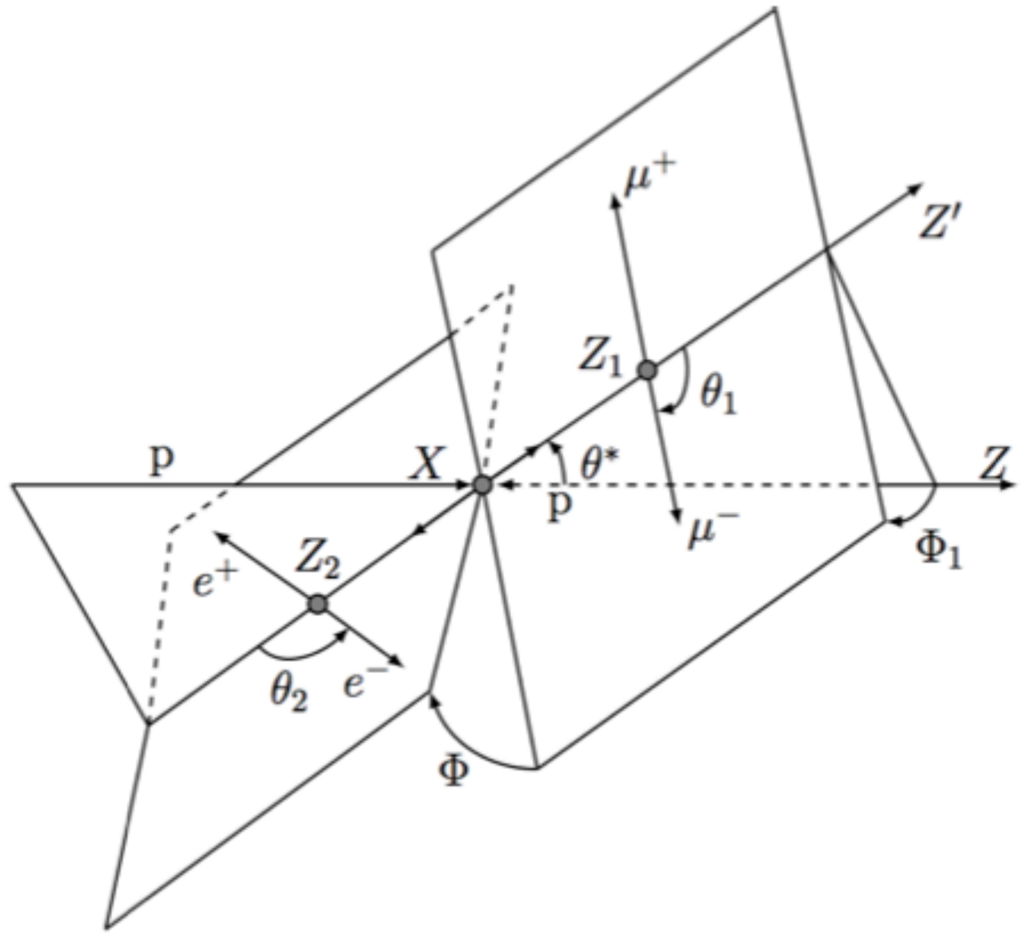
« Bread and Butter » Mass peak signals: the four leptons channel

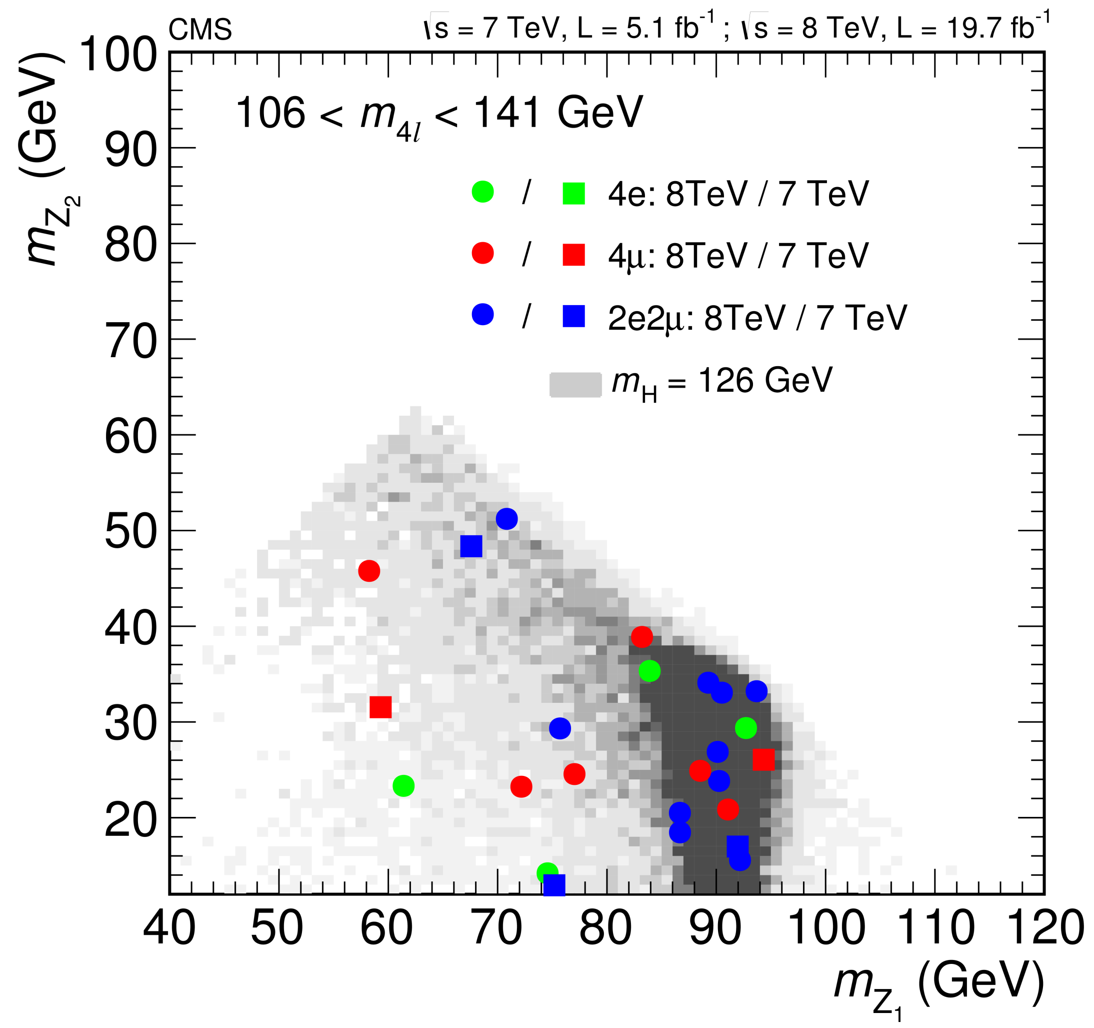


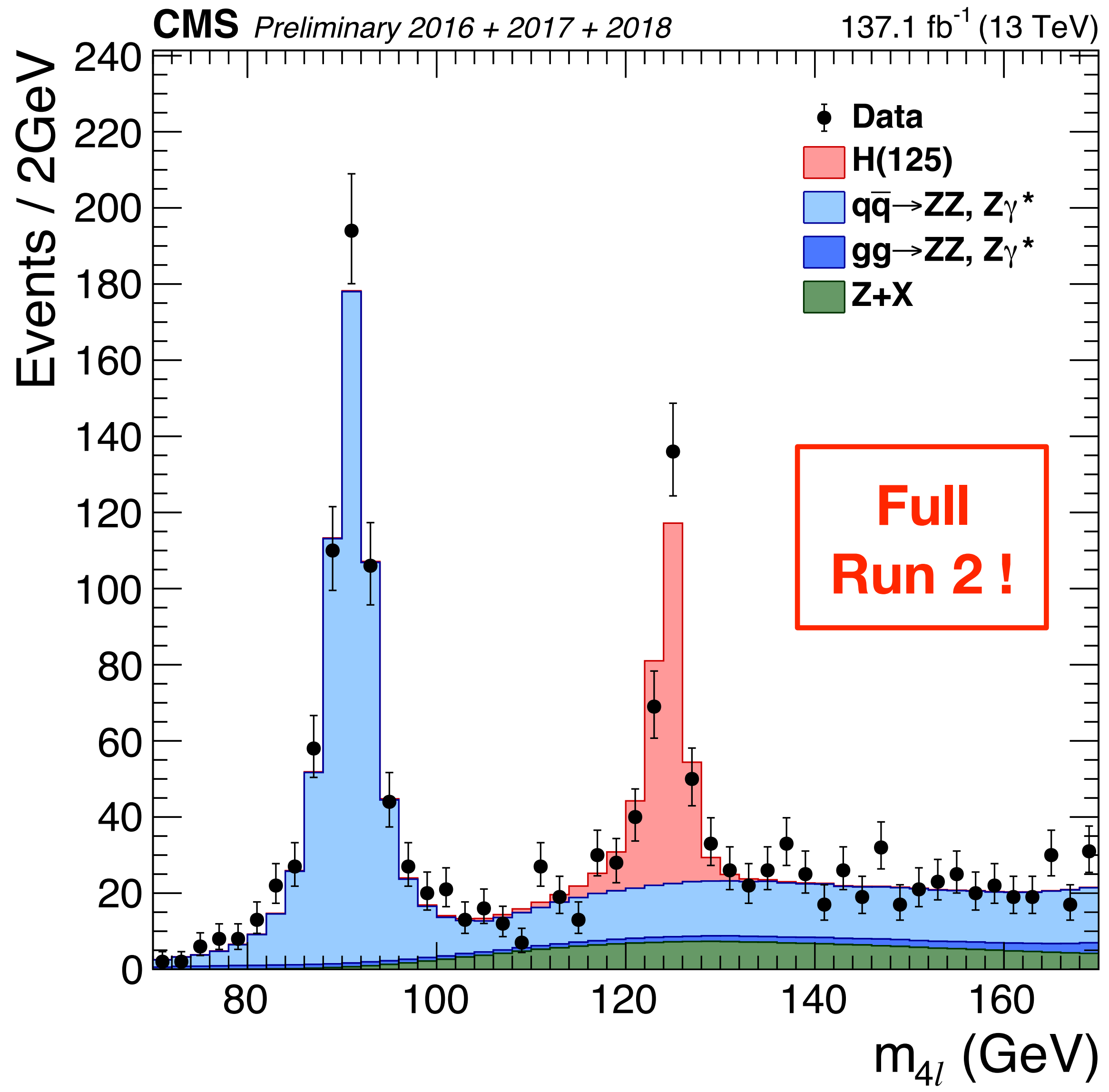


- Channel with High s/b ratio from approximately 2 up to more than 10!
- Backgrounds can be estimated from MC.
- Other important features:
  - Very low rate due to branchings of ZZ and Z to leptons! Efficiency is key!
  - The trailing lepton is at low pT.
  - The polarisation of the two Z can be reconstructed.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



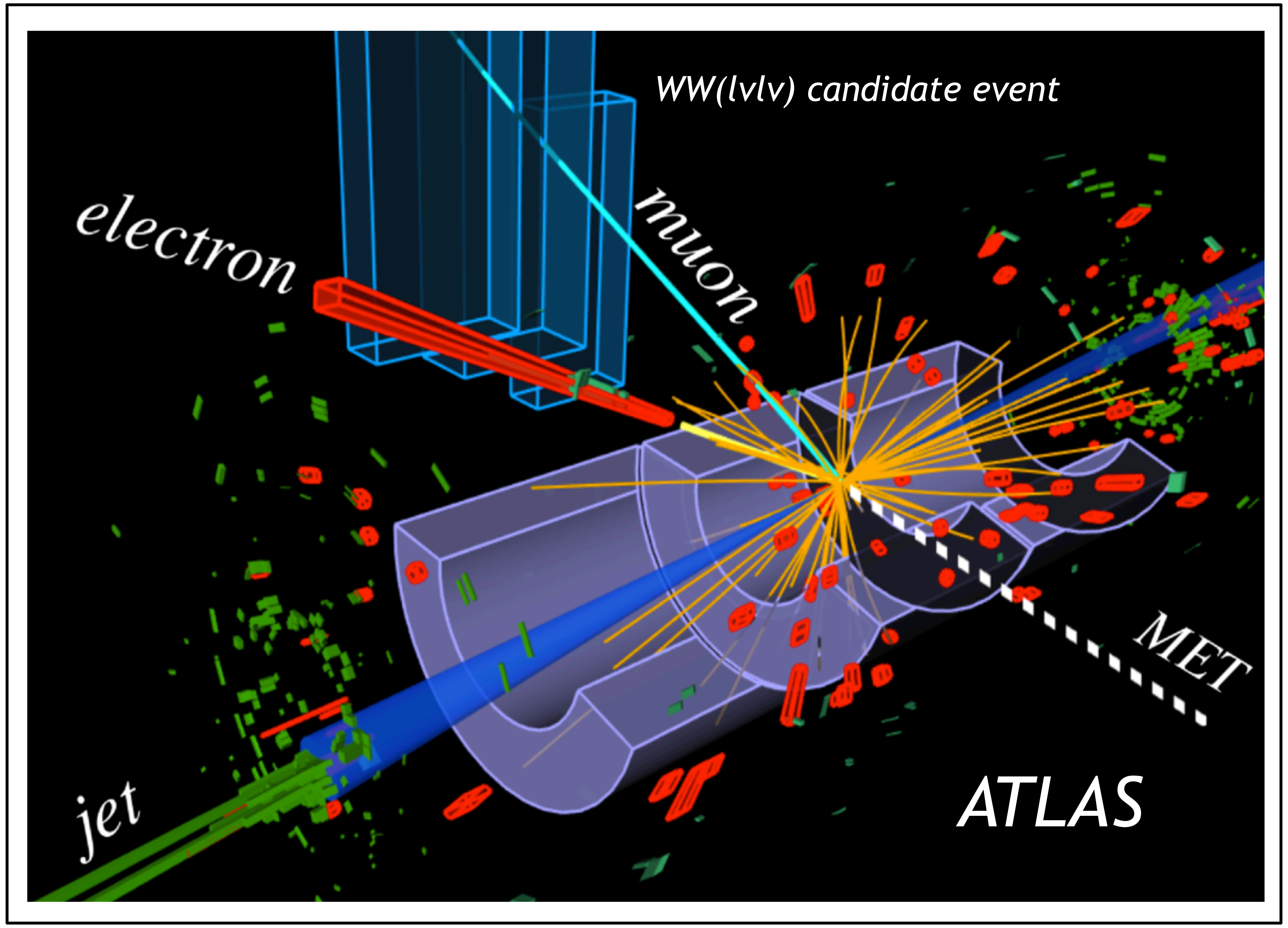






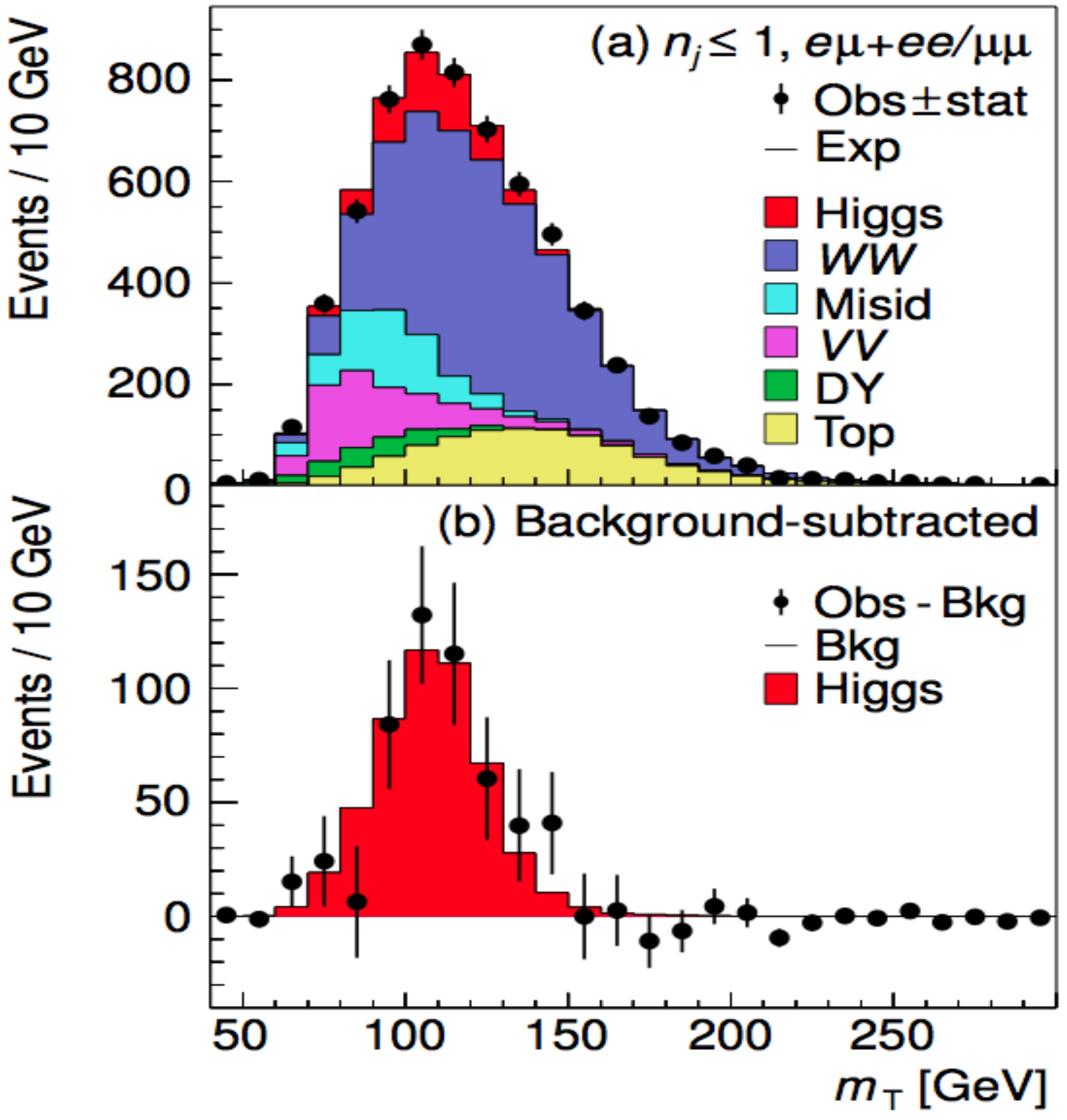
The Discovery Channels

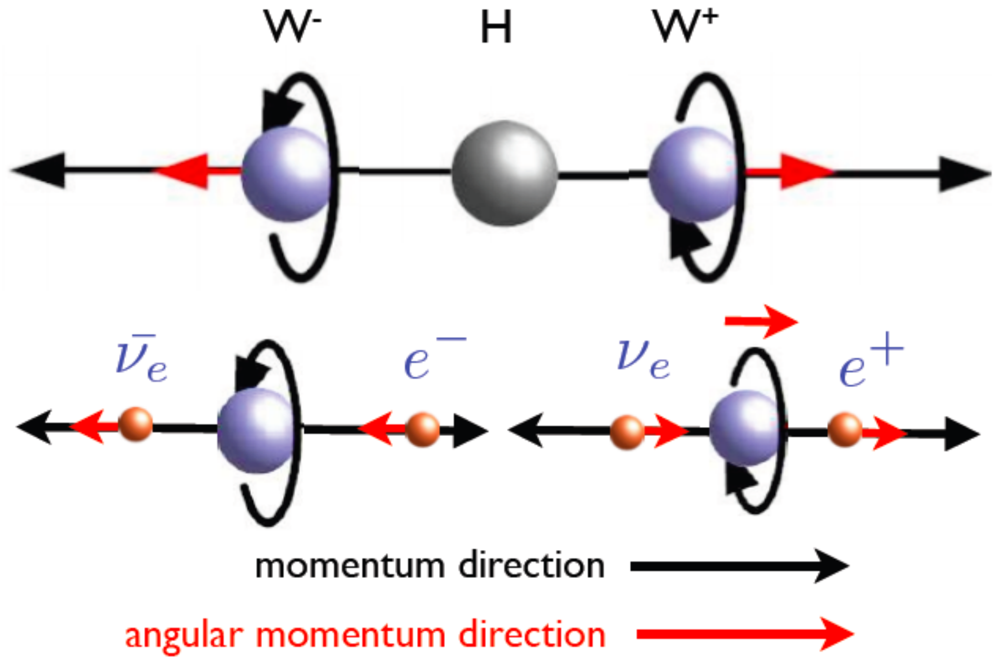
A discovery channel of a different kind: the WW

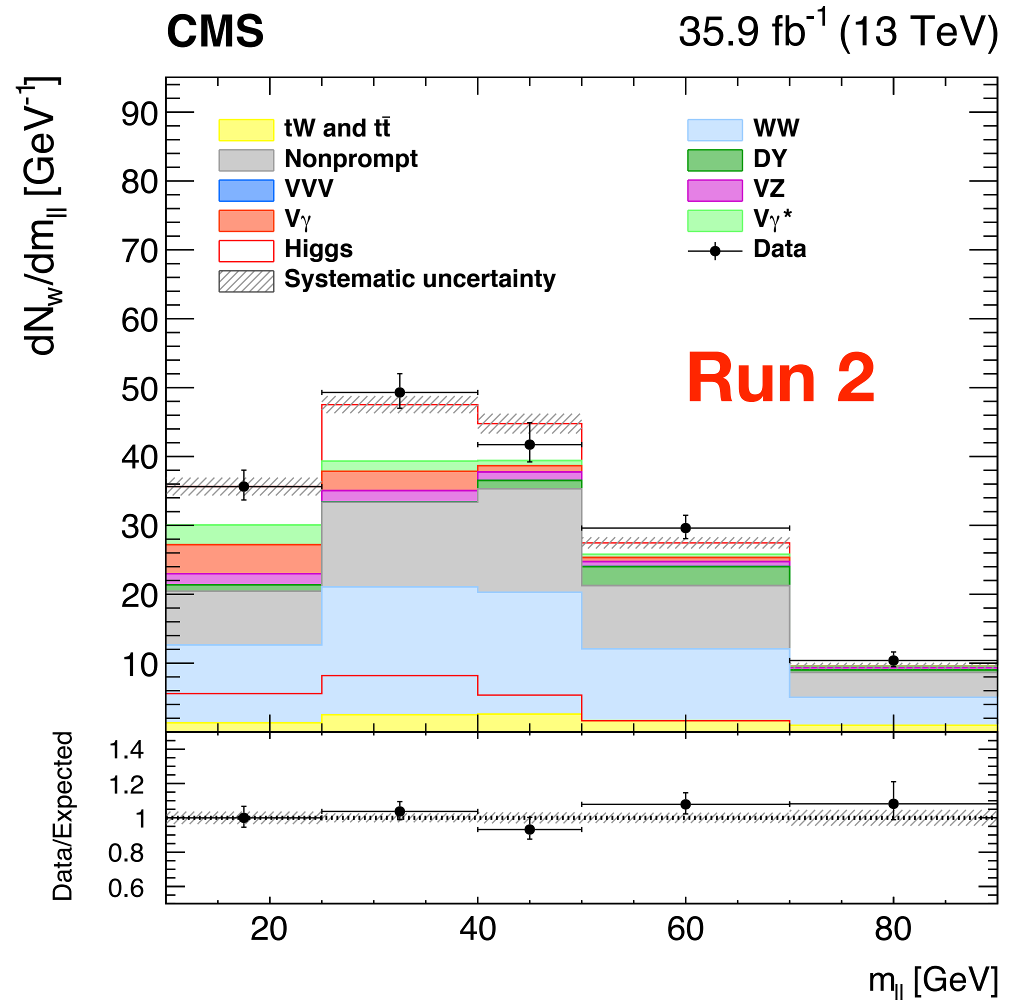


Requires good simulation of backgrounds and control regions in the data.

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





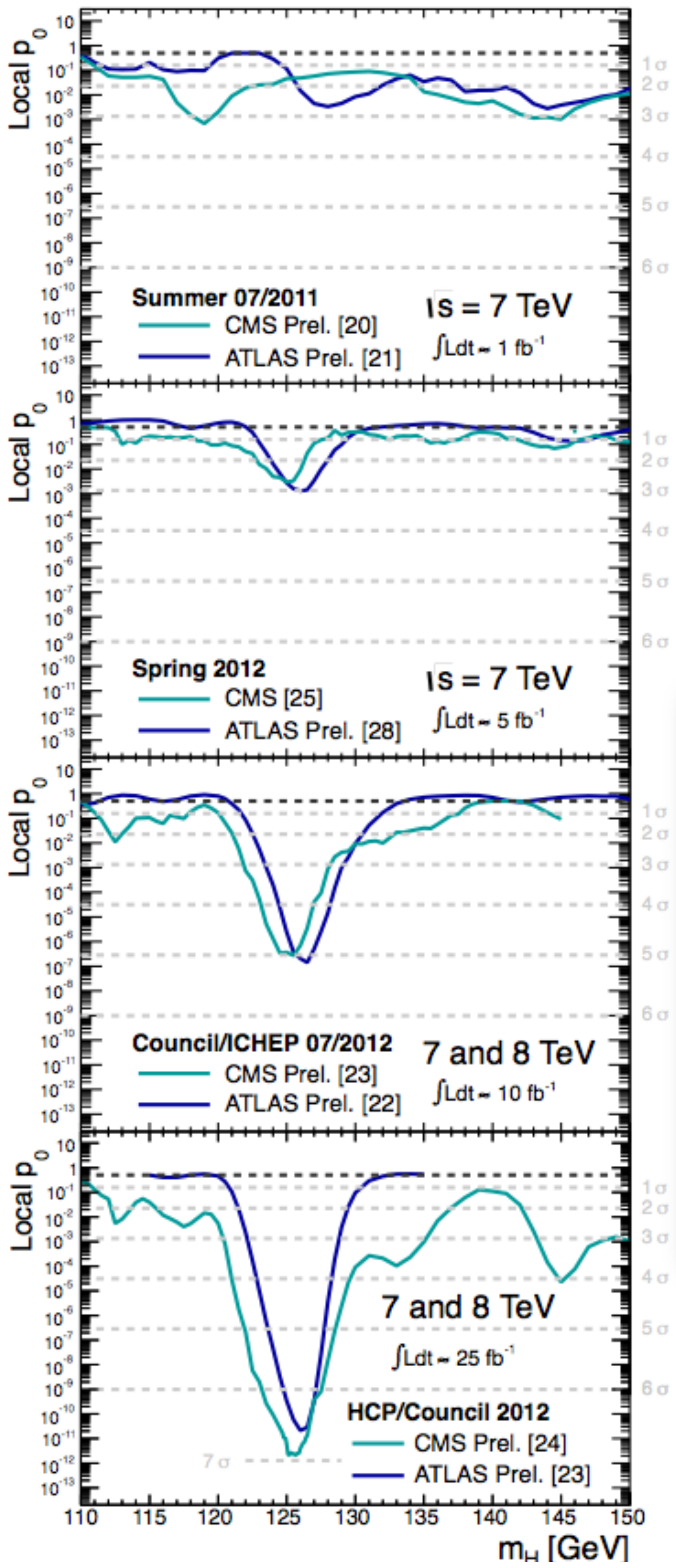


Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

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!**



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

✓ Strongly Motivated

✓ Significance increased with luminosity to reach unambiguous levels

✓ Two experiments

✓ Several channels

Higgs Discovery announcement July 4, 2012

2013

Mechanism contributing to… [full]

Francois Englert and Peter Higgs

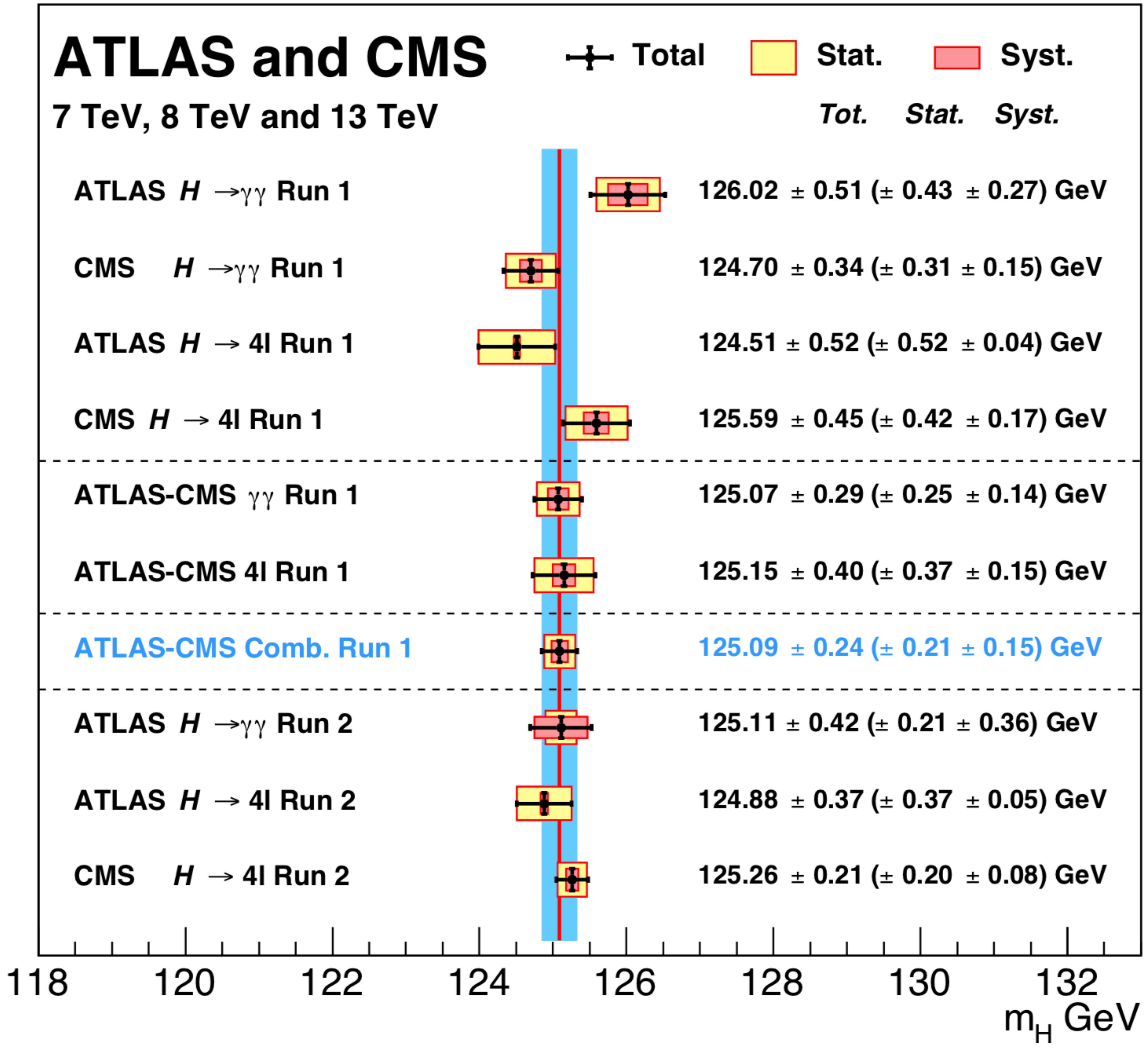
Measurements in the di-boson channels

Entering precision era in Higgs physics

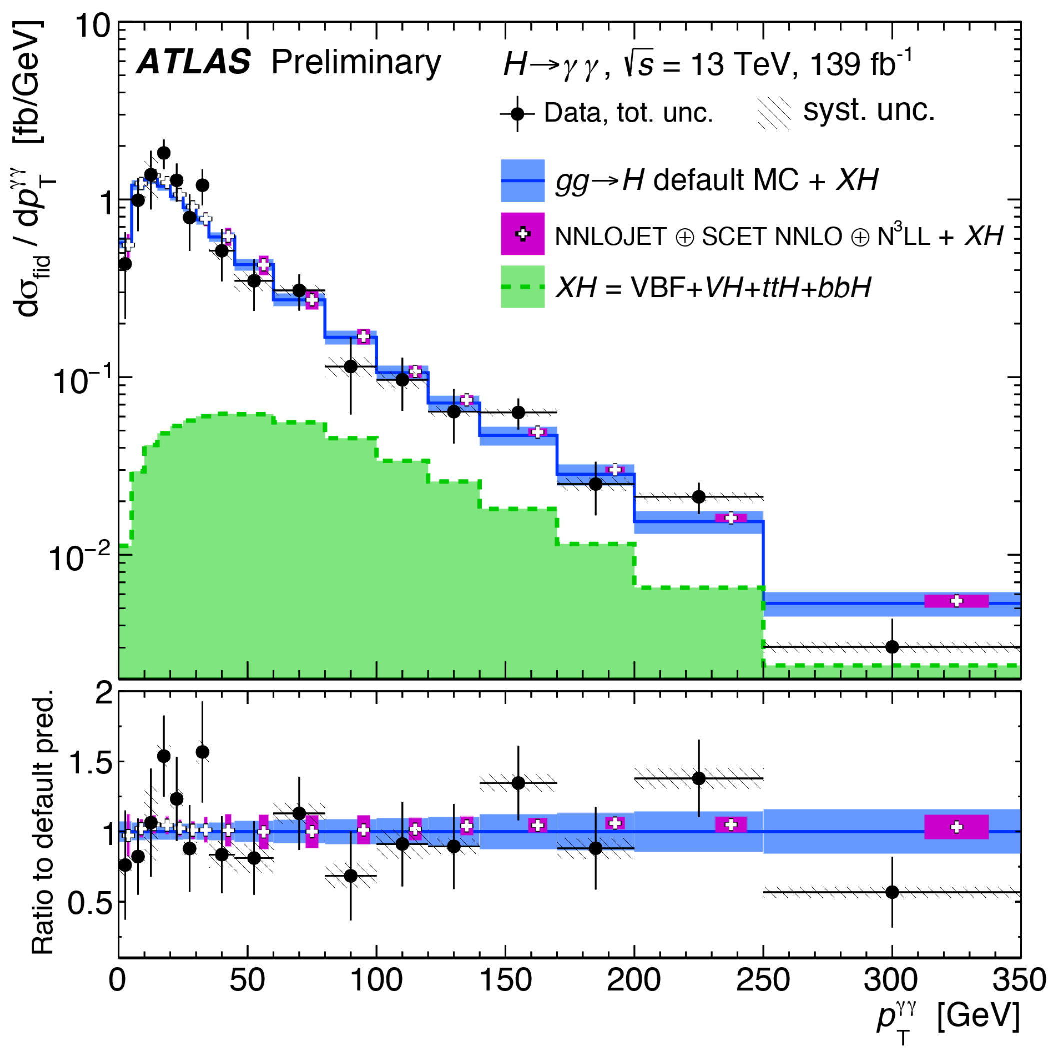
First Precision Measurement at the LHC?

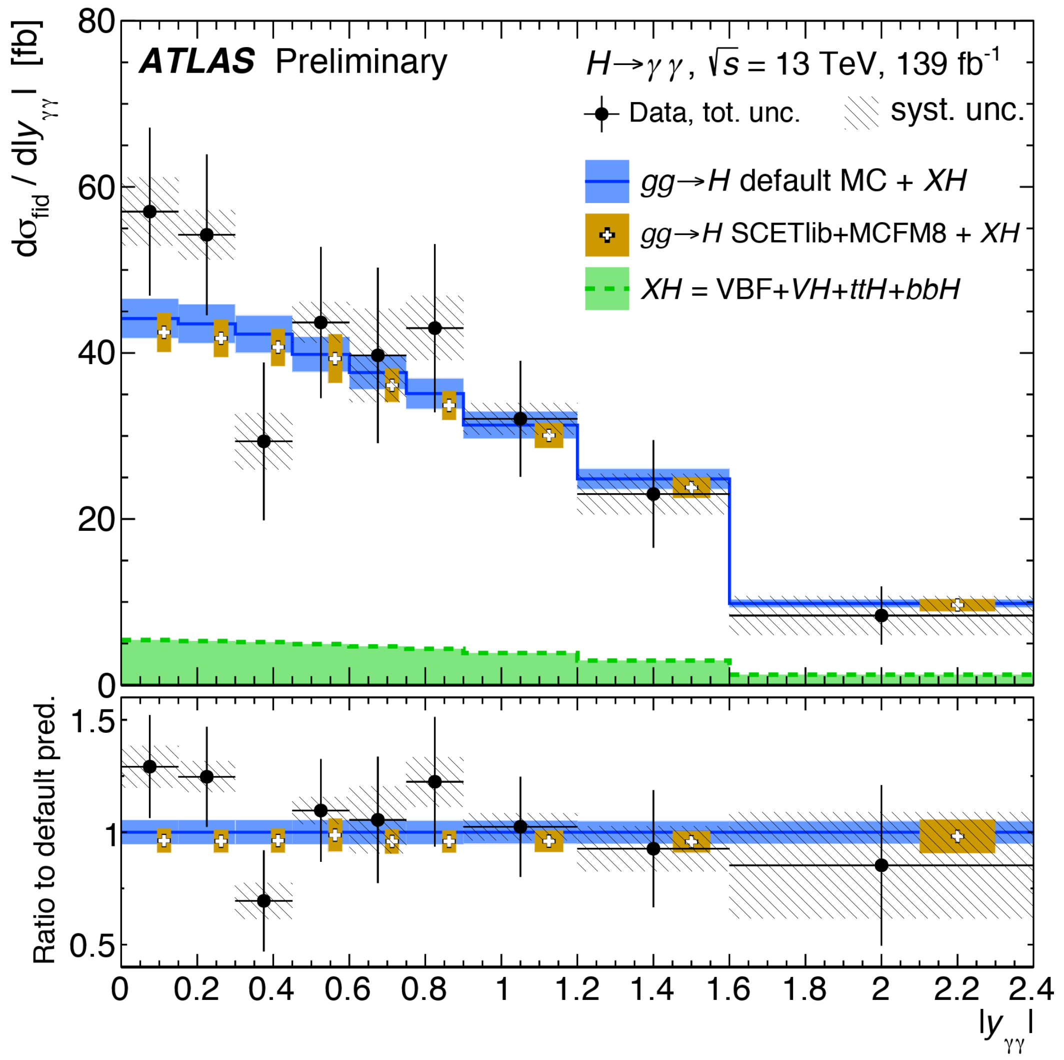
Higgs boson mass measurement

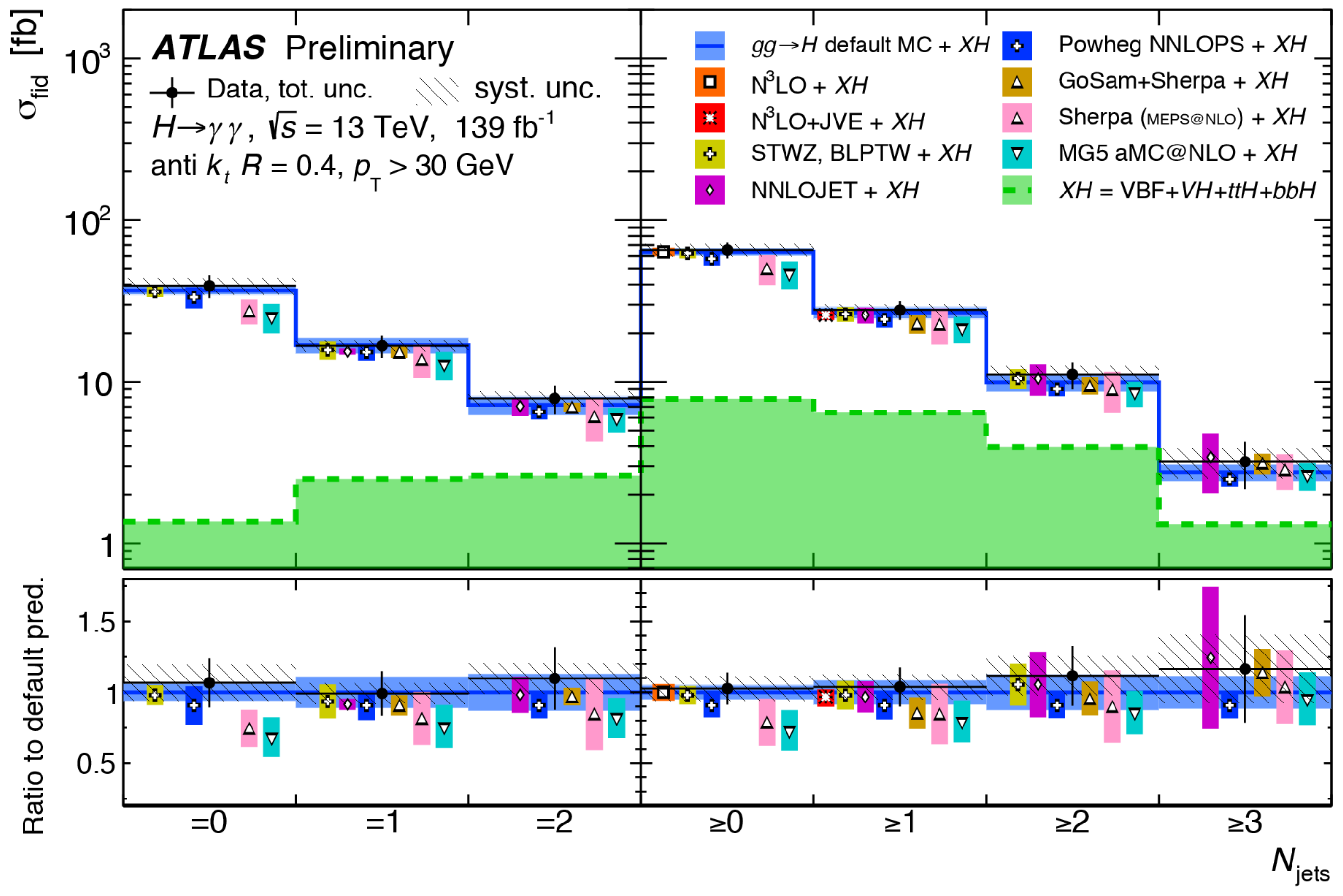
- Measurement done exclusively in the diphoton and 4-leptons channel.
- Optimizing the analysis in categories with best mass resolution (photon, electron and muons energy response).
- Reached at Run 1 a precision of 0.2%.
- Among (if not the) most precise measurement done at the LHC in 2013.

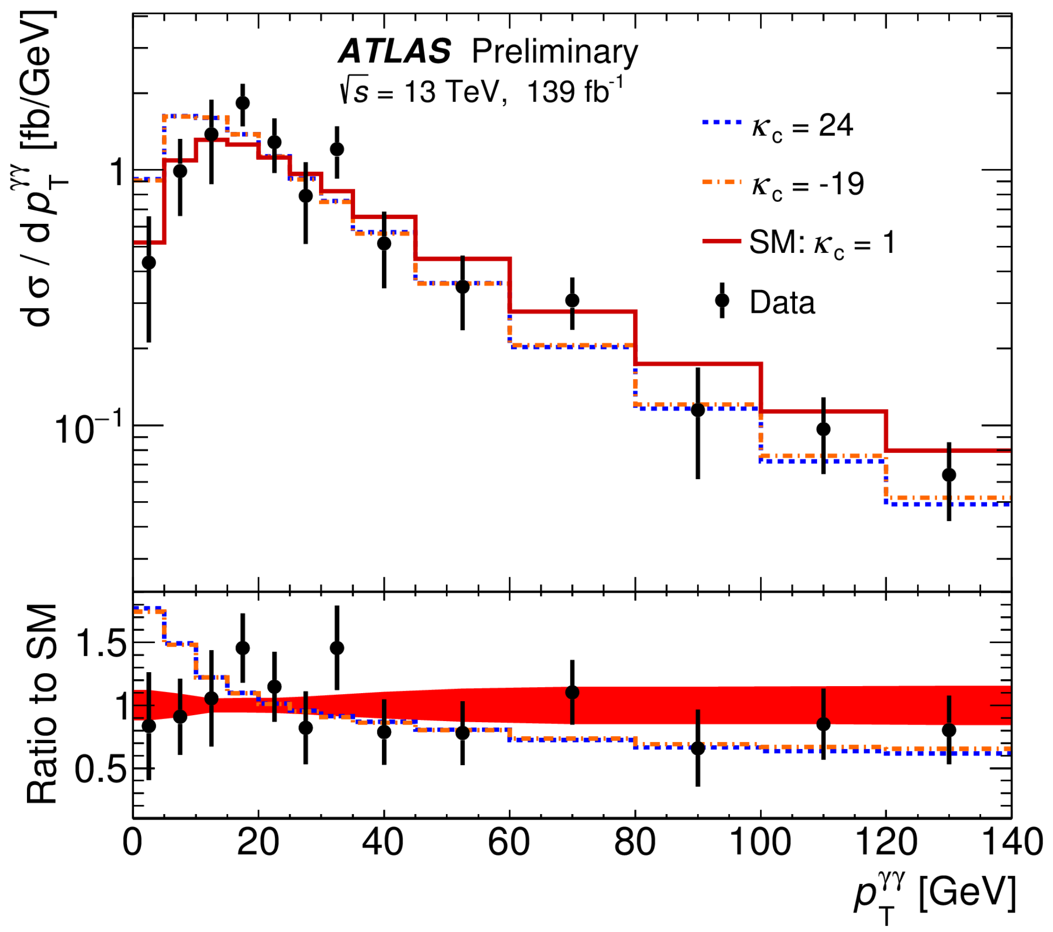


Differential Cross Section Measurements







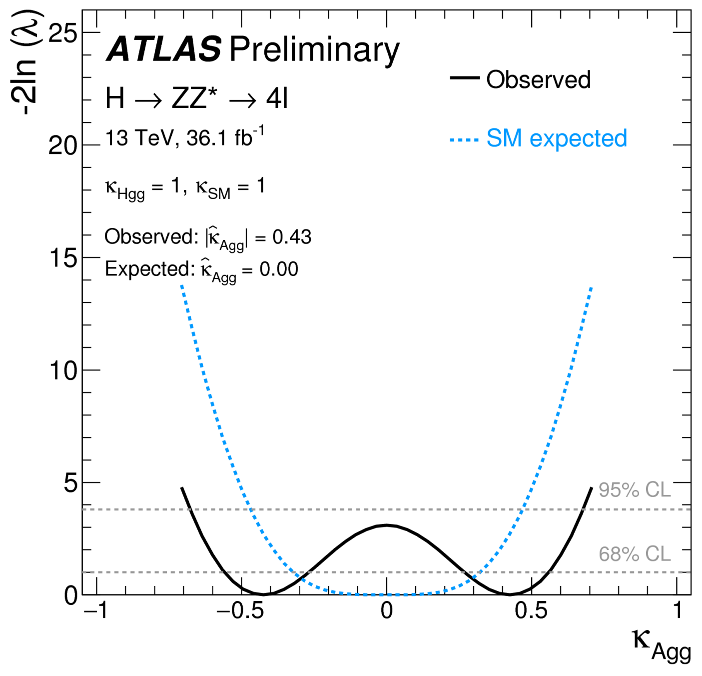


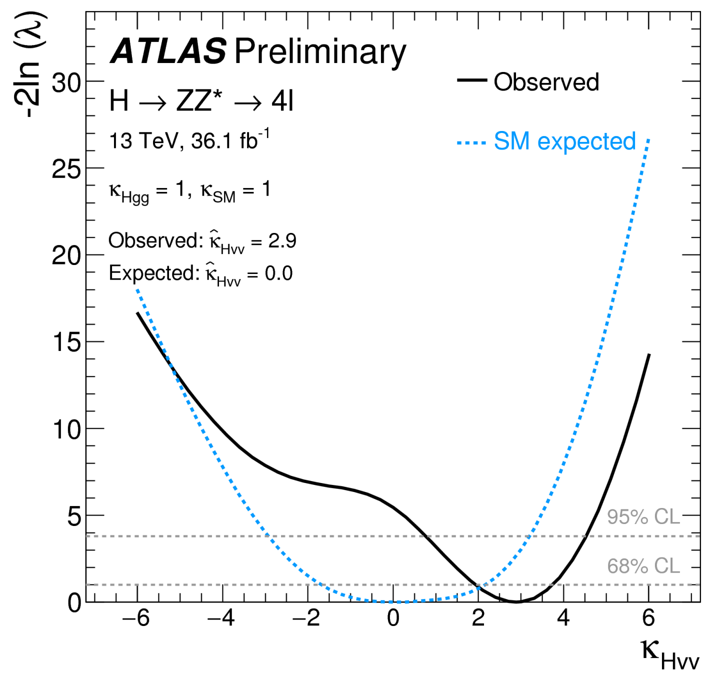
Measurement of fiducial and differential cross sections for Higgs production.

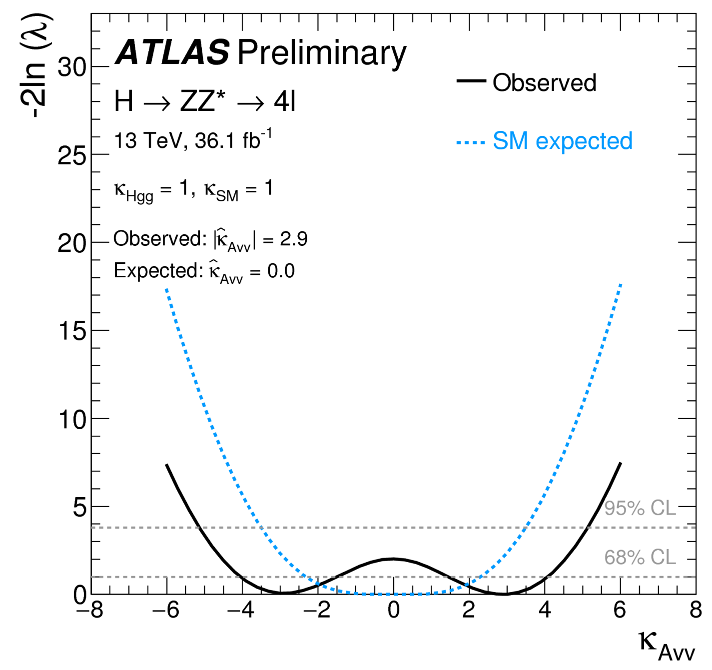
Measuring differential cross section open a vast number of interpretations in terms of properties of the Higgs boson:

- 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.

$$\mathcal{L}_0^V = \Big\{ c_\alpha \kappa_{\rm SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] - \tfrac{1}{4} \tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \tfrac{1}{2} \tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HWW} W_{\mu\nu}^+ W^{-\mu\nu} + s_\alpha \kappa_{AWW} W_{\mu\nu}^+ \tilde{W}^{-\mu\nu} \right] \Big\} X_0$$



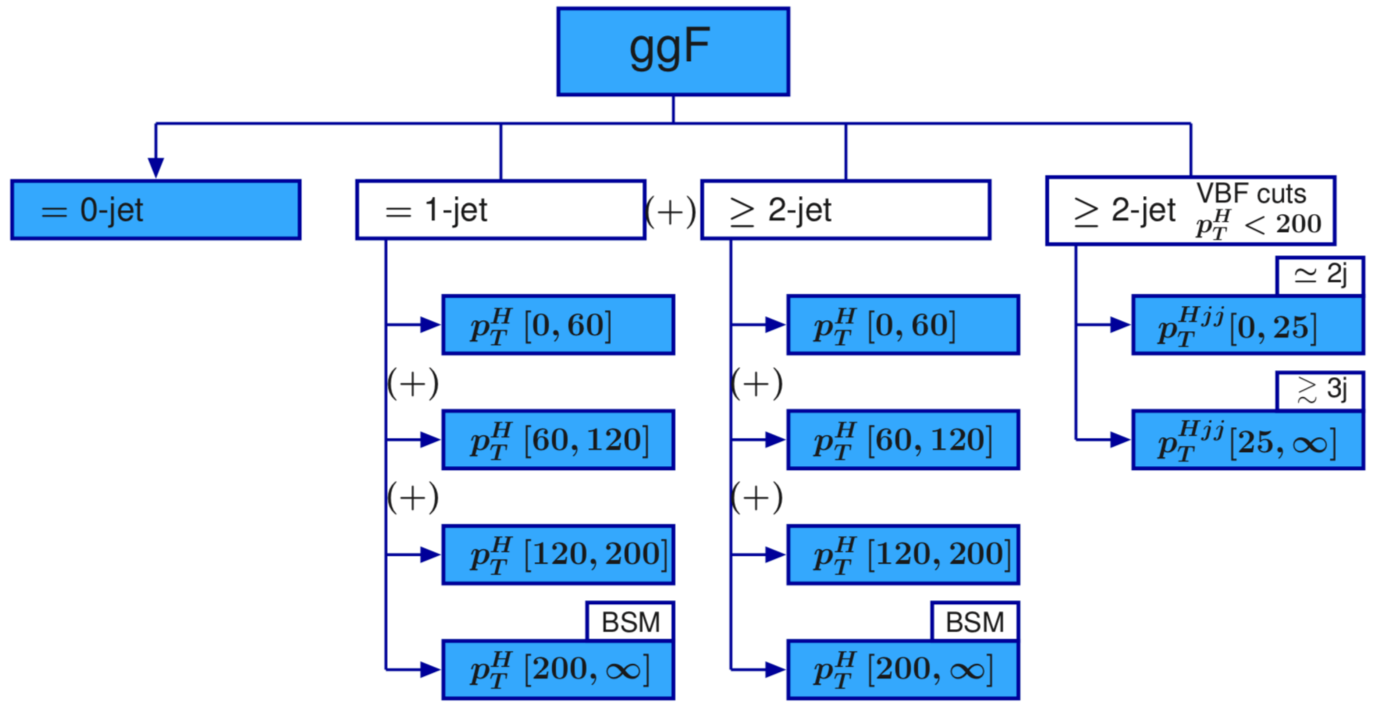




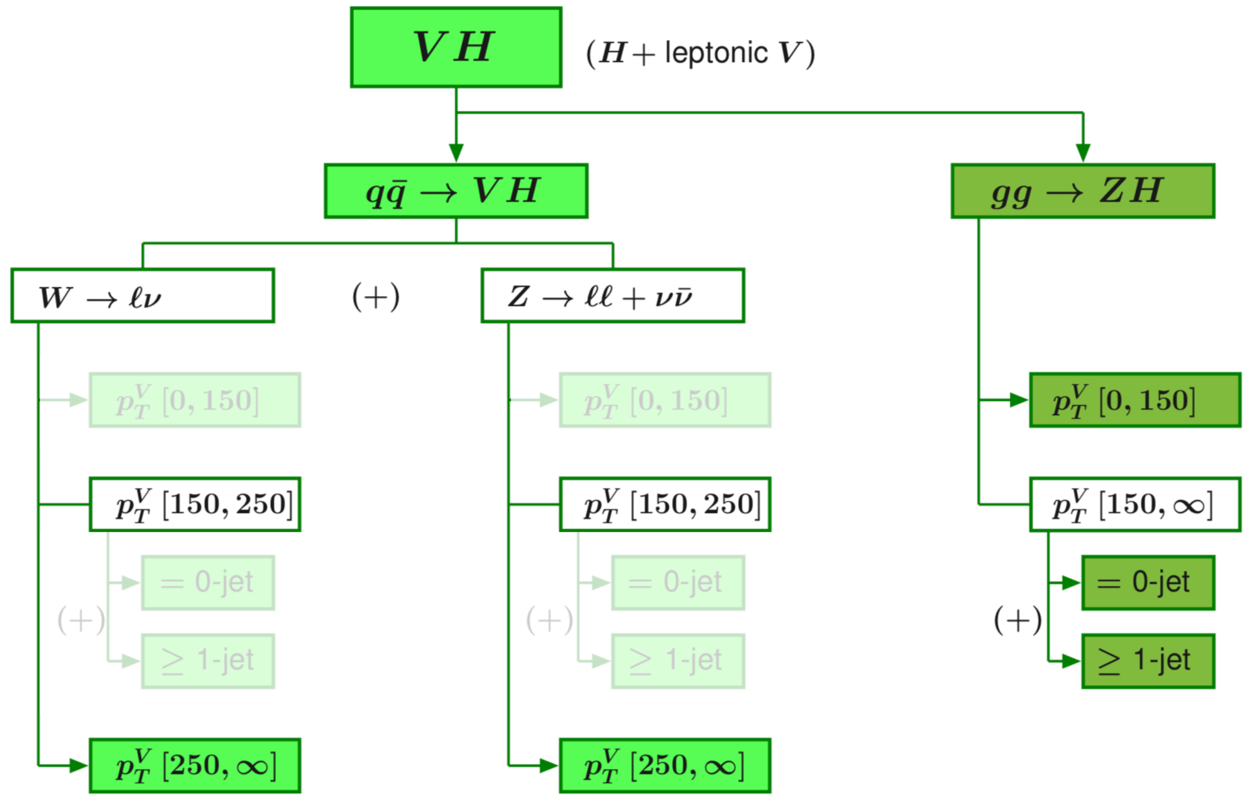
Hybrid Fiducial Approach: Simplified Template Cross Sections

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

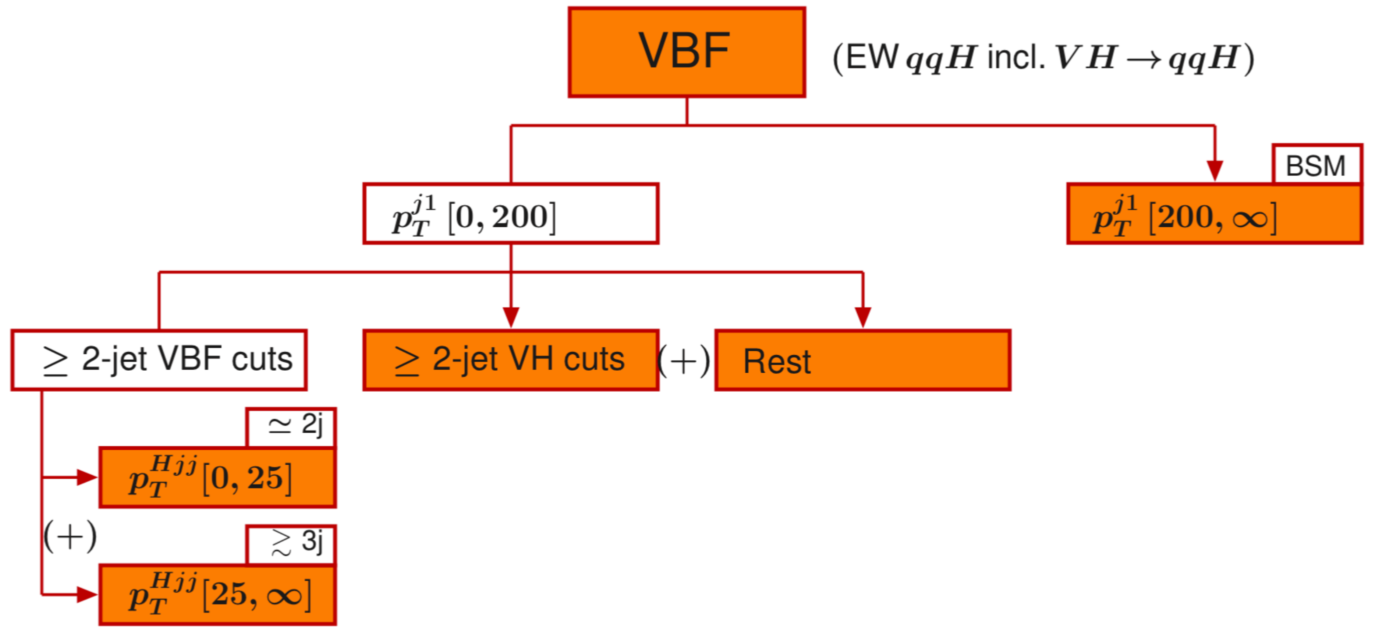
Inclusive (and most other channels) covered by discovery channels



VH covered at high pT also by VH(bb)



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



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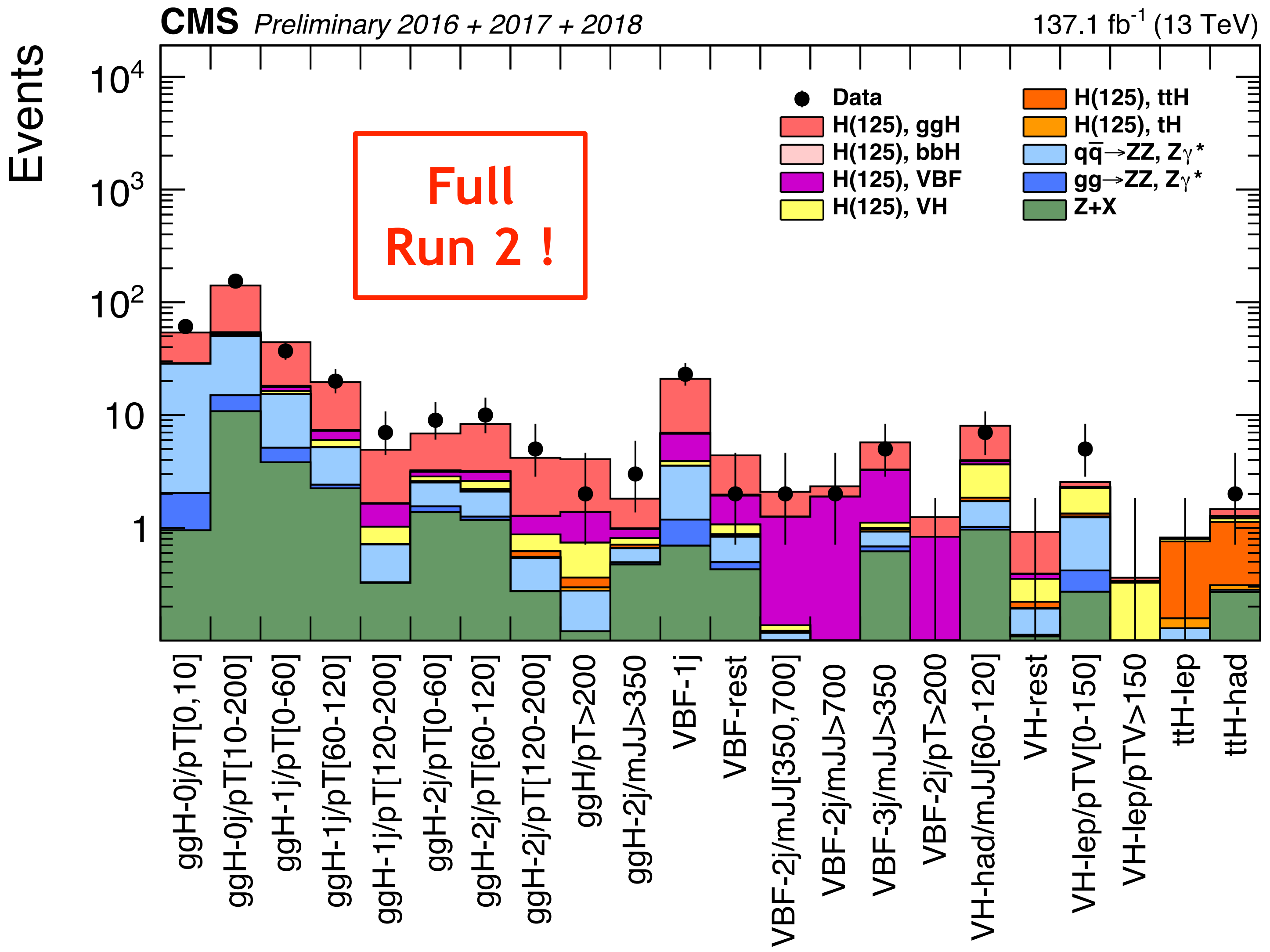
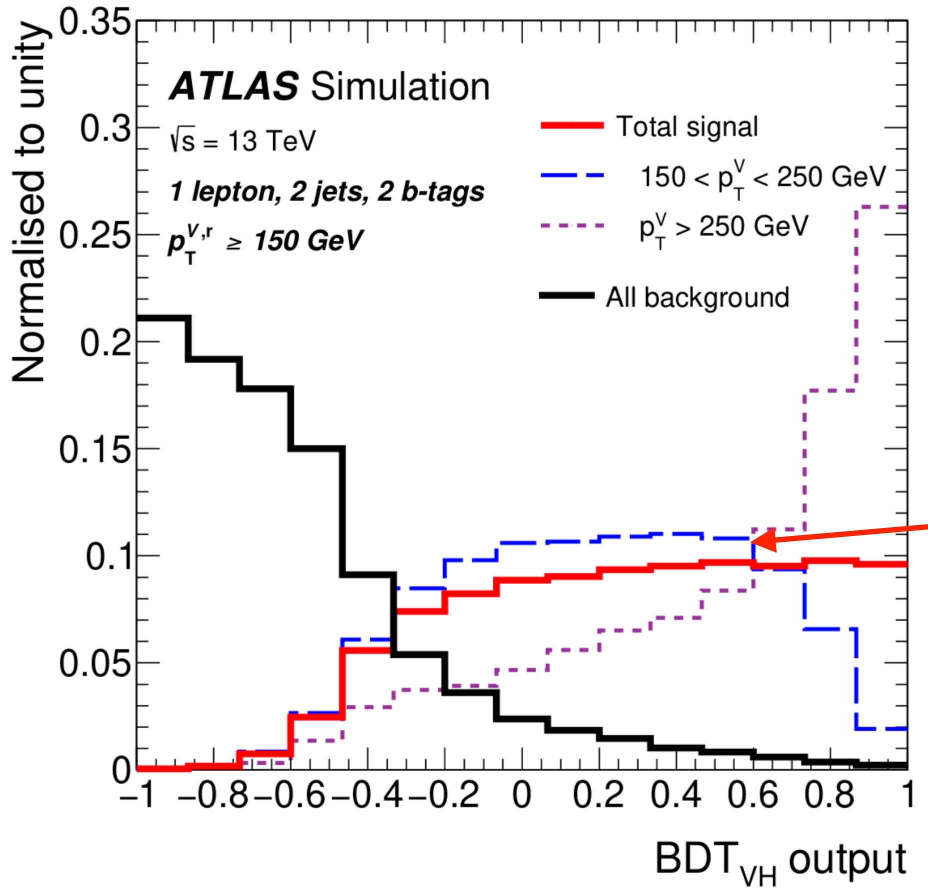
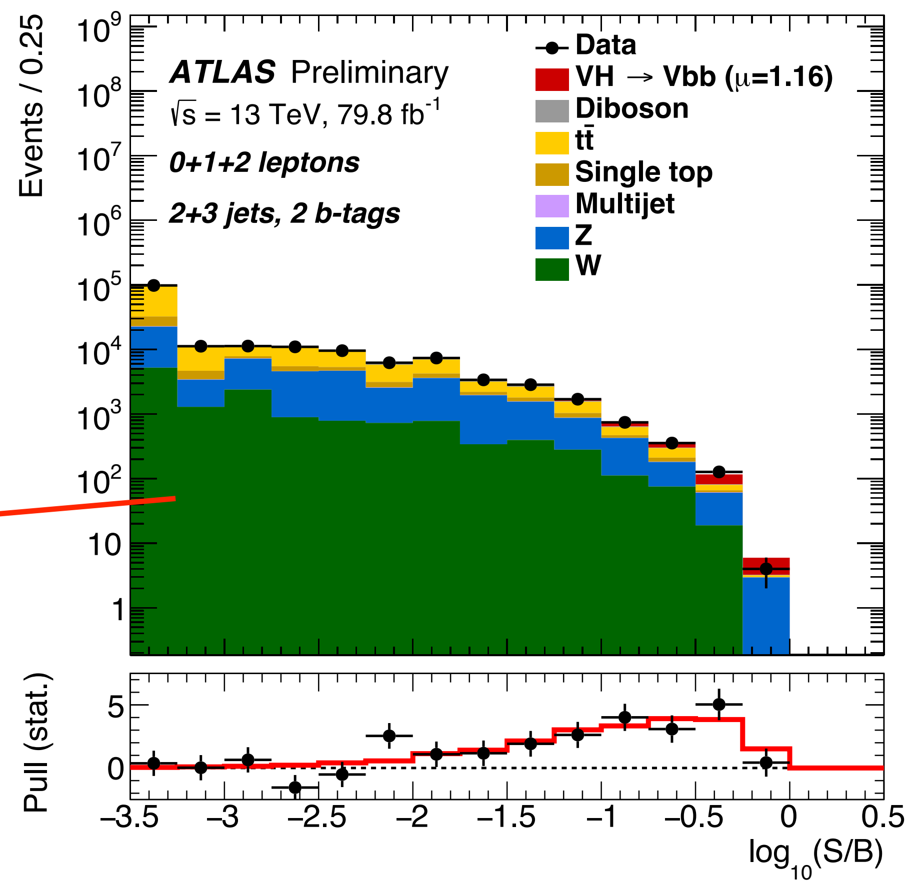
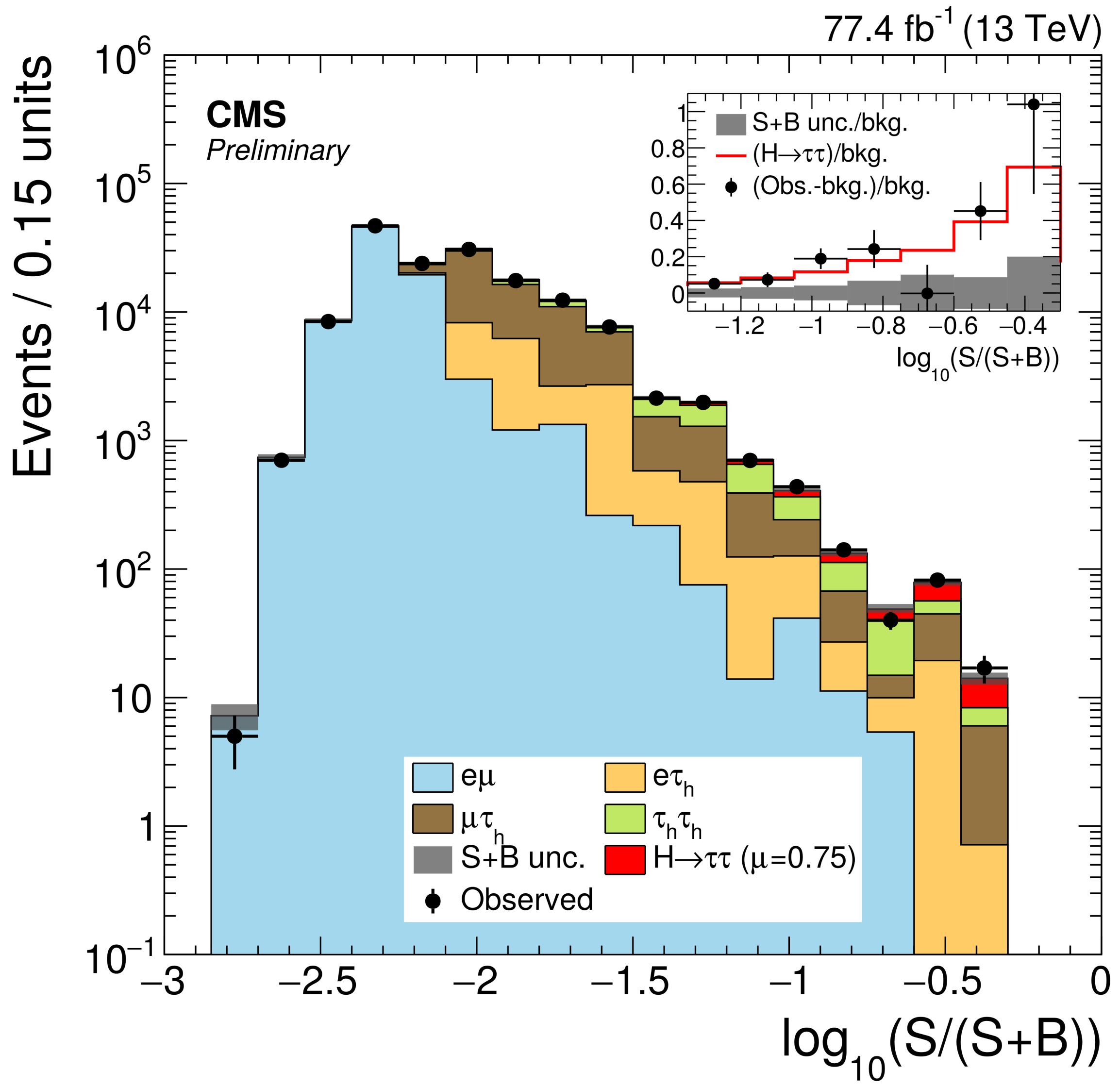






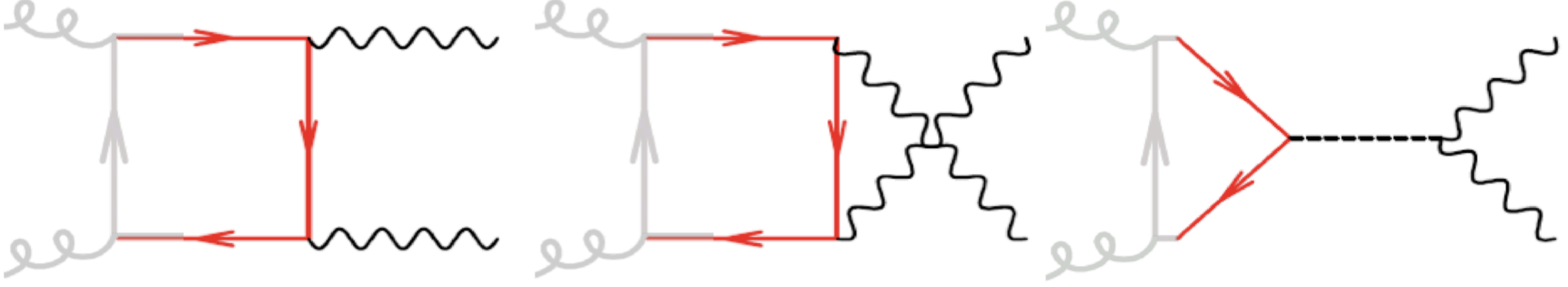


Off Shell Higgs

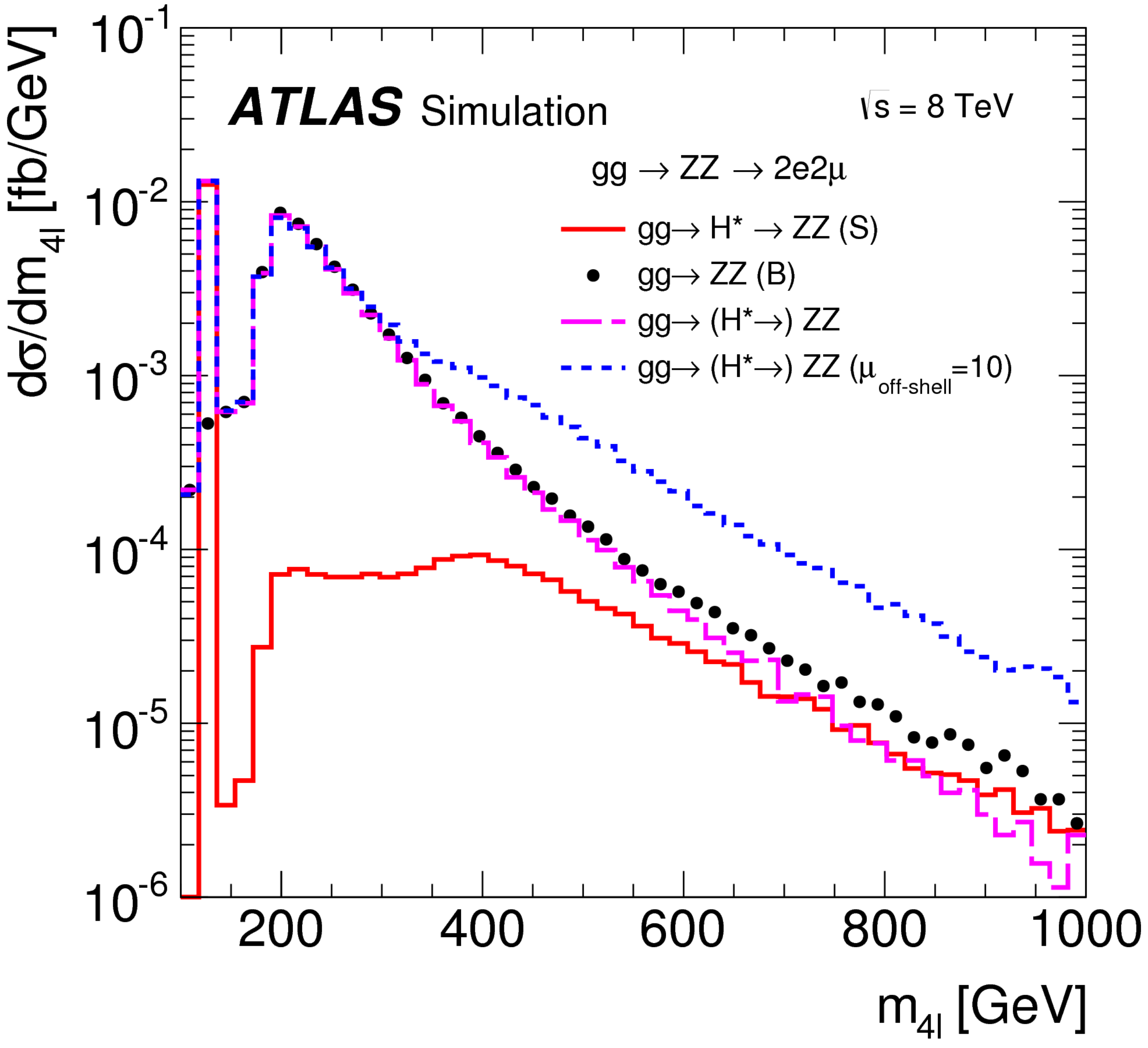
Study the Higgs boson as a propagator

Study the 4-leptons spectrum in the high mass regime where the Higgs boson acts as a propagator

From J. Campbell



$aE^2 + (b+c)m_t E$ $\quad$ $-aE^2 + (d-c)m_t E$ $\quad$ $-(b+d)m_t E$

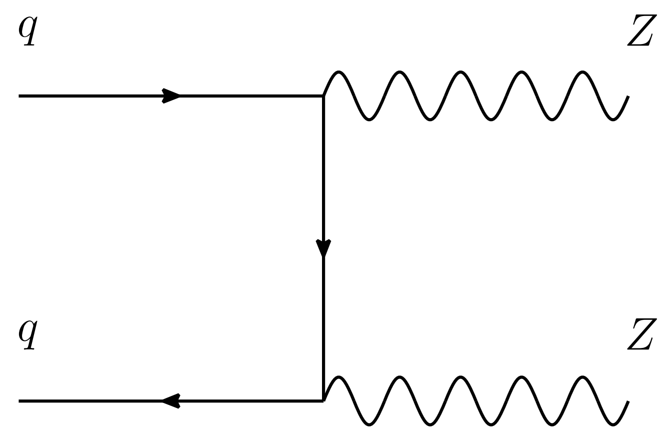


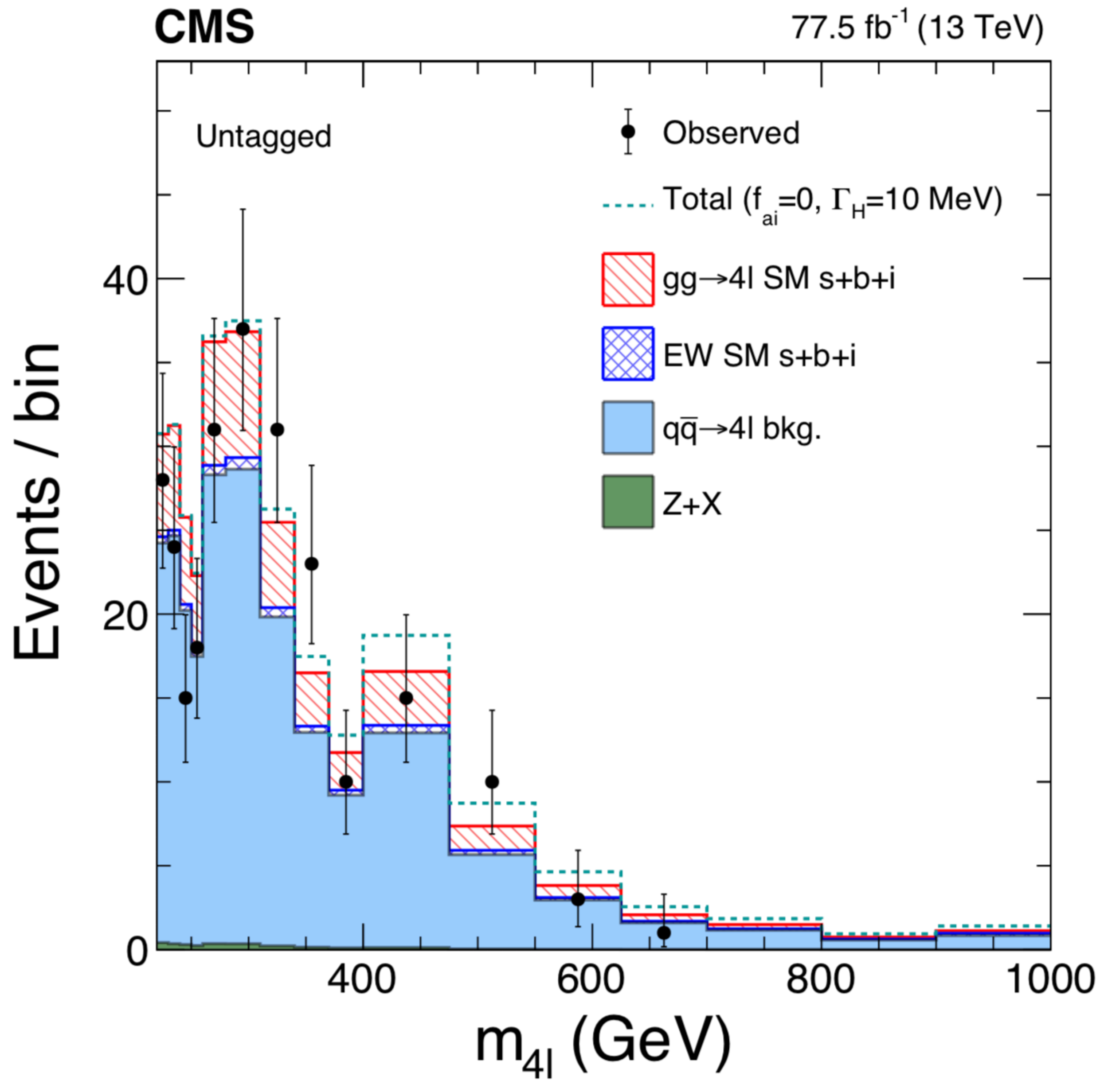
Measuring the Higgs contribution is then independent of the total width of the Higgs boson (sensitive to the product off shell of the Higgs boson to the coupling to the top and Z)

Assuming that these couplings run as in the Standard Model and measuring them on shell allows for a measurement of the width of the Higgs boson!

Highly non trivial due to:

- The negative interference
- The large other backgrounds





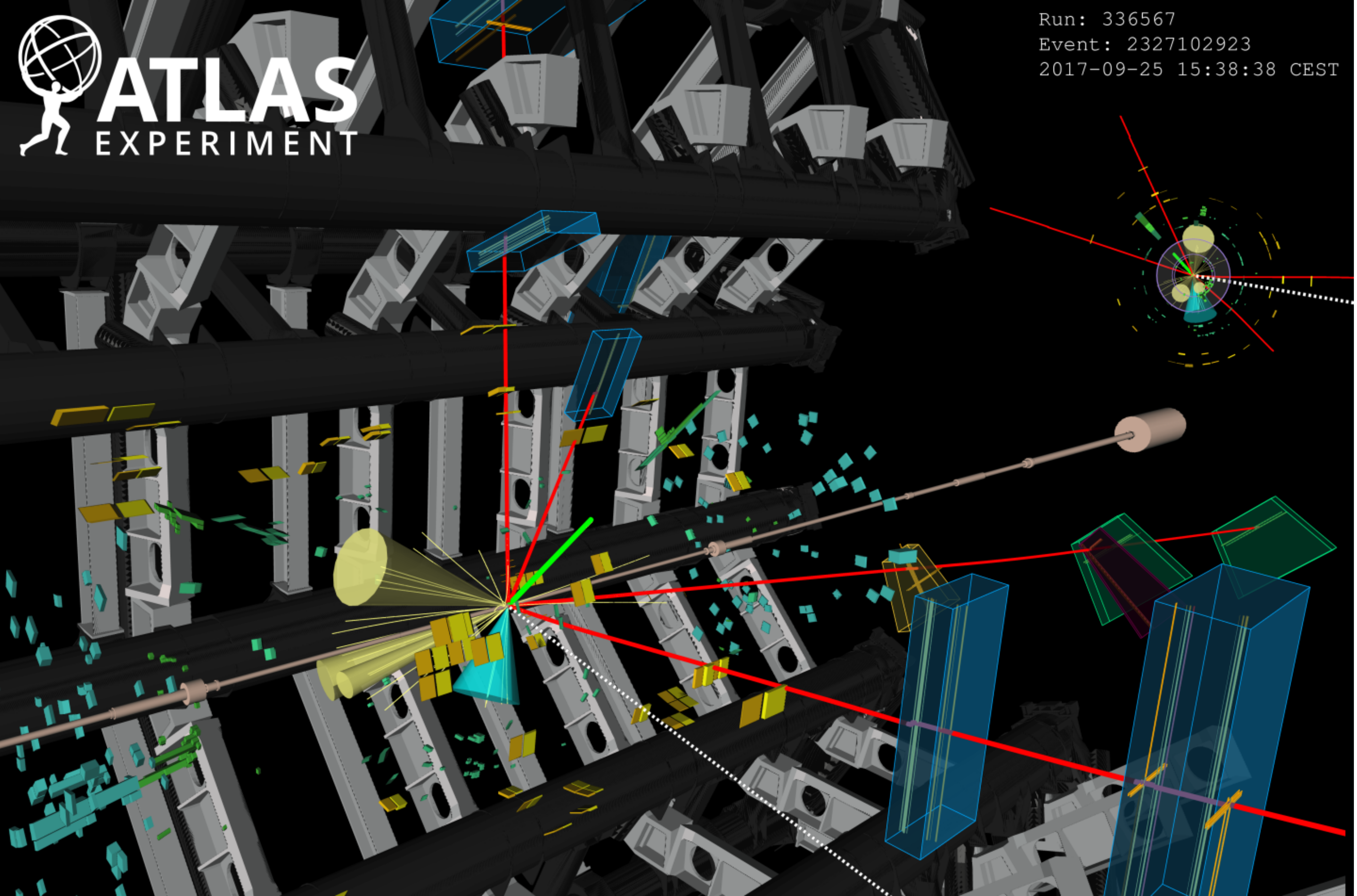
Limits on the total width are currently at approximately **10 MeV** (and exclude 0 at 95% CL).

HL-LHC: $\Gamma_H = 4.1^{+1.0}_{-1.1}$ MeV

Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab^{-1}

The Run 2 Landmark Results

Measurements 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.

$$s/b \sim 30$$

Run 2 Higgs Headlines

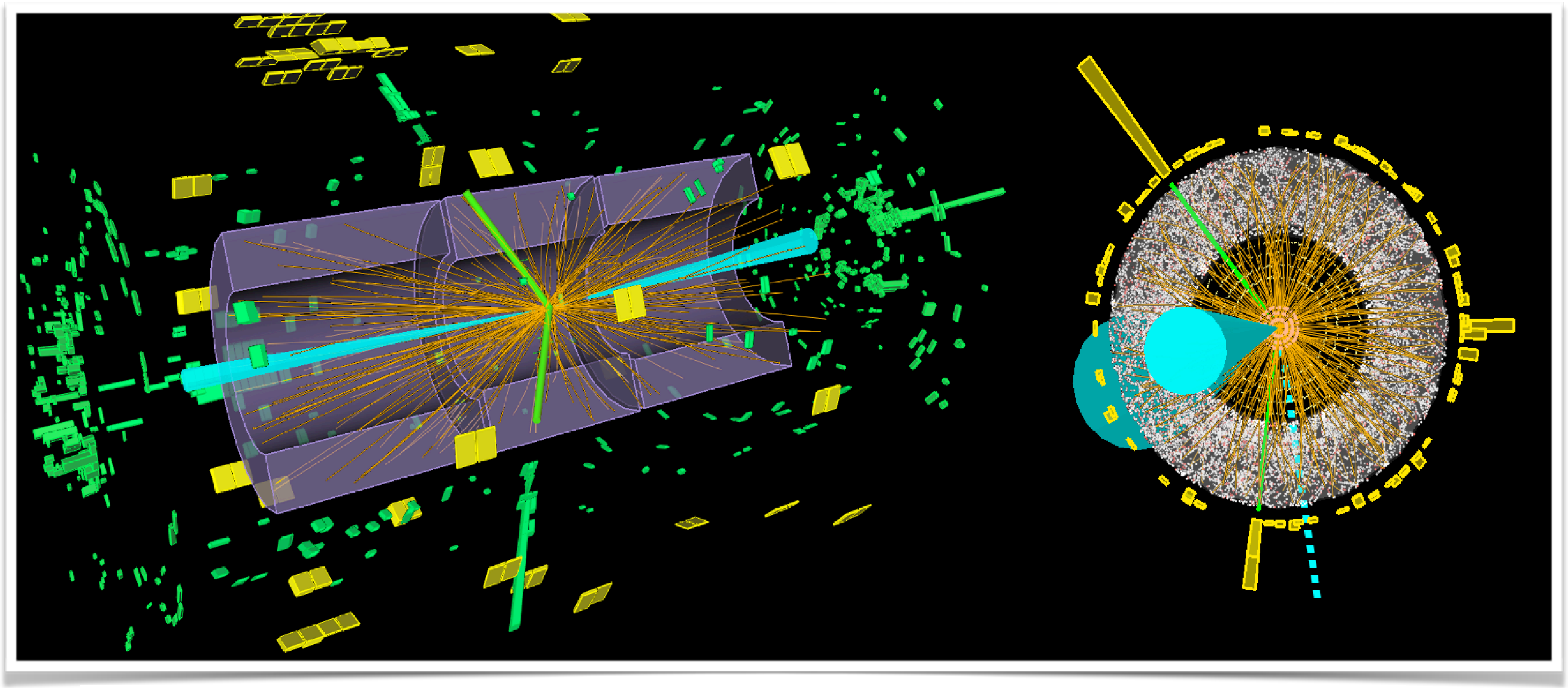
Run 2 Higgs Physics **major milestones** reached: **Third Generation (Charged) Observation Completed!**

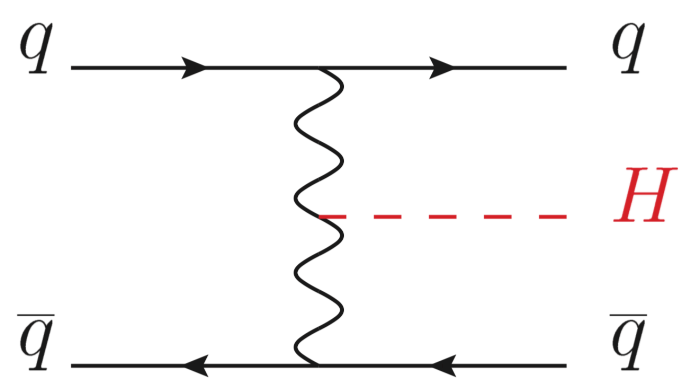
Yukawas at LHC		tau	b	top
ATLAS	Exp. Sig.	5.4 σ	5.5 σ	5.1 σ
	Obs. Sig.	6.4 σ	5.4 σ	6.3 σ
	mu	1.09 ± 0.35	1.01 ± 0.20	1.34 ± 0.21 *
CMS	Exp. Sig.	5.9 σ	5.6 σ	4.2 σ
	Obs. Sig.	5.9 σ	5.5 σ	5.2 σ
	mu	1.09 ± 0.27 *	1.04 ± 0.20	1.26 ± 0.26 **

* 13 TeV only derived from cross section measurements

** Lower uncertainty (upper uncertainty 31)

Higgs boson decays to Taus





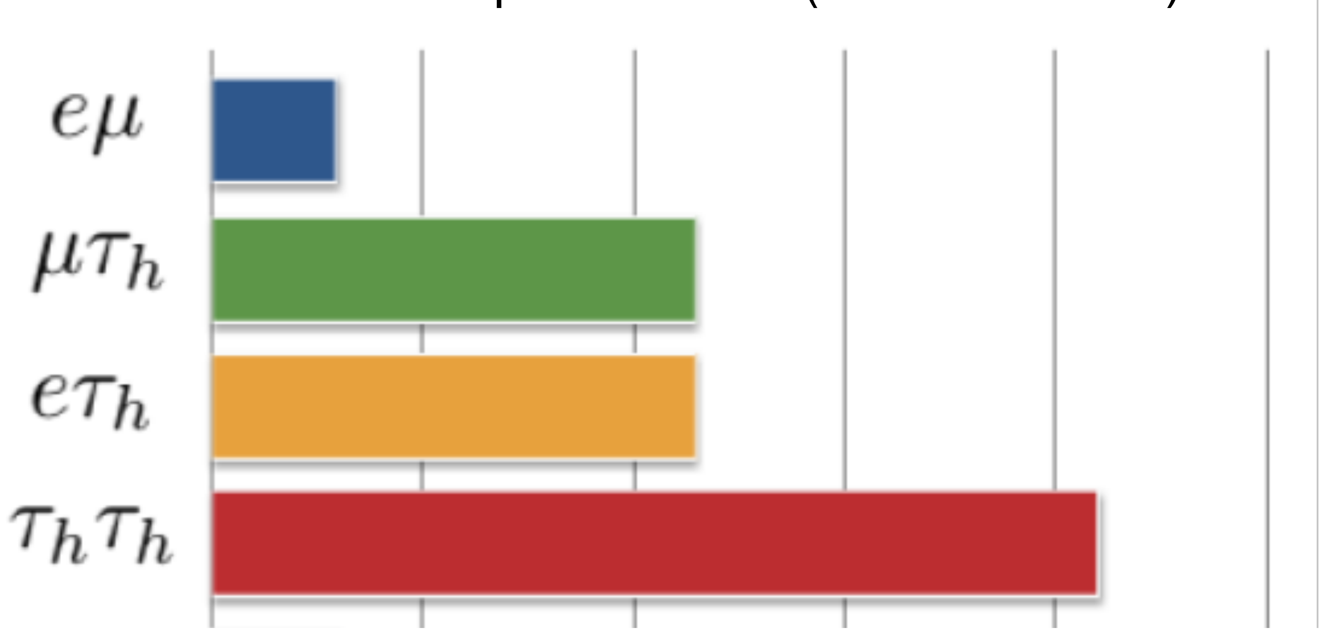
Special VBF process

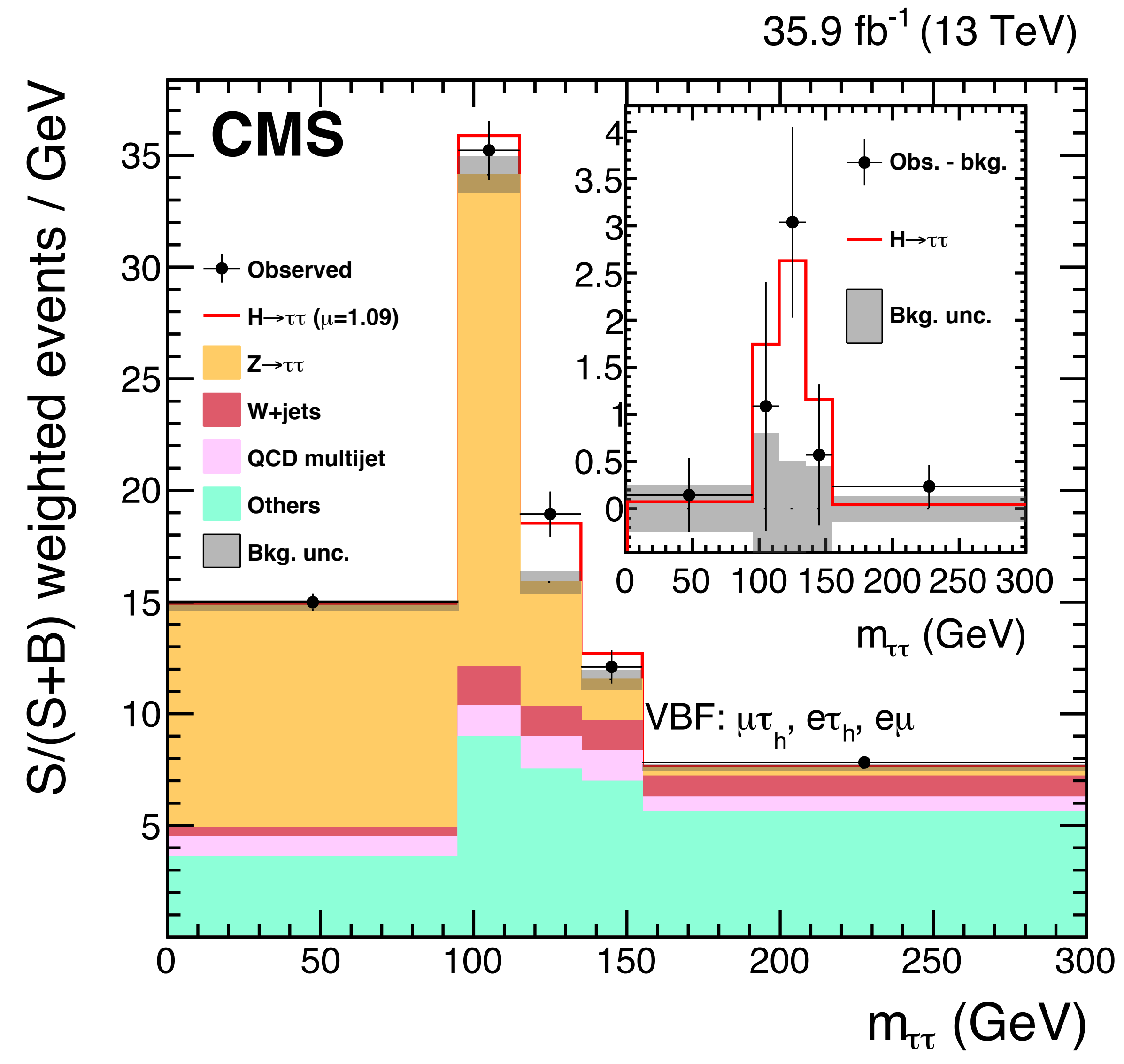
With two forward jets and a large rapidity gap between the jets (due to the color singlet exchange in the t-channel

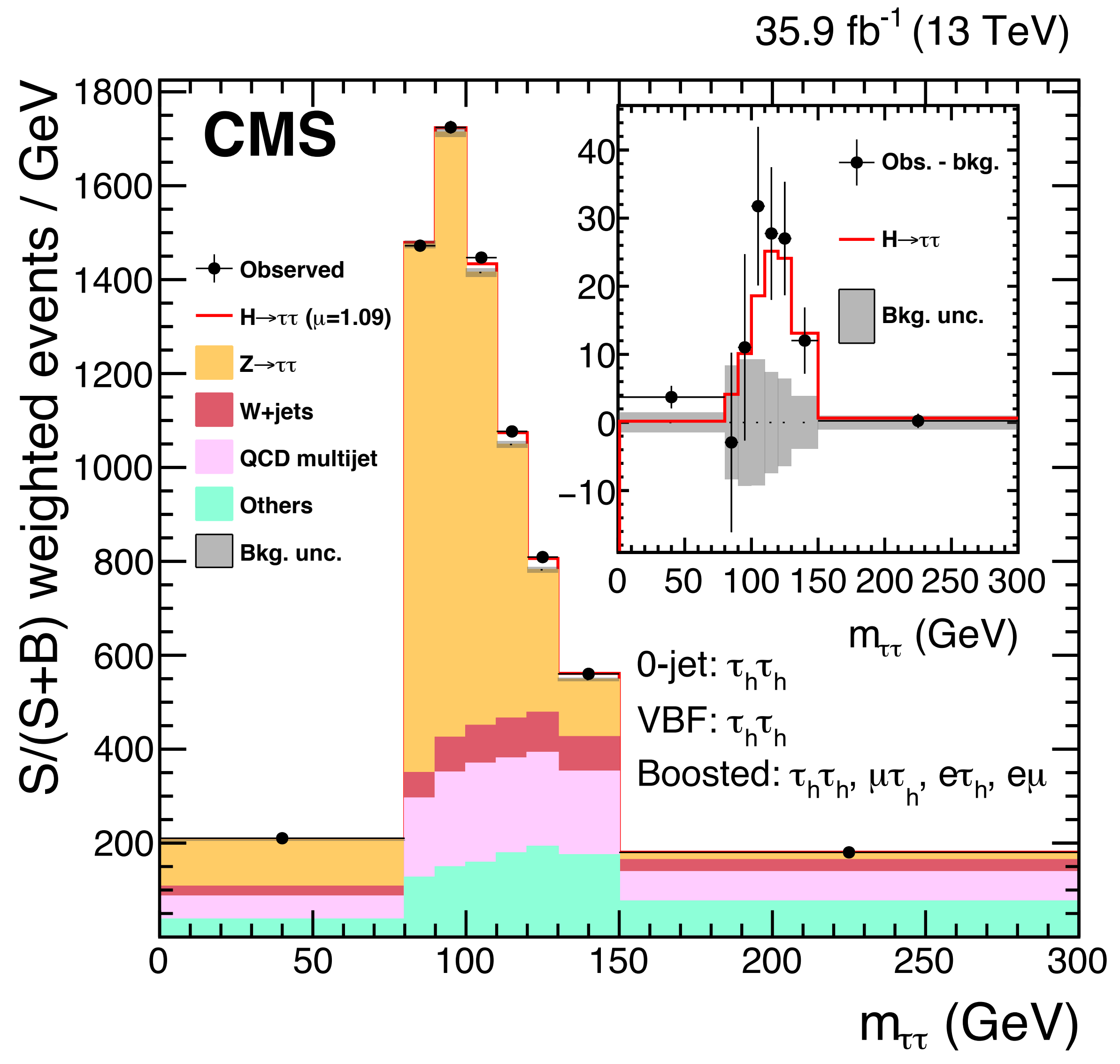
Background is Z production with two jets, in this region of phase space it is difficult to predict!

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

Tau to leptons ~18% (rest is hadrons)





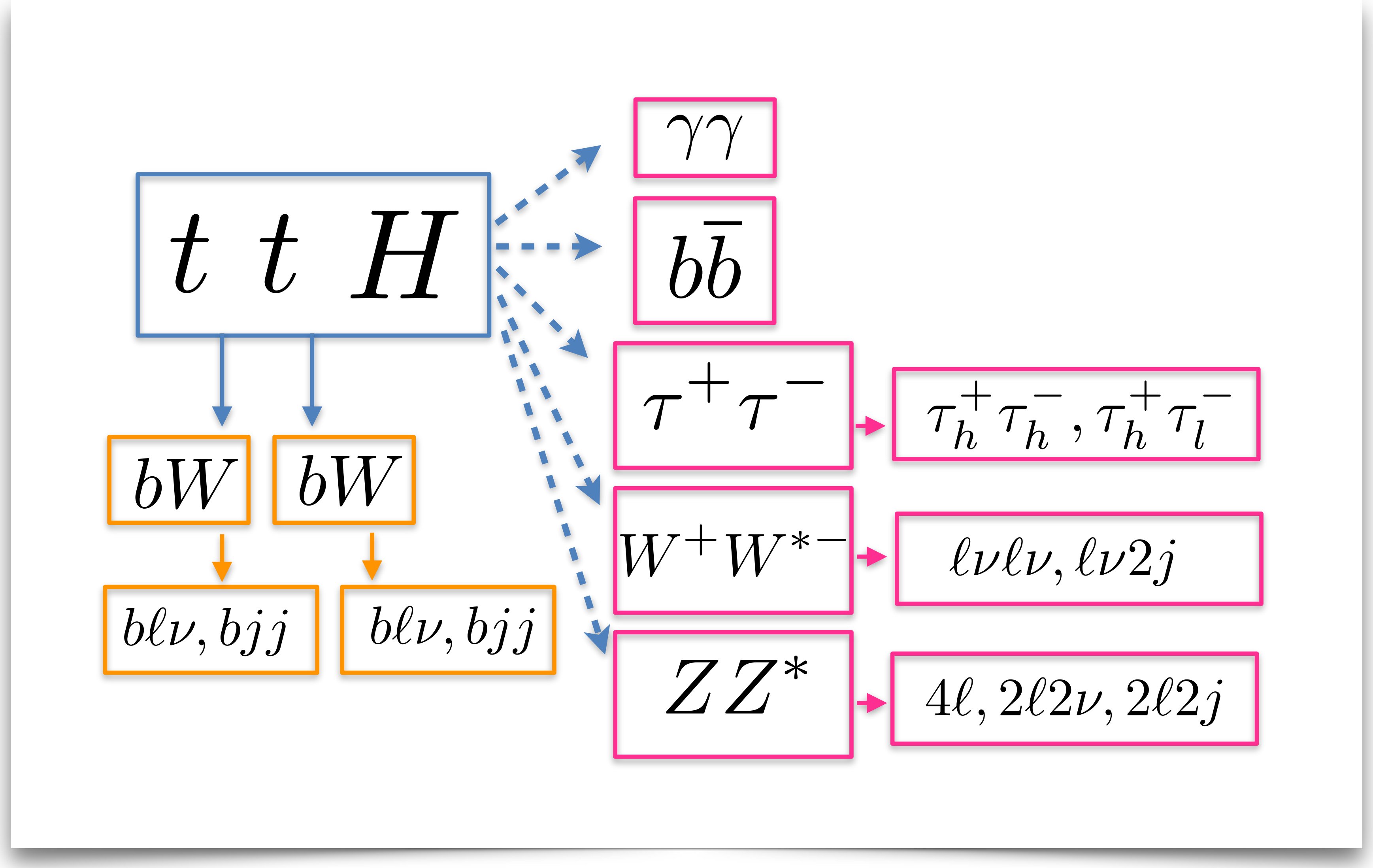


Analysis requires data driven methods to do so: e.g. the embedding of taus in Z to di-muon events.

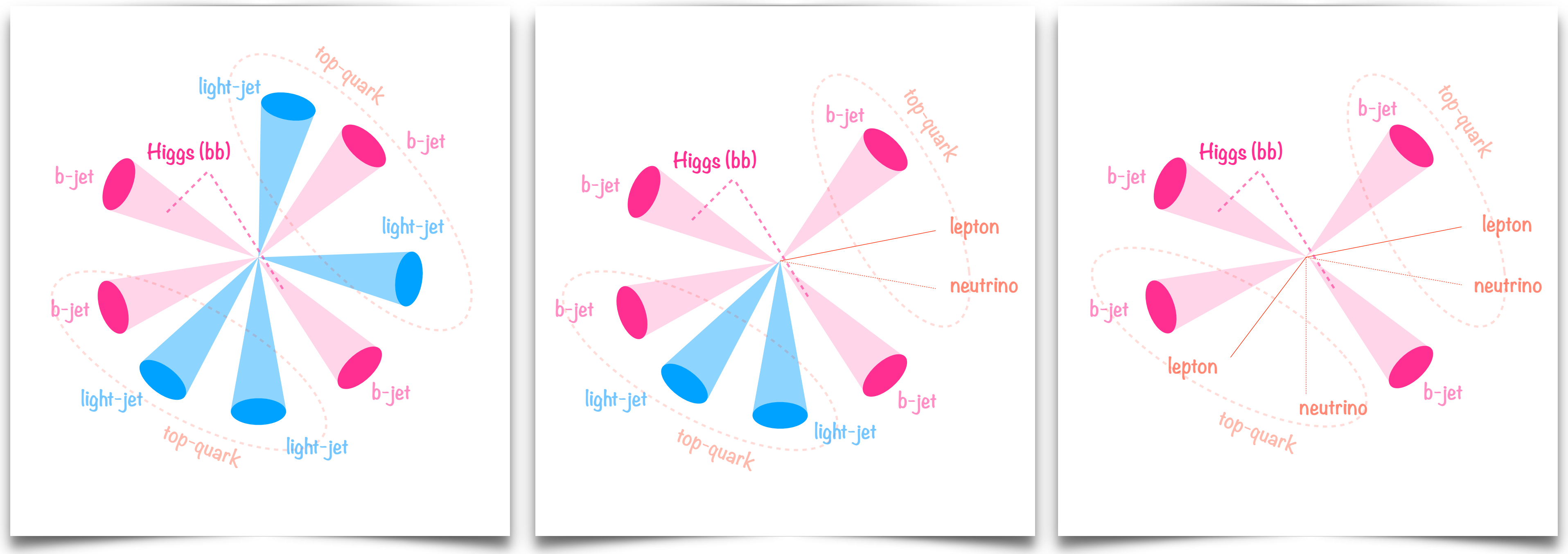
The tau polarisation can in principle be reconstructed, but this is very difficult and was not done yet.

Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!



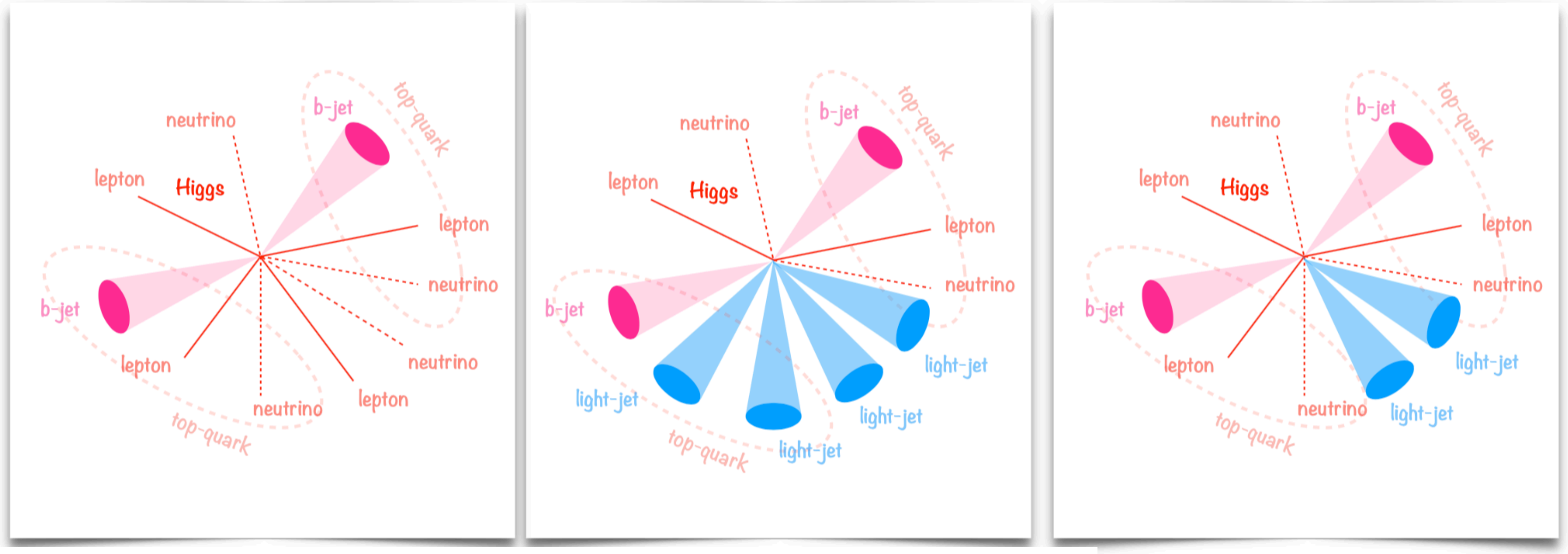
- Large number of final states which are typically very complex (mixture of b-jets, leptons, taus and photons)
- But, many different channels, also means different backgrounds and different systematic uncertainties and therefore also a strength!
- With the new Run at close to double centre-of-mass energy and increased statistics, changes in leading channels.

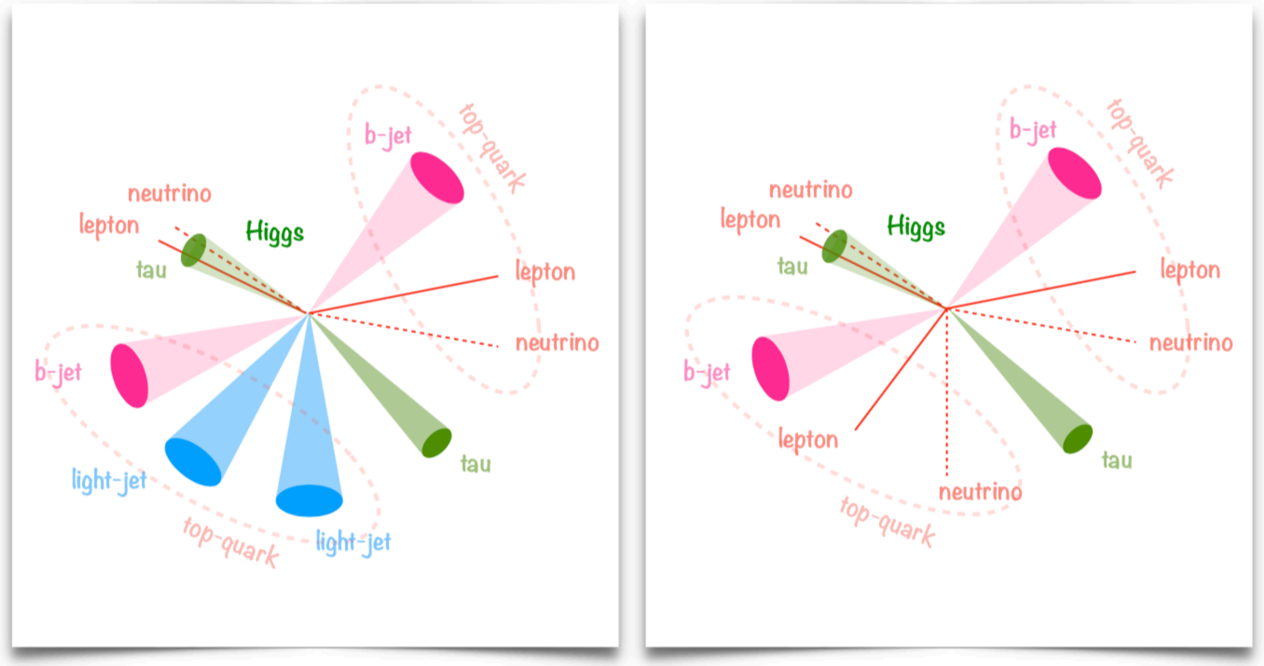


ttH(bb)

Very large backgrounds of top pair production associated with b jets

Dominated by background modelling uncertainties

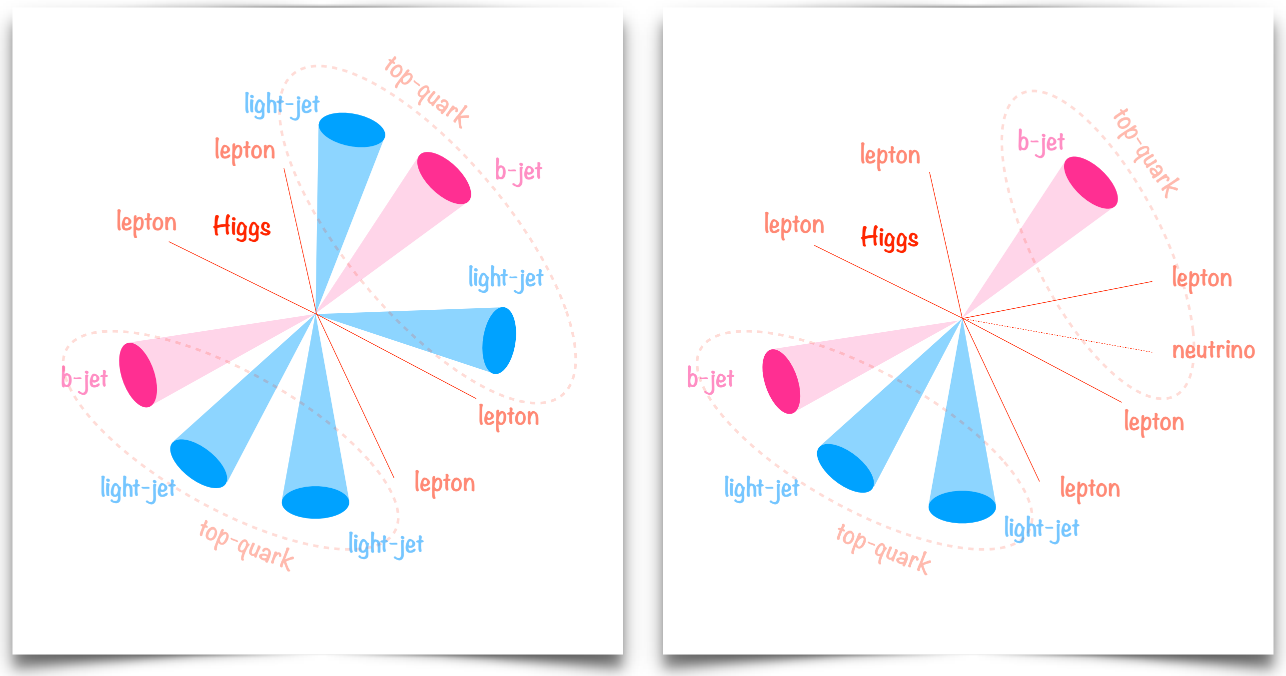




ttH(WW, ZZ and tau tau)

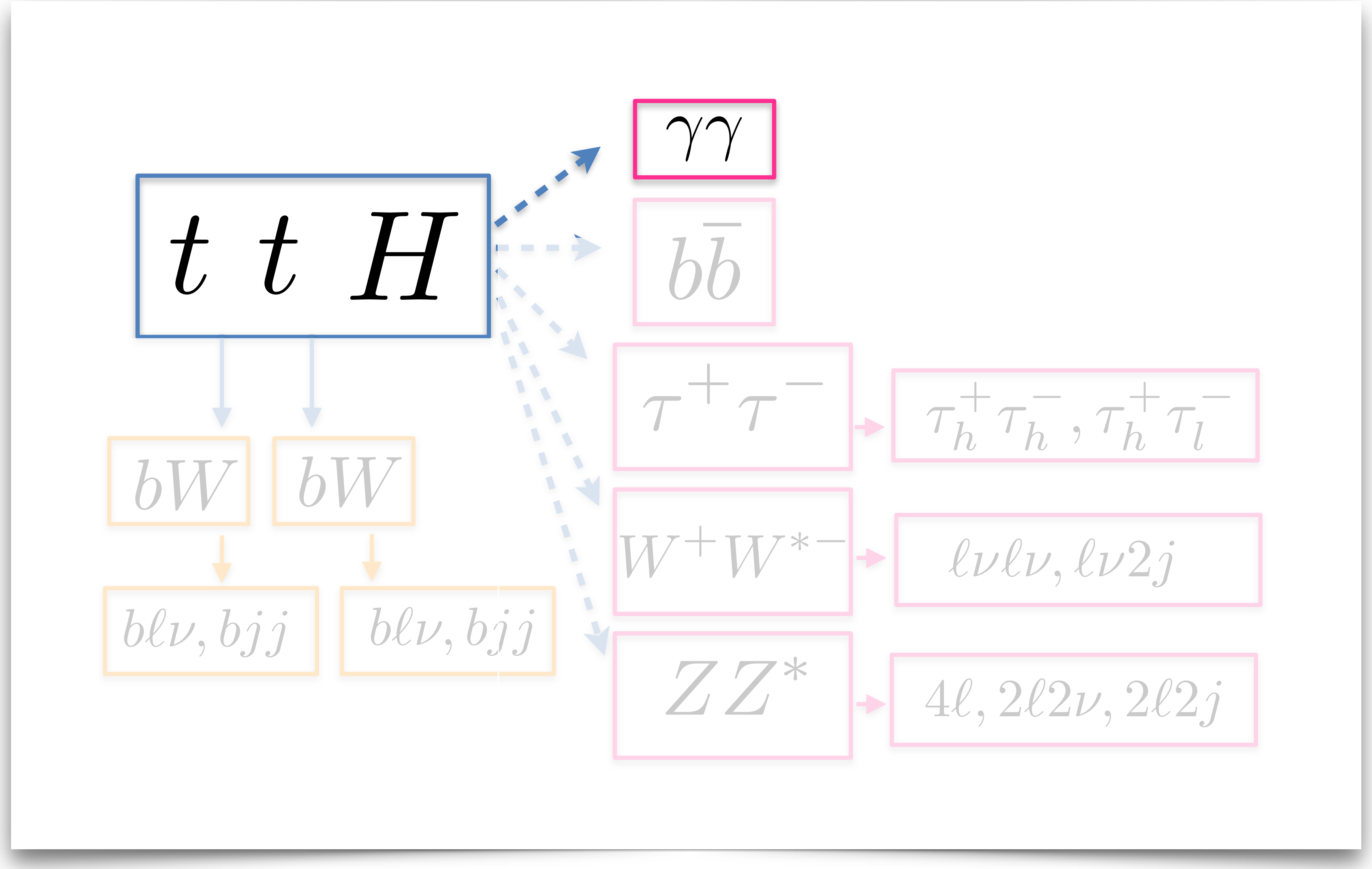
So-called multi-lepton channel

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

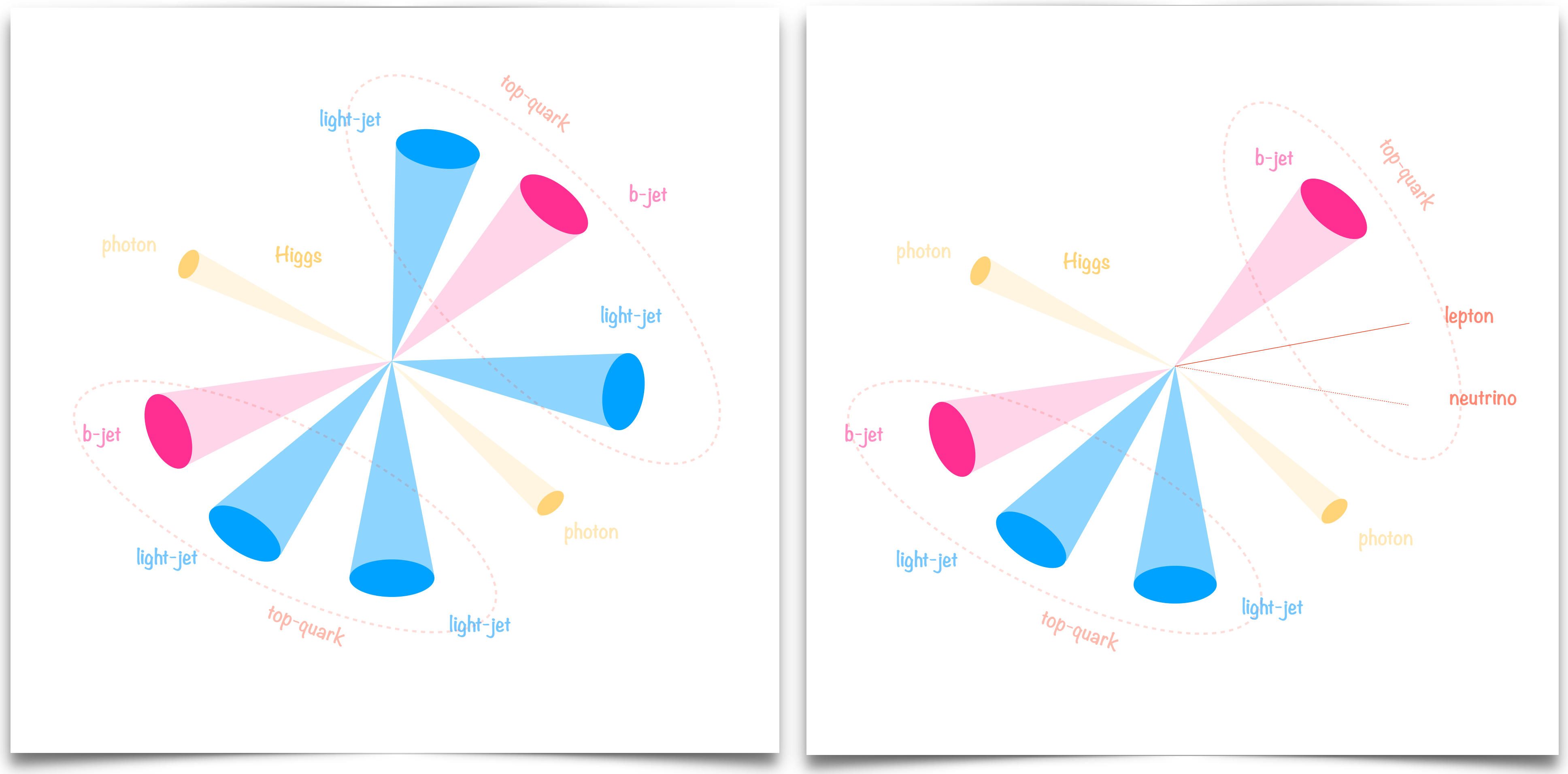


Direct probe of the top Yukawa coupling

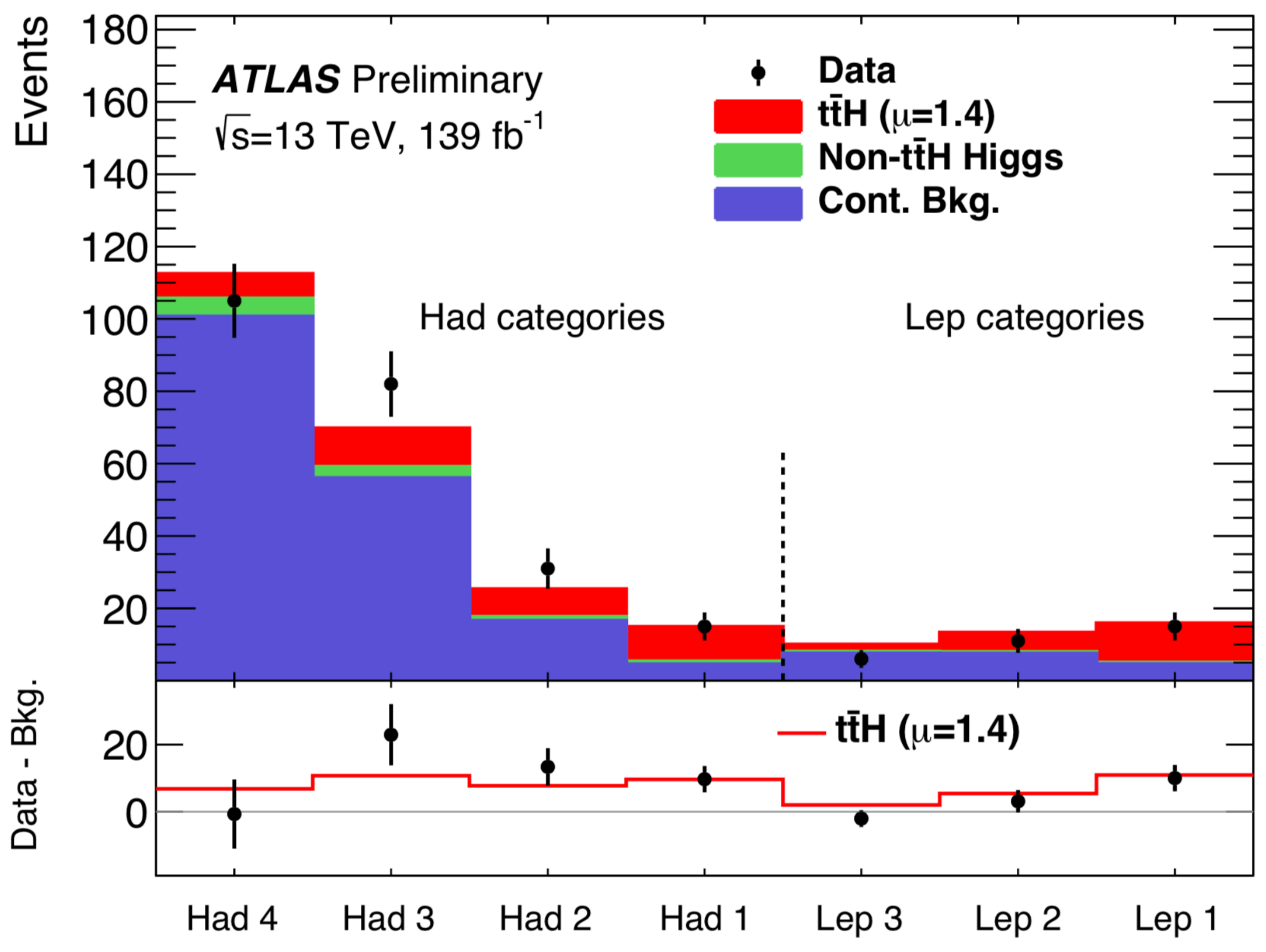
ttH Analyses at LHC: Massively Complex!

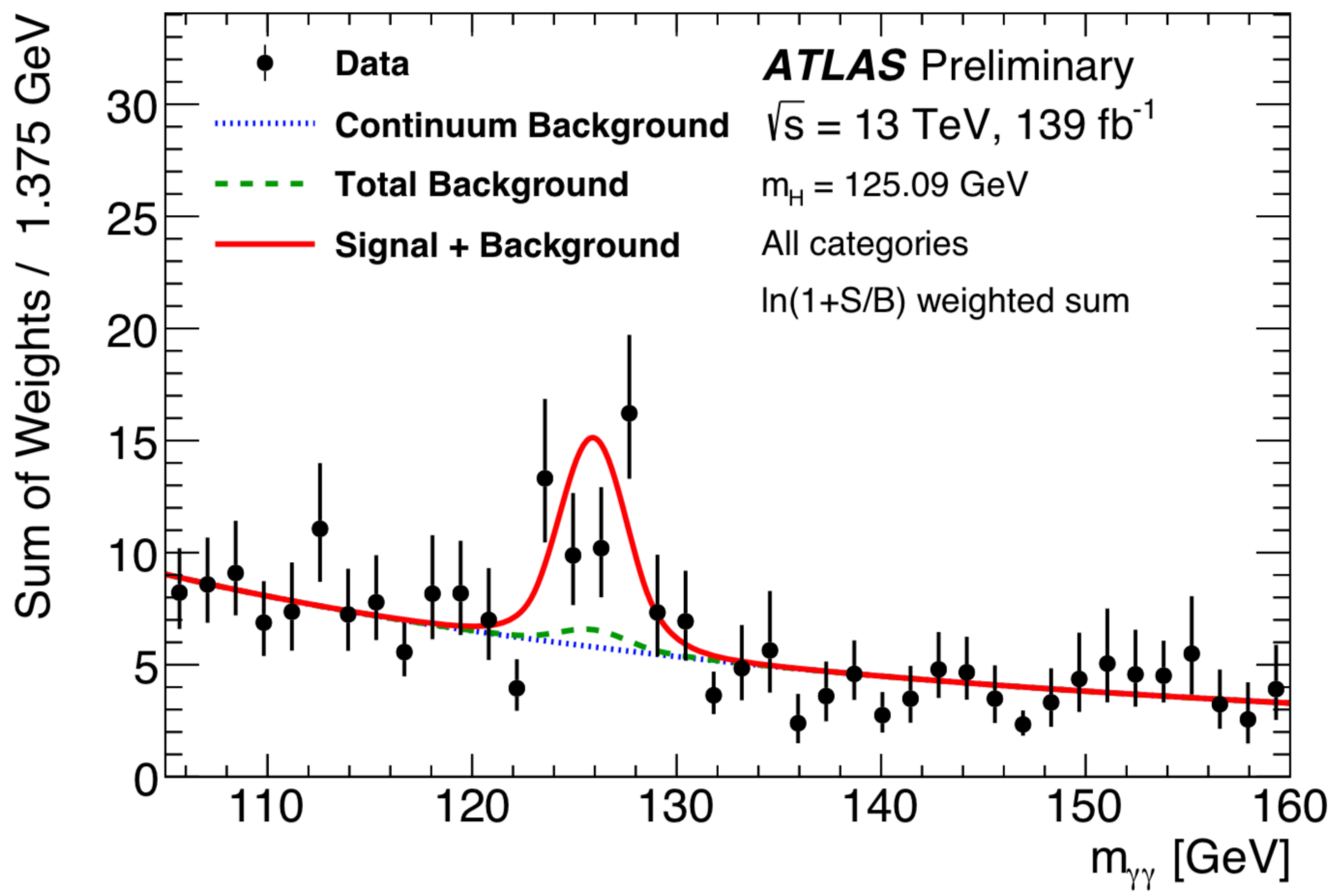


Currently most sensitive channel



Background and signal modelled using analytic functions.





Cross section dominated by statistical uncertainties:

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

Expected (4.2σ)

Observed 4.9σ

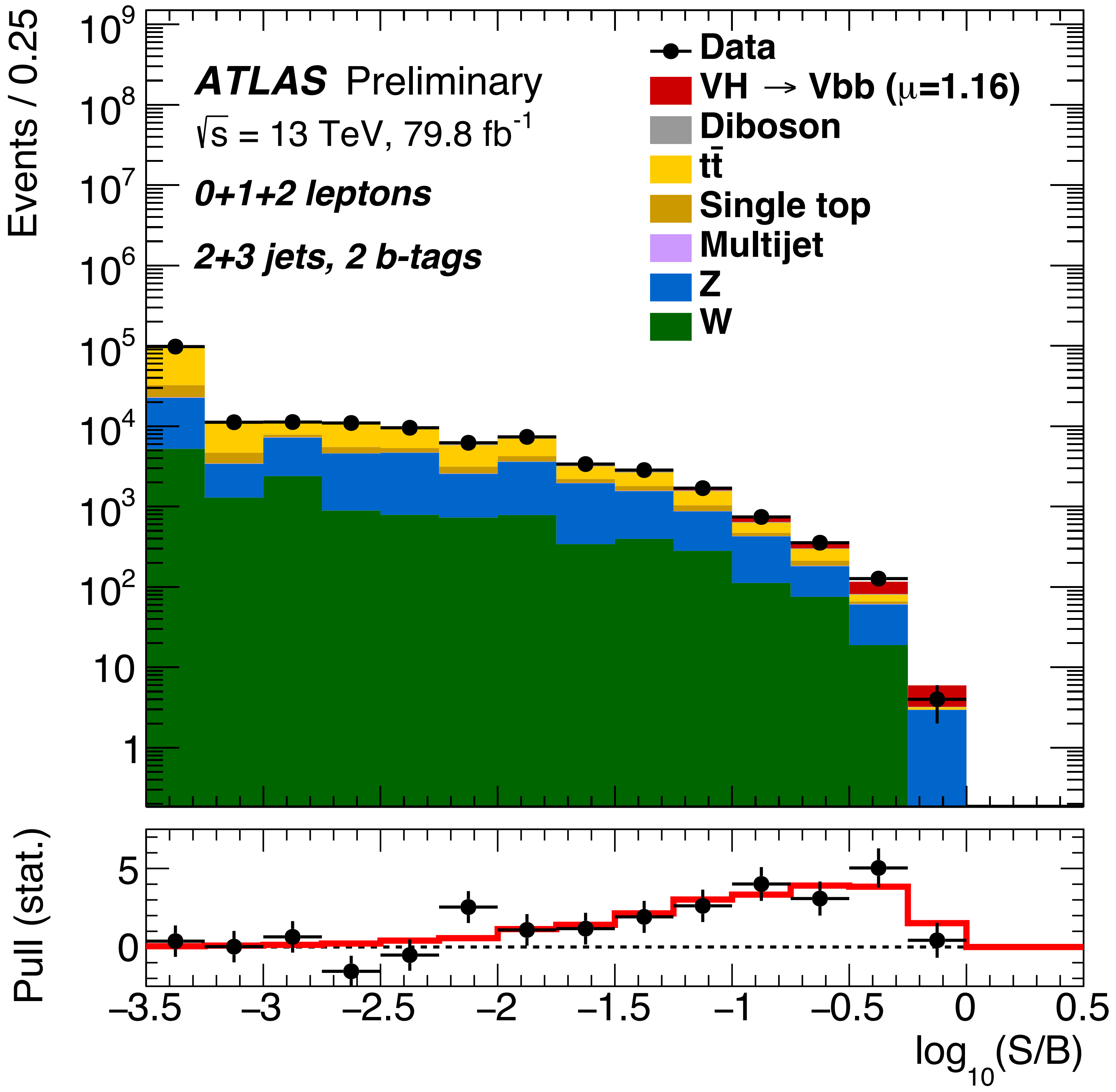
In combination with the other channels:

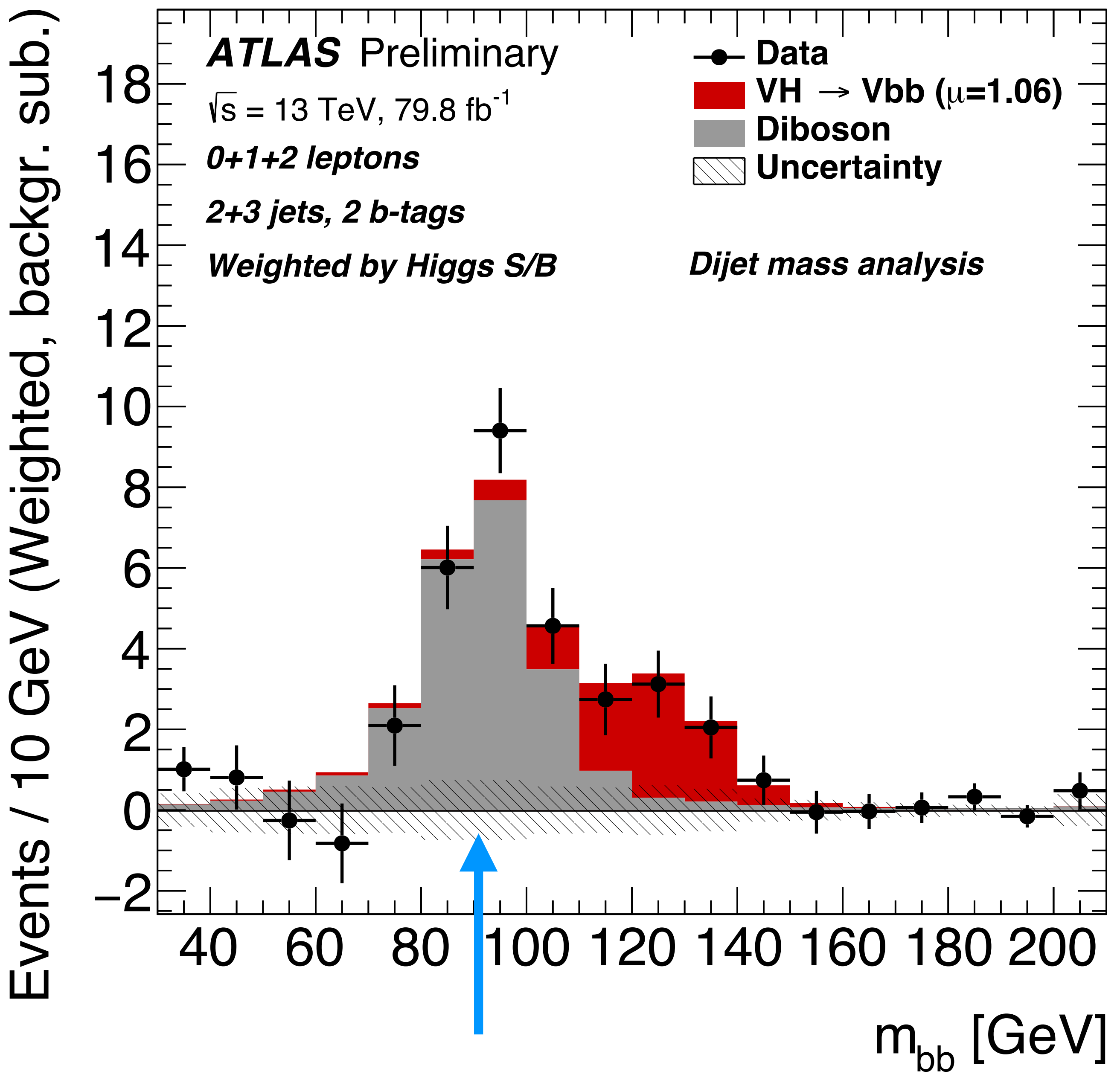
Expected 5.1σ

Observed 6.3σ

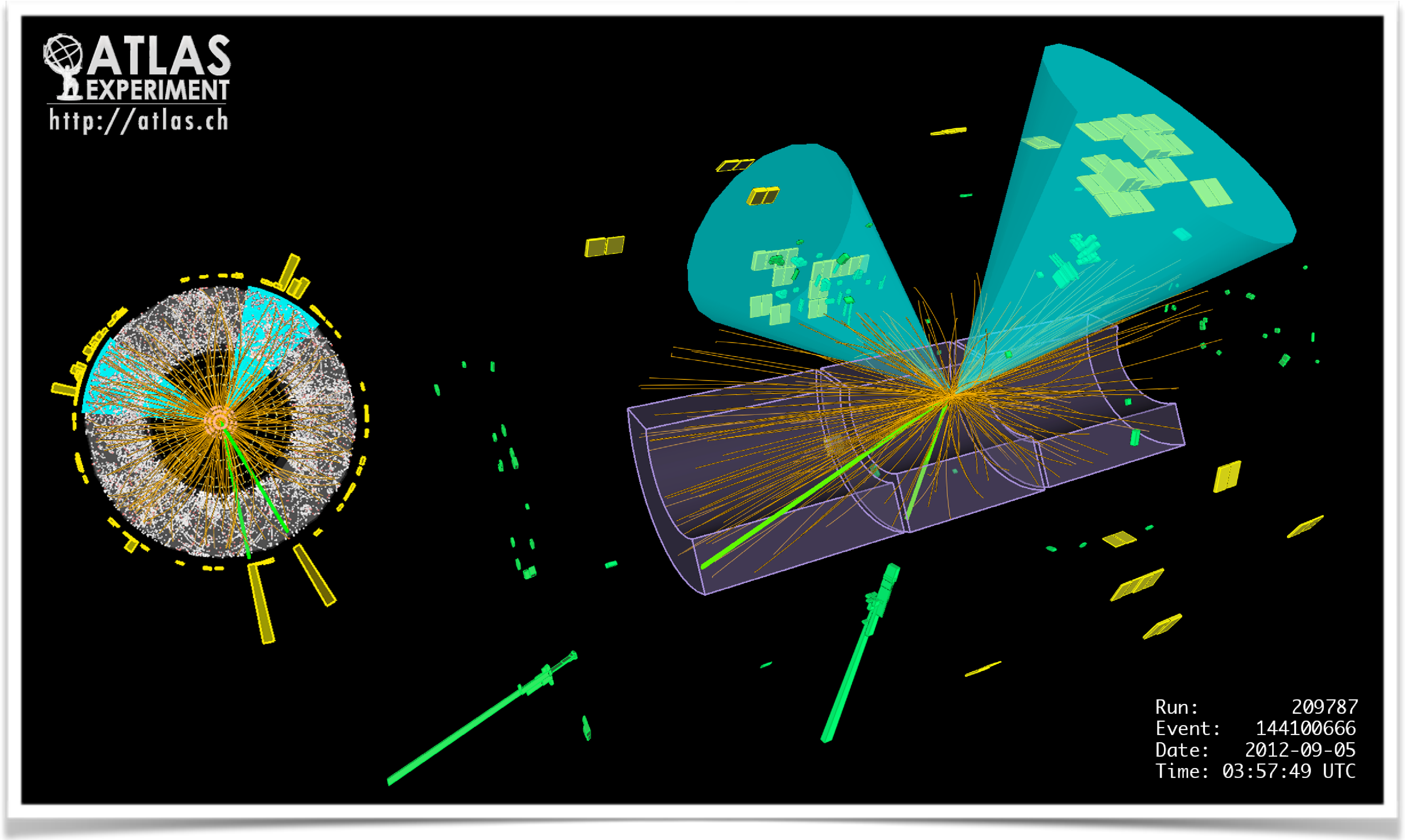
Observation!!

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!

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

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)

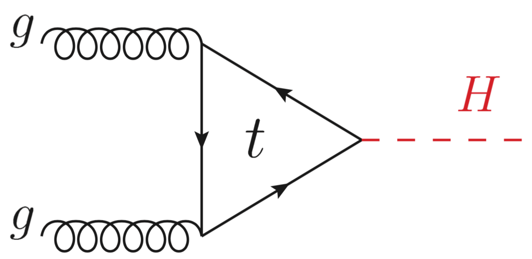
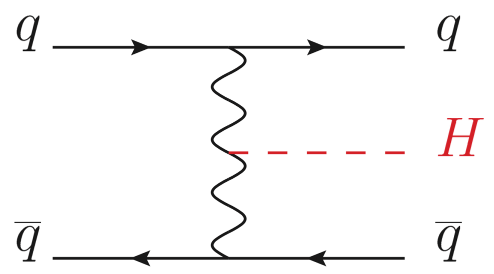
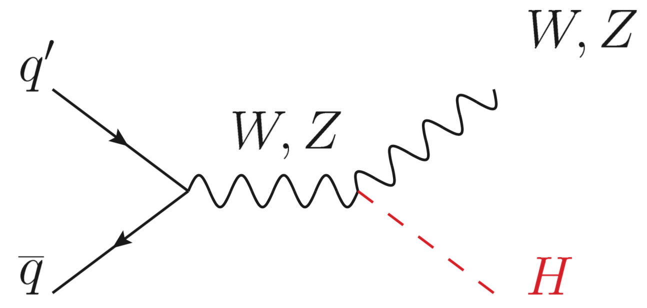
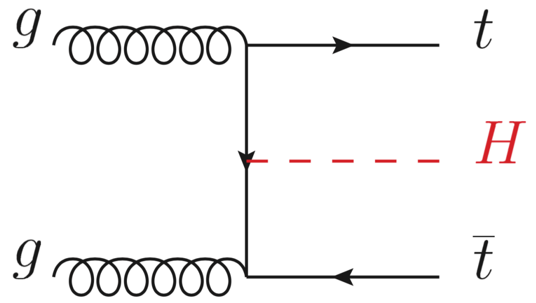
In combination with Run 1

5.4σ (observed) 5.5σ (expected)

Observation!!

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  ~4 M vets produced	VBF  ~300 k vets produced	VH  ~200 k vets produced	ttH  ~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

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.

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

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.

Introducing simple scale factors of the Standard Model couplings in a « naive » effective Lagrangian.

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

Simply reparametrise the mu values using the kappas!

For a complete description see (link) - Chapter 10

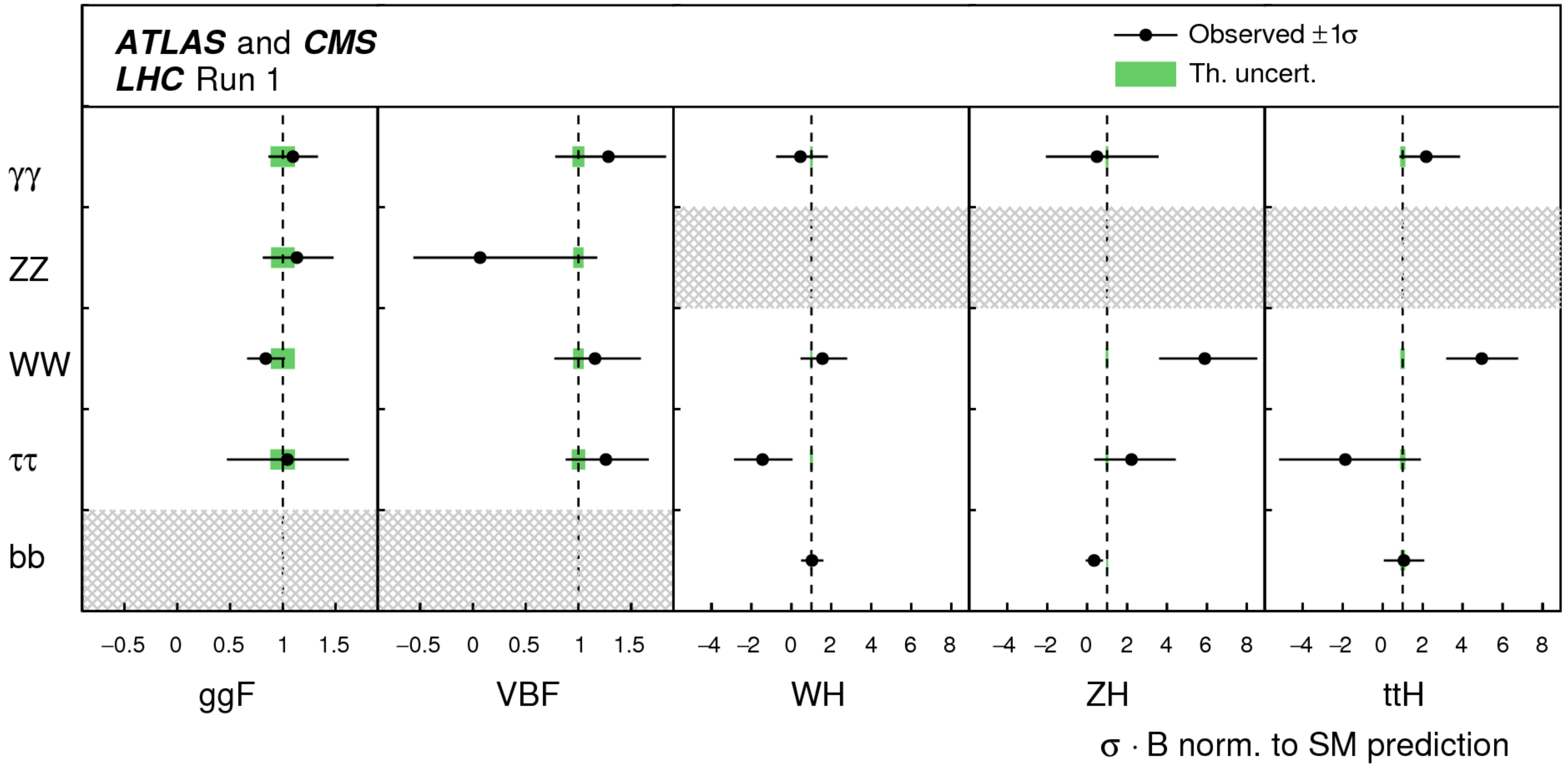
Overview of the Run 1 and Run 2 Couplings Measurements

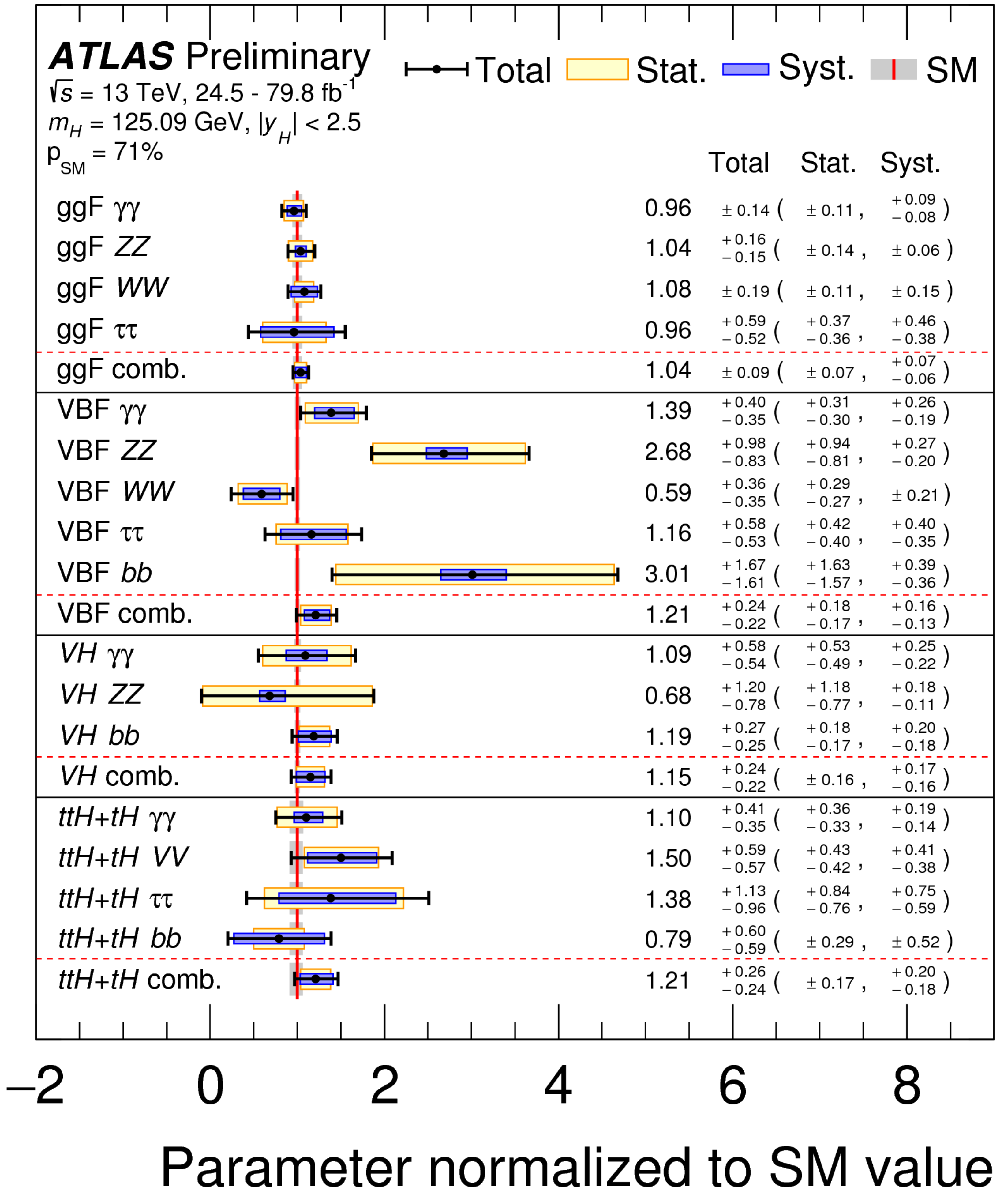
These measurement correspond to cross sections times branching fractions

$$\mu_{if} = \mu_i \mu_f$$

Run 2 measurements

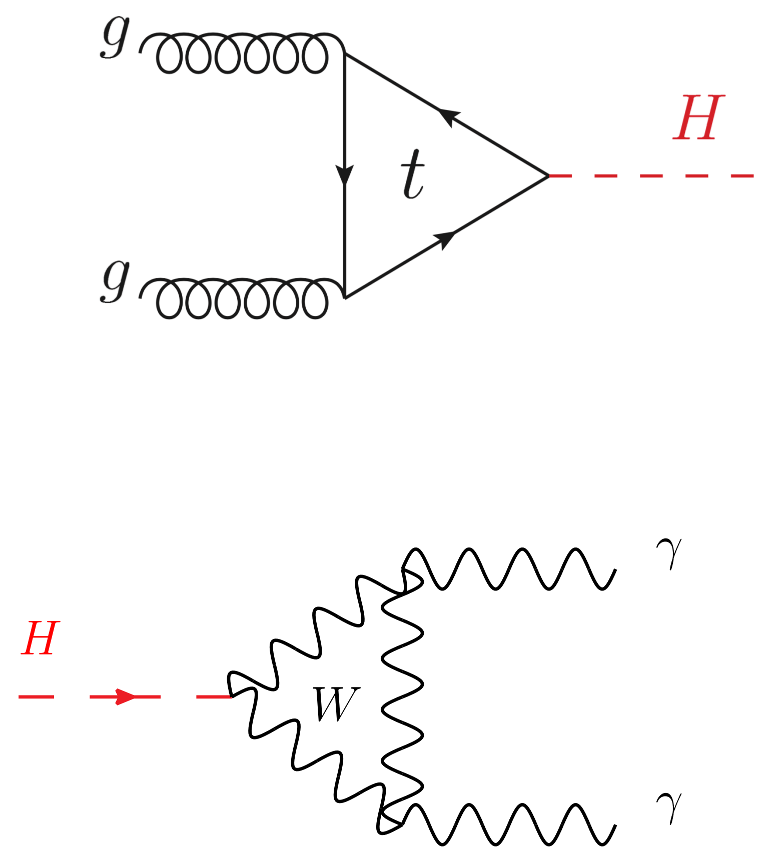
Run 1 measurements



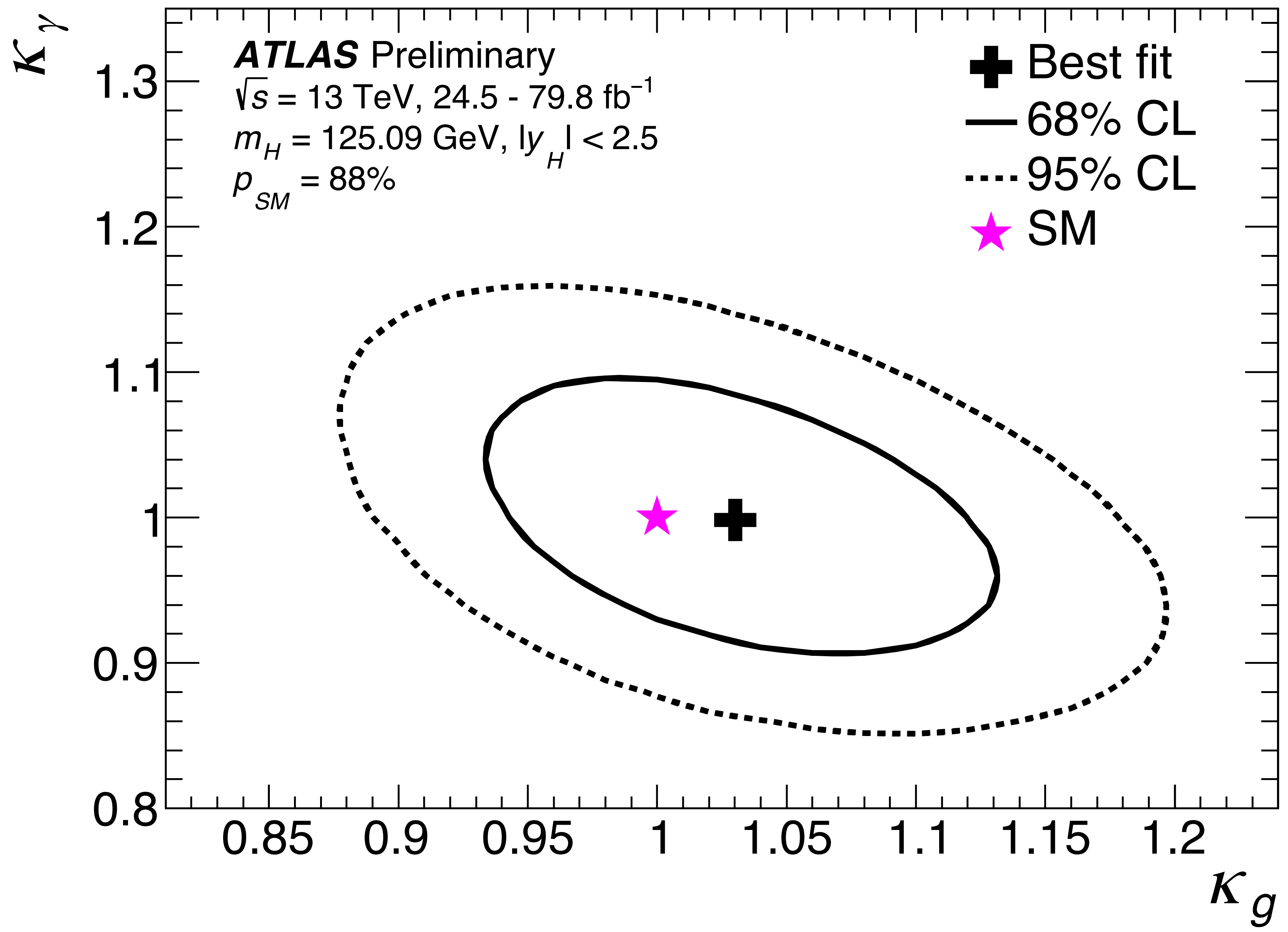


Run 2 Couplings Measurements

Choosing suitable assumptions to probe interesting new physics scenarios scenarios

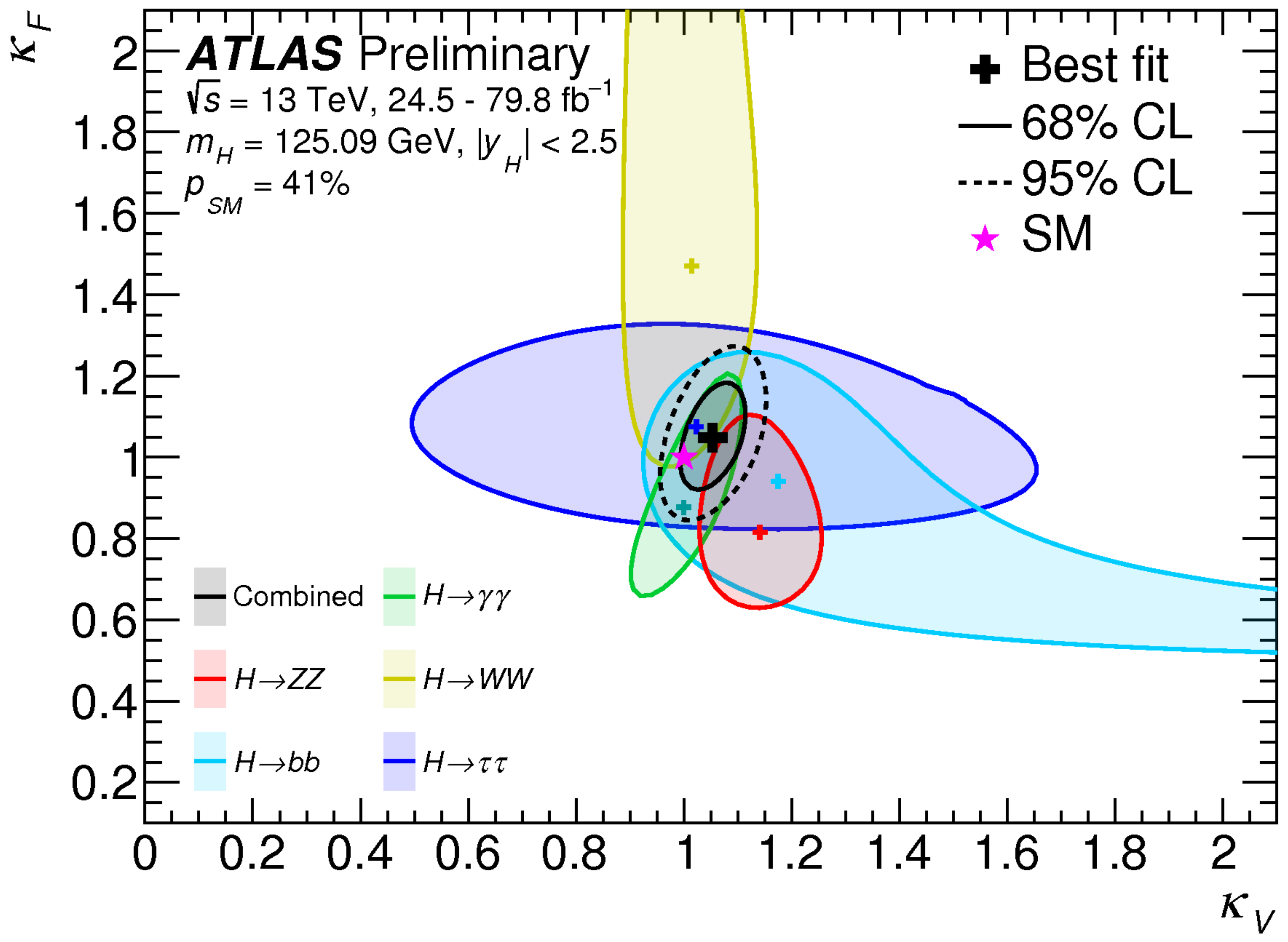


Probing new particles in the loops



All couplings are set to their Standard Model value except the effective couplings to the photon and the gluon (probing new physics in the loops).

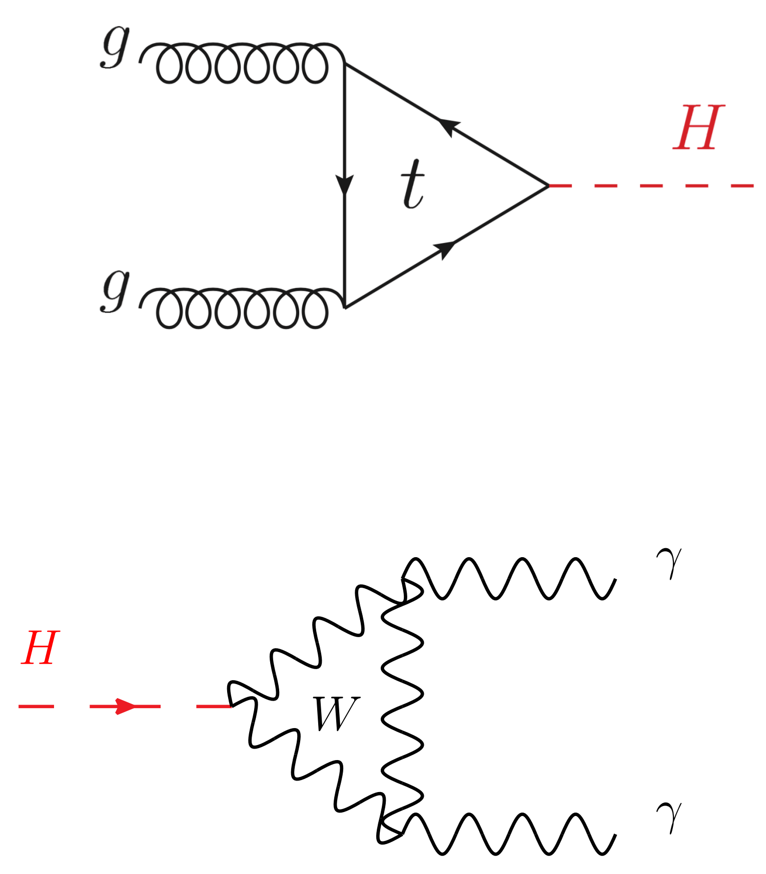
Probing the Gauge bosons vs fermions



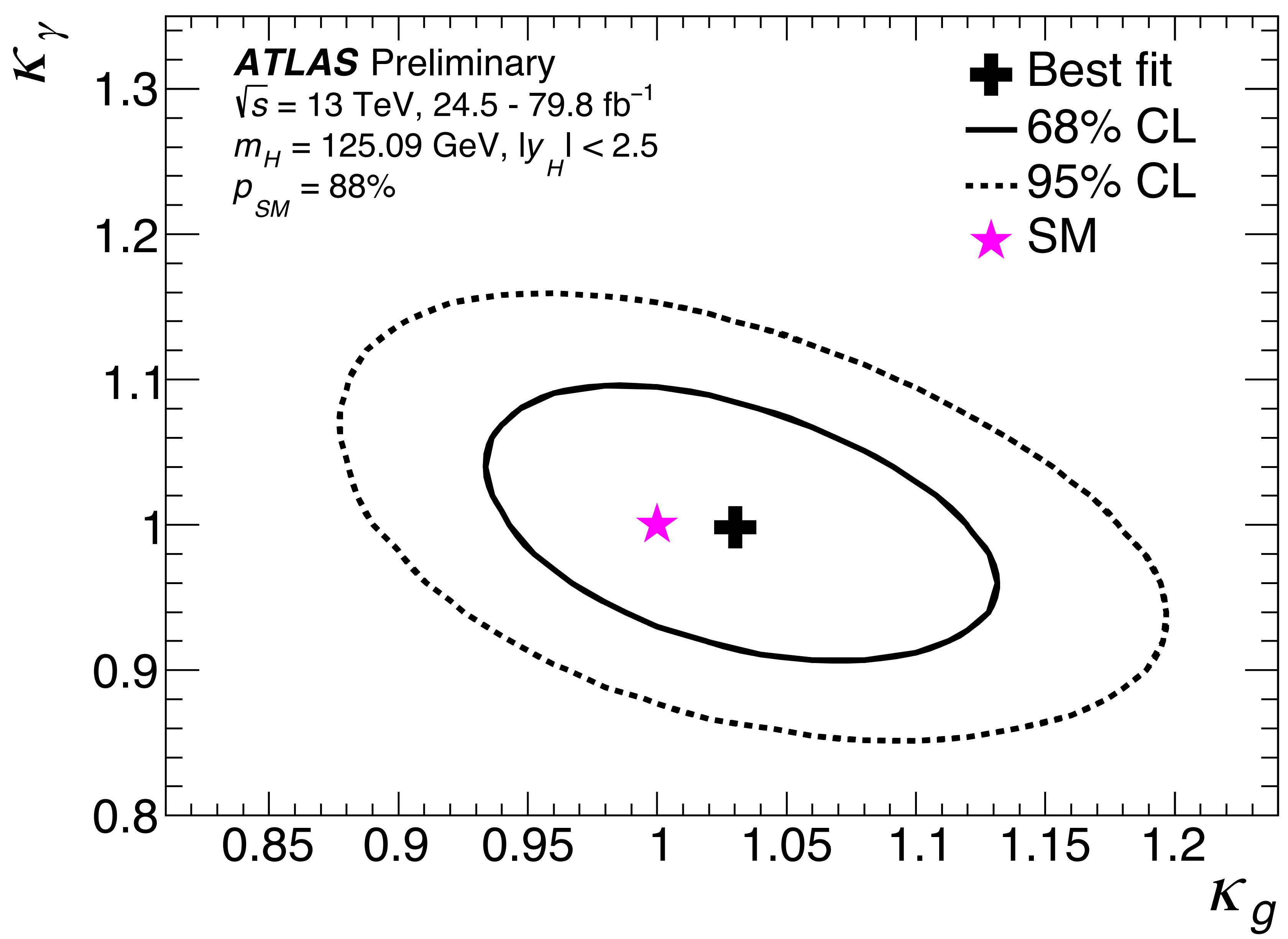
All fermion couplings are fixed to one parameter and similarly for all boson, the couplings to the gluons and the photons are resolved.

Run 2 Couplings Measurements

Choosing suitable assumptions to probe interesting new physics scenarios scenarios



Probing new particles in the loops



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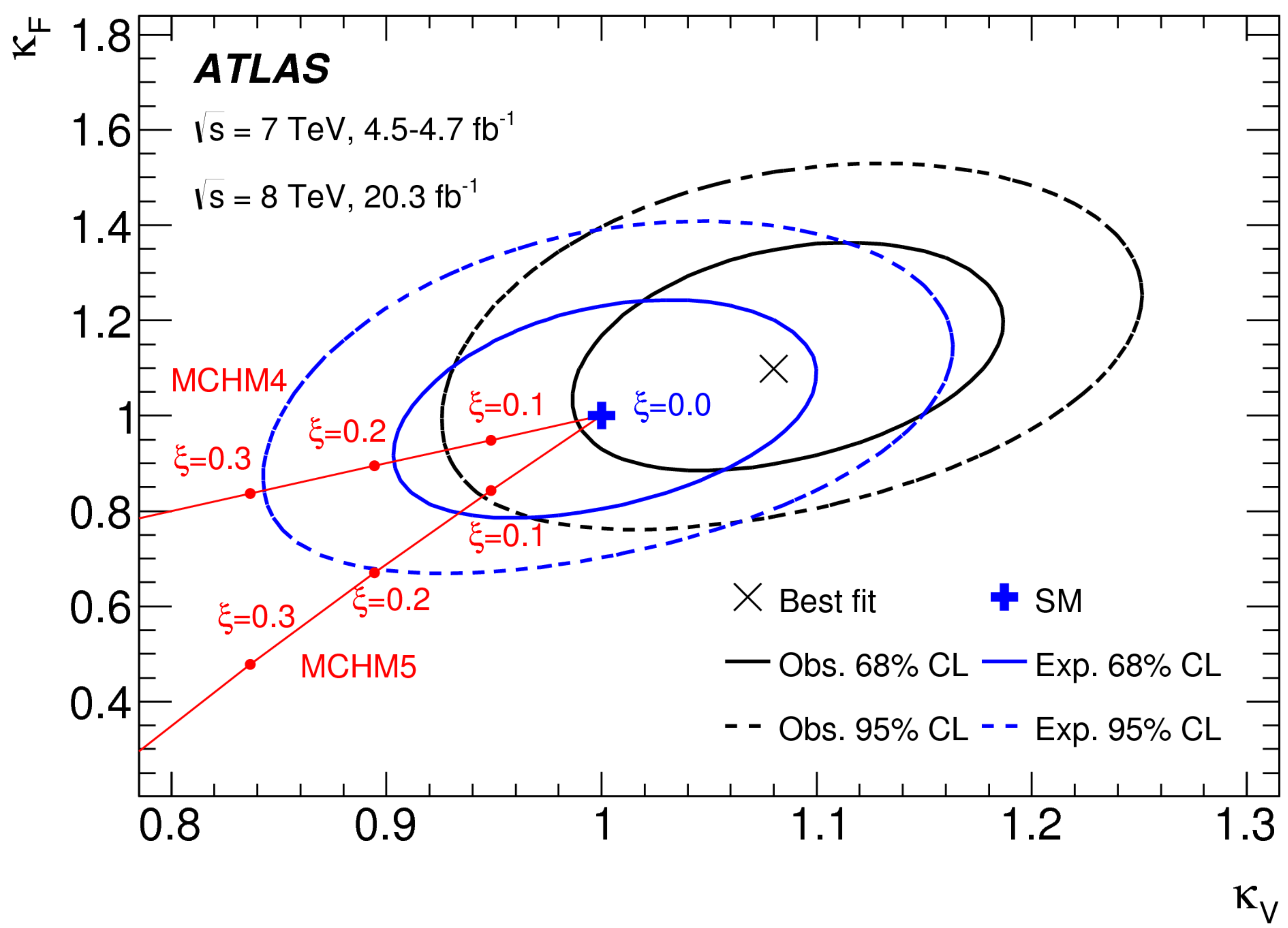
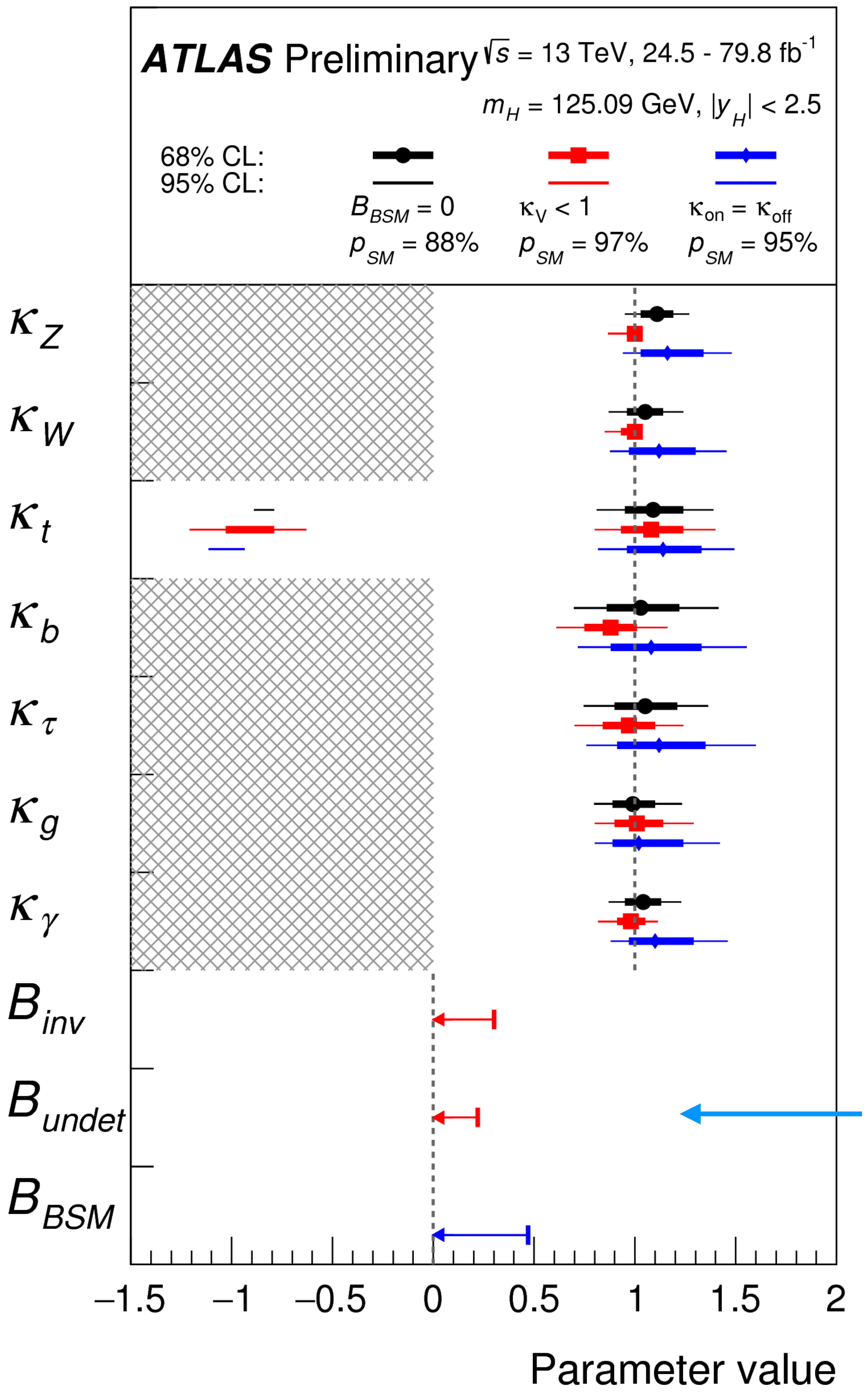
Probing the Gauge bosons vs fermions



All fermion couplings are fixed to one parameter and similarly for all boson, the couplings to the gluons and the photons are resolved.

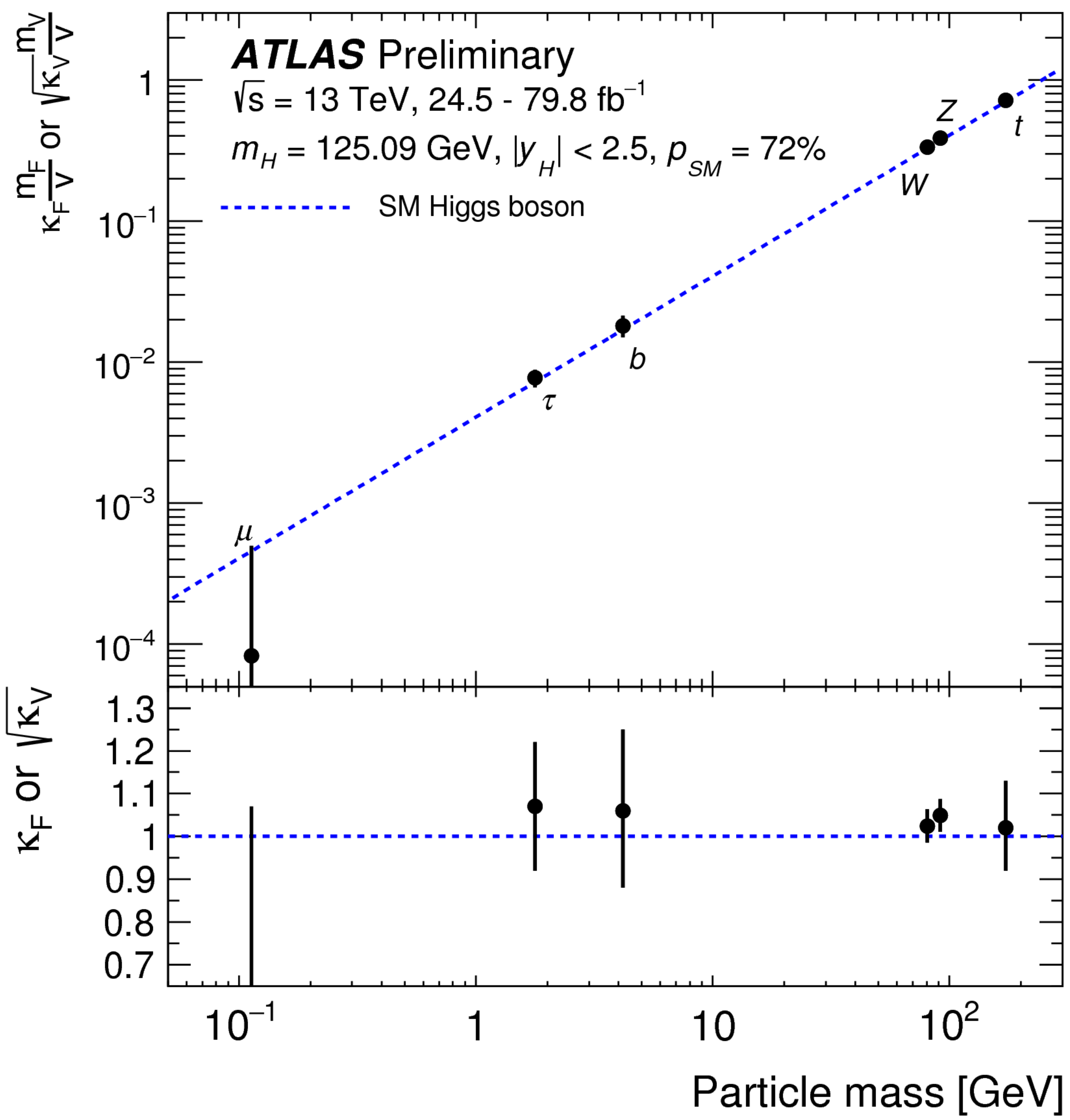
Constraining composite Higgs models

Run 2 Couplings Measurements



Couplings fit can constrain the total width with the assumption that kV<1

Caution not the same scale for gauge bosons and fermions

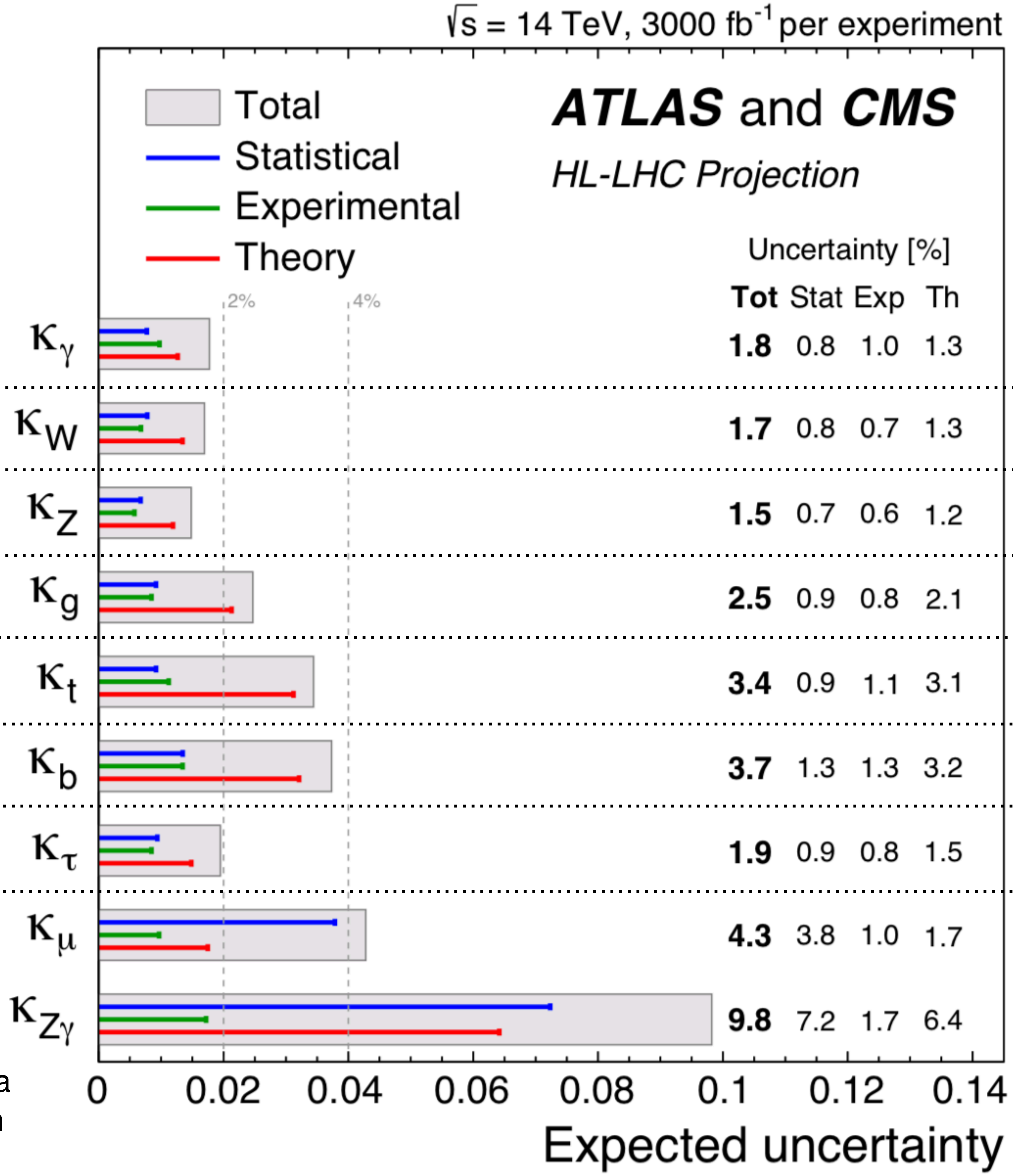


The Higgs boson is Standard Model like!

Combination of Main Decay and Production Channels Towards HL-LHC

Measurement of the couplings properties of the Higgs boson are key to further understand the nature of the Higgs boson (**is it composite?**)

	ATLAS - CMS Run 1 combination	ATLAS Run 2	HL-LHC
κ_γ	13%	9%	1.8%
κ_W	11%	8.6%	1.7%
κ_Z	11%	7.2%	1.5%
κ_g	14%	11%	2.5%
κ_t	30%	14%	3.4%
κ_b	26%	18%	3.7%
κ_τ	15%	14%	1.9%
	JHEP 08 (2016) 045	ATLAS-CONF-2019-04	HL-LHC YR 1902.00134



Experimental systematics non negligible

Measurements here assume no BSM in Higgs width

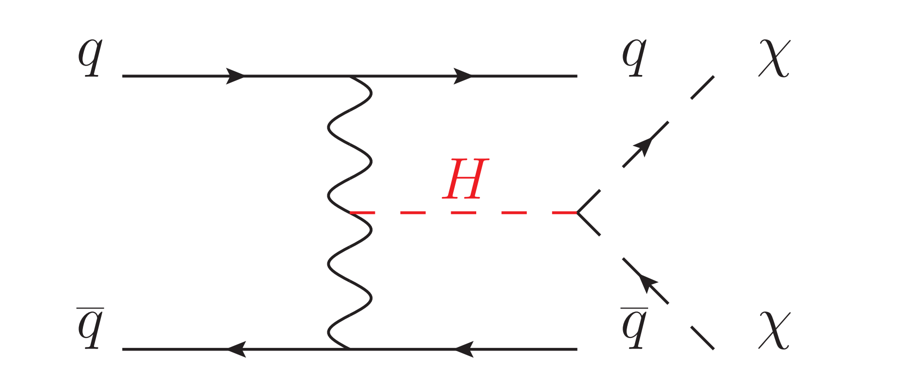
Improved TH and PDF uncertainties by a factor of 2 w.r.t. current (motivated from current PDF studies and current TH uncertainties assumptions)

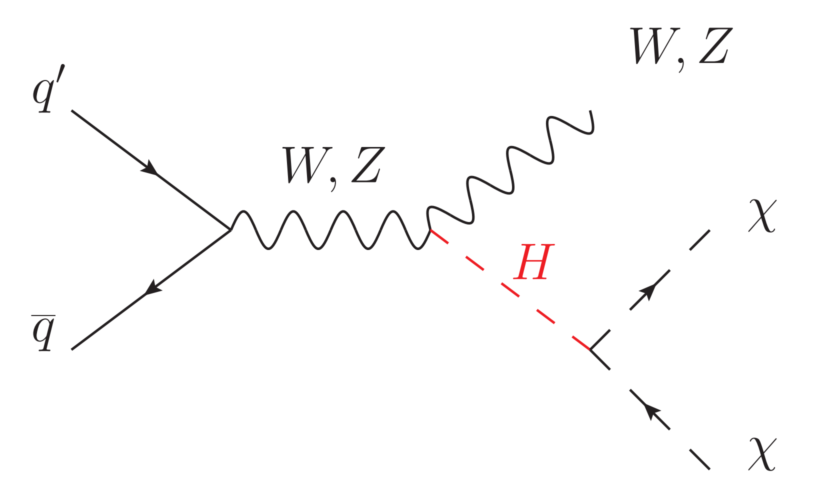
Searches for Rare decays and Rare Production modes

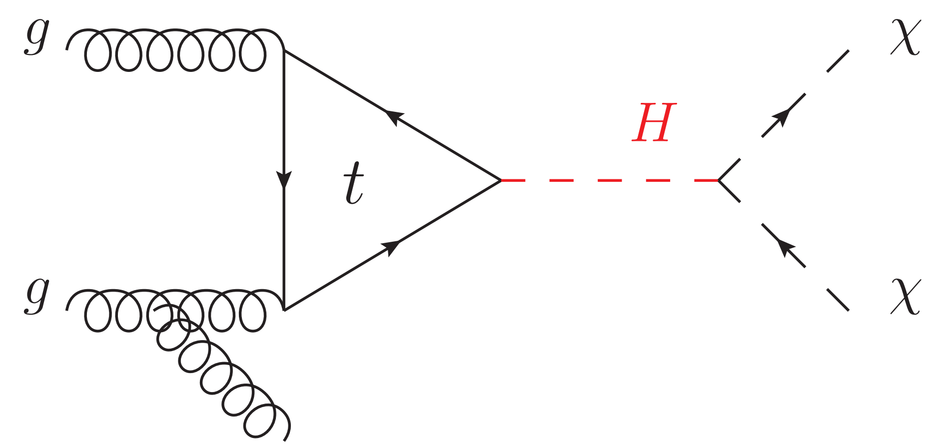
Rare Decays

Secon generation Yukawa

Invisible decays



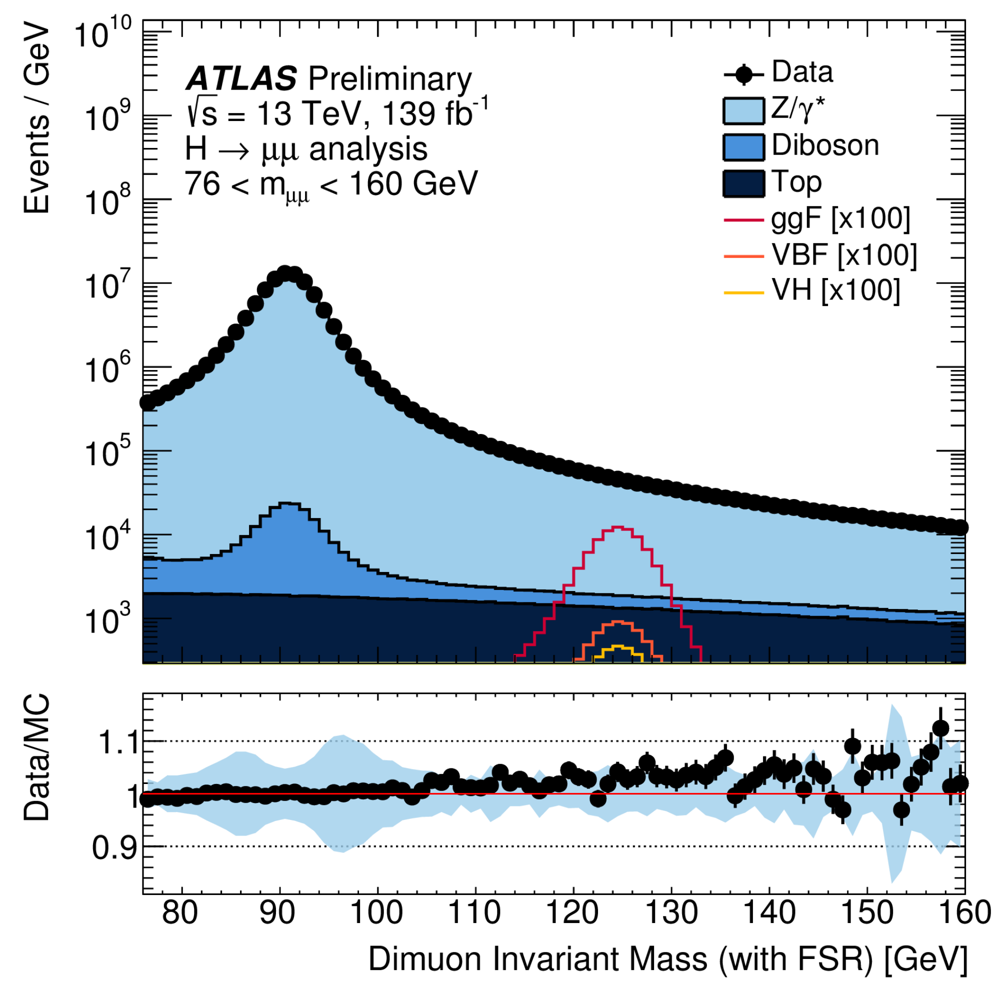


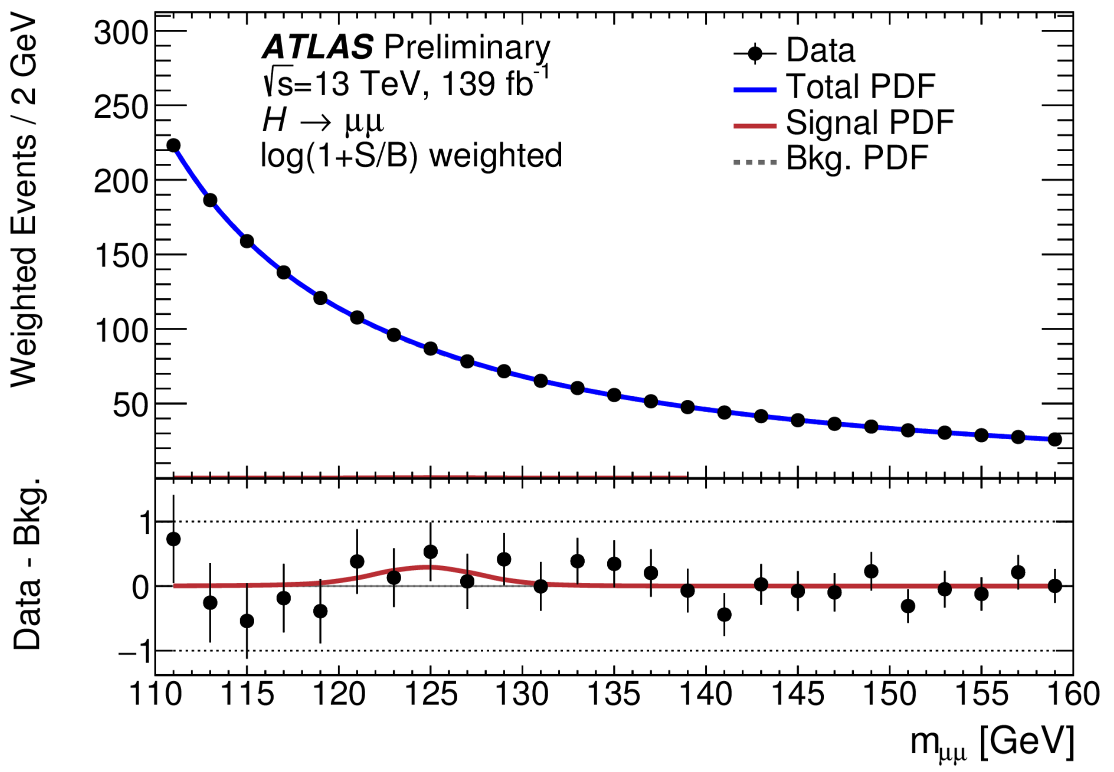


<20% @ 95% CL

HL-LHC 2.5%

di-muons



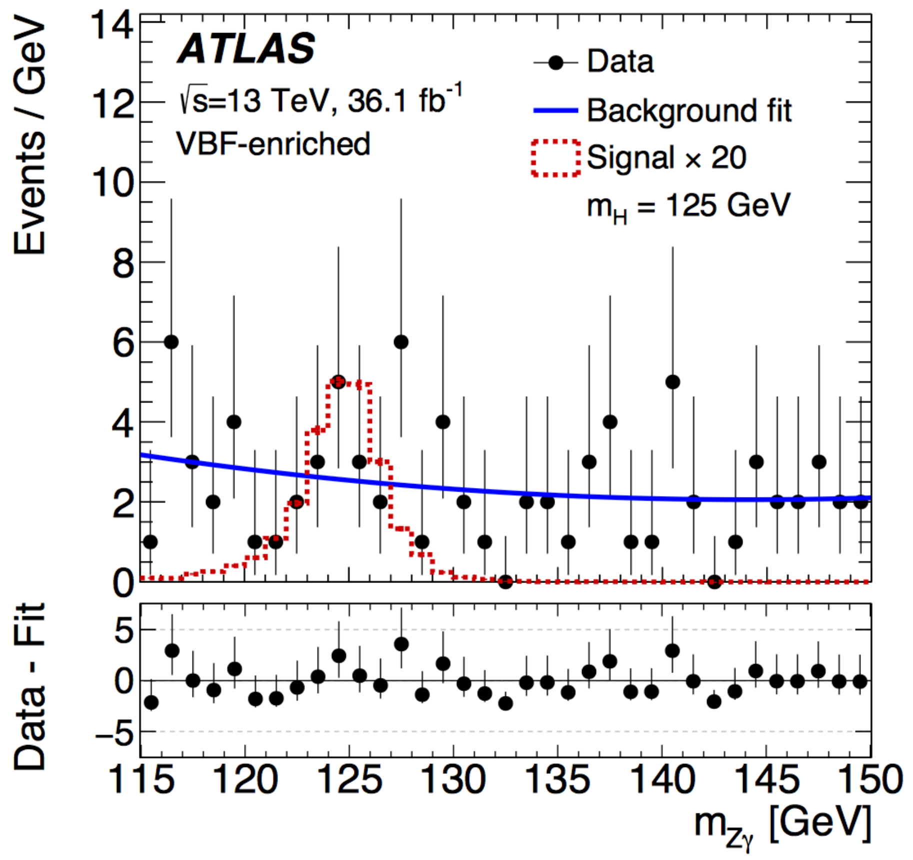


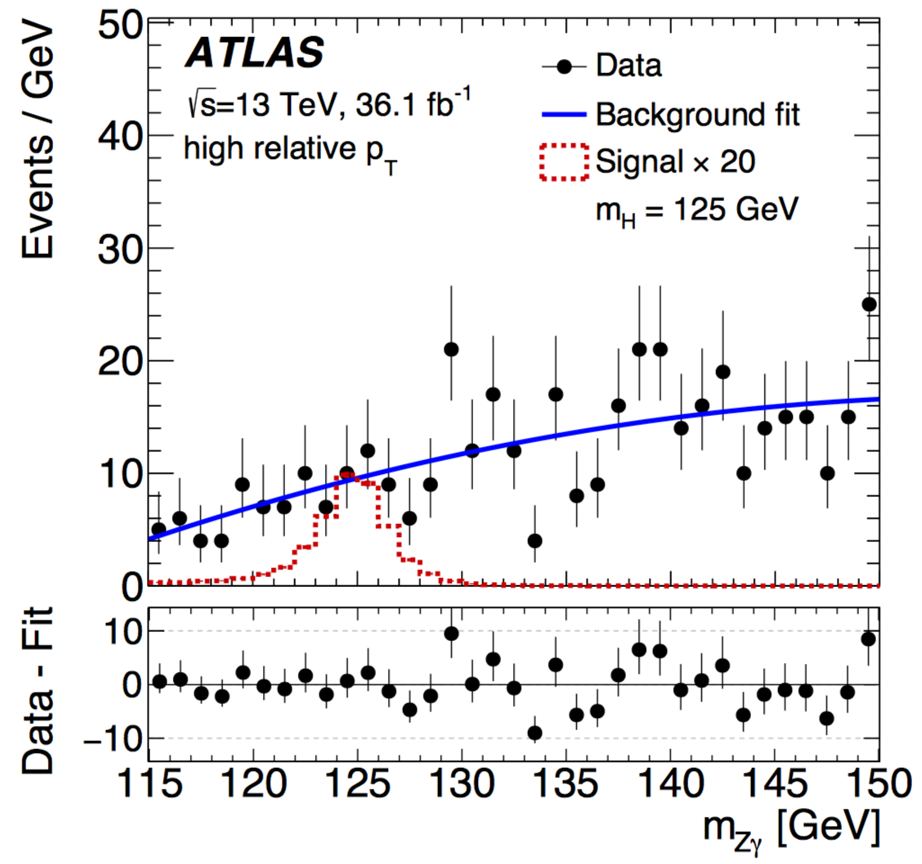
Limits currently ~2 x SM

0.8σ observed (1.5σ exp)

HL-LHC **~5%**

Z-photon

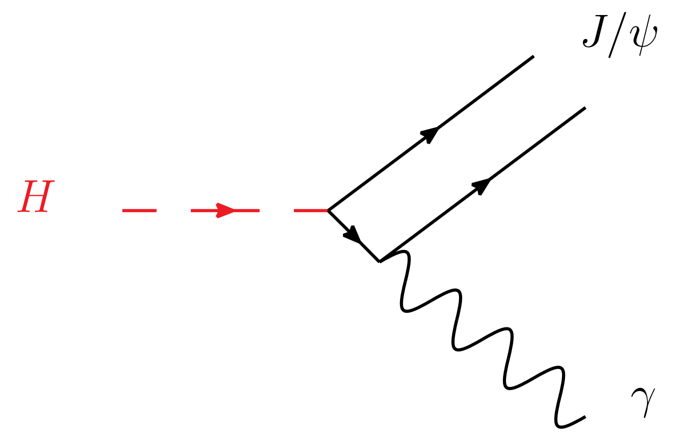




Limits currently ~6 x SM

HL-LHC **~10%**

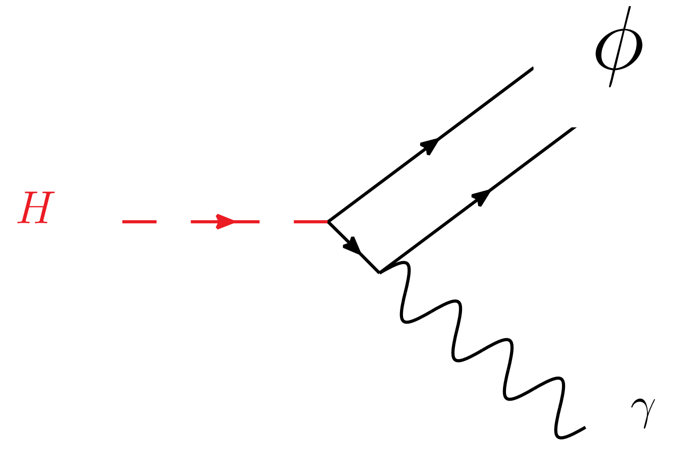
Quarkonia-photon



Potentially sensitive to charm Yukawa

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

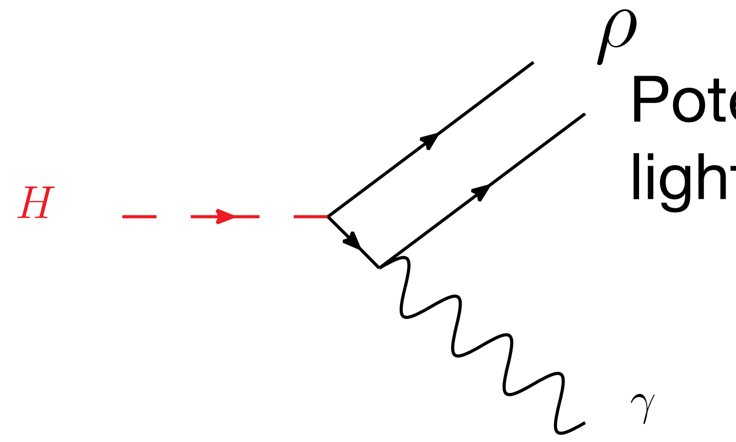
Higgs ~400 x SM



Potentially sensitive to strange Yukawa

$K^+K^-\gamma$

Higgs ~200 x SM



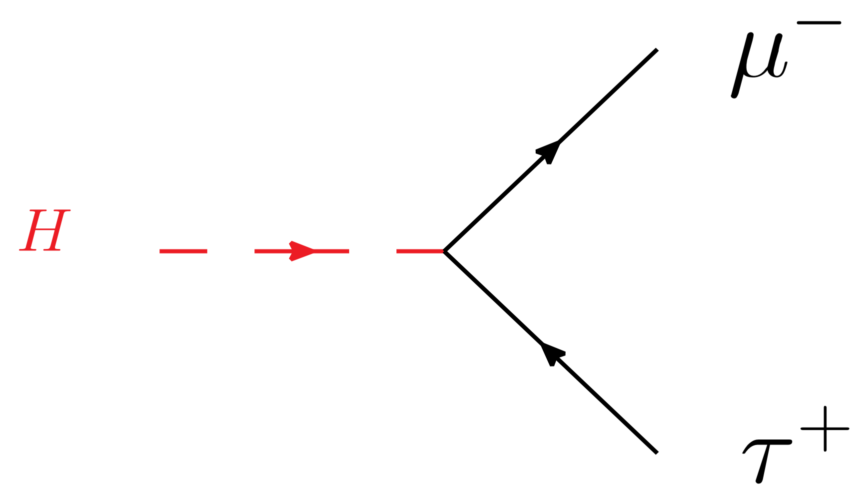
Potentially sensitive to light Yukawa

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

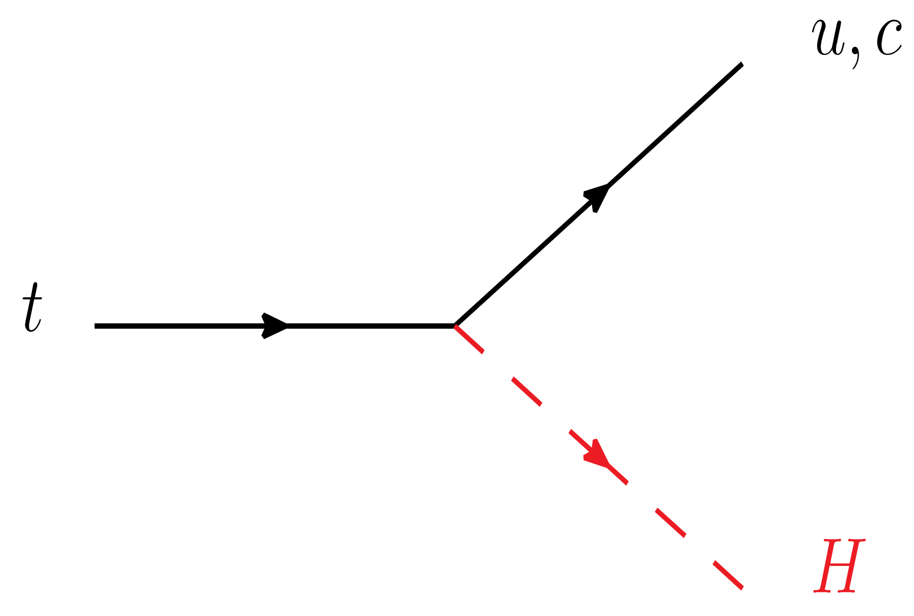
Higgs ~50 x SM

More rare decays and production Modes

Lepton flavor violating decays



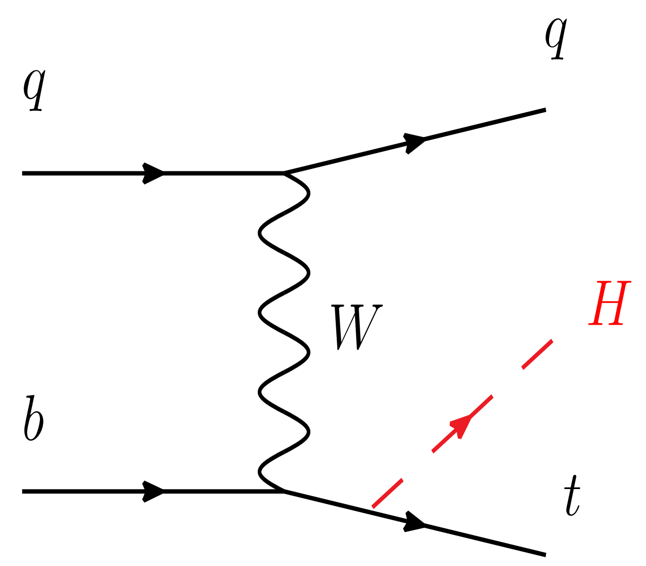
Flavor changing neutral curent decays of the top quark

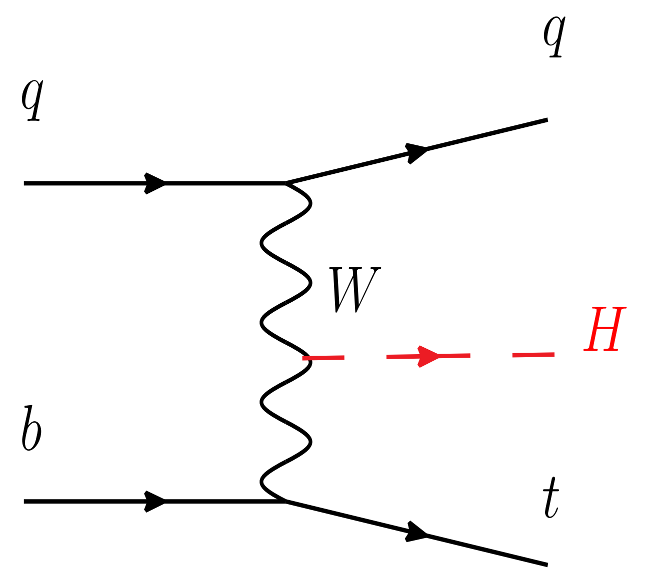


Various decay channels of the Higgs boson (diphoton, bb)

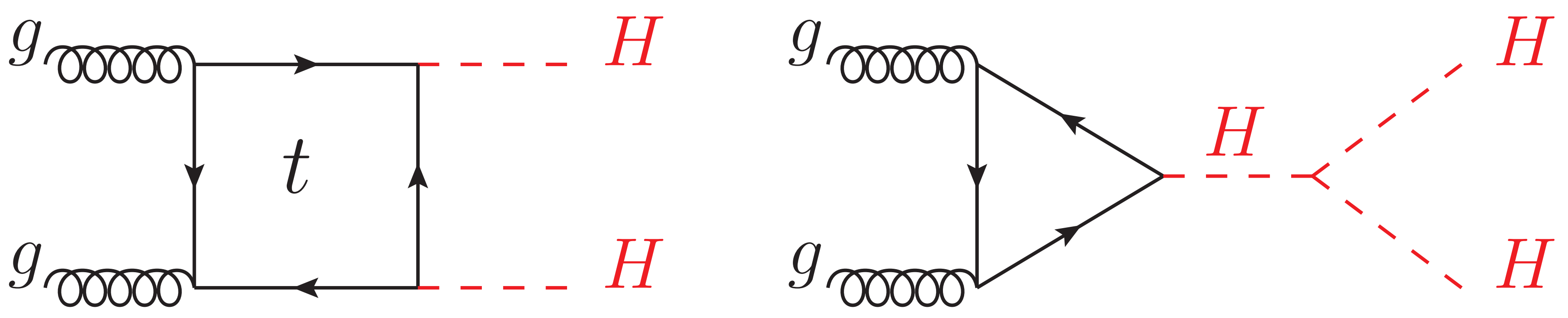
Single top associated production

Tree level interference between W and top





Double Higgs Production and Higgs Self Coupling



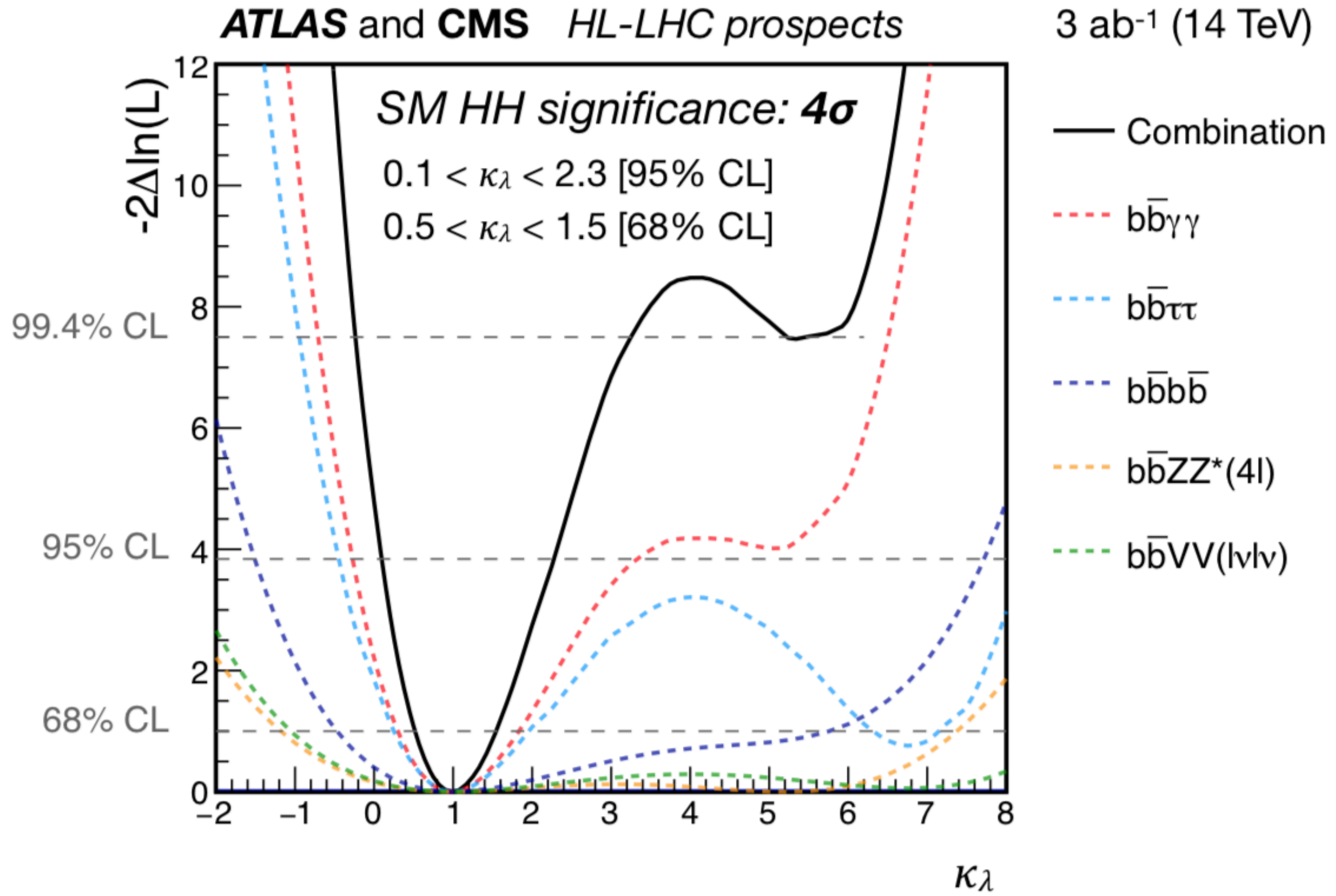
- The total production cross section is very small, huge amount of recent work to improve the prediction at full NLO (differential)!
- **Multiple channels investigated:** depending on the both Higgs decays considering (bb, yy, tautau, WW)
- Evolution of sensitivities has brought interesting surprises.

exp.	WW $\gamma\gamma$	bb $\gamma\gamma$	bb $\tau\tau$	bbWW	bbbb
$\sigma \times B$	0.1 %	0.26 %	7 %	25 %	34 %
ATLAS	<747 (386)	<22 (28)	<13 (15)	-	<13 (21)
CMS	-	<24 (19)	<30 (25)	<79 (89)	<75 (37)

CMS combination $\sigma_{HH} < 13 \times \sigma_{SM} \quad (15 \text{ exp.})$

ATLAS combination $-5.0 < \kappa_\lambda < 12.1$ (Differential HH information taken into account)

At HL-LHC

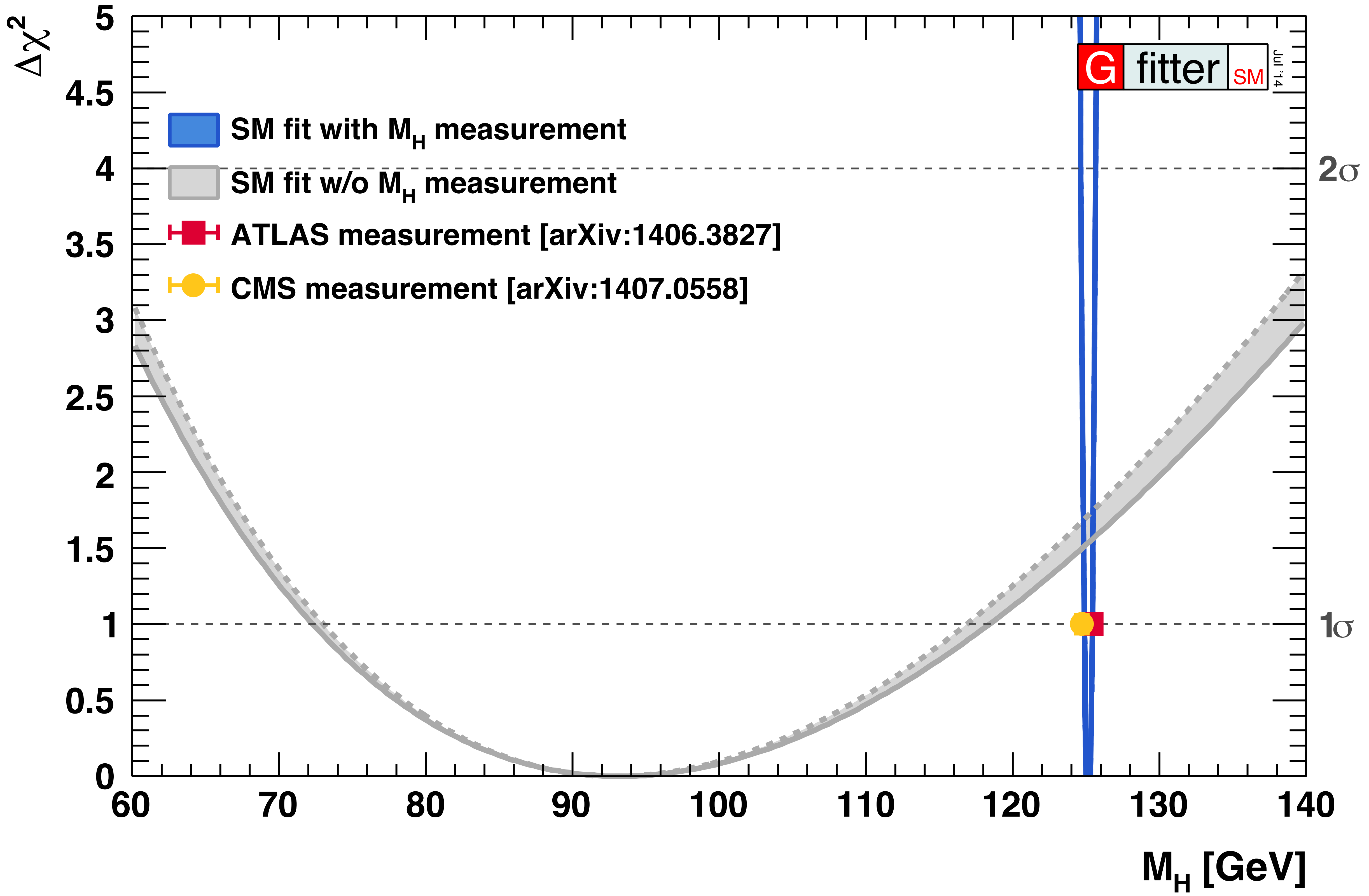


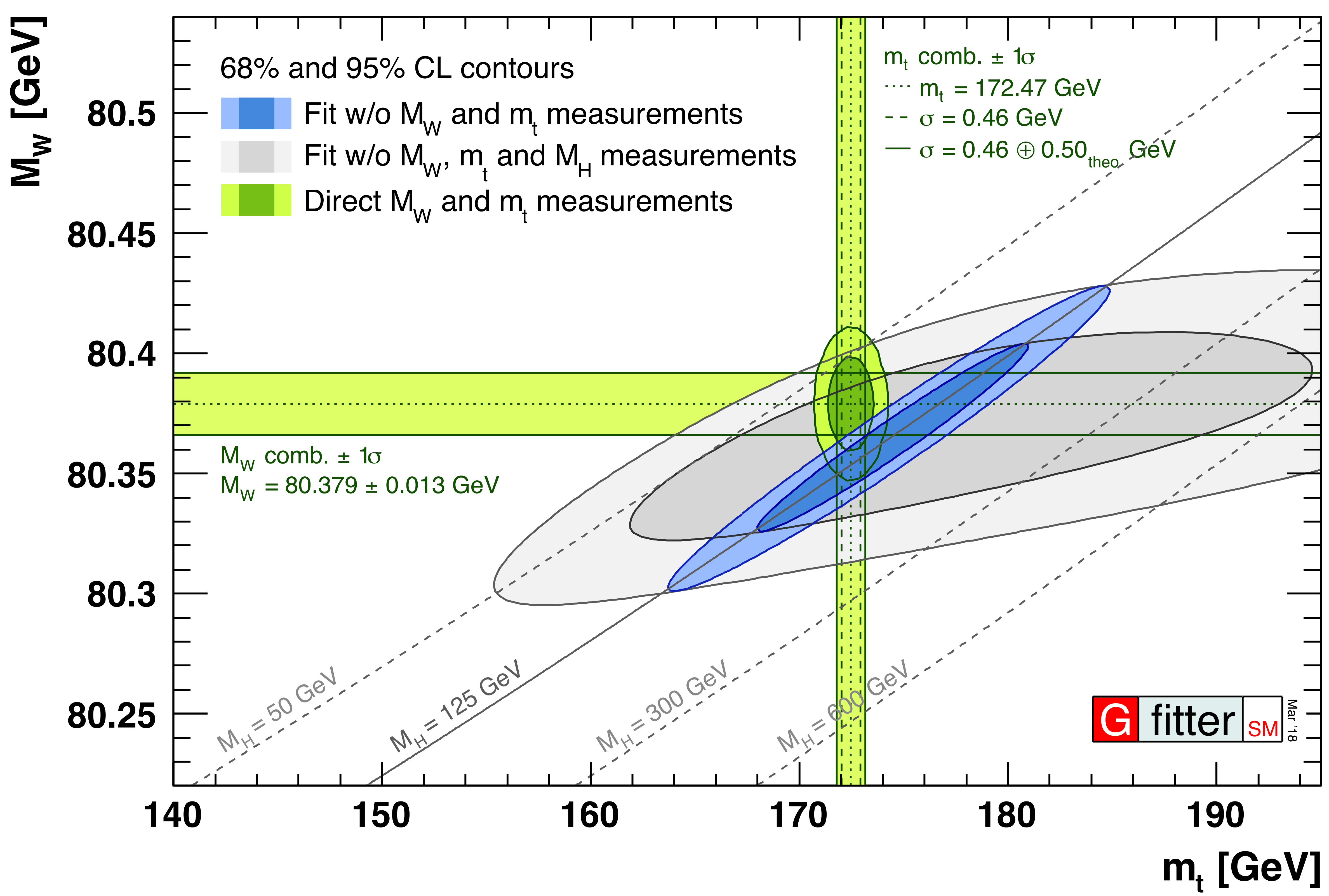
$$0.5 < \kappa_\lambda < 1.5$$

- Not quite 5σ observation of HH signal.
- significant exclusion of the secondary minimum.
- Closing up on a measurement, though not yet decisive.

Implications

Implications (I) – Global fit of the Standard Model





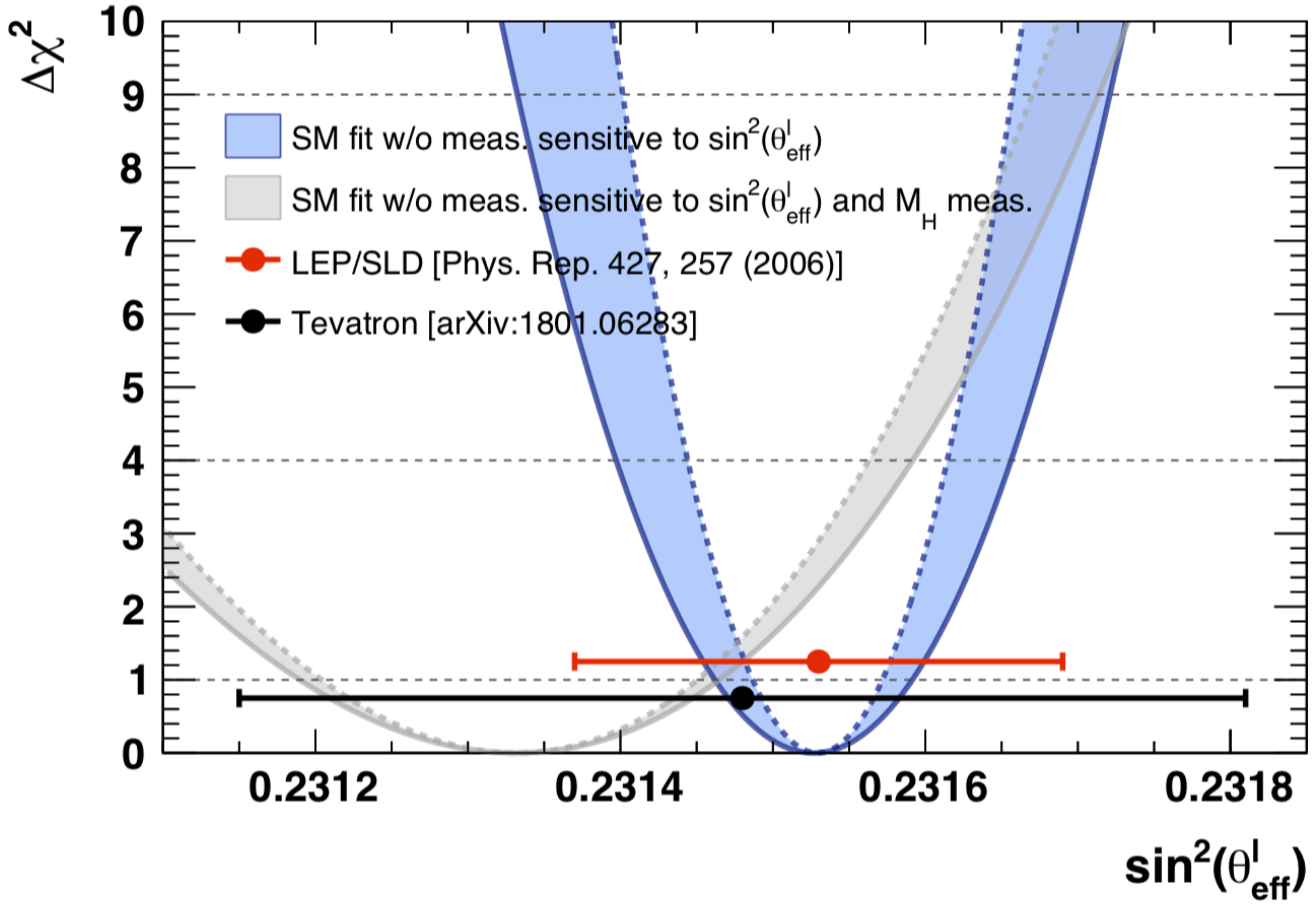
Starting from the indirect measurement of the mass of the Higgs boson discussed in Lecture 2.

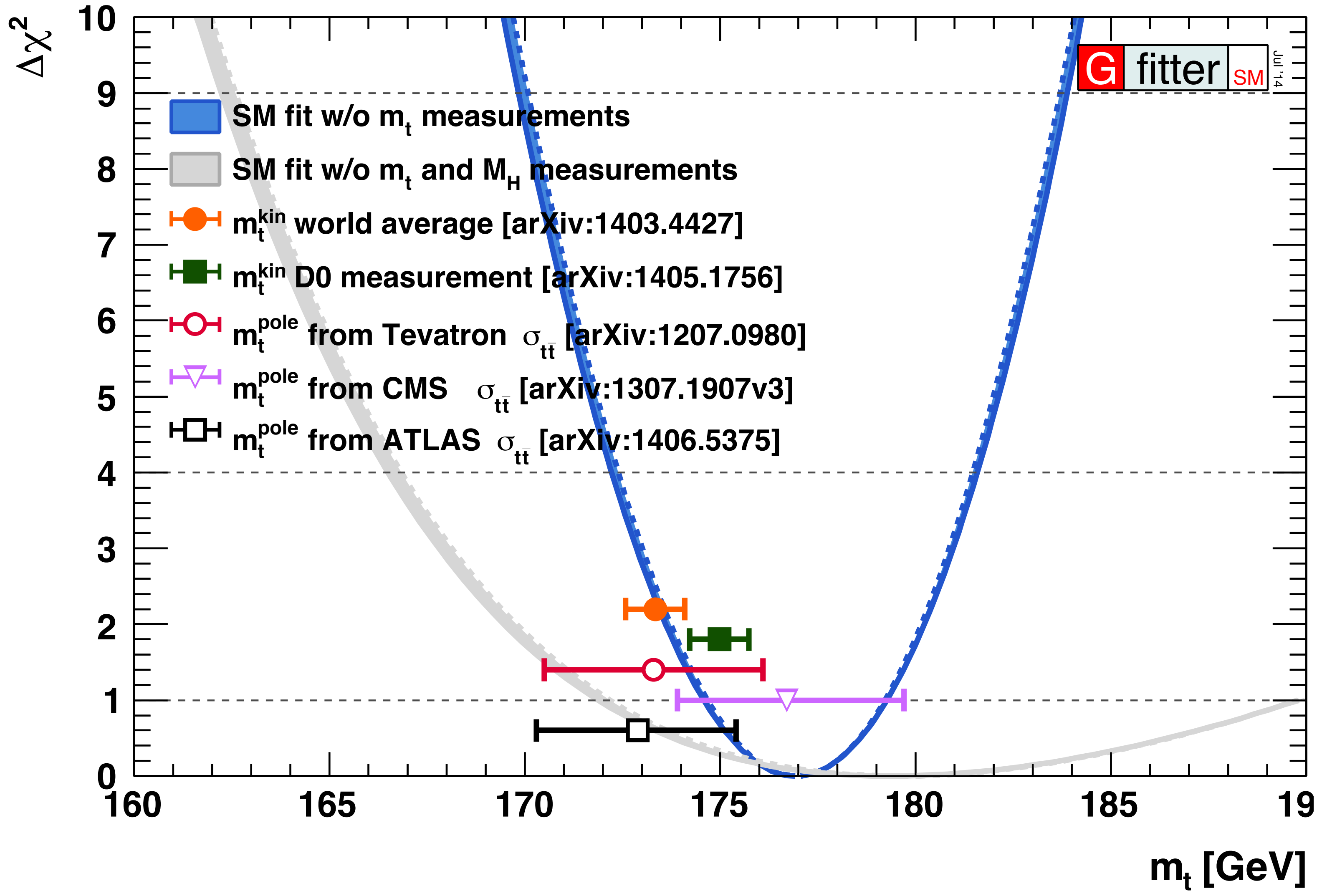
Direct measurement of the Higgs boson mass is much more precise than the indirect one.

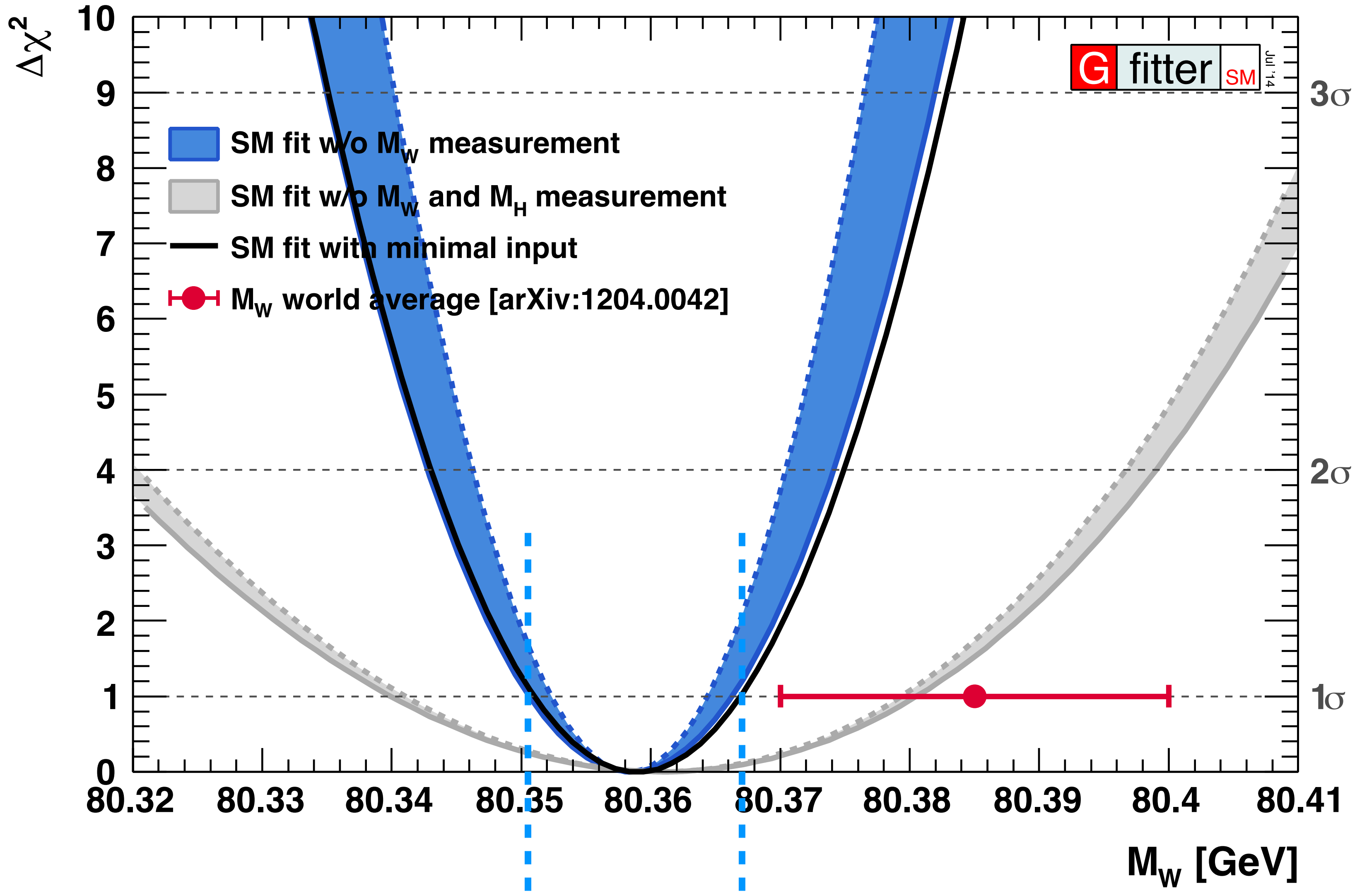
Knowing the Higgs boson mass has a large impact on global analysis.

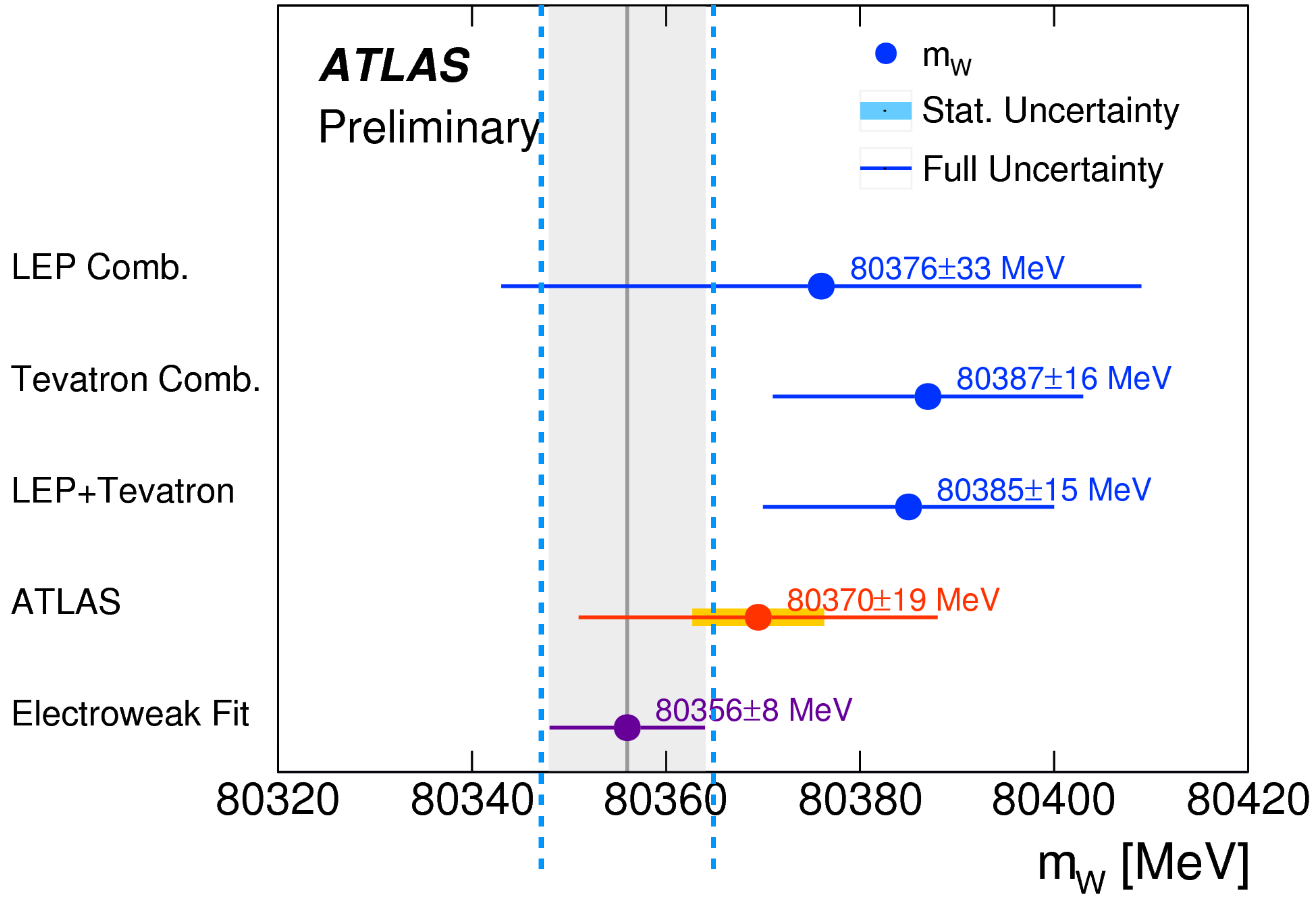
Knowing the Higgs boson mass precisely has little impact.

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.

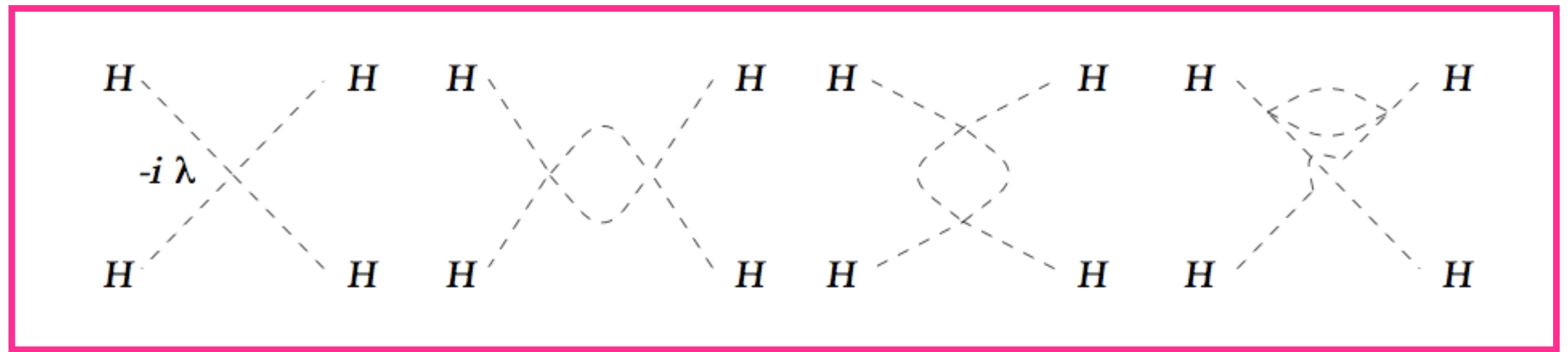
The Standard Model is consistent between direct and indirect measurements!!

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!

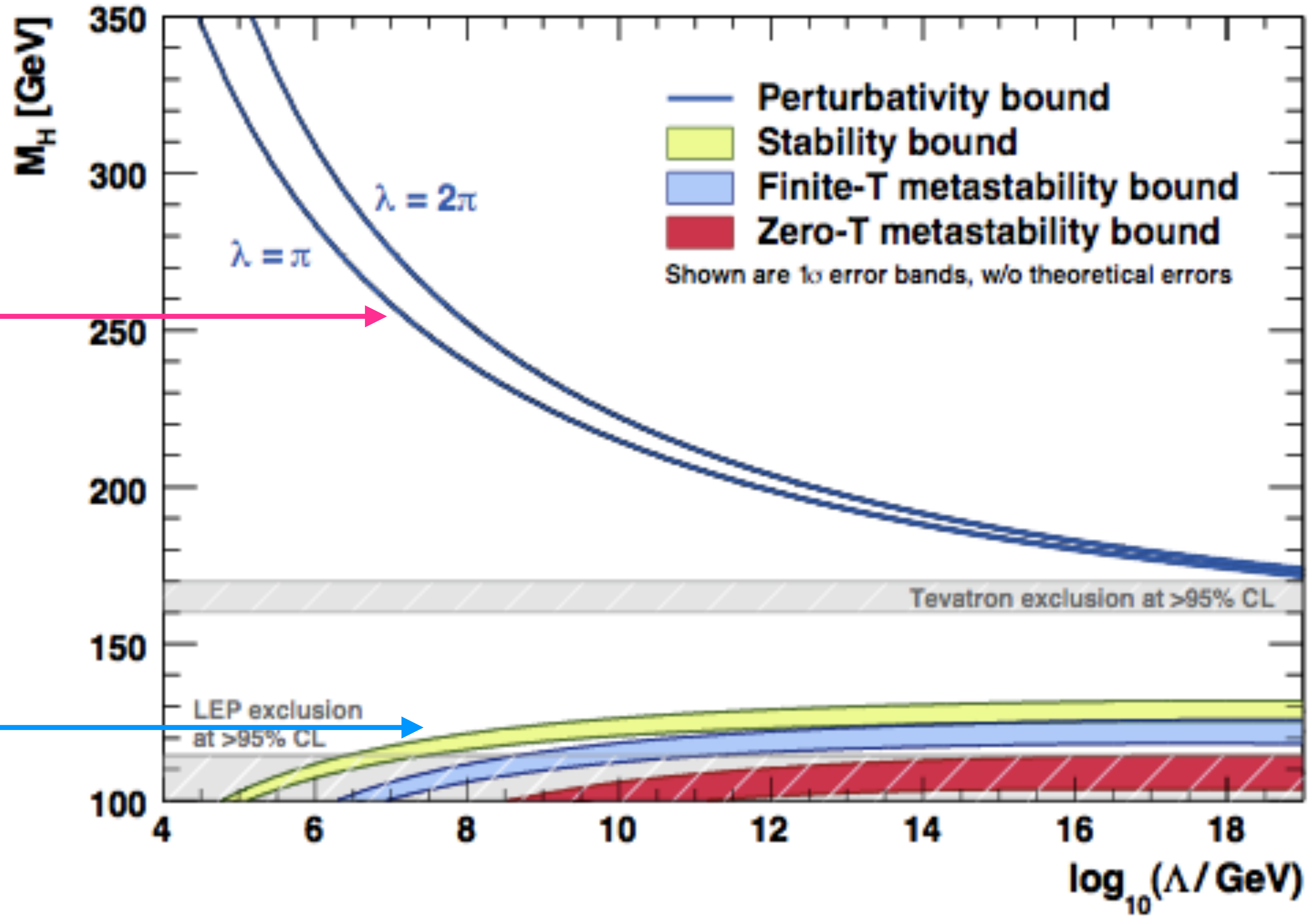
Implications (II) – Global fit of the Standard Model

Running of the Higgs self coupling: $$32\pi^2 \frac{\partial\lambda}{\partial\mu} = 24\lambda^2 - 6y_t^4 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2g^2 + \frac{9}{8}g^4$$

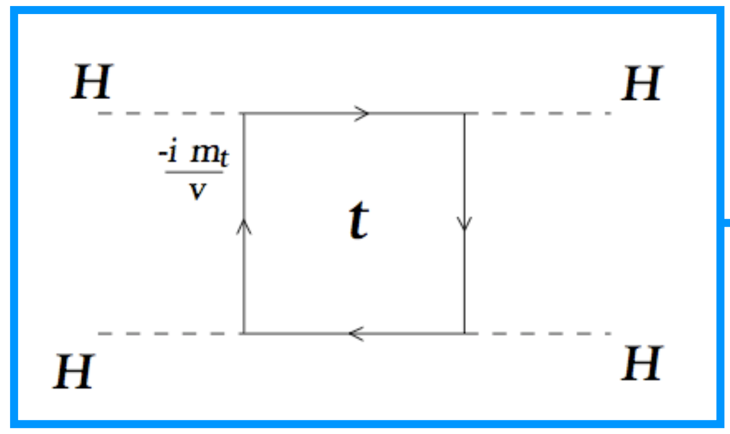


Dominant term for large values of the Higgs boson quartic coupling

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



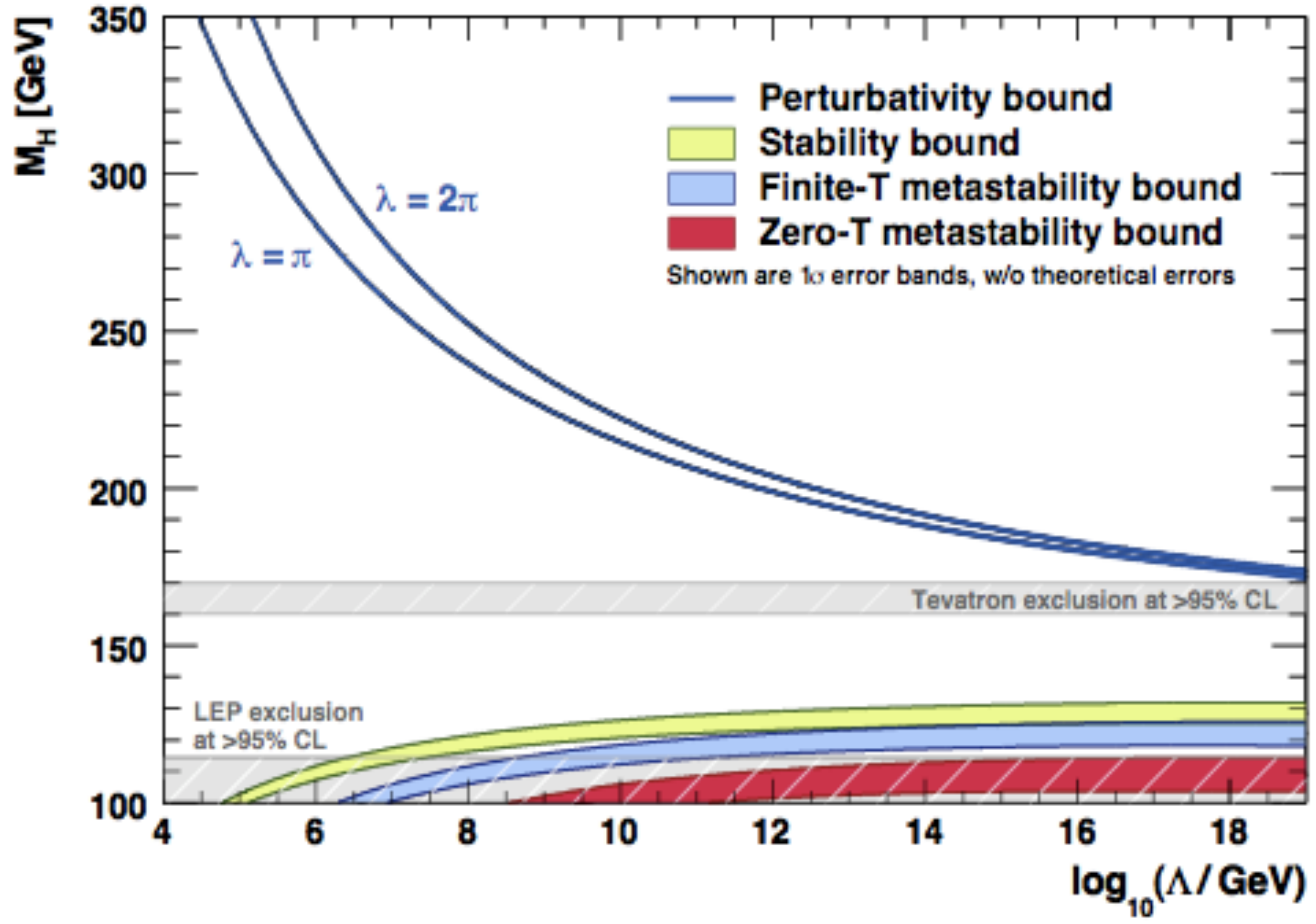
The simplified differential equation can be solved and derive a so-called « vacuum stability » bound.

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!

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?