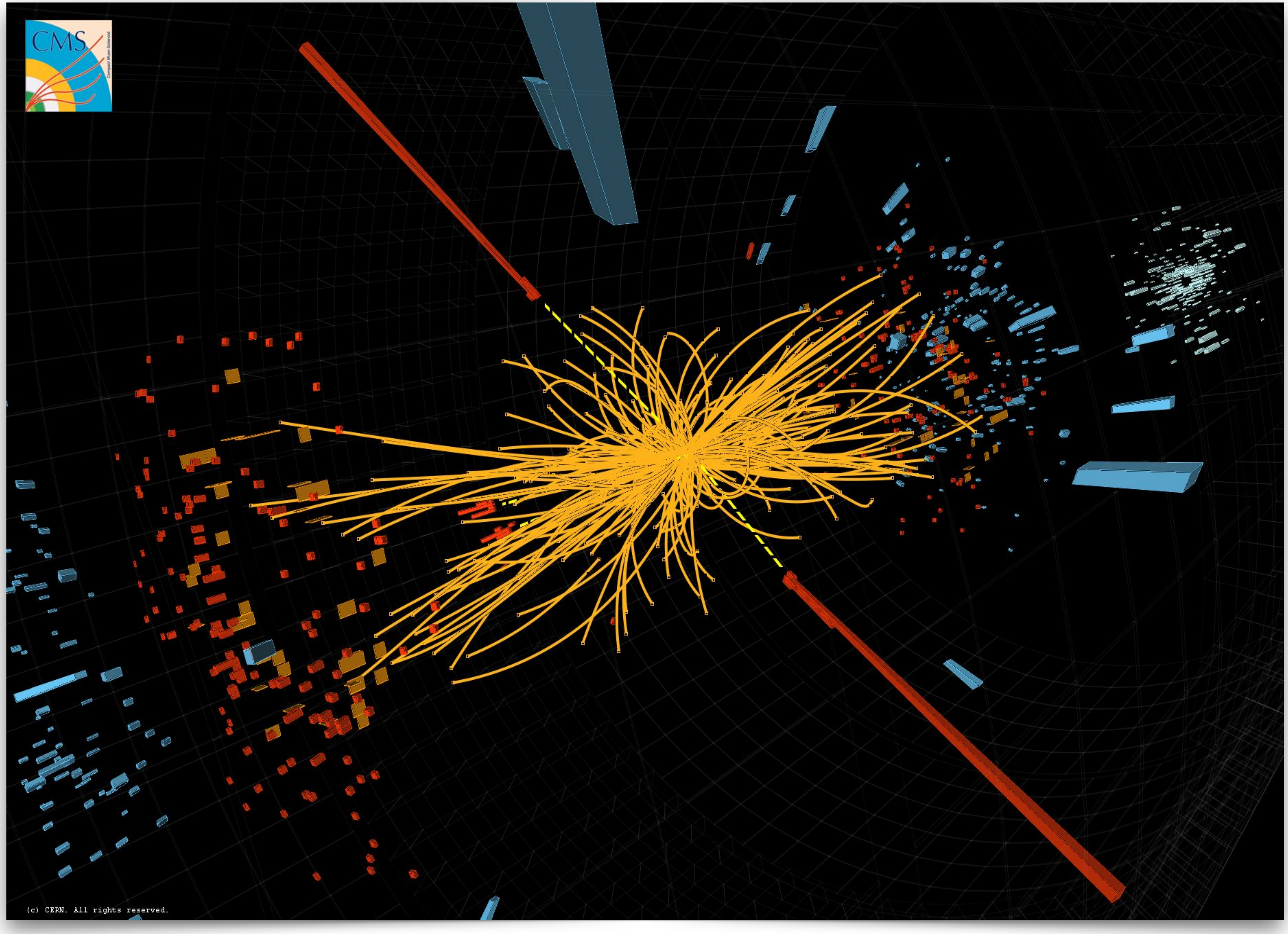
Experimental Physics at Hadron Collider

Lecture 3 - *The discovery of the Higgs boson and Higgs Physics*



Marumi Kado
LAL Orsay and
Sapienza Roma

CERN Summer Students
July 16-19, 2018

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

The Standard Model

The less elegant Higgs sector:

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

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

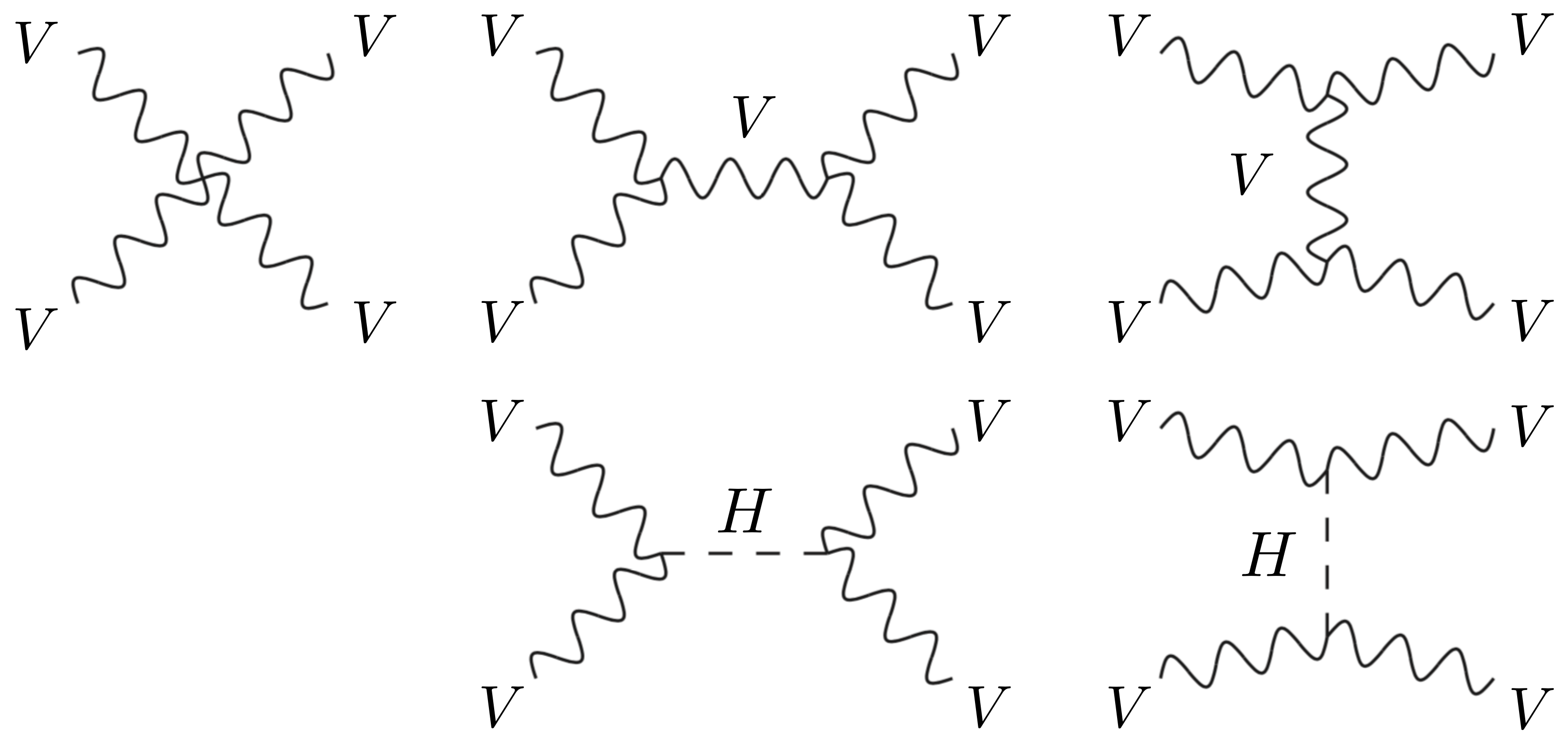
$$+ |D_\mu \phi|^2 - V(\phi)$$

… but without it, masses of gauge bosons and masses of fermions are not gauge invariant.

However: gauge W and Z bosons do have a mass!

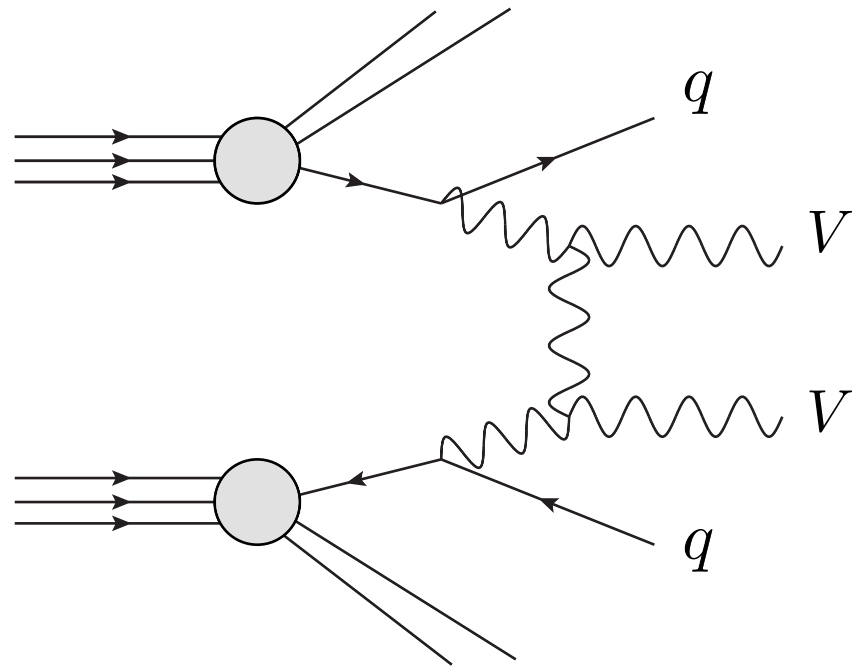
- The mechanism solves both issues.
- The Higgs mechanism also predicts the relation between the gauge boson masses and their couplings.
- The Higgs mechanism also predicts the existence of a Higgs boson.

The presence of a Higgs boson also solves another important issue, the unitarity of the longitudinal vector boson scattering:



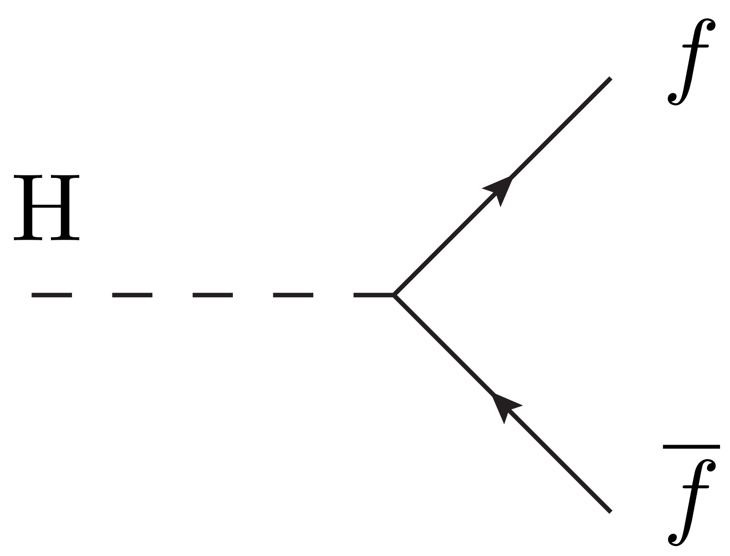
The preservation of the perturbative unitarity of the WW scattering, also imposes an upper limit on the Higgs boson of ~O(1 TeV).

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 1).

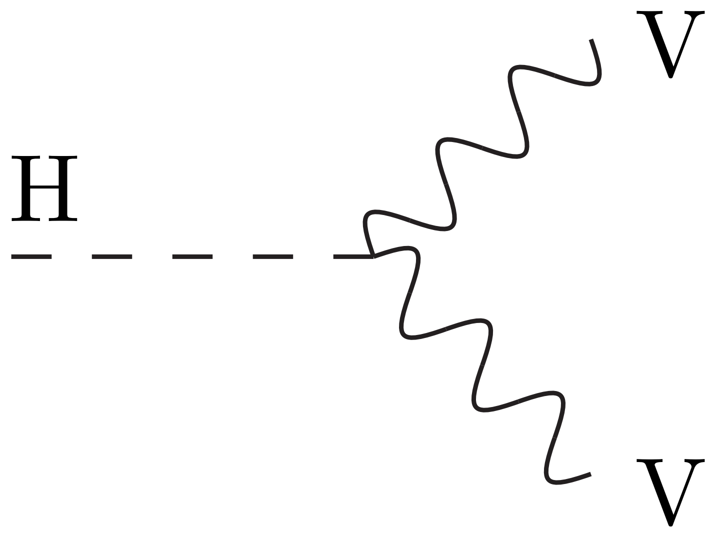


Higgs boson couplings (within the Standard Model)

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

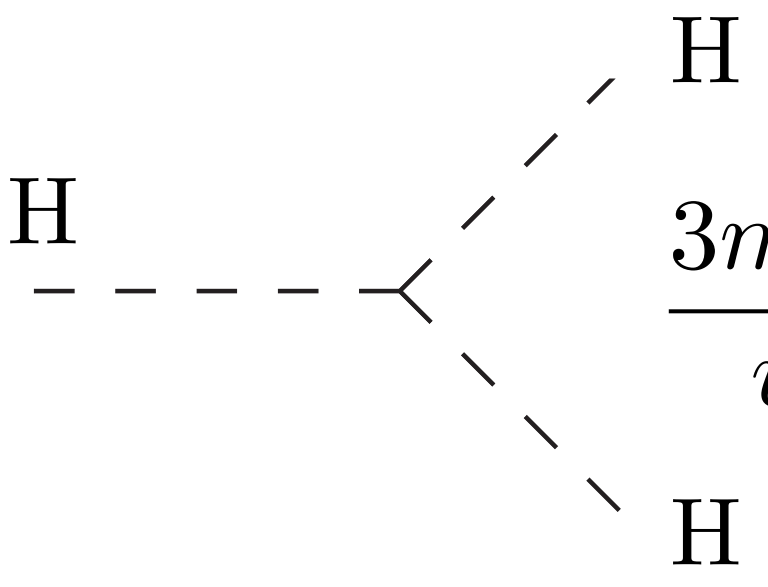


$\frac{m_f}{v}$ $\quad + \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$

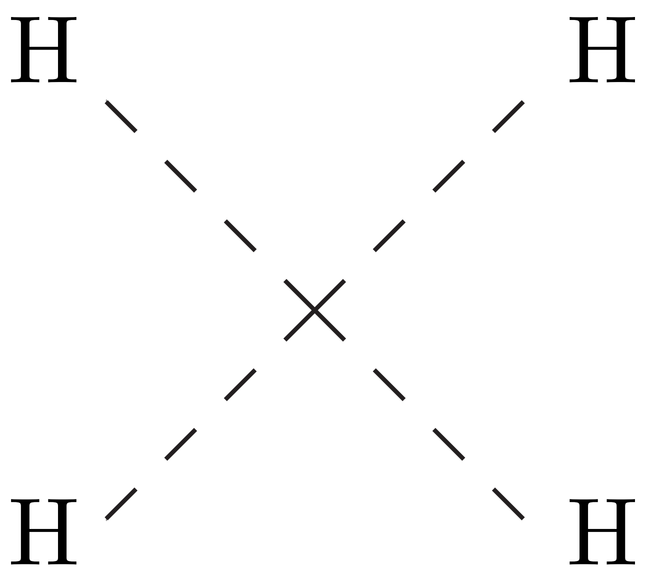


$\frac{2m_V^2}{v}$ $\quad + |D_\mu \phi|^2$

This term could not exist without a vev



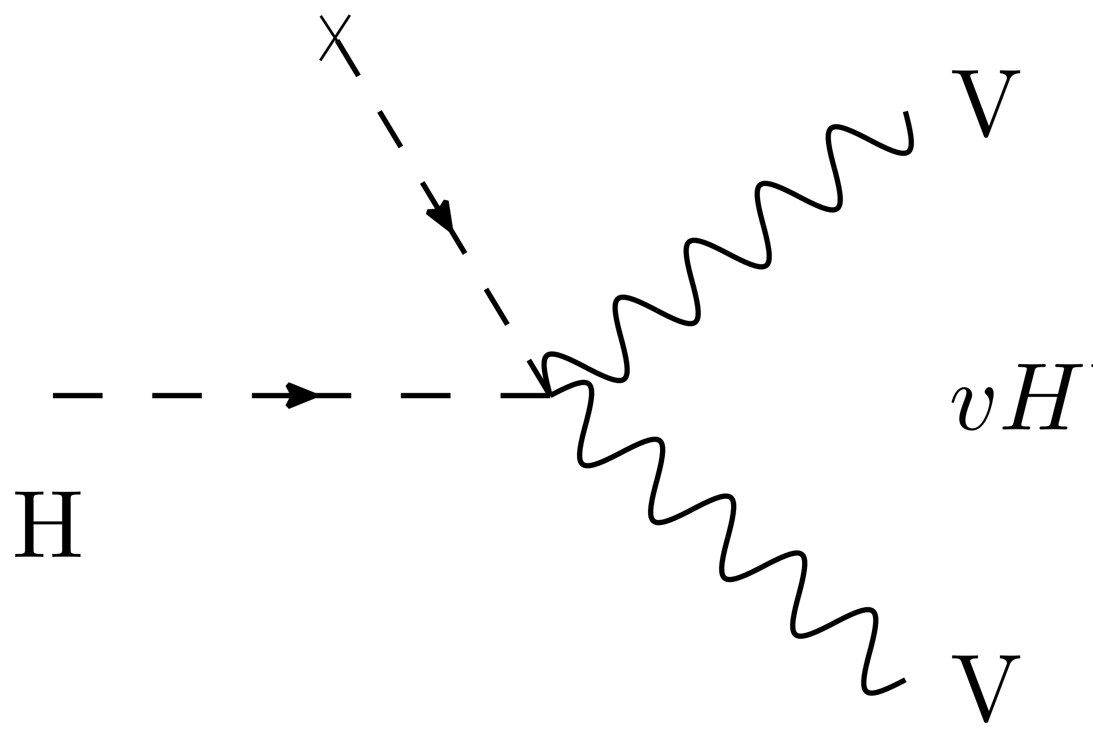
$\frac{3m_H^2}{v}$



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

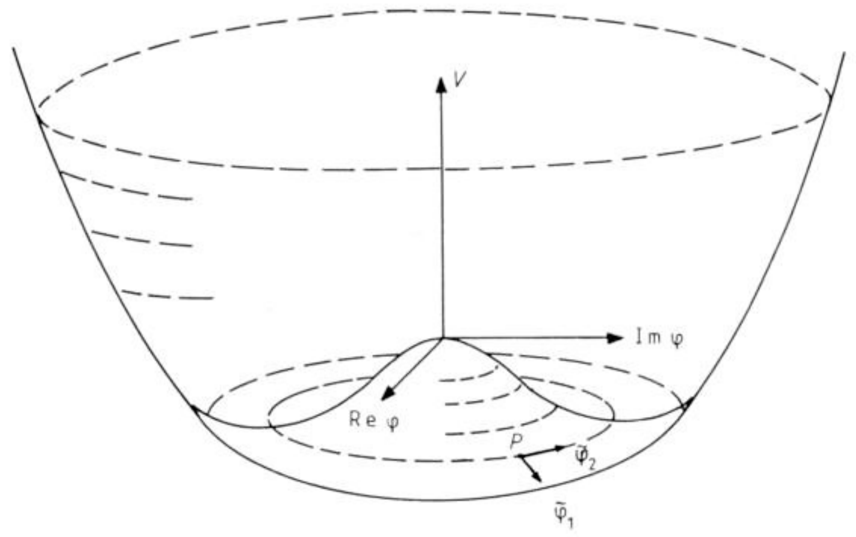
Is the Higgs boson responsible for the EW symmetry breaking also responsible for the masses of fermions?

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



$vHV^\mu V_\mu$

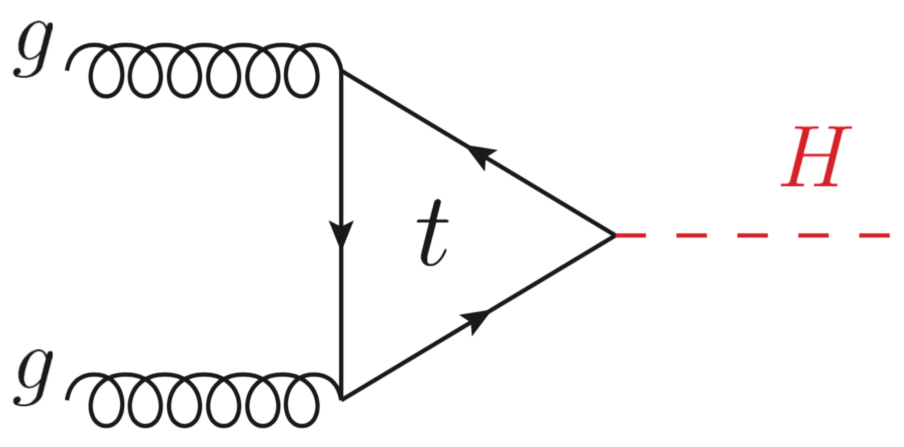
Proof of condensate !



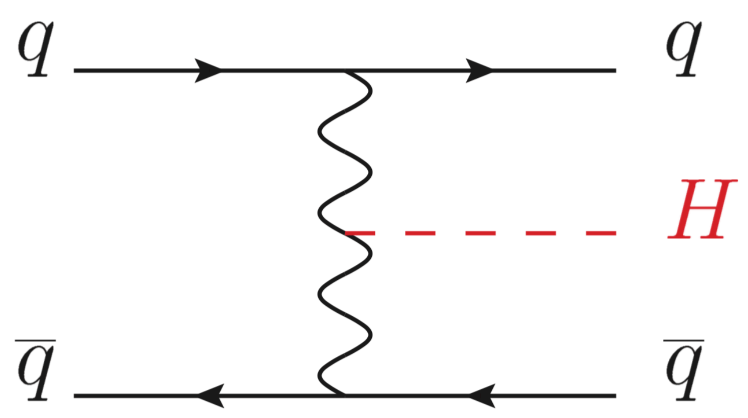
Is the shape of the Higgs potential that predicted by the Standard Model?

Higgs boson (main) Production Modes

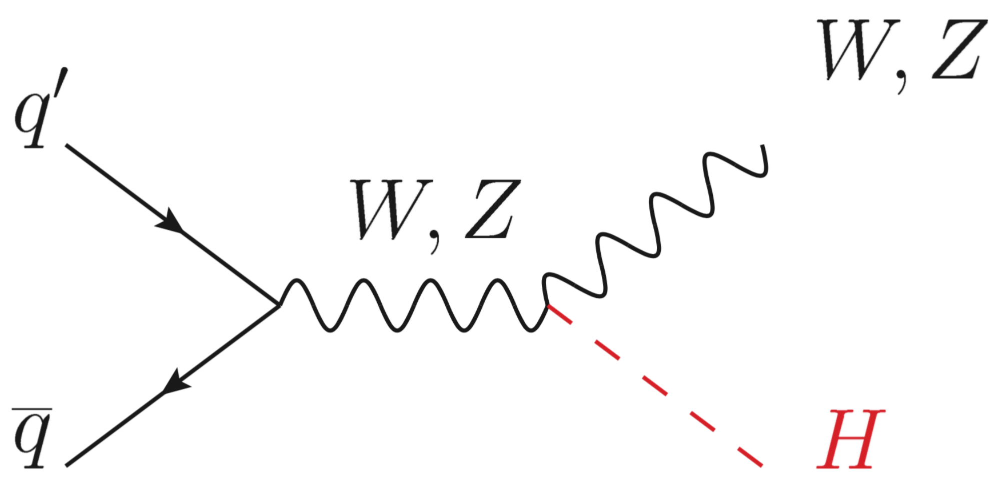
Production rates at
Run 2 for ~80 fb^{-1}



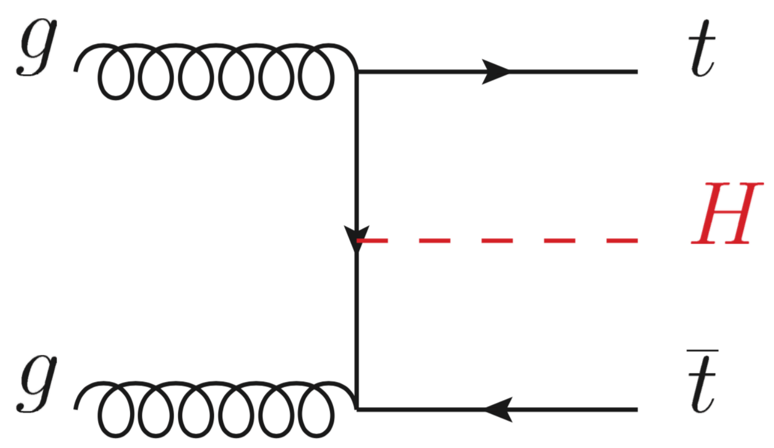
Gluon fusion process
~4 M events produced



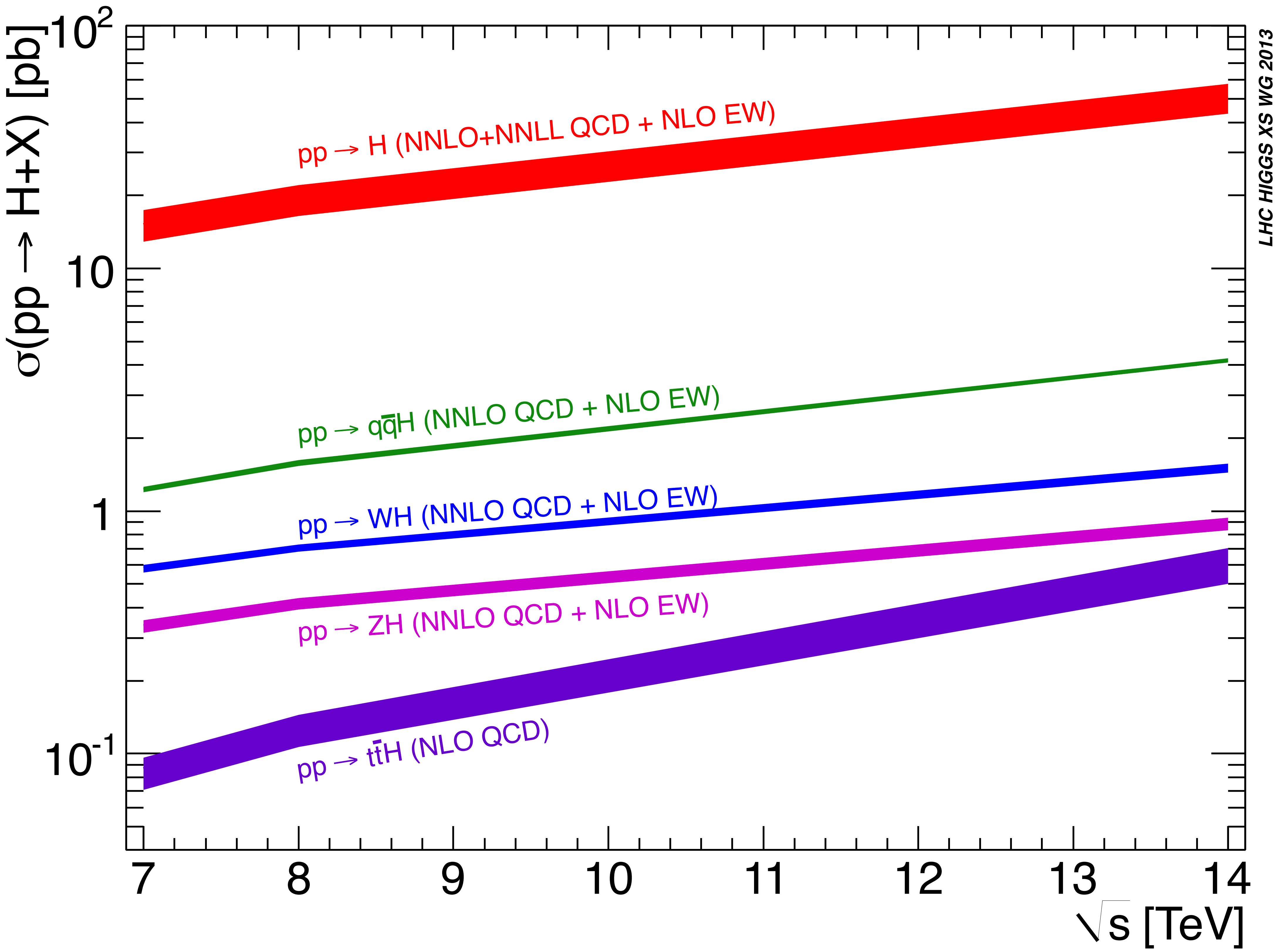
Vector Boson Fusion
Two forward jets and a large rapidity gap
~300 k events produced



W and Z Associated Production
~200 k events produced



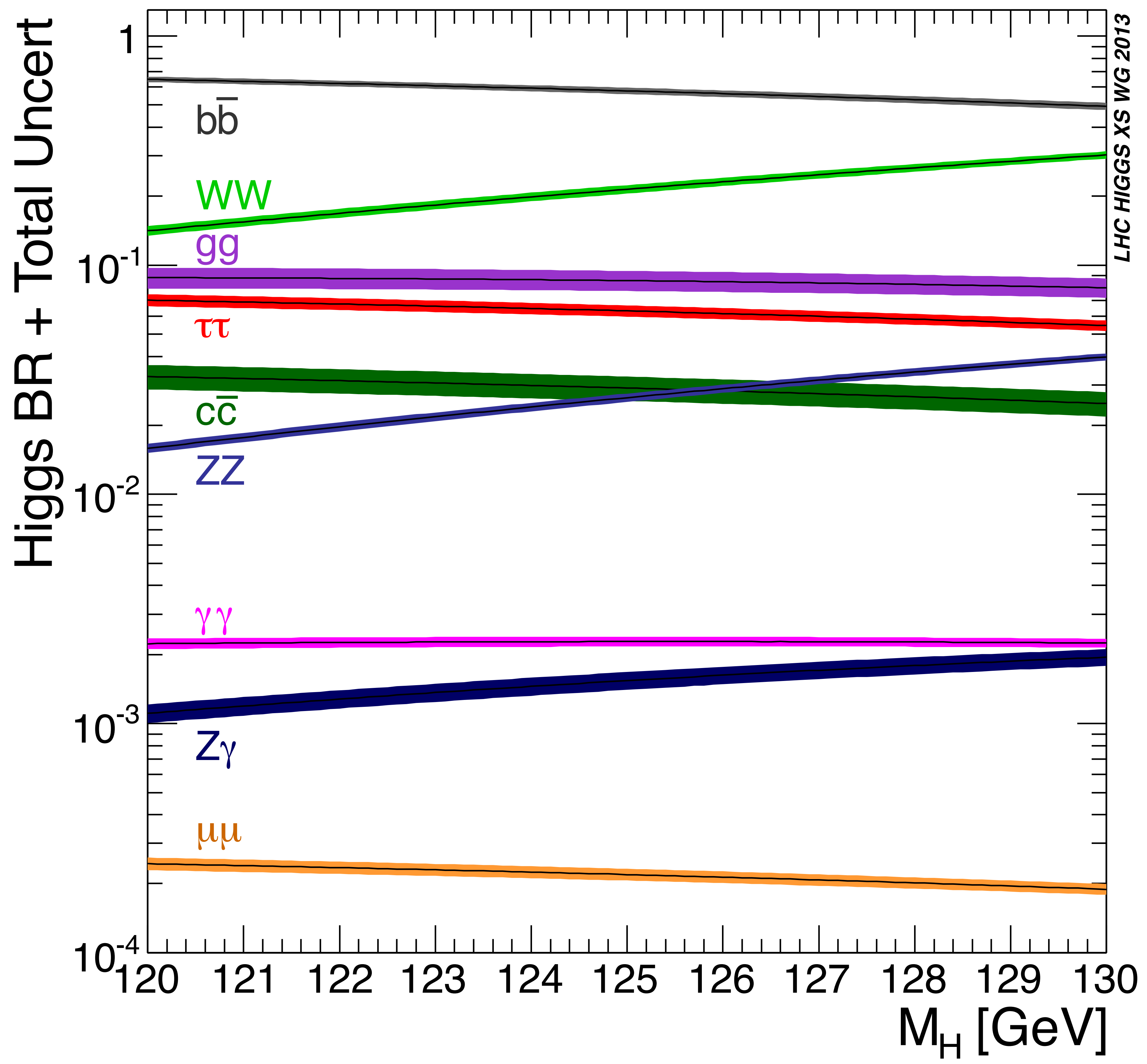
Top Assoc. Prod.
~40 k evts produced



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

Higgs Decay Channels

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

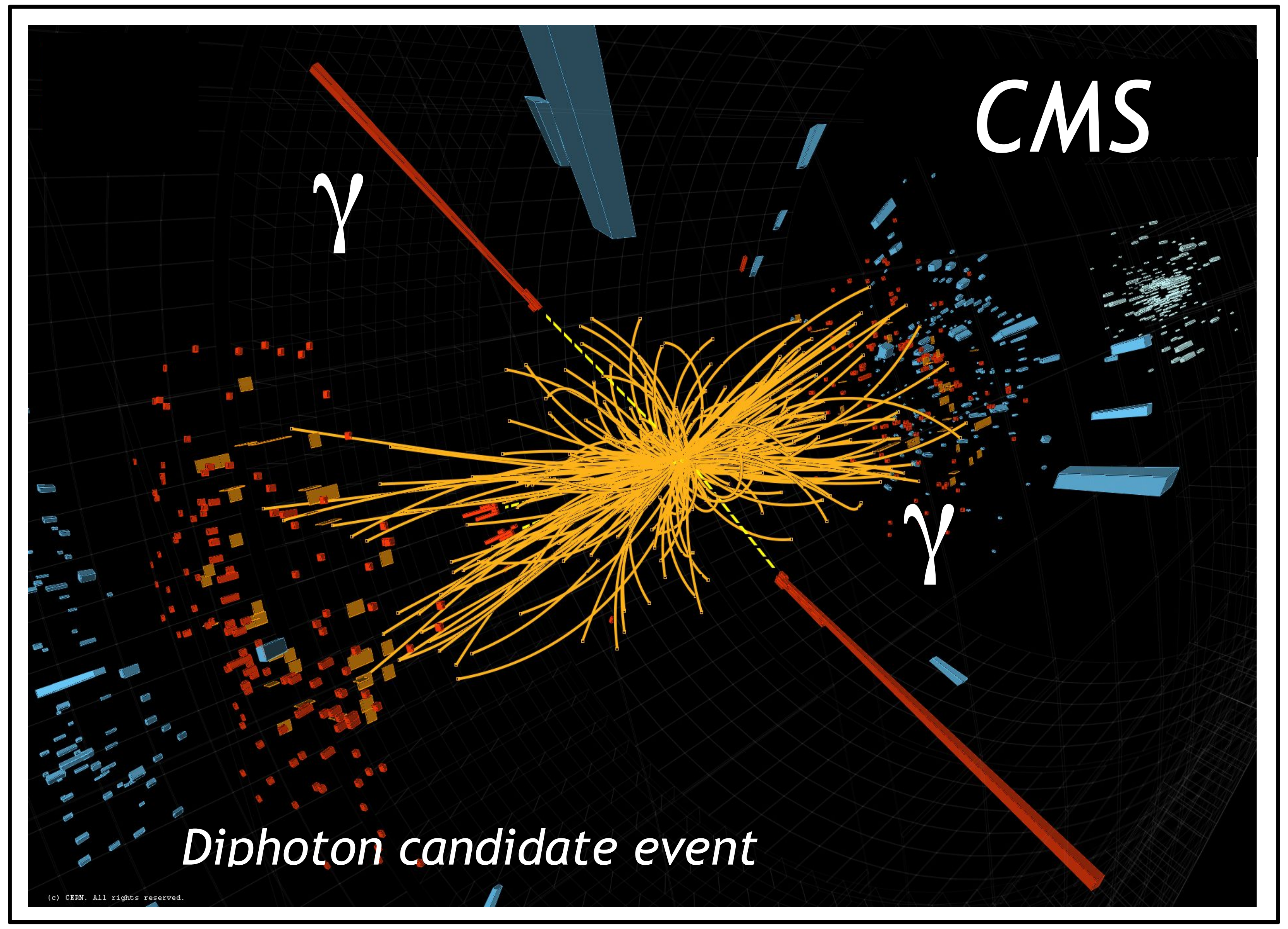


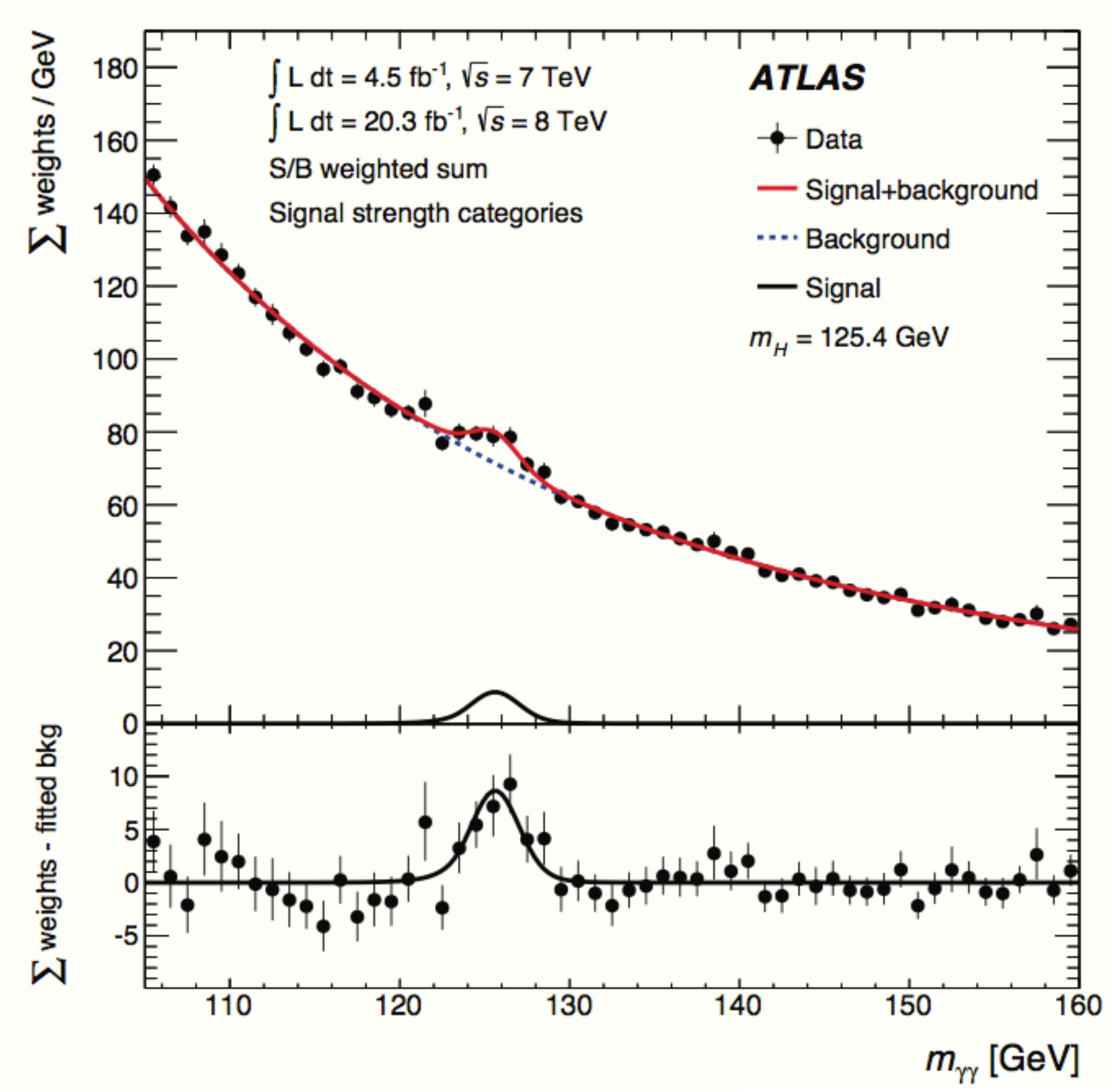
- Dominant: bb (57%)
- WW channel (22%)
- ττ channel (6.3%)
- ZZ channel (3%)
- cc channel (3%)
- The γγ channel (0.2%)
- The Zγ (0.2%)
- The μμ channel (0.02%)

The Discovery of the Higgs boson

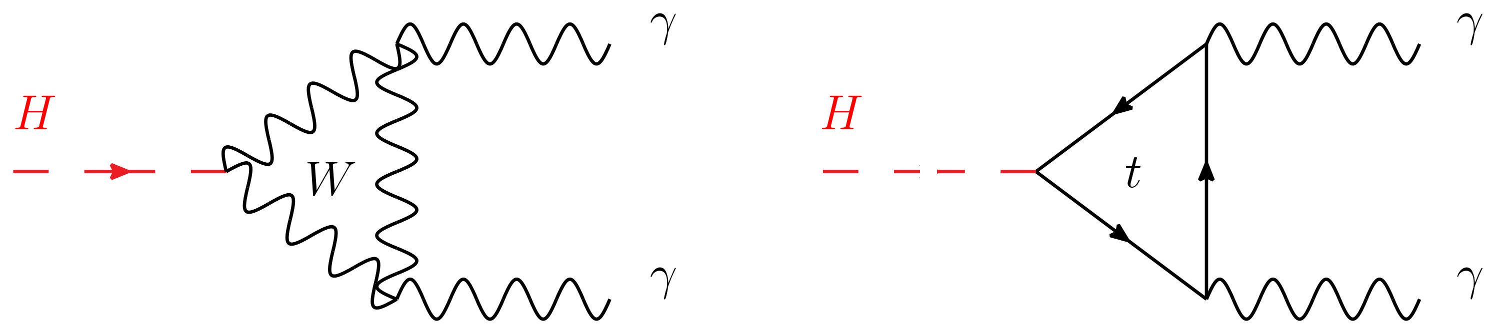
The Discovery Channels

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





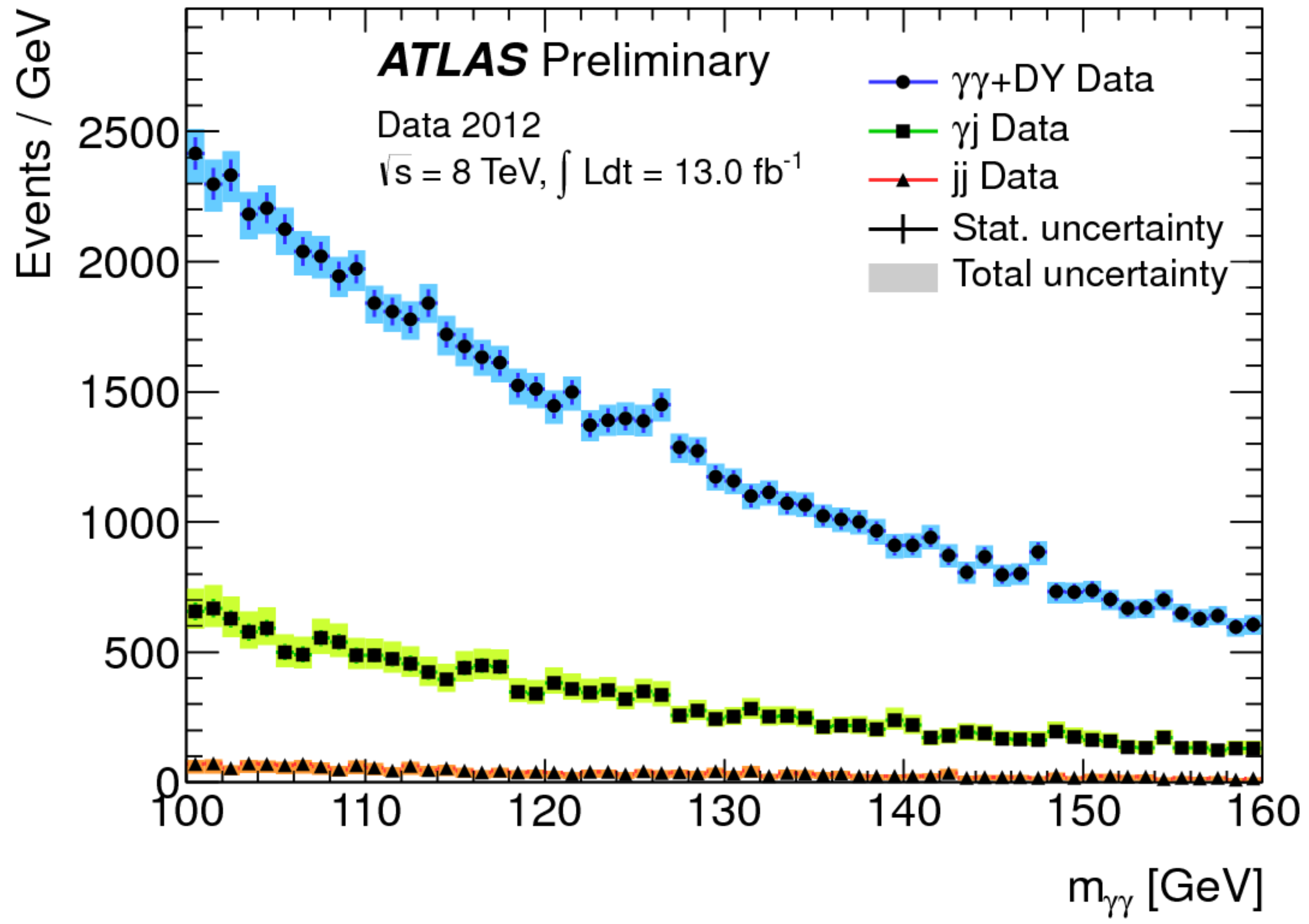
- Main production and decay processes occur through loops :



Excellent probe for new physics !

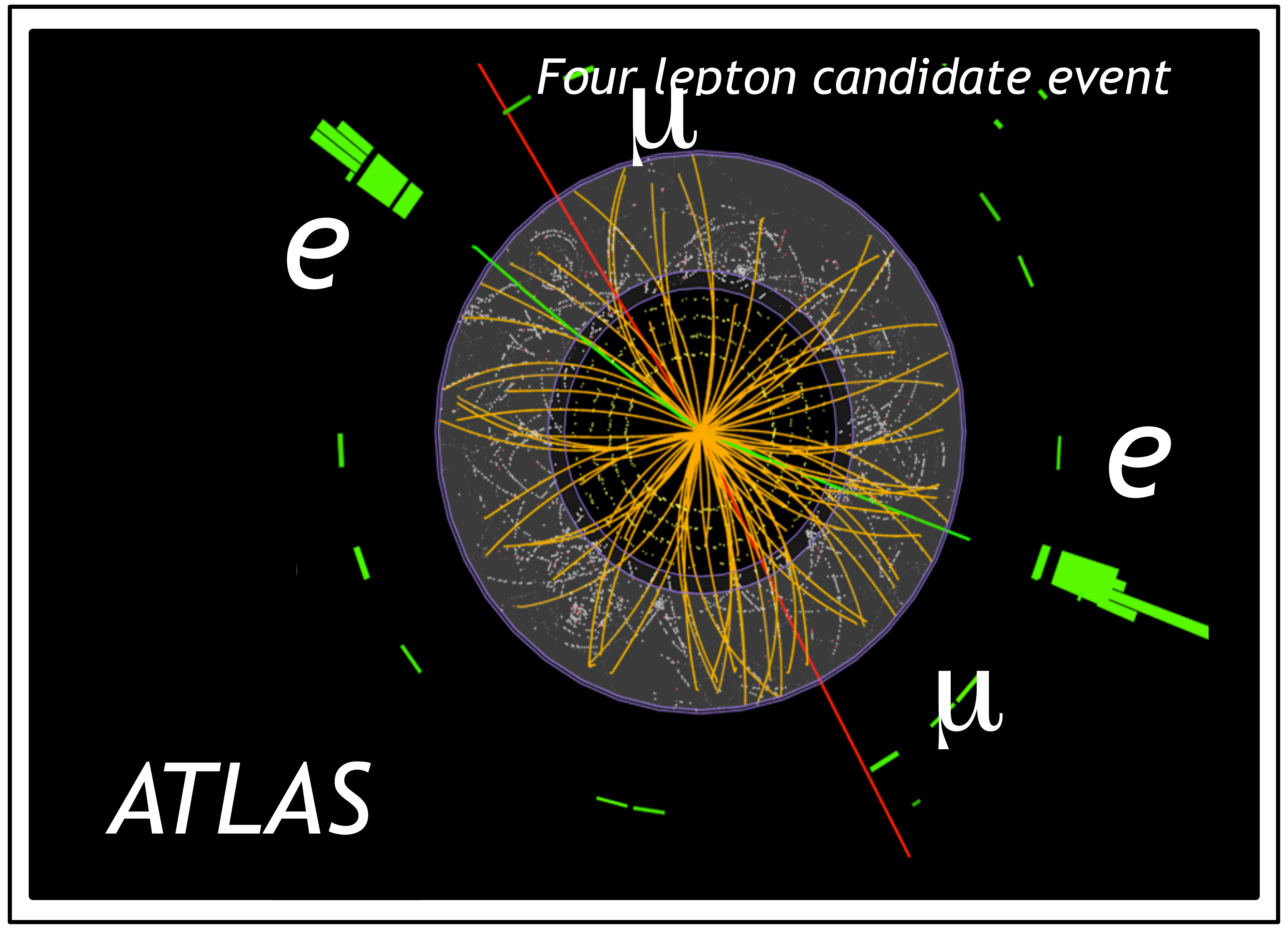
- High mass resolution channel O(1%) allowing data driven estimate of background in the sidebands.
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem

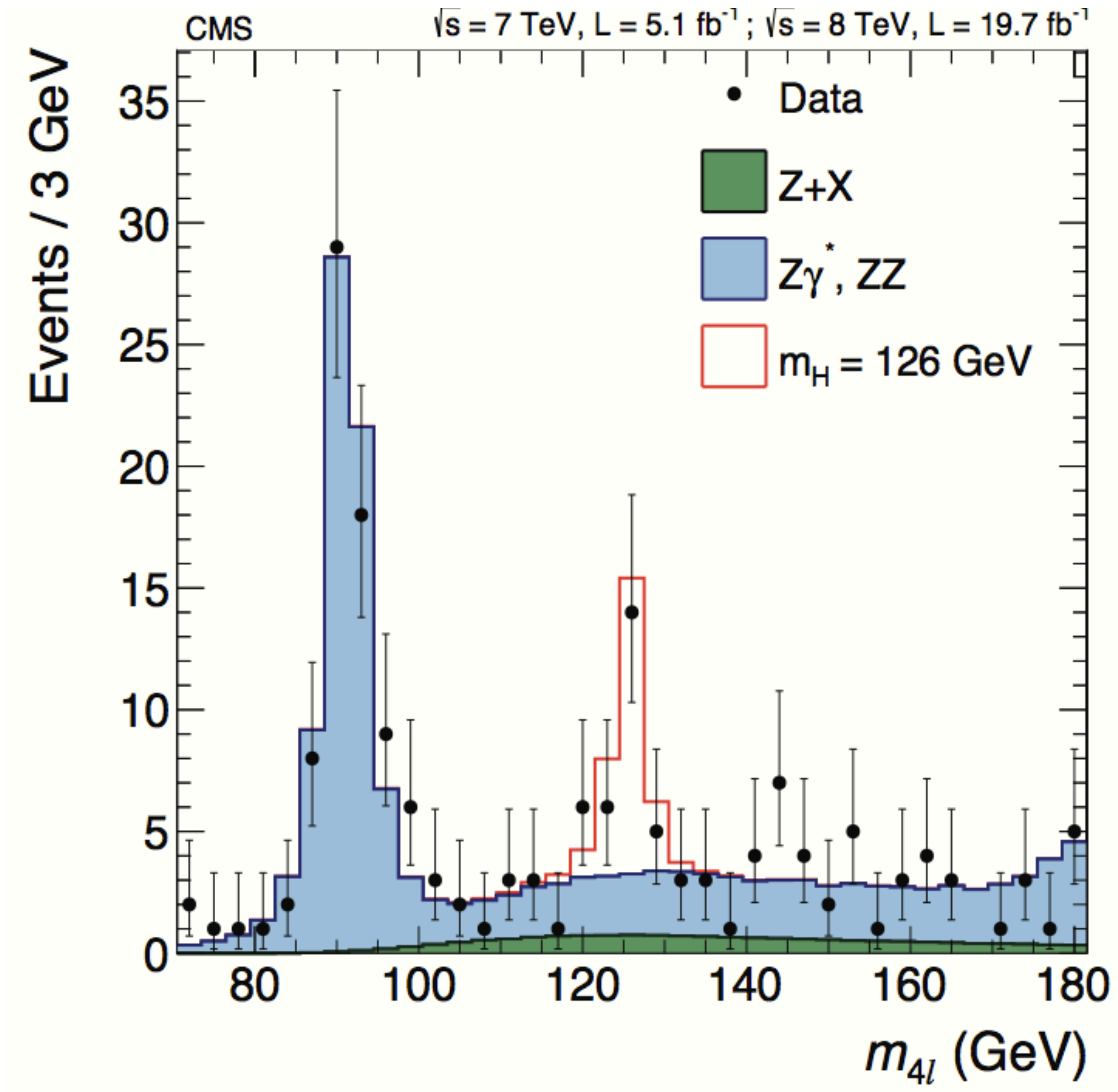
- Low signal over background but overall relatively high statistics of signal (O(300) at Run 1)
- Very simple selection cuts. The essence of the channel relies on the **quality of the detector response** and the **reconstruction**.
- Largest reducible background comes from jets! With another spin-0 particle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



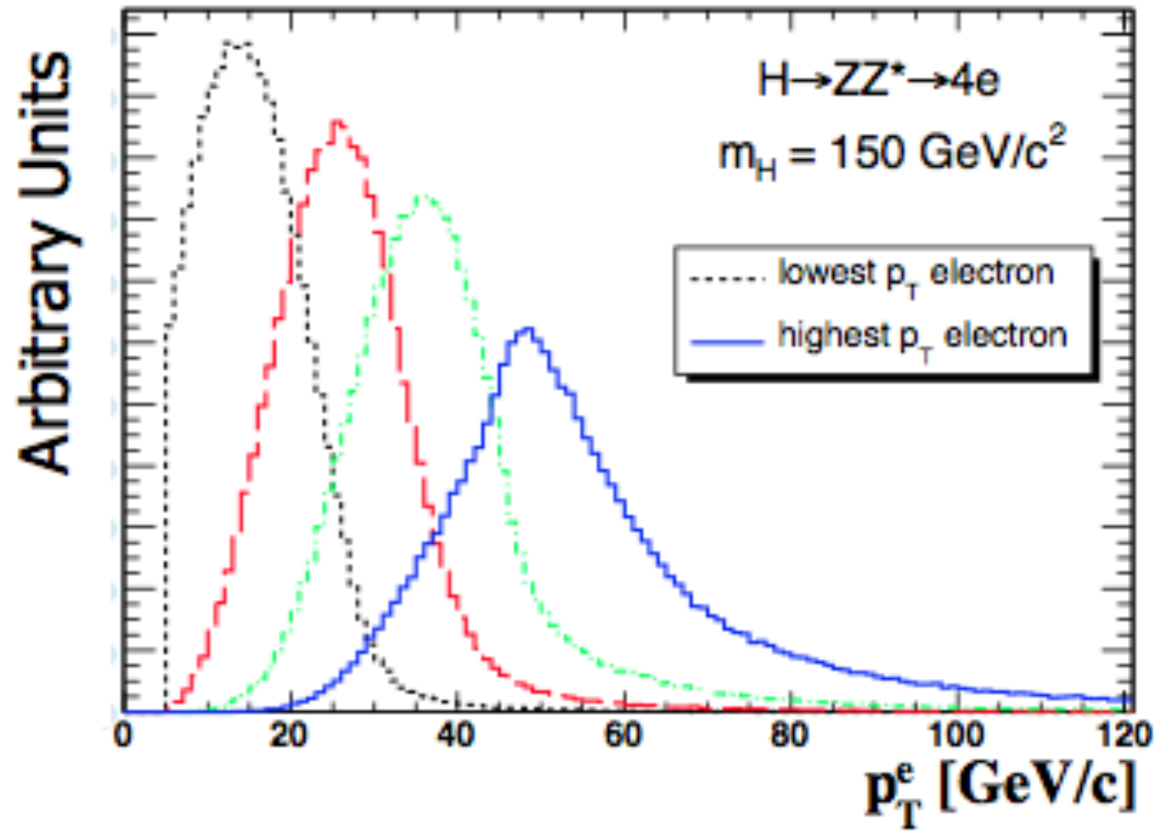
The Discovery Channels

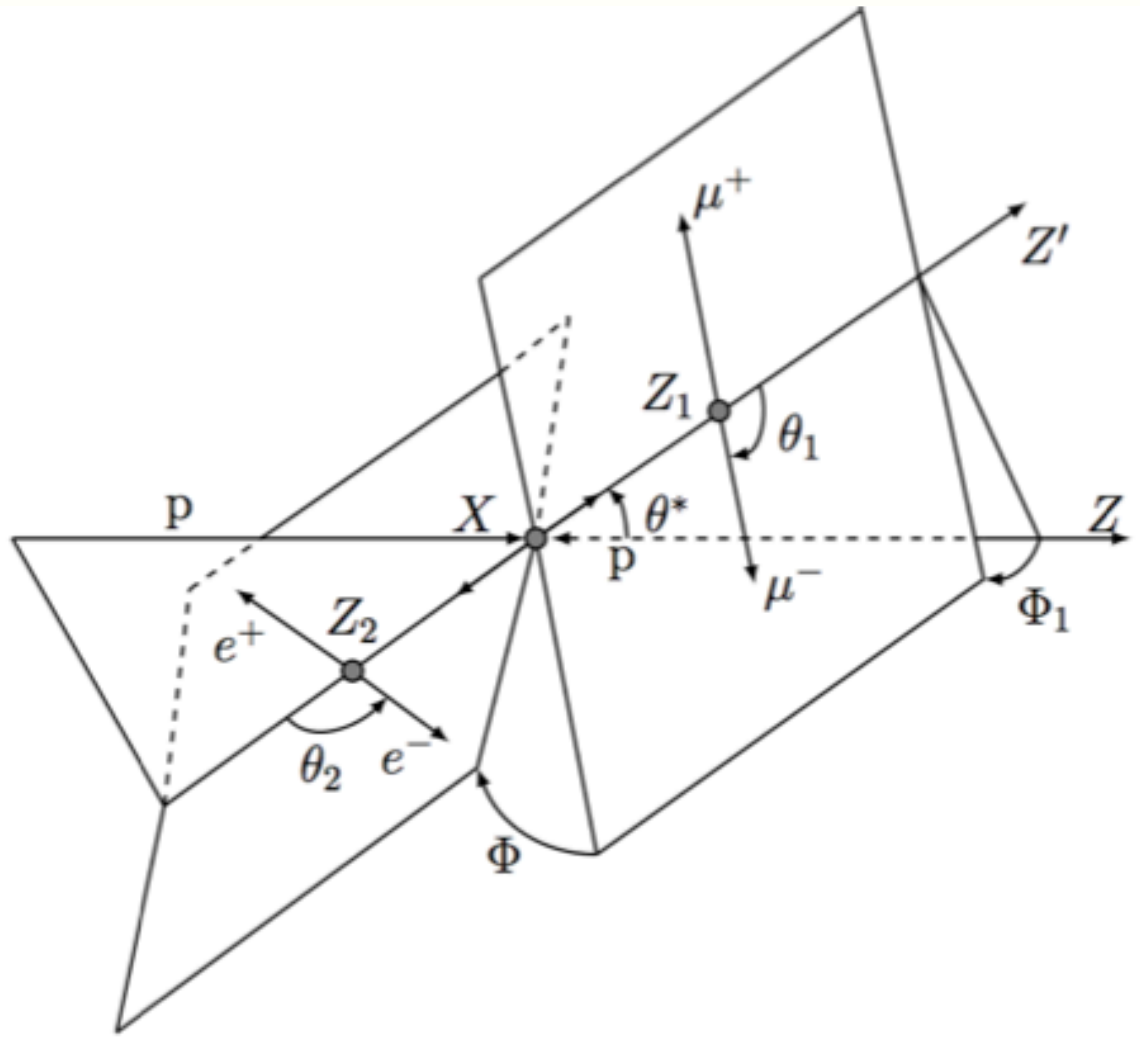
« Bread and Butter » Mass peak signals: the four leptons channel

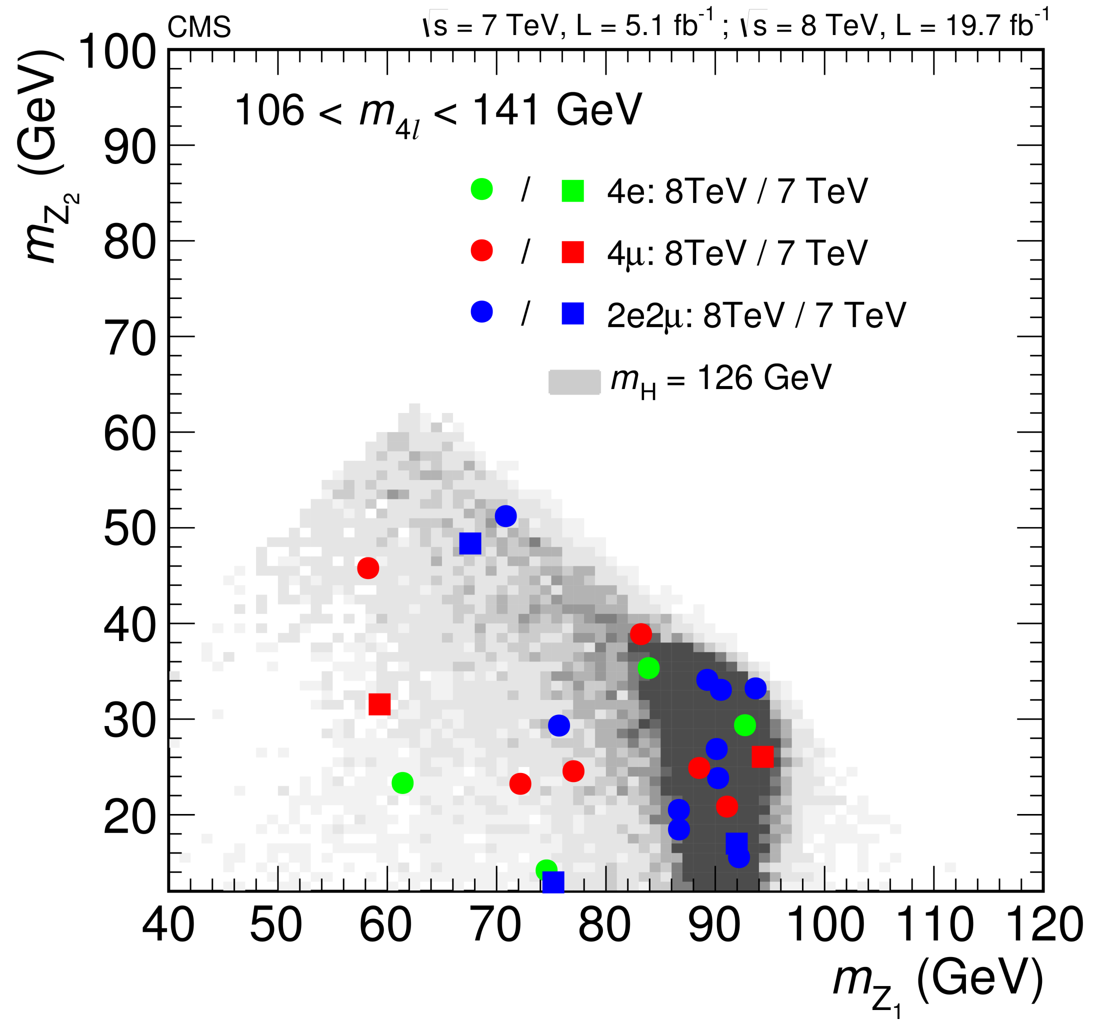




- Channel with High s/b ratio from approximately 2 up to more than 10!
- Backgrounds can be estimated from MC.
- Four leptons:
  - Very low rate due to branchings of ZZ and Z to leptons! Efficiency is key!
  - The trailing lepton is at low pT.
  - The polarisation of the two Z can be reconstructed.
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

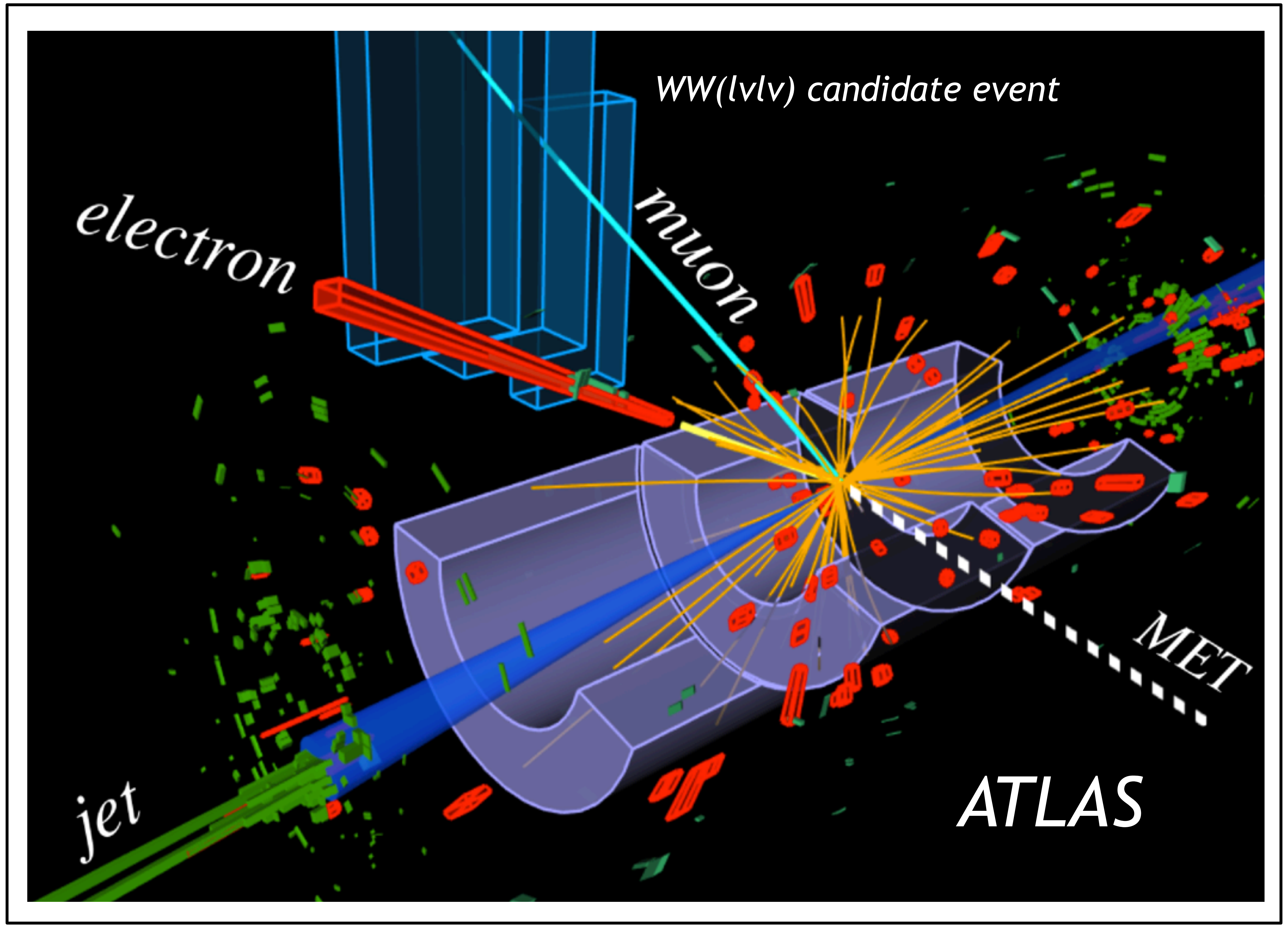






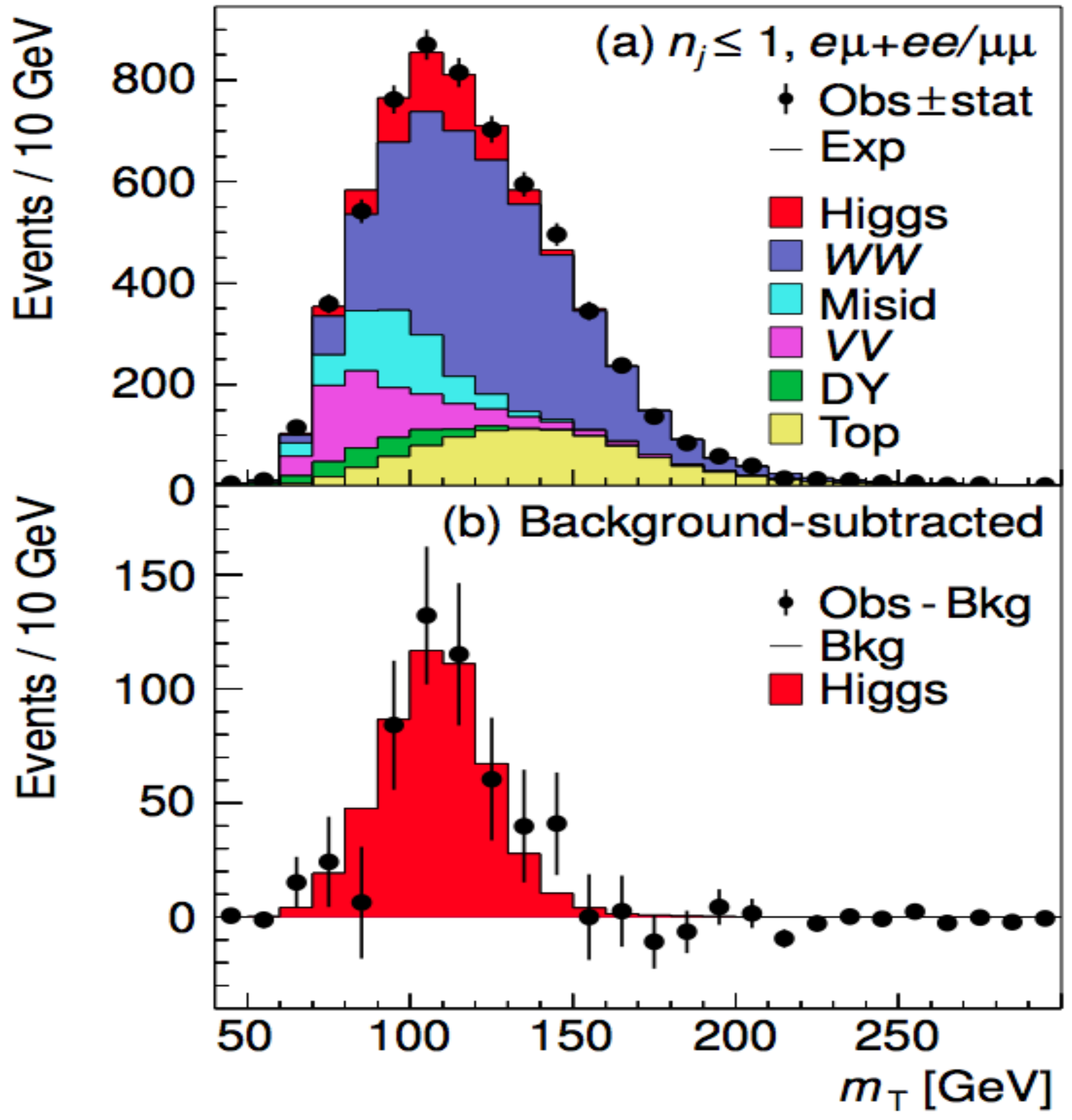
The Discovery Channels

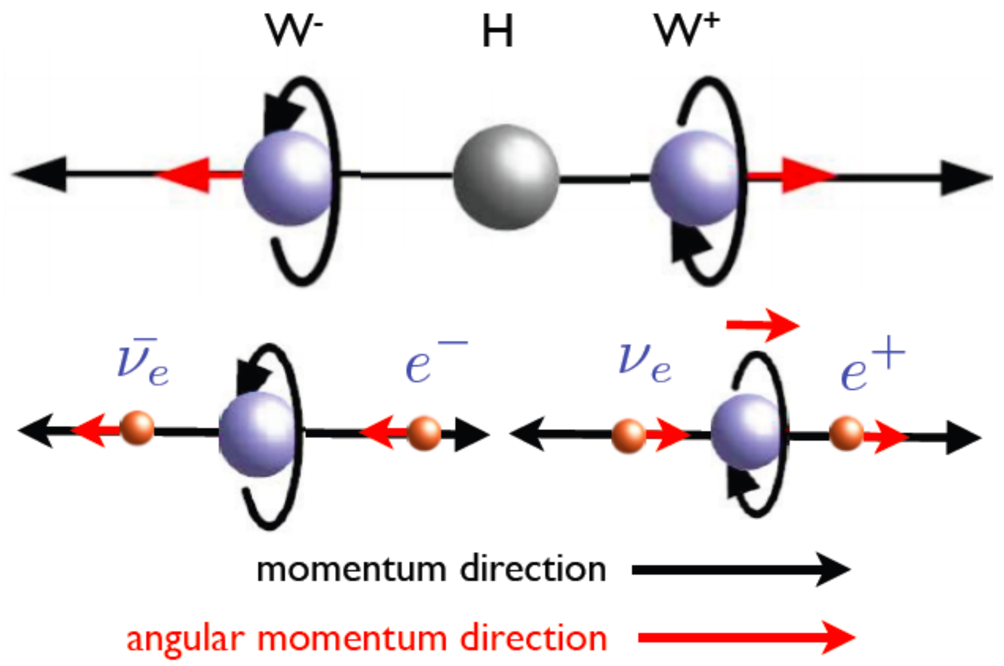
A discovery channel of a different kind: the WW



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.

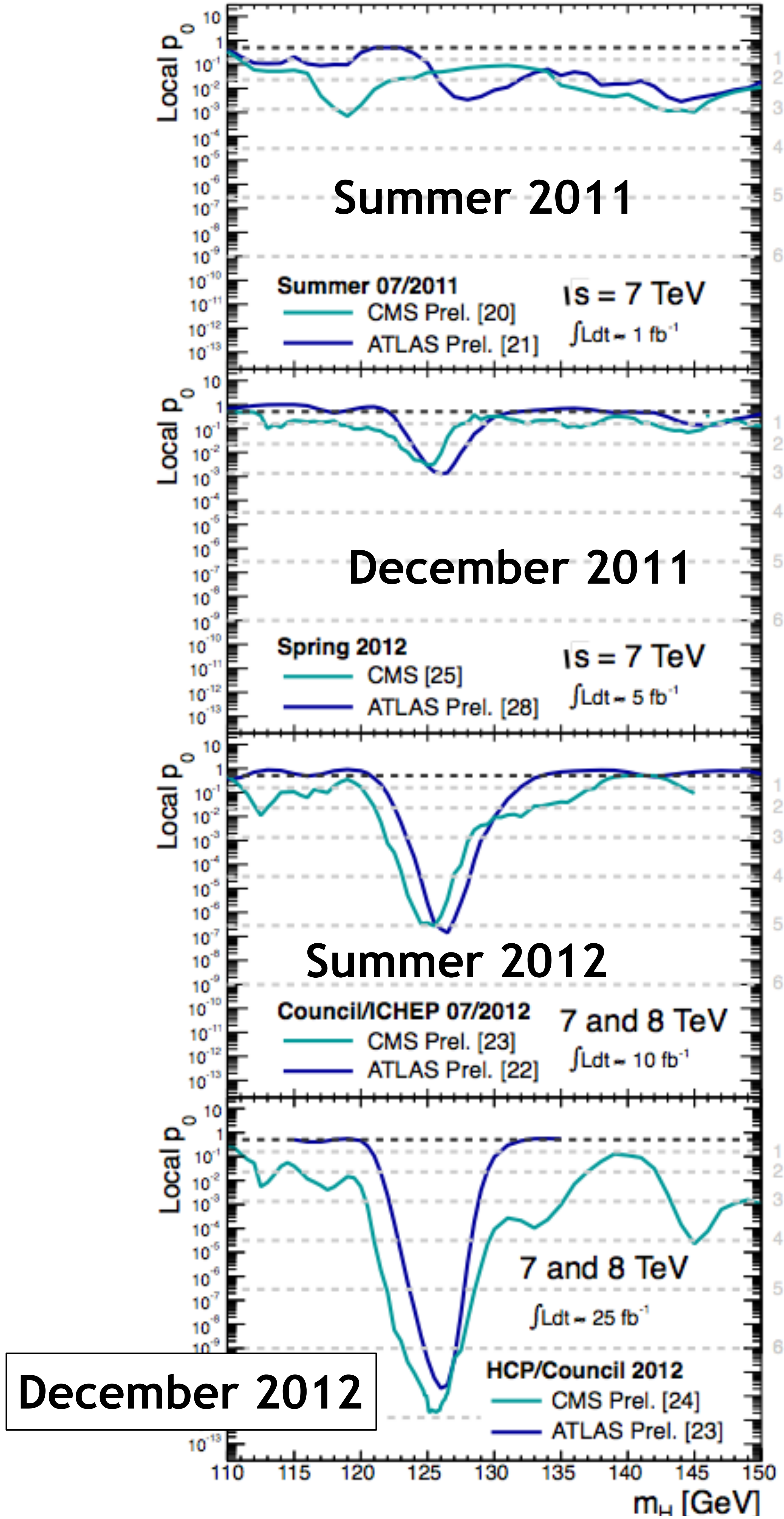




Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

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

PDG, review of Particle Physics



A Textbook and Timely Discovery

- Summer 2011: EPS and Lepton-Photon
  First (and last) focus on limits (scrutiny of the p_0)
- 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

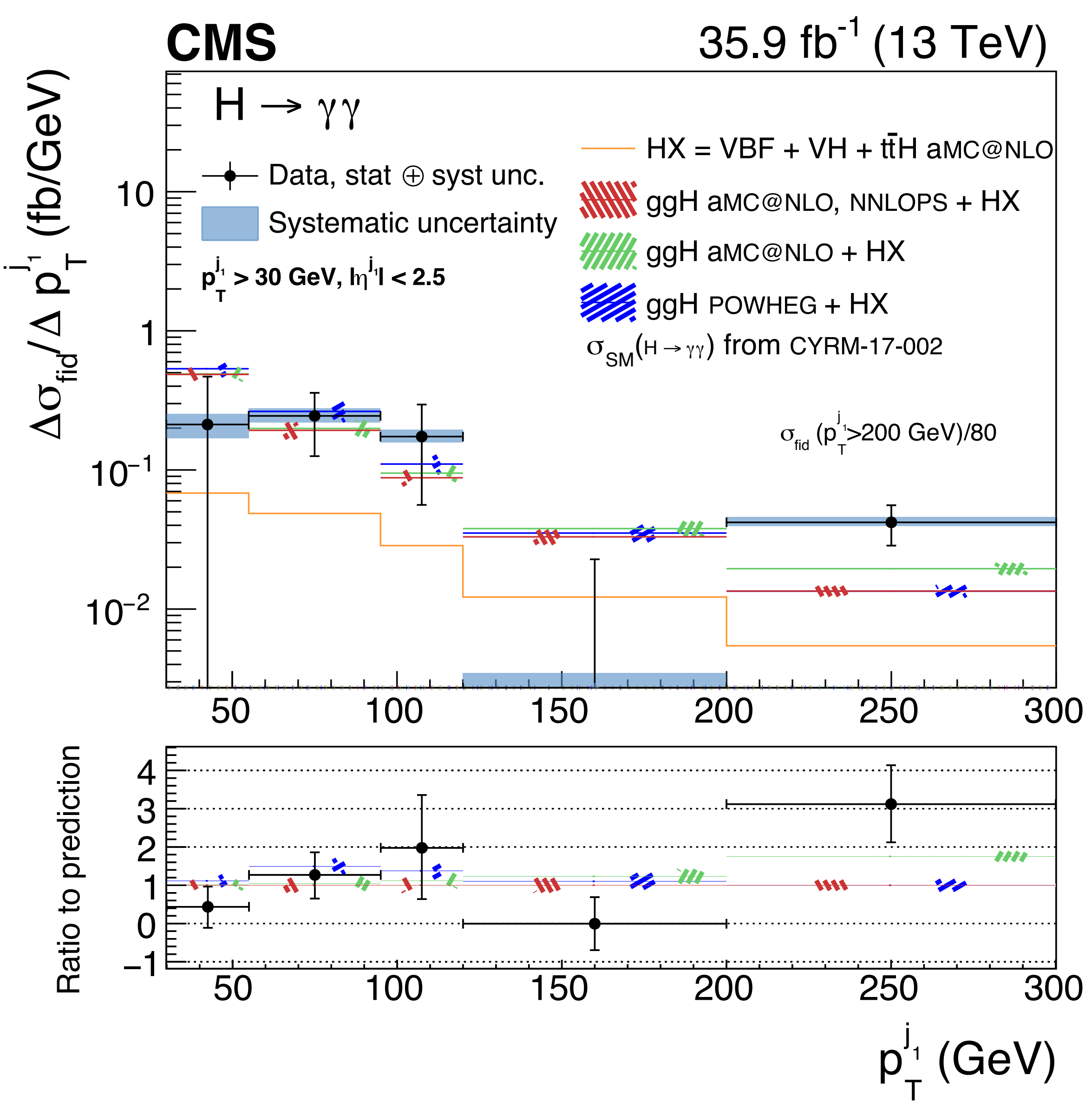
✓ Several channels

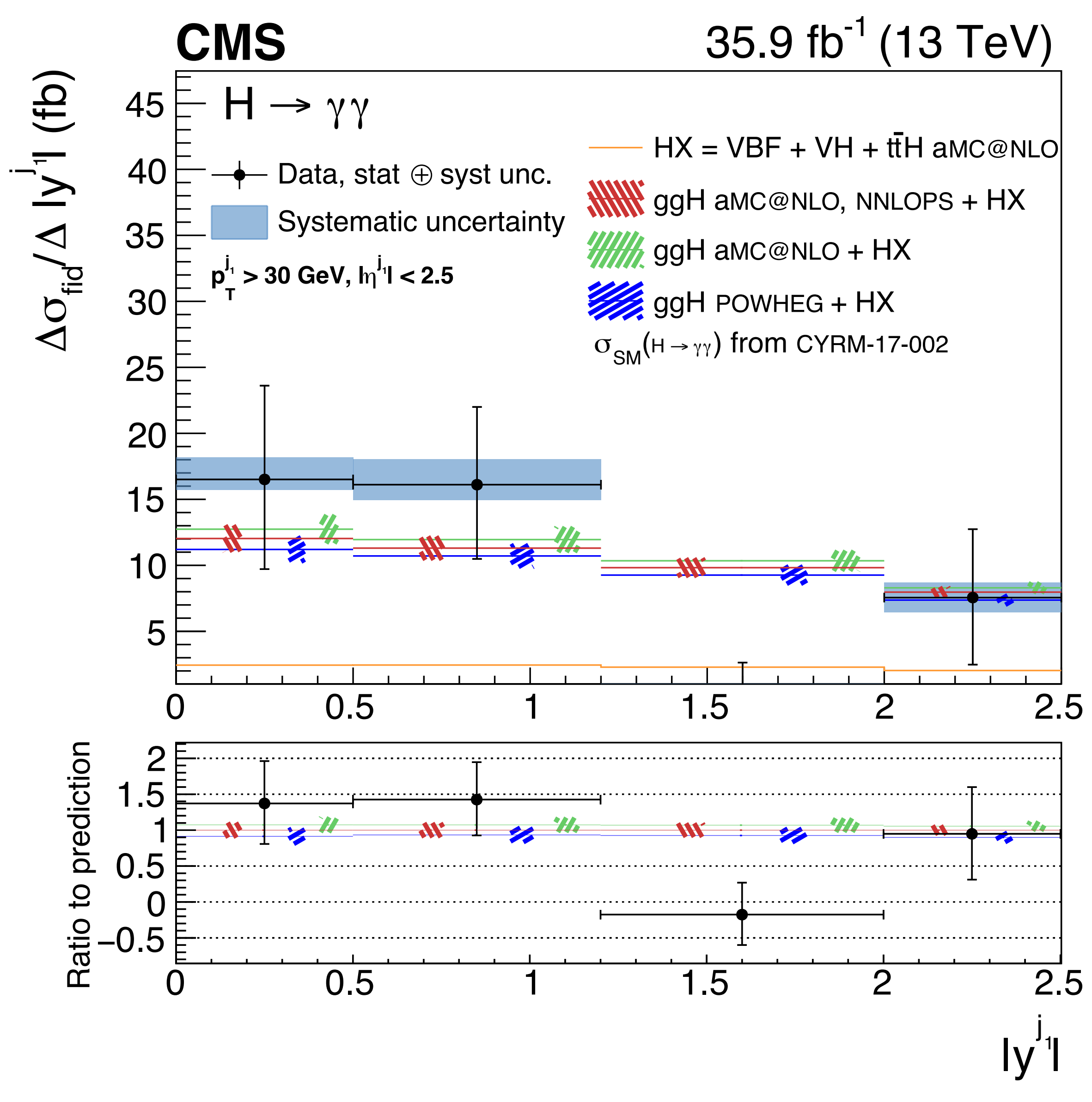
Higgs Discovery Announcement

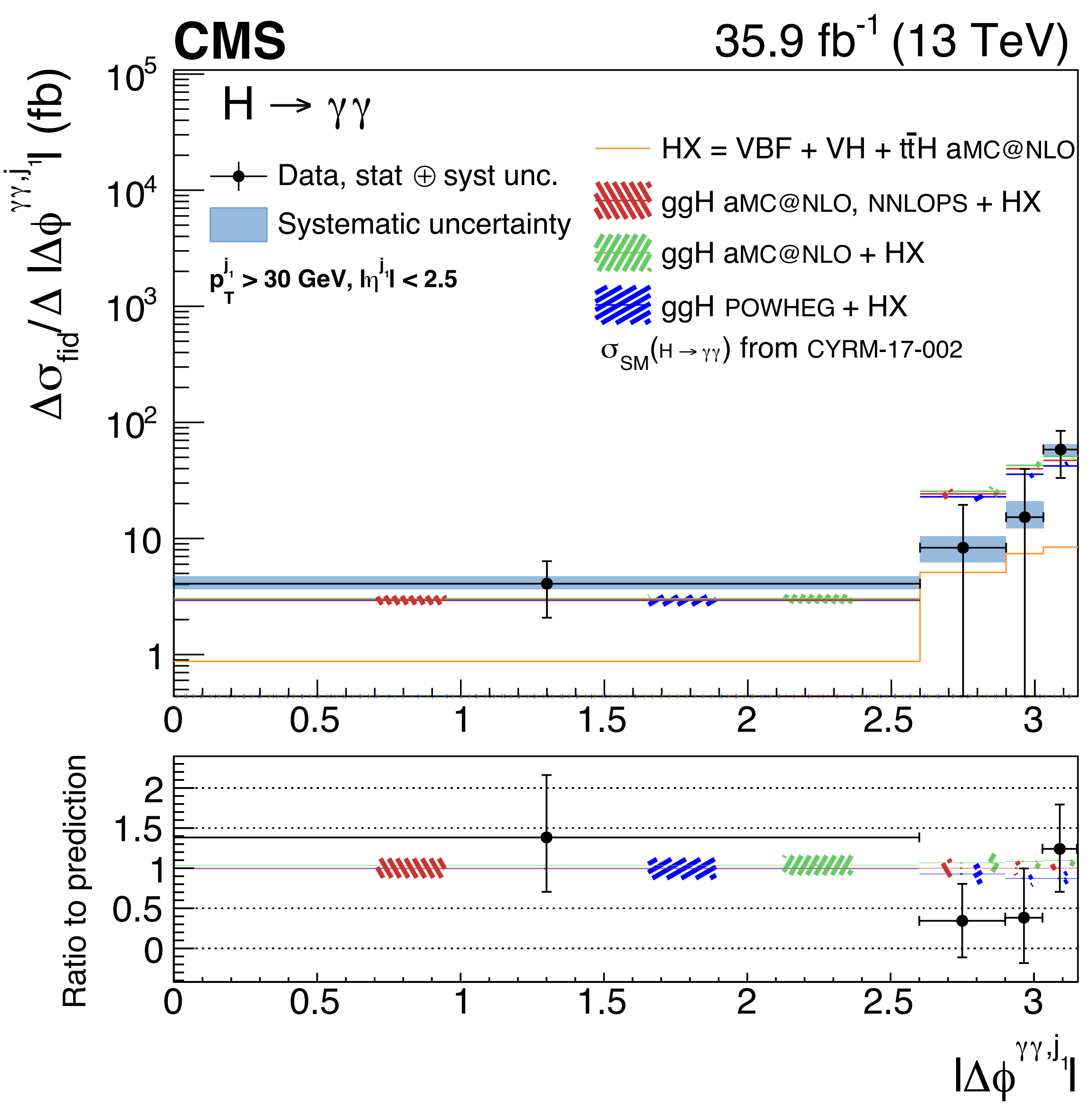
July 4th 2012

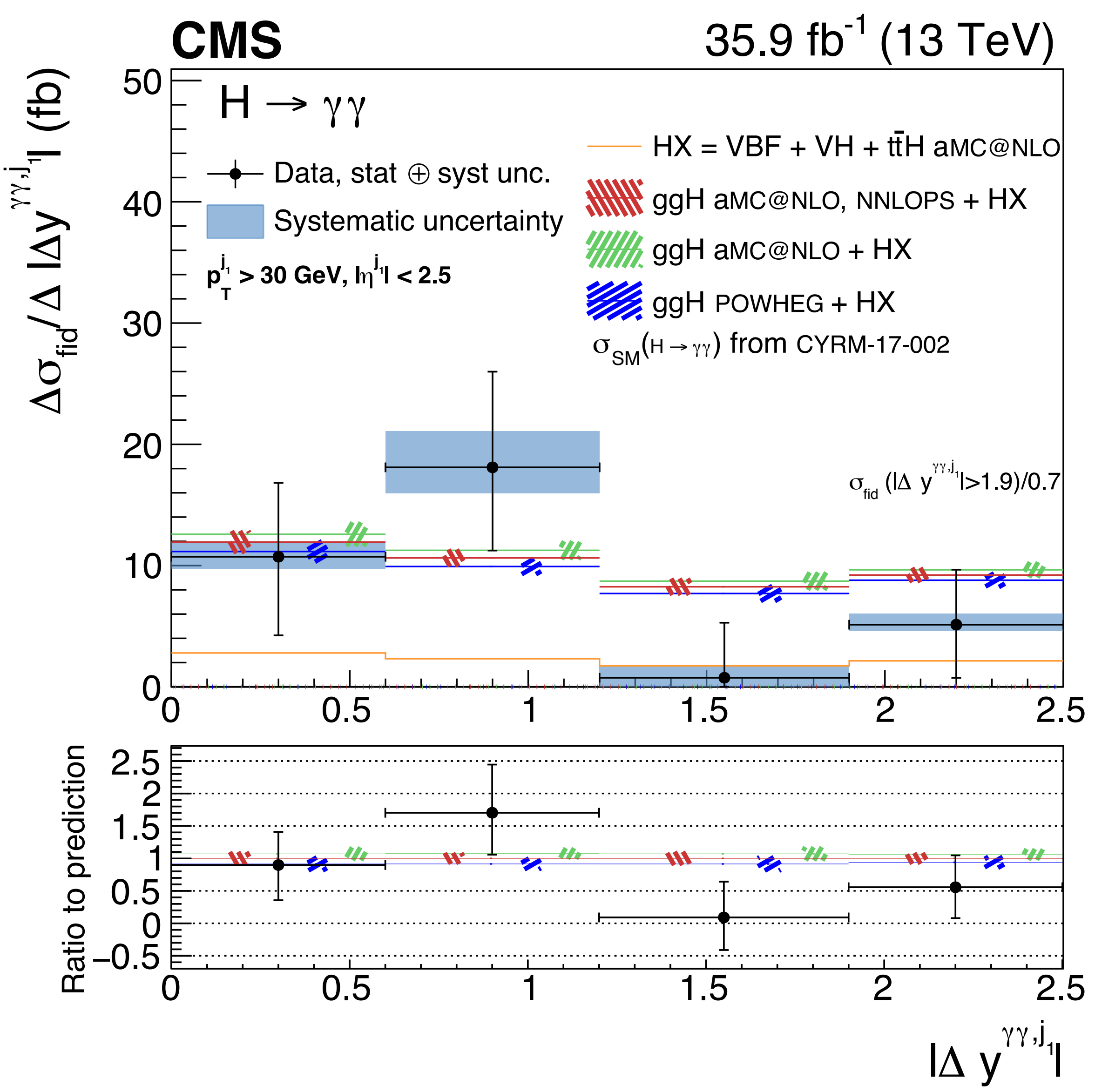
Measurements in the di-boson channels

Entering precision era in Higgs physics









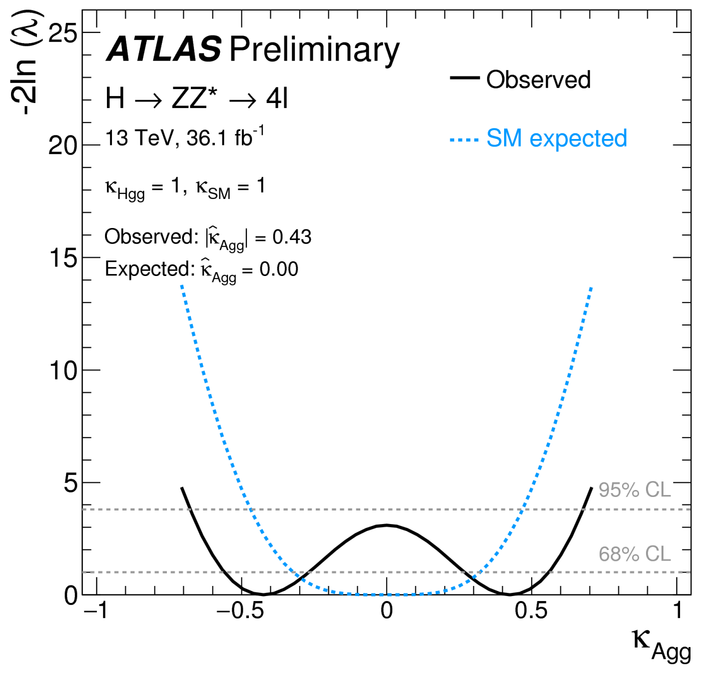
Measurement of fiducial and differential cross sections.

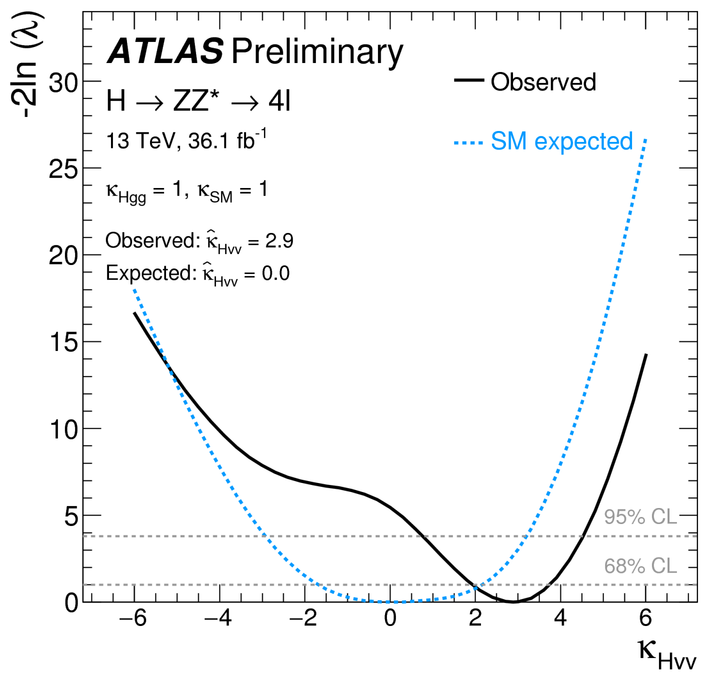
Measuring differential cross section open a vast number of interpretations in terms of properties of the Higgs boson:

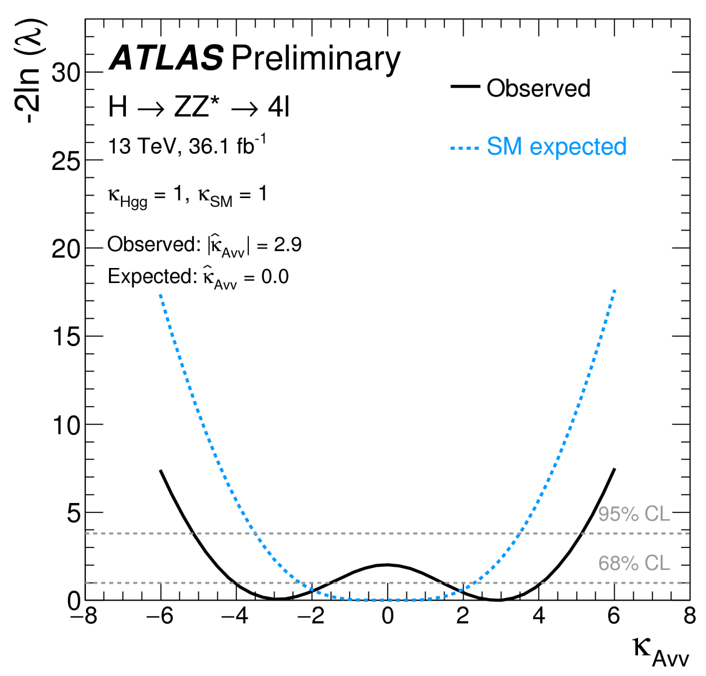
- Measure its spin/CP properties.

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

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



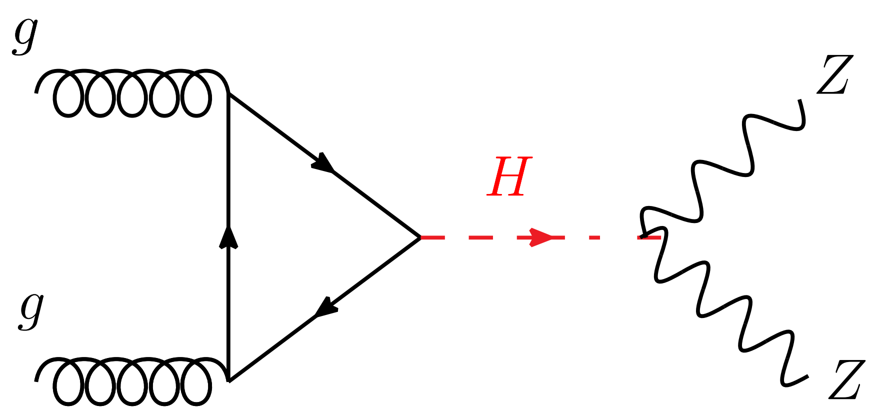


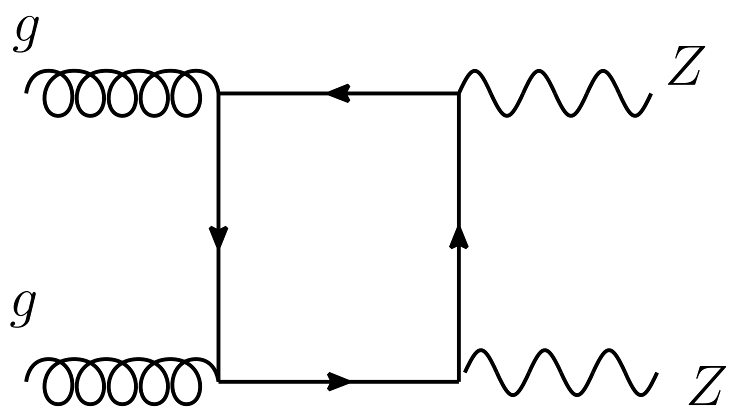


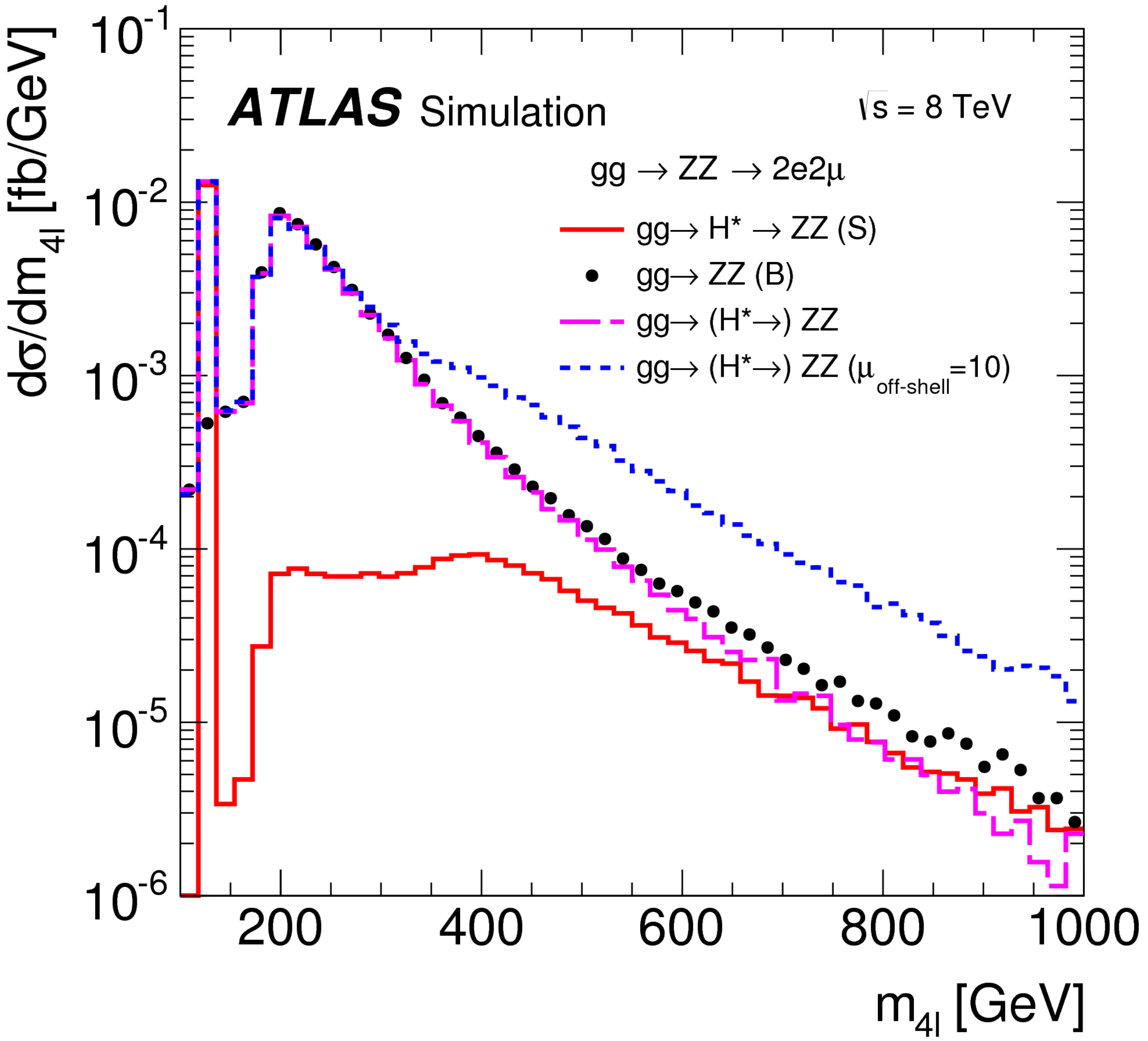
Off Shell Higgs

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





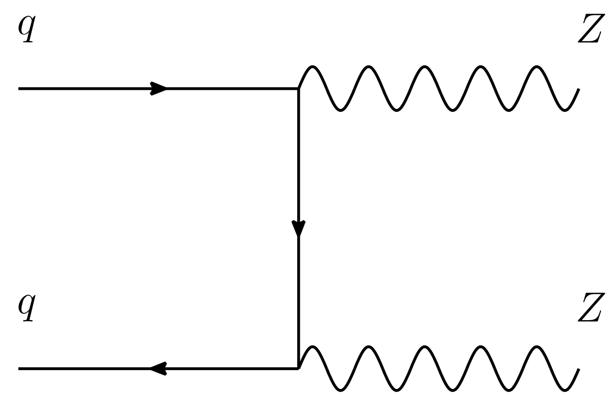


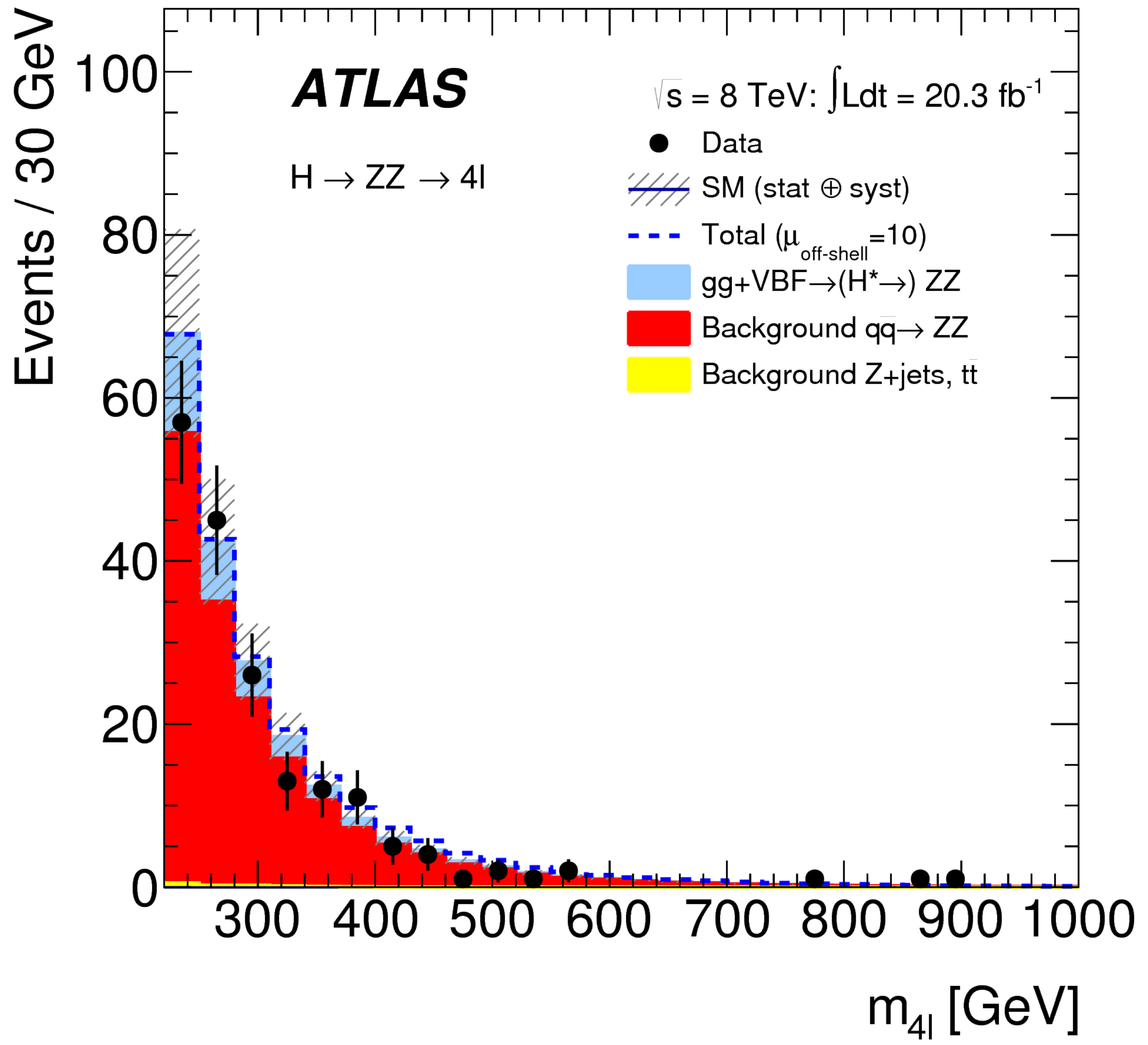
Measuring the Higgs contribution is then independent of the total width of the Higgs boson (sensitive to the product off shell of the Higgs boson to the coupling to the top and Z)

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 25 MeV

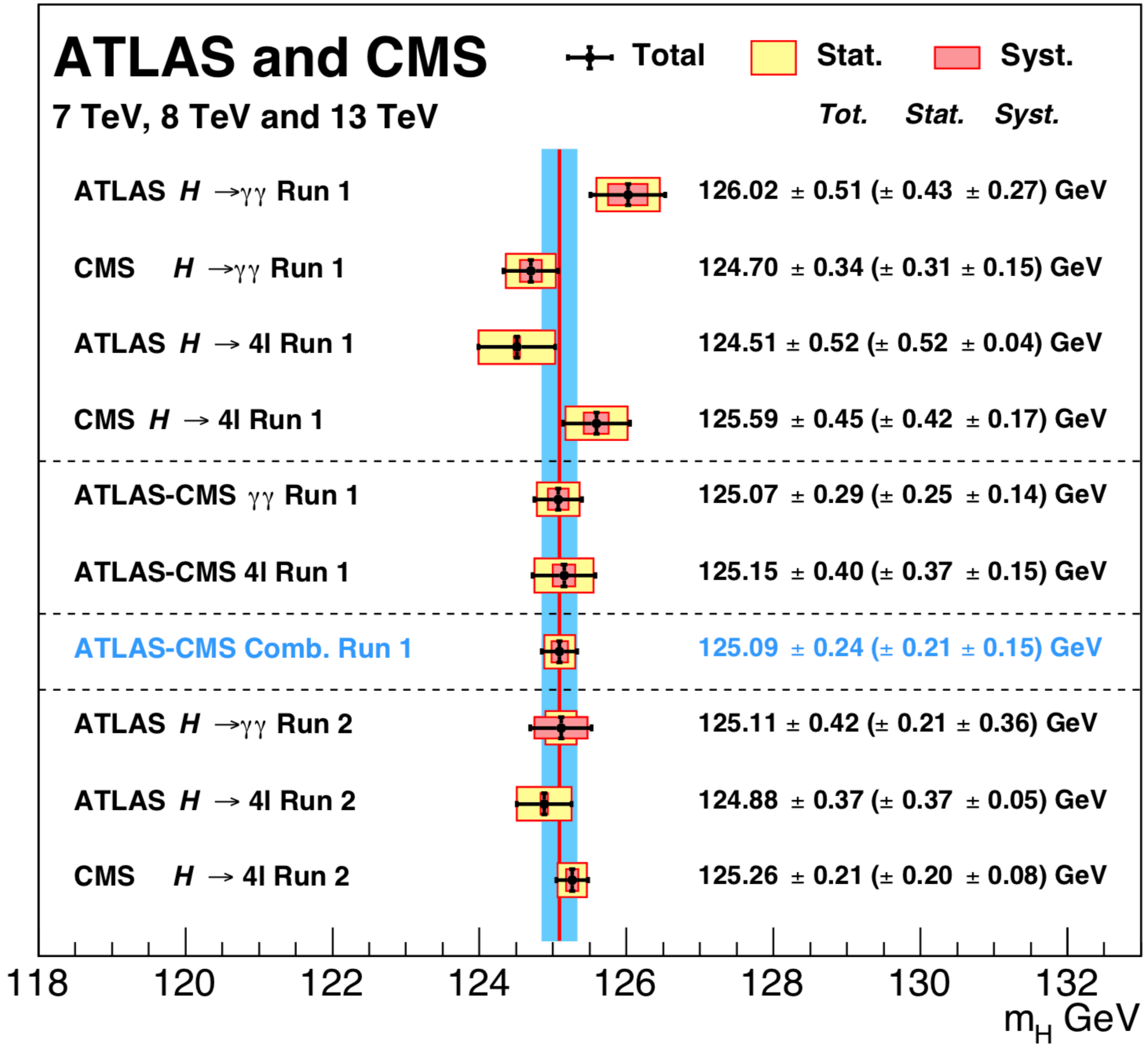
Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab-1:

$$\Gamma_H = 4.2^{+1.5}_{-2.1}\ MeV$$

First Precision Measurement at the LHC?

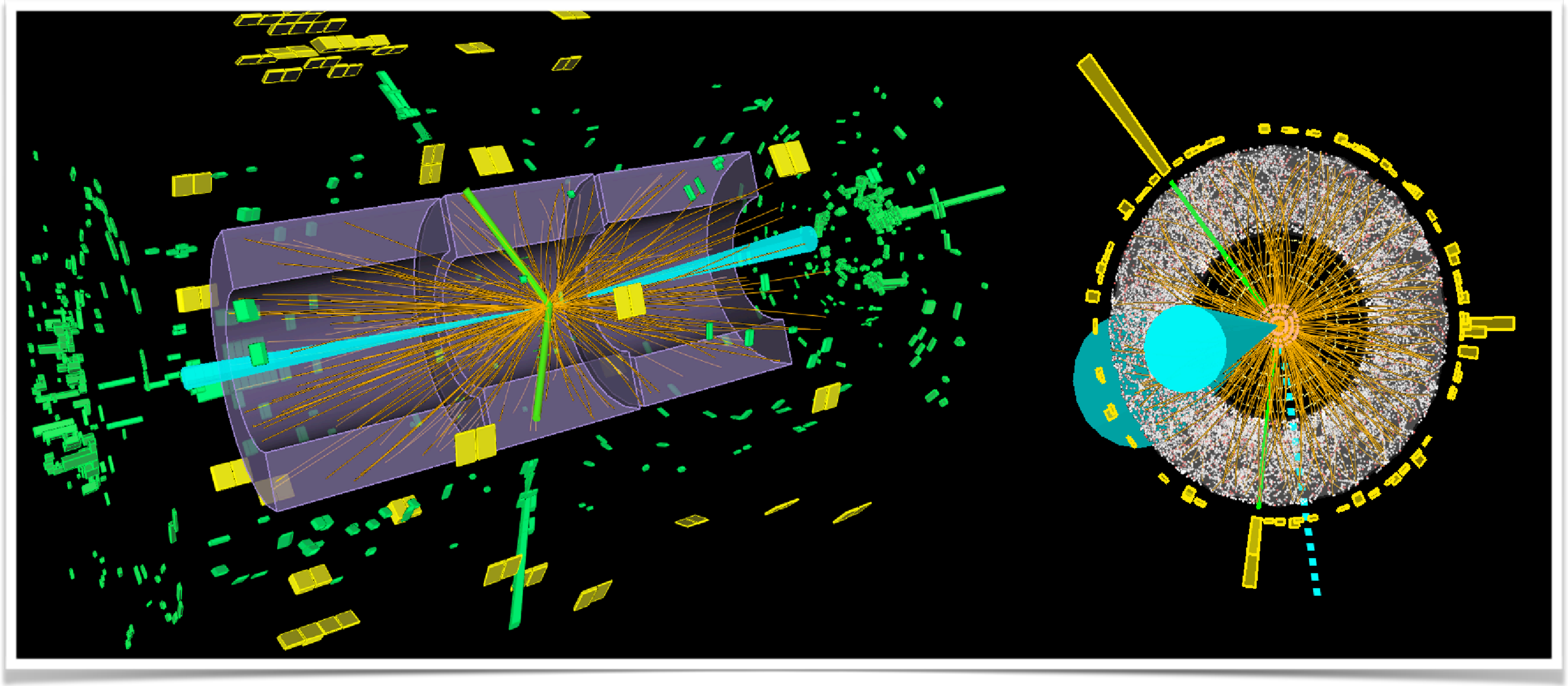
Higgs boson mass measurement

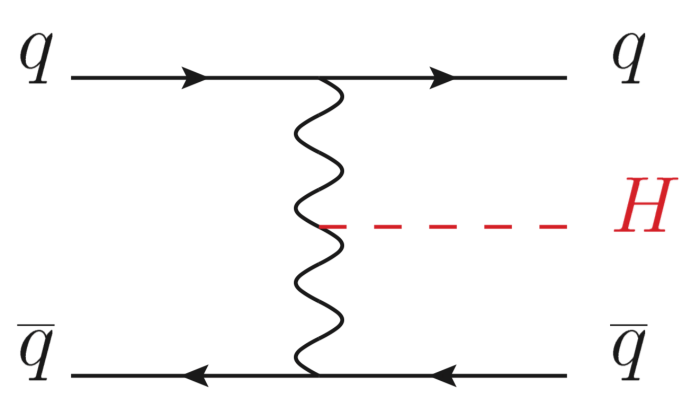
- Measurement done exclusively in the diphoton and 4-leptons channel.
- Optimizing the analysis in categories with best mass resolution (photon, electron and muons energy response).
- Reached at Run 1 a precision of 0.2%.
- Among (if not the) most precise measurement done at the LHC in 2013.



Measurements of Yukawa Couplingss

Higgs boson decays to Taus





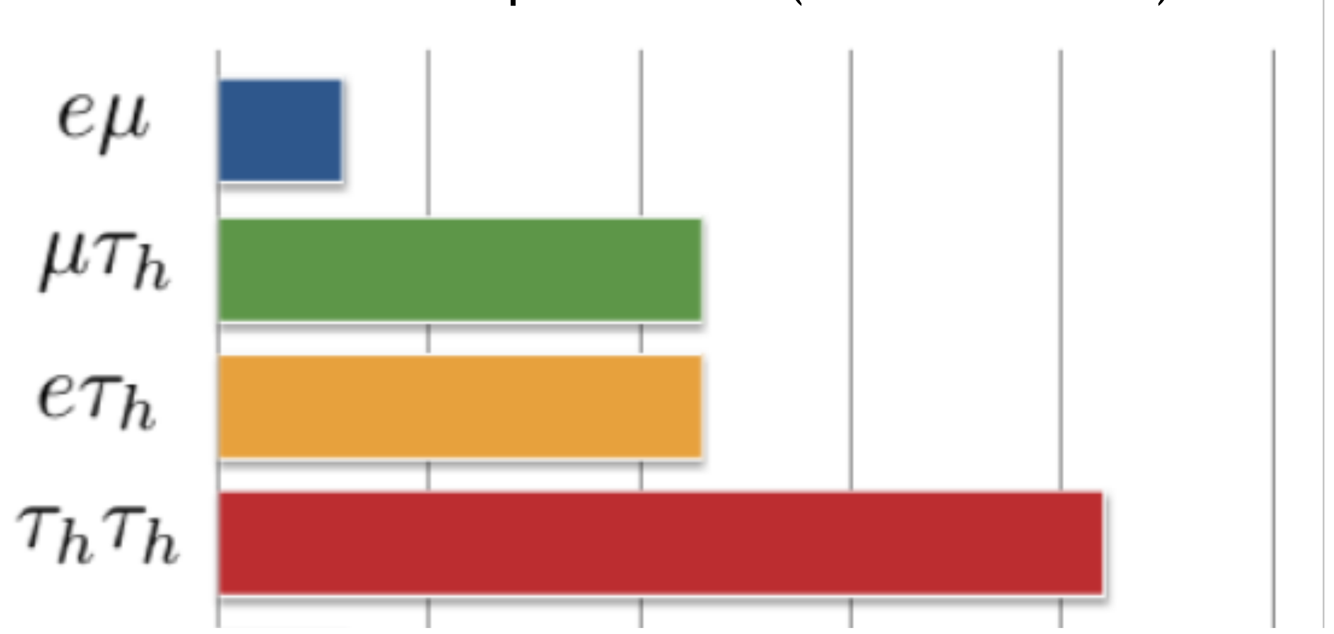
Special VBF process

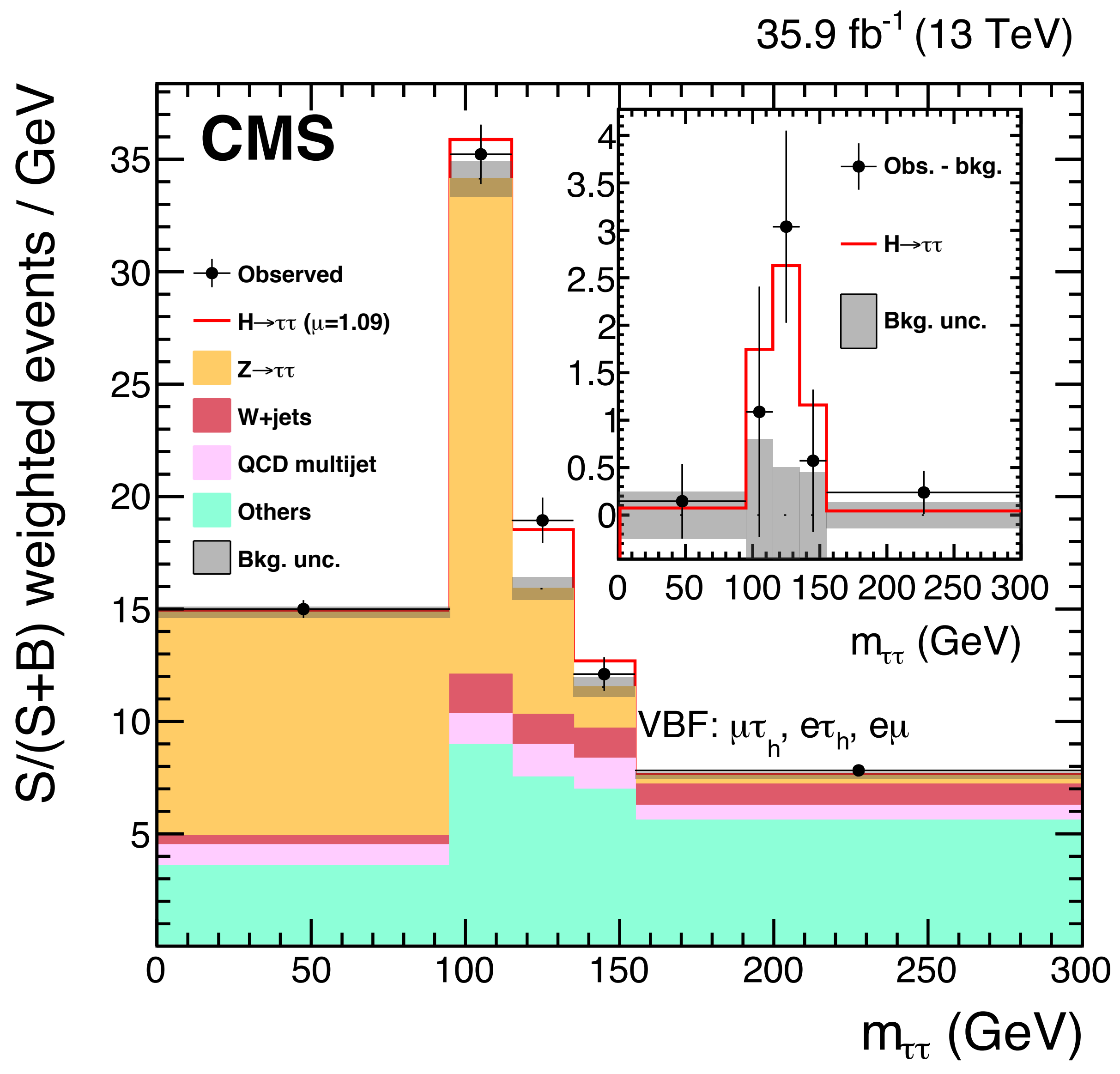
With two forward jets and a large rapidity gap between the jets (due to the color singlet exchange in the t-channel

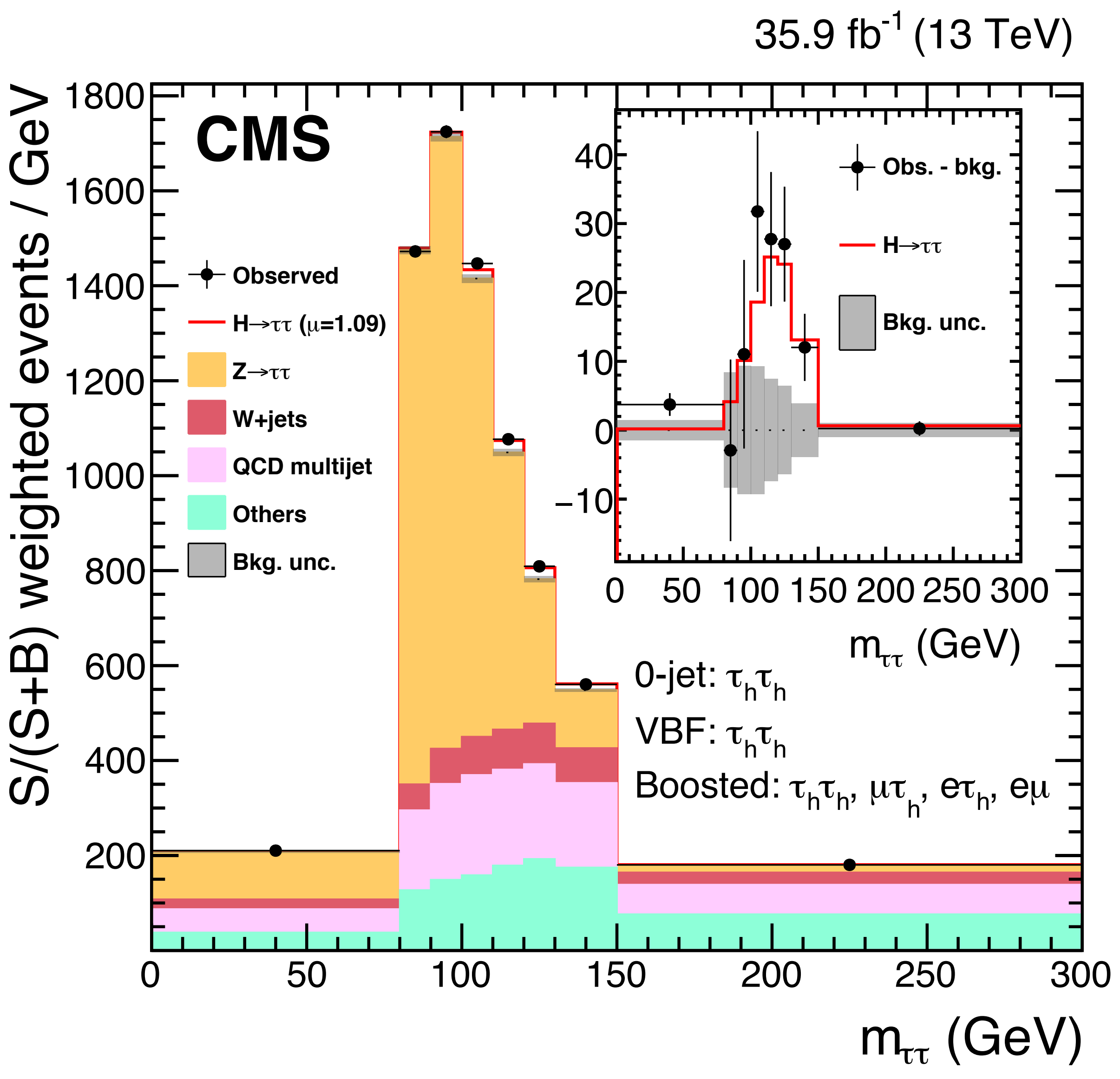
Background is Z production with two jets, in this region of phase space it is difficult to predict!

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

Tau to leptons ~18% (rest is hadrons)





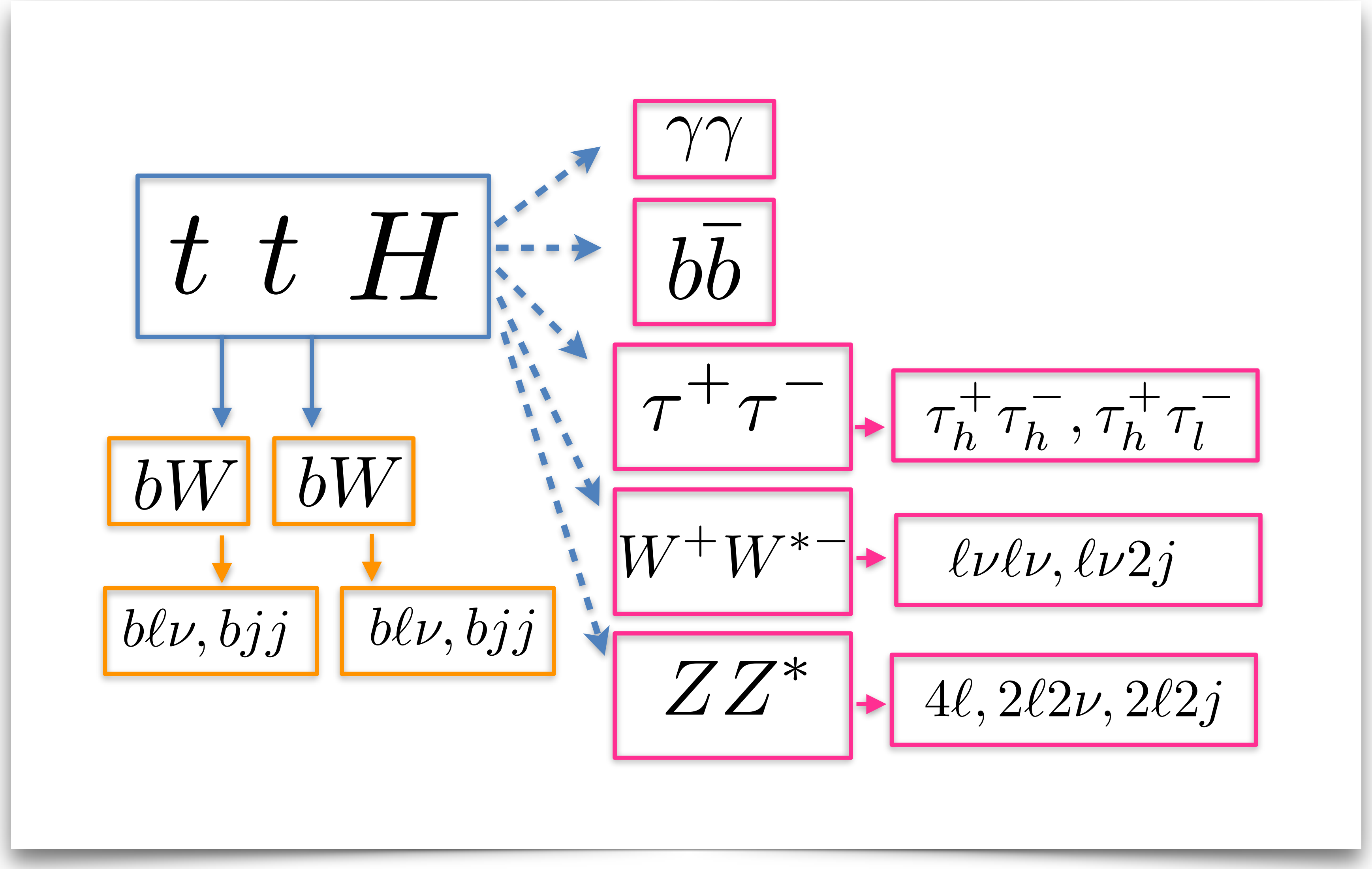


Analysis requires data driven methods to do so: e.g. the embedding of taus in Z to di-muon events.

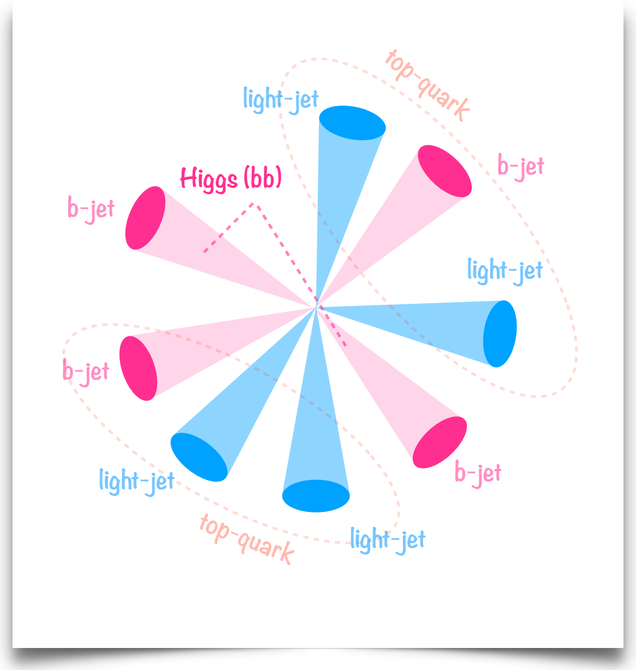
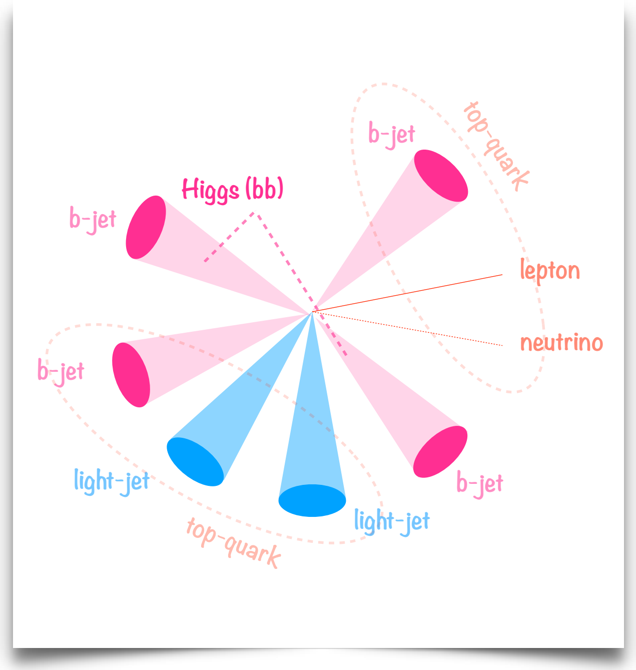
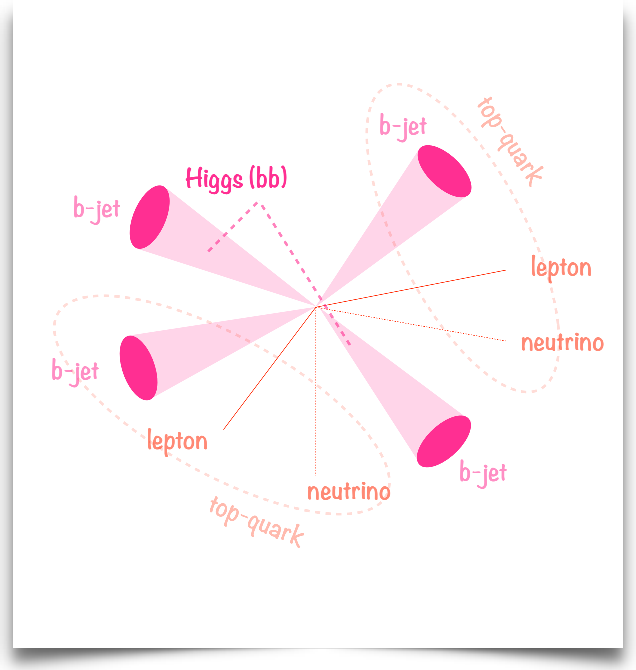
The tau polarisation can in principle be reconstructed, but this is very difficult and was not done yet.

Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!



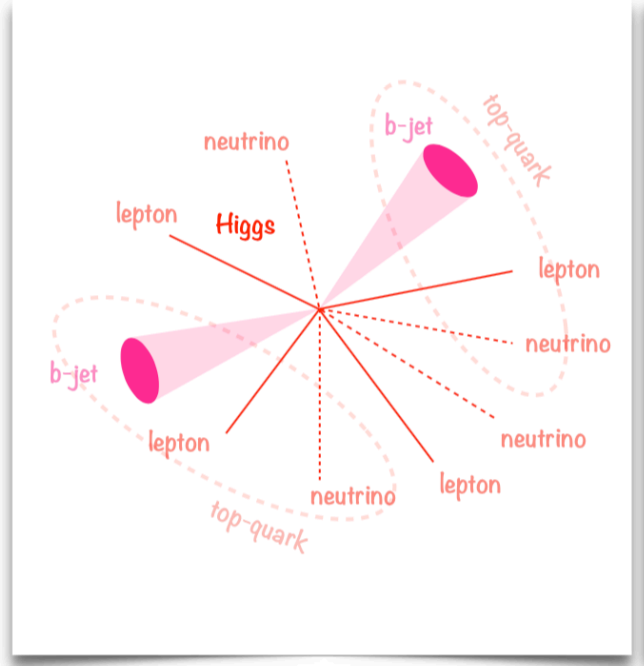
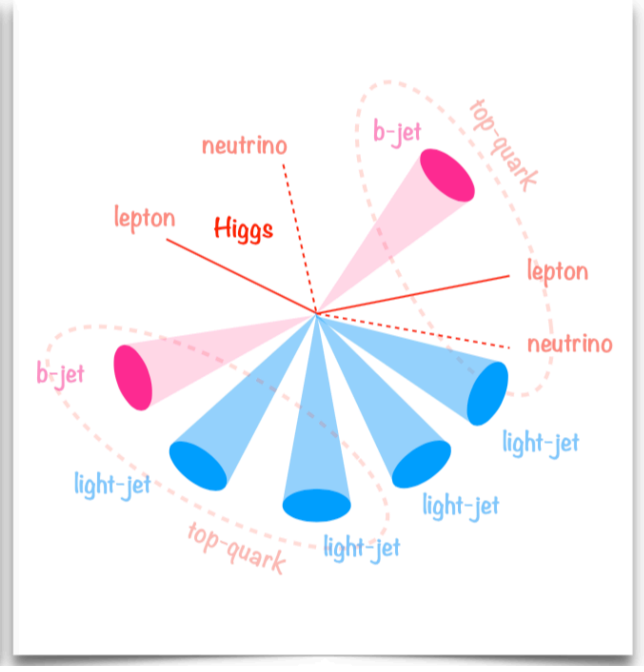
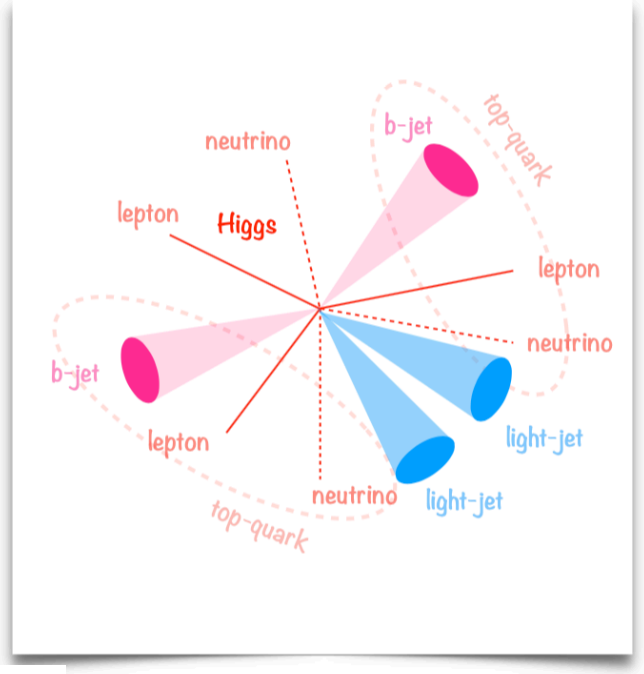
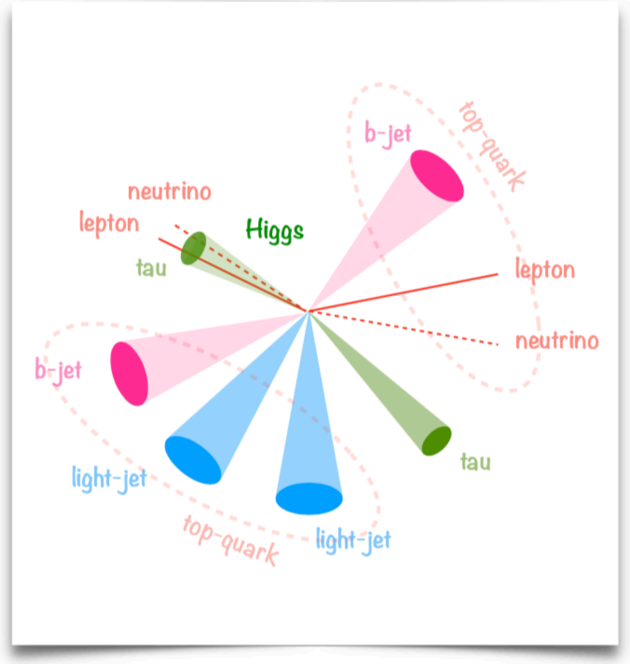
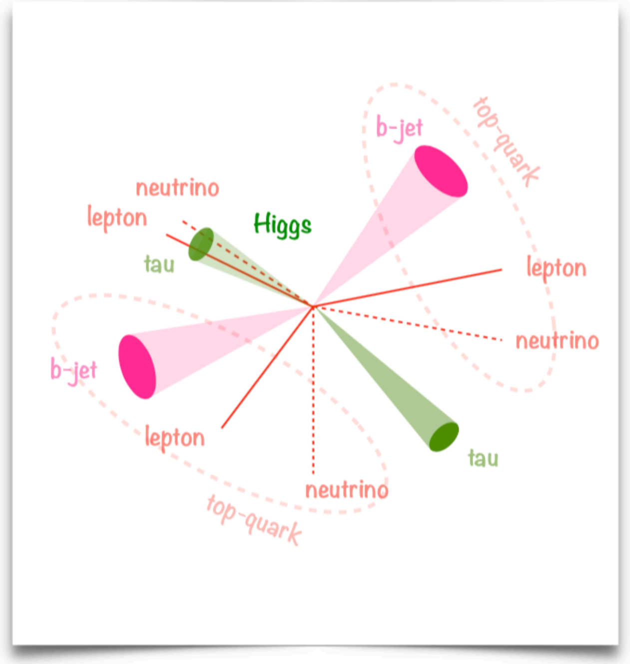
- Large number of final states which are typically very complex (mixture of b-jets, leptons, taus and photons)
- But, many different channels, also means different backgrounds and different systematic uncertainties and therefore also a strength!
- With the new Run at close to double centre-of-mass energy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

ttH(bb)

Very large backgrounds of top pair production associated with b jets

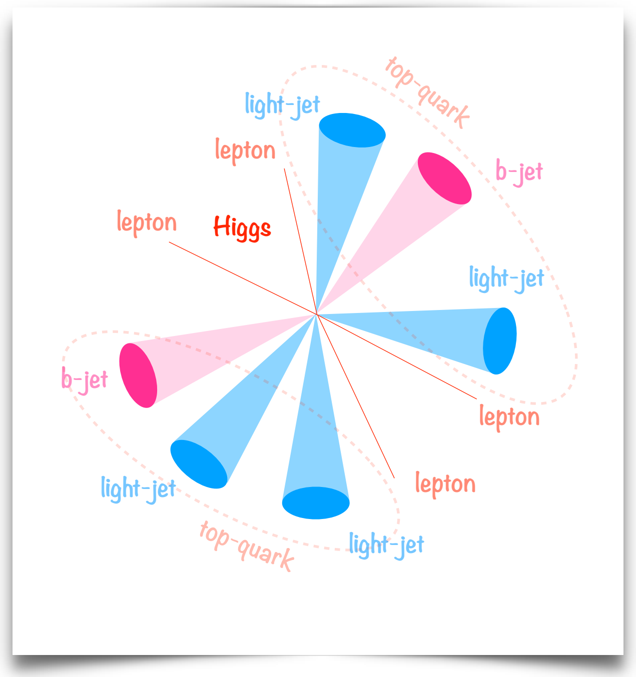
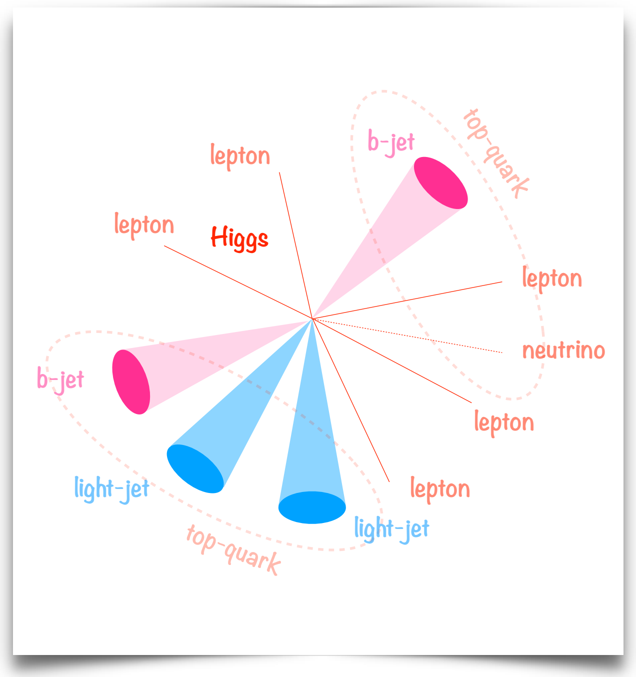
Dominated by background modelling uncertainties

ttH(WW, ZZ and tau tau)

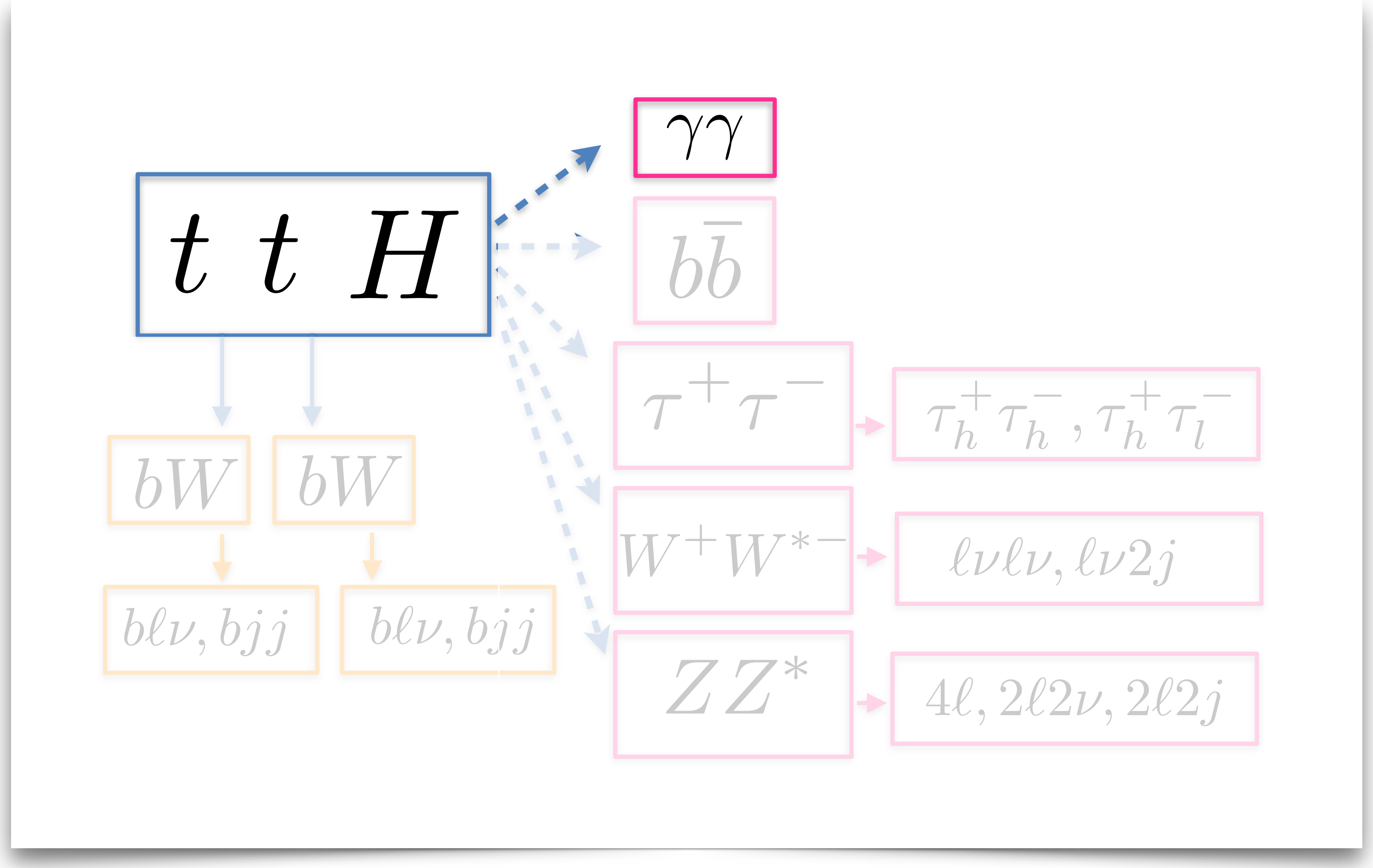
So-called multi-lepton channel

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

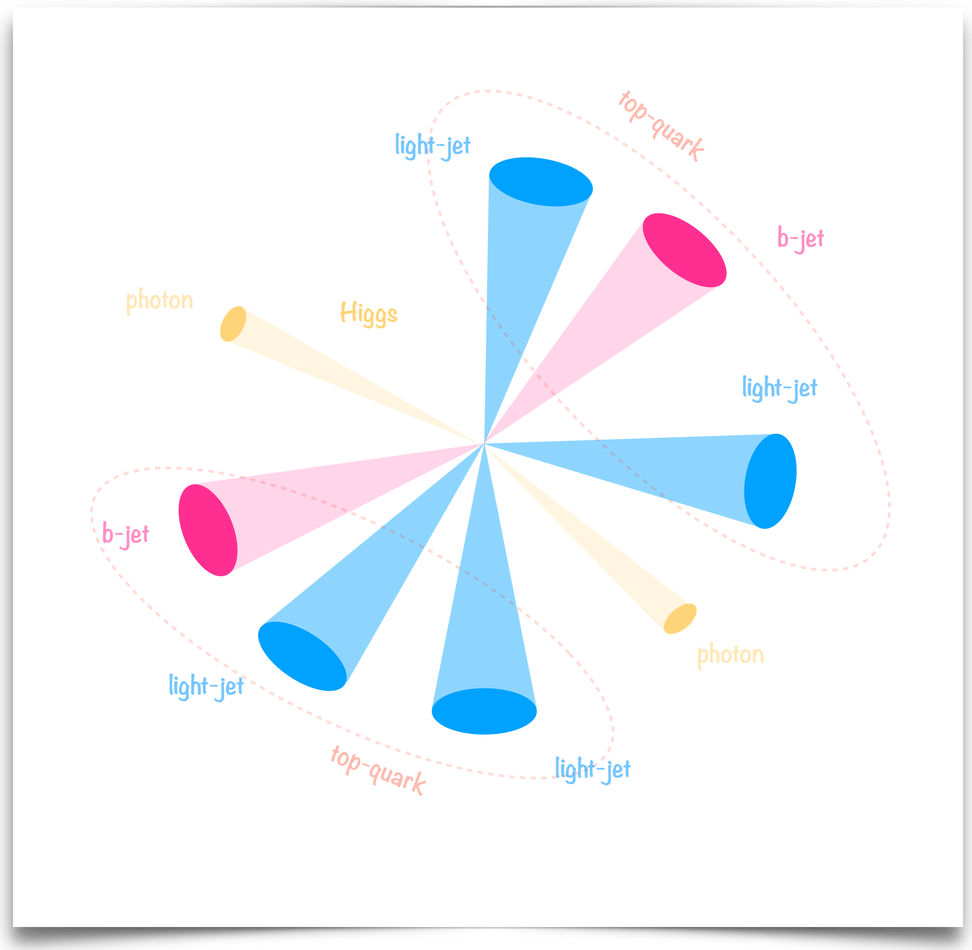



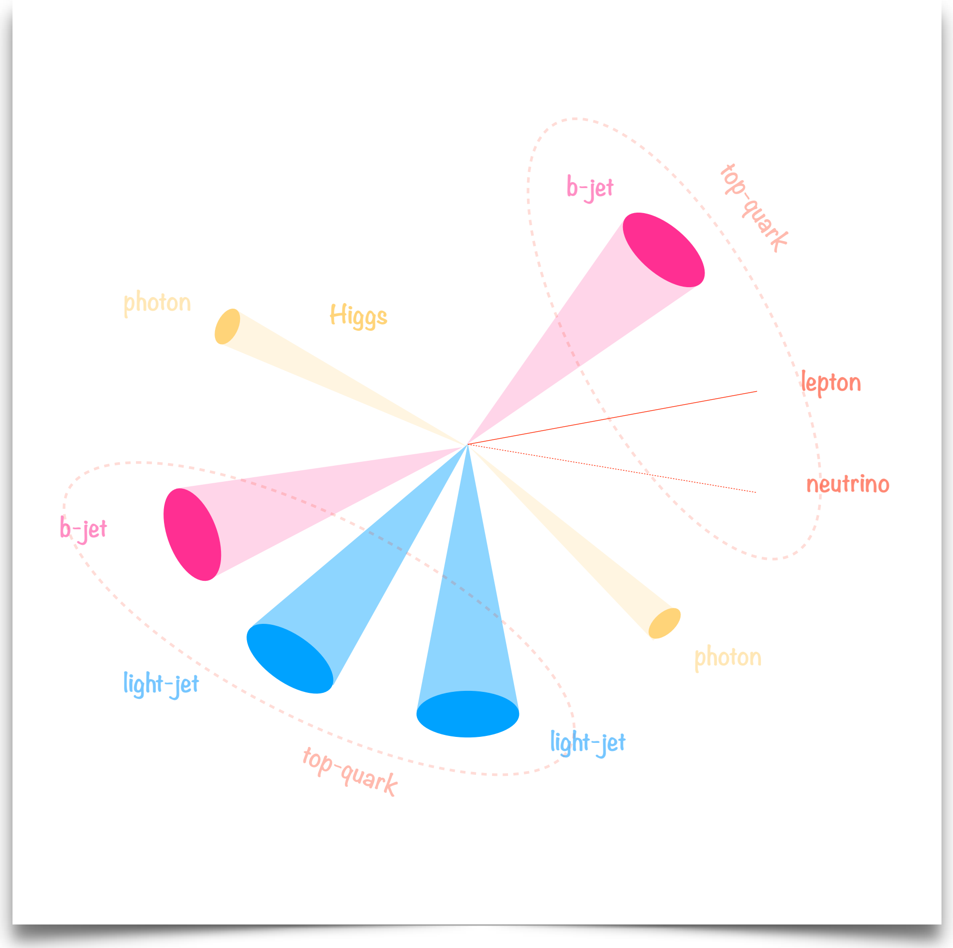
Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!



Currently cleanest and most sensitive channel



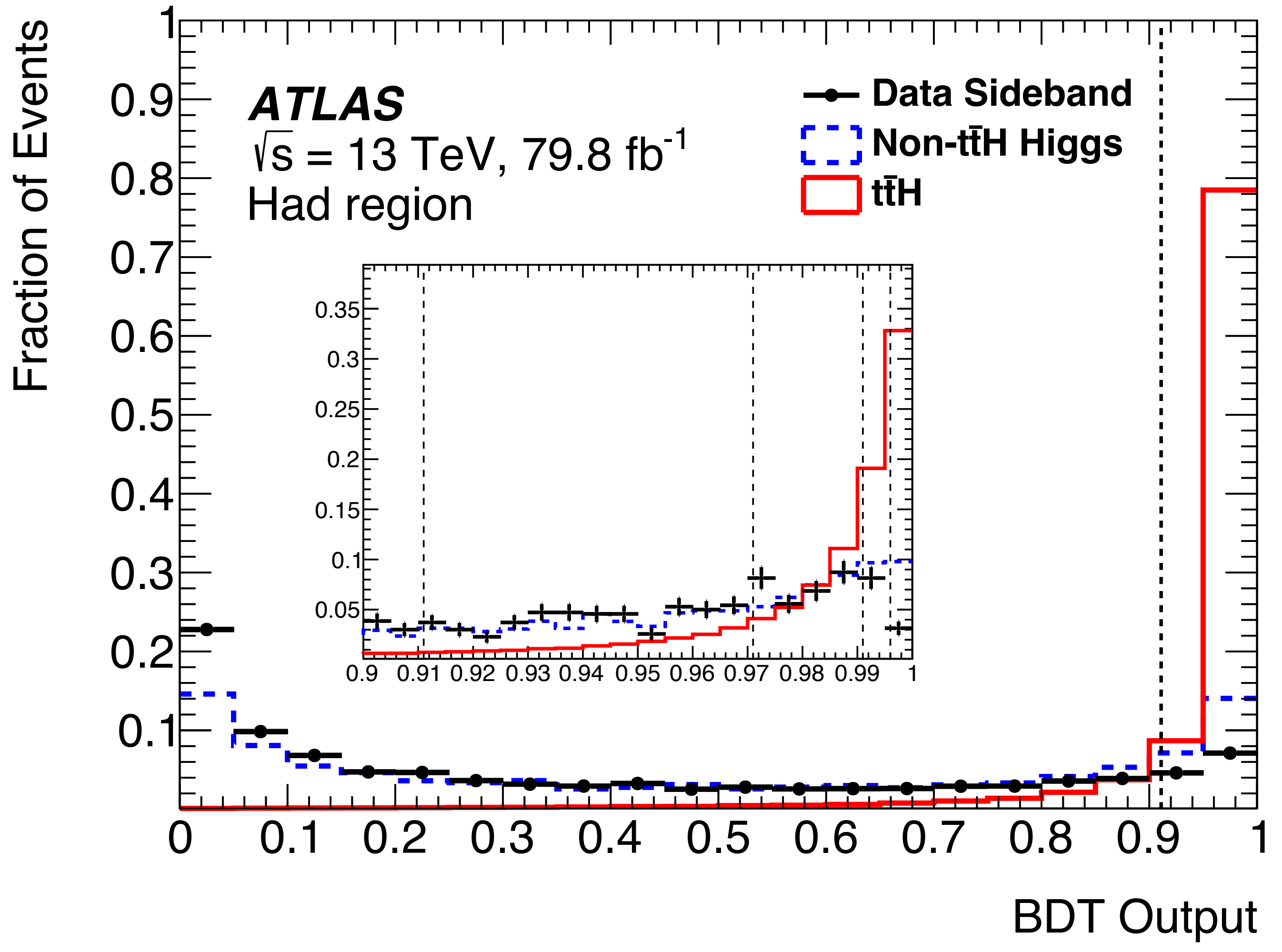


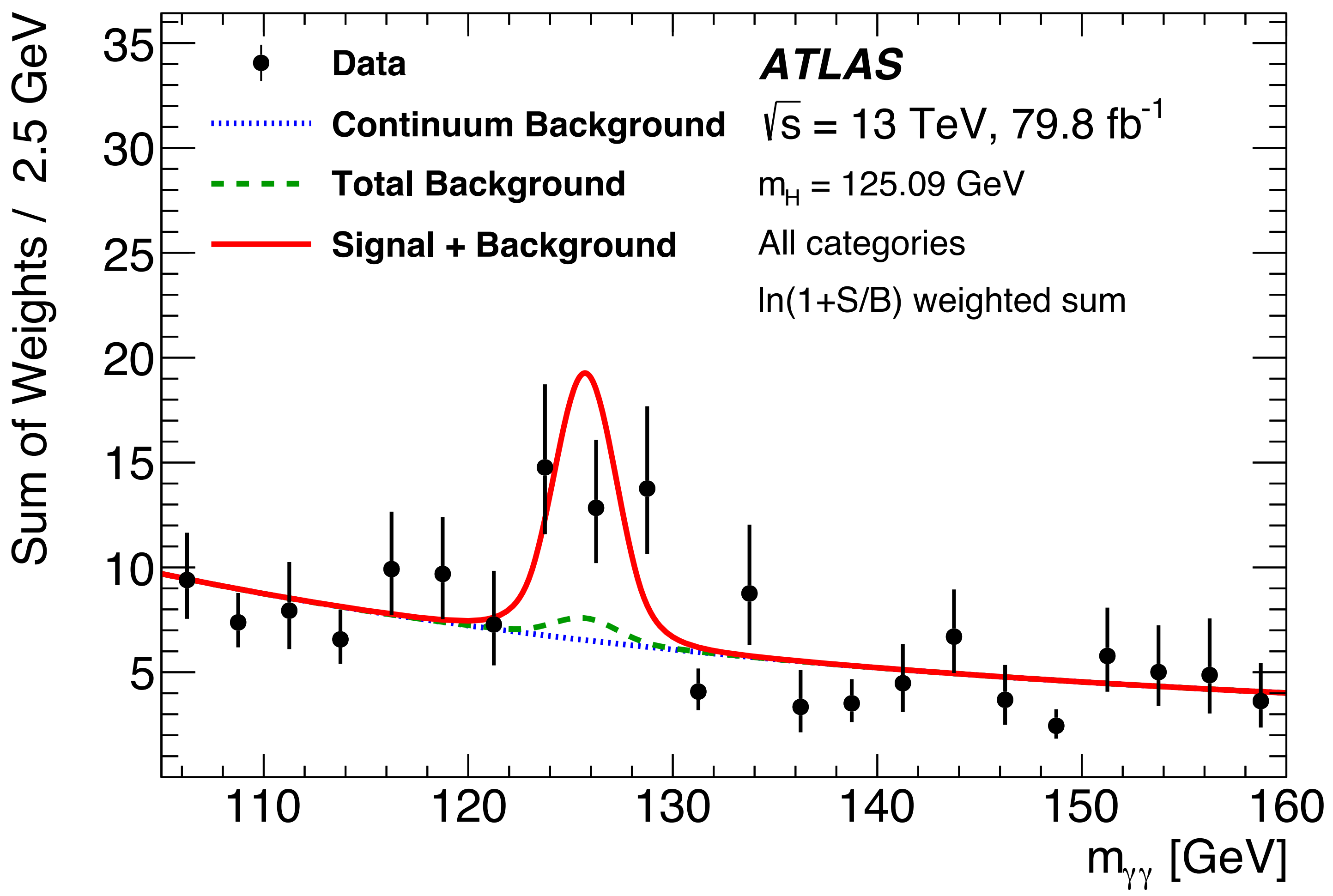
Two separate main channels **0L** and **1L** (inclusive)

« Machine learning » approach, training a BDT using « low level variables »

- 3-vector of photons (normalised to Myy
- 4-vectors of jets (up to 6 leading jets)
- 4-vectors of leptons (up to 2 leading leptons)

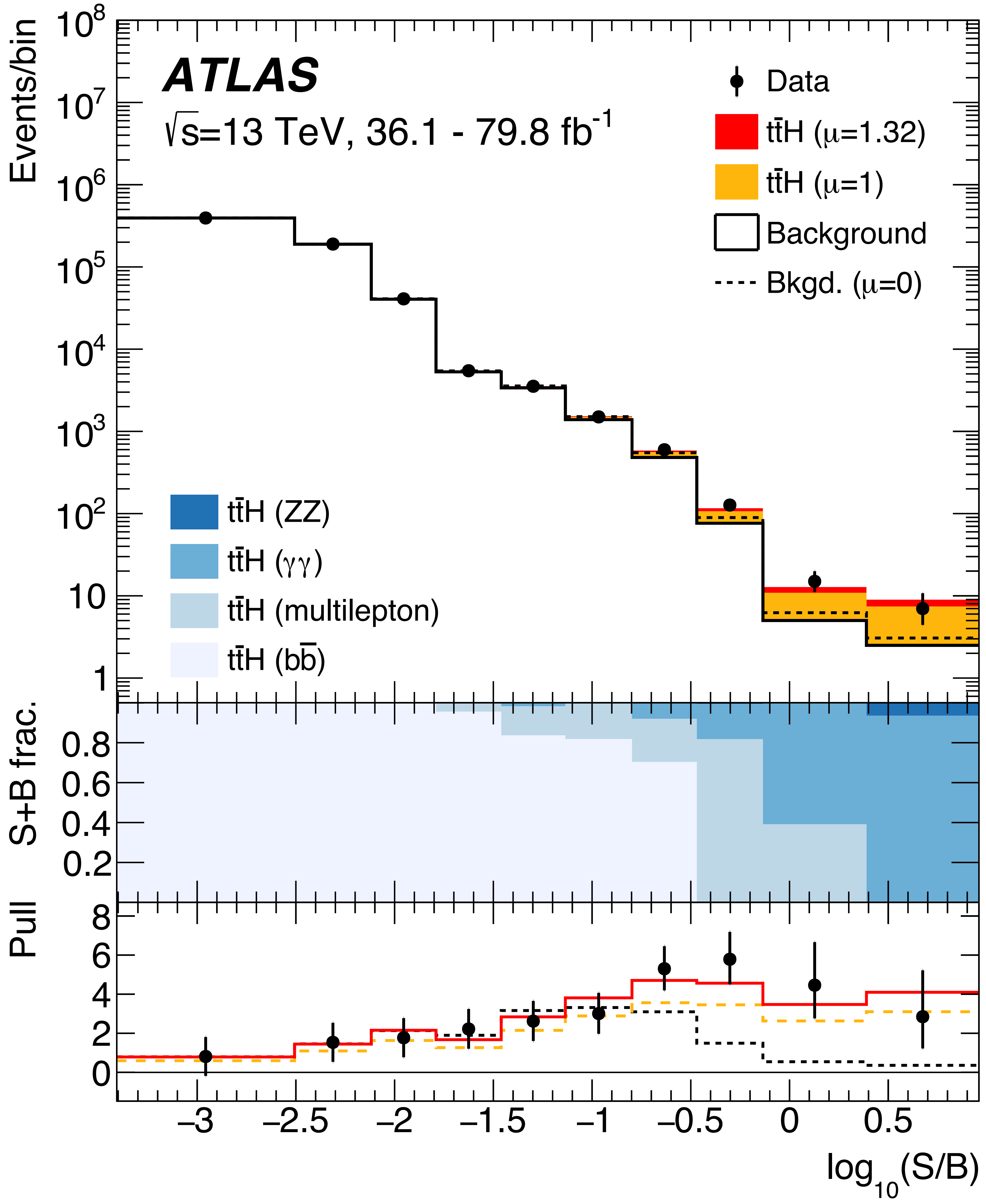
Background and signal modelled using analytic functions.





Direct probe of the top Yukawa coupling

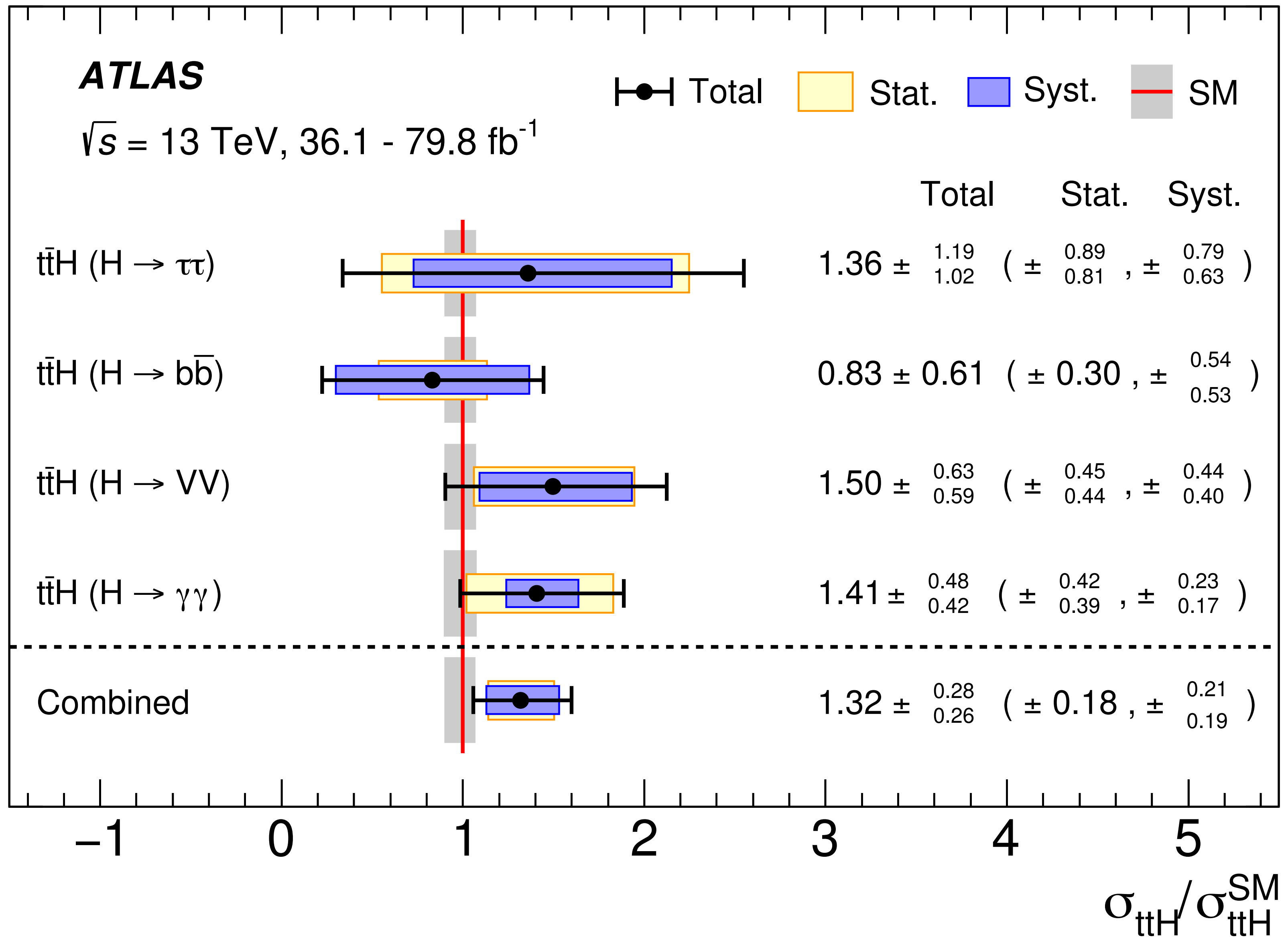
ttH Combining all channels with diphoton and 4-leptons categories



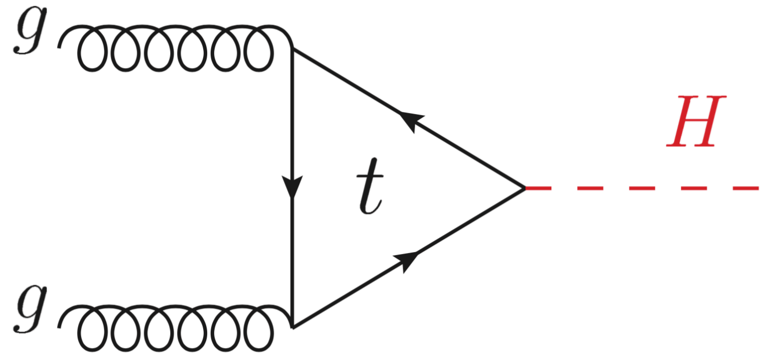
Analysis	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	$4.1\ \sigma$	$3.7\ \sigma$
$H \to$ multilepton	$4.1\ \sigma$	$2.8\ \sigma$
$H \to b\bar{b}$	$1.4\ \sigma$	$1.6\ \sigma$
$H \to ZZ^* \to 4\ell$	$0\ \sigma$	$1.2\ \sigma$
Combined (13 TeV)	$5.8\ \sigma$	$4.9\ \sigma$
Combined (7, 8, 13 TeV)	$6.3\ \sigma$	$5.1\ \sigma$

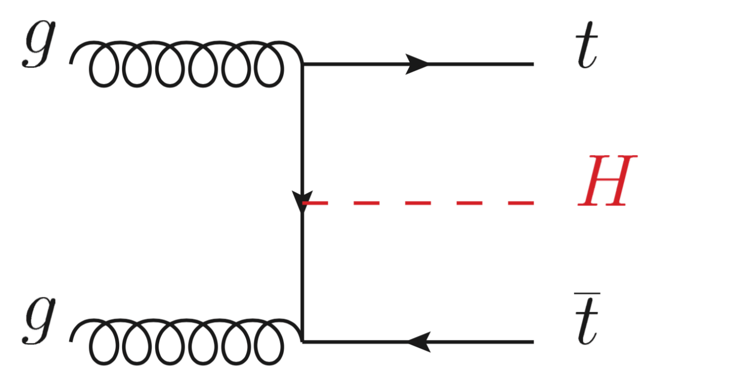
Observation!!

CMS has very similar results



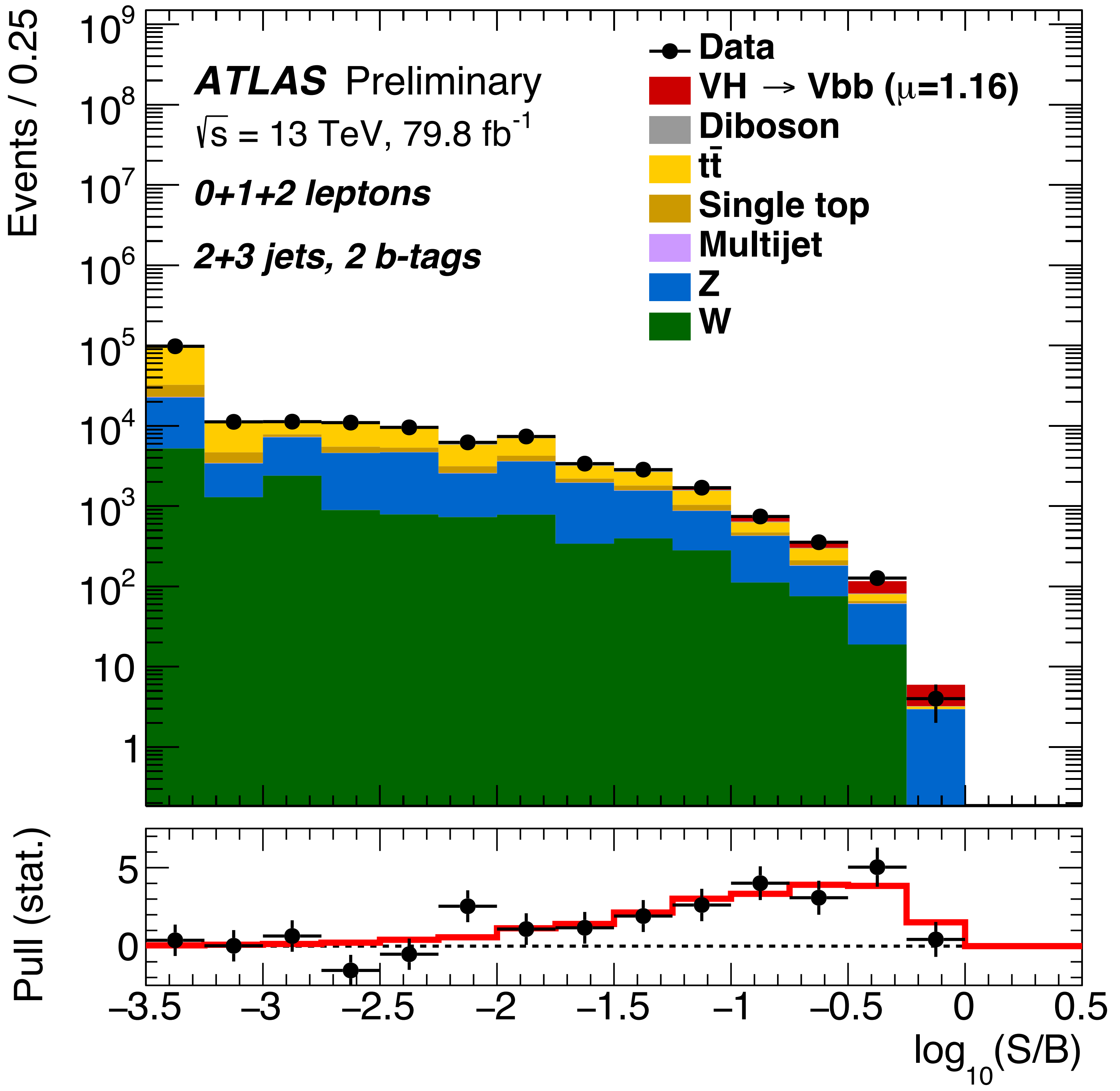
Consistency at 20% level between the direct and indirect measurement of the top Yukawa

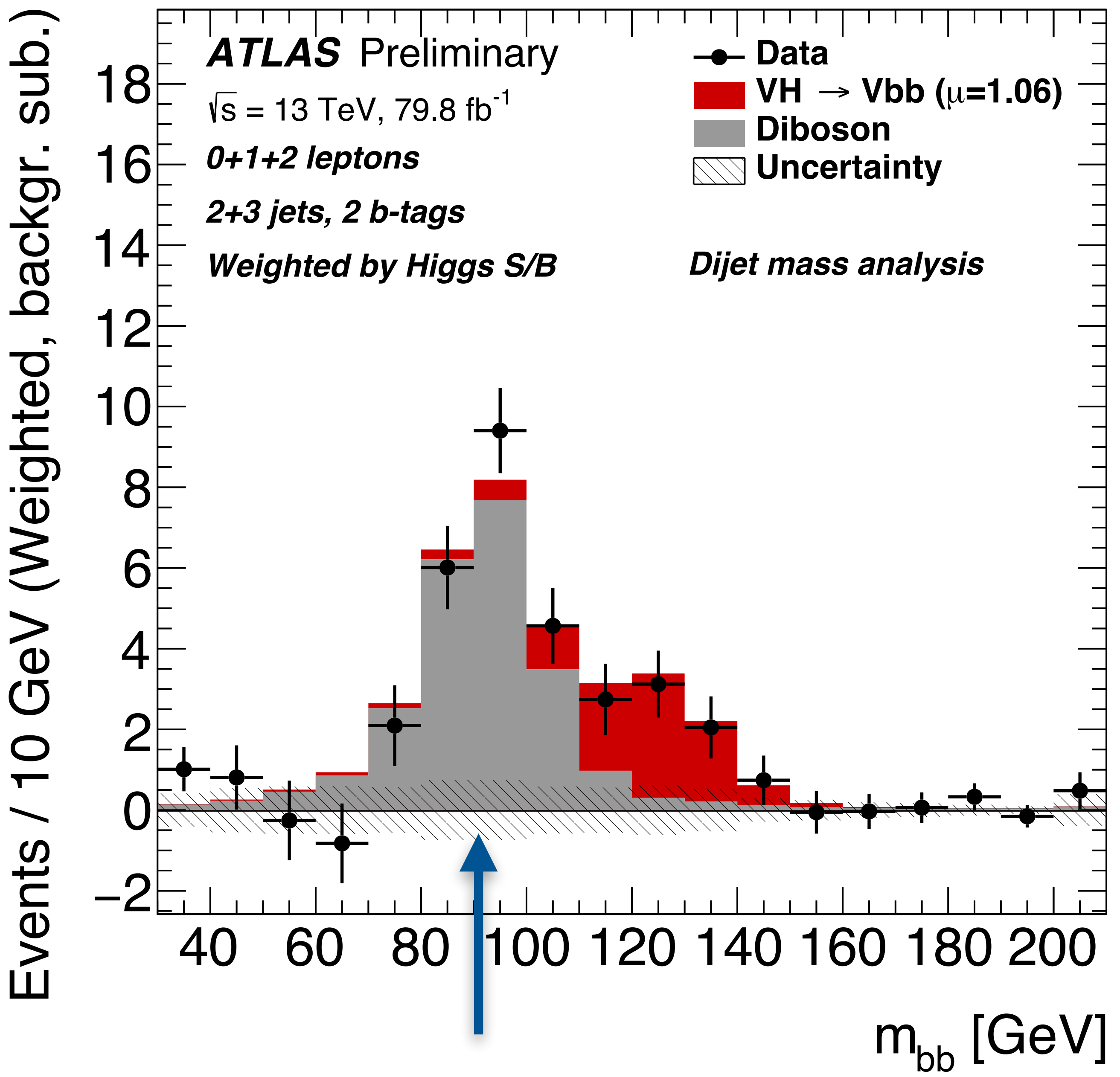




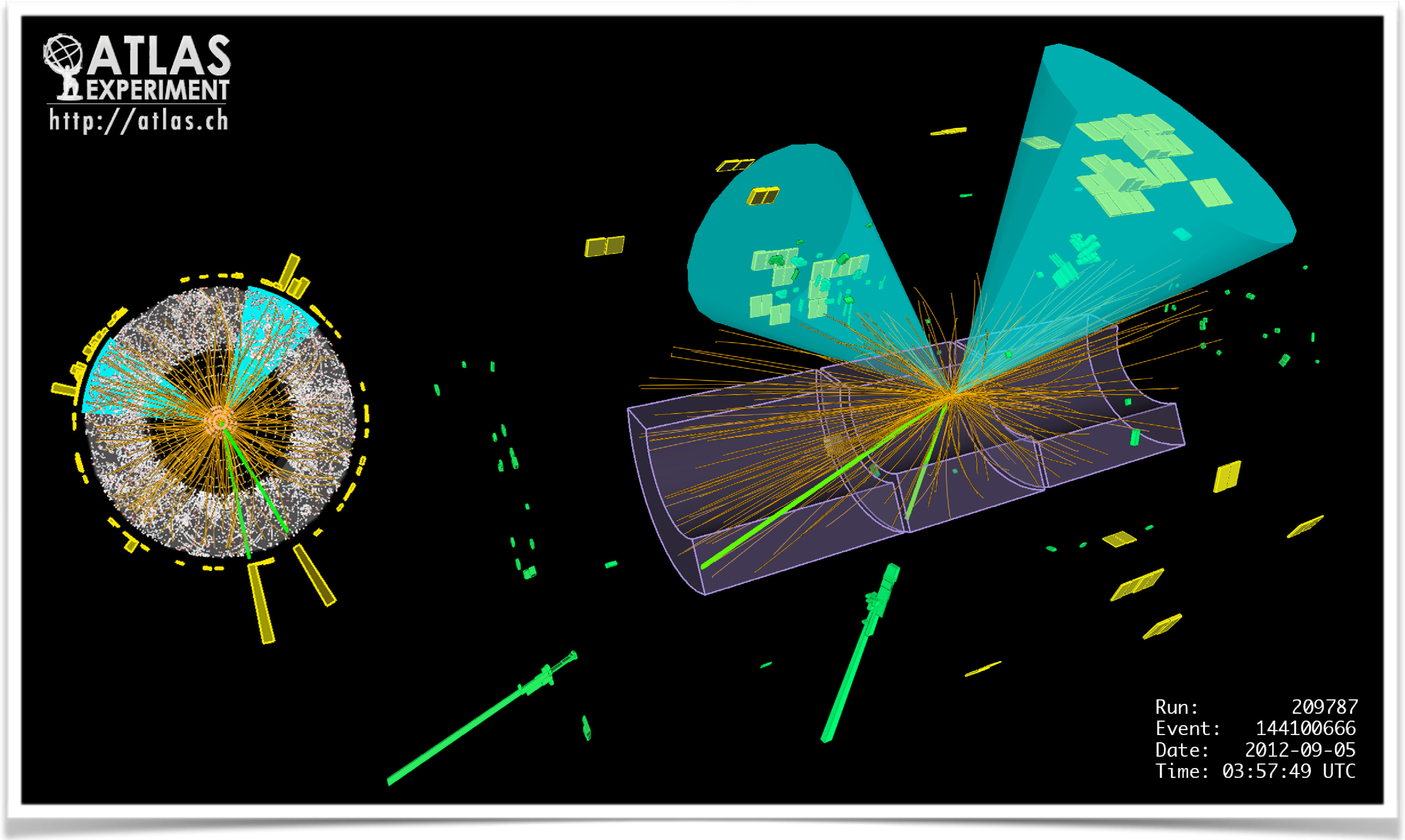
Higgs boson decays to b-quarks

Hot off the press (presented last week at the ICHEP conference)!





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



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

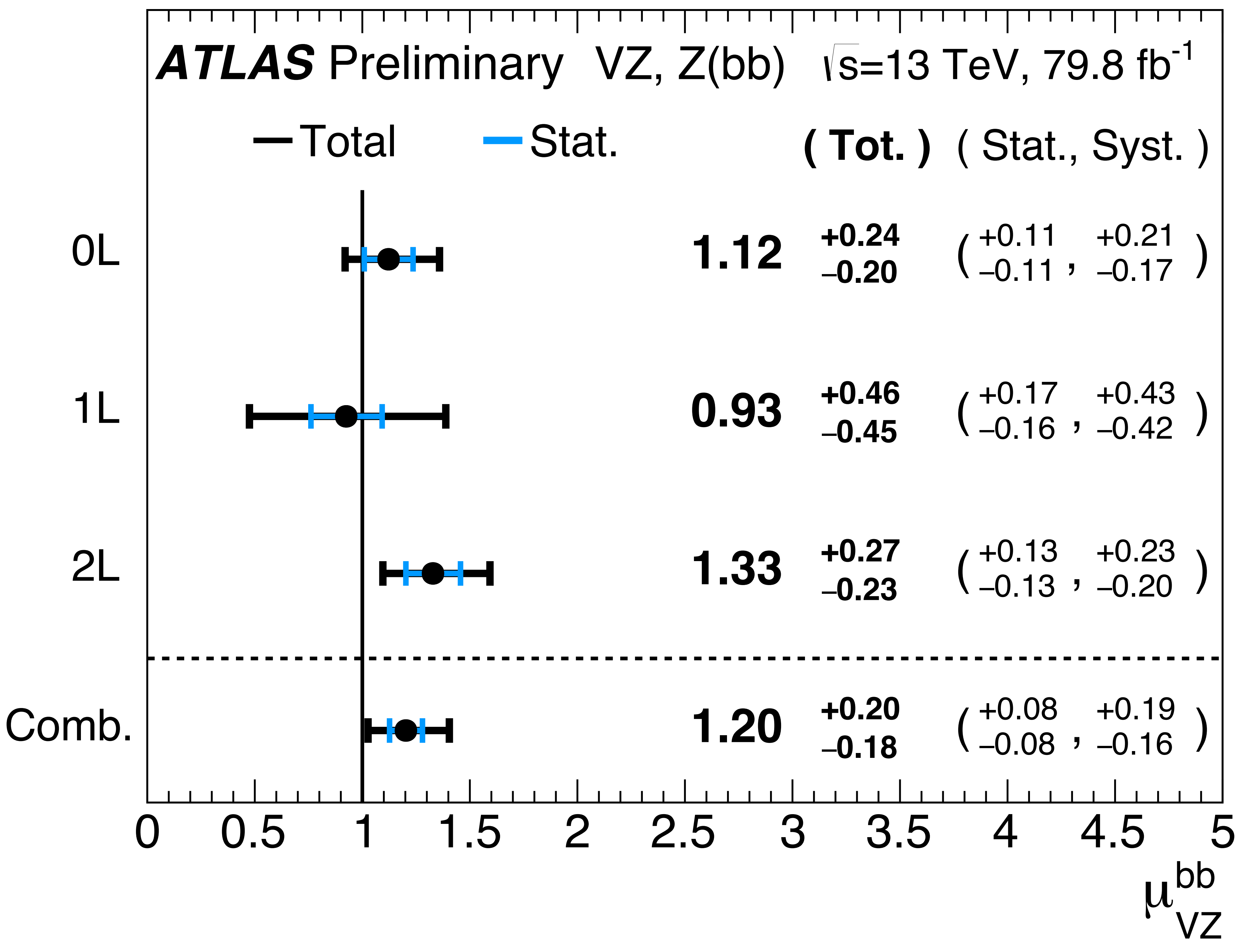
- 0 « leptons » (for neutrino decays of the Z)
- 1-lepton (W decaying to an electron or a muon)
- 2-leptons (Z decaying to electrons or muons)

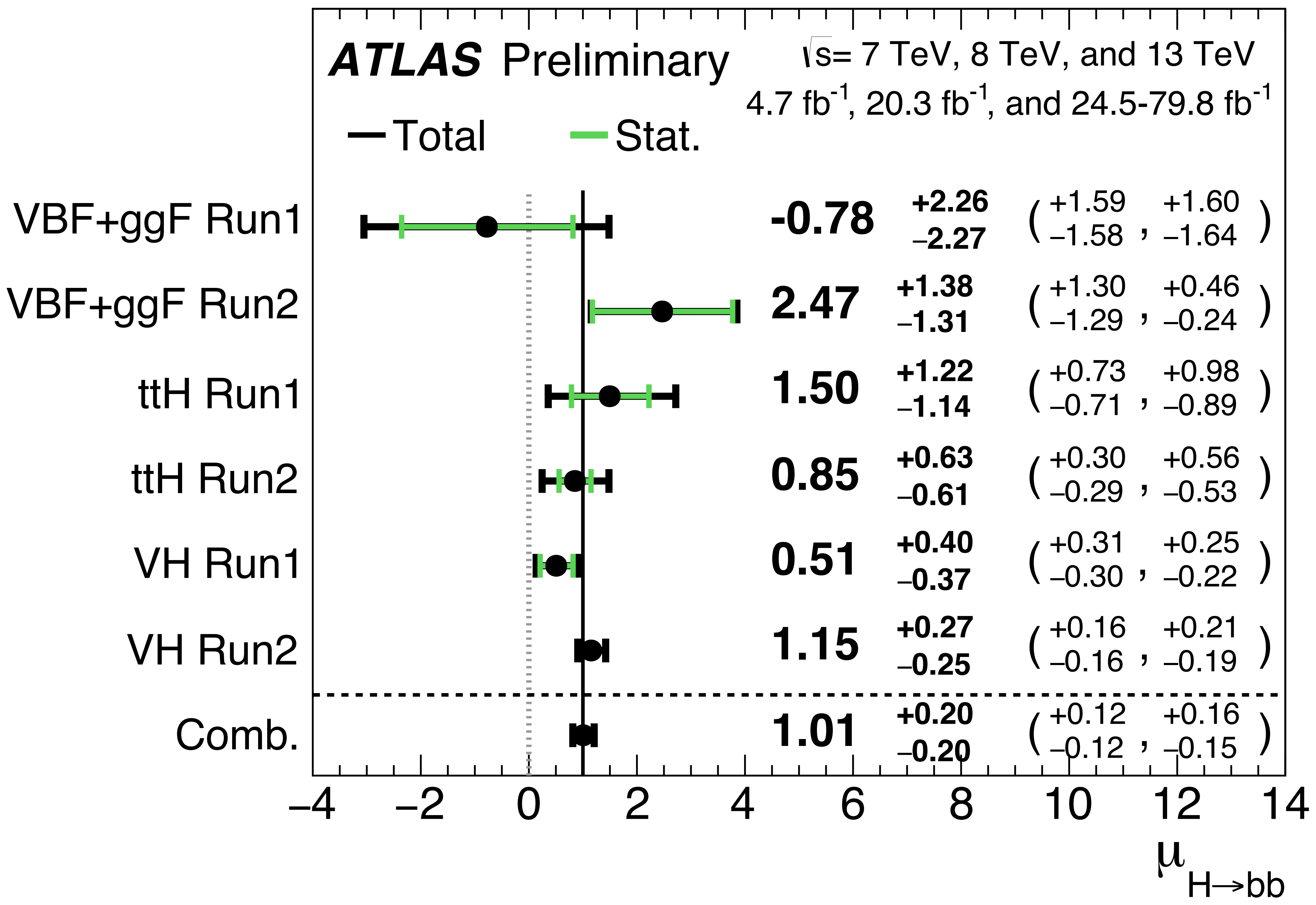
Main background is V+jets (in particular b-jets), relies on a good simulation, but is controlled in the mass side-bands!

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

Higgs boson decays to b-quarks

Hot off the press (presented last week at the ICHEP conference)!





In combination with Run 1

$$\mu = \frac{\sigma}{\sigma_{SM}} = 0.98 \pm 0.14\,(\mathrm{stat}) \pm 0.16\,(\mathrm{syst})$$

4.9σ (observed) 5.1σ (expected)

5.4σ (observed) 5.5σ (expected)

Observation!!

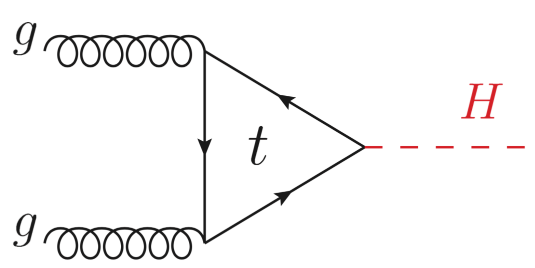
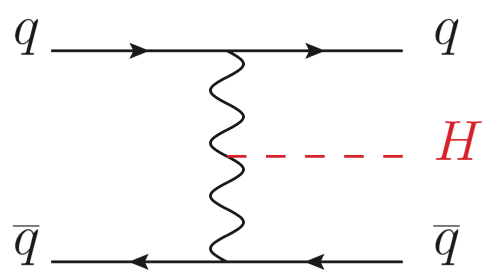
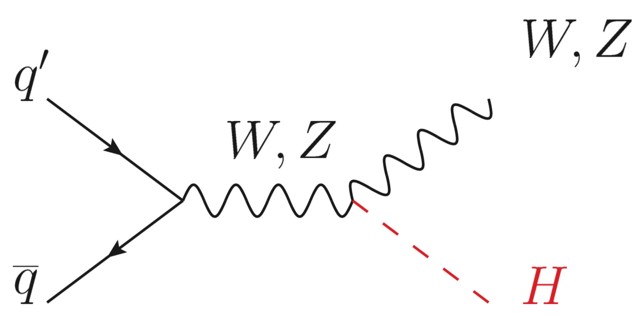
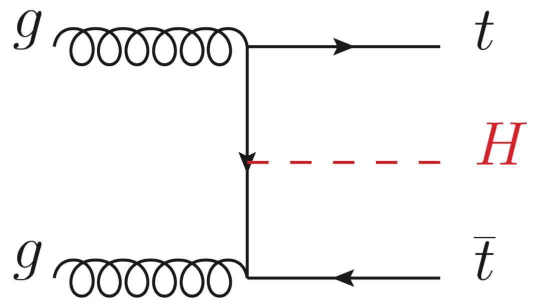
Panorama of Main Higgs Analyses

Already impressive harvest of results

ICHEP2018 SEOUL
JULY 4 - 11, 2018 COEX, SEOUL

high Energy

All production processes have been observed

	Channel categories	ggF	VBF	VH	ttH
					
Observed decay modes	γγ	✓	✓	✓	✓
	ZZ (llll)	✓	✓	✓	✓
	WW (lνlν)	✓	✓	✓	✓
	ττ	✓	✓	✓	✓
	bb	✓	✓	✓	✓
Remaining to be observed	Zγ and γγ*	✓	✓		
	μμ	✓	✓		
Strong limits will be sufficient	Invisible	✓ (monojet)	✓	✓	

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.

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

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.

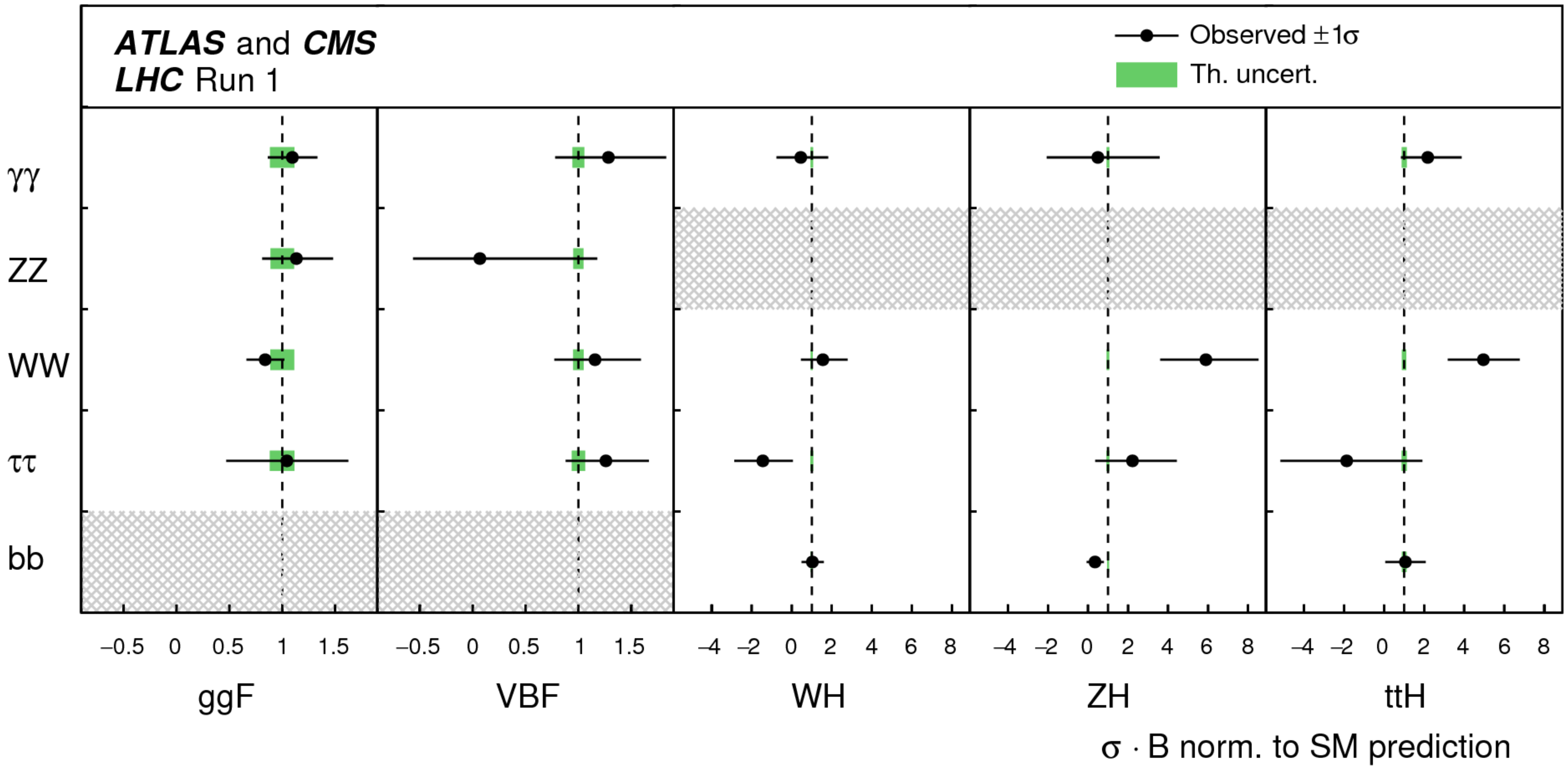
Introducing simple scale factors of the Standard Model couplings in a « naive » effective Lagrangian.

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

Overview of the Run 1 Higgs Couplings Measurements

These measurement correspond to cross sections times branching fractions

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



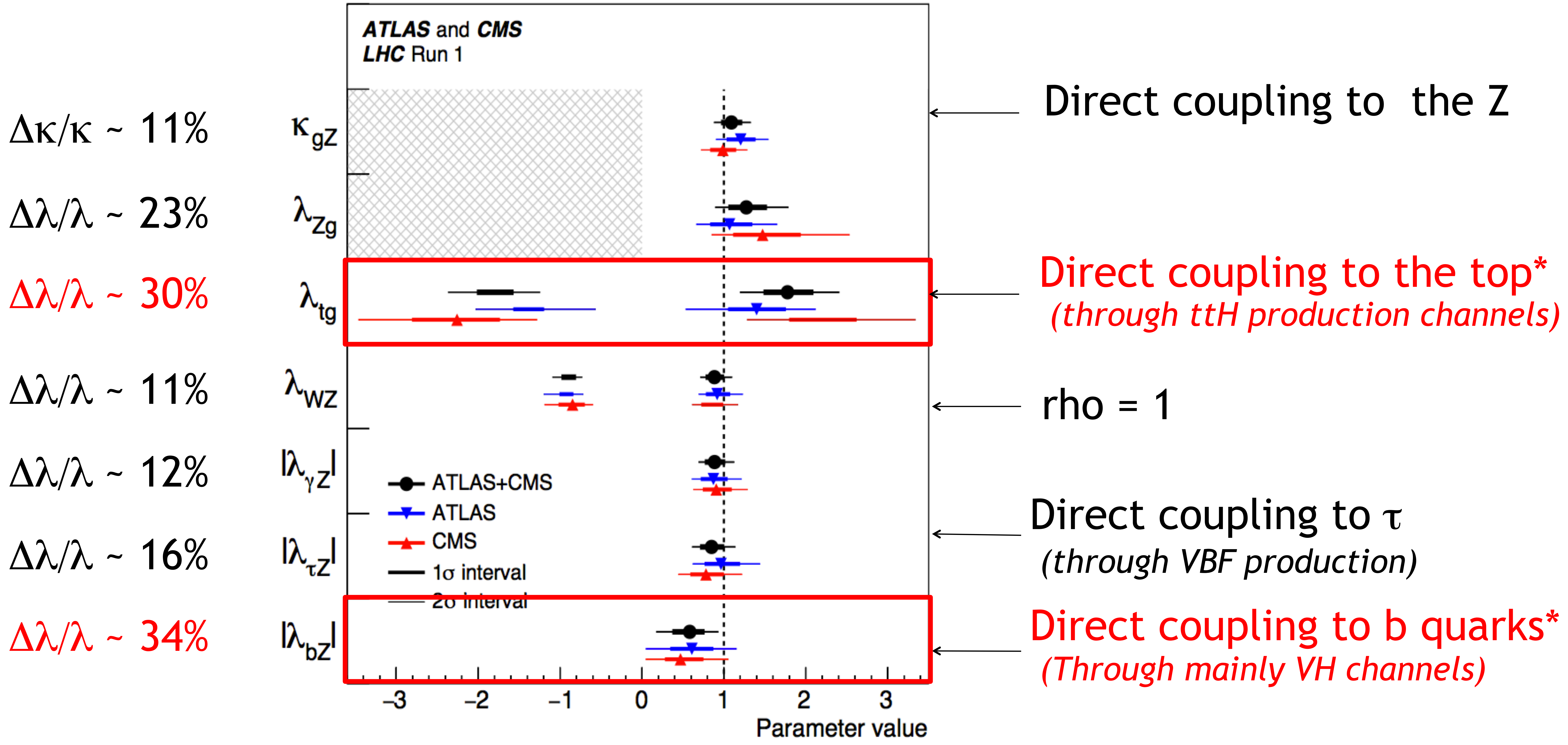
Precision reached with ATLAS and CMS combination at Run 1

$$\mu = 1.09 \quad \pm 0.11 \quad (\pm 0.07\,(Stat) \; \pm 0.04\,(Exp) \; \pm 0.03\,(Th.\,bkg) \; \pm 0.07\,(Th.\,sig)\,)$$

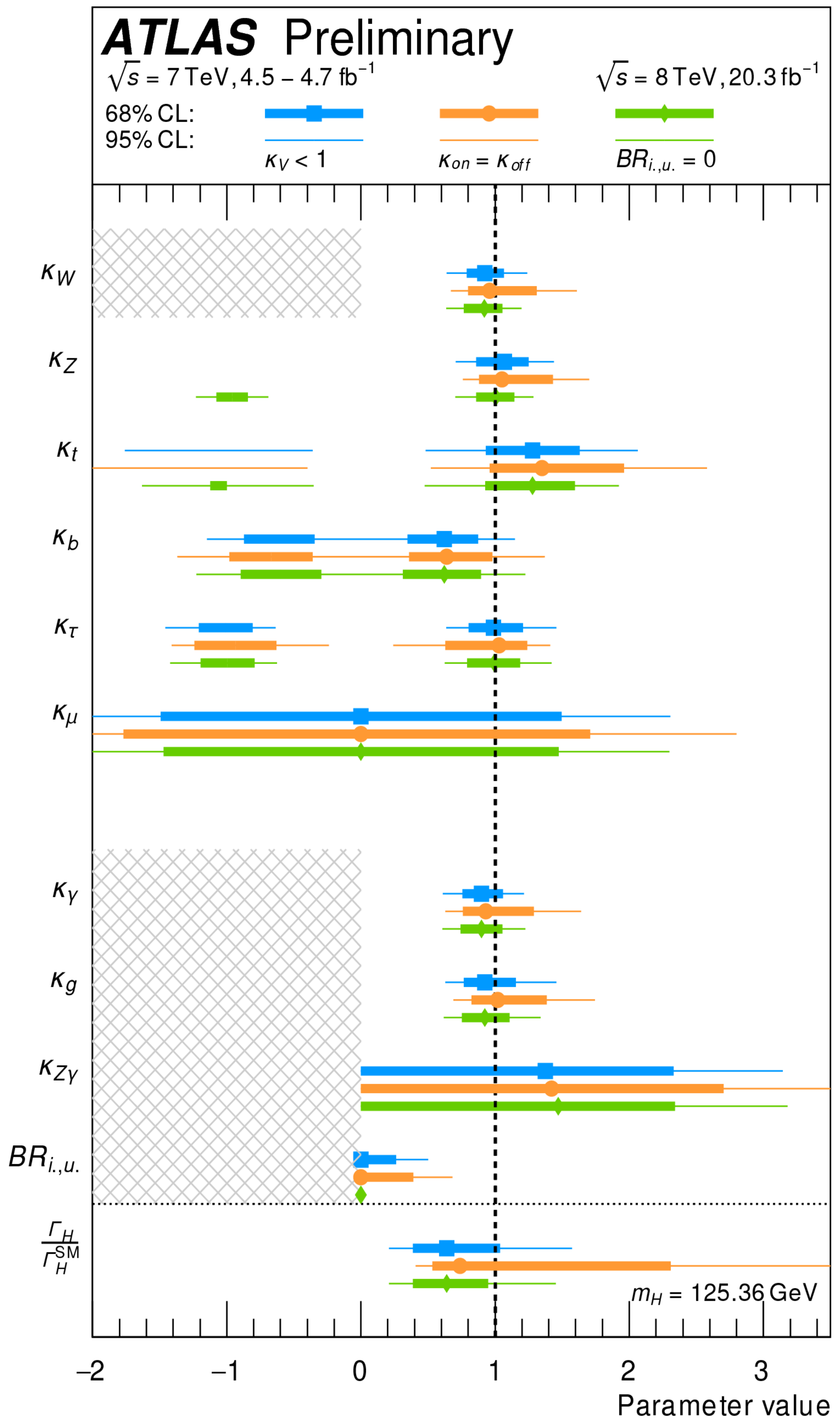
Signal strength illustrates the agreement of measurements with the SM and the importance of the TH input.

TH uncertainties have evolved already and improved significantly.

The most general and requiring least assumptions in the combination: measuring ratios of couplings!



Comment on the Absolute Measurement of Couplings



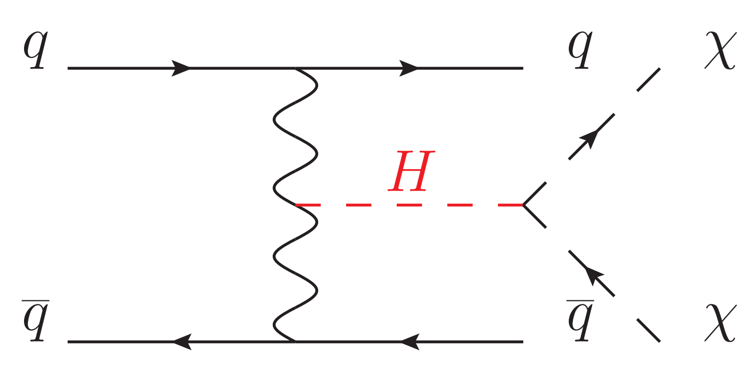
Absolute couplings measurements under specific conditions:

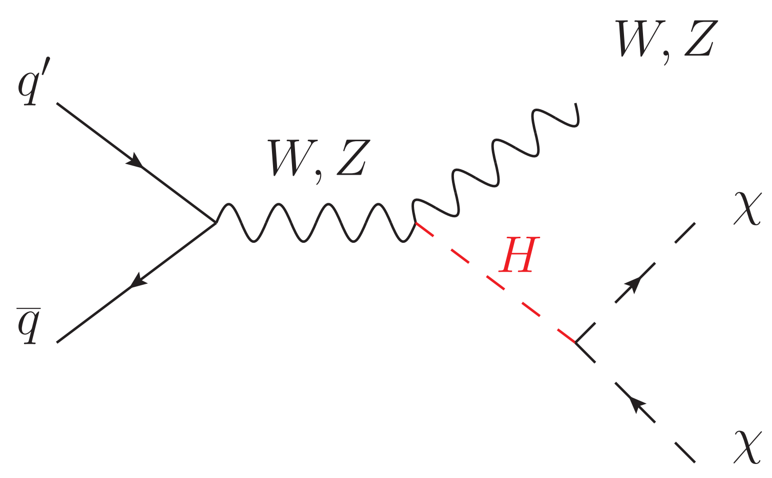
- **Green**: Constrain the width to SM field content only.
- **Blue**: Unitarity inspired constraint $k_V < 1$
- **Orange**: Use current constraints from Off-Shell coupling*

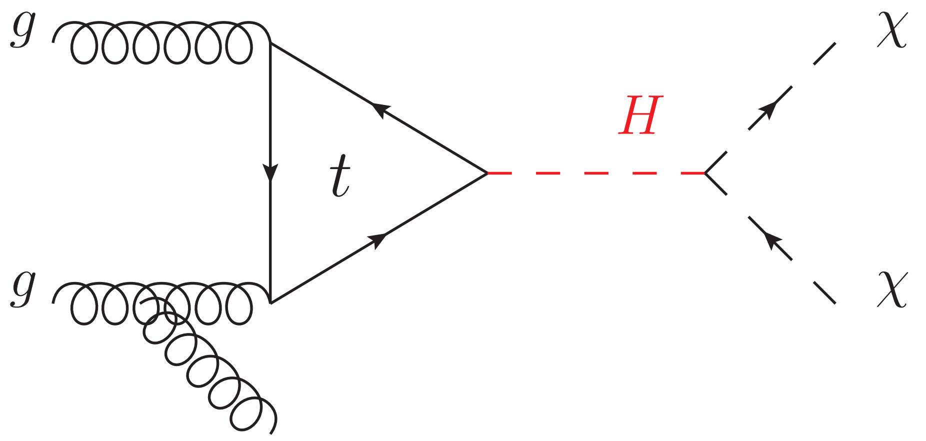
Searches for Rare decays and Rare Production modes

Rare Decays

Invisible decays



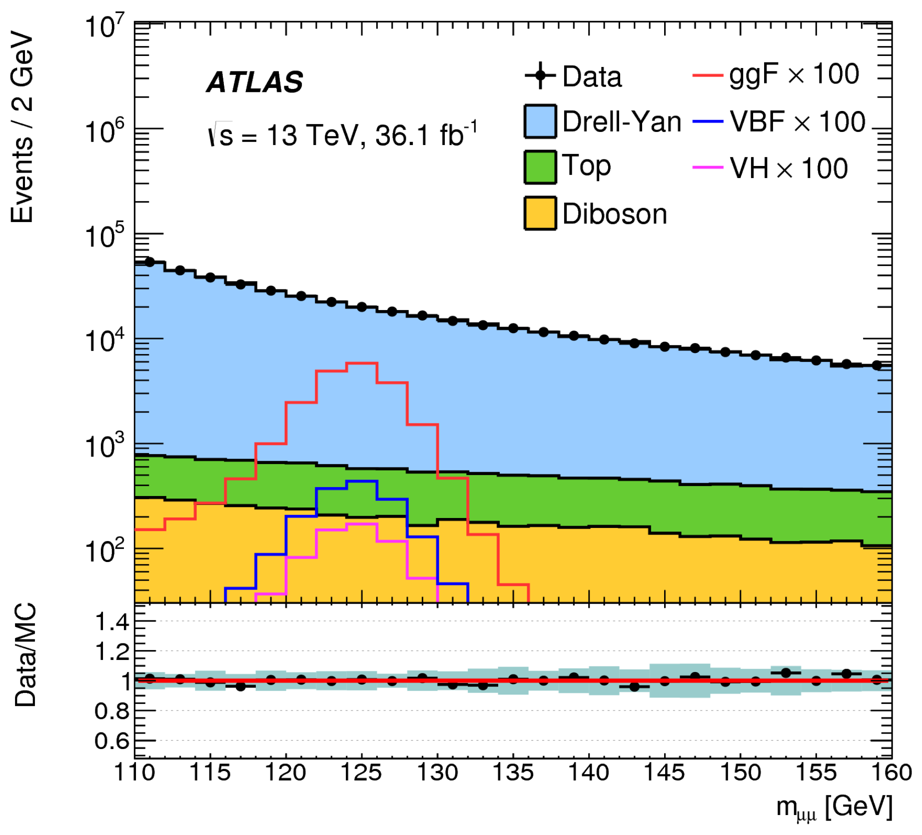


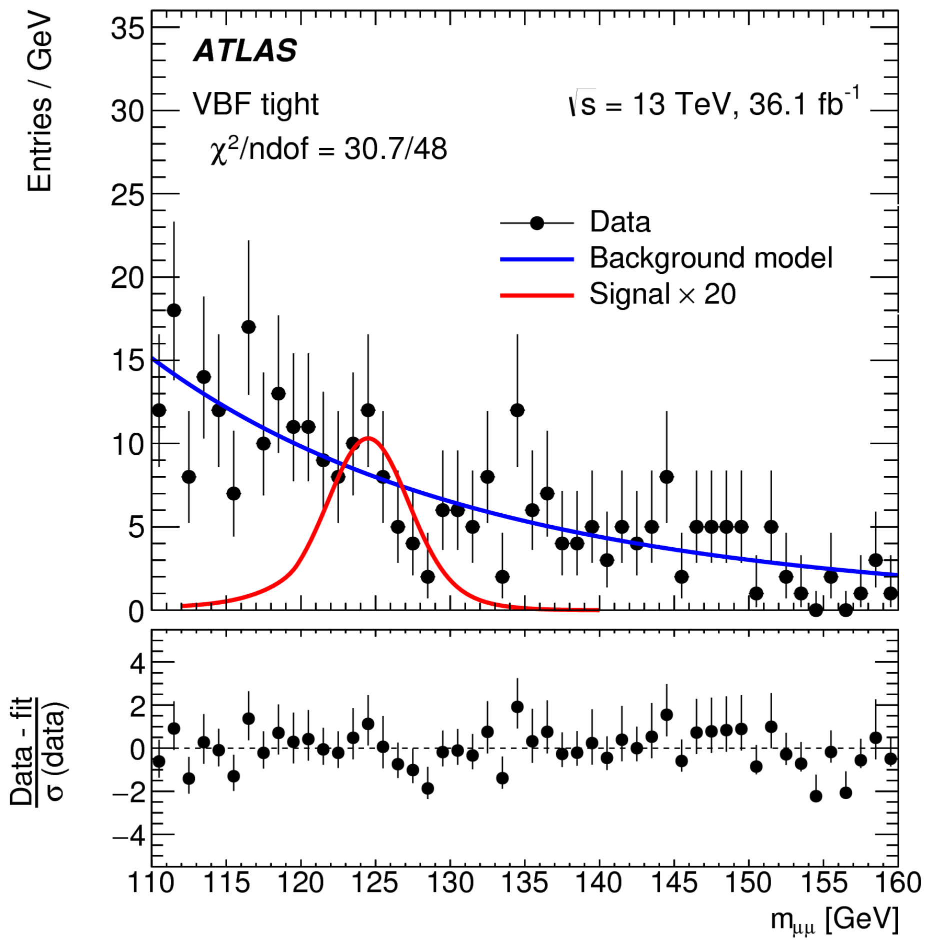


$$Br_{inv} < 0.24\ (0.23)$$

at 95% CL

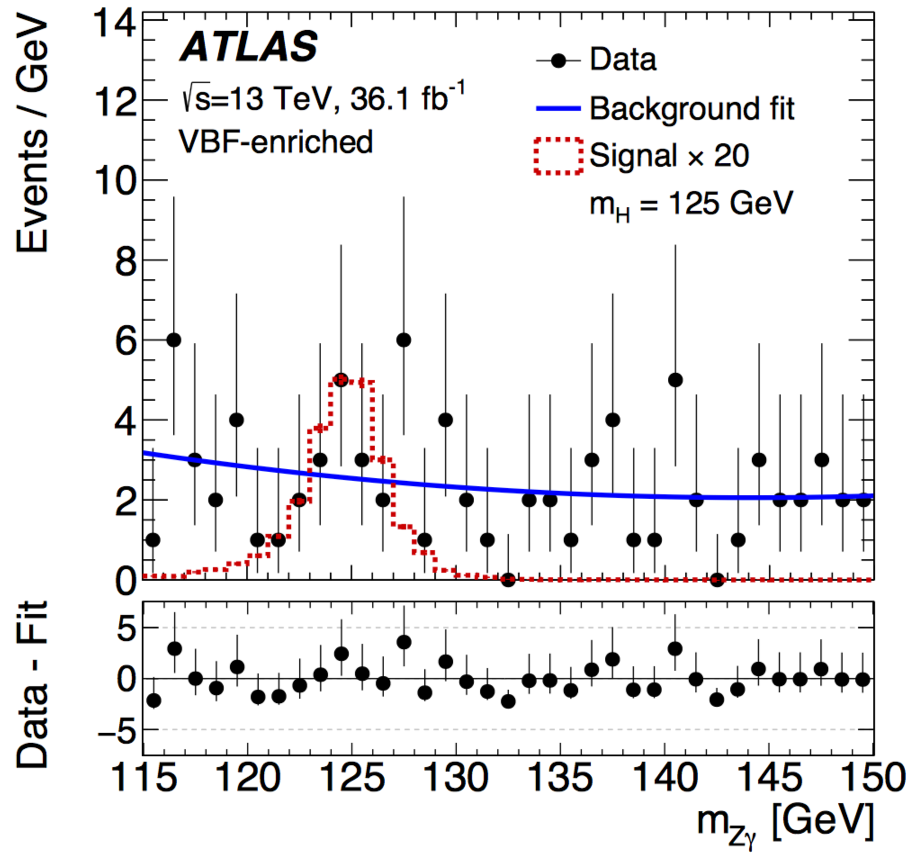
di-muons

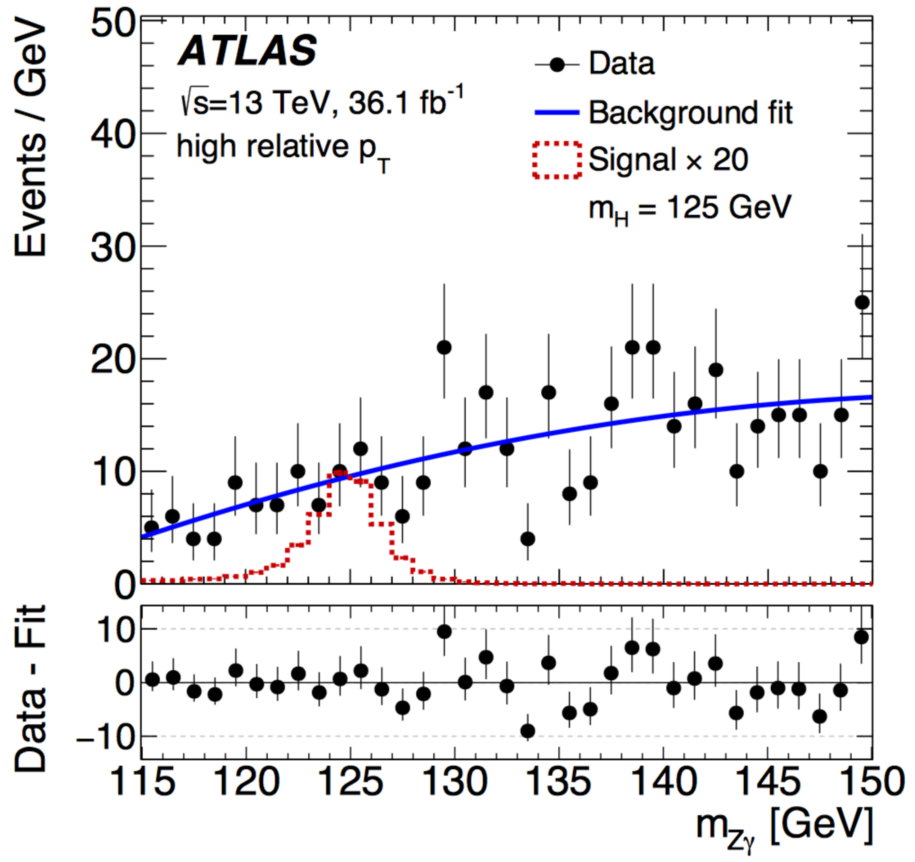




Limits currently ~2 x SM

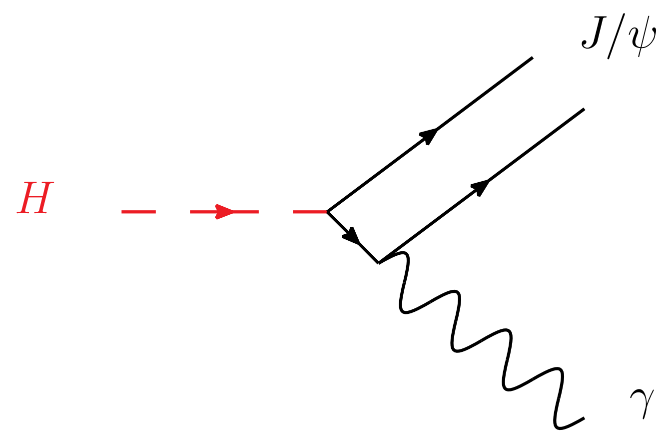
Z-photon





Limits currently ~6 x SM

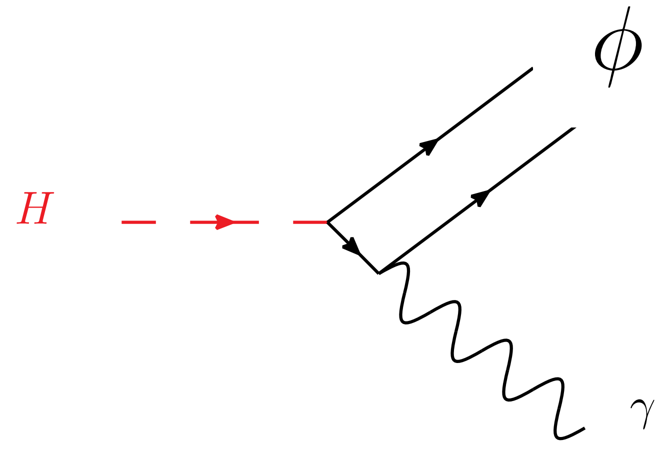
Quarkonia-photon



Potentially sensitive to charm Yukawa

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

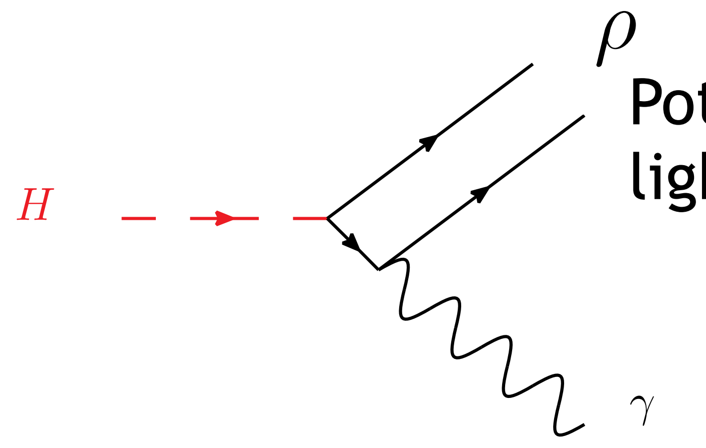
Higgs ~400 x SM



Potentially sensitive to strange Yukawa

$K^+K^-\gamma$

Higgs ~200 x SM



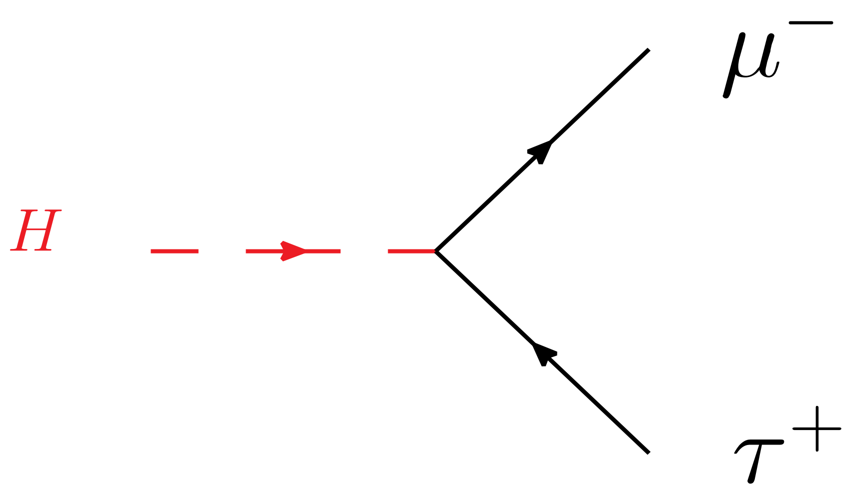
Potentially sensitive to light Yukawa

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

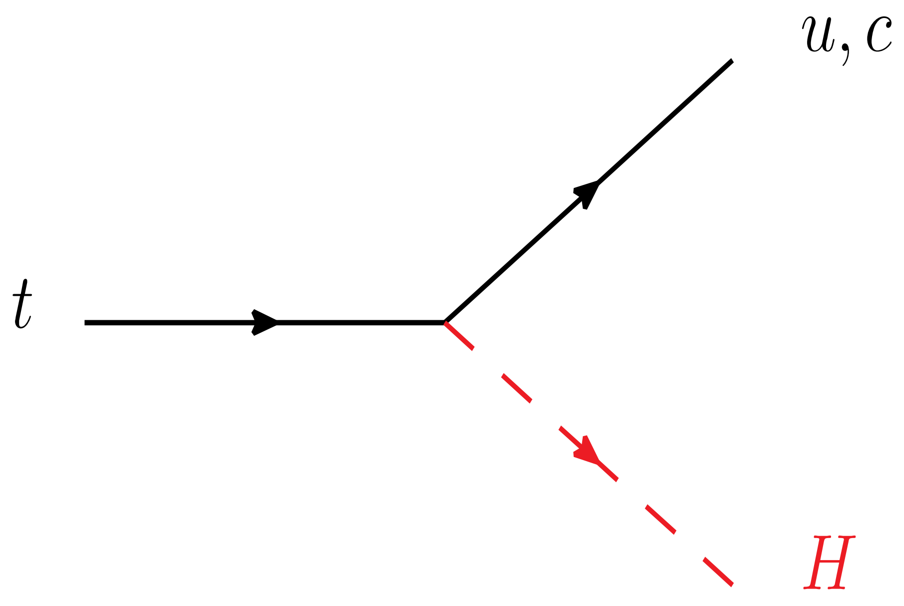
Higgs ~50 x SM

More rare decays and production Modes

Lepton flavor violating decays



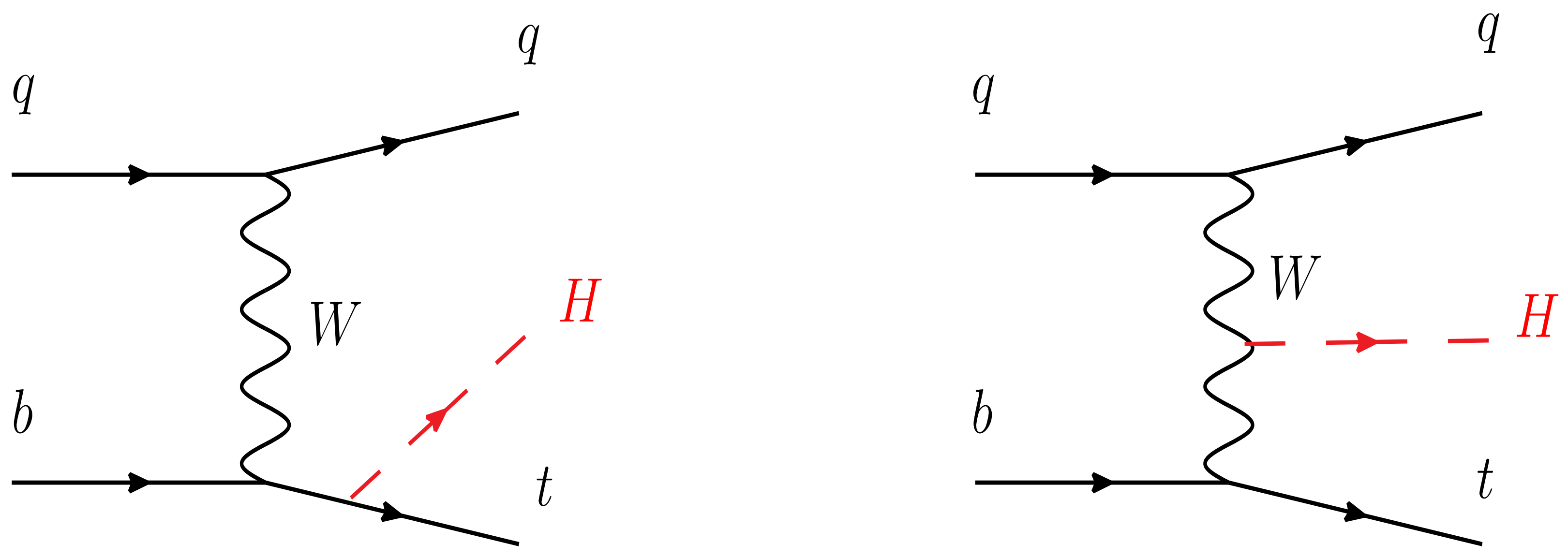
Flavor changing neutral curent decays of the top quark



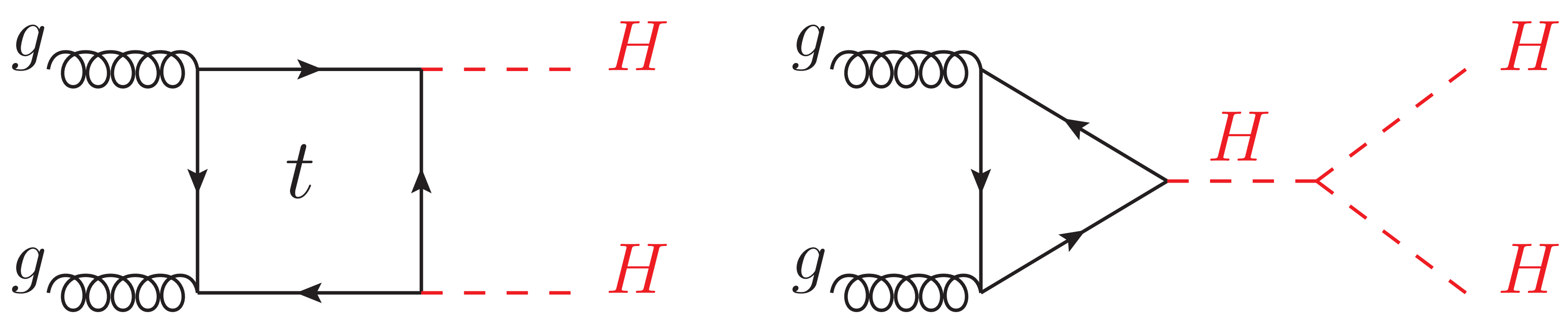
Various decay channels of the Higgs boson (gamma gamma, bb)

Single top associated production

Tree level interference between W and top



Double Higgs Production



- Search very similar to the Off Shell couplings of the Higgs boson in the two vector bosons channels. It is also done far Off shell in mass.

- Similarly to the Off-Shell analysis there is a large destructive interference between the triangle and the box contributions.

- The total production cross section is very small.

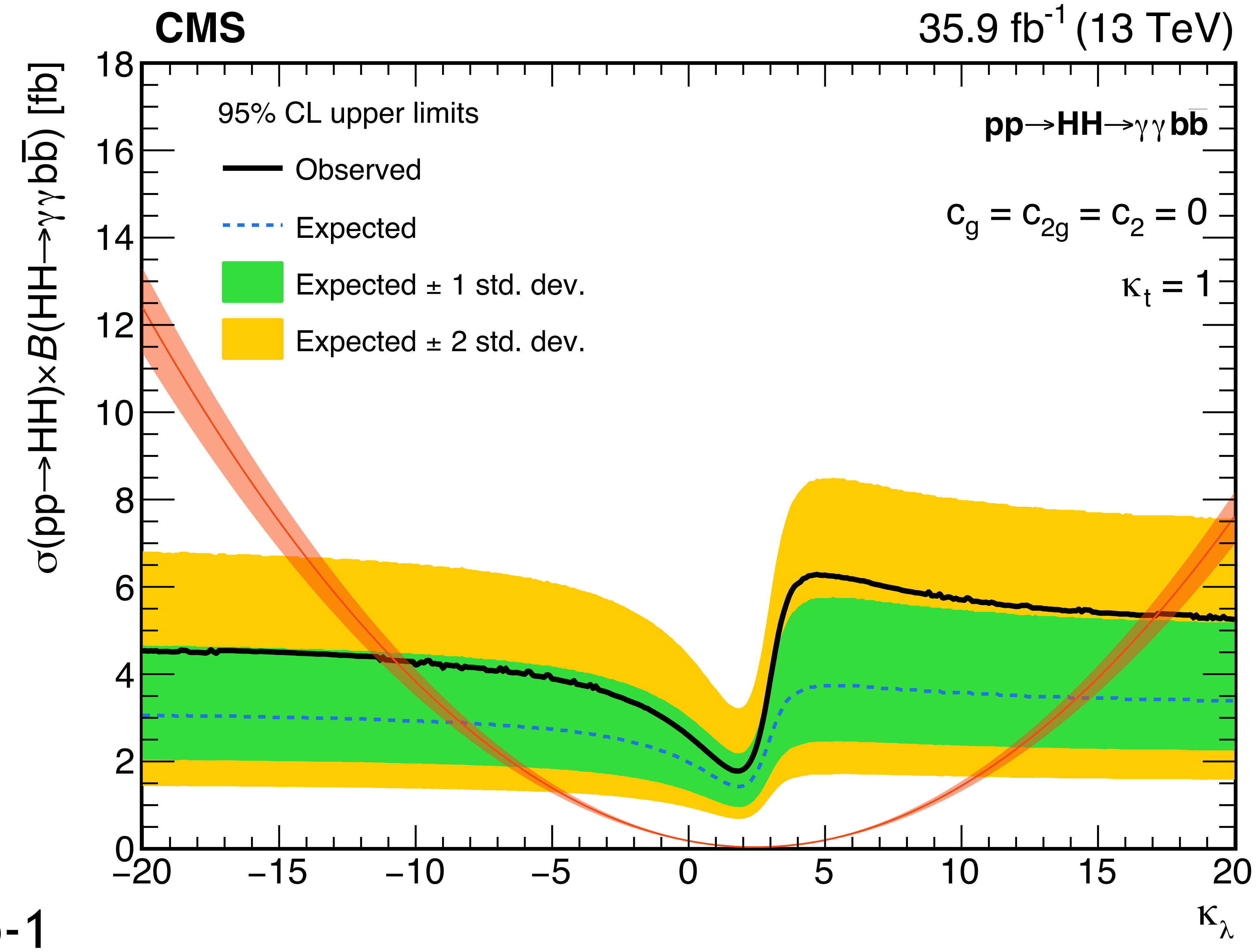
- The main channels are according to the decays of the Higgs boson and in terms of limits on the HH production (ratio to the SM expectation)

exp.	bb $\gamma\gamma$	bb $\tau\tau$	bbWW	bbbb	WW $\gamma\gamma$
ATLAS	<22 (28)	-	-	<29 (38)	<747 (386)
CMS	<24 (19)	<30 (25)	<79 (89)	<75 (37)	-

12 fb-1 (yellow)

36 fb-1 (orange)

Limits on the HH production do not translate immediately into constraints on the Higgs self coupling due to the non Higgs background and the signal-background interference!



More on this tomorrow!

Higgs physics Landscape

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- STXS
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma$, $\gamma\gamma^*$
- Muons $\mu\mu$
- LFV $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, $Z\Upsilon$, WD
- Phiγ, rhoγ

$$H^0$$

Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

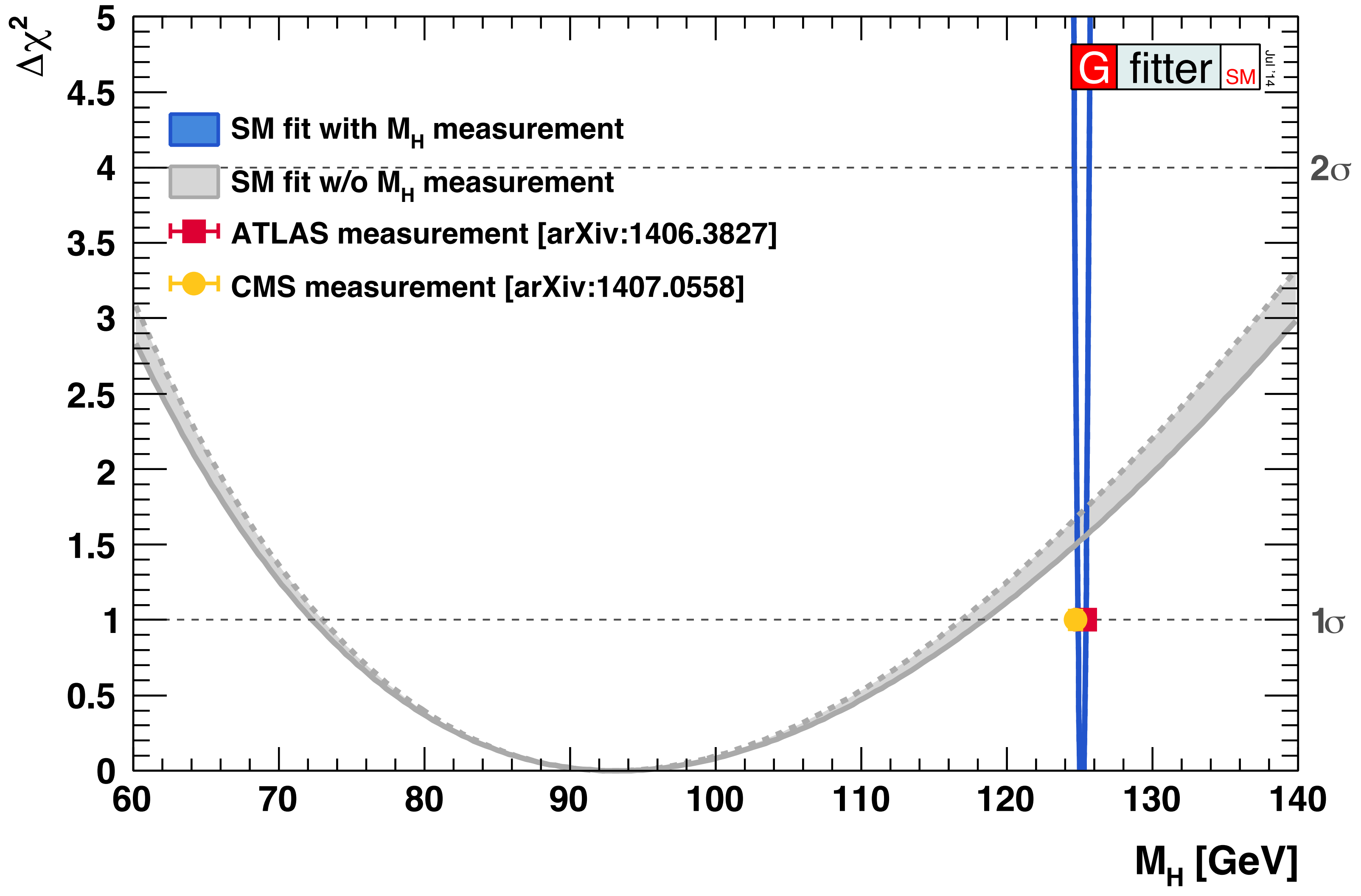
(Tomorrow)

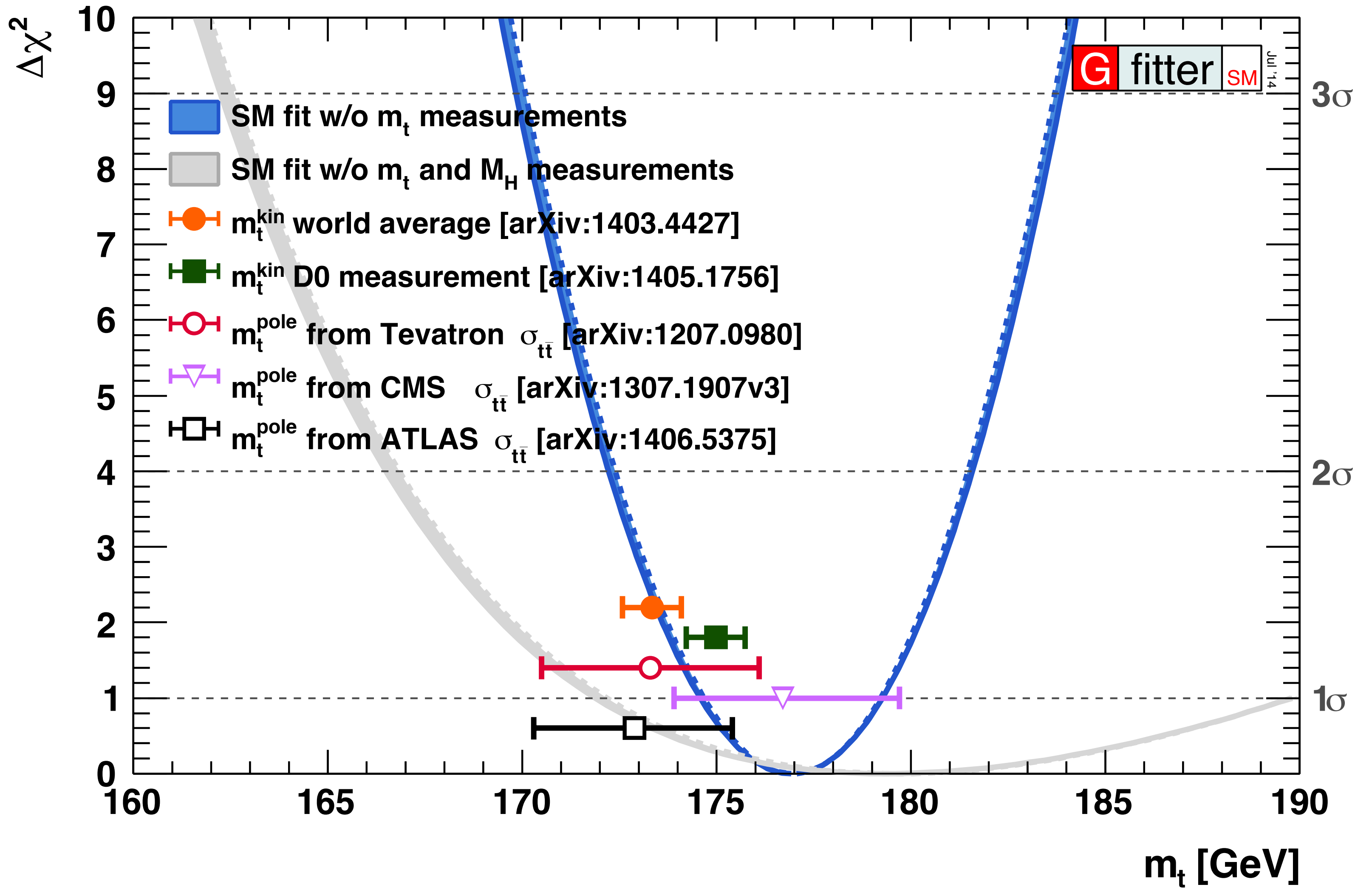
Rare Production
- tH
- FCNC top decays
- Di-Higgs production (and trilinear couplings)

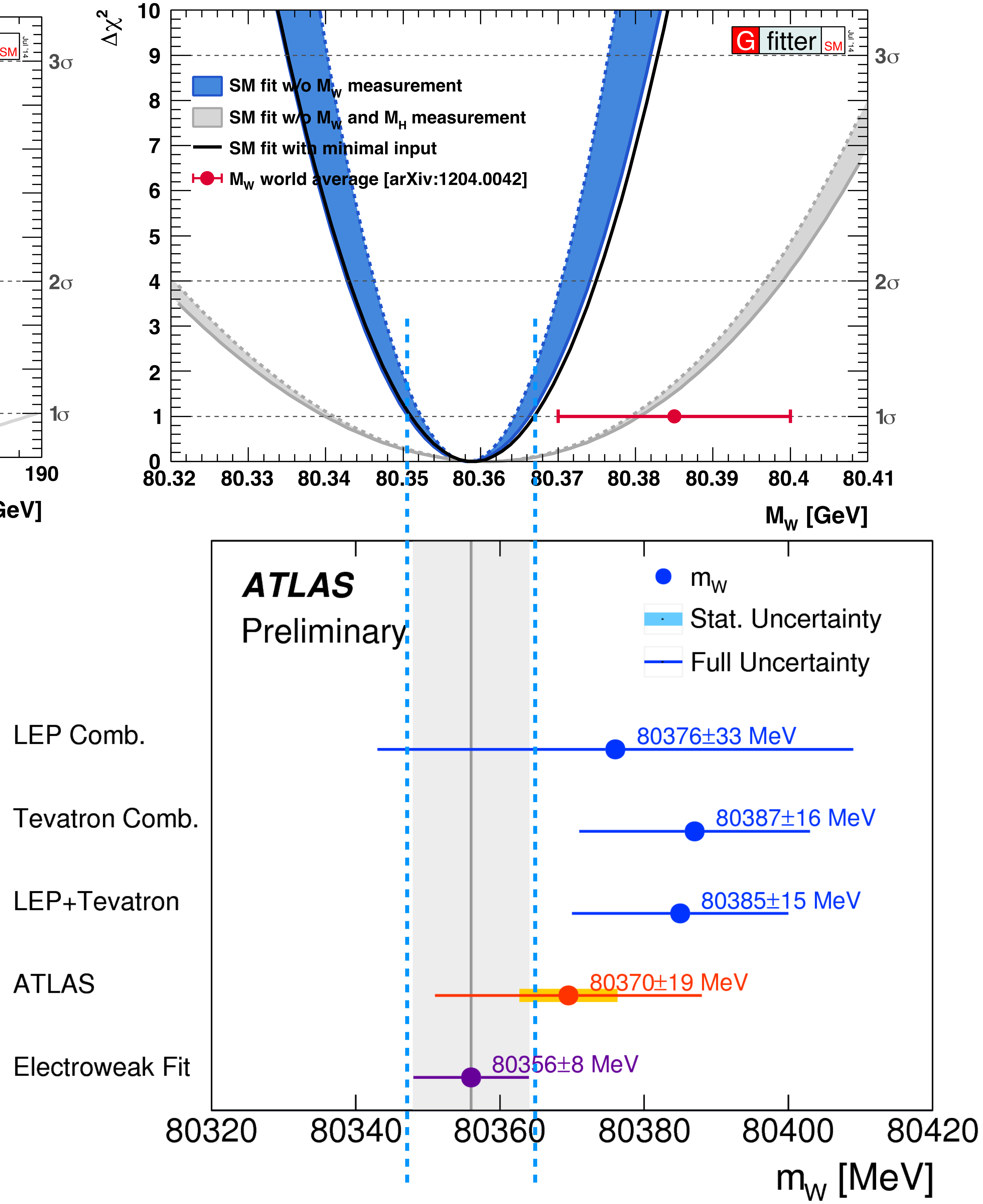
Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

(Tomorrow)

Implications (I) - Global fit of the Standard Model







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

Knowing the Higgs boson mass has a important effect on global analysis

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

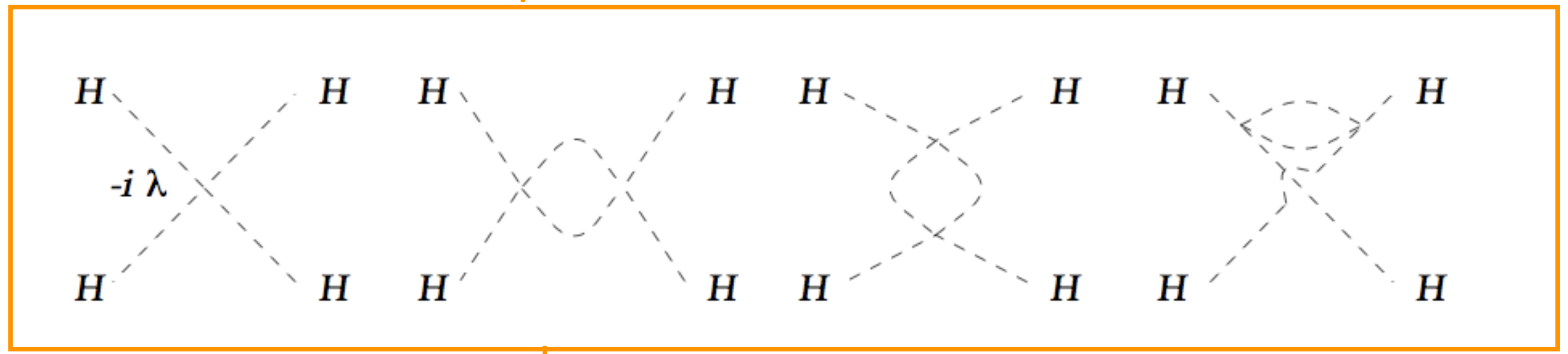
If there is new physics, it does not seem to be affecting the Standard Model through quantum corrections.

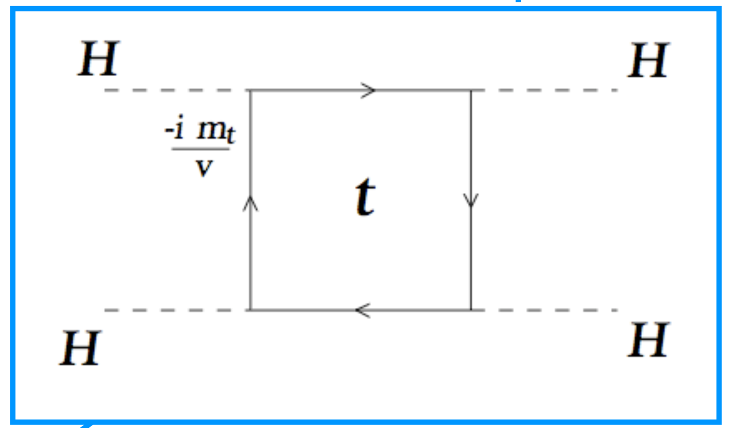
With the recent W mass measurement, the Standard Model is even more consistent!

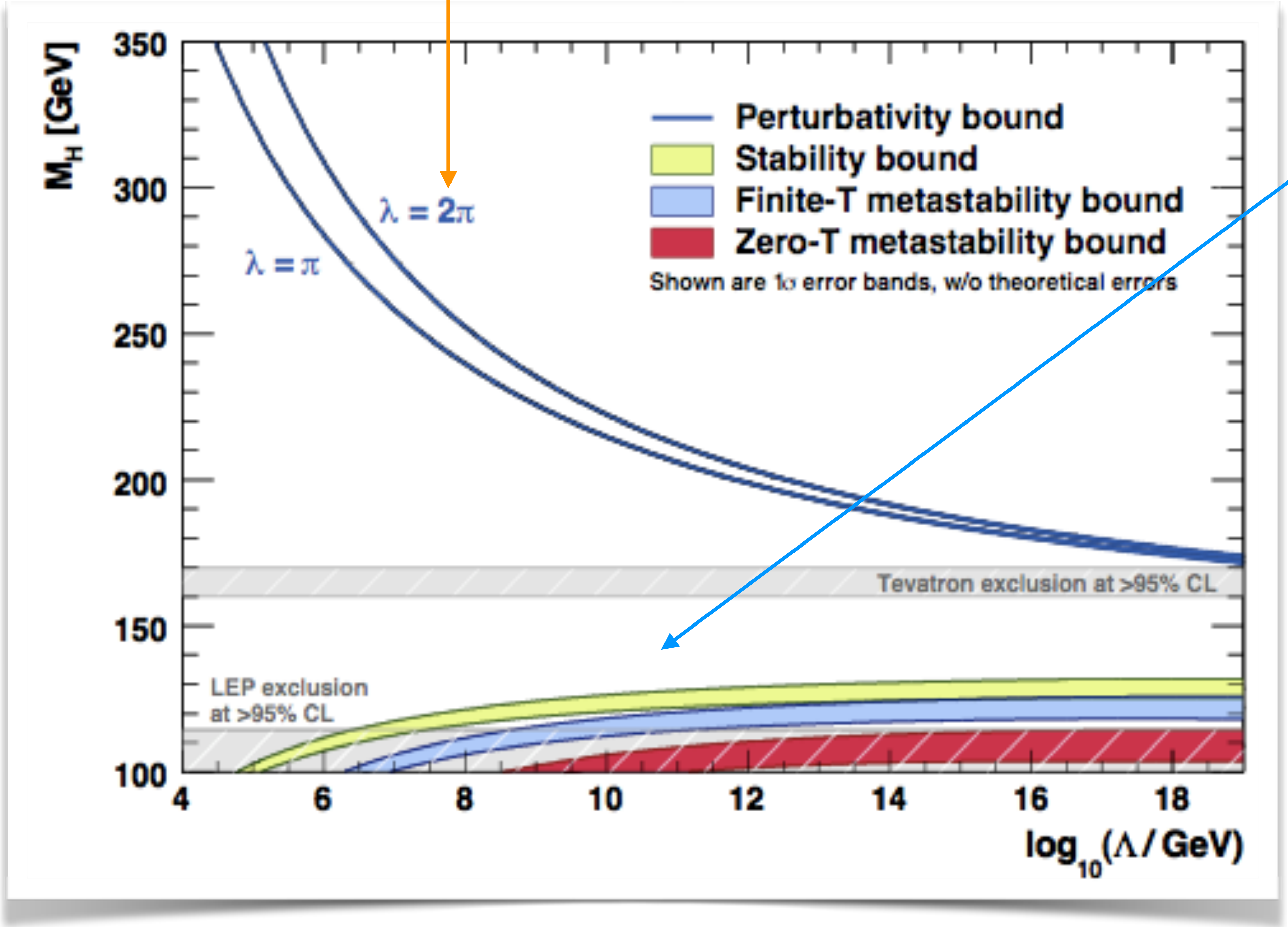
Implications II - TH consistency

Running of the Higgs self coupling:

$$32\pi^2 \frac{d\lambda}{dt} = 24\lambda^2 - (3g'^2 + 9g^2 - 24y_t^2)\lambda + \frac{3}{8}g'^4 + \frac{3}{4}g'^2 g^2 + \frac{9}{8}g^4 - 24y_t^4 + \cdots$$







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.

Nima Arkani Hamed

Triumph of the SM ?