Higgs Physics - Experiment

Main channels towards precision Higgs physics

CERN-Fermilab Hadron Collider Physics School

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CERN-FERMILAB
HADRON COLLIDER PHYSICS
Summer School

Outline of the Lectures

***Lecture 1**: Main Channels and Precision Higgs physics*

- Preamble
- Introduction
- The discovery of the Higgs boson
- Precision with diboson channels
- The Higgs boson width
- Measurement of 3^{d} generation Yukawas
- Run 2 milestones

***Lecture 2**: Combination, beyond the main channels and future challenges*

- A word about modelling
- Combined measurements of coupling properties
- Rare decays modes
- Rare production modes
- Di-Higgs production and the Higgs self coupling
- Probing an Extended Higgs sector
- EFTs in a tiny nutshell
- Higgs Physics at HL-LHC and beyond
- What have we learned?
- Conclusions and Outlook

Higgs physics Landscape

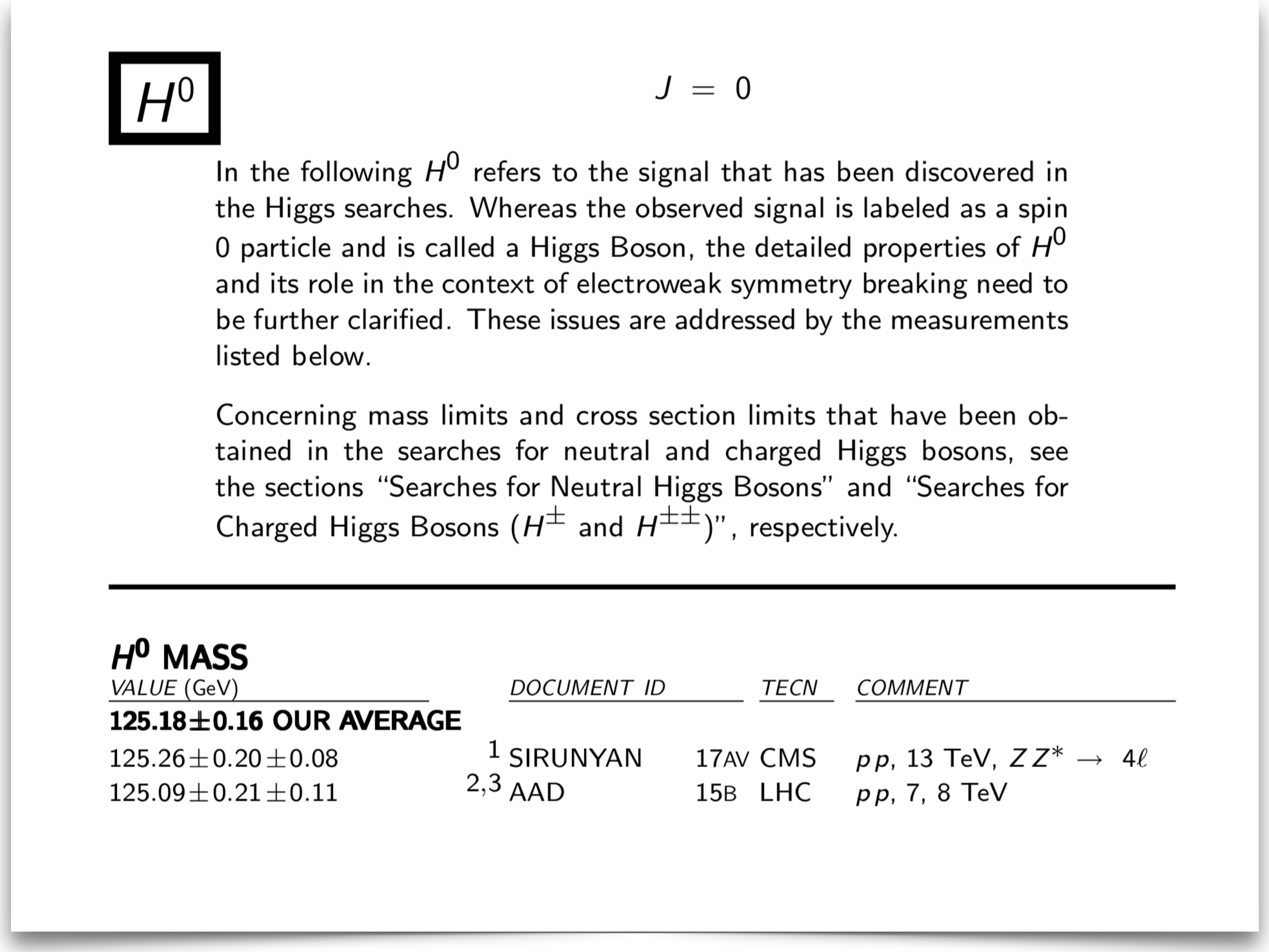
Preamble

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 $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, ZY, WD
- Phiγ, rhoγ

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

The Higgs particle



H^0 $J = 0$

In the following H^0 refers to the signal that has been discovered in the Higgs searches. Whereas the observed signal is labeled as a spin 0 particle and is called a Higgs Boson, the detailed properties of H^0 and its role in the context of electroweak symmetry breaking need to be further clarified. These issues are addressed by the measurements listed below.

Concerning mass limits and cross section limits that have been obtained in the searches for neutral and charged Higgs bosons, see the sections "Searches for Neutral Higgs Bosons" and "Searches for Charged Higgs Bosons ($H^{\pm}$ and $H^{\pm\pm}$)", respectively.

H^0 MASS

VALUE (GeV)	DOCUMENT ID		TECN	COMMENT
125.18±0.16 OUR AVERAGE				
125.26±0.20±0.08	[1] SIRUNYAN	17AV	CMS	pp, 13 TeV, $ZZ^* \to 4\ell$
125.09±0.21±0.11	[2,3] AAD	15B	LHC	pp, 7, 8 TeV

PDG Listing entry for the Higgs boson

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

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)

Covered by Claudio

Introduction

The Standard Model

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

The elegant gauge sector (tree parameters for EWK and one parameter for QCD)

Problem(s):

- There are terms (gauge boson and fermion masses) that have been measured to be non-zero and should be accounted for but are forbidden by gauge invariance.

- There are terms that should be there, but have been measured to be negligibly small (strong CP problem).

$$\theta \frac{\alpha_s}{8\pi} F^A_{\mu\nu} \tilde{F}^{A\mu\nu} \qquad \theta < 10^{-10}$$

From neutron electric dipole moment measurements

The splendid solution

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

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

The less elegant Higgs sector:

- Carries the largest number of parameters of the theory
- Not governed by symmetries
- Gauge Hierarchy (and Naturalness)
- Flavour hierarchy (includes neutrino masses)

… yet unsatisfactory ! (see lectures by Sally and Patrick)

Consequences and Predictions

How predictive is the Higgs mechanism?

Strong prediction of the Higgs mechanism:

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1$$

Protected by custodial symmetry at higher orders and measured.

Predicts the existence of a Higgs boson whose mass relates the quartic coupling (free parameter):

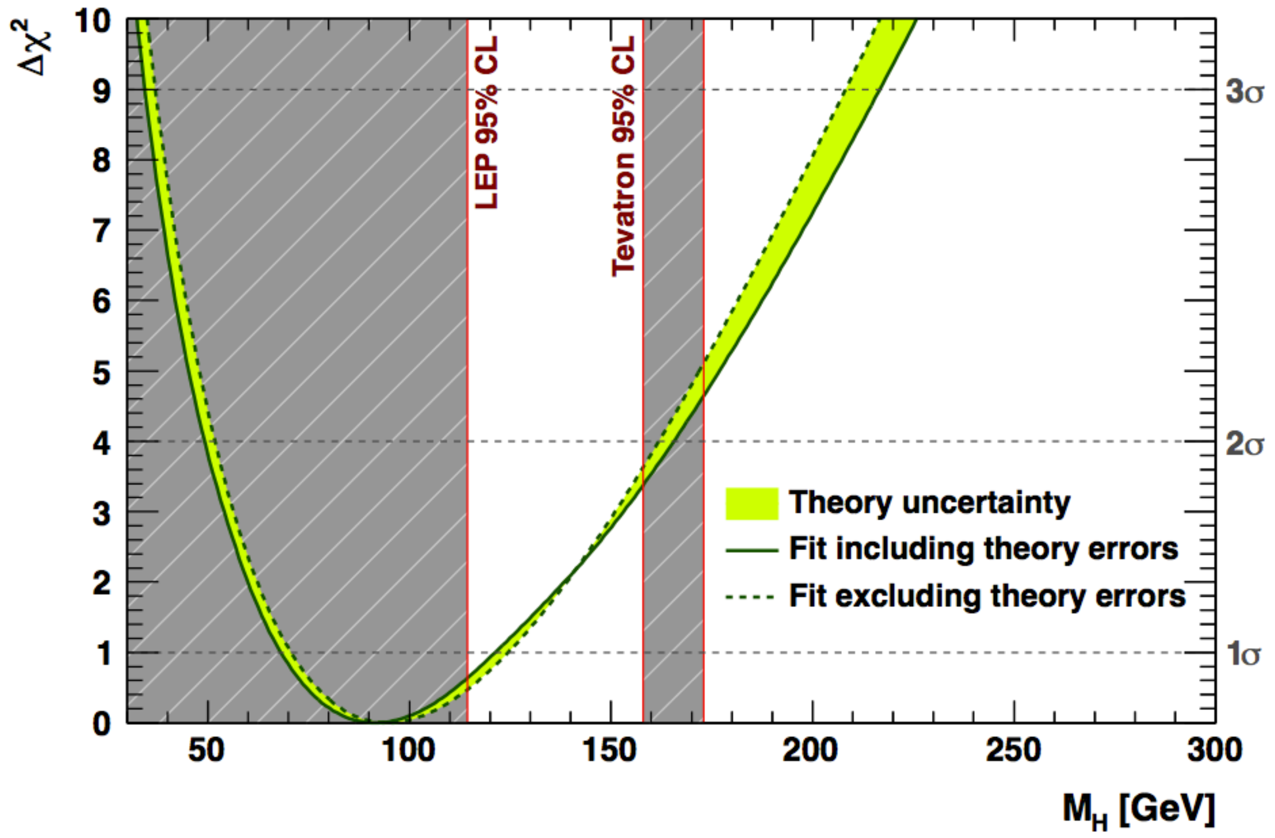
$$m_H = \sqrt{2\lambda} v$$

In the SM the Higgs potential is fully predicted once the Higgs mass is measured.

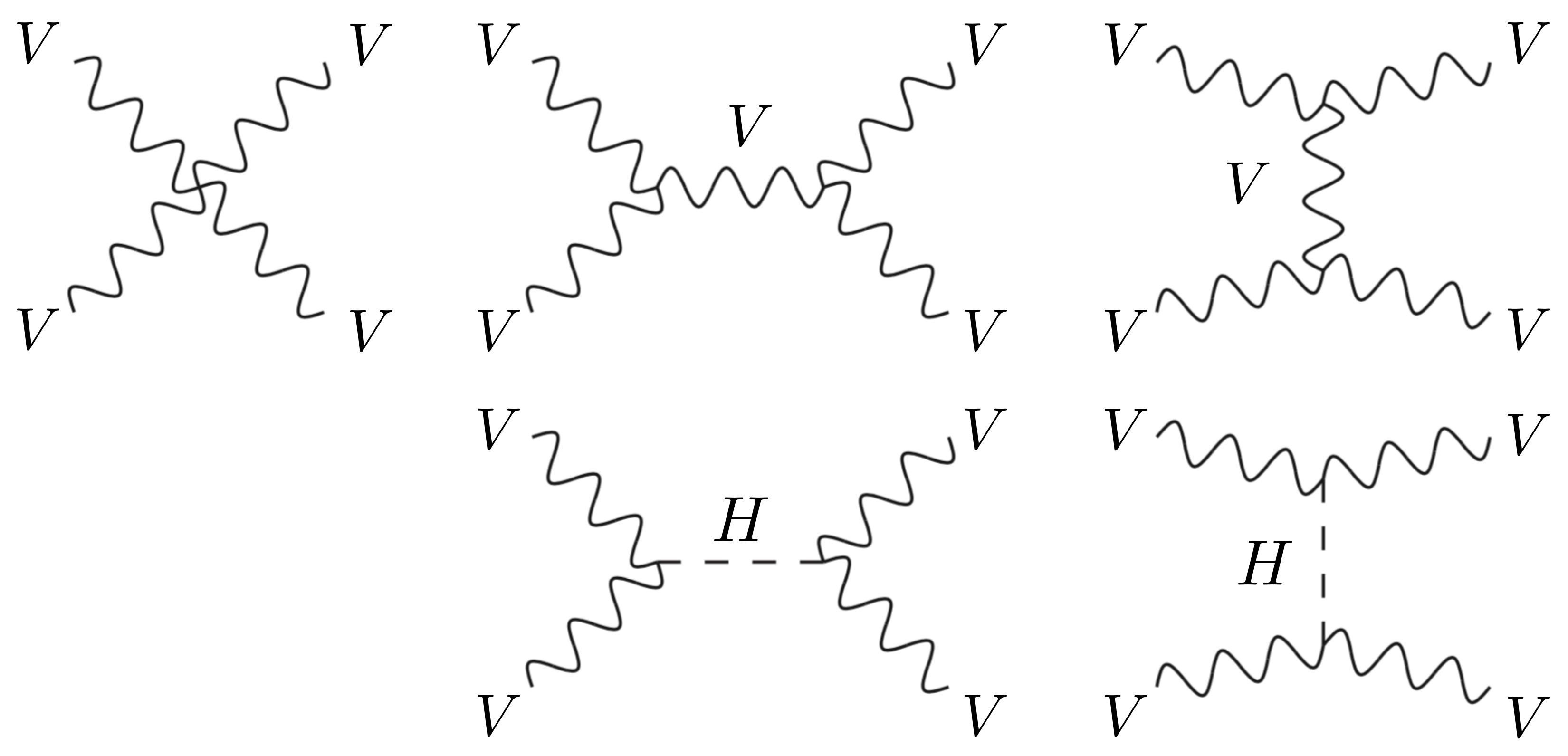
(note that the sign of the mass term in the potential, which is crucial for EWSB, is not specified by the SM - it is introduced by hand)

These predictions can be used to check the consistency of the measurements with the SM and indirectly measure the Higgs boson mass!

$$m_{\mathrm{H}} = 91^{+30}_{-23}\,\mathrm{GeV}$$

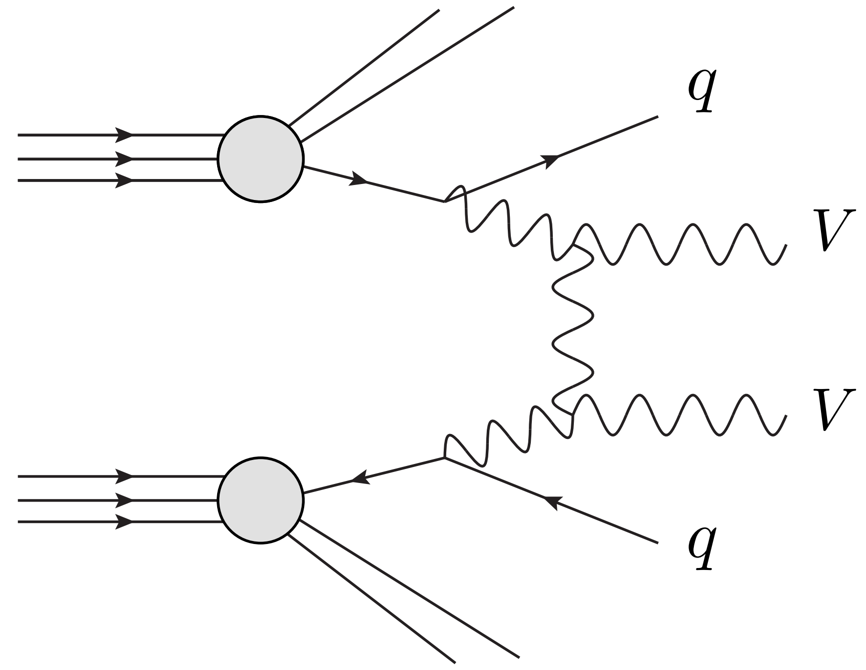


The presence of a Higgs boson also solves another important issue, the unitarity of the longitudinal vector boson scattering:



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

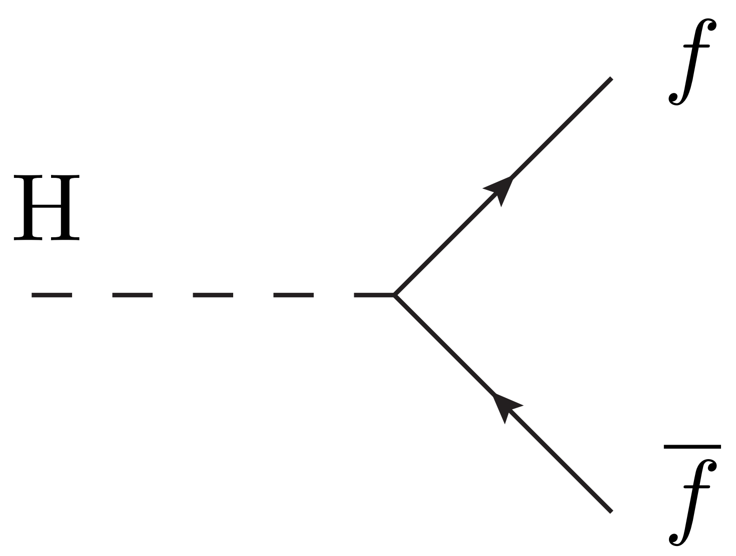
In the absence of a Higgs boson within this mass range, would imply the existence of strong dynamics which could be probed by the WW process.



The approximate « No loose theorem »

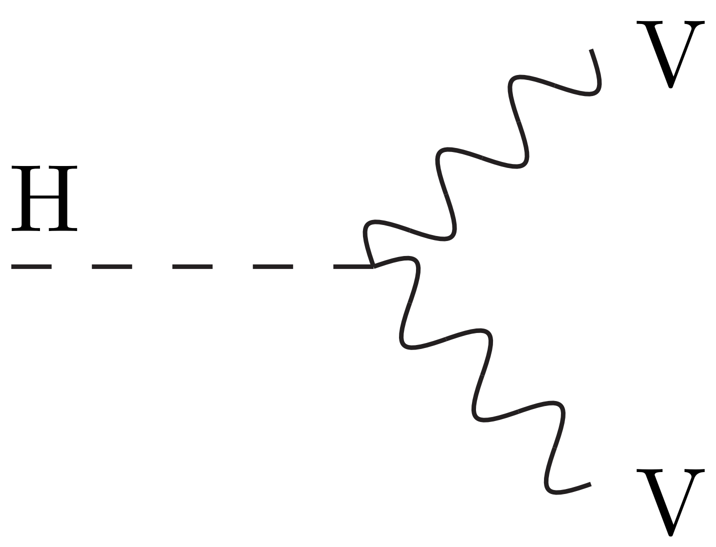
Higgs boson couplings (within the Standard Model)

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



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

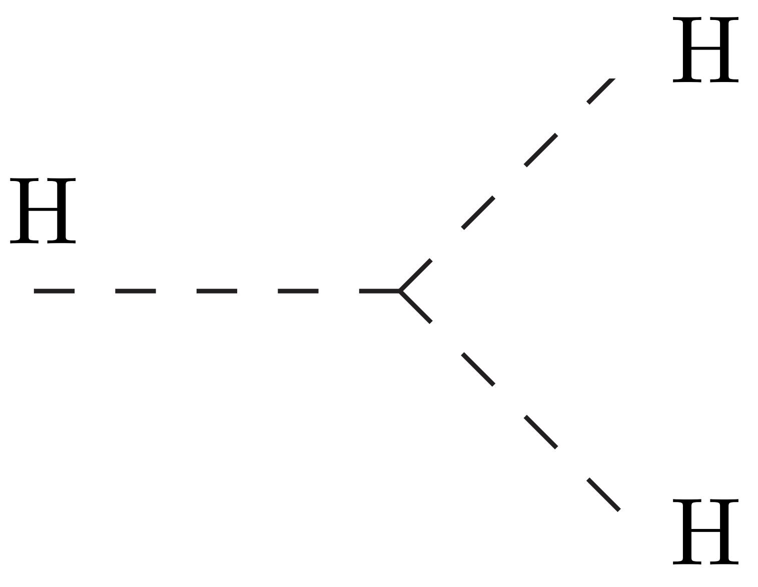
$$\bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$



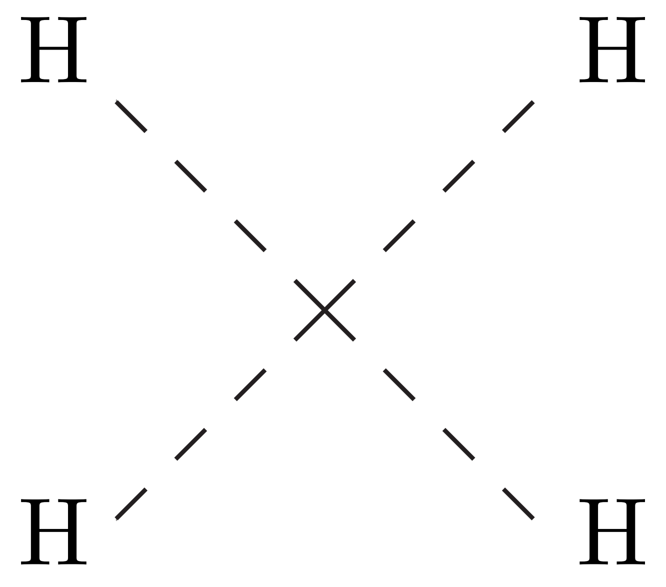
$$\frac{2m_V^2}{v}$$

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

This term could not exist without a vev



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

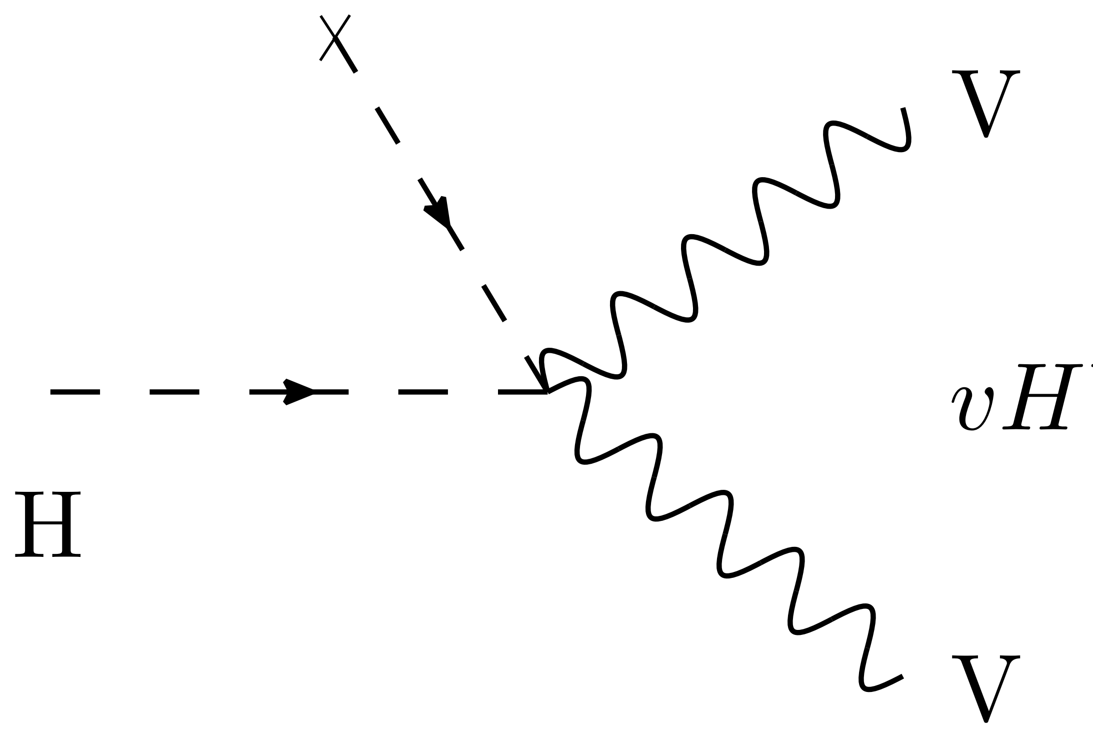


$$\frac{3m_H^2}{v^2}$$

$$V(\phi)$$

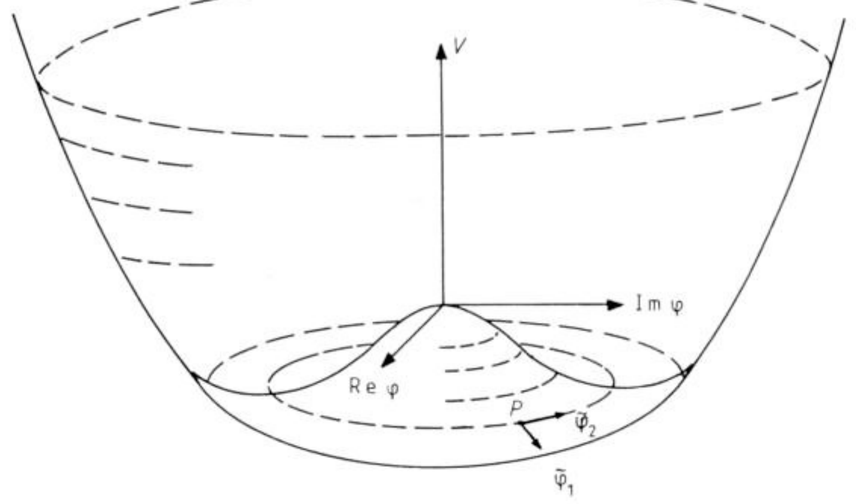
Is the Higgs boson responsible for the EW symmetry breaking also responsible for the masses of fermions?

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



$$vHV^\mu V_\mu$$

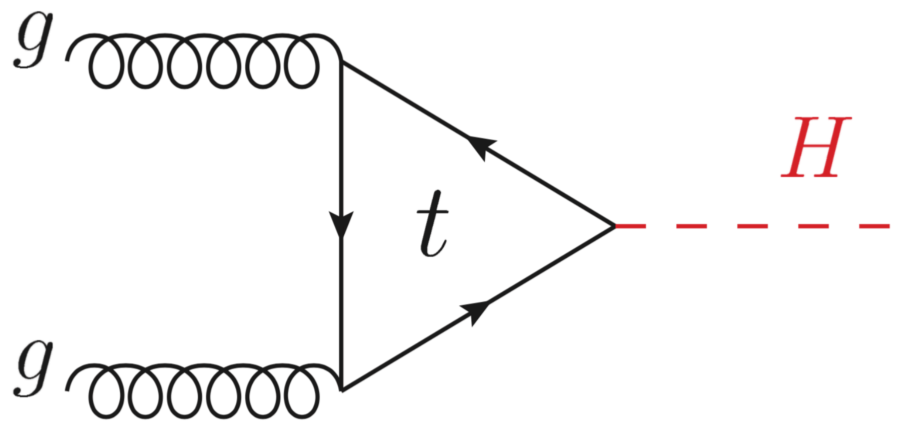
Proof of condensate !



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

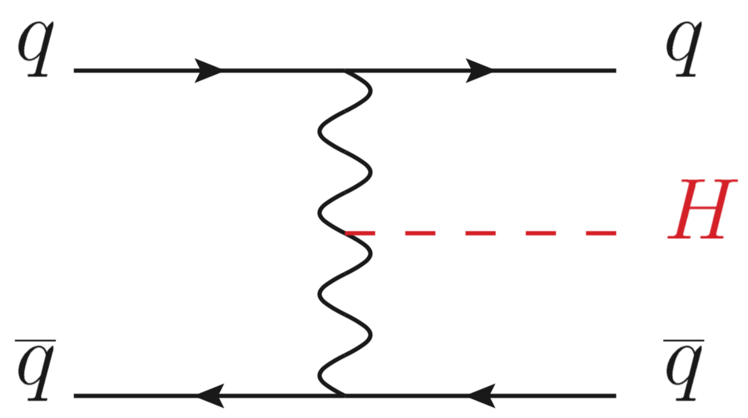
Higgs boson (main) Production Modes

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



Gluon fusion process

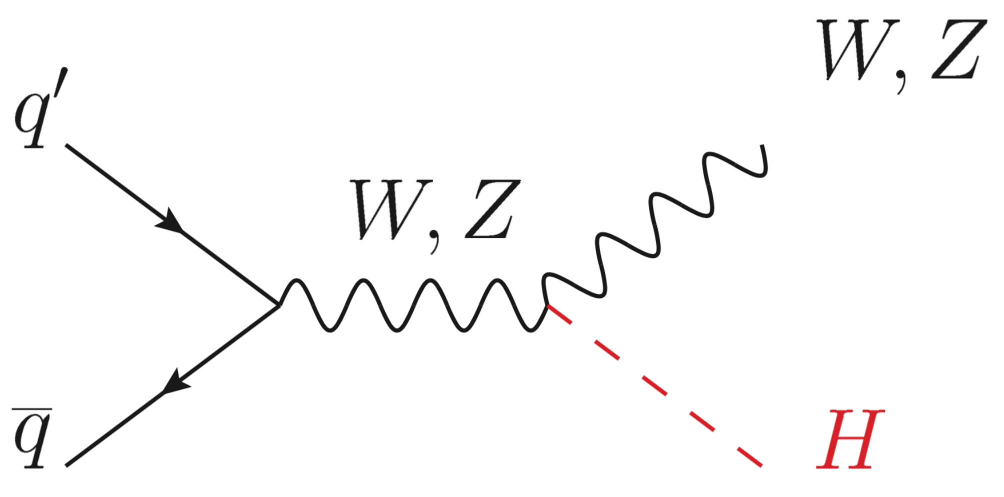
~4 M events produced



Vector Boson Fusion

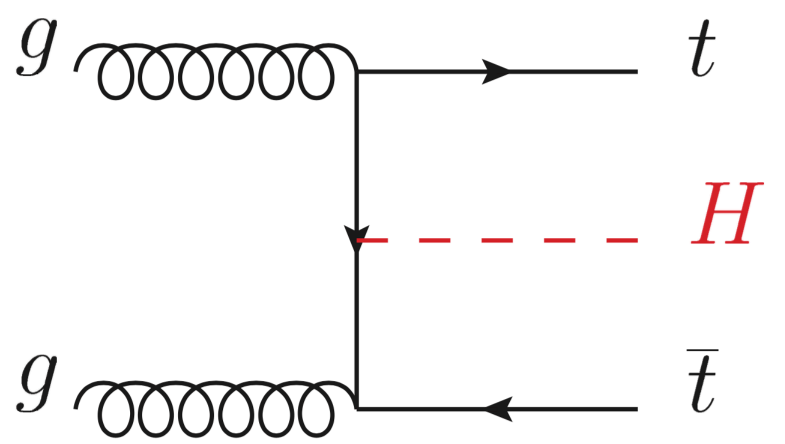
Two forward jets and a large rapidity gap

~300 k events produced



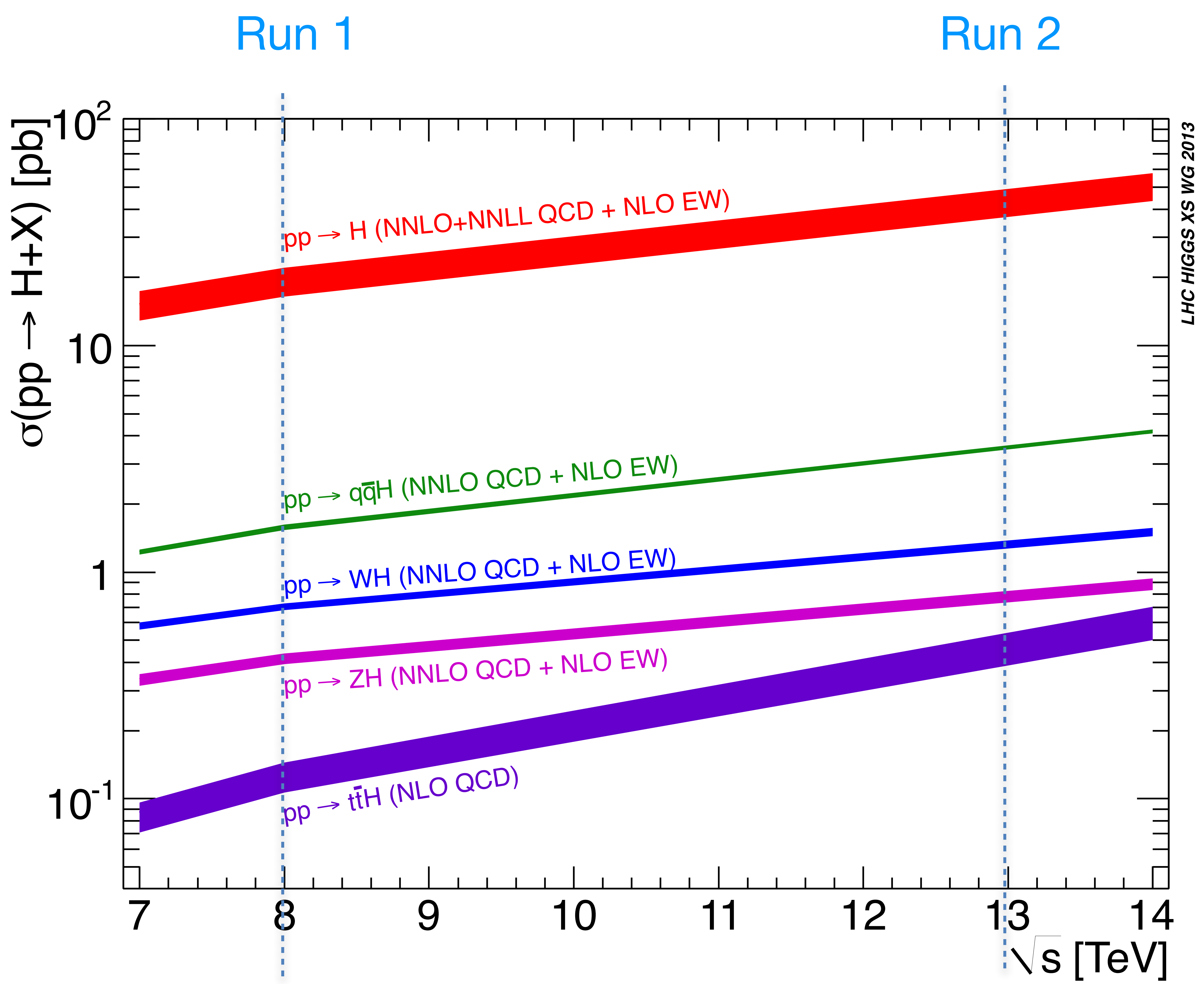
W and Z Associated Production

~200 k events produced



Top Assoc. Prod.

~40 k evts produced

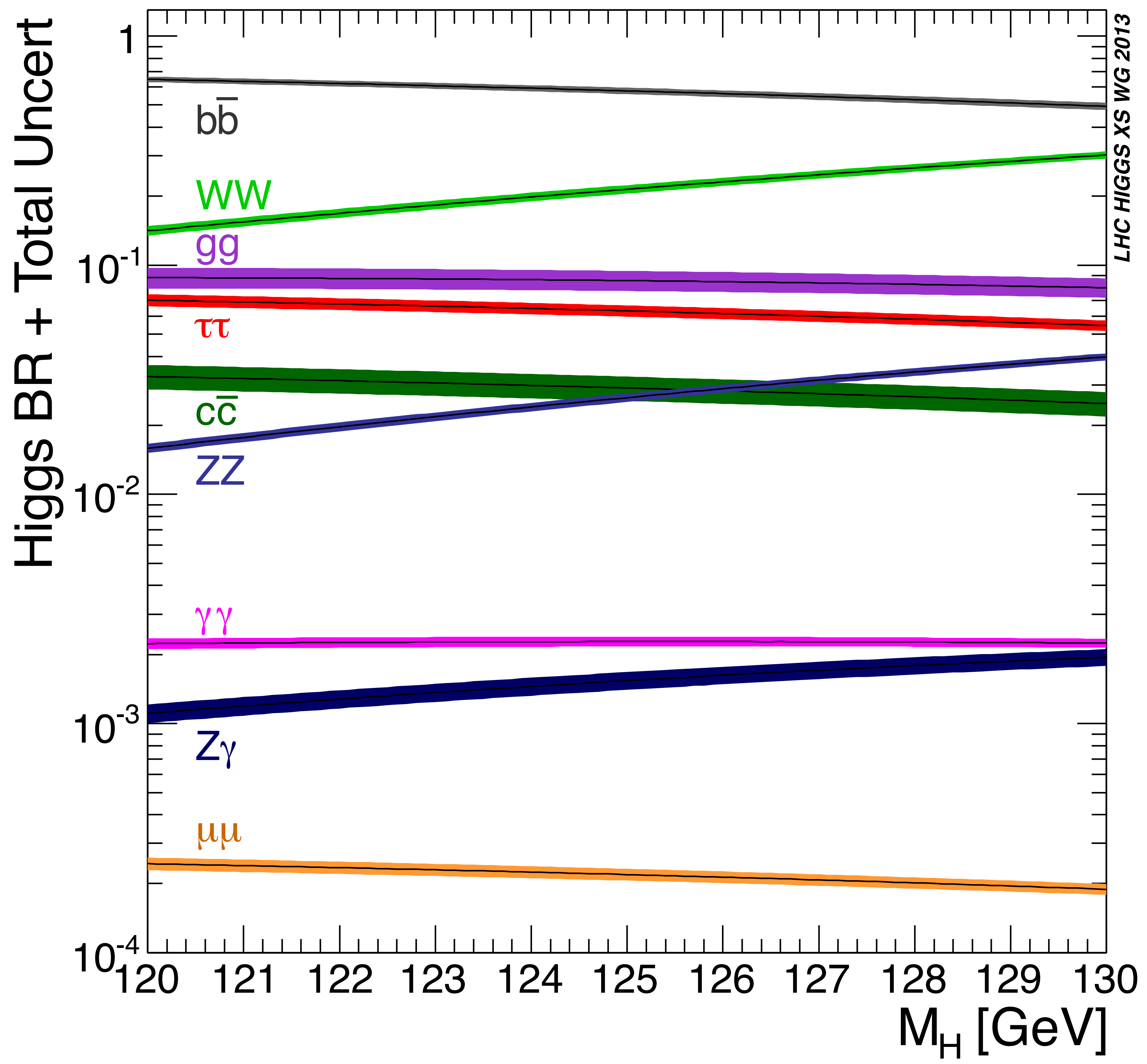


Cross section dependence on the centre-of-mass energy favours higher mass systems in the final state (i.e. the ttH production process)

From Run 1 to Run 2 typical increase of Higgs processes cross sections x2 except for ttH x4.

Higgs Decay Channels

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

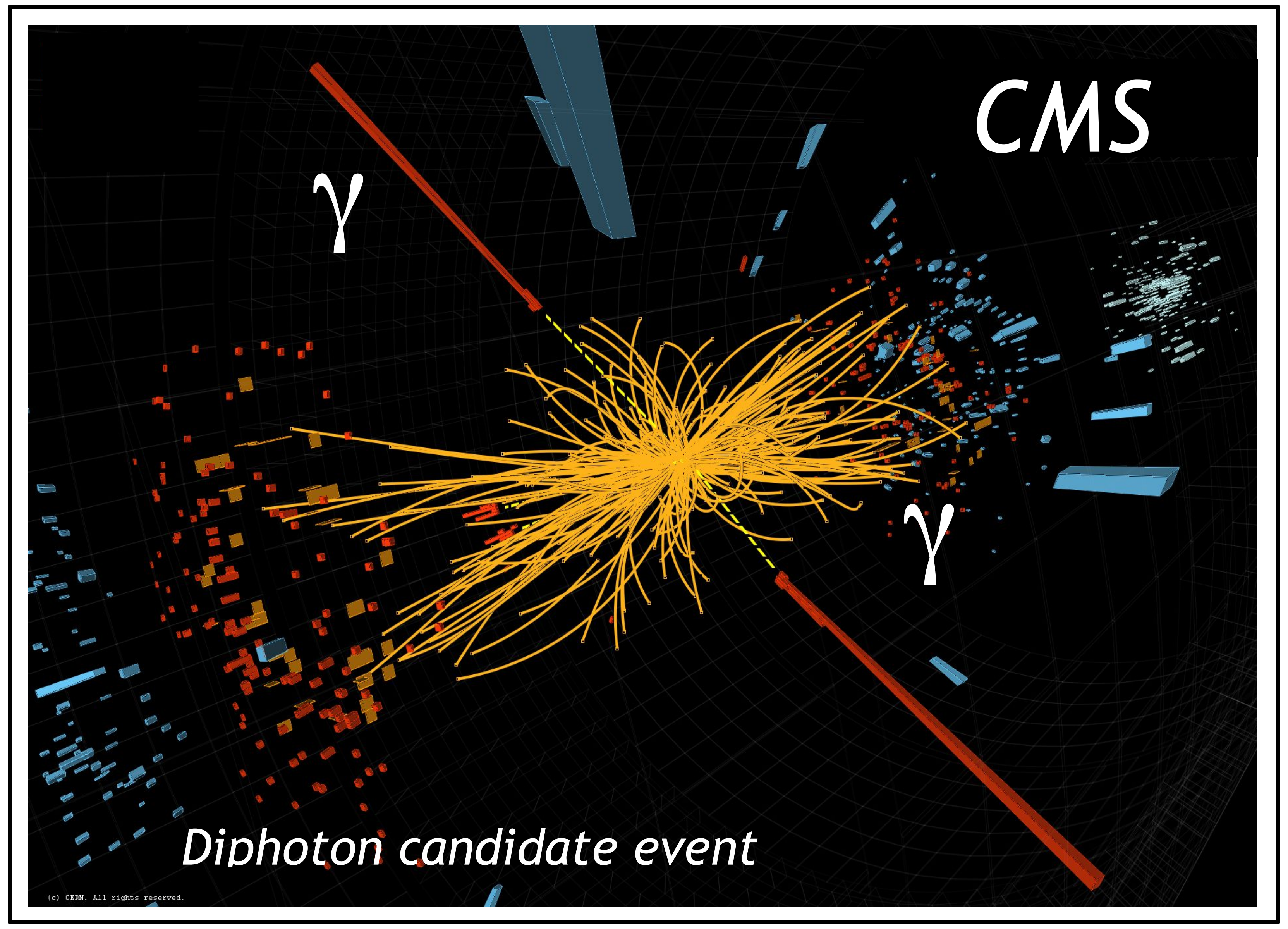


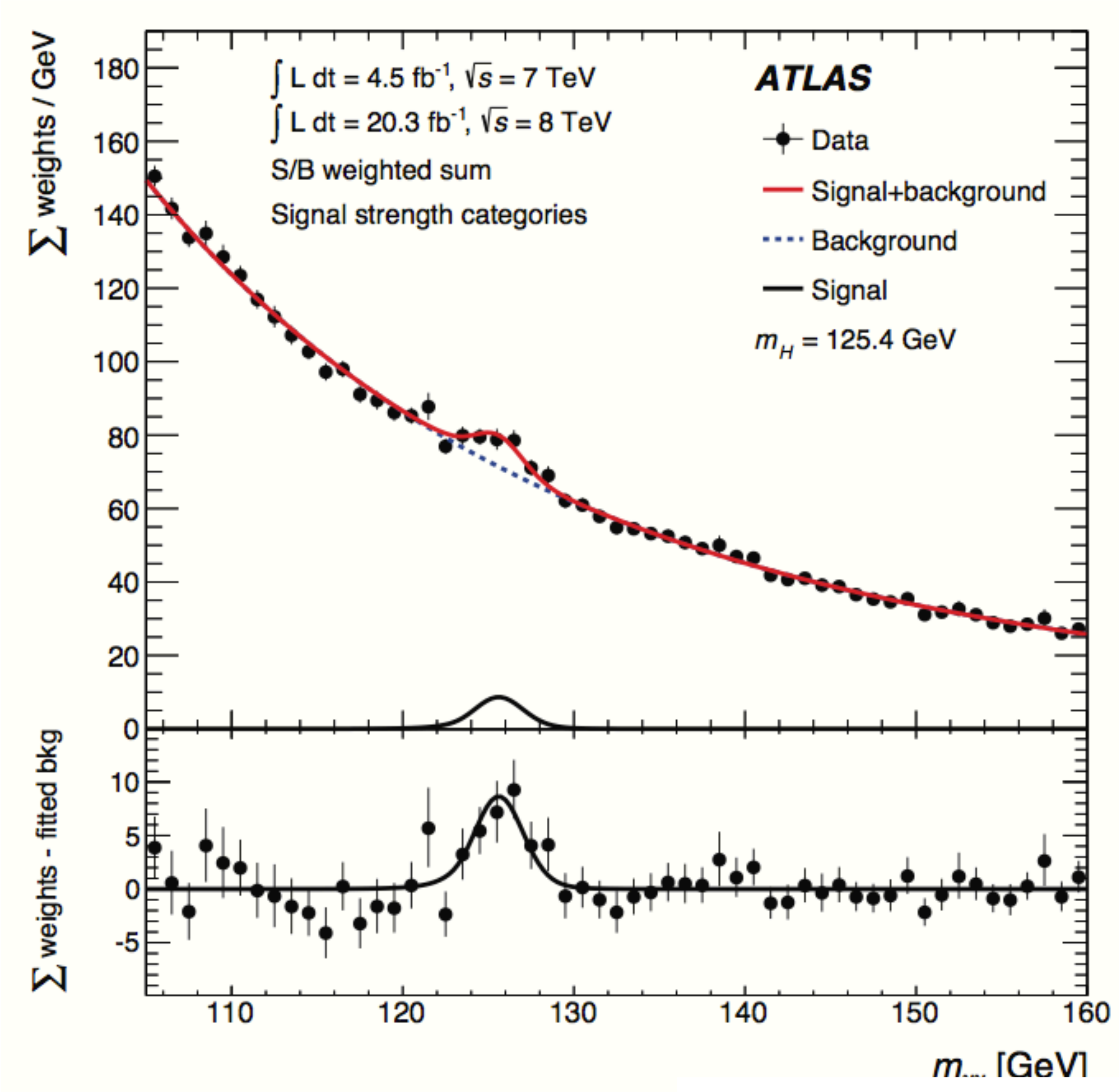
- Dominant: bb (57%)
- WW channel (22%)
- ττ channel (6.3%)
- ZZ channel (3%)
- cc channel (3%)
- The γγ channel (0.2%)
- The Zγ (0.2%)
- The μμ channel (0.02%)

The Discovery of the Higgs boson

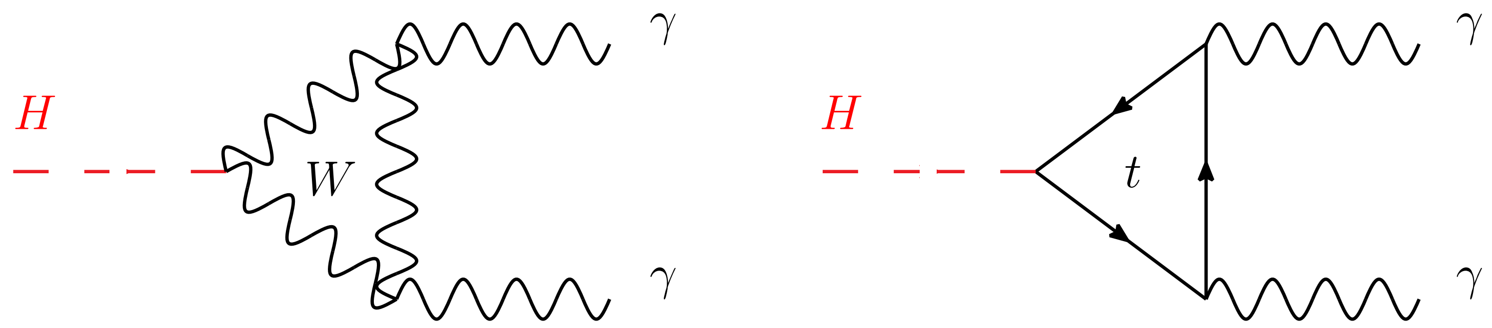
The Discovery Channels

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





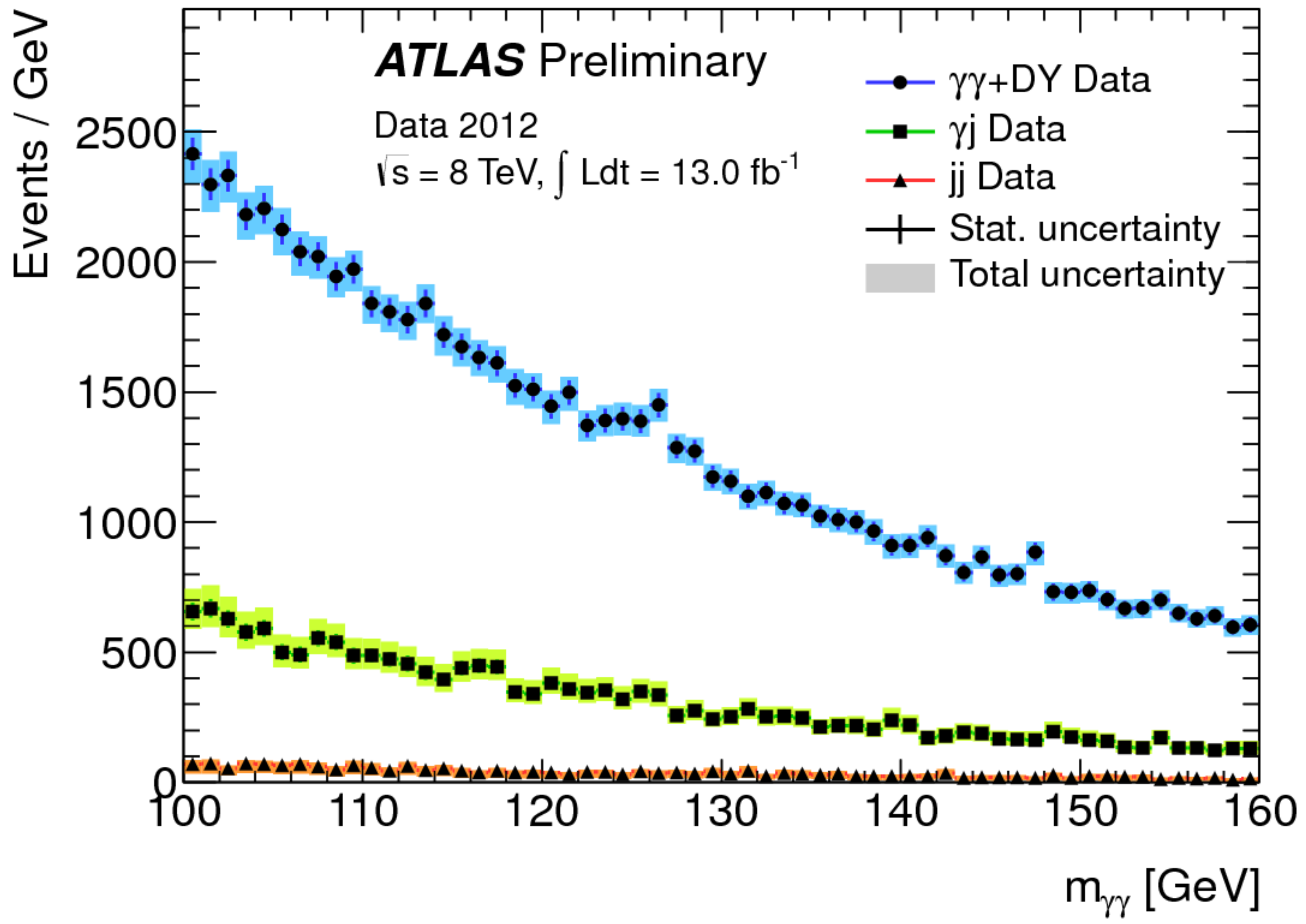
- Main production and decay processes occur through loops :



Excellent probe for new physics !

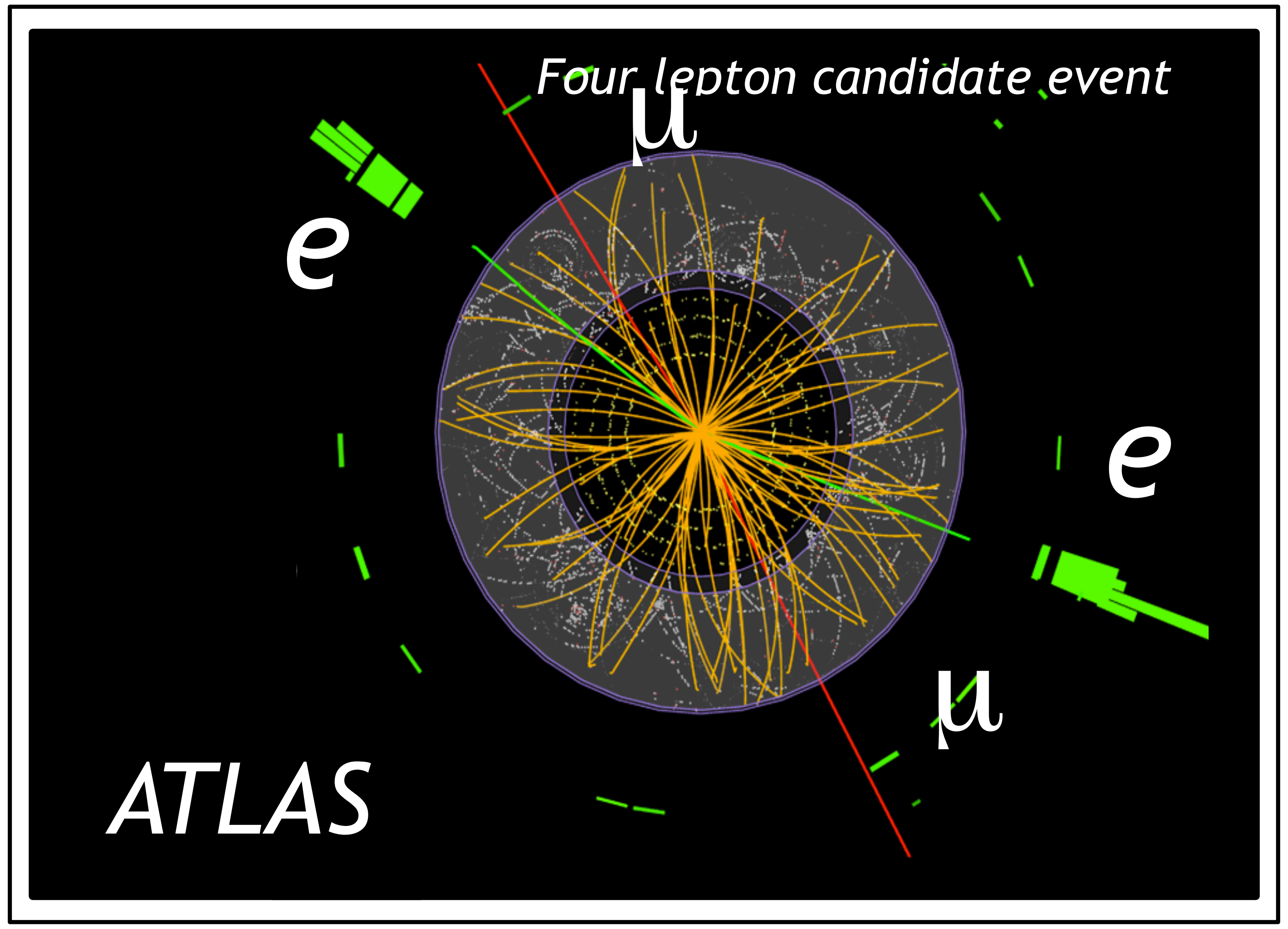
- High mass resolution channel O(1%) allowing data driven estimate of background in the sidebands.
- If observed implies that it does not originate from spin 1 : Landau-Yang theorem

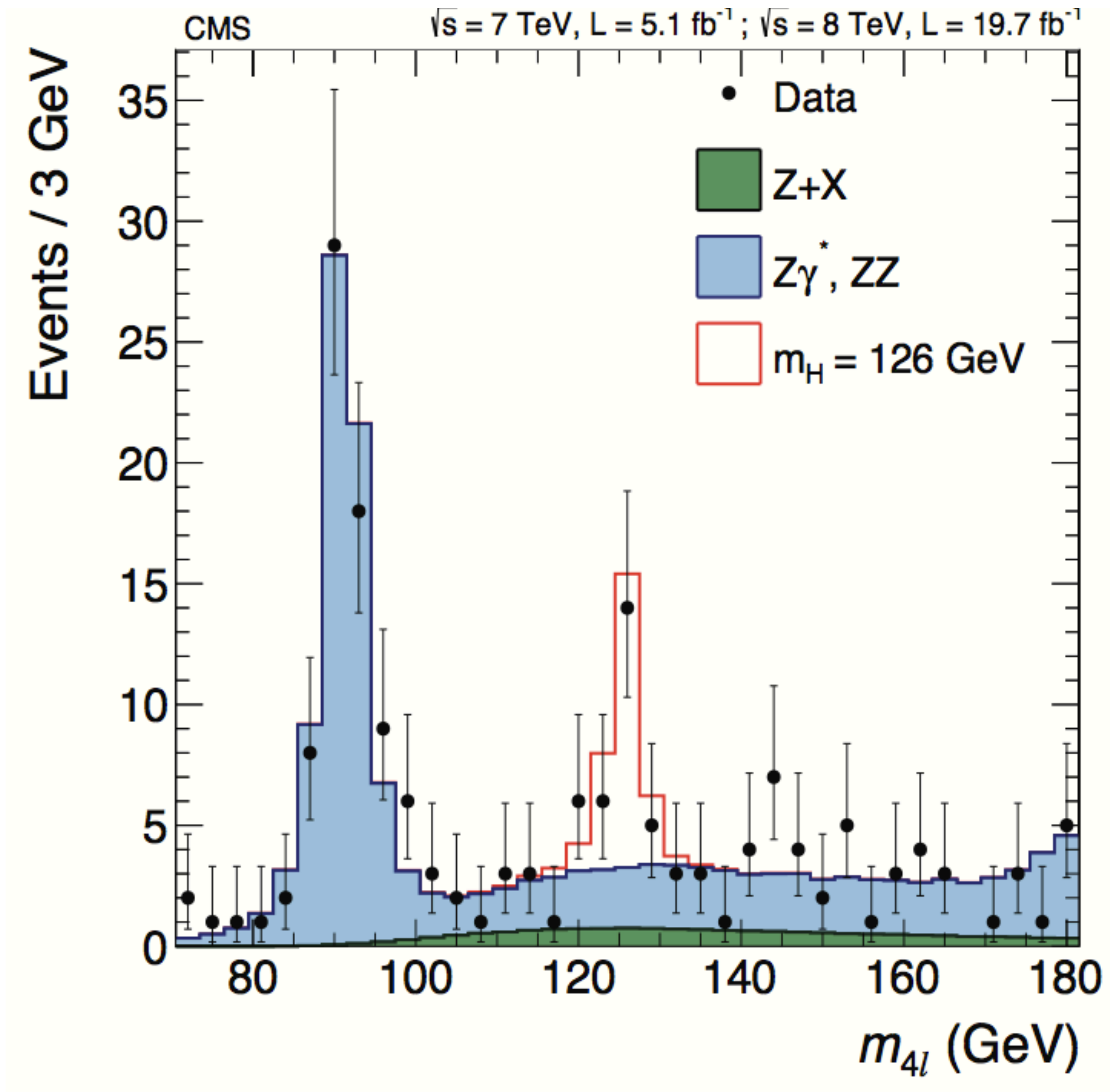
- Low signal over background but overall relatively high statistics of signal (O(300) at Run 1)
- Very simple selection cuts. The essence of the channel relies on the **quality of the detector response** and the **reconstruction**.
- Largest reducible background comes from jets! With another spin-0 particle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



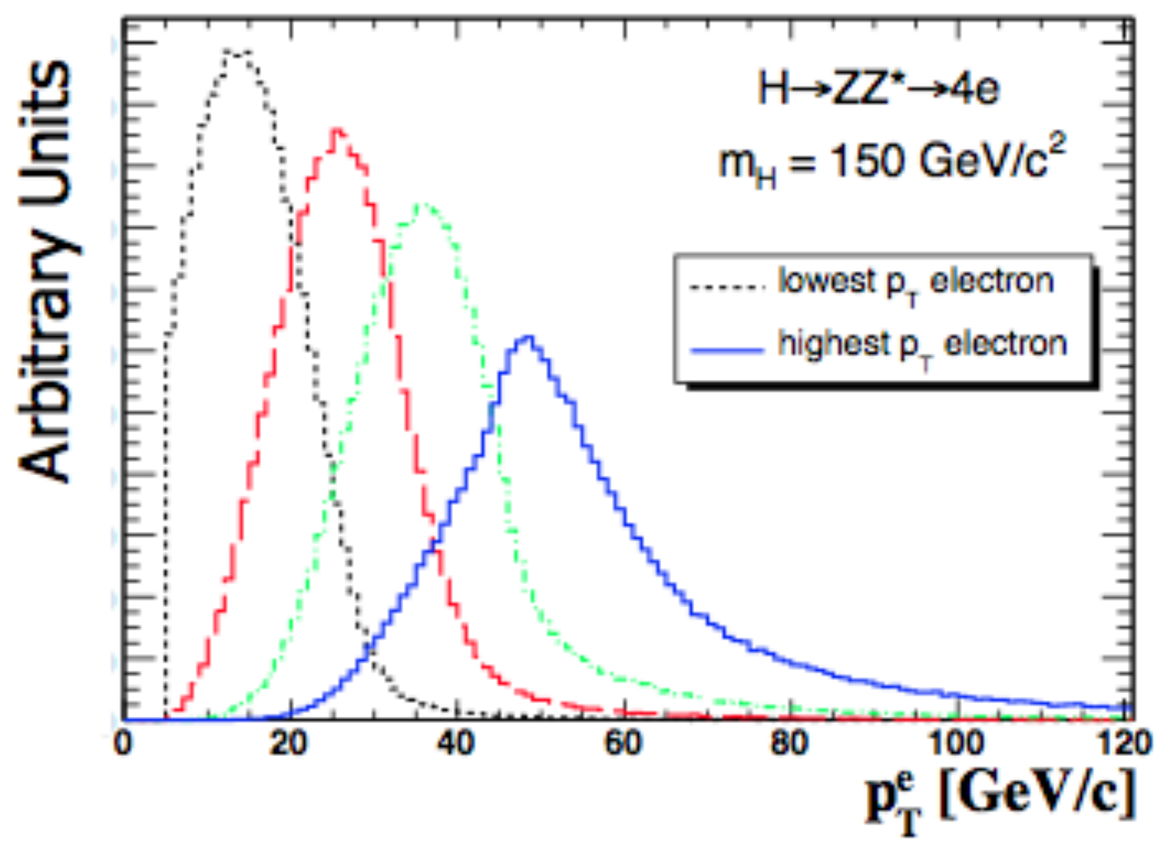
The Discovery Channels

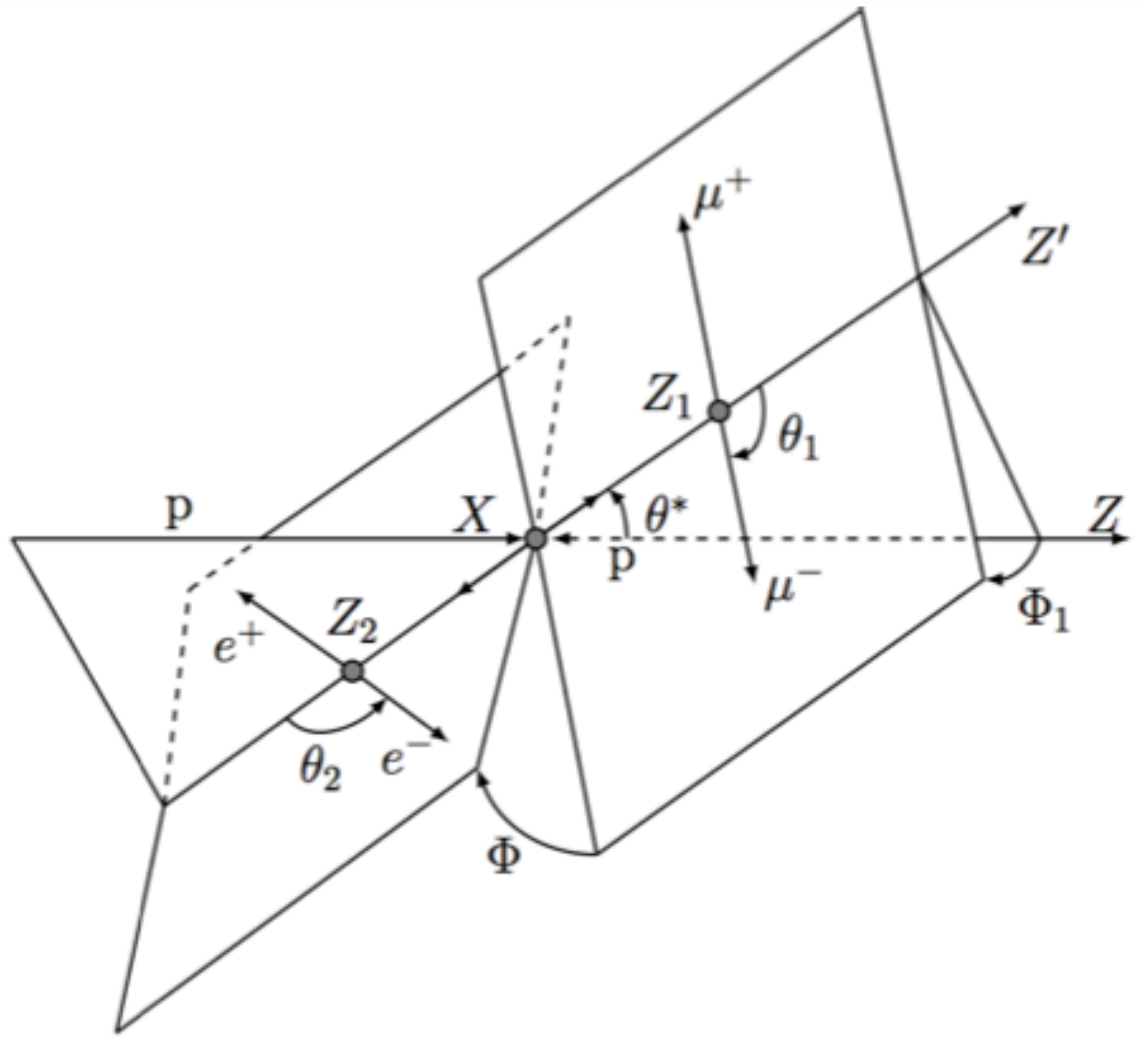
« **Bread and Butter** » Mass peak signals: the four leptons channel

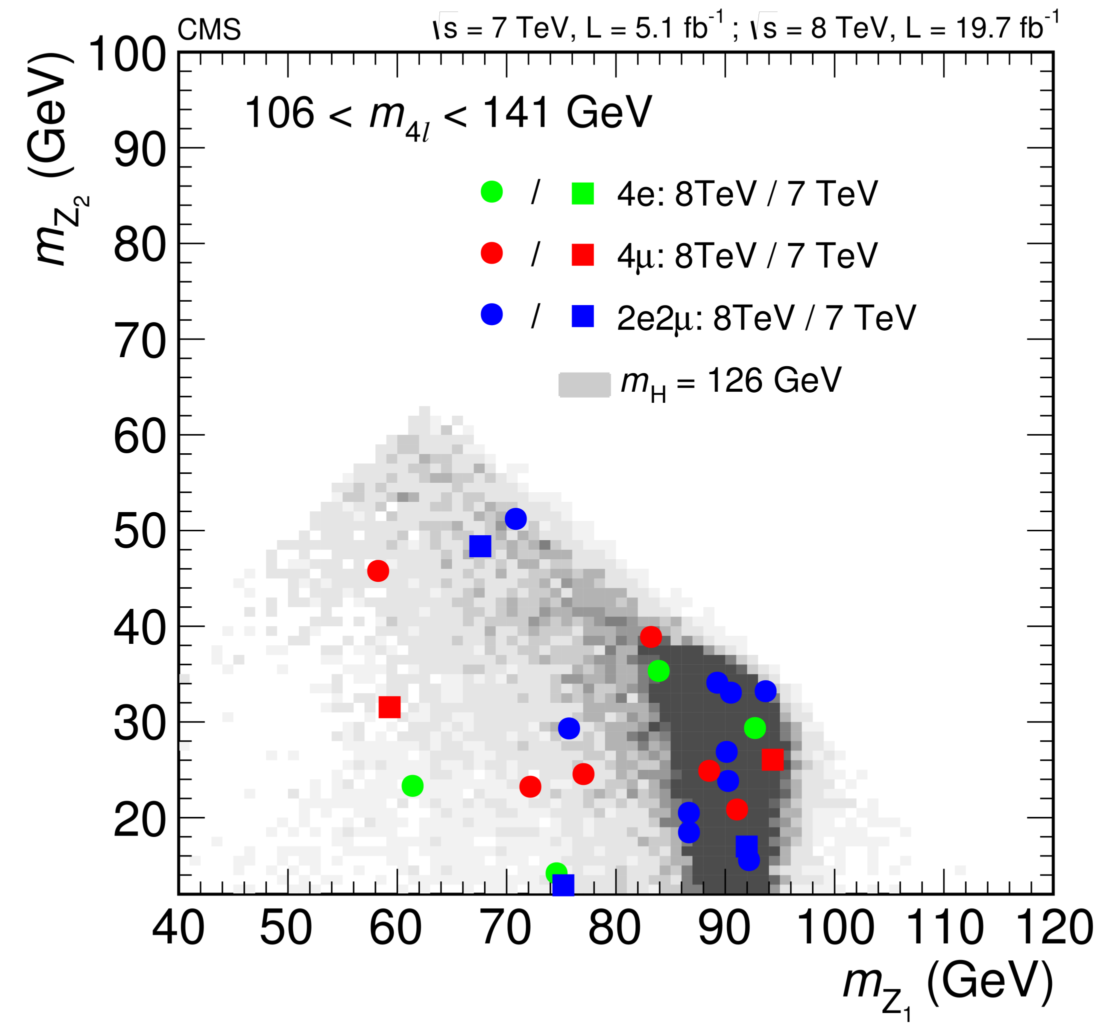




- Channel with High s/b ratio from approximately 2 up to more than 10!
- Backgrounds can be estimated from MC.
- Four leptons:
  - Very low rate due to branchings of ZZ and Z to leptons! Efficiency is key!
  - The trailing lepton is at low pT.
  - The polarisation of the two Z can be reconstructed.
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

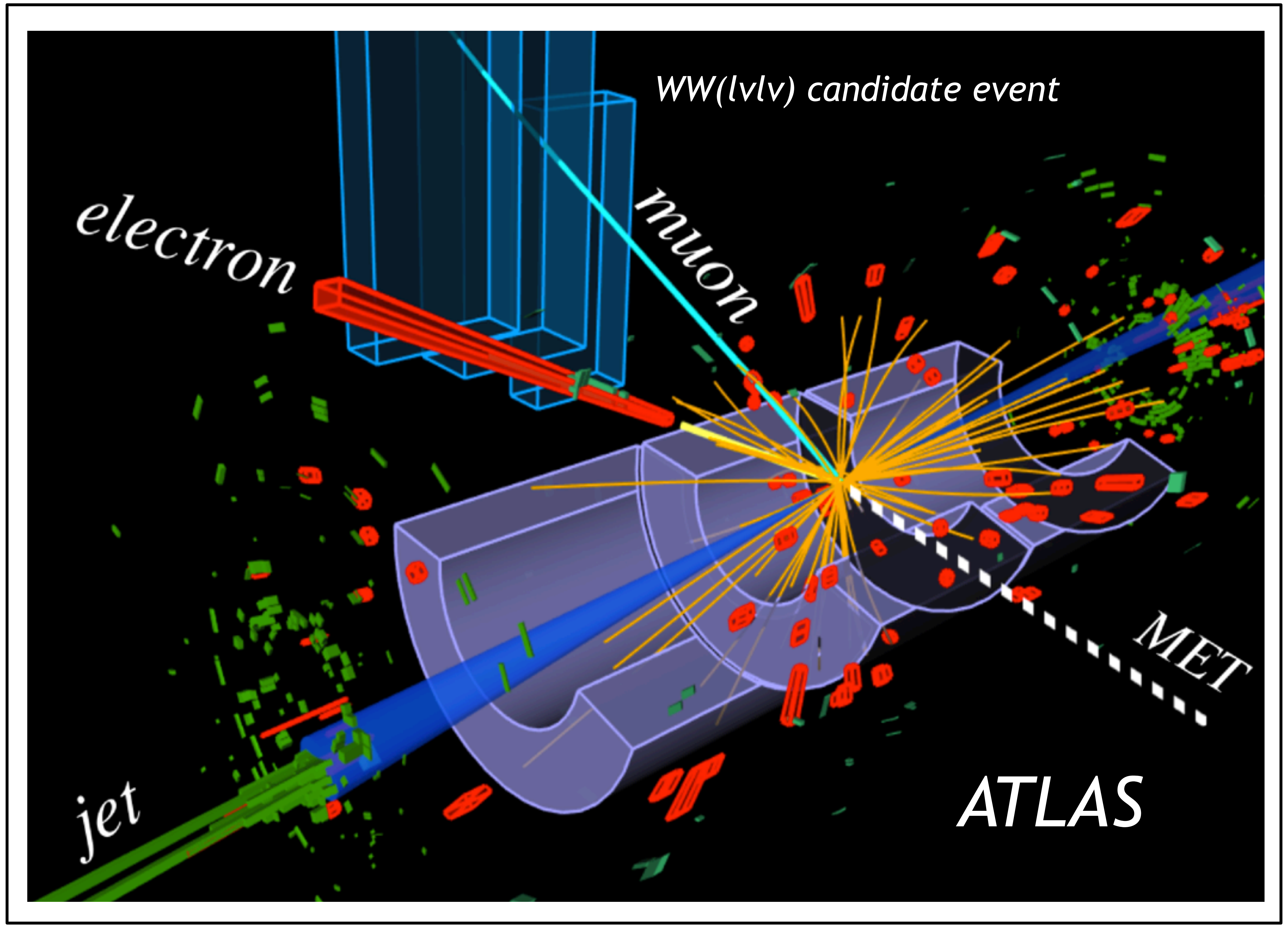






The Discovery Channels

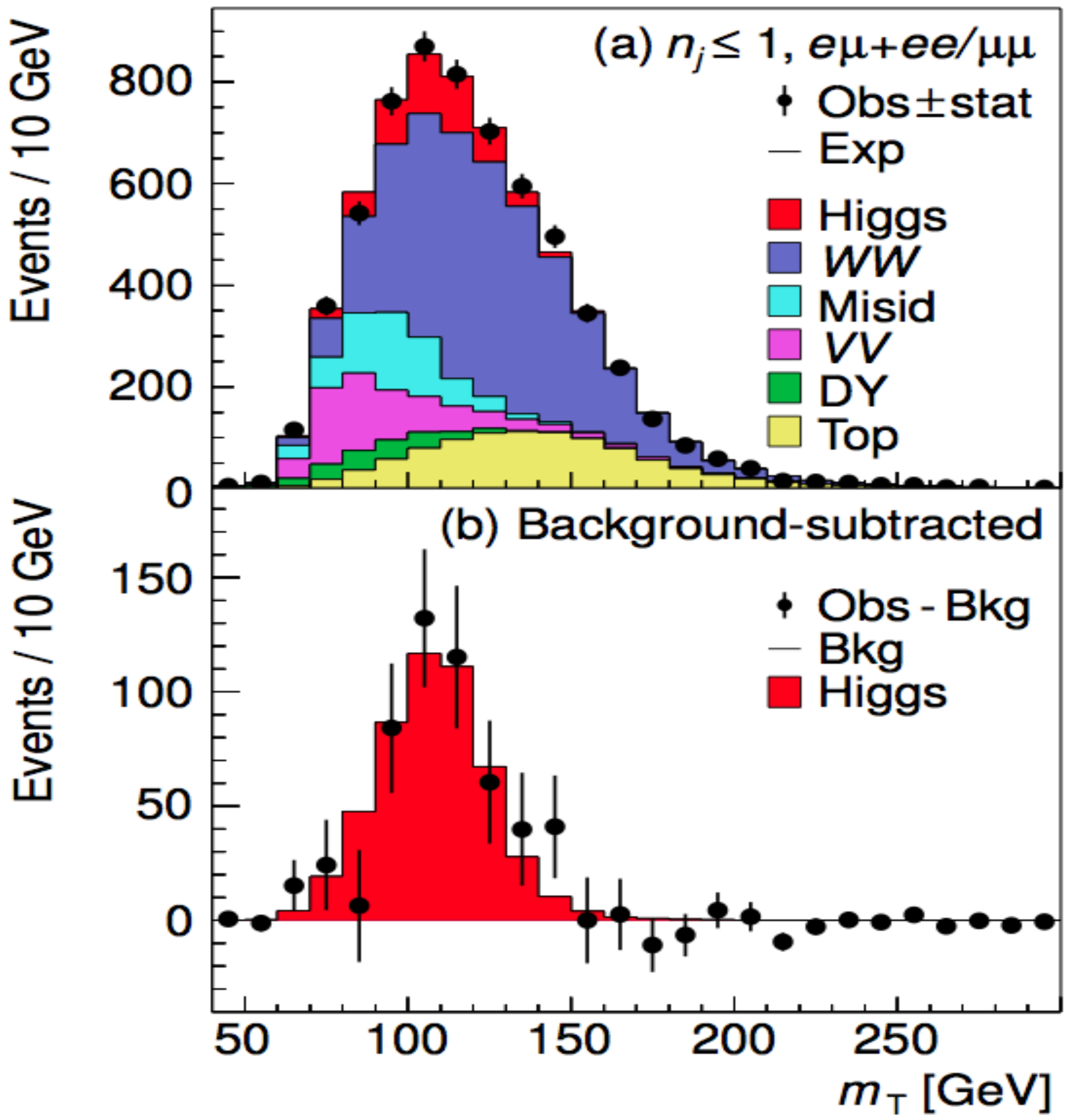
A discovery channel of a different kind: the WW

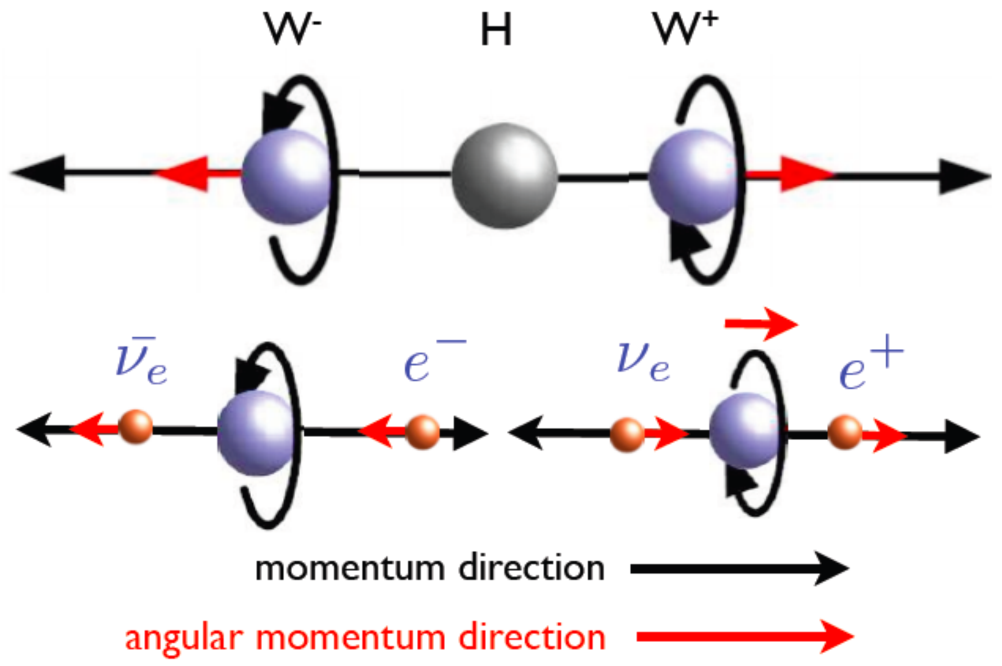


Events are separated into categories of number of jets from 0 to 2 (with the addition of VBF).

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.

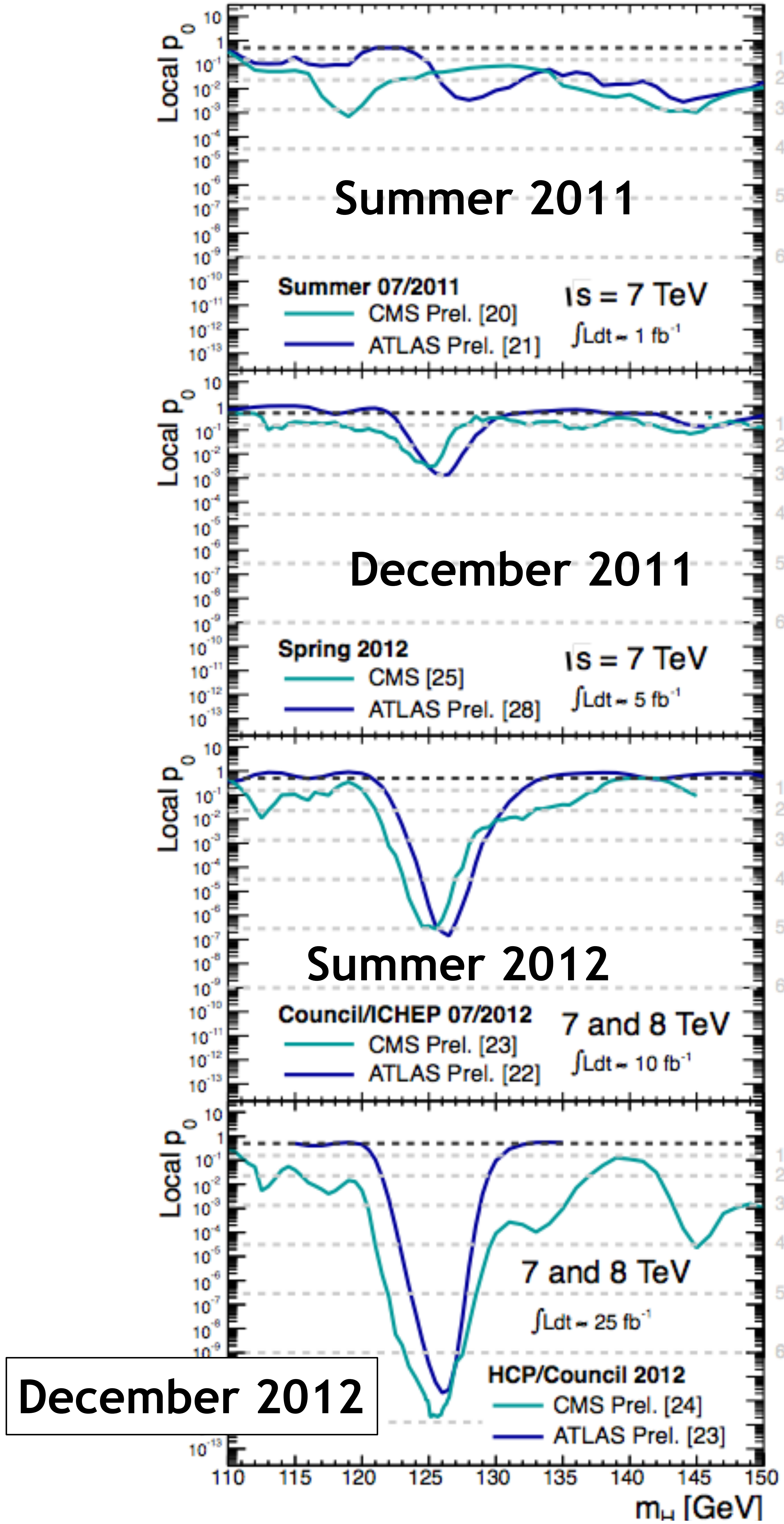




Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

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

(Precision) Measurements in the di-boson channels

First Precision Measurement at the LHC?

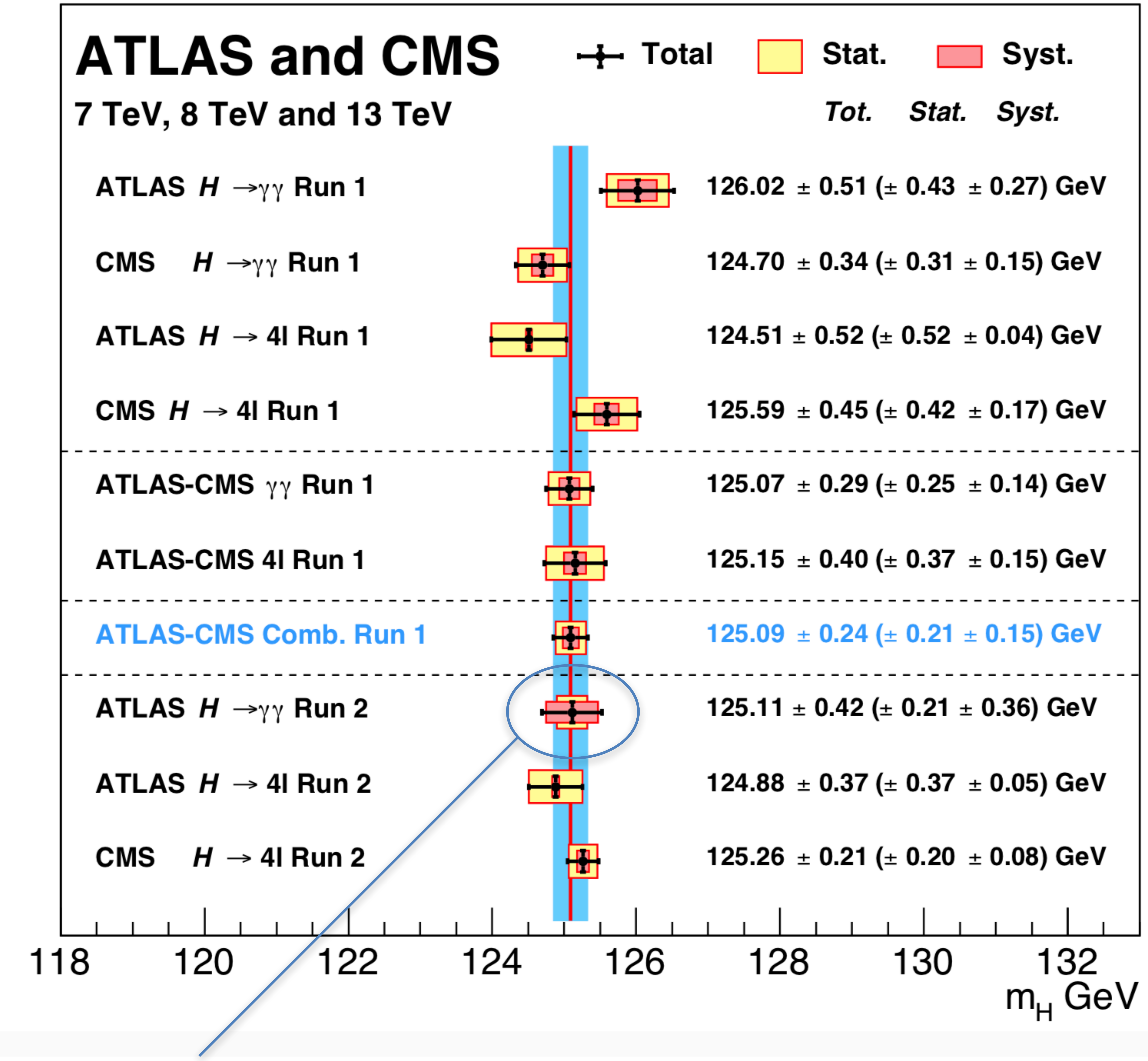
Higgs boson mass measurement

- Measurement done exclusively in bread and butter channels: 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.

Current PDG average:

$$m_H = 128.18 \pm 0.16$$

- Systematic uncertainties fully dominated by experimental systematics. All the intricacy of the measurement relies on the calibration of photons, electrons and muons.



Preliminary photon energy calibration: diphoton is limited by systematic uncertainties (photon energy scale mainly)

First Precision Measurement at the LHC?

Higgs boson mass measurements

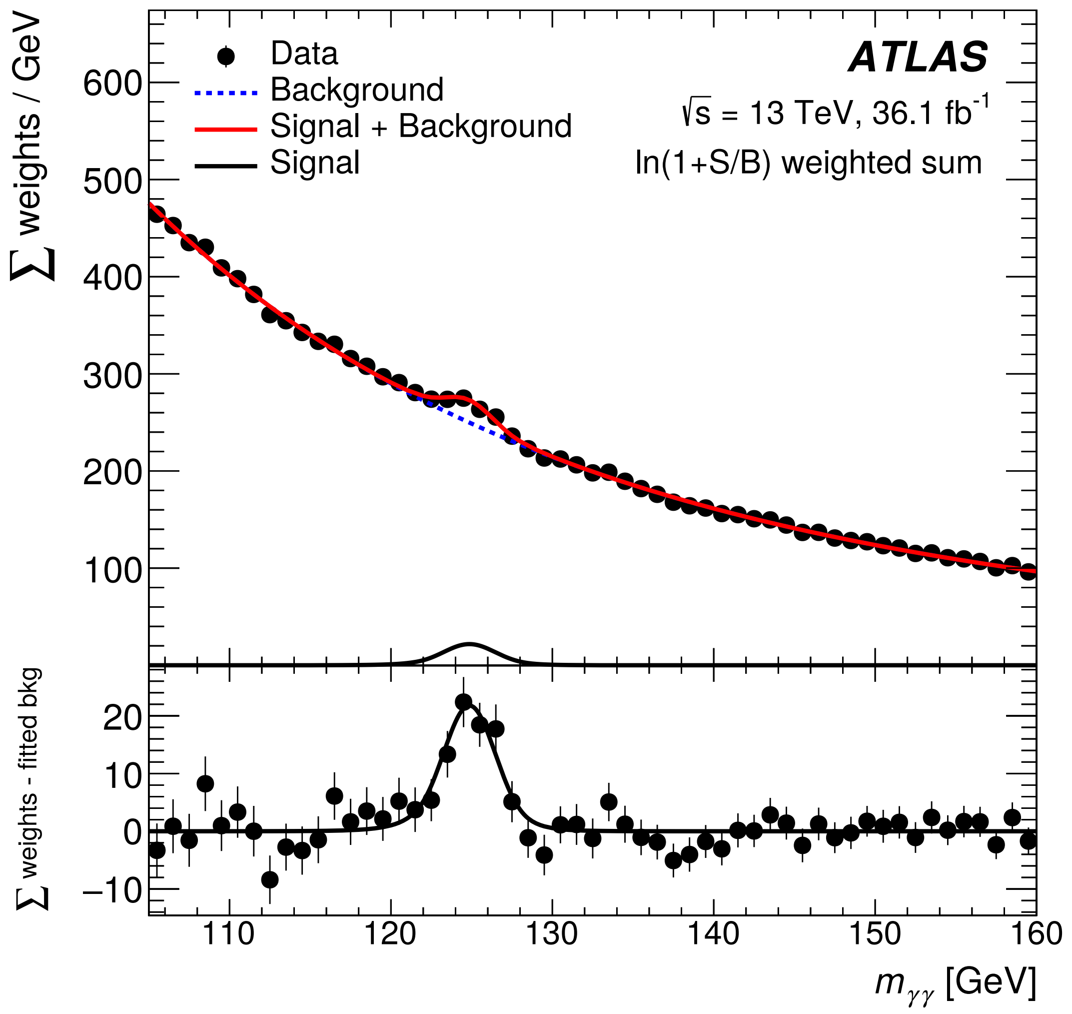
Latest measurement by ATLAS in the diphoton channel (updated with latest systematics):

$$m_H^{\gamma\gamma} = 125.32 \pm 0.19\,(\mathrm{stat}) \pm 0.29\,(\mathrm{syst})$$

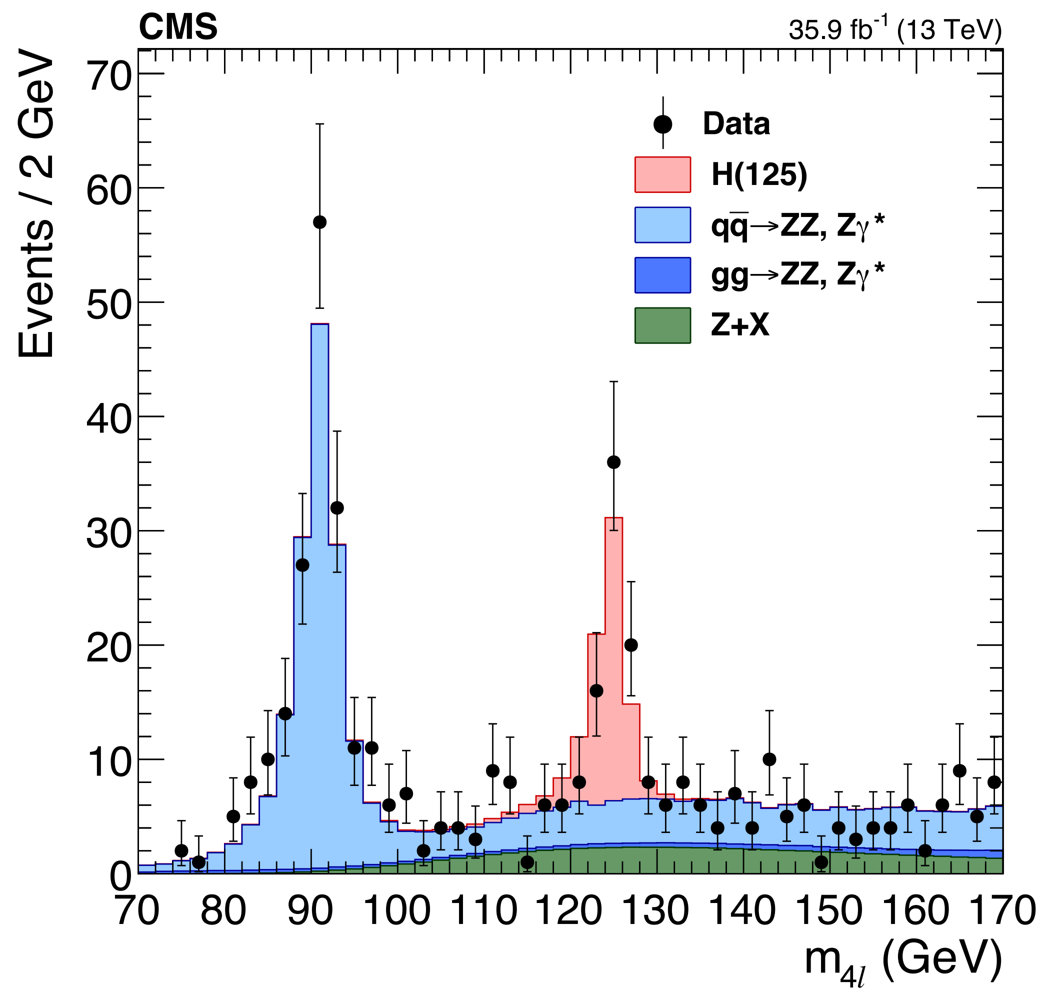
Measurement done using categories based on the photon energy response performance.

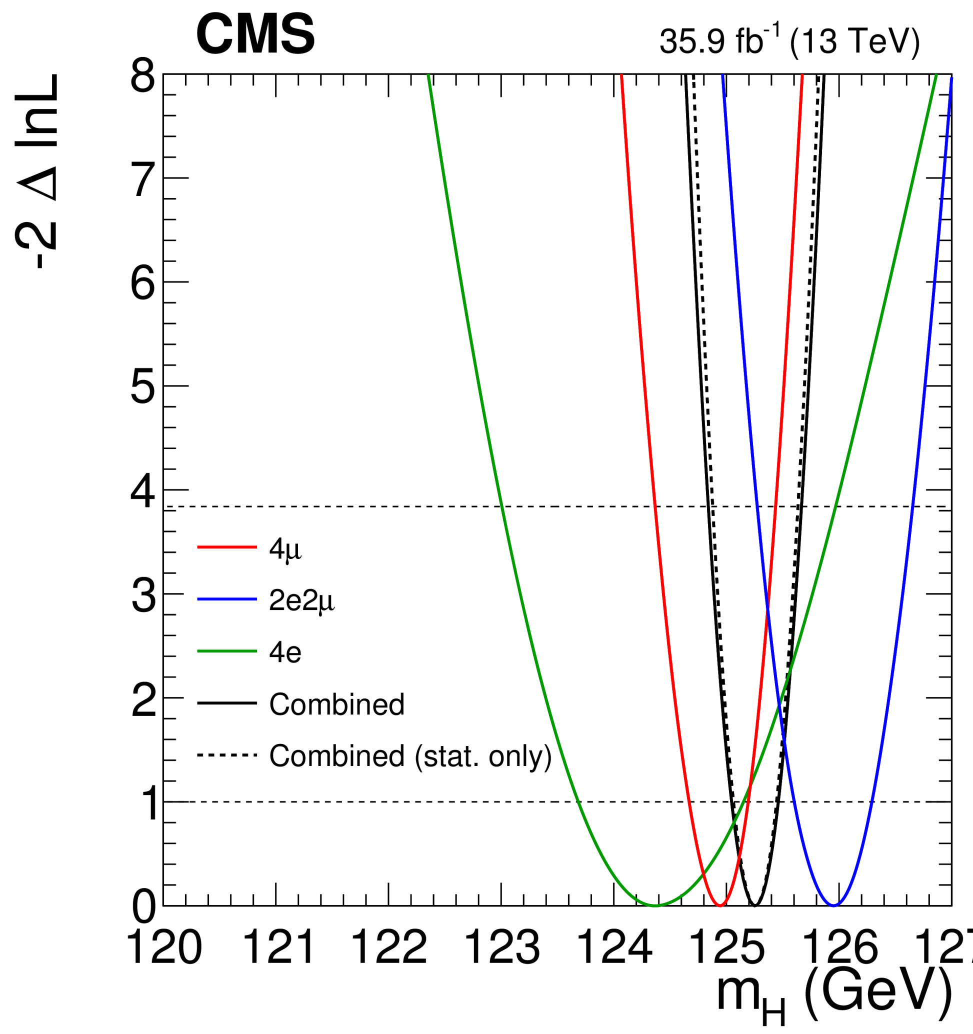
Already dominated by (calibration) systematic uncertainties.

Key aspect in the photon calibration is the extrapolation of the calibration of the electrons (using Z and J/Psi mainly) to the photons.



Measurement is dominated by the cleanest 4-mu channel





- Measurement improved using a Z mass constraint on the highest mass SFOS dilepton pair and the per event resolutions.

- Given the transverse momentum range of the muons, the CMS detector has a significantly better precision (mostly due to the larger magnetic field).

Challenge: Improve the calibration of muons, electrons and photons.

Cross Sections Definitions

Total, fiducial, differential and unfolded

Typically at LHC measurement of number of events in a given dataset, with a set of selection cuts corresponding to a given integrated luminosity L.

Total cross section $$\sigma_{tot} = \frac{N_{evts}}{\mathcal{A} \times \varepsilon \times \int \mathcal{L}dt}$$

Where σ_{tot} is the total cross section for a given process (which includes the decay branching fractions), A the acceptance of the process, ε is experimental efficiency (online and offline) and L is the integrated luminosity.

$$\mathcal{A}$$

The acceptance A is derived from the definition of a **fiducial volume** and is the ratio of number of events produced in the fiducial volume to the total number of events. It is an extrapolation factor estimated by theory (typically with Monte Carlo).

Fiducial cross section $$\sigma_{fid} = \frac{N_{evts}}{\varepsilon \times \int \mathcal{L}dt}$$

With a proper definition of the fiducial region, ε should bear little model dependence.

Differential cross section w.r.t. (truth level) variable t

The notion of differential cross section in HEP is binned in truth level variables and measurements in correspond reconstruction level variable: r

Truth distribution $f(t)$

Reconstructed distribution $g(r)$

Generating the reconstructed distribution (detect. simulation) $$f(t) \rightarrow g(r)$$

Unfolding estimating the truth from the reconstructed $$g(r) \rightarrow f(t)$$

To be solved numerically the problem needs to be discretised:

$$f(t) \rightarrow \mathbf{x} \qquad g(r) \rightarrow \mathbf{y}$$

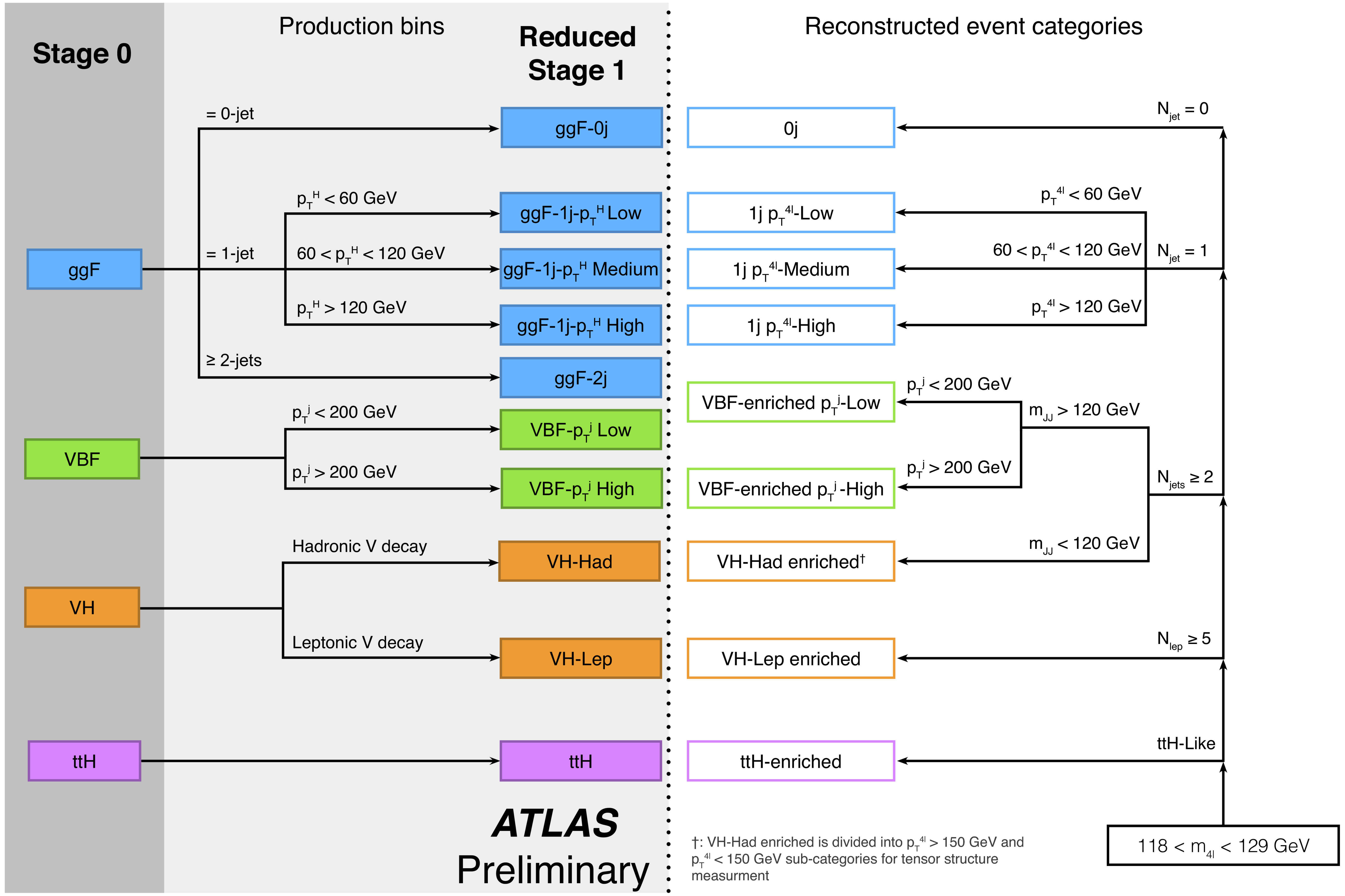
$$\mathbf{x} = \mathbf{A}^{-1}\mathbf{y}$$

For the case where the number of truth and reconstructed bins are the same

Concrete Example

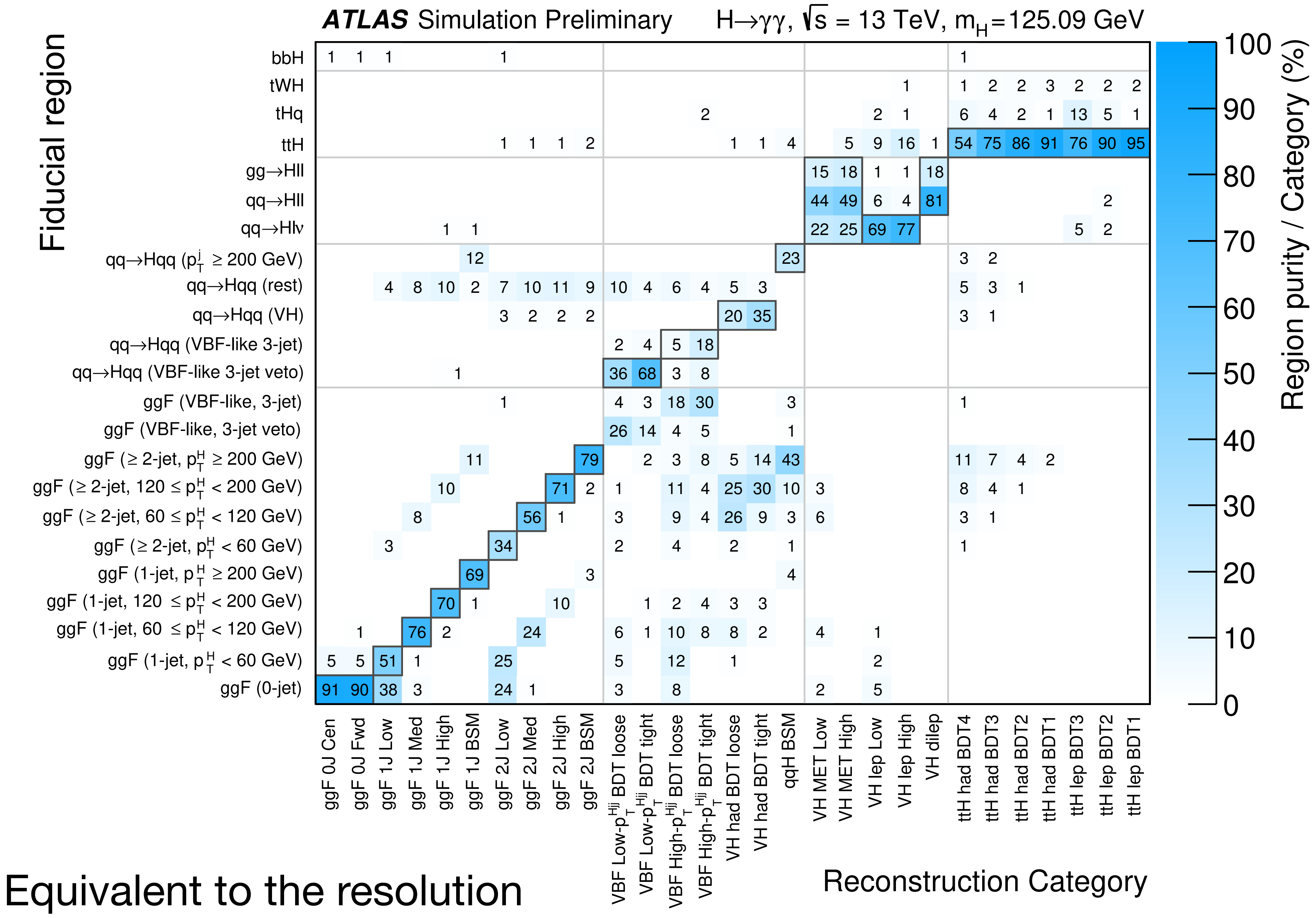
Cross section measurements in the diphoton channel: the goal is to measure as precisely as possible individual production processes (ggF, VBF, VH and ttH) in different regions of phase space.

- Define a fiducial region for the photons (in pT and eta).
- Define fiducial cuts at truth particle level on the pT of the Higgs and number and kinematics of the additional jets or leptons in the events.
- Define reconstruction level cuts corresponding to the fiducial volume of interest.
- The definition of the fiducial volume is guided both by the TH interest and the experimental capabilities.



Hybrid Approach

Correspondence table between the fiducial region and reconstruction regions for the signal to be measured

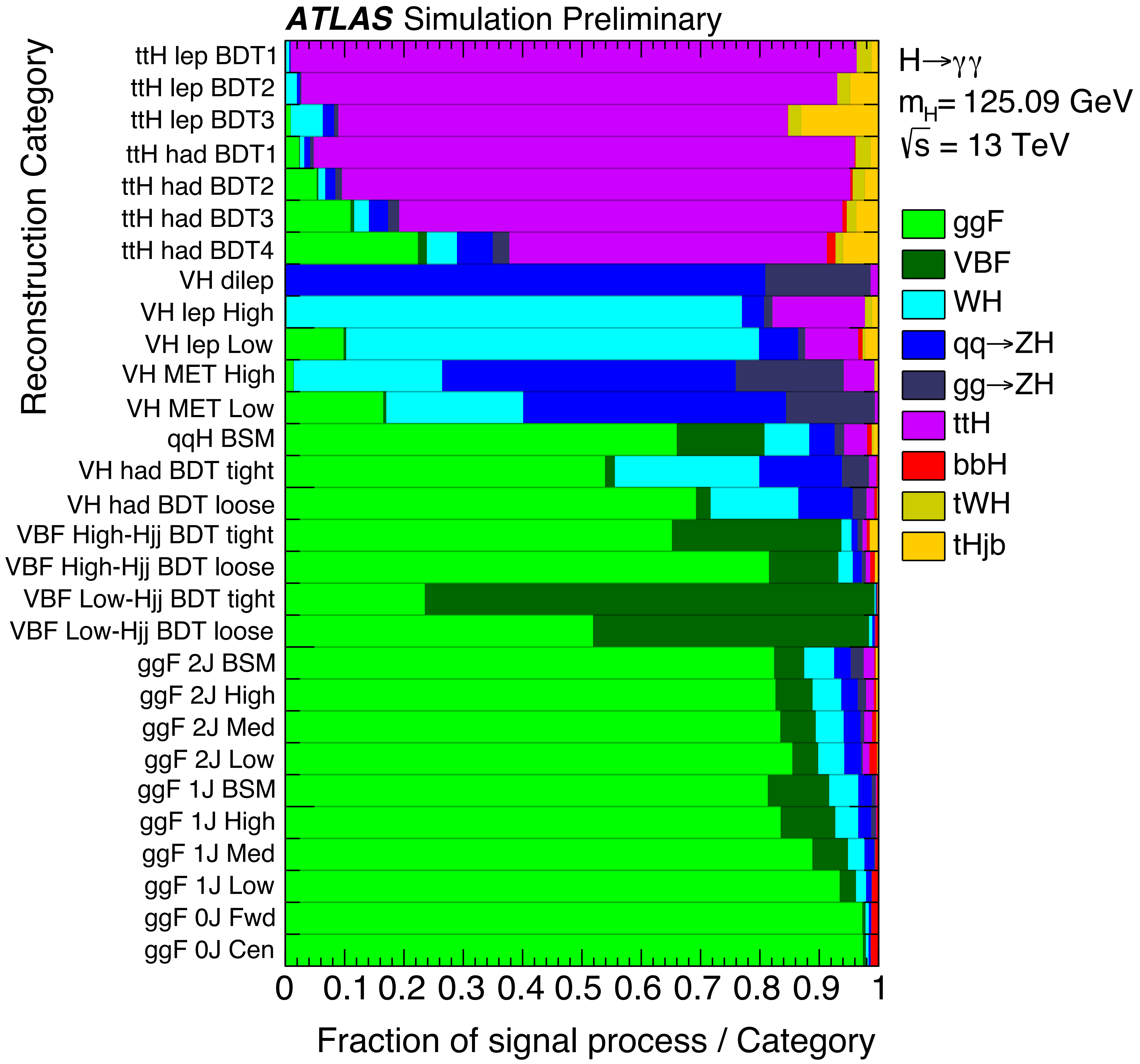


Equivalent to the resolution matrix for an unfolding.

Note: the resolution matrix has to be built using a specific signal definition.

The goal of the unfolding is to be independent of this choice. Requires a proper definition of fiducial regions and unfolding.

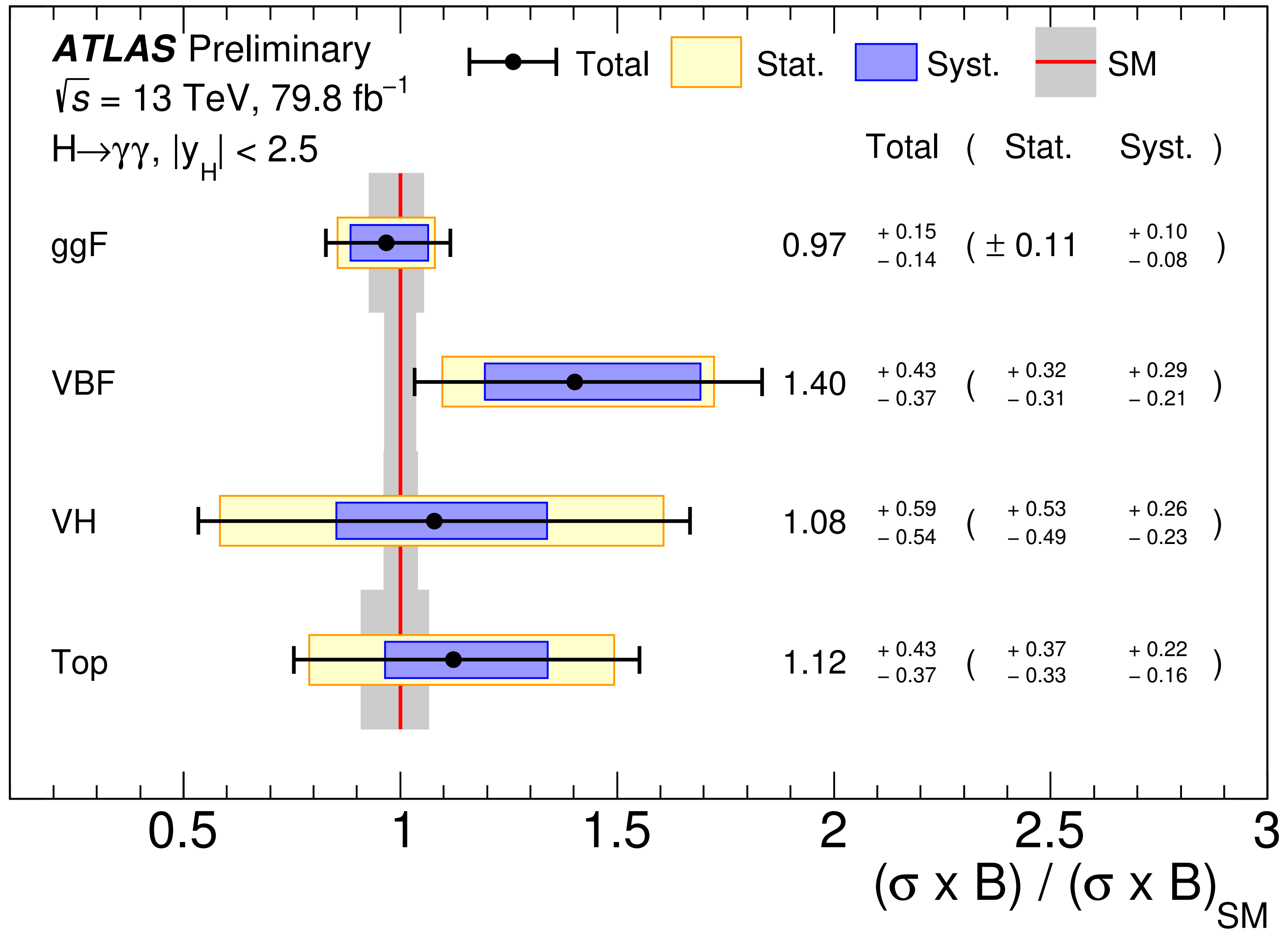
To measure specific production processes, a hybrid approach is used making use of the categories to separate the different signals.

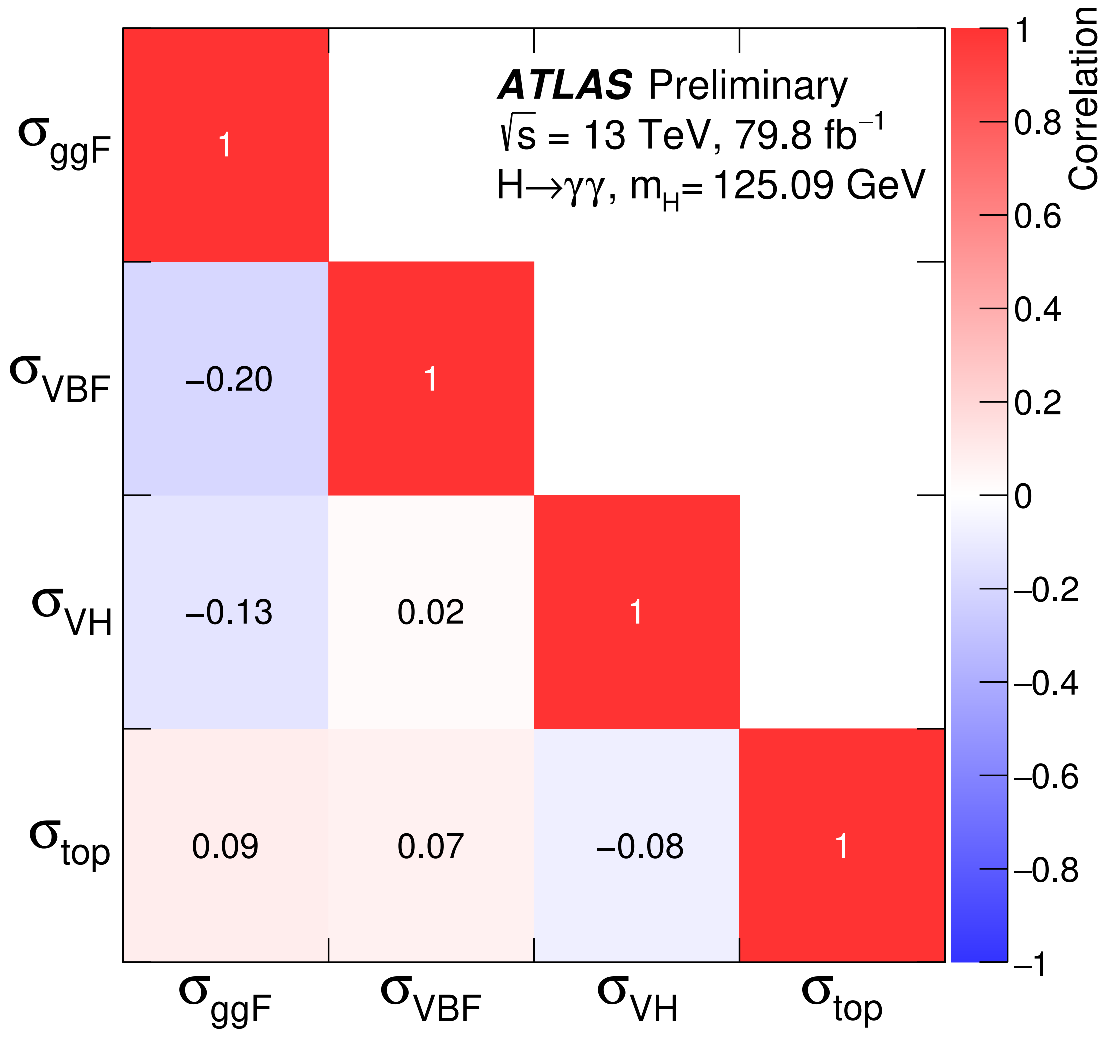


Hybrid Approach

For coupling properties measurements

Specific processes total cross sections are extracted from the fit (stage 0)

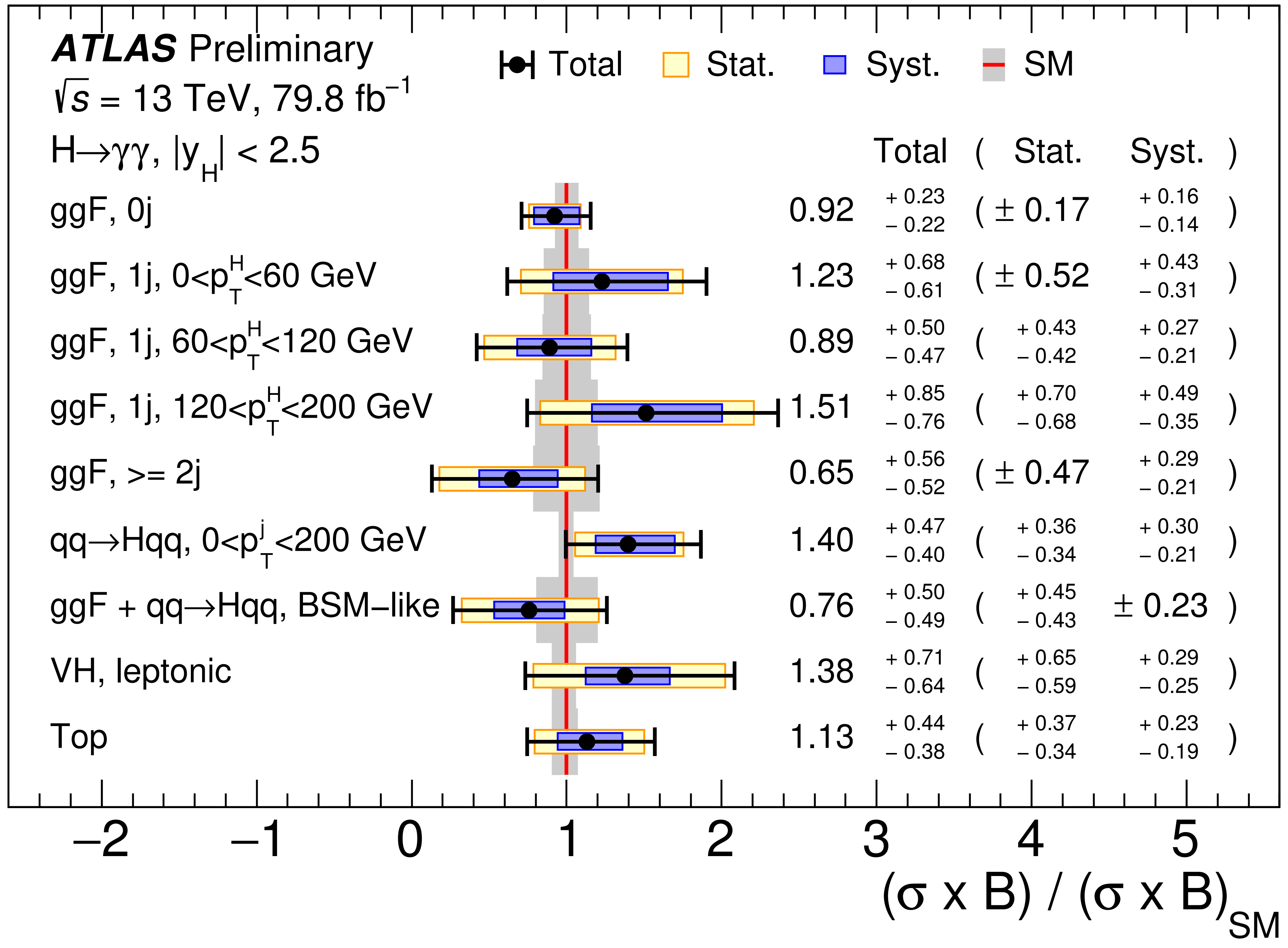




These measurements rely on the specific (SM) predicted acceptance of each process and the fact that no additional production processes are present.

All our couplings measurements are based on this assumption.

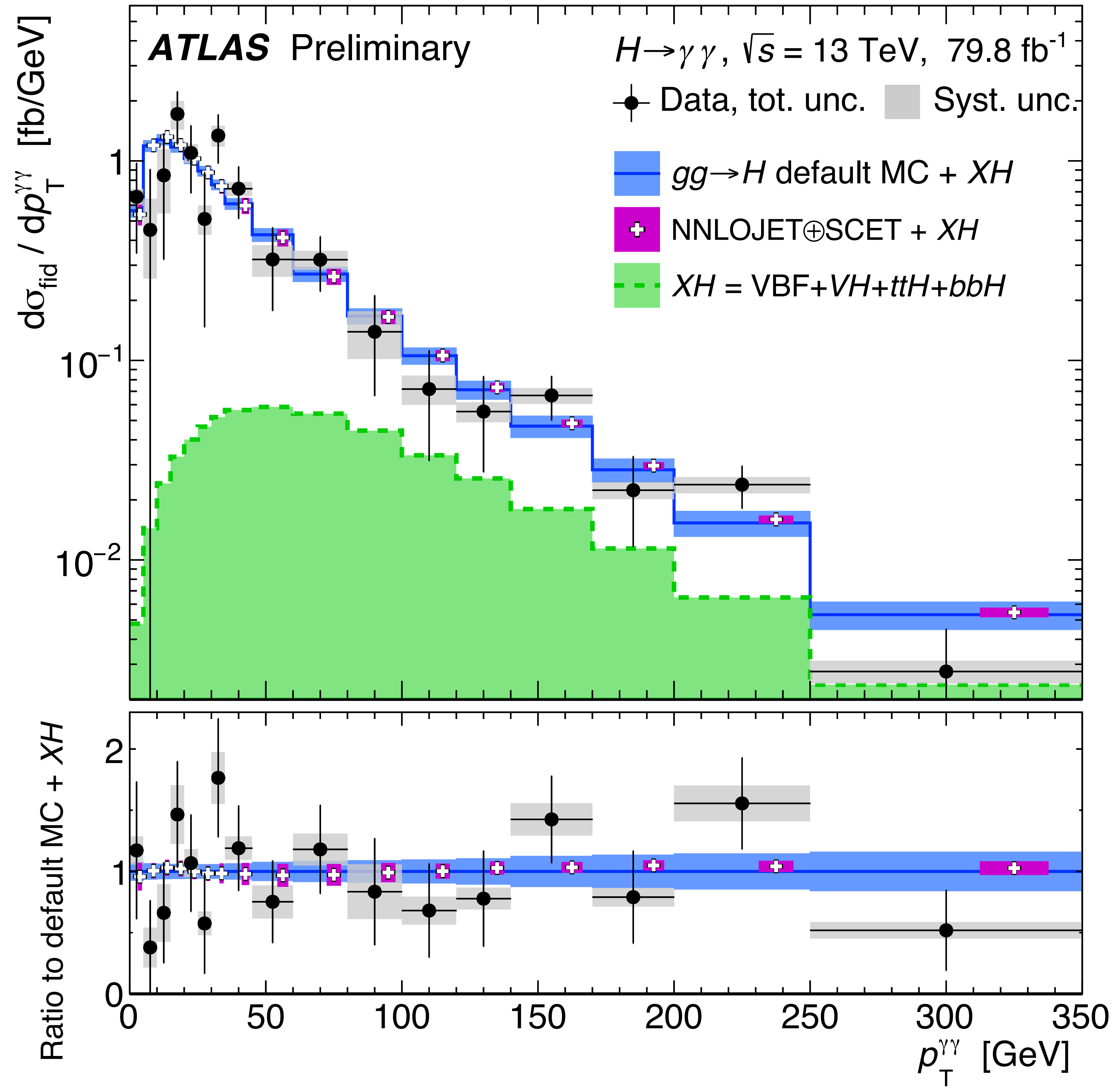
Similar measurements can be done in a more hybrid approach where fiducial regions are defined on the Higgs pT and properties of additional jets or leptons.



These still rely on assumption of (SM) acceptances but are very useful in the case of an EFT approach (will be discussed in tomorrow's lecture).

These are referred to as Simplified Template Cross Sections

Fiducial and Differential Cross Sections

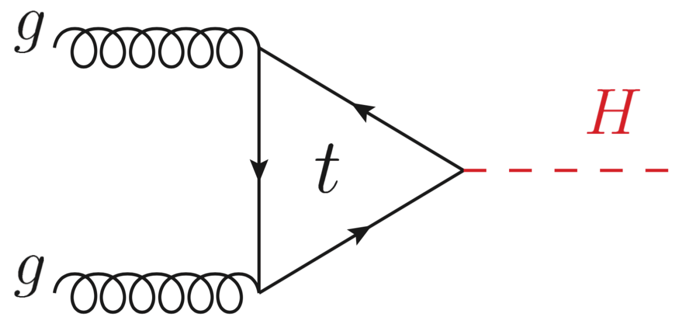


Example of measurement of (fully) fiducial and unfolded differential cross sections.

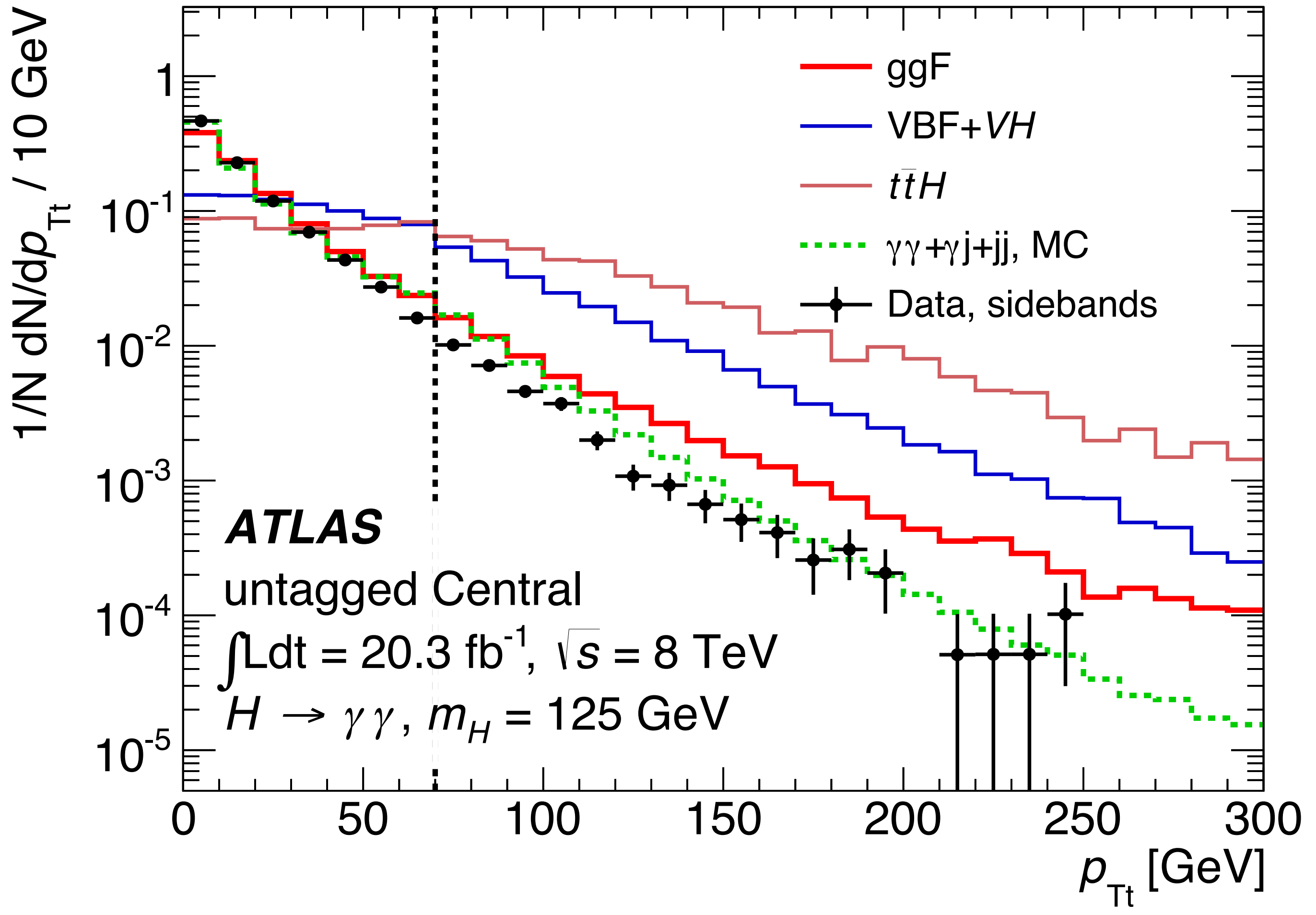
These measurements are the least model dependent and can then be compared to theory predictions.

Higgs transverse momentum is particularly important.

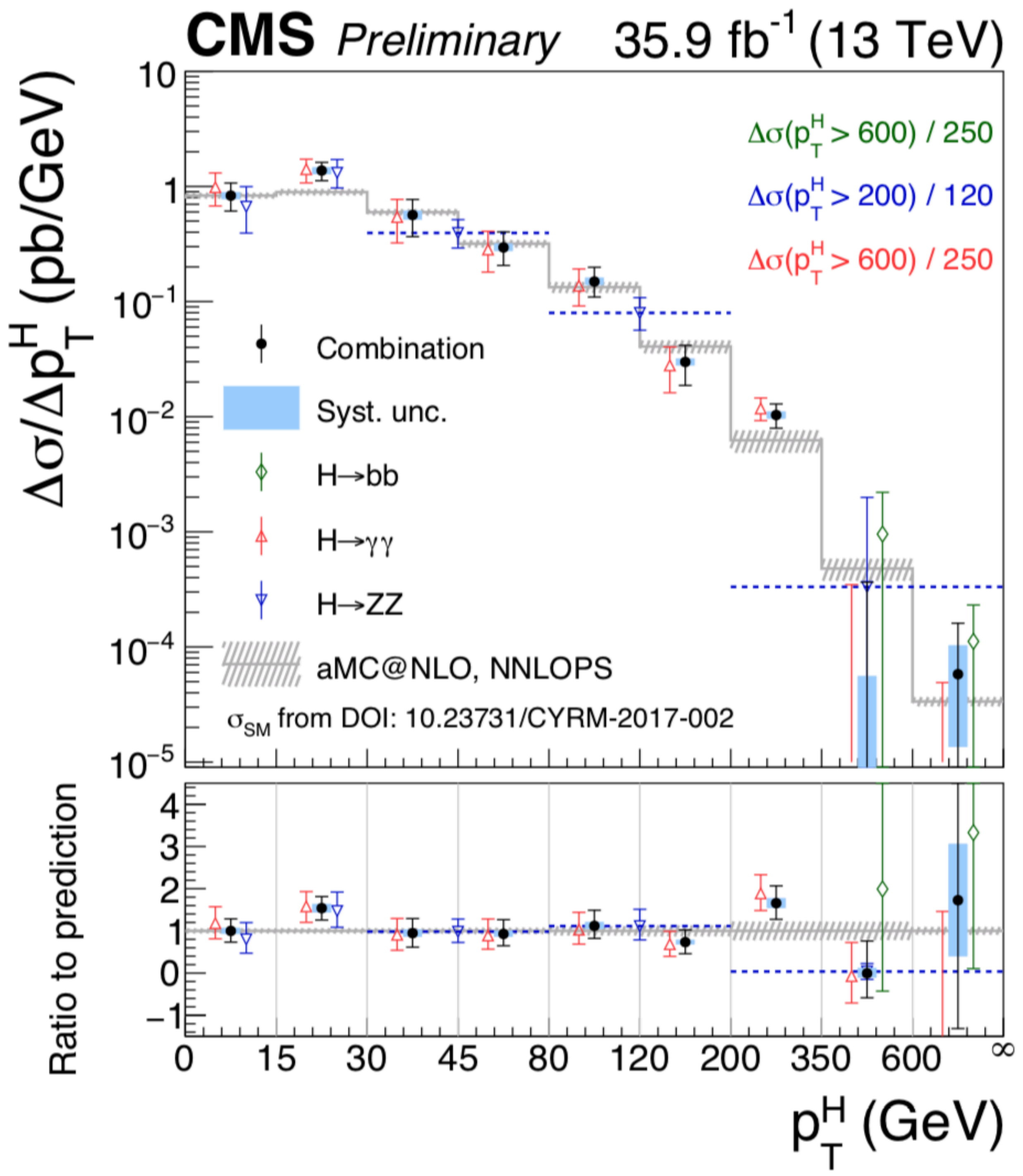
- The inclusive Higgs pT distribution has played an important role in the discovery (discriminating against backgrounds).
- Sensitive to the physics occurring in the production loop.

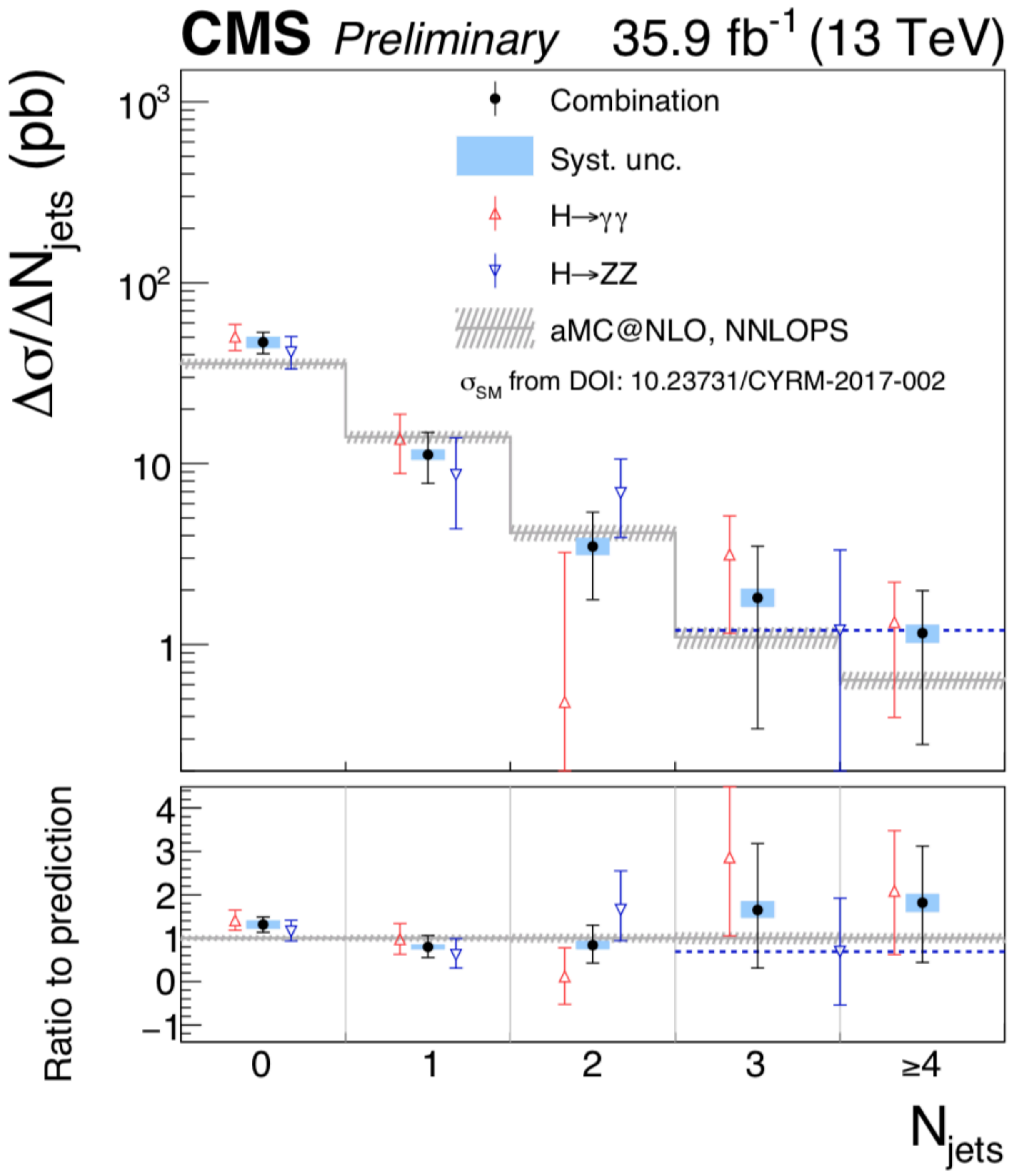


Important for all Higgs production processes, but even more so for exclusive production modes.



Hybrid Differential Cross Sections





Fiducial (and fiducial unfolded differential) are specific to a final state and cannot be combined across channels (e.g. diphoton and 4-leptons).

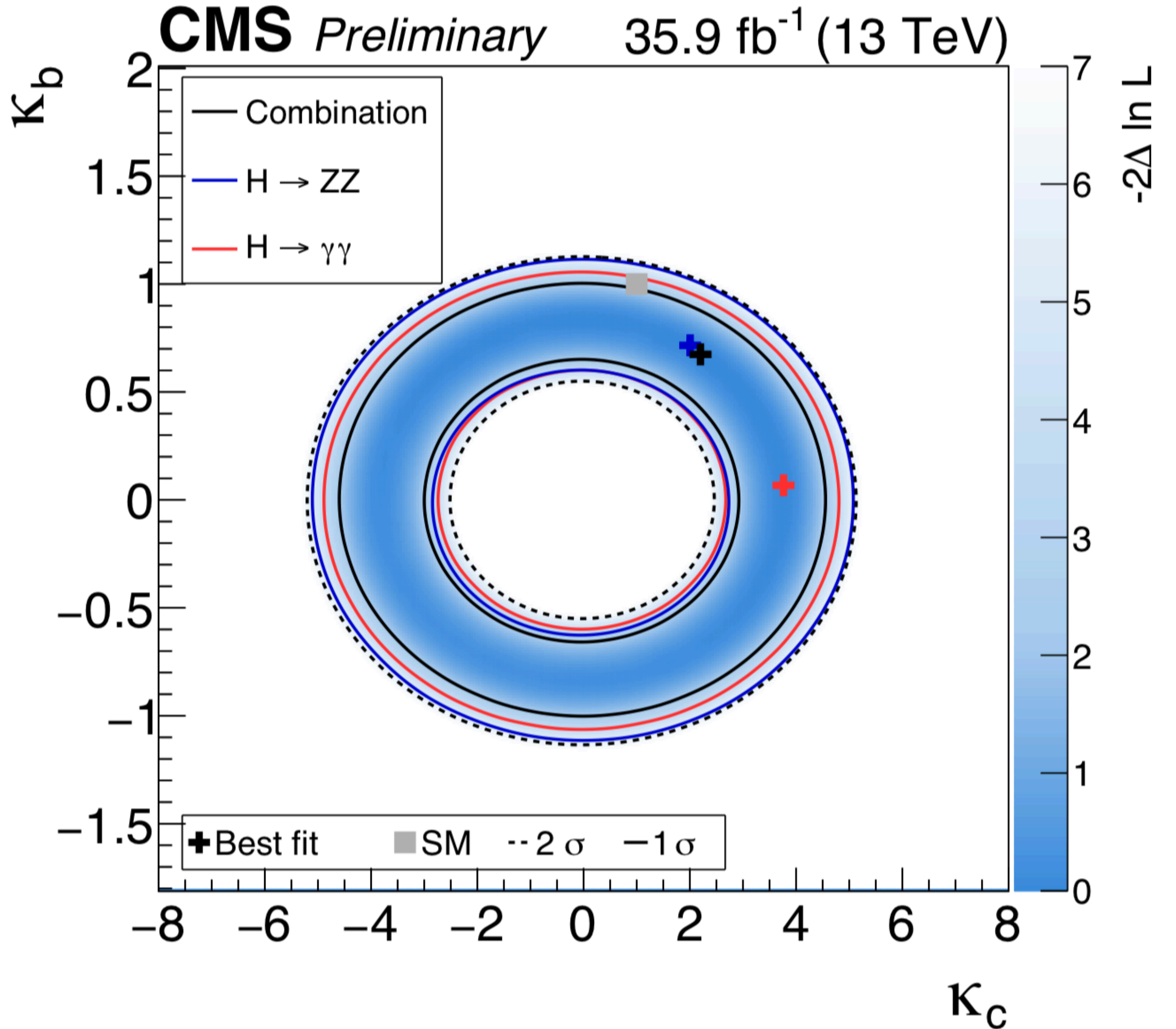
In order to combine fiducial cross section, partially fiducial volumes are defined (e.g. integrating the entire phase space for the decay).

These « hybrid » cross sections can then be combined.

e.g. Combined differential cross sections from three different decay channels.

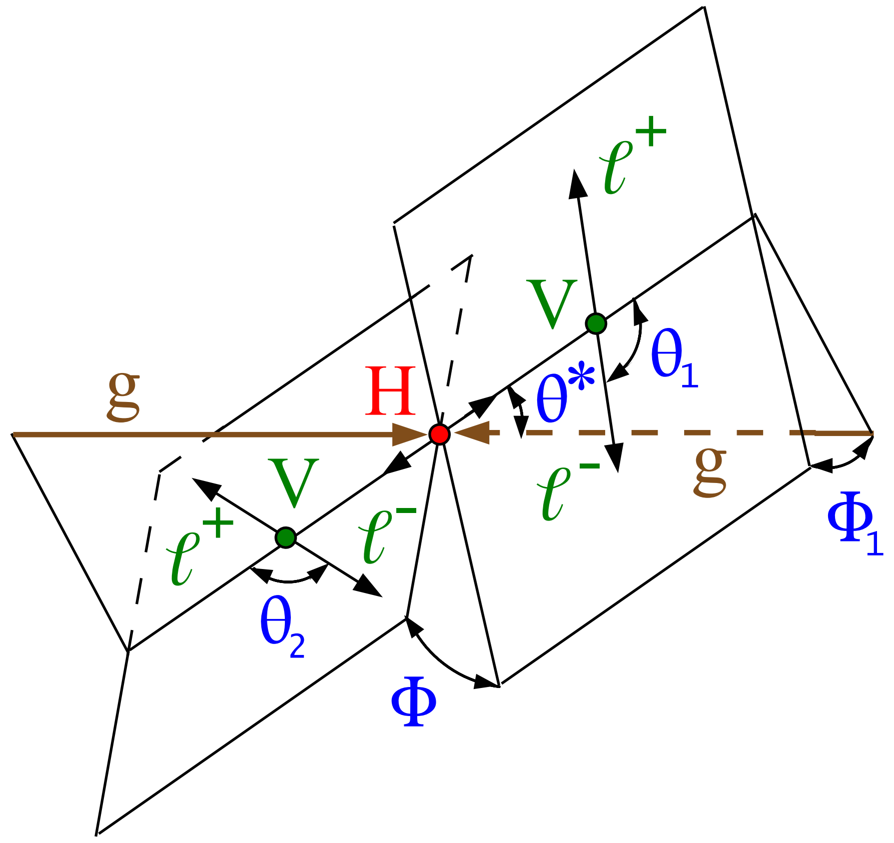
Differential cross section can then be used for further interpretations.

Recent indirect measurement of the b and c Yukawa couplings through their effecting the production loop.



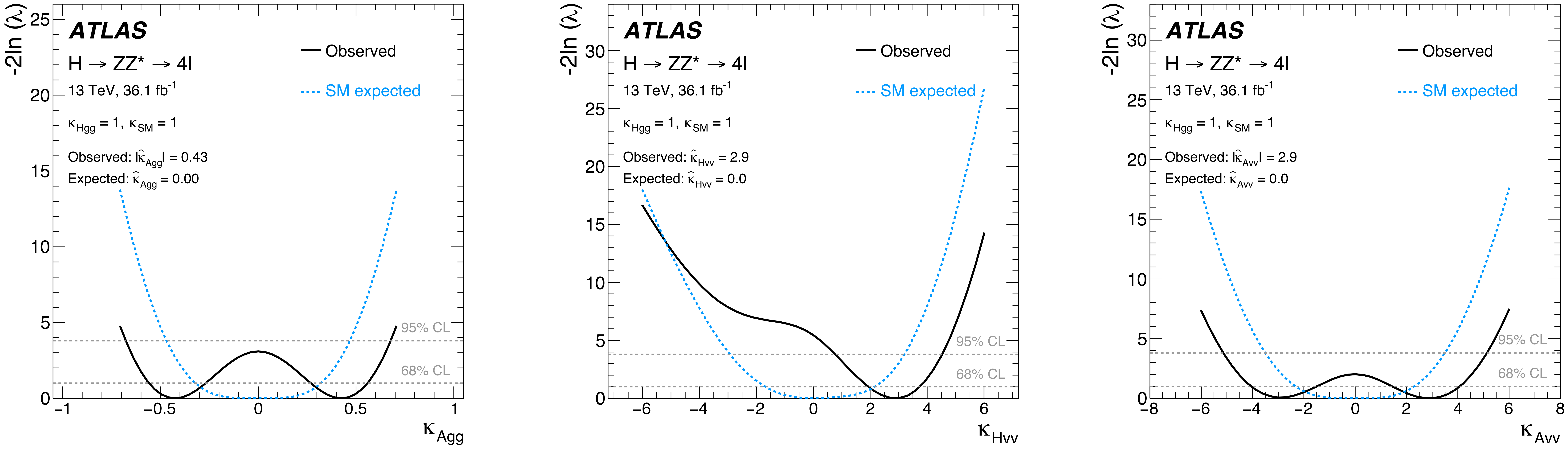
Interpretation using the Reconstructed Categories

In the case of of the 4-leptons analysis, the categorisation in the various STXS bins defined, has sensitivity (through the angular distributions of the leptons in the event) to the probe tensor structure (CP mixing properties) of the Higgs boson.

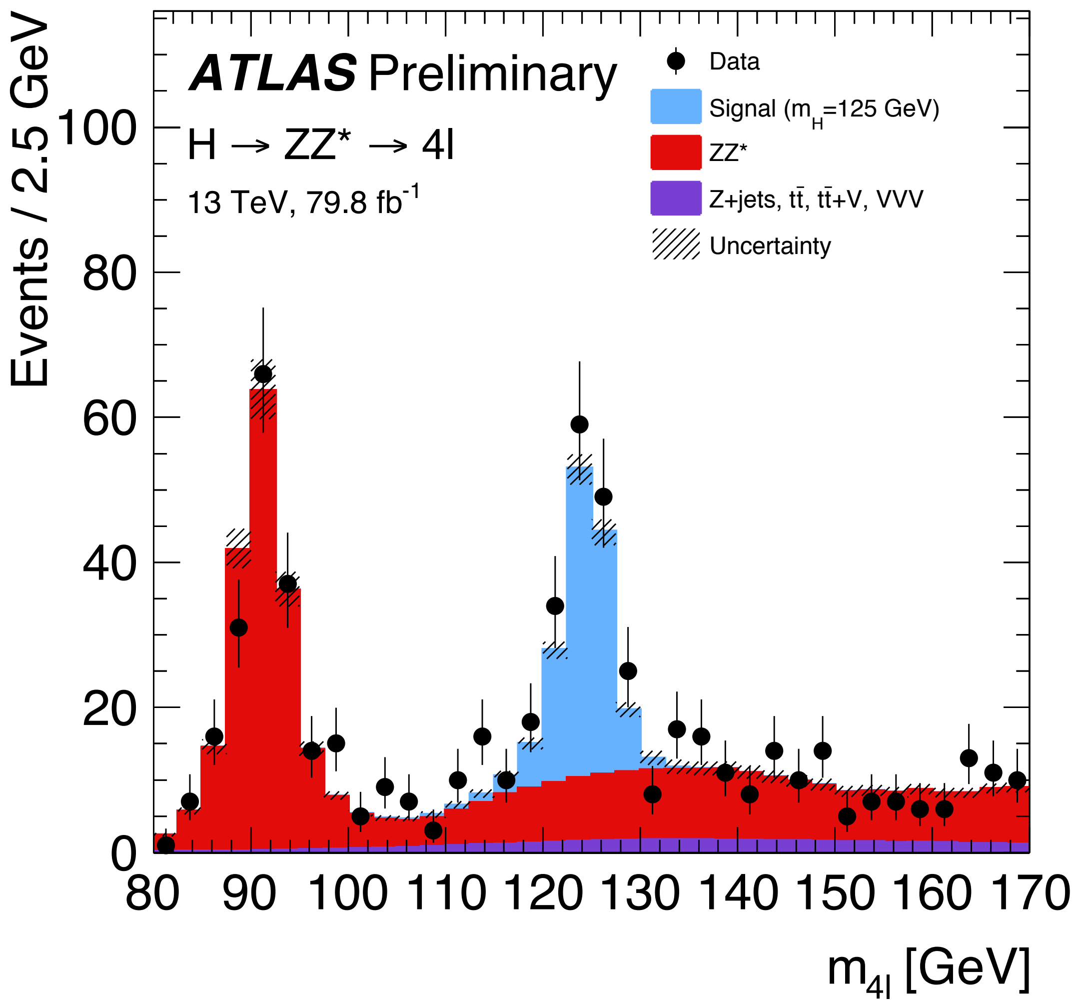


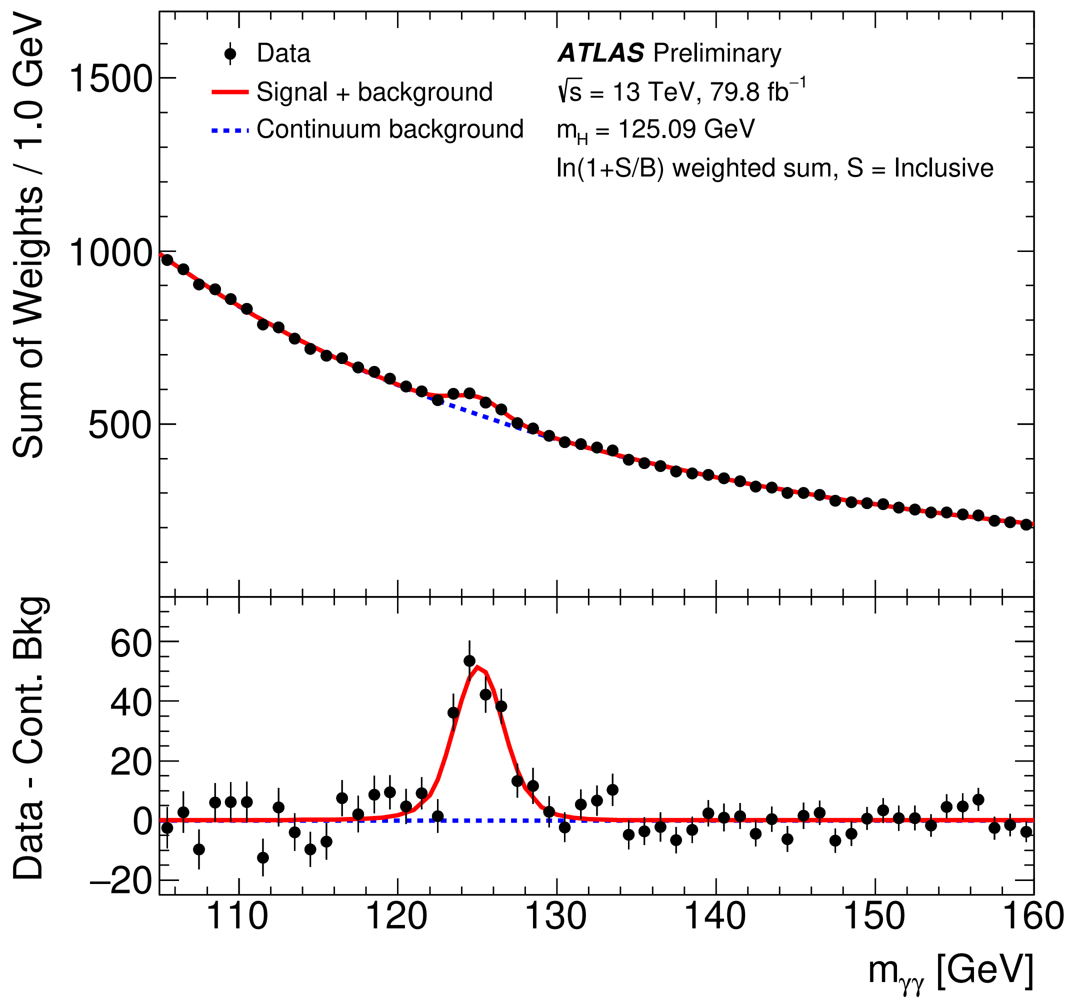
$$\mathcal{L}_0^V = \left\{ c_\alpha \kappa_{\rm SM} \left[\tfrac{1}{2} g_{HZZ} Z_\mu Z^\mu + g_{HWW} W_\mu^+ W^{-\mu} \right] - \tfrac{1}{4} \tfrac{1}{\Lambda} \left[c_\alpha \kappa_{HZZ} Z_{\mu\nu} Z^{\mu\nu} + s_\alpha \kappa_{AZZ} Z_{\mu\nu} \tilde{Z}^{\mu\nu} \right] - \tfrac{1}{2} \tfrac{1}{\Lambda}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

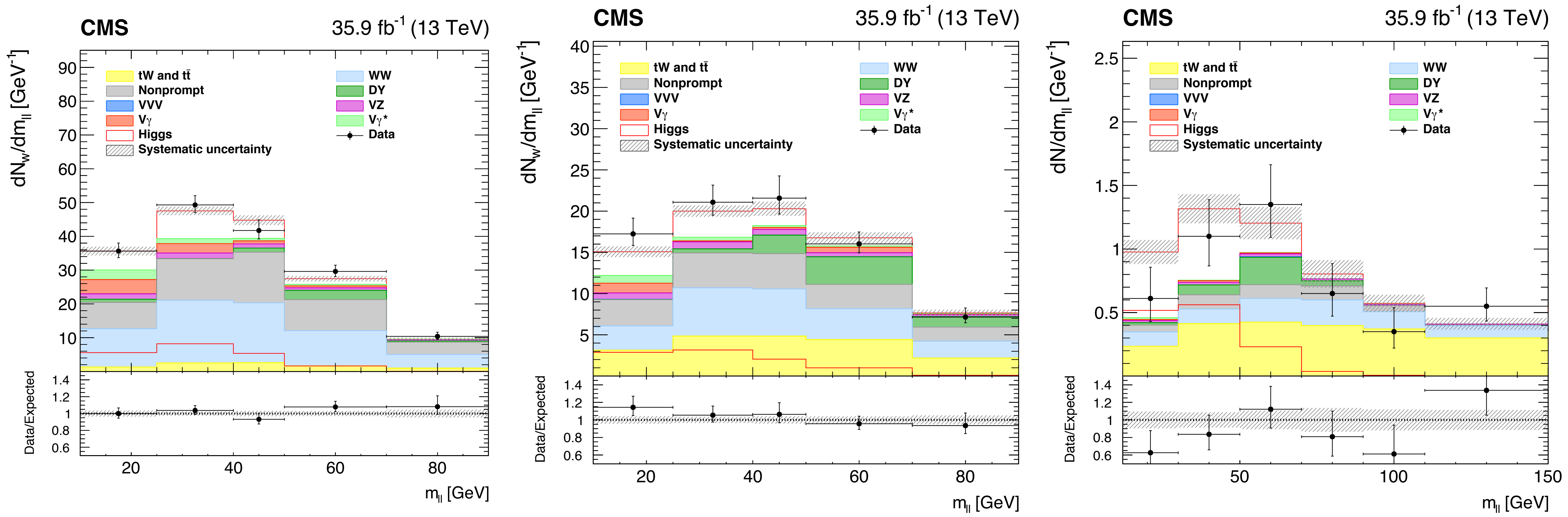
This uses each bin of BDT distributions in the STXS overall bins.



Other Diboson Channels Challenges







The WW channel was already dominated by systematic uncertainties at Run 1.

Superbly clean channel, with only ~3% of the data.

Splendid opportunities in differential distributions, more exclusive production modes and exploring regions of phase space.

The diphoton channels start to be limited by experimental systematic uncertainties

$$\sigma = 60.4 \pm 6.1\ (\mathrm{stat}) + 6.0\ (\mathrm{exp}) + 0.3\ (\mathrm{th})\ \mathrm{fb}$$

Mostly photon energy response resolution and background modelling.

Interesting experimental challenge!

Many sources of systematic uncertainties:

- Background modelling (WW for the 0-jet)
- Non prompt lepton estimates
- b-tagging (through the veto)
- JET energy scale
- etc…

Difficult and challenging channel, but the high statistics will provide interesting opportunities.

The Higgs Width

The Natural Width of the Higgs Boson

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

The Higgs total width in the SM is very small therefore small couplings to the Higgs can be easily visible: tool for discovery!

- At LHC only cross section x branching ratio, no direct access to the Higgs total cross section (unlike e^+e^- collider from recoil mass spectrum).

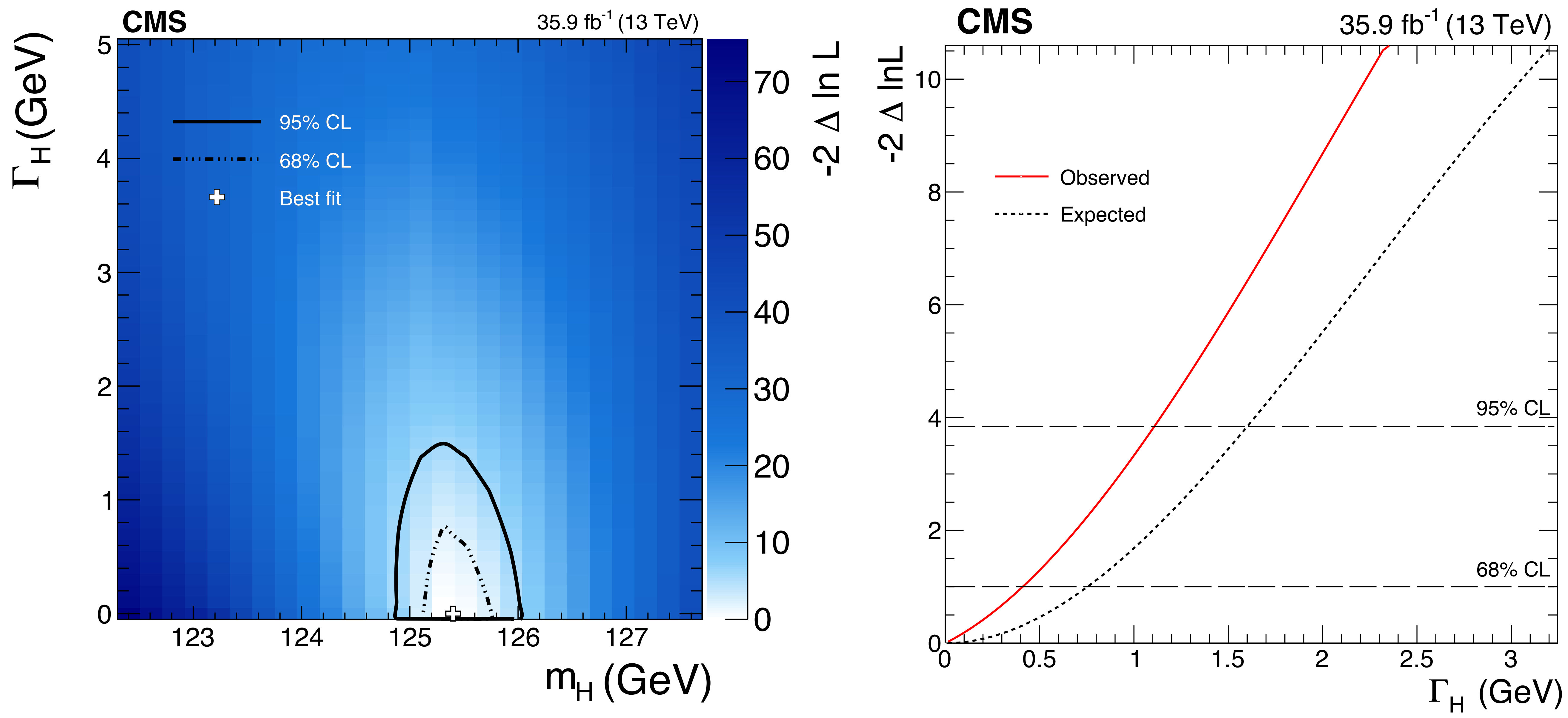
- At LHC direct measurements of ratios of couplings.

- In order to have absolute coupling measurements need to constrain the total width.

Thought to be impossible* prior to the Higgs discovery, a flurry of new ideas appeared to measure the Higgs boson width.

*Modulo weak constraints through the mass resonance line shape in the di-photon and the four leptons channels.

When fitting the Higgs signal line shape for the mass, also the total width can be fitted.

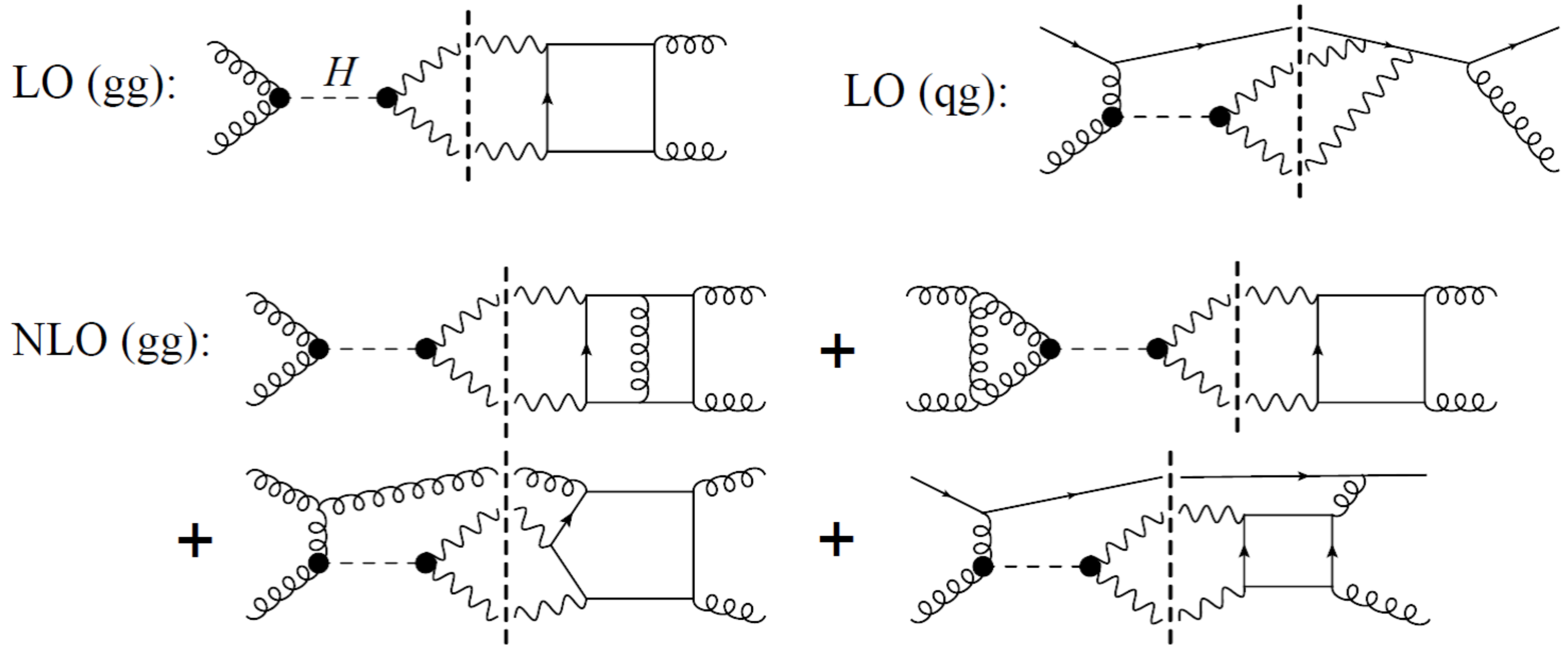


$$\Gamma^H_{SM} < 1.10 \text{ GeV at } 95\% \text{ CL}$$

Original Approaches to Constrain the Higgs boson Width

Diphoton signal-continuum background interference

Interference between the signal ggF production and the box diphoton production:



- Rate: the size of the interference inclusively is 2% and depends on the width of the Higgs boson. Comparing rates with other processes such as e.g. the four lepton channel in similar regions of phase space can constrain the total width.

- Worth exploring specific regions of phase space.

- Mass shift: This interference has first been studied when noticing (Martin, Dixon and Li) that the distortion in the reconstructed mass shape was sizeable (despite the very small width).

- Induced a mass shift of approximately 35 MeV.

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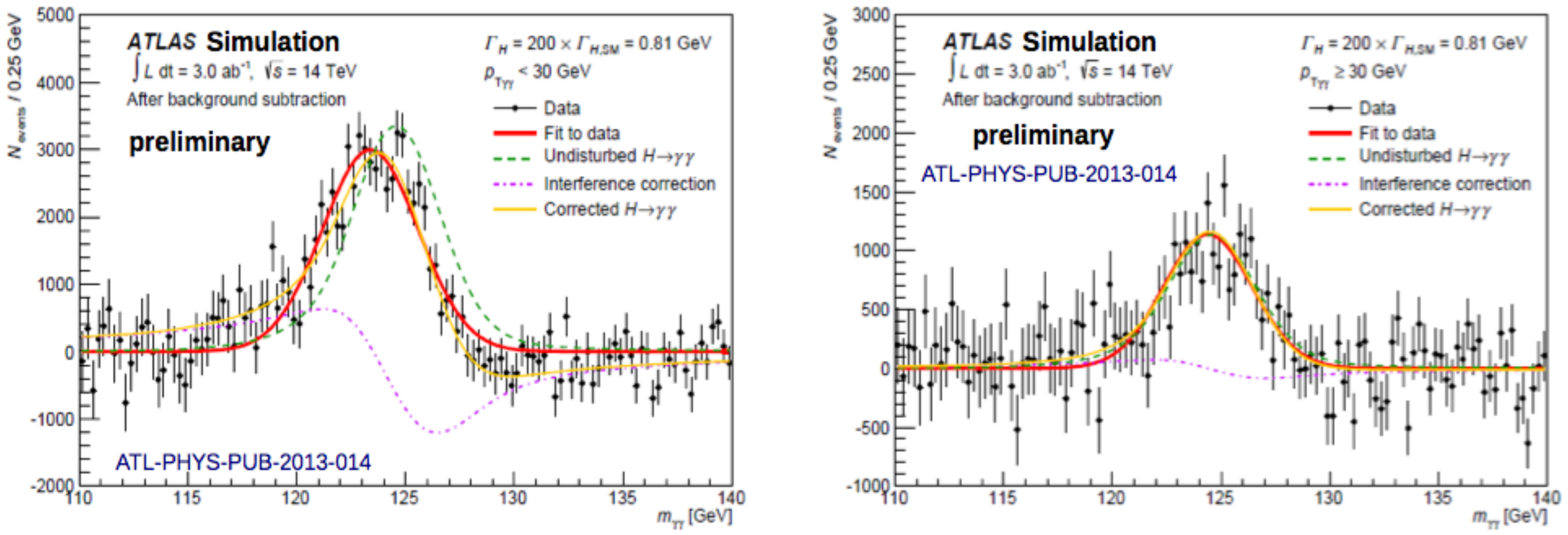


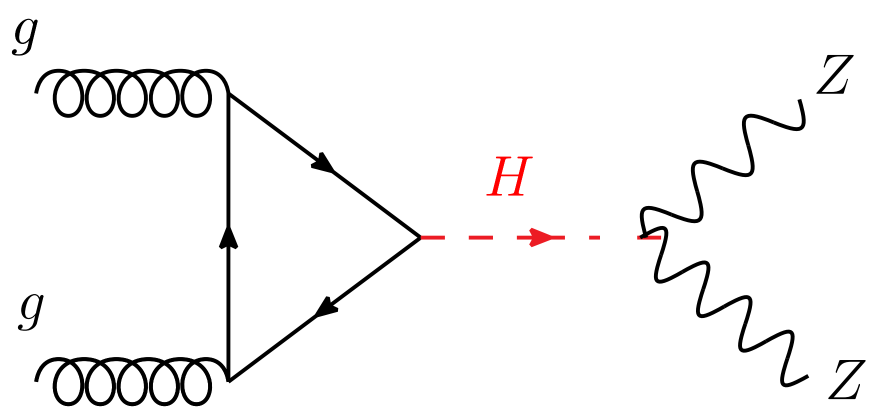
- The mass shift has an interesting dependence on the Higgs transverse momentum and on the Higgs width.
- Constraints using a Higgs boson mass measurements was proposed and carried out

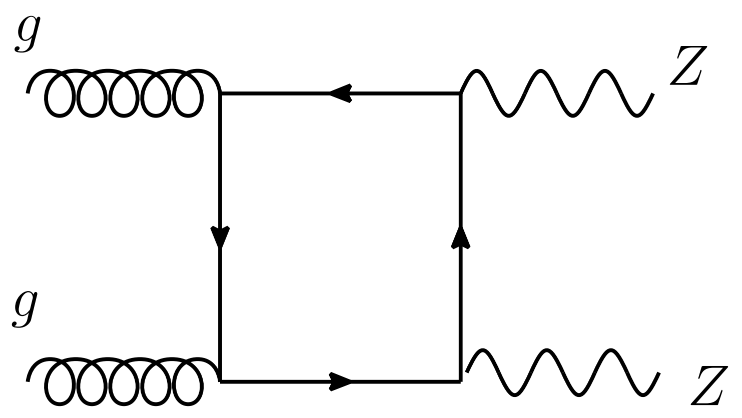
$$\Gamma^{H}_{SM} < 200 \text{ MeV}$$ At HL-LHC

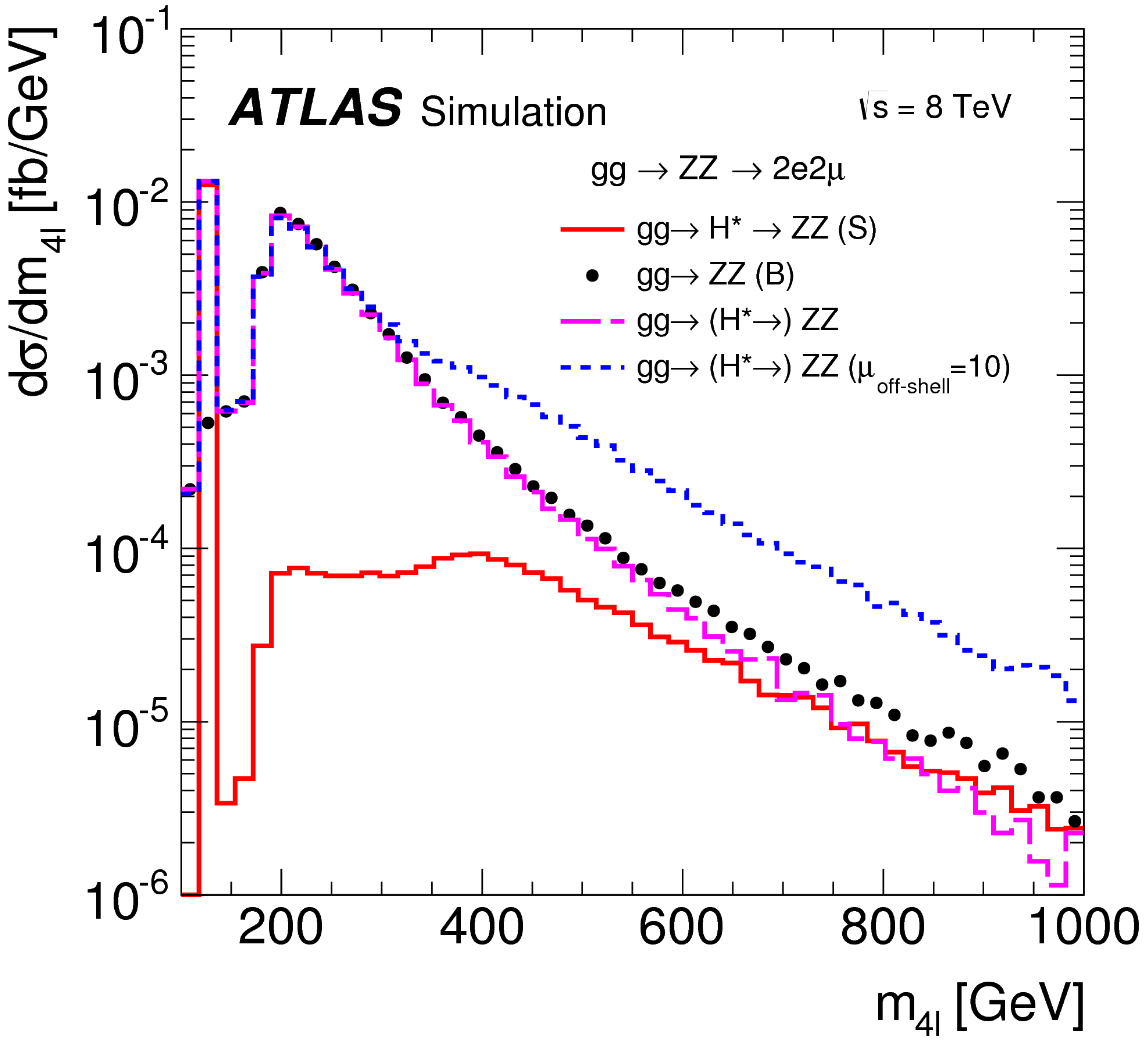
Off Shell Higgs

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!

$$\mu_{off\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

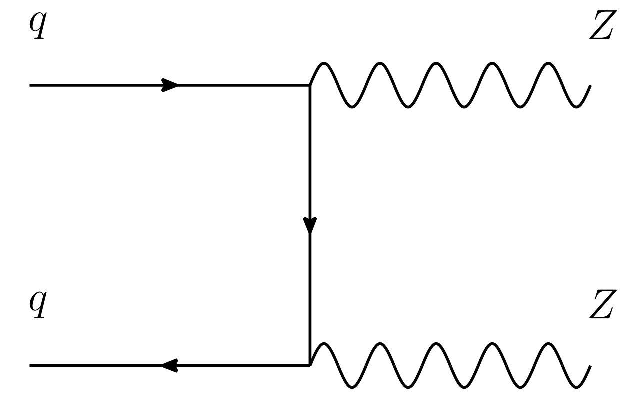
$$\mu_{on\ shell} = \frac{(\kappa_t^2 \kappa_V^2)_{on\ shell}}{\Gamma_H / \Gamma_H^{SM}}$$

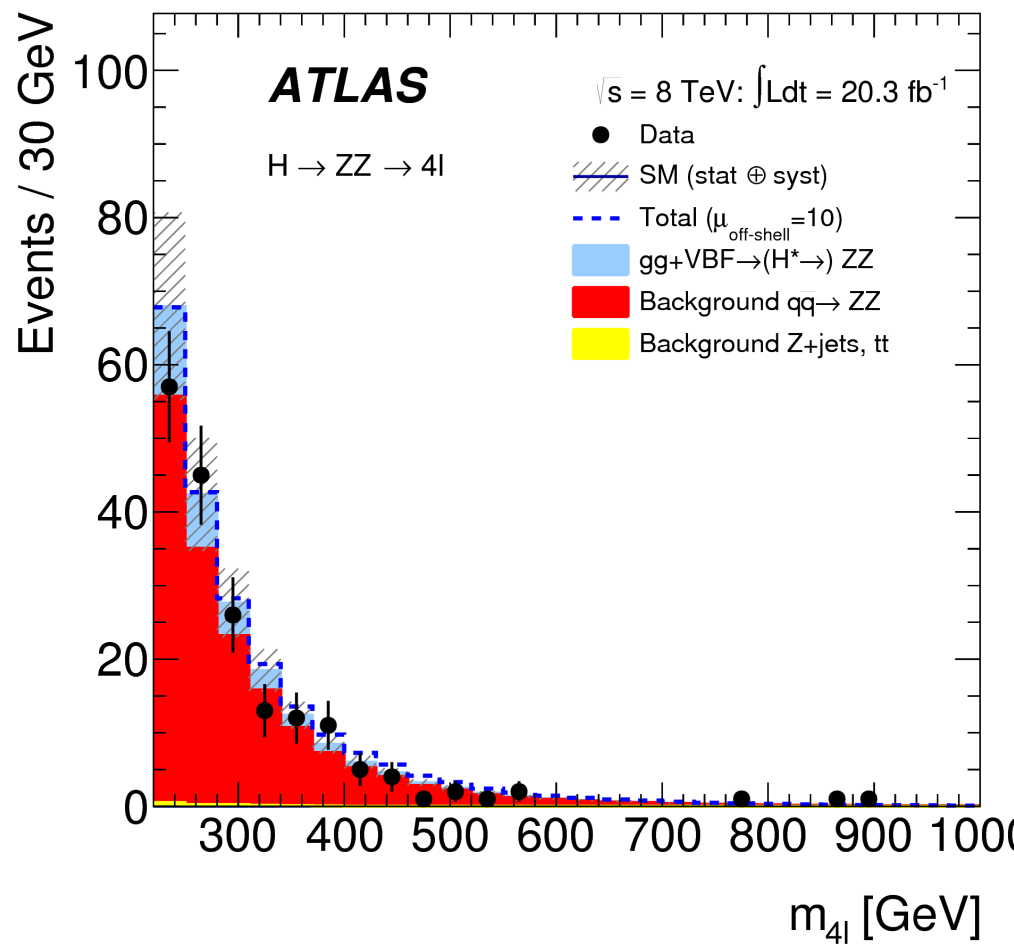
$$(\kappa_t^2 \kappa_V^2)_{on\ shell} = (\kappa_t^2 \kappa_V^2)_{off\ shell}$$

$$\Gamma_H = \frac{\mu_{off\ shell}}{\mu_{on\ shell}} \times \Gamma_H^{SM}$$

Highly non trivial due to:

- The negative interference
- The large other backgrounds





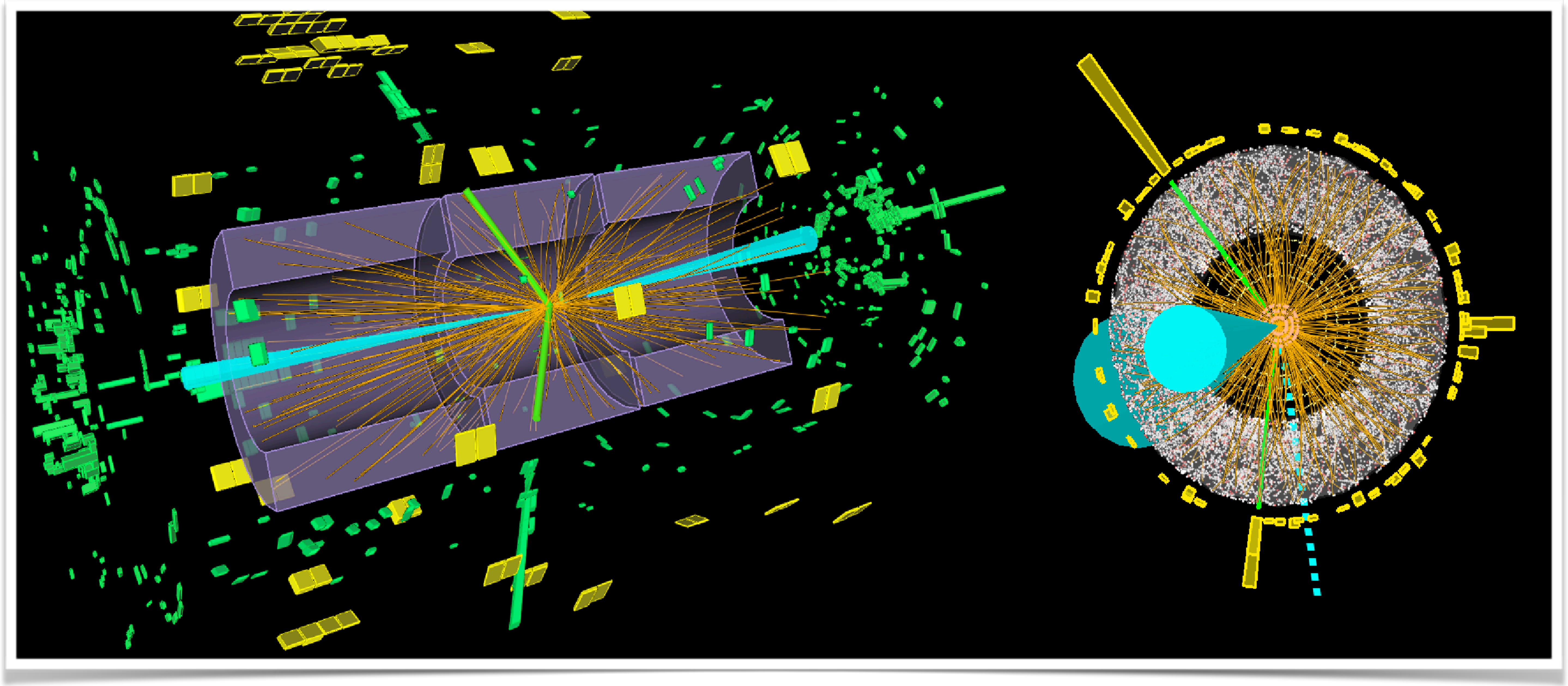
Limits on the total width are currently at approximately 15 MeV

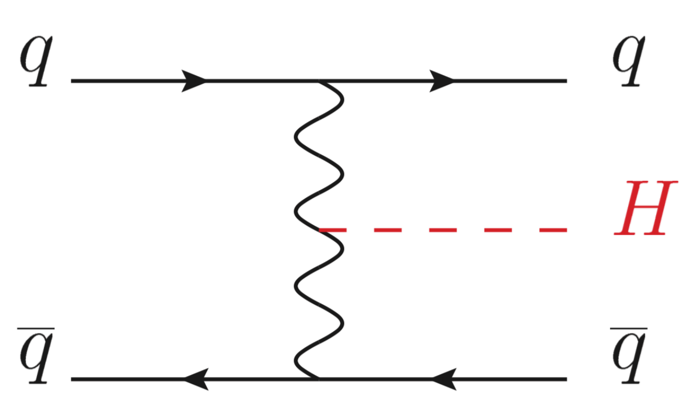
Preliminary HL-LHC results show that a reasonable sensitivity can be obtained with 3 ab-1:

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

Measurements of 3[d] generation Yukawa Couplings

Higgs boson decays to Taus





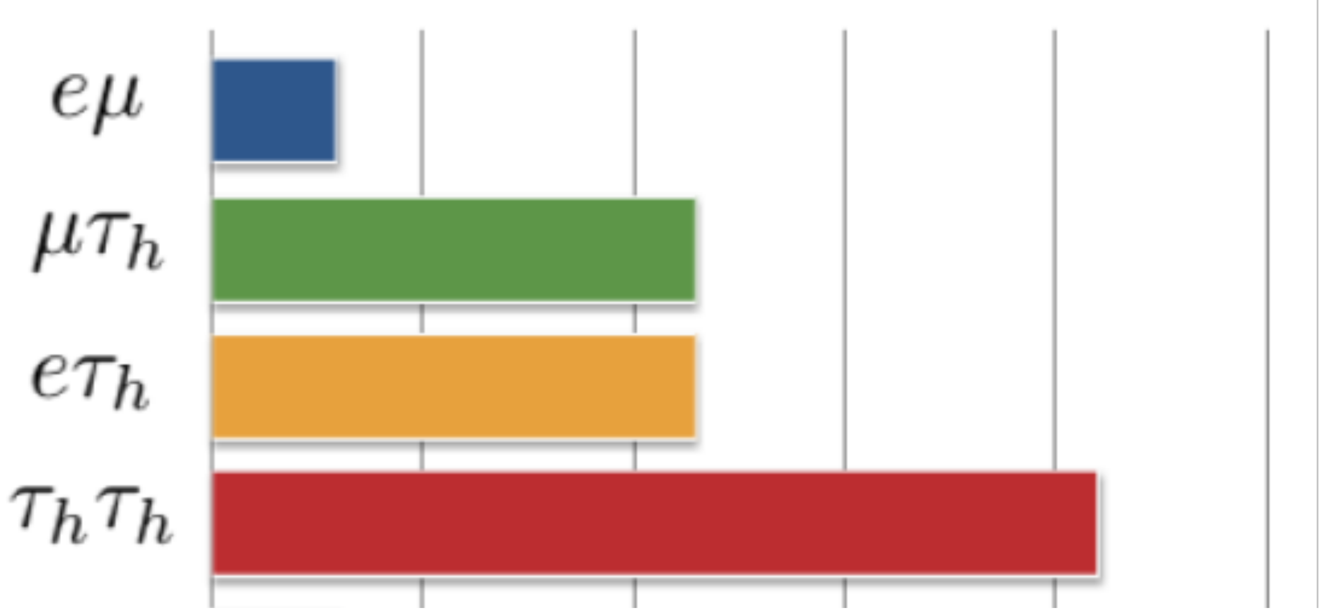
Special VBF process

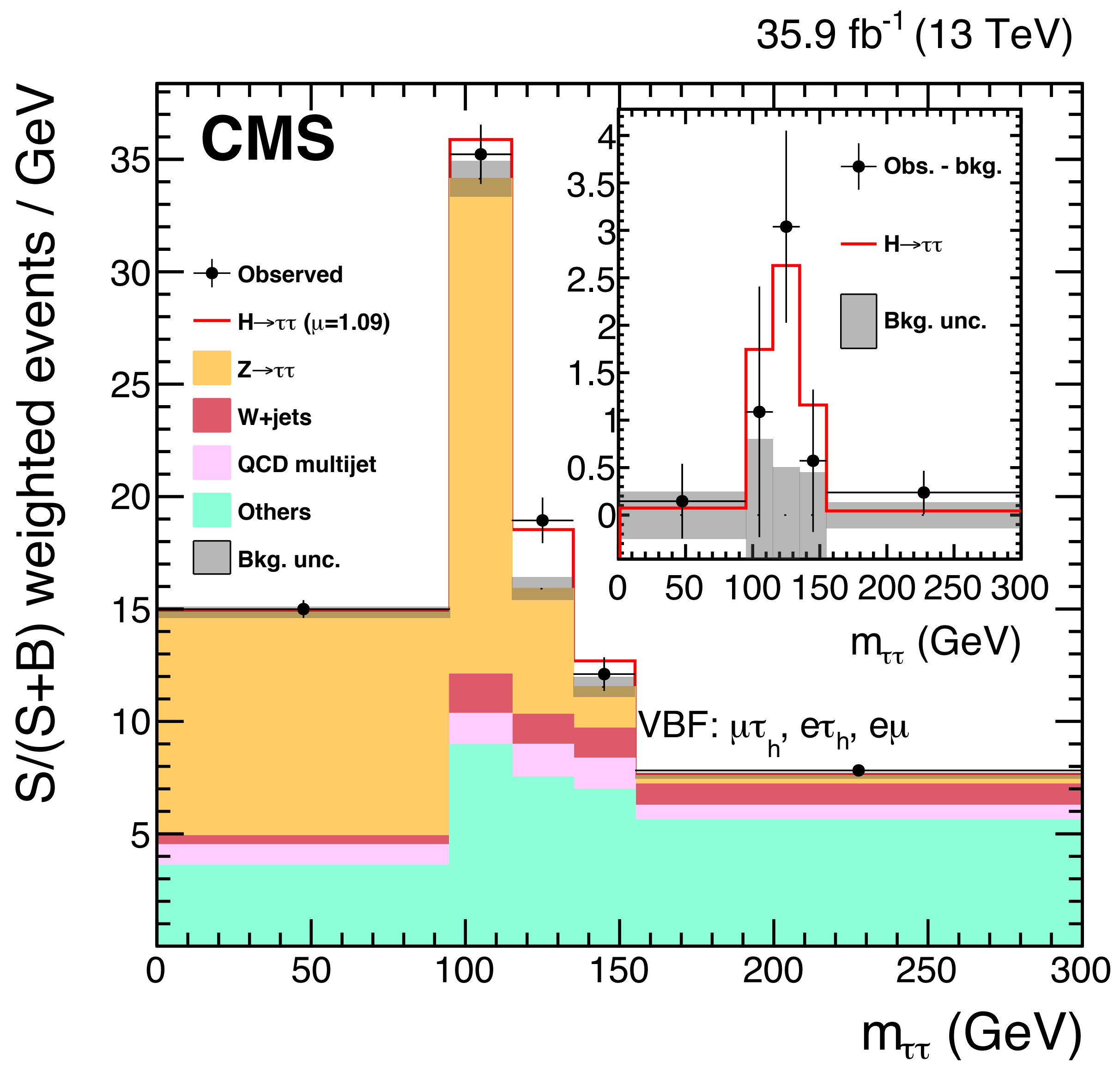
With two forward jets and a large rapidity gap between the jets (due to the color singlet exchange in the t-channel

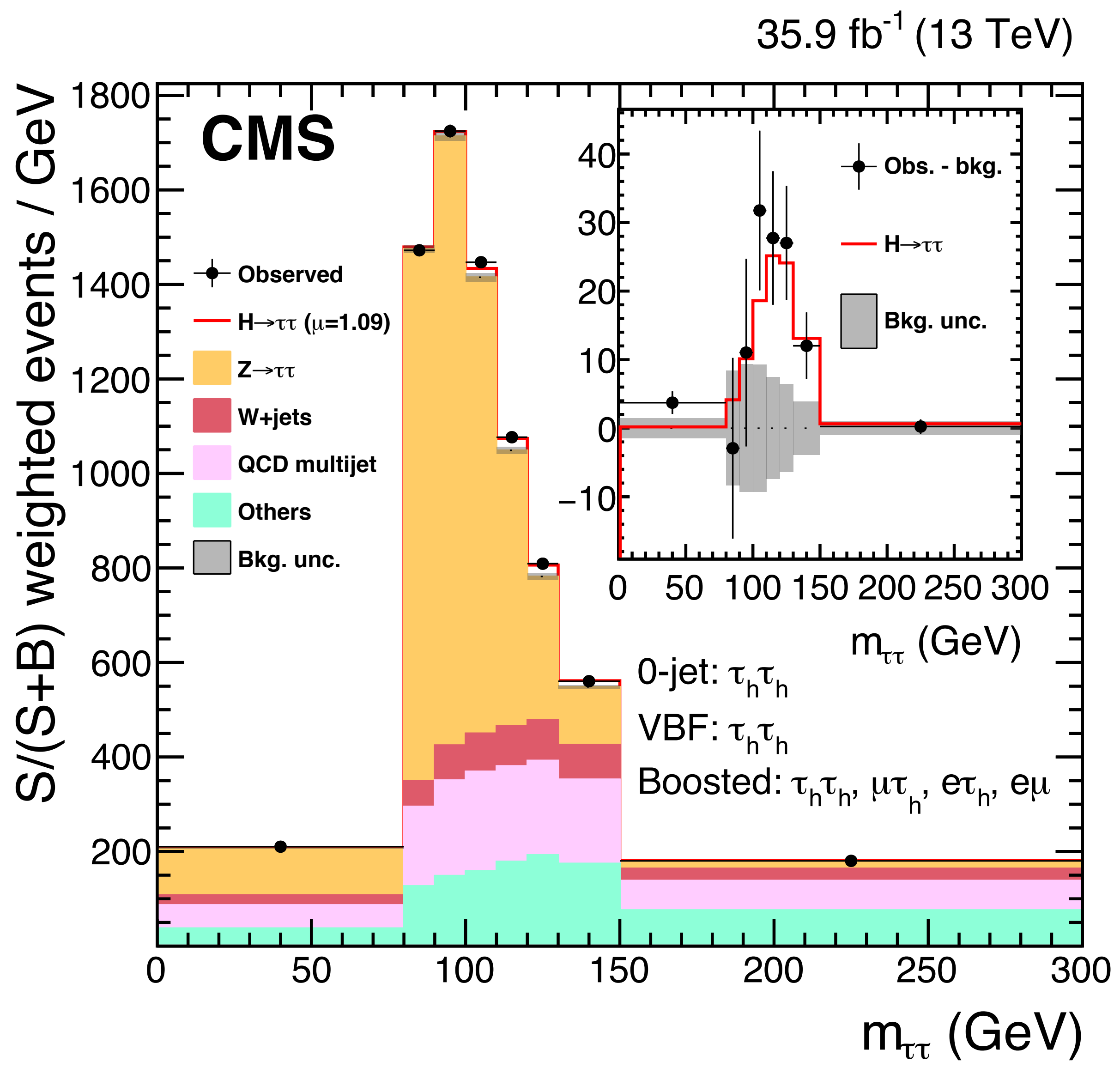
Background is Z production with two jets, in this region of phase space it is difficult to predict!

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

Tau to leptons ~18% (rest is hadrons)







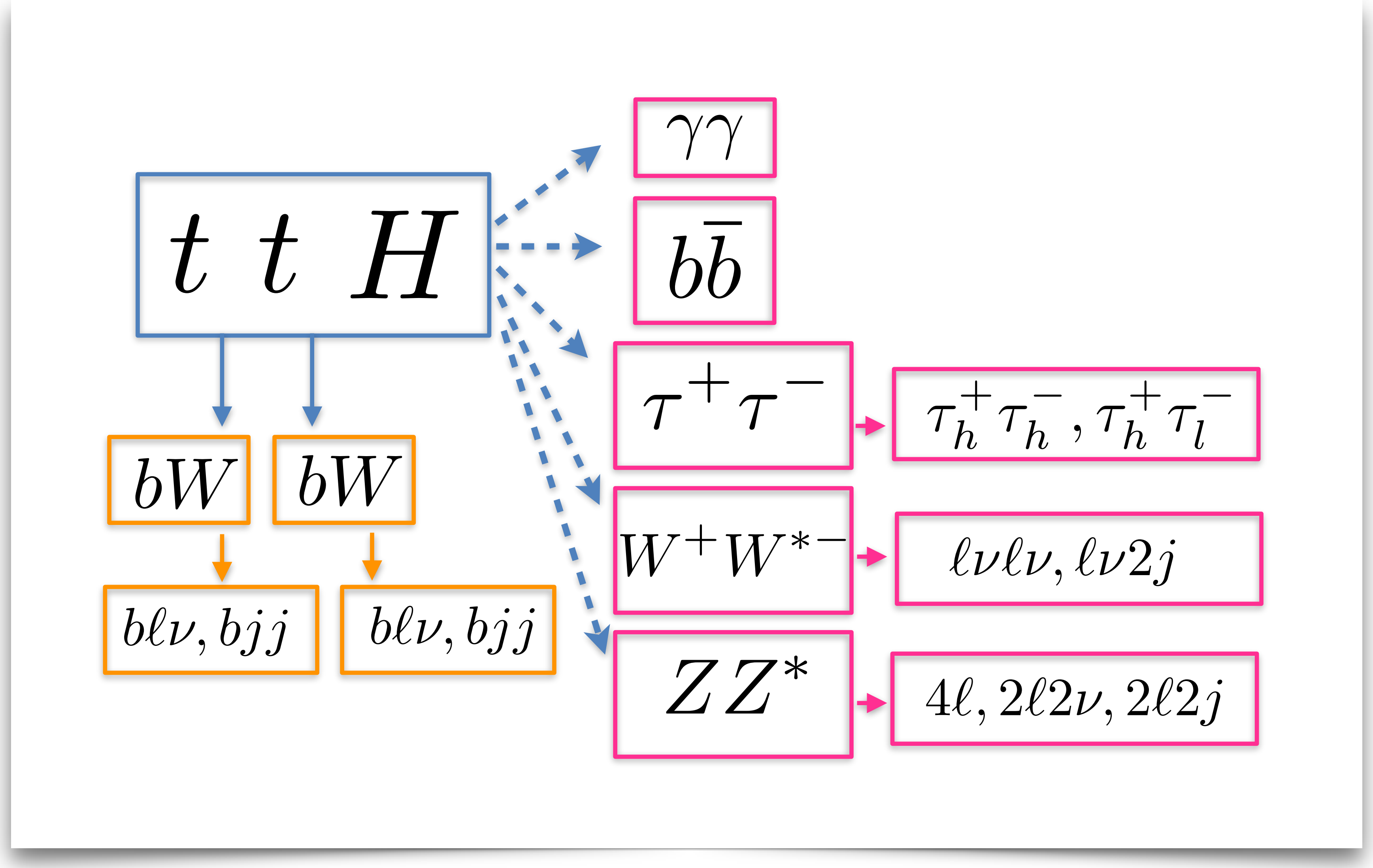
Analysis requires data driven methods to do so: e.g. the embedding of taus in Z to di-muon events.

Observation!!

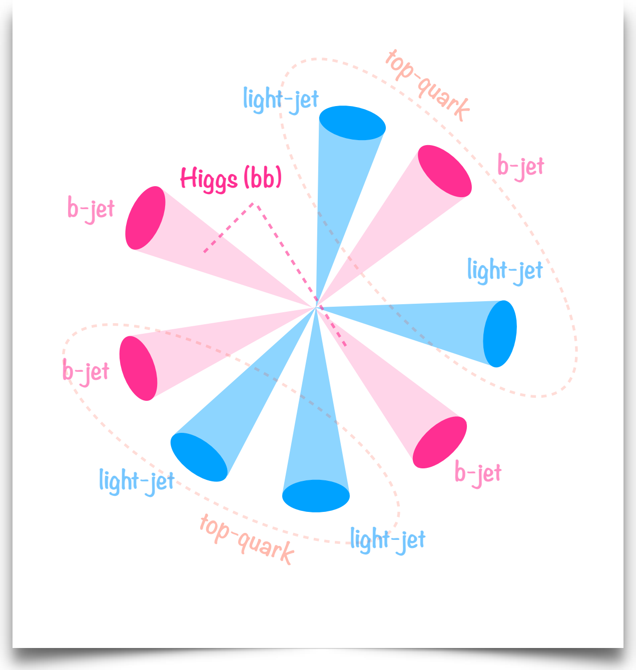
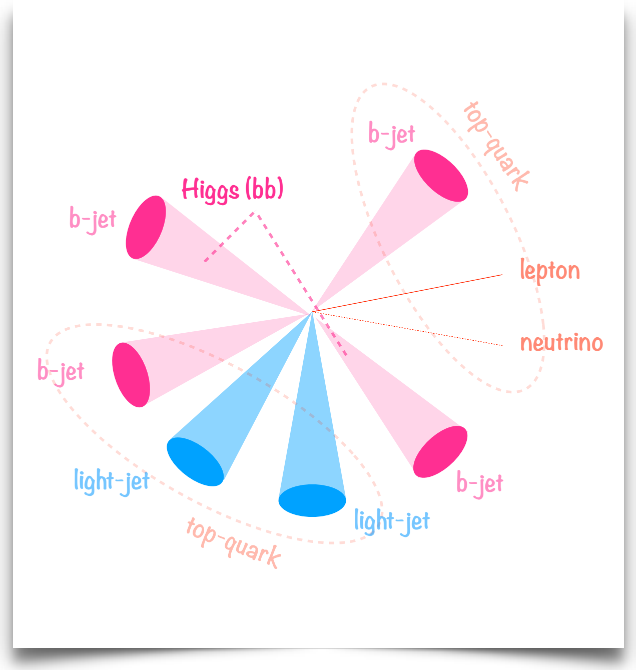
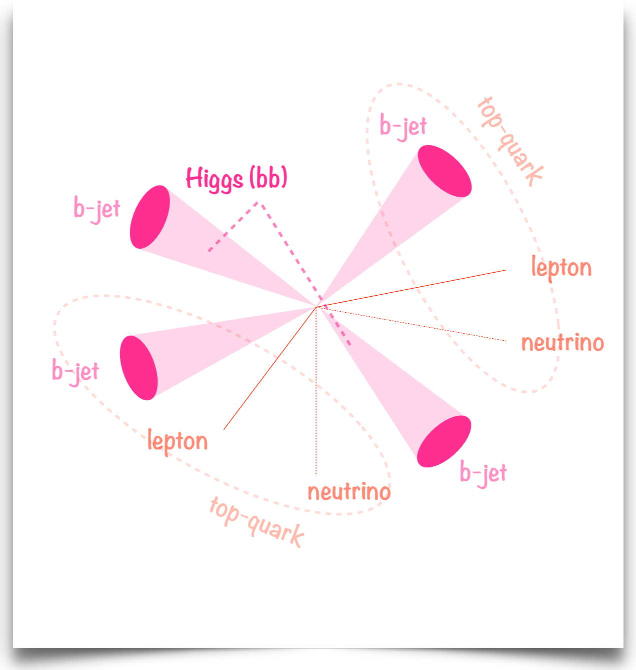
5.9σ observed 5.9σ expected

Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!



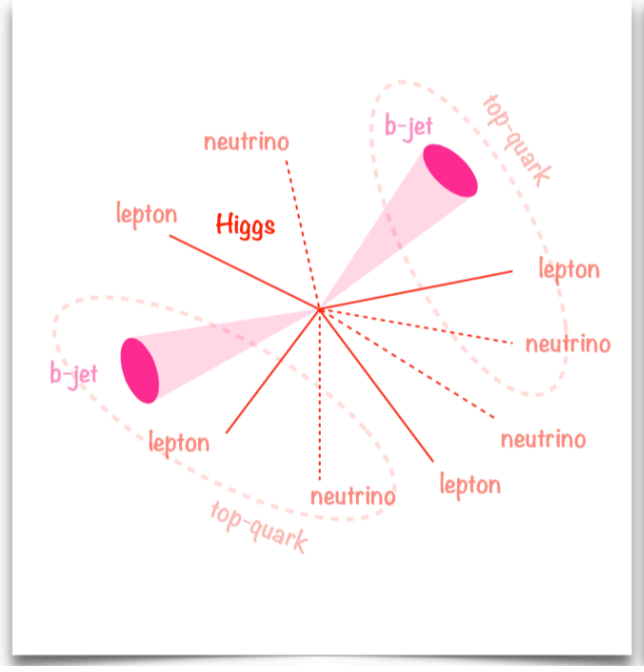
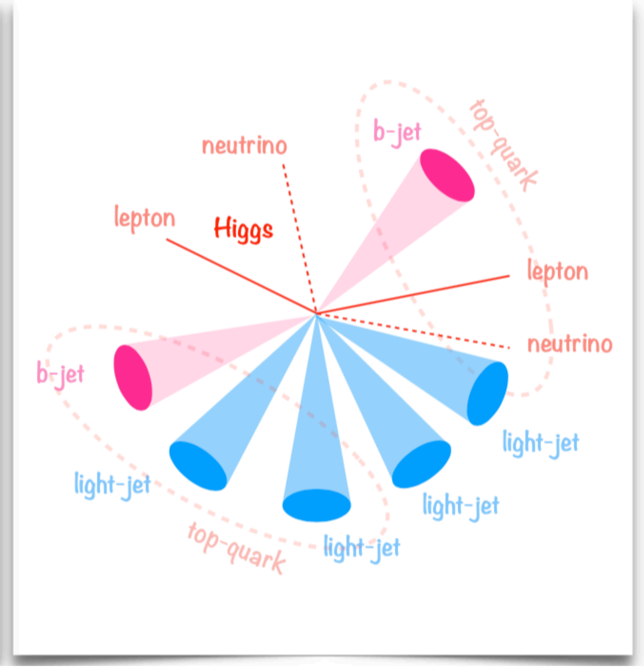
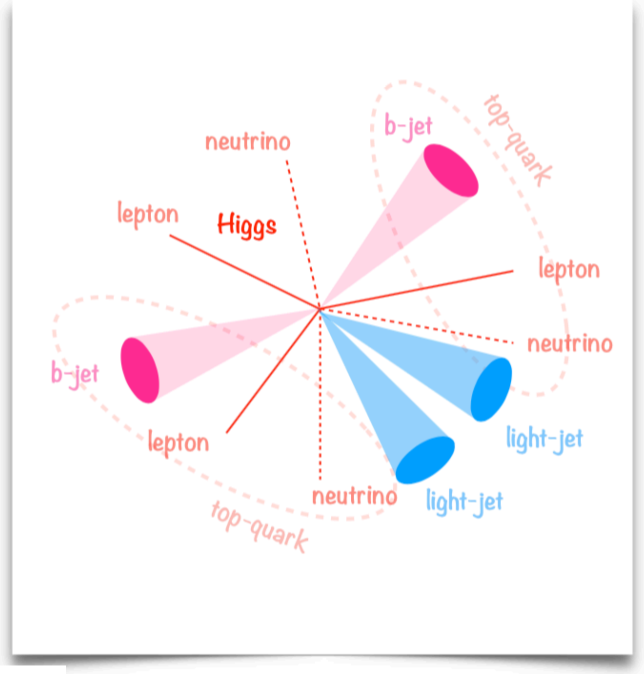
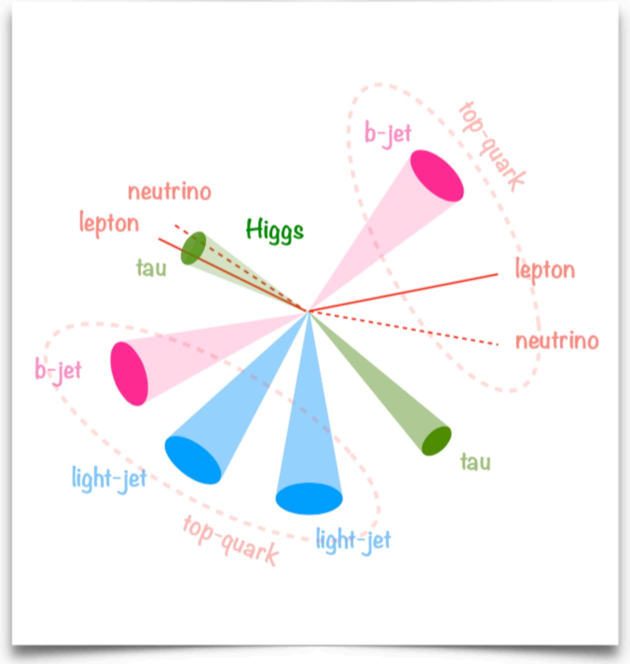
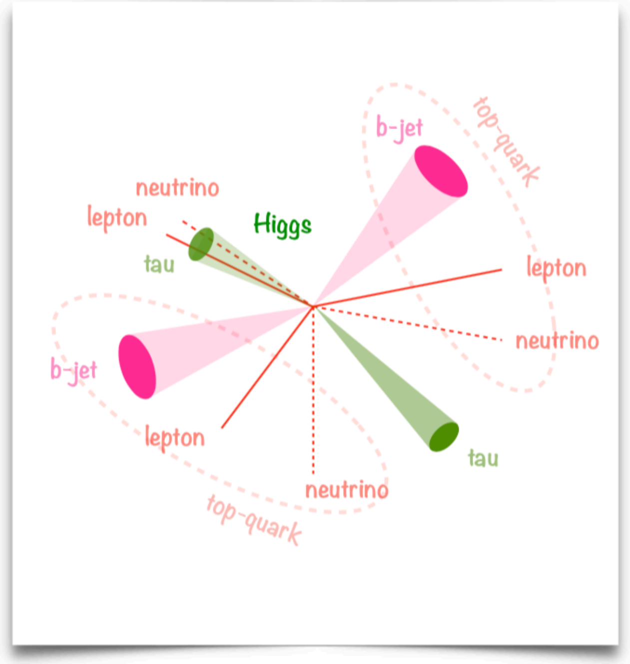
- Large number of final states which are typically very complex (mixture of b-jets, leptons, taus and photons)
- But, many different channels, also means different backgrounds and different systematic uncertainties and therefore also a strength!
- With the new Run at close to double centre-of-mass energy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

ttH(bb)

Very large backgrounds of top pair production associated with b jets

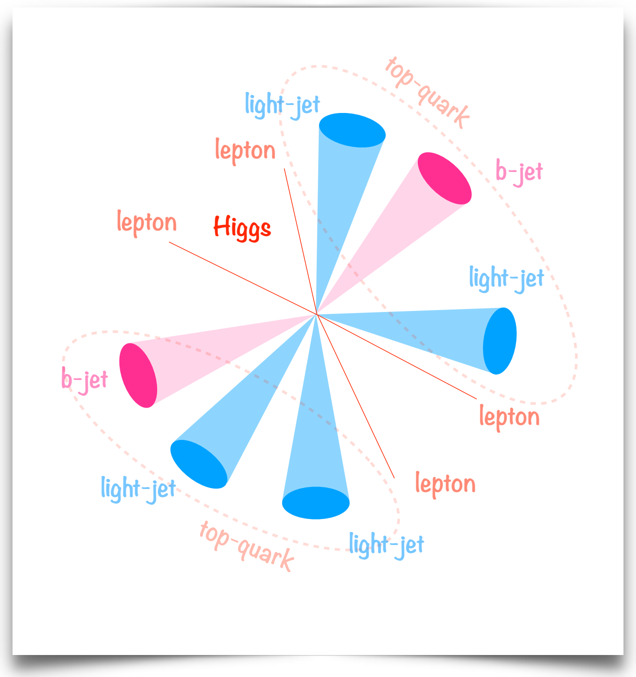
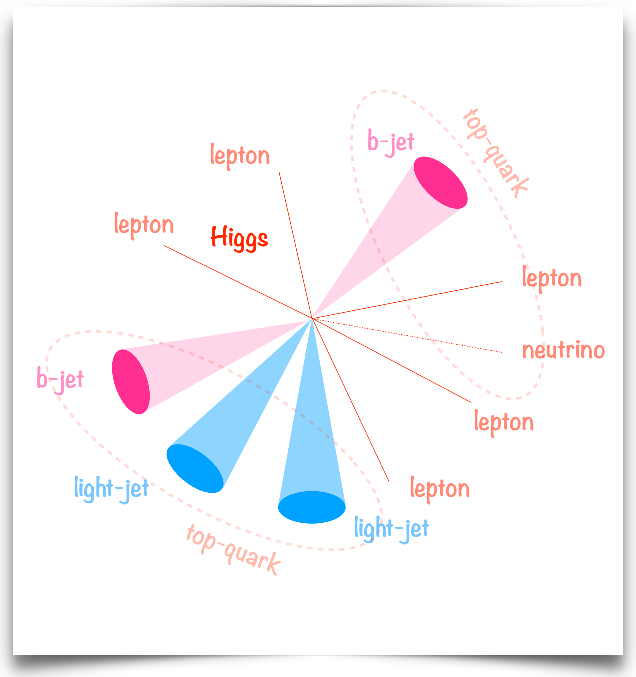
Dominated by background modelling uncertainties

ttH(WW, ZZ and tau tau)

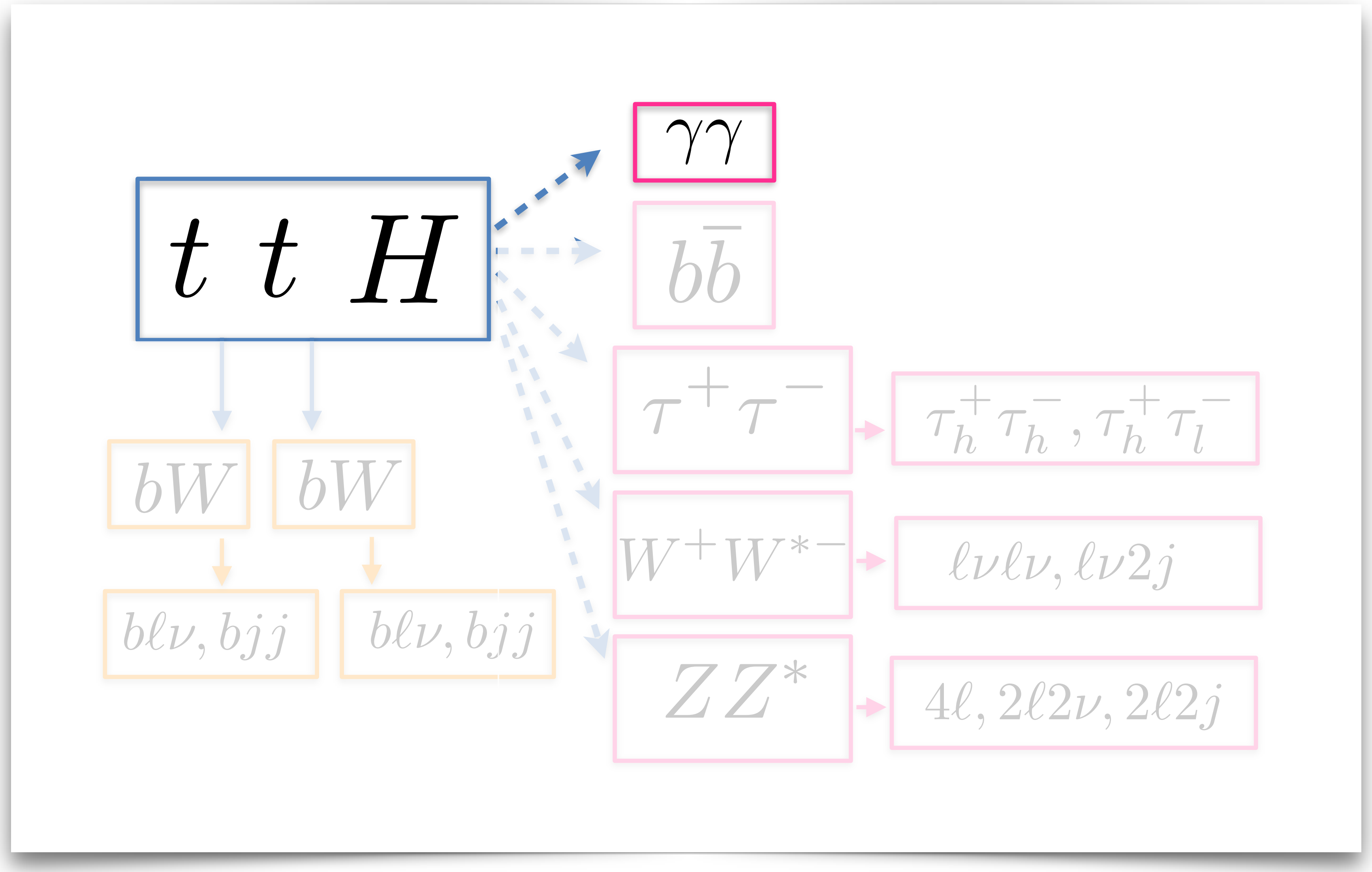
So-called multi-lepton channel

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

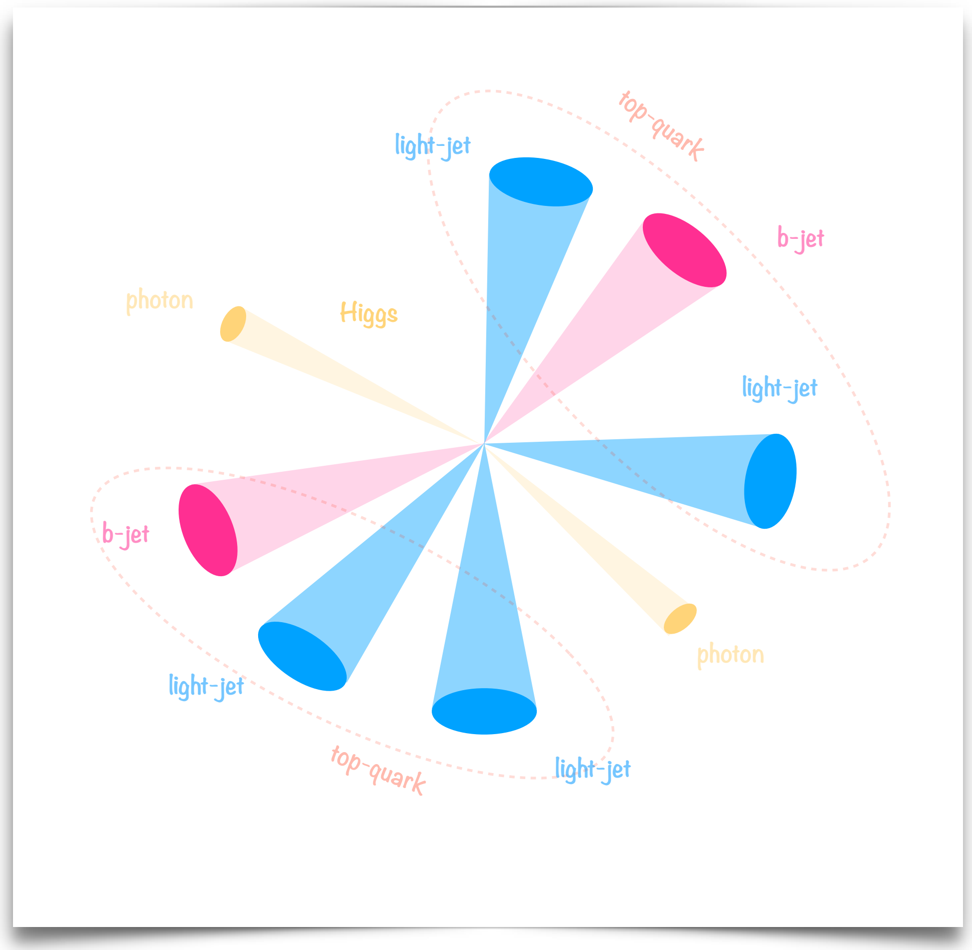



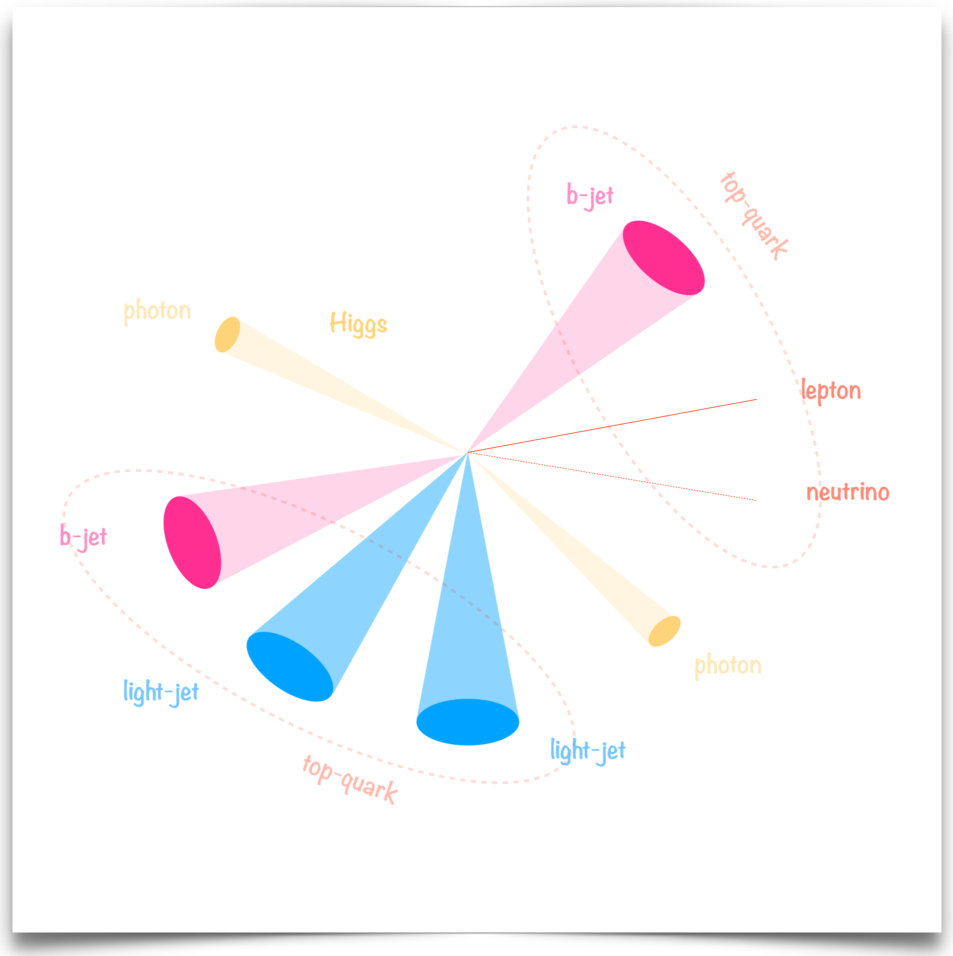
Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!



Currently cleanest and most sensitive channel



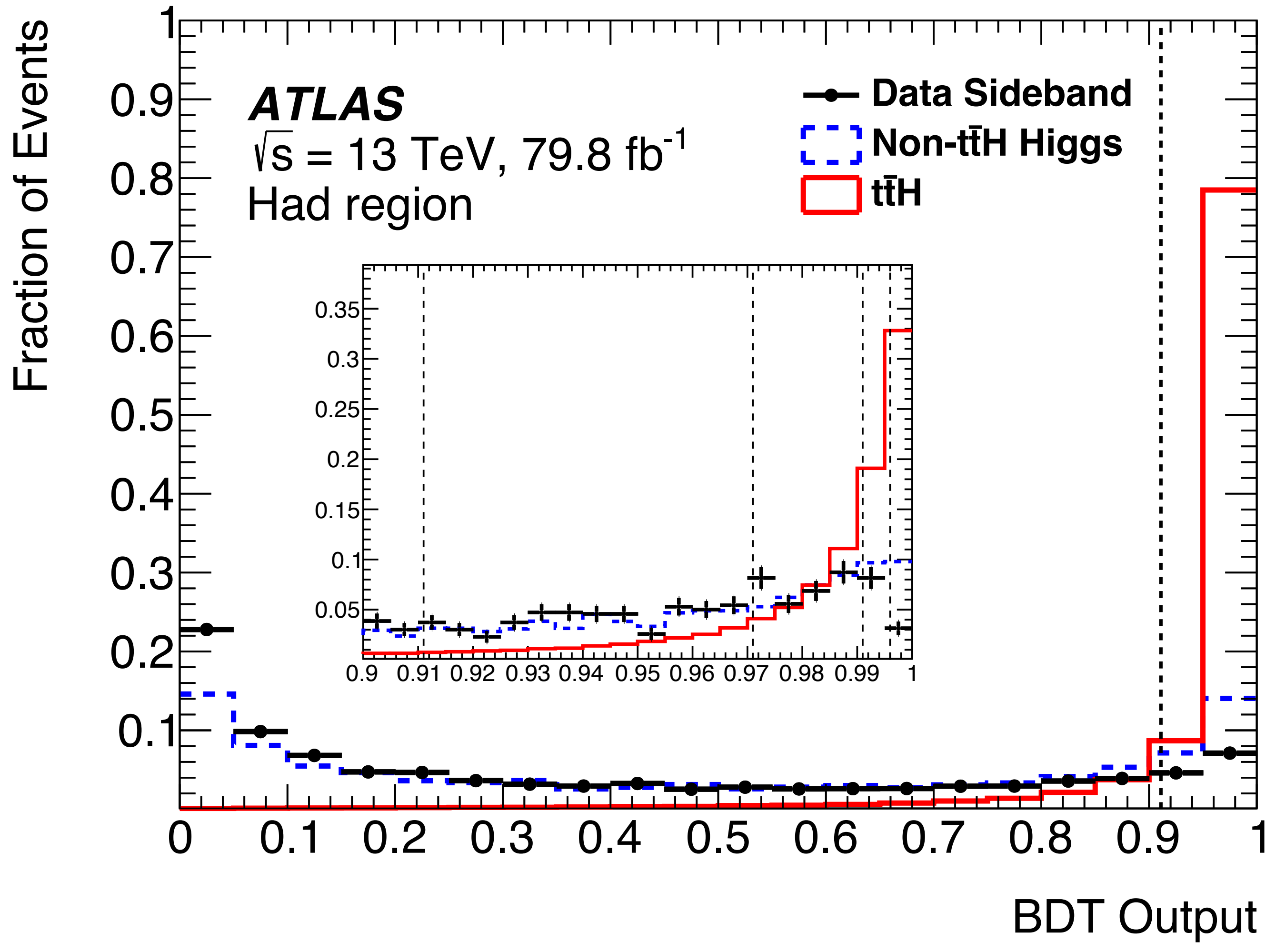


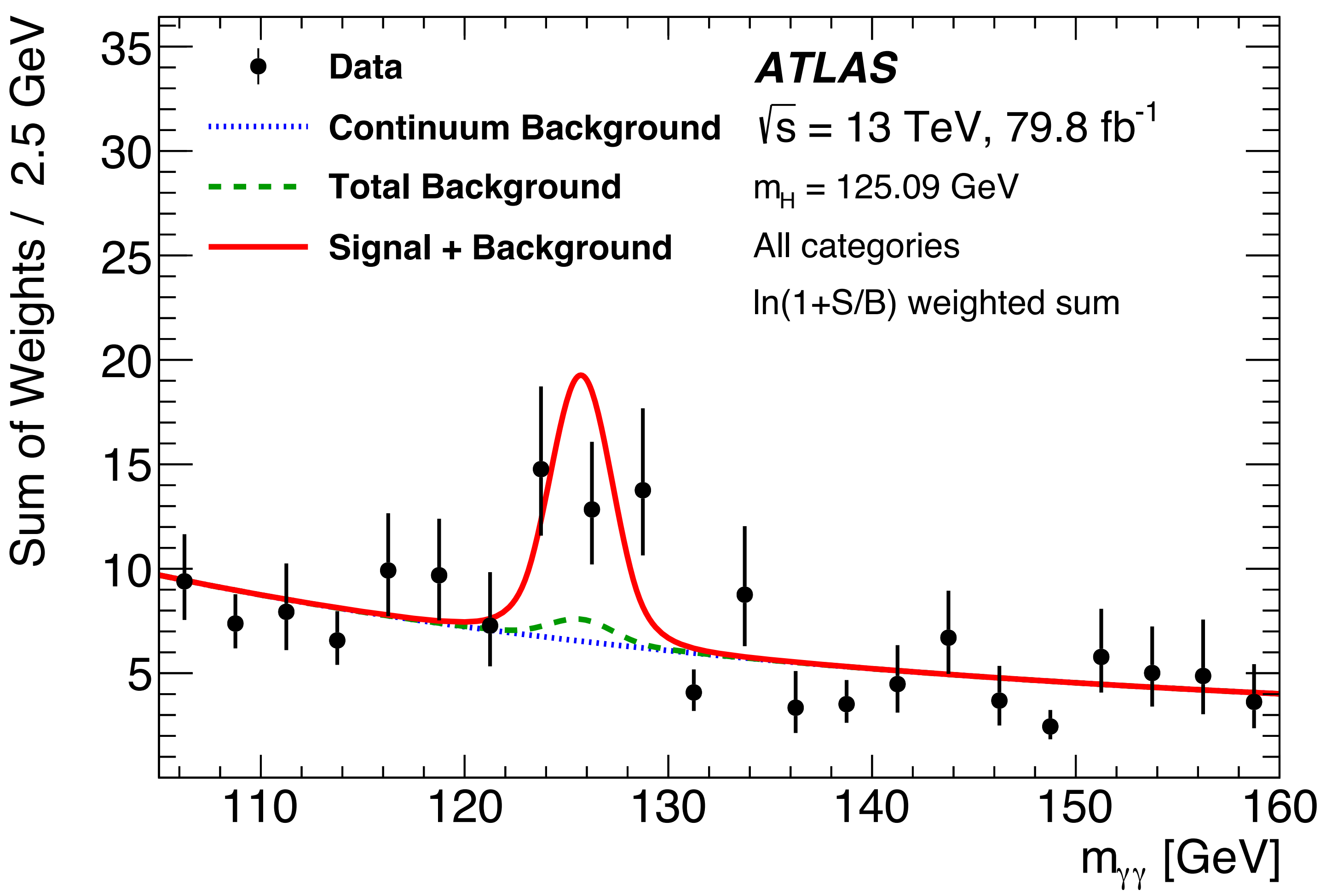
Two separate main channels **0L** and **1L** (inclusive)

« 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)

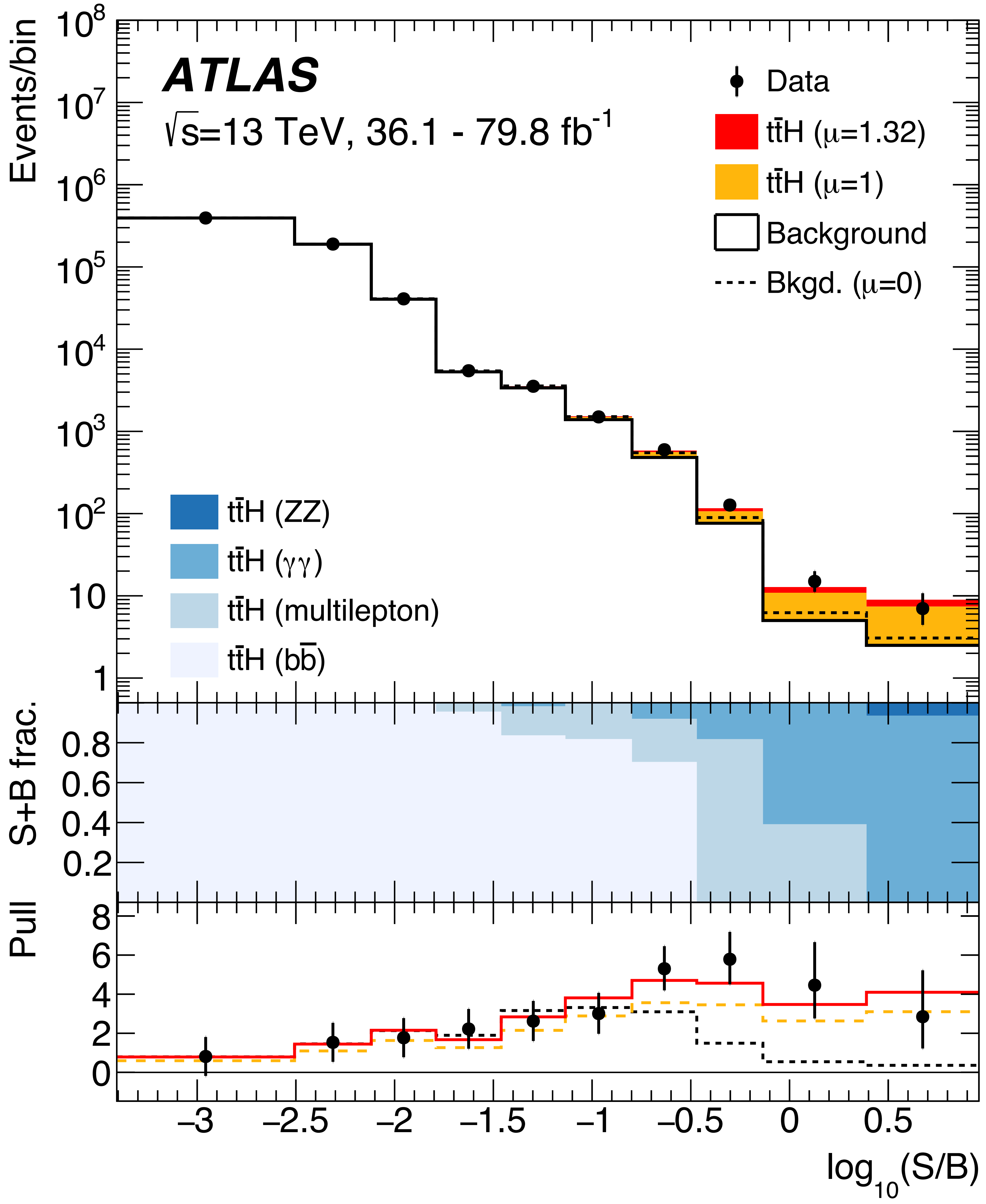
Background and signal modelled using analytic functions.





Direct probe of the top Yukawa coupling

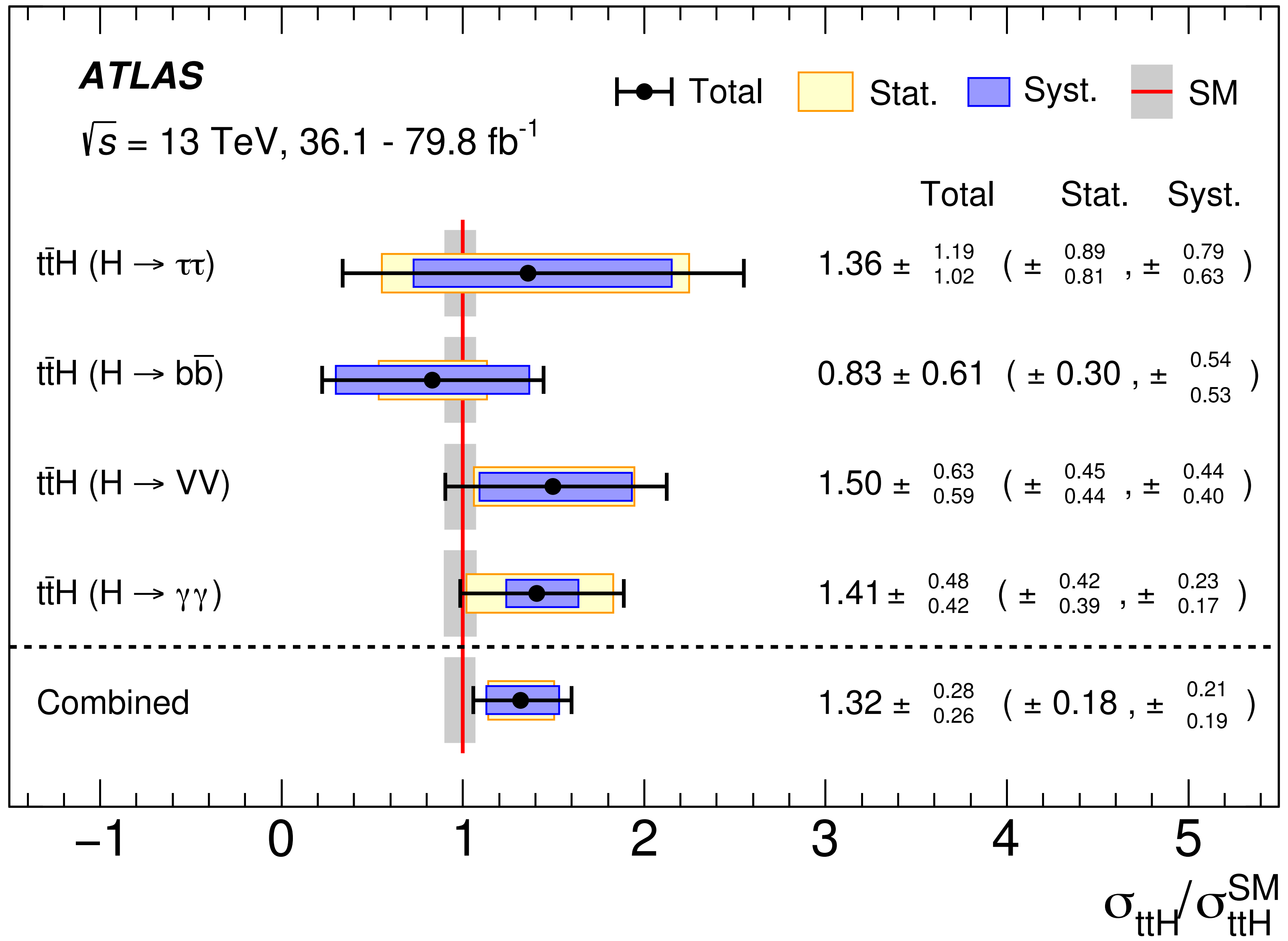
ttH Combining all channels with diphoton and 4-leptons categories



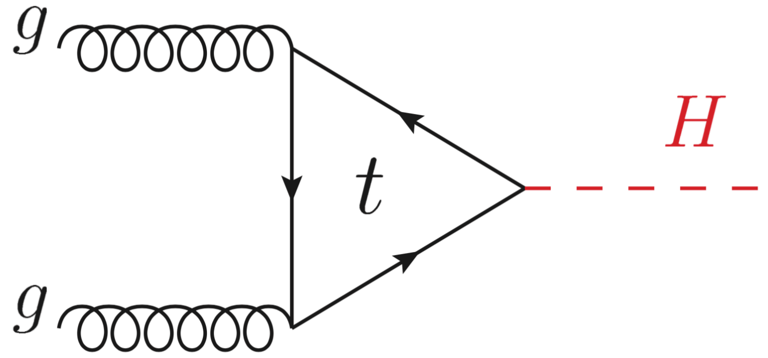
Analysis	Obs. sign.	Exp. sign.
$H \to \gamma\gamma$	$4.1\ \sigma$	$3.7\ \sigma$
$H \to$ multilepton	$4.1\ \sigma$	$2.8\ \sigma$
$H \to b\bar{b}$	$1.4\ \sigma$	$1.6\ \sigma$
$H \to ZZ^* \to 4\ell$	$0\ \sigma$	$1.2\ \sigma$
Combined (13 TeV)	$5.8\ \sigma$	$4.9\ \sigma$
Combined (7, 8, 13 TeV)	$6.3\ \sigma$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

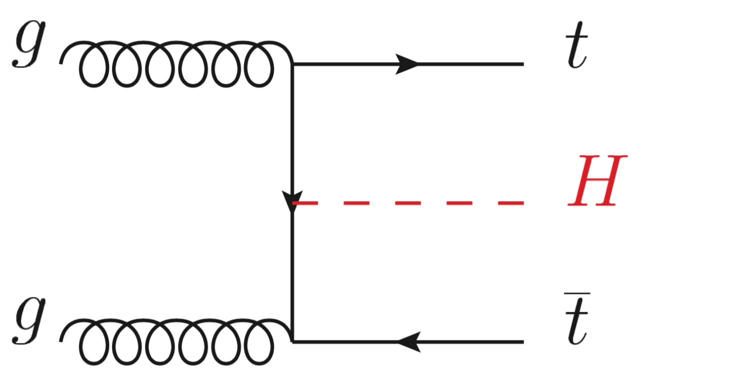
← Observation!!

CMS has very similar results



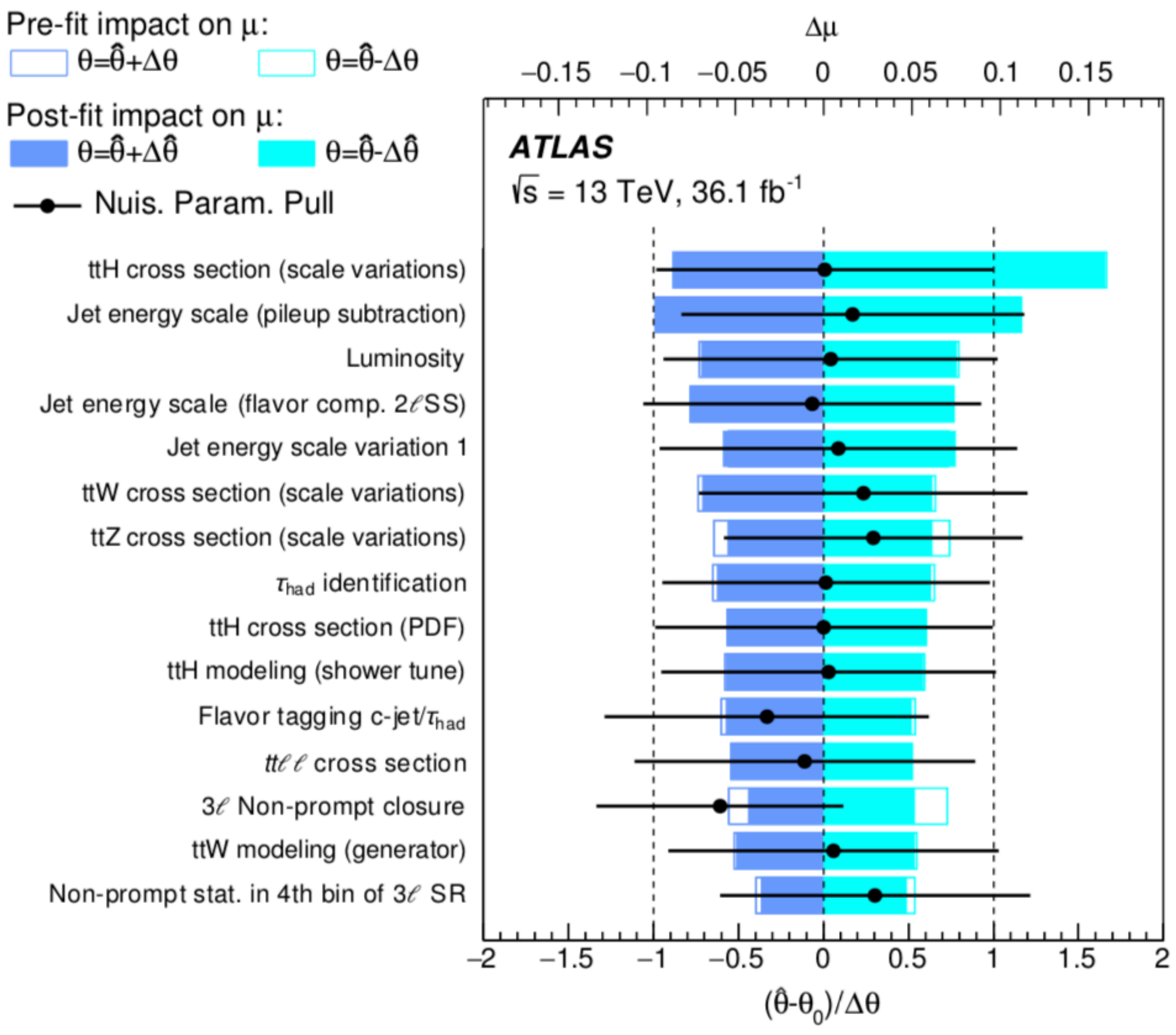
Consistency at 20% level between the direct and indirect measurement of the top Yukawa



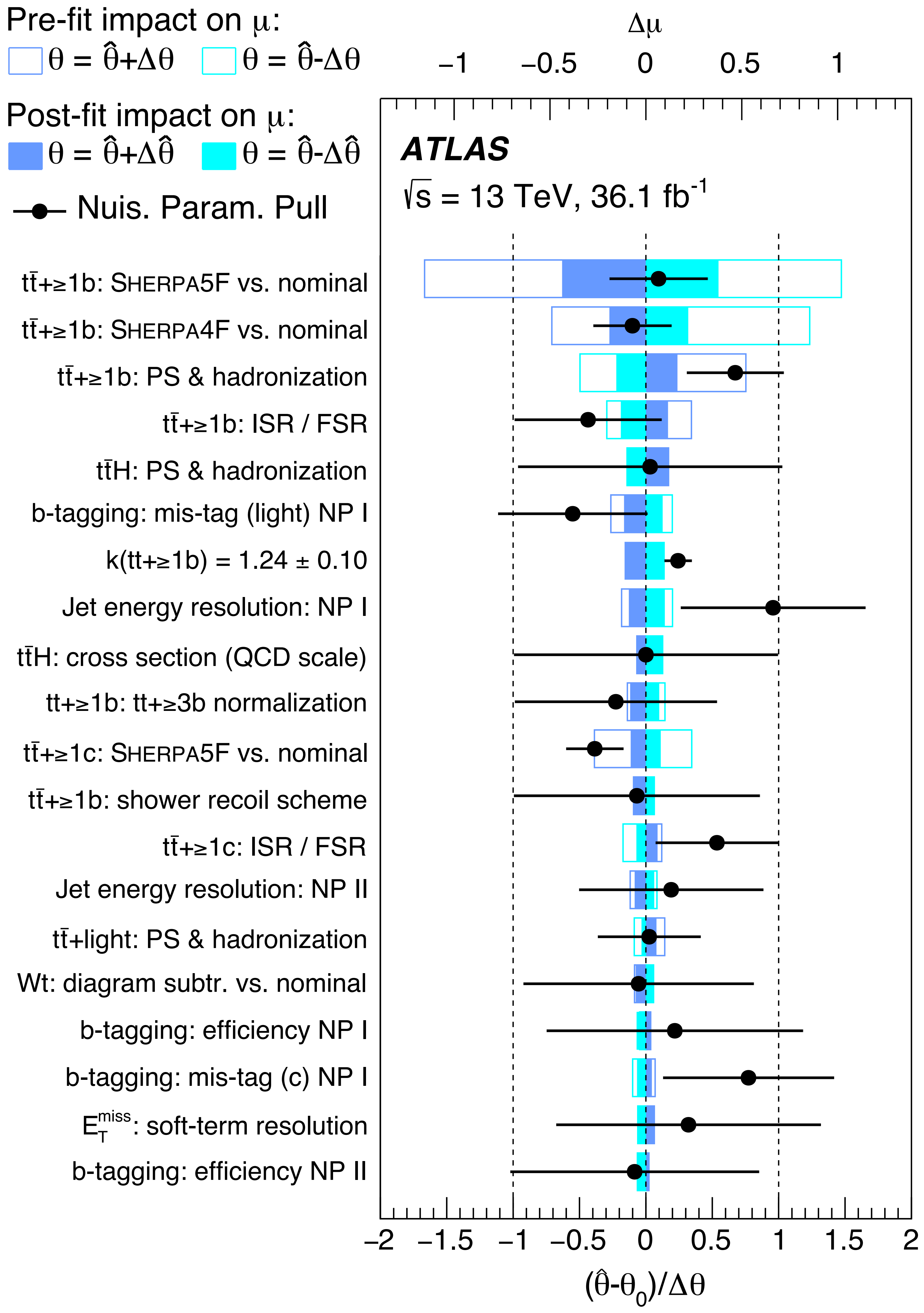


The Profiling Paradigm

How to read a Ranking Plot of Nuisance Parameters

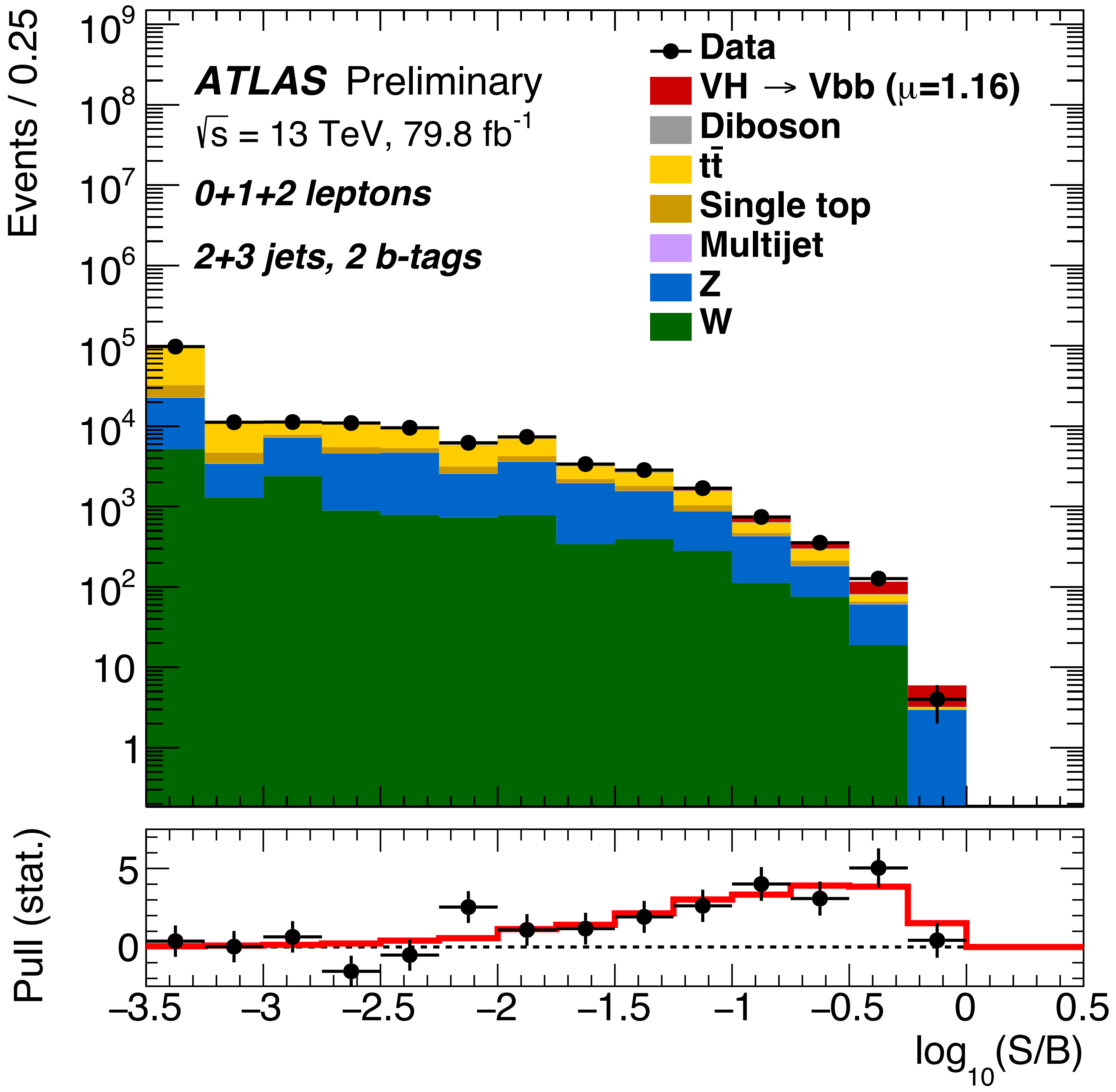


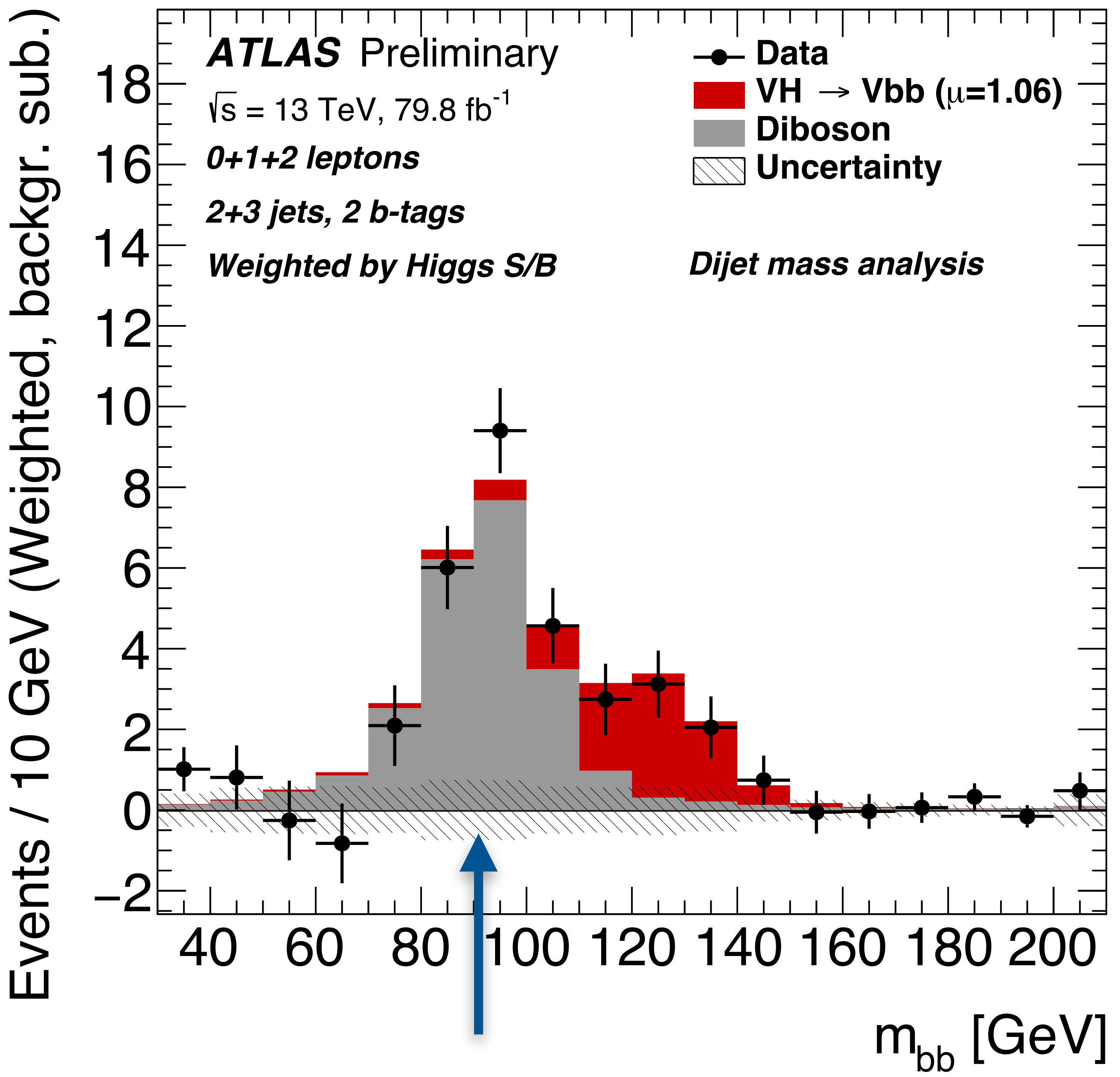
- **Dots:** value of the parameter θ measured after the fit in the data (all with initial constraint of 1).
- A parameter is constrained if its postfit uncertainty is smaller than 1 (it cannot be larger).
- A parameter is pulled if its post-fit value is not 0.
- Impact on μ is absolute
- **Note:** Comparing the post fit parameter with 0 and the post fit error does not illustrate compatibility between data and auxiliary measurement.

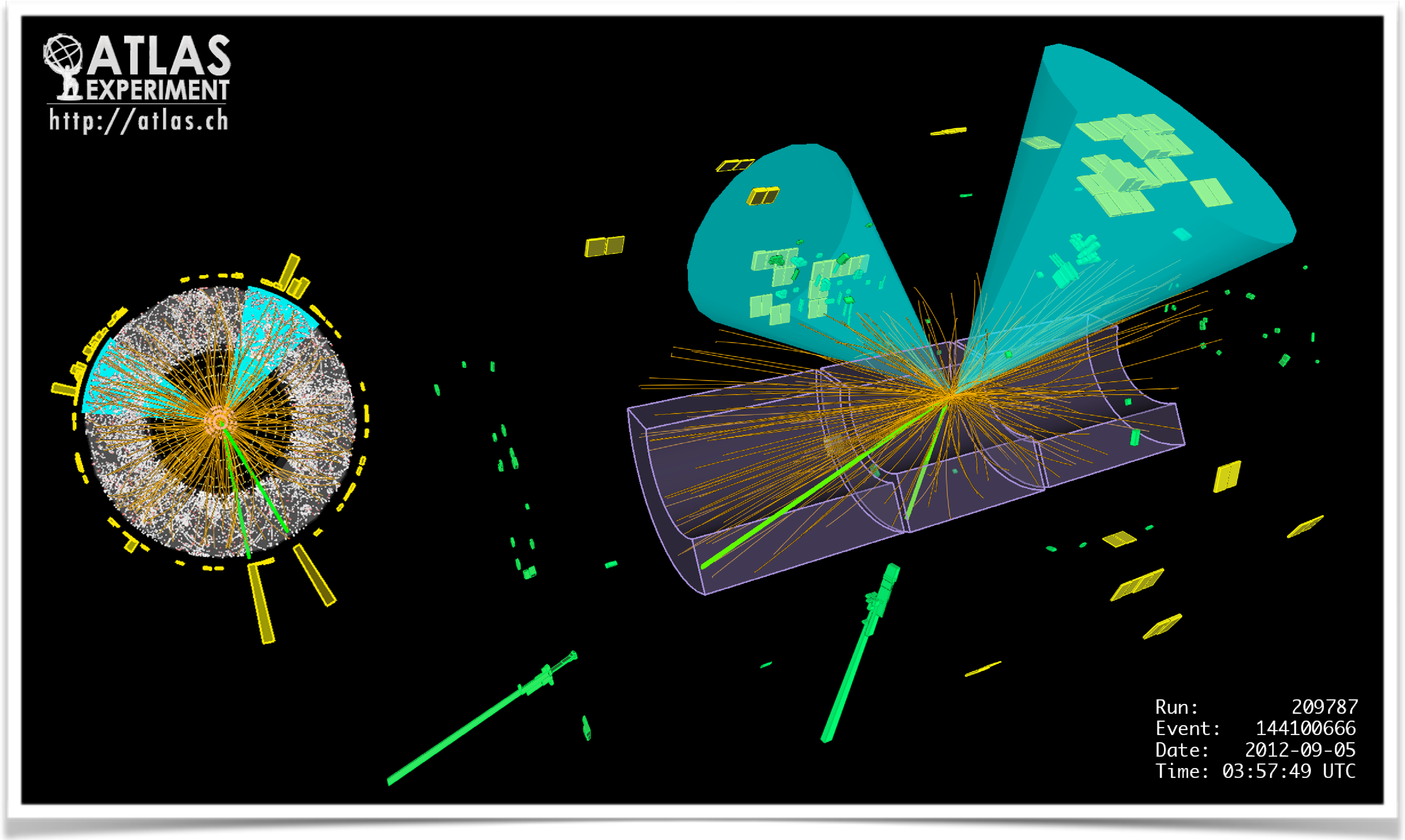


Higgs boson decays to b-quarks

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:

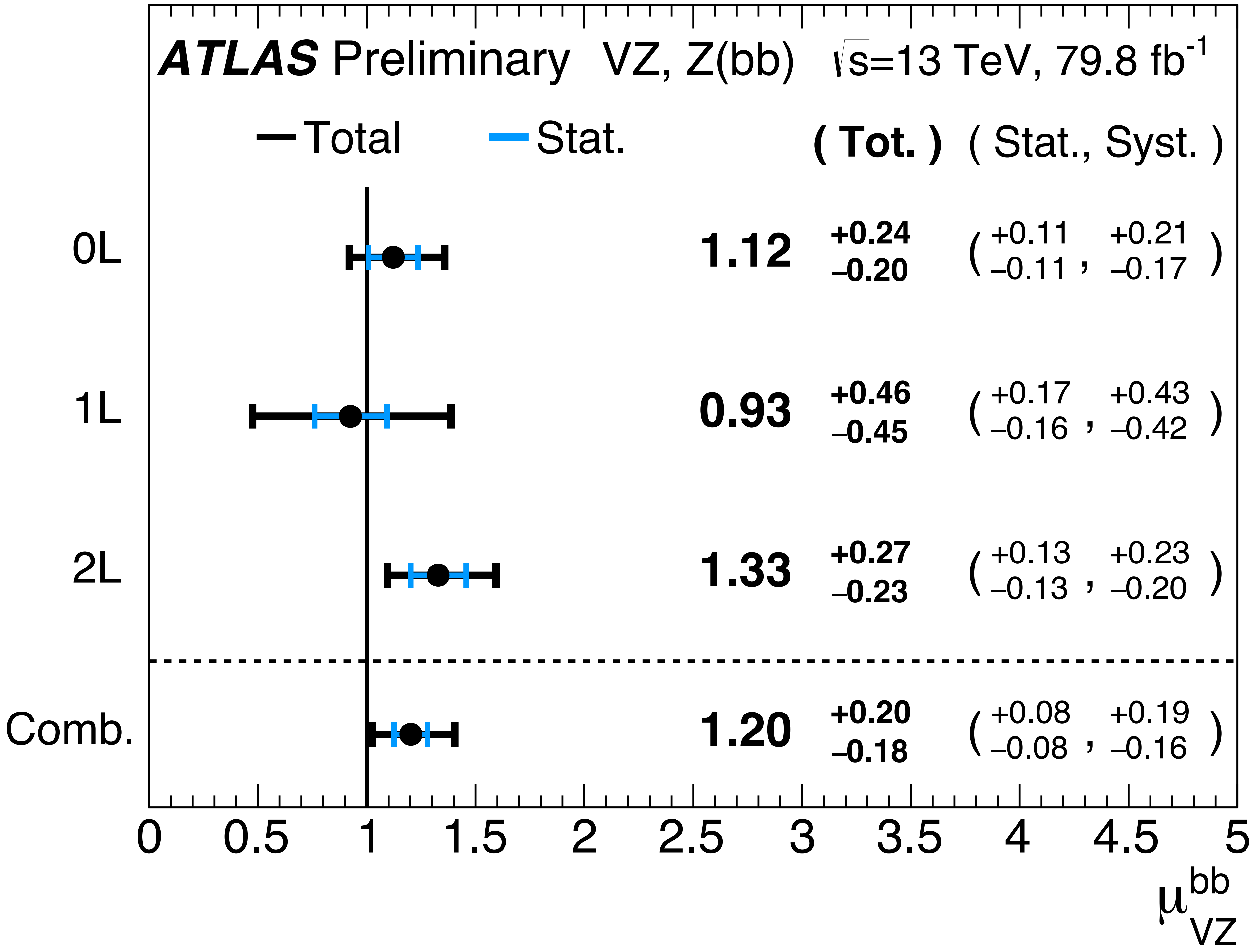
- 0 « leptons » (for neutrino decays of the Z)
- 1-lepton (W decaying to an electron or a muon)
- 2-leptons (Z decaying to electrons or muons)

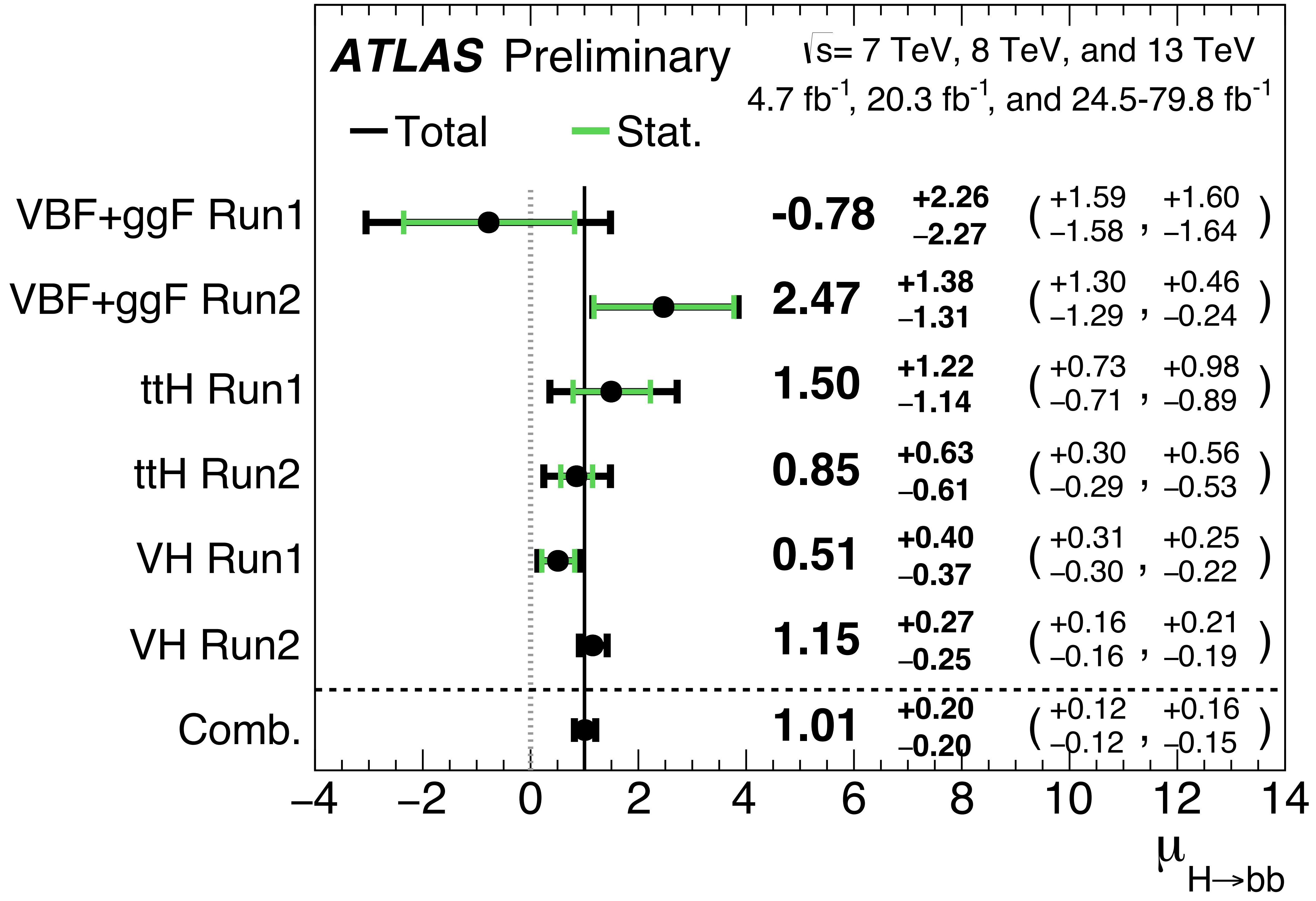
Main background is V+jets (in particular b-jets), relies on a good simulation, but is controlled in the mass side-bands!

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

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

$$4.9\sigma\ (\mathrm{observed}) \quad 5.1\sigma\ (\mathrm{expected})$$

Observation!!

$$5.4\sigma\ (\mathrm{observed}) \quad 5.5\sigma\ (\mathrm{expected})$$

Run 2 Higgs Physics Milestones Already Reached!

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)

3^d Generation Yukawa Measurements Challenges

All measurements are already systematics dominated.

$\tau^+\tau^-$ Channels

CMS result (example)

$$\mu = 1.28 \pm 0.10\ (\mathrm{stat}) \pm 0.11\ (\mathrm{syst}) \pm 0.10\ (\mathrm{th})$$

With higher statistics, categorise in regions of improved mass reconstruction.

Improved embedding techniques to better control the Z-jets background.

TIghter or more exclusive selection of the the taus to improve fake rejection.

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

ttH Channels

ATLAS result (example)

$$\mu = 1.32 \pm 0.18\ (\mathrm{stat}) \pm 0.21\ (\mathrm{syst}) \pm 0.10\ (\mathrm{th})$$

Very important channels at LHC, need to investigate all possible ways to gain precision.

How to improve more difficult channels (ttHbb and ML), with higher statistics move to more exclusive regions of phase space (e.g. boosted for ttH(bb) which has lower combinatorial).

Require **ancillary measurements** to further costrain systematic uncertainties (perhaps simultaneous measurements - ttH and tt-HF or ttH and ttV)

VH(bb) Channels

ATLAS result (example)

$$\mu = 1.01 \pm 0.12\ (\mathrm{stat}) \pm 0.16\ (\mathrm{syst})$$

Very important channels at LHC, need to investigate all possible ways to gain precision.

Ancillary measurements of V-jets and in particular heavy flavour.

With higher statistics explore more extreme phase space and perhaps boosted regime.

In general for all channels, improve reconstruction algorithms performance and calibration (ID, scale, resolution, F-tagging, etc…)