Experimental SM and Higgs Physics at LHC

Lecture 3

Higgs Physics

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Outline

Experimental SM and Higgs Physics at LHC

Lecture 1*: Basic Concepts, the LHC and precision measurements with Drell-Yan W and Z processes.*

Lecture 2*: Associated and multi- Vector boson production, and top quark*

Lecture 3*: Higgs Physics*

Lecture 4: *More Higgs Physics and Global interpretation*

- **Disclaimer:** These lectures will be focused mostly on ATLAS and CMS (LHCb covered by Marco Gersabeck and QCD and jet physics covered by Peter Uwer)
- **Excellent resources for keeping up-to-date with the latest results**: Physics Briefings from ATLAS and CMS.

The Standard Model of Particle Physics

Back to the SM Lagrangian

The Gauge sector of the Lagrangian density:

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

Beauty: simplicity of these expressions, and interactions governed by gauge symmetries only 3 (EW) and 2 (QCD) parameters!

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

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

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

The Higgs Field and Fundamental Questions

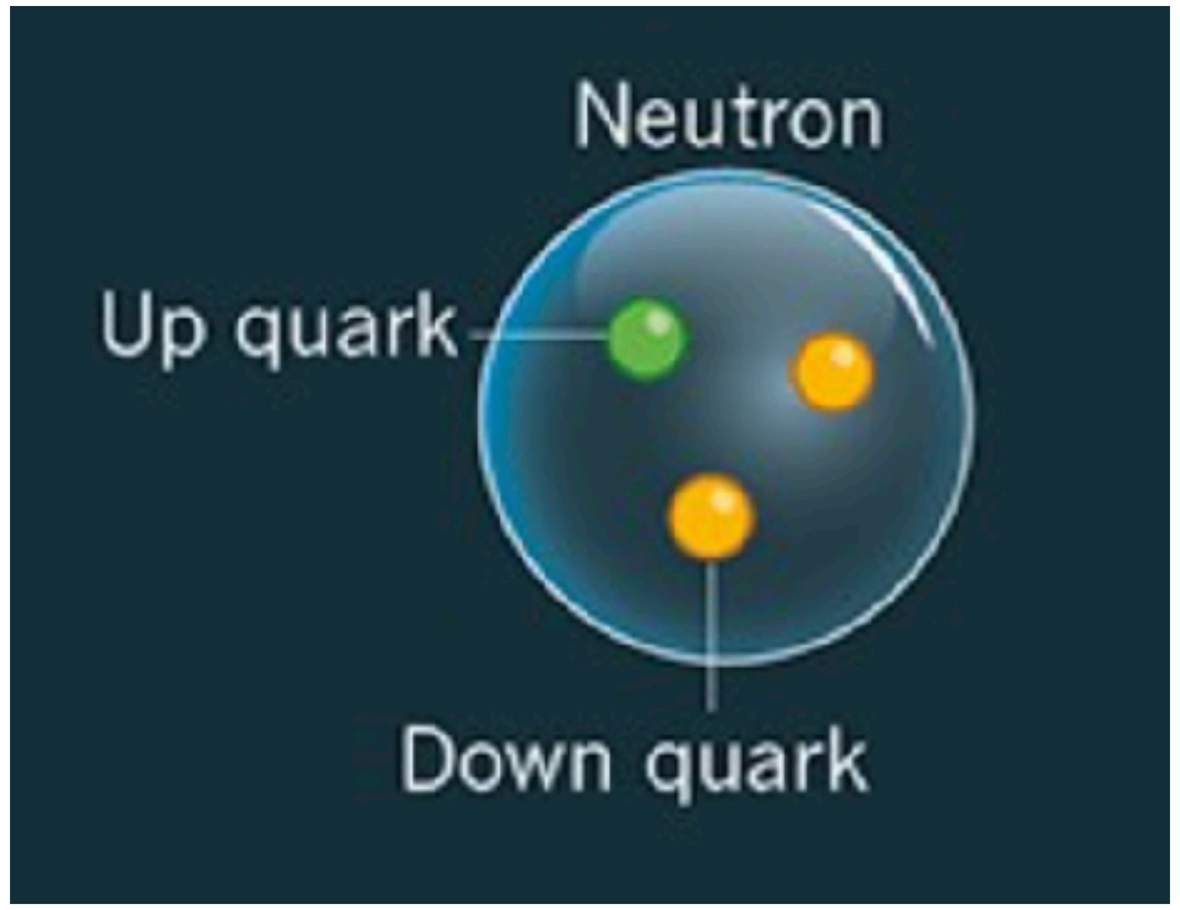
The Higgs particle is related to most of the fundamental questions we have about nature

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

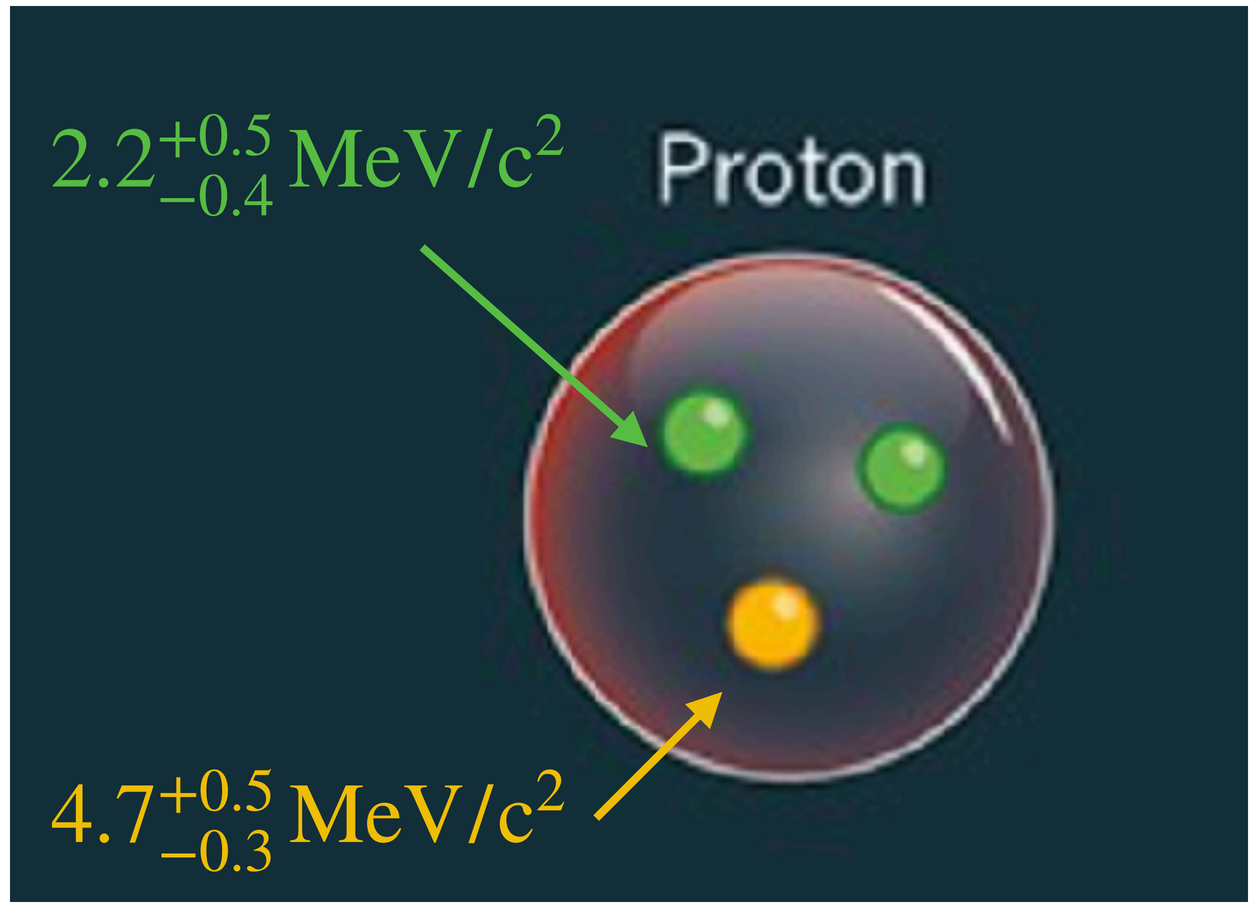
However the SM is very far from explaining everything!

- The (origin of) Higgs mass is one of the greatest mysteries of fundamental physics! The Naturalness problem
- The nature of Dark Matter , is the Higgs responsible for its mass?
- The nature of Dark Energy The cosmological constant problem
- The origin of the asymmetry between matter and anti-matter in the universe? CP Violation and EW Phase transition
- The nature of neutrinos, their masses and the widely different masses between fermions. Flavour Hierarchy problem
- Why do electrons have precisely the same charge as the protons? Grand Unification
- Why is the electric dipole moment of the neutron so small? Answers involve a scalar field the axion The Strong CP problem
- What fuels inflation - involves the existence of a fundamental scalar, the **inflaton**?
- Gravity at small distance scales - attempted descriptions also often imply a fundamental scalar field the **Dilaton**

The Higgs and the Nucleon Masses



939.56542052(54) MeV/c^2



938.27208816(29) MeV/c^2

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

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

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

1% from electromagnetic effects (slightly larger for proton)

4% from its constituent quarks

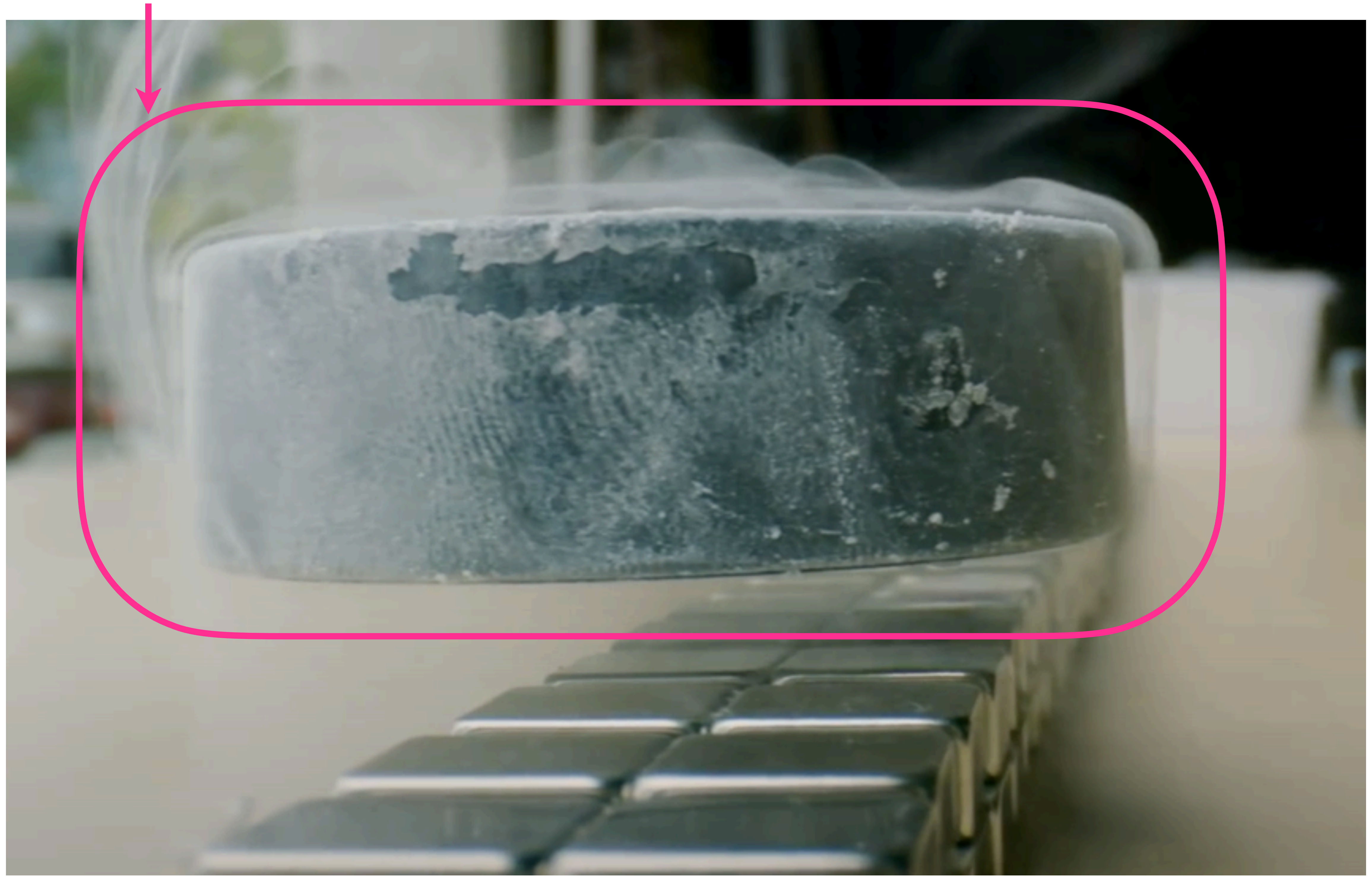
With even just slightly different masses, nuclei as we know them would not be stable…

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

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

An Accurate Analogy

The universe



Superconductivity

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

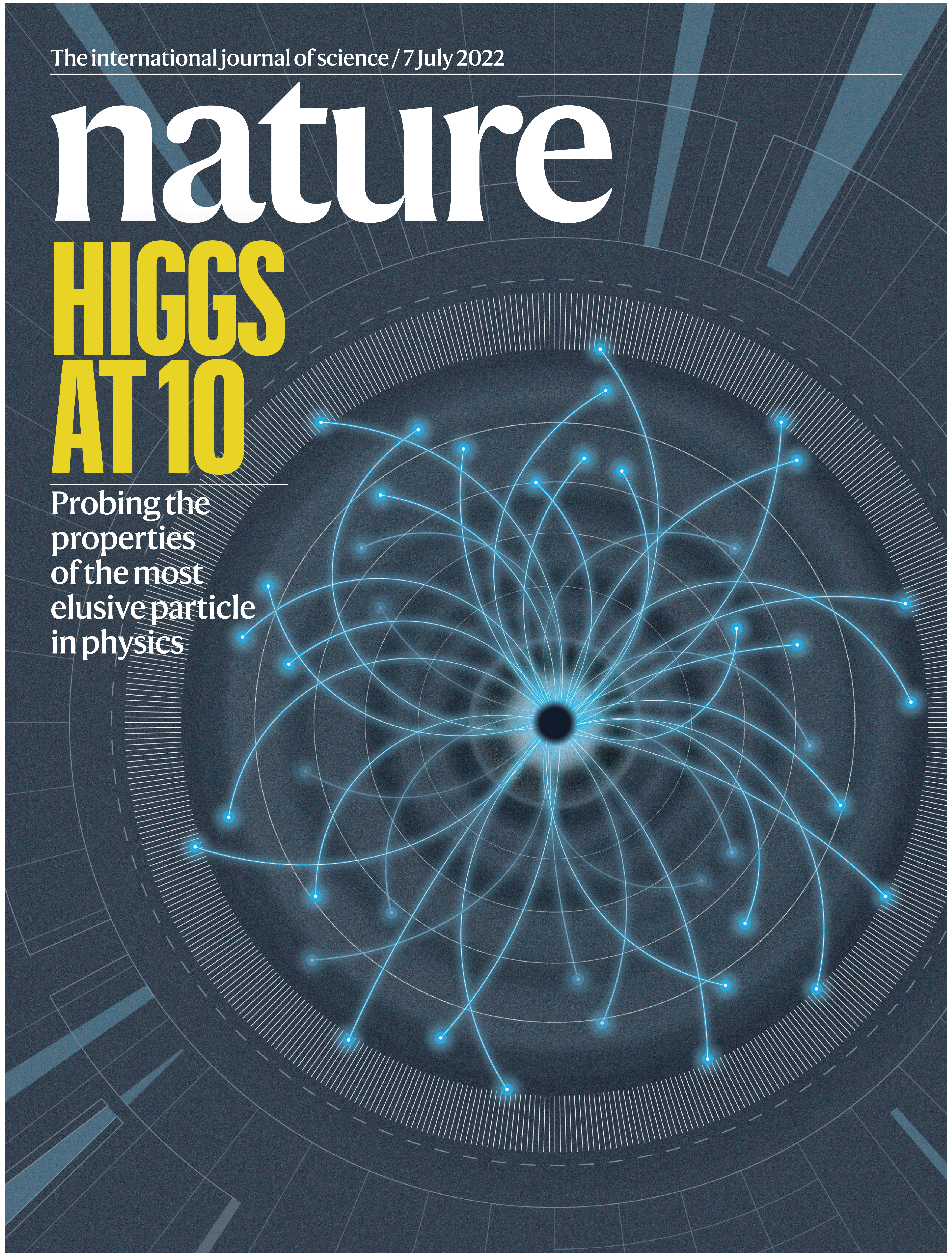
1950 – Landau and Ginzburg
JETP 20 (1950) 1064

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

Is the Higgs boson composite?

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

Already more than a Decade Ago!



nature portfolio

nature > collection

Collection | 04 July 2022

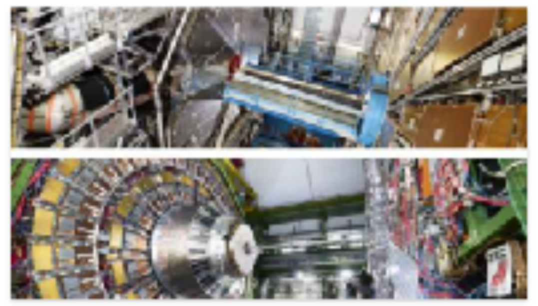
The Higgs boson discovery turns ten

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

CERN 10 years HIGGS boson discovery

Higgs 10 symposium at CERN

CERN news



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

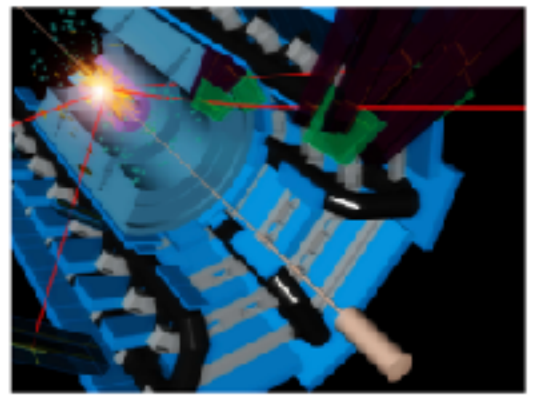
The collaborations have used the largest samples of proton–proton collision data recorded so far by the experiments to study the unique particle in unprecedented detail

News | Physics | 04 July, 2022

Higgs10: When spring 2012 turned to summer

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

News | At CERN | 04 July, 2022



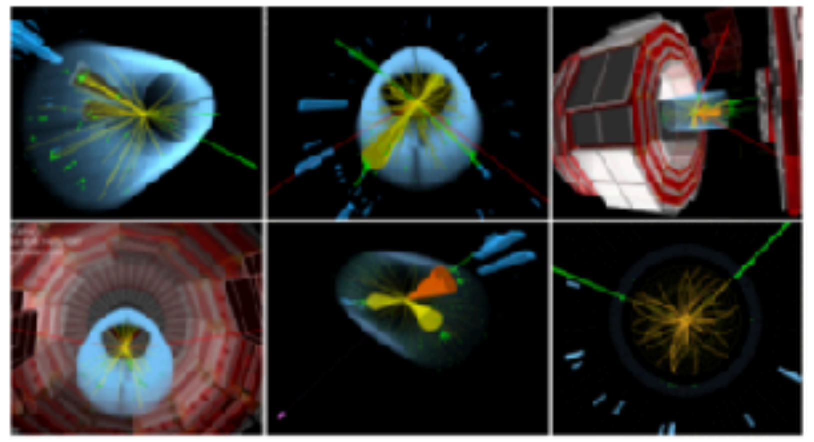
10 years of Higgs research

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

Press Statement | 4 July 2022

ATLAS news

CMS news

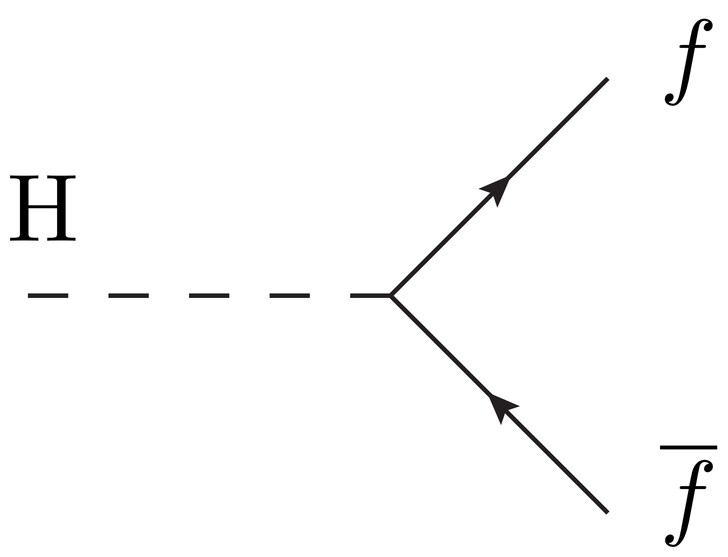


THE HIGGS BOSON TURNS 10: RESULTS FROM THE CMS EXPERIMENT

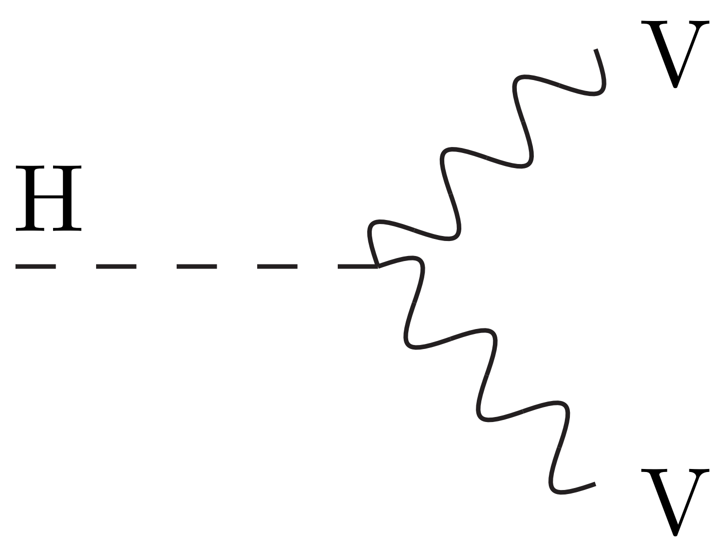
04 JUL 2022 | AJAFARI | PHYSICS

Three Pillars of Higgs Physics

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

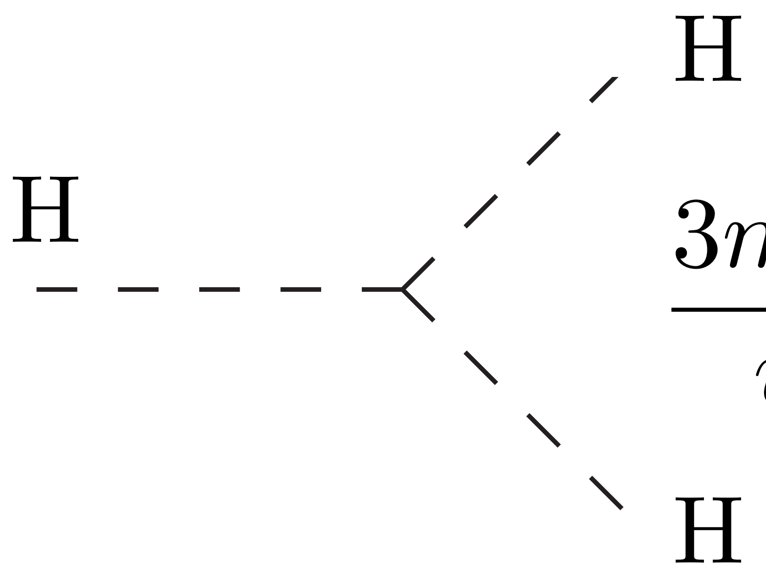


$\frac{m_f}{v}$ $+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$

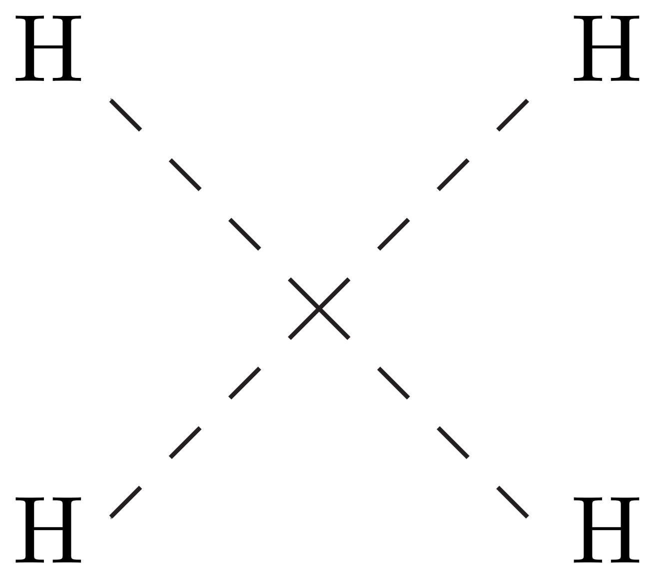


$\frac{2m_V^2}{v}$ $+ |D_\mu \phi|^2$

This term could not exist without a vev



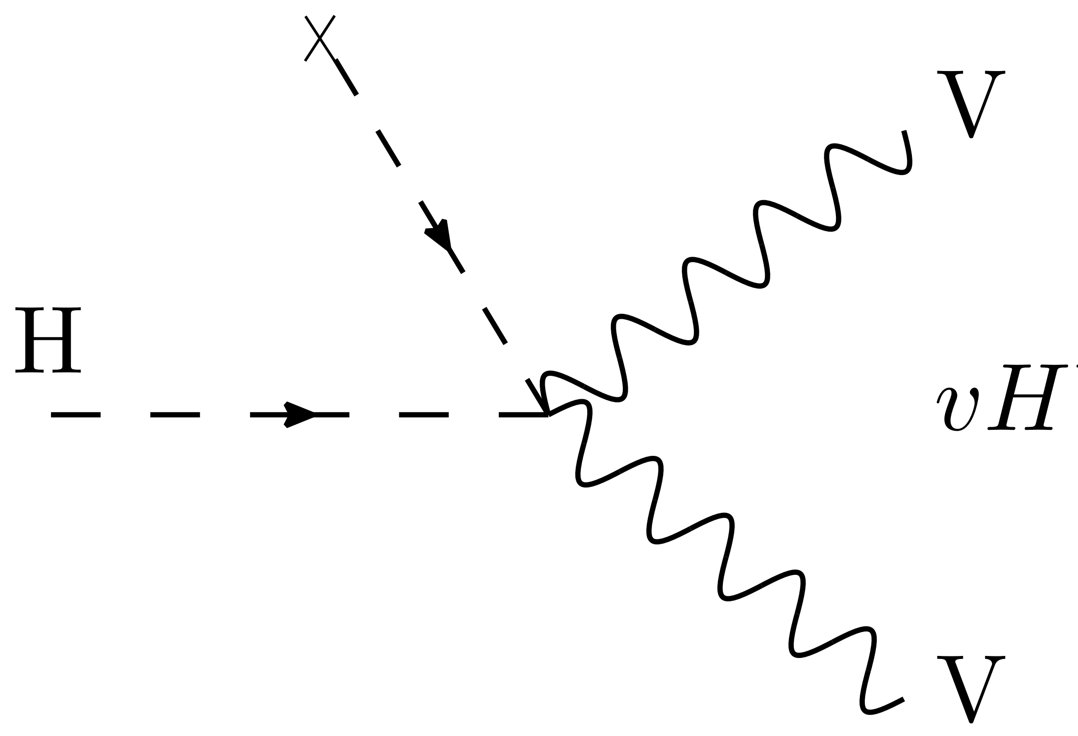
$\frac{3m_H^2}{v}$



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

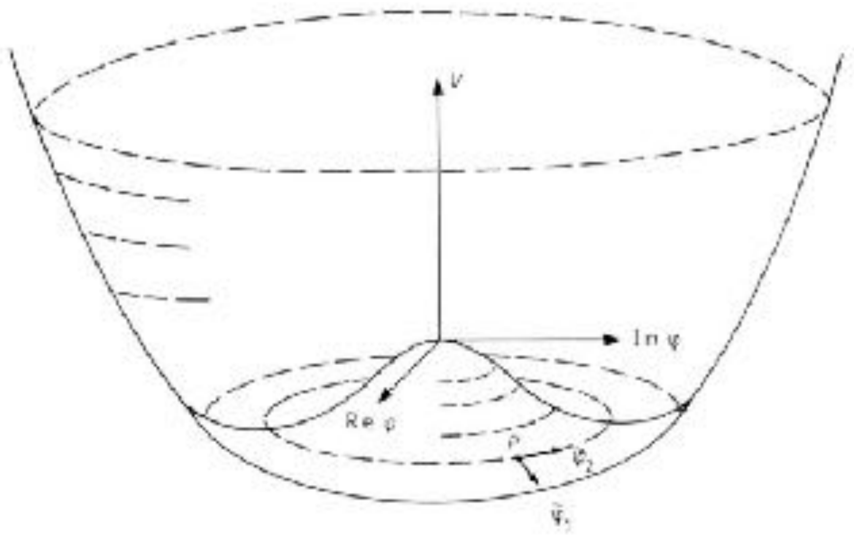
Is the Higgs boson responsible for the EW symmetry breaking also responsible for the masses of fermions?

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?

HL-LHC is a Higgs Factory

Outcome of the 2013 European Strategy: HL-LHC!

European Strategy 2012-2013 Recommendations

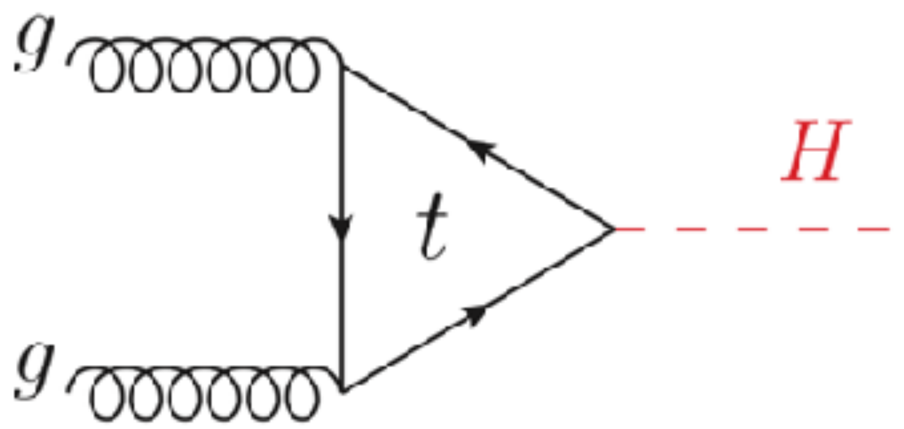
HL-LHC is a **Higgs factory** ~160 M Higgs events

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

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

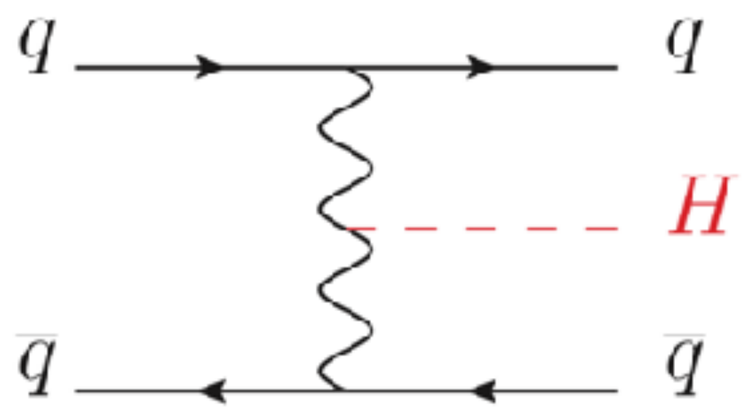
Signatures of the Higgs Boson

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



Gluon fusion process

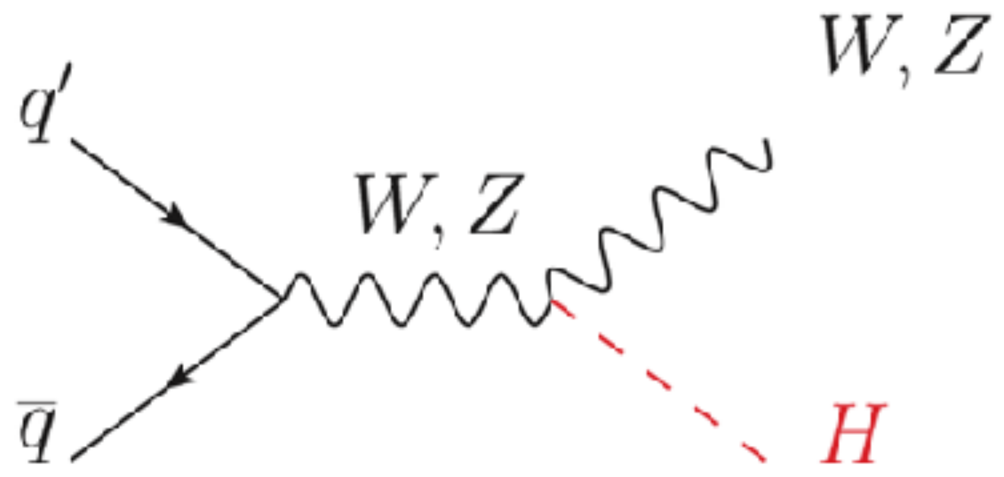
~8 M events produced



Vector Boson Fusion

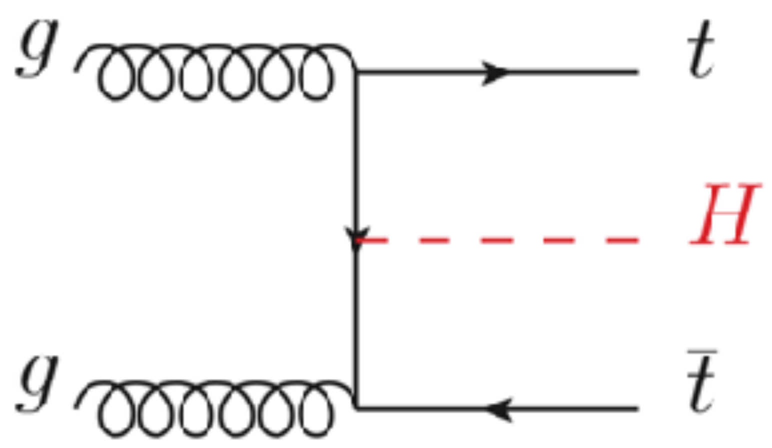
Two forward jets and a large rapidity gap

~600 k events produced



W and Z Associated Production

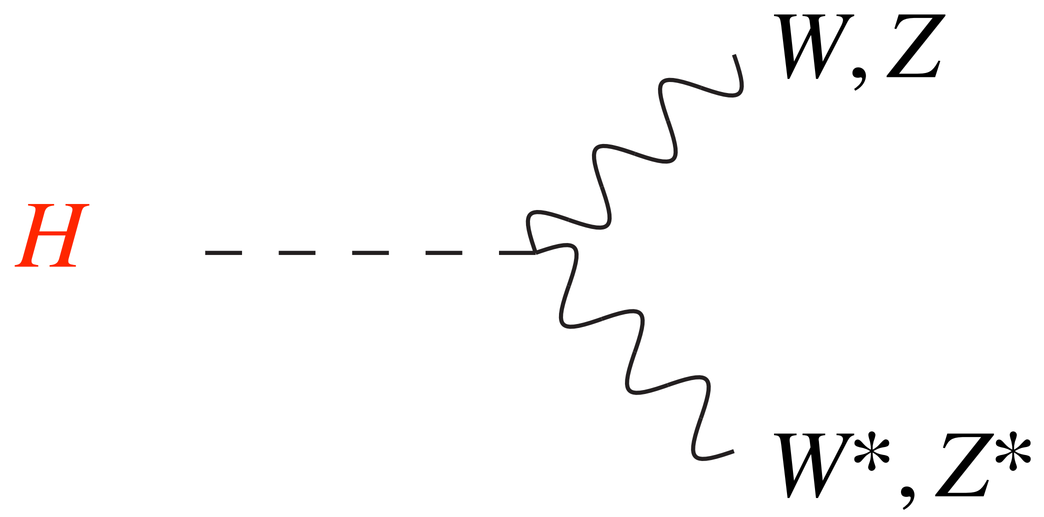
~400 k events produced



Top Assoc. Prod.

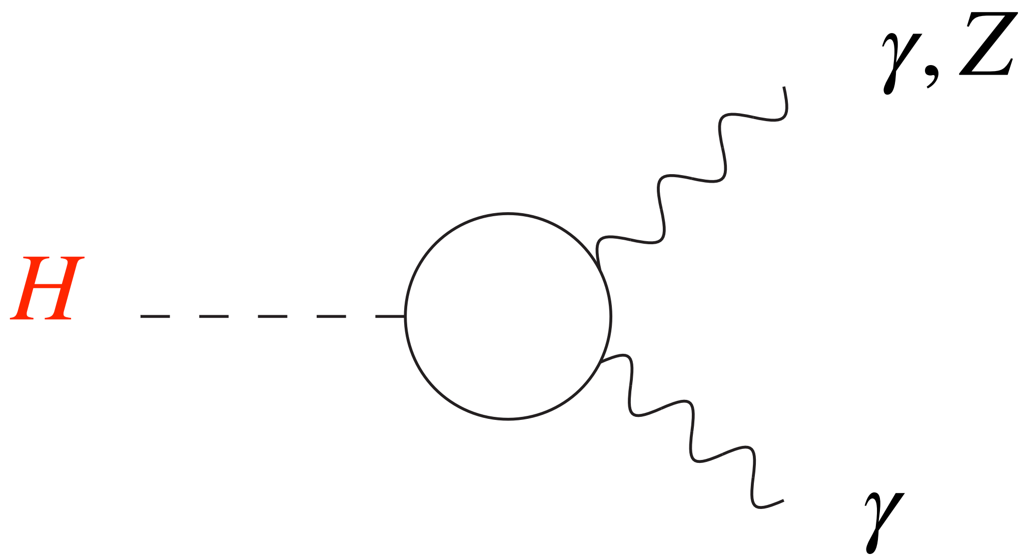
~80 k evts produced

Decay branching fractions



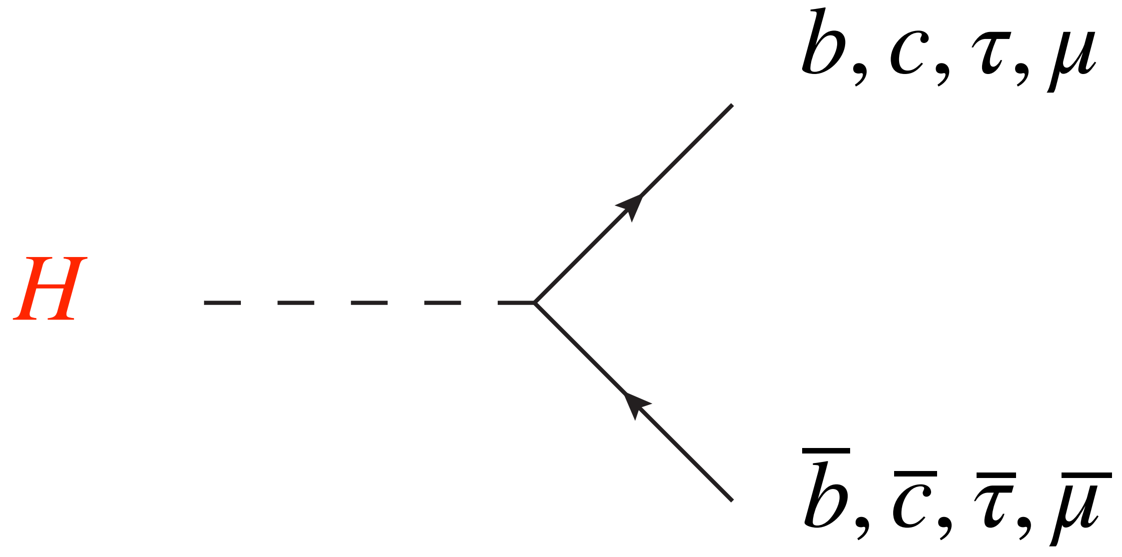
$\mathrm{Br}(H \to WW^*) = 22\,\%$

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



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

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



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

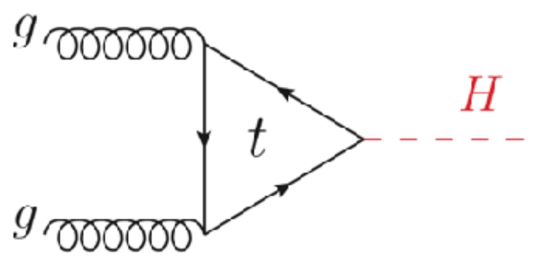
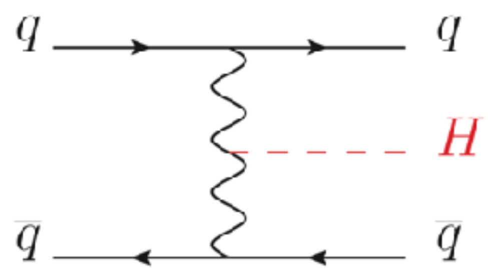
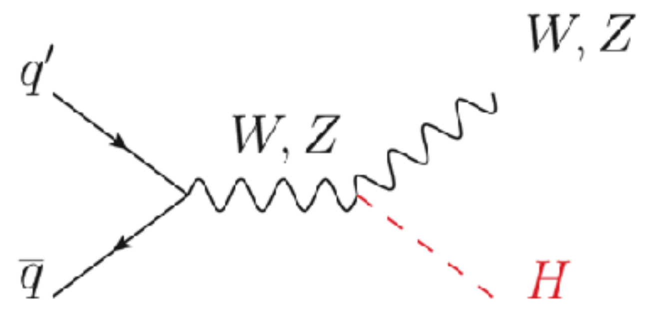
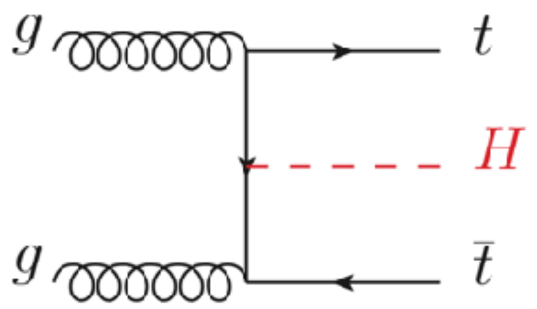
$\mathrm{Br}(H \to \tau^+\tau^-) = 6.3\,\%$

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

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

Nano Overview of Main Higgs Analyses at (HL) LHC

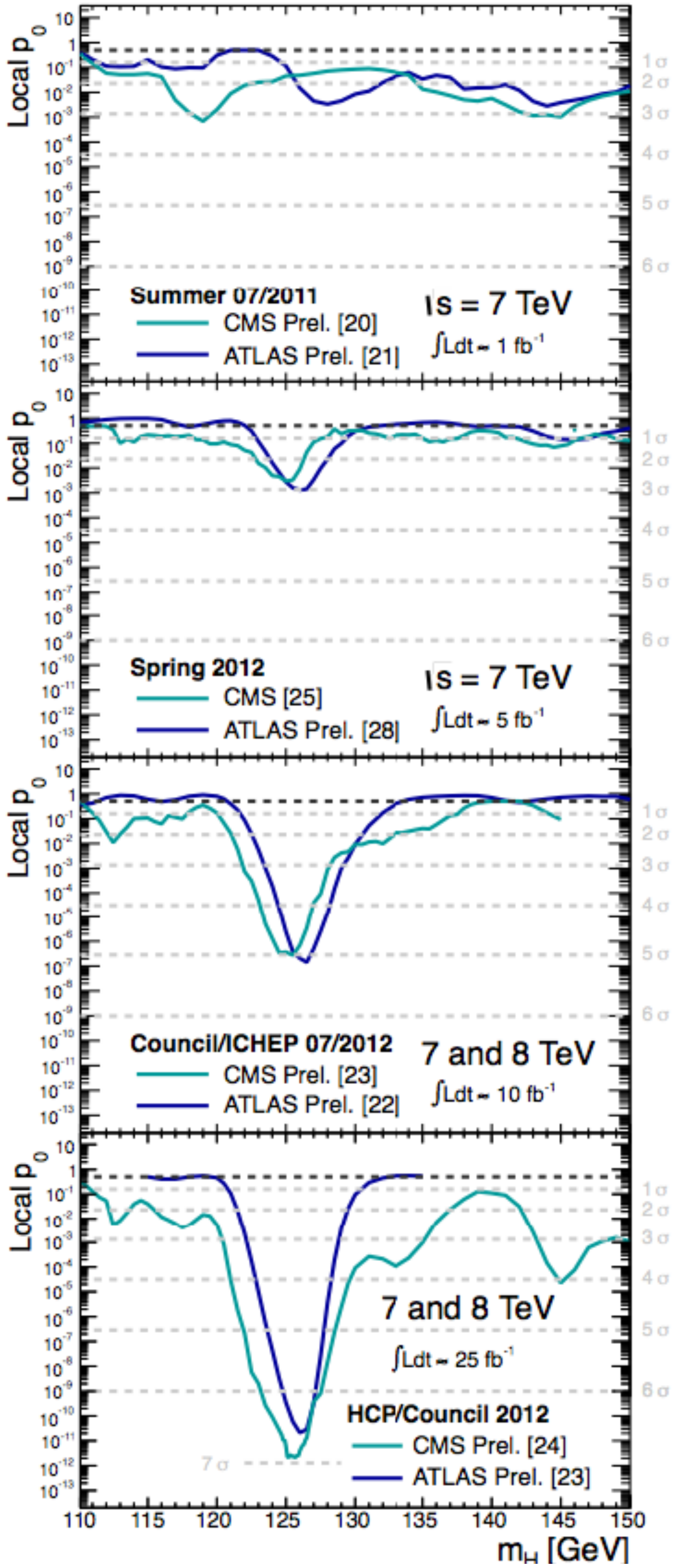
Most channels already covered at the Run 2 with only 3% (80 fb-1) of full HL-LHC dataset!

	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

The Discovery Channels

The Discovery of the Higgs Boson

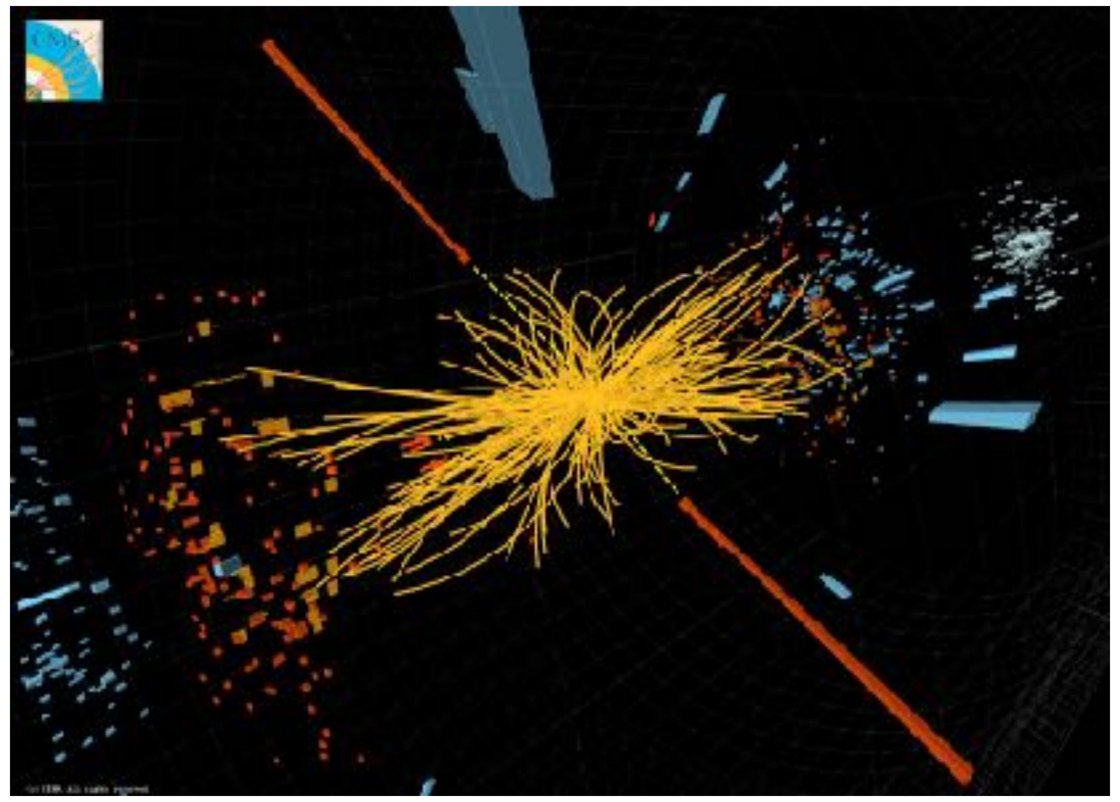


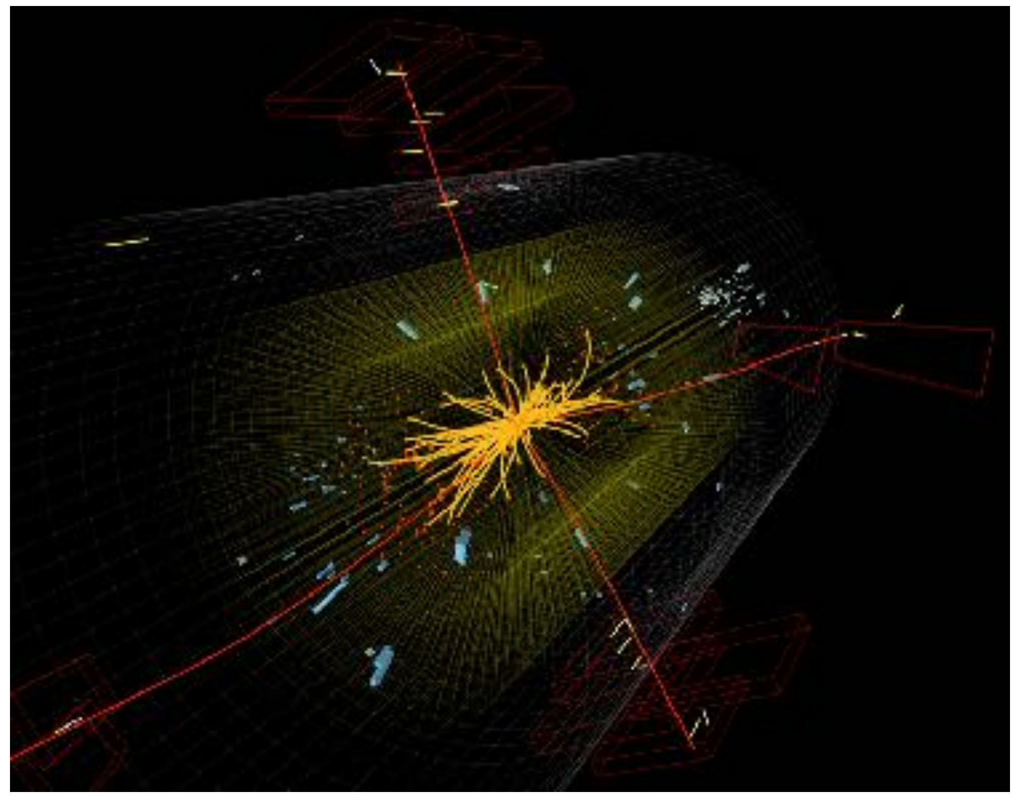
News | Published: 10 July 2012

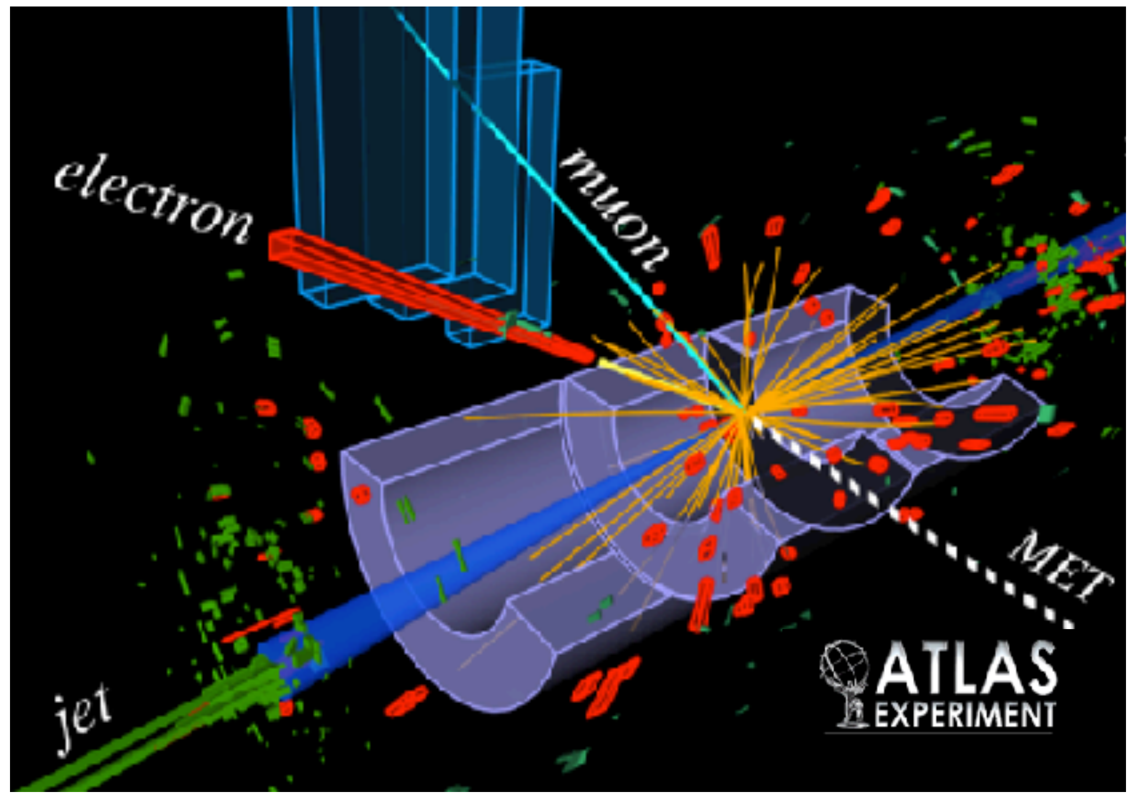
Higgs triumph opens up field of dreams

Geoff Brumfiel

Nature **487**, 147–148 (2012) | Cite this article







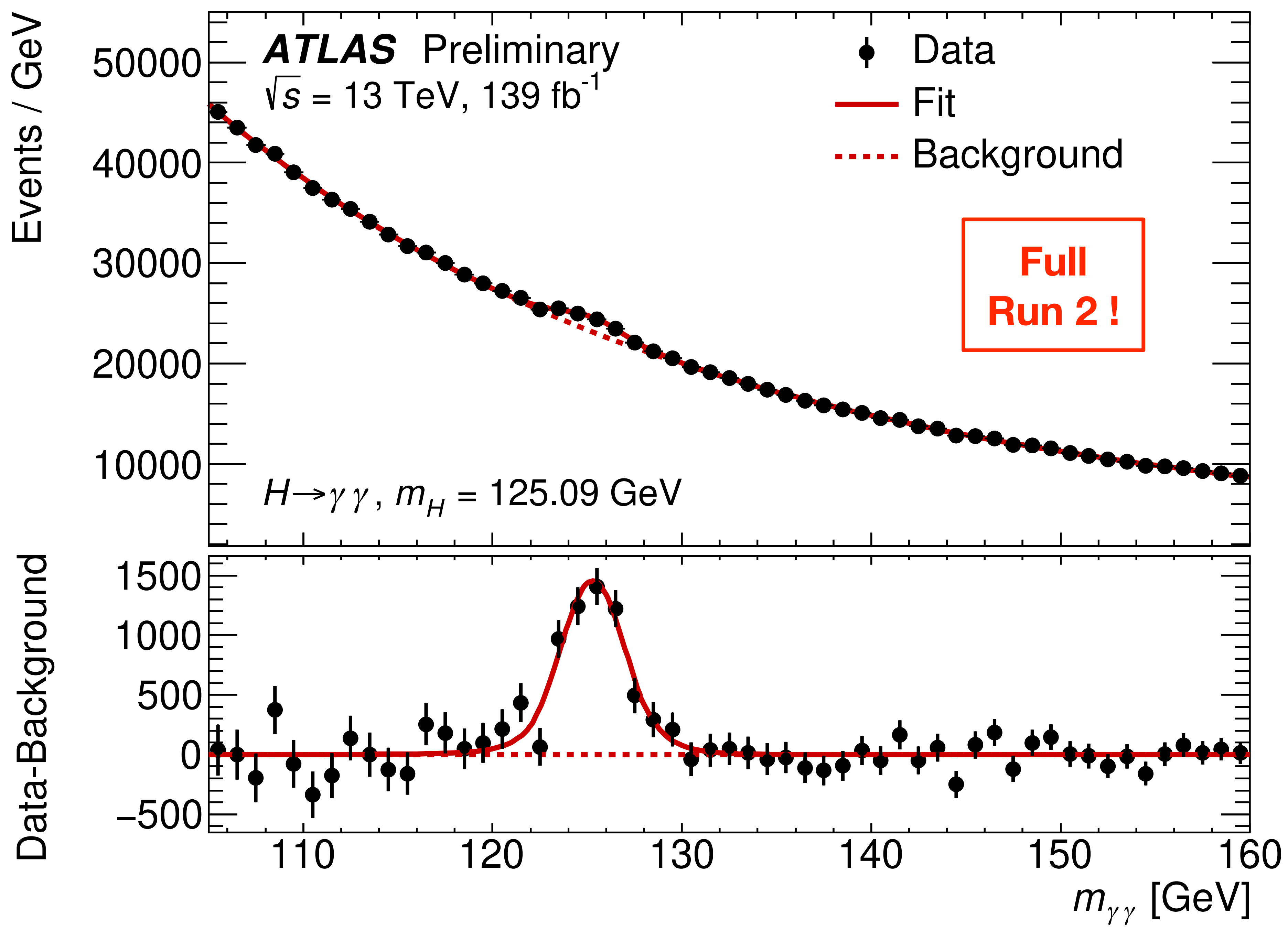
The discovery of the Higgs boson is a landmark result in particle physics

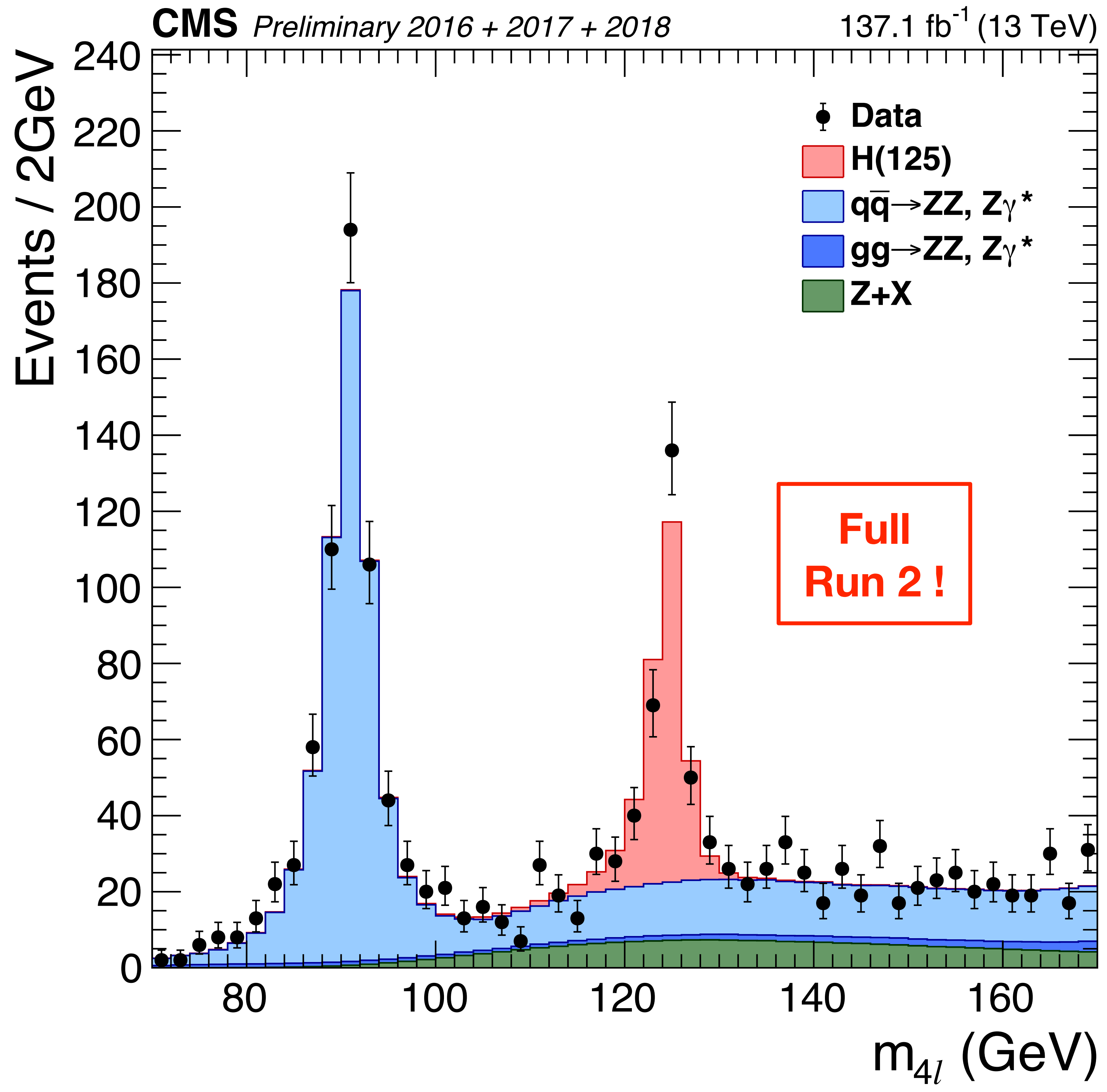
- A textbook discovery (achieved faster than anticipated)
- A gift of nature (a Higgs boson mass maximising the number of channels in which to measure its coupling properties)

At the time of the discovery the Higgs boson mass was already known to be 125 GeV at 0.5% precision.

The Discovery Channels

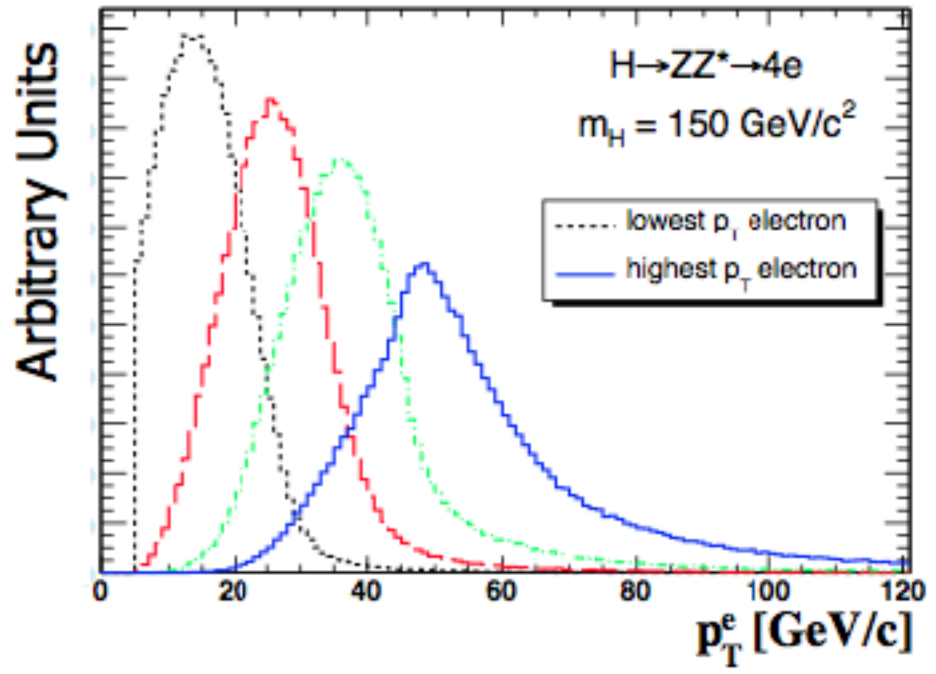
« Bread and Butter » Mass peak signals: the diphoton channel

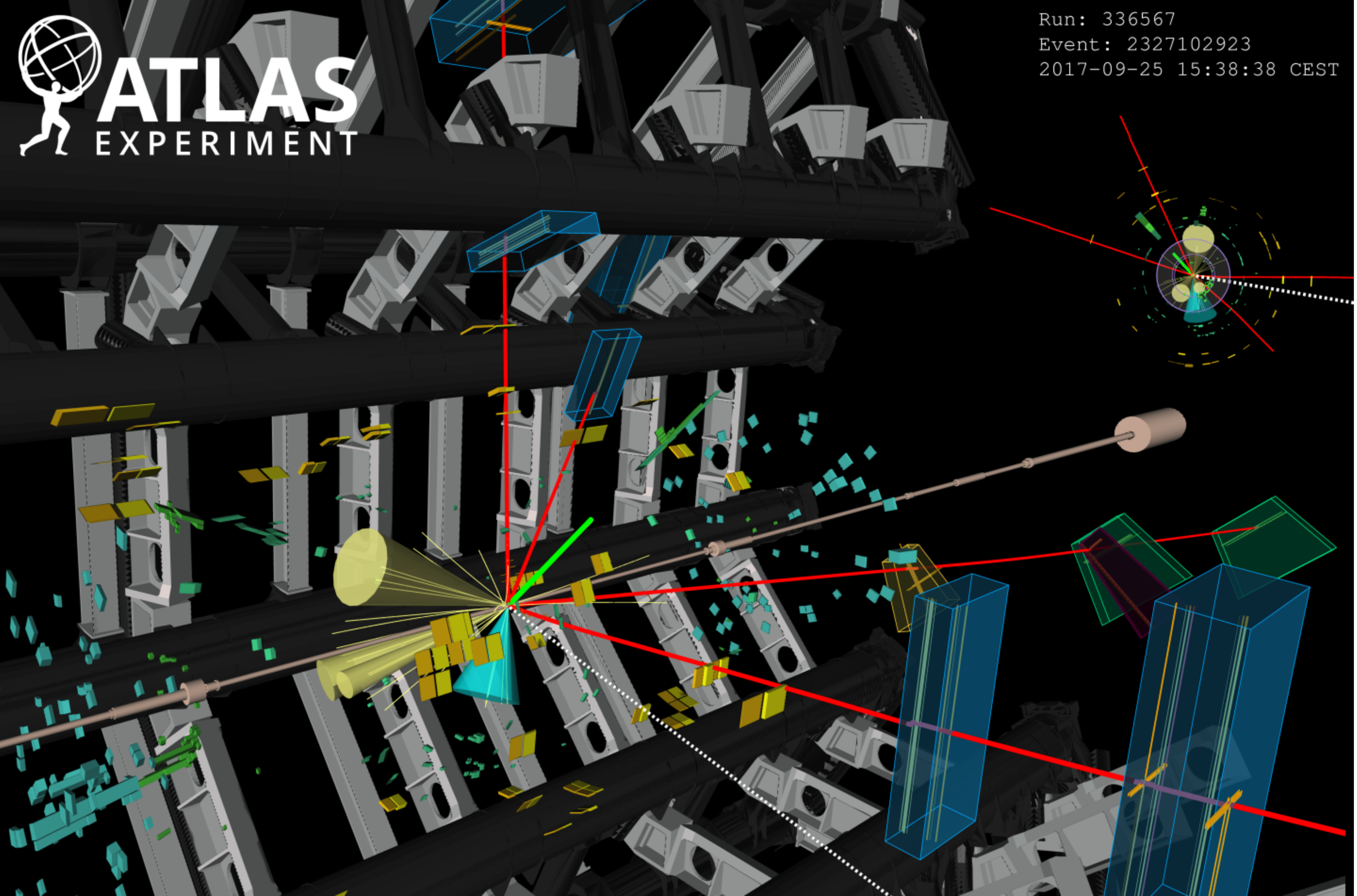




- Low signal over background but overall relatively high statistics of signal (O(300) at Run 1)
  - High mass resolution channel O(1%) allowing data driven estimate of background in the sidebands.
    - If observed implies that it does not originate from spin 1 : Landau-Yang theorem

- Channel with High s/b ratio
- Very low rate due to branchings of ZZ and Z to leptons! Efficiency is key!
- The trailing lepton is at low pT.





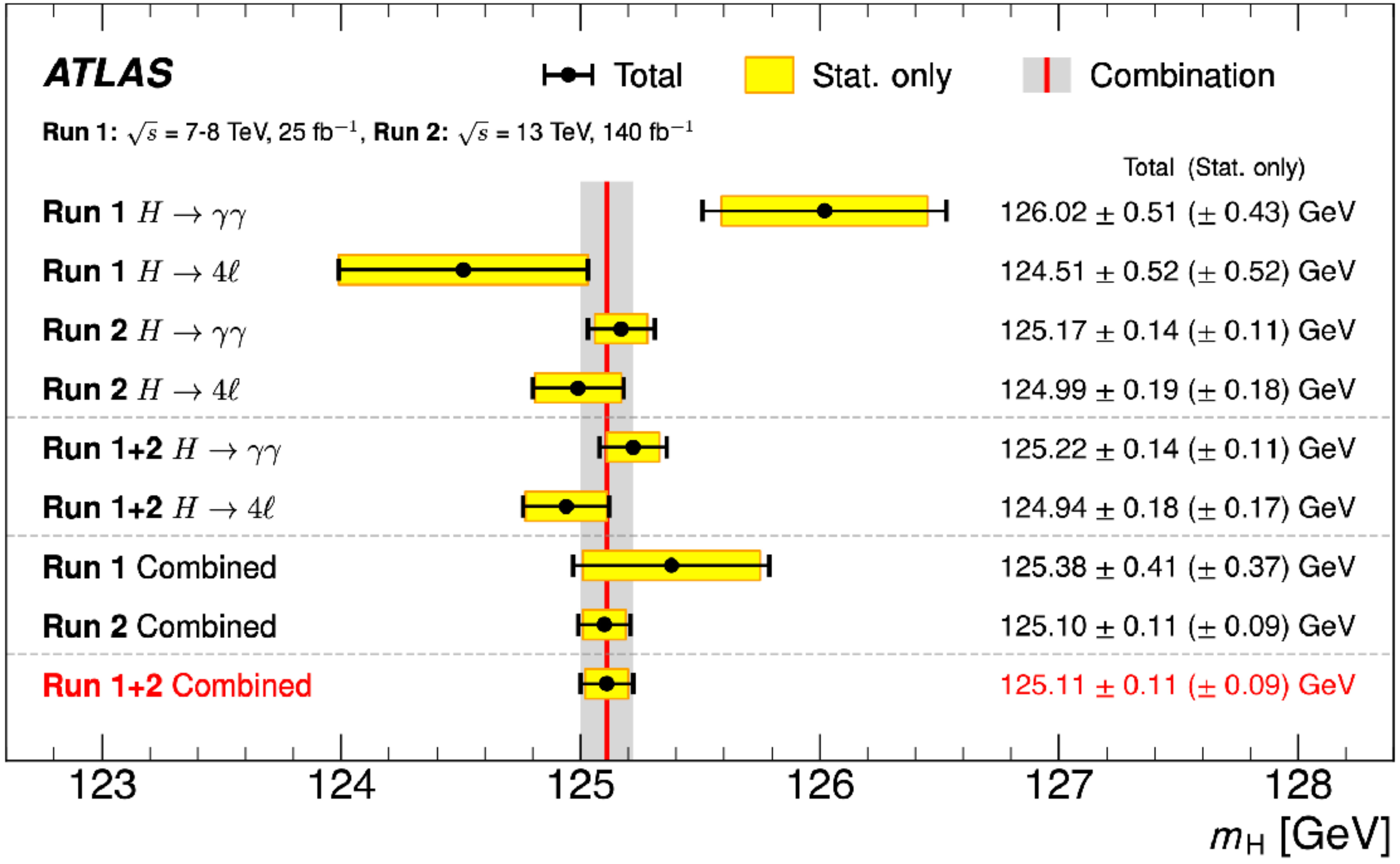
4 muon event with mass 124.4 GeV, one Z mass of 89,3 GeV and the lower mass of 33 GeV, one electron, four jets, lowest pT has tighest b-tagging.

$$s/b \sim 30$$

First Precision Measurement at the LHC!

Higgs boson mass measurement

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

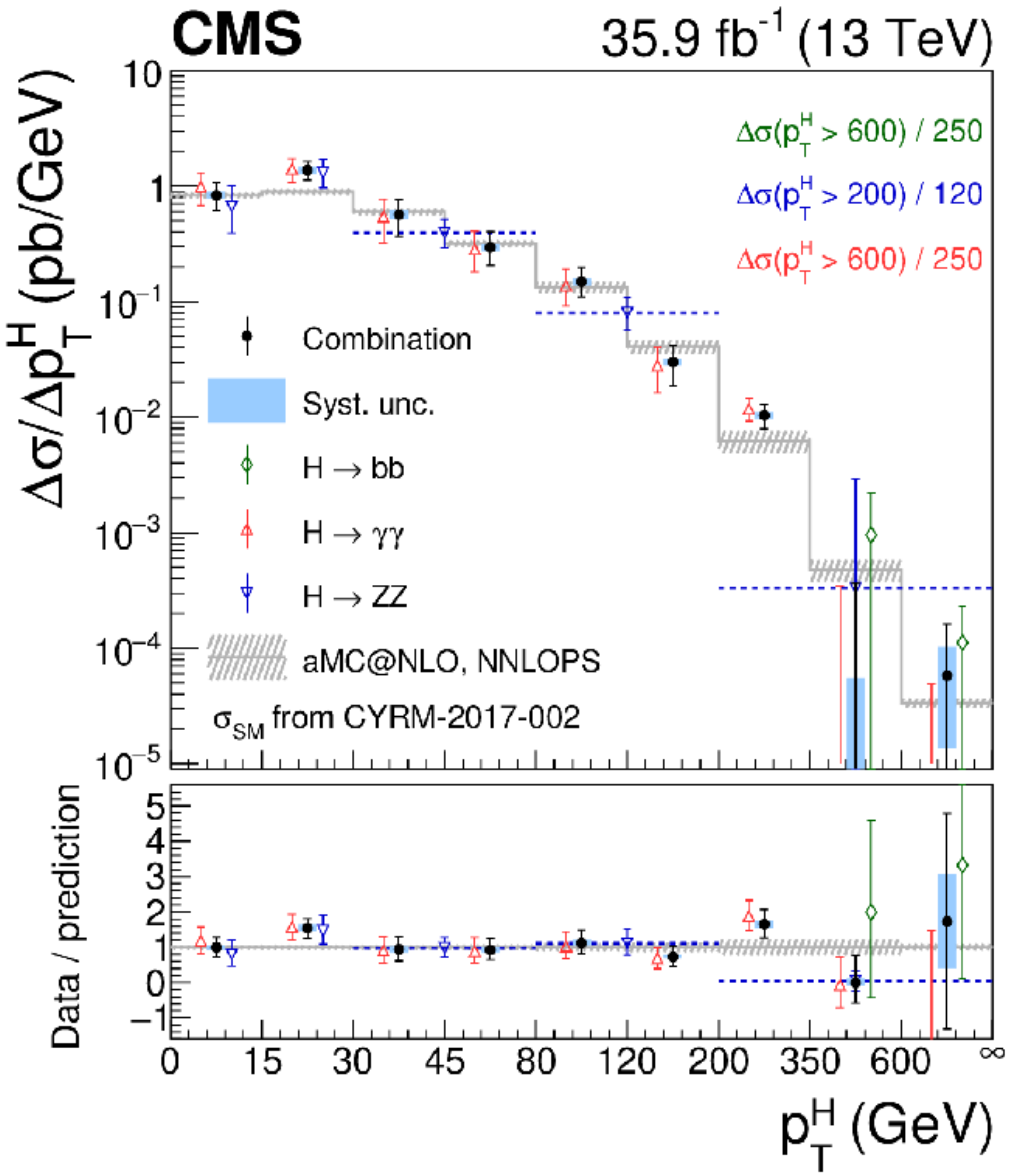


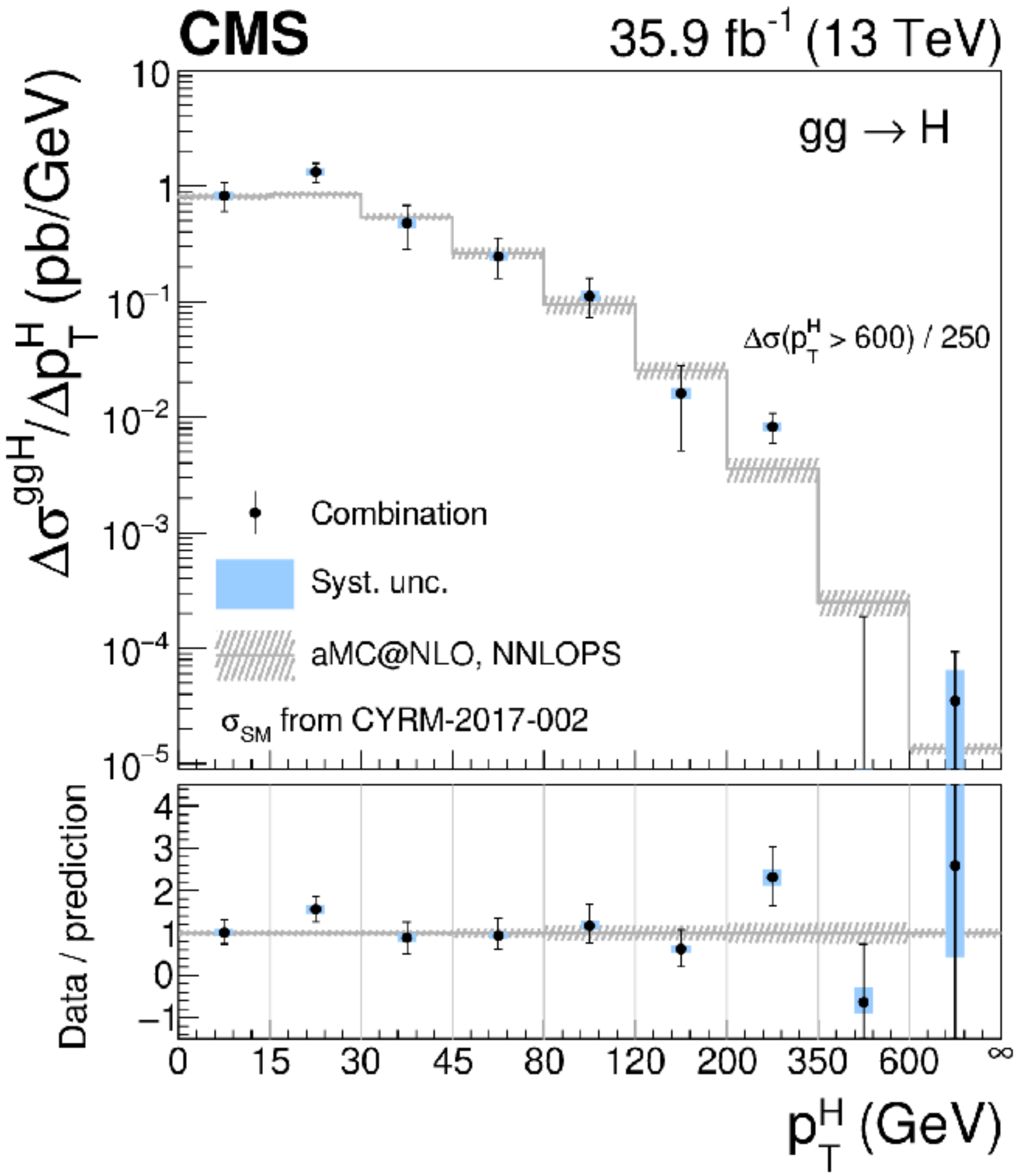
Precision foreseen at HL-LHC 10-20 MeV

Similar precision by CMS

Differential (fiducial and unfolded) Cross Section Measurements

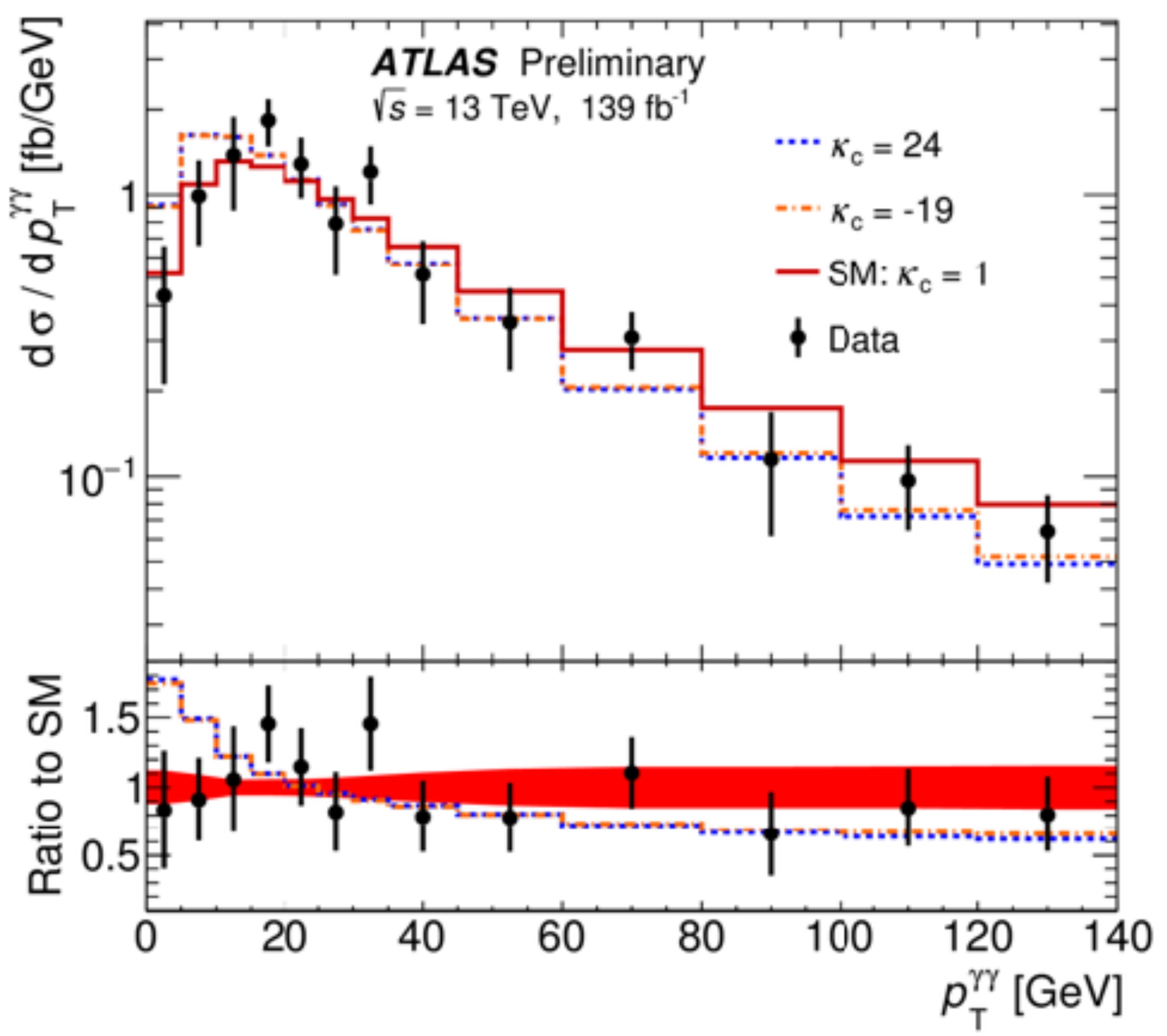
Partially fiducial and unfolded differential cross section measurement in pT (not updated for illustration)

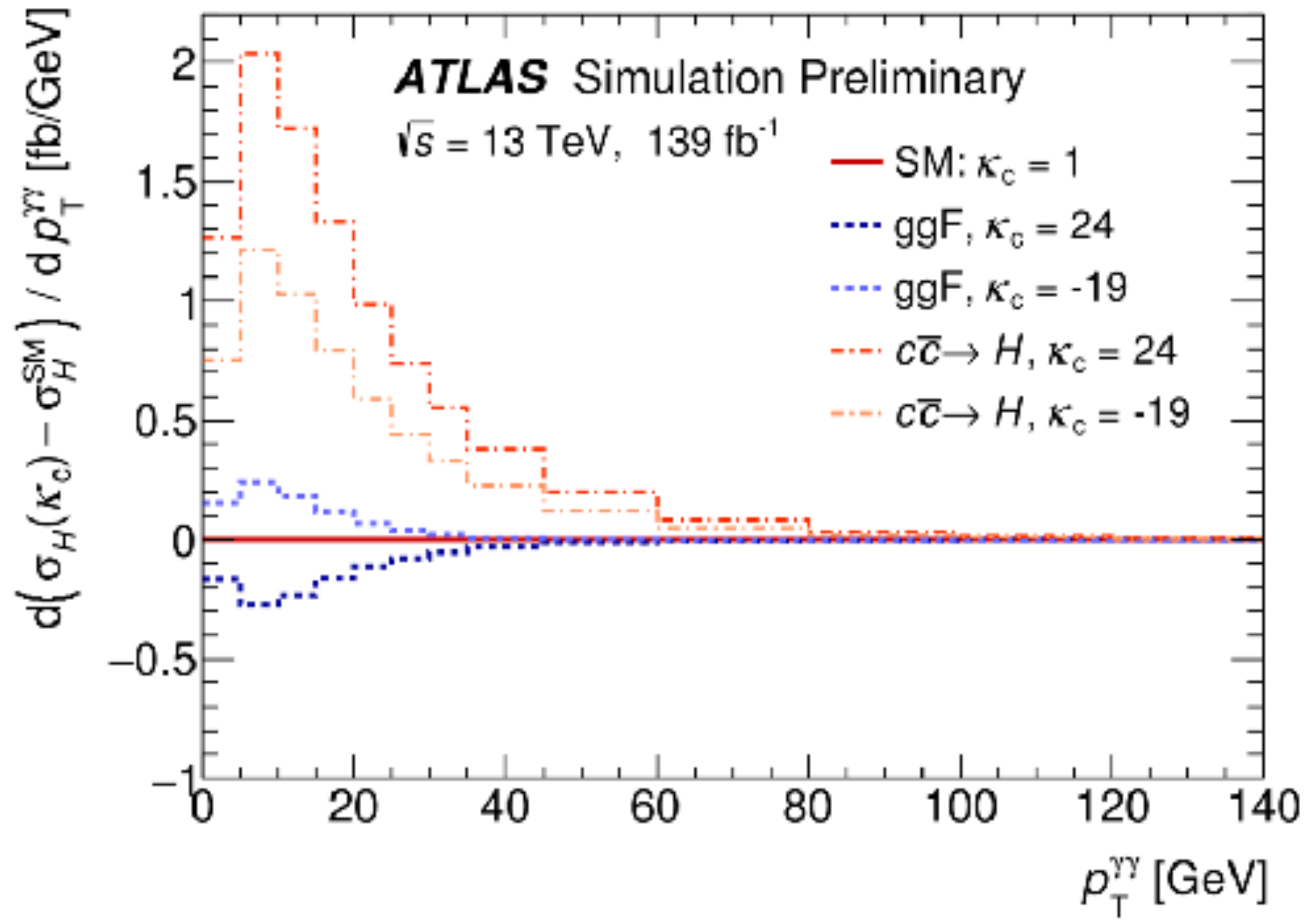


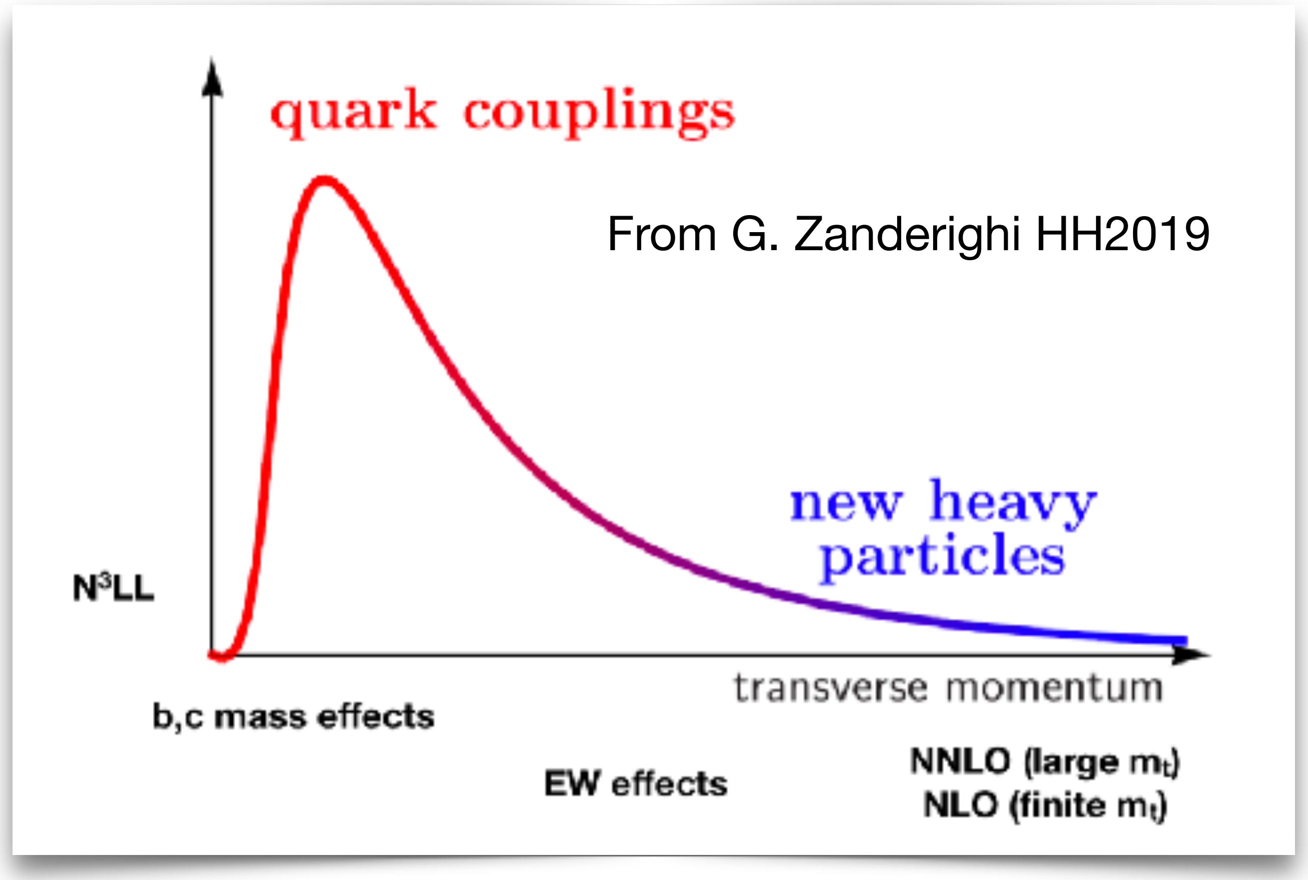


Differential (fiducial and unfolded) Cross Section Measurements

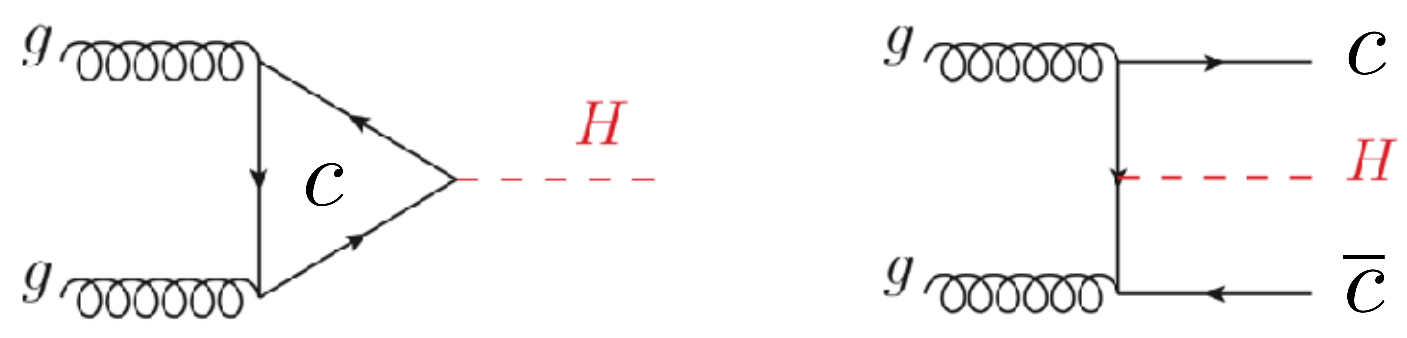
Fiducial and unfolded differential cross section measurement in pT







Indirect measurement of the b and c Yukawa couplings through loop:



Significant at large values of κ_c

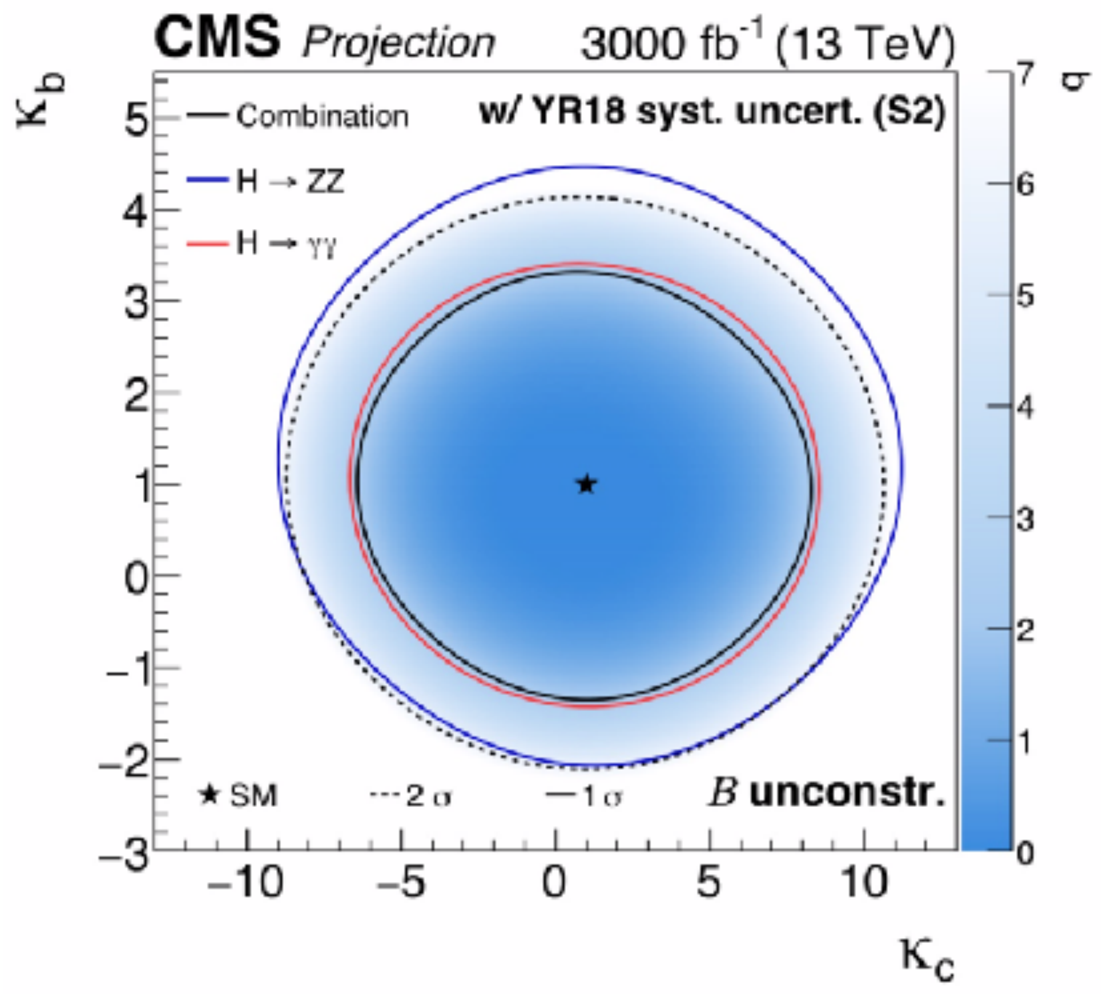
Current 95% CL limits on κ_c:

$$-19 < \kappa_c < 24$$

CMS HL-LHC projection (see YR)

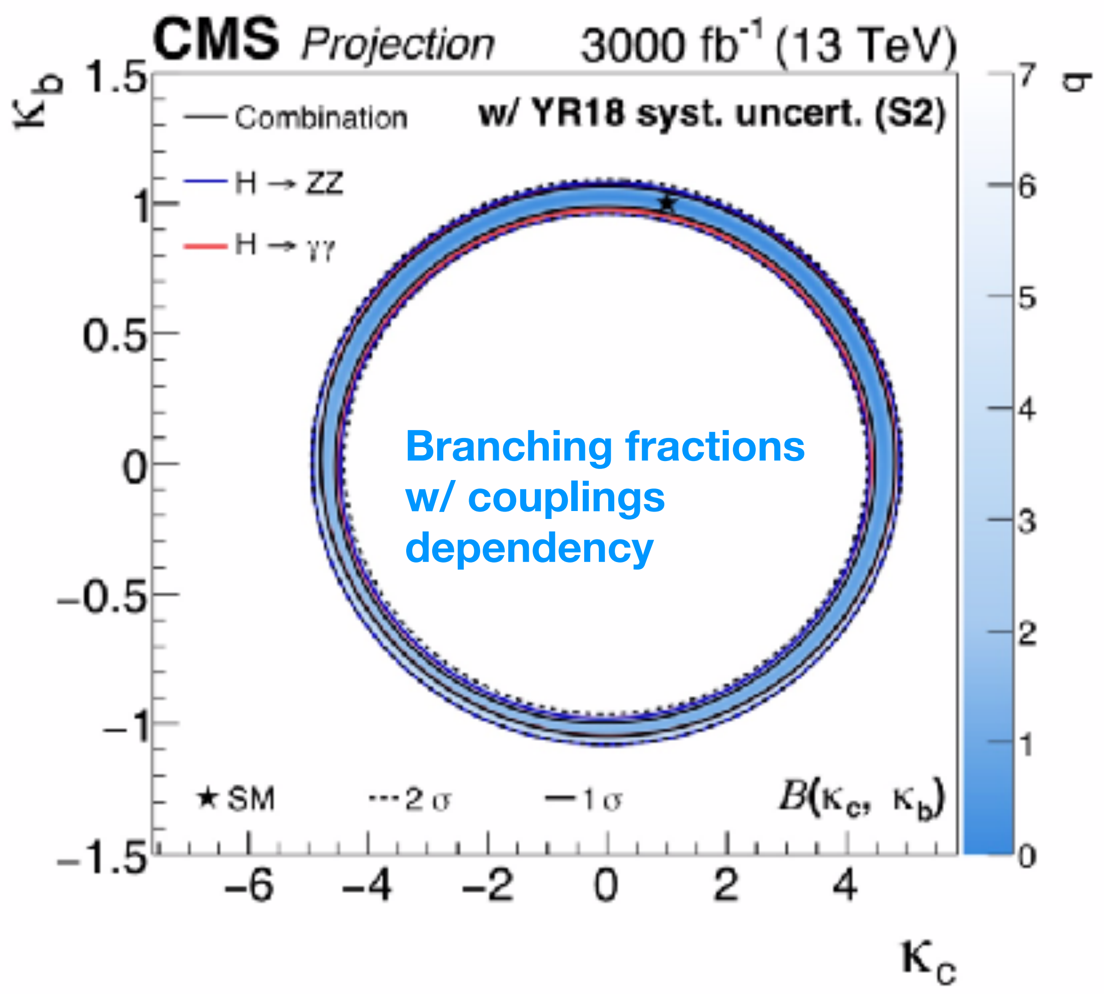
Shape only

~8 x SM



Parametrised branchings

~4 x SM



Searches for Higgs production with charm tagged are starting.

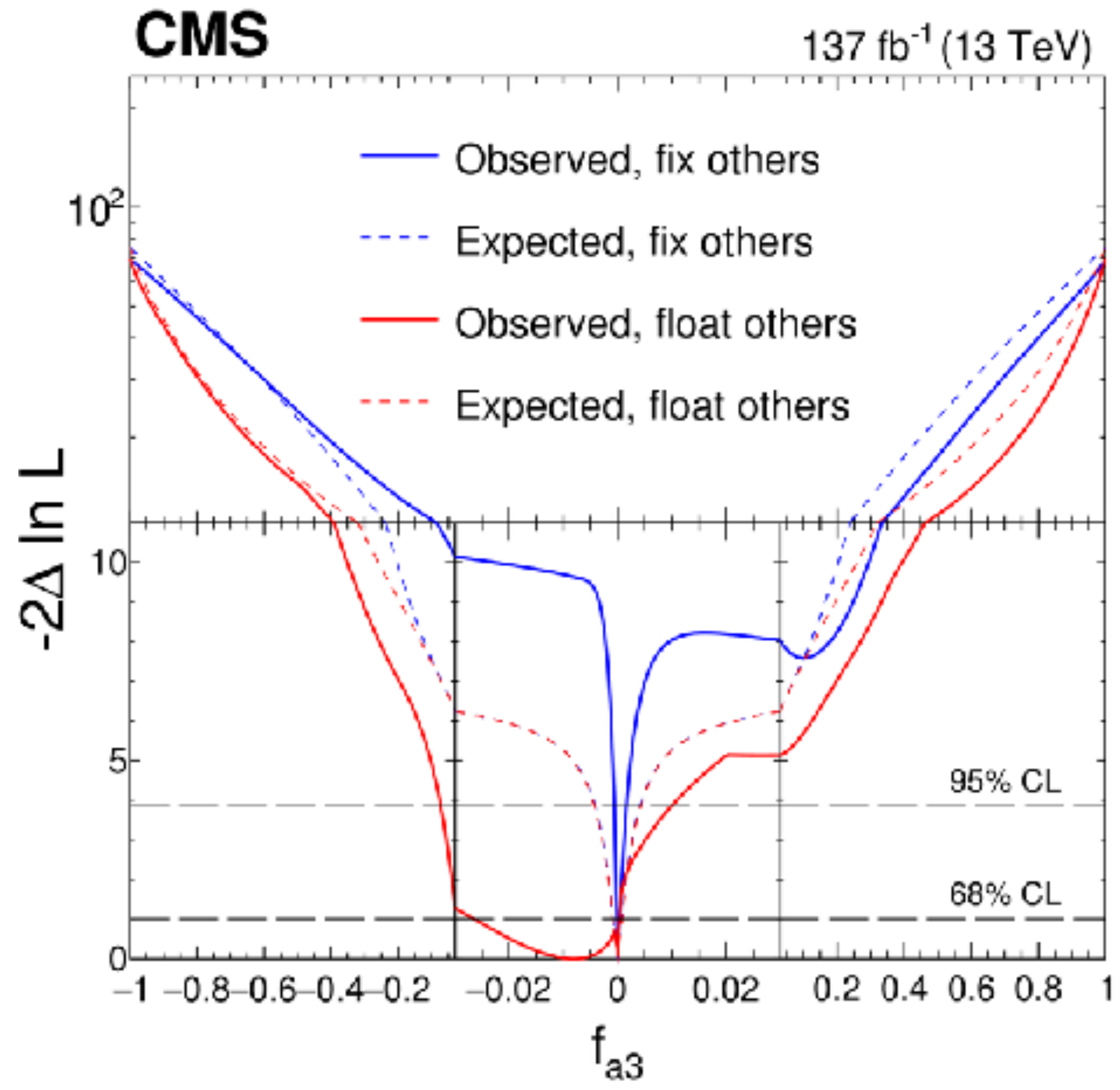
CP Properties of Higgs Couplings in Diboson Channels

CP odd Higgs couplings to vector bosons only at higher orders (expected to be suppressed)

$$\mathcal{L}_0^{W,Z} \supset \left\{ \cos(\alpha)\kappa_{\rm SM}\left[\frac{1}{2}g_{HZZ}Z_\mu Z^\mu + g_{HWW}W^+_\mu W^{-\mu}\right] - \frac{1}{4\Lambda}\left[\cos(\alpha)\kappa_{HZZ}Z_{\mu\nu}Z^{\mu\nu} + \sin(\alpha)\kappa_{AZZ}Z_{\mu\nu}\tilde{Z}^{\mu\nu}\right] - \frac{1}{2\Lambda}\left[\cos(\alpha)\kappa_{HWW}W^+_{\mu\nu}W^{-\mu\nu} + \sin(\alpha)\kappa_{AWW}W^+_{\mu\nu}\tilde{W}^{-\mu\nu}\right]\right\} H$$

$$A \sim \left[a_1^{VV} - \frac{\kappa_1^{VV}q_1^2 + \kappa_2^{VV}q_2^2}{(\Lambda_1^{VV})^2} - \frac{\kappa_3^{VV}(q_1+q_2)^2}{(\Lambda_Q^{VV})^2}\right] m_{V_1}^2 \varepsilon_{V_1}^* \varepsilon_{V_2}^* + a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

Example **Measurement from CMS** based on amplitudes and angular distributions of leptons!

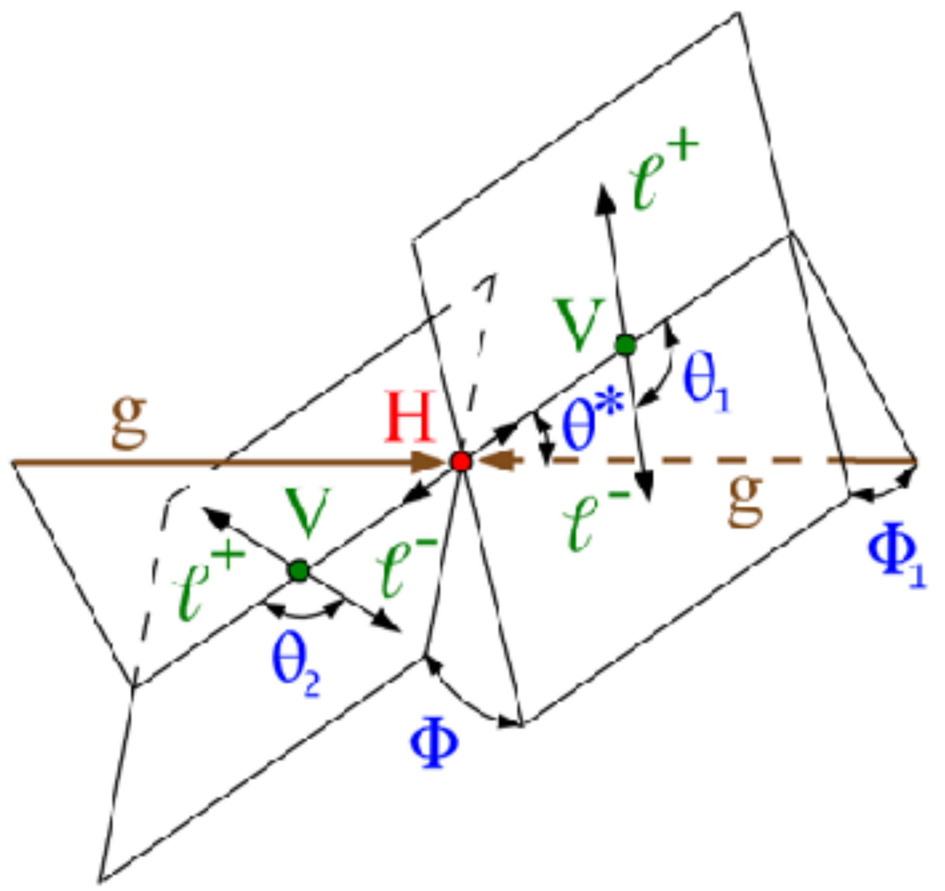


$$f_{\mu\nu}^{*(i)} = \varepsilon_i^\mu q^\nu - \varepsilon_i^\nu q^\mu$$

$$f_{a_i} = \frac{|a_i|^2\sigma_i}{\sum_{j=1,2,3}|a_j|^2\sigma_j}$$

$$\phi_{a_i} = \arg\left(\frac{a_i}{a_1}\right)$$

Illustration of 5 production and decay angles for the 4-leptons (most sensitive to the CP mixing)



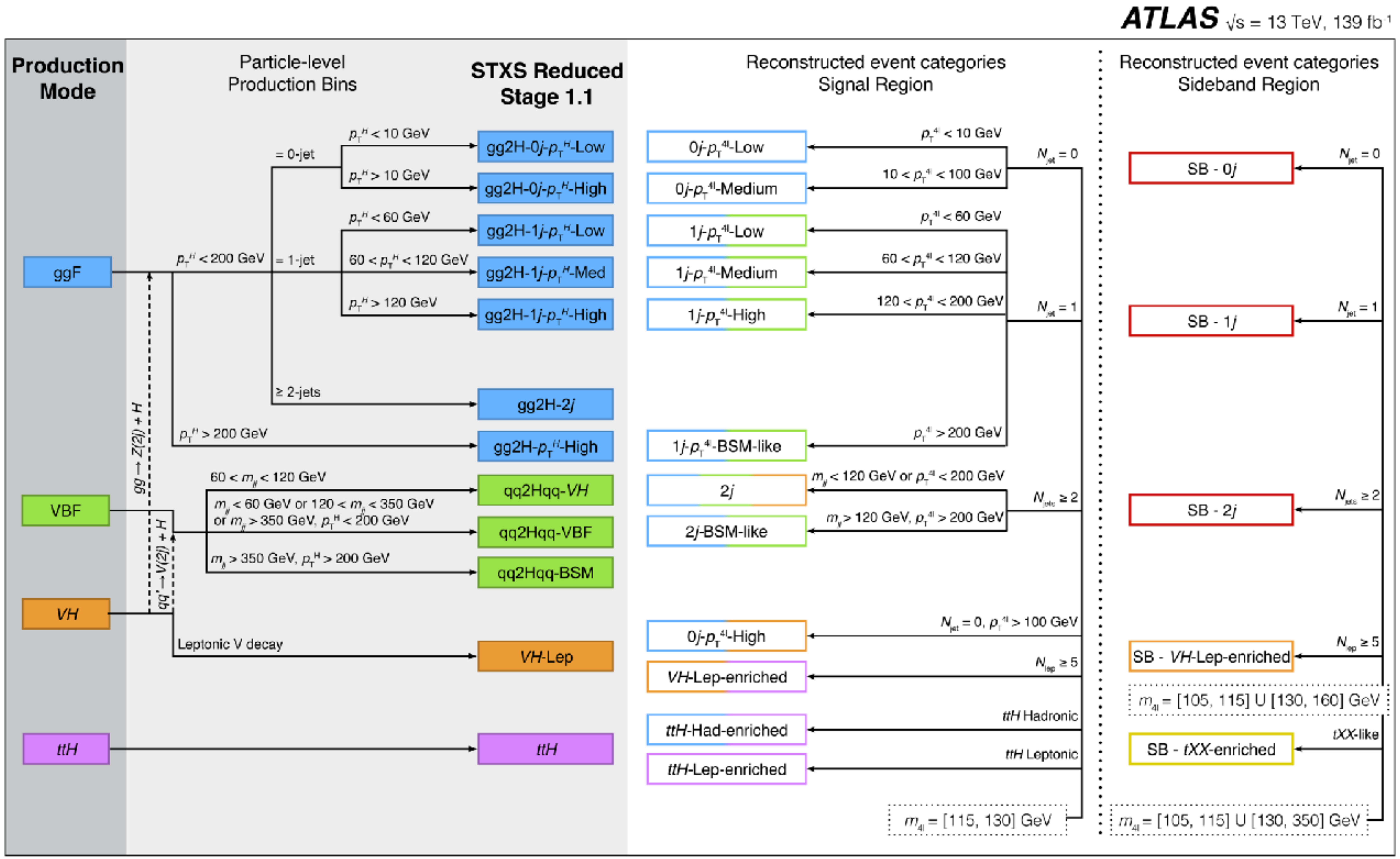
CP violating fraction for a scalar Higgs of <2% at 68% CL (and ~10-20% at 95% CL)

Similar analysis also done in ATLAS

Hybrid Approach: Simplified Template Cross Sections

Example in the **four leptons channel**: the goal is to measure as precisely as possible individual production processes (ggF, VBF, VH and ttH) in different regions of phase space.

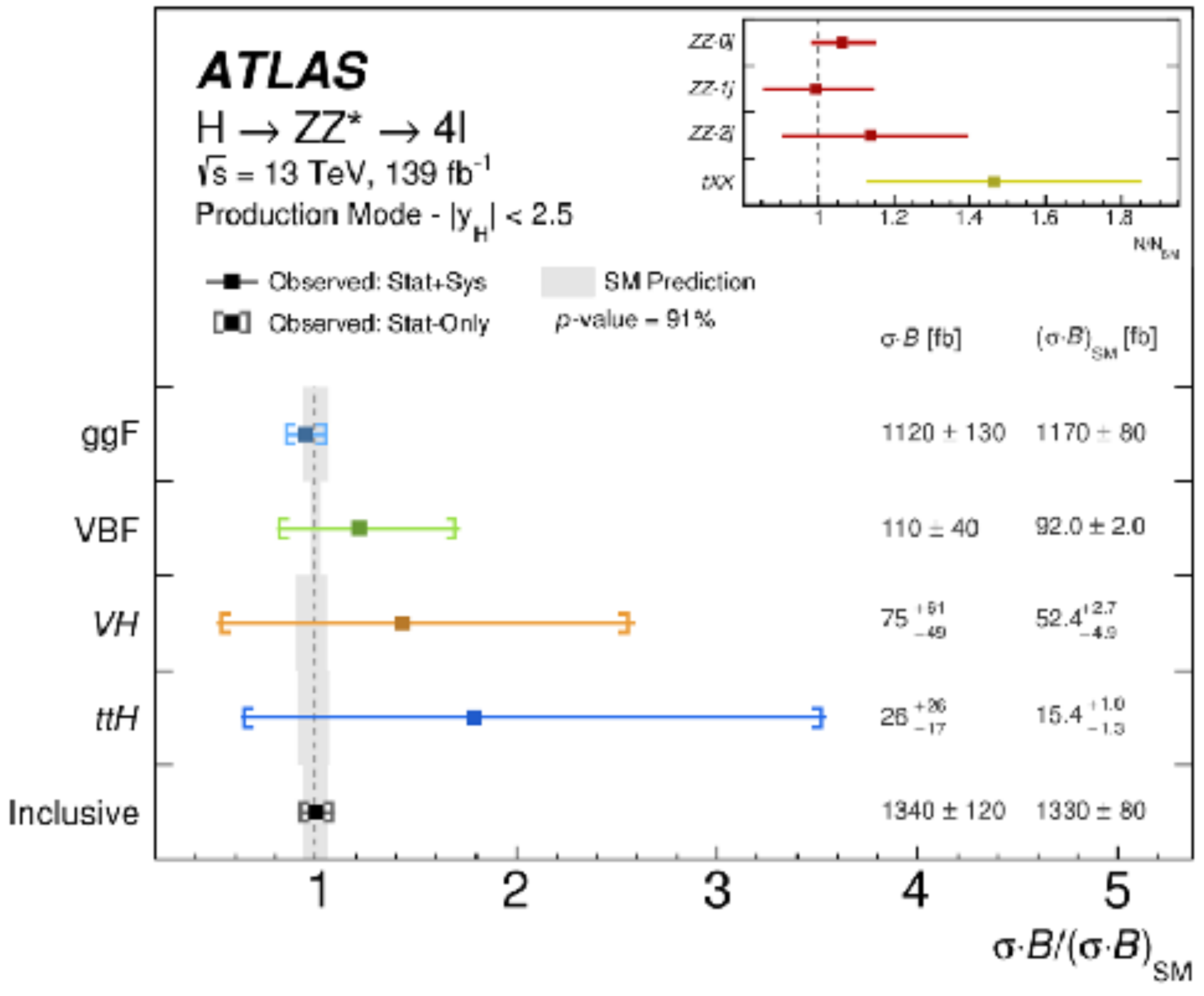
- Define fiducial cuts at truth particle level on the pT of the **Higgs (not its decay products!)** and number and kinematics of the additional jets or leptons in the events.
- Define reconstruction level cuts corresponding to the fiducial volume of interest.
- The definition of the fiducial volume is guided both by the TH interest and the experimental capabilities.

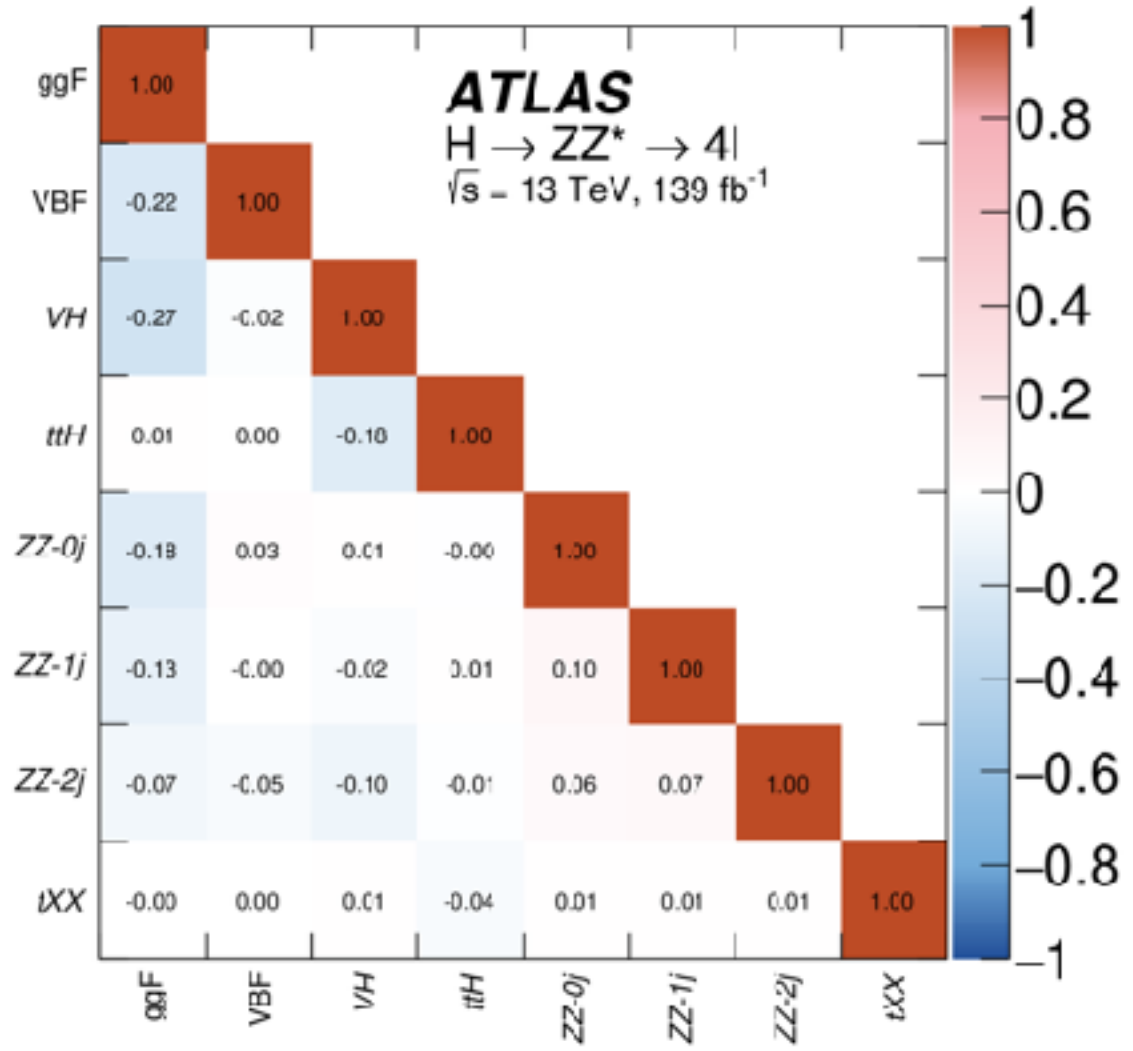


Hybrid Approach

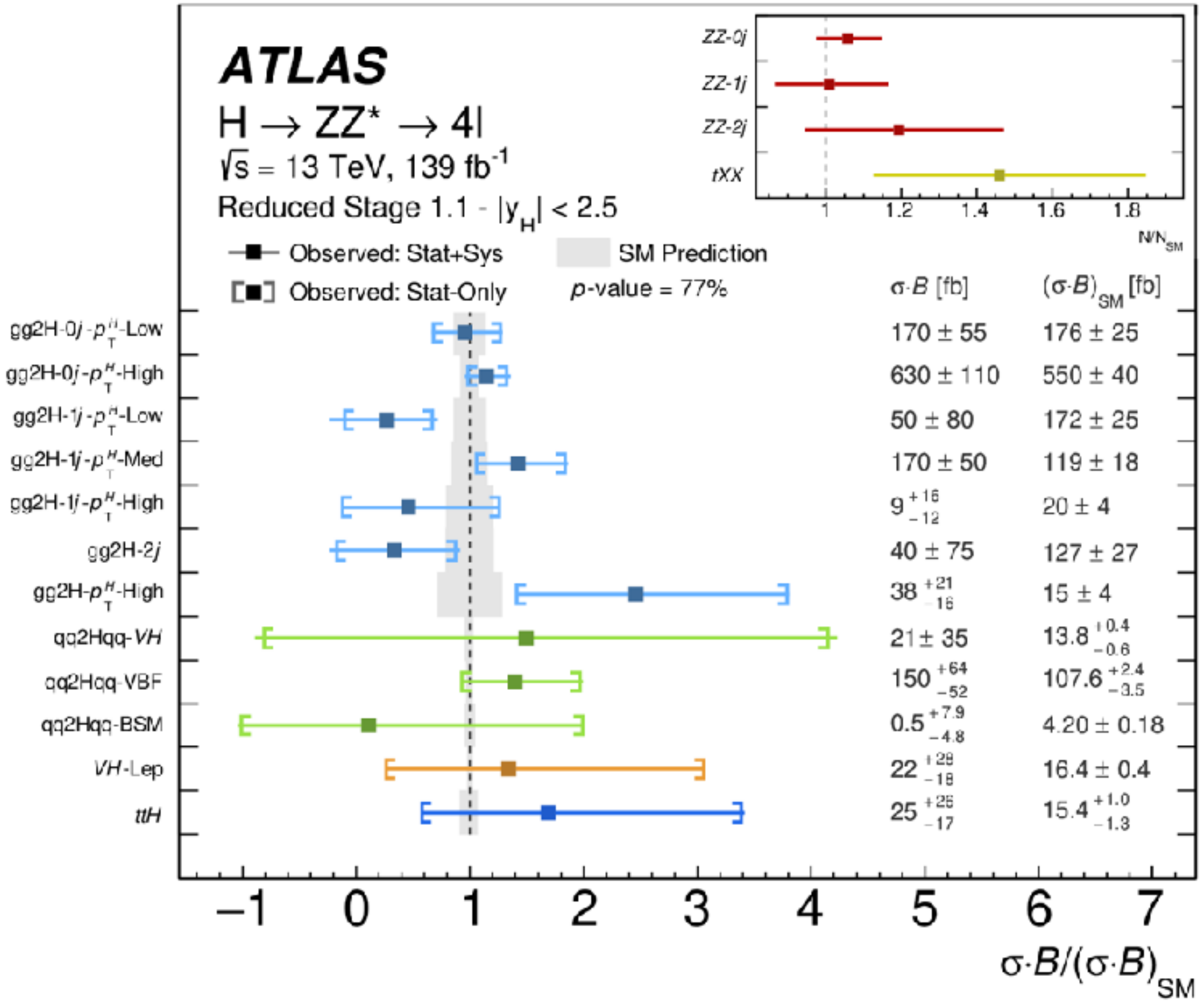
Four lepton channel example

Specific processes total cross sections are extracted from a global fit





Similar measurements can be done in a more exclusive approach with more fiducial cuts are defined:



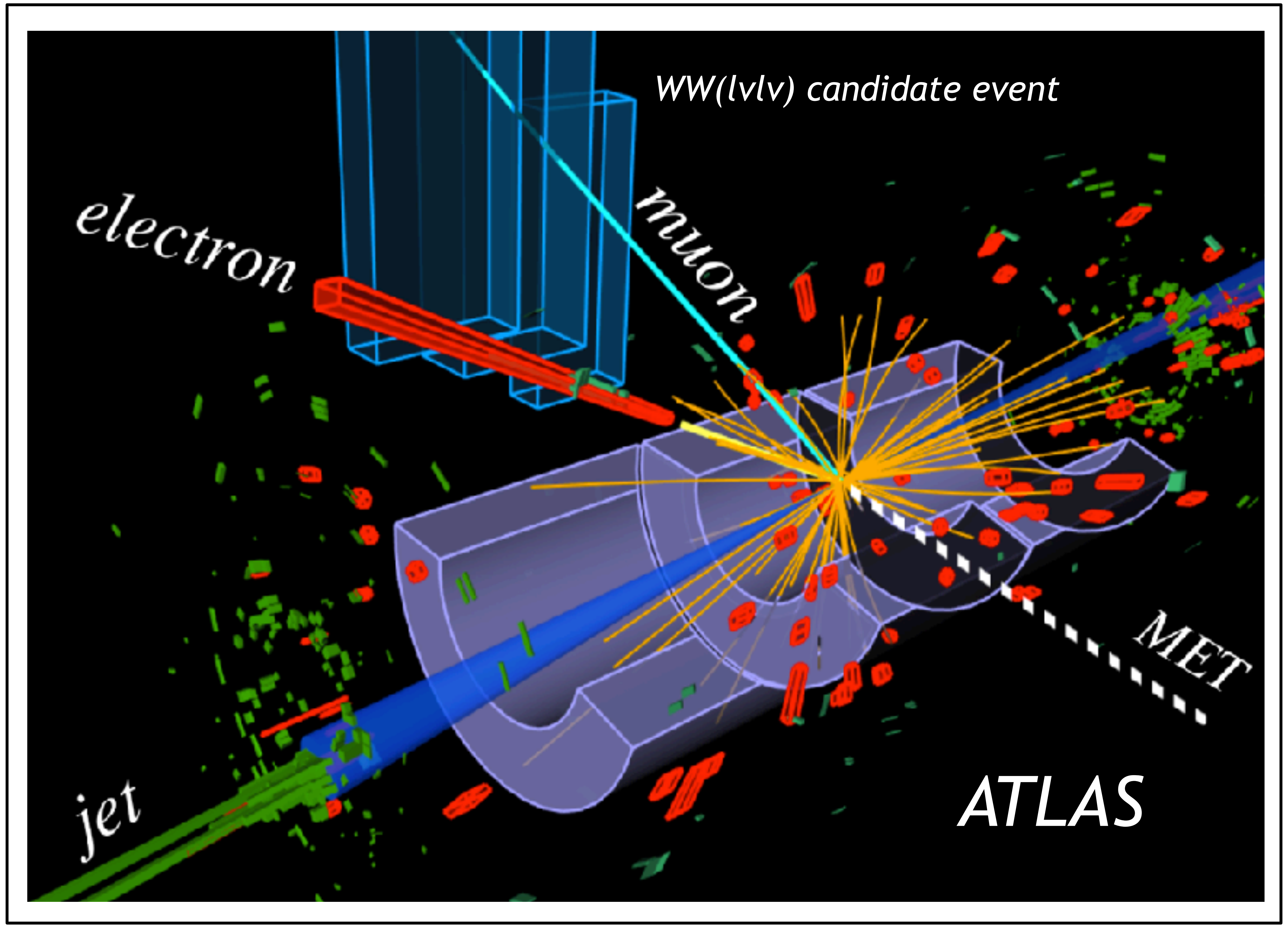
These measurements rely on the specific (SM) predicted acceptance of each process and the fact that no additional production processes are present.

All our couplings measurements are based on this assumption.

These still rely on assumption of (SM) acceptances but are very useful in the case of an EFT approach.

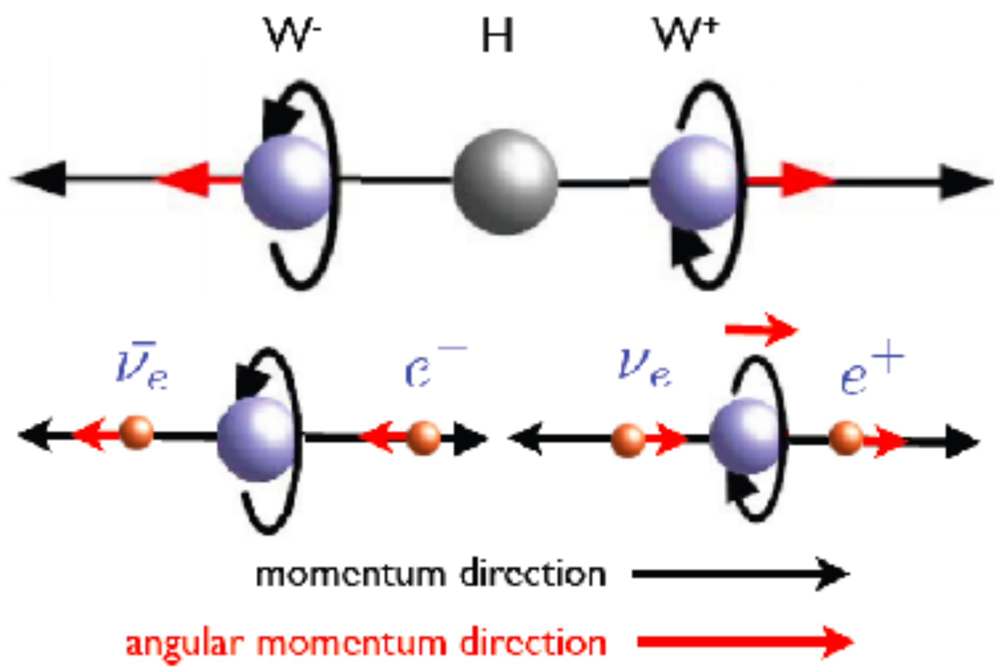
The Discovery Channels

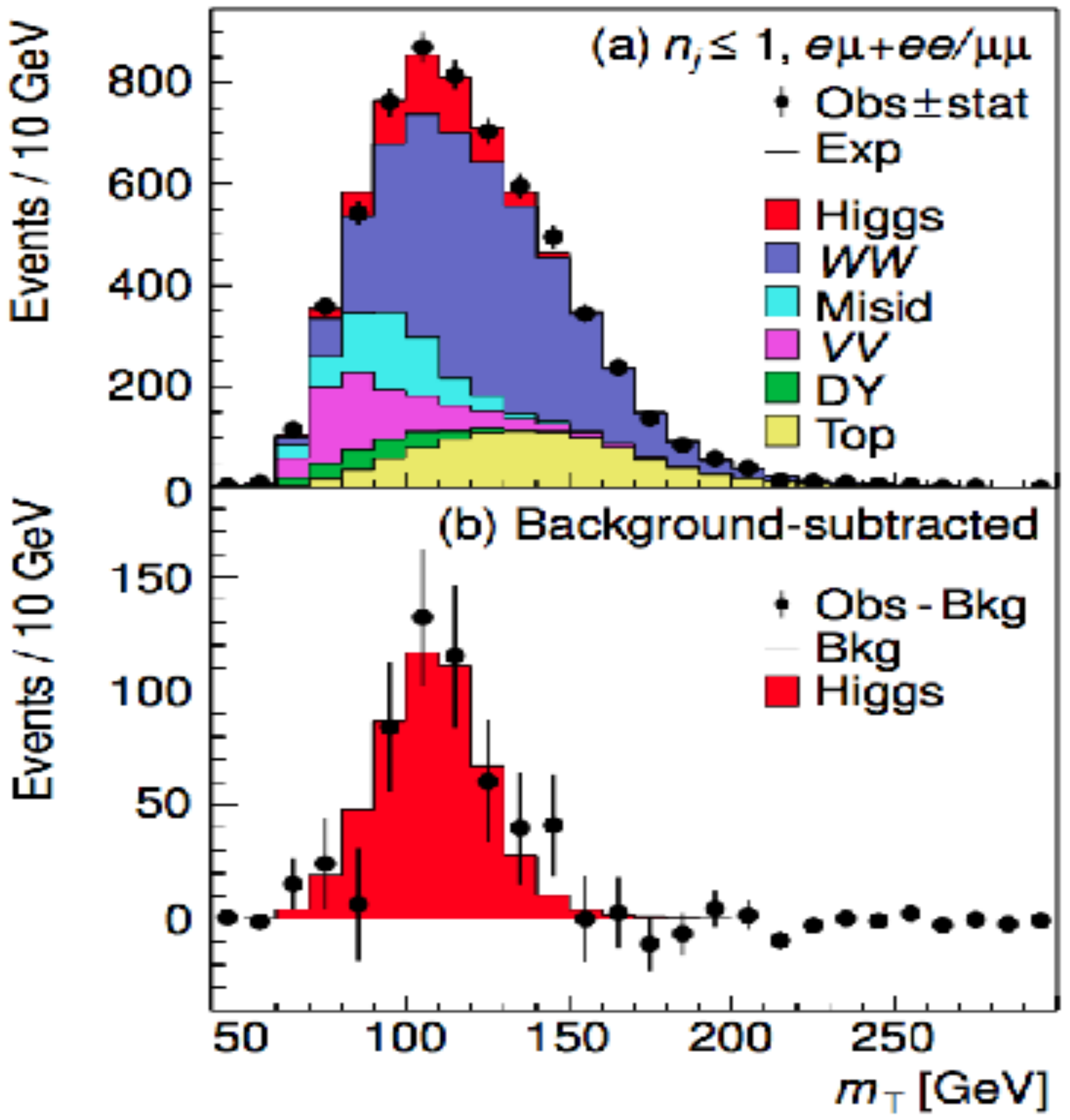
A discovery channel of a different kind: the WW

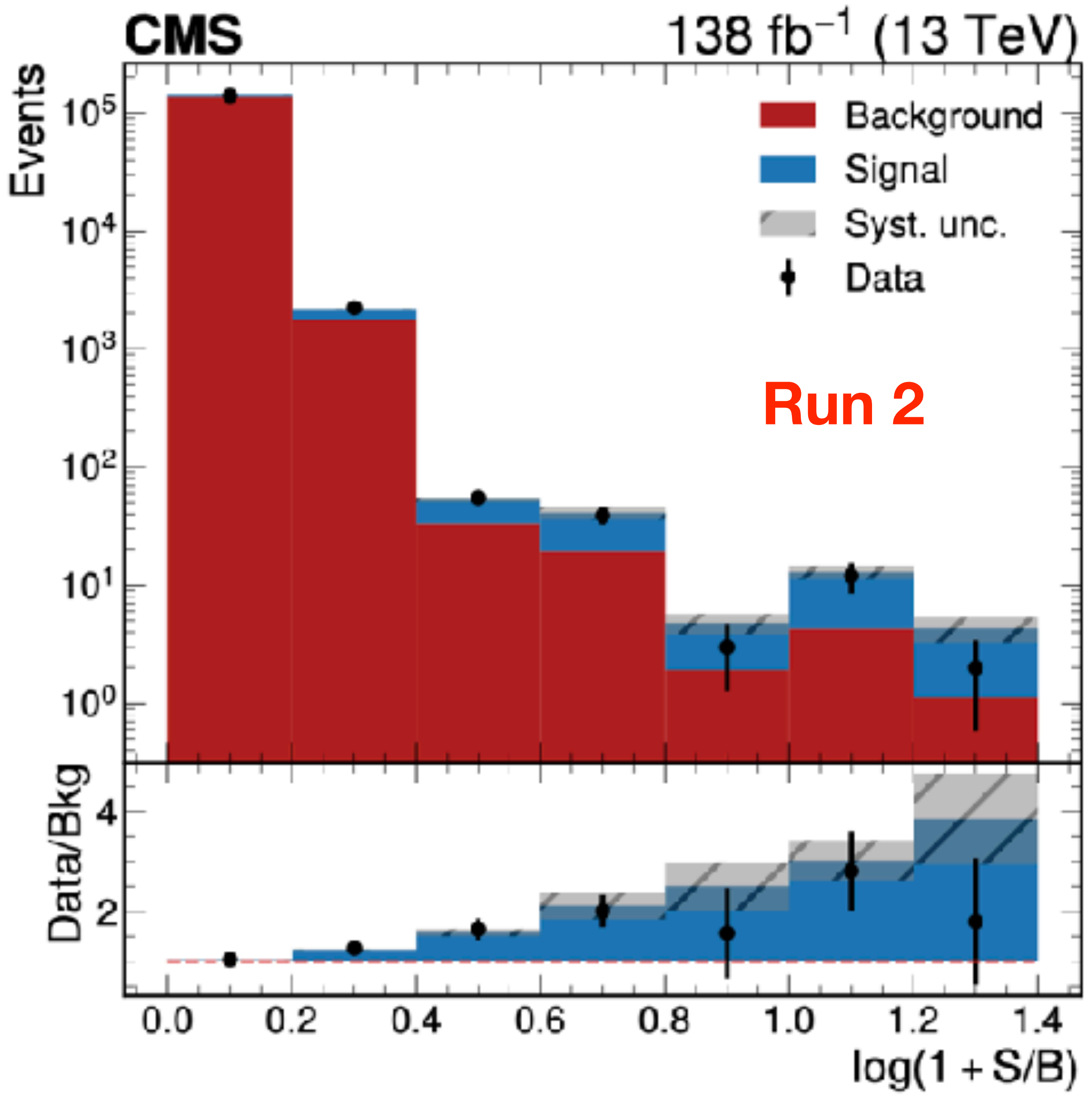


Requires good simulation of backgrounds and control regions in the data.

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







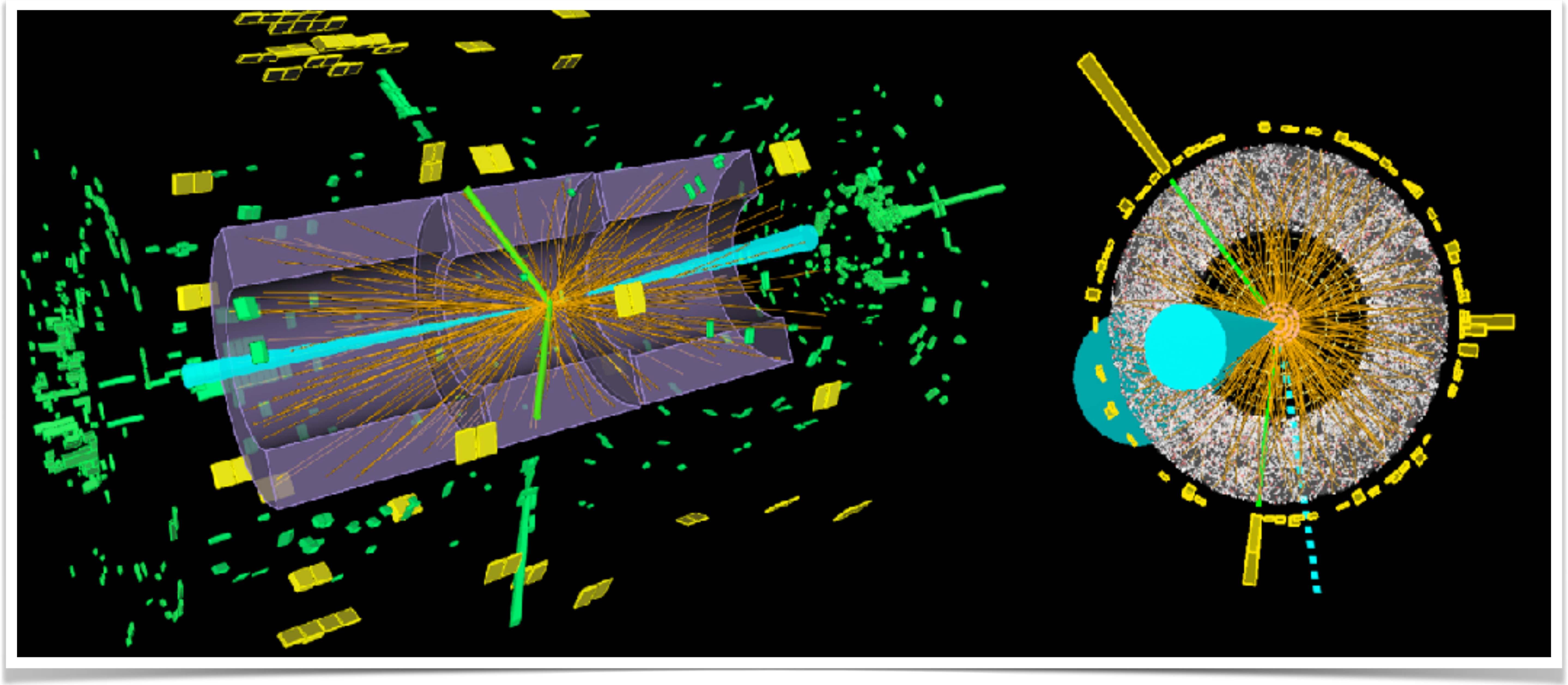
Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

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

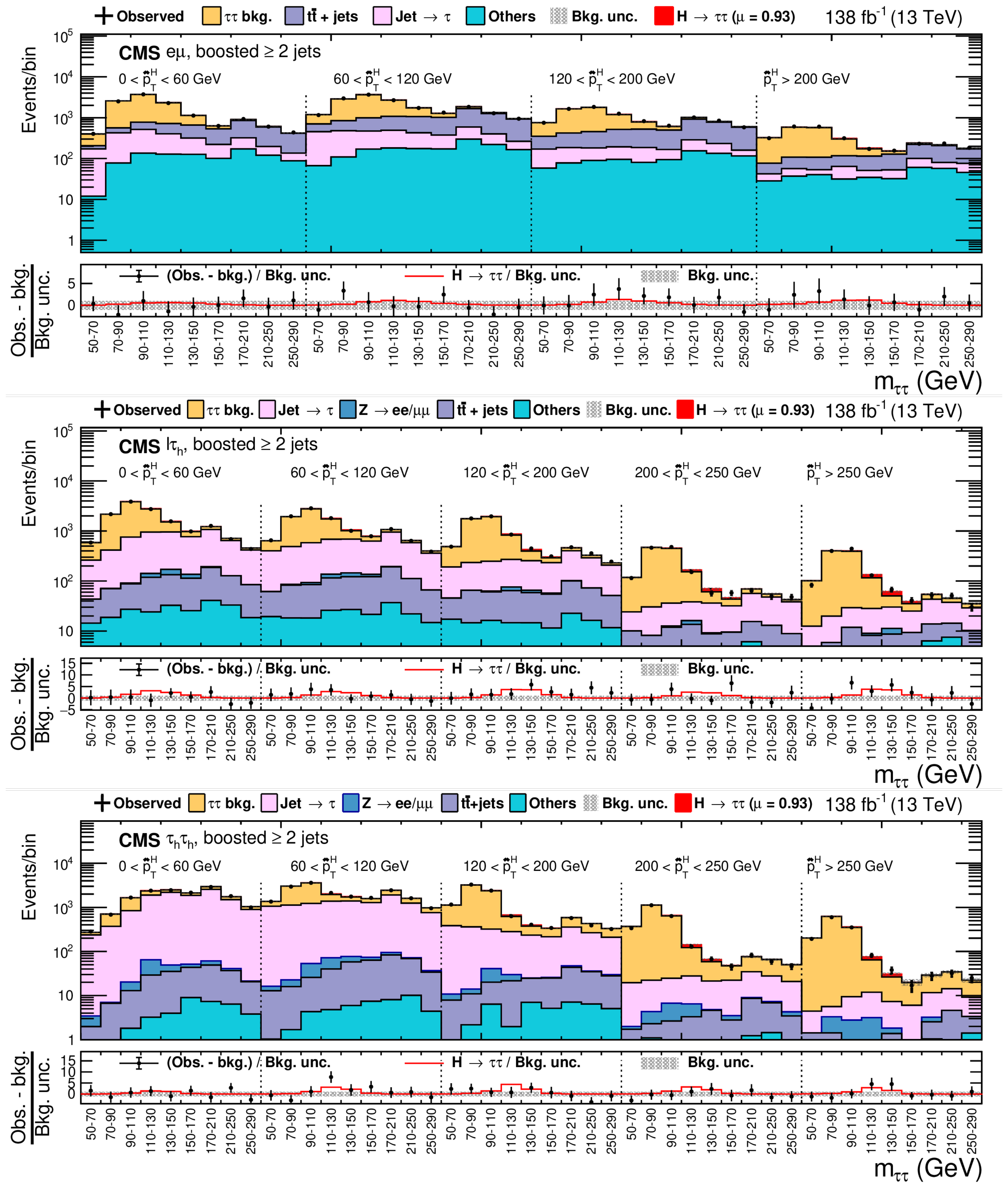
The Run 2 Landmark Results

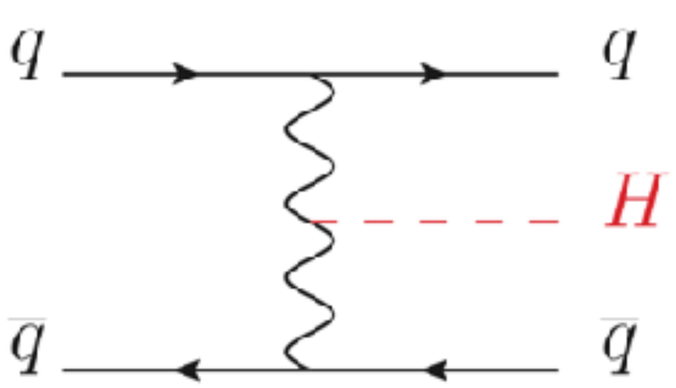
Observation and Measurement of 3^{d} generation Yukawa Couplings

Higgs boson decays to Taus



[Eur. Phys. J. C 83 (2023) 562]

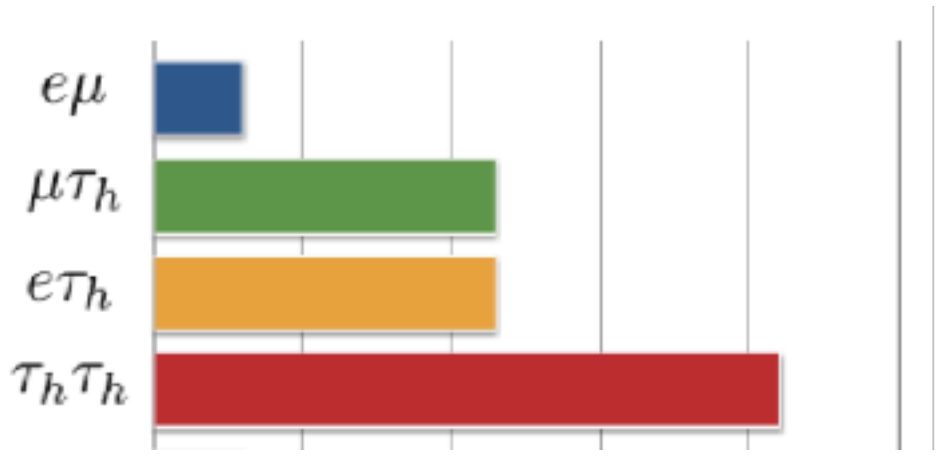




VBF process

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

Tau to leptons ~18% (rest is hadrons)

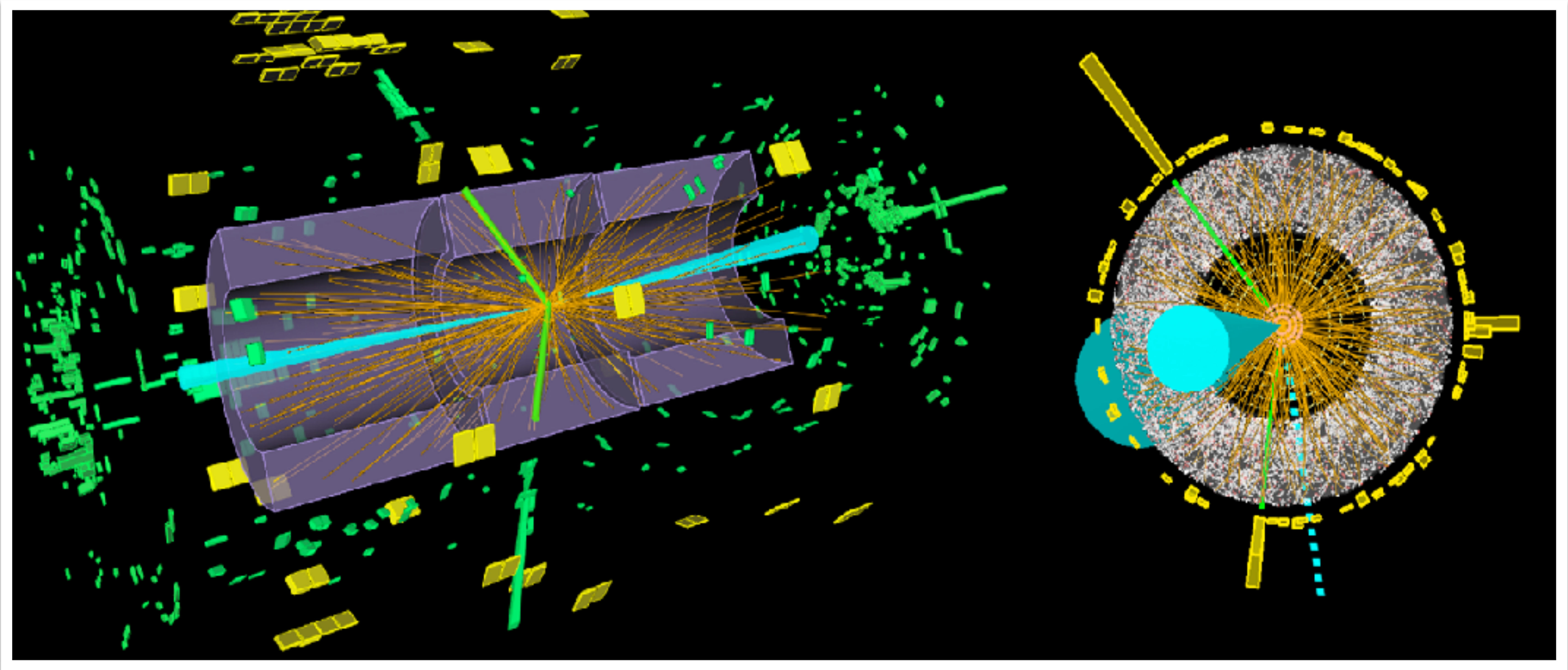


Background is Z production with two jets, in this region of phase space it is difficult to predict!

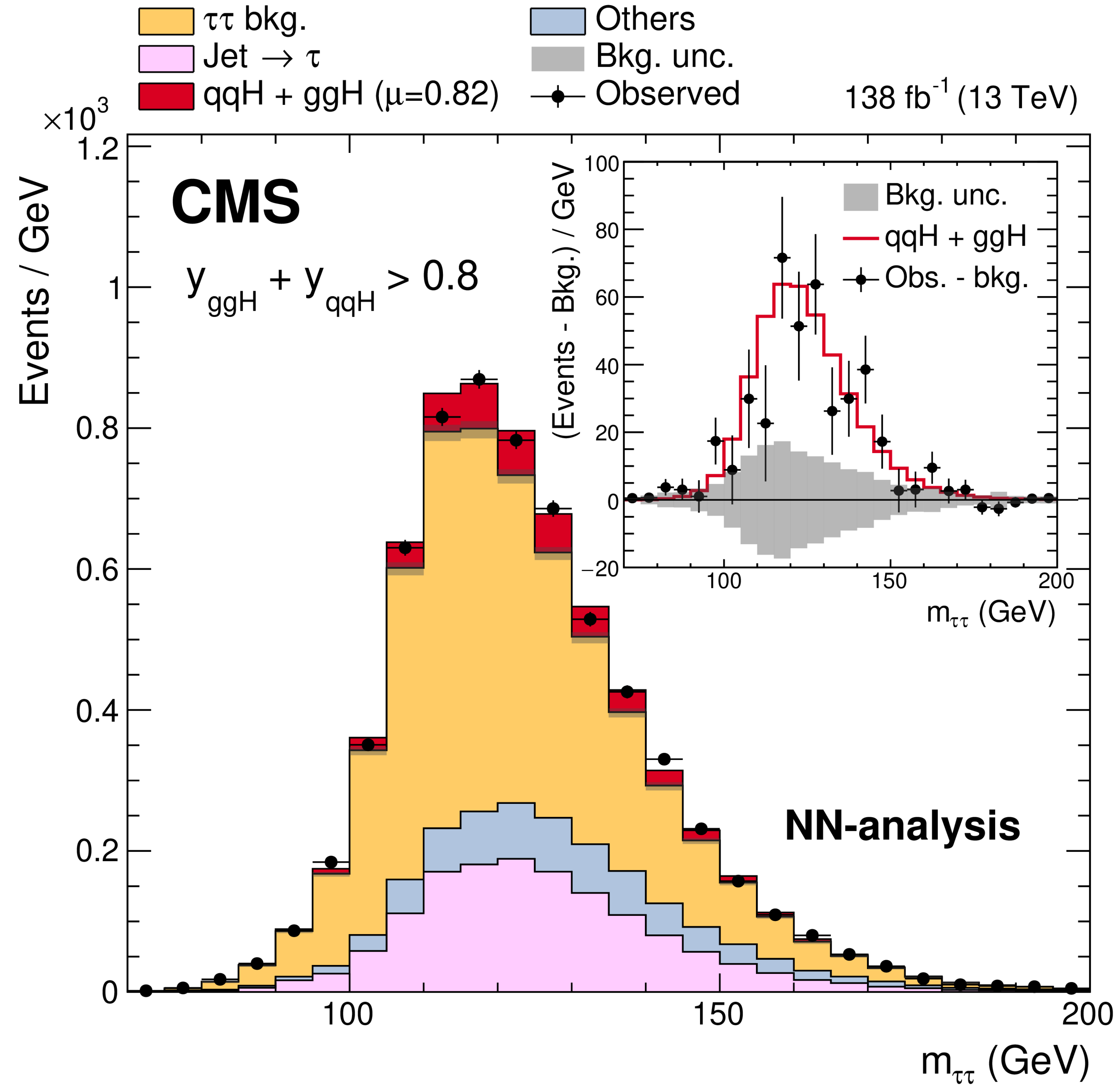
Analysis based on several channels depending on the decay mode of the tau.

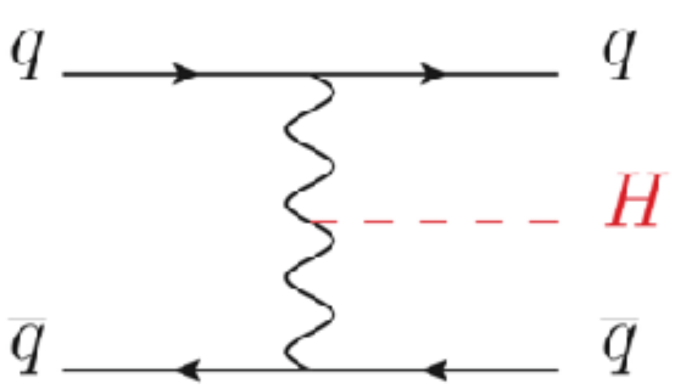
Analysis requires data driven methods e.g. the embedding of taus in Z to di-muon events.

Higgs boson decays to Taus



[Eur. Phys. J. C 83 (2023) 562]





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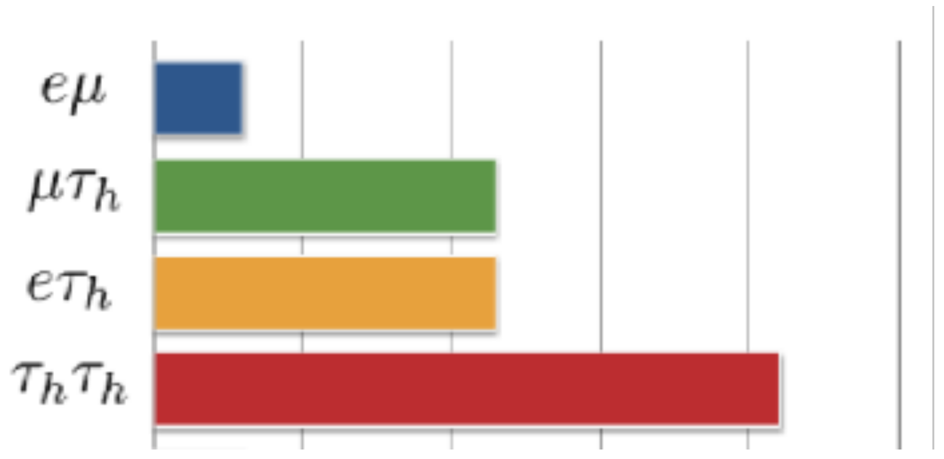


Background is Z production with two jets, in this region of phase space it is difficult to predict!

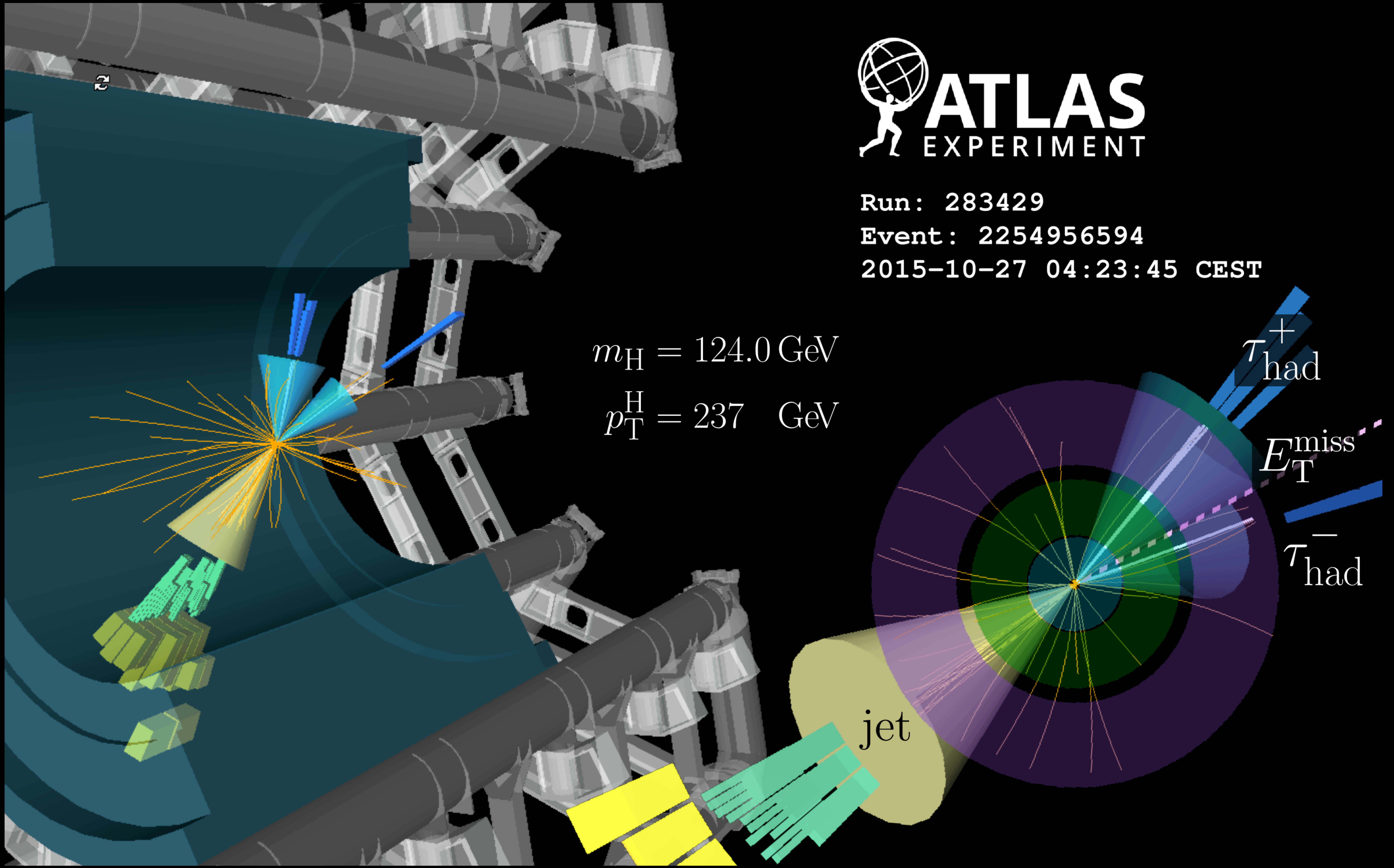
Analysis based on several channels depending on the decay mode of the tau.

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

Analysis done in large number of categories covering ggH, VBF, WH and ZH production processes (**STXS bins)**

With two analyses NN and CB (Cut Based)

Higgs Yukawa to taus CP Properties



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

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

Higgs Yukawa to taus CP Properties

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

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

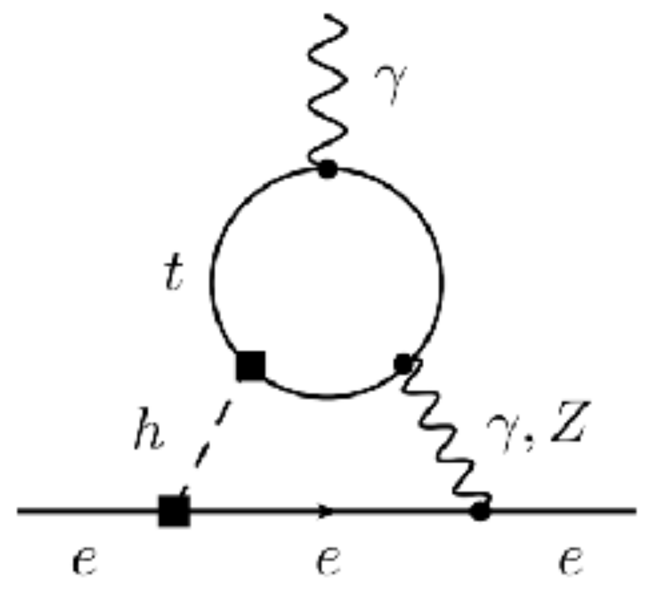
Non zero $\tilde{\kappa}_f$ implies CP violation in the Yukawa interaction

EDMs of the electron (and neutron, proton) are an important probe for CP violating effects. Very suppressed in the SM/ CKM (where it arises at four loops).

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

Larger if neutrinos are Majorana

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



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

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

ACME II limit: $\left|\frac{d_e}{e}\right| < 1.1\ 10^{-29}\ \text{cm}$

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

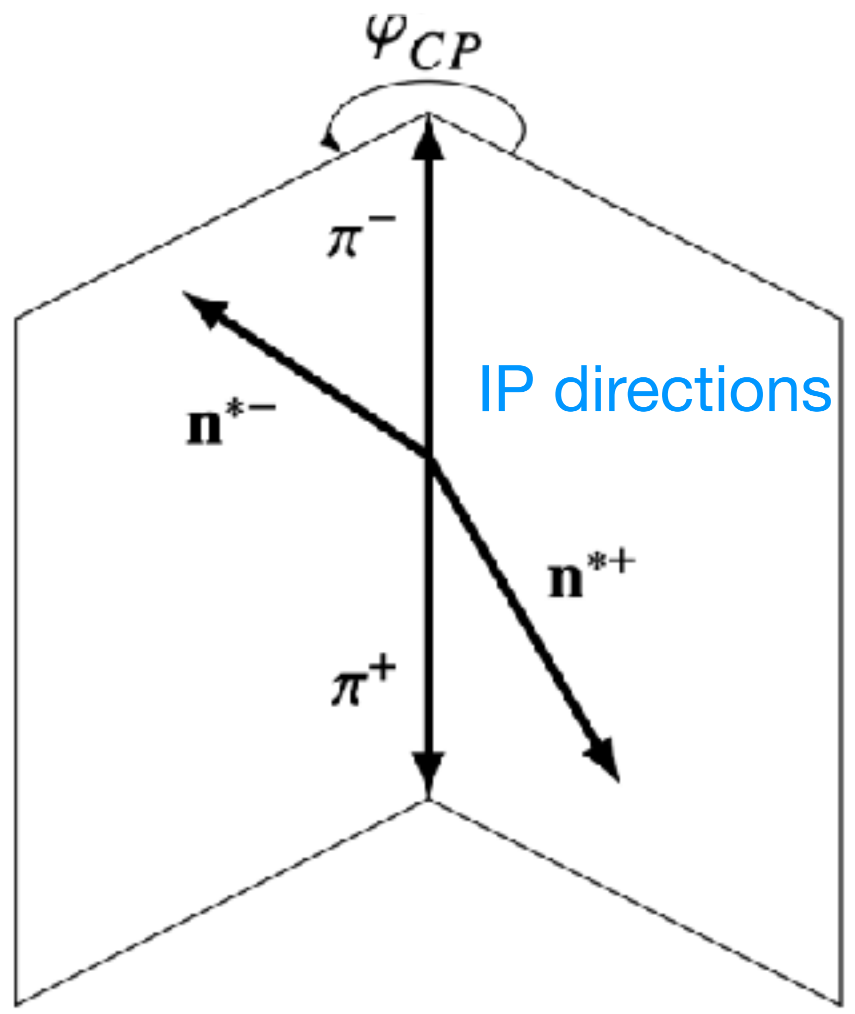
The electron EDM constraint is weaker for taus $\tilde{\kappa}_\tau < 0.3$

Higgs Yukawa to taus CP Properties

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

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

Zero Momentum Frame



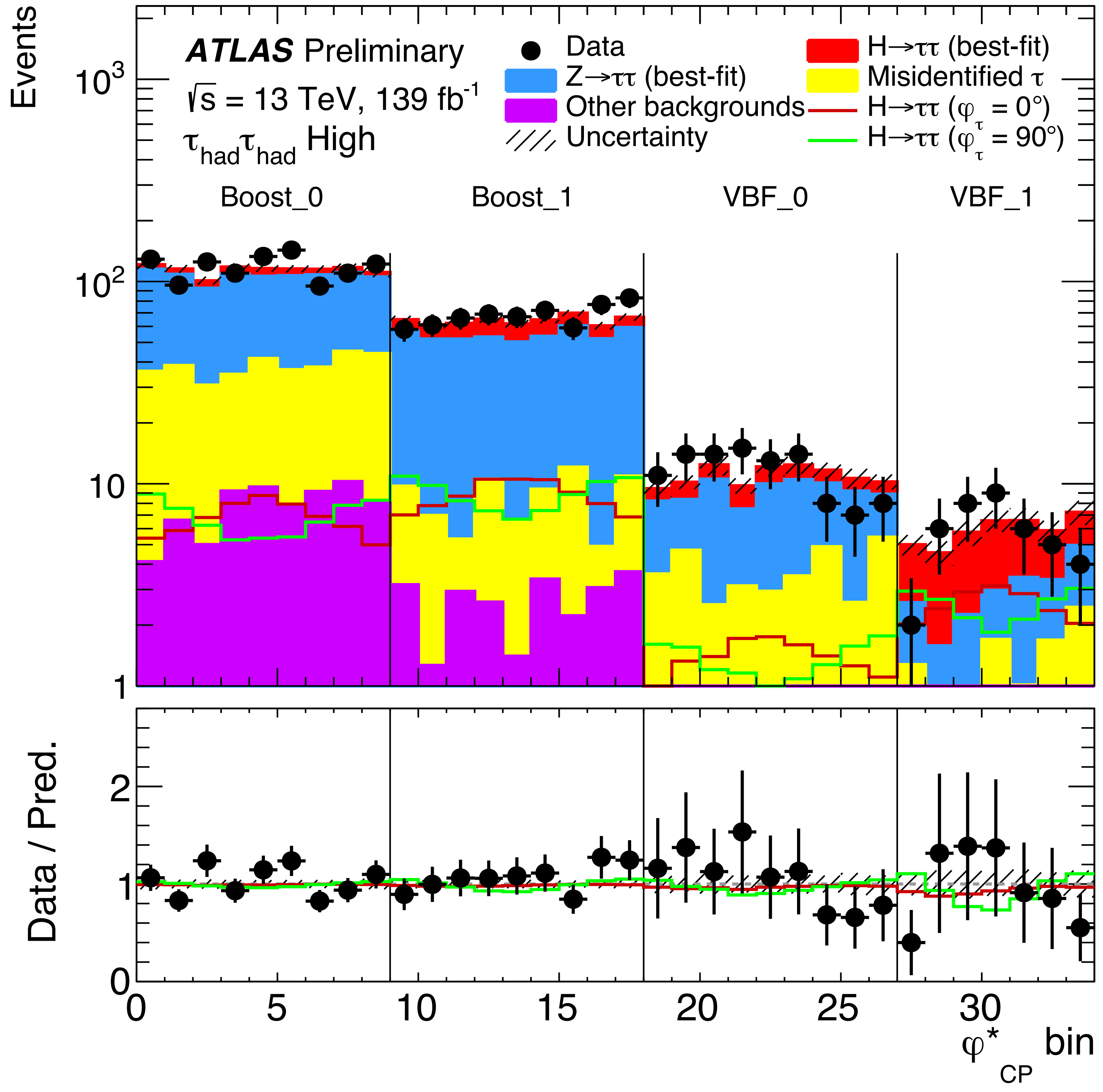
Tau transverse spin correlation sensitive variable

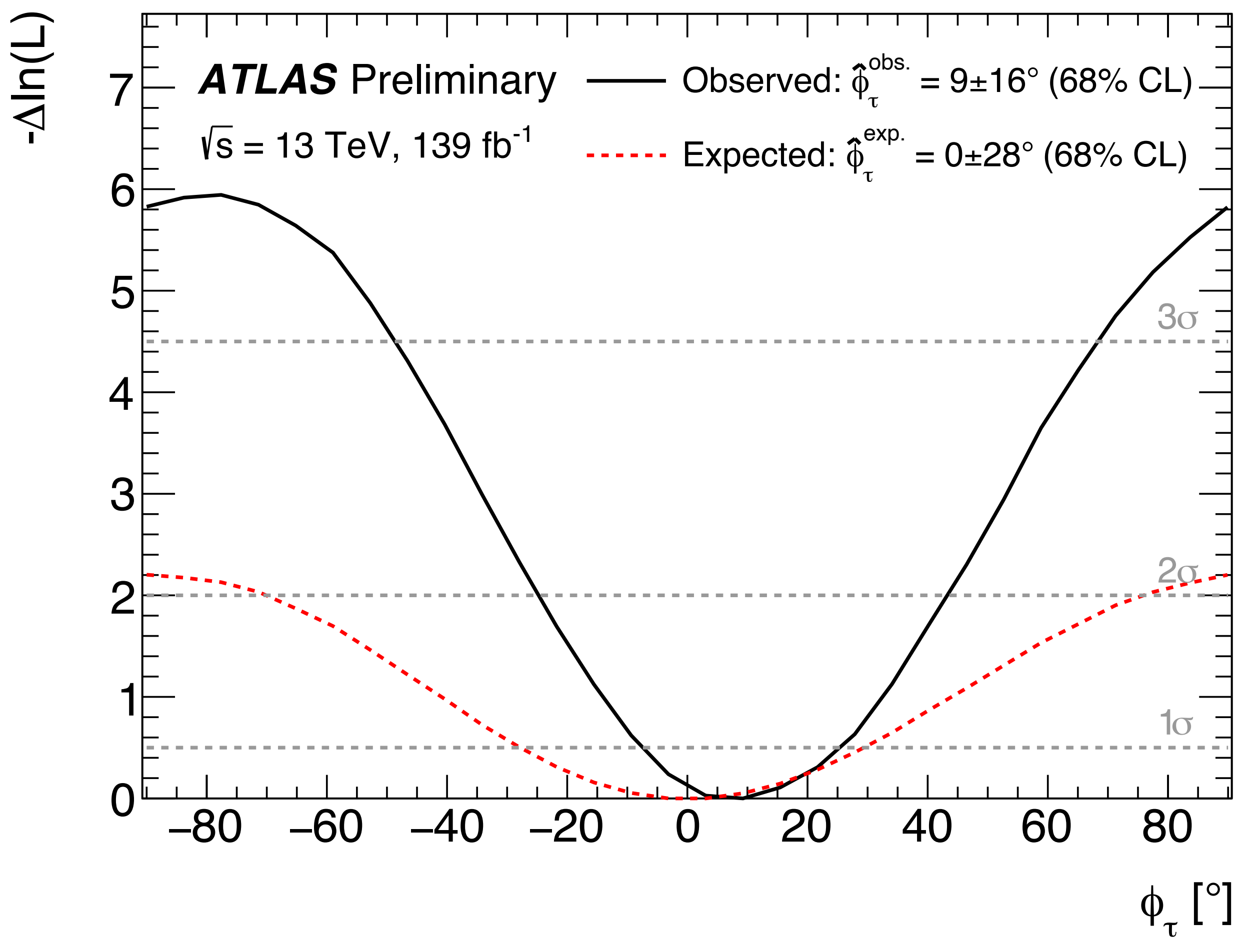
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{v}\kappa_\tau(\cos\phi_\tau\bar{\tau}\tau + \sin\phi_\tau\bar{\tau}i\gamma_5\tau)H$$

Fit the ϕ_τ parameter to the ϕ^*_{CP}

Using several decay modes of the taus

Boosted and VBF (using a BDT) categories

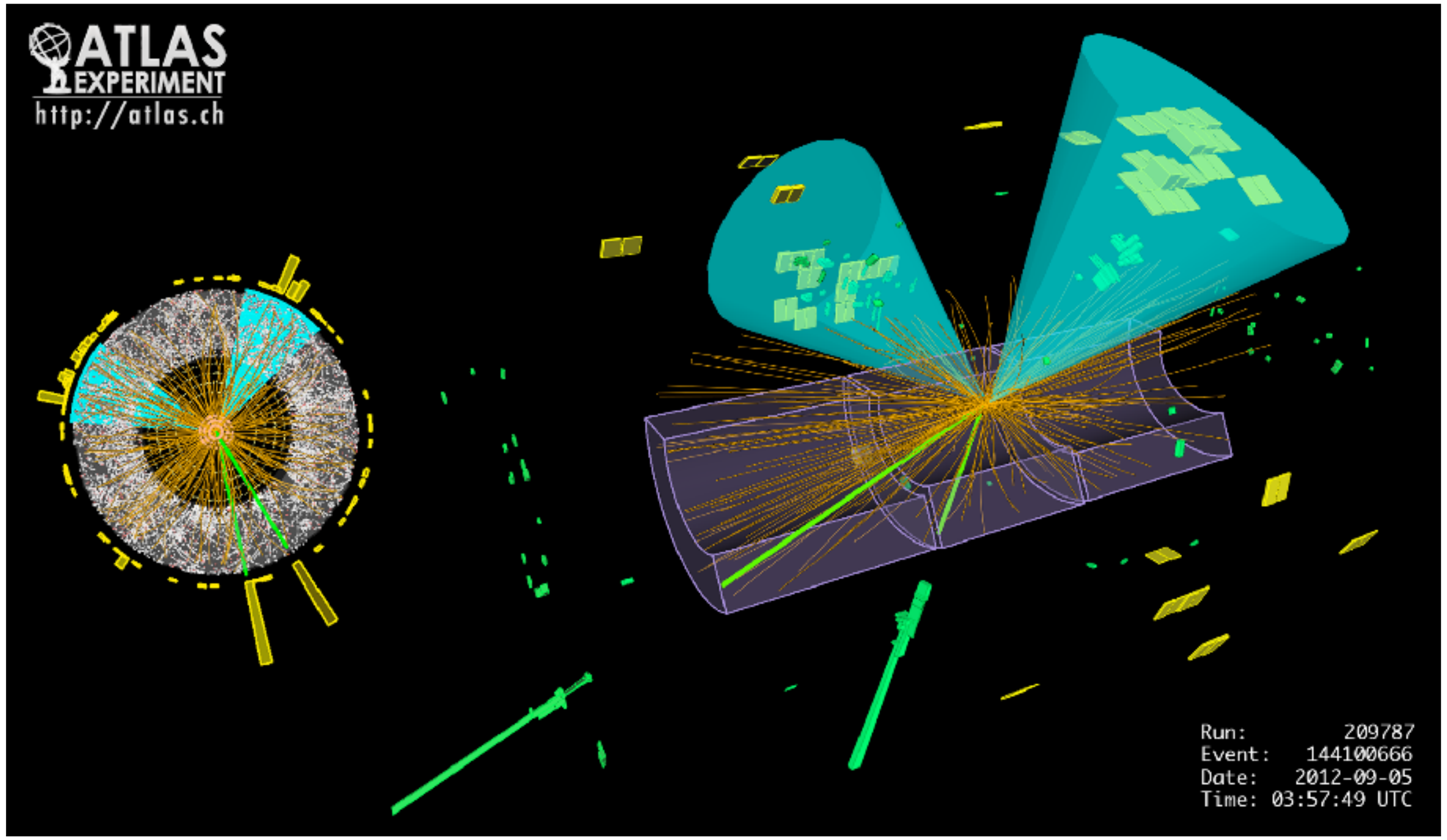


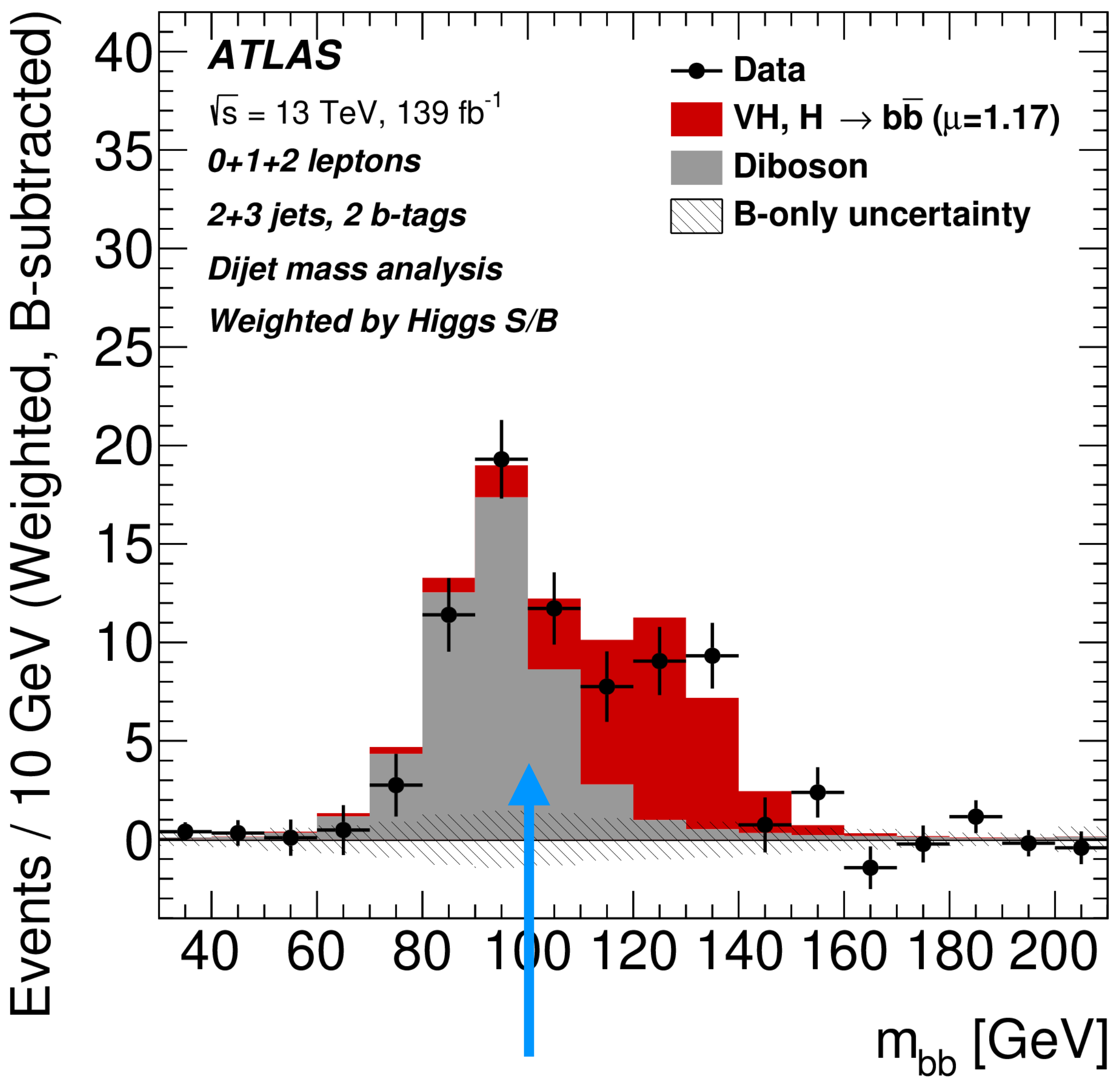


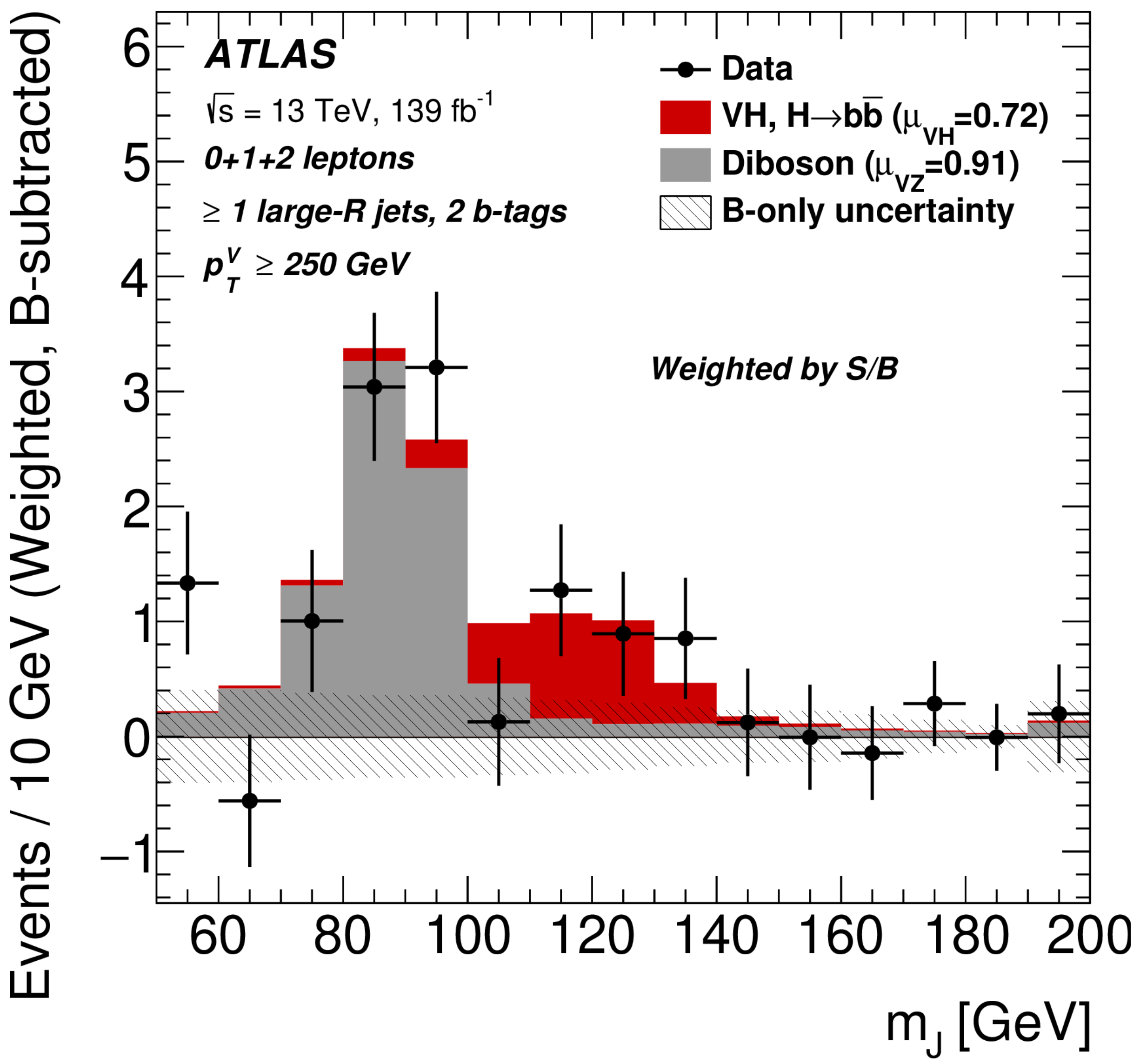
Pure CP-Odd hypothesis excluded at 3.4σ

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

Higgs boson decays to b-quarks







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 both in the resolved and boosted regimes:

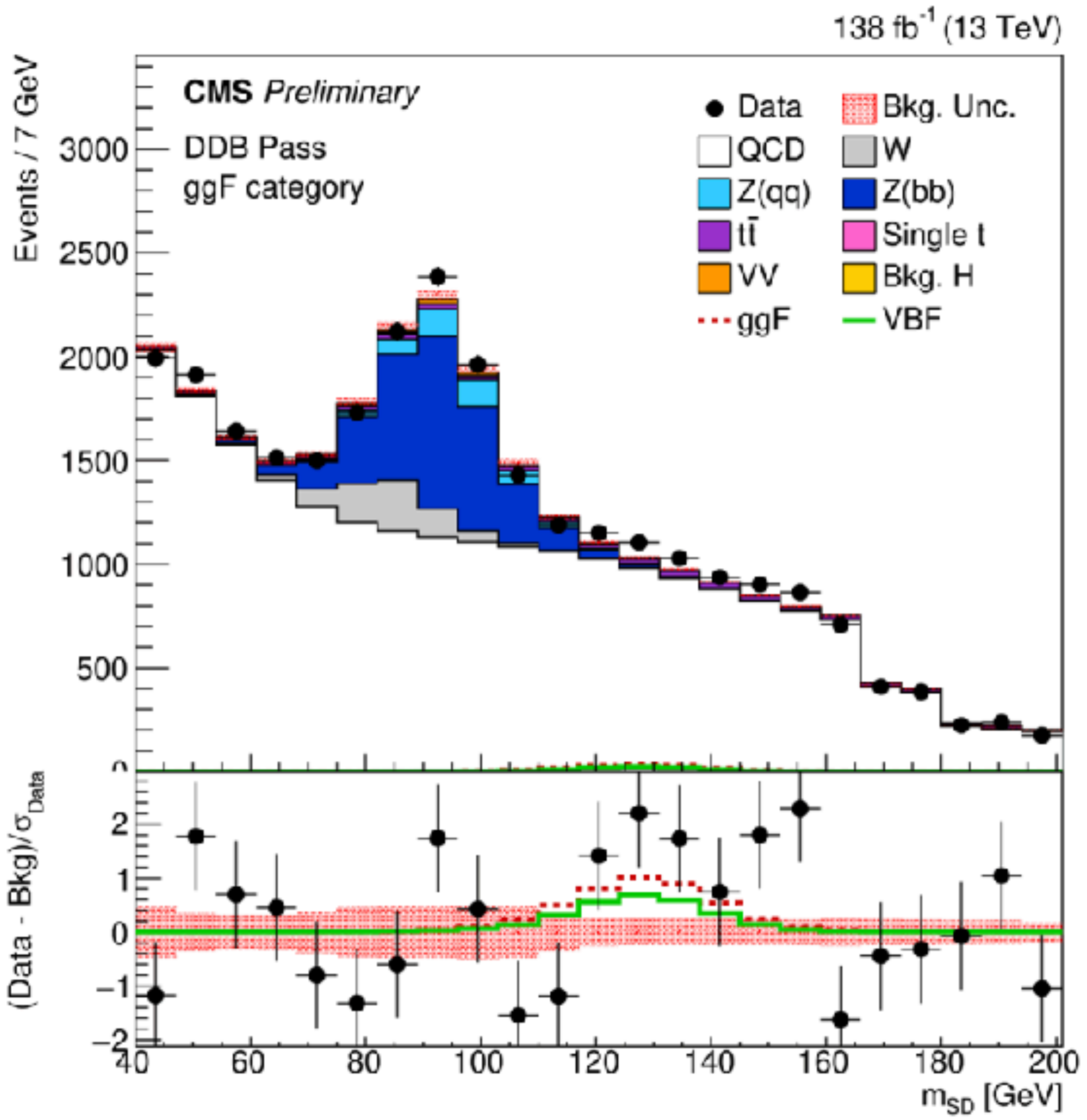
- 0 « leptons » (for neutrino decays of the Z)
- 1-lepton (W decaying to an electron or a muon)
- 2-leptons (Z decaying to electrons or muons)

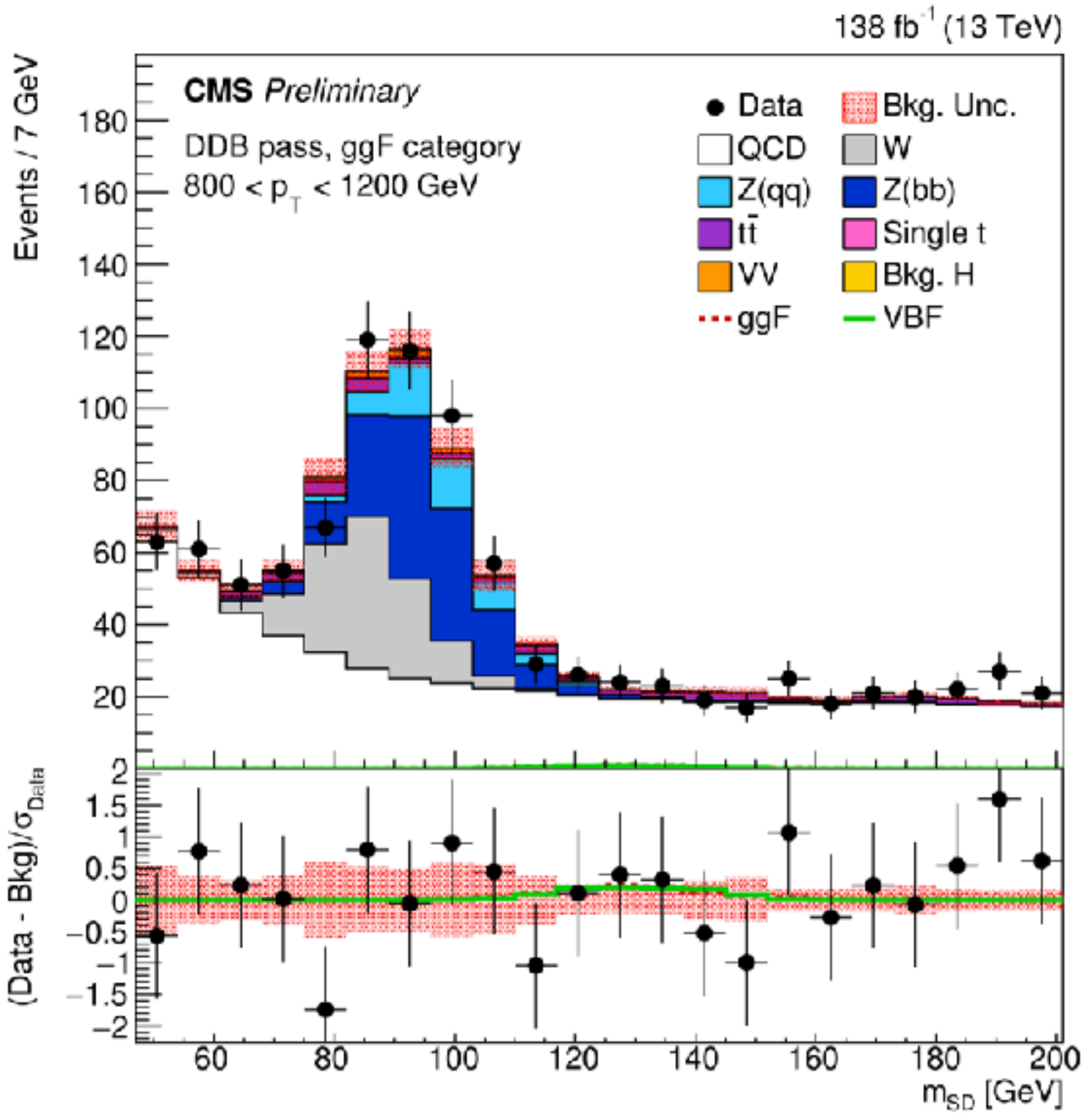
Main background are V+jets (in particular b-jets) and top production, relies on a simulation and ancillary measurements, but is controlled in the mass side-bands!

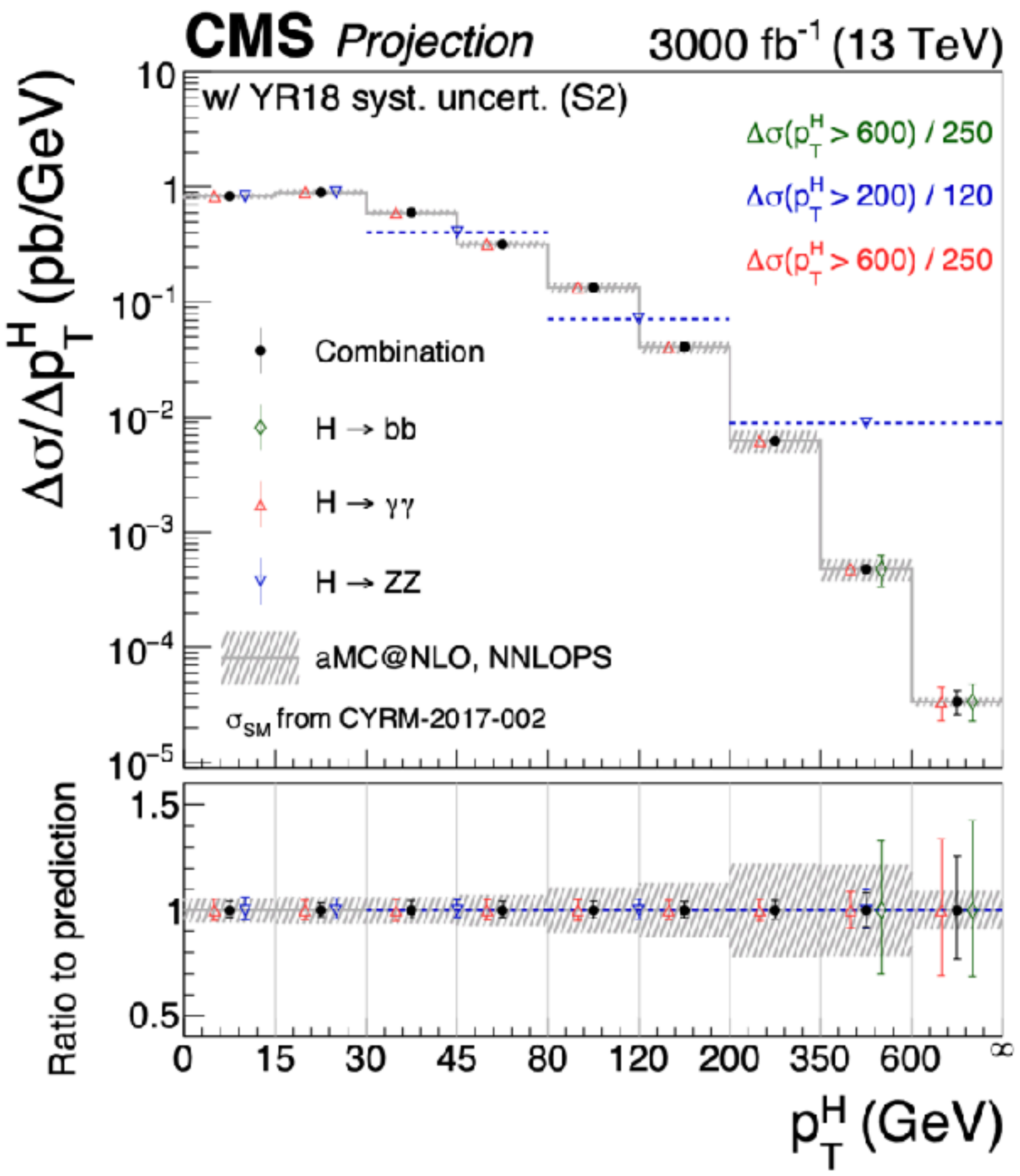
Very important measurement of VZ process with Z to b quarks as a check.

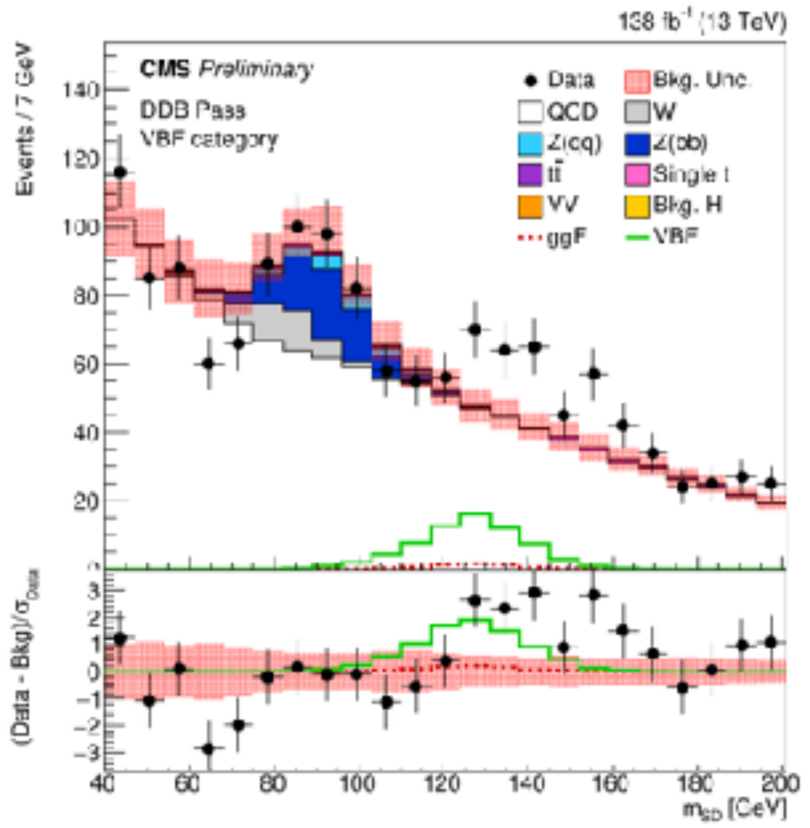
Now both the WH and ZH have been firmly established!

Boosting the Higgs Boson!









Was thought to be completely impossible!

VBF significance is 3.0 σ (0.9 σ)

ggF significance of 1.2 σ (0.9 σ)

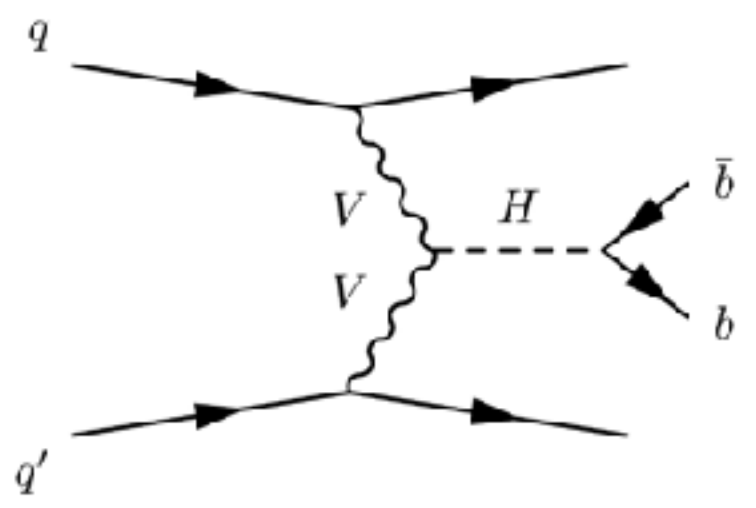
It can play an important role in the measurements of the inclusive production at high transverse momentum!

Extremely interesting for indirect NP constraints!

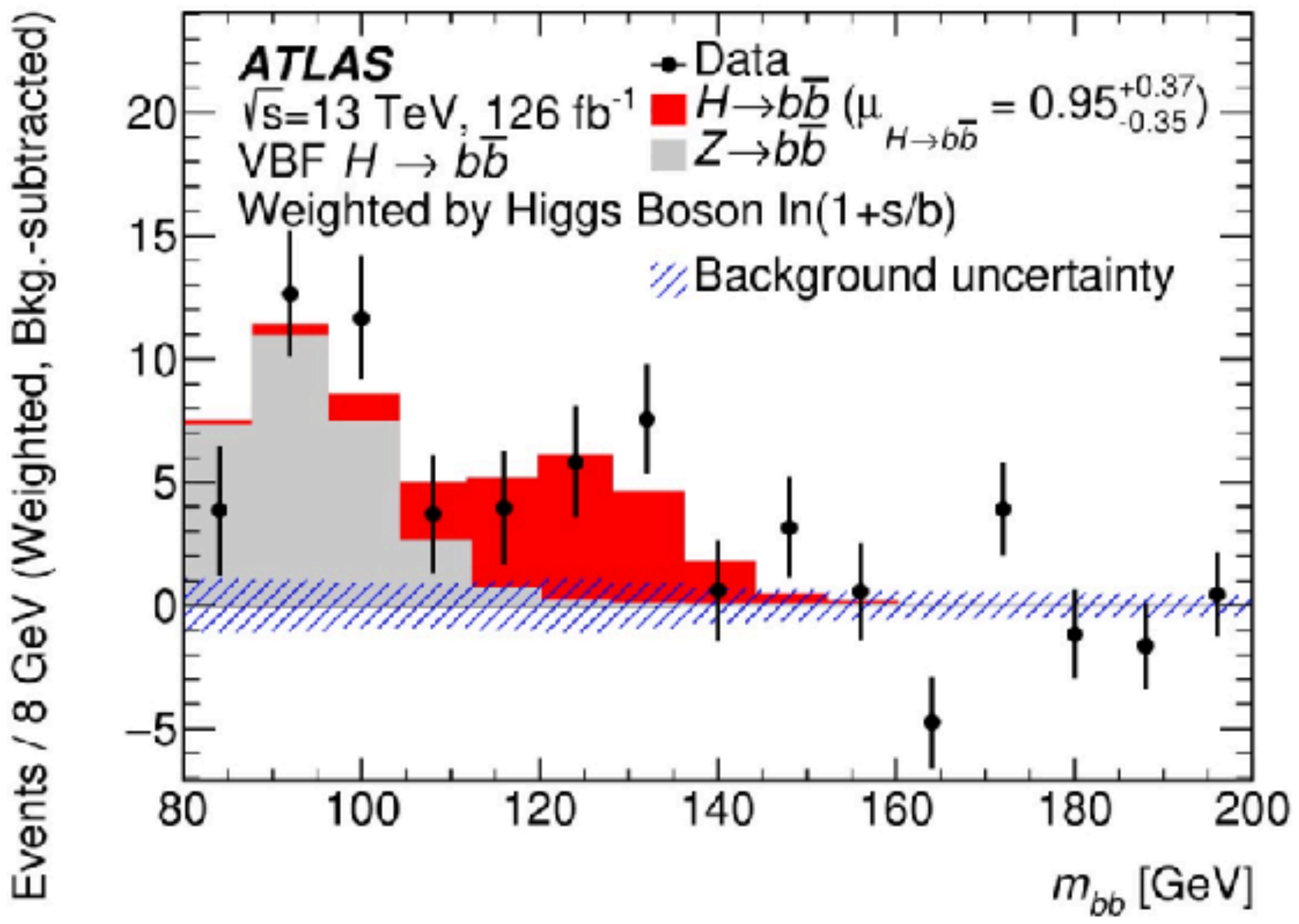
Higgs boson decays to b-quarks in VBF Production

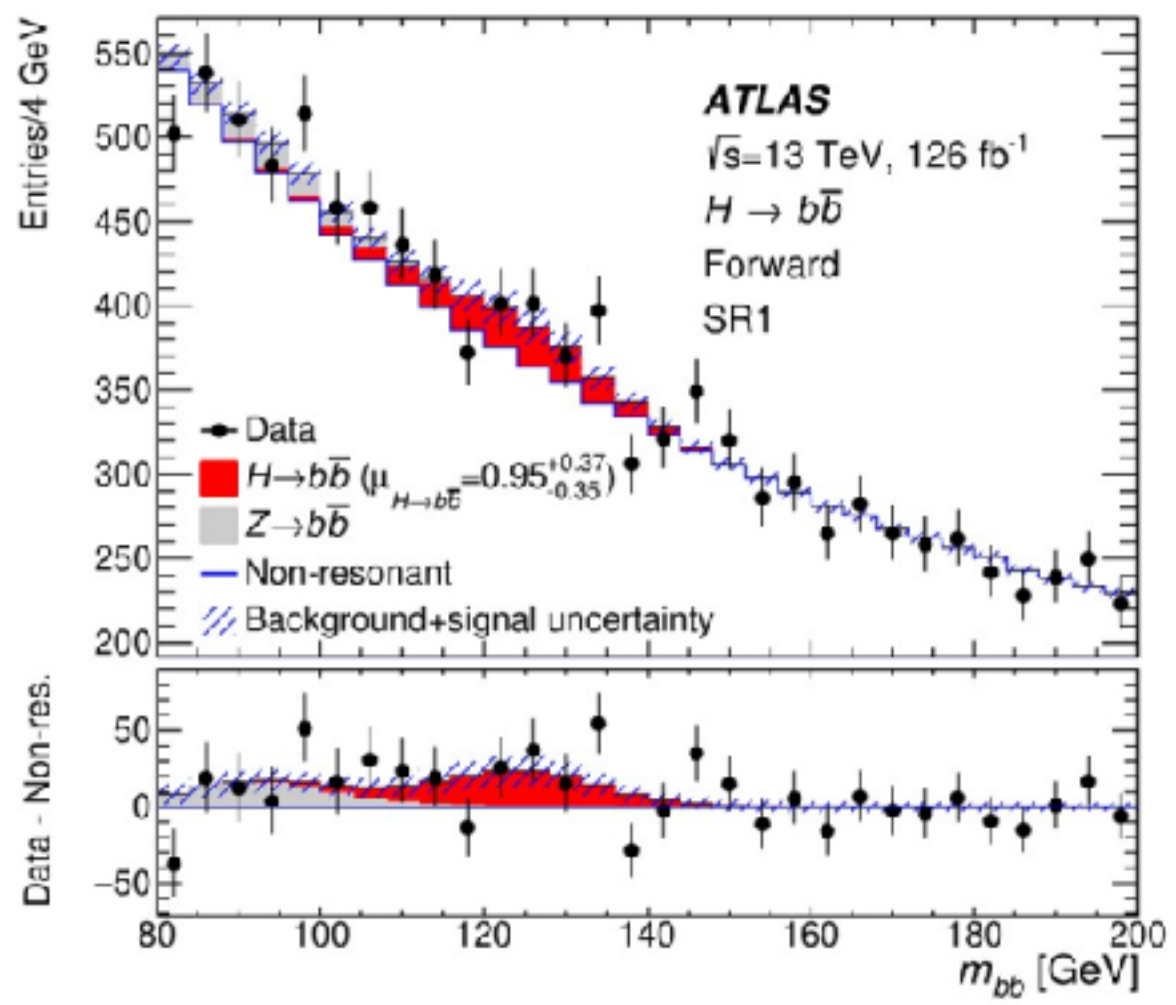
EPJC 81 (2021)

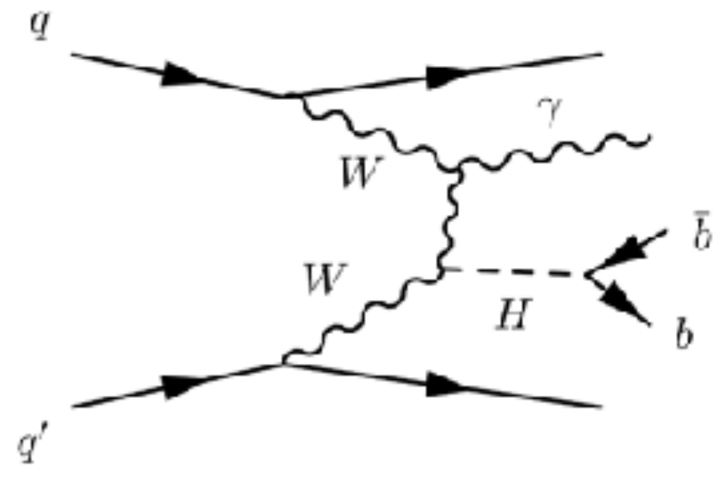
VBF analysis with Higgs in bb including channel with photon

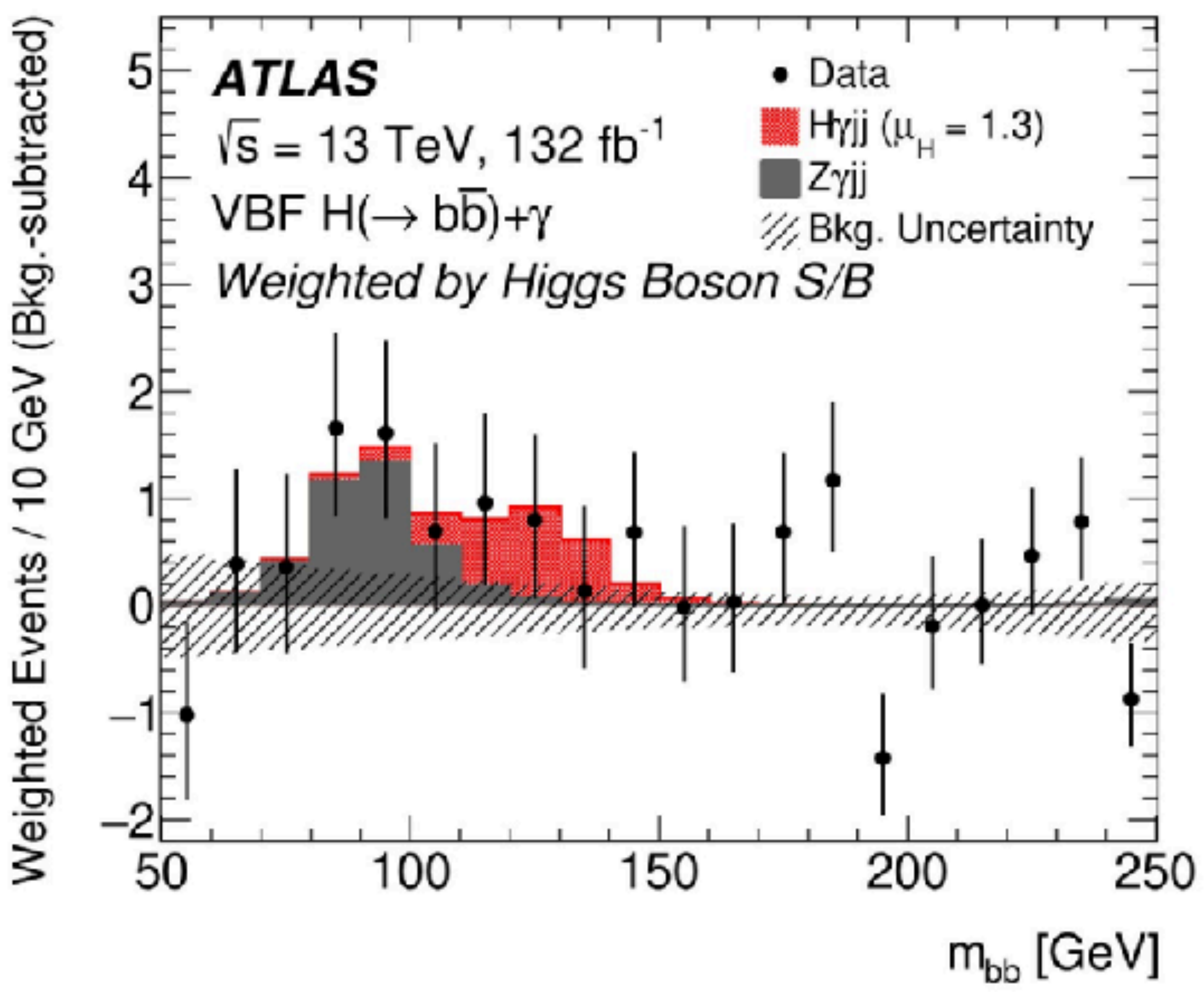


Non trivial trigger requirements!









Taking advantage of the VBF with a photon topology which reduces significantly QCD background which has a destructive interference! It is also very useful to trigger on.

VBF-inclusive Continuous background from low selection NN - Z background from embedding!

$$0.95^{+0.31}_{-0.31}(\mathrm{stat.})^{+0.20}_{-0.17}(\mathrm{syst.})$$

2.7σ (2.9σ expected)

VBF-photon Fit of signal (and peaking background) on smoothly fallen background

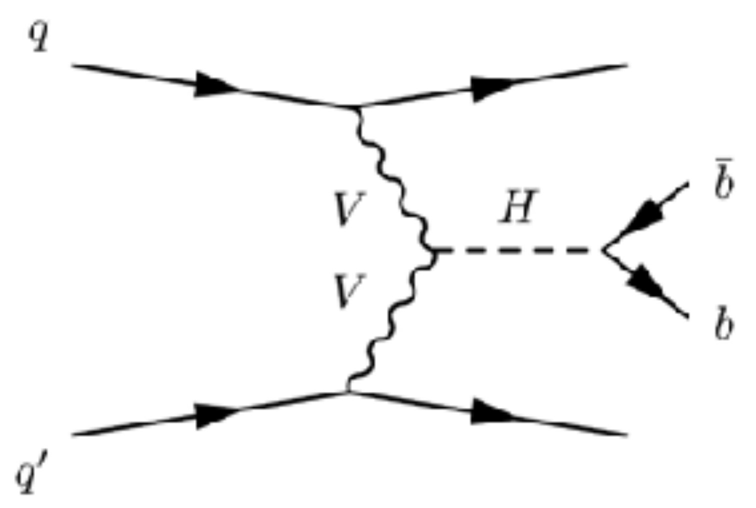
$$1.3 \pm 1.0(stat.) \pm 0.3(syst.)$$

1.3σ (1.0σ expected)

Higgs boson decays to b-quarks in VBF Production

EPJC 81 (2021)

VBF analysis with Higgs in bb including channel with photon



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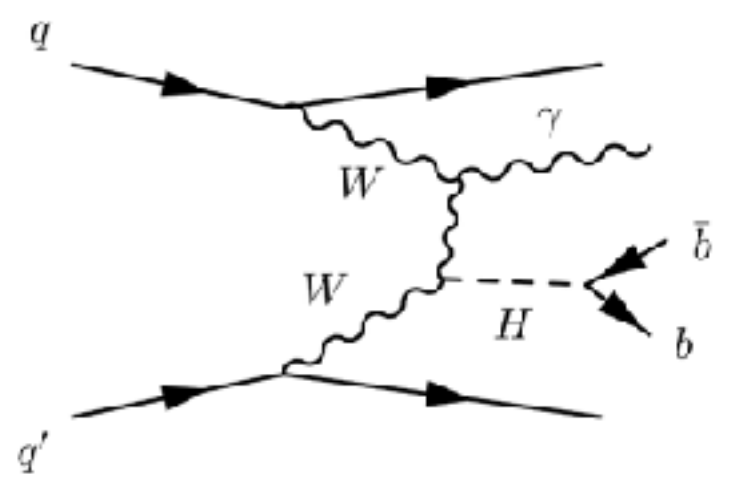

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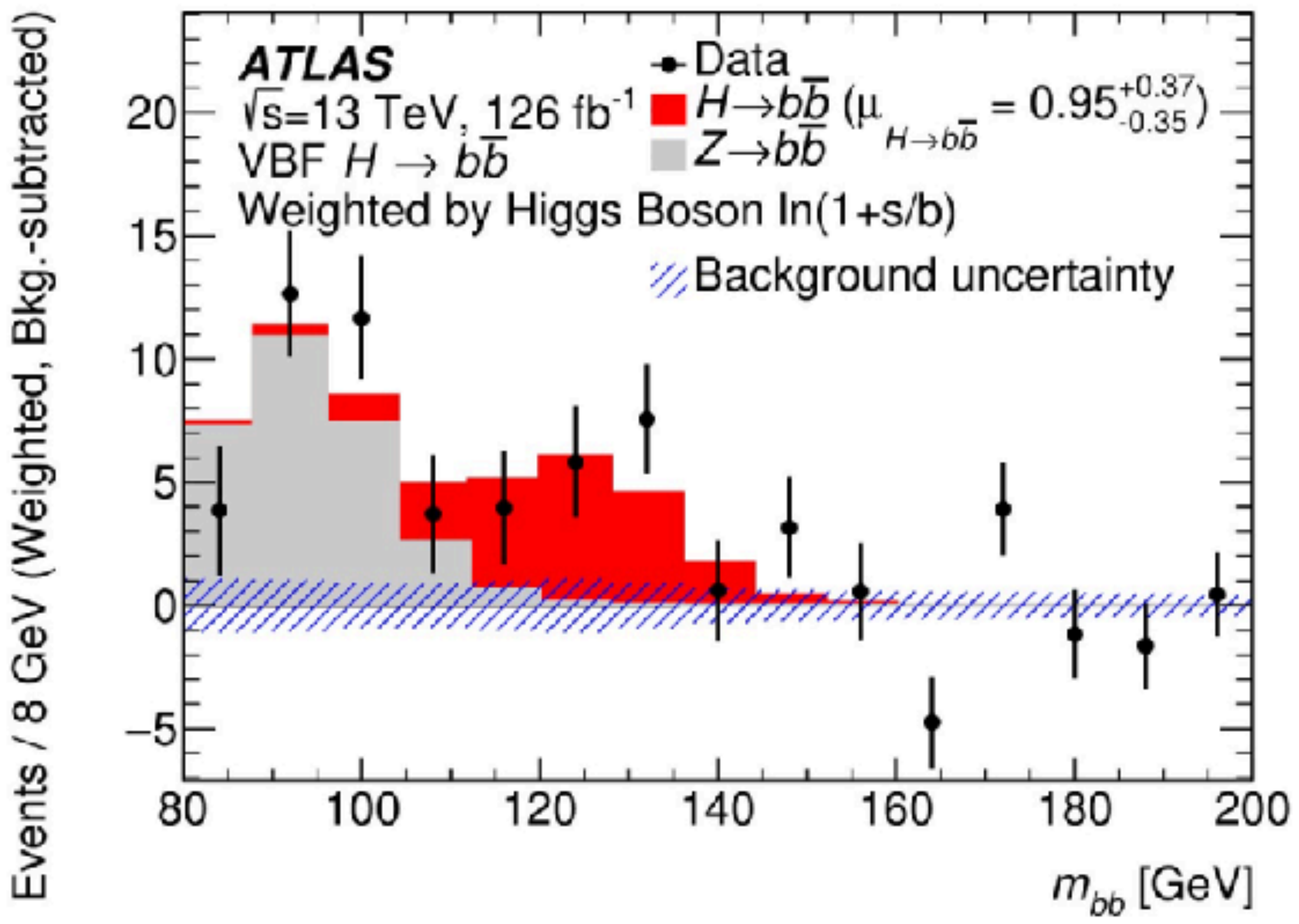
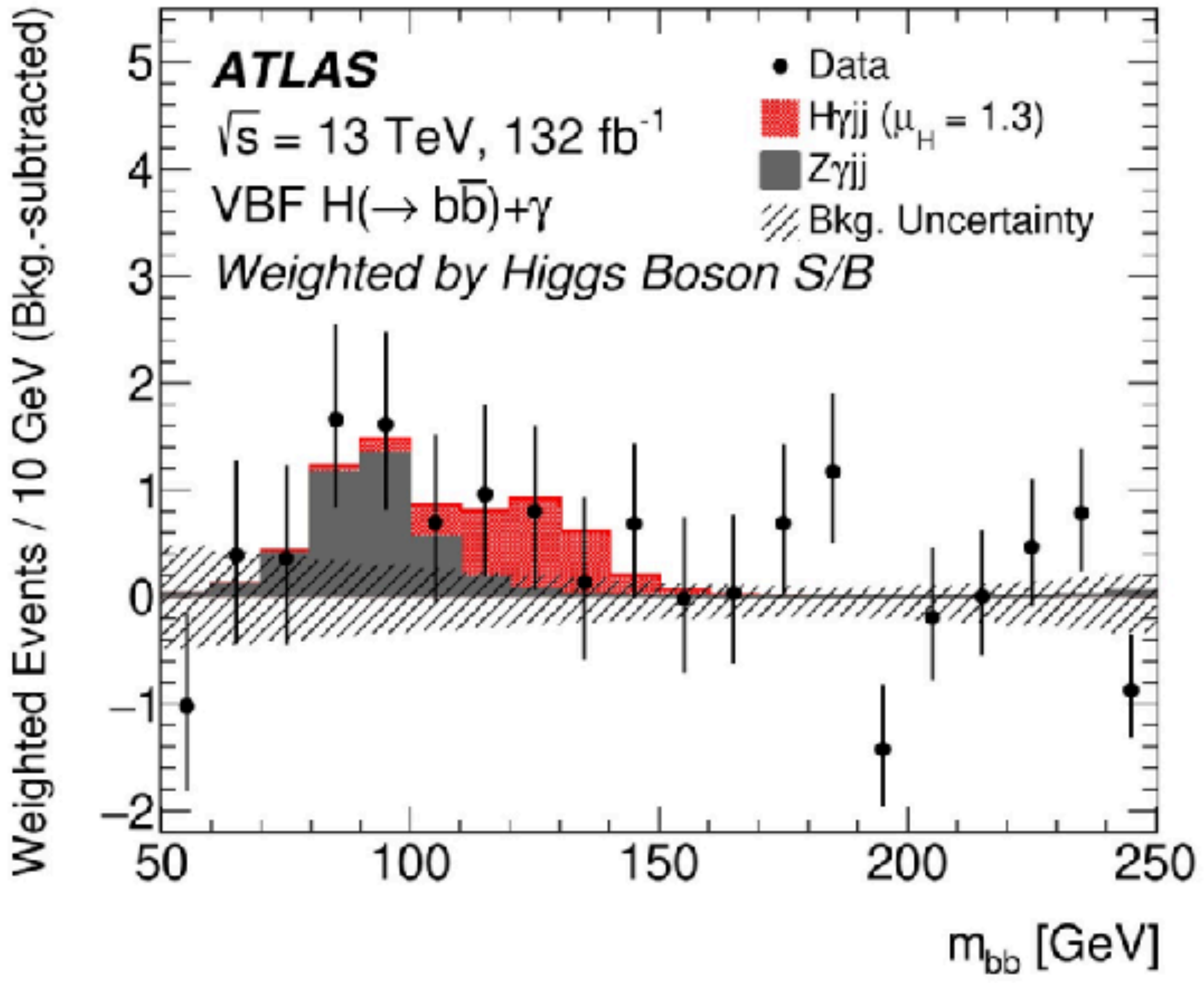
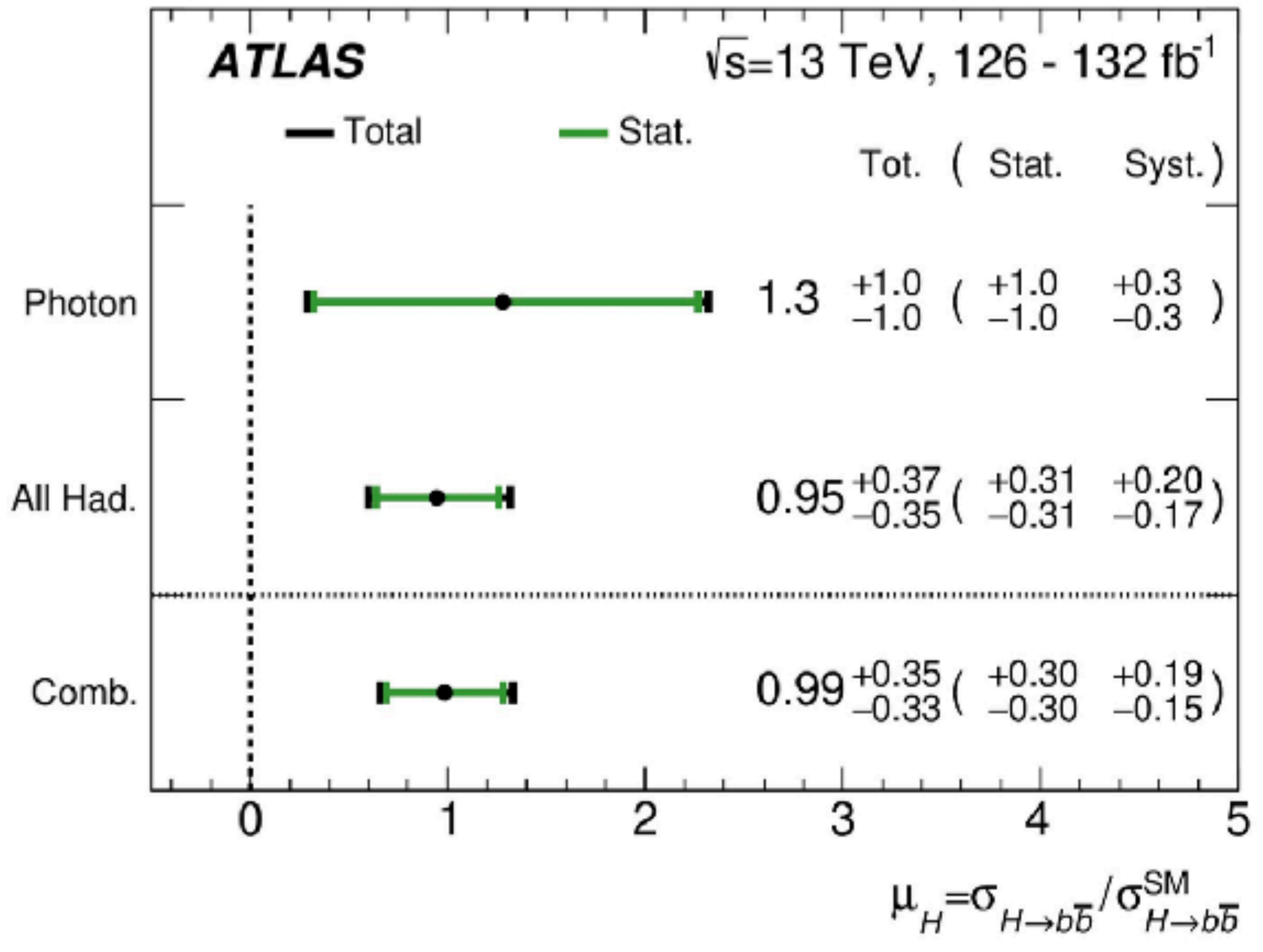






3.0σ (3.0σ expected)

Evidence!

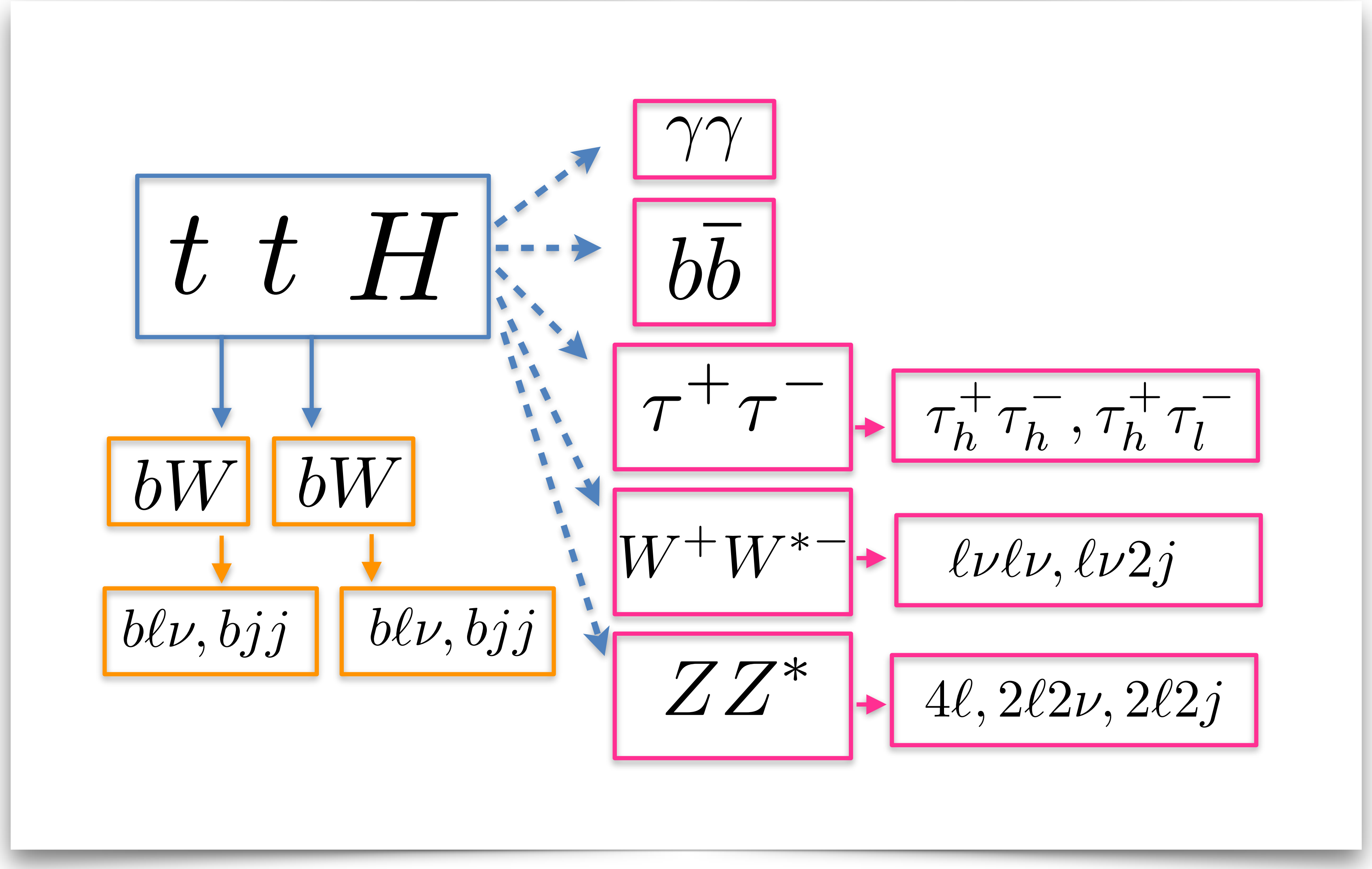
Probing the Top Yukawa Coupling

Outstanding goal of the LHC as likely* the next collider to provide a direct measurement would be a future radon collider!

*Possible at an e^+e^- collider but would require high c.o.m. energy

Direct probe of the top Yukawa coupling

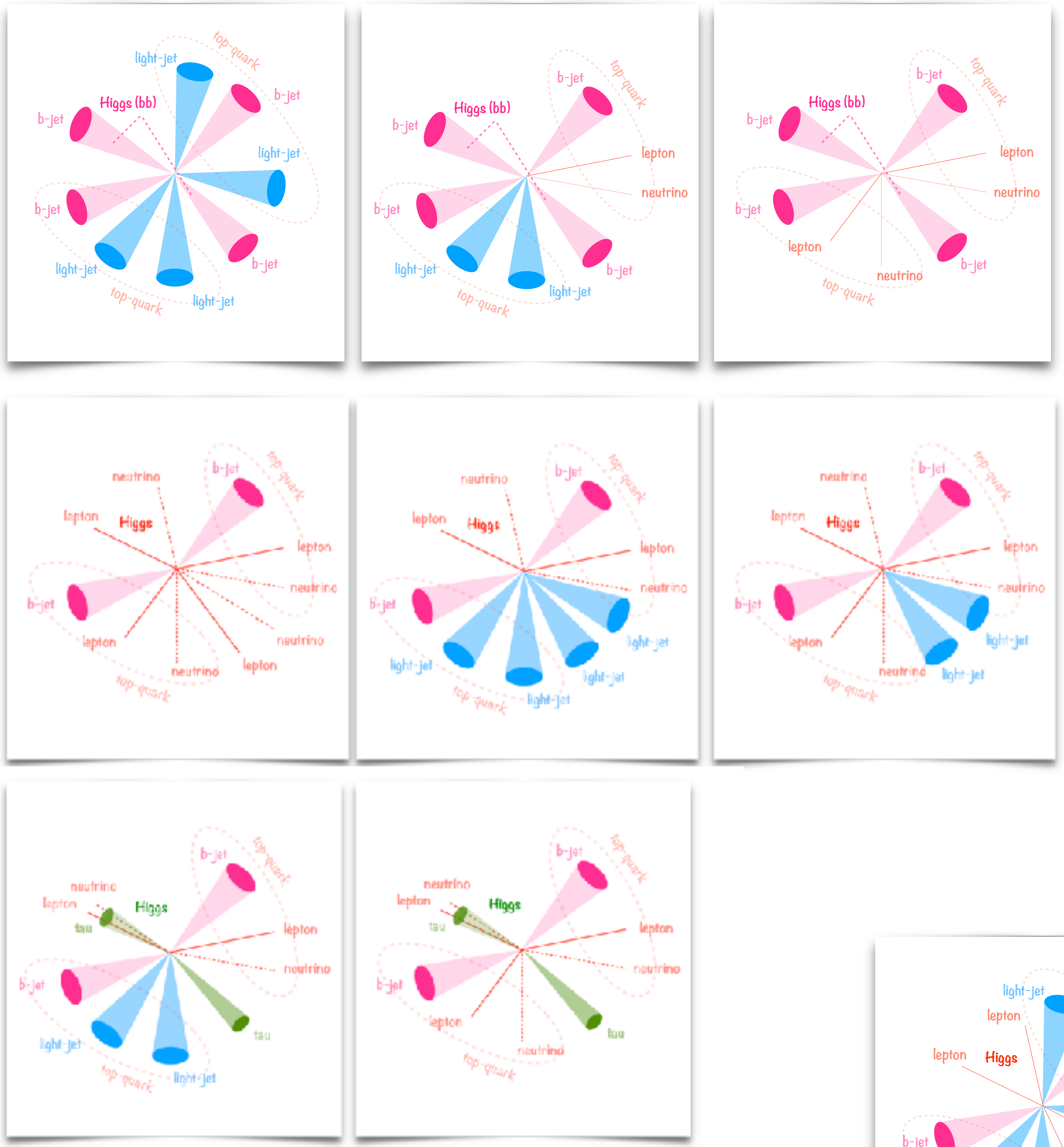
ttH Analyses at LHC: Massively Complex!



*Large increase of cross section from Run 1 to Run 2!

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

- Different backgrounds and different systematic uncertainties and therefore also a strength!



ttH(bb)

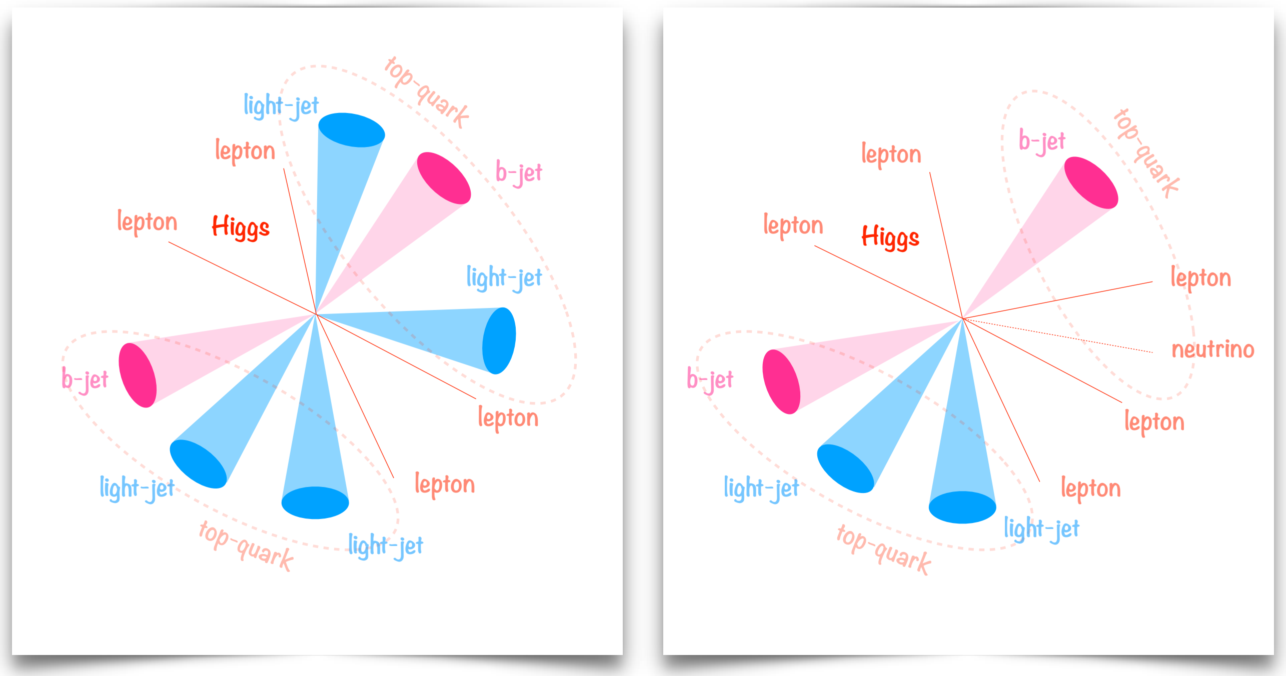
Very large backgrounds of top pair production associated with b jets

Dominated by background modelling uncertainties

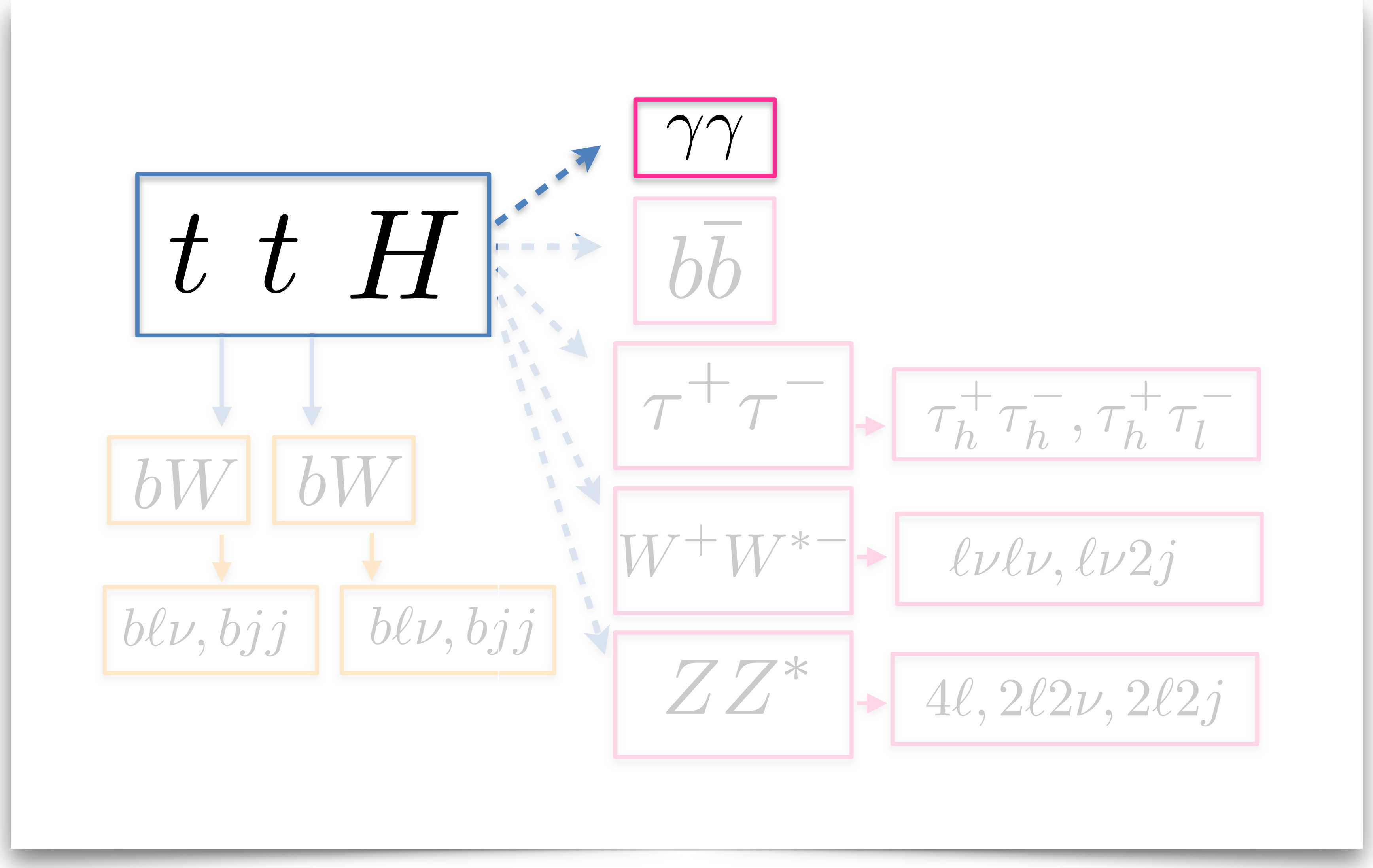
ttH(WW, ZZ and tau tau)

So-called multi-lepton channel

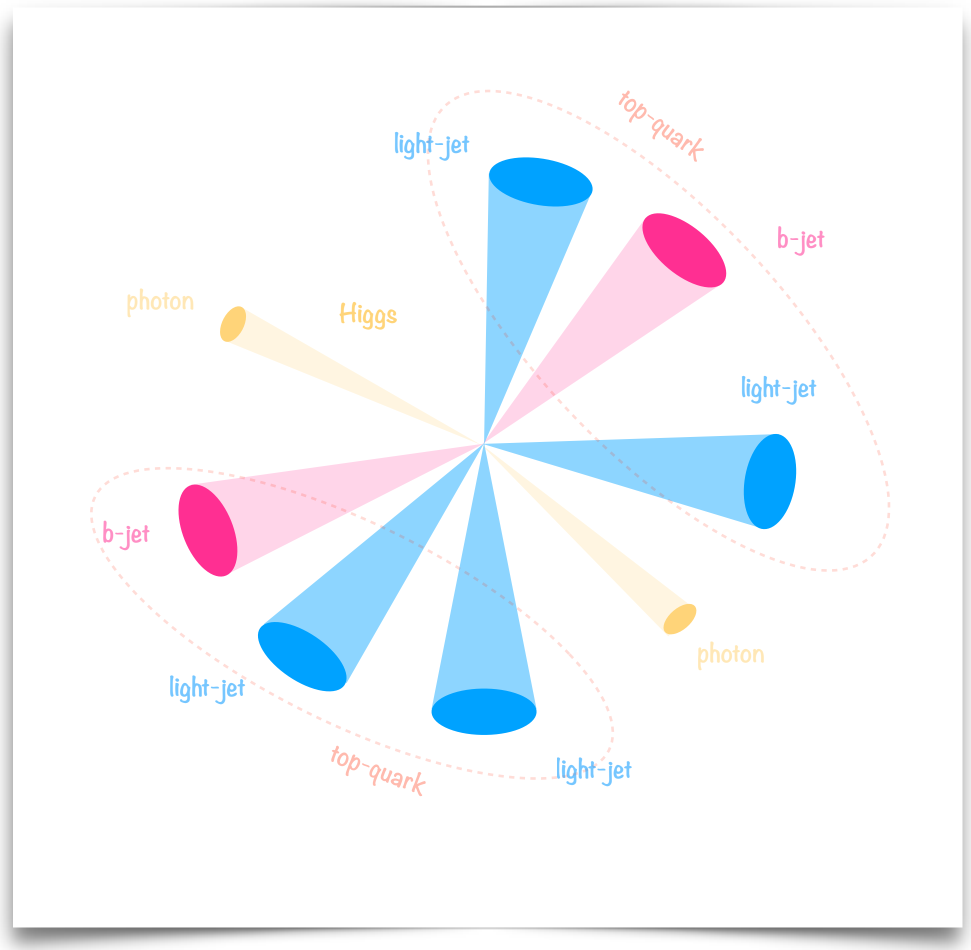
Large number of topologies intricate reducible backgrounds of jets faking leptons.

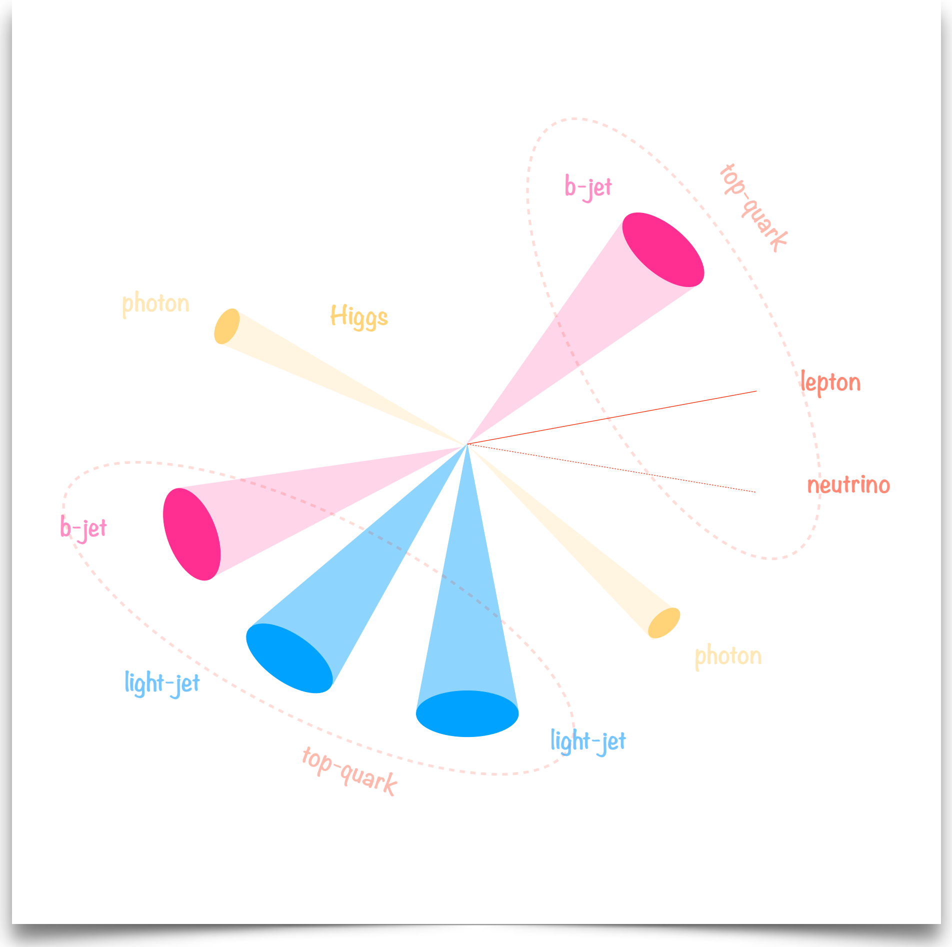


Direct probe of the top Yukawa coupling

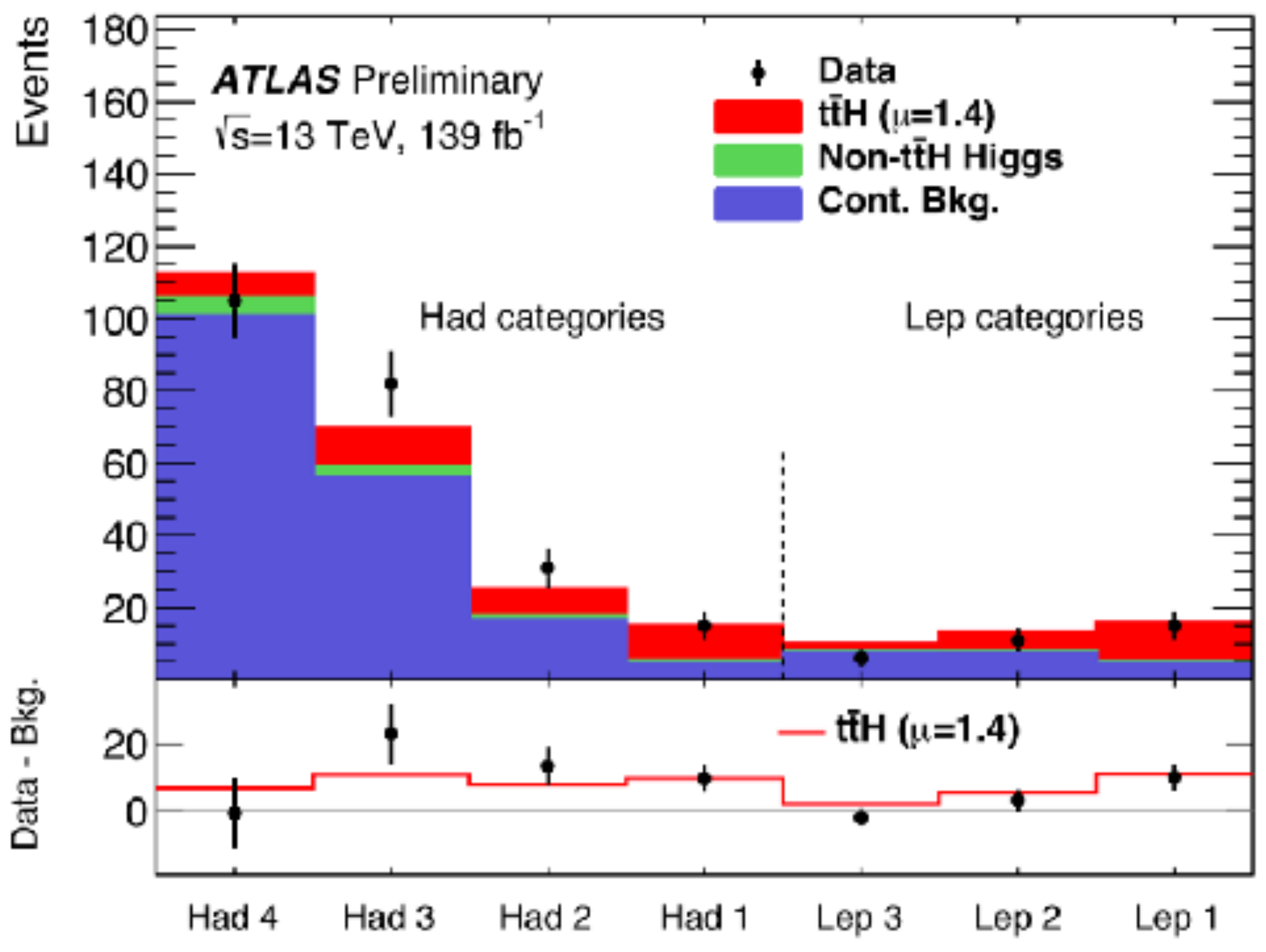


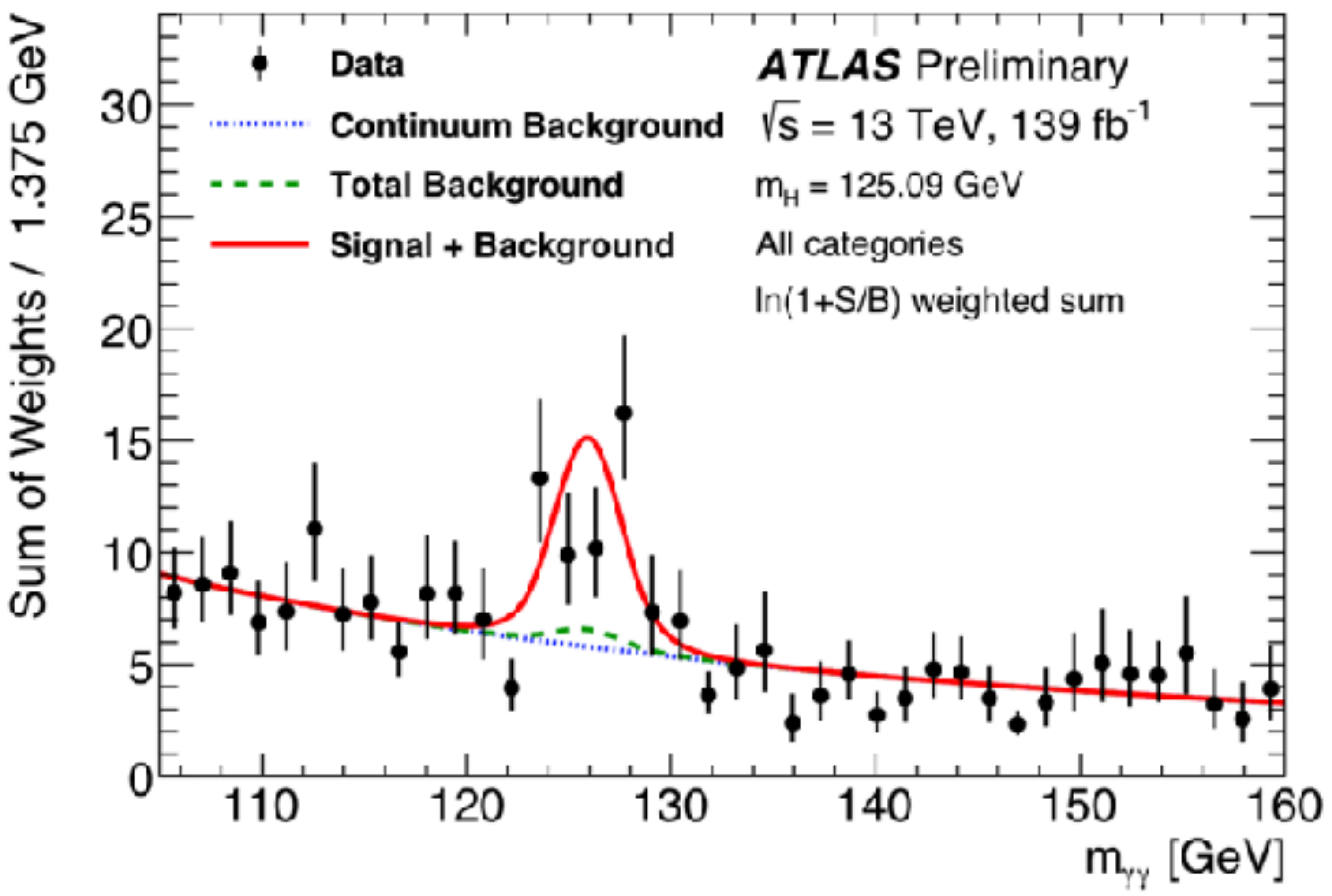
Most sensitive channel at the time of the ttH discovery





Background and signal modelled using analytic functions.





Cross section dominated by statistical uncertainties:

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

Expected (4.2σ)

Observed 4.9σ

In combination with the other channels:

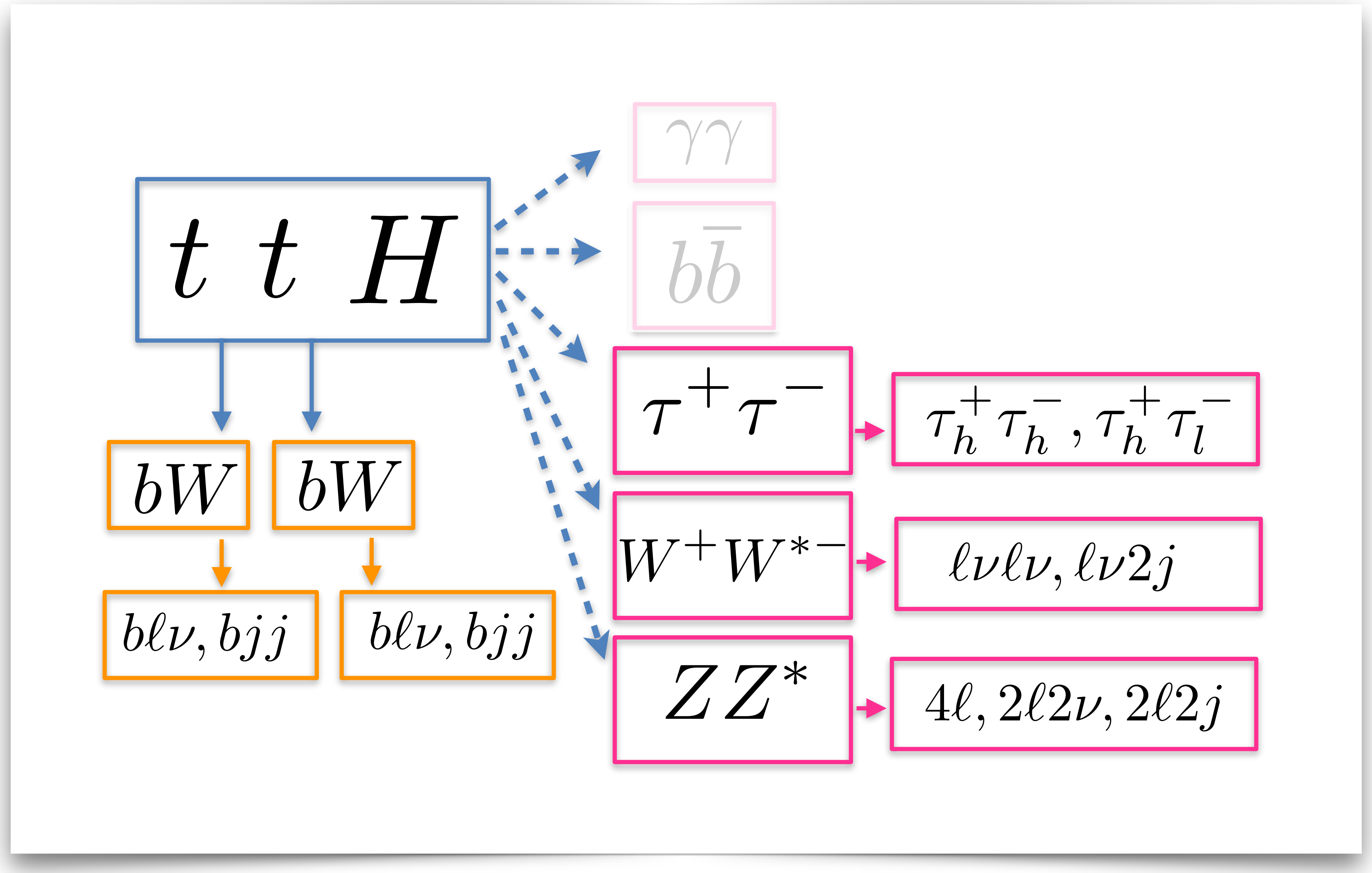
Expected 5.1σ

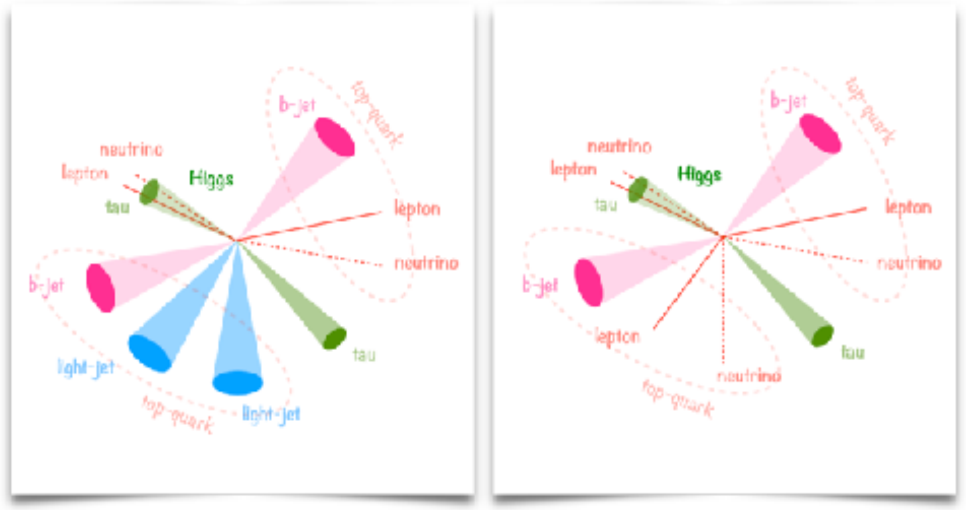
Observed 6.3σ

Clear observation!!

Direct probe of the top Yukawa coupling

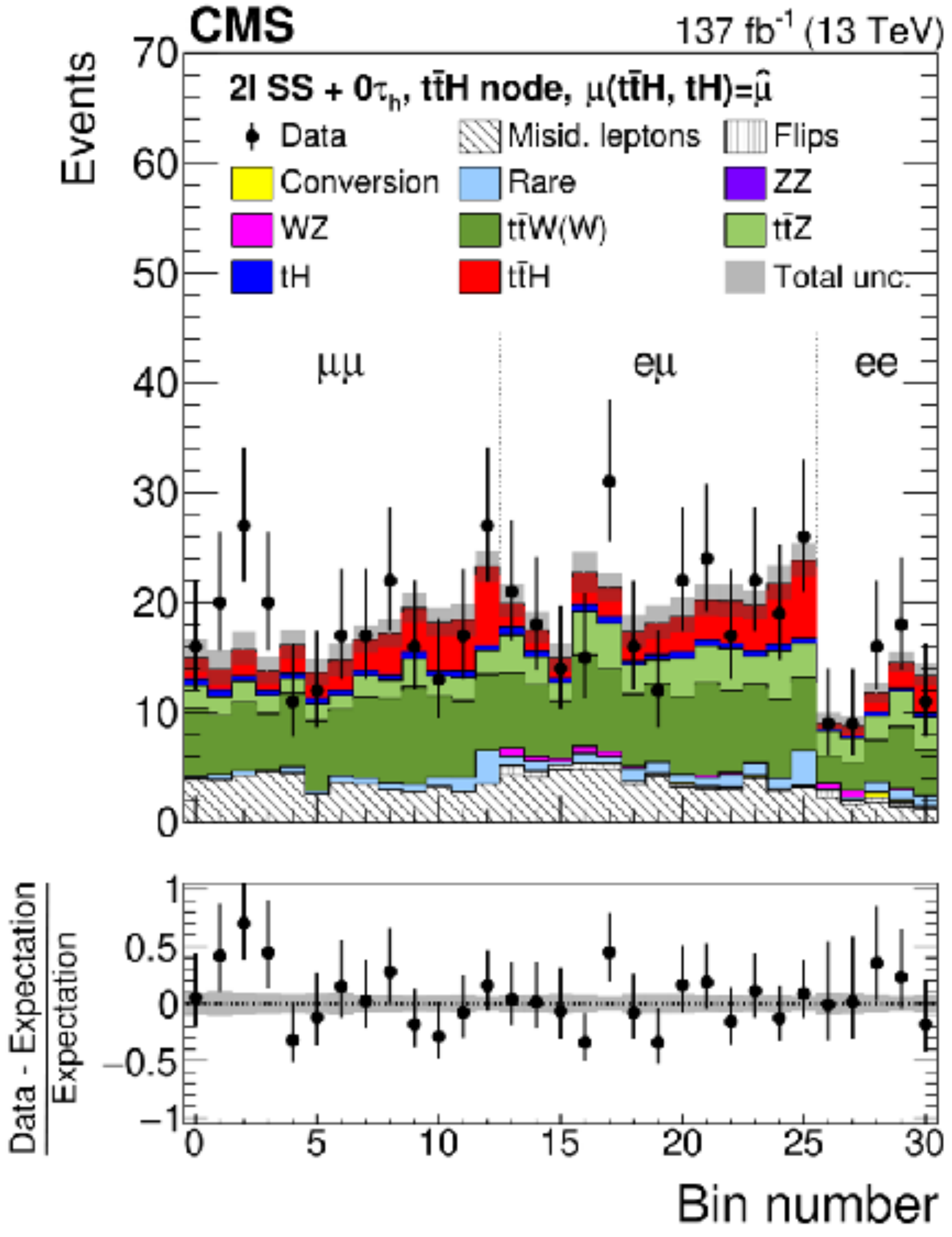
ttH Analyses at LHC: Massively Complex!

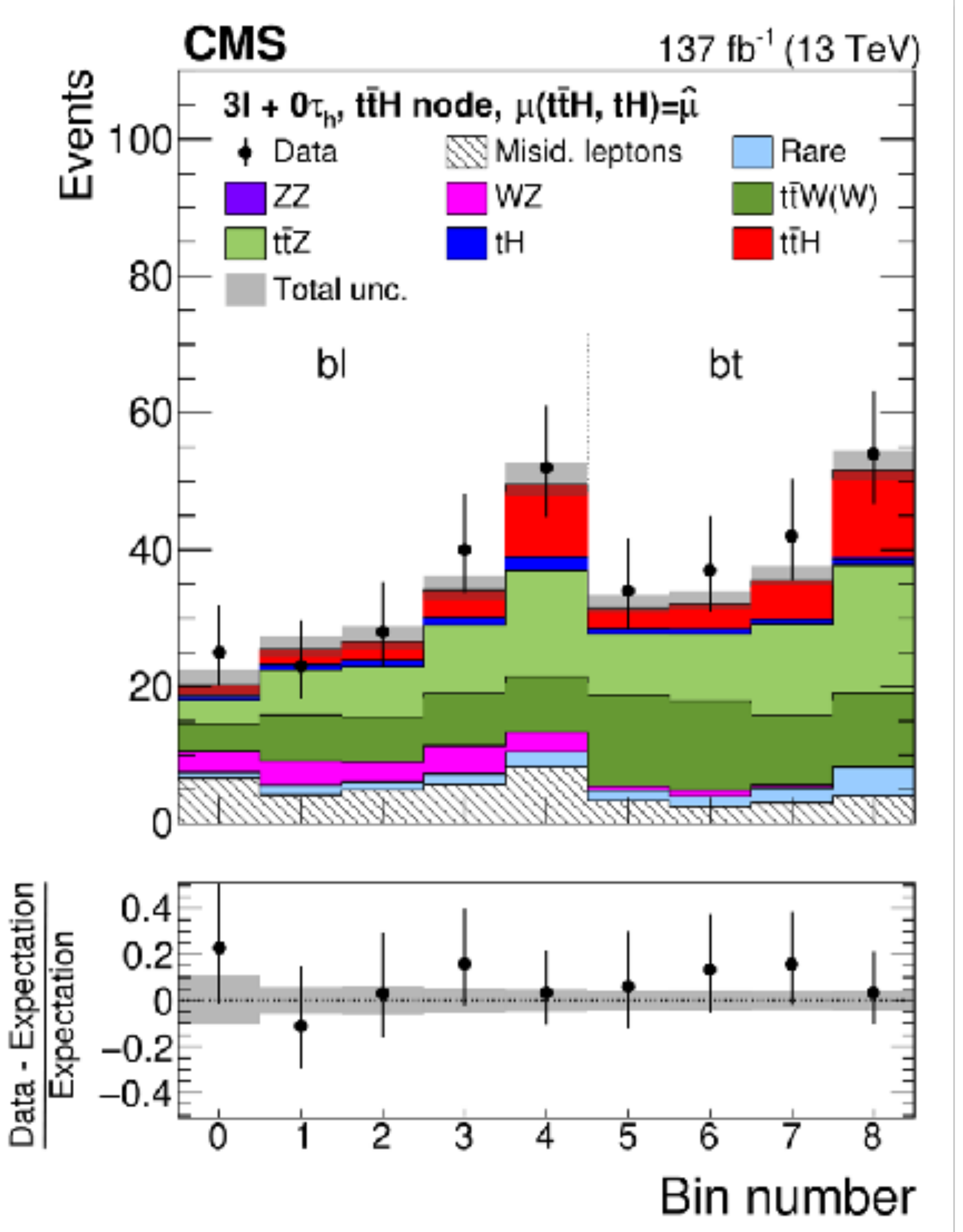




"Inclusive approach" (still) with 10 channels: 1L, 2L-SS, and 3L as well as 0-, 1- and 2-hadronically decaying taus

The 2L-SS and 3L-SS are the most sensitive:

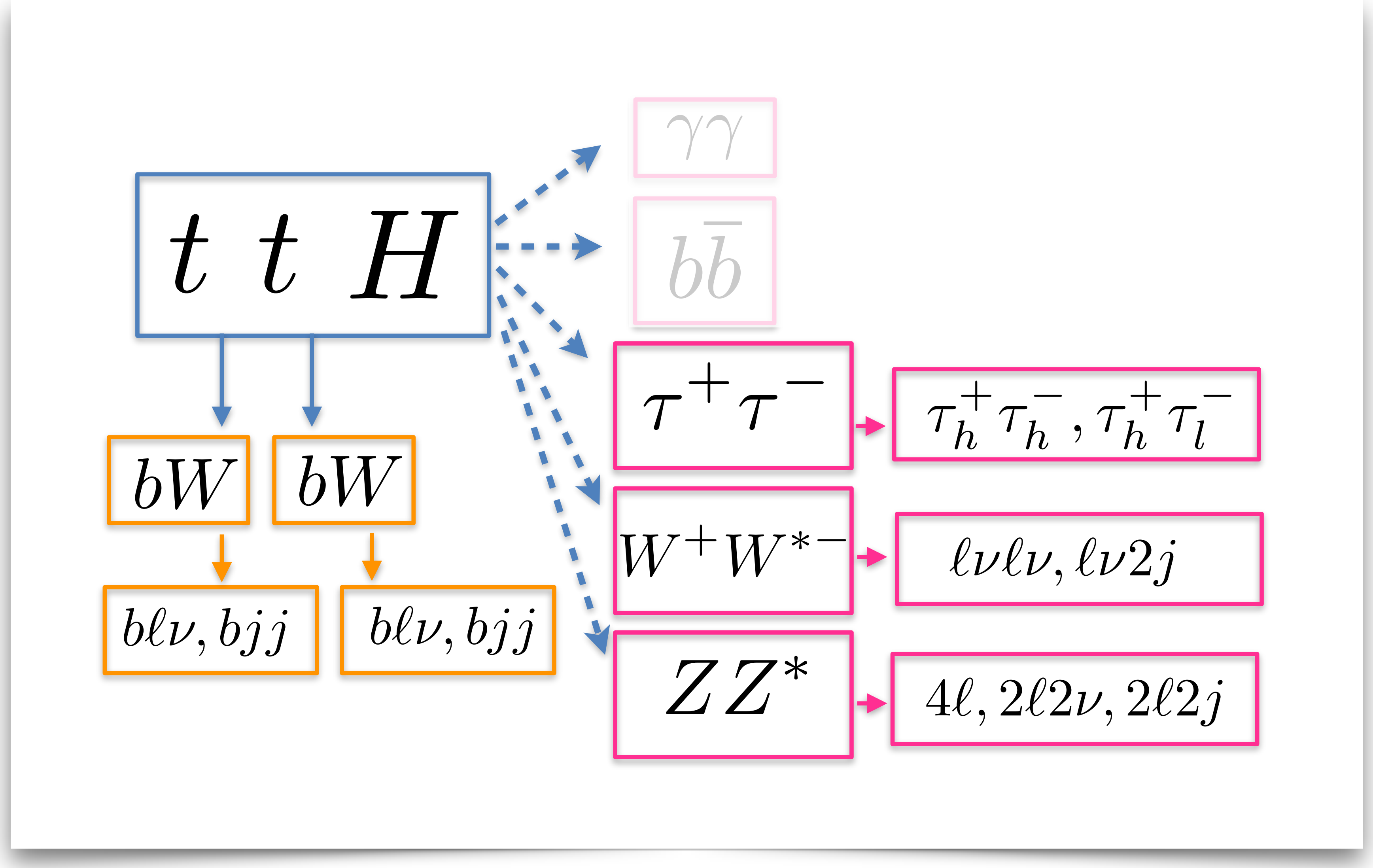


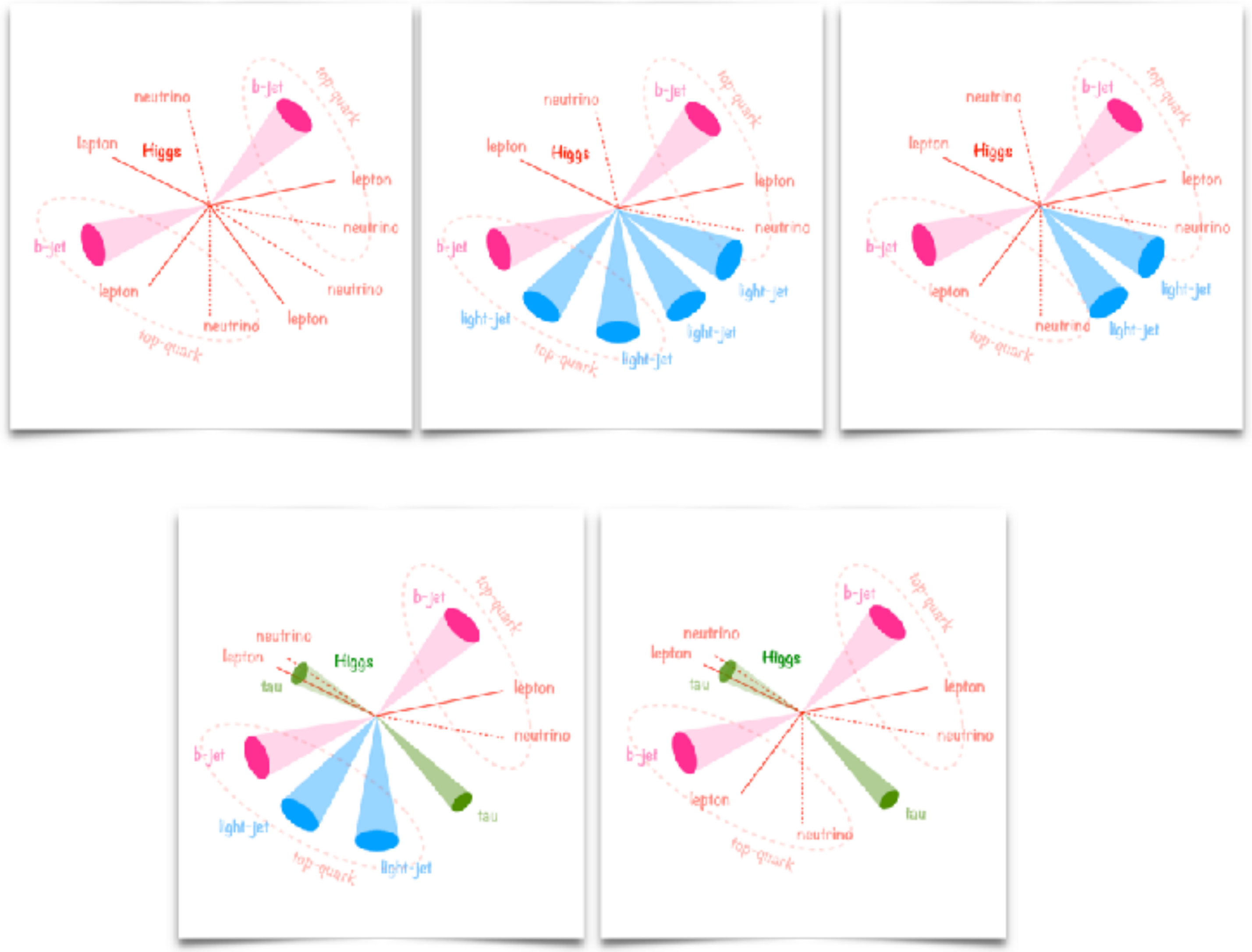


- **Dominant backgrounds from ttW and ttZ which require a very good modelling!**
- **To get there requires an excellent rejection of fake leptons!**

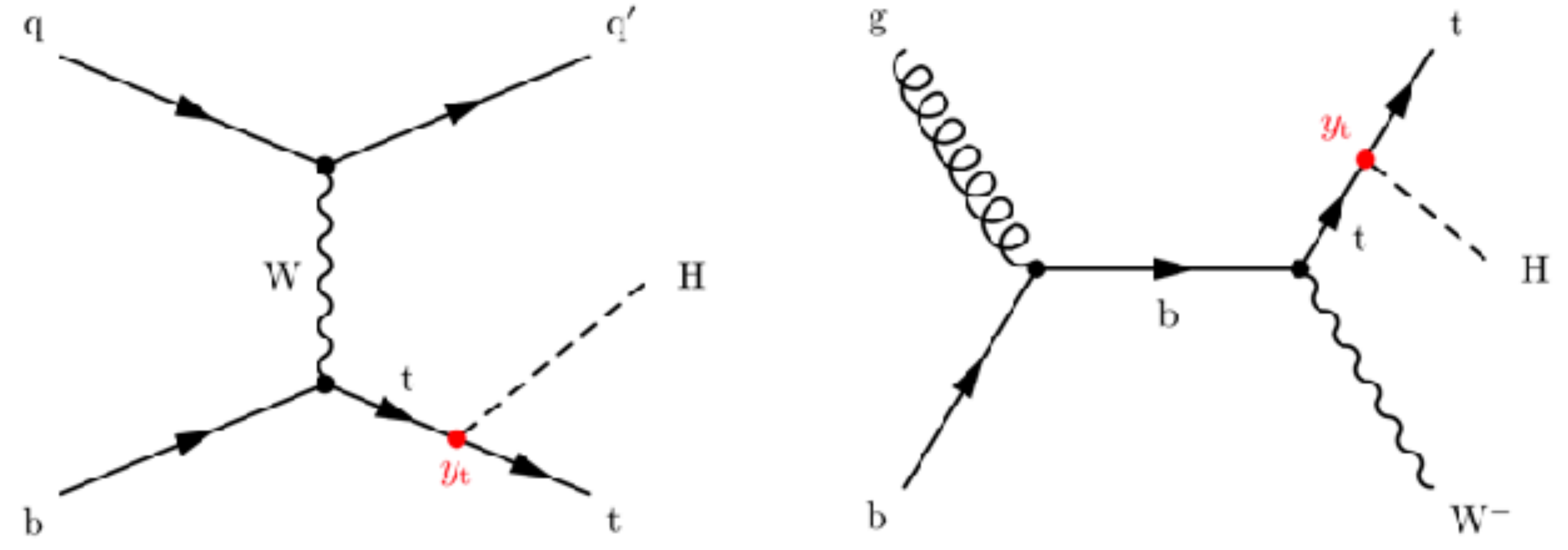
Direct probe of the top Yukawa coupling

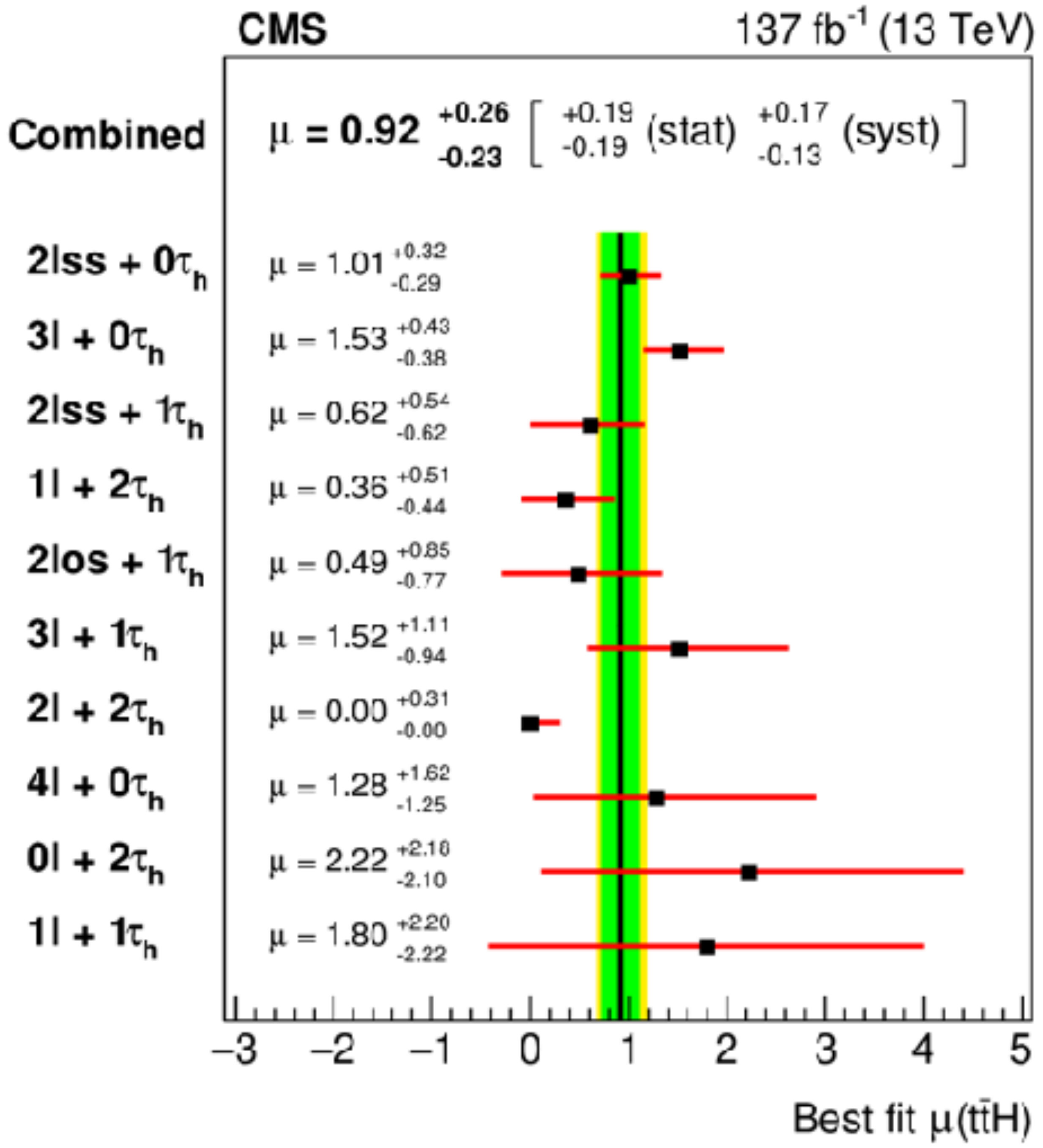
ttH Analyses at LHC: Massively Complex!

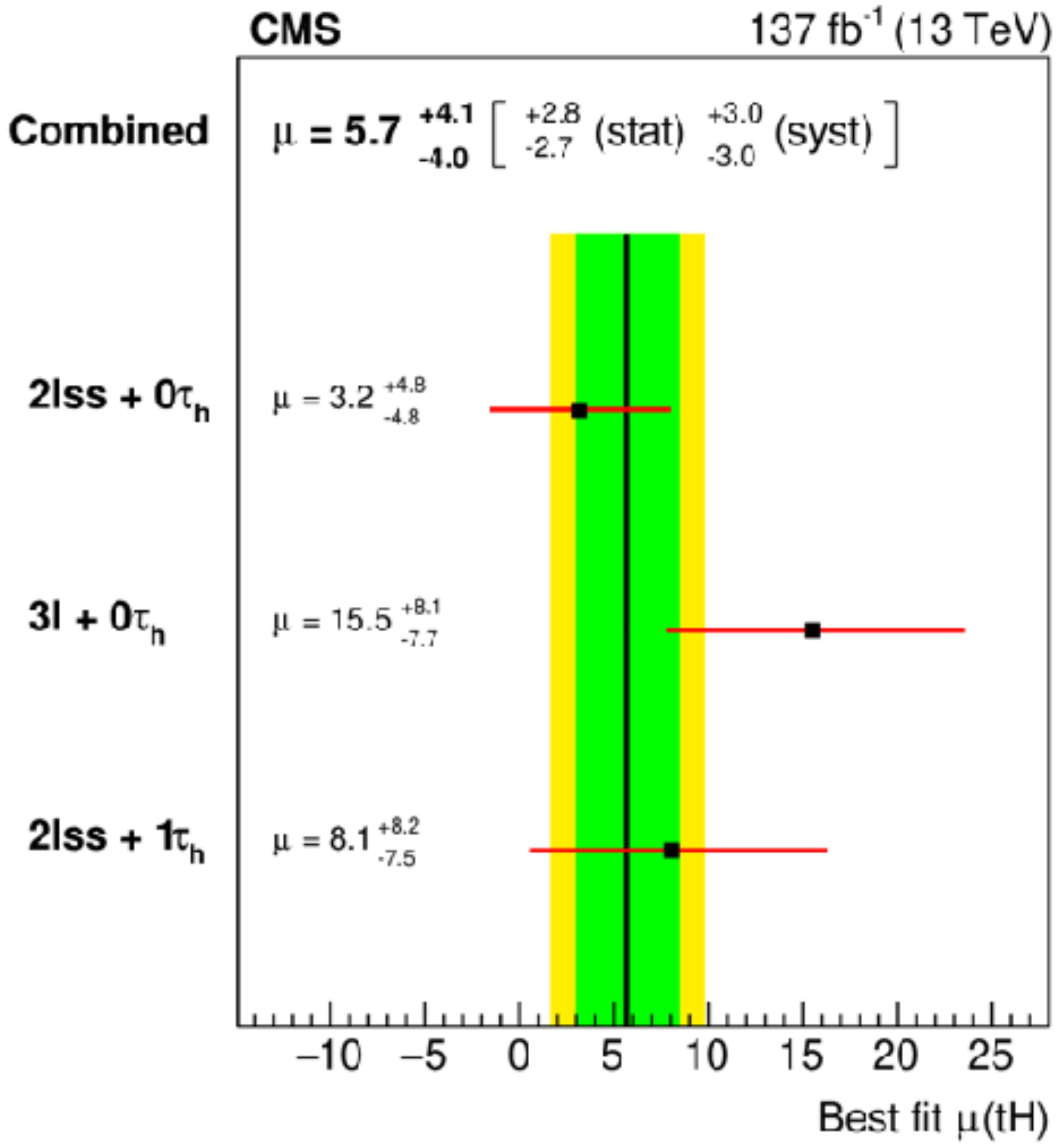




Result also covers single-top-Higgs production modes.





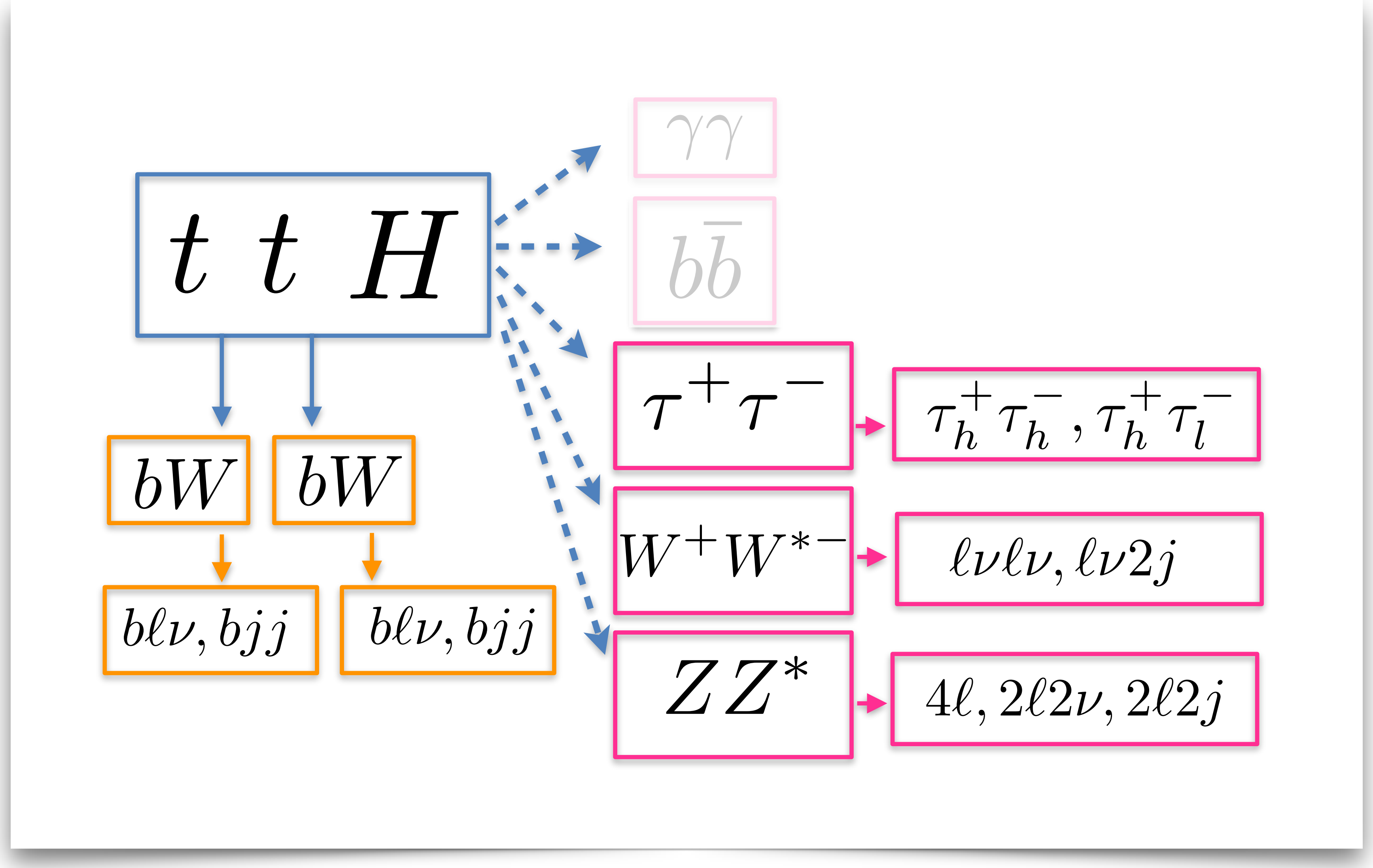


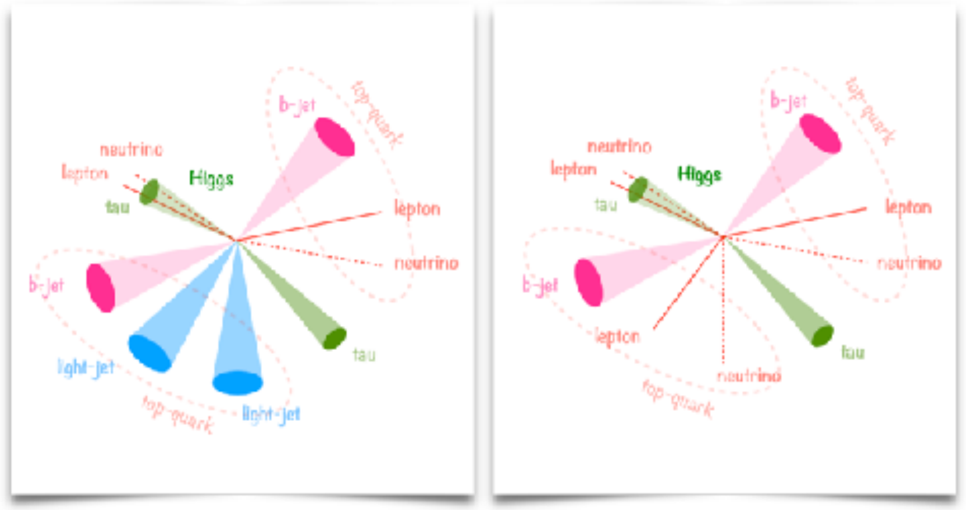
Above 5 s.d. deviation sensitivity and 4.7 s.d. observed significance!

Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!

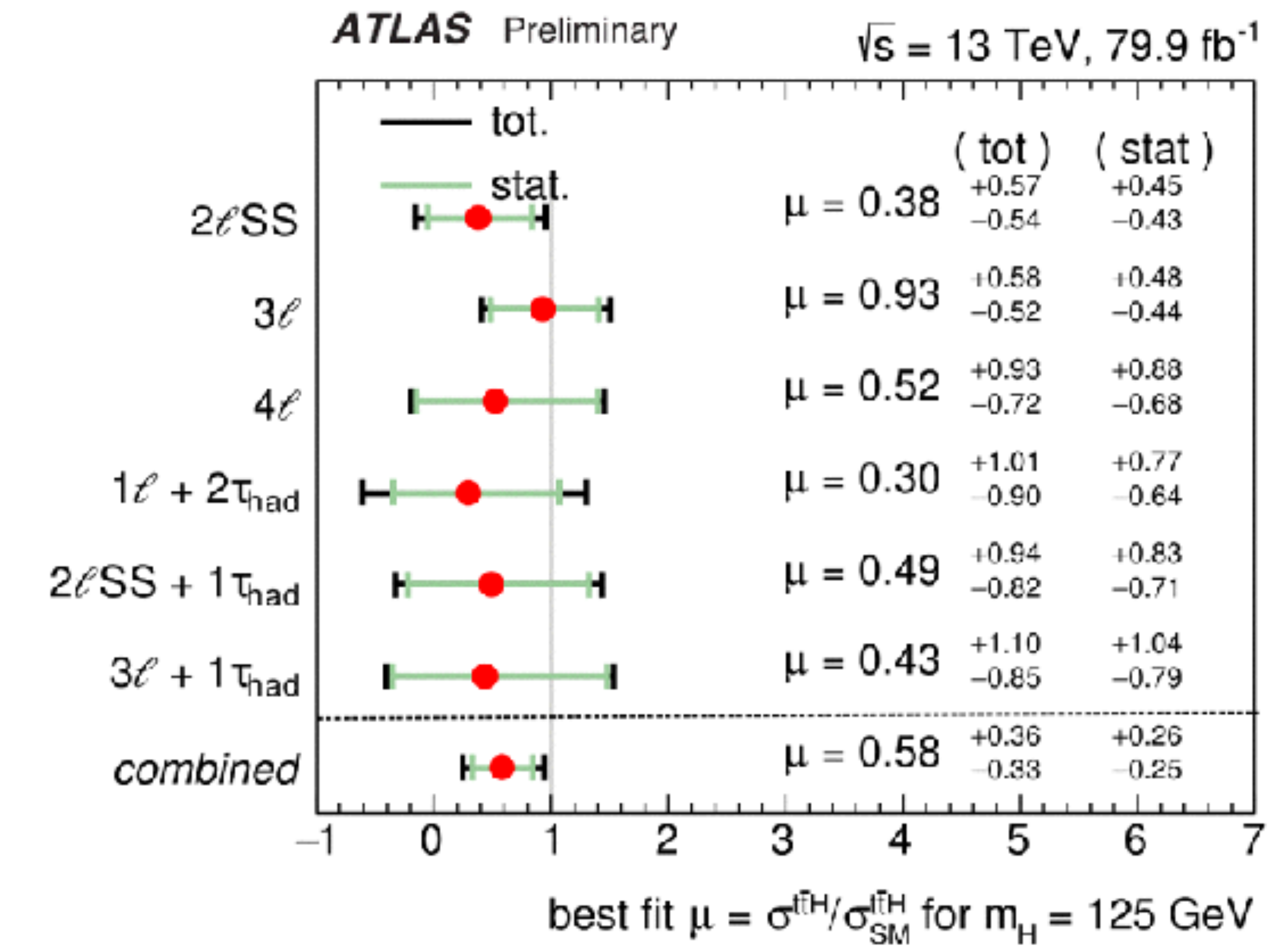
ATLAS-CONF-2019-045

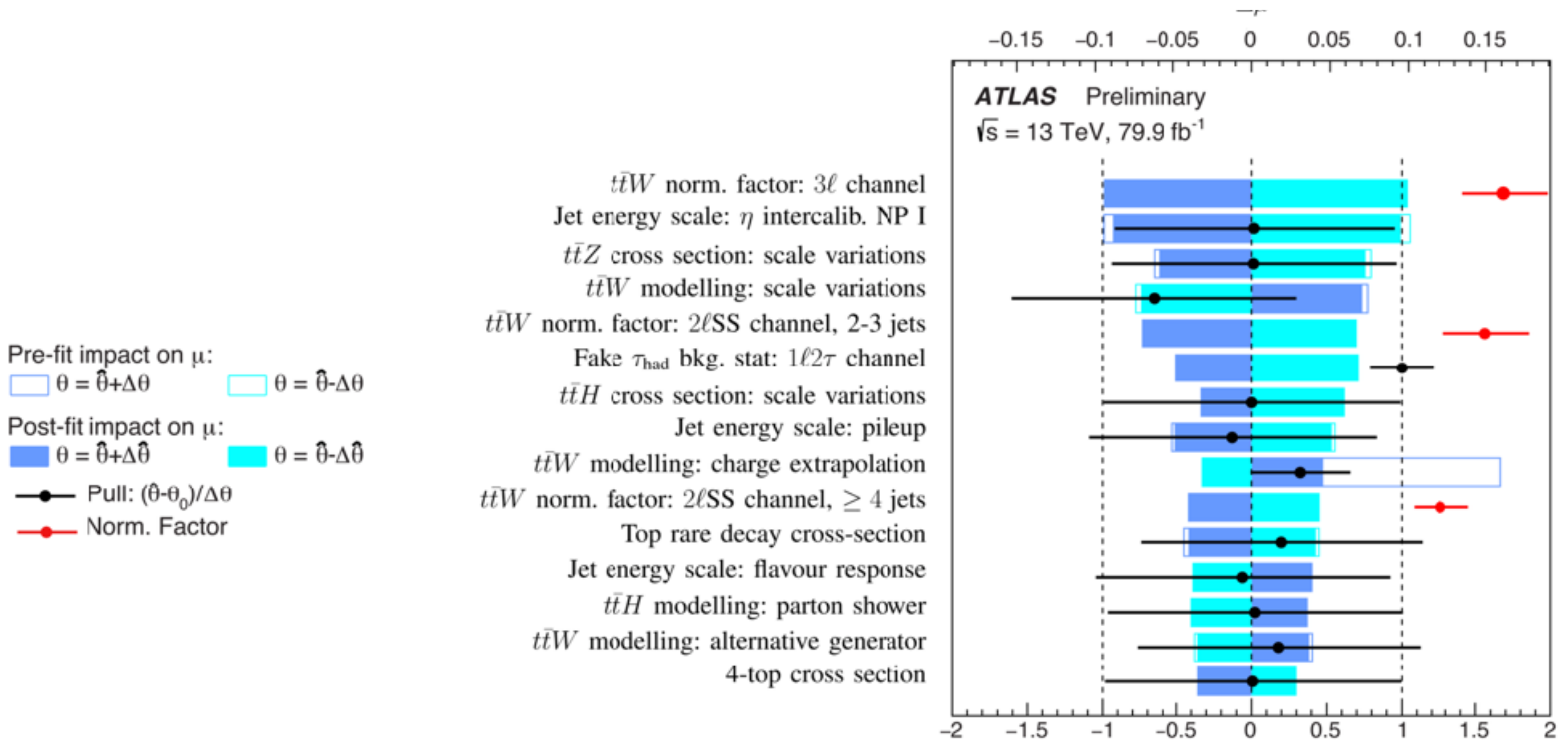




Similar analysis in ATLAS: **Normalisation of the ttW background is high by approximately 2 s.d. (also high in CMS):**

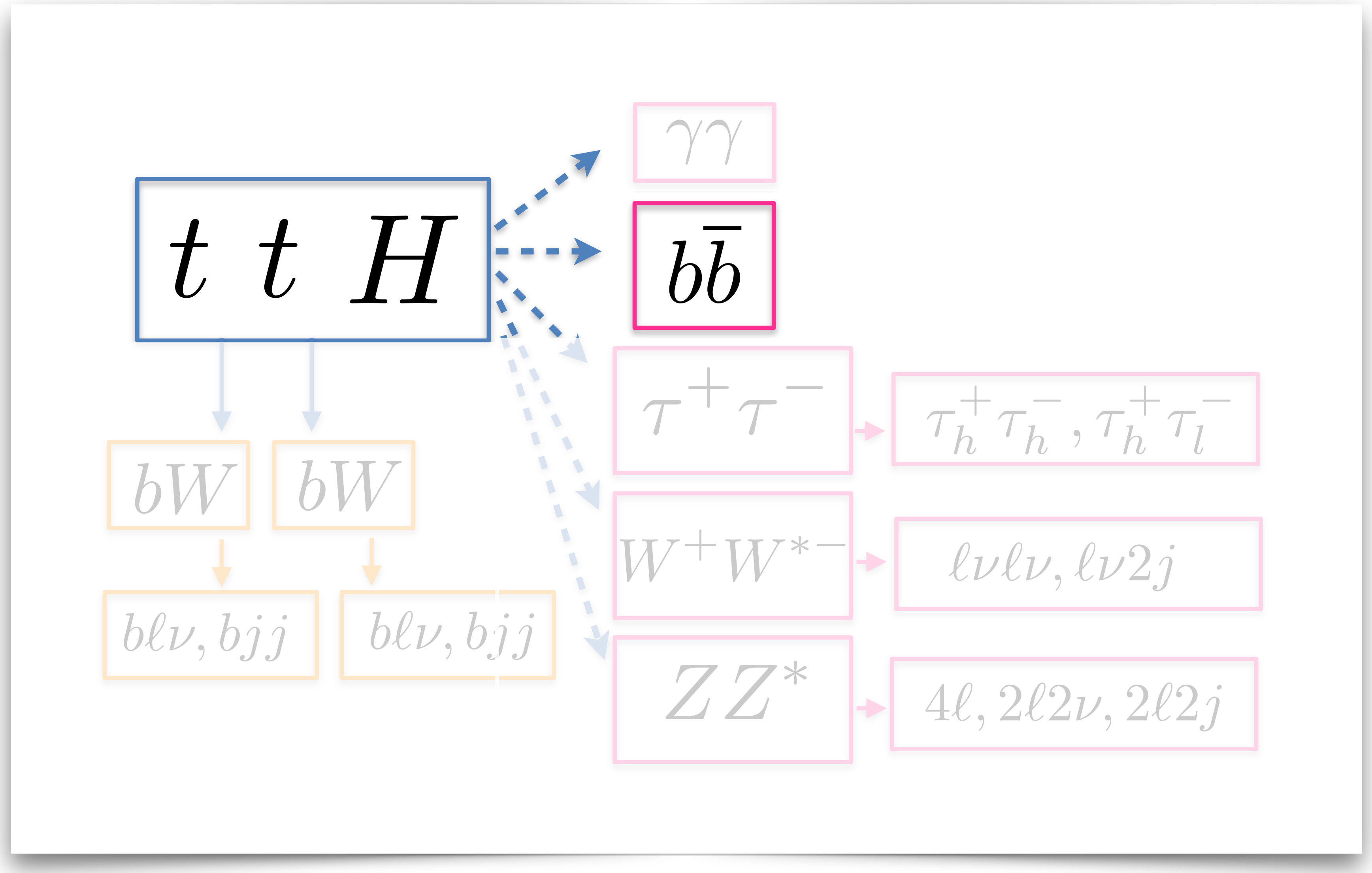
An improved description of the *ttW* background is needed to reach greater precision in the future. (see yesterday's lecture)



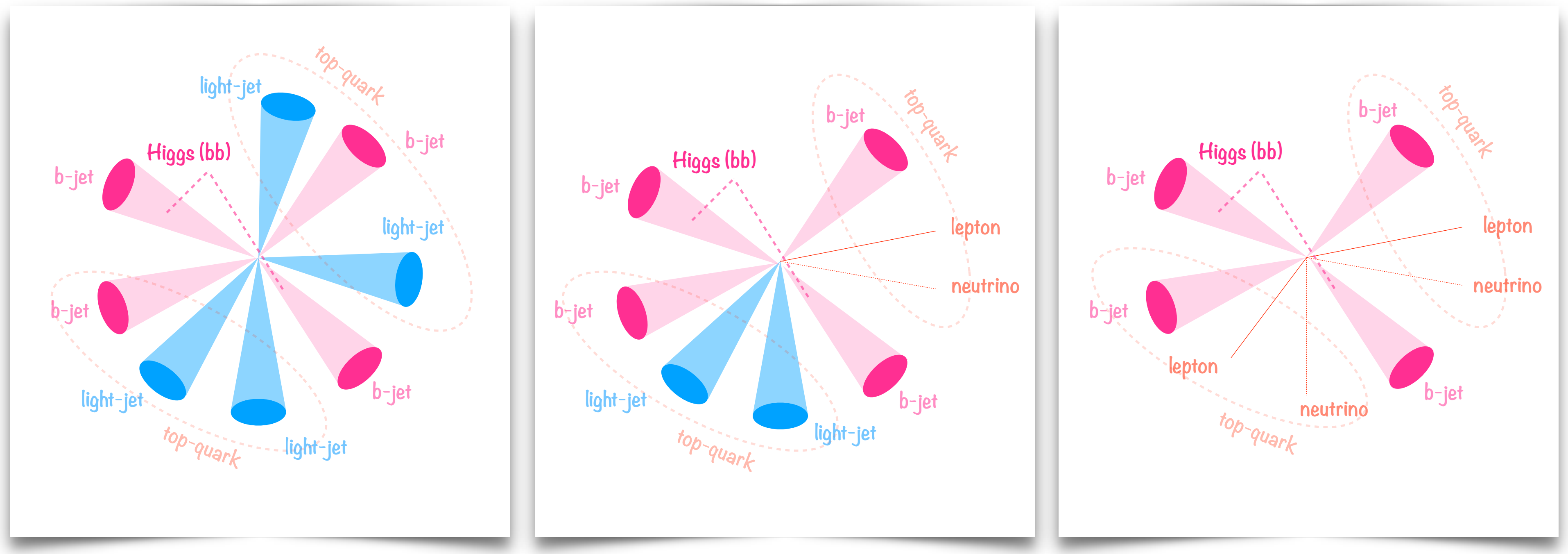


Direct probe of the top Yukawa coupling in ttH(bb)

ttH Analyses at LHC: Massively Complex!

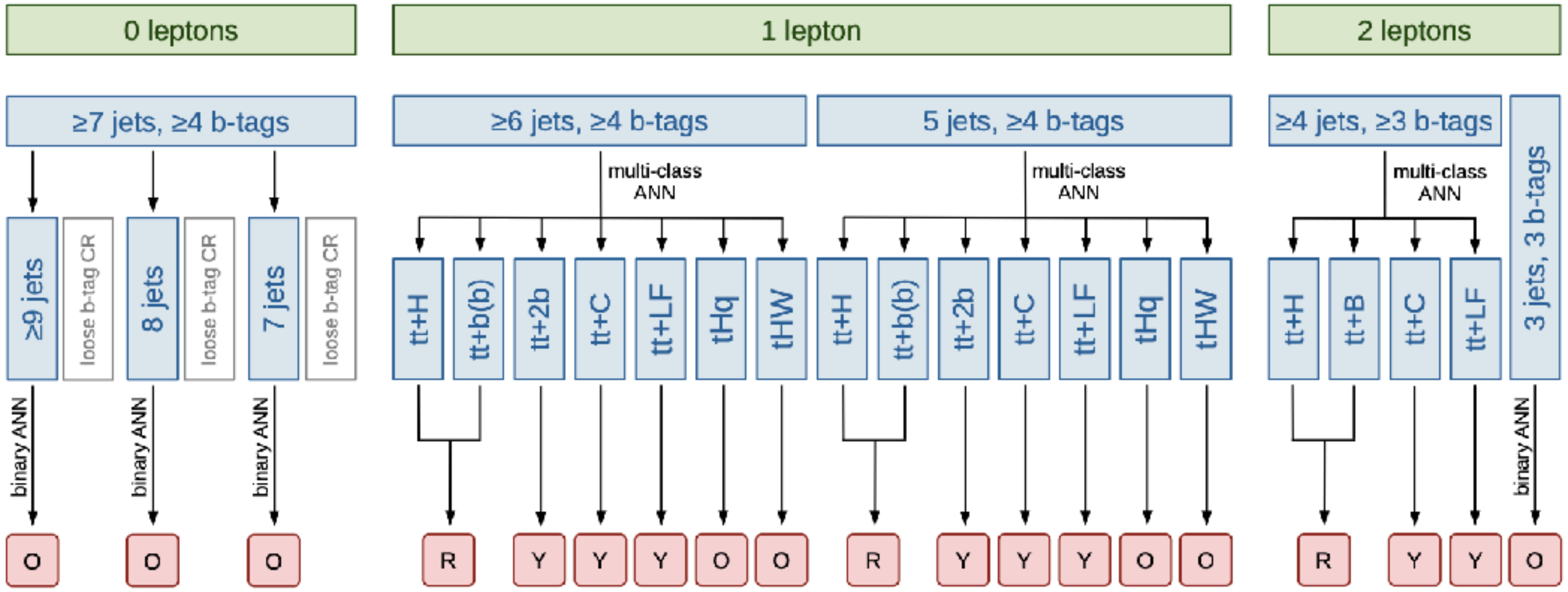


Extremely challenging channel



Very large combinatorial background 4 b-jets in all cases!

Complex final state requiring a large number of possible topologies!



Distribution in template fit, event yield (Y), ANN output (O), likelihood ratio of ANN outputs (R)

Full Run 2 Dataset and all topologies, including the intricate fully hadronic final state!

Direct probe of the top Yukawa coupling

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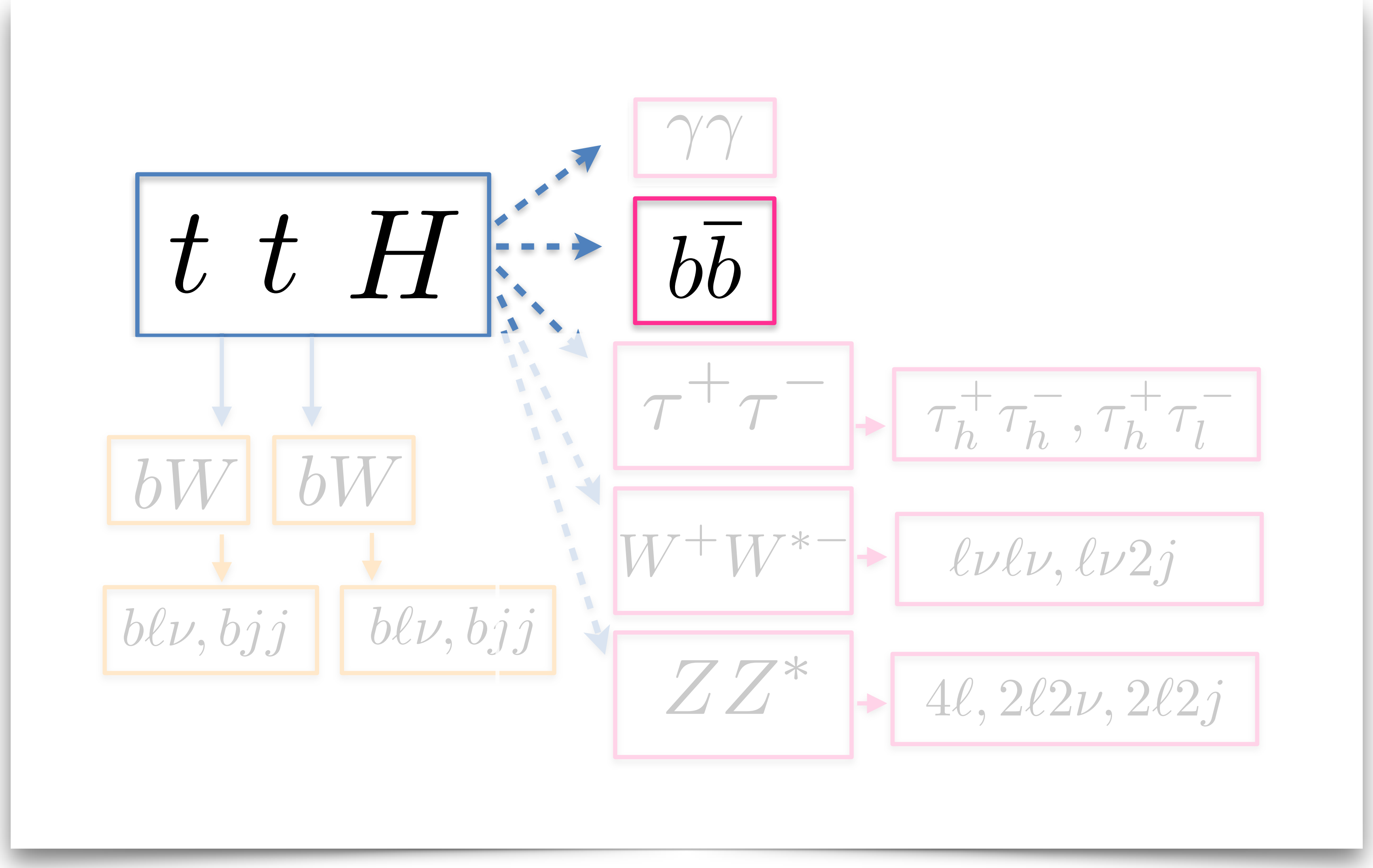

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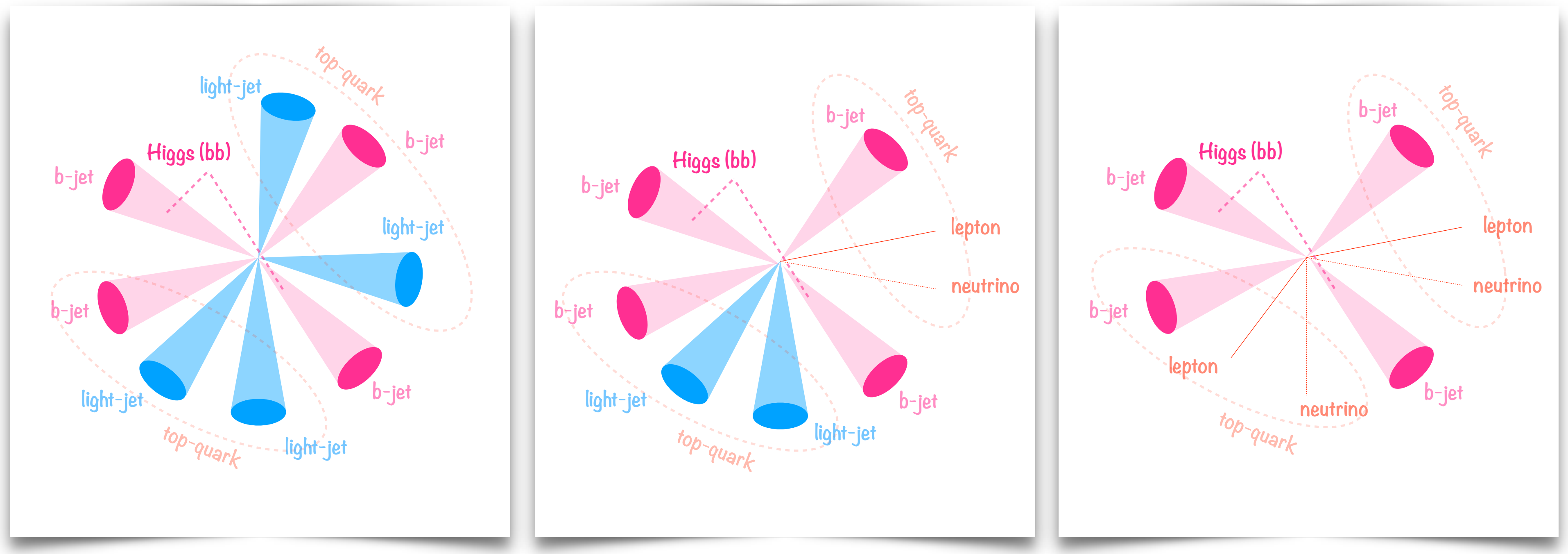

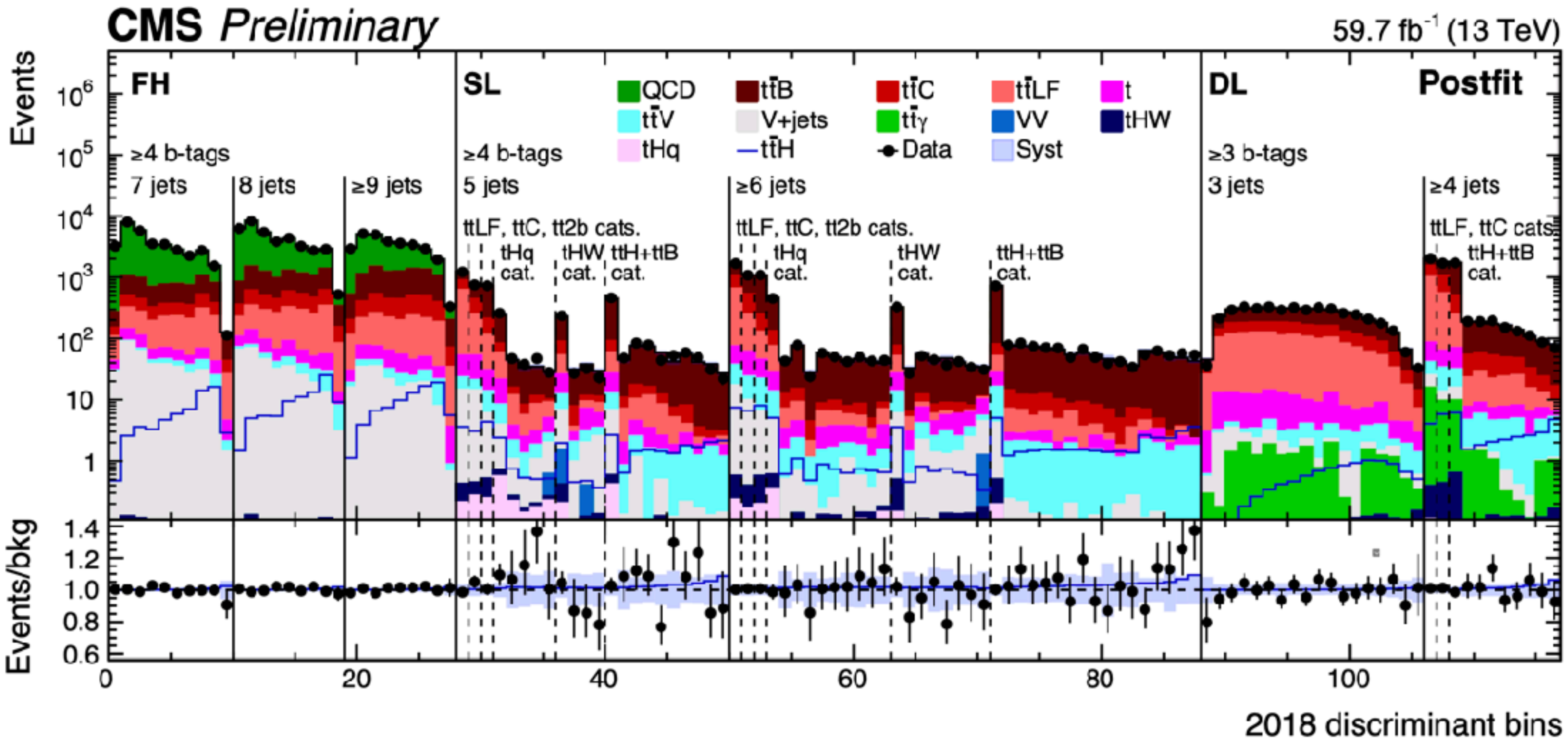

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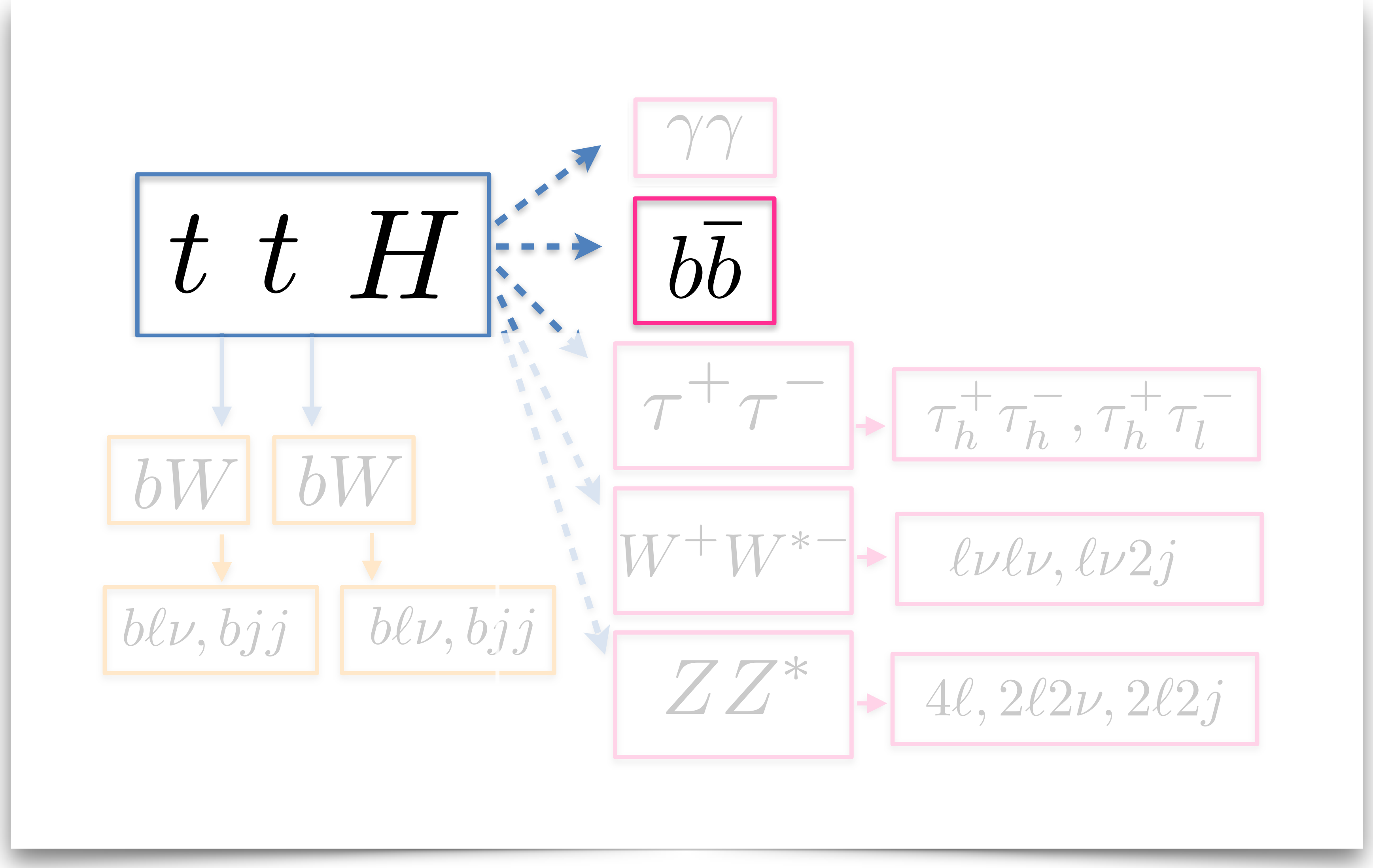

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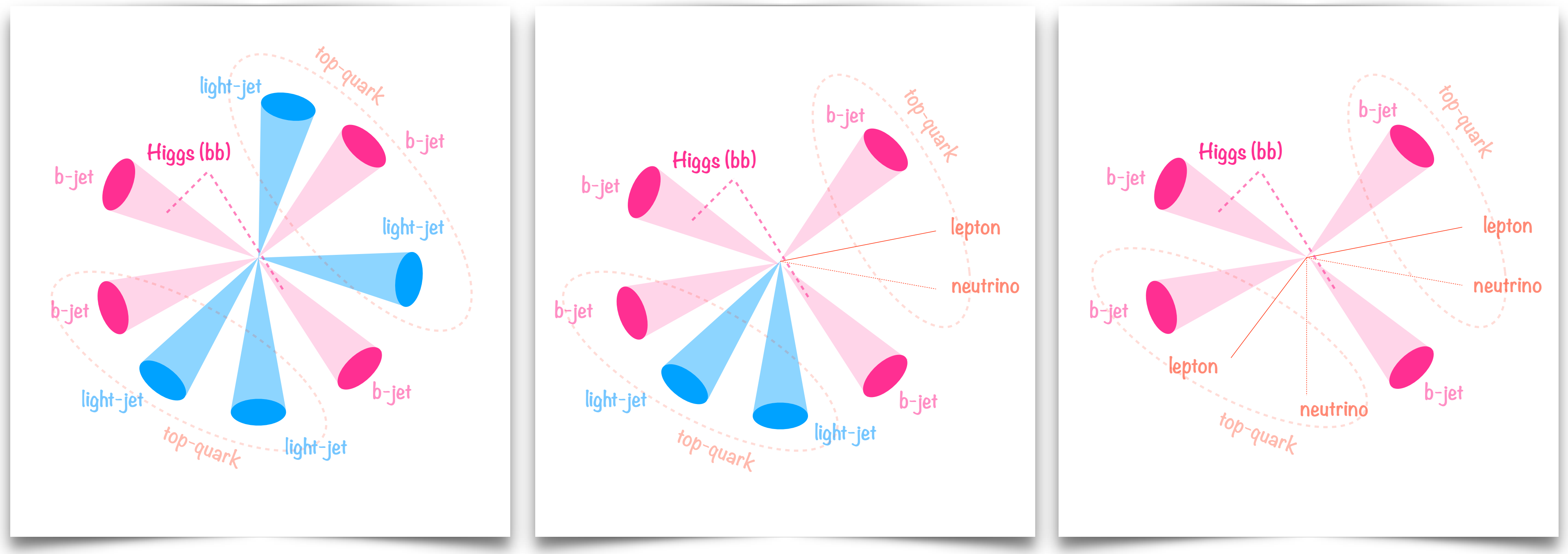

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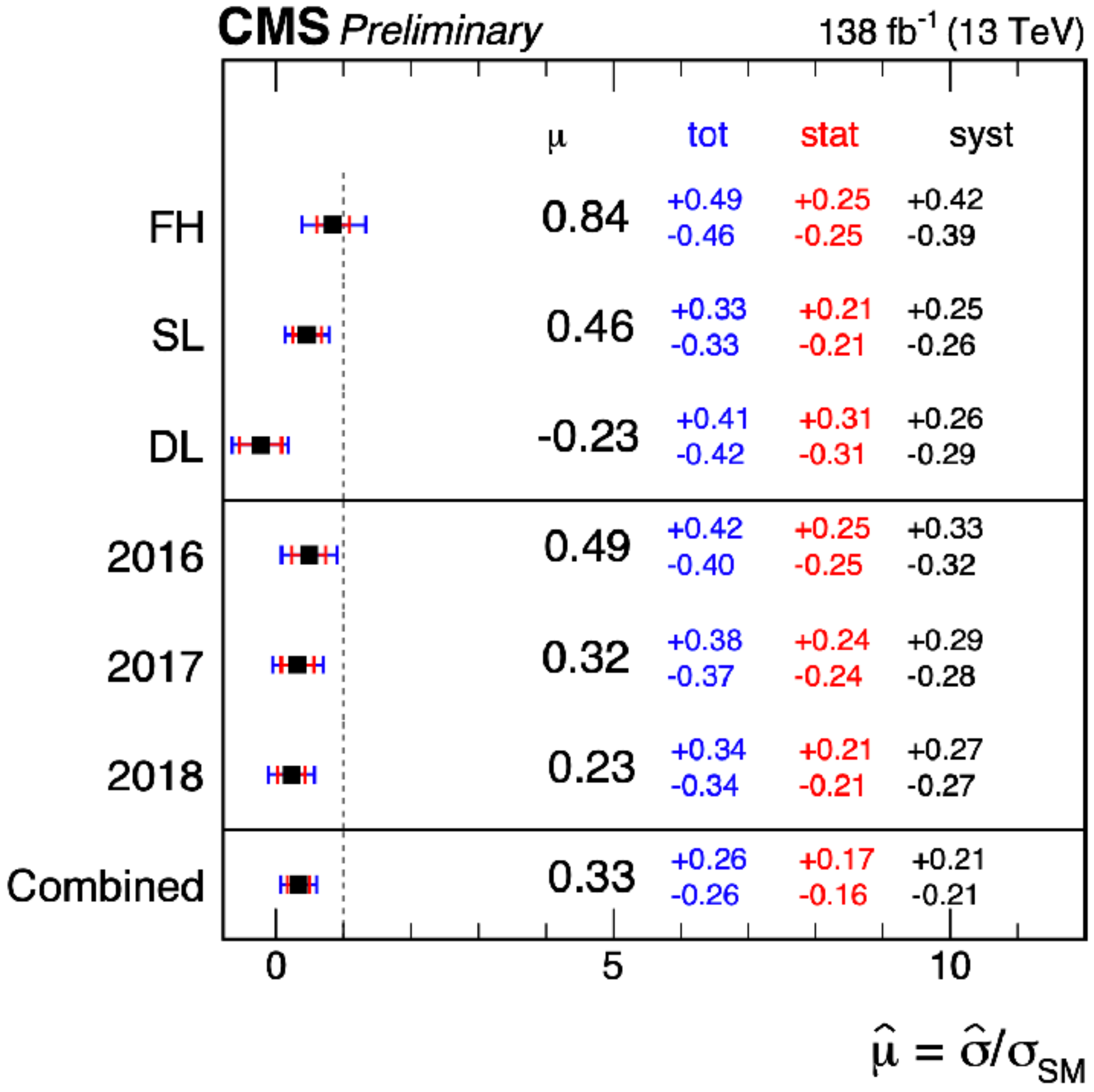


SL as expected is the most powerful equivalent stat-syst contributions

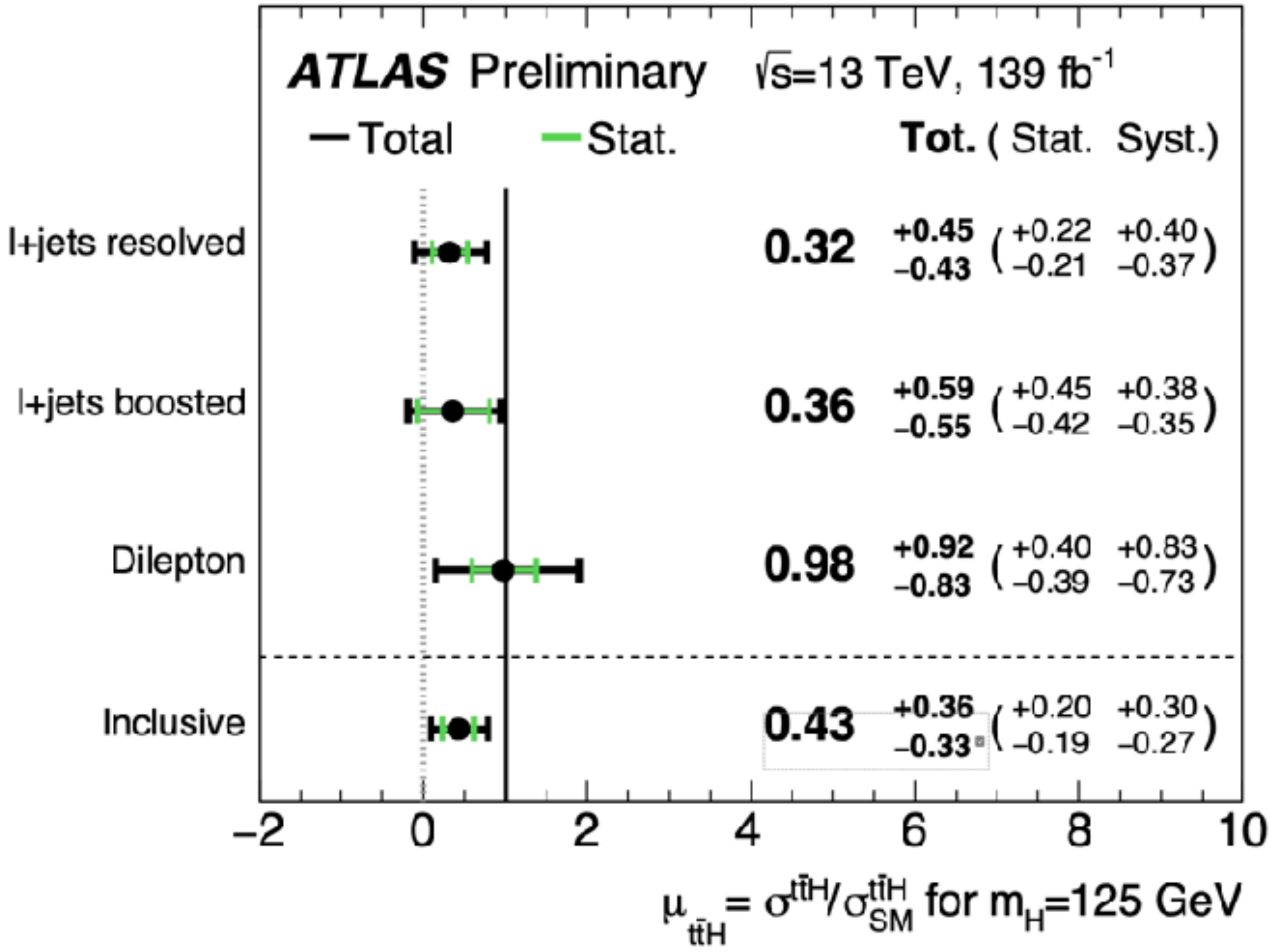
FH Dominated by syst uncertainties

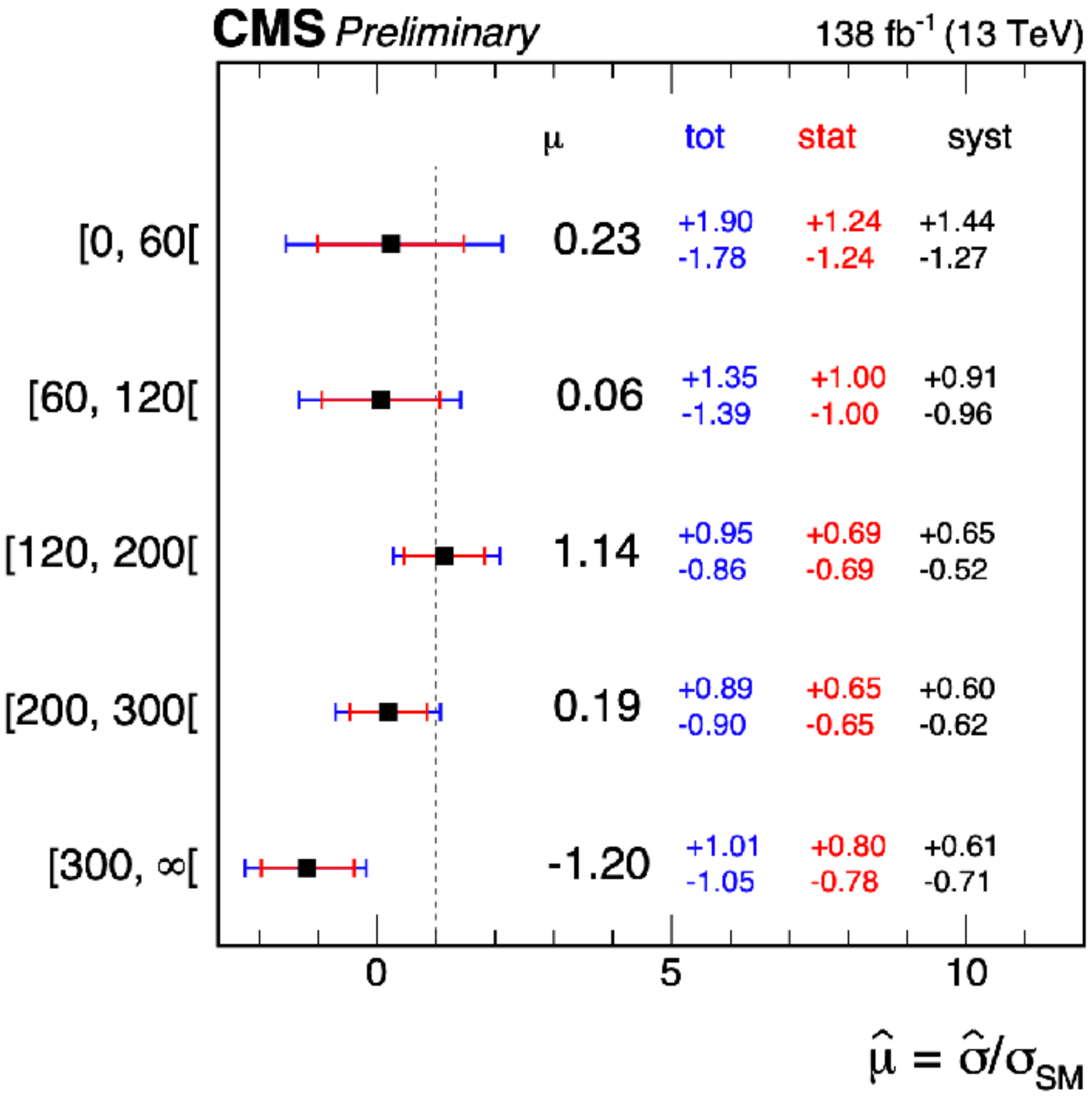
DL Stat still largest

Direct probe of the top Yukawa coupling in ttH(bb)

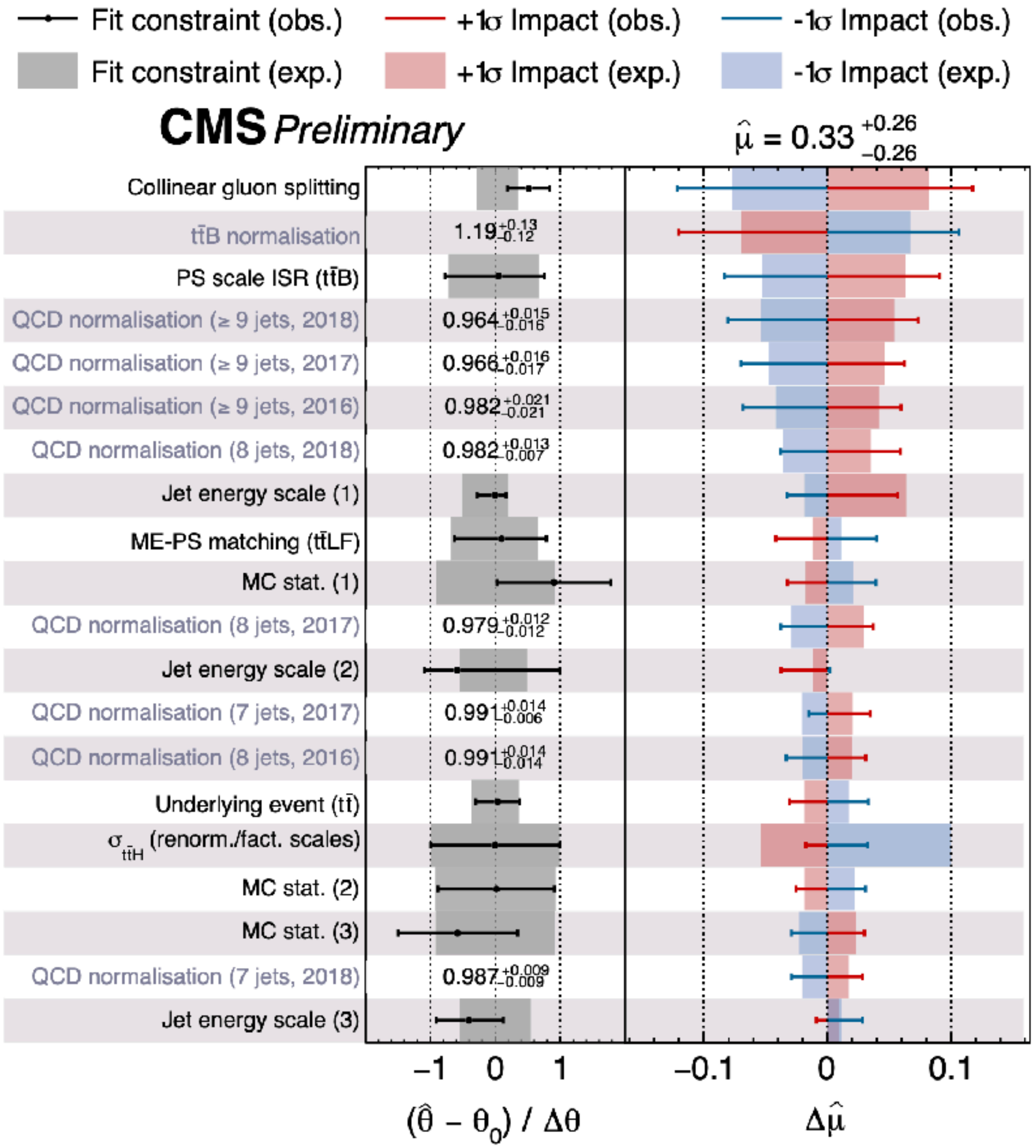
A closer look

- Expected sensitivity of the channel is 4.1 s.d.
- Observed excess has only 1.3 s.d.
- Compatibility with SM at the level of ~2.6 s.d. (fairly significant deficit evenly distributed across years but not as a function of Higgs pT - see STXS measurements)
- The ATLAS ttH(bb) in the 1L channel is consistent with the results seen in CMS.



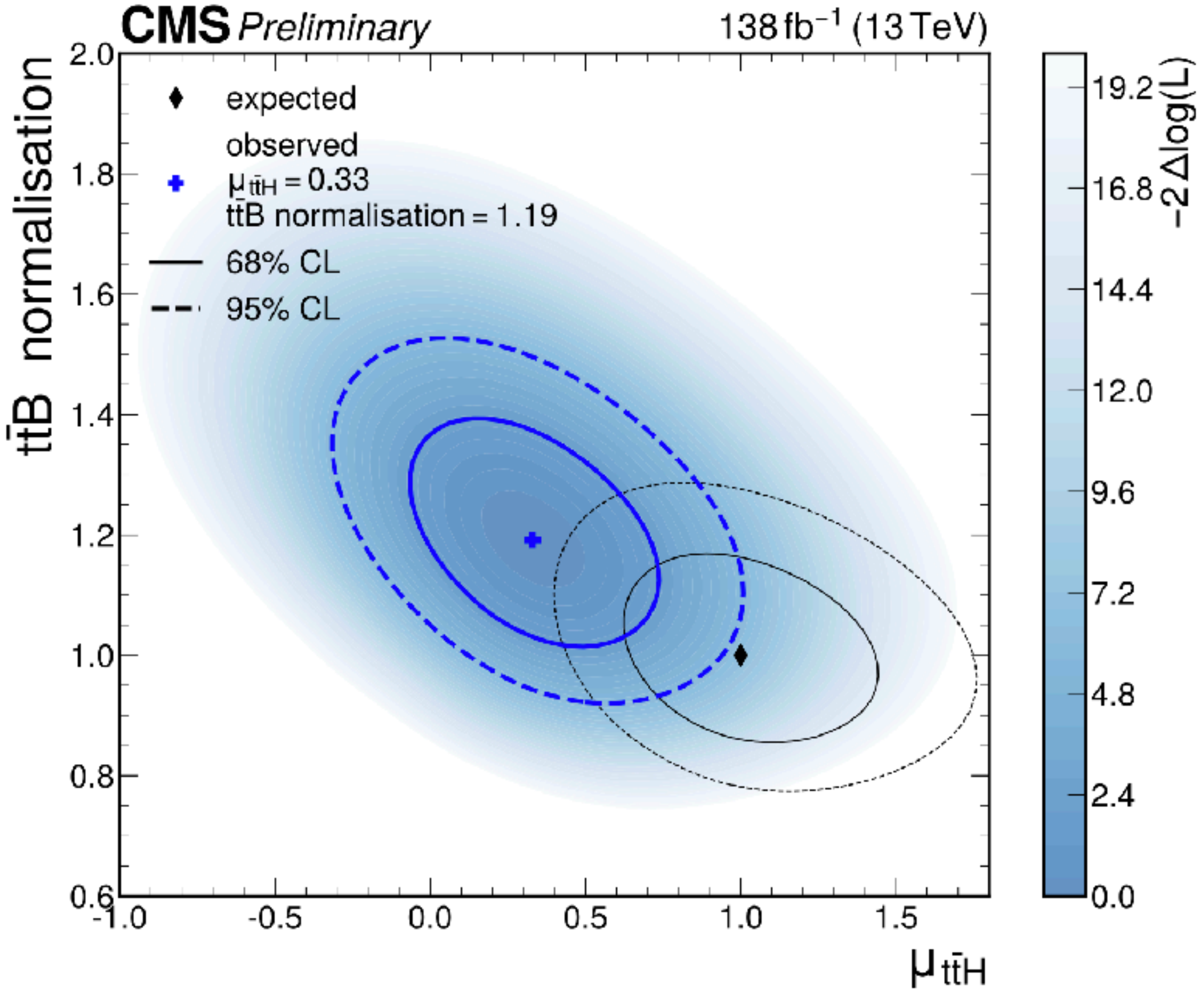


Direct probe of the top Yukawa coupling in ttH(bb)



tt + 2b fiducially close to each other is a separate contribution since subject to different systematic uncertainties referred to as **collinear gluon splitting**.

ttB events with at least one additional jet containing a B hadron in the fiducial volume

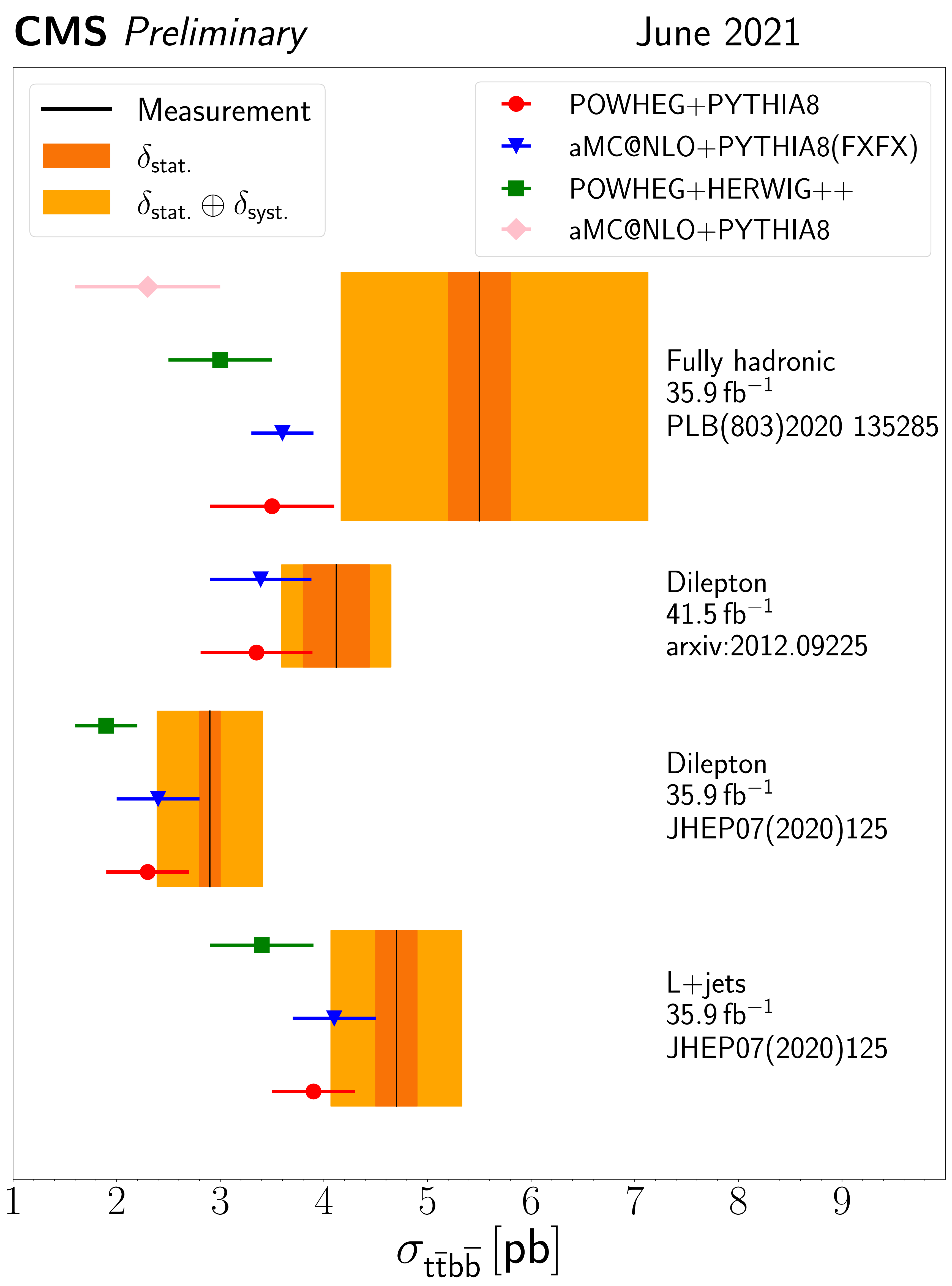


Ancillary Measurement of ttbb by CMS

Associated production of a top quark pair and additional two b quarks in the final state

Measurements done in all channels both in the full tt phase space with two additional HF jets and in the fiducial phase space*.

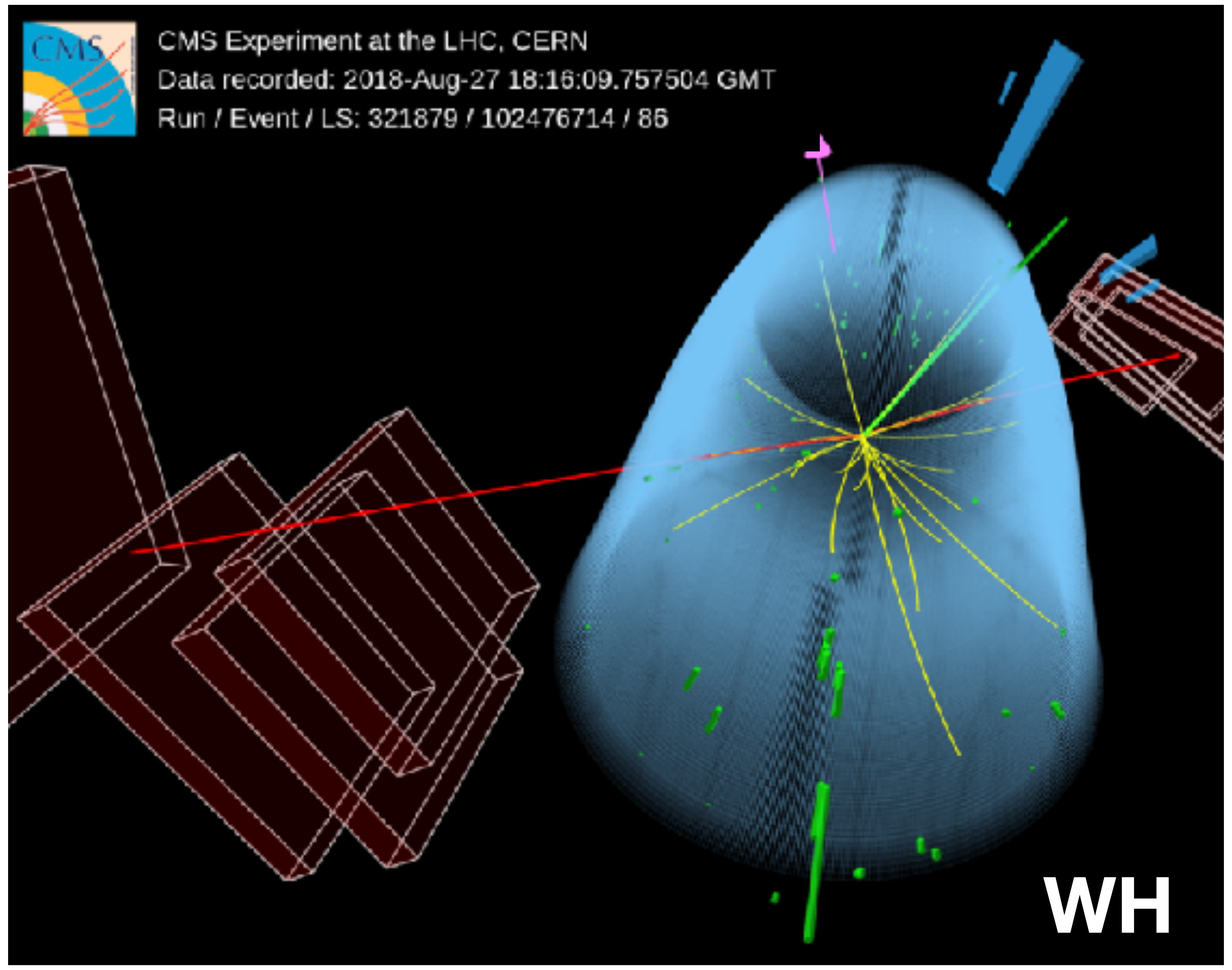
This summary of results reports the full phase space measurements.

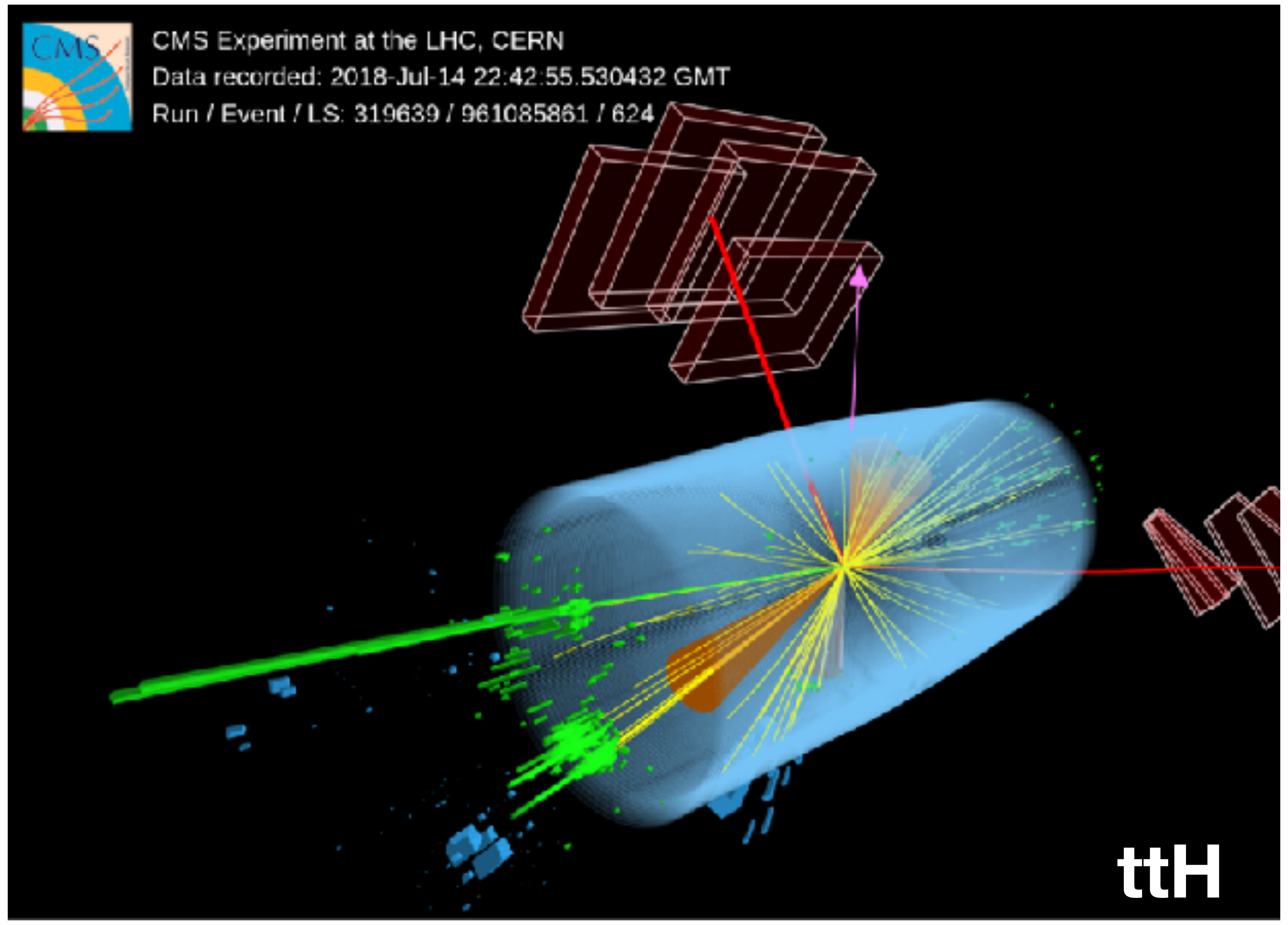


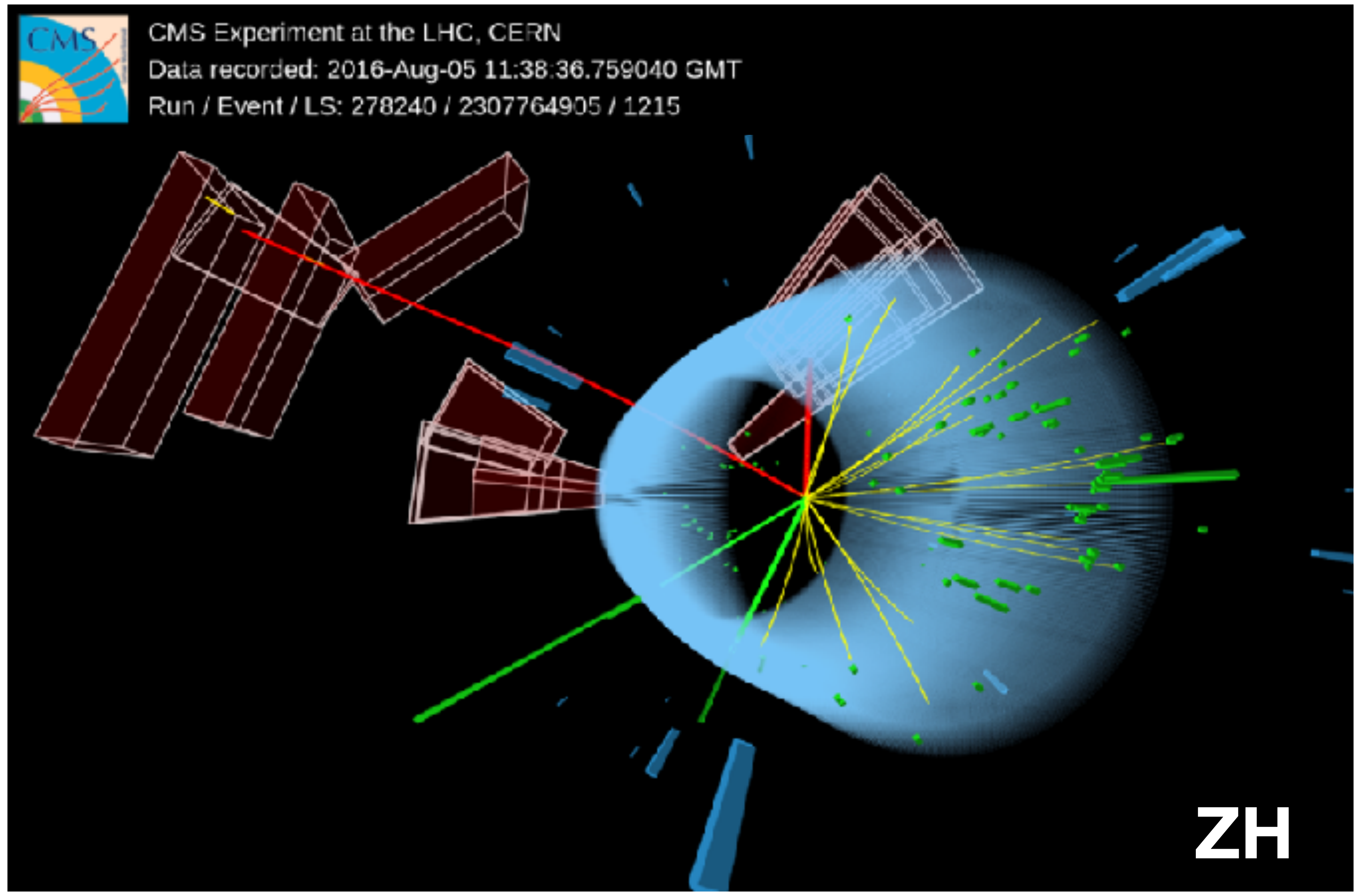
*Additional jet pT requirements are not uniform across measurements.

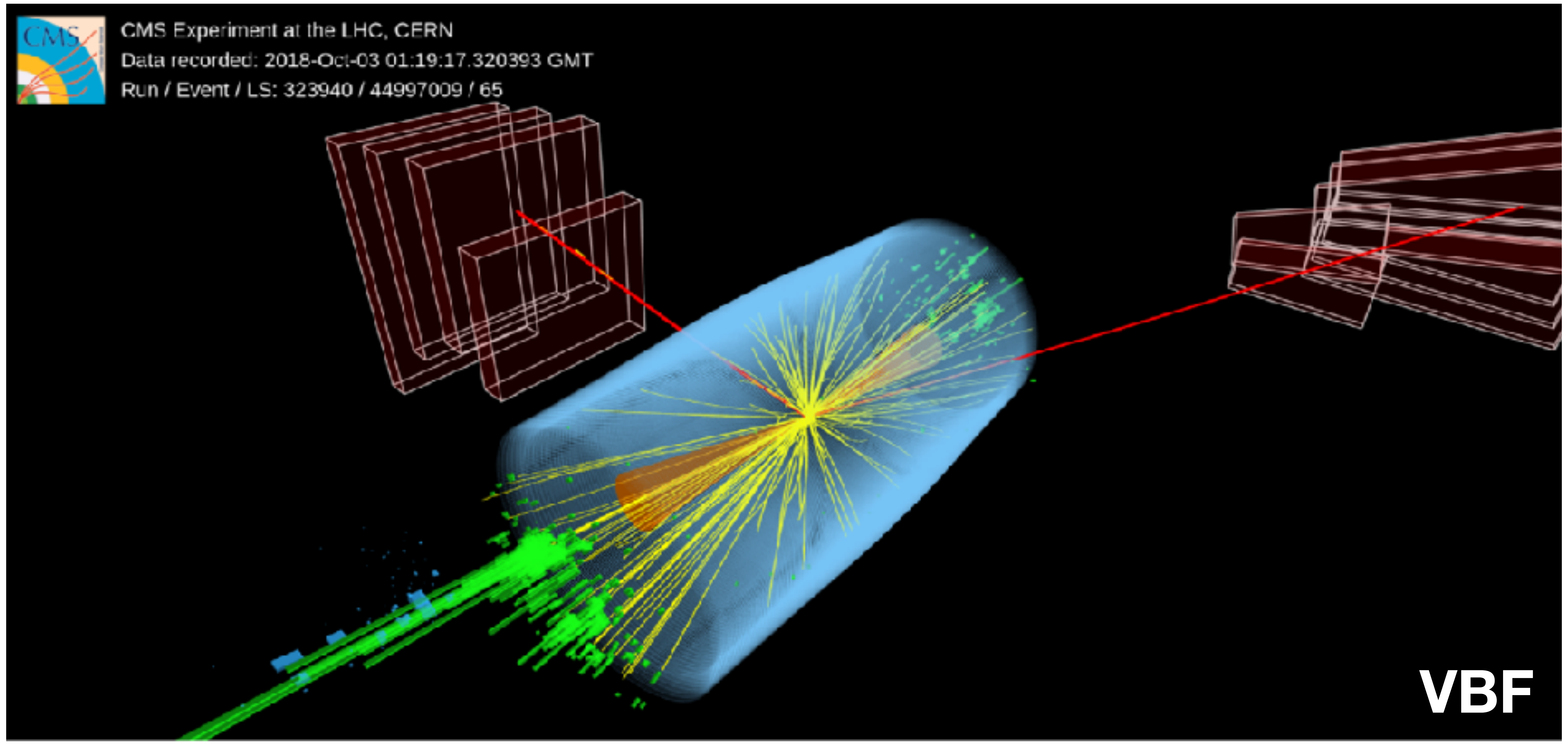
Early evidences for Rare processes

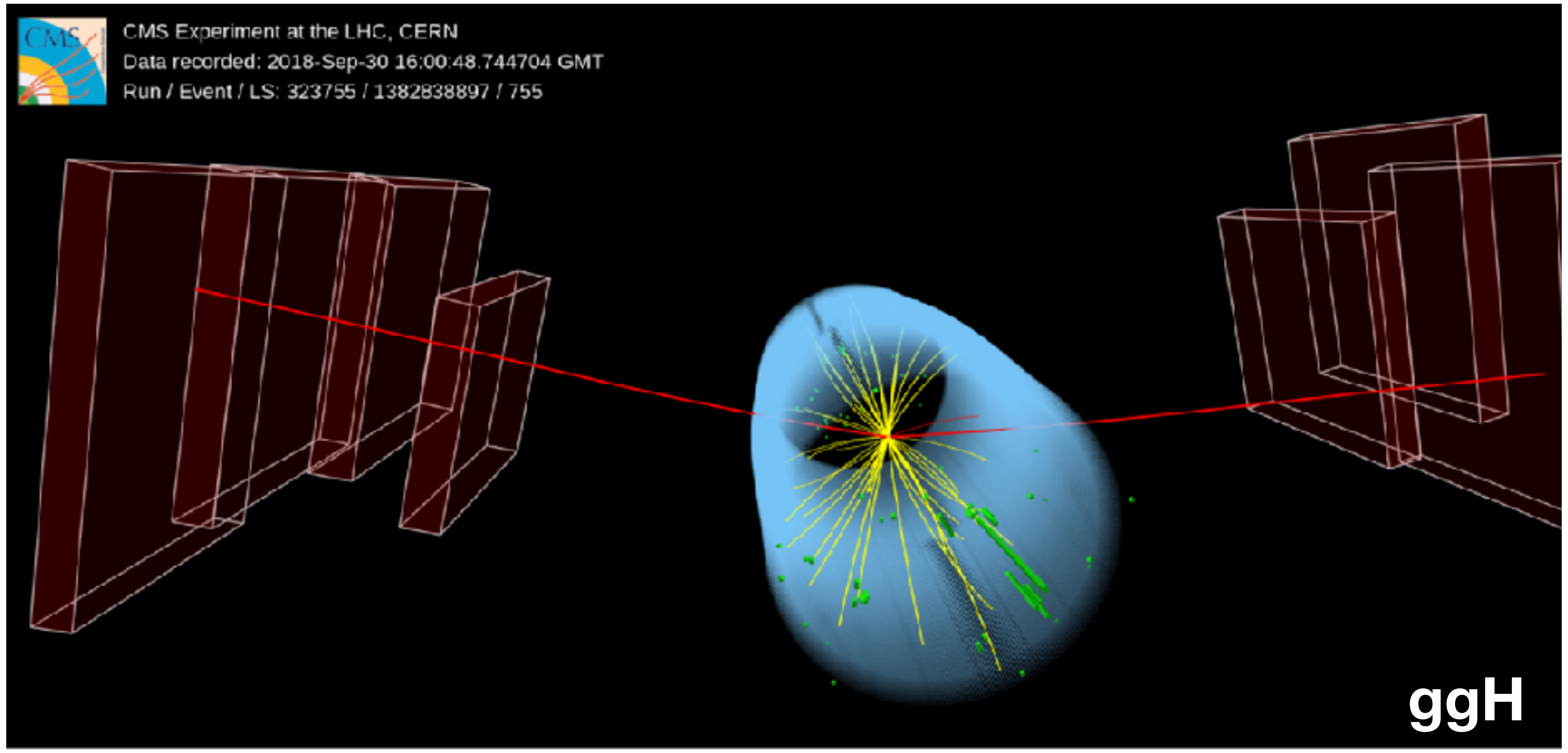
Evidence for $H \rightarrow \mu^+\mu^-$









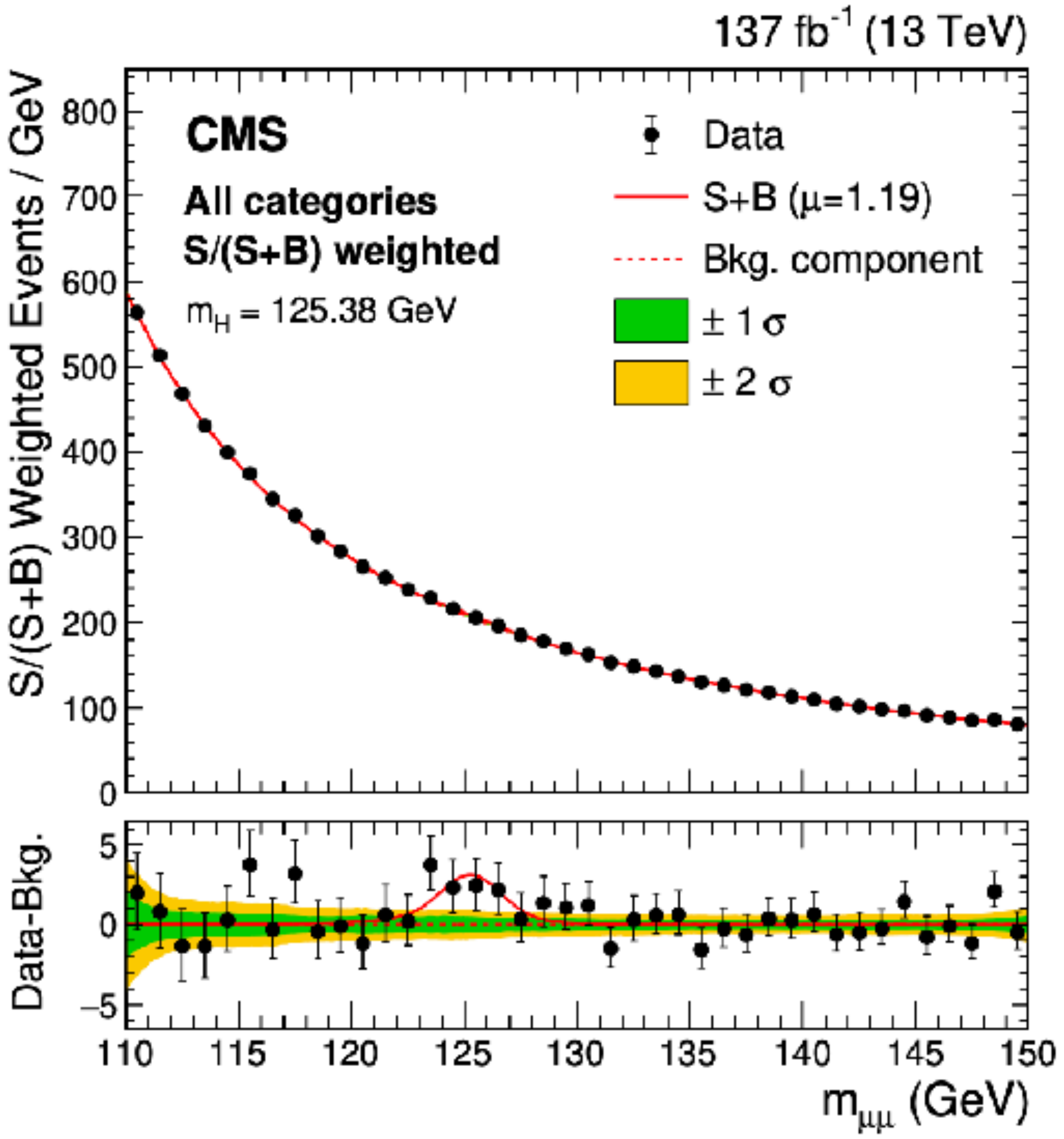


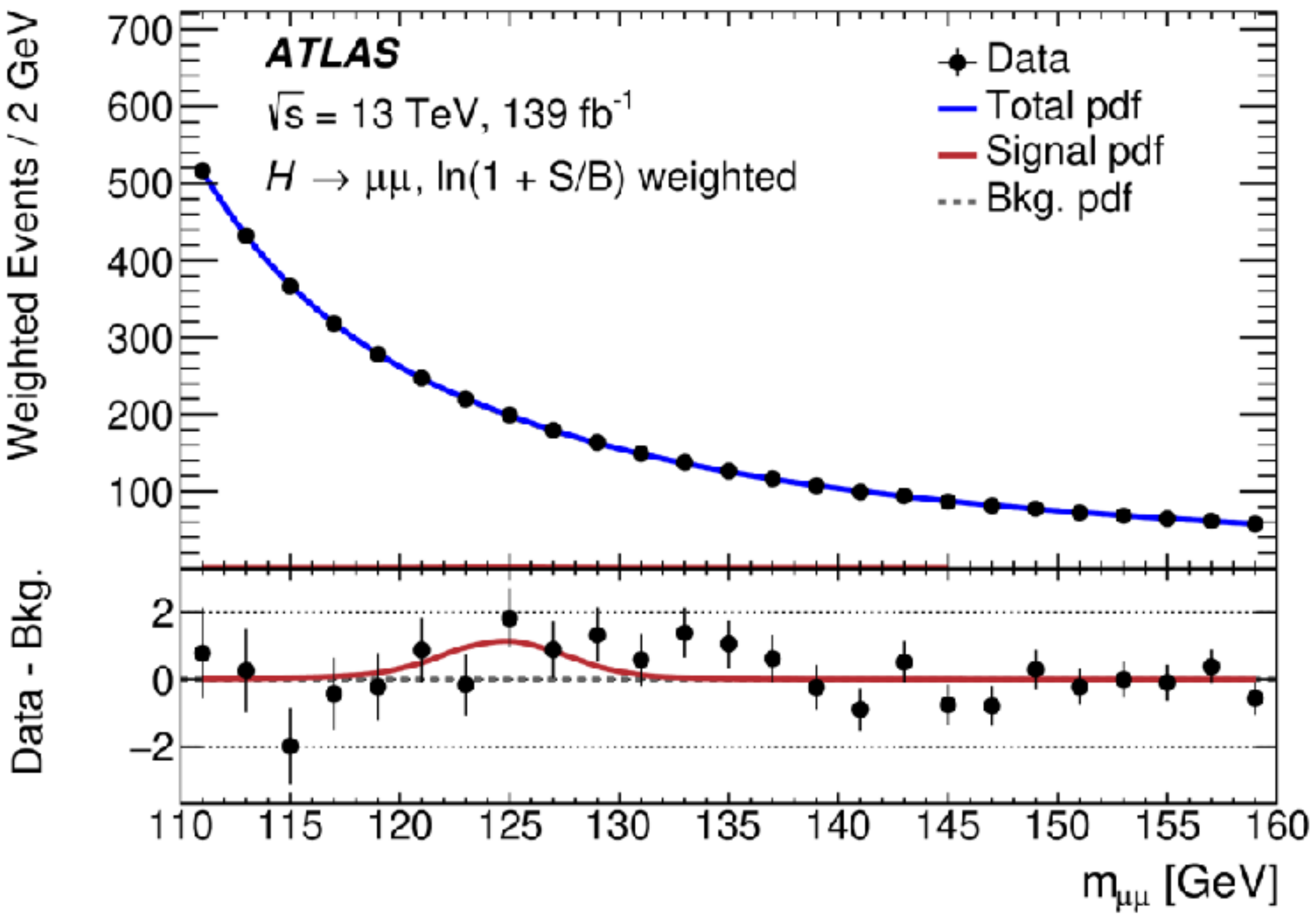
Evidence for Second Generation Yukawa Coupling

Very challenging channel!

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

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





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

CMS Result

Expected 2.5σ

Observed 3.0σ

$$\mu = 1.19 \pm 0.43$$

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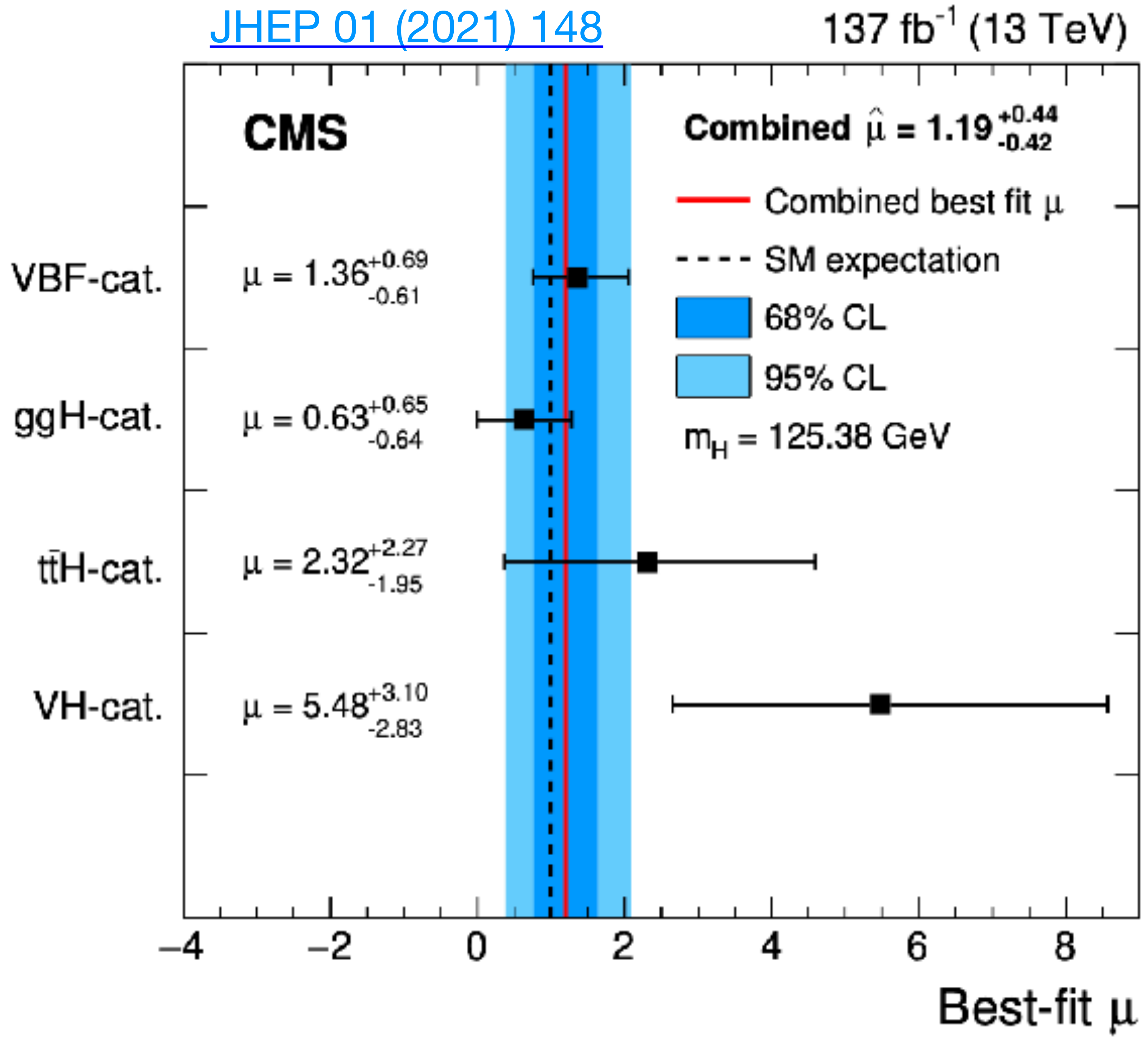
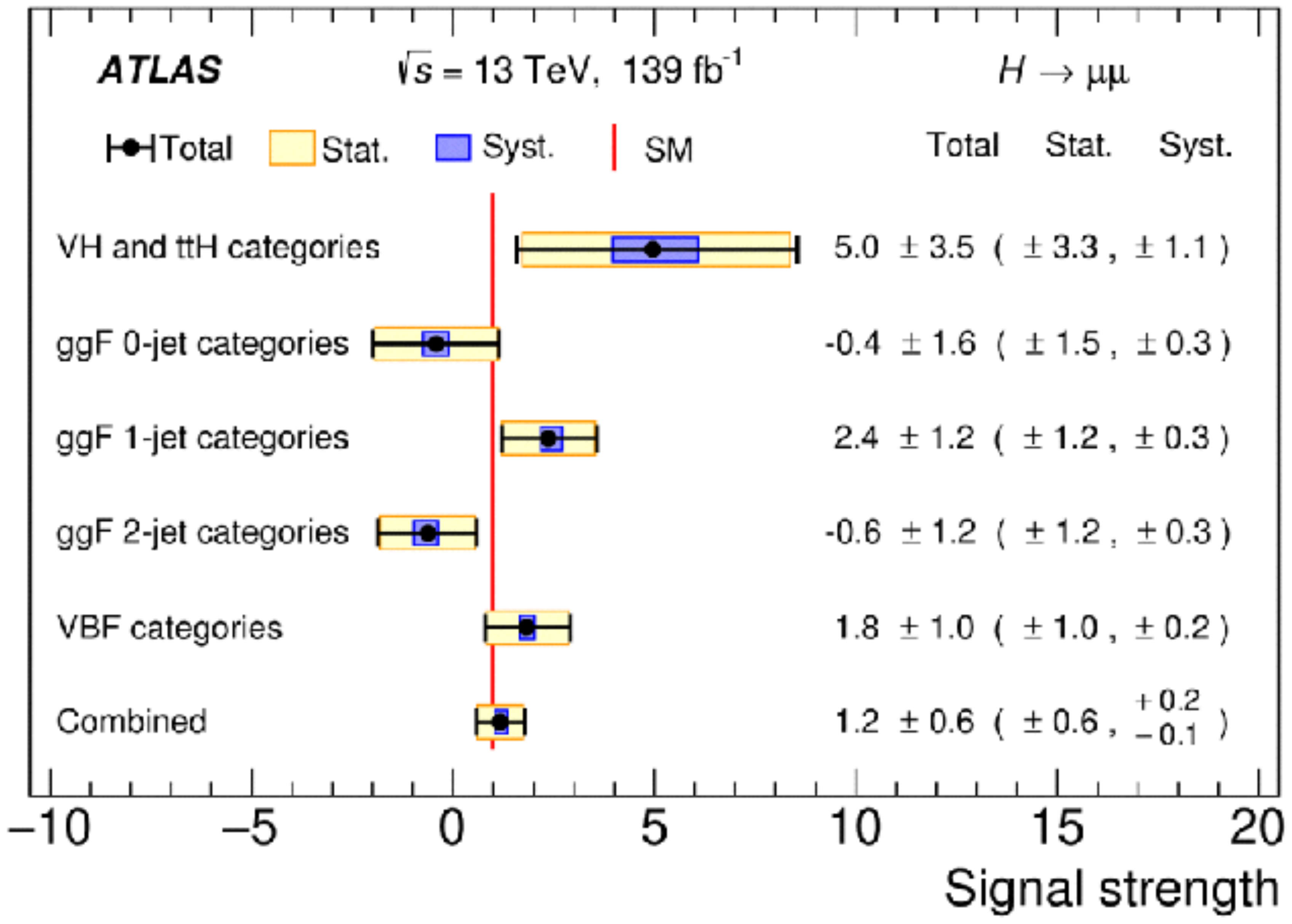


PLB 812



ATLAS Result

Expected 1.7σ

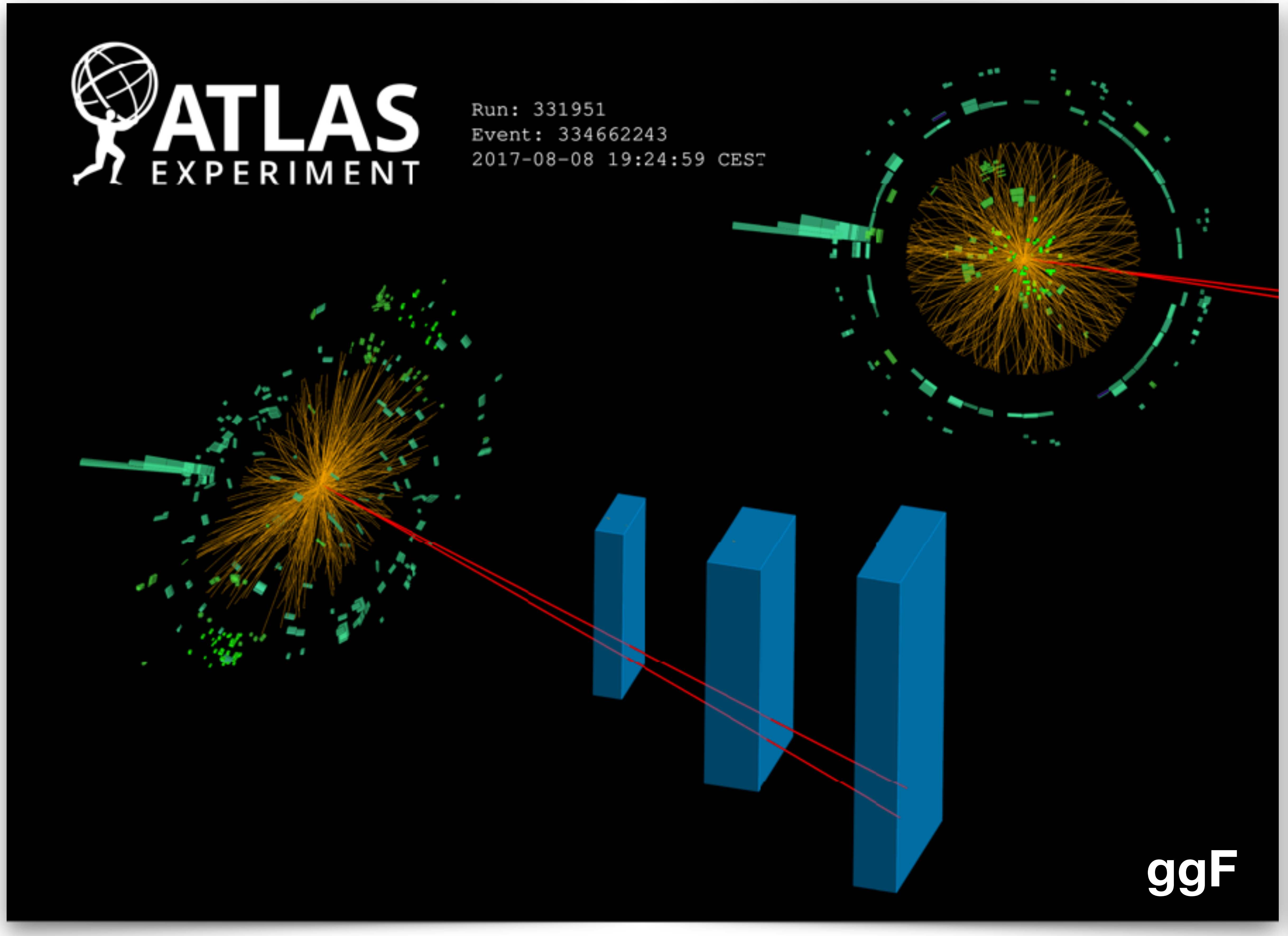
Observed 2.0σ

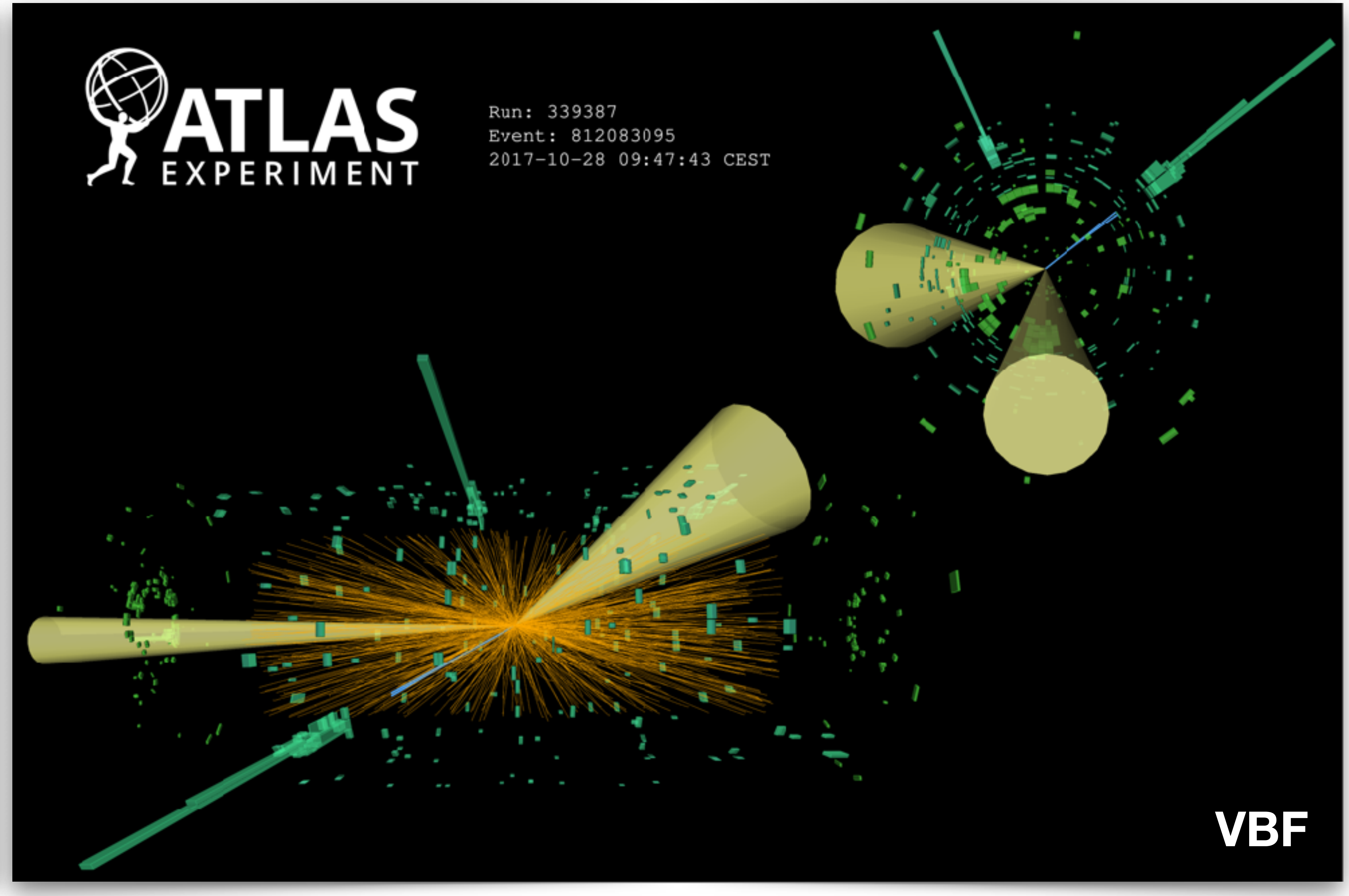
$$\mu = 1.2 \pm 0.6$$

HL-LHC ~5%

Result dominated by statistical uncertainty, but watch systematics!

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





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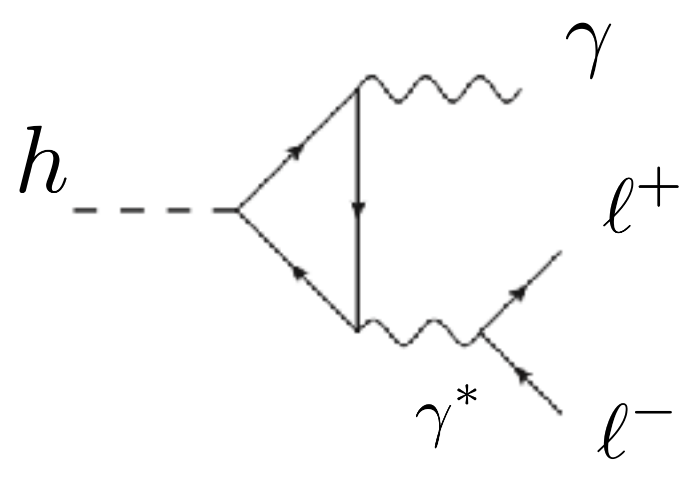


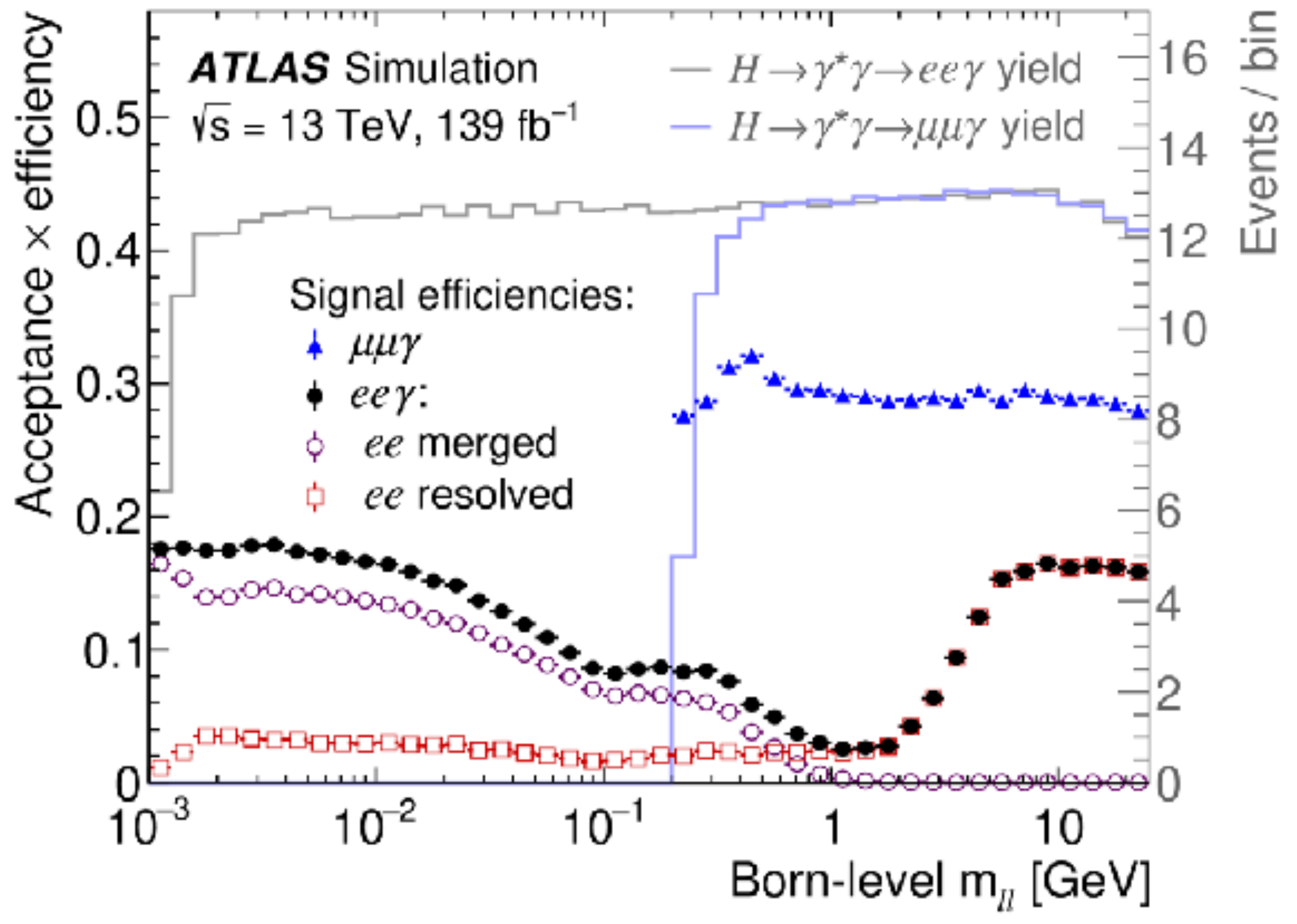
Search initially made in this case in the dimuon channel only (in the low di-lepton mass limit the shower of electrons merge).

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

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

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

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



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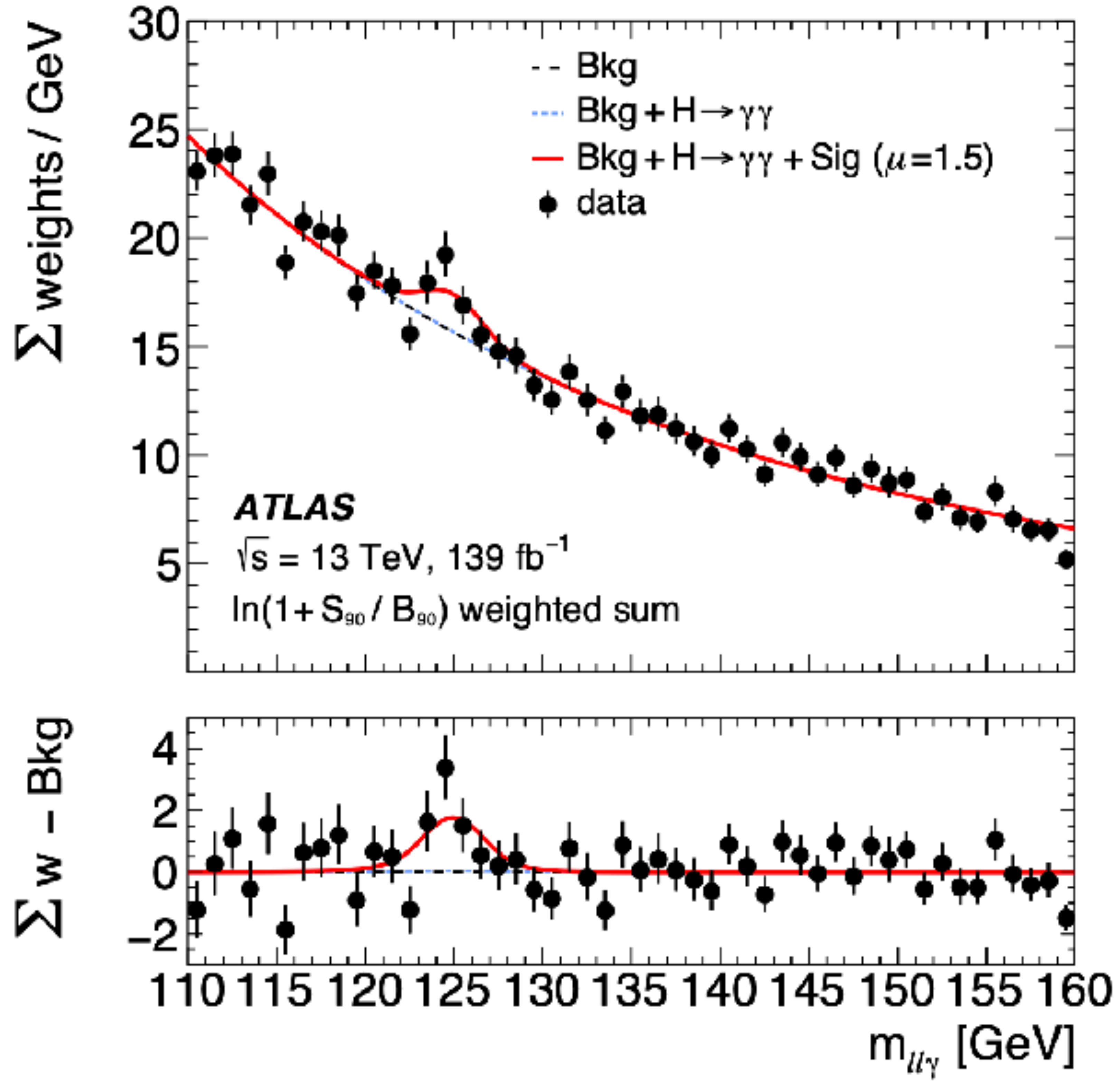


- 3 x 3 categories (VBF, high pT ggF, low pT ggF) $\otimes$ (ee resolved, ee merged, $\mu\mu$)
- Contributions from J/ψ are removed with a mass cut

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

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

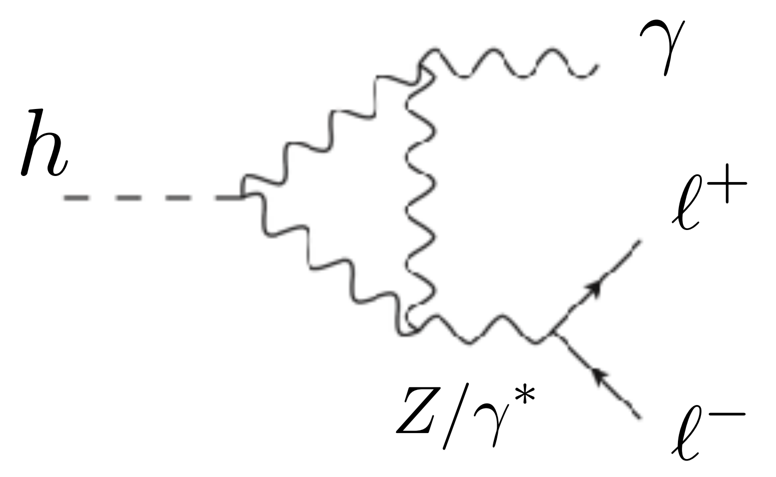
Expected 2.1σ

Observed 3.2σ

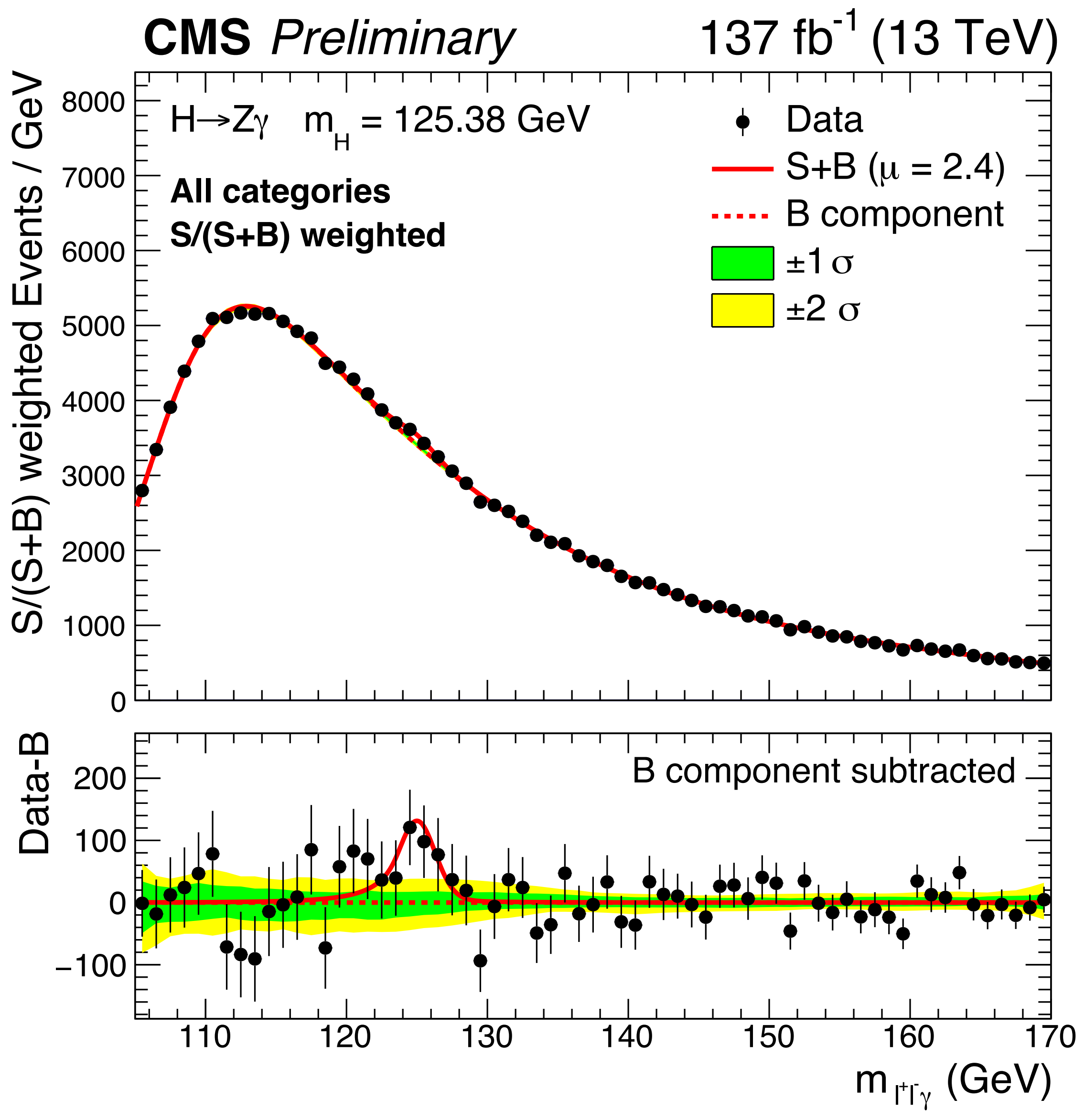
Searches for the $H \to Z\gamma$ Decay Mode

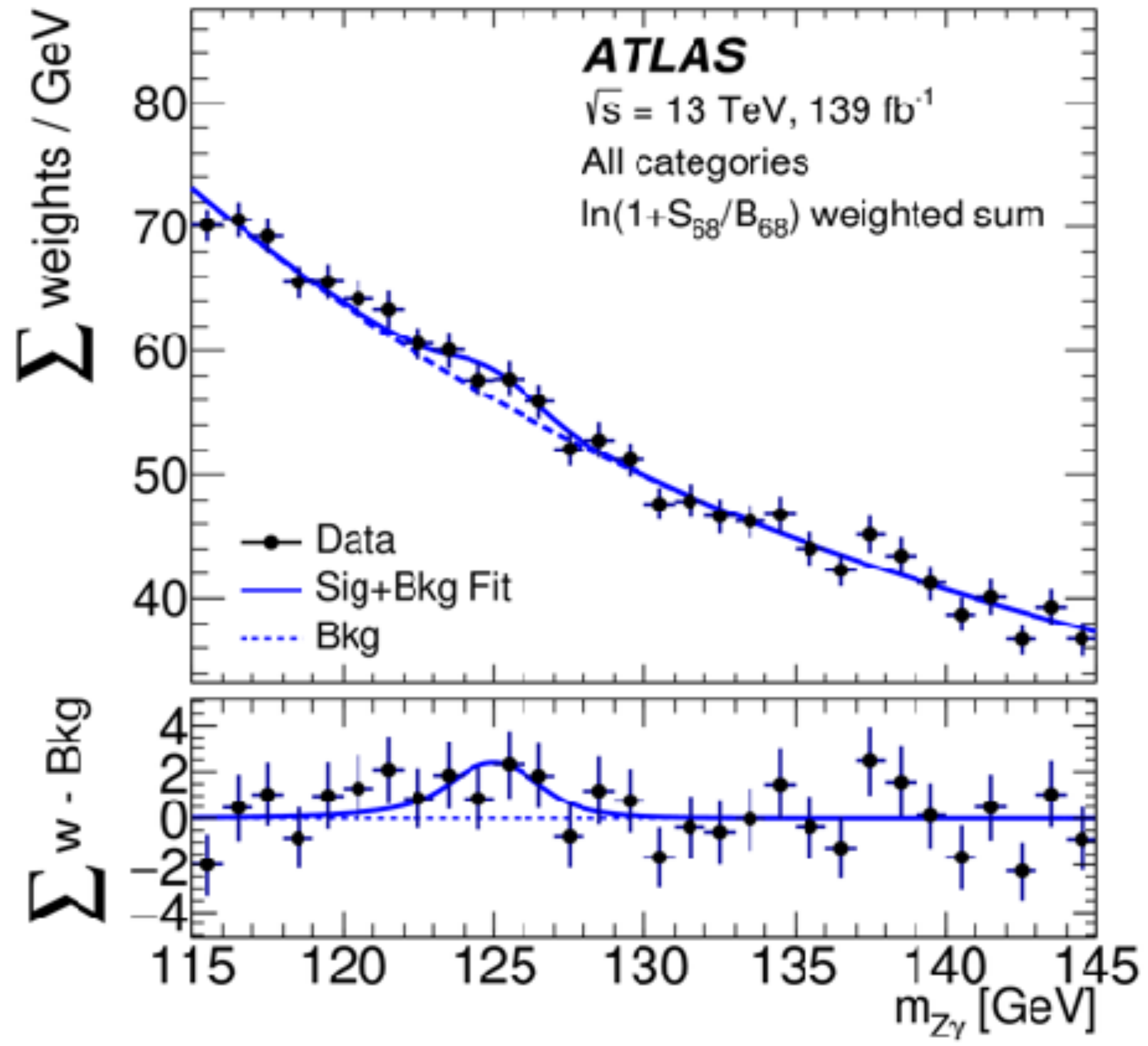
Z-photon $|H^2|W^a_{\mu\nu}W^{\mu\nu a}$

Field tensor coupling not measured yet!

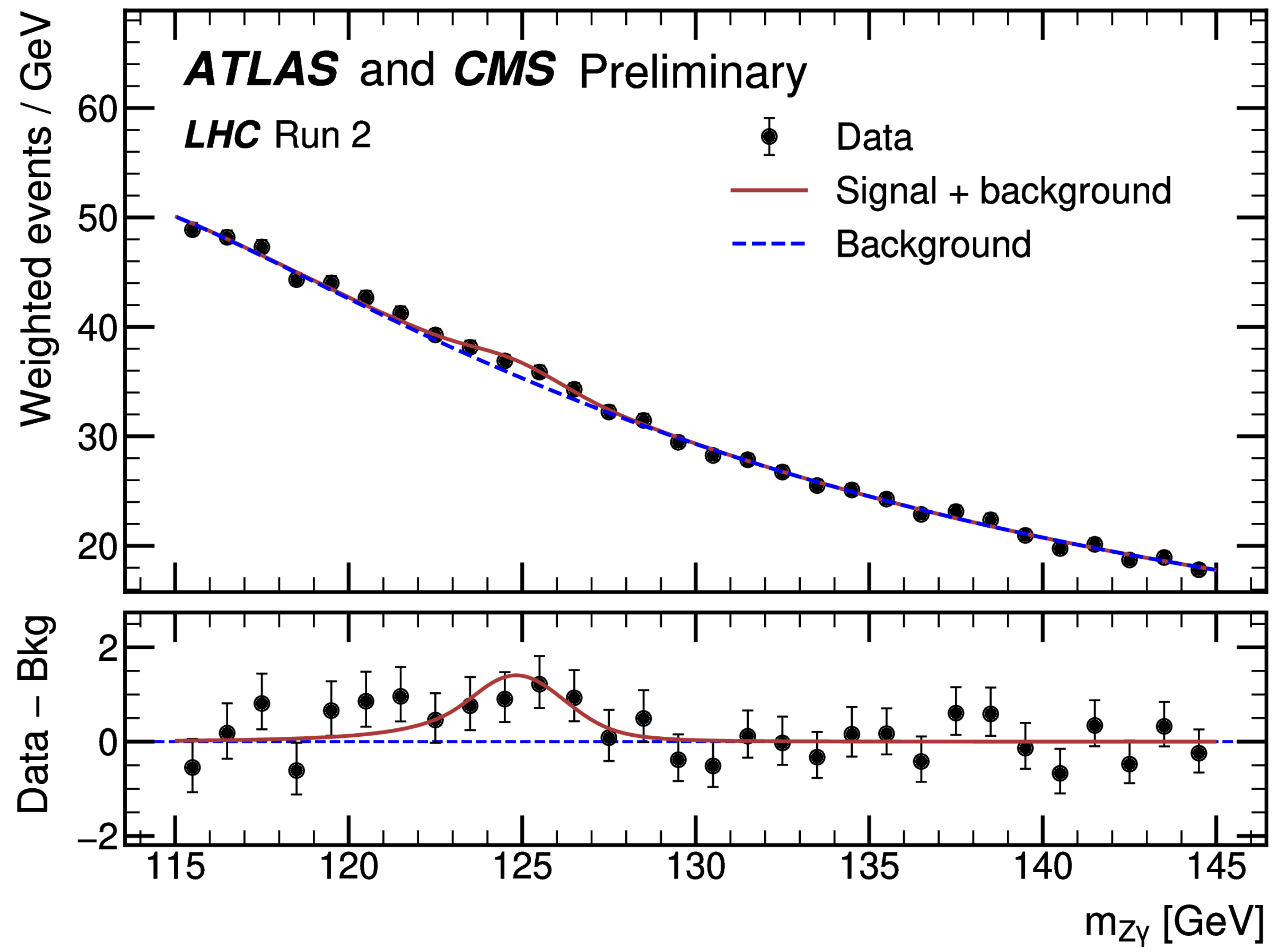


~ 2.3% of $Br(\gamma\gamma)$





Combined ATLAS and CMS mass spectrum!



CMS Result

ggF, VBF, VH and ttH enriched

Expected 1.2σ

Observed 2.7σ

ATLAS Result

ggF and VBF enriched

Expected 1.2σ

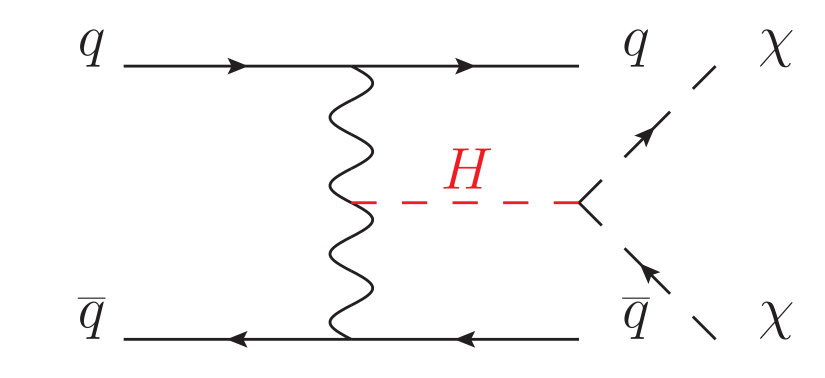
Observed 2.2σ

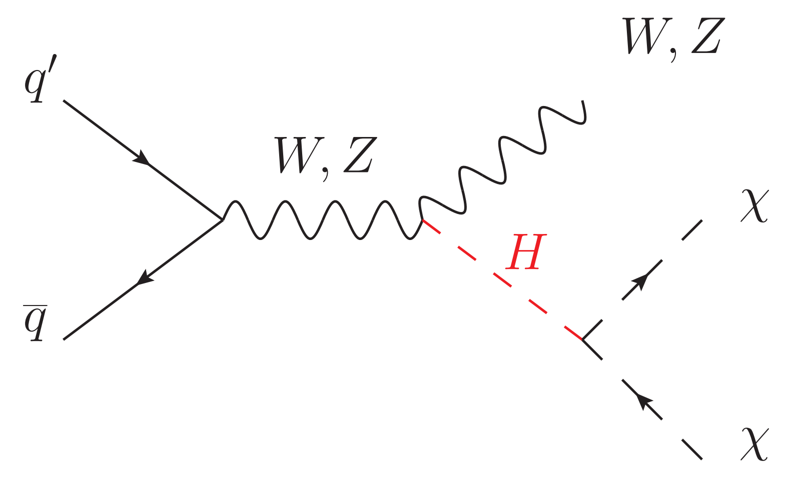
Combined search yields 3.4σ observed and 1.6σ expected (consistent with the SM expectation at the 1.9σ): First evidence!

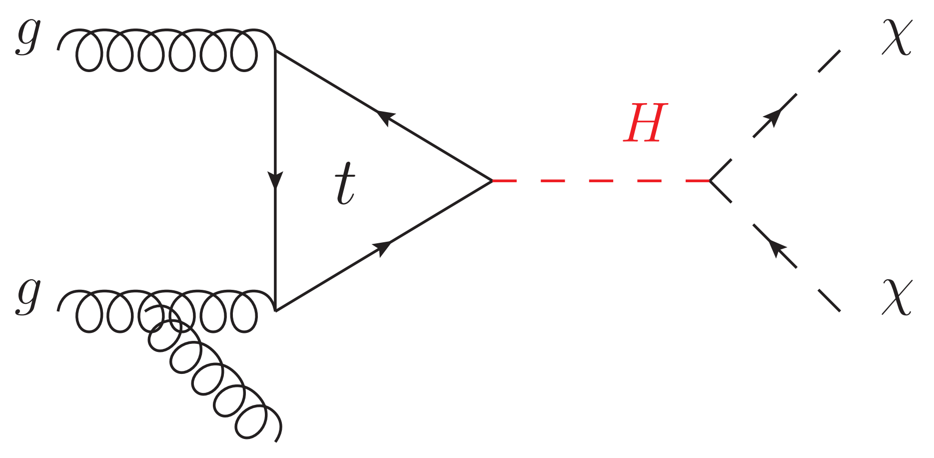
HL-LHC ~10%

More Rare Decays and Production

Invisible decays



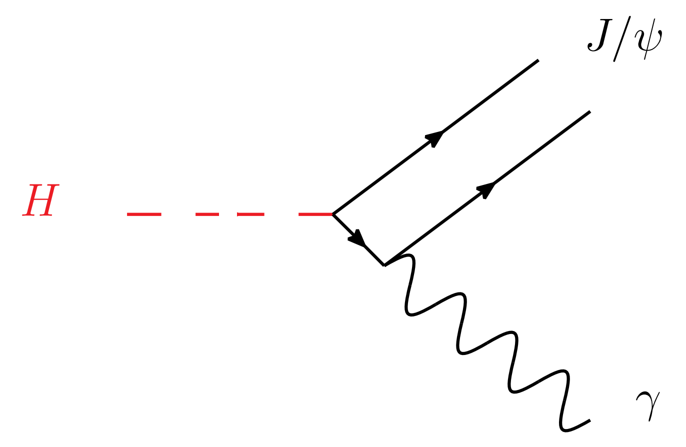




<11% @ 95% CL

HL-LHC 2.5%

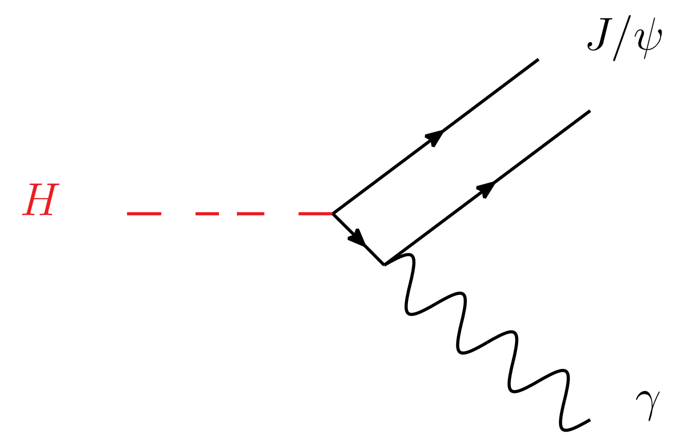
Quarkonia-photon



Potentially sensitive to charm Yukawa

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

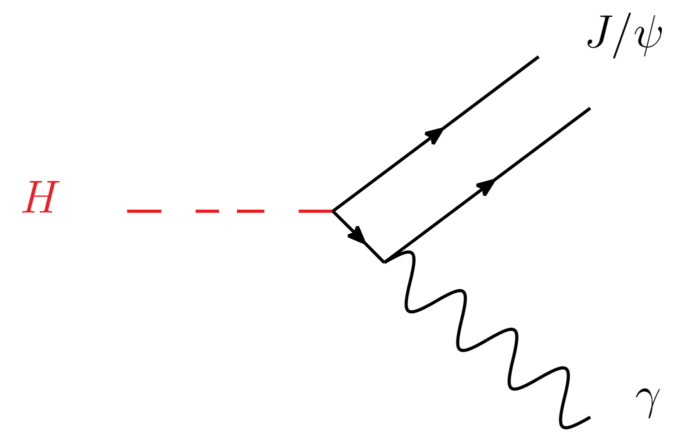
~100 x SM



Potentially sensitive to strange Yukawa

$K^+K^-\gamma$

~200 x SM

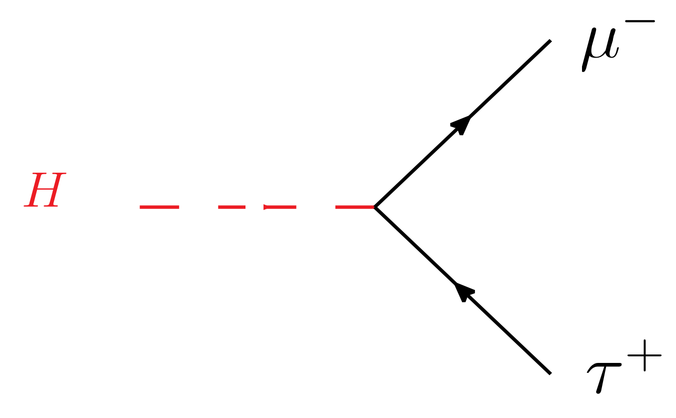


Potentially sensitive to light Yukawa

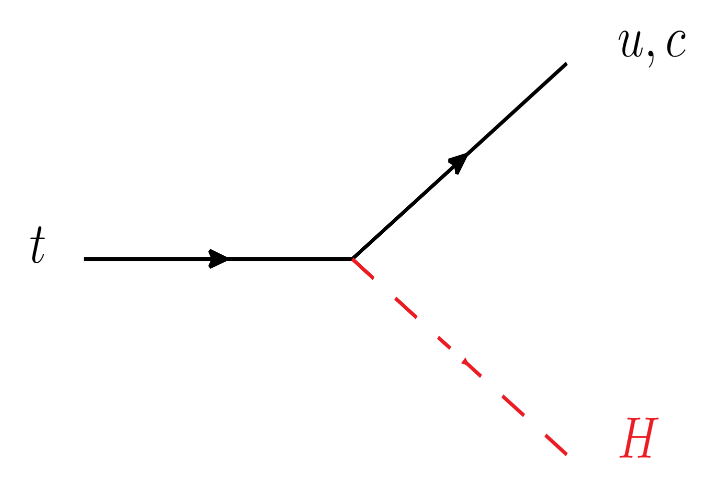
$\pi^+\pi^-\gamma$

~50 x SM

Lepton flavor violating decays

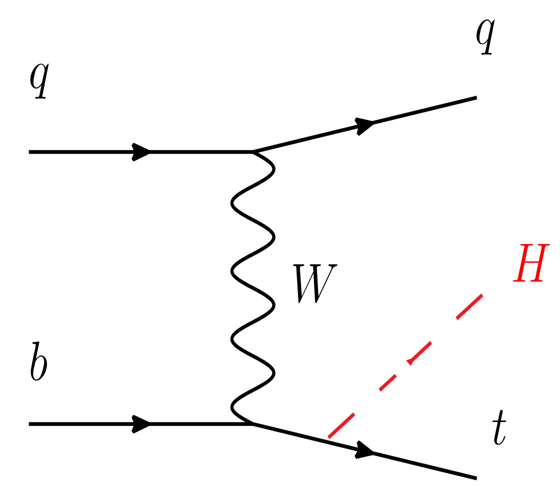


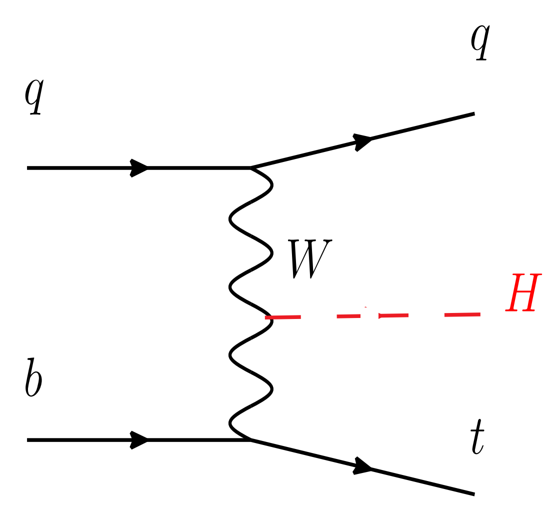
FCNC decays of the top quark



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

Single top associated production

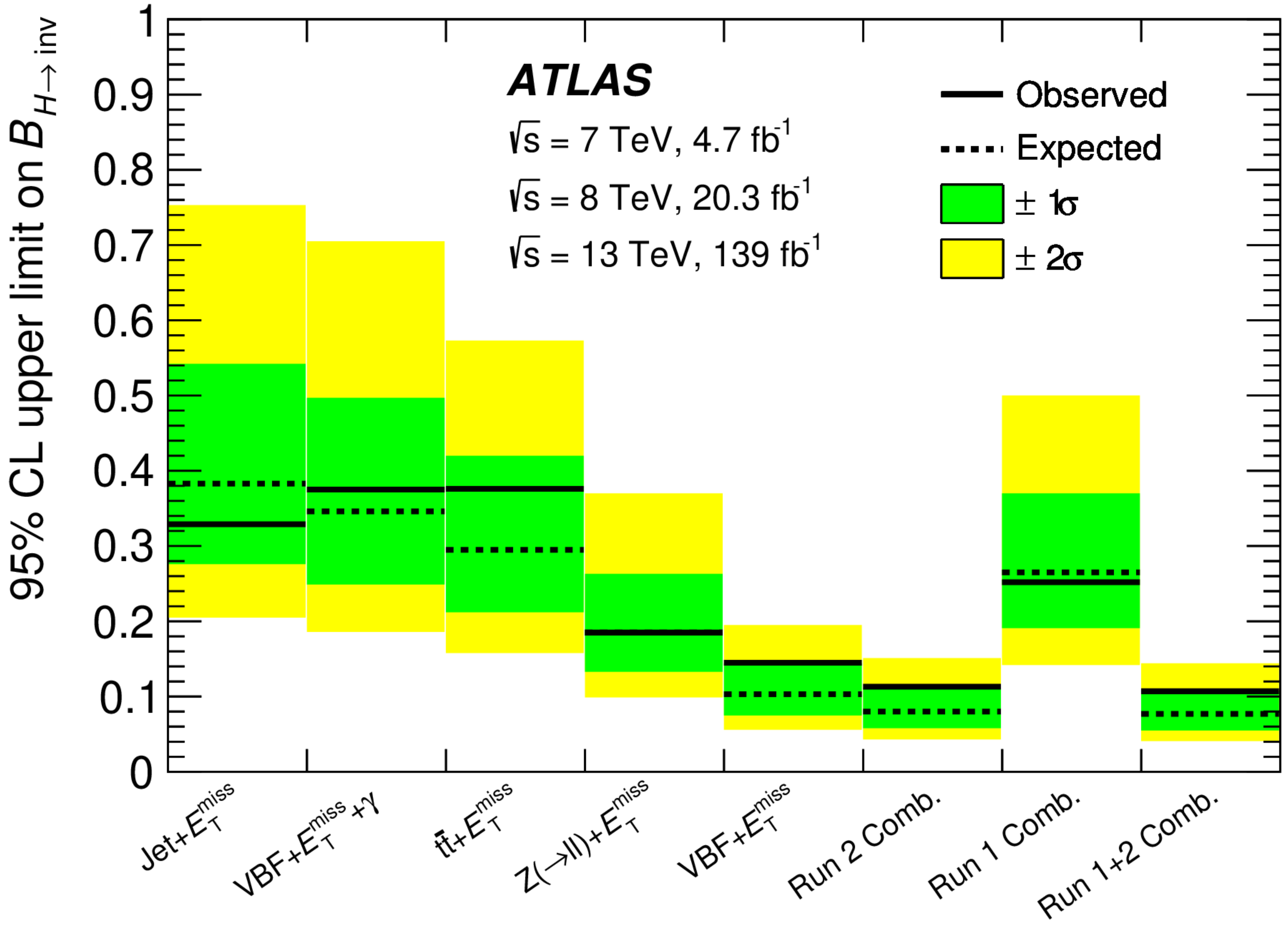




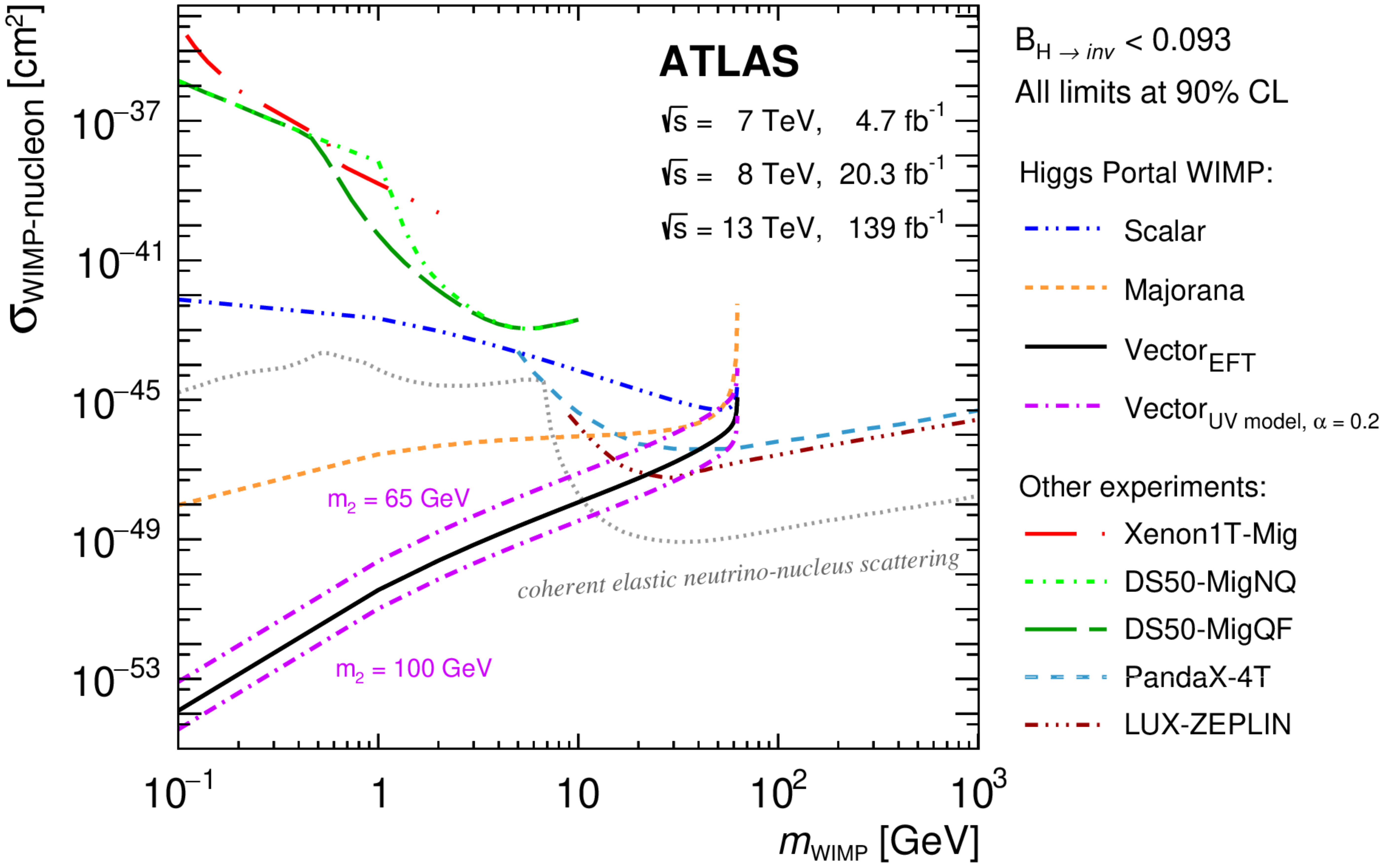
Tree level interference between W and top

Invisible Higgs Decays

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



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



Should reach 2% level at HL-LHC! Major milestone for Run 3