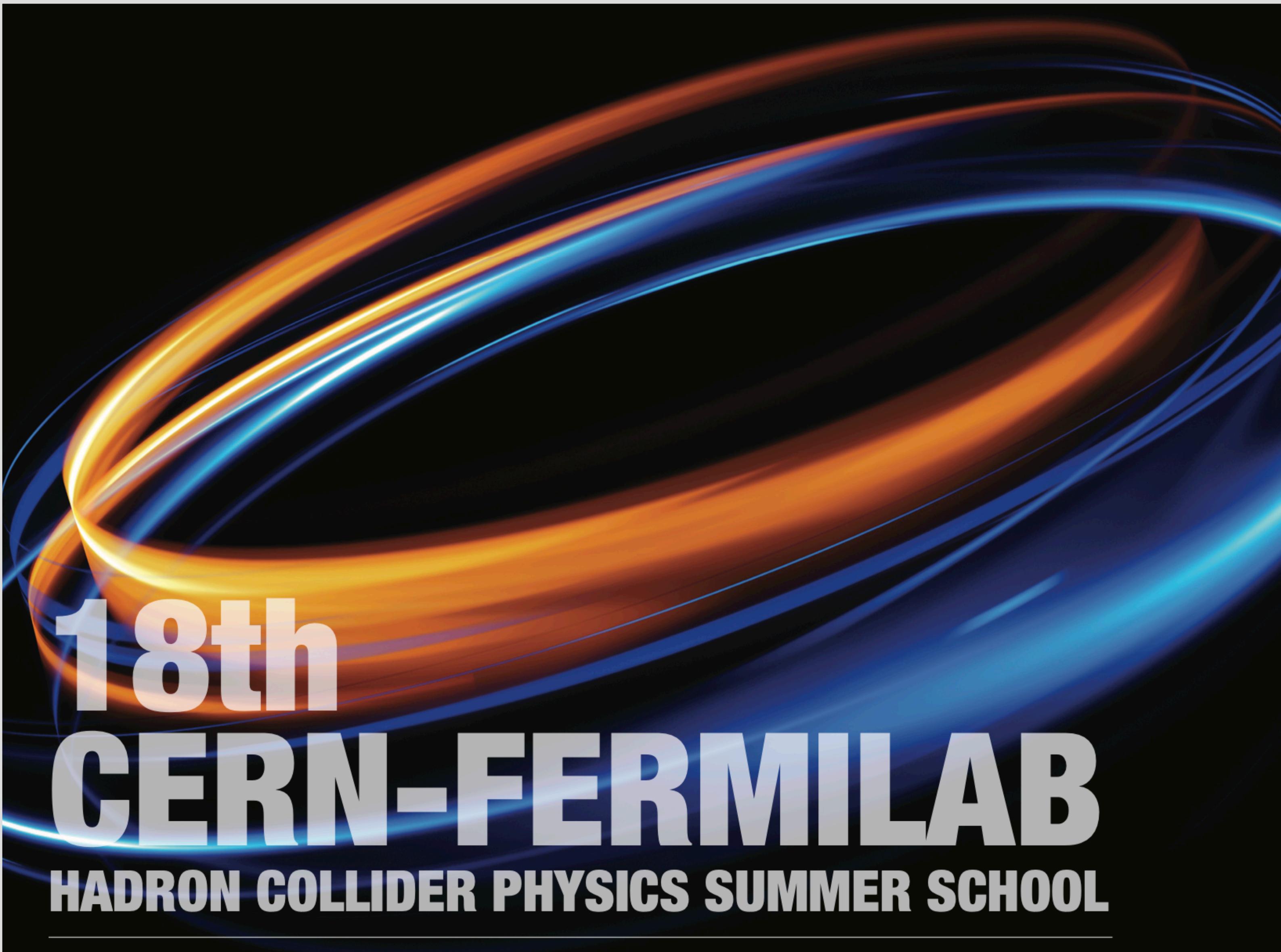


Experimental SM and Higgs Physics



18th
CERN-FERMILAB
HADRON COLLIDER PHYSICS SUMMER SCHOOL



Standard Model and Higgs

Lecture 3 *Higgs Physics*

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CERN-Fermilab School of Physics
August 29, 2023

Outline

2

Lecture 1: Basic concepts, QCD, jets and Z production

- Introduction (rather long)
- Luminosity and total cross section
- Jet production measurements and the measurement of the strong coupling constant
- Drell-Yan Z production and the measurements of the weak mixing angle and the strong coupling constant

Lecture 2: EW Precision at Hadron Colliders

- Drell-Yan W production and the W mass measurement
- Associated production of vector bosons and jets
- Multi-boson production (W, Z and photons)
- Top production and top properties measurements

Lecture 3: Higgs Physics

- Diboson channels for Higgs measurements
- Measuring the Yukawa couplings of the Higgs boson
- Differential and Simplified Template cross sections
- CP properties of the Higgs boson
- Invisible Higgs boson decays
- Rare Higgs boson decays

Lecture 4: More Higgs Physics and Global interpretation

- Higgs couplings measurements
- The Yukawa coupling of the Higgs boson to charm quarks
- Off shell Higgs boson coupling and Higgs width
- Di-Higgs boson production and Higgs boson trilinear self coupling
- Precision EW Fit
- SMEFT Global fits
- Challenges for Run-3 and the HL-LHC

2

The Standard Model

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

}

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

$$\theta \frac{\alpha_s}{8\pi} F_{\mu\nu}^A \tilde{F}^{A\mu\nu}$$

$$\theta < 10^{-10} \quad \text{From neutron electric dipole moment measurements}$$

The **strong CP problem**

$$+ \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. \\ + D_\mu \phi l^2 - V(\phi)$$

}

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)

Splendid, yet unsatisfactory (see Greg's Lectures)!

The Standard Model

The less elegant Higgs sector:

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

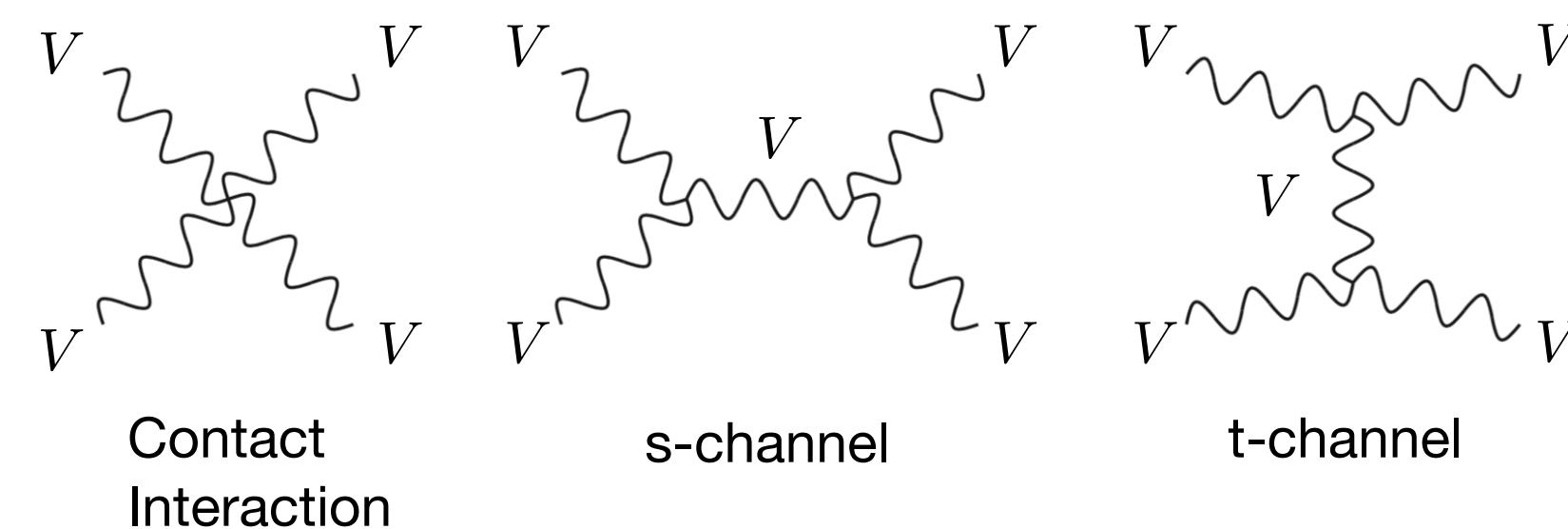
$$+ \bar{\psi}_i \gamma_{ij} \psi_j \phi + h.c.$$

$$+ D_\mu \phi^\dagger - V(\phi)$$

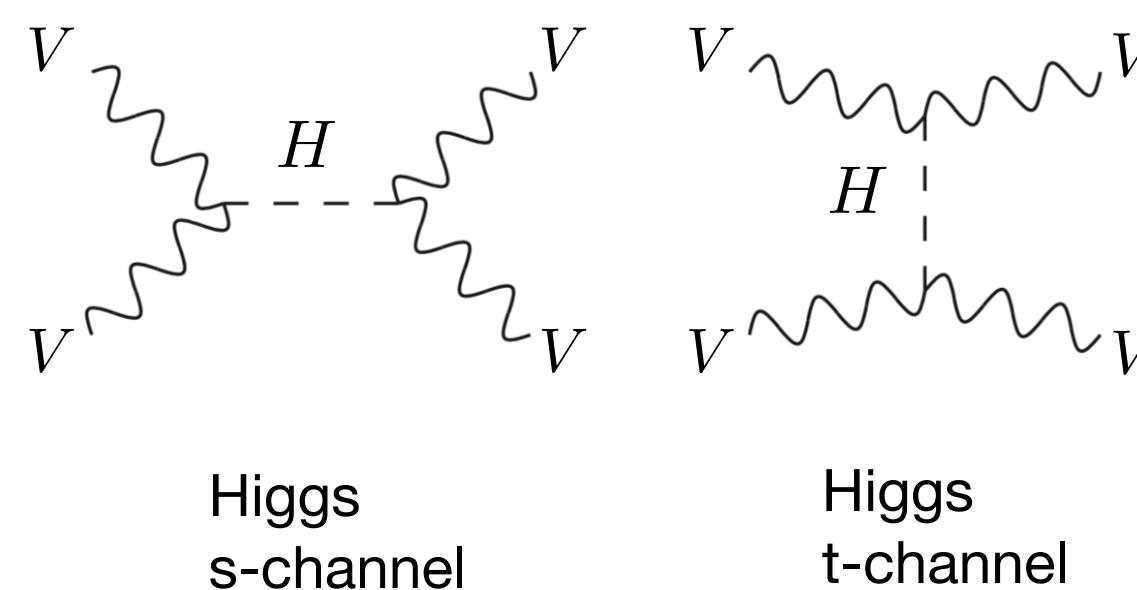
However: Higgs mechanism is absolutely necessary both for gauge boson and fermion masses!

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

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



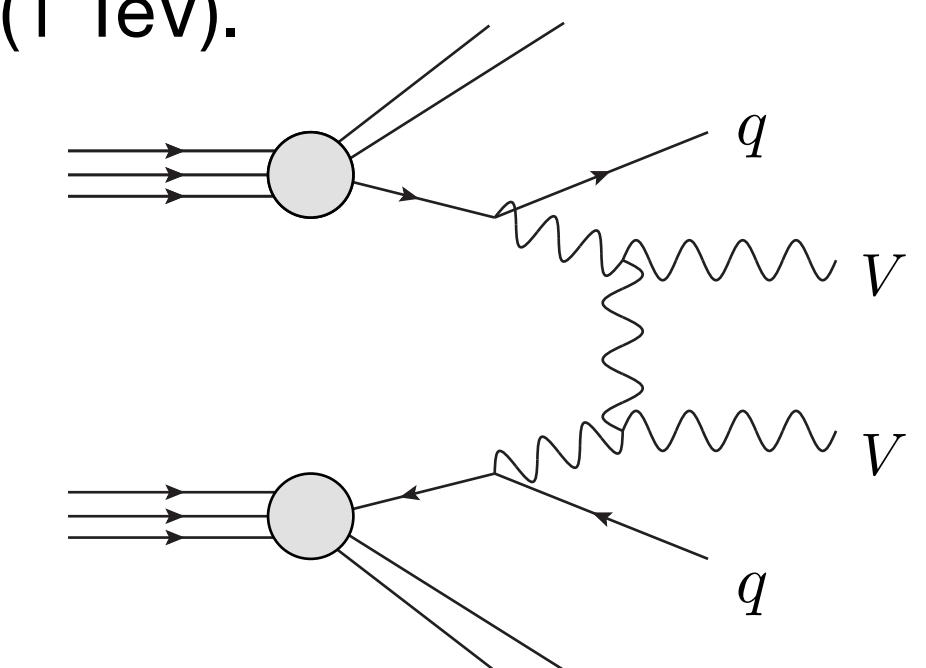
$$\mathcal{M} = g^2 \left(\frac{E}{M_W} \right)^2$$



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

The preservation of the perturbative unitarity of the WW scattering, imposes an upper limit on the Higgs boson of $\sim O(1 \text{ TeV})$.

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



The Higgs Particle

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

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

However the SM is very far from explaining everything!

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

Involve
fundamental
scalars

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

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!

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

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

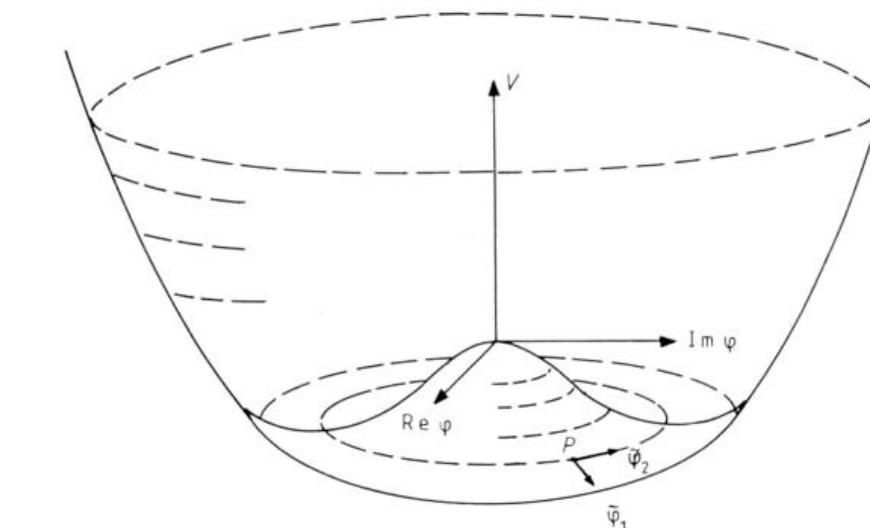
This term could not exist without a vev

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

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?

Proof of condensate!

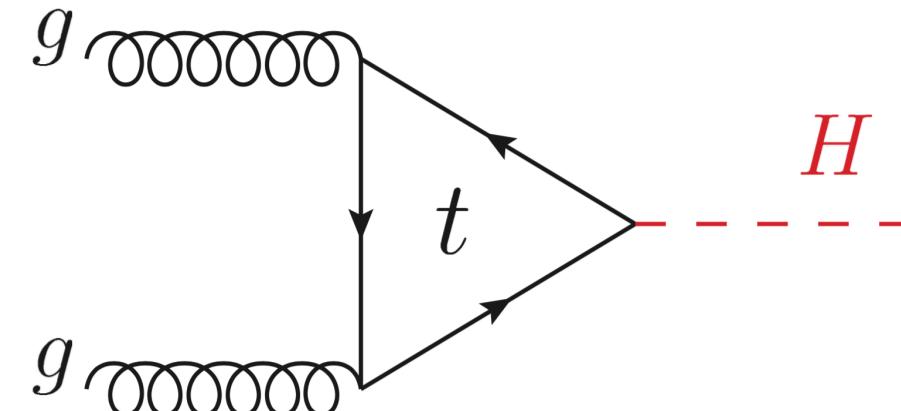


Is the shape of the Higgs potential that predicted by the Standard Model?

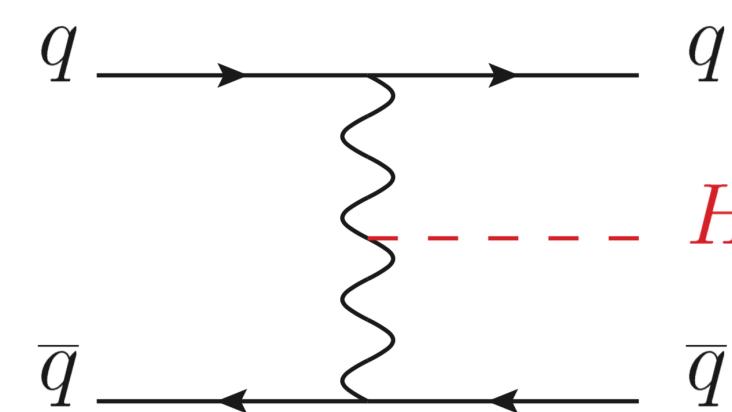
Higgs boson (main) Production and Decay Modes

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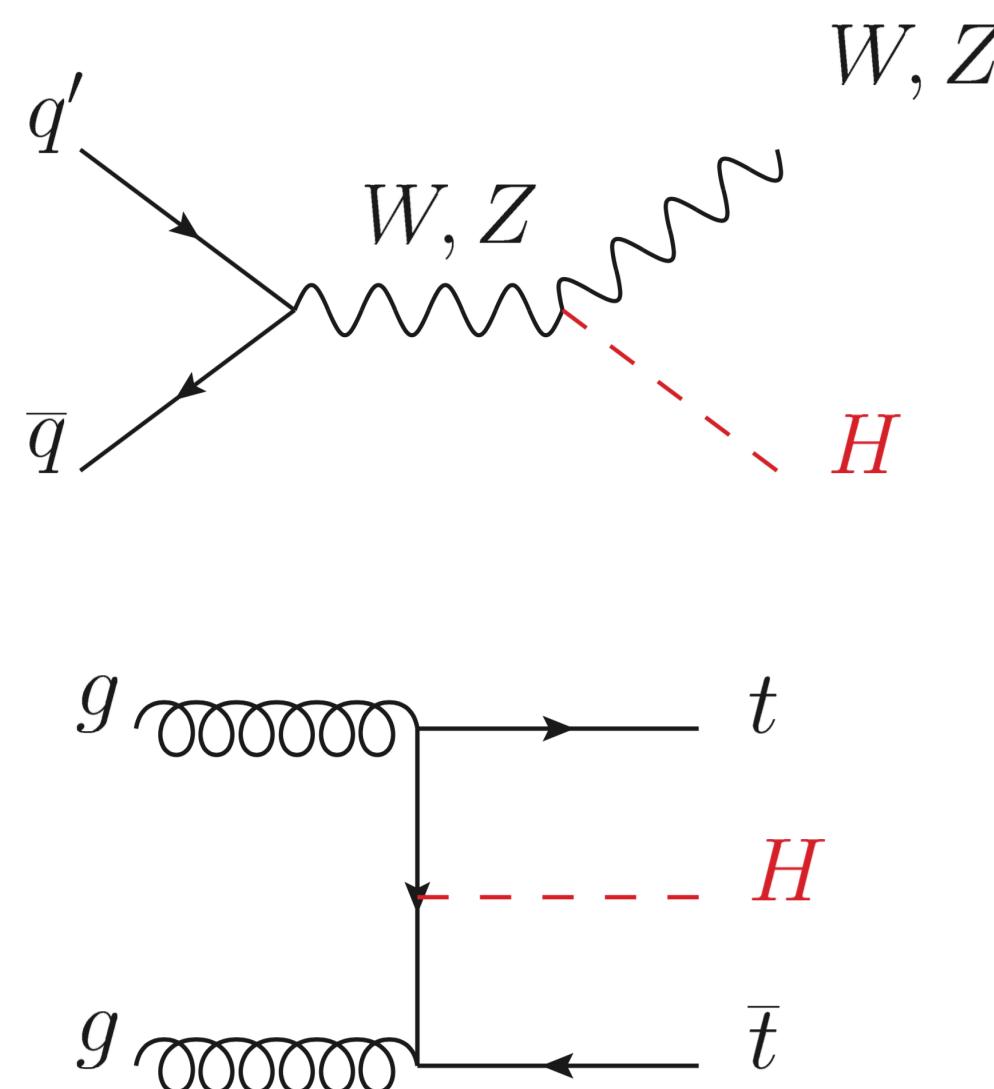
Production rates at Run 2 (13 TeV) for $\sim 150 \text{ fb}^{-1}$



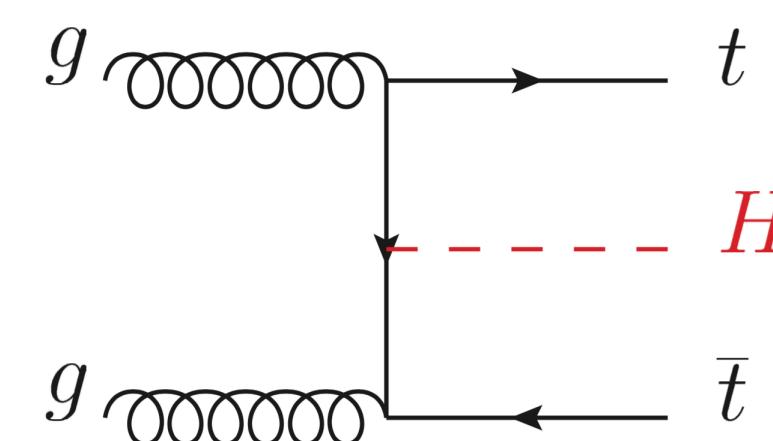
Gluon fusion process
 $\sim 8 \text{ M events produced}$



Vector Boson Fusion
 Two forward jets and a large rapidity gap
 $\sim 600 \text{ k events produced}$

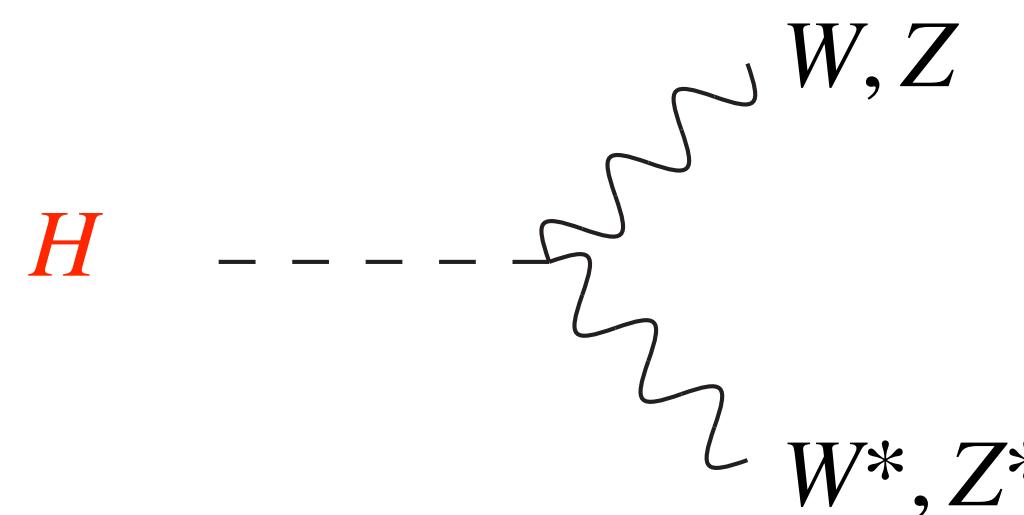


W and Z Associated Production
 $\sim 400 \text{ k events produced}$

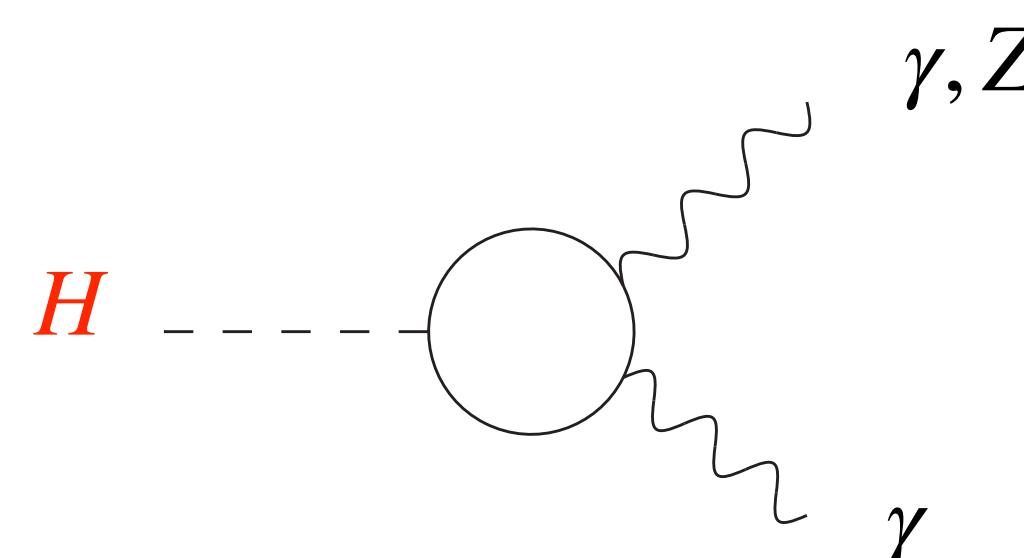


Top Assoc. Prod.
 $\sim 80 \text{ k evts produced}$

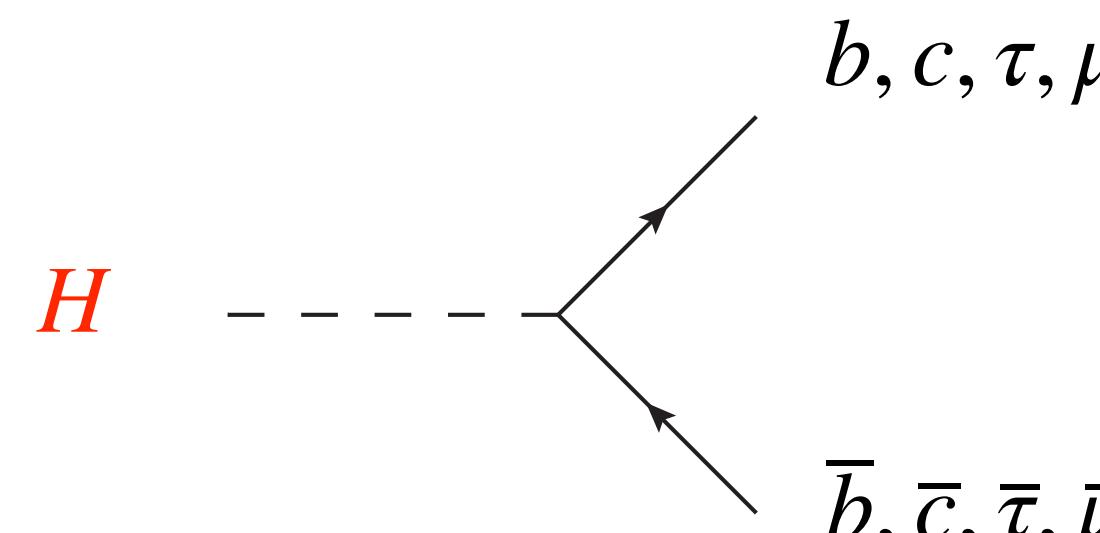
Decay branching fractions



$$\text{Br}(H \rightarrow WW^*) = 22\%$$



$$\text{Br}(H \rightarrow ZZ^*) = 3\%$$



$$\text{Br}(H \rightarrow b\bar{b}) = 57\%$$

$$\text{Br}(H \rightarrow \tau^+\tau^-) = 6.3\%$$

$$\text{Br}(H \rightarrow c\bar{c}) = 3\%$$

$$\text{Br}(H \rightarrow \mu^+\mu^-) = 0.02\%$$

HL-LHC is a Higgs Factory

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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](#)

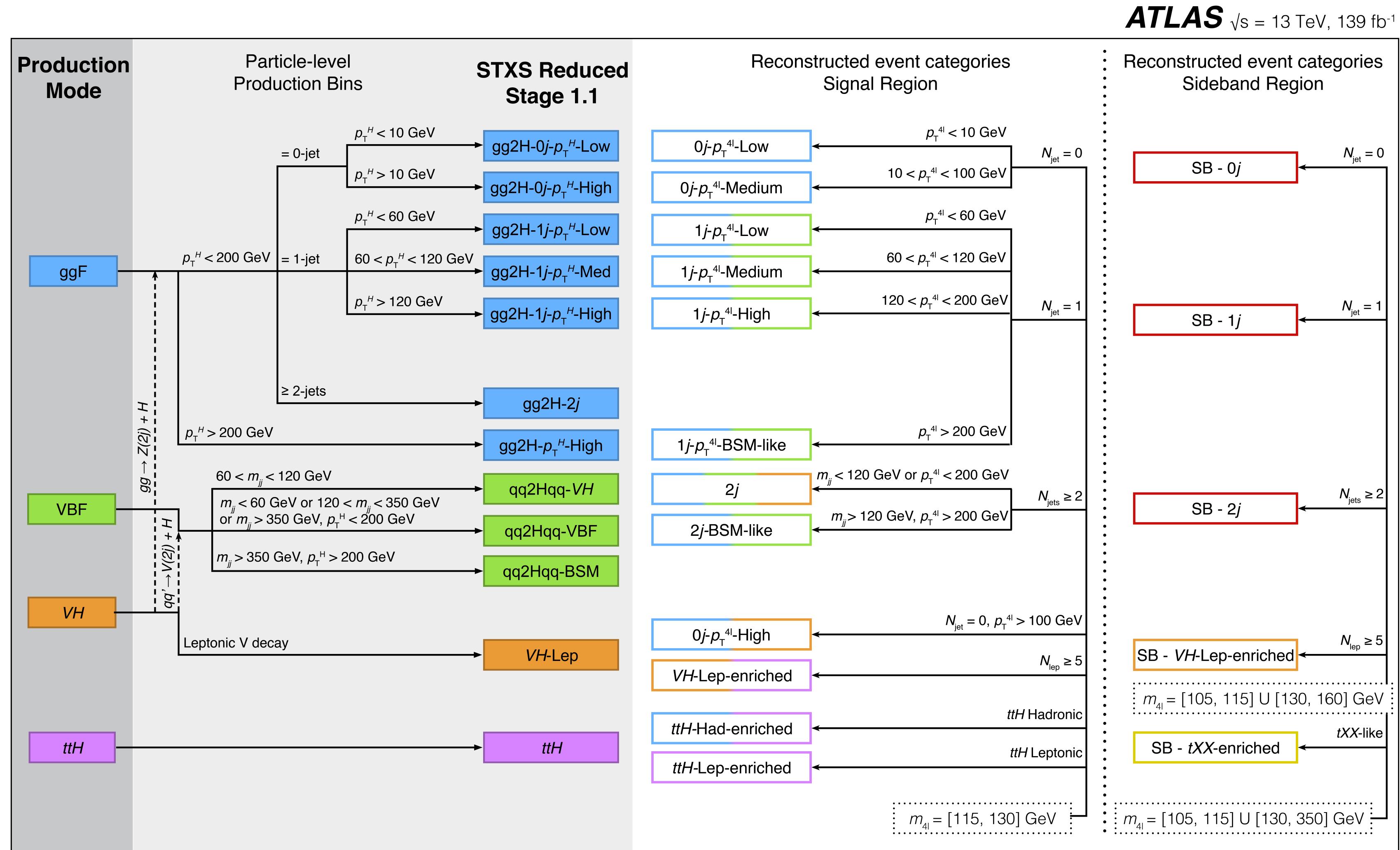
Process	ggF	HH	ttH
13 TeV / 8 TeV	2.3	2.4	3.9
13.6 TeV / 13 TeV	7%	11%	13%
14 TeV / 13.6 TeV	6%	7%	7%

Hybrid Approach: Simplified Template Cross Sections

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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.

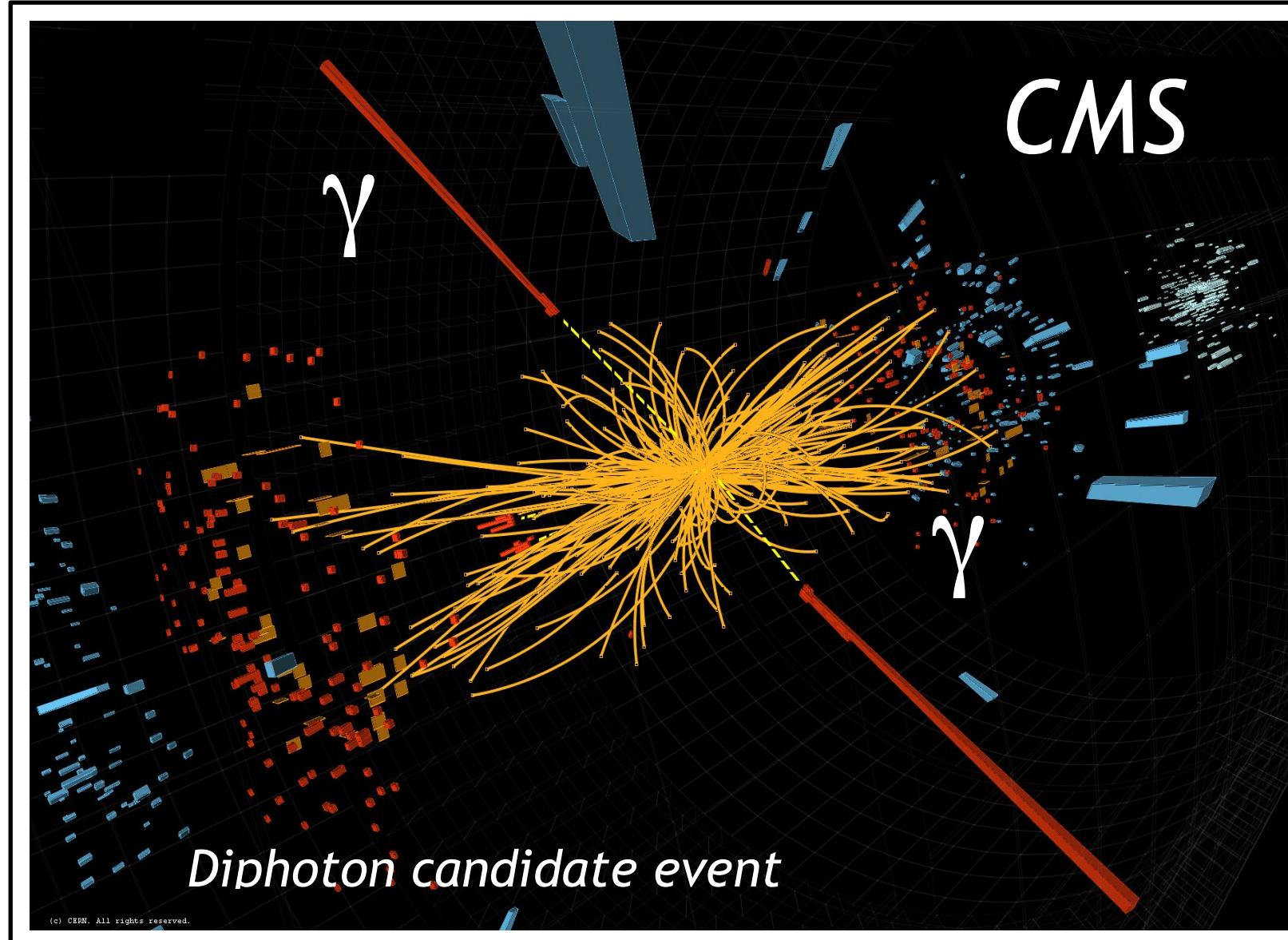
- Define fiducial cuts at truth particle level on the pT of the **Higgs (not its decay products!)** and number and kinematics of the additional jets or leptons in the events.
- Define reconstruction level cuts corresponding to the fiducial volume of interest.
- The definition of the fiducial volume is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



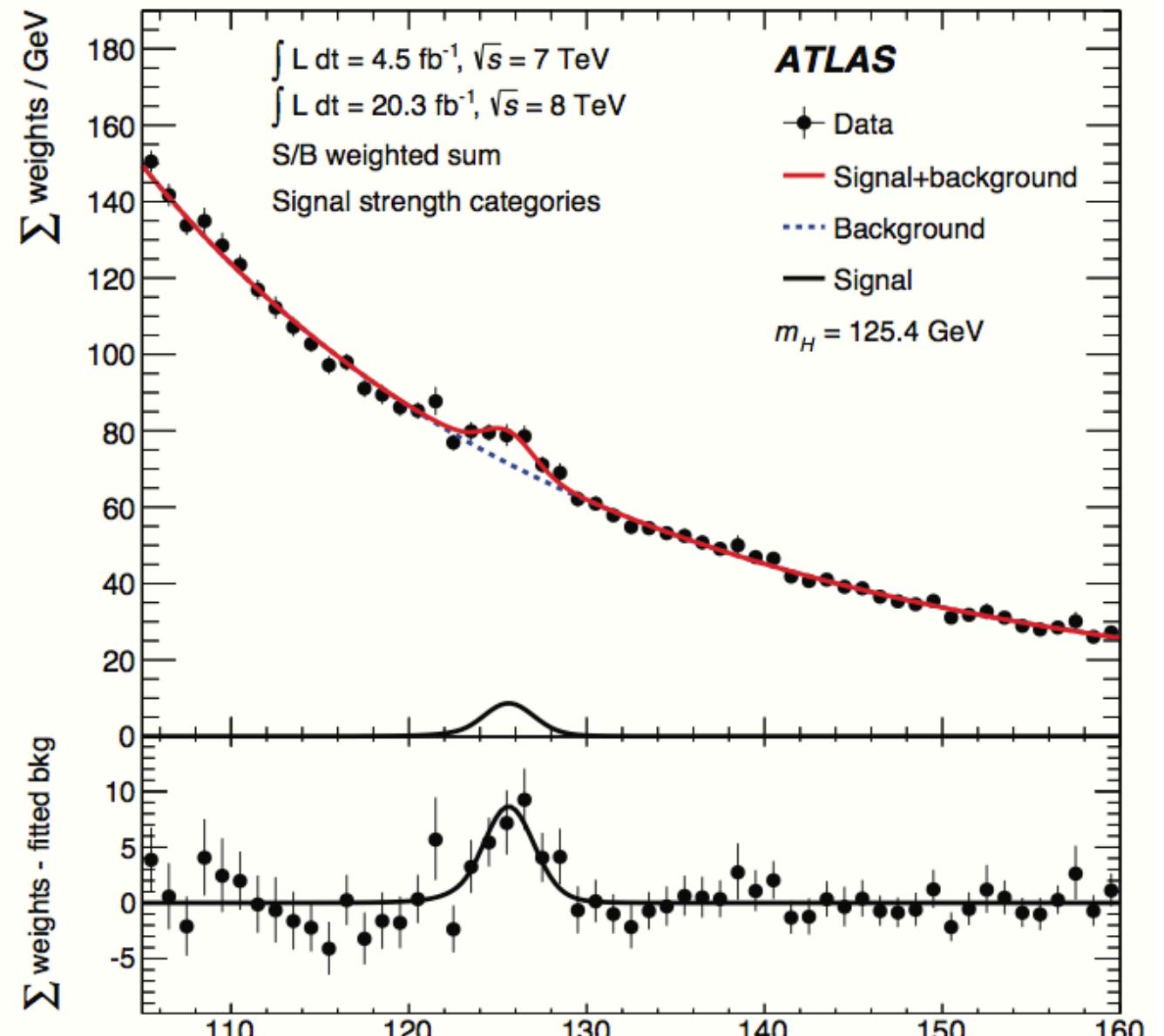
The di-Boson Channels and Run 1 Landmark Result

The Discovery Channels

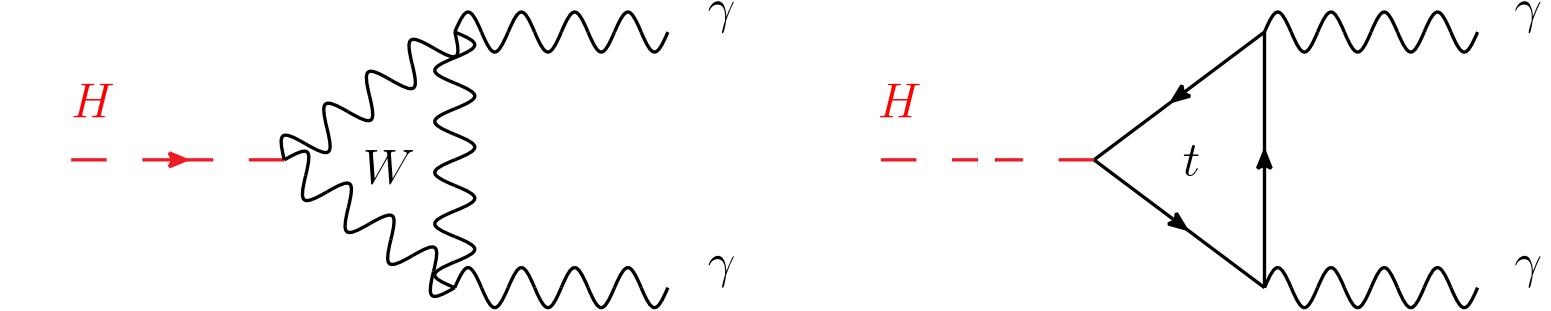
« Bread and Butter » Mass peak signals: the diphoton channel



- Low signal over background but overall relatively high statistics of signal ($O(300)$ at Run 1)
- 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.

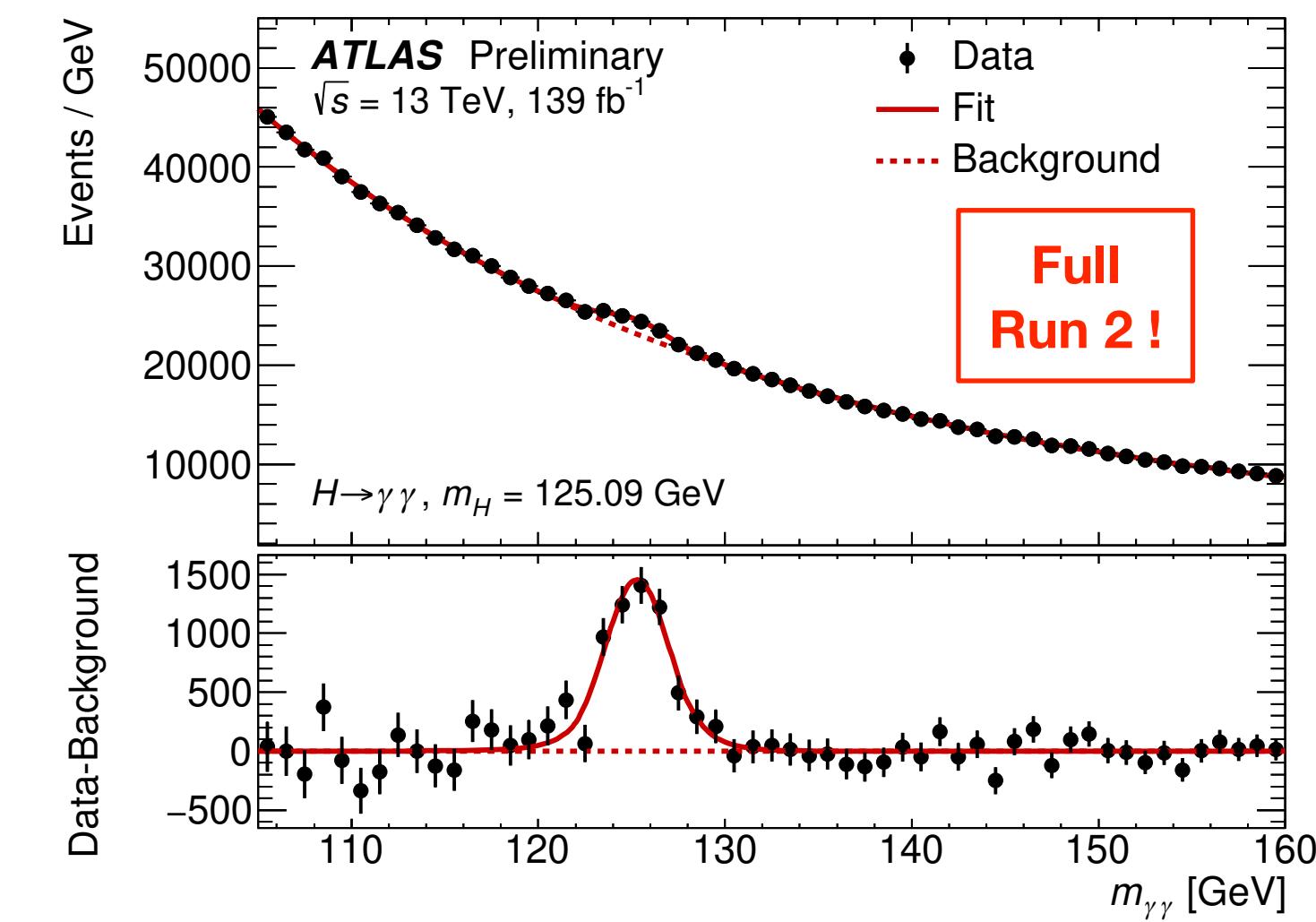
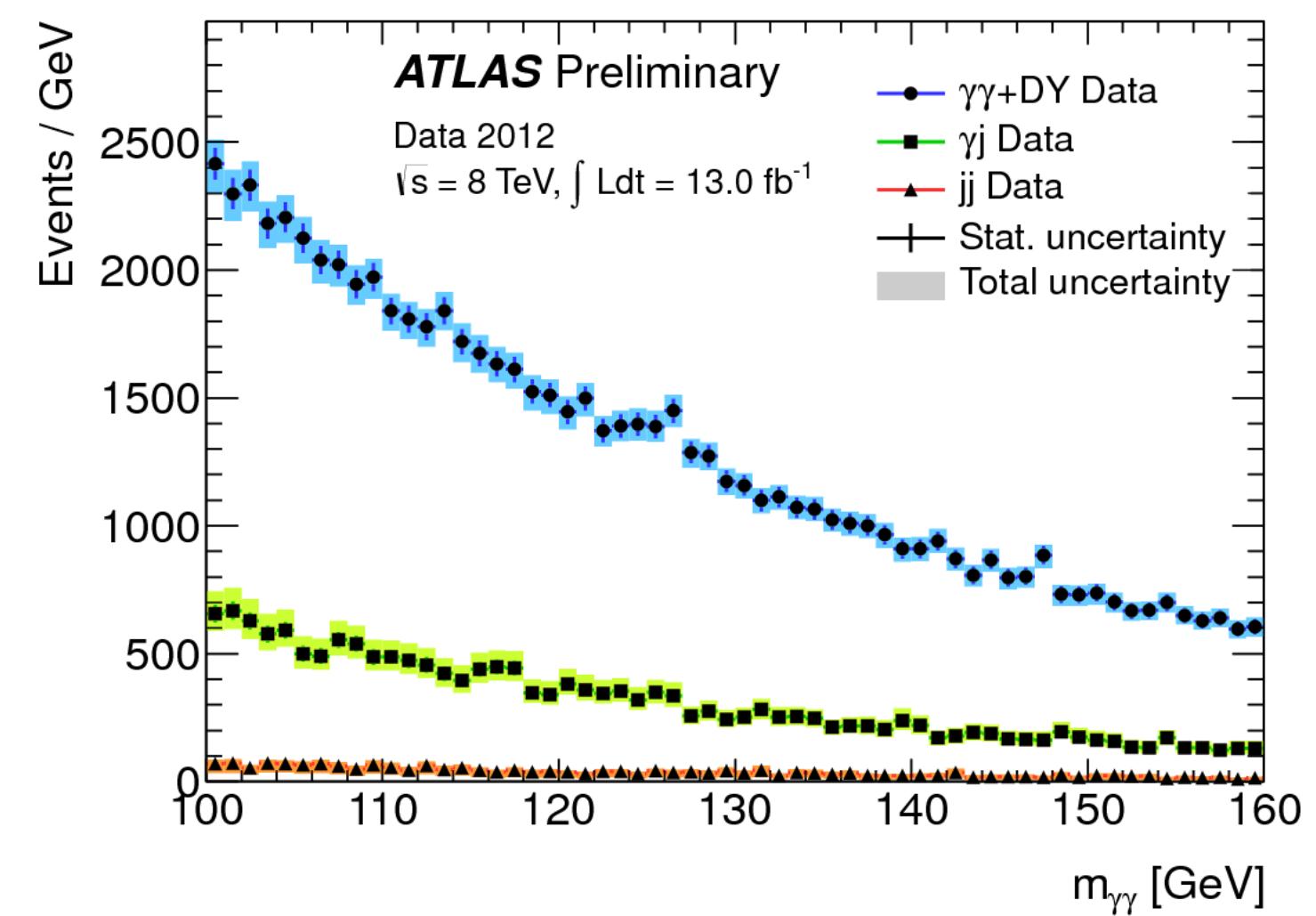


- Main production and decay processes occur through loops :



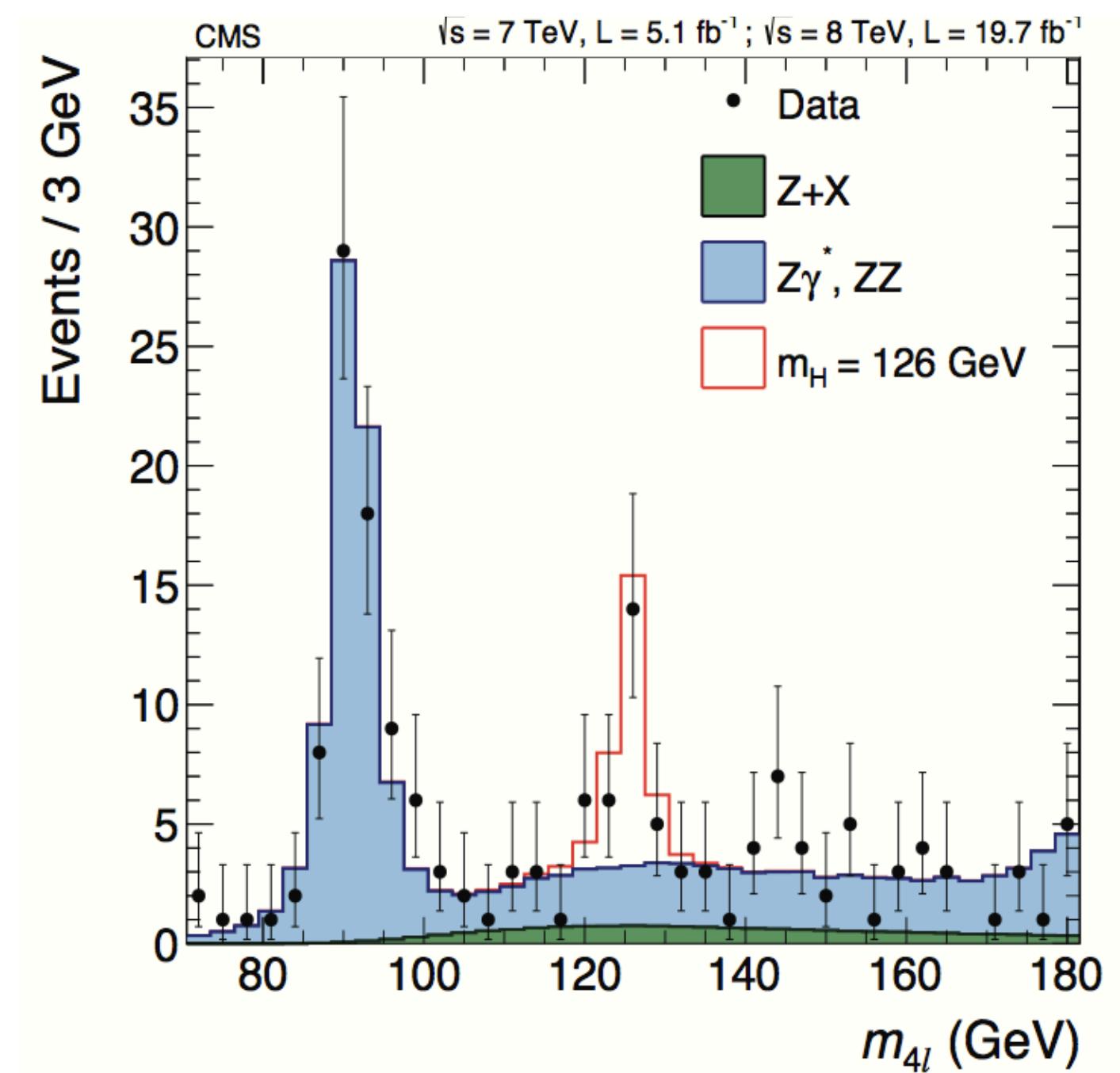
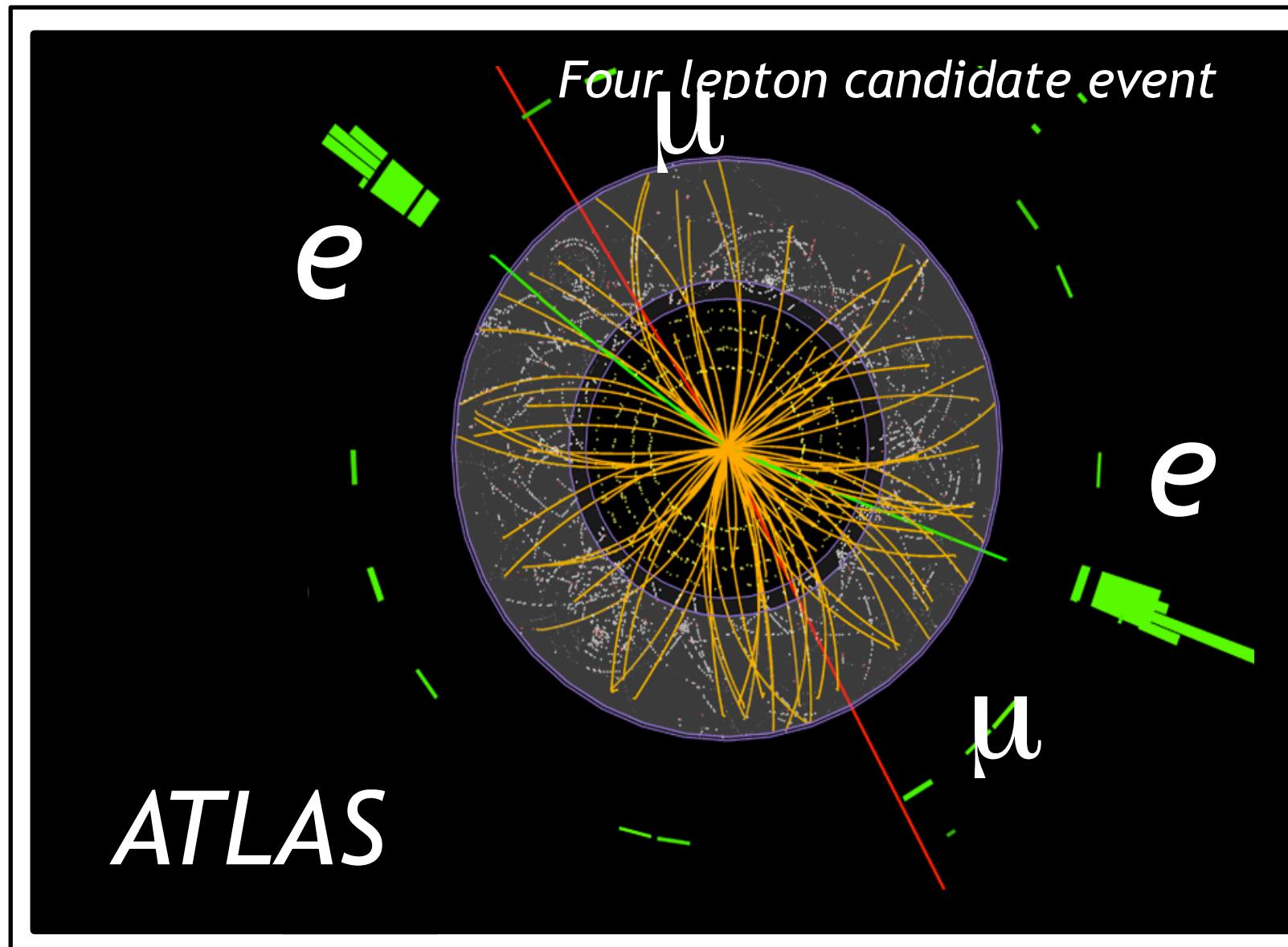
Excellent probe for new physics !

- 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

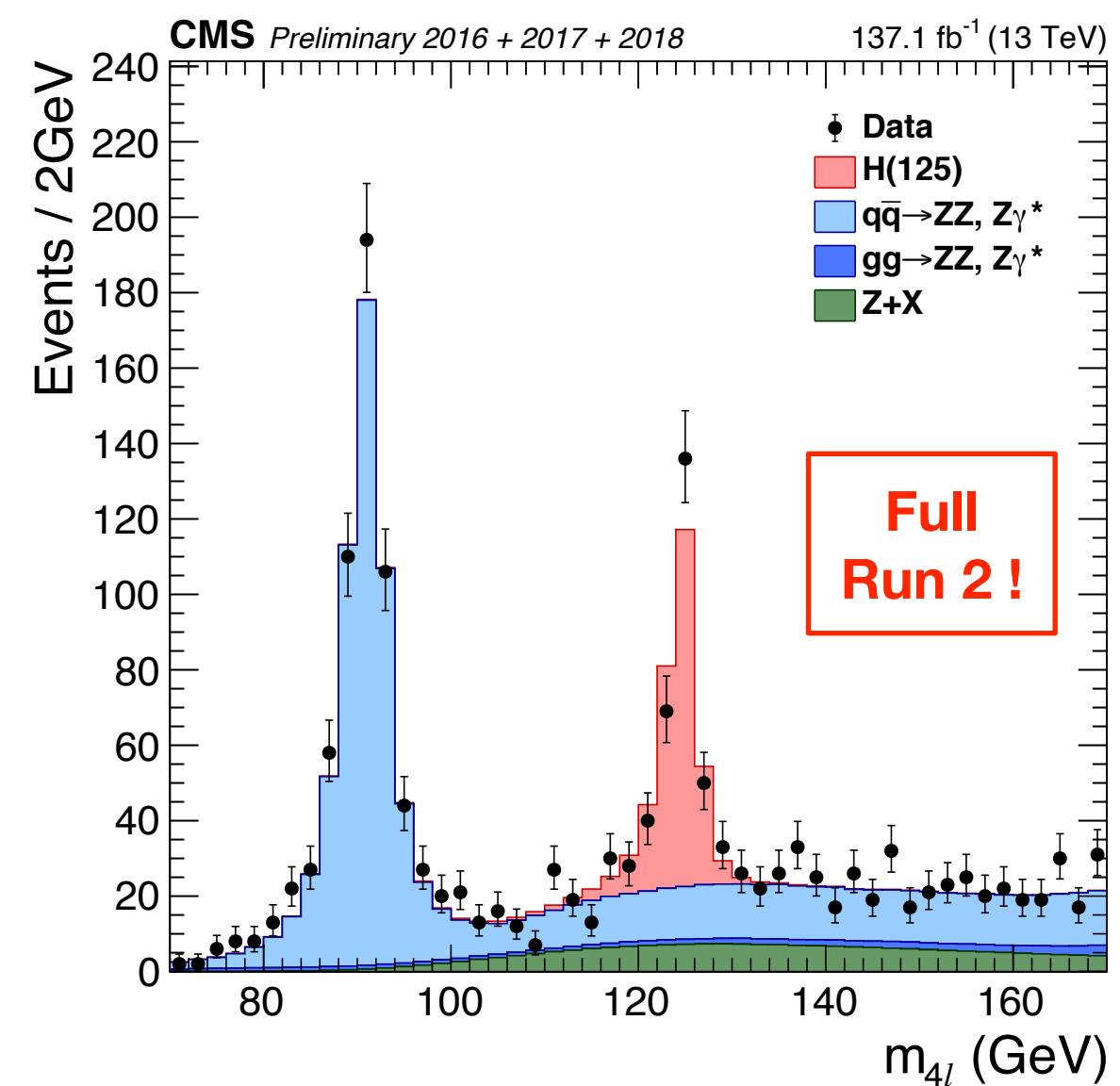
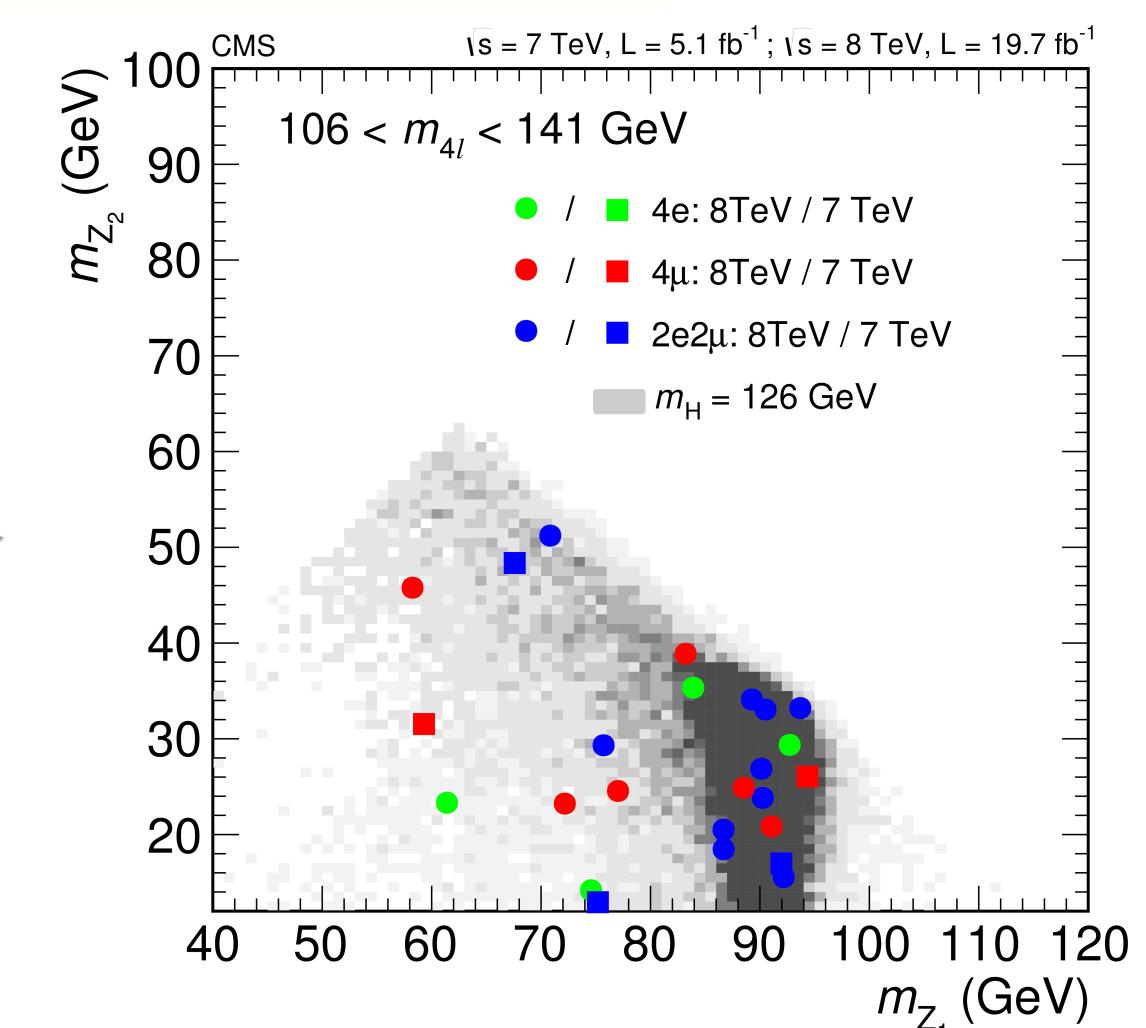
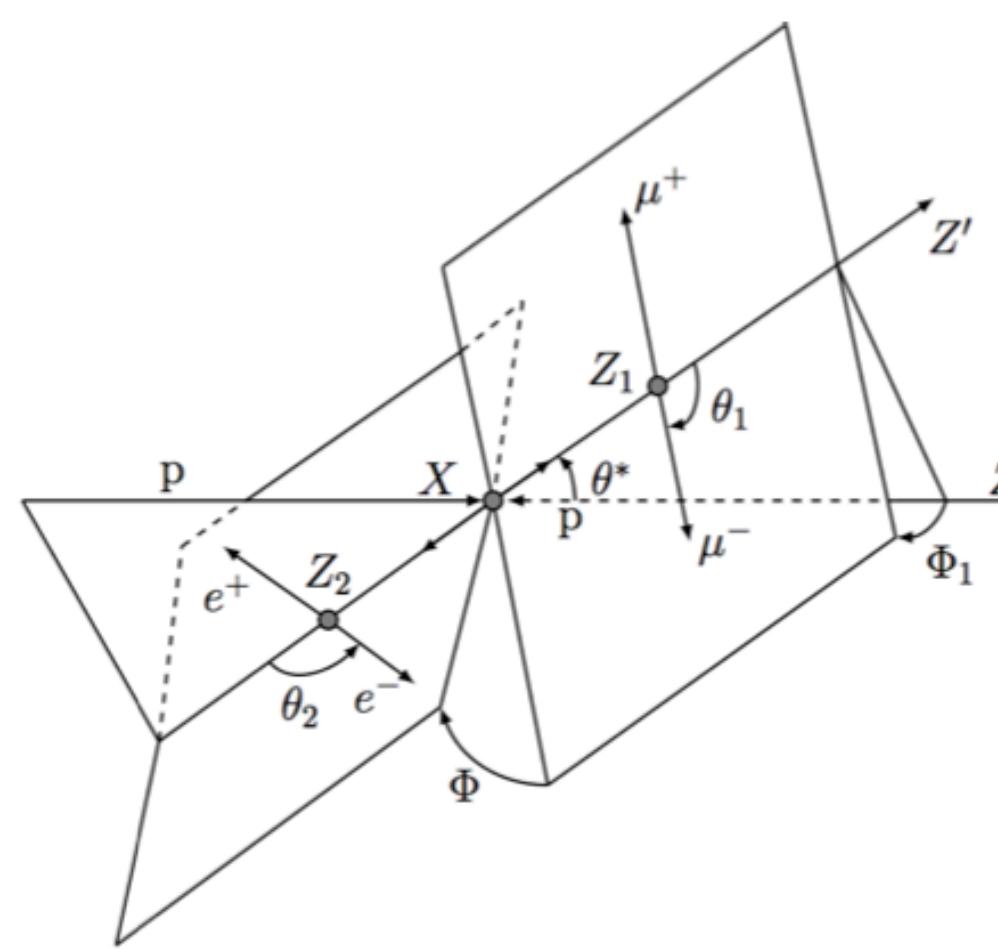
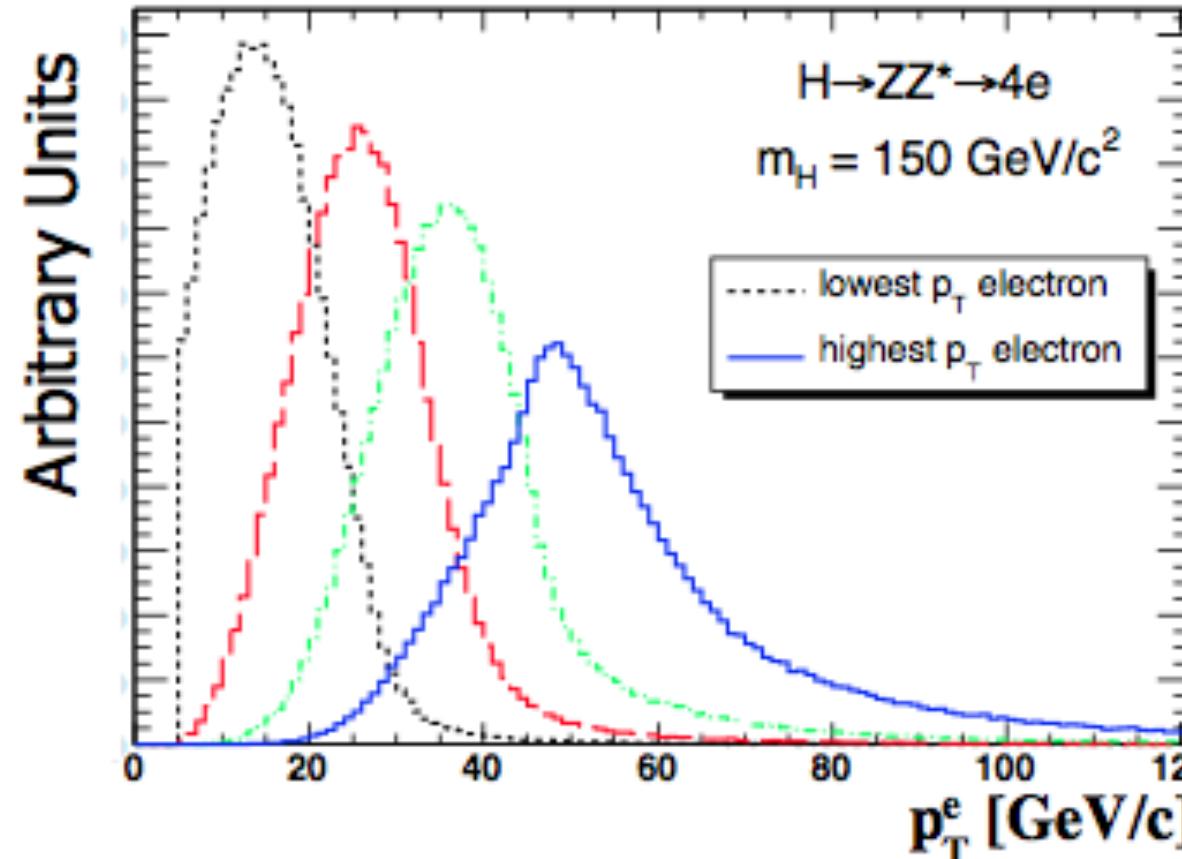


The Discovery Channels

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



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

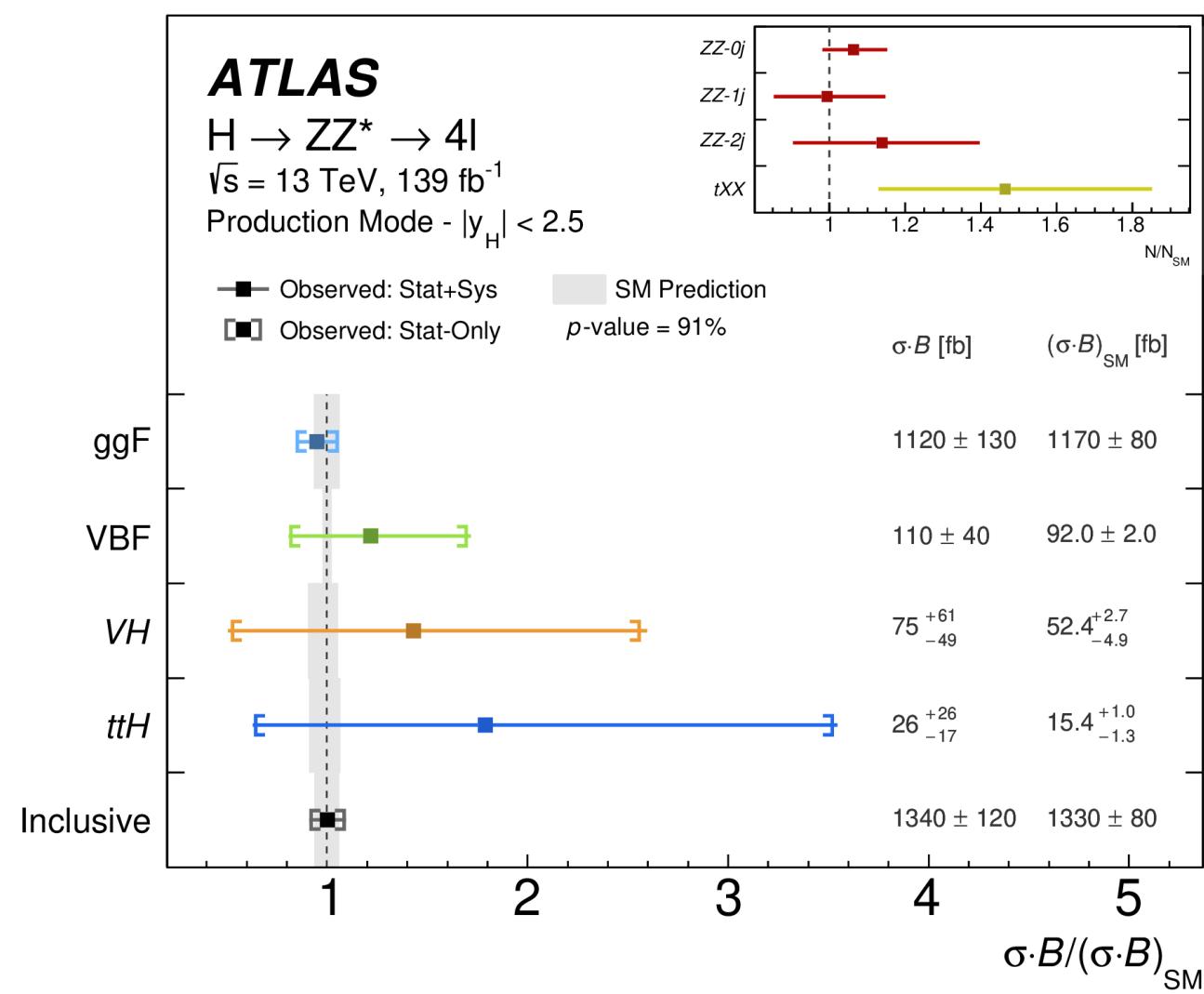


Hybrid Approach

Four lepton channel example

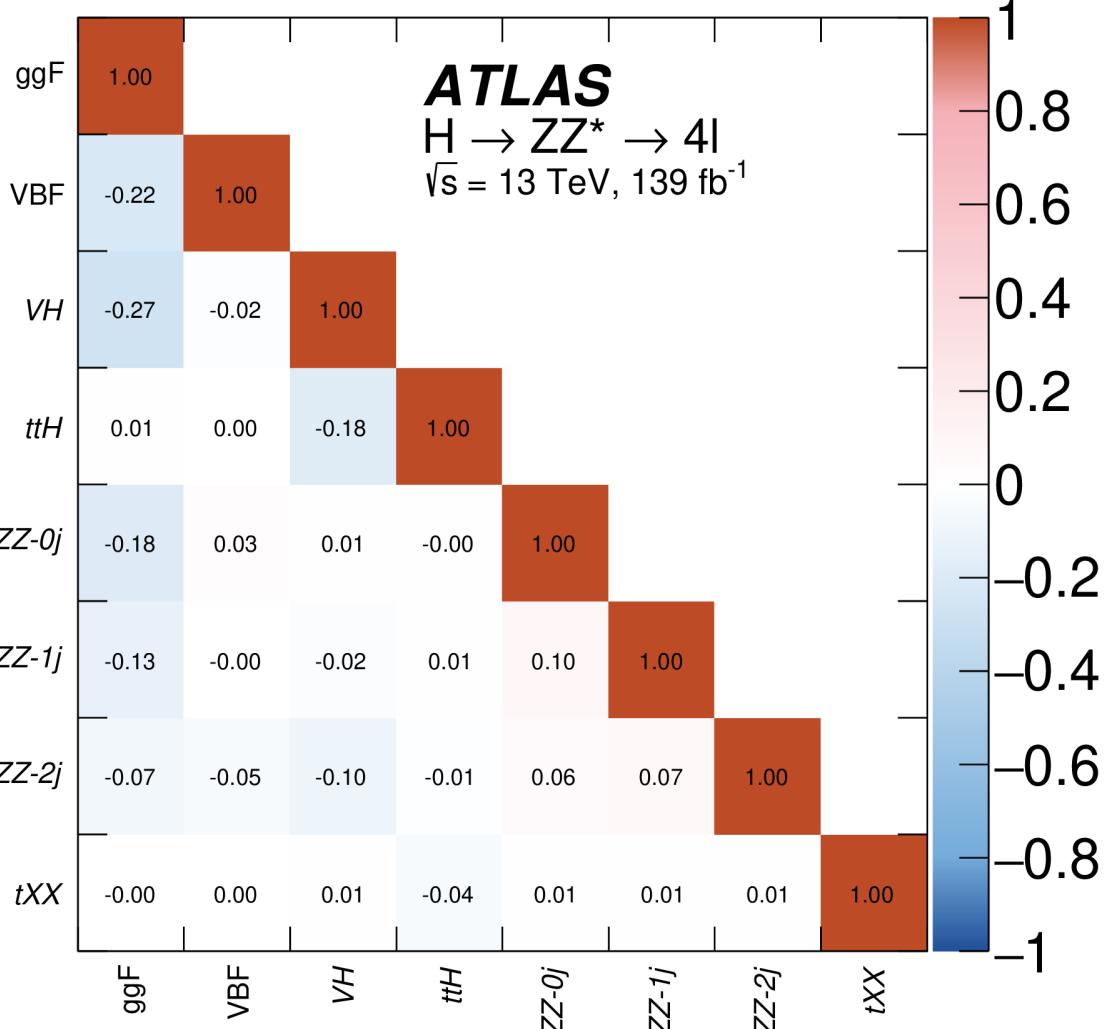
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Specific processes total cross sections are extracted from a global fit

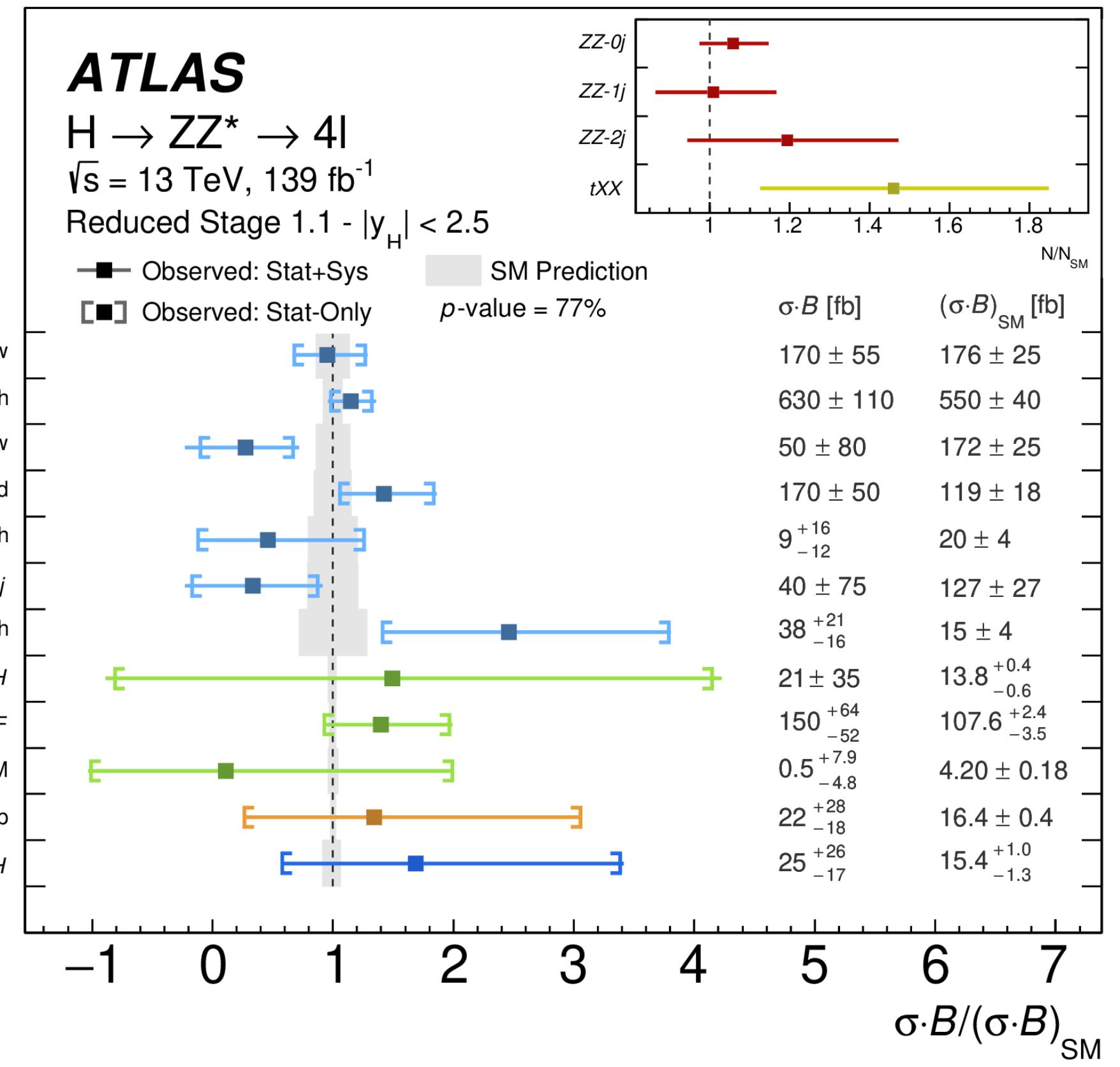


These measurements rely on the specific (SM) predicted acceptance of each process and the fact that no additional production processes are present.

All our couplings measurements are based on this assumption.



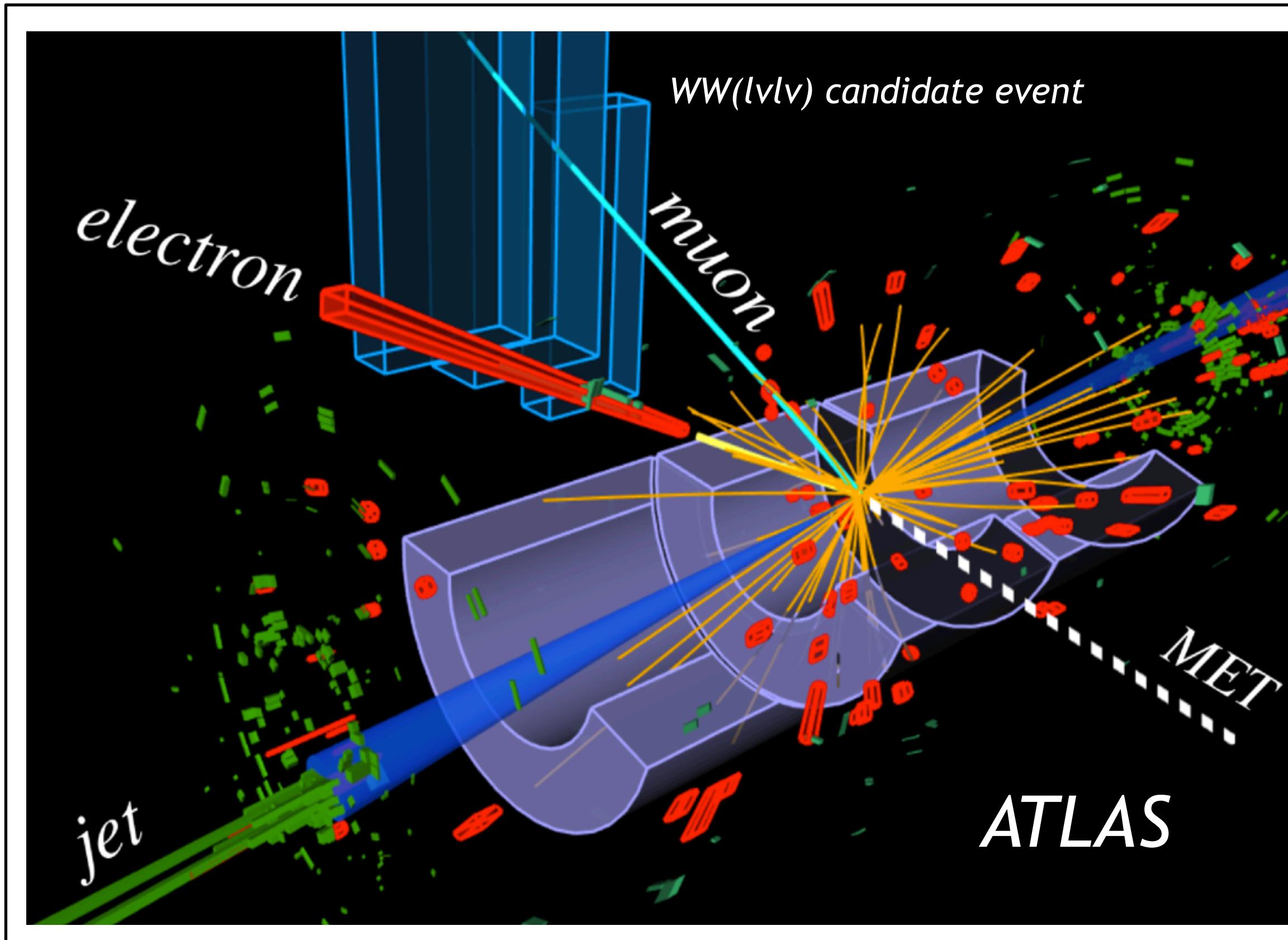
Similar measurements can be done in a more exclusive approach with more fiducial cuts are defined:



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

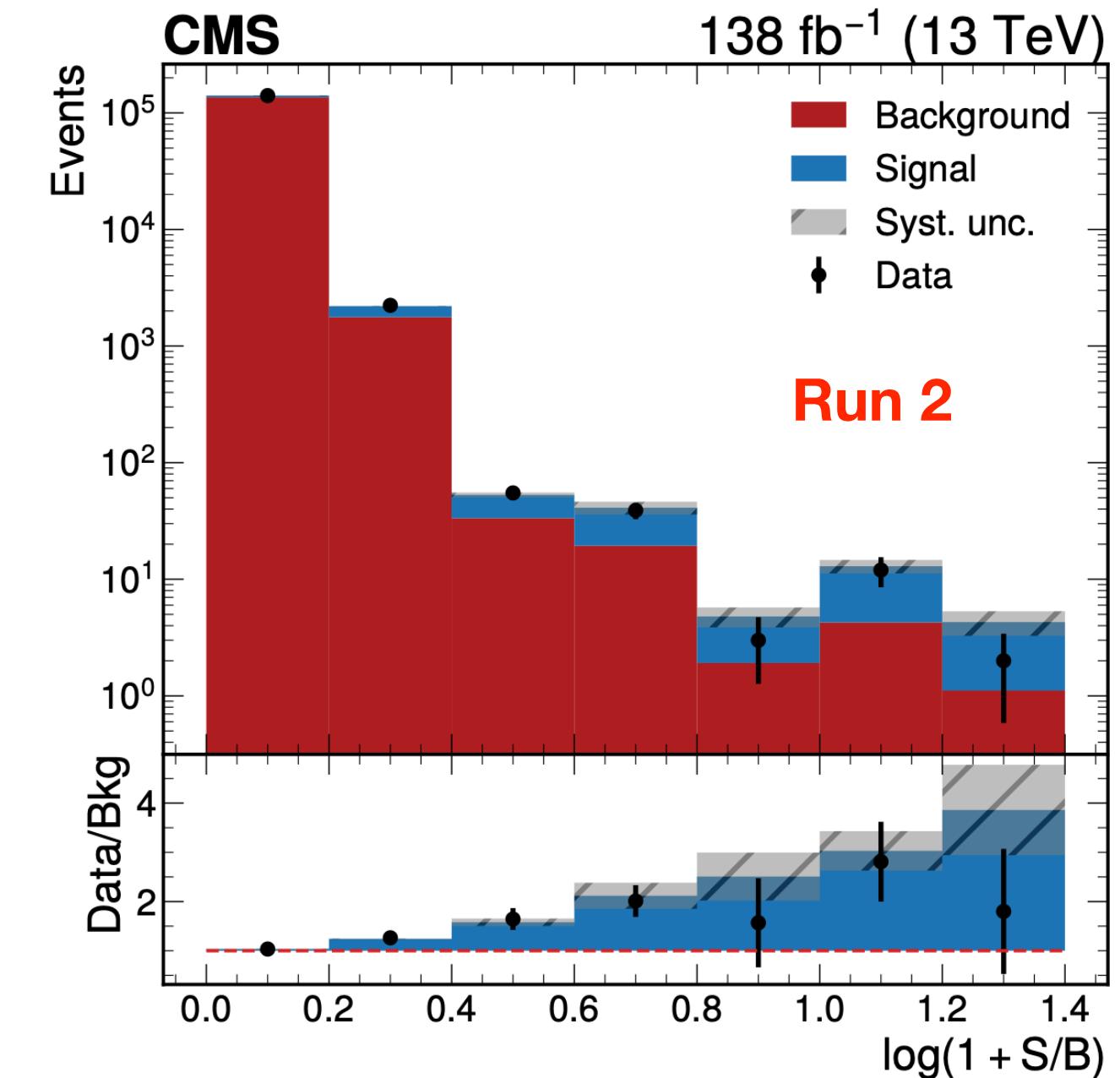
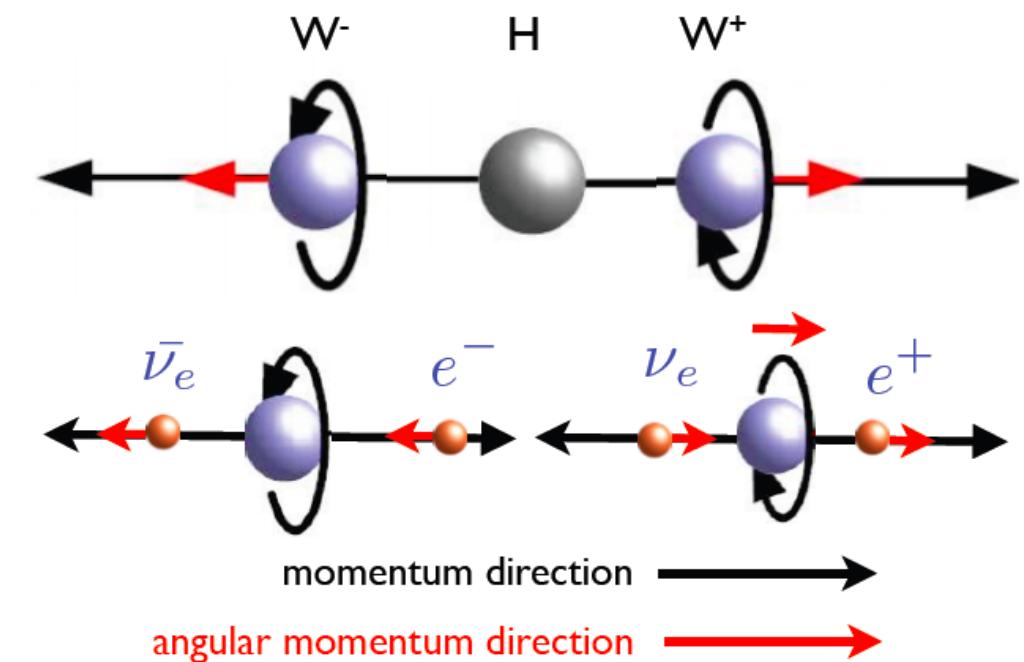
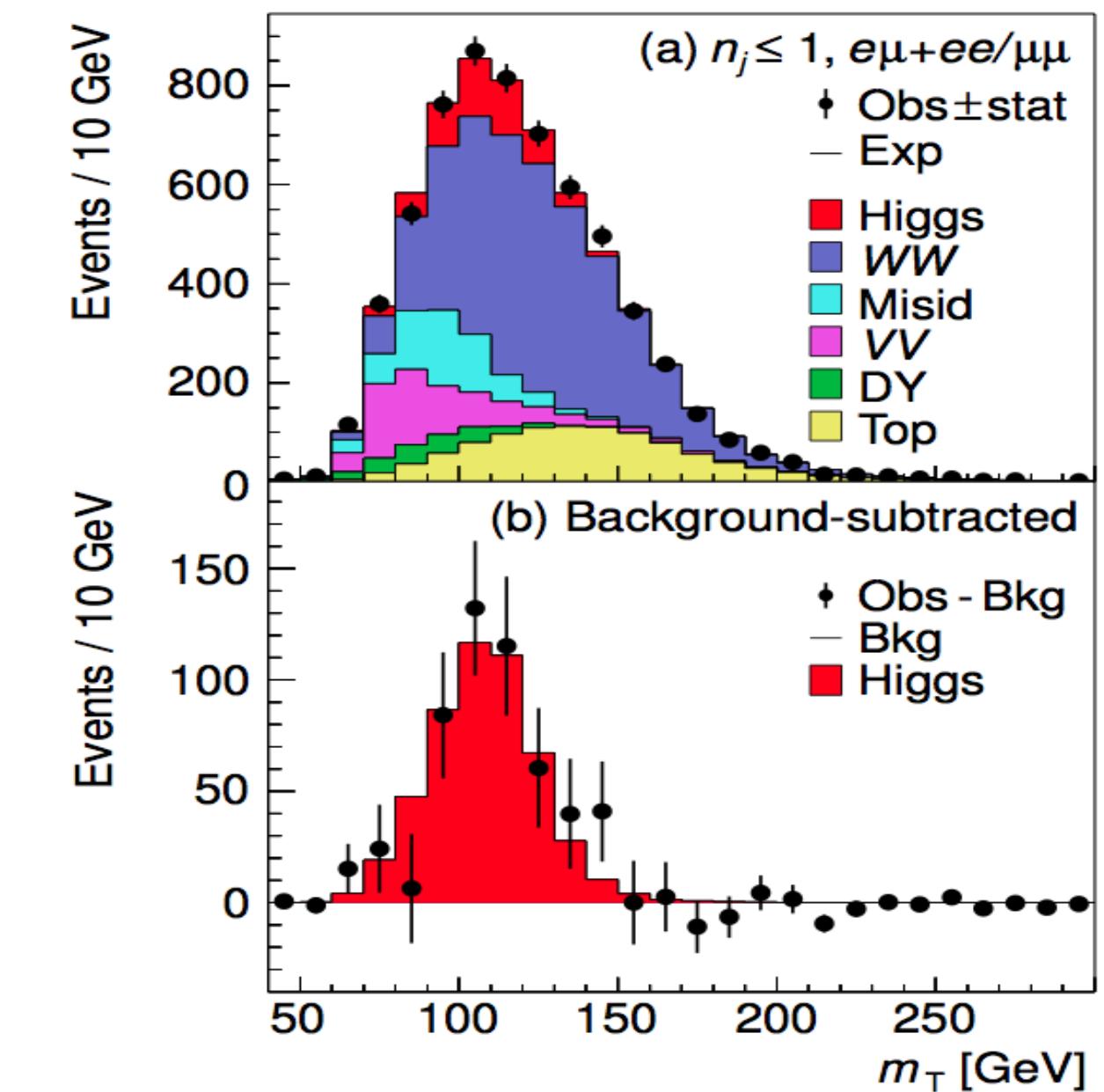


Channel where each of the W decays to leptons, the mass resolution is spoiled by the neutrinos!

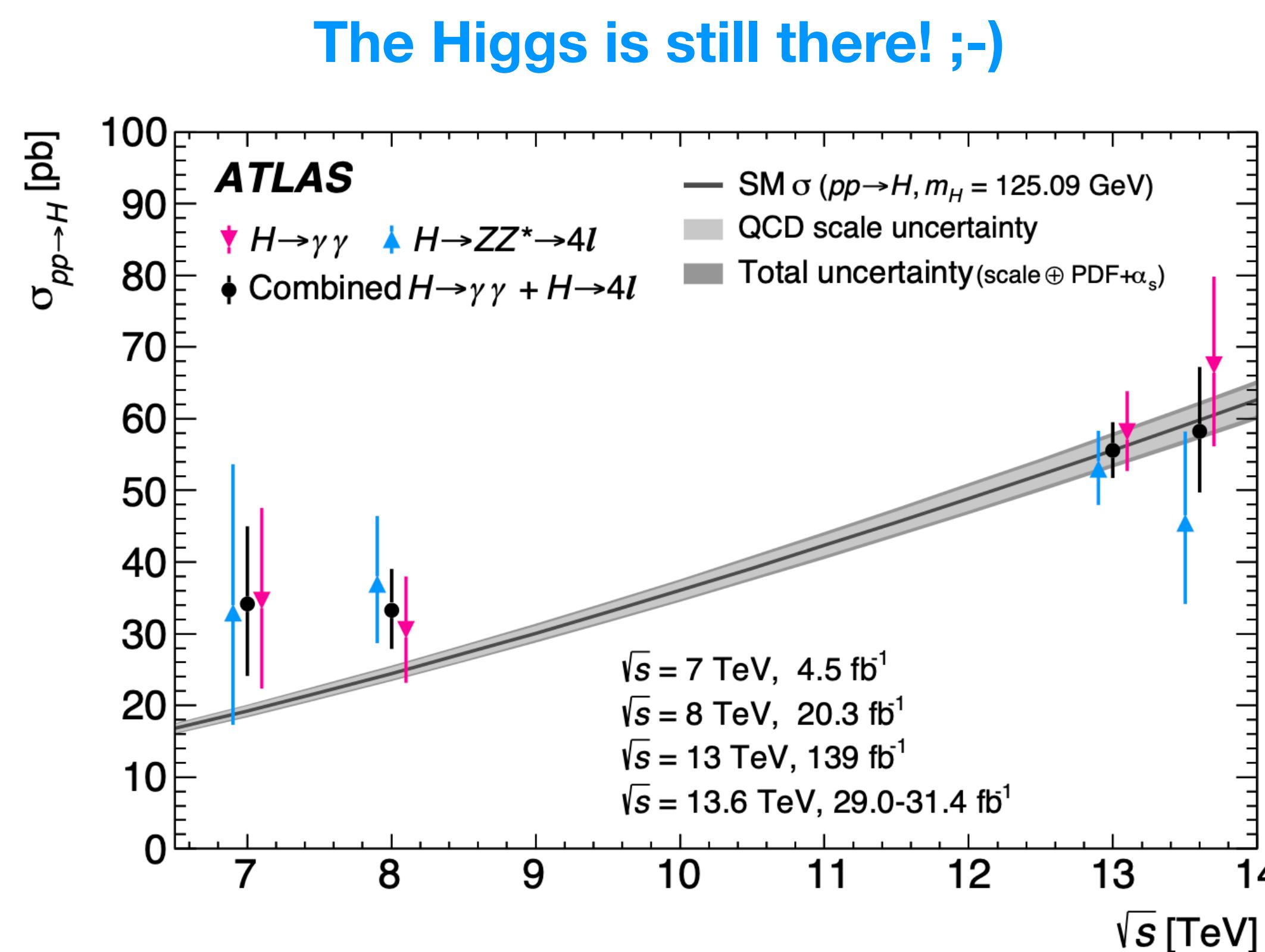
Large event rate, but also large backgrounds from the WW and top production.

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**.

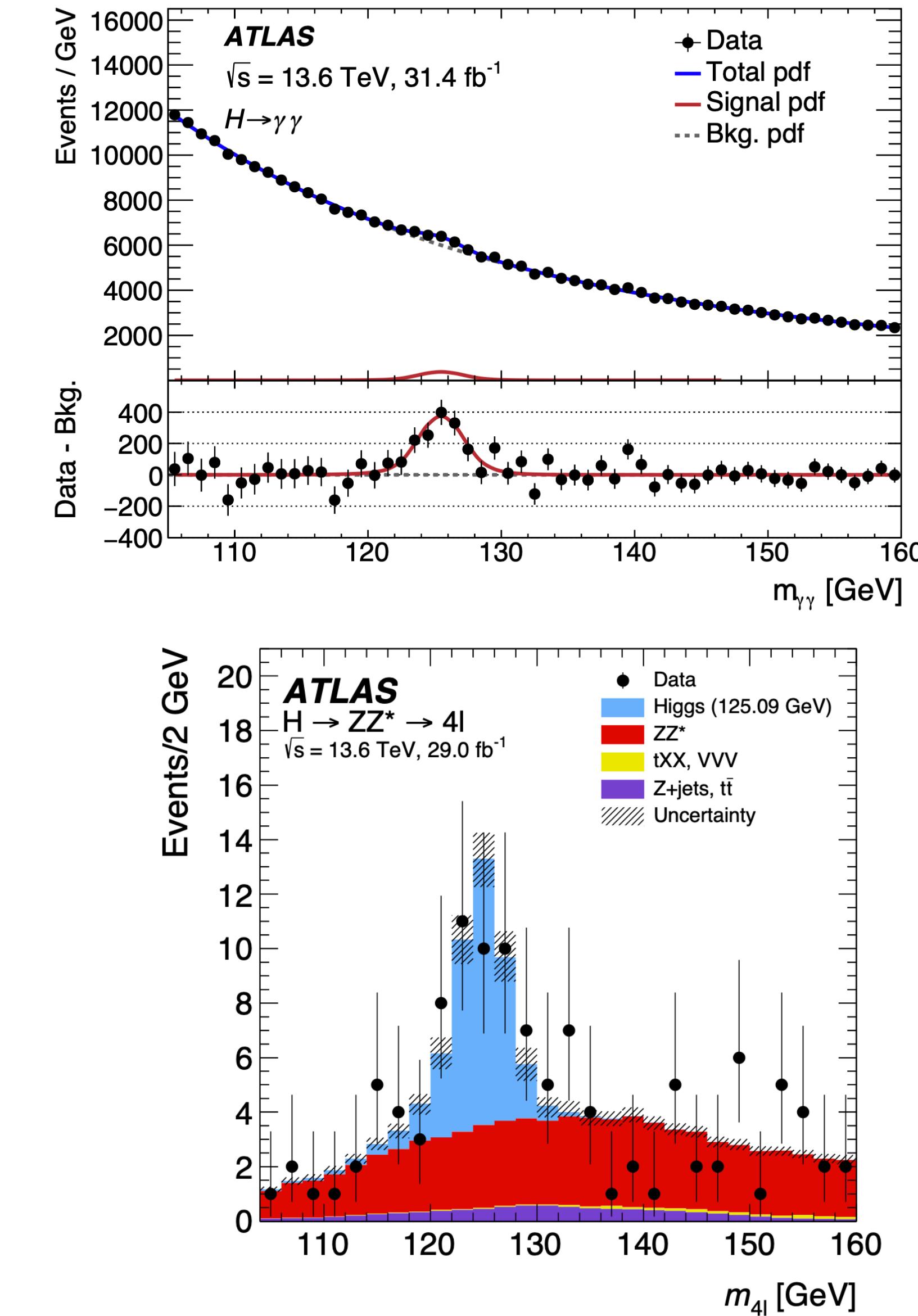


Latest Run 3 Results



13.6 TeV Cross Section measurements

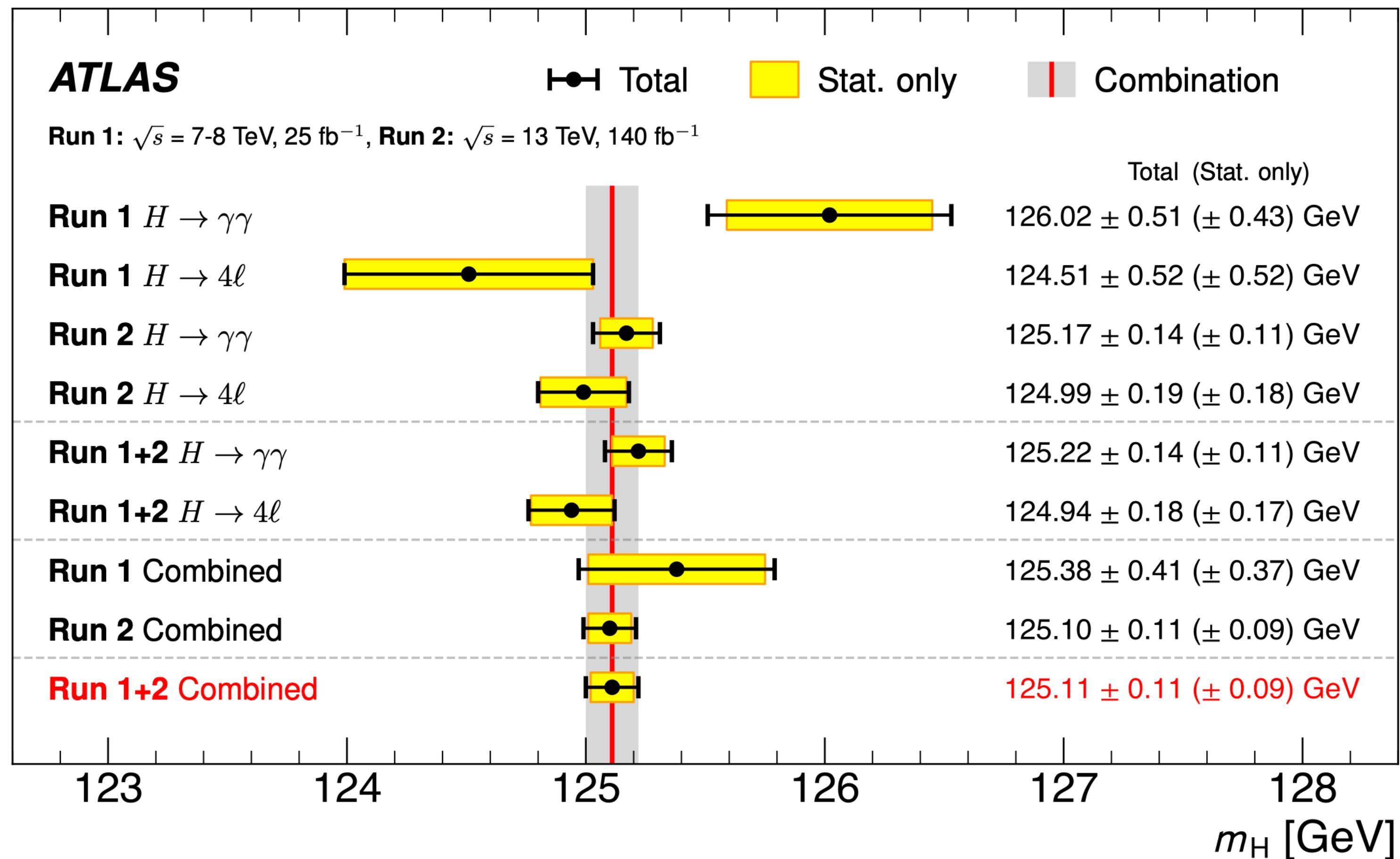
Fiducial and total cross sections measured in agreement with the SM.



First Precision Measurement at the LHC!

Higgs boson mass measurement

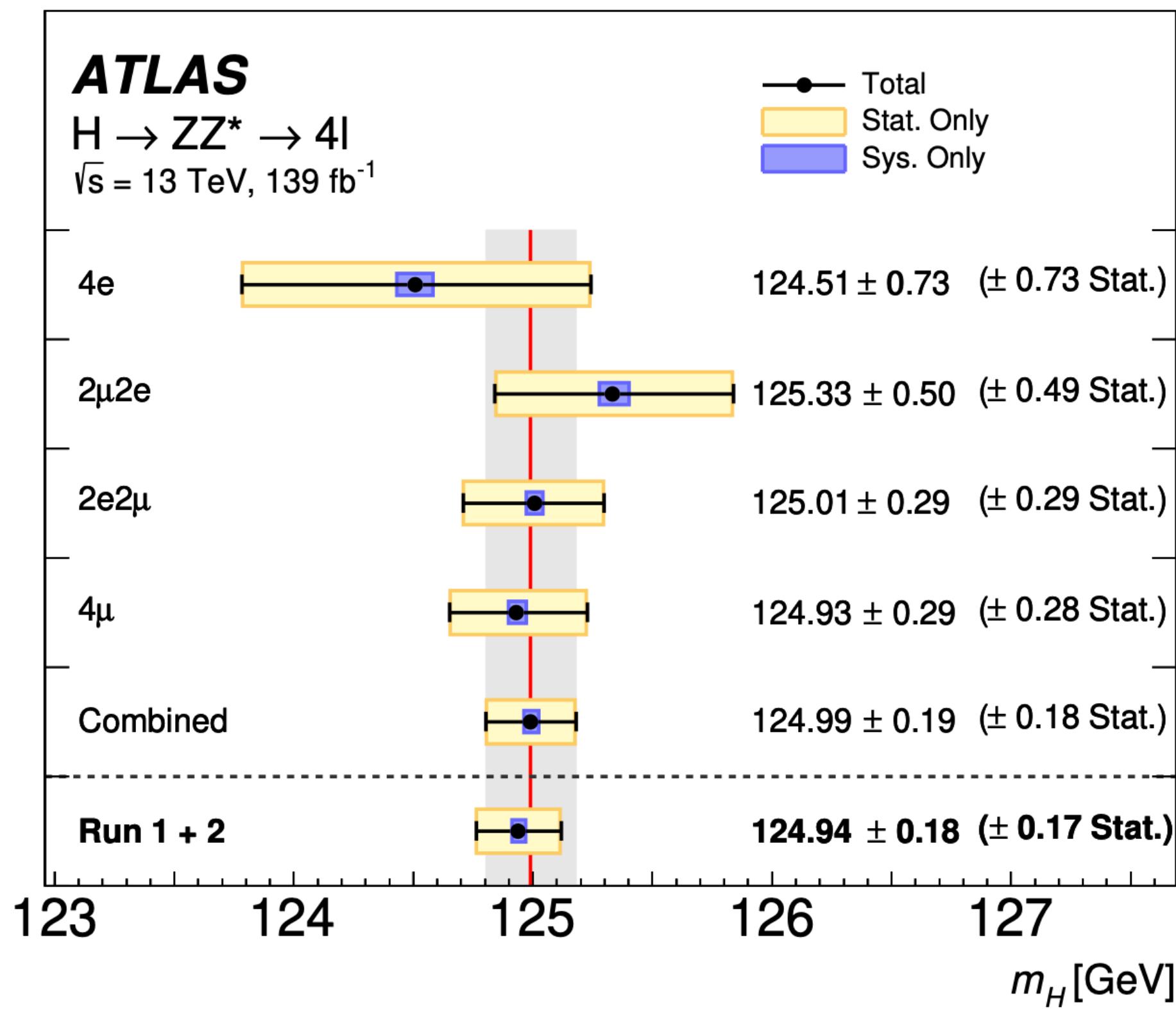
- Measurement done exclusively in the diphoton and 4-leptons channel.
- Optimizing the analysis in categories with best mass resolution (photon, electron and muons energy response).
- Systematics dominated by experimental uncertainties.
- Reached at Run 1 a precision of 0.2%.
- Precision reached 0.09% (below permil!)
- Best single measurement reached in the diphoton channel at 13 TeV!
- Photon and leptons calibration is key!
- **Diphoton systematic uncertainty reached 90 MeV! Great achievement!**



Measurement of the Higgs Boson Mass

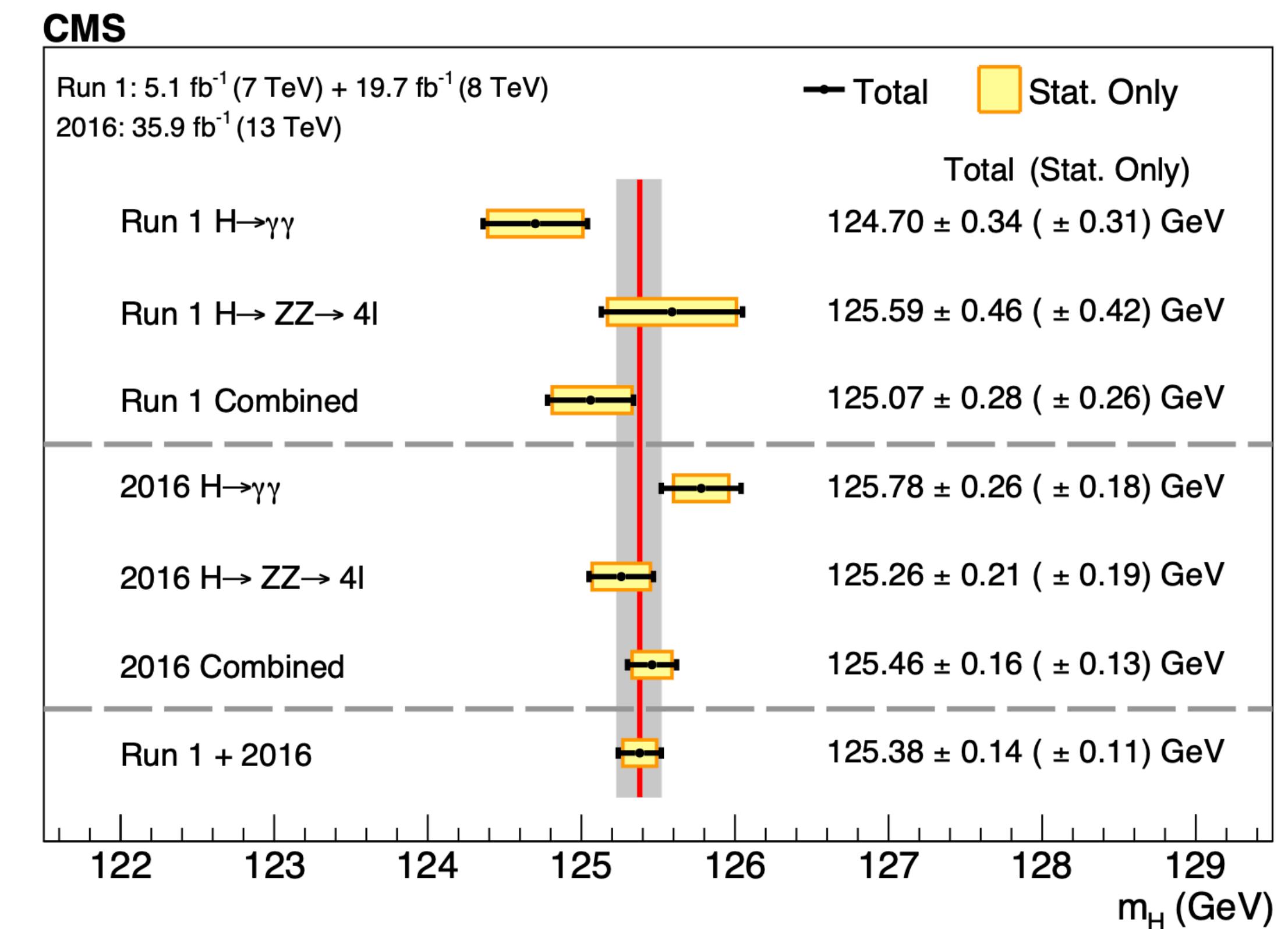
17

Latest 4l measurement from [ATLAS](#):



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

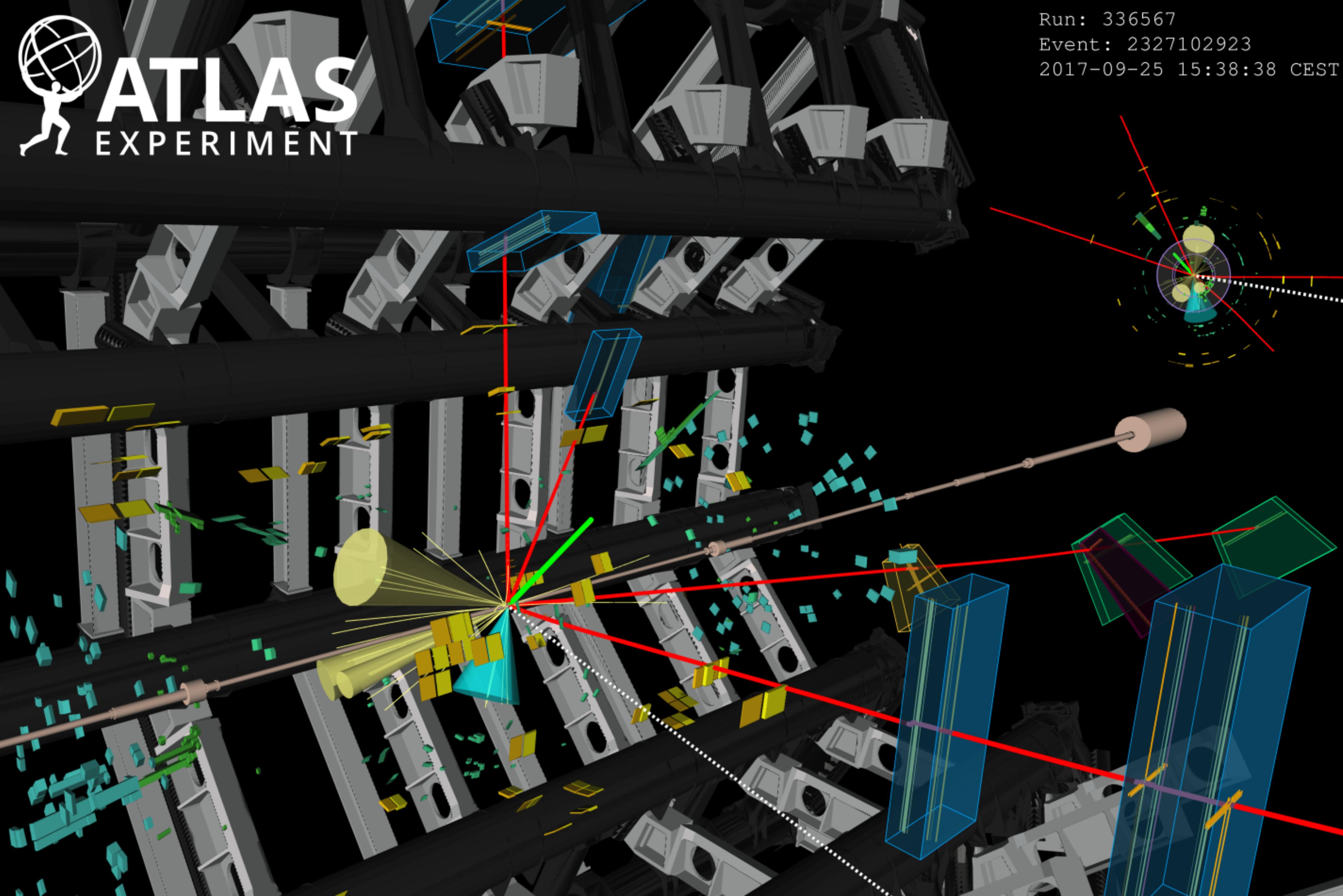
Precise measurement from [CMS](#):



Excellent precision with partial Run 2 dataset.



Run: 336567
Event: 2327102923
2017-09-25 15:38:38 CEST



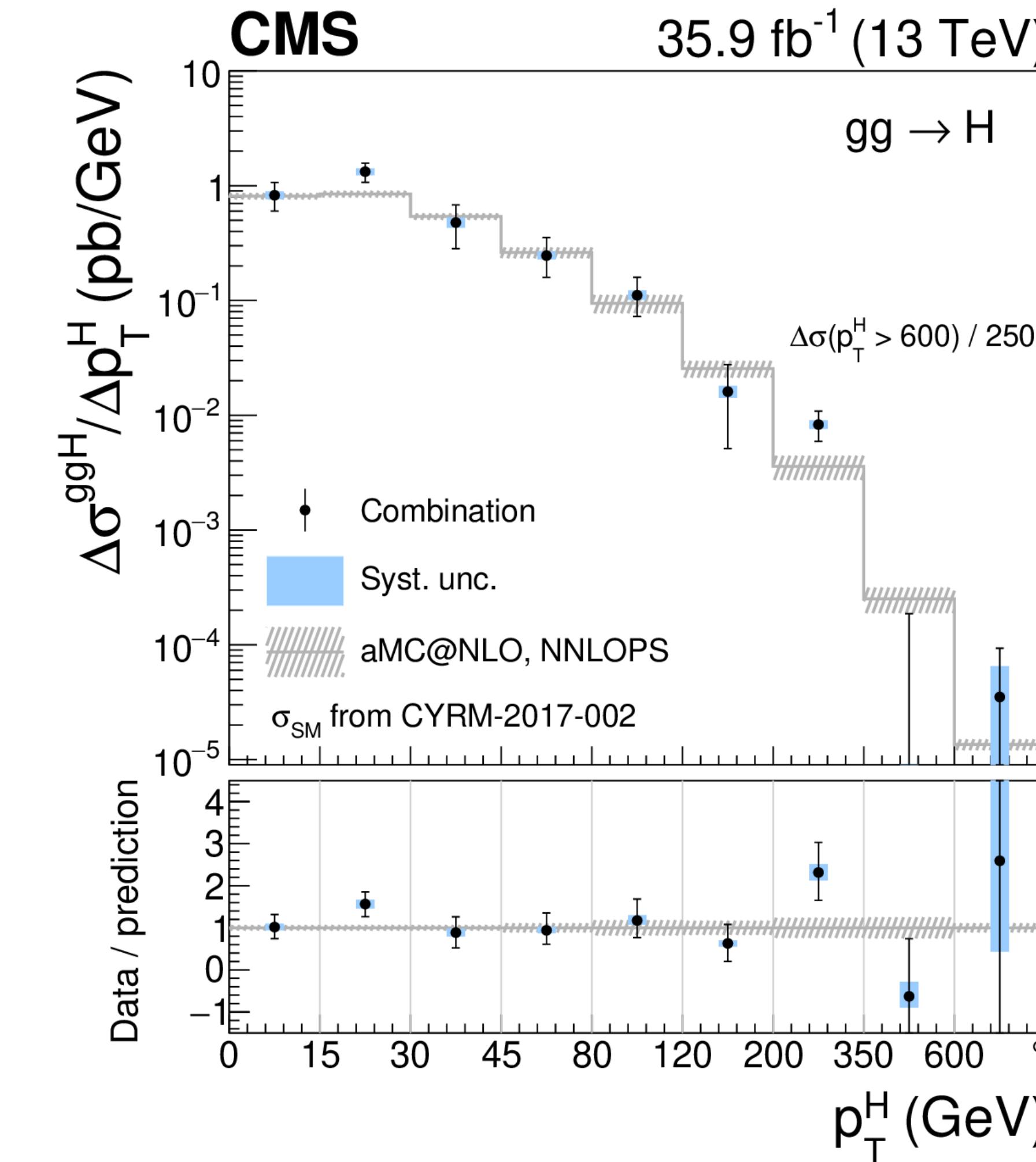
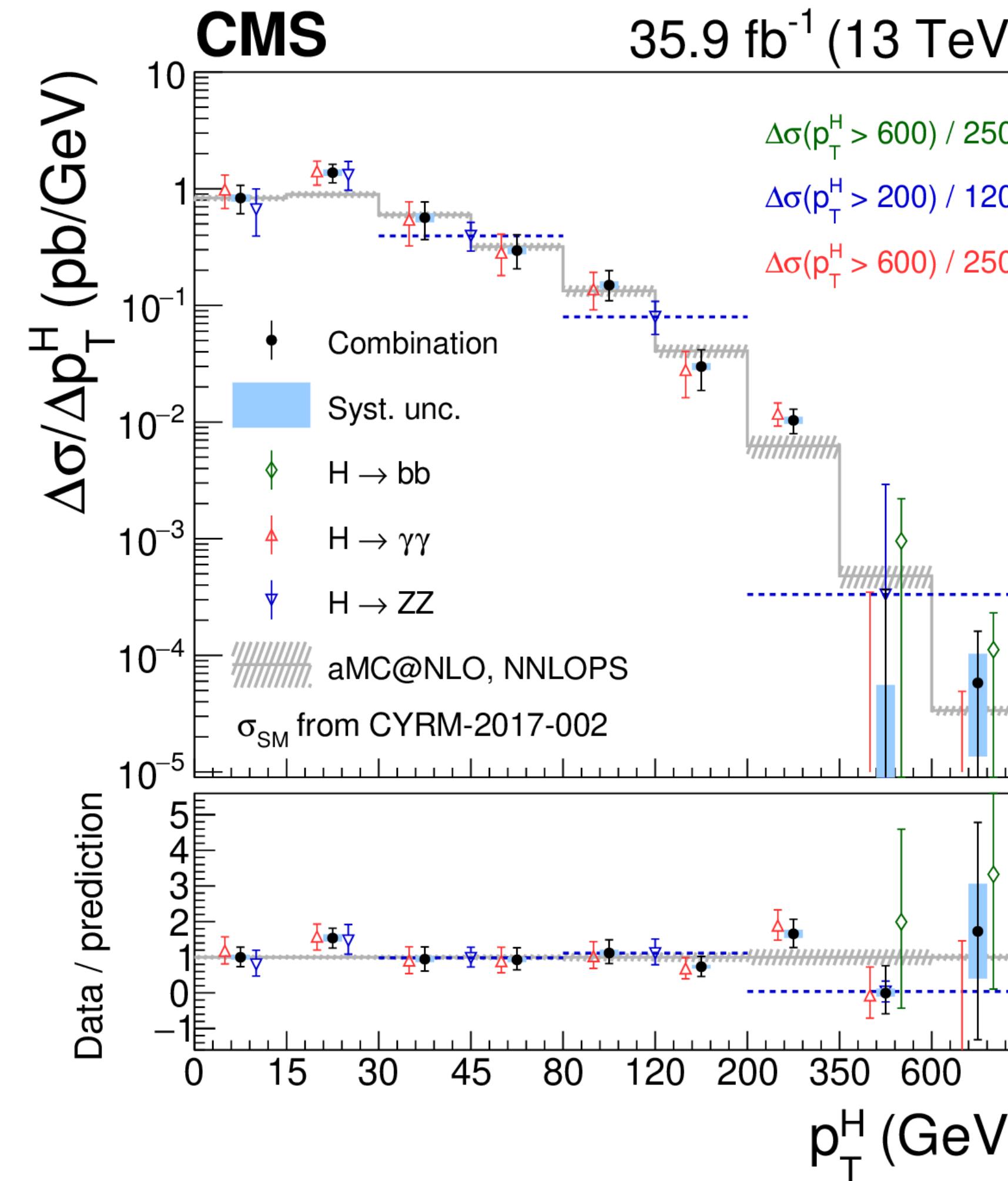
4 muon event
with mass 124.4
GeV, one Z mass
of 89.3 GeV and
the lower mass of
33 GeV, one
electron, four jets,
lowest pT has
highest b-tagging.

$s/b \sim 30$

Differential (fiducial and unfolded) Cross Section Measurements

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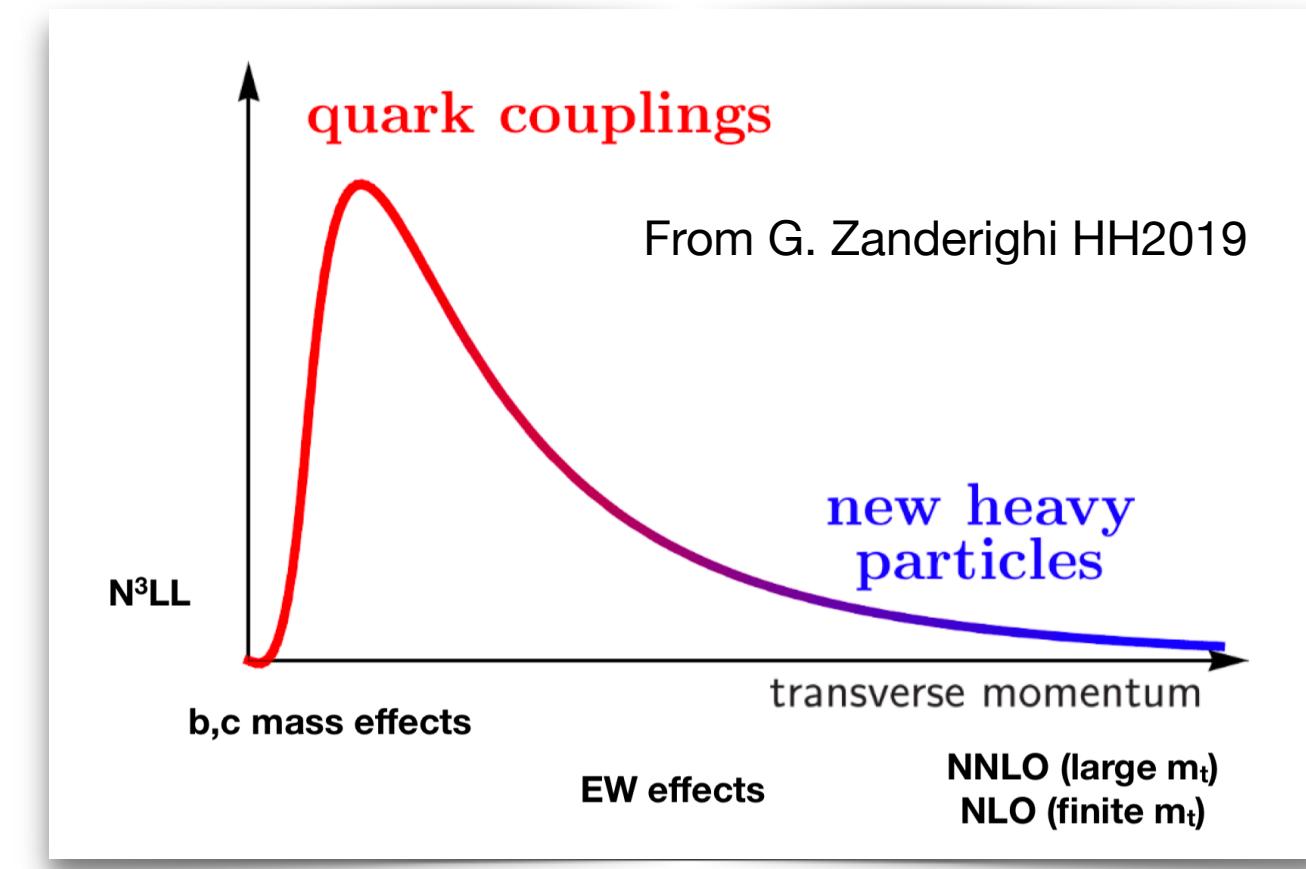
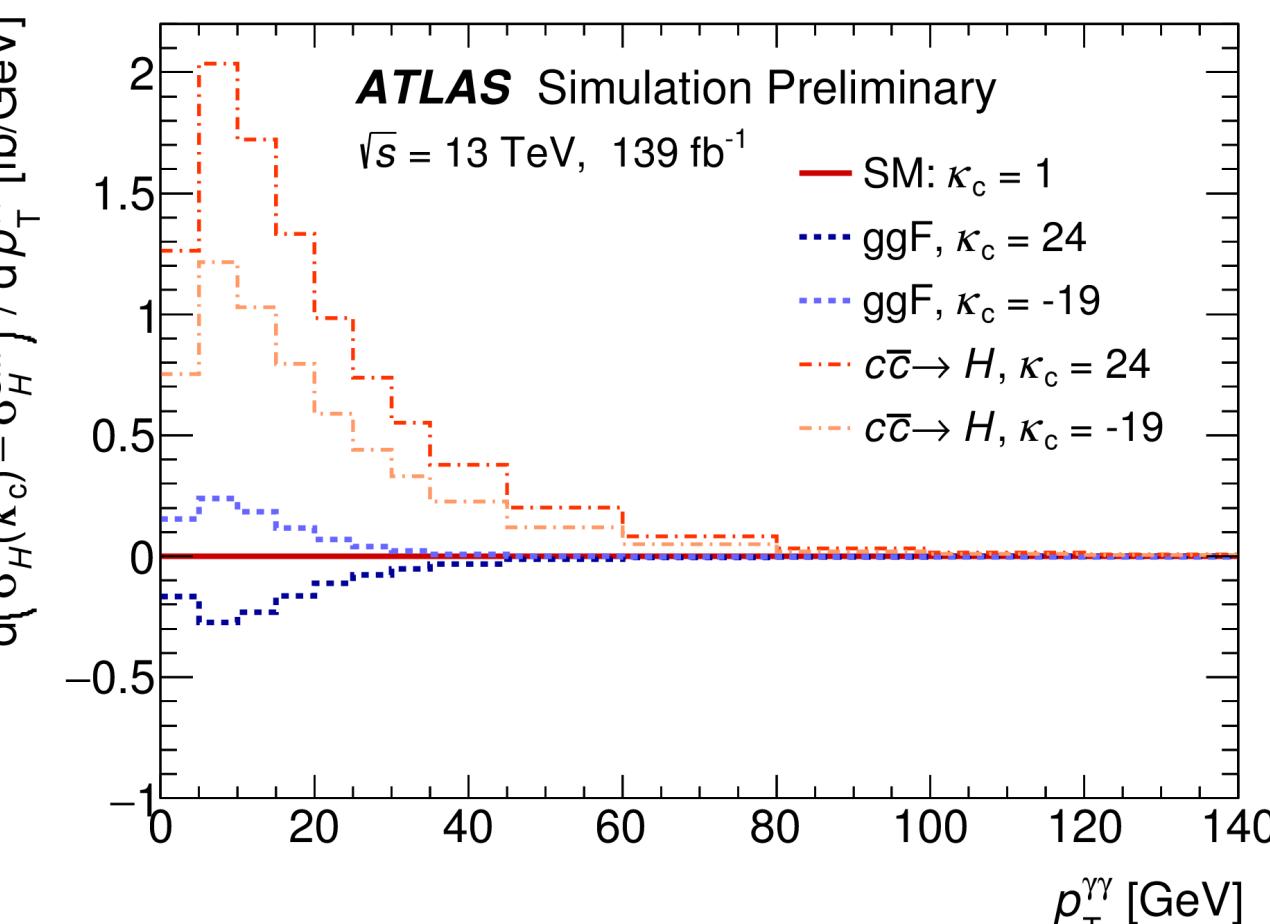
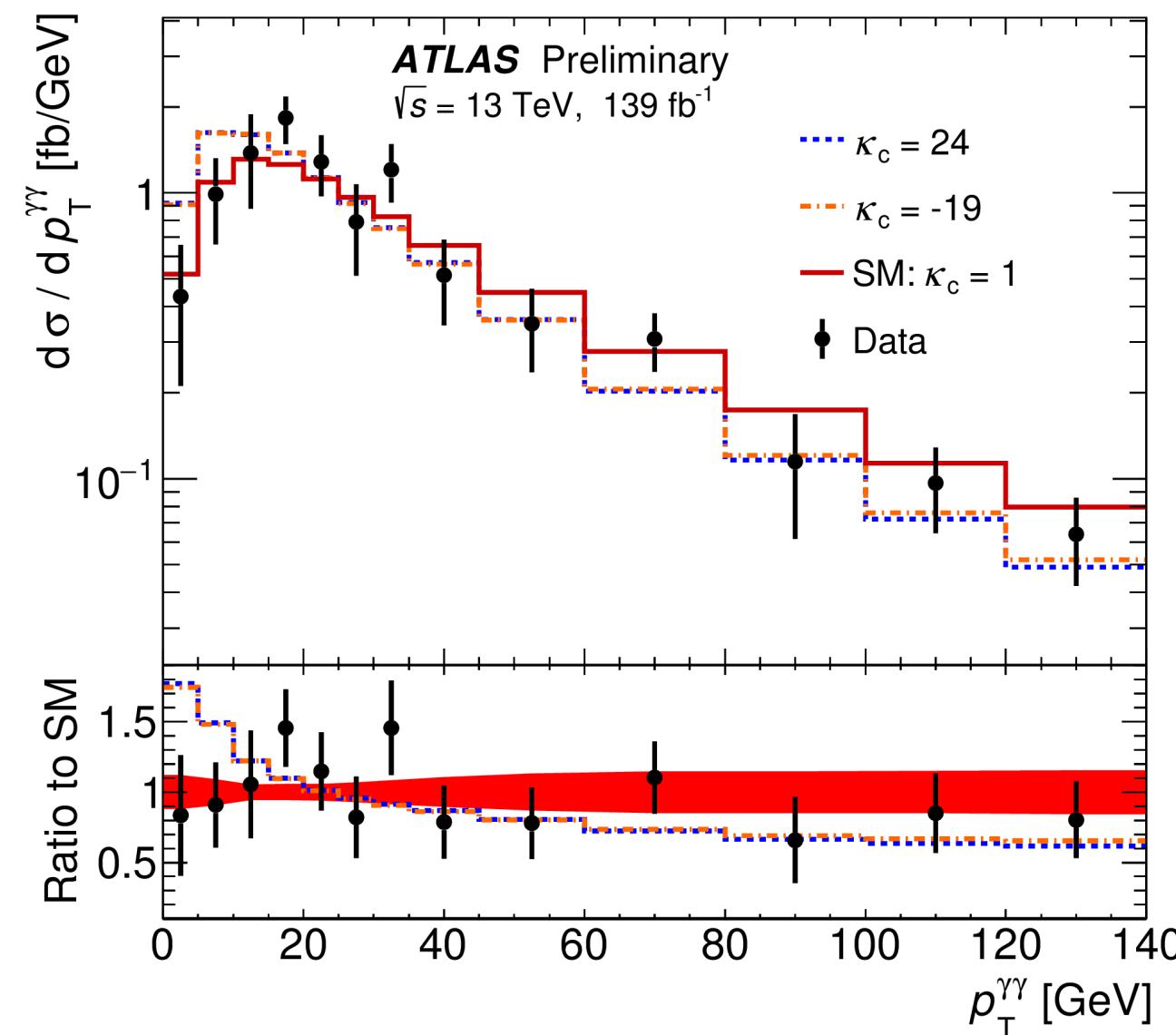
Partially fiducial and unfolded differential cross section measurement in pT (not updated for illustration)



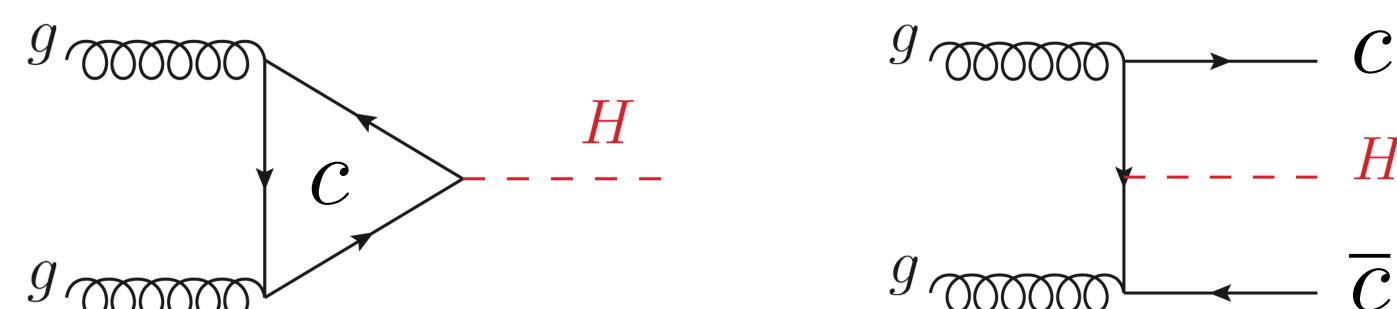
Differential (fiducial and unfolded) Cross Section Measurements

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Fiducial and unfolded differential cross section measurement in pT



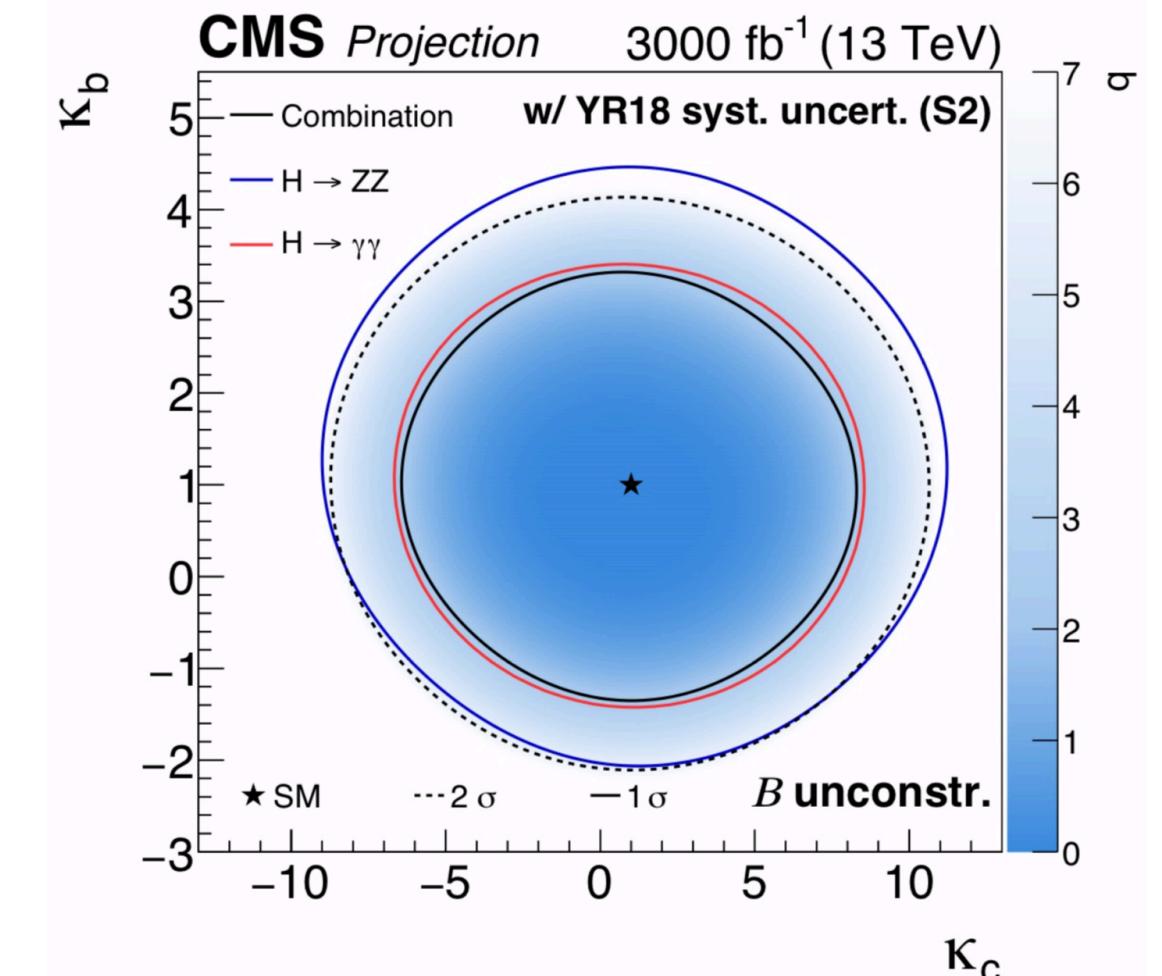
Indirect measurement of the b and c Yukawa couplings through loop:



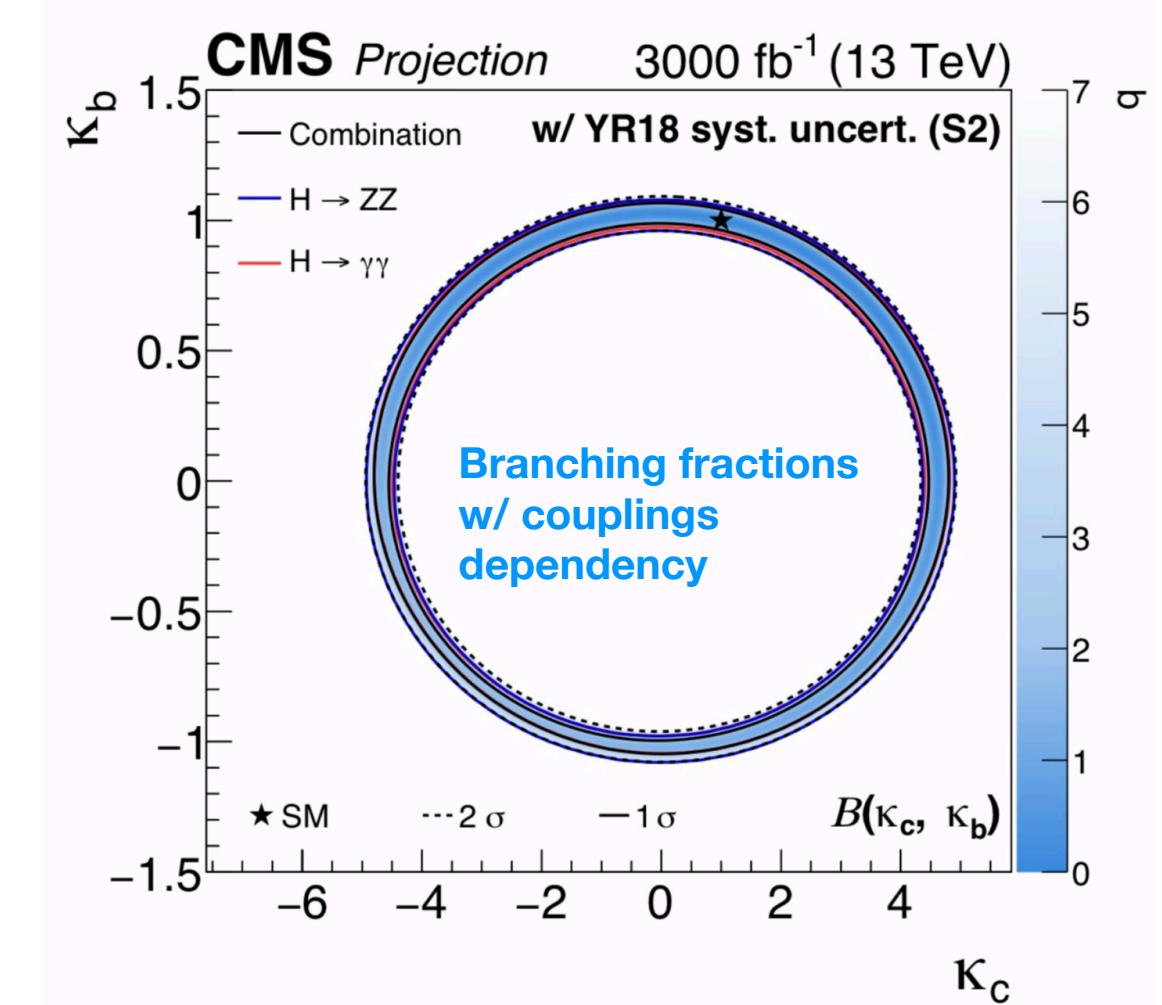
Significant at large values of κ_c

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

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CP boson Higgs couplings only at higher orders (expected to be suppressed)

Measurement from CMS in the ZZ* (4l) channels in the ggF, VH and VBF production modes also with constraints on the Htt coupling using the ttH(diphoton) channel

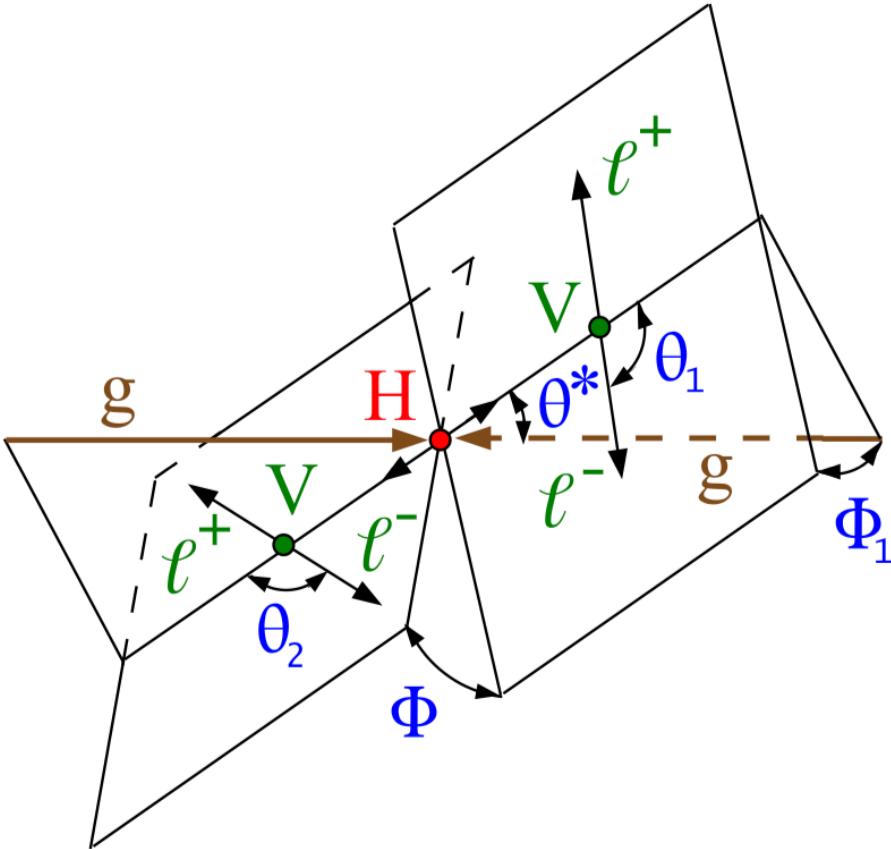


Illustration of 5 production and decay angles for the 4-leptons (most sensitive to the CP mixing)

Analysis based on Matrix Element optimal observables

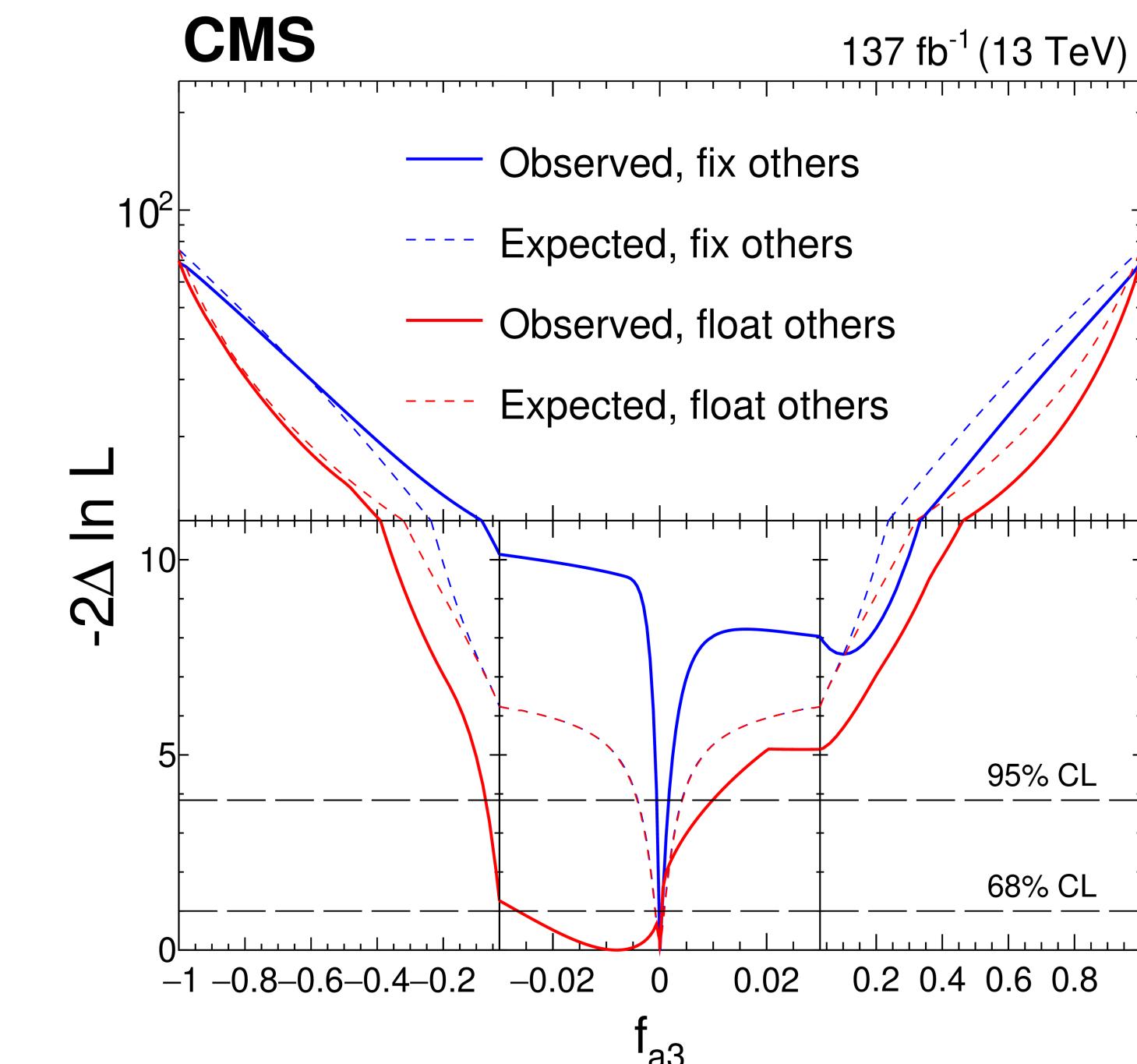
$$A \sim \left[a_1^{VV} - \frac{\kappa_1^{VV} q_1^2 + \kappa_2^{VV} q_2^2}{(\Lambda_1^{VV})^2} - \frac{\kappa_3^{VV} (q_1 + q_2)^2}{(\Lambda_Q^{VV})^2} \right] m_{V1}^2 \varepsilon_{V1}^* \varepsilon_{V2}^*$$

$$+ a_2^{VV} f_{\mu\nu}^{*(1)} f^{*(2)\mu\nu} + a_3^{VV} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2)\mu\nu}$$

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

$$\tilde{f}_{\mu\nu}^{*(i)} = \frac{1}{2} \varepsilon_{\mu\nu\rho\sigma} f^{*(i)\rho\sigma}$$

$$f_{a_i} = \frac{|a_i|^2 \sigma_i}{\sum_{j=1,2,3} |a_j|^2 \sigma_j}, \quad \phi_{a_i} = \arg \left(\frac{a_i}{a_1} \right)$$



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

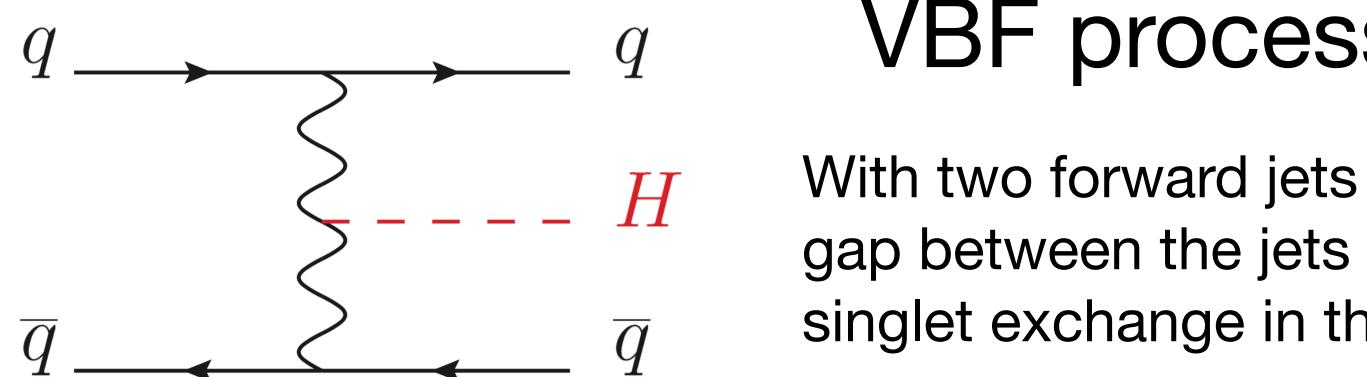
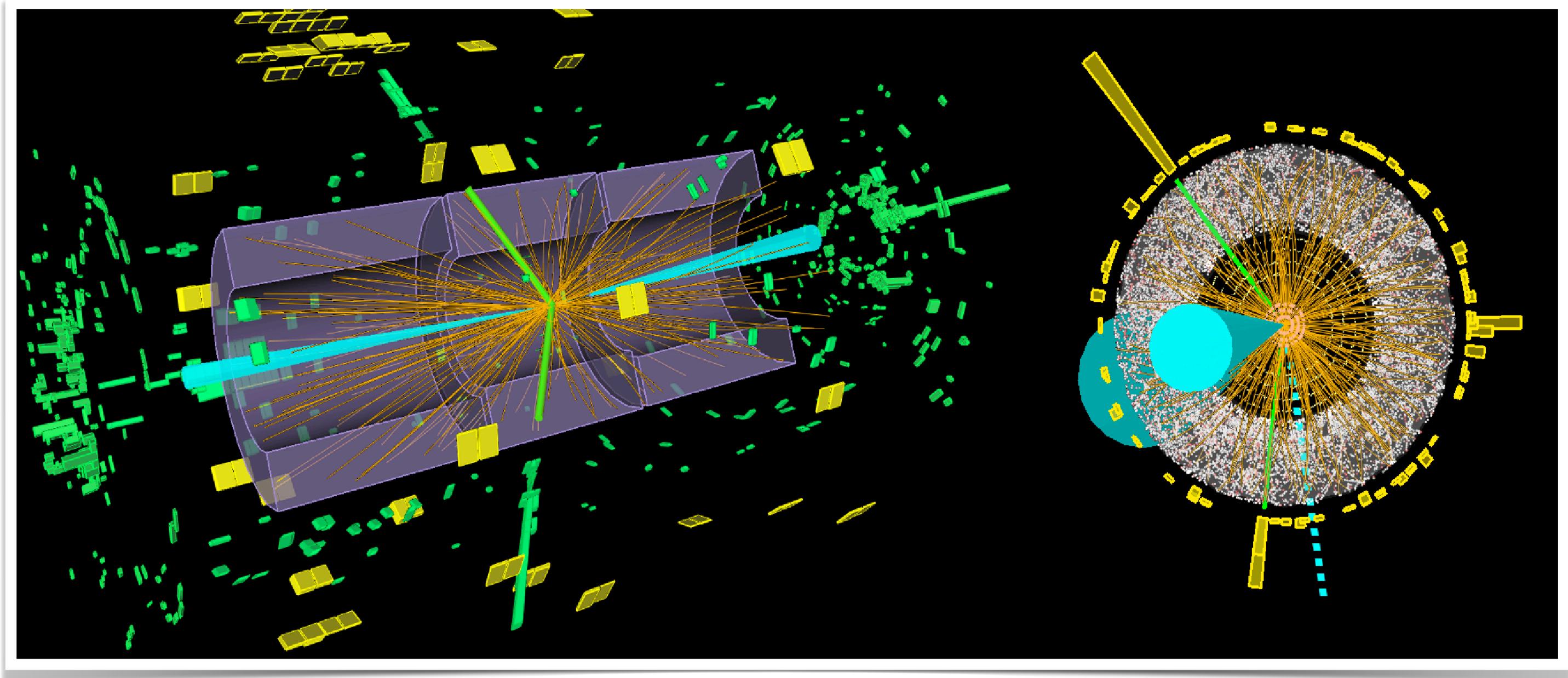
Similar analysis in ATLAS, also using the VBF process in the tau channel

The Run 2 Landmark Results

Observation and Measurement of 3^d generation Yukawa Couplings

Higgs boson decays to Taus

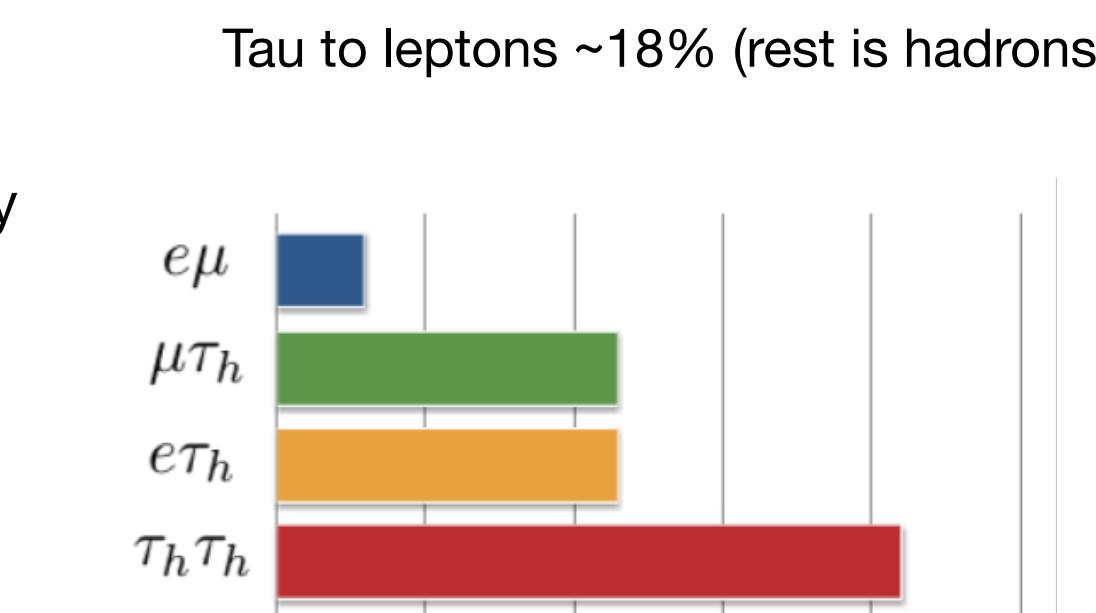
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With two forward jets and a large rapidity gap between the jets (due to the color singlet exchange in the t-channel)

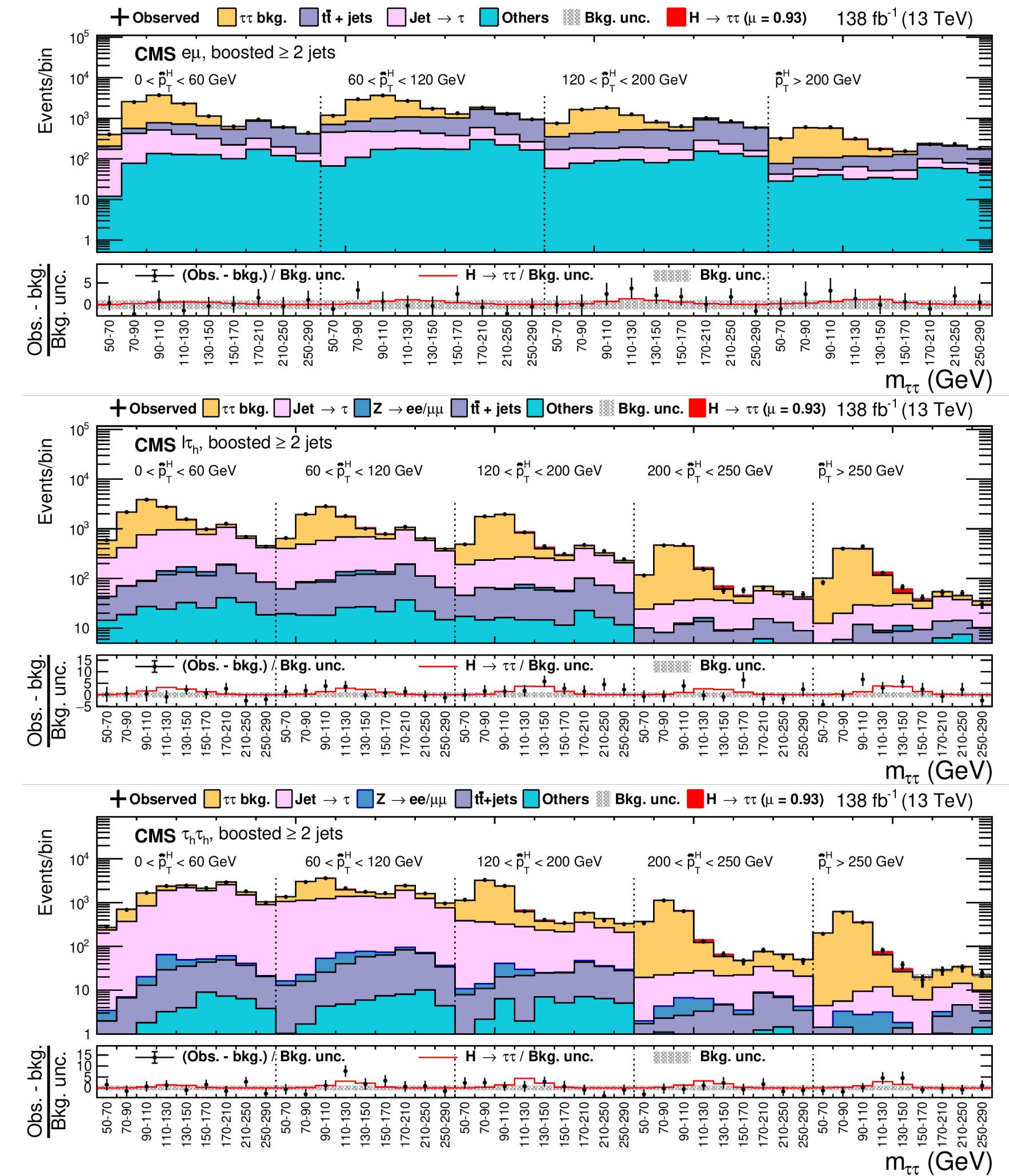
Background is Z production with two jets, in this region of phase space it is difficult to predict!

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



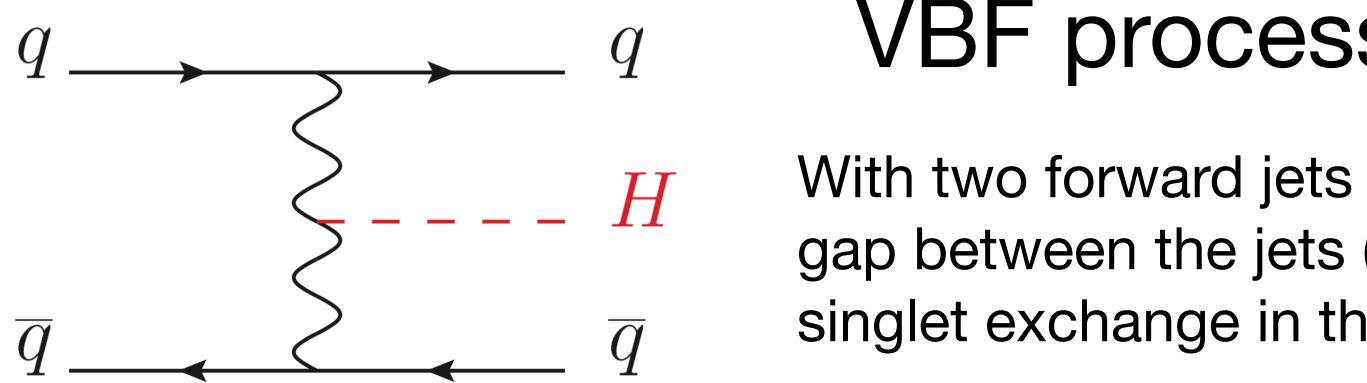
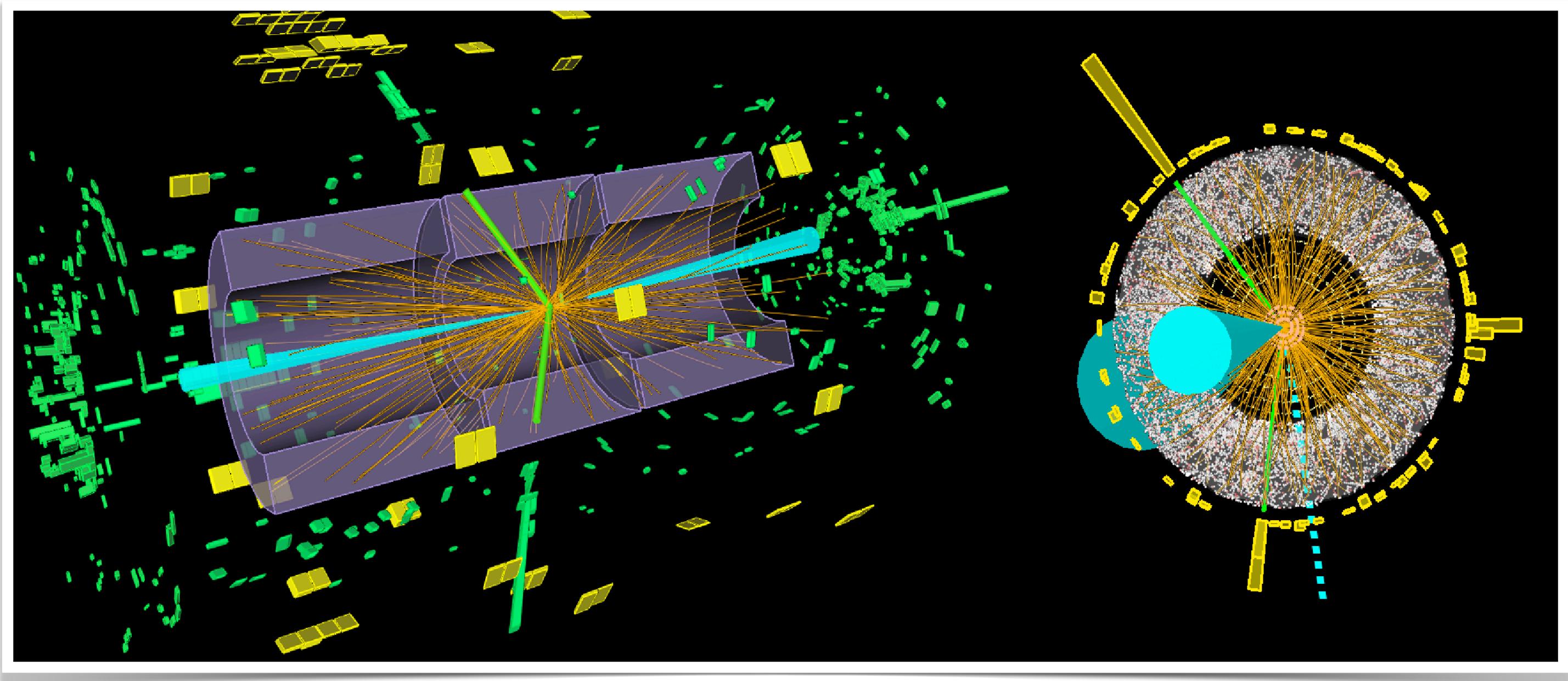
Analysis requires data driven methods to do so: e.g. the embedding of taus in Z to di-muon events.

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



Higgs boson decays to Taus

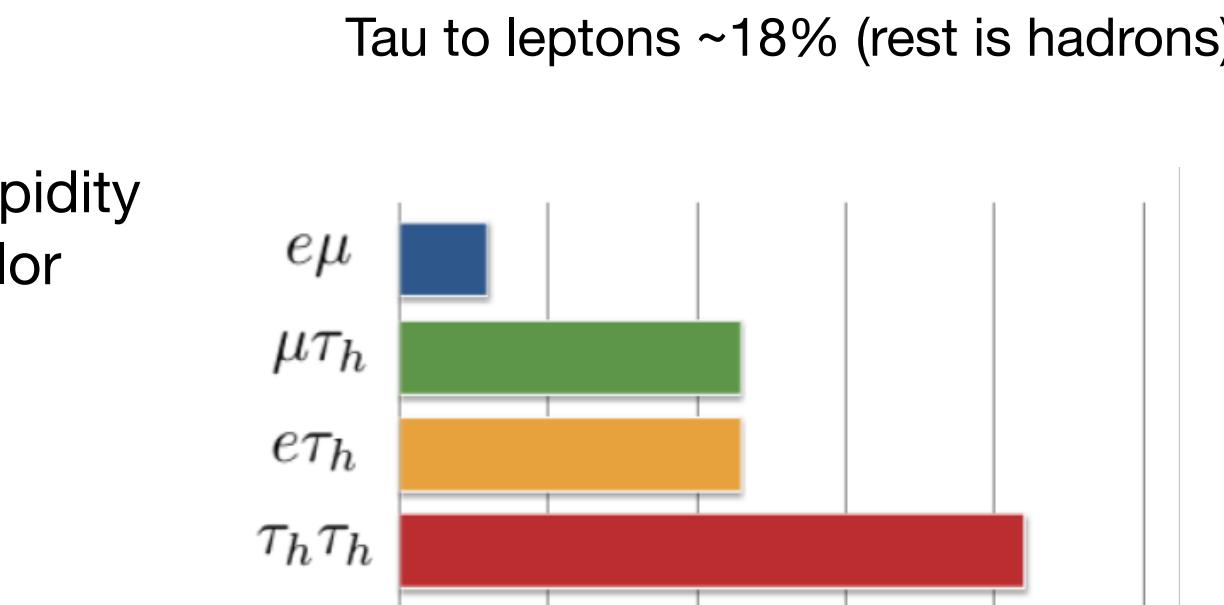
24



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

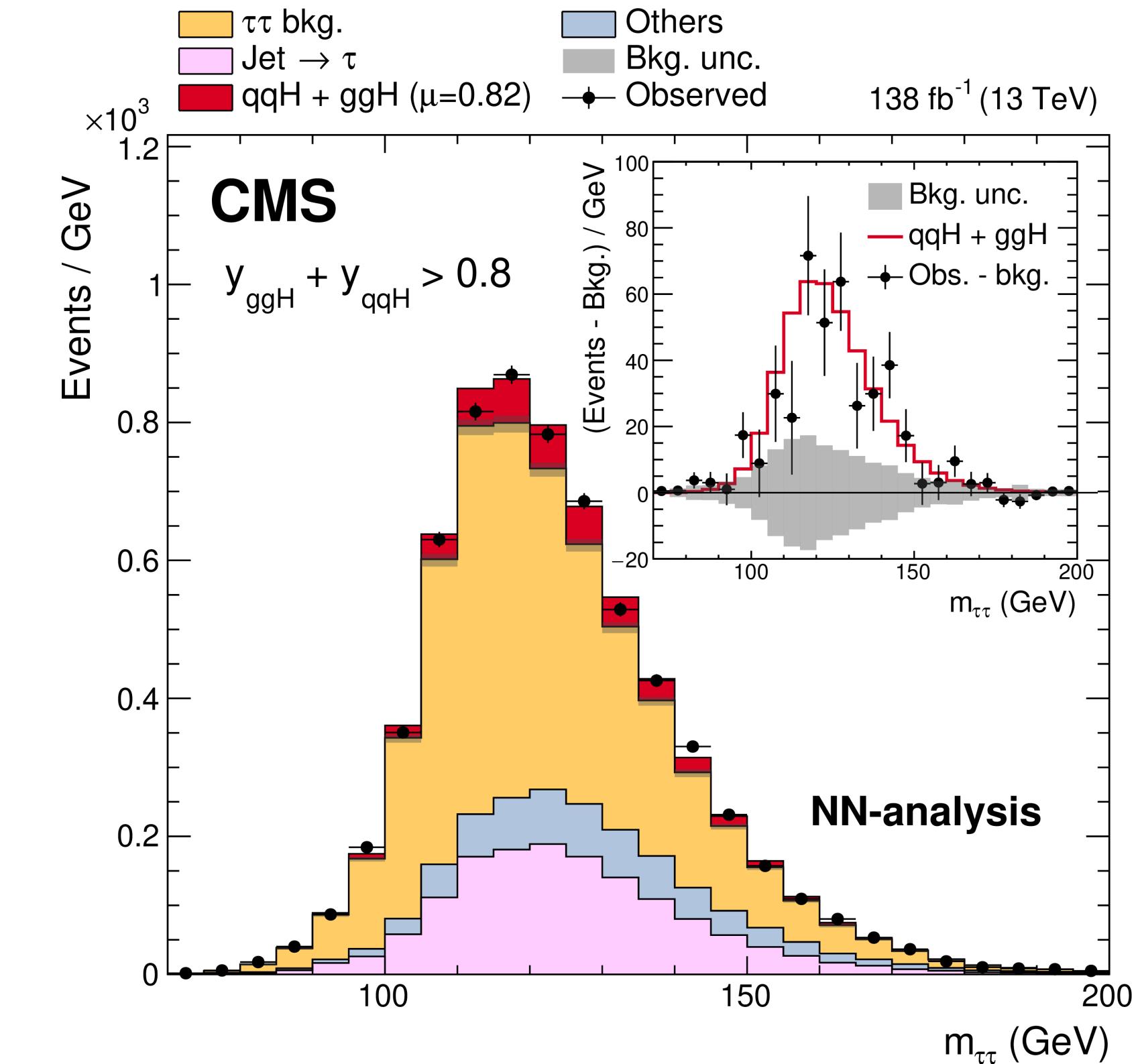
Background is Z production with two jets, in this region of phase space it is difficult to predict!

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



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

[Eur. Phys. J. C 83 \(2023\) 562](https://doi.org/10.1140/epjc/s10050-023-12082-0)

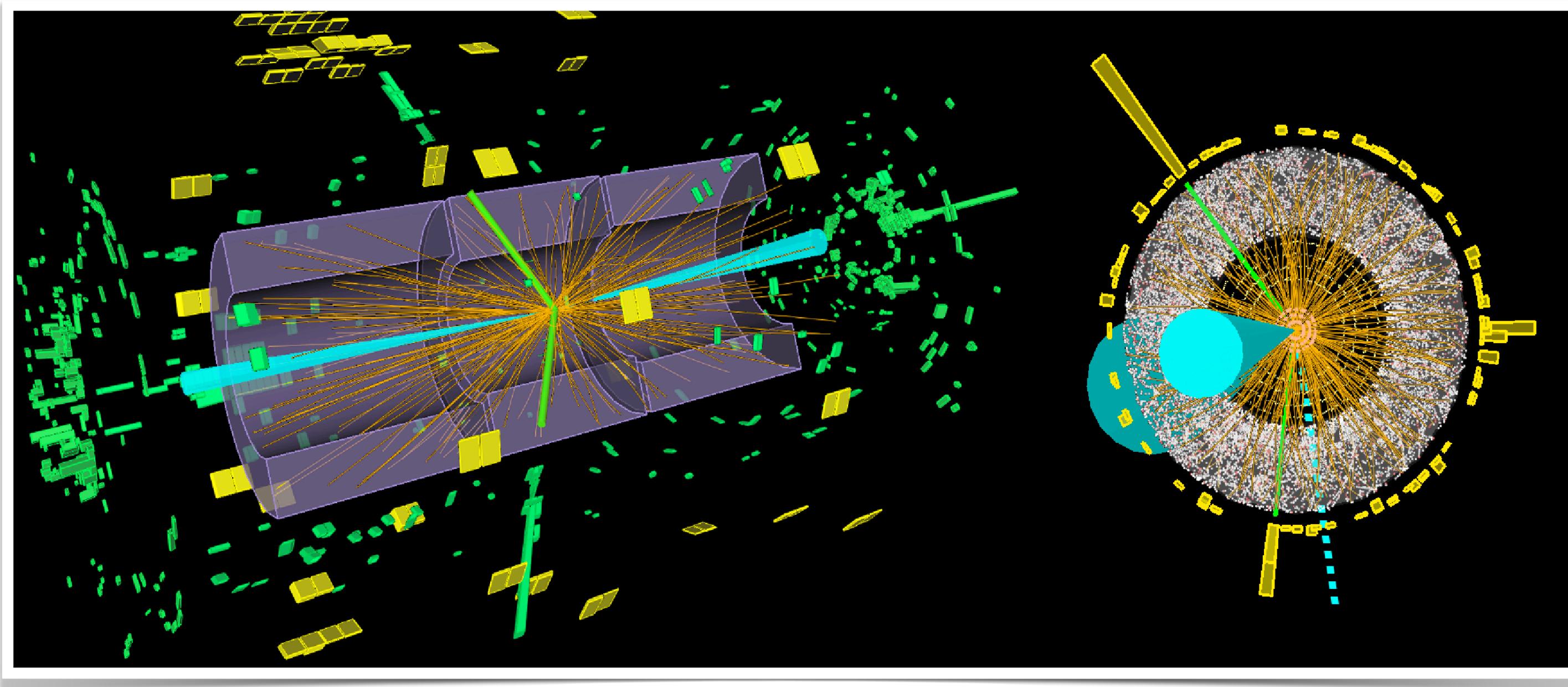


Analysis done in large number of categories covering ggH, VBF, WH and ZH production processes (**STXS bins**)

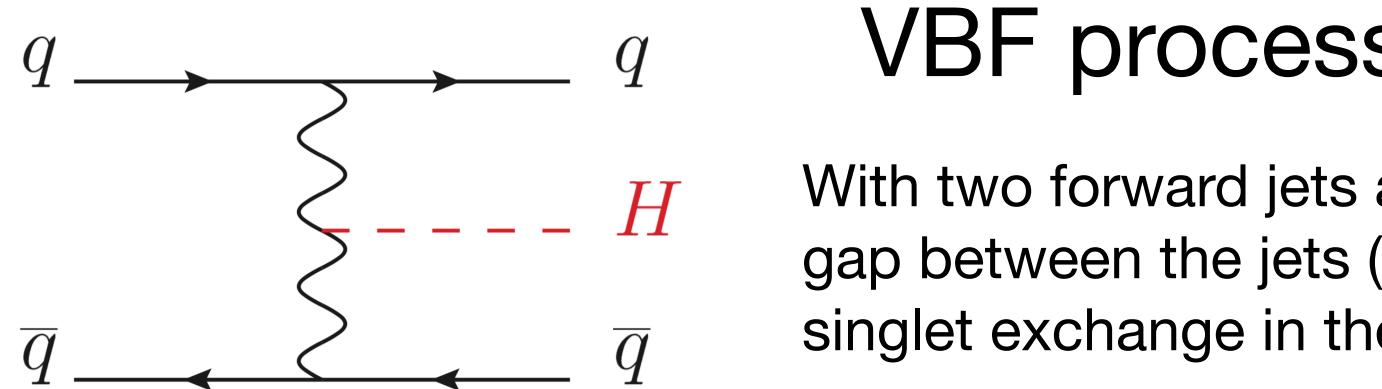
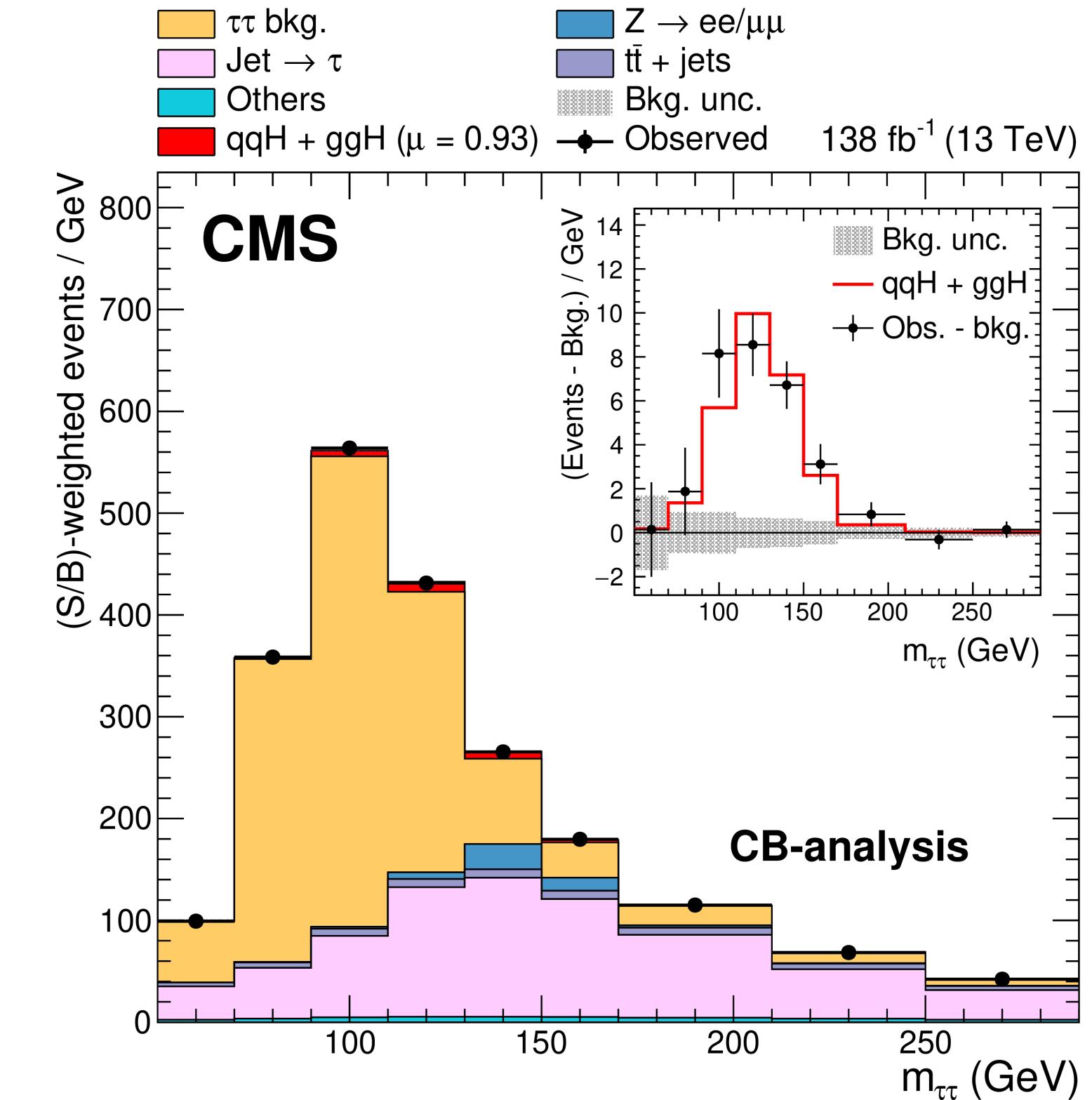
With two analyses NN and CB (Cut Based)

Higgs boson decays to Taus

25



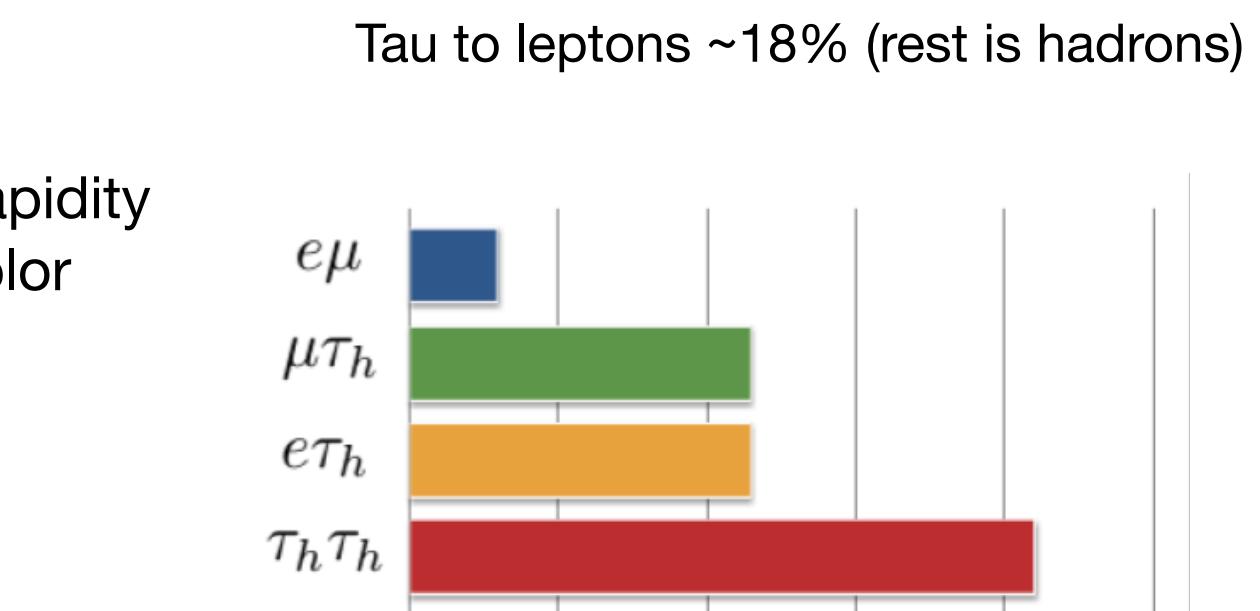
[Eur. Phys. J. C 83 \(2023\) 562](https://doi.org/10.1140/epjc/s10050-023-12080-0)



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.



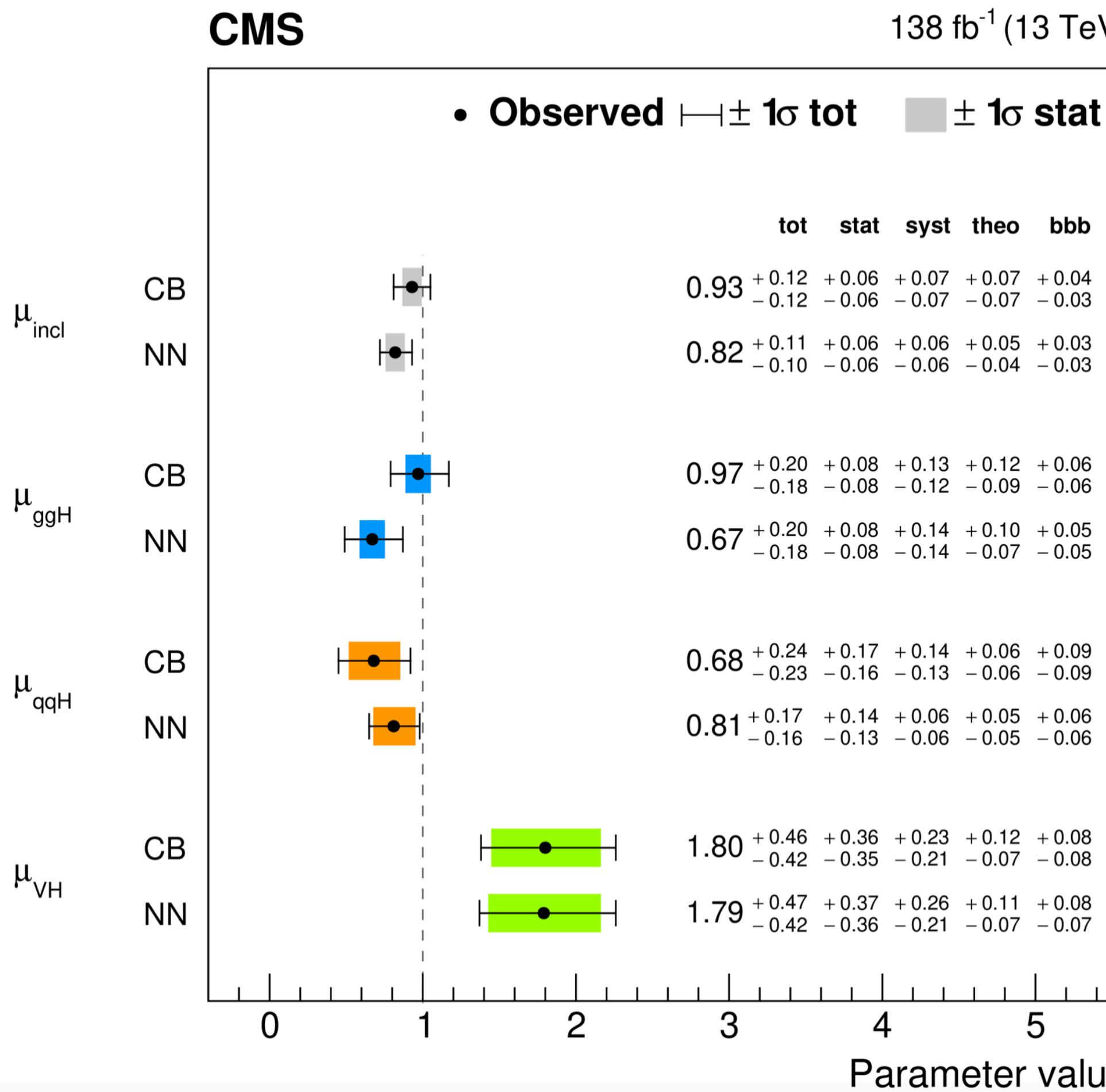
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Analysis done in large number of categories covering ggH, VBF, WH and ZH production processes (**STXS bins**)

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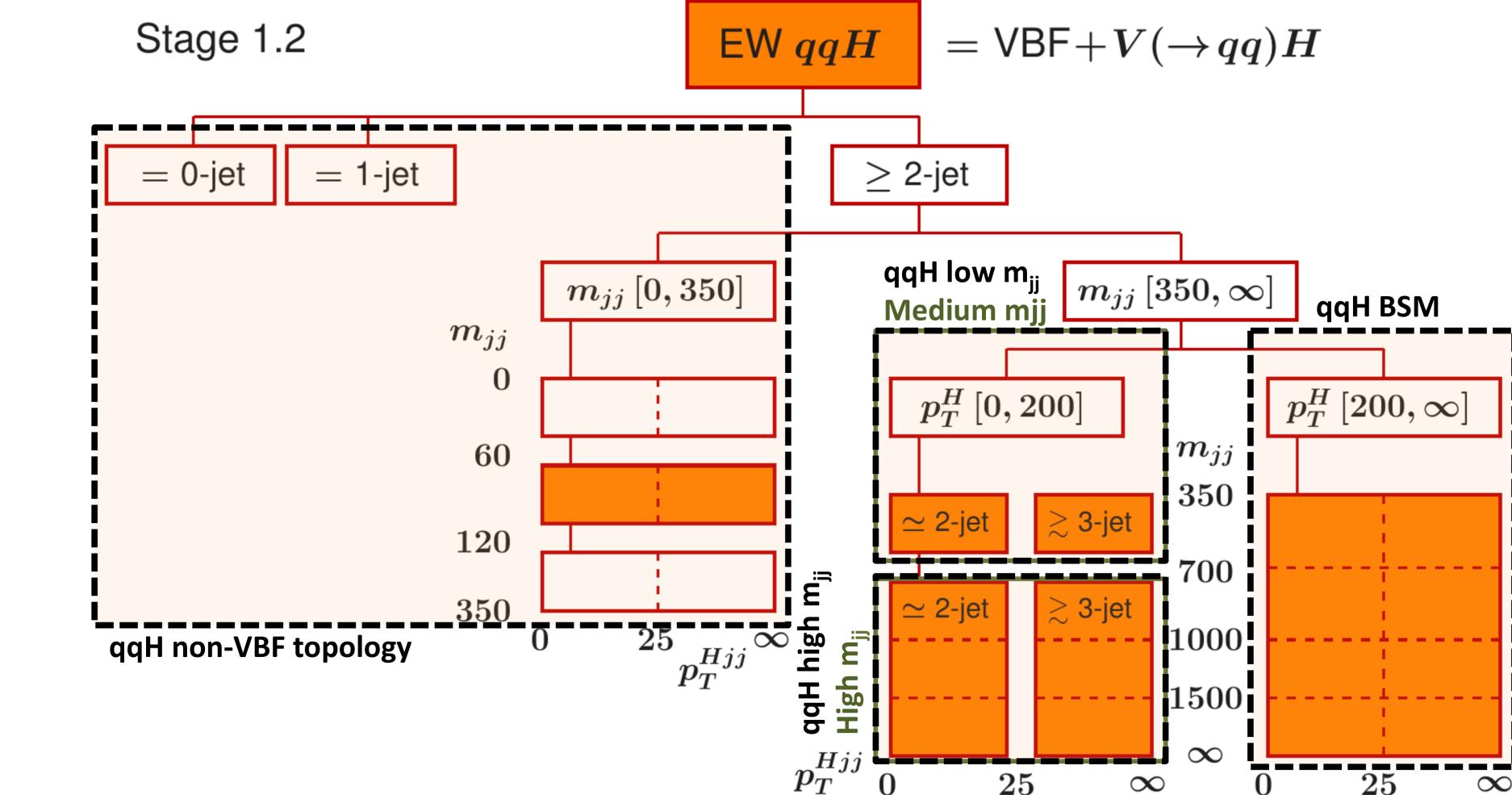
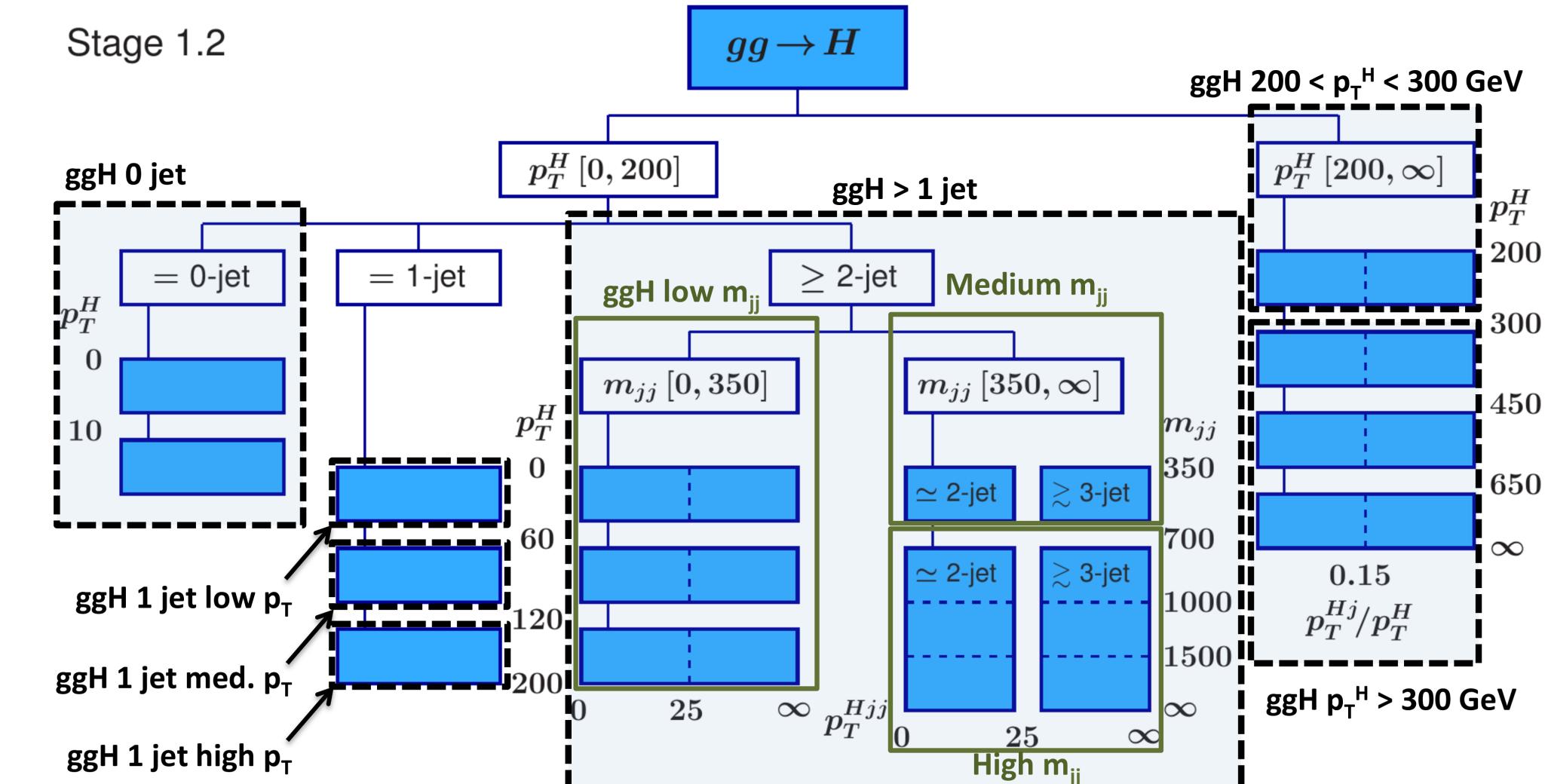
Higgs boson decays to Taus

26



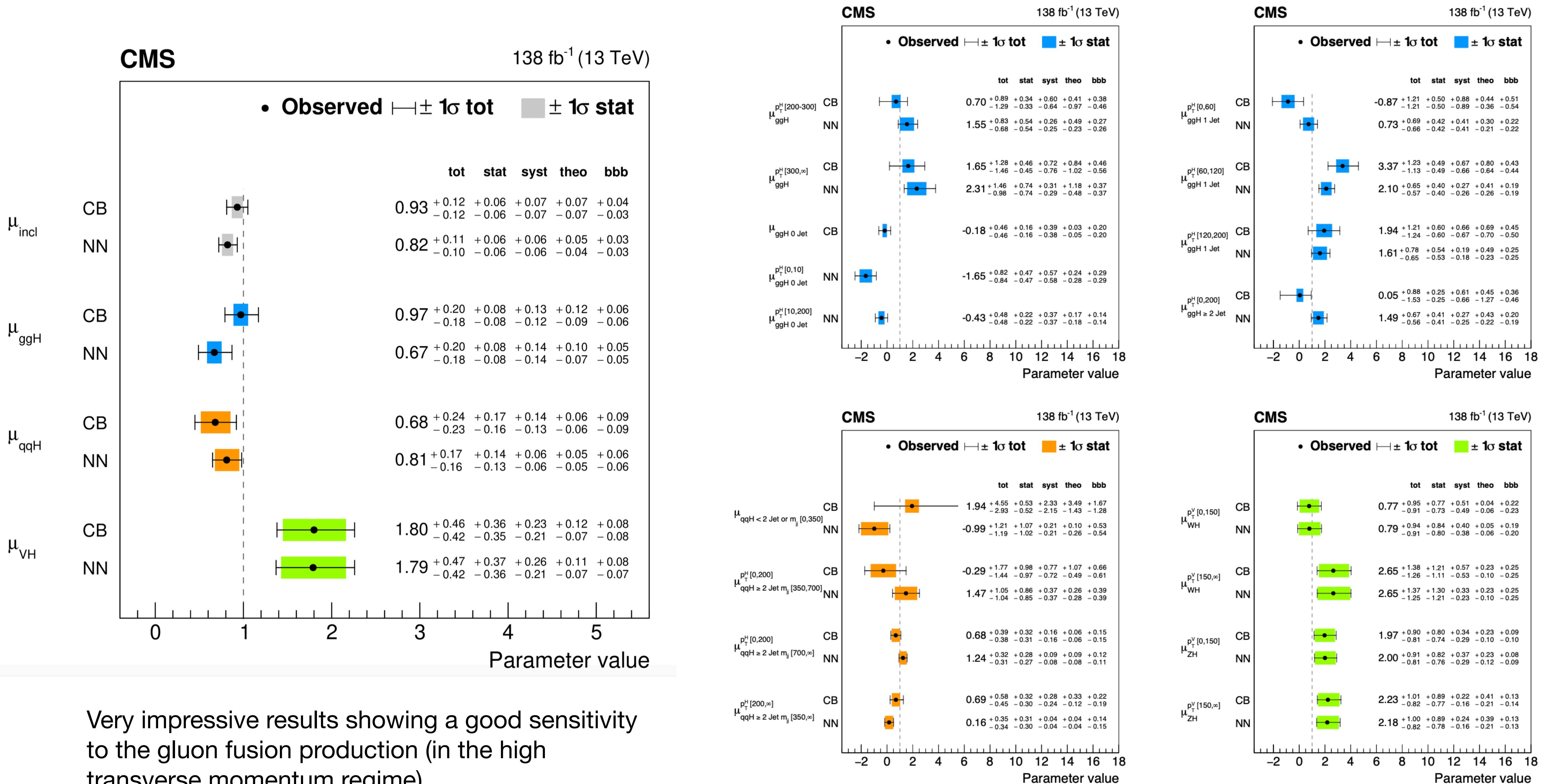
Very impressive results showing a good sensitivity to the gluon fusion production (in the high transverse momentum regime).

Separating in STXS parameters...



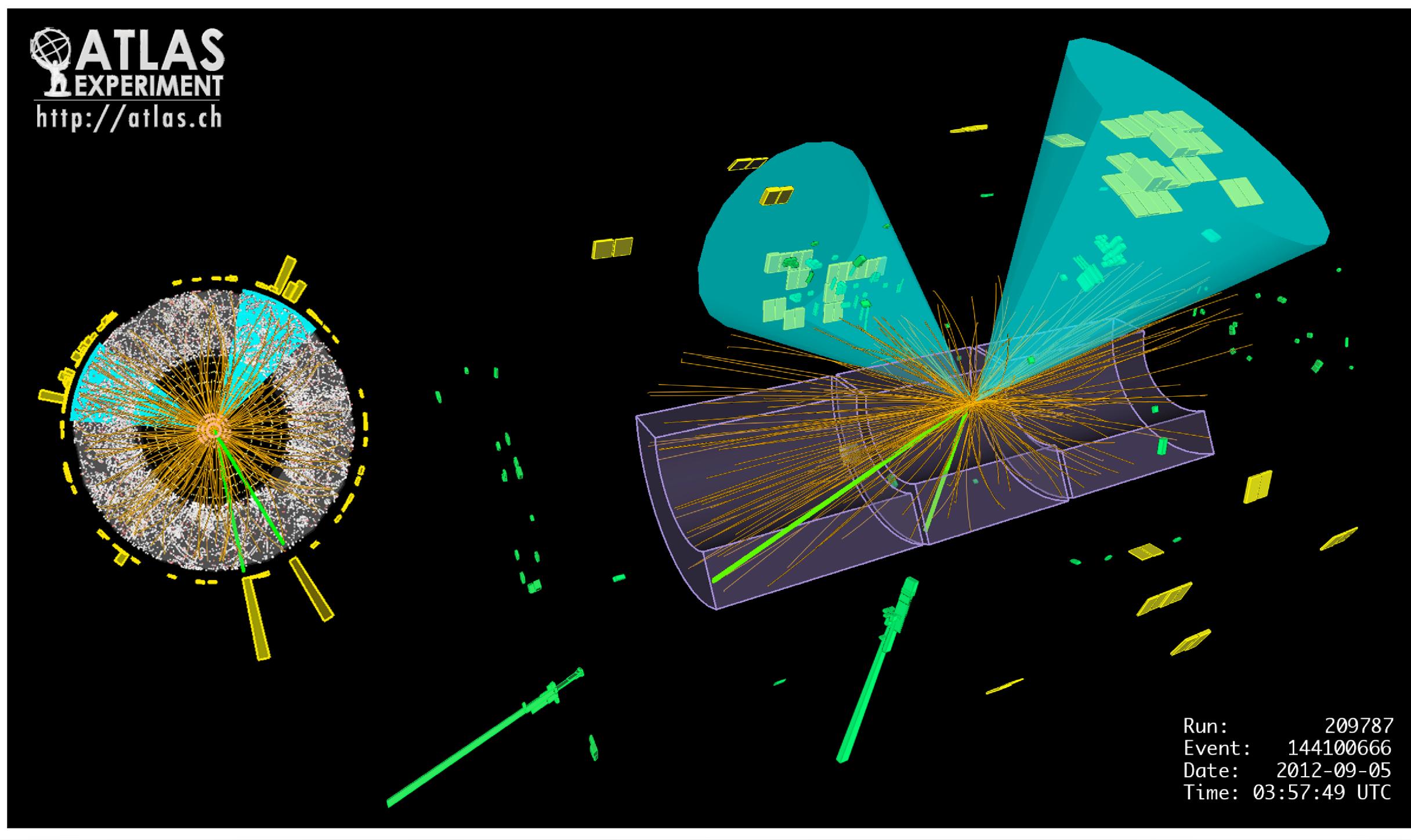
Higgs boson decays to Taus

27



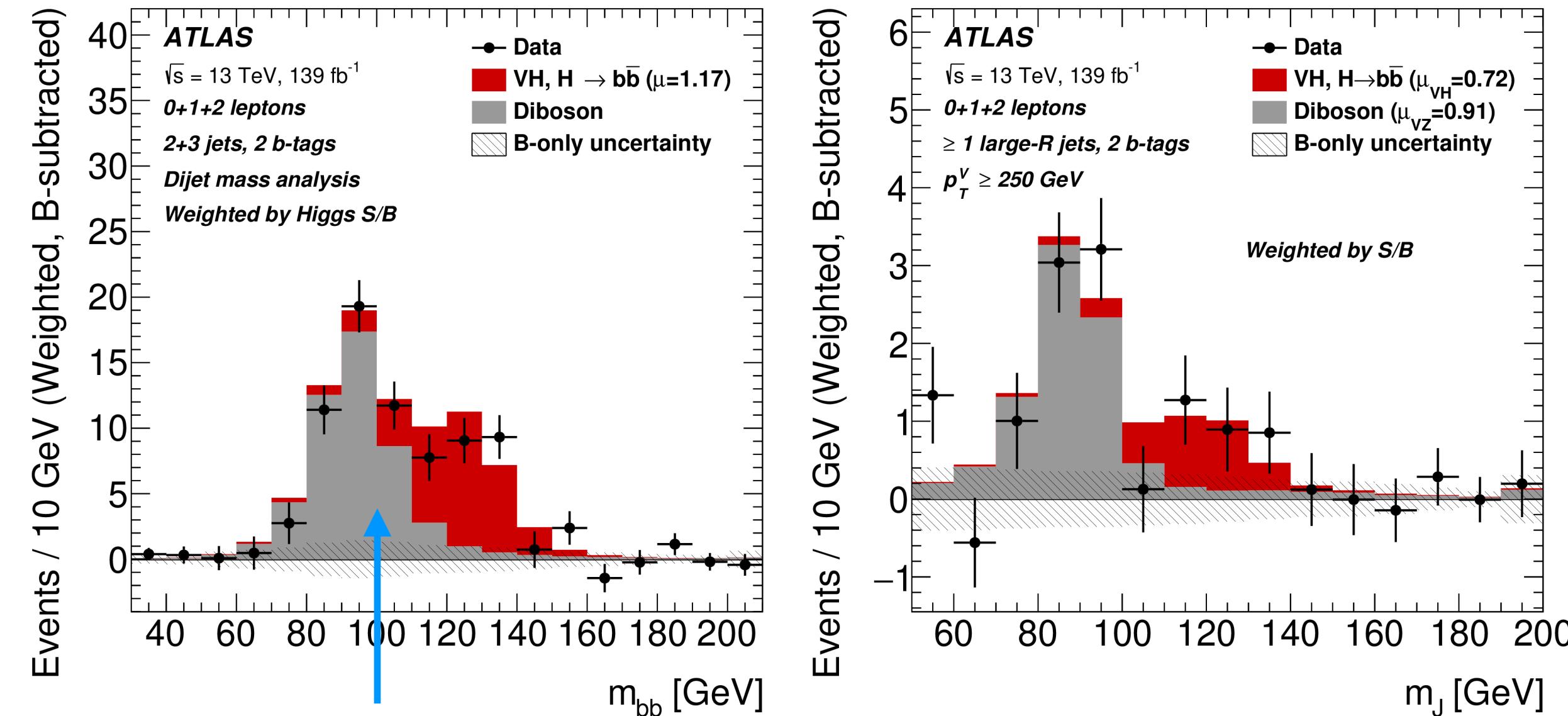
Higgs boson decays to b-quarks

28



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)



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

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.

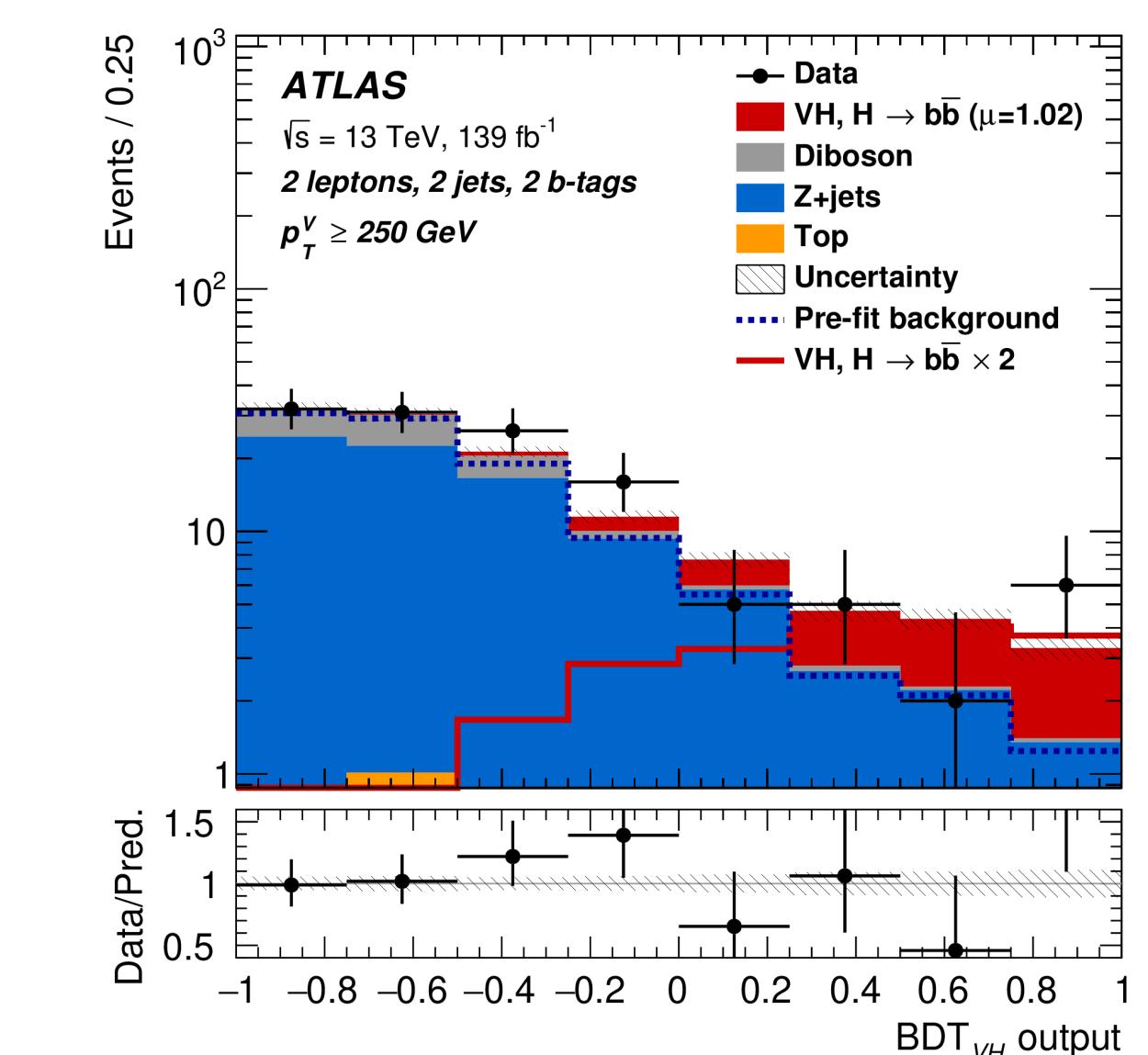
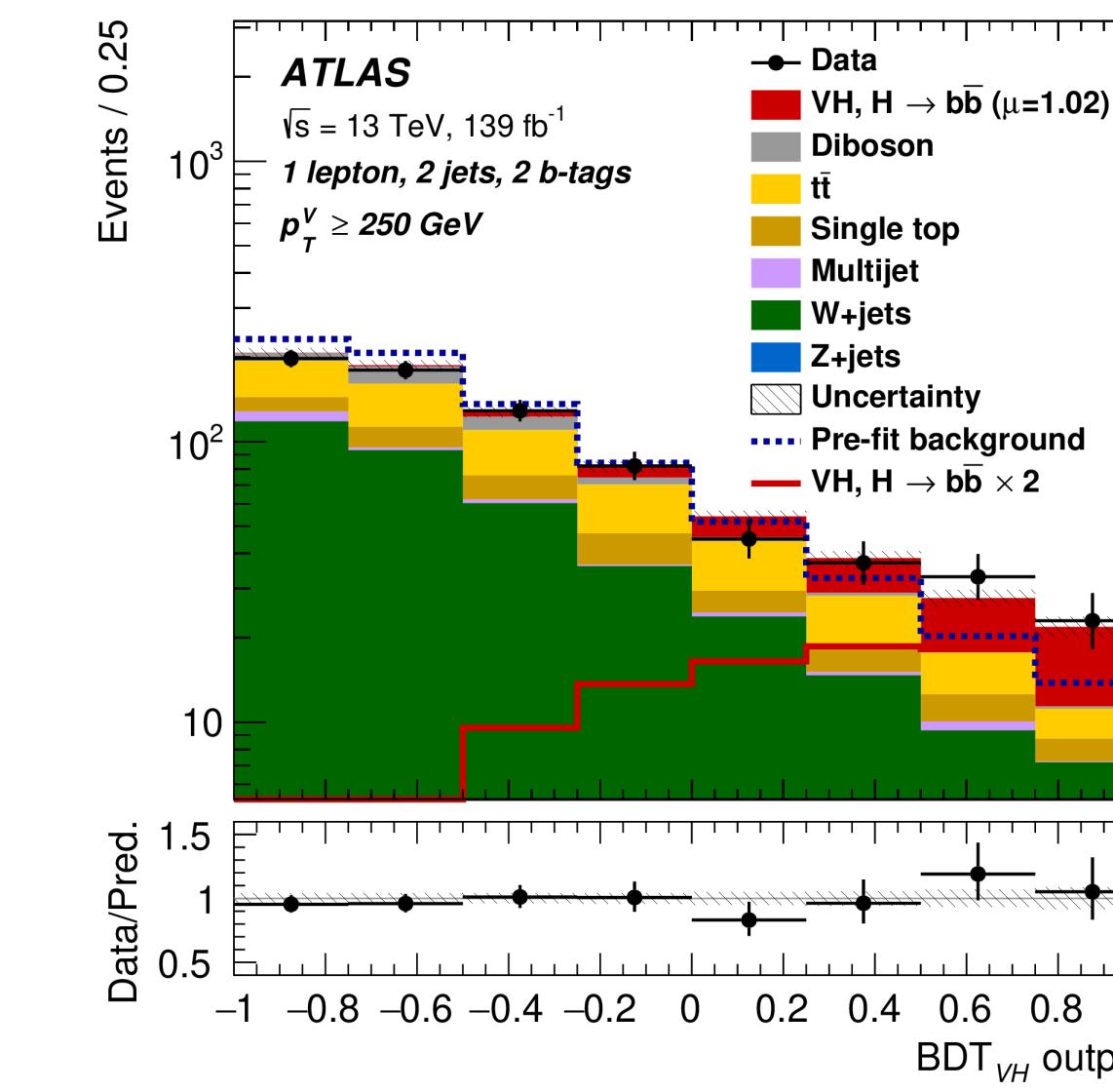
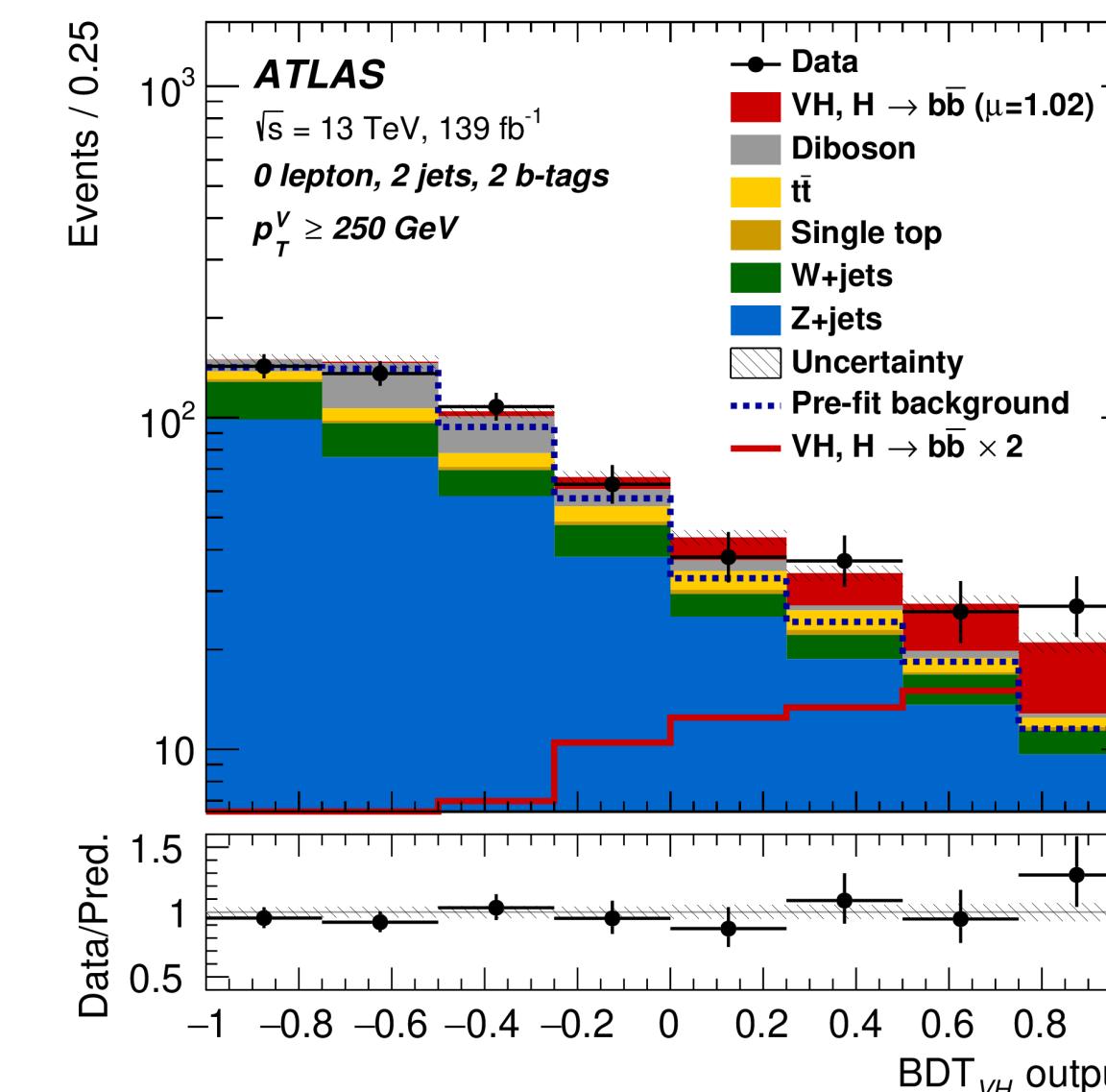
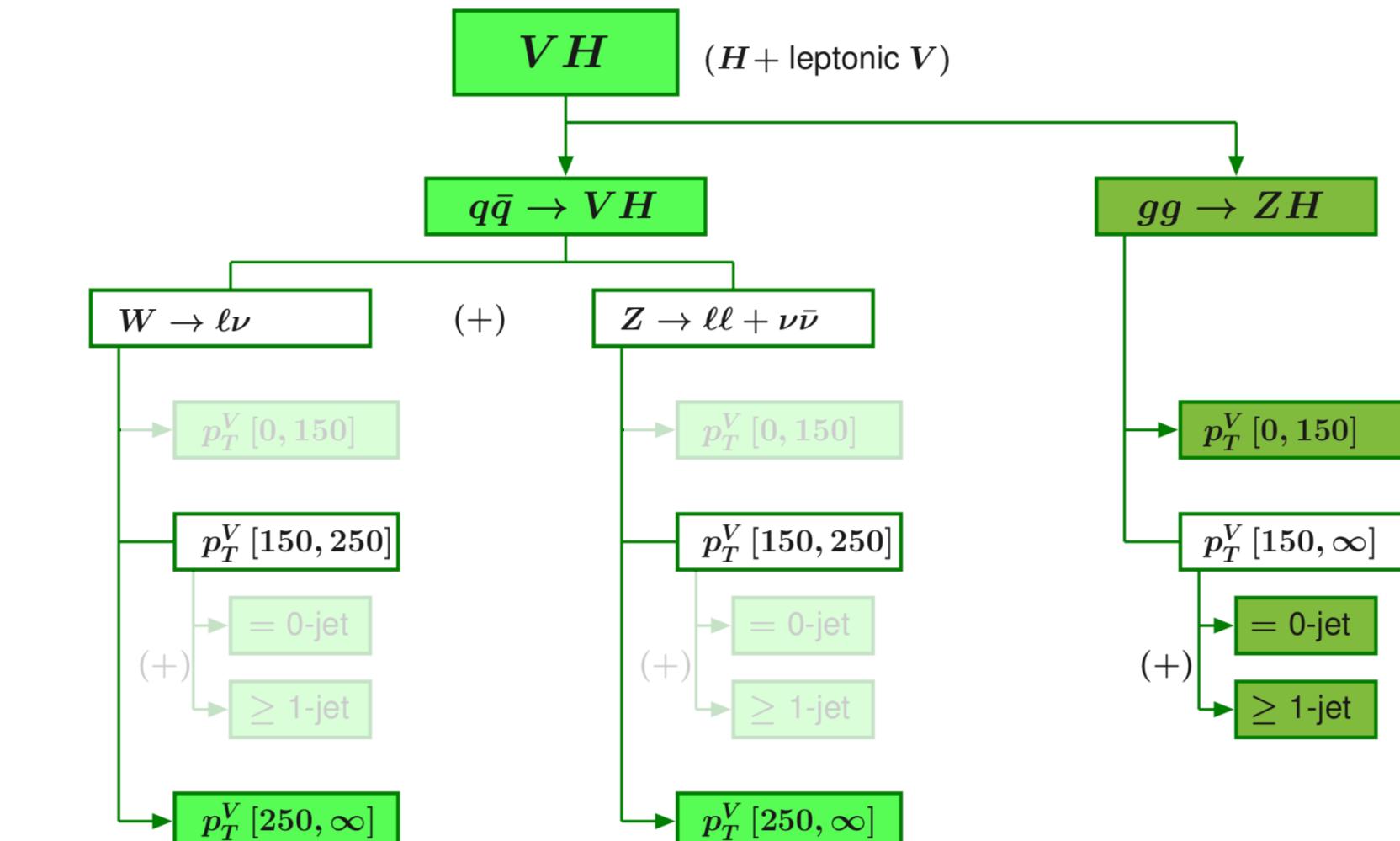
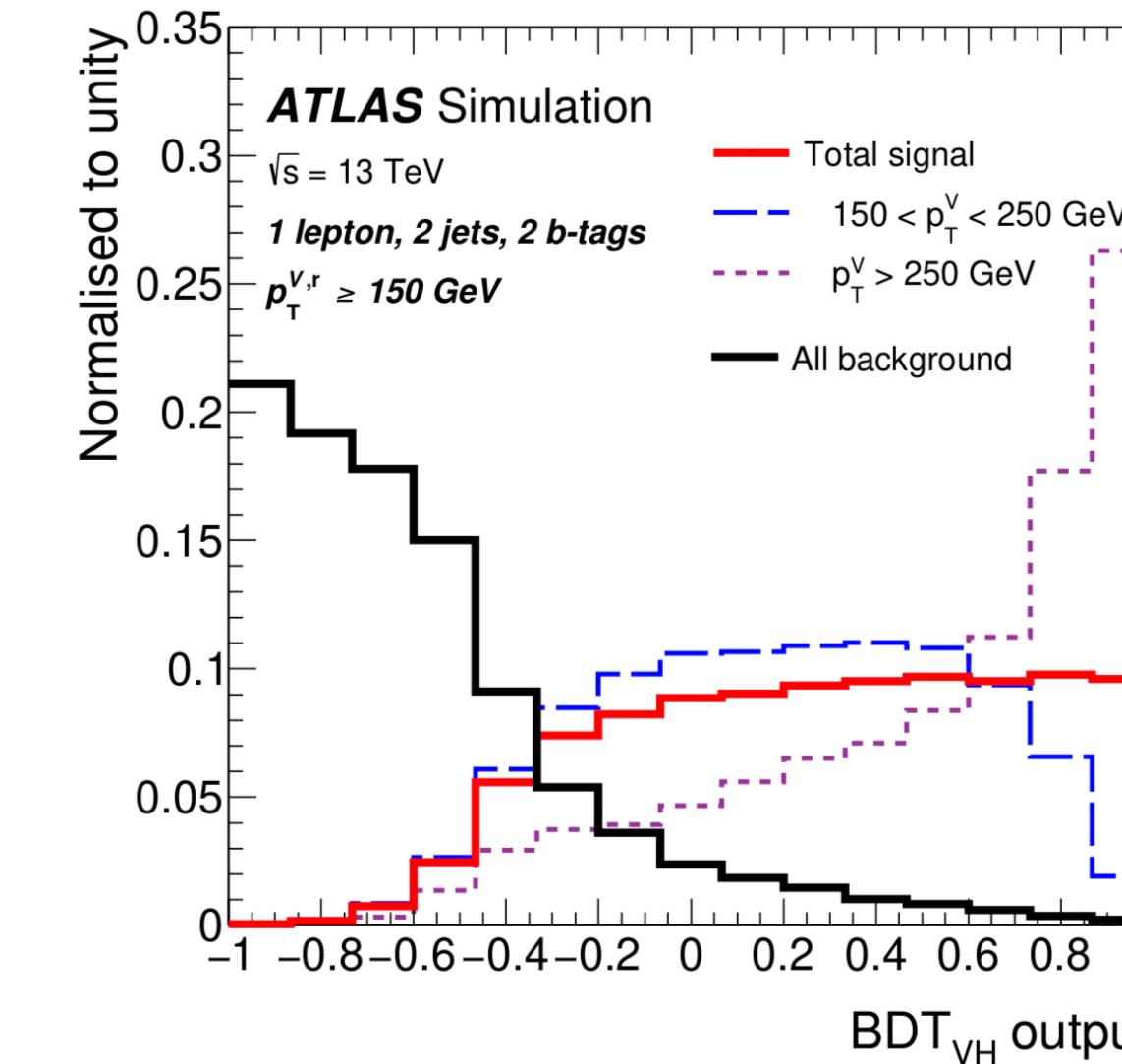
Now both the WH and ZH have been firmly established!

Hybrid Fiducial Approach: Simplified Template Cross Sections

29

VH(bb) is a prime channel to constrain VH at high transverse momentum!

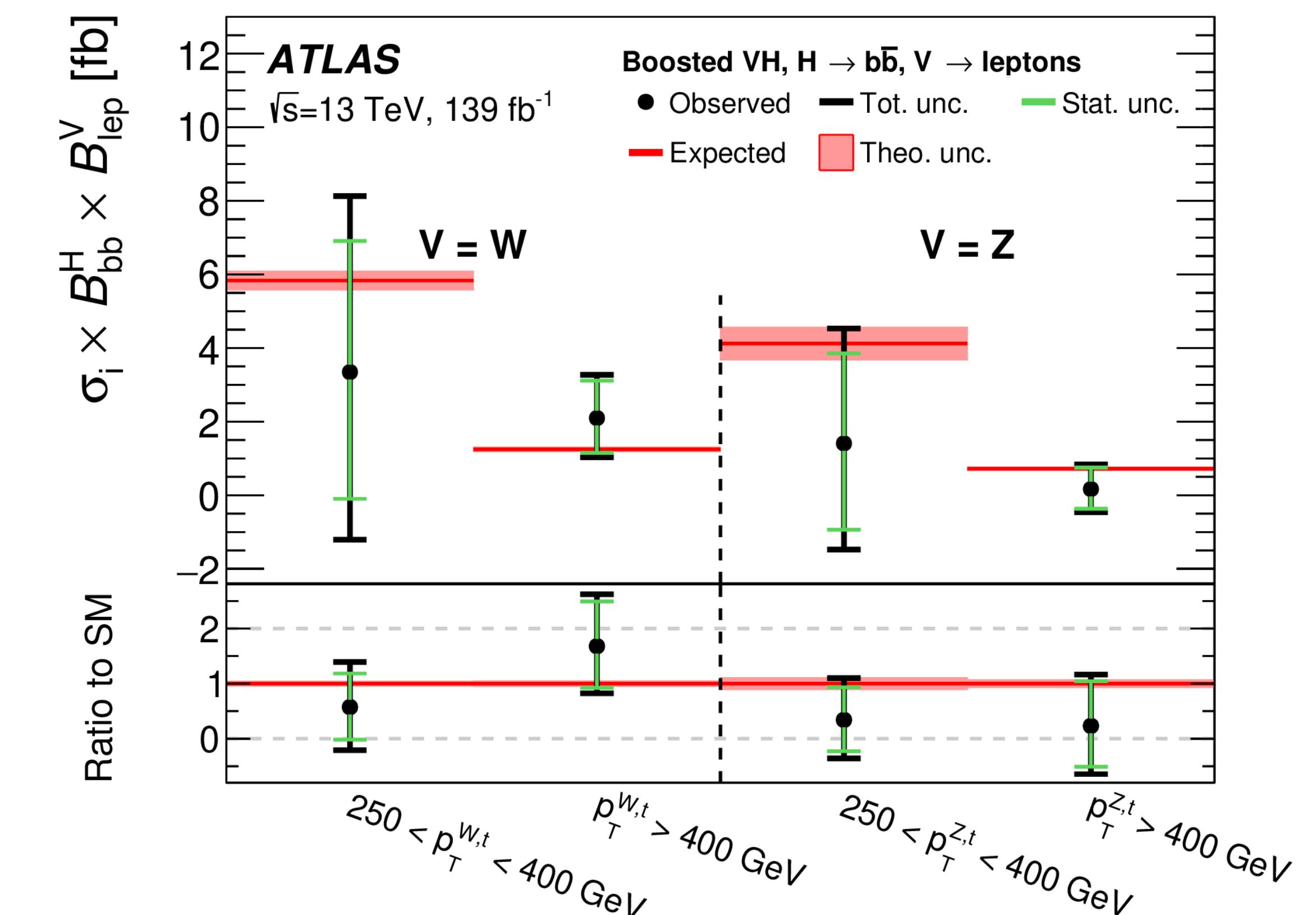
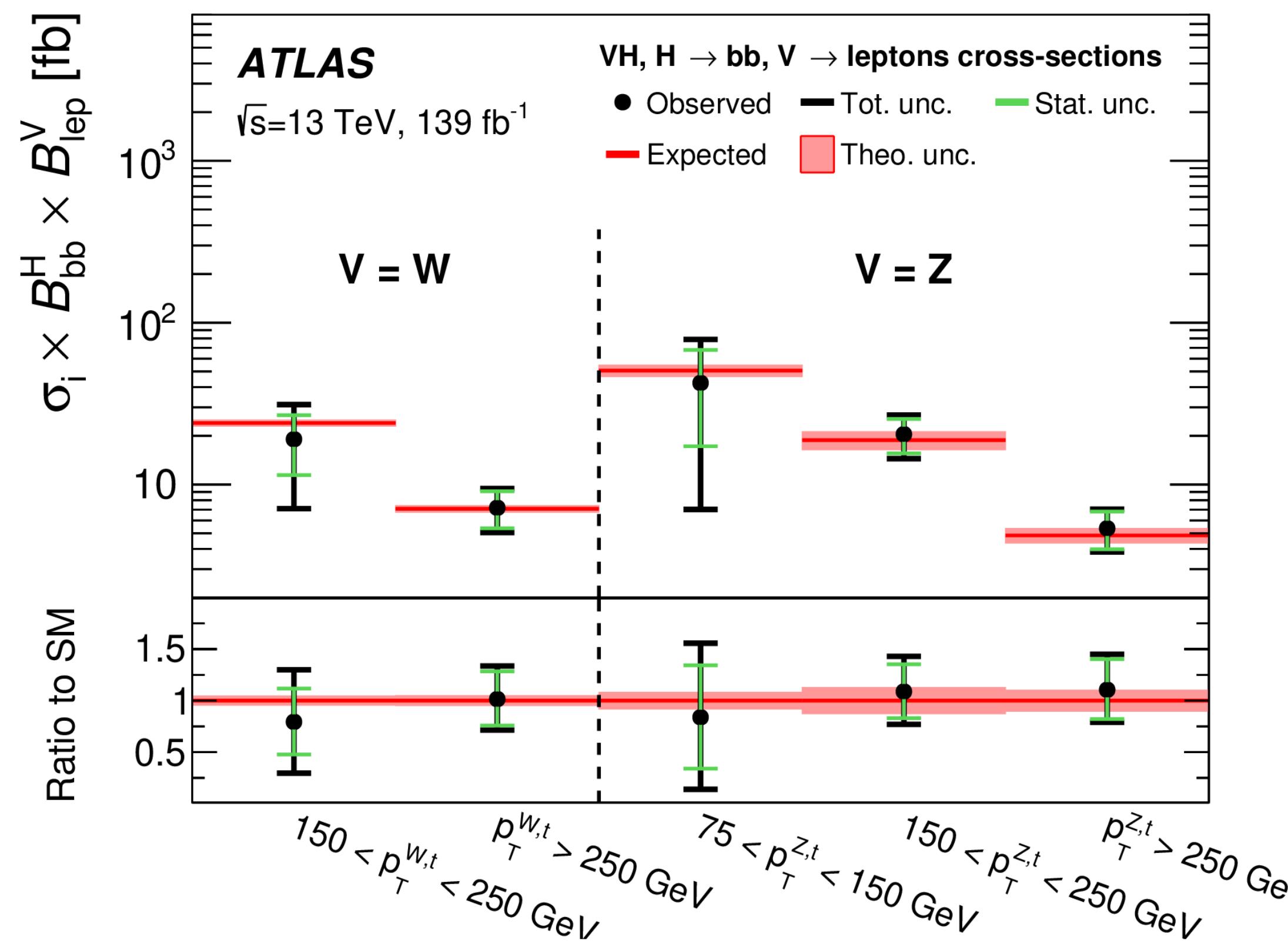
Transverse momentum is a key discriminating variable between signal and background!



VH(bb) Simplified Template Cross Sections

30

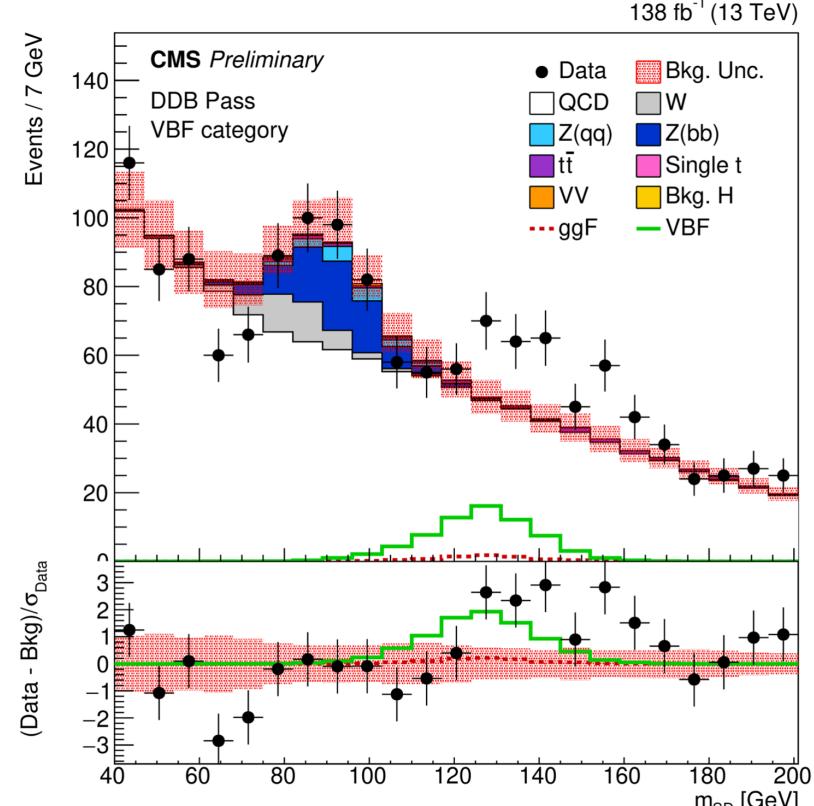
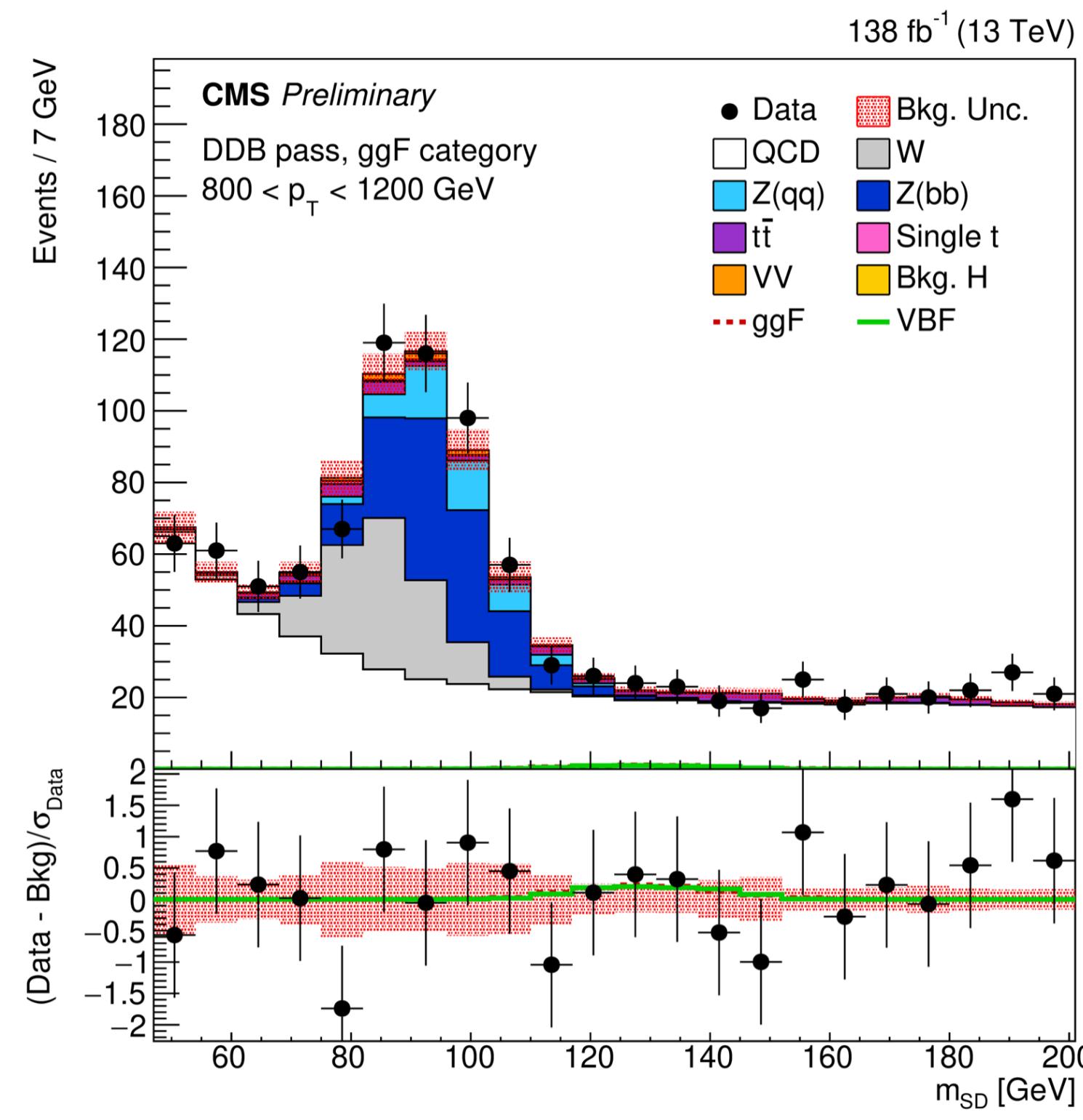
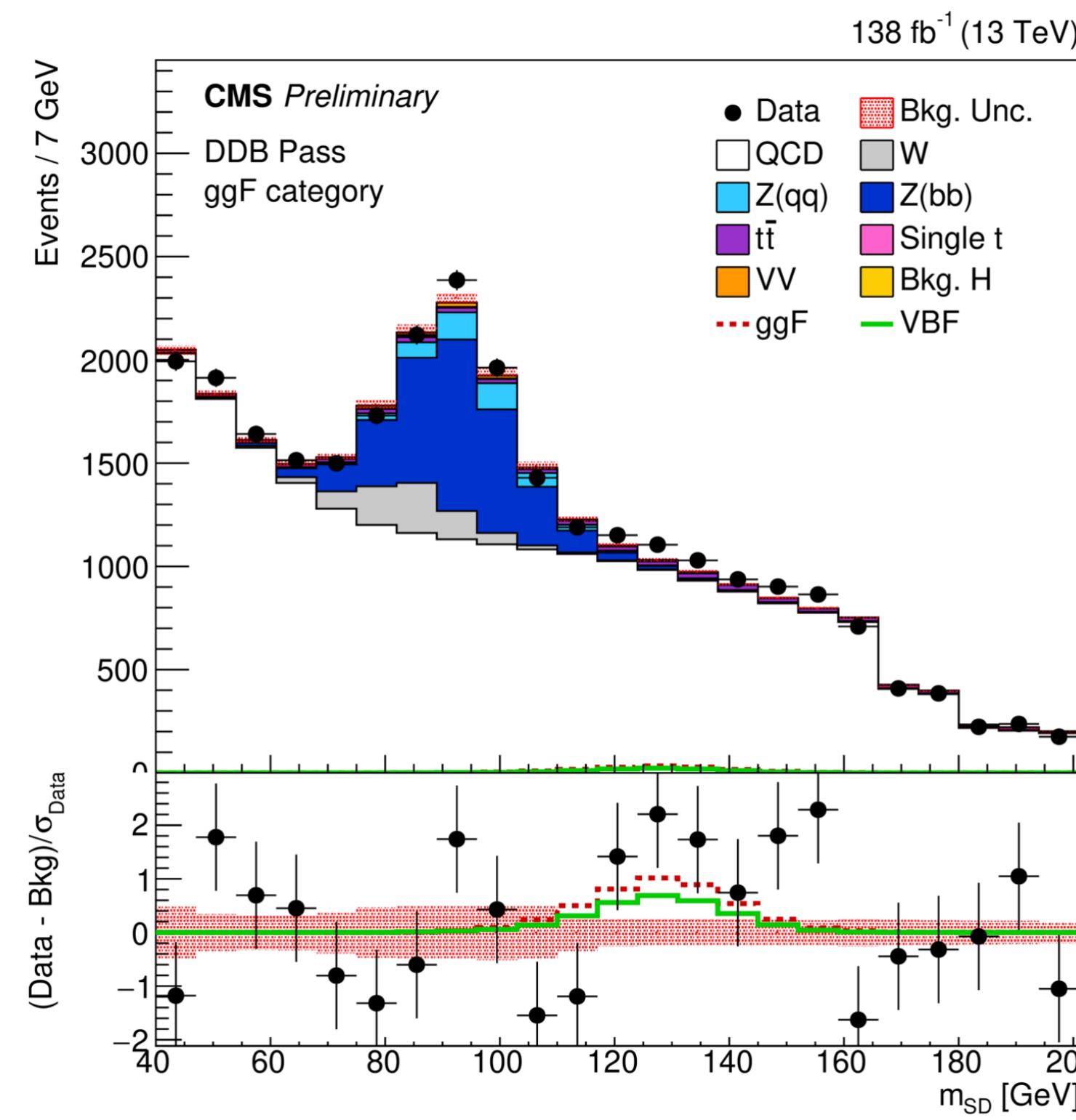
VH(bb) is a prime channel to constrain VH at high transverse momentum!



Measurement also done with the boosted jet reconstruction techniques (covering high transverse momenta of the vector boson).

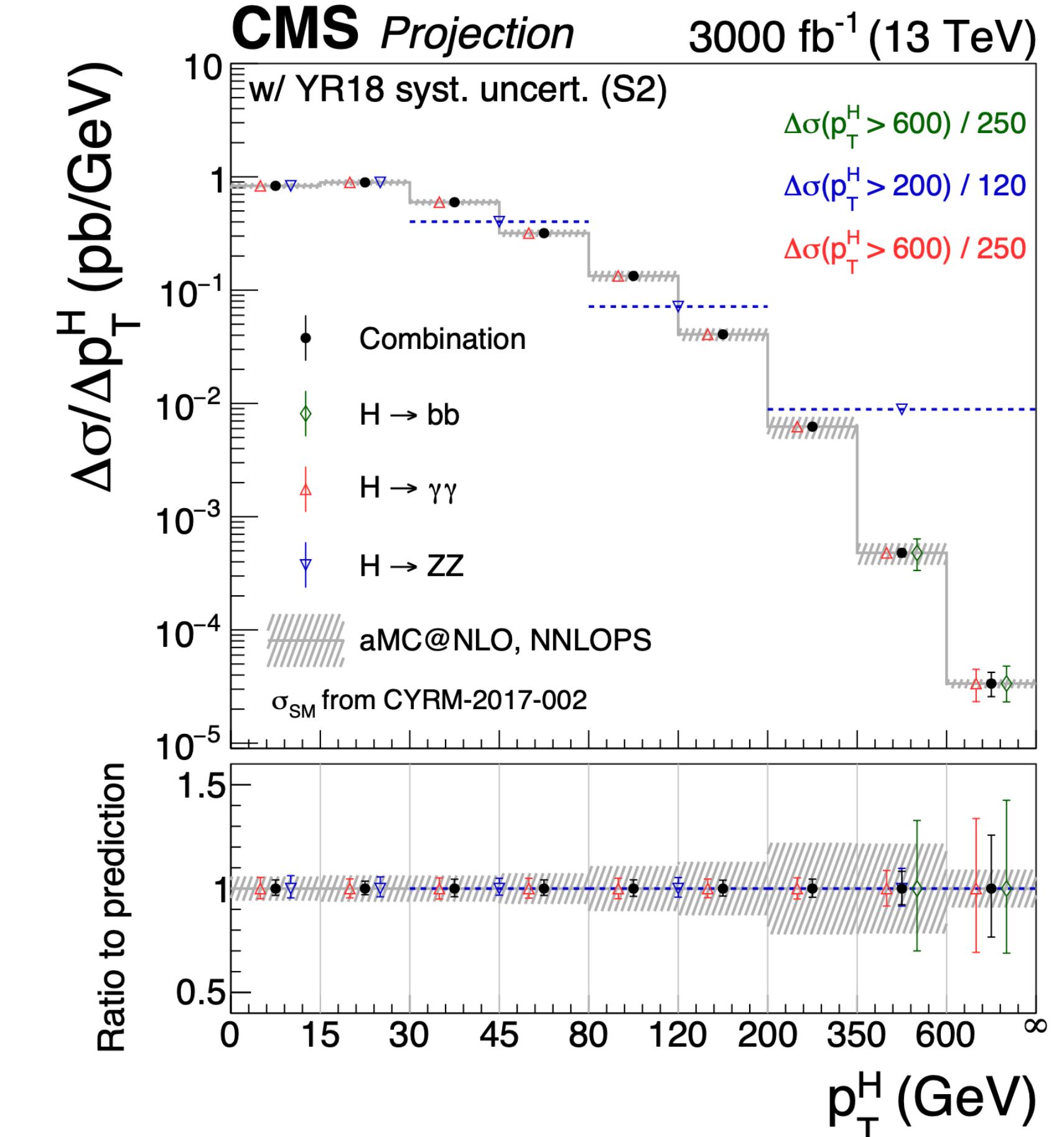
Boosting the Higgs Boson!

31



Was thought to be completely impossible!

VBF significance is 3.0σ (0.9σ)
ggF significance of 1.2σ (0.9σ)



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

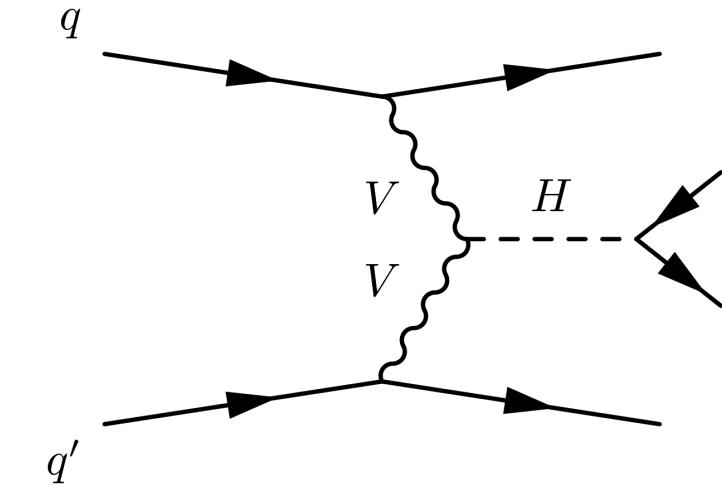
Extremely interesting for indirect NP constraints!

Higgs boson decays to b-quarks in VBF Production

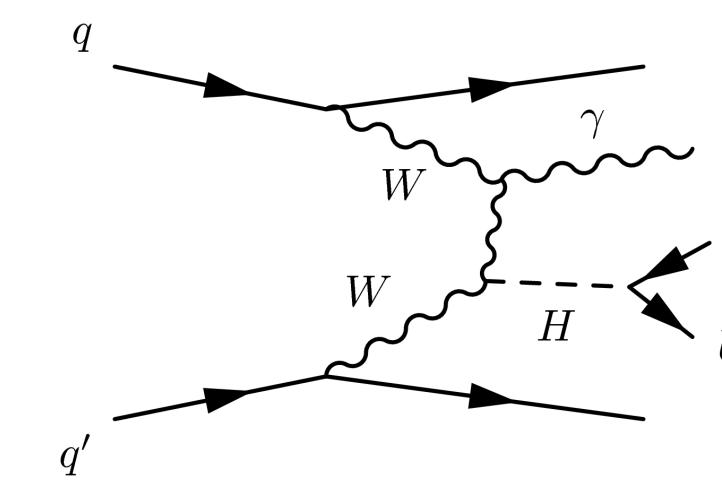
32

[EPJC 81 \(2021\)](#)

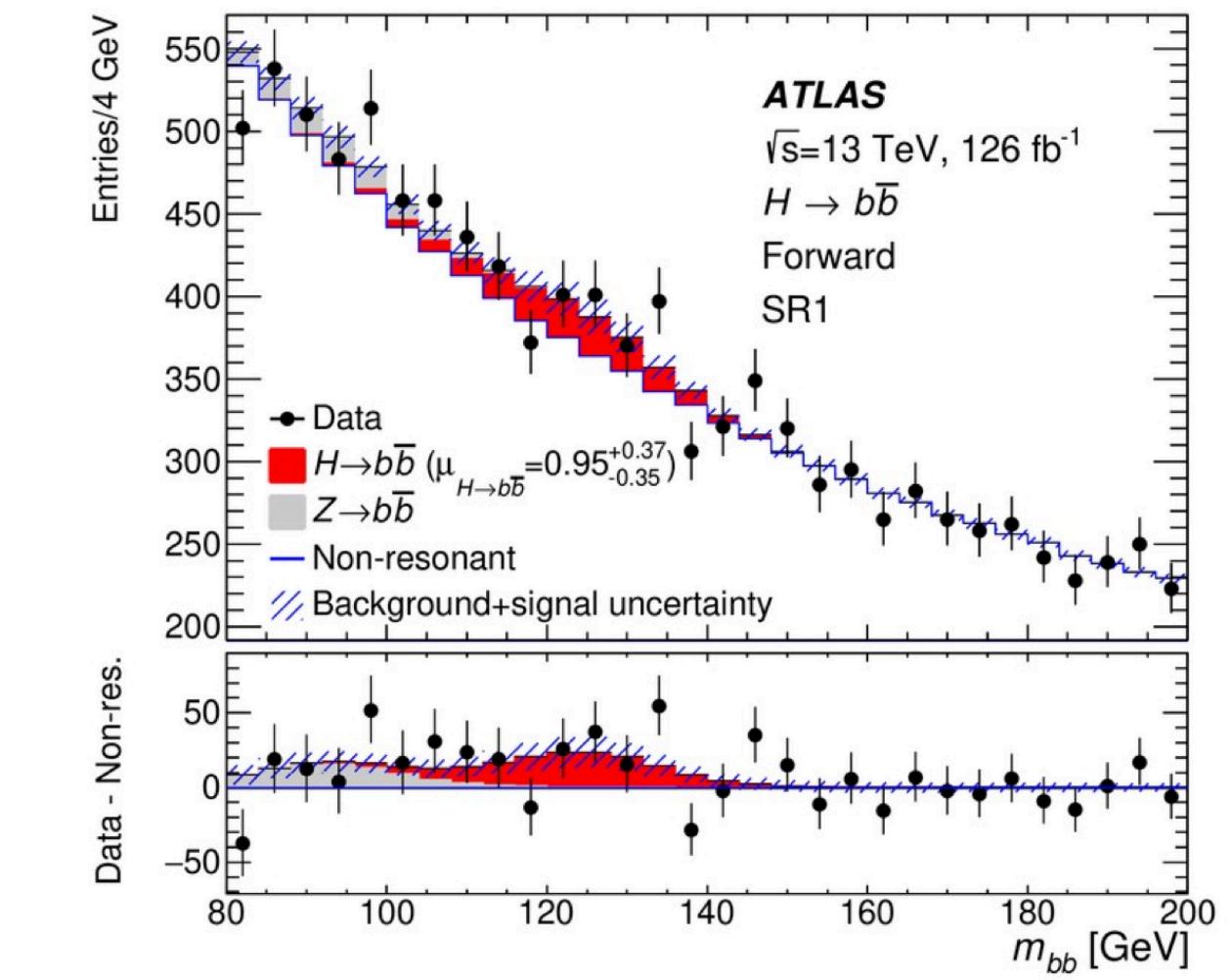
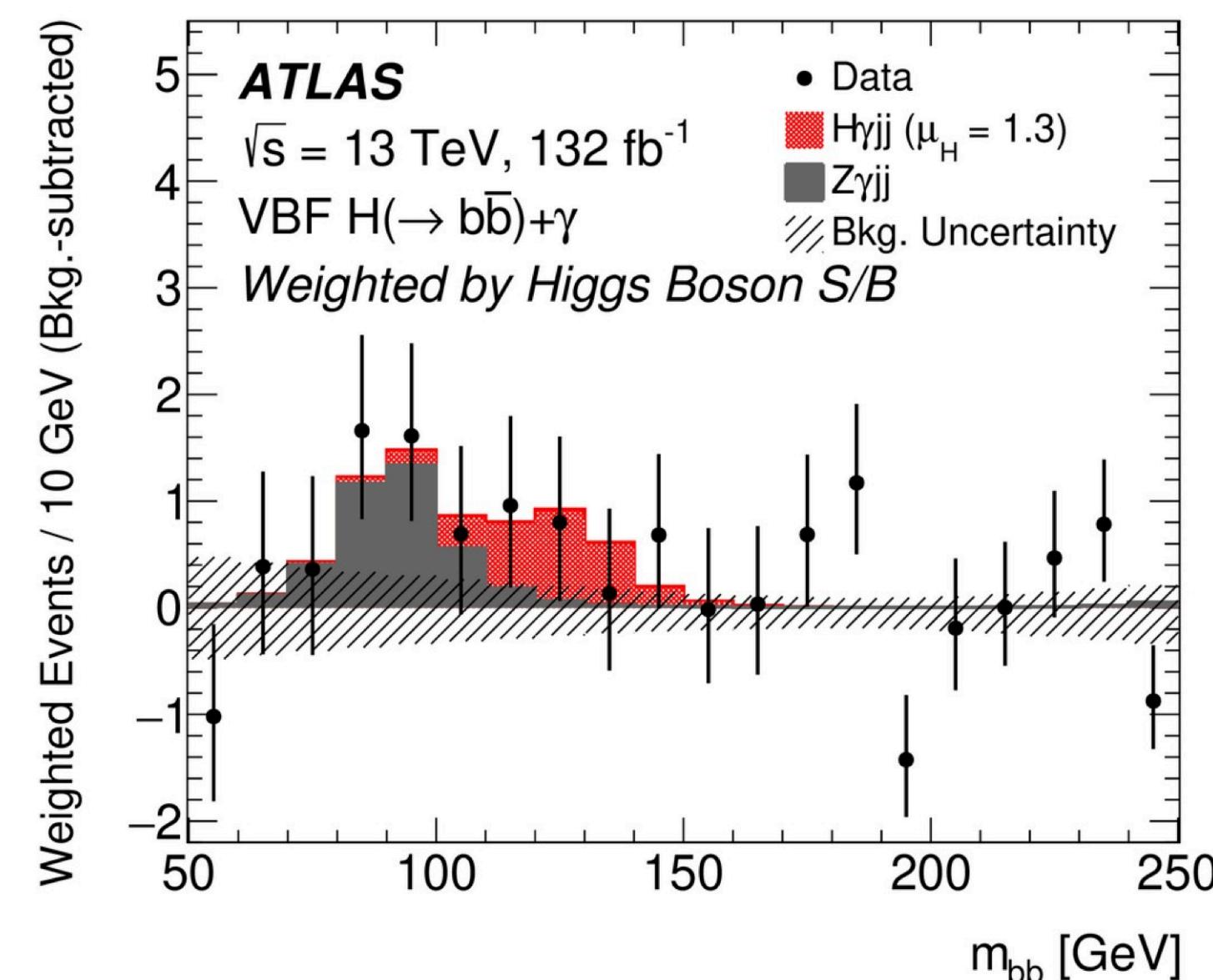
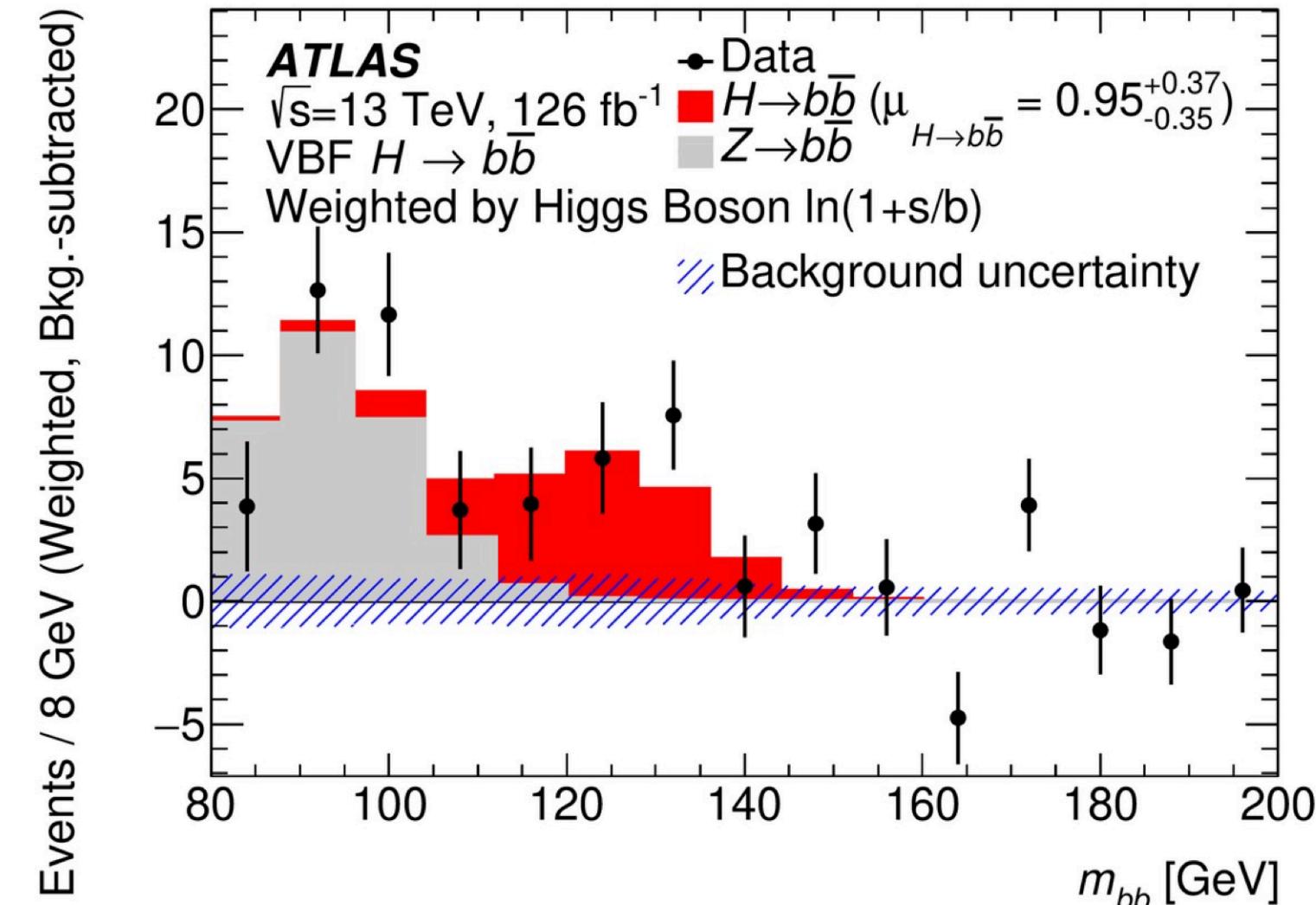
VBF analysis with Higgs in bb including channel with photon



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!

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

2.7 σ (2.9 σ expected)

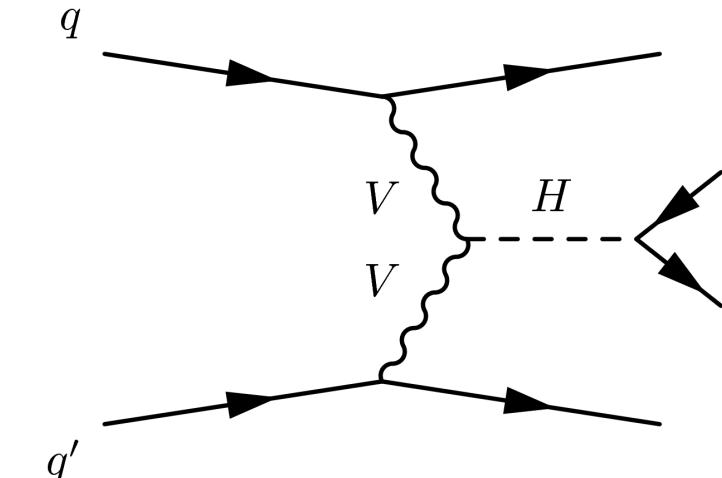
VBF-photon Fit of signal (and peaking background) on smoothly fallen background
 $1.3 \pm 1.0 (\text{stat.}) \pm 0.3 (\text{syst.})$
1.3 σ (1.0 σ expected)

Higgs boson decays to b-quarks in VBF Production

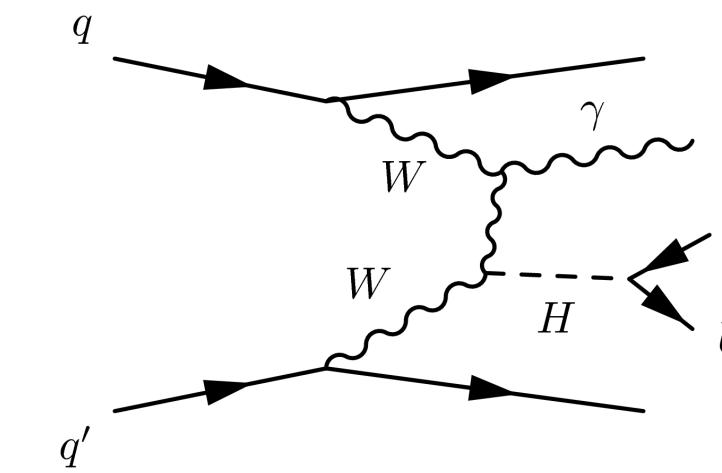
33

[EPJC 81 \(2021\)](#)

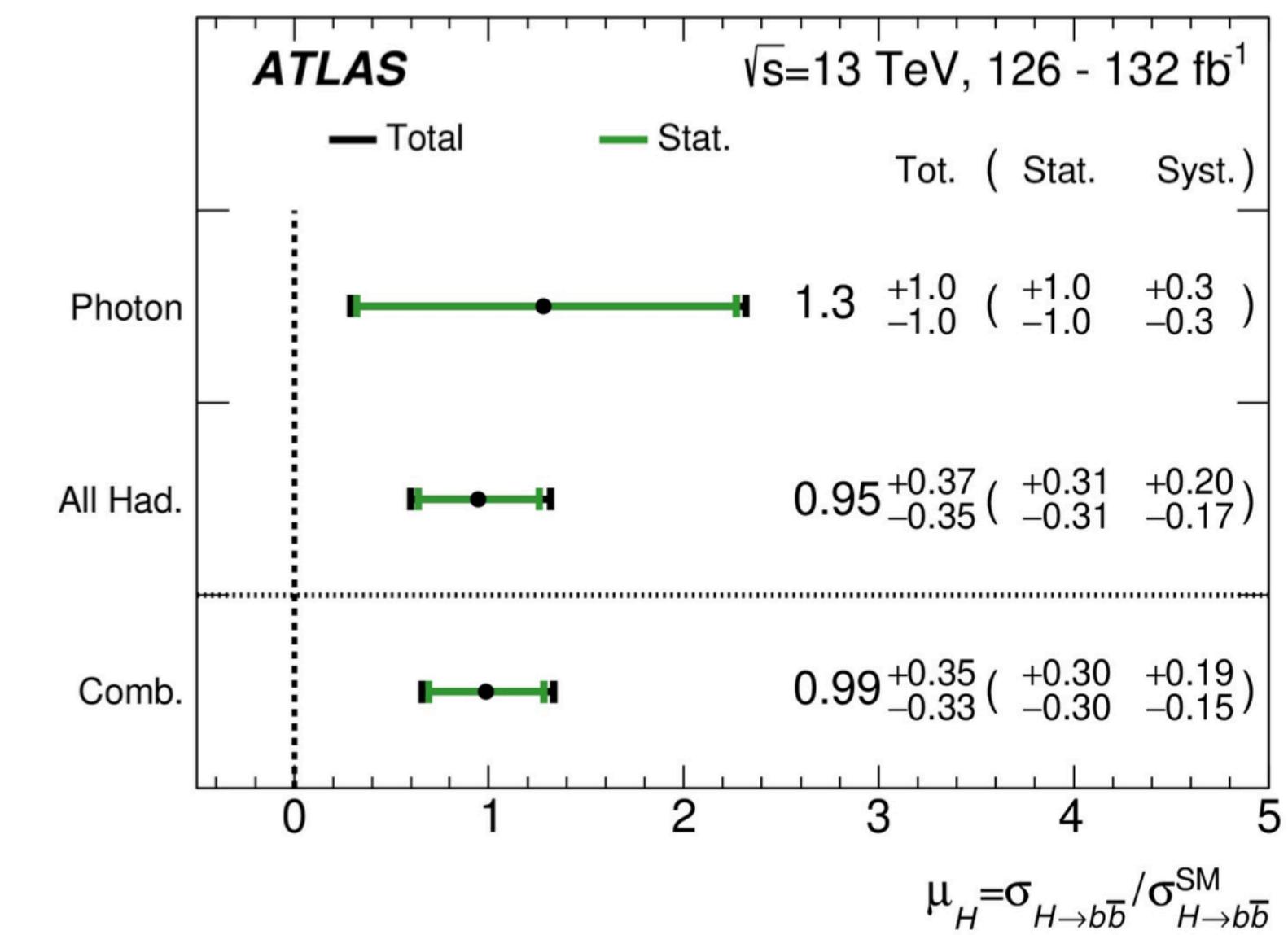
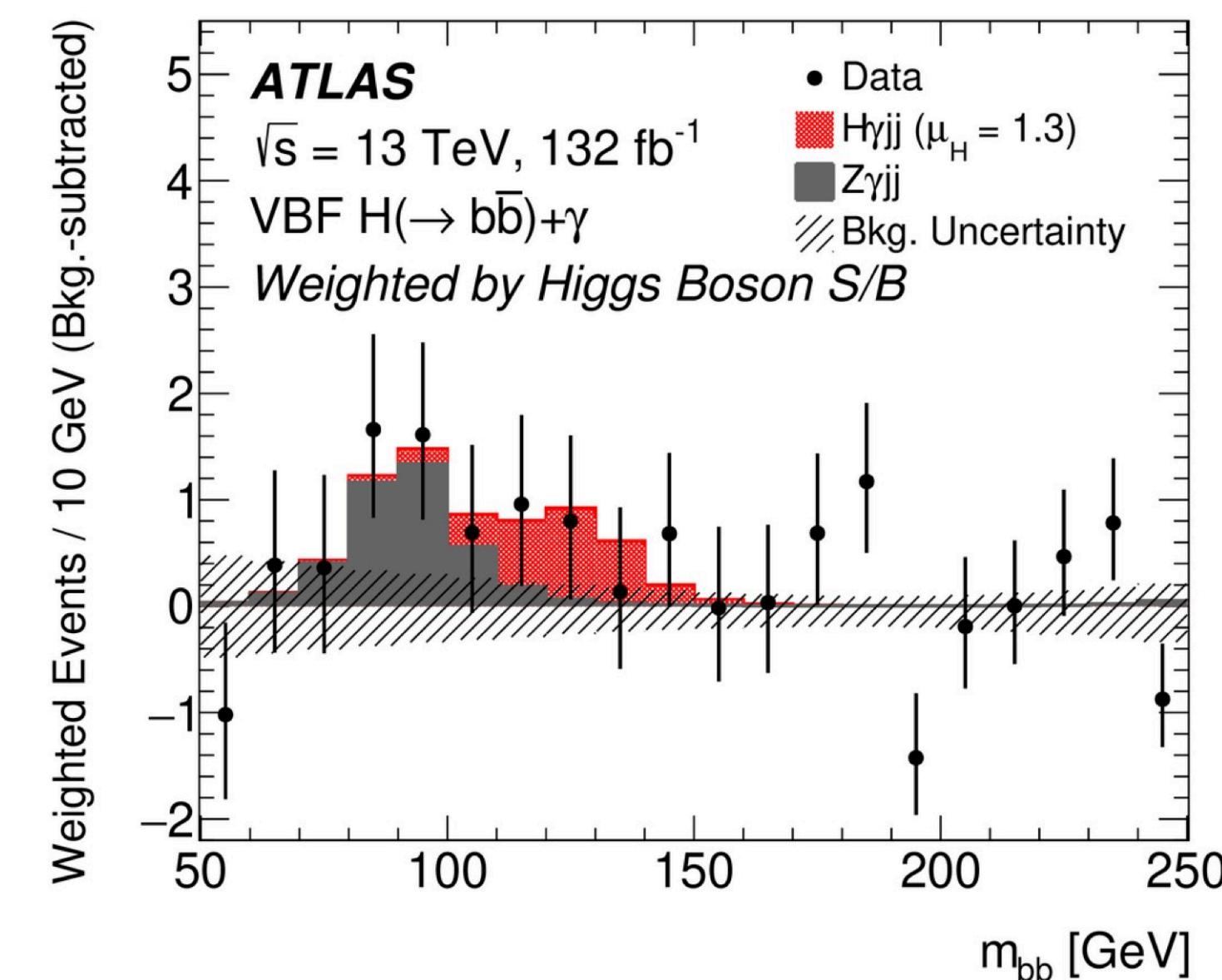
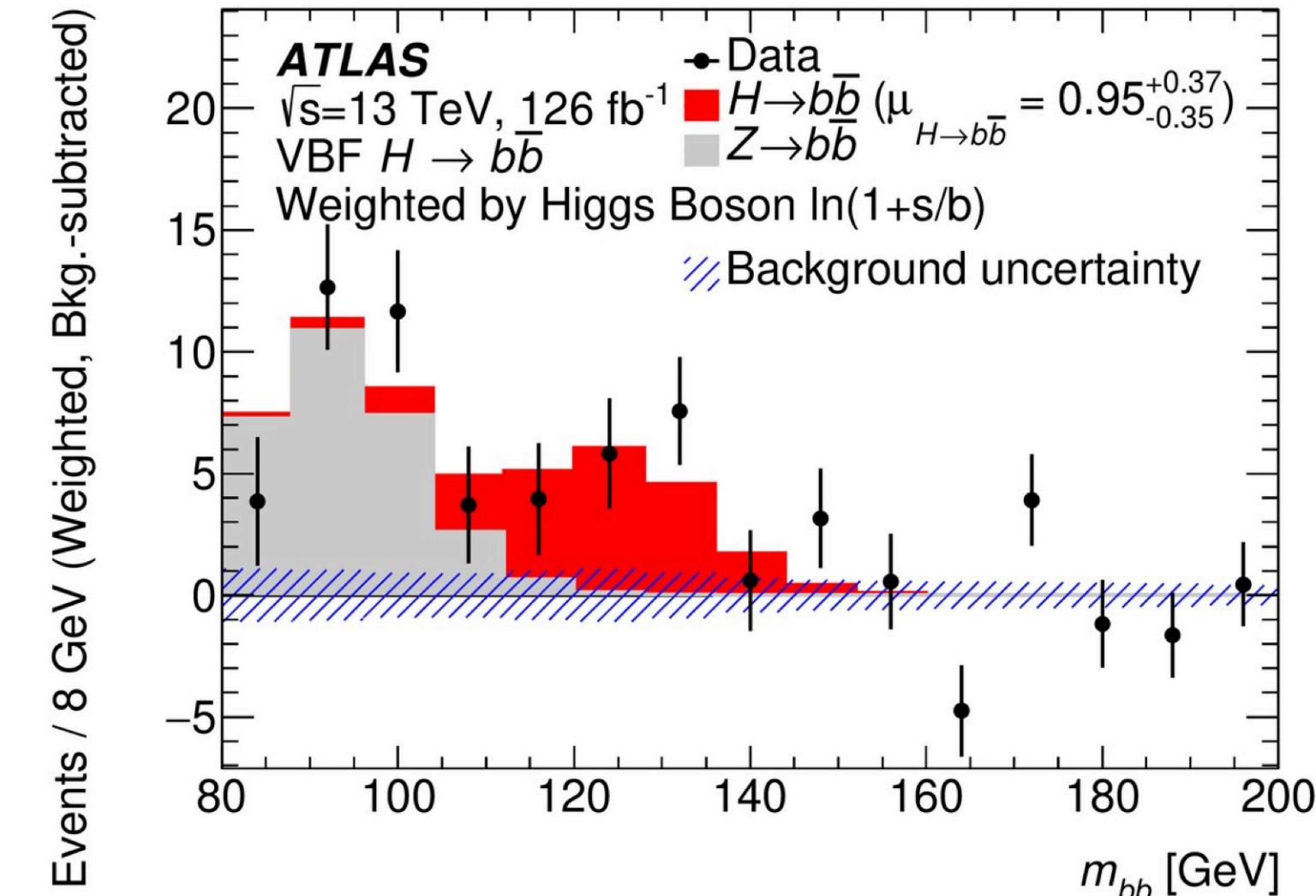
VBF analysis with Higgs in bb including channel with photon



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.



3.0 σ (3.0 σ expected)

Evidence!

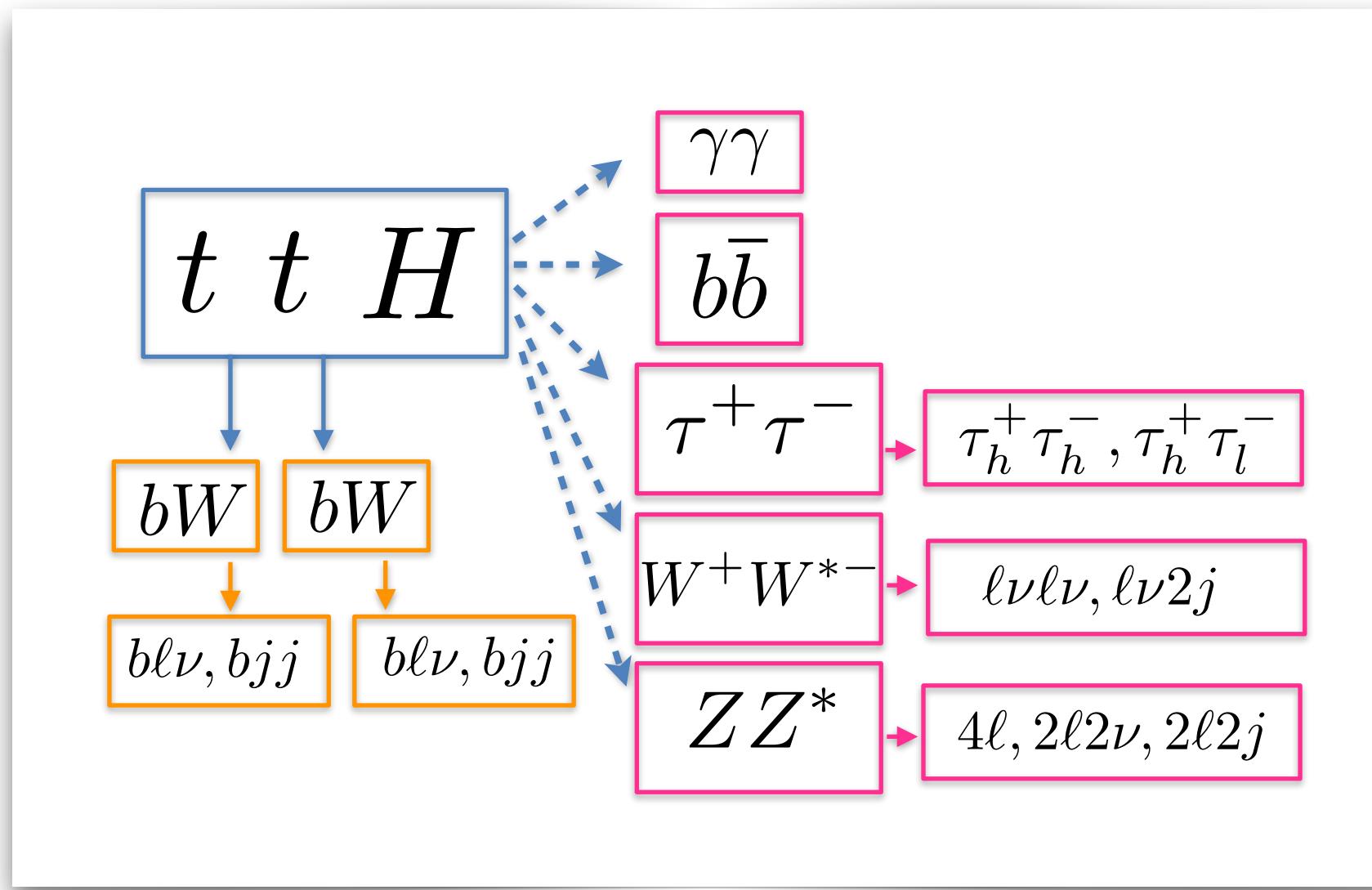
Probing the Top Yukawa Coupling

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

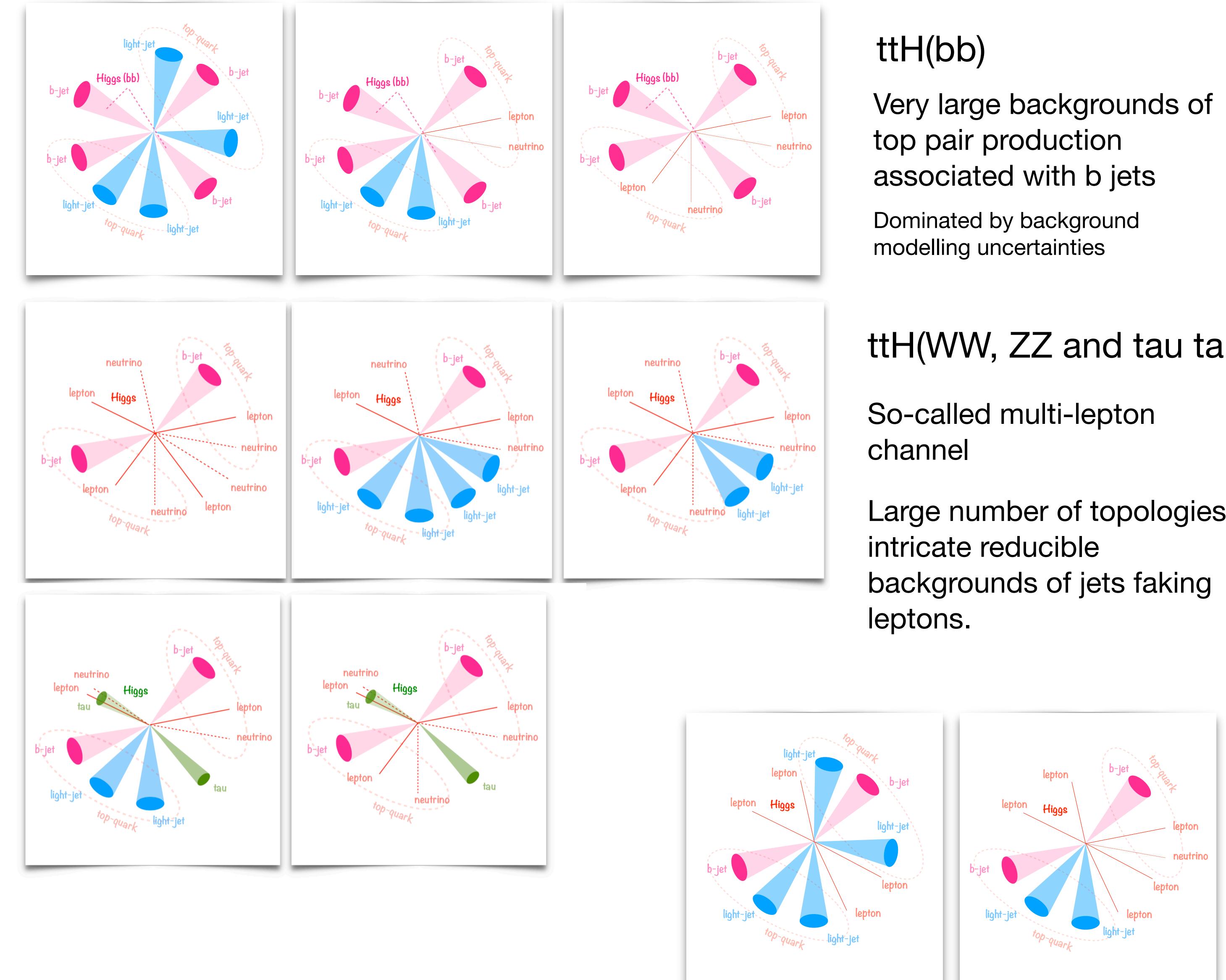
*Possible at an e^+e^- collider but would require high c.o.m. energy

Direct probe of the top Yukawa coupling

ttH Analyses at LHC: Massively Complex!



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



ttH(bb)

Very large backgrounds of top pair production associated with b jets
Dominated by background modelling uncertainties

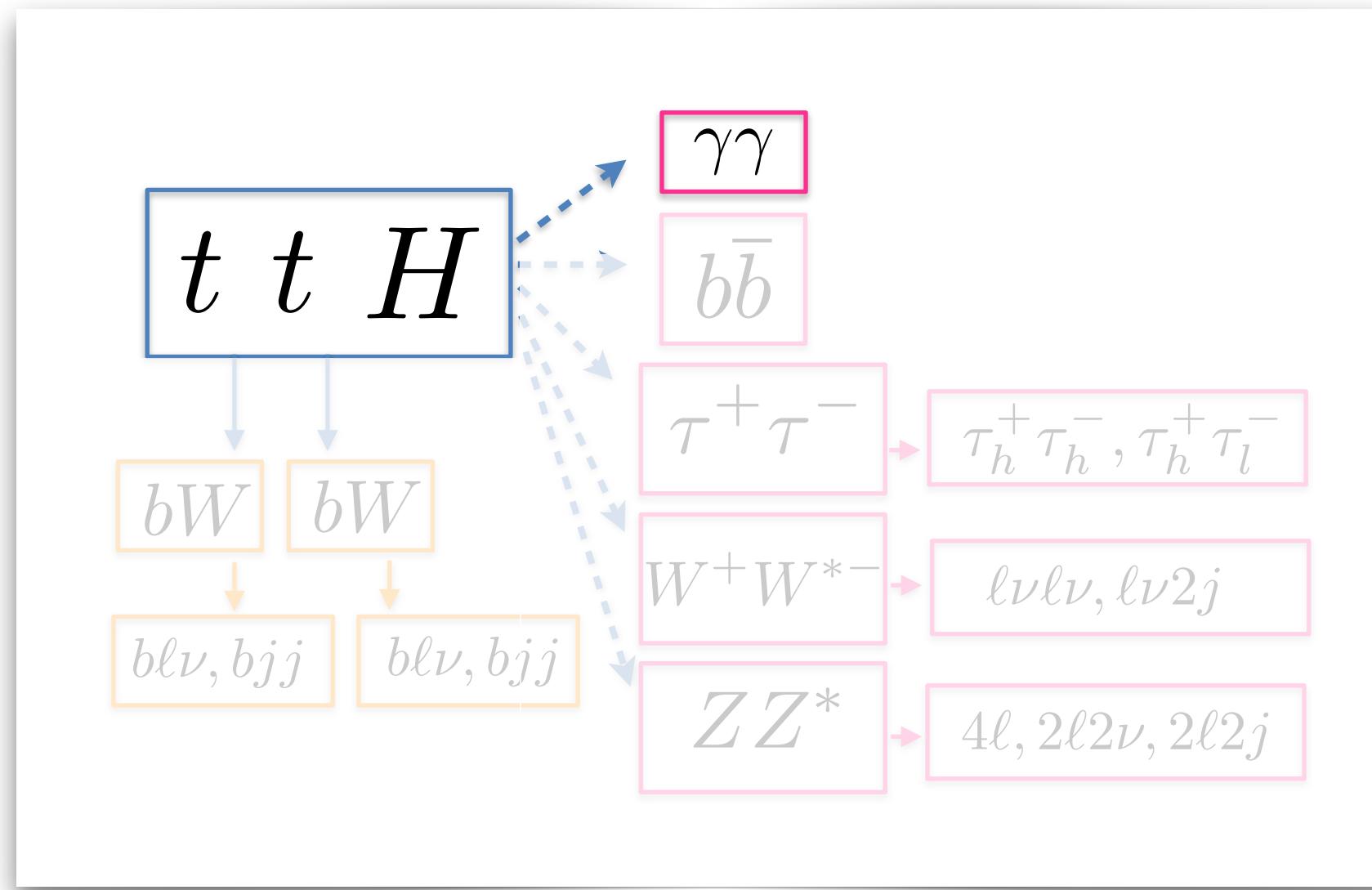
ttH(WW, ZZ and tau tau)

So-called multi-lepton channel

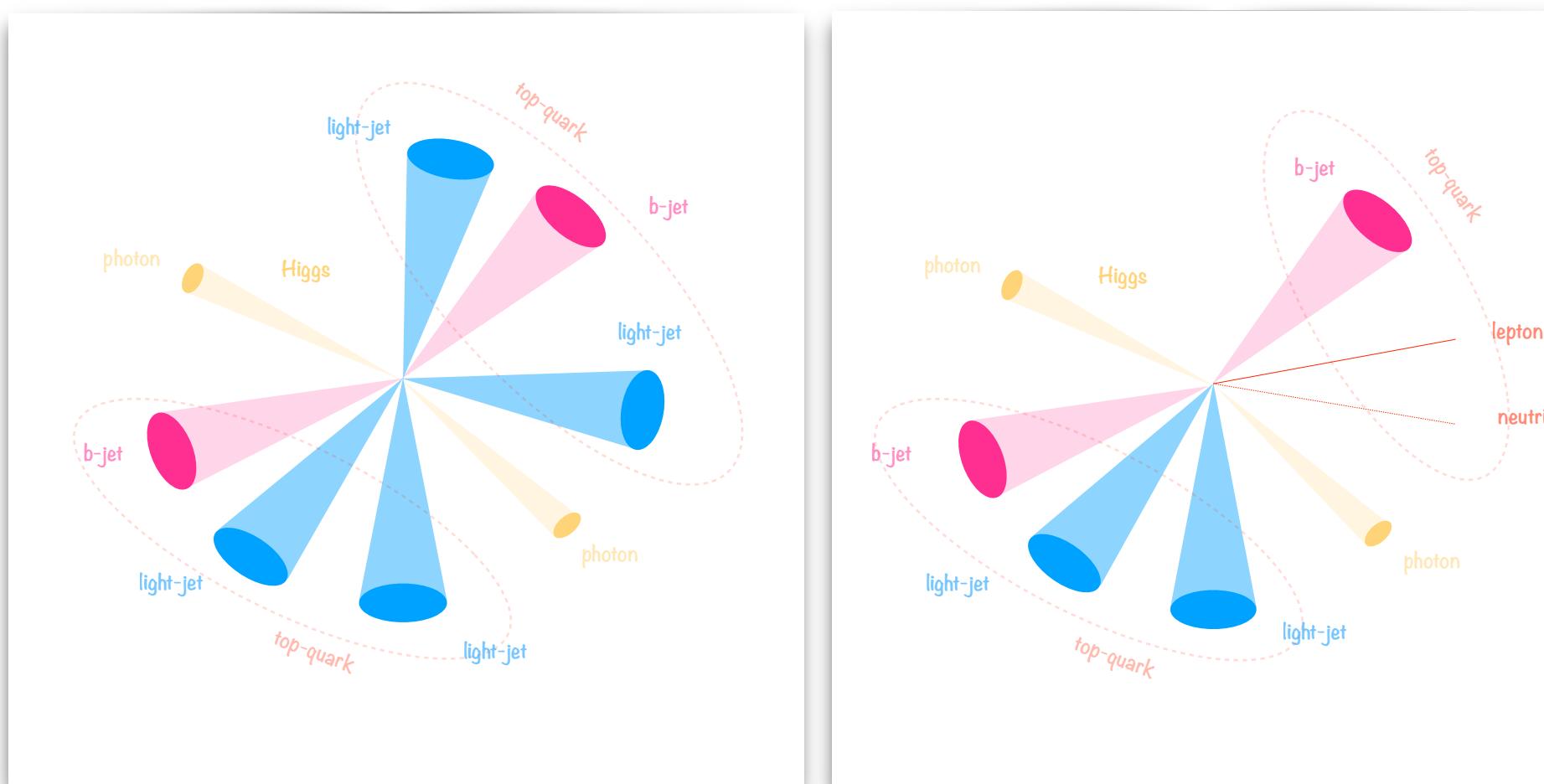
Large number of topologies intricate reducible backgrounds of jets faking leptons.

Direct probe of the top Yukawa coupling

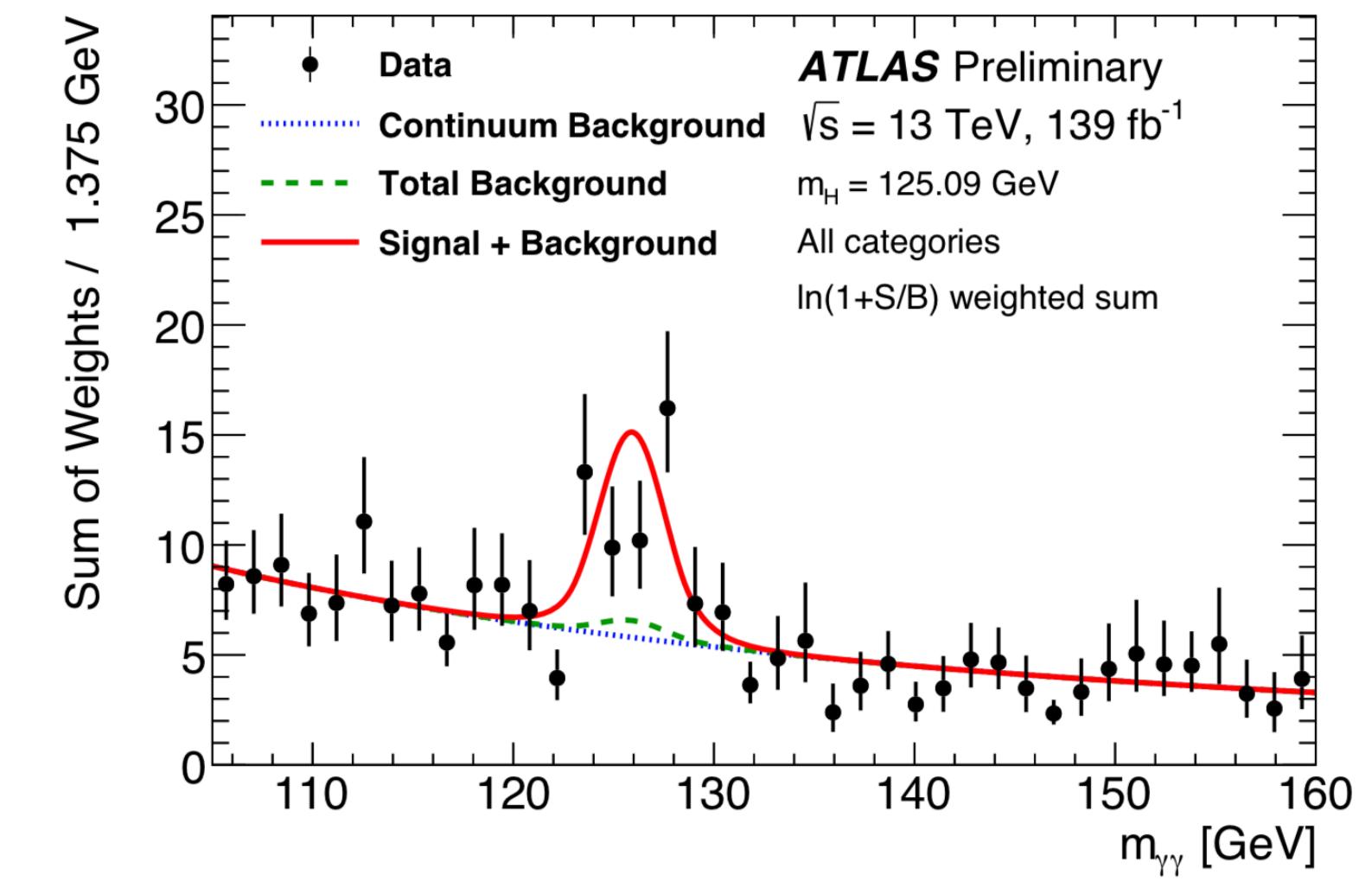
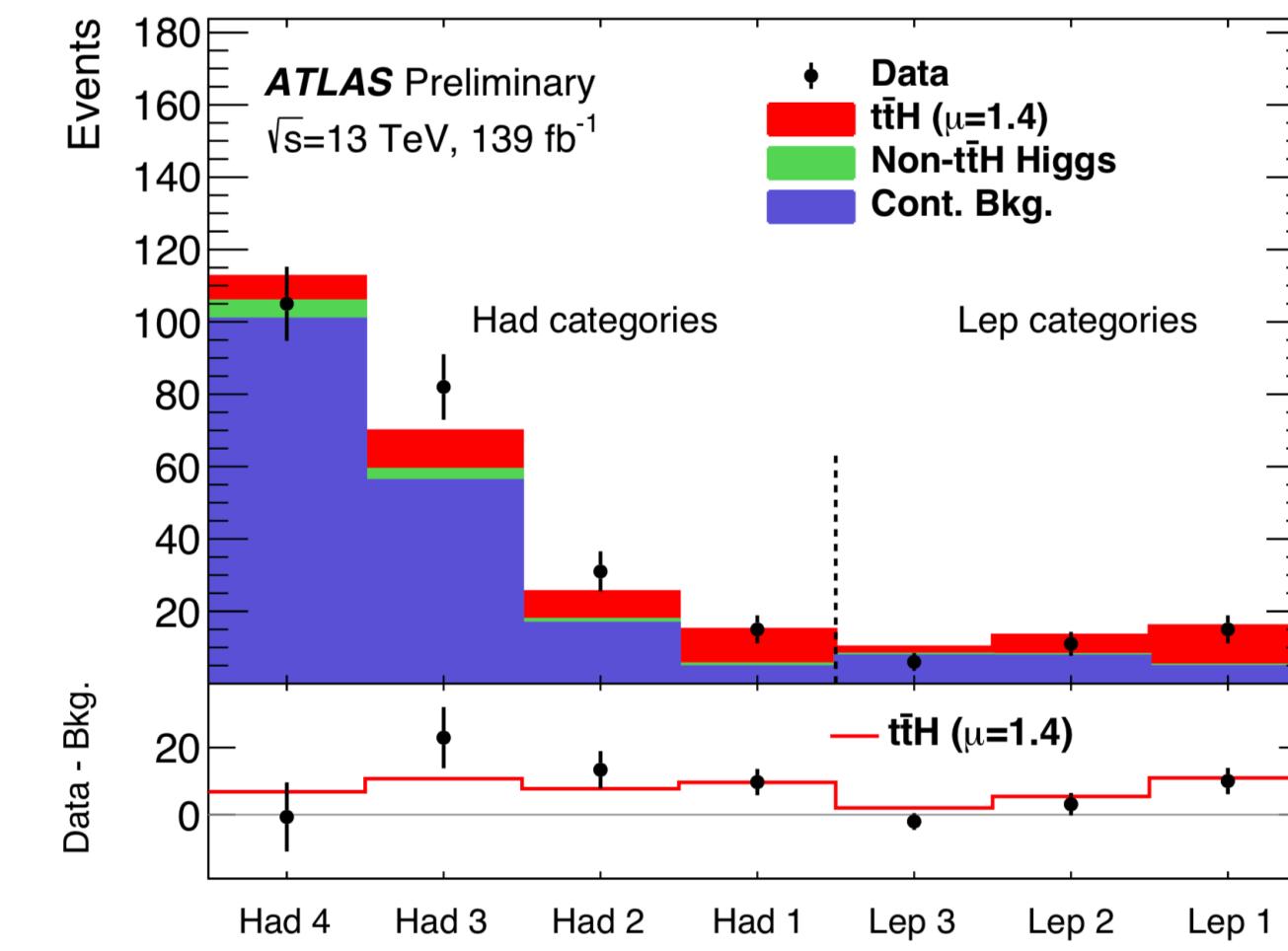
ttH Analyses at LHC: Massively Complex!



Currently most sensitive channel



Background and signal modelled using analytic functions.



Cross section dominated by statistical uncertainties:

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

Expected (4.2σ)

Observed 4.9σ

In combination with the other channels:

Expected 5.1σ

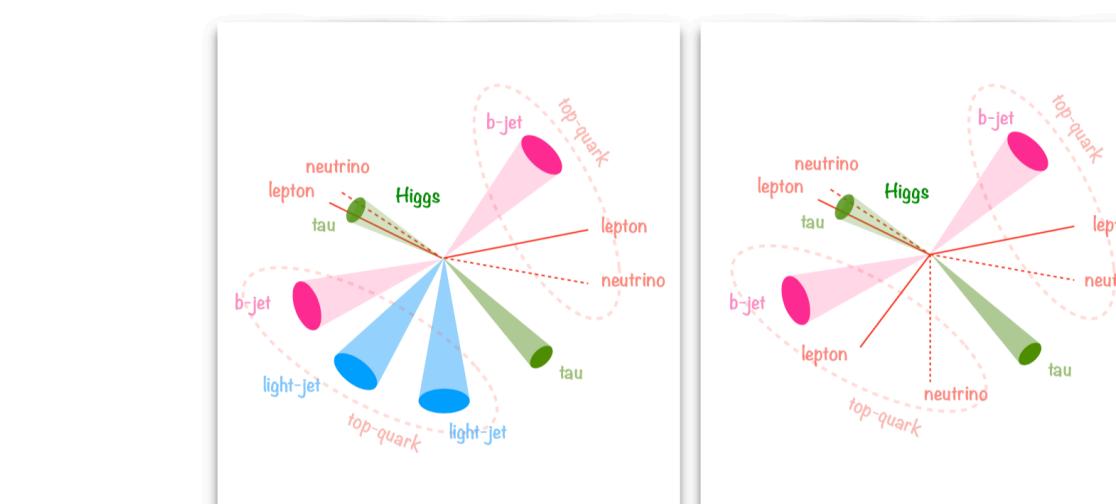
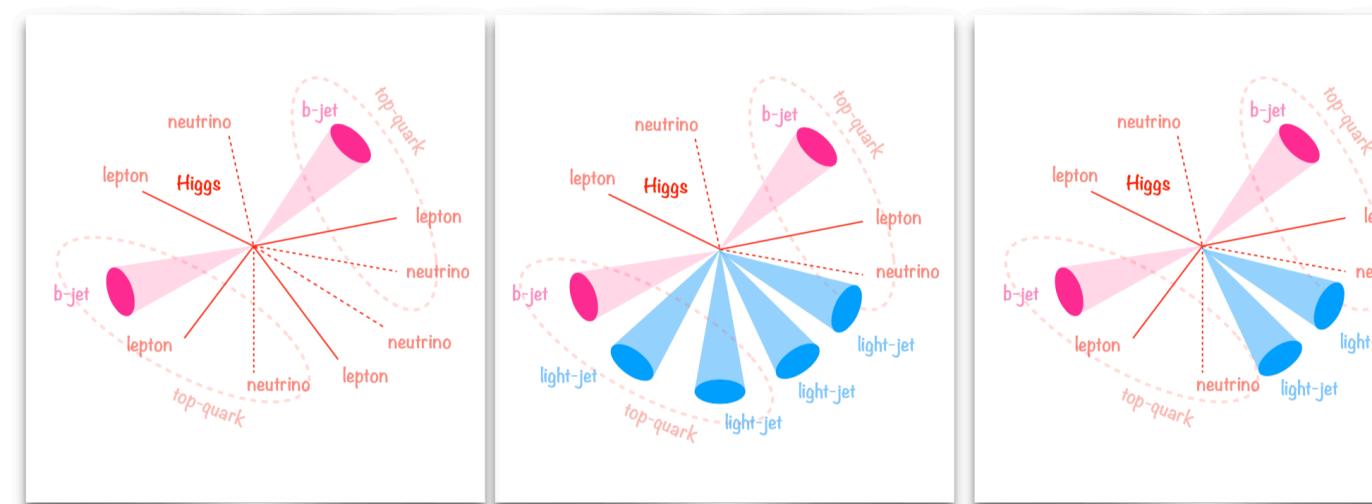
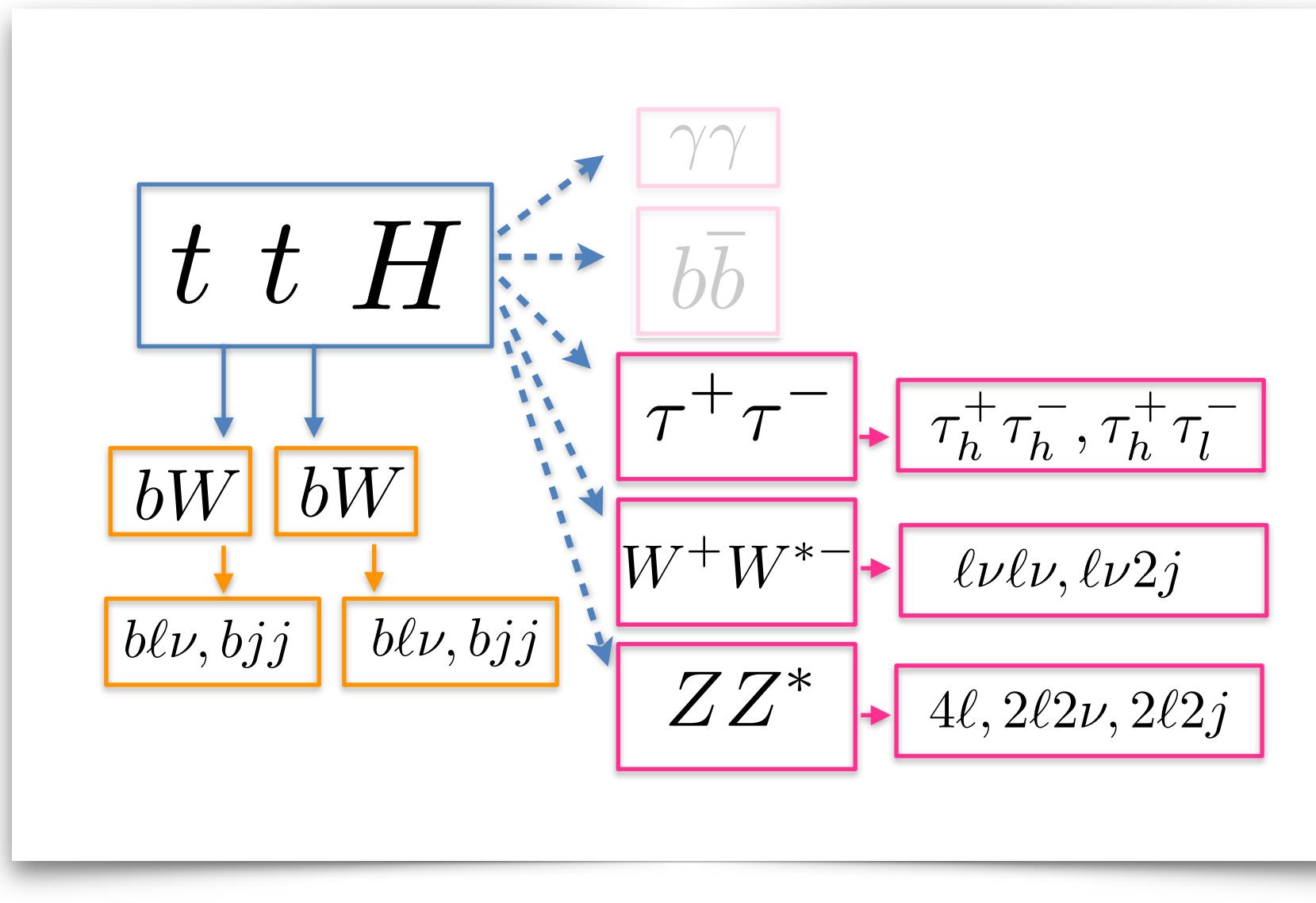
Observed 6.3σ

Clear observation!!

Direct probe of the top Yukawa coupling

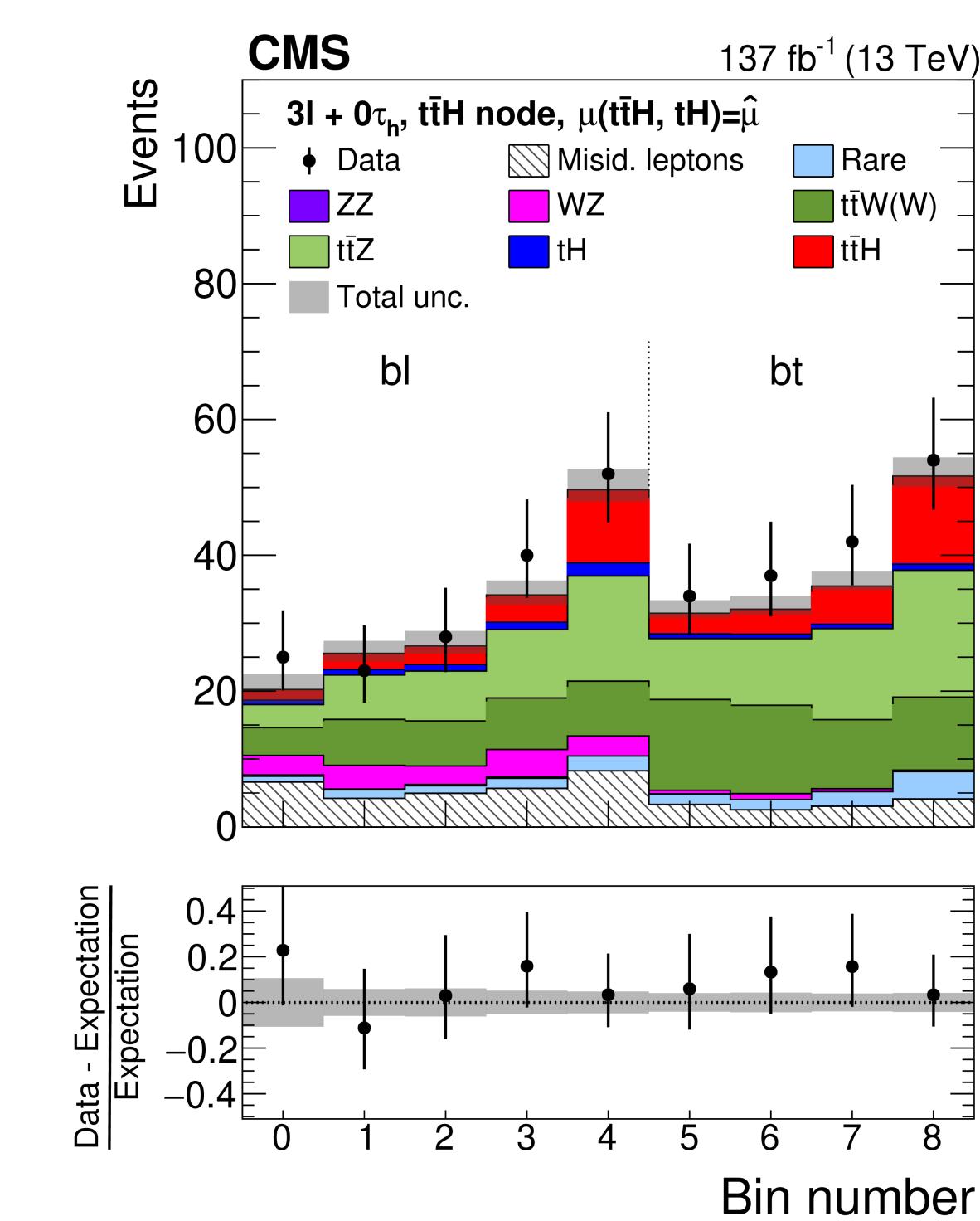
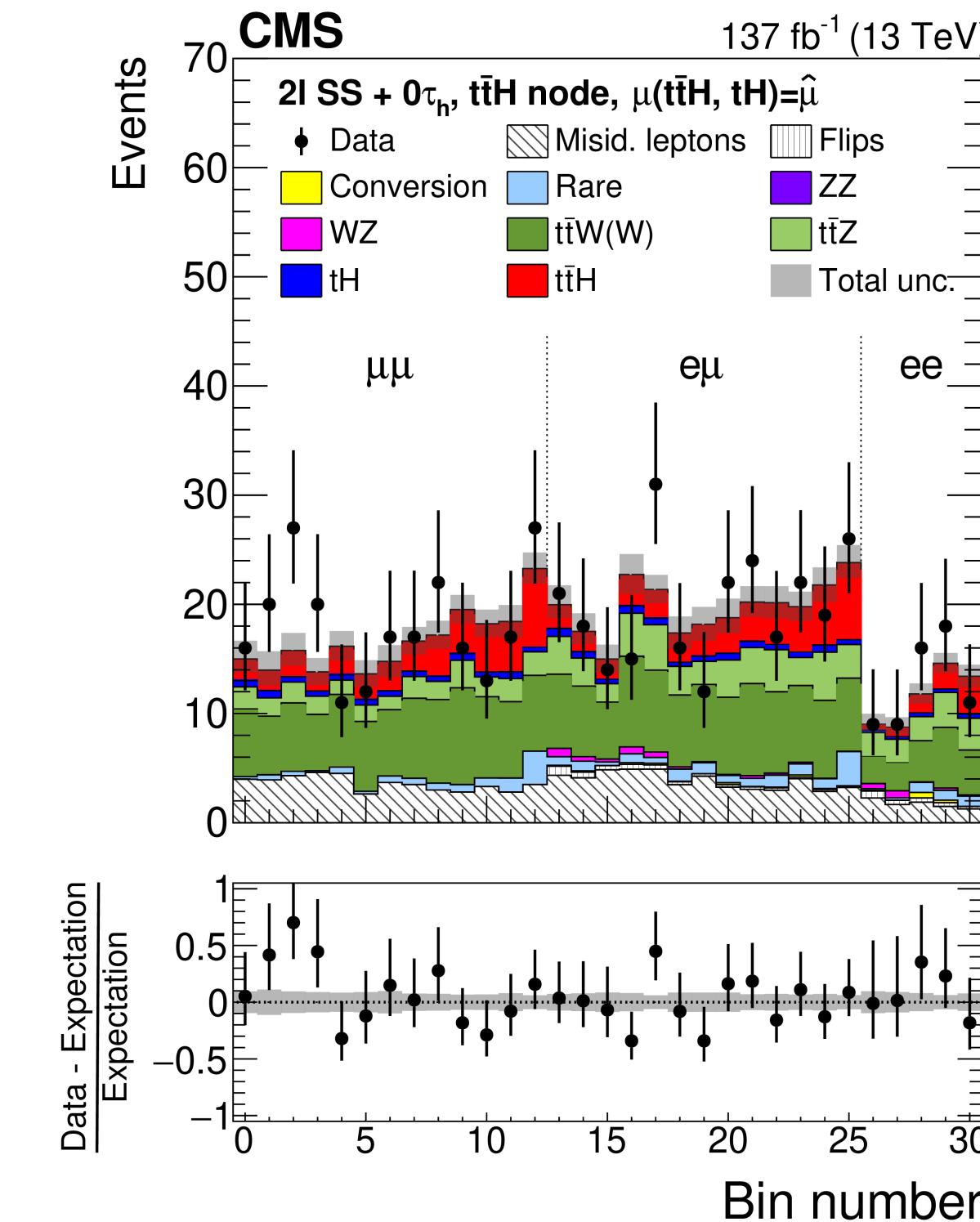
37

ttH Analyses at LHC: Massively Complex!



Due to the large multiplicity of final states, an inclusive approach (still) with 10 channels including 1L, 2L-SS, and 3L as well as 0-, 1- and 2-hadronically decaying taus

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

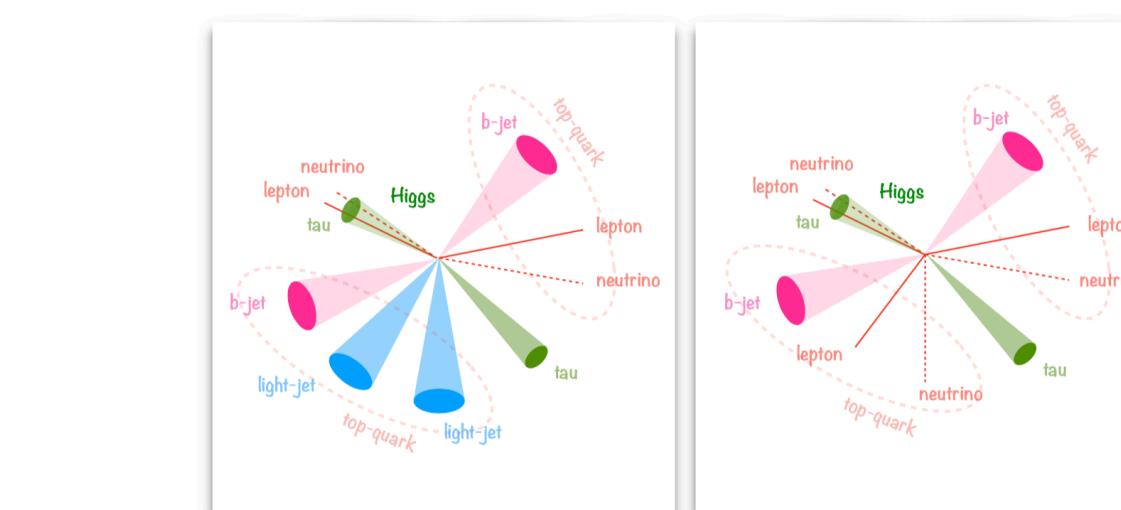
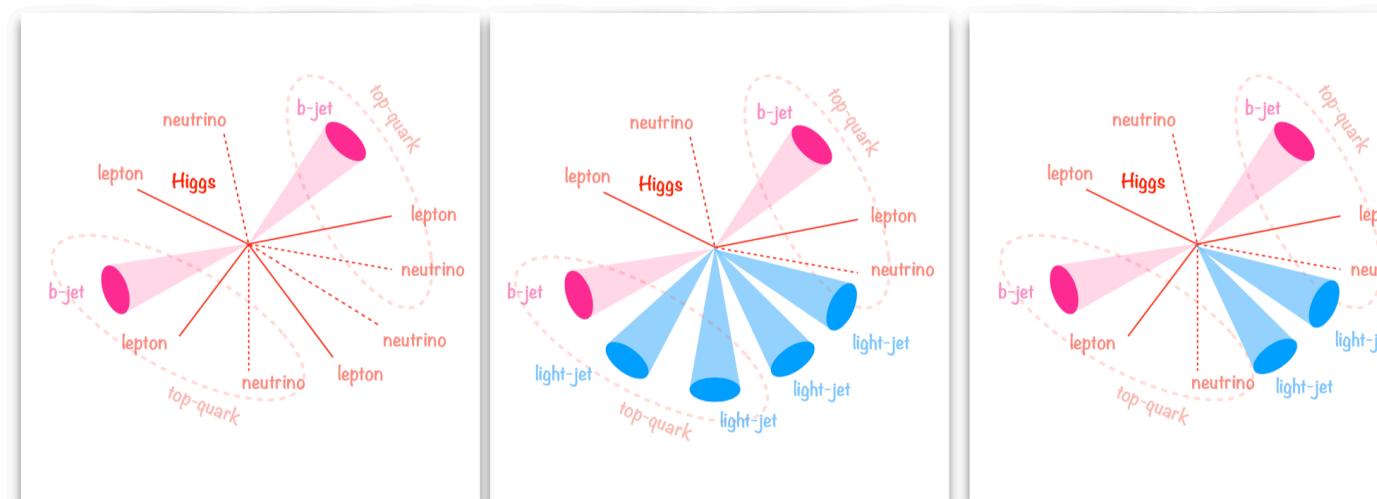
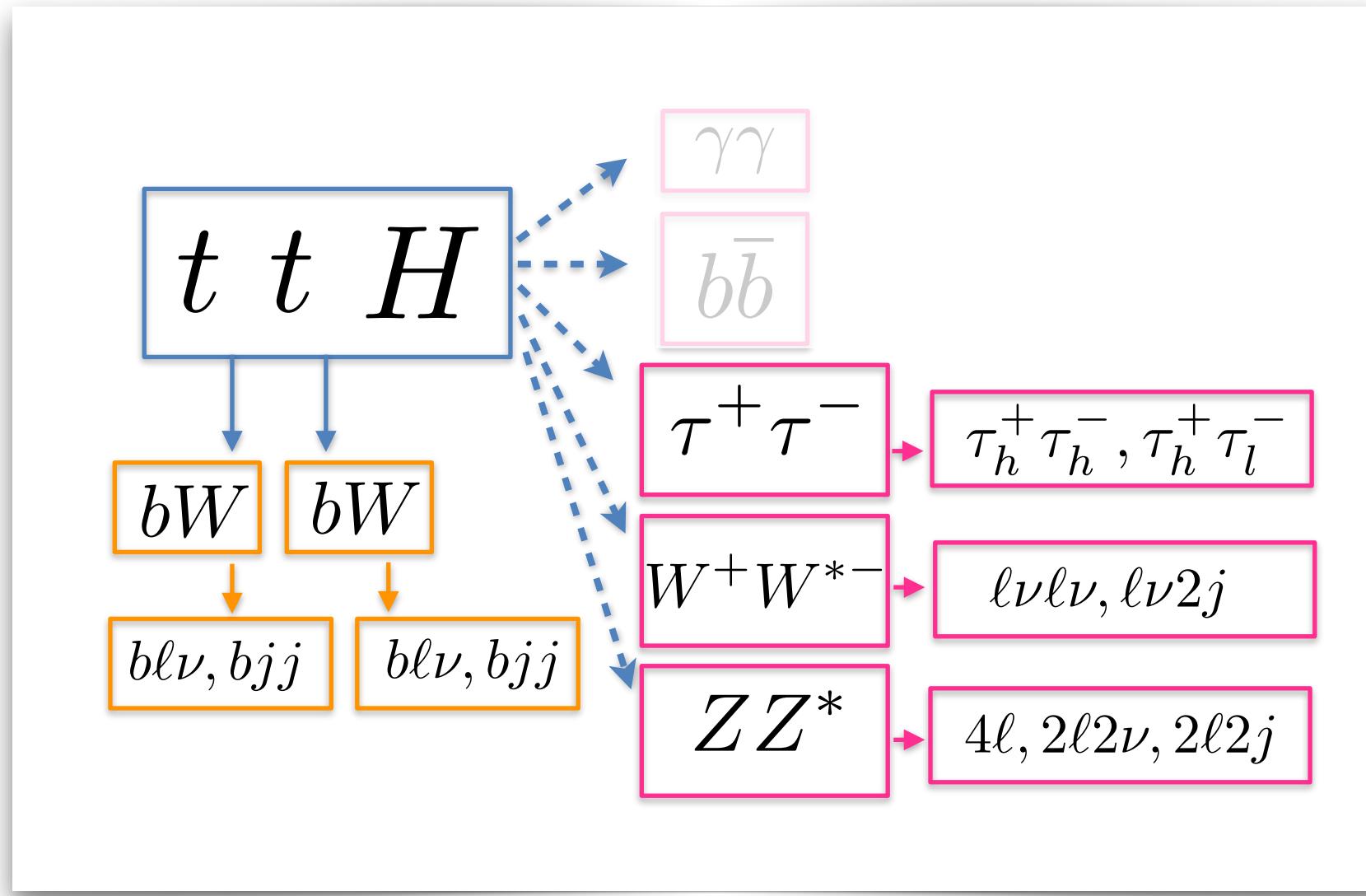


- Dominant backgrounds from ttW and ttZ which require a very good modelling!
- To get there requires an excellent rejection of fake leptons!

Direct probe of the top Yukawa coupling

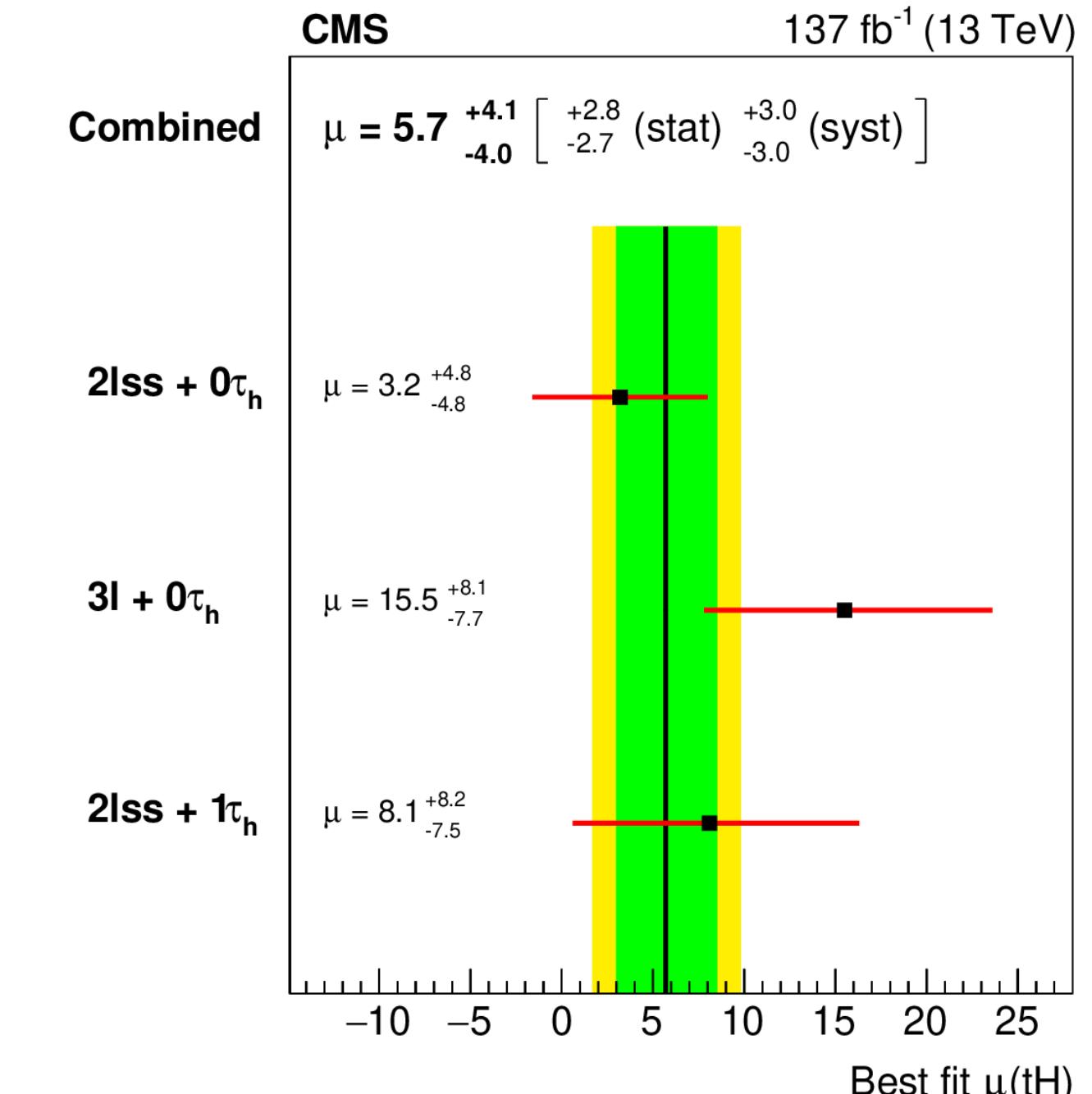
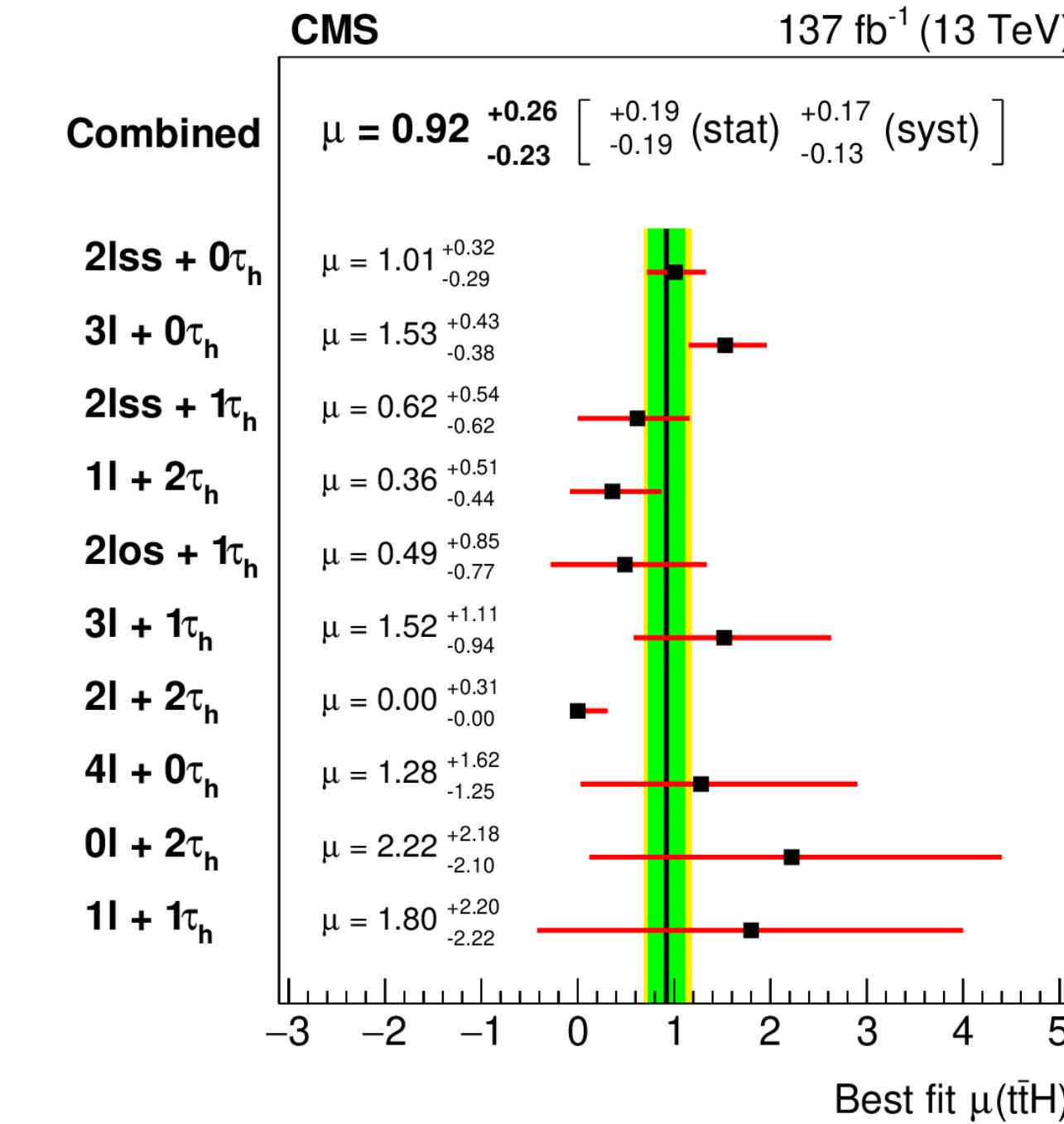
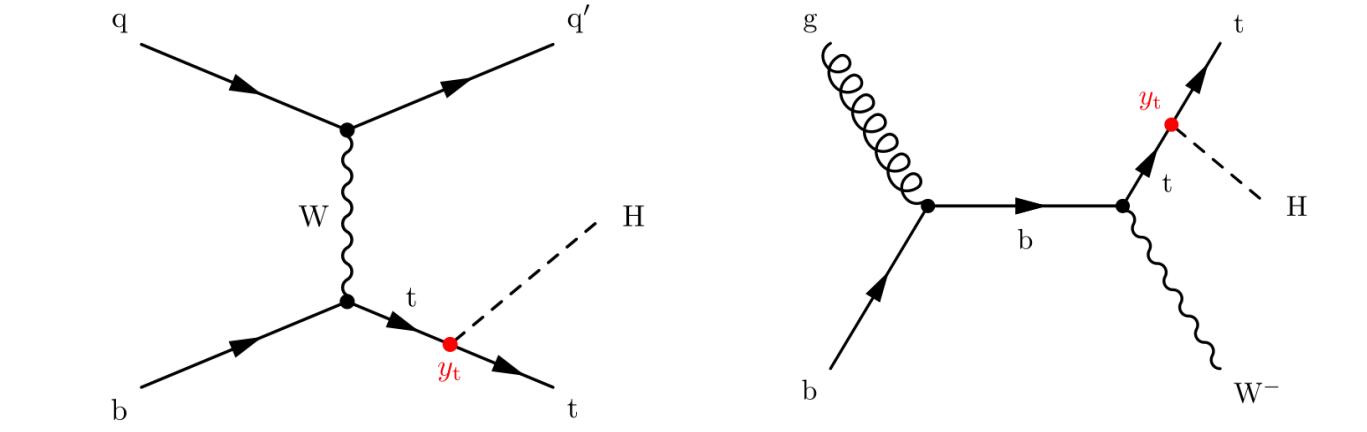
38

ttH Analyses at LHC: Massively Complex!



Due to the large multiplicity of final states, an inclusive approach (still) with 10 channels including 1L, 2L-SS, and 3L as well as 0-, 1- and 2-hadronically decaying taus

Analysis also aims at tHq production

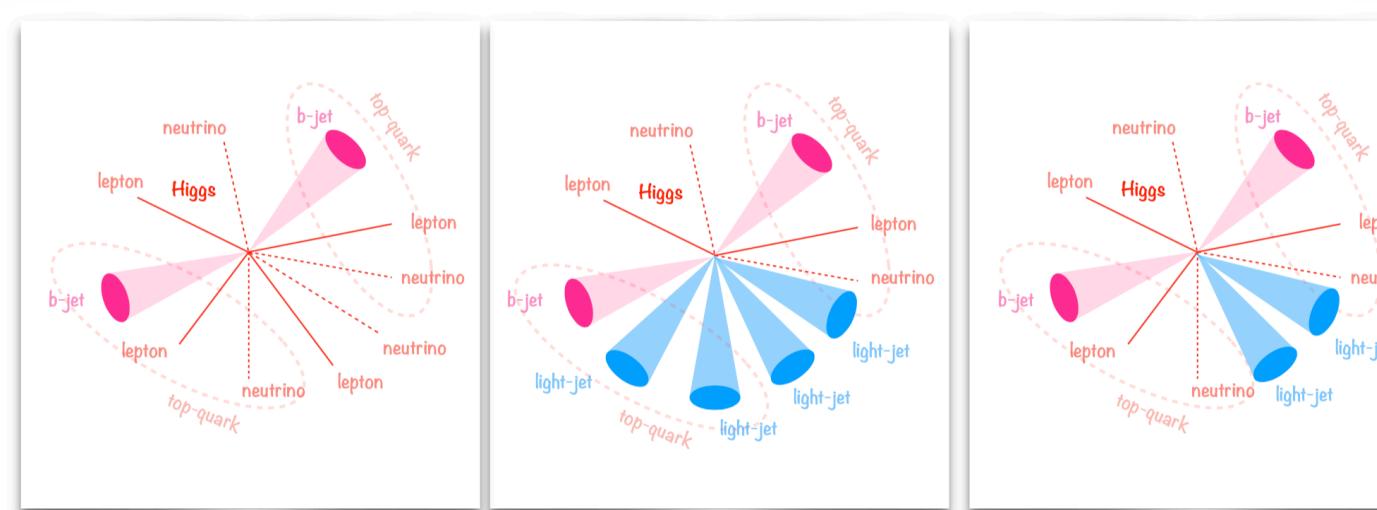
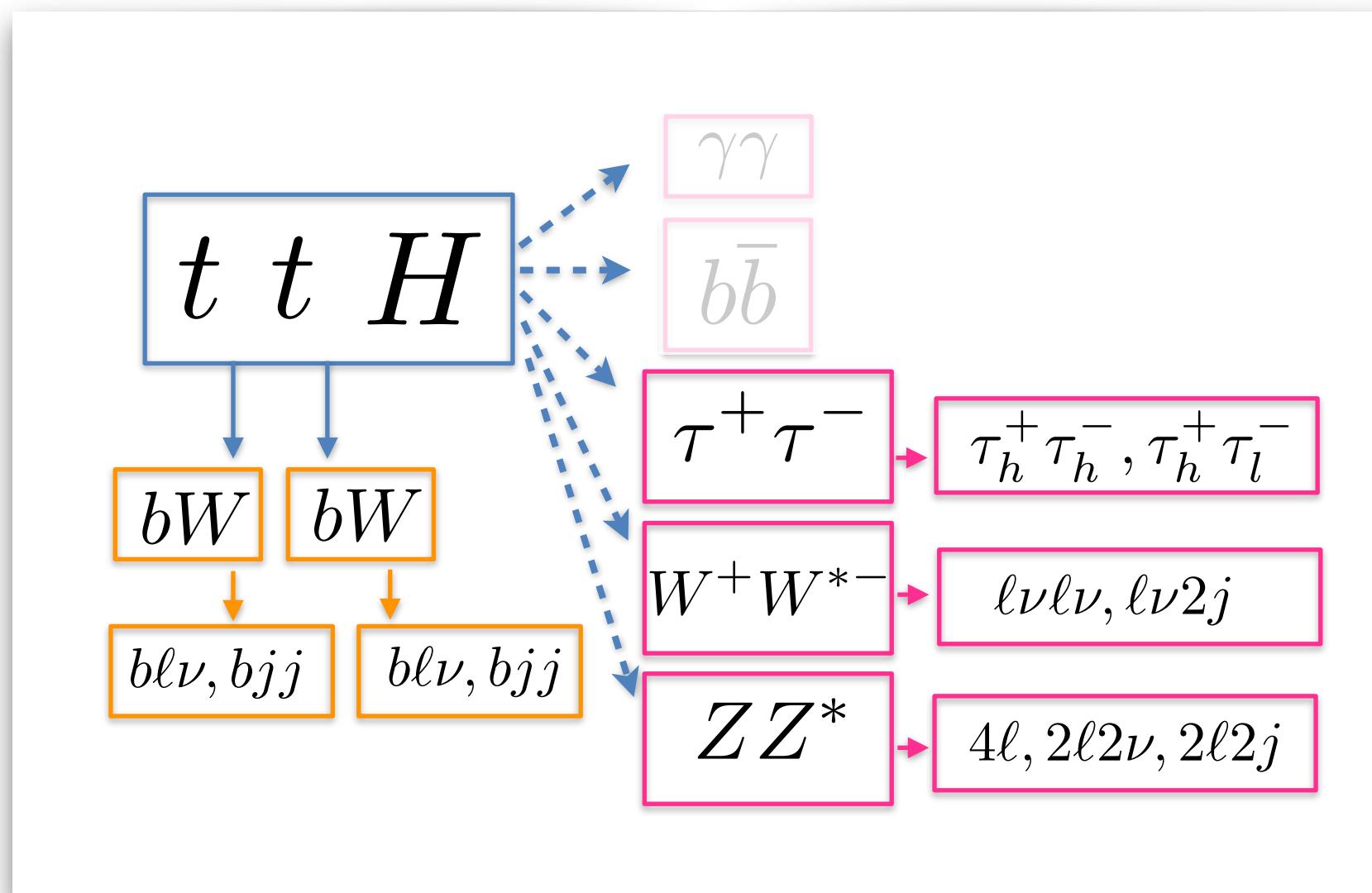


Above 5 s.d. deviation sensitivity and 4.7 s.d. observed significance!

Direct probe of the top Yukawa coupling

39

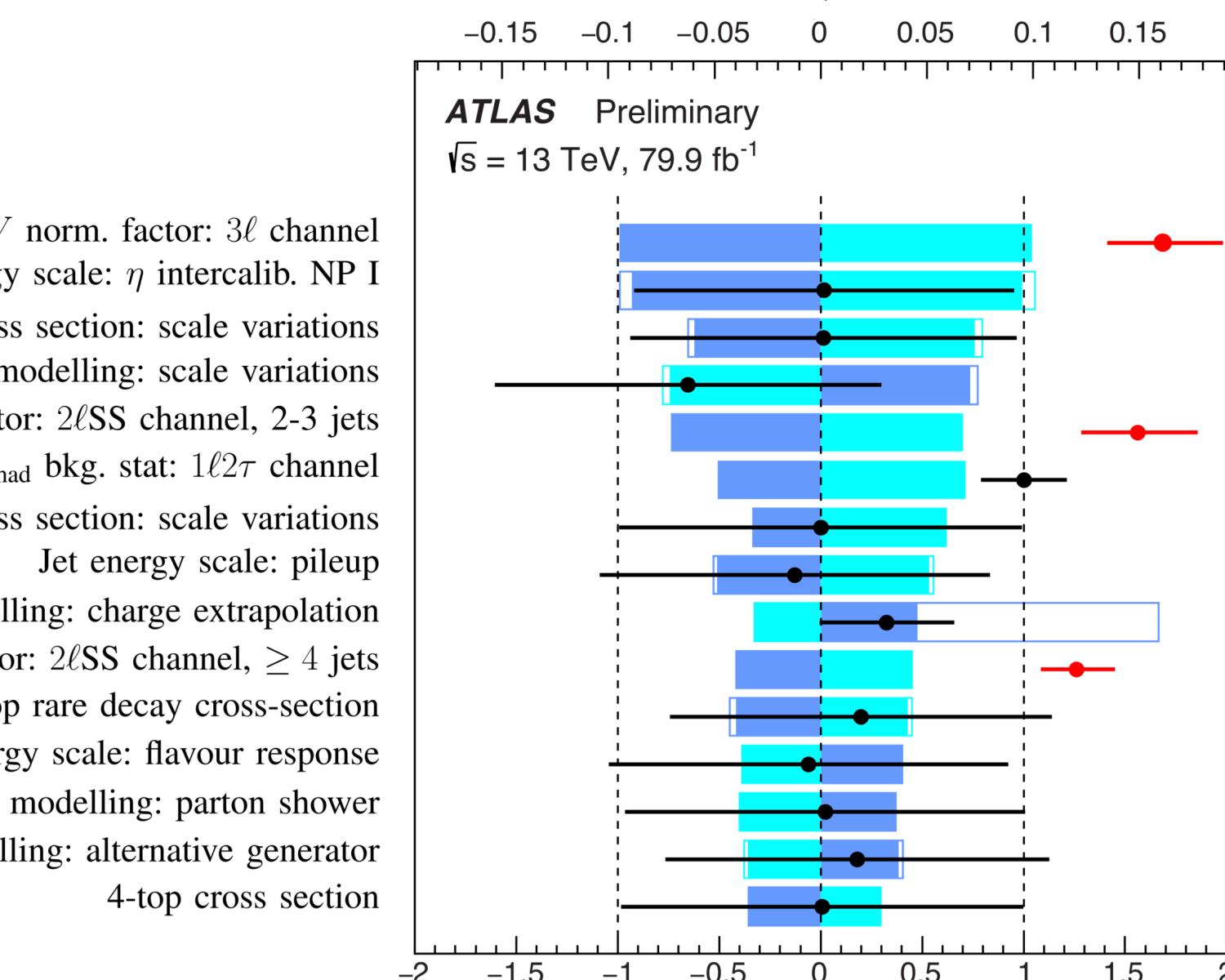
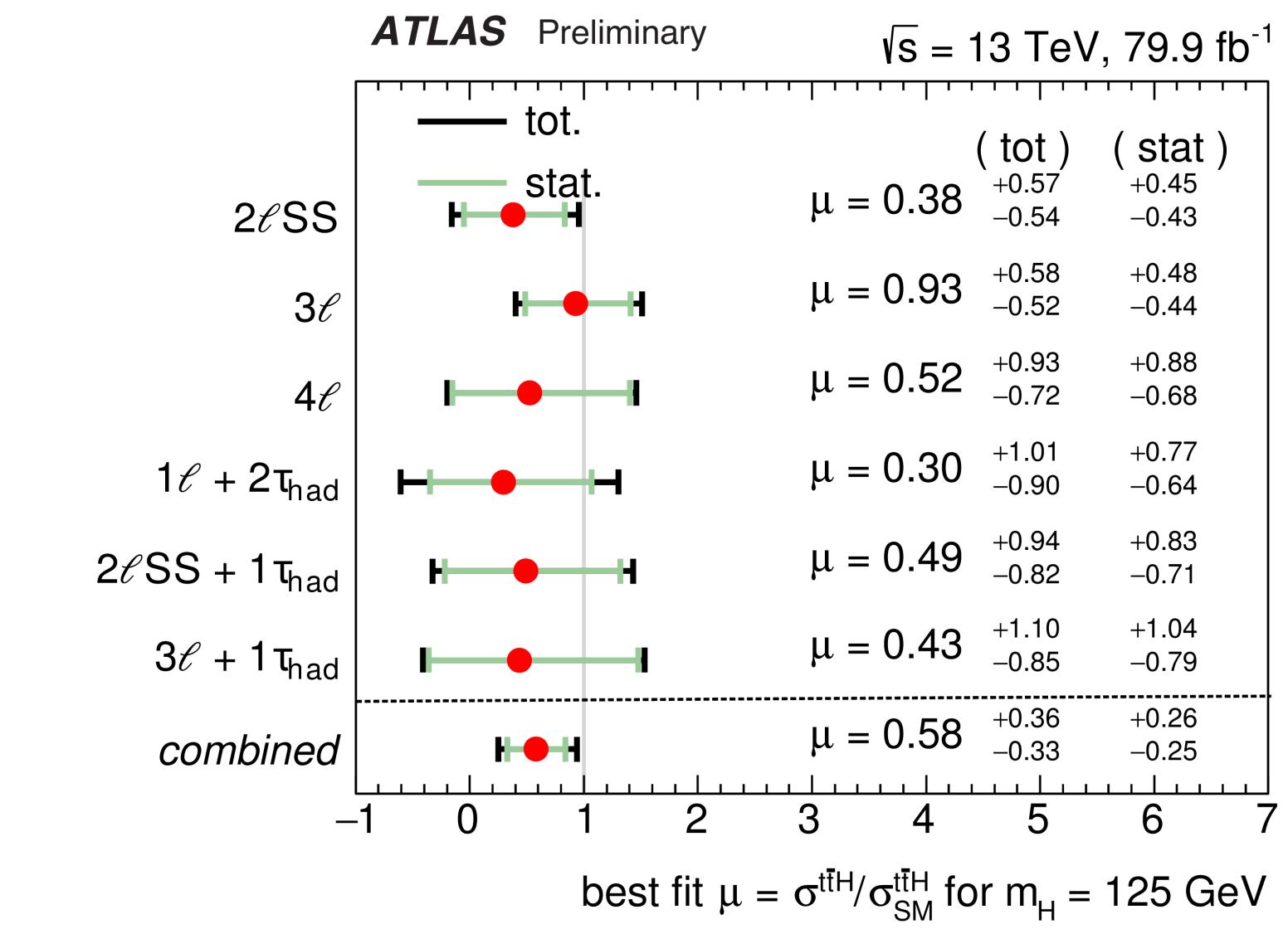
ttH Analyses at LHC: Massively Complex!



[ATLAS-CONF-2019-045](#)

Similar analysis in ATLAS has shown that the normalisation of the $t\bar{t}W$ background is high by approximately 2 s.d. (also high in CMS):

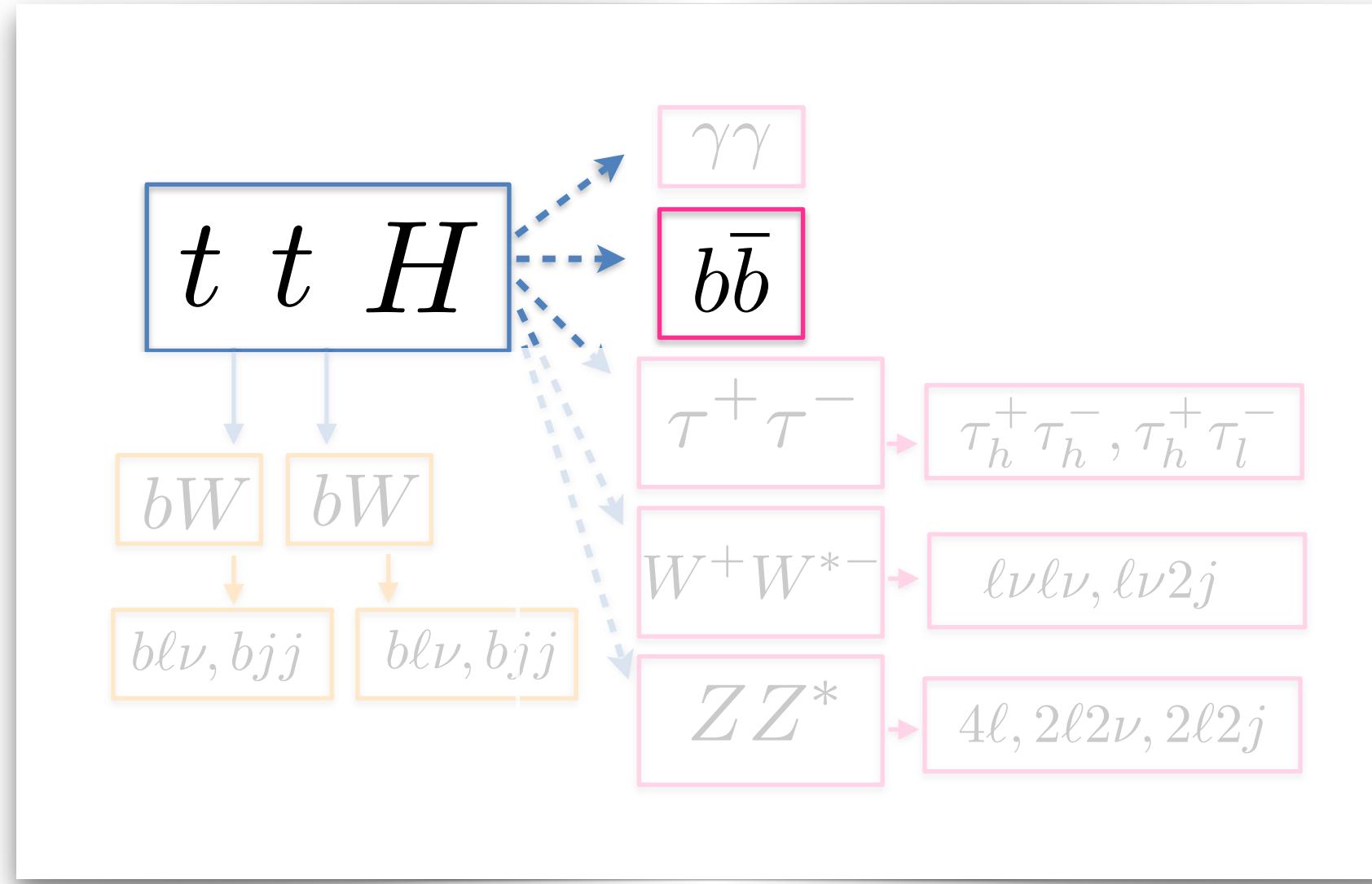
An improved description of the $t\bar{t}W$ background is needed to reach greater precision in the future. (see yesterday's lecture)



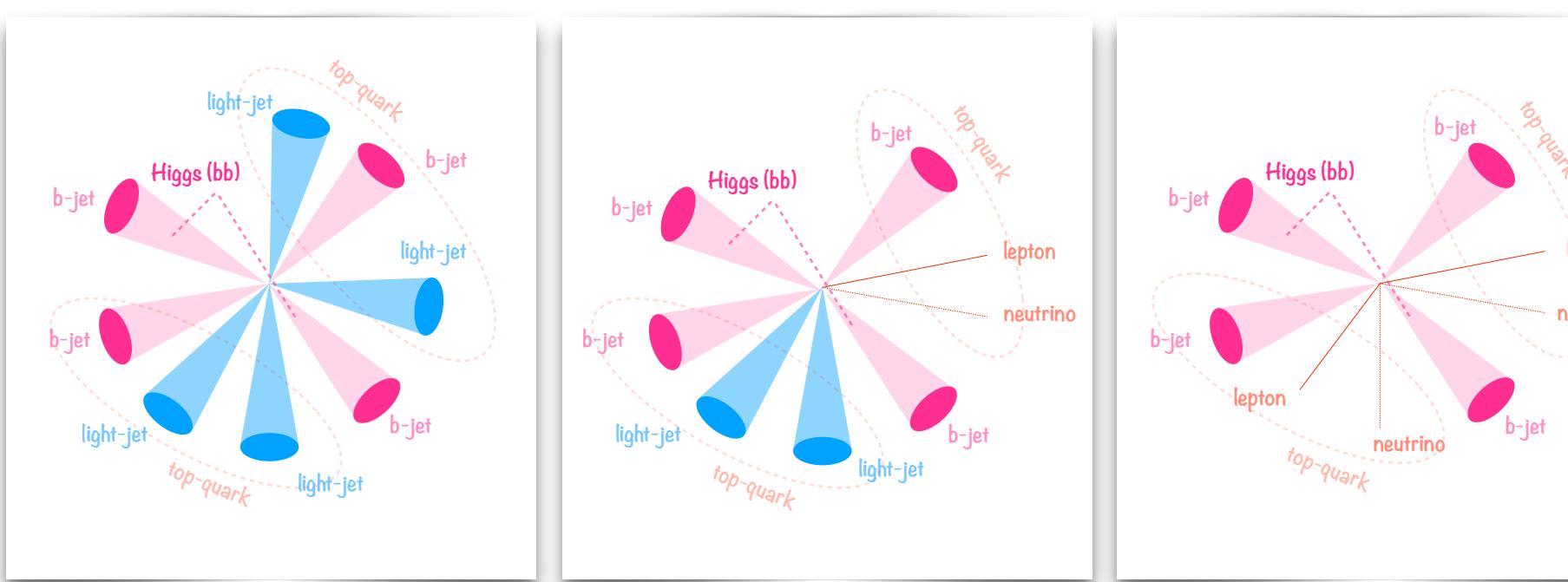
Direct probe of the top Yukawa coupling in ttH(bb)

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ttH Analyses at LHC: Massively Complex!



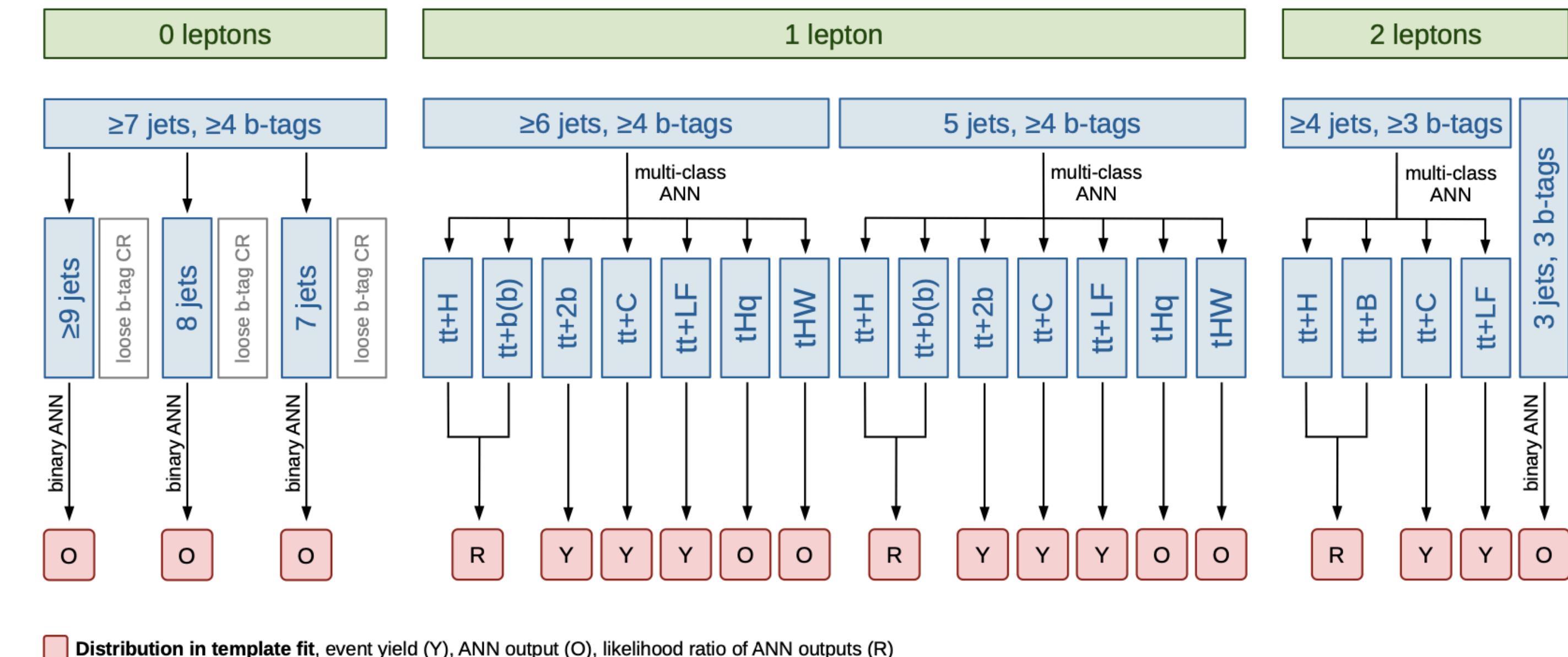
Extremely challenging channel



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



Result presented last week at the [EPS-HEP2023](#) conference in Hamburg!

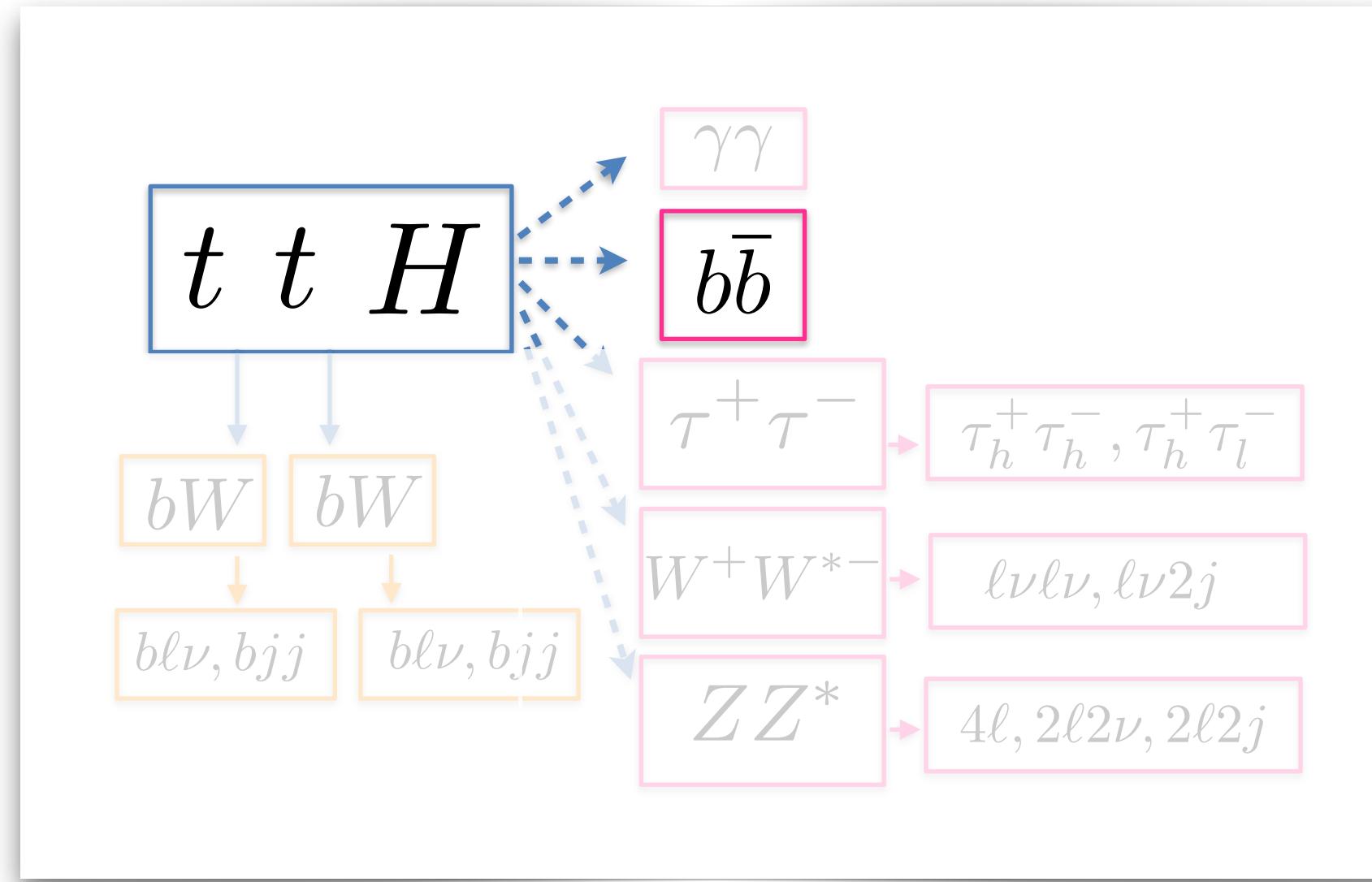


Full Run 2 Dataset and all topologies, including the intricate fully hadronic final state!

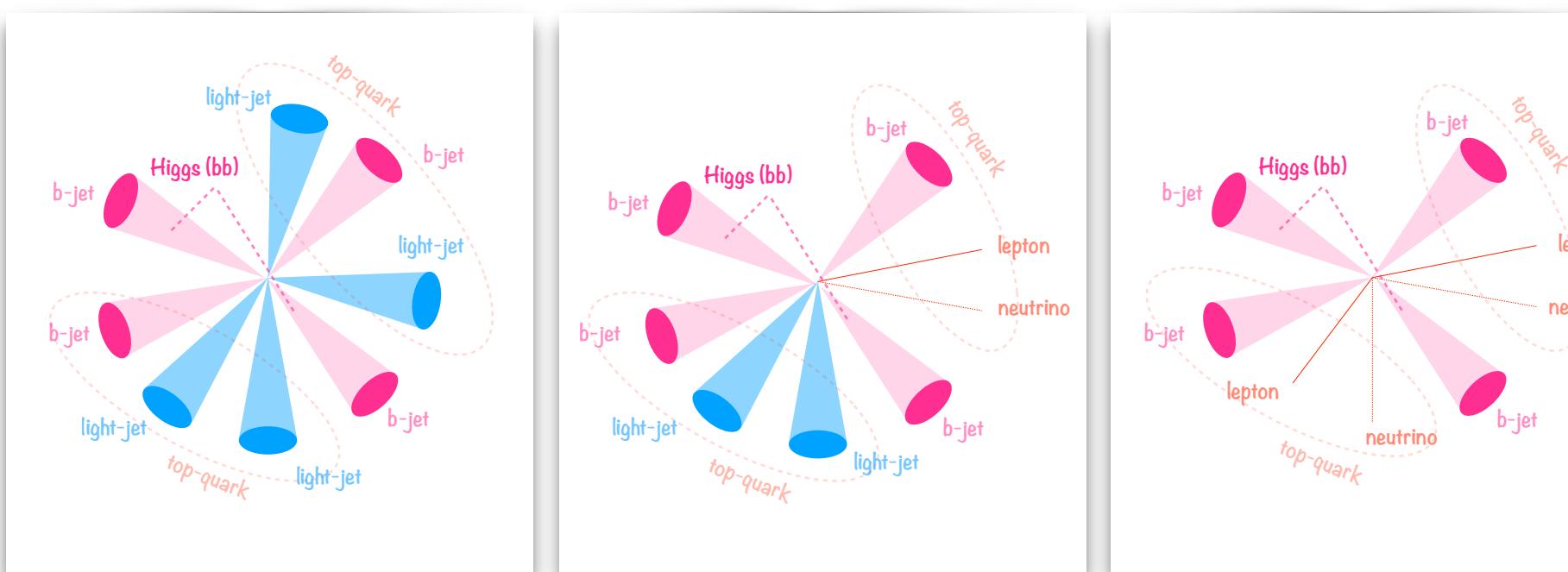
Direct probe of the top Yukawa coupling

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ttH Analyses at LHC: Massively Complex!



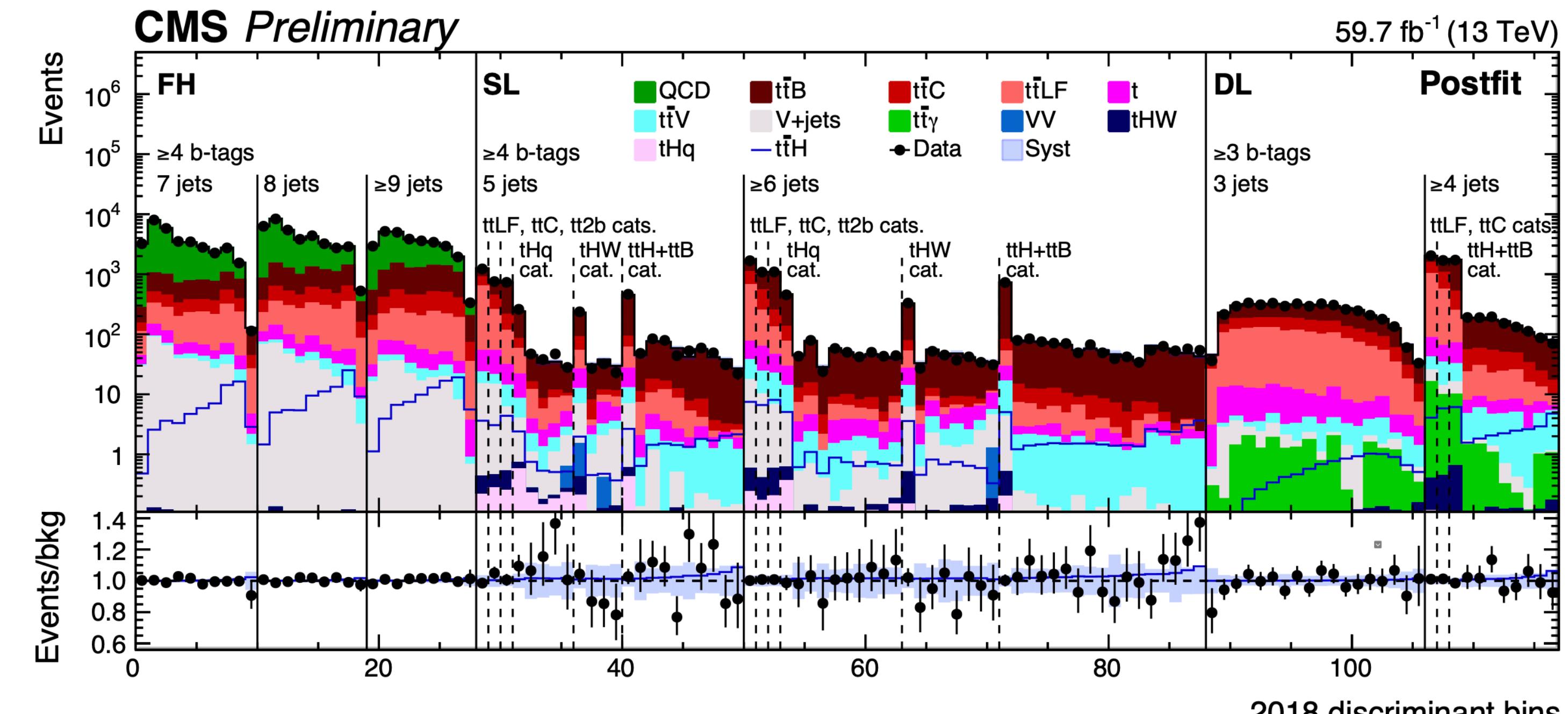
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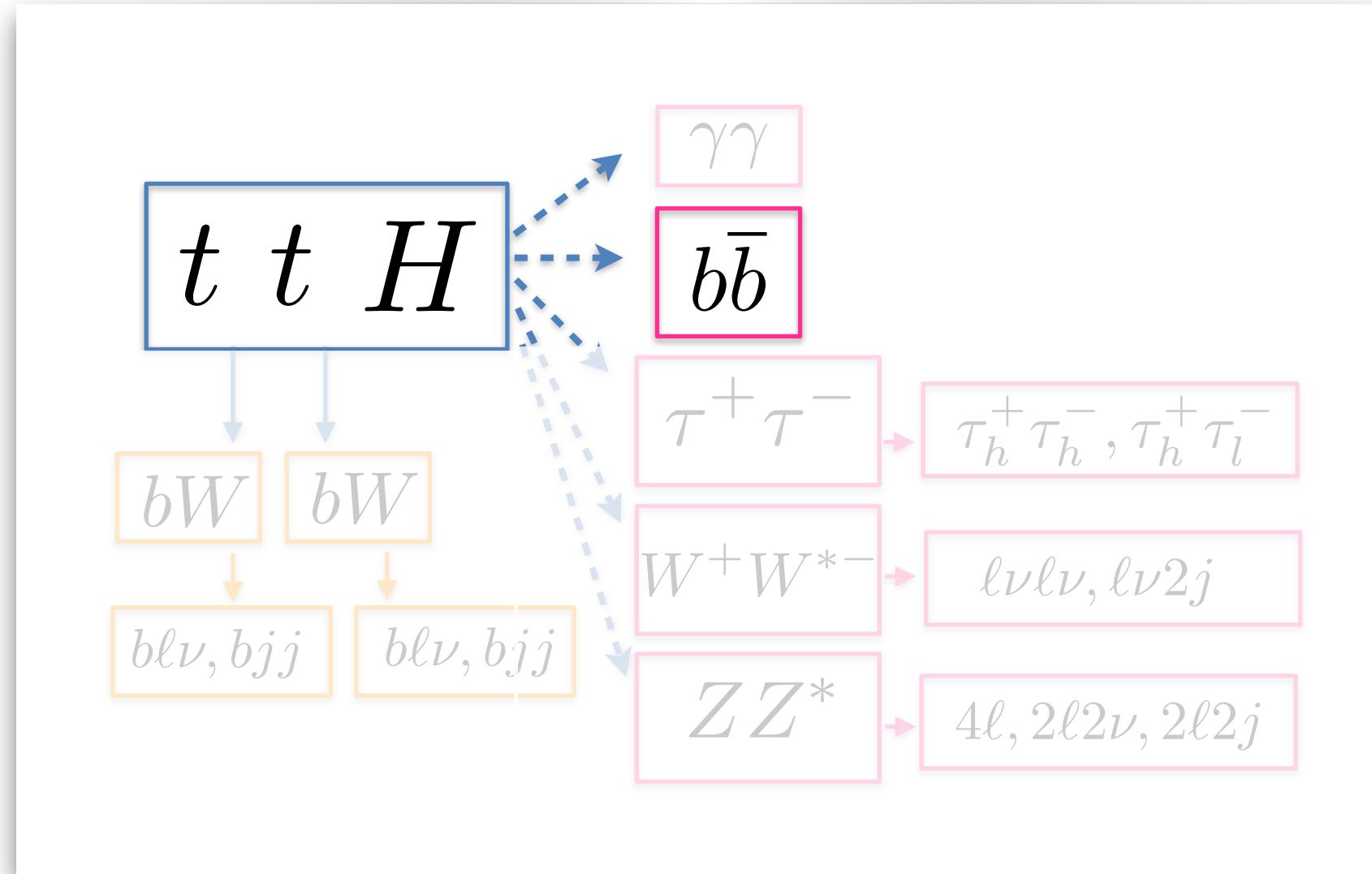


Full Run 2 Dataset and all topologies, including the intricate fully hadronic final state!

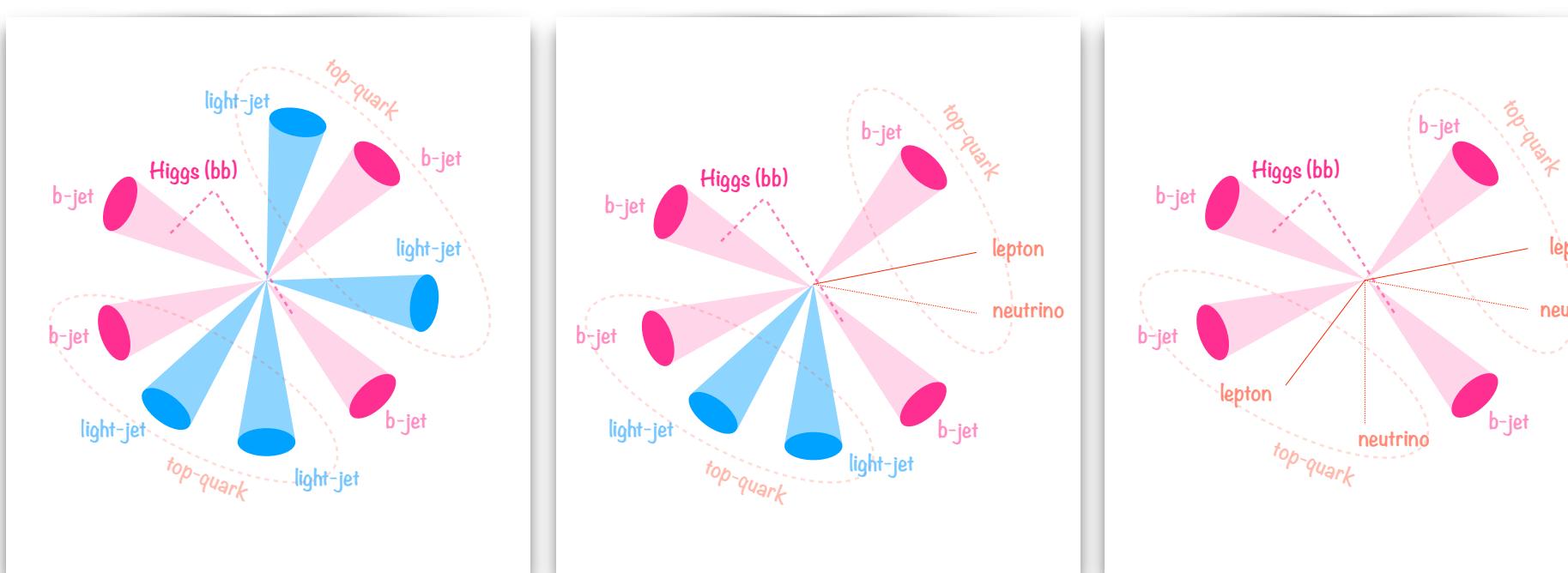
Direct probe of the top Yukawa coupling in ttH(bb)

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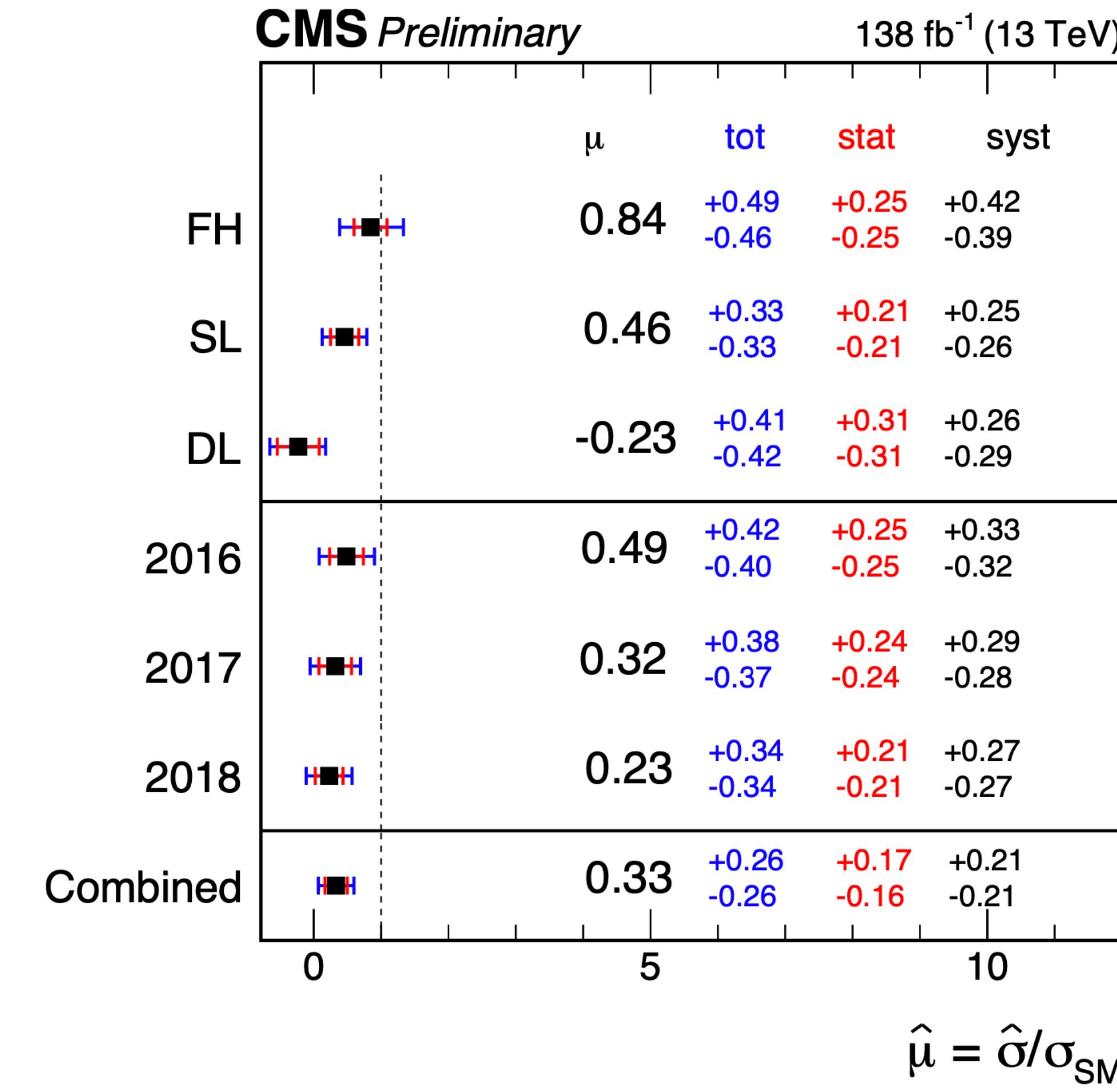
ttH Analyses at LHC: Massively Complex!



Extremely challenging channel



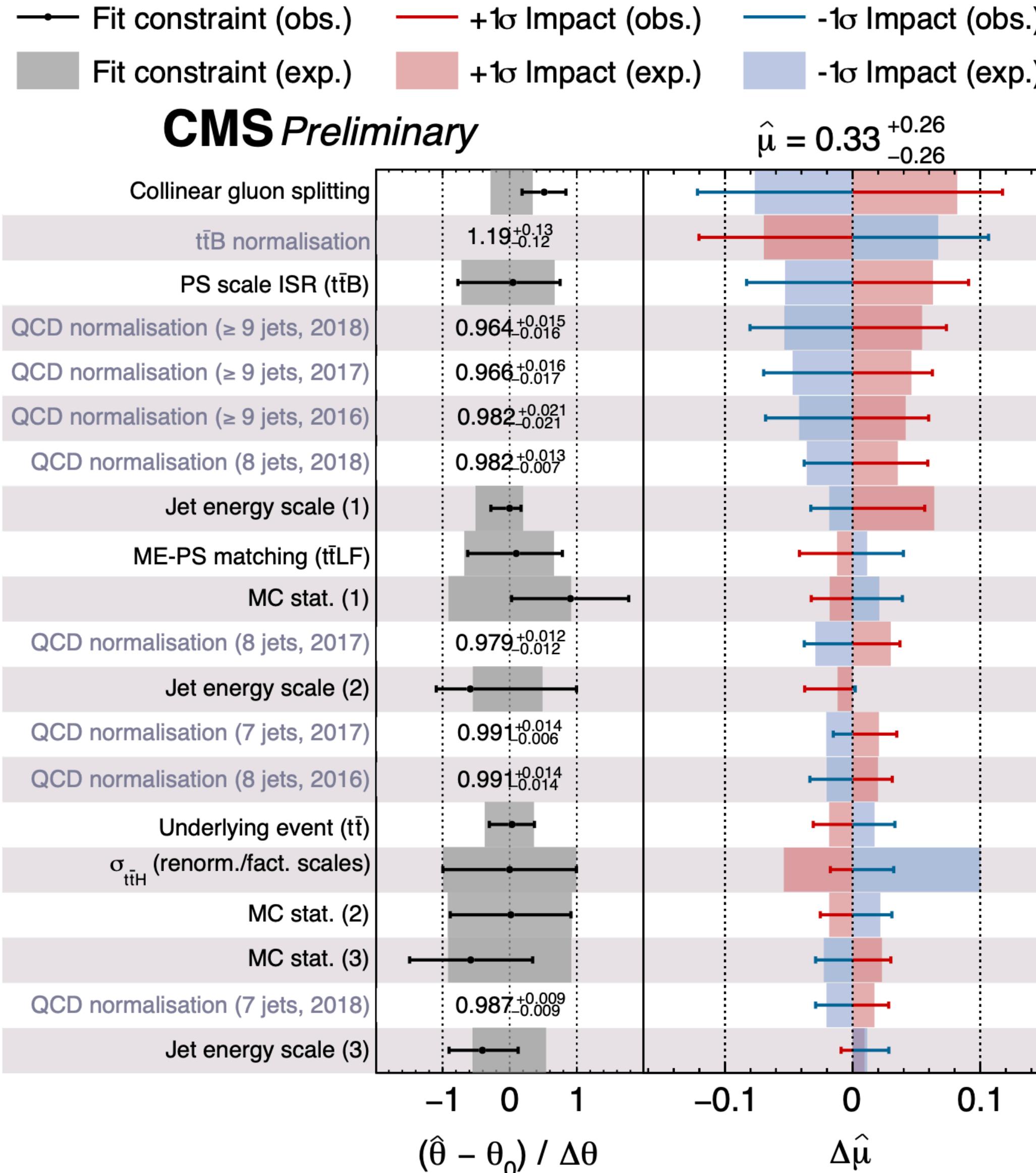
Very large combinatorial background 4 b-jets in all cases!



SL as expected is the most powerful equivalent stat-syst contributions
FH Dominated by syst uncertainties
DL Stat still largest

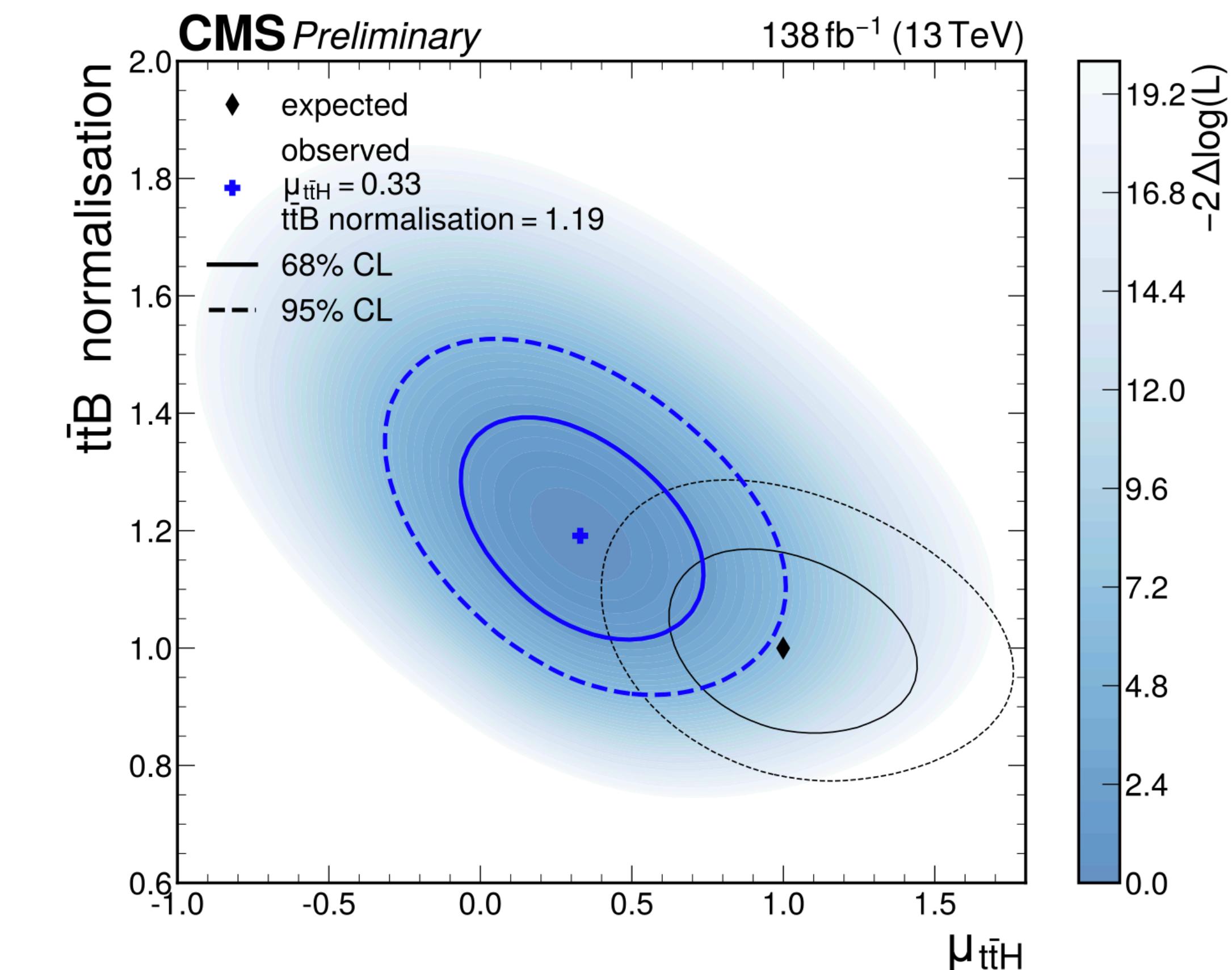
Direct probe of the top Yukawa coupling in ttH(bb)

43



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

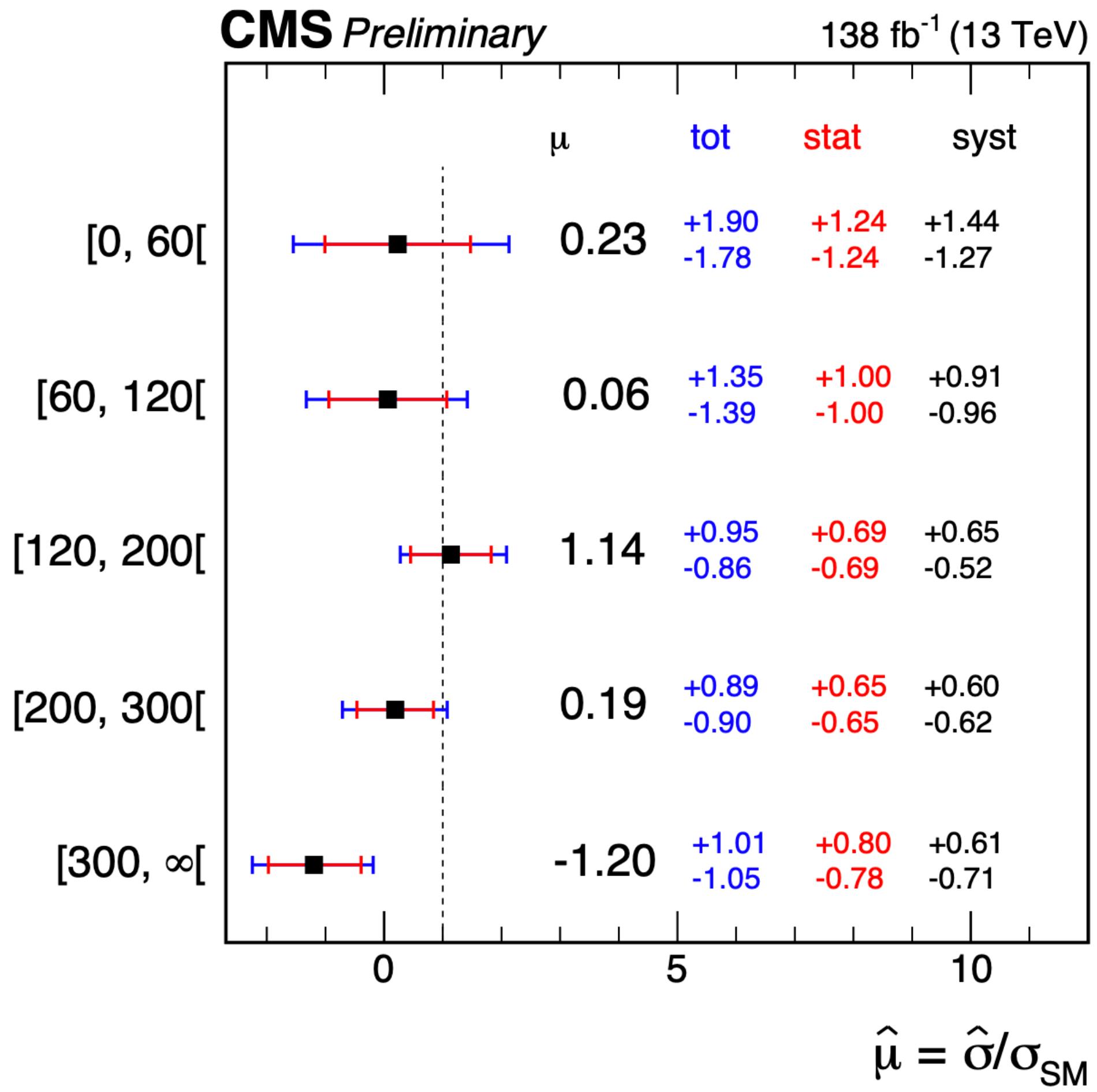
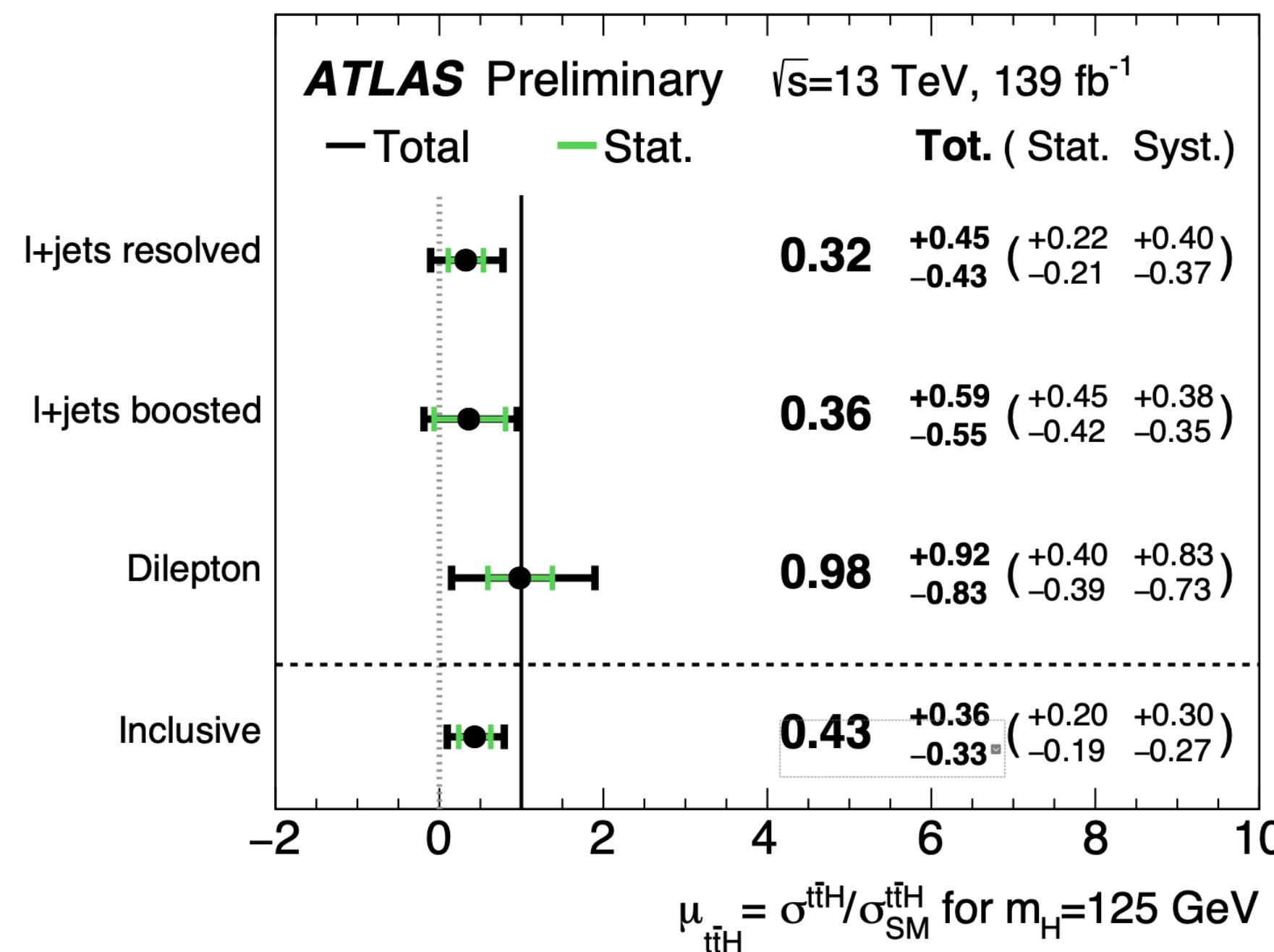


Direct probe of the top Yukawa coupling in ttH(bb)

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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.



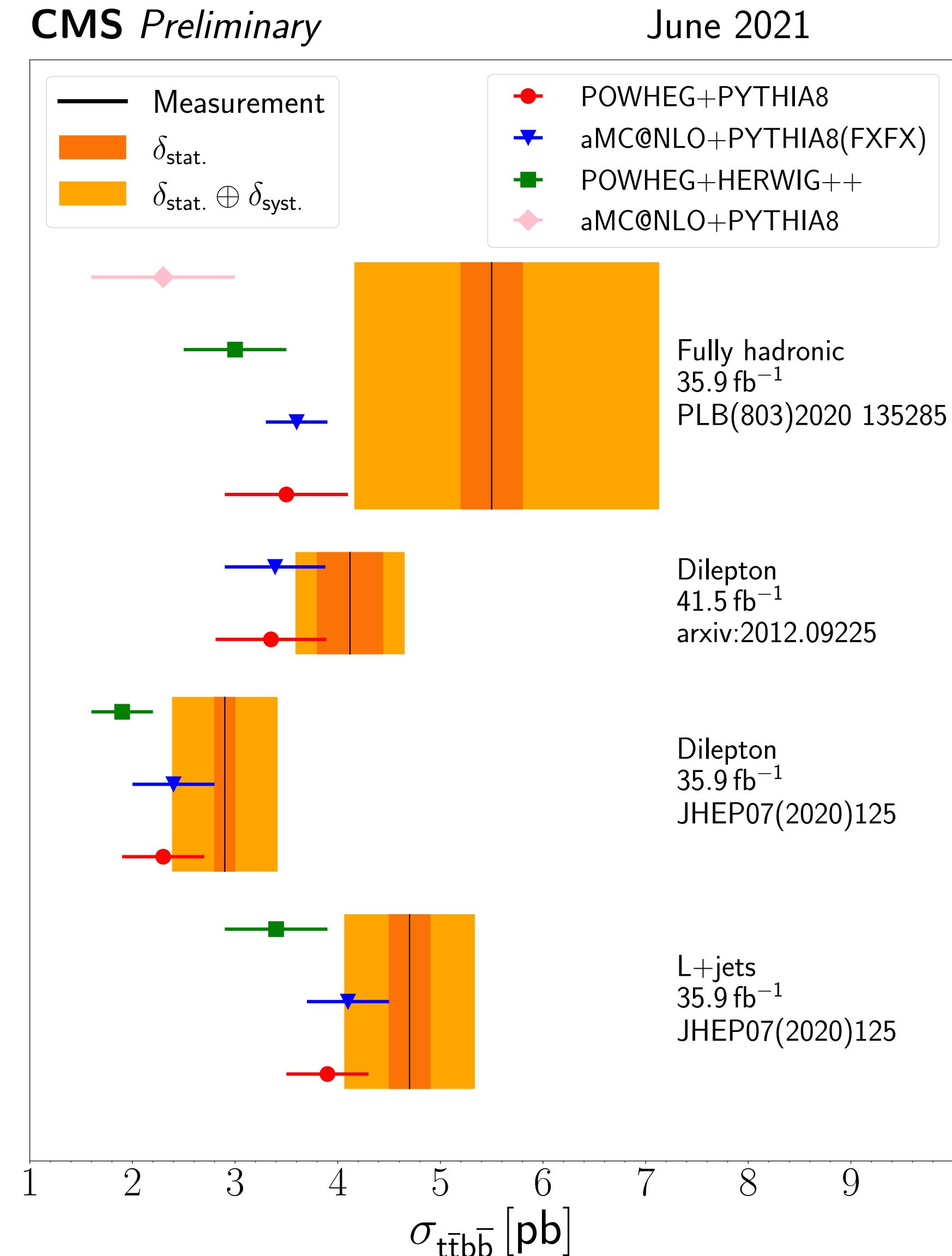
Ancillary Measurement of ttbb by CMS

45

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.

What about CPV Fermion Couplings?

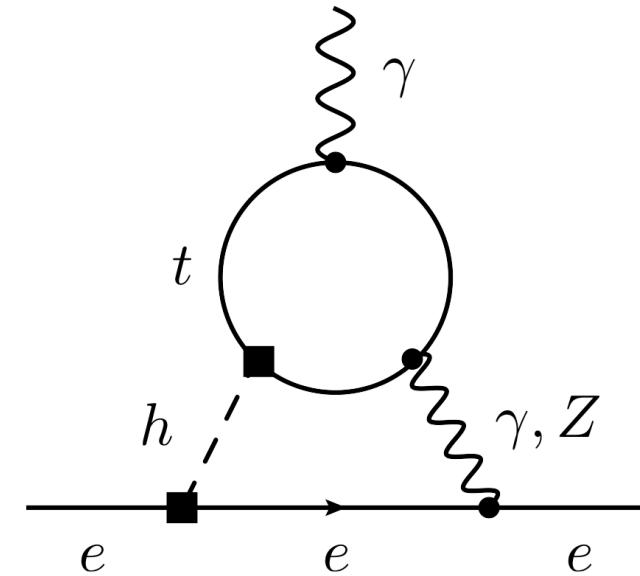
The pseudoscalar coupling of the Higgs boson to fermions not probed directly (yet)

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

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

However indirect probes through electron (and neutron) EDM Very suppressed in the SM (where it arises at four loops)

A good probe for NP BSM!



From J. Brod., U. Haisch and J. Zupan 2013

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

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

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

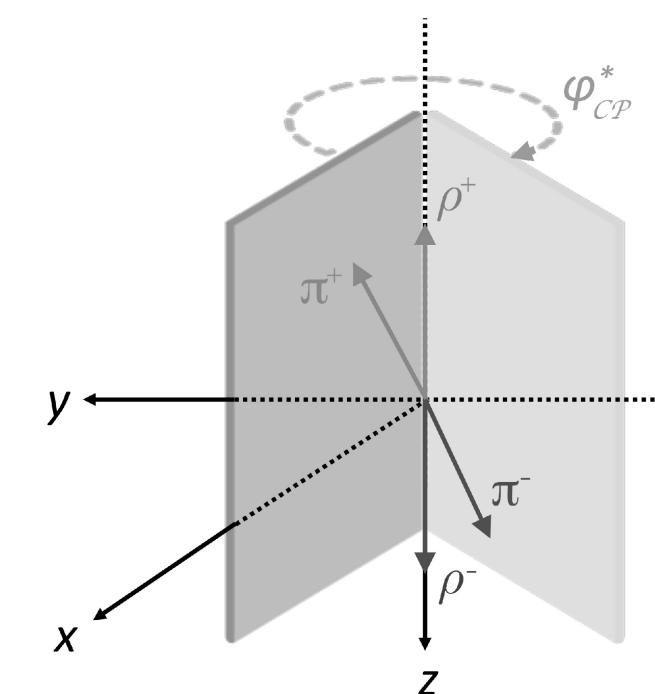
Assuming electron Yukawa SM $\tilde{\kappa}_t < 0.001$

This strong constraint is model dependent, still interesting to probe directly through the ttH production channel.

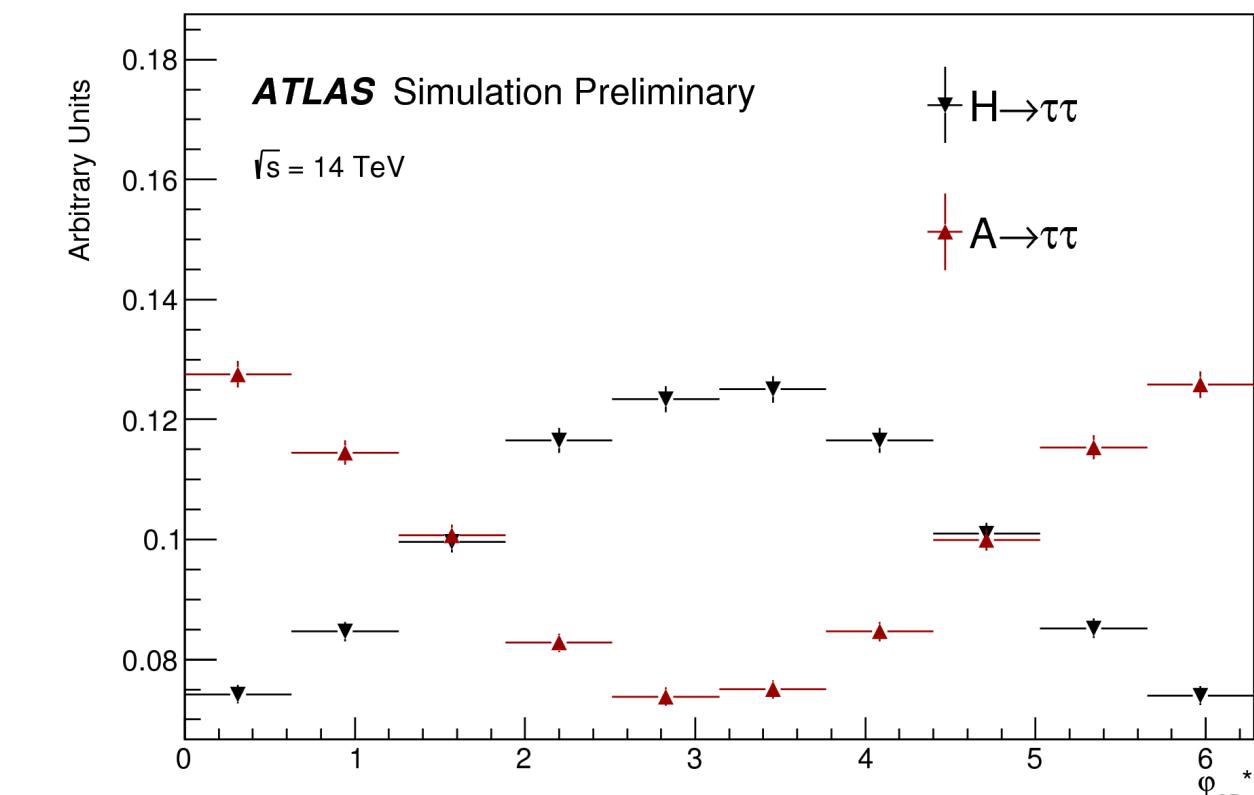
First preliminary study using the $h \rightarrow b\bar{b}$ mode and top pair angular variables in the di-leptonic and semi-leptonic modes shows that and exclusion of a pure CP-odd is possible already at Run 3.

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

First attempts to constrain this coupling using tau polarisation observables



Sensitivity of ~0.3 at 68% CL at HL-LHC

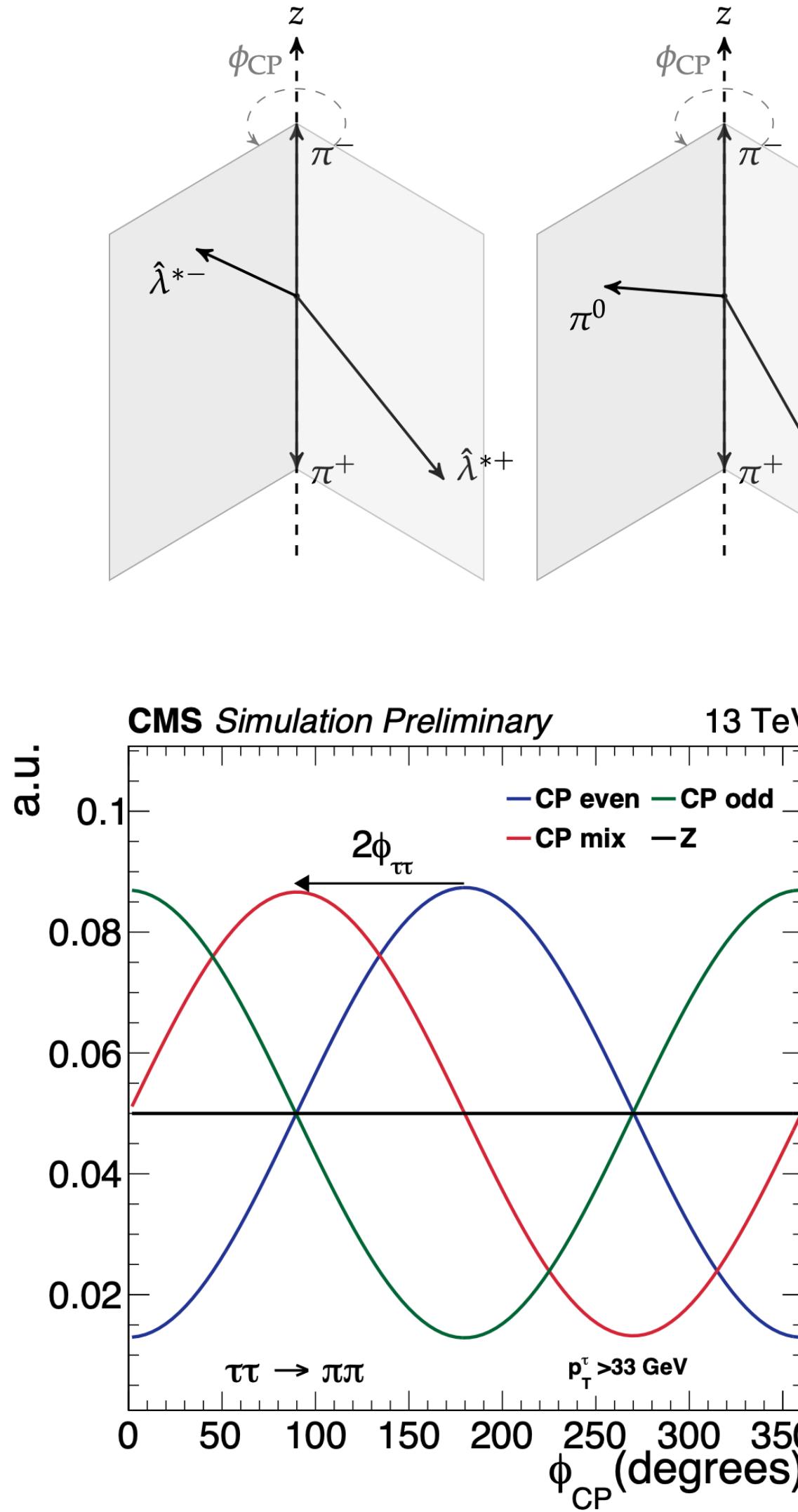


CP properties of the Tau Yukawa

Through polarisation sensitive variable

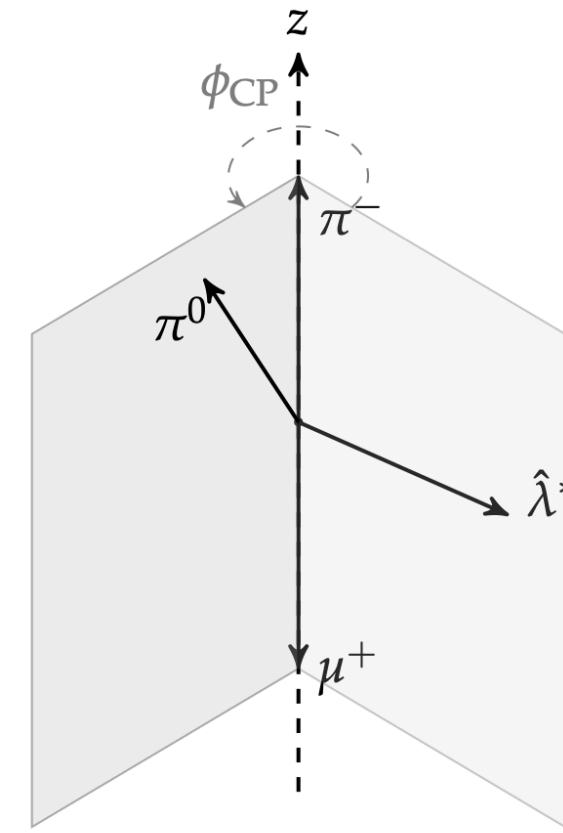
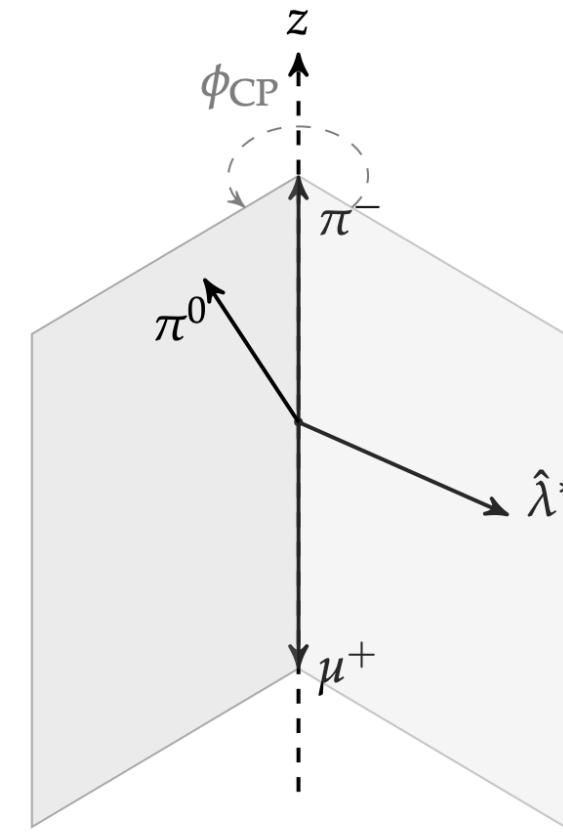
47

[CMS PAS HIG-20-006](#)

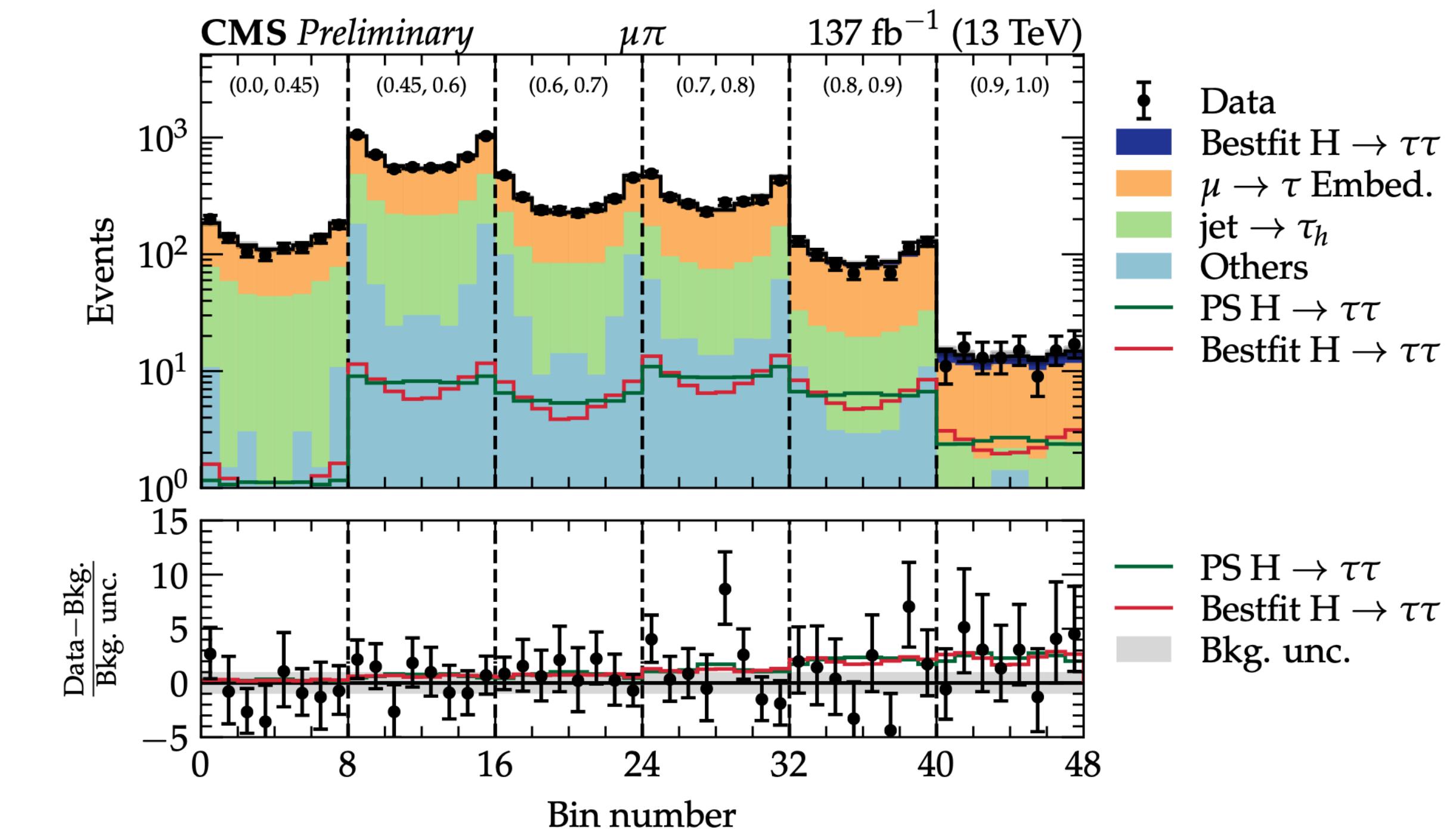


Uses either the impact parameter direction for single-prong taus (π^\pm) only or using the π^0 momentum for the $\tau \rightarrow \pi^\pm \pi^0 [\rho(770 \text{ MeV})] \nu_\tau$

This method works also for the three prong tau decays with a $\rho^0 \rightarrow \pi^+ \pi^-$



Tau decays are selected with a BDT and the ϕ_{CP} distribution is considered in different bins of this BDT score



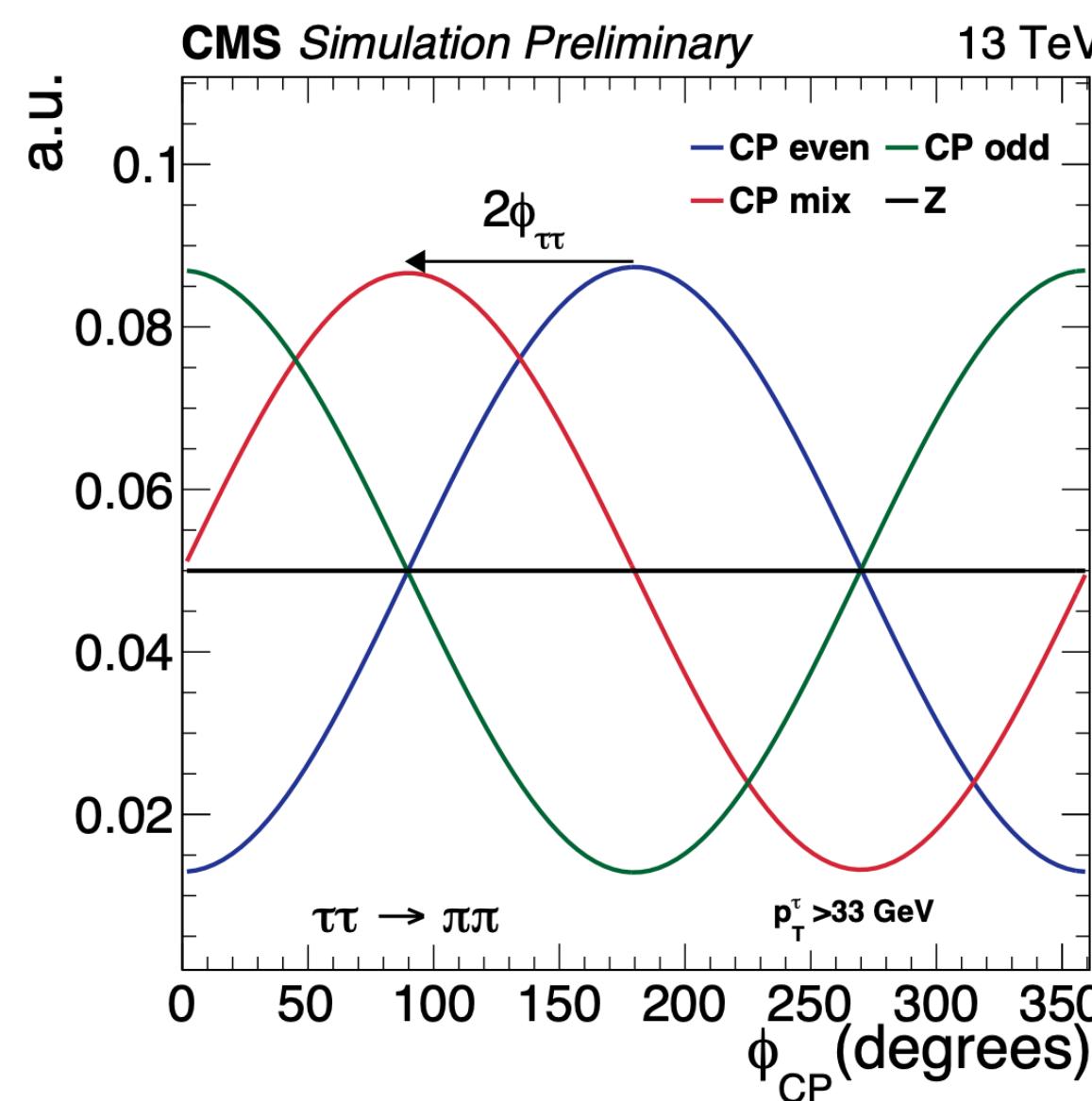
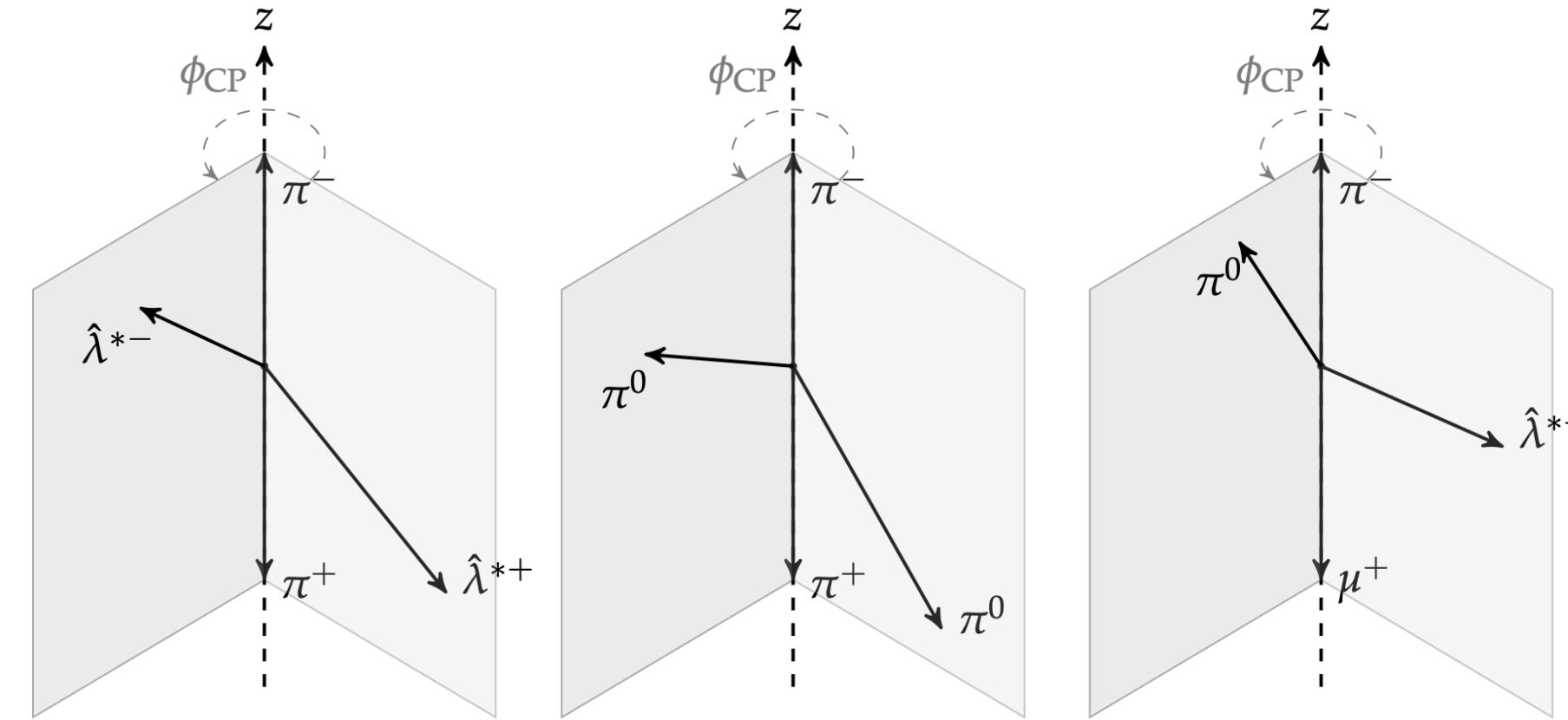
Tau decays are selected with a BDT and the ϕ_{CP} distribution is considered in different bins of this BDT score

CP properties of the Tau Yukawa

Through polarisation sensitive variable

48

[CMS PAS HIG-20-006](#)

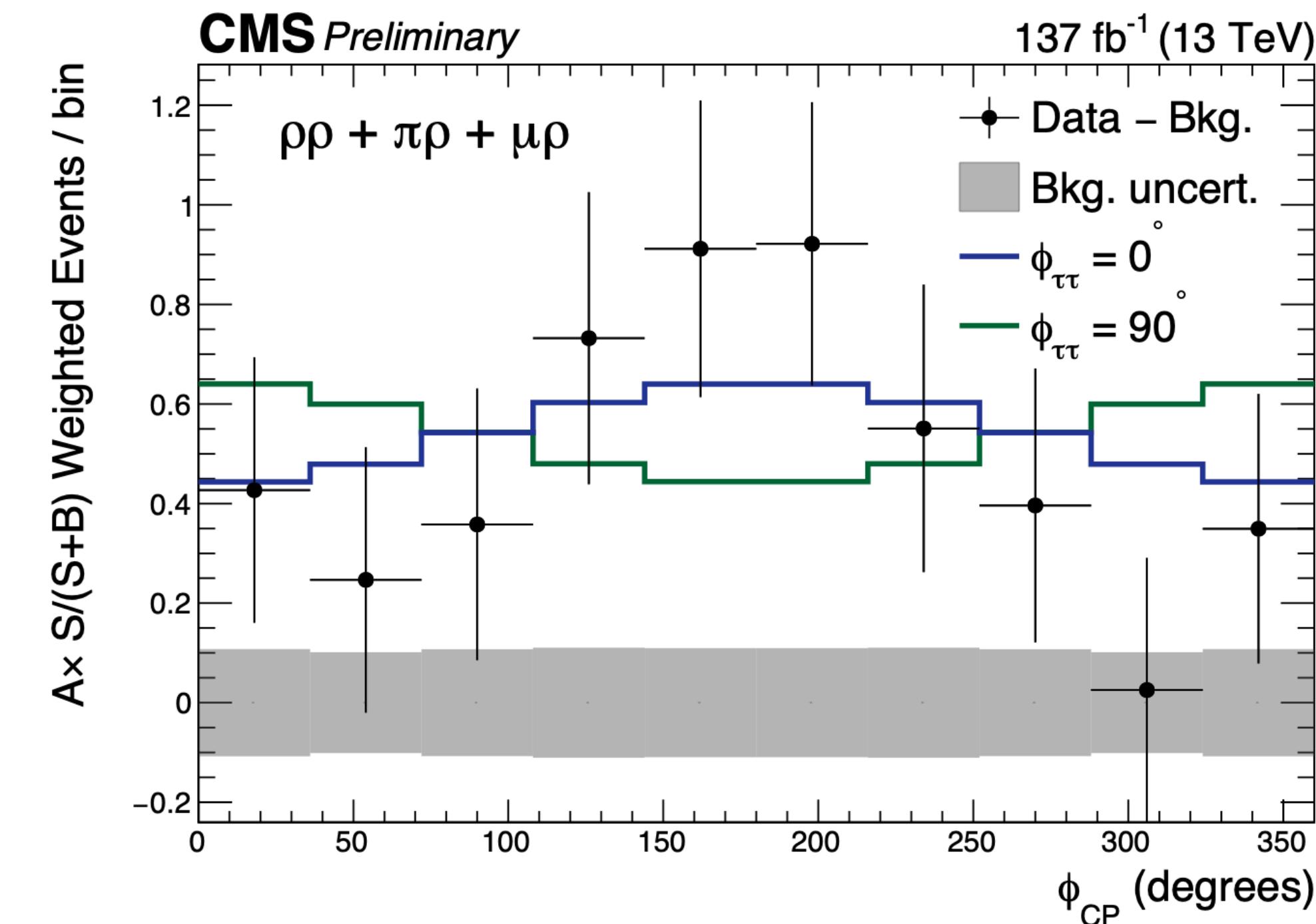


Uses either the impact parameter direction for single-prong taus (π^\pm) only or using the π^0 momentum for the $\tau \rightarrow \pi^\pm \pi^0$ [$\rho(770 \text{ MeV})$] ν_τ

This method works also for the three prong tau decays with a $\rho^0 \rightarrow \pi^+ \pi^-$

Tau decays are selected with a BDT and the ϕ_{CP} distribution is considered in different bins of this BDT score

Overall weighted distribution for all channels:

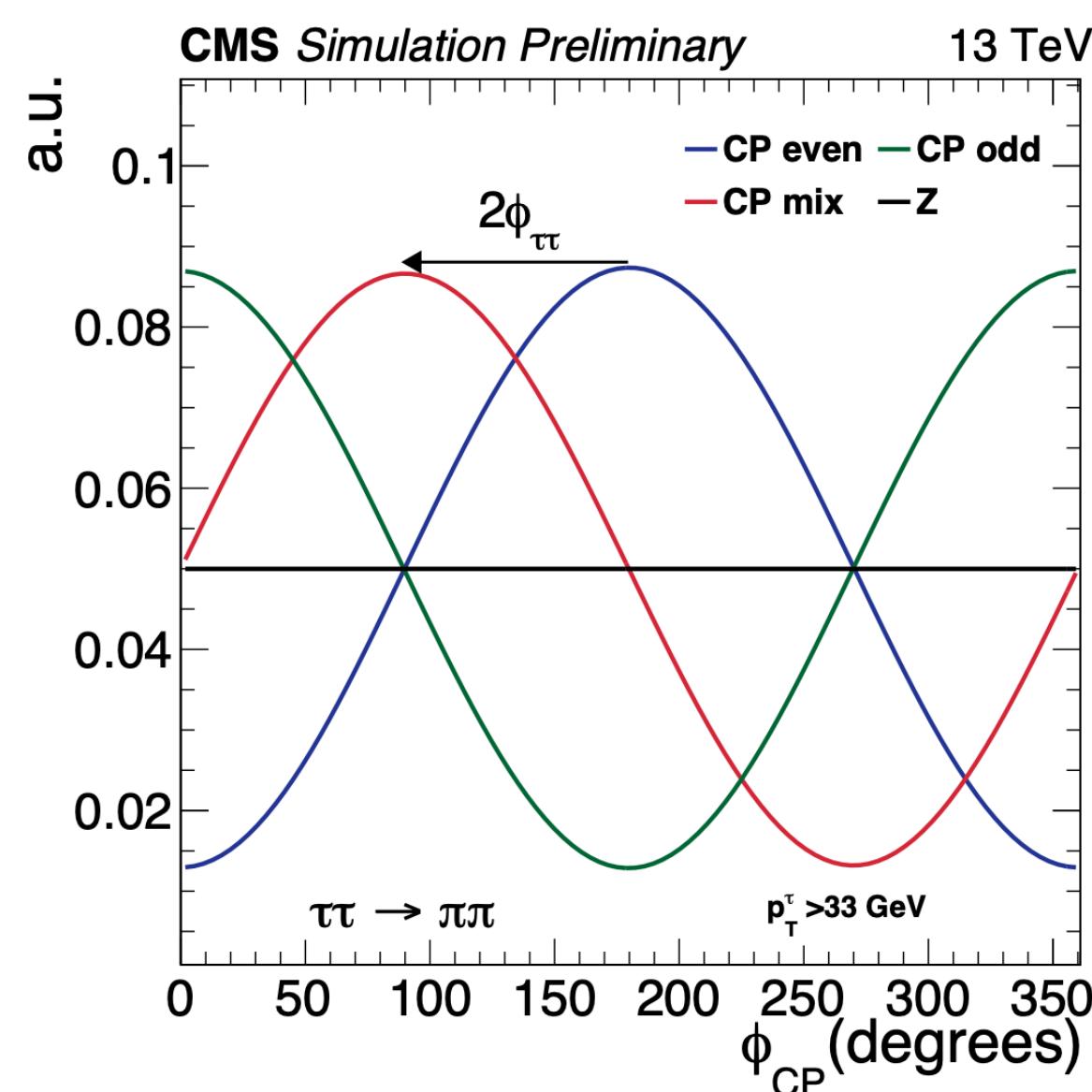
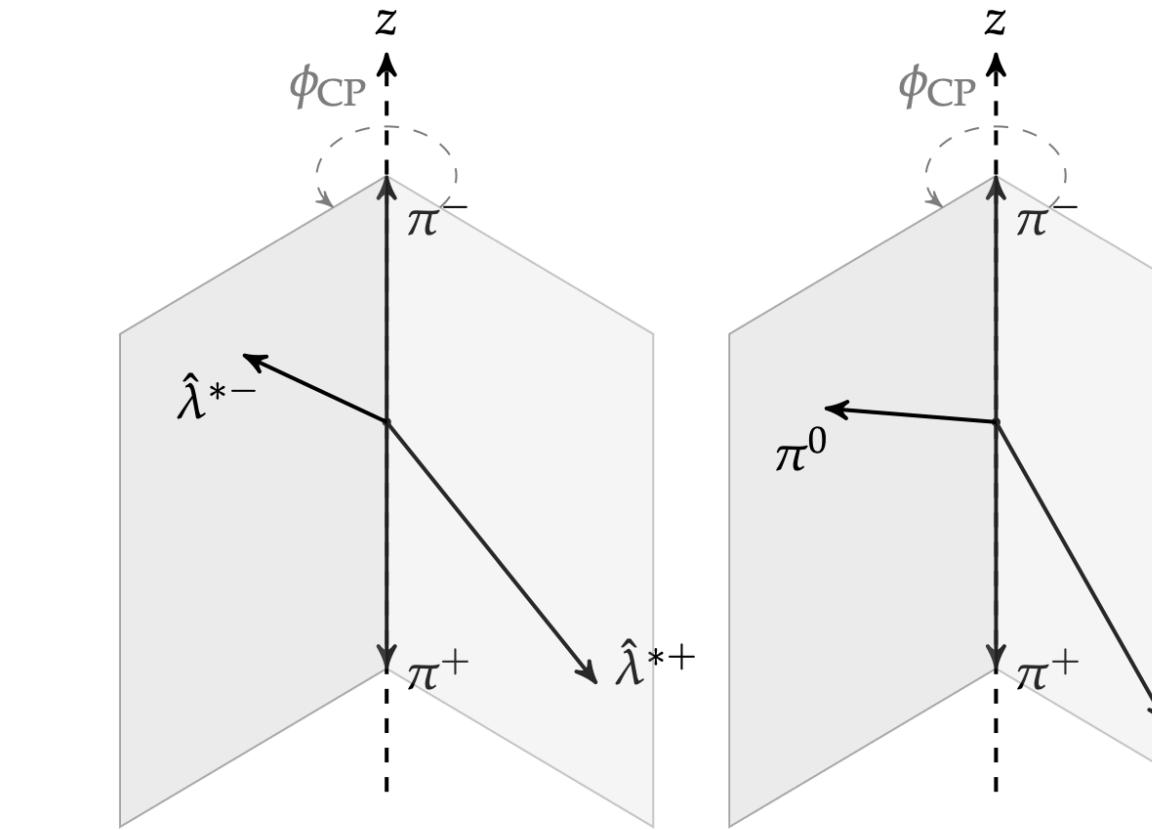


CP properties of the Tau Yukawa

Through polarisation sensitive variable

49

[CMS PAS HIG-20-006](#)



Uses either the impact parameter direction for single-prong taus (π^\pm) only or using the π^0 momentum for the $\tau \rightarrow \pi^\pm \pi^0 [\rho(770 \text{ MeV})] \nu_\tau$

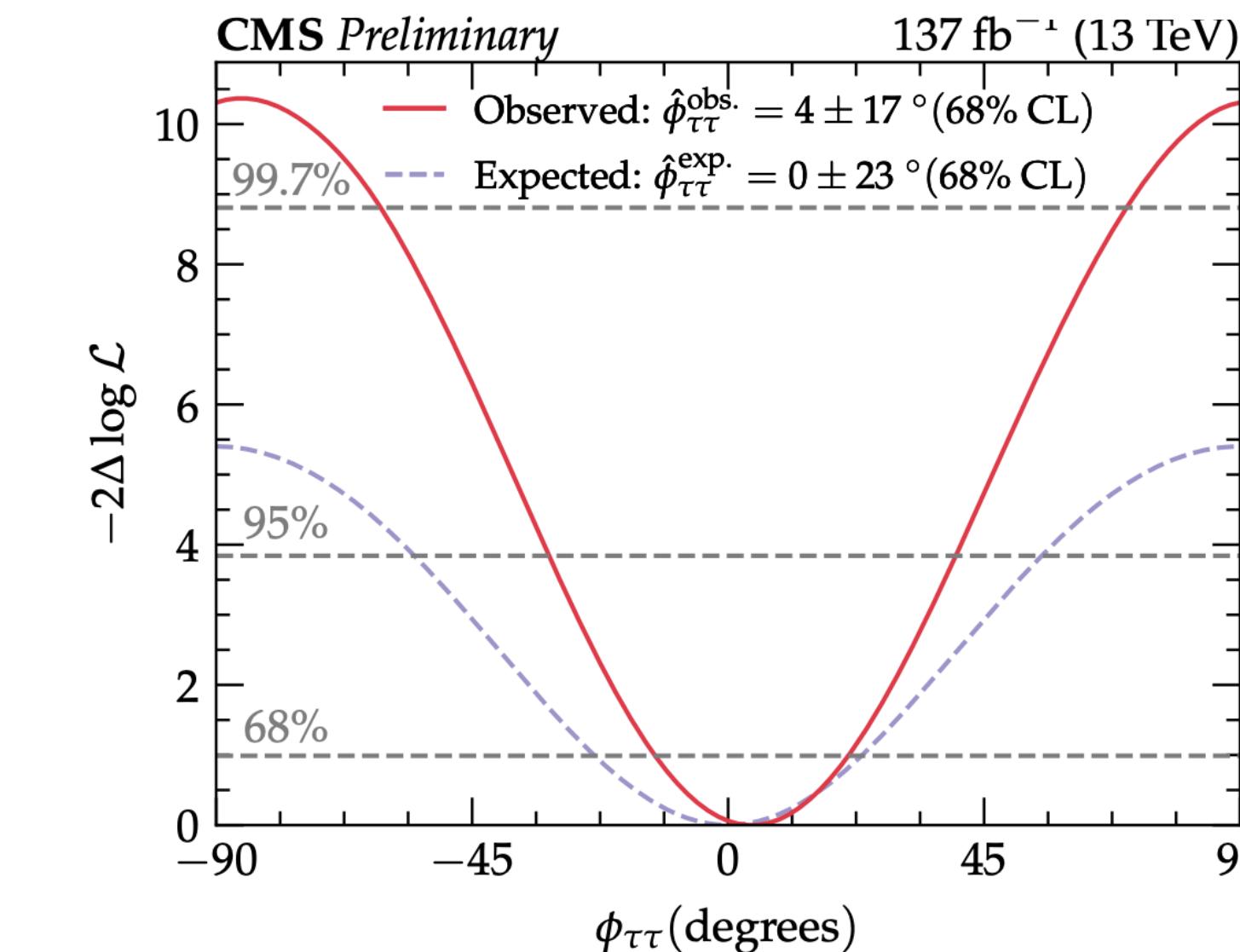
This method works also for the three prong tau decays with a $\rho^0 \rightarrow \pi^+ \pi^-$

Tau decays are selected with a BDT and the ϕ_{CP} distribution is considered in different bins of this BDT score

Fit is performed in order to estimate the ratio of the CP-odd to CP-even couplings - CP mixing angle:

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

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



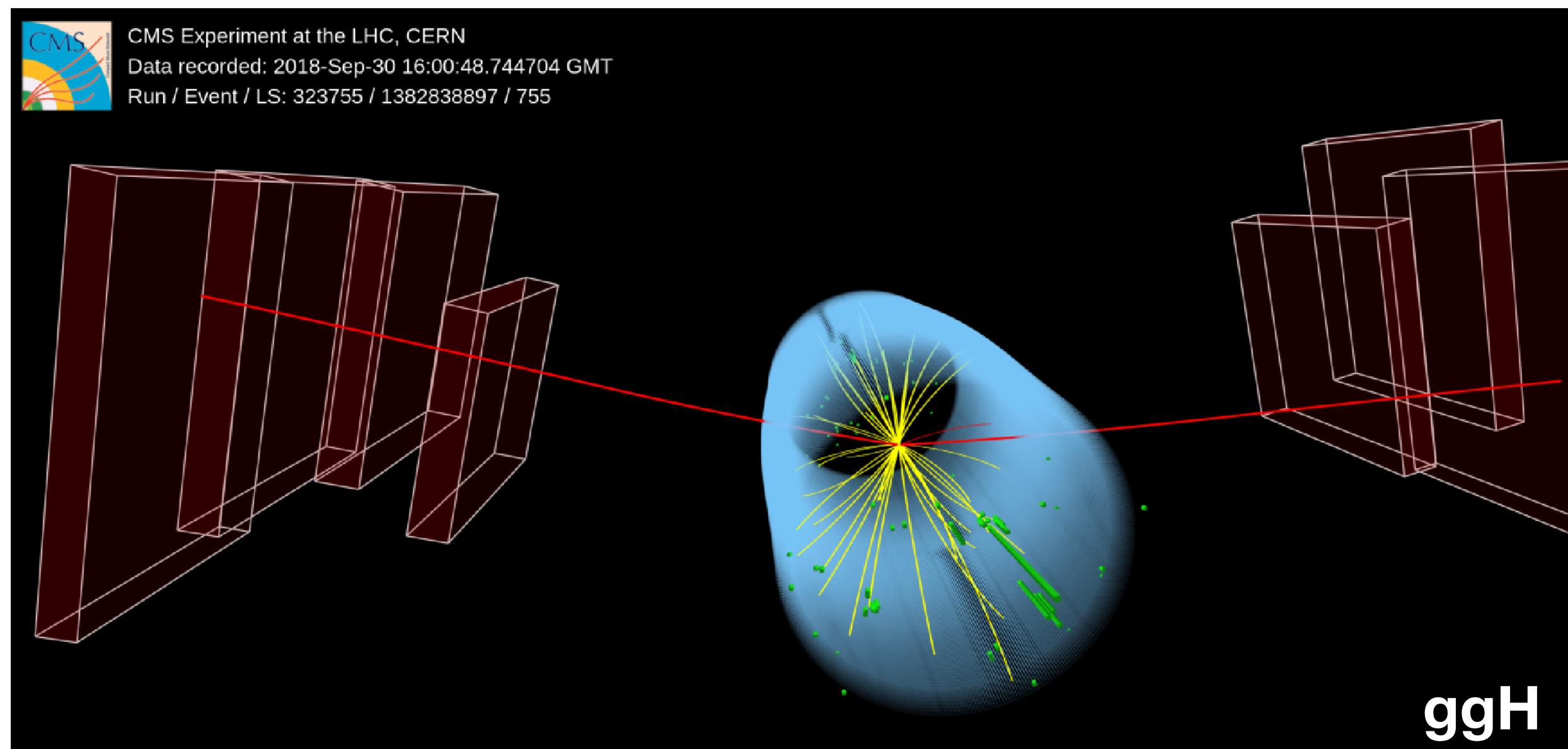
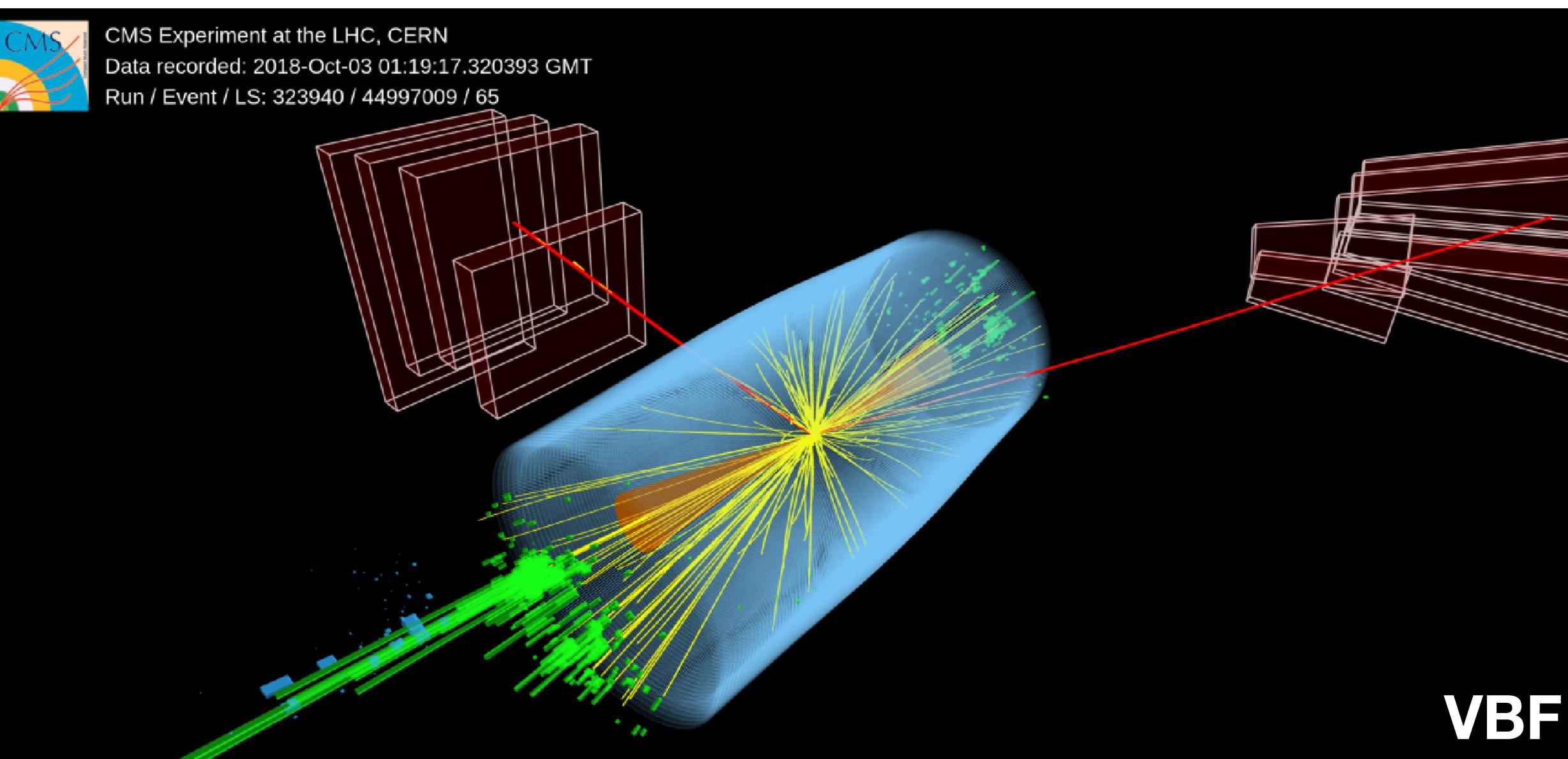
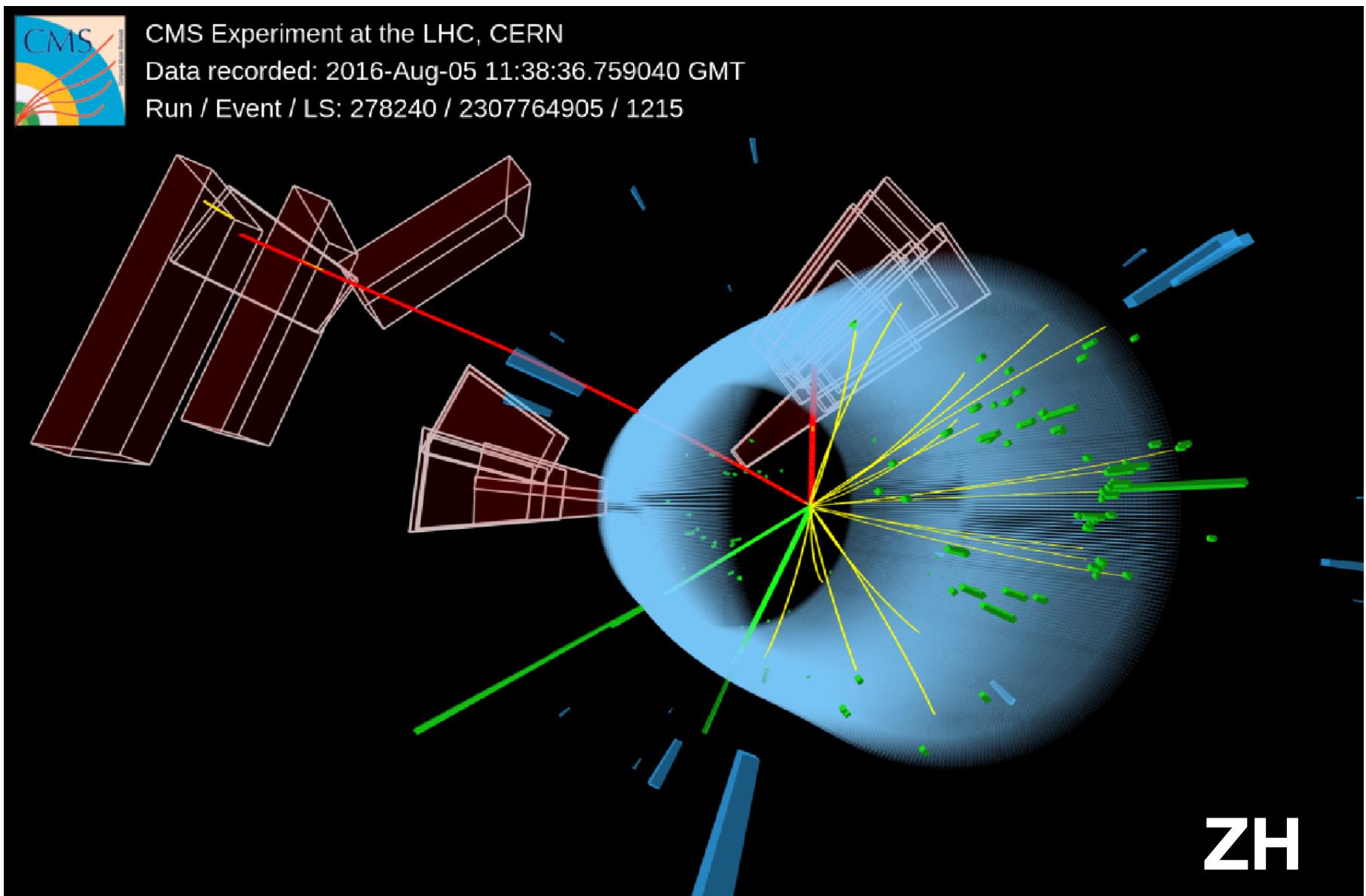
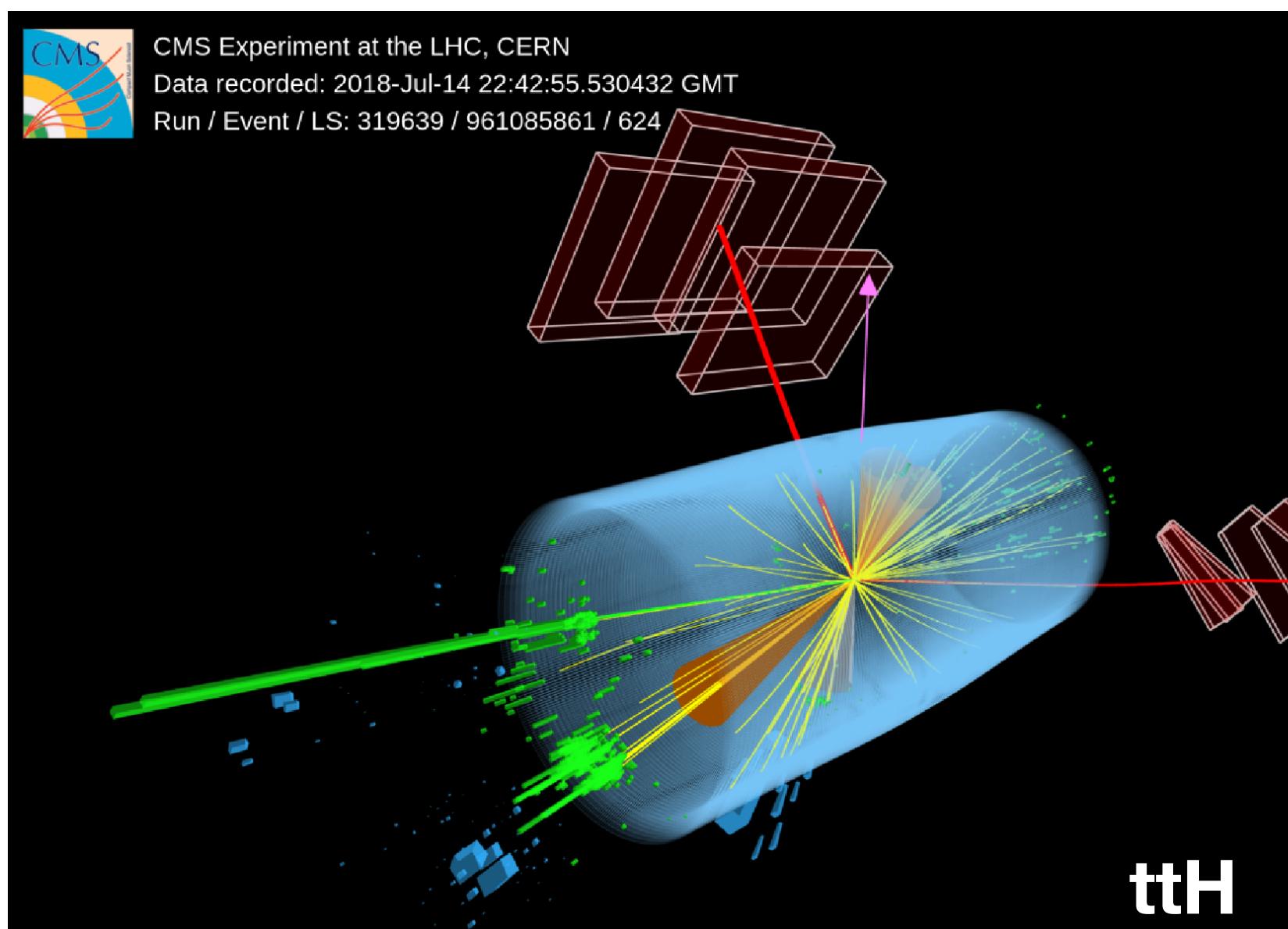
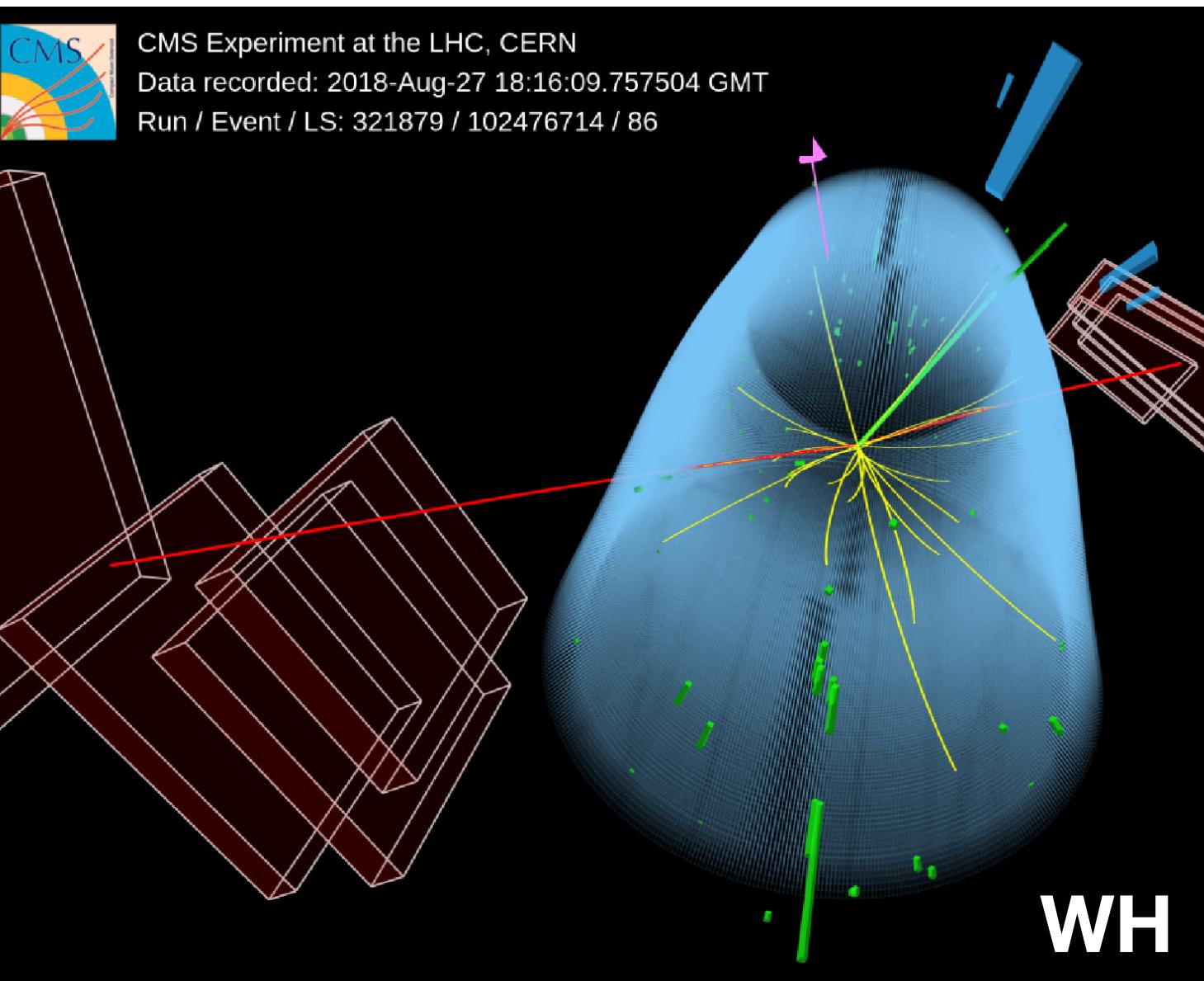
$$\phi_{\tau\tau} = 4 \pm 17^\circ \text{ (23}^\circ \text{ exp.)}$$

CP-even preferred vs CP-Odd at $\sim 3\sigma$ level

Early evidences for Rare processes

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

51



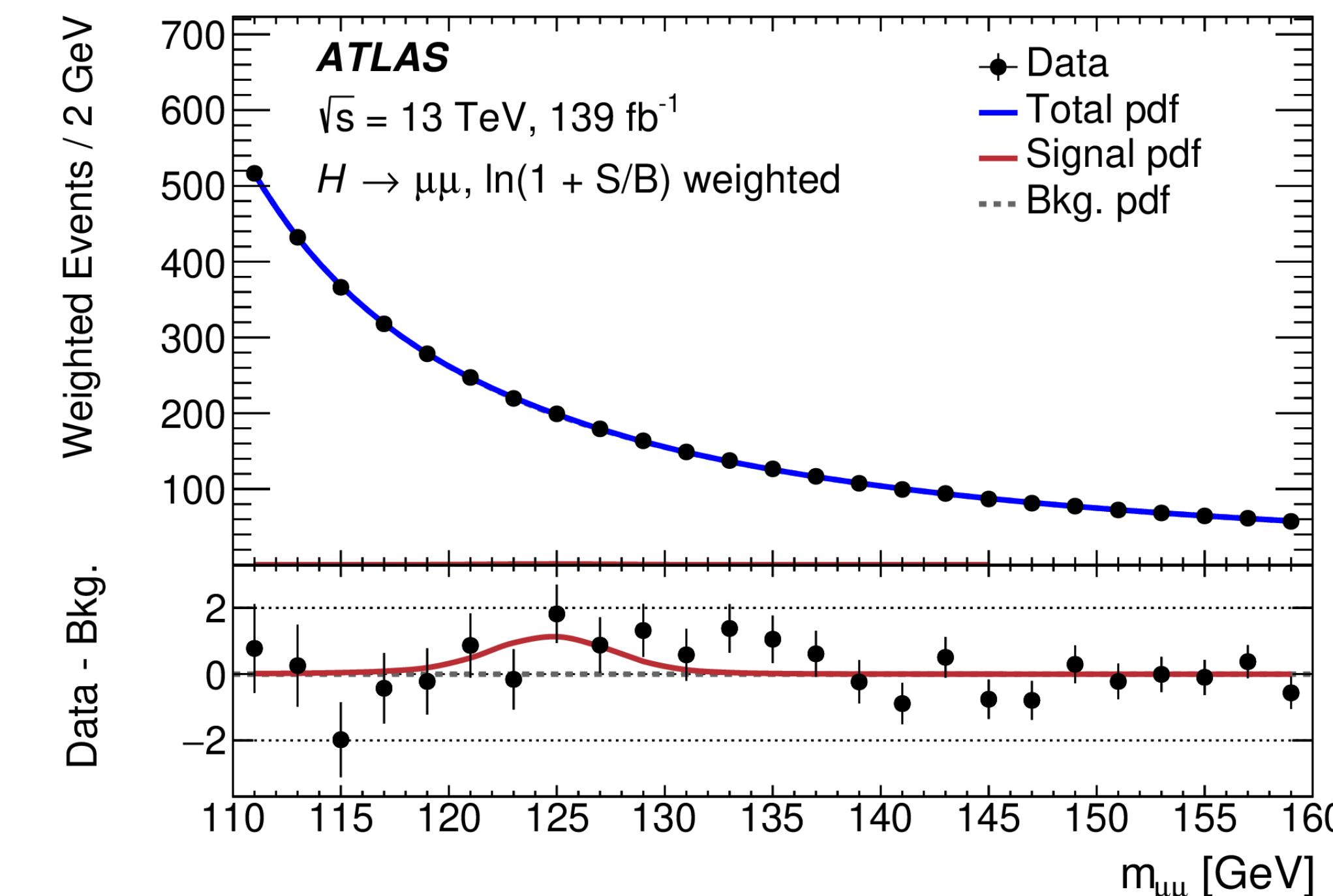
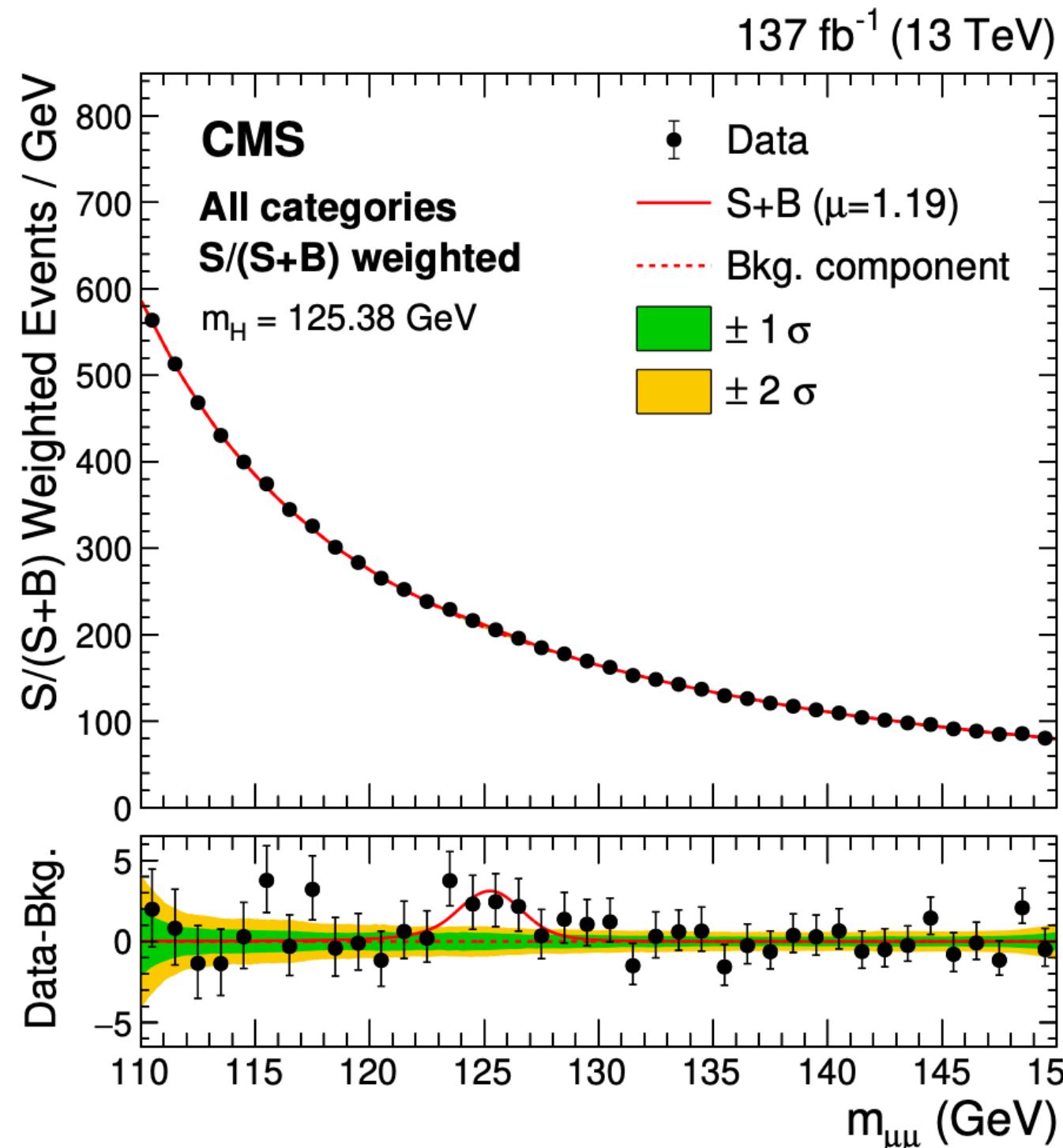
Evidence for Second Generation Yukawa Coupling

52

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!



Evidence for Second Generation Yukawa Coupling

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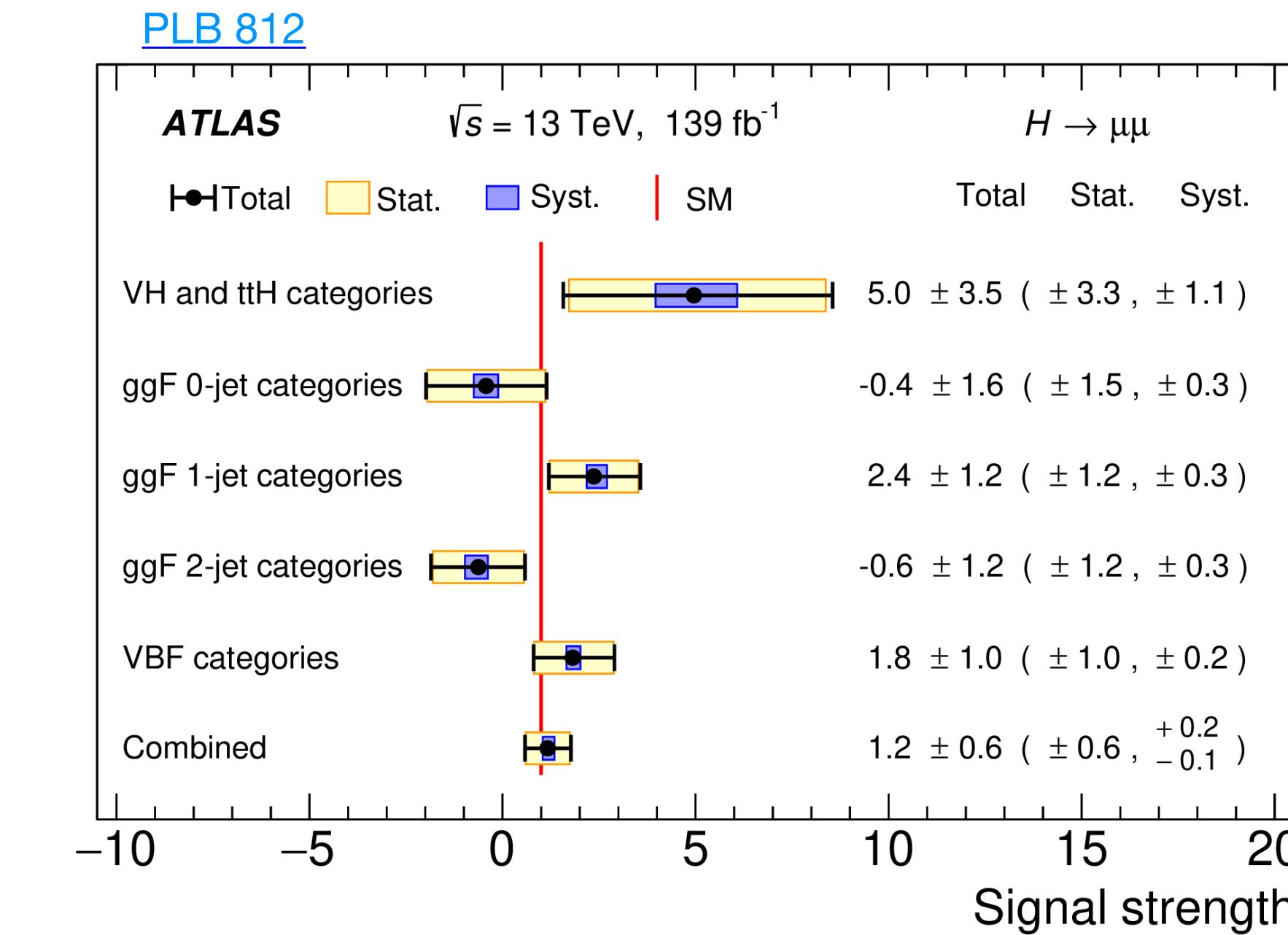
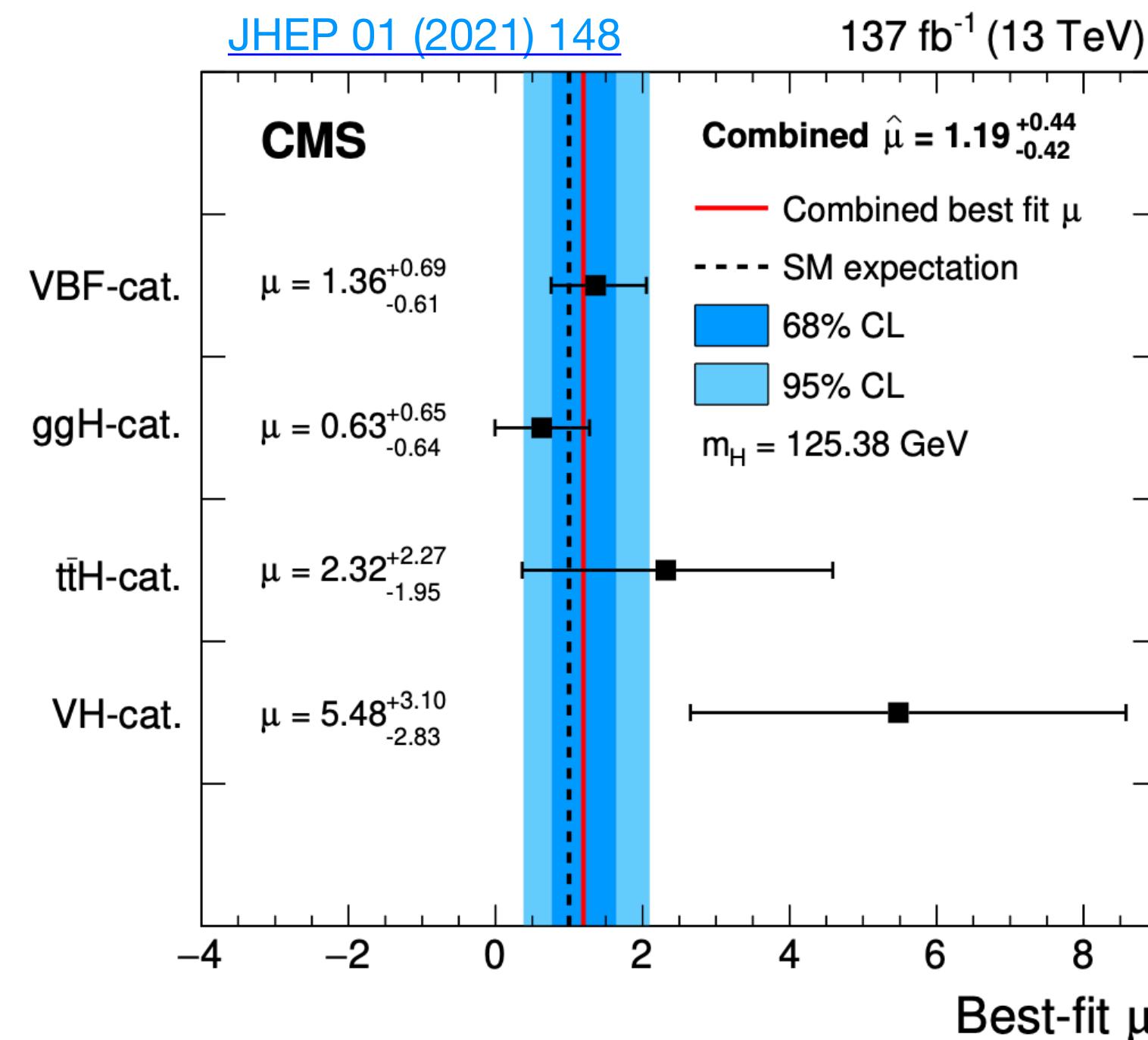
Summary of all categories Estimate the background parameters through a fit of an analytical form!

CMS Result

Expected 2.5σ

Observed 3.0σ

$$\mu = 1.19 \pm 0.43$$



HL-LHC ~5%

Result dominated by statistical uncertainty, but watch systematics!

ATLAS Result

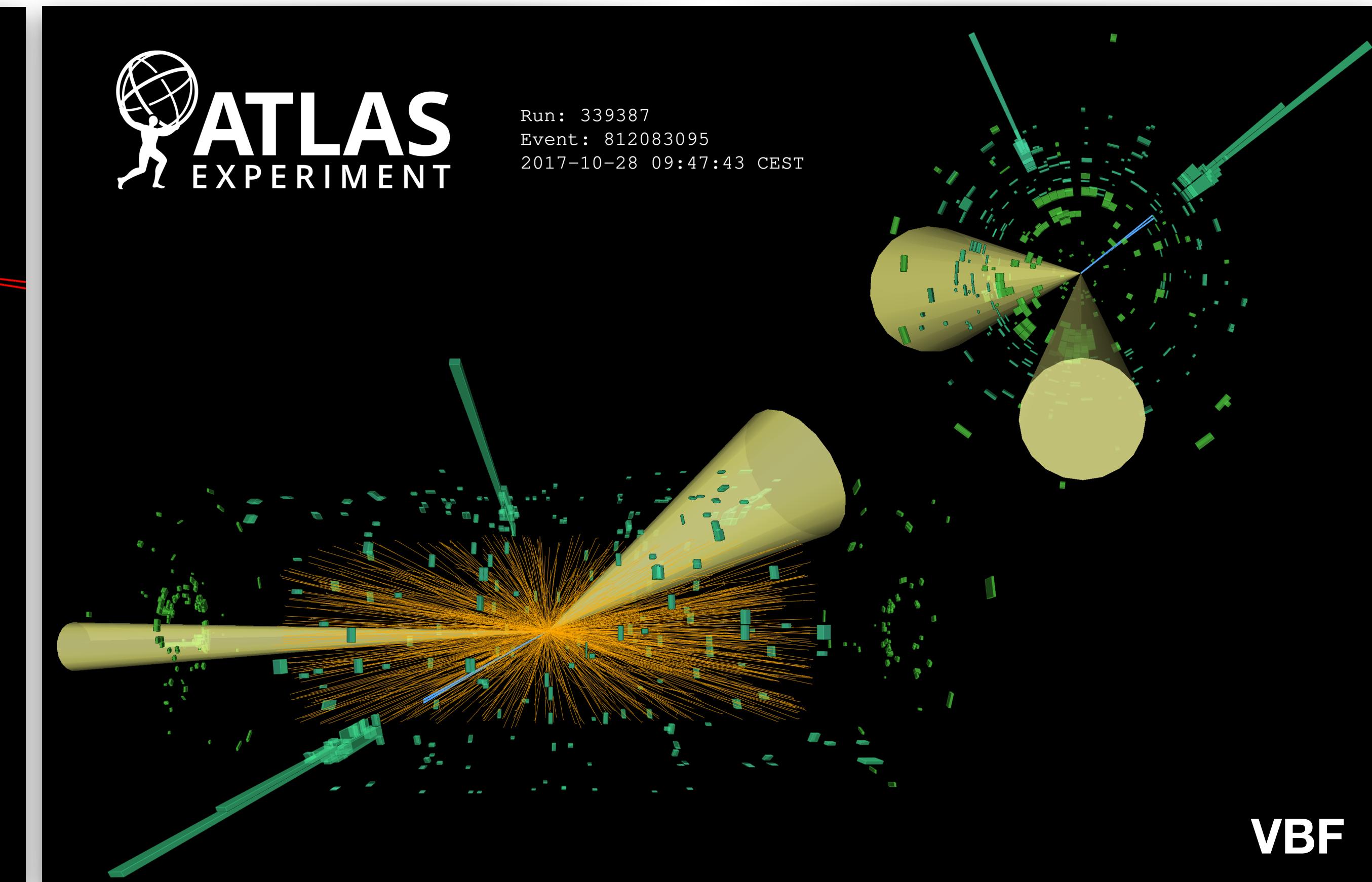
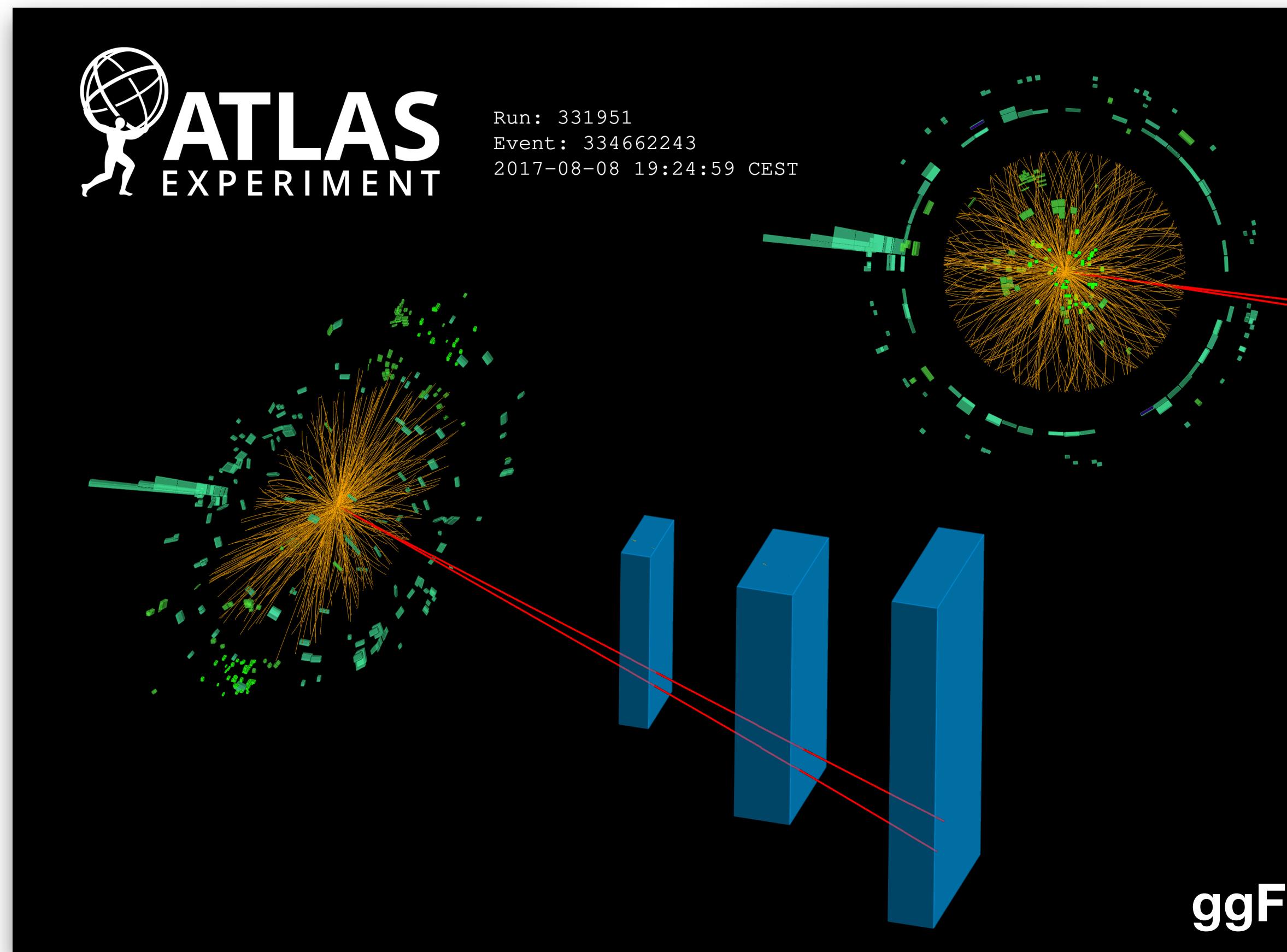
Expected 1.7σ

Observed 2.0σ

$$\mu = 1.2 \pm 0.6$$

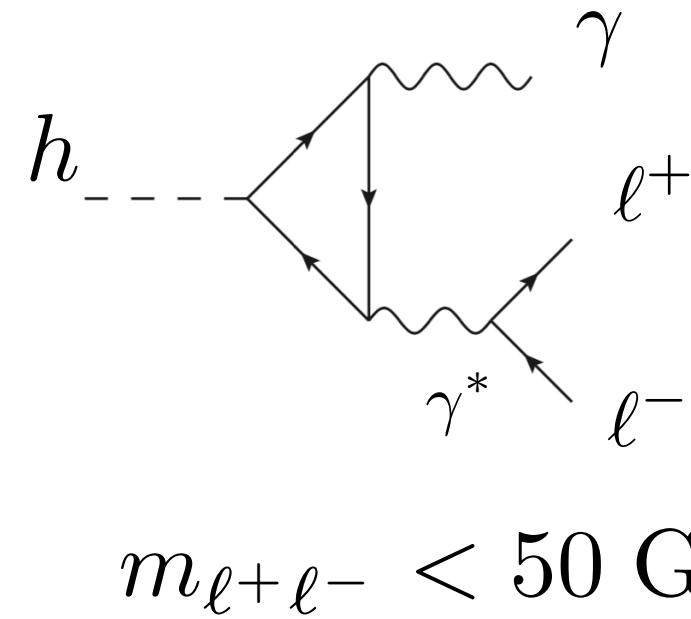
Evidence for $H \rightarrow \gamma^*\ell^+\ell^-$

54



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

55

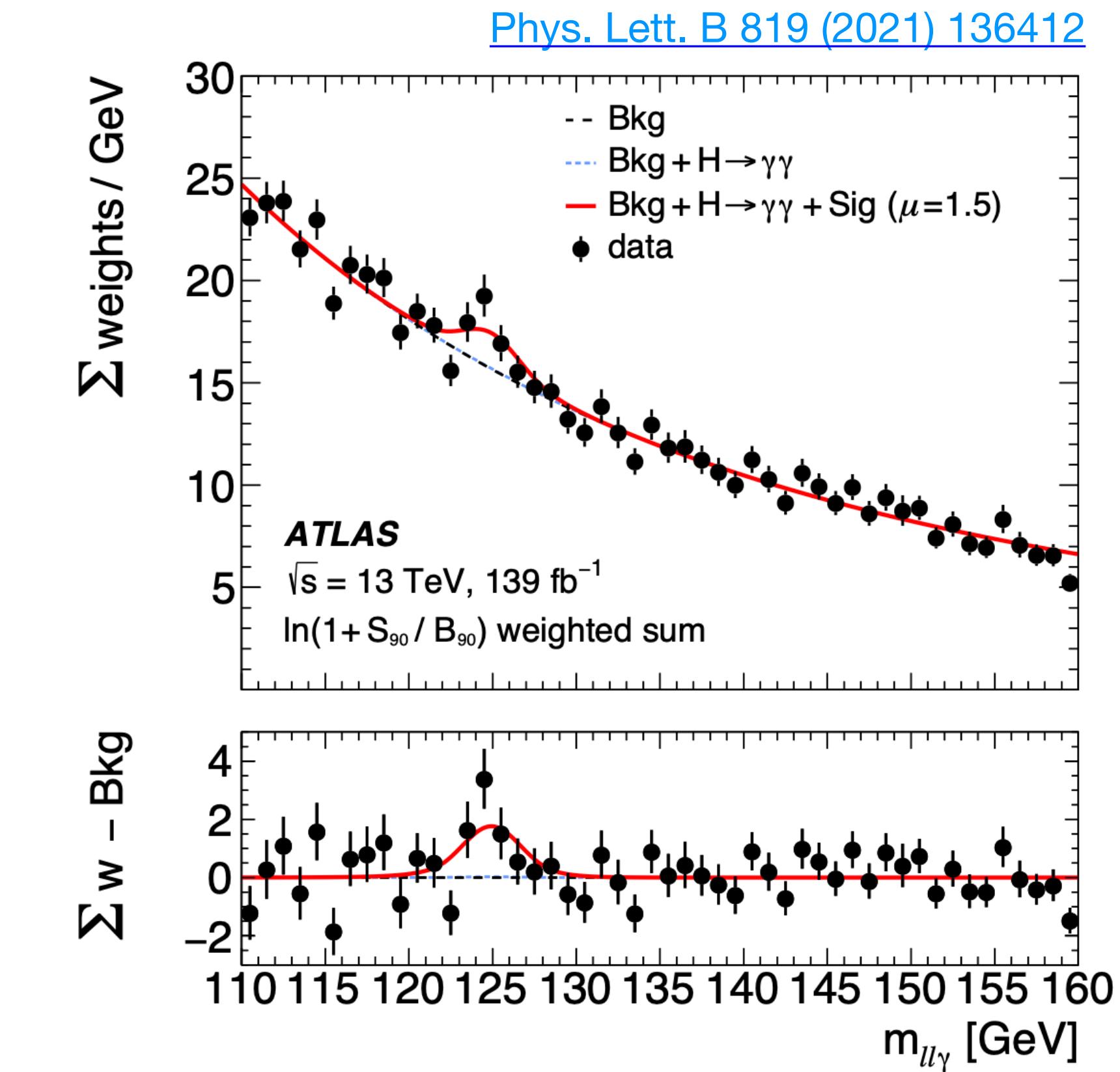
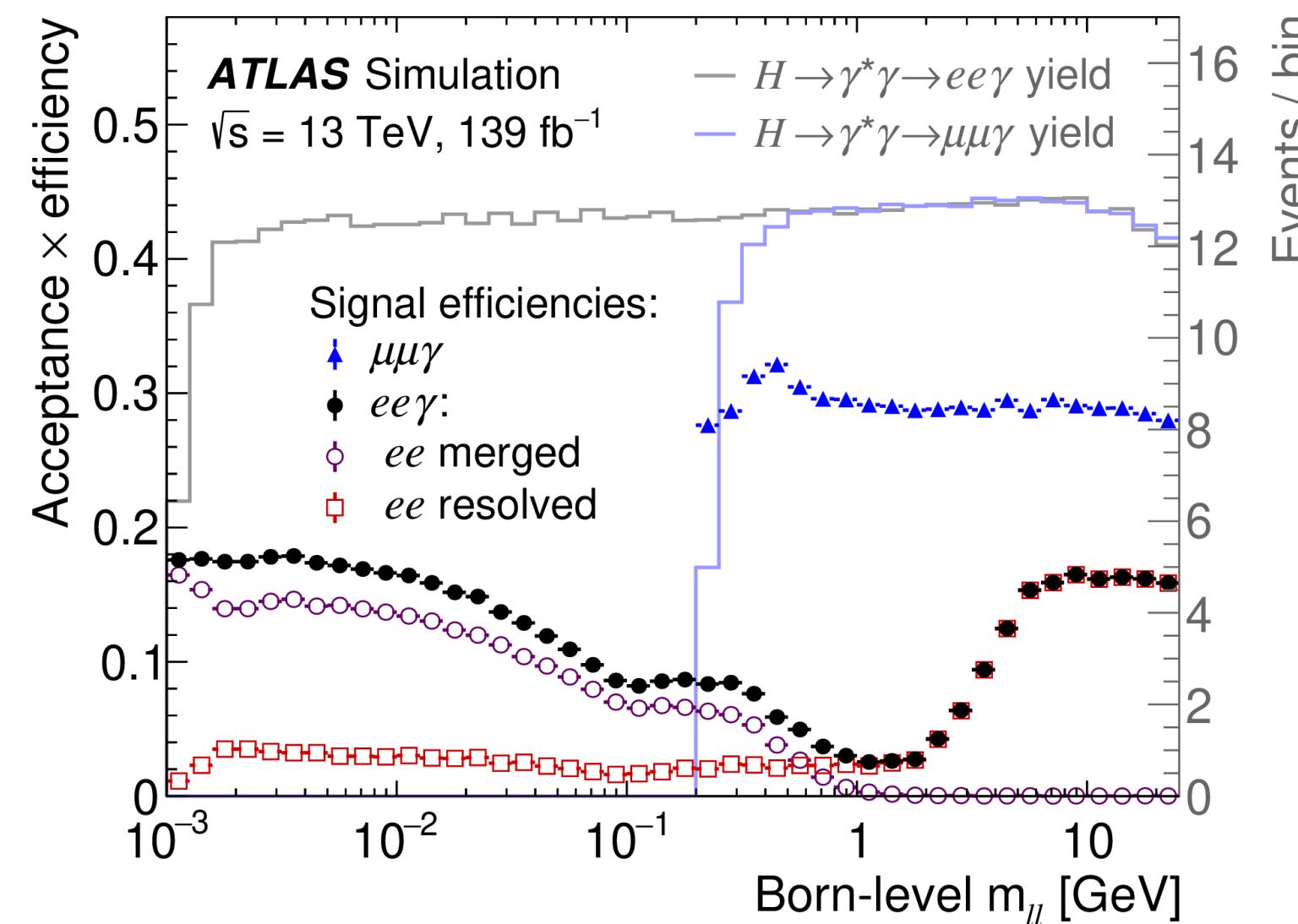


Search initially made in this case in the dimuon channel only (in the low di-lepton mass limit the shower of electrons merge).

$\sim 1.7\% \text{ of } Br(\gamma\gamma)$

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!



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

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

Expected 2.1σ
Observed 3.2σ

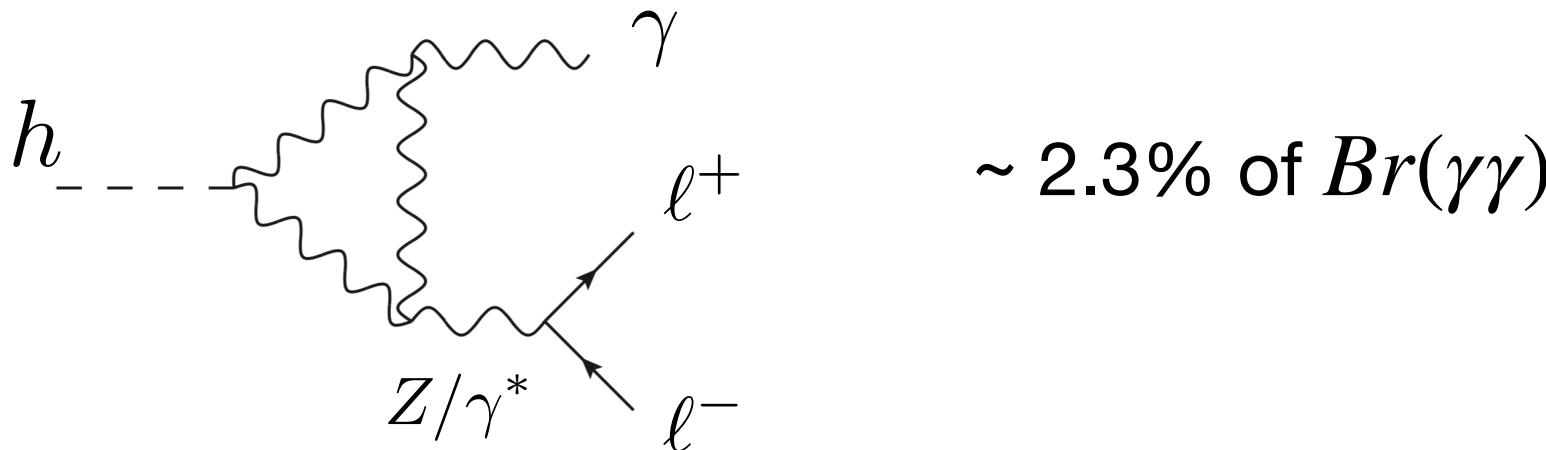
- 3 x 3 categories (VBF, high pT ggF, low pT ggF) \otimes (ee resolved, ee merged, $\mu\mu$)
- Contributions from J/ψ are removed with a mass cut

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

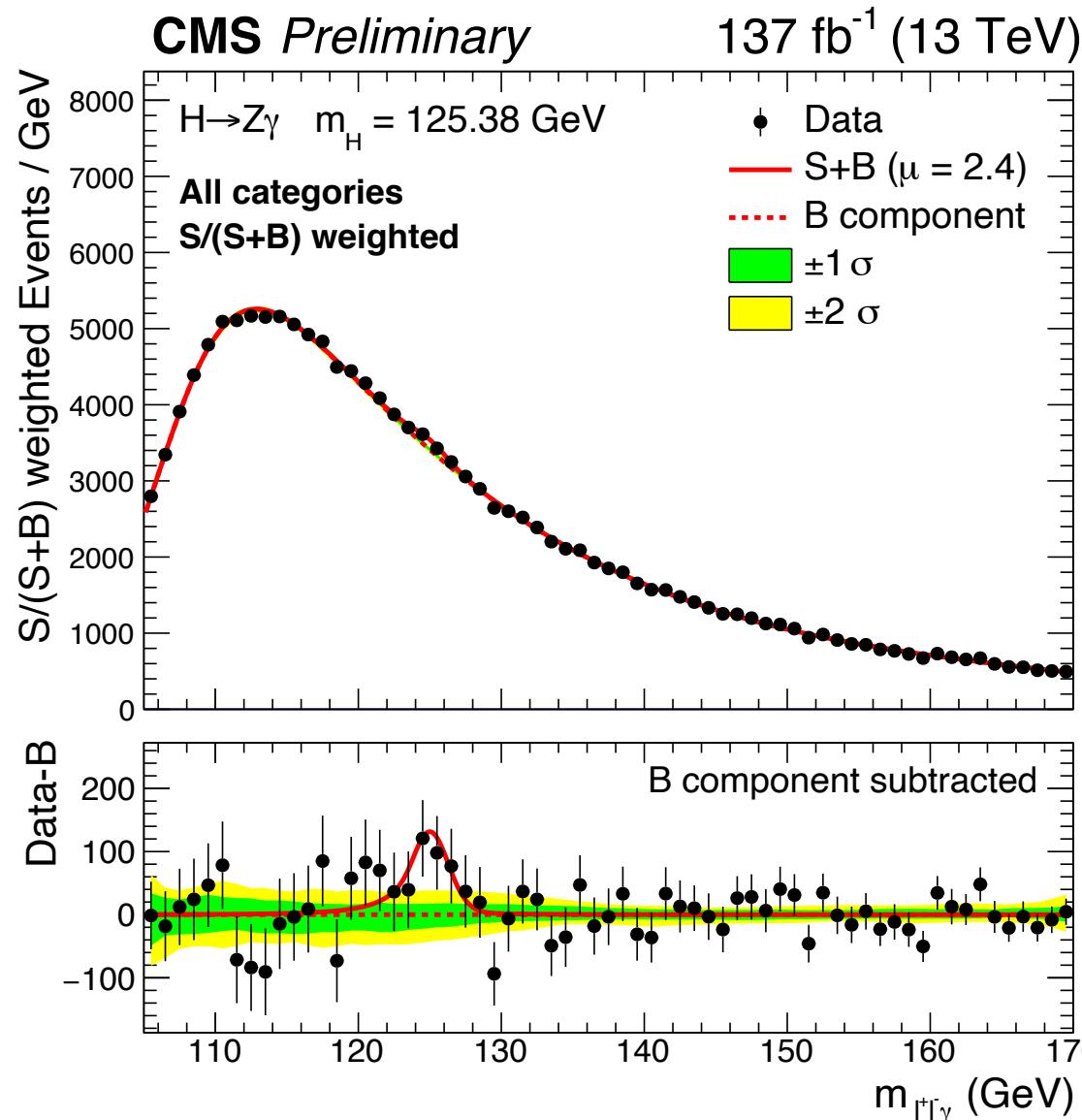
56

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

Field tensor coupling not measured yet!



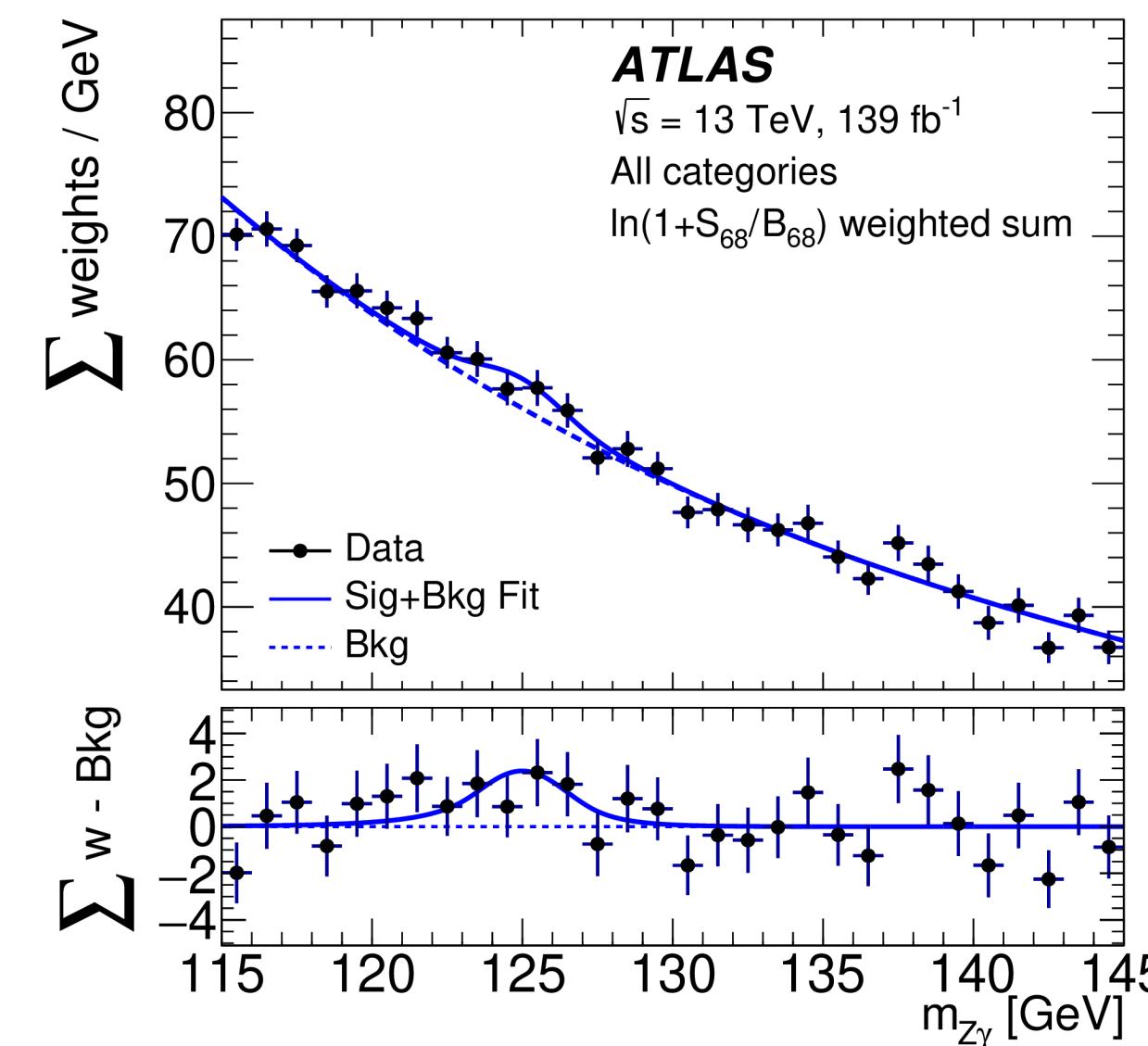
$\sim 2.3\% \text{ of } Br(\gamma\gamma)$



CMS Result

ggF, VBF, VH and ttH enriched

Expected 1.2σ
Observed 2.7σ

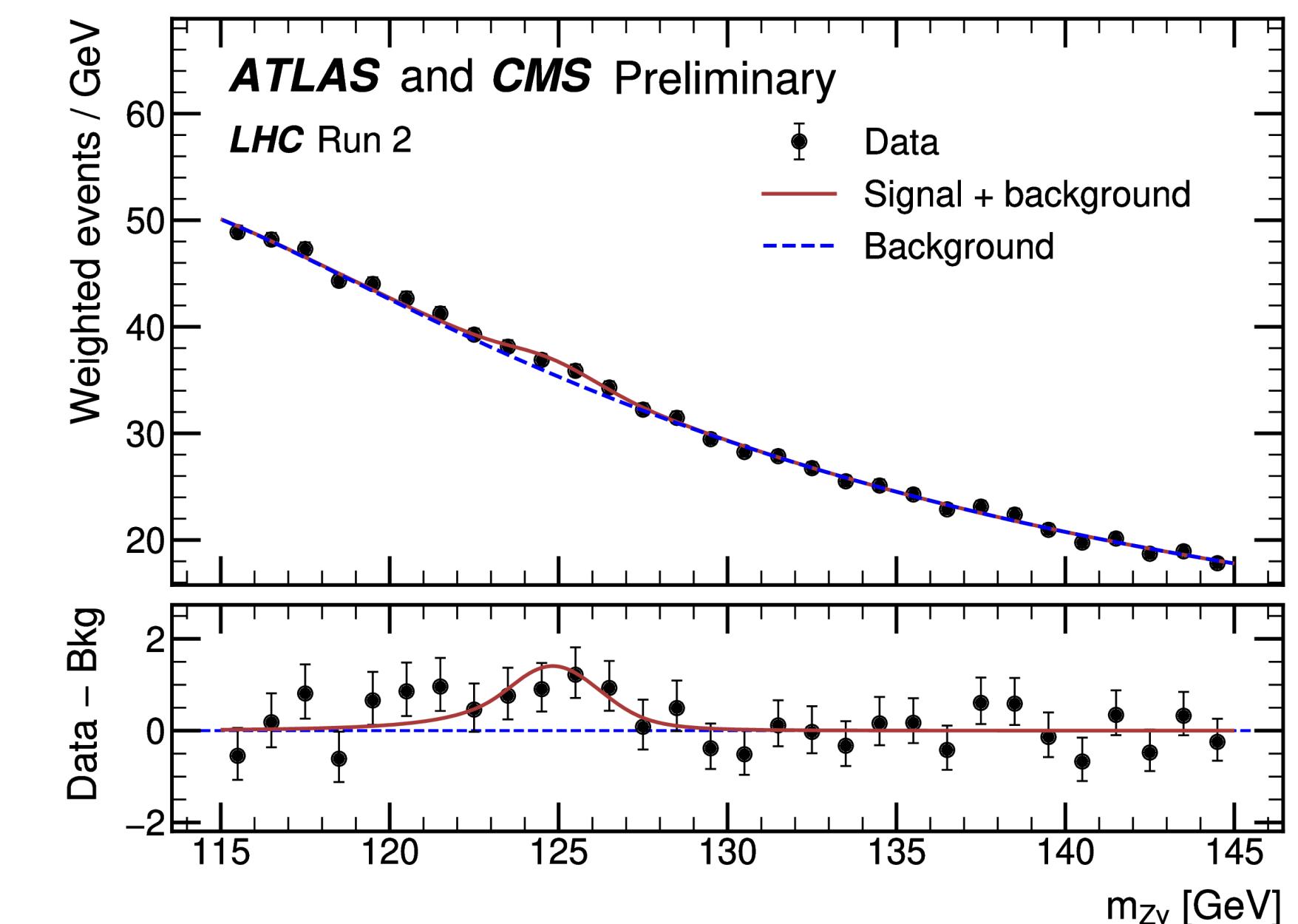


ATLAS Result

ggF and VBF enriched

Expected 1.2σ
Observed 2.2σ

Combined ATLAS and CMS mass spectrum!

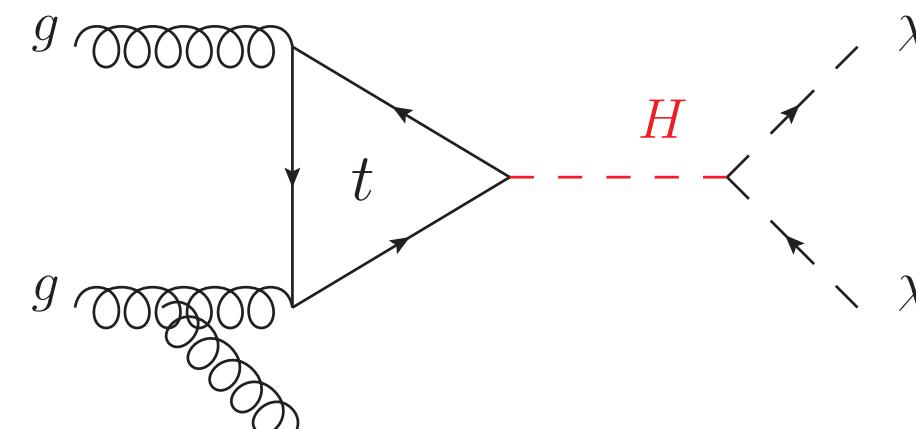
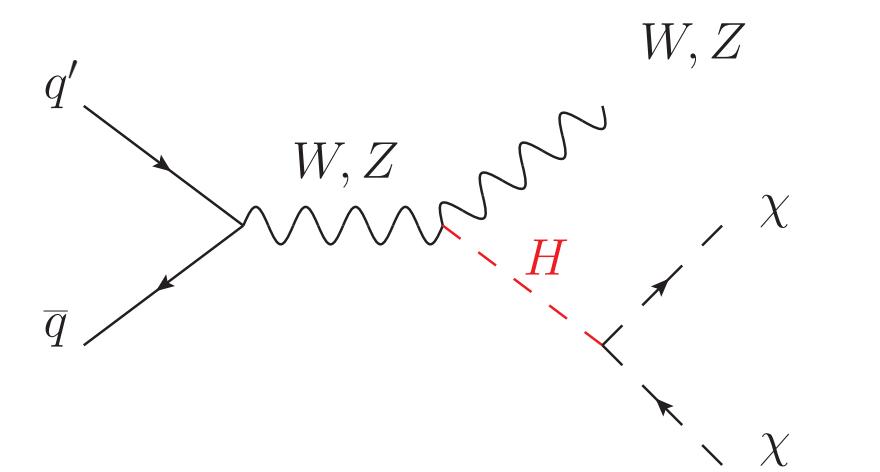
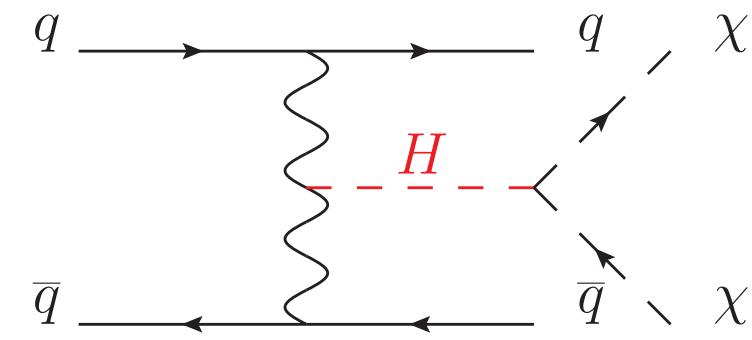


Combined search yields 3.4σ observed and 1.6σ expected
(consistent with the SM expectation at the 1.9σ): First evidence!

HL-LHC ~10%

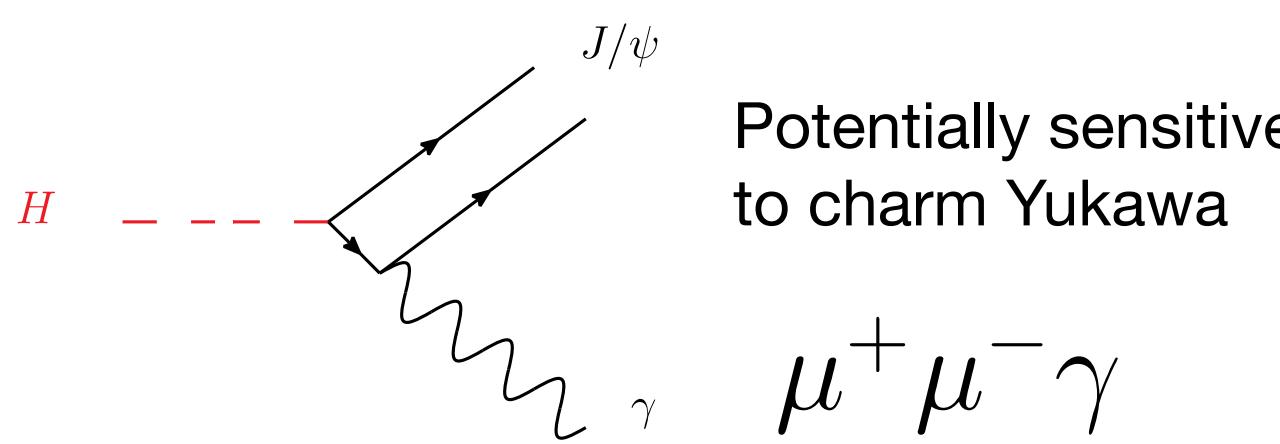
More Rare Decays and Production

Invisible decays



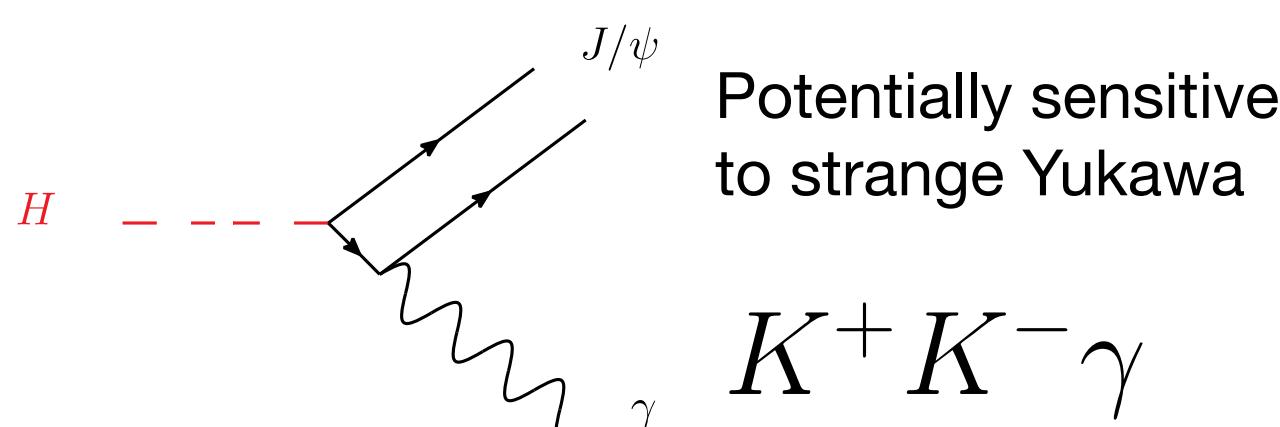
<11% @ 95% CL
HL-LHC 2.5%

Quarkonia-photon



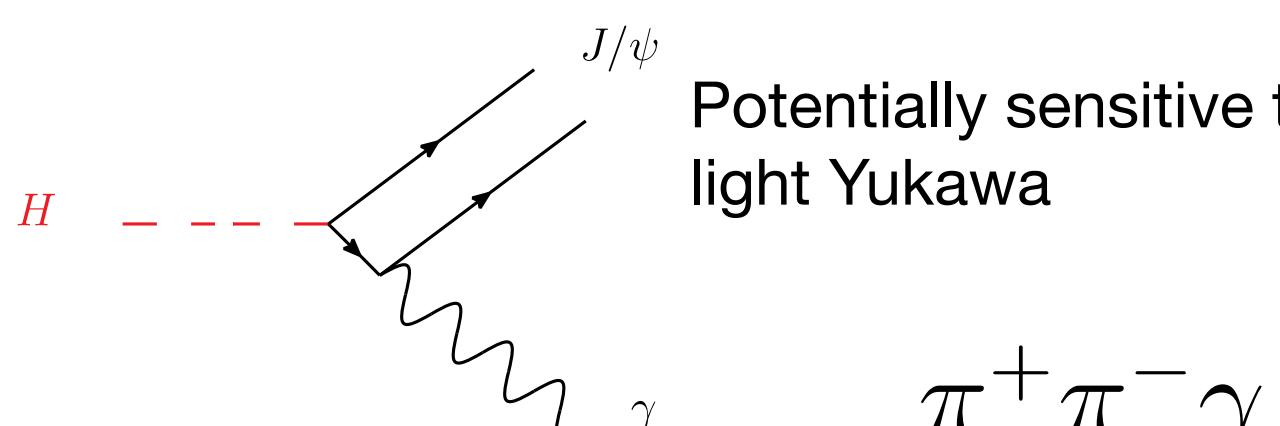
Potentially sensitive to charm Yukawa

$\sim 100 \times \text{SM}$



Potentially sensitive to strange Yukawa

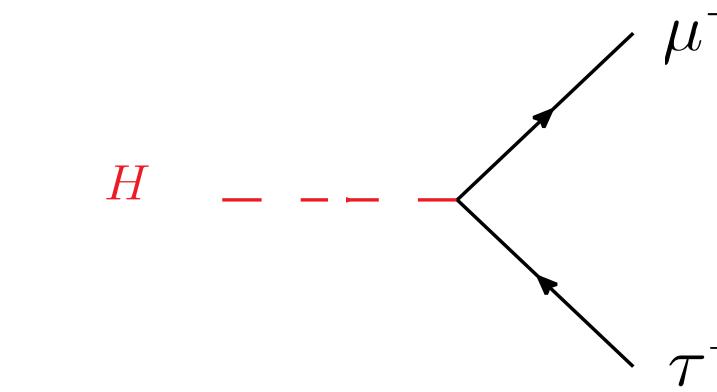
$\sim 200 \times \text{SM}$



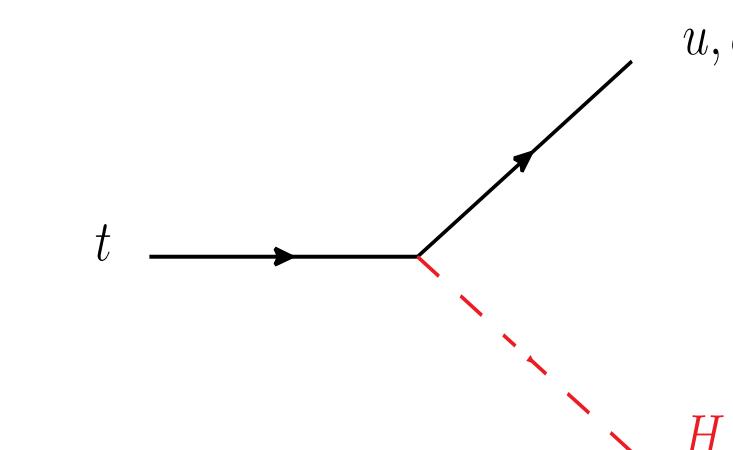
Potentially sensitive to light Yukawa

$\sim 50 \times \text{SM}$

Lepton flavor violating decays

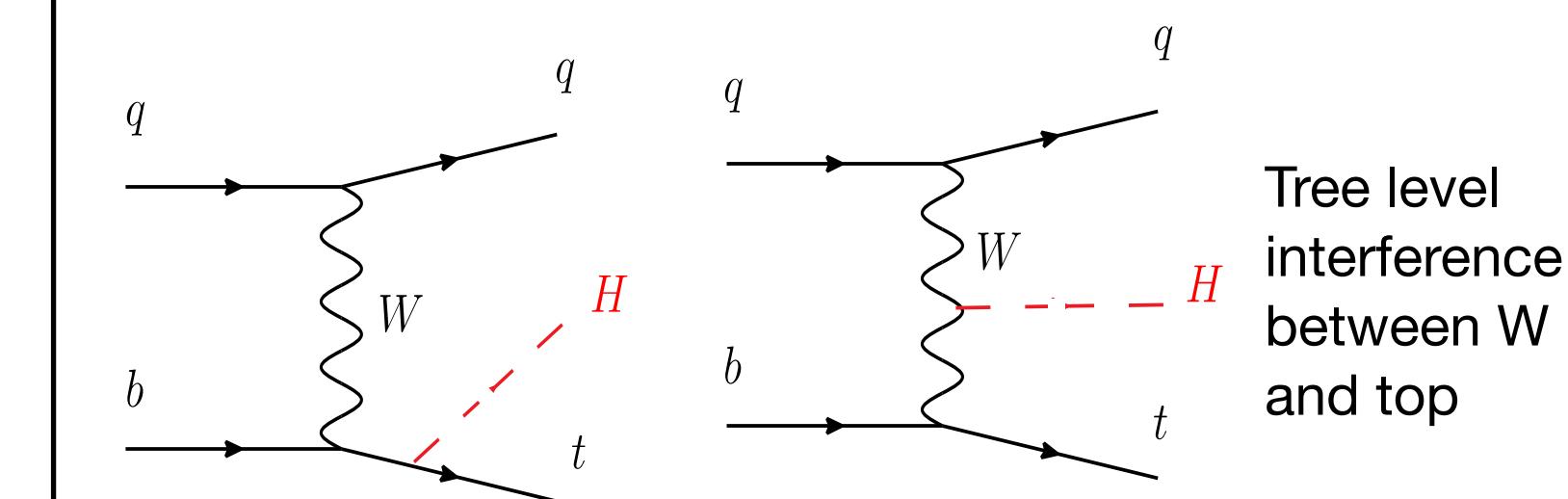


FCNC decays of the top quark



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

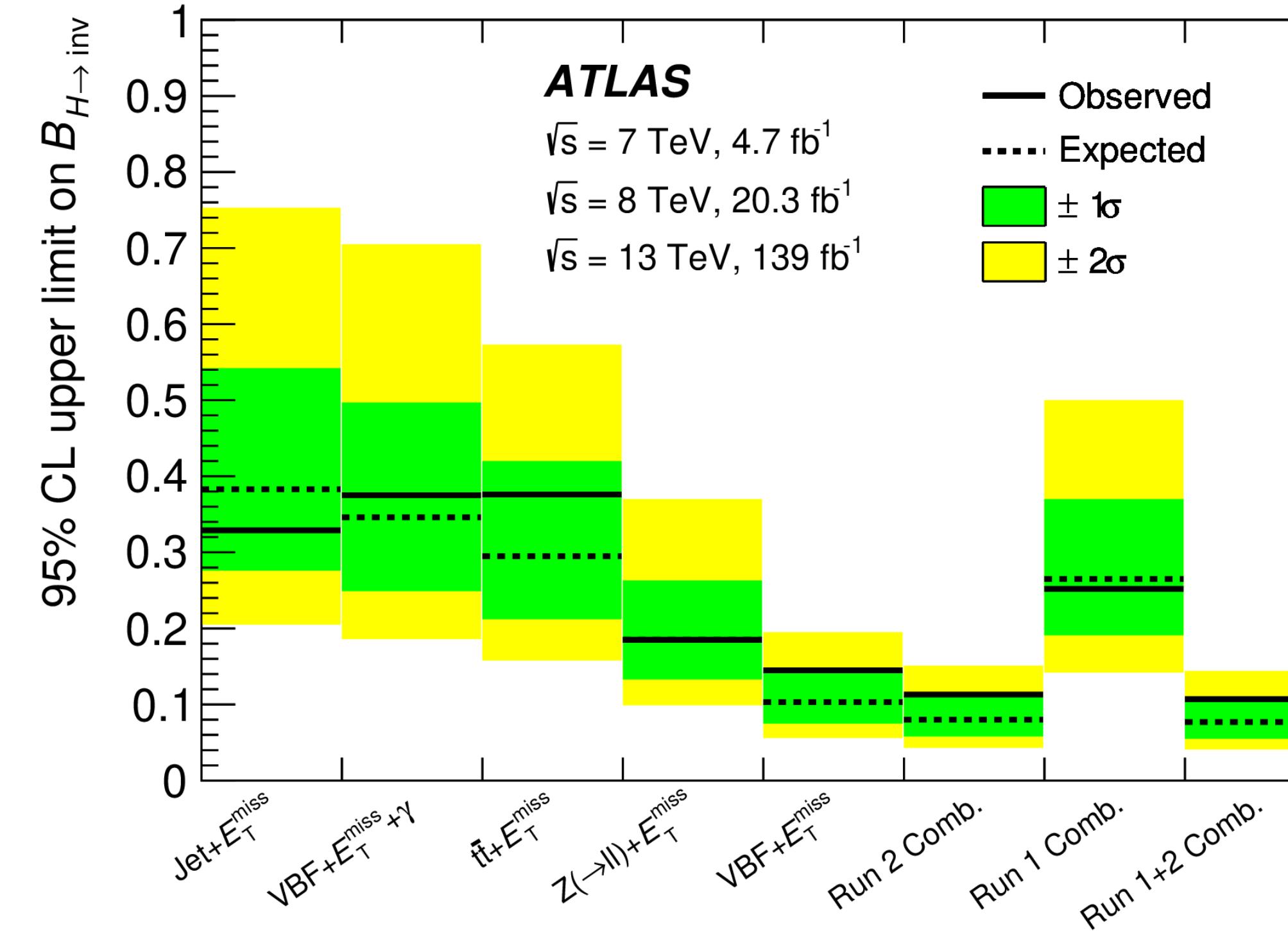
Single top associated production



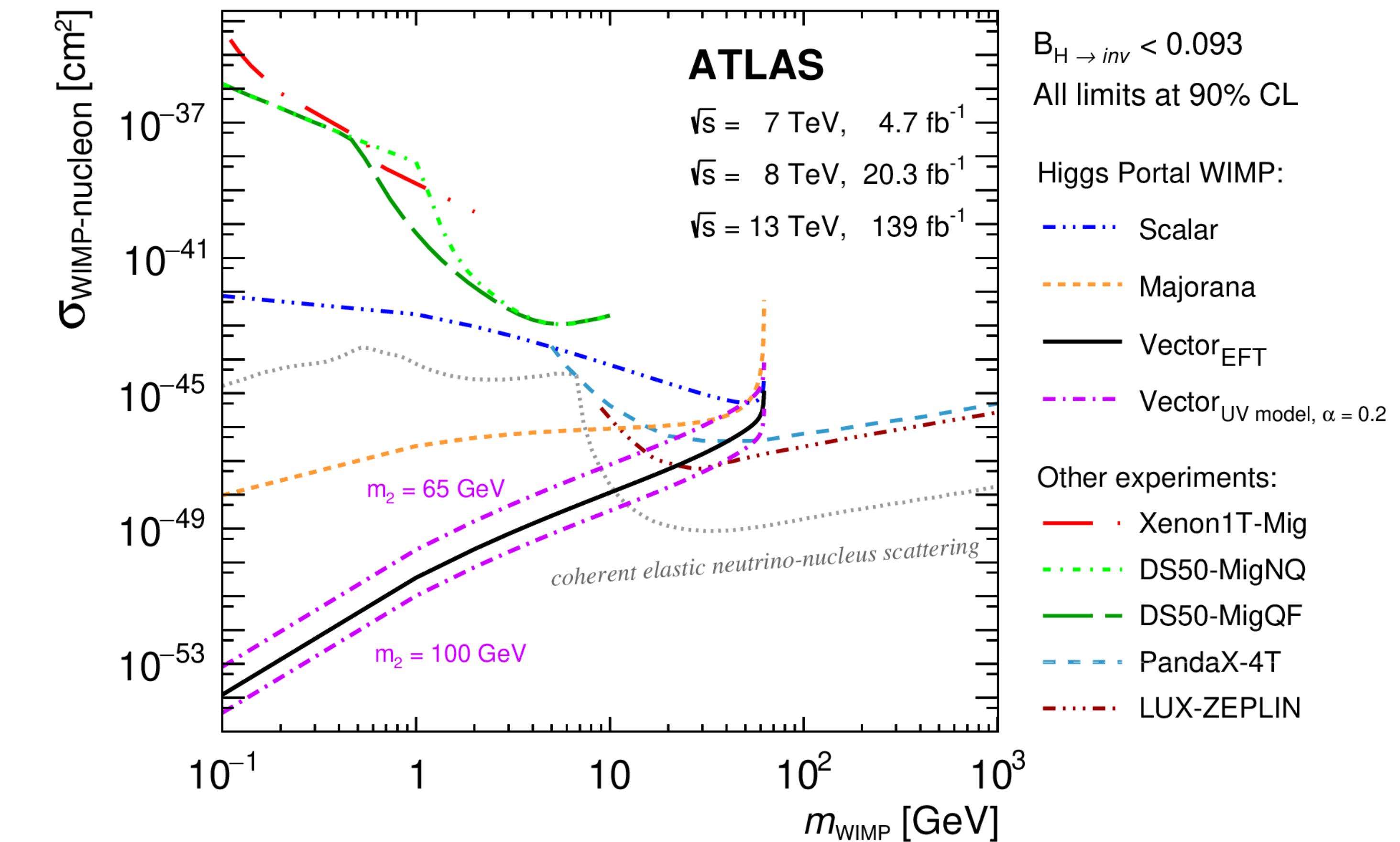
Tree level interference between W and top

Invisible Higgs Decays

To be precise: upper limit on the $H \rightarrow \text{invisible}$ branching of **0.107** (0.077) at the 95% CL



In the SM the $H \rightarrow \text{invisible}$ branching of **0.1%**



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