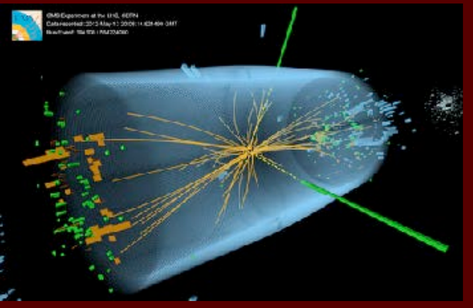
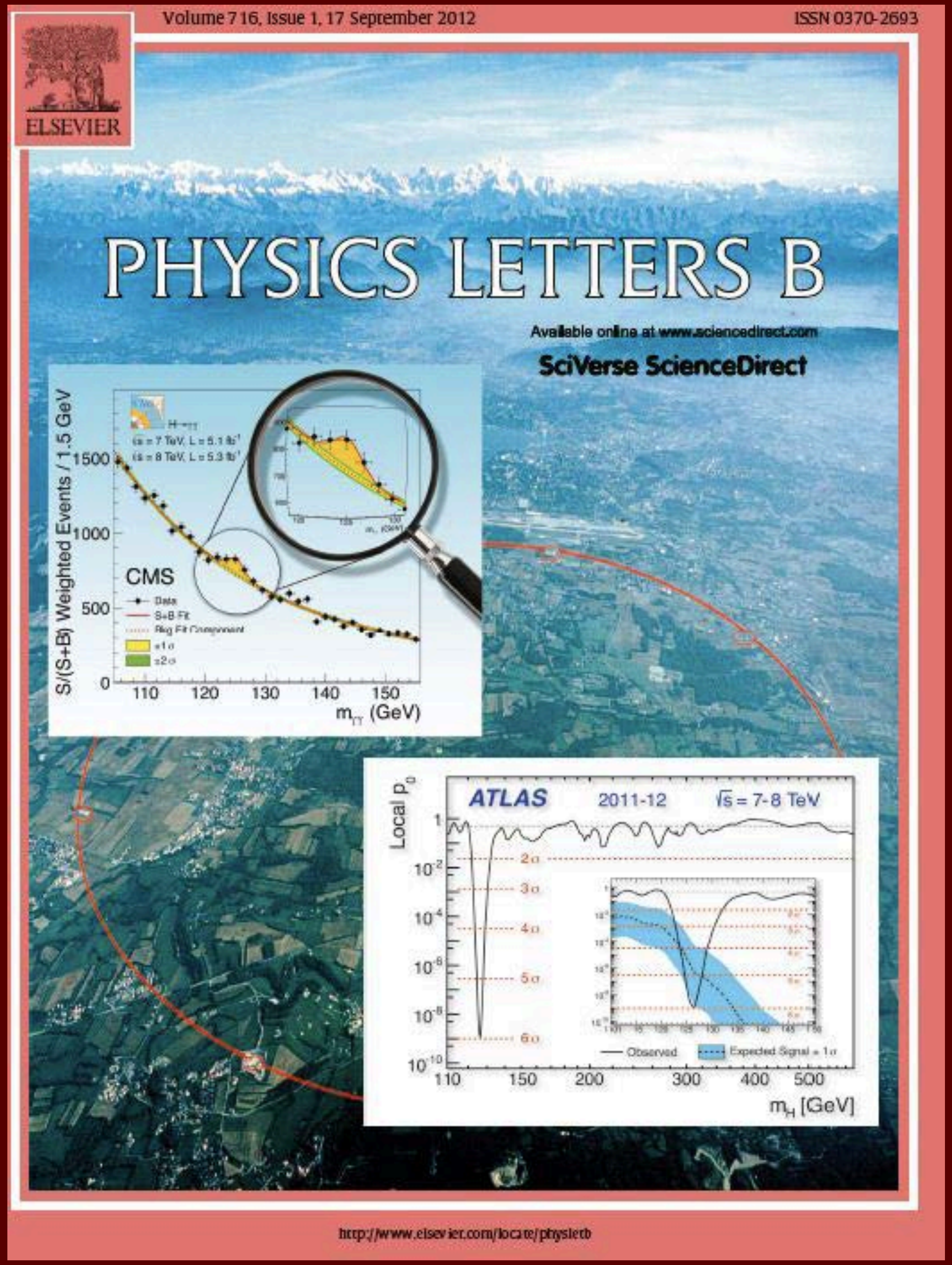


# Ten Years on -
# The Higgs Boson at the LHC.

Roger Rusack
The University of Minnesota

# *Ten Years Ago This July.*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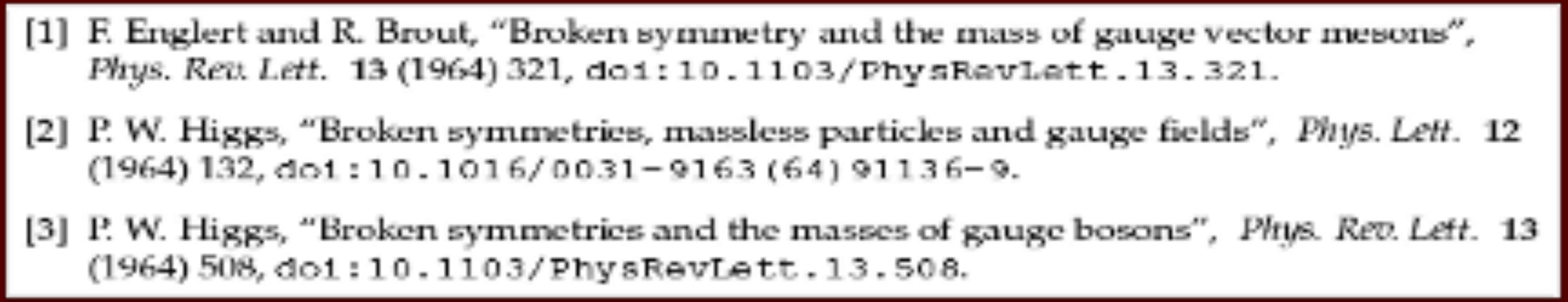
# *Before July 2012*

Almost 60 years ago the first ideas of the Higgs mechanism

**1964**



[1] F. Englert and R. Brout, "Broken symmetry and the mass of gauge vector mesons", *Phys. Rev. Lett.* 13 (1964) 321, `doi:10.1103/PhysRevLett.13.321`.

[2] P. W. Higgs, "Broken symmetries, massless particles and gauge fields", *Phys. Lett.* 12 (1964) 132, `doi:10.1016/0031-9163(64)91136-9`.

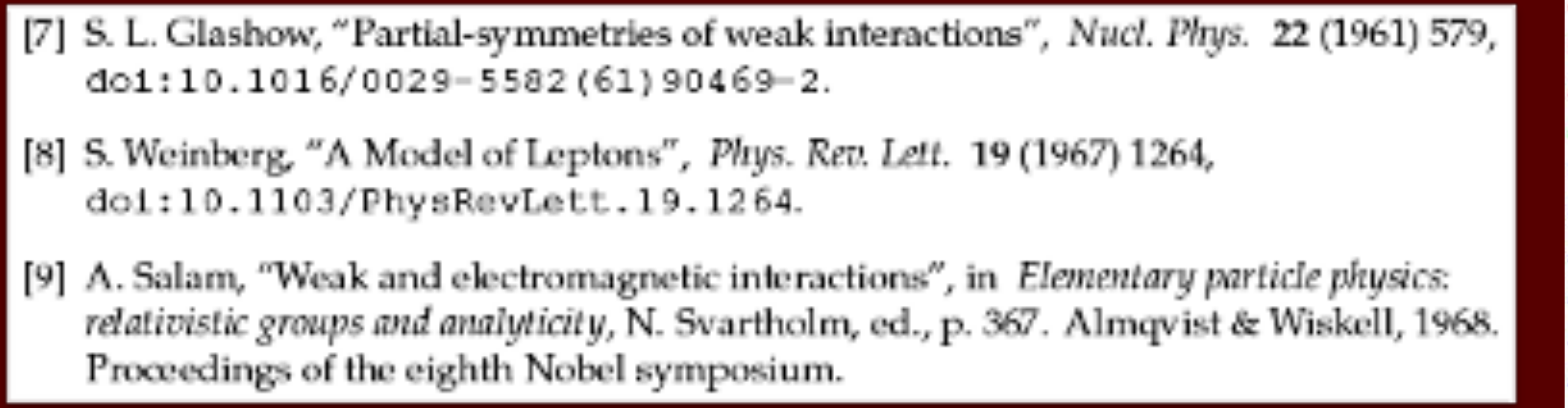
[3] P. W. Higgs, "Broken symmetries and the masses of gauge bosons", *Phys. Rev. Lett.* 13 (1964) 508, `doi:10.1103/PhysRevLett.13.508`.

These papers on *spontaneous symmetry breaking mechanism* attracted very little attention at the time, the *boson* attracted even less interest (T. Kibble).

1961

1967

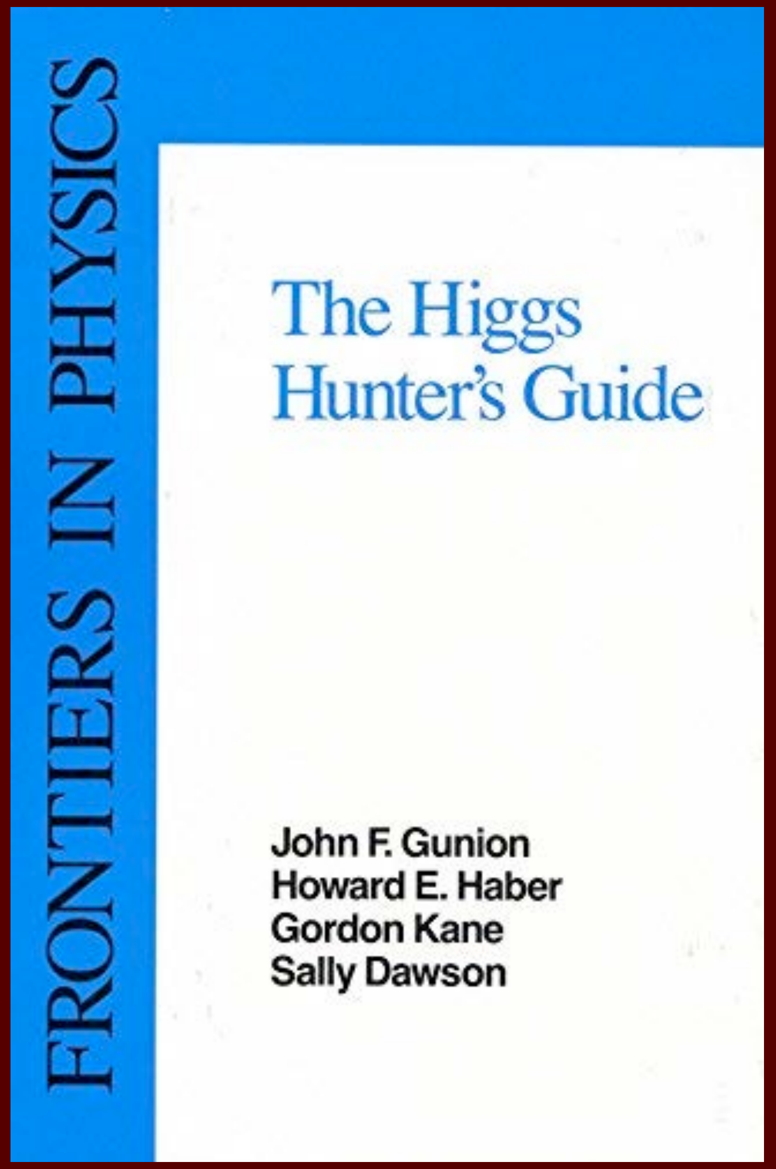
1968



[7] S. L. Glashow, "Partial-symmetries of weak interactions", *Nucl. Phys.* 22 (1961) 579, `doi:10.1016/0029-5582(61)90469-2`.

[8] S. Weinberg, "A Model of Leptons", *Phys. Rev. Lett.* 19 (1967) 1264, `doi:10.1103/PhysRevLett.19.1264`.

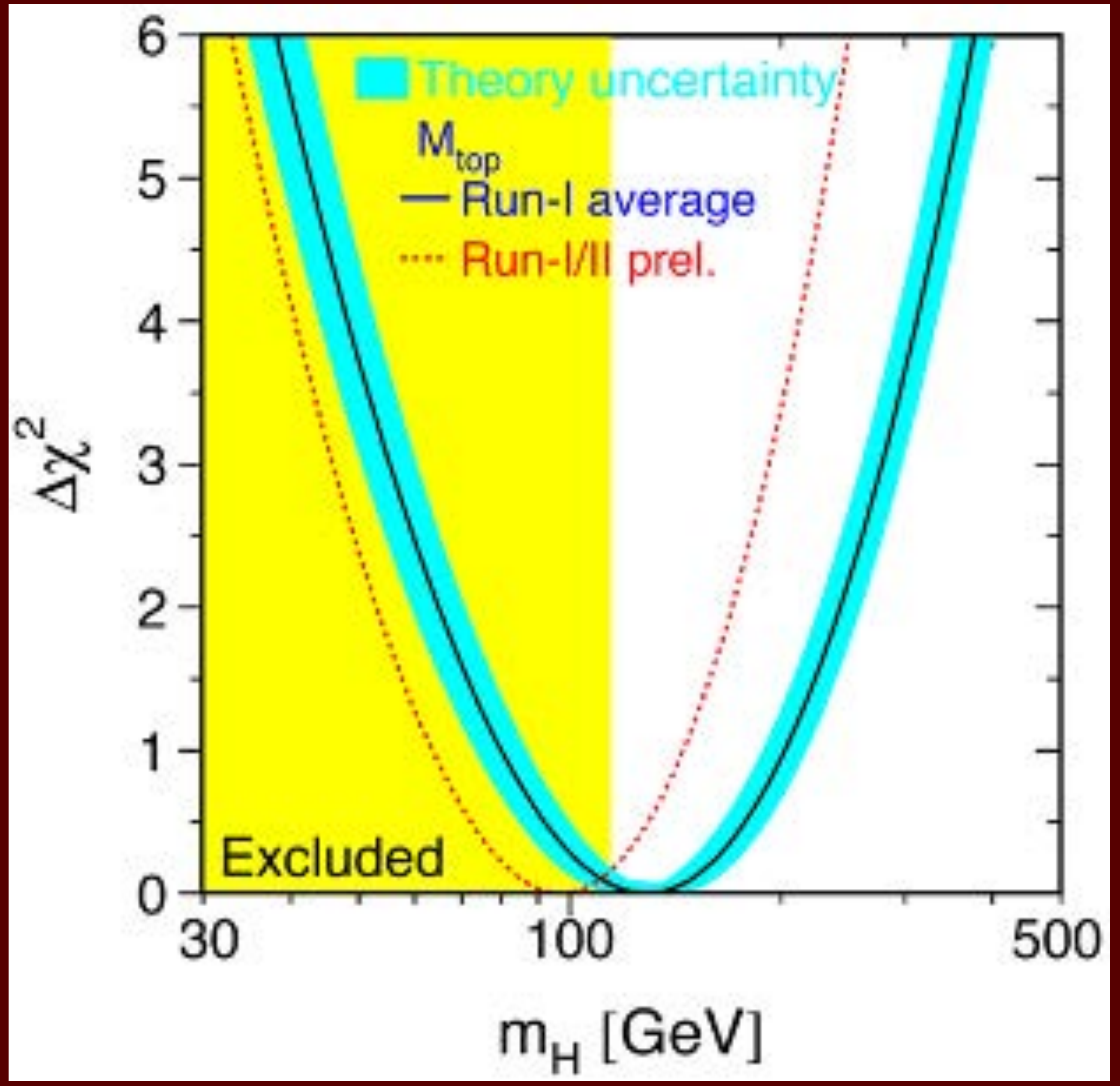
[9] A. Salam, "Weak and electromagnetic interactions", in *Elementary particle physics: relativistic groups and analyticity*, N. Svartholm, ed., p. 367. Almqvist & Wiskell, 1968. Proceedings of the eighth Nobel symposium.



A book we all had on our bookshelves

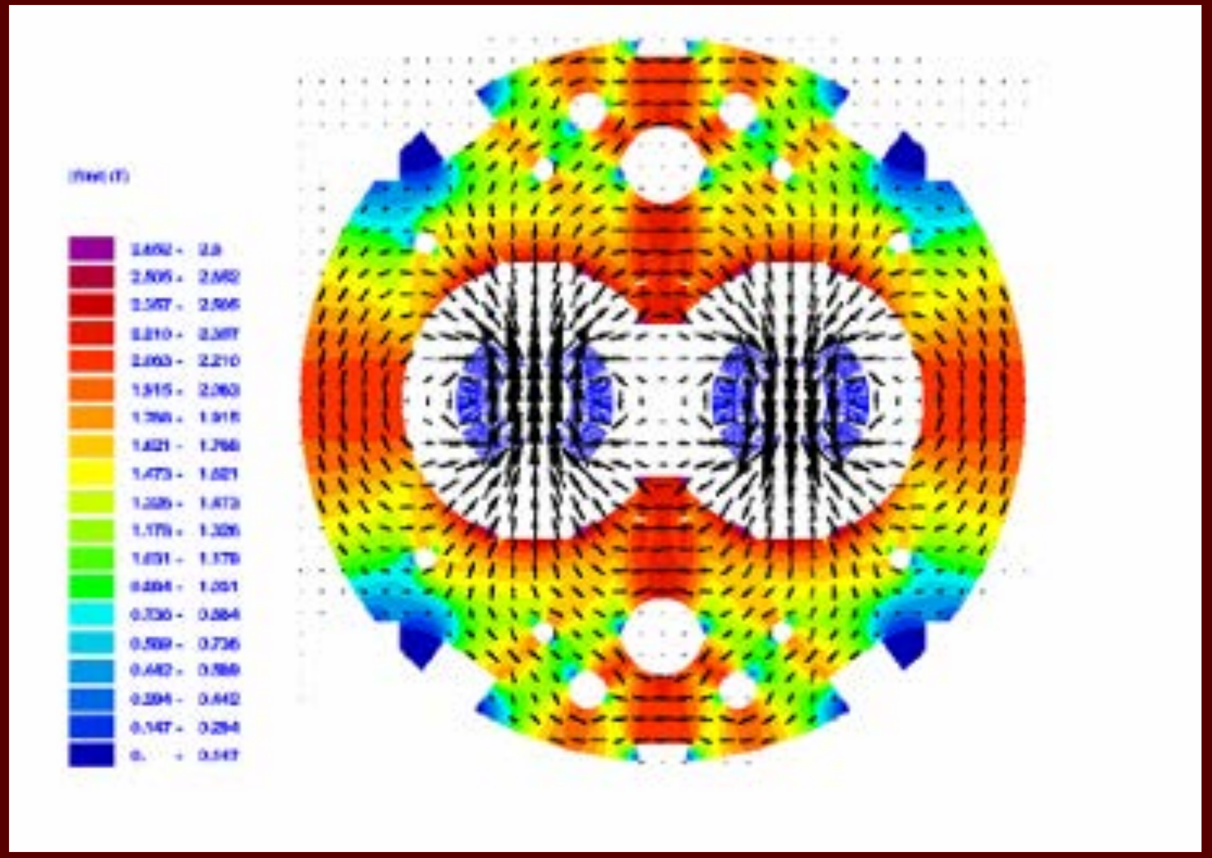
Then there were precision measurements of EWK parameters at LEP giving hints of where to look

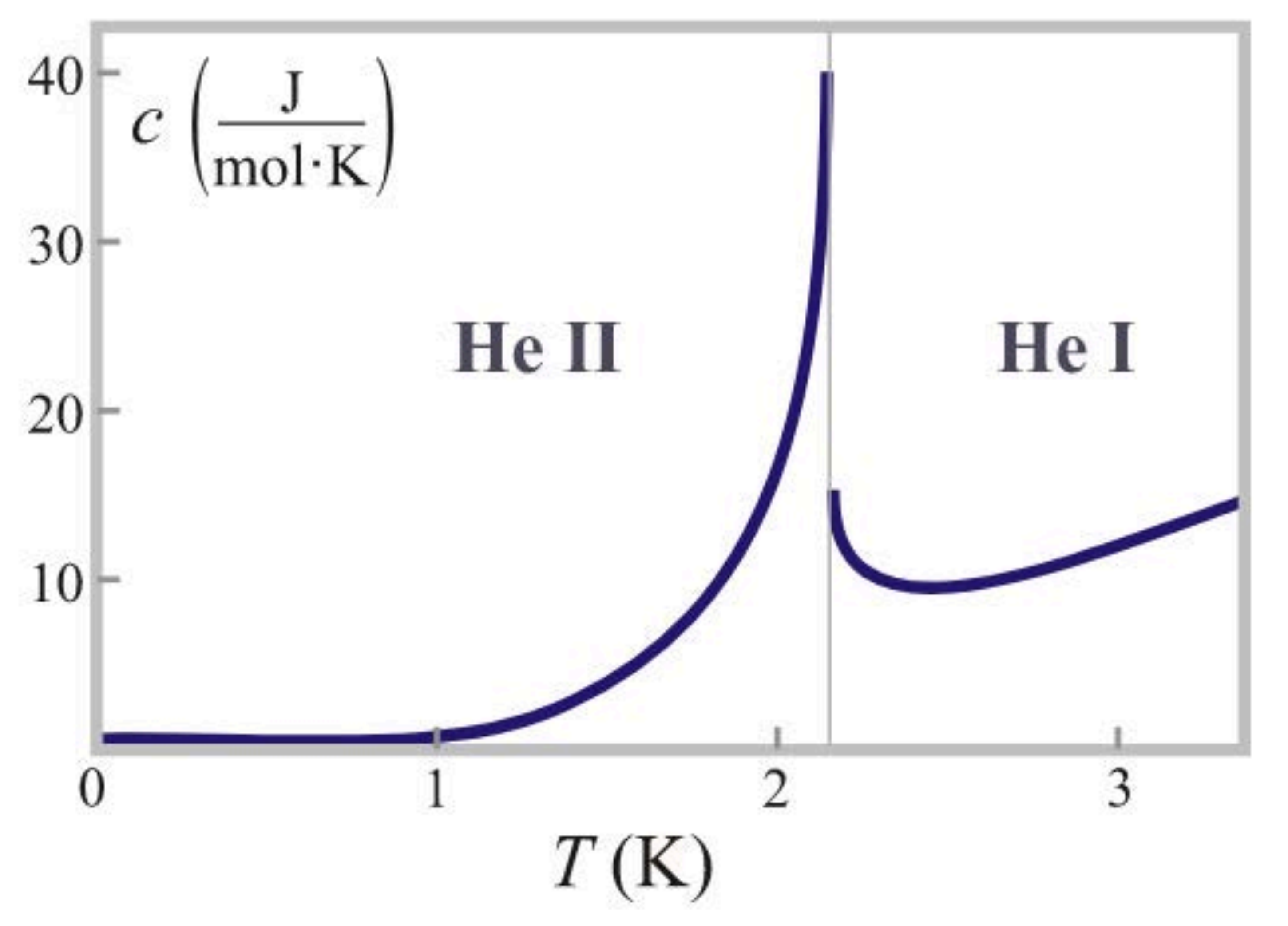
| | Measurement | Fit |
|---|---|---|
| $\Delta\alpha_{had}^{(5)}(m_Z)$ | 0.02758 ± 0.00035 | 0.02767 |
| $m_Z$ [GeV] | 91.1875 ± 0.0021 | 91.1874 |
| $\Gamma_Z$ [GeV] | 2.4952 ± 0.0023 | 2.4959 |
| $\sigma_{had}^0$ [nb] | 41.540 ± 0.037 | 41.478 |
| $R_l$ | 20.767 ± 0.025 | 20.742 |
| $A_{fb}^{0,l}$ | 0.01714 ± 0.00095 | 0.01643 |
| $A_l(P_\tau)$ | 0.1465 ± 0.0032 | 0.1480 |
| $R_b$ | 0.21629 ± 0.00066 | 0.21579 |
| $R_c$ | 0.1721 ± 0.0030 | 0.1723 |
| $A_{fb}^{0,b}$ | 0.0992 ± 0.0016 | 0.1038 |
| $A_{fb}^{0,c}$ | 0.0707 ± 0.0035 | 0.0742 |
| $A_b$ | 0.923 ± 0.020 | 0.935 |
| $A_c$ | 0.670 ± 0.027 | 0.668 |
| $A_l$(SLD) | 0.1513 ± 0.0021 | 0.1480 |
| $\sin^2\theta_{eff}^{lept}(Q_{fb})$ | 0.2324 ± 0.0012 | 0.2314 |
| $m_W$ [GeV] | 80.410 ± 0.032 | 80.377 |
| $\Gamma_W$ [GeV] | 2.123 ± 0.067 | 2.092 |
| $m_t$ [GeV] | 172.7 ± 2.9 | 173.3 |

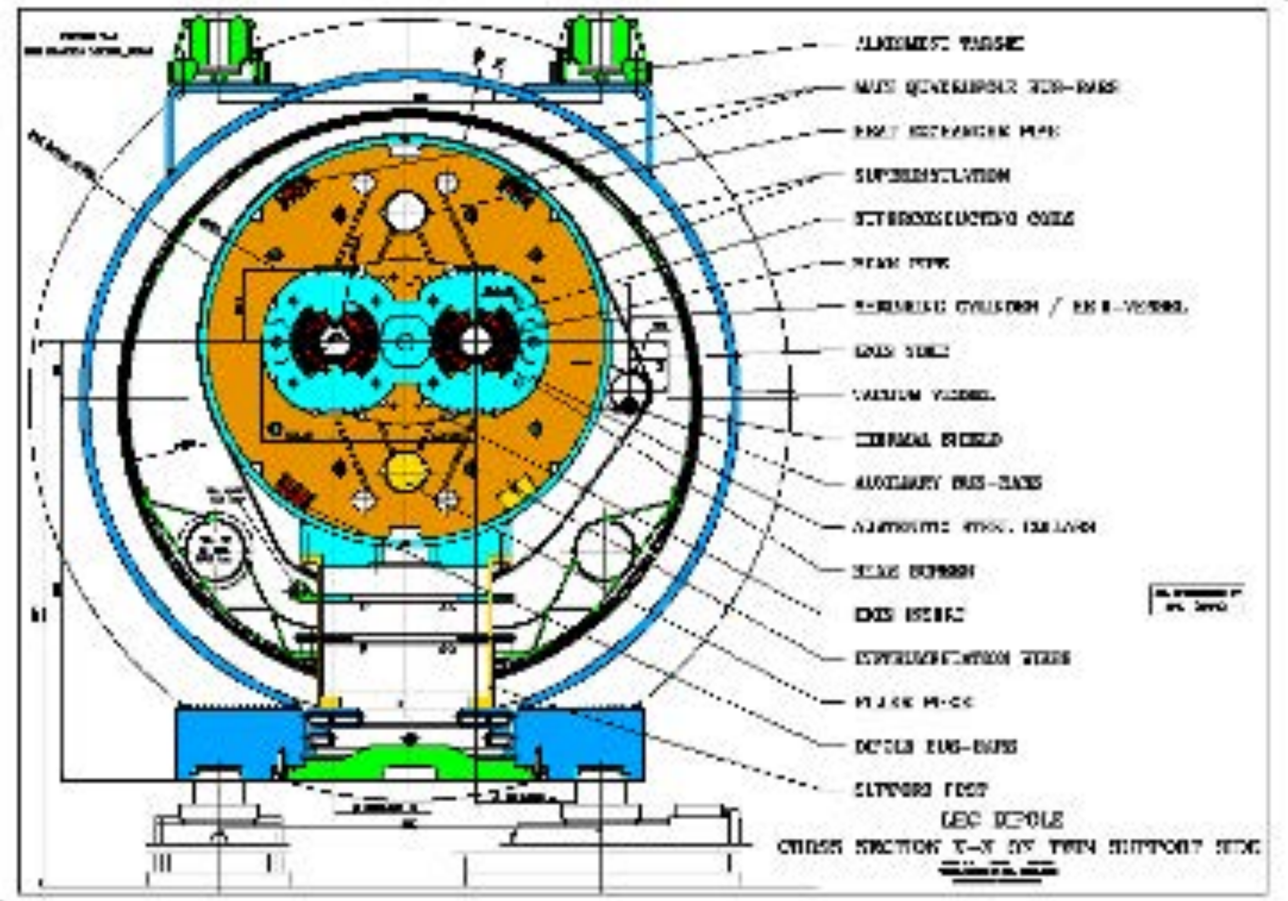


Sifbrand de Jong @ EPS 2005

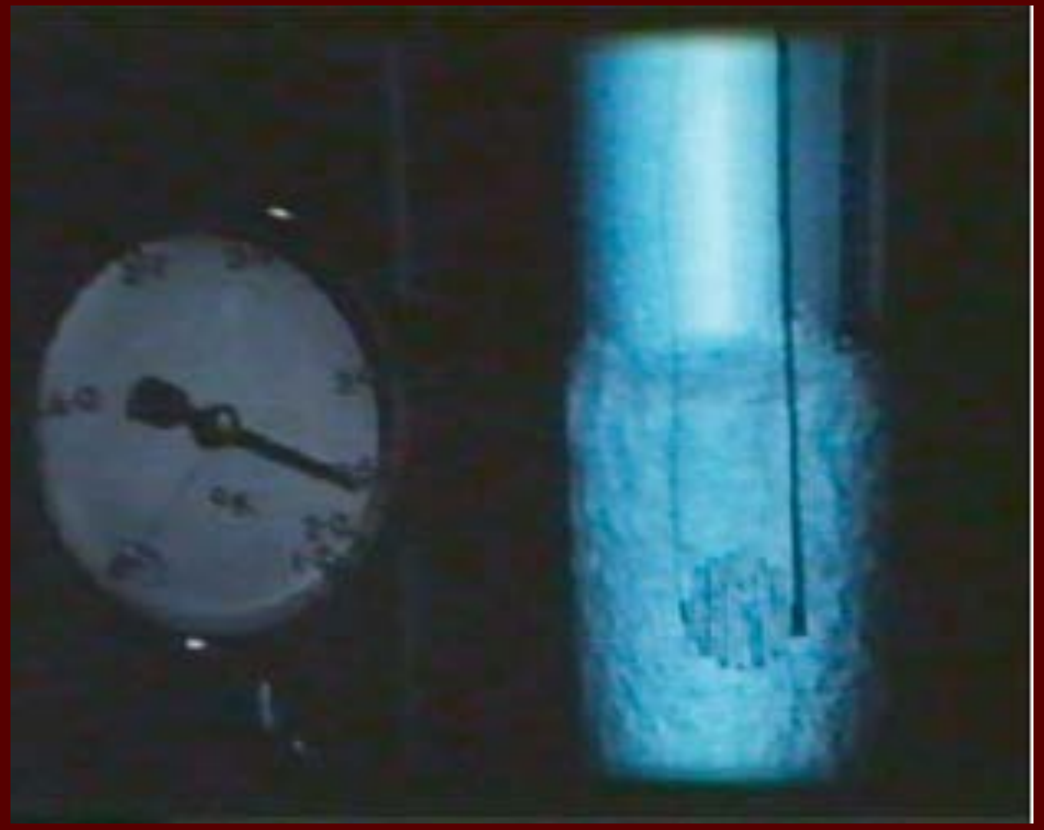
# *A marvel of engineering was required*



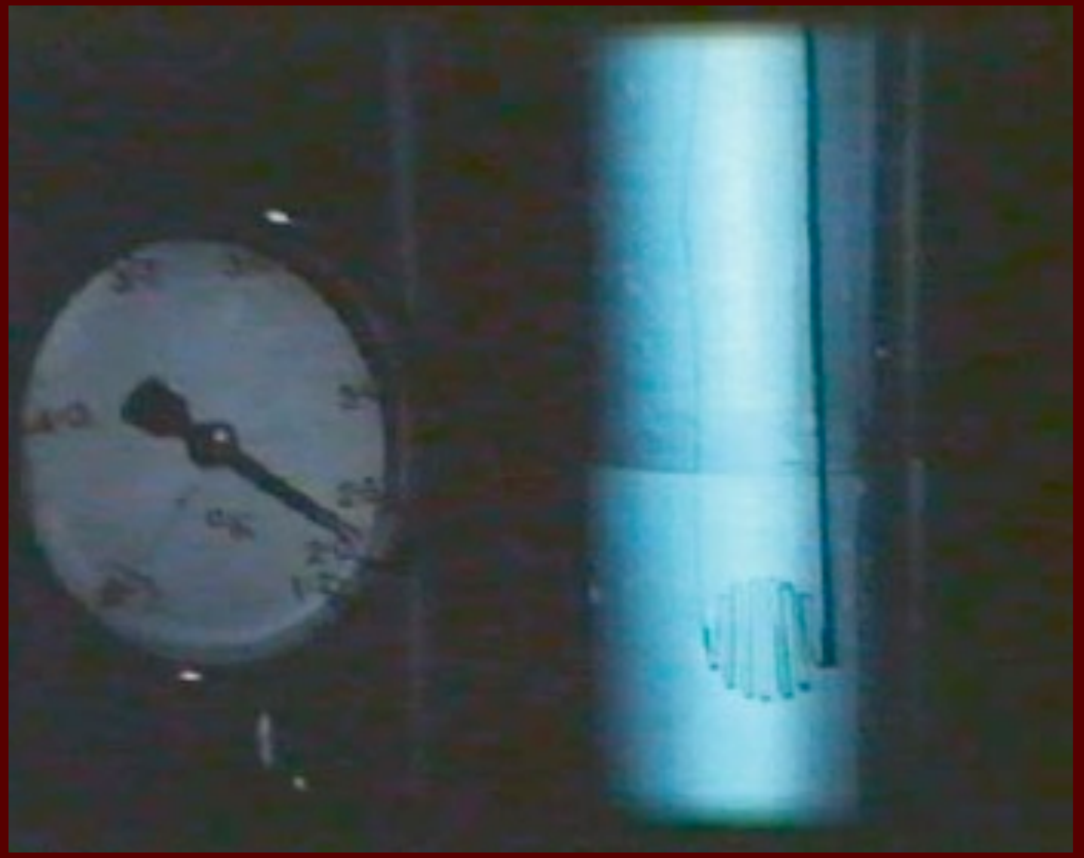




LHC magnet



Helium above the lambda point 2.4K

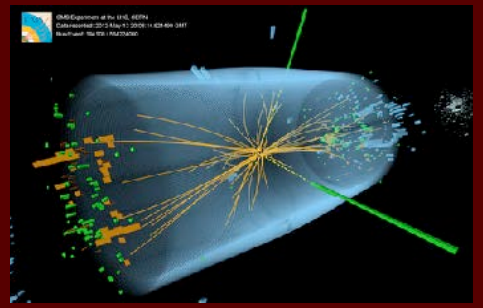


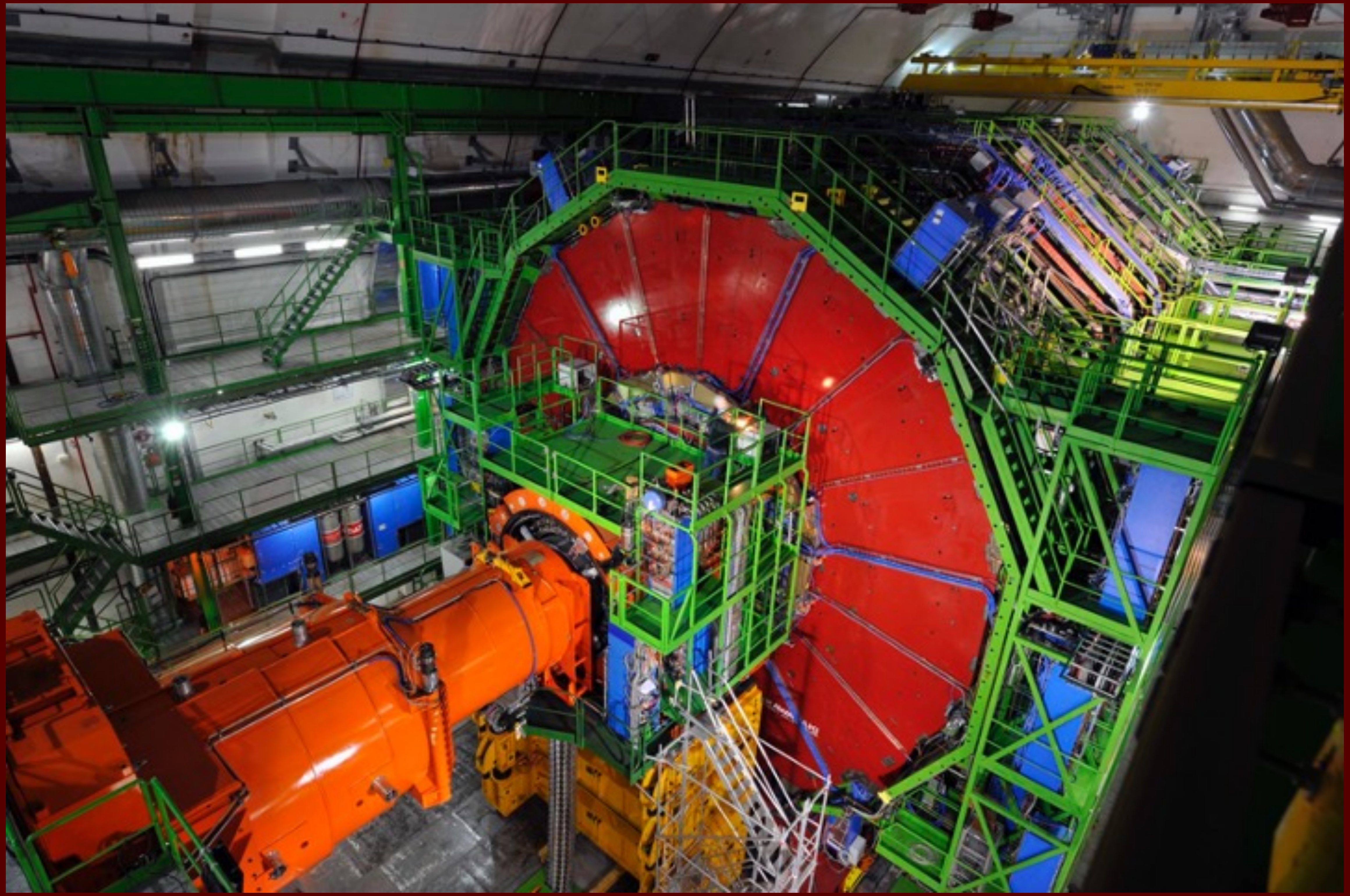
Helium at 2.1 K

Below the lambda point He is a superfluid and the thermal conductivity is ‘infinite’*.

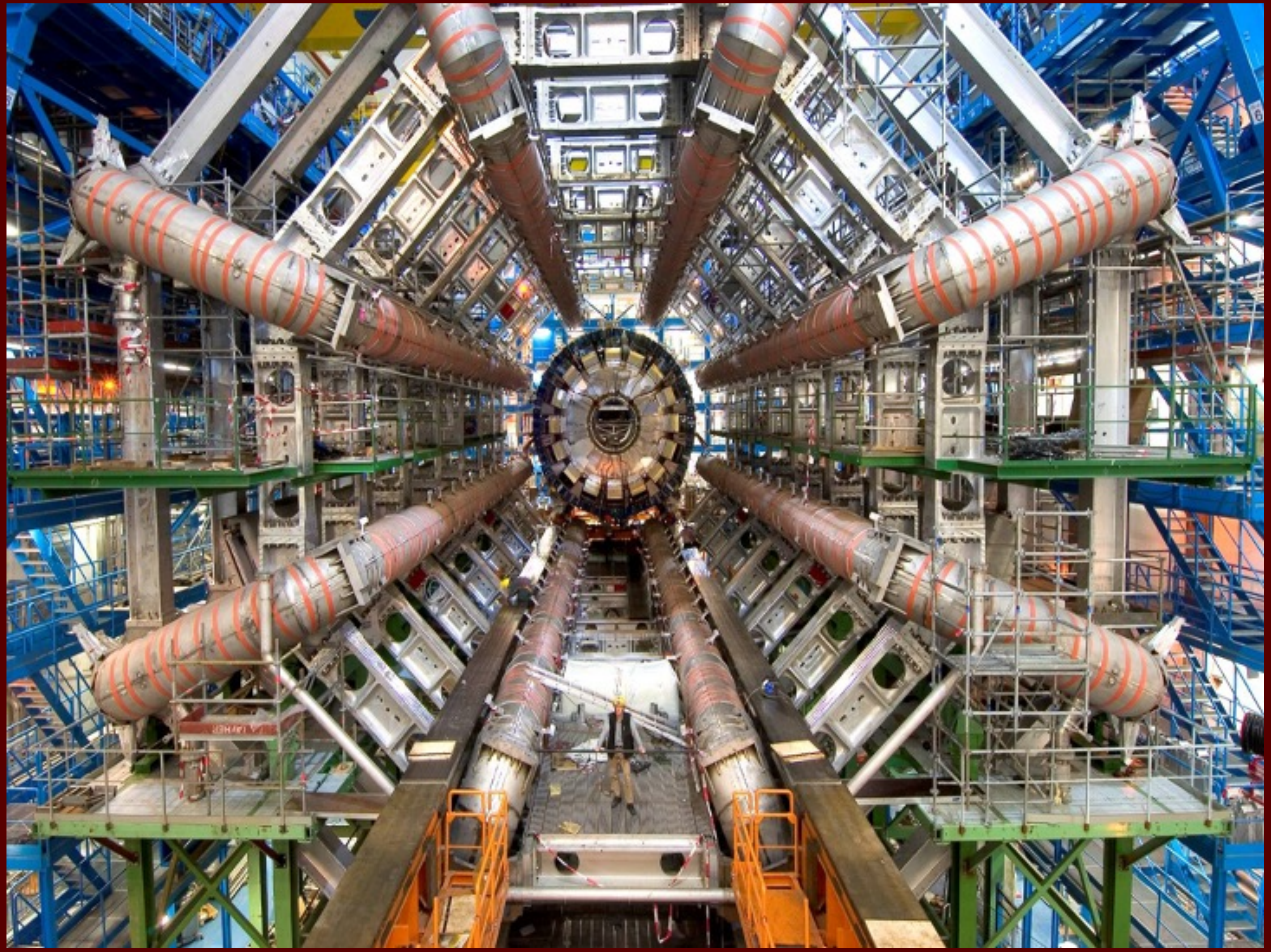
*about 100 times better than the best copper anyway.

# *The Detectors*





The CMS detector at P5 near Cessy France

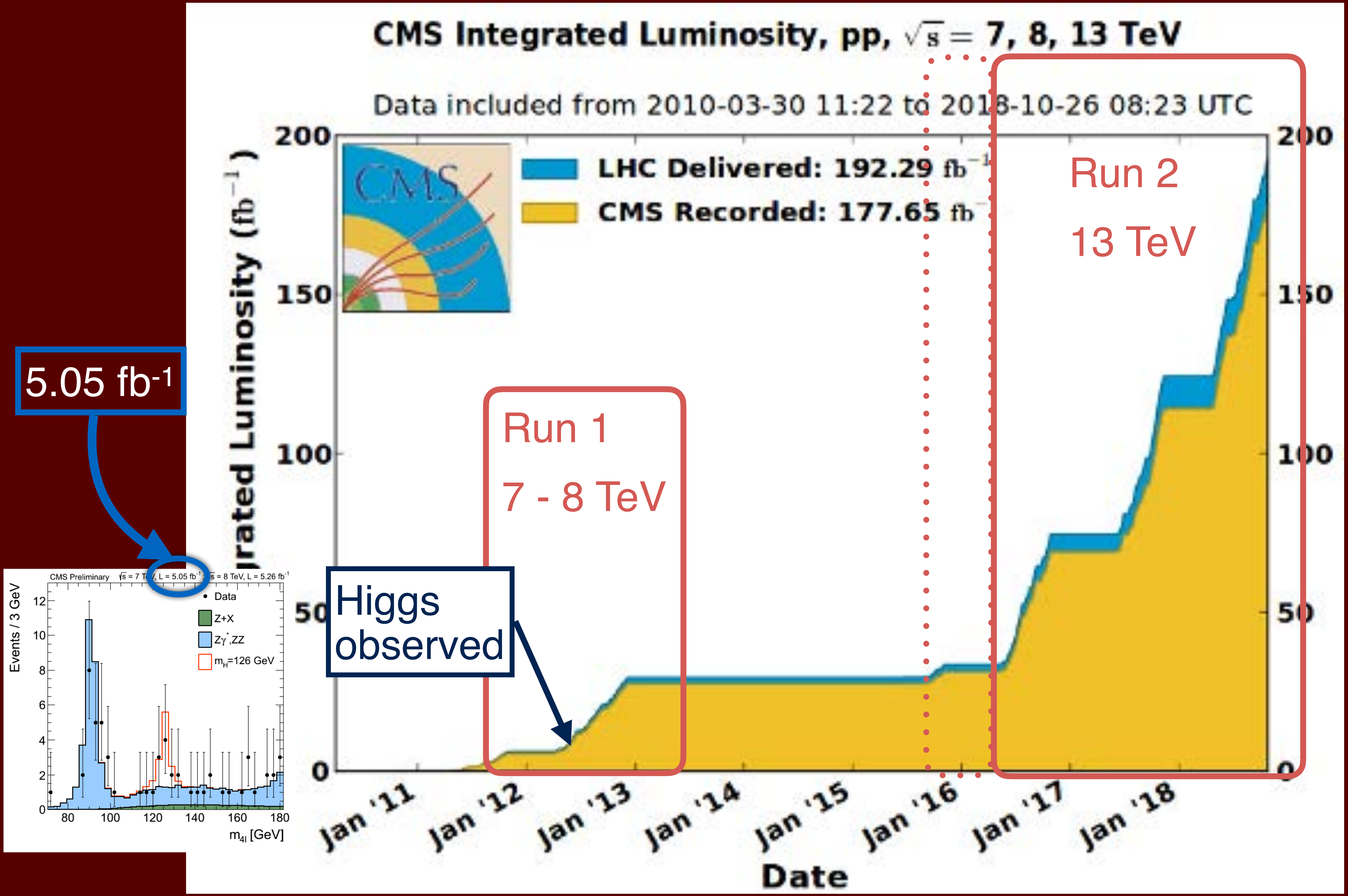


The ATLAS detector at P1, Meyrin

CMS with a 4T B-field, precision EM calorimetry, a silicon tracker and muons detection in the return yoke.

ATLAS with air-core toroids for muon detectiion and a liquid argon EM calorimeter.

# Since July 4th 2012 much has changed.



~140 fb$^{-1}$ delivered at 13 TeV.

# *The Higgs Sector*

One of the main goals of the CERN LHC program was to find the Higgs boson and to study the Higgs sector of the standard model

$$\mathscr{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \bar{\psi}\gamma^{\mu}D_{\mu}\psi + h.c. + |D_{\mu}\Phi|^{2} + \psi_{i}y_{ij}\psi_{j}\Phi - V(\Phi)$$

A gauge interaction

similar to what we have seen before.

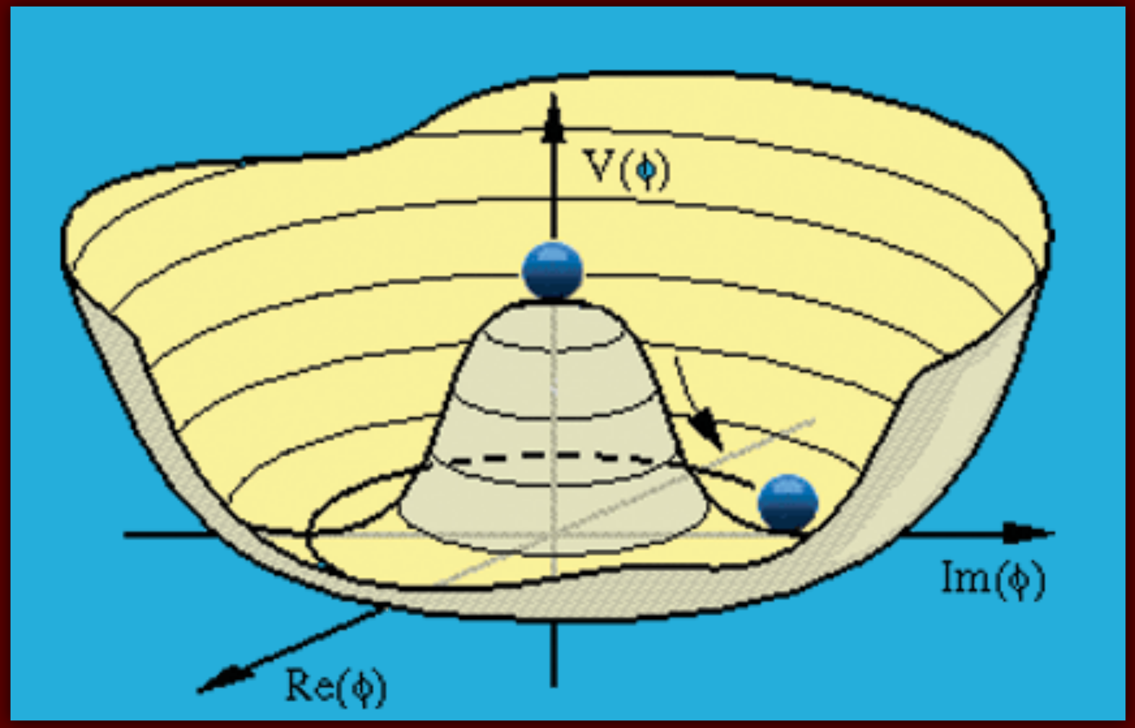
A potential:

$V(\phi) \approx -\mu^2(\phi\phi^\dagger) + \lambda(\phi\phi^\dagger)^2$

The keystone of the BEH mechanism and the SM. Never probed

A Yukawa interaction

unlike anything we have probed from before.

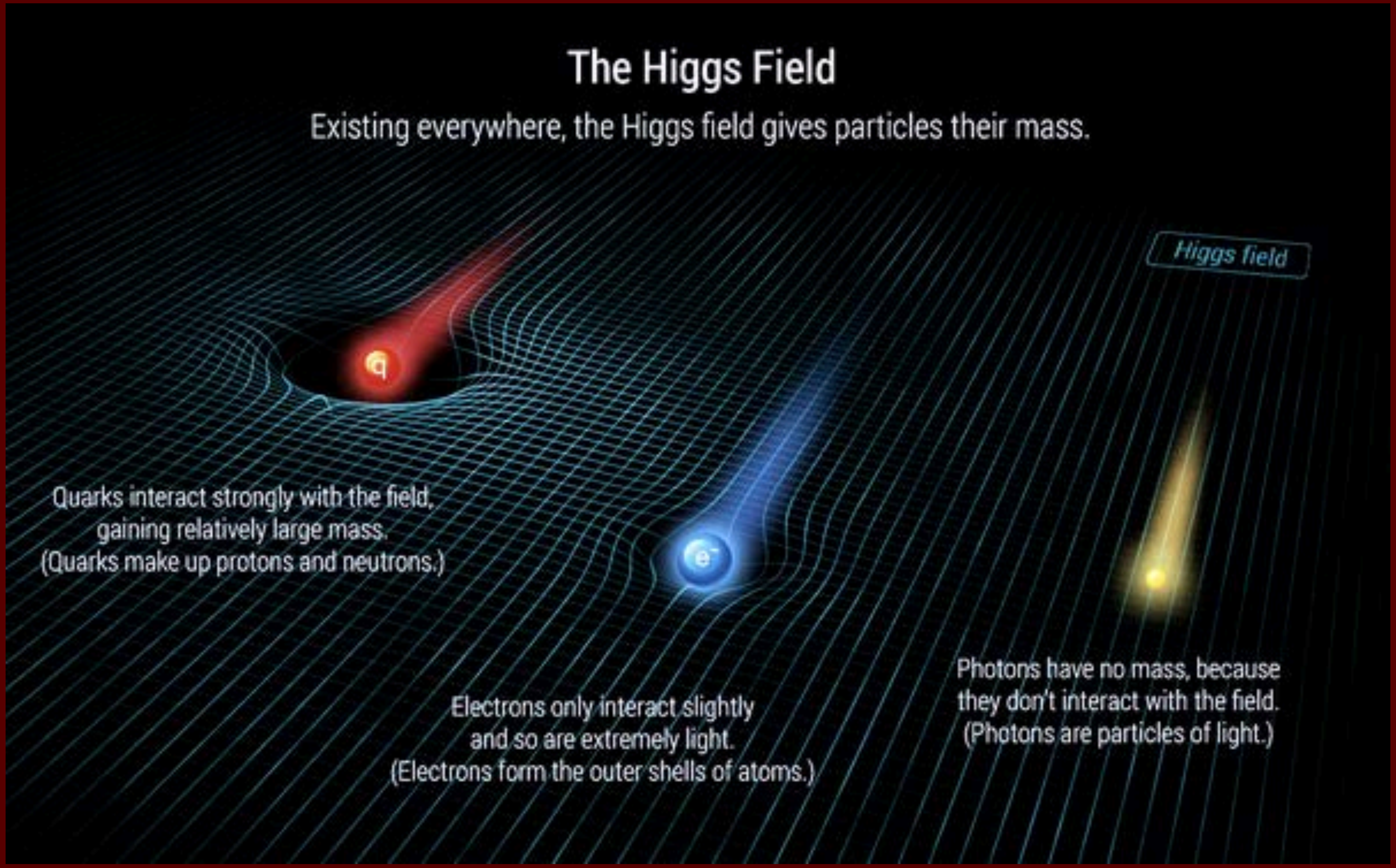


# *The Higgs Field - Basics*

The Higgs mechanism is an elementary part of the standard model.

Introduced to ensure gauge invariance with massive vector bosons.

The Higgs field permeates the universe with a non-zero vacuum expectation value of 246 GeV.



The Higgs Field

Existing everywhere, the Higgs field gives particles their mass.

Quarks interact strongly with the field, gaining relatively large mass. (Quarks make up protons and neutrons.)

Electrons only interact slightly and so are extremely light. (Electrons form the outer shells of atoms.)

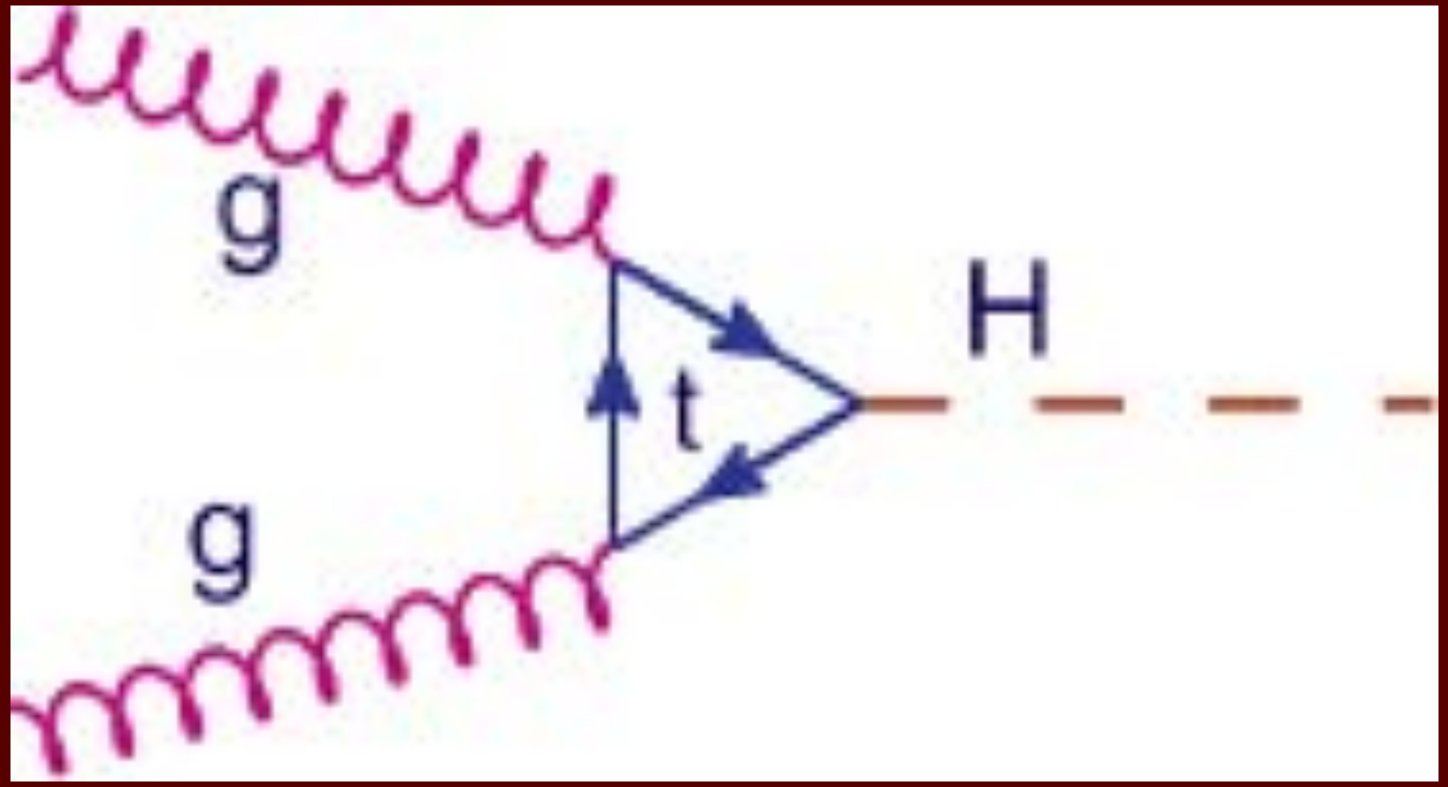
Photons have no mass, because they don't interact with the field. (Photons are particles of light.)

The Higgs boson is a quantum excitation of the field.

Knowing the mass of the Higgs boson we can calculate the coupling of the Higgs boson to all the elementary particles.

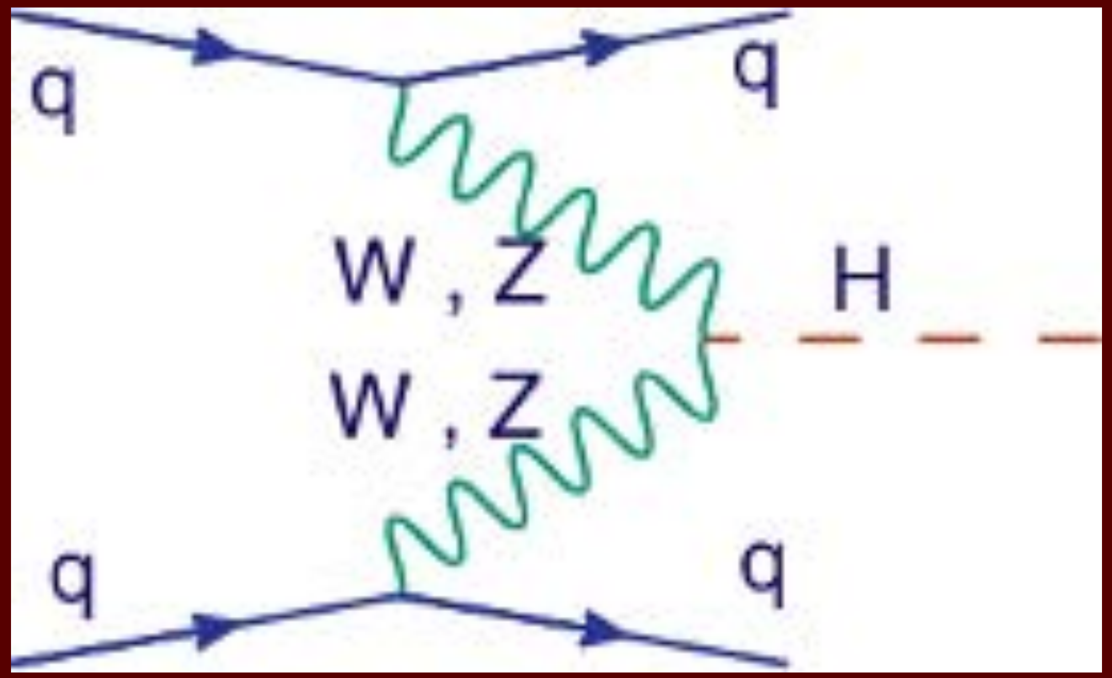
# *Production Modes*

49 pb / 6.9M Higgs in 140 fb$^{-1}$



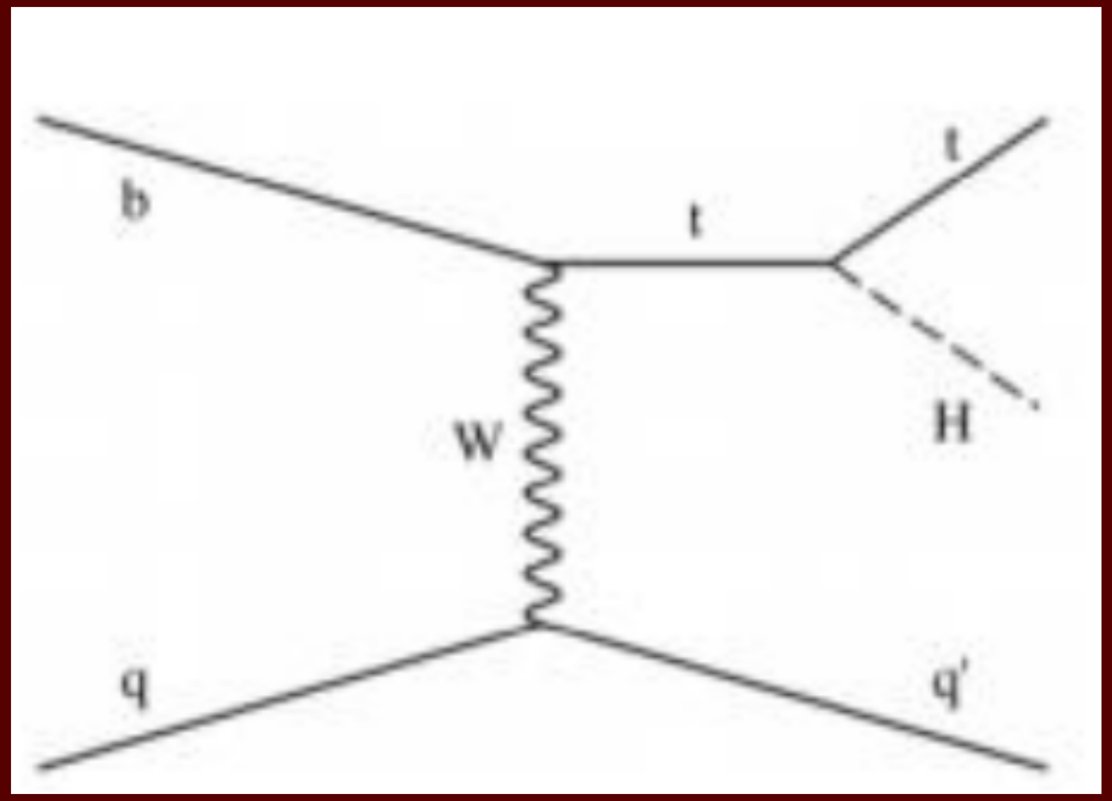
Gluon-Gluon fusion (ggf)

3.8 pb / 520k Higgs in 140 fb$^{-1}$



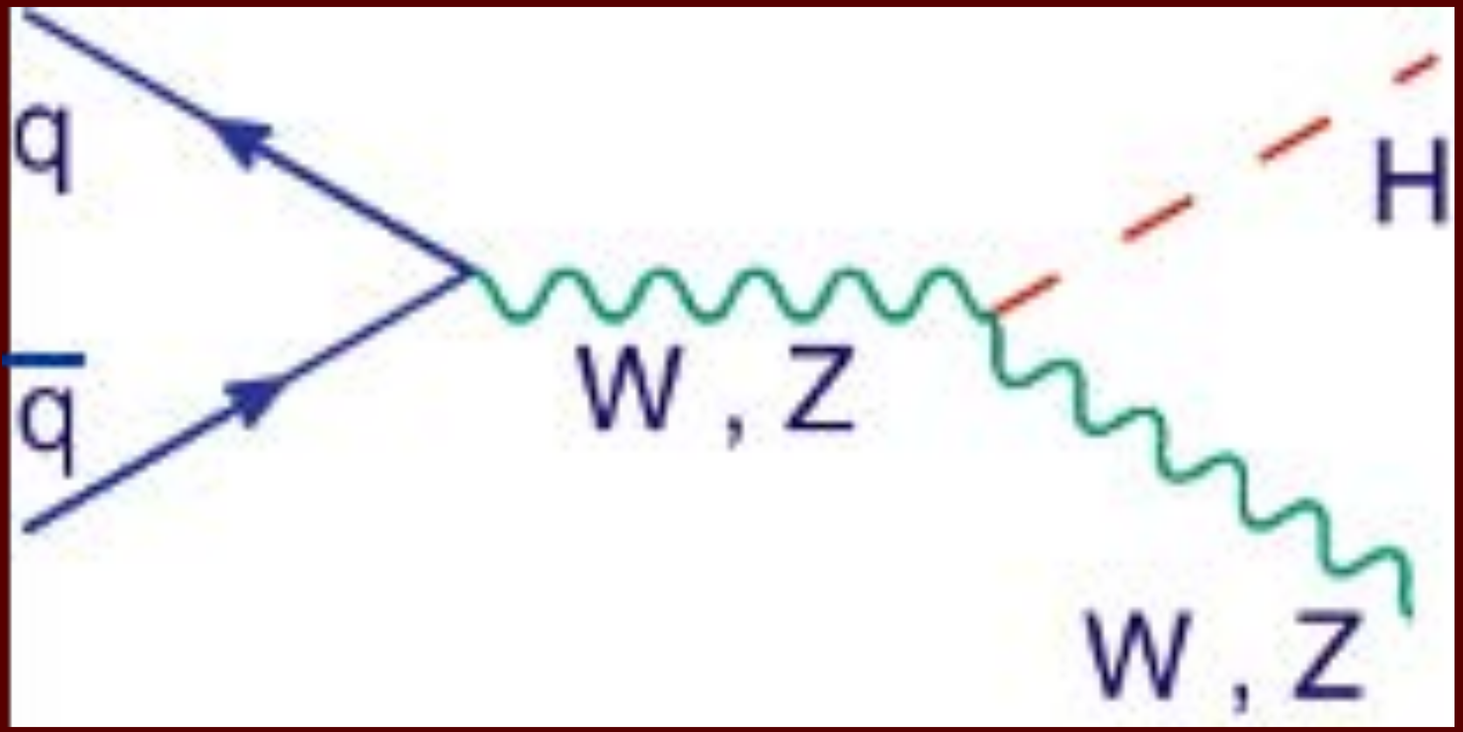
Vector boson fusion (VBF)

0.07 pb / 10k Higgs in 140 fb$^{-1}$



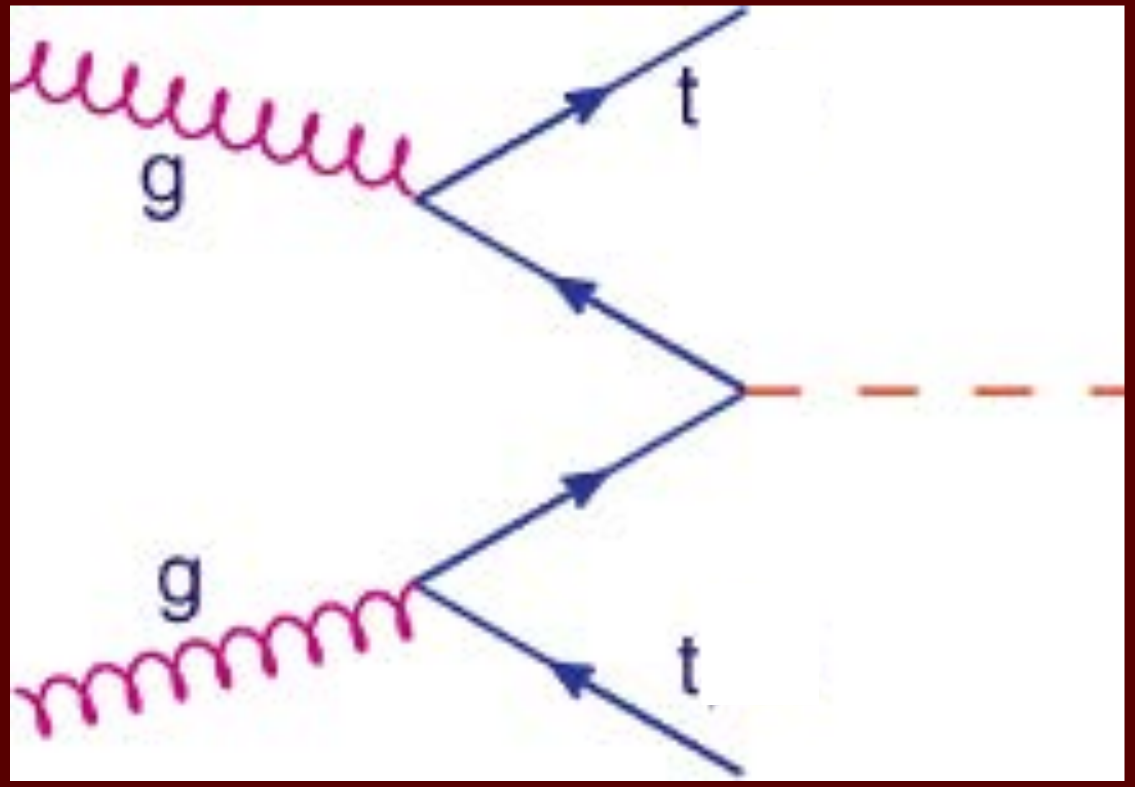
tH production

2.3 pb / 320k Higgs in 140 fb$^{-1}$



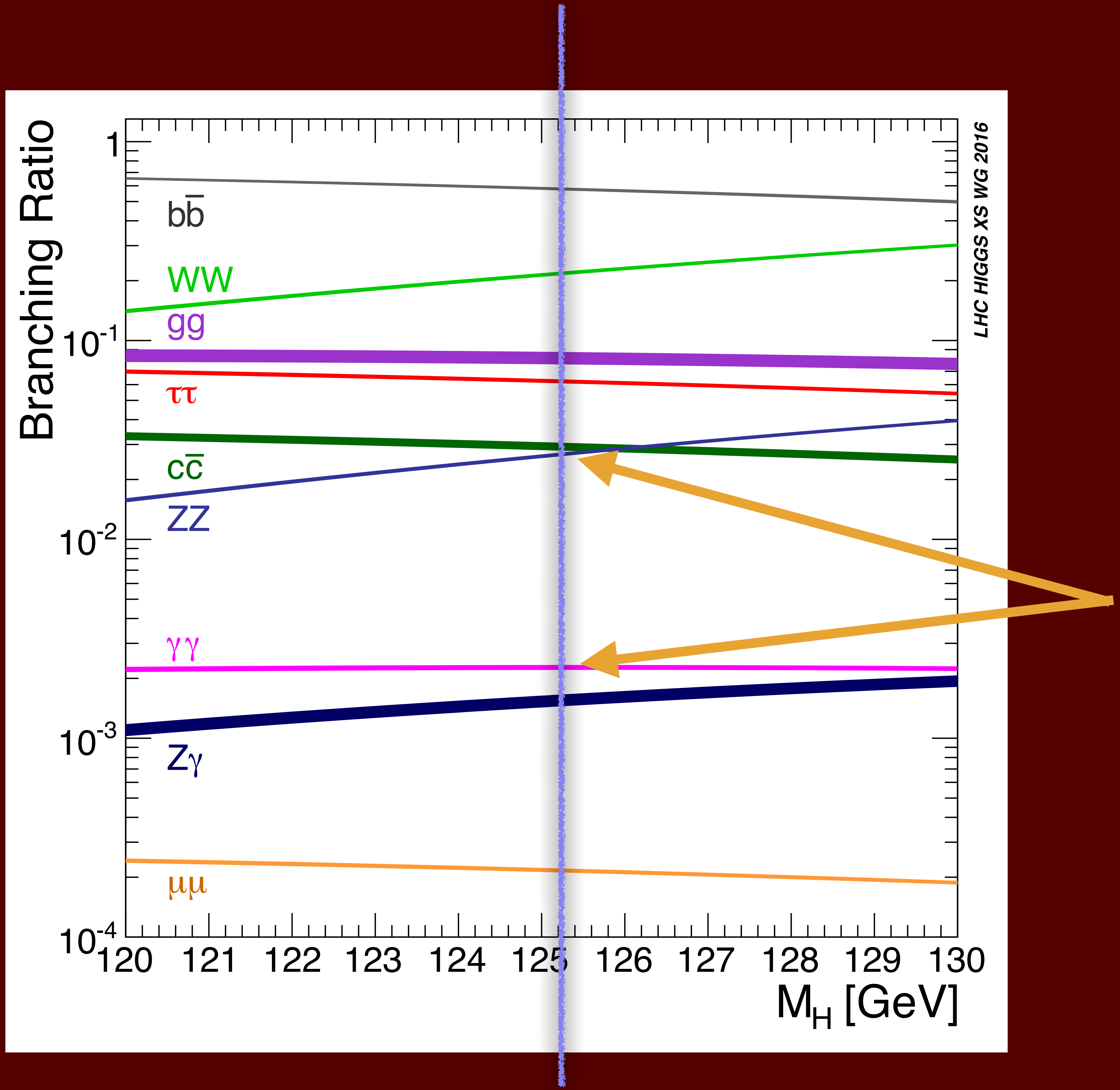
VH Production

0.5 pb / 70k Higgs in 140 fb$^{-1}$



$t\bar{t}H$ producton

# *Cross Sections and Branching Ratios*



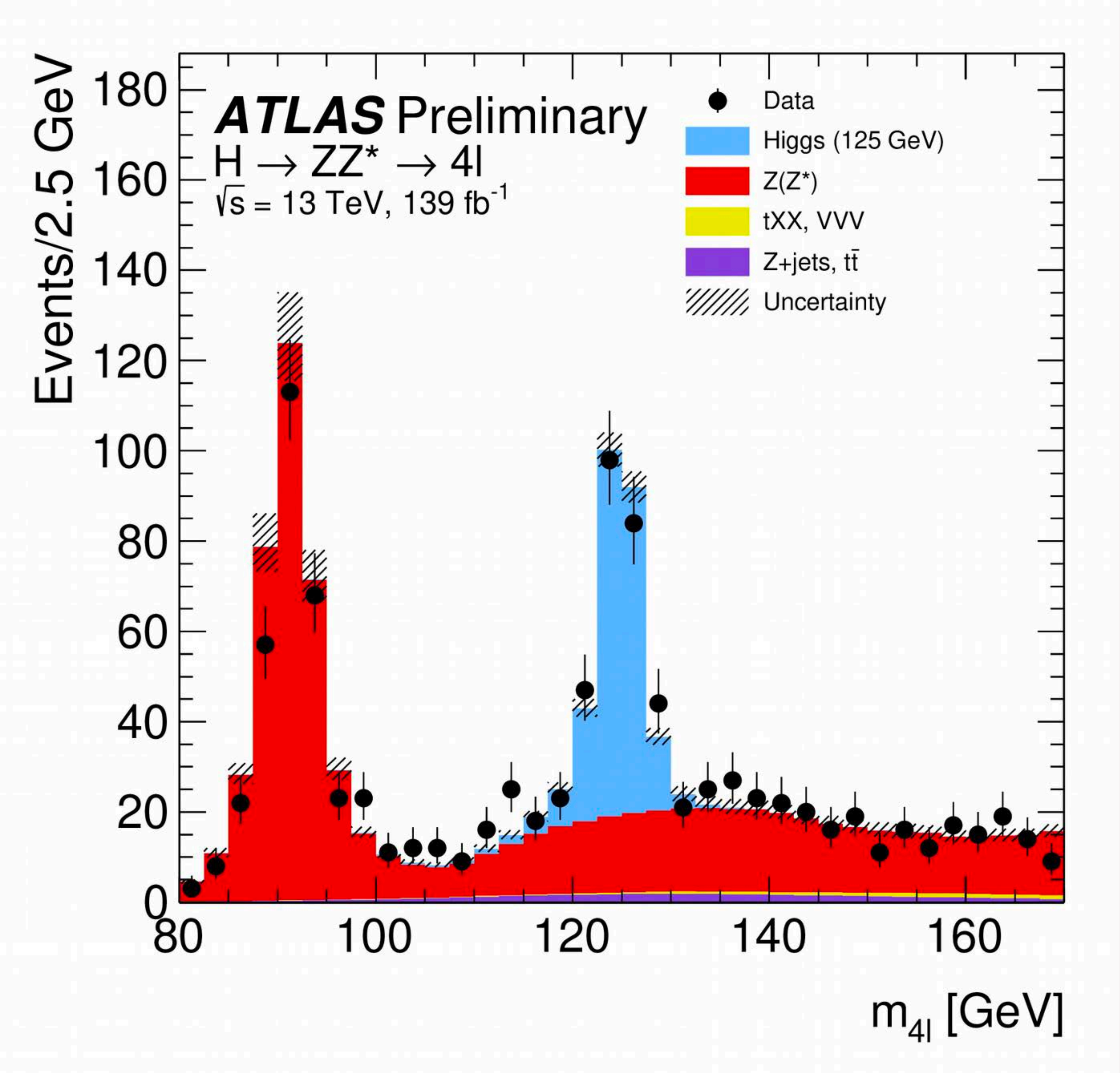
The coupling of the Higgs boson to other elementary particles is proportional to the mass.

The channels with the cleanest signals and best understood backgrounds are ZZ* and $\gamma\gamma$.

Mass of the Higgs Boson 125.38 ± 0.14 GeV (CMS)

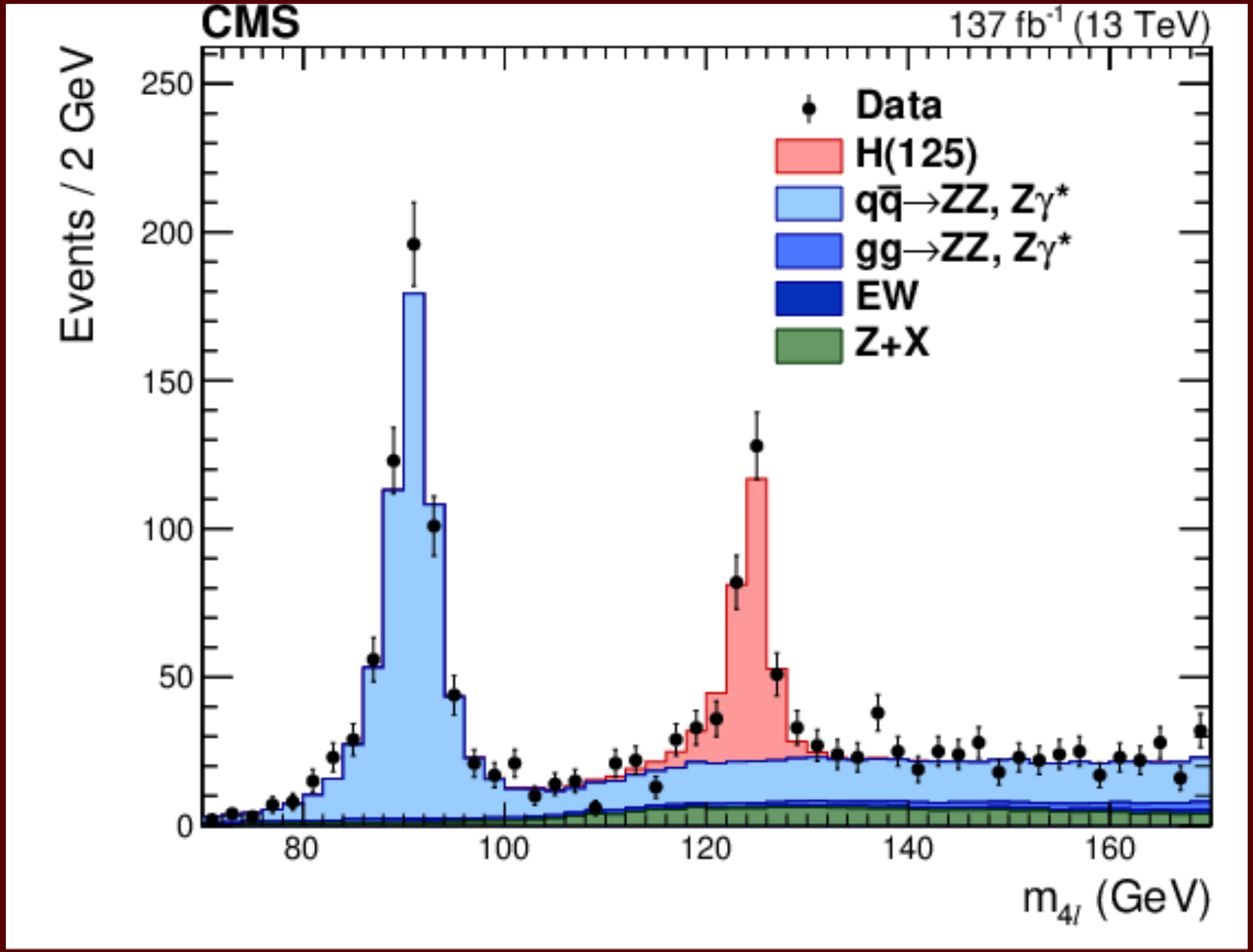
# *Recent* $ZZ^* \to 4\ell$ *from ATLAS and CMS*

Eur. Phys. J. C 80 , 10 (2020) 957



Full run 2 $H \to ZZ^* \to 4\ell$

Eur. Phys. J. C 81, 488 (2021)



Full run 2 $H \to ZZ^* \to 4\ell$

# *The Higgs Potential and the Mass*

$$\mathscr{L}_{SM} = \ldots - V(\Phi)$$

$$\begin{aligned} V(\Phi) &= -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2 \\ &= V_0 + \frac{1}{2}m_H^2 H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4 \end{aligned}$$

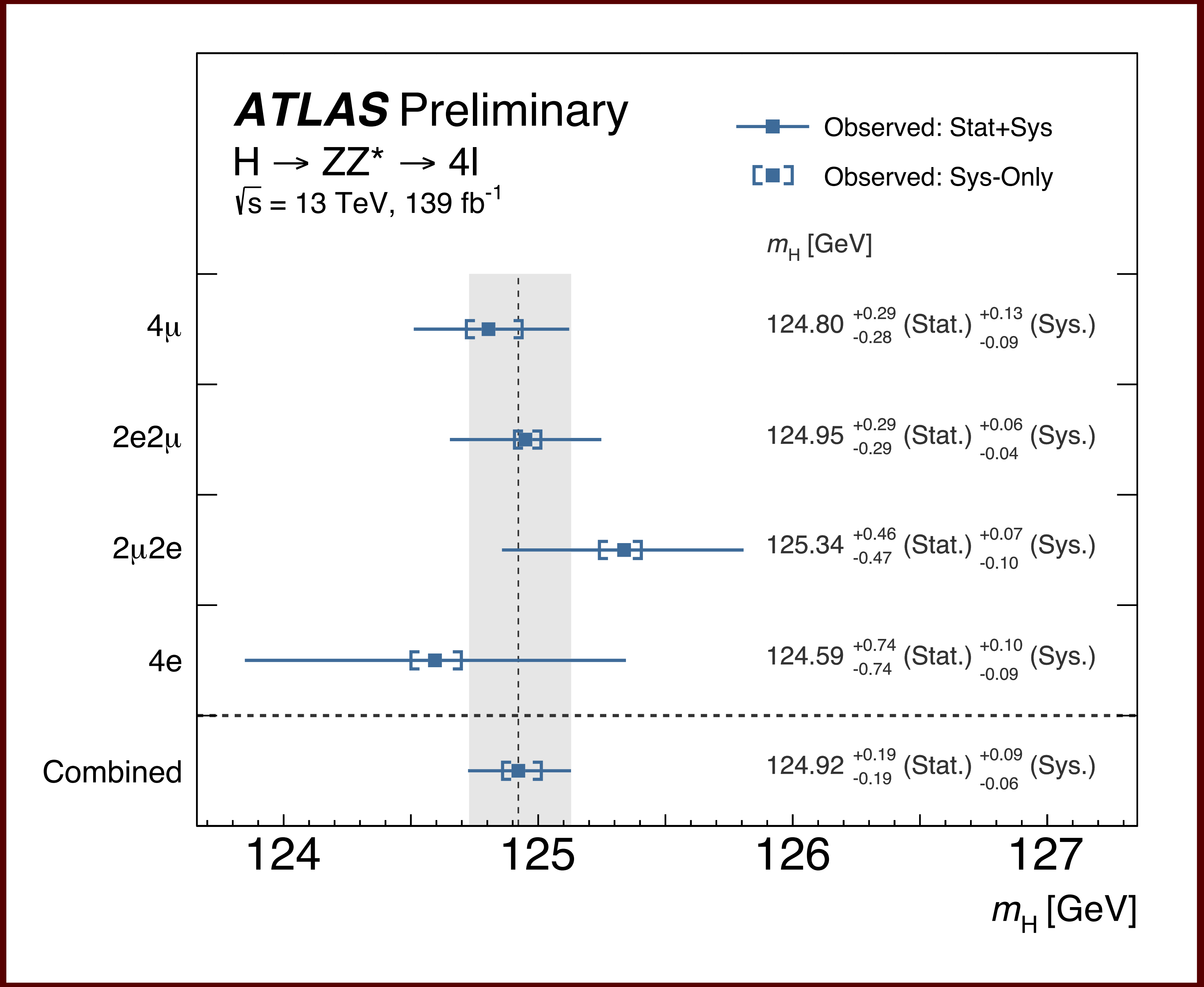
$\mu$ and $\lambda$ are the free parameters of the Higgs potential with $v^2 = -\frac{-\mu^2}{\lambda}$ and $m_H^2 = 2\lambda v^2$

From $m_W = \frac{1}{2}g_W v$ we obtain the vacuum expectation value of the Higgs field to be 246 GeV.

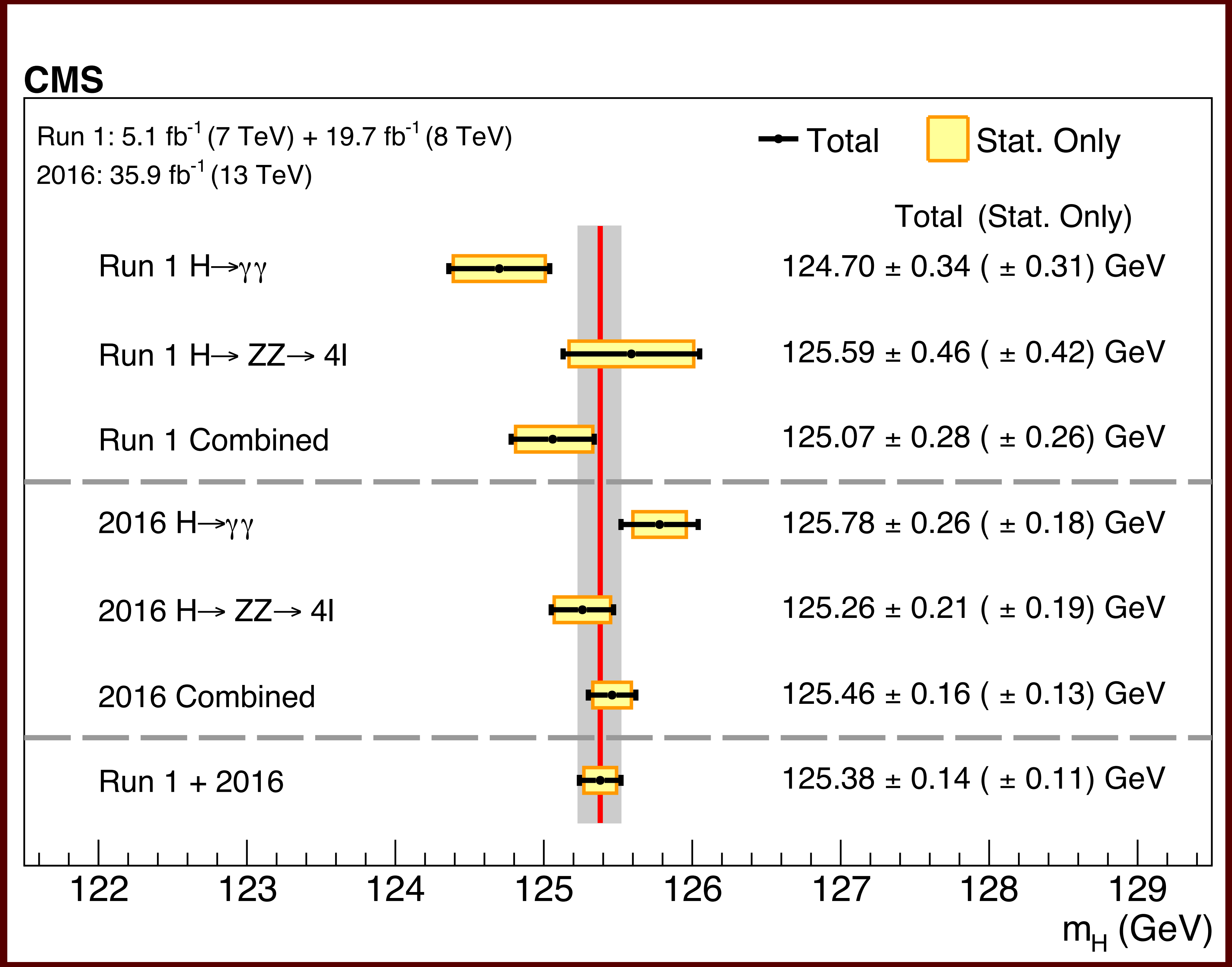
So knowing the Higgs boson mass one can find $\lambda$ and the Higgs potential.

# The Mass

$H \to ZZ^* \to 4\ell$



$H \to \gamma\gamma, ZZ^* \to 4\ell$



$$m_H = 124.92 \pm 0.19\ (\mathrm{stat})\ ^{+0.09}_{-0.06}\ (\mathrm{syst})\ \mathrm{GeV}$$

$$m_H = 125.38 \pm 0.14\ (\pm\ 0.11)\ \mathrm{GeV}$$

Measurement made in the $ZZ^*$ and $H \to \gamma\gamma$ channels
precision limited by both statistics and systematics

# *The Width*

Knowing the Higgs potential all the Yukawa terms and the Gauge terms are defined.

All the couplings to all particles can be calculated → Higgs width ($\Gamma_H$).

The standard model width $\Gamma_H^{SM} = 4.1\ \mathrm{MeV}$ or $\tau_H \sim 1.6 \times 10^{-22}\mathrm{s}$.

Both are too small to be measured directly in a pp-collider.

But:

$$\sigma_{on-shell} \sim \frac{g^2_{prod} \cdot g^2_{decay}}{\Gamma_H} \quad \text{and} \quad \sigma_{off-shell} \sim \frac{g^2_{prod} \cdot g^2_{decay}}{s^4}$$

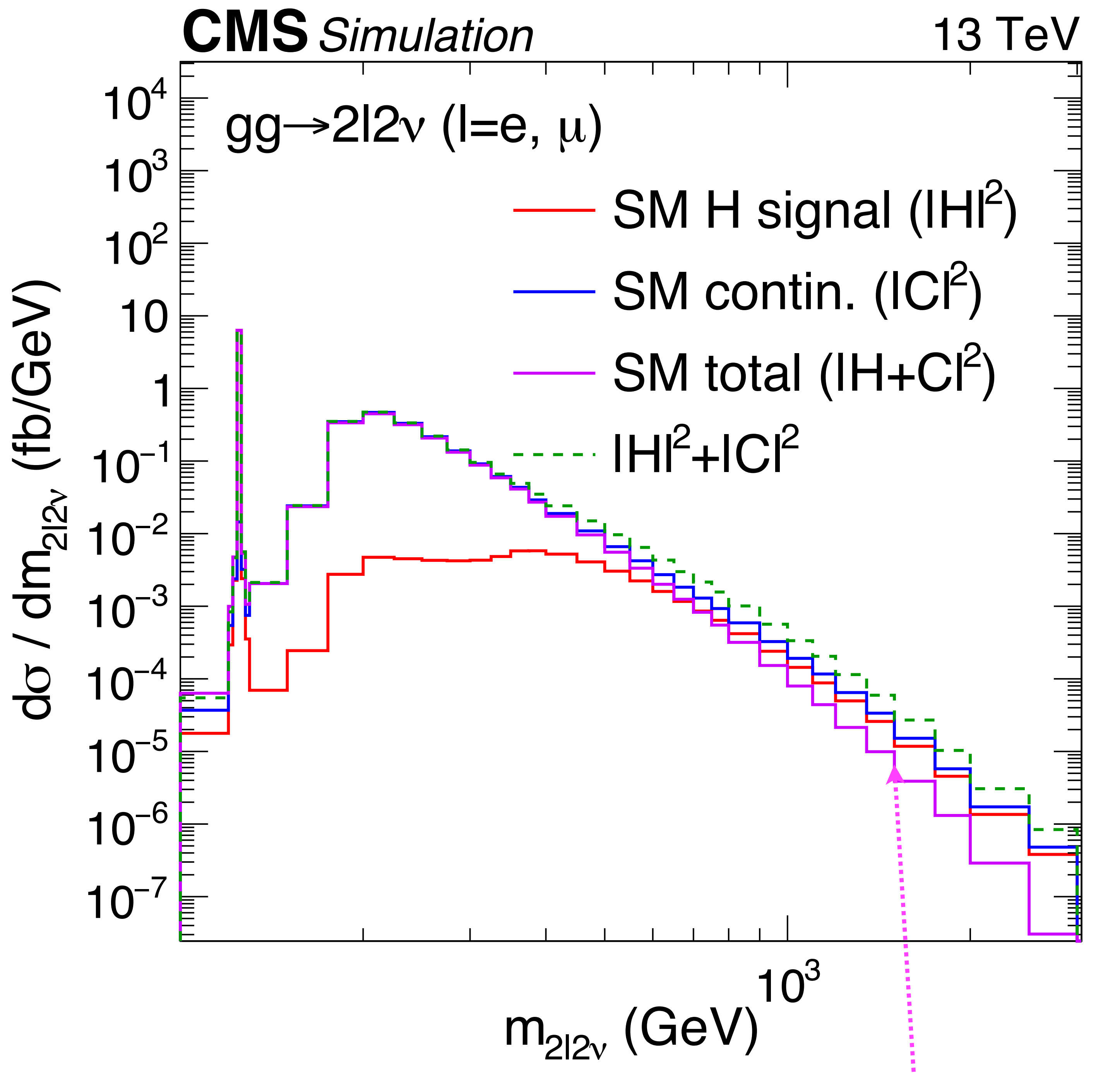
So iff $\mu^H_{\mathrm{off-shell}} \equiv \mu^H_{\mathrm{on-shell}}$ we can measure the width from the ratio of the on-shell to the off-shell yields.

# *The Width*

$$\frac{\sigma^{\text{off-shell}}_{vv\to H\to 4\ell}}{\sigma^{\text{on-shell}}_{vv\to H\to 4\ell}} \propto \Gamma_H$$

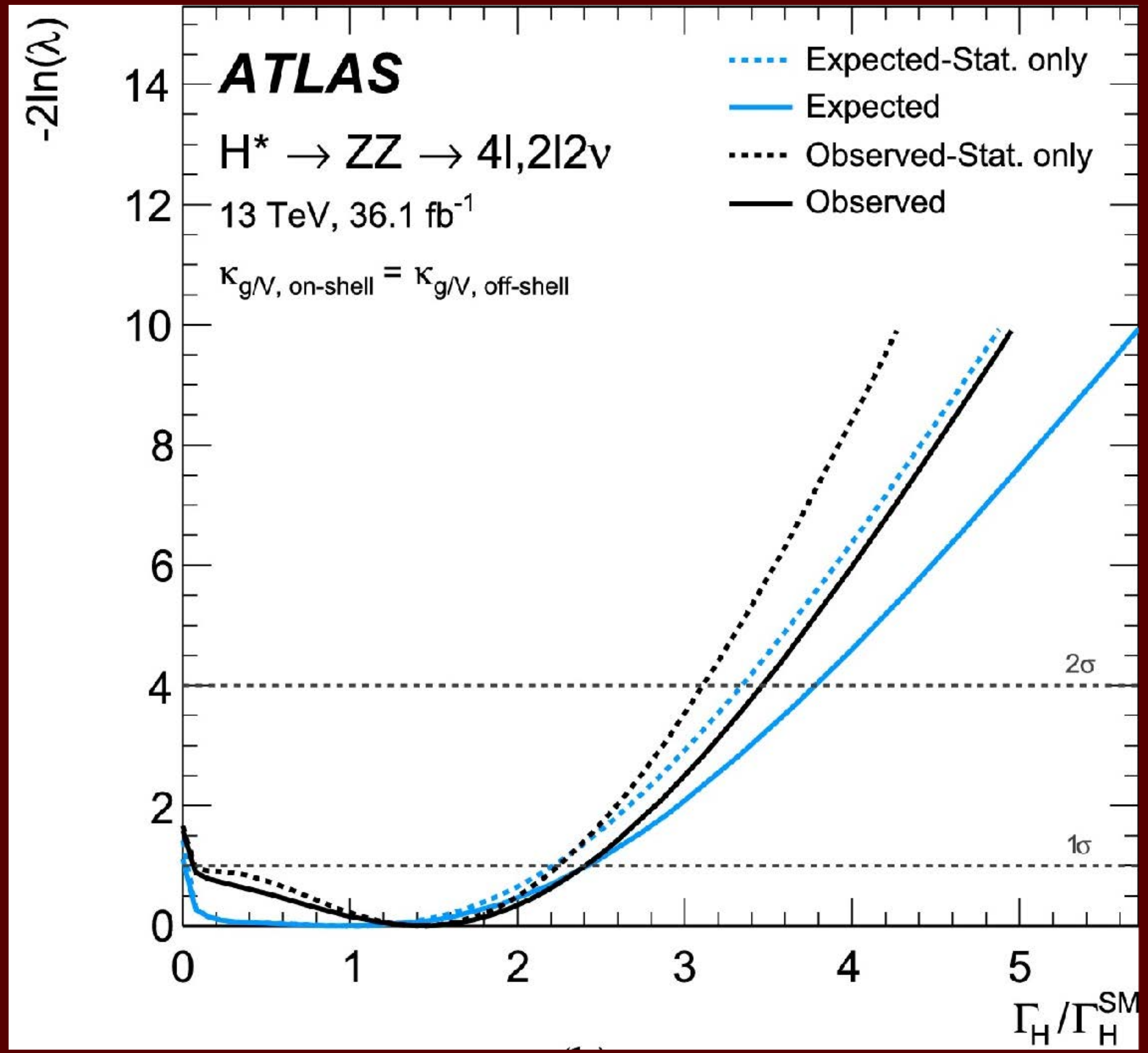
$vv = gg, WW, ZZ, Z\gamma, \gamma\gamma$

Phys. Lett. B 786 (2018) 223



non-resonant ZZ interferes destructively with off-shell H

$H \to ZZ^* \to 4\ell, H \to 2\ell 2\nu$



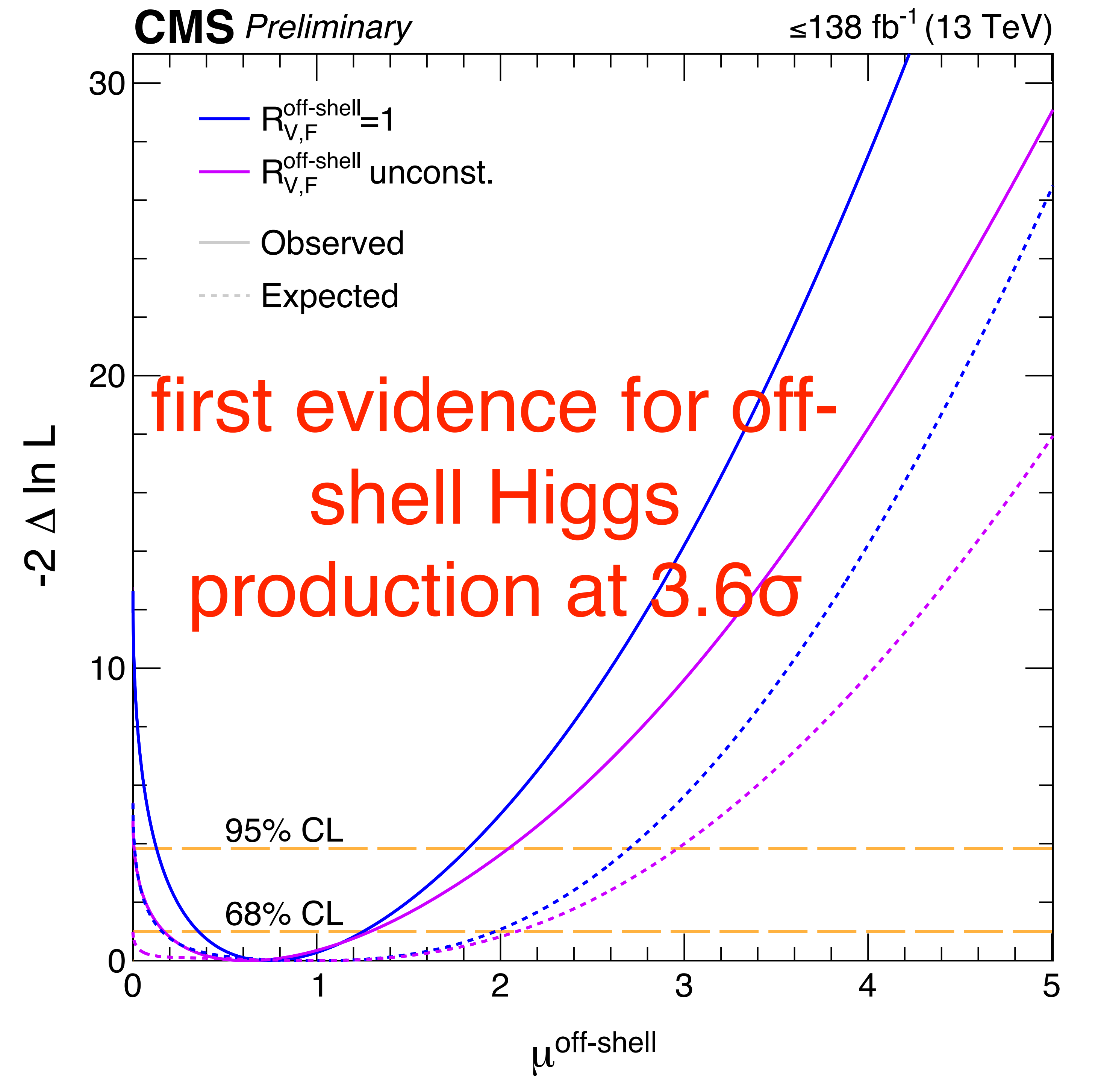
$\Gamma_H < 14.4$ MeV

2015 and 2016 data

# The Width

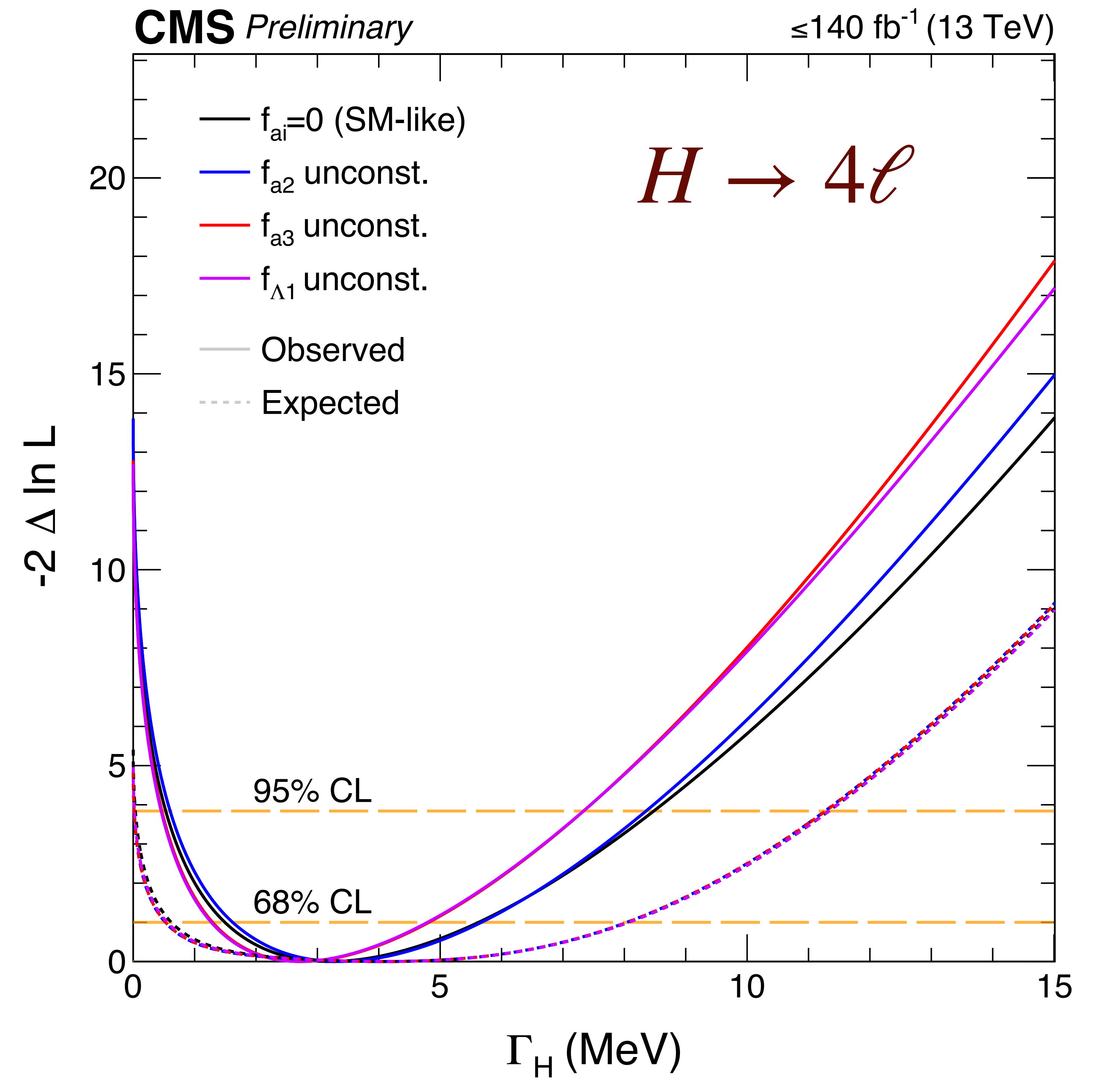
CMS-PAS-HIG-21-013

$H \to 4\ell$ and $H \to 2\ell 2\nu$ events and both on-shell and off-shell events .



first evidence for off-shell Higgs production at 3.6σ

$0.08 < \Gamma_H < 9.16$ MeV



$$\Gamma_H = 3.2\ ^{+2.4}_{-1.7}\ \text{MeV}$$

$$\frac{\sigma^{\text{off-shell}}_{vv\to H\to 4\ell}}{\sigma^{\text{on-shell}}_{vv\to H\to 4\ell}} \propto \Gamma_H$$

$vv = gg, WW, ZZ, Z\gamma, \gamma\gamma$

$\sigma(\Gamma_H) \sim 50\,\%\,\Gamma_H$ the most precise measurement up to now

# *Cross Sections and Branching Ratios*

$$\mathscr{L}_{SM} = \ldots + |D_\mu \Phi|^2 + \psi_i y_{ij} \psi_j \Phi \ldots .$$

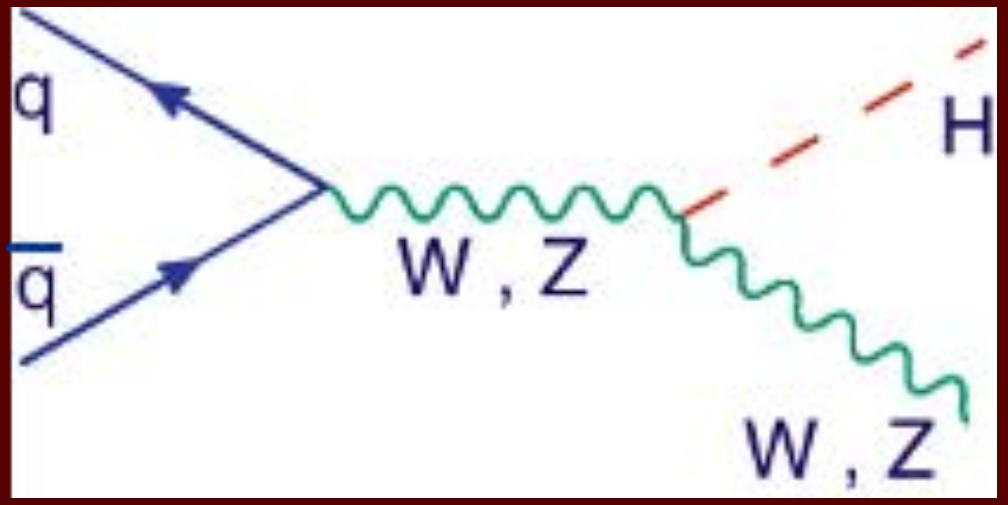
Gauge Couplings:
Tested with ZH, WH, etc measurements

Yukawa Couplings:
Explore with H couplings to fermions.

The Yukawa couplings of the fermions to the Higgs field are given by:

$$g_f = \sqrt{2}\frac{m_f}{v}$$

This is ~ 1 for the top quark and 2 x $10^{-6}$ for electrons



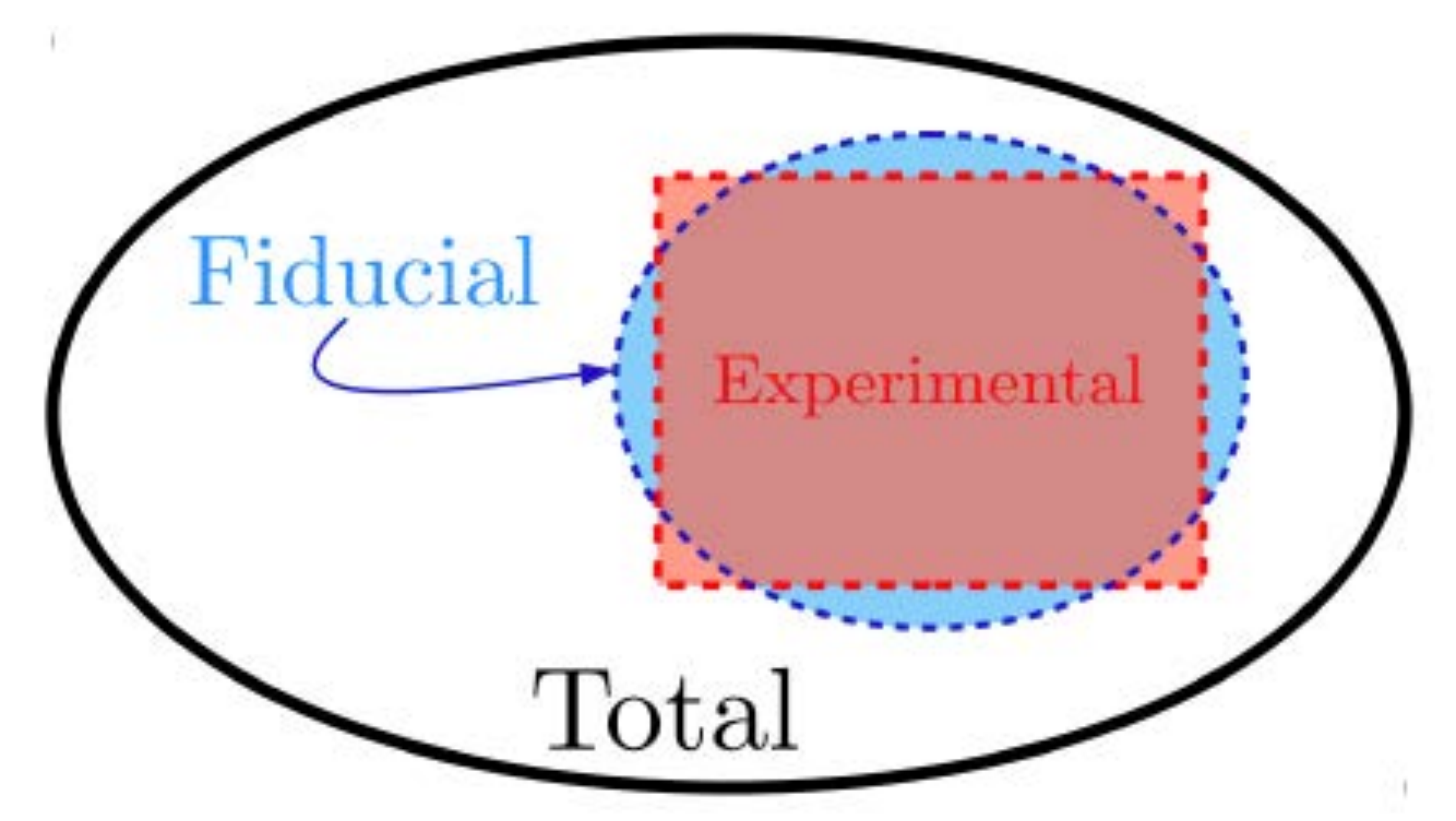
VH Production

Coupling of the Higgs boson to the vector bosons given by: $\frac{1}{2}g_V^2 v$

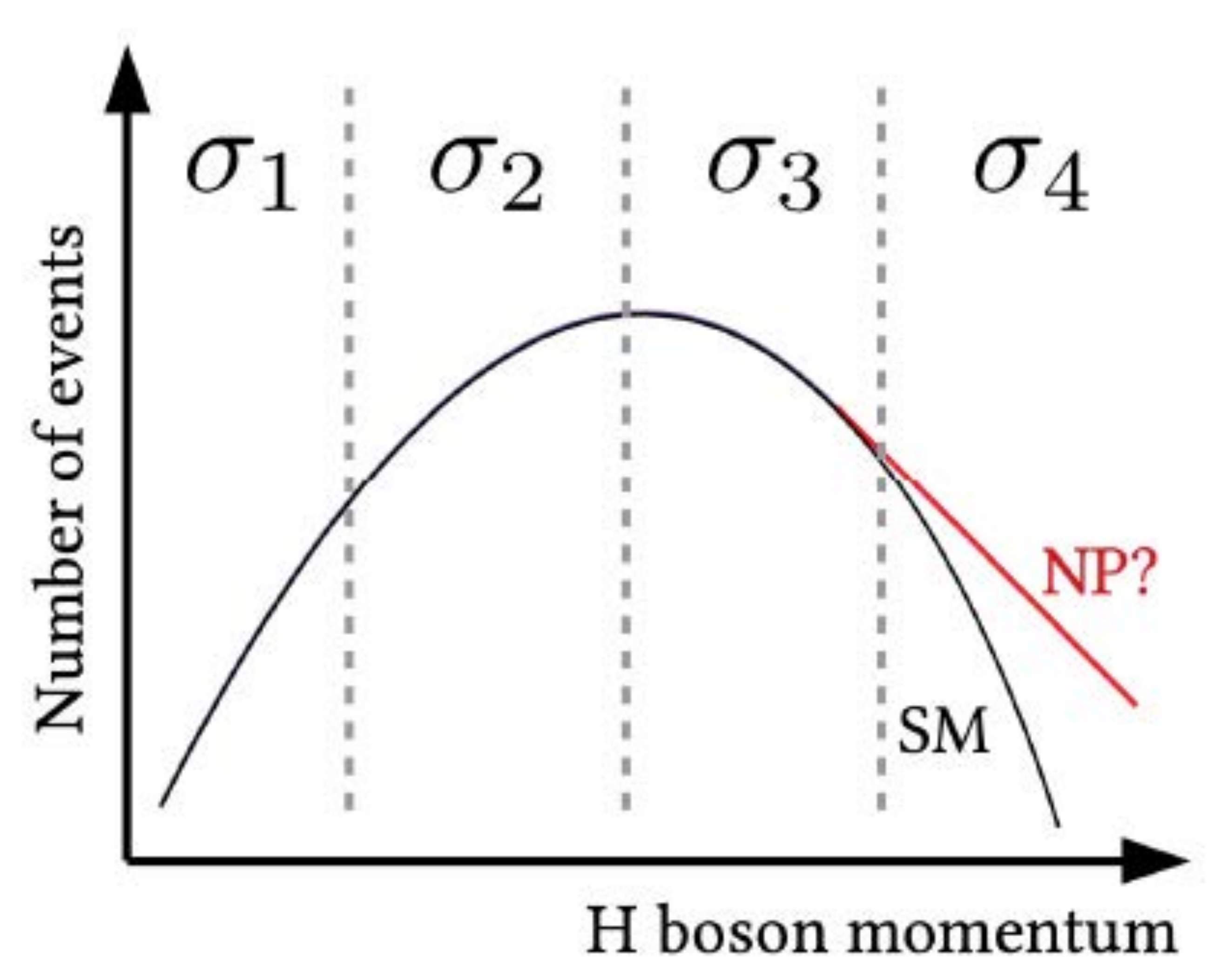
# *Differential and Fiducial Cross Sections*

Fiducial cross-sections are intended to be as model independent as possible.

Match to the experimental conditions  and phase space.



Then divide that region up further



The shape information provided by differential cross sections can be exploited for a range of further interpretations.

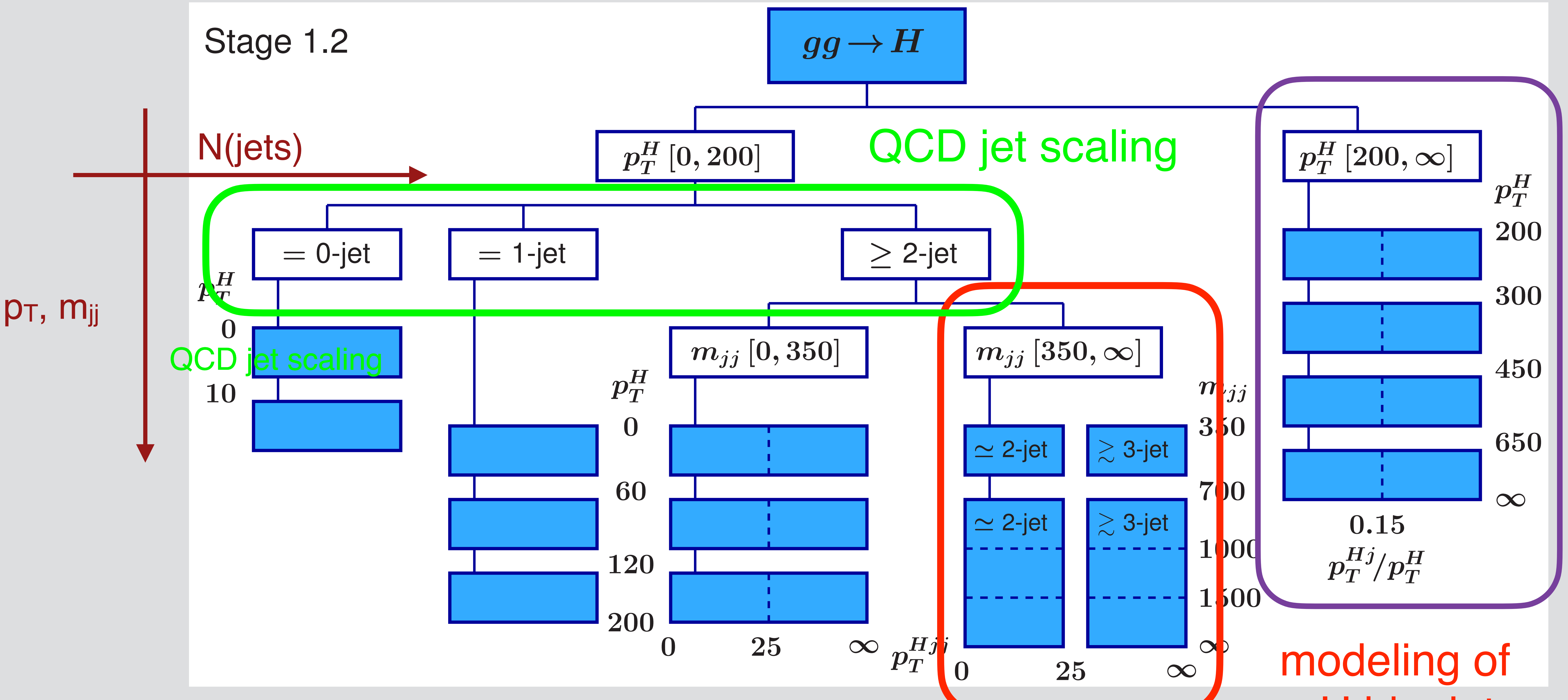
The distributions of different observables can be potentially modified due by BSM effects

# *STXS Measurement*

With 140 $fb^{-1}$ of data we can divide up the measurements into multiple bins.

To compare between experiment and theory we use the Standard Template Cross Sections

STXS for short.

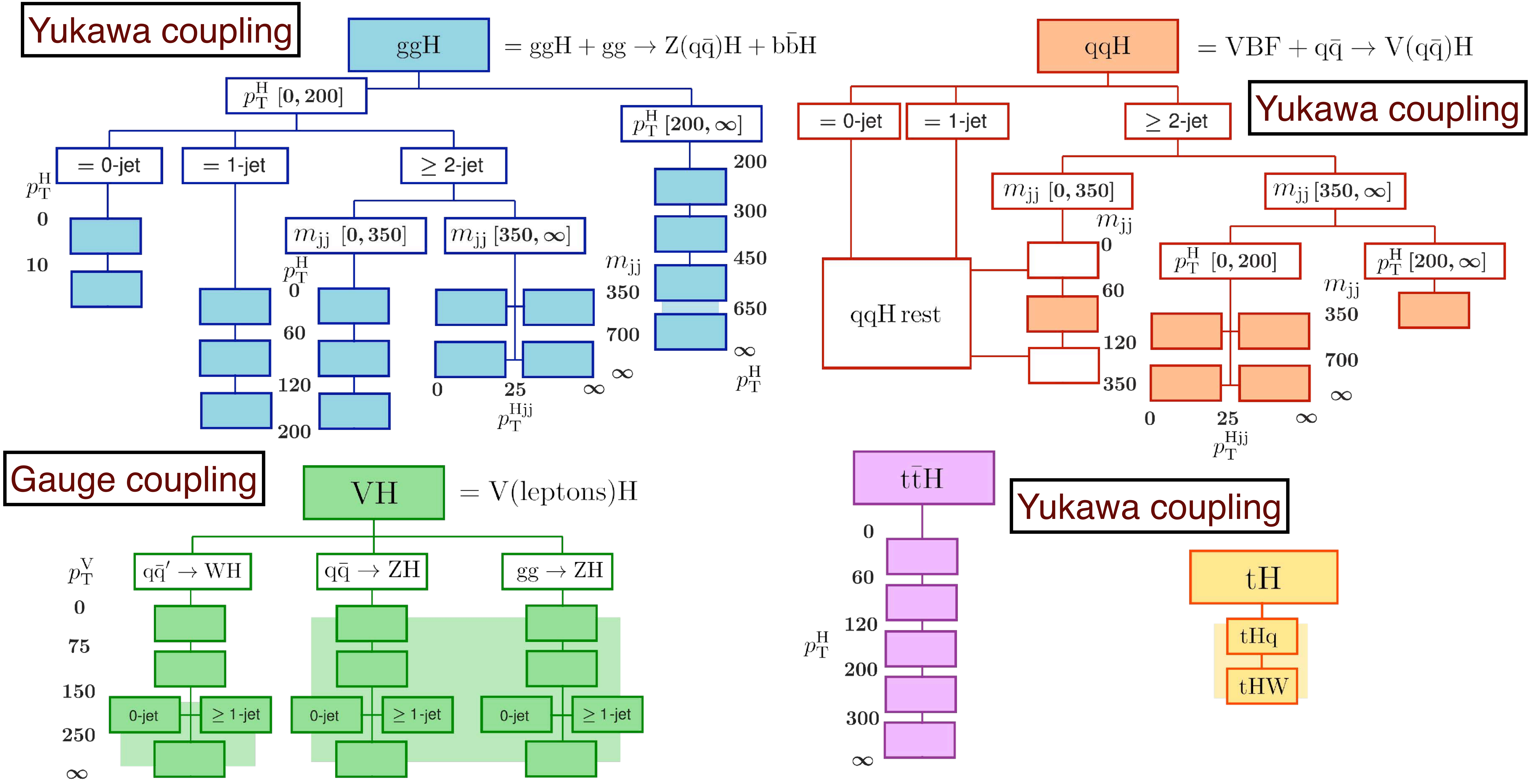


High $p_T$: probe EFT operators, and BSM contributions

modeling of ggH bkg into VBF

# *STXS Framework*

Yukawa coupling



Yukawa coupling

Gauge coupling

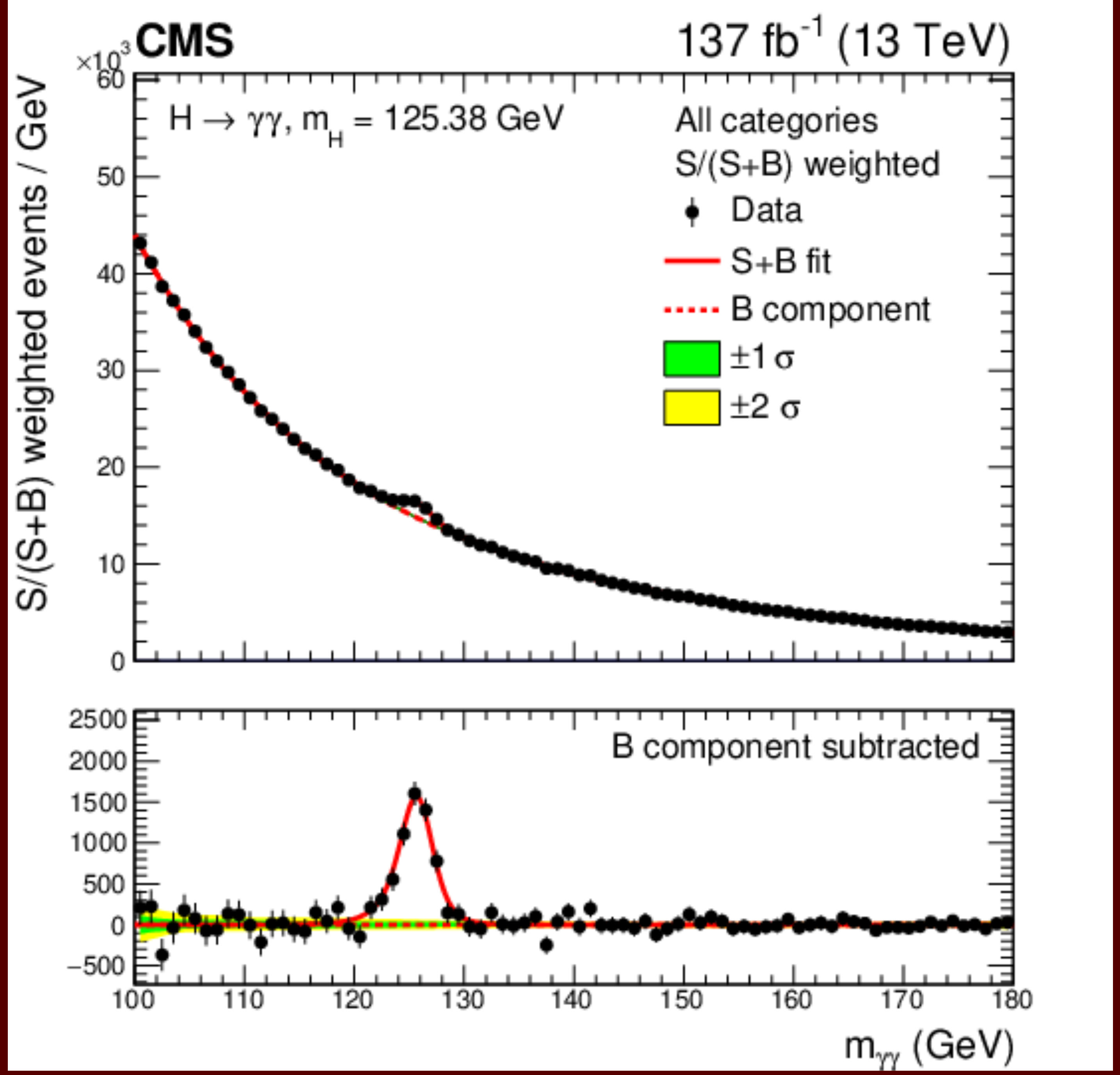
Yukawa coupling

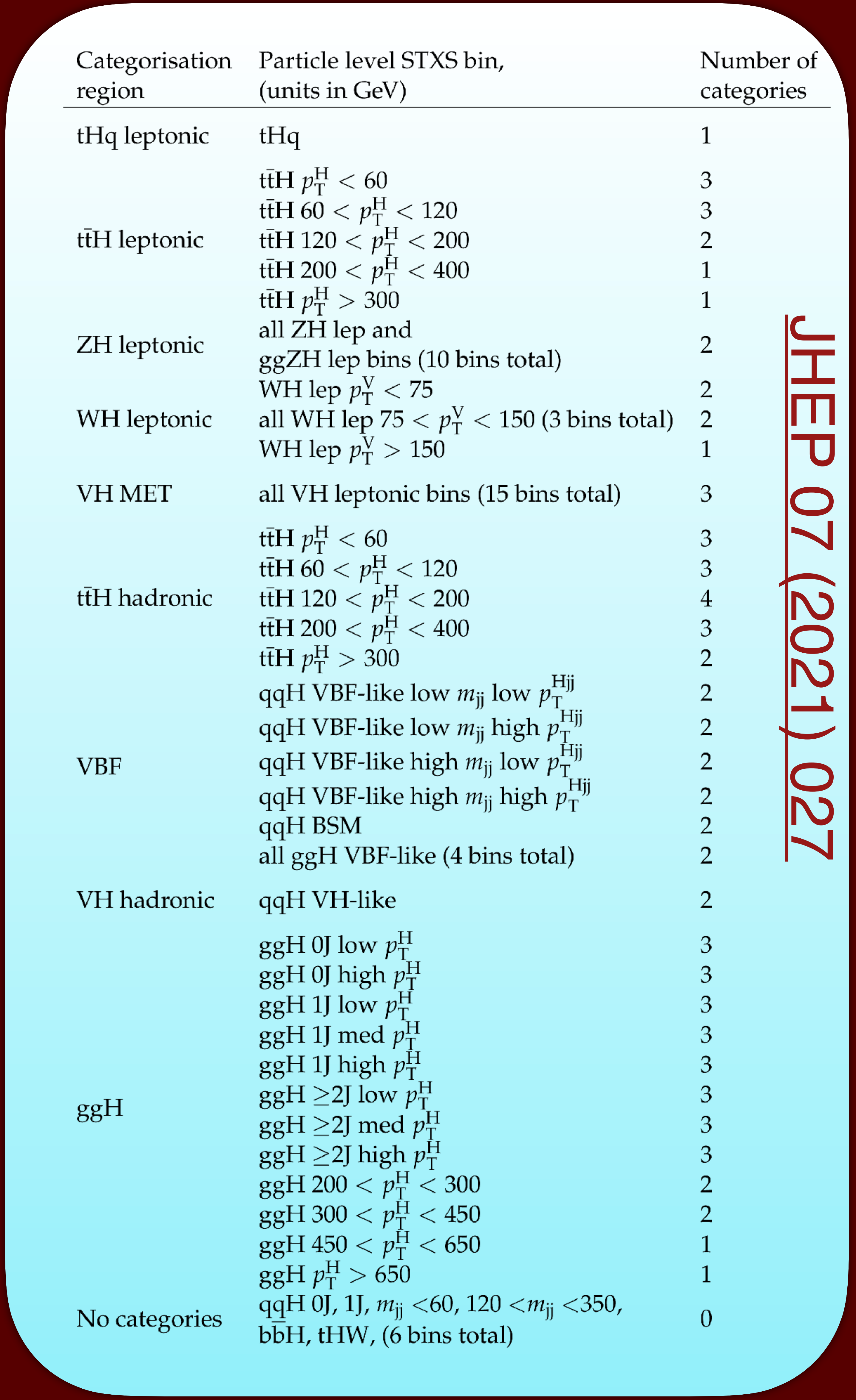
# STXS $H \to \gamma\gamma$

81 different STXS analyses categories

$H \to \gamma\gamma$ is well suited to STXS measurements sensitive to all production modes

Clean signal with high efficiency and well understood backgrounds

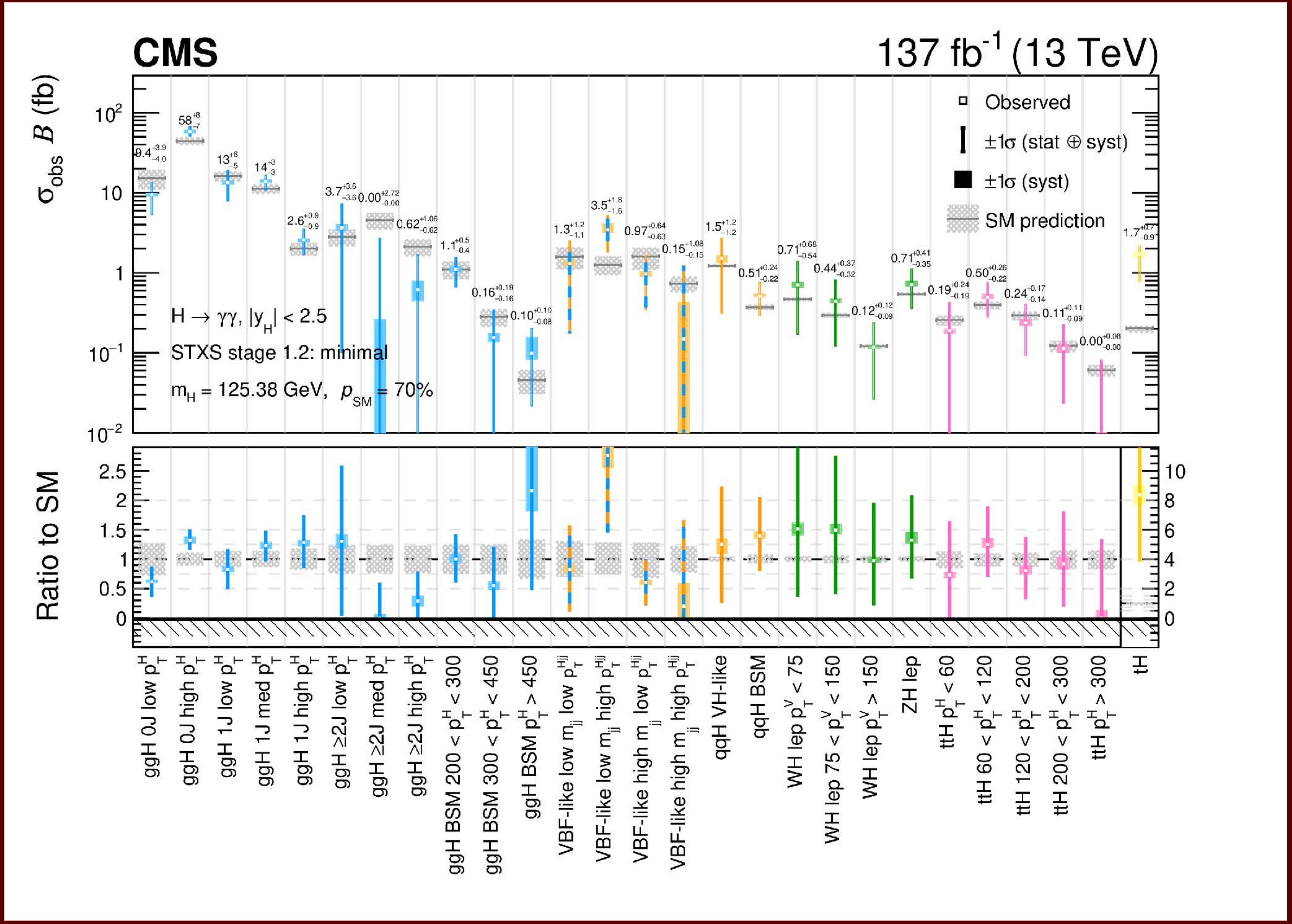


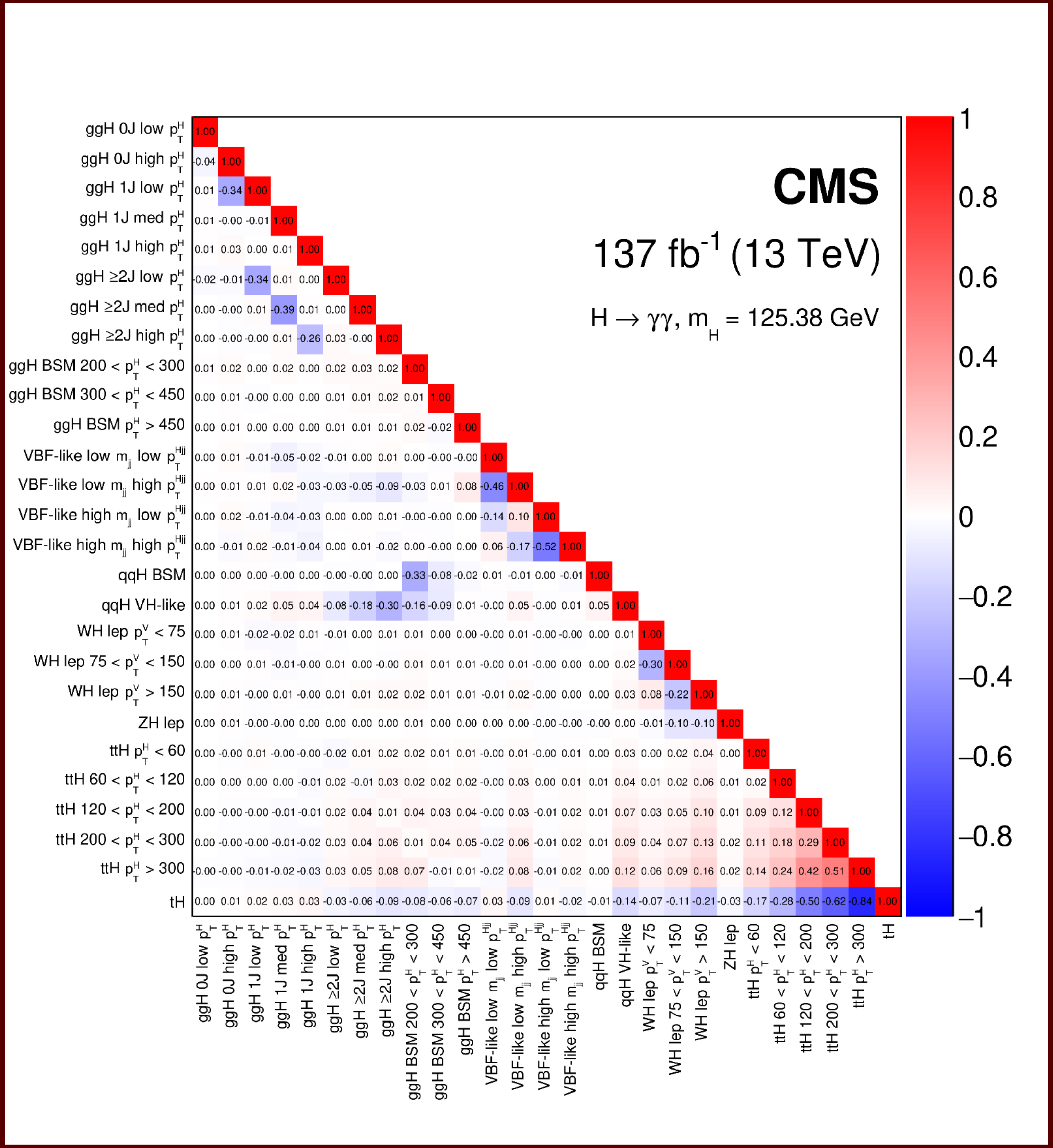


| Categorisation region | Particle level STXS bin, (units in GeV) | Number of categories |
|---|---|---|
| tHq leptonic | tHq | 1 |
| $\mathrm{t\bar{t}H}$ leptonic | $\mathrm{t\bar{t}H}\ p_{\mathrm{T}}^{\mathrm{H}} < 60$ | 3 |
| | $\mathrm{t\bar{t}H}\ 60 < p_{\mathrm{T}}^{\mathrm{H}} < 120$ | 3 |
| | $\mathrm{t\bar{t}H}\ 120 < p_{\mathrm{T}}^{\mathrm{H}} < 200$ | 2 |
| | $\mathrm{t\bar{t}H}\ 200 < p_{\mathrm{T}}^{\mathrm{H}} < 400$ | 1 |
| | $\mathrm{t\bar{t}H}\ p_{\mathrm{T}}^{\mathrm{H}} > 300$ | 1 |
| ZH leptonic | all ZH lep and ggZH lep bins (10 bins total) | 2 |
| WH leptonic | WH lep $p_{\mathrm{T}}^{\mathrm{V}} < 75$ | 2 |
| | all WH lep $75 < p_{\mathrm{T}}^{\mathrm{V}} < 150$ (3 bins total) | 2 |
| | WH lep $p_{\mathrm{T}}^{\mathrm{V}} > 150$ | 1 |
| VH MET | all VH leptonic bins (15 bins total) | 3 |
| $\mathrm{t\bar{t}H}$ hadronic | $\mathrm{t\bar{t}H}\ p_{\mathrm{T}}^{\mathrm{H}} < 60$ | 3 |
| | $\mathrm{t\bar{t}H}\ 60 < p_{\mathrm{T}}^{\mathrm{H}} < 120$ | 3 |
| | $\mathrm{t\bar{t}H}\ 120 < p_{\mathrm{T}}^{\mathrm{H}} < 200$ | 4 |
| | $\mathrm{t\bar{t}H}\ 200 < p_{\mathrm{T}}^{\mathrm{H}} < 400$ | 3 |
| | $\mathrm{t\bar{t}H}\ p_{\mathrm{T}}^{\mathrm{H}} > 300$ | 2 |
| VBF | qqH VBF-like low $m_{\mathrm{jj}}$ low $p_{\mathrm{T}}^{\mathrm{Hjj}}$ | 2 |
| | qqH VBF-like low $m_{\mathrm{jj}}$ high $p_{\mathrm{T}}^{\mathrm{Hjj}}$ | 2 |
| | qqH VBF-like high $m_{\mathrm{jj}}$ low $p_{\mathrm{T}}^{\mathrm{Hjj}}$ | 2 |
| | qqH VBF-like high $m_{\mathrm{jj}}$ high $p_{\mathrm{T}}^{\mathrm{Hjj}}$ | 2 |
| | qqH BSM | 2 |
| | all ggH VBF-like (4 bins total) | 2 |
| VH hadronic | qqH VH-like | 2 |
| ggH | ggH 0J low $p_{\mathrm{T}}^{\mathrm{H}}$ | 3 |
| | ggH 0J high $p_{\mathrm{T}}^{\mathrm{H}}$ | 3 |
| | ggH 1J low $p_{\mathrm{T}}^{\mathrm{H}}$ | 3 |
| | ggH 1J med $p_{\mathrm{T}}^{\mathrm{H}}$ | 3 |
| | ggH 1J high $p_{\mathrm{T}}^{\mathrm{H}}$ | 3 |
| | ggH $\geq$2J low $p_{\mathrm{T}}^{\mathrm{H}}$ | 3 |
| | ggH $\geq$2J med $p_{\mathrm{T}}^{\mathrm{H}}$ | 3 |
| | ggH $\geq$2J high $p_{\mathrm{T}}^{\mathrm{H}}$ | 3 |
| | ggH $200 < p_{\mathrm{T}}^{\mathrm{H}} < 300$ | 2 |
| | ggH $300 < p_{\mathrm{T}}^{\mathrm{H}} < 450$ | 2 |
| | ggH $450 < p_{\mathrm{T}}^{\mathrm{H}} < 650$ | 1 |
| | ggH $p_{\mathrm{T}}^{\mathrm{H}} > 650$ | 1 |
| No categories | qqH 0J, 1J, $m_{\mathrm{jj}}$ <60, 120 <$m_{\mathrm{jj}}$ <350, $\mathrm{b\bar{b}H}$, tHW, (6 bins total) | 0 |

JHEP 07 (2021) 027

# STXS $H \rightarrow \gamma\gamma$





| | ggH 0J low $p_T^H$ | ggH 0J high $p_T^H$ | ggH 1J low $p_T^H$ | ggH 1J med $p_T^H$ | ggH 1J high $p_T^H$ | ggH ≥2J low $p_T^H$ | ggH ≥2J med $p_T^H$ | ggH ≥2J high $p_T^H$ | ggH BSM 200 < $p_T^H$ < 300 | ggH BSM 300 < $p_T^H$ < 450 | ggH BSM $p_T^H$ > 450 | VBF-like low $m_{jj}$ low $p_T^{Hjj}$ | VBF-like low $m_{jj}$ high $p_T^{Hjj}$ | VBF-like high $m_{jj}$ low $p_T^{Hjj}$ | VBF-like high $m_{jj}$ high $p_T^{Hjj}$ | qqH BSM | qqH VH-like | WH lep $p_T^V$ < 75 | WH lep 75 < $p_T^V$ < 150 | WH lep $p_T^V$ > 150 | ZH lep | ttH $p_T^H$ < 60 | ttH 60 < $p_T^H$ < 120 | ttH 120 < $p_T^H$ < 200 | ttH 200 < $p_T^H$ < 300 | ttH $p_T^H$ > 300 | tH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| ggH 0J low $p_T^H$ | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | | | |
| ggH 0J high $p_T^H$ | -0.04 | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | | |
| ggH 1J low $p_T^H$ | 0.01 | -0.34 | 1.00 | | | | | | | | | | | | | | | | | | | | | | | | |
| ggH 1J med $p_T^H$ | 0.01 | -0.00 | -0.01 | 1.00 | | | | | | | | | | | | | | | | | | | | | | | |
| ggH 1J high $p_T^H$ | 0.01 | 0.03 | 0.00 | 0.01 | 1.00 | | | | | | | | | | | | | | | | | | | | | | |
| ggH ≥2J low $p_T^H$ | -0.02 | -0.01 | -0.34 | 0.01 | 0.00 | 1.00 | | | | | | | | | | | | | | | | | | | | | |
| ggH ≥2J med $p_T^H$ | 0.00 | -0.00 | 0.01 | -0.39 | 0.01 | 0.00 | 1.00 | | | | | | | | | | | | | | | | | | | | |
| ggH ≥2J high $p_T^H$ | 0.00 | -0.00 | -0.00 | 0.01 | -0.26 | 0.03 | -0.00 | 1.00 | | | | | | | | | | | | | | | | | | | |
| ggH BSM 200 < $p_T^H$ < 300 | 0.01 | 0.02 | 0.00 | 0.02 | 0.00 | 0.02 | 0.03 | 0.02 | 1.00 | | | | | | | | | | | | | | | | | | |
| ggH BSM 300 < $p_T^H$ < 450 | 0.00 | 0.01 | -0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.02 | 0.01 | 1.00 | | | | | | | | | | | | | | | | | |
| ggH BSM $p_T^H$ > 450 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.01 | 0.01 | 0.01 | 0.02 | -0.02 | 1.00 | | | | | | | | | | | | | | | | |
| VBF-like low $m_{jj}$ low $p_T^{Hjj}$ | 0.00 | 0.01 | -0.01 | -0.05 | -0.02 | -0.01 | 0.00 | 0.01 | 0.00 | -0.00 | -0.00 | 1.00 | | | | | | | | | | | | | | | |
| VBF-like low $m_{jj}$ high $p_T^{Hjj}$ | 0.00 | 0.01 | 0.01 | 0.02 | -0.03 | -0.03 | -0.05 | -0.09 | -0.03 | 0.01 | 0.08 | -0.46 | 1.00 | | | | | | | | | | | | | | |
| VBF-like high $m_{jj}$ low $p_T^{Hjj}$ | 0.00 | 0.02 | -0.01 | -0.04 | -0.03 | 0.00 | 0.00 | 0.01 | -0.00 | -0.00 | 0.00 | -0.14 | 0.10 | 1.00 | | | | | | | | | | | | | |
| VBF-like high $m_{jj}$ high $p_T^{Hjj}$ | 0.00 | -0.01 | 0.02 | -0.01 | -0.04 | 0.00 | 0.01 | -0.02 | 0.00 | -0.00 | 0.00 | 0.06 | -0.17 | -0.52 | 1.00 | | | | | | | | | | | | |
| qqH BSM | 0.00 | 0.00 | 0.00 | -0.00 | 0.00 | -0.00 | -0.00 | 0.00 | -0.33 | -0.08 | -0.02 | 0.01 | -0.01 | 0.00 | -0.01 | 1.00 | | | | | | | | | | | |
| qqH VH-like | 0.00 | 0.01 | 0.02 | 0.05 | 0.04 | -0.08 | -0.18 | -0.30 | -0.16 | -0.09 | 0.01 | -0.00 | 0.05 | -0.00 | 0.01 | 0.05 | 1.00 | | | | | | | | | | |
| WH lep $p_T^V$ < 75 | 0.00 | 0.01 | -0.02 | -0.02 | 0.01 | -0.01 | 0.00 | 0.01 | 0.01 | 0.00 | 0.00 | -0.00 | 0.01 | -0.00 | -0.00 | 0.00 | 0.01 | 1.00 | | | | | | | | | |
| WH lep 75 < $p_T^V$ < 150 | 0.00 | 0.00 | 0.01 | -0.01 | -0.00 | 0.01 | 0.00 | -0.00 | 0.01 | 0.01 | 0.01 | -0.00 | 0.01 | -0.00 | 0.00 | 0.00 | 0.02 | -0.30 | 1.00 | | | | | | | | |
| WH lep $p_T^V$ > 150 | 0.00 | 0.01 | -0.00 | 0.01 | -0.00 | 0.01 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | -0.01 | 0.02 | -0.00 | 0.00 | 0.00 | 0.03 | 0.08 | -0.22 | 1.00 | | | | | | | |
| ZH lep | 0.00 | 0.01 | -0.00 | -0.00 | 0.00 | 0.00 | 0.00 | 0.00 | 0.01 | 0.00 | 0.00 | 0.00 | 0.00 | -0.00 | -0.00 | -0.00 | 0.00 | -0.01 | -0.10 | -0.10 | 1.00 | | | | | | |
| ttH $p_T^H$ < 60 | 0.00 | -0.00 | 0.01 | -0.00 | -0.00 | -0.02 | 0.01 | 0.02 | 0.02 | 0.01 | 0.01 | -0.00 | 0.01 | -0.00 | 0.01 | 0.00 | 0.03 | 0.00 | 0.02 | 0.04 | 0.00 | 1.00 | | | | | |
| ttH 60 < $p_T^H$ < 120 | 0.00 | 0.00 | 0.00 | 0.00 | -0.01 | 0.02 | -0.01 | 0.03 | 0.02 | 0.02 | 0.02 | -0.00 | 0.03 | 0.00 | 0.01 | 0.01 | 0.04 | 0.01 | 0.02 | 0.06 | 0.01 | 0.02 | 1.00 | | | | |
| ttH 120 < $p_T^H$ < 200 | 0.00 | -0.00 | -0.00 | -0.01 | -0.01 | 0.02 | 0.04 | 0.01 | 0.04 | 0.03 | 0.04 | -0.00 | 0.03 | -0.01 | 0.02 | 0.01 | 0.07 | 0.03 | 0.05 | 0.10 | 0.01 | 0.09 | 0.12 | 1.00 | | | |
| ttH 200 < $p_T^H$ < 300 | 0.00 | -0.00 | -0.00 | -0.01 | -0.02 | 0.03 | 0.04 | 0.06 | 0.01 | 0.04 | 0.05 | -0.02 | 0.06 | -0.01 | 0.02 | 0.01 | 0.09 | 0.04 | 0.07 | 0.13 | 0.02 | 0.11 | 0.18 | 0.29 | 1.00 | | |
| ttH $p_T^H$ > 300 | -0.00 | -0.00 | -0.01 | -0.02 | -0.03 | 0.03 | 0.05 | 0.08 | 0.07 | -0.01 | 0.01 | -0.02 | 0.08 | -0.01 | 0.02 | 0.00 | 0.12 | 0.06 | 0.09 | 0.16 | 0.02 | 0.14 | 0.24 | 0.42 | 0.51 | 1.00 | |
| tH | 0.00 | 0.01 | 0.02 | 0.03 | 0.03 | -0.03 | -0.06 | -0.09 | -0.08 | -0.06 | -0.07 | 0.03 | -0.09 | 0.01 | -0.02 | -0.01 | -0.14 | -0.07 | -0.11 | -0.21 | -0.03 | -0.17 | -0.28 | -0.50 | -0.62 | -0.84 | 1.00 |

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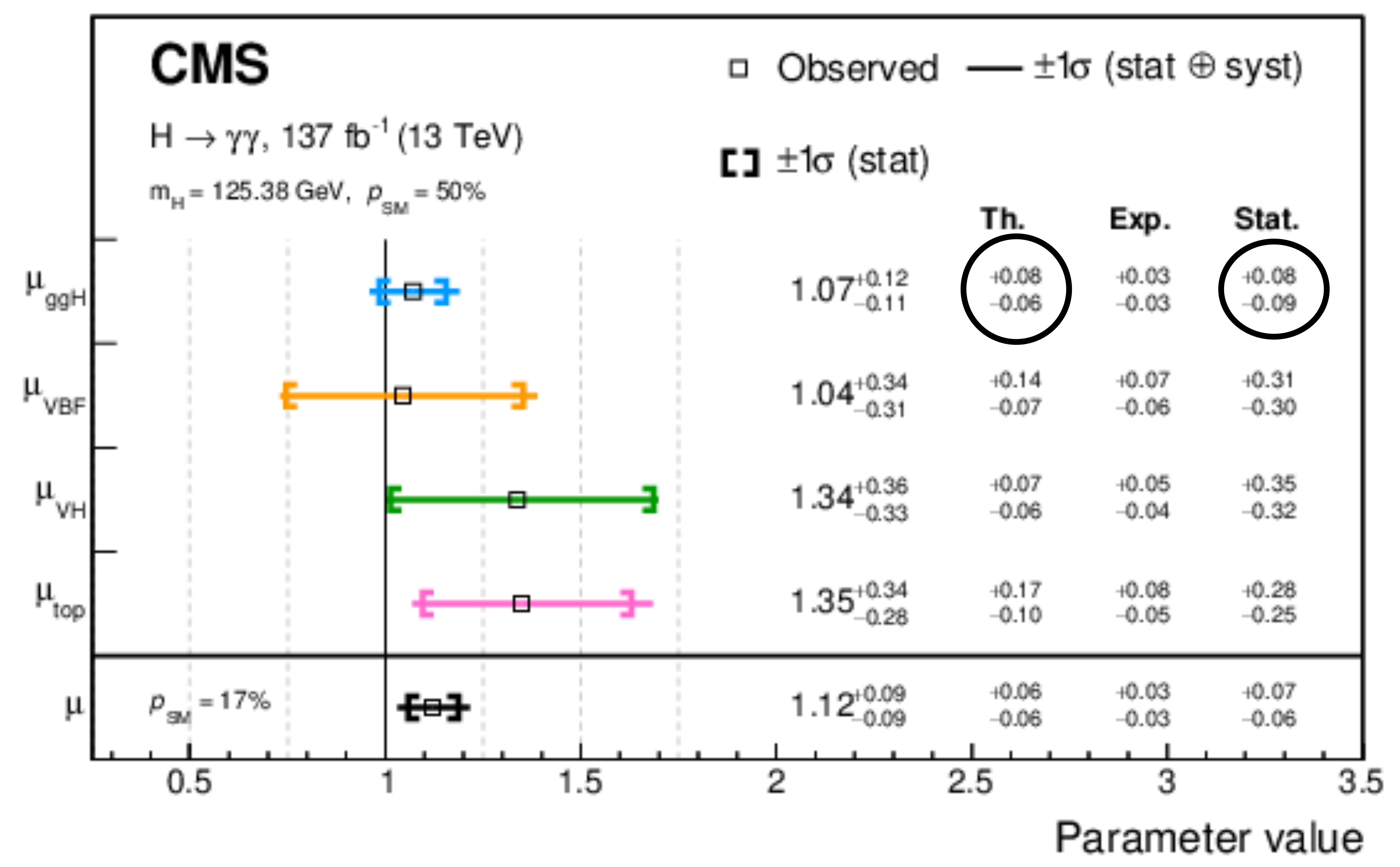
# STXS $H \rightarrow \gamma\gamma$

The statistical precision of the gluon-gluon fusion production mode is now at the same level as the uncertainty in the theory prediction.



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# *STXS for $H \to ZZ^*$*

ATLAS-CONF-2021-053

$gg \to H \times B_{ZZ^*}$

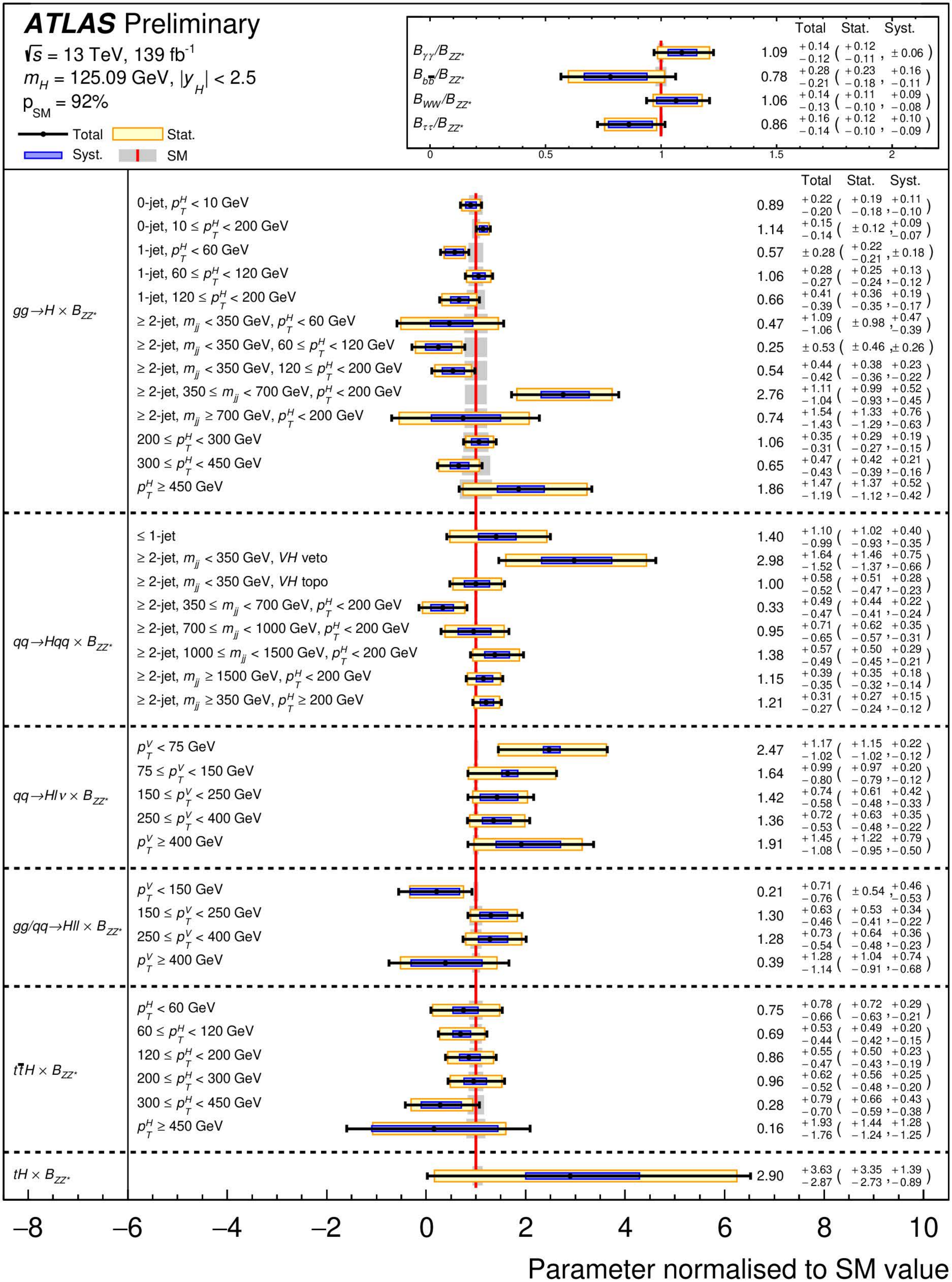
$qq \to Hqq \times B_{ZZ^*}$

$qq \to H\ell\nu \times B_{ZZ^*}$

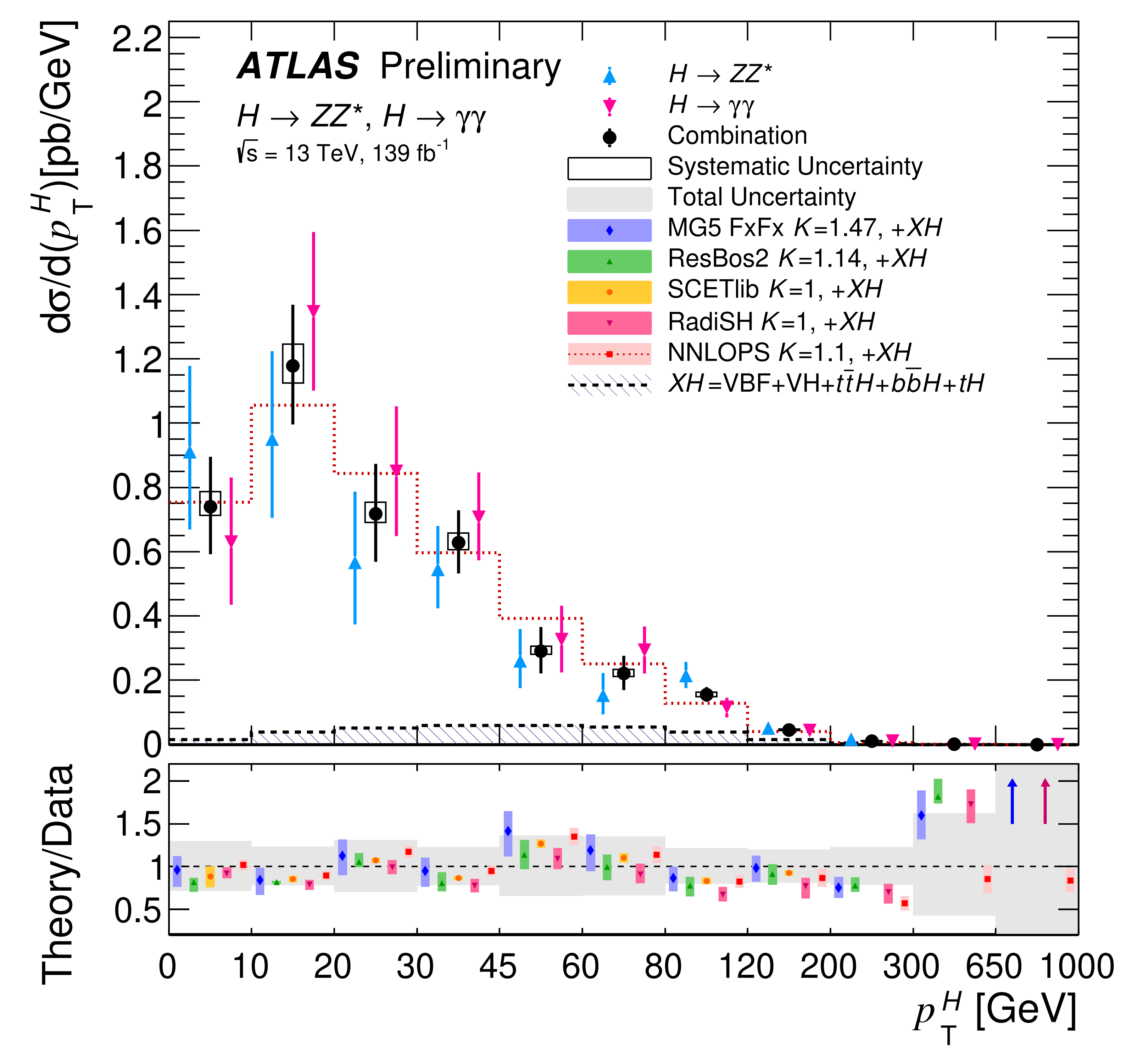
$gg/qq \to H\ell\ell \times B_{ZZ^*}$

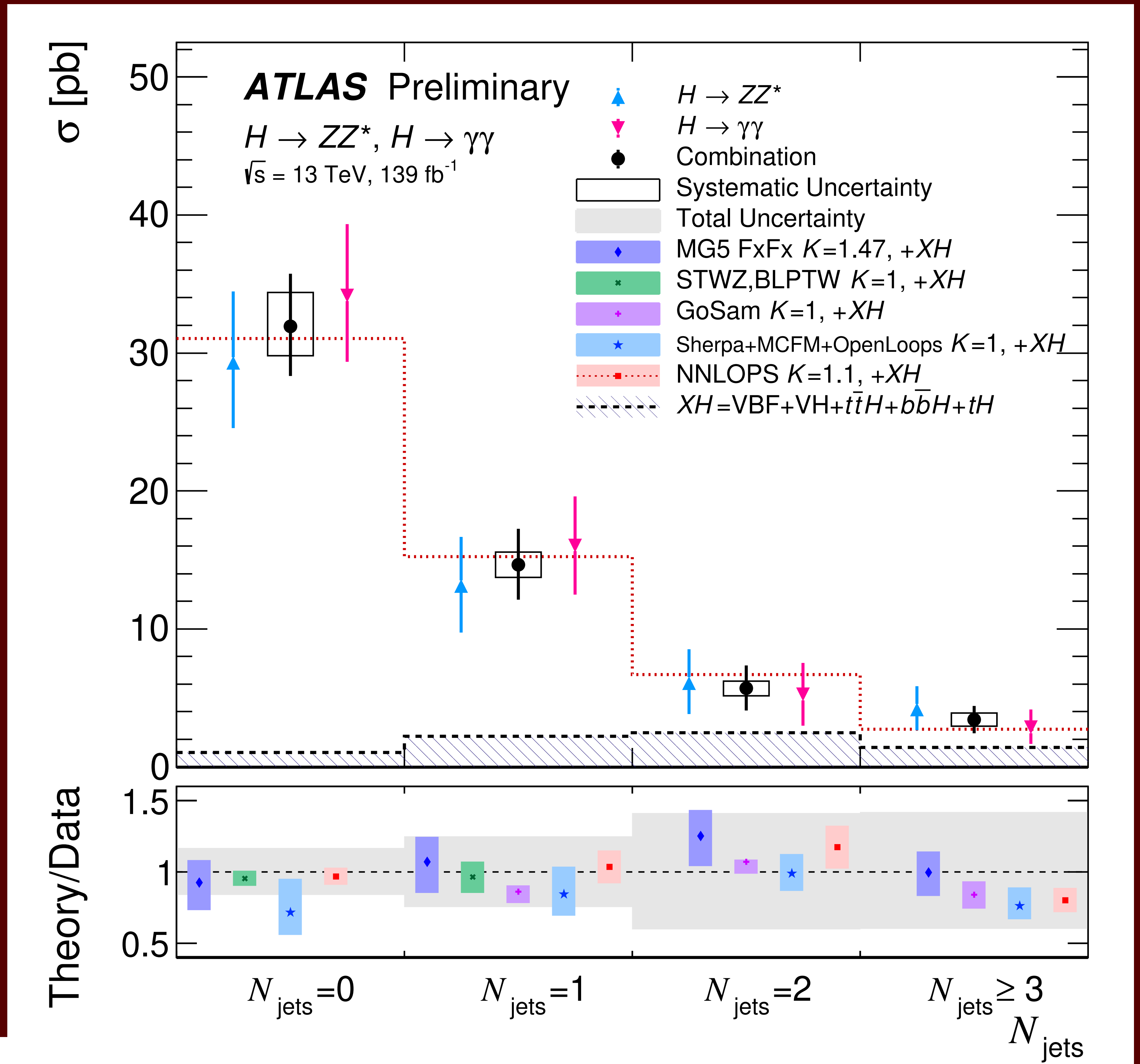
$t\bar{t}H \times B_{ZZ^*}$

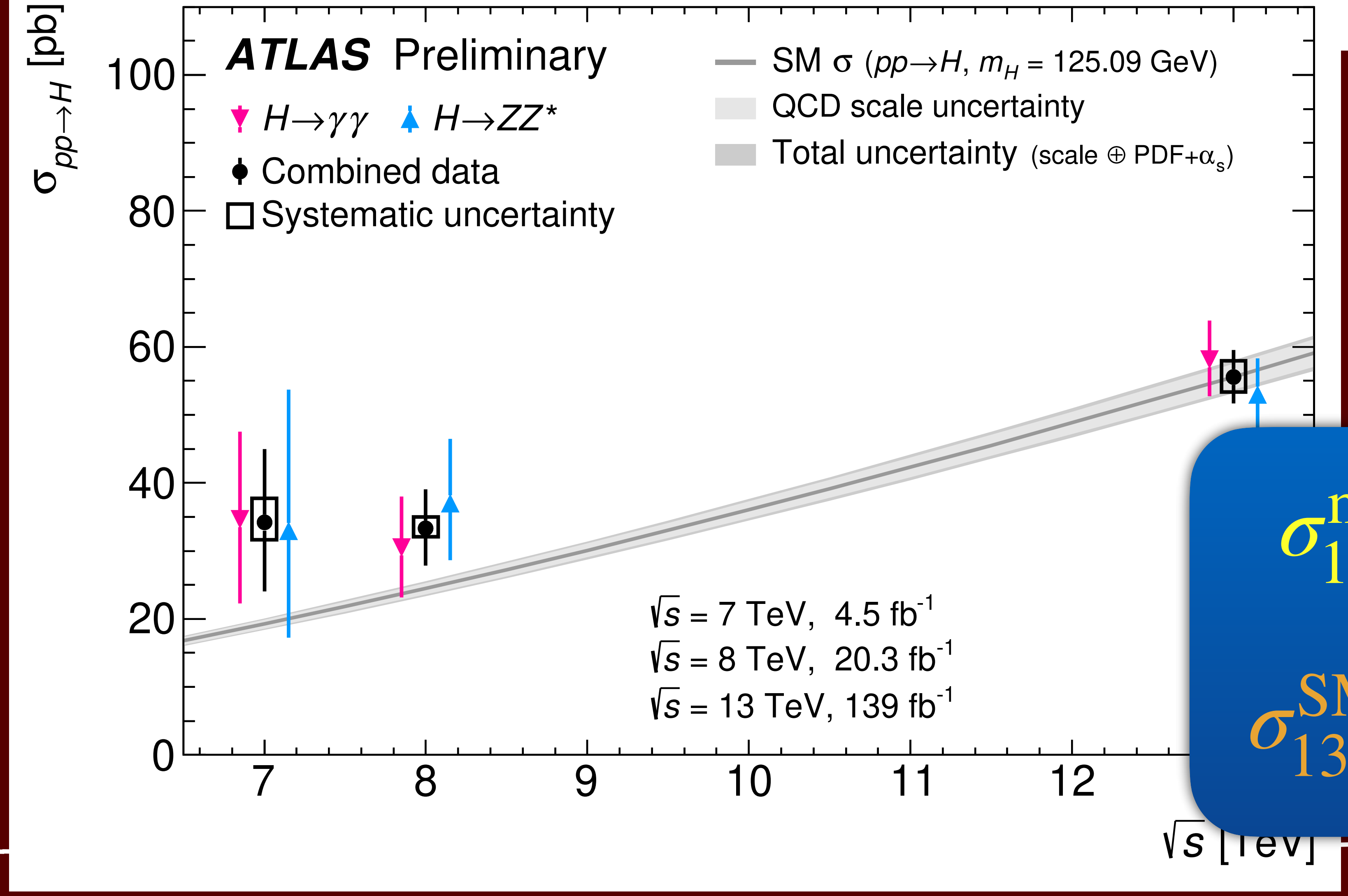
$tH \times B_{ZZ^*}$



# Combination of $H \to \gamma\gamma$ and $H \to ZZ^* \to 4\ell$ by ATLAS for differential and inclusive cross-sections with full Run 2







$$\sigma^{\text{meas}}_{13\ \text{TeV}} = 55.5^{+4.0}_{-3.8}\ \text{pb}$$

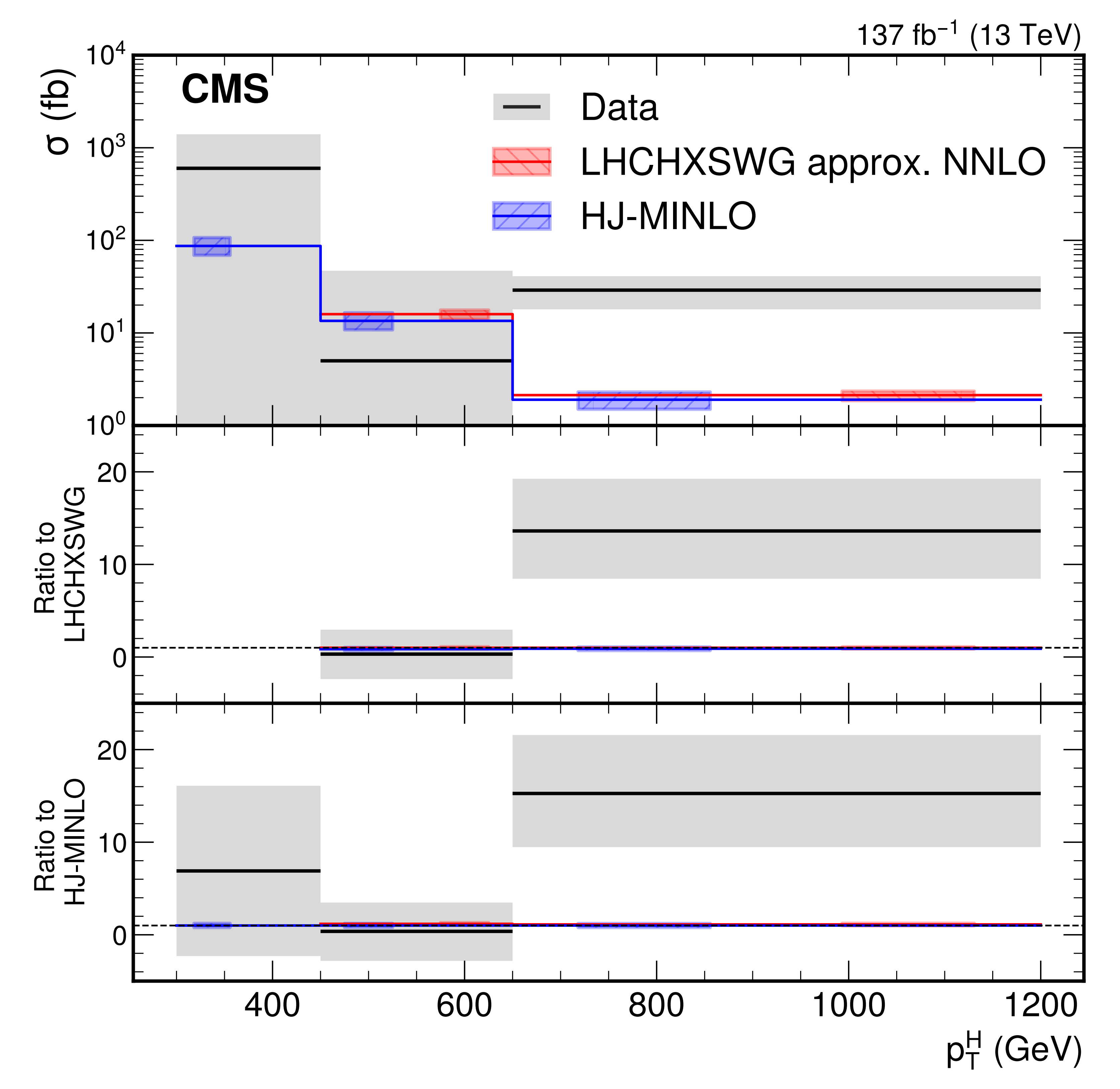
$$\sigma^{\text{SM}}_{13\ \text{TeV}} = 55.6 \pm 2.5\ \text{pb}$$

# SXTS $H \rightarrow b\bar{b}$

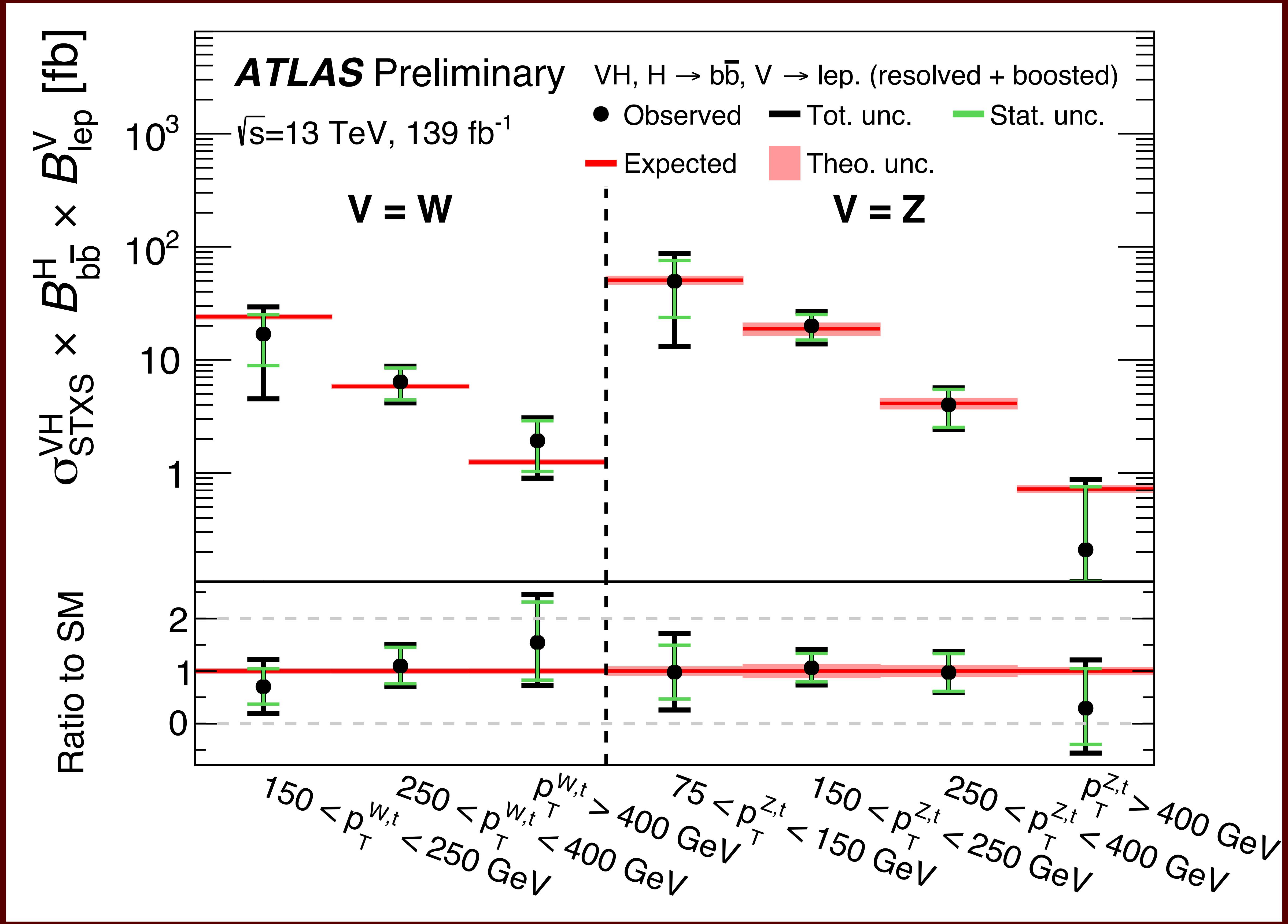
Observed WH and ZH. Differential cross-sections analysis sensitive to $p_T$>250 GeV, probing $p_T$>400 GeV

$$\mu_{WH}^{b\bar{b}} = 1.03 \pm 0.19\ (\text{stat})\ ^{+0.21}_{-0.19}\ (\text{syst})$$

$$\mu_{ZH}^{b\bar{b}} = 0.97 \pm 0.17\ (\text{stat})\ ^{+0.18}_{-0.15}\ (\text{syst})$$

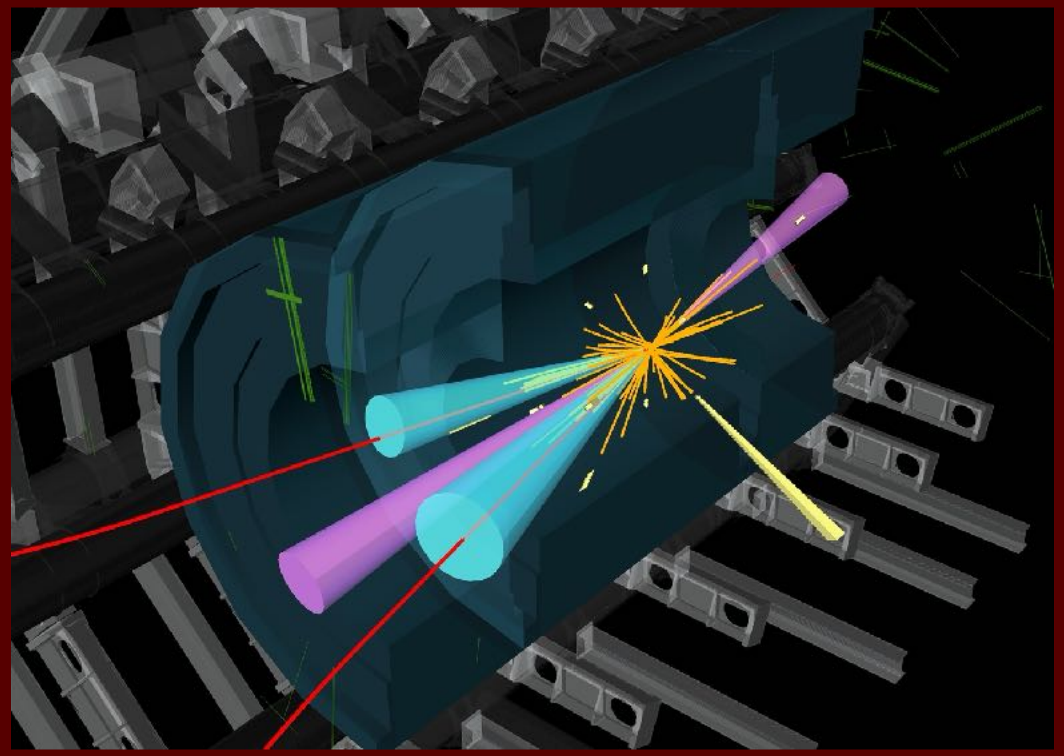


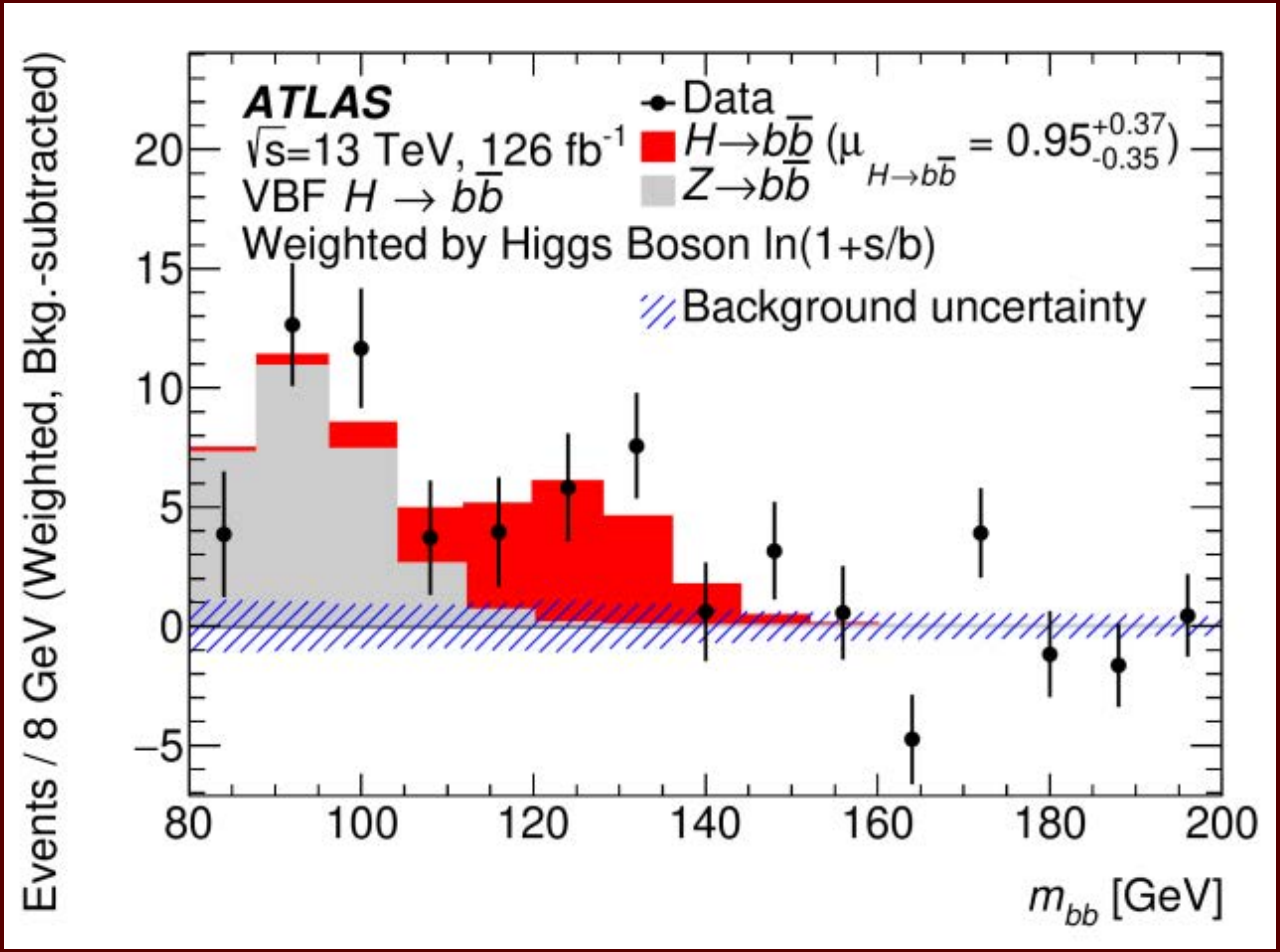
JHEP 12 (2020) 085



ATLAS-CONF-2021-051

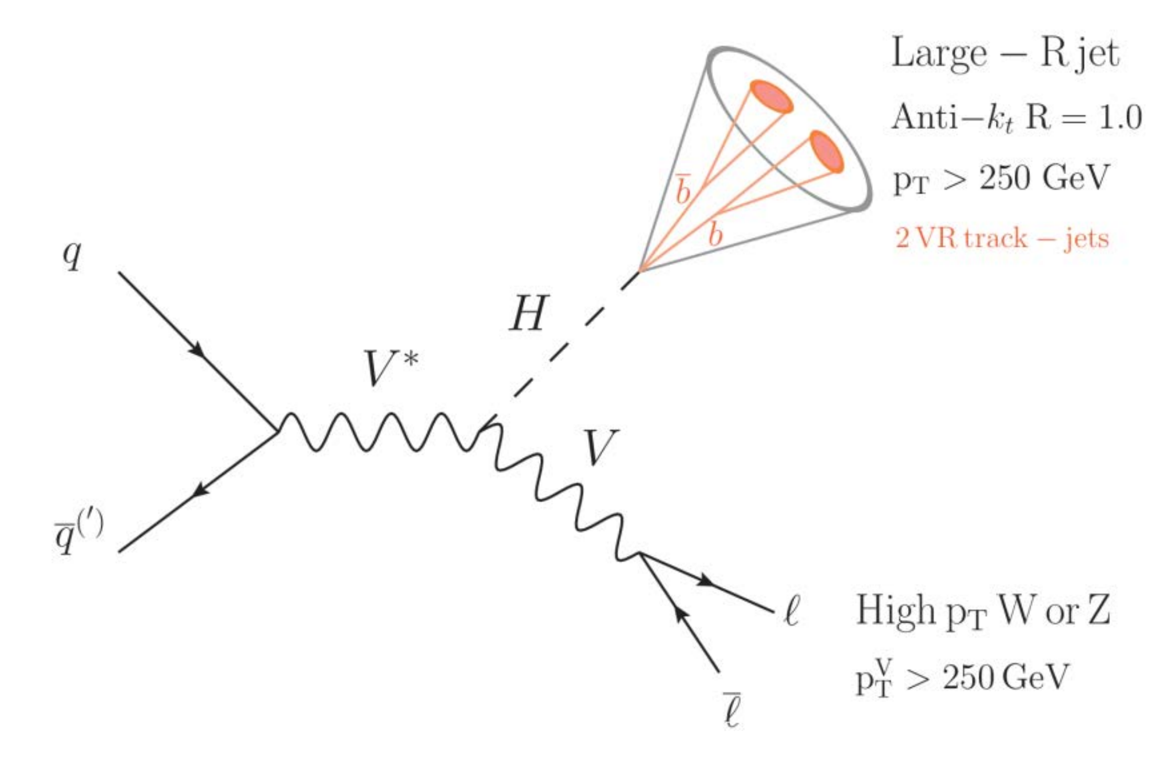
# $H \to b\bar{b}$




ATLAS
$\sqrt{s}$=13 TeV, 126 fb$^{-1}$
VBF $H \to b\bar{b}$
Weighted by Higgs Boson ln(1+s/b)
Data
$H\to b\bar{b}$ ($\mu_{H\to b\bar{b}} = 0.95^{+0.37}_{-0.35}$)
$Z\to b\bar{b}$
Background uncertainty
Events / 8 GeV (Weighted, Bkg.-subtracted)
$m_{bb}$ [GeV]
−5
0
5
10
15
20
80
100
120
140
160
180
200

# $H \to b\bar{b}$ at high $p_T$.

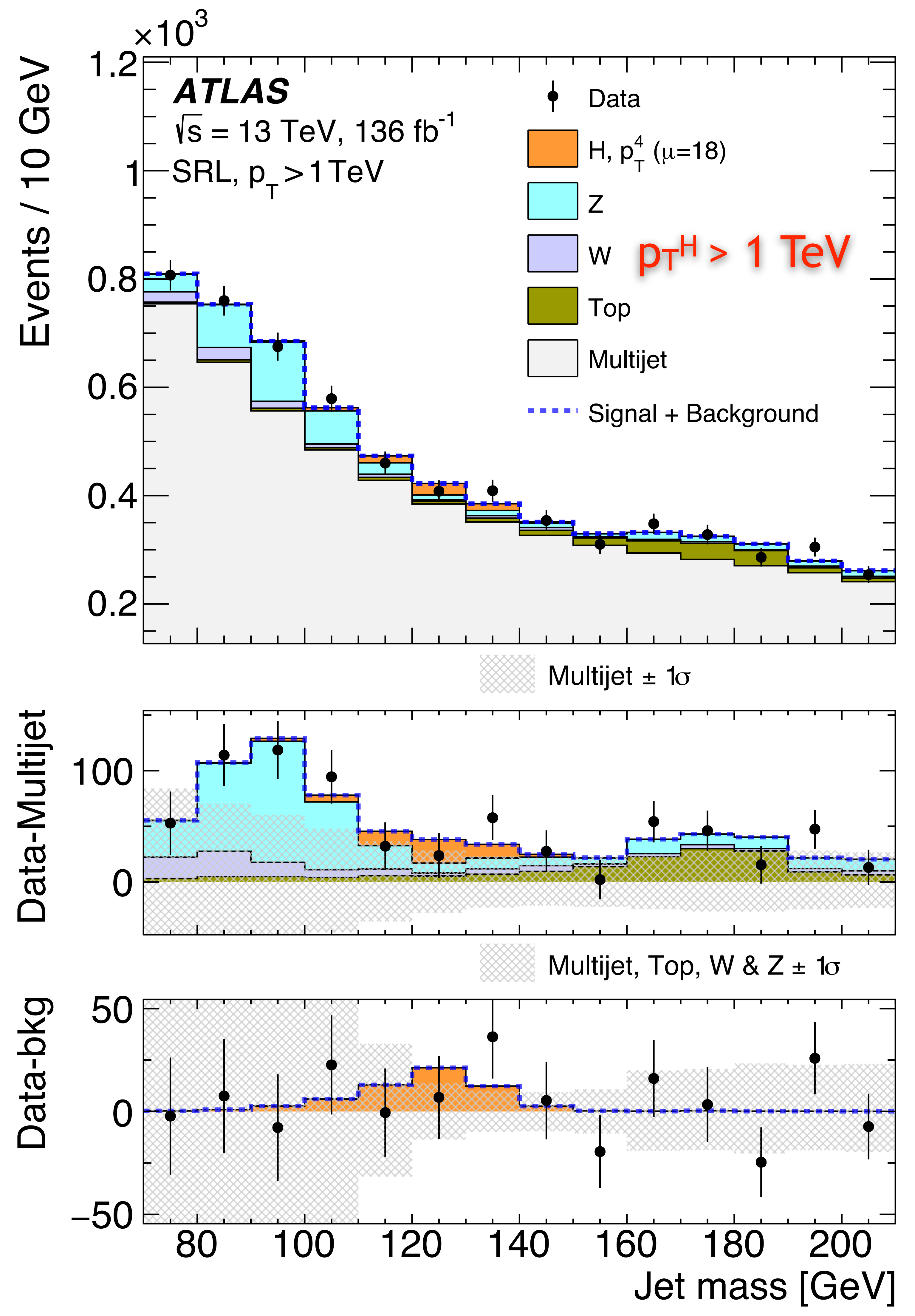
$$\mathscr{L}_{SM} = \ldots + |D_\mu \Phi|^2 + \ldots$$



Very challenging channel
$VH,\ H \to b\bar{b}$

detect highly boosted jets.

HIGG-21-018



$p_T^H > 1$ TeV

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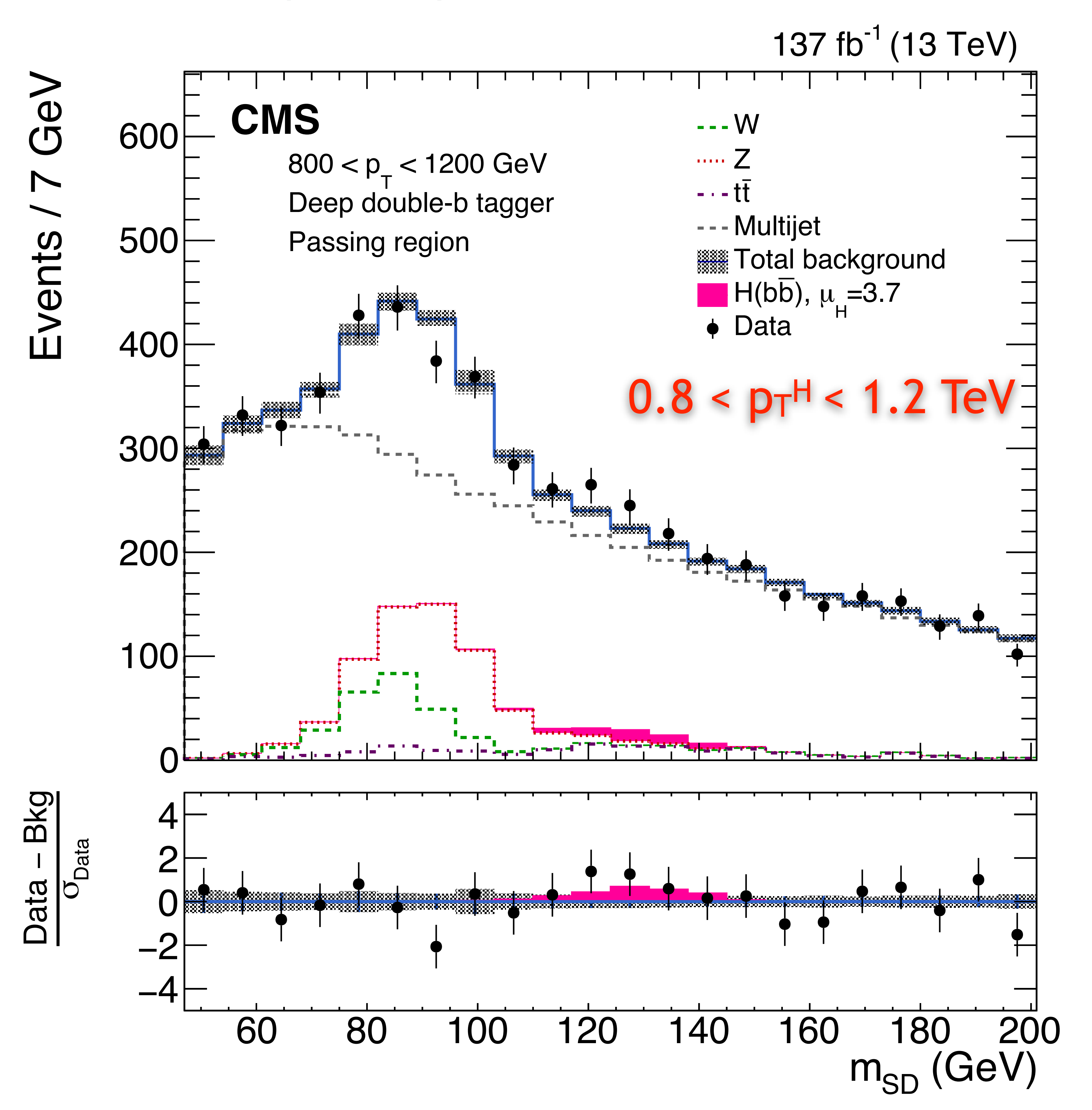
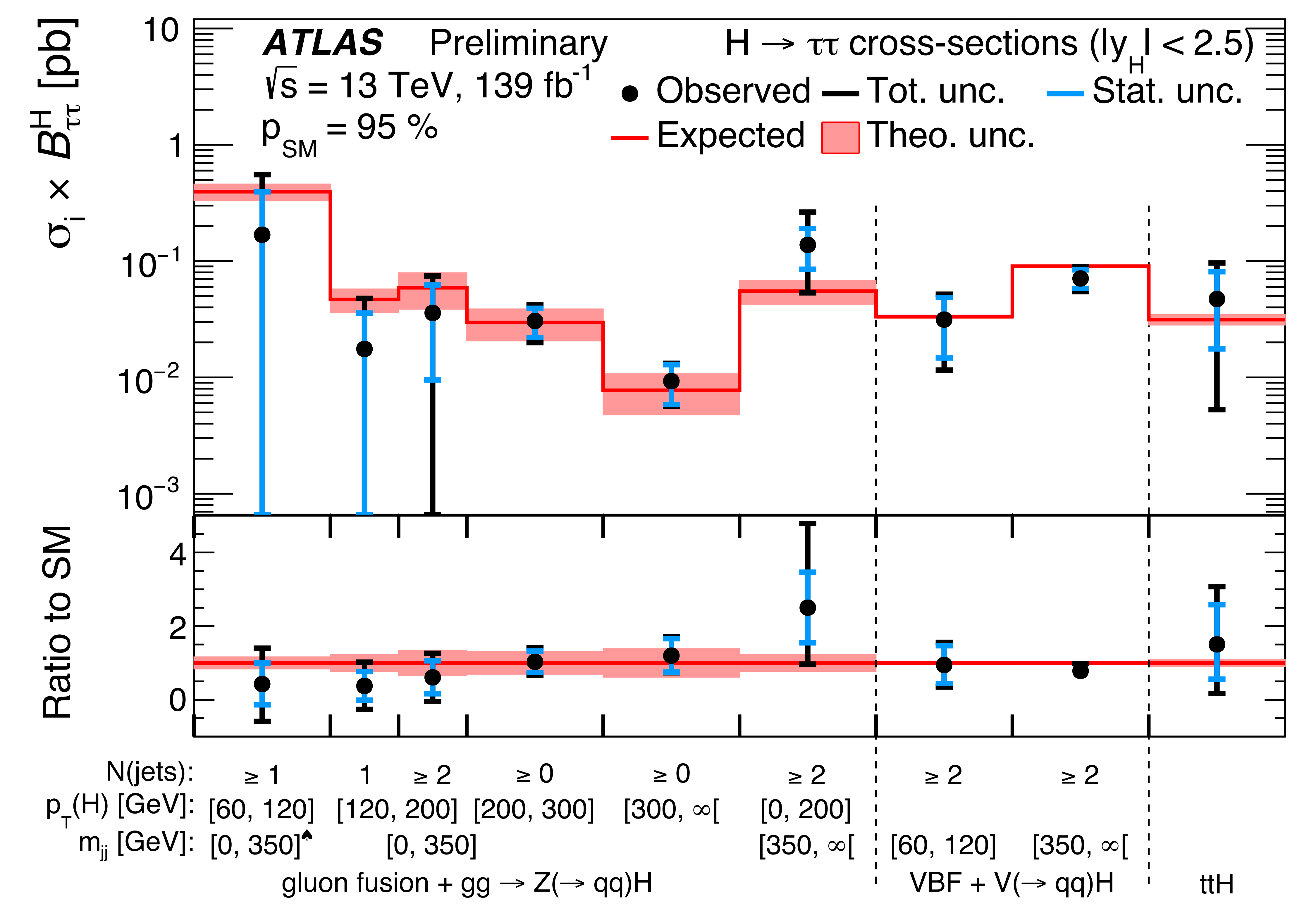


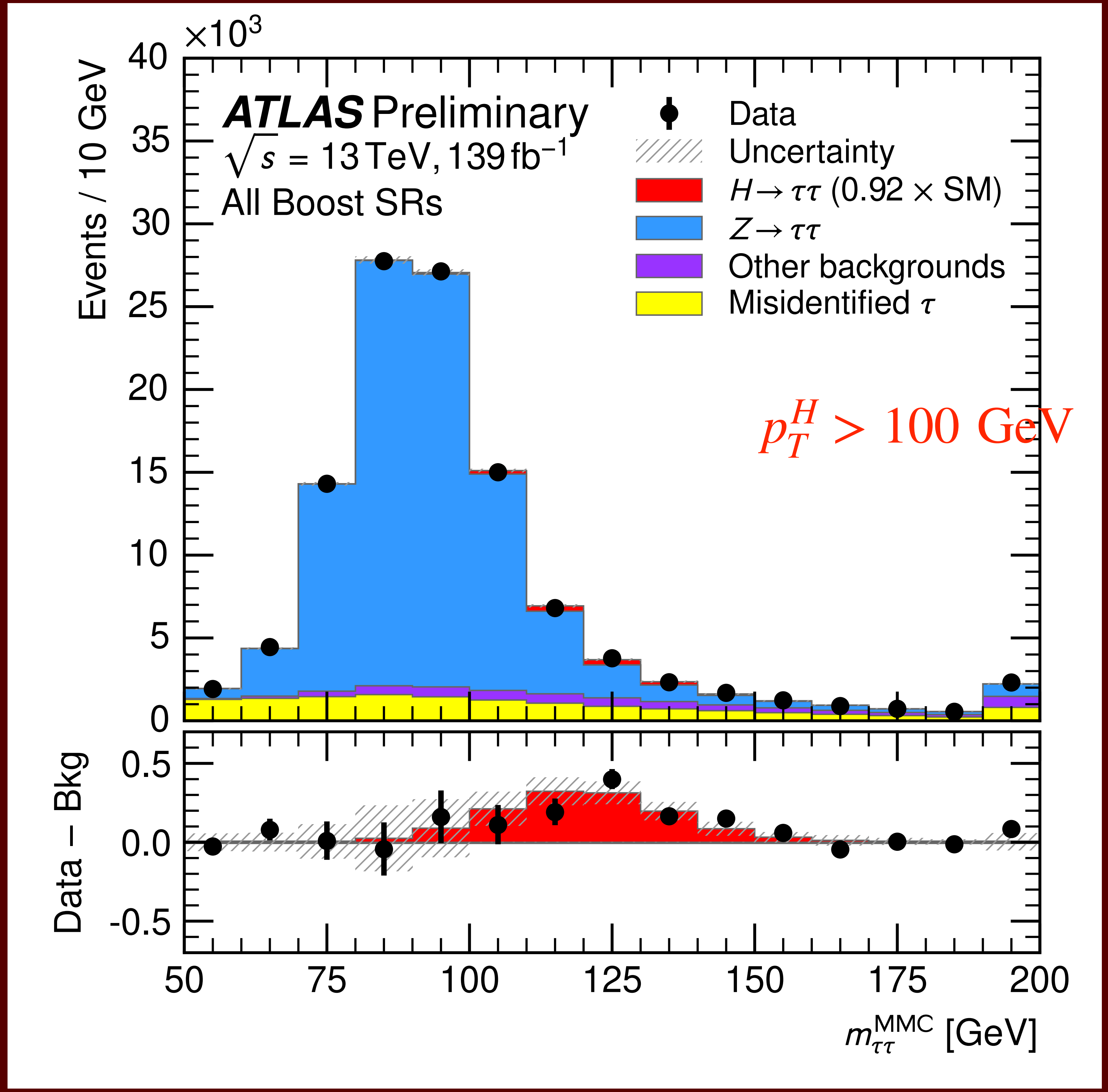
$0.8 < p_T^H < 1.2$ TeV

# $H \rightarrow \tau\tau$

- Bring sensitivity to region of the phase space not well measured by $H \rightarrow \gamma\gamma$ and $H \rightarrow 4\ell$.
- Principally the VBF production mode and the high $p_T$ region..
  - gluon-fusion: Higgs $p_T$ > 300 GeV
  - VBF: $m_{jj}$ > 700 GeV

ATLAS-CONF-2021-044
CMS-PAS-HIG-19-010



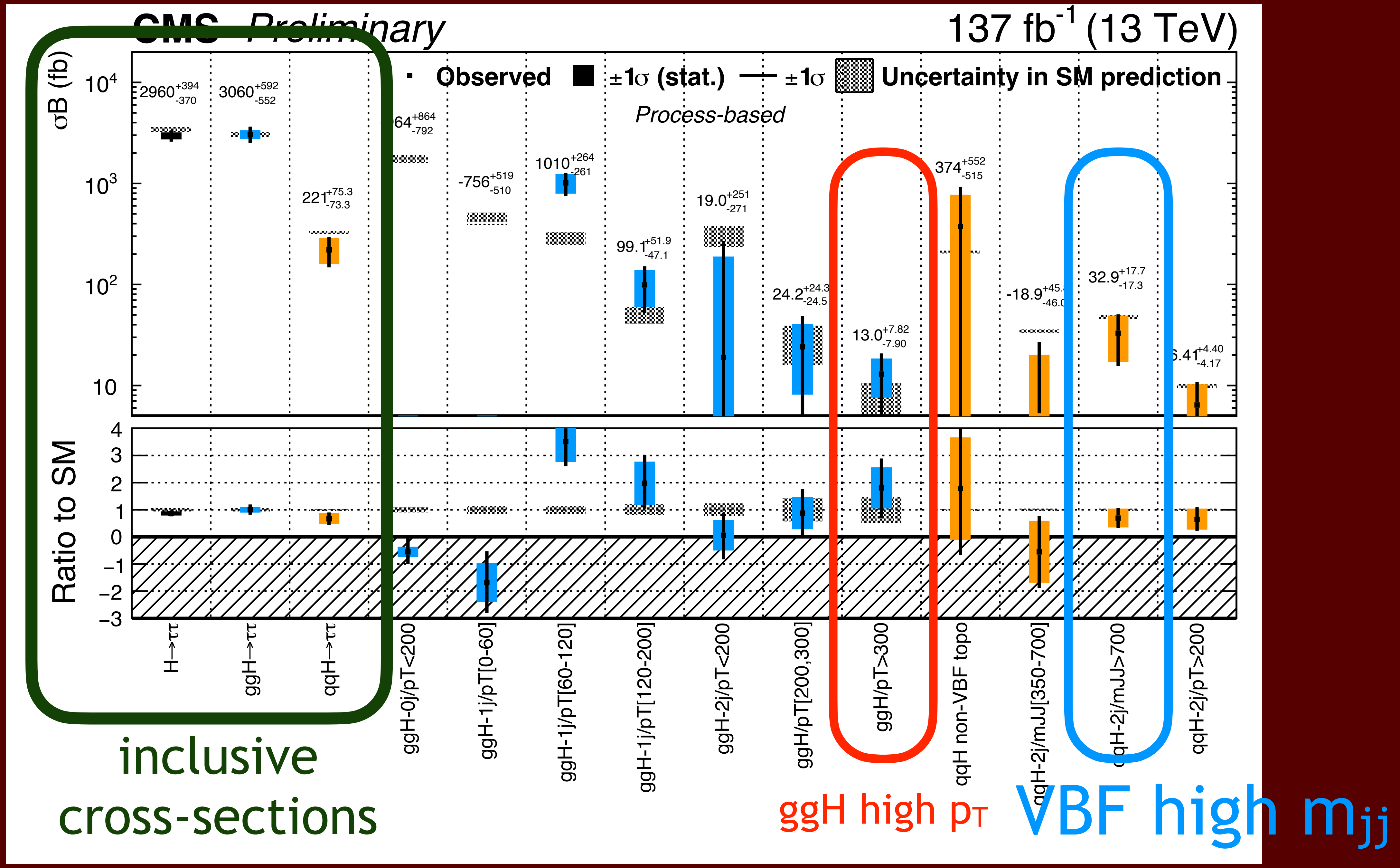


$p_T^H > 100$ GeV

# $H \to \tau\tau$

ATLAS-CONF-2021-044
CMS-PAS-HIG-19-010

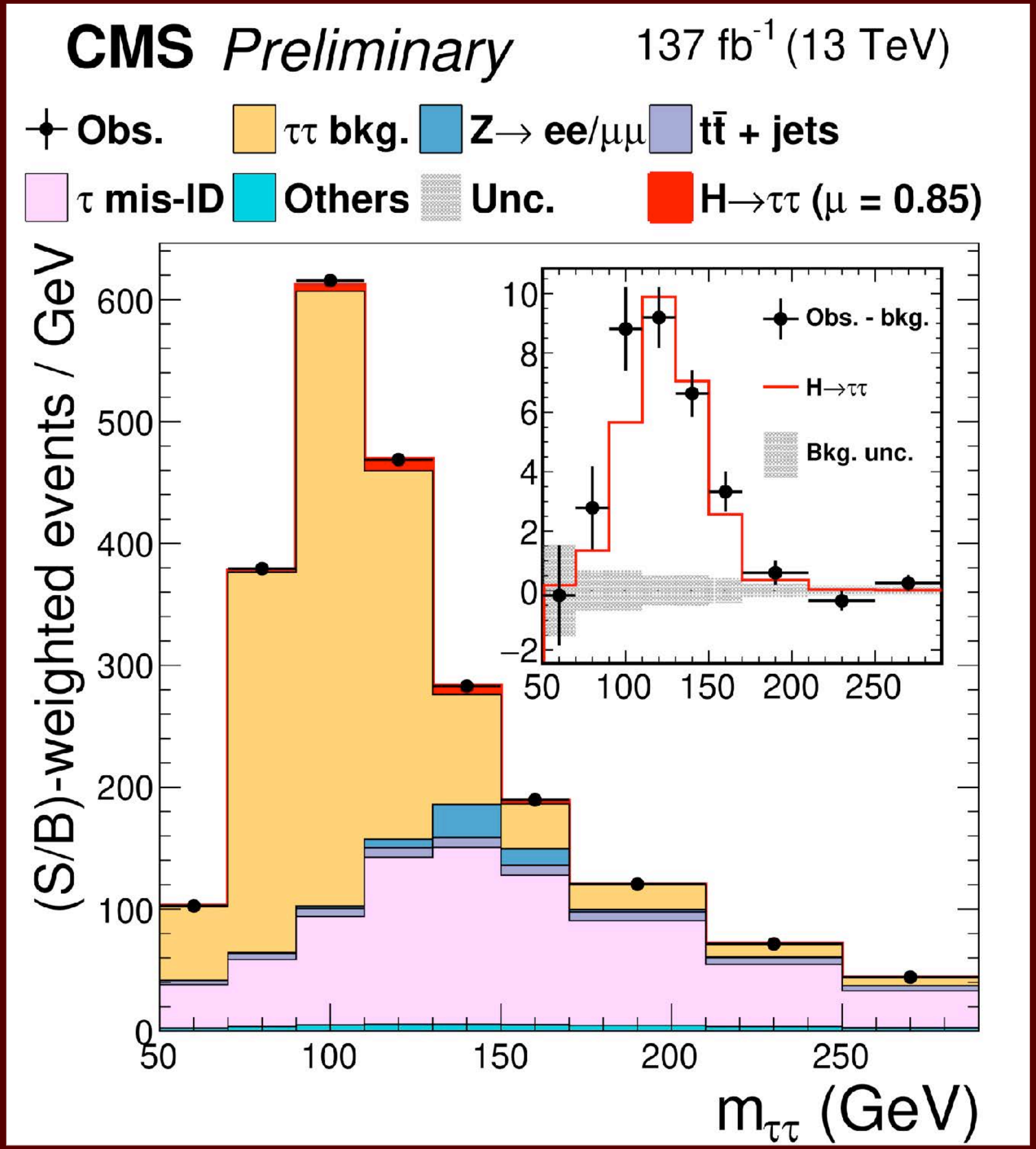
- Bring sensitivity to region of the phase space not well measured by $H \to \gamma\gamma$ and $H \to 4\ell$, i.e. ggF high $p_T$H and especially VBF:
  - gluon-fusion: Higgs $p_T$ > 300 GeV
  - VBF: $m_{jj}$ > 700 GeV



inclusive cross-sections

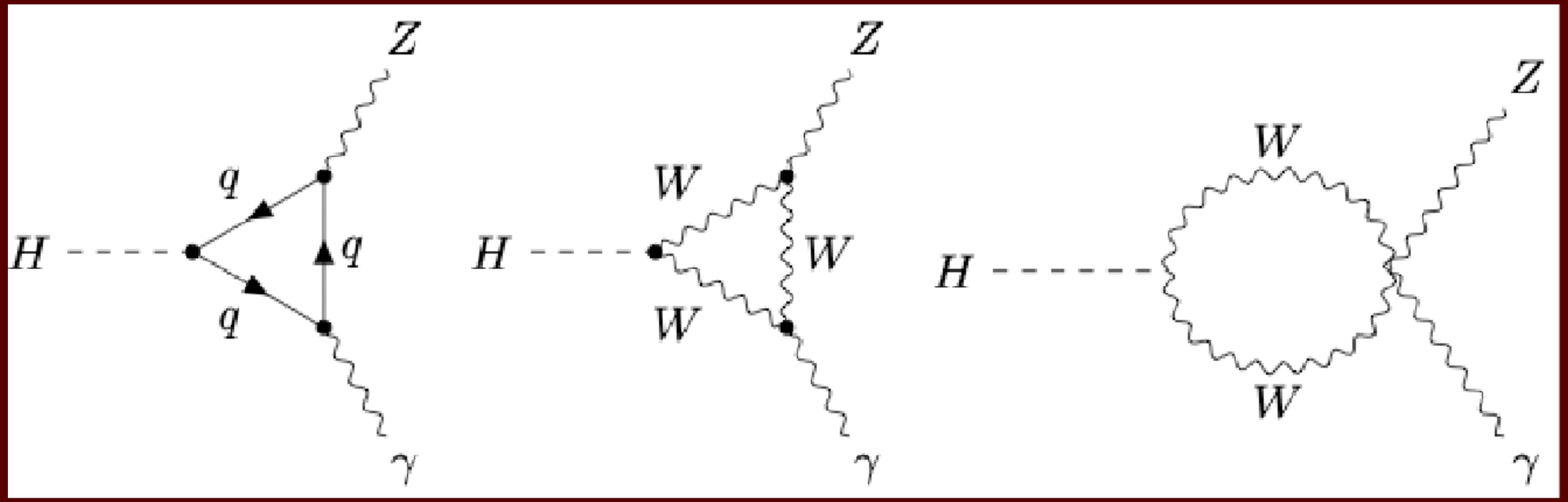
ggH high $p_T$

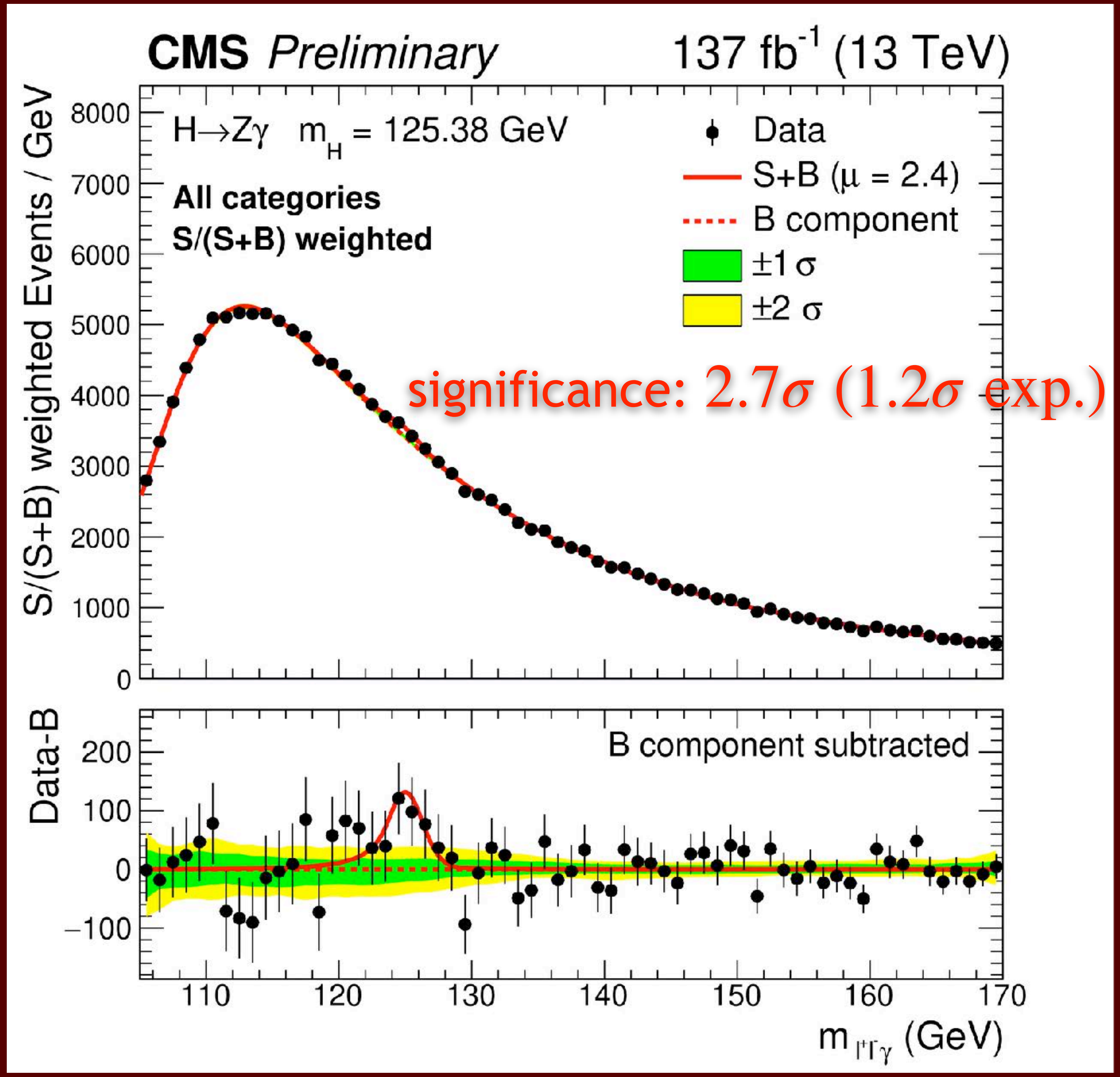
VBF high $m_{jj}$



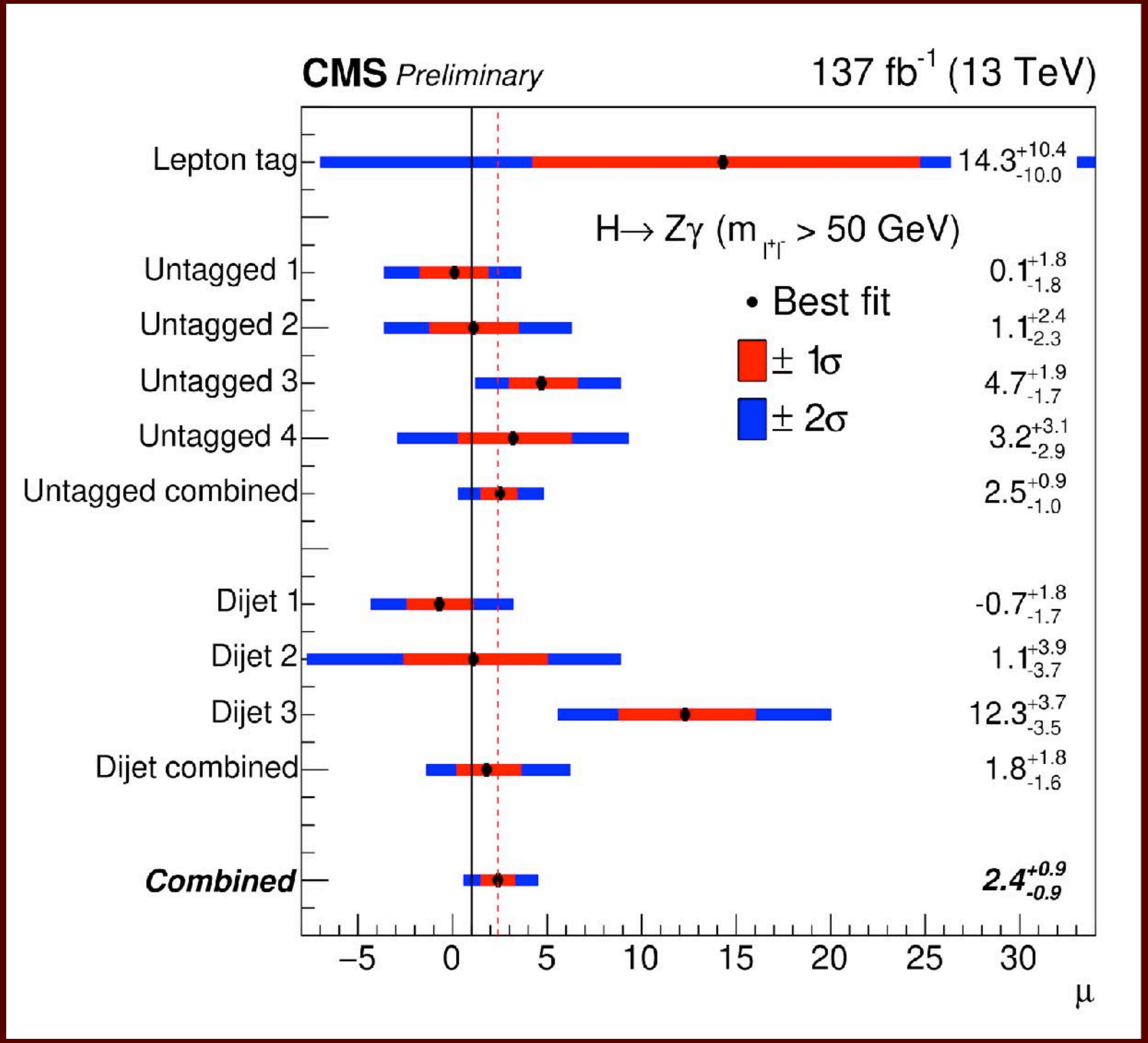
# *Digging Deeper in Higgs Gauge Couplings - H → Zγ*

$$\mathscr{L}_{SM} = \ldots + |D_\mu \Phi|^2 + \ldots$$





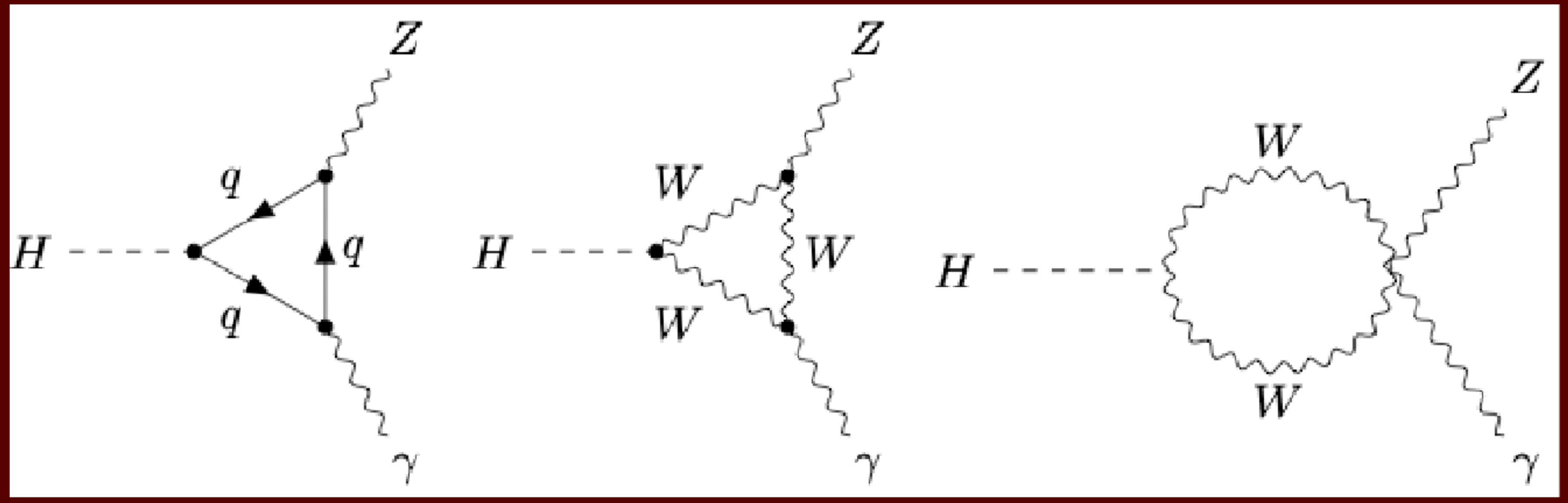
significance: 2.7$\sigma$ (1.2$\sigma$ exp.)



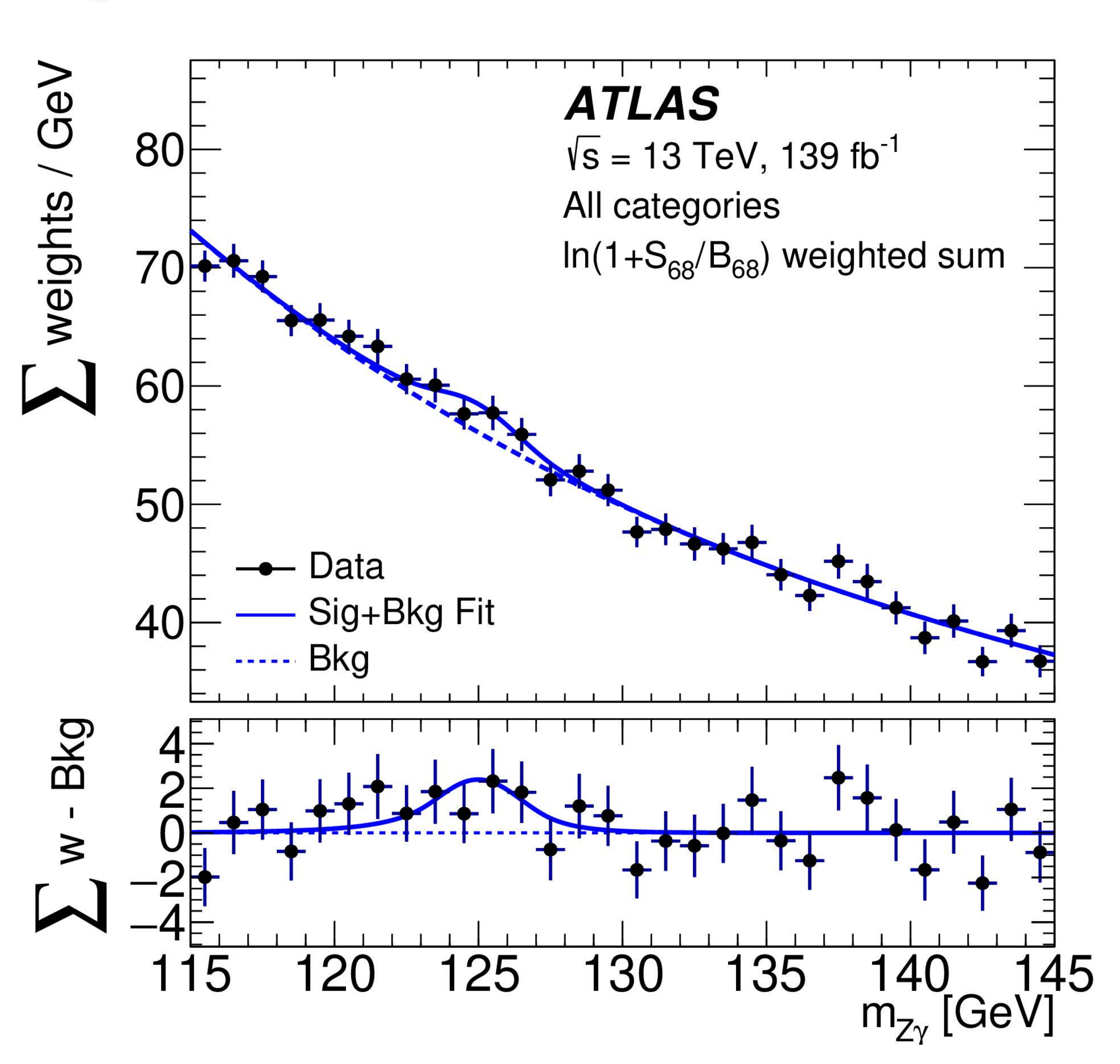
CMS-PAS-HIG-19-014

# *Digging Deeper in Higgs Gauge Couplings - $H \to Z\gamma$*

$$\mathscr{L}_{SM} = \ldots + |D_\mu \Phi|^2 + \ldots$$

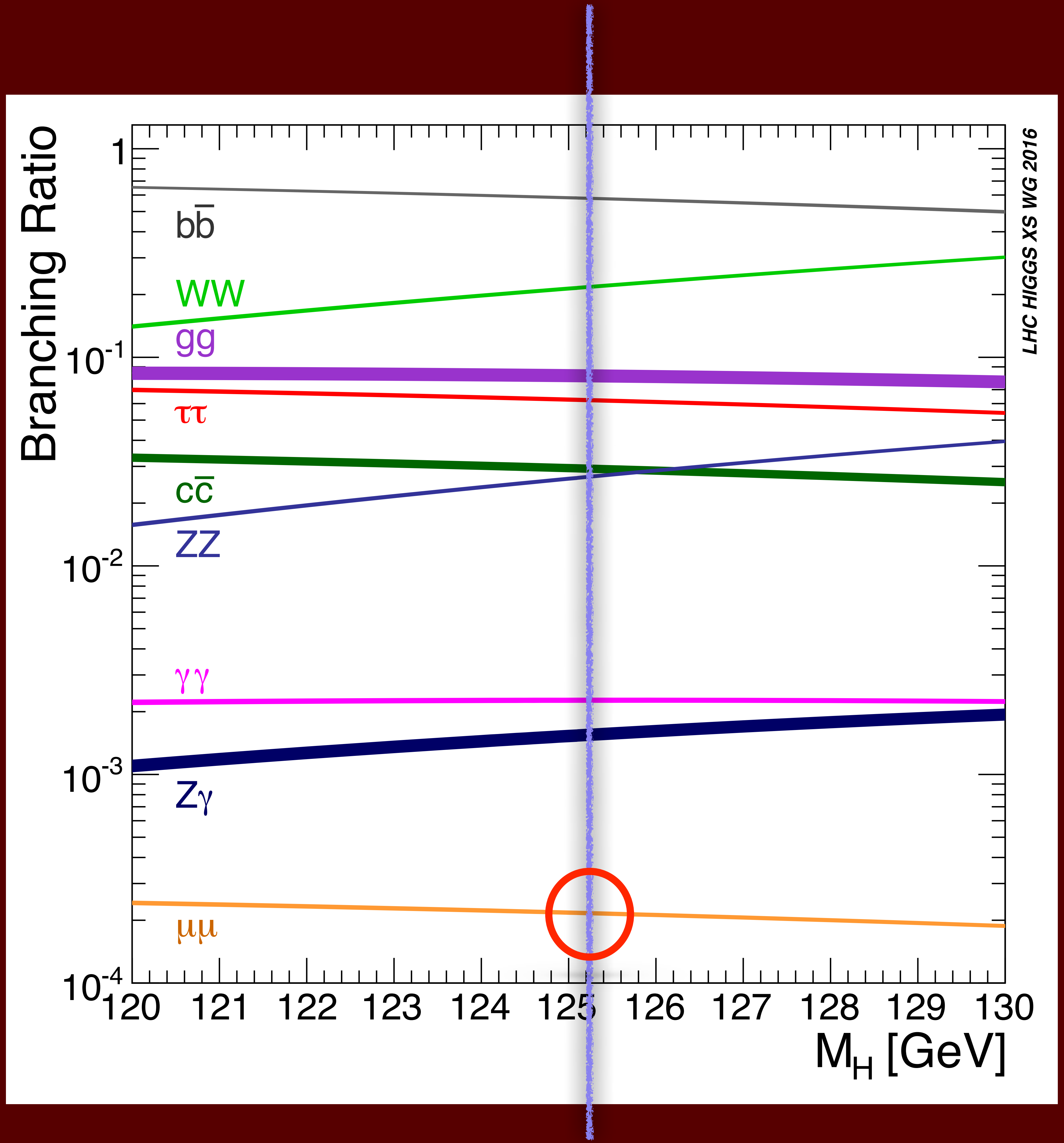


significance: $2.2\sigma$ ($1.2\sigma$ exp.)



Phys. Lett. B 809 (2020) 135754

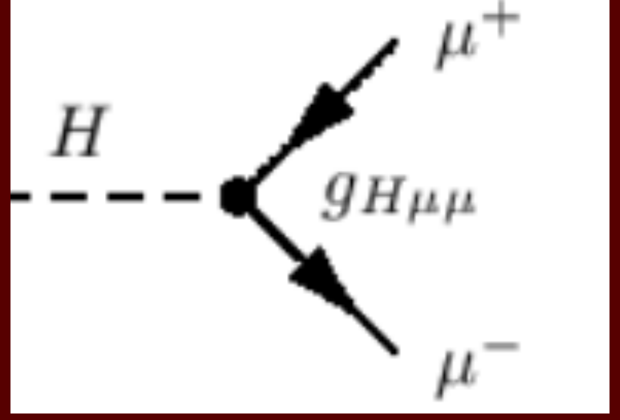
# *Reaching Down to the Rare Decay Channels*



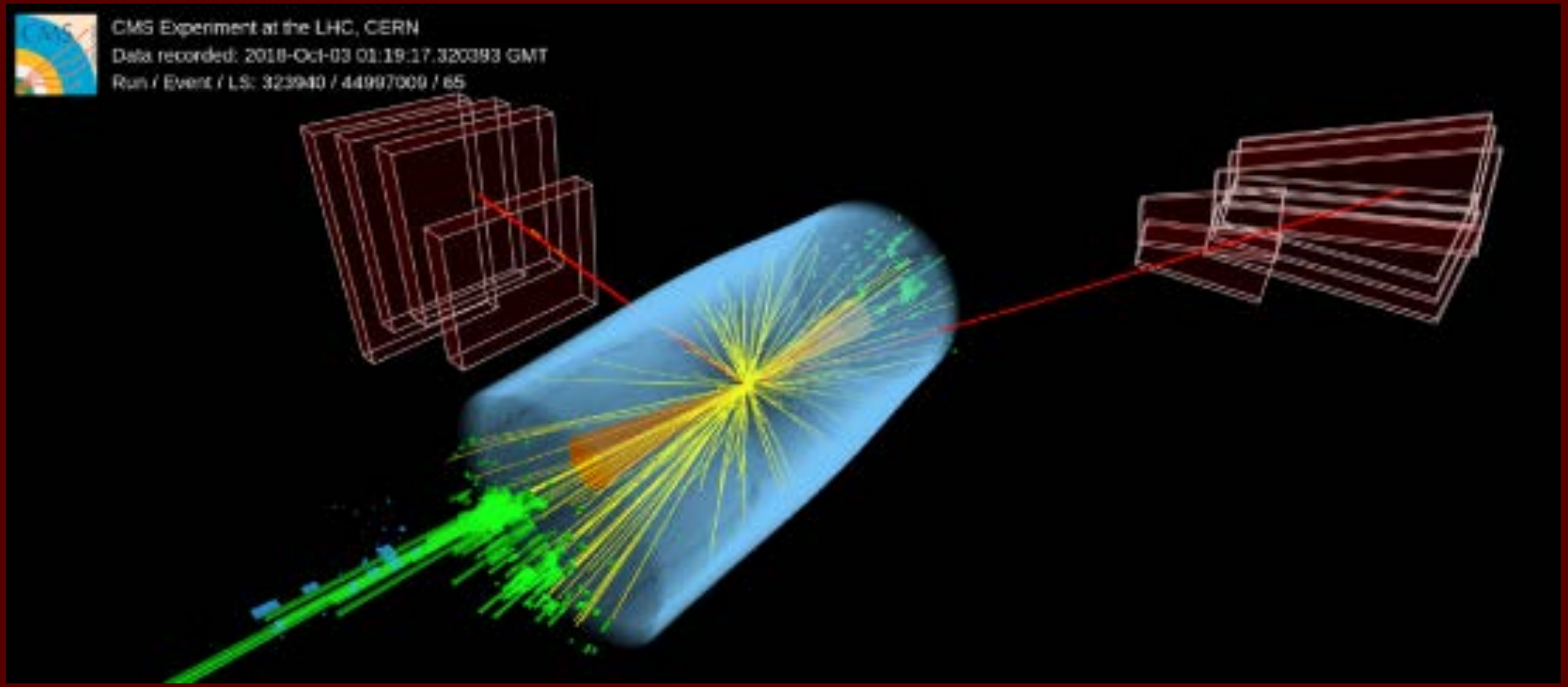
With the branching ratios ∝ the fermion mass we have only recently with the full statics of Run 2 we been able to identify the $\mu\mu$ decay channel.

Branching ratio is ~ $2 \times 10^{-4}$

# $H \to \mu\mu$



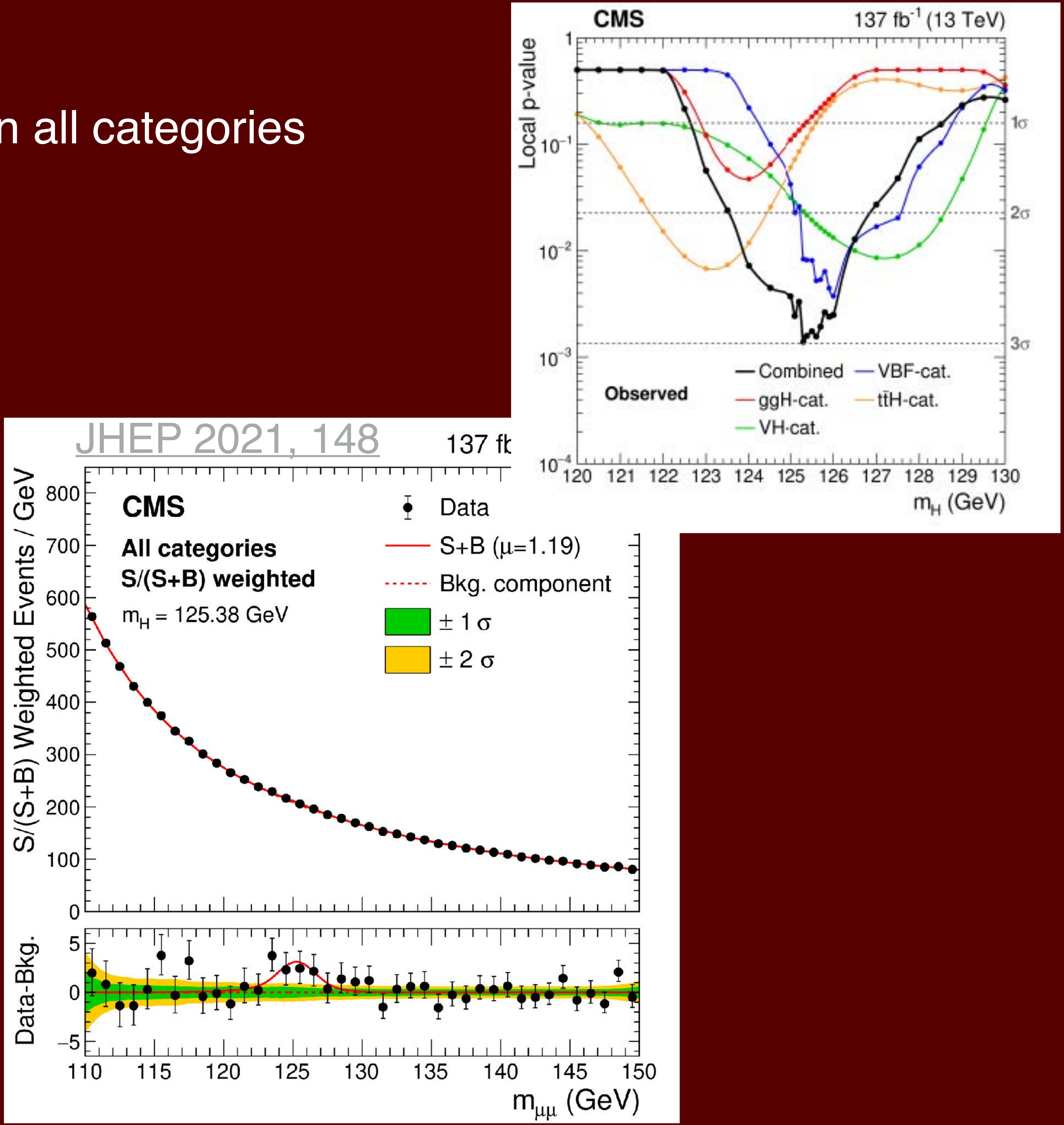
Measured in all categories



Significance = 3.0 $\sigma$, expected 2.5

Measured signal strength: $\mu = 1.19^{+0.44}_{-0.42}$

ATLAS significance = 2.0.



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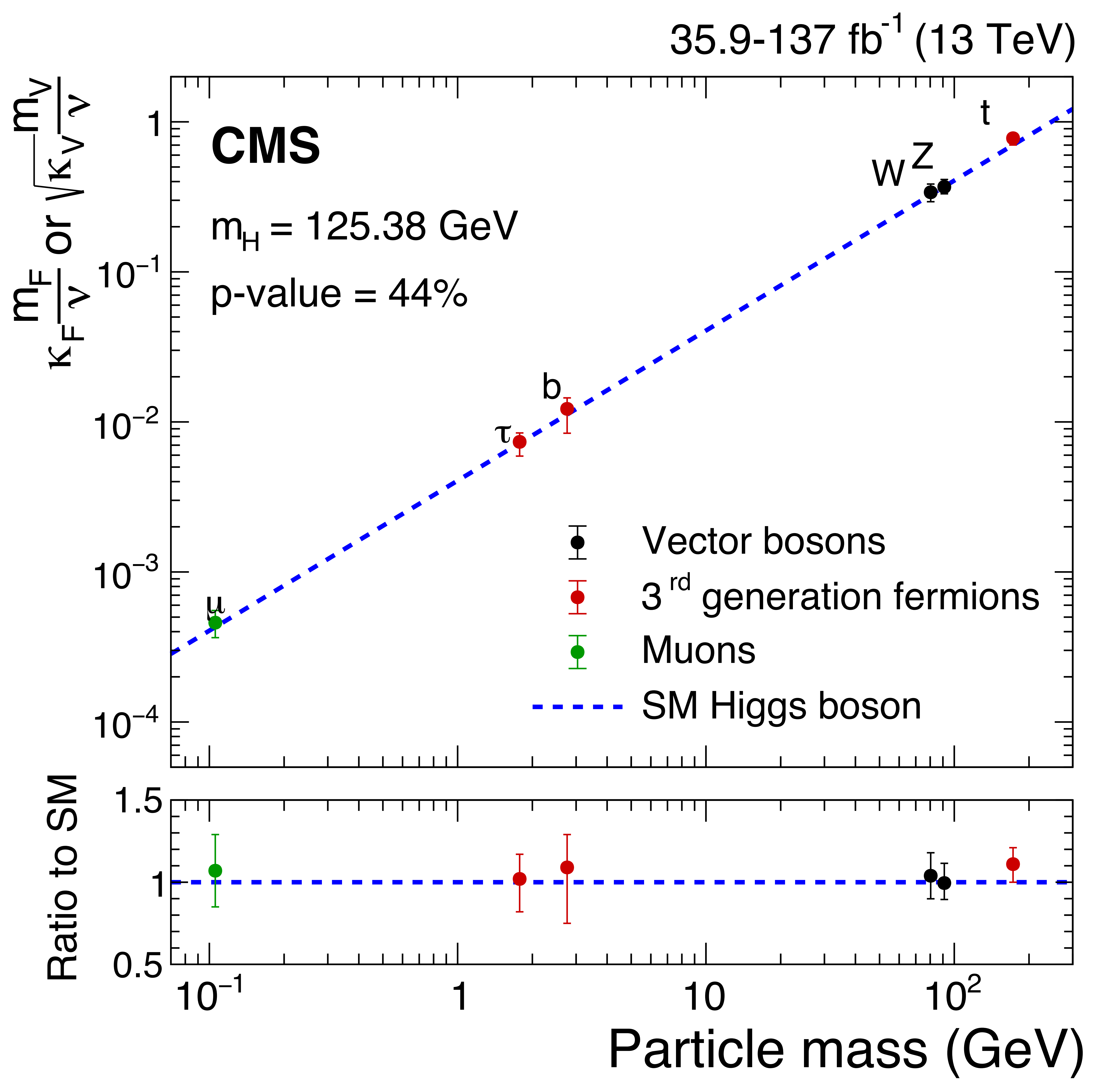
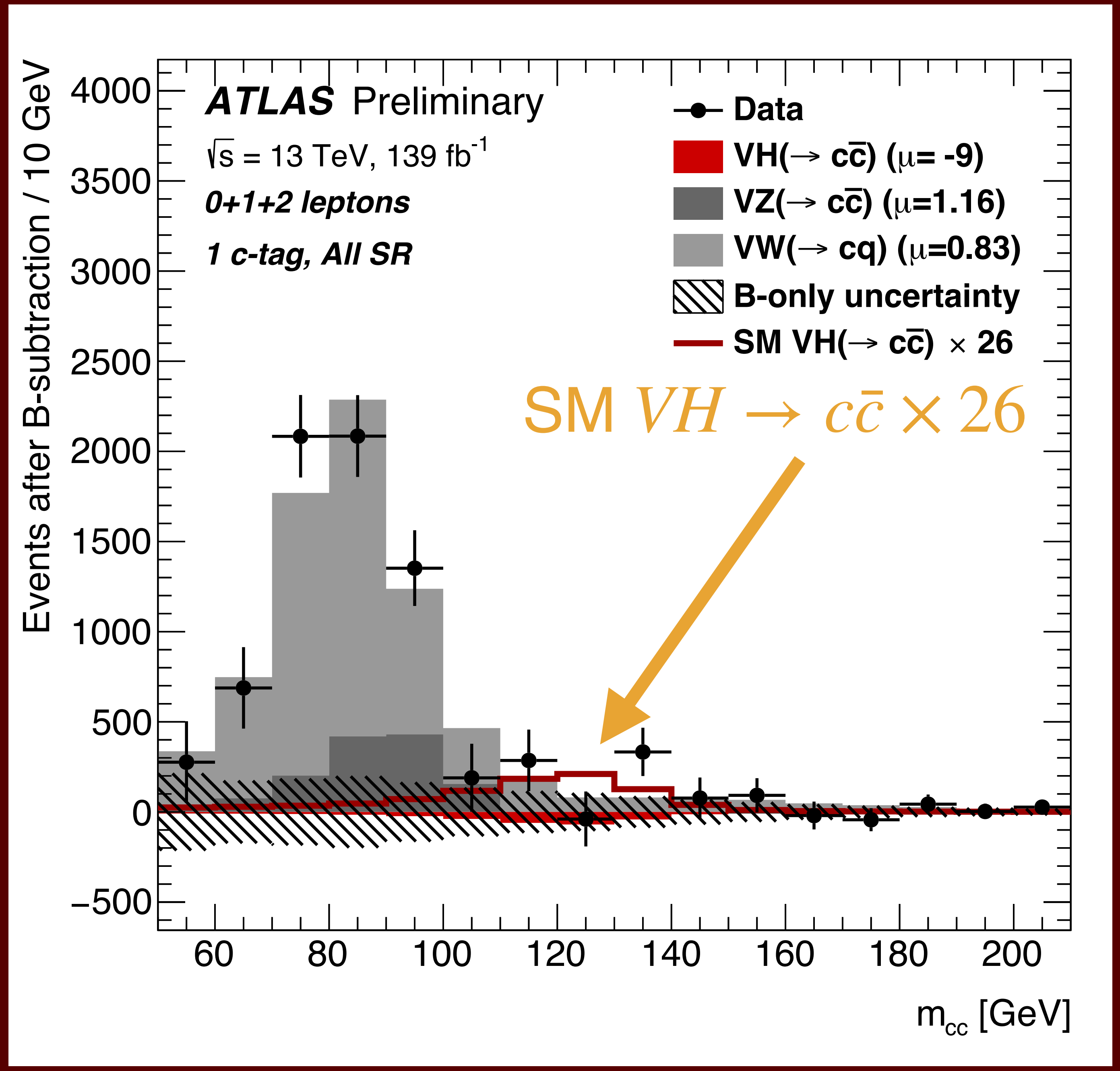
Higgs coupling across three orders of magnitude in mass.

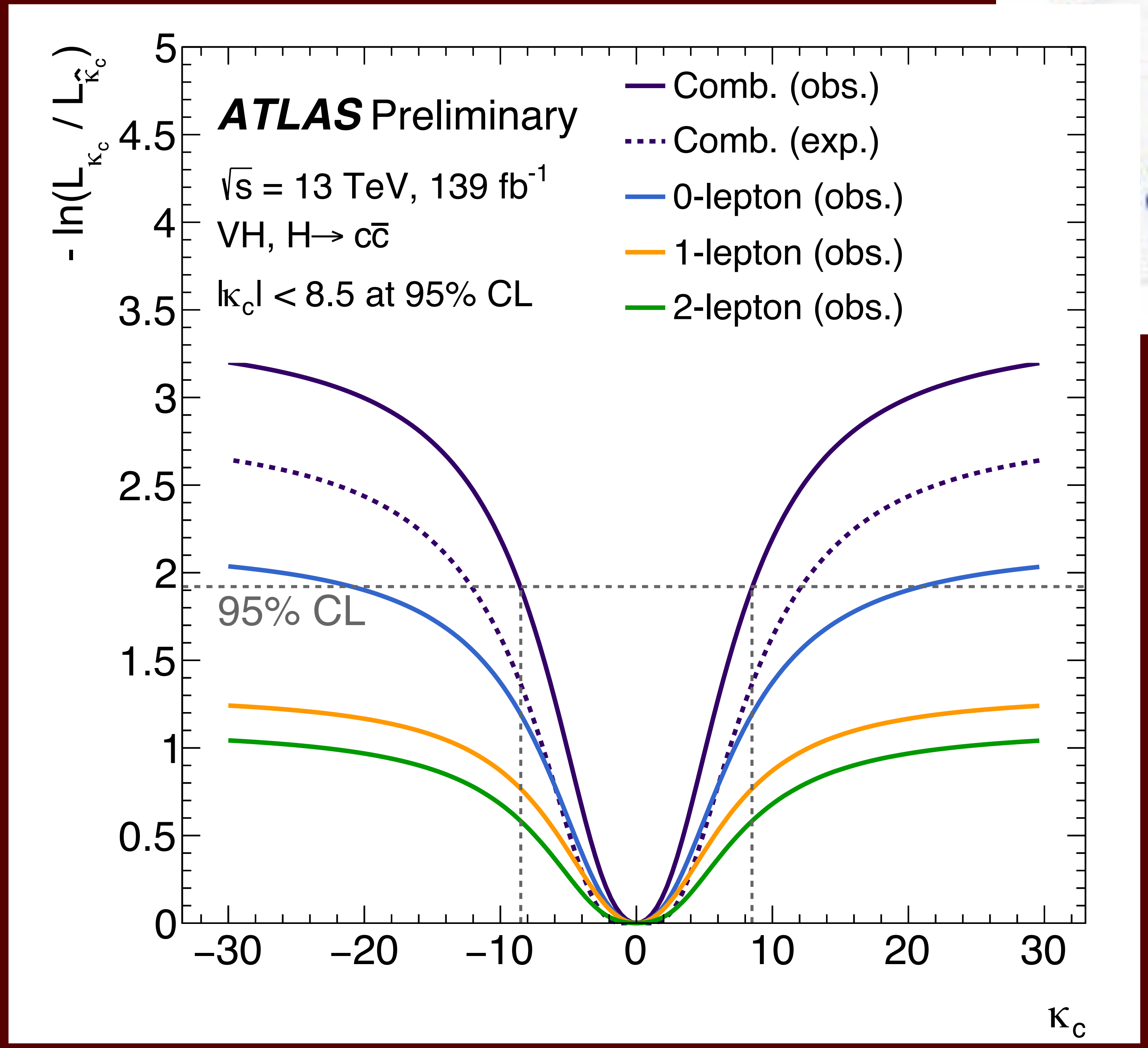


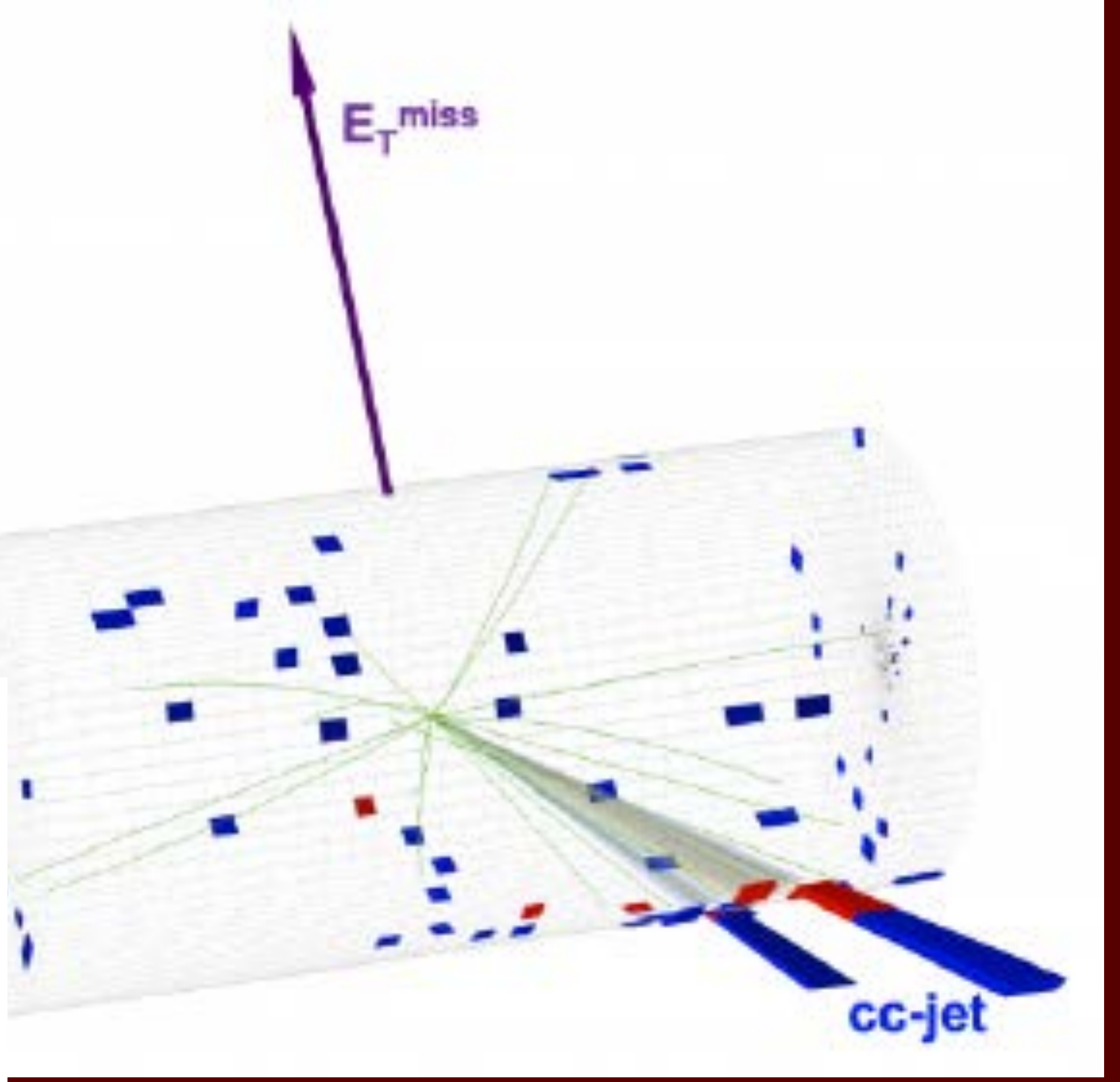
# $H \to c\bar{c}$

Getting there.



SM $VH \to c\bar{c} \times 26$



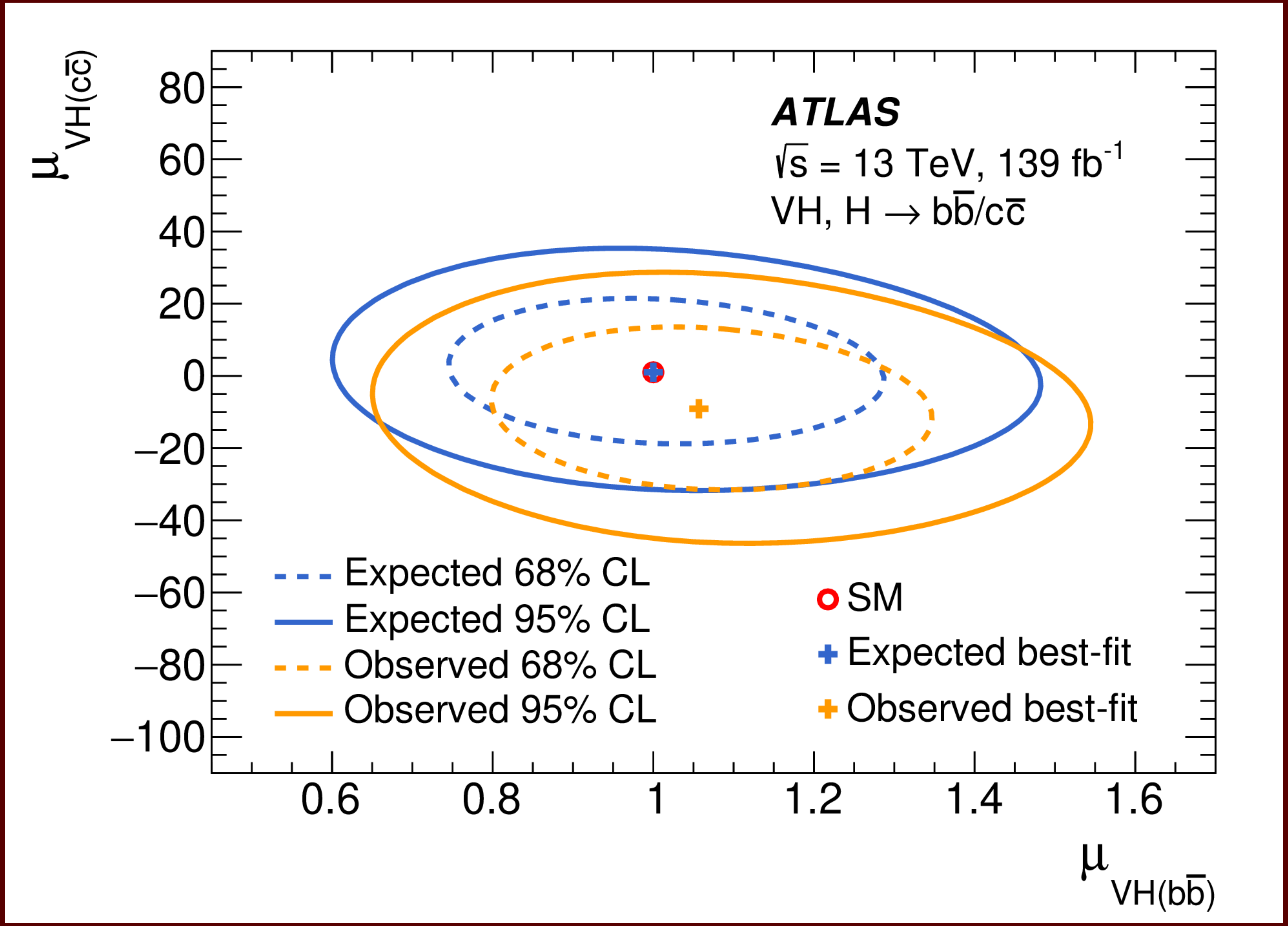


Data-background, including $WH(\to c\bar{c}), VZ, VW$: **3.8$\sigma$ for** $VW(\to cq)$

first limits on $\kappa_c$ coupling:
$\sigma/\sigma^{SM} < 26$ (31 exp.)

arXiv:2201.11428

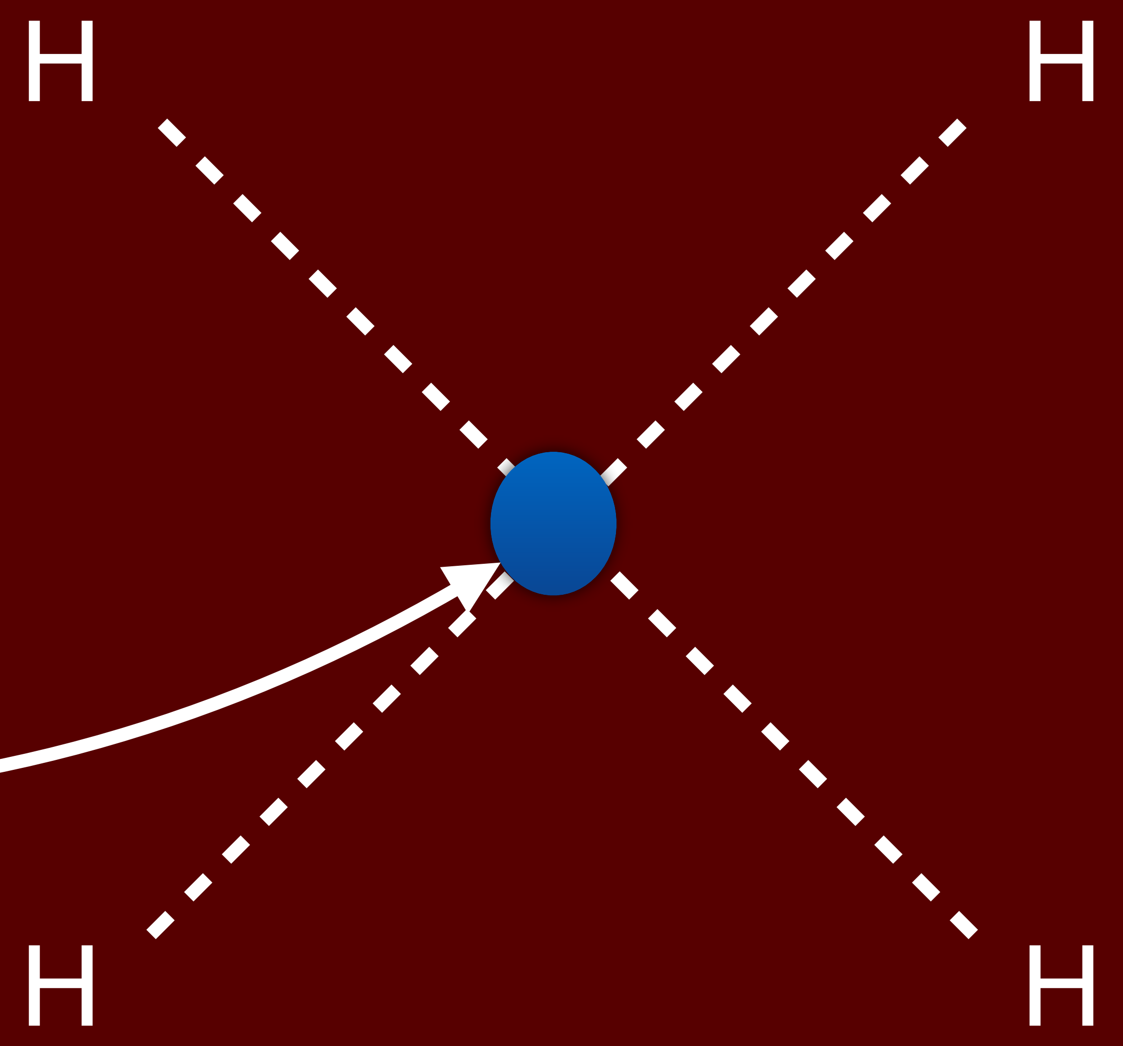
# $H \to c\bar{c}$ and $H \to b\bar{b}$



The observed and expected values of $\mu_{VHc\bar{c}}$ and $\mu_{VHb\bar{b}}$

# The Higgs Boson Self-Coupling

$$V(\Phi) = -\mu^2\Phi^\dagger\Phi + \lambda(\Phi^\dagger\Phi)^2$$
$$= V_0 + \frac{1}{2}m_H^2H^2 + \lambda v H^3 + \frac{1}{4}\lambda H^4$$

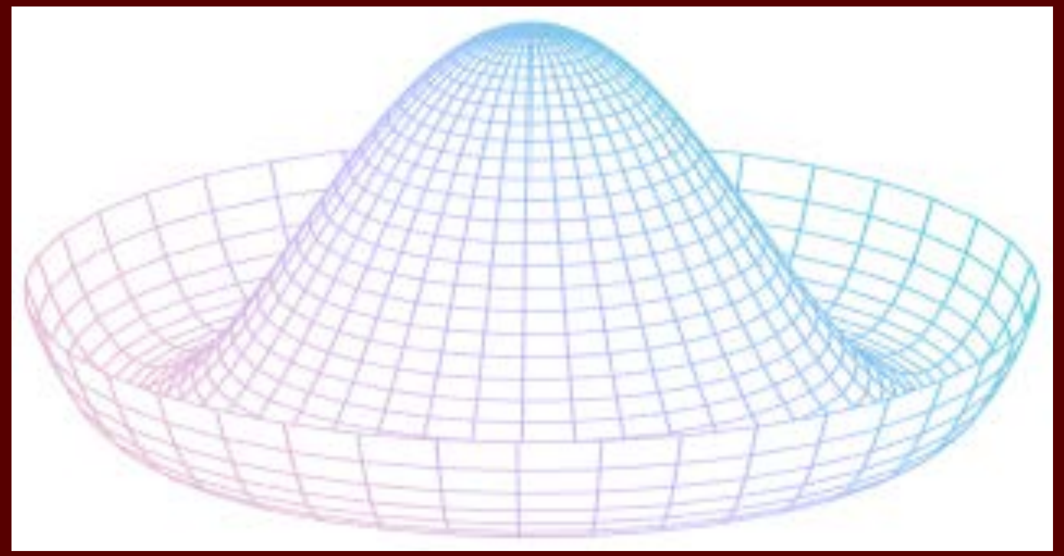


From the Higgs boson mass find $\lambda$ from $\lambda = m_H^2/2v^2 \sim 0.13$

$\lambda$ determines the strength of the Higgs self-coupling → measure it from HH production

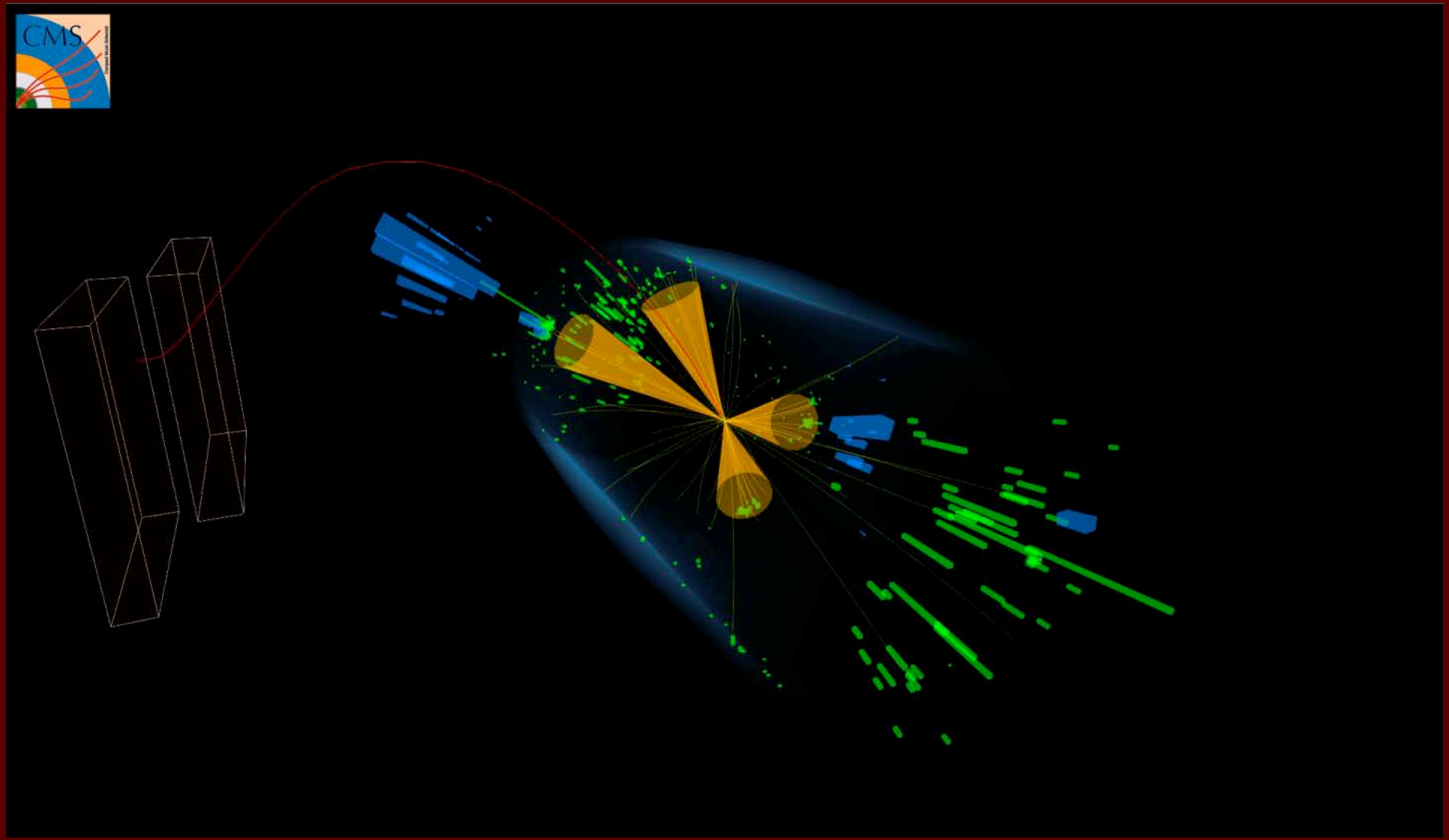
This is a particularly hard measurement: ggF $\sigma = 31^{+1.4}_{-1.2}$ fb and VBF $\sigma = 1.726 \pm 0.036$ fb at 13 TeV.

There are many different analyses searching for this decay channel

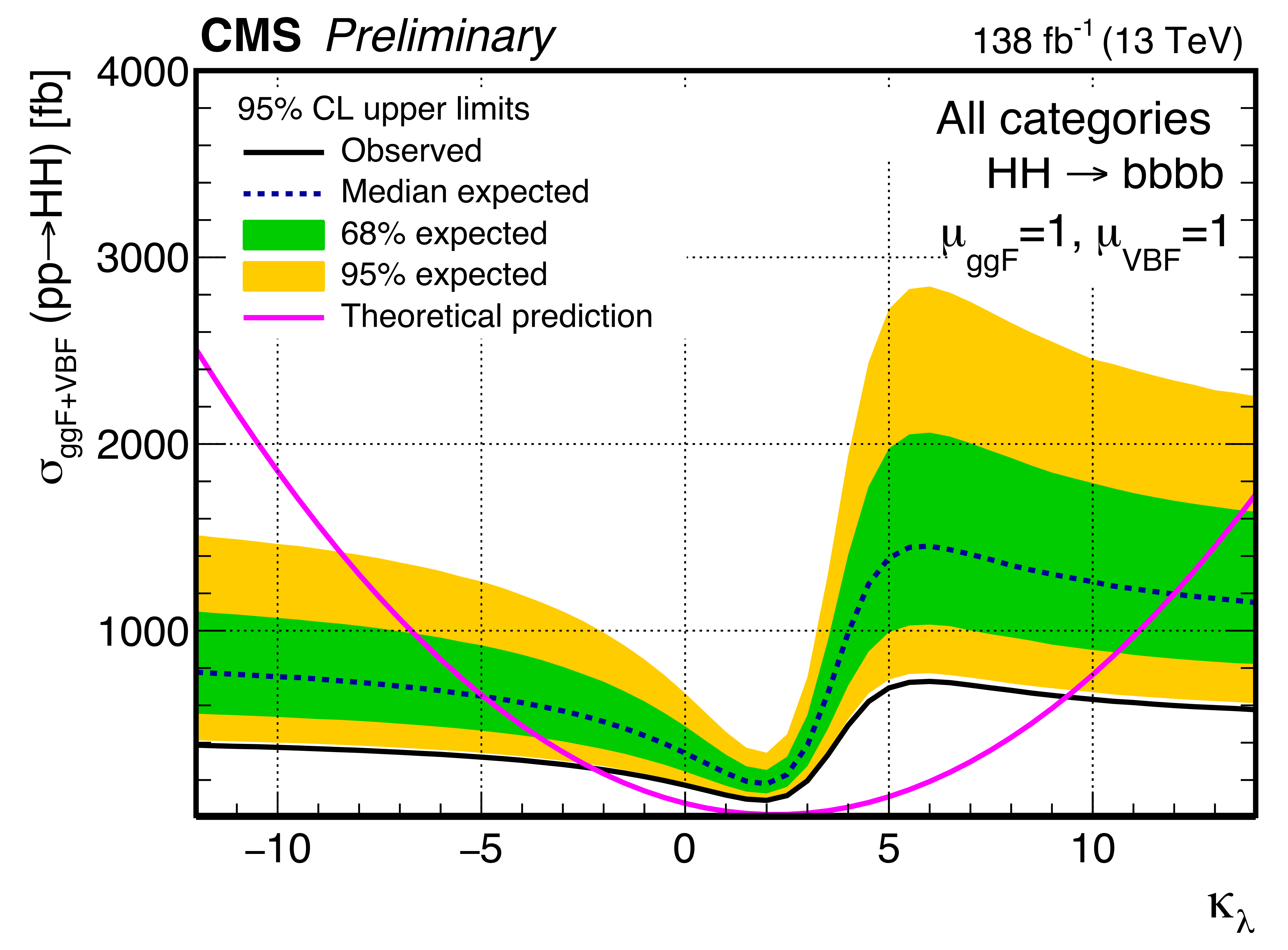


# $HH \to bbbb$

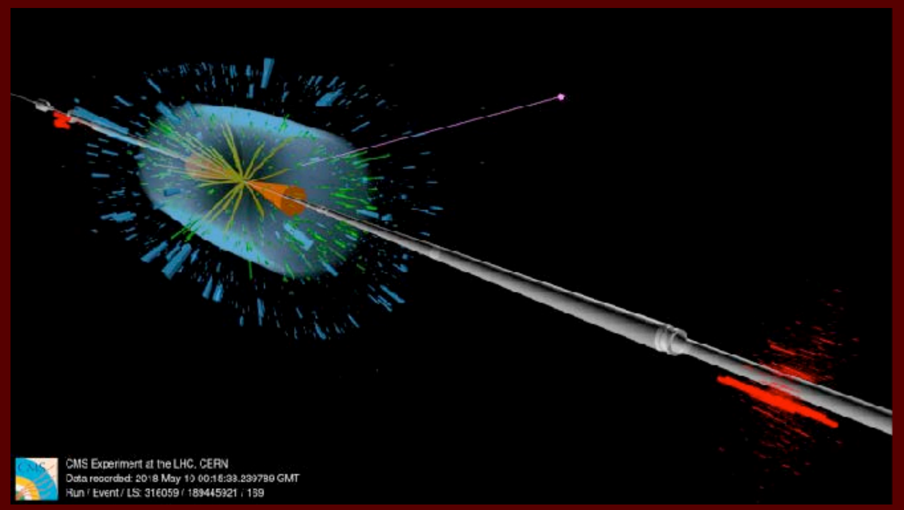
Search strategy is to select events with 4 high $p_T$ b-jets



CMS-PAS-HIG-20-005



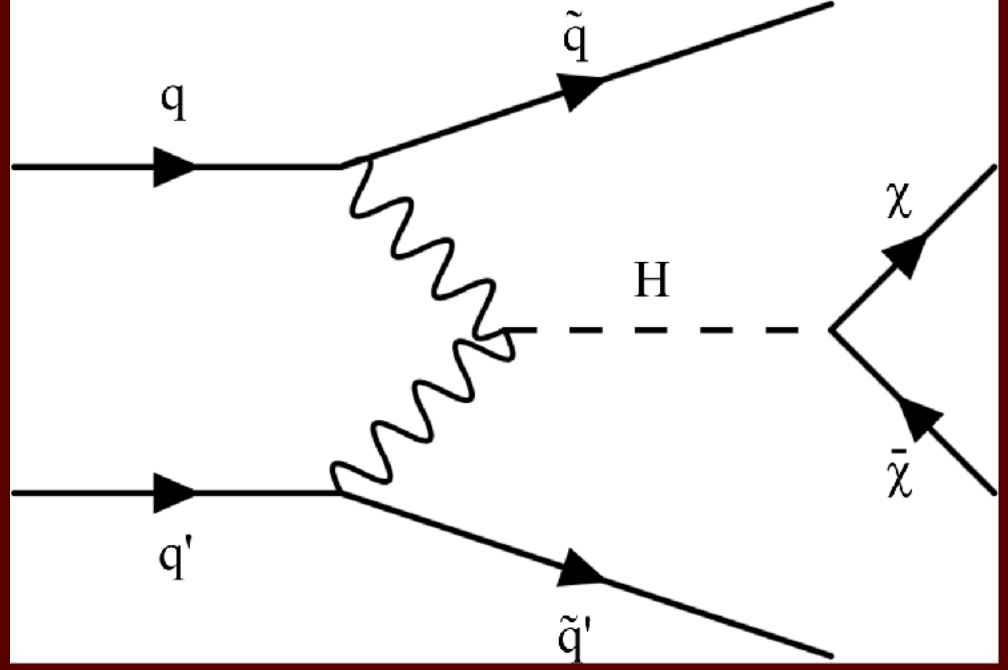
# *H* → *Invisible*



Does the dark matter particle get its mass by coupling to the Higgs boson?

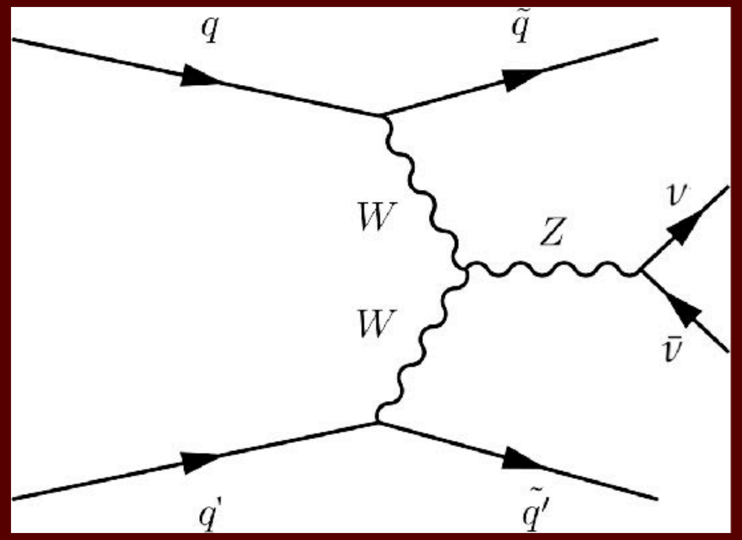
Does the Higgs couple to dark matter?

Signature in VBF are two forward jets and a large central missing momentum

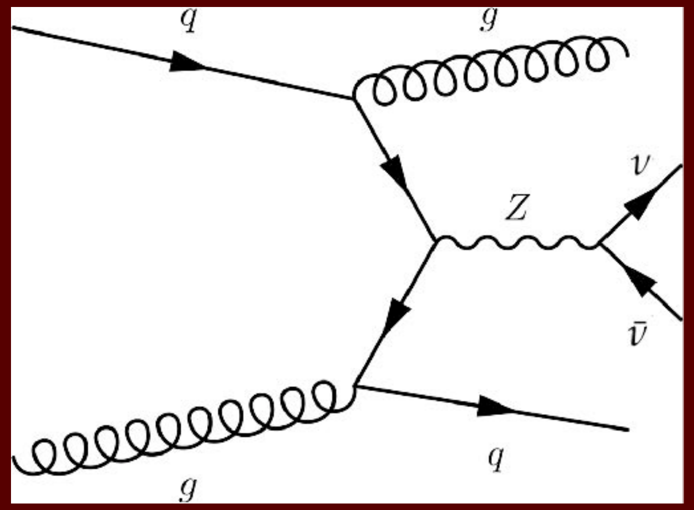


Precise estimates of the backgrounds are essential for this measurement.

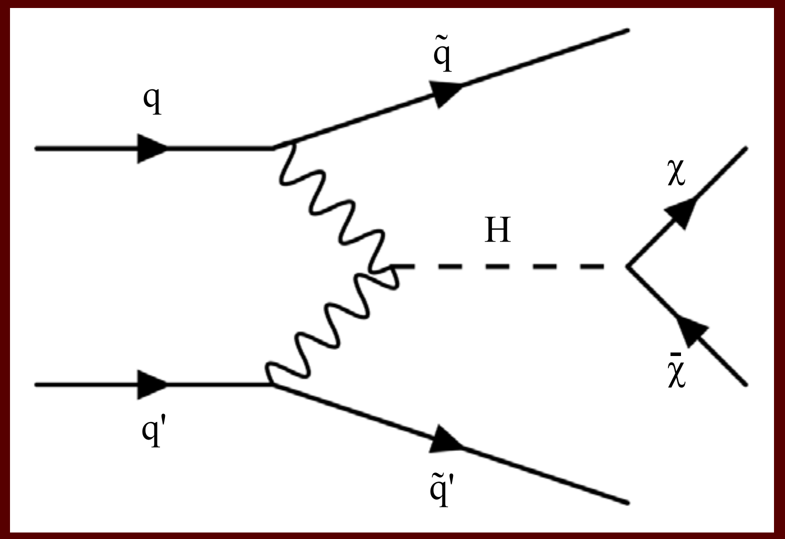
They are:



and this



# *Higgs to Invisible*



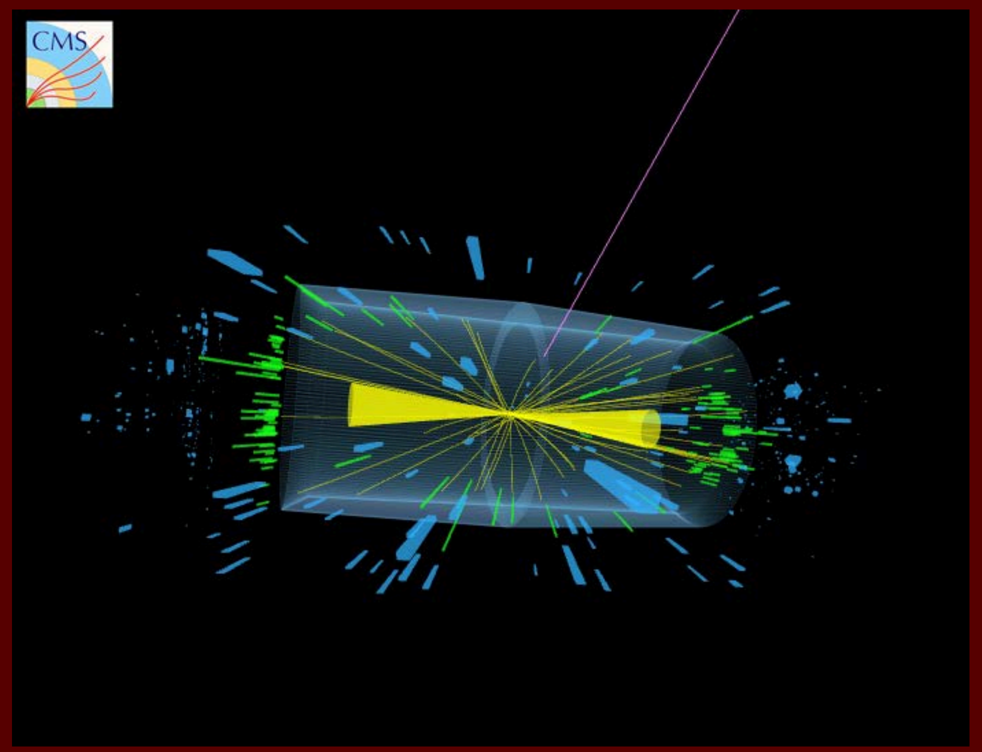
Search strategies

ATLAS: VBF combined with $ttH$ and $VH$ production modes

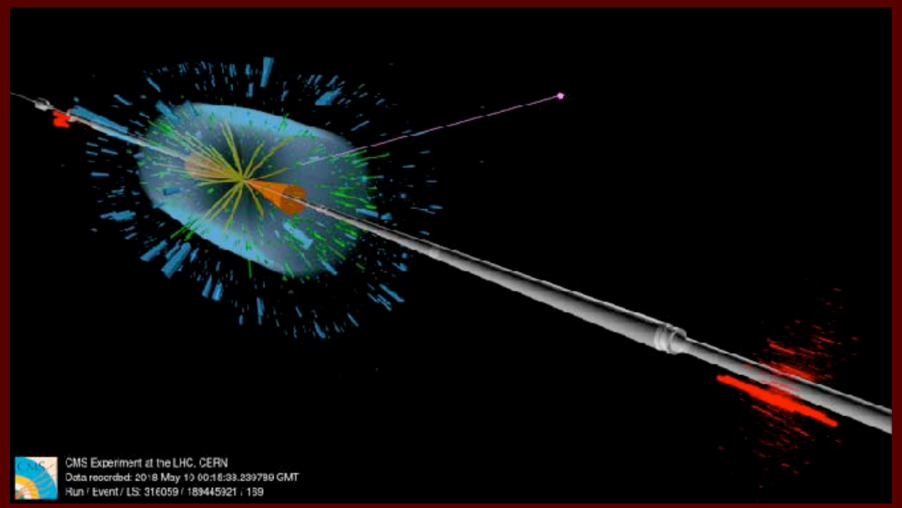
- $V = Z \to \ell\ell;\ V = (W, Z) \to \text{hadrons}$

CMS: Search for 2 forward jets with high $M_{jj}$ and high $|\Delta\eta_{jj}|$ + MET

- Dominant backgrounds: $W \to \ell\nu$ and $Z \to \nu\nu$ +jets
- systematically dominated by V+jets modeling



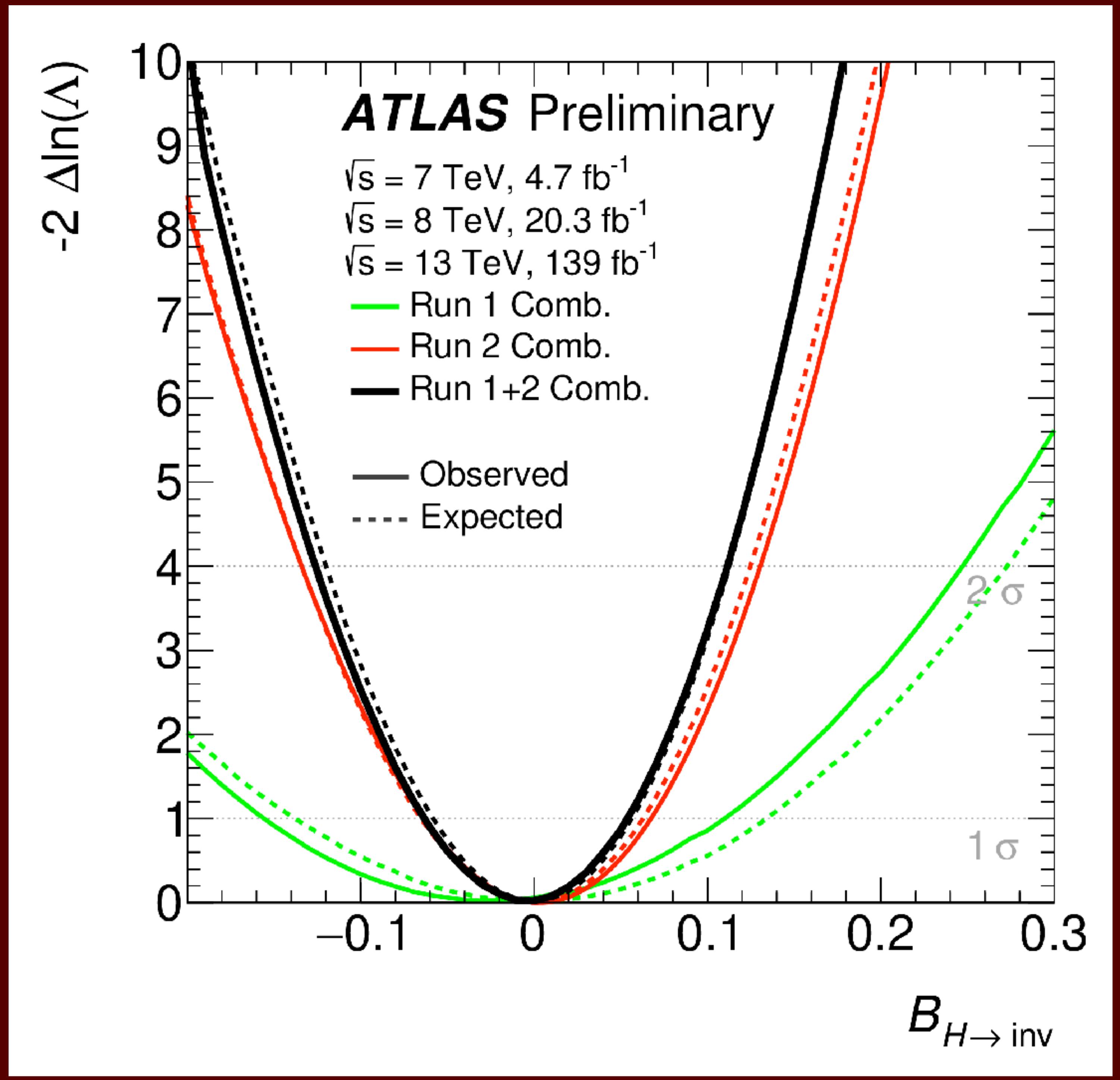
# $H \to Invisible$

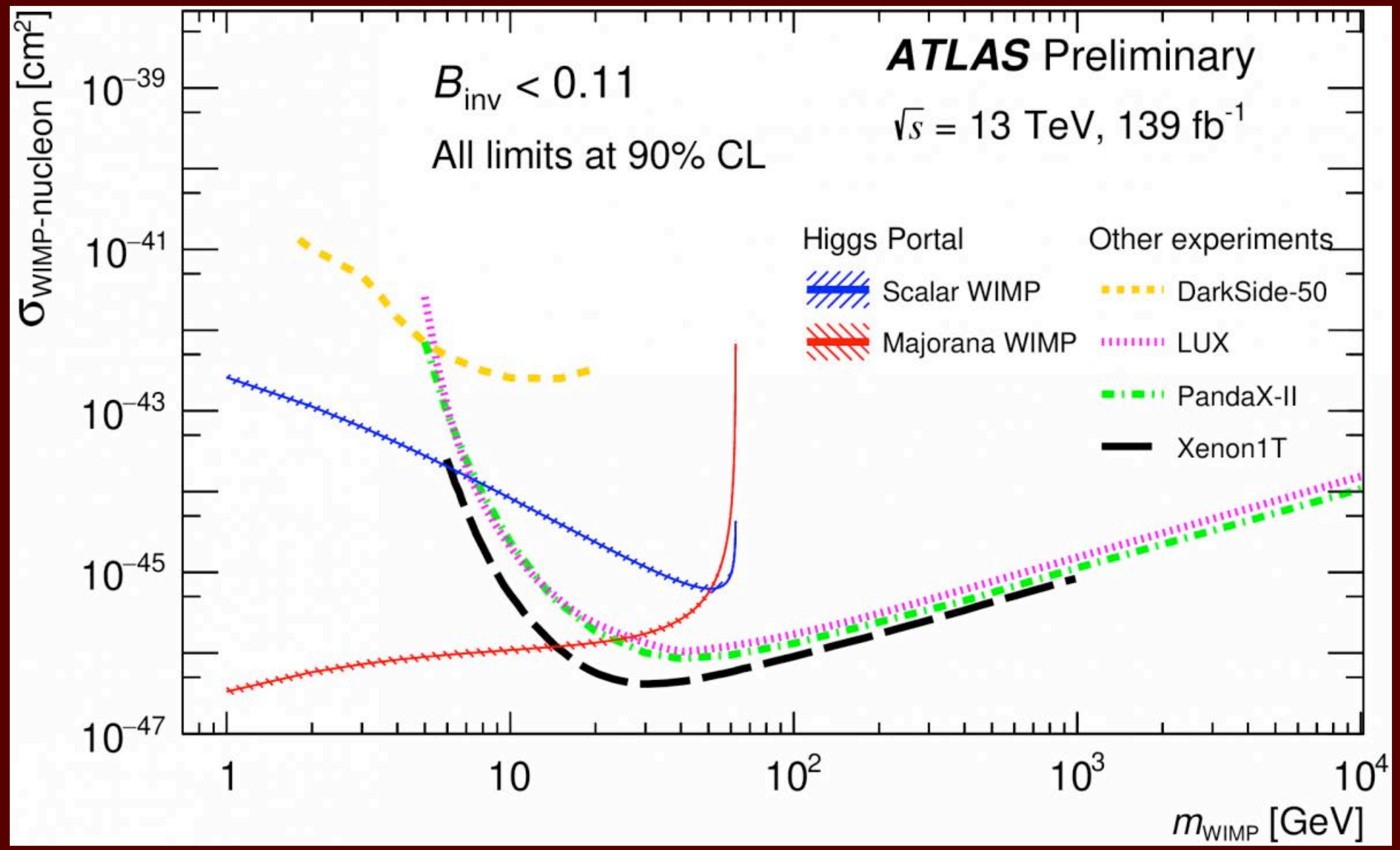


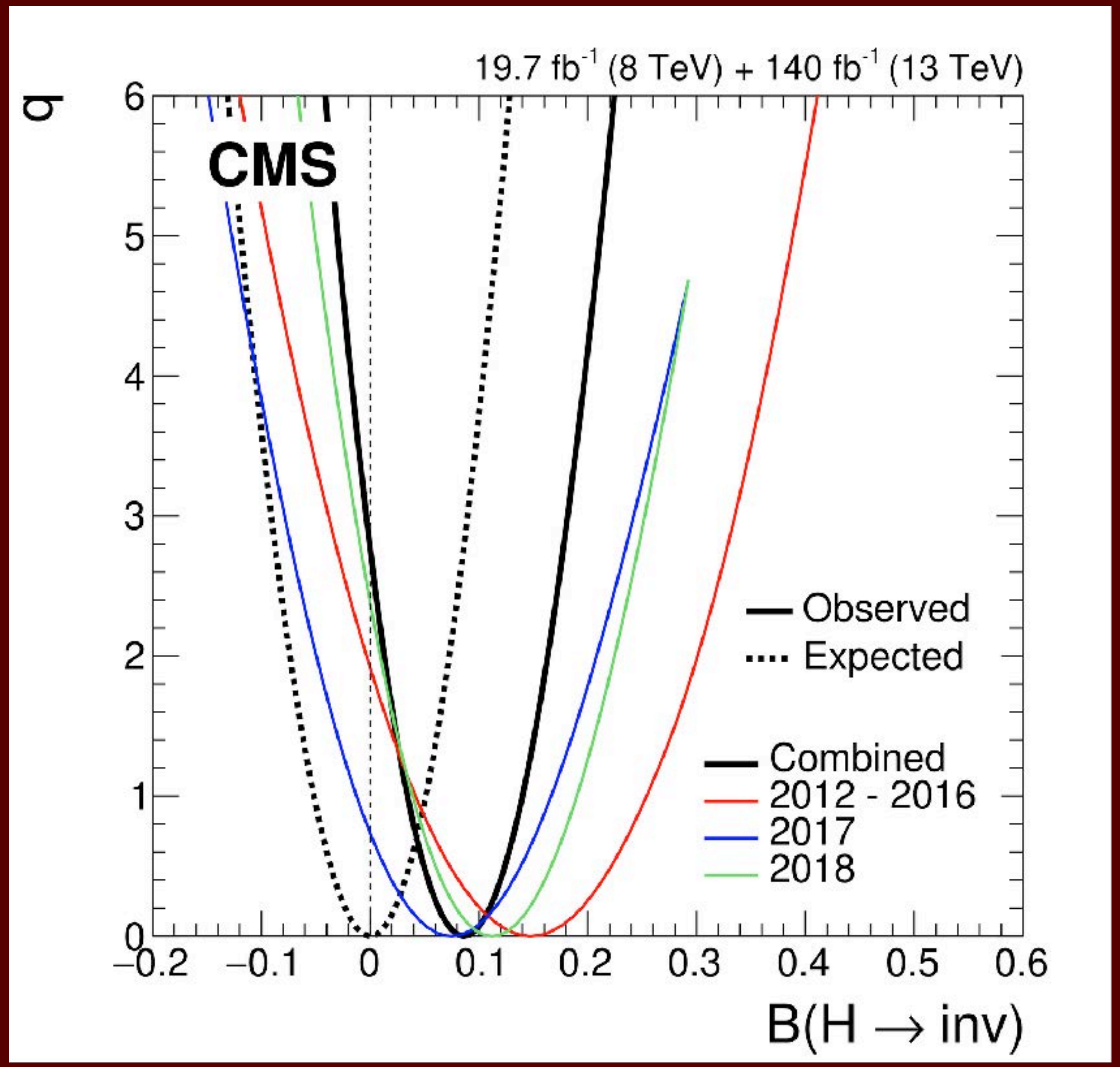
ATLAS-CONF-2020-008
HIGG-2018-26
CMS-PAS-HIG-20-003
ATLAS-CONF-2020-052

Does the Higgs couple to a dark matter particle?

Dark matter limits set through EFT assuming a new physics scale of ~1 TeV.







ATLAS : BR($H \to$ inv) < 0.11 (exp 0.11)

CMS : BR($H \to$ inv) < 0.18 (exp 0.10)

# What Lies Ahead?

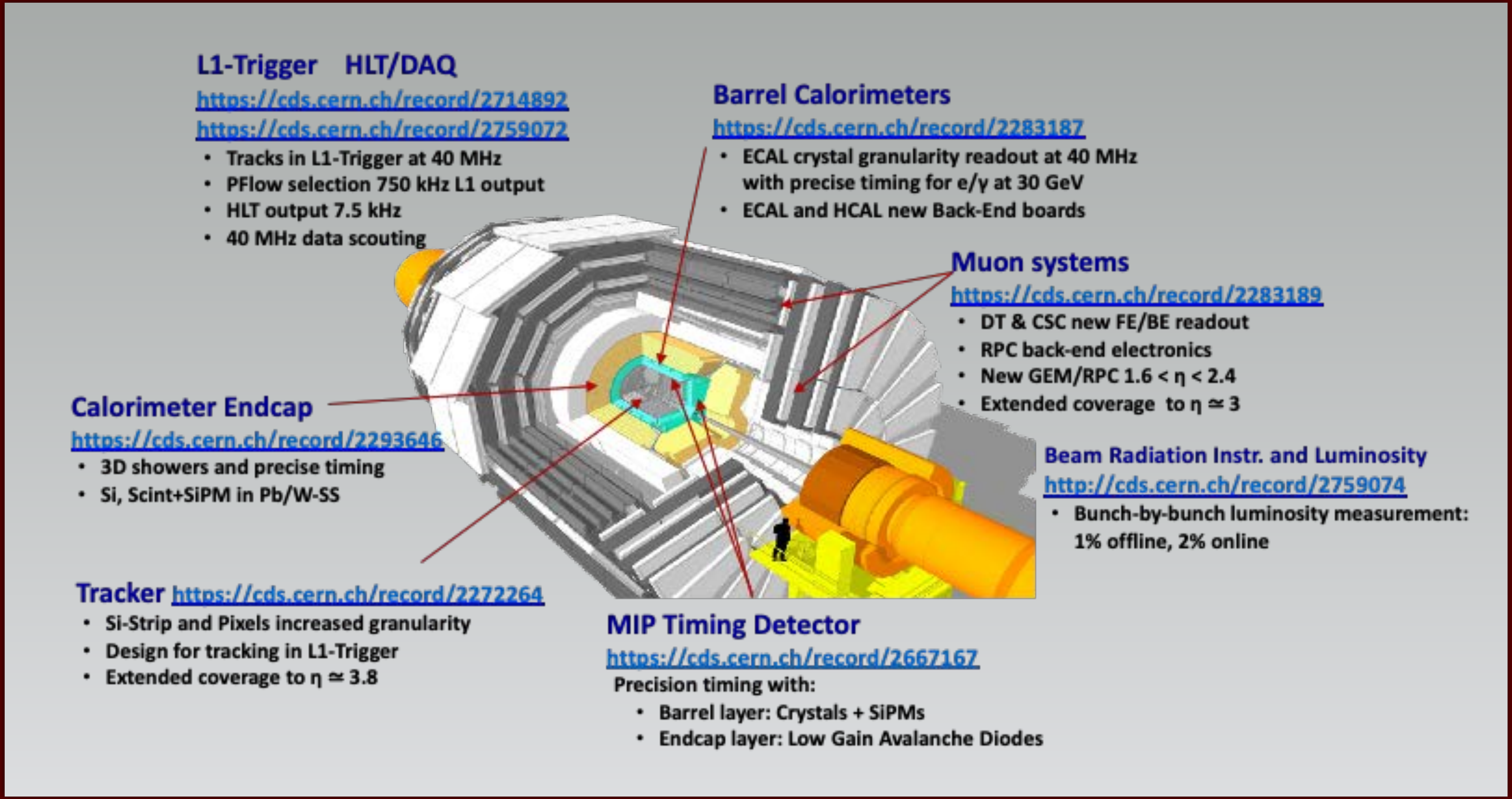
Run 3 will start this year with an anticipated 350 $\text{fb}^{-1}$ collected by 2025.

Beyond that there is the HL-LHC where an expected 3,000 $\text{fb}^{-1}$ will be delivered.

Nearly one thousand times the luminosity of the original observation of 2012.

# New Detectors for the HL-LHC

Both CMS and ATLAS are preparing major upgrades for the HL-LHC era. New silicon trackers advanced triggers, precision timing detectors, new calorimeters (CMS) for the same performance that we have now.



**L1-Trigger HLT/DAQ**

https://cds.cern.ch/record/2714892

https://cds.cern.ch/record/2759072

- Tracks in L1-Trigger at 40 MHz
- PFlow selection 750 kHz L1 output
- HLT output 7.5 kHz
- 40 MHz data scouting

**Barrel Calorimeters**

https://cds.cern.ch/record/2283187

- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards

**Muon systems**

https://cds.cern.ch/record/2283189

- DT & CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3

**Calorimeter Endcap**

https://cds.cern.ch/record/2293646

- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

**Beam Radiation Instr. and Luminosity**

http://cds.cern.ch/record/2759074

- Bunch-by-bunch luminosity measurement: 1% offline, 2% online

**Tracker** https://cds.cern.ch/record/2272264

- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

**MIP Timing Detector**

https://cds.cern.ch/record/2667167

Precision timing with:

- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

# *Better Detectors & Better Theory at the HL-LHC*

Better triggers and data rates → maintain thresholds at or below current levels.

Precision timing (~30 ps) detectors → reduce confusion from overlapping events.

New machine learning techniques → improved signal selection and background rejection.

Improvements to the PDF's → better background estimates

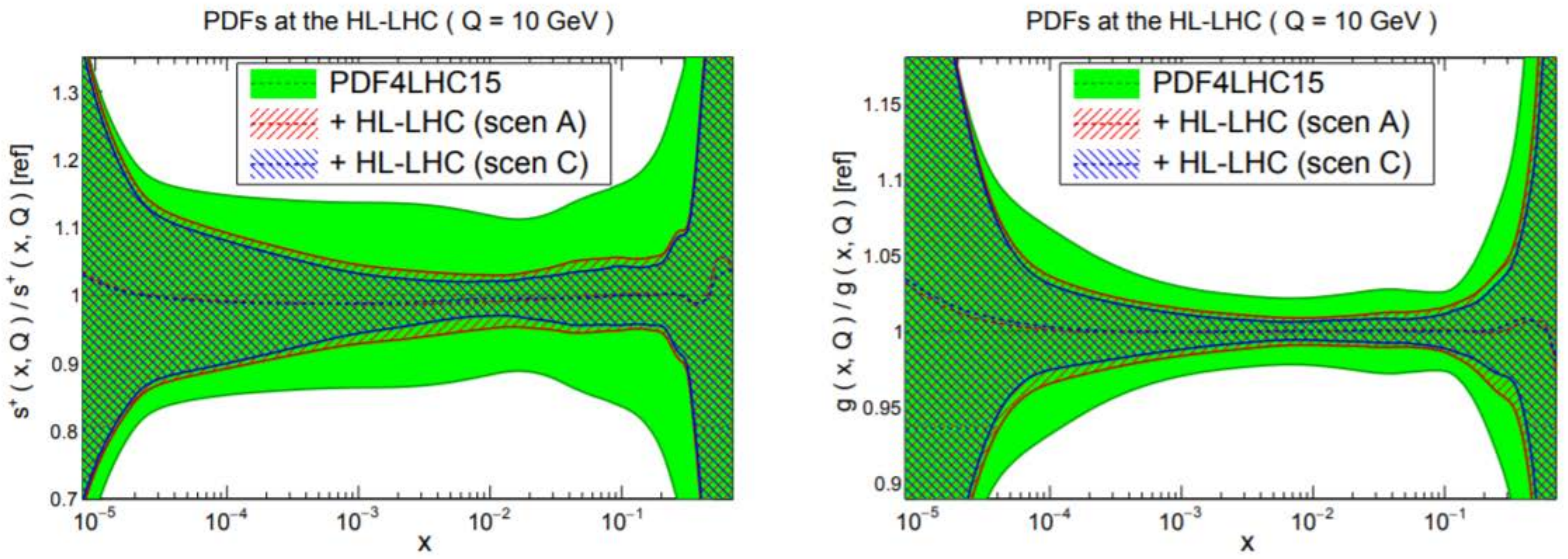


Fig. 7: Comparison of the PDF4LHC15 set with the profiled sets with HL–LHC pseudo-data. We show the strange (left) and gluon (right) PDFs normalised to the central value of the baseline.

Expected improvements in the strange PDF (left) and the gluon PDF (right)

# Summary

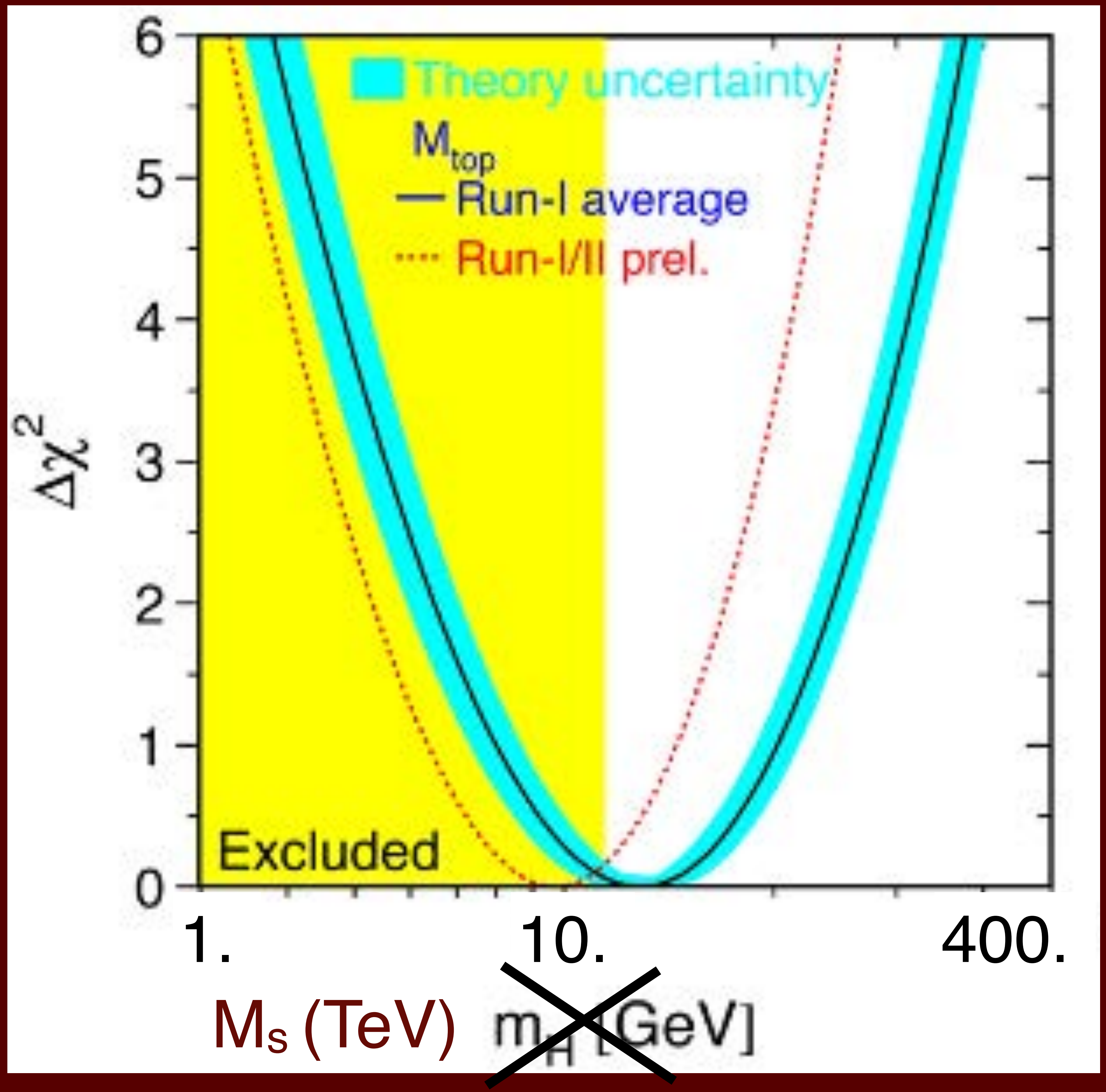
In the past ten years we have gone from discovery to precision measurements with a quality like that at LEP.

This could not have happened without:

- The marvel of engineering that is the LHC
- The engineering feat of our detectors
- The high quality generators like Pythia, Madgraph, and Herwig
- Precise detector simulations by GEANT4.
- New deep learning techniques to identify the signals.
- Advances in our theoretical models.

The data we will collect with the upgraded detectors will allow us to explore the outer reaches of the standard model as we did at LEP

Let us hope that one day we will make plots like we did for the Higgs where new phenomena has to be to guide us into the future.



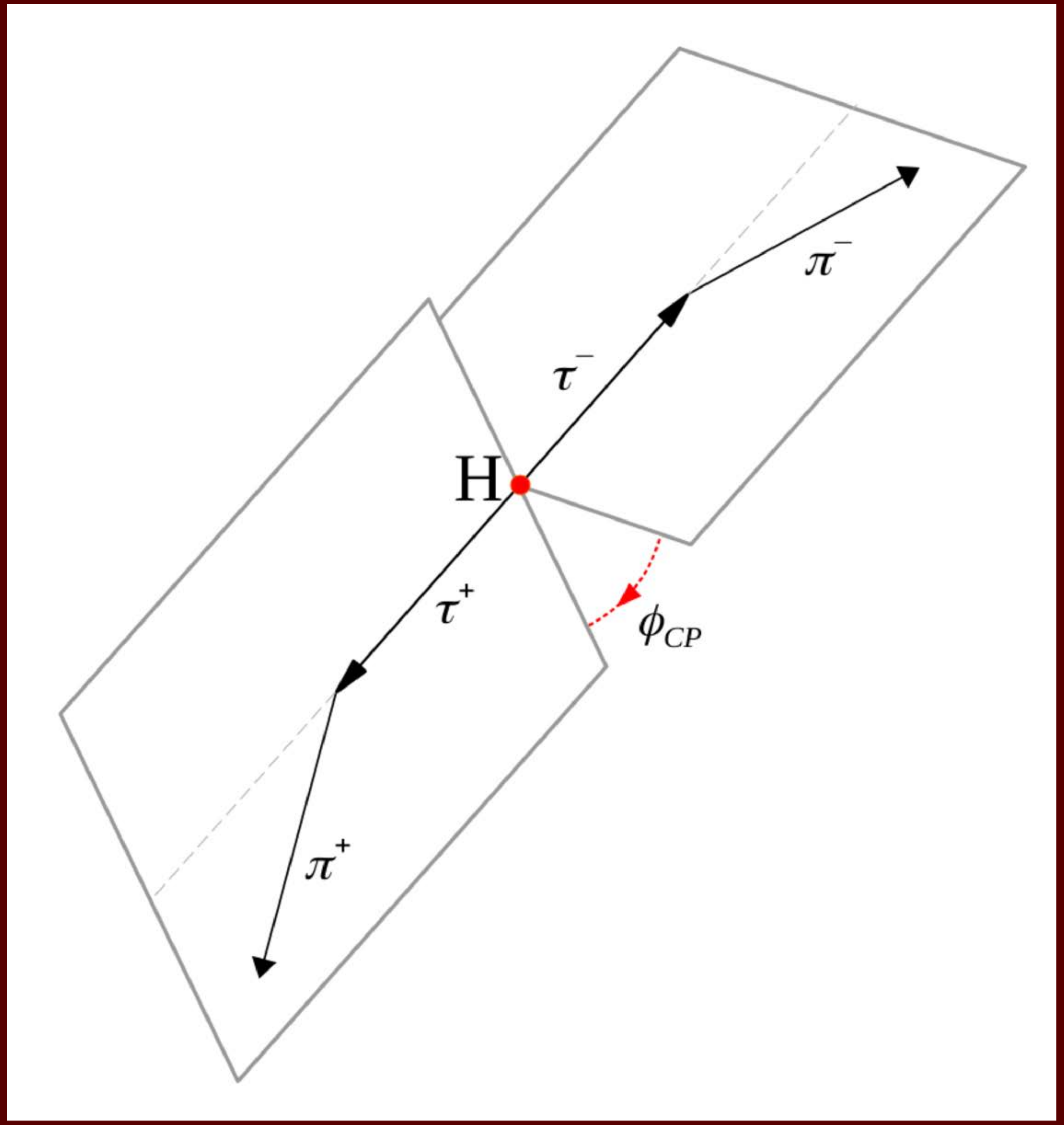
# Backup

# *The Higgs Charge-Parity (CP)*

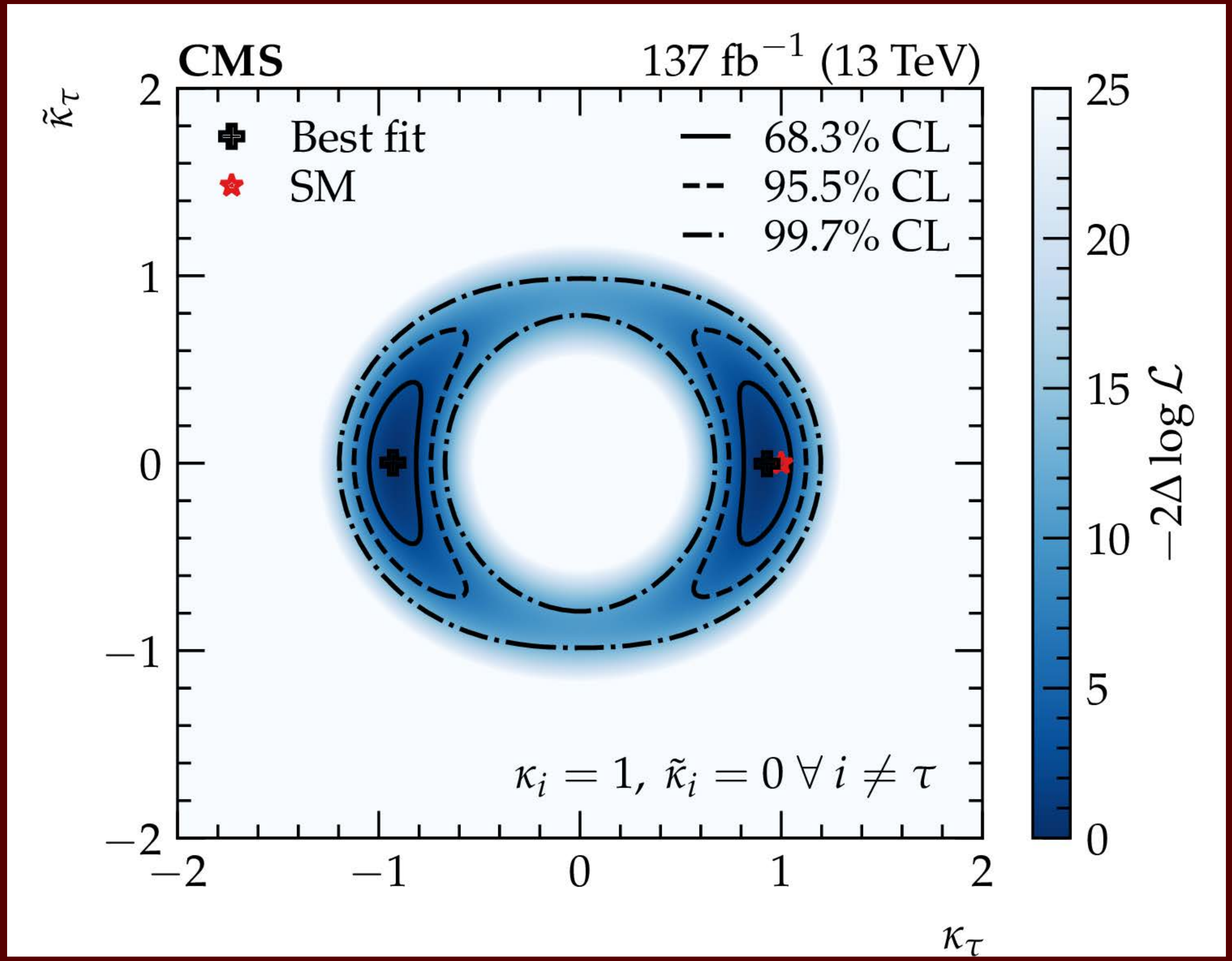
In a measurement of the process $H \to \tau\tau$ the CP structure of the Yukawa coupling between the Hig
boson and t leptons is studied:

Using different decay channels of the $\tau$'s and reconstructing the angle between the planes - $\phi_{cp}$.

CP-odd is disfavored by 3 $\sigma$



Decay planes of $H \to \tau\tau$.
$\phi_{CP}$ the angle between the decay planes



http://arxiv.org/abs/2110.04836

The mixing angle is $-1° \pm 19°$