LHC Physics - Higgs

Lydia Beresford

DESY Summer Student Lectures

05.08.25

Physics Goals of the LHC

wikimedia

Search for the Higgs Boson

The Standard Model (SM)

See lectures by:
Hyungjin Kim for more on HEP Theory
Markus Diehl for more on QCD

$$\mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$
$$+ i \bar{\psi} \not{D} \psi + h.c.$$
$$+ \psi_i y_{ij} \psi_j \phi + h.c.$$
$$+ |D_\mu \phi|^2 - V(\phi)$$

Higgs-fermion interactions

Higgs-self interactions

Higgs-gauge boson (W,Z) interactions

The Brout-Englert-Higgs mechanism in the SM

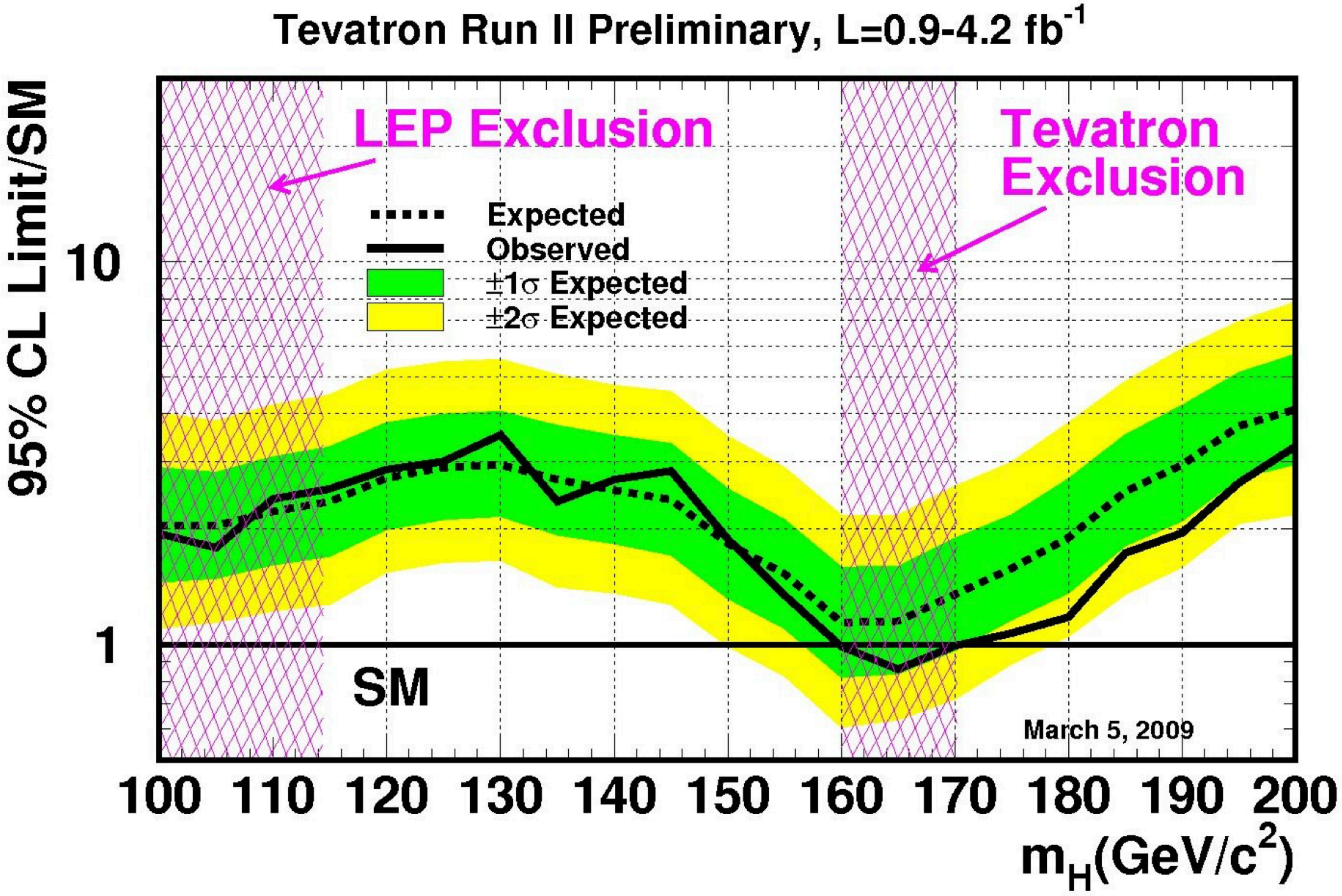
Introduction of the presence of a scalar field into the SM leads to

- **Particles acquire mass**
  - **Bosons:** $W^{\pm}$ and Z through electroweak symmetry breaking
  - **Fermions:** $\propto$ Yukawa y_{ij} couplings
- **Prediction of the existence of a particle → Higgs Boson**
  - **Higgs Boson interacts with itself**

https://phdcomics.com/comics.php?f=1489

The situation before the LHC

Status 2009: SM Higgs mass above 114 GeV and NOT in range 160-170 GeV



Prediction from EW fits 2012: SM Higgs mass 95^{+30}_{-23} GeV

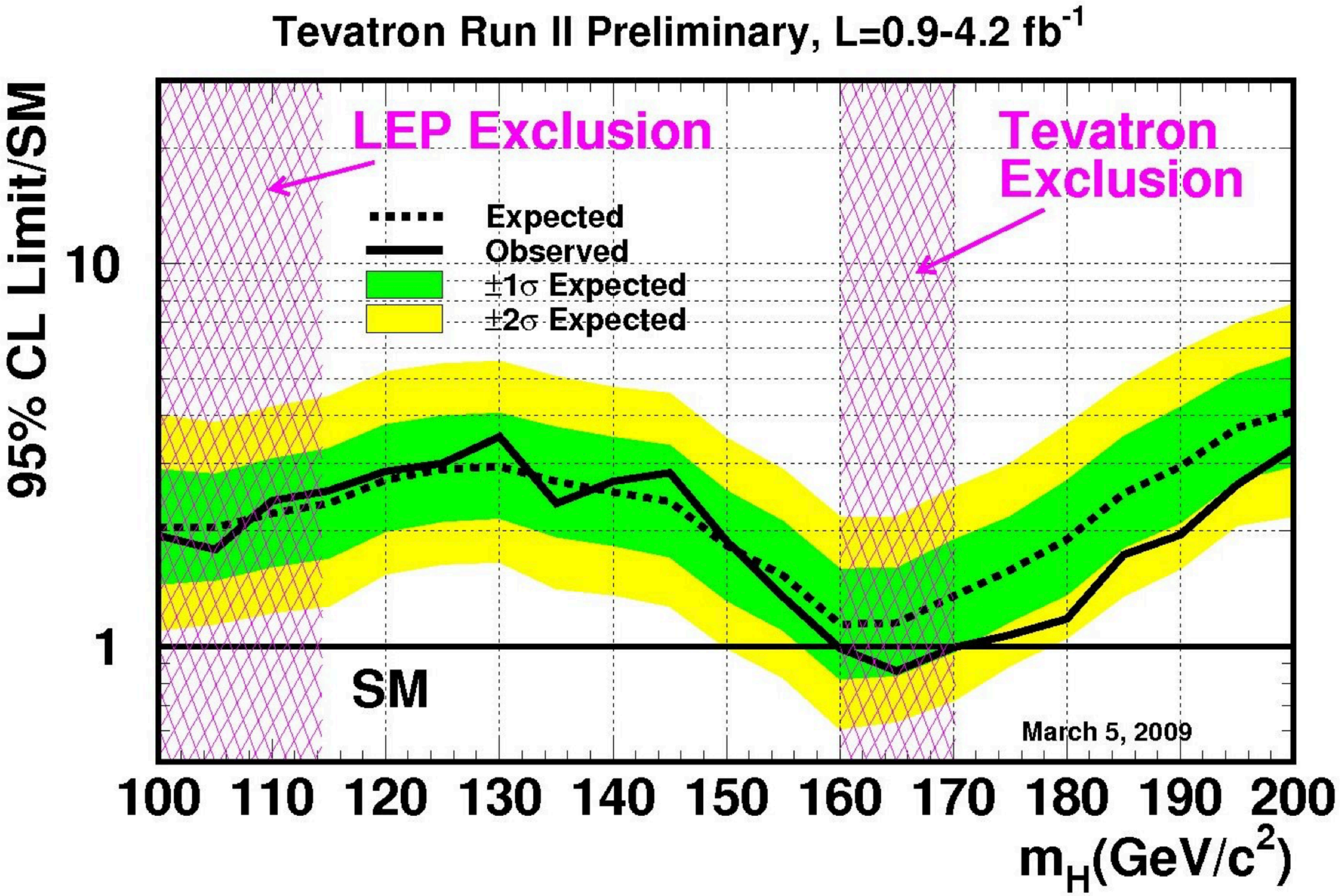
DOI:10.22323/1.084.0229

Interlude: how to read limit plots

Limit plots are used if we don't see a significant signal

y-axis = 95% CL upper limit on "signal strength"

$\mu = \sigma_{\text{meas}}/\sigma_{\text{SM}}$



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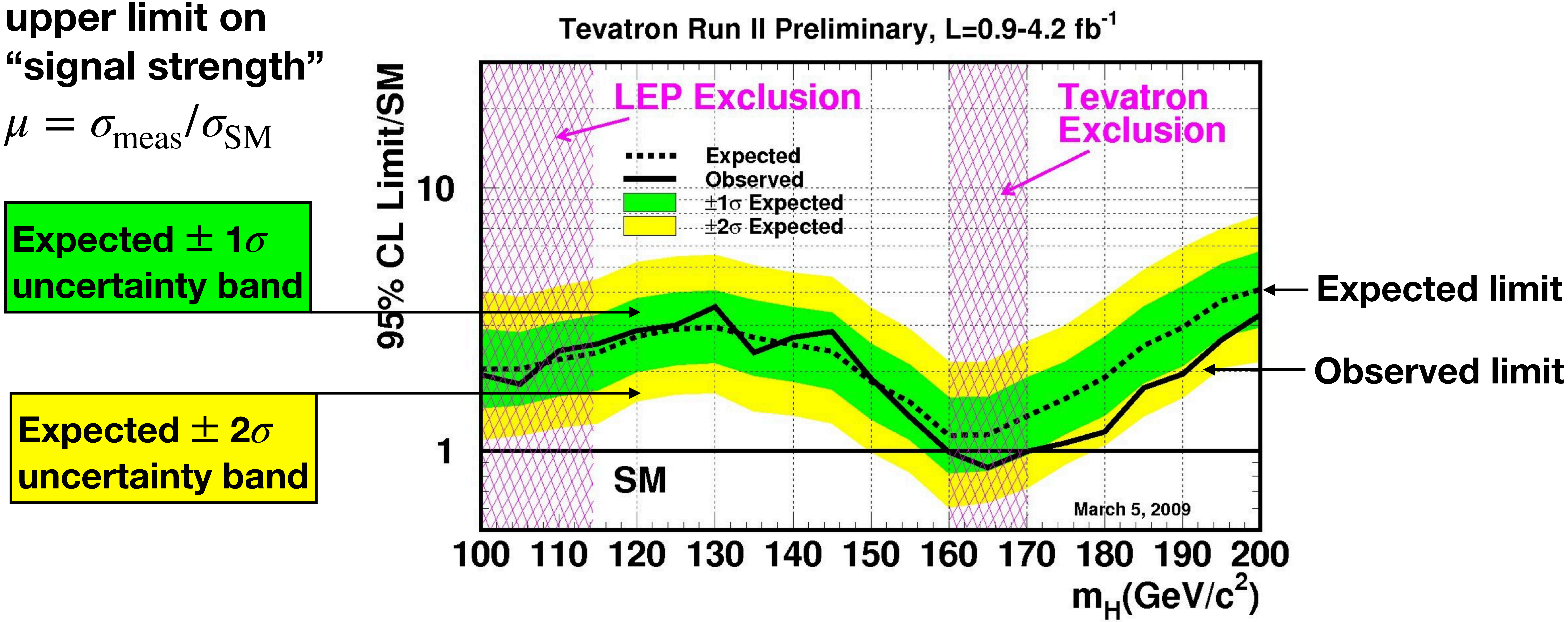


With 95% confidence level, we can say that the real signal strength is smaller than the indicated value (calculate for each mass point separately)

DOI:10.22323/1.084.0229

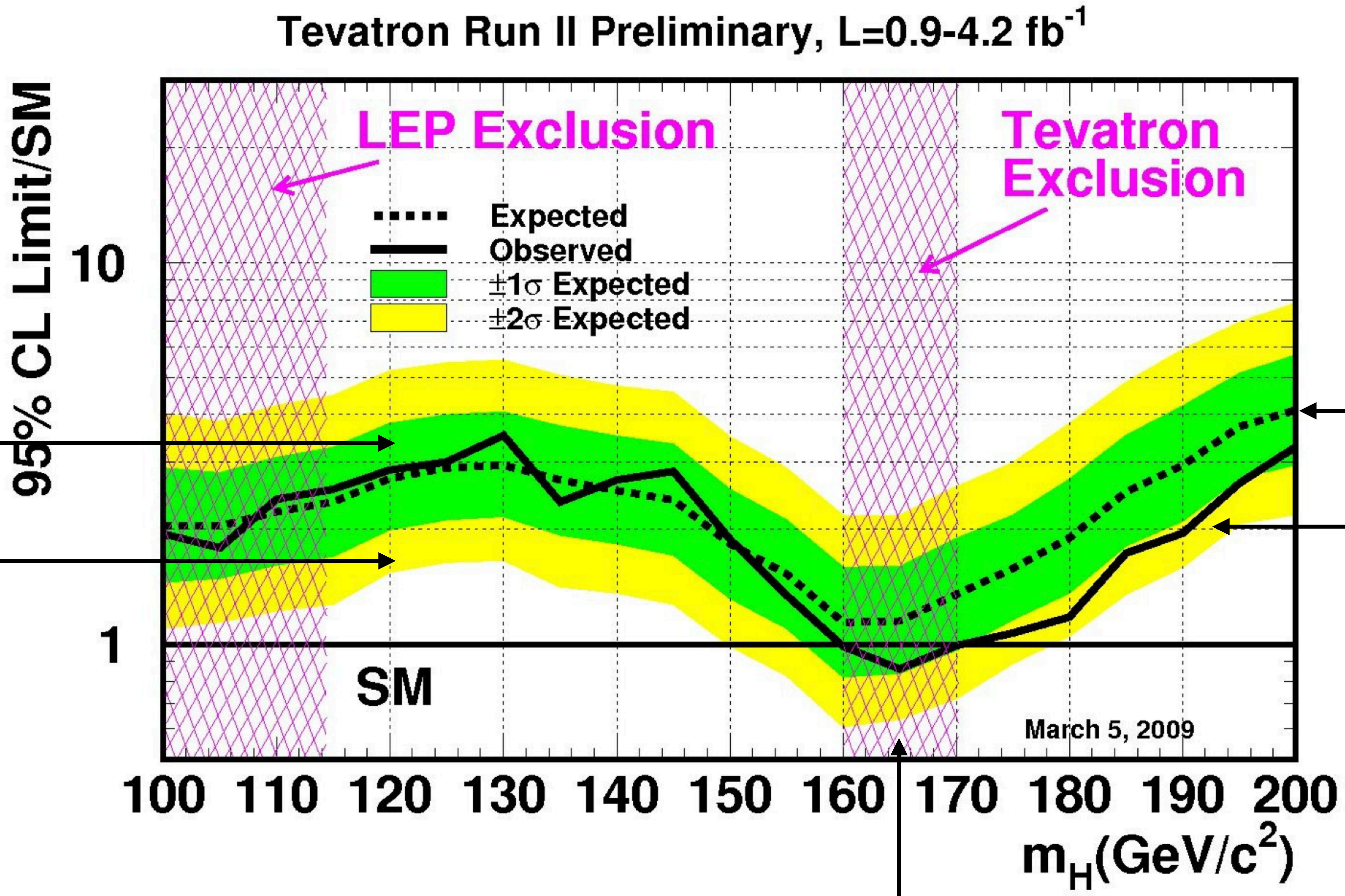
Interlude: how to read limit plots

y-axis = 95% CL upper limit on "signal strength"

$\mu = \sigma_{\text{meas}}/\sigma_{\text{SM}}$

Expected $\pm$ 1σ uncertainty band

Expected $\pm$ 2σ uncertainty band



Expected limit

Observed limit

Excluded Tevatron range since observed limit goes below 1

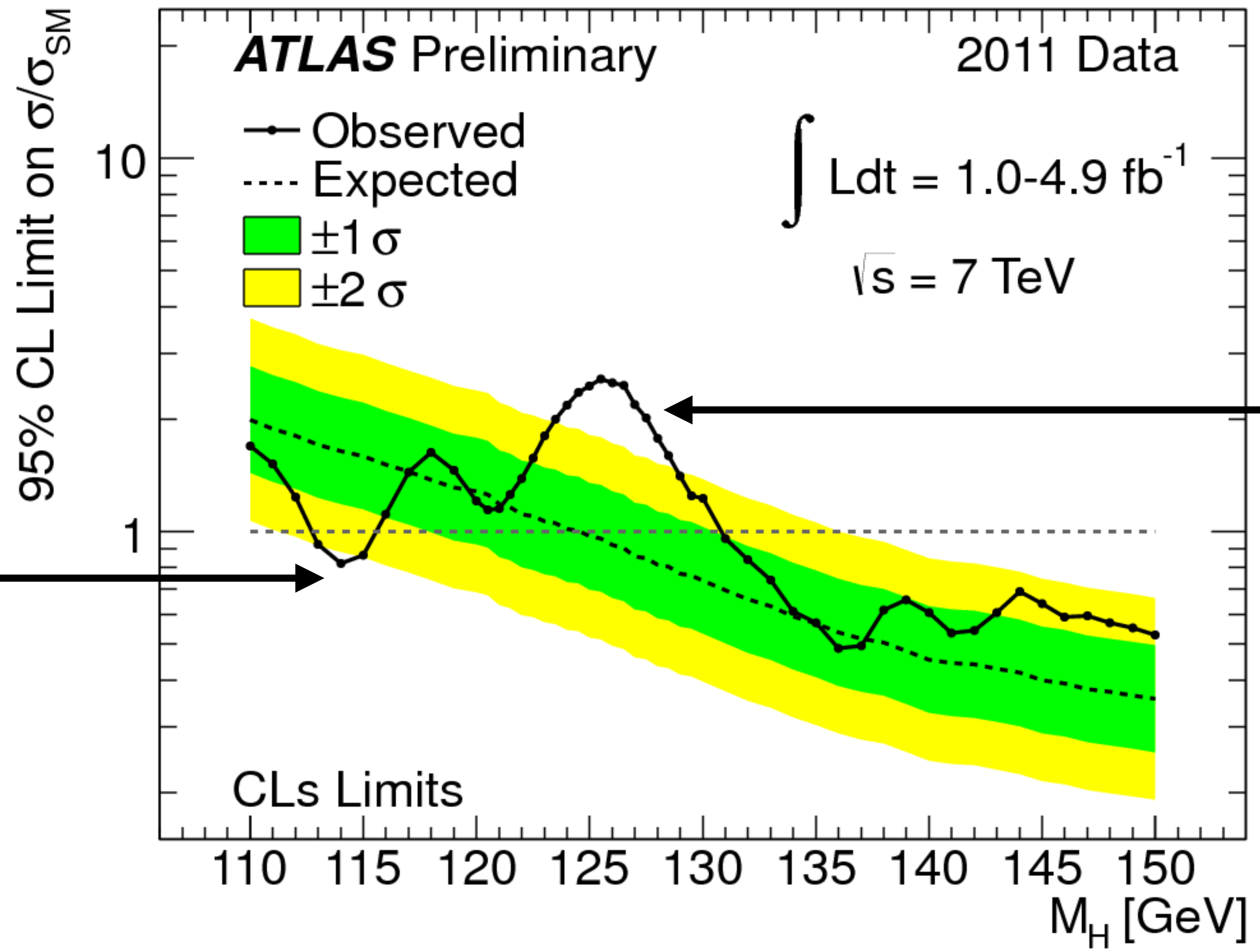
DOI:10.22323/1.084.0229

Interlude: how to read limit plots

The limit for a given model will improve by adding more data

However if a signal is there the observed limit does not improve anymore

If the observed limit is better than the expected → you have a deficit

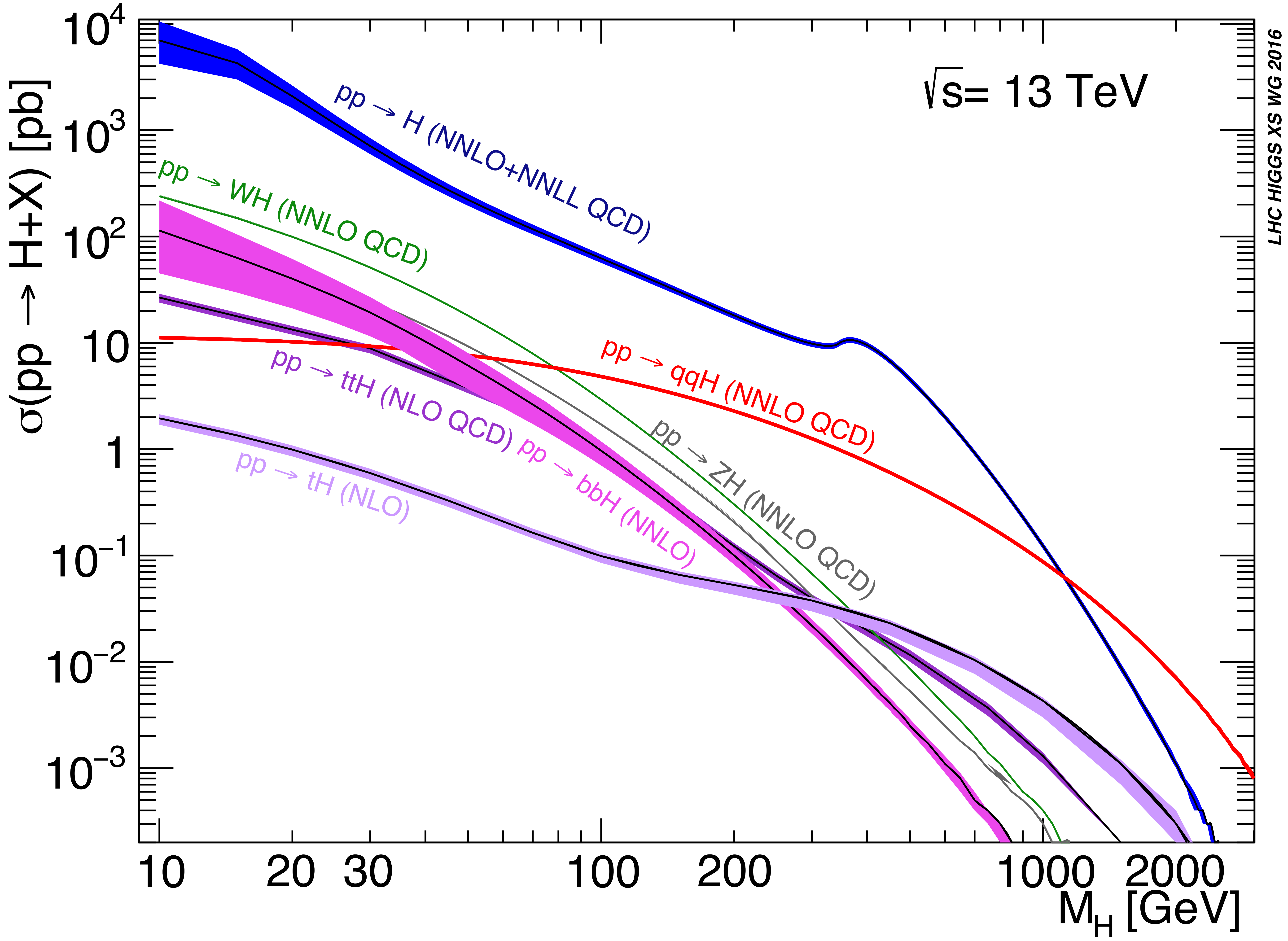


If the observed limit is worse than the expected → you have an excess

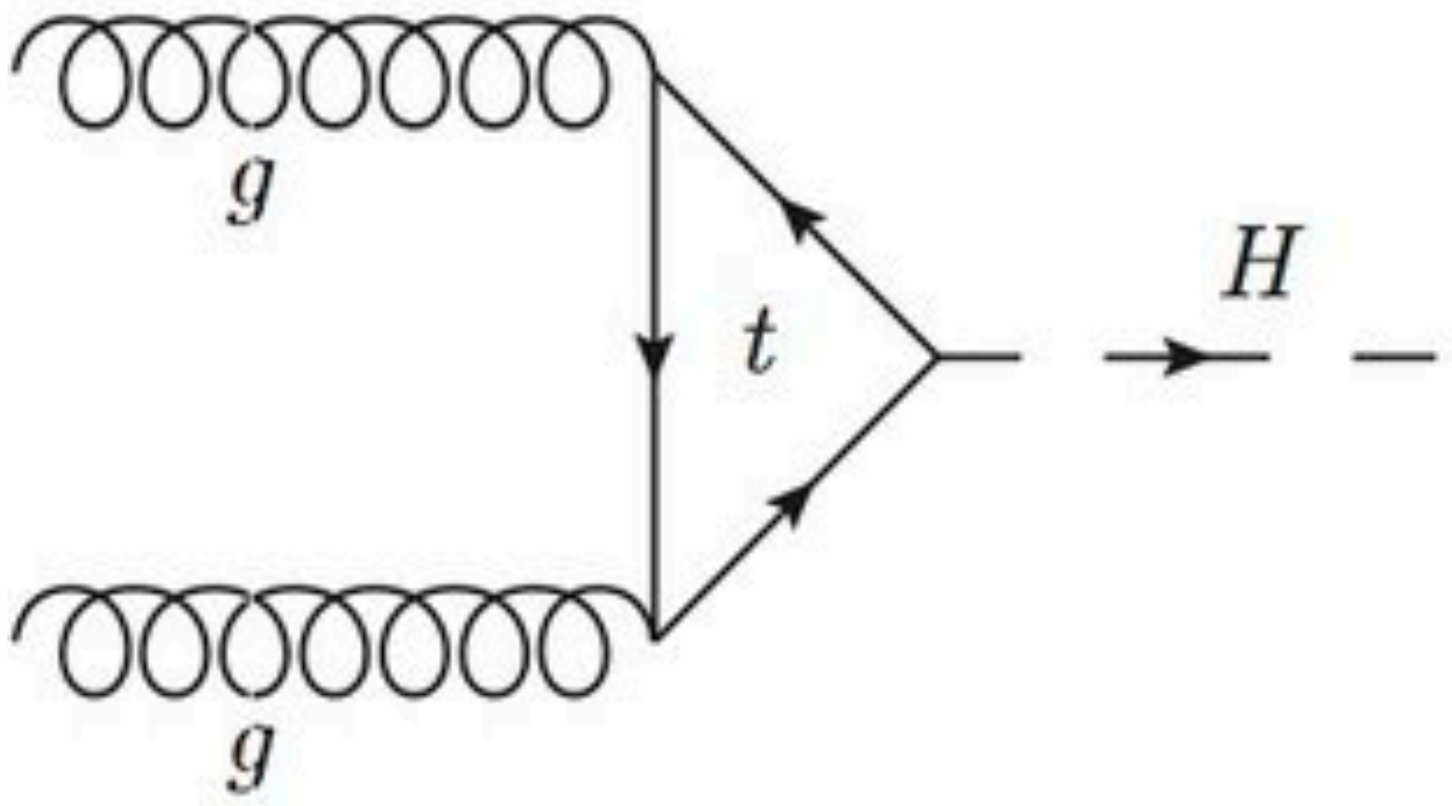
"better" = lower on the y-axis here

Higgs production modes at the LHC

Higgs production cross section as a function of M_H



Gluon fusion (ggF)



HiggsXSBR

DOI:10.13140/RG.2.2.24097.02408

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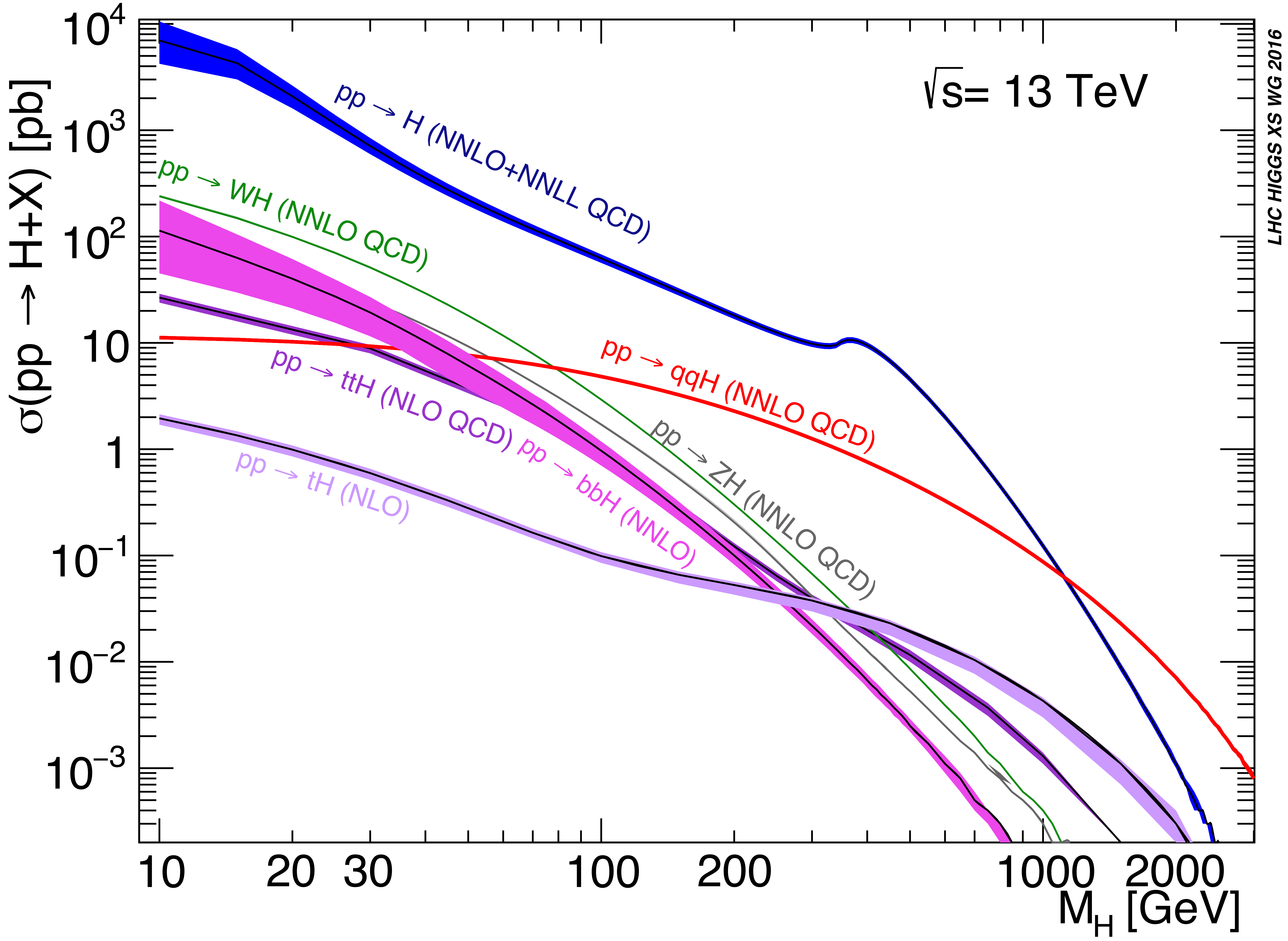
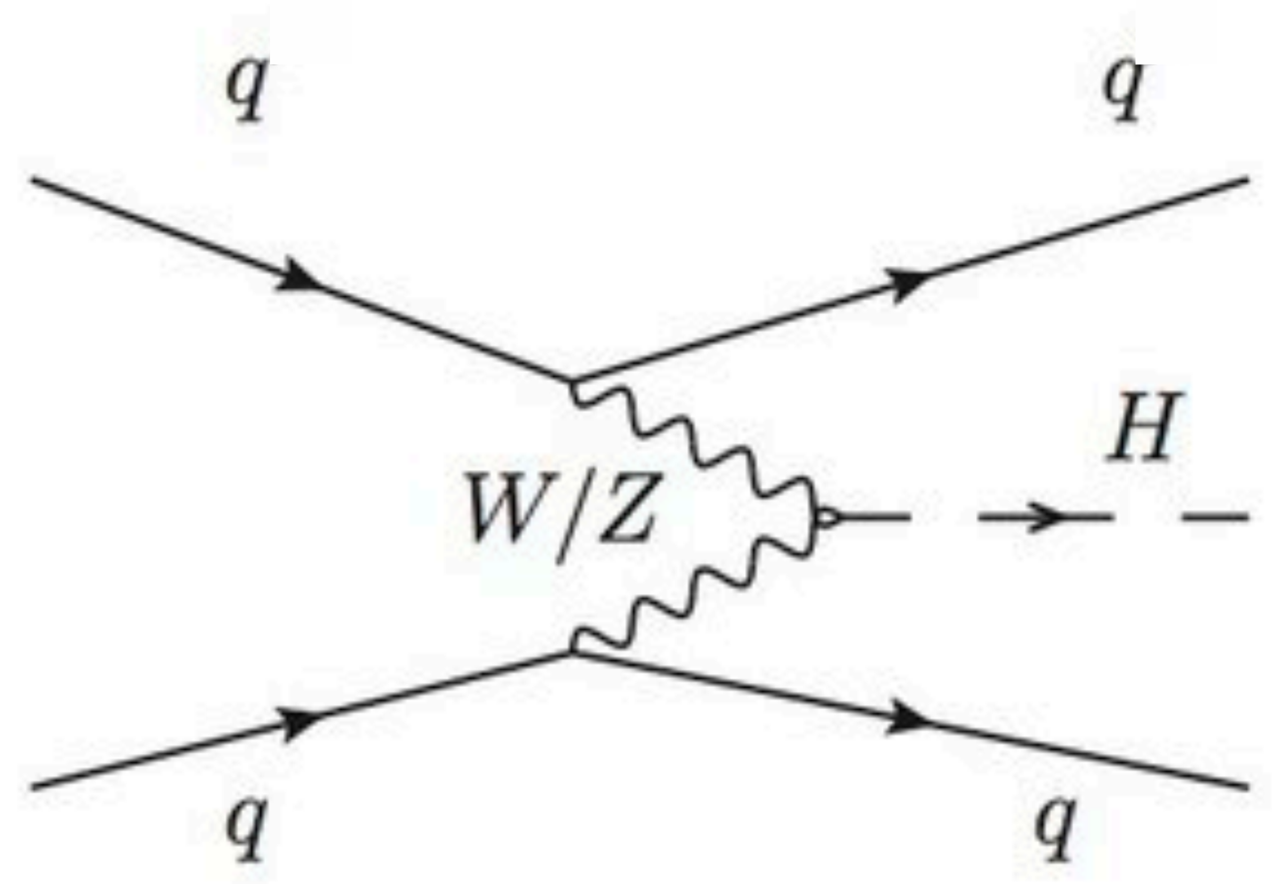


Vector-boson fusion (VBF)



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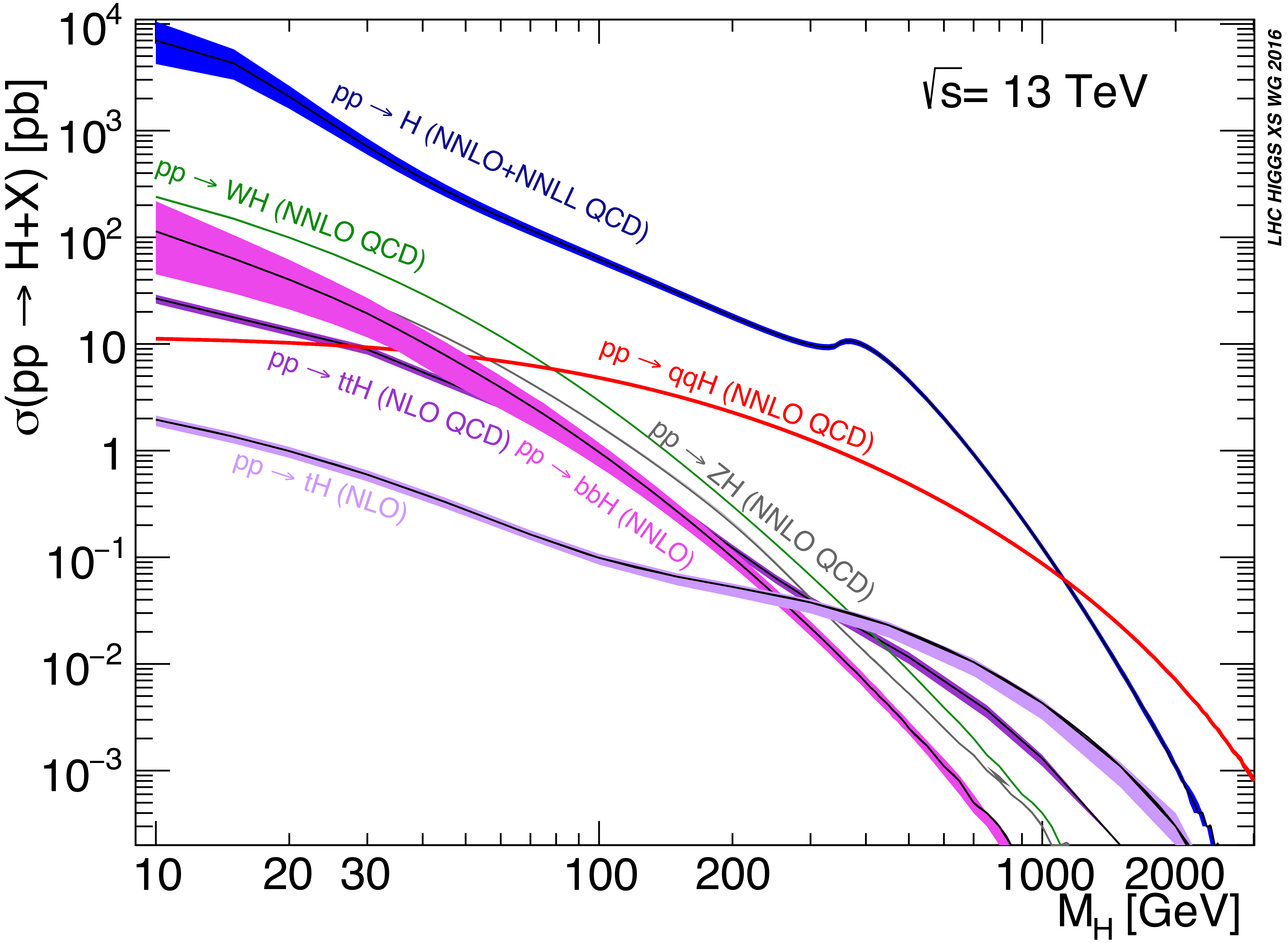
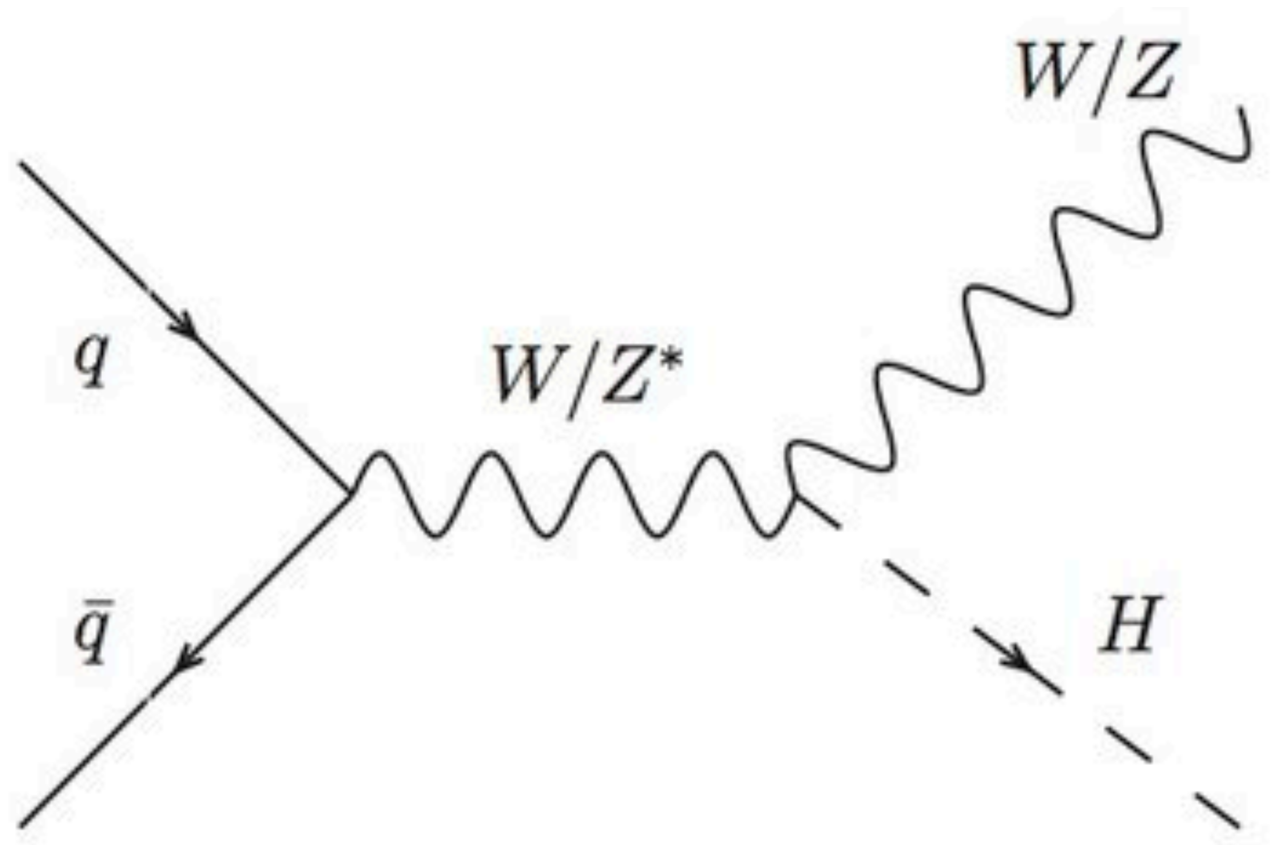


Higgs-strahlung (VH)



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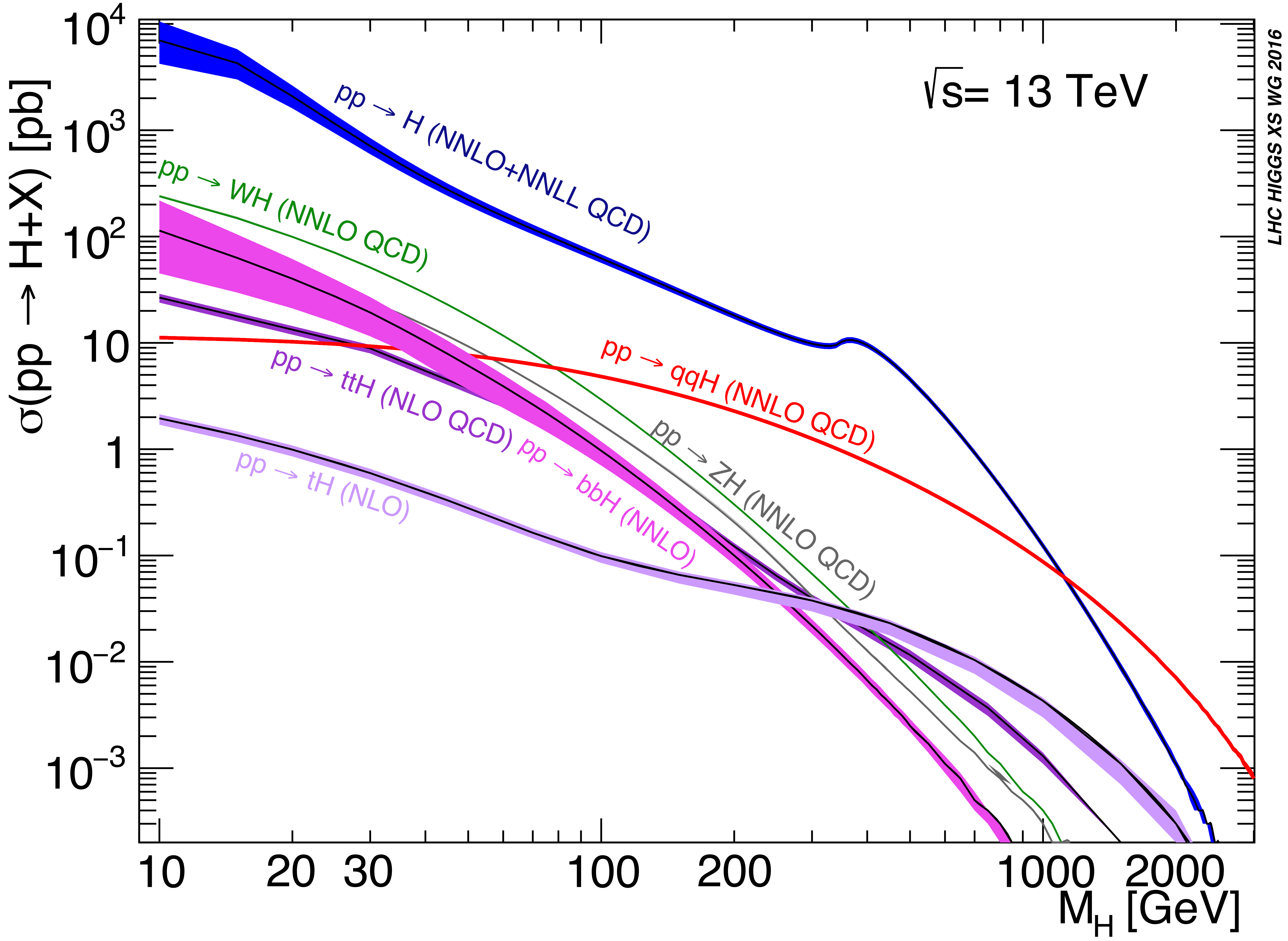
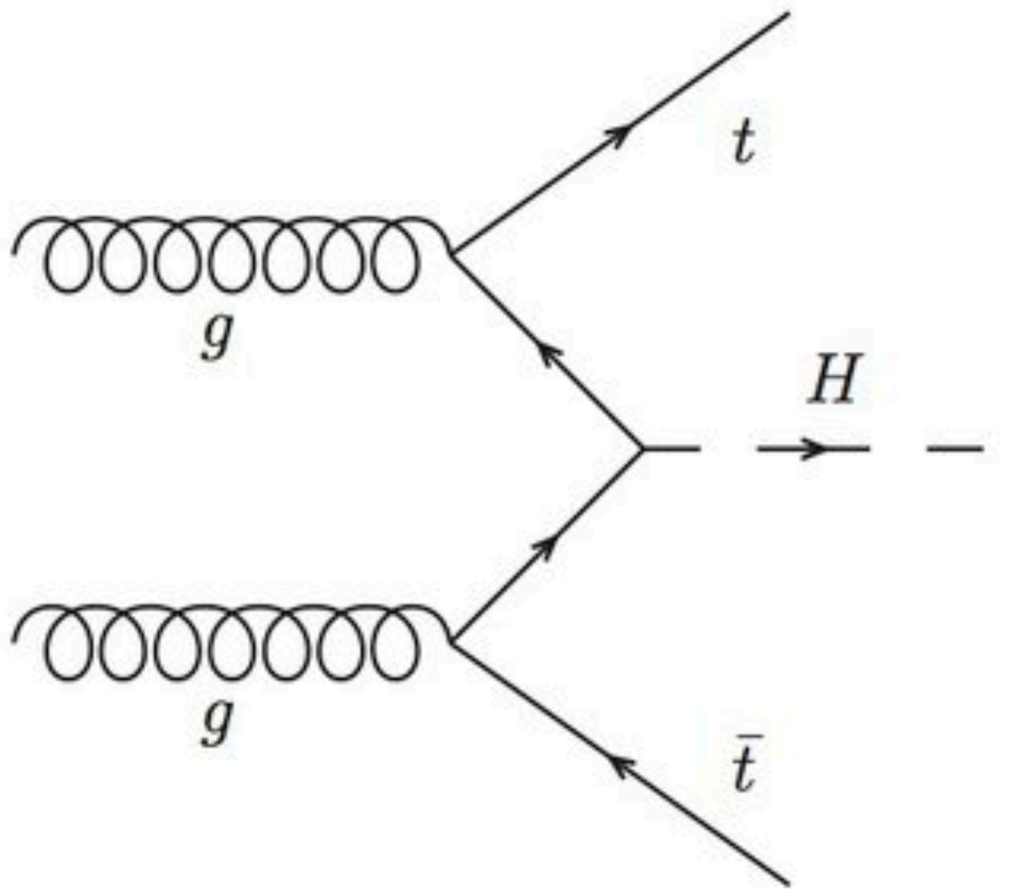


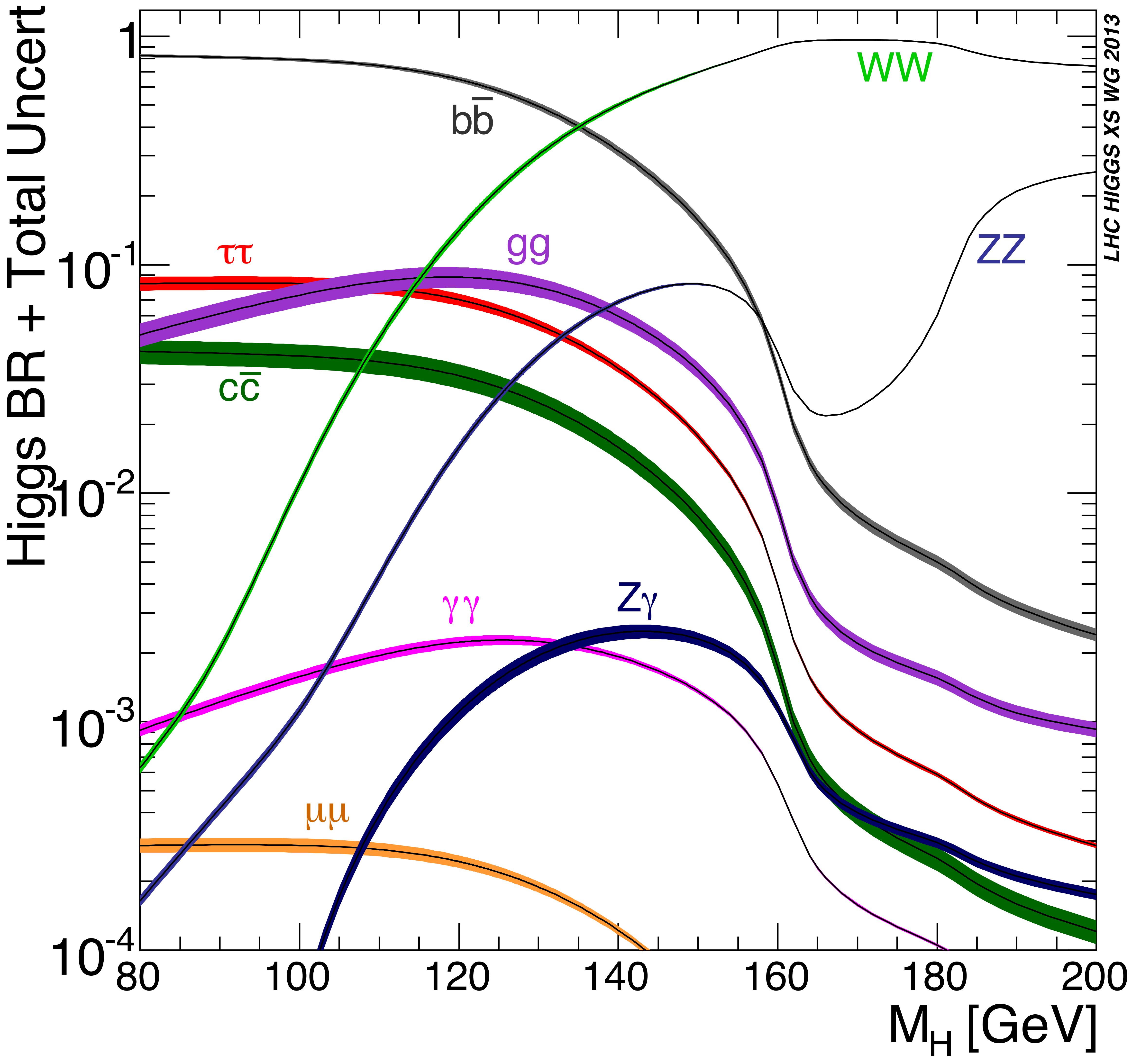
Higgs production in association with $t\bar{t}$ (ttH)



[HiggsXSBR]

DOI:10.13140/RG.2.2.24097.02408

Higgs decay modes: a little bit of everything



HiggsXSBR

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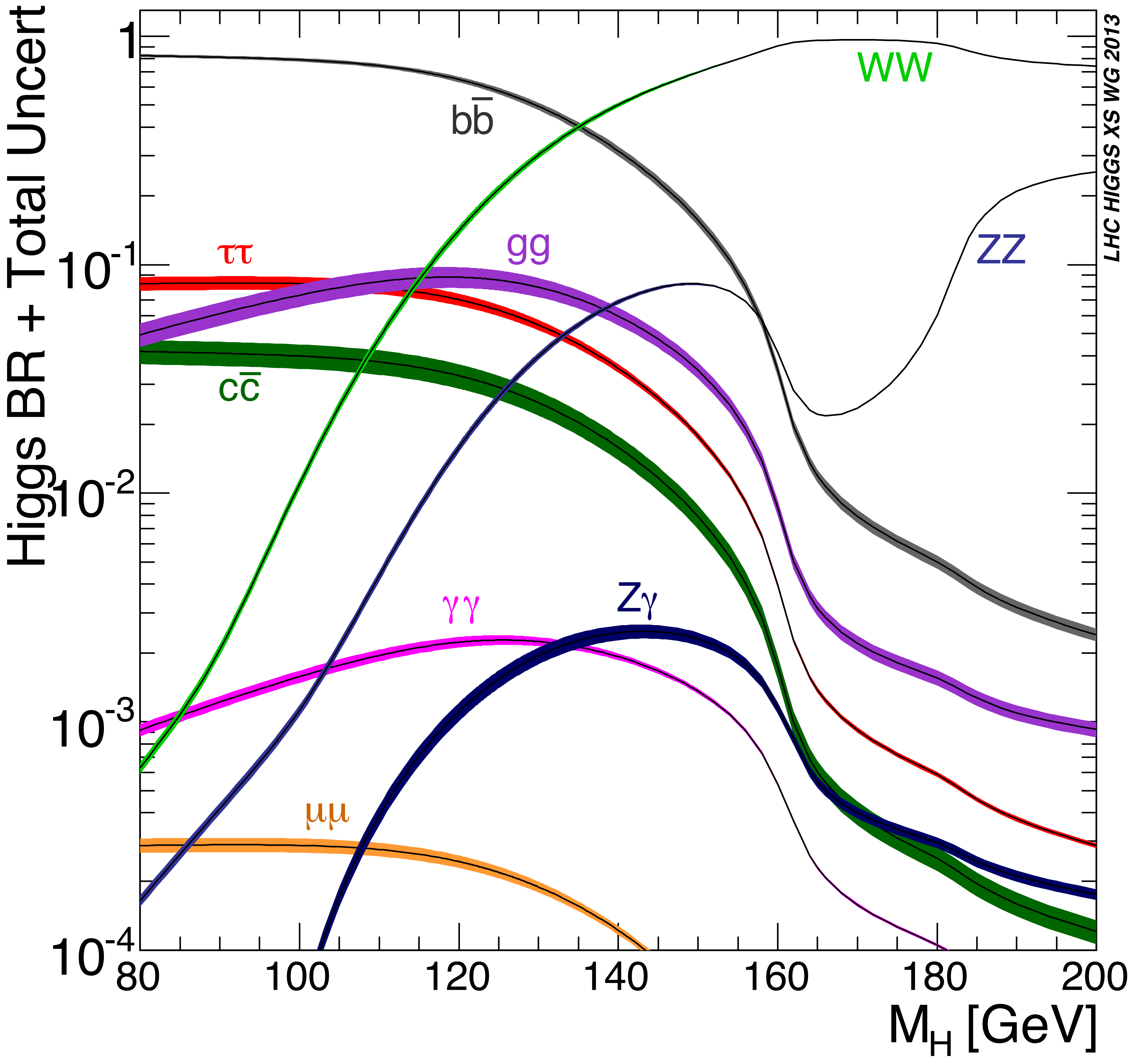
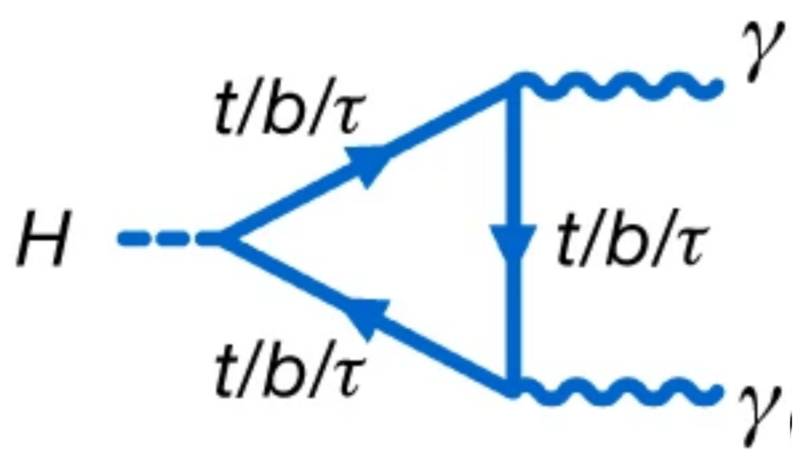


Quiz: can you name the three main Higgs “discovery channels”?

HiggsXSBR

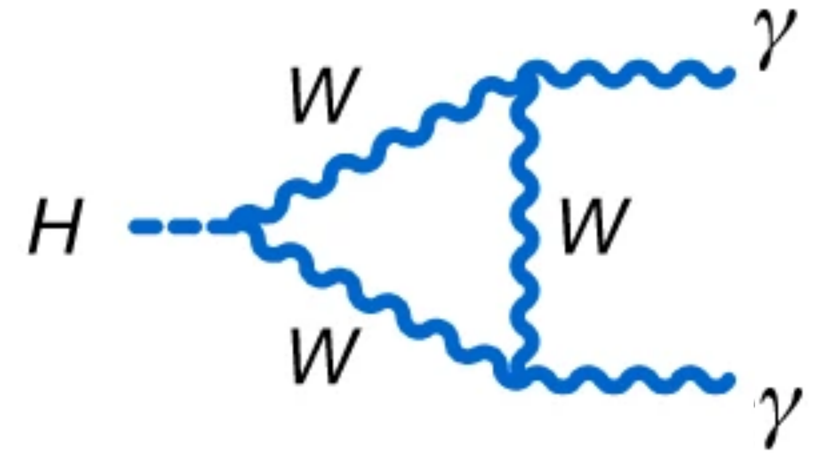
Nature 607 52–59 (2022)

Higgs to $\gamma\gamma$

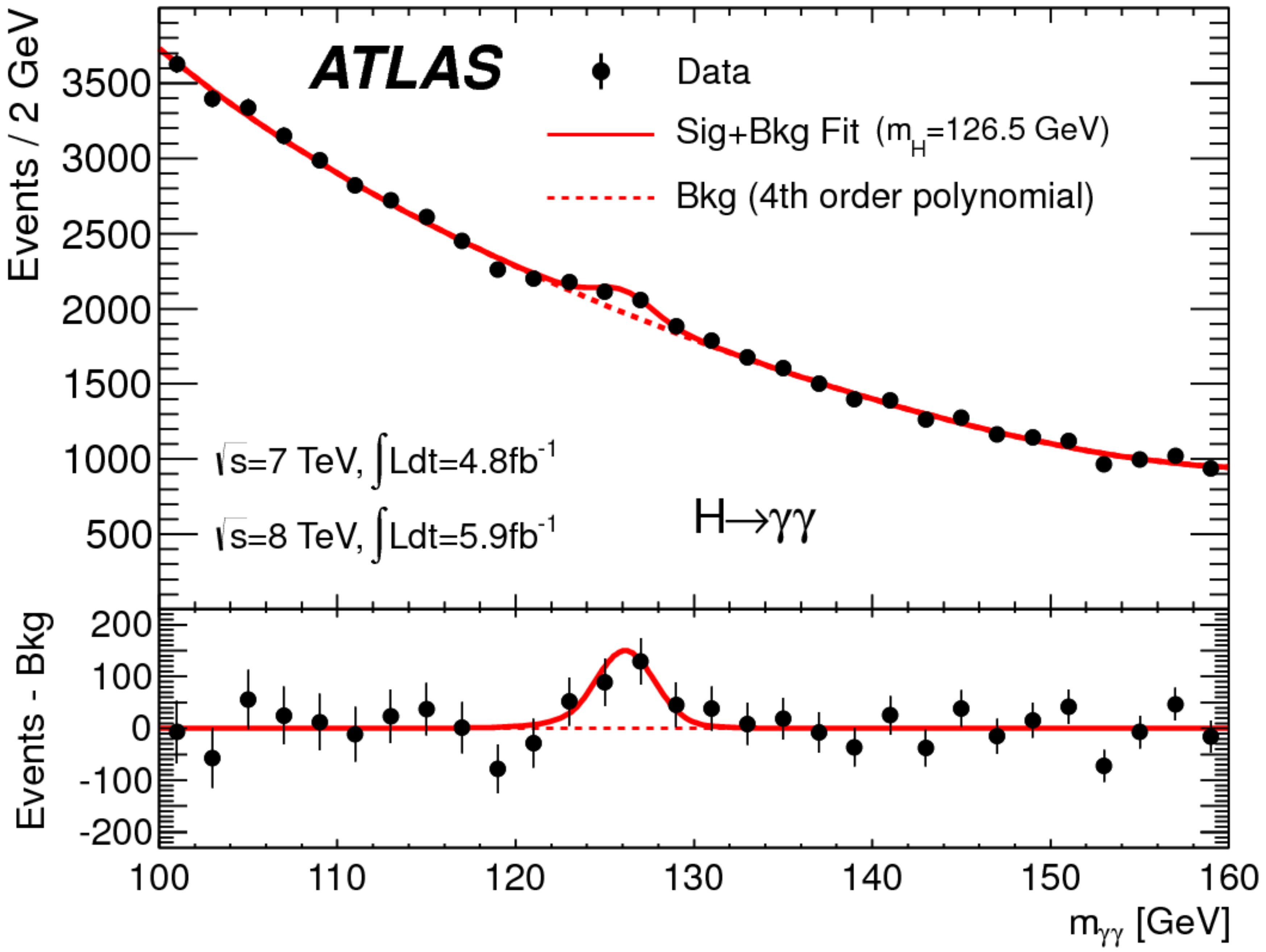


Fairly clean signature: 2 photons & reconstruct m$\gamma\gamma$

- Very good mass resolution → Excellent channel to measure m$\gamma\gamma$
- Large but smoothly falling di-photon background

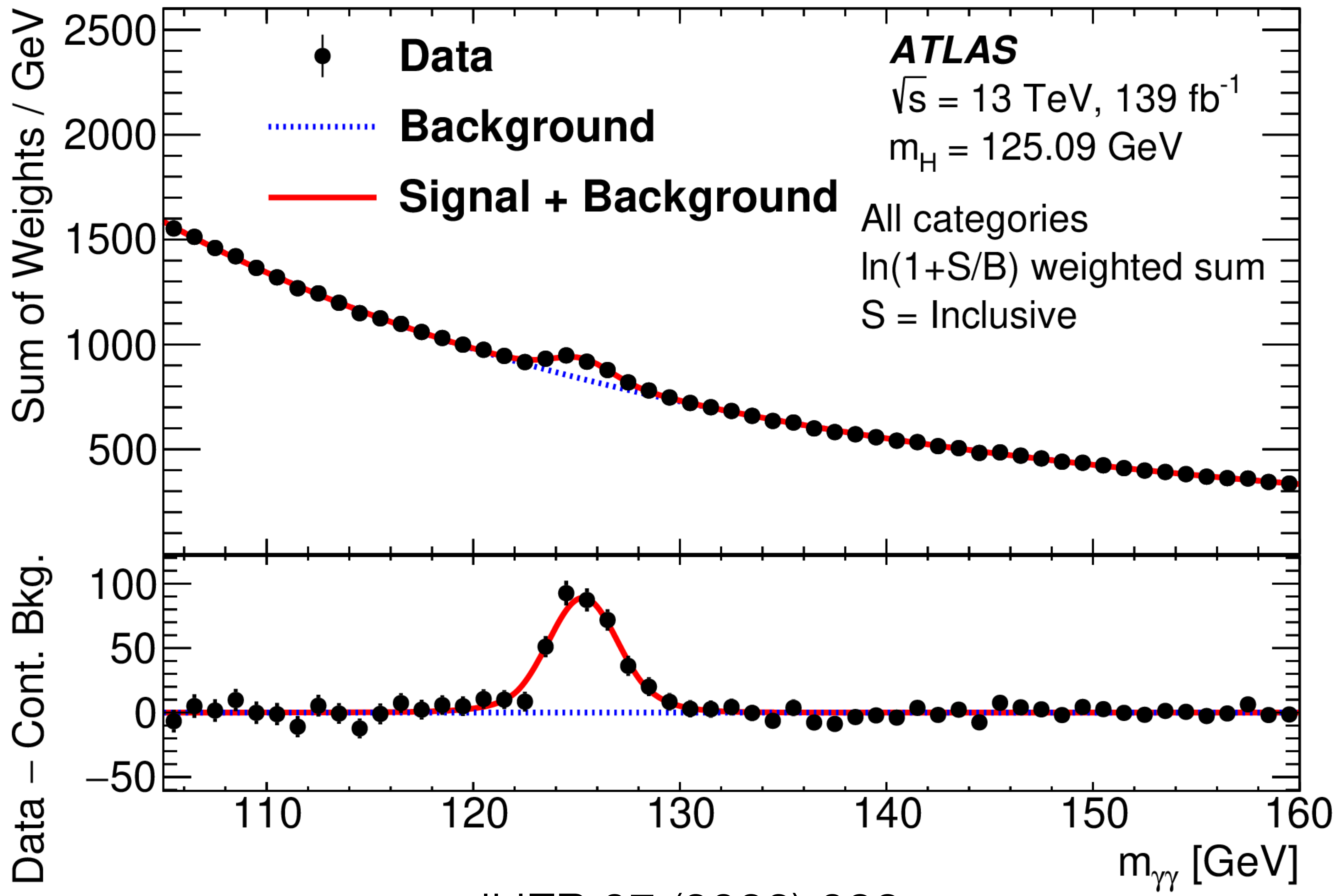


Higgs discovery



Phys. Lett. B 716 (2012) 1-29

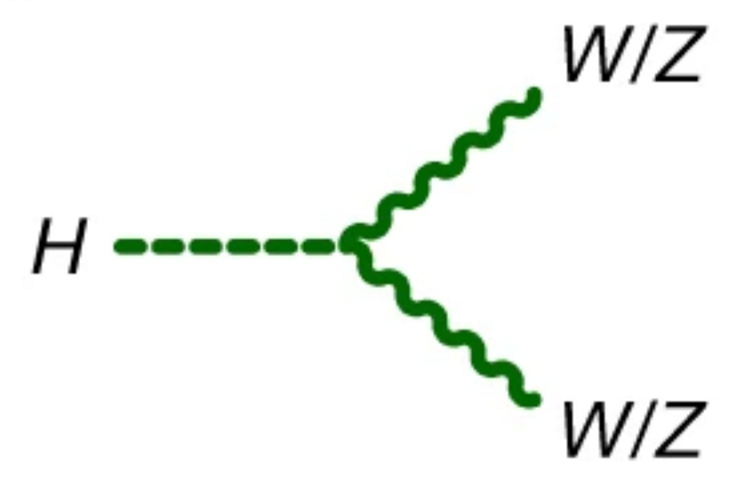
Full Run 2



JHEP 07 (2023) 088

Higgs to ZZ

Nature 607 52–59 (2022)

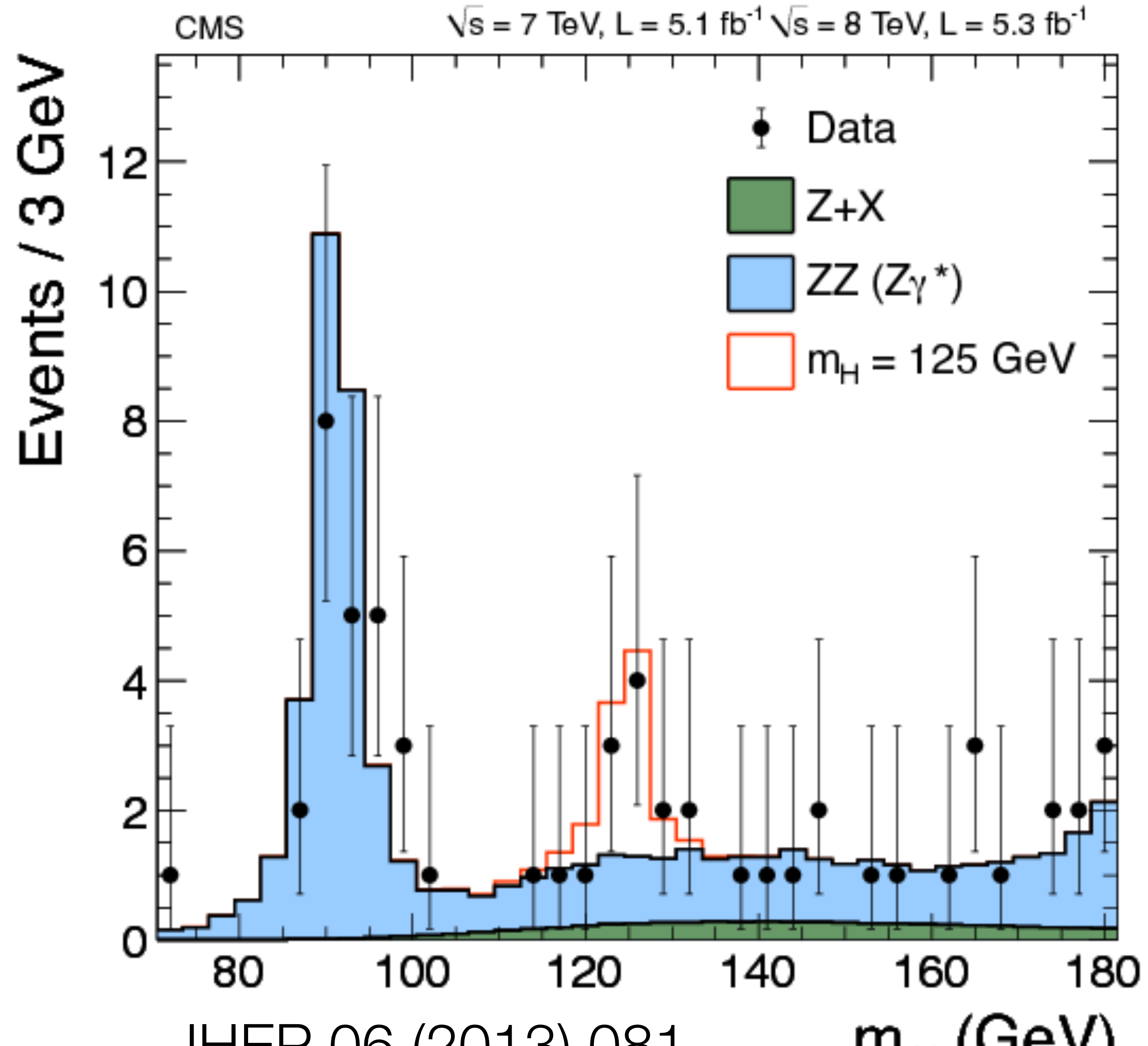


Very clean signature: 4 leptons (electrons & muons, 2 same flavour opposite sign pairs)

Channel with high S/B ratio

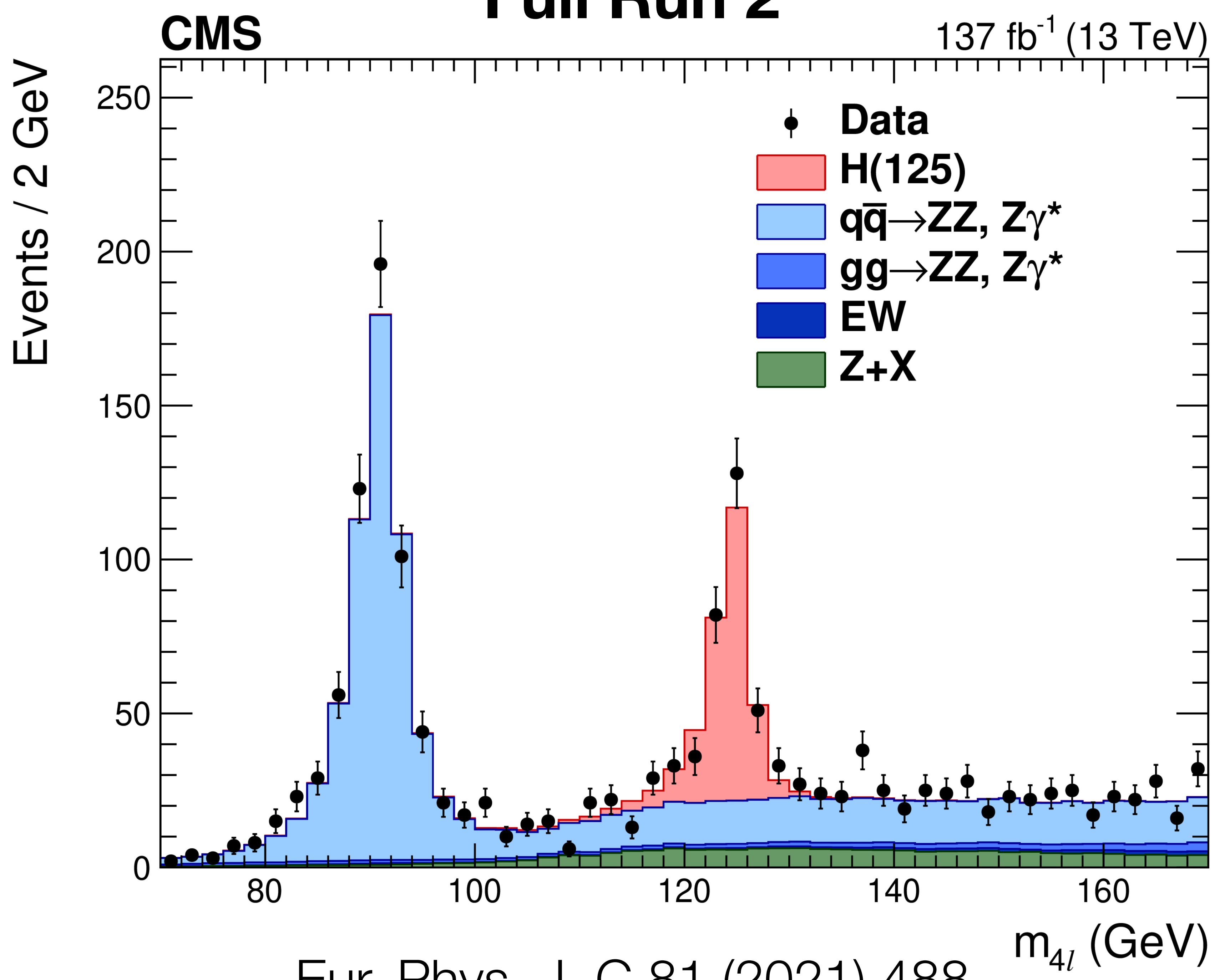
- Low rate due to branching fraction of ZZ and Z → leptons

Higgs discovery



JHEP 06 (2013) 081

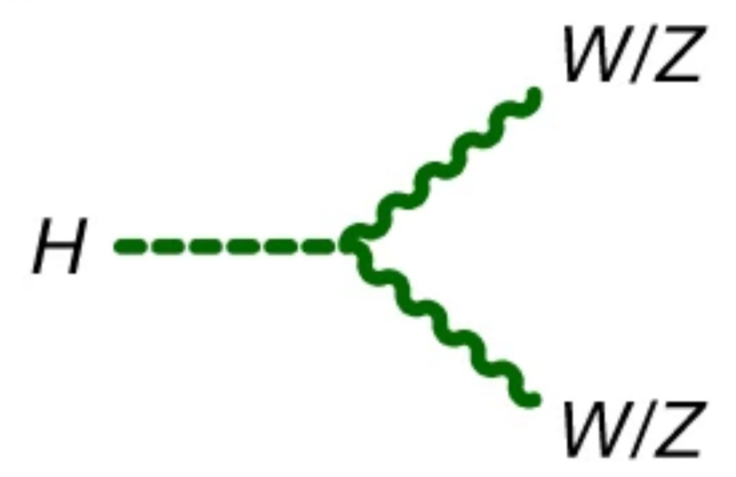
Full Run 2



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

Higgs to ZZ

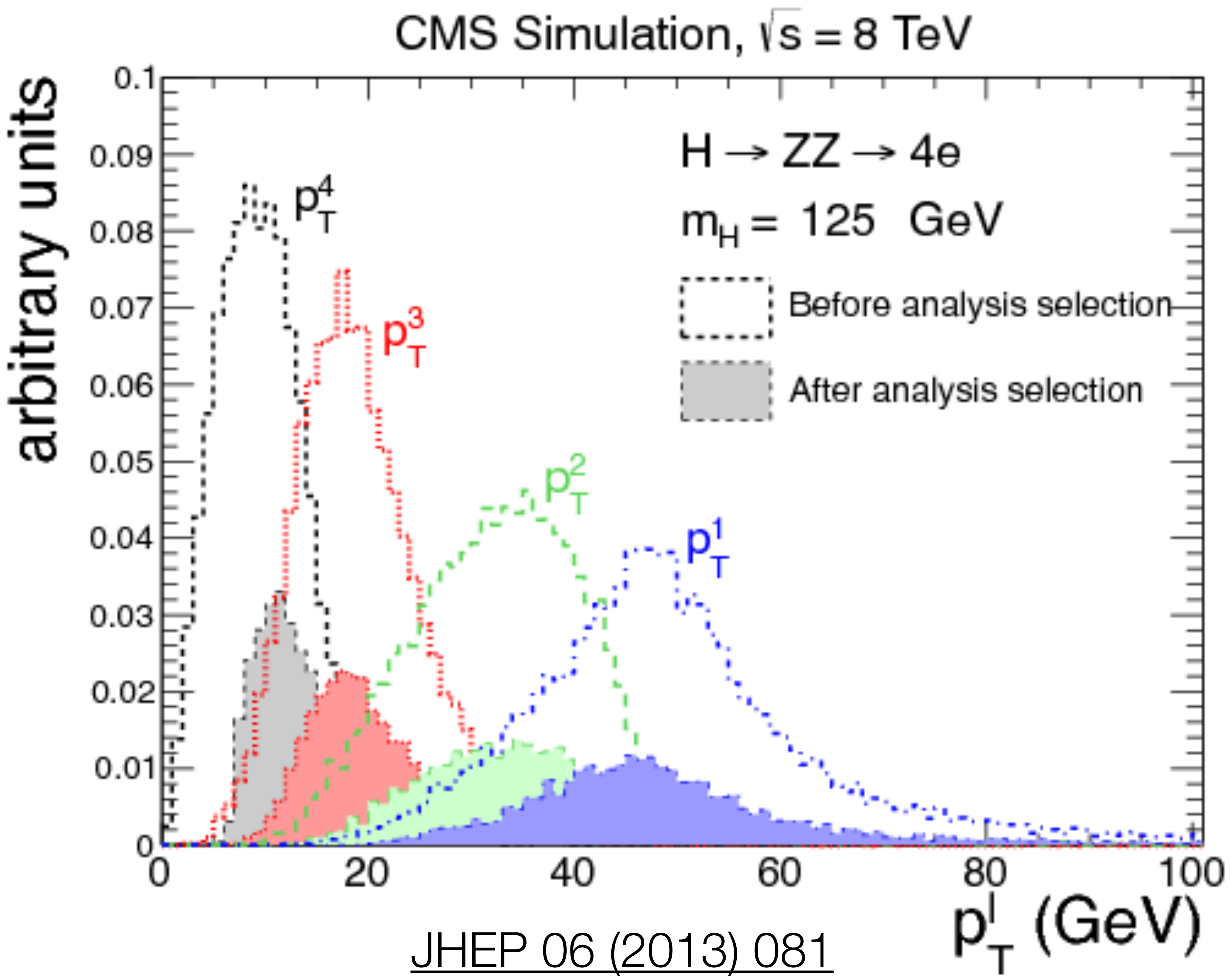
Nature 607 52–59 (2022)



Very clean signature: 4 leptons (electrons & muons, 2 same flavour opposite sign pairs)

Channel with high S/B ratio

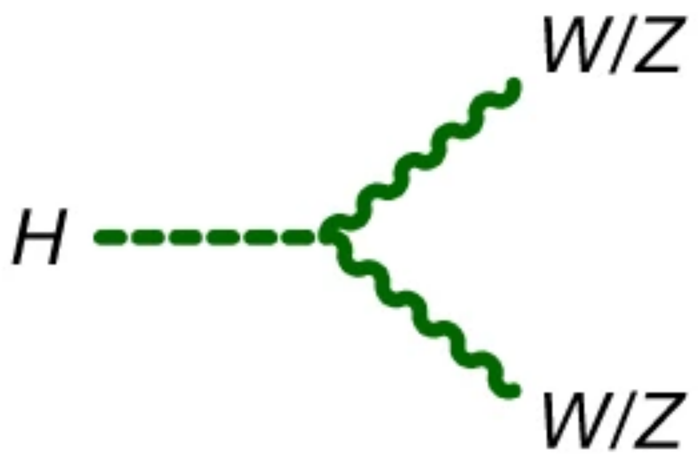
- Low rate due to branching fraction of ZZ and Z → leptons
- Typically one Z is on-mass shell & the trailing lepton is at low p_T



JHEP 06 (2013) 081

Higgs to WW

Nature 607 52–59 (2022)

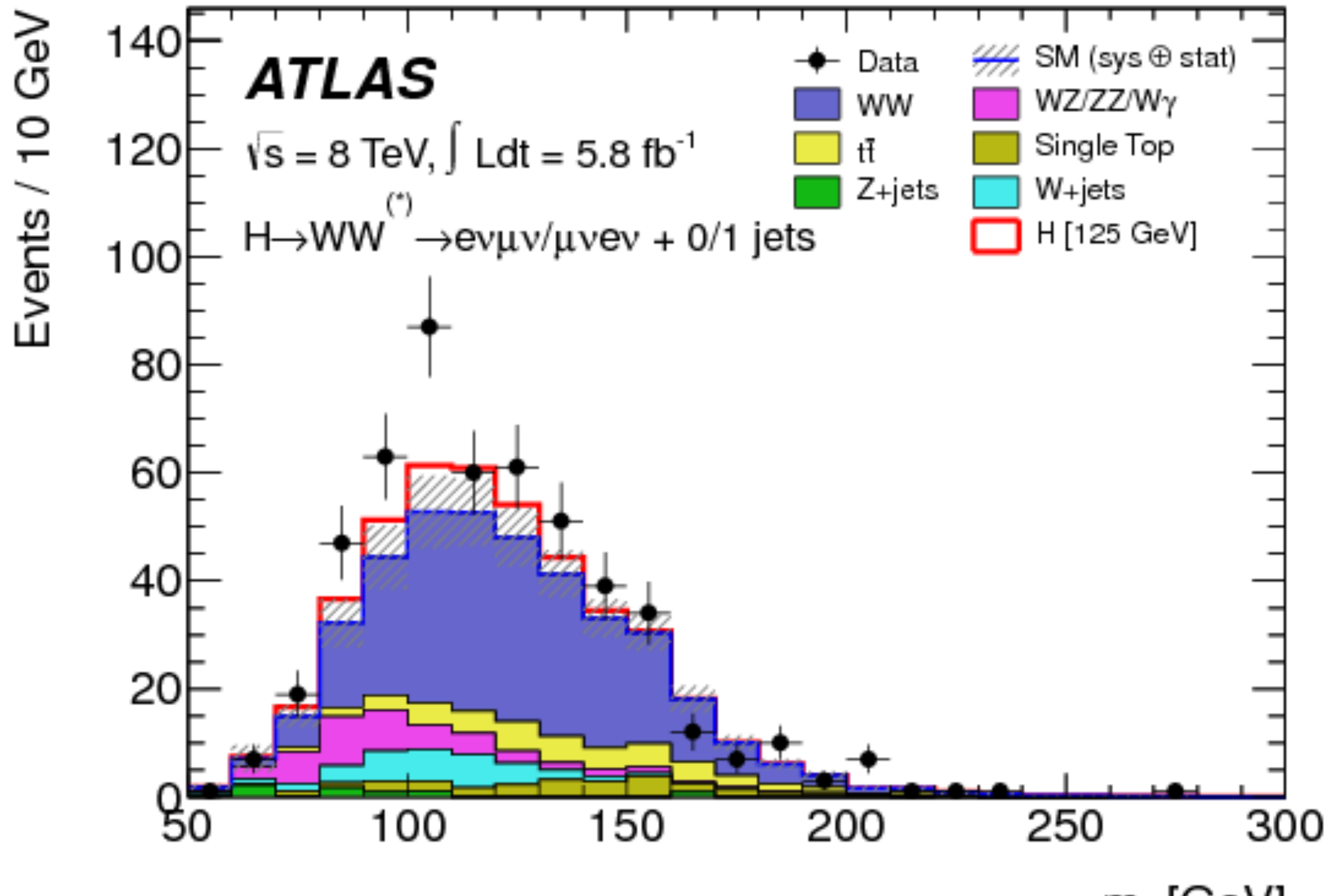


Final states including two leptons & two neutrinos

- Higgs mass diluted by presence of neutrinos → m_T variable is used

Large event rate but also large bkgs from SM WW and top pair production

Higgs discovery



Phys. Lett. B 716 (2012) 1-29

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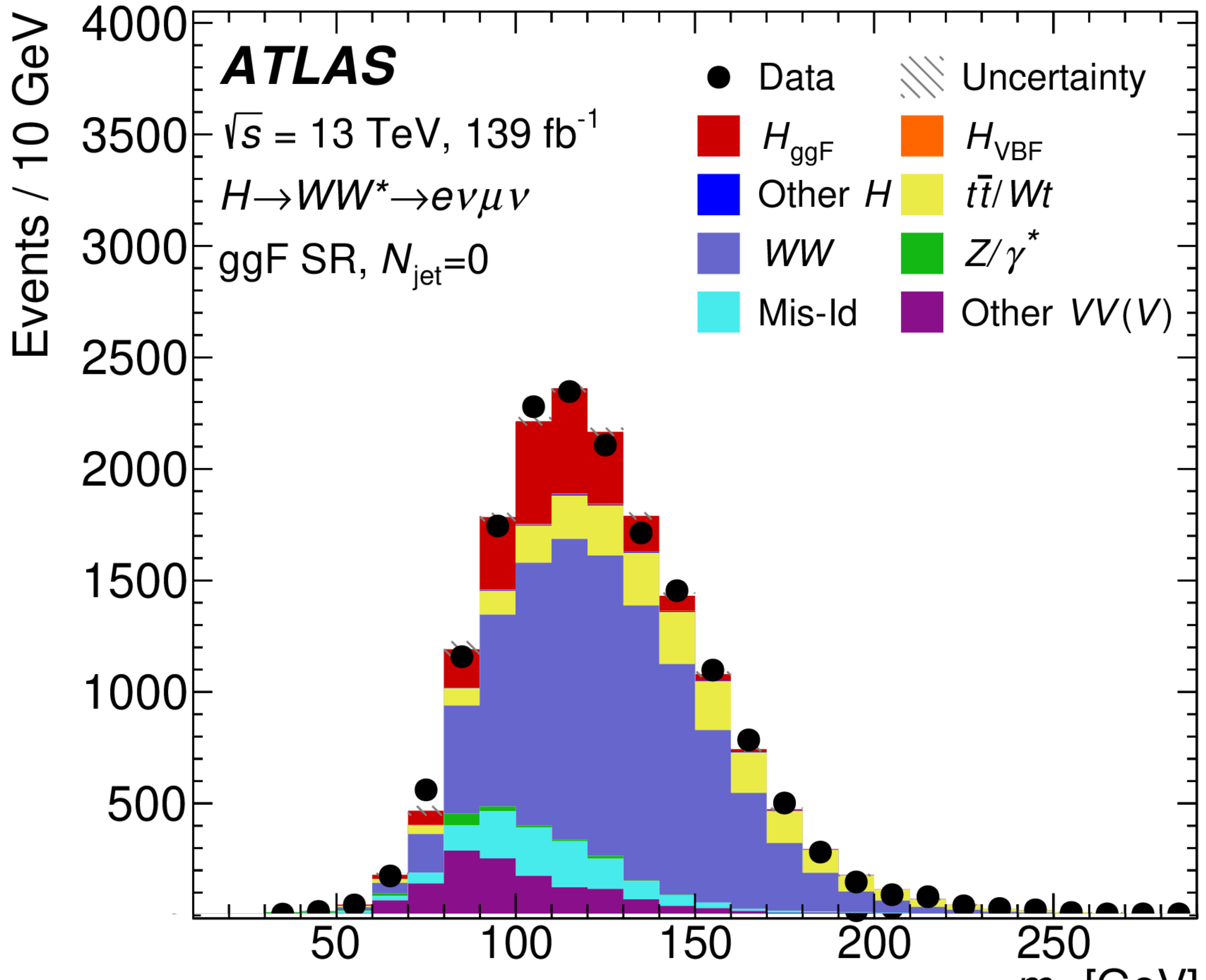
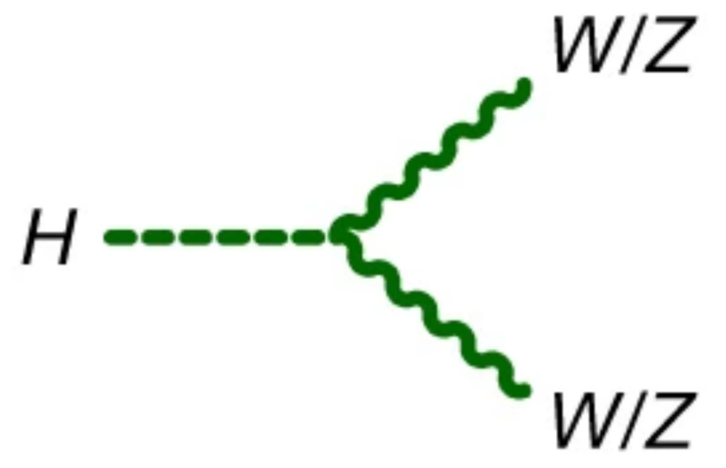


Phys. Rev. D 108 (2023) 032005

Nature 607 52–59 (2022)

Aside: control regions

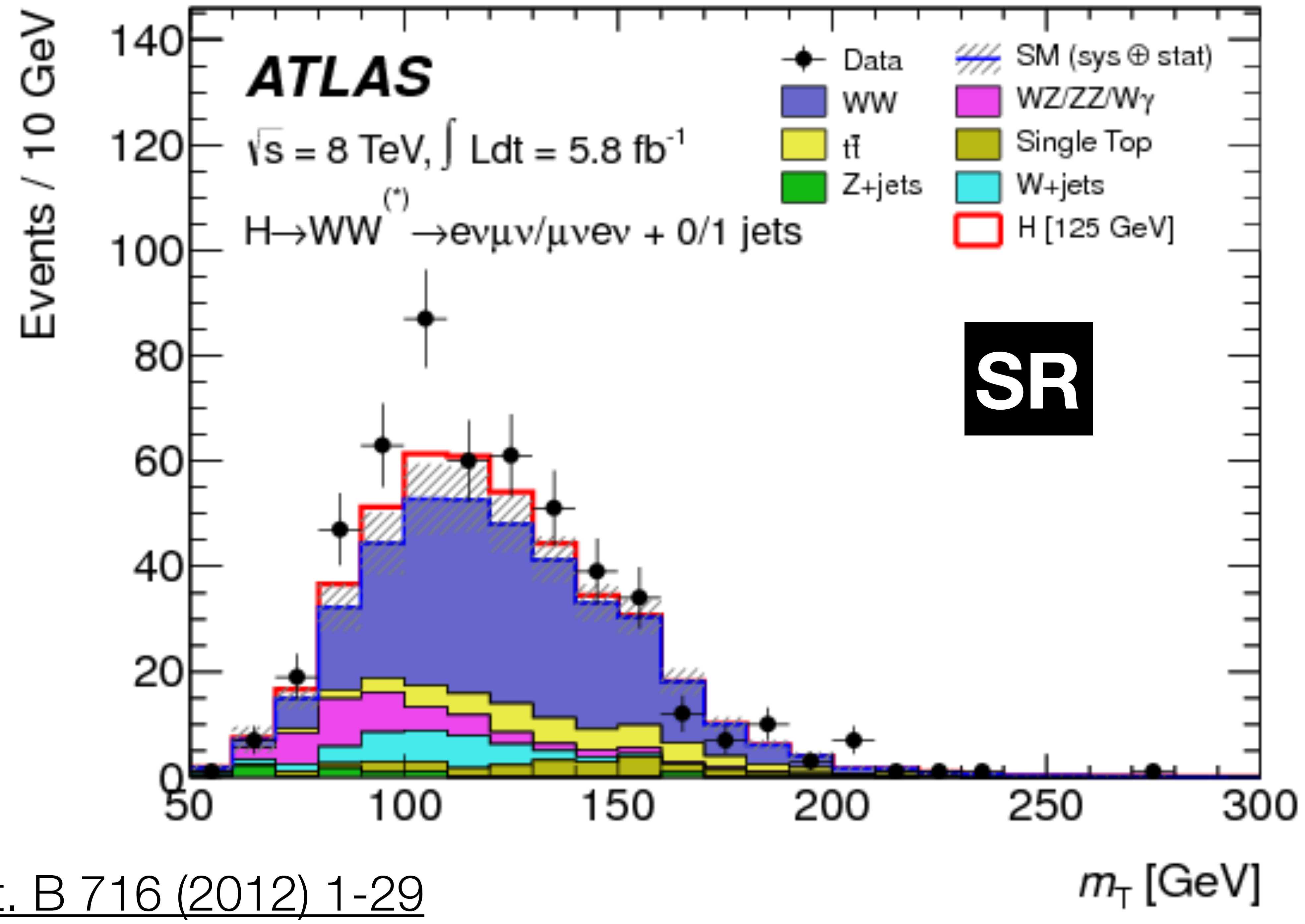


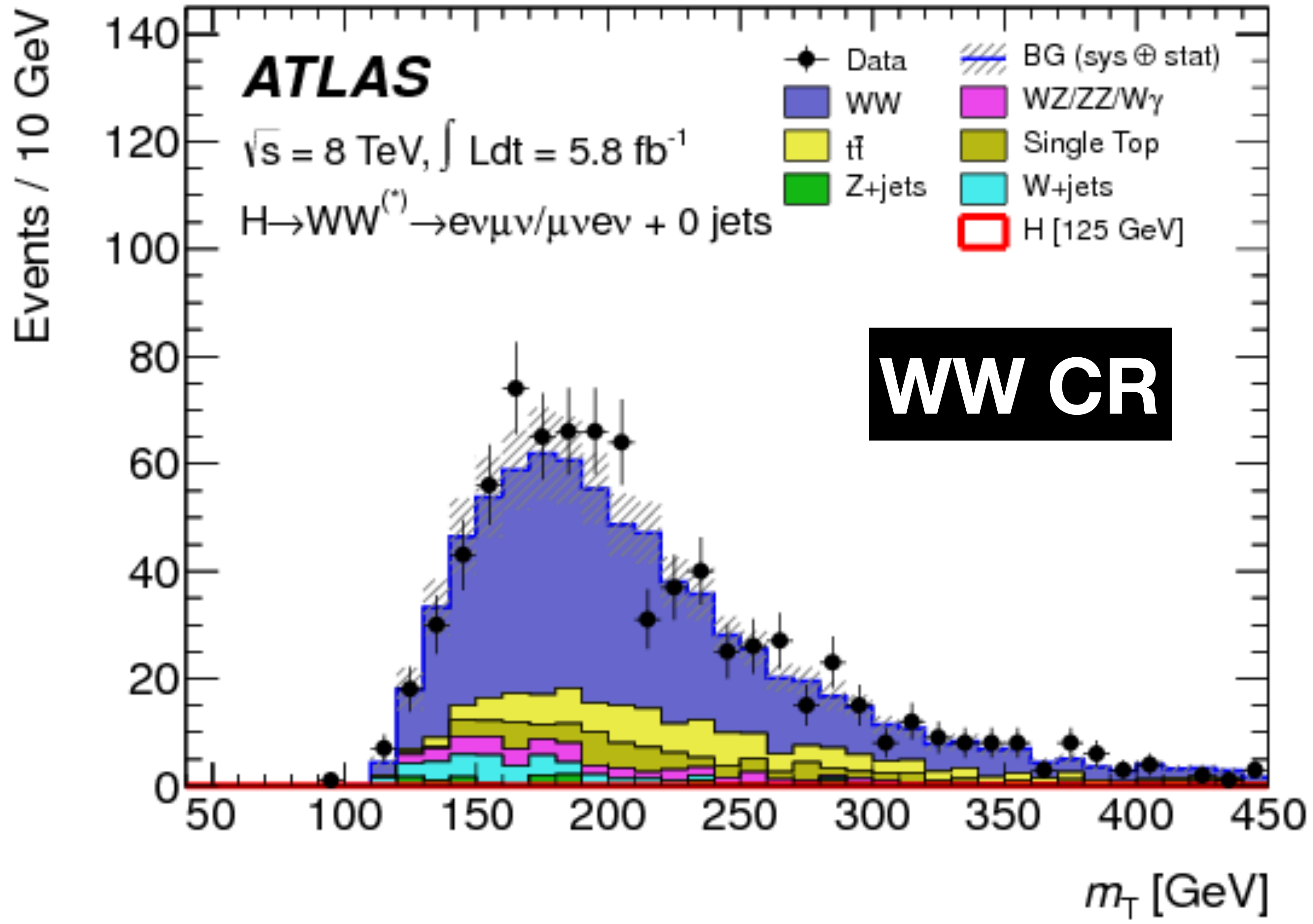
Large event rate but also large bkgs from SM WW and top production

→ Control regions in data needed to estimate backgrounds

Control Region (CR):

- Little or no signal expected
- Statistically independent to the Signal Region (SR)



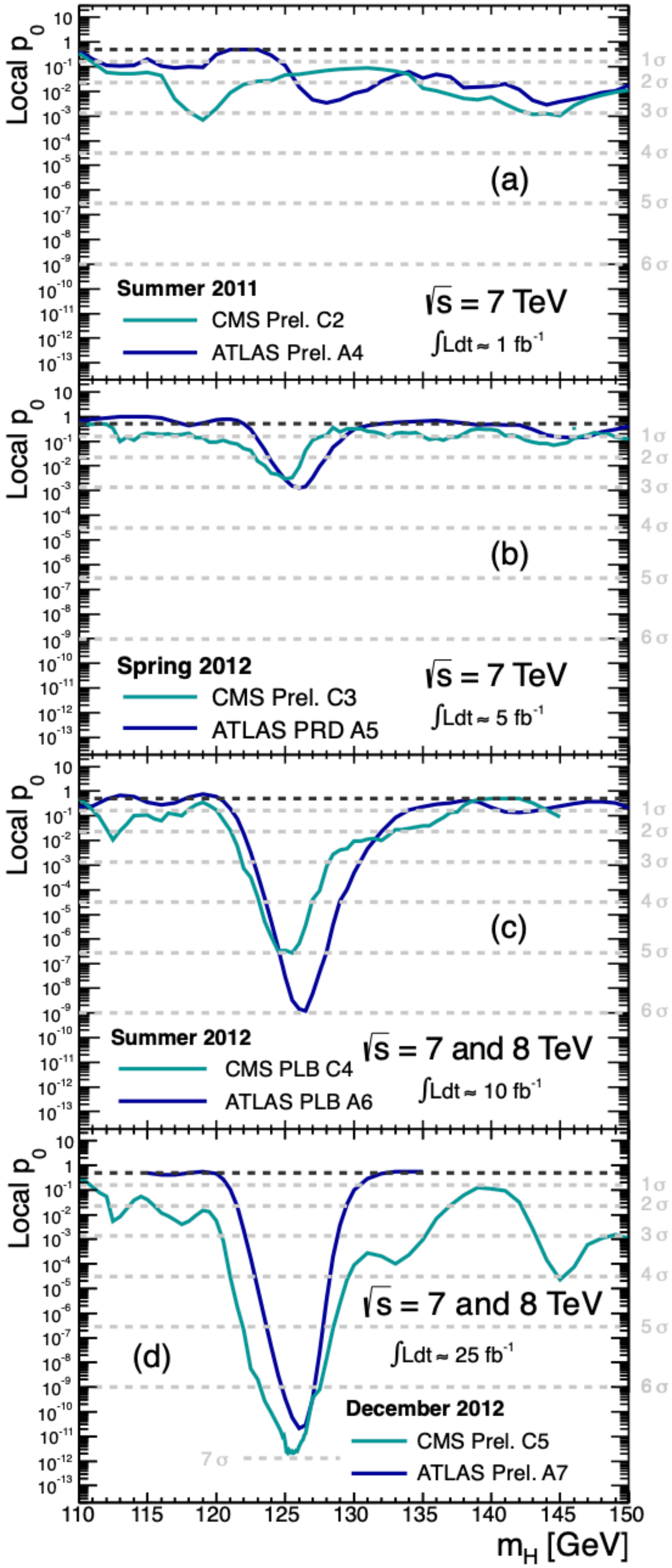


Phys. Lett. B 716 (2012) 1-29

Discovery!

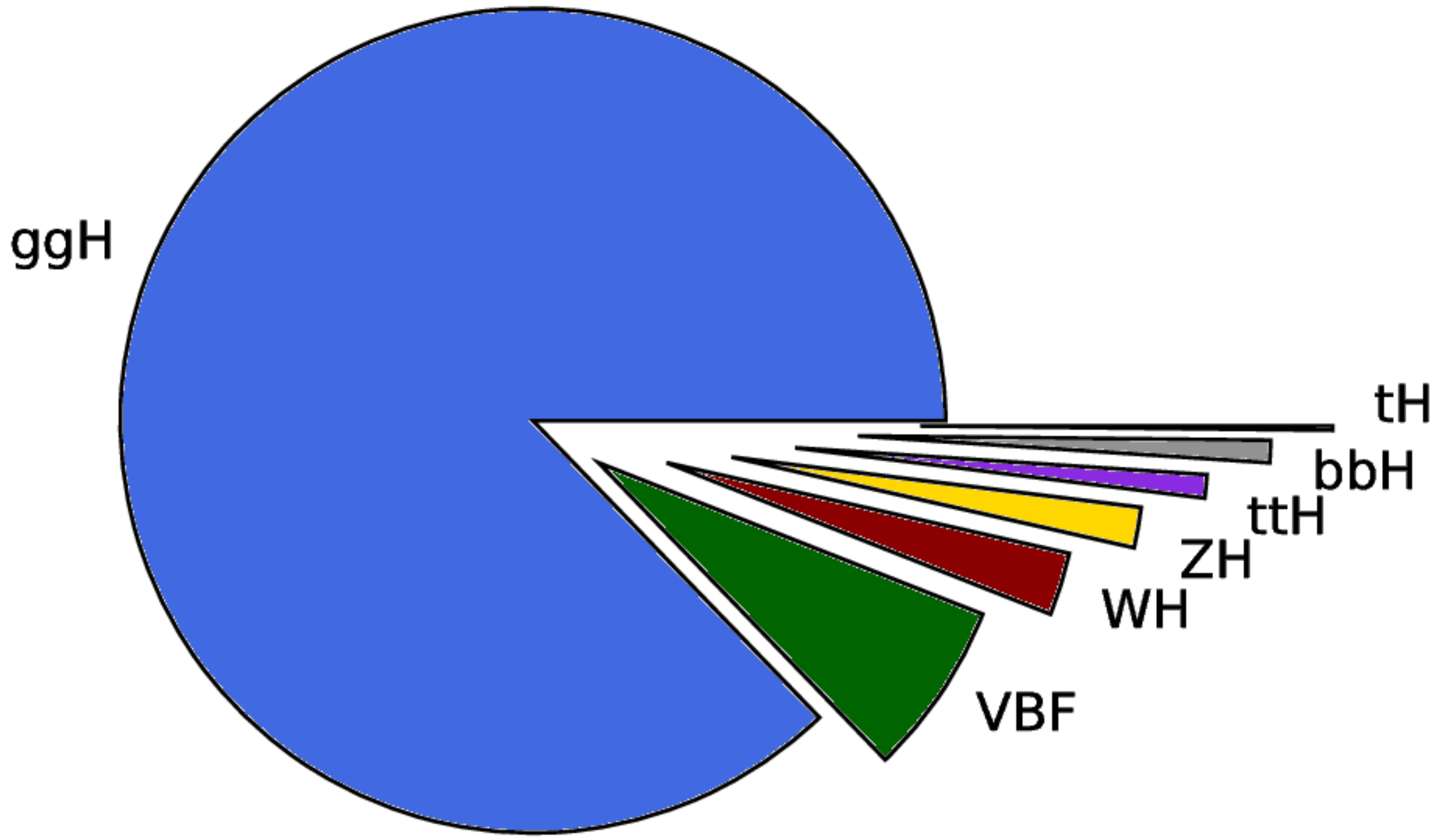
- **Strongly motivated**
- **Significance ↑ with luminosity**
- **Two experiments: ATLAS & CMS**
- **Several channels**

p-value reflects consistency of observed data with the absence of signal



PDG 2013

Higgs production modes at the LHC



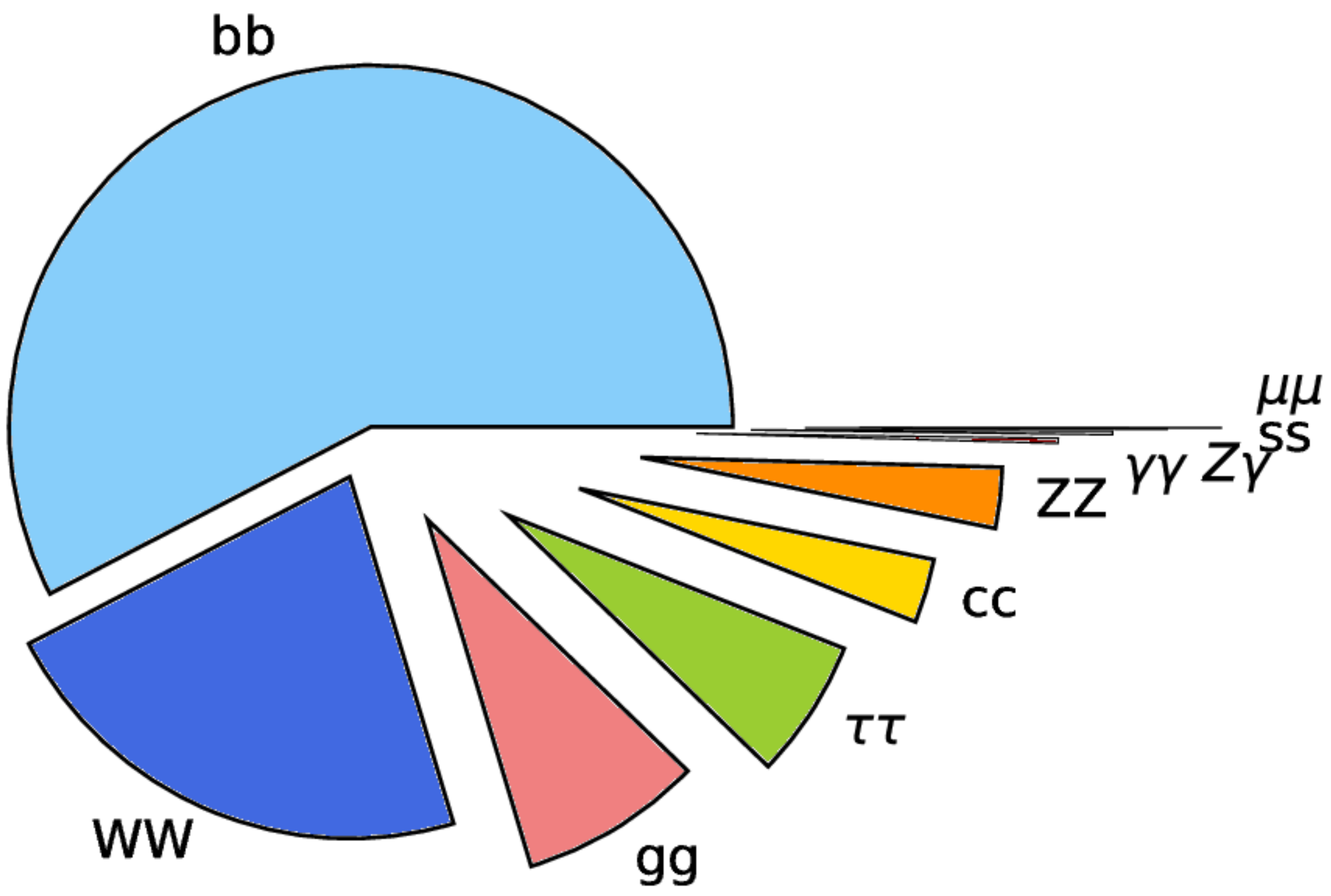
Production mode	Cross section (pb)
ggH	48.31 $\pm$ 2.44
VBF	3.771 $\pm$ 0.807
WH	1.359 $\pm$ 0.028
ZH	0.877 $\pm$ 0.036
ttH	0.503 $\pm$ 0.035
bbH	0.482 $\pm$ 0.097
tH	0.092 $\pm$ 0.008

At m_H = 125 GeV

- gg→H: main production mode
- Followed by VBF then WH

Nature 607 52–59 (2022)

Higgs decay modes: a little bit of everything



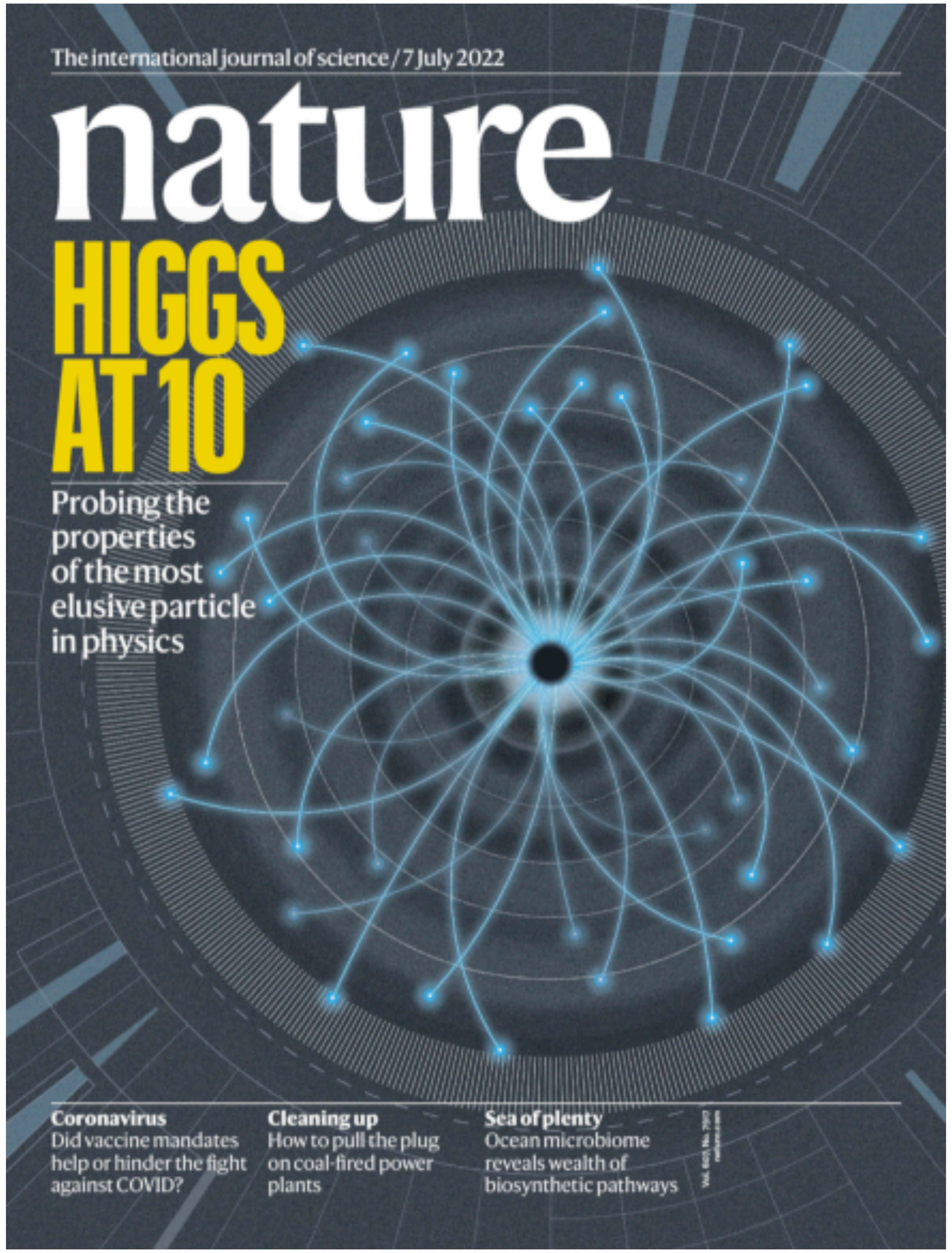
Decay channel	Branching fraction (%)
bb	57.63 ± 0.70
WW	22.00 ± 0.33
gg	8.15 ± 0.42
$\tau\tau$	6.21 ± 0.09
cc	2.86 ± 0.09
ZZ	2.71 ± 0.04
$\gamma\gamma$	0.227 ± 0.005
$Z\gamma$	0.157 ± 0.009
ss	0.025 ± 0.001
$\mu\mu$	0.0216 ± 0.0004

At m_H = 125 GeV

- H→bb: main decay mode but large bkgs
- H → $\gamma\gamma$, H→ZZ and H→WW are the "discovery channels"

Nature 607 52–59 (2022)

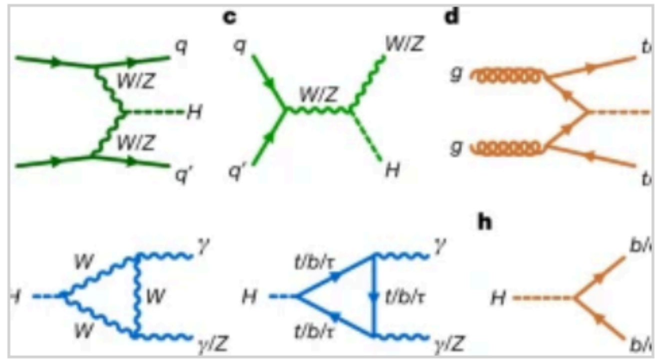
The Higgs turned 10!



A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery

Ten years after the discovery of the Higgs boson, the ATLAS experiment at CERN probes its kinematic properties with a significantly larger dataset from 2015–2018 and provides further insights on its interaction with other known particles.

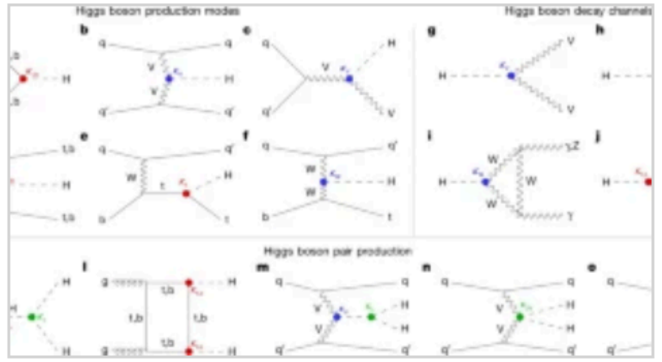
The ATLAS Collaboration



A portrait of the Higgs boson by the CMS experiment ten years after the discovery

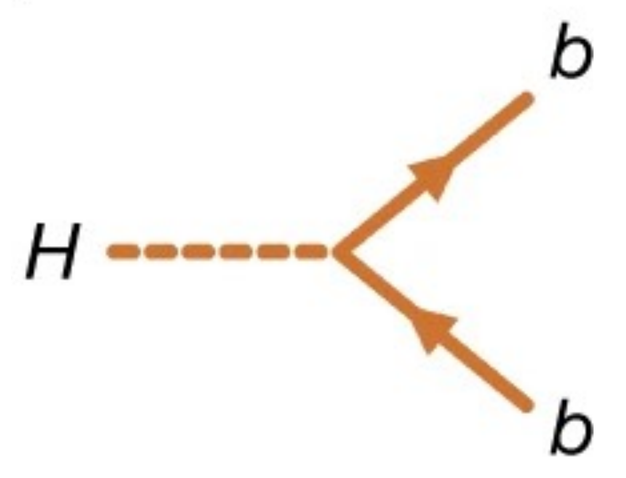
The most up-to-date combination of results on the properties of the Higgs boson is reported, which indicate that its properties are consistent with the standard model predictions, within the precision achieved to date.

The CMS Collaboration



Nature 607 52–59 (2022)

Higgs to $b\bar{b}$



Highest branching ratio of Higgs decays to two b-quarks

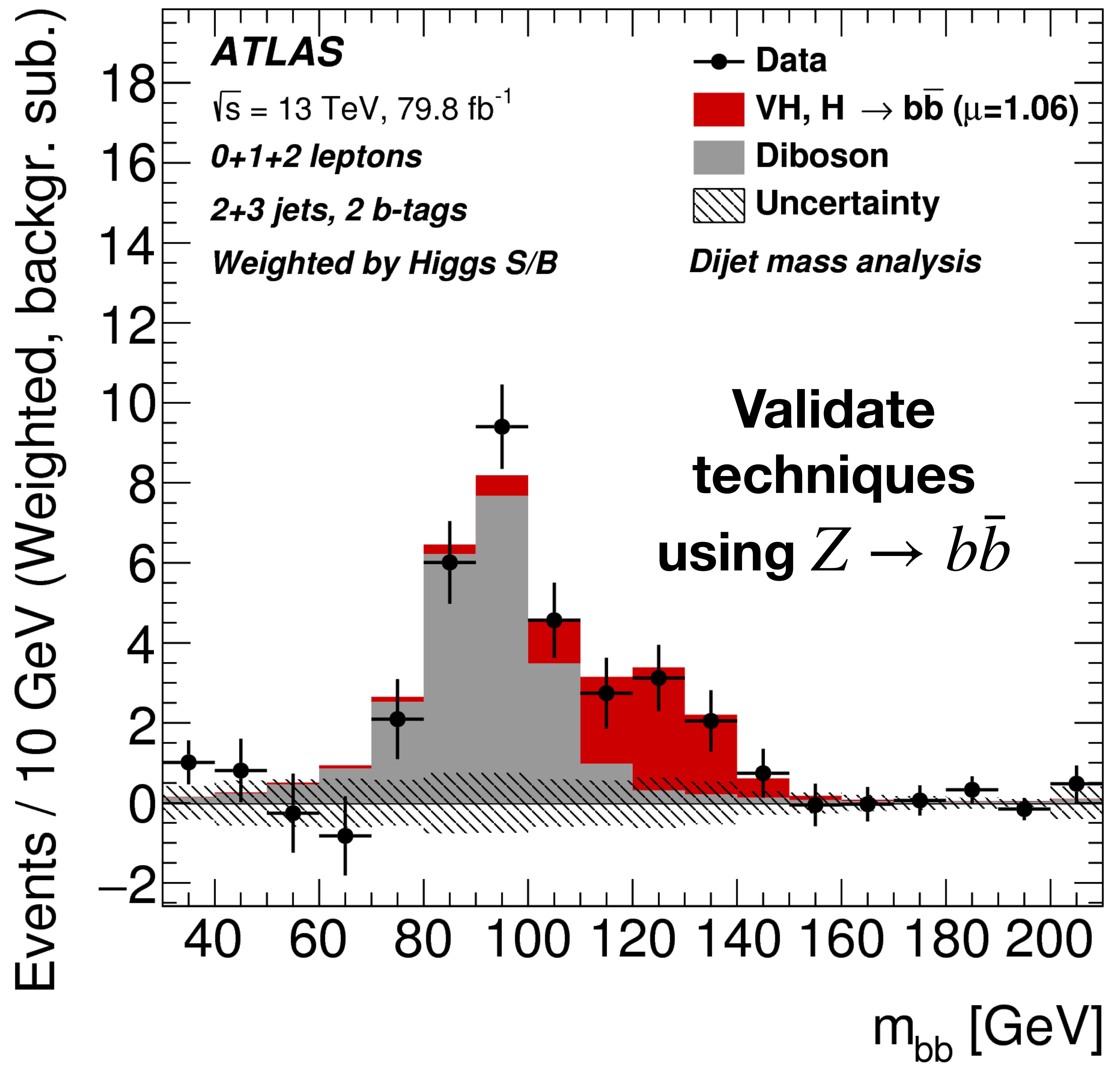
- Large SM backgrounds
- Statistical combination of various “channels” or “regions”
- Often machine learning techniques used

3 main channels targeting WH & ZH:

0 leptons (Z $\rightarrow \nu\nu$),

1 lepton (W $\rightarrow \mu\nu$, $e\nu$),

2 leptons (Z $\rightarrow \mu\mu$, ee)



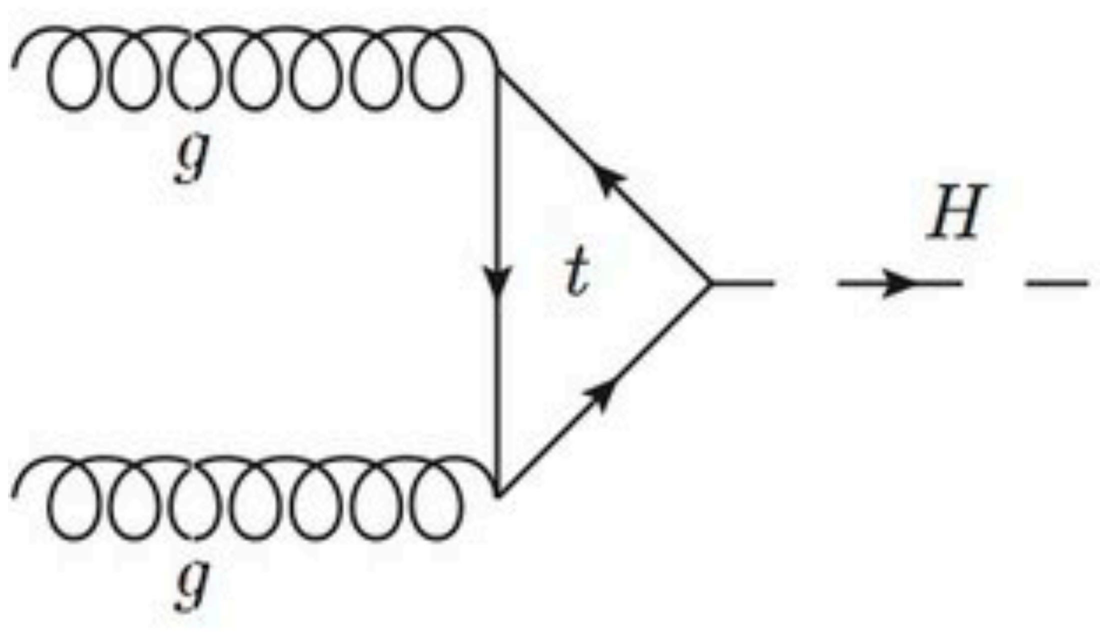
Validate techniques using $Z \rightarrow b\bar{b}$

See lectures by Stephen Jiggins for introduction to Machine Learning

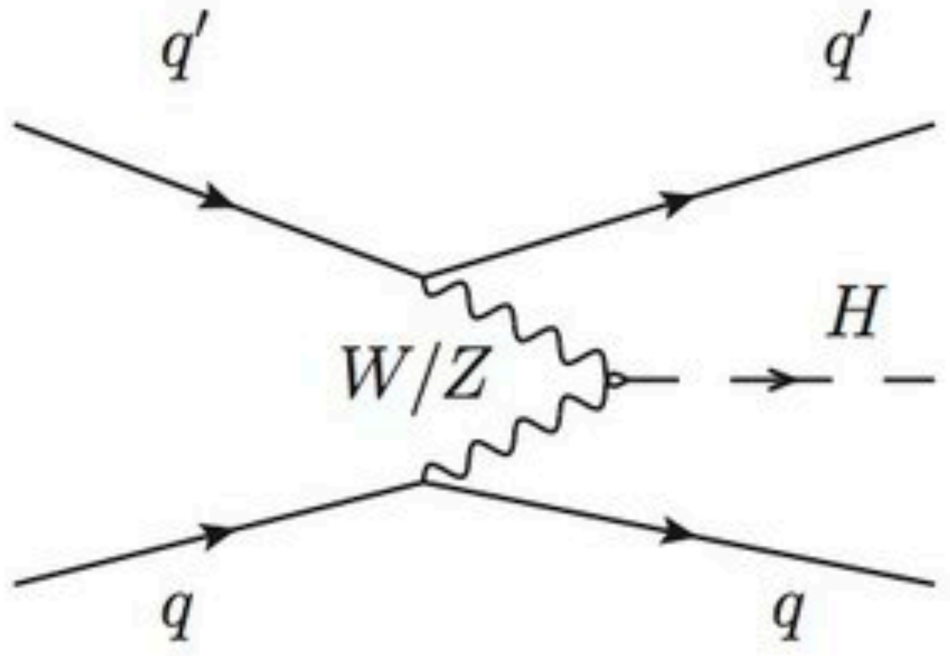
Phys. Lett. B 786 (2018) 59

Higgs production modes at the LHC

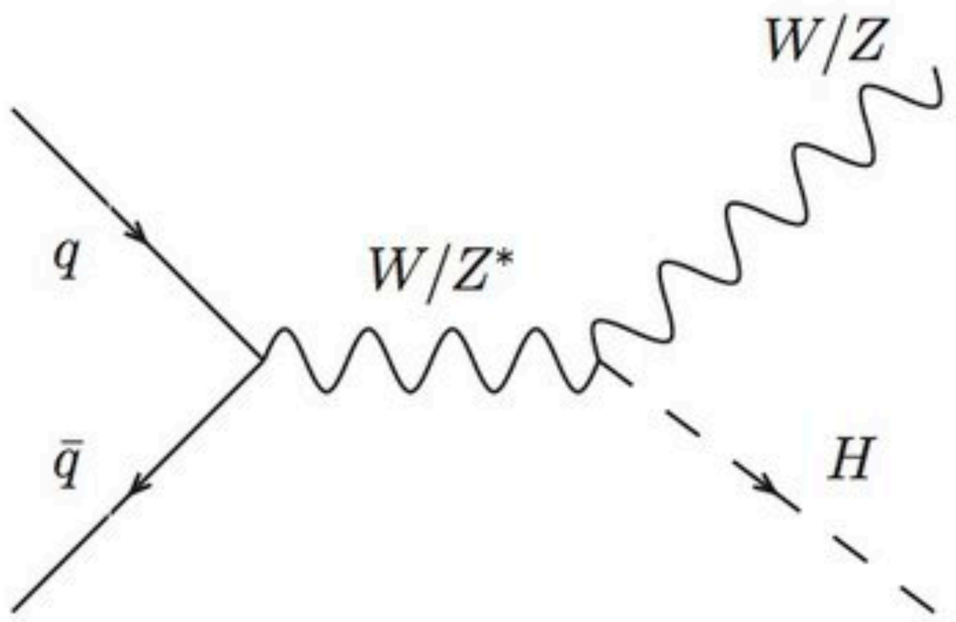
Gluon fusion (ggF)



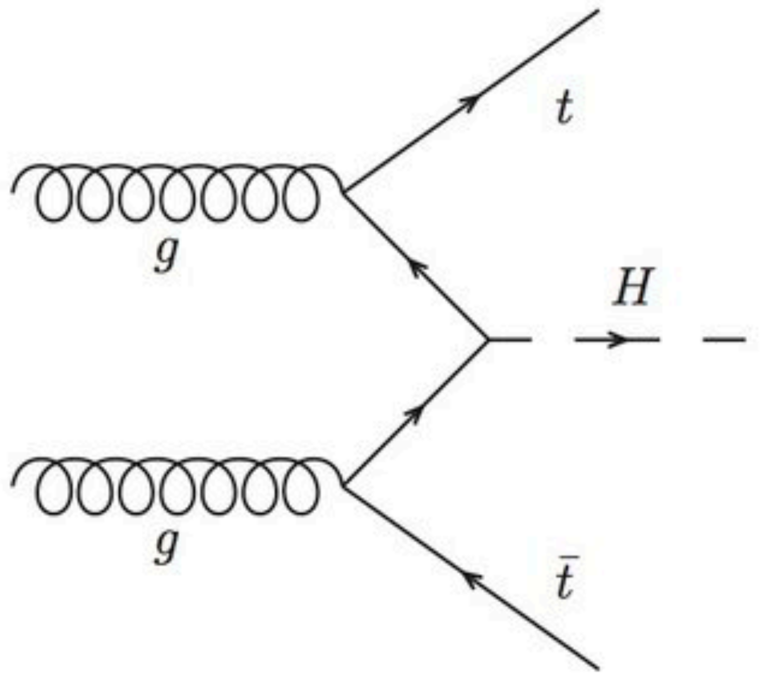
Vector-boson fusion (VBF)



Higgs-strahlung (VH)



Higgs production in association with $t\bar{t}$ (ttH)



Observation of the **ttH** process provides direct access to the top Yukawa coupling of the Higgs

DOI:10.13140/RG.2.2.24097.02408

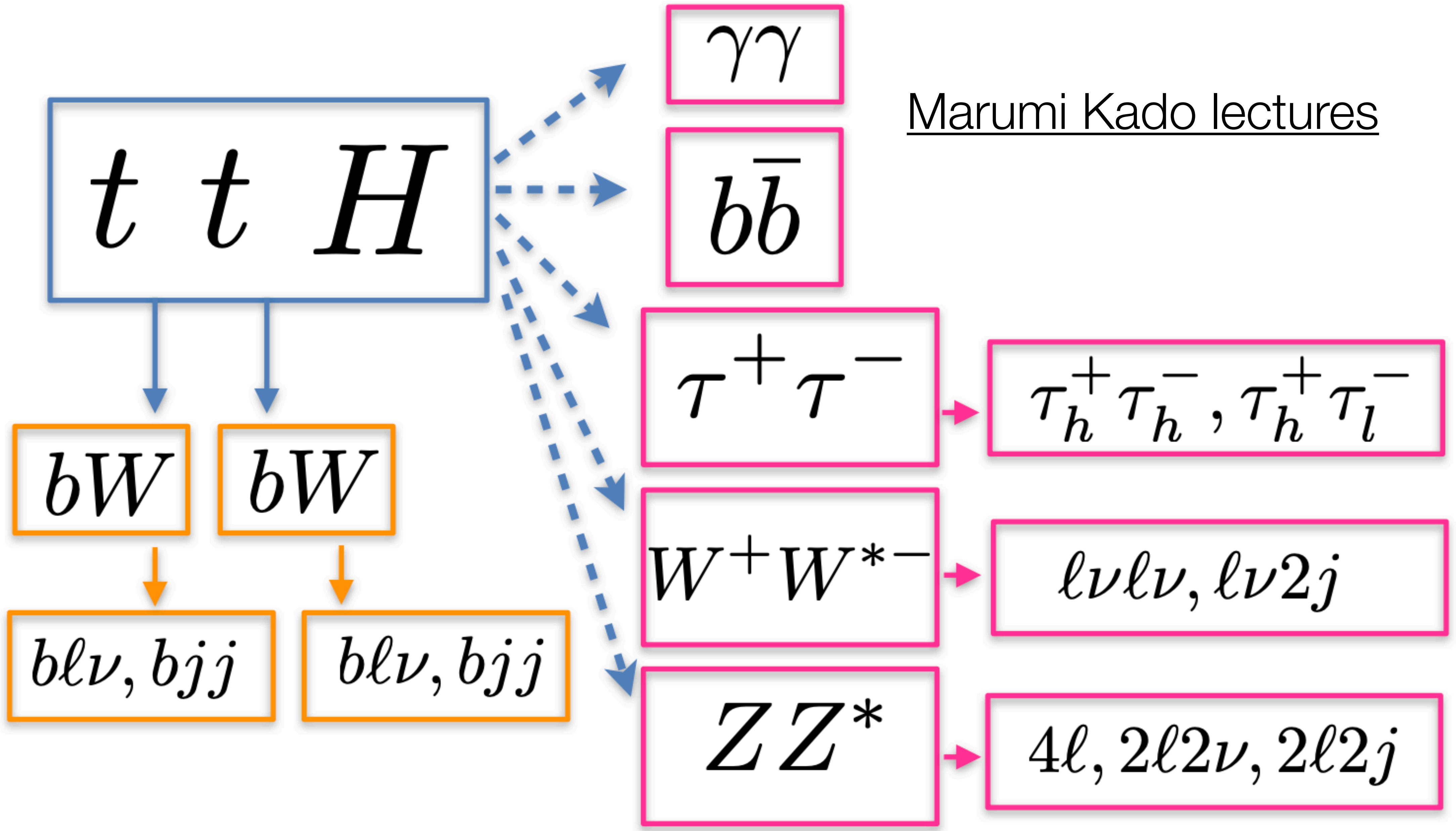
ttH: direct probe of top Yukawa coupling

- **Very small production cross section:**
  one of latest discoveries

- **Large number of complex final states:**
  Mixture of b-jets, leptons, taus and photons

- **Many different channels:** many different bkgs and different systematic uncertainties

  → Excellent way to cross check each other



Marumi Kado lectures

What does the SM predict for the Higgs boson?

Width

~4 MeV for 125 GeV

Spin and CP

Scalar: spin 0, CP even

Couplings

Higgs-Fermion couplings ∝ fermion mass

Higgs-Boson couplings ∝ boson mass^2

→ **SM Higgs sector is overall very predictive:**

Knowing the fermion masses, only free parameter is m_H

https://phdcomics.com/comics.php?f=1489

Let's test these predictions

- **Measure all properties:**
  Mass, spin, CP, couplings

- **Deviations could point to physics beyond the SM**

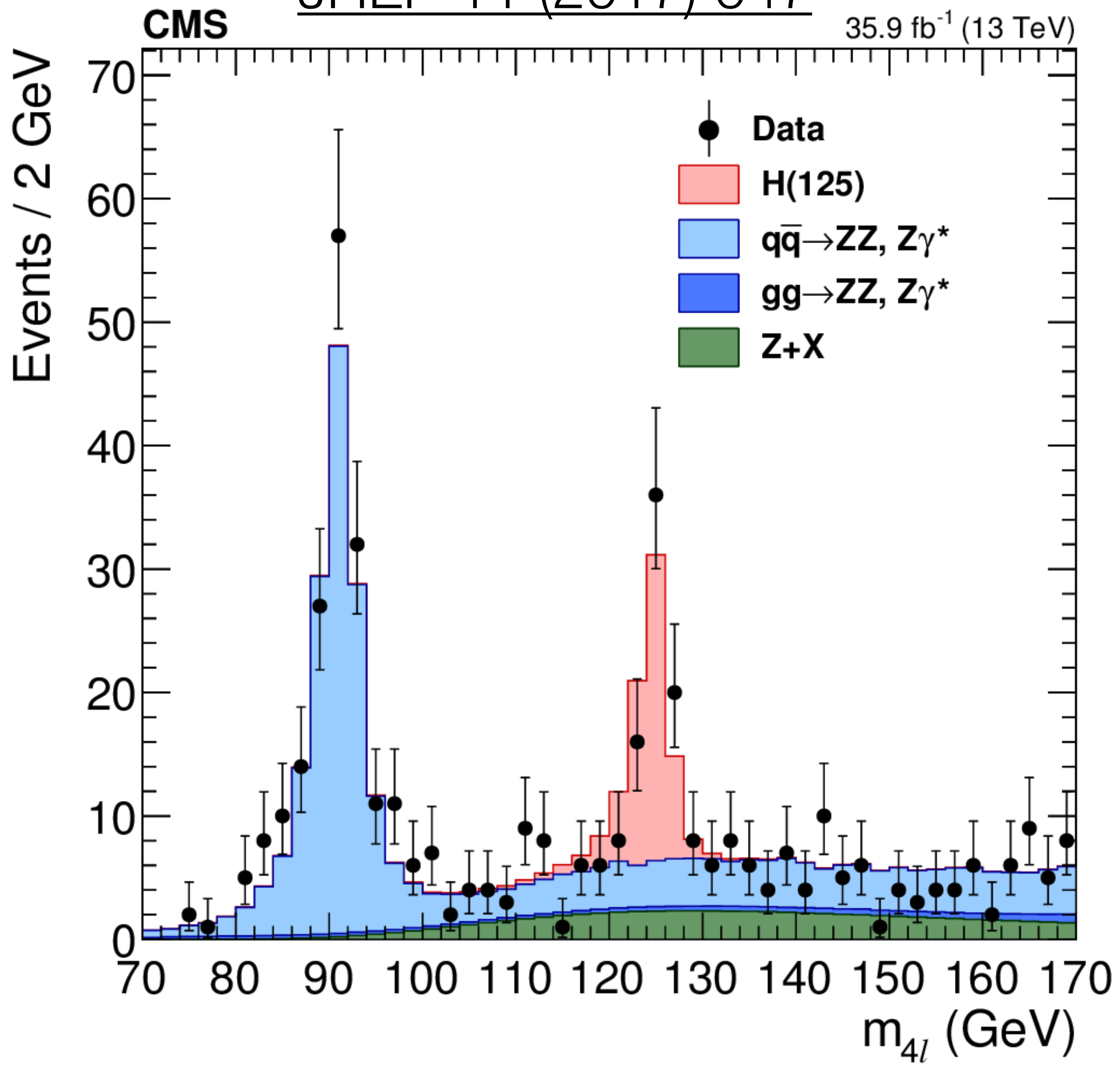
- **Higgs can also play an important role in searches for new physics**

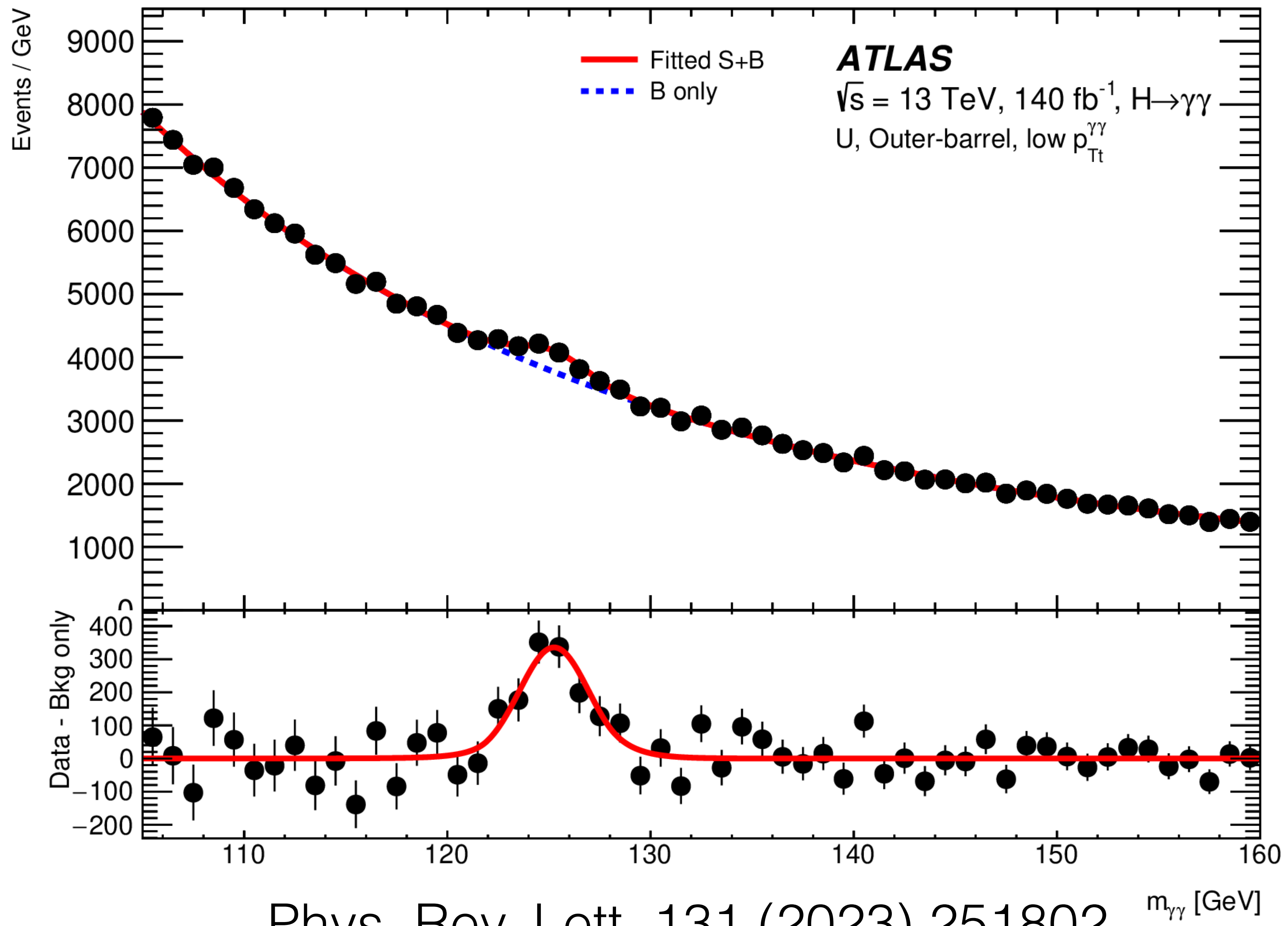
https://phdcomics.com/comics.php?f=1489

Higgs mass measurements

- **Not predicted by SM**
- **Mass measurements in "golden channels": H $\rightarrow \gamma\gamma$ and H$\rightarrow$ZZ**
- **Optimised analyses in channels with best mass resolution** (photon, electron and muon)
- **Reached 0.09% precision**

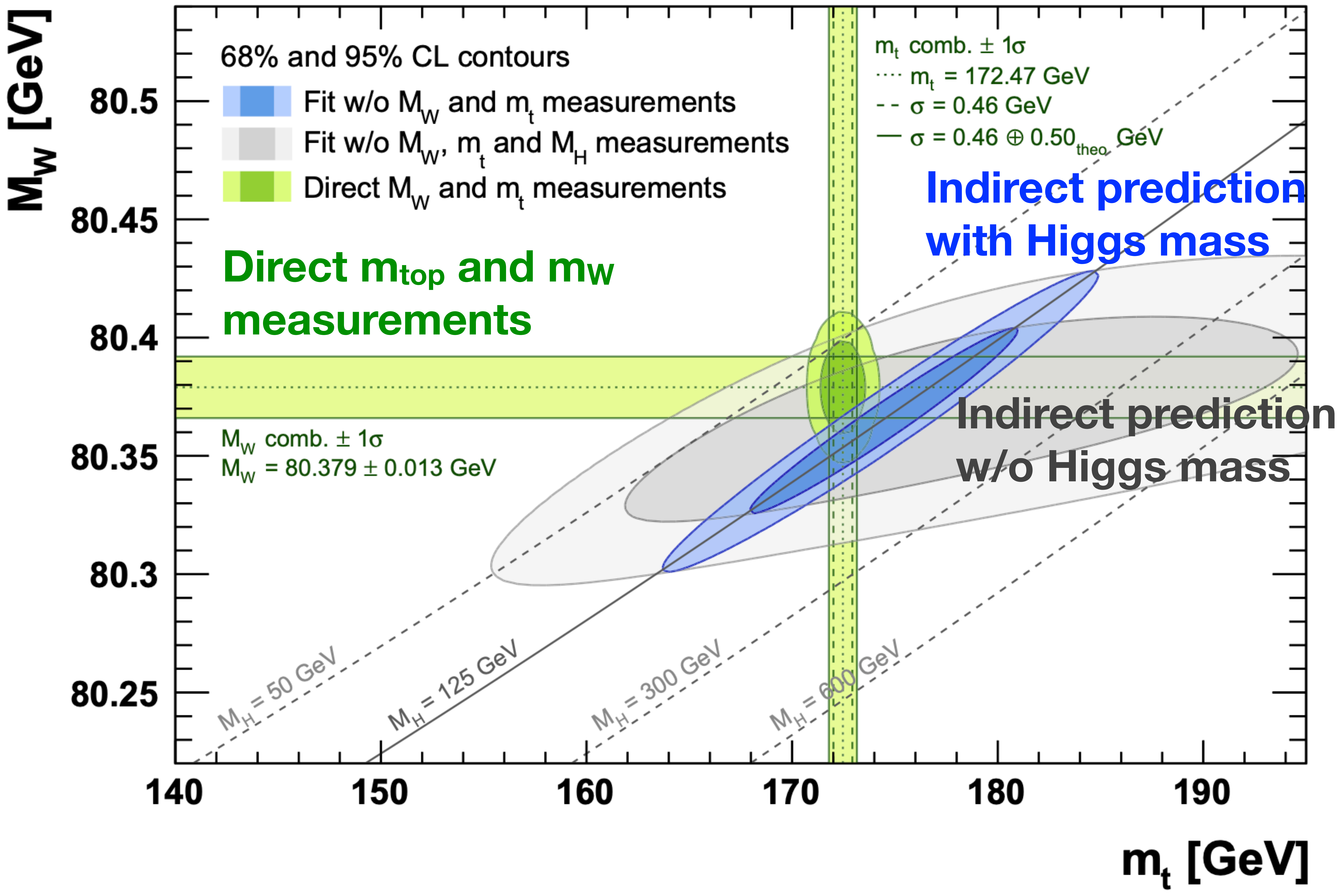
JHEP 11 (2017) 047





Phys. Rev. Lett. 131 (2023) 251802

Standard Model fits after the Higgs discovery: 2022



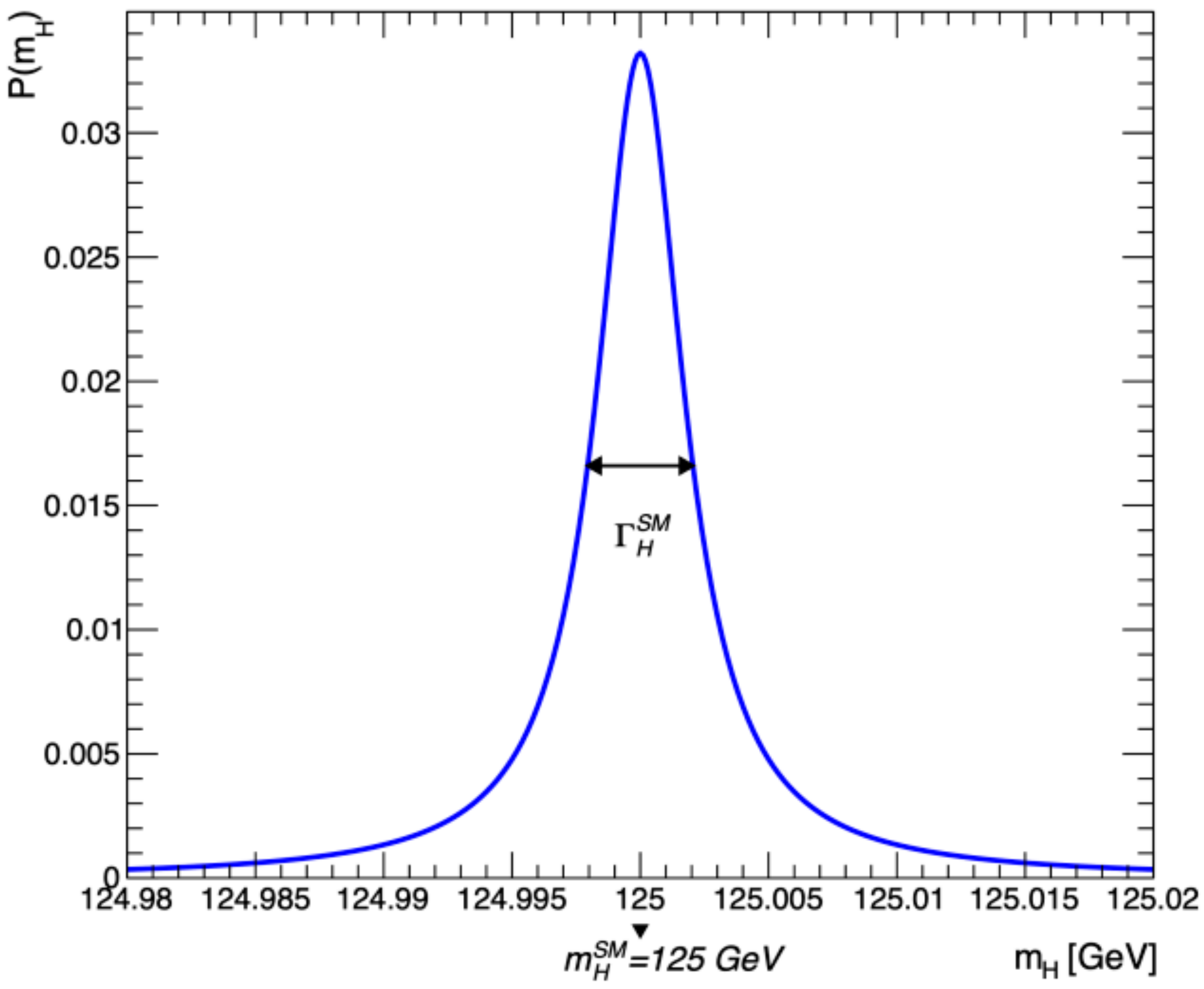
Knowing the Higgs boson mass has large impact on global fits

(compare grey vs blue)

10.1140/epjc/s10052-018-6131-3

Higgs width

Breit-wigner line shape



- **What is the "width" of a particle?**
- Heisenberg uncertainty principle implies energy (i.e. also mass) of all unstable particles must have uncertainty

  Width is inversely proportional to lifetime
- **Larger the width smaller the lifetime**
- **Higgs width predicted to be ~4 MeV**

https://atlas.cern/Updates/Briefing/Higgs-Total-Width

Higgs width

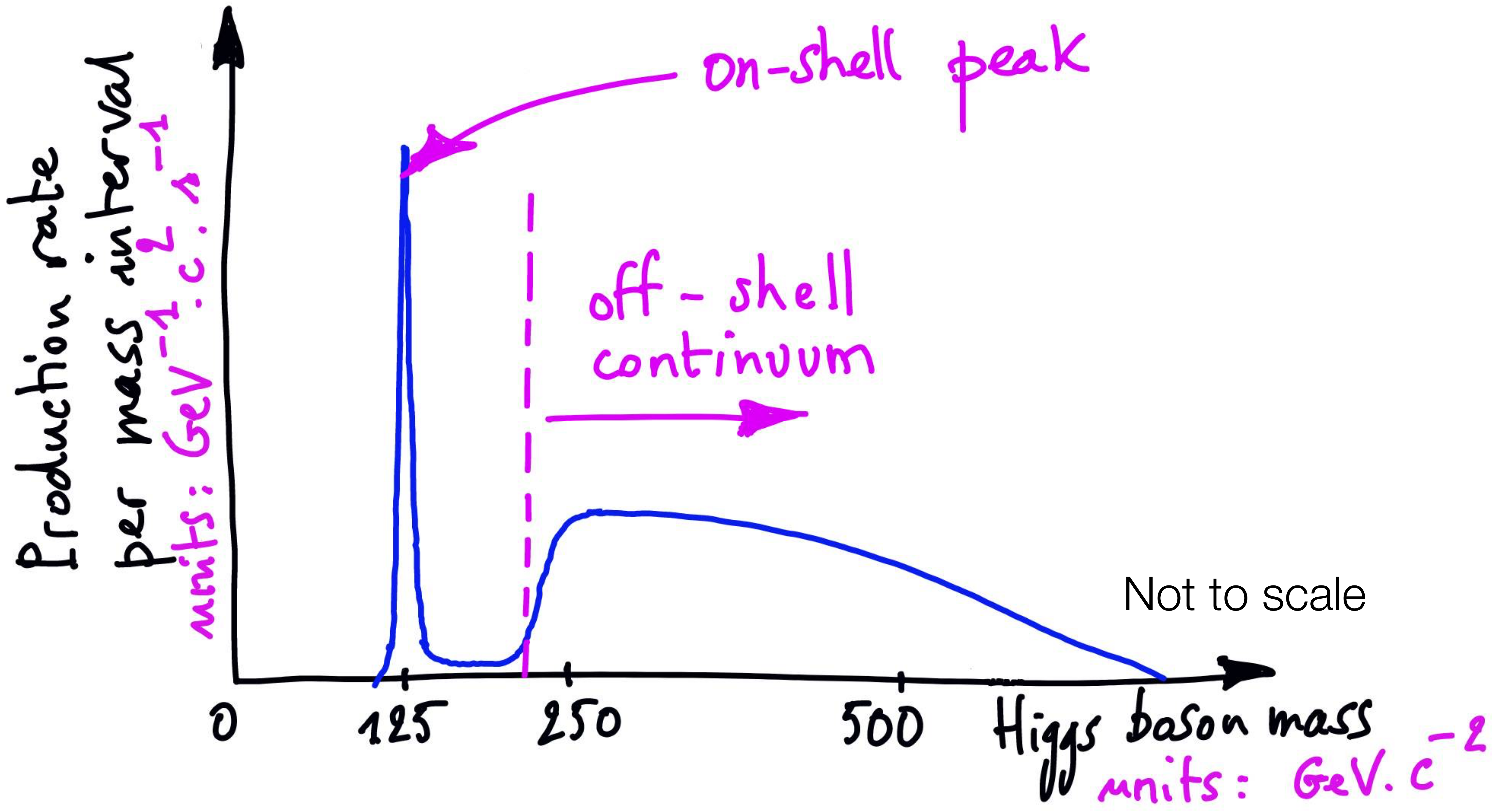
Two ways to access Higgs width:

- **Direct mass measurement:** Limited by experimental resolution to ~1-2 GeV
- **Indirect methods e.g. using off-shell signal strength (away from peak):**

  On-shell cross section depends on width, off-shell does not
  → **ratio is sensitive to width!**

Latest CMS result (H→ZZ):

$$\Gamma_H = 3.0^{+2.0}_{-1.5}\ \text{MeV}$$



Higgs width

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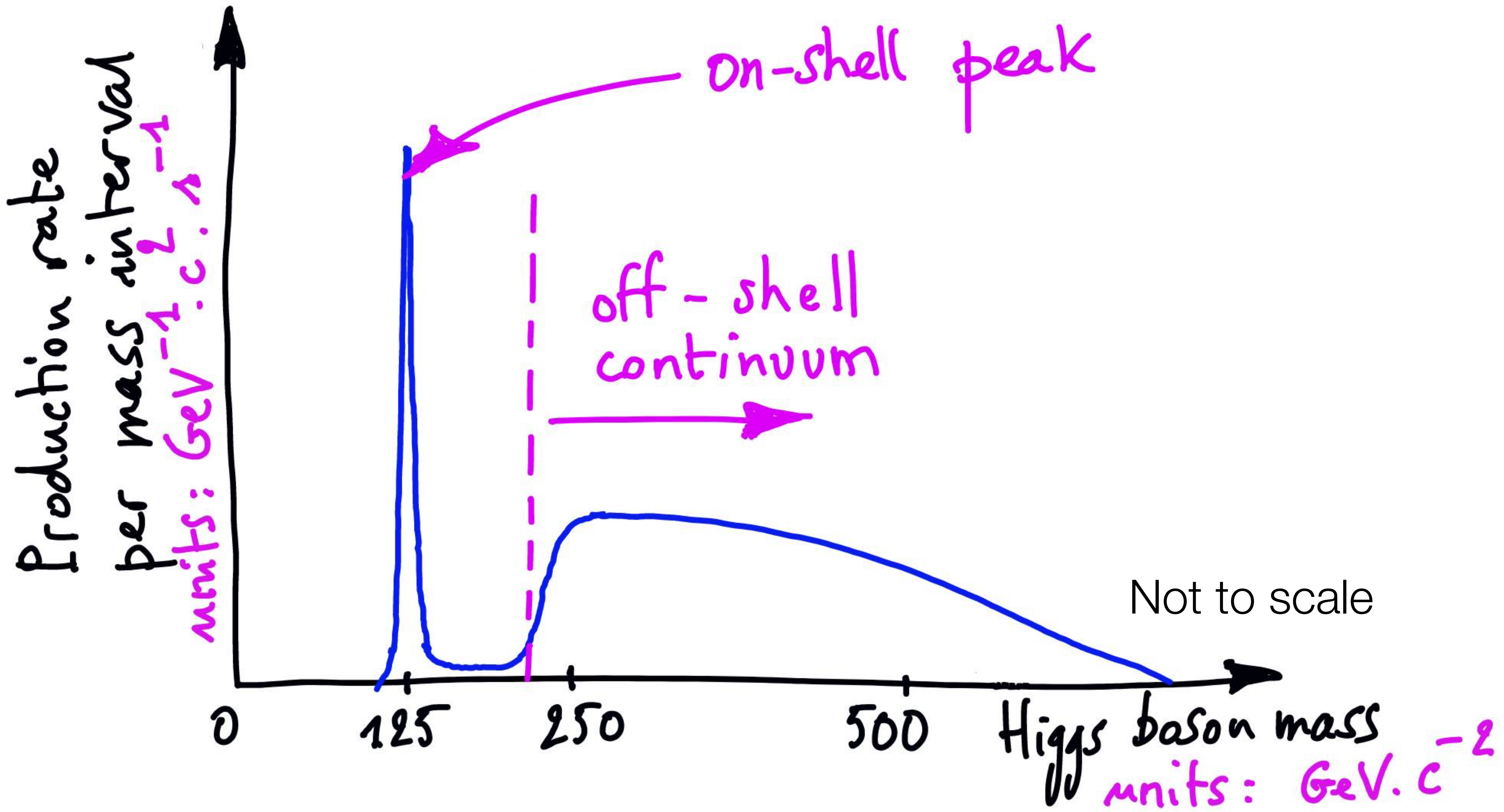
On-shell cross section depends on width, off-shell does not

→ **ratio is sensitive to width!**

Quiz: why would a Higgs width > SM prediction be exciting?



Nature Physics 18, 1329–1334 (2022)

https://cms.cern/news/life-higgs-boson

Higgs spin and Charge-Parity (CP)

Spin (SM = 0)

- **Spin 1 excluded** using ZZ, WW decays (and by H → $\gamma\gamma$)
- **Spin 2 excluded** at a high confidence level

→ **Very likely spin 0 as predicted for the SM Higgs**

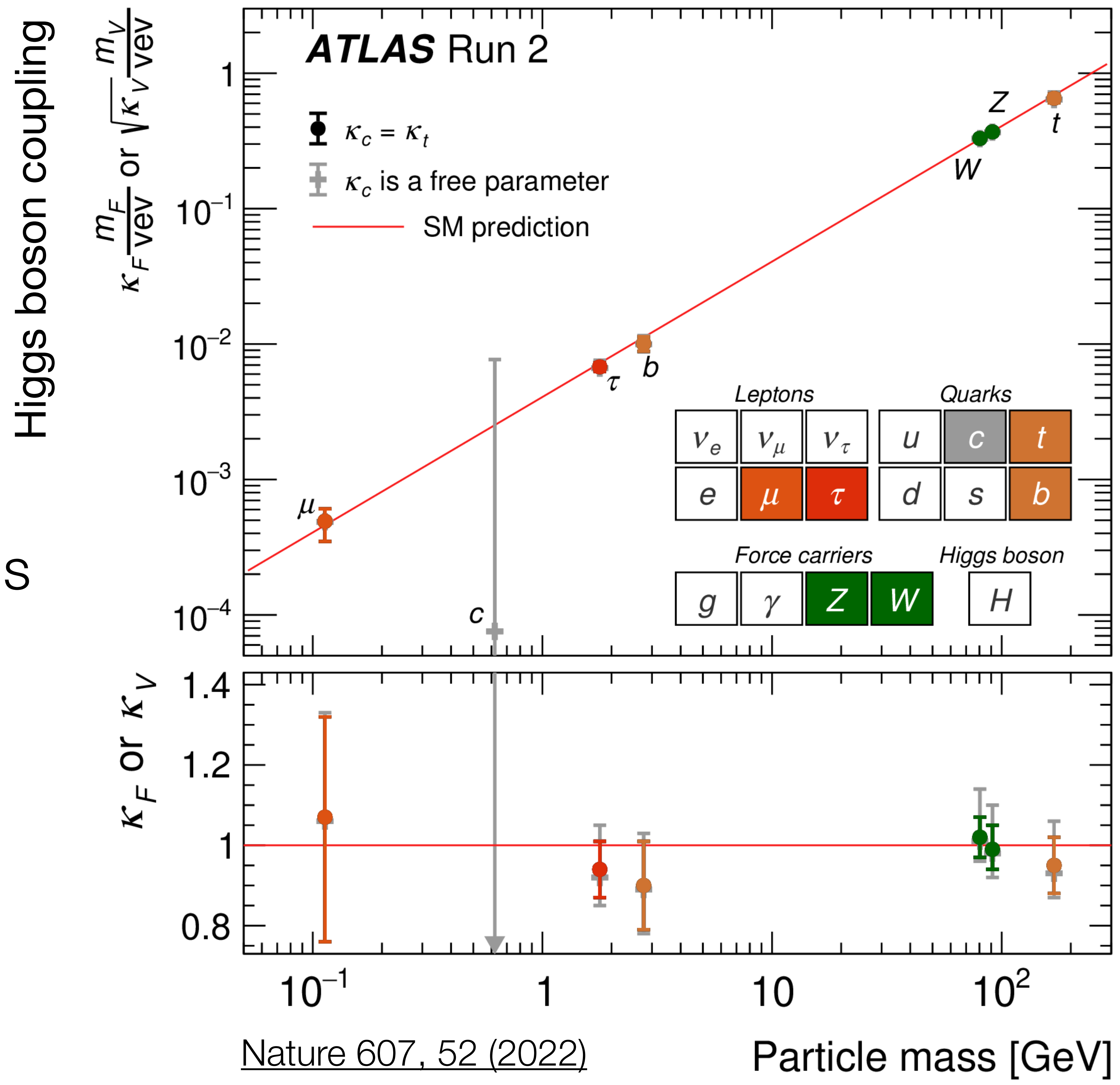
CP (SM: even)

- **Odd excluded** at > 99.9% (ATLAS, CMS)
- **Admixtures** (CP even and CP odd couplings) **still possible**

More info: CP

Higgs couplings

So far all measured couplings consistent with SM



Higgs-Fermion couplings

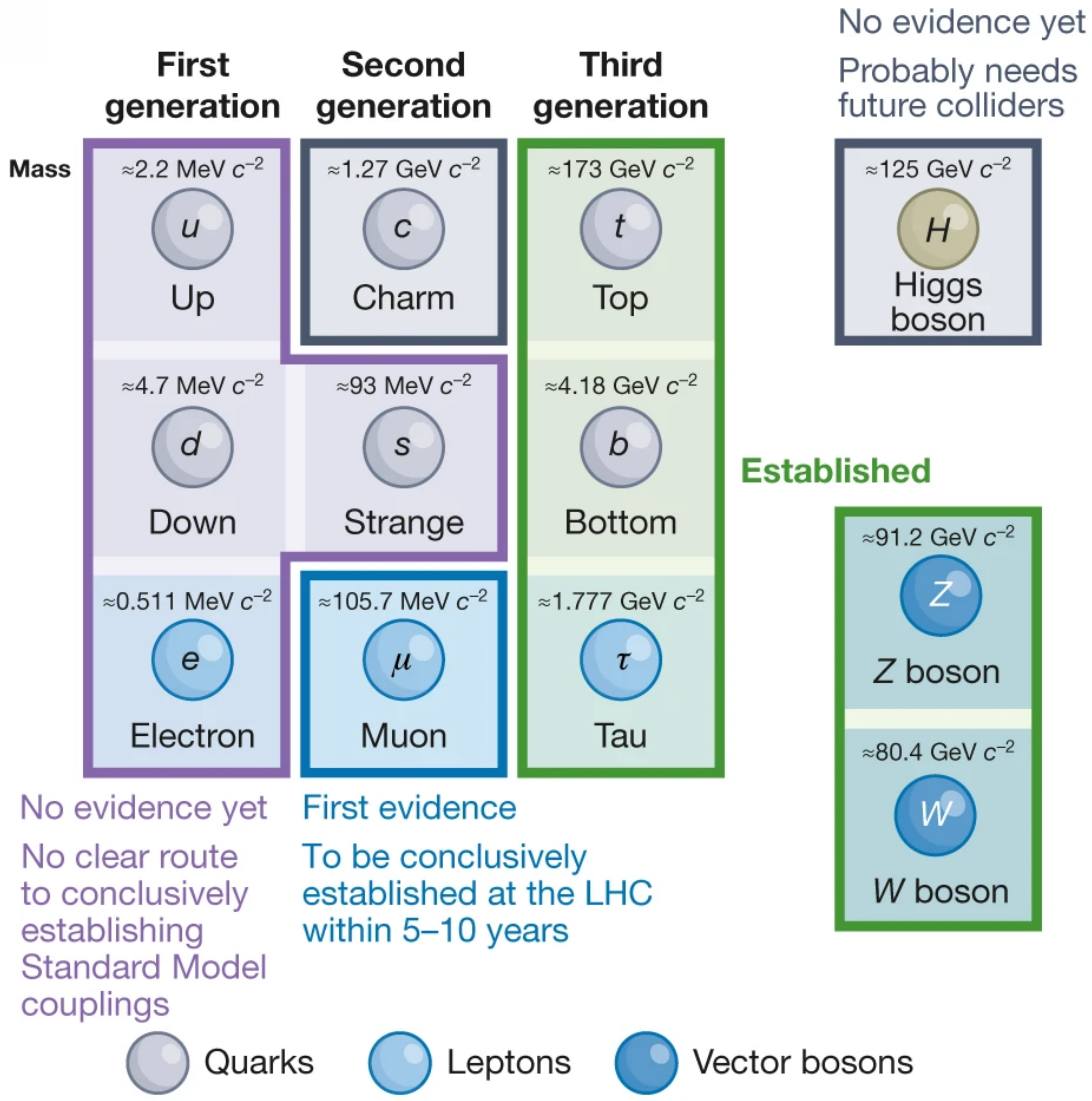
∝ fermion mass

Higgs-Boson couplings

∝ boson mass²

Nature 607, 52 (2022)

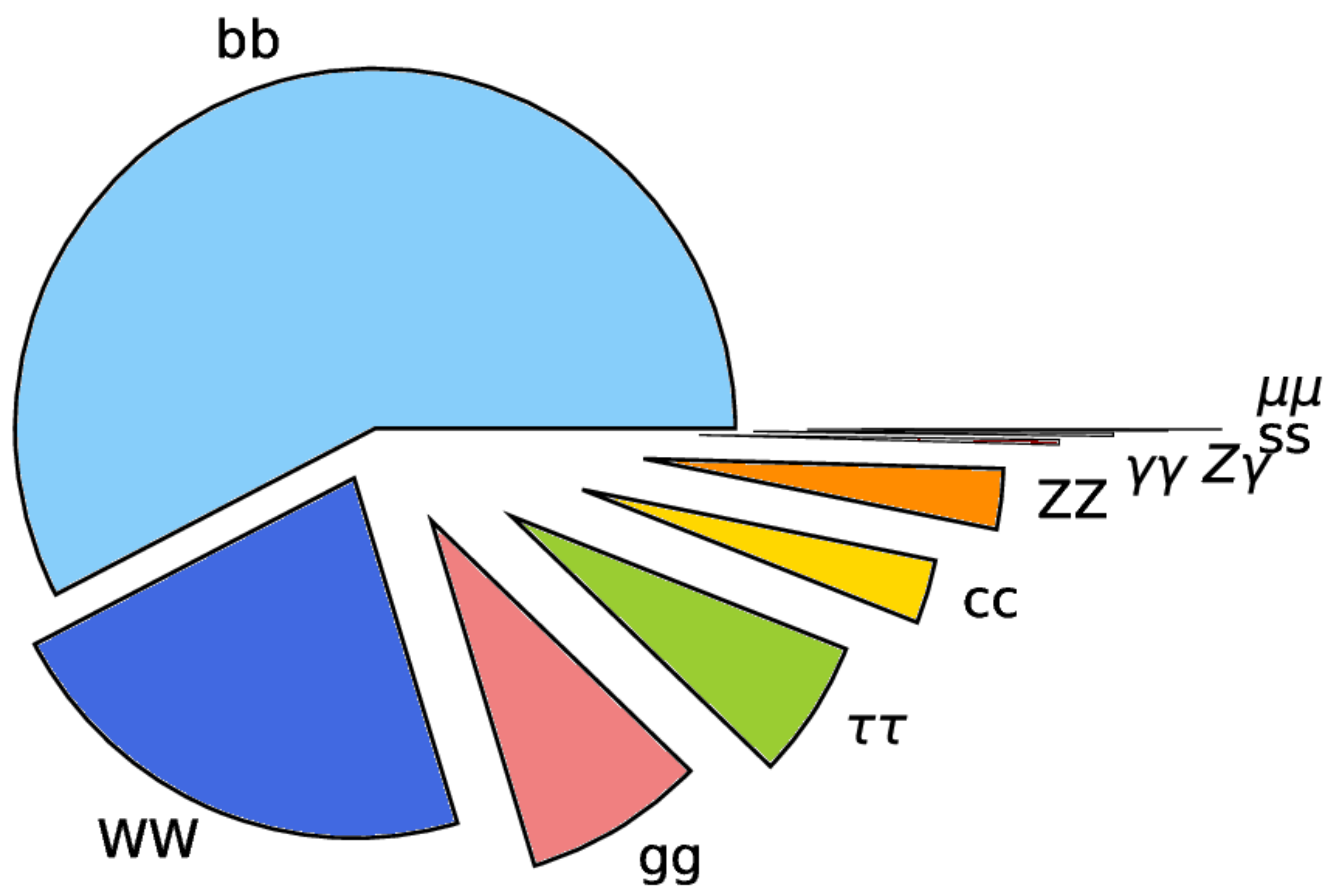
Higgs couplings summary



Nature volume 607, 41–47 (2022)

Undiscovered decays

Example H → $\mu\mu$



Nature 607 52–59 (2022)

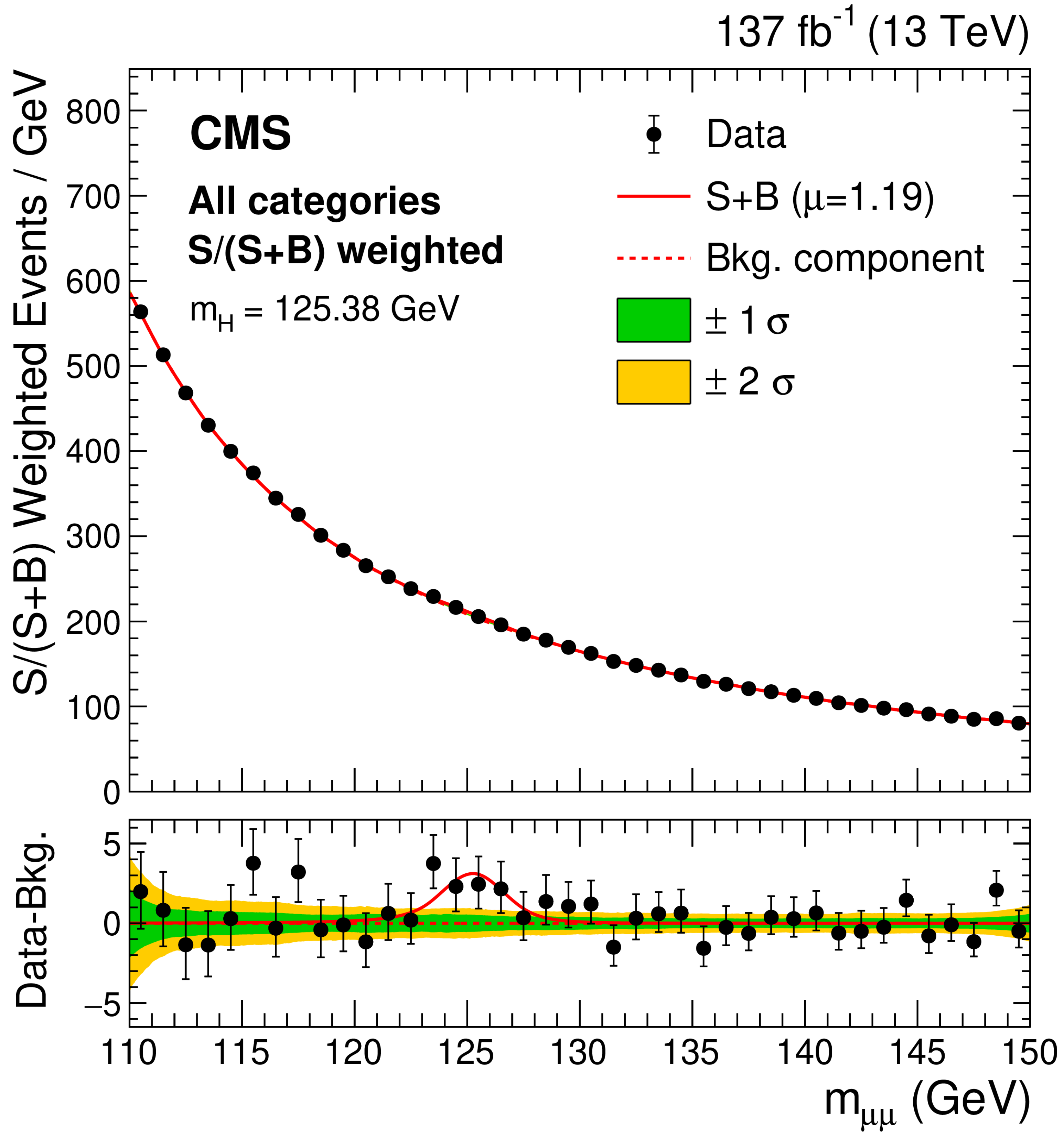
p-value reflects consistency of observed data with the absence of signal

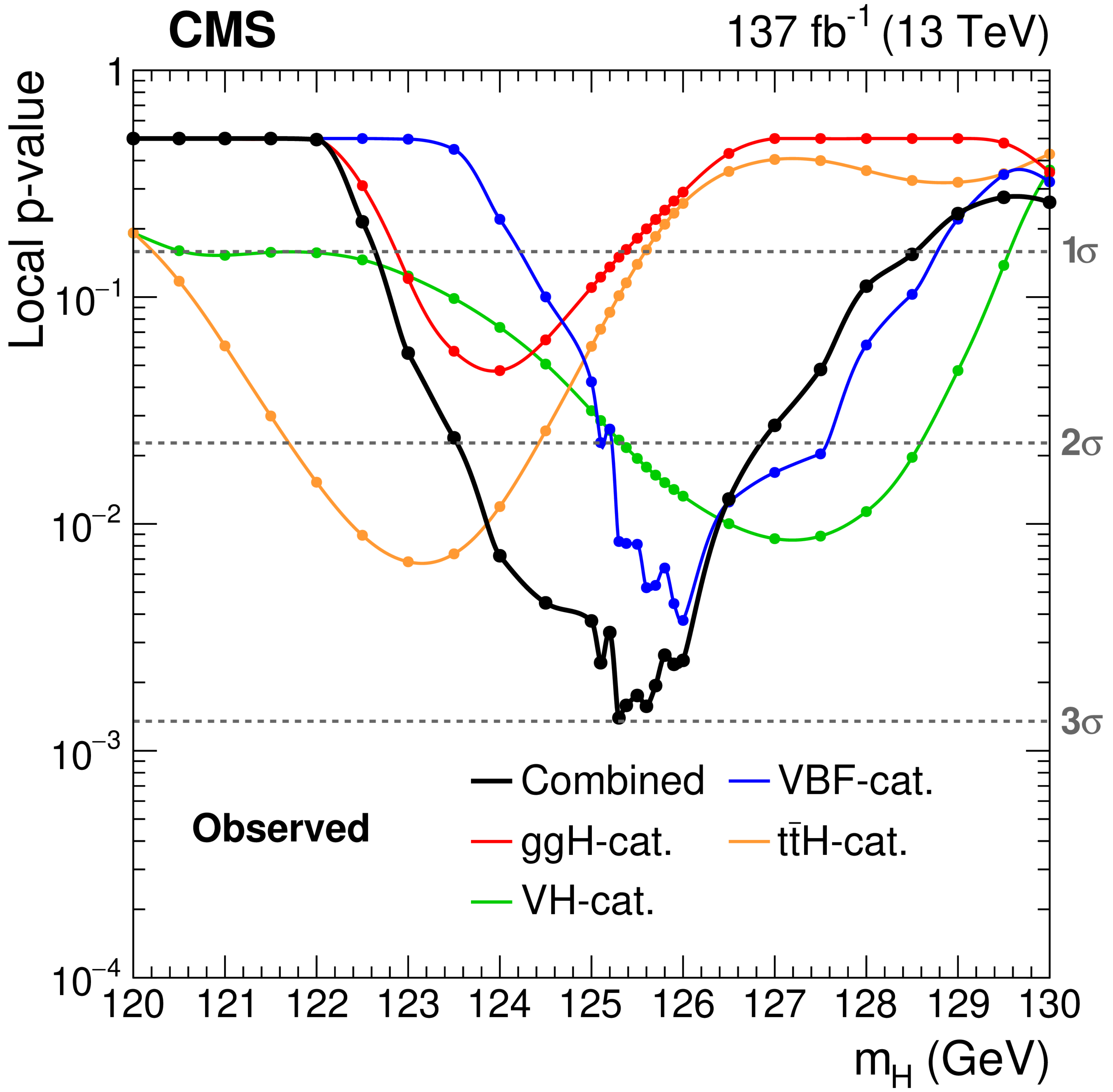
Challenging: small coupling, large Drell-Yan bkg

→ Categorise events by production mode

→ Use of sophisticated machine learning techniques

ATLAS and CMS both achieved evidence (> 3σ)



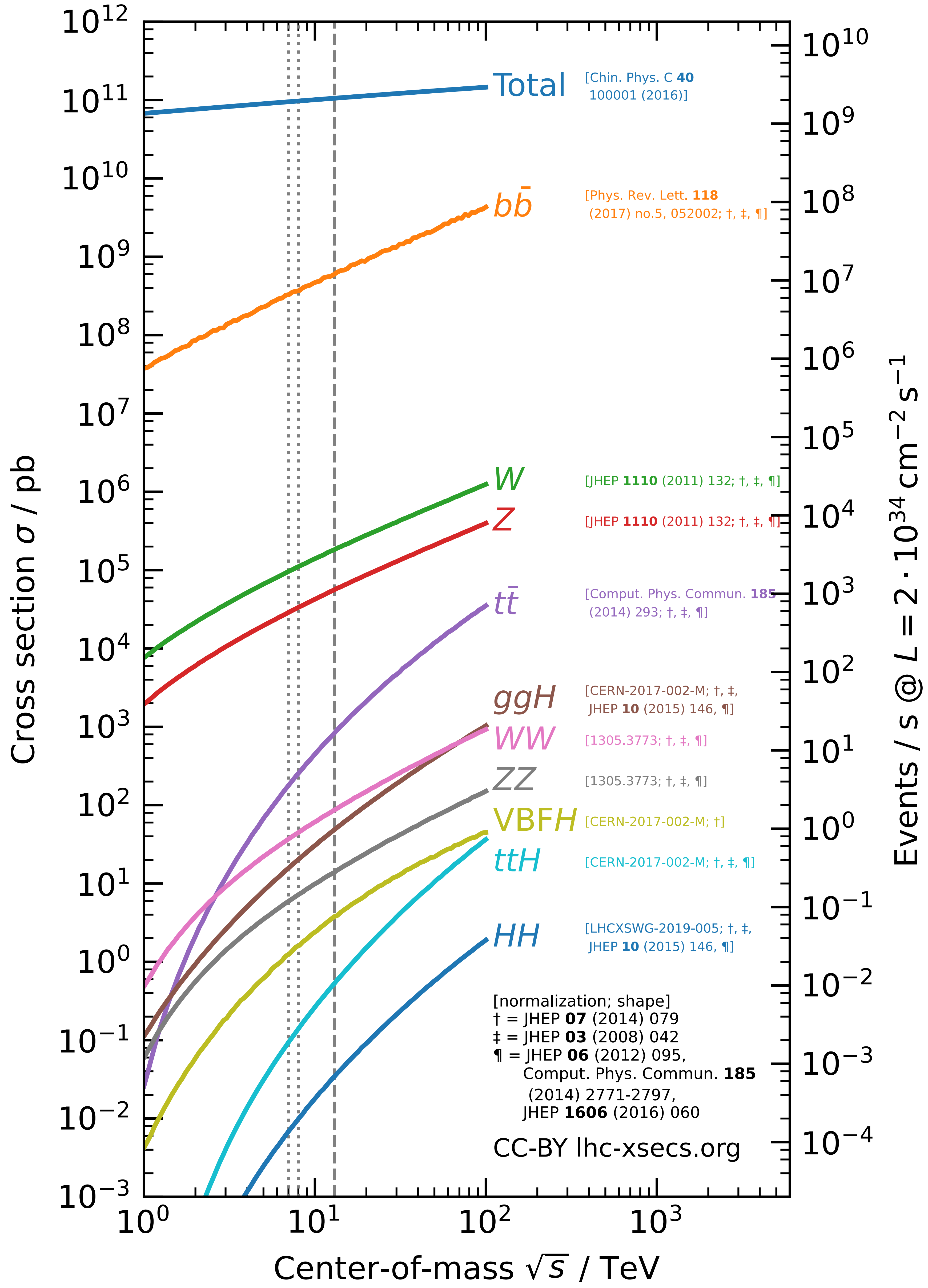


2507.03595

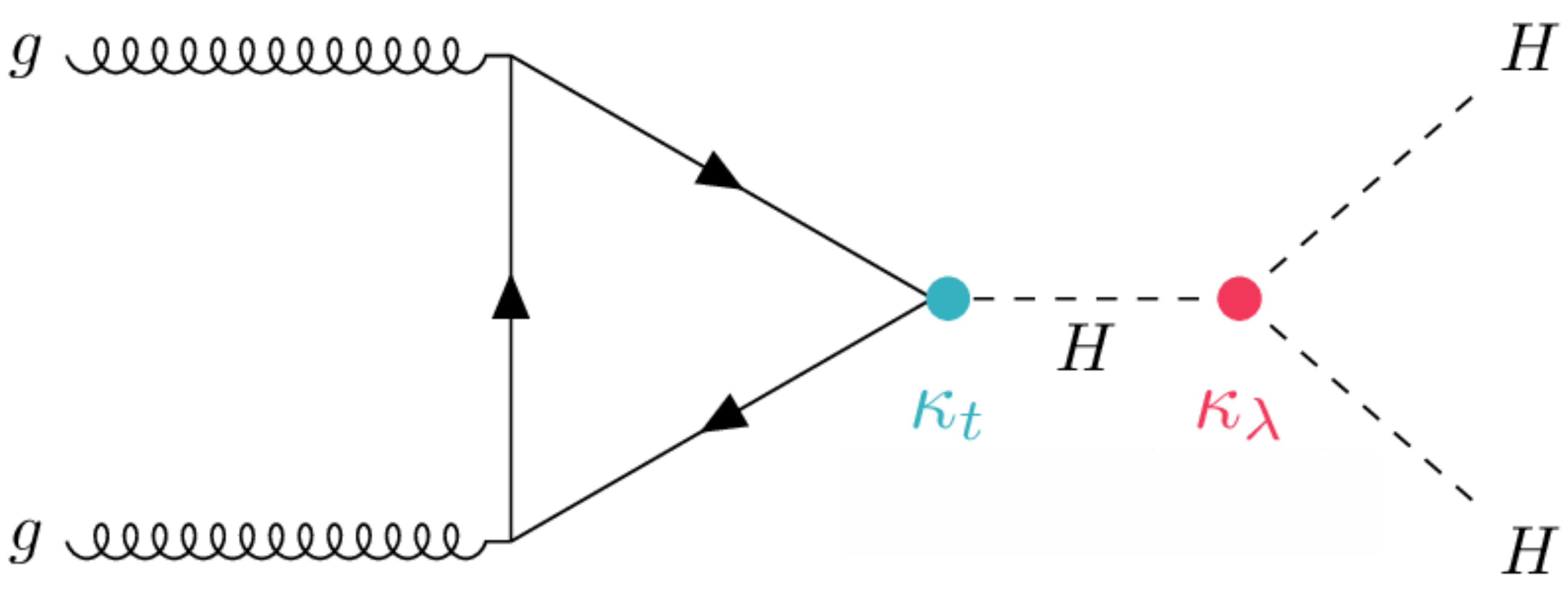
JHEP 01 (2021) 148

Di-Higgs production

F. Sauerburger,
LHC cross section plot,
https://lhc-xsecs.org



Holy grail: di-Higgs production



arXiv:2406.09971

- **Extremely interesting but very rare** ~1000x rarer than H
- **Enables us to test the Higgs self-coupling**
- **Deviations from SM expected in many BSM models**

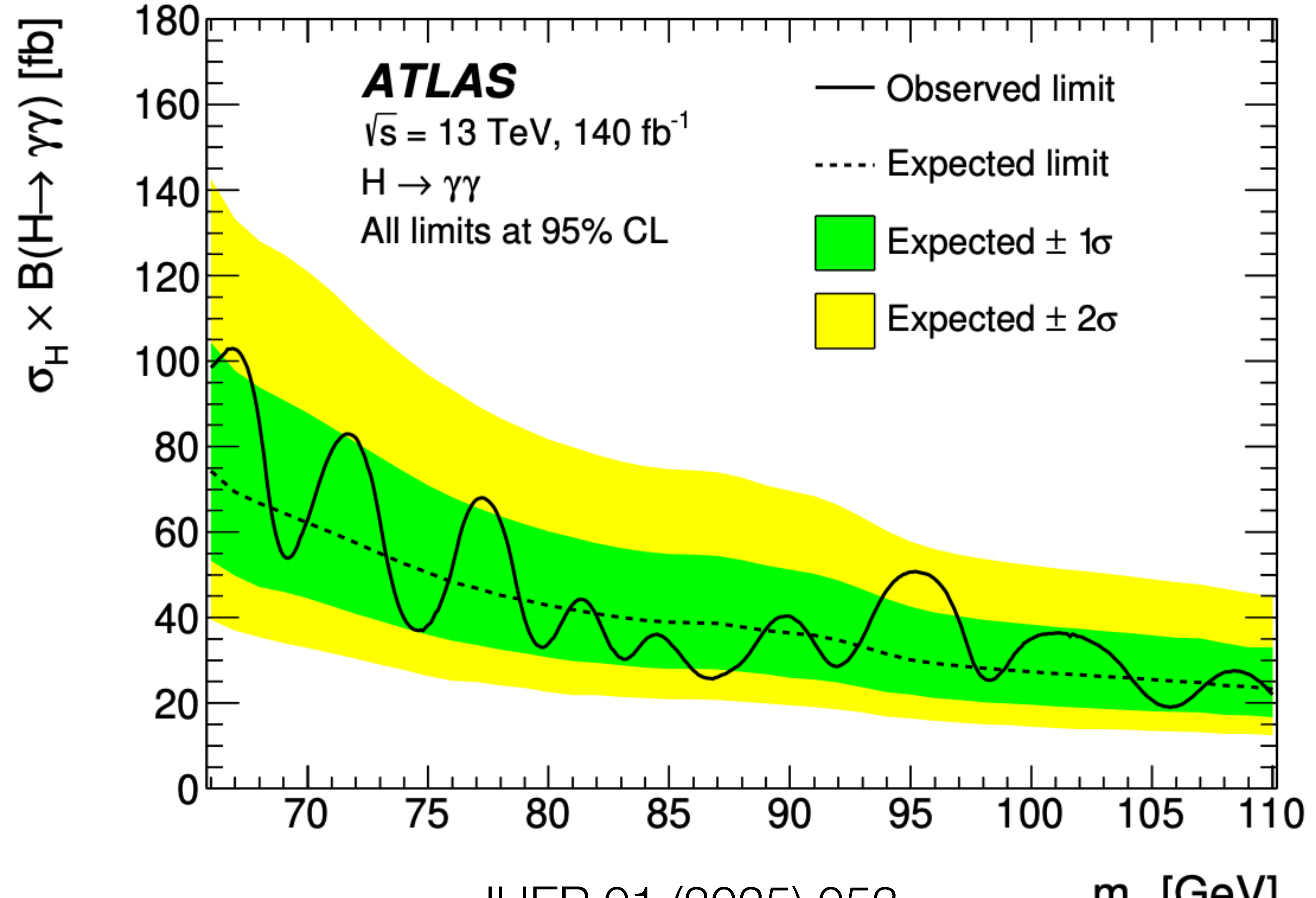
Higgs-self coupling will be a key focus at the HL-LHC

BSM Higgs searches

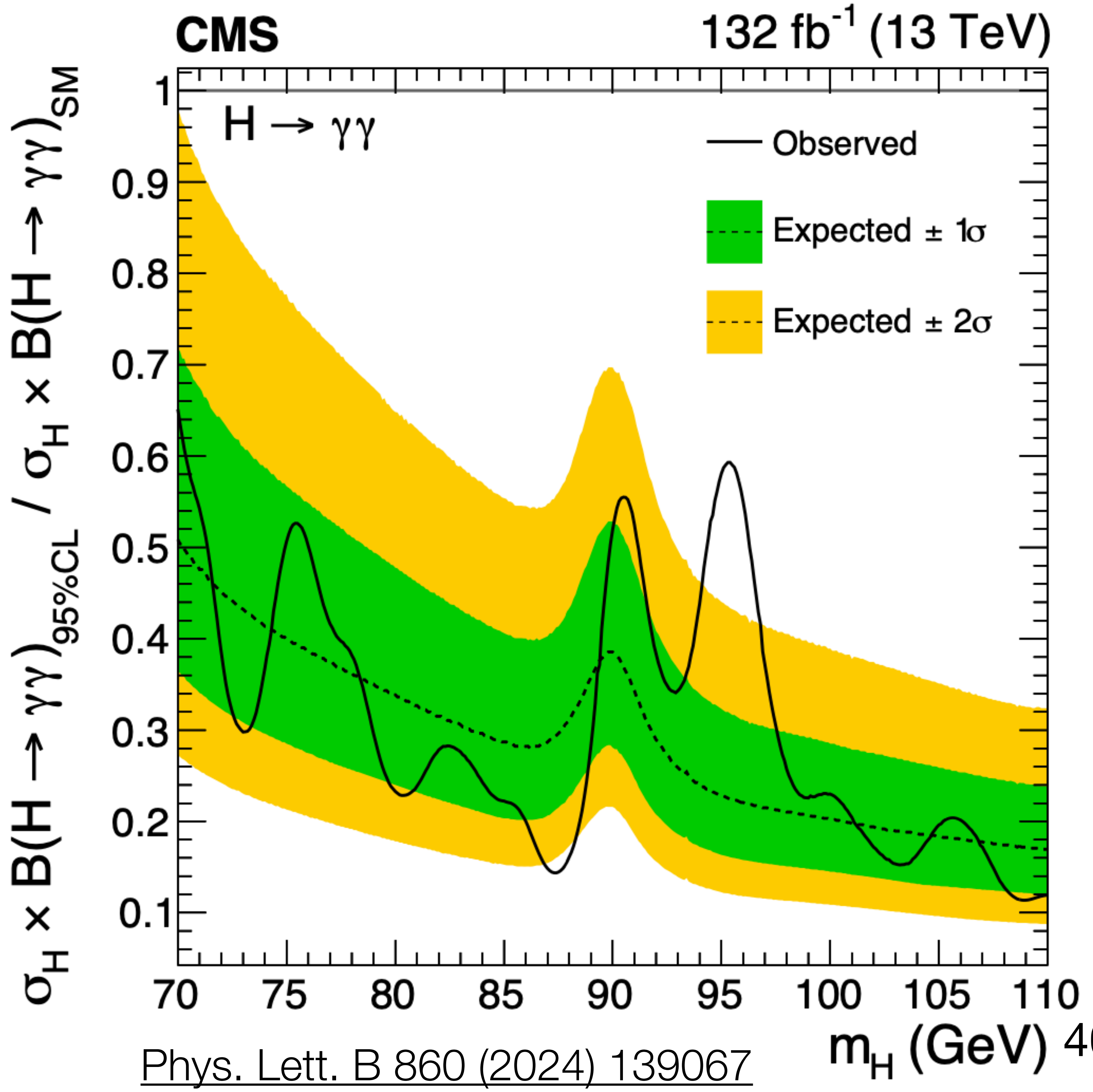
We indirectly search for BSM physics via precisely measuring the Higgs

We also perform direct searches e.g.

- Flavour violating searches e.g. H $\rightarrow e\mu$
- Invisible decays of Higgs bosons
- Additional Higgs bosons: lighter, heavier, charged?



JHEP 01 (2025) 053



Phys. Lett. B 860 (2024) 139067

Next lecture

wikimedia

Search for New Physics

The Standard Model - fundamental particles

Situation before LHC

Fermilab, 1977

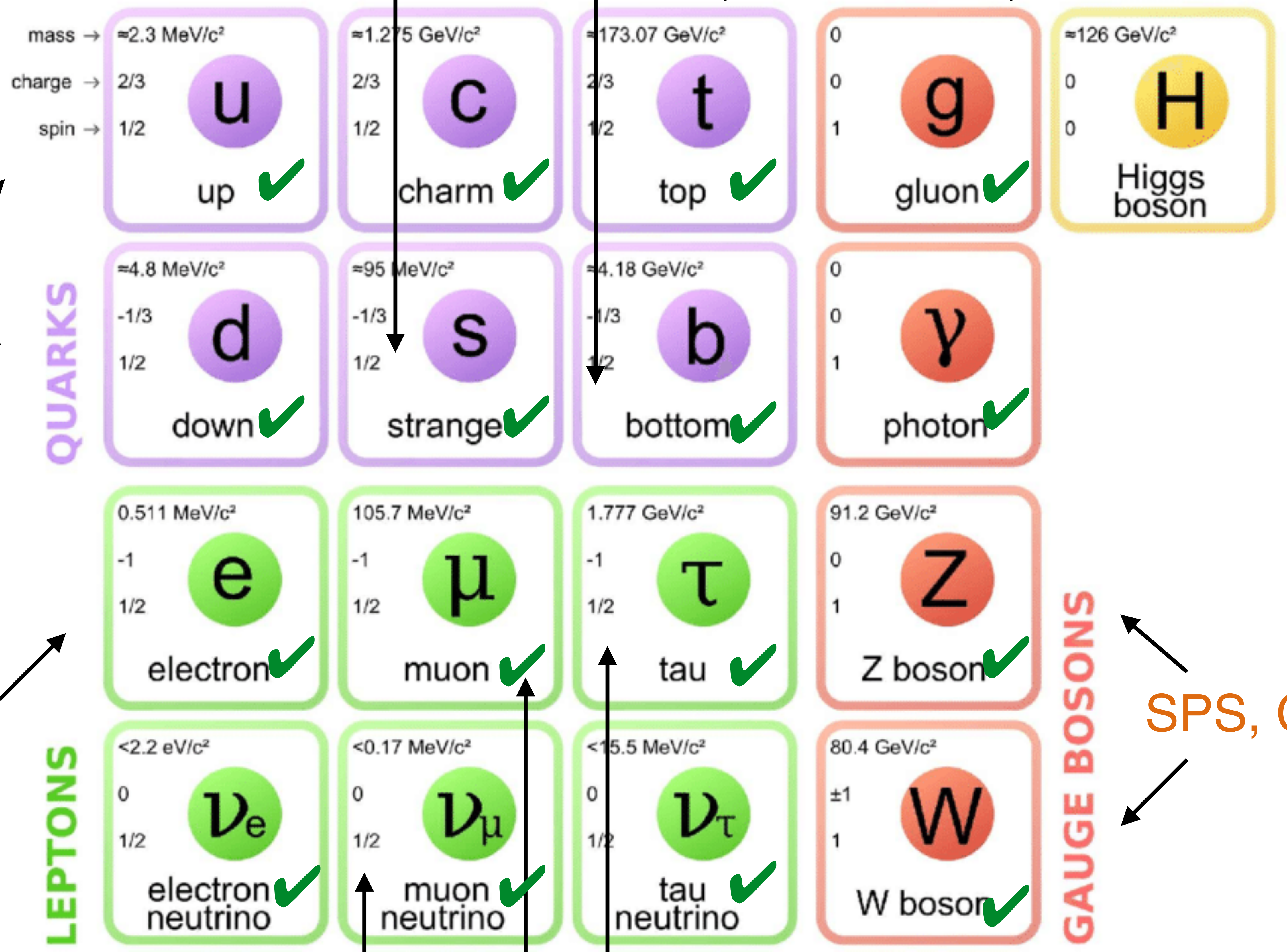
SLAC,BNL, 1974

SLAC, 1968

Tevatron,Fermilab, 1995

PETRA, DESY, 1979

SLAC, 1968



SPS, Cern, 1983

Thompson 1897

BNL,1962

DONUT, Fermilab, 2000

Cowan/Reines,1956

Cosmics, 1936

SLAC, 1975

The Higgs boson - very brief theory reminder

Higgs mechanism:
- makes use of one Higgs doublet of complex scalar fields
- to spontaneously break the SU(2)L × U(1)Y symmetry
- to generate in a gauge invariant way
- the masses of the $W^{\pm}$, Z gauge bosons and the fermions

Basically:
In order to give the gauge bosons mass and keep gauge invariance
-> introduce a Higgs field, with a scalar potential
-> find ground state -> express in terms of ground state

-> Higgs boson
-> Gauge bosons with mass
-> Higgs-particle couplings terms ——> Higgs couplings ~ boson mass^2
Higgs couplings ~ fermion mass

Higgs Charge Parity

Charge conjugation = replace particles with corresponding antiparticles
Parity = reverse spatial coordinates of system (like mirror image)

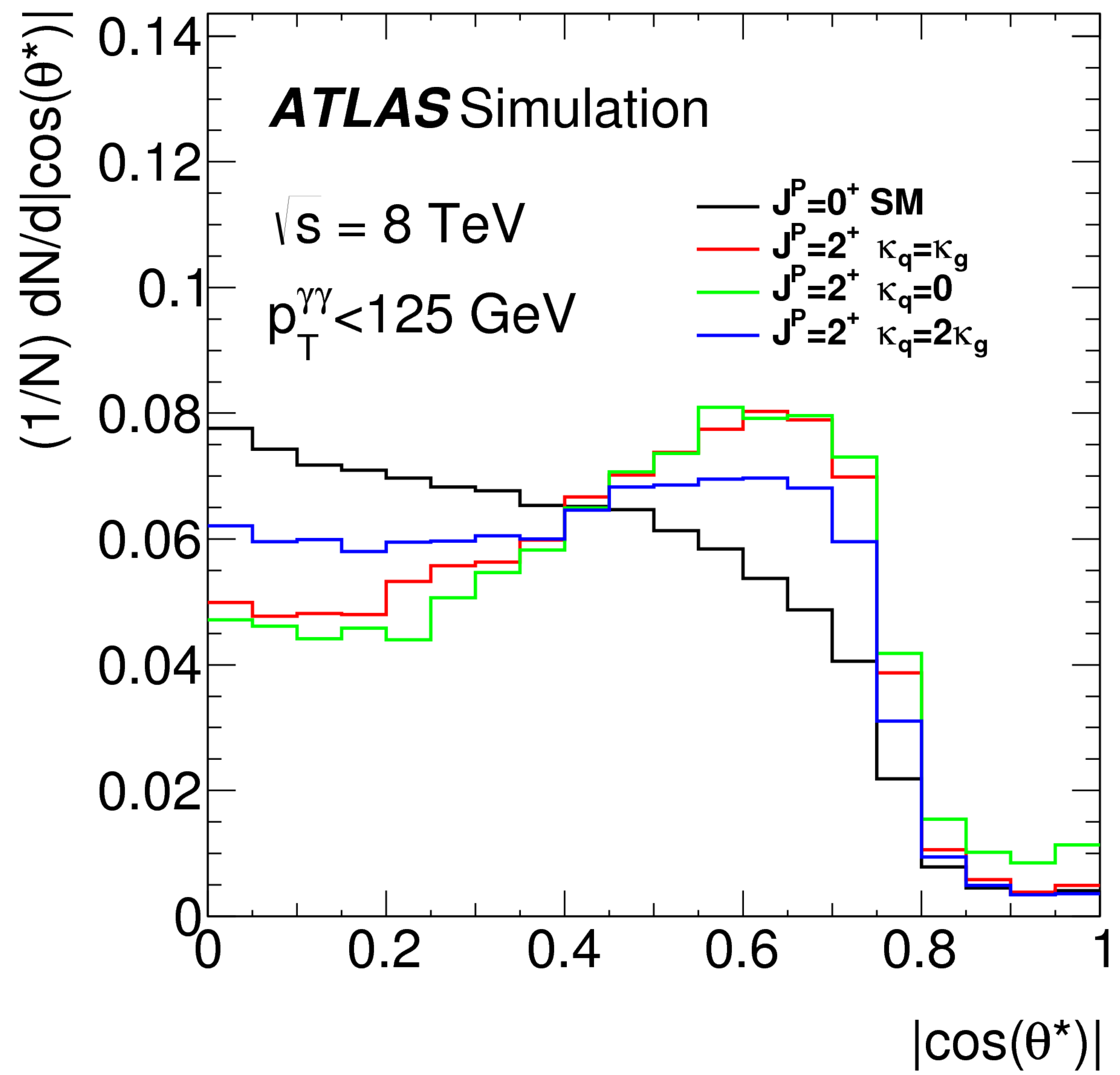
If coupling of Higgs boson to other particles does not change under CP
→ CP-even (scalar)

If all coordinates are flipped, like left and right are flipped in a normal mirror
→ Coupling is CP-odd (pseudoscalar)

https://cms.cern/news/Mirror-mirror-on-the-wall-who-is-the-most-CP-even-of-them-all

Spin and CP

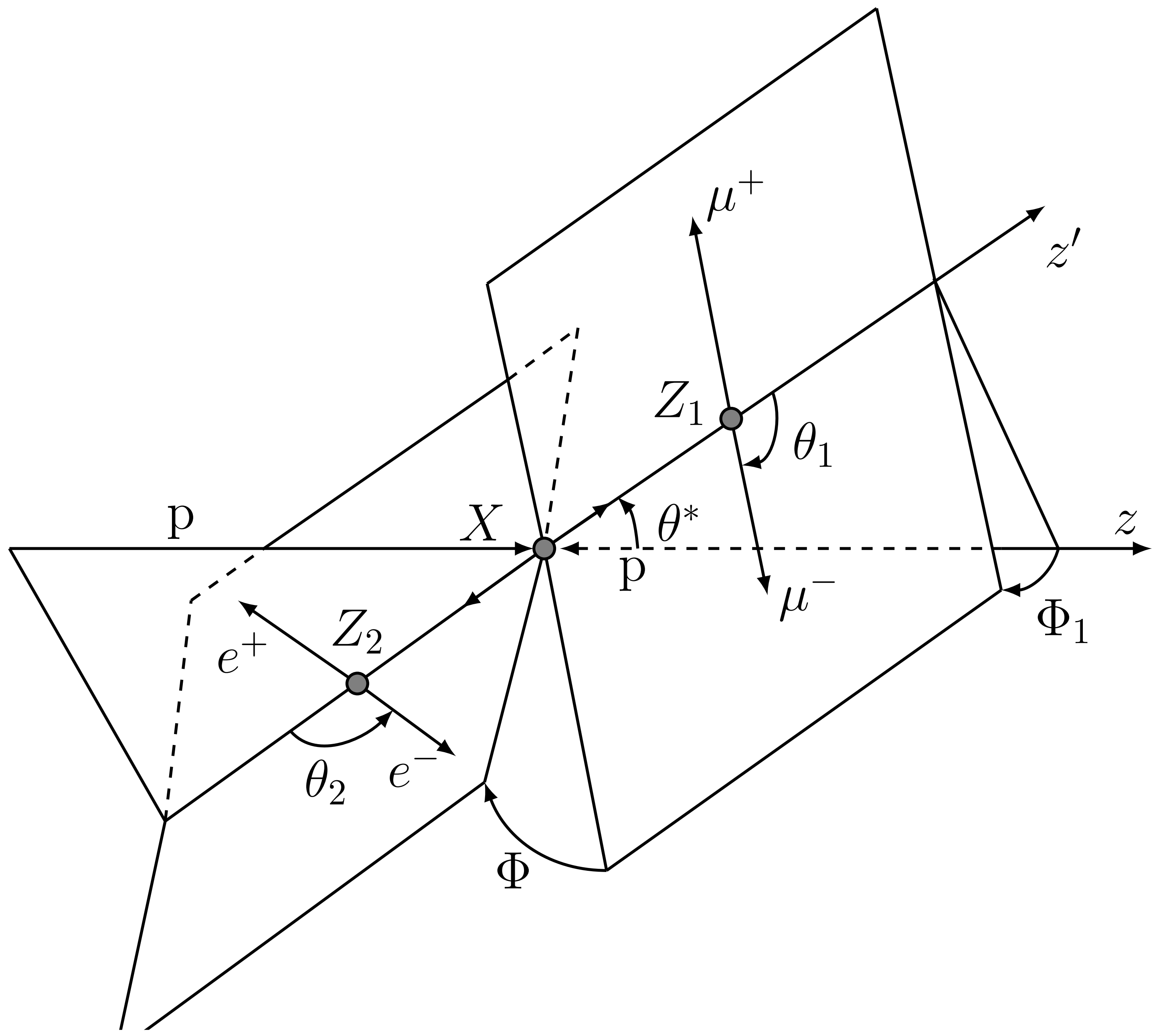
Effect of spin on $|\cos\theta^*|$ of the two photons

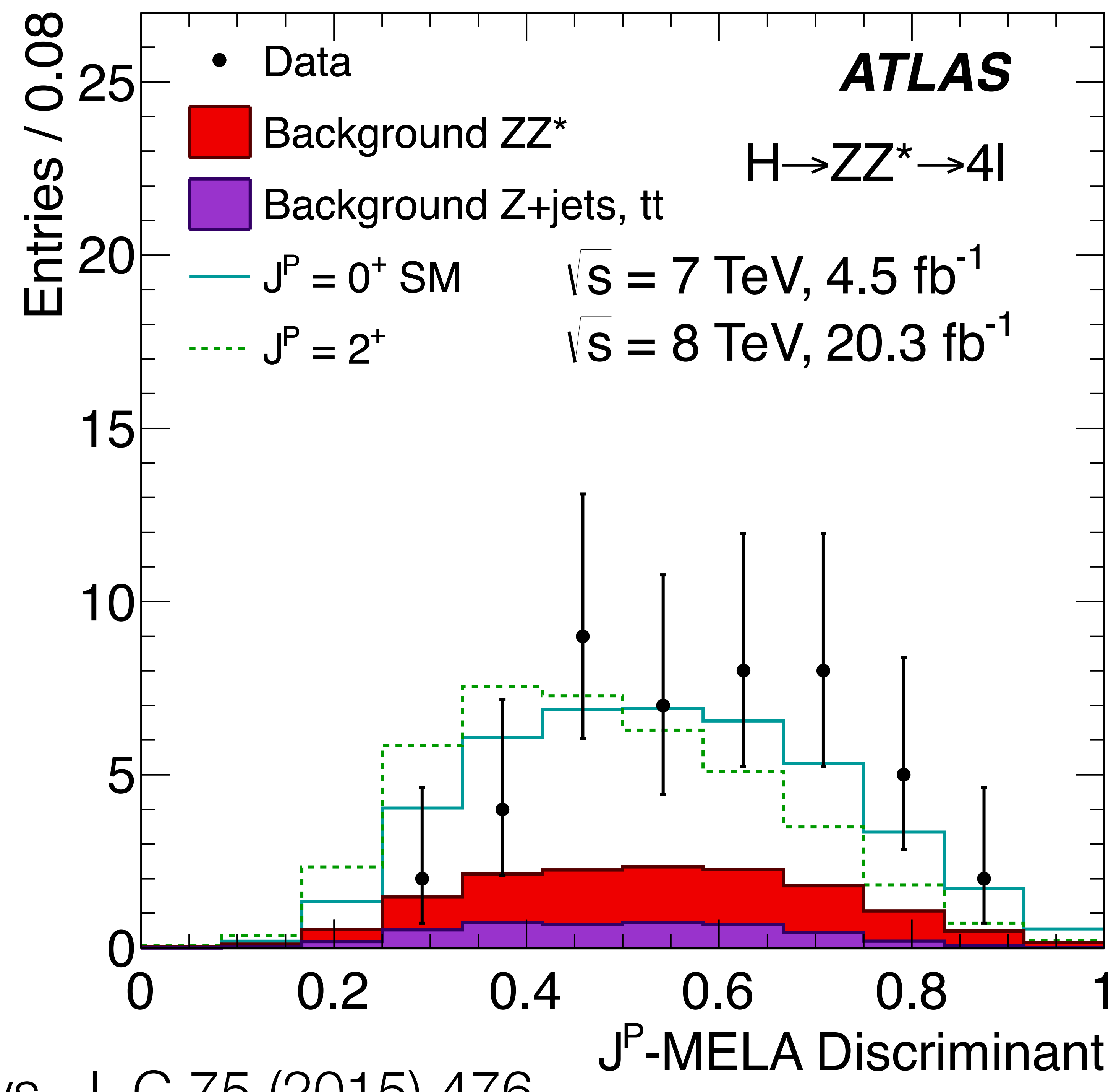


$$|\cos\theta^*| = \frac{|\sinh(\Delta\eta^{\gamma\gamma})|}{\sqrt{1+(p_T^{\gamma\gamma}/m_{\gamma\gamma})^2}} \frac{2p_T^{\gamma_1} p_T^{\gamma_2}}{m_{\gamma\gamma}^2}$$

Eur. Phys. J. C 75 (2015) 476

Variables can be defined in the $H \to ZZ$ decay that are sensitive to spin and parity



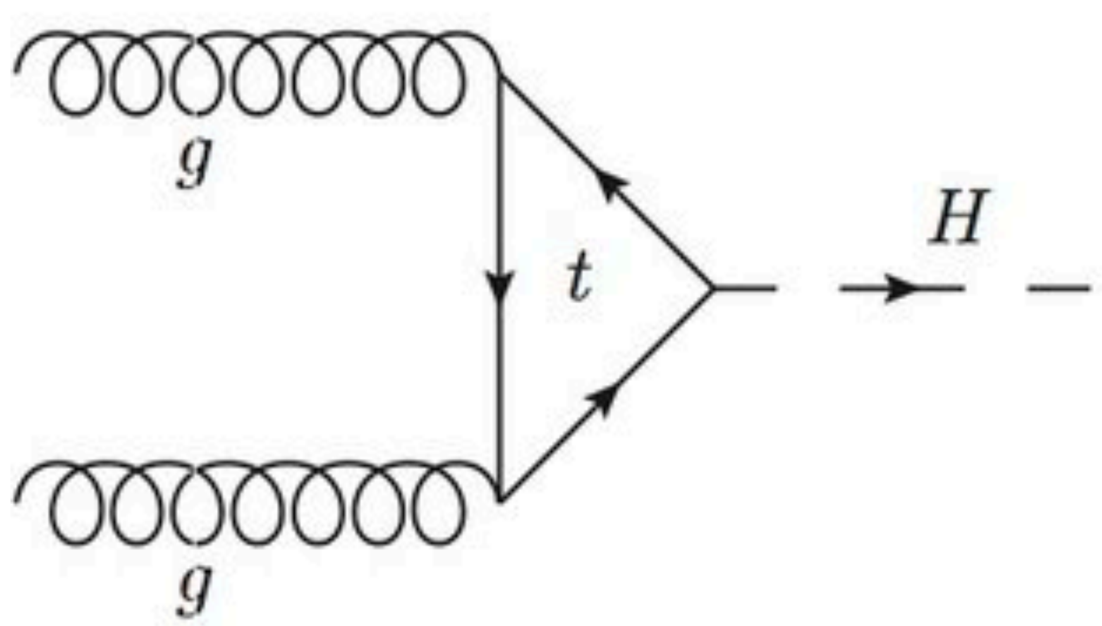


Eur. Phys. J. C 75 (2015) 476

Higgs production modes at the LHC

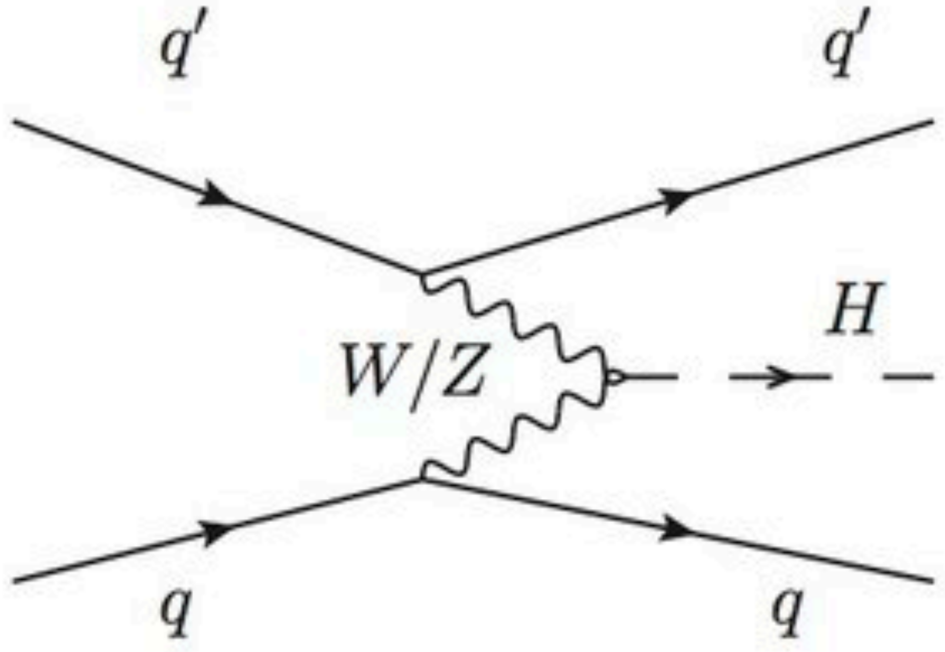
Run 2 production rates shown (13 TeV, ~150 fb^{-1})

Gluon fusion (ggF)



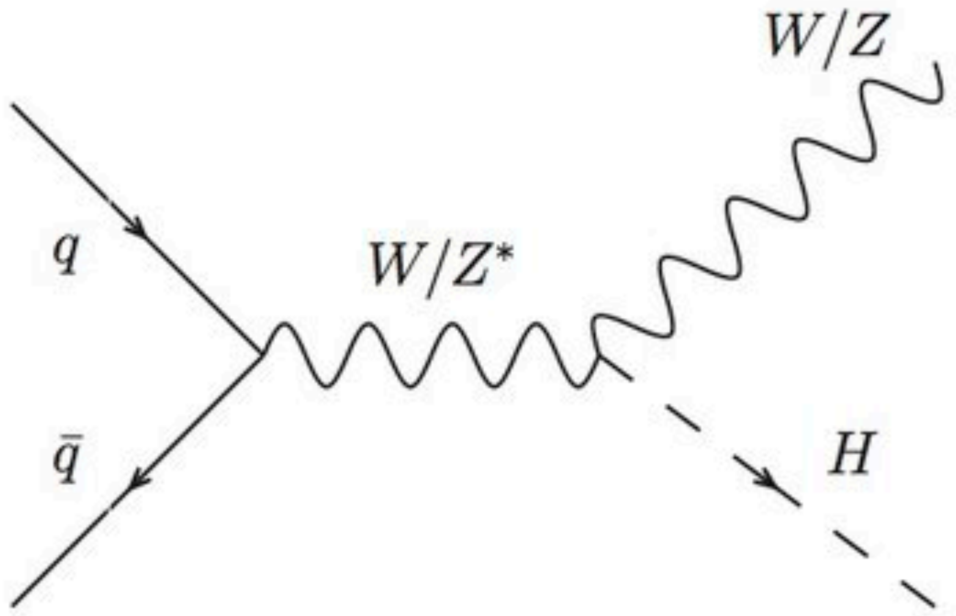
~8 M events

Vector-boson fusion (VBF)



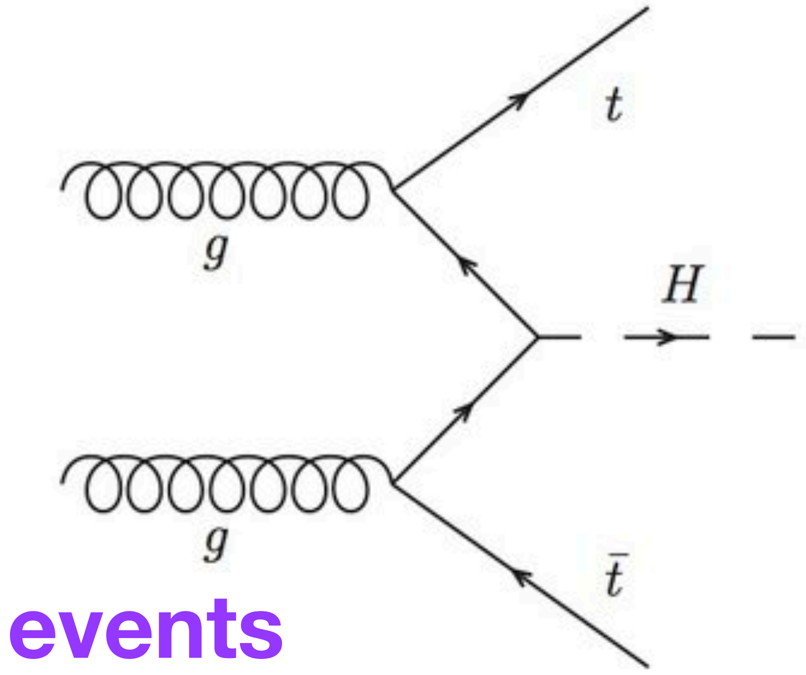
~600 k events

Higgs-strahlung (VH)



~400 k events

Higgs production in association with $t\bar{t}$ (ttH)

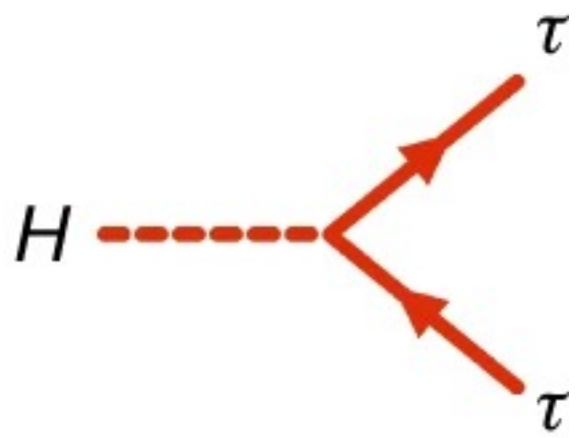


~80 k events

DOI:10.13140/RG.2.2.24097.02408

Nature 607 52–59 (2022)

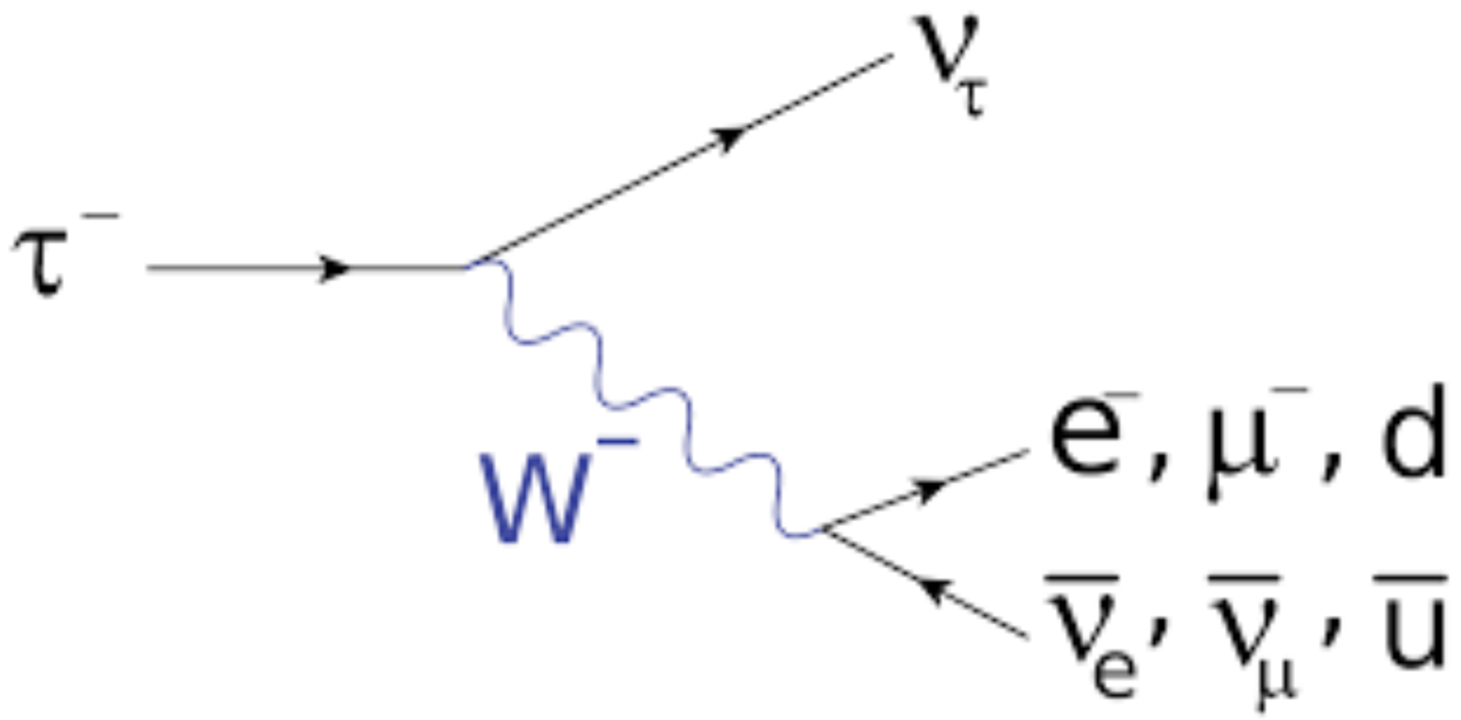
Higgs to $\tau\tau$



τ leptons are complicated to reconstruct

- Various decay modes including neutrinos
- Analysis through statistical combination of variety of channels

The only lepton heavy enough to decay to hadrons



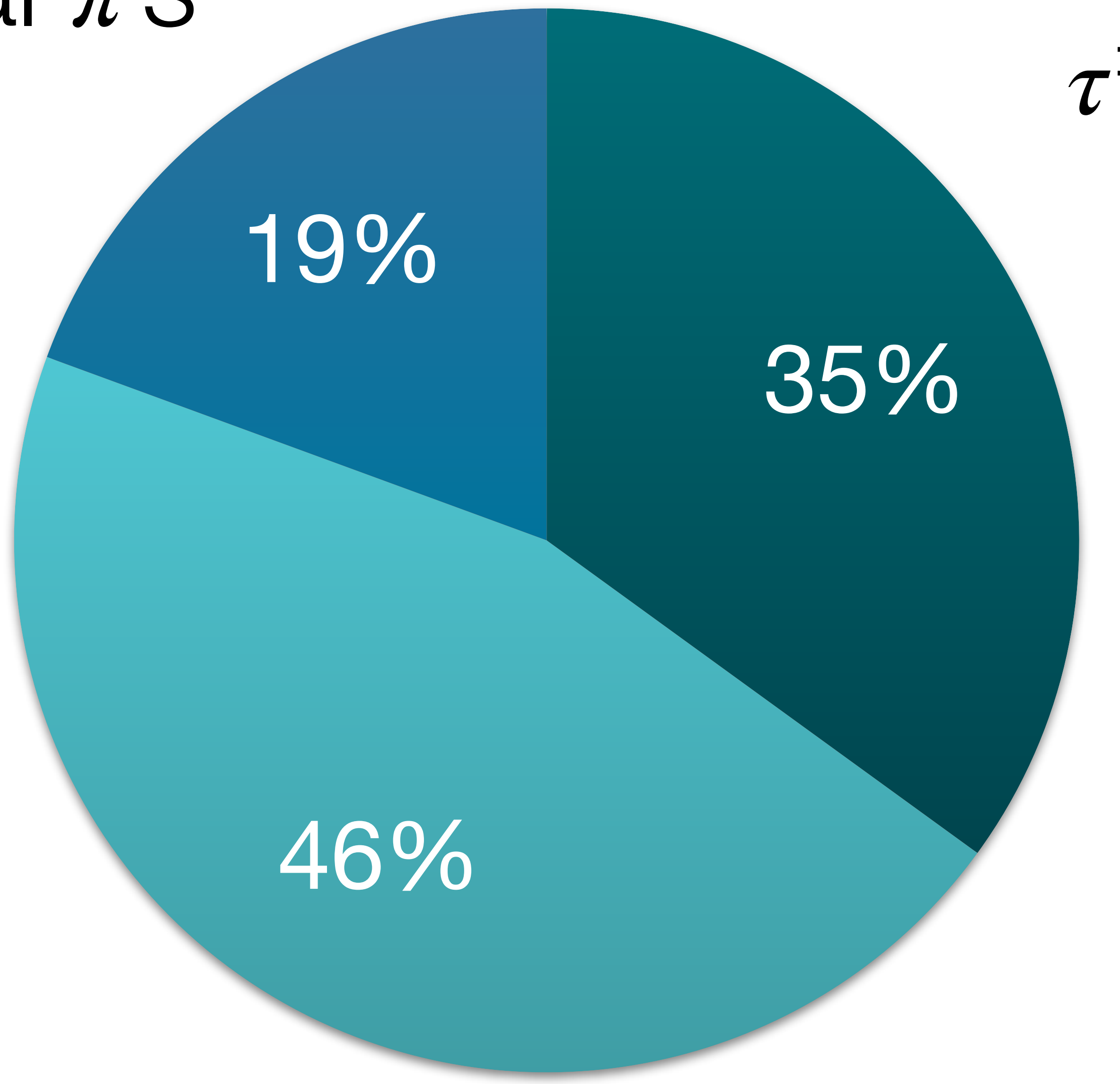
3 prong

$\tau^{\pm} \to \pi^{\pm}\pi^{\mp}\pi^{\pm}\nu_{\tau}$

$+ \geq 0$ neutral π's

Leptonic

$\tau^{\pm} \to l^{\pm}\nu_{l}\nu_{\tau}$



1 prong

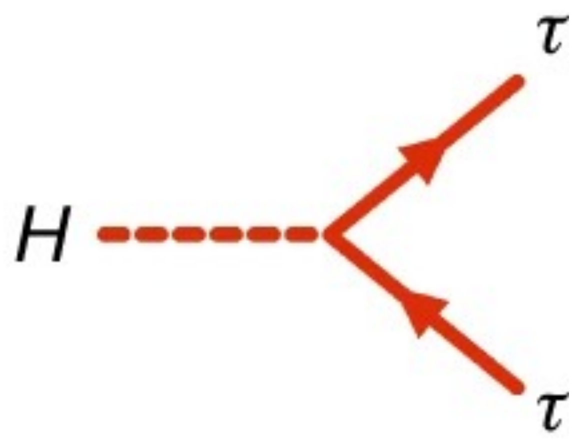
$\tau^{\pm} \to \pi^{\pm}\nu_{\tau}$

$+ \geq 0$ neutral π's

wikipedia

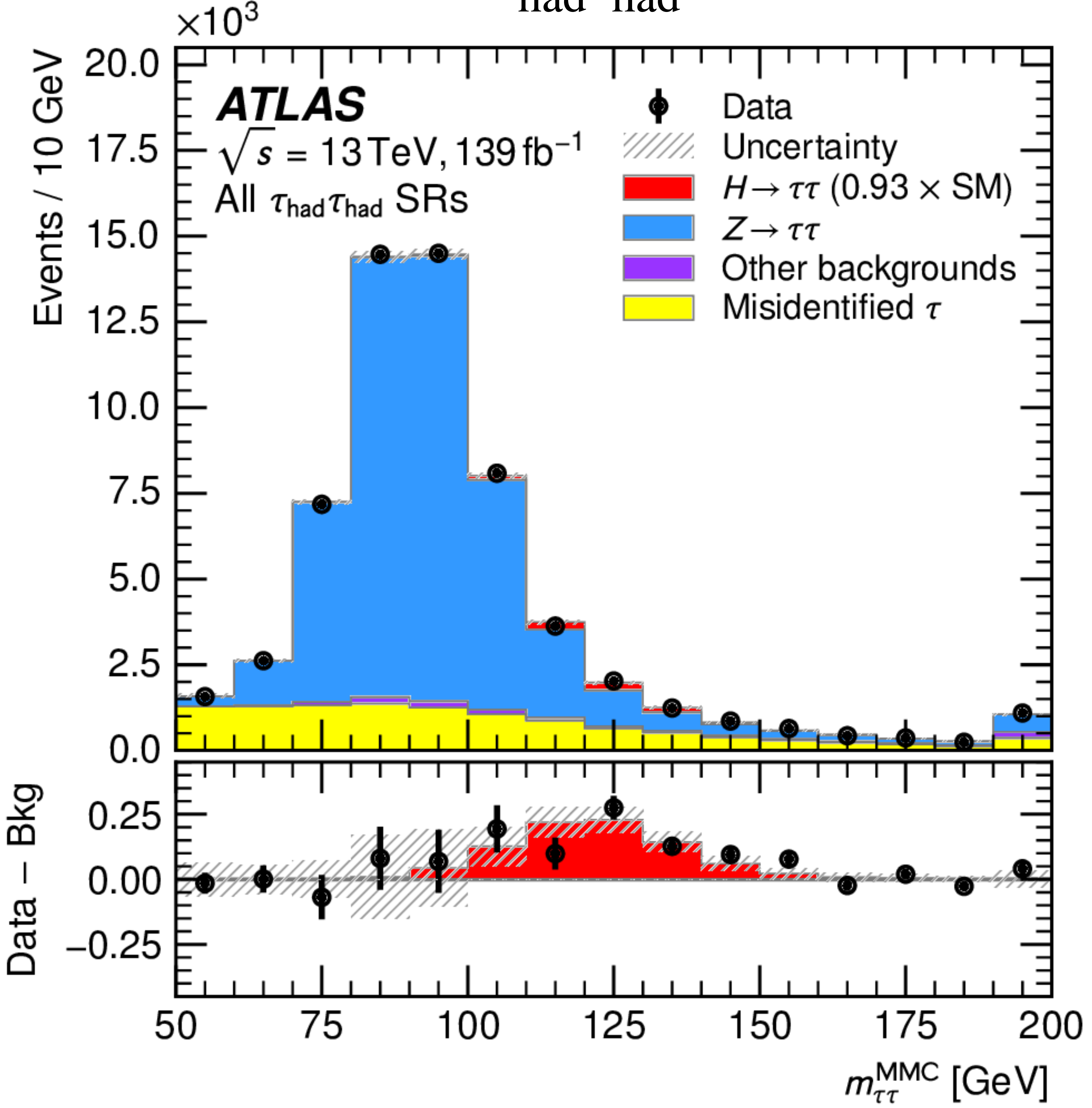
Nature 607 52–59 (2022)

Higgs to $\tau\tau$

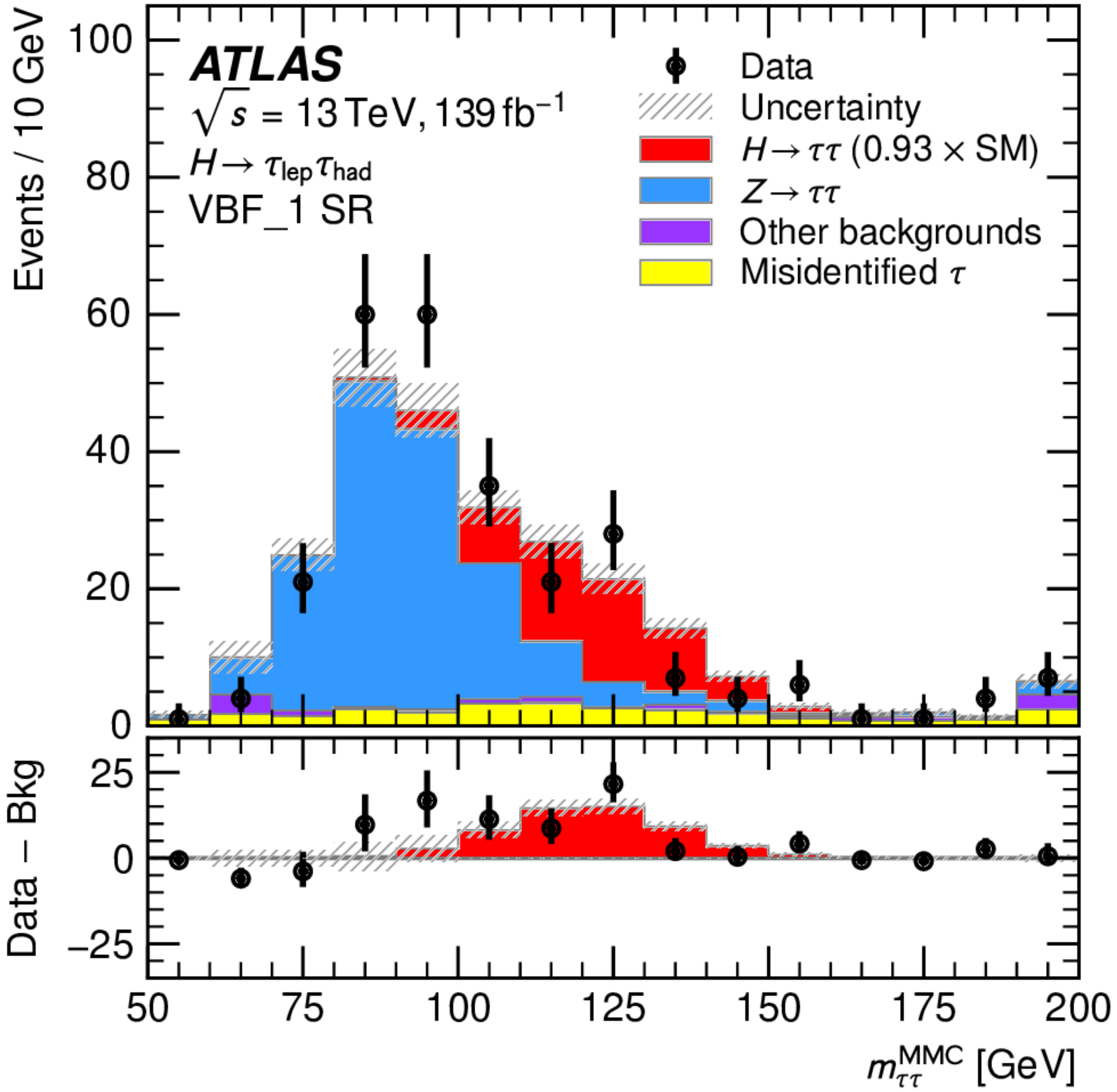


Large backgrounds from $Z \rightarrow \tau\tau$ + jets

All $\tau_{had}\tau_{had}$ SRs



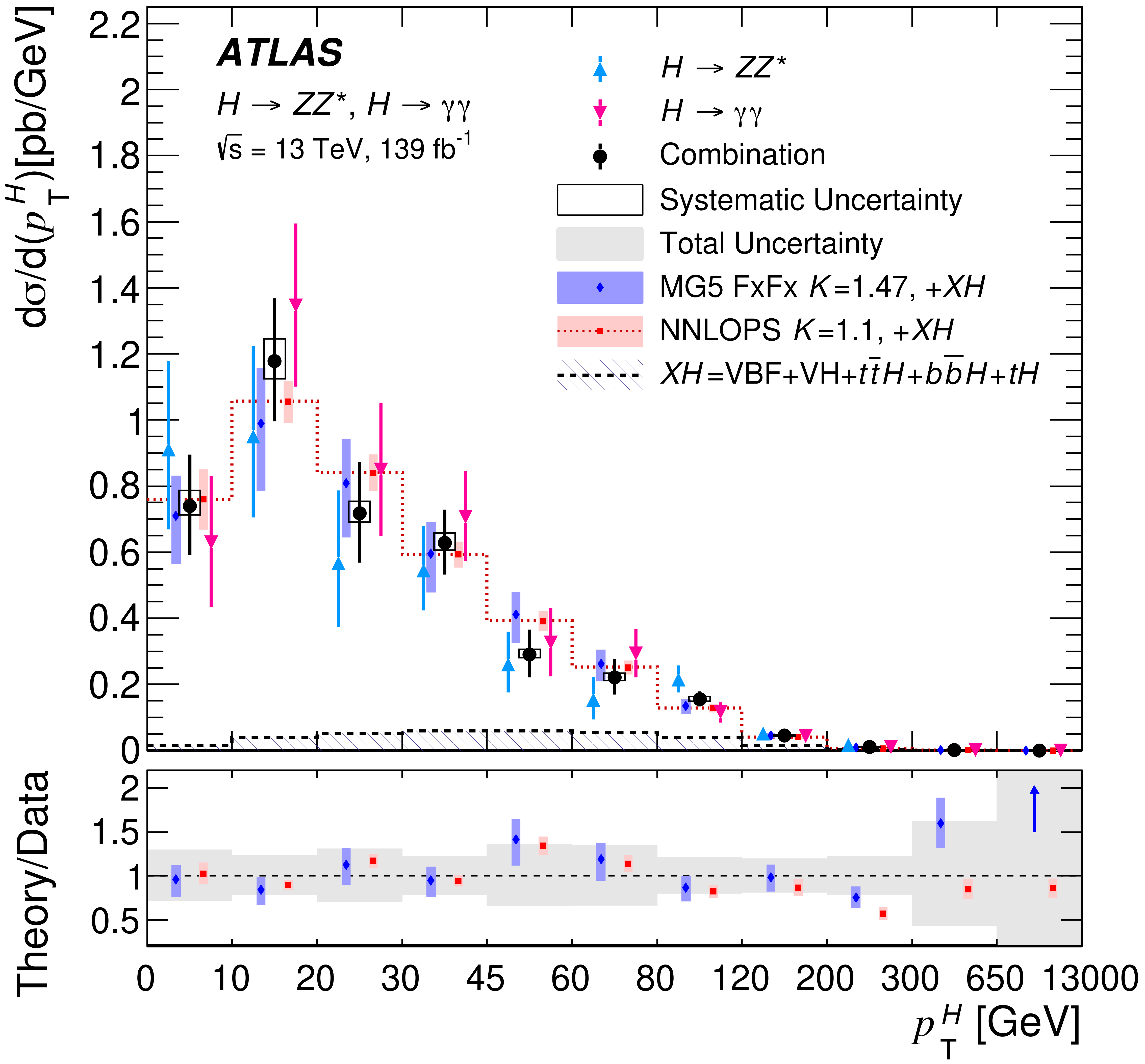
VBF $\tau_{lep}\tau_{had}$



JHEP 08 (2022) 175

Differential Higgs measurement

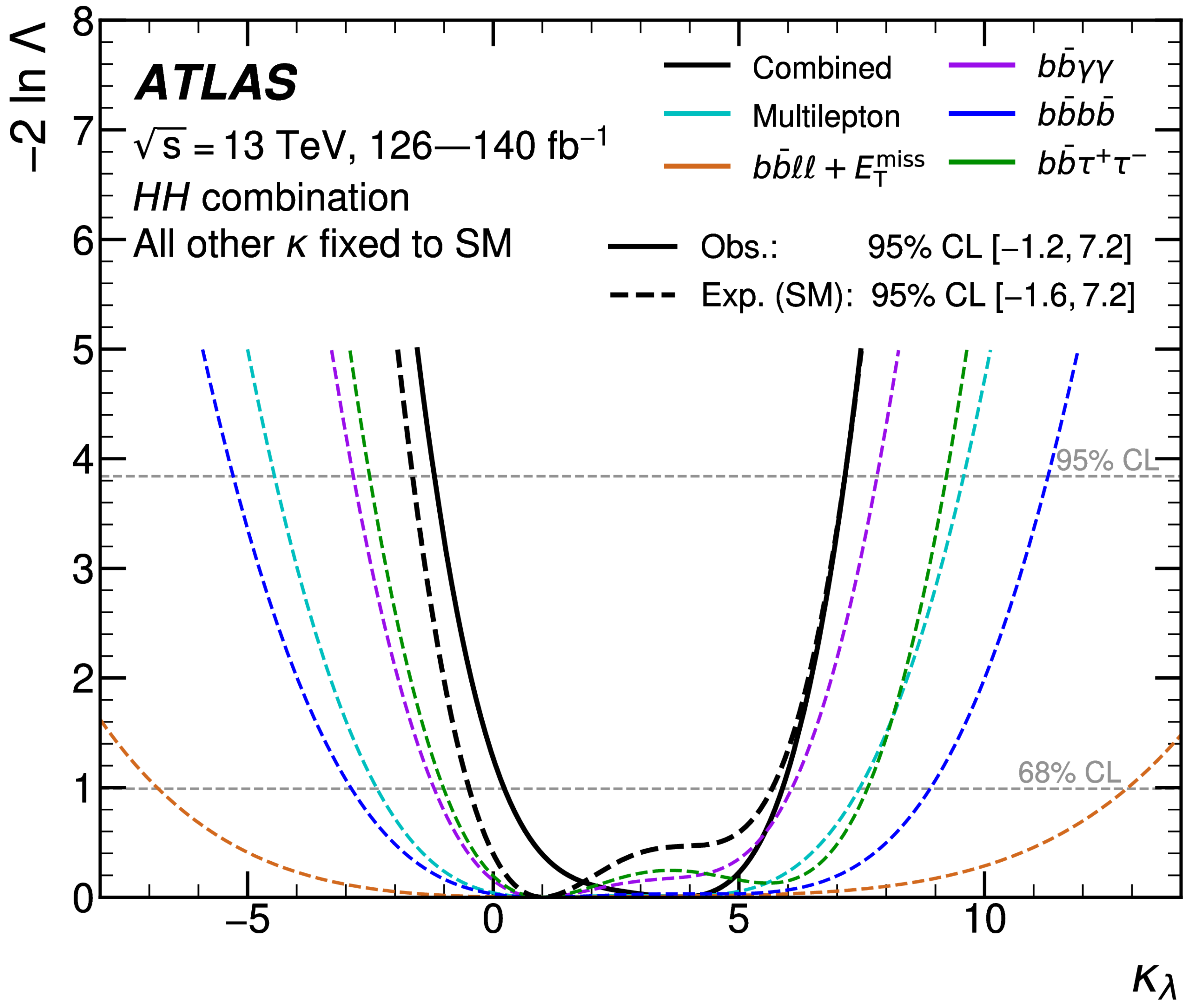
Enough Higgs candidates to perform **differential measurements** for variety of observables



JHEP 05 (2023) 028

Di-Higgs production

ATLAS Run 2 combination:

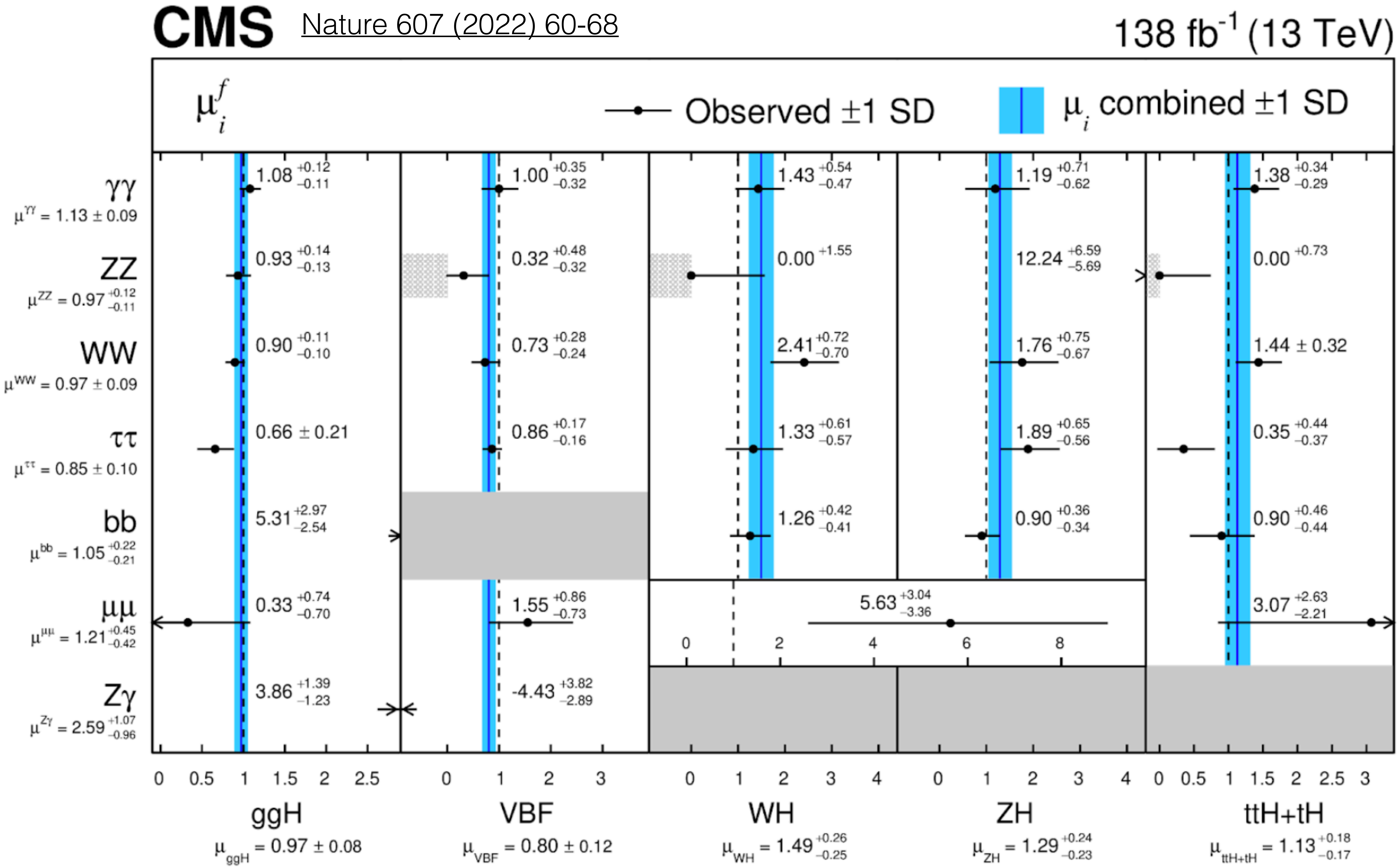


Higgs-self coupling will be a key focus at the HL-LHC

arXiv:2406.09971

Putting it all together

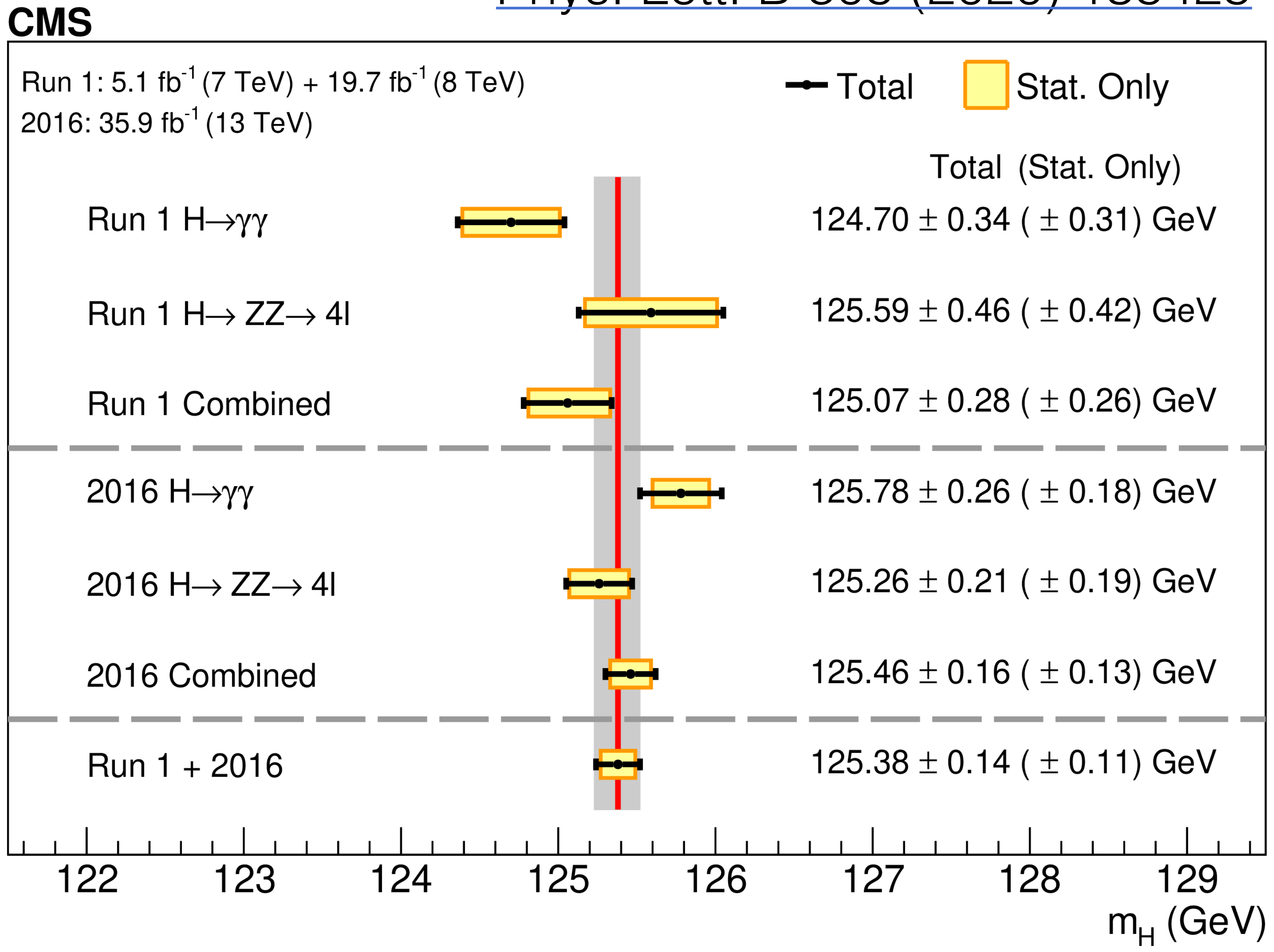
Almost all production modes established

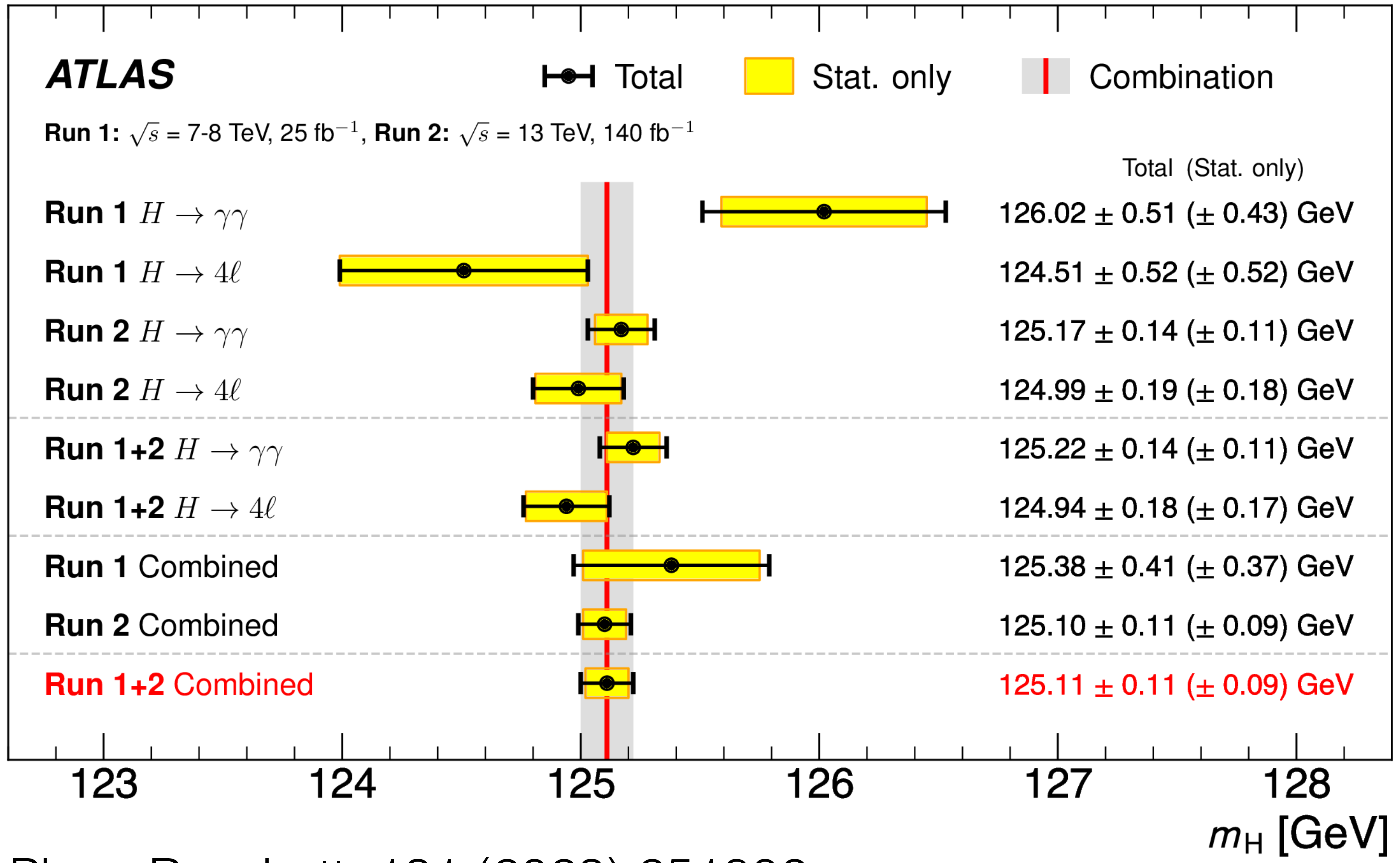


Higgs mass measurements

- **Not predicted by SM**
- **Mass measurements in "golden channels": H → $\gamma\gamma$ and H→ZZ**
- **Optimised analyses in categories with best mass resolution** (photon, electron and muon energy response)
- **Reached 0.09% precision**

Phys. Lett. B 805 (2020) 135425





Phys. Rev. Lett. 131 (2023) 251802

H→WW control region

Owing to spin correlations in the $WW^{(*)}$ system arising from the spin-0 nature of the SM Higgs boson and the V-A structure of the W boson decay vertex, the charged leptons tend to emerge from the primary vertex pointing in the same direction [107]. This kinematic feature is exploited for all jet multiplicities by requiring that $|\Delta\phi_{\ell\ell}| < 1.8$, and the dilepton invariant mass, $m_{\ell\ell}$, be less than 50 GeV for the 0-jet and 1-jet channels. For the 2-jet channel, the $m_{\ell\ell}$ upper bound is increased to 80 GeV.

6.2.3. WW control sample

The MC predictions of the WW background in the 0-jet and 1-jet analyses, summed over lepton flavours, are normalised using control regions defined with the same selections as for the signal region except that the $\Delta\phi_{\ell\ell}$ requirement is removed and the upper bound on $m_{\ell\ell}$ is replaced with a lower bound: $m_{\ell\ell} > 80$ GeV.

Phys. Lett. B 716 (2012) 1-29