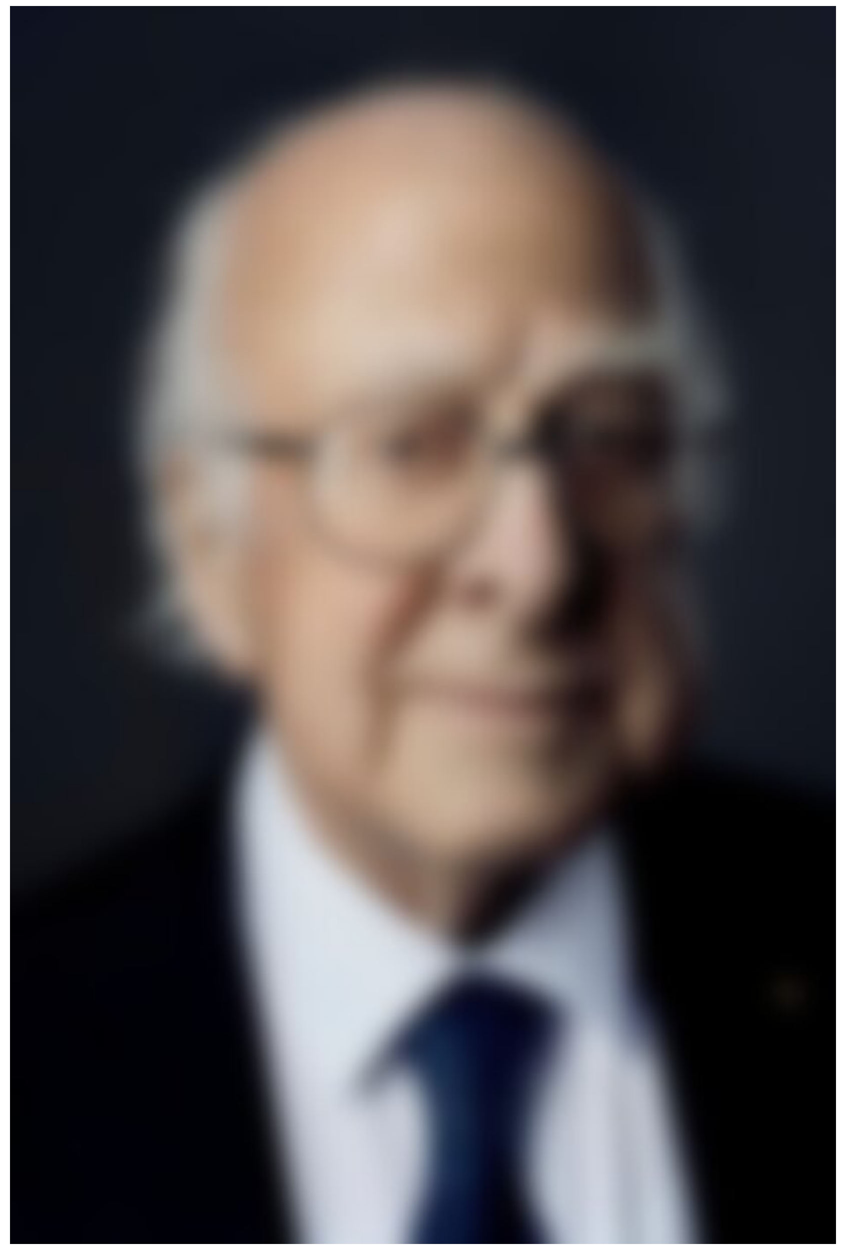
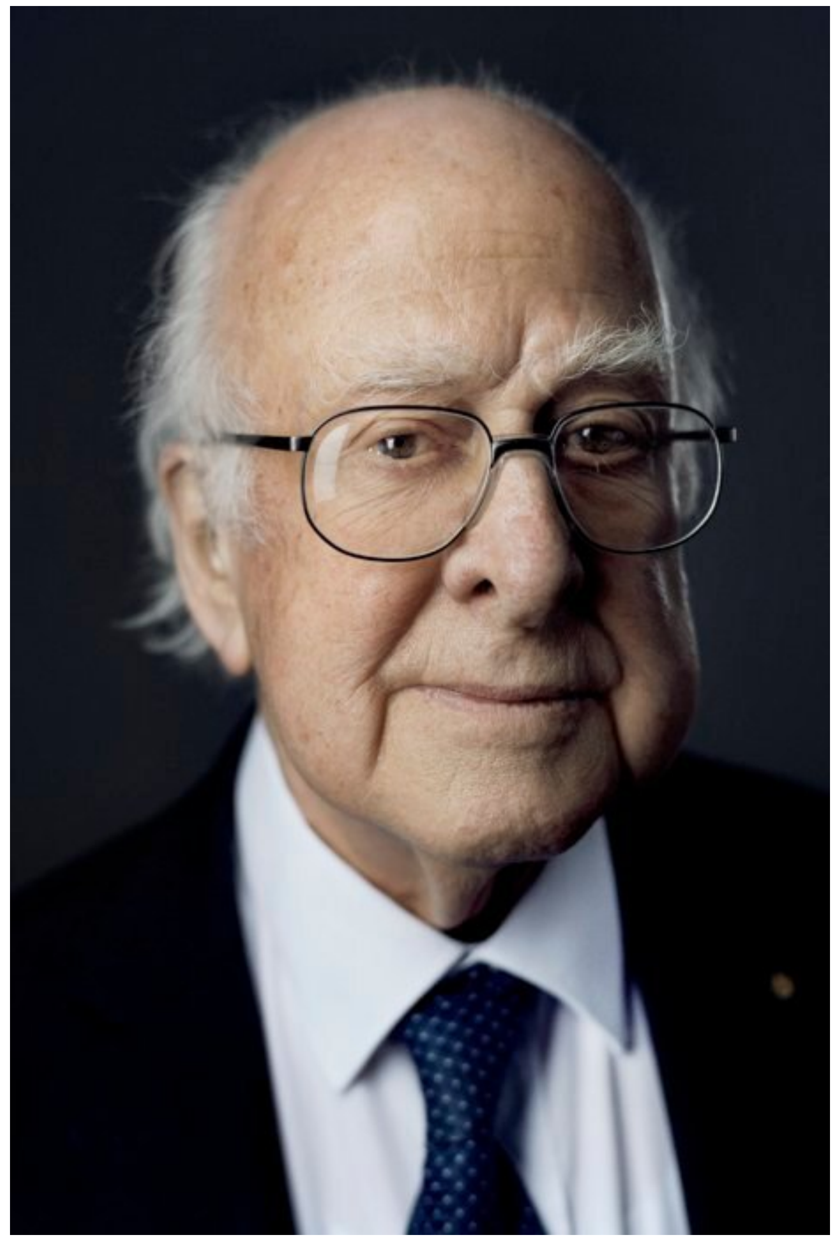
10 years of Higgs boson in ATLAS:



from discovery

to precision



Giovanni Marchiori (APC)

IRN Terascale
18 October 2022

APC

CNRS IN2P3 Les deux infinis

ATLAS EXPERIMENT

10 years ago..

- 4th July 2012 @CERN: (experimental) birth of the Higgs boson

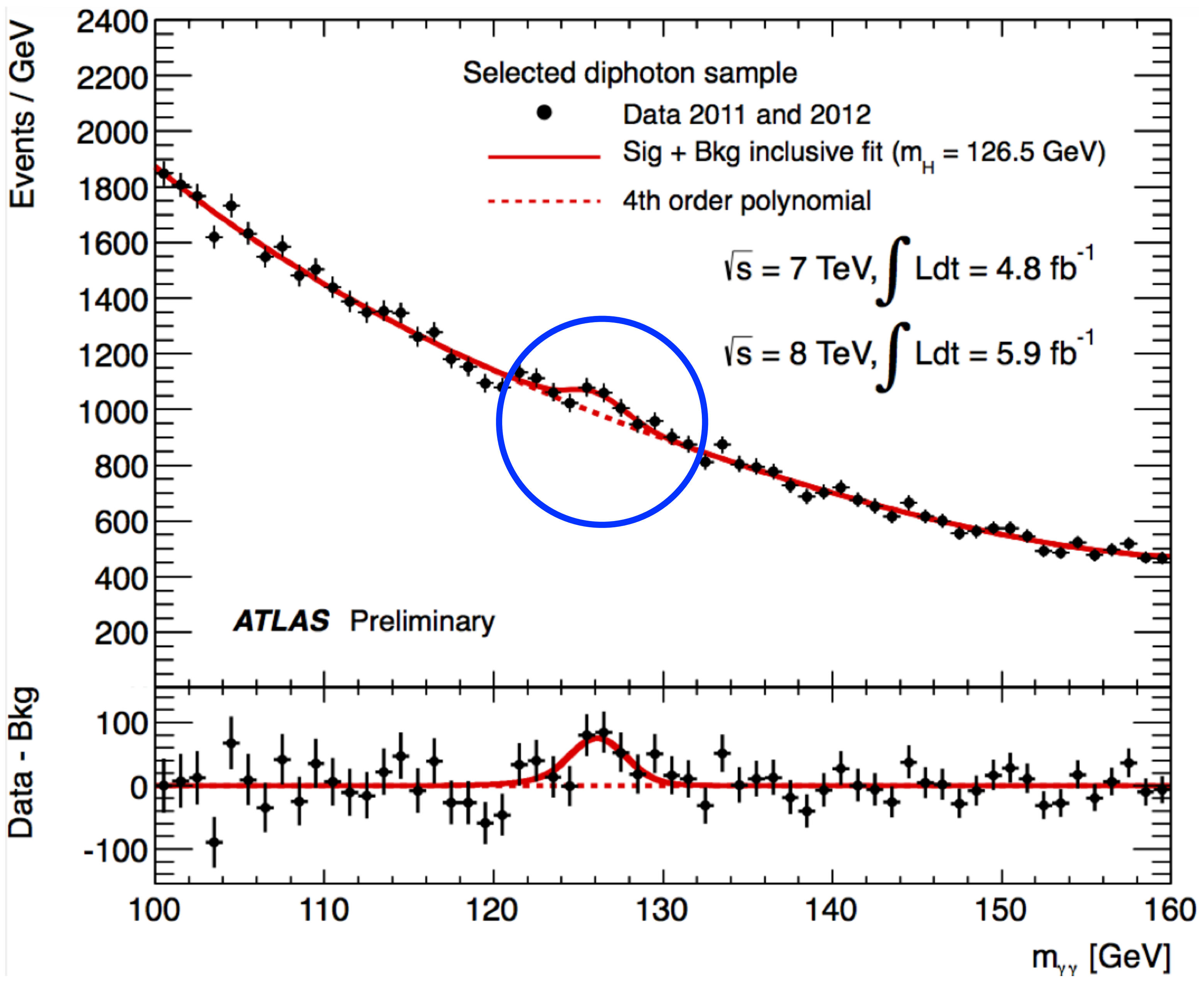
https://indico.cern.ch/event/197461/

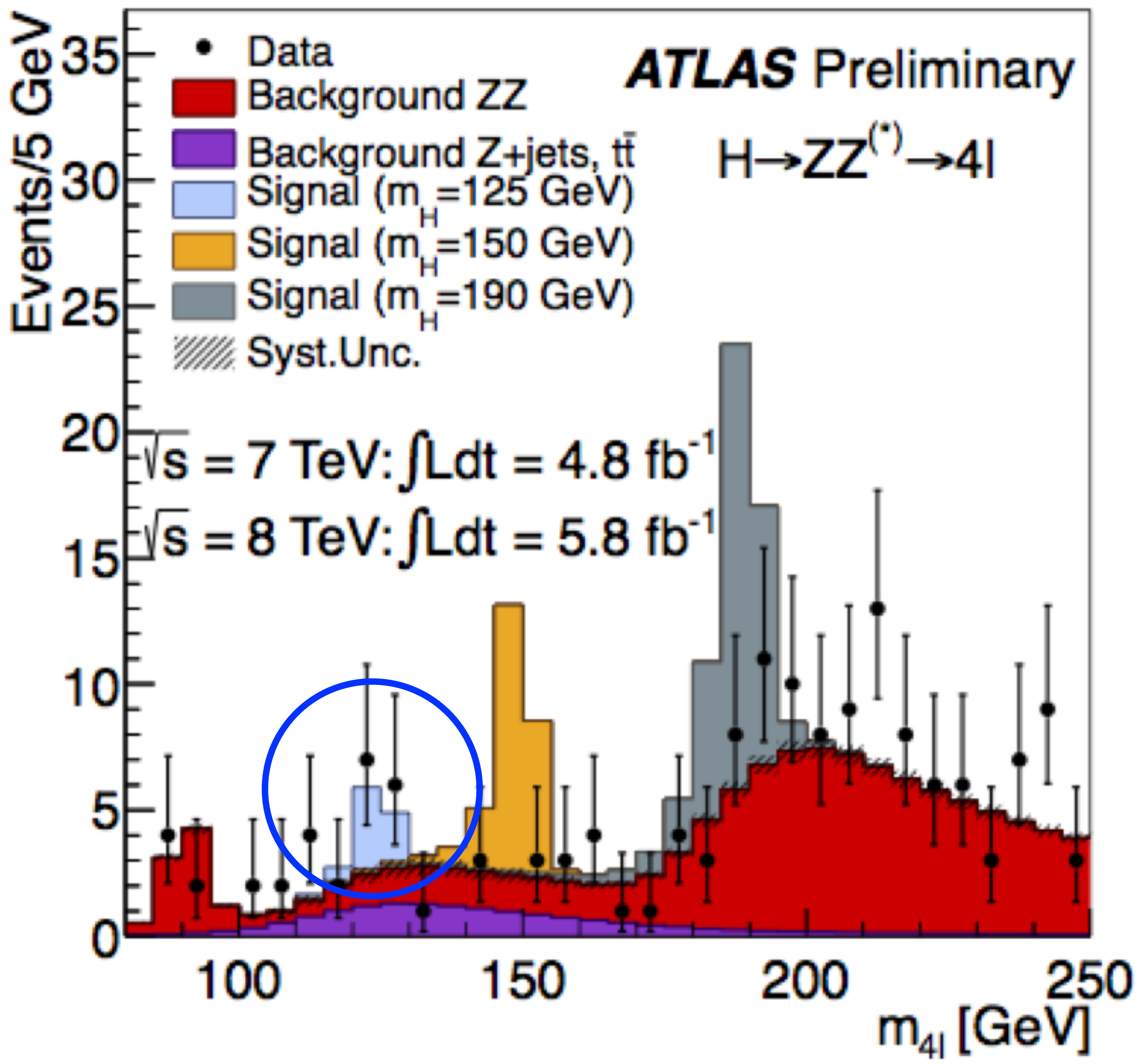
F. Gianotti (ATLAS) *R. Heuer (CERN)* *J. Incandela (CMS)*

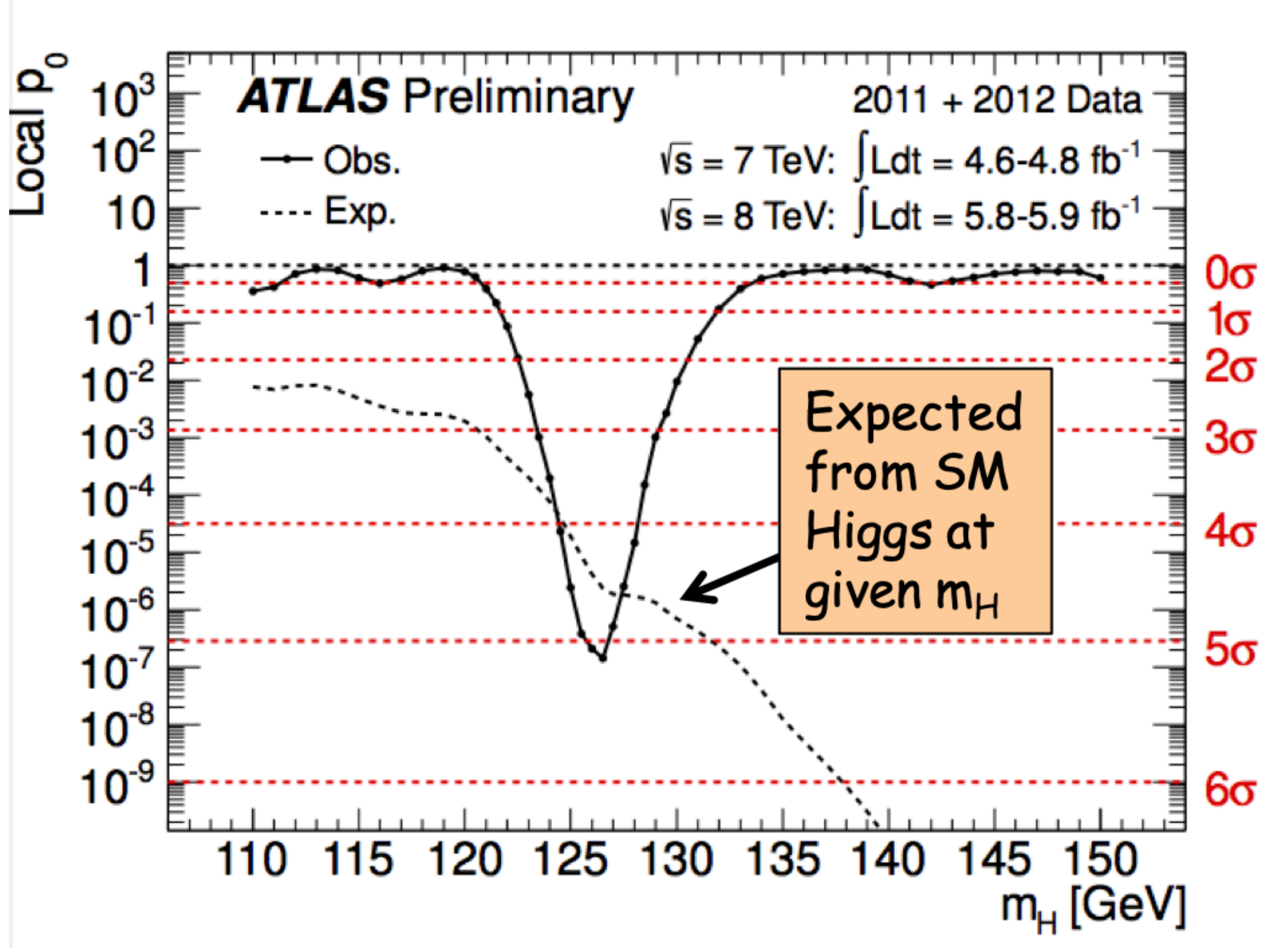
F. Englert *P. Higgs*

The Higgs boson discovery

- Analysis of up to 5/fb @ 7 TeV + 5/fb @ 8 TeV
- Main sensitivity / evidences from cleanest decay channels: H→γγ and H→ZZ(*)→4l (full dataset)

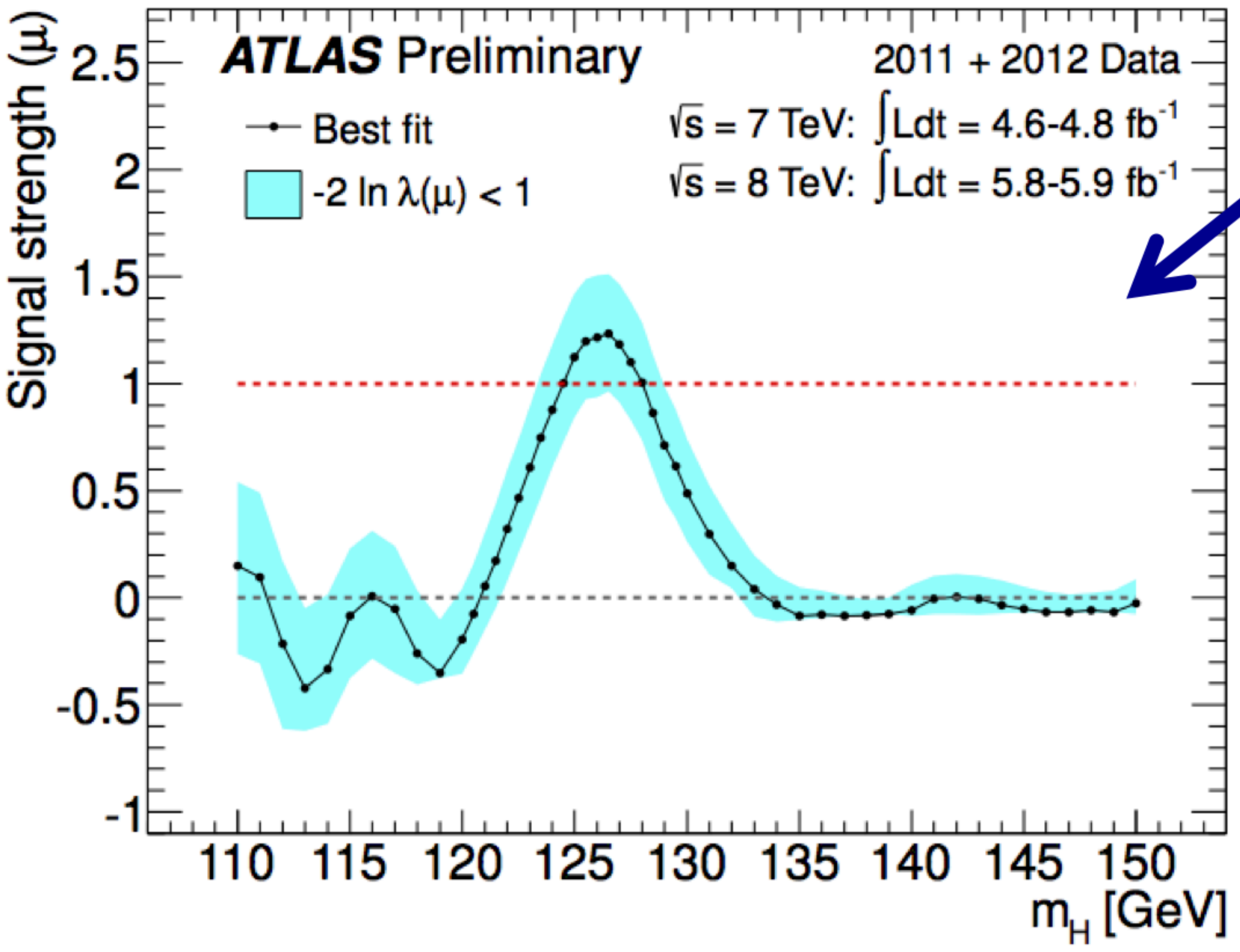






The Higgs boson discovery

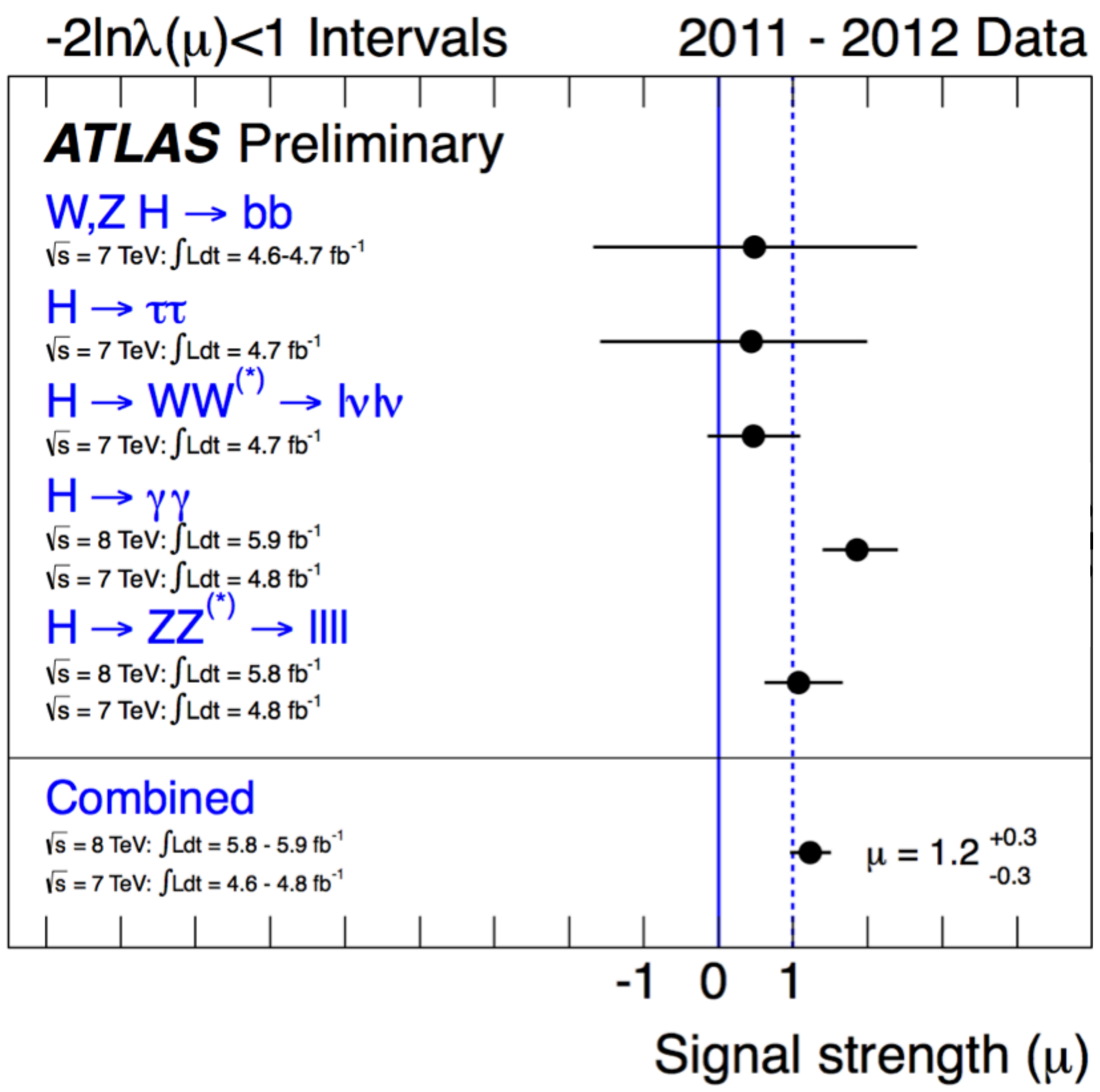
- Analysis of up to 5/fb @ 7 TeV + 5/fb @ 8 TeV
- Main sensitivity / evidences from cleanest decay channels: H→γγ and H→ZZ(*)→4l (full dataset)
- Some additional sensitivity from additional decay channels. All "signal strengths" in agreement with Standard Model (SM) of 1, O(25%) relative uncertainty after combination



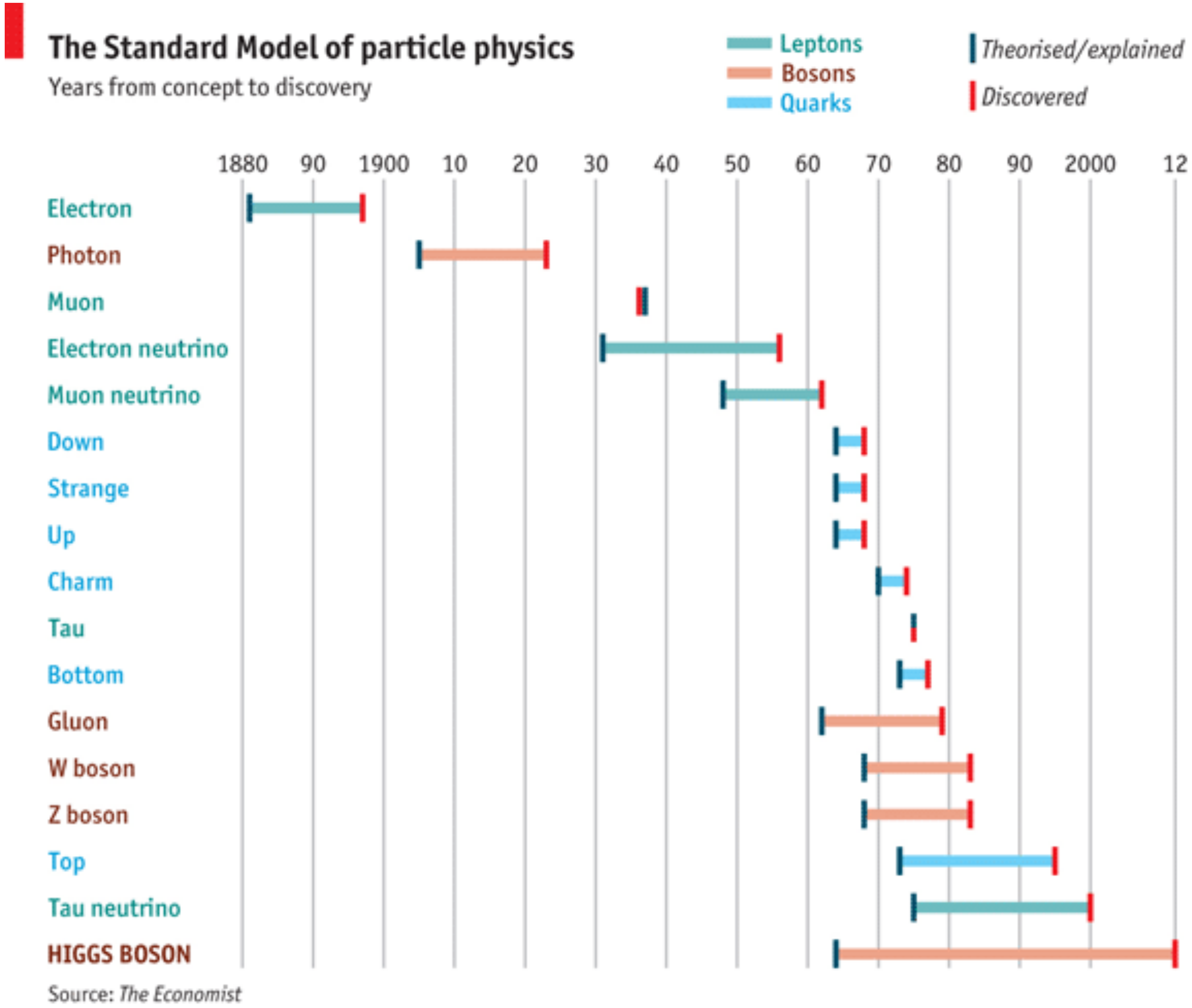
"signal strength"

Best-fit value at 126.5 GeV: μ = 1.2 ± 0.3

$$\mu = \frac{(\sigma \cdot \mathrm{BR})_{\mathrm{obs}}}{(\sigma \cdot \mathrm{BR})_{\mathrm{SM}}}$$



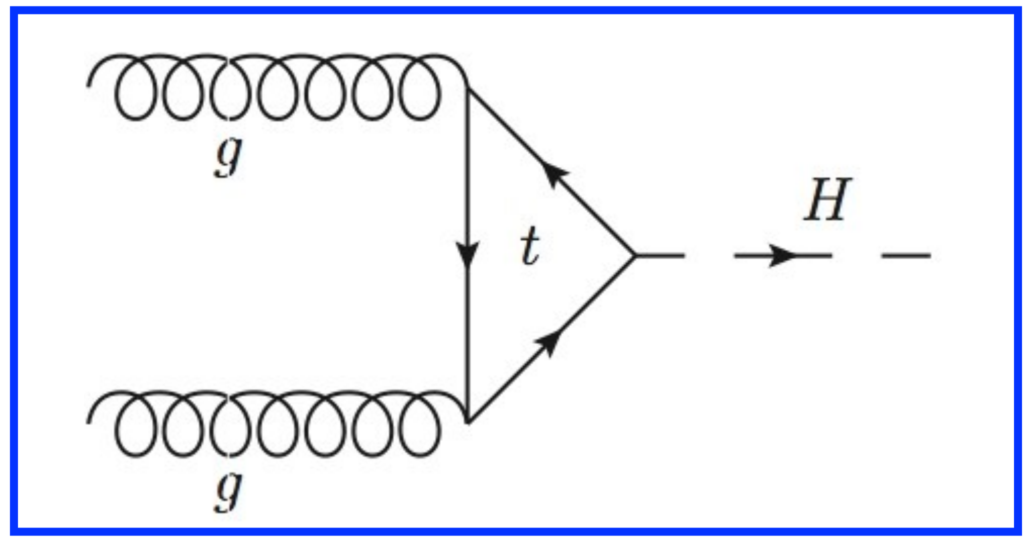
A long journey…



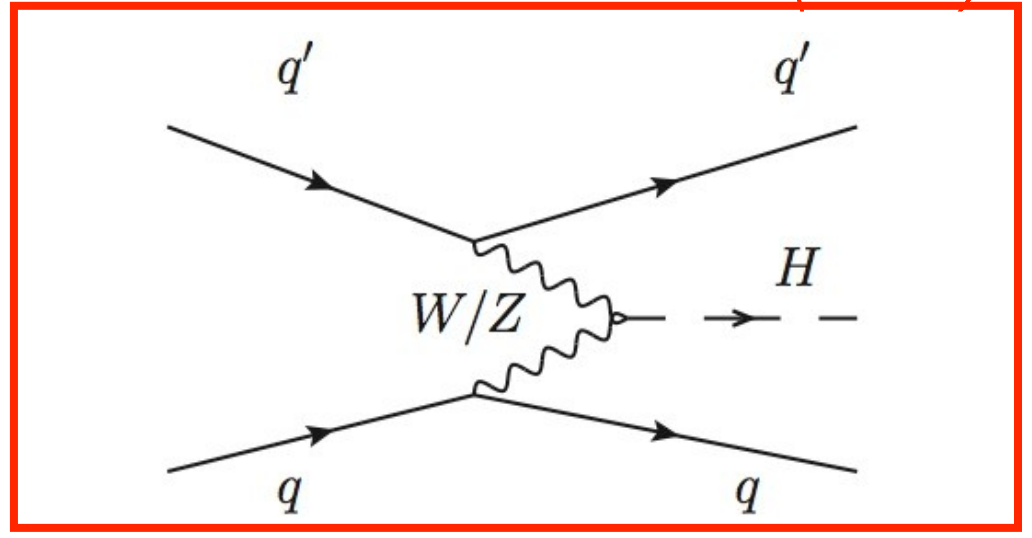
Producing a Higgs boson at the LHC

σ

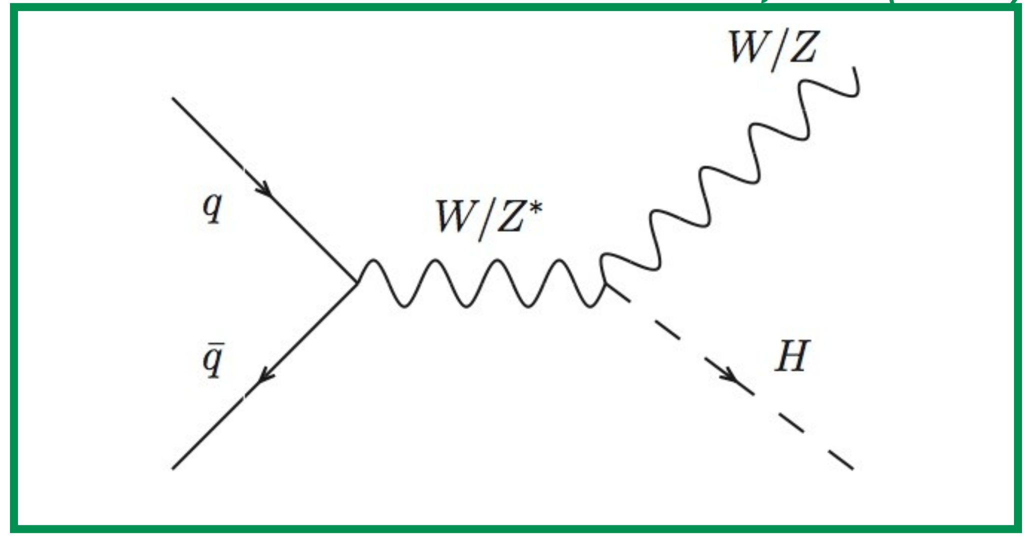
gluon-gluon fusion (ggF)



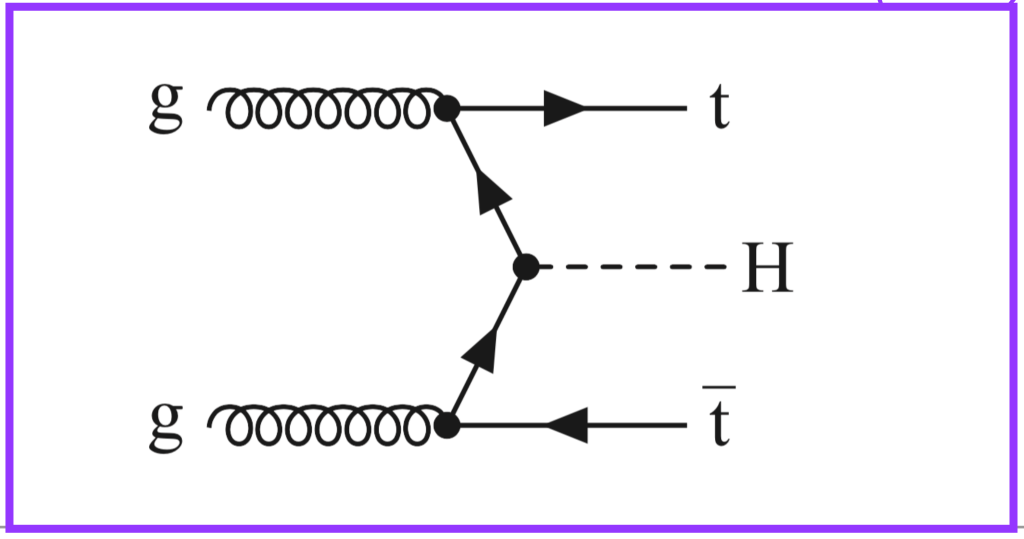
vector boson fusion (VBF)

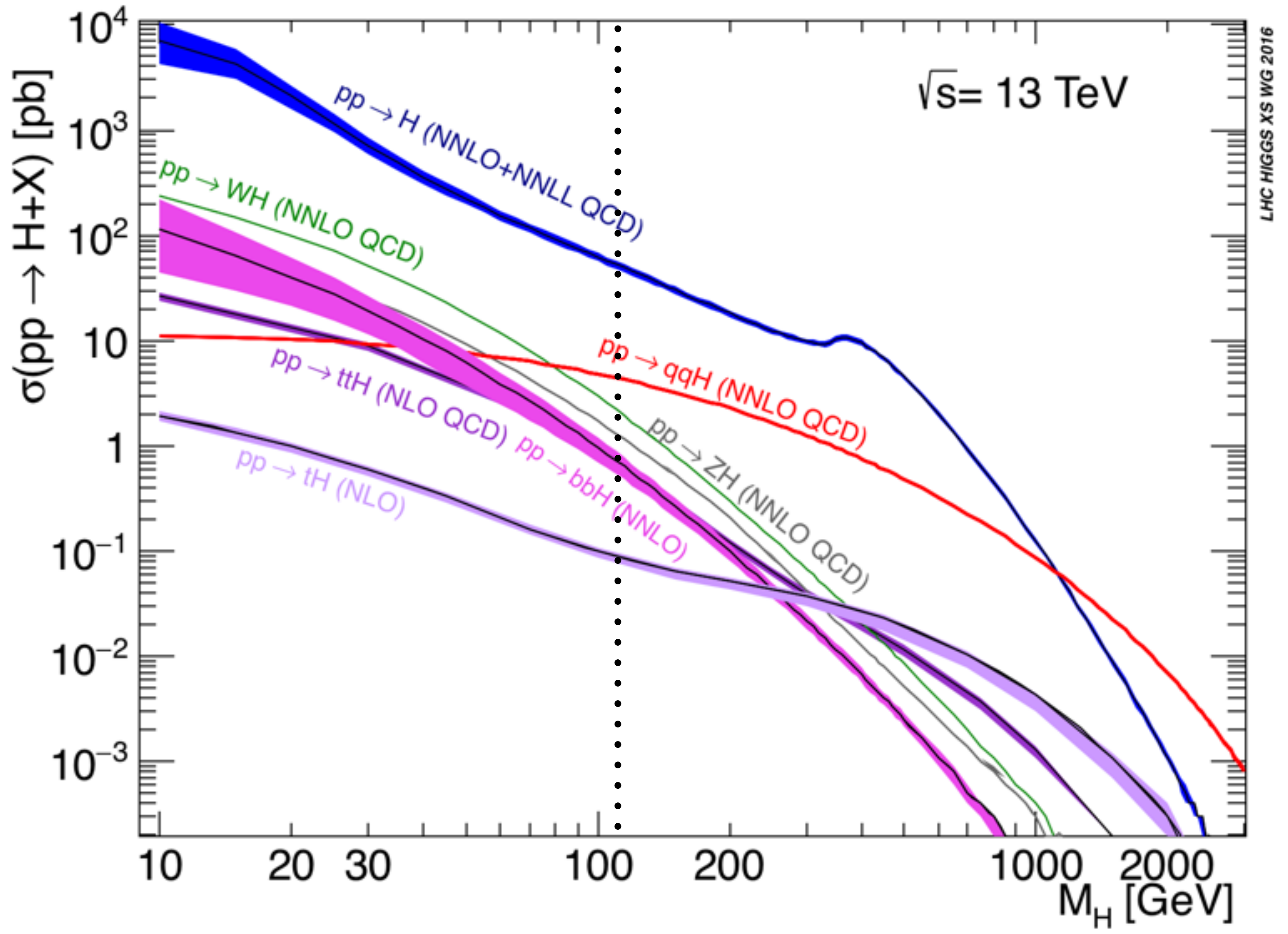


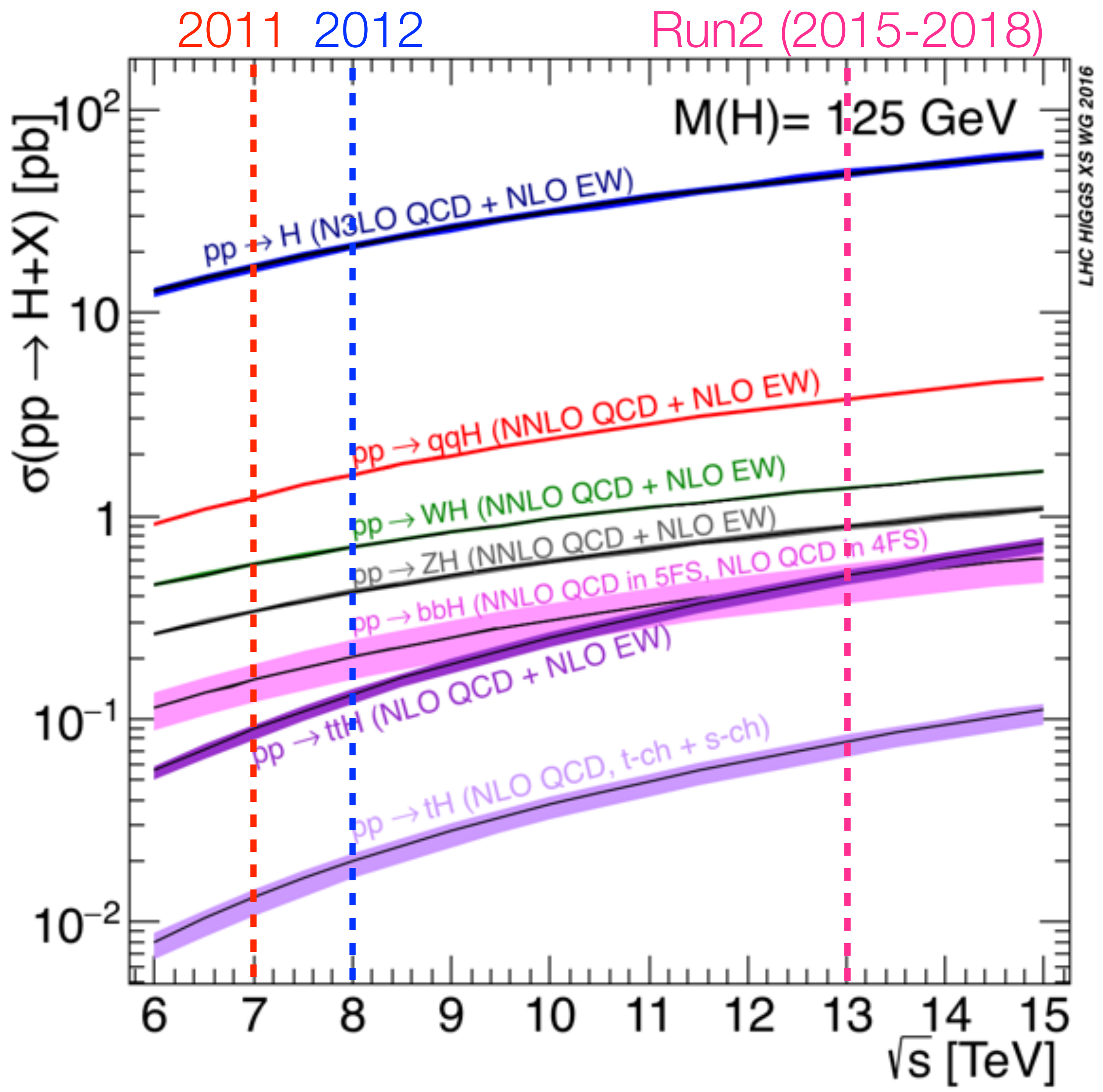
associated with V=W, Z (VH)



associated with ttbar (ttH)







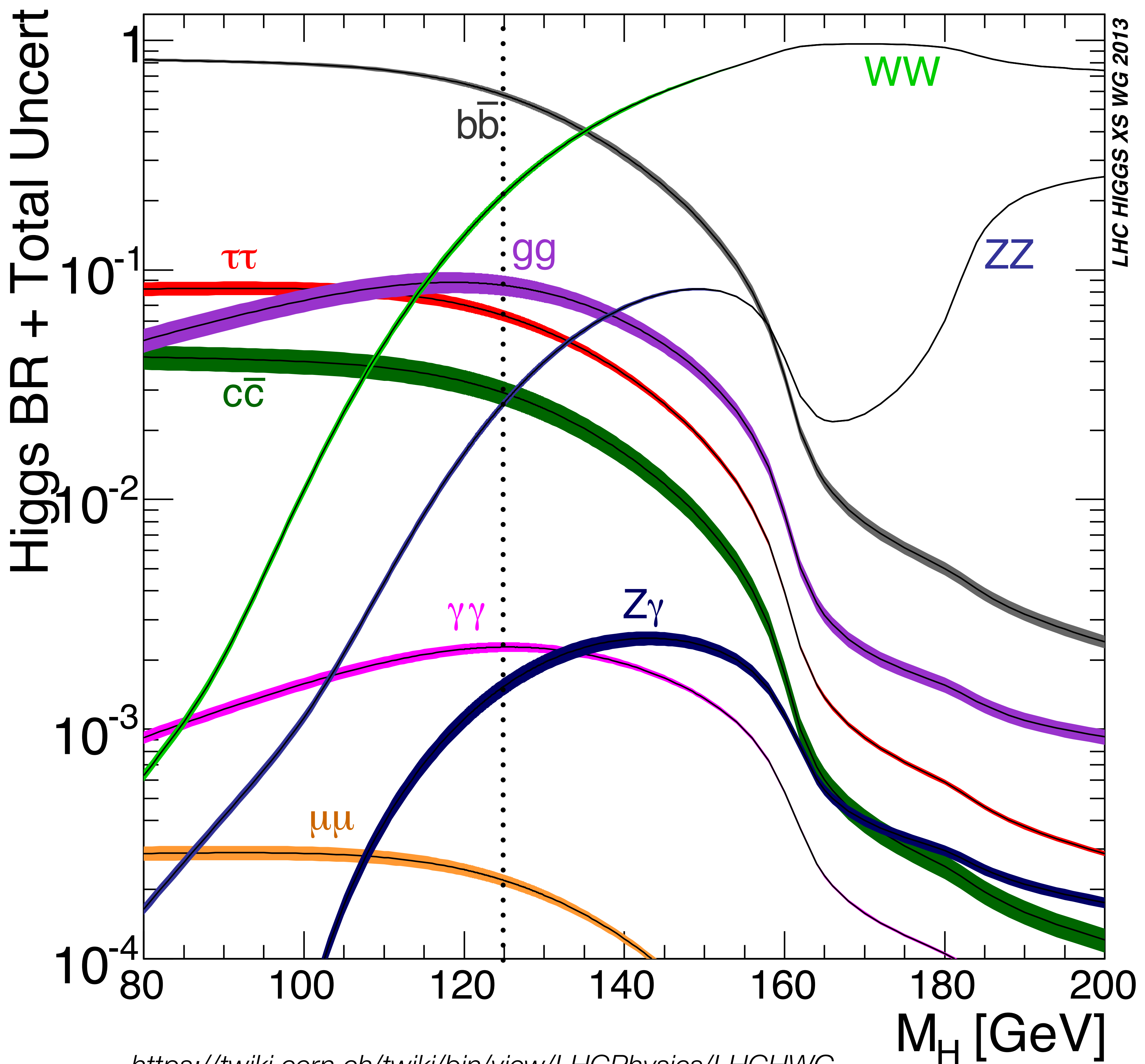
	σ √s=13 TeV m=125 GeV	N(Higgs) in 140/fb
ggF	49 pb	6.9M
VBF	3.8 pb	530k
VH	2.3 pb	320k
ttH	0.5 pb	70k
TOTAL	**56 pb**	**7.8M**

~600k Higgs bosons produced in Run1, 8M in Run2

⇒ LHC = 'Large Higgs Creator'!

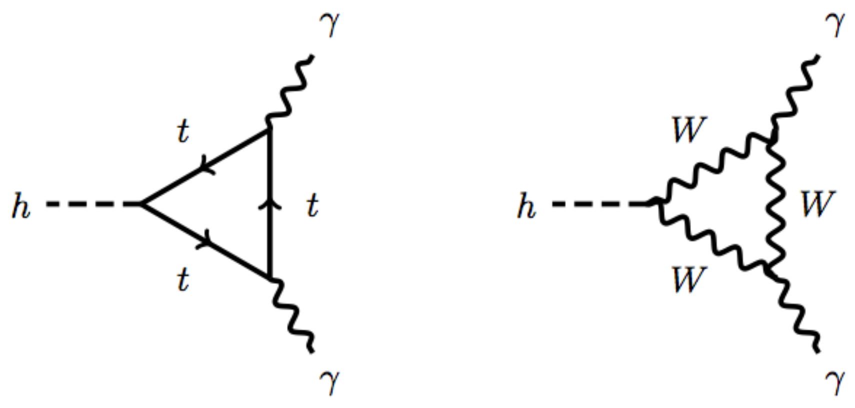
https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG

Higgs boson decays



https://twiki.cern.ch/twiki/bin/view/LHCPhysics/LHCHWG

Loop-induced effective photon coupling:



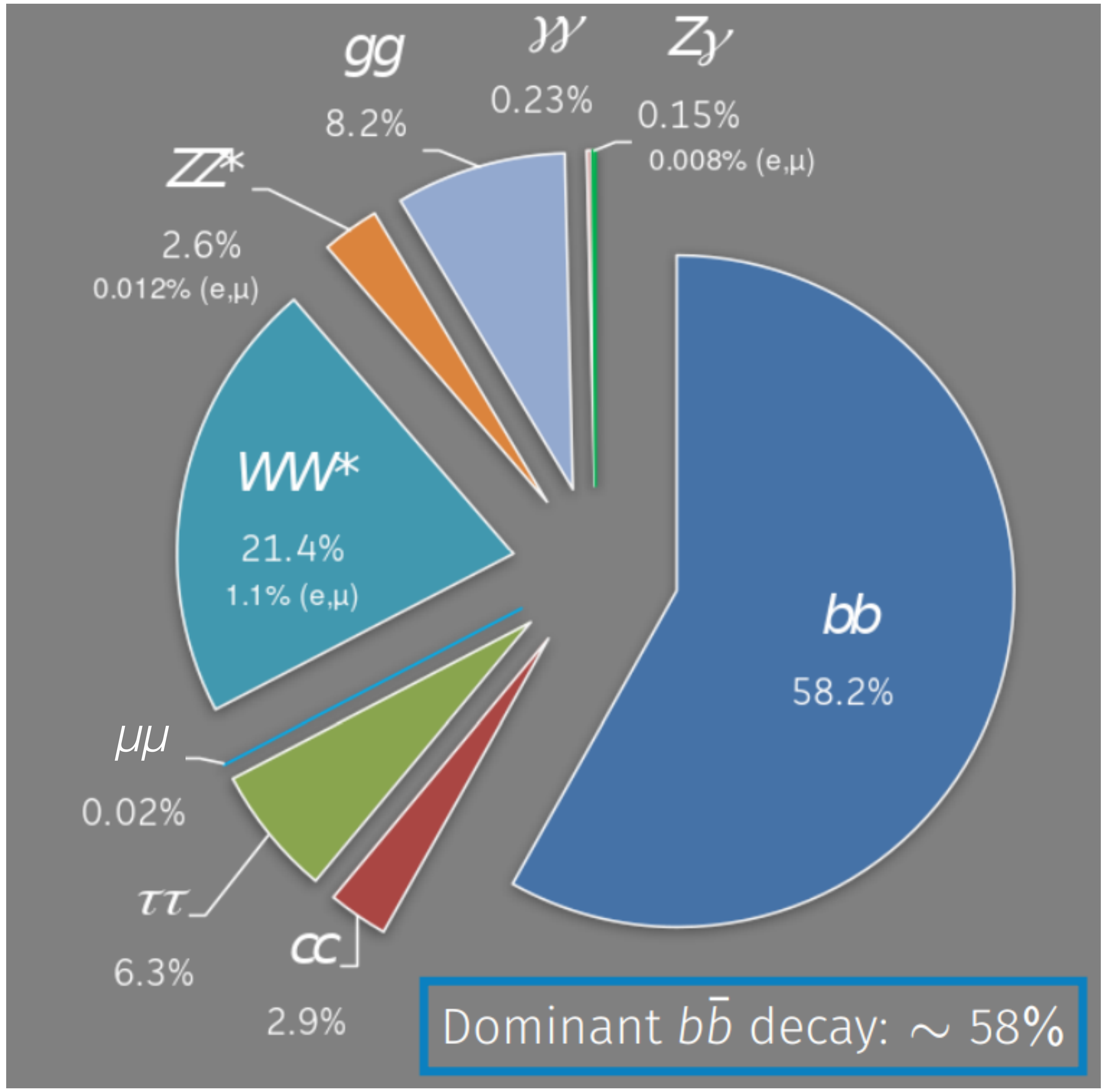
gg: high BR, but very poor q/g discrimination

→4l

ZZ, **γγ**: high mass resolution channels mass and precise differential measurements

WW: High BR, but low mass resolution

μμ: very small BR, but access to coupling to 2nd generation fermions

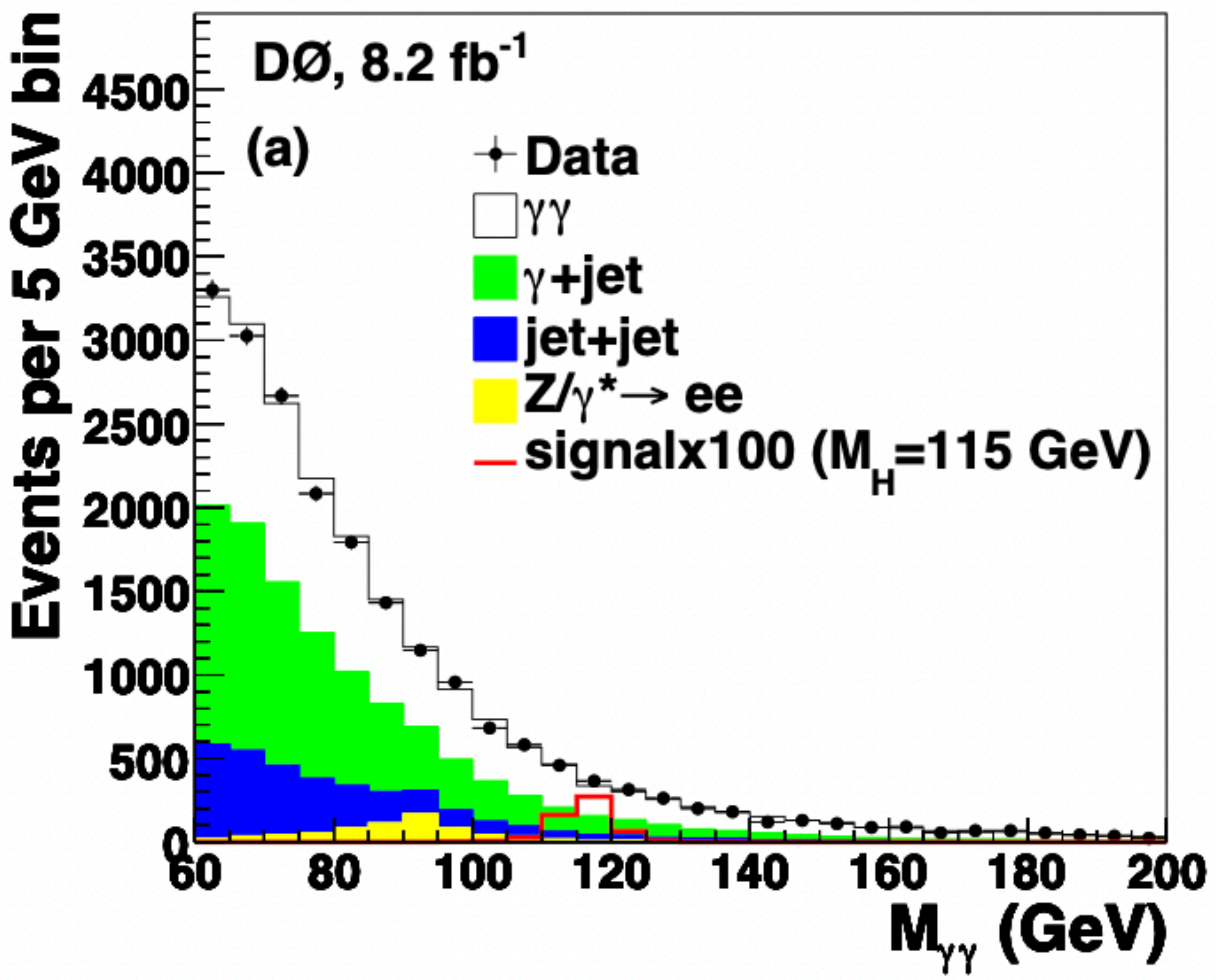


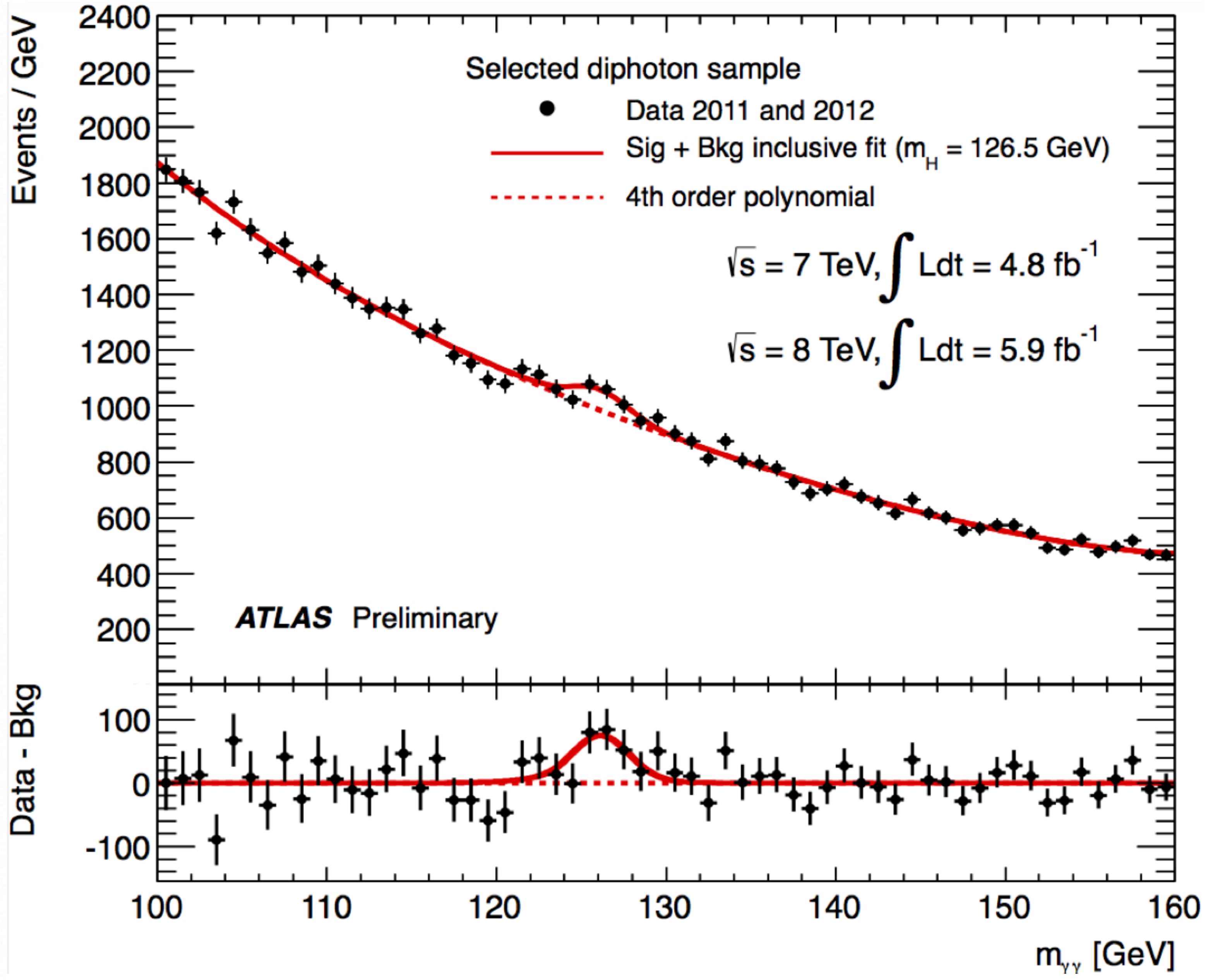
bb, **ττ**: high BR, but low S/B, important to directly probe Higgs boson coupling to fermions

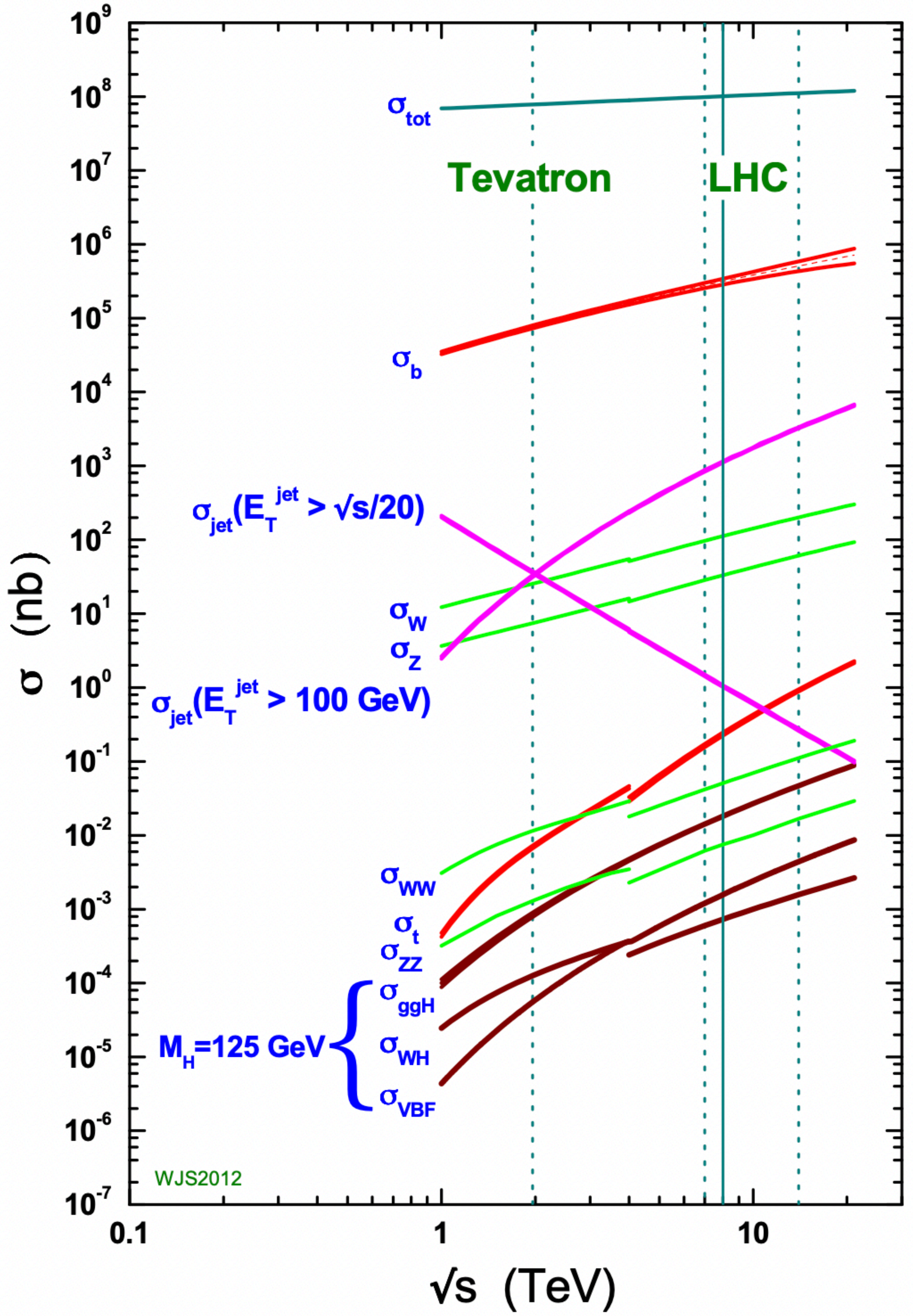
cc: decent BR, but poor q,g rejection => challenging for coupling to 2nd gen fermions

Ingredients for the discovery - or why the LHC beat the Tevatron

- Large production cross section: LHC ~30x Tevatron
  - ➡ 30x larger yield at time of discovery (~same luminosity, 10/fb)
- State-of-the-art detectors with efficient and precise reconstruction and identification of leptons, photons & jets
  - ➡ 2x efficiency with S/B ~ an order of magnitude larger in $H\rightarrow\gamma\gamma$
- Use of multivariate techniques (BDTs) to “tag" rarer production modes with better S/B
  - ➡ 20-50% improvements in analysis sensitivity







Fast forward to 2022…

- 10 years after the Higgs boson discovery, we have been able to understand many more of its properties and compare them to the predictions of the Standard Model:
  - Mass
  - Width
  - Spin & parity
  - Main decay and production modes
  - Rare decays
  - Couplings to other particles
  - Differential cross sections
  - Self-coupling
  - beyond-SM interactions (anomalous couplings to SM particles, CP violation, coupling to dark matter sector..)

PDG 2012

Higgs Bosons — H^0 and $H^\pm$, Searches for

The July 2012 news about Higgs searches is described in the addendum to the Higgs review in the data listings, but is not reflected here.

The limits for H_1^0 and A^0 refer to the m_h^{max} benchmark scenario for the supersymmetric parameters.

H^0 Mass $m > 115.5$ and none 127–600 GeV, CL = 95%

H_1^0 in Supersymmetric Models ($m_{H_1^0} < m_{H_2^0}$)

Mass $m >$ 92.8 GeV, CL = 95%

PDG 2022

H^0 $J = 0$

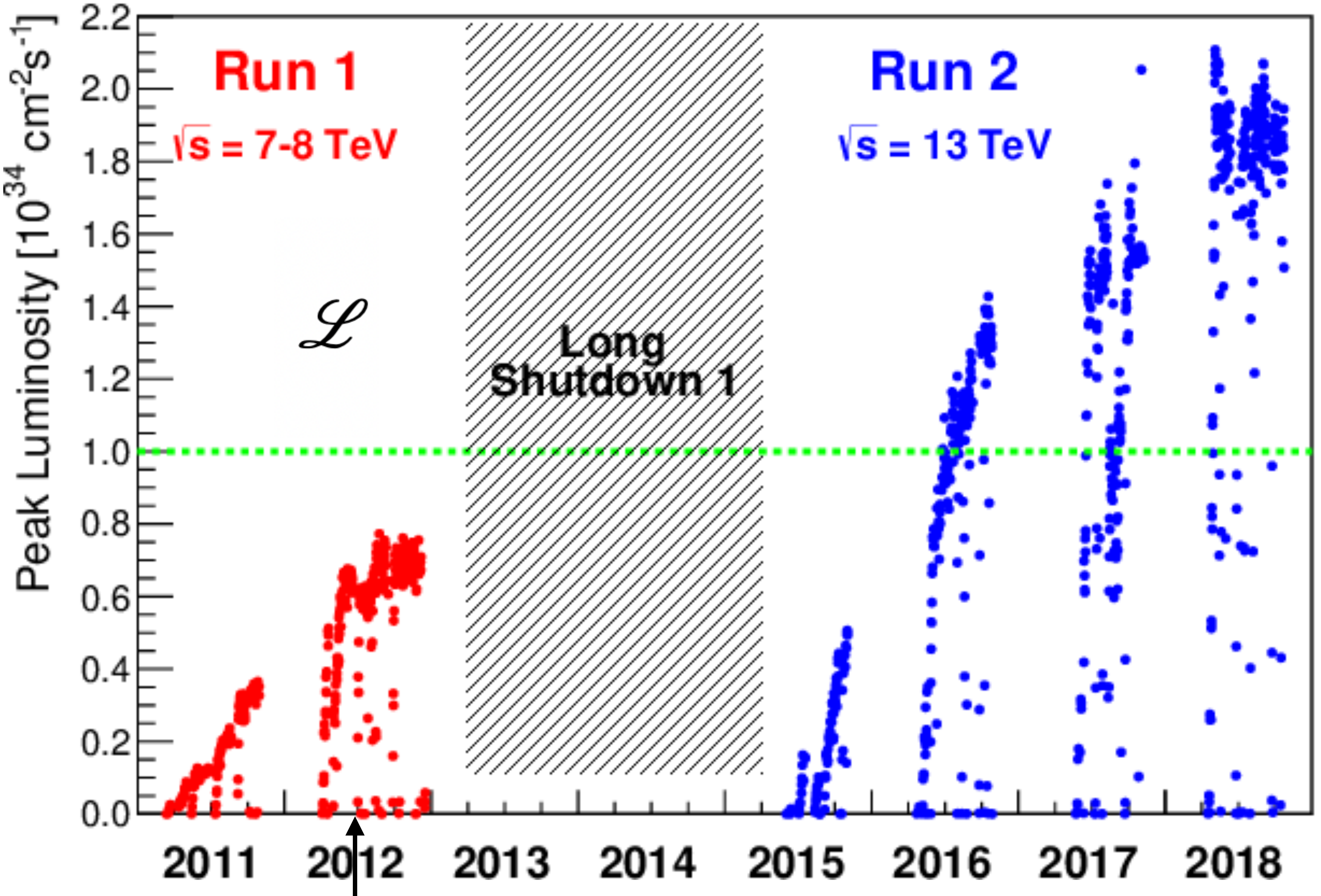
Mass $m = 125.25 \pm 0.17$ GeV (S = 1.5)
Full width $\Gamma = 3.2^{+2.8}_{-2.2}$ MeV (assumes equal on-shell and off-shell effective couplings)

H^0 Signal Strengths in Different Channels

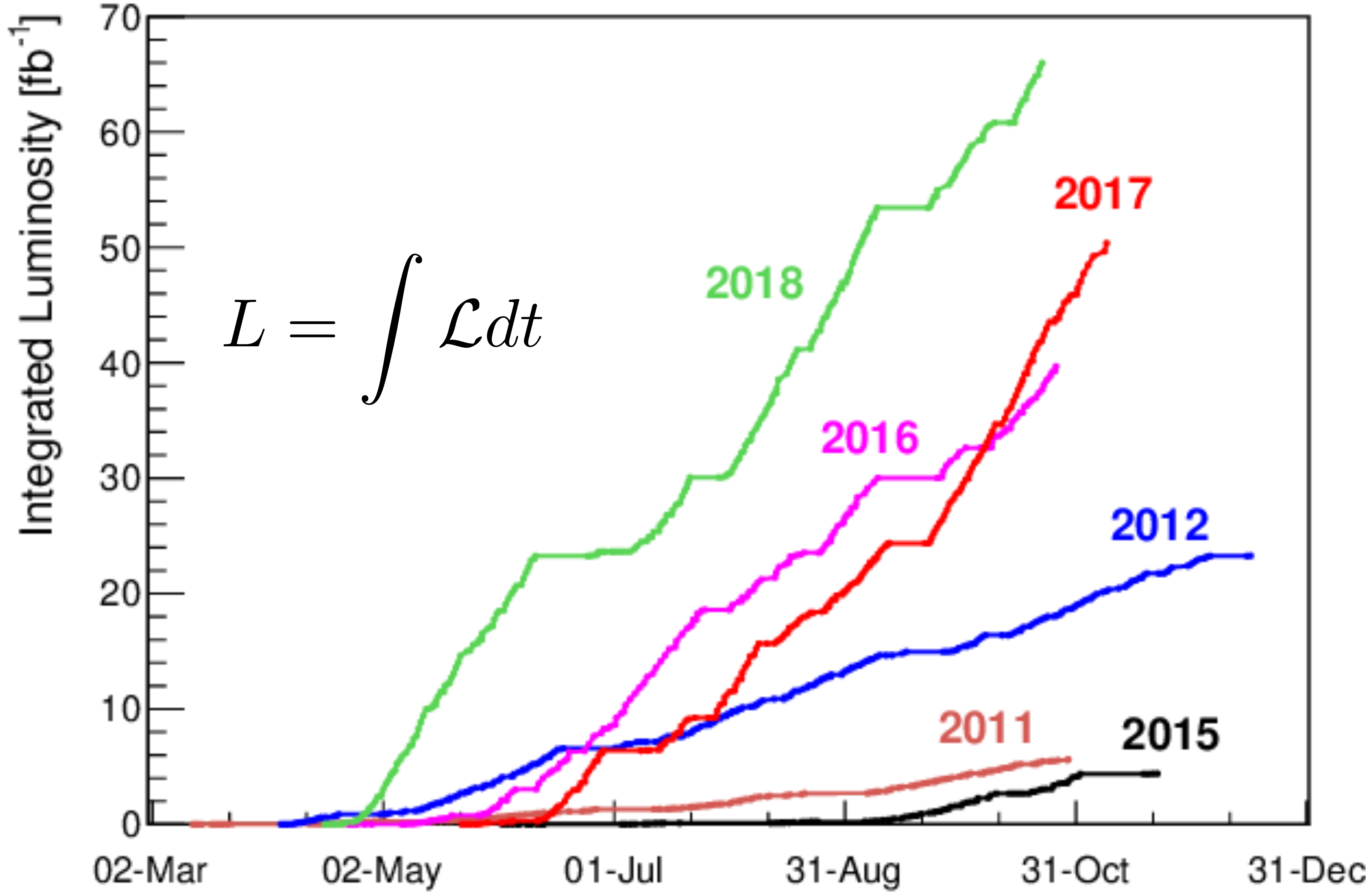
Combined Final States = 1.13 ± 0.06
$WW^* = 1.19 \pm 0.12$
$ZZ^* = 1.01 \pm 0.07$
$\gamma\gamma = 1.10 \pm 0.07$
$c\bar{c}$ Final State = 37 ± 20
$b\bar{b} = 0.98 \pm 0.12$
$\mu^+\mu^- = 1.19 \pm 0.34$
$\tau^+\tau^- = 1.15^{+0.16}_{-0.15}$
$Z\gamma < 3.6$, CL = 95%
$\gamma^*\gamma$ Final State = 1.5 ± 0.5
$t\bar{t}H^0$ Production = 1.10 ± 0.18
tH^0 production = 6 ± 4
H^0 Production Cross Section in pp Collisions at $\sqrt{s} = 13$ TeV = 56 ± 4 pb

LHC luminosity evolution

$$N_H = L\sigma_H$$



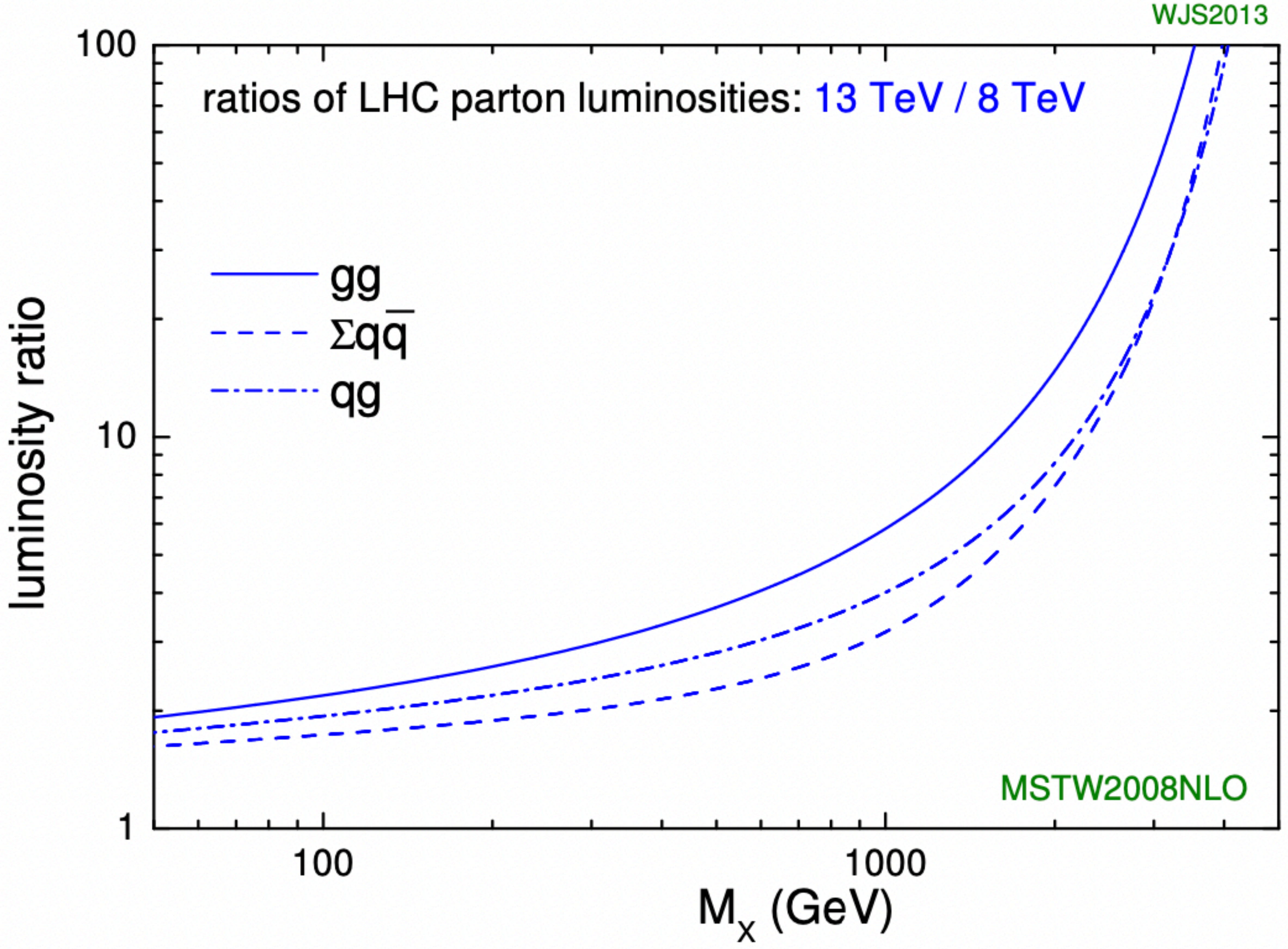
discovery

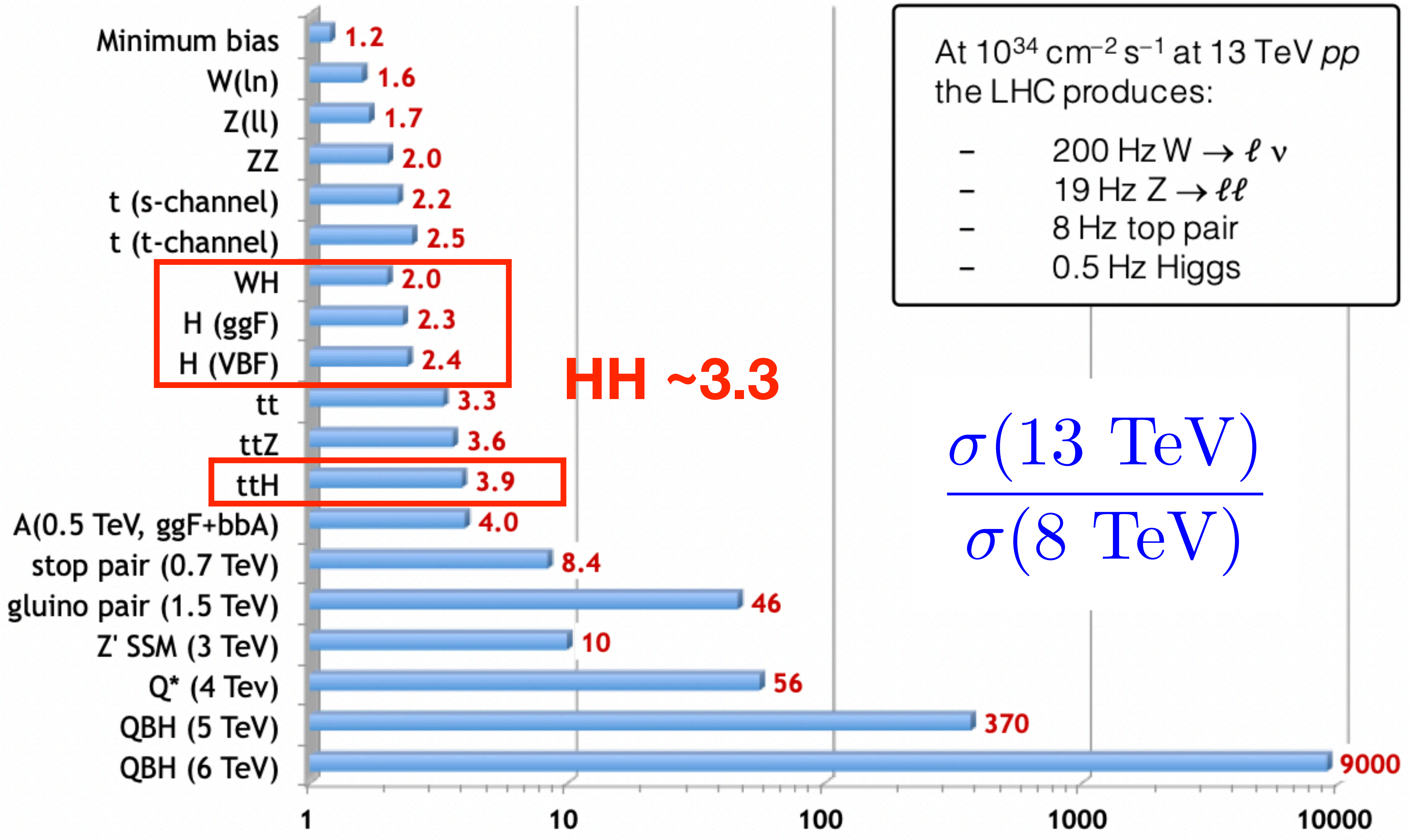


L = 25/fb at 7-8 TeV in Run1
L = 140/fb at 13 TeV in Run2

Higgs boson cross sections: from 8 to 13 TeV

$$N_H = L\sigma_H$$





HH ~3.3

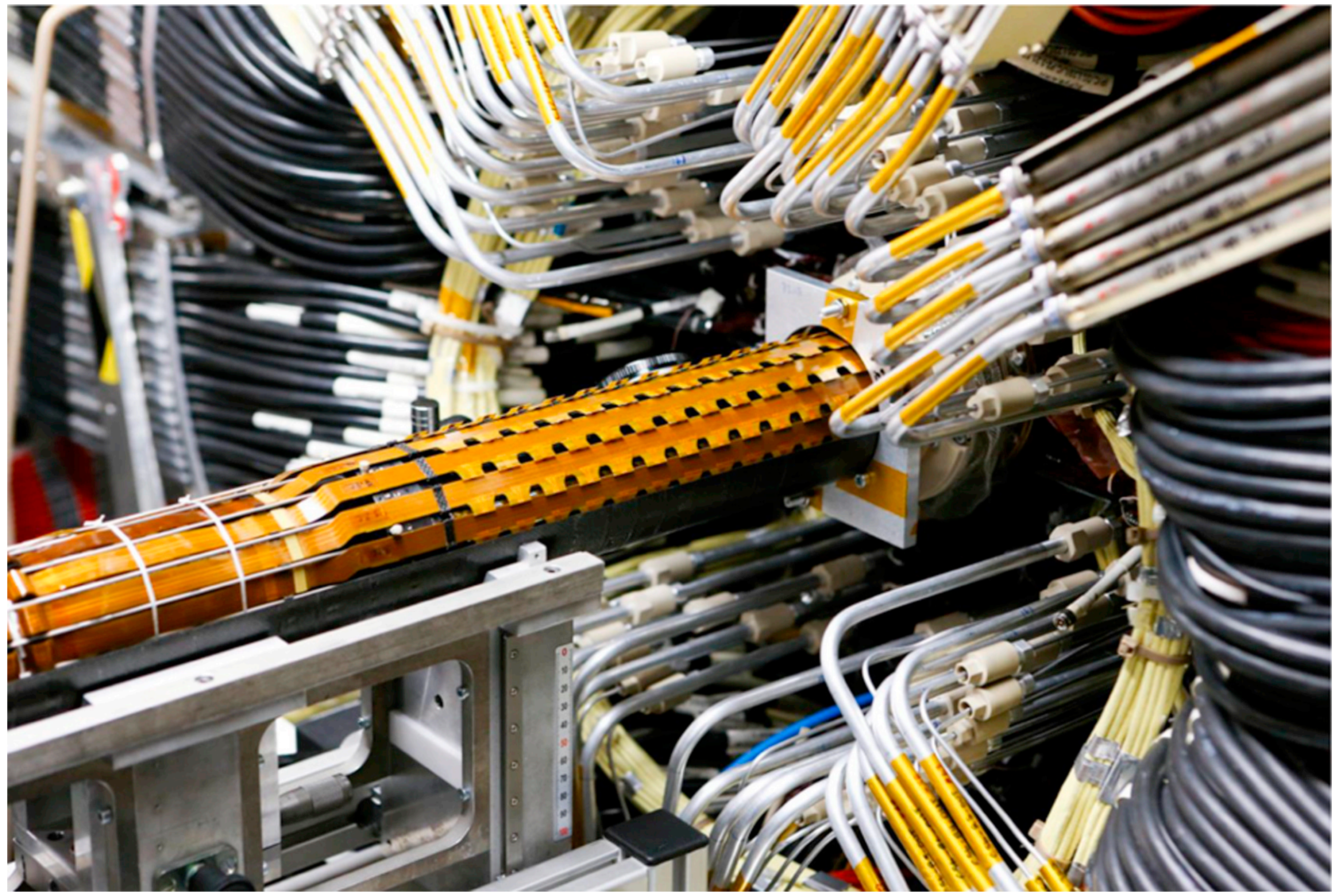
At 10^{34} cm^{-2} s^{-1} at 13 TeV *pp* the LHC produces:

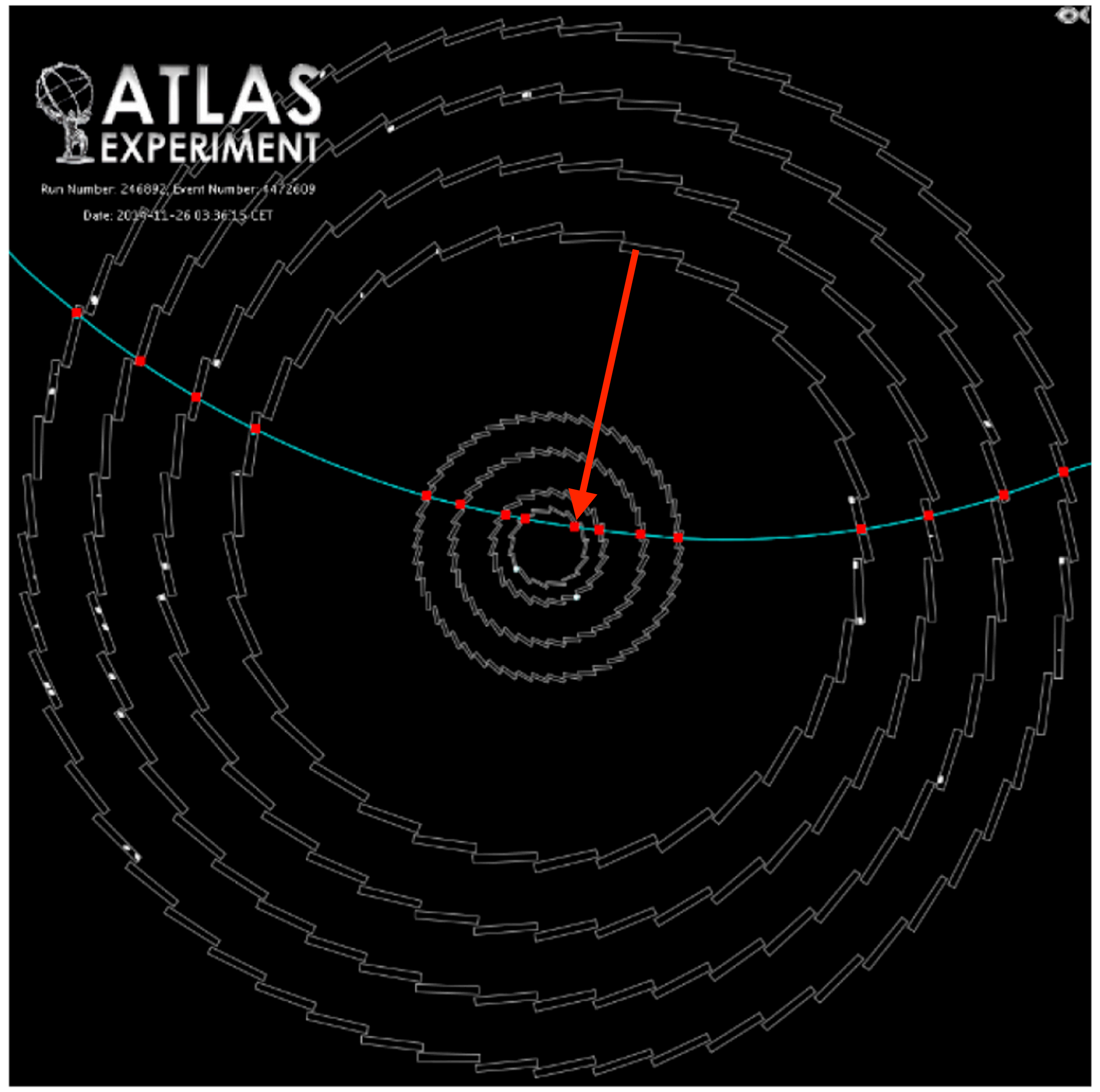
- 200 Hz $W \to \ell\nu$
- 19 Hz $Z \to \ell\ell$
- 8 Hz top pair
- 0.5 Hz Higgs

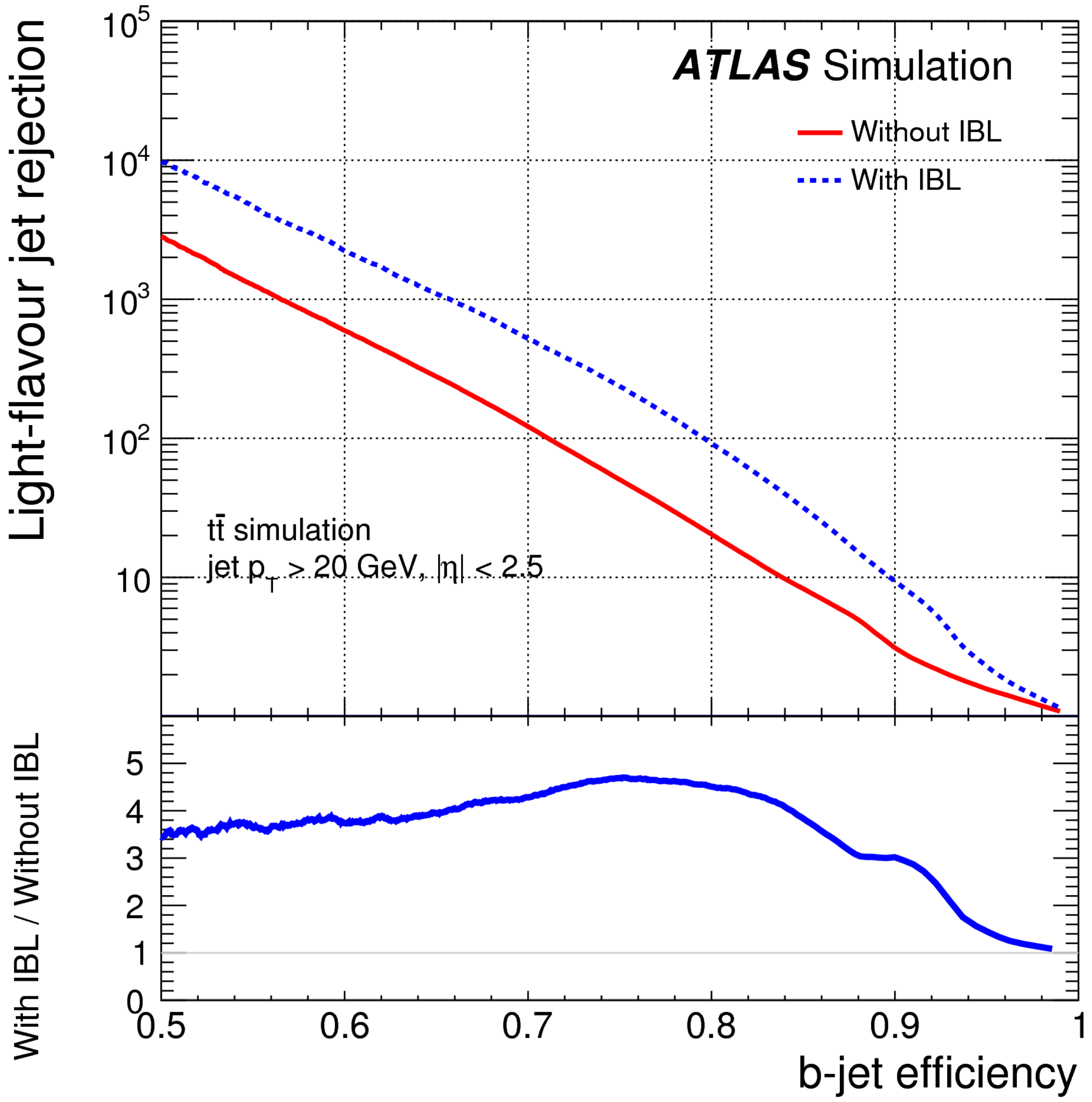
$$\frac{\sigma(13\ \mathrm{TeV})}{\sigma(8\ \mathrm{TeV})}$$

Improved detectors & analysis techniques

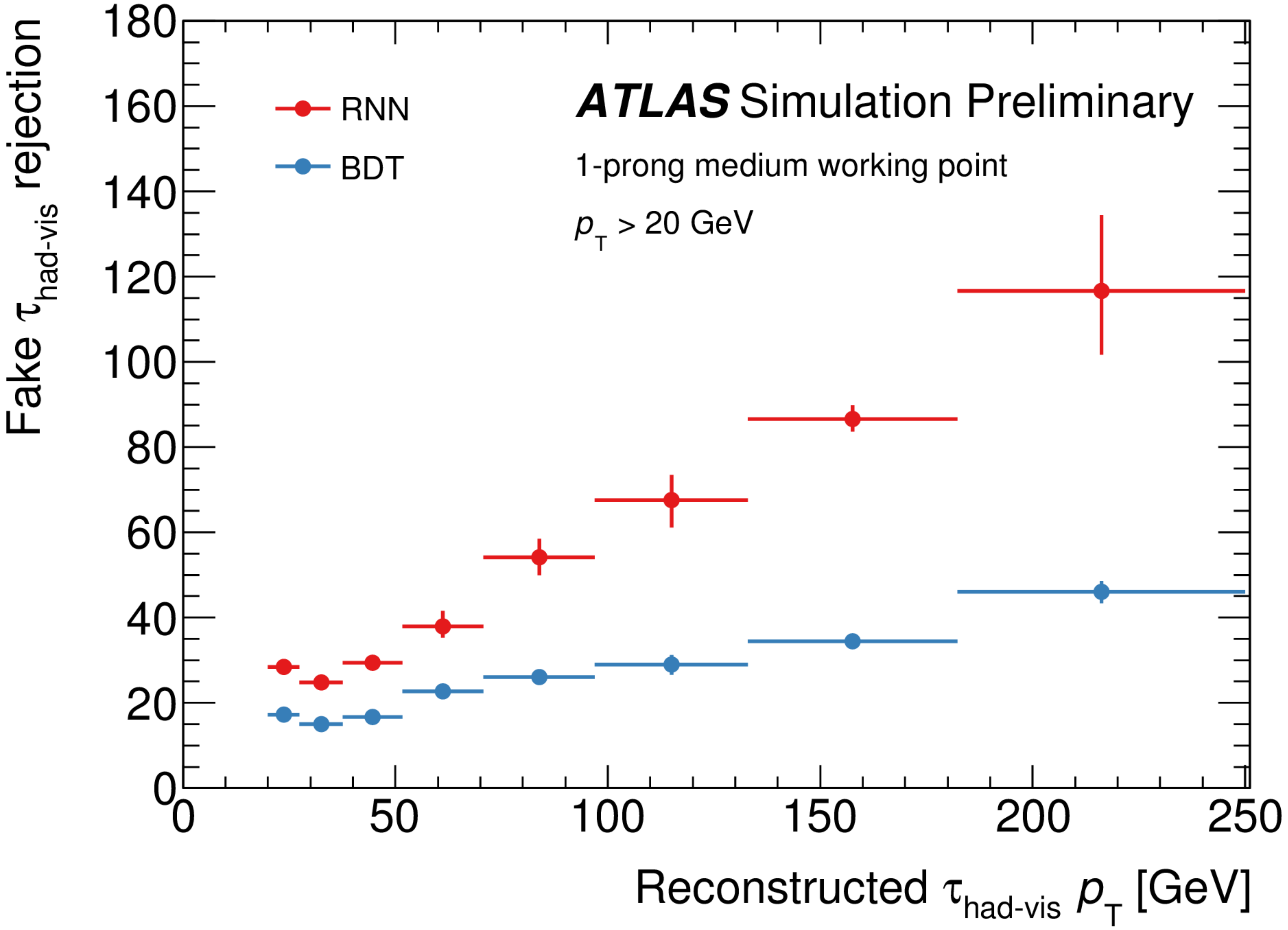
Insertable b-layer (IBL) and flavour tagging







(Recursive) neural networks for identification of hadronic tau decays



Improved theory predictions

higher-order calculations (ggF: NNLO -> N3LO)

NNLO+NNLL					
Cross Section (pb)	+QCD Scale %	-QCD Scale %	±(PDF+α_s) %	±PDF %	±α_s %
4.414E+01	+7.6	-8.1	±3.1	±1.8	±2.5

N3LO						
Cross Section (pb)	+Theory %	-Theory %	TH Gaussian %	±(PDF+α_s) %	±PDF %	±α_s %
4.858E+01	+4.6	-6.7	±3.9	±3.2	±1.9	±2.6

state-of-the-art MC generators (at least NLO; NNLO in ggF)

NNLOPS simulation of Higgs boson production

Keith Hamilton,[a,b,1] **Paolo Nason,**[c] **Emanuele Re**[d] **and Giulia Zanderighi**[d]

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[b] *Theory Division, CERN, CH–1211, Geneva 23, Switzerland*
[c] *INFN, Sezione di Milano Bicocca, Piazza della Scienza 3, 20126 Milan, Italy*
[d] *Rudolf Peierls Centre for Theoretical Physics, University of Oxford, 1 Keble Road, U.K.*

E-mail: keith.hamilton@ucl.ac.uk, paolo.nason@mib.infn.it, e.re1@physics.ox.ac.uk, g.zanderighi1@physics.ox.ac.uk

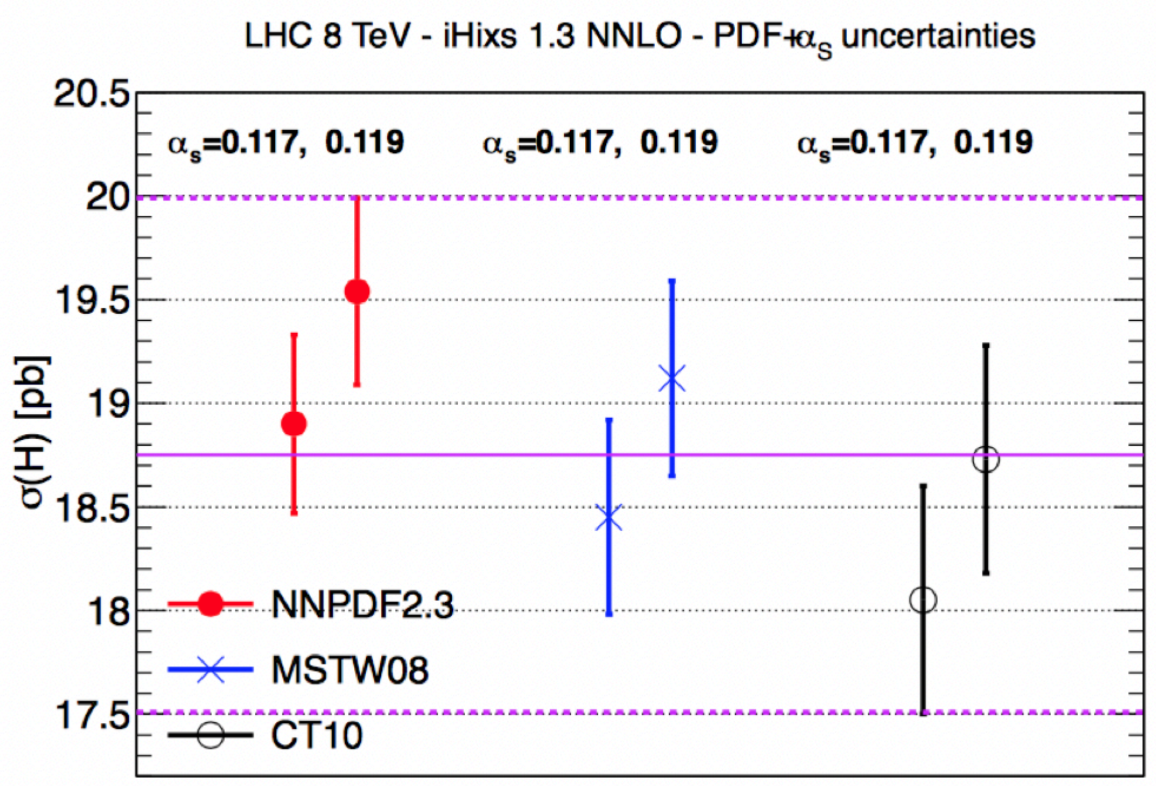
Abstract: We detail a simulation of Higgs boson production via gluon fusion, accurate at next-to-next-to-leading order in the strong coupling, including matching to a parton

JHEP10(2013)222

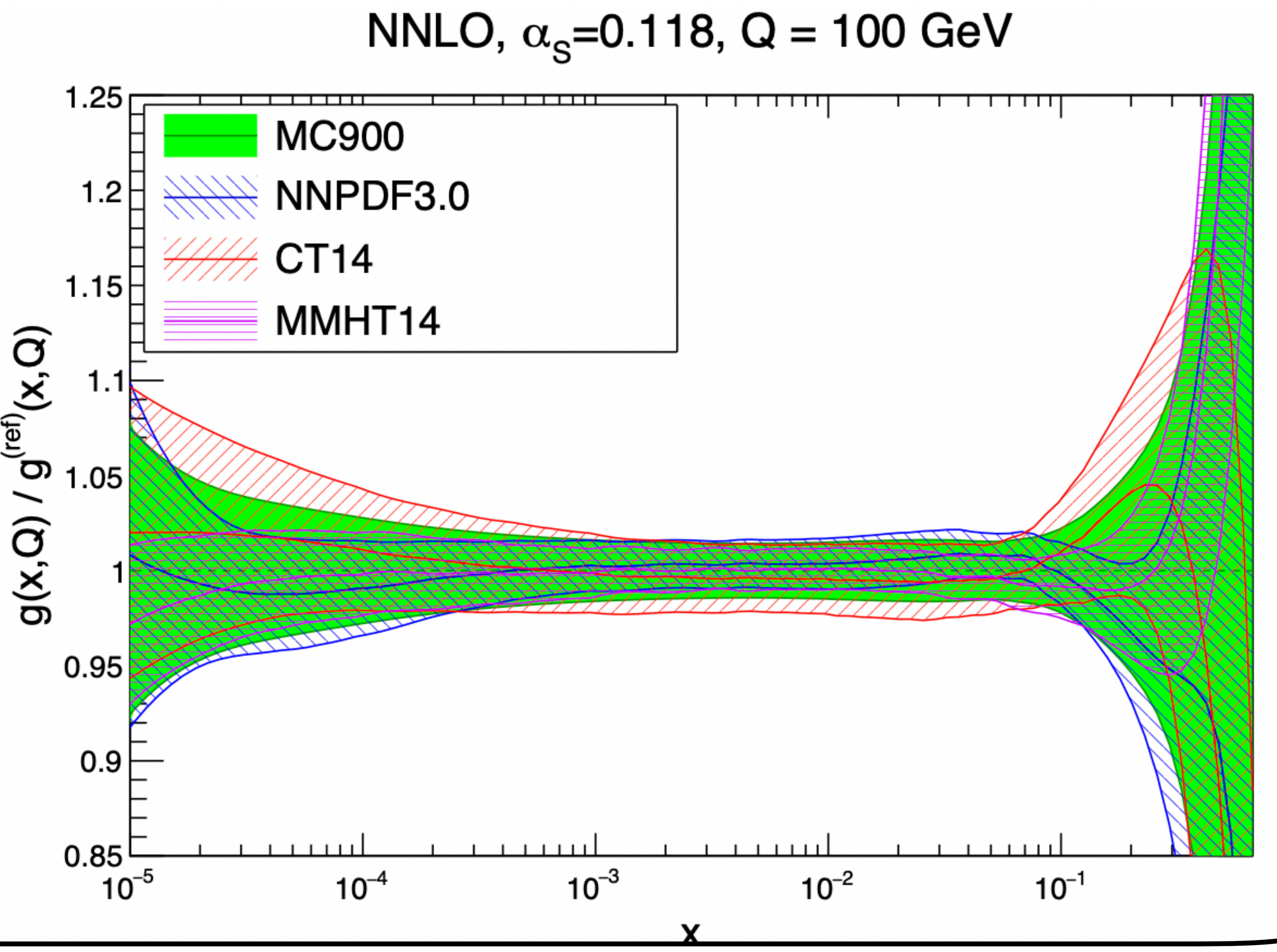
improved PDF sets (including data from LHC Run1)

THE OLD PDF4LHC RECOMMENDATION

HIGGS IN GLUON FUSION



Using the full envelope was conservative but statically not optimal

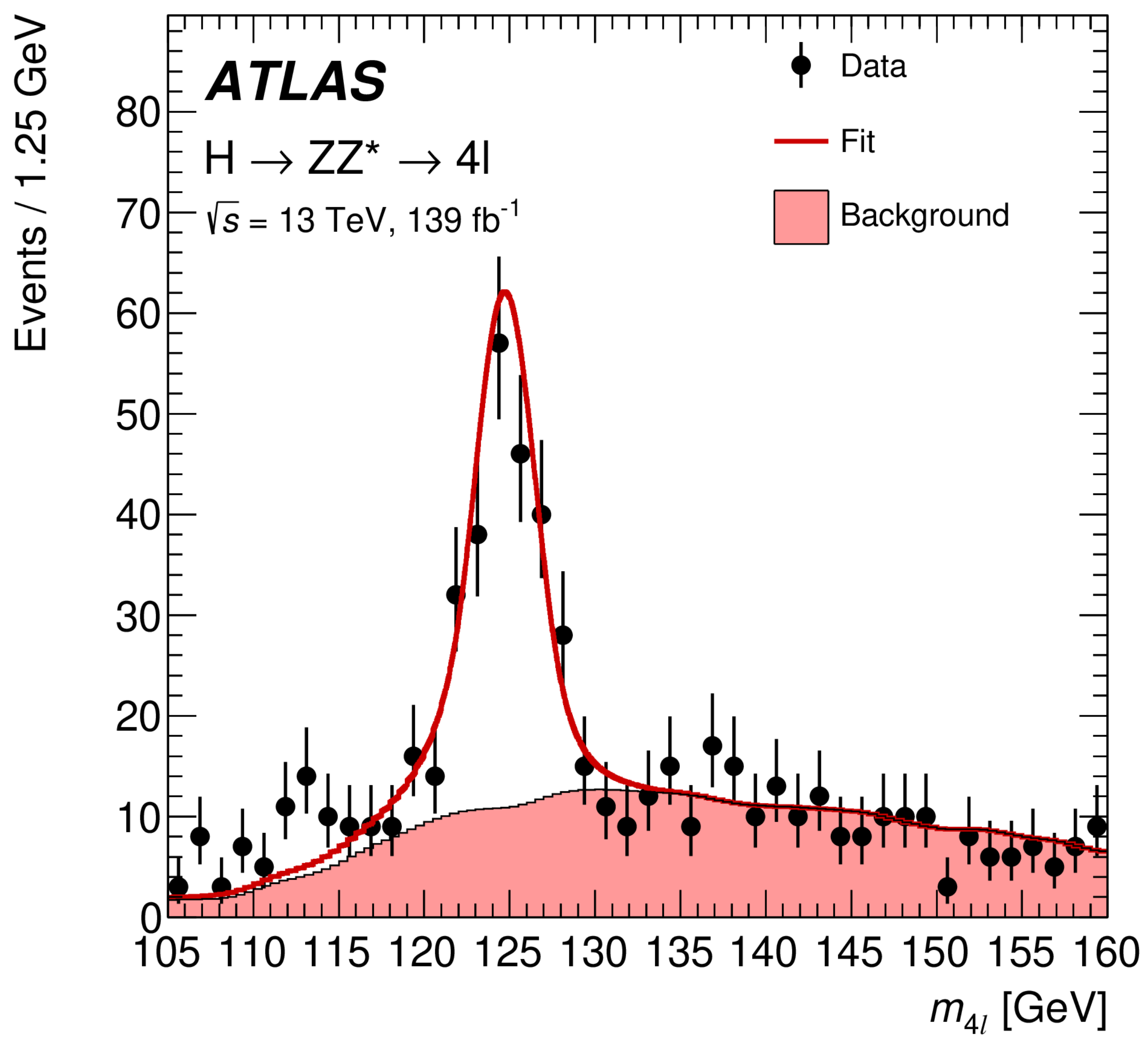


=> smaller modelling uncertainties in measurements, and reduced uncertainties in TH predictions compared to data

Higgs boson mass

- Measured in high-resolution channels (γγ, ZZ→4l) from the position of the invariant mass peak
- Precision limited by statistical (ZZ) or experimental (γγ) systematic uncertainties
- Requires precise lepton and photon energy calibration (use control samples such as Z→ee, μμ)

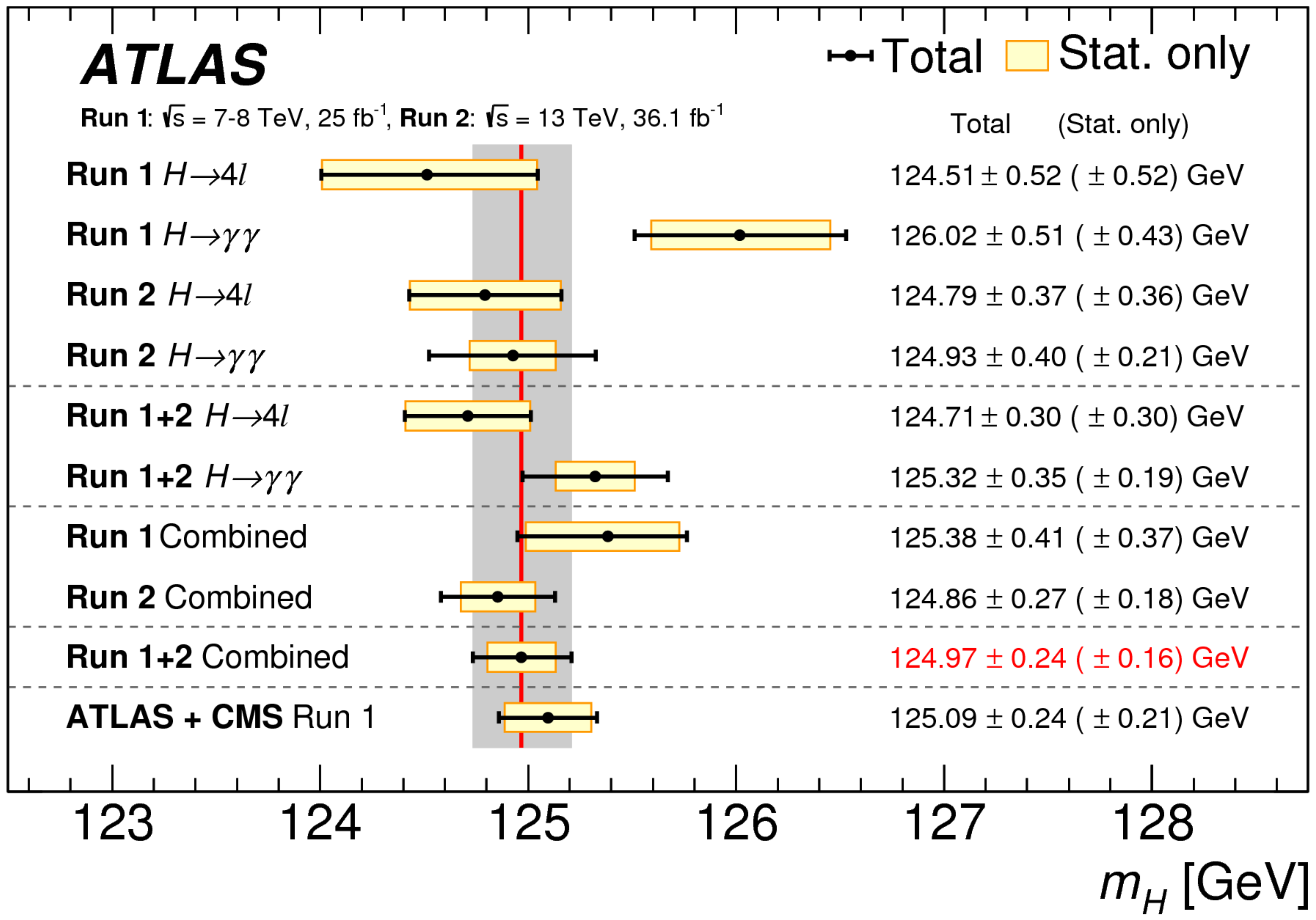
H→ZZ→4l, 139/fb* *arXiv:2207.00320, submitted to PLB*



$$m_H = 124.94 \pm 0.17(\text{stat.}) \pm 0.03(\text{syst.})\ \text{GeV}$$

- **Run1 + full Run2: 0.14% precision**

H→ZZ→4l + H→γγ, 36/fb* *Phys. Lett. B 784 (2018) 345*



- **Run1 + partial Run2: 0.19% precision**

One of the most precisely measured electroweak parameters!

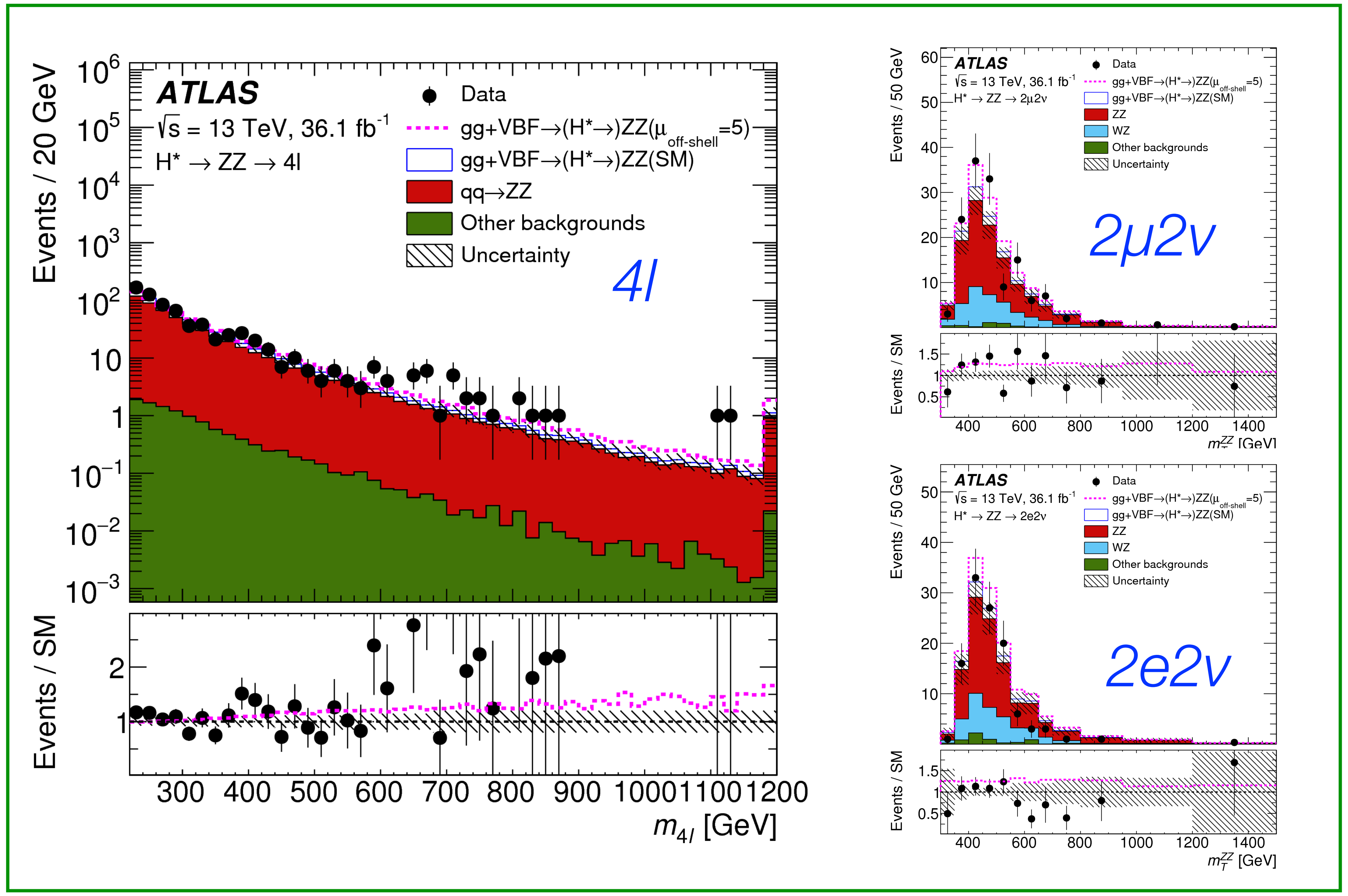
Higgs boson width

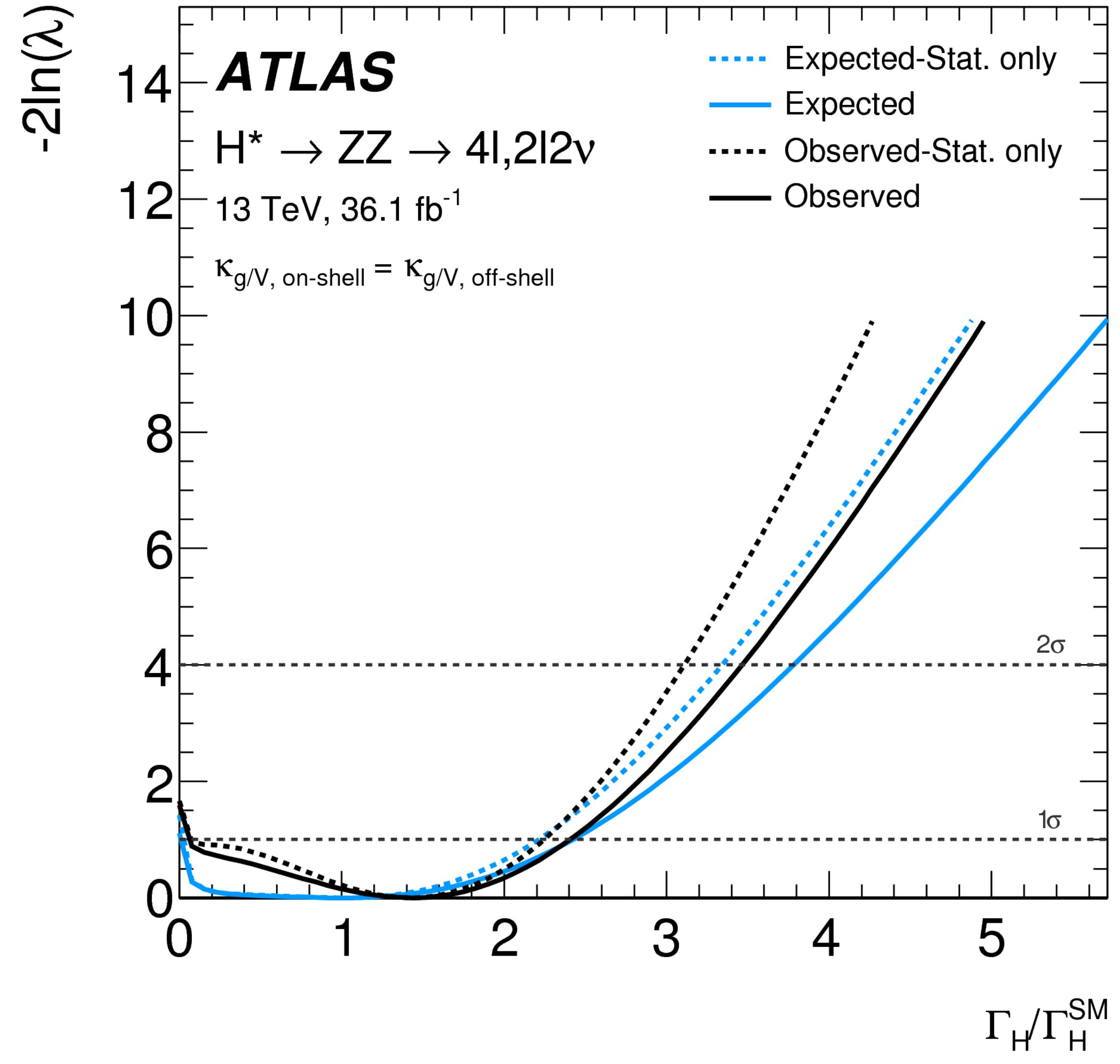
- SM Higgs boson **width (4.1 MeV) << experimental resolution (1–2 GeV) => too small** to be measured directly (direct limits ~ 1 GeV)
- Can be inferred **from ratio of off-shell/on-shell pp→H*→ZZ** (or WW) xsections

$$\mu_{\text{on-shell}} = \frac{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell}}}{\sigma^{gg\to H\to ZZ^*}_{\text{on-shell,SM}}} = \frac{\kappa^2_{g,\text{on-shell}} \cdot \kappa^2_{Z,\text{on-shell}}}{\Gamma_H/\Gamma_H^{\text{SM}}}, \qquad \mu_{\text{off-shell}} = \frac{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell}}}{\sigma^{gg\to H^*\to ZZ}_{\text{off-shell,SM}}} = \kappa^2_{g,\text{off-shell}} \cdot \kappa^2_{Z,\text{off-shell}},$$

with some **assumptions:**

- running of the couplings as in the SM: $\kappa_{\text{off-shell}} = \kappa_{\text{on-shell}}$
- no new signals in the search reason, apart from a possibly enhanced off-shell Higgs contribution





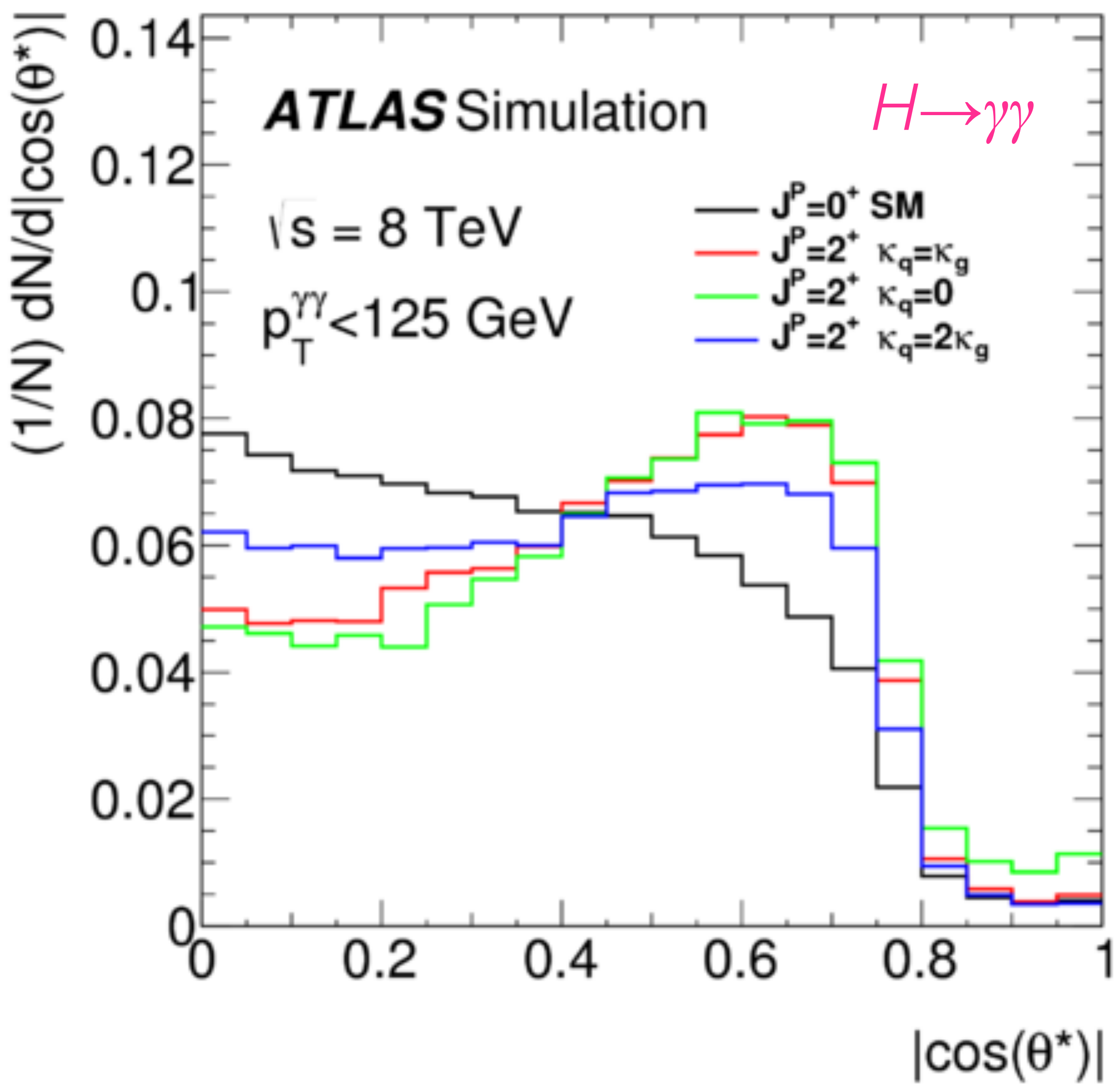
[Phys. Lett. B 786 (2018) 223](#)

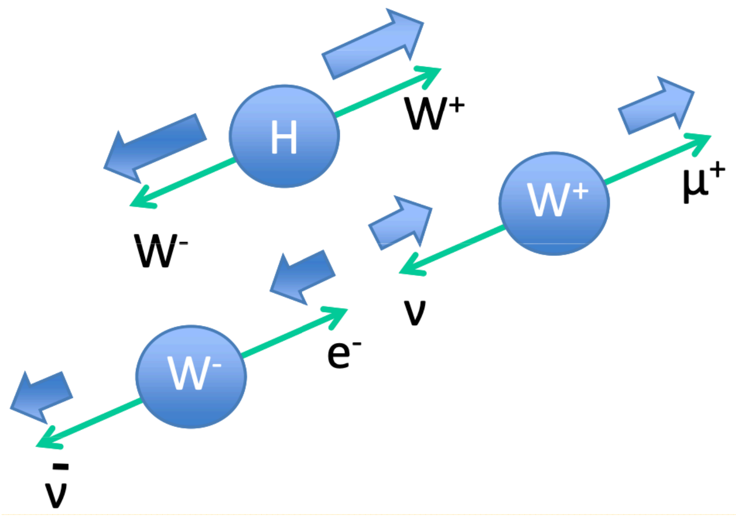
95% CL upper limits		Observed	Expected
$\mu_{\text{off-shell}}$	$ZZ \to 4\ell$ analysis	4.5	4.3
	$ZZ \to 2\ell 2\nu$ analysis	5.3	4.4
	Combined	3.8	3.4
$\Gamma_H/\Gamma_H^{\text{SM}}$	Combined	3.5	3.7

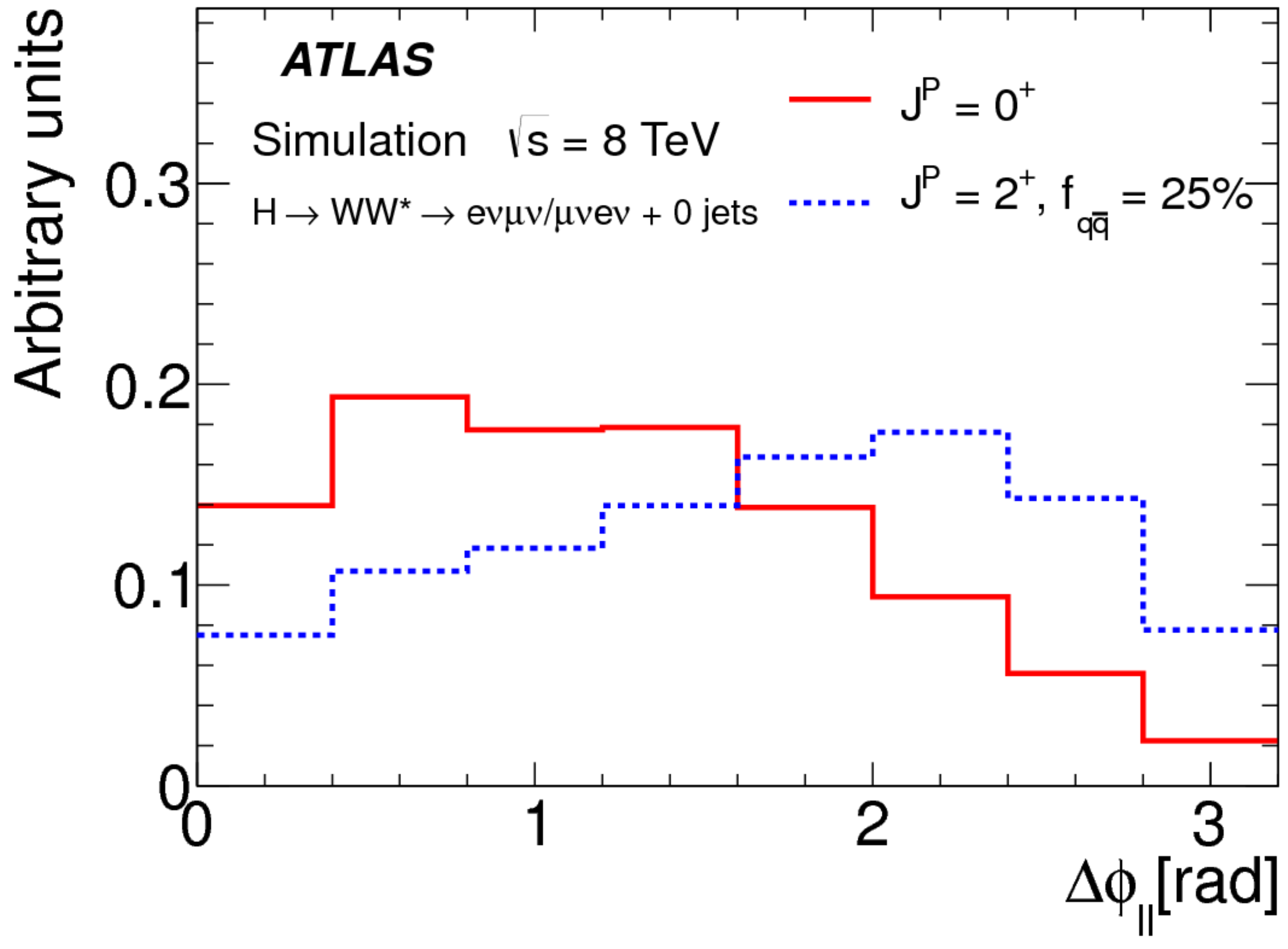
25% precision at HL-LHC… but model-dependent!

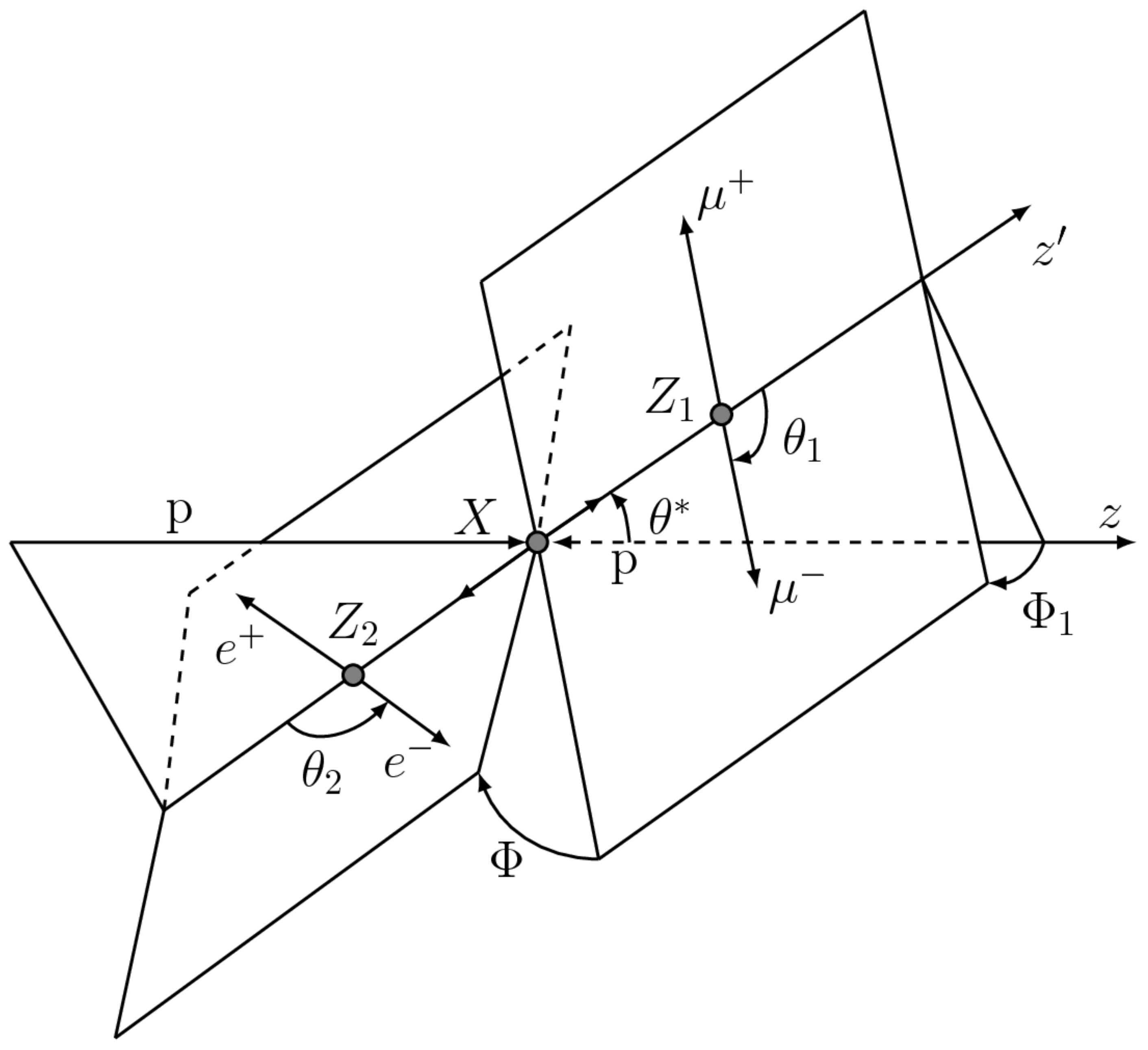
Higgs boson spin and parity

- **Spin 1 forbidden** by observation of H→γγ decay (Landau-Yang's theorem)
- **J^P = 0^-, 0^+ non-SM** (different tensor structure of the HVV couplings), and various graviton-like **2^+** scenarios are **tested** one-by-one against the SM 0^+ hypothesis exploiting **angular distributions that are sensitive to J^P**
  - Polar angle θ* of photon in γγ CM frame (flat for spin-0, quadratic in cosθ* for spin 2)
  - Azimuthal opening angle between two leptons in H→WW (small for spin-0, large for spin-2 due to W coupling to left-handed fermions)
  - Decay angles and dilepton invariant masses in H→ZZ→4l

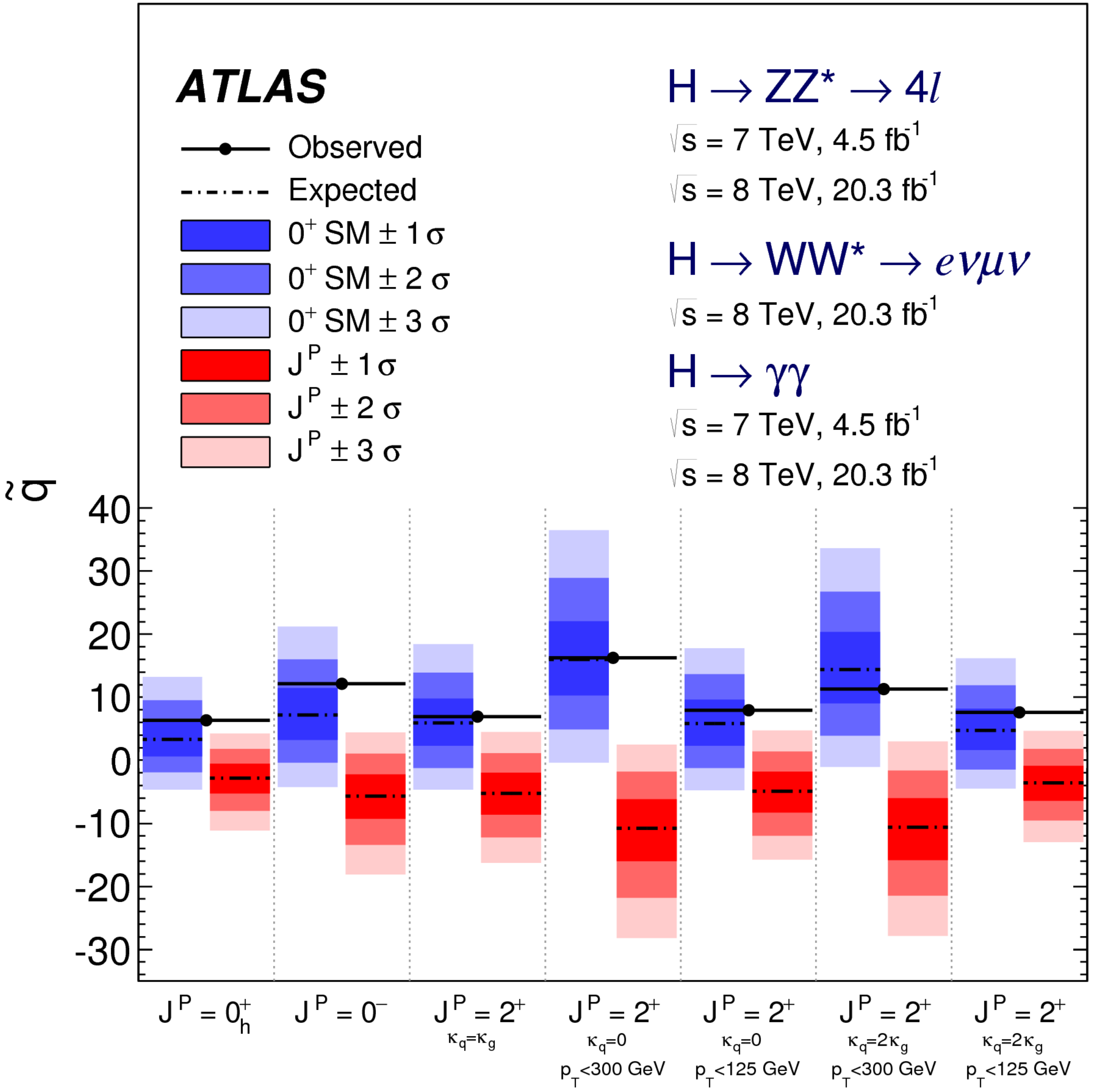








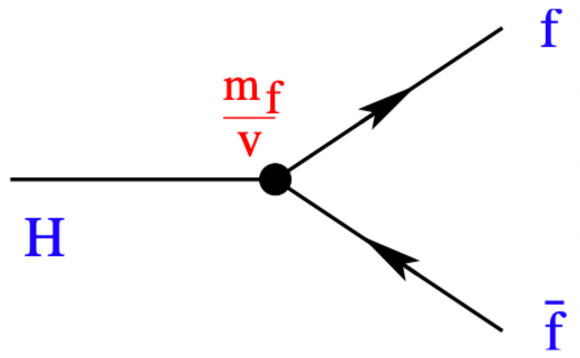
Higgs boson spin and parity



Eur. Phys. J. C75 (2015) 476

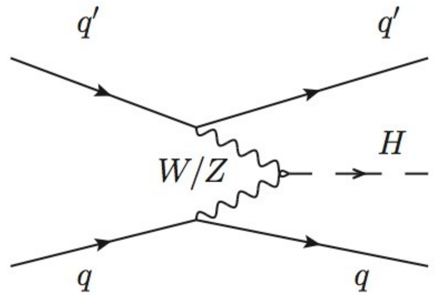
All alternative hypotheses disfavoured at > 3σ

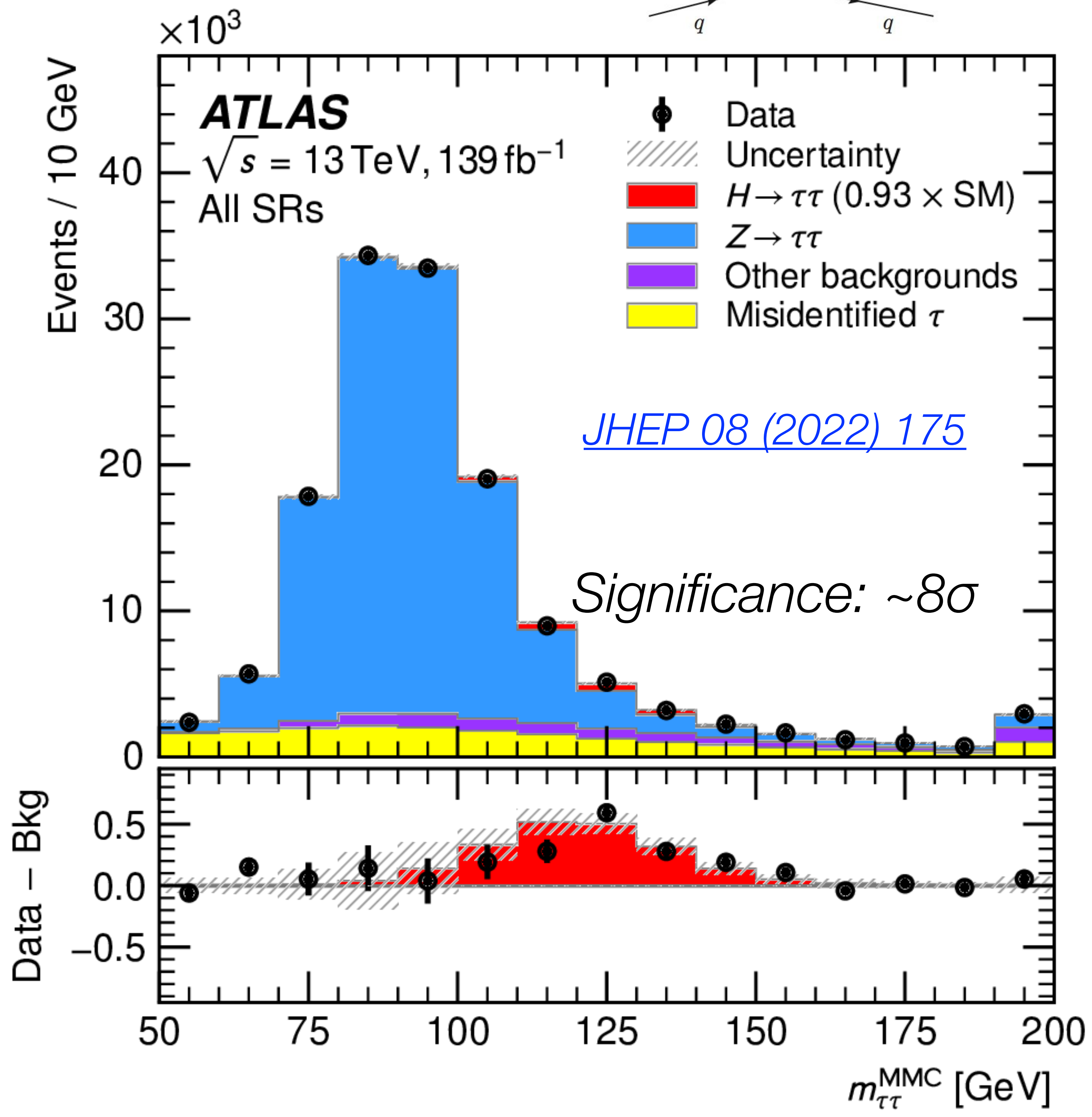
Observation of Higgs boson decays to τ-leptons and to b-quarks



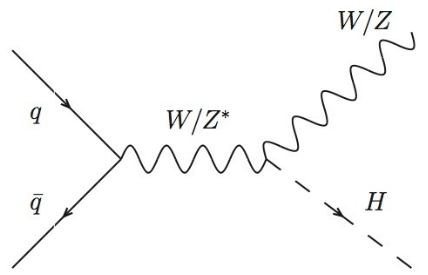
- First observation with partial Run2 datasets. More detailed/granular studies performed with full dataset
- Best sensitivity provided by production modes with lower x-section but much better bkg rejection than gluon fusion
  - VBF (~8% of σ_H) for H→ττ,   V(→leptons)H (~0.9% of σ_H) for H→bb
- Large sensitivity boost from use of multivariate techniques for object reconstruction and S/B discrimination in Run2 analyses

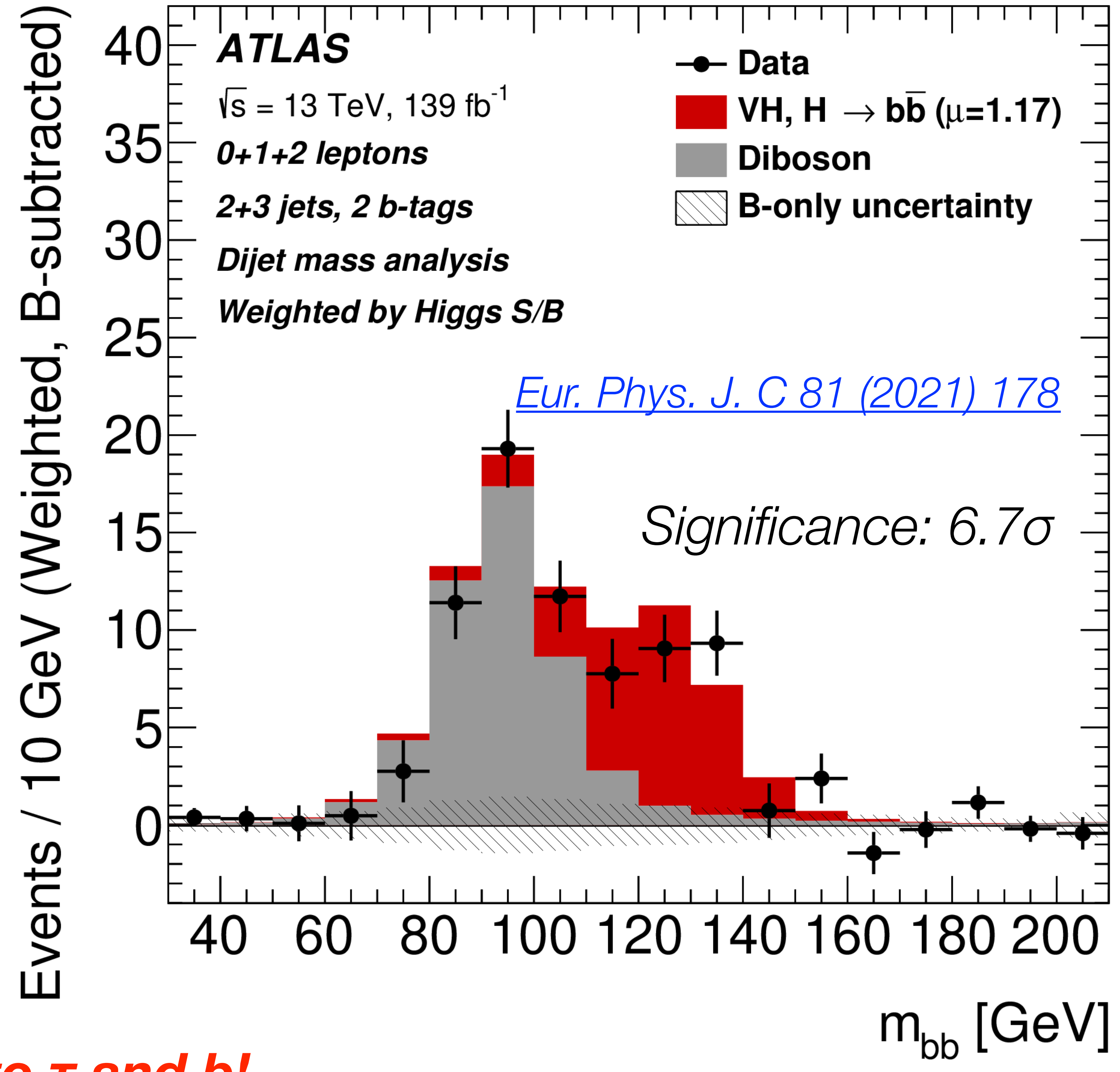
H→ττ





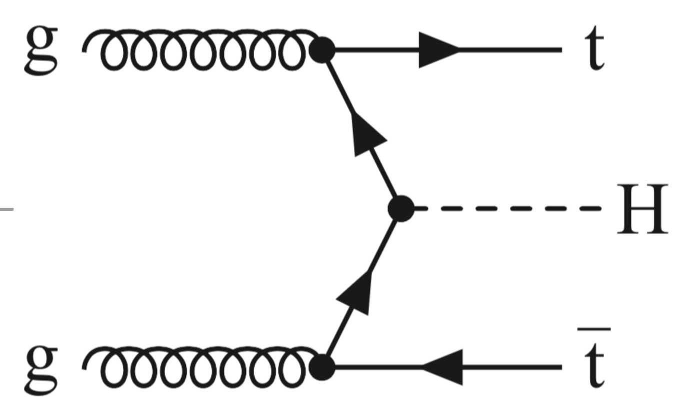
H→bb



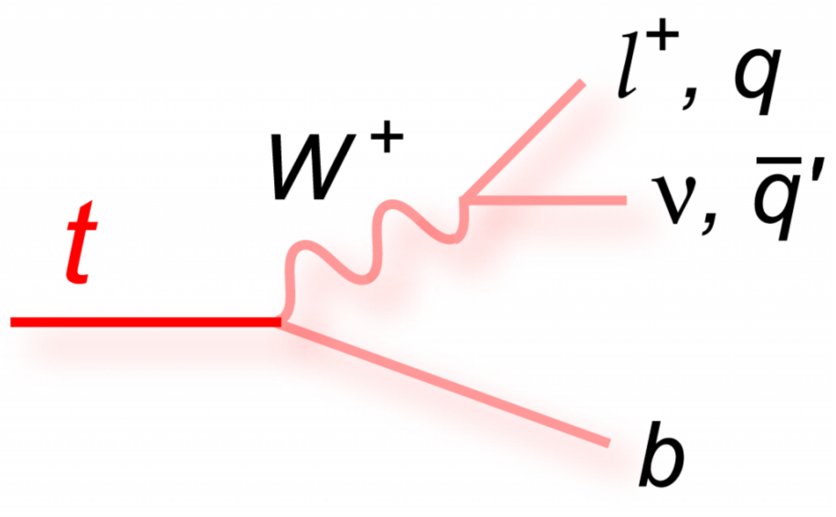


Evidence of Yukawa couplings to τ and b!

Observation of Higgs boson production with ttbar pairs



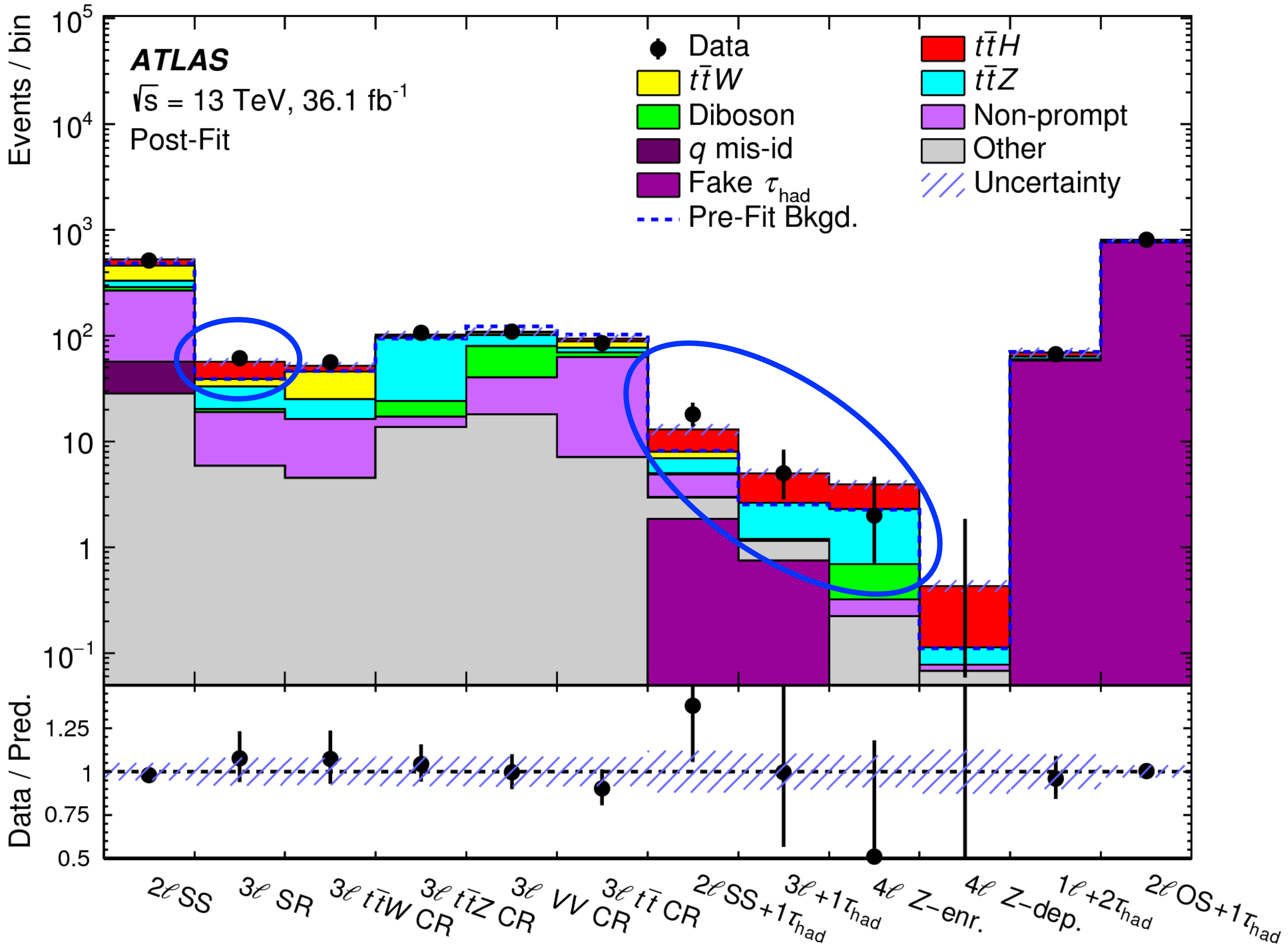
- ttbar pair identified by presence of b-jets, large jet multiplicity, possibly leptons and missing momentum
- Best sensitivity provided by decay modes with leptons (WW, ττ) or photons



Analysis	Integrated luminosity [fb^{-1}]	Expected significance	Observed significance
$H \to \gamma\gamma$	79.8	3.7 σ	4.1 σ
$H \to$ multilepton	36.1	2.8 σ	4.1 σ
$H \to b\bar{b}$	36.1	1.6 σ	1.4 σ
$H \to ZZ^* \to 4\ell$	79.8	1.2 σ	0 σ
Combined (13 TeV)	36.1−79.8	4.9 σ	5.8 σ
Combined (7, 8, 13 TeV)	4.5, 20.3, 36.1−79.8	5.1 σ	6.3 σ

Multileptons

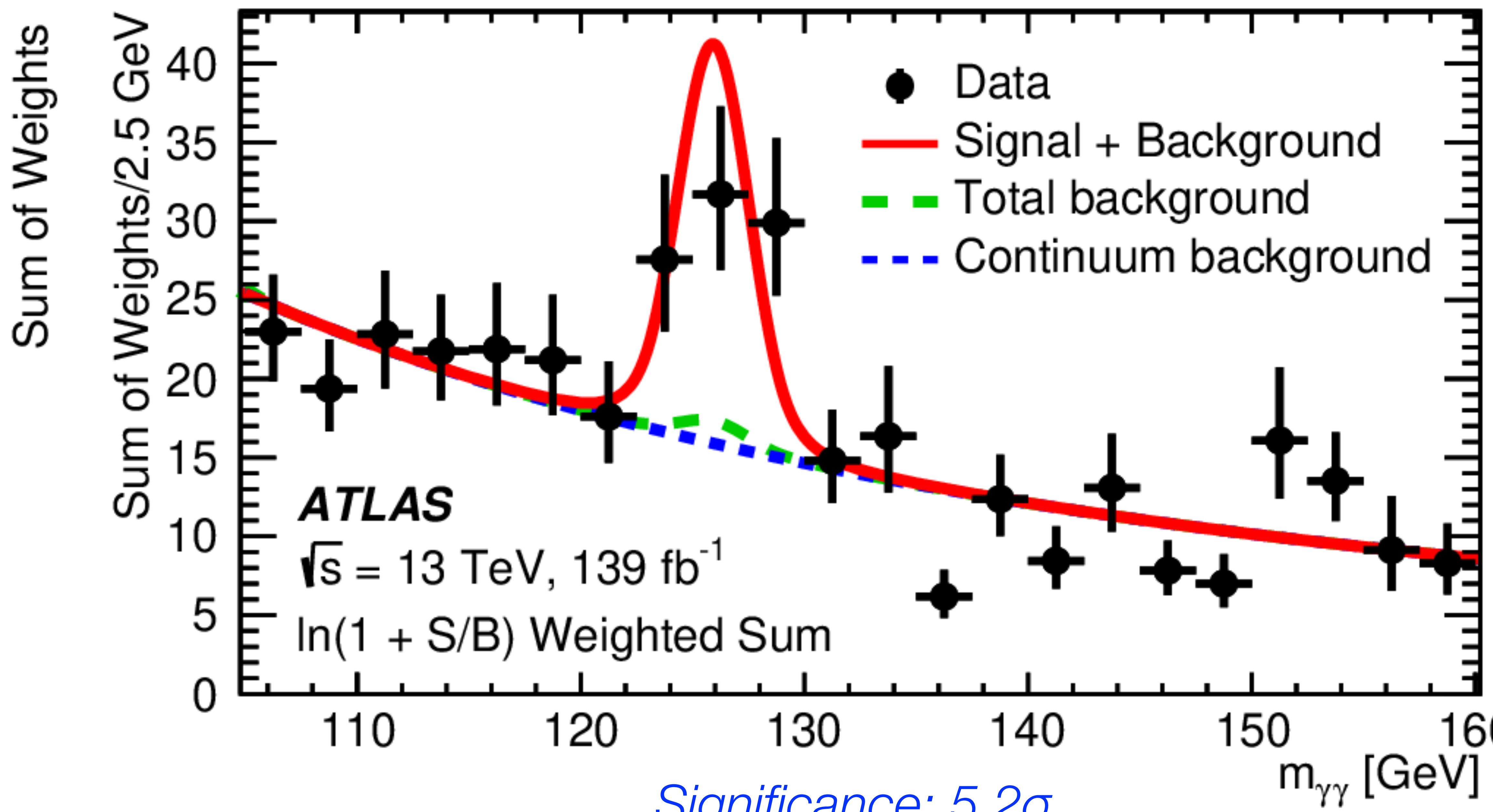
Phys. Rev. D 97 (2018) 072003



Significance: 4.1σ

H→γγ

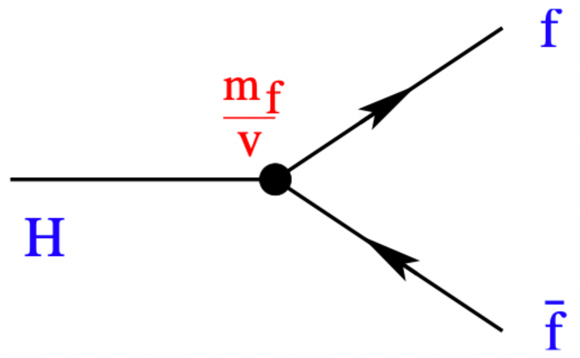
Phys. Rev. Lett. 125 (2020) 061802



Significance: 5.2σ

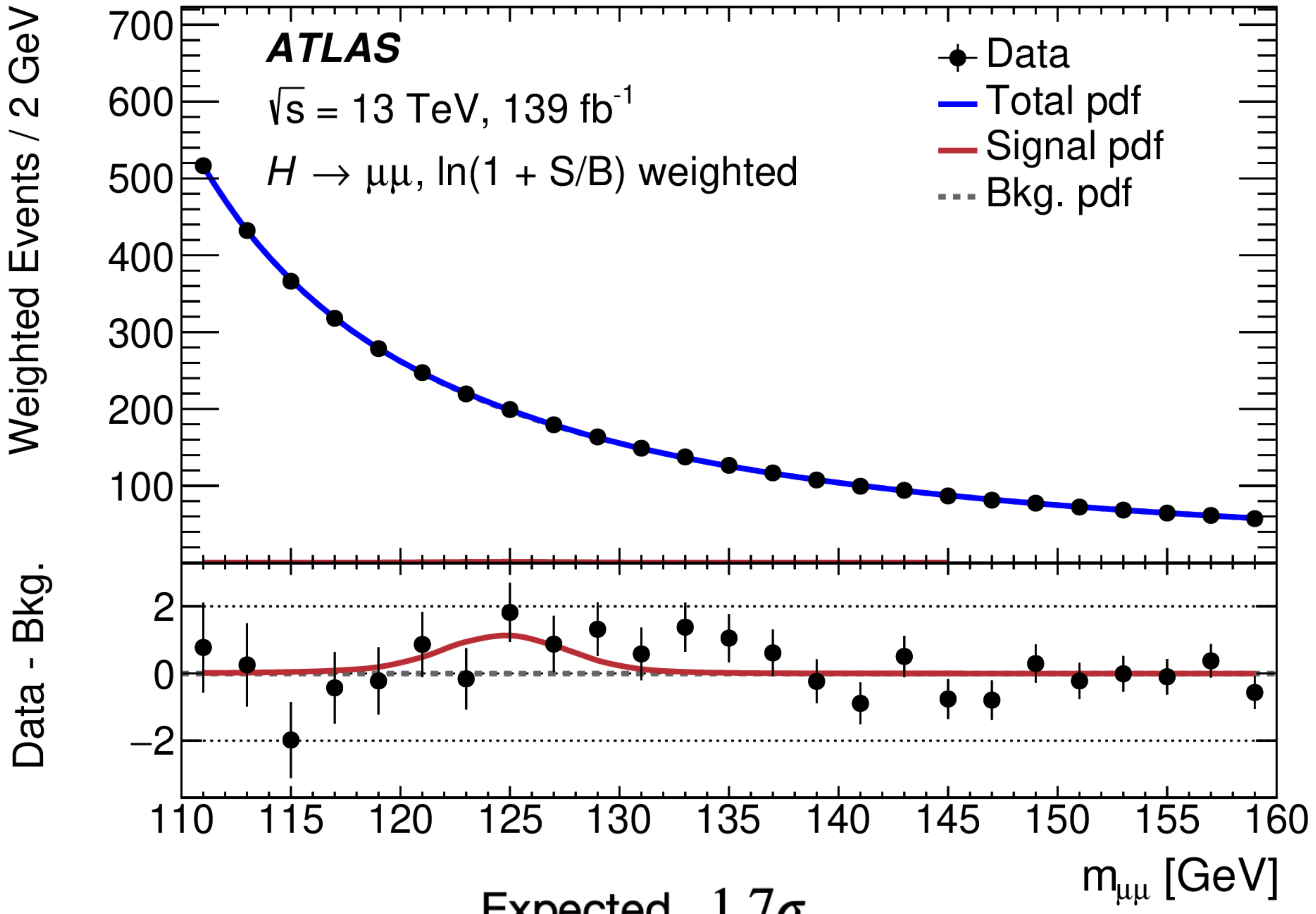
Direct evidence of Yukawa couplings to the top quark!

The challenging Yukawa couplings to 2nd-generation fermions



- H→μμ: very small BR (0.02%), important background from $Z^{(*)}$→μμ, but good resolution
- H→cc: small BR (2%), poor resolution. Large bkg from QCD ⇒ search in V(→leptons)H. Poor c-tagging ⇒ bkg from H→bb

H→μμ [Phys. Lett. B 812 (2021) 135980]

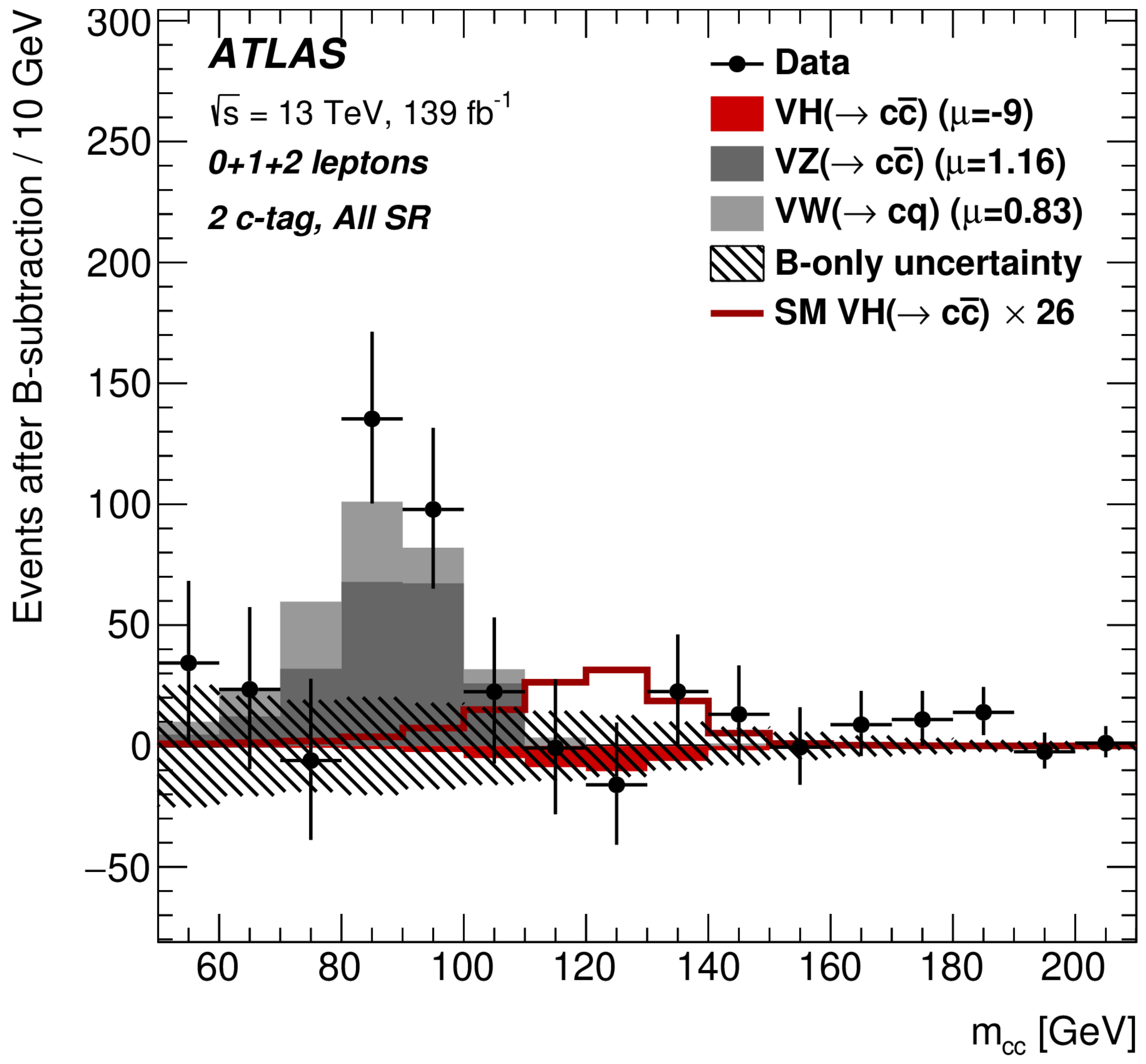


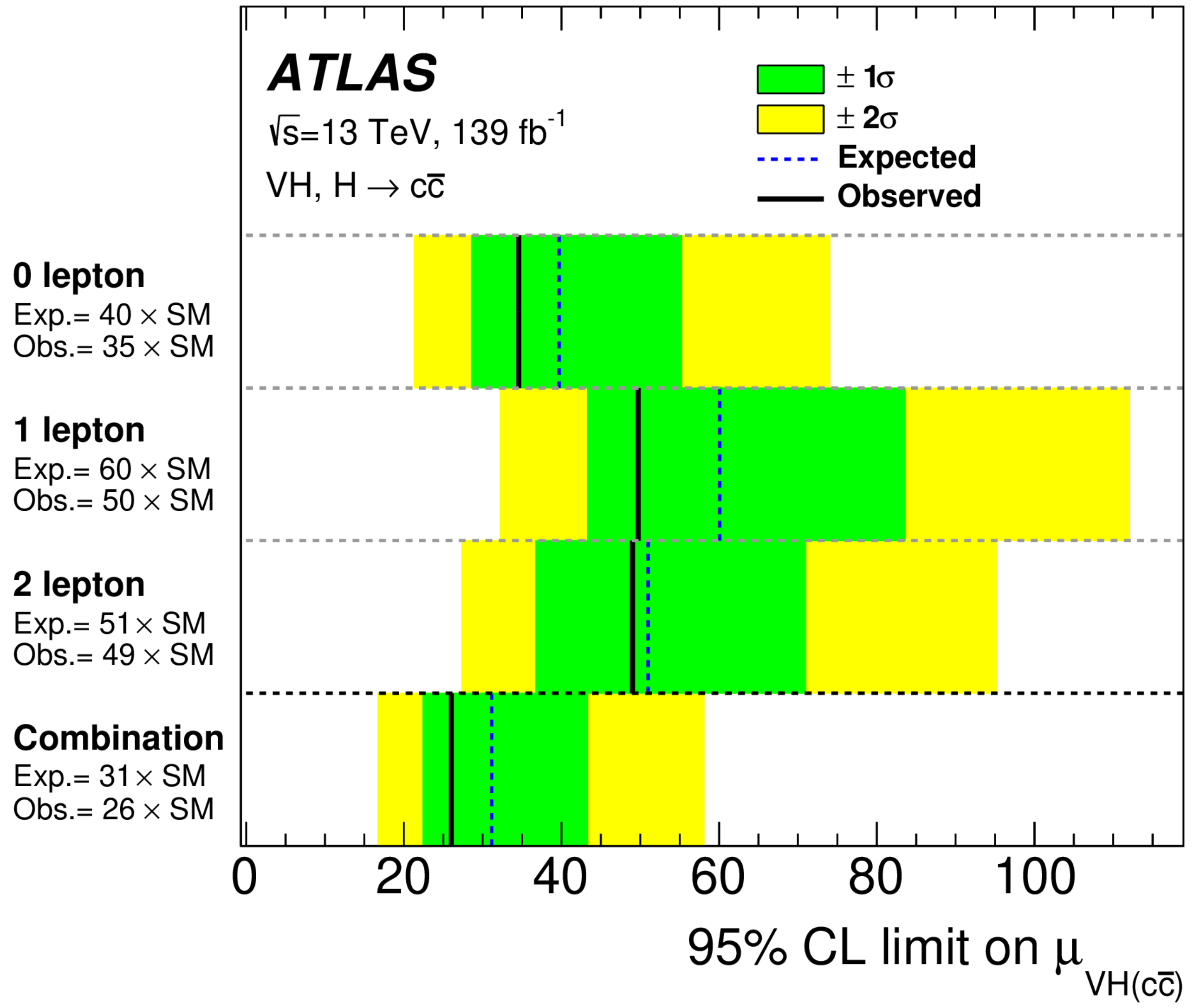
Expected 1.7σ

Observed 2.0σ

$\mu = 1.2 \pm 0.6$

H→cc [Eur. Phys. J. C 82 (2022) 717]





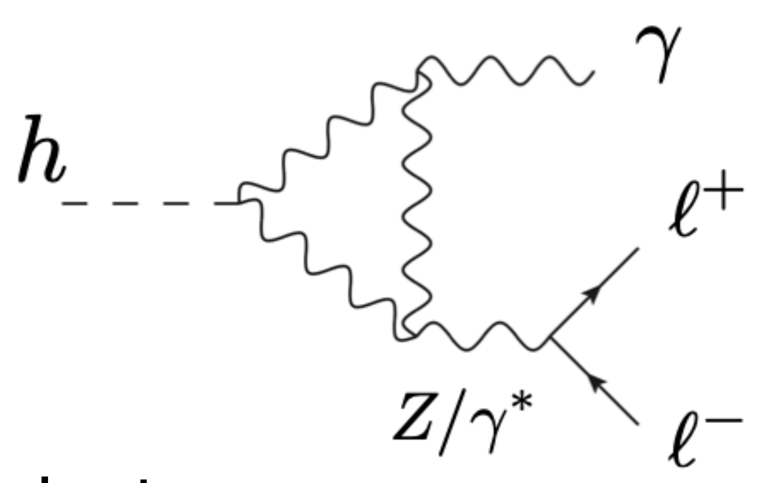
$|\kappa_c| < 8.5\ (12.4)$

3σ evidence in CMS! Expect observation in Run3

Still a long way before the observation… maybe at HL-LHC?

(Decays to 1st generation fermions (ee) also searched for but no evidence found and UL set at $7 \cdot 10^4$ the SM prediction of $5 \cdot 10^{-9}$)

Rare (resonant and non resonant) decays to $l^+l^-\gamma$

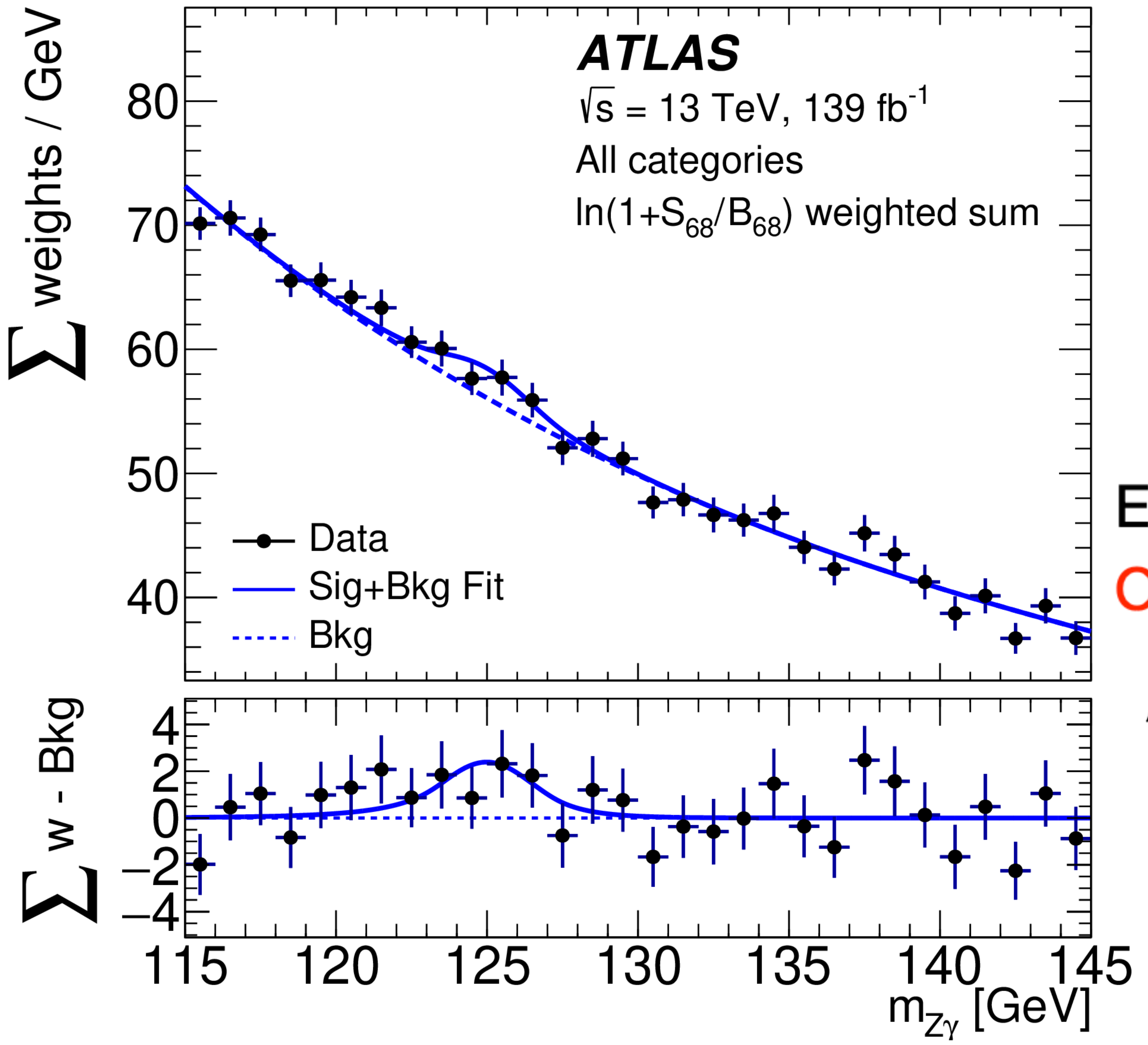


- H→Zγ→llγ (l=e,μ): ~4.4% of BR(γγ)
  - Tensor coupling, not measured yet: $|H^2|W^a_{\mu\nu}W^{\mu\nu a}$
  - Large Zγ background, low-momentum leptons and photons
- H→llγ (l=e,μ), m_{ll}<30 GeV: ~5% of BR(γγ)
  - Dedicated reconstruction of very close-by electrons (EM showers partially overlapping in the calorimeter)

Potential BSM physics that could explain flavour anomalies could also modify these rates

H→Zγ→llγ

[Phys. Lett. B 809 (2020) 135754]



Expected 1.2σ

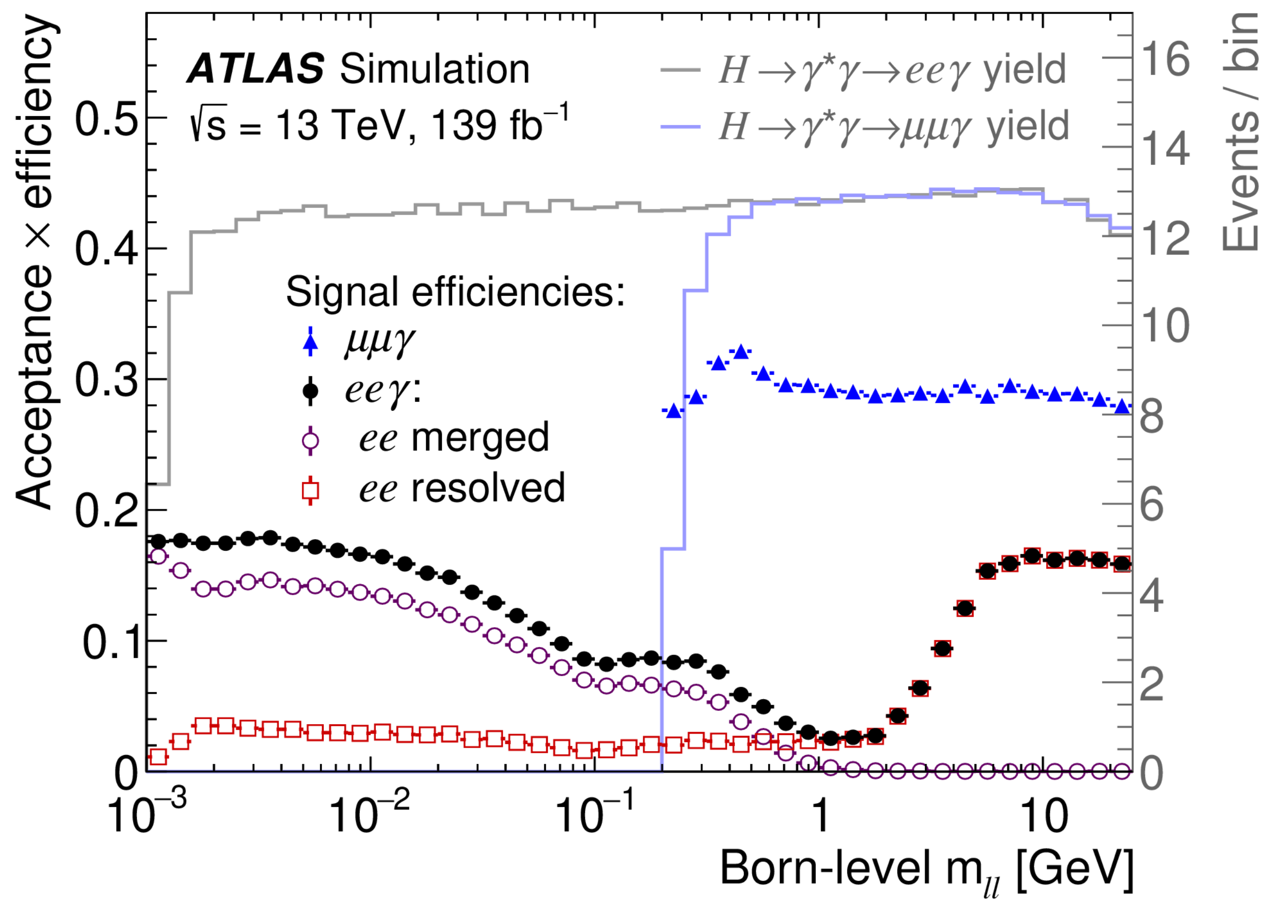
Observed 2.2σ

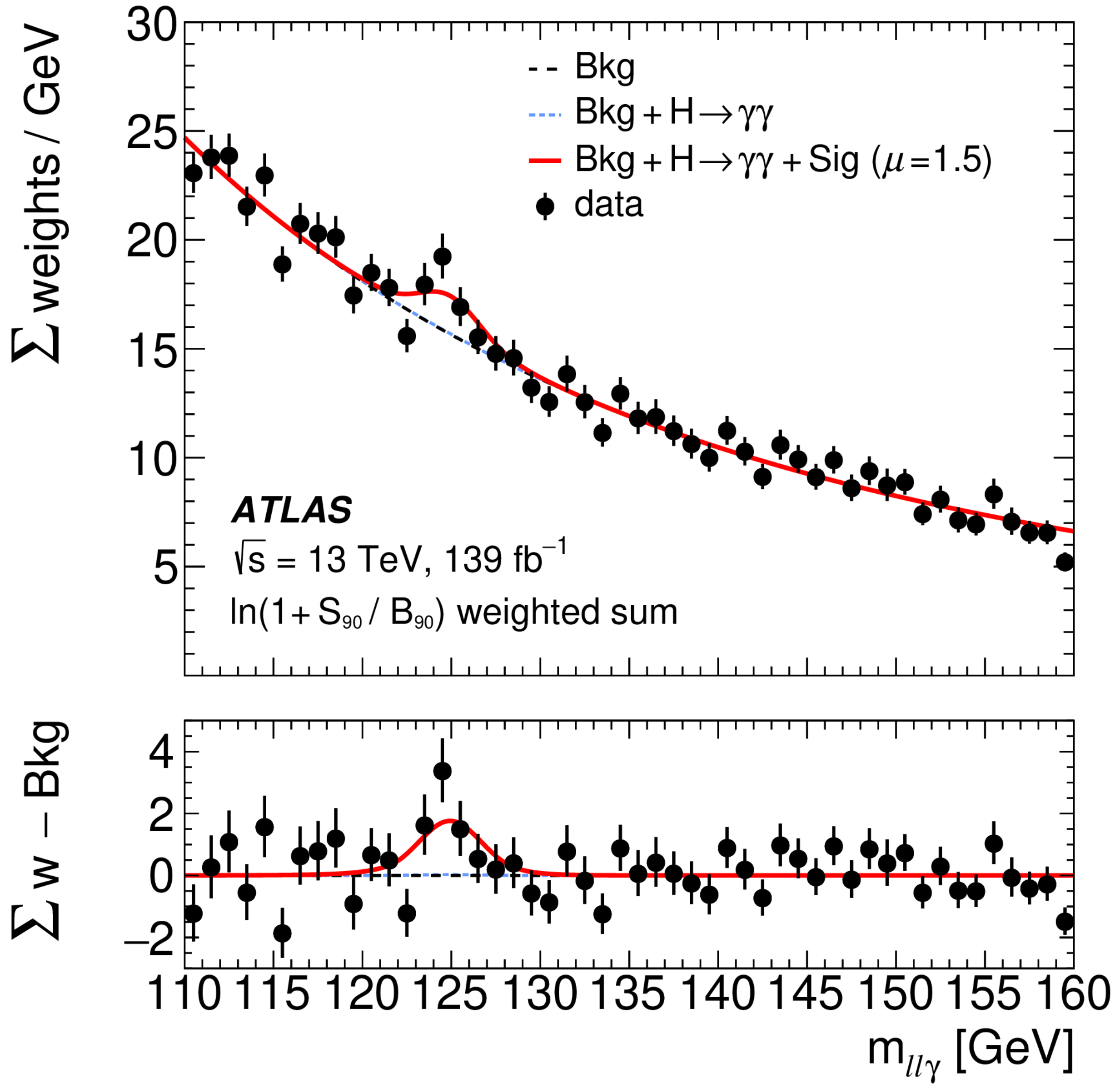
$\mu_{Z\gamma} = 2.0 \pm 0.9$

Similar excess in CMS. Potential evidence in Run3?

*H→γ*γ→llγ*

[Phys. Lett. B 819 (2021) 136412]





Expected 2.1σ

Observed 3.2σ

$\mu = 1.5 \pm 0.5$

First evidence! Keep watching with more data to look for SM deviations (compositeness, CP violation)

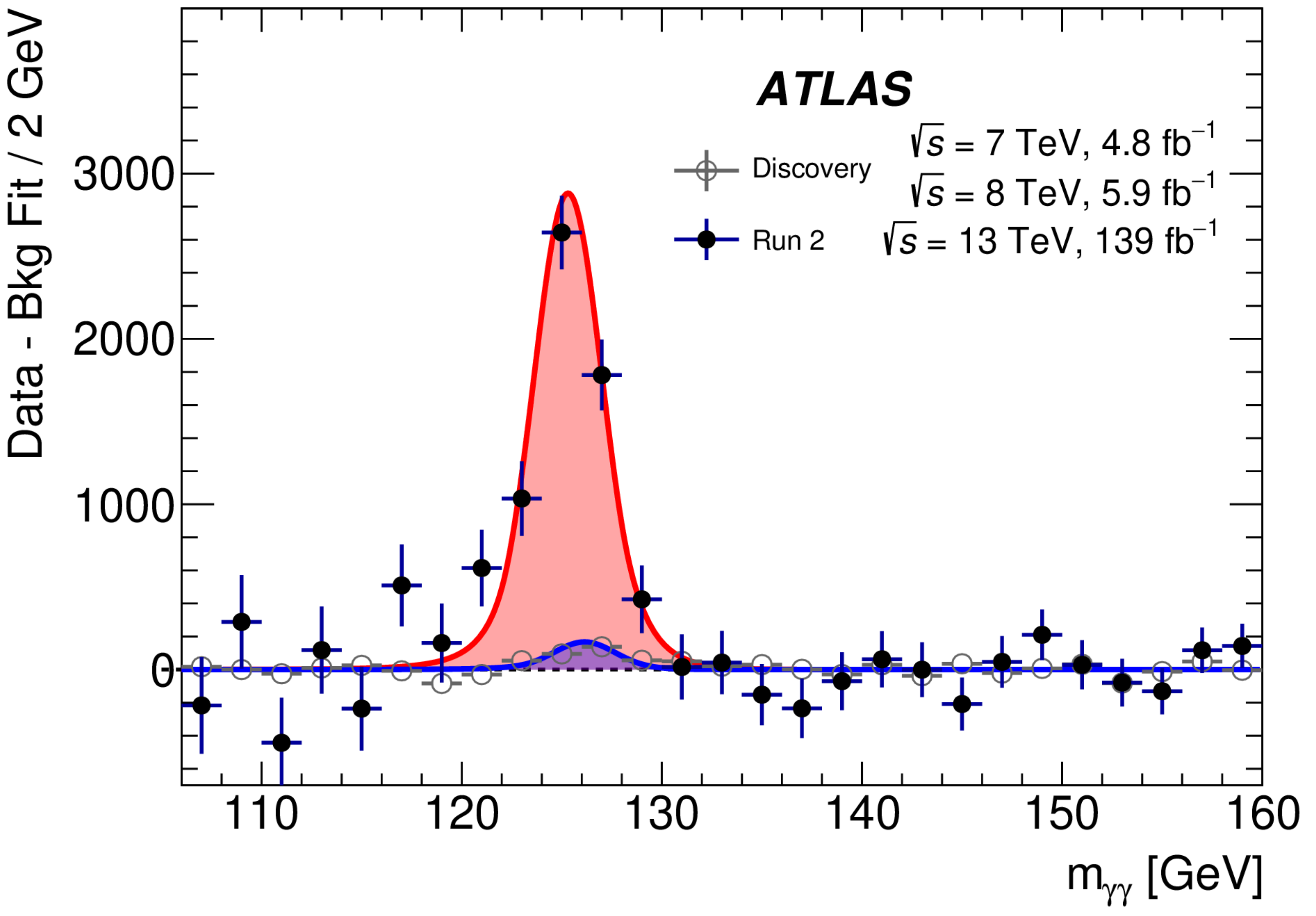
More precision in the bosonic channel, and putting all together

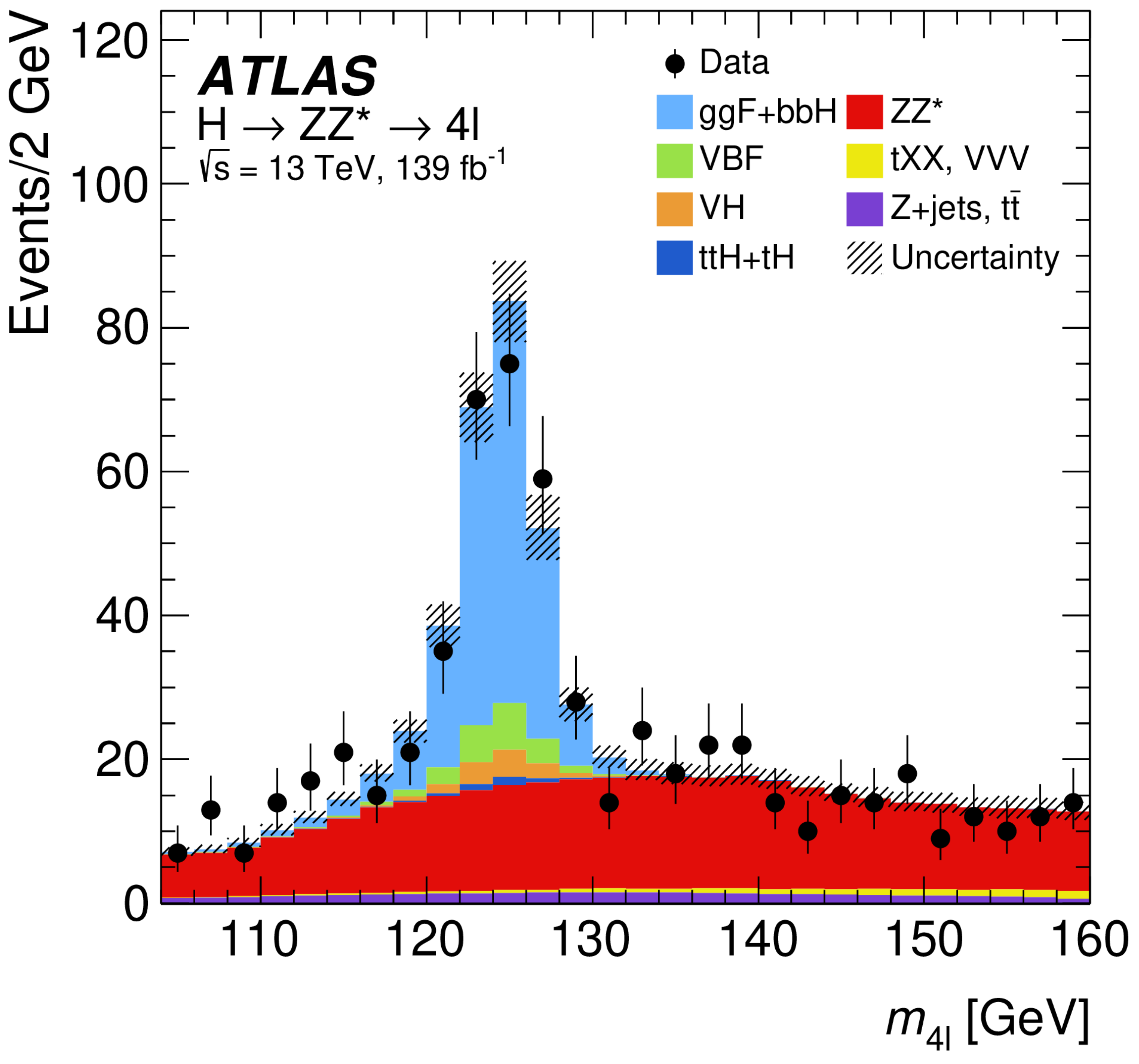
- Measurements of σ*BR in the full phase space, per production process and in simplified fiducial volumes (“bins”) of the phase space close have been performed in the 5 main Higgs boson decay channels with the full Run2 data: bb, ττ, and the “discovery channels” γγ, ZZ→4l and WW→e**ν**μ**ν** with the full Run2 data

- Exploit different signatures of main production modes, define event categories enriched in one particular production mode or bin

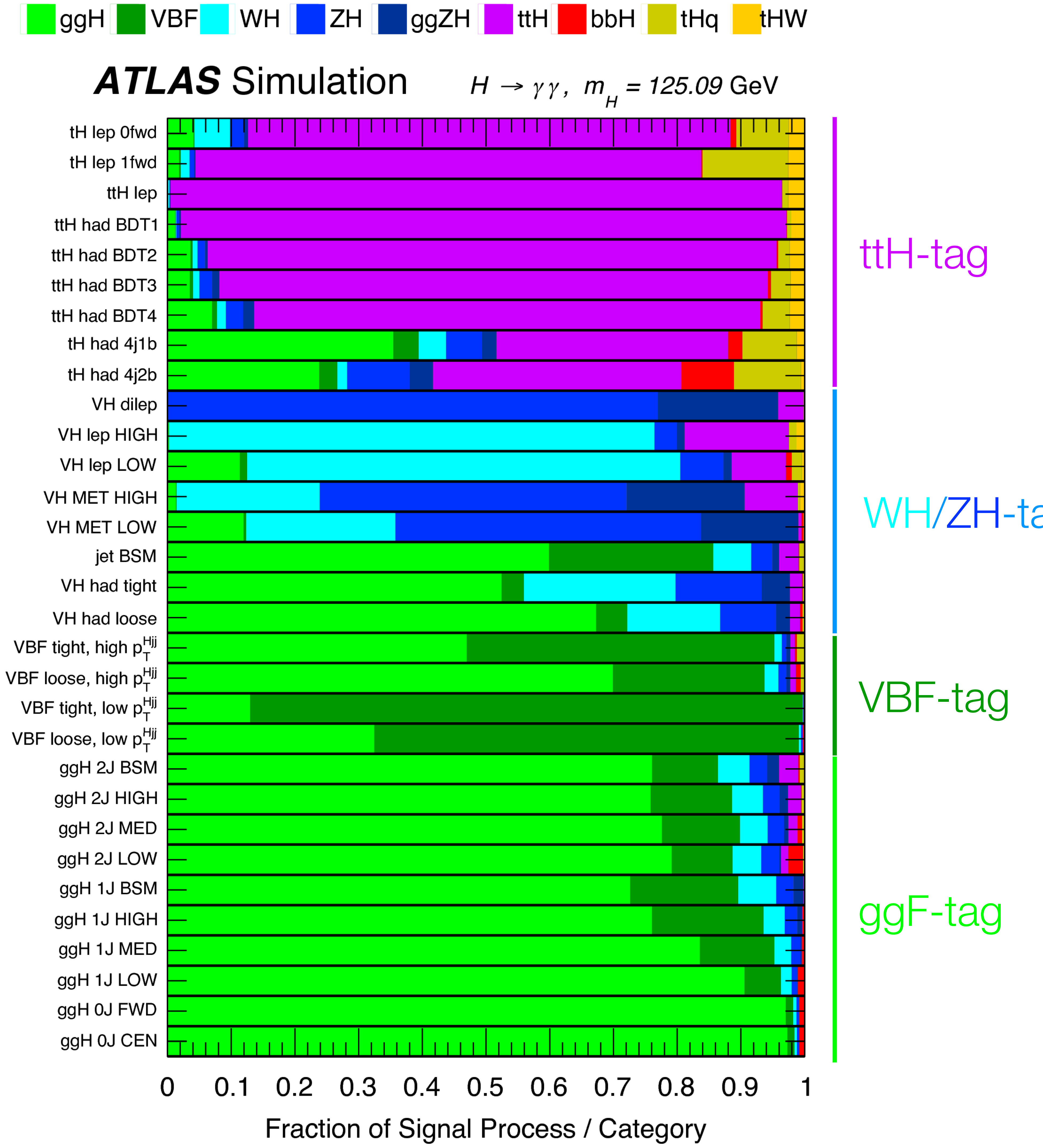
- Simultaneous fit to event yields in various categories allows measurement of signal strengths for each production and decay mode or bin

γγ: arXiv:2207.00348
ZZ: Eur. Phys. J. C 80 (2020) 957
WW: arxiv:2207.00338



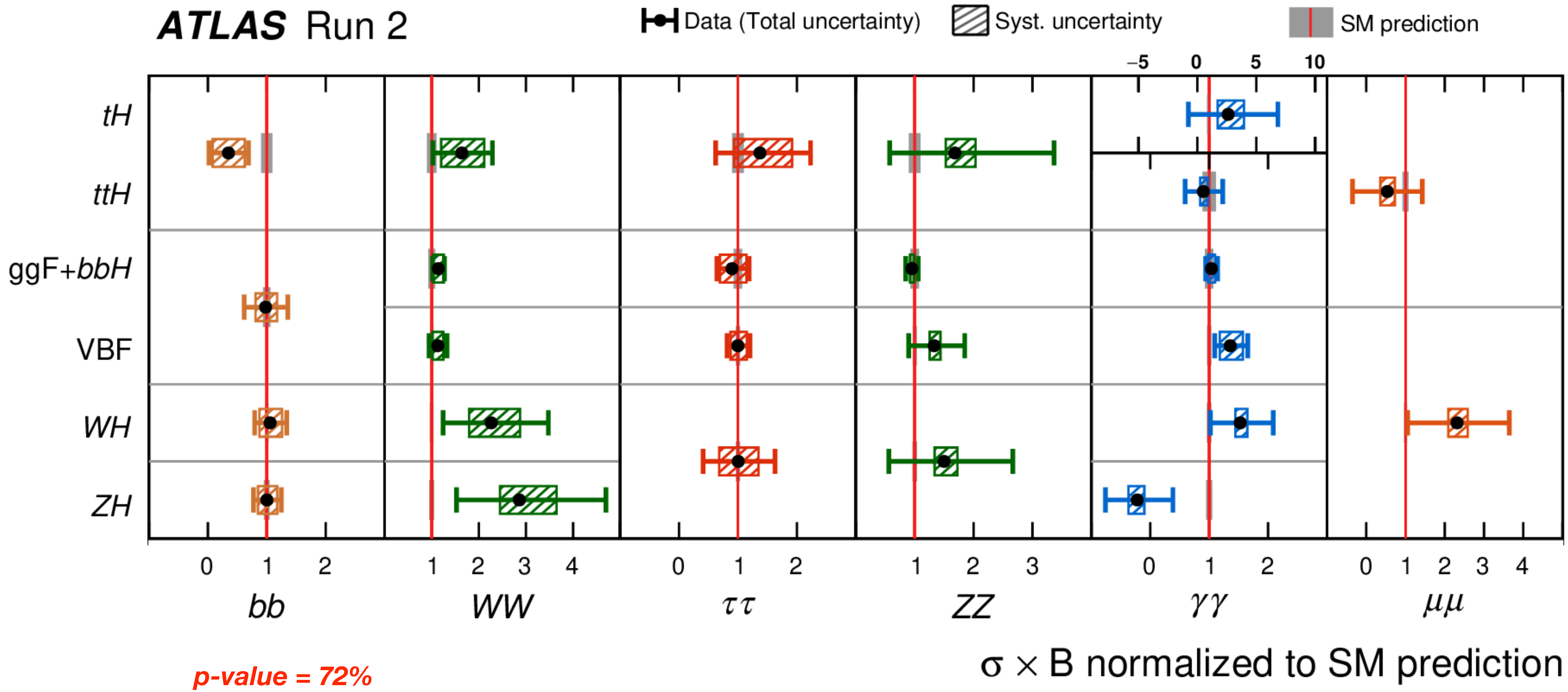


e.g. H→γγ (Phys. Rev. D 98 (2018) 052005)



More precision in the bosonic channel, and putting all together

[Nature 607, 52 (2022)](https://doi.org/10.1038/s41586-022-04893-w)



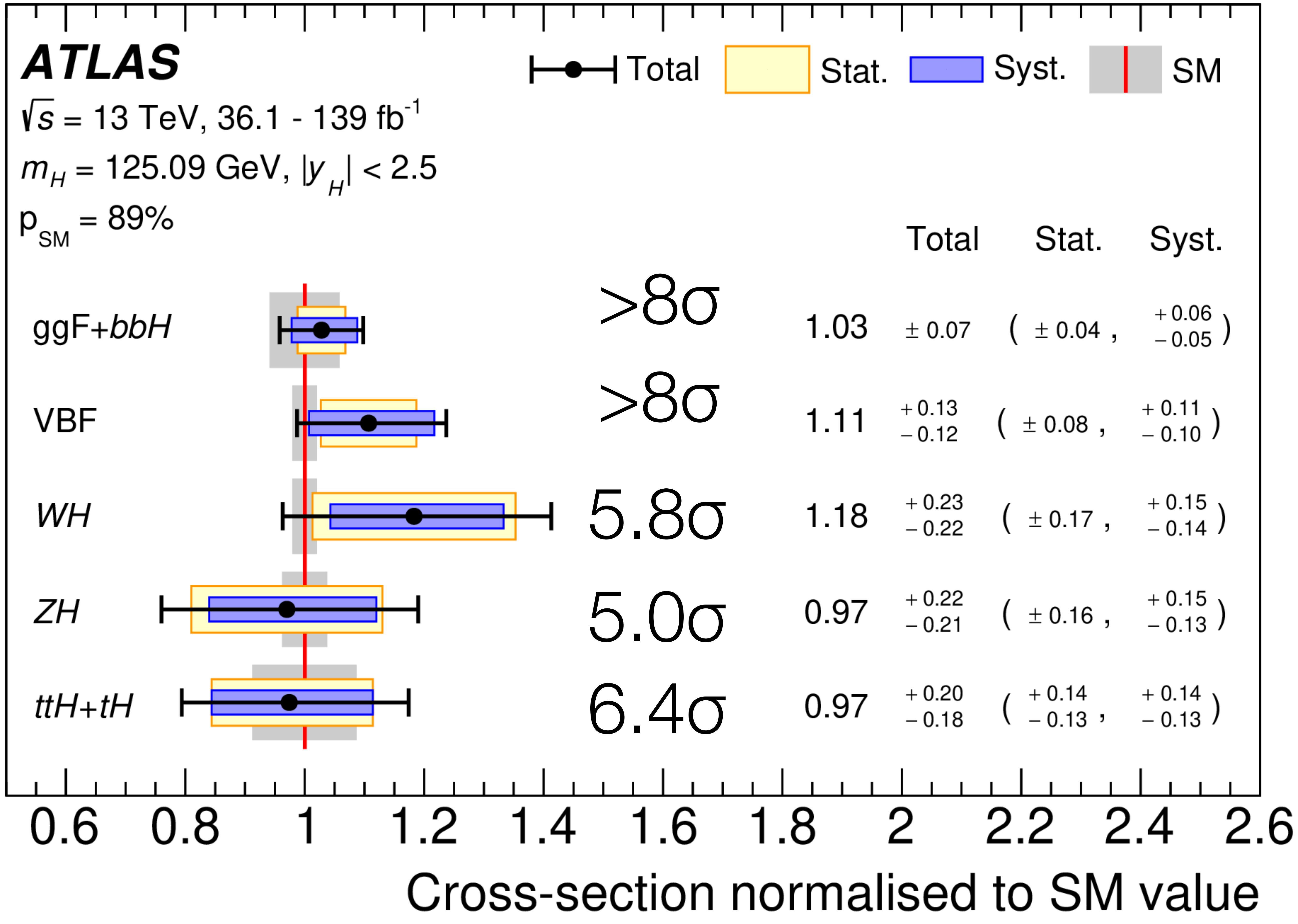
p-value = 72%

Measurements of production mode cross-sections

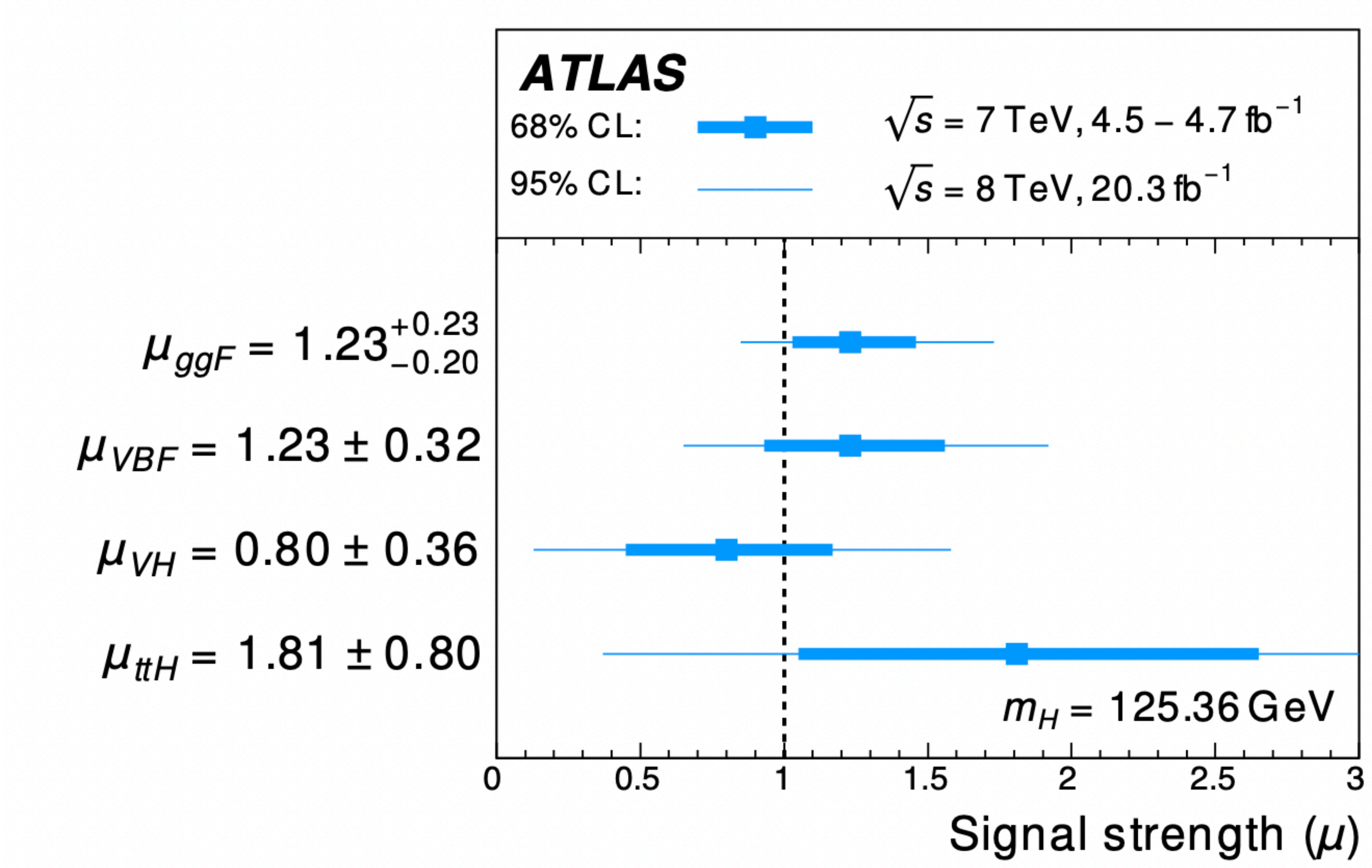
- Assume SM branching ratios and measure production mode cross-sections

[Nature 607, 52 (2022)]

Run 2



Run 1

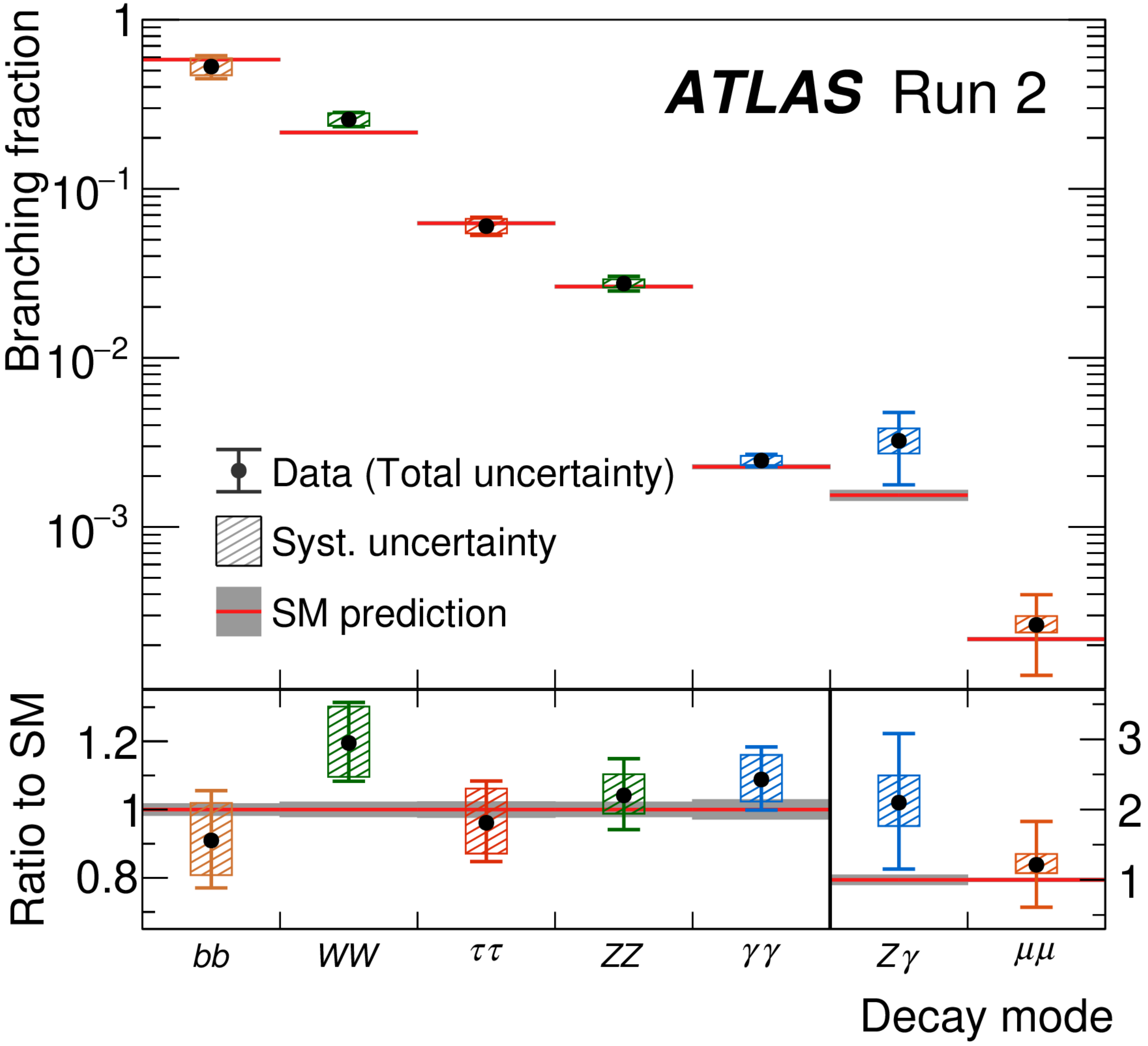


Process	VBF	ttH	WH	ZH	VH
Observed	4.3	2.5	2.1	0.9	2.6
Expected	3.8	1.5	2.0	2.1	3.1

Observation of all main production modes and 3-5x reduction in uncertainties compared to Run1 (precision 7-22%)

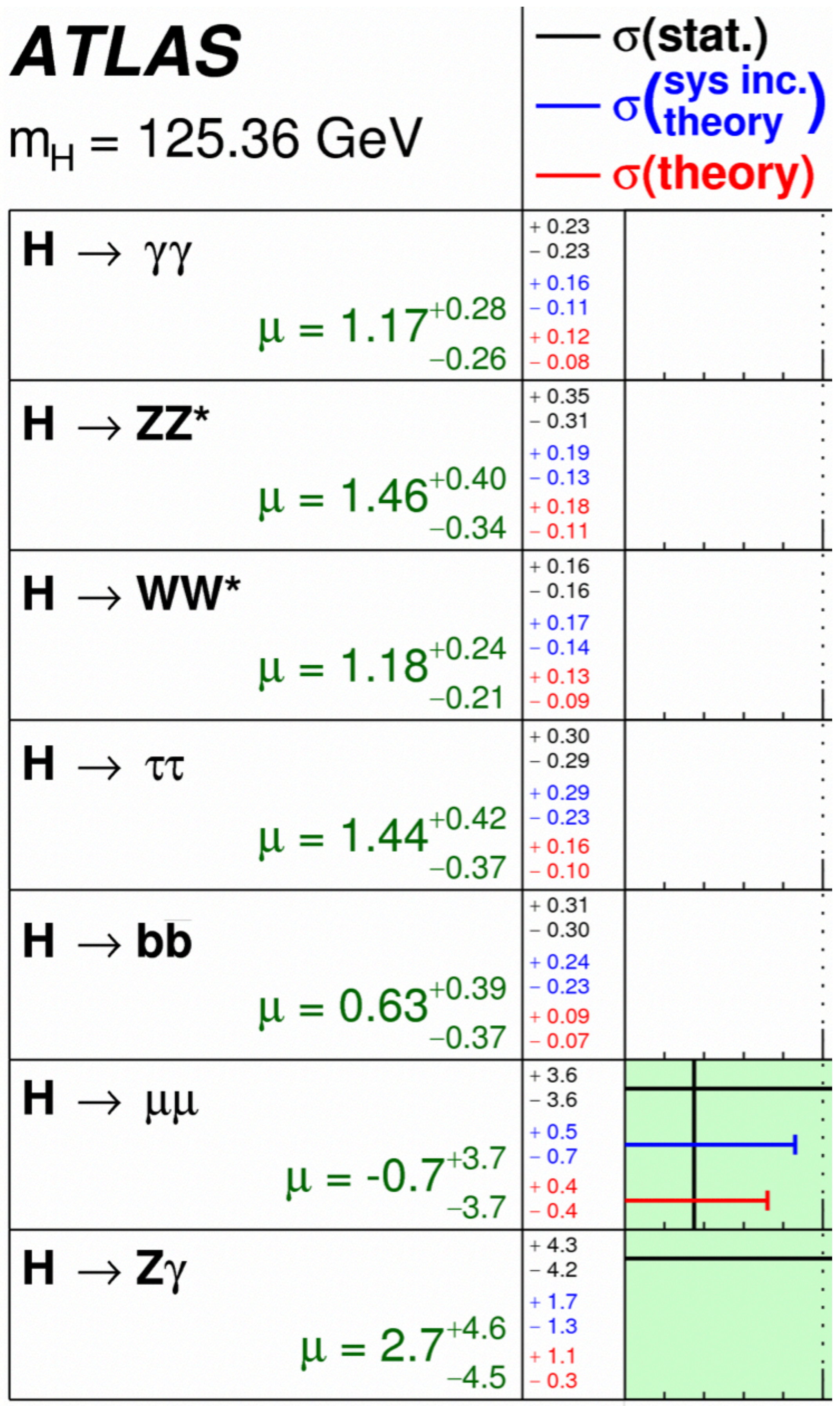
Measurement of decay branching ratios

- Assume SM production mode cross-sections and measure branching ratios



Run 1

[Nature 607, 52 (2022)](#)



Uncertainties in main decay channels now at 10-12% level

Inclusive signal strength

- Assuming a global scale factor affecting equally all production modes and decay channels:

Nature 607, 52 (2022)

$$\mu_{if} = (\sigma_i/\sigma_i^{SM}) \times \left(B_f/B_f^{SM}\right) = \mu$$

- Run2 result:

$$\mu = 1.05 \pm 0.06 = 1.05 \pm 0.03\,(\text{stat.}) \pm 0.03\,(\text{exp.}) \pm 0.04\,(\text{sig. th.}) \pm 0.02\,(\text{bkg. th.}).$$

- Compare to Run1:

$$\mu = 1.18^{+0.15}_{-0.14} = 1.18 \pm 0.10\,(\text{stat.}) \pm 0.07\,(\text{syst.})^{+0.08}_{-0.07}\,(\text{theo.}),$$

Improvement in relative precision: 14% (Run 1) ➔ 6% (Run 2)

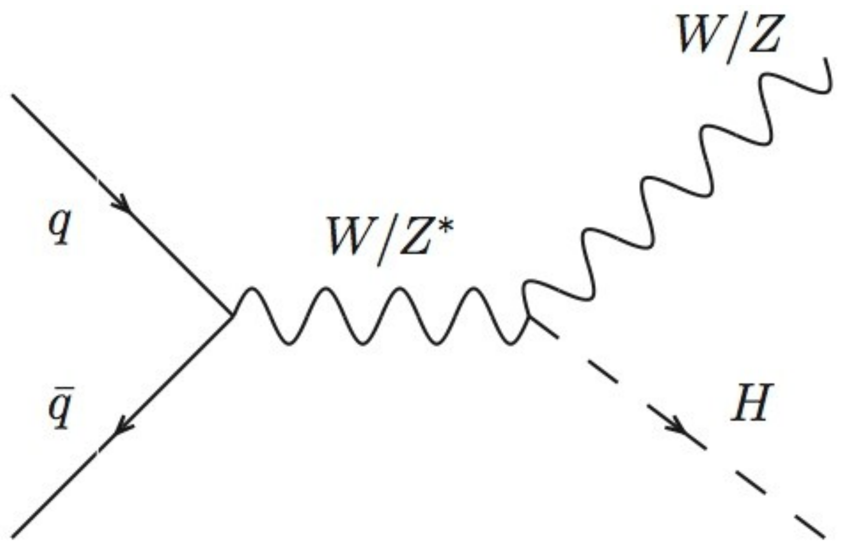
Theory uncertainty: 7% (Run 1) ➔ 4% (Run 2)

Measurement of Higgs boson couplings to other particles

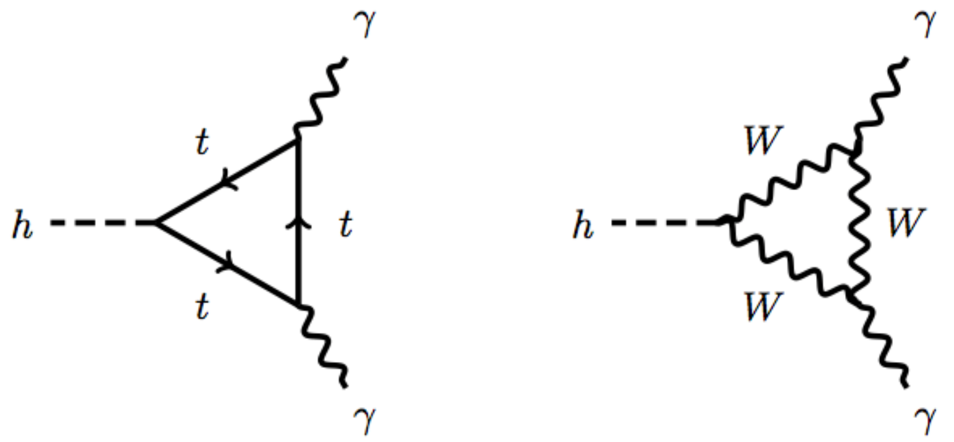
- Assuming that the signals in the different channels are due to a single, narrow, CP-even resonance, the signal strengths can be parametrised in terms of coupling scaling factors κ

$$(\sigma \cdot \mathrm{BR})(i \to \mathrm{H} \to f) = \frac{\sigma_i^{SM} \kappa_i^2 \cdot \Gamma_f^{SM} \kappa_f^2}{\Gamma_H^{SM} \kappa_H^2}$$

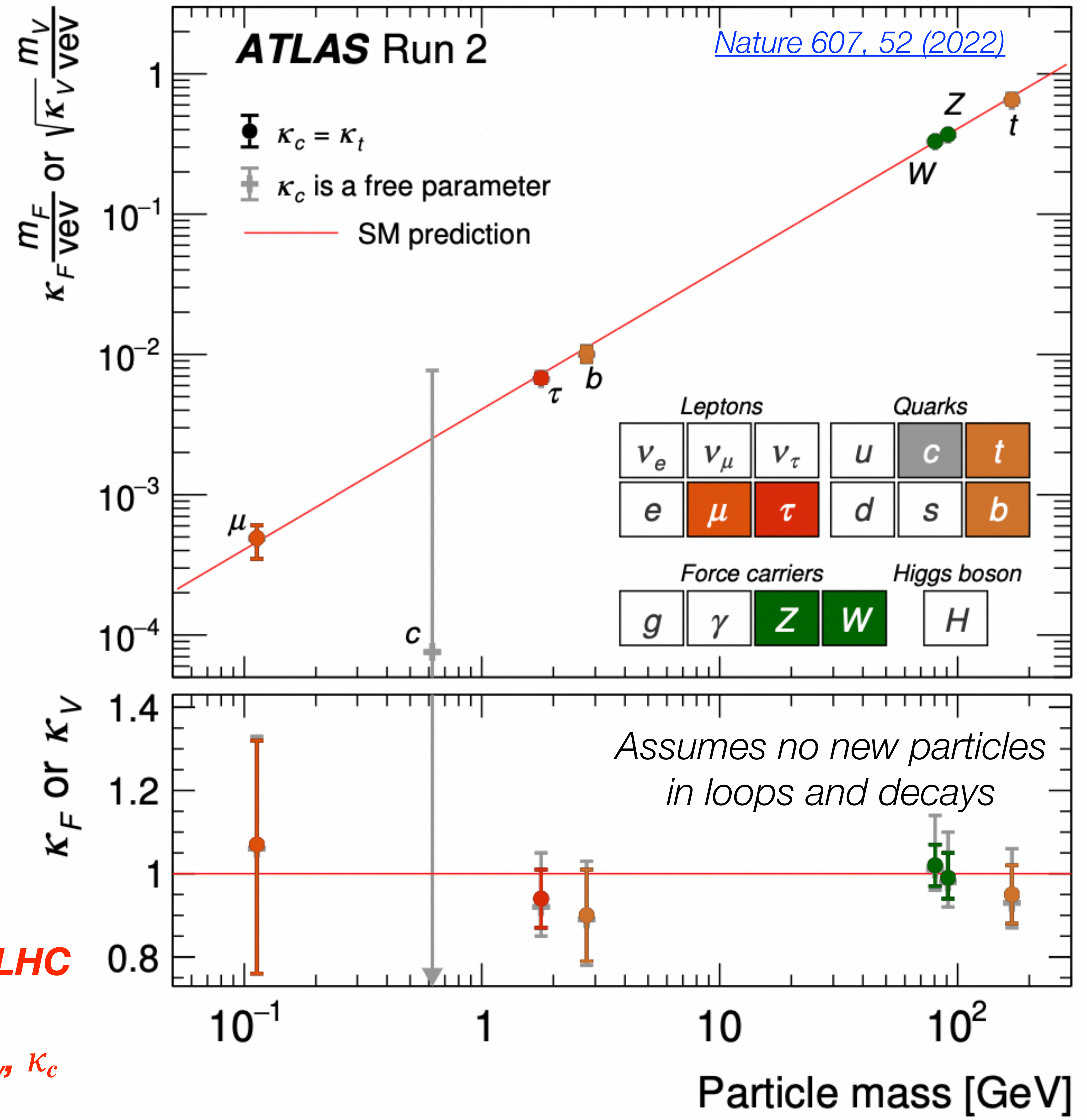
- A couple of examples:



$$\sigma \propto \kappa_W^2, \kappa_Z^2$$



$$\Gamma^{\gamma\gamma} \propto 1.59\, \kappa_W^2 + 0.07\, \kappa_t^2 - 0.67\, \kappa_W \kappa_t$$

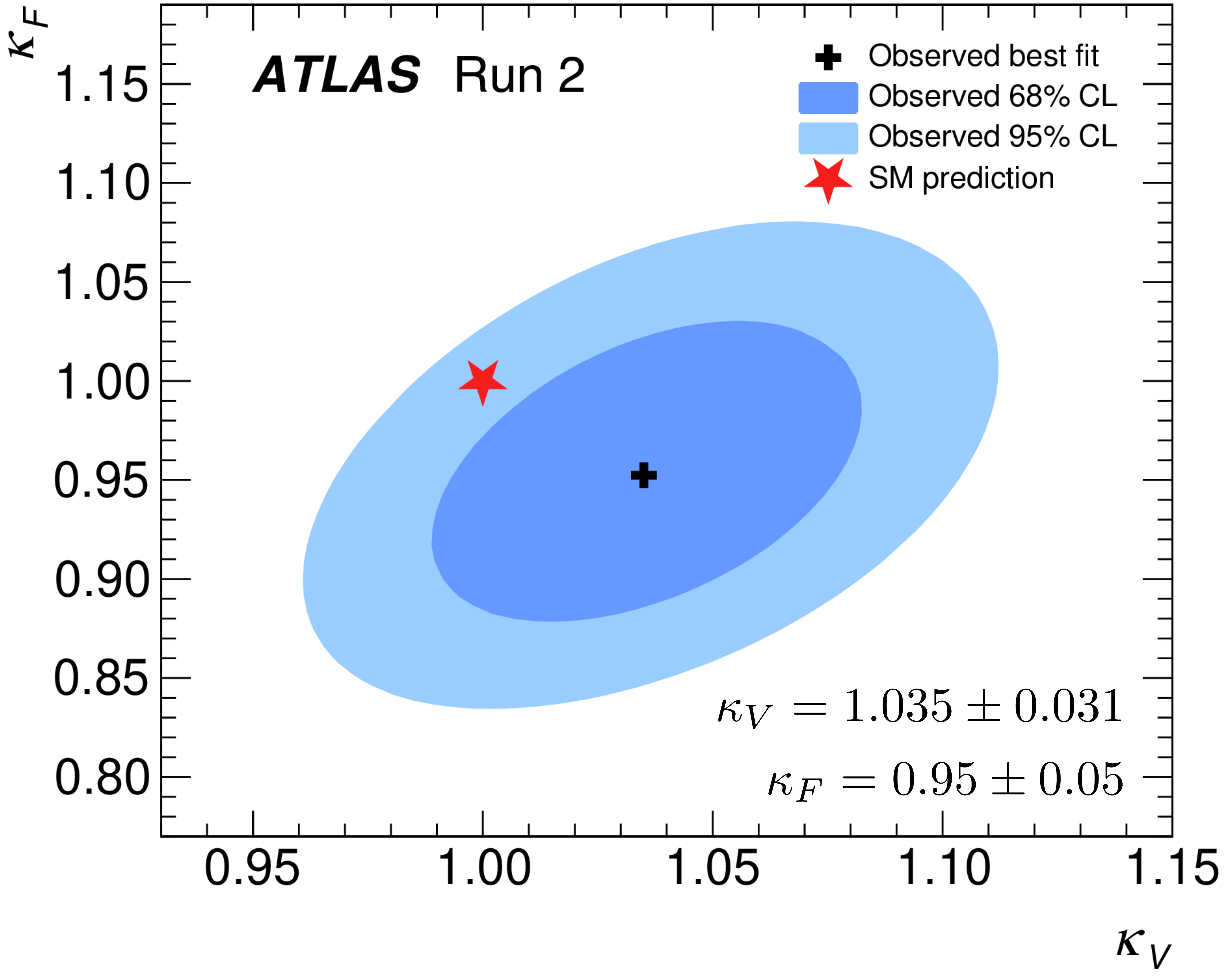


All measured couplings to fermions and bosons agree with the SM

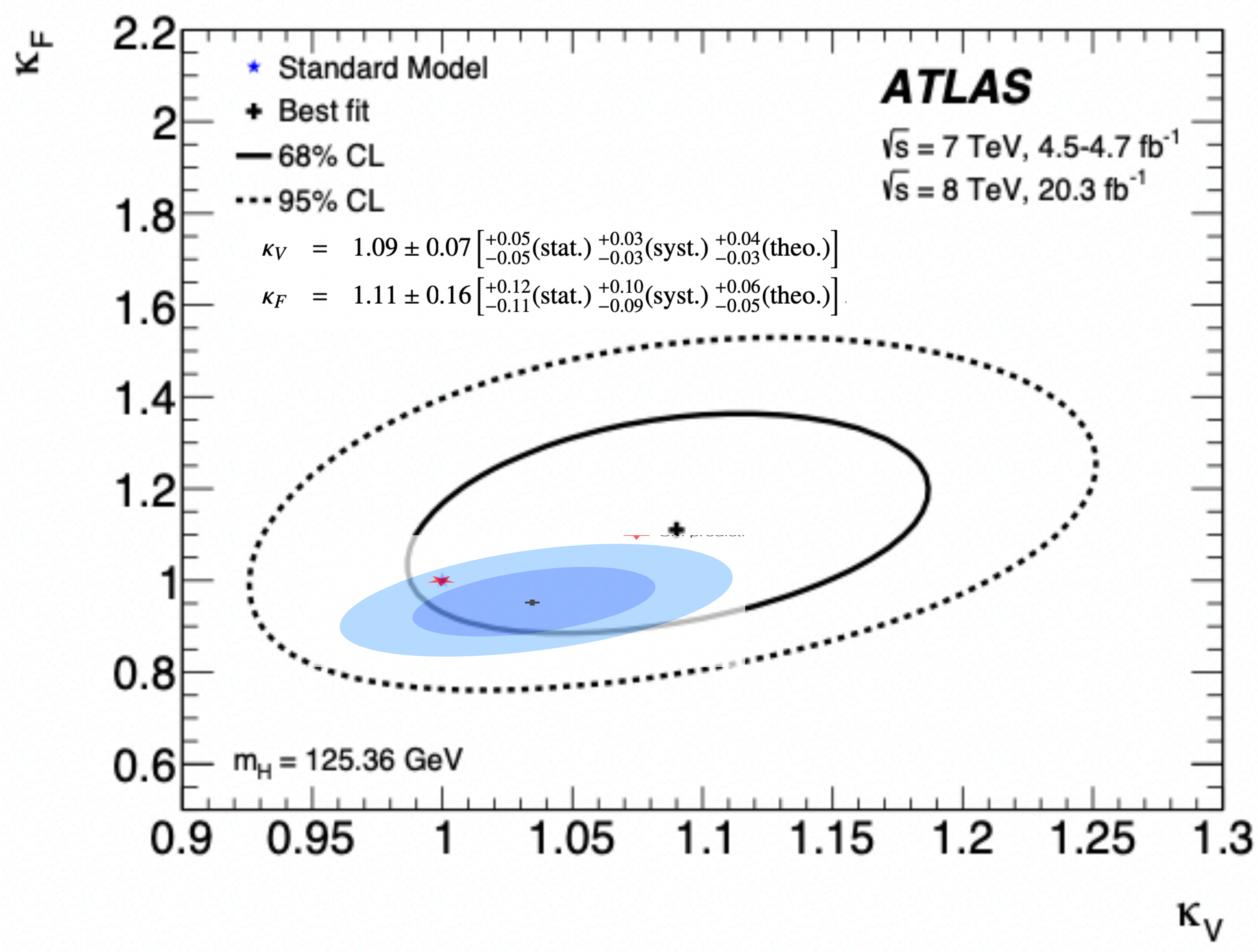
Current uncertainties (5-11%, 30% for μ) to be reduced by x3 at HL-LHC

In all scenarios, statistical ~ systematic uncertainty except for κ_μ, $\kappa_{Z\gamma}$, κ_c

Measurement of Higgs boson couplings to other particles



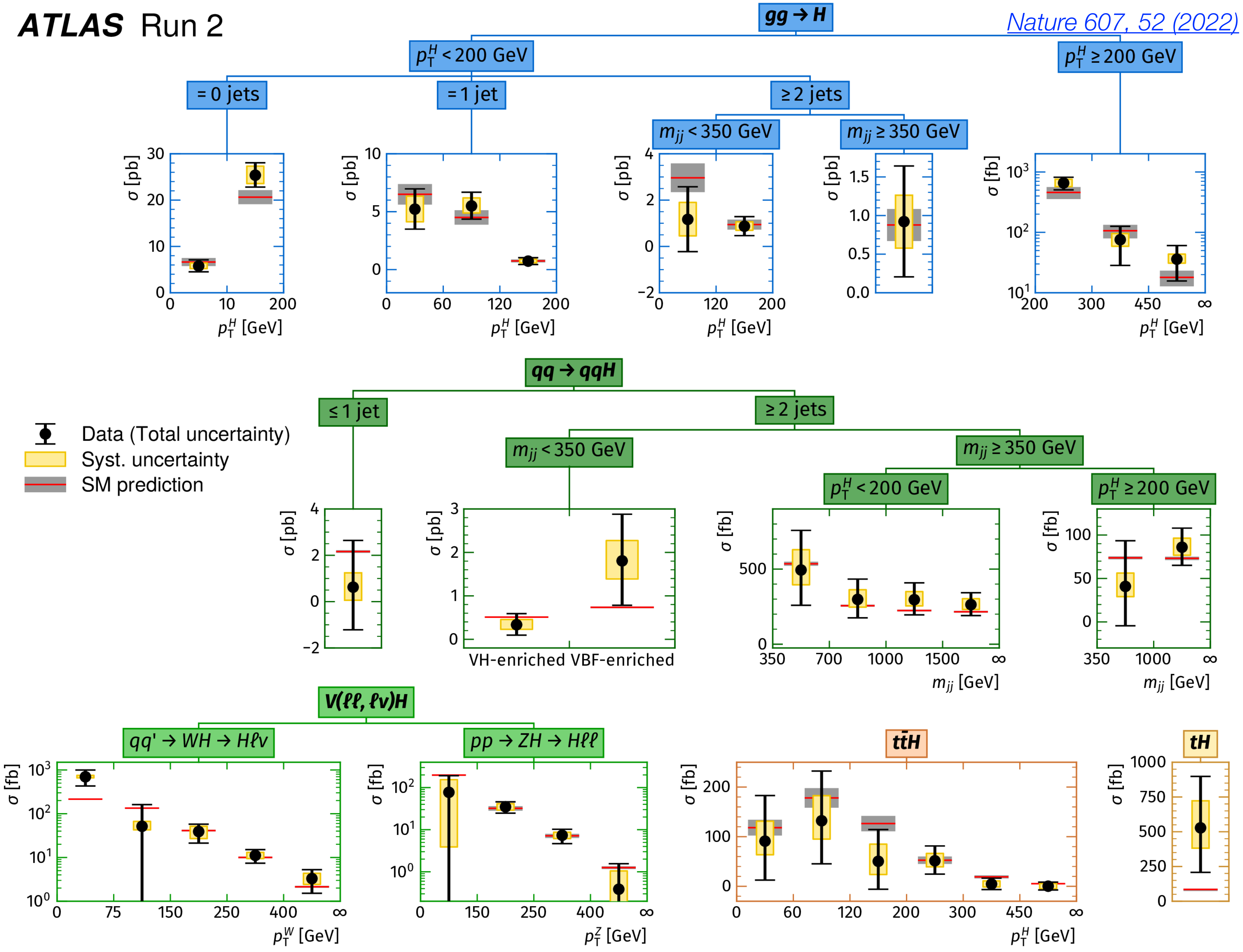
Nature 607, 52 (2022)



Measurement of “simplified template cross-sections” (STXS)

- Measurements of σ*BR in simplified fiducial volumes defined based on particle-level quantities such as p_T^H, N(jets), m_{jj}, ..
  - Reduce extrapolation uncertainties to full phase space
  - Provide less model-dependent measurements that can be used even in the future for setting constraints on SM (with more precise calculations) or other theories
  - Allow searching more in detail / systematic way for deviations from SM due to anomalous couplings through e.g. EFT-based interpretation

[Nature 607, 52 (2022)](#)



Good agreement with SM (p-value 94%)

Most measurement statistically limited

Further granularity possible w/ more data

Effective field theory interpretation

- Effective Lagrangian built with SM fields at lowest order in expansion in 1/Λ (Λ = new physics energy scale):

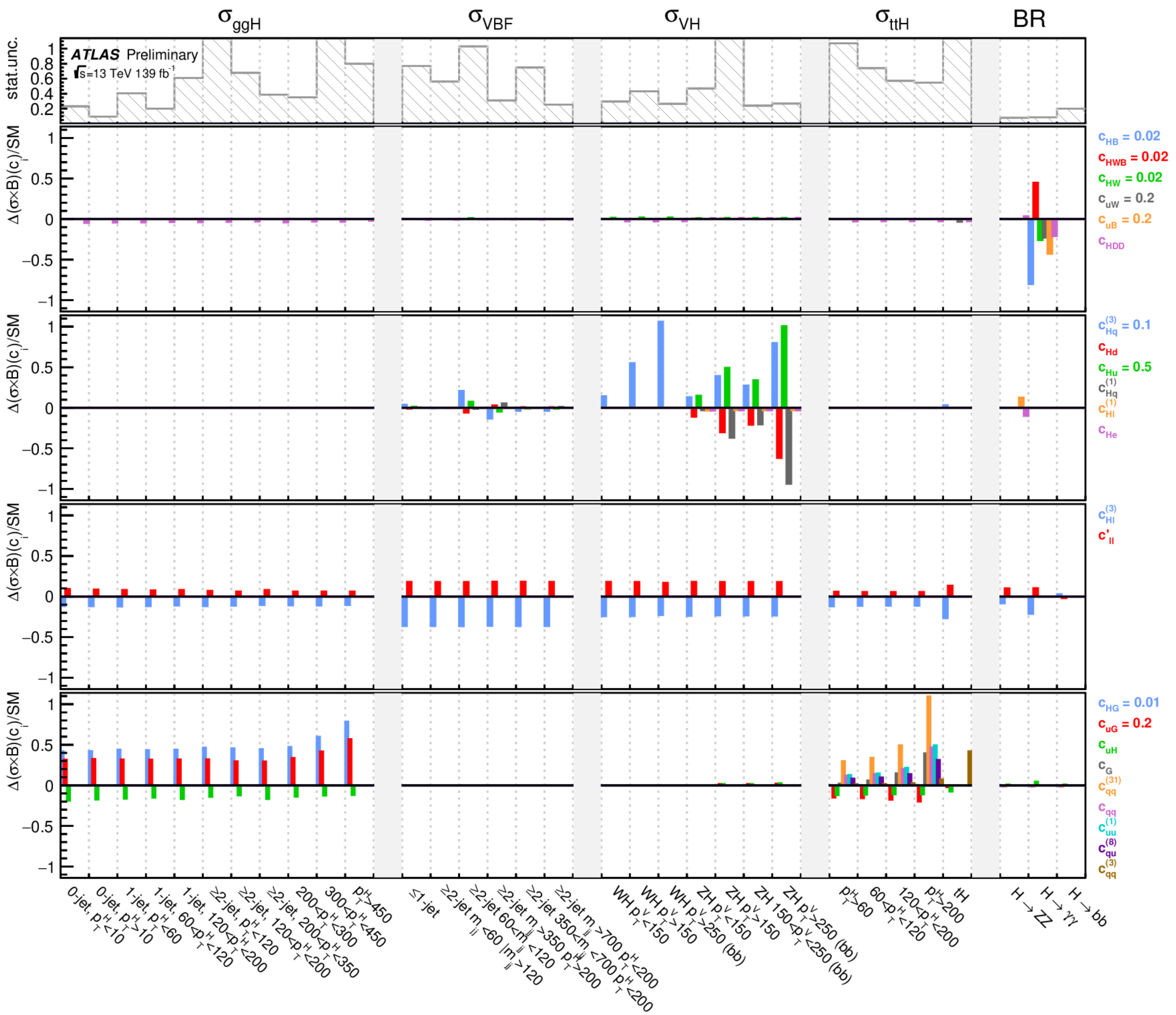
ATLAS-CONF-2020-053

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_i \frac{C_i^{(d)}}{\Lambda^{(d-4)}} O_i^{(d)} \quad \text{for } d > 4.$$

d=6, Λ=1 TeV

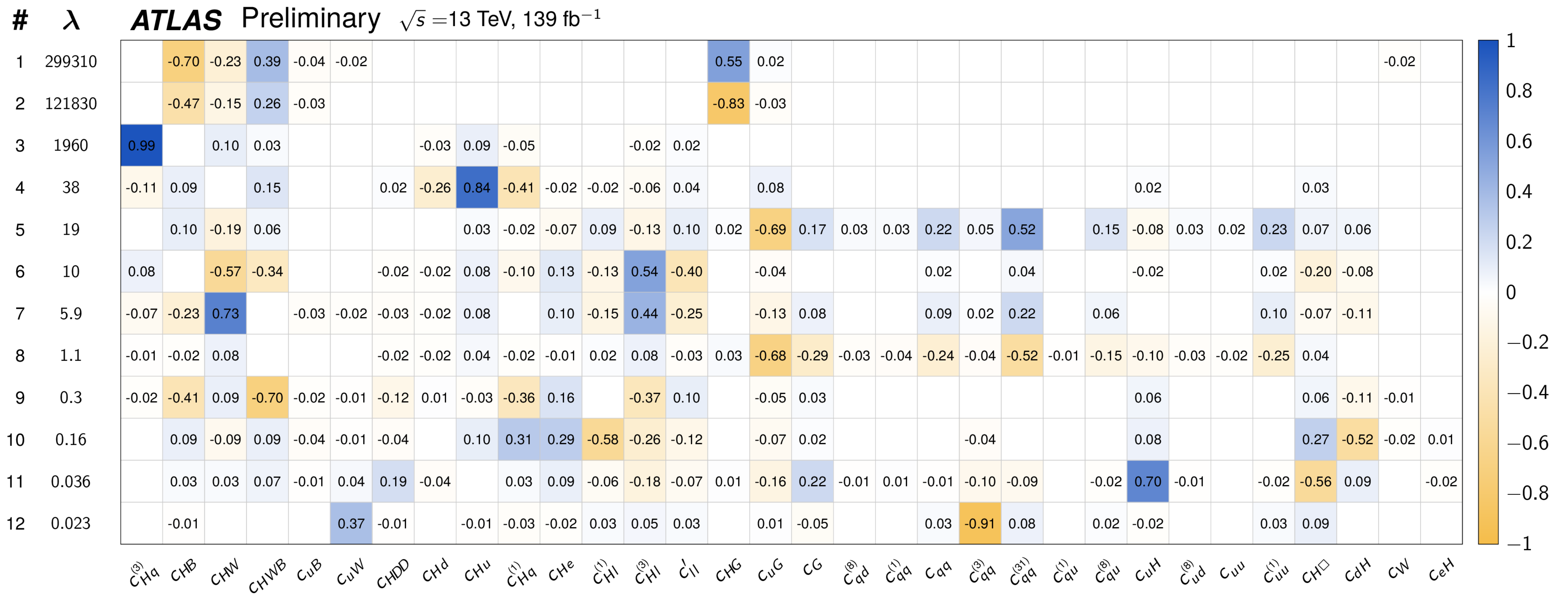
- Several operators induce anomalous couplings between the Higgs and the SM fields that modify the STXS predictions

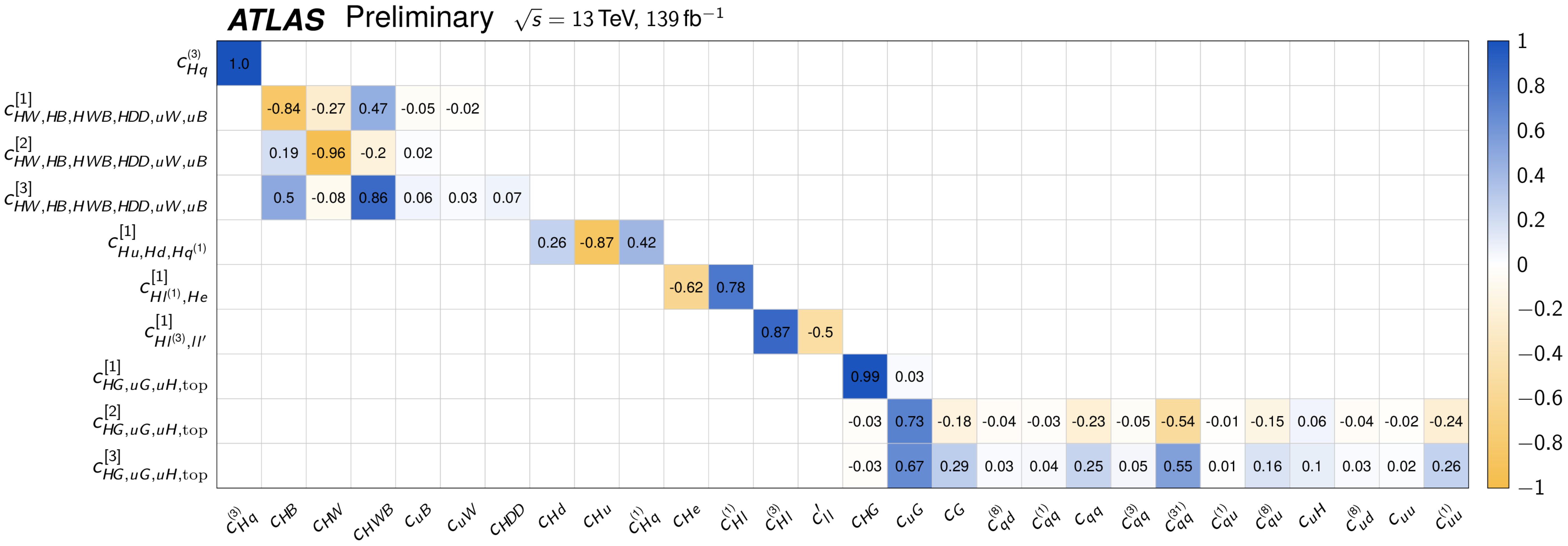
Wilson coefficient	Operator	Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$	c_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{H}\,G^A_{\mu\nu}$
c_{HDD}	$(H^\dagger D^\mu H)^*\,(H^\dagger D_\mu H)$	c_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{H}\,W^I_{\mu\nu}$
c_{HG}	$H^\dagger H\,G^A_{\mu\nu}G^{A\mu\nu}$	c_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{H}\,B_{\mu\nu}$
c_{HB}	$H^\dagger H\,B_{\mu\nu}B^{\mu\nu}$	c'_{ll}	$(\bar{l}_p\gamma_\mu l_t)(\bar{l}_r\gamma^\mu l_s)$
c_{HW}	$H^\dagger H\,W^I_{\mu\nu}W^{I\mu\nu}$	$c^{(1)}_{qq}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{HWB}	$H^\dagger\tau^I H\,W^I_{\mu\nu}B^{\mu\nu}$	$c^{(3)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	c_{qq}	$(\bar{q}_p\gamma_\mu q_t)(\bar{q}_r\gamma^\mu q_s)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r\widetilde{H})$	$c^{(31)}_{qq}$	$(\bar{q}_p\gamma_\mu\tau^I q_t)(\bar{q}_r\gamma^\mu\tau^I q_s)$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r\widetilde{H})$	c_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p\gamma^\mu l_r)$	$c^{(1)}_{uu}$	$(\bar{u}_p\gamma_\mu u_t)(\bar{u}_r\gamma^\mu u_s)$
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p\tau^I\gamma^\mu l_r)$	$c^{(1)}_{qu}$	$(\bar{q}_p\gamma_\mu q_t)(\bar{u}_r\gamma^\mu u_s)$
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p\gamma^\mu e_r)$	$c^{(8)}_{ud}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p\gamma^\mu q_r)$	$c^{(8)}_{qu}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p\tau^I\gamma^\mu q_r)$	$c^{(8)}_{qd}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p\gamma^\mu u_r)$	c_W	$\epsilon^{IJK}W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p\gamma^\mu d_r)$	c_G	$f^{ABC}G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

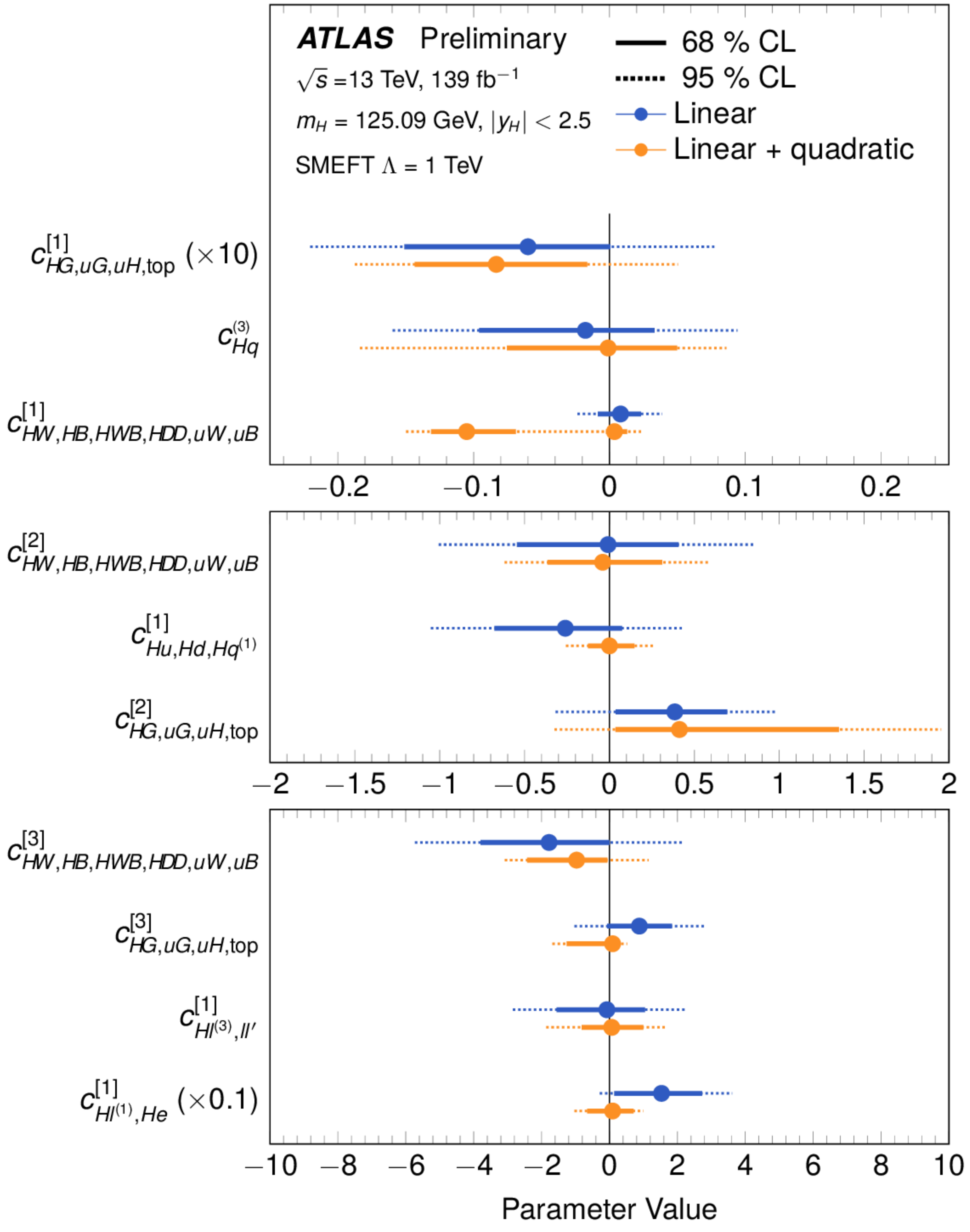


Effective field theory interpretation (II)

- Not enough measurements to constrain all coefficients => do PCA analysis to find rotated basis of operators with maximum sensitivity







Expect to see more of this in the future
Combination with EW/top measurements for even more global interpretation

Going even more fiducial: (fiducial) differential cross-sections

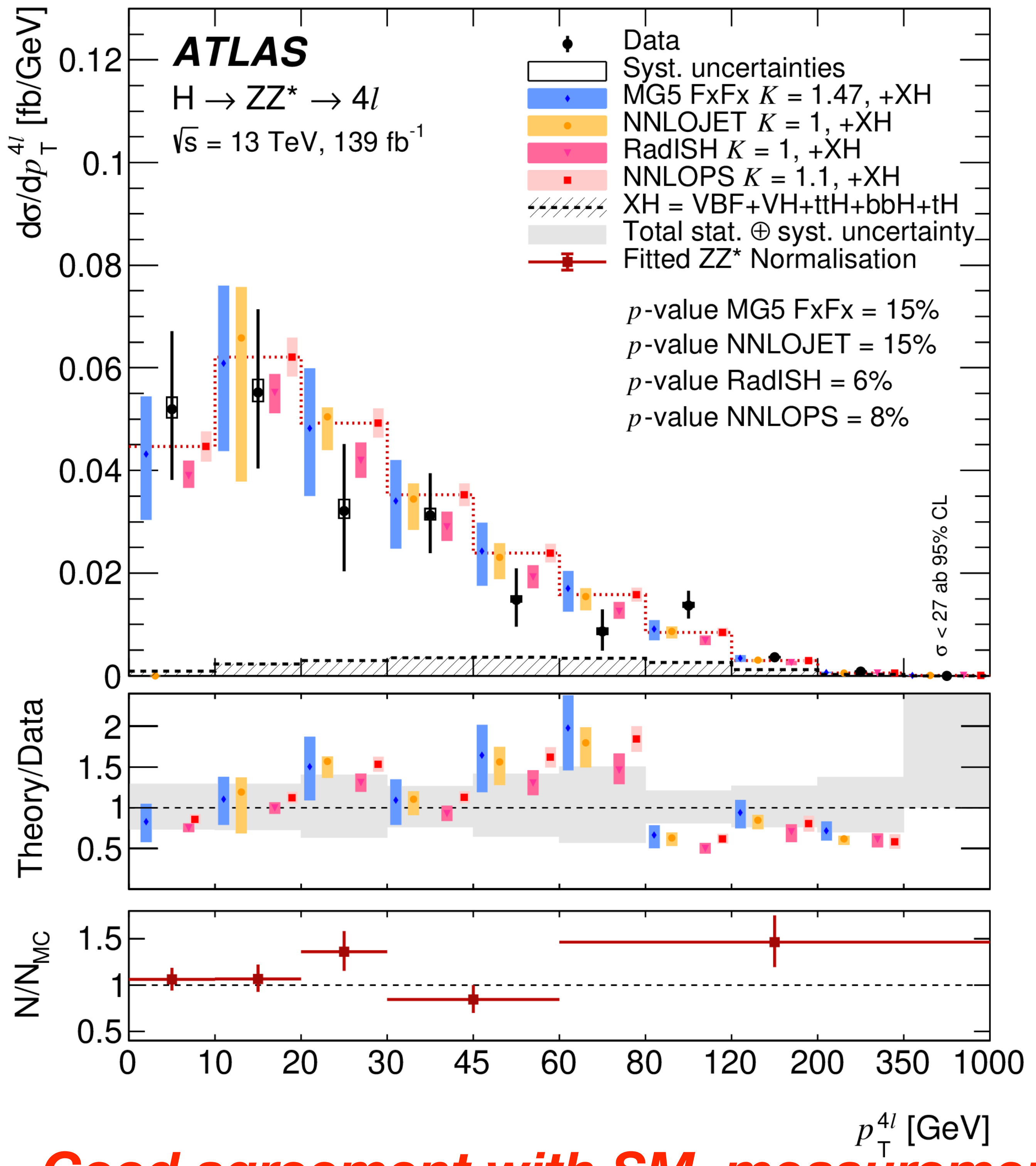
- More granular measurement as a function of several observables characterising the kinematics of Higgs boson production (Higgs p_T, N_{jets}, leading-jet p_T, invariant mass of leading and subleading jets (if present), …)

  ➡Measured observables can be sensitive to production mode xsection ratios / spin / CP / Higgs boson couplings ..

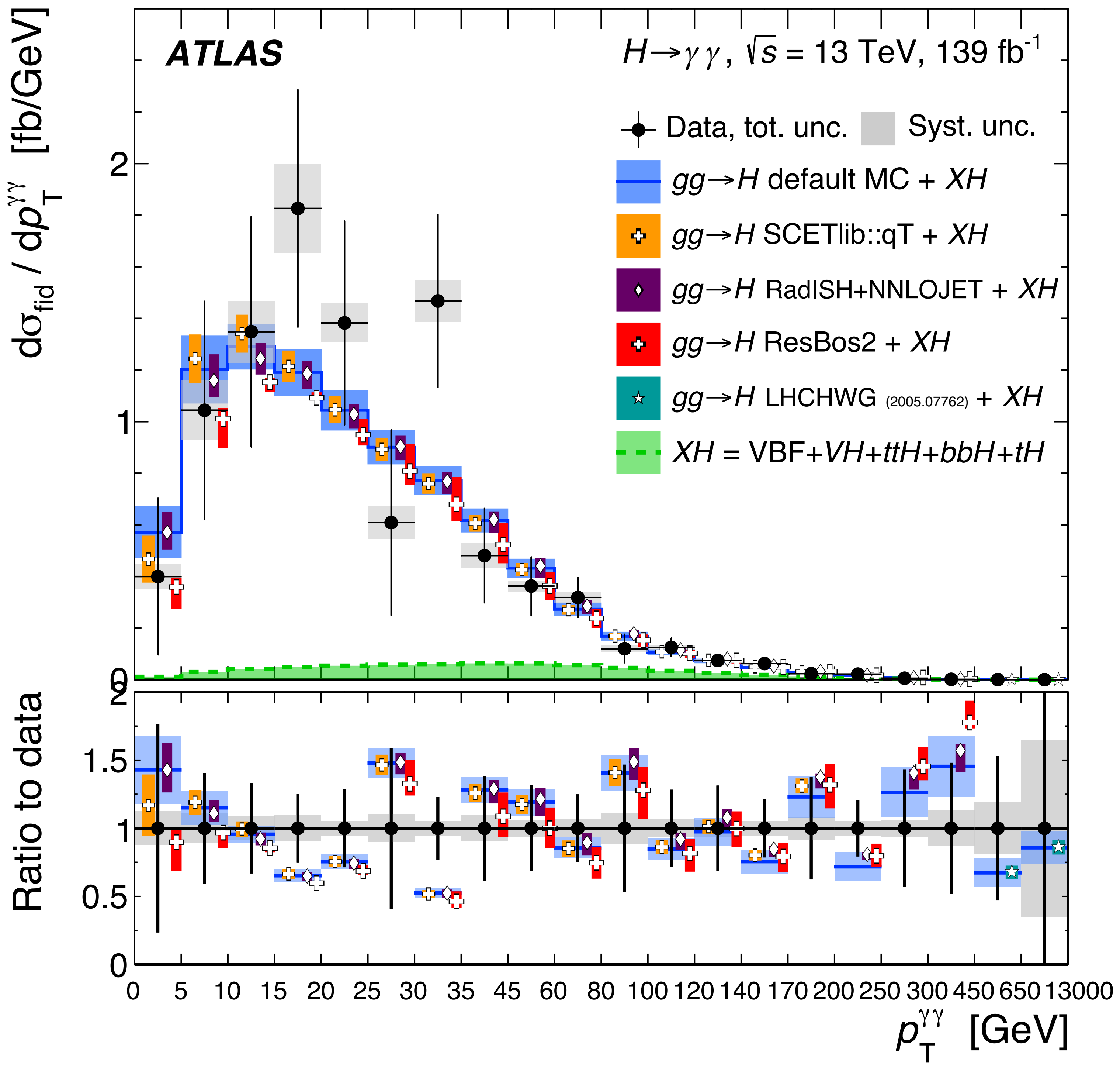
- In fiducial phase space, very close to experimental selection

  ➡Minimise model dependence from extrapolation from selected to full phase space; efficiency similar for all production modes

H→4l Eur. Phys. J. C 80 (2020) 942

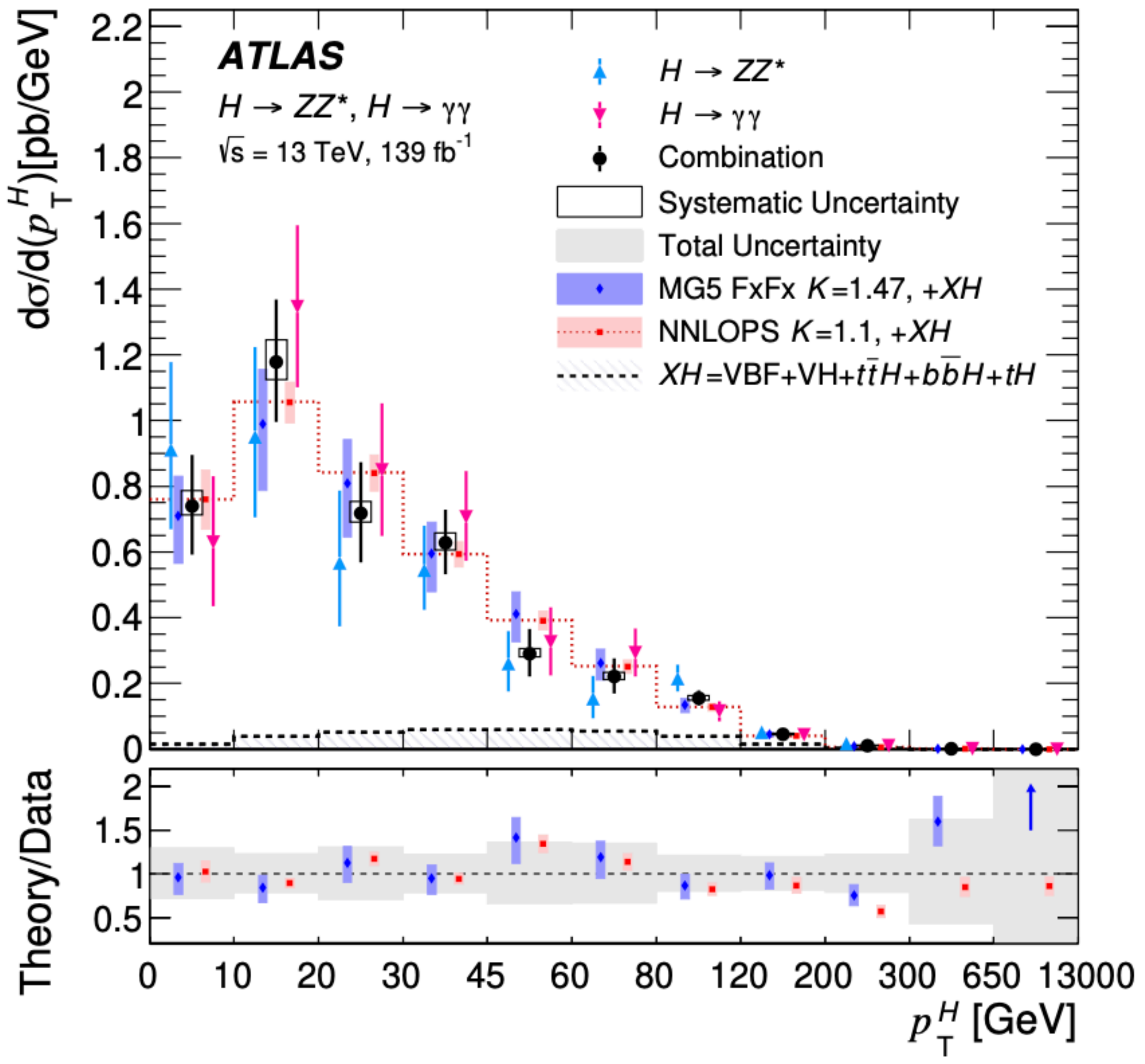


H→γγ JHEP 08 (2022) 027



Combination (in full phase space)

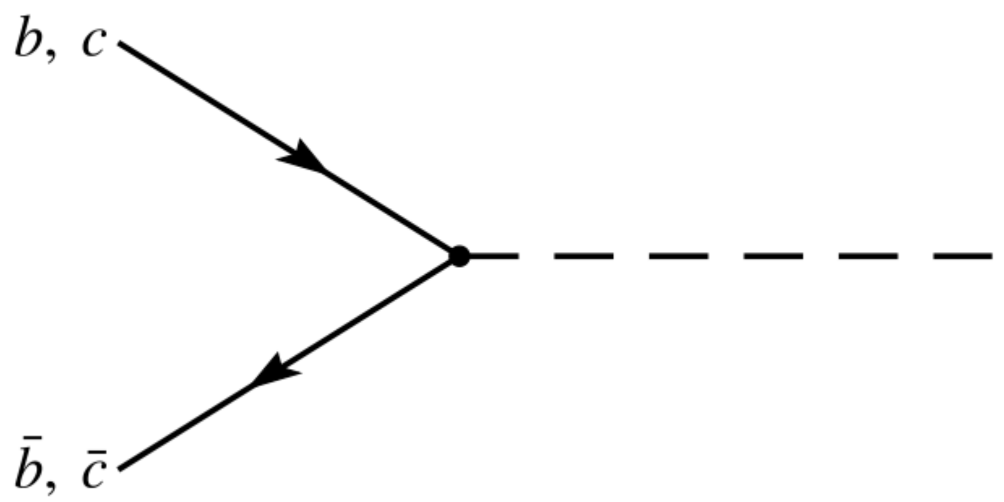
arXiv:2207.08615

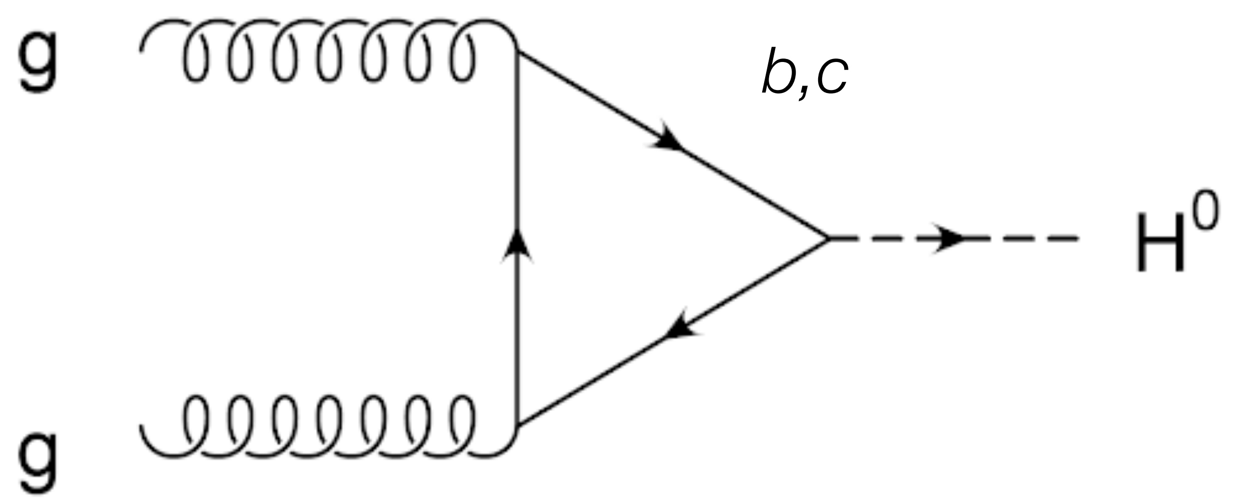


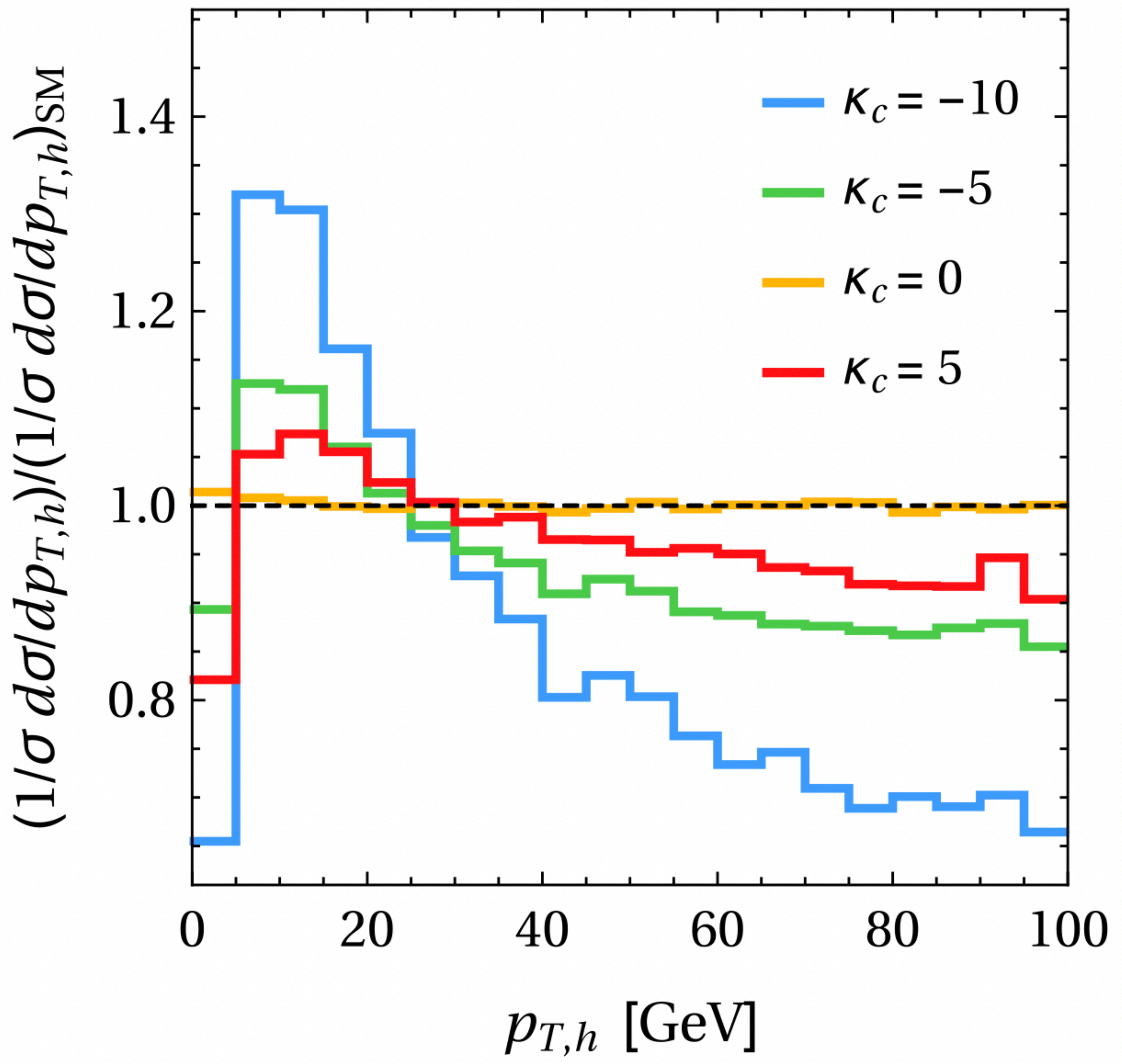
Good agreement with SM, measurements statistically limited

Differential cross sections: κ_b, κ_c interpretation

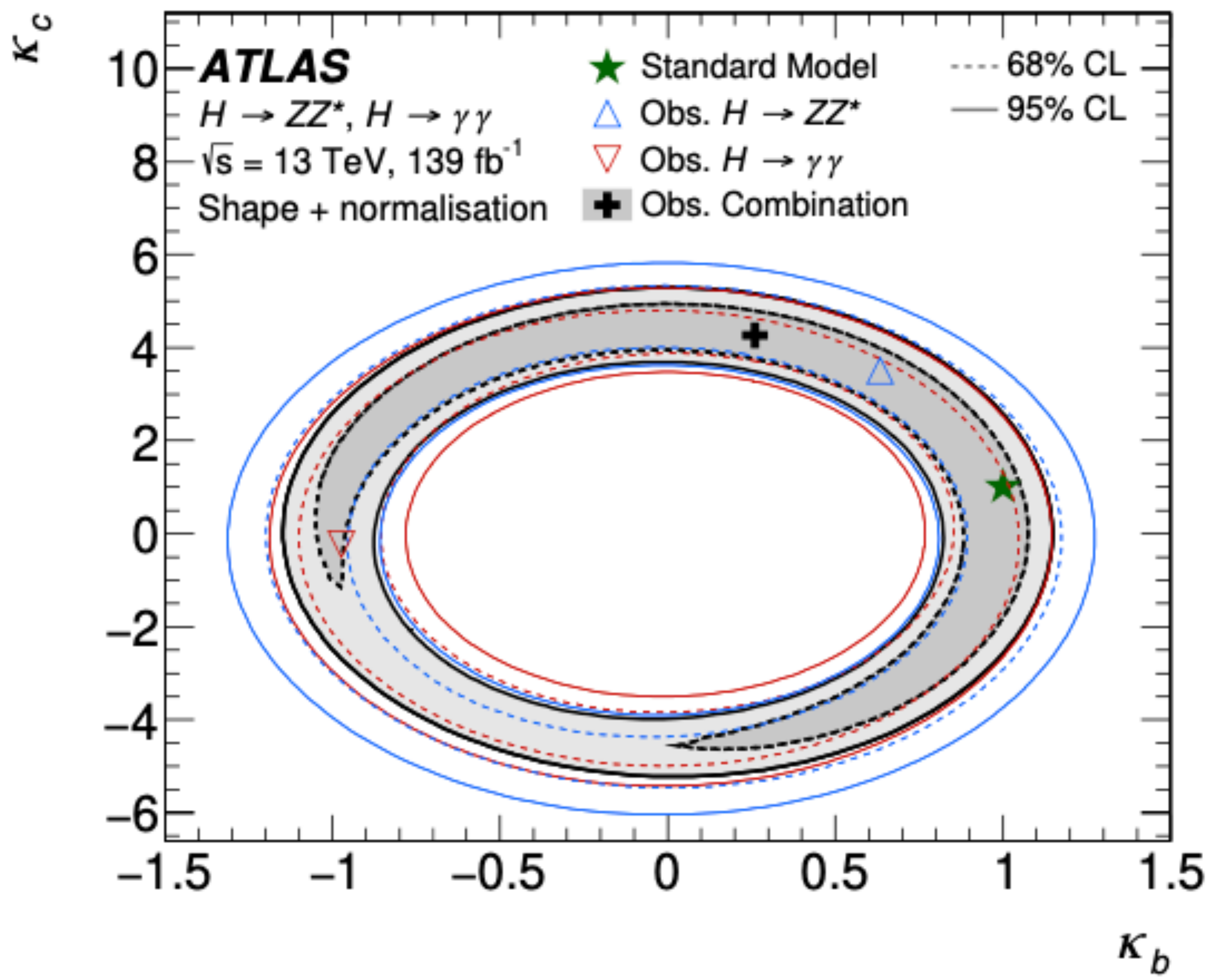
- Constrain Higgs b, c couplings indirectly from observed $p_T(H)$ spectra

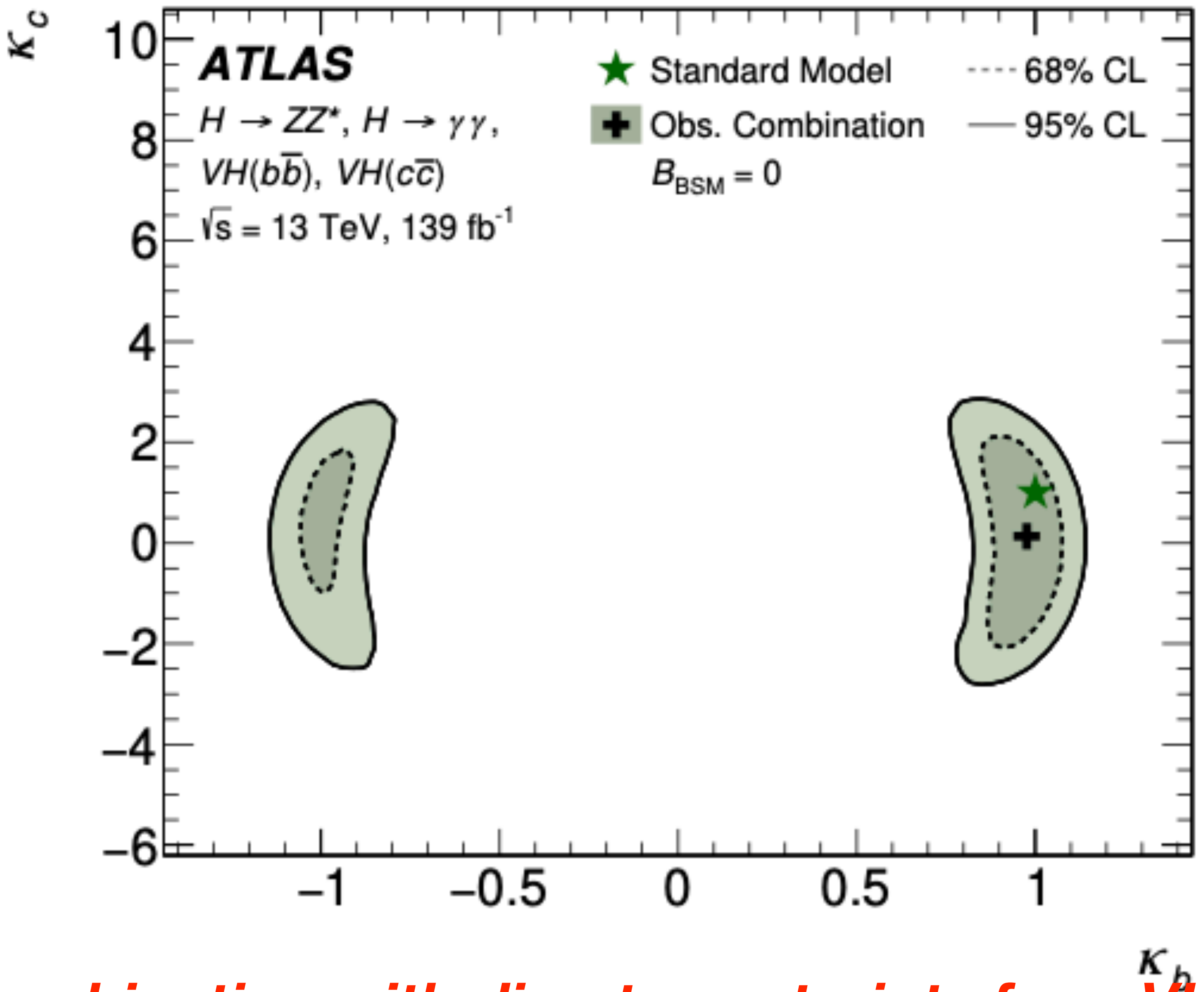






arXiv:2207.08615





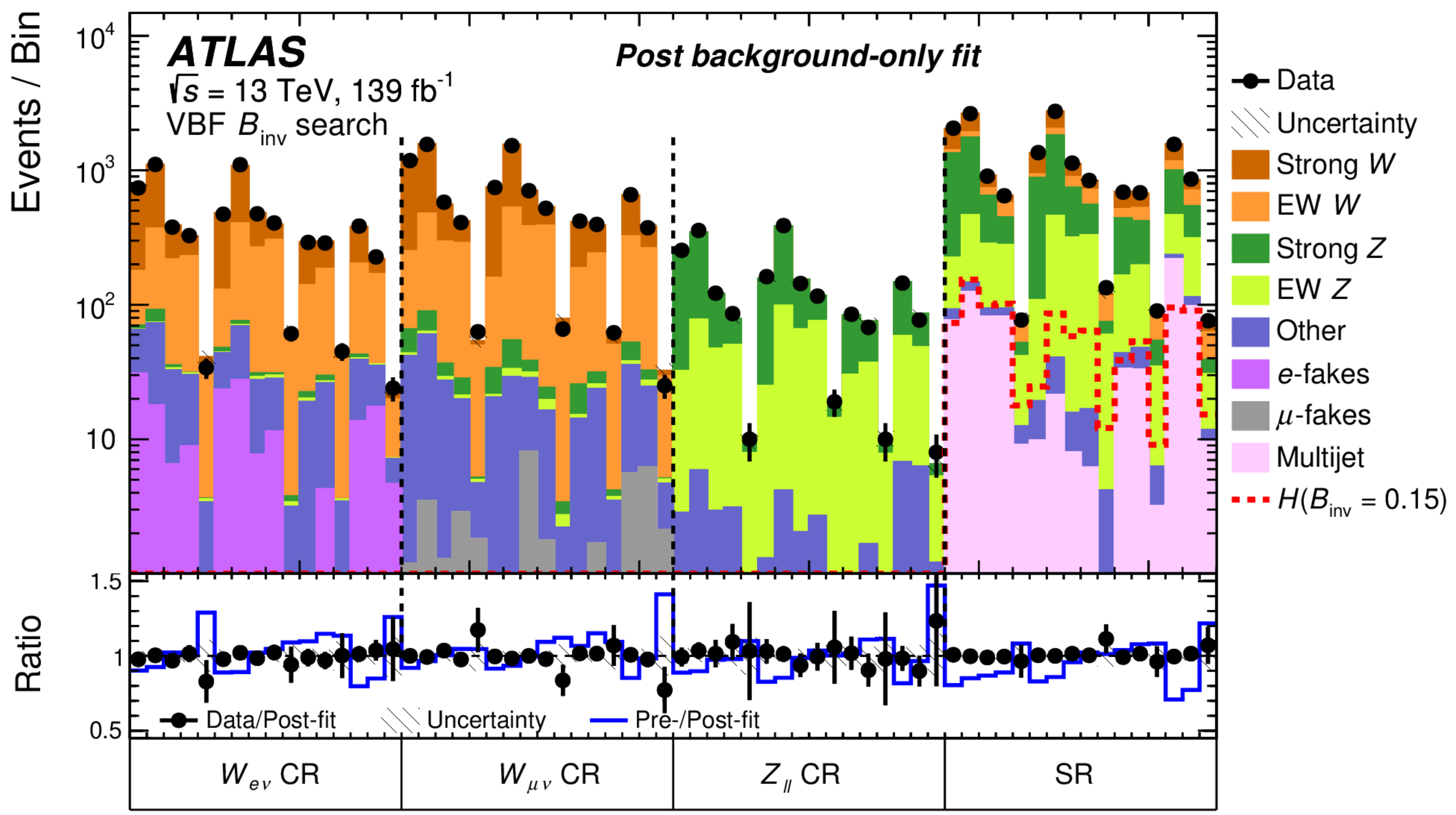
Constraints on κ_c similar to those from direct searches

Combination with direct constraints from VH(qq) ($|\kappa_c|<2.5$)

Exotic Higgs decays?

Invisible decays (e.g. to dark matter)

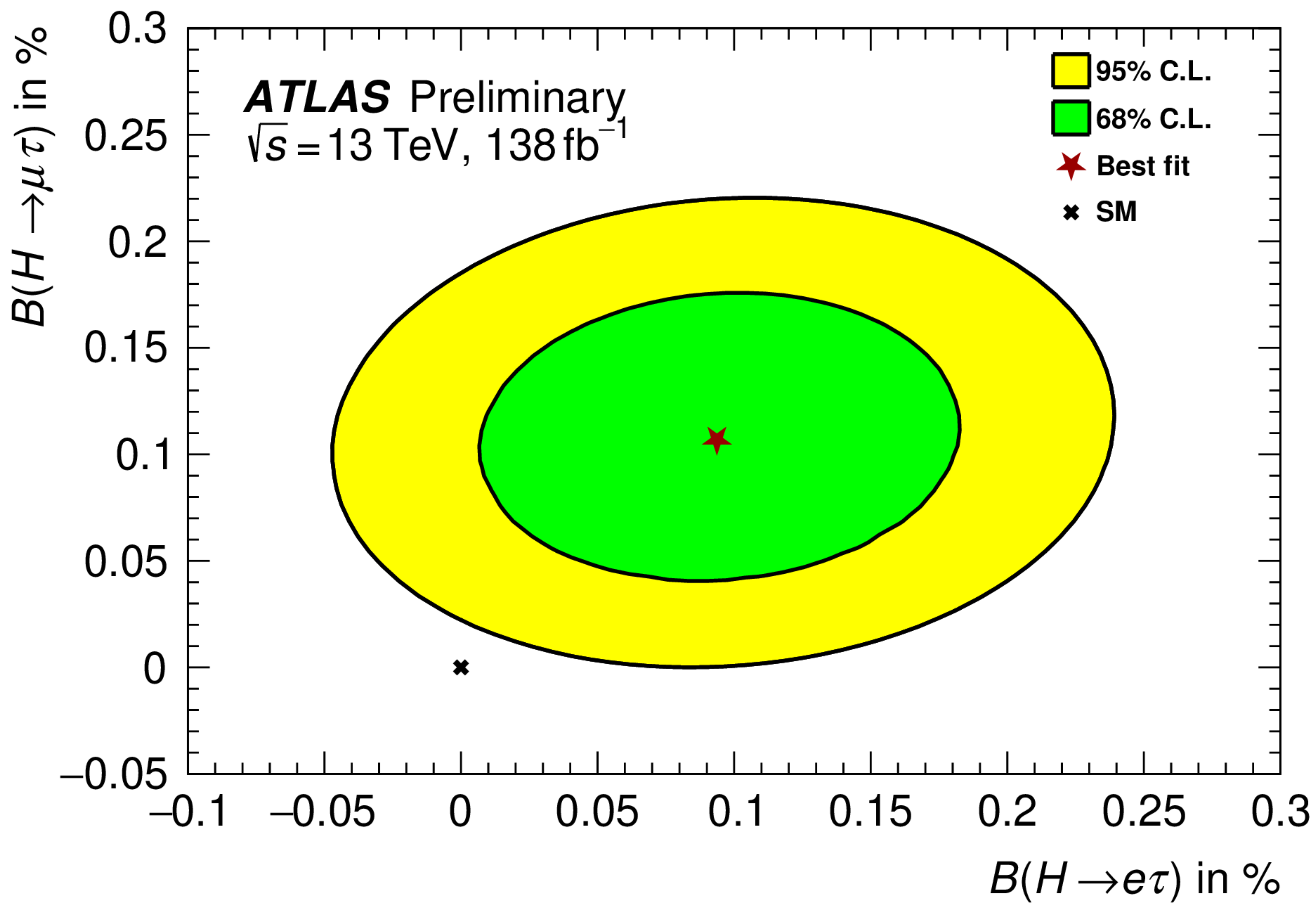
[JHEP 08 (2022) 104]



BR inv < 15% in VBF channel (Run2 only), ~11% including others

Lepton-flavour violating decays

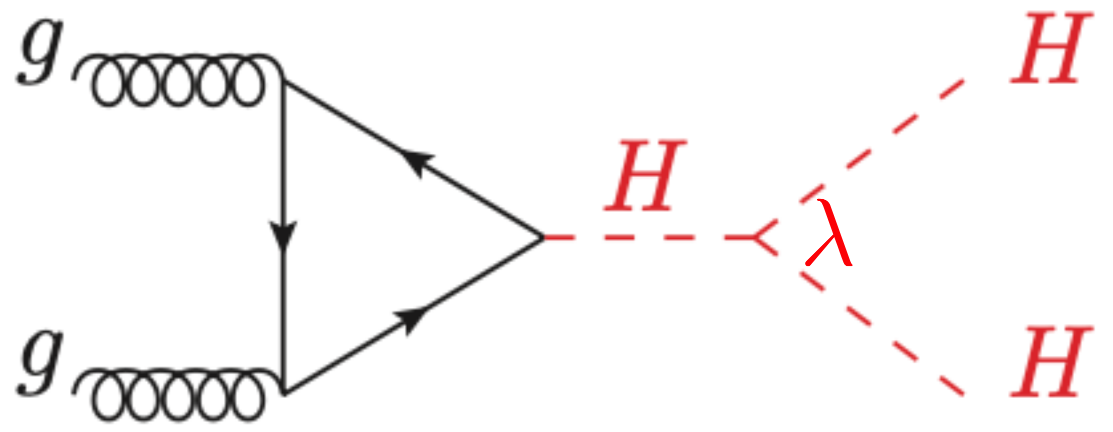
[ATLAS-CONF-2022-060]



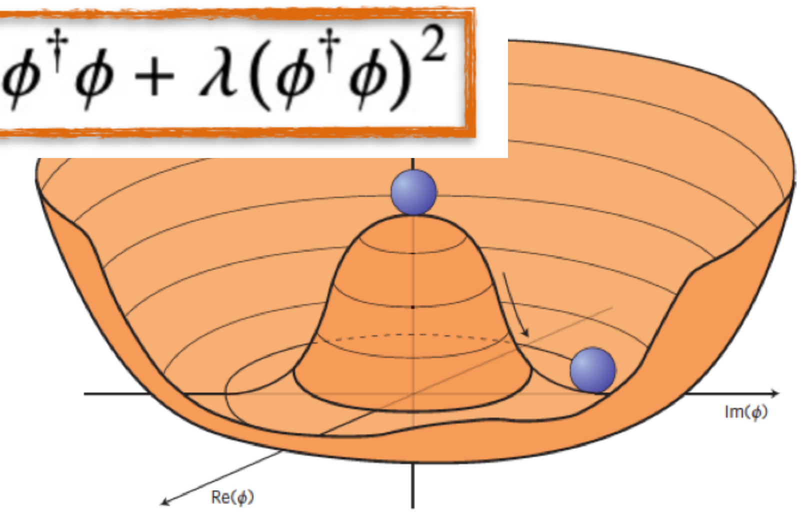
Upper limits at per mille level

Does the Higgs couple to itself?

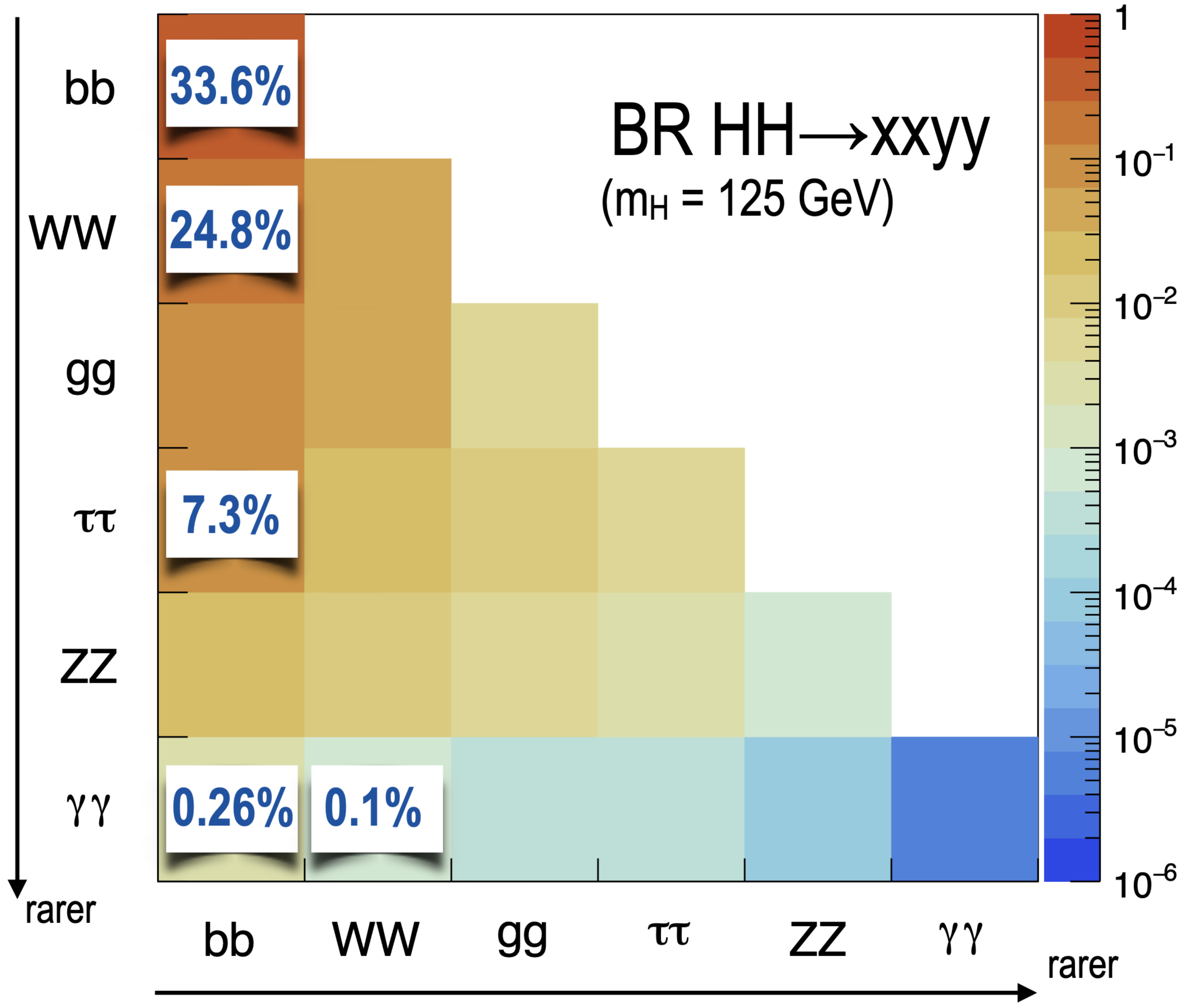
- One of the novelties of Run2 was the **systematic search for di-Higgs production** in as many decay channels as possible
- Double-Higgs production = direct probe of Higgs self-coupling λ ⇒ **crucial for determining shape of Higgs field potential**



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



- **Tiny cross section** ~1/1000 of Higgs production (33 fb at 13 TeV) ⇒ **extremely challenging!**
- **Multiple topologies investigated.** No significant signal seen yet ⇒ upper limits!



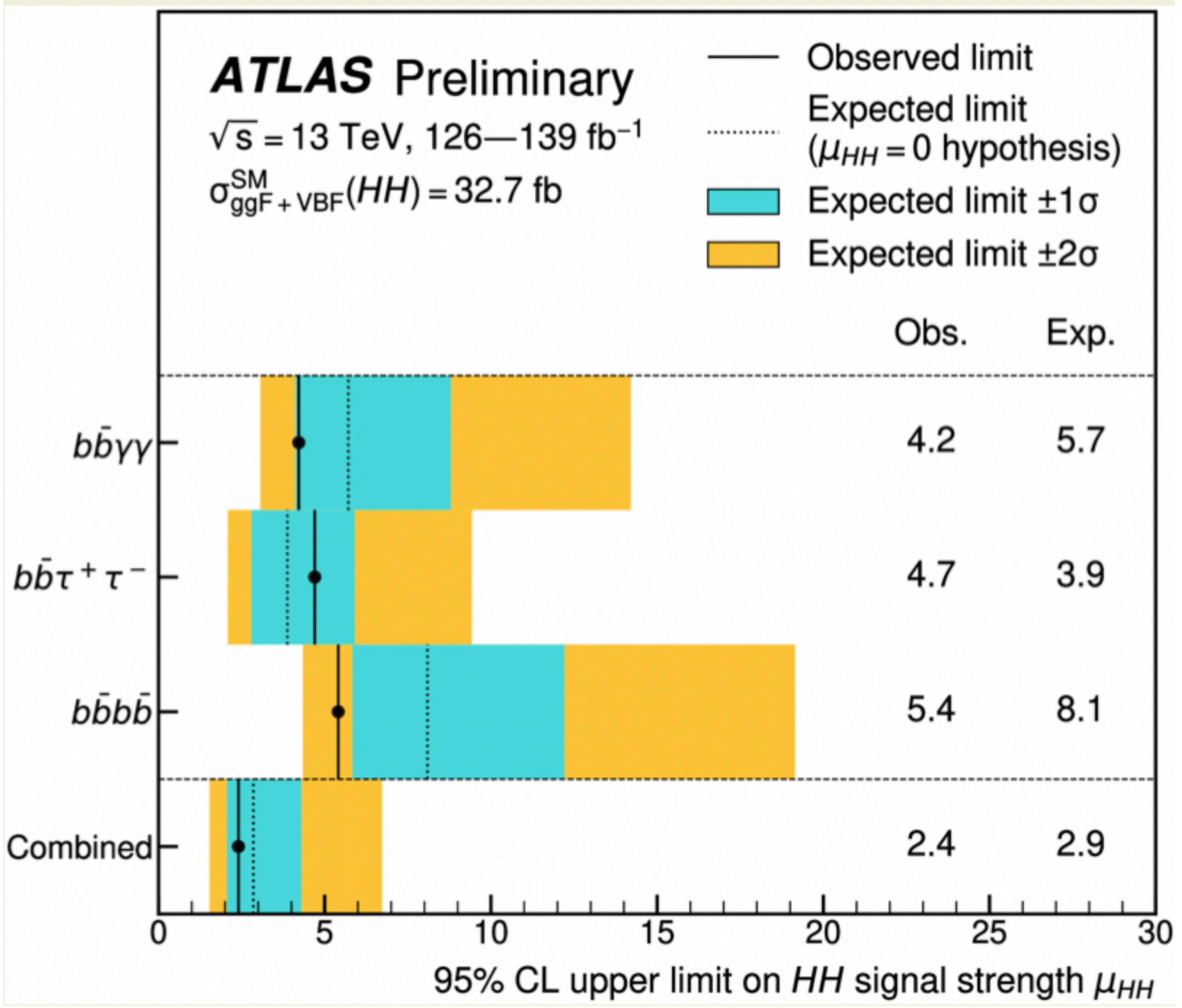
bbγγ/bbττ/4b

bbγγ: arXiv:2112.11876
bbbb: ATLAS-CONF-2022-035
bbtt: ATLAS-CONF-2021-030

combination

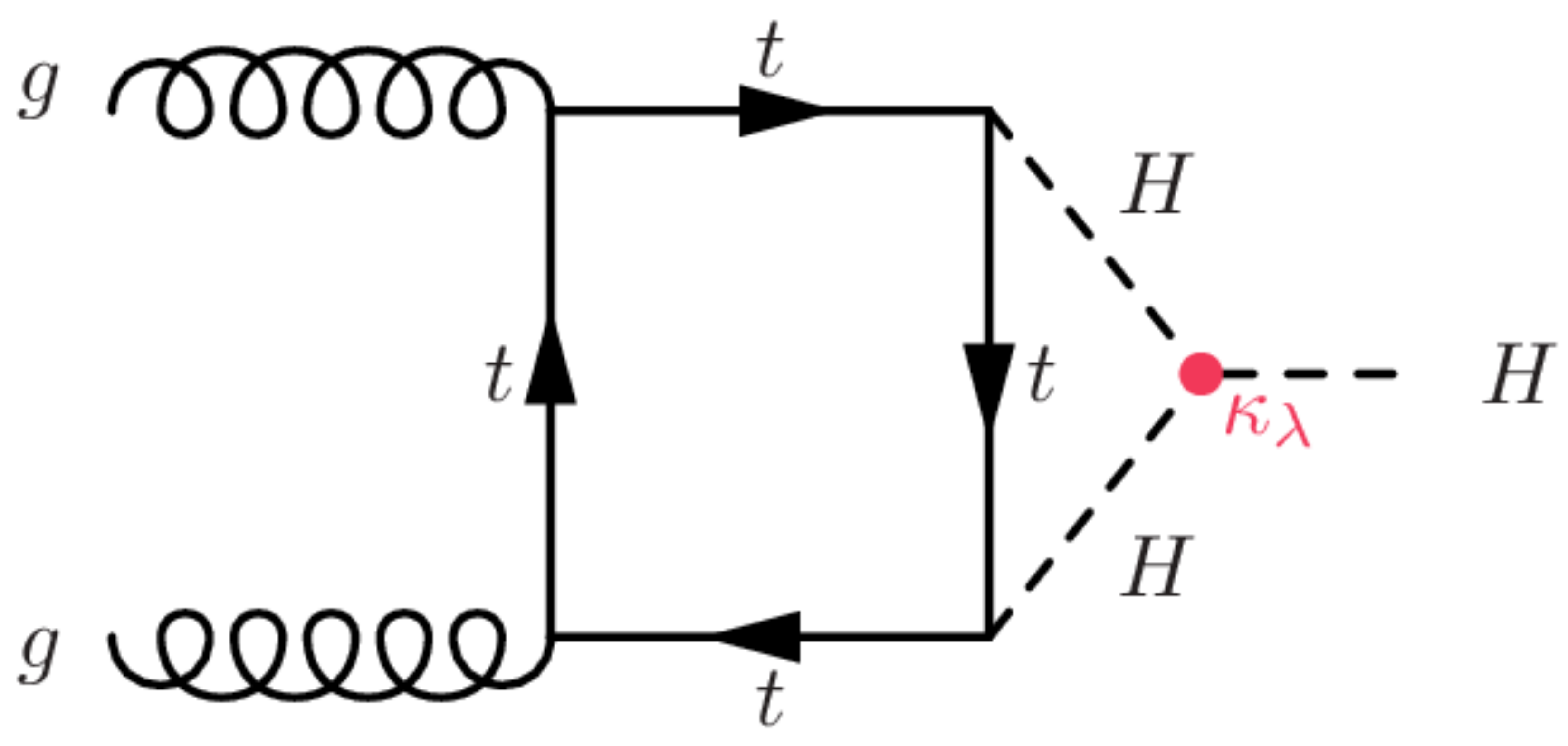
ATLAS-CONF-2022-050

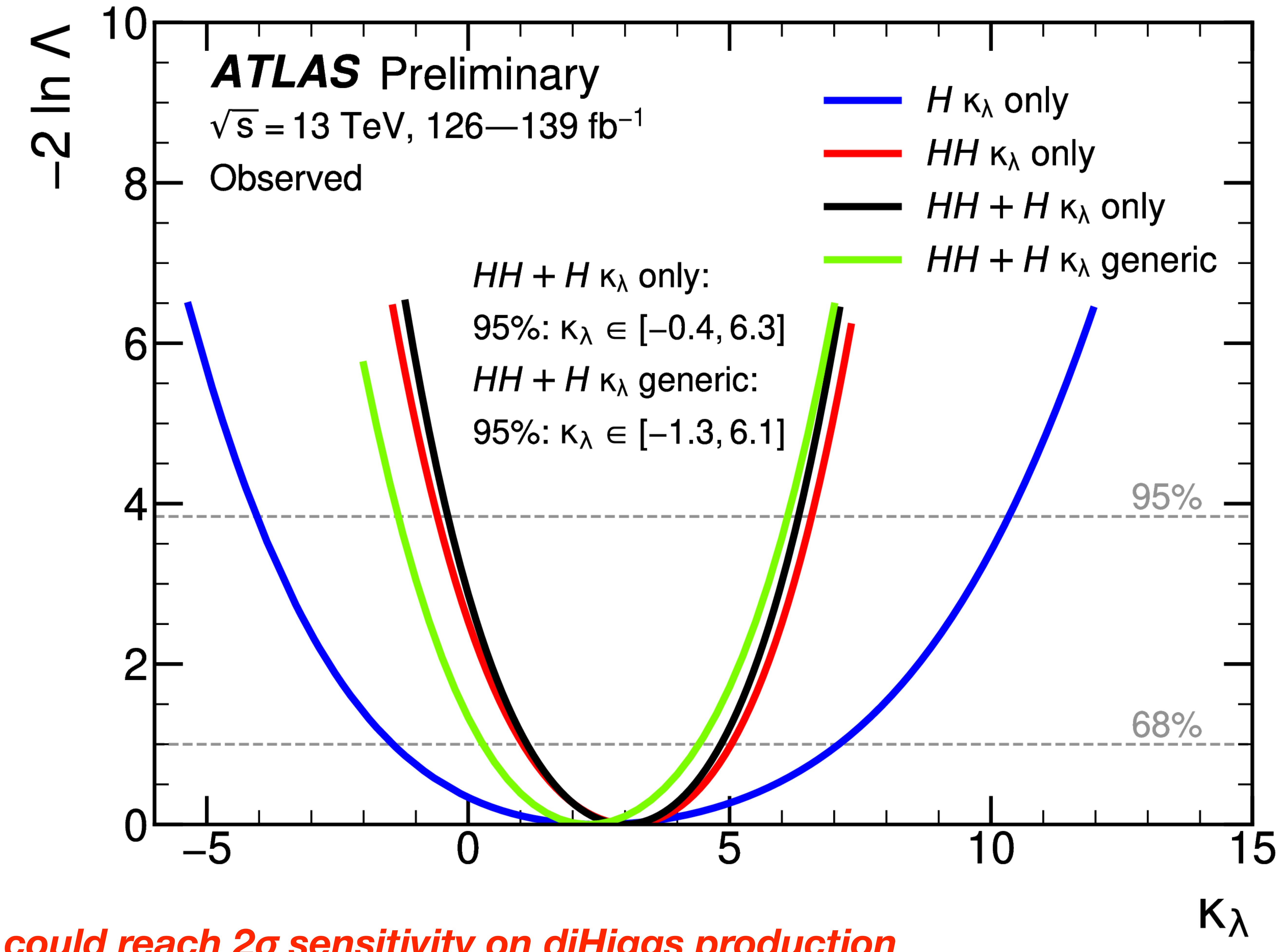
μ < 2.4 (2.9)



Higgs boson self-coupling

- Taking into account the λ dependence of the cross-section, limits on λ are determined
- Large correlation with other Higgs couplings (in particular to top) resolved by combining with single-Higgs measurements
  - Little increase in sensitivity on λ also provided by single-H xsection measurements from triple-Higgs vertex diagrams (NLO corrections)





Profile κ_λ only: -0.4 < κ_λ < 6.3 (95%CL)

Profile κ_λ, κ_t, κ_V, κ_b, κ_τ: -1.3 < κ_λ < 6.1 (95% CL)

With the other channels + full Run 3 ATLAS+CMS could reach 2σ sensitivity on diHiggs production

Conclusion

- 10 years after its landmark discovery, the Higgs boson is now a grown-up kid
- Its characteristics resemble remarkably the SM predictions
  - Though accuracy of some measurement is still O(10%) or worse
- The Higgs physics programme of ATLAS and the (HL)-LHC is only in its infancy
  - Expect ~3x the current data adding Run3 (2022-2025) and 20x by the end of the HL-LHC
  - On the watchlist (among others): rare and invisible decays, di-Higgs production (self-coupling), CP violation in Higgs interactions, …

Thanks for listening and many thanks to the organisers!

Extra material

Inputs for the global coupling combination

Decay mode	Targeted production processes	$\mathcal{L}$ [fb^{-1}]	Ref.	Fits deployed in
$H \to \gamma\gamma$	ggF, VBF, $WH, ZH, t\bar{t}H, tH$	139	[31]	All
$H \to ZZ$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139	[28]	All
	$t\bar{t}H + tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H \to WW$	ggF, VBF	139	[29]	All
	WH, ZH	36.1	[30]	All but fit of kinematics
	$t\bar{t}H + tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H \to Z\gamma$	inclusive	139	[32]	All but fit of kinematics
$H \to b\bar{b}$	WH, ZH	139	[33, 34]	All
	VBF	126	[35]	All
	$t\bar{t}H + tH$	139	[36]	All
	inclusive	139	[37]	Only for fit of kinematics
$H \to \tau\tau$	ggF, VBF, $WH + ZH, t\bar{t}H + tH$	139	[38]	All
	$t\bar{t}H + tH$ (multilepton)	36.1	[39]	All but fit of kinematics
$H \to \mu\mu$	ggF + $t\bar{t}H + tH$, VBF + $WH + ZH$	139	[40]	All but fit of kinematics
$H \to c\bar{c}$	$WH + ZH$	139	[41]	Only for free-floating κ_c
$H \to$ invisible	VBF	139	[42]	κ models with $B_{\mathrm{u.}}$ & $B_{\mathrm{inv.}}$
	ZH	139	[43]	κ models with $B_{\mathrm{u.}}$ & $B_{\mathrm{inv.}}$

Higgs boson selection efficiency

H(125 GeV) — approximate numbers

Channel	Produced		Selected	Mass resolution
$H \to \gamma\gamma$	18,200		6,440	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$	210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$	5,880	20%
$H \to \tau\tau$	490,000		2,380	15%
$H \to bb$	4,480,000		9,240	10%

A. Hoecker, CERN

- Out of 8M Higgs boson events only about 20k are selected and used to study the properties of the Higgs boson!

Higgs couplings fit in the presence of extra particles in loops or invisible decays

- Left: invisible/undetected BR fixed to zero
- Right: invisible/undetected BR floating
  - Use BR(inv) experimental upper limit
  - Assume κ_W, κ_Z<=1

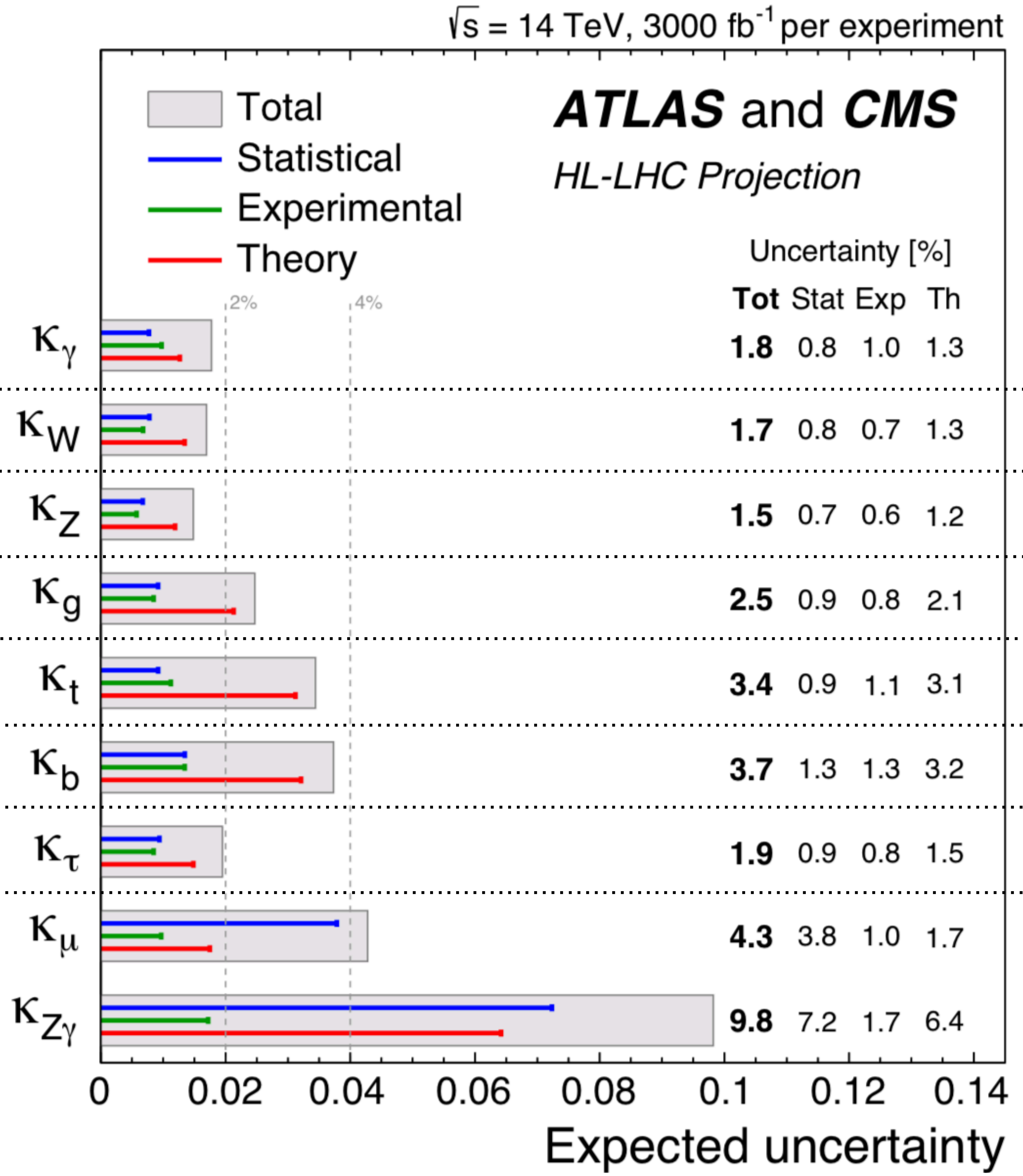
	(a) $B_{inv.} = B_{u.} = 0$	(b) $B_{inv.}$ free, $B_{u.} \geq 0$, $\kappa_{W,Z} \leq 1$
κ_Z	$0.99^{+0.06}_{-0.06}$	$0.98^{+0.02}_{-0.05}$
κ_W	$1.05^{+0.06}_{-0.06}$	$1.00_{-0.02}$
κ_t	$0.94^{+0.11}_{-0.11}$	$0.94^{+0.11}_{-0.11}$
κ_b	$0.89^{+0.11}_{-0.11}$	$0.82^{+0.09}_{-0.08}$
κ_τ	$0.93^{+0.07}_{-0.07}$	$0.91^{+0.07}_{-0.06}$
κ_μ	$1.06^{+0.25}_{-0.30}$	$1.04^{+0.23}_{-0.30}$
κ_g	$0.95^{+0.07}_{-0.07}$	$0.94^{+0.07}_{-0.06}$
κ_γ	$1.01^{+0.06}_{-0.06}$	$0.98^{+0.05}_{-0.05}$
$\kappa_{Z\gamma}$	$1.38^{+0.31}_{-0.37}$	$1.35^{+0.29}_{-0.36}$
$B_{inv.}$	-	< 0.13
$B_{u.}$	-	< 0.12

HL-LHC Higgs couplings projections

M. Kado, *Higgs 2021*

NEW Higgs 2021

	ATLAS - CMS Run 1 combination	ATLAS Run 2	CMS Run 2	Current precision
κ_γ	13%	1.04 ± 0.06	$1.01^{+0.09}_{-0.14}$	6%
κ_W	11%	1.06 ± 0.06	$-1.11^{+0.14}_{-0.09}$	6%
κ_Z	11%	0.99 ± 0.06	0.96 ± 0.07	6%
κ_g	14%	$0.92^{+0.07}_{-0.06}$	$1.16^{+0.12}_{-0.11}$	7%
κ_t	30%	0.92 ± 0.10	1.01 ± 0.11	11%
κ_b	26%	0.87 ± 0.11	$1.18^{+0.19}_{-0.27}$	11%
κ_τ	15%	0.92 ± 0.07	0.94 ± 0.12	8%
	JHEP 08 (2016) 045	ATLAS-CONF-2021-53	CMS-PAS-HIG-19-005	

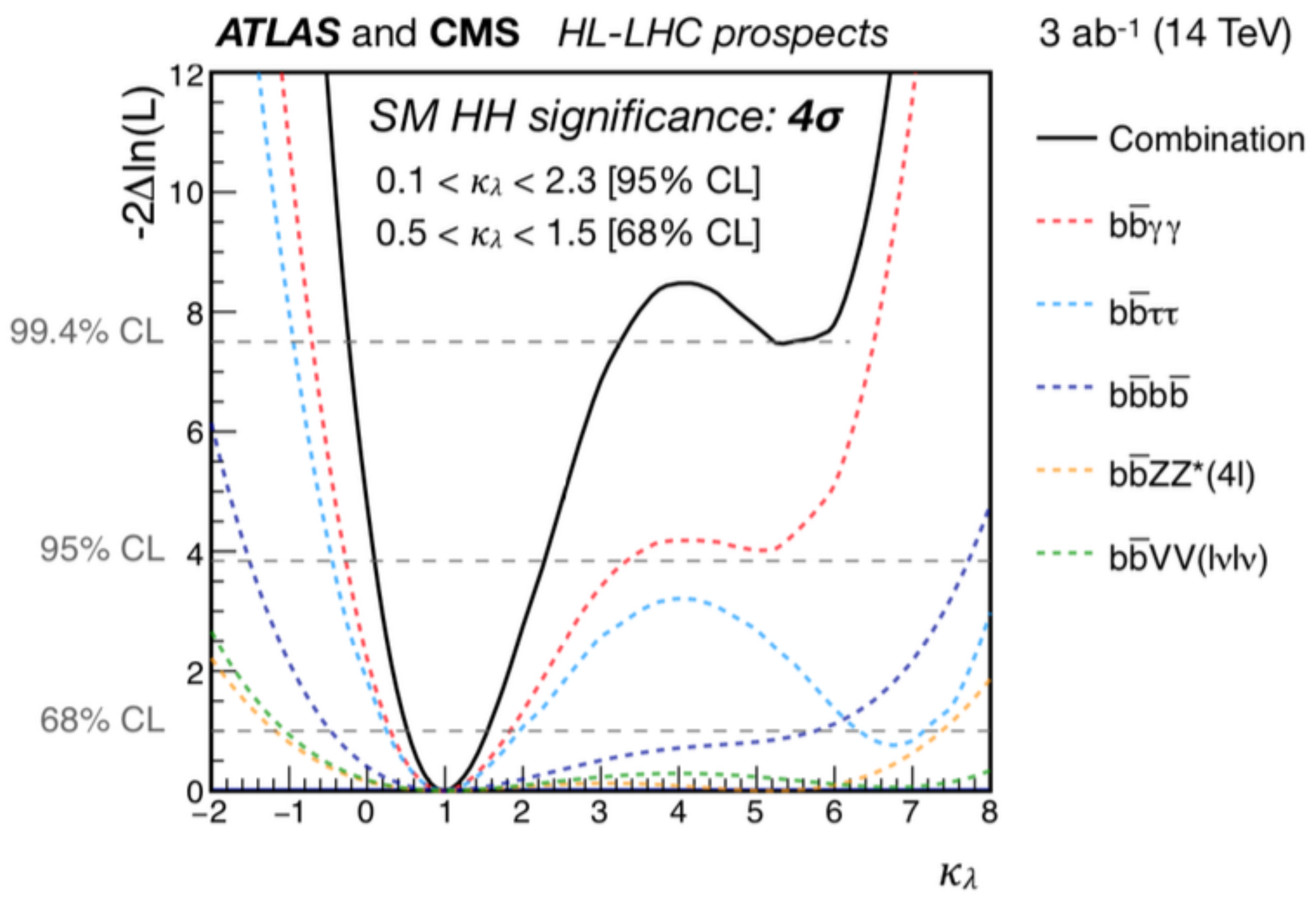


Measurements here assume no BSM in Higgs width

Still 25 times more data and reduction of a factor of 3 uncertainty!

Higgs boson self-coupling

- HL-LHC projection (~2038, ~20x more data than Run2): $0.5 < \kappa_\lambda < 1.5$
  - could constrain models which predict strong first-order electroweak phase transitions
  - complementary to information provided by gravitational waves detected by space-based interferometers

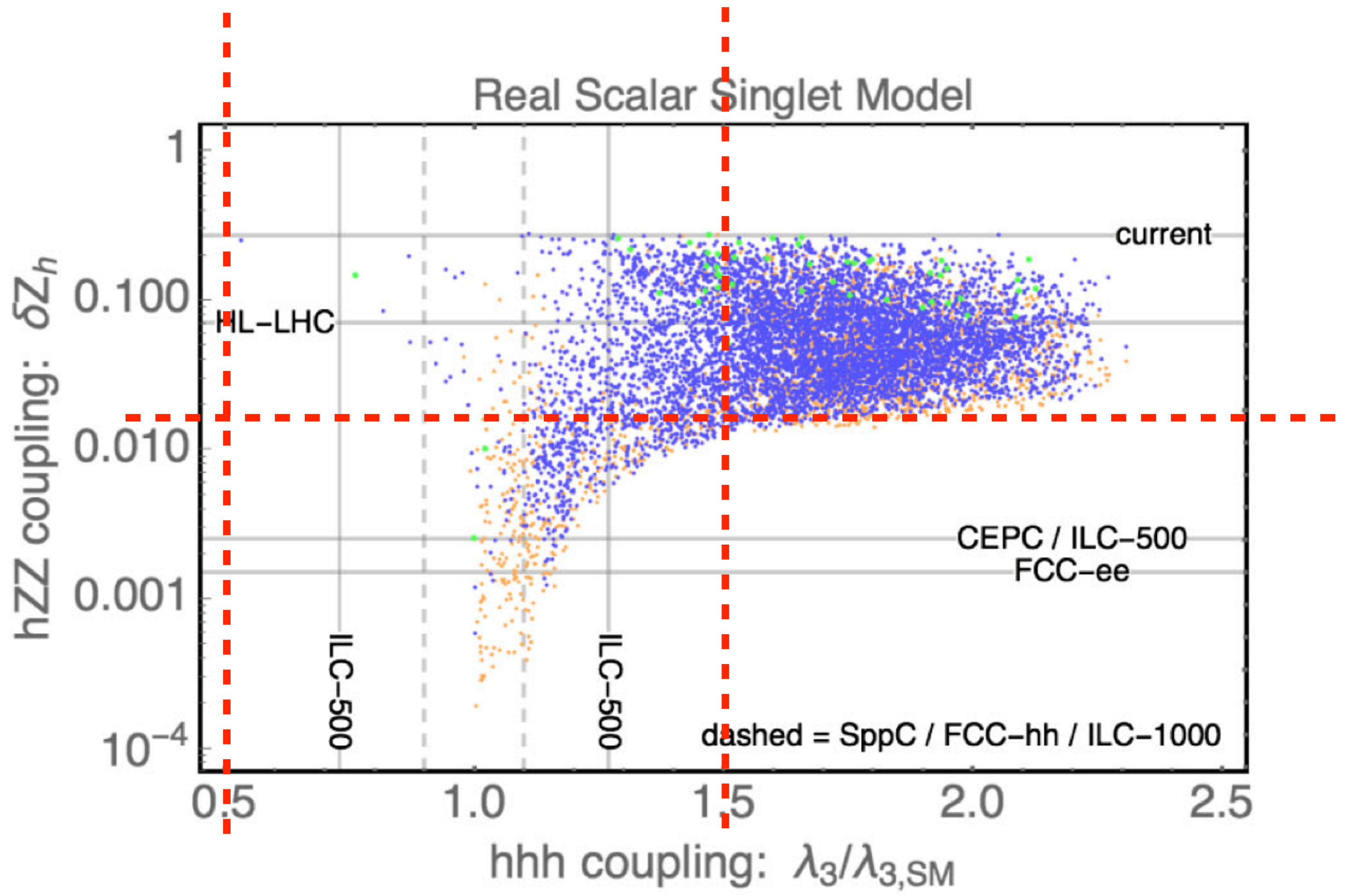


[Phys. Rev. D 94 (2016) 7, 075008](#)

PHYSICAL REVIEW D **94,** 075008 (2016)

Probing the electroweak phase transition with Higgs factories and gravitational waves

Peisi Huang,[1,2,*] Andrew J. Long,[1,†] and Lian-Tao Wang[1,3,‡]

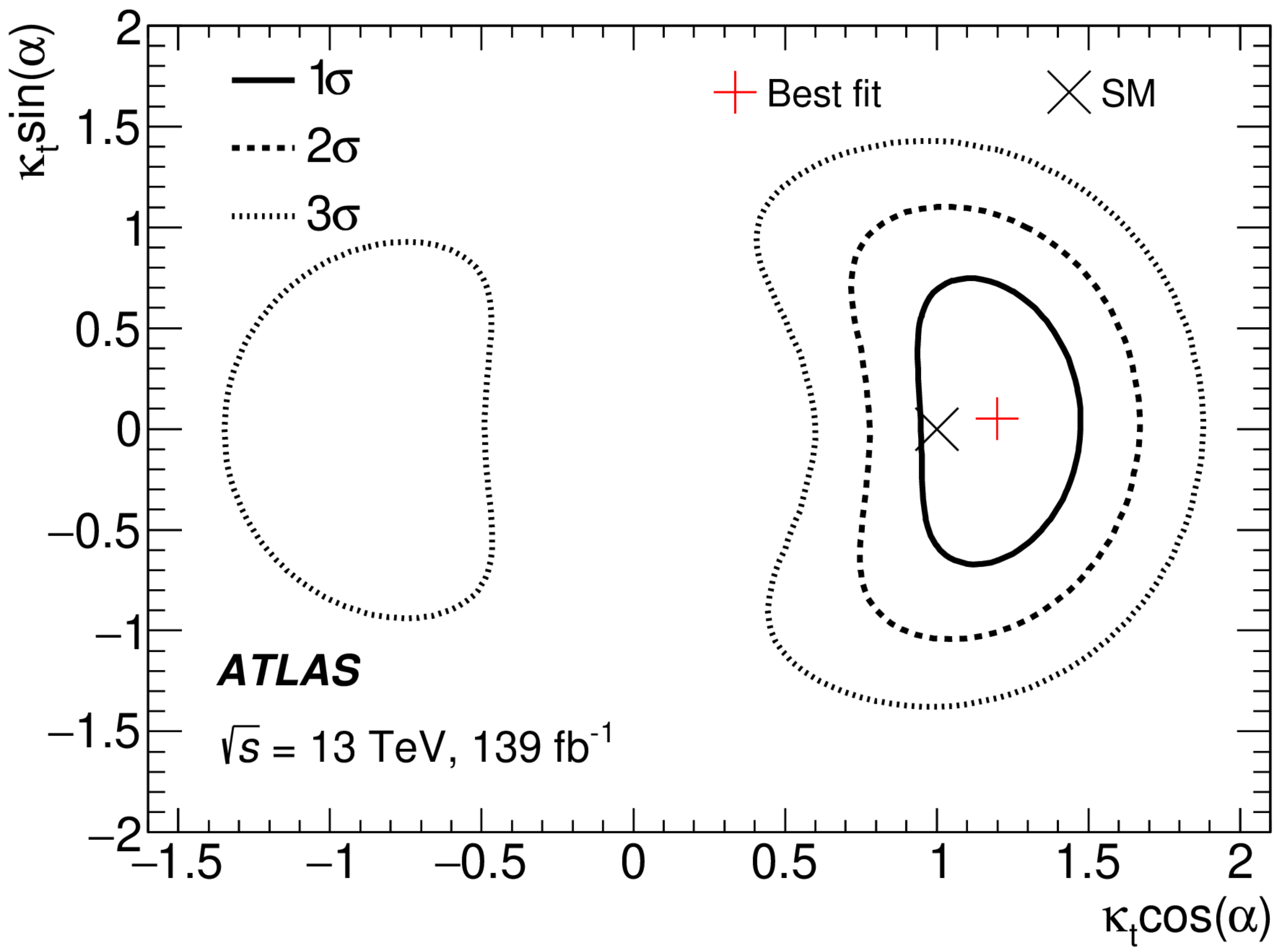


1. Parameter space scan for the singlet model of II A. An orange point indicates a first-order phase transition, a blue point indicates a strongly first-order phase transition (3.4), and a green point indicates a very strong first-order phase transition with potentially detectable gravitational wave signal at eLISA. The right panels shows the predicted gravitational wave spectrum today along with the projected sensitivity of eLISA [2].

Higgs boson CP

- CPV in t-H interactions with ttH(γγ): [*Phys. Rev. Lett. 125, 061802 (2020)*]

$$\mathcal{L}_{t\bar{t}H} = -\kappa_t' y_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$$

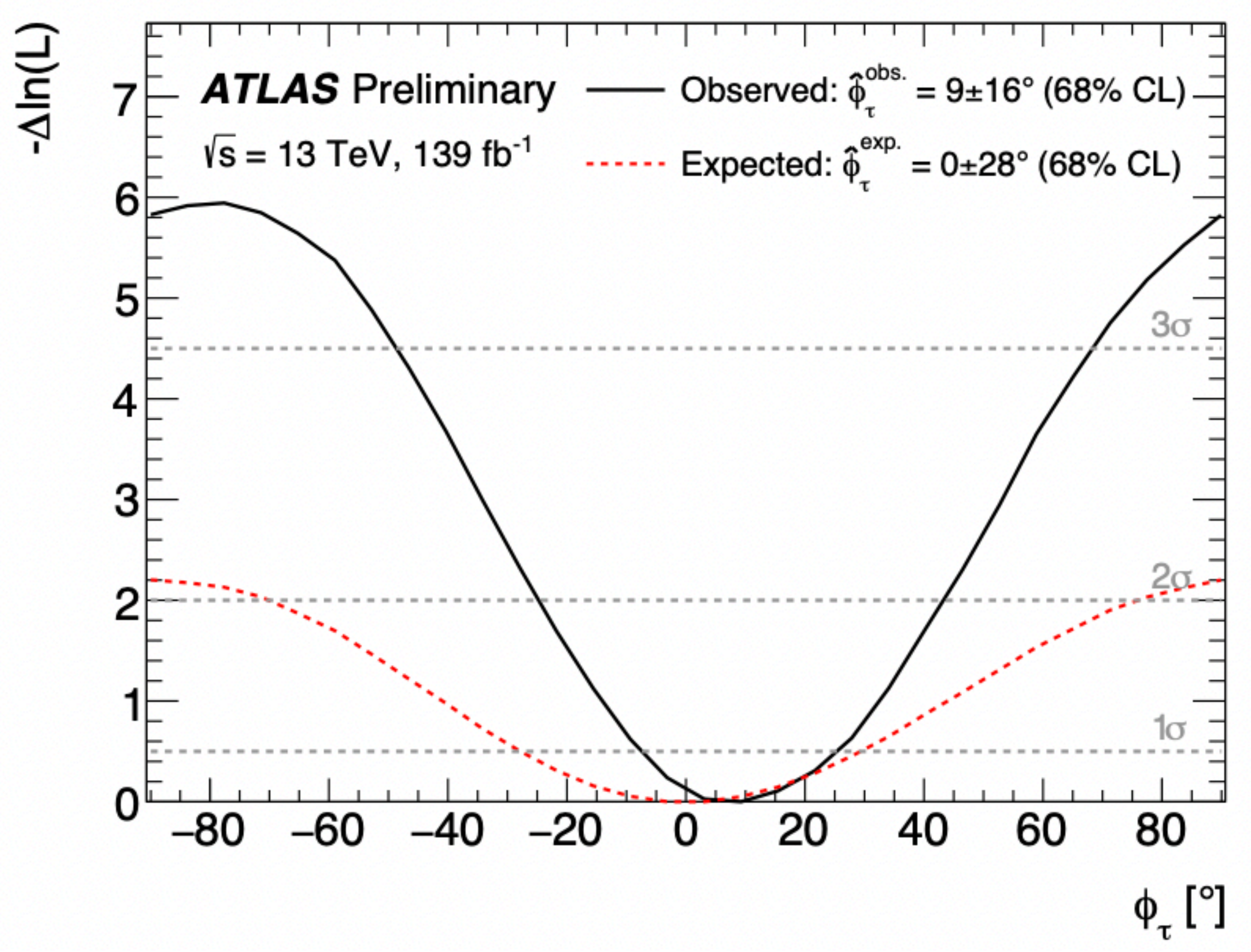


pure CP-odd coupling excluded at 3.9σ

|α| > 43 deg excluded @ 95% CL.

- CPV in τ-H interactions with H→ττ: [*ATLAS-CONF-2022-032*]

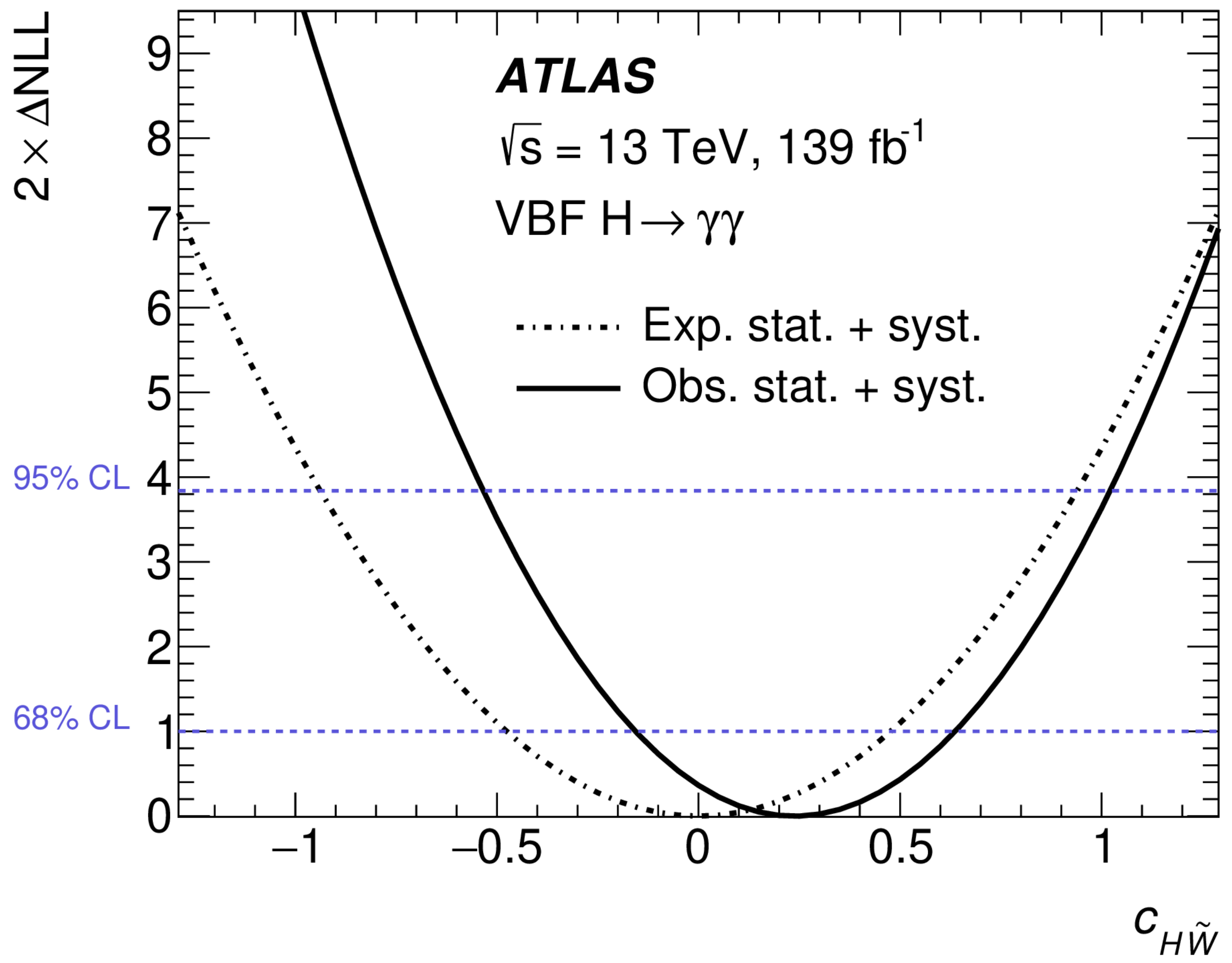
$$\mathcal{L}_{H\tau\tau} = -\frac{m_\tau}{\nu}\kappa_\tau (\cos\phi_\tau \bar{\tau}\tau + \sin\phi_\tau \bar{\tau} i\gamma_5 \tau) H$$



$\phi_\tau = 9 \pm 16°$ (28° exp)

pure CP-odd coupling excluded at 3.4 σ

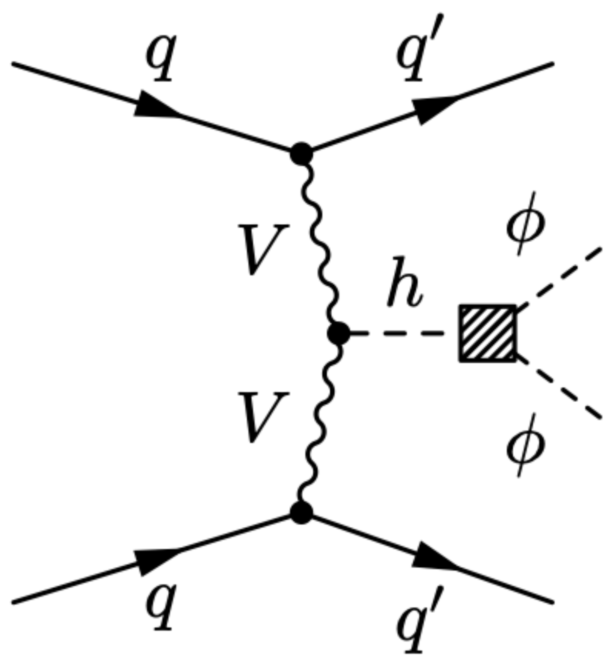
- CPV in HVV interactions with VBF: [*arXiv:2208.02338*]



	68% (exp.)	95% (exp.)	68% (obs.)	95% (obs.)
$c_{H\tilde{W}}$ (inter. only)	[−0.48, 0.48]	[−0.94, 0.94]	[−0.16, 0.64]	[−0.53, 1.02]
$c_{H\tilde{W}}$ (inter.+quad.)	[−0.48, 0.48]	[−0.95, 0.95]	[−0.15, 0.67]	[−0.55, 1.07]

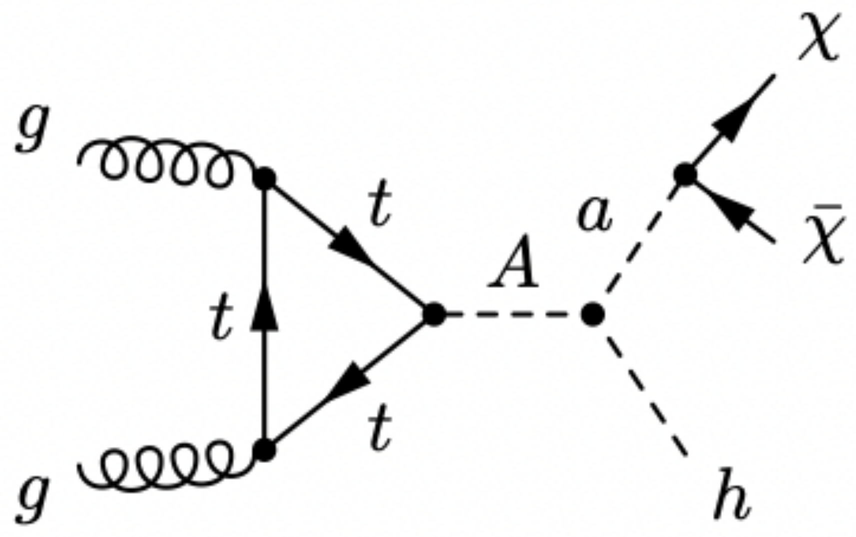
Higgs boson as a portal to dark matter?

- IF dark matter is composed of neutral, weakly-interacting, massive particle (WIMP), and the dark sector is coupled to the Higgs, Higgs physics at collider experiments could shed light on it (for a review see e.g. https://arxiv.org/abs/2109.13597)

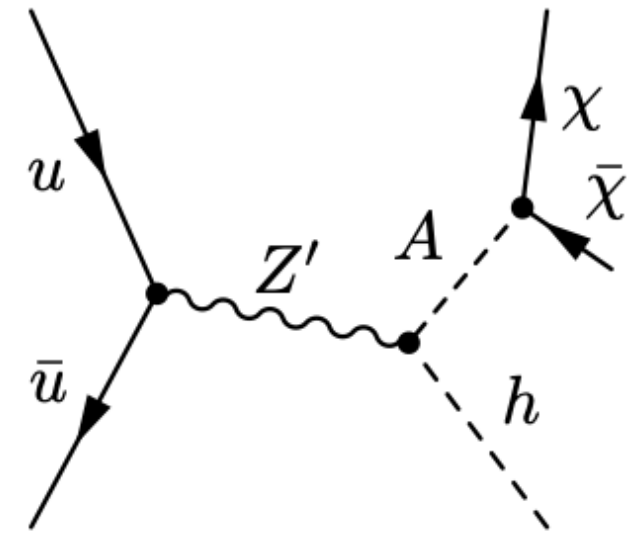


(a) Higgs portal ($m_{DM}<m_H/2$)

invisible Higgs decays
⇒ BR(H→invisible)



(b) Portals with extended Higgs sectors
(e.g.: 2HDM+a)



(c) Portals with extended Higgs and gauge sectors
(e.g.: 2HDM+Z')

"mono-Higgs": Higgs recoils against invisible particles (large missing momentum)
(+ searches for heavier Higgs bosons and Z' resonances)

mono-H(bb)

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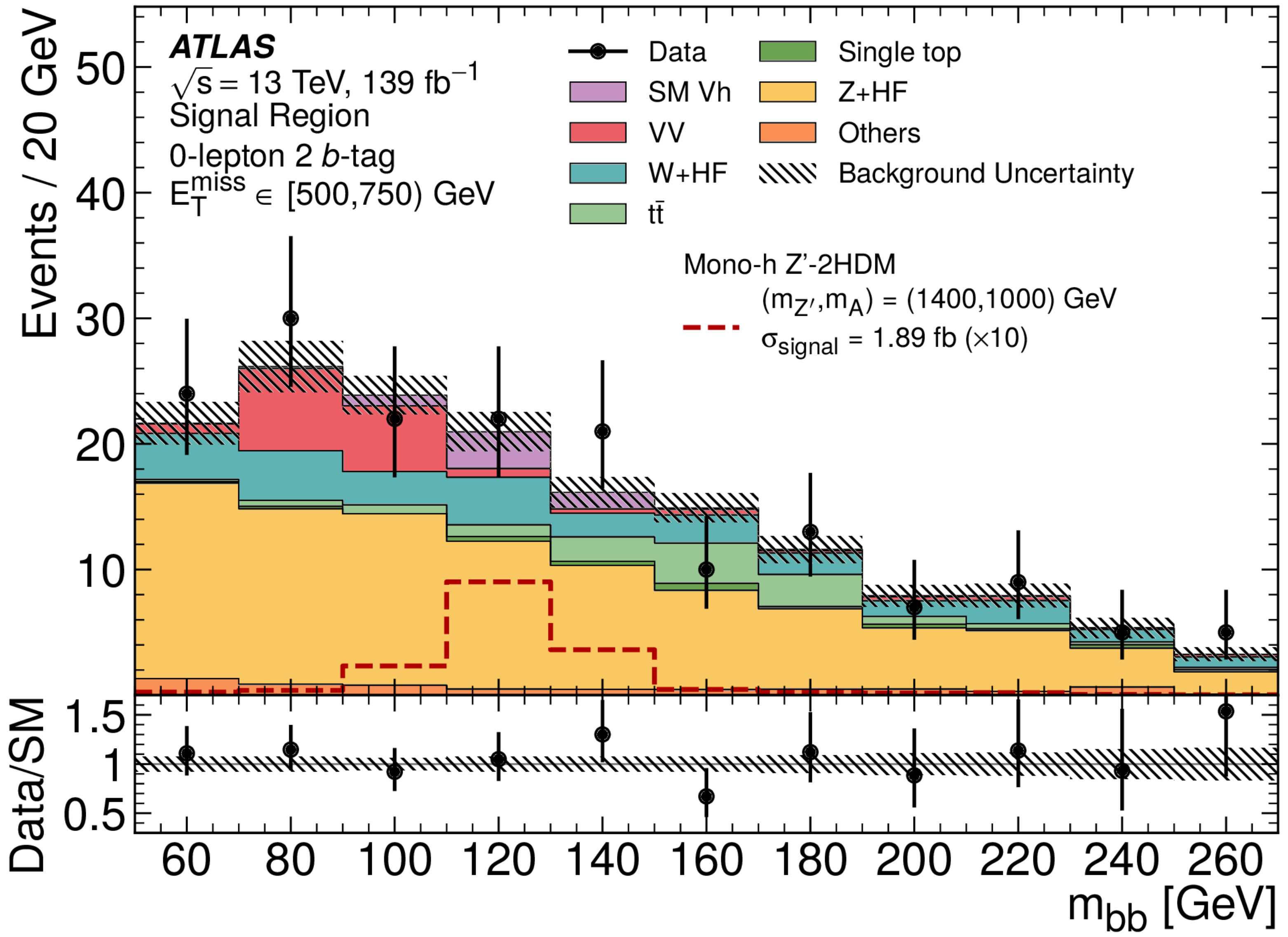
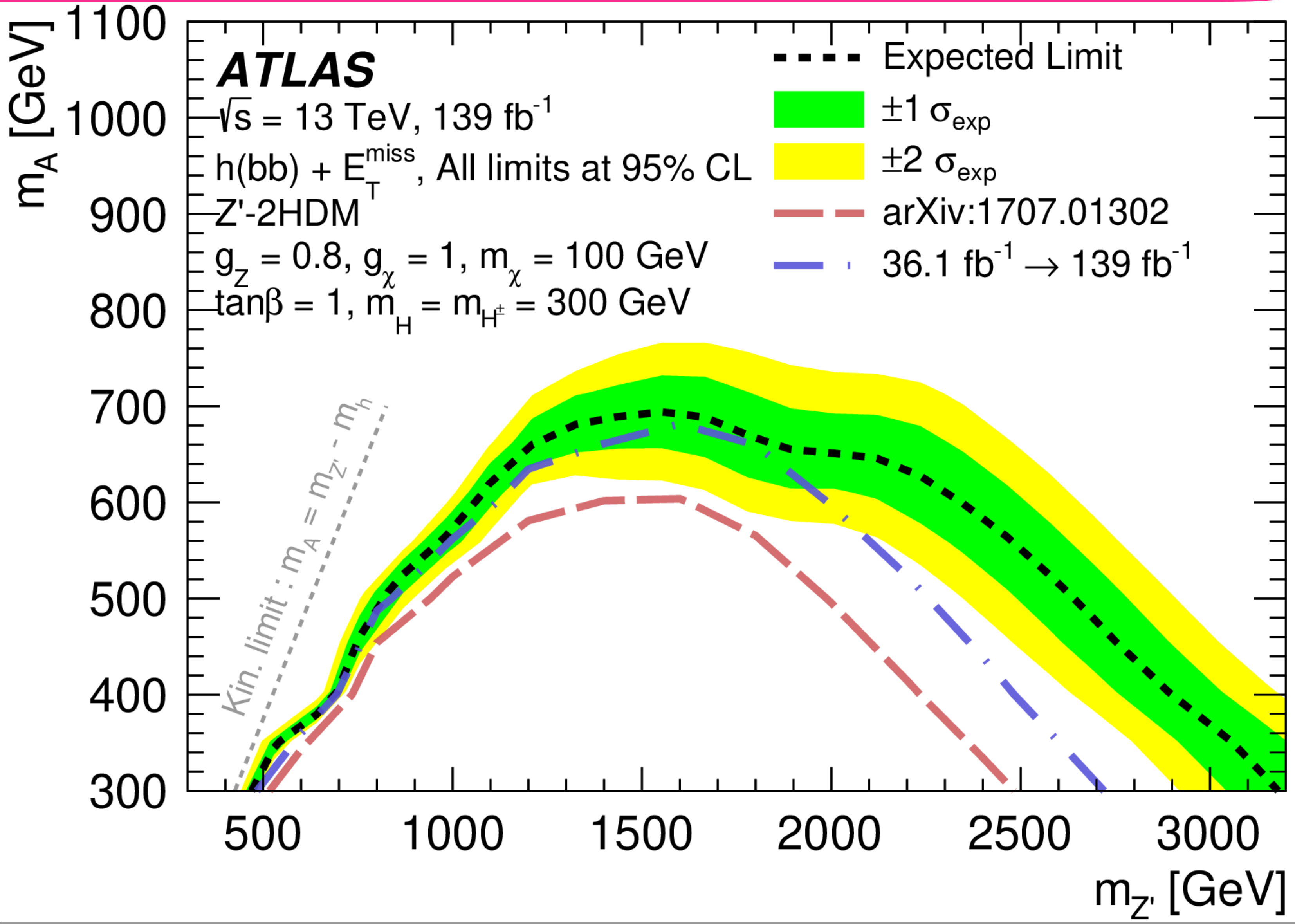
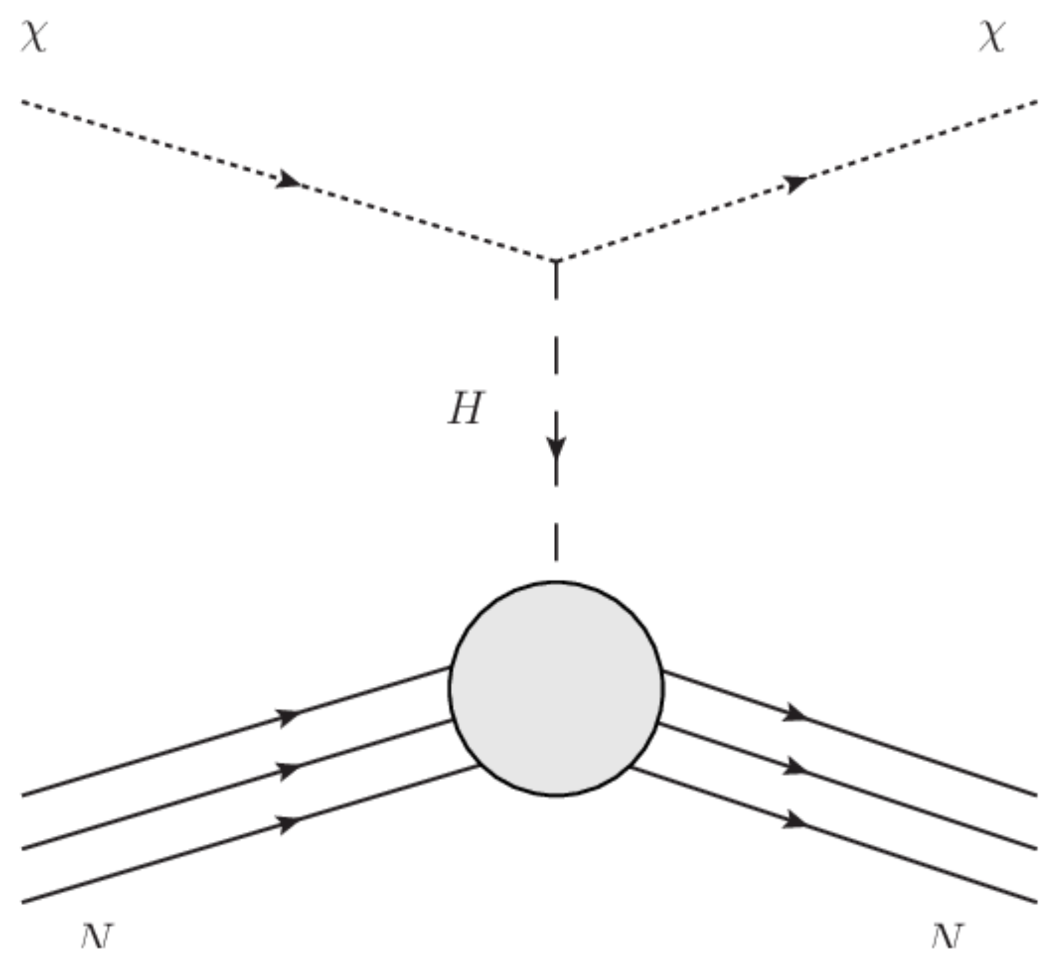




Higgs invisible decays and WIMP-nucleon cross-section

Higgs portal model: the Higgs boson is assumed to be the only mediator in the WIMP–nucleon scattering



The upper limit on the invisible BR is converted to an upper limit on the partial width for the decay:

$$\Gamma_H^{\text{inv}} = \frac{\text{BF}(H \to \text{ invisible})}{1 - \text{BF}(H \to \text{ invisible})} \times \Gamma_H,$$

This in turn implies an upper limit on the Higgs-DM coupling λ:

$$\Gamma^{\text{inv}}_{H\to SS} = \frac{\lambda^2_{HSS} v^2 \beta_S}{64\pi m_H},$$

$$\Gamma^{\text{inv}}_{H\to VV} = \frac{\lambda^2_{HVV} v^2 m_H^3 \beta_V}{256\pi m_V^4}\left(1 - 4\frac{m_V^2}{m_H^2} + 12\frac{m_V^4}{m_H^4}\right),$$

$$\Gamma^{\text{inv}}_{H\to ff} = \frac{\lambda^2_{Hff} v^2 m_H \beta_f^3}{32\pi\Lambda^2},$$

$$\beta_\chi = \sqrt{1 - 4m_\chi^2/m_H^2}\ (\chi = S,\ V,\ f),$$

which can then be converted into a limit on the WIMP-proton cross-section:

$$\sigma^{\text{SI}}_{SN} = \frac{\lambda^2_{HSS}}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_S + m_N)^2},$$

$$\sigma^{\text{SI}}_{VN} = \frac{\lambda^2_{HVV}}{16\pi m_H^4}\frac{m_N^4 f_N^2}{(m_V + m_N)^2},$$

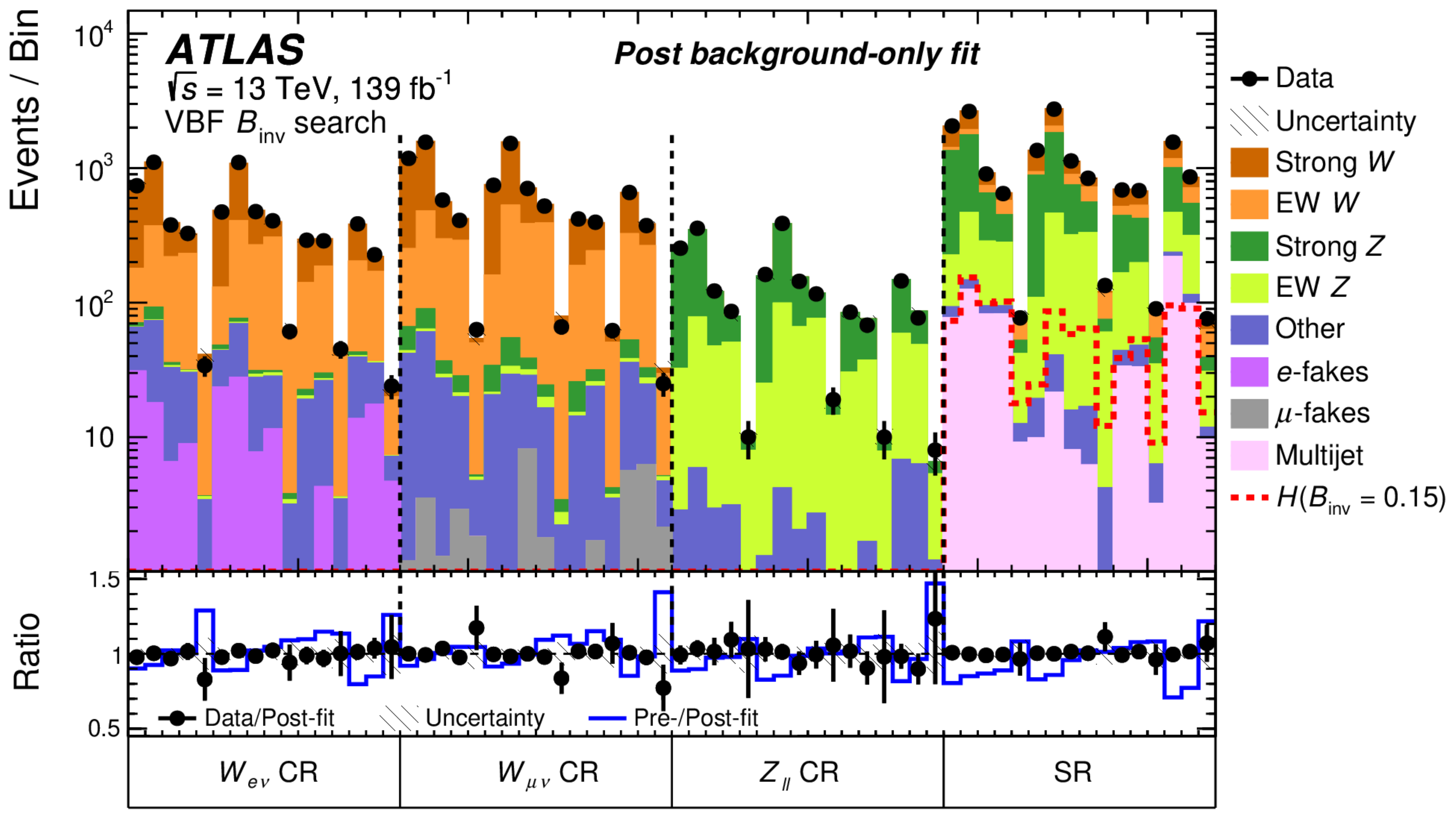
$$\sigma^{\text{SI}}_{fN} = \frac{\lambda^2_{Hff}}{4\pi\Lambda^2 m_H^4}\frac{m_N^4 m_f^2 f_N^2}{(m_f + m_N)^2},$$

Vacuum expectation value	$v/\sqrt{2}$	174 GeV
Higgs boson mass	m_H	125 GeV
Higgs boson width	Γ_H	4.07 MeV
Nucleon mass	m_N	939 MeV
Higgs–nucleon coupling form factor	f_N	$0.33^{+0.30}_{-0.07}$

Higgs boson invisible decays

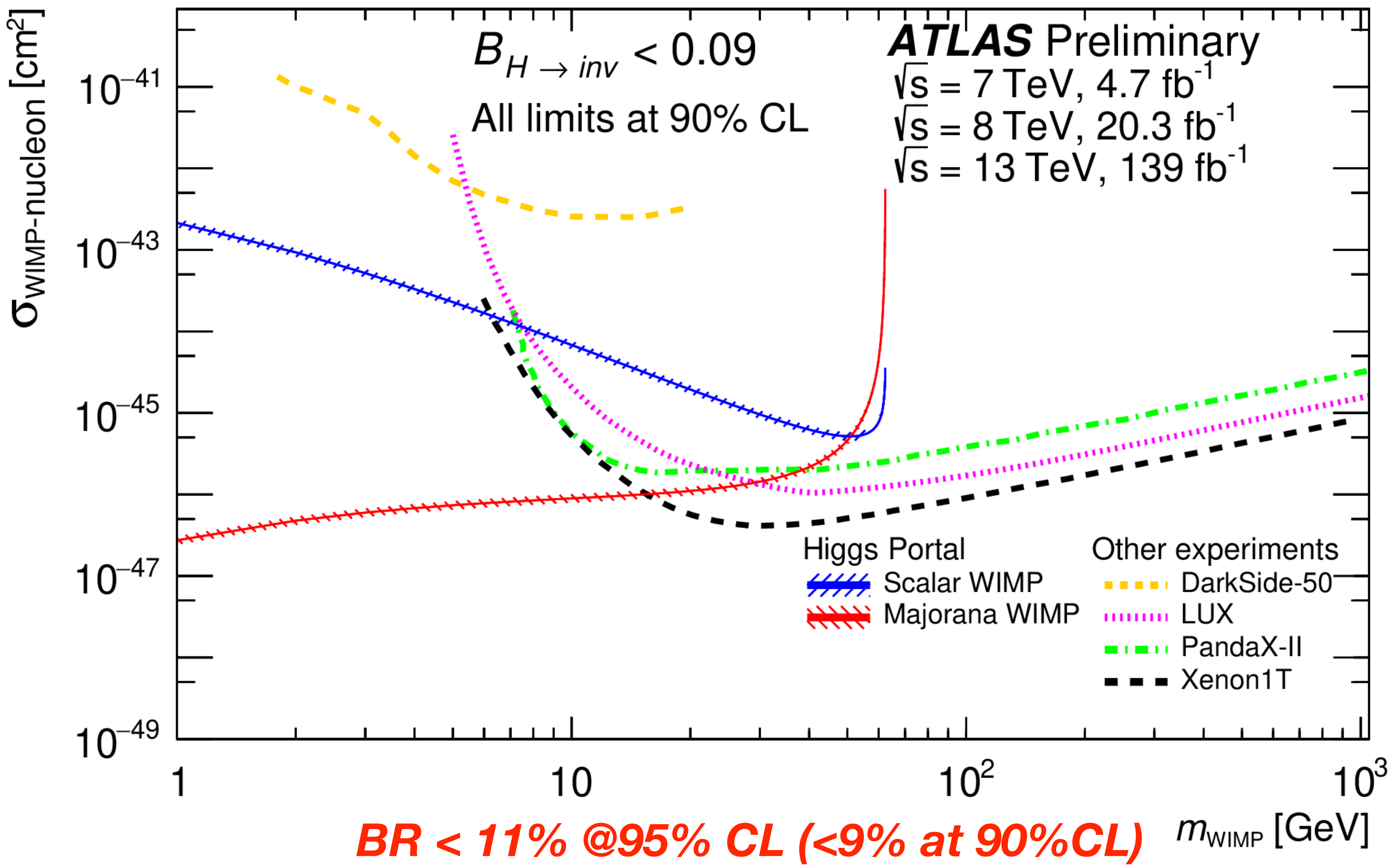
- BR(H→invisible) = 0.1% in SM ($H \to ZZ^{(*)} \to 4\nu$), too small for detection (poor missing momentum resolution, backgrounds from Z→νν)
- If Higgs decays to dark matter particles, BR(H→invisible) could be enhanced to a detectable level
- Most sensitive signature: VBF-tagged jets + large missing momentum
- Further combination with other searches (such as V(lep)H, V(had)H, ..)

VBF H→invisible (Run2) [JHEP 08 (2022) 104]



BR(H→invisible)<14.5% @95%CL

Combination [ATLAS-CONF-2020-052]



BR < 11% @95% CL (<9% at 90%CL)
Constraints on spin-independent WIMP-nucleon x-section complementary to direct searches