Latest LHC results on Higgs boson

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Lecture at pre-school of “Higgs potential and BSM opportunity”, Nanjing, 2021/8/27

Outline

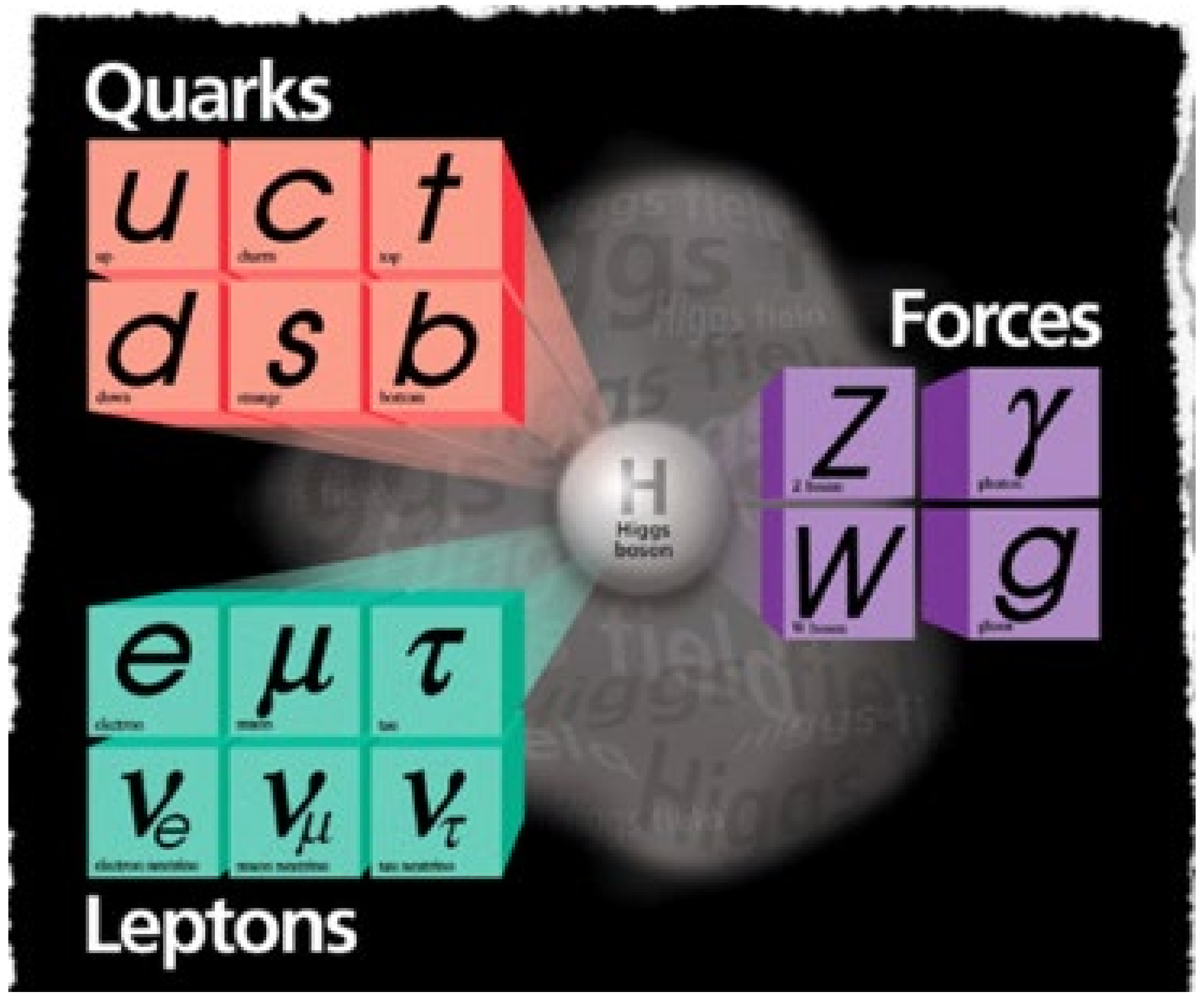
- Mass
- Rare decays
- Differential cross sections and distributions
- Di-Higgs and self-couplings
- Search for new physics beyond the SM

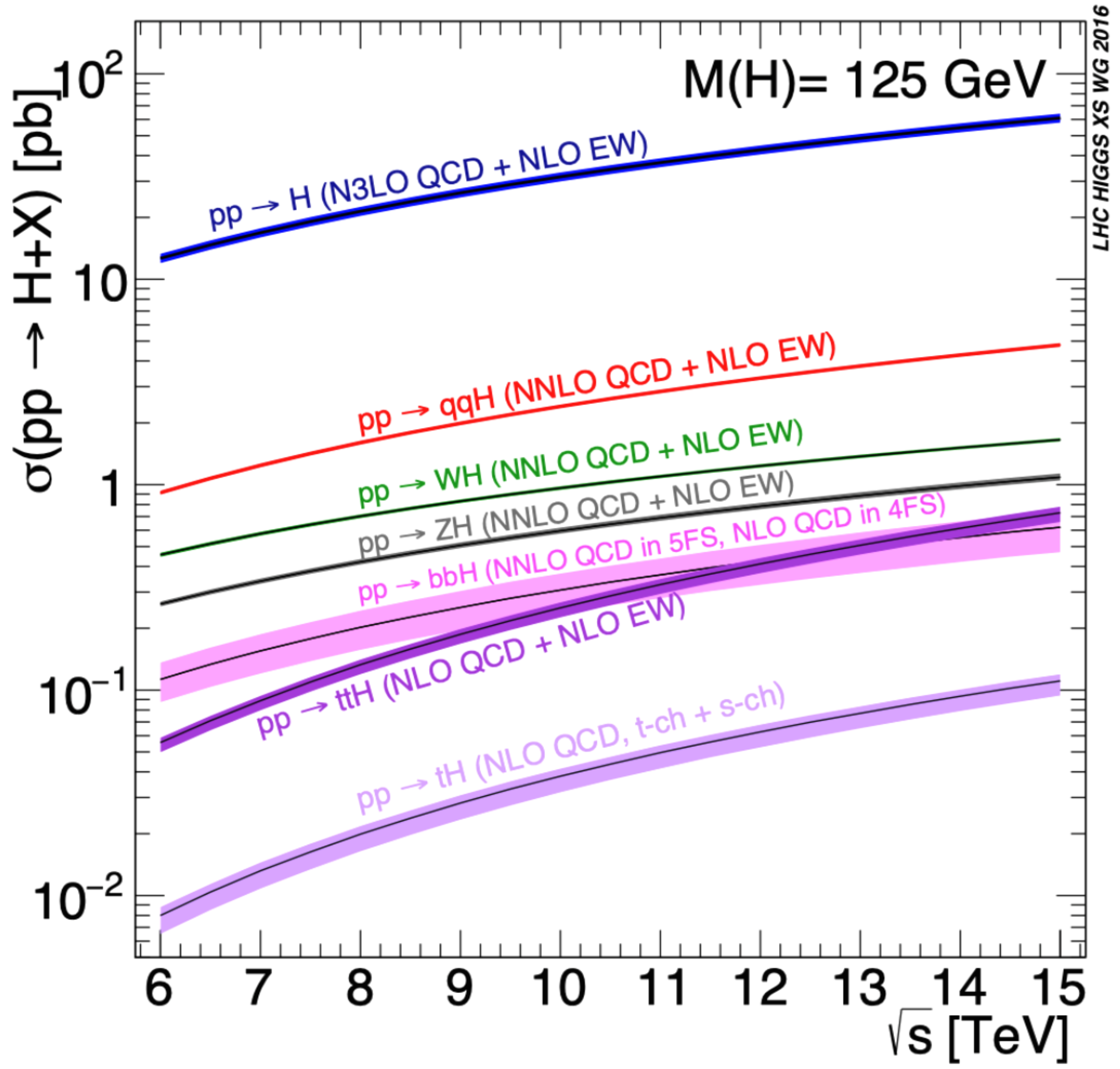
e full list a

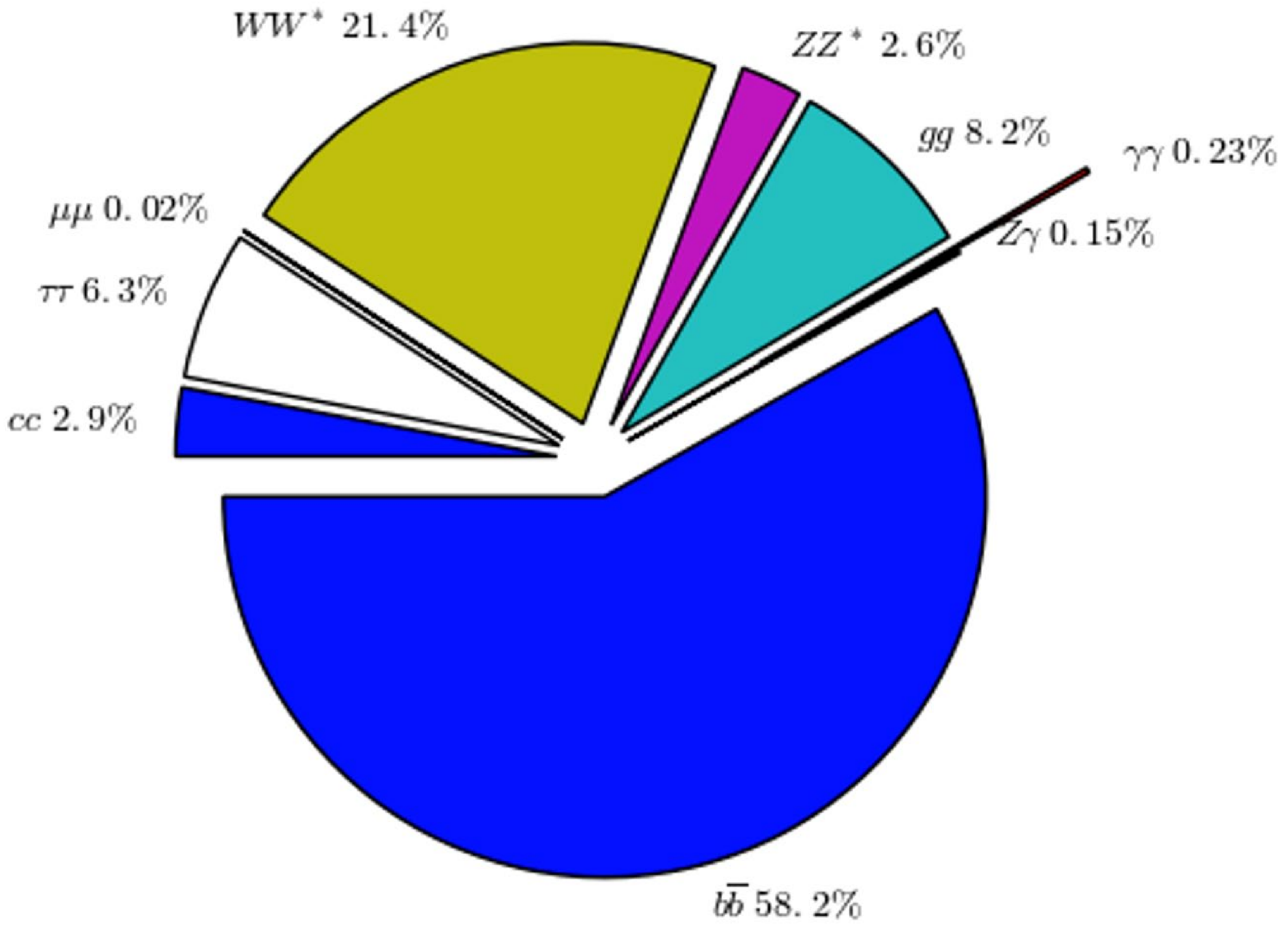
https://twiki.cern.ch/twiki/bin/view/AtlasPublic
http://cms-results.web.cern.ch/cms-results/public-results/publica

Brief introduction to Higgs boson

- Predicted in 1964, discovered in 2012
- The only scalar elementary particle in SM
- Attributes masses to all elementary particles

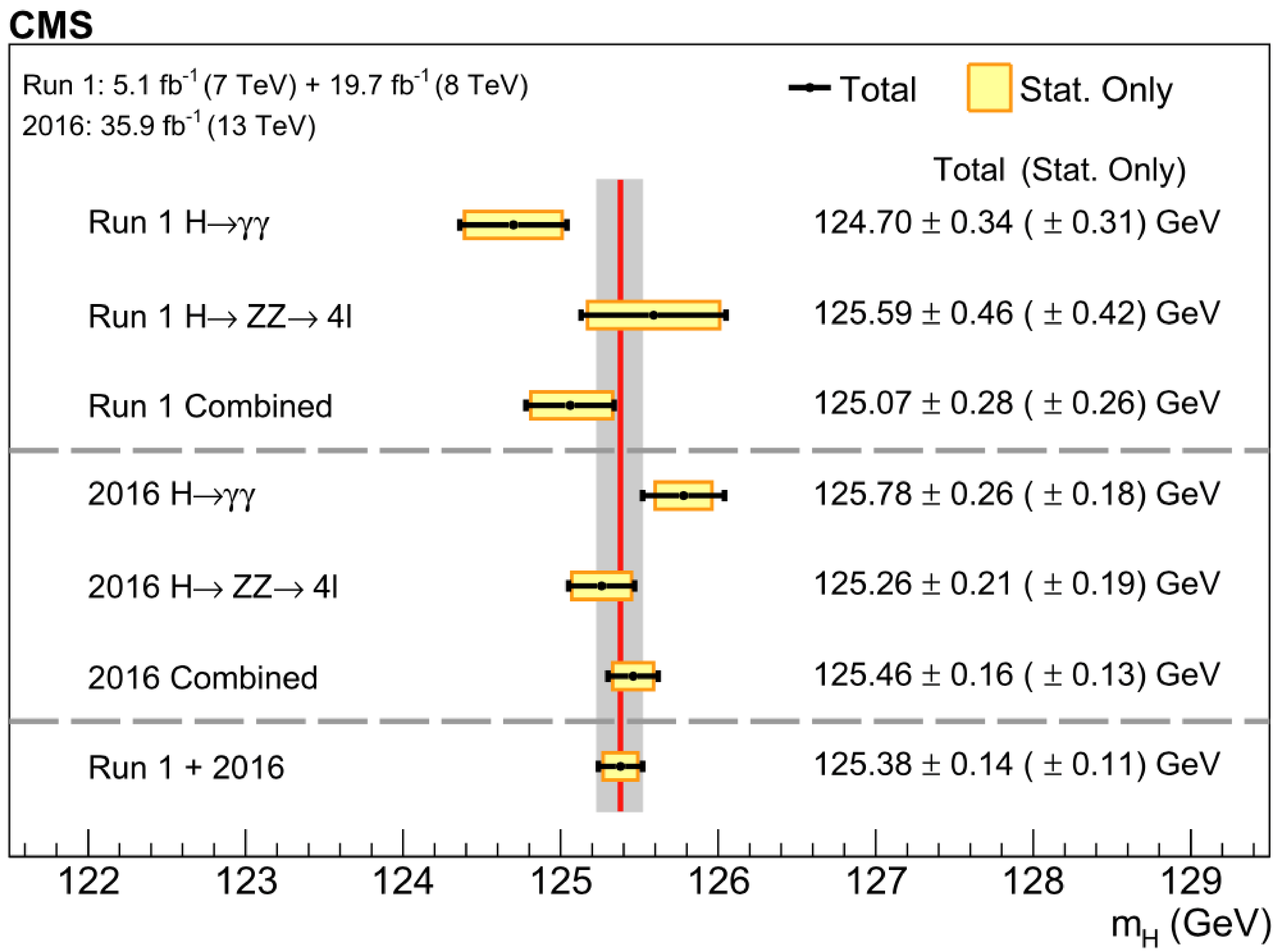






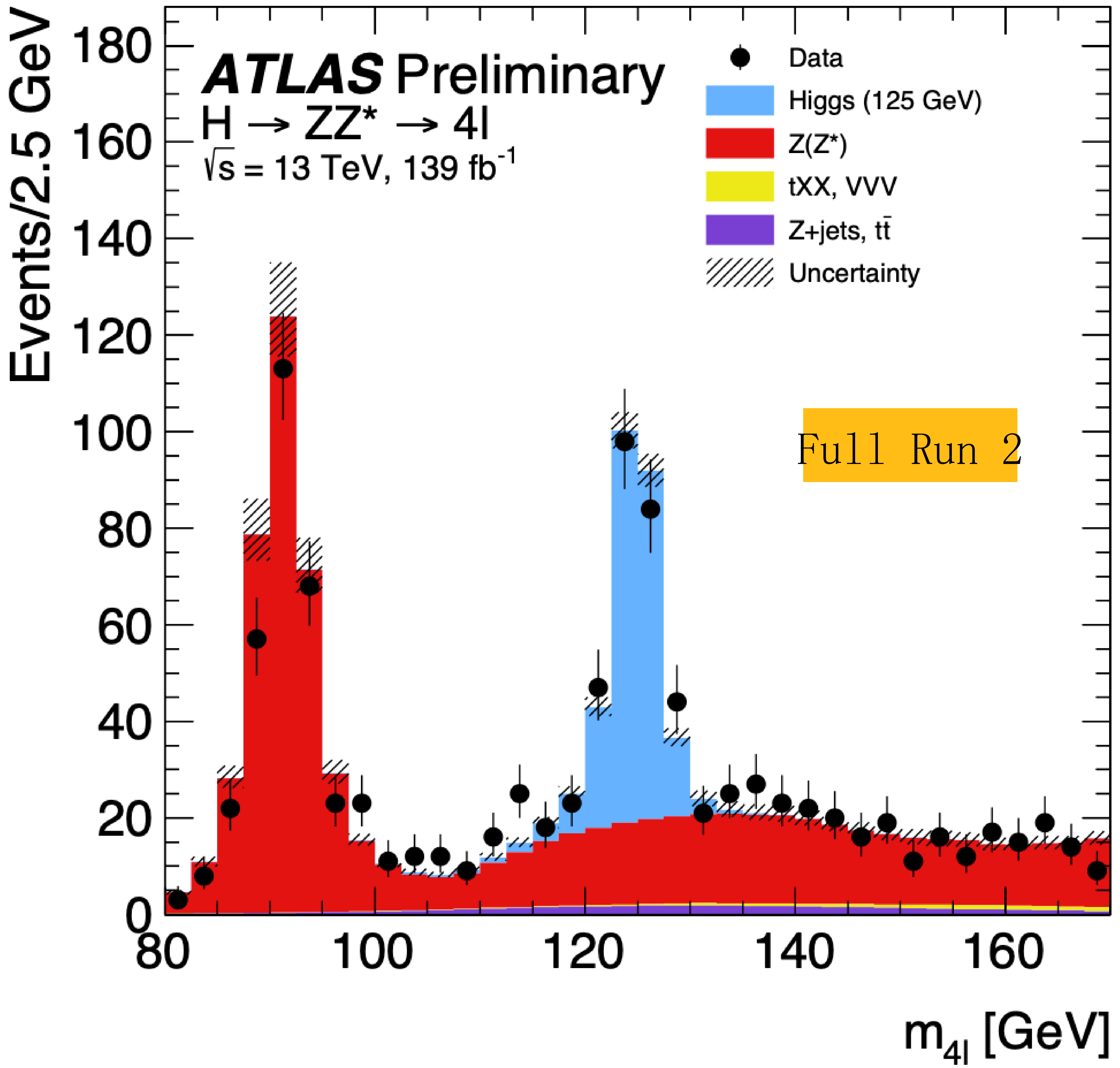
ATLAS full Run 2 : Hzz [ATLAS-CONF-2020-005]

Higgs mass

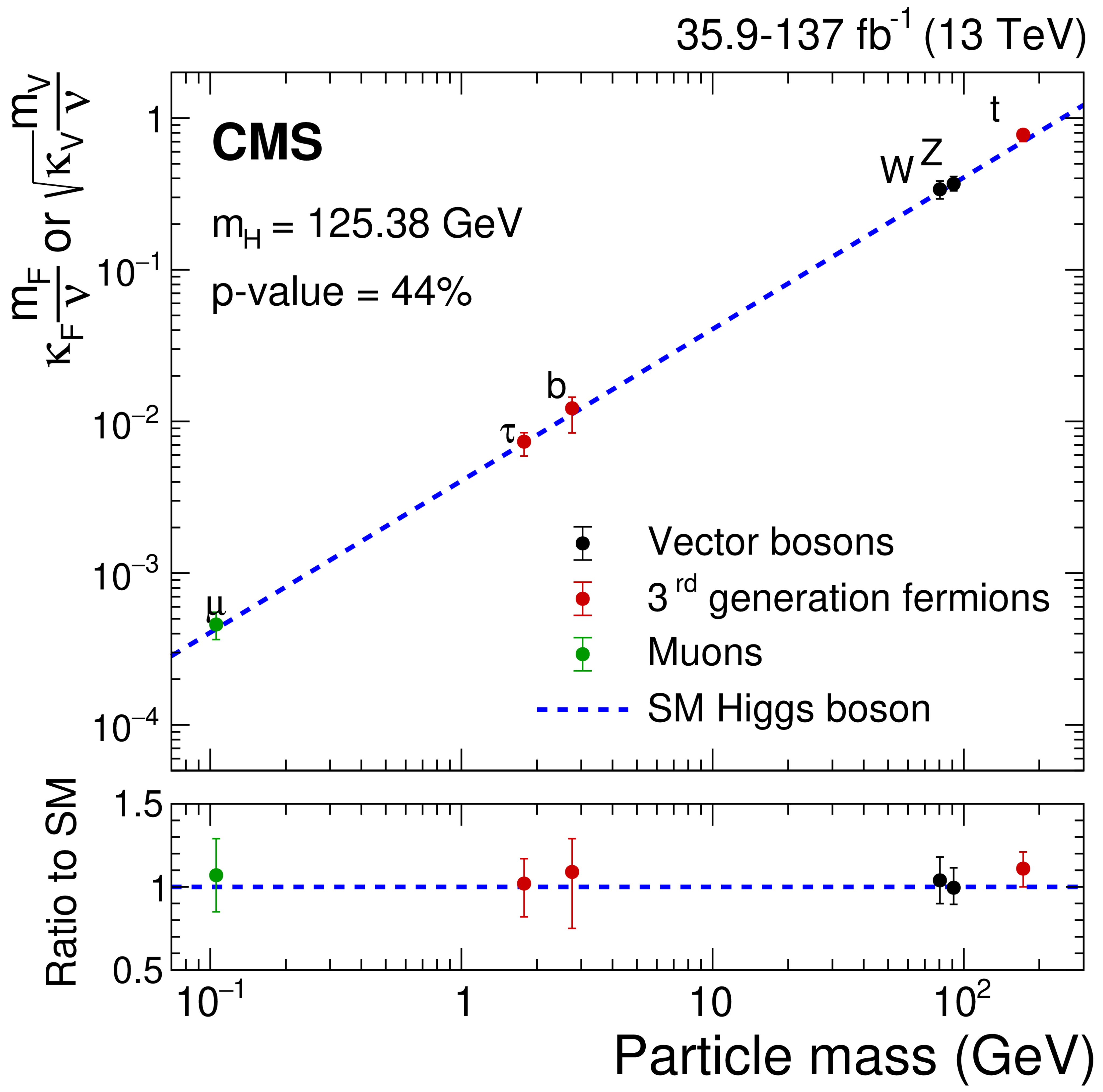


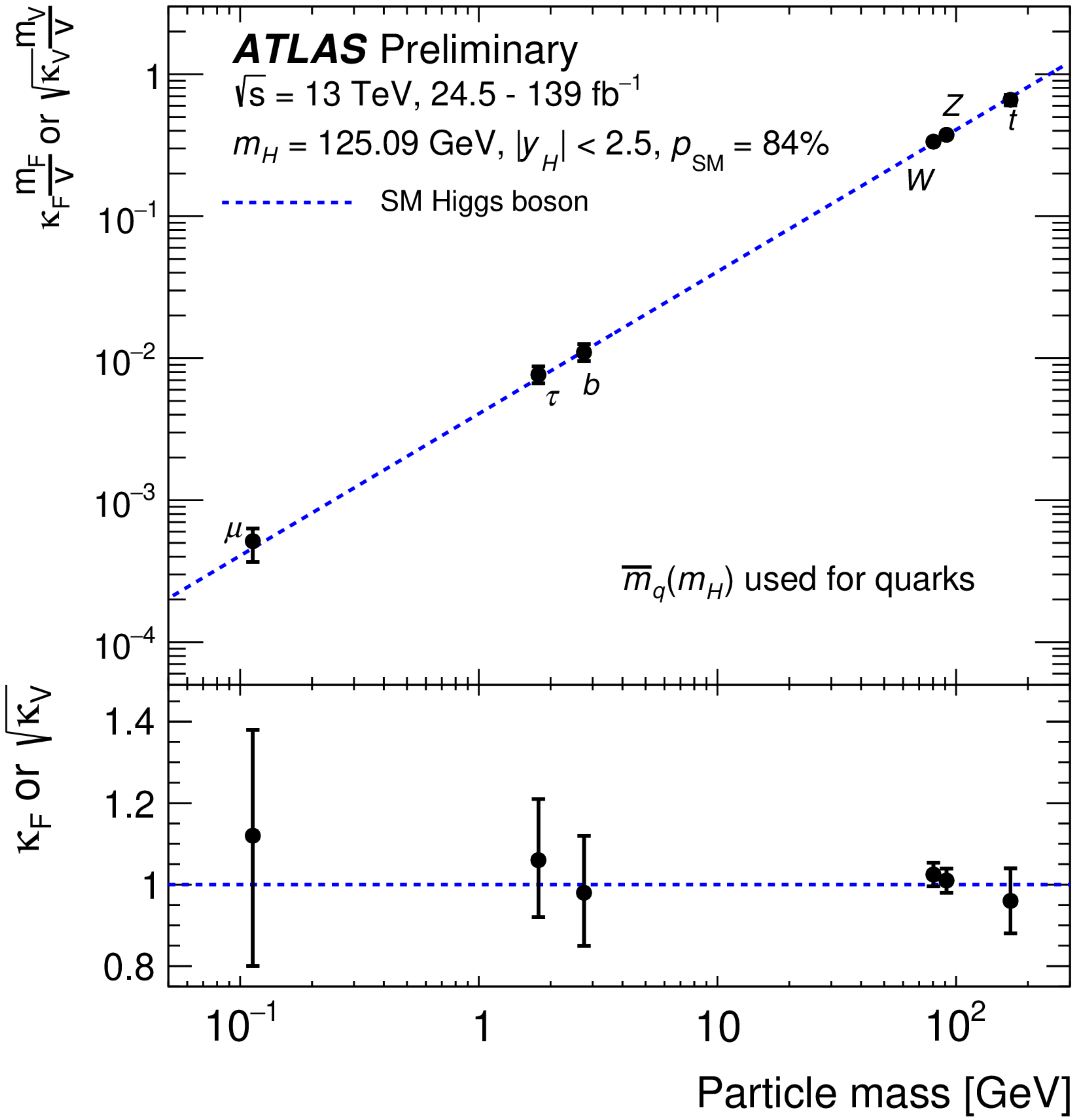
Run 1 CMS+ATLAS	$125.09 \pm 0.24\text{GeV}$
ATLAS Run 1 + 36/fb Run 2	$124.97 \pm 0.24\text{GeV}$
CMS Run 1+36/fb Run 2	$125.38 \pm 0.14\text{GeV}$

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



Overview of the couplings





Searches for/Evidences of rare decay modes

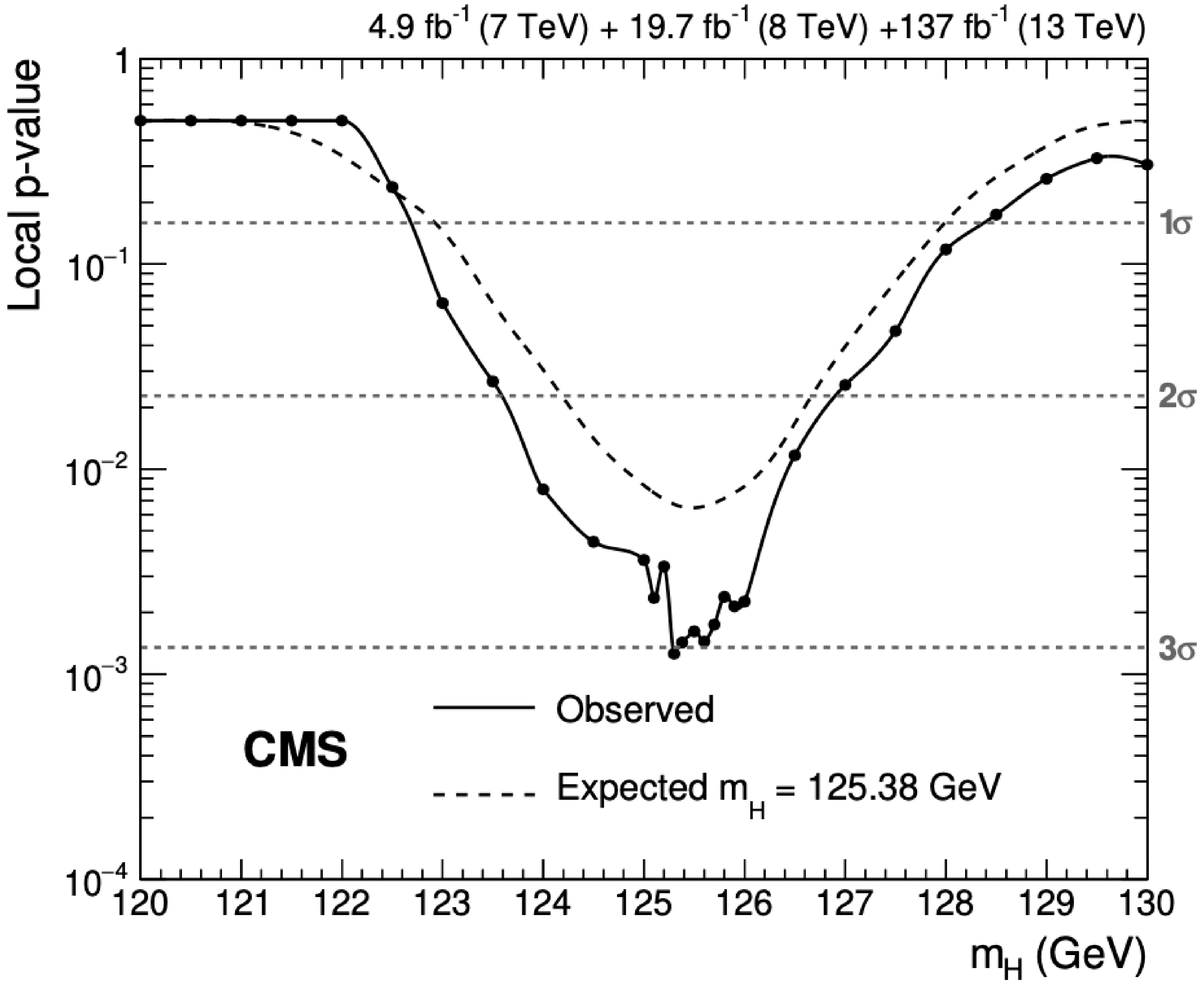
Channel	CMS	ATLAS
$\mu\mu$	140/fb, 3σ	140/fb, 2σ
cc	36/fb, μ<70(95%CL)	140/fb, μ<26(95%CL)
$ll\gamma$	36/fb, μ<3.9(95%CL)	140/fb, 3σ

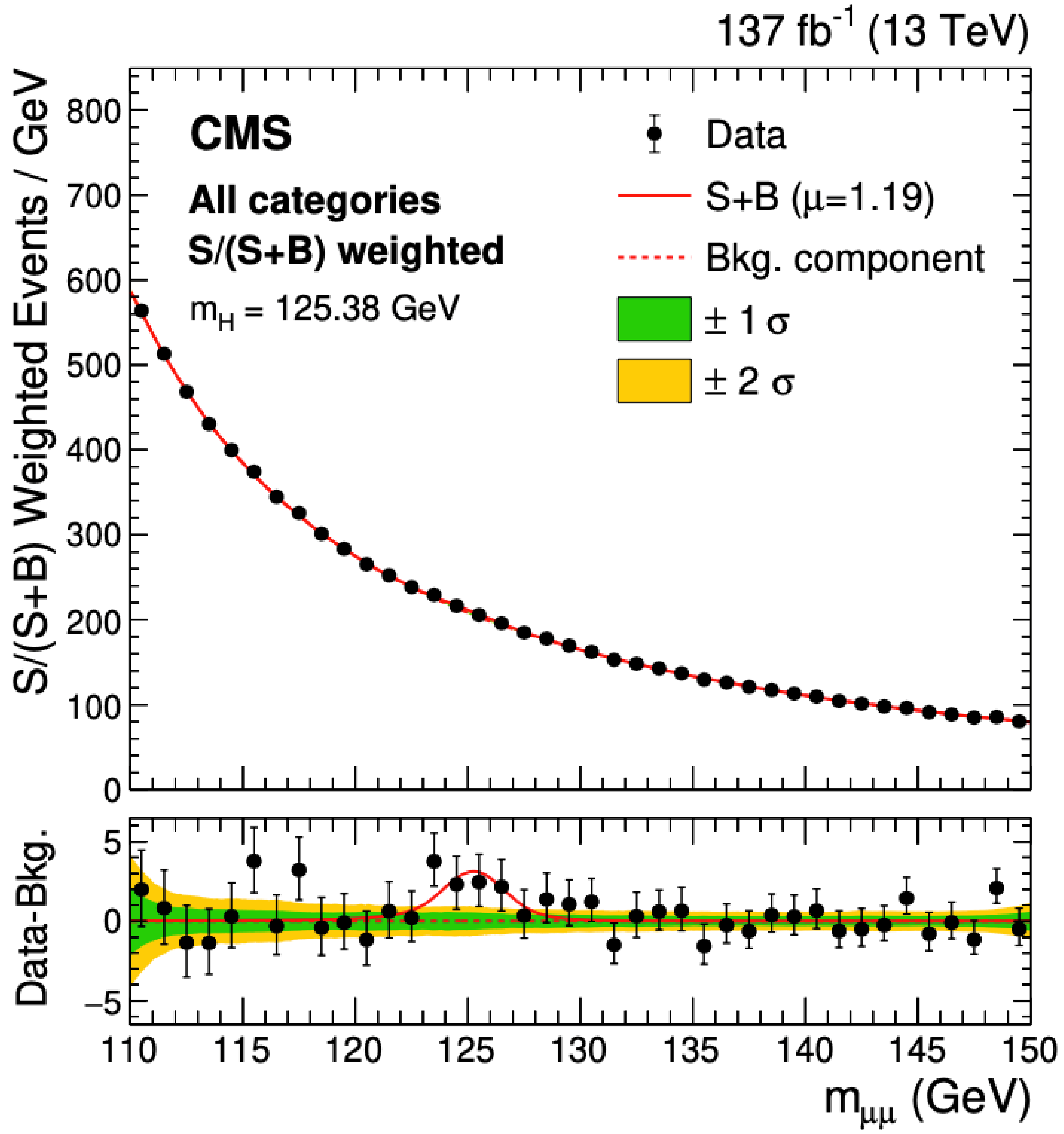
CMS JHEP 01(2021)148

Rare decay: di-muon (CMS)

$$B(H \rightarrow \mu^+\mu^-) = 2.18 \times 10^{-4}$$

Full Run 2





Production category	Observed (expected) signif.	Observed (expected) UL on μ
VBF	2.40 (1.77)	2.57 (1.22)
ggH	0.99 (1.56)	1.77 (1.28)
$t\bar{t}H$	1.20 (0.54)	6.48 (4.20)
VH	2.02 (0.42)	10.8 (5.13)
Combined $\sqrt{s} = 13\,\text{TeV}$	2.95 (2.46)	1.94 (0.82)
Combined $\sqrt{s} = 7,\ 8,\ 13\,\text{TeV}$	$\boxed{2.98\ (2.48)}$	1.93 (0.81)

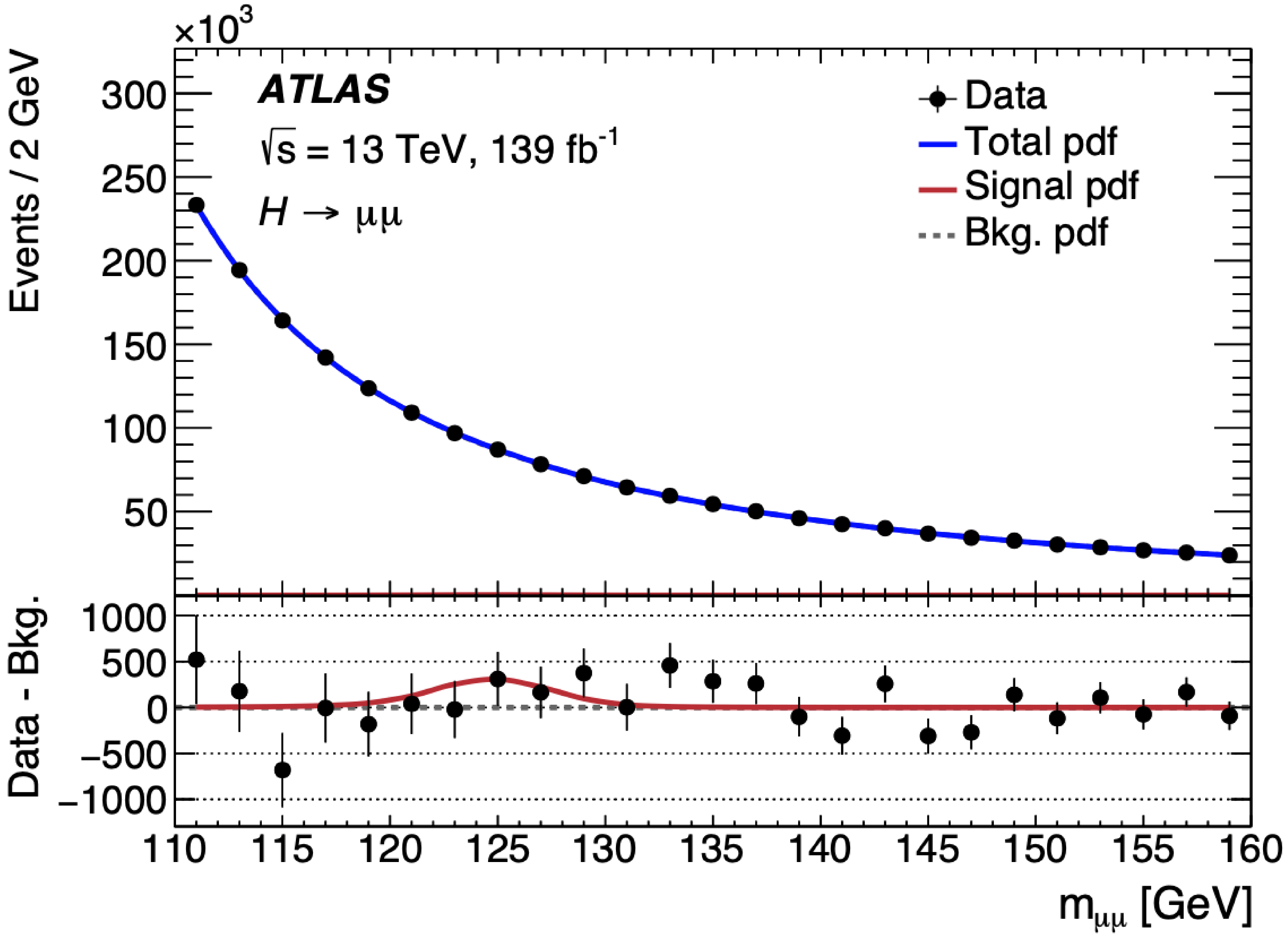
First evidence

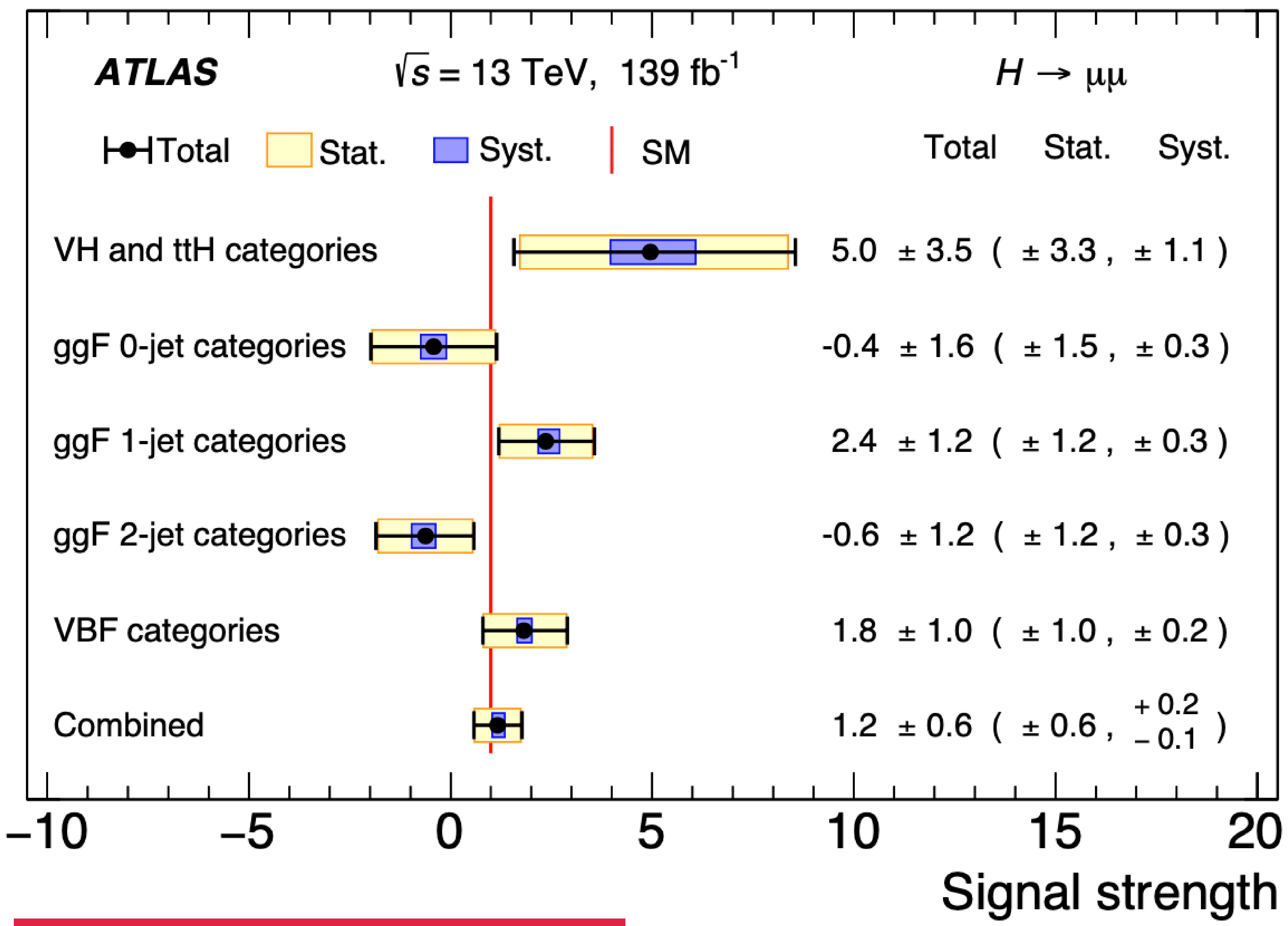
S / B defined by ± HWHM around 125.38 GeV of each category

Rare decay : di-muon (ATLAS)

Phys. Lett. B 812 (2021) 135

Full Run 2



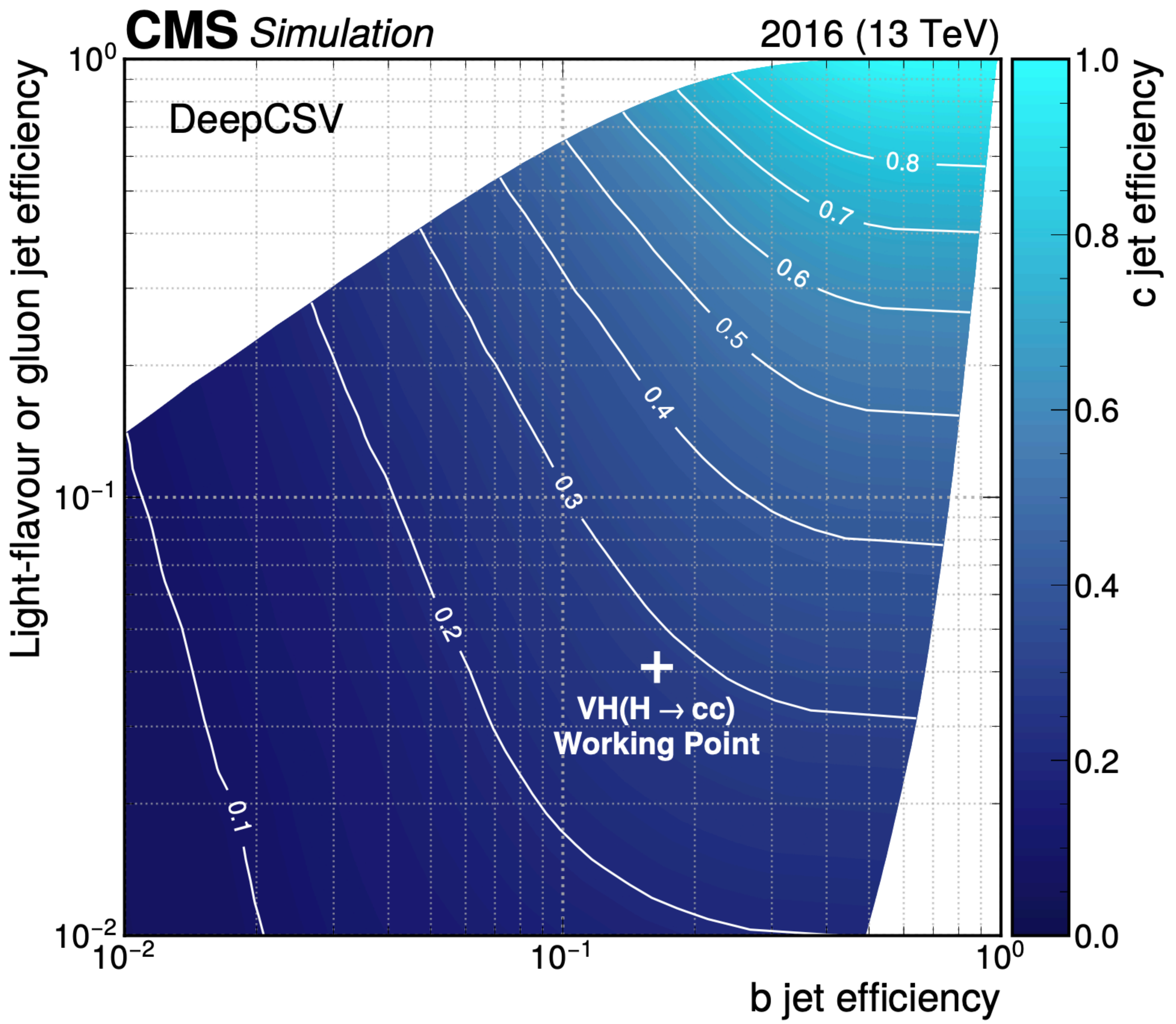


ignificance: 2 (1.7) sigma

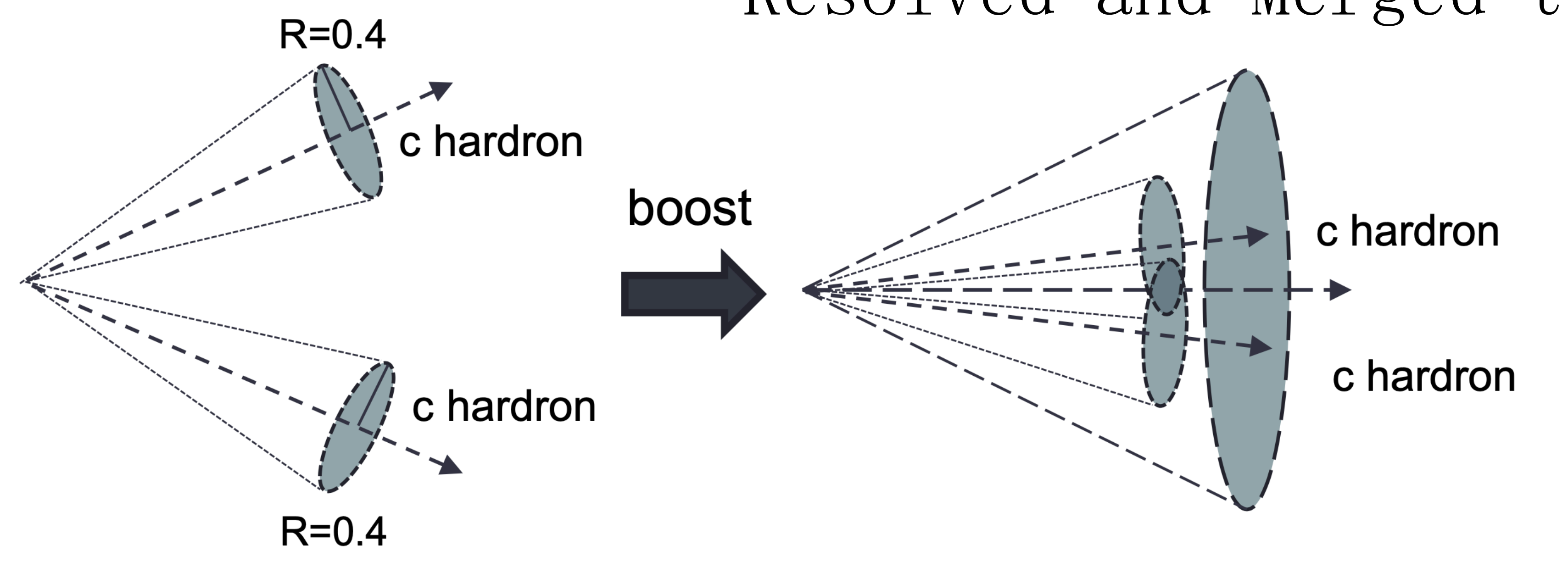
JHEP 03(2020)131

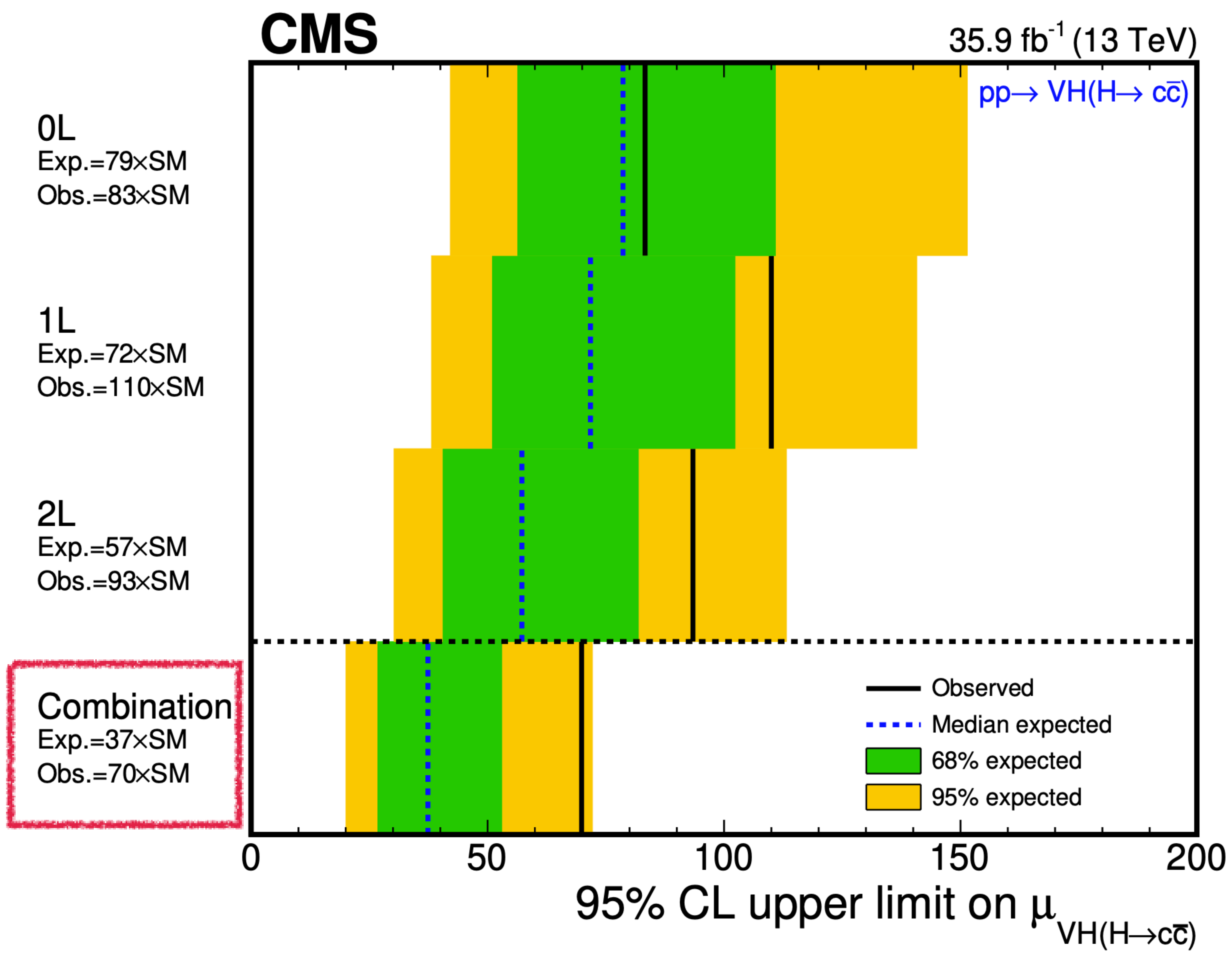
VH, H—>cc (CMS)

Deep Neural Net multi-classification



Resolved and Merged topologies





VH, H—>cc (ATLAS)

Full Run 2

Binned ML fit to extract 3 parameters

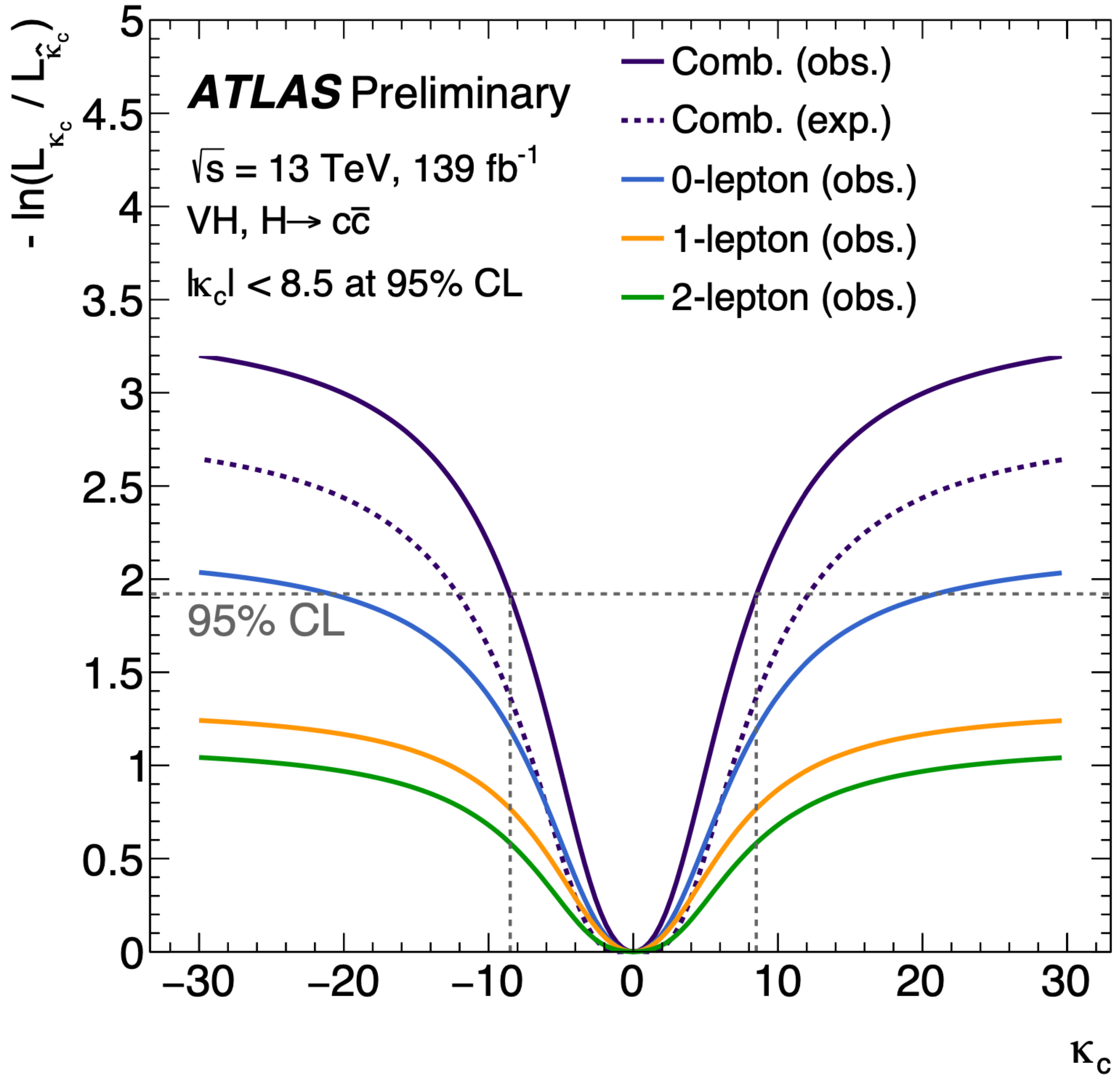
$$\mu_{VH(c\bar{c})} = -9 \pm 10\,(\text{stat.}) \pm 12\,(\text{syst.})$$

$$\mu_{VW(cq)} = 0.83 \pm 0.11\,(\text{stat.}) \pm 0.21\,(\text{syst.})$$

$$\mu_{VZ(c\bar{c})} = 1.16 \pm 0.32\,(\text{stat.}) \pm 0.36\,(\text{syst.})$$

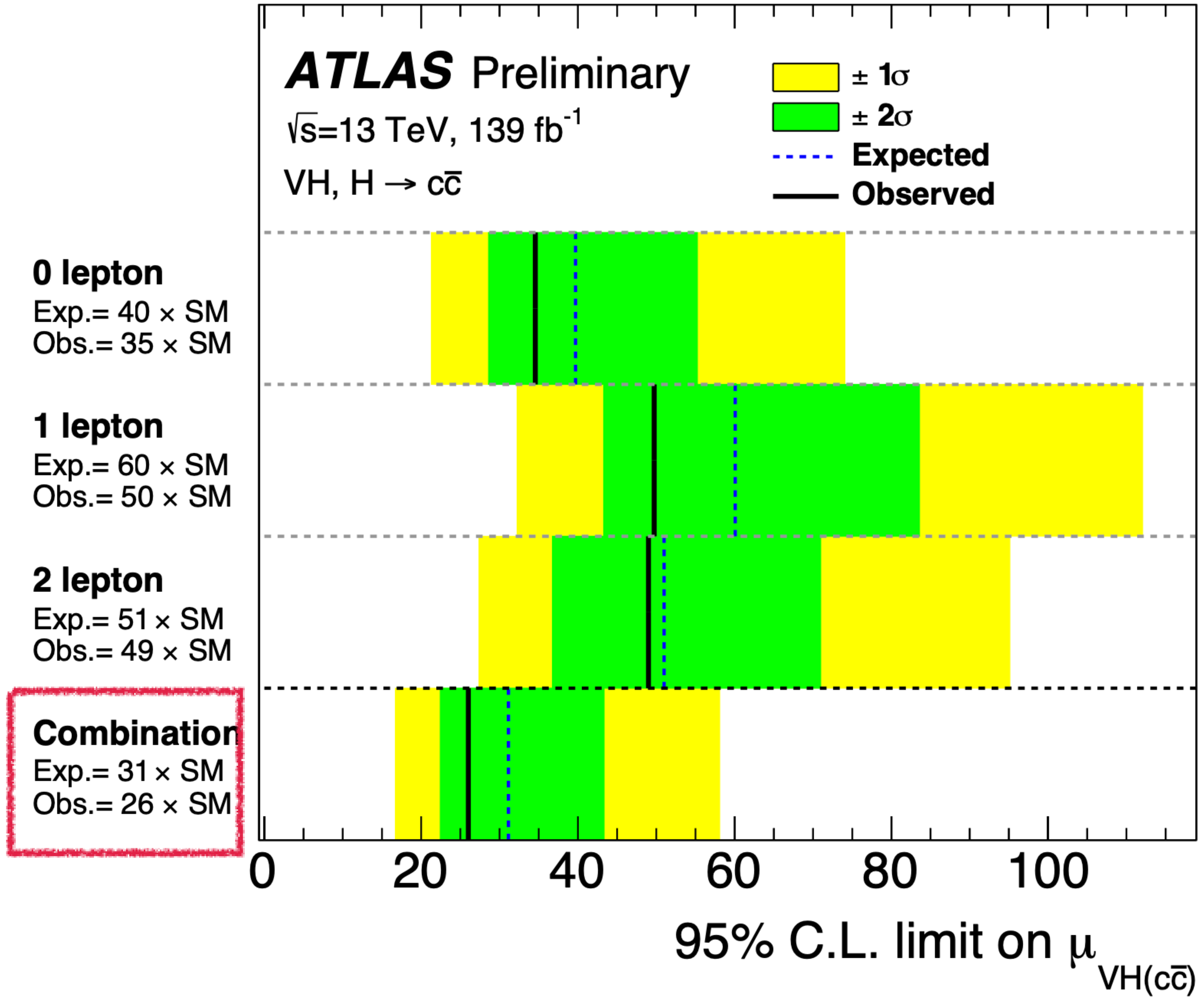
DL1c c-tagging, MV2 veto on b-jets:

c-jet eff.	b-jet eff.	light jet eff.
27%	8%	1.6%



Assuming Kc only affects the decay BF, all other couplings are fixed by SM:

$$\mu_{VH(c\bar{c})}(\kappa_c) = \frac{\kappa_c^2}{1 + B^{\text{SM}}_{H\rightarrow c\bar{c}}(\kappa_c^2 - 1)}$$

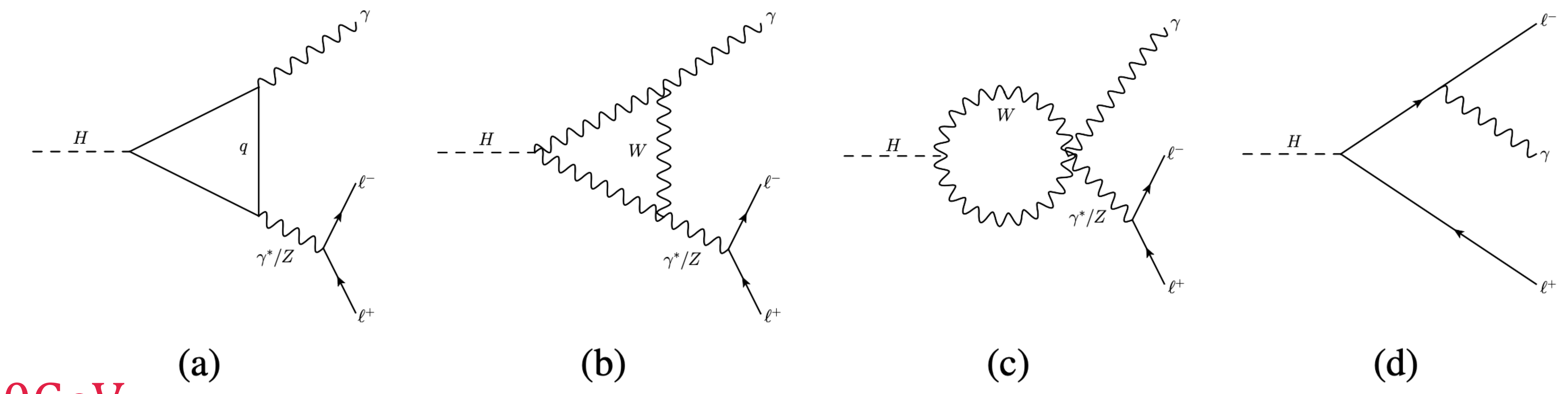


H—>llγ/Zγ(ATLAS)

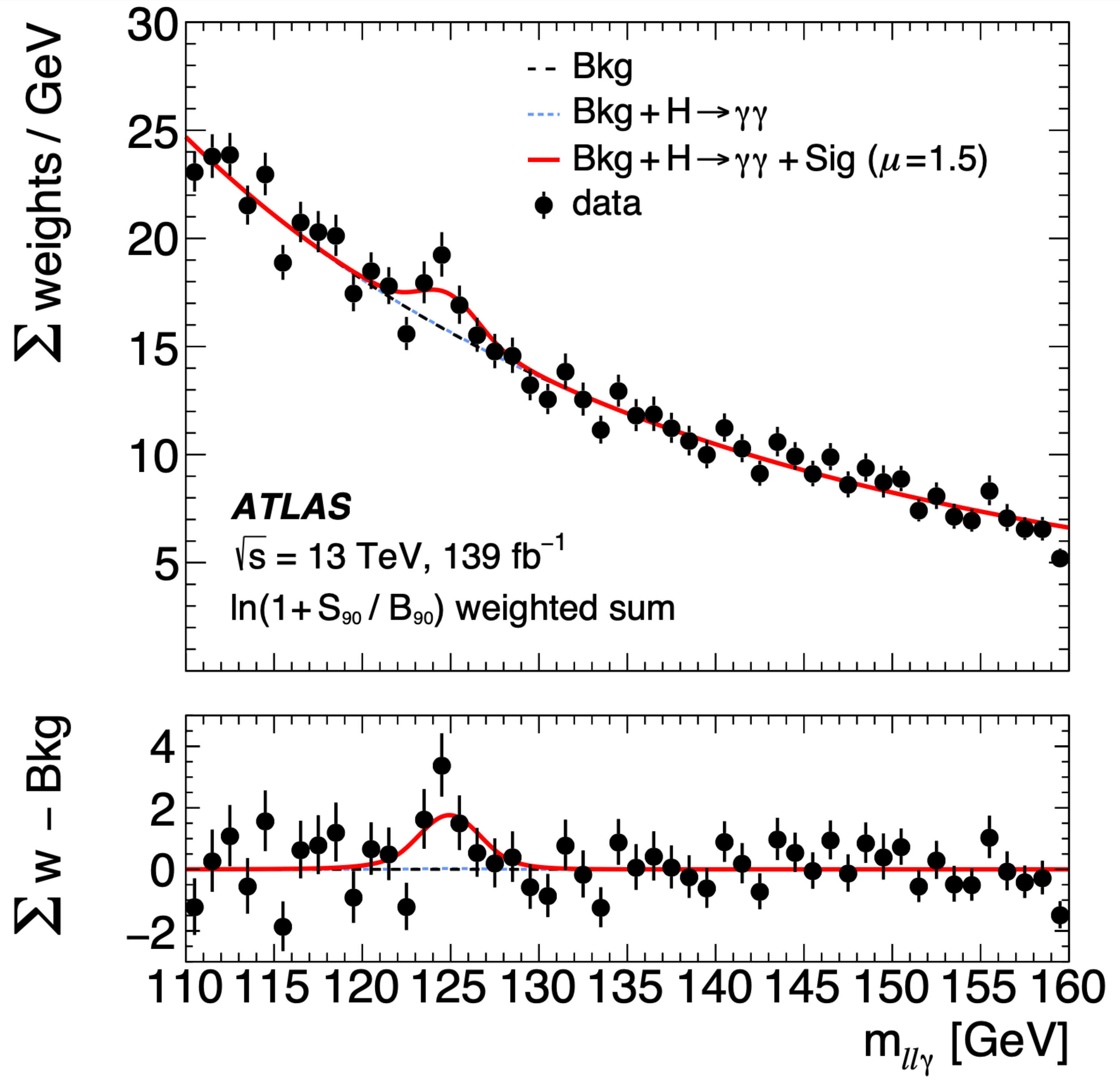
[ATLAS arXiv:2103.10322 submitted to PLB]

Full Run 2

Probe BSM couplings and CP violation in Higgs sector

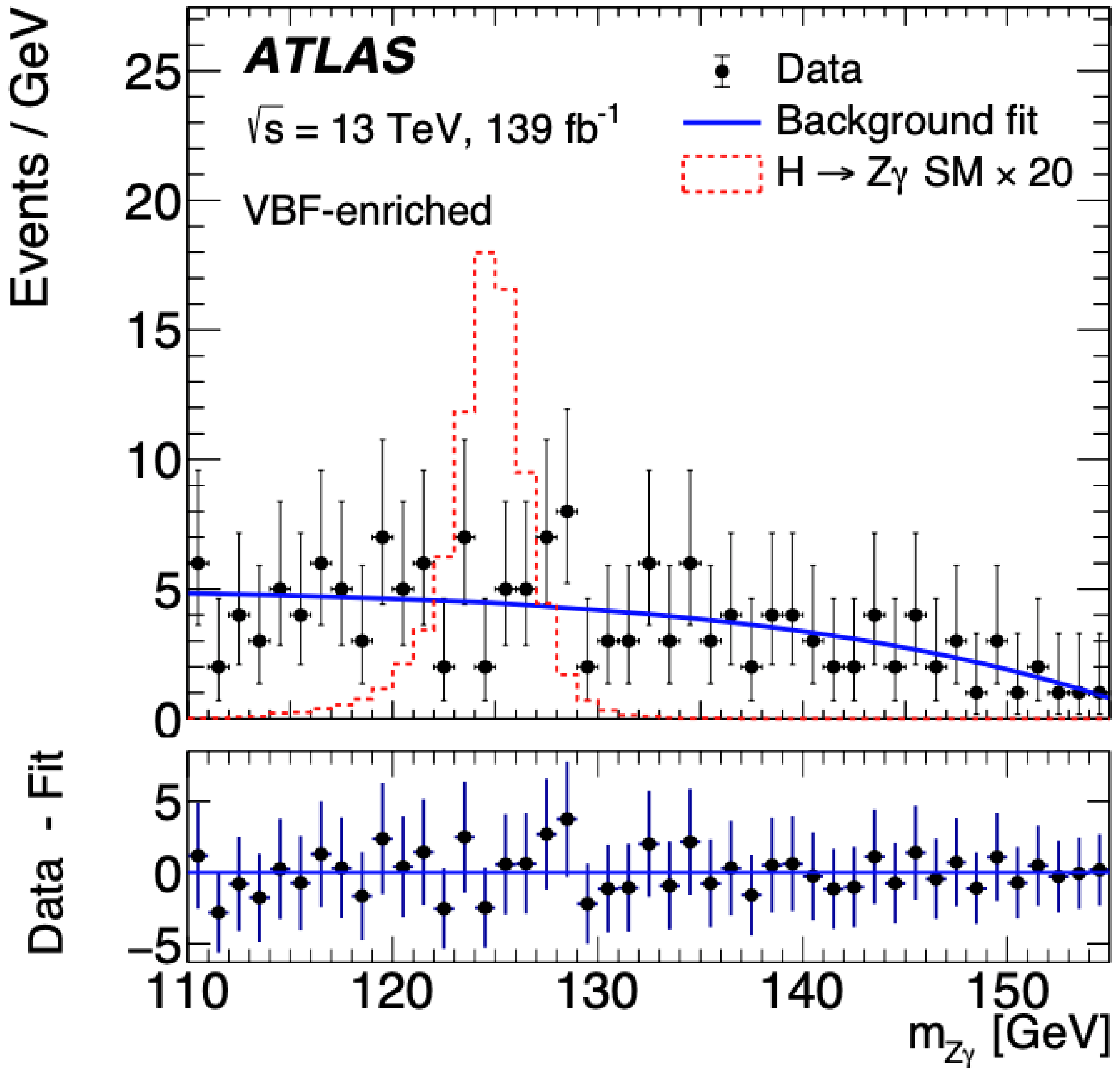


$m_{ll} < 30\text{GeV}$



Significance : 3.2(2.1) sig

Significance : 2(1.2) sigm



$$\sigma \times B(H \to ll\gamma) = 8.7^{+2.8}_{-2.7}\text{fb}$$

$50\text{GeV} < m_{ll} < 101\text{GeV}$

$105\text{GeV} < m_{Z\gamma} < 160\text{GeV}$

Category-dependent weights applied

S90 : number of signal events in the smallest bin that contains 90% of the signal

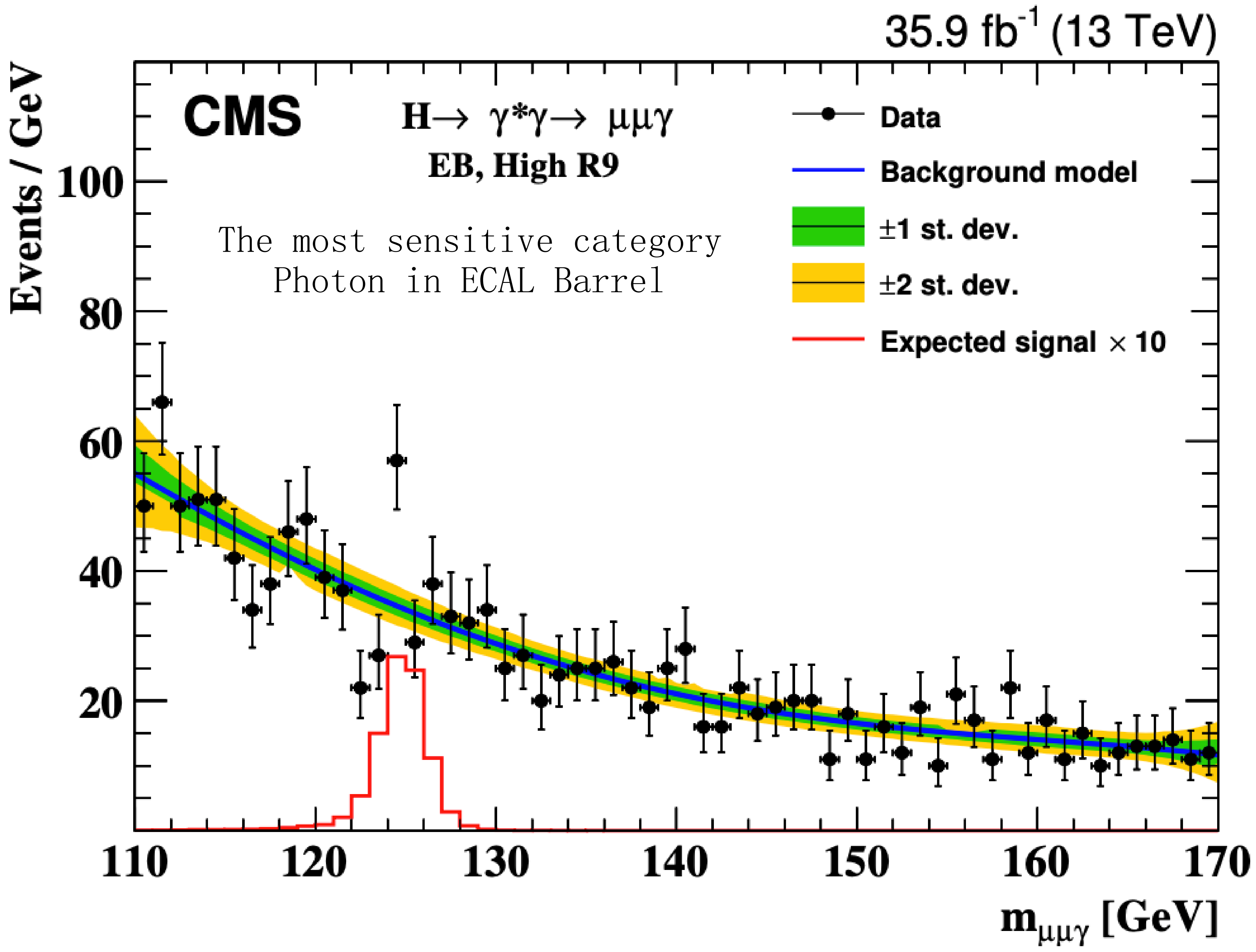
B90: number of background events in the same bin

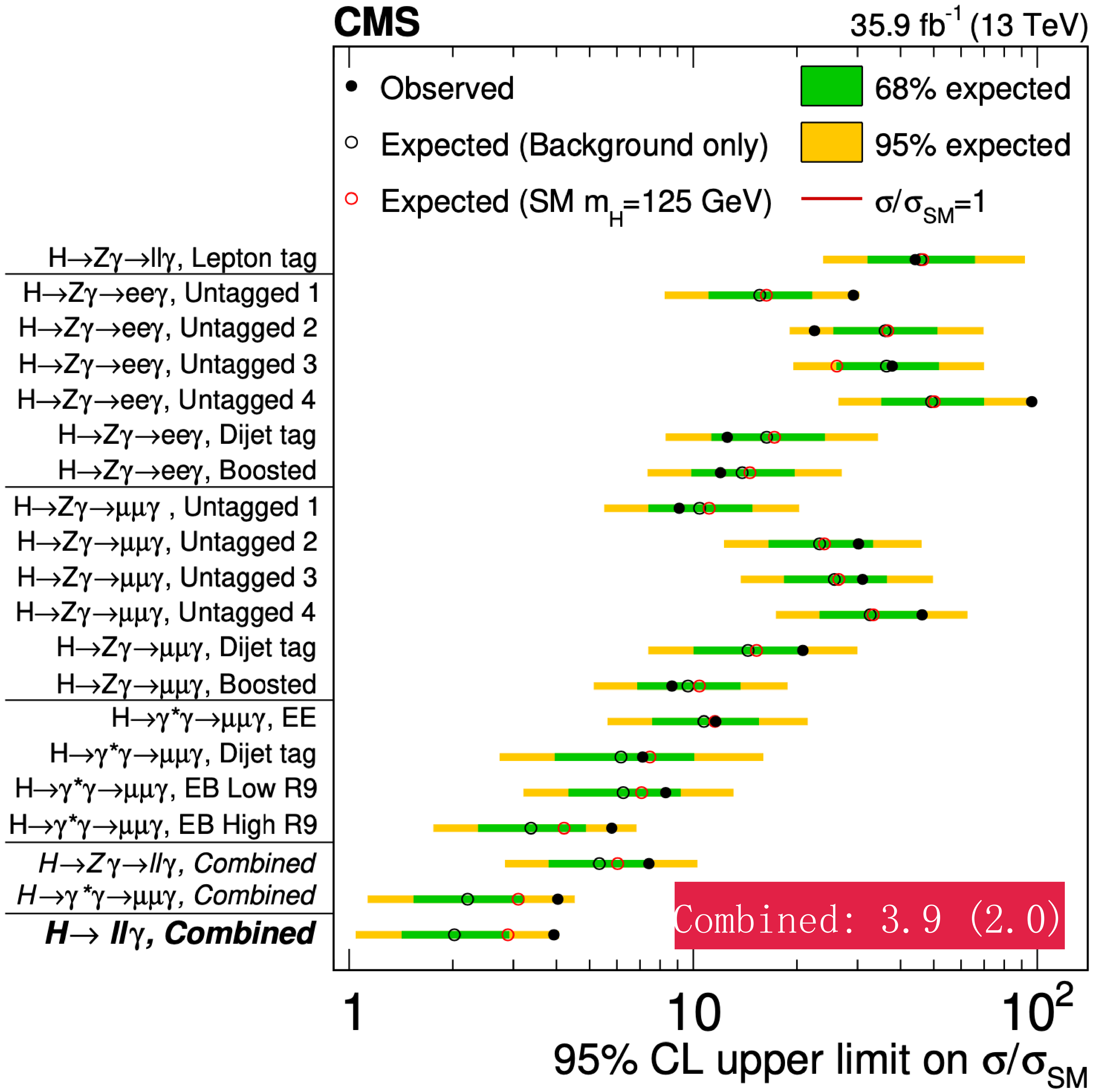
CMS JHEP11(2018)152

H—>ll$\boldsymbol{\gamma}$(CMS)

$$H \rightarrow \gamma^*\gamma \rightarrow \mu\mu\gamma$$
$$H \rightarrow Z\gamma$$

Separated by $m_{ll} = 50\text{GeV}$





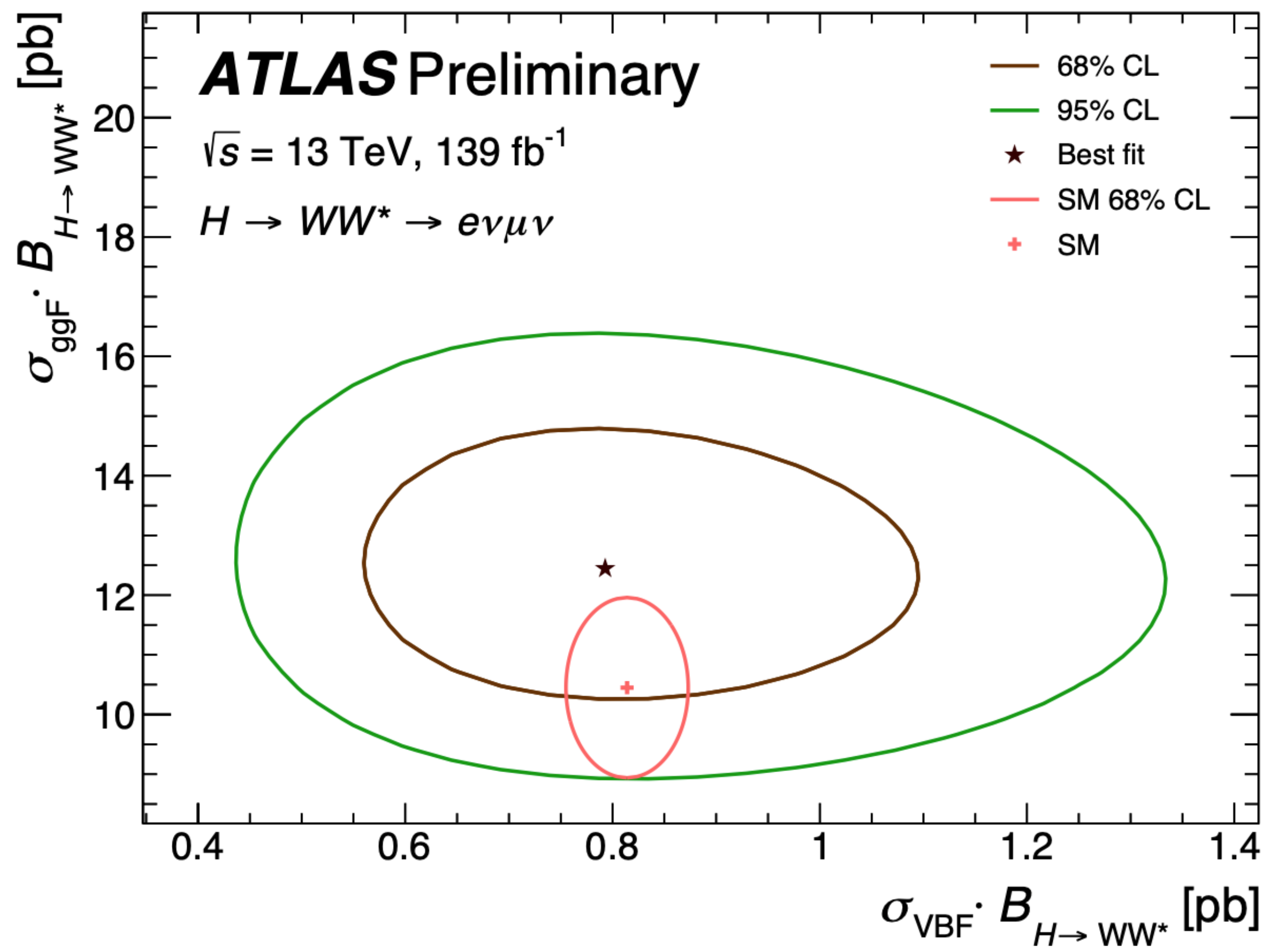
Differential measurements

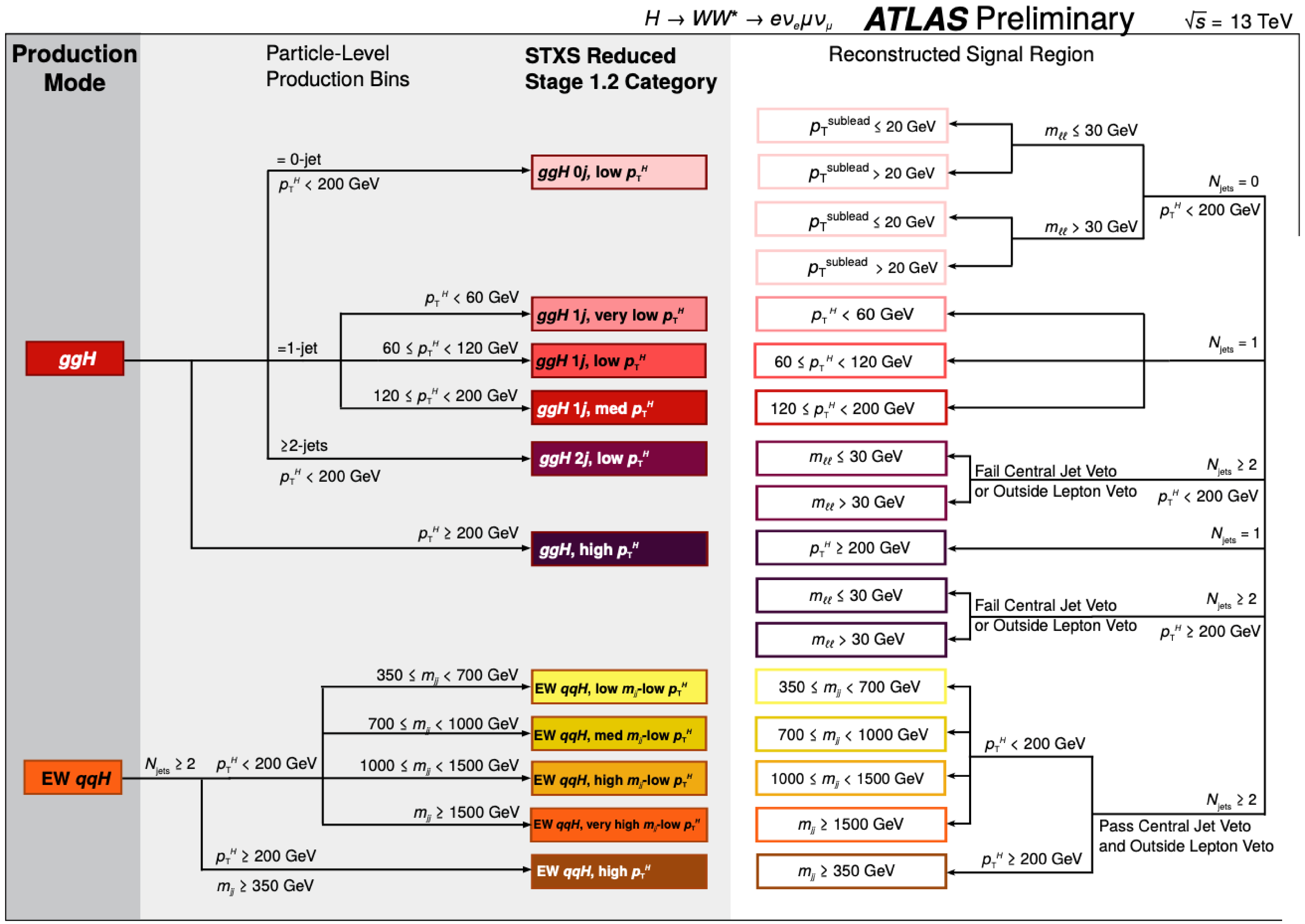
	CMS	ATLAS
$\tau\tau$	140/fb	36/fb (not covered today)
bb	140/fb(boosted)	140/fb
WW	140/fb(backup)	140/fb
$\gamma\gamma$	140/fb	140/fb
4-lepton	140/fb	140/fb

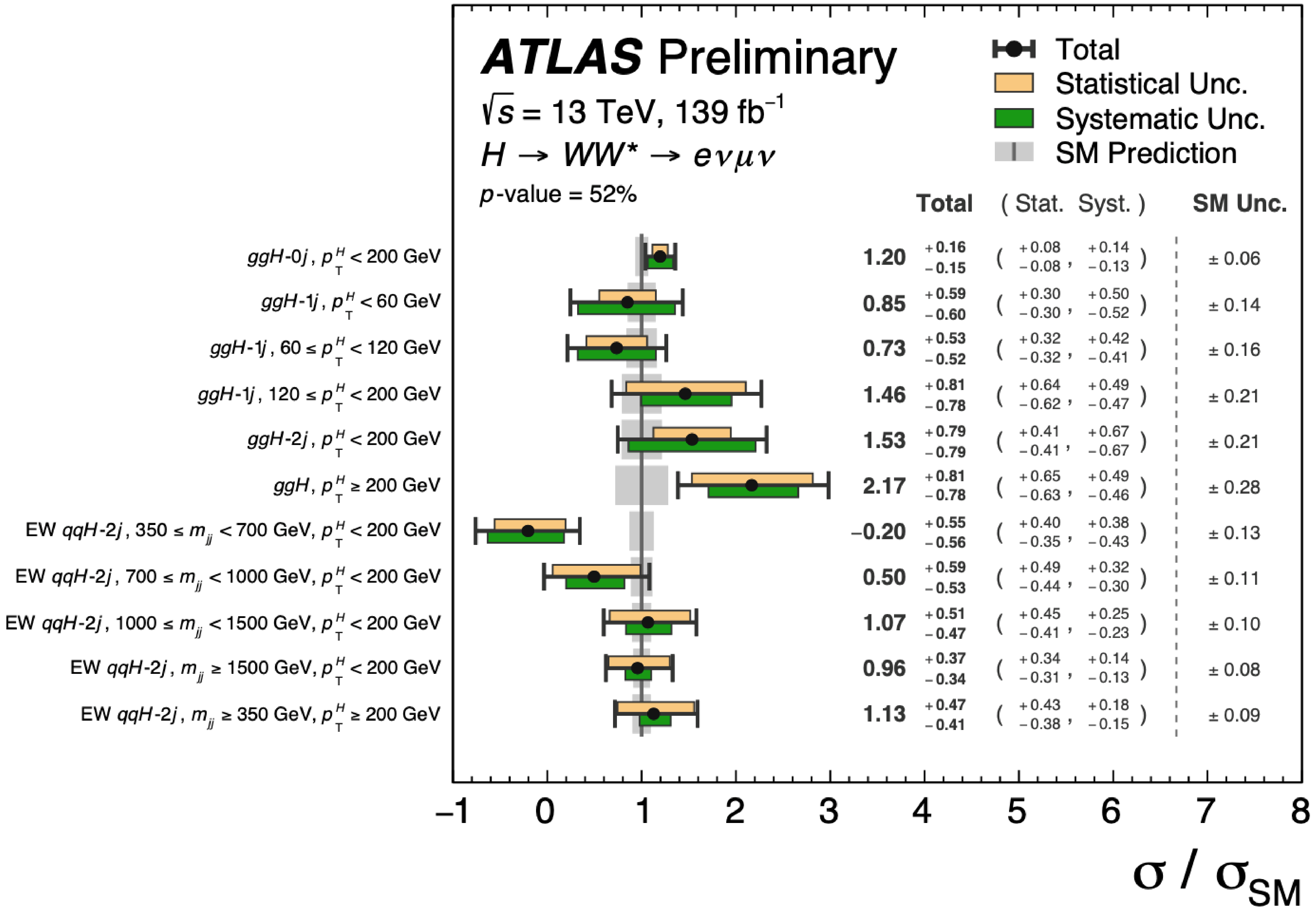
ATLAS H——>WW

Full Run 2

easurement of cross sections in 11 STXS categories with e+μ final state







STXS combination and SMEFT (ATLAS)

Inputs

Analysis		Integrated lumi (fb^{-1})	Reference	STXS stage	Used in MSSM	Used in EFT
$H \to \gamma\gamma$	(all production modes)	139	[15]	1.2	✓	✓
$H \to ZZ^* \to 4\ell$	(all production modes)	139	[10]	1.2	✓	✓
$H \to b\bar{b}$	(VH)	139	[11]	1.2	✓	✓
$H \to WW^*$	(ggH, VBF)	36.1	[18]	1.0	✓	-
$H \to \tau\tau$	(ggH, VBF)	36.1	[19]	1.0	✓	-
$H \to b\bar{b}$	(VBF)	24.5 – 30.6	[16]	0	✓	-
$H \to b\bar{b}$	$(t\bar{t}H)$	36.1	[17]	0	✓	-
$H \to$ multilepton	$(t\bar{t}H)$	36.1	[20]	0	✓	-
$H \to \mu\mu$	(all production modes)	139	[21]	0	✓	-

Parameterisation (dim-6 operators)

$$\sigma_{\mathrm{STXS}} = \sigma_{\mathrm{SM}} + \sigma_{\mathrm{int}} + \sigma_{\mathrm{BSM}}$$

$$\sigma_{\mathrm{STXS}} = \sigma_{\mathrm{SM}}^{\mathrm{((N)N)NLO}} \times \left(1 + \frac{\sigma_{\mathrm{int}}^{\mathrm{(N)LO}}}{\sigma_{\mathrm{SM}}^{\mathrm{(N)LO}}} + \frac{\sigma_{\mathrm{BSM}}^{\mathrm{(N)LO}}}{\sigma_{\mathrm{SM}}^{\mathrm{(N)LO}}}\right)$$

$$(\sigma \times B)^{i,H\to X} = \sigma^i \times B^{H\to X} = \left(\sigma_{\mathrm{SM}}^i + \sigma_{\mathrm{int}}^i + \sigma_{\mathrm{BSM}}^i\right) \times \left(\frac{\Gamma_{\mathrm{SM}}^{H\to X} + \Gamma_{\mathrm{int}}^{H\to X} + \Gamma_{\mathrm{BSM}}^{H\to X}}{\Gamma_{\mathrm{SM}}^{H} + \Gamma_{\mathrm{int}}^{H} + \Gamma_{\mathrm{BSM}}^{H}}\right)$$

$$\frac{\sigma_{\mathrm{int}}^i}{\sigma_{\mathrm{SM}}^i} = \sum_j A_j^{\sigma_i} c_j \qquad \frac{\sigma_{\mathrm{BSM}}^i}{\sigma_{\mathrm{SM}}^i} = \sum_{jk} B_{jk}^{\sigma_i} c_j c_k$$

$$\frac{\Gamma_{\mathrm{int}}^{H\to X}}{\Gamma_{\mathrm{SM}}^{H\to X}} = \sum_j A_j^{\Gamma^{H\to X}} c_j \qquad \frac{\Gamma_{\mathrm{BSM}}^{H\to X}}{\Gamma_{\mathrm{SM}}^{H\to X}} = \sum_{jk} B_{jk}^{\Gamma^{H\to X}} c_j c_k$$

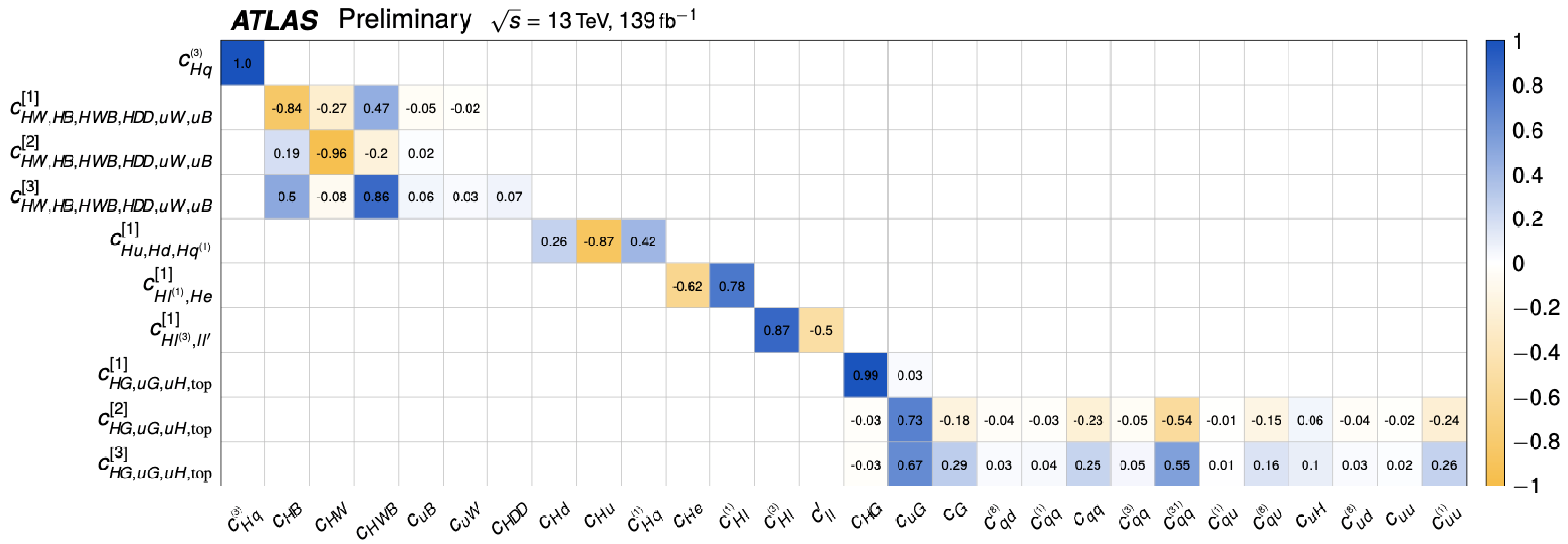
$$\frac{\Gamma_{\mathrm{int}}^{H}}{\Gamma_{\mathrm{SM}}^{H}} = \sum_j A_j^{\Gamma^H} c_j \qquad \frac{\Gamma_{\mathrm{BSM}}^{H}}{\Gamma_{\mathrm{SM}}^{H}} = \sum_{jk} B_{jk}^{\Gamma^H} c_j c_k,$$

Fit with and without quadratic terms

Fit parameters

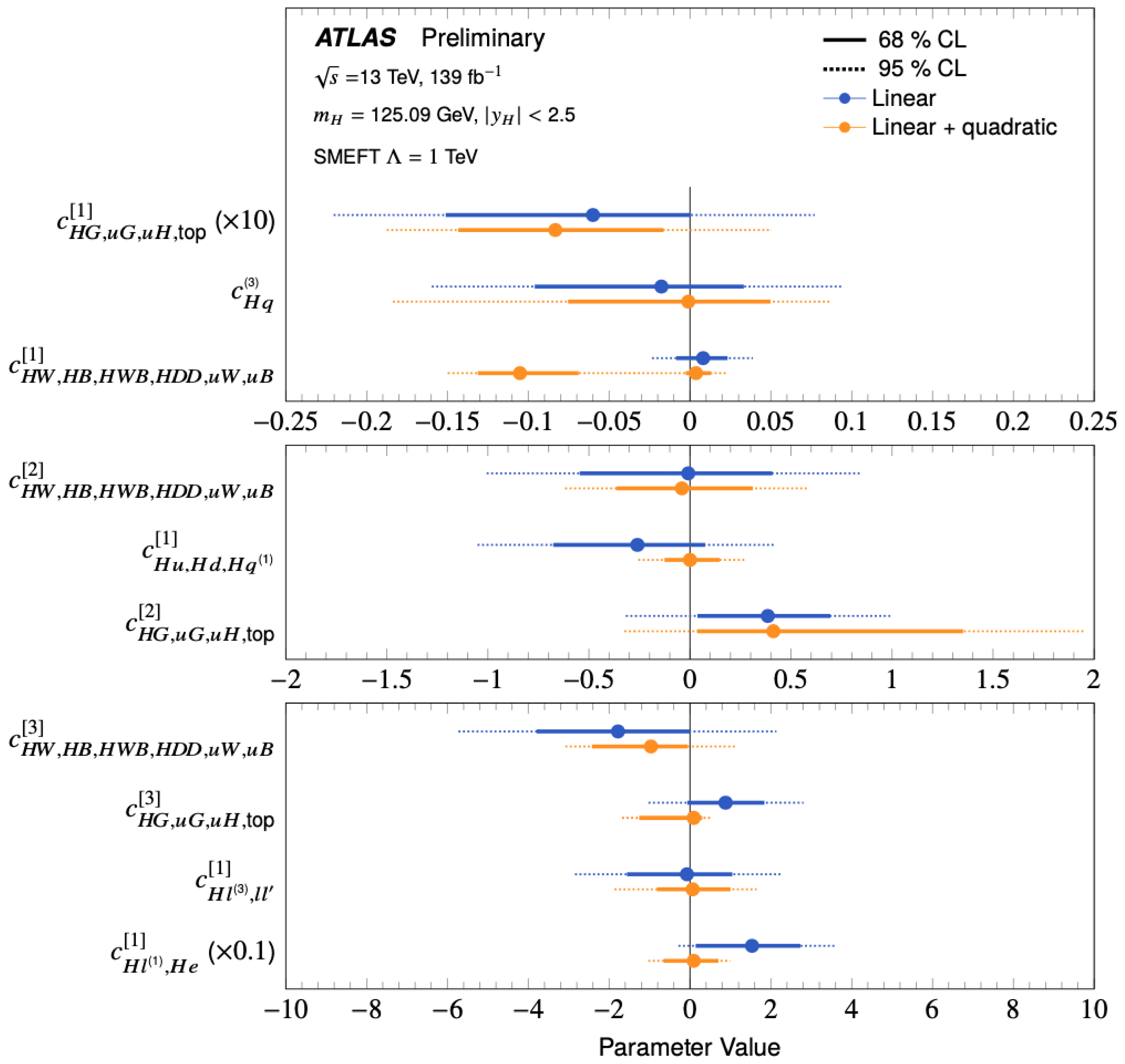
Rotation matrix Warsaw basis —> fit basis
Obtained by block diagonalizing expected Covariance matrix

$$\begin{aligned}\{c_i\} \;=\; &\{c_{Hq}^{(3)}\} \times \\ &\{c_{HG}, c_{uG}, c_{uH}, c_{qq}^{(1)}, c_{qq}, c_{qq}^{(3)}, c_{qq}^{(31)}, c_{uu}, c_{uu}^{(1)}, c_{ud}^{(8)}, c_{qu}^{(1)}, c_{qu}^{(8)}, c_{qd}^{(8)}, c_G\} \times \\ &\{c_{HW}, c_{HB}, c_{HWB}, c_{HDD}, c_{uW}, c_{uB},\} \times \\ &\{c_{Hl}^{(1)}, c_{He}\} \times \\ &\{c_{Hl}^{(3)}, c_{ll}'\} \times \\ &\{c_{Hu}, c_{Hd}, c_{Hq}^{(1)}\}.\end{aligned}$$

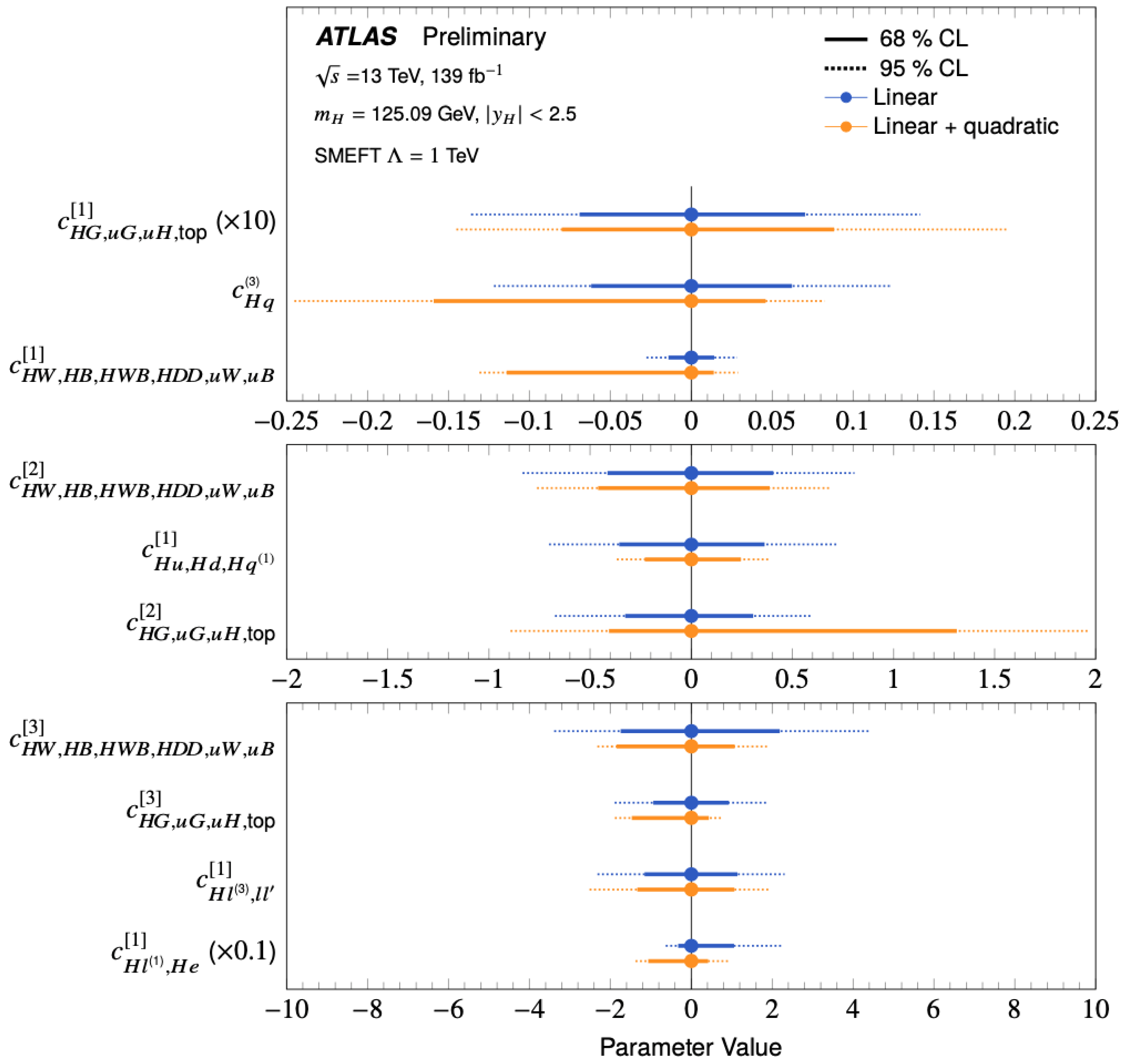


Fit results

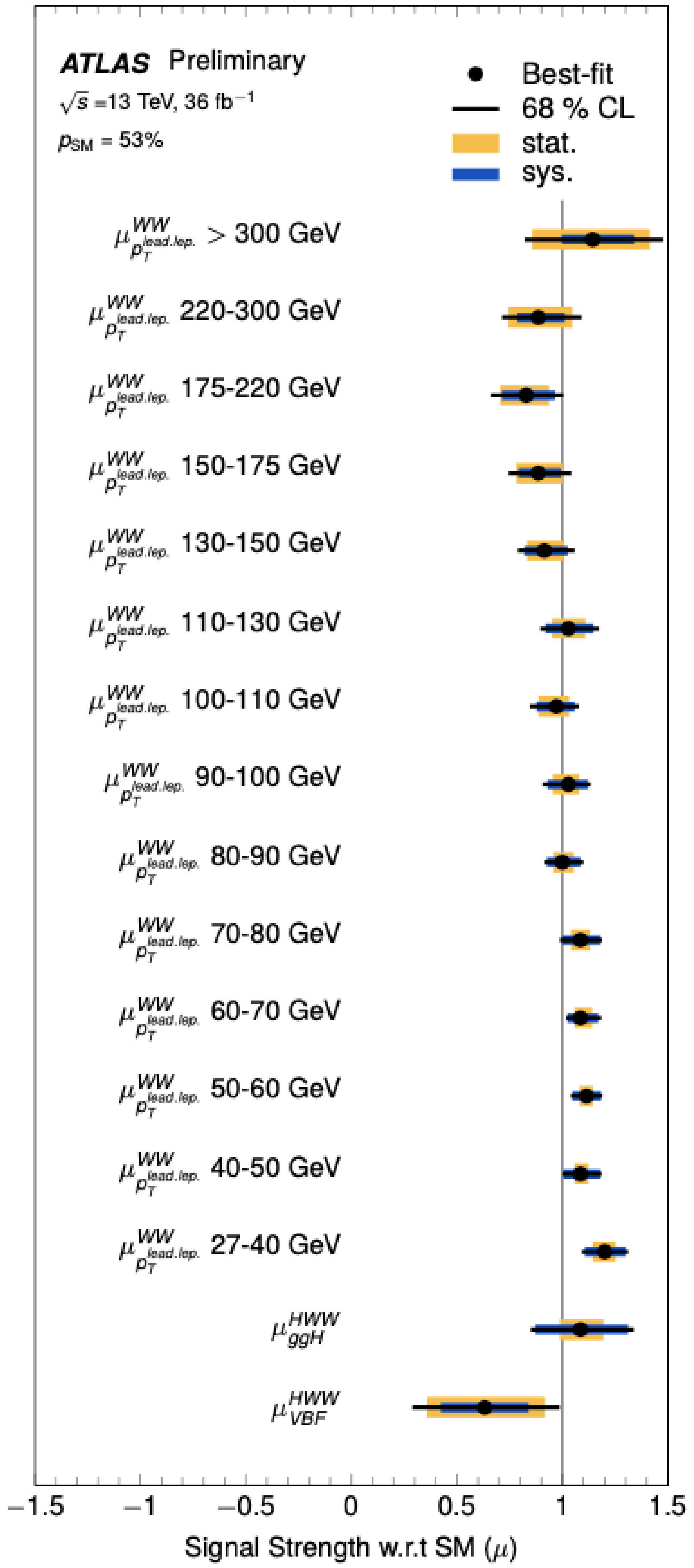
Observed



Expected



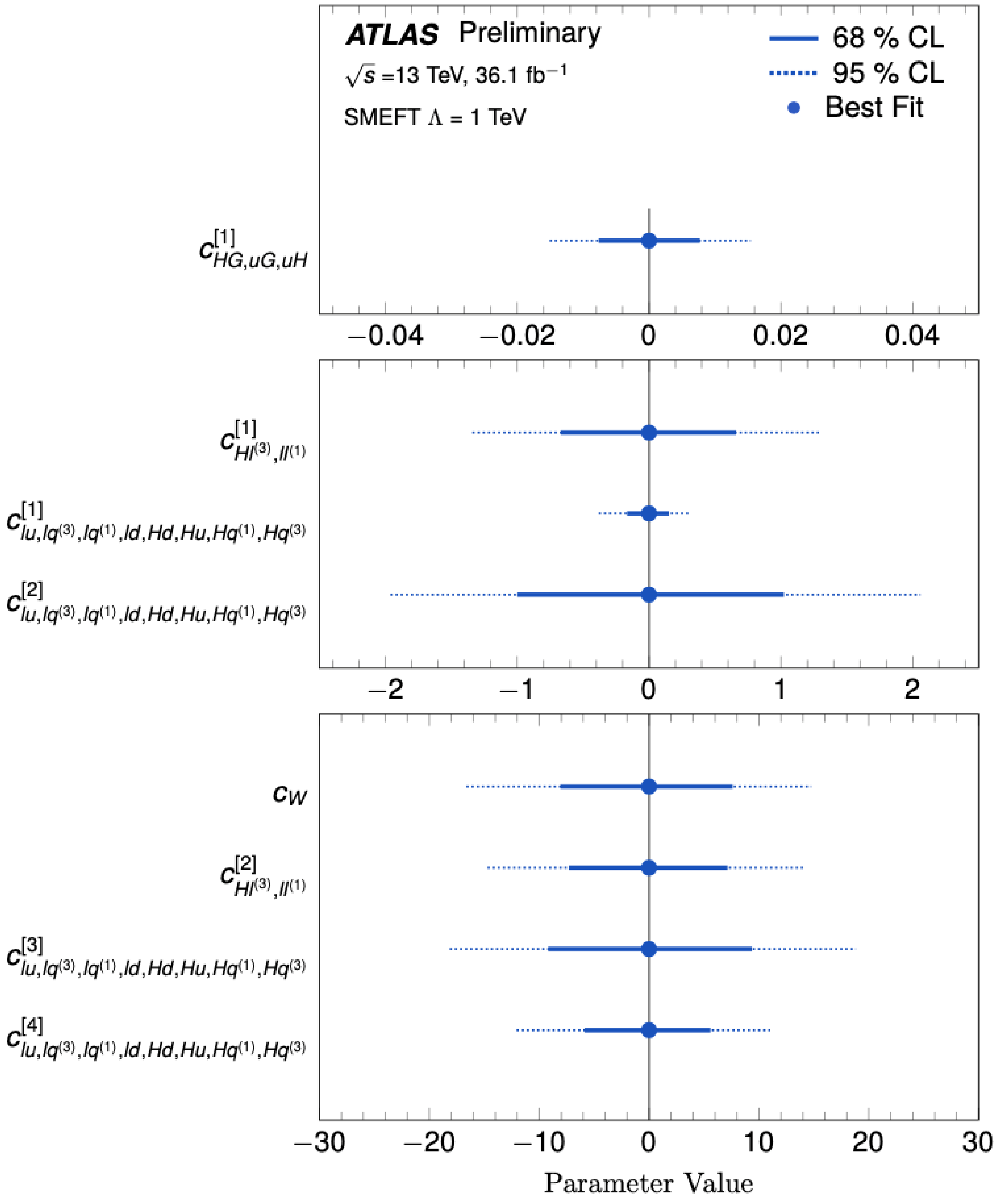
SM WW and HWW combination (ATLAS)



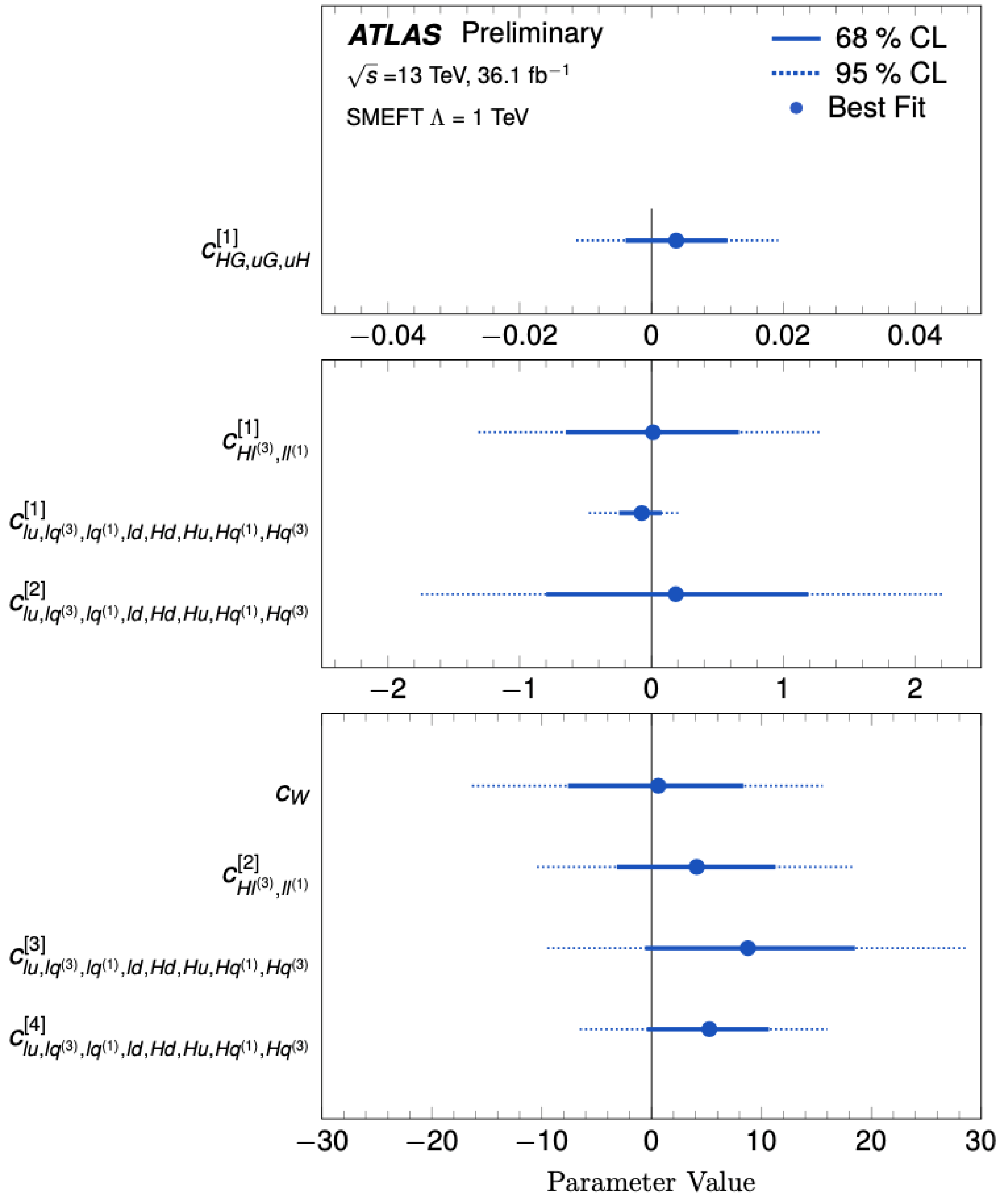
Input: unfolded leading lepton p_T distribution (14 bins)

SM WW ($M_{e\mu}$ > 55 GeV) and HWW ($M_{e\mu}$ < 55 GeV)

expected

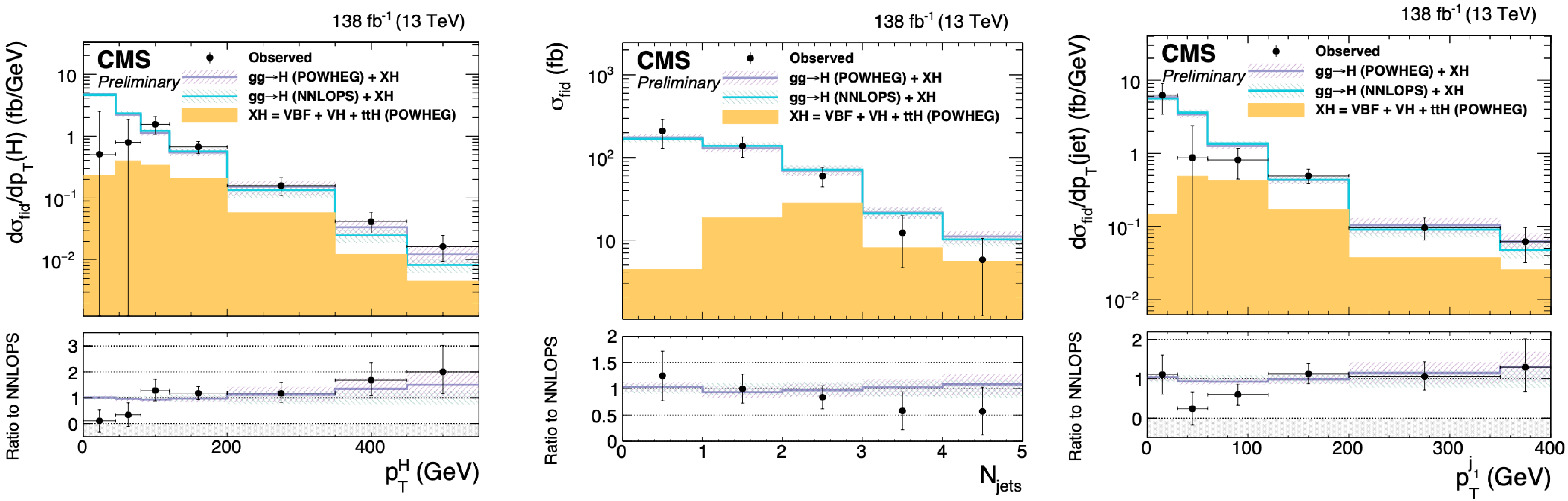


observed



H—>ττ (CMS)

Full Run 2



ormalization and shapes consistent with expectation

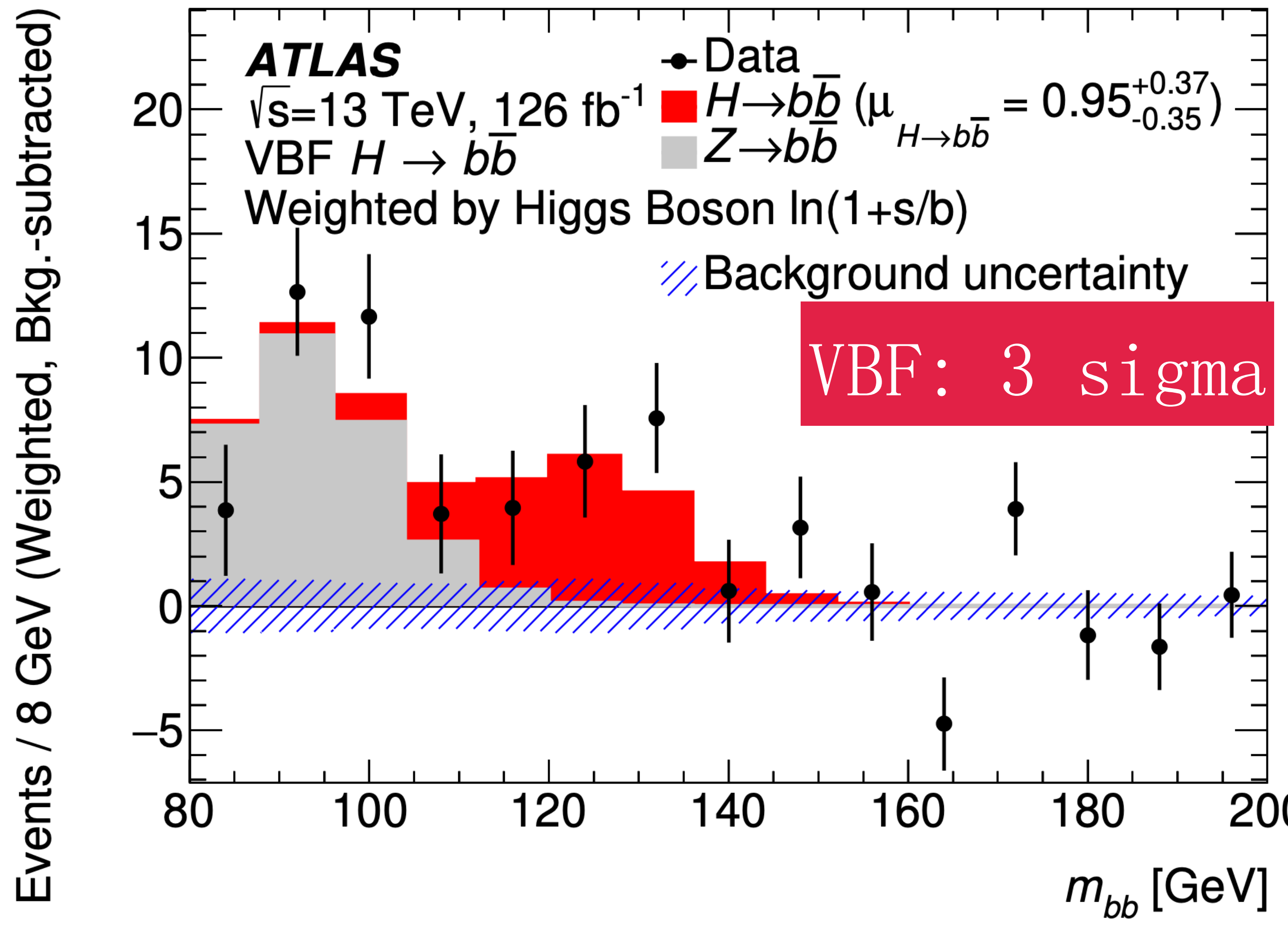
[VBF Measurement (3-sigma), accepted by EPJC]

[VH, boosted (2.1 sigma) PLB 816(2021)136204]

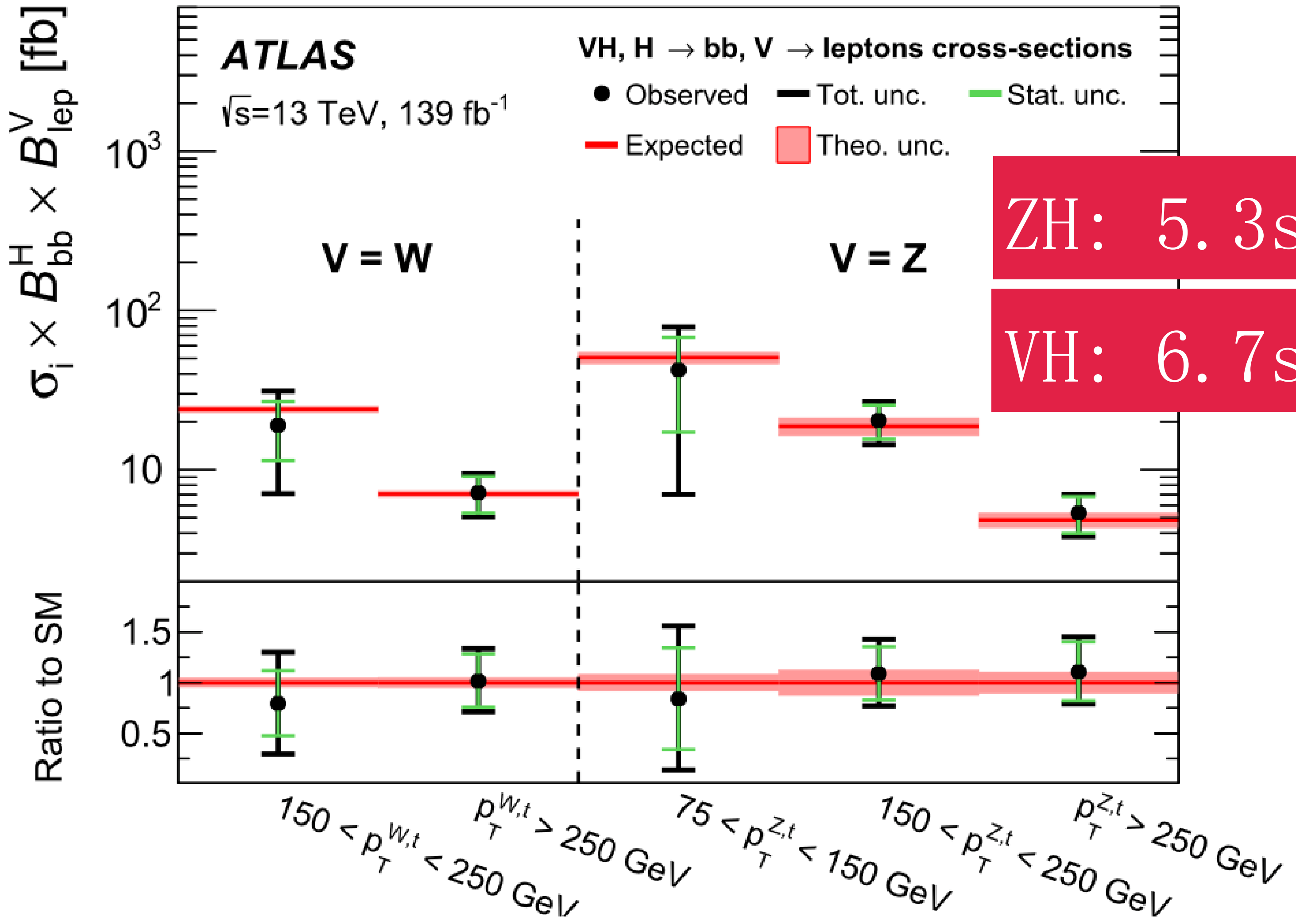
[VH measurement (6.7-sigma) EPJC 81(2021)178]

H —> bb (ATLAS)

Full Run 2

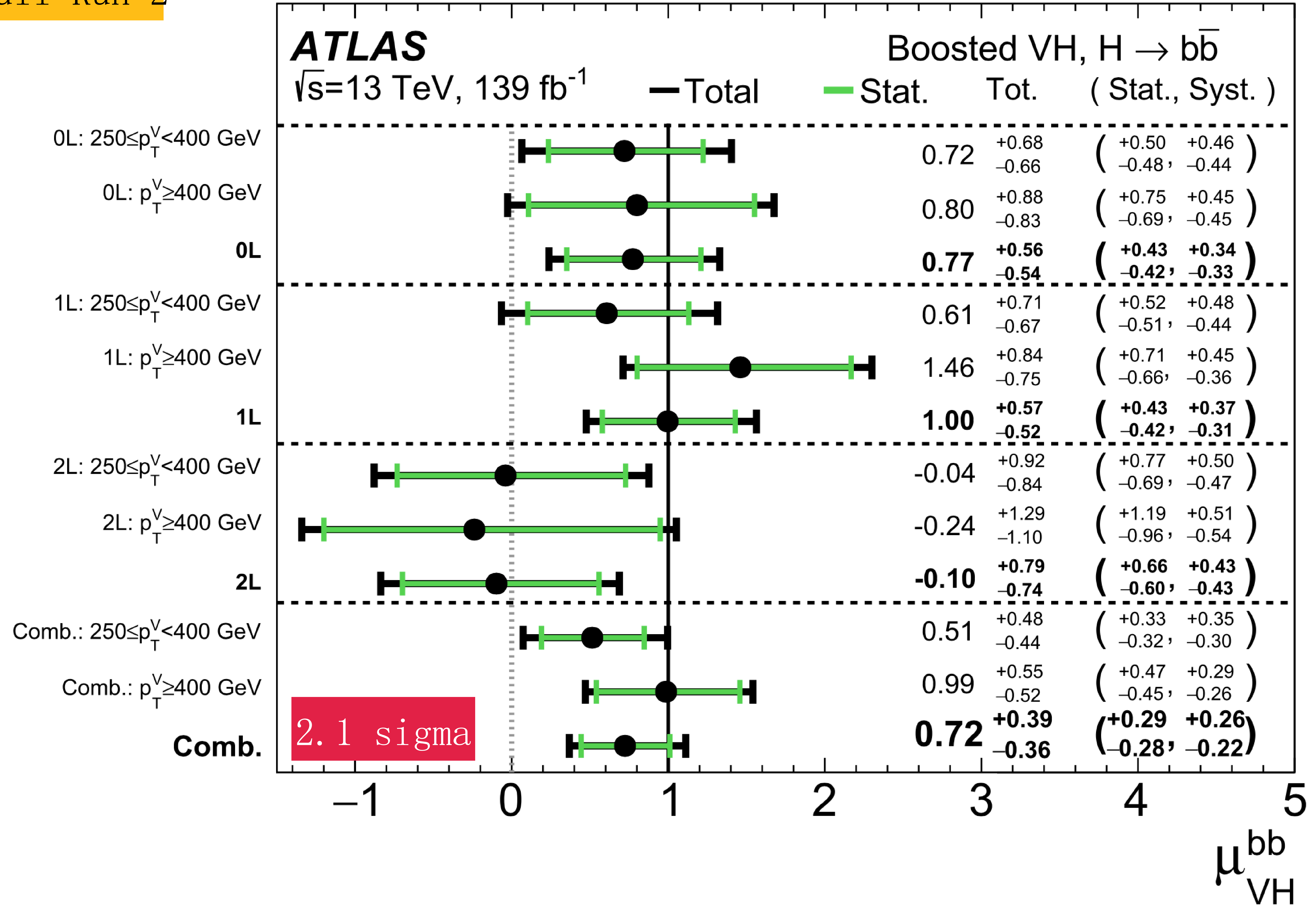


VBF: 3 sigma



ZH: 5.3sigma

VH: 6.7sigma



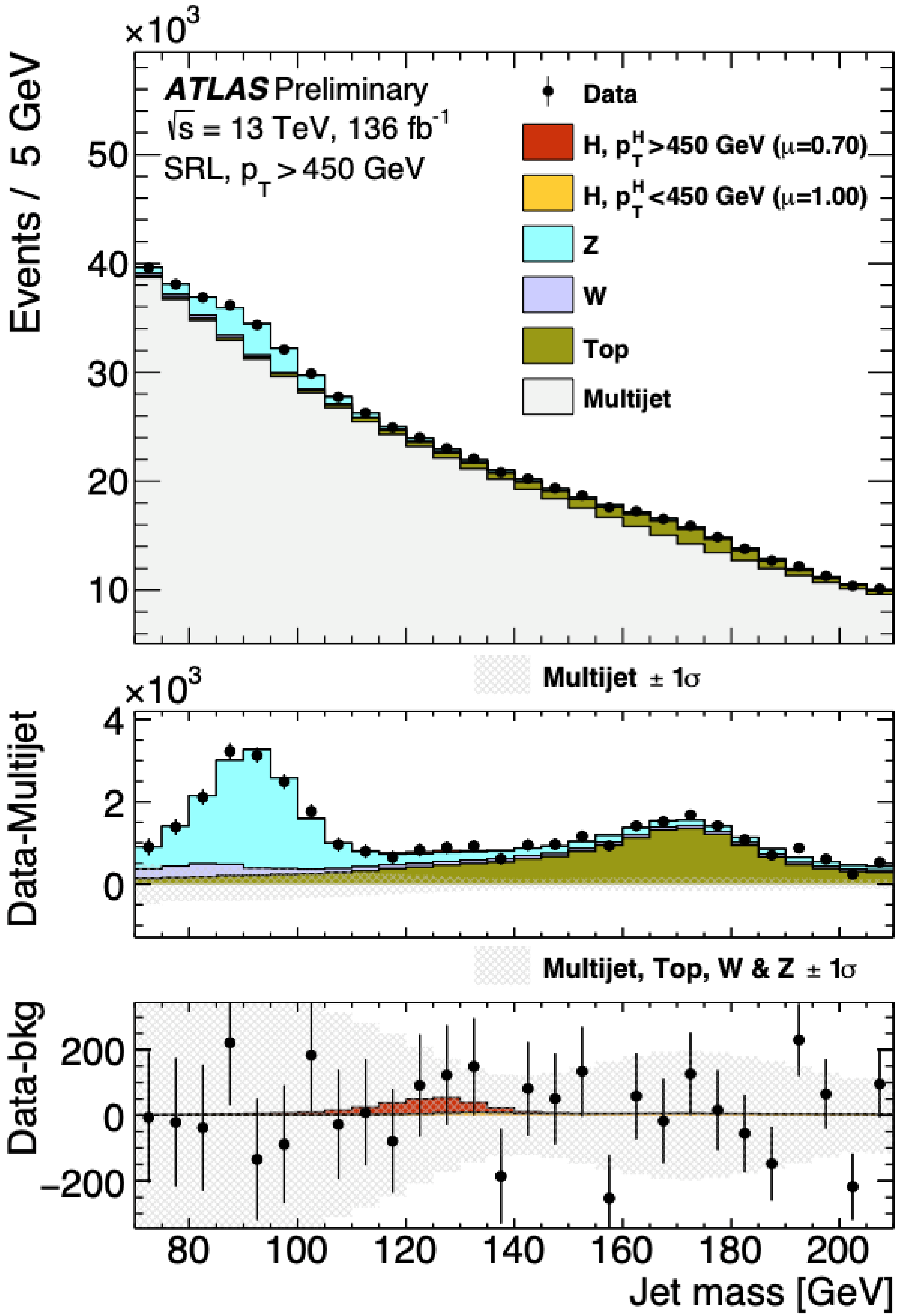
2.1 sigma

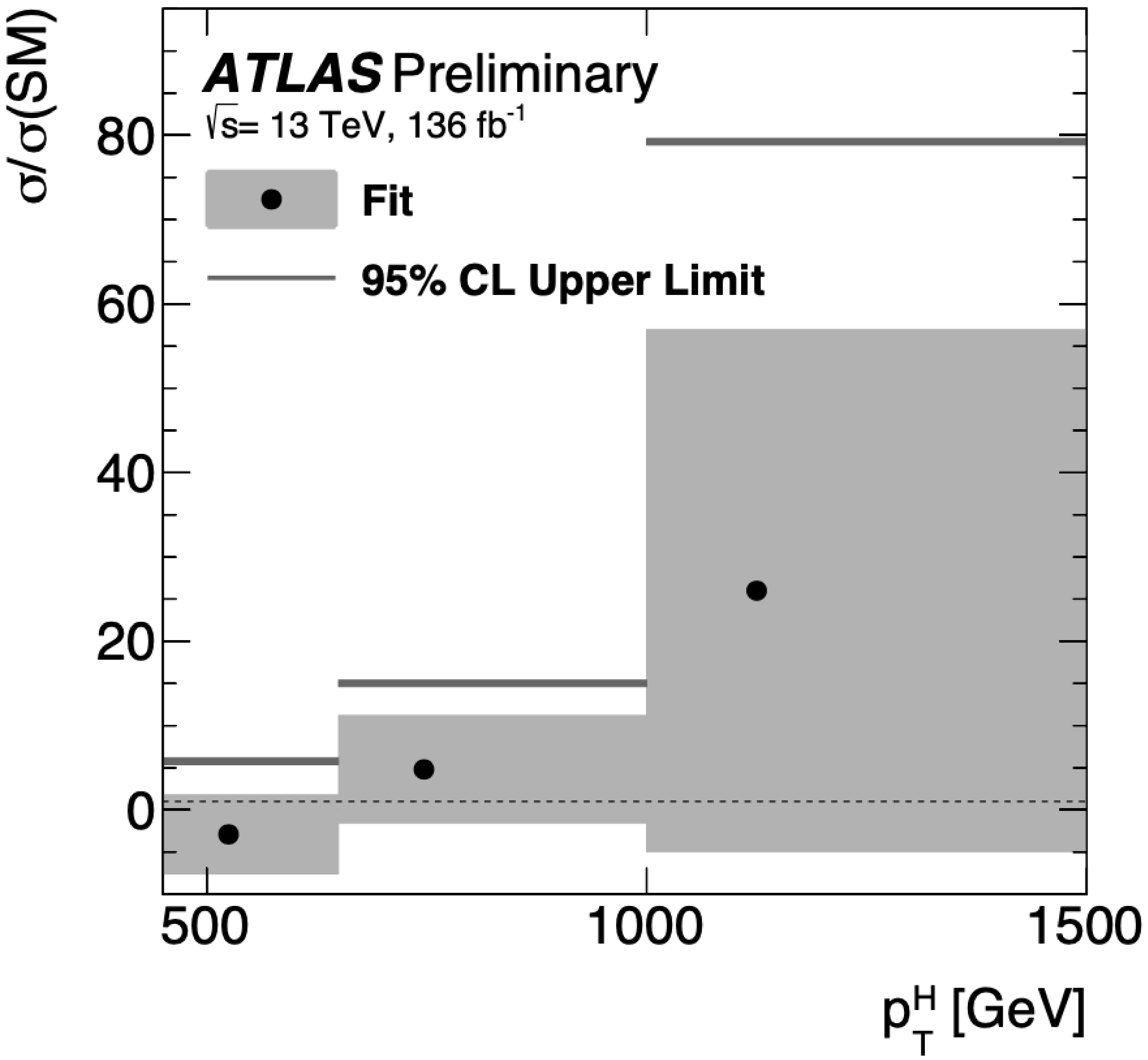
$$\mu_{VH}^{bb} = 1.02^{+0.18}_{-0.17} = 1.02^{+0.12}_{-0.11}(\text{stat.})^{+0.14}_{-0.13}(\text{syst.})$$

ATLAS-CONF-2021-010

Boosted H—>bb (inclusive)

Full Run 2



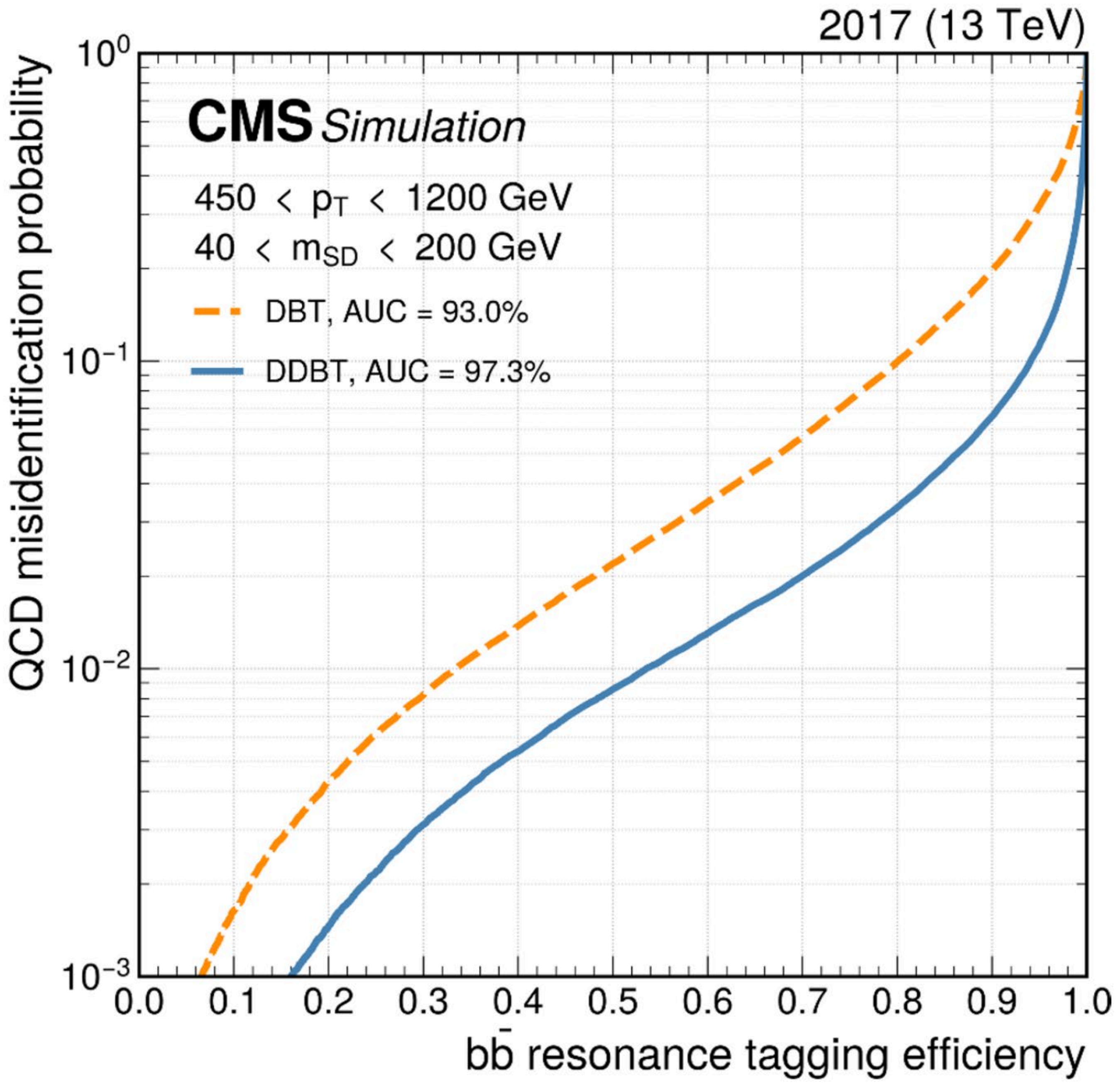


[Highly boosted: JHEP 12(2020)085](#)

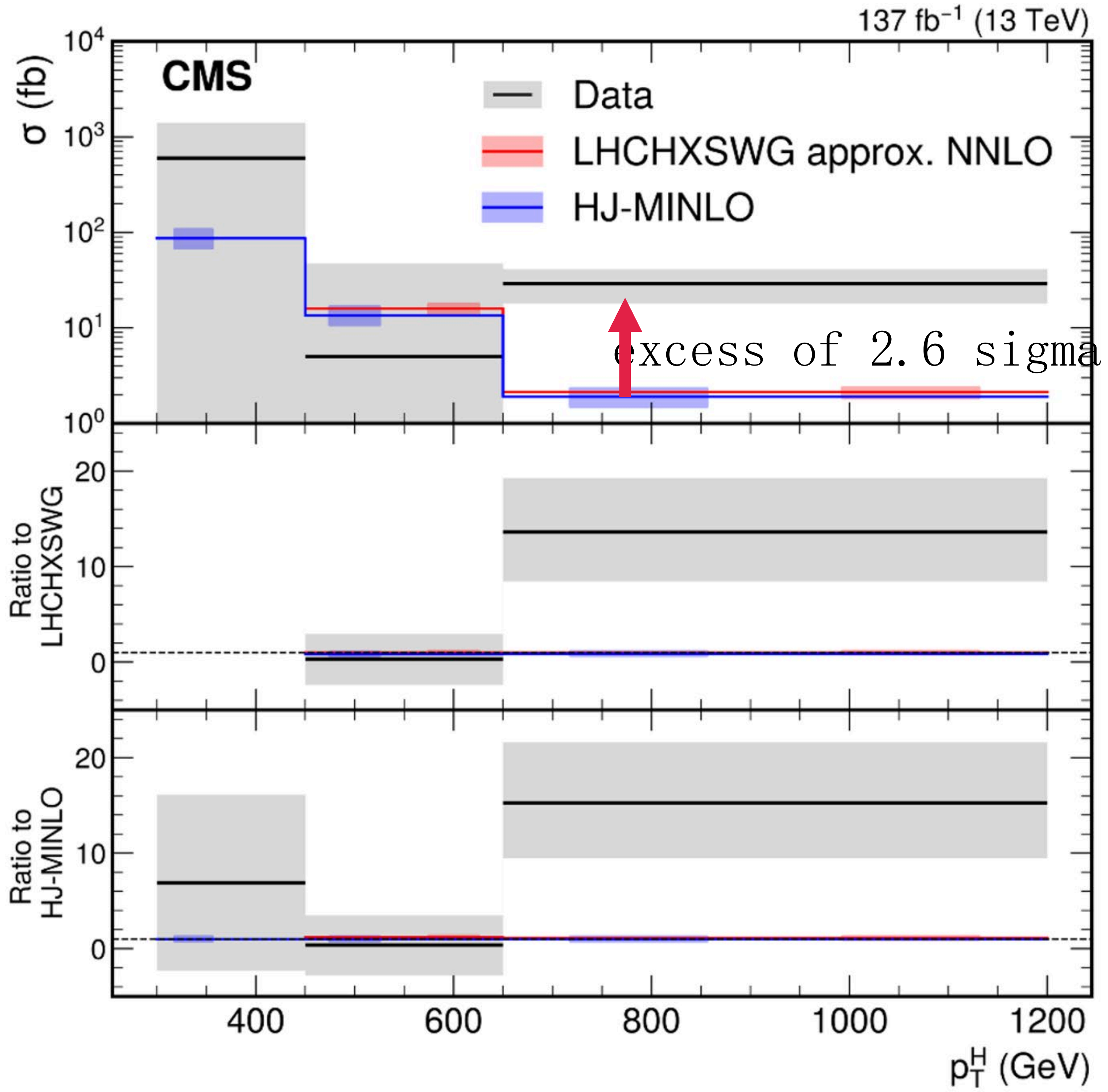
[H->bb observation PRL121(2018)121801](#)

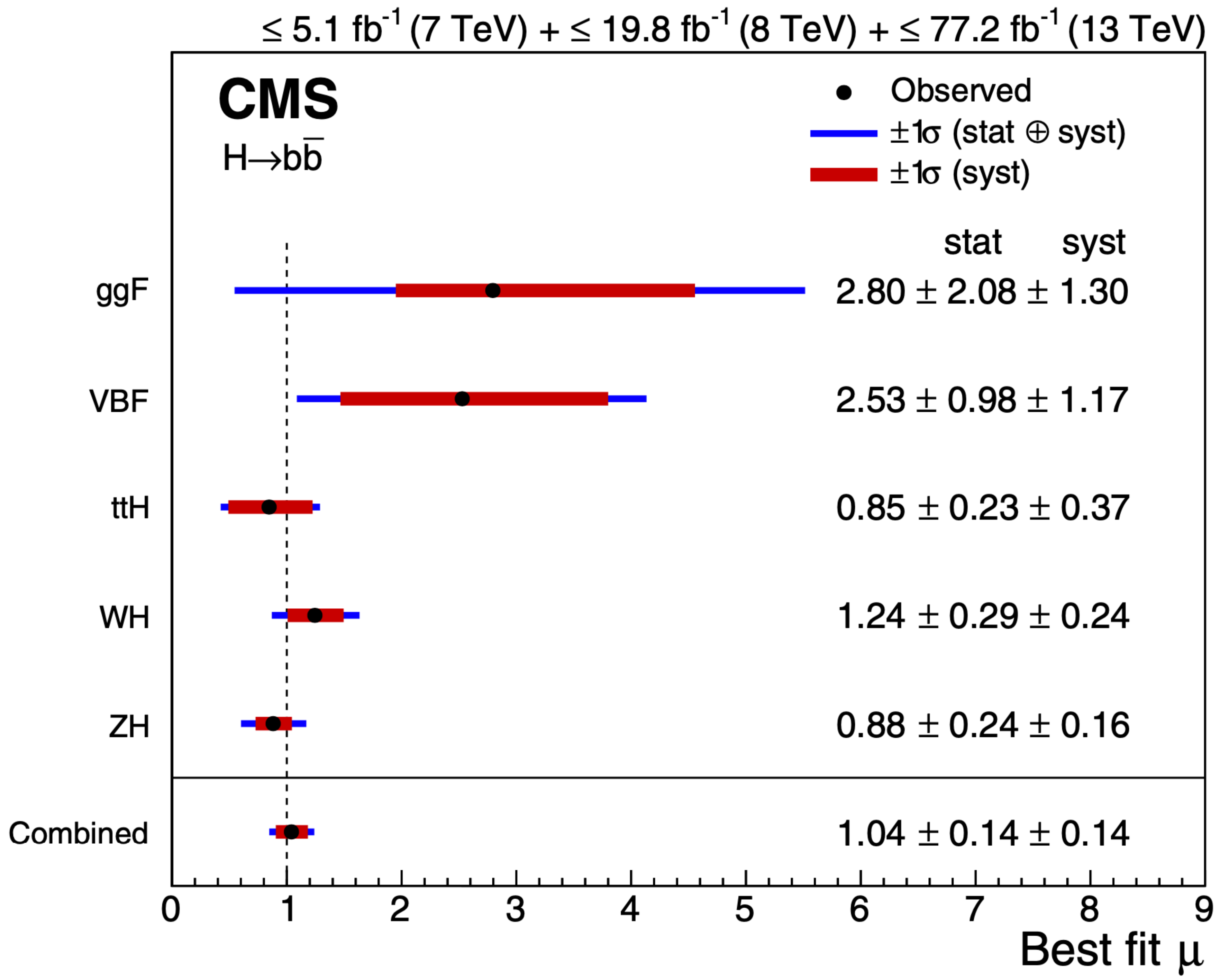
H—>bb (CMS)

Full Run 2



Deep Double B-Tag to suppress background





Combination: 5.6(6.5) sigma

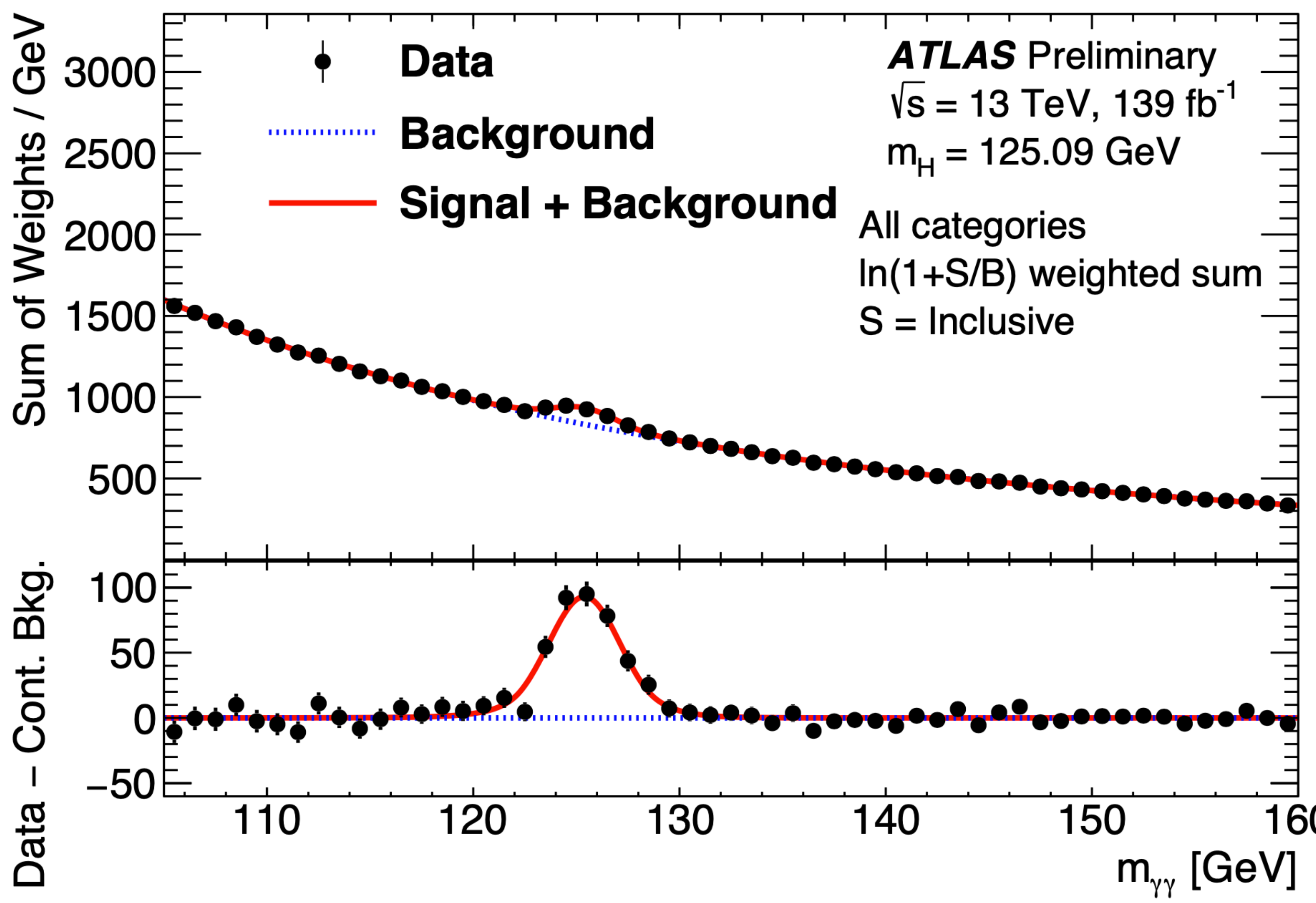
$$\mu_H = 3.7 \pm 1.2(\text{stat})^{+0.8}_{-0.7}(\text{syst})^{+0.8}_{-0.5}(\text{theo}) = 3.7^{+1.6}_{-1.5}$$

Background-only ruled out at 2.5 sigma
Excess w.r.t SM: 1.9 sigma

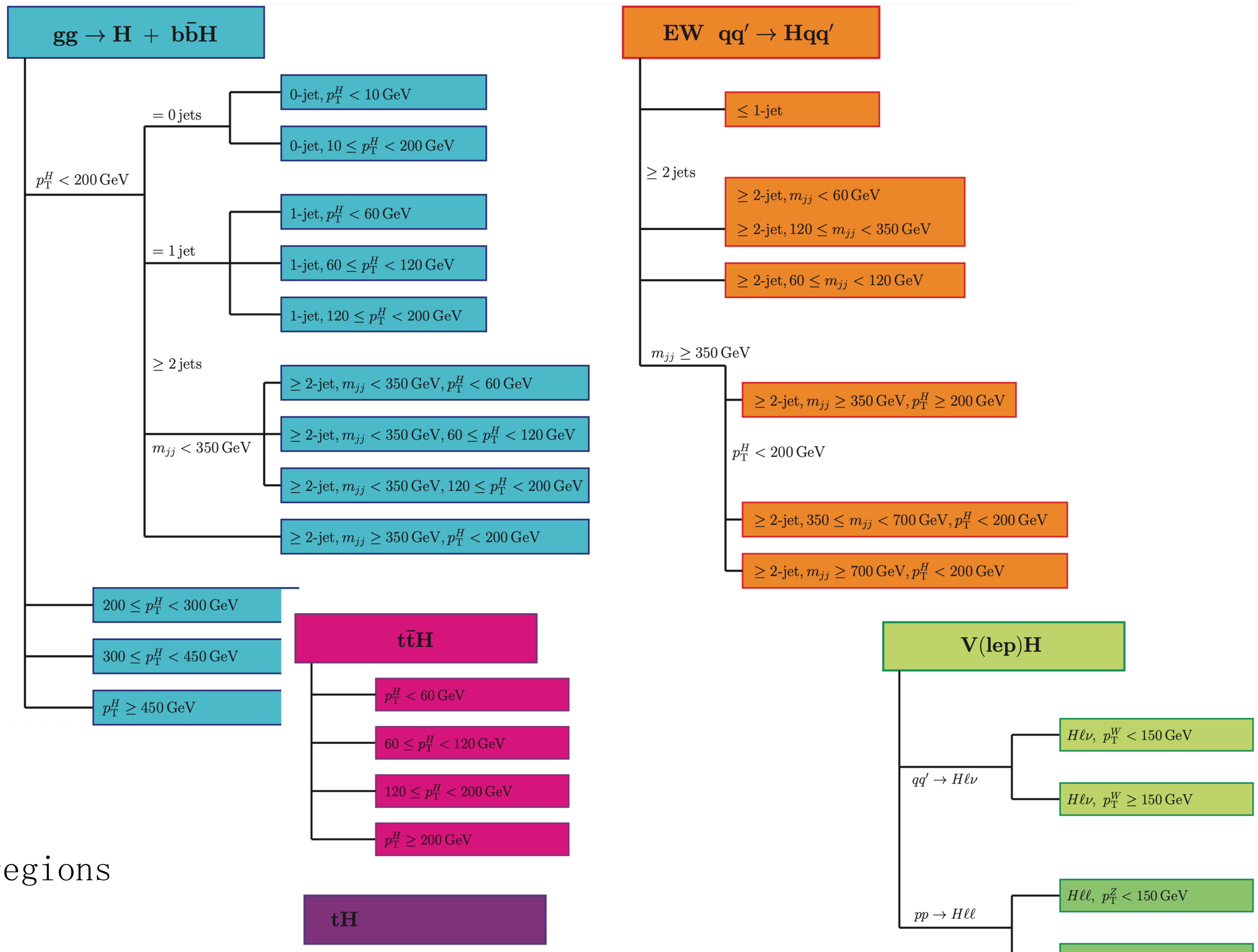
ATLAS-CONF-2020-026

H—>$\gamma\gamma$ STXS (ATLAS)

Full Run 2



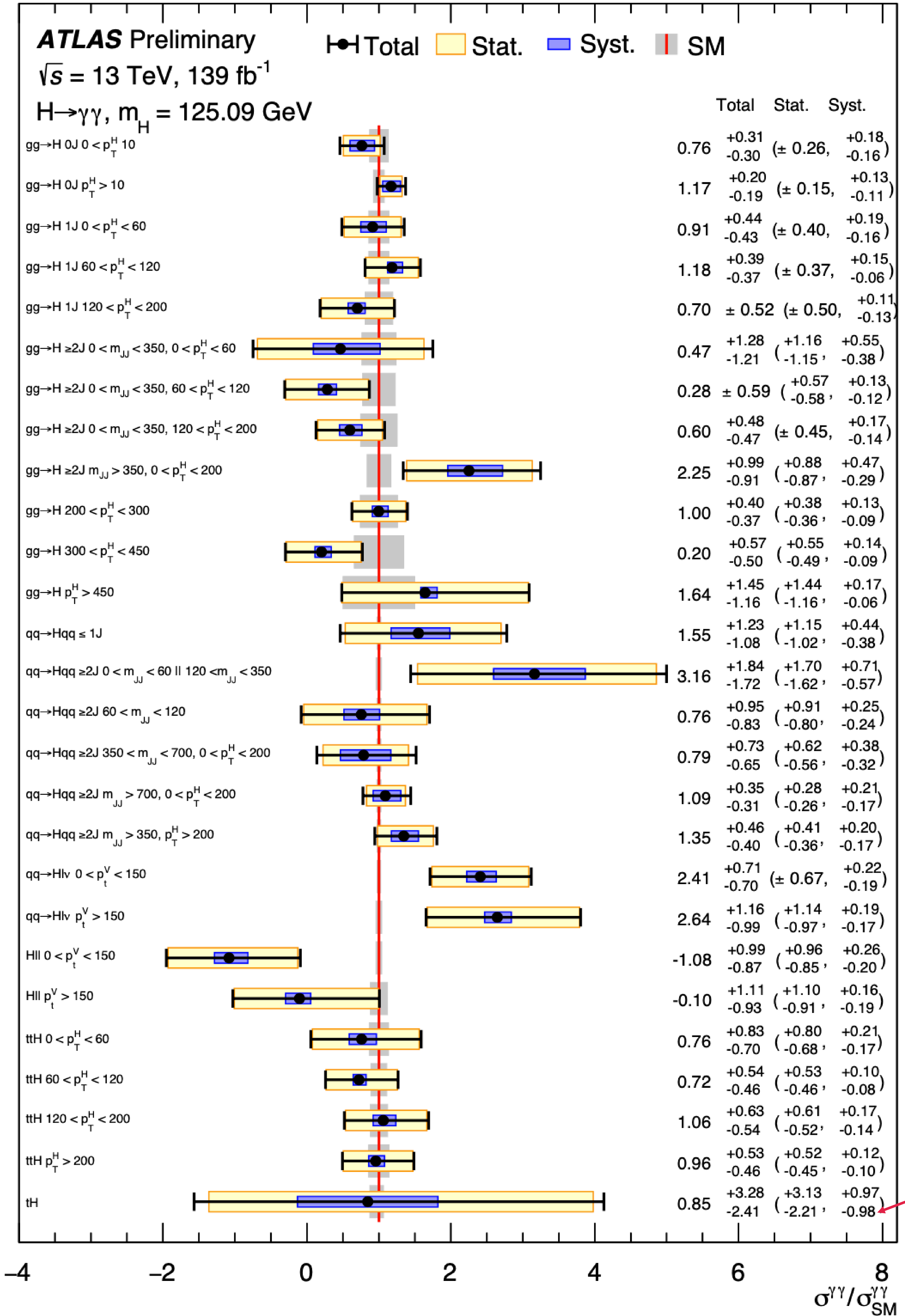
Events in each category weighted by ln(1+s/b), s/b = s/b ratio in the narrowest bin that contains 90% of the signal



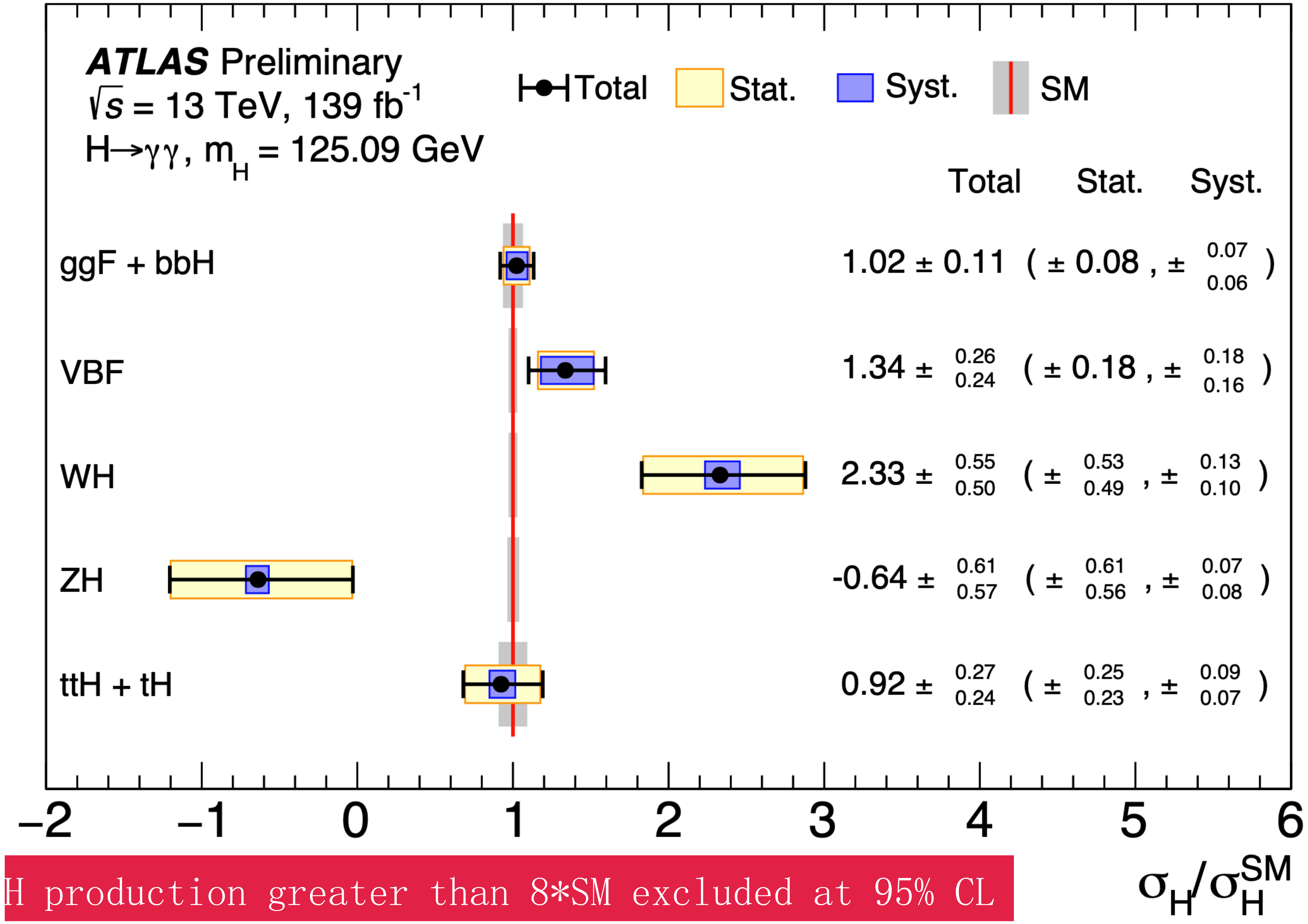
27 fiducial cross sections measured with 44 regions

Total cross section with $|y_H| < 2.5$: 127 ± 10fb
SM prediction:115 ± 5fb

Higgs—>γγ STXS results



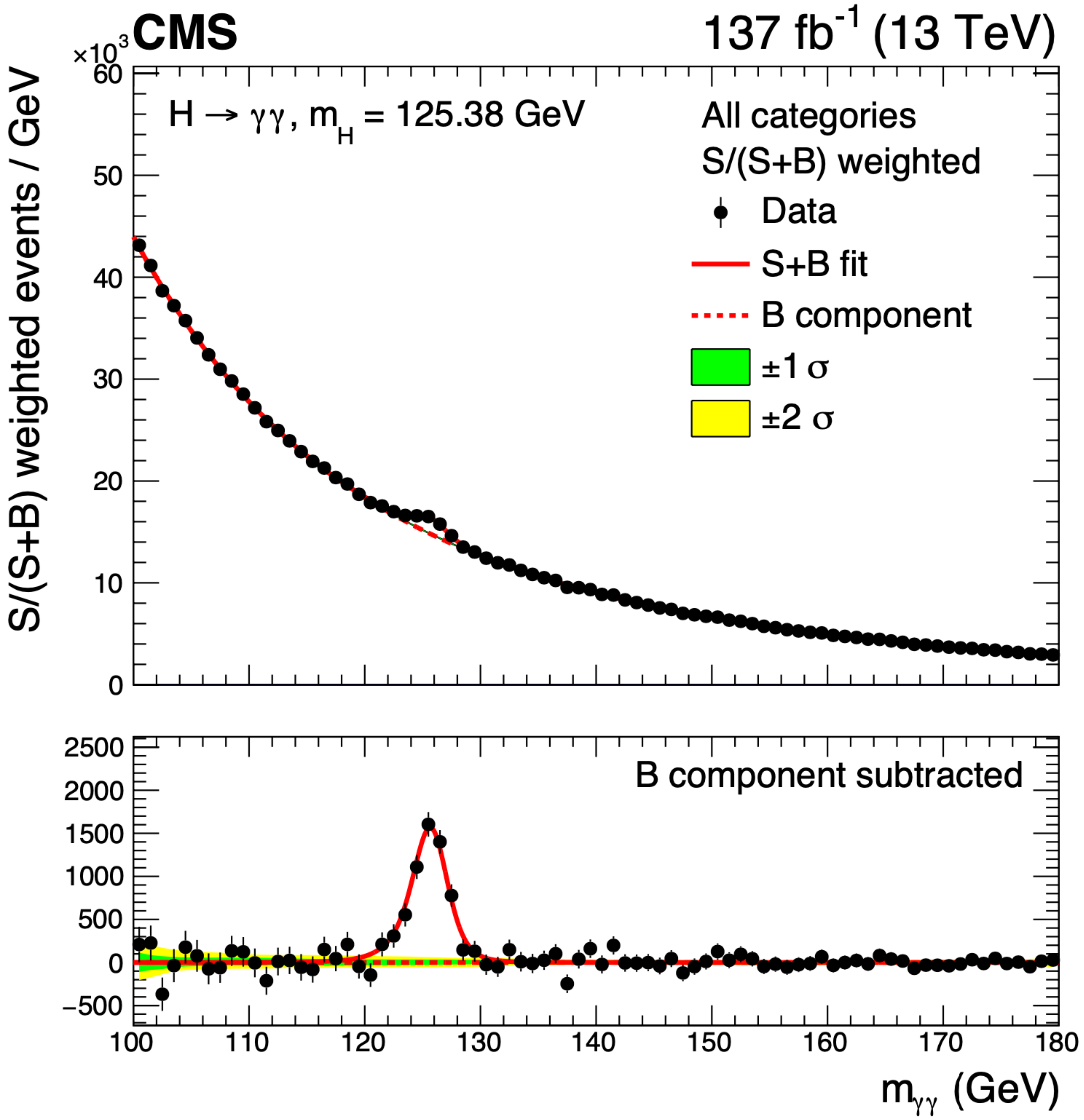
Full Run 2



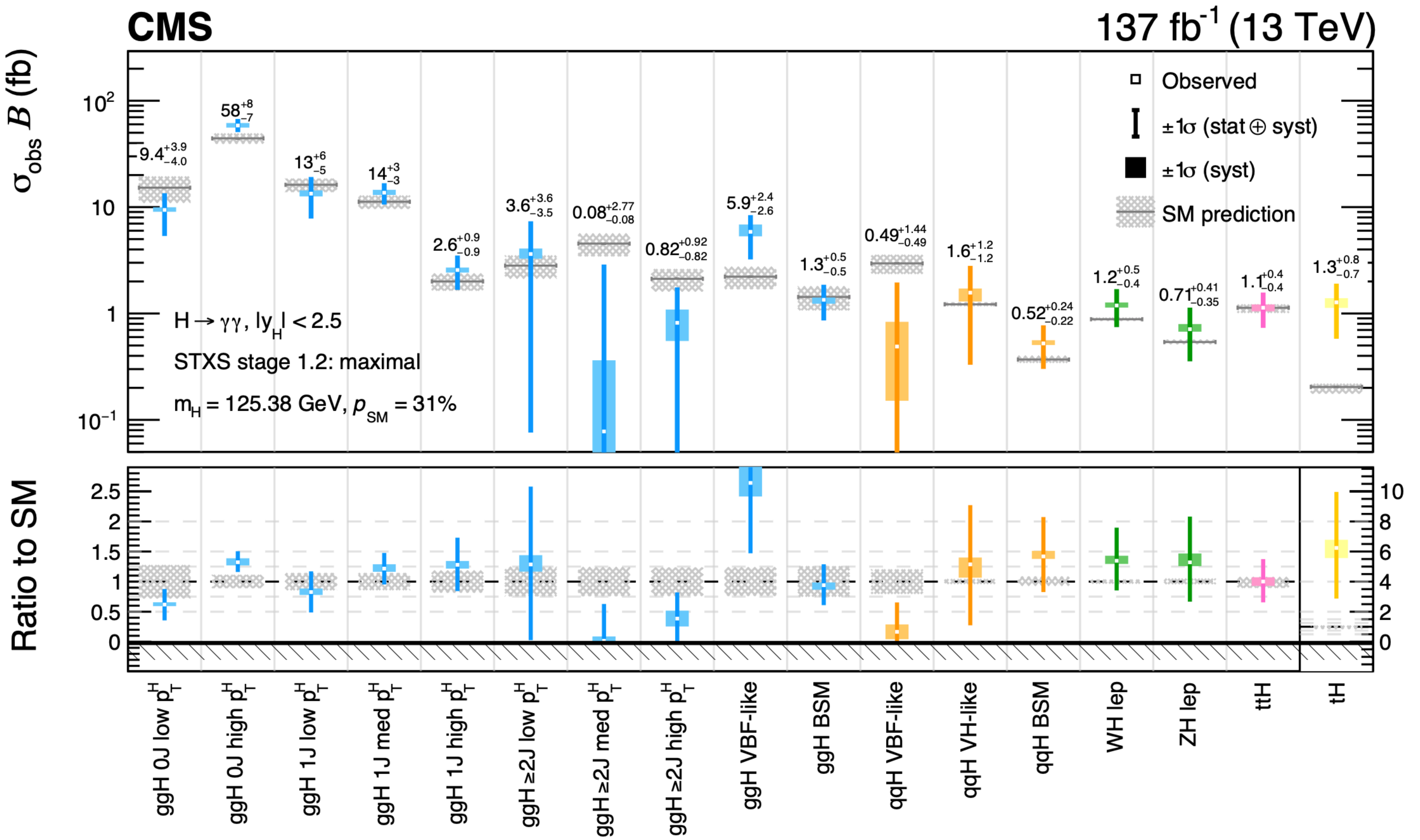
tH production greater than 8*SM excluded at 95% CL

arXiv:2103.06956
Accepted by JHEP

Higgs—>$\gamma\gamma$ STXS (CMS)



Full Run 2

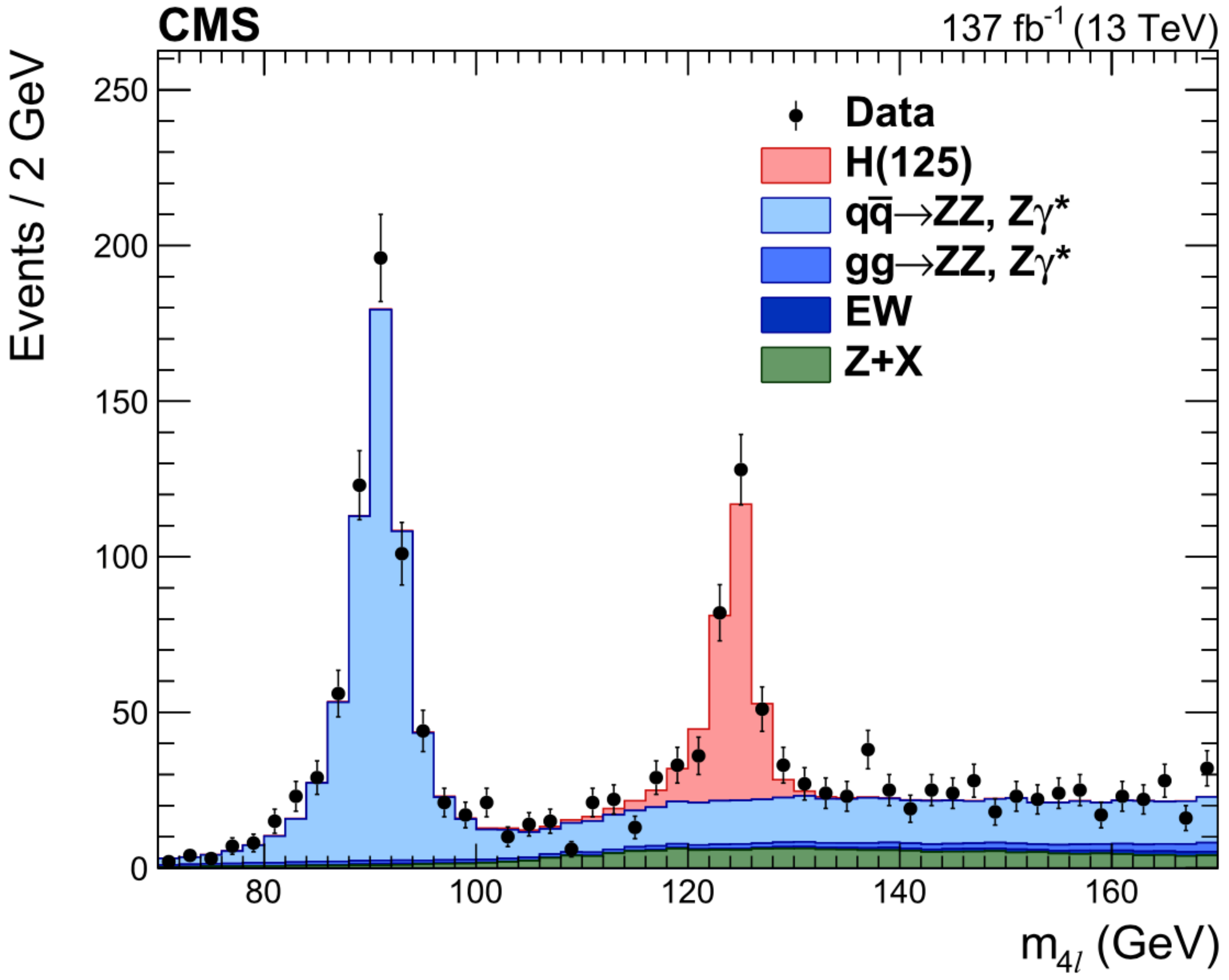


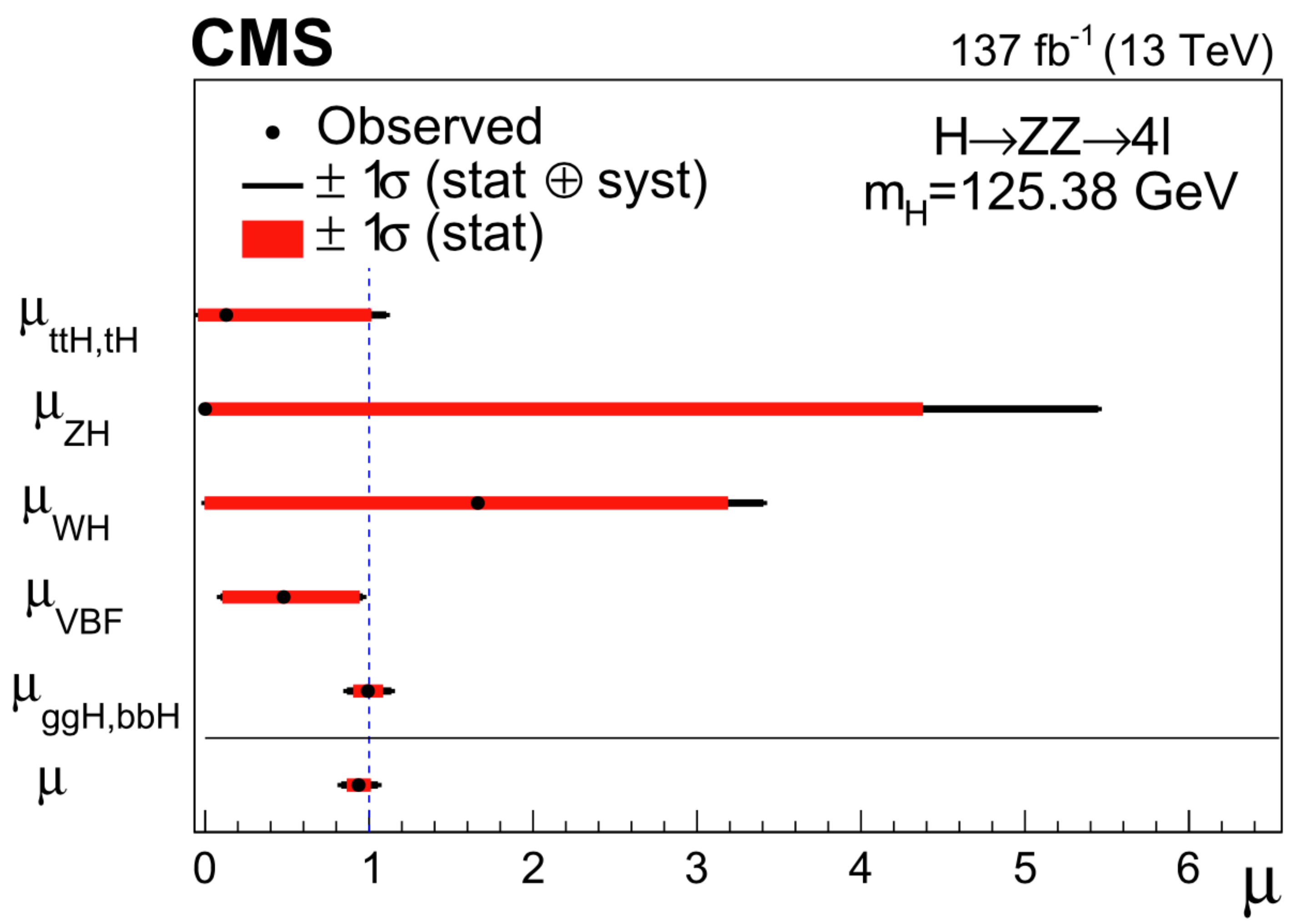
Results also presented as constraints on coupling modifiers

Events in each category weighted by S/(S+B)
S/B = expected signal/background in the bin of (m_H − sigma, m_H+sigma)

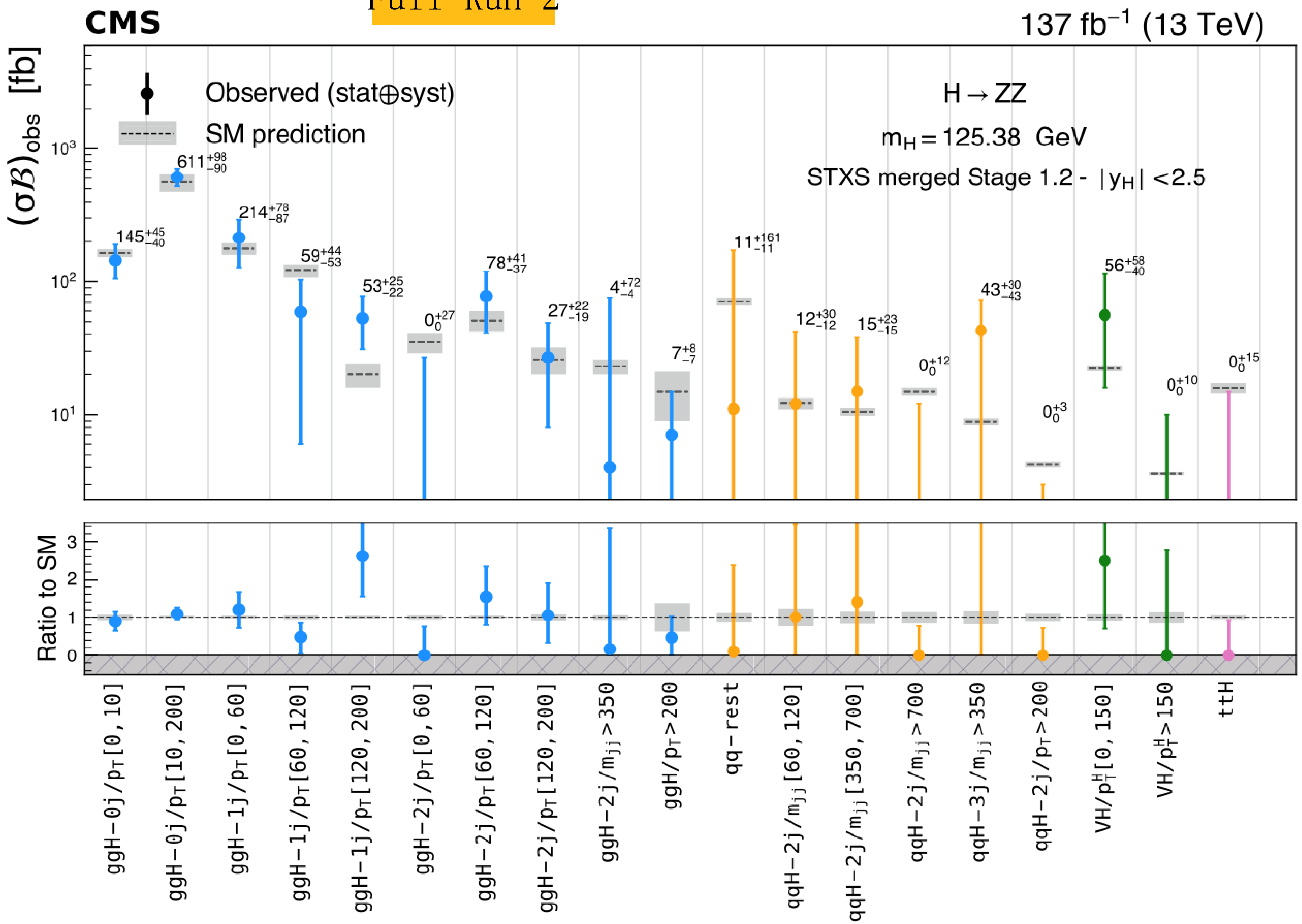
EPJC 81(2021)488

H—> 4 lepton cross section (CMS)





Full Run 2



Constraints from H—>4-lepton (CMS)

$$A(\mathrm{Hff}) = -\frac{m_\mathrm{f}}{v}\bar{\psi}_\mathrm{f}\left(\boxed{\kappa_\mathrm{f}} + \mathrm{i}\boxed{\tilde{\kappa}_\mathrm{f}}\gamma_5\right)\psi_\mathrm{f}$$

Matrix-element discriminator (or ML approximation) widely used

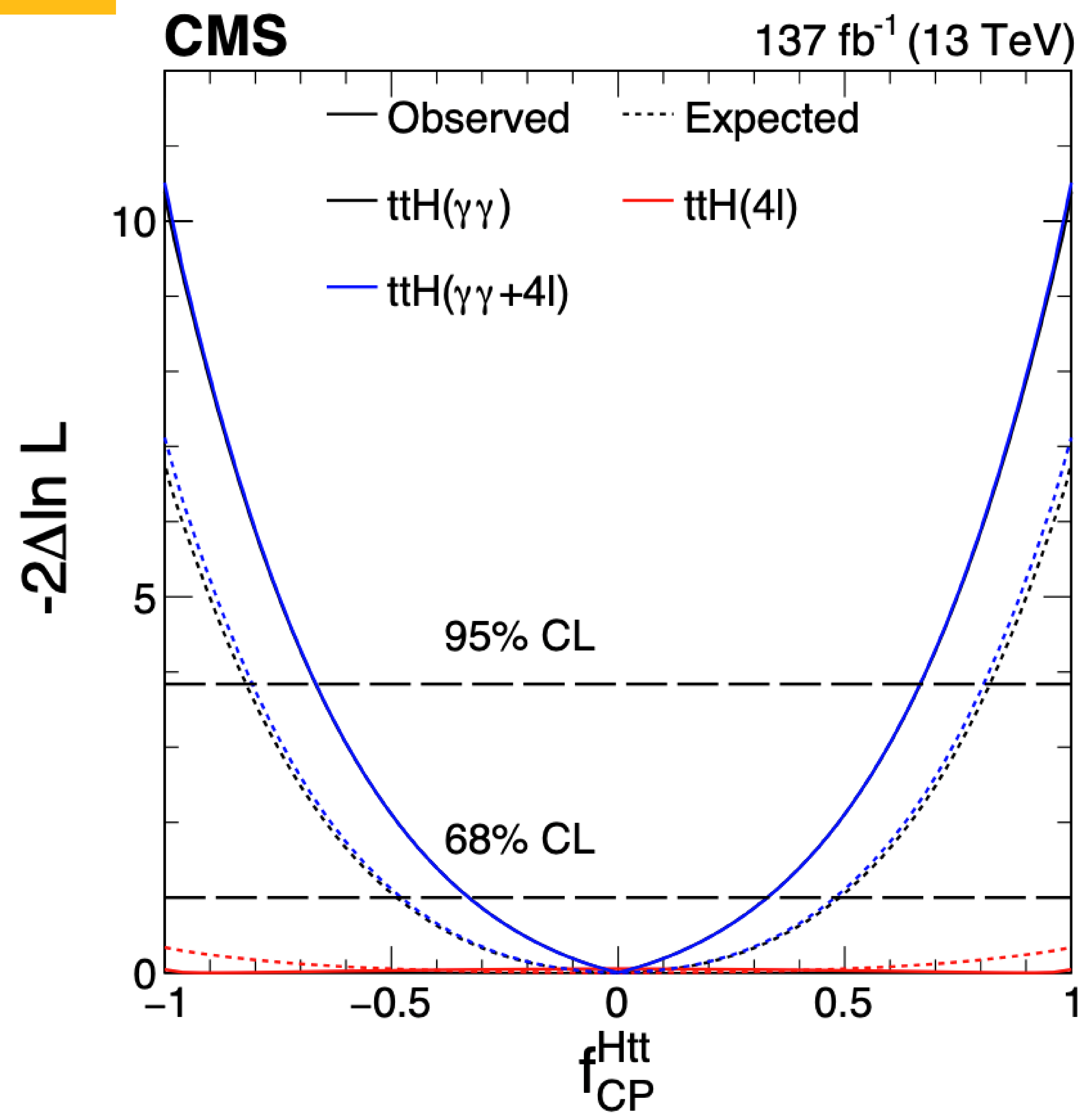
$$A(\mathrm{HV_1V_2}) = \frac{1}{v}\left[\boxed{a_1^{\mathrm{VV}}} + \frac{\boxed{\kappa_1^{\mathrm{VV}}} q_{\mathrm{V1}}^2 + \boxed{\kappa_2^{\mathrm{VV}}} q_{\mathrm{V2}}^2}{\left(\Lambda_1^{\mathrm{VV}}\right)^2} + \frac{\boxed{\kappa_3^{\mathrm{VV}}}(q_{\mathrm{V1}}+q_{\mathrm{V2}})^2}{\left(\Lambda_Q^{\mathrm{VV}}\right)^2}\right] m_{\mathrm{V1}}^2 \epsilon_{\mathrm{V1}}^* \epsilon_{\mathrm{V2}}^*$$
$$+\frac{1}{v}\boxed{a_2^{\mathrm{VV}}} f_{\mu\nu}^{*(1)} f^{*(2),\mu\nu} + \frac{1}{v}\boxed{a_3^{\mathrm{VV}}} f_{\mu\nu}^{*(1)} \tilde{f}^{*(2),\mu\nu},$$

From SU(2)xU(1) symmetry

$$a_1^{\mathrm{WW}} = a_1^{\mathrm{ZZ}} + \cancel{\frac{\Delta m_\mathrm{W}}{m_\mathrm{W}}},$$

vanishes when $\Delta m_W = 0$

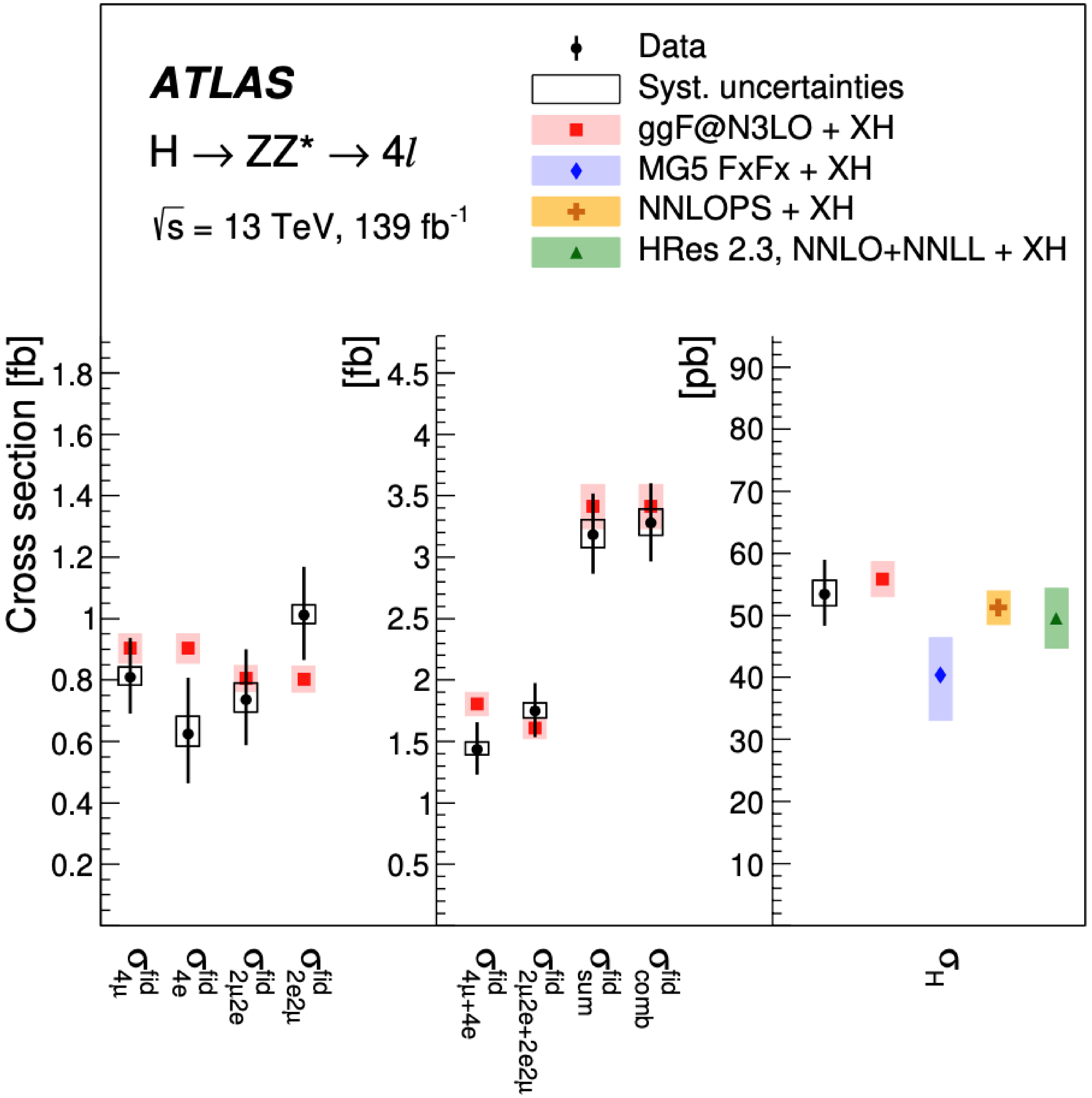
$$a_2^{\mathrm{WW}} = c_\mathrm{w}^2 a_2^{\mathrm{ZZ}} + s_\mathrm{w}^2 a_2^{\gamma\gamma} + 2 s_\mathrm{w} c_\mathrm{w} a_2^{\mathrm{Z}\gamma},$$
$$a_3^{\mathrm{WW}} = c_\mathrm{w}^2 a_3^{\mathrm{ZZ}} + s_\mathrm{w}^2 a_3^{\gamma\gamma} + 2 s_\mathrm{w} c_\mathrm{w} a_3^{\mathrm{Z}\gamma},$$
$$\frac{\kappa_1^{\mathrm{WW}}}{(\Lambda_1^{\mathrm{WW}})^2}(c_\mathrm{w}^2 - s_\mathrm{w}^2) = \frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + 2 s_\mathrm{w}^2 \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_\mathrm{Z}^2} + 2\frac{s_\mathrm{w}}{c_\mathrm{w}}(c_\mathrm{w}^2 - s_\mathrm{w}^2)\frac{a_2^{\mathrm{Z}\gamma}}{m_\mathrm{Z}^2},$$
$$\frac{\kappa_2^{\mathrm{Z}\gamma}}{(\Lambda_1^{\mathrm{Z}\gamma})^2}(c_\mathrm{w}^2 - s_\mathrm{w}^2) = 2 s_\mathrm{w} c_\mathrm{w}\left(\frac{\kappa_1^{\mathrm{ZZ}}}{(\Lambda_1^{\mathrm{ZZ}})^2} + \frac{a_2^{\gamma\gamma} - a_2^{\mathrm{ZZ}}}{m_\mathrm{Z}^2}\right) + 2(c_\mathrm{w}^2 - s_\mathrm{w}^2)\frac{a_2^{\mathrm{Z}\gamma}}{m_\mathrm{Z}^2}$$

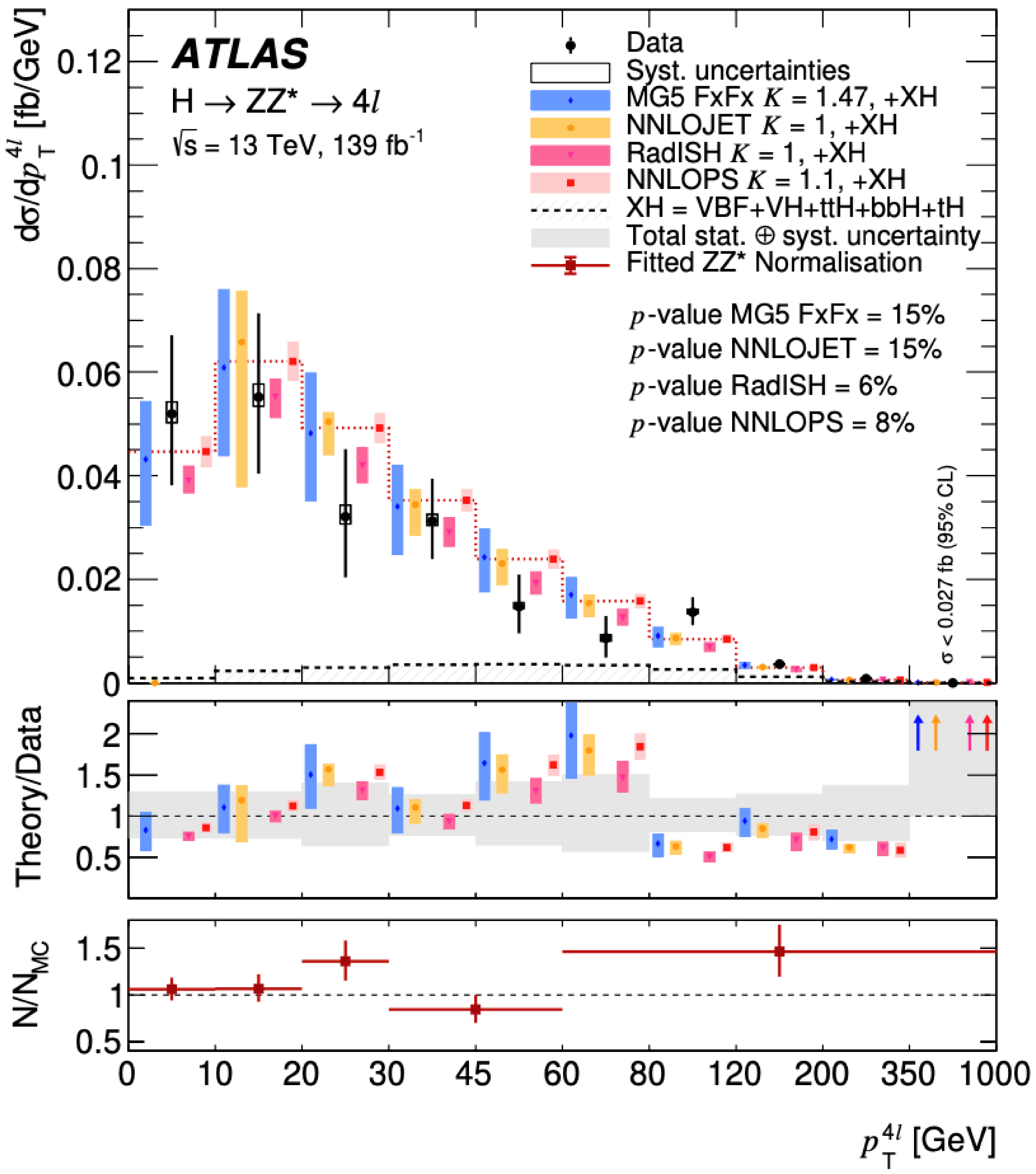


Cross section fraction $f_{\mathrm{CP}}^{\mathrm{Hff}} = \frac{|\tilde{\kappa}_\mathrm{f}|^2}{|\kappa_\mathrm{f}|^2 + |\tilde{\kappa}_\mathrm{f}|^2}\,\mathrm{sign}\left(\frac{\tilde{\kappa}_\mathrm{f}}{\kappa_\mathrm{f}}\right)$

H—>4-lepton cross sections (ATLAS)

Full Run 2

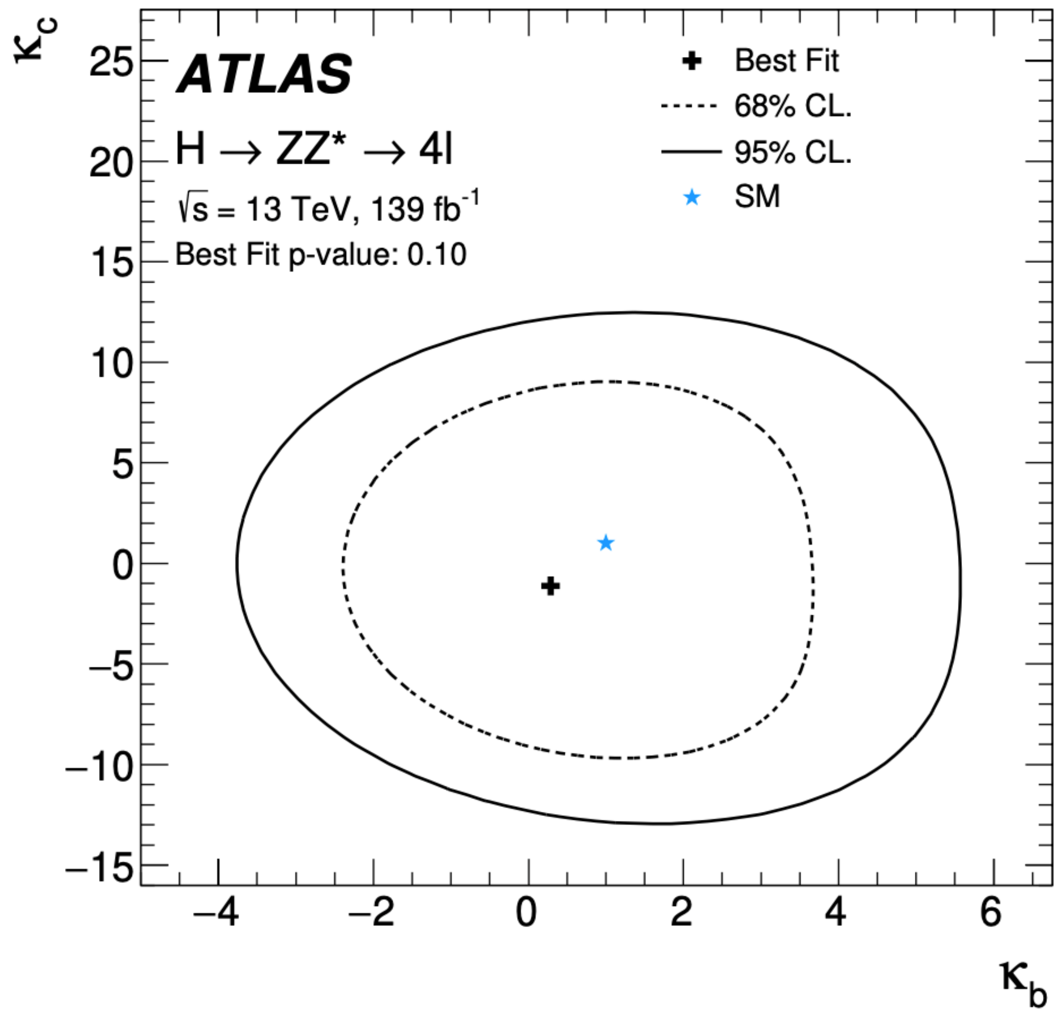




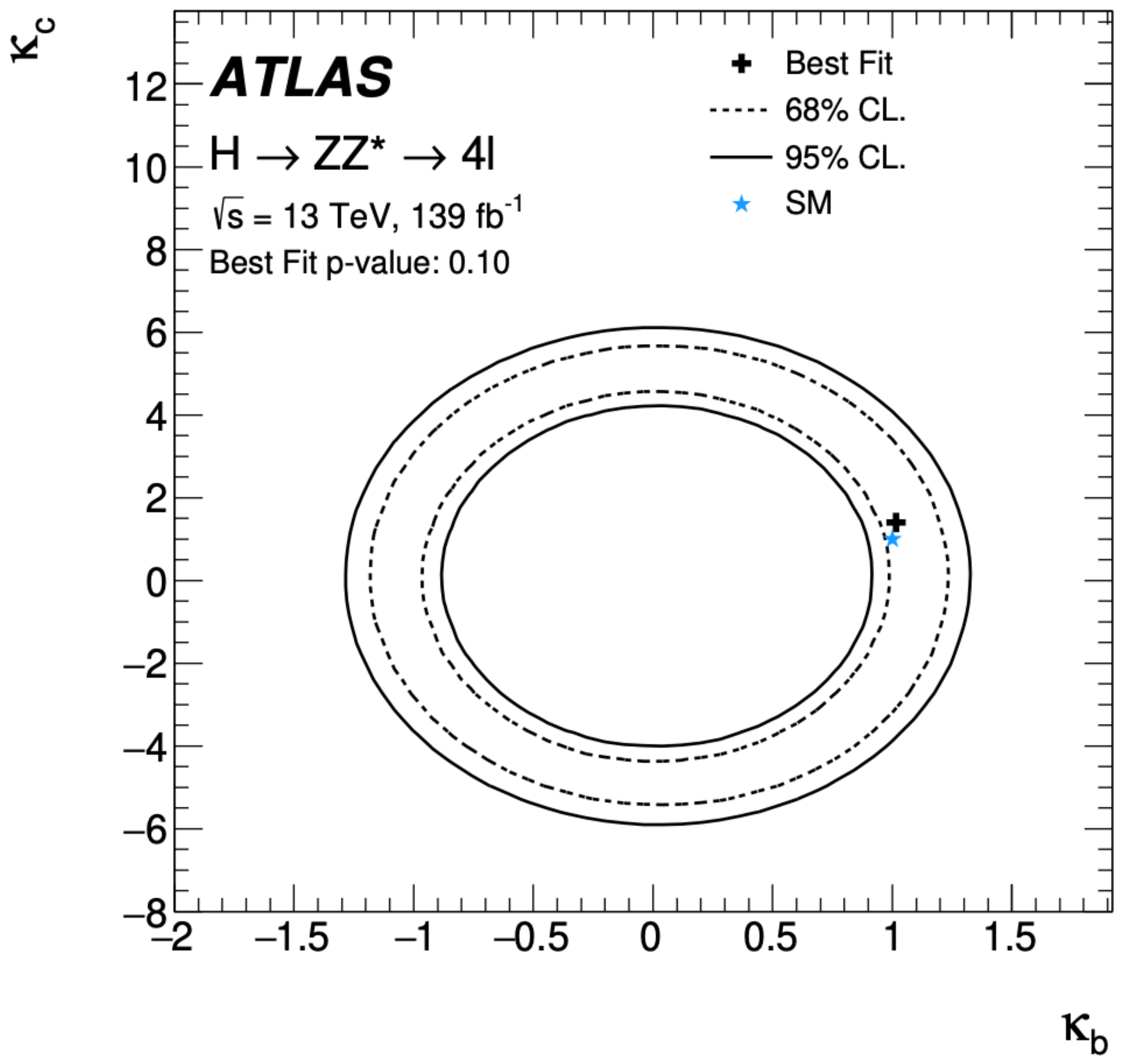
H—>4-lepton constrains couplings (ATLAS)

p_T^{4l} to constrain indirectly Yukawa couplings of b/c

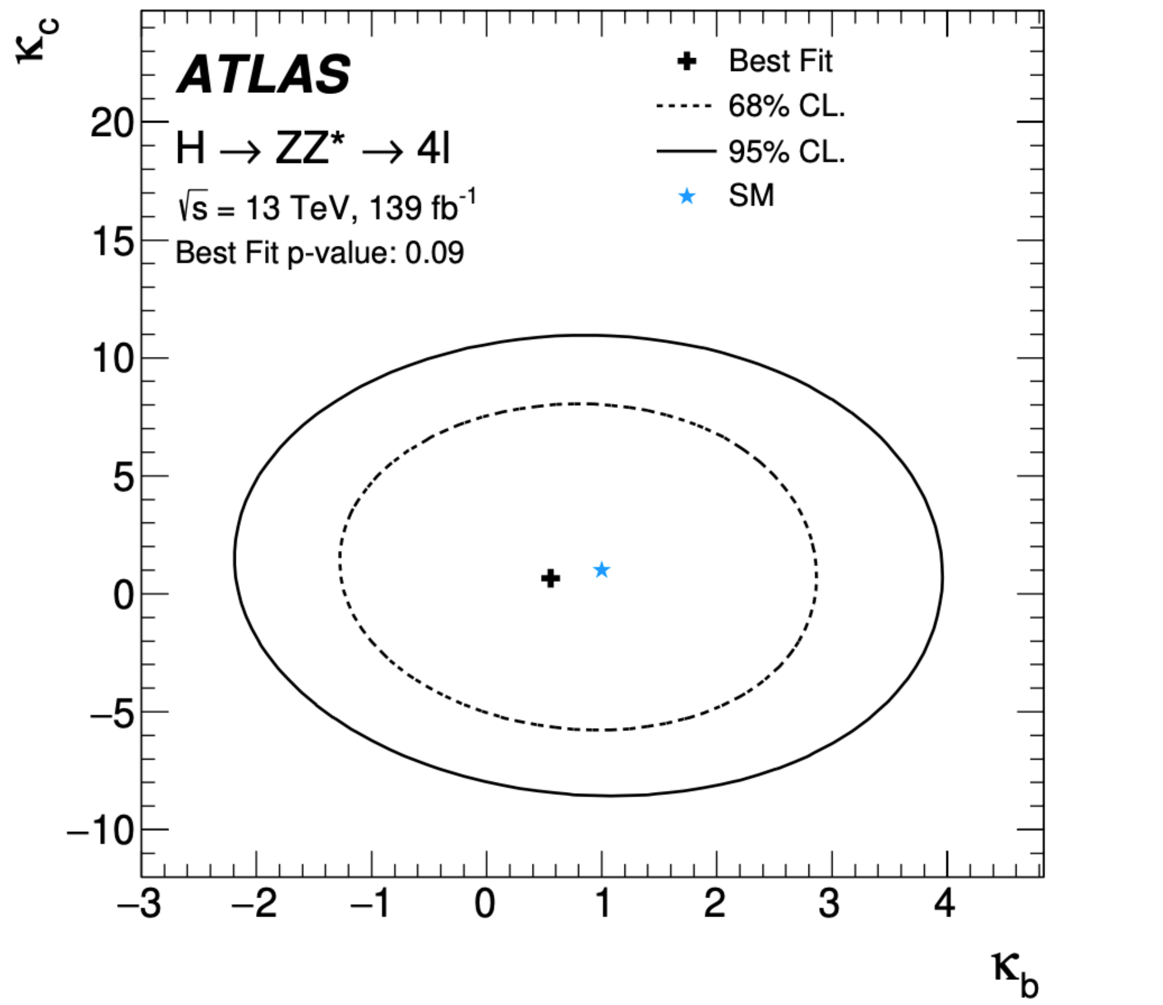
shape



shape + modification to total width and B

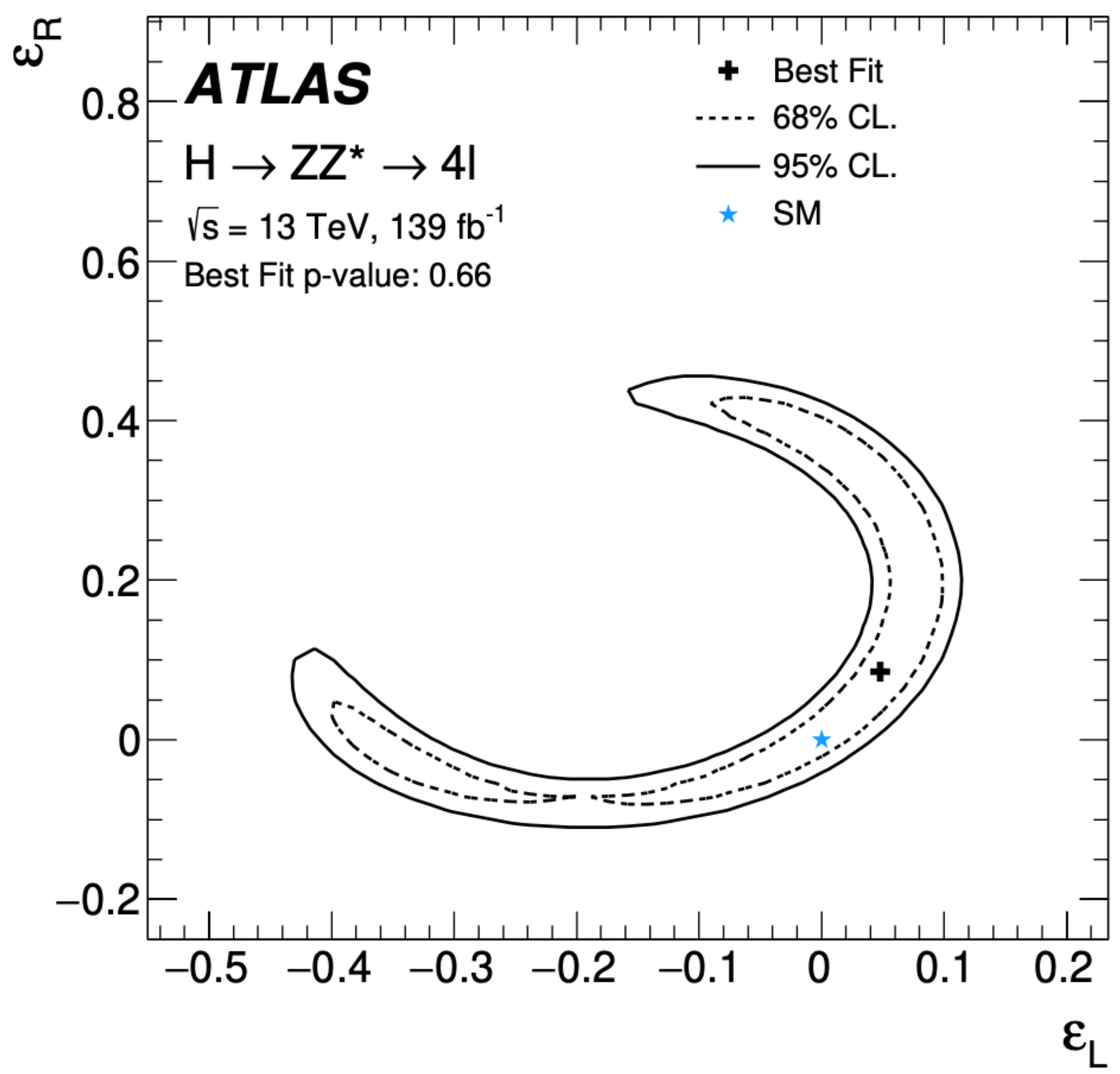


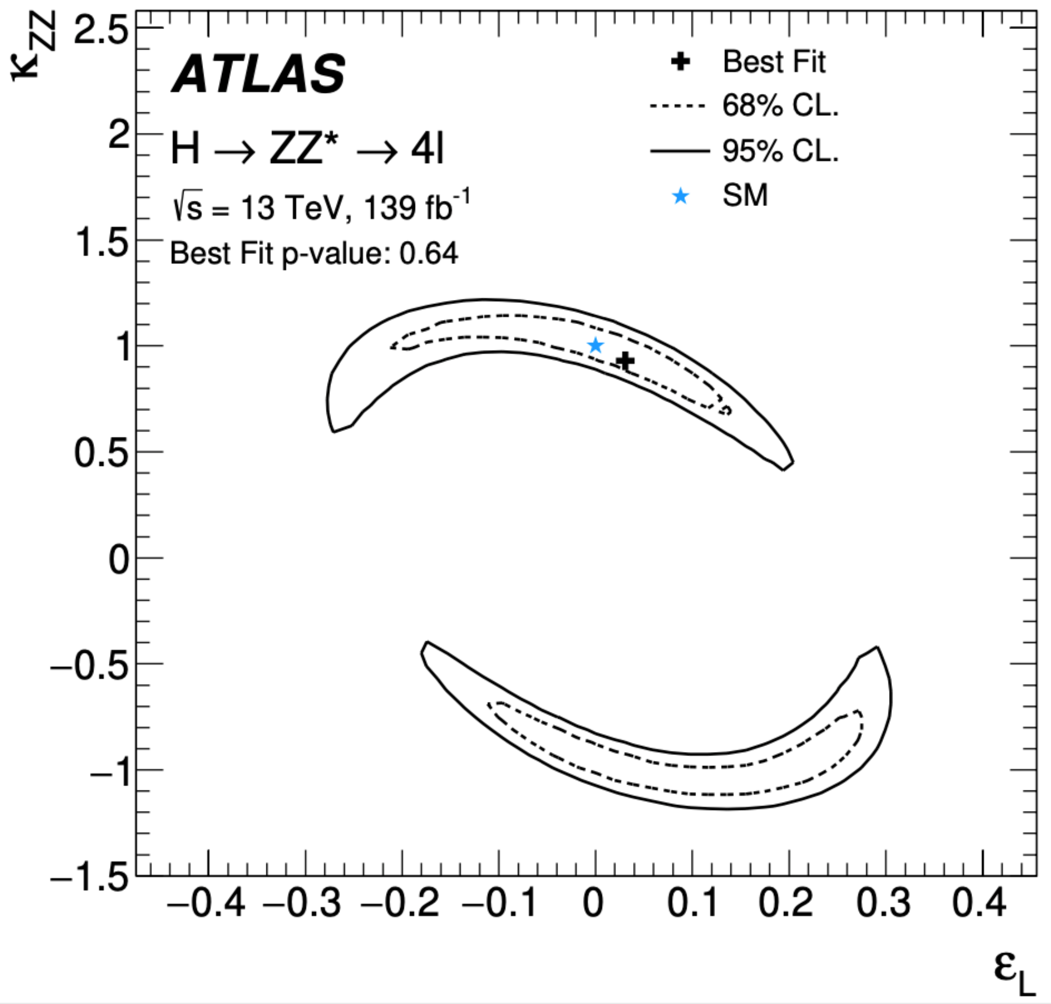
hape + cross section(theo)



Following JHEP10(2018)073

Pseudo-observables to interpret the measurement:
parameterized as contact interactions of H with Z bosons and leptons (L,R)





EFT interpretation in backup

Search for HH production

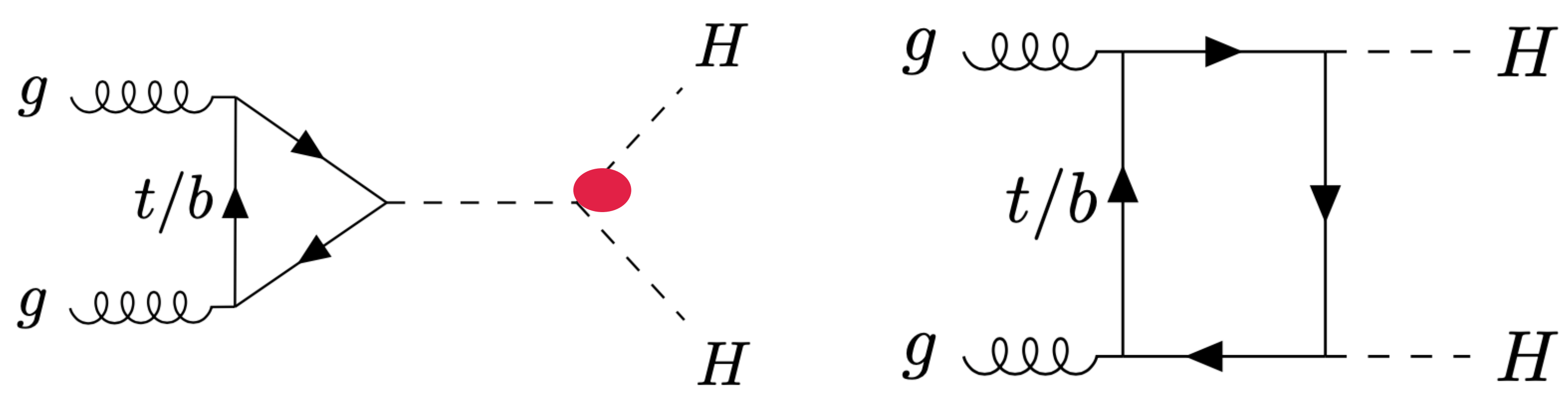
Results from full Run 2
CMS : $\gamma\gamma$bb, bbbb
ATLAS: $\gamma\gamma$bb, WWbb

PhysRevLett 122(2019)121803

Search for HH production(CMS)

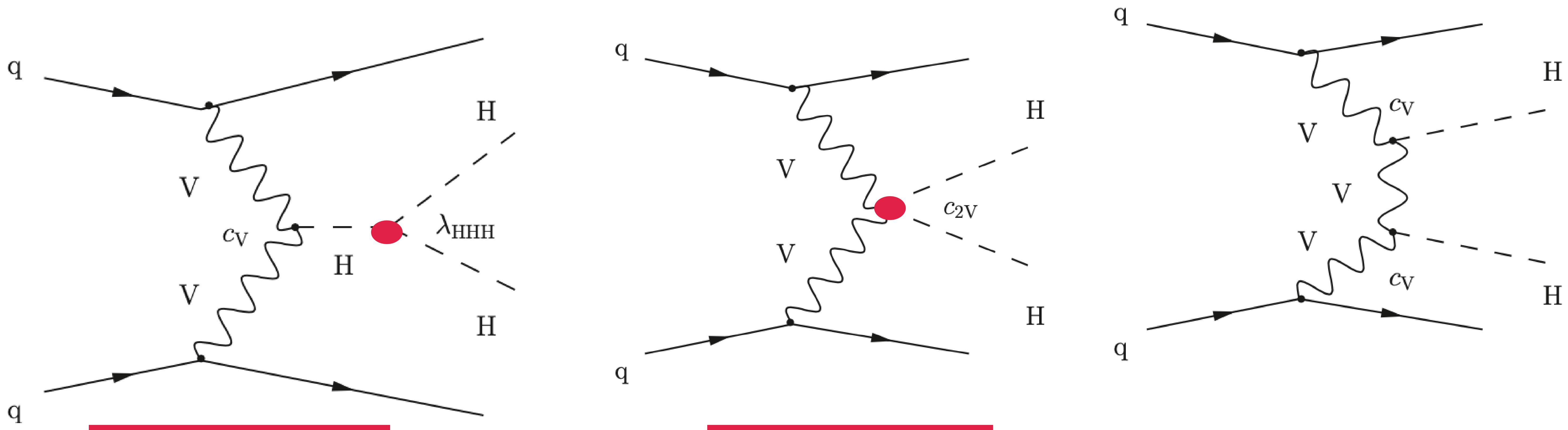
ggs self-coupling gives access to the shape of the scalar field potential
HH production is sensitive to the self-coupling

$\sigma_{HH} = 31.05 \pm 1.90\text{fb}$ (ggF NNLO)



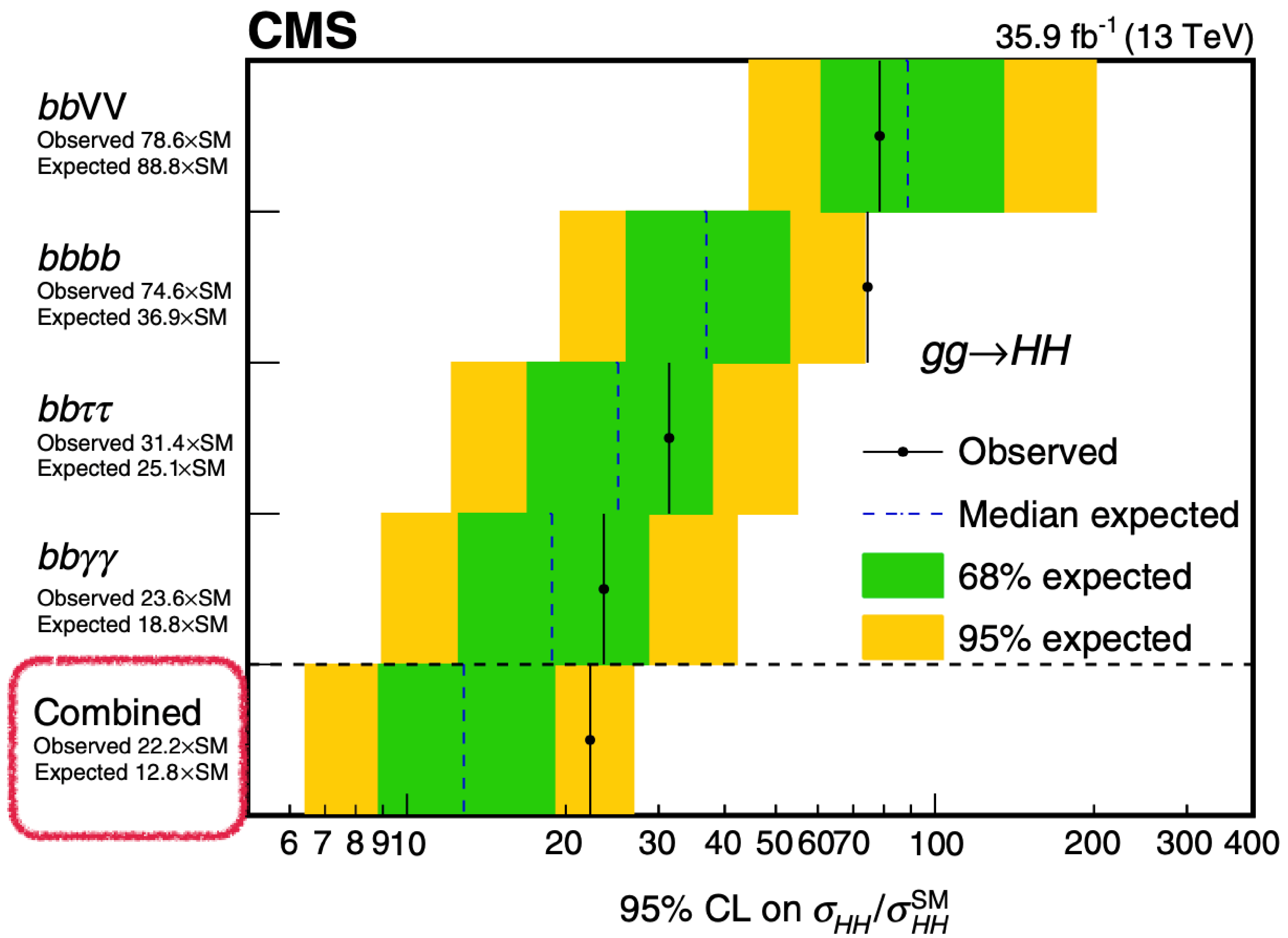
Channel	BR(%)	S/B	Comment
bb$\gamma\gamma$	0.26	5%	Most sensitive,2D mass fit
bb$\tau\tau$	7.3	0.4%	Categorization, BDT
bbbb	33.6	1%	4 b-jets/2 large-R jets, BDT
bbVV(bblνlν)	2.72	0.18%	DNN

$\sigma_{HH} = 1.73 \pm 0.04\text{fb}$ (VBF NNLO)



Self-coupling

VVHH vertex

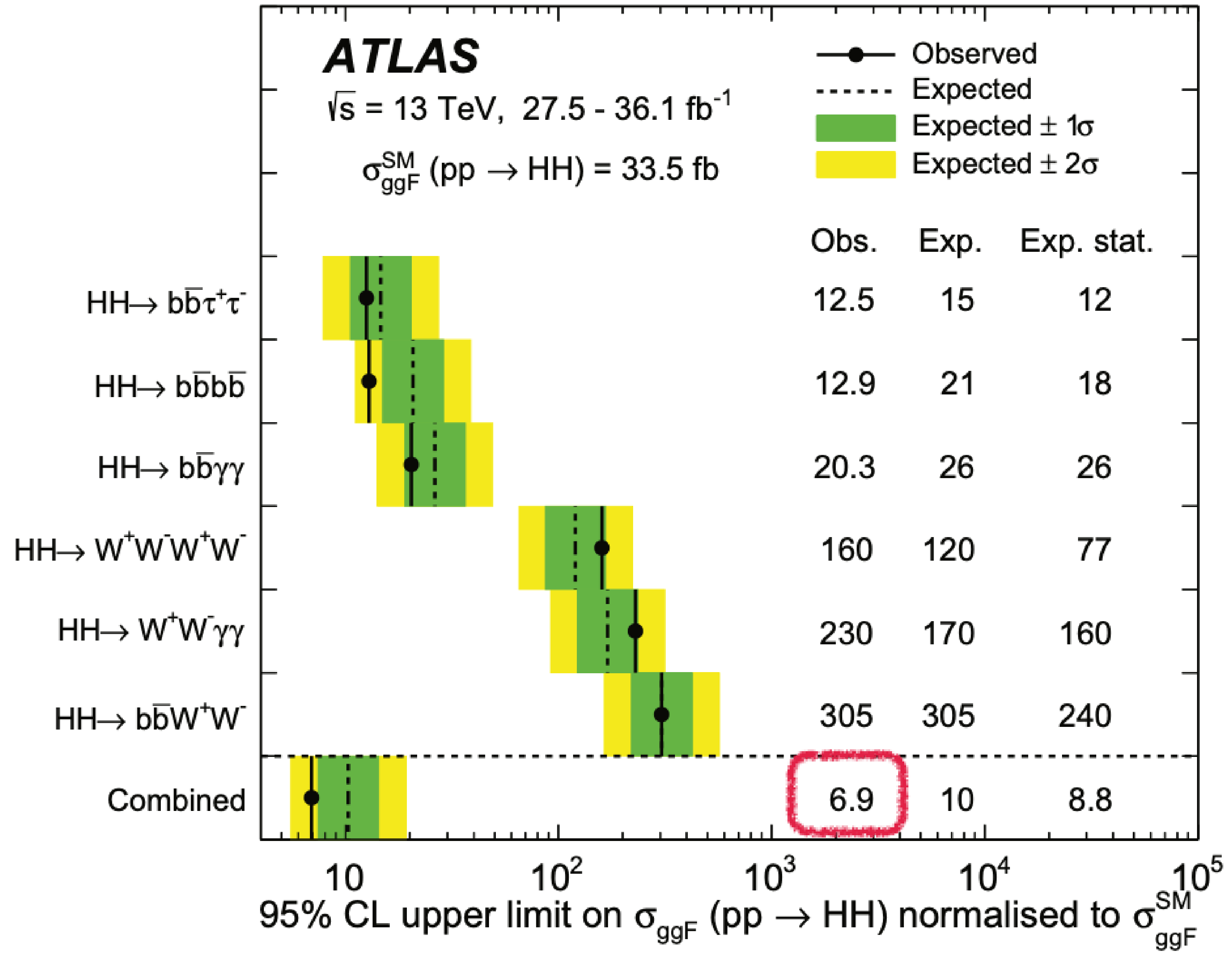


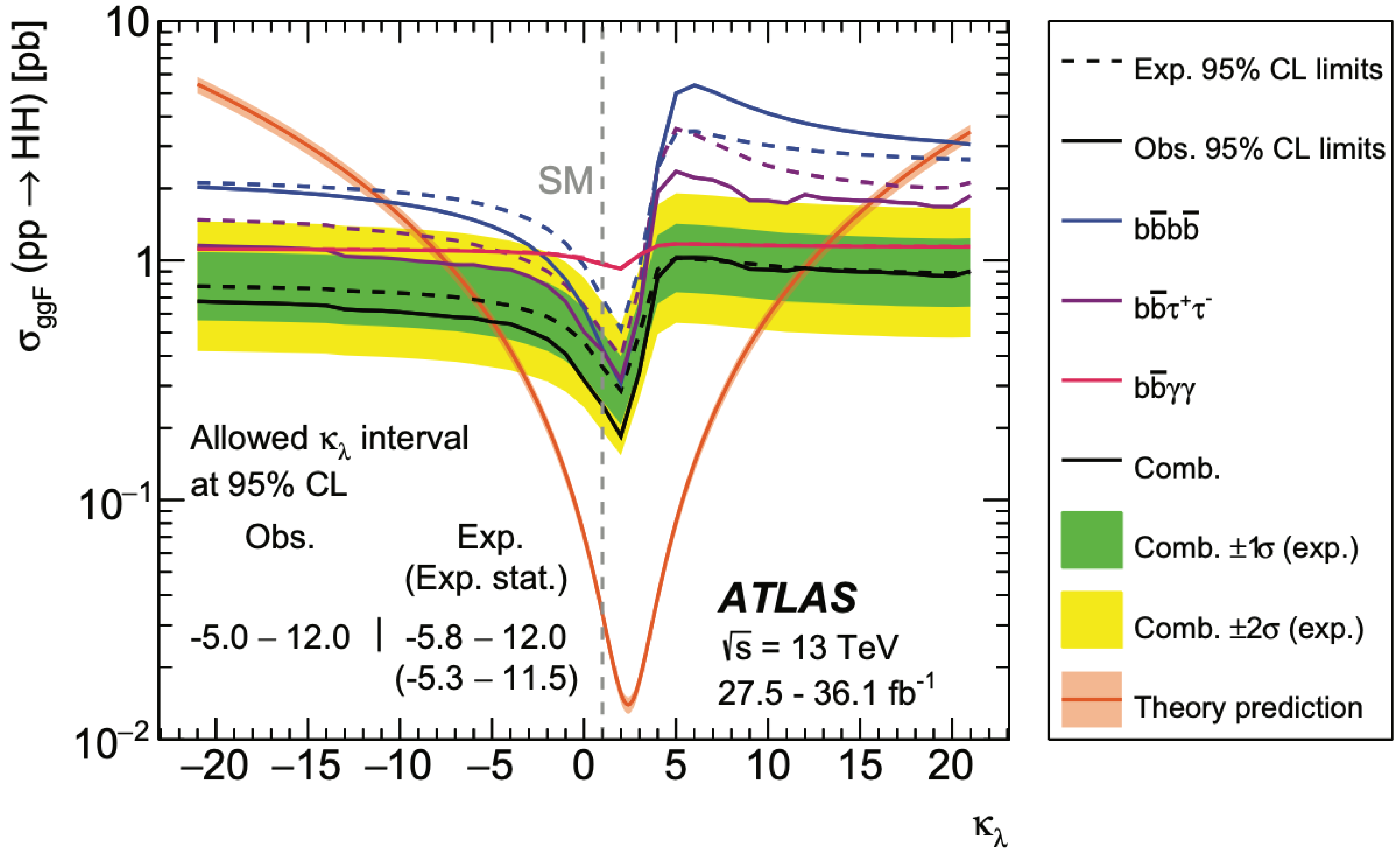
Phys.Lett. B 800(2020) 135103

Search for HH production (ATLAS)

	$b\bar{b}b\bar{b}$	$b\bar{b}W^+W^-$	$b\bar{b}\tau^+\tau^-$	$W^+W^-W^+W^-$	$b\bar{b}\gamma\gamma$	$W^+W^-\gamma\gamma$
$\mathcal{B}(HH \to x\bar{x}y\bar{y})$	0.34	0.25	0.073	0.046	$2.6 \cdot 10^{-3}$	$1.0 \cdot 10^{-3}$
$\mathcal{L}_{\text{int}}$ [fb^{-1}]	27.5 [36.1]	36.1	36.1	36.1	36.1	36.1
Categories	2 [2–5]	1 [1]	3 [2–3]	9 [9]	2 [2]	1 [1]
Discriminant	m_{HH} [m_{HH}]	c.e. [m_{HH}]	BDT [BDT]	c.e. [c.e.]	$m_{\gamma\gamma}$ [m_{HH}]	$m_{\gamma\gamma}$ [$m_{\gamma\gamma}$]
Model	NR [S/G]	NR [S/G]	NR [S/G]	NR [S]	NR [S]	NR [S]
$m_{S/G}$ [TeV]	[0.26–3.00]	[0.50–3.00]	[0.26–1.00]	[0.26–0.50]	[0.26–1.00]	[0.26–0.50]

c.e = counting events
NR = SM HH(non-resonant)
S/G = Scalar/Graviton

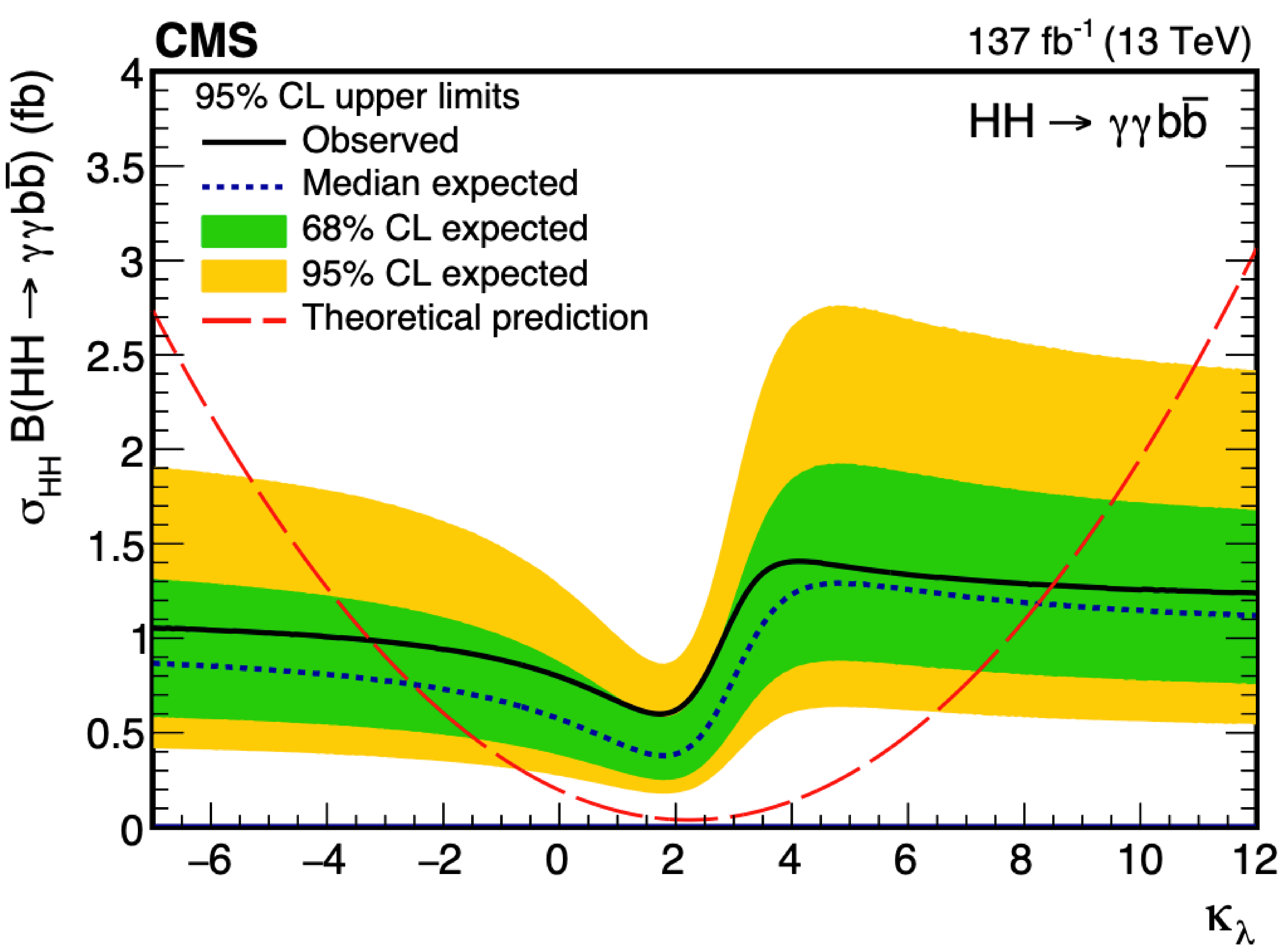




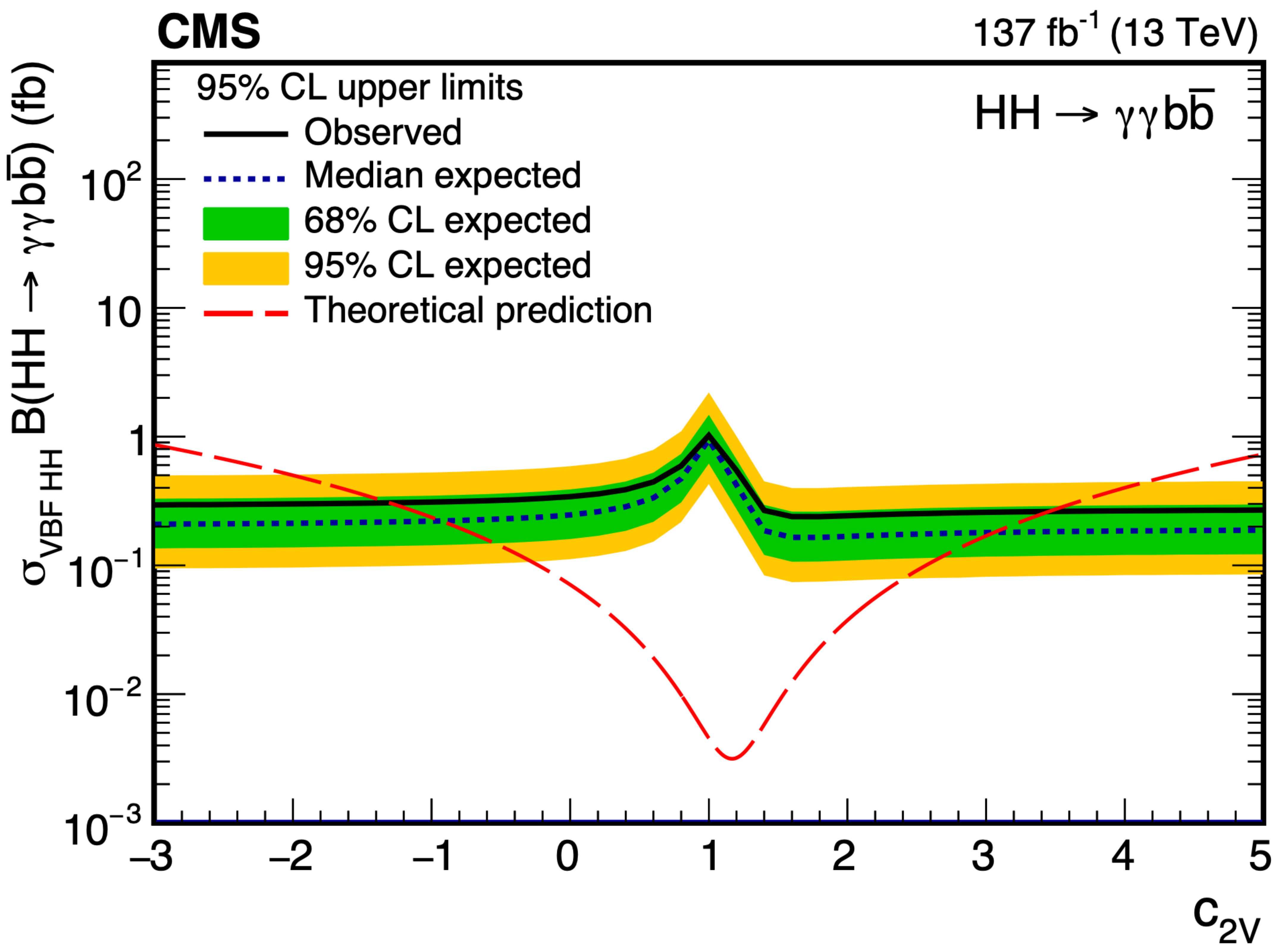
Update from full Run 2 data—$\boldsymbol{\gamma\gamma}$bb (CMS)

Full Run 2

$\sigma_{HH}\mathcal{B}(HH \to \gamma\gamma b\bar{b}) < 7.7(5.2) * \text{SM at 95\% CL.}$



$-3.3 < \kappa_\lambda < 8.5(-2.5 < \kappa_\lambda < 8.2)$ at 95% CL.

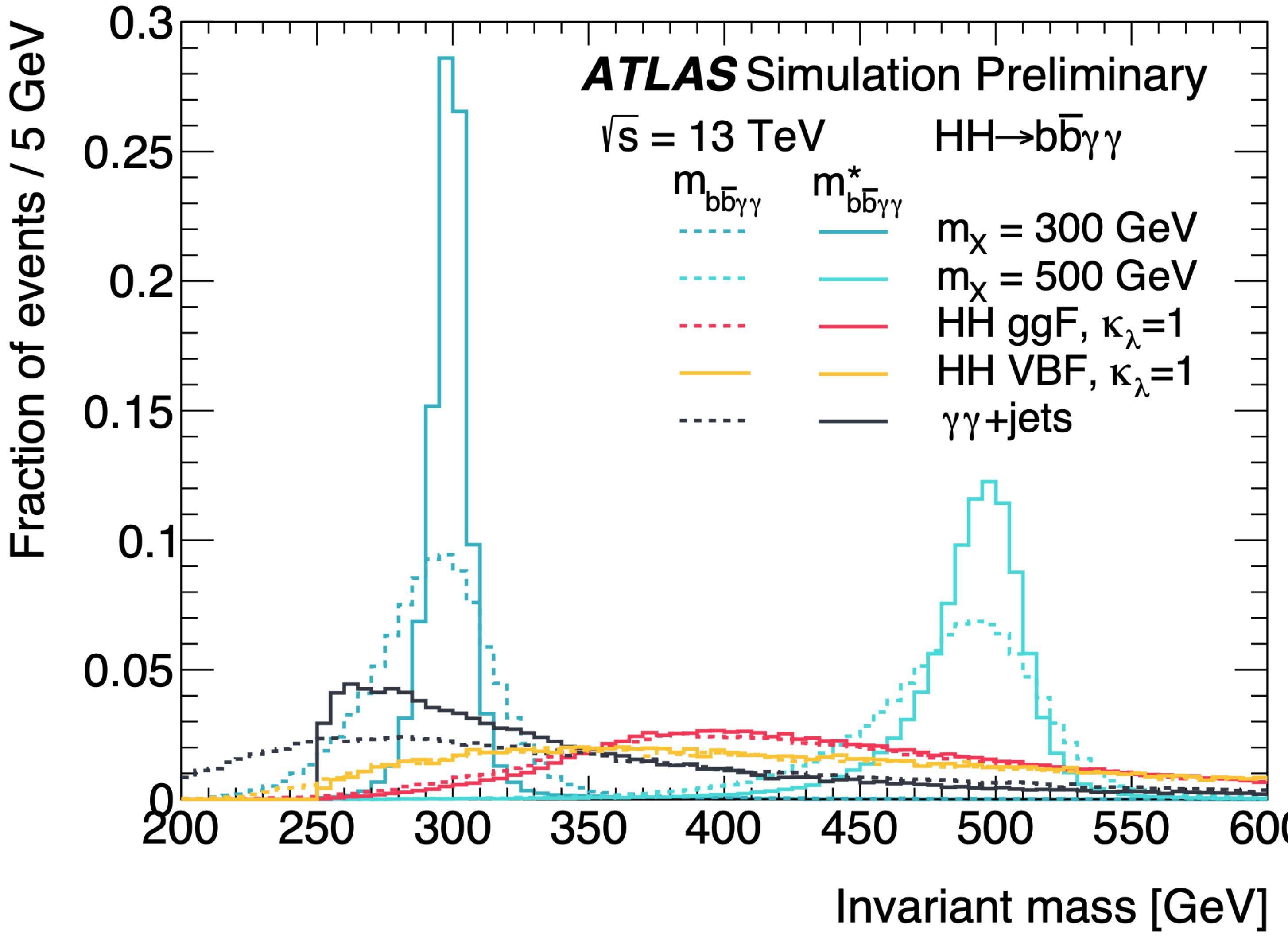


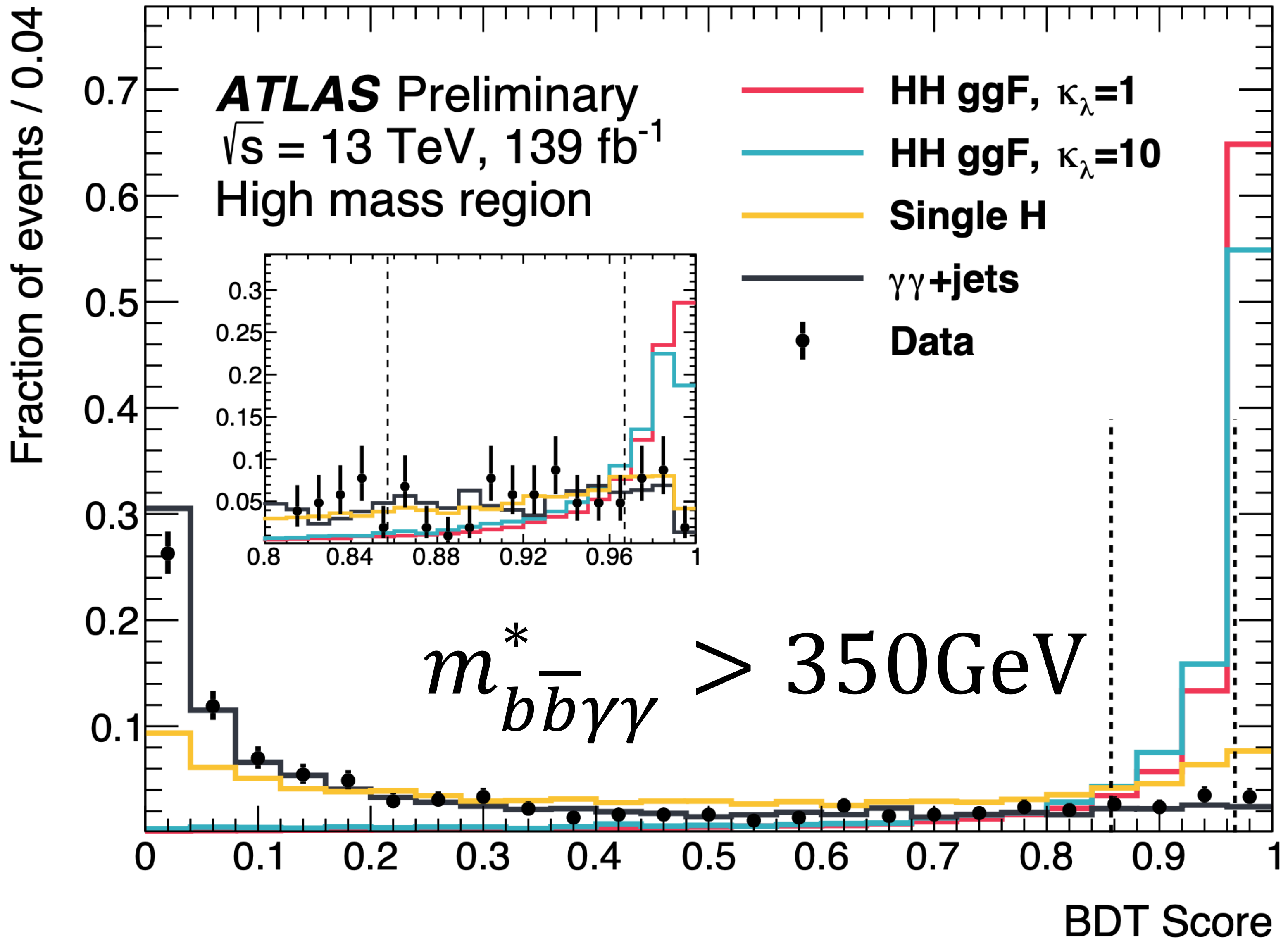
$-1.3 < c_{2V} < 3.5(-0.9 < c_{2V} < 3.1)$ at 95%CL.

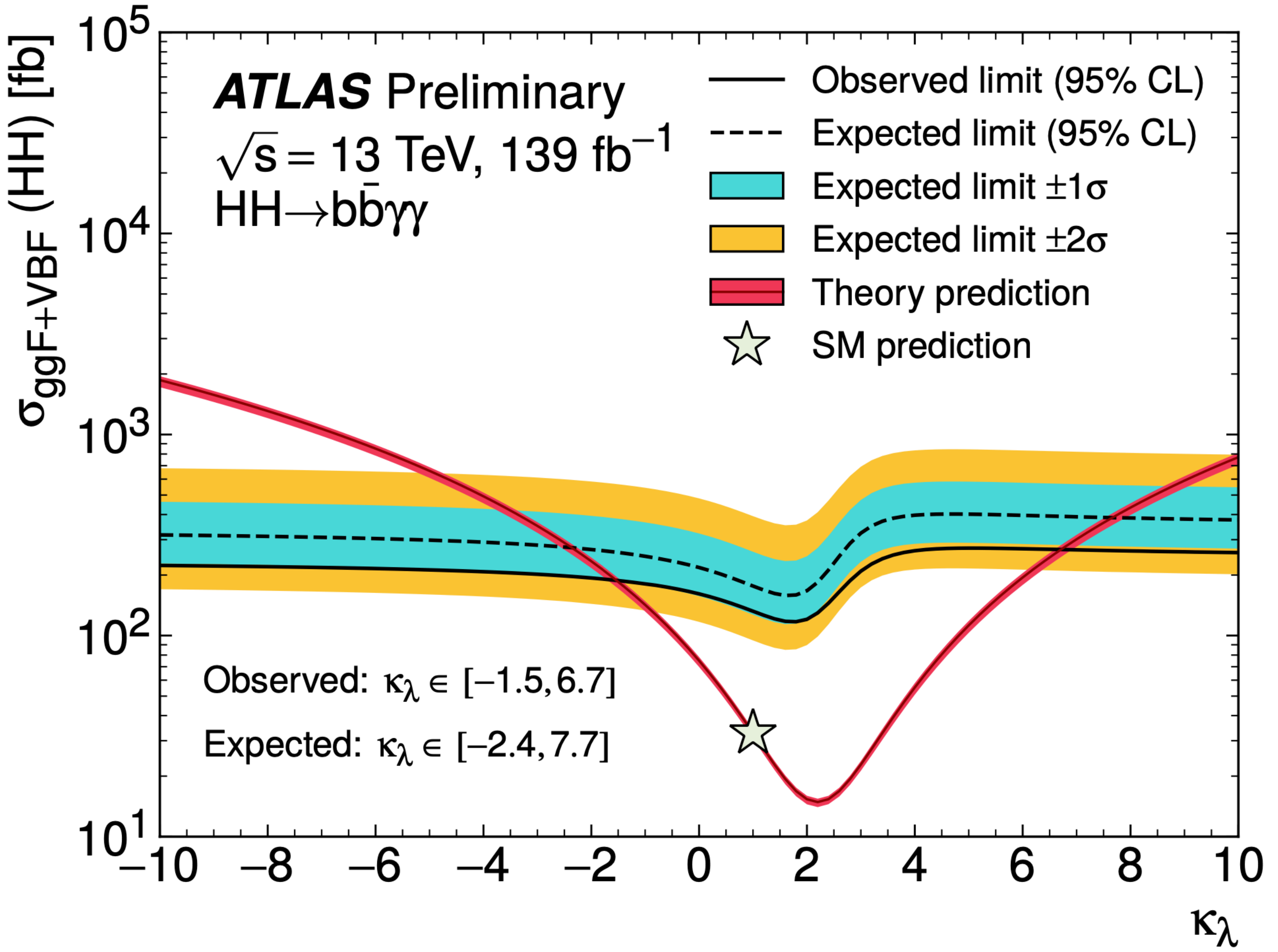
HH—>$\boldsymbol{\gamma\gamma}$bb with full Run 2 data(ATLAS)

ATLAS-CONF-2021-016

Full Run 2







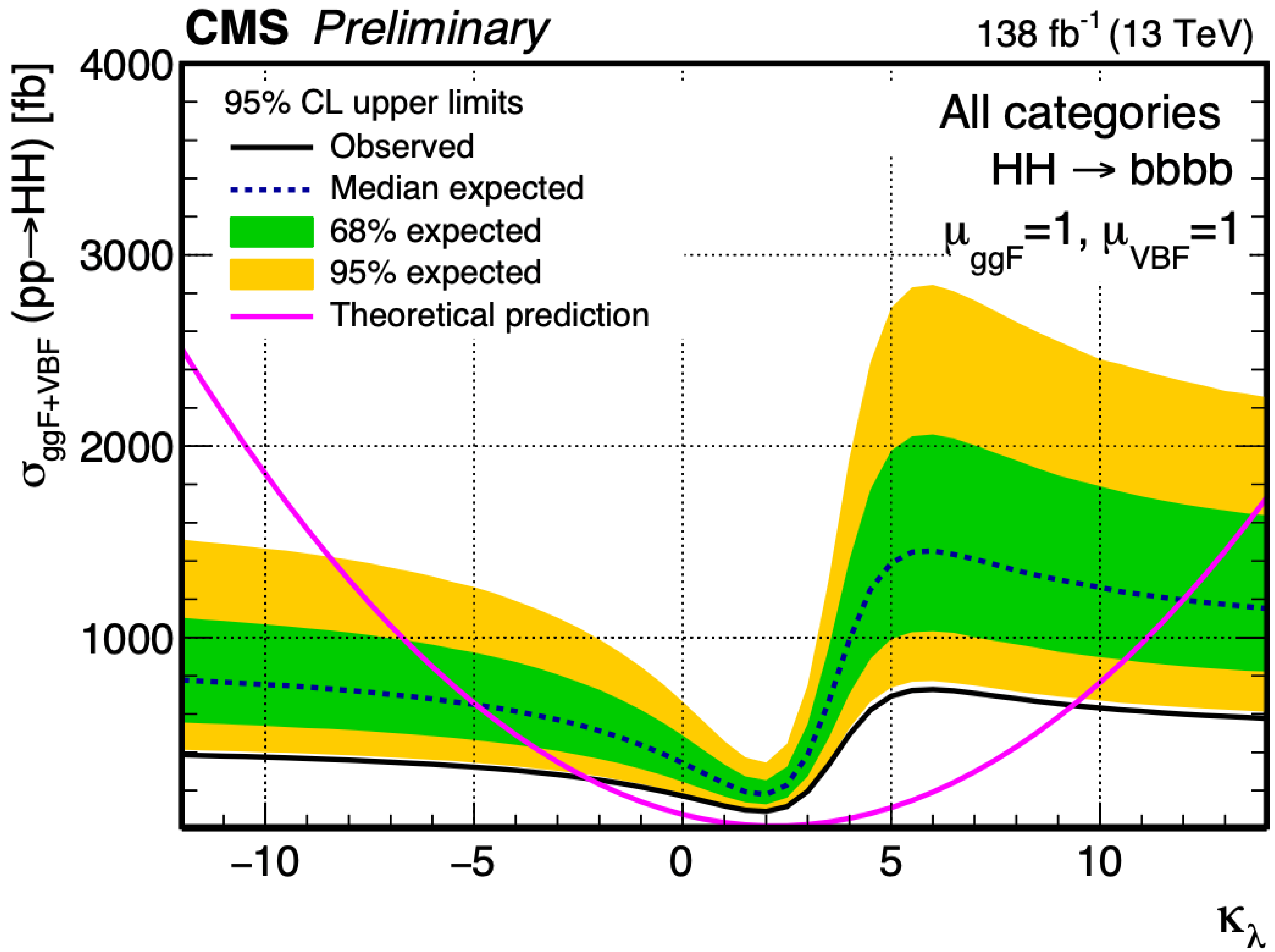
$$m^*_{b\bar{b}\gamma\gamma} = m_{b\bar{b}\gamma\gamma} - m_{\gamma\gamma} - m_{b\bar{b}} + 250\text{GeV}$$

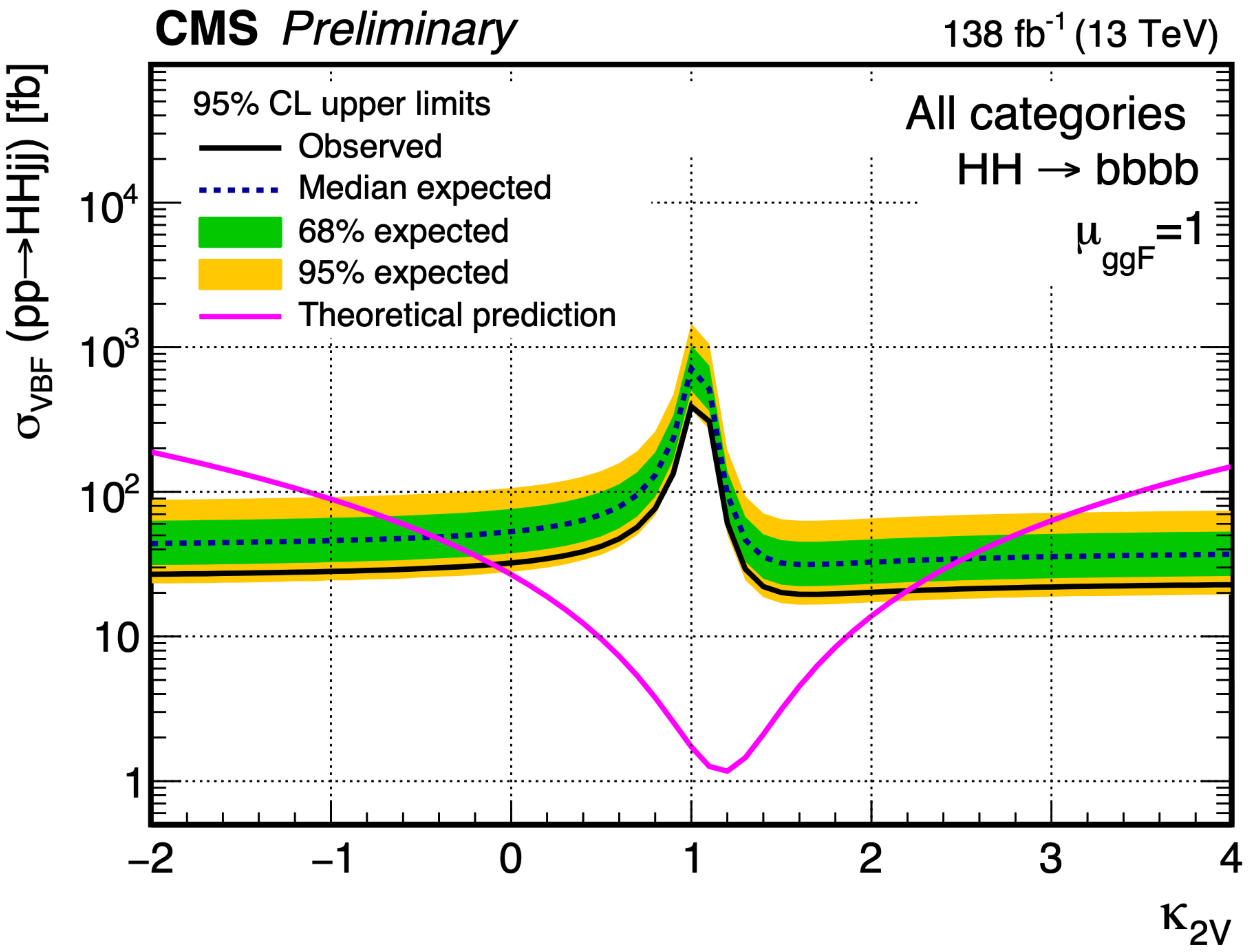
$$\sigma(pp \to HH) = 4.1(5.5) * \text{SM at } 95\% \text{ CL}$$

[PAS HIG-20-005]

Update from full Run 2 data— bbbb(CMS)

Full Run 2





$-2.3 < \kappa_\lambda < 9.4(-5.0 < \kappa_\lambda < 12.0)$at95%CL.

$-0.1 < \kappa_{2V} < 2.2(-0.4 < \kappa_{2V} < 2.5)$ at 95% CL

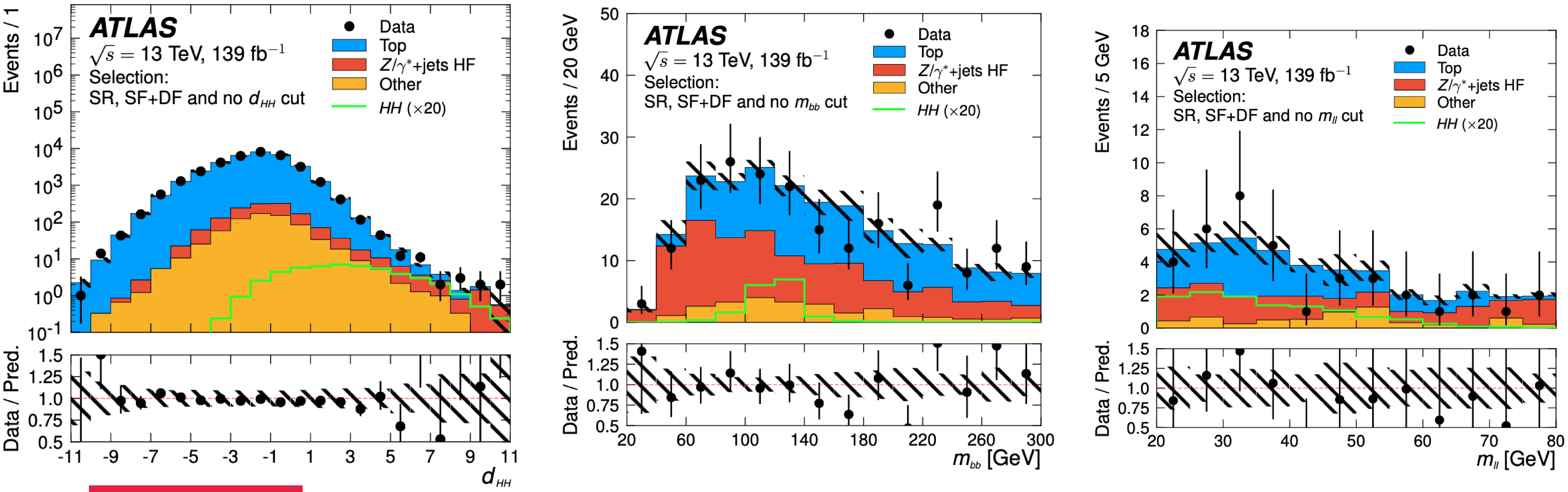
σ(ggF HH) $< 3.6(7.3) *$ SM at 95% CL

σ(VBF HH) $< 226(412) *$ SM at 95% CL

Phys.Lett.B 801(2020)135145

HH—>WWbb with full Run 2 data(ATLAS)

Full Run 2



DNN classifier

	-2σ	-1σ	**Expected**	$+1\sigma$	$+2\sigma$	**Observed**
$\sigma(gg \to HH)$ [pb]	0.5	0.6	0.9	1.3	1.9	1.2
$\sigma(gg \to HH)/\sigma^{SM}(gg \to HH)$	14	20	29	43	62	40

Search for BSM with H decays

DM
LLP

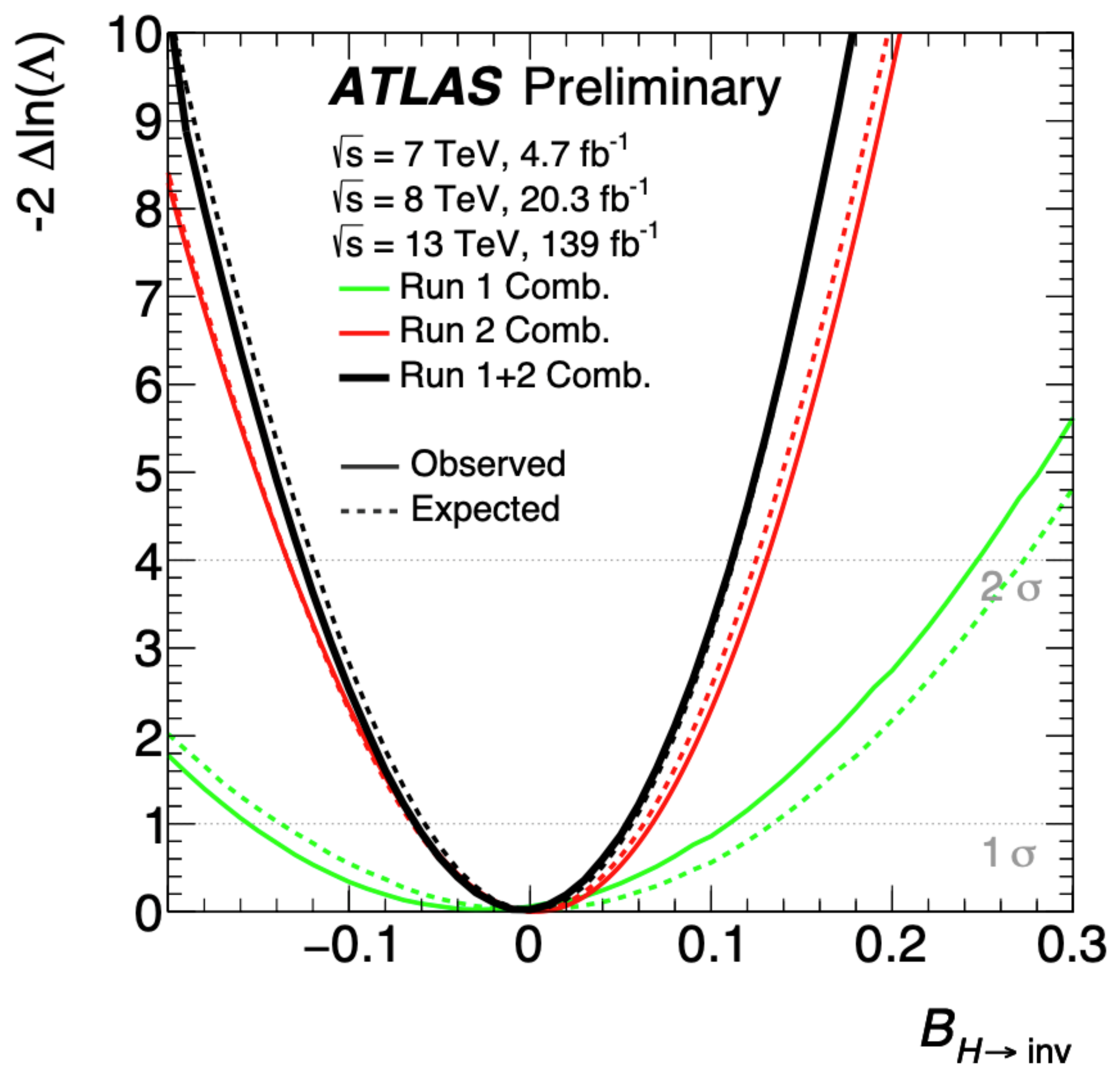
ATLAS-CONF-2020-052
Phys.Lett.B 04(2019)025

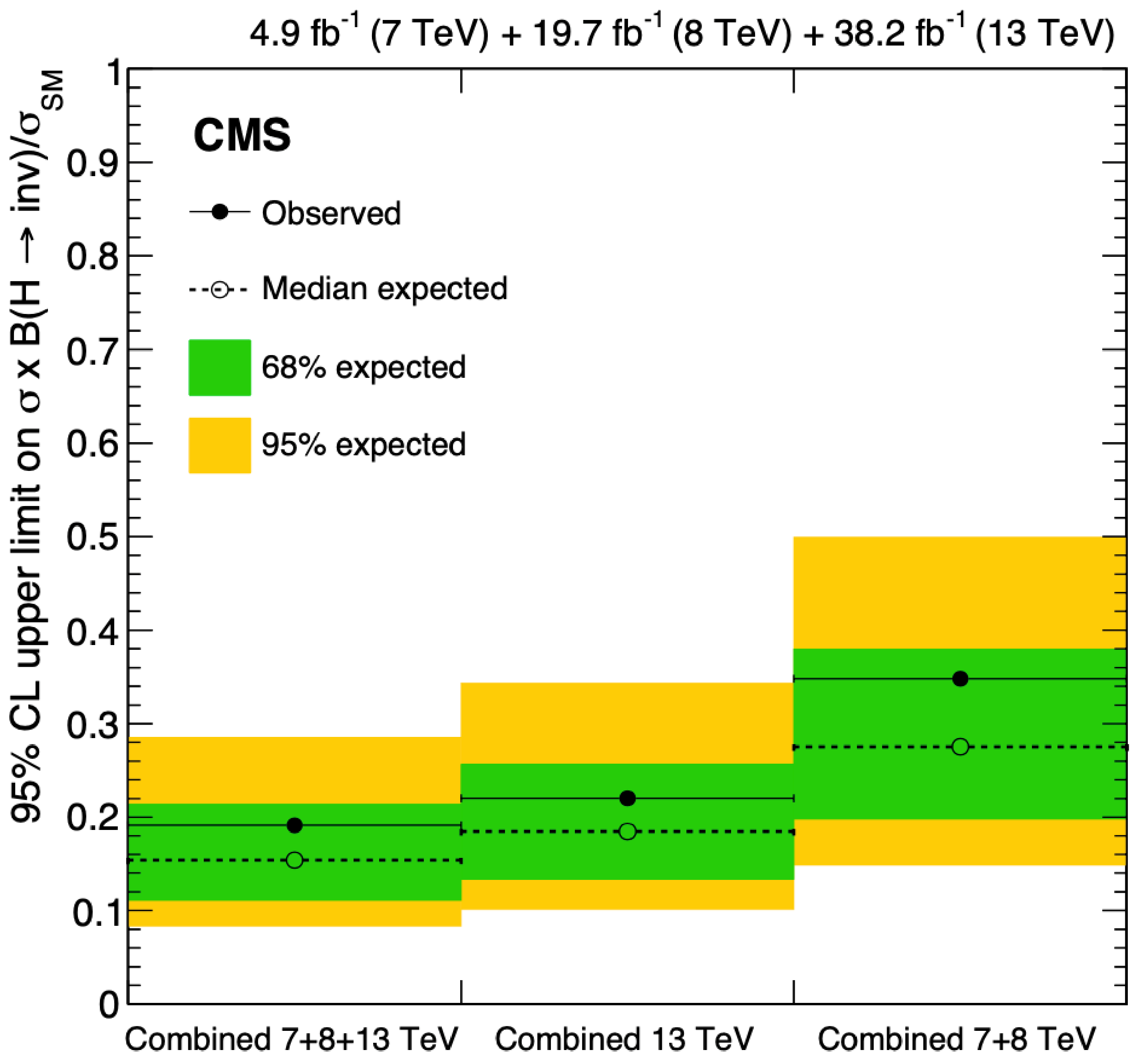
Combination of H—>Invisible (ATLAS)

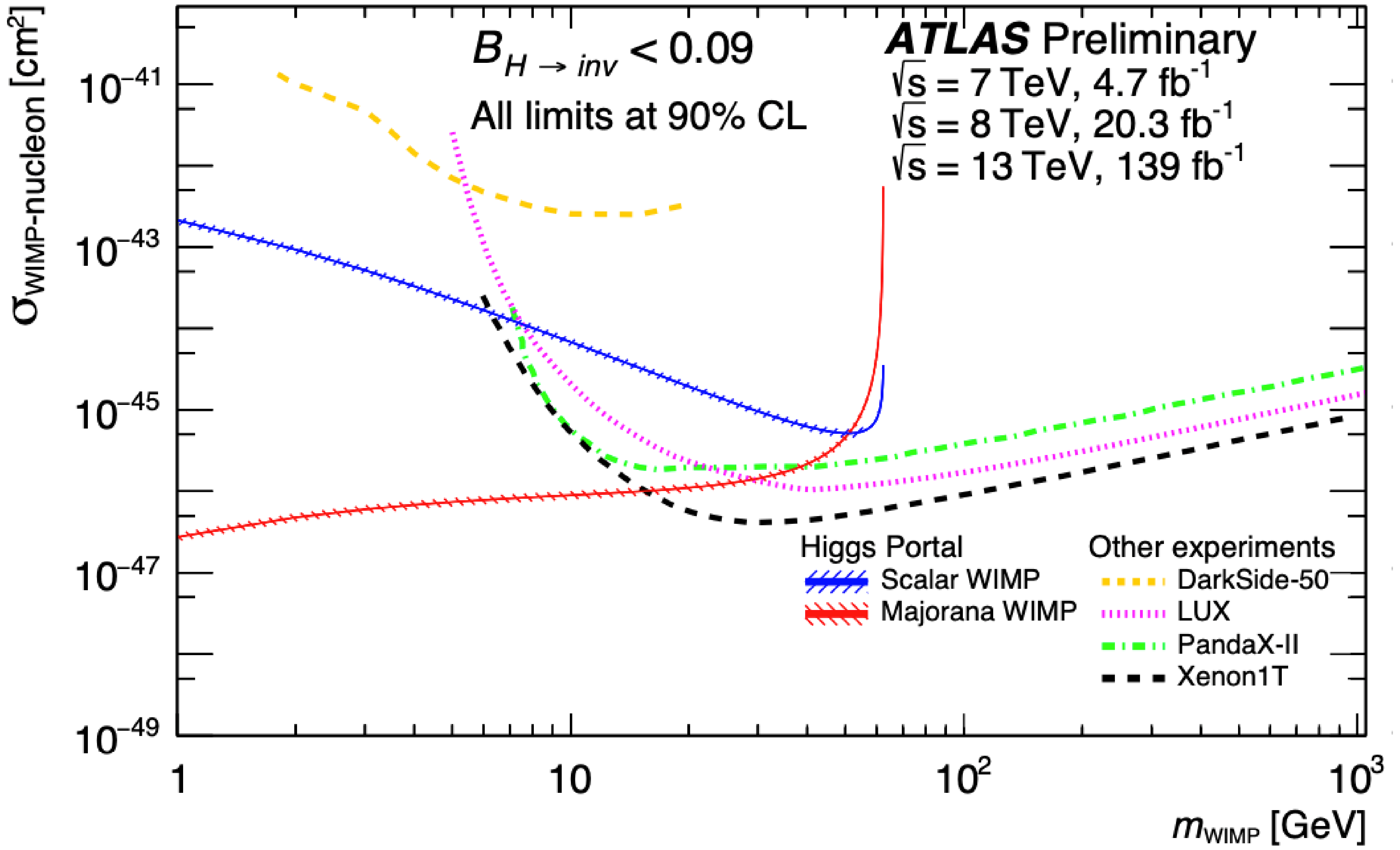
$In\ SM,\ BF(H \rightarrow ZZ \rightarrow \nu\bar{\nu}\nu\bar{\nu}) \approx 0.001$

Invisible decay sensitive to BSM, e.g portal to DM

Full Run 1 + Run 2







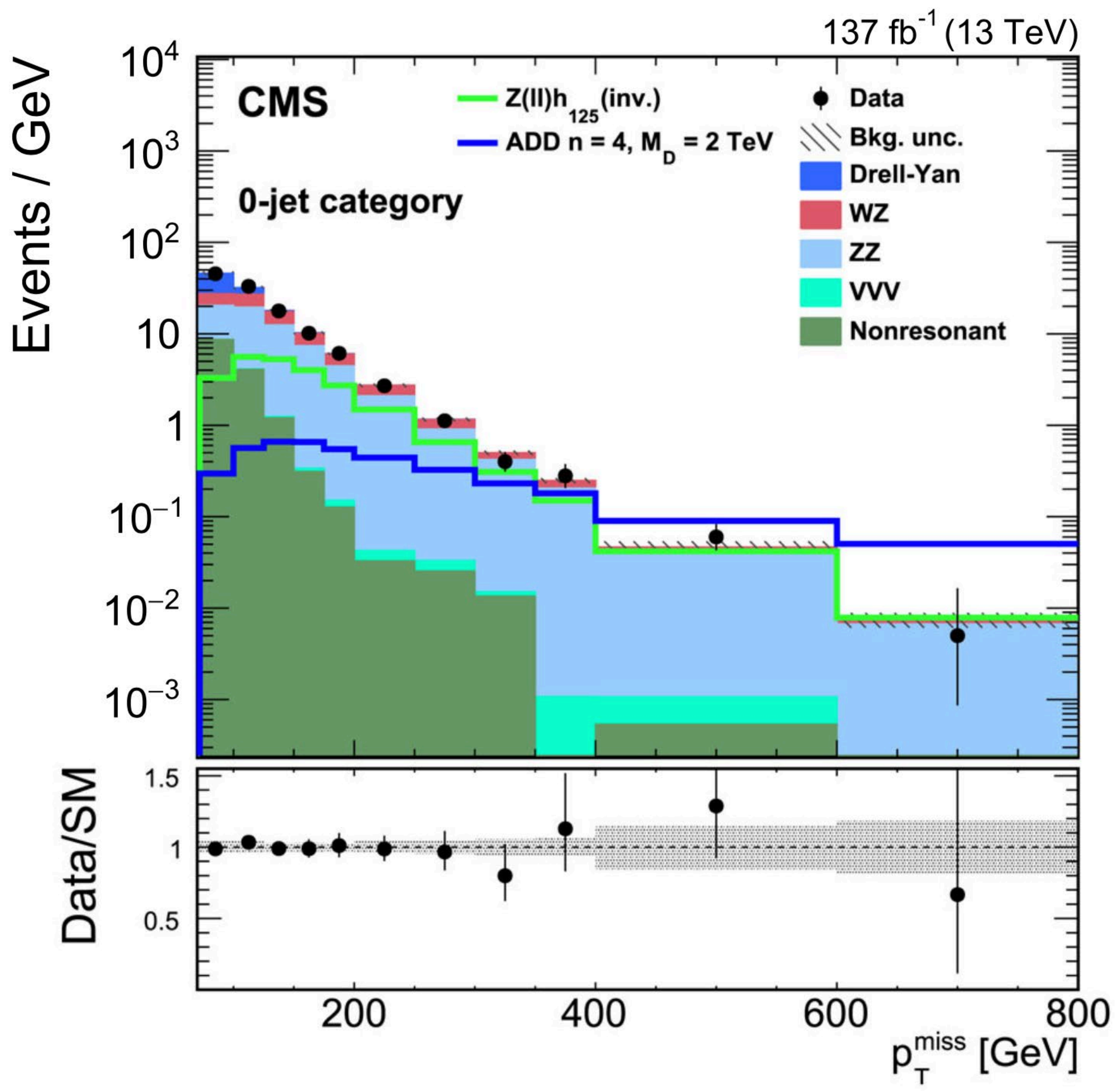
Best Fit: 0.00 ± 0.06

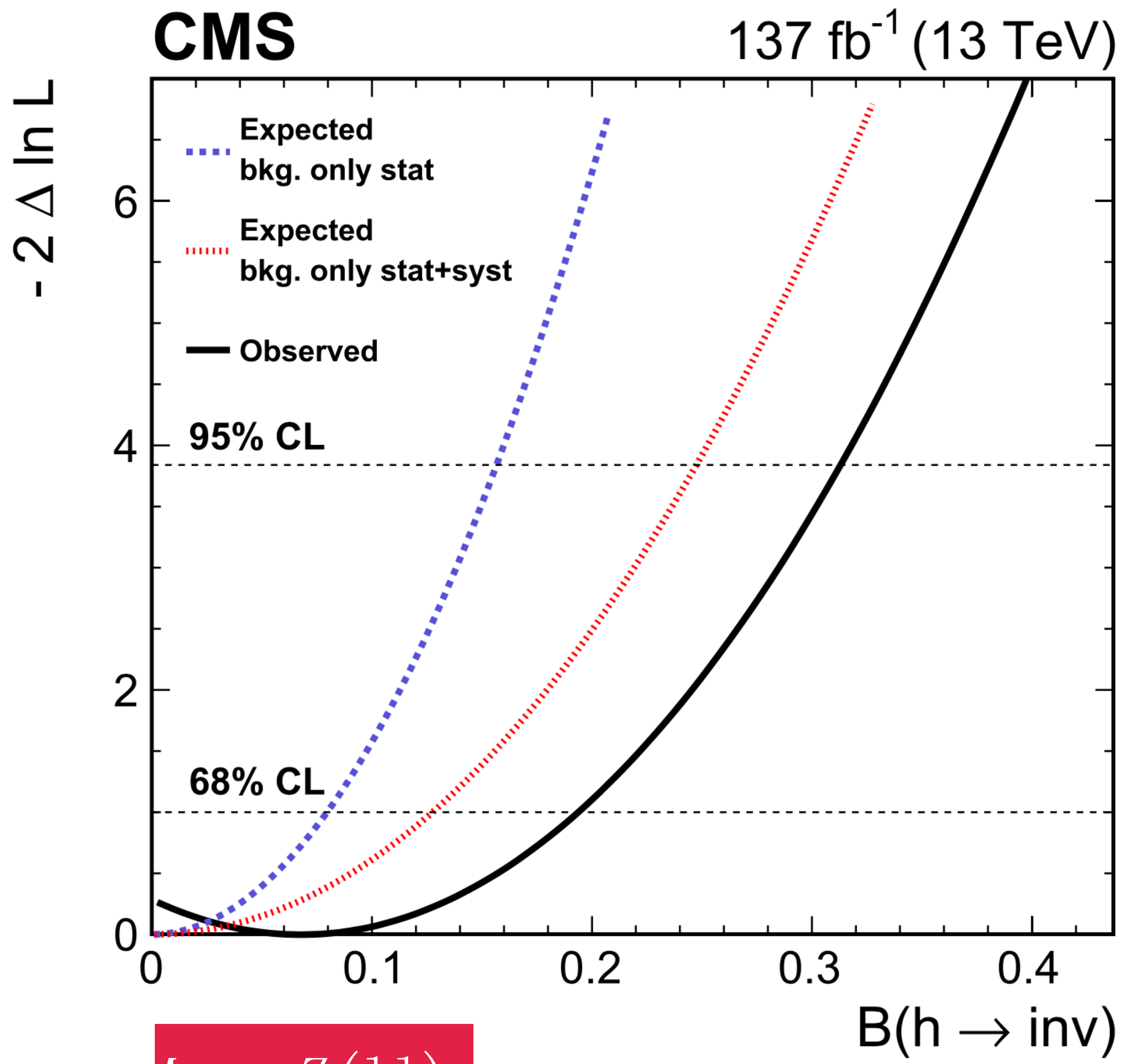
Upper Limit at 95% CL : 0.11

CMS WIMP cross section in backup

Mono-Z and Mono-jet (CMS)

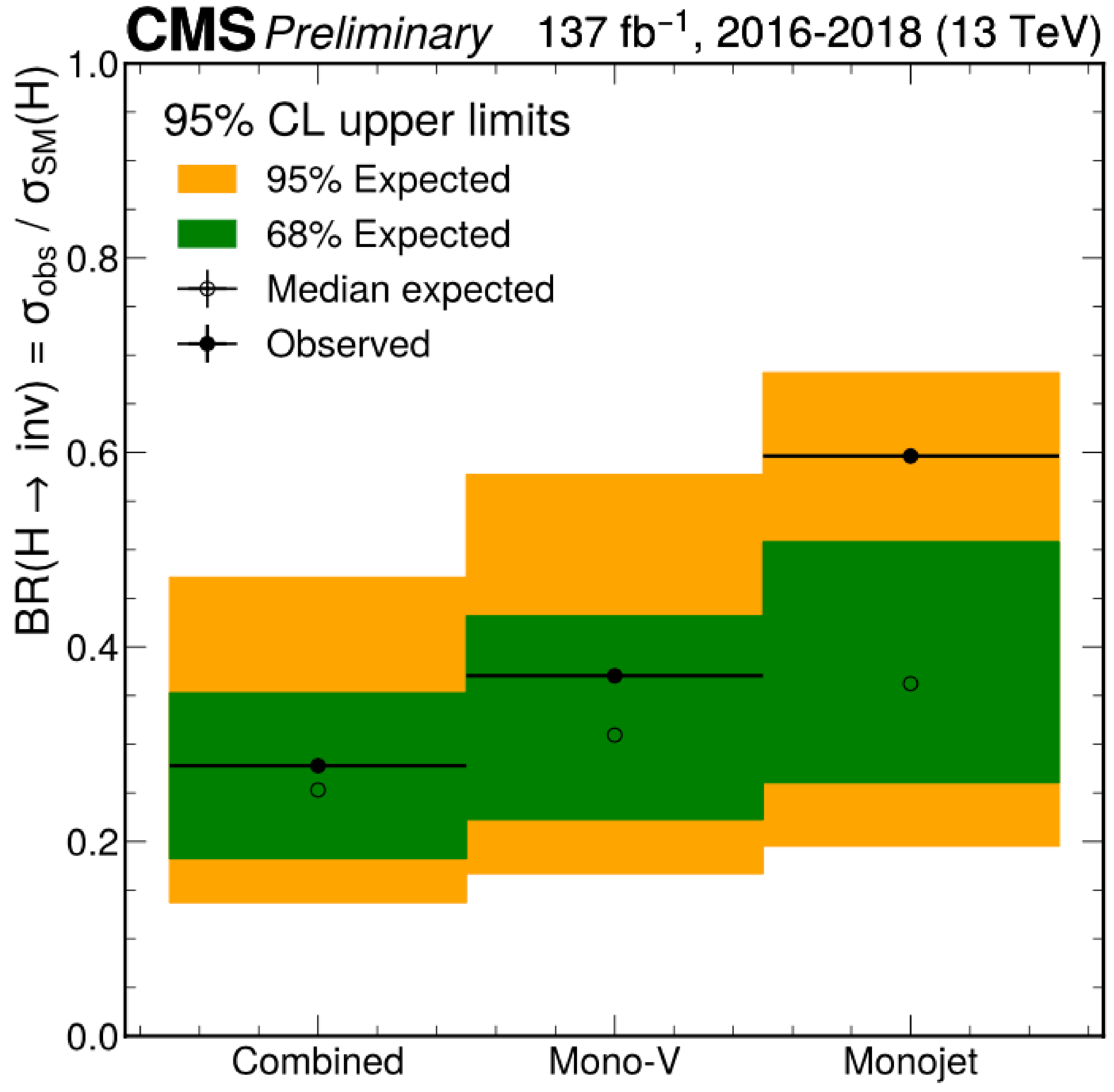
Full Run 2





Mono-Z(ll)

B(H->inv) < 29%(25%) at 95% CL



ono-jet and mono-V(large-R jet)

B(H->inv) < 28.8%(25.3%) at 95% CL

ATLAS-CONF-2021-005

H—>Long-Lived Particles(CMS/ATLAS)

CMS arXiv:2012.01581

Full Run 2

Many BSM predicts Higgs —>LLP decays

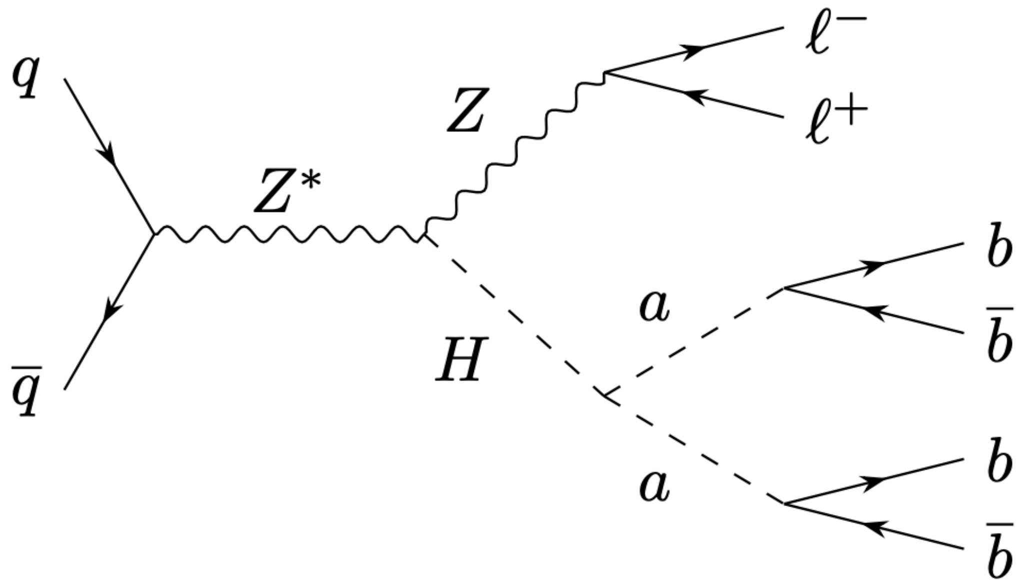
Example: minimal scalar extension

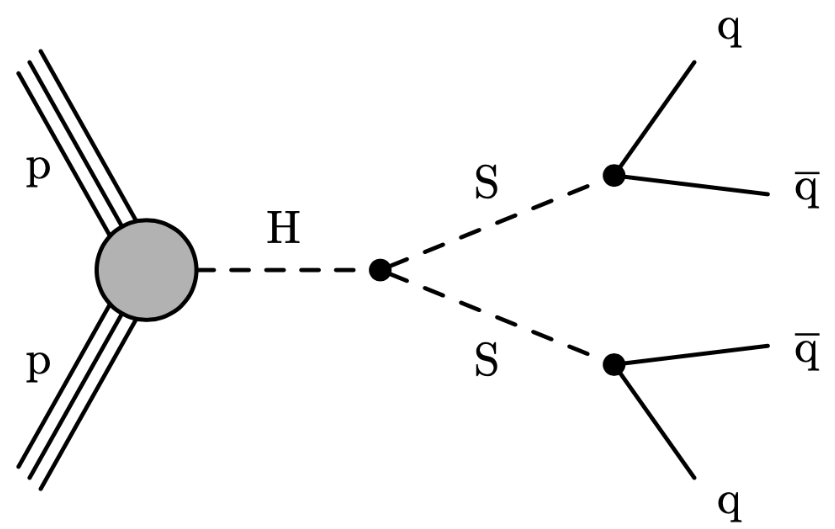
Portal interaction: $\epsilon|S|^2 H^\dagger H$

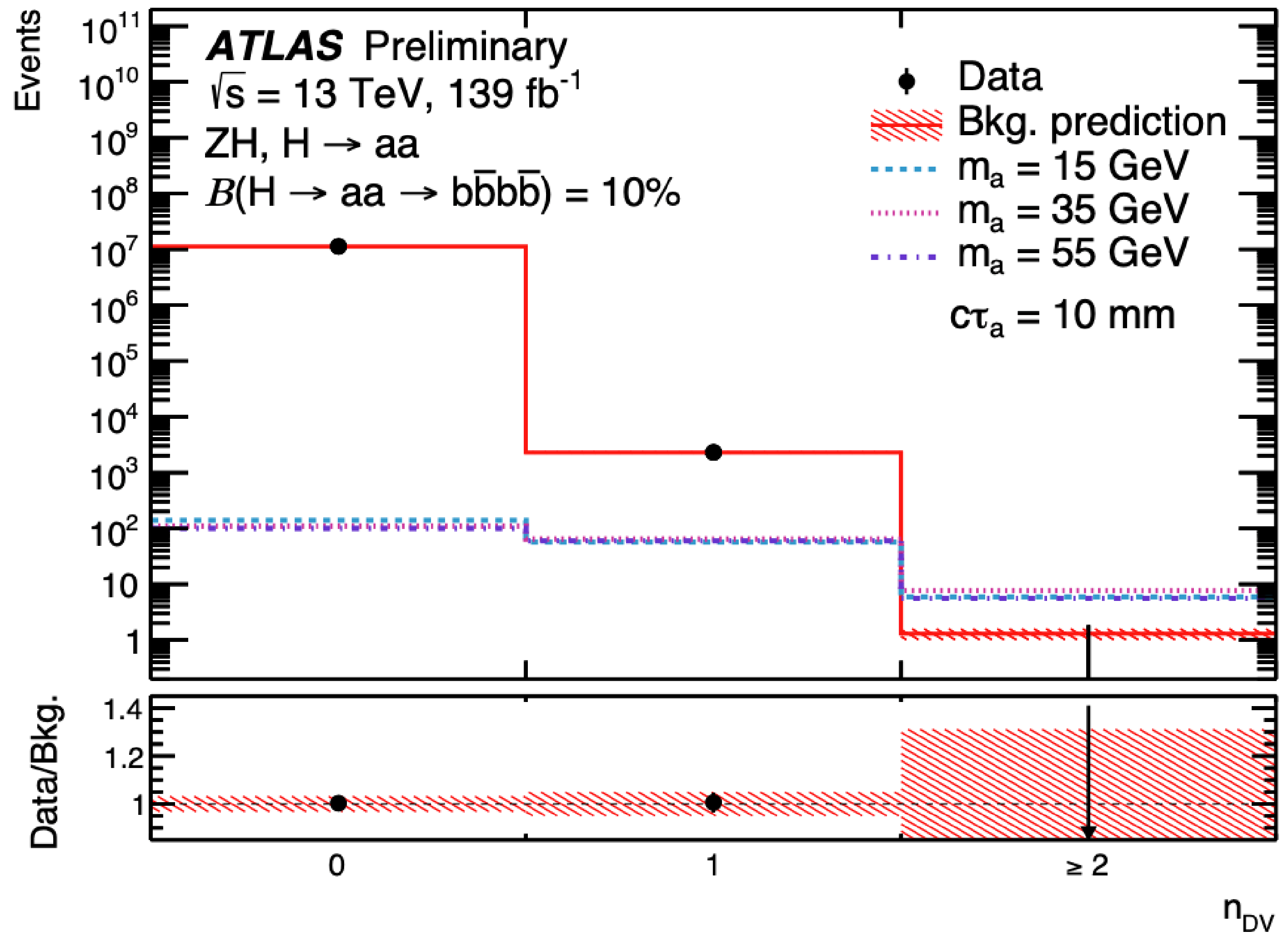
Benchmark model:

pseudoscalar a, decay exclusively to $b\bar{b}$

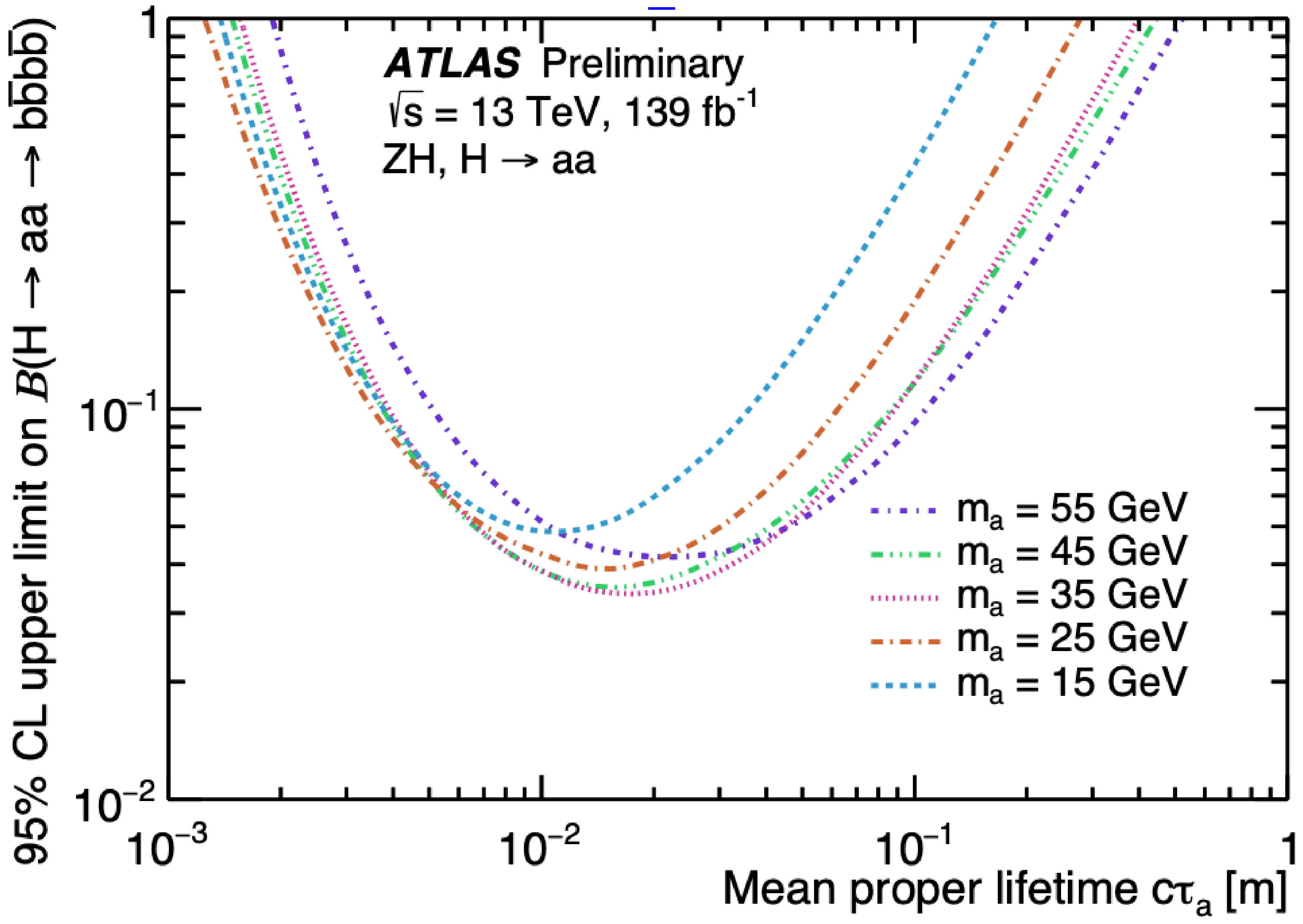
Parameters: $c\tau_a, m_a$

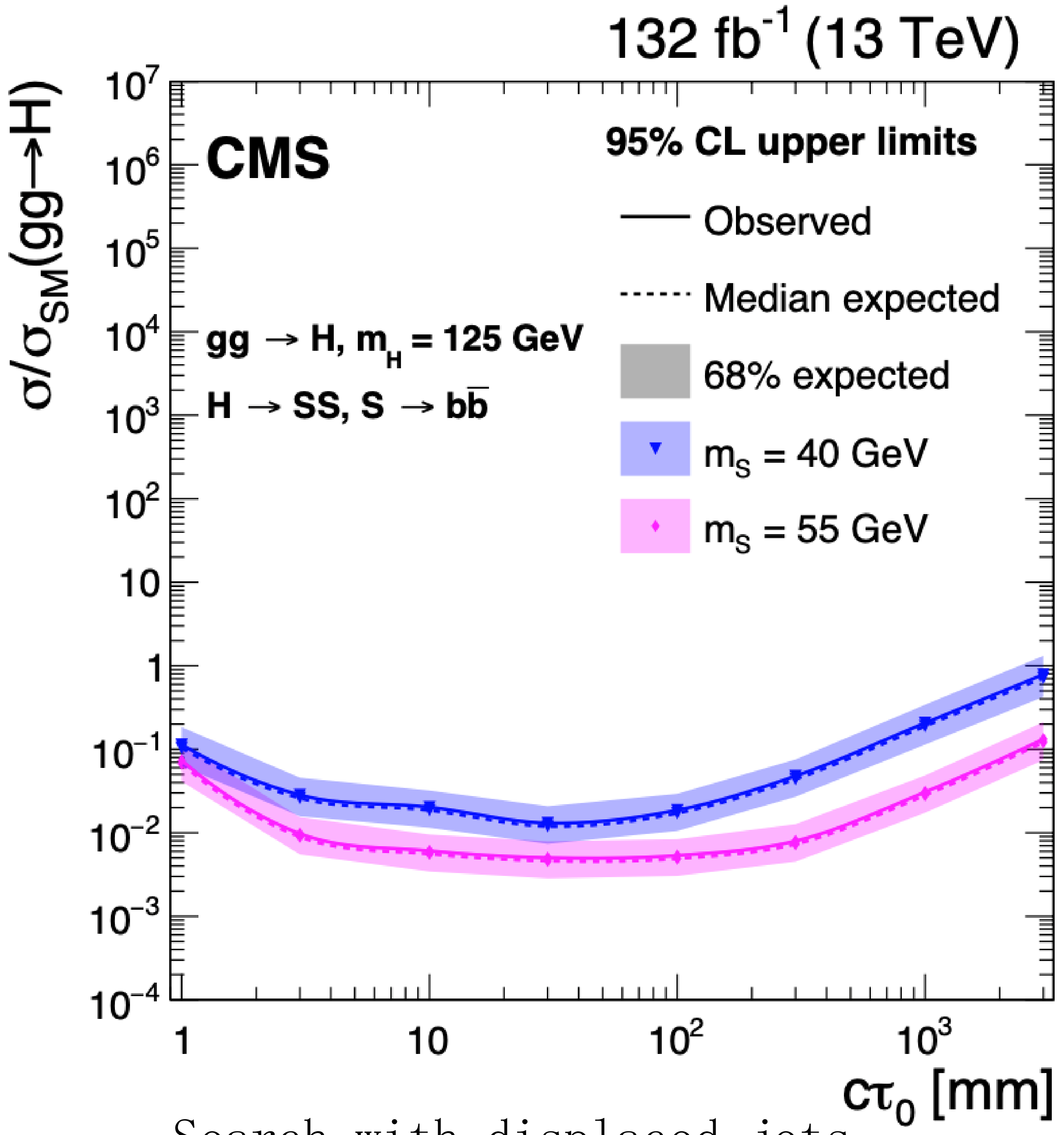






Search with displaced vertices





Search with displaced jets

Summary

- H(125)
  - Newly established decay modes: $\mu\mu$, llγ
  - High-stat decay modes: differential (STXS) measurements
  - HH: probing the self-coupling
  - BSM (e.g. DM, LLP) constrained by H(125)

BACK UP

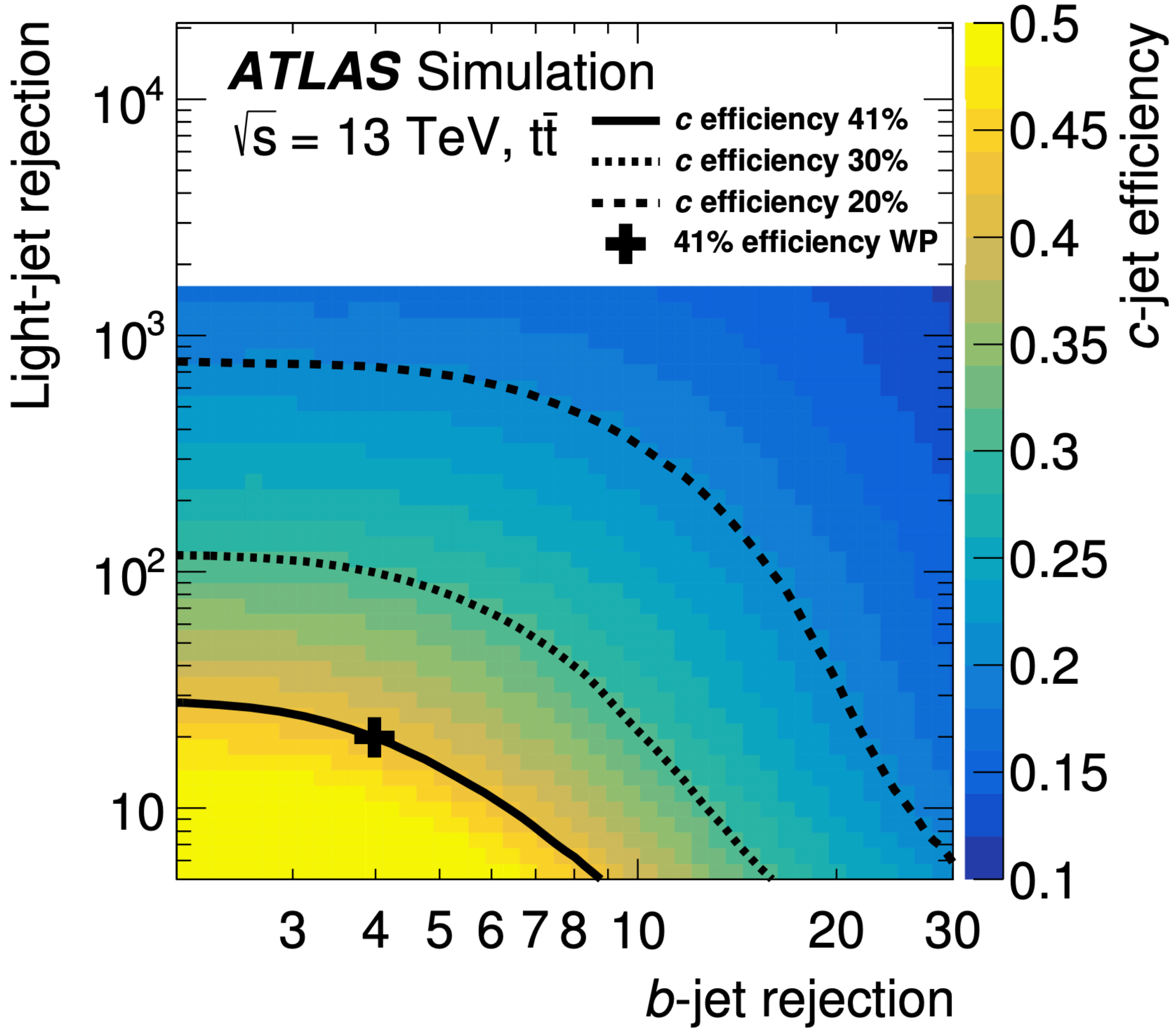
PRL120(2018)211802

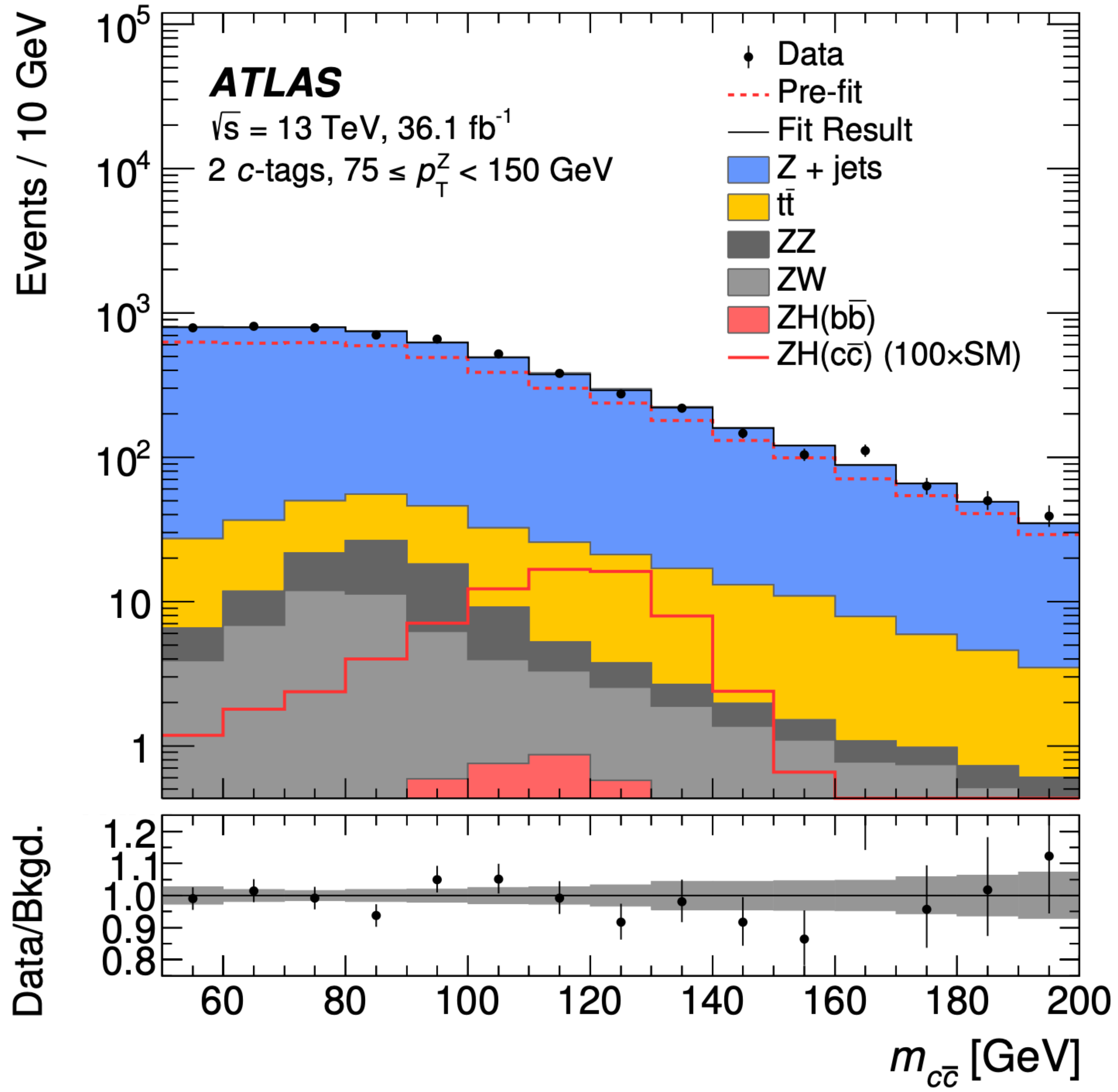
charm-charm decay (ATLAS)

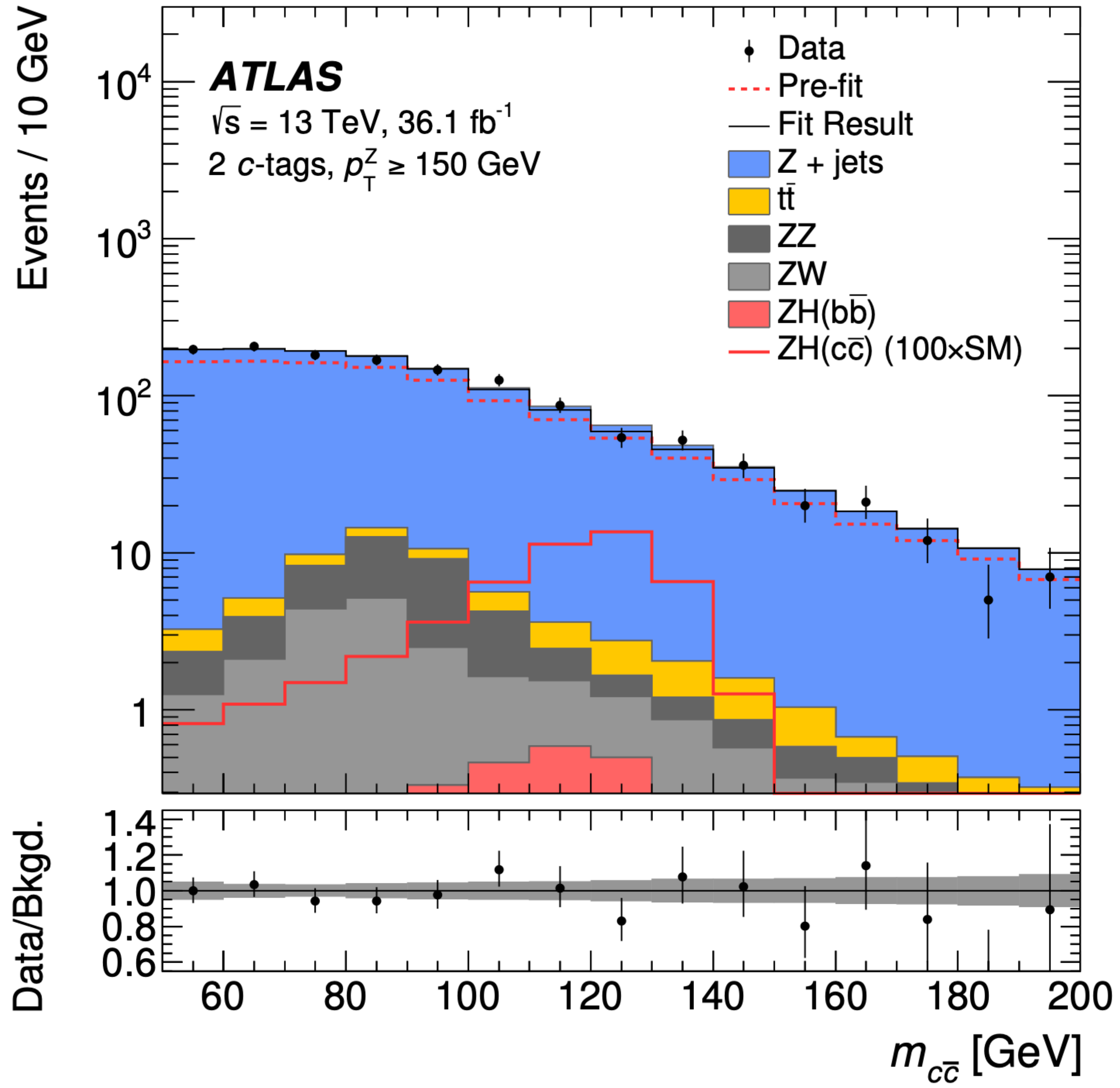
$ZH \rightarrow l^+ l^- c\bar{c}$

BDT classifier to distinguish b/c/light jets

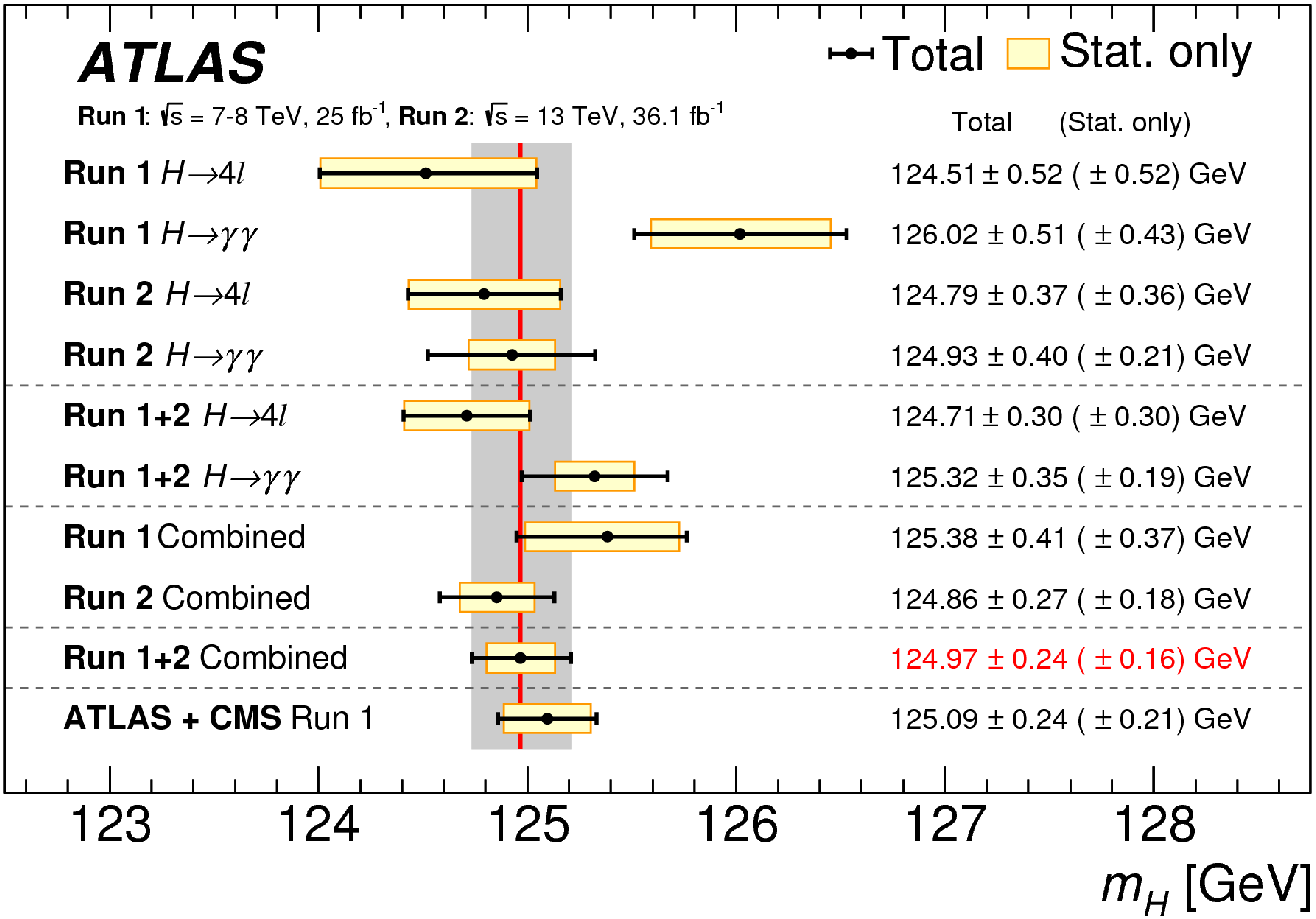
4 categories of different signal purity (# of c-tags and Z p_T)
Search in the mass spectrum of the leading two-jet system







pper limit on signal strength
110 (150^{+80}_{-40}) at 95% CL



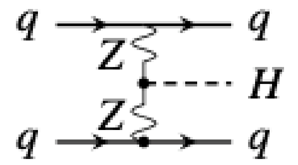
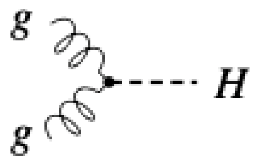
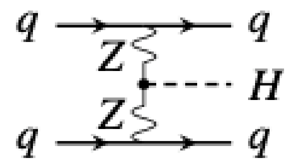
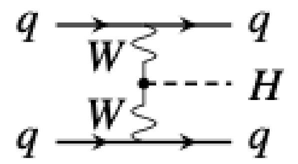
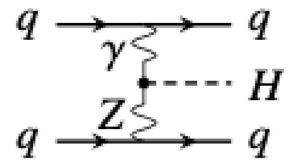
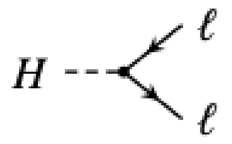
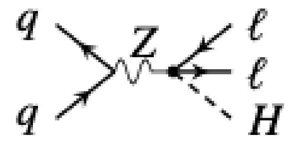
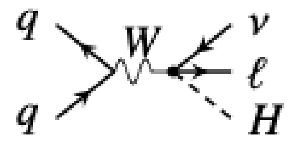
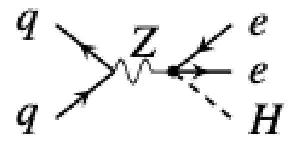
ATLAS
Run 1: √s = 7-8 TeV, 25 fb-1, Run 2: √s = 13 TeV, 36.1 fb-1
Total
Stat. only
Total (Stat. only)
Run 1 H→4l
124.51 ± 0.52 (± 0.52) GeV
Run 1 H→γγ
126.02 ± 0.51 (± 0.43) GeV
Run 2 H→4l
124.79 ± 0.37 (± 0.36) GeV
Run 2 H→γγ
124.93 ± 0.40 (± 0.21) GeV
Run 1+2 H→4l
124.71 ± 0.30 (± 0.30) GeV
Run 1+2 H→γγ
125.32 ± 0.35 (± 0.19) GeV
Run 1 Combined
125.38 ± 0.41 (± 0.37) GeV
Run 2 Combined
124.86 ± 0.27 (± 0.18) GeV
Run 1+2 Combined
124.97 ± 0.24 (± 0.16) GeV
ATLAS + CMS Run 1
125.09 ± 0.24 (± 0.21) GeV
123
124
125
126
127
128
mH [GeV]

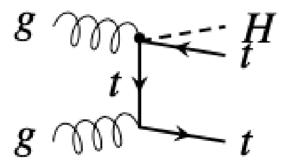
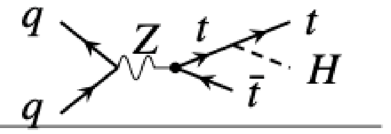
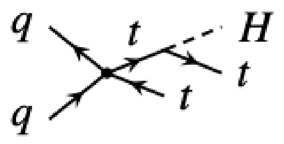
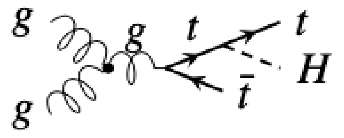
Dim-6 Warsaw basis

Wilson coefficient	Operator
$c_{H\Box}$	$(H^\dagger H)\Box(H^\dagger H)$
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$
c_{uH}	$(H^\dagger H)(\bar{q}_p u_r \widetilde{H})$
c_{dH}	$(H^\dagger H)(\bar{q}_p d_r \widetilde{H})$
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$

Wilson coefficient	Operator
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$
c'_{ll}	$(\bar{l}_p \gamma_\mu l_t)(\bar{l}_r \gamma^\mu l_s)$
$c^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$
$c^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$
c_{qq}	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$
$c^{(31)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$
c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$
$c^{(1)}_{uu}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$
$c^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$
$c^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$
$c^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
$c^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$
c_W	$\epsilon^{IJK} W^{I\nu}_\mu W^{J\rho}_\nu W^{K\mu}_\rho$
c_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$

Most relevant EFT operators

Coefficient	Operator	Example process
c_{HDD}	$\left(H^\dagger D^\mu H\right)^* \left(H^\dagger D_\mu H\right)$	
c_{HG}	$H^\dagger H\, G^A_{\mu\nu} G^{A\mu\nu}$	
c_{HB}	$H^\dagger H\, B_{\mu\nu} B^{\mu\nu}$	
c_{HW}	$H^\dagger H\, W^I_{\mu\nu} W^{I\mu\nu}$	
c_{HWB}	$H^\dagger \tau^I H\, W^I_{\mu\nu} B^{\mu\nu}$	
c_{eH}	$(H^\dagger H)(\bar{l}_p e_r H)$	
$c^{(1)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{l}_p \gamma^\mu l_r)$	
$c^{(3)}_{Hl}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{l}_p \tau^I \gamma^\mu l_r)$	
c_{He}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{e}_p \gamma^\mu e_r)$	
$c^{(1)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_p \gamma^\mu q_r)$	
$c^{(3)}_{Hq}$	$(H^\dagger i\overleftrightarrow{D}^I_\mu H)(\bar{q}_p \tau^I \gamma^\mu q_r)$	
c_{Hu}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_p \gamma^\mu u_r)$	
c_{Hd}	$(H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{d}_p \gamma^\mu d_r)$	

Coefficient	Operator	Example process
c_{uG}	$(\bar{q}_p \sigma^{\mu\nu} T^A u_r)\widetilde{H}\, G^A_{\mu\nu}$	
c_{uW}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\tau^I \widetilde{H}\, W^I_{\mu\nu}$	
c_{uB}	$(\bar{q}_p \sigma^{\mu\nu} u_r)\widetilde{H}\, B_{\mu\nu}$	
$c^{(1)}_{qq}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c^{(3)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	
c_{qq}	$(\bar{q}_p \gamma_\mu q_t)(\bar{q}_r \gamma^\mu q_s)$	
$c^{(31)}_{qq}$	$(\bar{q}_p \gamma_\mu \tau^I q_t)(\bar{q}_r \gamma^\mu \tau^I q_s)$	
c_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	
$c^{(1)}_{uu}$	$(\bar{u}_p \gamma_\mu u_t)(\bar{u}_r \gamma^\mu u_s)$	
$c^{(1)}_{qu}$	$(\bar{q}_p \gamma_\mu q_t)(\bar{u}_r \gamma^\mu u_s)$	
$c^{(8)}_{ud}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
$c^{(8)}_{qu}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$	
$c^{(8)}_{qd}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$	
c_G	$f^{ABC} G^{A\nu}_\mu G^{B\rho}_\nu G^{C\mu}_\rho$	

ATLAS H->4L fiducical definition

Leptons and jets	
Leptons	$p_T > 5$ GeV, $\|\eta\| < 2.7$
Jets	$p_T > 30$ GeV, $\|y\| < 4.4$
Lepton selection and pairing	
Lepton kinematics	$p_T > 20, 15, 10$ GeV
Leading pair (m_{12})	SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Subleading pair (m_{34})	remaining SFOC lepton pair with smallest $\|m_Z - m_{\ell\ell}\|$
Event selection (at most one quadruplet per event)	
Mass requirements	50 GeV$< m_{12} <$ 106 GeV and 12 GeV$< m_{34} <$ 115 GeV
Lepton separation	$\Delta R(\ell_i, \ell_j) > 0.1$
Lepton/Jet separation	$\Delta R(\ell_i, \text{jet}) > 0.1$
J/ψ veto	$m(\ell_i, \ell_j) > 5$ GeV for all SFOC lepton pairs
Mass window	105 GeV$< m_{4\ell} <$ 160 GeV
If extra lepton with $p_T > 12$ GeV	Quadruplet with largest matrix element value

ATLAS Diboson Searches - 95% CL Exclusion Limits

Status: June 2021

ATLAS Preliminary

$\mathcal{L}$ = (36.1 – 139) fb^{-1} $\sqrt{s}$ = 13 TeV

	Model	Channel†	Strategy*	Limit	Reference
Extra dimensions	Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	$R \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.2 TeV	Eur. Phys. J. C 80 (2020) 1165
	Bulk RS ($k\pi r_c = 35$, $\Lambda_R = 3$ TeV)	$R \to WW, ZZ \to qqqq$	boosted	1.3-3.0 TeV	JHEP 06 (2020) 042
	RS1 ($k/\overline{M}_{Pl} = 0.01$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-2.2 TeV	arXiv:2102.13405
	RS1 ($k/\overline{M}_{Pl} = 0.05$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-3.9 TeV	arXiv:2102.13405
	RS1 ($k/\overline{M}_{Pl} = 0.1$)	$G_{KK} \to \gamma\gamma$	resolved	0.5-4.5 TeV	arXiv:2102.13405
	Bulk RS ($k/\overline{M}_{Pl} = 0.5$)	$G_{KK} \to WW \to e\nu\mu\nu$	resolved	0.2-0.75 TeV	Eur. Phys. J. C 78 (2018) 24
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to ZZ \to \ell\ell\ell'\ell', \nu\nu\ell\ell$	resolved	0.6-1.75 TeV	Eur. Phys. J. C 81 (2021) 332
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW \to e\nu\mu\nu$	resolved	0.2-1.1 TeV	Eur. Phys. J. C 78 (2018) 24
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-2.0 TeV	Eur. Phys. J. C 80 (2020) 1165
	Bulk RS ($k/\overline{M}_{Pl} = 1.0$)	$G_{KK} \to WW, ZZ \to qqqq$	boosted	1.3-1.8 TeV	JHEP 06 (2020) 042
Gauge bosons	HVT ($g_F = -0.55$, $g_H = -0.56$)	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.25-2.26 TeV	Phys. Lett. B 787 (2018) 68
	HVT ($g_F = -0.55$, $g_H = -0.56$)	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.3-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT ($g_F = -0.55$, $g_H = -0.56$)	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.4-2.95 TeV	ATLAS-CONF-2021-026
	HVT ($g_F = -0.55$, $g_H = -0.56$)	$W' \to WZ \to qqqq$	boosted	1.3-3.4 TeV	JHEP 06 (2020) 042
	HVT ($g_F = -0.55$, $g_H = -0.56$)	$W' \to WH \to qqbb$	boosted	1.5-2.9 TeV	Phys. Rev. D 102 (2020) 112008
	HVT ($g_F = -0.55$, $g_H = -0.56$)	$Z' \to WW \to e\nu\mu\nu$	resolved	0.2-1.3 TeV	Eur. Phys. J. C 78 (2018) 24
	HVT ($g_F = -0.55$, $g_H = -0.56$)	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.3-3.5 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT ($g_F = -0.55$, $g_H = -0.56$)	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.3-2.9 TeV	ATLAS-CONF-2020-043
	HVT ($g_F = -0.55$, $g_H = -0.56$)	$Z' \to WW \to qqqq$	boosted	1.3-2.9 TeV	JHEP 06 (2020) 042
	HVT ($g_F = -0.55$, $g_H = -0.56$)	$Z' \to ZH \to qqbb$	boosted	1.5-2.2 TeV	Phys. Rev. D 102 (2020) 112008
	HVT ($g_F = 0.14$, $g_H = -2.9$)	$W' \to WZ \to \ell\nu\ell'\ell'$	resolved	0.8-2.46 TeV	Phys. Lett. B 787 (2018) 68
	HVT ($g_F = 0.14$, $g_H = -2.9$)	$W' \to WZ \to \nu\nu qq, \ell\nu qq, \ell\ell qq$	resolved, boosted	0.8-4.3 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT ($g_F = 0.14$, $g_H = -2.9$)	$W' \to WH \to \ell\nu bb$	resolved, boosted	0.8-3.15 TeV	ATLAS-CONF-2021-026
	HVT ($g_F = 0.14$, $g_H = -2.9$)	$W' \to WZ \to qqqq$	boosted	1.3-3.6 TeV	JHEP 06 (2020) 042
	HVT ($g_F = 0.14$, $g_H = -2.9$)	$W' \to WH \to qqbb$	boosted	1.5-3.2 TeV	Phys. Rev. D 102 (2020) 112008
	HVT ($g_F = 0.14$, $g_H = -2.9$)	$Z' \to WW \to \ell\nu qq$	resolved, boosted	0.8-3.9 TeV	Eur. Phys. J. C 80 (2020) 1165
	HVT ($g_F = 0.14$, $g_H = -2.9$)	$Z' \to ZH \to \nu\nu bb, \ell\ell bb$	resolved, boosted	0.8-3.2 TeV	ATLAS-CONF-2020-043
	HVT ($g_F = 0.14$, $g_H = -2.9$)	$Z' \to WW \to qqqq$	boosted	1.3-3.1 TeV	JHEP 06 (2020) 042
	HVT ($g_F = 0.14$, $g_H = -2.9$)	$Z' \to ZH \to qqbb$	boosted	1.5-2.65 TeV	Phys. Rev. D 102 (2020) 112008

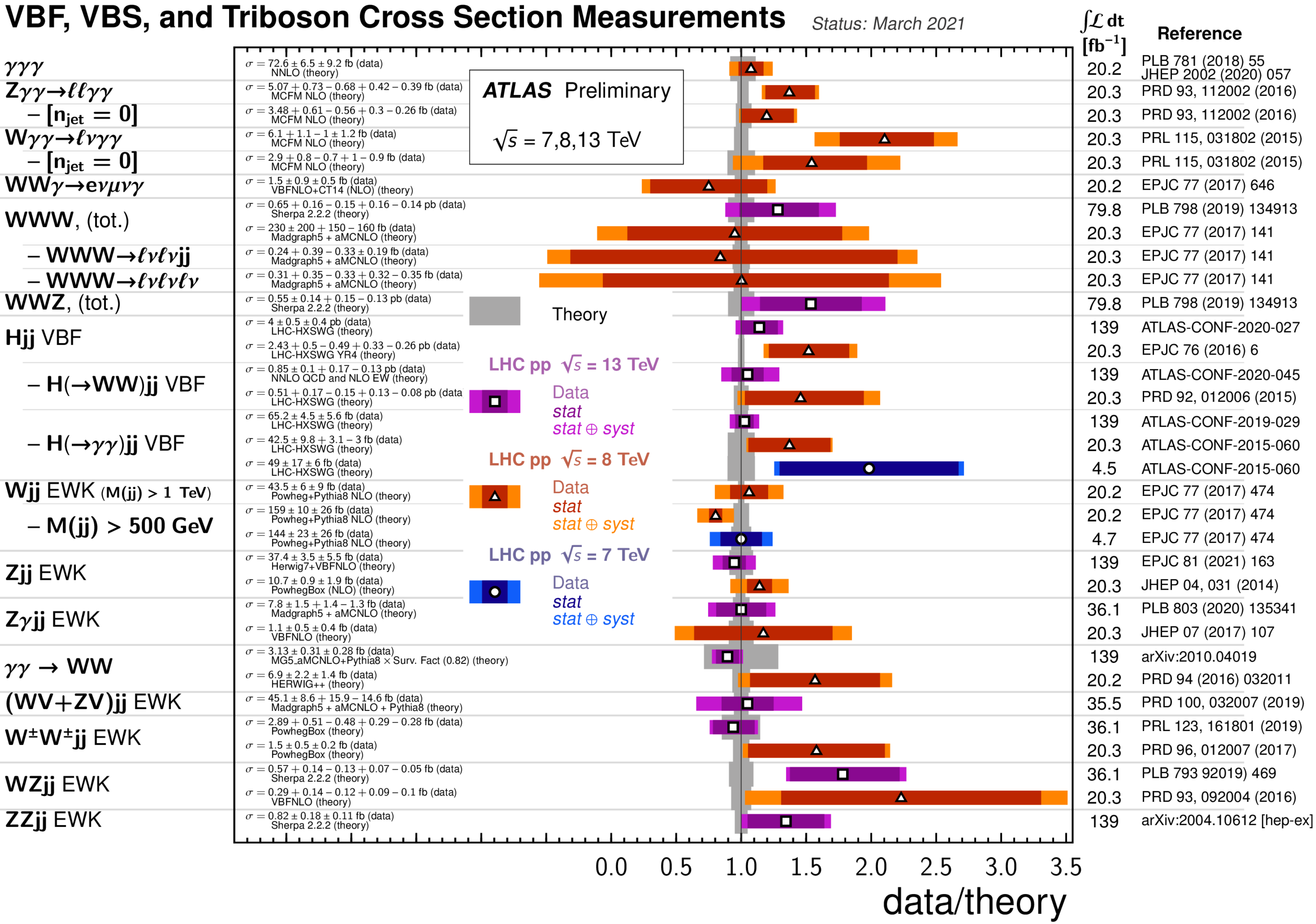
0.2 0.4 0.6 0.8 1 2 3 4 5

Excluded mass range [TeV]

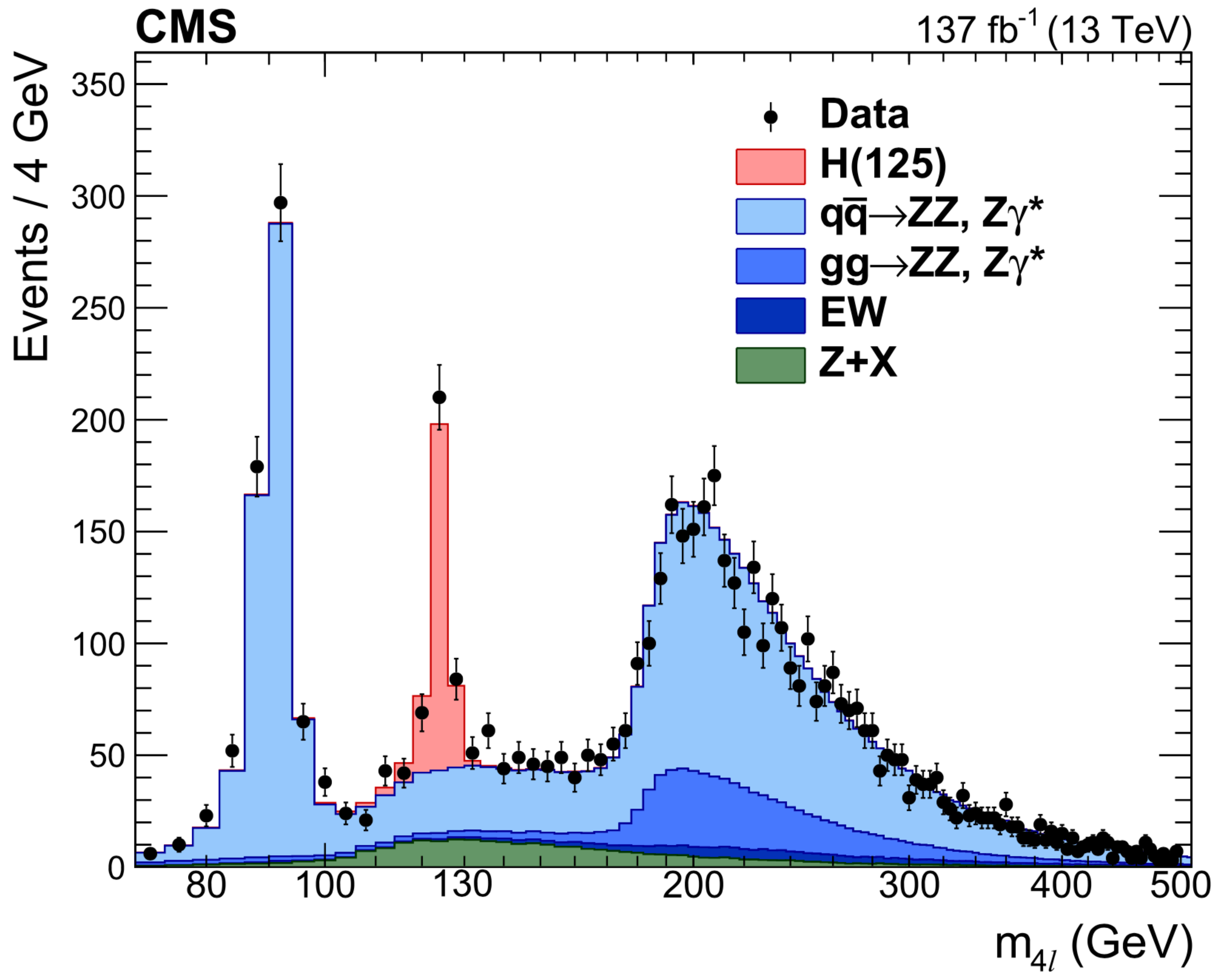
$\sqrt{s}$ = 13 TeV, $\mathcal{L}$ = 36.1 fb^{-1} $\sqrt{s}$ = 13 TeV, $\mathcal{L}$ = 139 fb^{-1}

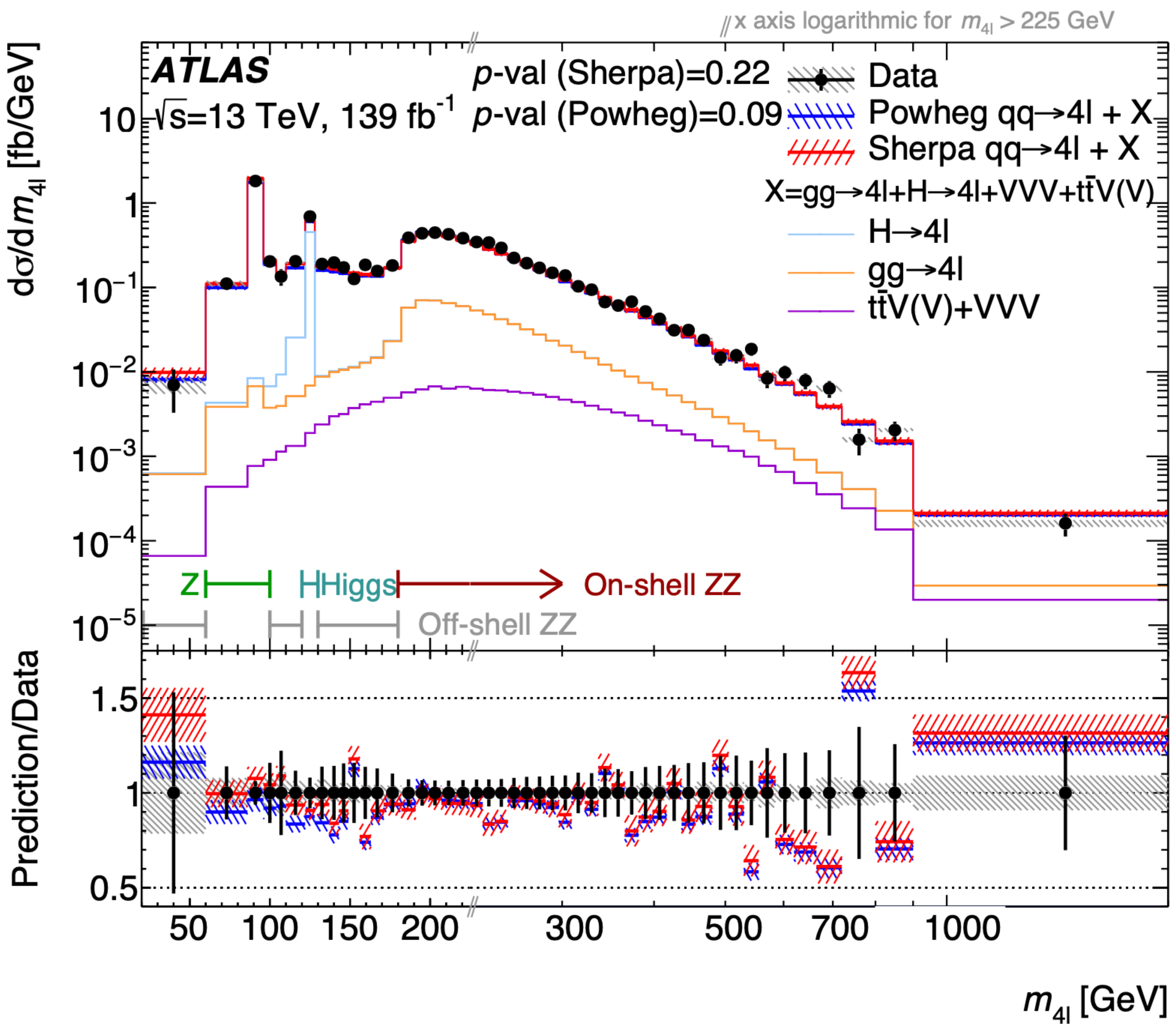
*small-radius (large-radius) jets are used in resolved (boosted) events

†with $\ell = \mu, e$


VBF, VBS, and Triboson Cross Section Measurements
Status: March 2021
∫ℒ dt [fb⁻¹]
Reference
ATLAS Preliminary
√s = 7,8,13 TeV
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
γγγ
Zγγ→ℓℓγγ
– [n_jet = 0]
Wγγ→ℓνγγ
– [n_jet = 0]
WWγ→eνμνγ
WWW, (tot.)
– WWW→ℓνℓνjj
– WWW→ℓνℓνℓν
WWZ, (tot.)
Hjj VBF
– H(→WW)jj VBF
– H(→γγ)jj VBF
Wjj EWK (M(jj) > 1 TeV)
– M(jj) > 500 GeV
Zjj EWK
Zγjj EWK
γγ → WW
(WV+ZV)jj EWK
W±W±jj EWK
WZjj EWK
ZZjj EWK
σ = 72.6 ± 6.5 ± 9.2 fb (data) NNLO (theory)
σ = 5.07 + 0.73 − 0.68 + 0.42 − 0.39 fb (data) MCFM NLO (theory)
σ = 3.48 + 0.61 − 0.56 + 0.3 − 0.26 fb (data) MCFM NLO (theory)
σ = 6.1 + 1.1 − 1 ± 1.2 fb (data) MCFM NLO (theory)
σ = 2.9 + 0.8 − 0.7 + 1 − 0.9 fb (data) MCFM NLO (theory)
σ = 1.5 ± 0.9 ± 0.5 fb (data) VBFNLO+CT14 (NLO) (theory)
σ = 0.65 + 0.16 − 0.15 + 0.16 − 0.14 pb (data) Sherpa 2.2.2 (theory)
σ = 230 ± 200 + 150 − 160 fb (data) Madgraph5 + aMCNLO (theory)
σ = 0.24 + 0.39 − 0.33 ± 0.19 fb (data) Madgraph5 + aMCNLO (theory)
σ = 0.31 + 0.35 − 0.33 + 0.32 − 0.35 fb (data) Madgraph5 + aMCNLO (theory)
σ = 0.55 ± 0.14 + 0.15 − 0.13 pb (data) Sherpa 2.2.2 (theory)
σ = 4 ± 0.5 ± 0.4 pb (data) LHC-HXSWG (theory)
σ = 2.43 + 0.5 − 0.49 + 0.33 − 0.26 pb (data) LHC-HXSWG YR4 (theory)
σ = 0.85 ± 0.1 + 0.17 − 0.13 pb (data) NNLO QCD and NLO EW (theory)
σ = 0.51 + 0.17 − 0.15 + 0.13 − 0.08 pb (data) LHC-HXSWG (theory)
σ = 65.2 ± 4.5 ± 5.6 fb (data) LHC-HXSWG (theory)
σ = 42.5 ± 9.8 + 3.1 − 3 fb (data) LHC-HXSWG (theory)
σ = 49 ± 17 ± 6 fb (data) LHC-HXSWG (theory)
σ = 43.5 ± 6 ± 9 fb (data) Powheg+Pythia8 NLO (theory)
σ = 159 ± 10 ± 26 fb (data) Powheg+Pythia8 NLO (theory)
σ = 144 ± 23 ± 26 fb (data) Powheg+Pythia8 NLO (theory)
σ = 37.4 ± 3.5 ± 5.5 fb (data) Herwig7+VBFNLO (theory)
σ = 10.7 ± 0.9 ± 1.9 fb (data) PowhegBox (NLO) (theory)
σ = 7.8 ± 1.5 + 1.4 − 1.3 fb (data) Madgraph5 + aMCNLO (theory)
σ = 1.1 ± 0.5 ± 0.4 fb (data) VBFNLO (theory)
σ = 3.13 ± 0.31 ± 0.28 fb (data) MG5_aMCNLO+Pythia8 × Surv. Fact (0.82) (theory)
σ = 6.9 ± 2.2 ± 1.4 fb (data) HERWIG++ (theory)
σ = 45.1 ± 8.6 + 15.9 − 14.6 fb (data) Madgraph5 + aMCNLO + Pythia8 (theory)
σ = 2.89 + 0.51 − 0.48 + 0.29 − 0.28 fb (data) PowhegBox (theory)
σ = 1.5 ± 0.5 ± 0.2 fb (data) PowhegBox (theory)
σ = 0.57 + 0.14 − 0.13 + 0.07 − 0.05 fb (data) Sherpa 2.2.2 (theory)
σ = 0.29 + 0.14 − 0.12 + 0.09 − 0.1 fb (data) VBFNLO (theory)
σ = 0.82 ± 0.18 ± 0.11 fb (data) Sherpa 2.2.2 (theory)
20.2 PLB 781 (2018) 55 JHEP 2002 (2020) 057
20.3 PRD 93, 112002 (2016)
20.3 PRD 93, 112002 (2016)
20.3 PRL 115, 031802 (2015)
20.3 PRL 115, 031802 (2015)
20.2 EPJC 77 (2017) 646
79.8 PLB 798 (2019) 134913
20.3 EPJC 77 (2017) 141
20.3 EPJC 77 (2017) 141
20.3 EPJC 77 (2017) 141
79.8 PLB 798 (2019) 134913
139 ATLAS-CONF-2020-027
20.3 EPJC 76 (2016) 6
139 ATLAS-CONF-2020-045
20.3 PRD 92, 012006 (2015)
139 ATLAS-CONF-2019-029
20.3 ATLAS-CONF-2015-060
4.5 ATLAS-CONF-2015-060
20.2 EPJC 77 (2017) 474
20.2 EPJC 77 (2017) 474
4.7 EPJC 77 (2017) 474
139 EPJC 81 (2021) 163
20.3 JHEP 04, 031 (2014)
36.1 PLB 803 (2020) 135341
20.3 JHEP 07 (2017) 107
139 arXiv:2010.04019
20.2 PRD 94 (2016) 032011
35.5 PRD 100, 032007 (2019)
36.1 PRL 123, 161801 (2019)
20.3 PRD 96, 012007 (2017)
36.1 PLB 793 92019) 469
20.3 PRD 93, 092004 (2016)
139 arXiv:2004.10612 [hep-ex]
0.0 0.5 1.0 1.5 2.0 2.5 3.0 3.5
data/theory

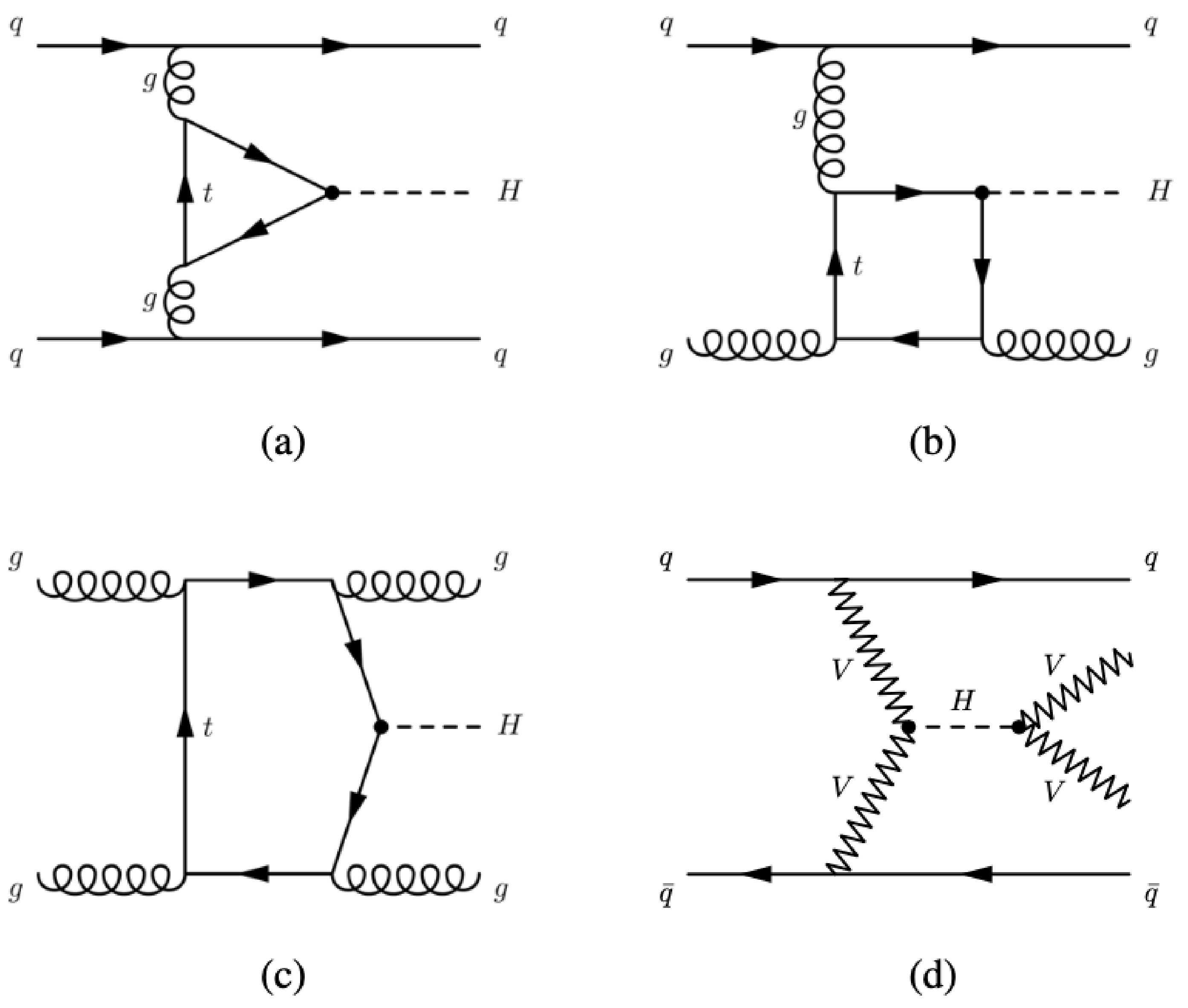
Measurements with 4-lepton final state

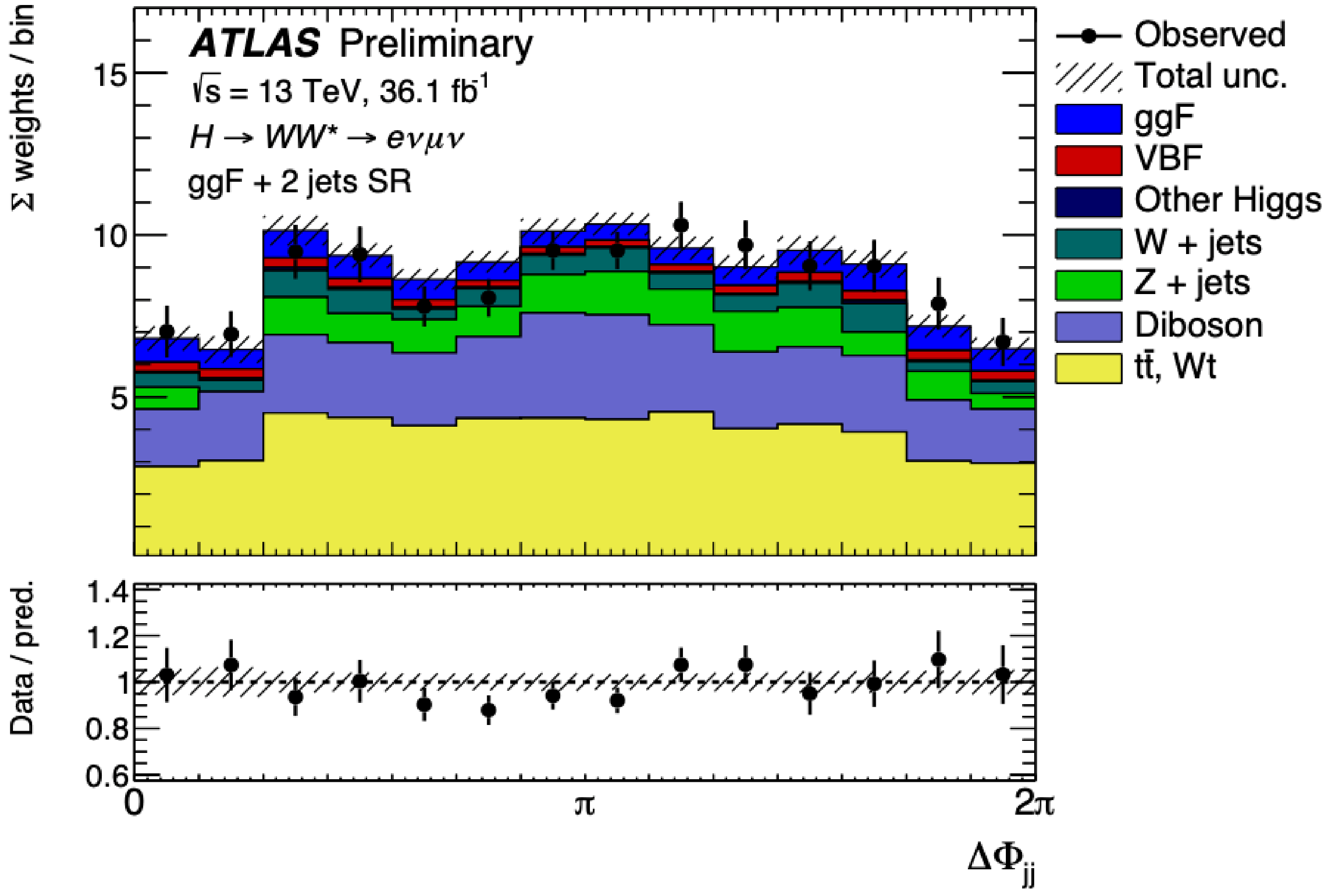


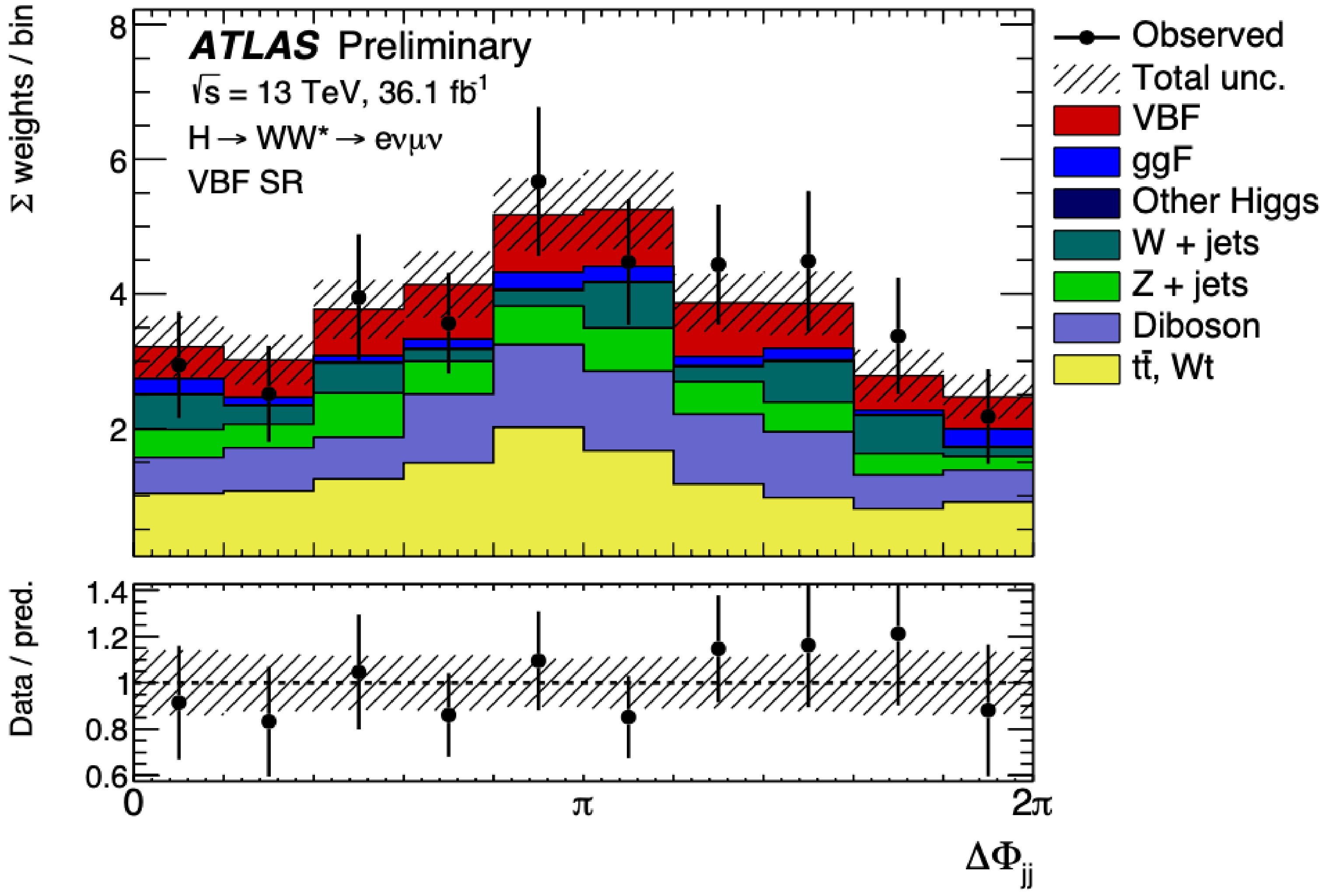


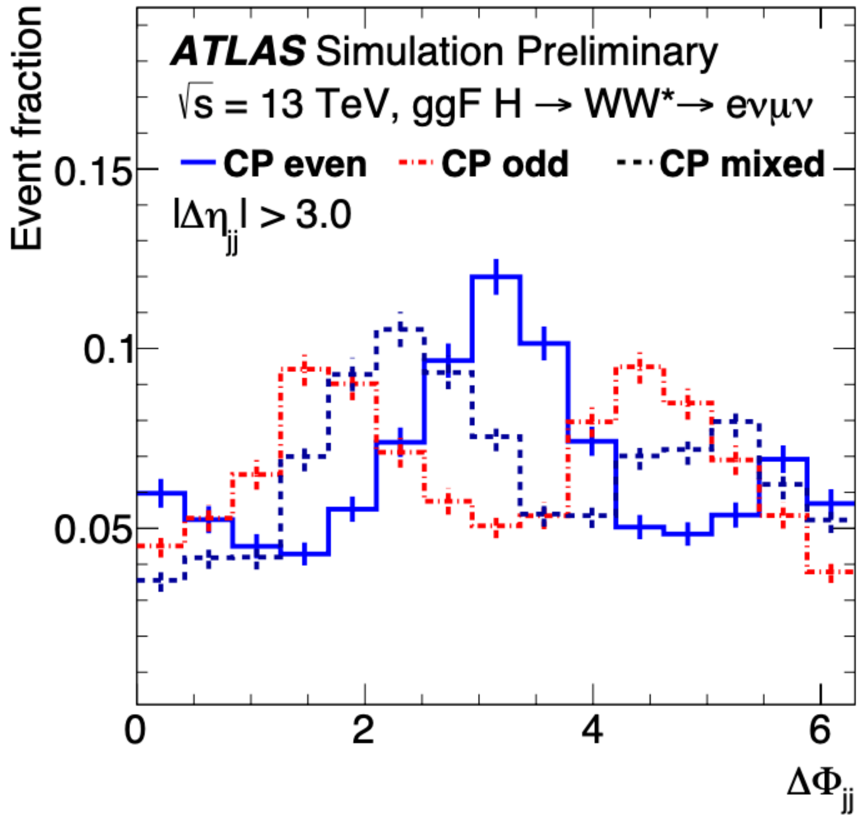
ATLAS-CONF-2020-055

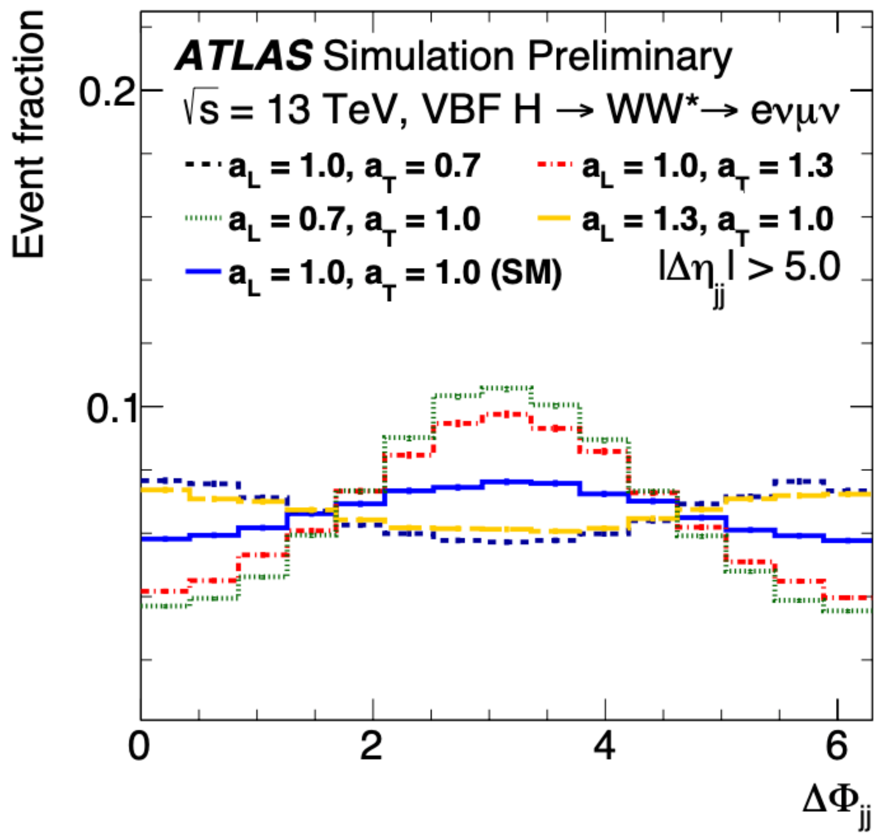
H+2j —>WW+2j (ATLAS)











$$\kappa_{Agg}/\kappa_{Hgg} = 0.0 \pm 0.4\,(stat) \pm 0.3\,(syst)$$

$$a_L = 0.91^{+0.10}_{-0.18}\,(stat)^{+0.09}_{-0.18}\,(syst)$$

$$a_T = 1.16 \pm 0.4\,(stat)^{+0.4}_{-0.3}\,(syst)$$

Test CP-odd/CP-even Hgg effective coupling and T/L polarized HVV coupling

VBS ZZ (CMS)

Phys. Lett. B 812(2020)135992

Full Run 2

	Perturbative order	SM σ (fb)	Measured σ (fb)
		ZZjj inclusive	
	LO	0.275 ± 0.021	
EW	NLO QCD	0.278 ± 0.017	$0.33^{+0.11}_{-0.10}\,(\mathrm{stat})^{+0.04}_{-0.03}\,(\mathrm{syst})$
	NLO EW	$0.242^{+0.015}_{-0.013}$	
EW+QCD		5.35 ± 0.51	$5.29^{+0.31}_{-0.30}\,(\mathrm{stat}) \pm 0.47\,(\mathrm{syst})$
		VBS-enriched (loose)	
EW	LO	0.186 ± 0.015	$0.180^{+0.070}_{-0.060}\,(\mathrm{stat})^{+0.021}_{-0.012}\,(\mathrm{syst})$
	NLO QCD	0.197 ± 0.013	
EW+QCD		1.21 ± 0.09	$1.00^{+0.12}_{-0.11}\,(\mathrm{stat}) \pm 0.07\,(\mathrm{syst})$
		VBS-enriched (tight)	
EW	LO	0.104 ± 0.008	$0.09^{+0.04}_{-0.03}\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$
	NLO QCD	0.108 ± 0.007	
EW+QCD		0.221 ± 0.014	$0.20^{+0.05}_{-0.04}\,(\mathrm{stat}) \pm 0.02\,(\mathrm{syst})$

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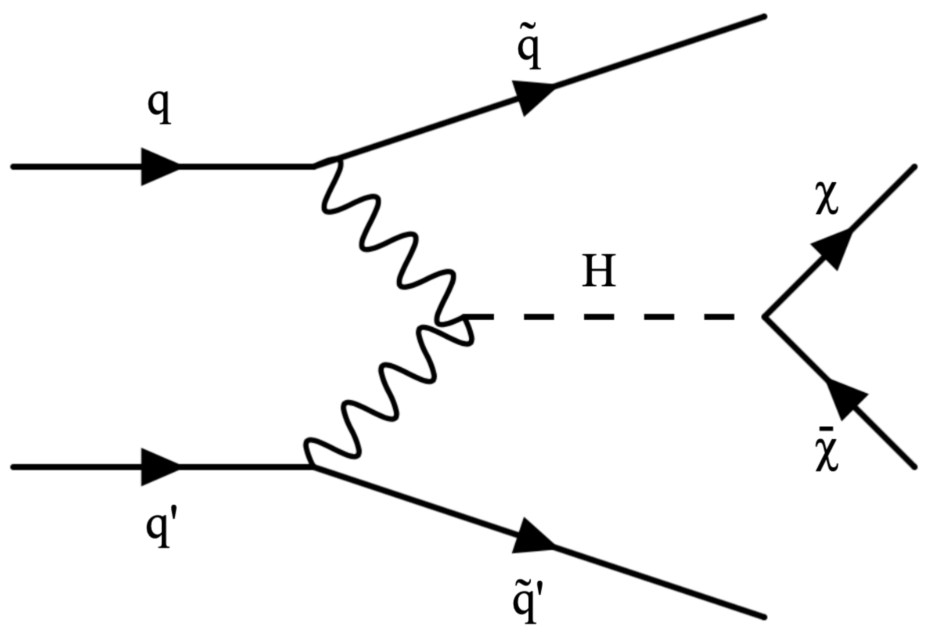
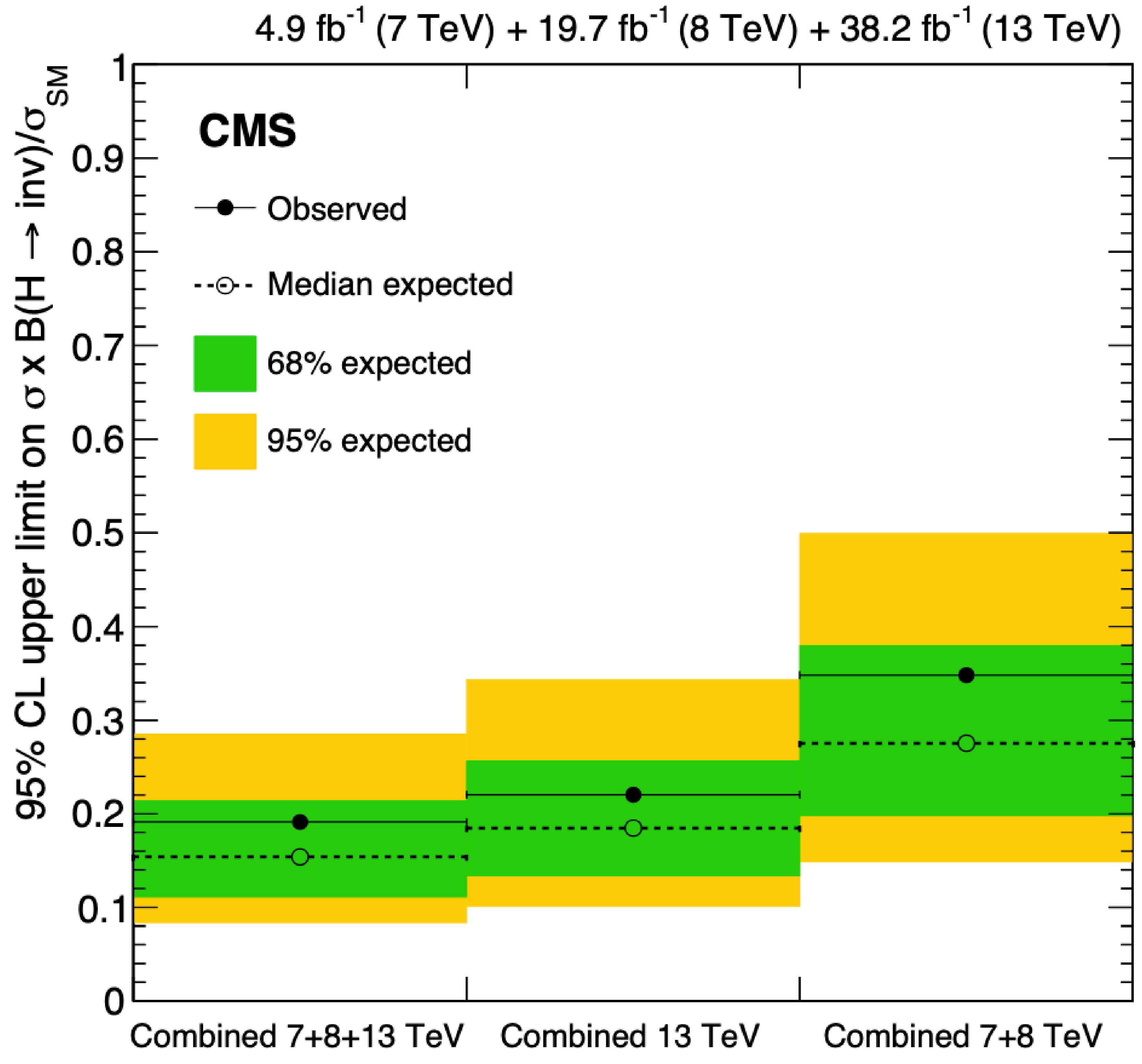
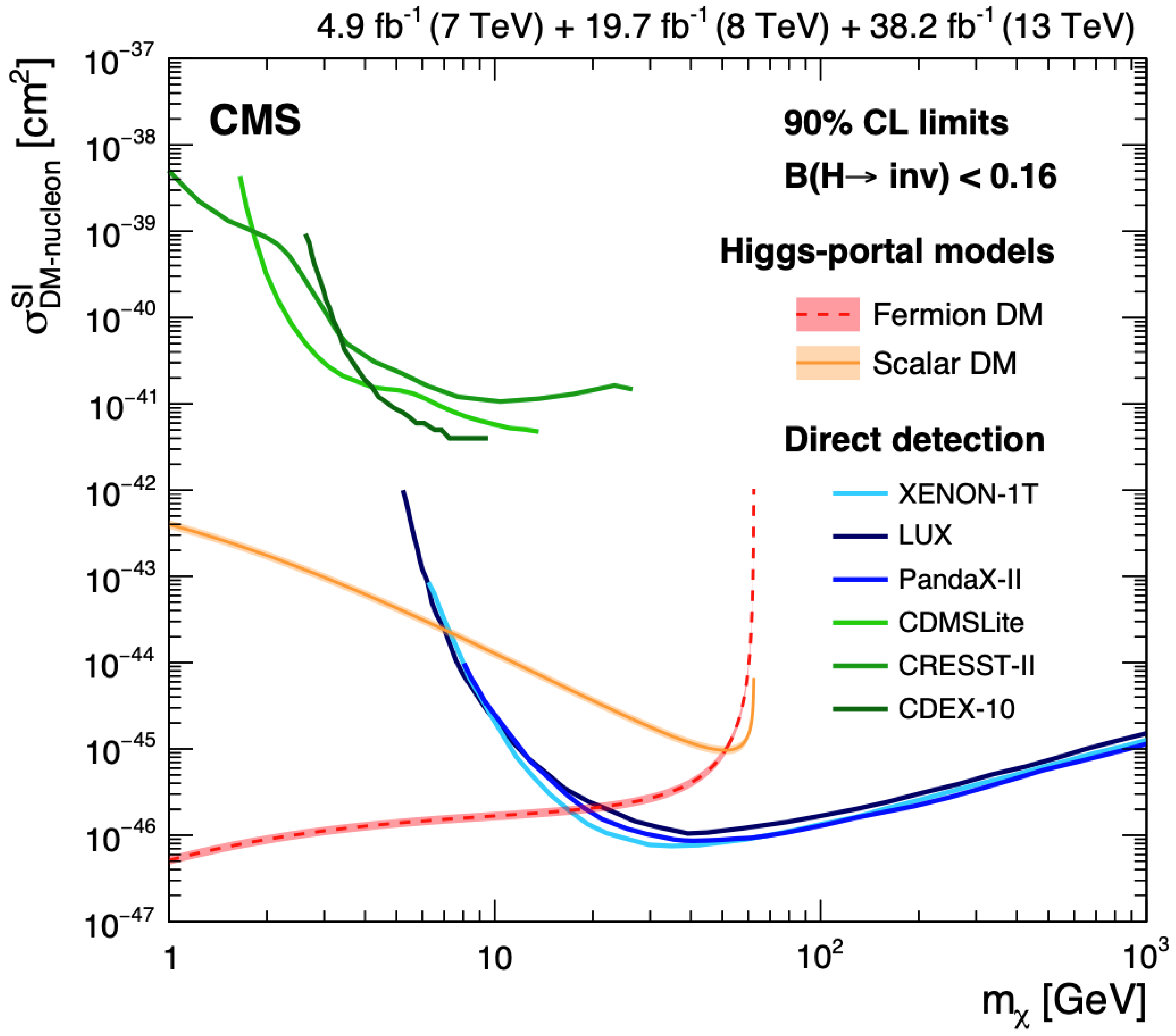
Search for H—>invisible (CMS)







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CMS H->WW differential

Measurement with e$\boldsymbol{\mu}$ final state

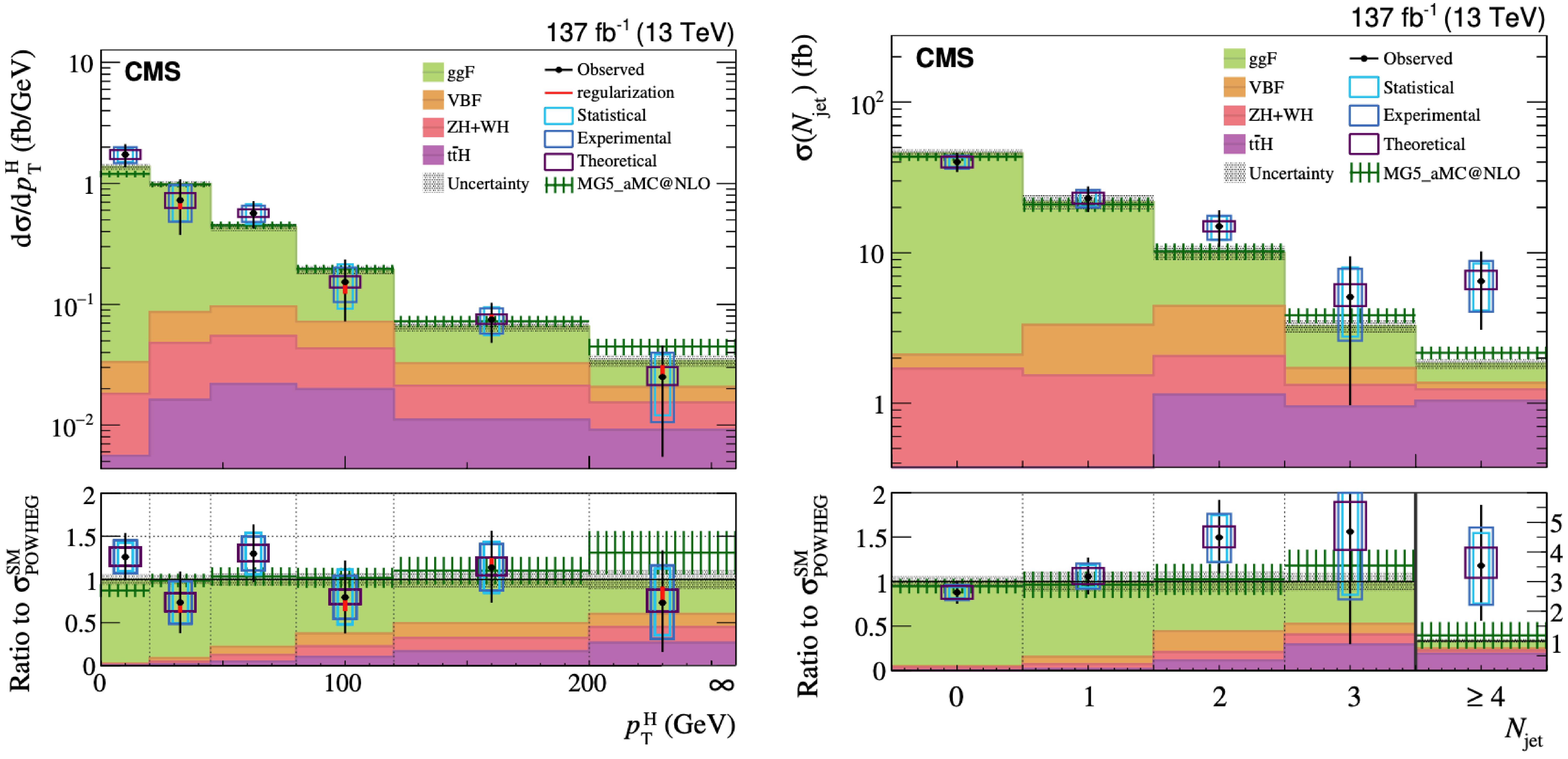
Full Run 2

Fiducial definition

Observable	Condition
Lepton origin	Direct decay of $H \to W^+W^-$
Lepton flavors; lepton charge	e μ (not from τ decay); opposite
Leading lepton p_T	$p_T^{l_1} > 25$ GeV
Trailing lepton p_T	$p_T^{l_2} > 13$ GeV
$\lvert\eta\rvert$ of leptons	$\lvert\eta\rvert < 2.5$
Dilepton mass	$m^{ll} > 12$ GeV
p_T of the dilepton system	$p_T^{ll} > 30$ GeV
Transverse mass using trailing lepton	$m_T^{l_2} > 30$ GeV
Higgs boson transverse mass	$m_T^H > 60$ GeV

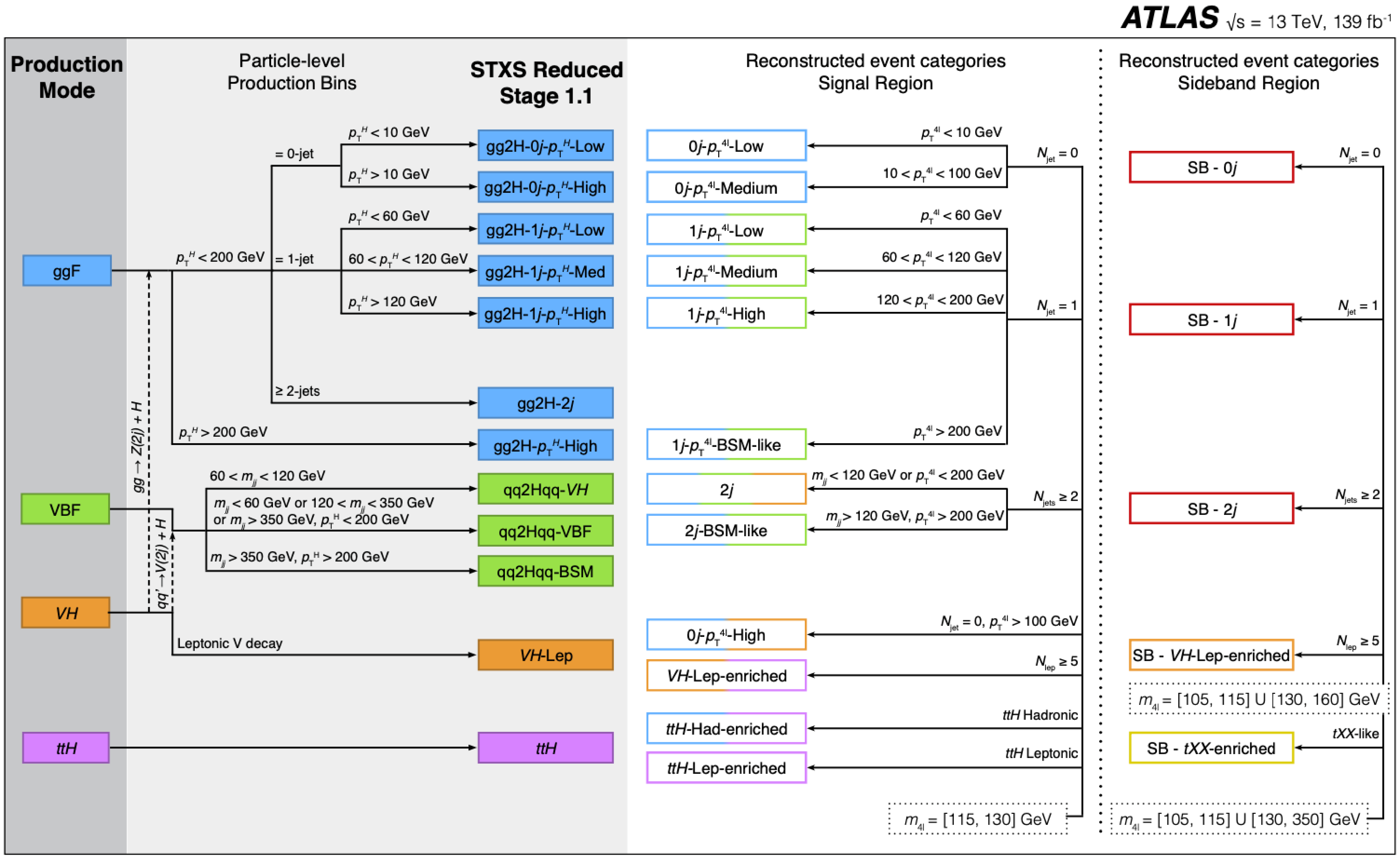
$$\sigma_{fid.}^{SM} = 82.5 \pm 4.2\,fb$$

$$\sigma_{fid.}^{obs} = 86.5 \pm 9.5\,fb$$



Fiducial cross section in bins

H—>4-lepton STXS



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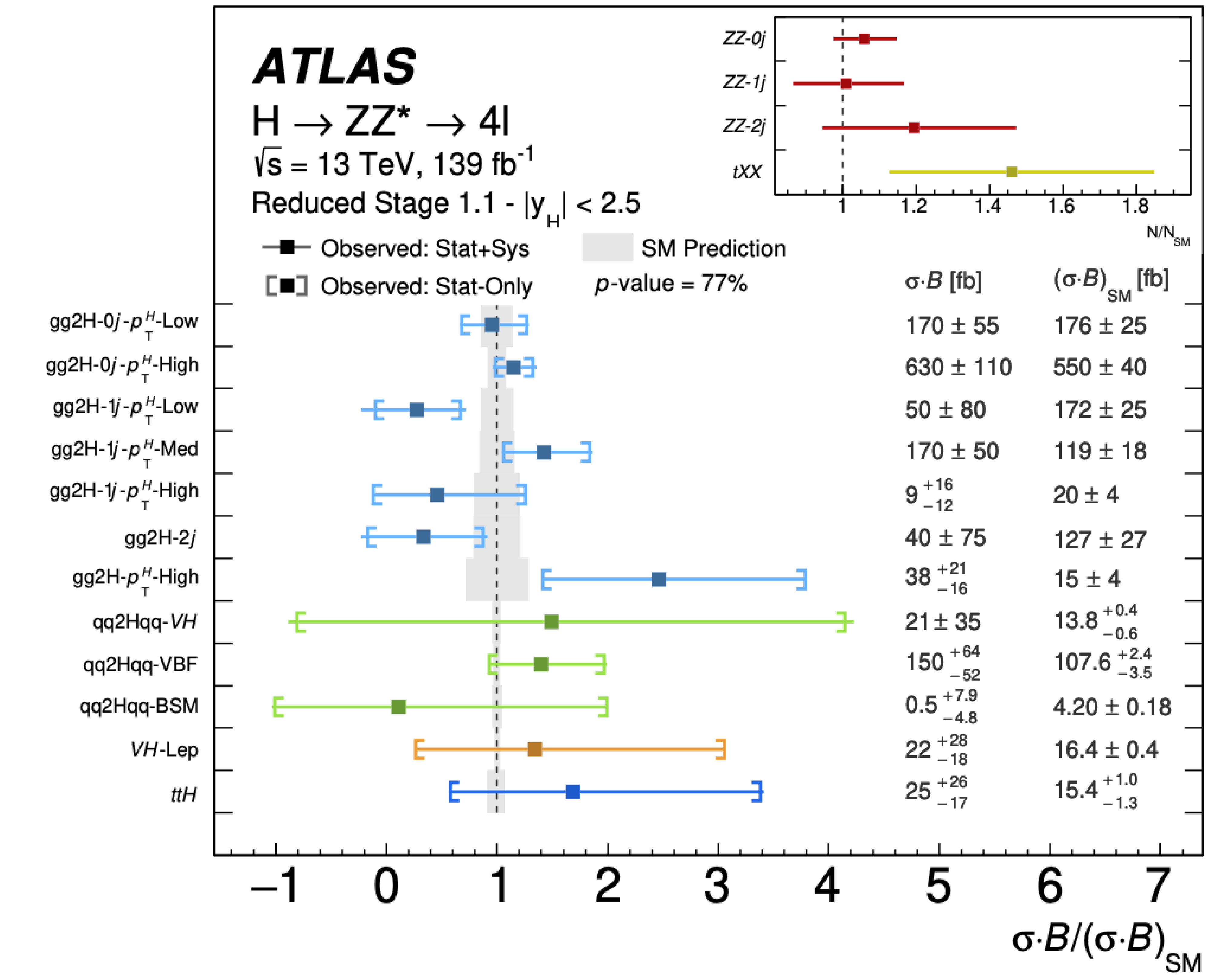
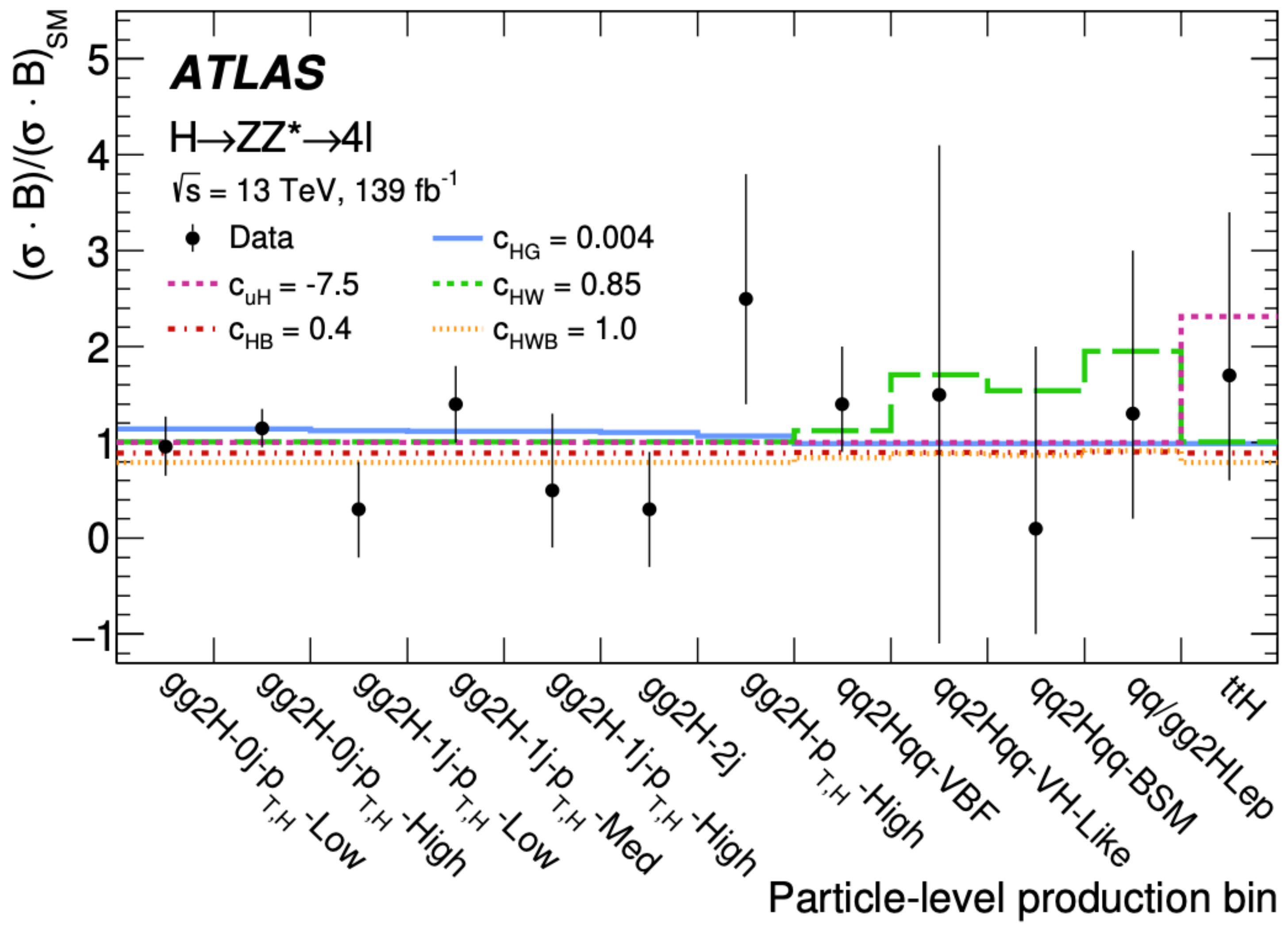
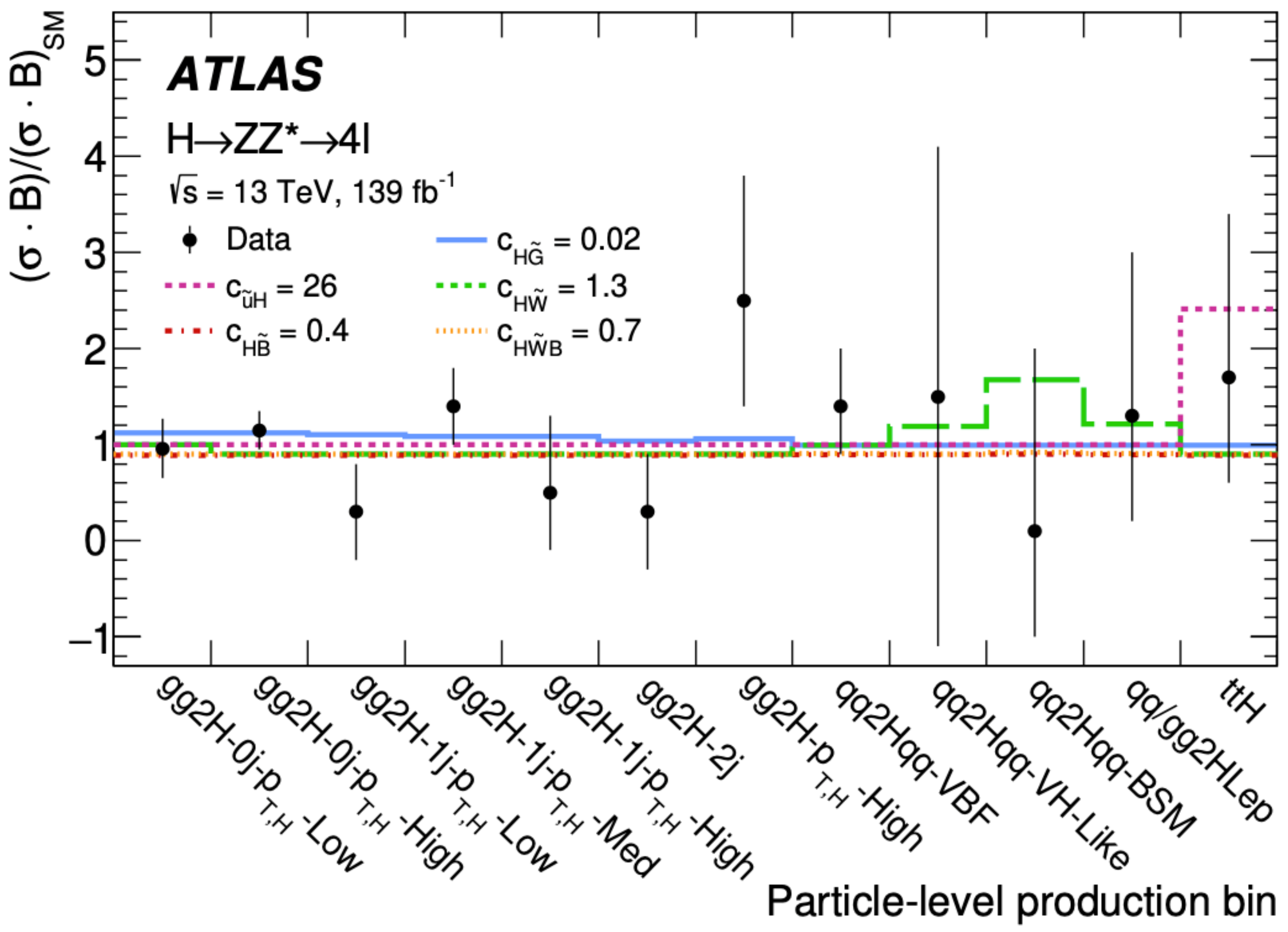
H—>4-lepton STXS results and EFT(ATLAS)



	CP-even			CP-odd			Impact on	
Operator	Structure	Coeff.	Operator	Structure	Coeff.	production	decay
O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	c_{uH}	O_{uH}	$HH^\dagger \bar{q}_p u_r \tilde{H}$	$c_{\tilde{u}H}$	ttH	-
O_{HG}	$HH^\dagger G^A_{\mu\nu} G^{\mu\nu A}$	c_{HG}	$O_{H\tilde{G}}$	$HH^\dagger \tilde{G}^A_{\mu\nu} G^{\mu\nu A}$	$c_{H\tilde{G}}$	ggF	Yes
O_{HW}	$HH^\dagger W^l_{\mu\nu} W^{\mu\nu l}$	c_{HW}	$O_{H\widetilde{W}}$	$HH^\dagger \widetilde{W}^l_{\mu\nu} W^{\mu\nu l}$	$c_{H\widetilde{W}}$	VBF, VH	Yes
O_{HB}	$HH^\dagger B_{\mu\nu} B^{\mu\nu}$	c_{HB}	$O_{H\widetilde{B}}$	$HH^\dagger \widetilde{B}_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{B}}$	VBF, VH	Yes
O_{HWB}	$HH^\dagger \tau^l W^l_{\mu\nu} B^{\mu\nu}$	c_{HWB}	$O_{H\widetilde{W}B}$	$HH^\dagger \tau^l \widetilde{W}^l_{\mu\nu} B^{\mu\nu}$	$c_{H\widetilde{W}B}$	VBF, VH	Yes





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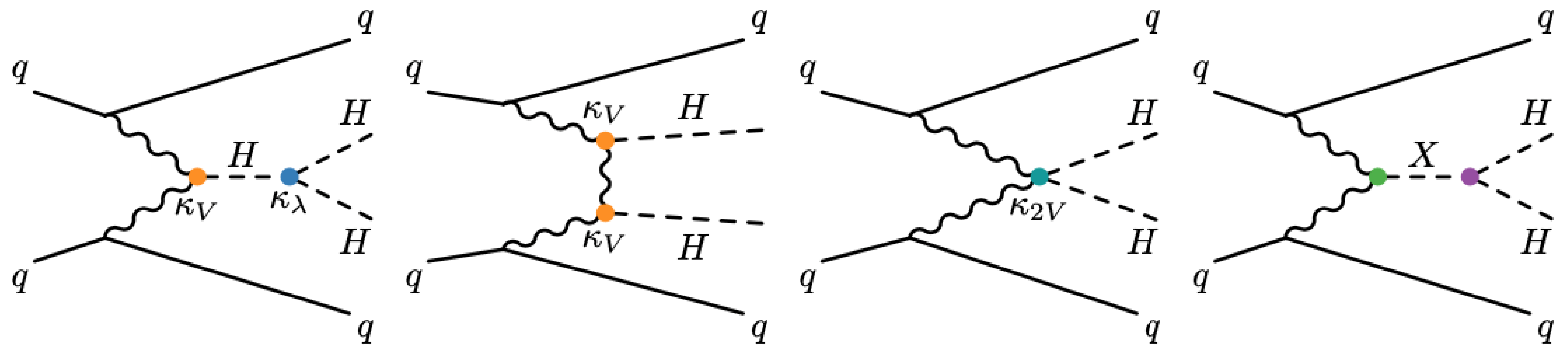
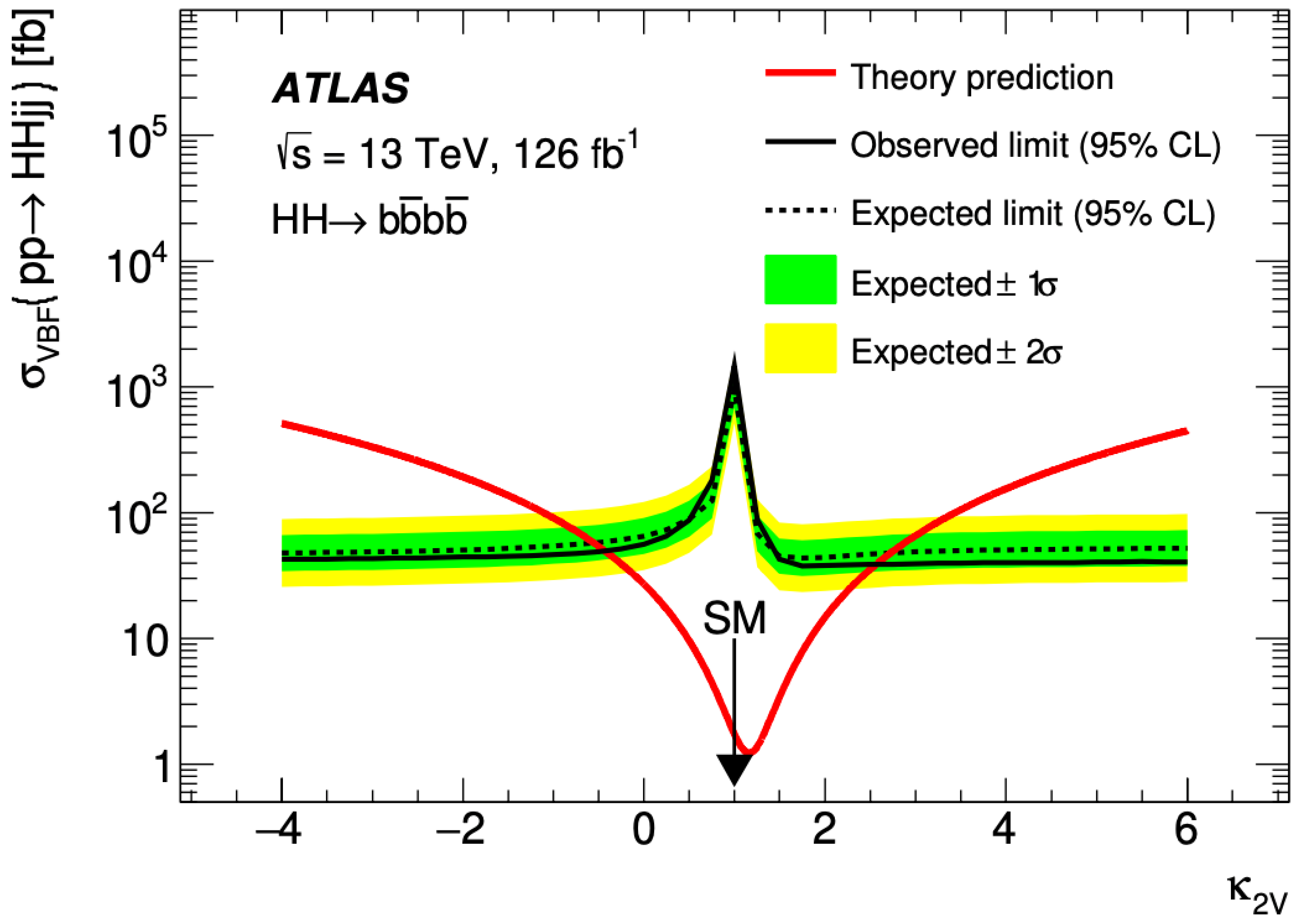
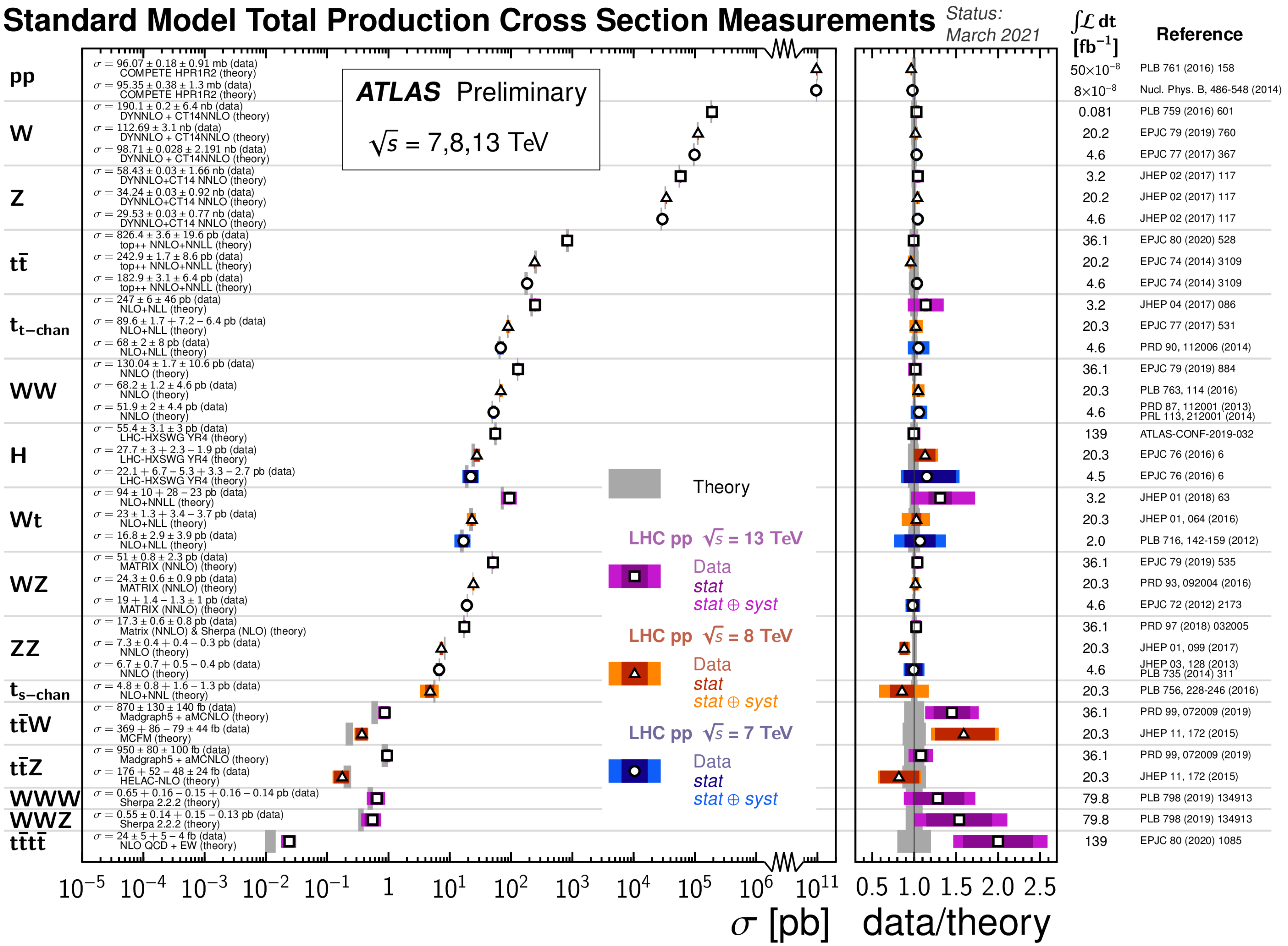
VBF HH —> bbbb (ATLAS)



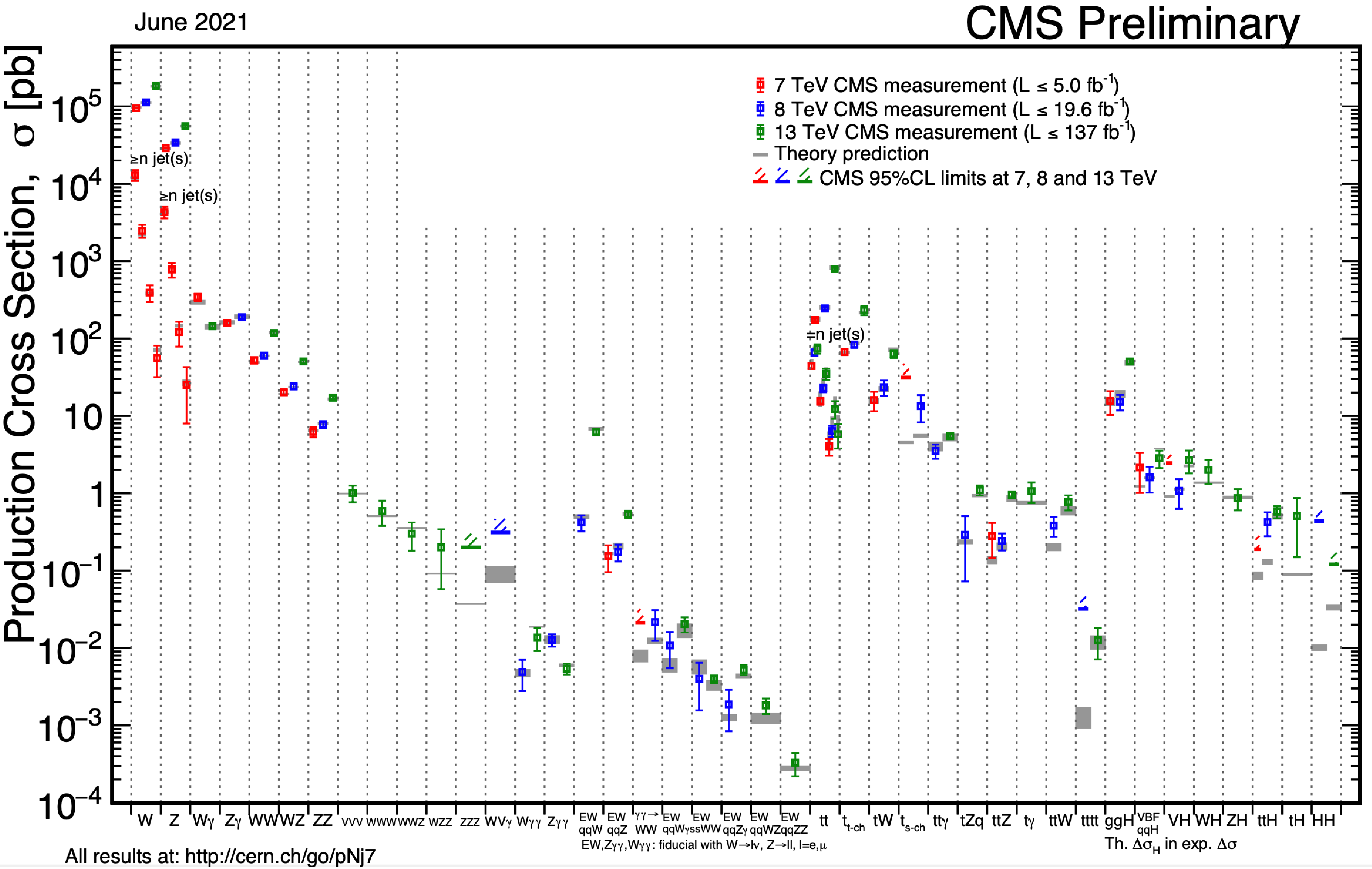
	Observed	-2σ	-1σ	Expected	$+1\sigma$	$+2\sigma$
σ_{VBF} [fb]	1460	510	690	950	1330	1780
$\sigma_{\mathrm{VBF}}/\sigma_{\mathrm{VBF}}^{\mathrm{SM}}$	840	290	400	550	770	1030



$-0.43 < \kappa_{2V} < 2.56(-0.55 < \kappa_{2V} < 2.72)$ *at 95% CL*



Standard Model Total Production Cross Section Measurements
Status: March 2021
ATLAS Preliminary
√s = 7,8,13 TeV
∫ℒ dt [fb⁻¹]
Reference
pp
σ = 96.07 ± 0.18 ± 0.91 mb (data) COMPETE HPR1R2 (theory)
σ = 95.35 ± 0.38 ± 1.3 mb (data) COMPETE HPR1R2 (theory)
W
σ = 190.1 ± 0.2 ± 6.4 nb (data) DYNNLO + CT14NNLO (theory)
σ = 112.69 ± 3.1 nb (data) DYNNLO + CT14NNLO (theory)
σ = 98.71 ± 0.028 ± 2.191 nb (data) DYNNLO + CT14NNLO (theory)
Z
σ = 58.43 ± 0.03 ± 1.66 nb (data) DYNNLO+CT14 NNLO (theory)
σ = 34.24 ± 0.03 ± 0.92 nb (data) DYNNLO+CT14 NNLO (theory)
σ = 29.53 ± 0.03 ± 0.77 nb (data) DYNNLO+CT14 NNLO (theory)
tt̄
σ = 826.4 ± 3.6 ± 19.6 pb (data) top++ NNLO+NNLL (theory)
σ = 242.9 ± 1.7 ± 8.6 pb (data) top++ NNLO+NNLL (theory)
σ = 182.9 ± 3.1 ± 6.4 pb (data) top++ NNLO+NNLL (theory)
t t−chan
σ = 247 ± 6 ± 46 pb (data) NLO+NLL (theory)
σ = 89.6 ± 1.7 + 7.2 − 6.4 pb (data) NLO+NLL (theory)
σ = 68 ± 2 ± 8 pb (data) NLO+NLL (theory)
WW
σ = 130.04 ± 1.7 ± 10.6 pb (data) NNLO (theory)
σ = 68.2 ± 1.2 ± 4.6 pb (data) NNLO (theory)
σ = 51.9 ± 2 ± 4.4 pb (data) NNLO (theory)
H
σ = 55.4 ± 3.1 ± 3 pb (data) LHC-HXSWG YR4 (theory)
σ = 27.7 ± 3 + 2.3 − 1.9 pb (data) LHC-HXSWG YR4 (theory)
σ = 22.1 + 6.7 − 5.3 + 3.3 − 2.7 pb (data) LHC-HXSWG YR4 (theory)
Wt
σ = 94 ± 10 + 28 − 23 pb (data) NLO+NNLL (theory)
σ = 23 ± 1.3 + 3.4 − 3.7 pb (data) NLO+NLL (theory)
σ = 16.8 ± 2.9 ± 3.9 pb (data) NLO+NLL (theory)
WZ
σ = 51 ± 0.8 ± 2.3 pb (data) MATRIX (NNLO) (theory)
σ = 24.3 ± 0.6 ± 0.9 pb (data) MATRIX (NNLO) (theory)
σ = 19 + 1.4 − 1.3 ± 1 pb (data) MATRIX (NNLO) (theory)
ZZ
σ = 17.3 ± 0.6 ± 0.8 pb (data) Matrix (NNLO) & Sherpa (NLO) (theory)
σ = 7.3 ± 0.4 + 0.4 − 0.3 pb (data) NNLO (theory)
σ = 6.7 ± 0.7 + 0.5 − 0.4 pb (data) NNLO (theory)
t s−chan
σ = 4.8 ± 0.8 + 1.6 − 1.3 pb (data) NLO+NNL (theory)
tt̄W
σ = 870 ± 130 ± 140 fb (data) Madgraph5 + aMCNLO (theory)
σ = 369 + 86 − 79 ± 44 fb (data) MCFM (theory)
tt̄Z
σ = 950 ± 80 ± 100 fb (data) Madgraph5 + aMCNLO (theory)
σ = 176 + 52 − 48 ± 24 fb (data) HELAC-NLO (theory)
WWW
σ = 0.65 + 0.16 − 0.15 + 0.16 − 0.14 pb (data) Sherpa 2.2.2 (theory)
WWZ
σ = 0.55 ± 0.14 + 0.15 − 0.13 pb (data) Sherpa 2.2.2 (theory)
tt̄tt̄
σ = 24 ± 5 + 5 − 4 fb (data) NLO QCD + EW (theory)
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
10⁻⁵ 10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1.0 1.5 2.0 2.5
data/theory
50×10⁻⁸ PLB 761 (2016) 158
8×10⁻⁸ Nucl. Phys. B, 486-548 (2014)
0.081 PLB 759 (2016) 601
20.2 EPJC 79 (2019) 760
4.6 EPJC 77 (2017) 367
3.2 JHEP 02 (2017) 117
20.2 JHEP 02 (2017) 117
4.6 JHEP 02 (2017) 117
36.1 EPJC 80 (2020) 528
20.2 EPJC 74 (2014) 3109
4.6 EPJC 74 (2014) 3109
3.2 JHEP 04 (2017) 086
20.3 EPJC 77 (2017) 531
4.6 PRD 90, 112006 (2014)
36.1 EPJC 79 (2019) 884
20.3 PLB 763, 114 (2016)
4.6 PRD 87, 112001 (2013) PRL 113, 212001 (2014)
139 ATLAS-CONF-2019-032
20.3 EPJC 76 (2016) 6
4.5 EPJC 76 (2016) 6
3.2 JHEP 01 (2018) 63
20.3 JHEP 01, 064 (2016)
2.0 PLB 716, 142-159 (2012)
36.1 EPJC 79 (2019) 535
20.3 PRD 93, 092004 (2016)
4.6 EPJC 72 (2012) 2173
36.1 PRD 97 (2018) 032005
20.3 JHEP 01, 099 (2017)
4.6 JHEP 03, 128 (2013) PLB 735 (2014) 311
20.3 PLB 756, 228-246 (2016)
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
36.1 PRD 99, 072009 (2019)
20.3 JHEP 11, 172 (2015)
79.8 PLB 798 (2019) 134913
79.8 PLB 798 (2019) 134913
139 EPJC 80 (2020) 1085



June 2021
CMS Preliminary
Production Cross Section, σ [pb]
7 TeV CMS measurement (L ≤ 5.0 fb^{-1})
8 TeV CMS measurement (L ≤ 19.6 fb^{-1})
13 TeV CMS measurement (L ≤ 137 fb^{-1})
Theory prediction
CMS 95%CL limits at 7, 8 and 13 TeV
≥n jet(s)
≥n jet(s)
=n jet(s)
W Z Wγ Zγ WW WZ ZZ VVV WWW WWZ WZZ ZZZ WVγ Wγγ Zγγ EW qqW EW qqZ γγ→WW EW qqWγ EW ssWW EW qqZγ EW qqWZ EW qqZZ tt $t_{t\text{-ch}}$ tW $t_{s\text{-ch}}$ ttγ tZq ttZ tγ ttW tttt ggH VBF qqH VH WH ZH ttH tH HH
EW,Zγγ,Wγγ: fiducial with W→lν, Z→ll, l=e,μ
Th. $\Delta\sigma_H$ in exp. $\Delta\sigma$
All results at: http://cern.ch/go/pNj7