Di-Higgs searches in ATLAS and CMS

LHCP, Puebla, Mexico, 20-25 May 2019

Xiaohu SUN on behalf of the ATLAS and CMS collaborations

2019-05-23

UNIVERSITY OF ALBERTA
EDMONTON·ALBERTA·CANADA

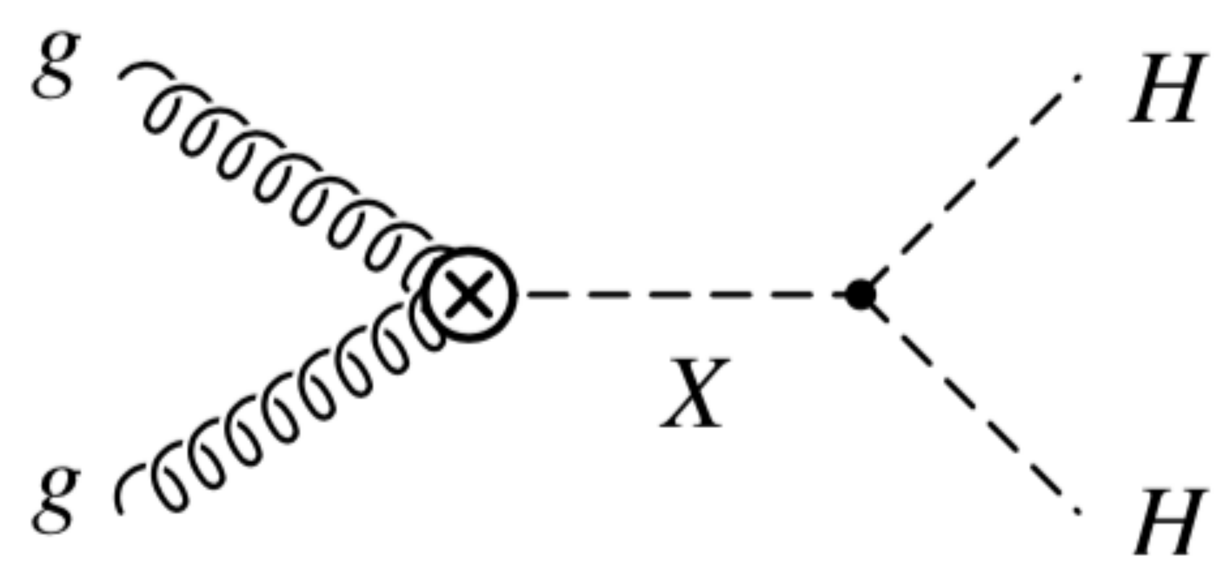
Introduction

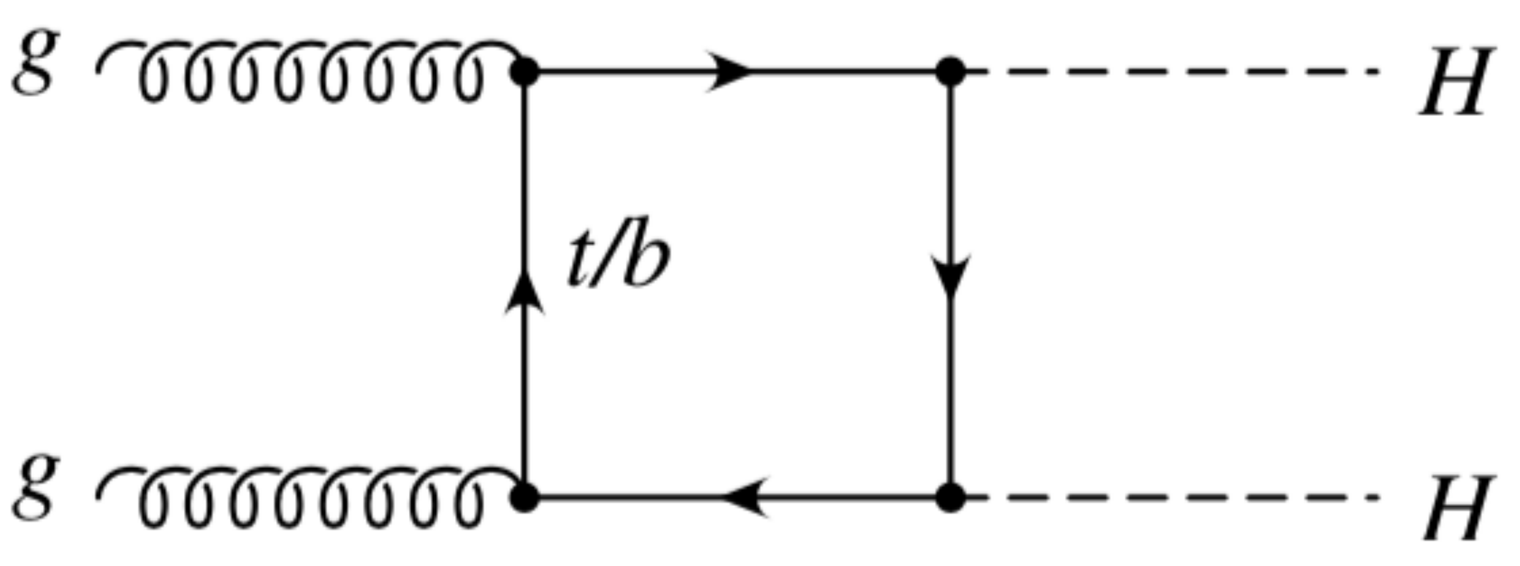
- Search di-Higgs (HH) production
  - Standard Model (SM) **non-resonant** di-Higgs allows to directly probe Higgs self-coupling κ_λ ($=\lambda_{3,measure}/\lambda_{3,SM}$), study the Higgs potential and constrain EFT couplings
  - BSM **resonant** di-Higgs originates from a heavy scalar or spin2 particle (EWK singlet, MSSM, 2HDM, RS KK graviton models etc.)

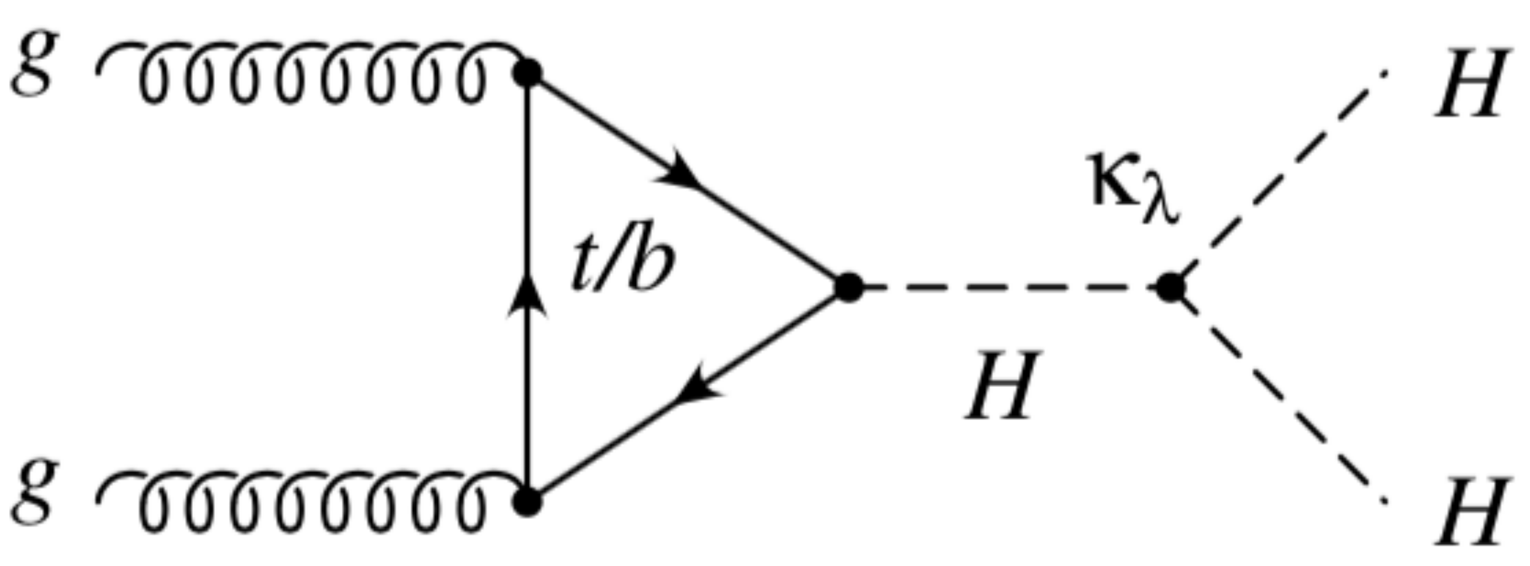
$$V = -\mu^2 \Phi^\dagger \Phi + \lambda(\Phi^\dagger \Phi)^2$$

$$V \to -\frac{M_H^2}{2} H^2 + \lambda_3 H^3 + \lambda_4 H^4$$

$$\lambda_3 = \frac{M_H^2}{2v} \sim .13v$$



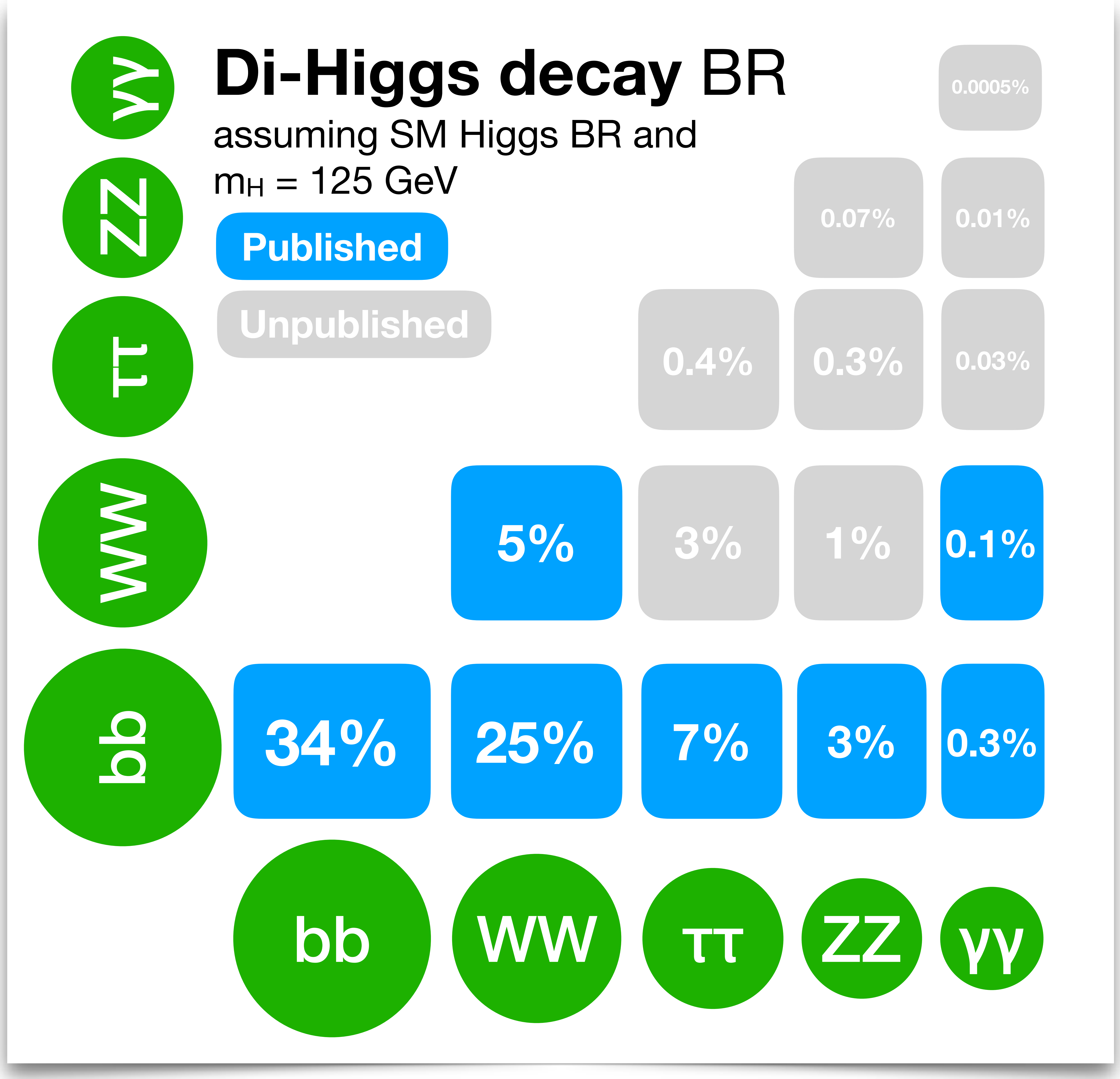




* The VBS contents are re-arranged into P. Chang's talk on Friday plenary

*For HH also see talks of N. Ilic on Tuesday, N. Readioff and G. Palacino Wednesday

Di-Higgs experimental status



A pair of Higgs bosons provides a variety of decay modes

H→bb is usually chosen for one Higgs boson given the largest branching ratio

H→others is usually used to deploy triggers and suppress backgrounds

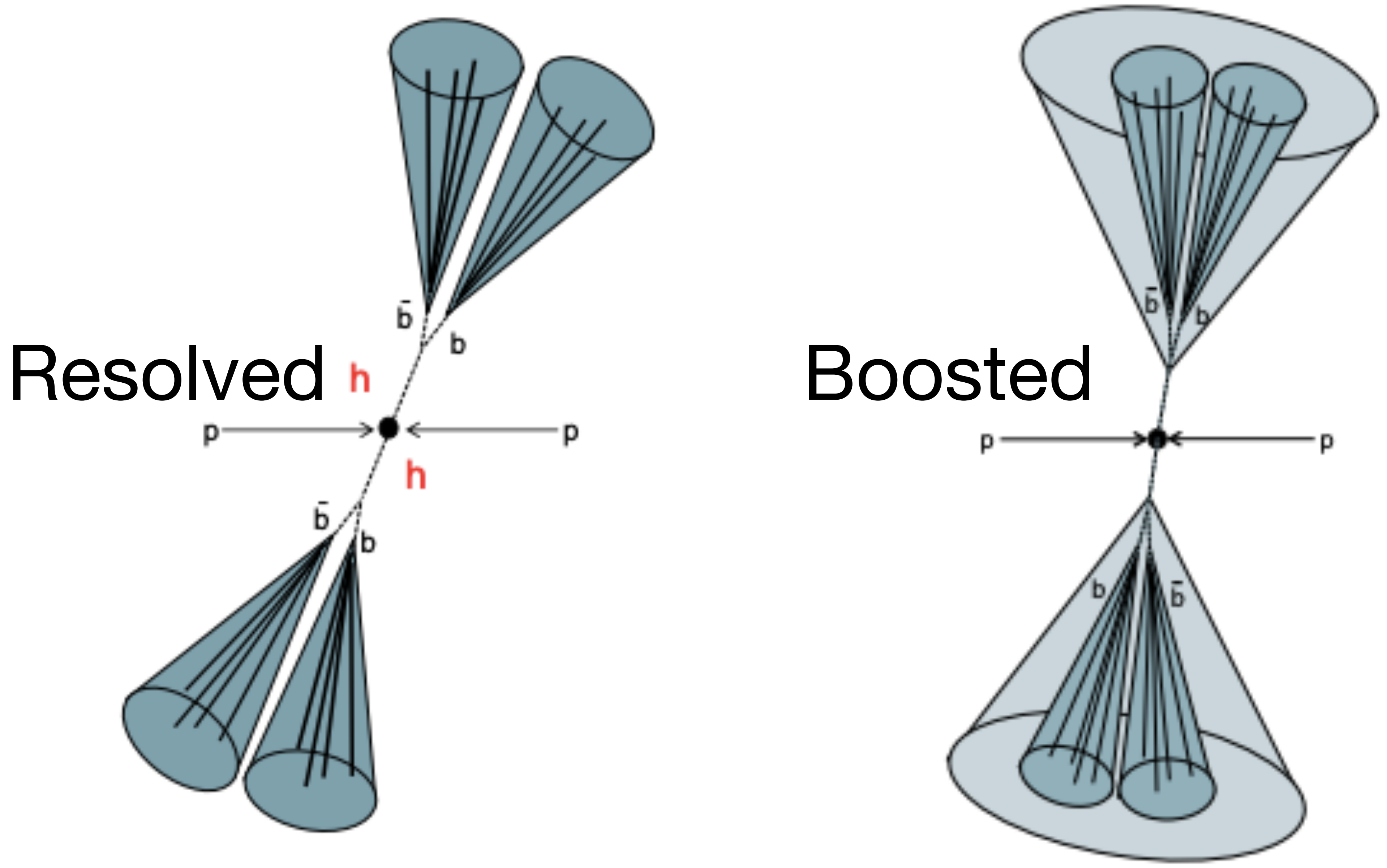
Small BRs like **H→γγ/ZZ** can have strong sensitivity given their low-background level. They are large parts of the search projects

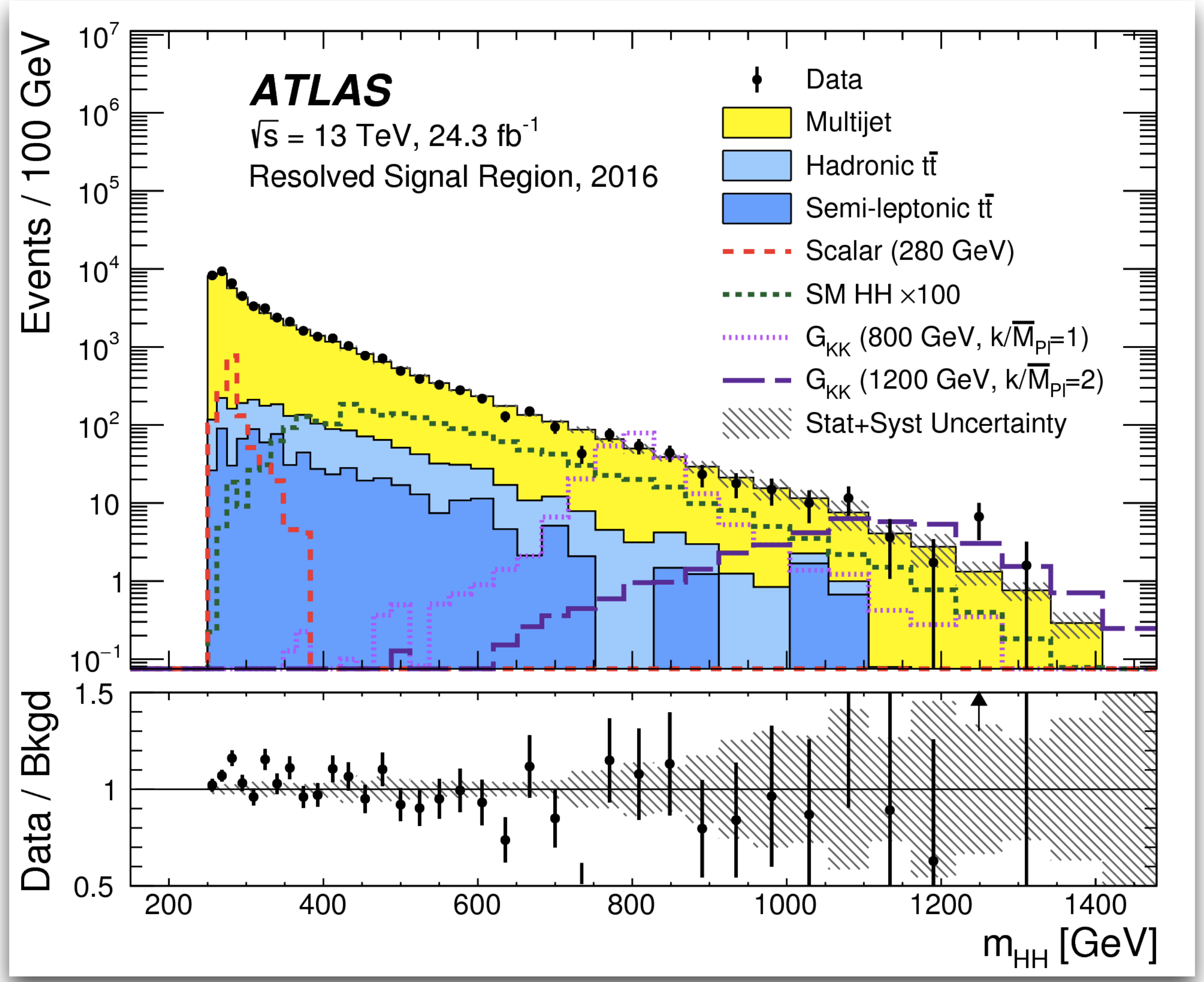
Experimental results to date from ATLAS and CMS are shown in this Higgs-decay matrix

HH→bbbb (ATLAS)

JHEP 01 (2019) 030

- Largest branching ratio
- **Resolved**: 4 b-tagged anti-k_T jets (small-R)
- Jet pairing: ΔR(j,j) and mass difference between the 2 dijet system are used to pair the jets (90% correctness)
- **Boosted** (**merged**): 2 anti-k_T jets (large-R), with 1 or 2 b-tagged track-jets associated to each large-R jet
- Dominant backgrounds are multijet and tt



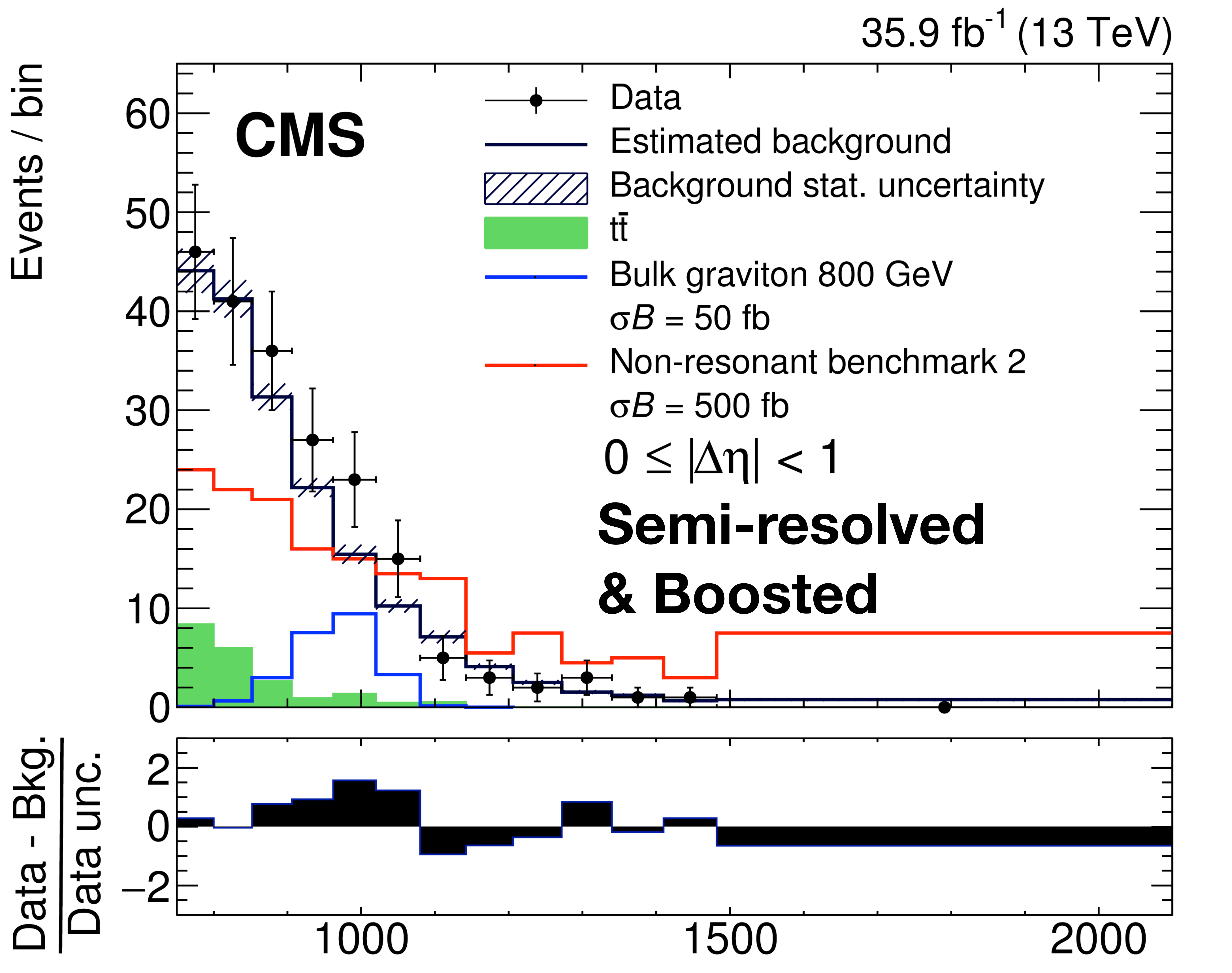


Fit on m_{HH} for non-resonant and resonant

HH→bbbb (CMS)

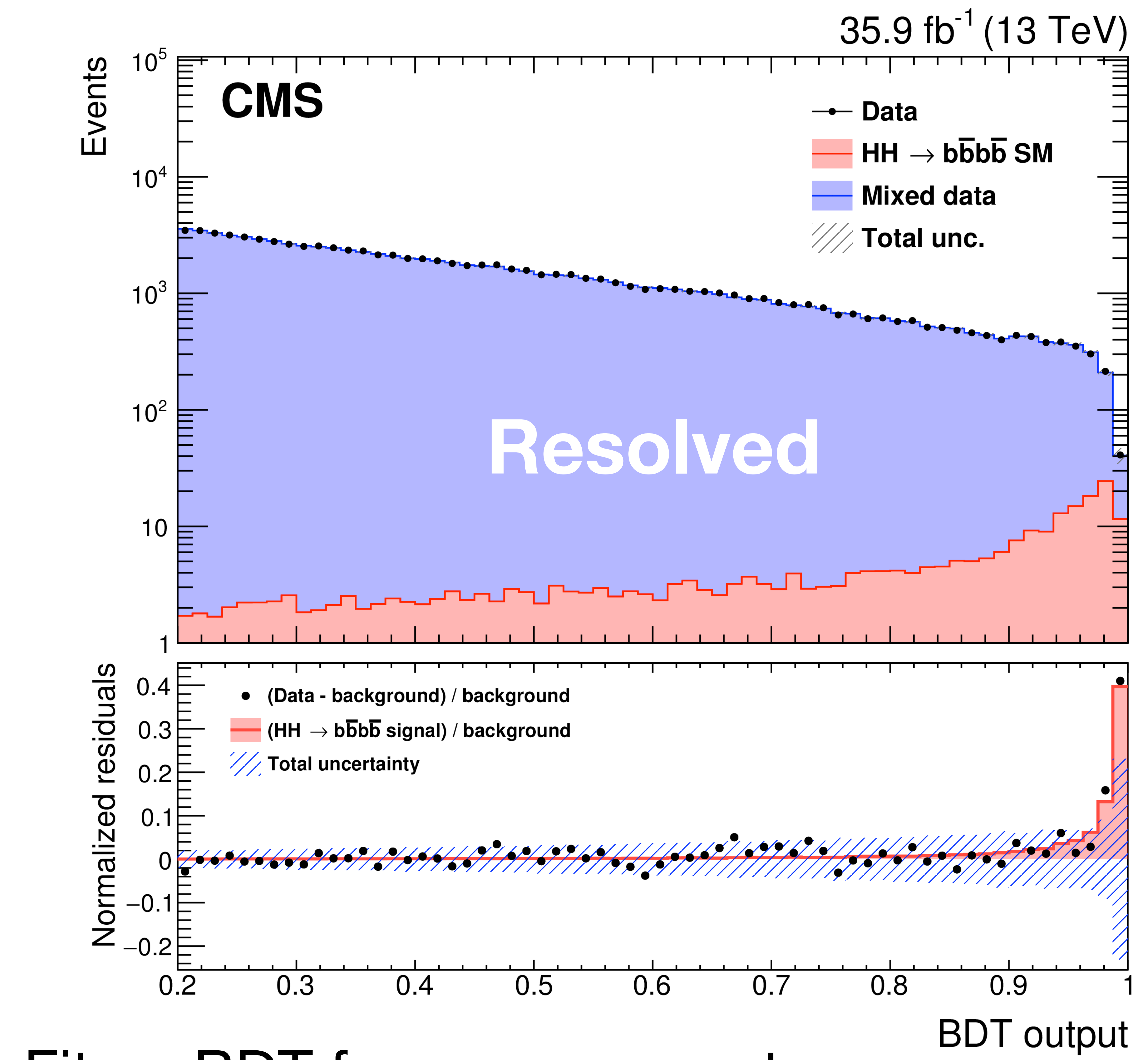
JHEP04(2019)112
JHEP 08 (2018) 152 JHEP 01 (2019) 040

Besides resolved and boosted, **semi-resolved** is explored: 2 b-tagged anti-k_T jets (small-R) and 1 b-tagged anti-k_T jets (large-R)



Fit on m_{HH} for resonant

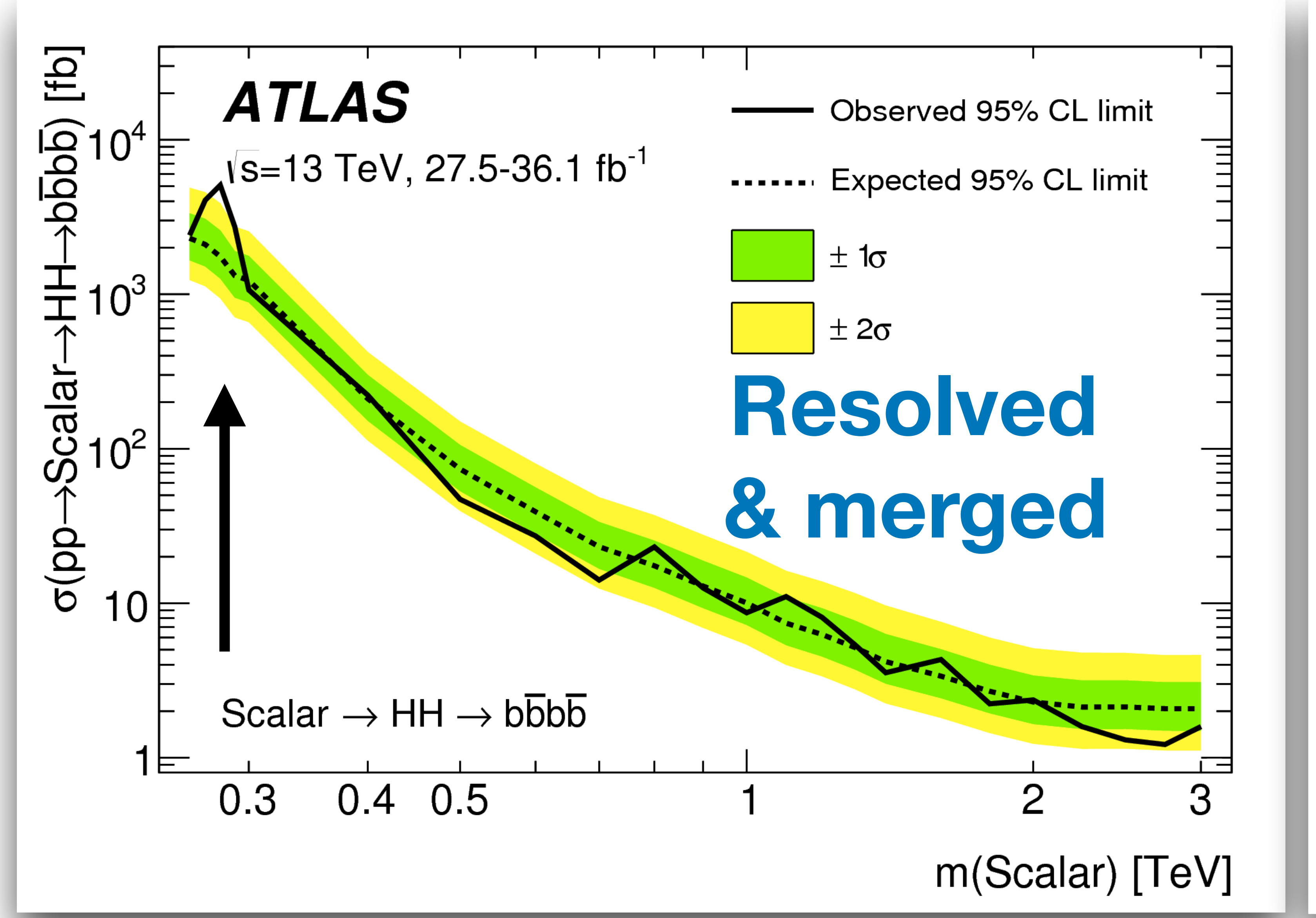
Jet pairing: mass difference between the 2 dijet system is used to pair the jets (54% correctness)

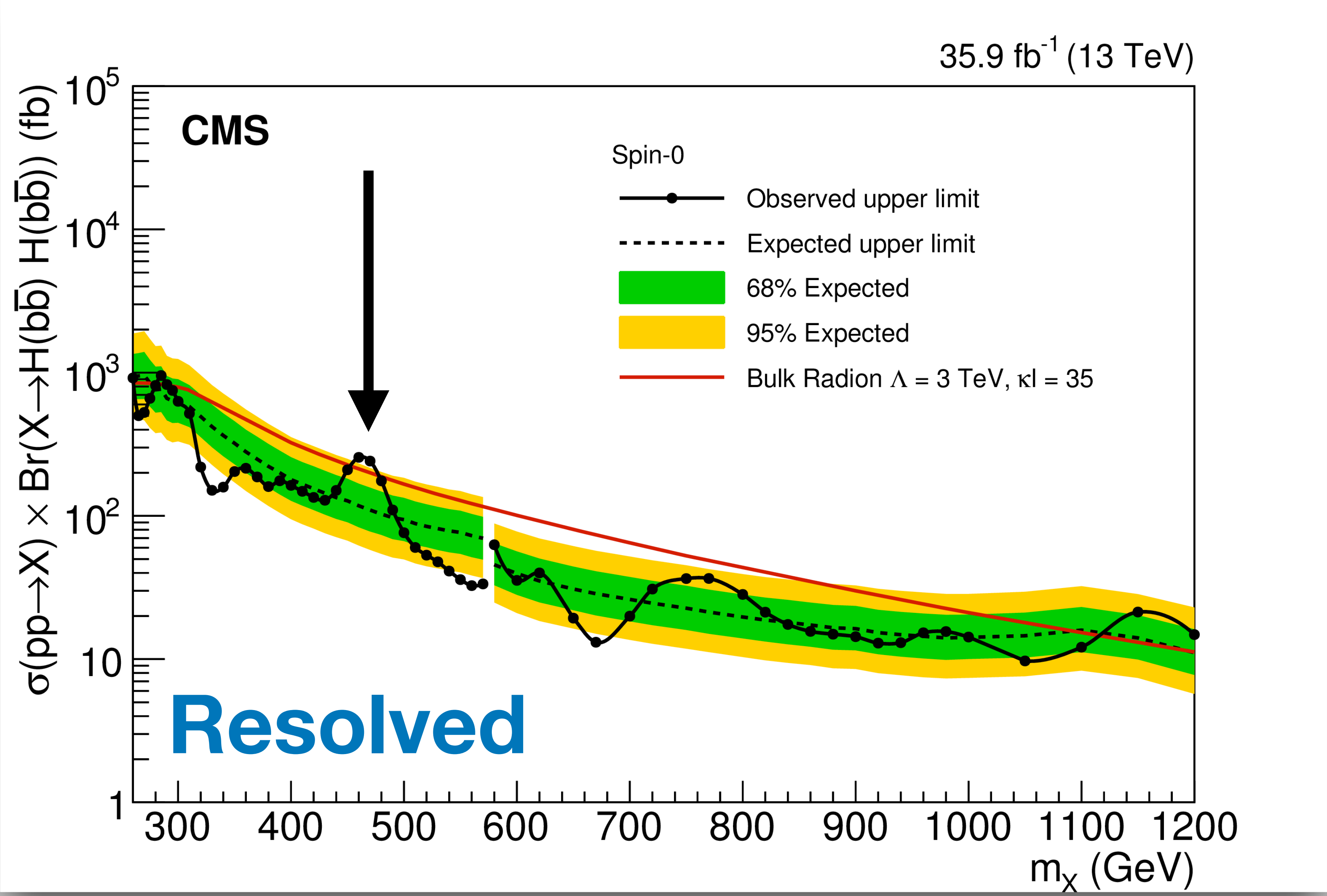


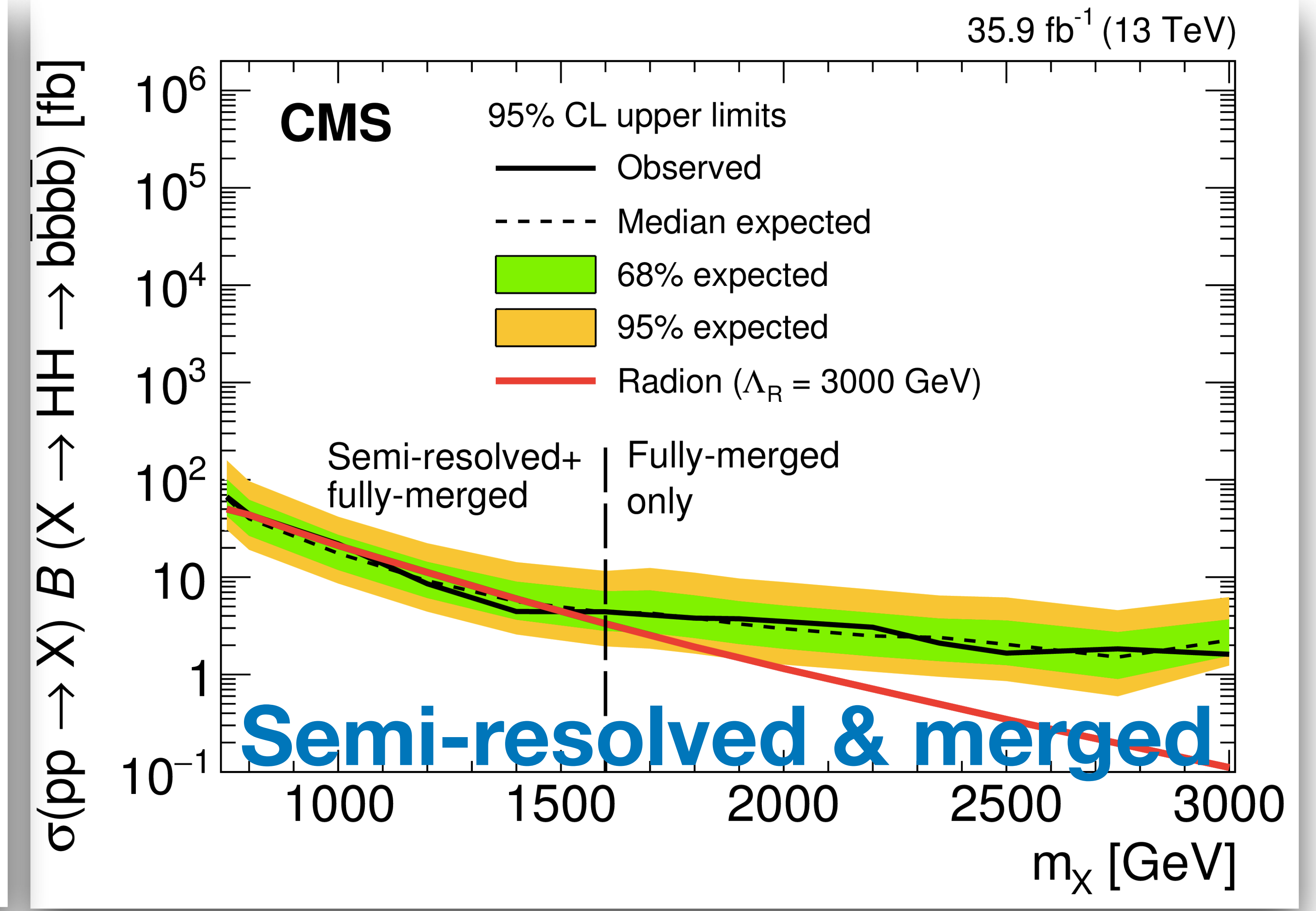
Fit on BDT for non-resonant

HH→bbbb

JHEP 01 (2019) 030 JHEP04(2019)112
JHEP 08 (2018) 152 JHEP 01 (2019) 040







Resonant searches

- Searches up to 3 TeV
- Local excess with spin0:
  - **280 GeV** with a maximal local (global) significance of 3.6σ (2.3σ) in ATLAS (CMS **bbγγ** and **bbττ** have small excess close here)
  - **460 GeV** with a maximal local (global) significance of 2.6σ (negligible) in CMS
- These excess are consistent with statistical fluctuation

Non-resonant searches

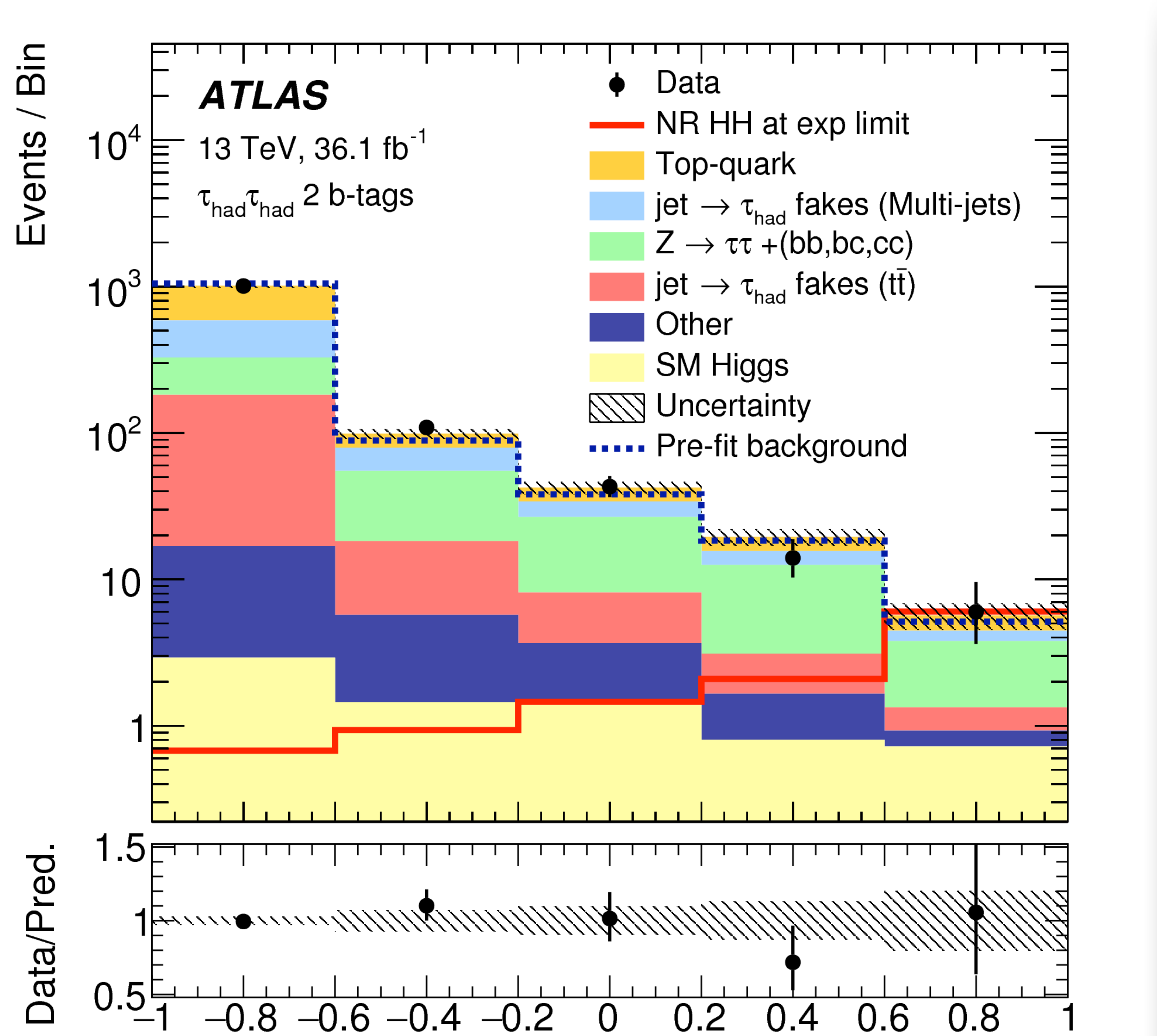
- Limits on SM HH production in the unit of σ_{SM}(pp→HH):
  - 13 (**21**) in ATLAS
  - 75 (**37**) in CMS
- Put constraints on κ_λ and on EFT couplings in CMS

HH→bbττ (non-resonant)

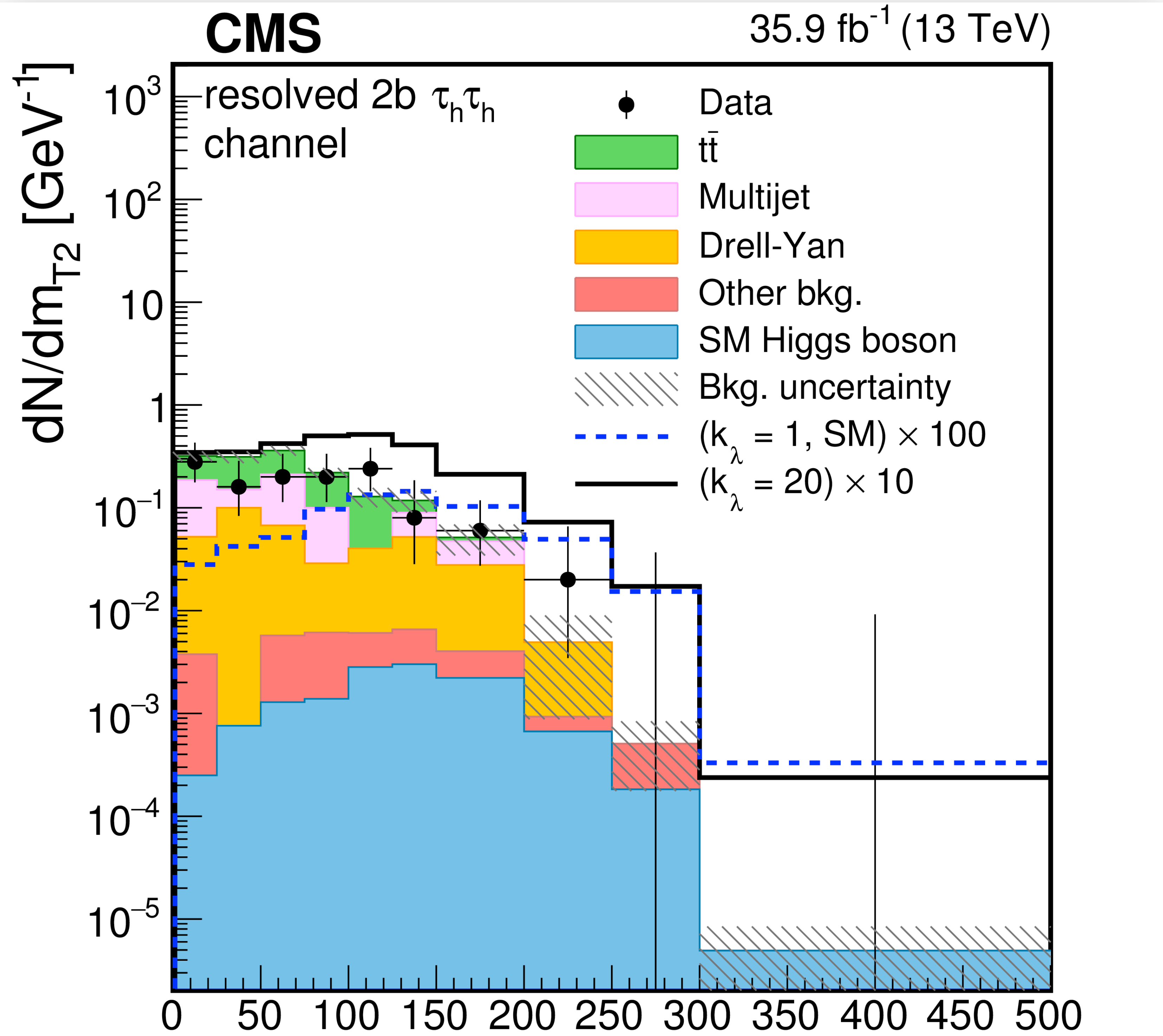
PhysRevLett.122.089901 JHEP 01 (2019) 051
Phys. Lett. B 778 (2018) 101

- **ATLAS**: 2 b-tagged jets, 1 leptonic τ + 1 hadronic τ or 2 hadronic τ
- **CMS**: additionally require 1 b-tagged large-R jet for high-mass resonant searches
- Limits on SM HH production in the unit of $\sigma_{SM}(pp \to HH)$:
  - 13 (**15**) in ATLAS
  - 30 (**25**) in CMS
- Put constraints on κ_λ , κ_t in CMS

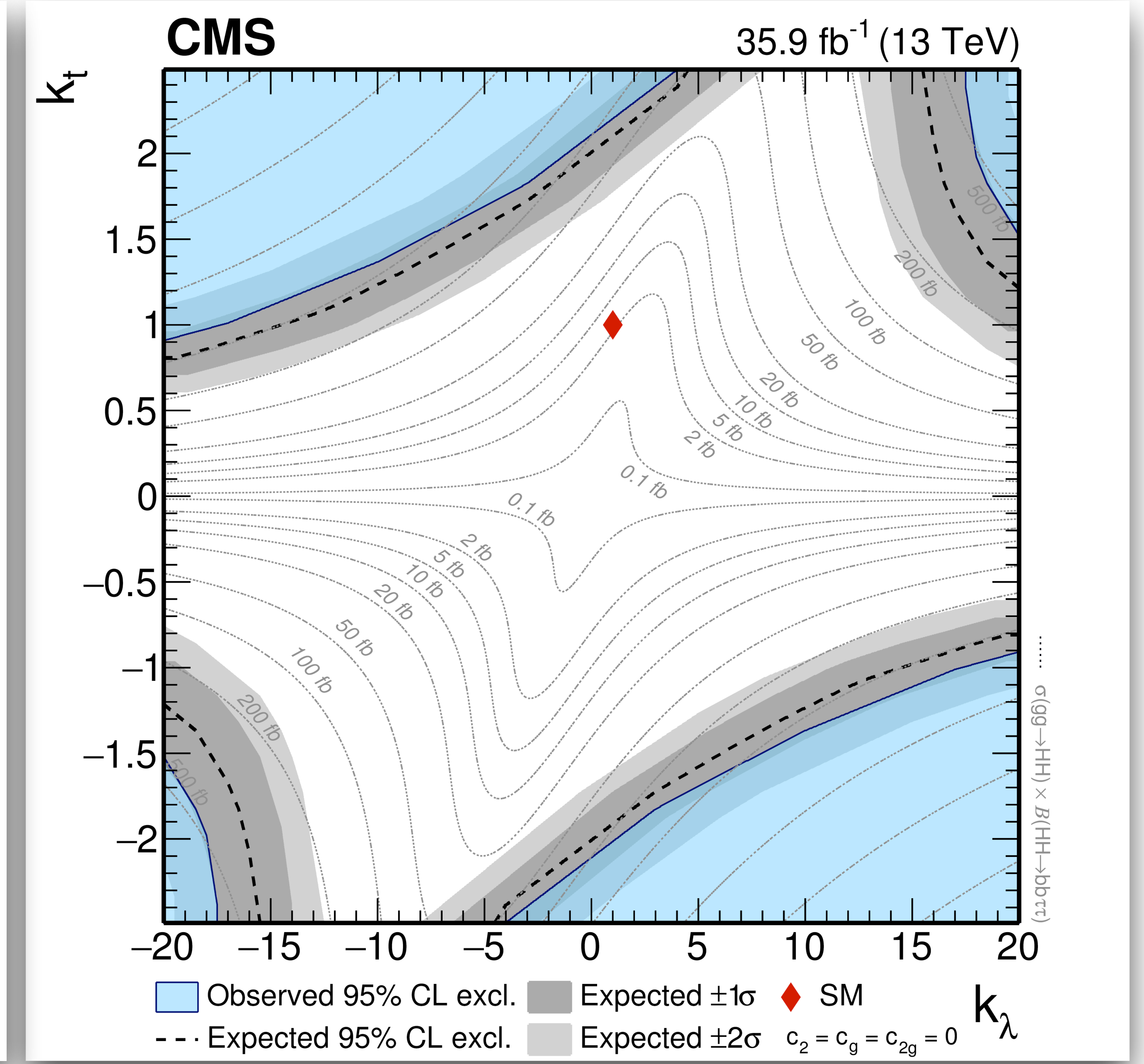
$$\sigma(pp \to HH) \sim k_t^4 \left[|B|^2 + \frac{k_\lambda}{k_t}(B^*T + TB^*) + \left(\frac{k_\lambda}{k_t}\right)^2 |T|^2 \right]$$



Fit on BDT



Fit on m_{T2}



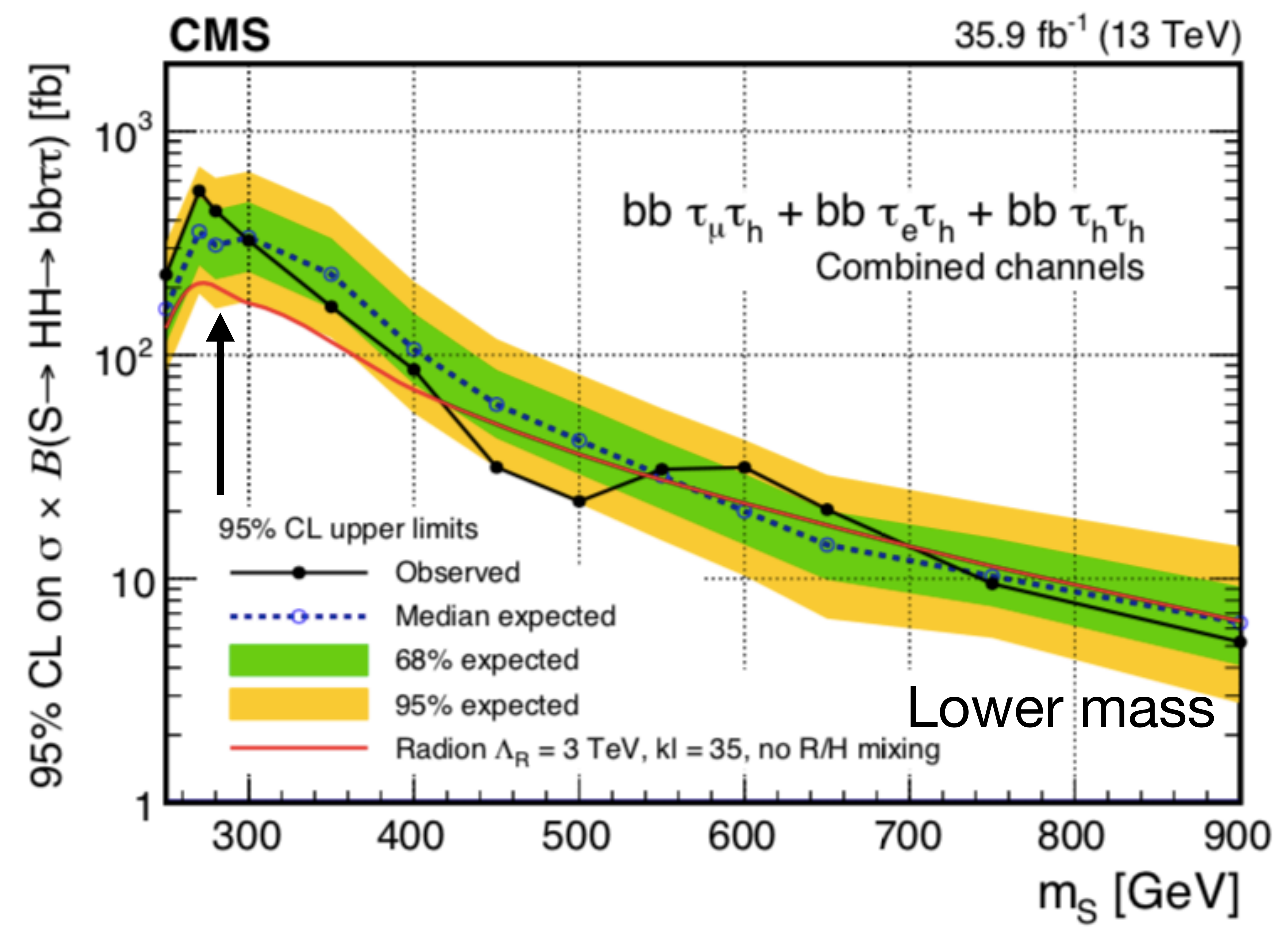
PhysRevLett.122.089901 JHEP 01 (2019) 051
Phys. Lett. B 778 (2018) 101

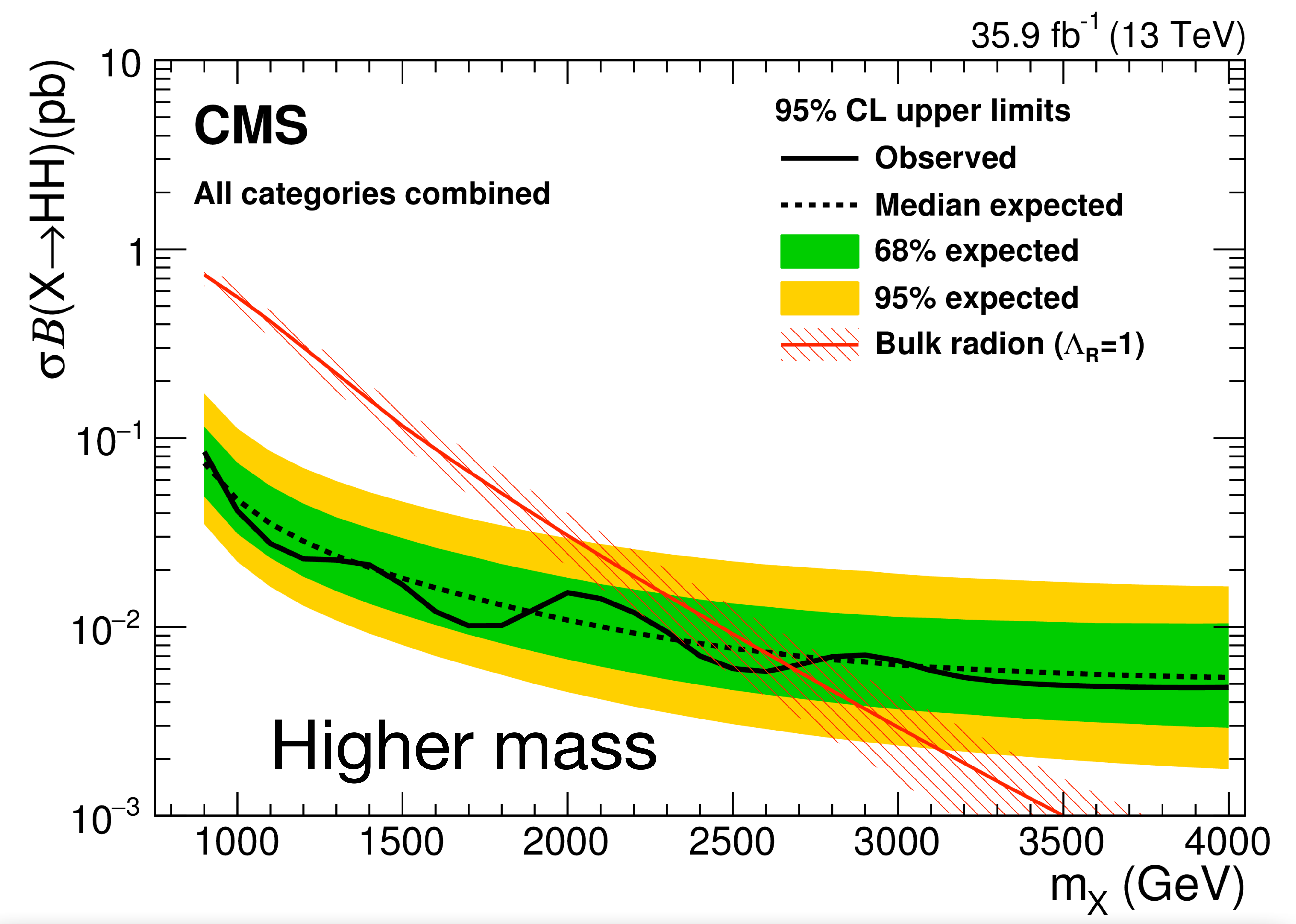
HH→bbττ (resonant)

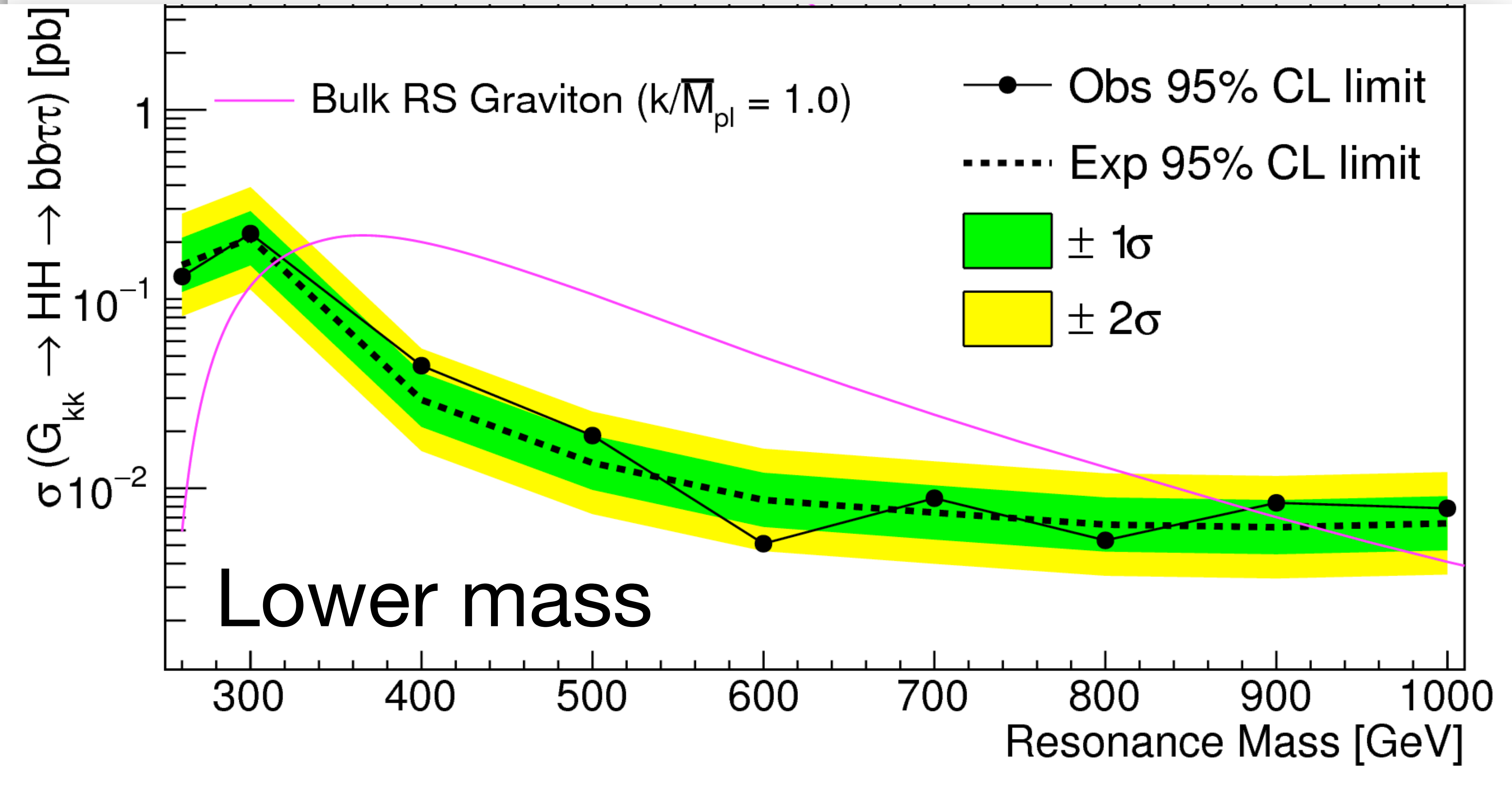
- **ATLAS**: fit on BDT for resonant as well
- **CMS**: fit on m_{HH}

Search is up to 4 TeV

No significant data excess is observed





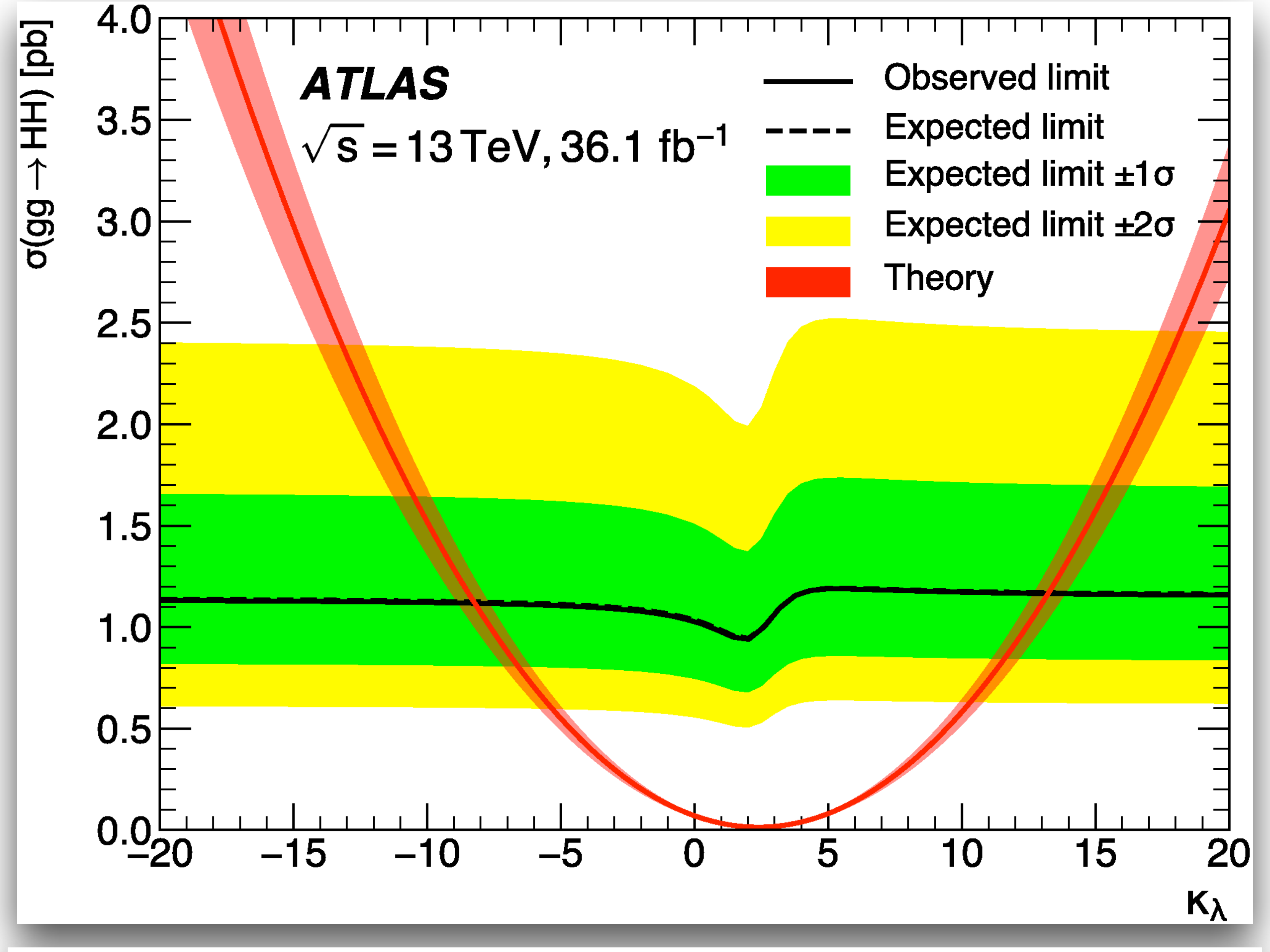


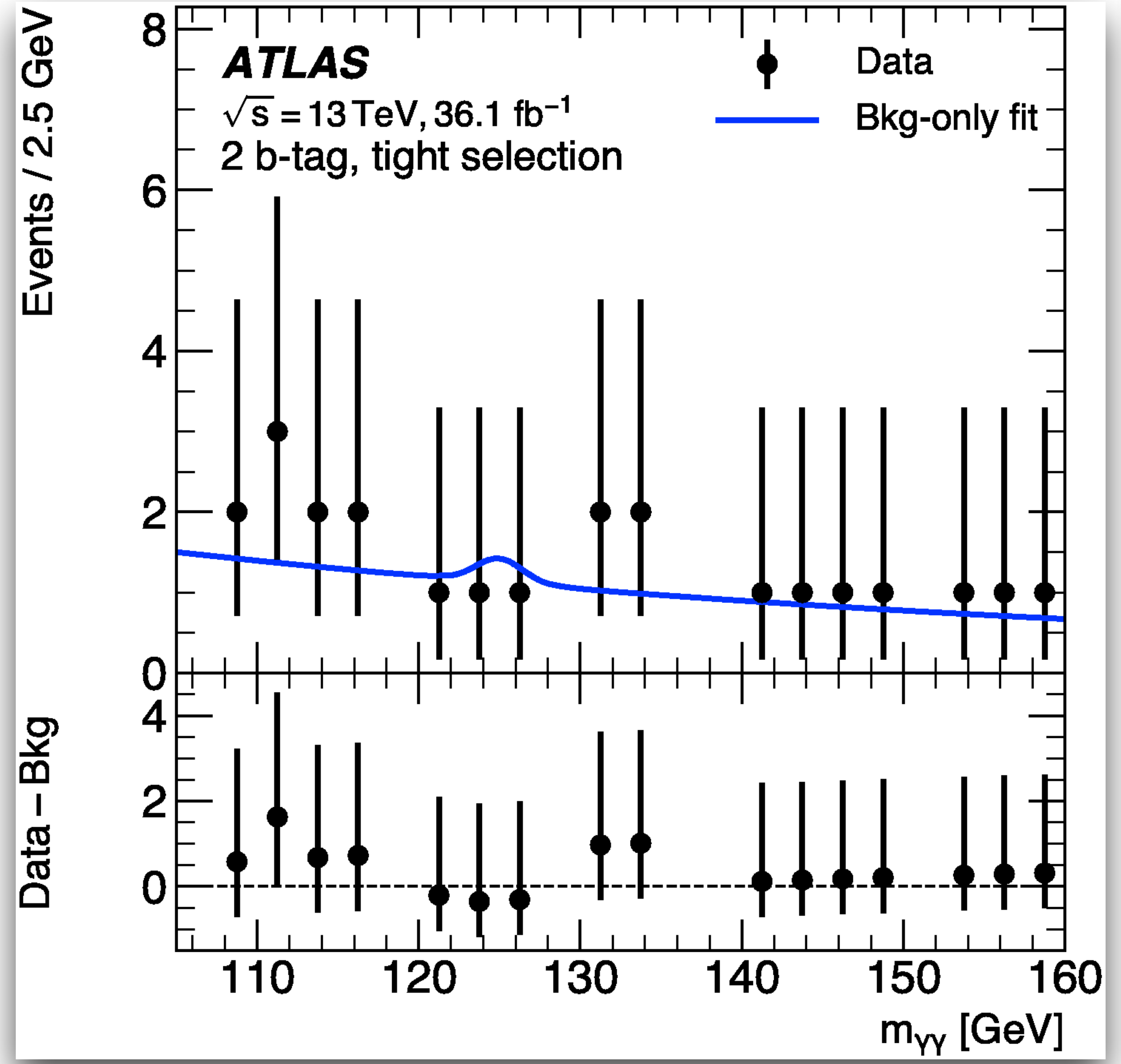
HH→bbγγ

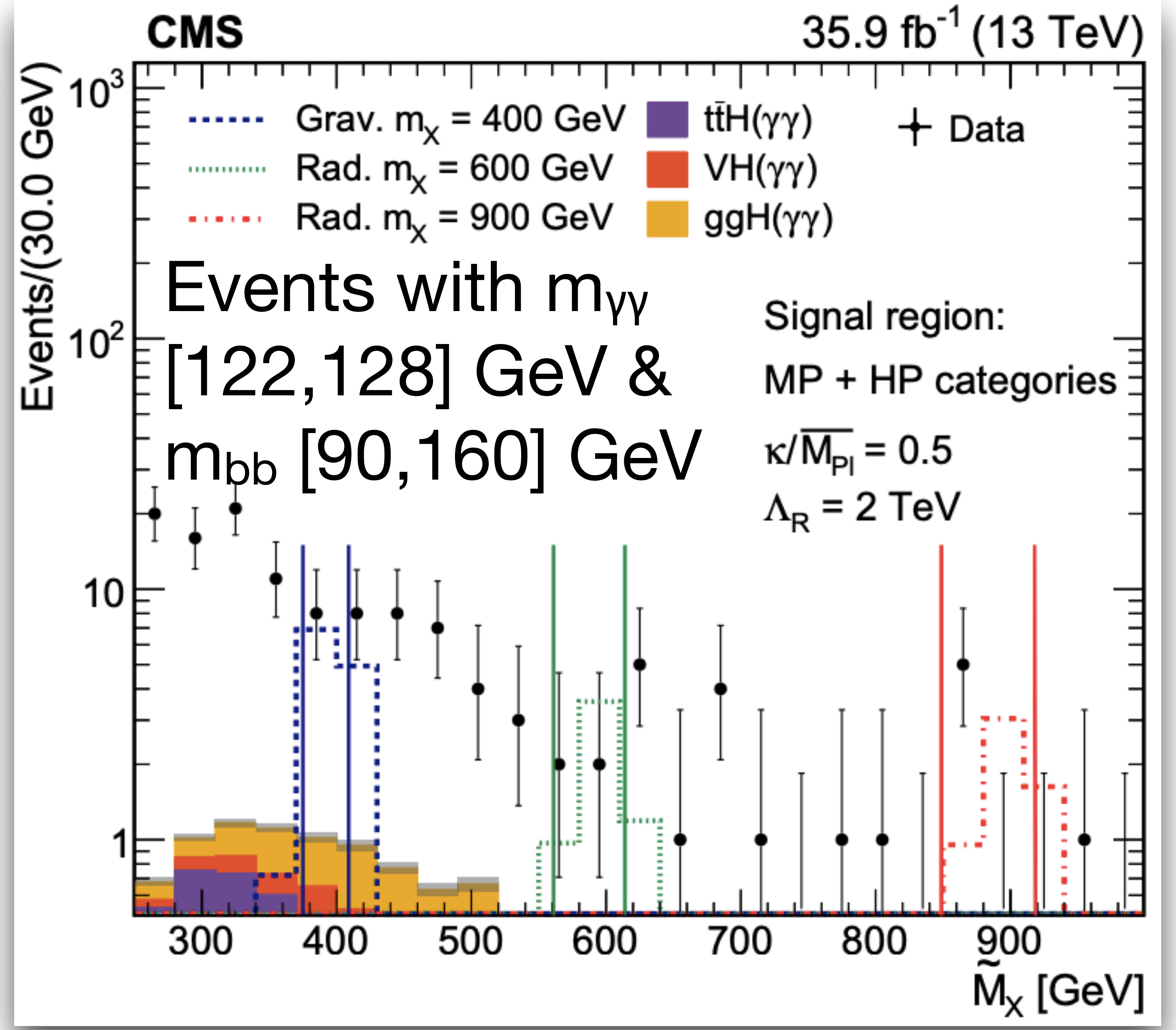
JHEP 11 (2018) 040 Phys. Lett. B 788 (2018) 7

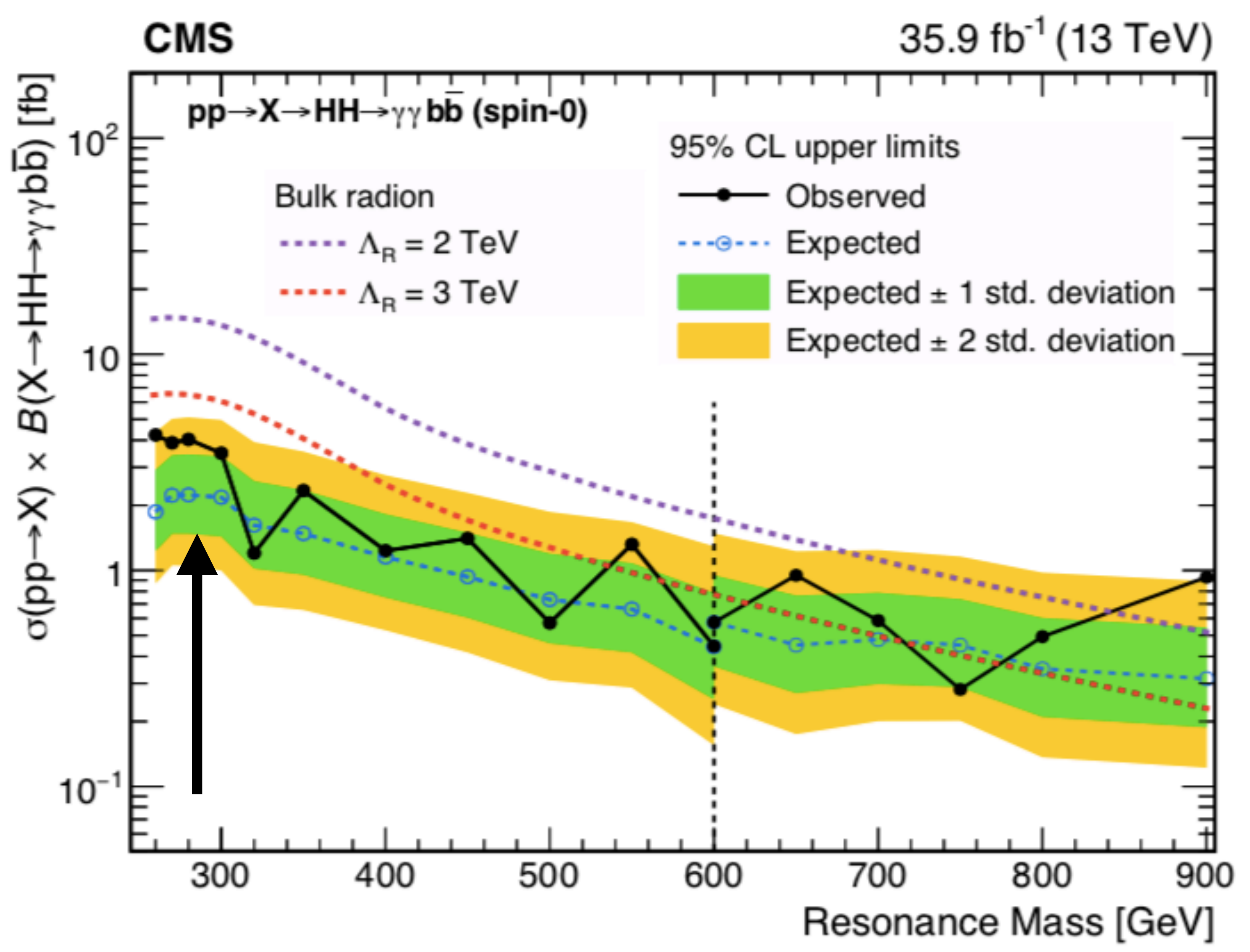
- **ATLAS**: 1 or 2 b-tagged jets, 2 photons, BDT used in choosing b-jet in 1 b-tagged events
- **CMS**: 2 b-tagged jets, 2 photons, and a BDT cut
- ATLAS: unbind fit on $m_{\gamma\gamma}$, $m_{\gamma\gamma bb}$
- CMS: unbind fit on 2D $m_{\gamma\gamma}$ - m_{bb}

- Limits on SM HH production in the unit of $\sigma_{SM}(pp\rightarrow HH)$:
  - 22 (**28**) in ATLAS
  - 24 (**19**) in CMS
- Put constraints on κ_λ
  - [-8.2,13.2] ([-8.3,13.2]) in ATLAS
  - [-11,17] in CMS due to excess









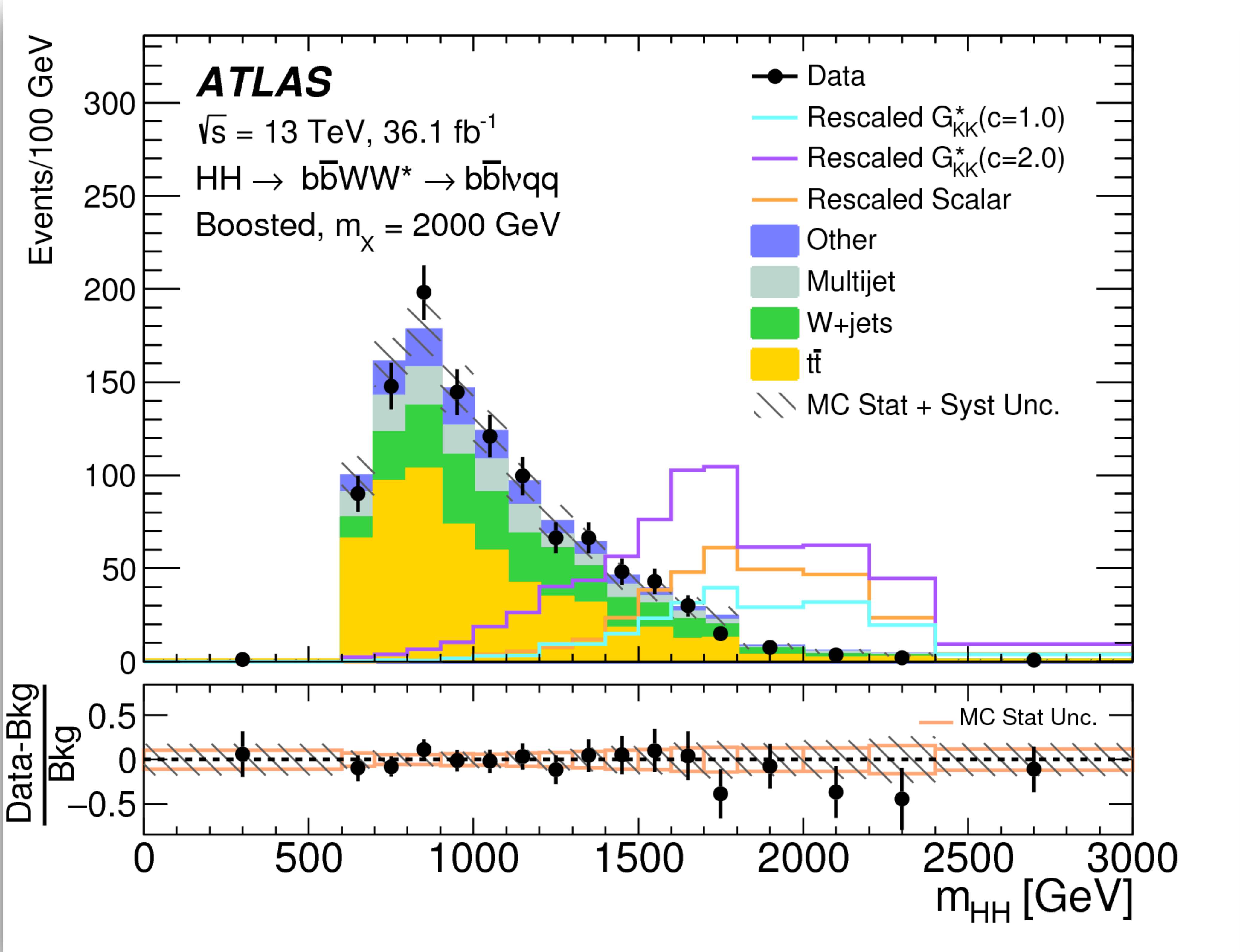
HH→bbVV (1L)

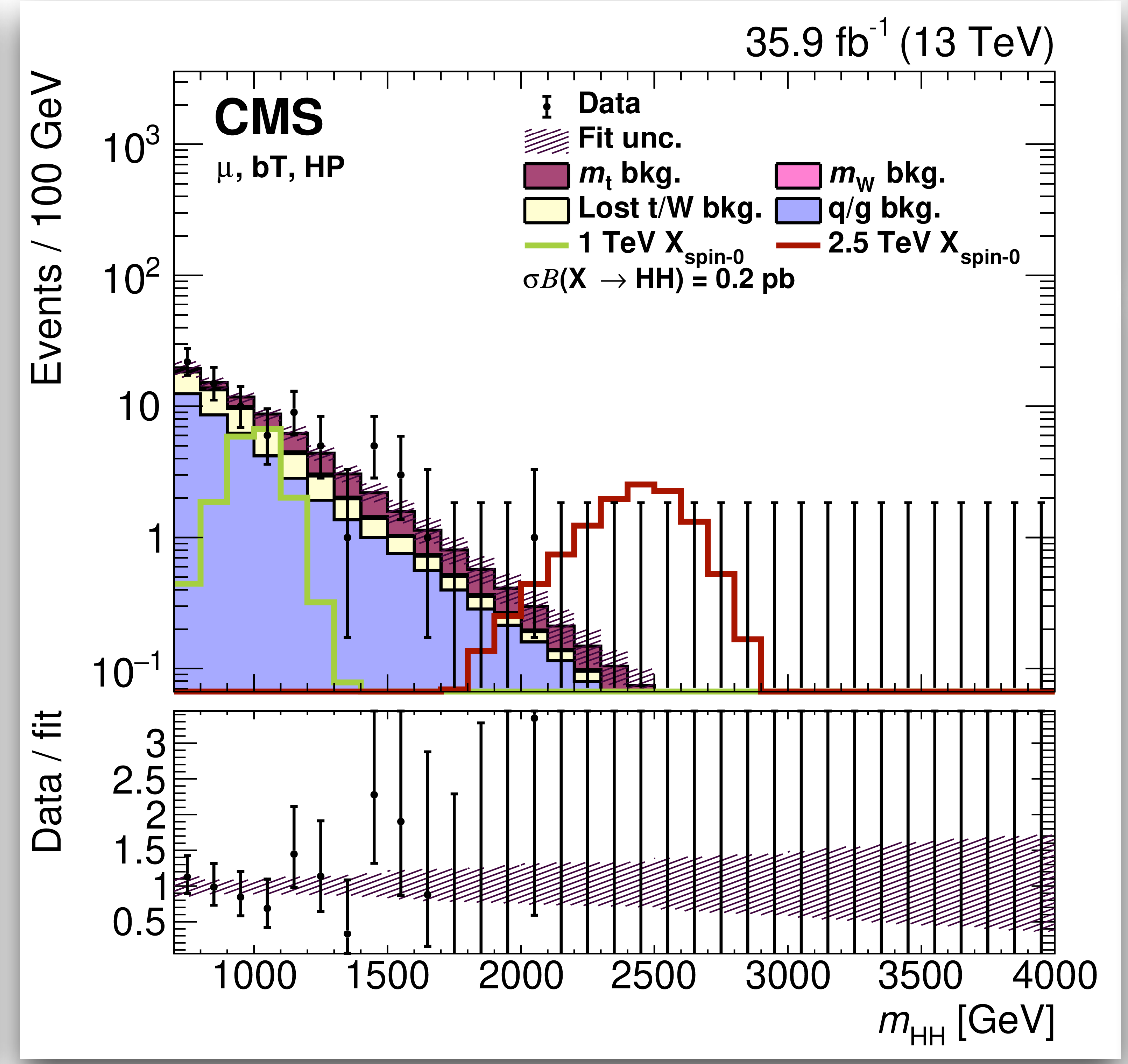
JHEP 04 (2019) 092 1904.04193

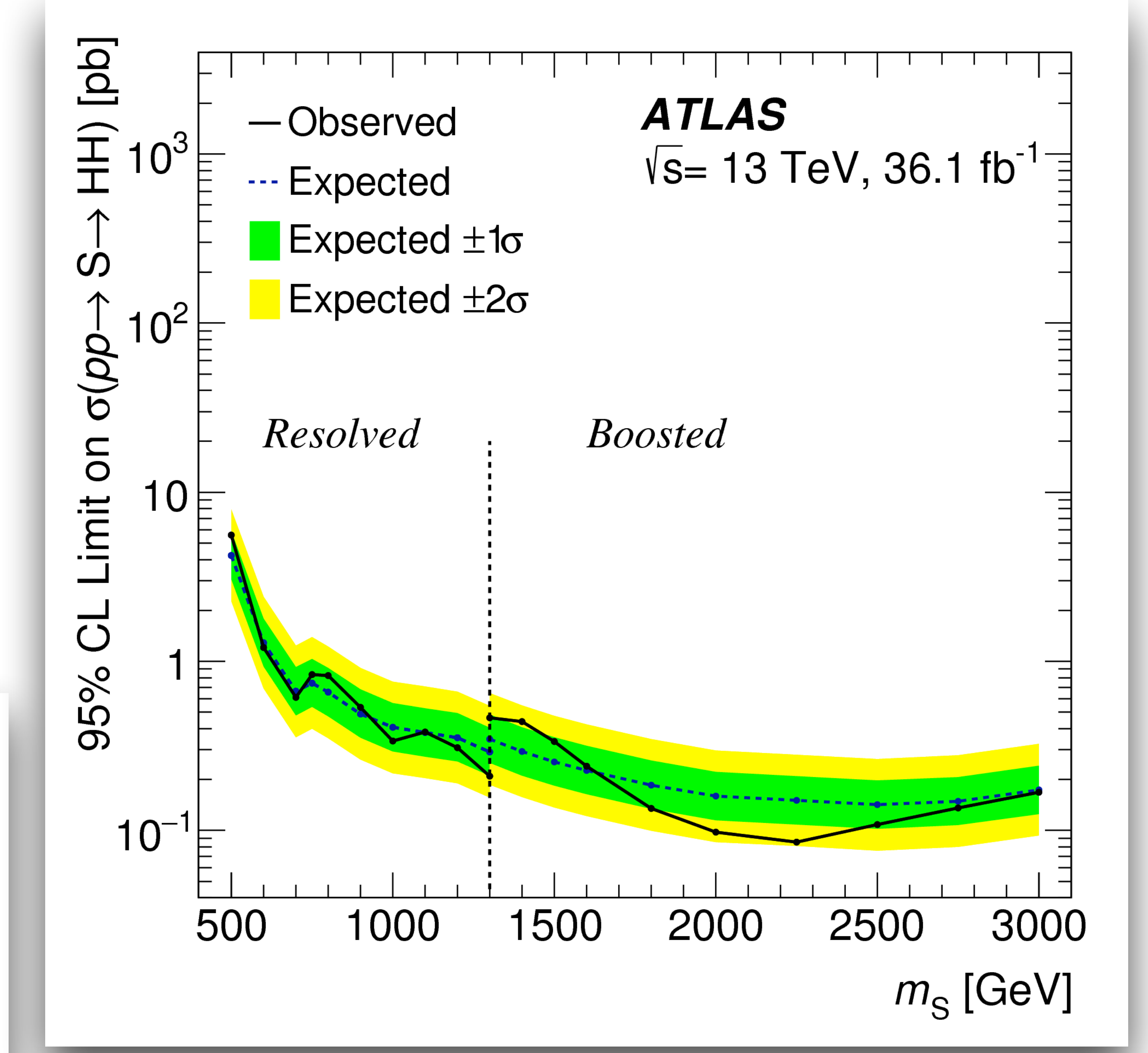
HH→bbWW→bblvqq

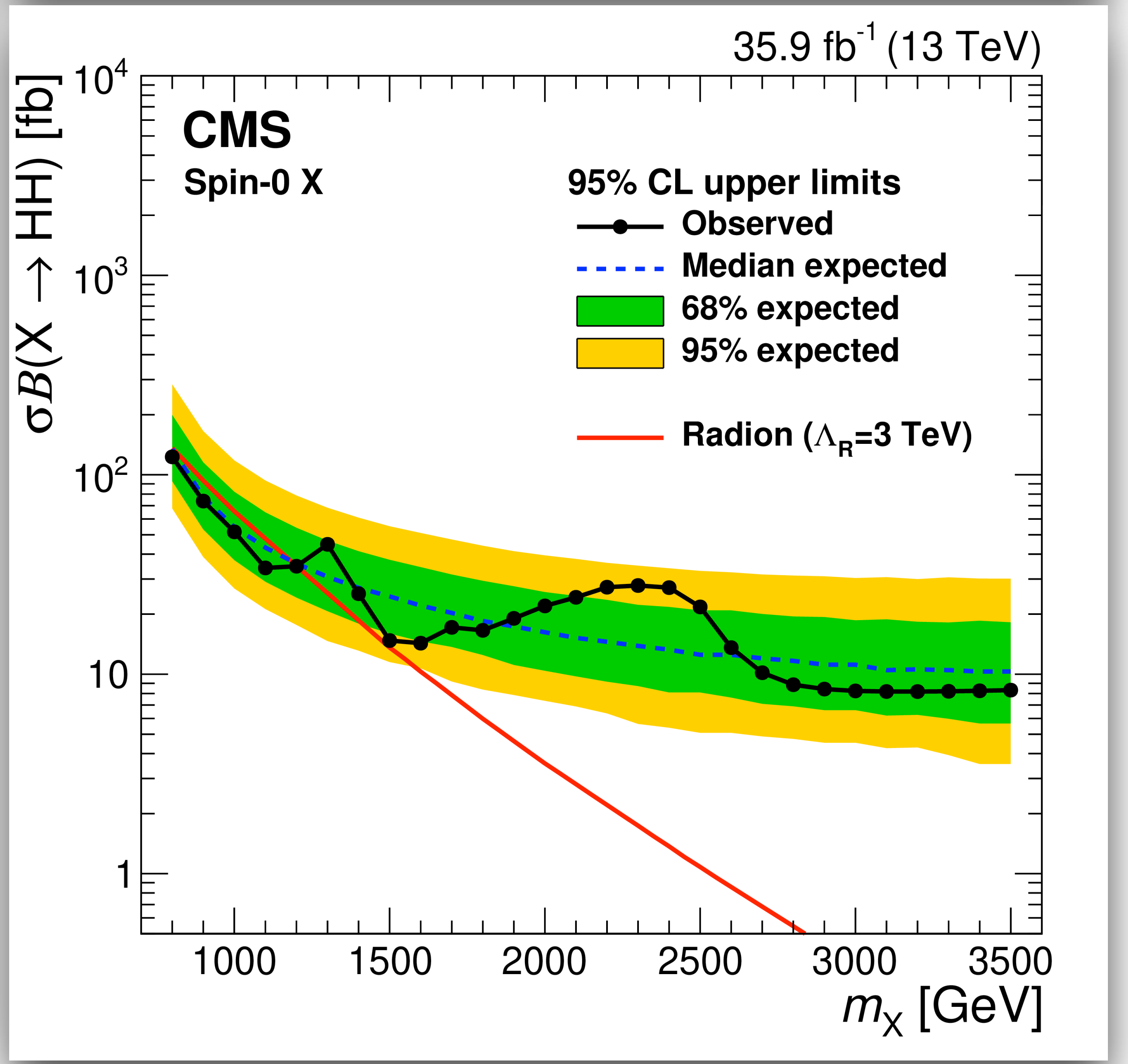
- **ATLAS**: 1 lepton, **2 light jets for W**, 2 b-tagged jets (for resolved) and 1 large-R jet with track-jets b-tagging (for boosted) for H
- **CMS**: 1 lepton, **2 large-R jets for W & H**

- ATLAS: counting experiment in resolved; fit on m_{HH} in boosted
- CMS: fit on m_{HH}-m_{bb} in 12 categories



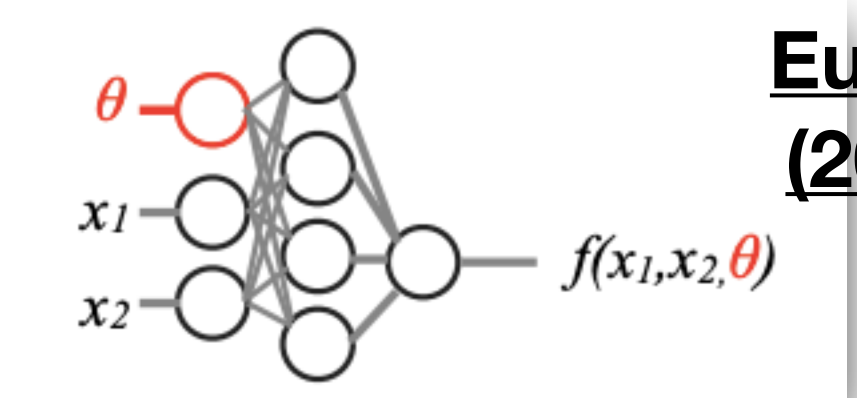






HH→bbVV (2L, CMS)

JHEP 01 (2018) 054 CMS-PAS-HIG-17-032

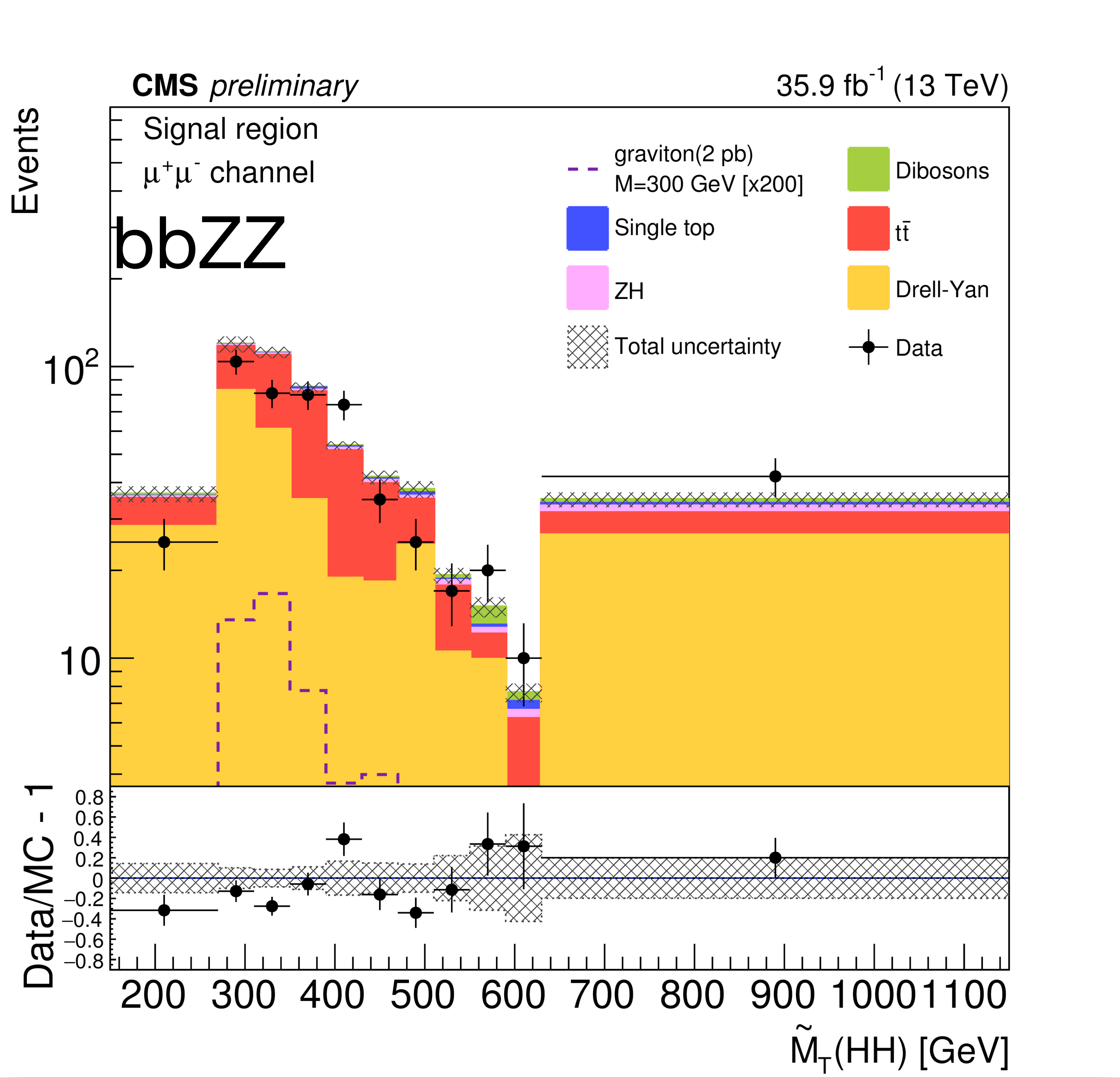


Eur. Phys. J. C (2016) 76: 235

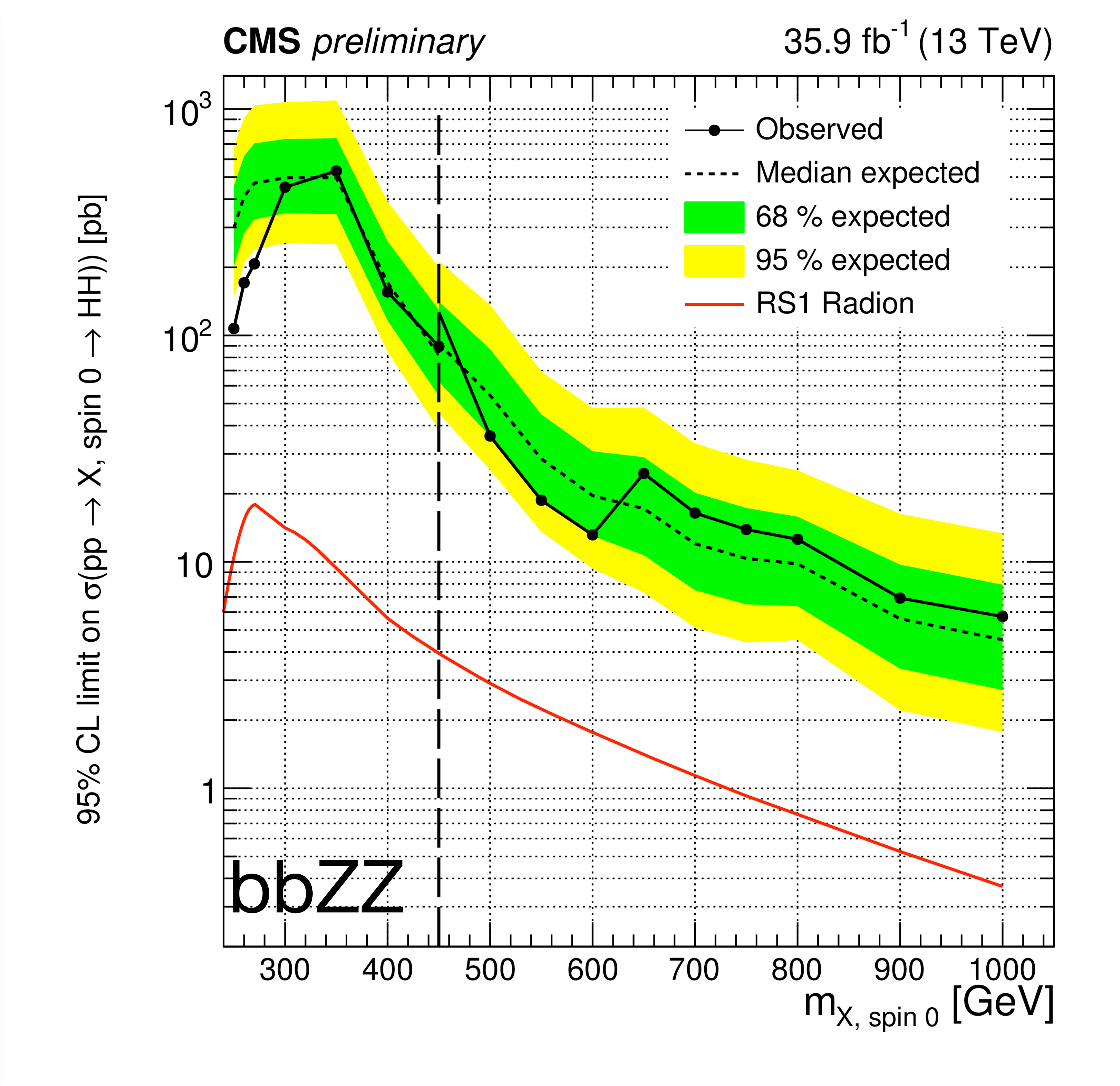
HH→bbWW→bblvlv or HH→bbZZ→bbllvv

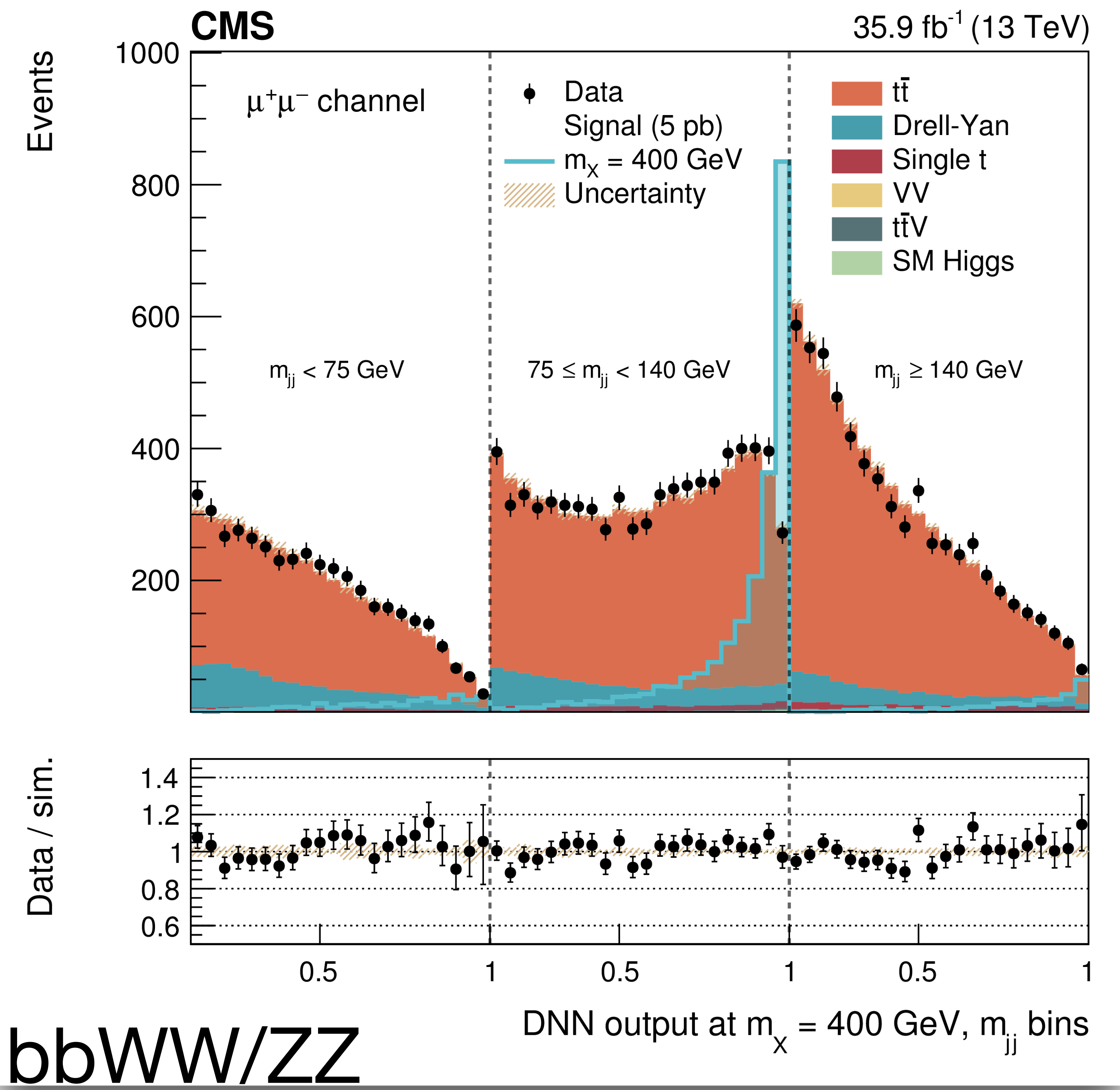
- bbZZ analysis: 2 leptons, missing transverse energy, 2 b-tagged jets, 2 distinct BDTs trained for 2 mass ranges separately, **on-shell Z only**
- bbWW/ZZ: 2 leptons, 2 b-tagged jets, **$12<m_{ll}<m_Z-15$ GeV (off-shell Z)** to suppress quarkonia resonances, DY, tt, fit on parameterised DNN

- Limits on SM HH production in the unit of σ_{SM}(pp→HH):
  - 89 (**79**) in CMS bbWW/ZZ



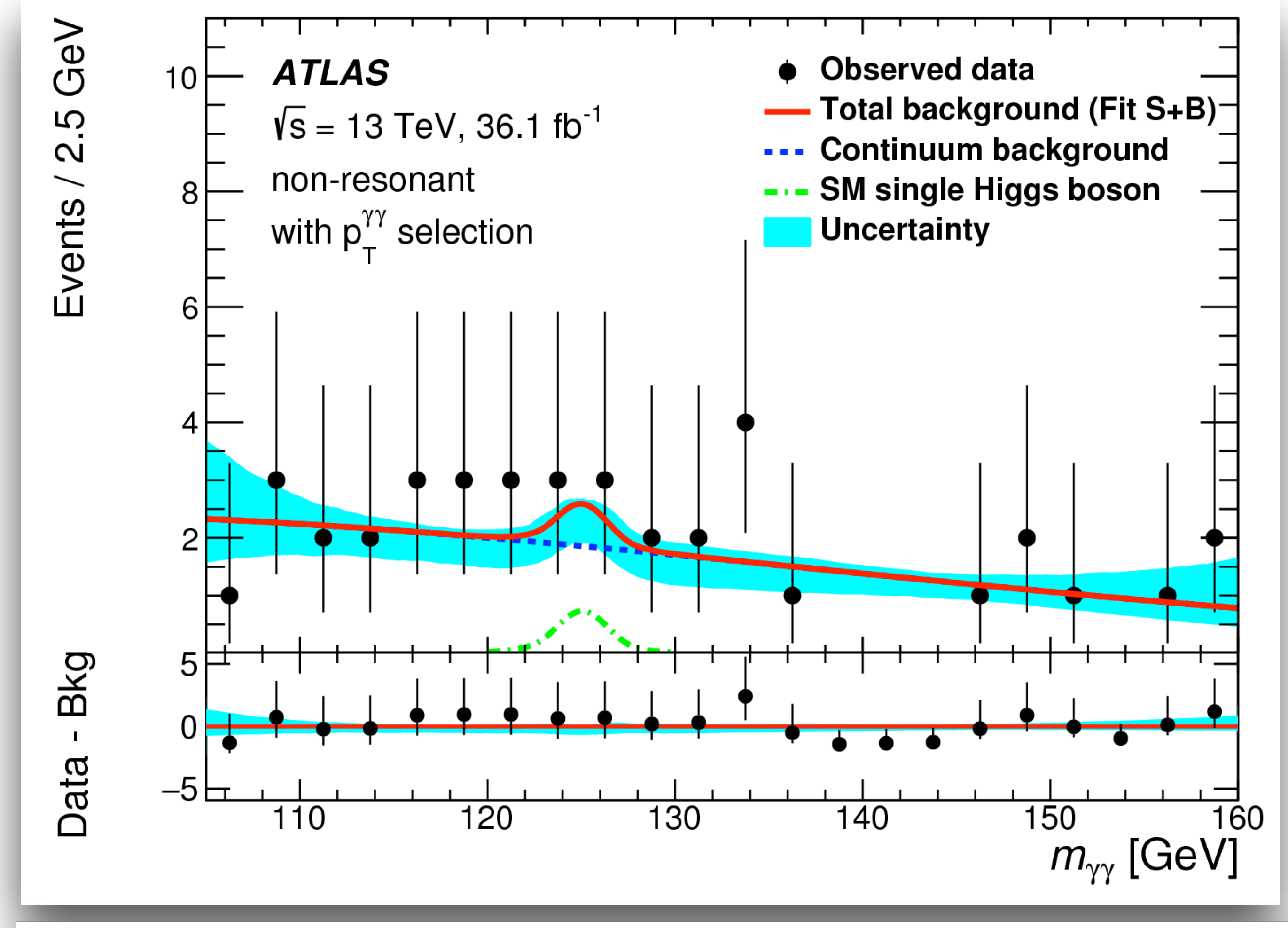
Fit on the transverse mass of HH



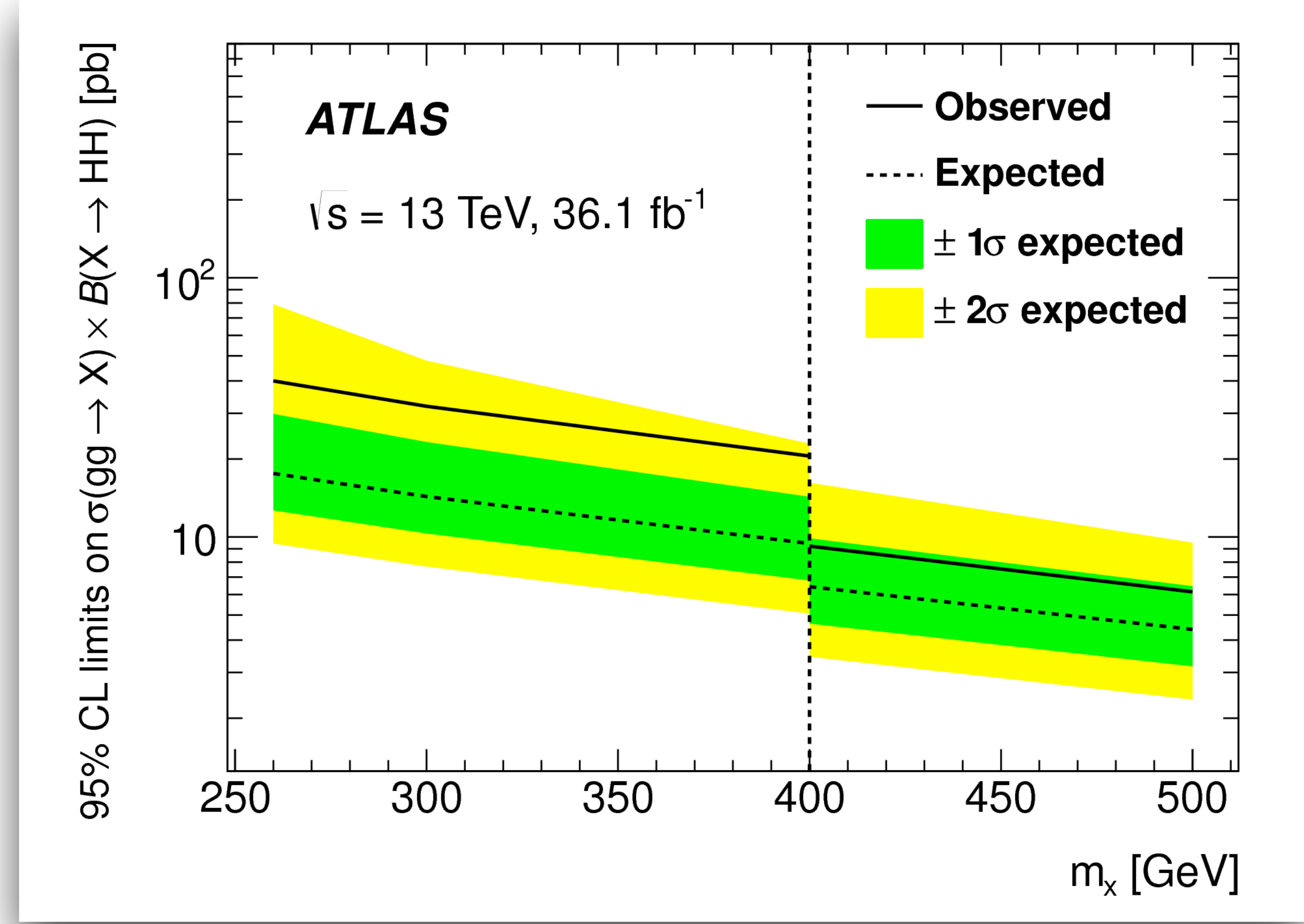


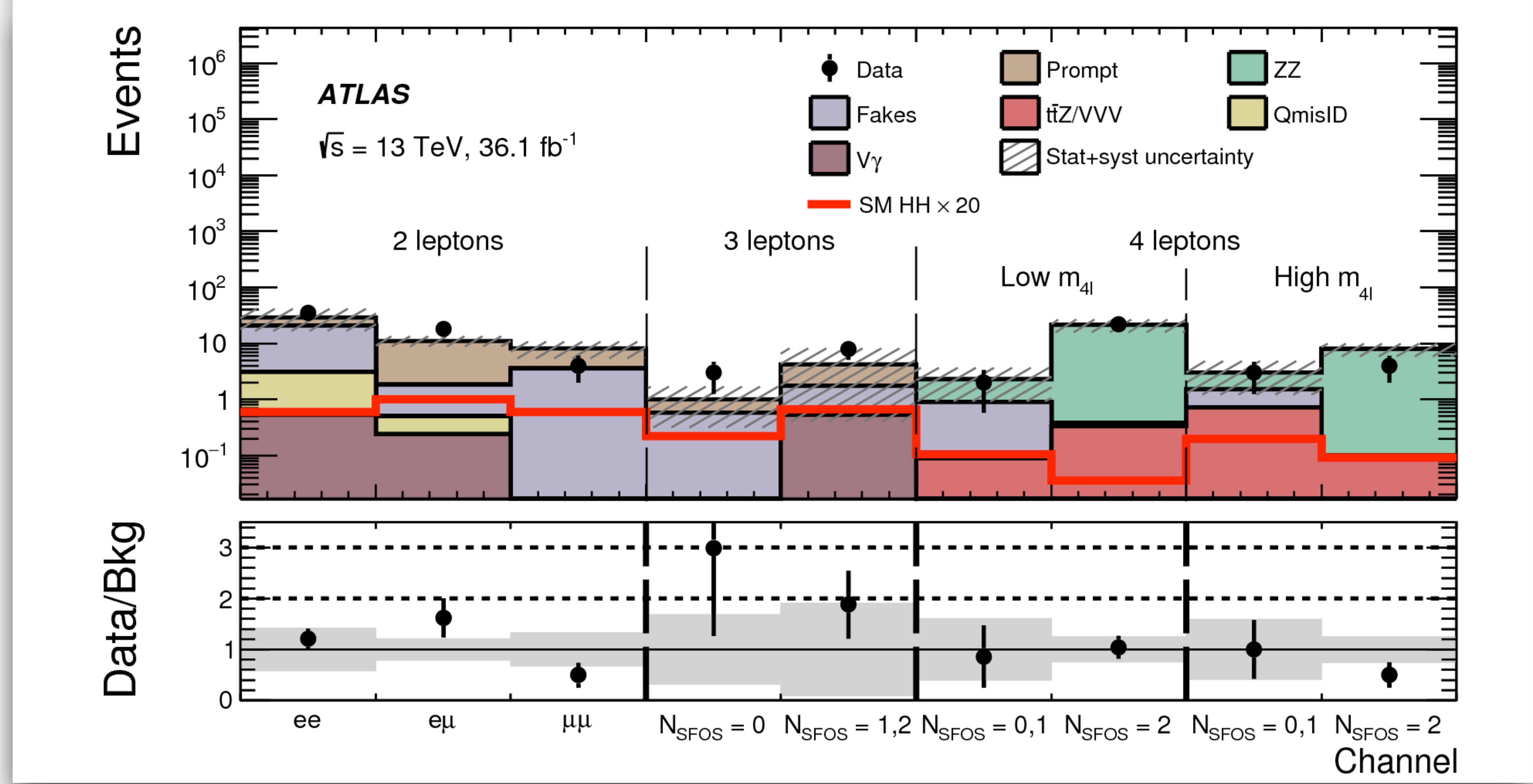
HH→WWγγ, WWWW

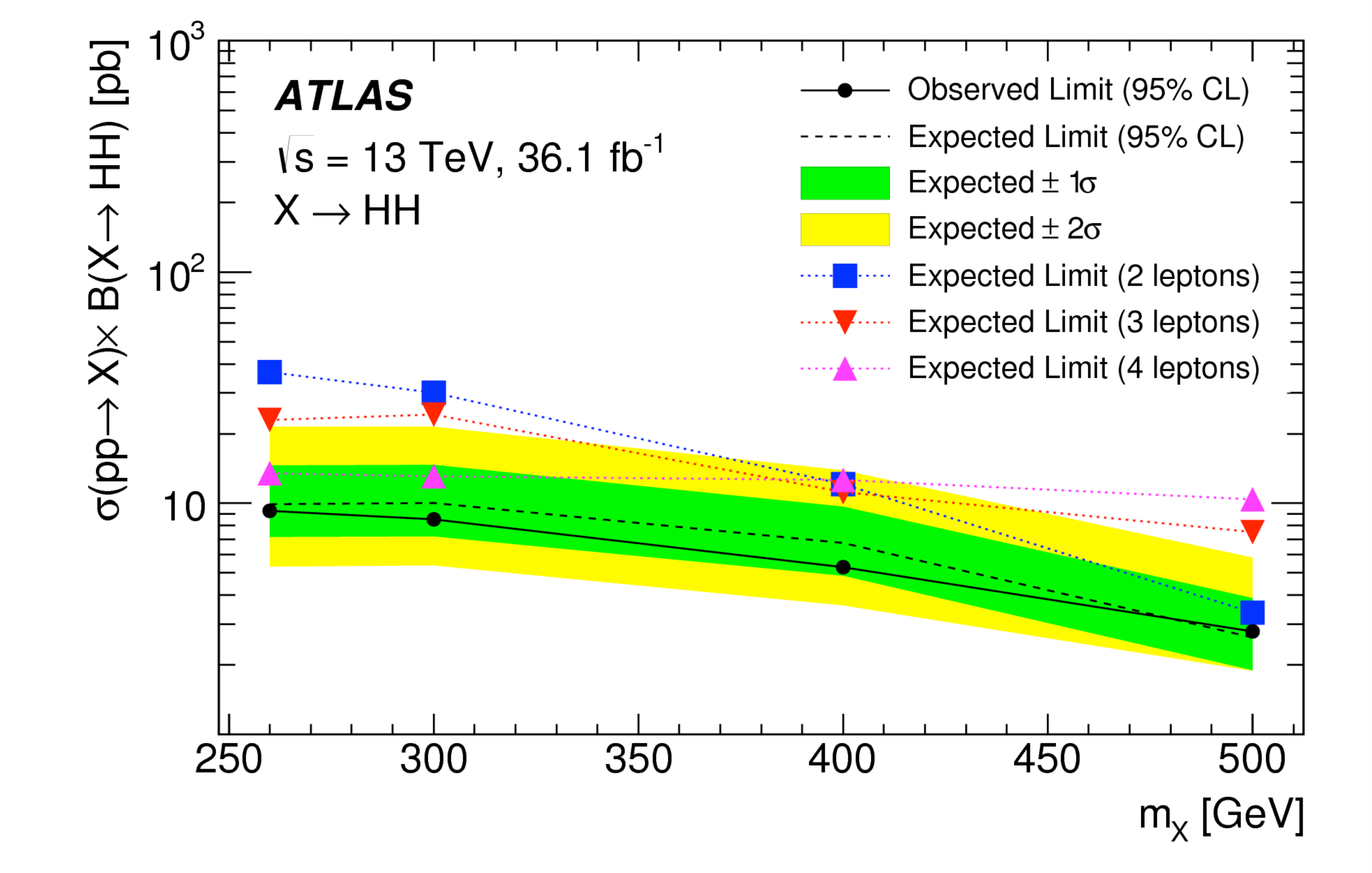
Eur. Phys. J. C 78 (2018) 1007
arXiv:1811.11028



- **WWγγ**: 1 lepton, 2 jets and 2 photons; fit on $m_{\gamma\gamma}$
- **WWWW**: 2/3/4 leptons; event counting
  - X→SS ($m_S \neq 125$ GeV) is probed
- Limits on SM HH production in the unit of σ_{SM}(pp→HH):
  - 230 (**160**) in WWγγ; 160 (**120**) in WWWW



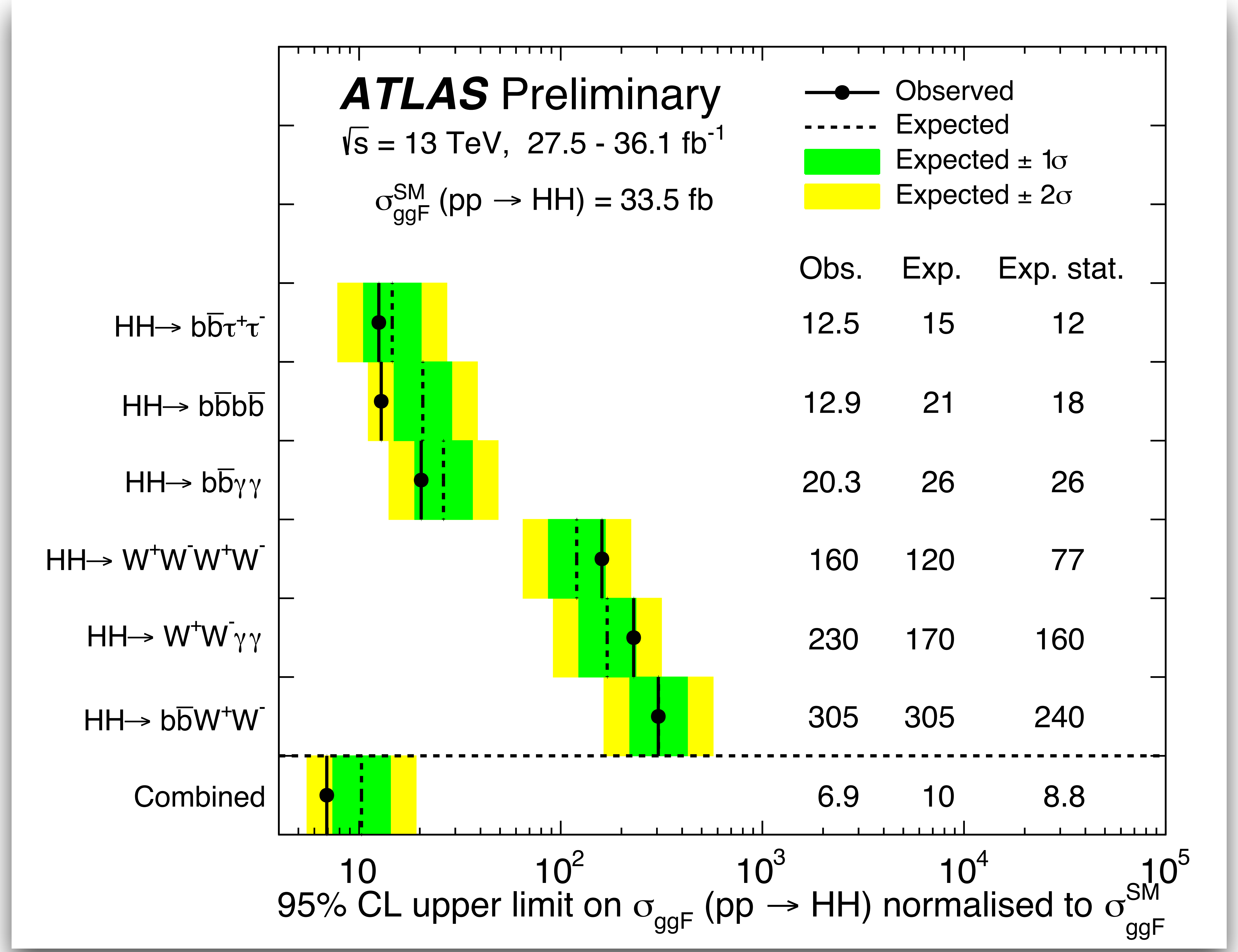


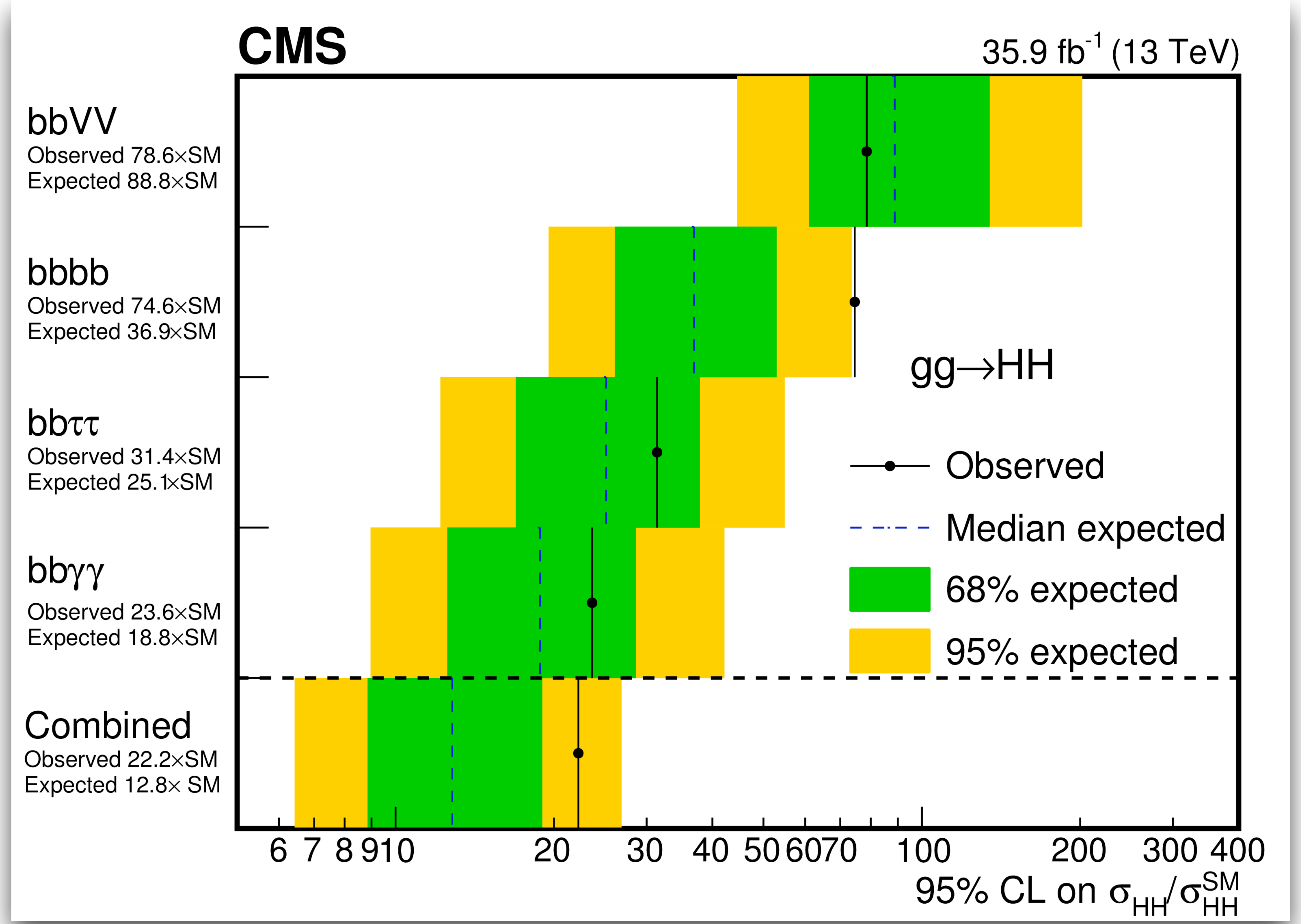


HH combination

ATLAS coming soon

Phys. Rev. Lett. 122 (2019) 121803





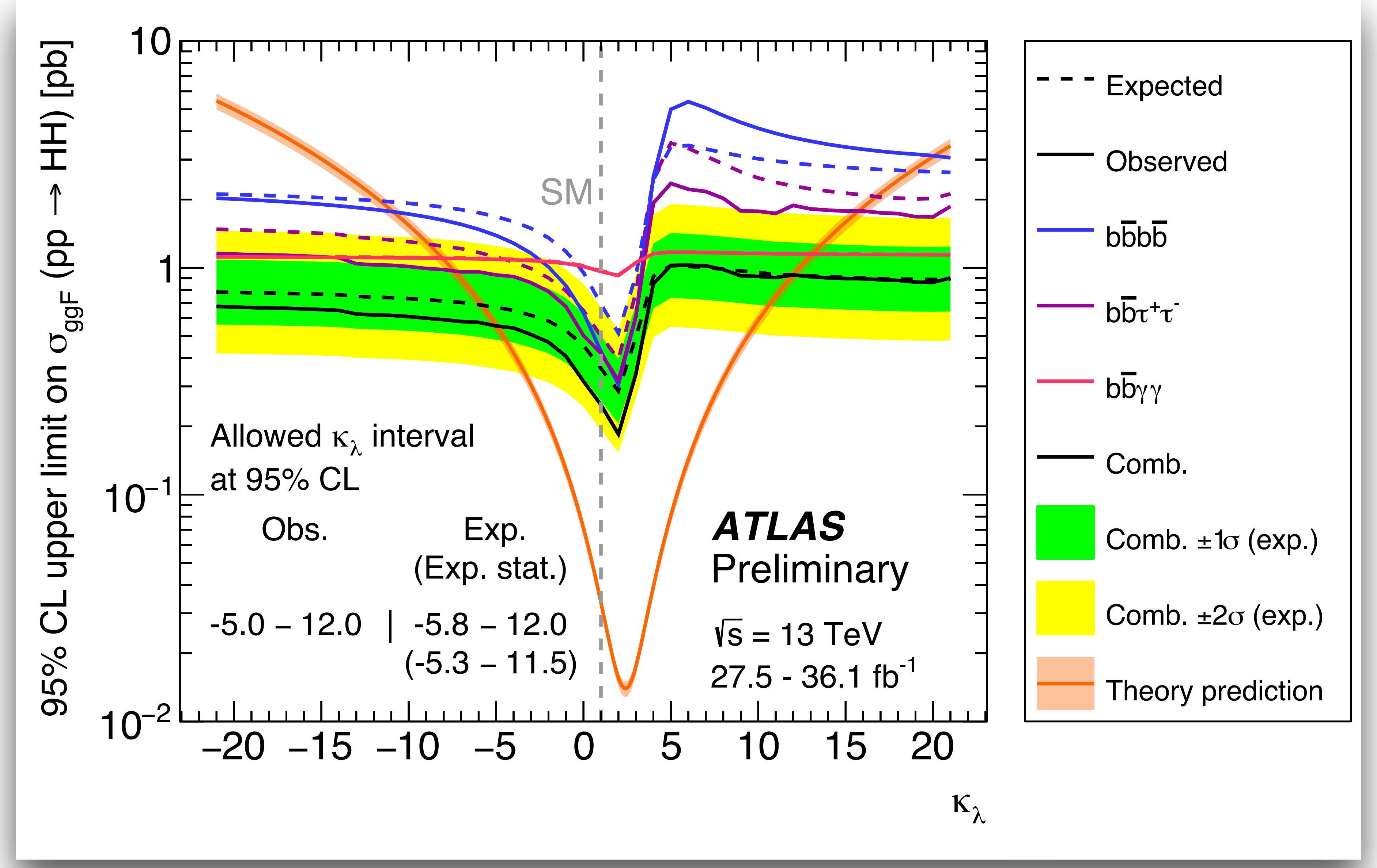
ATLAS combined upper limits:
6.9 (**10**) x SM HH cross-section

CMS combined upper limits:
22 (**13**) x SM HH cross-section

HH combination

ATLAS coming soon

Phys. Rev. Lett. 122 (2019) 121803

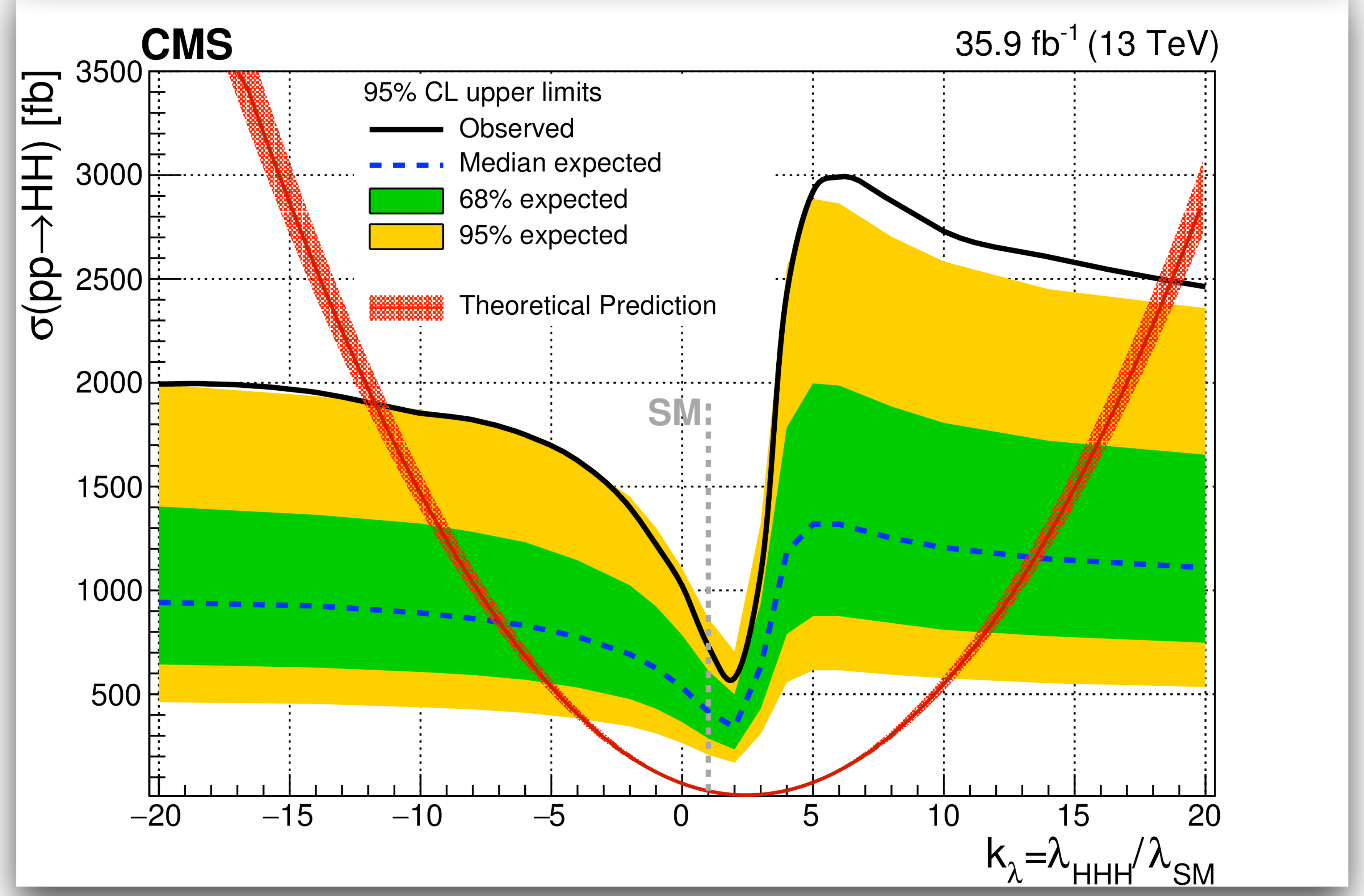


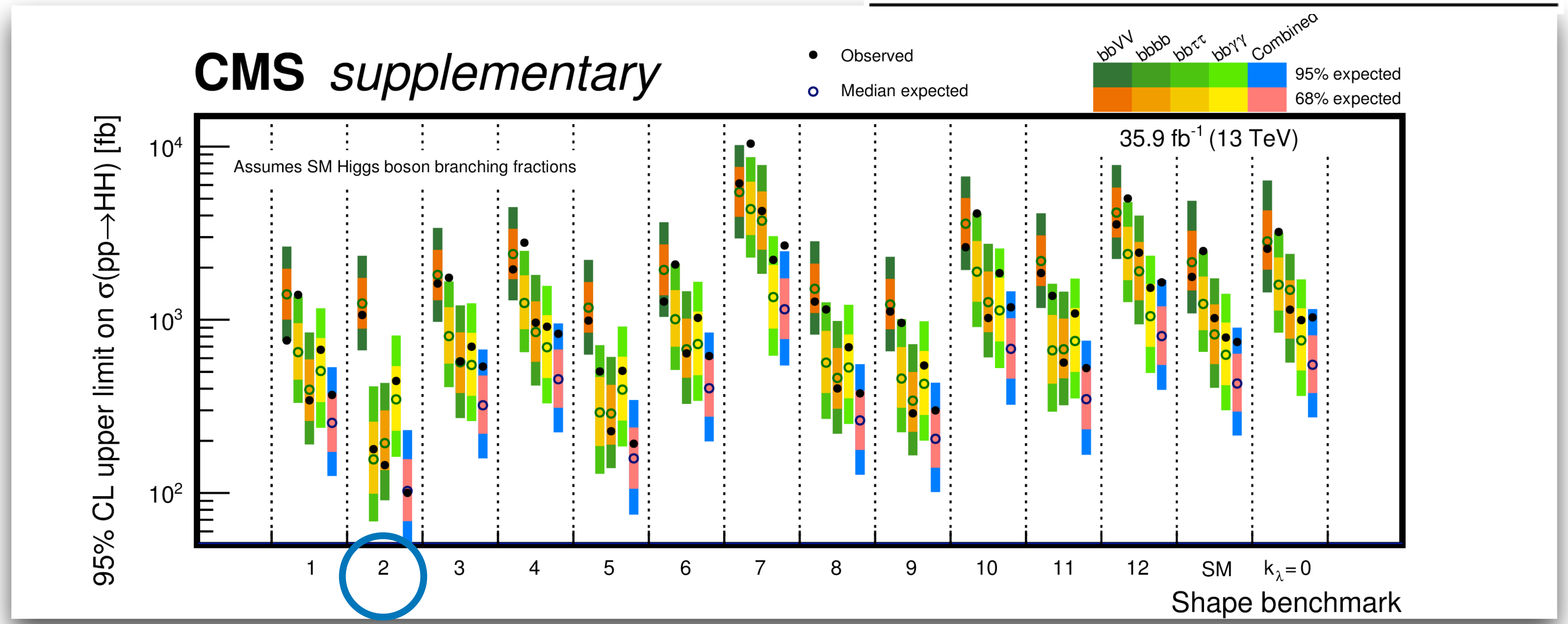
Constraints on κ_λ at 95% CL

- ATLAS: [-5.0,12] (**[-5.8,12]**)
- CMS: [-11.8,18.8] (**[-7.1,13.6]**)

Limits are set on cross-section in benchmarks with EFT Higgs couplings

Benchmark	κ_λ	κ_t	c_2	c_g	c_{2g}
1	7.5	1.0	-1.0	0.0	0.0
2	1.0	1.0	0.5	-0.8	0.6
3	1.0	1.0	-1.5	0.0	-0.8
4	-3.5	1.5	-3.0	0.0	0.0
5	1.0	1.0	0.0	0.8	-1.0
6	2.4	1.0	0.0	0.2	-0.2
7	5.0	1.0	0.0	0.2	-0.2
8	15.0	1.0	0.0	-1.0	1.0
9	1.0	1.0	1.0	-0.6	0.6
10	10.0	1.5	-1.0	0.0	0.0
11	2.4	1.0	0.0	1.0	-1.0
12	15.0	1.0	1.0	0.0	0.0
SM	1.0	1.0	0.0	0.0	0.0

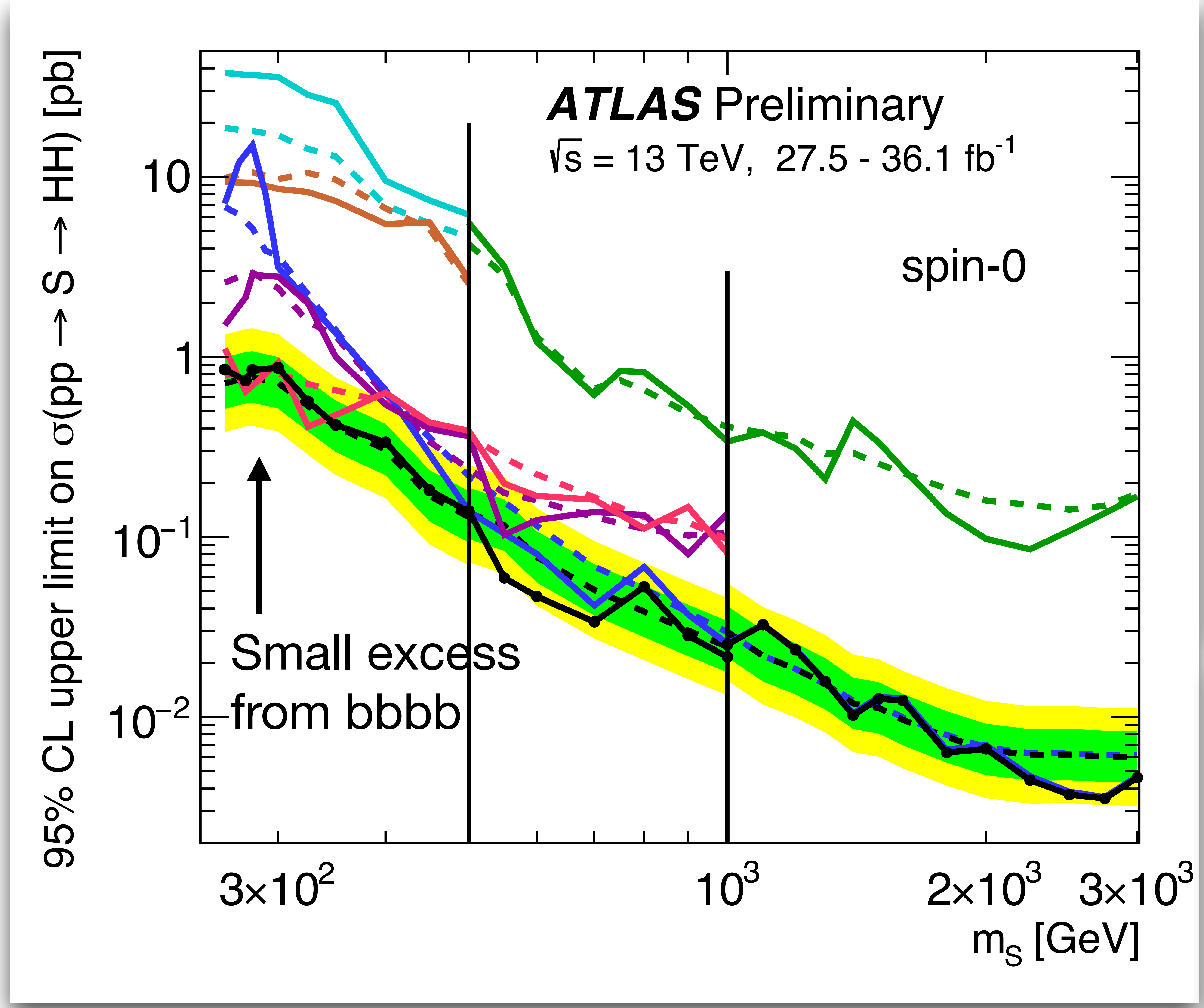


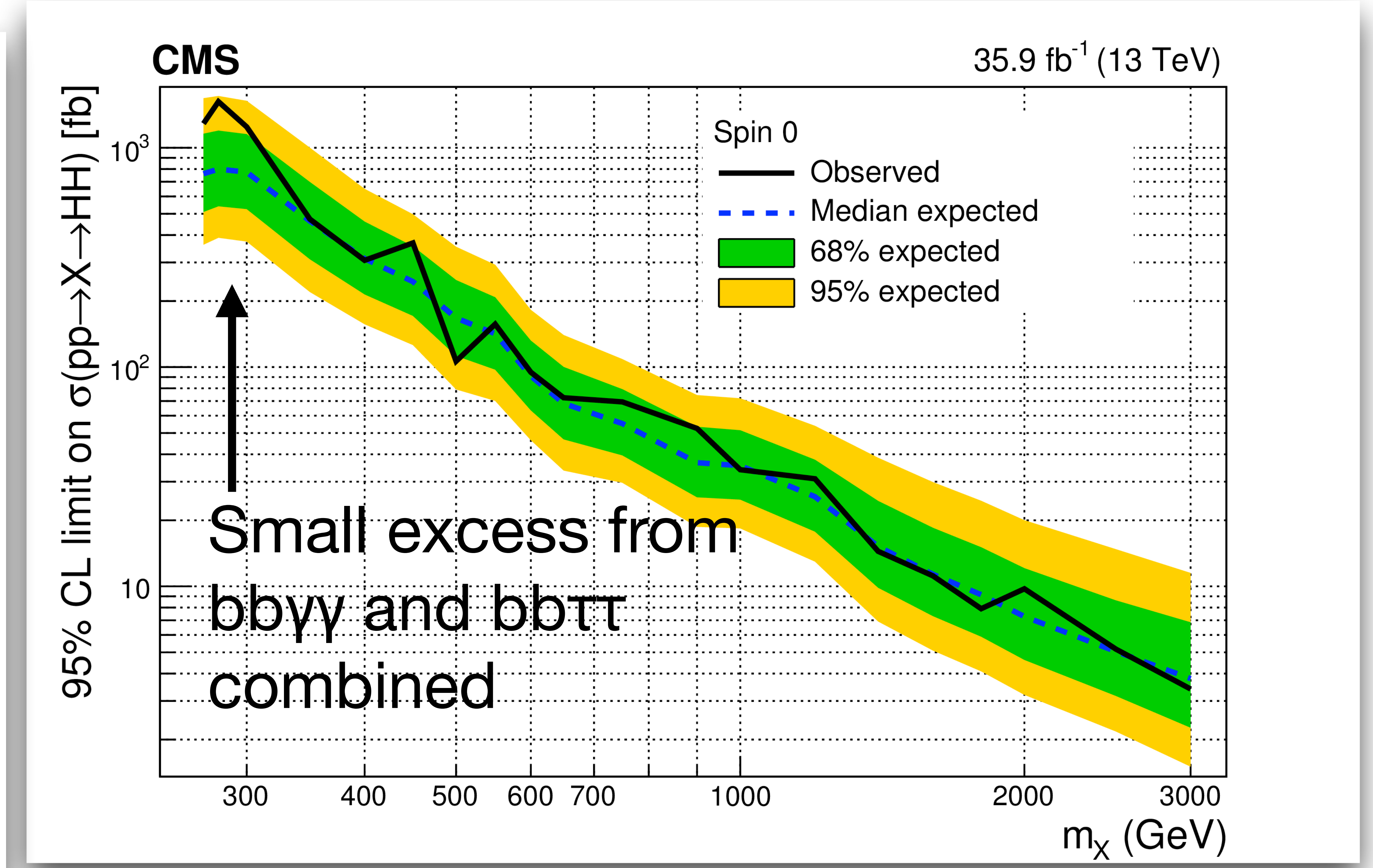


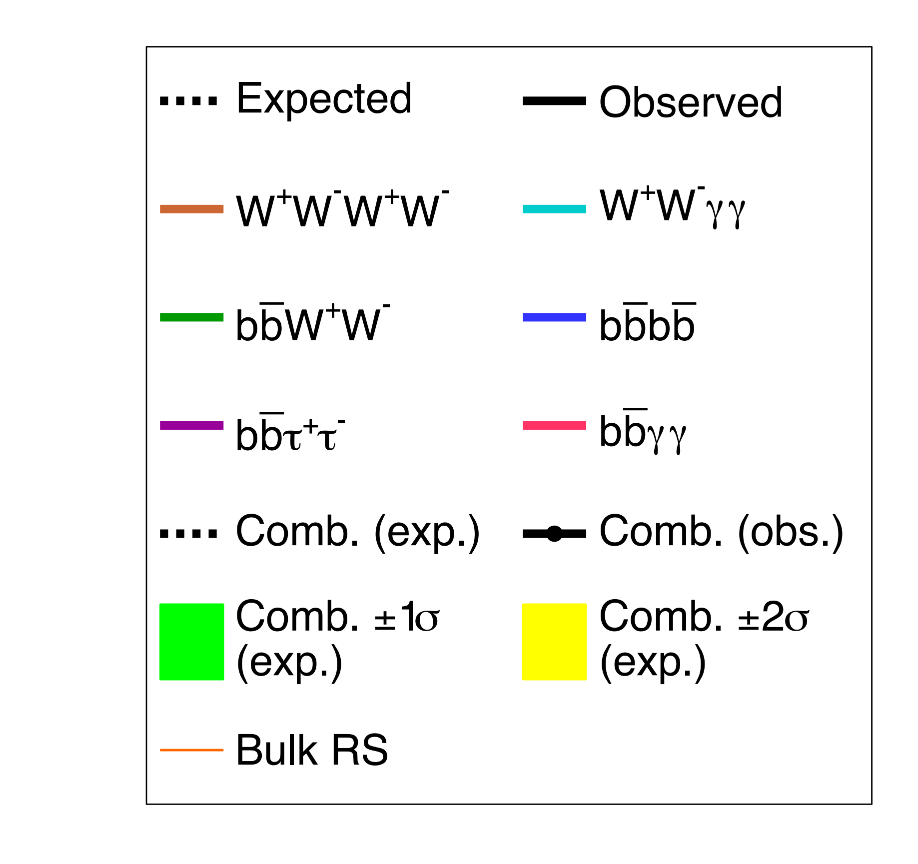
HH combination

ATLAS coming soon

Phys. Rev. Lett. 122 (2019) 121803





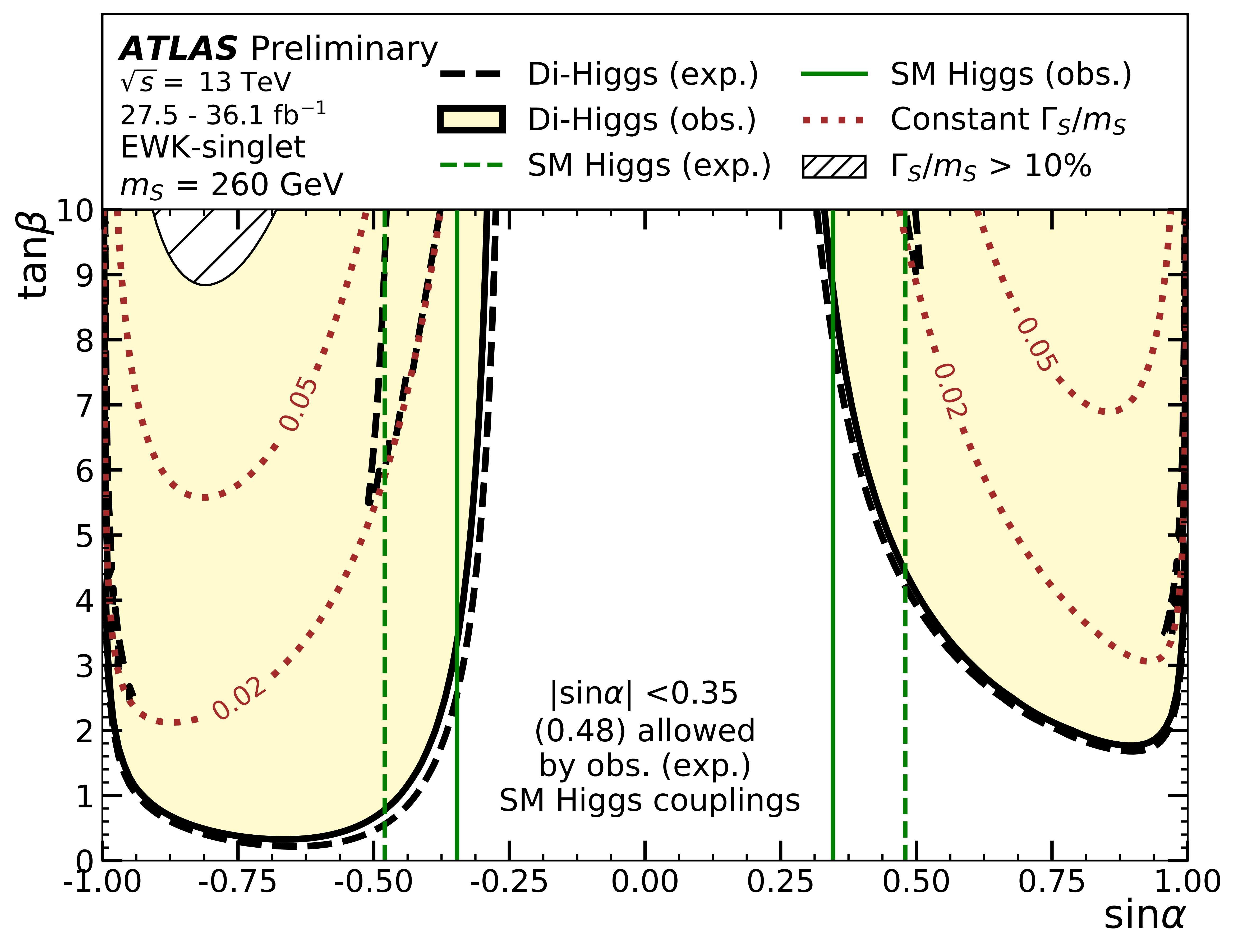


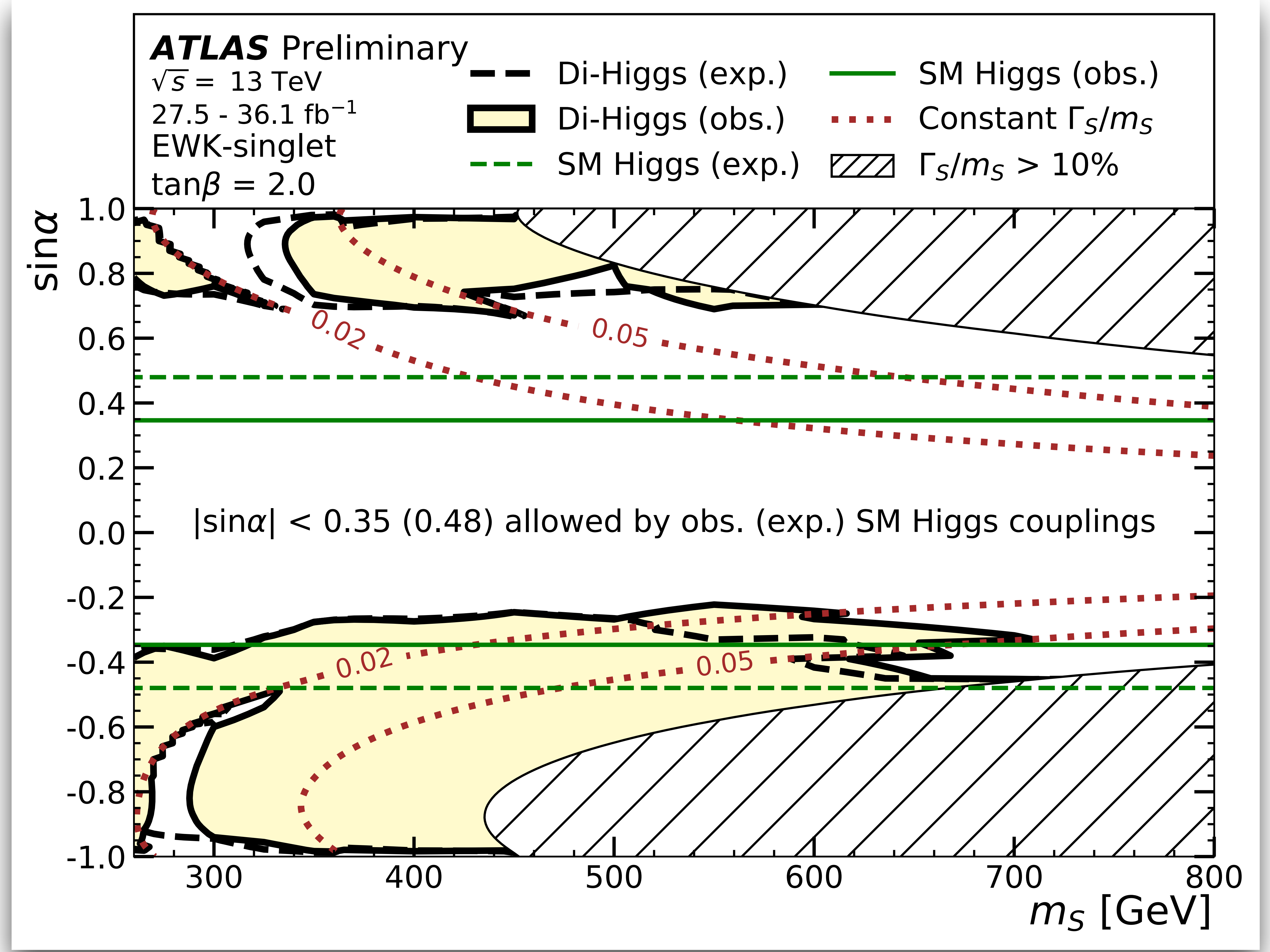
- Limits are set on spin0 and spin2 resonant HH searches assuming SM H BRs

HH combination

ATLAS coming soon

Phys. Rev. Lett. 122 (2019) 121803



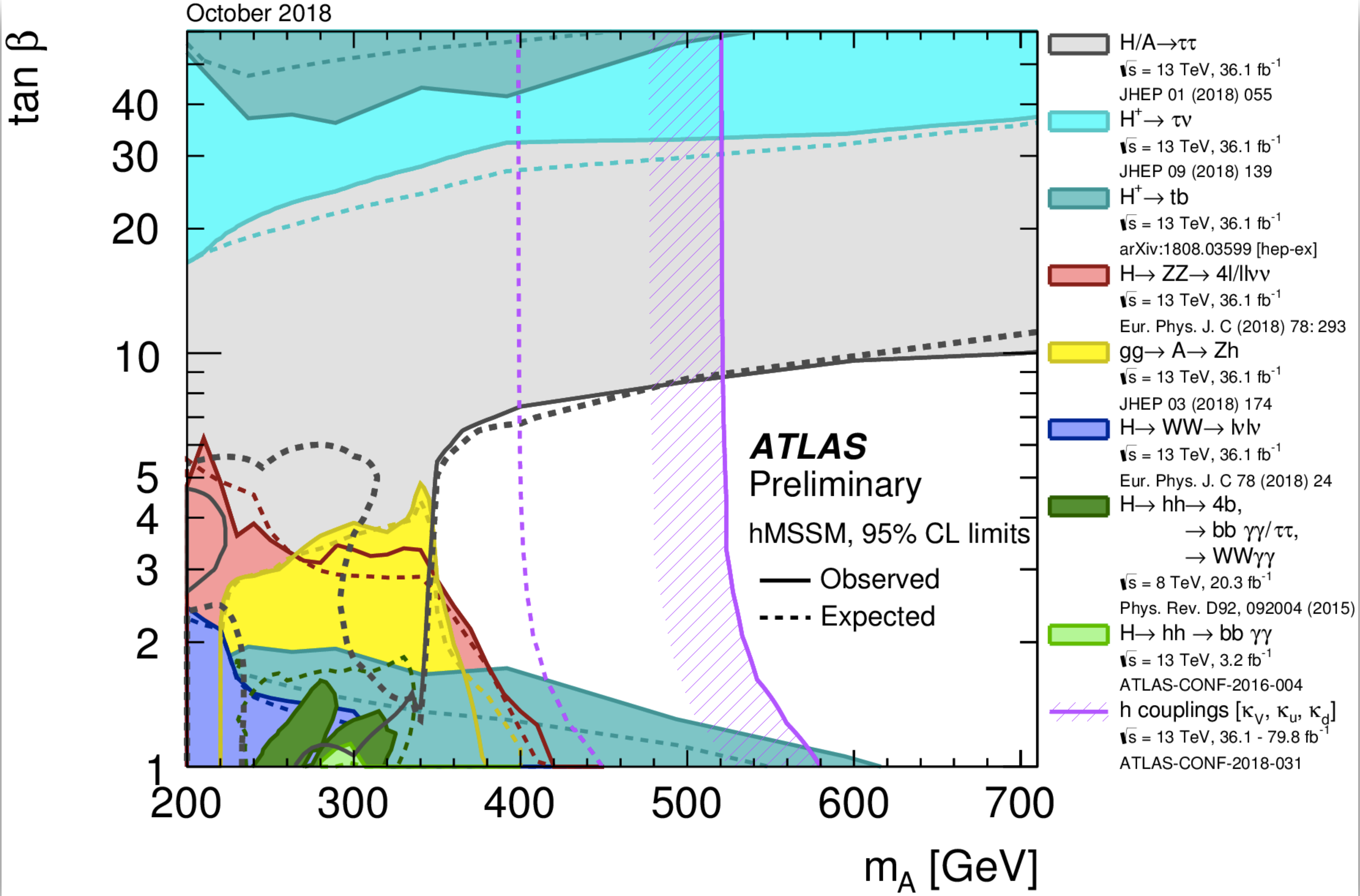


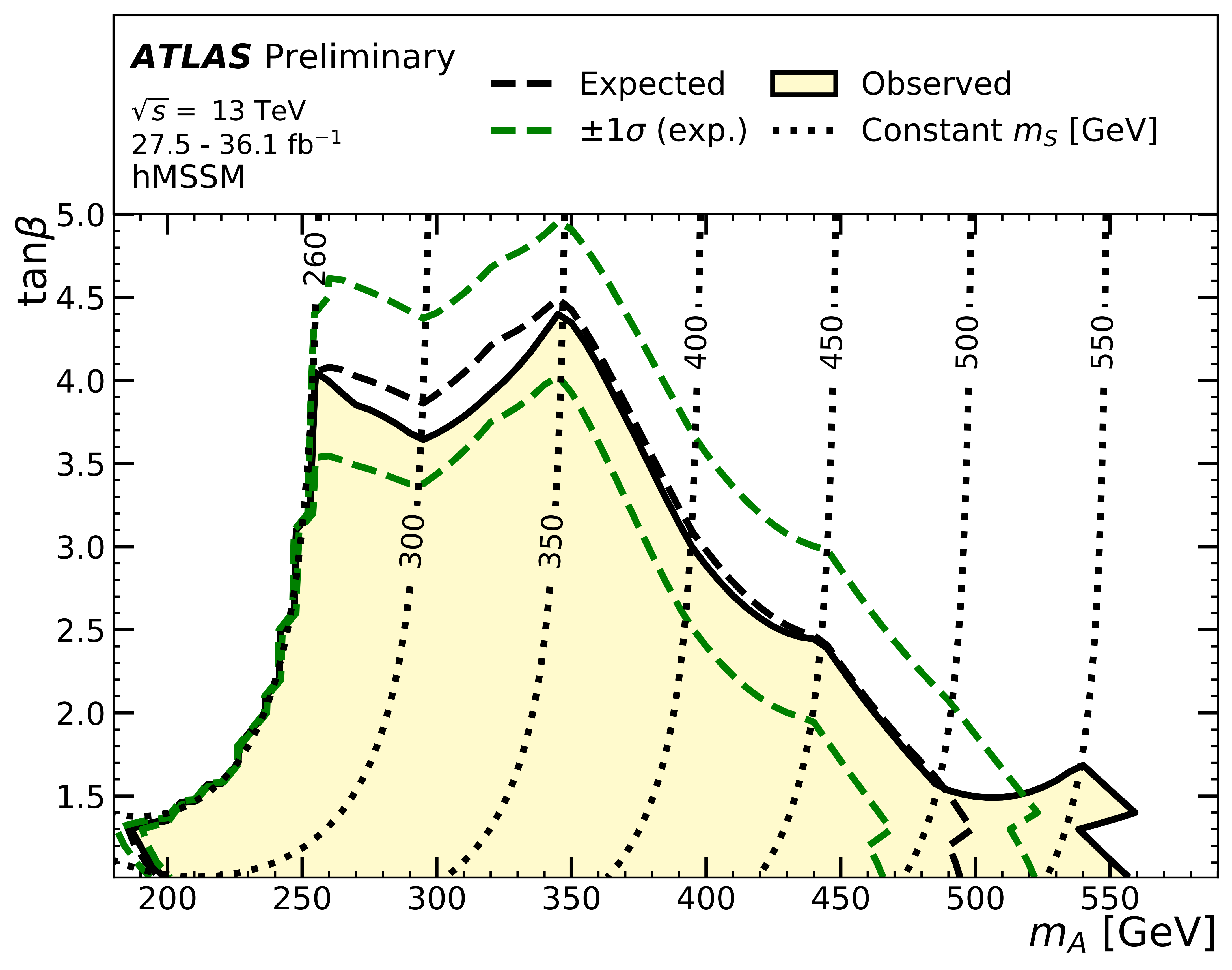
- Constraints are imposed on EWK single model
- HH limits are comparable to indirectly SM single Higgs measurement in many regions

HH combination

ATLAS coming soon

ATLAS Higgs summary plots





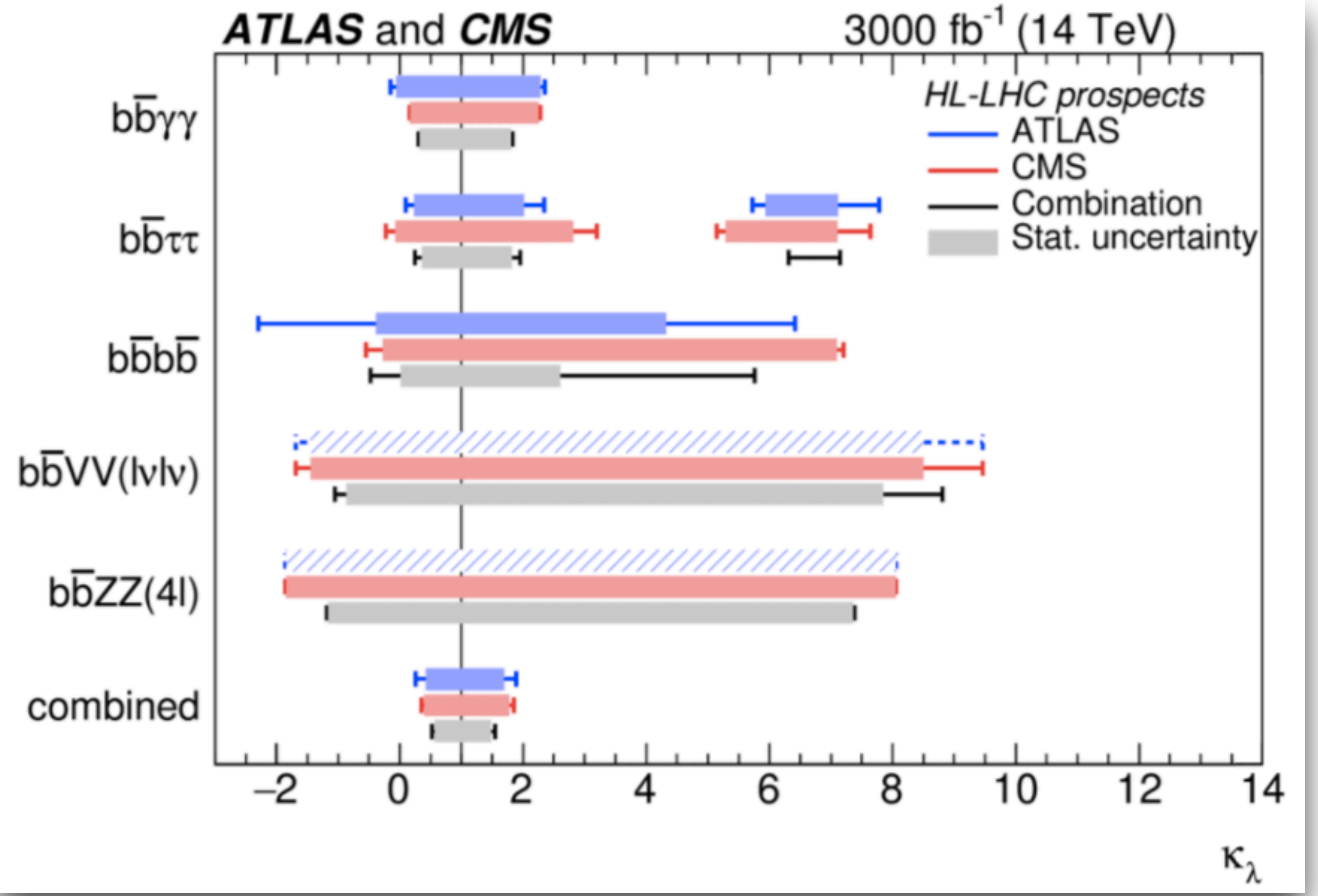
- Left: BSM Higgs searches (including Run1 HH exclusion); right: new HH exclusions
- New HH exclusions:
  - 2x more exclusion on tanβ than Run1; extend to 550 GeV on m_A

Di-Higgs @ HL-LHC

1902.00134
CMS-PAS-FTR-18-019
ATL-PHYS-PUB-2018-053

- ATLAS includes bbbb, bbττ and bbγγ
- CMS includes bbbb, bbττ, bbγγ, bbVV (2-lepton) and bbZZ (4-lepton)

	Statistical-only		Statistical + Systematic	
	ATLAS	CMS	ATLAS	CMS
$HH \to b\bar{b}b\bar{b}$	1.4	1.2	0.61	0.95
$HH \to b\bar{b}\tau\tau$	2.5	1.6	2.1	1.4
$HH \to b\bar{b}\gamma\gamma$	2.1	1.8	2.0	1.8
$HH \to b\bar{b}VV(ll\nu\nu)$	-	0.59	-	0.56
$HH \to b\bar{b}ZZ(4l)$	-	0.37	-	0.37
combined	3.5	2.8	3.0	2.6
	Combined 4.5		Combined 4.0	



Combine ATLAS and CMS:

- Expected significance 4σ
- **Expected precision on signal strength ~25%**

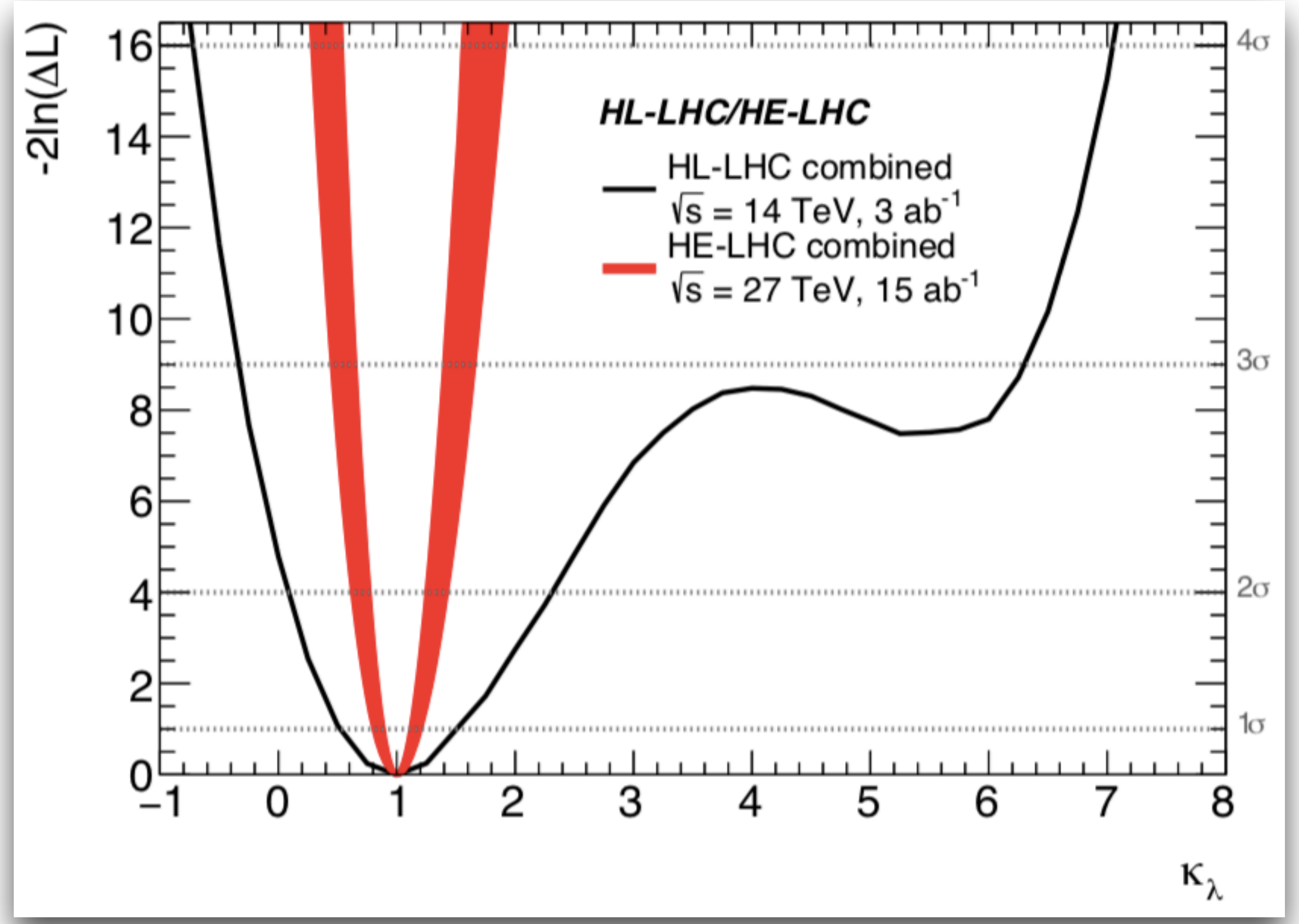
Combined ATLAS and CMS (stat.+syst.): 68% CL interval on κ_λ $0.52 \le \kappa_\lambda \le 1.5$ (indirect probe with loop correction in single Higgs “exclusive”: $-0.1 \le \kappa_\lambda \le 2.3$)

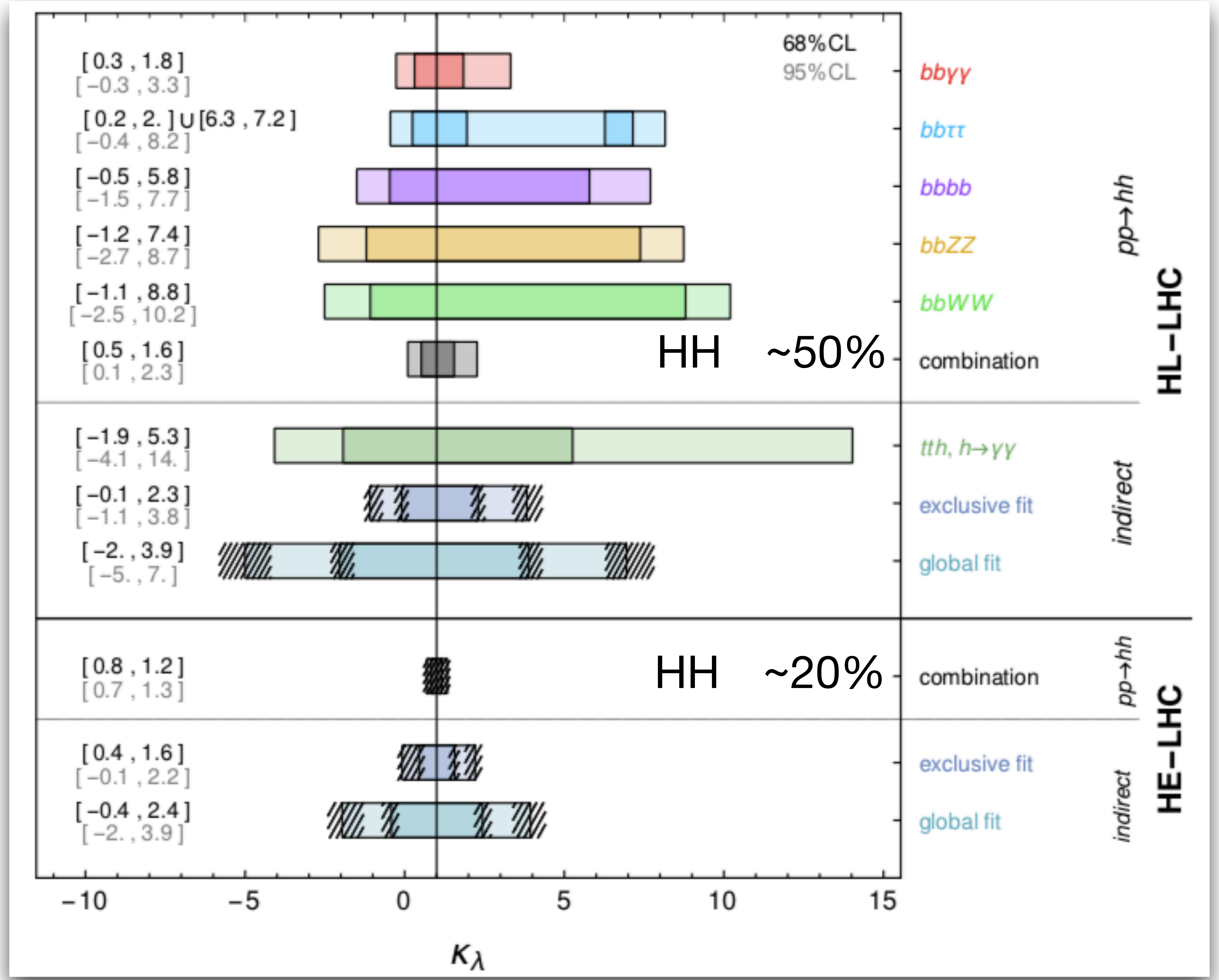
Expected precision on κ_λ ~50%

Di-Higgs @ HE-LHC

1902.00134
ATL-PHYS-PUB-2018-053

- Scale up to HE-LHC from HL-LHC: cross section x4, luminosity 15 ab^{-1}
- Studied **bbττ** and **bbγγ** with ATLAS assuming no systematic uncertainties
- Significance: 10.7σ in bbττ, 7.1σ in bbγγ
- **Precision on κ_λ: 20% (40%) in bbττ (bbγγ)**



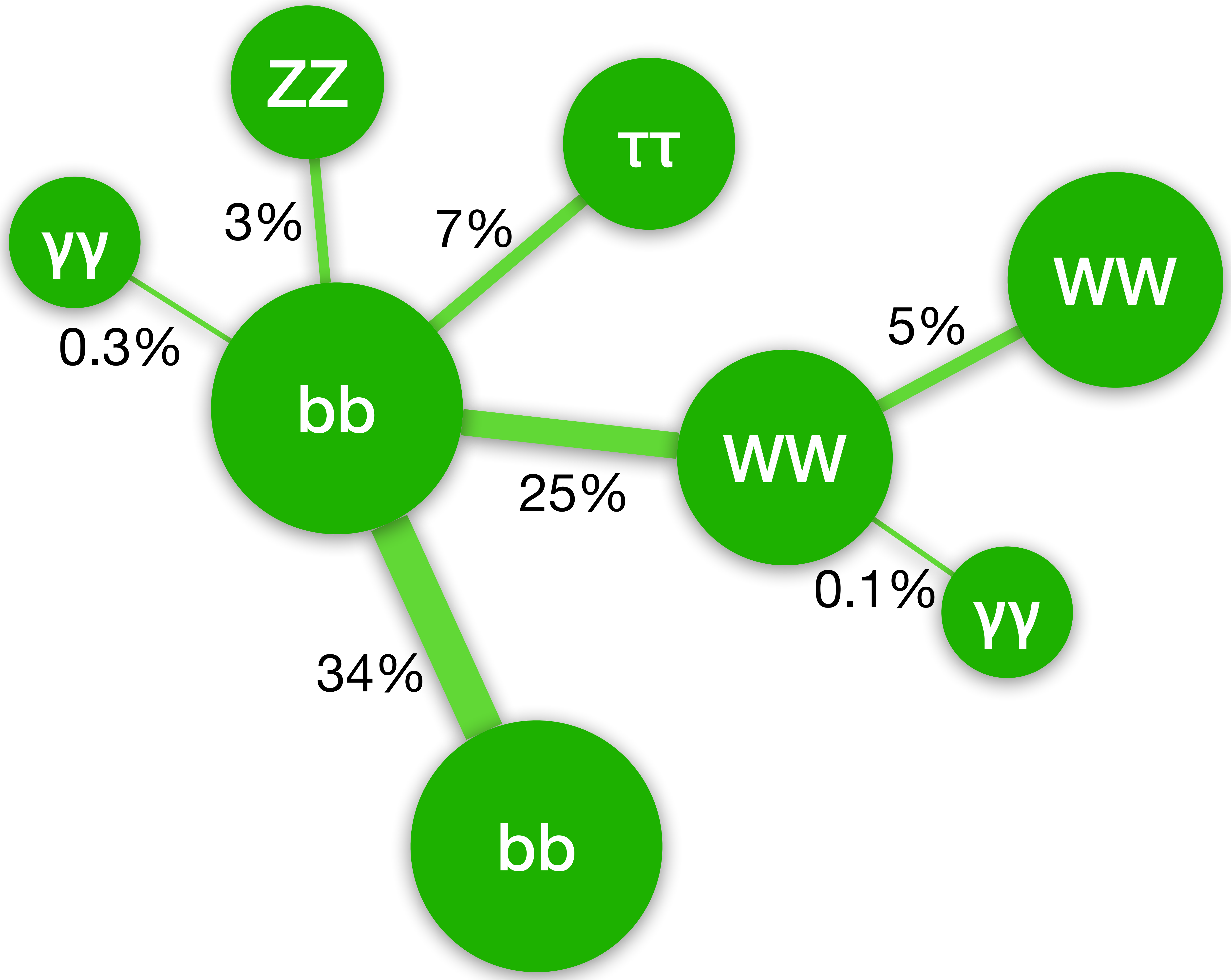


Summary

- Extensive searches for di-Higgs are being performed in ATLAS and CMS
- Di-Higgs: 5x better upper limits compared to Run1 results
    - Approach a few times of SM di-Higgs cross-section
    - Start to study the second leading production mode VBF
    - Reach several TeV for di-Higgs resonance (more heavy resonance results in J. Ngadiuba's talk on Tuesday)
    - Expect evidence of SM di-Higgs production at the HL-LHC
    - Expect to measure Higgs-self coupling with 50% (20%) precession in HL-LHC (HE-LHC)
- Many other prospects are not included due to time (resonant HH 4b, VBF non-resonant, HH implications for theory etc.). See 1902.00134 !

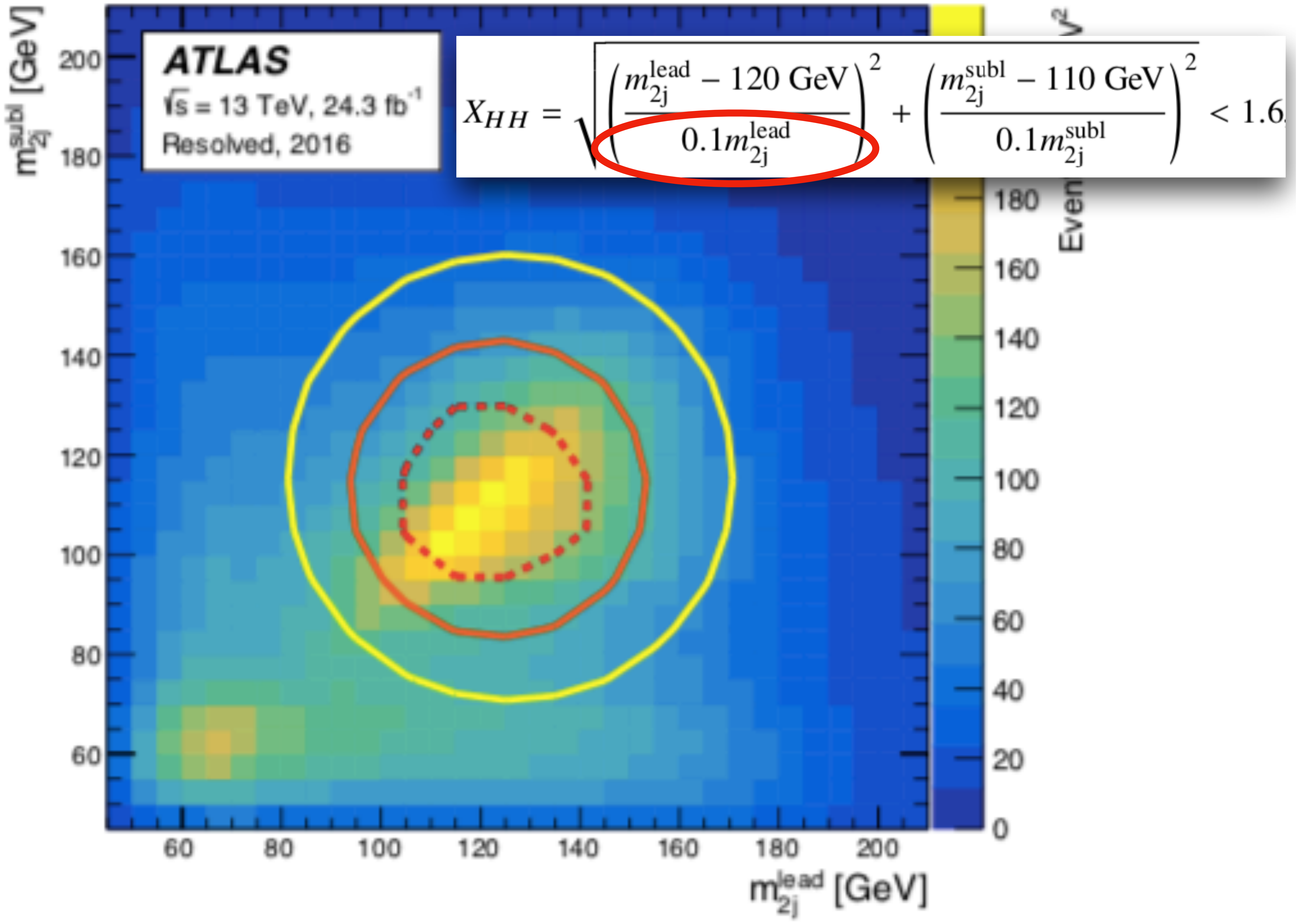
Backup slides

Di-Higgs experimental status



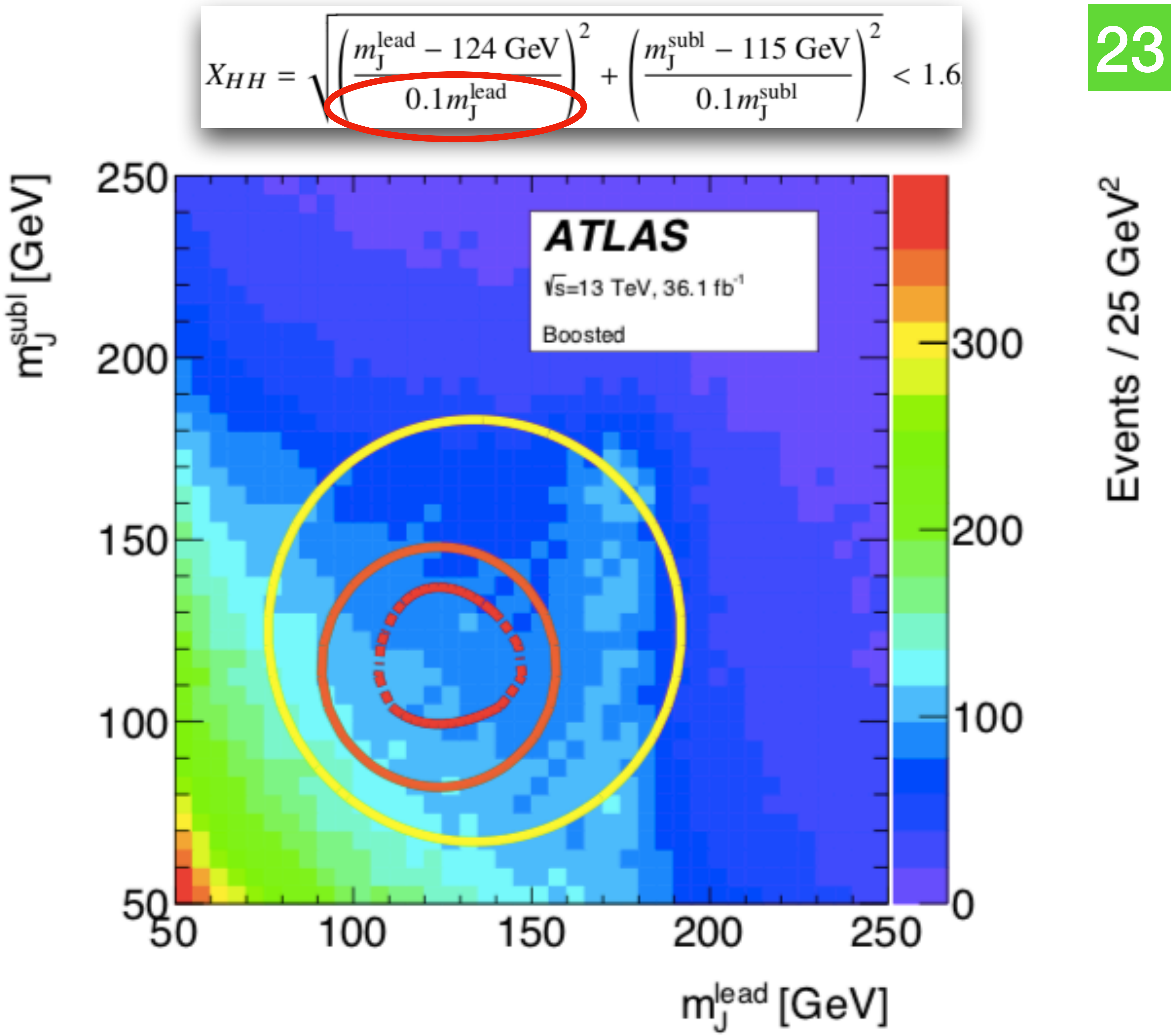
Each connection with its branching ratio presents a decay combination explored by ATLAS/CMS

ATLAS 4b



(b) Multijet Background

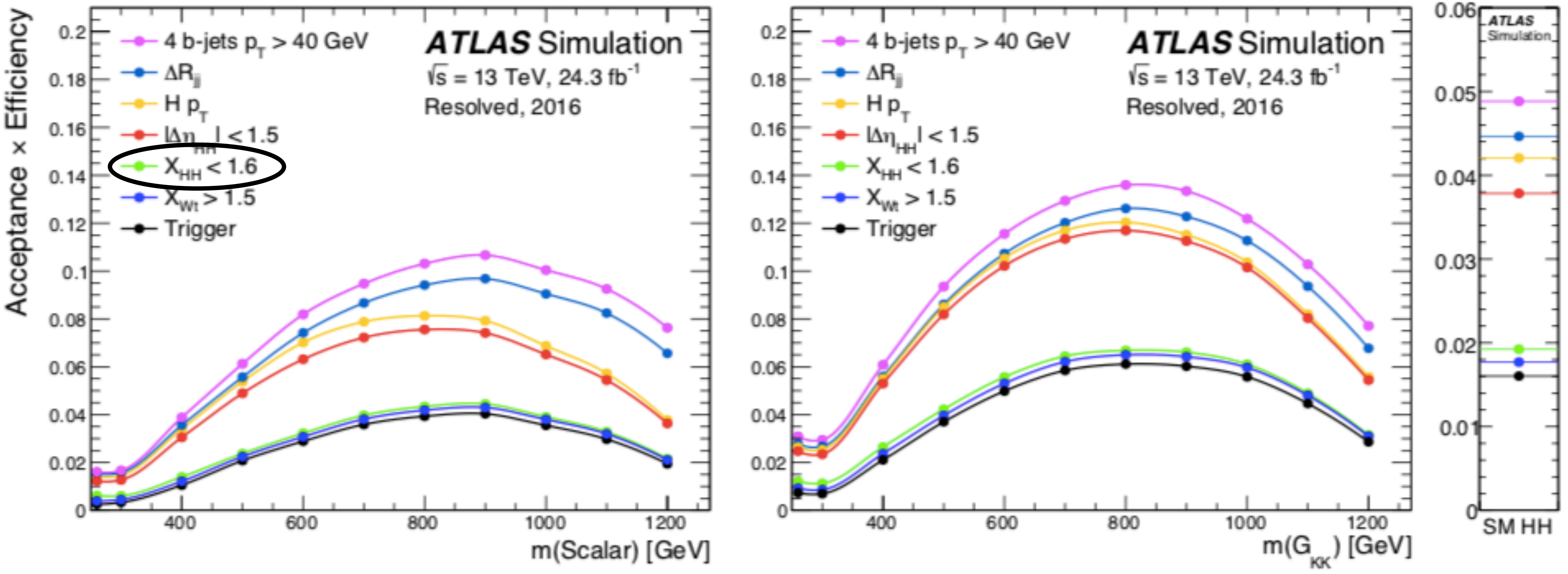
Dataset	f	μ_{multijet}	$\alpha_{t\bar{t}}^{\text{hadronic}}$	$\alpha_{t\bar{t}}^{\text{semileptonic}}$
2015	0.22	0.0838 ± 0.0038	1.19 ± 0.45	1.44 ± 0.48
2016	0.15	0.2007 ± 0.0031	1.15 ± 0.25	1.7 ± 0.19



Category	μ_{multijet}	$\alpha_{t\bar{t}}$
Two-tag	0.06273 ± 0.00057	0.986 ± 0.019
Three-tag	0.1626 ± 0.0043	0.800 ± 0.073
Four-tag	0.0332 ± 0.0043	0.89 ± 0.60

ATLAS 4b

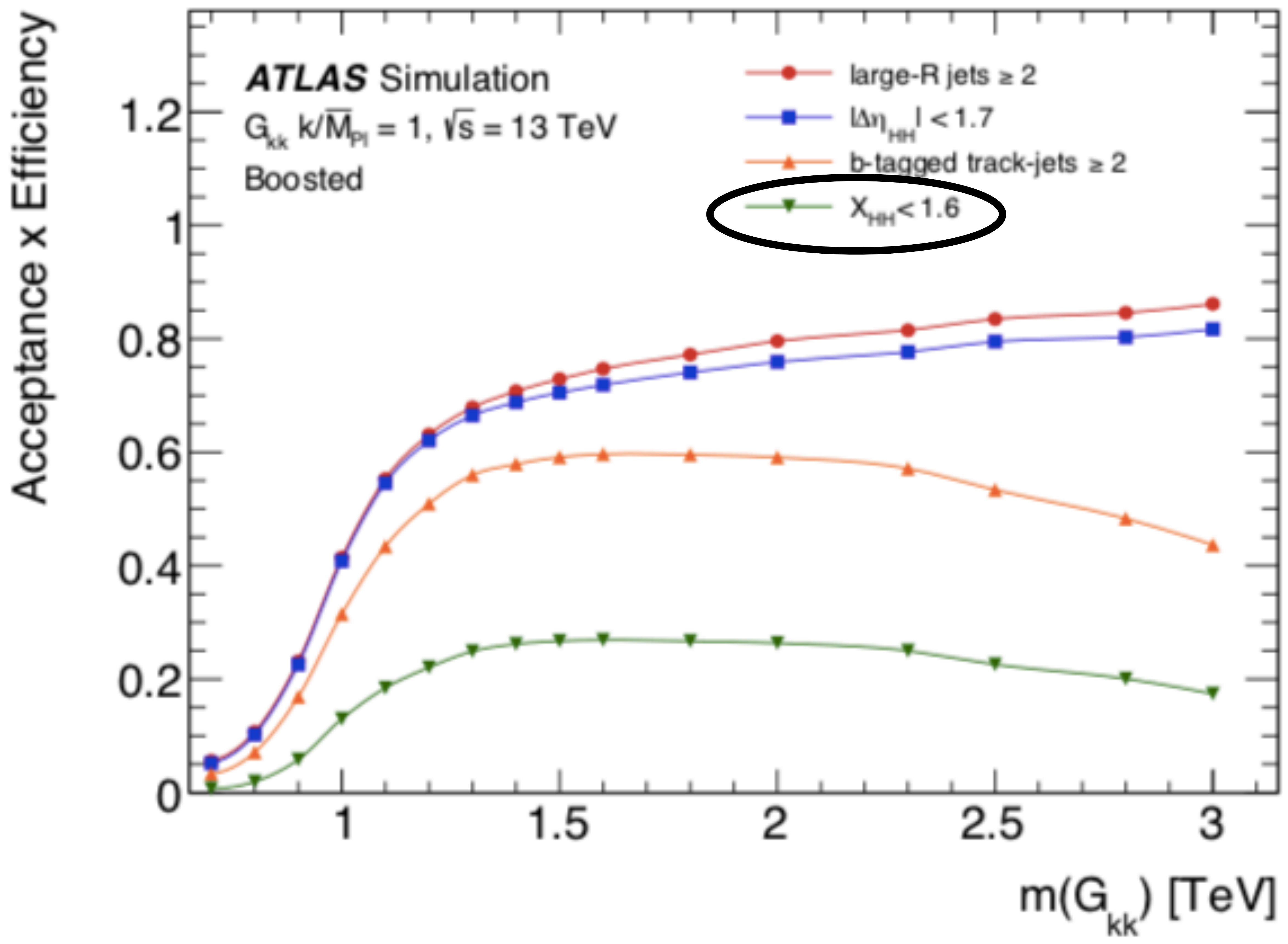
Resolved

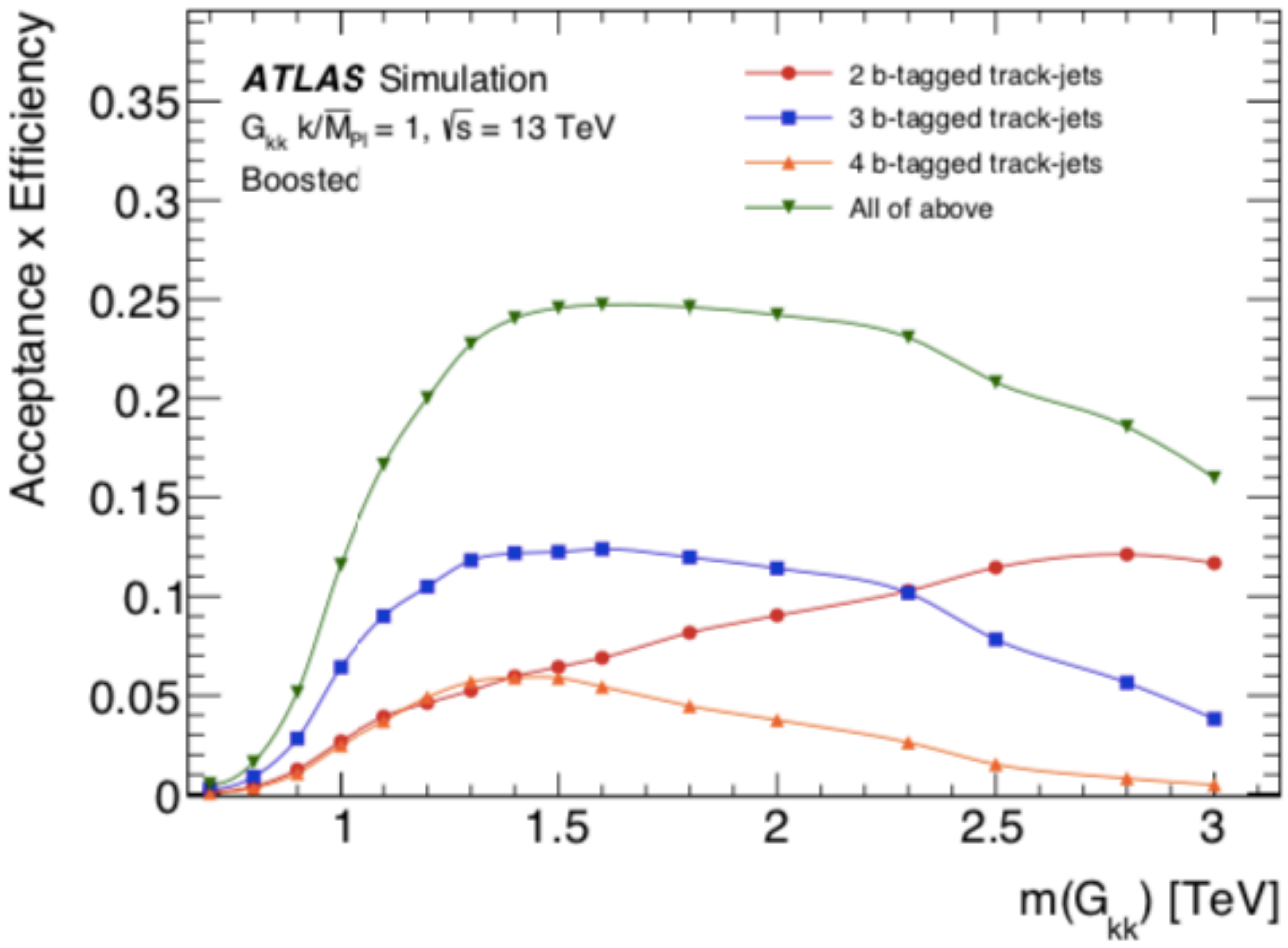


(a) Scalar Signal (b) Spin-2 Signal (c) SM HH

ATLAS 4b

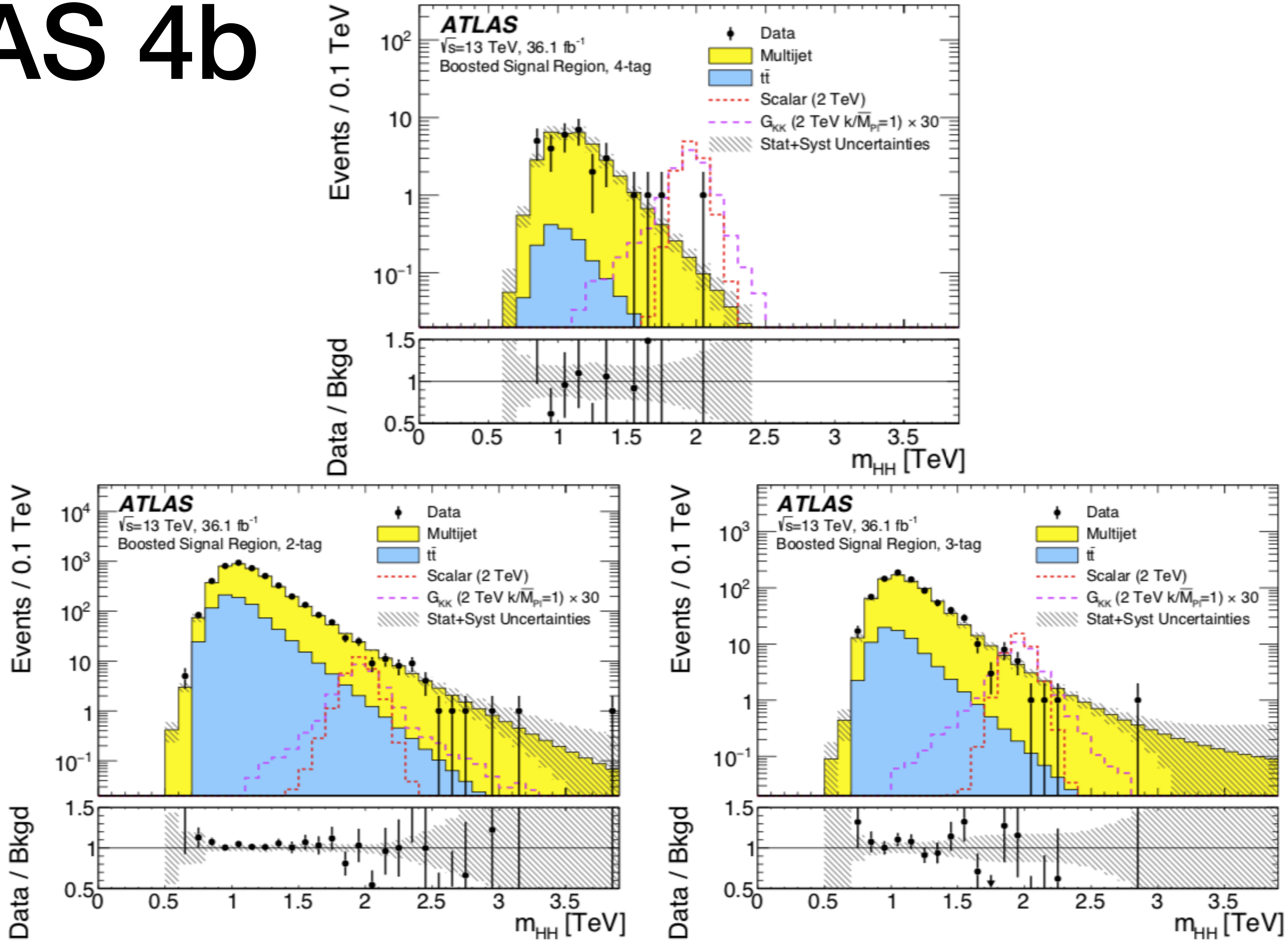
Boosted





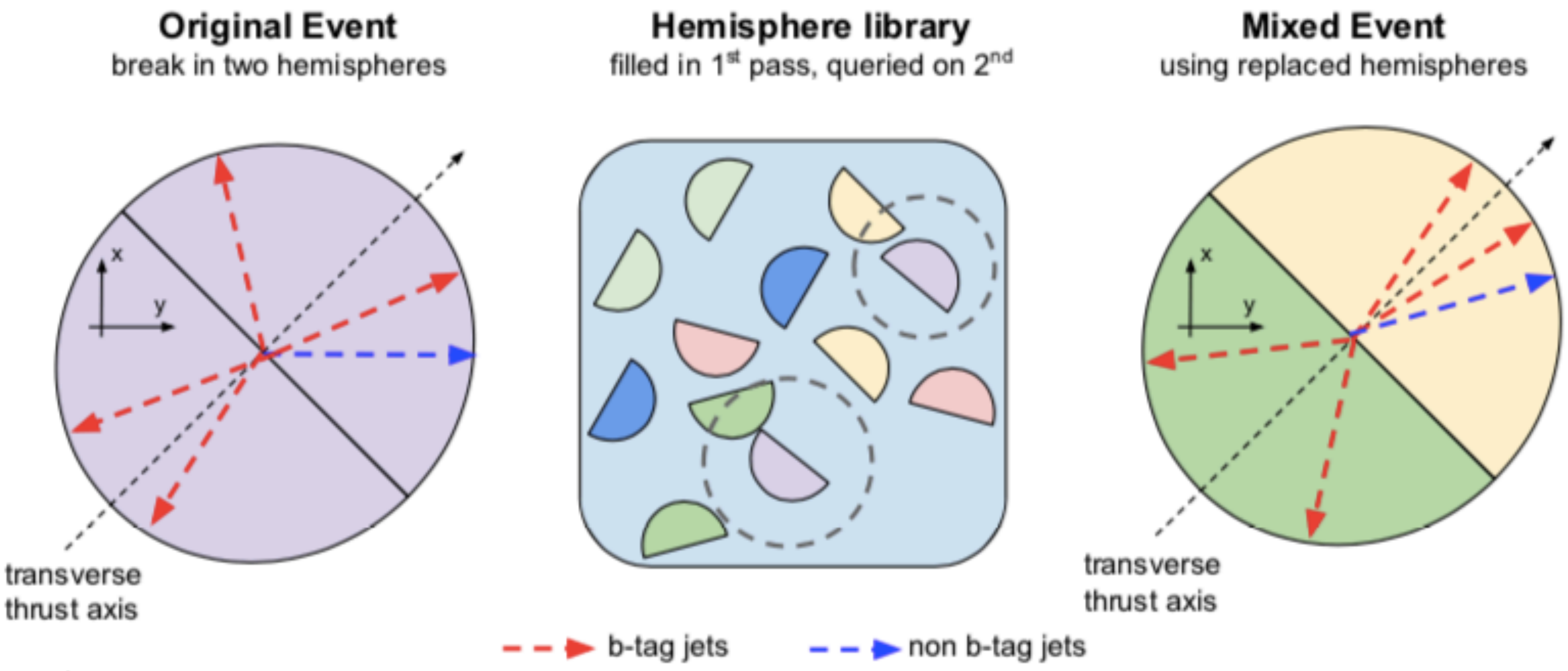
ATLAS 4b

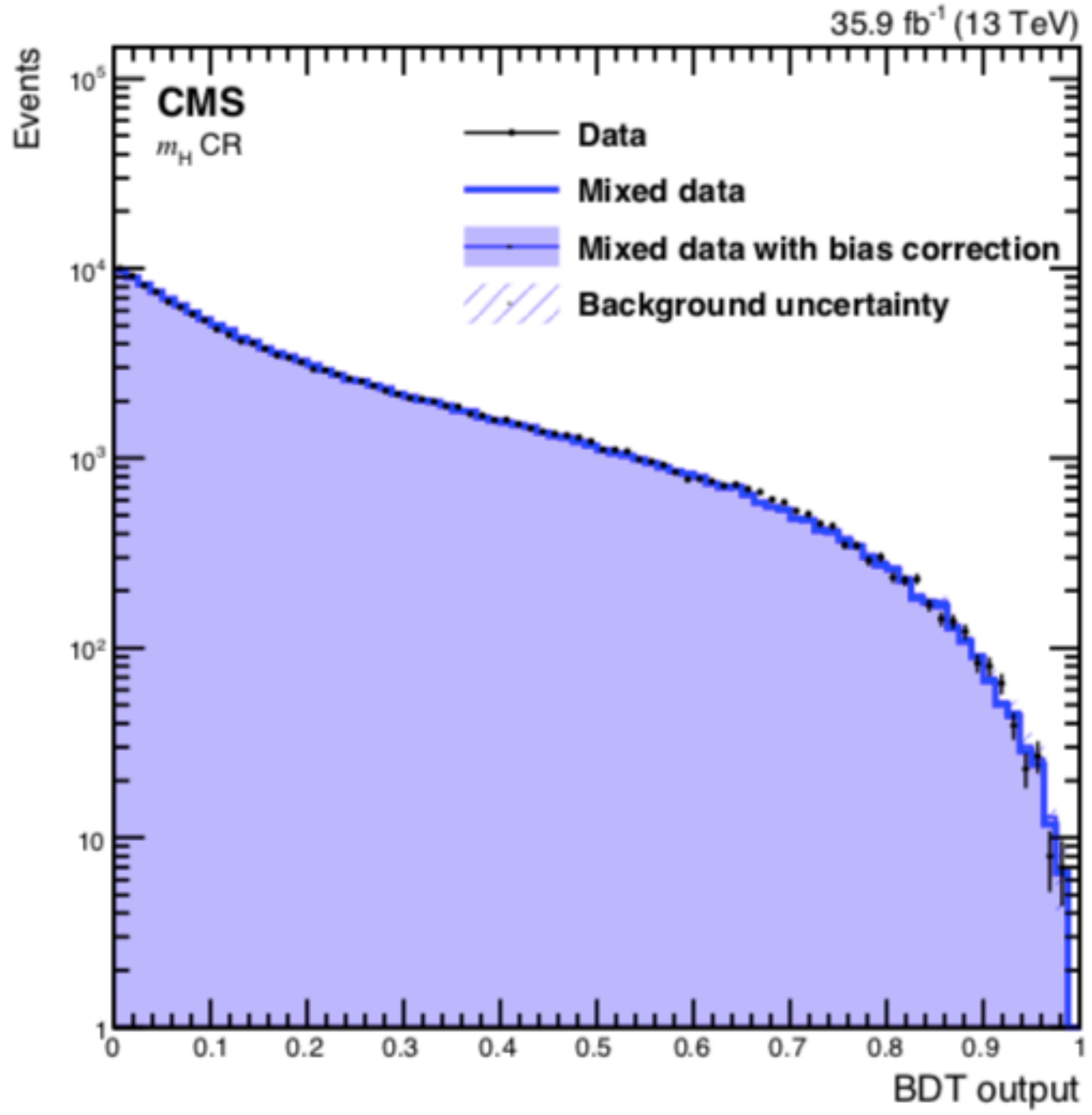
Boosted

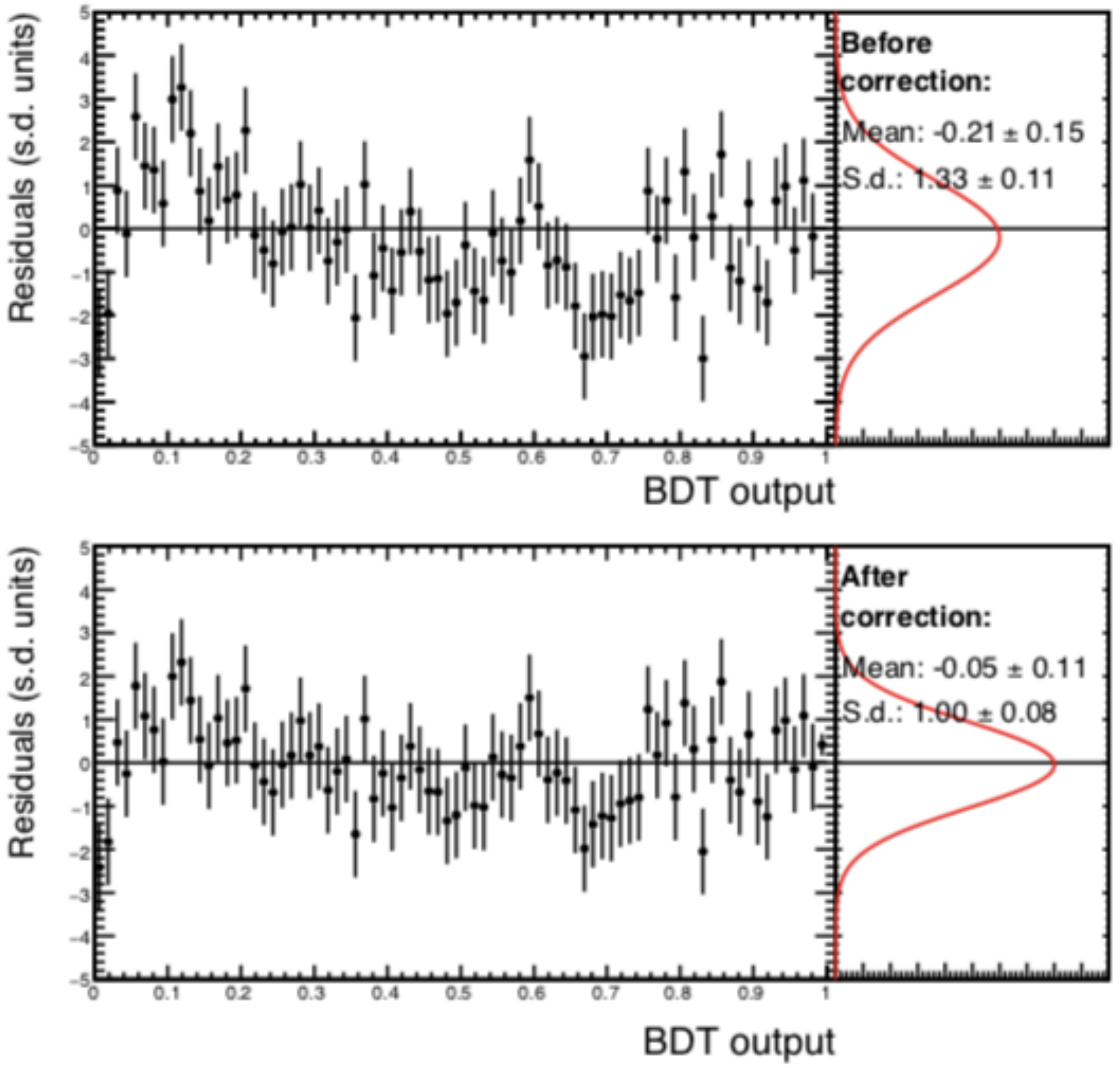


CMS 4b

Resolved, for non-resonant

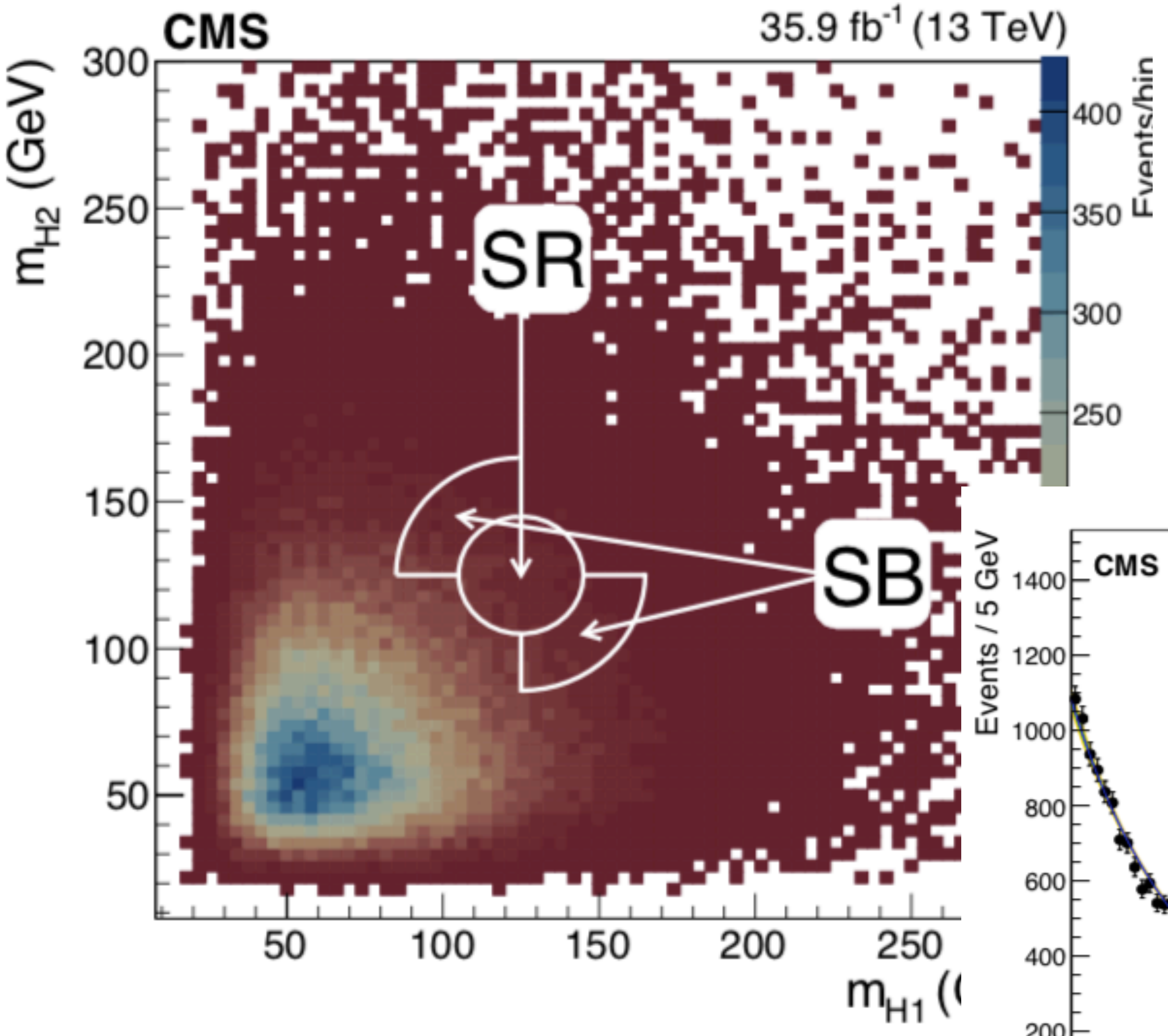


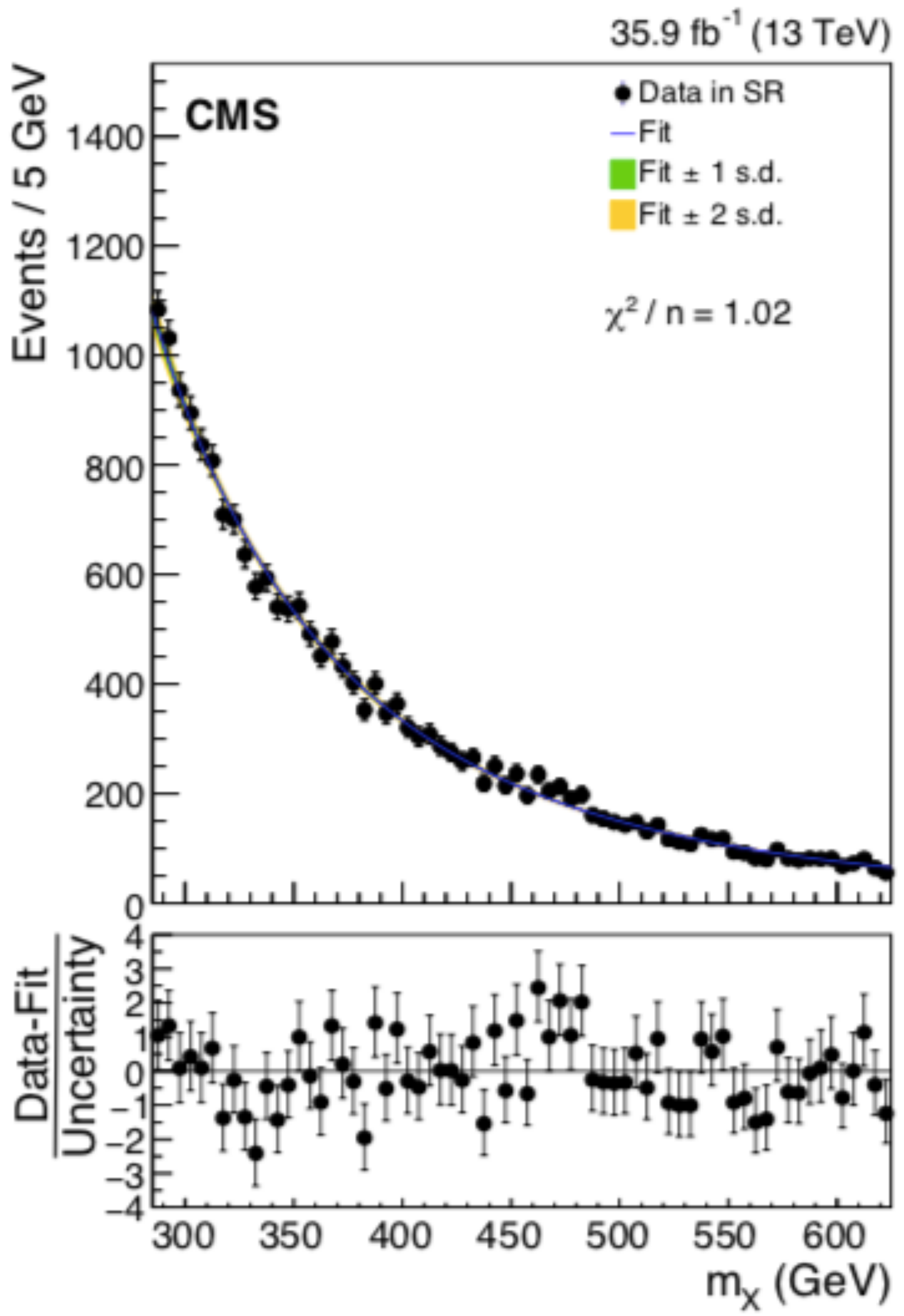




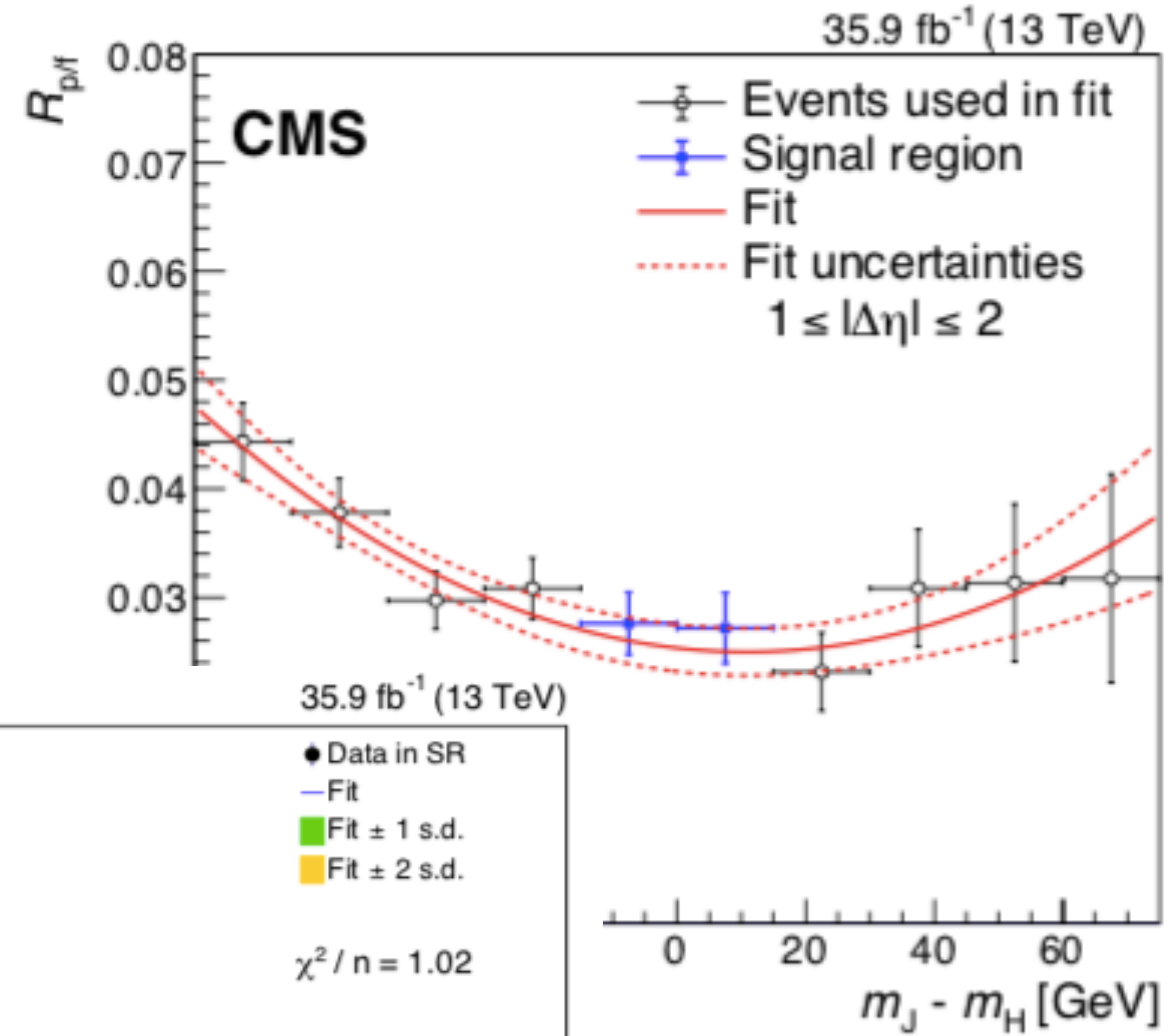
CMS 4b

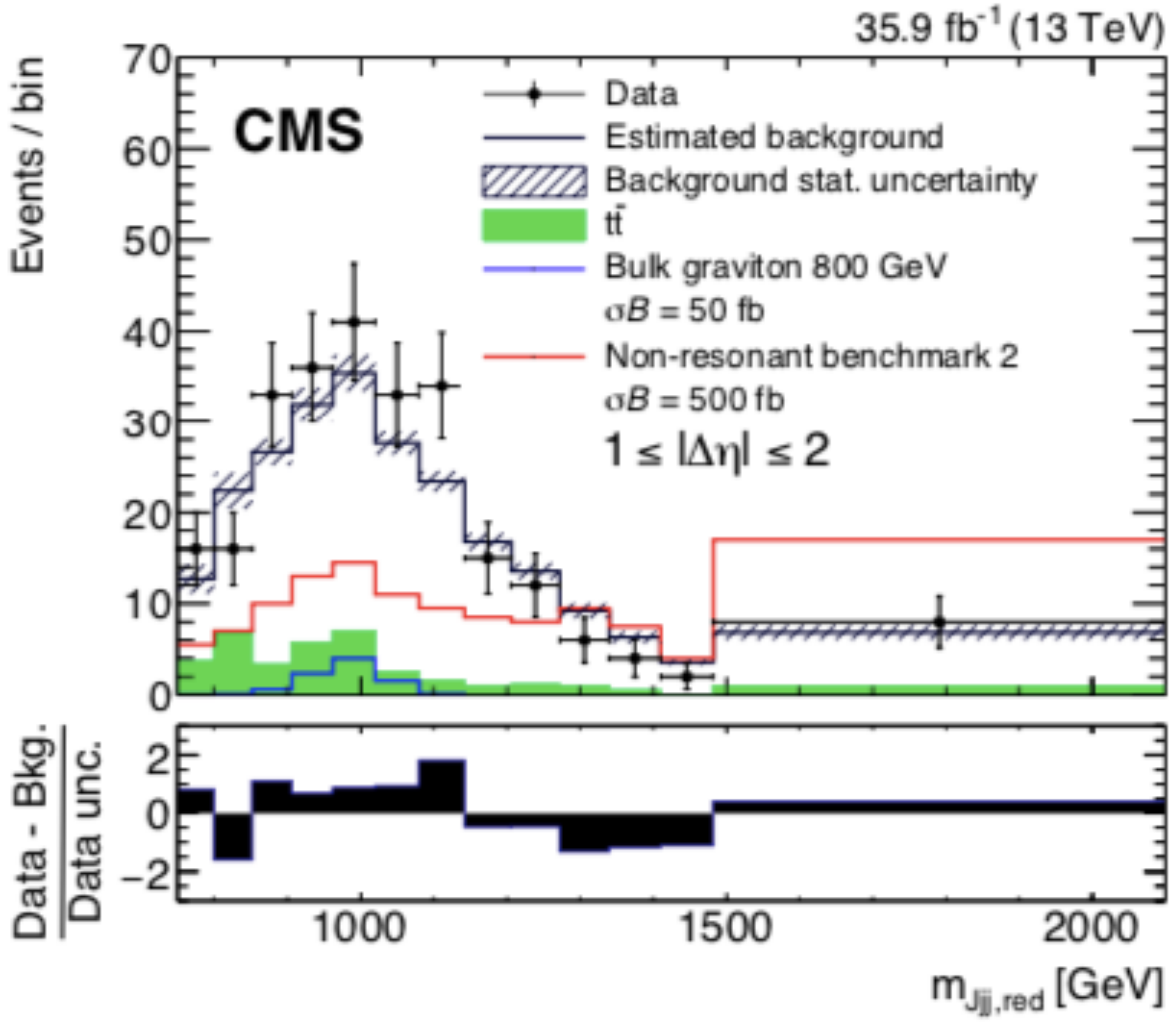
$$m_{\mathrm{Jjj,red}} \equiv m_{\mathrm{Jjj}} - (m_{\mathrm{J}} - m_{\mathrm{H}}) - (m_{\mathrm{jj}}(\mathrm{j}_1, \mathrm{j}_2) - m_{\mathrm{H}})$$





Resolved, for resonant



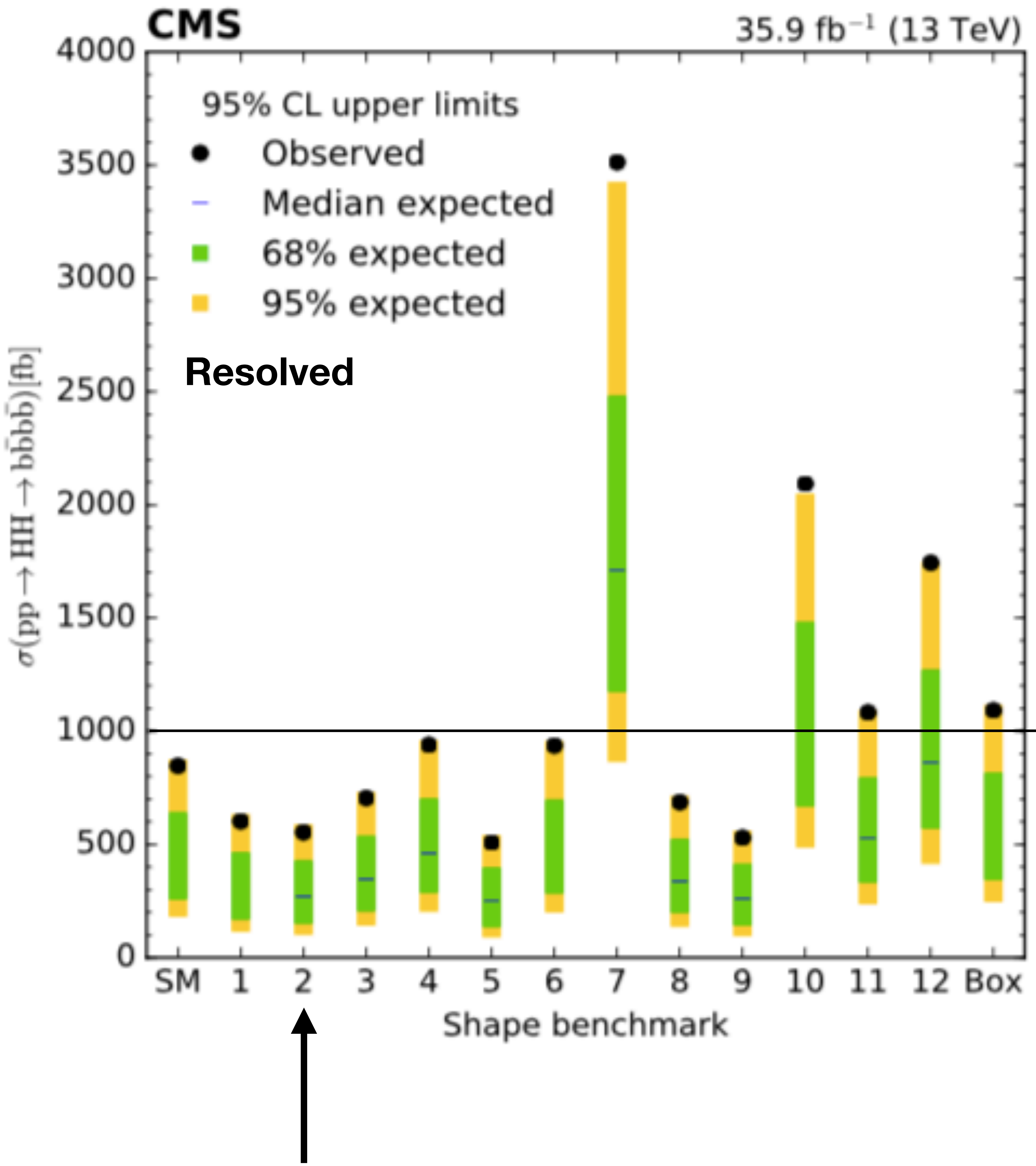


Semi-resolved & merged

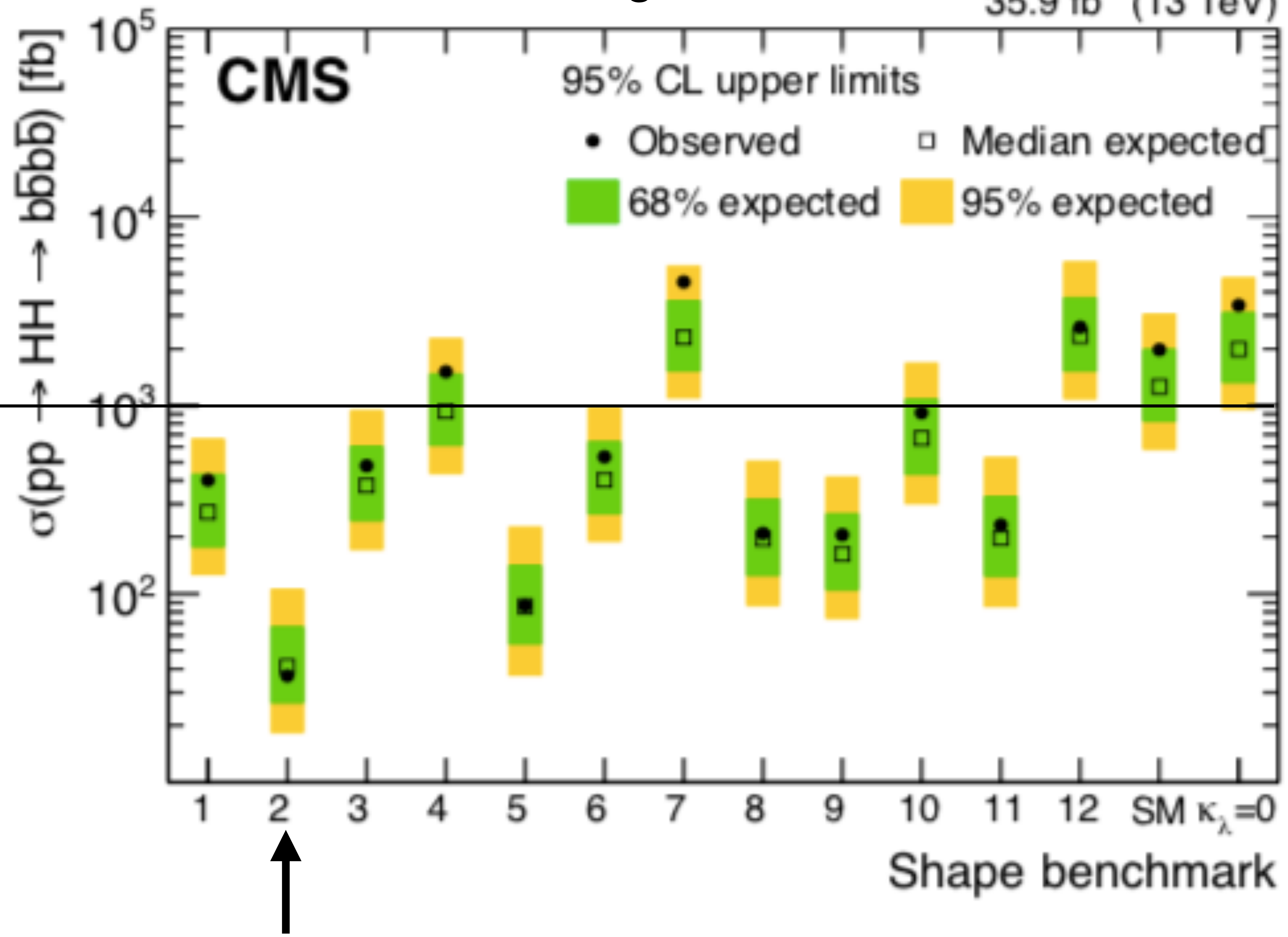
We define the pass-fail ratio $R_{p/f}$ as the ratio of events for which the AK8 jet passes and fails the double-b tagger tagging requirement.

CMS 4b

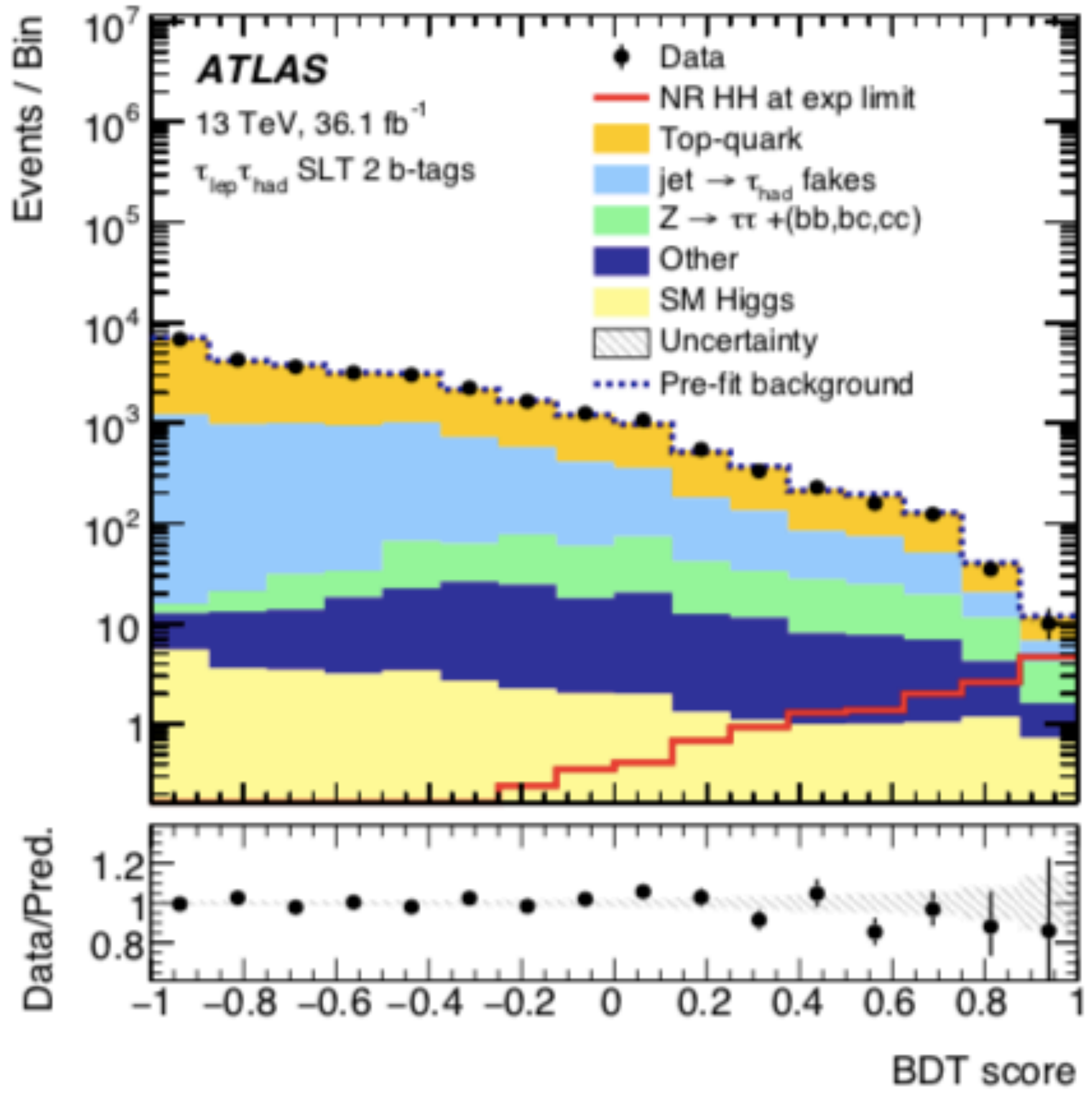
Resolved

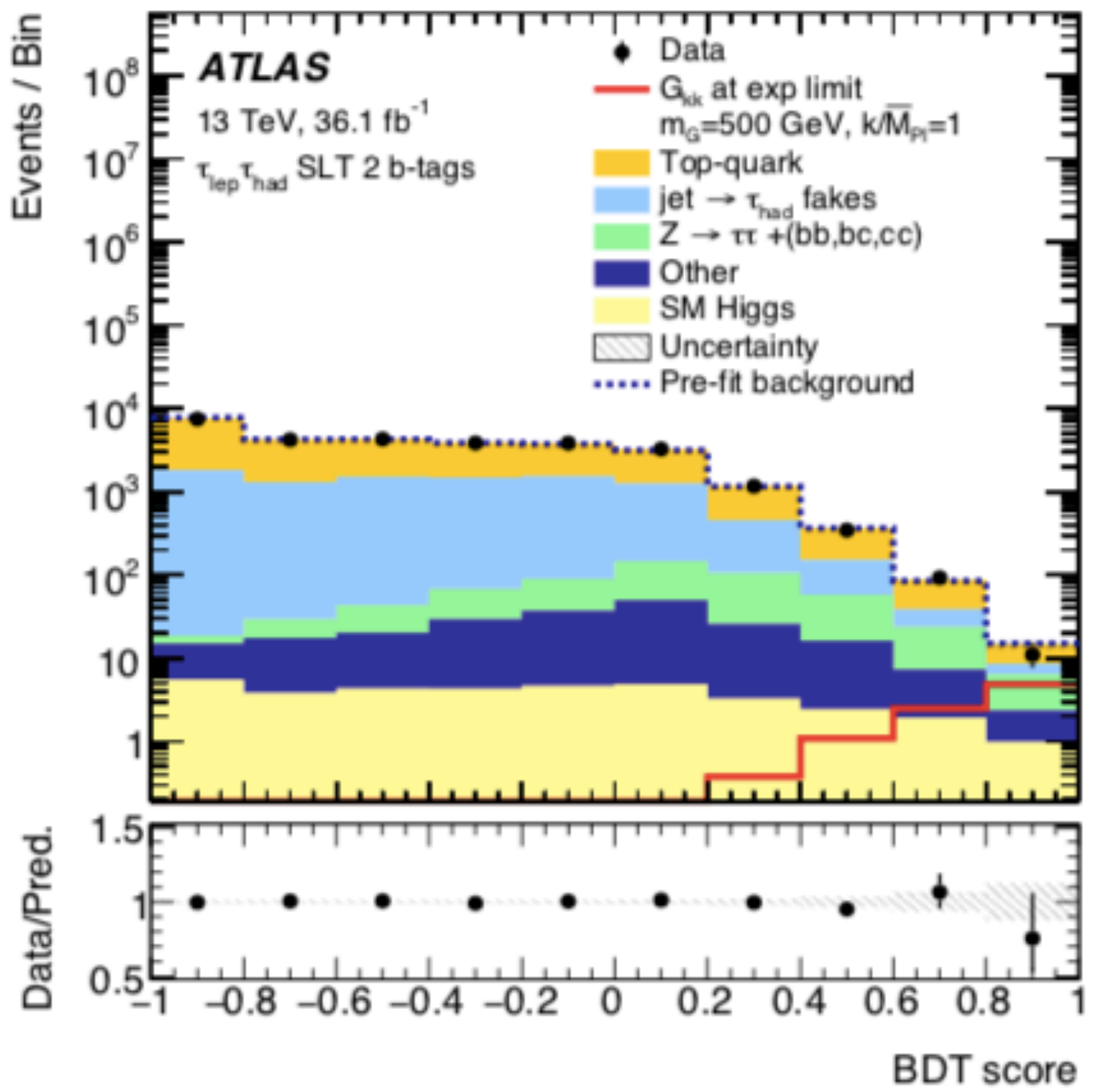


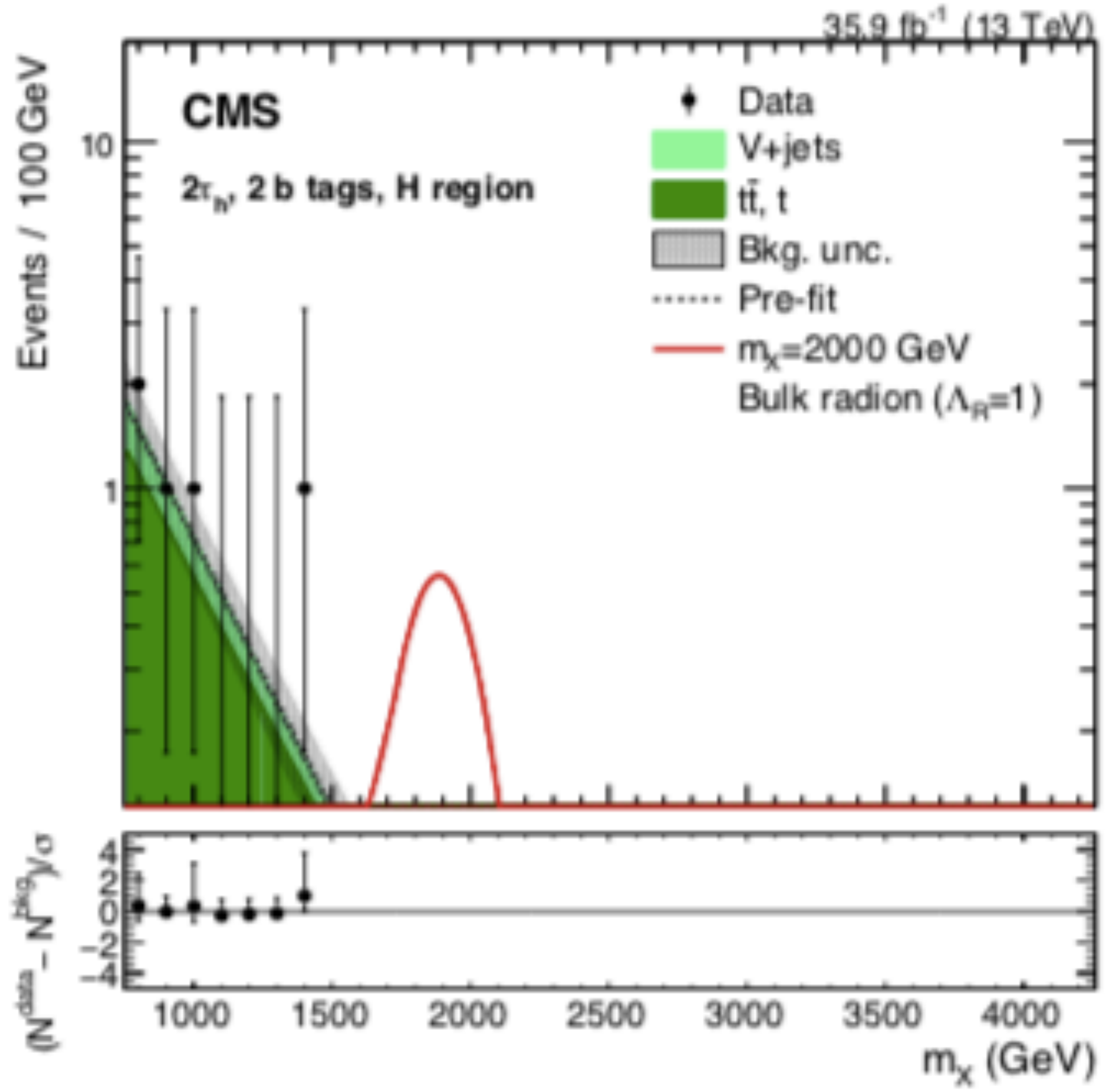
Semi-resolved & merged

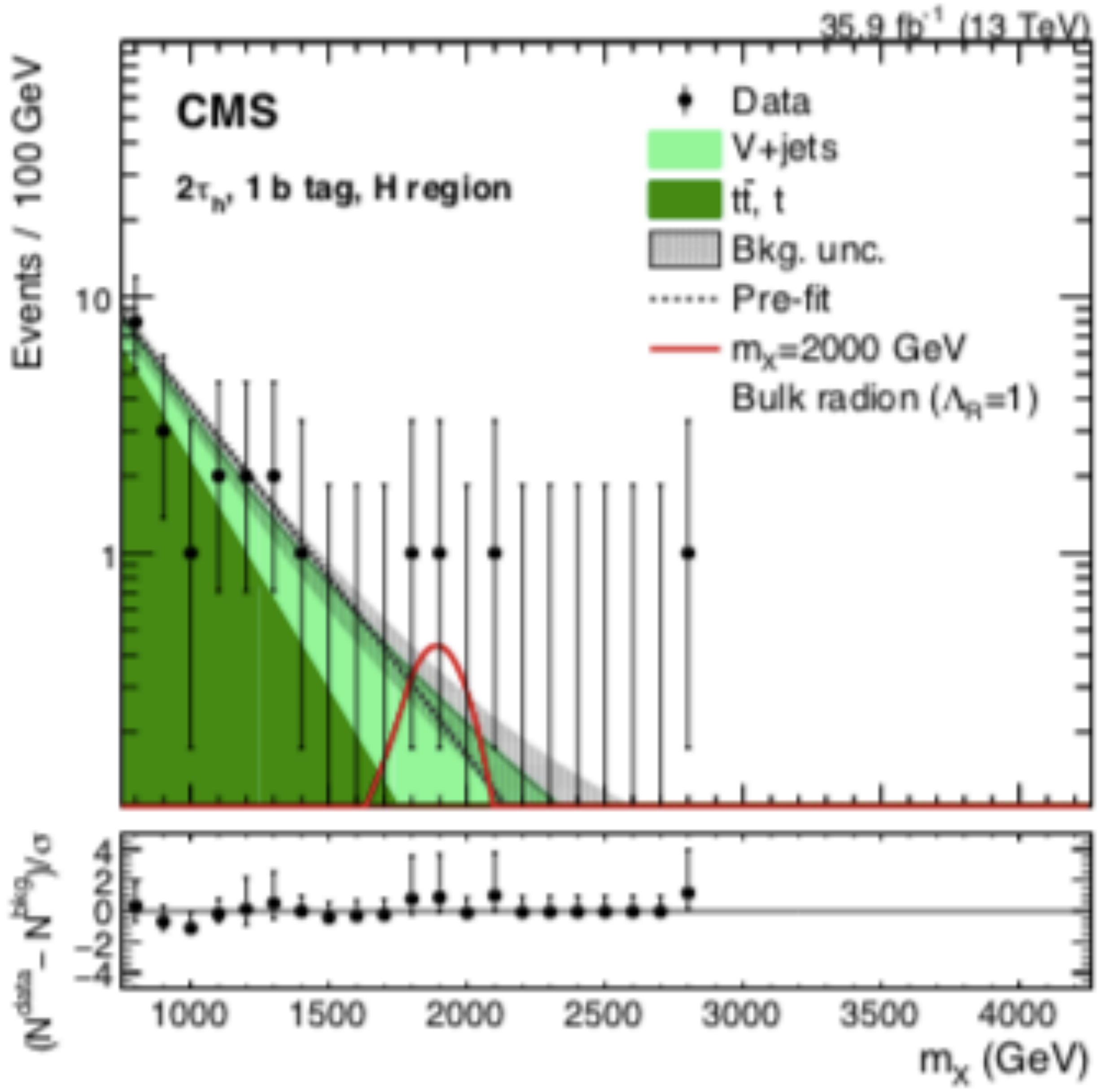


bbtautau





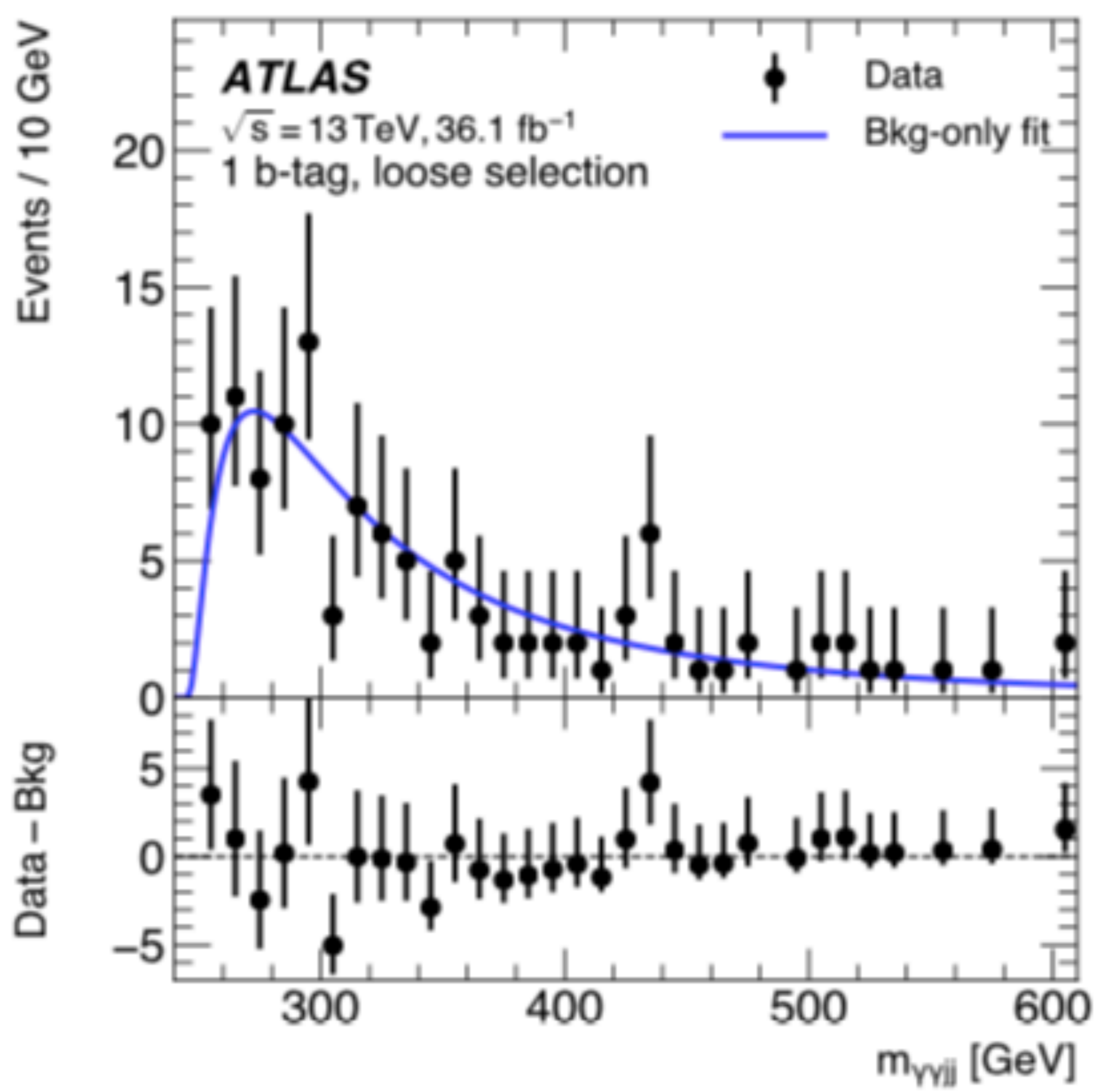


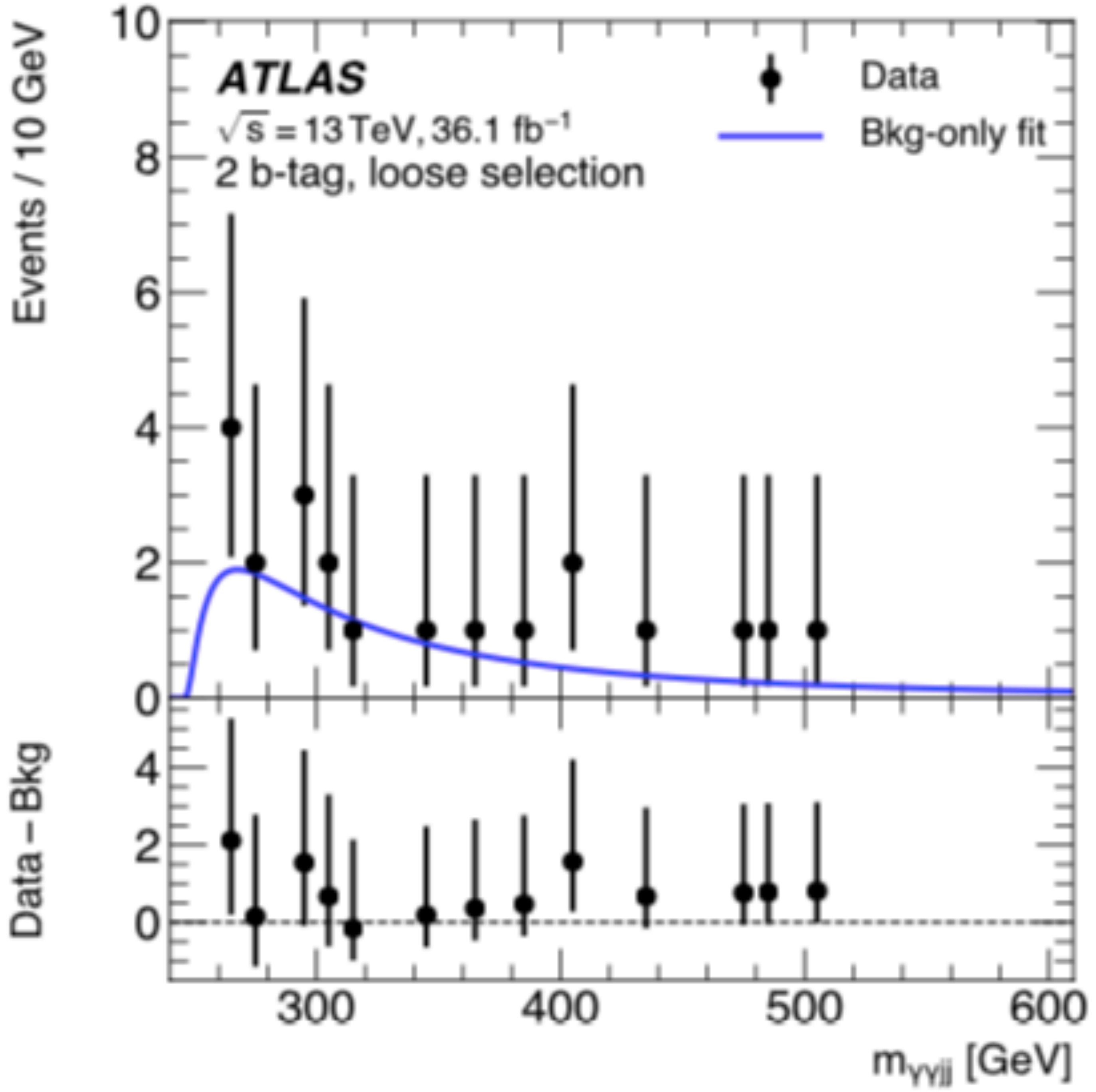


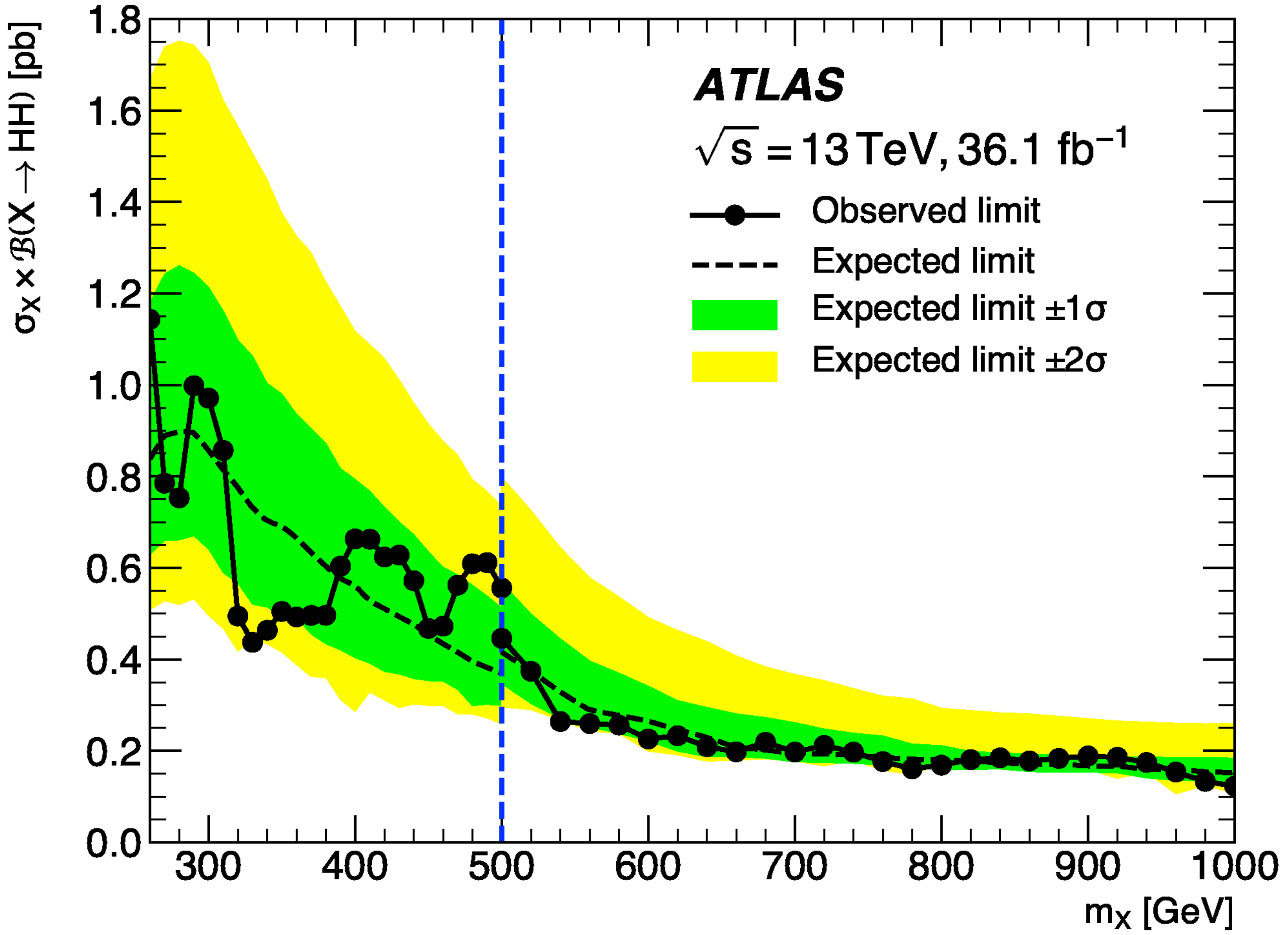
ATLAS

Source	Uncertainty (%)
Total	± 54
Data statistics	± 44
Simulation statistics	± 16
Experimental Uncertainties	
Luminosity	± 2.4
Pileup reweighting	± 1.7
τ_{had}	± 16
Fake-τ estimation	± 8.4
b-tagging	± 8.3
Jets and E_T^{miss}	± 3.3
Electron and muon	± 0.5
Theoretical and Modeling Uncertainties	
Top	± 17
Signal	± 9.3
$Z \to \tau\tau$	± 6.8
SM Higgs	± 2.9
Other backgrounds	± 0.3

bbyy







An additional study is performed including both VBF HH and ggHH production mechanisms in the definition of the scaling factor

$$\mu_{\mathrm{HH}}^{\mathrm{ext}} = \frac{\sigma_{gg\to\mathrm{HH}}^{\mathrm{BSM}} + \sigma_{\mathrm{VBF\ HH}}^{\mathrm{BSM}}}{\sigma_{gg\to\mathrm{HH}}^{\mathrm{SM}} + \sigma_{\mathrm{VBF\ HH}}^{\mathrm{SM}}} \quad (3)$$

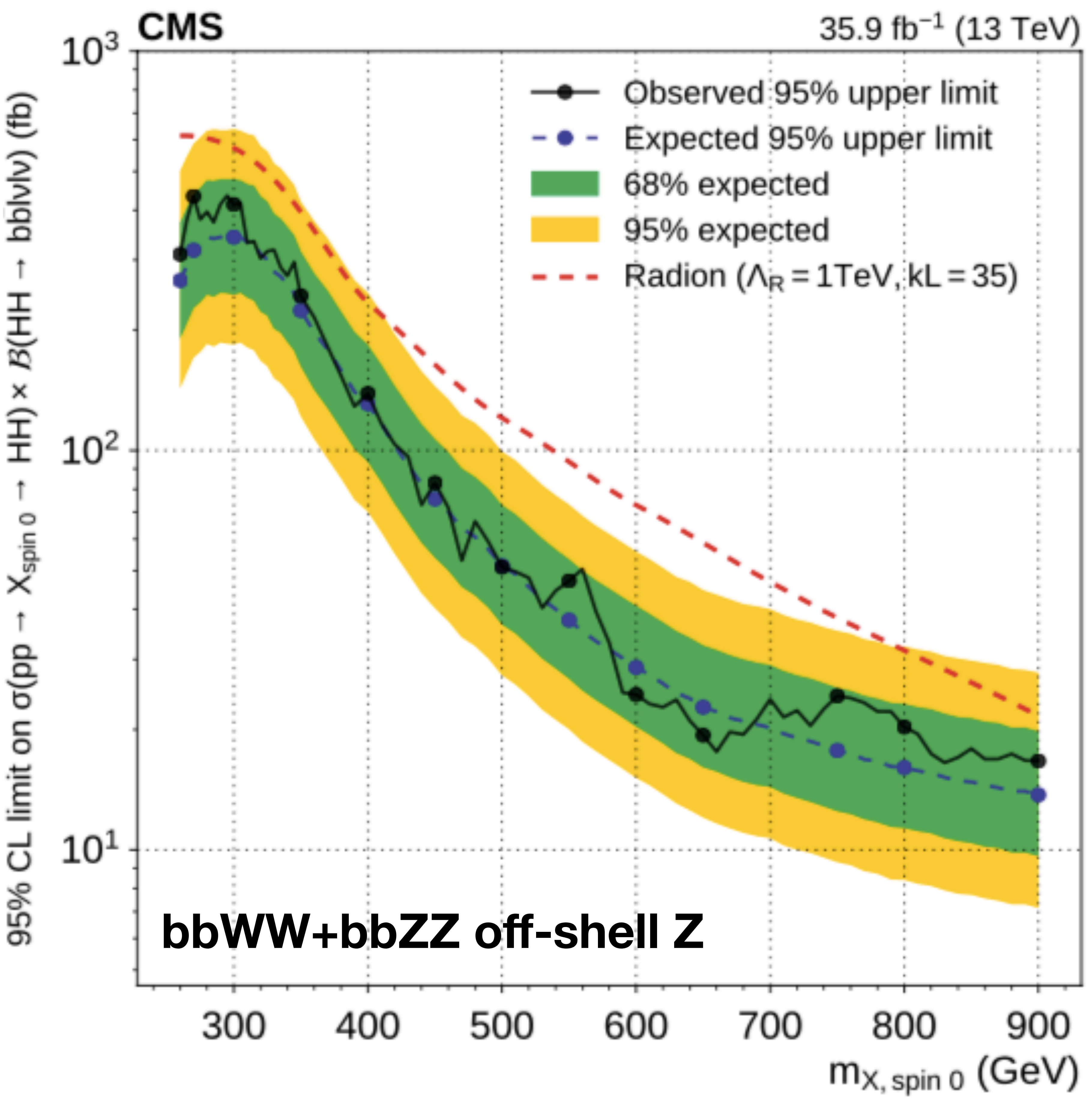
where $\sigma_{\mathrm{VBF\ HH}}^{\mathrm{SM}} = 1.64^{+0.05}_{-0.06}$ fb [6]. The expected sensitivity of the analysis for $\mu_{\mathrm{HH}}^{\mathrm{ext}}$ improves by 1.3% compared to μ_{HH}. The improvement is smaller than the relative contribution of the VBF production cross section to the total one in the SM because of the nonoptimal selection efficiency of this analysis for the VBF events, as explained in Section 5.

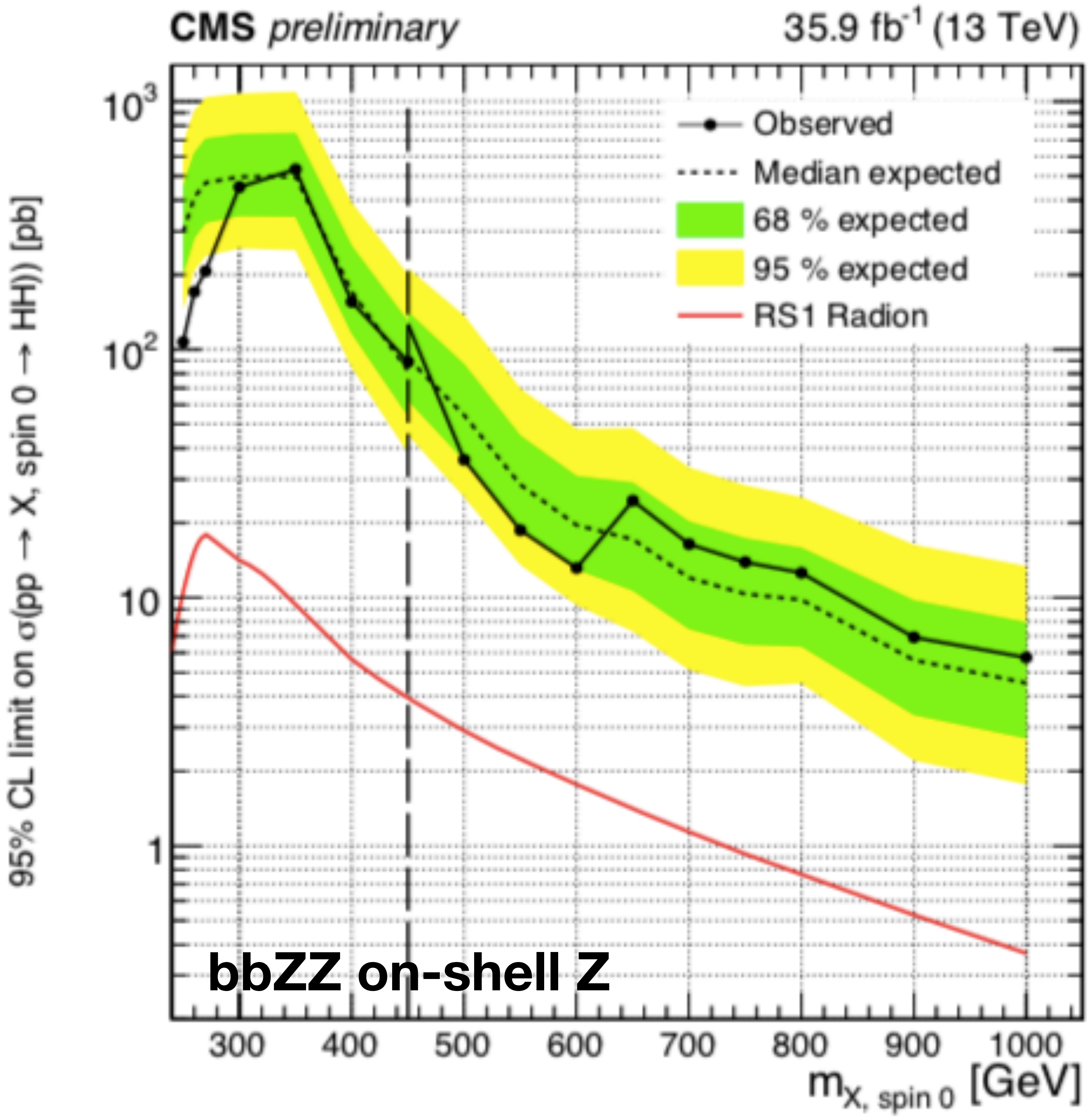
CMS

VBF consideration

bbVV lvlv+llvv

The HH candidates are reconstructed in three regions that are chosen in the kinematic space defined by the dilepton invariant mass $m_{\ell\ell}$ and the invariant mass m_{bb} of the two b-jets. The signal region (SR) is defined by the requirements $76 < m_{\ell\ell} < 106$ GeV and $90 < m_{bb} < 150$ GeV. The choice of the latter requirement is guided by the mass resolution of the dijet system and is asymmetric around the Higgs boson mass because a fraction of b quarks decays semileptonically with a neutrino escaping detection, thus leading to a lower reconstructed dijet mass. The first control region (CR), dominated by $t\bar{t}$ events (CRTT), is defined by the condition $m_{\ell\ell} > 106$ GeV and the same m_{bb} requirement as for the SR. The second control region, which contains primarily Drell-Yan events (CRDY), is defined by the requirement for m_{bb} to be in the range from 20 to 90 GeV or above 150 GeV, while keeping the $m_{\ell\ell}$ selection of the SR definition. The two control regions (CRs) are used in this measurement to evaluate the amount of the dominant backgrounds (Drell-Yan and $t\bar{t}$) in the SR via the simultaneous fit of all three regions, as described in Section 8.

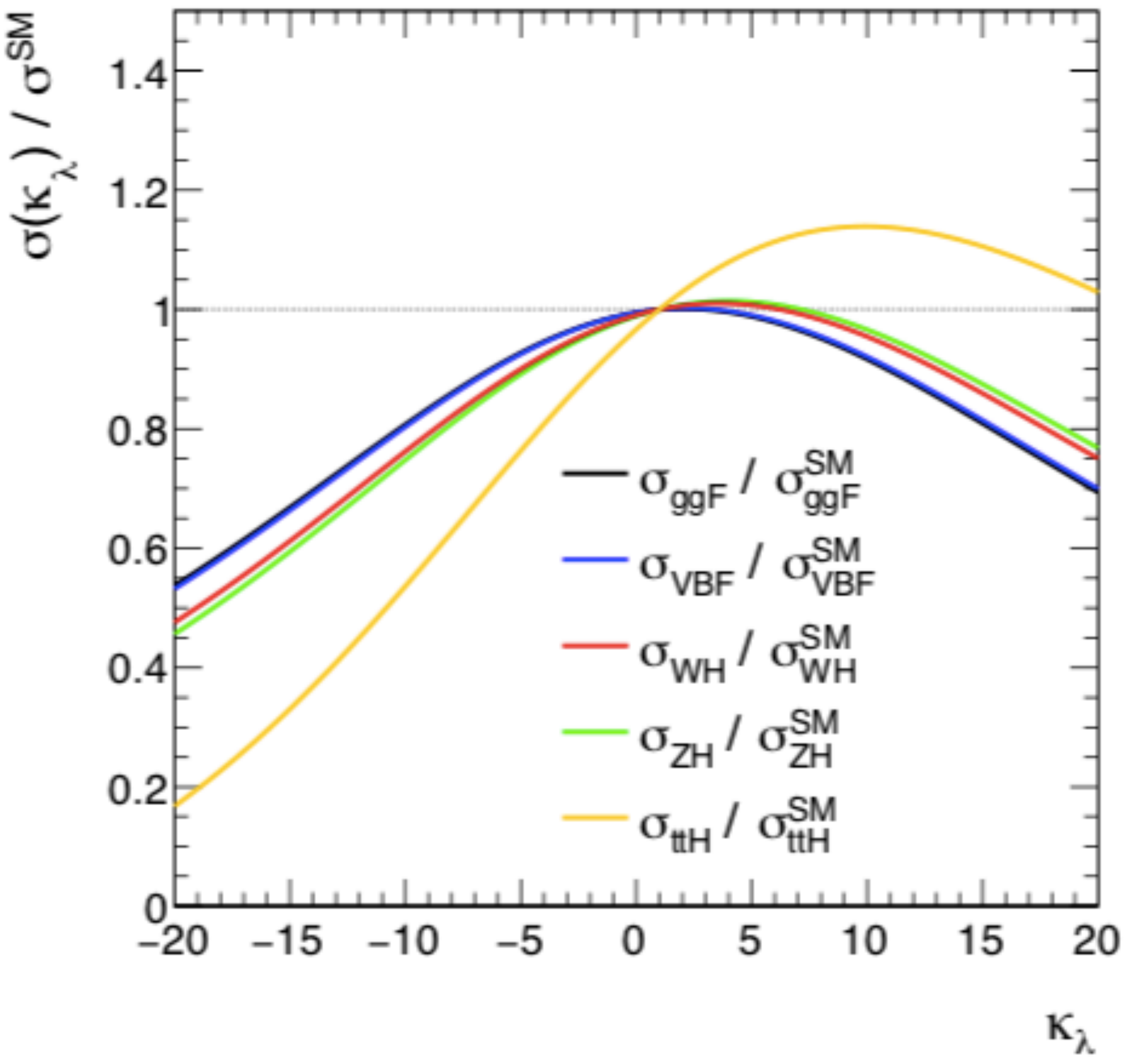


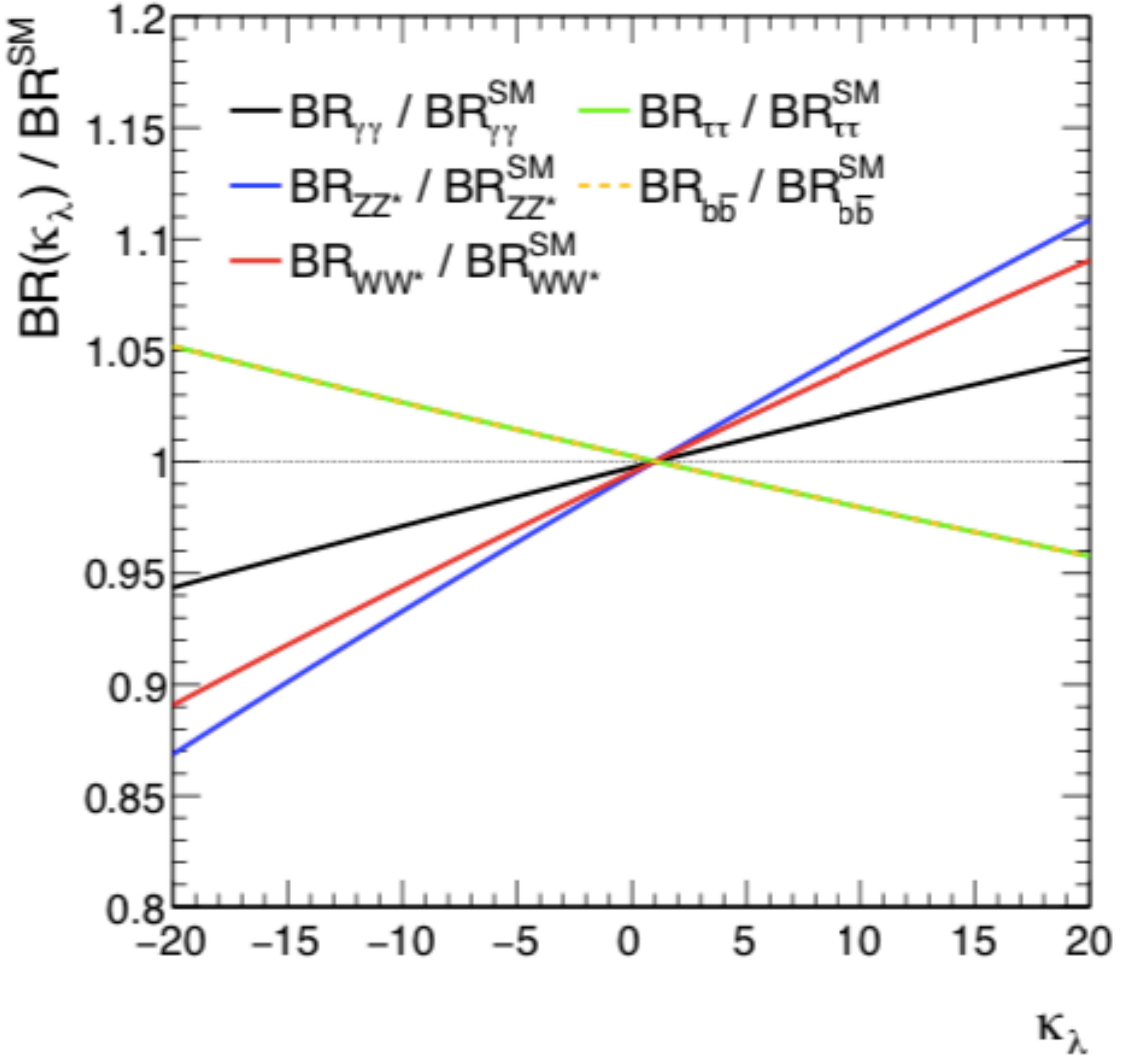


bbZZ on-shell Z seems slightly more sensitive in higher mass searches than bbWW+bbZZ with off-shell Z

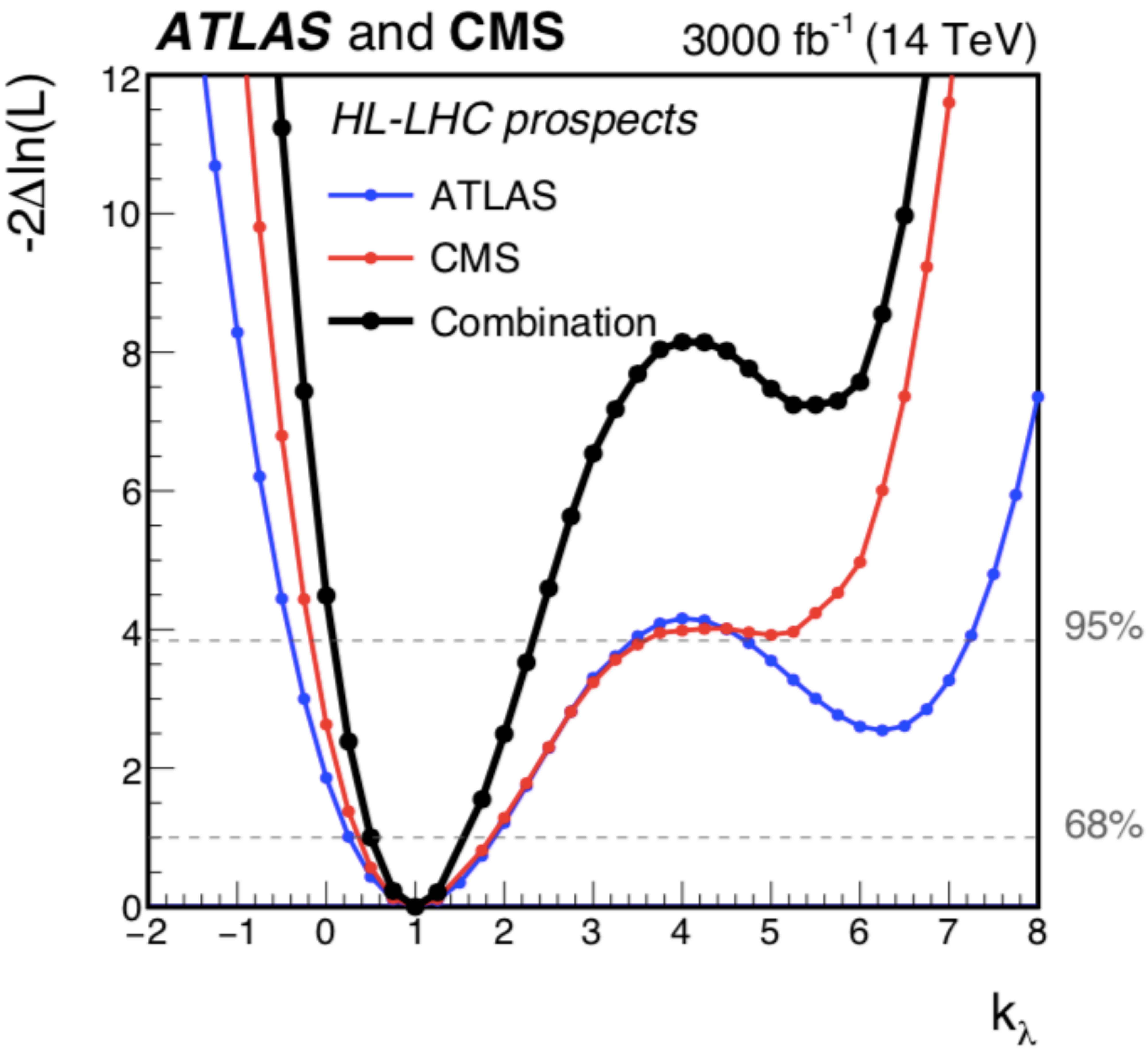
Single Higgs

ATL-PHYS-PUB-2019-009

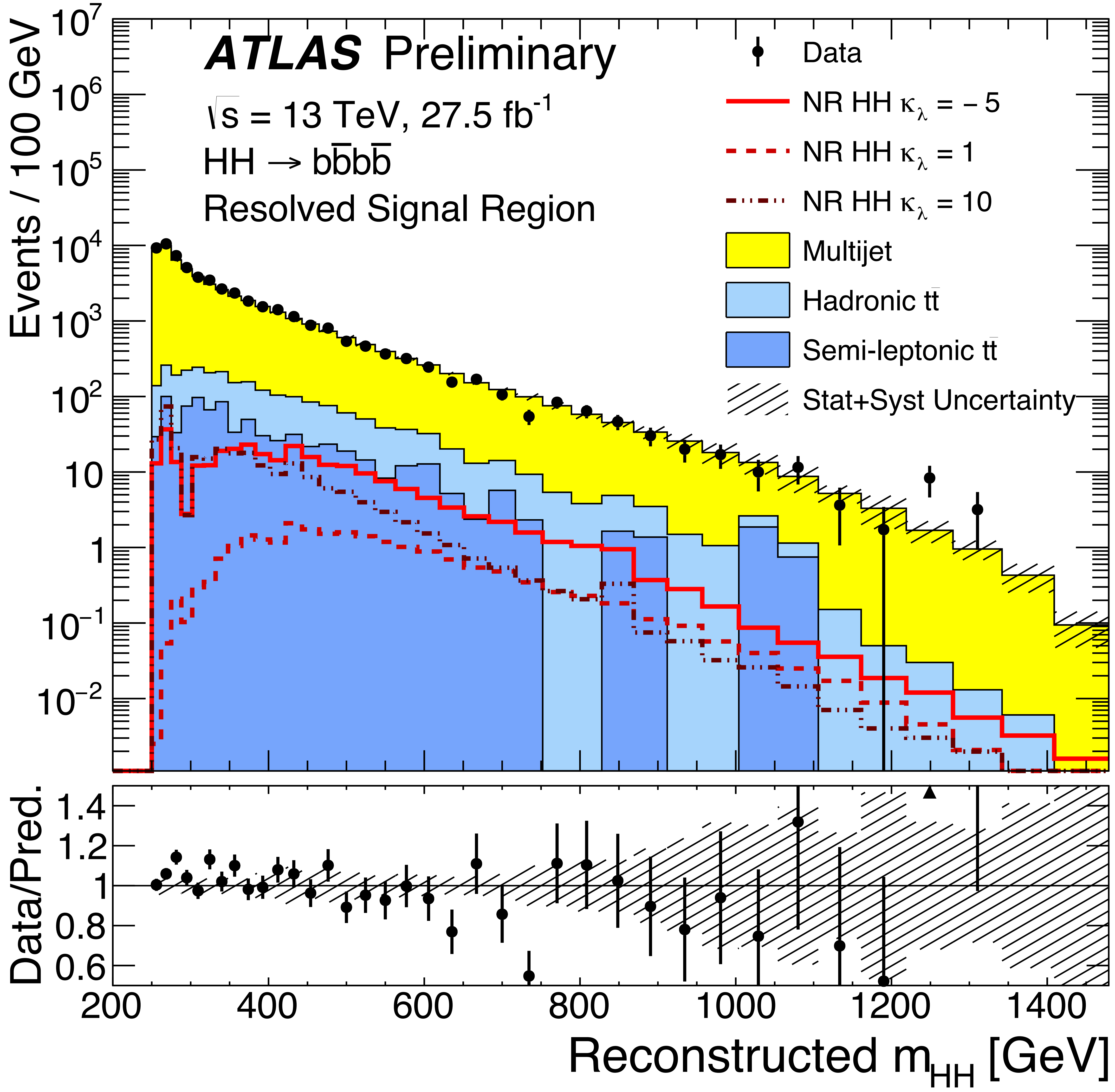


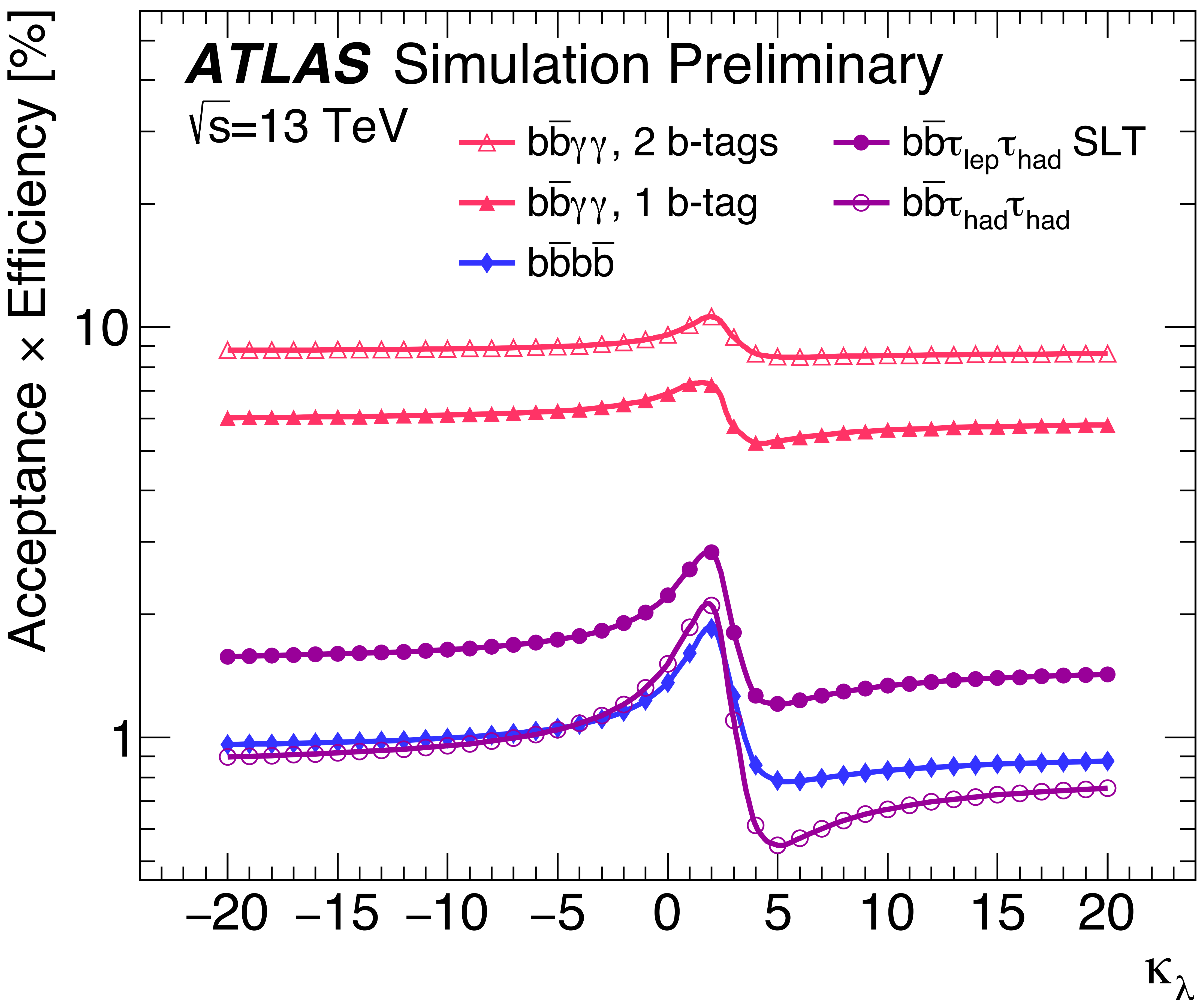


HH HL-LHC

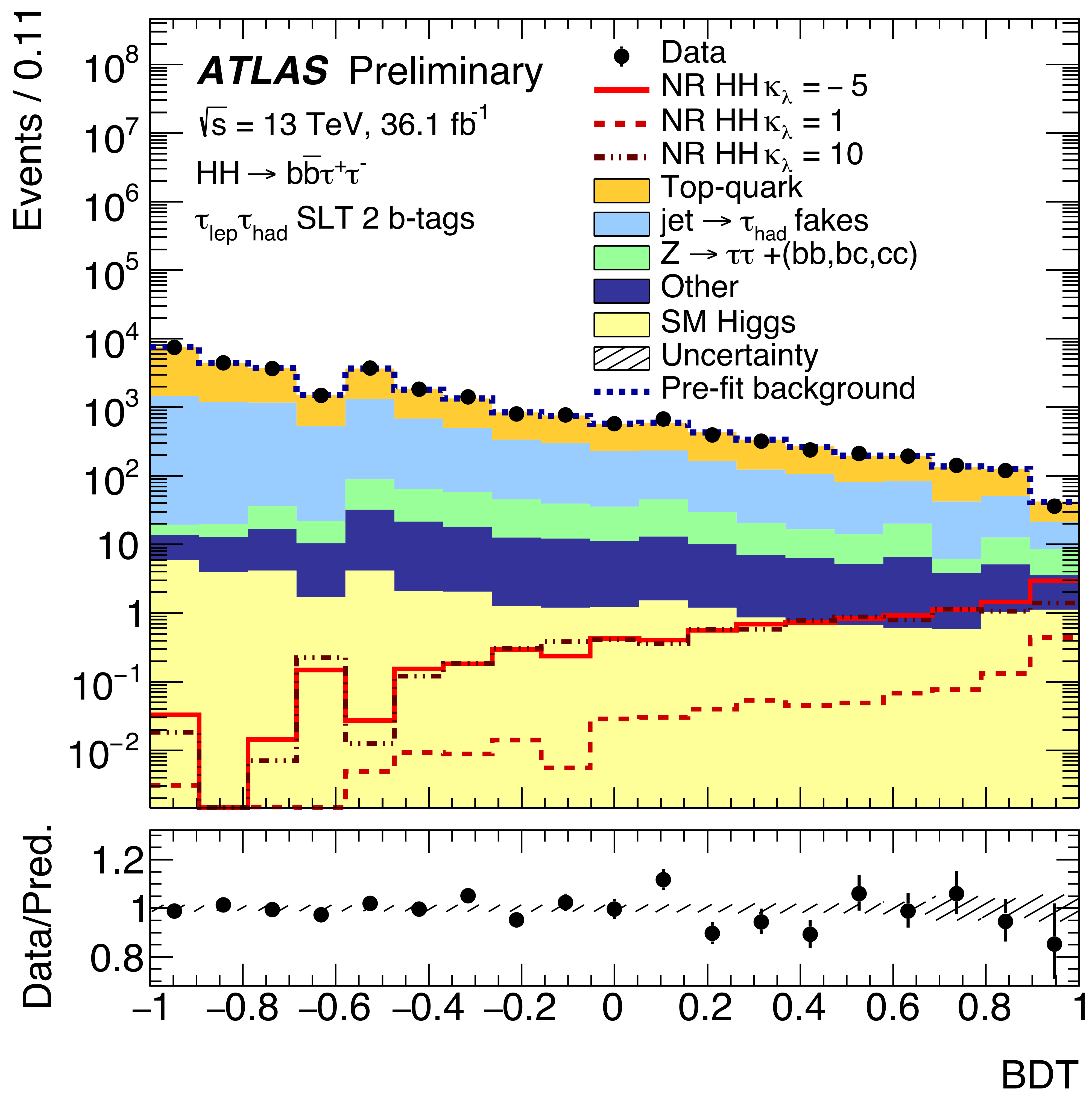

ATLAS and CMS
3000 fb-1 (14 TeV)
HL-LHC prospects
ATLAS
CMS
Combination
-2Δln(L)
95%
68%
kλ
12
10
8
6
4
2
0
−2
−1
0
1
2
3
4
5
6
7
8

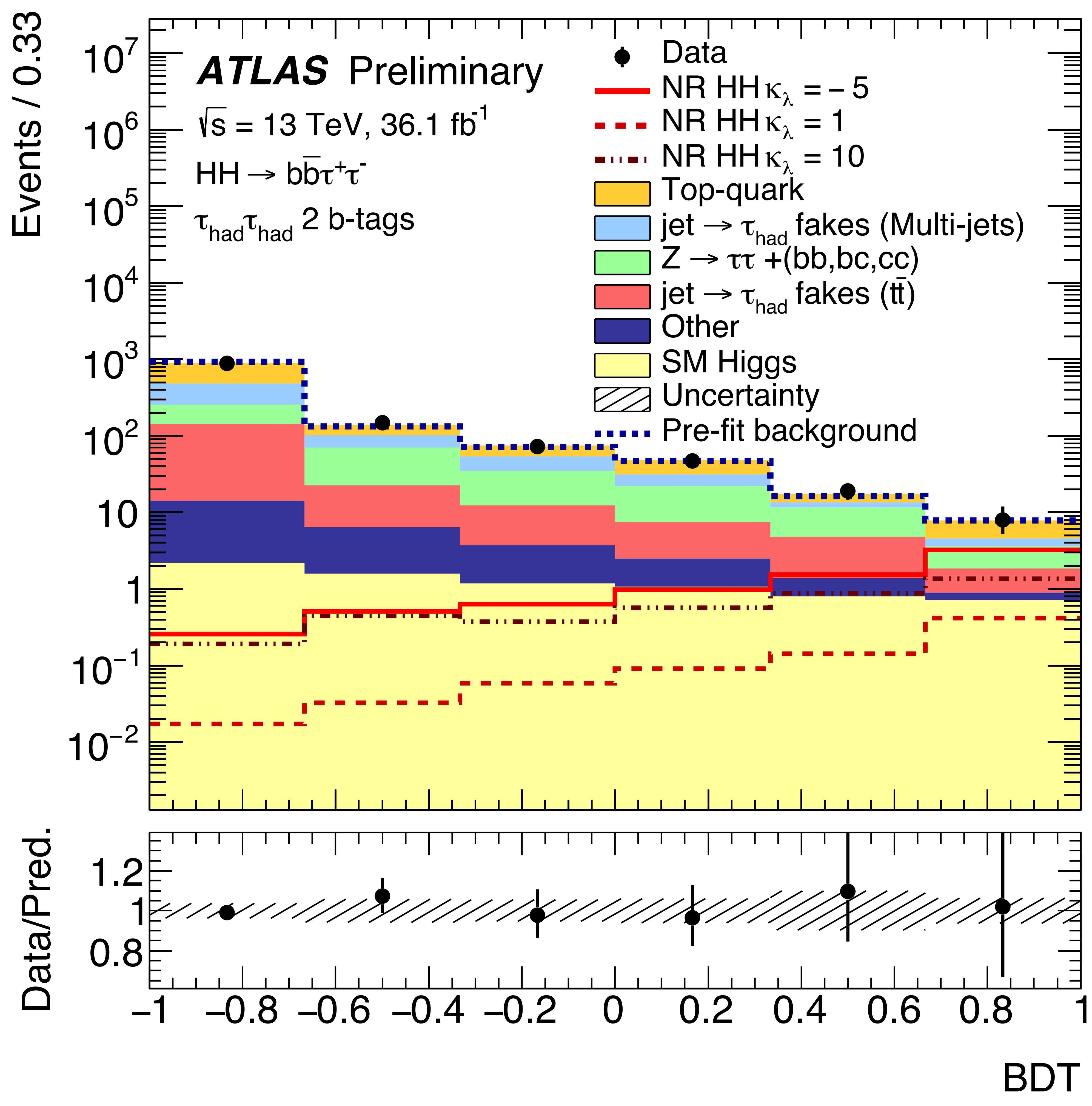
HH combination



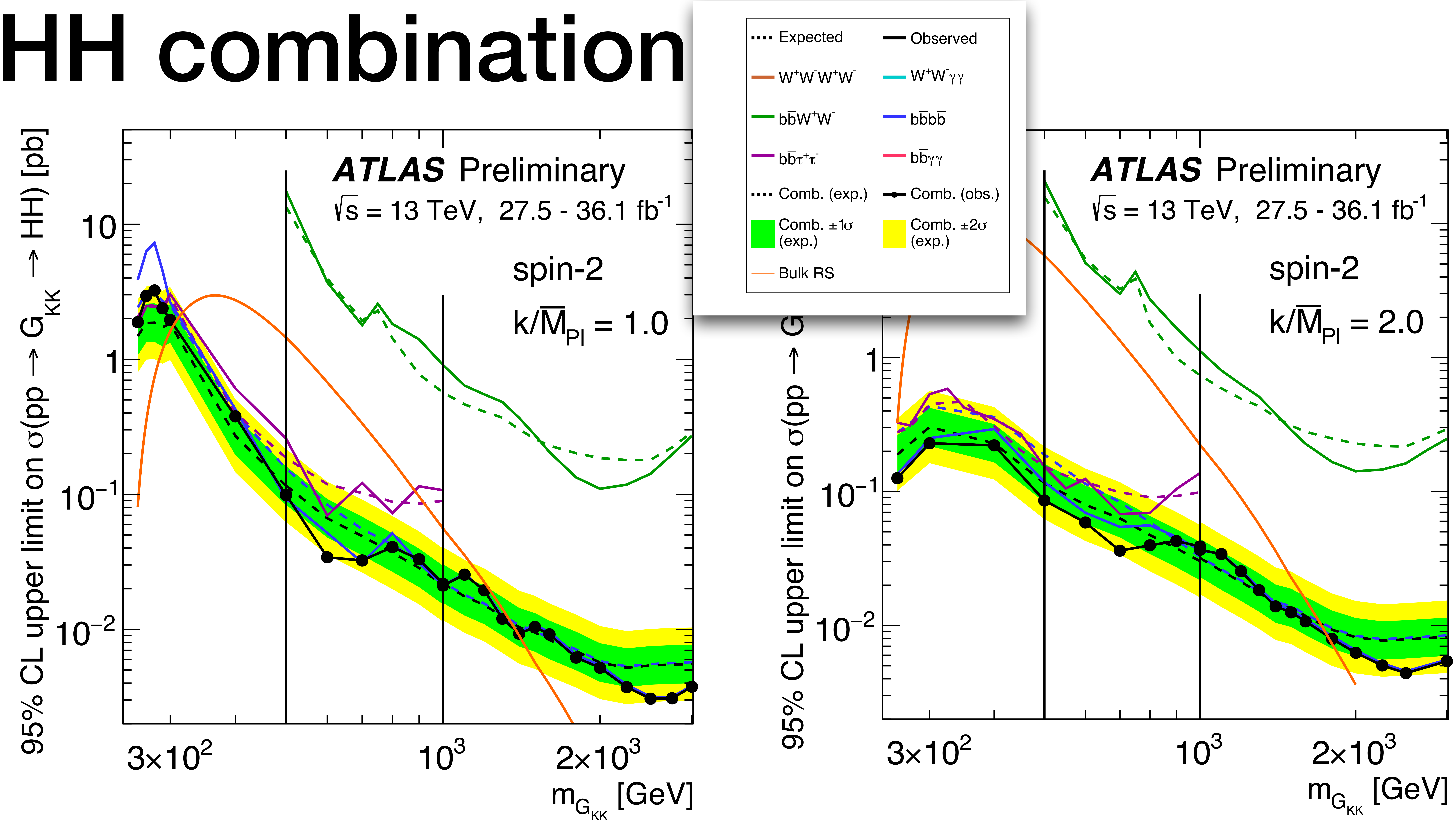


HH combination

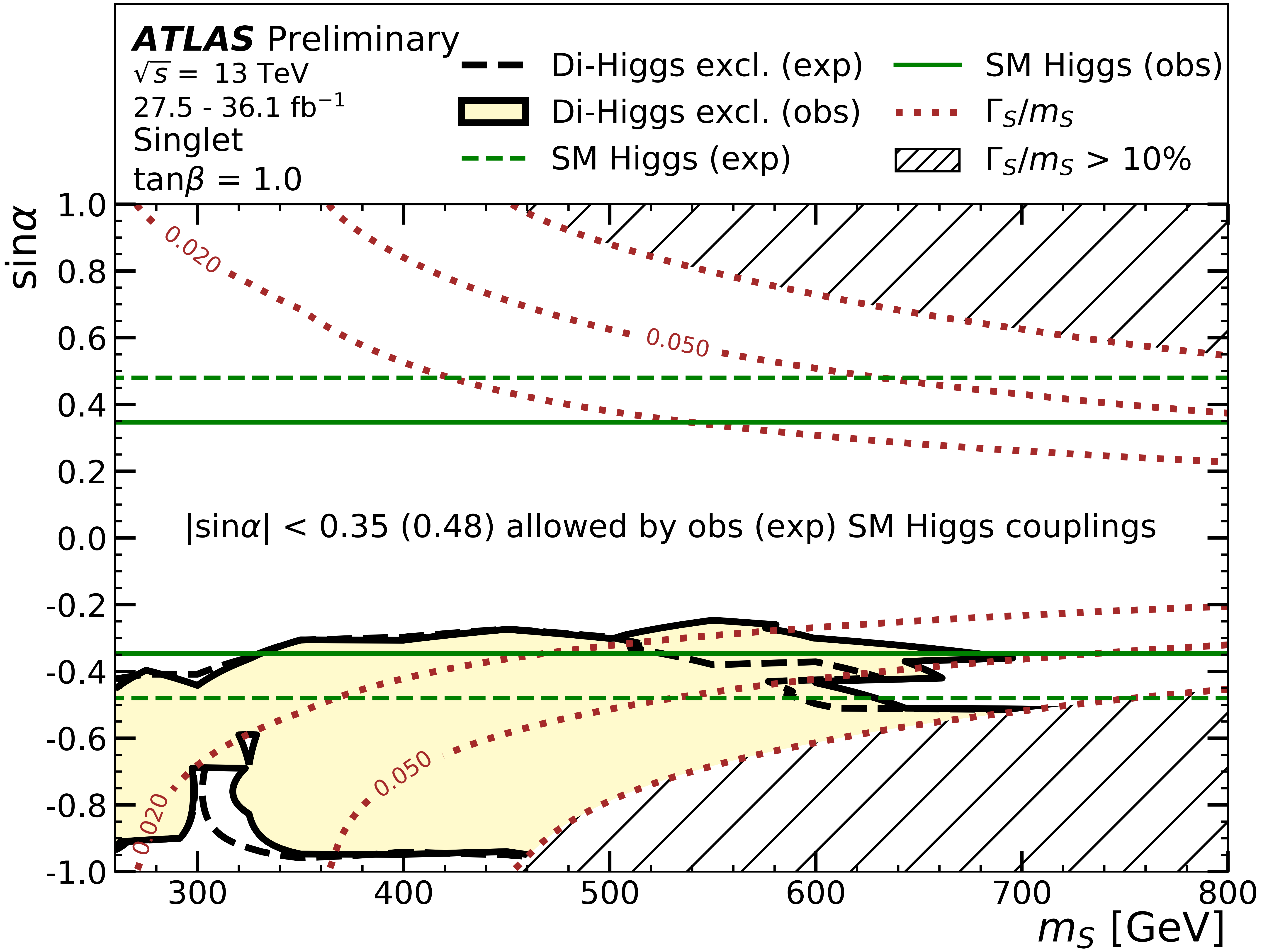




HH combination



HH combination



HH combination