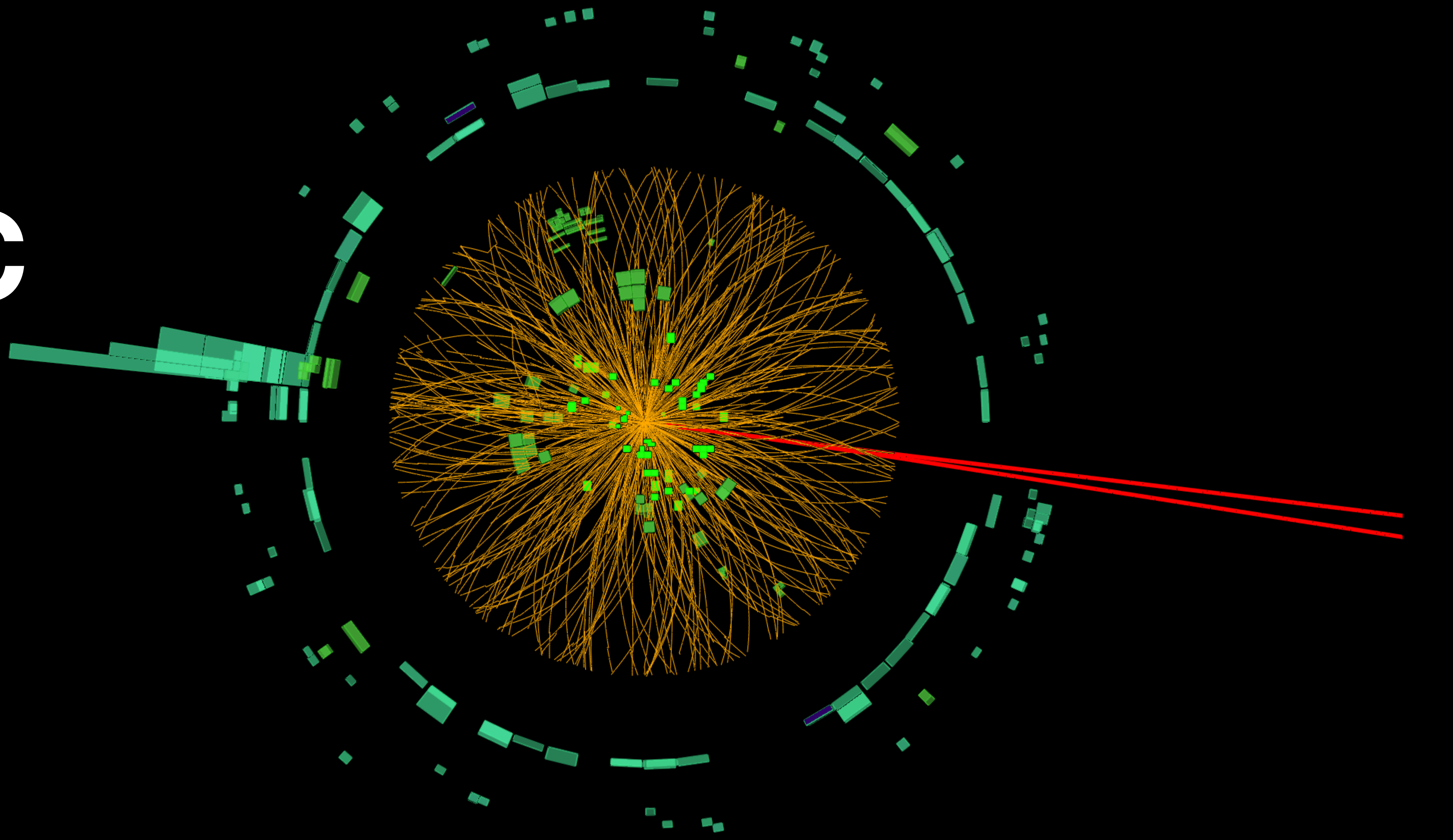
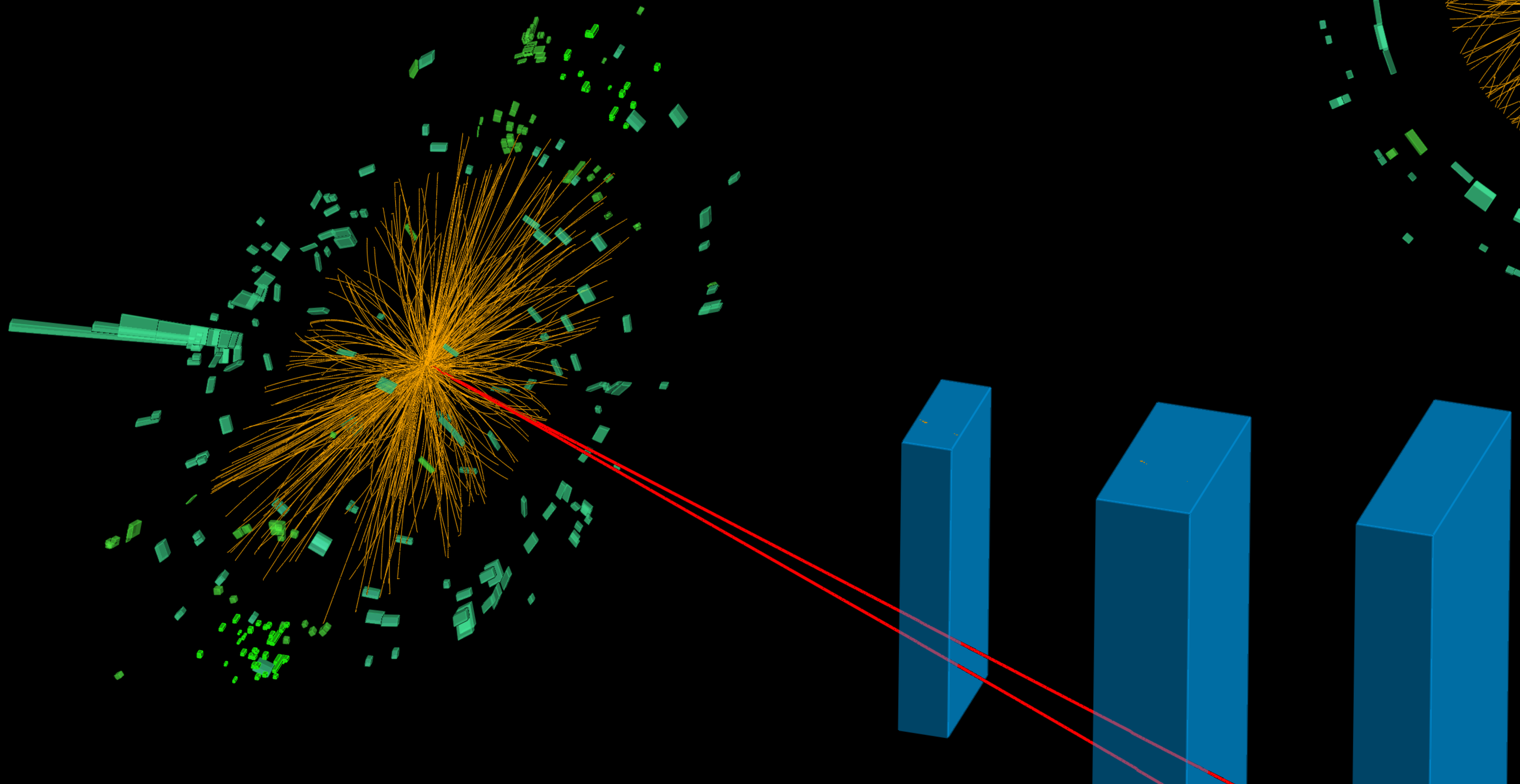
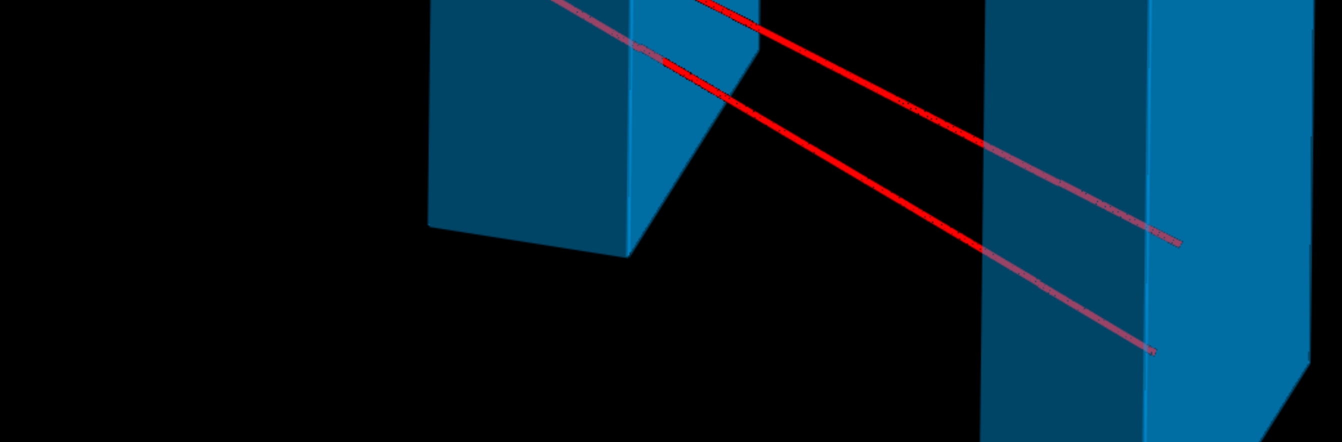
Recent Higgs boson measurements at the LHC







Mateusz Dyndal

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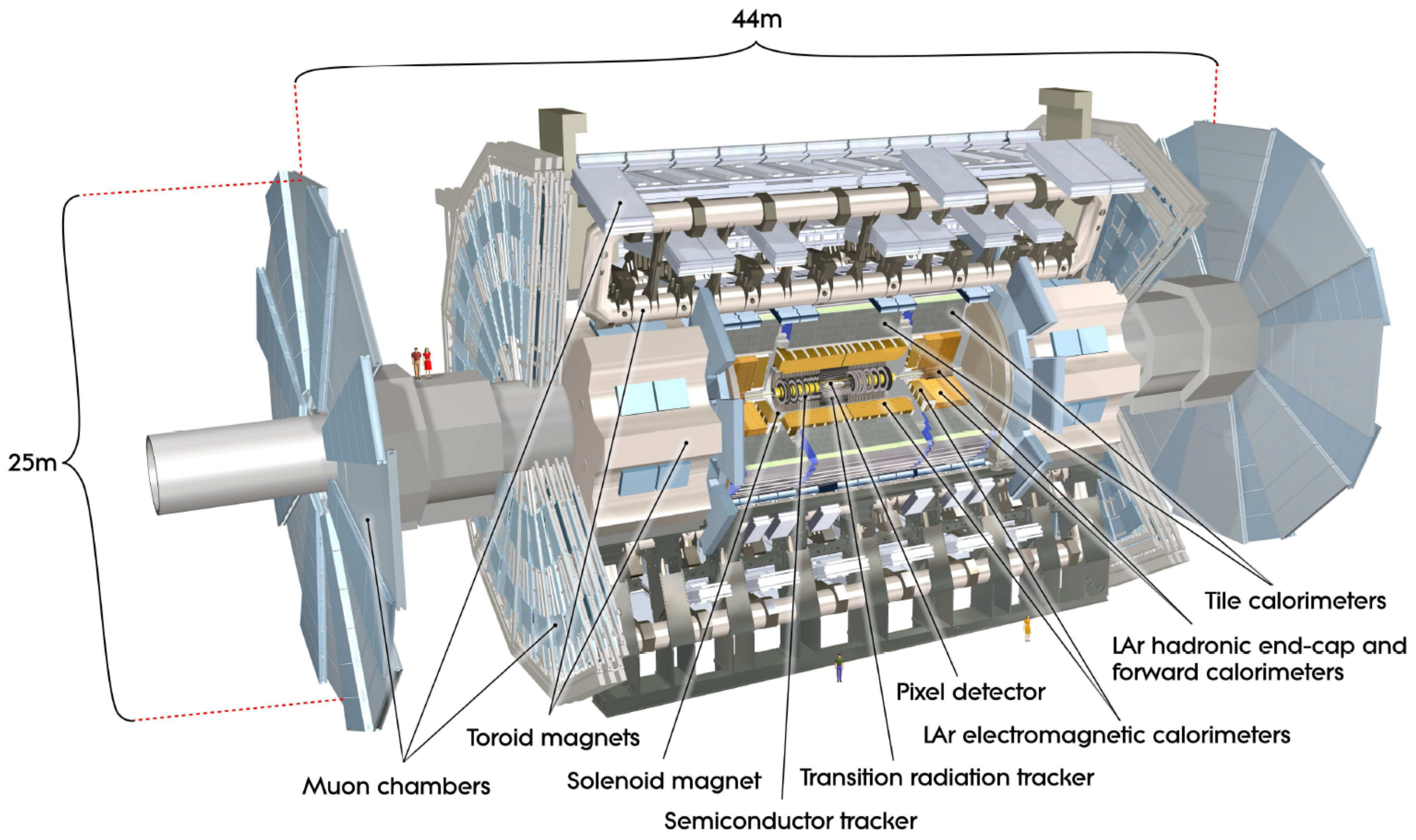
Outline

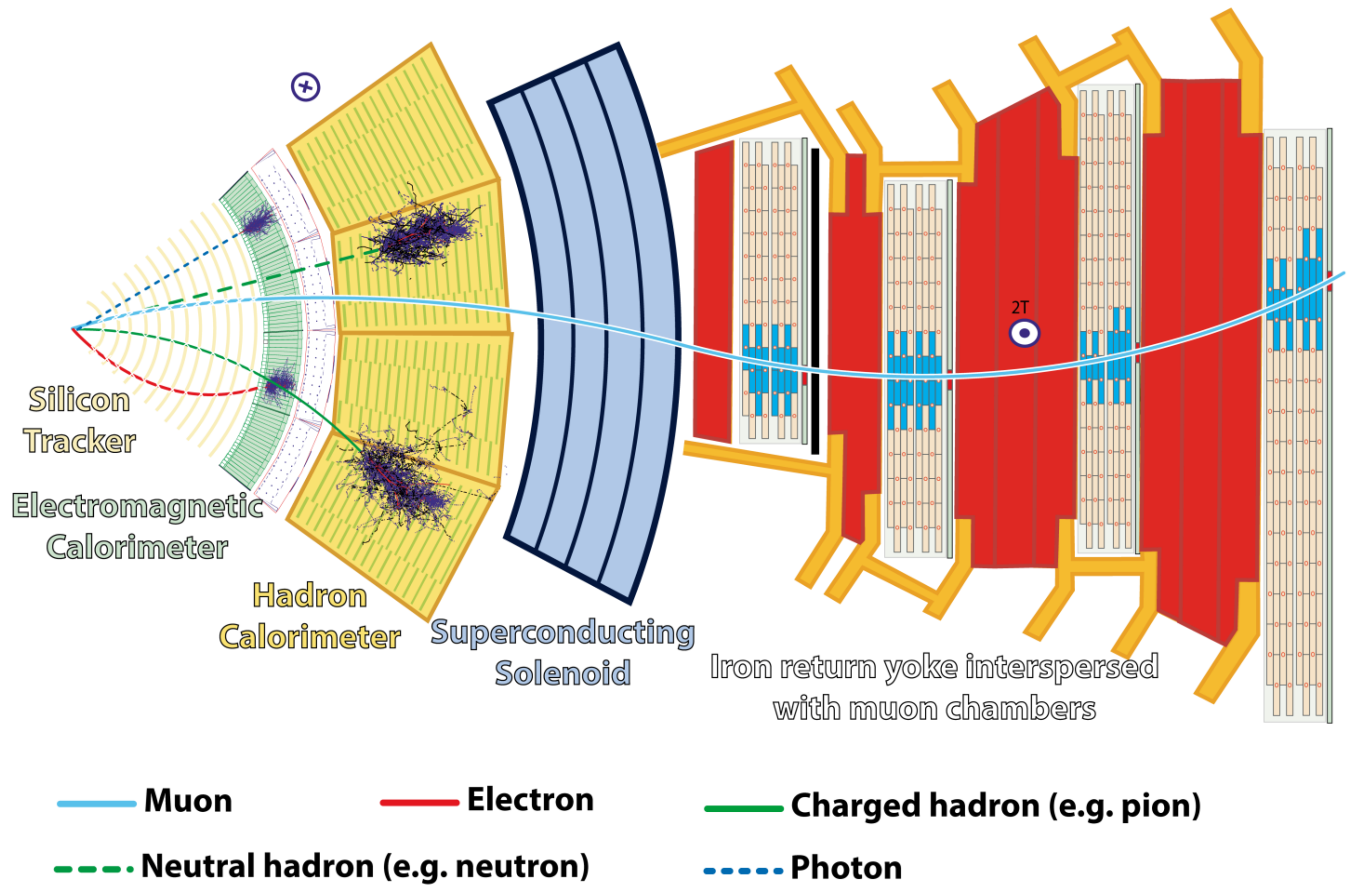
- Introduction
- Higgs mass measurements
- Higgs cross section measurements
- Combined measurements of Higgs coupling parameters
- Measurements of CP structure of Higgs boson couplings
- Recent searches of Higgs to invisible decay
- Search for di-Higgs production
- Search for H→cc decay
- Evidence for Higgs to muon pair decay
- Search for Higgs to two leptons + photon decay
- Future prospects

*not covering all topics, only selected recent updates are presented

The ATLAS and CMS detectors at the LHC

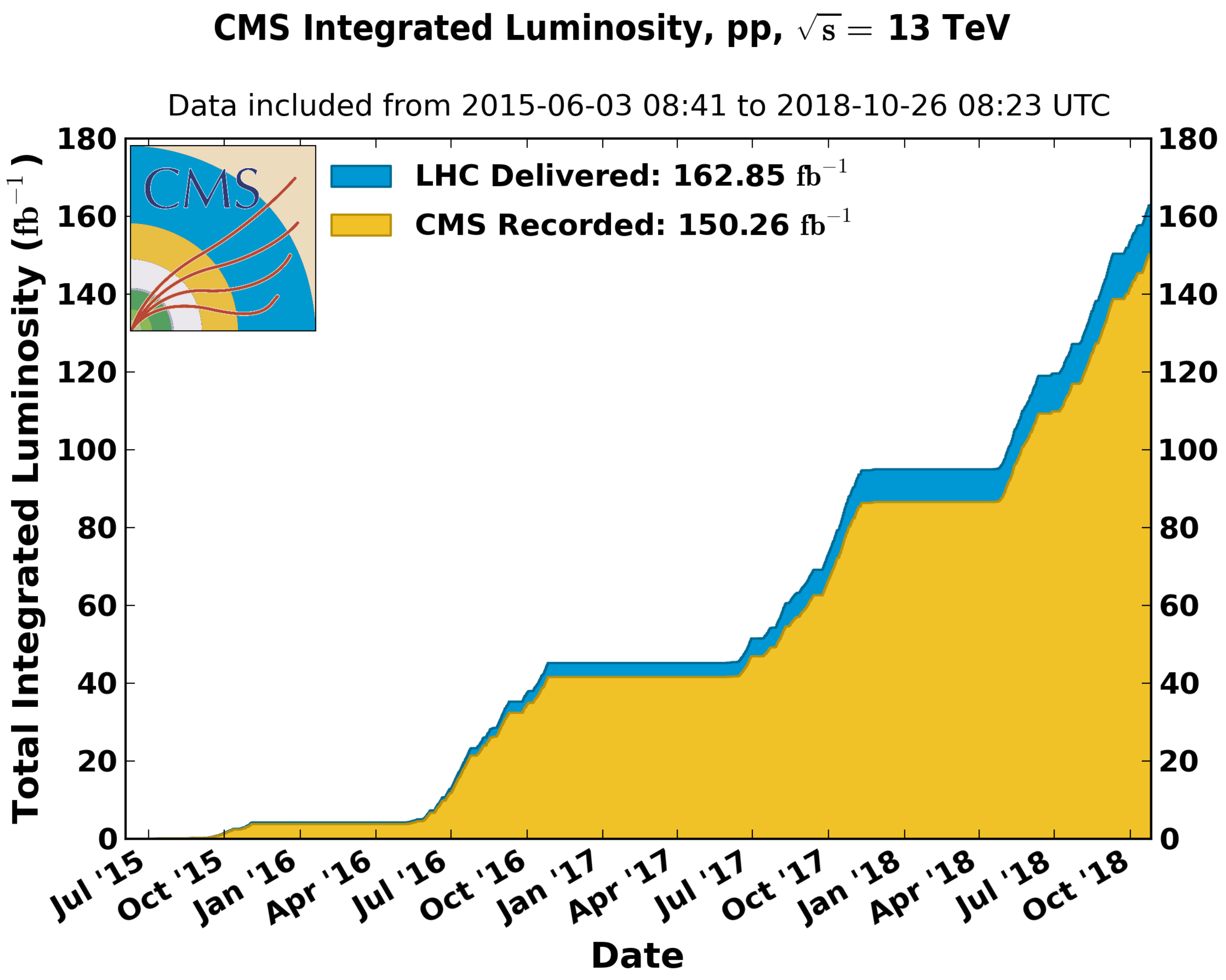
- Two general-purpose particle physics experiments
  - Designed to exploit the full discovery potential and vast range of physics opportunities that LHC provides

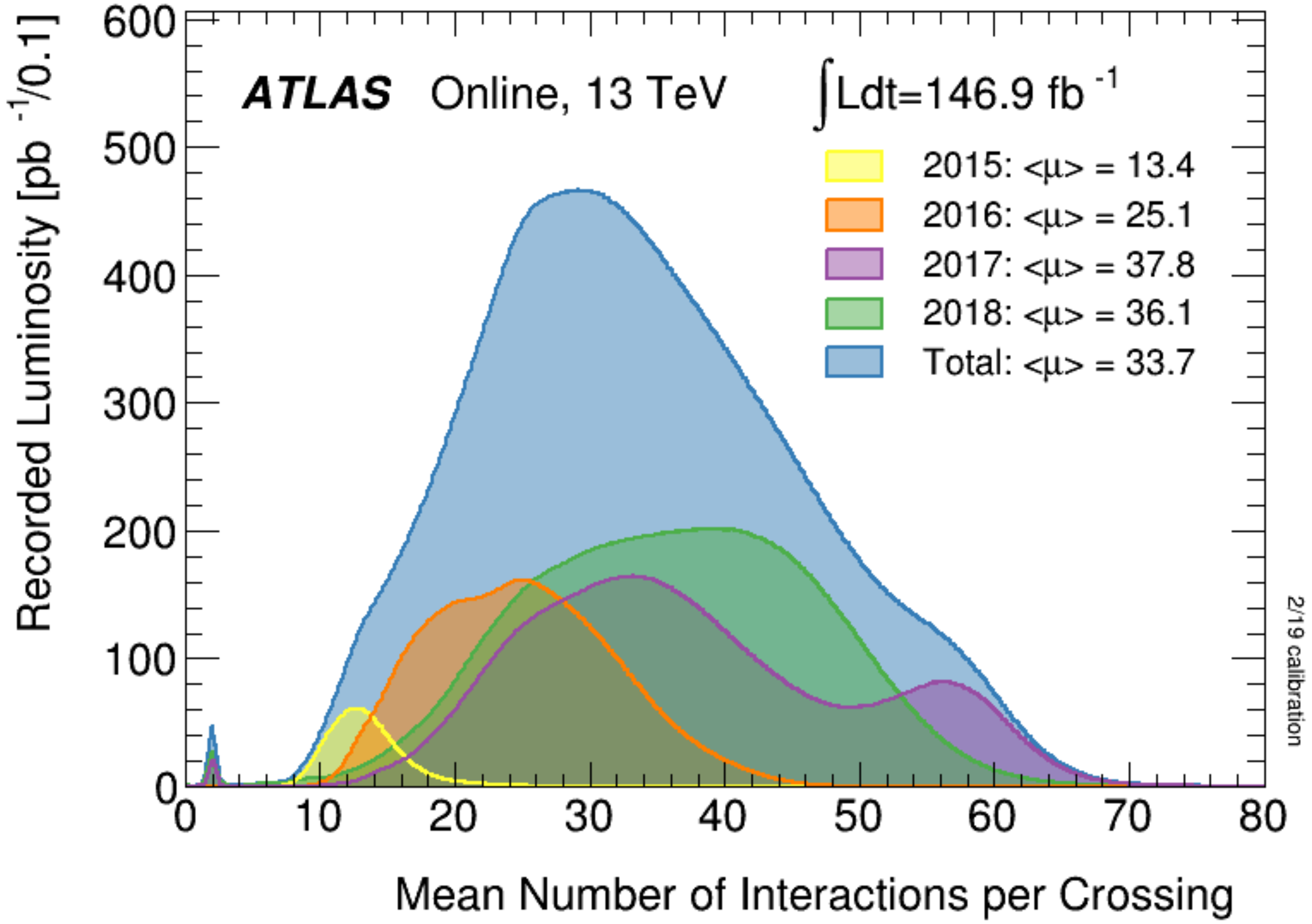




ATLAS and CMS Run 2 period (2015-2018)

- ATLAS and CMS experiments have each successfully collected **~140 fb^{-1}** luminosity at **pp 13 TeV** centre-of-mass energy in full Run 2 period
  - Big thanks to the CERN accelerator team for the excellent LHC performance!

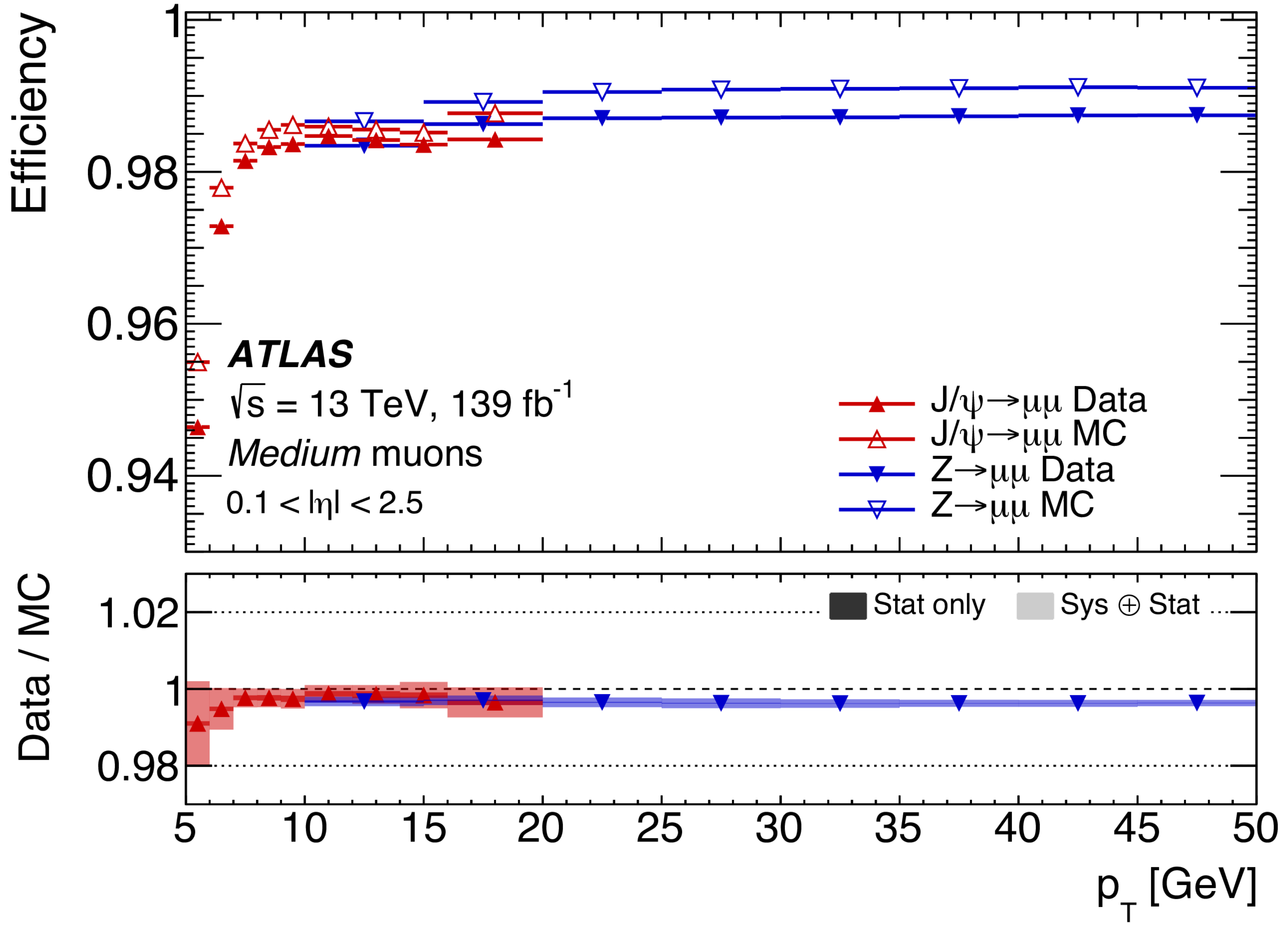


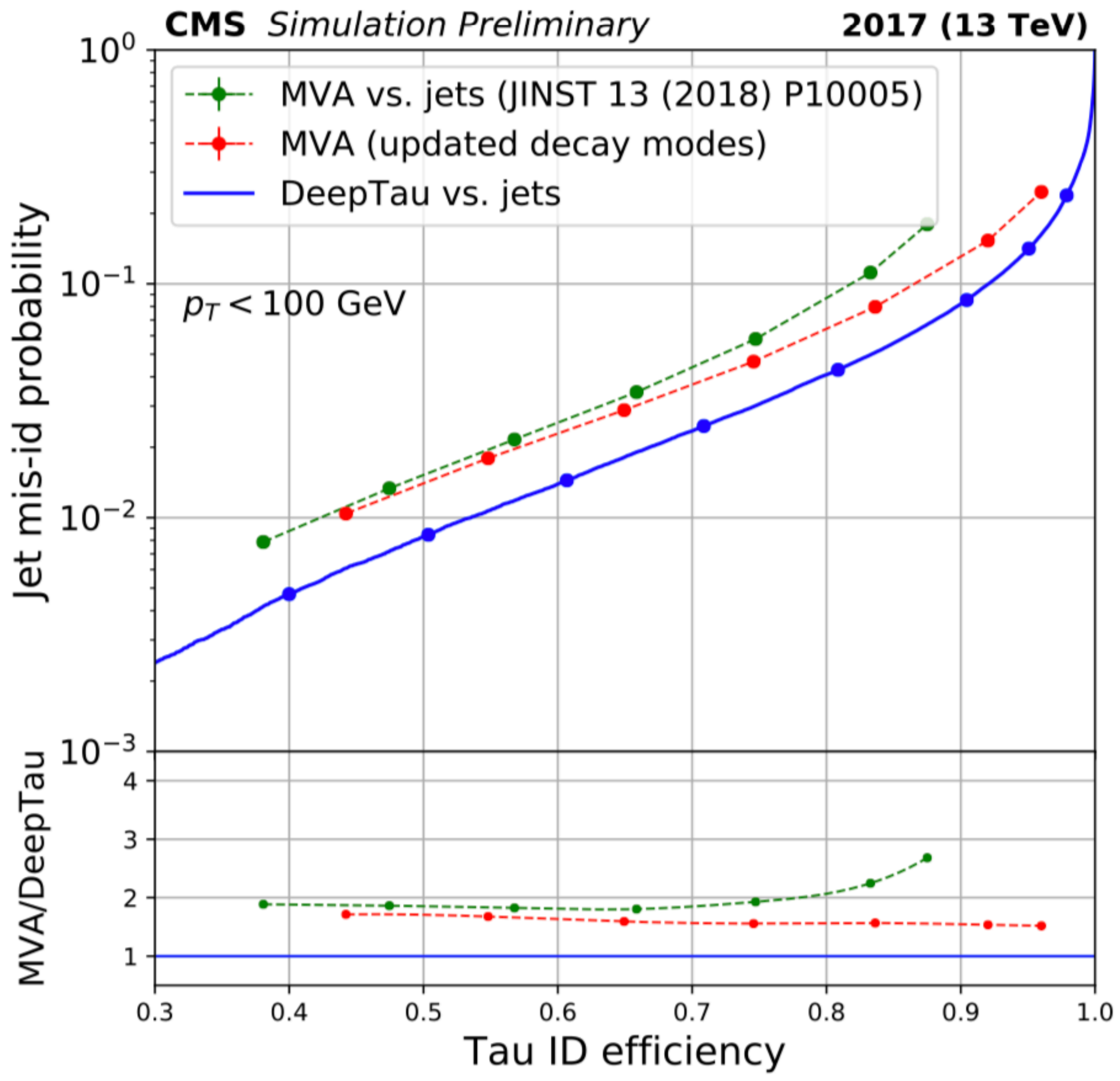


ATLAS and CMS detectors performance

- Good understanding of the detector is critical
- Reconstruction of physics objects (e, γ, μ, τ, jets, …) precisely known from careful data-driven calibrations
- Several improvements during the last years using machine learning techniques (e.g. b-tagging, τ-identification,…)

arXiv:2012.00578

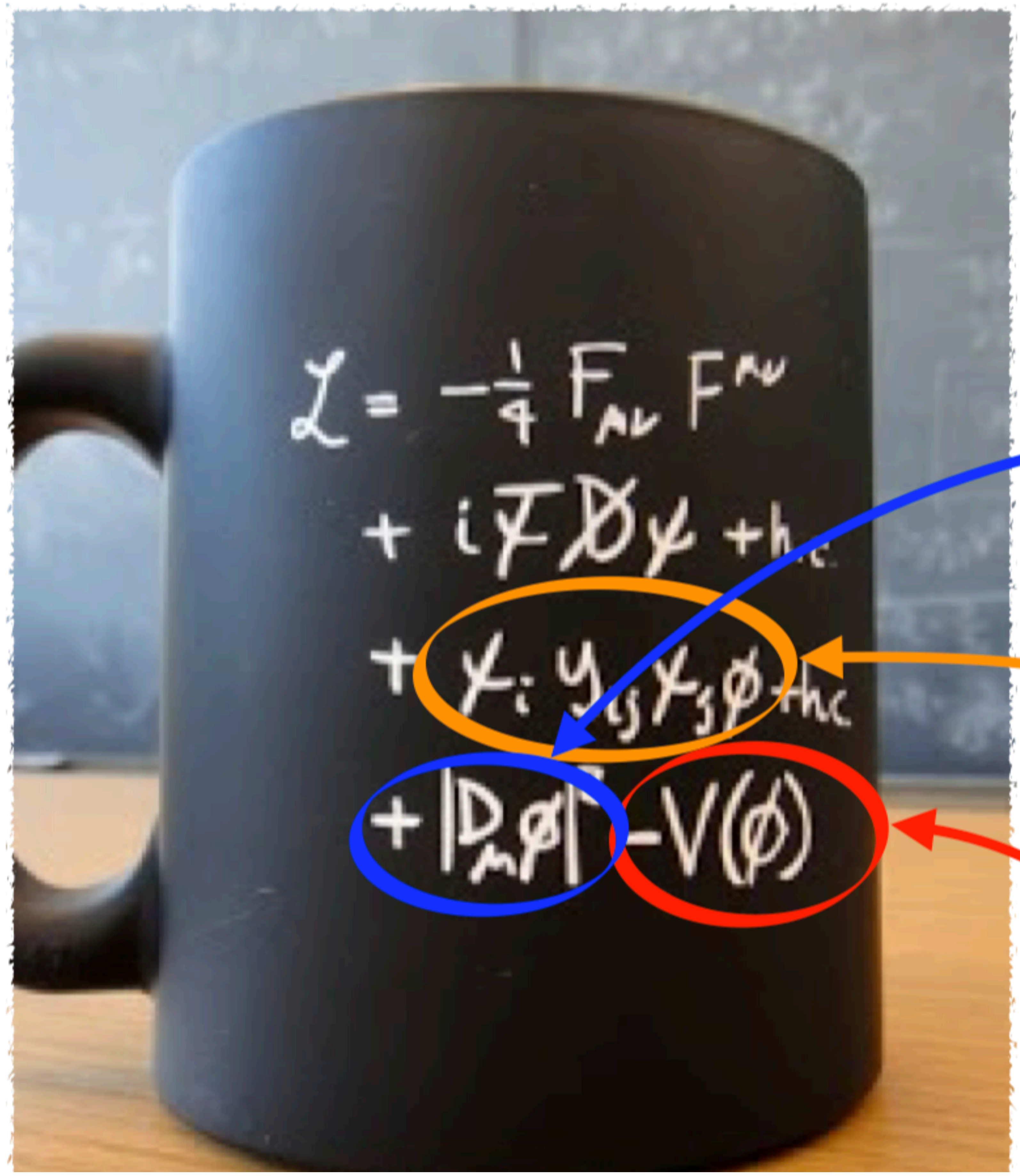




CMS-DP-2019-033

The Higgs boson

It is the only fundamental scalar with spin 0 we have seen so far



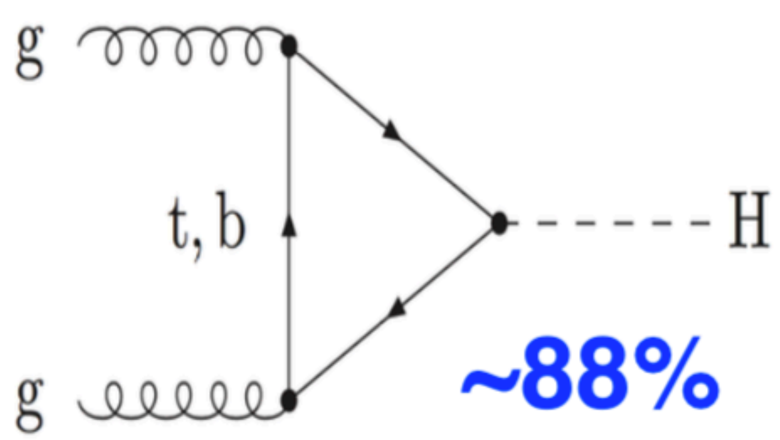
Discovery allows to access a new sector in the Lagrangian:

- Scalar-Gauge boson interactions
- Yukawa couplings (new type of interaction)
- Higgs potential: cornerstone of BEH mechanism, not yet probed experimentally

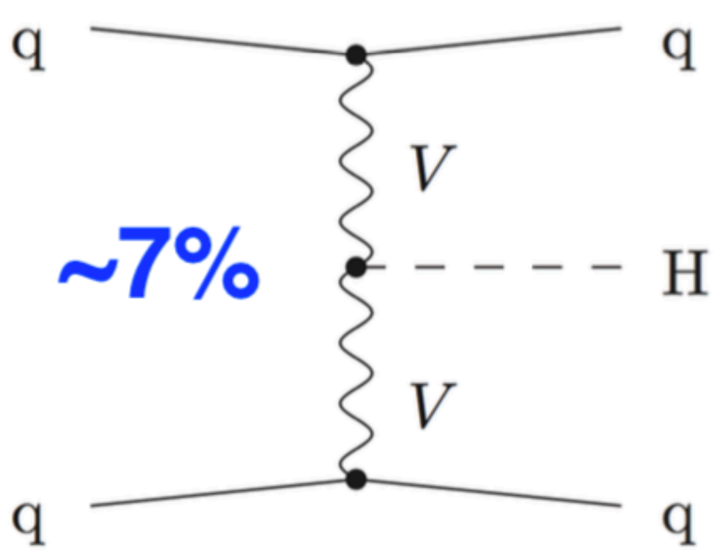
from G. Zanderighi Higgs Hunting'19 talk

Higgs boson production and decay at the LHC

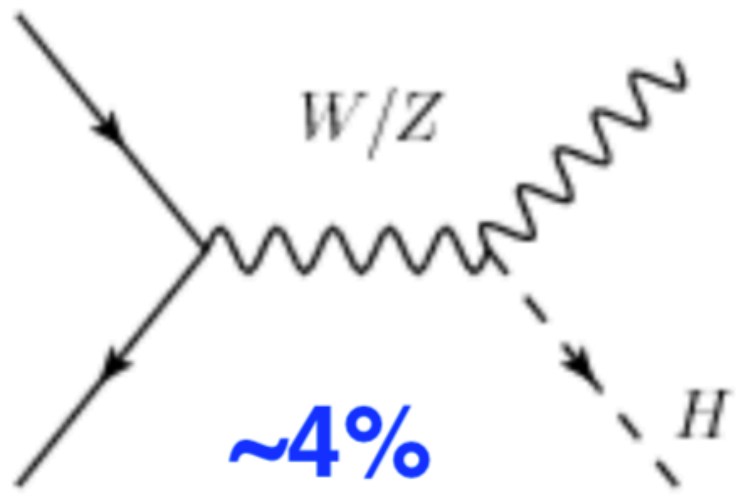
gluon-gluon fusion(ggF)



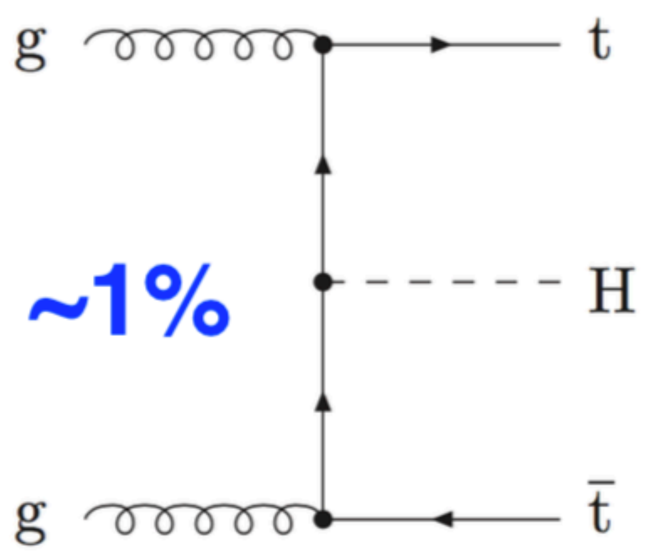
Vector boson fusion(VBF)

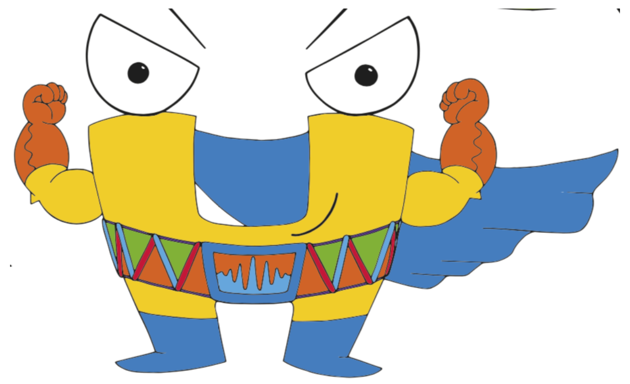


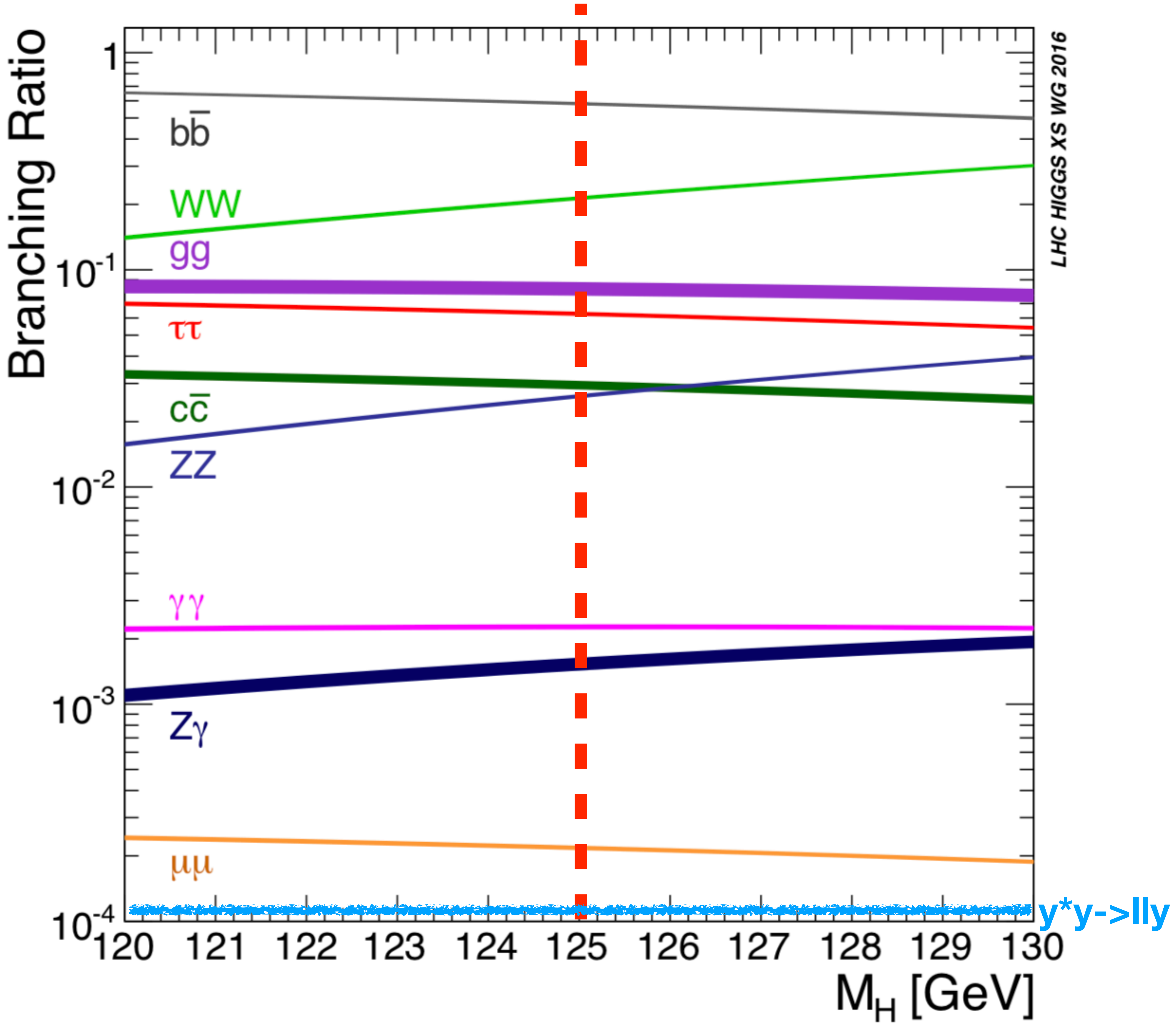
Higgs associated production with vector bosons (VH)



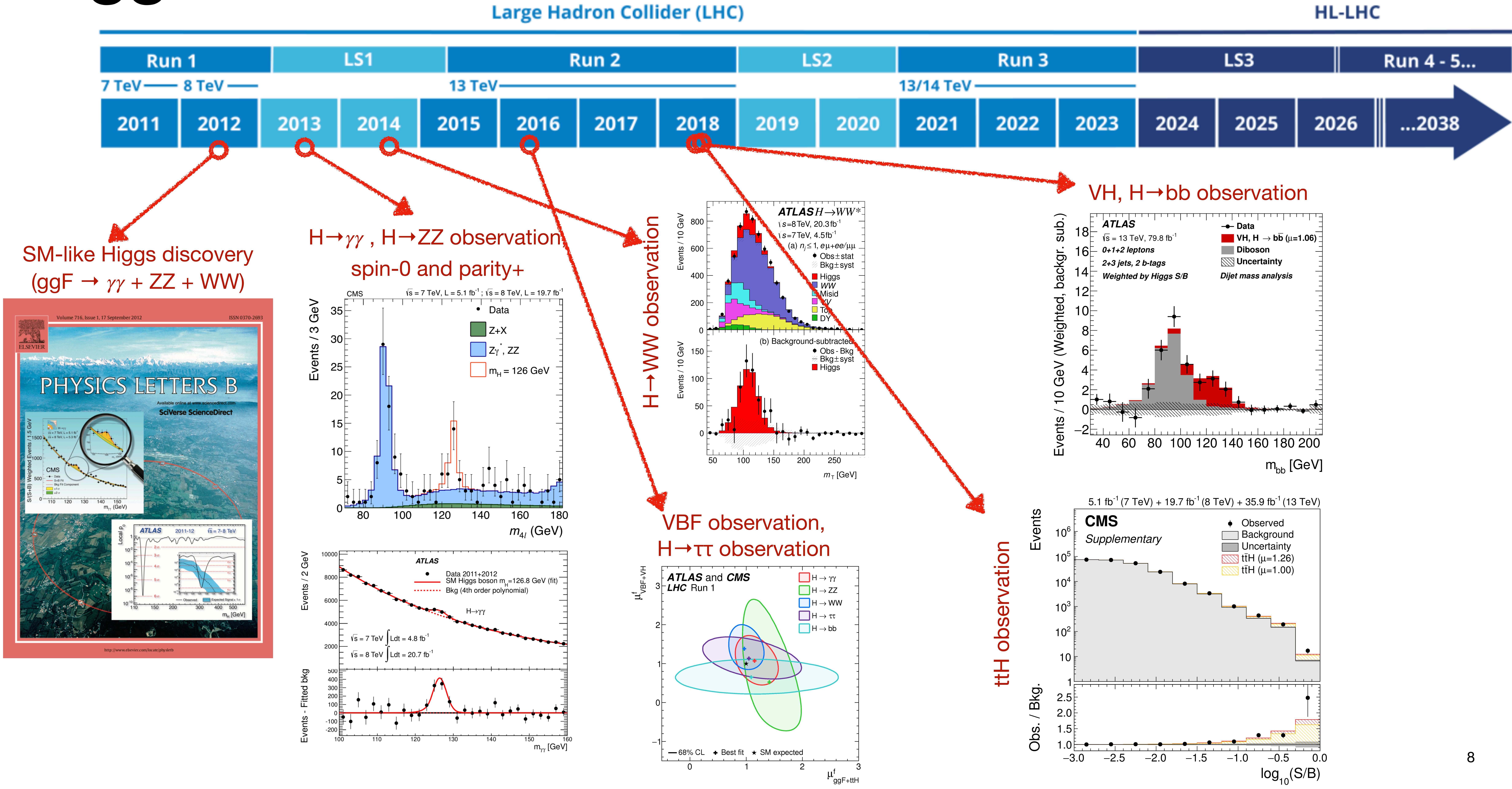
Higgs associated production with a top-quark pair (ttH)





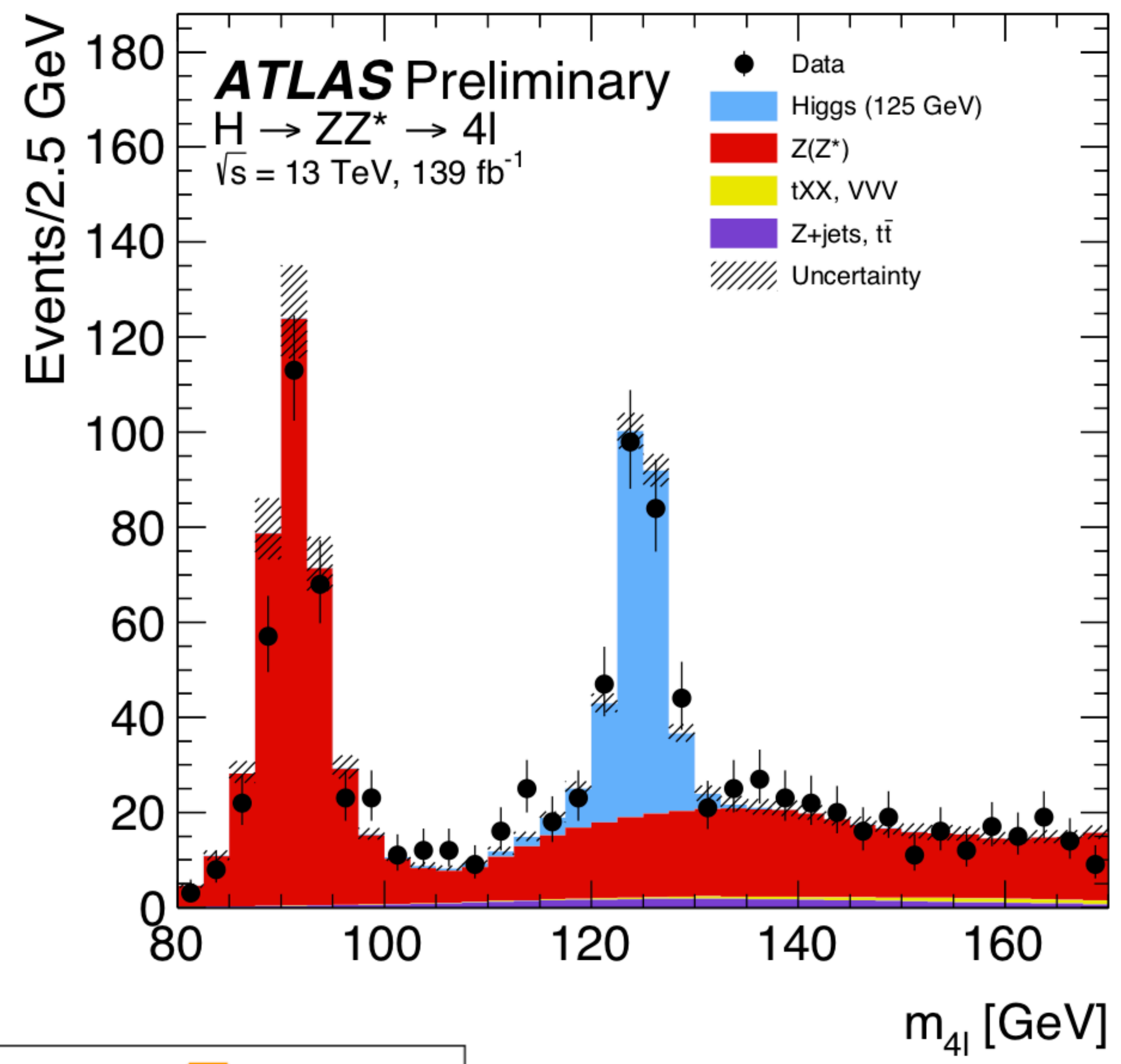


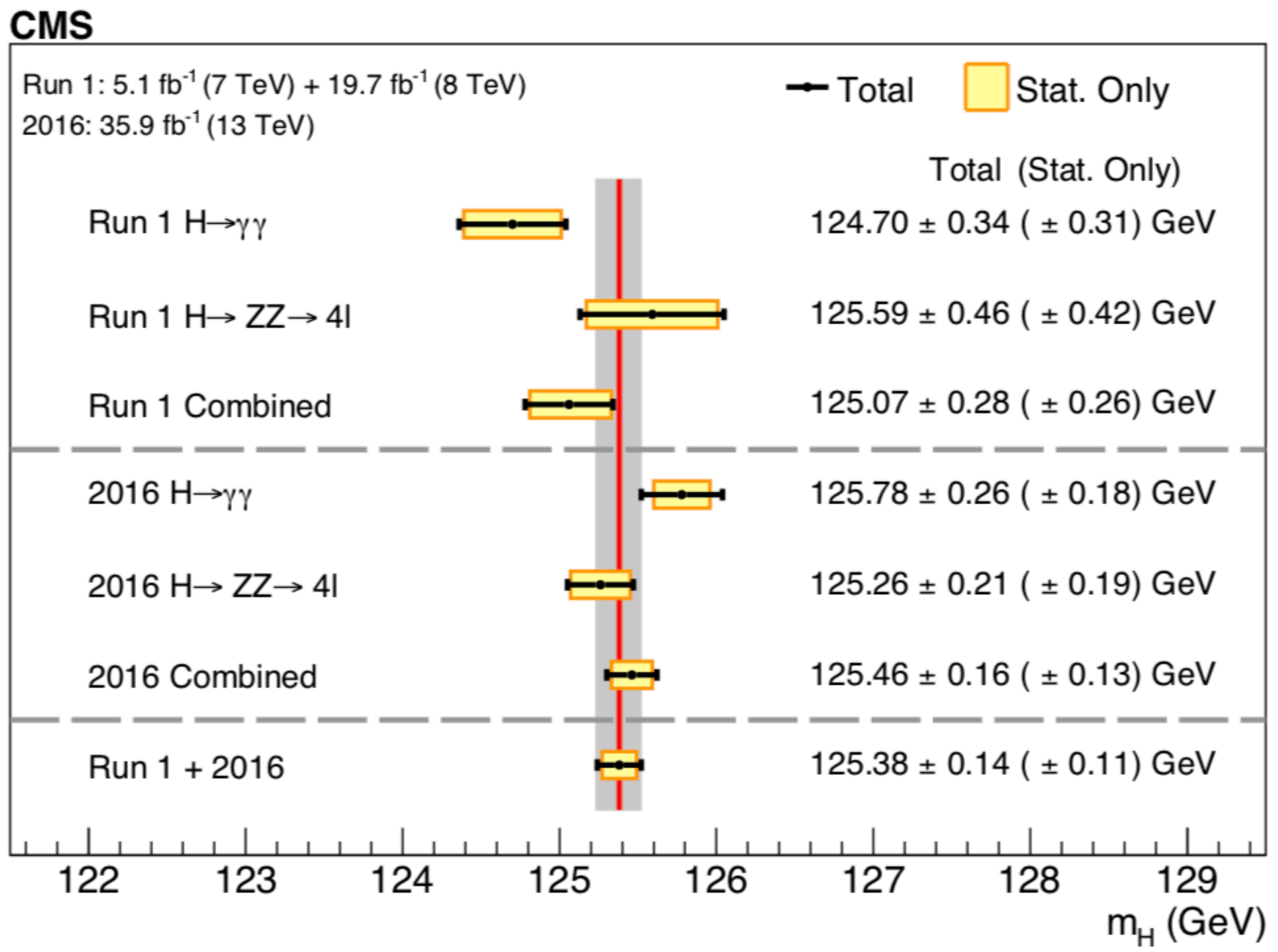
Higgs boson observation timeline at the LHC



Higgs boson mass measurements

- Run 1 (ATLAS+CMS): m_H = 125.09 ±0.21(stat) ±0.11(syst) GeV (0.2% precision) Phys.Rev.Lett. 114 (2015) 191803
- ATLAS Run 2 measurement $H \to ZZ \to 4l$ (139 fb^{-1})
  - **m_H = 124.92 ± 0.21 GeV** ATLAS-CONF-2020-005
- CMS Run 2 measurement in $H \to \gamma\gamma$ and $H \to ZZ \to 4l$ (36 fb^{-1}), in combination with CMS Run 1 measurements:
  - **m_H = 125.38 ± 0.14 GeV** Phys. Lett. B 805 (2020) 135425
  - Most precise measurement at present (0.11%)
- Measurements still dominated by statistical uncertainty

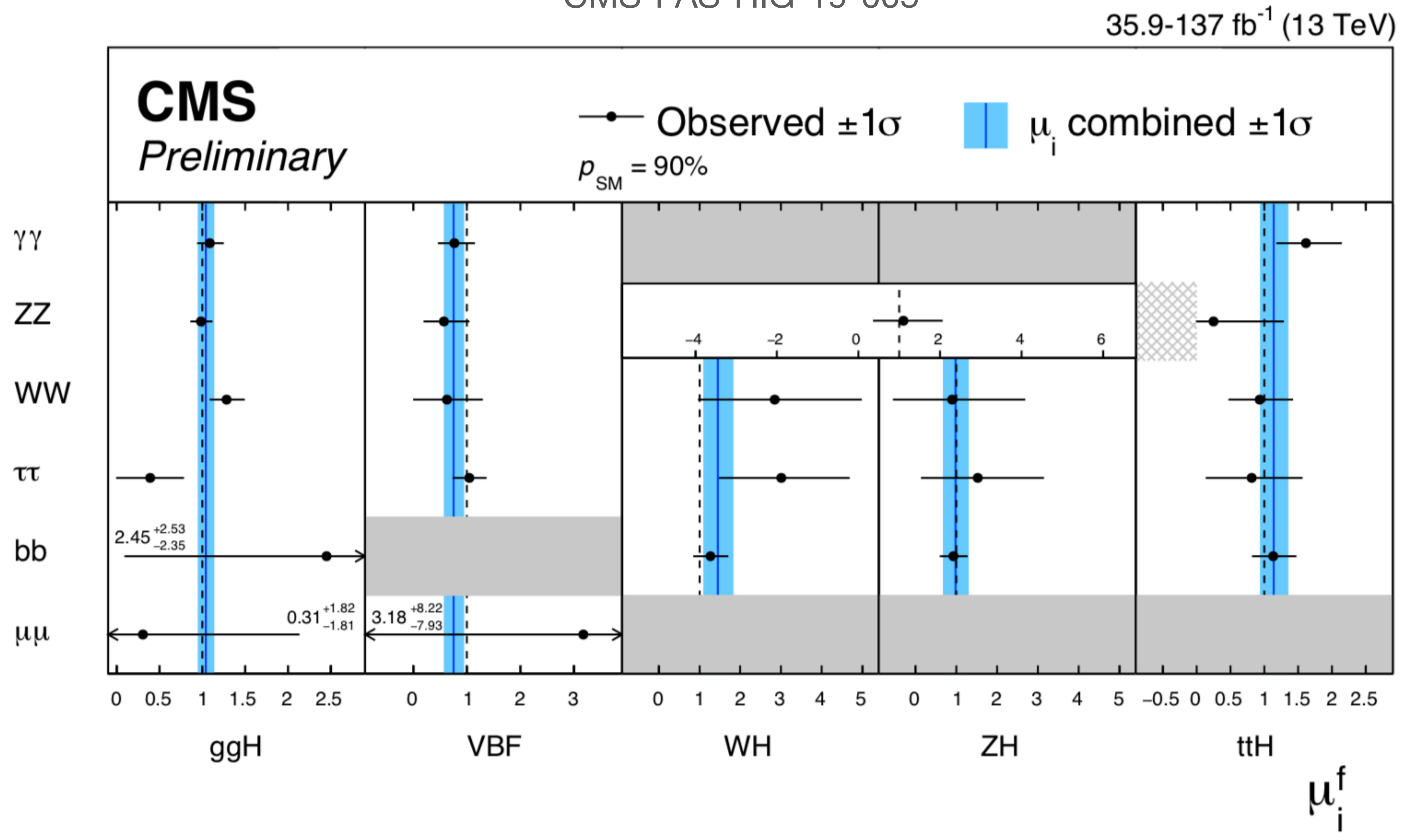




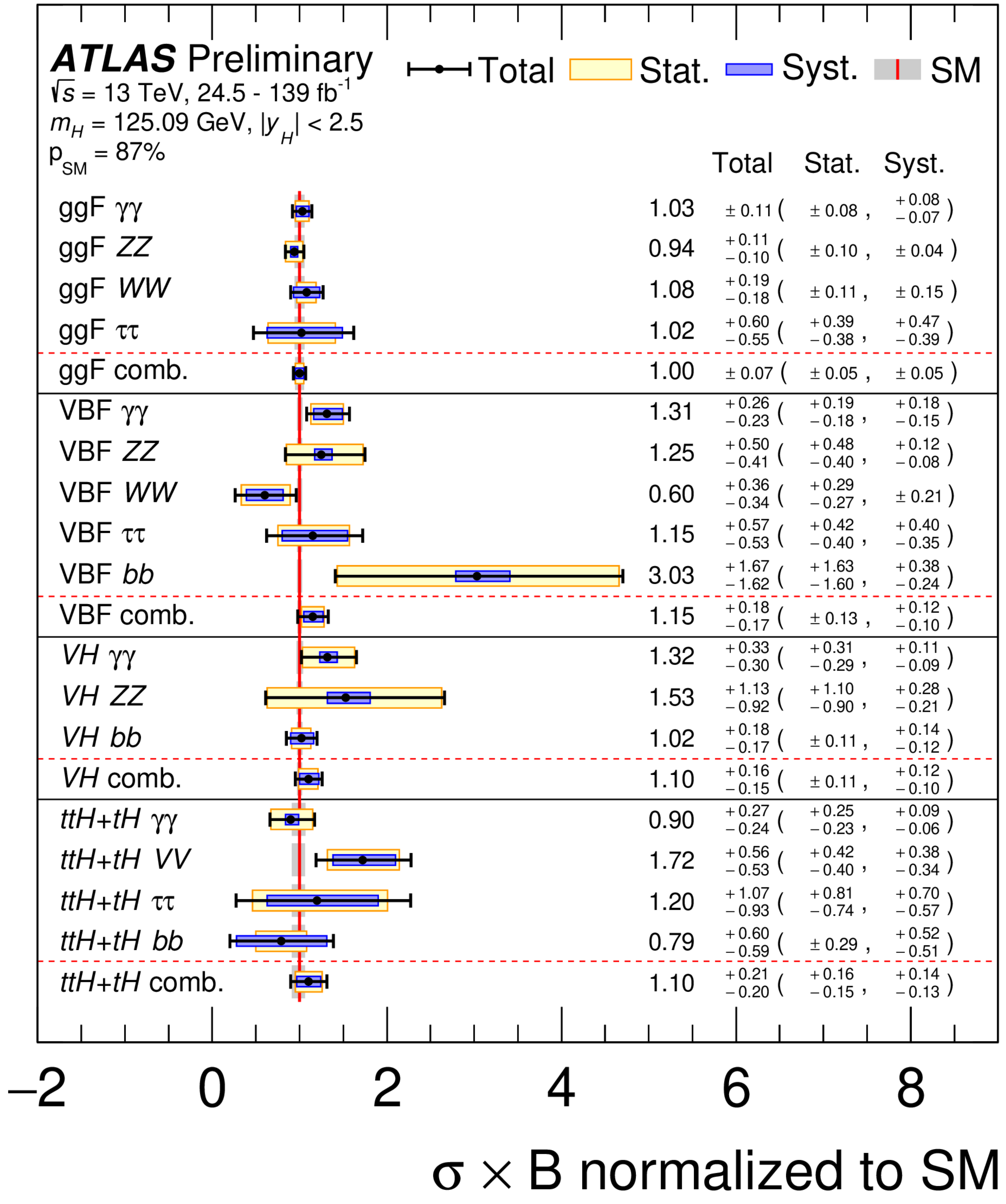
Higgs signal strength measurements

- Inclusive Higgs signal strength combination:
  - **μ = 1.02 ± 0.07** [±0.04(th) ±0.04(exp) ±0.04(stat)] (CMS)
  - **μ = 1.06 ± 0.07** (ATLAS)
  - in good agreement with the SM prediction

CMS-PAS-HIG-19-005

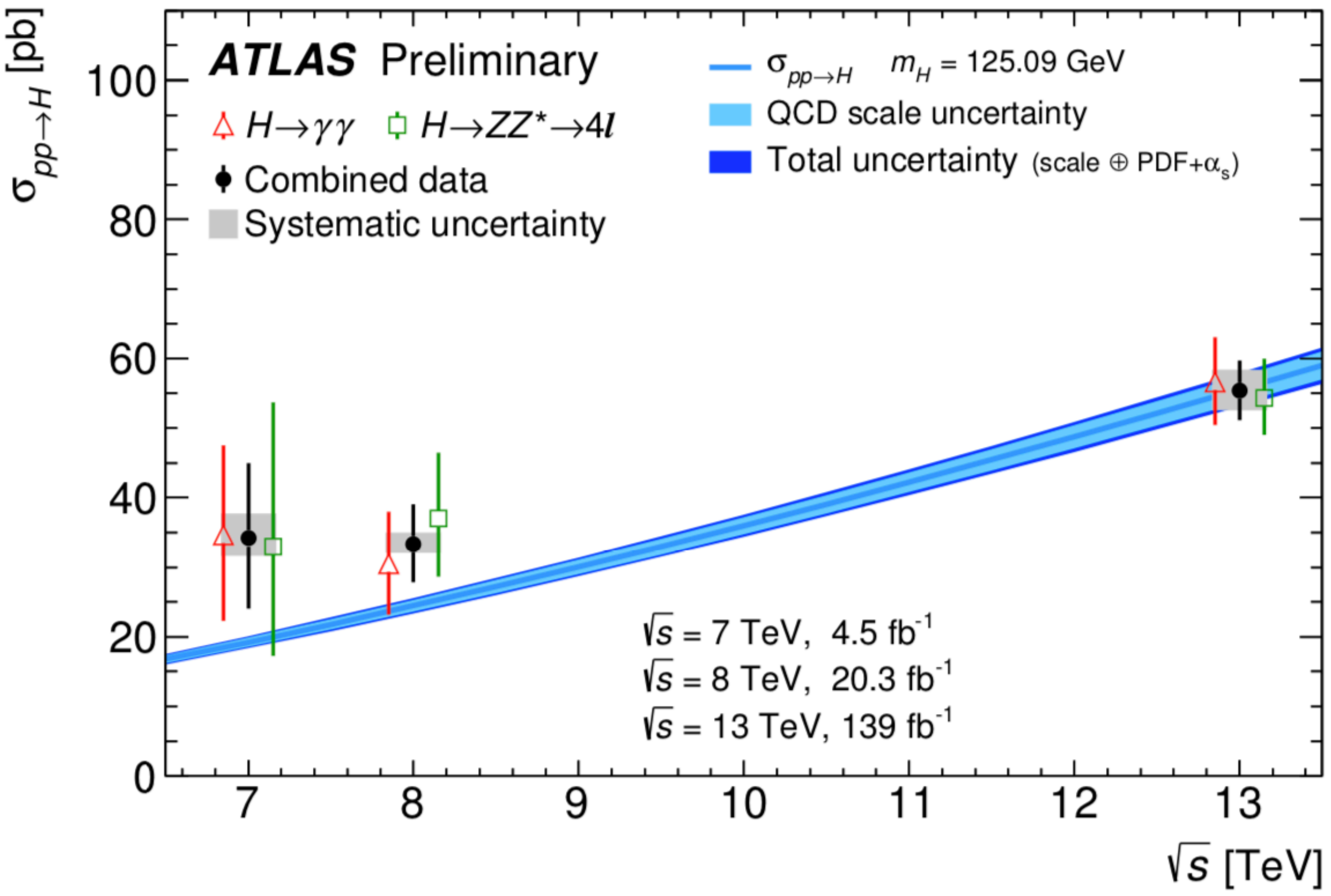


ATLAS-CONF-2020-027



Higgs cross section measurements

- Inclusive cross-section measurement in γγ and ZZ channels at 7, 8 and 13 TeV
  - Total Higgs boson production cross section at 13 TeV is **55.4 ±3.1(stat) ±2.9(syst) pb**
  - In agreement with the Standard Model prediction

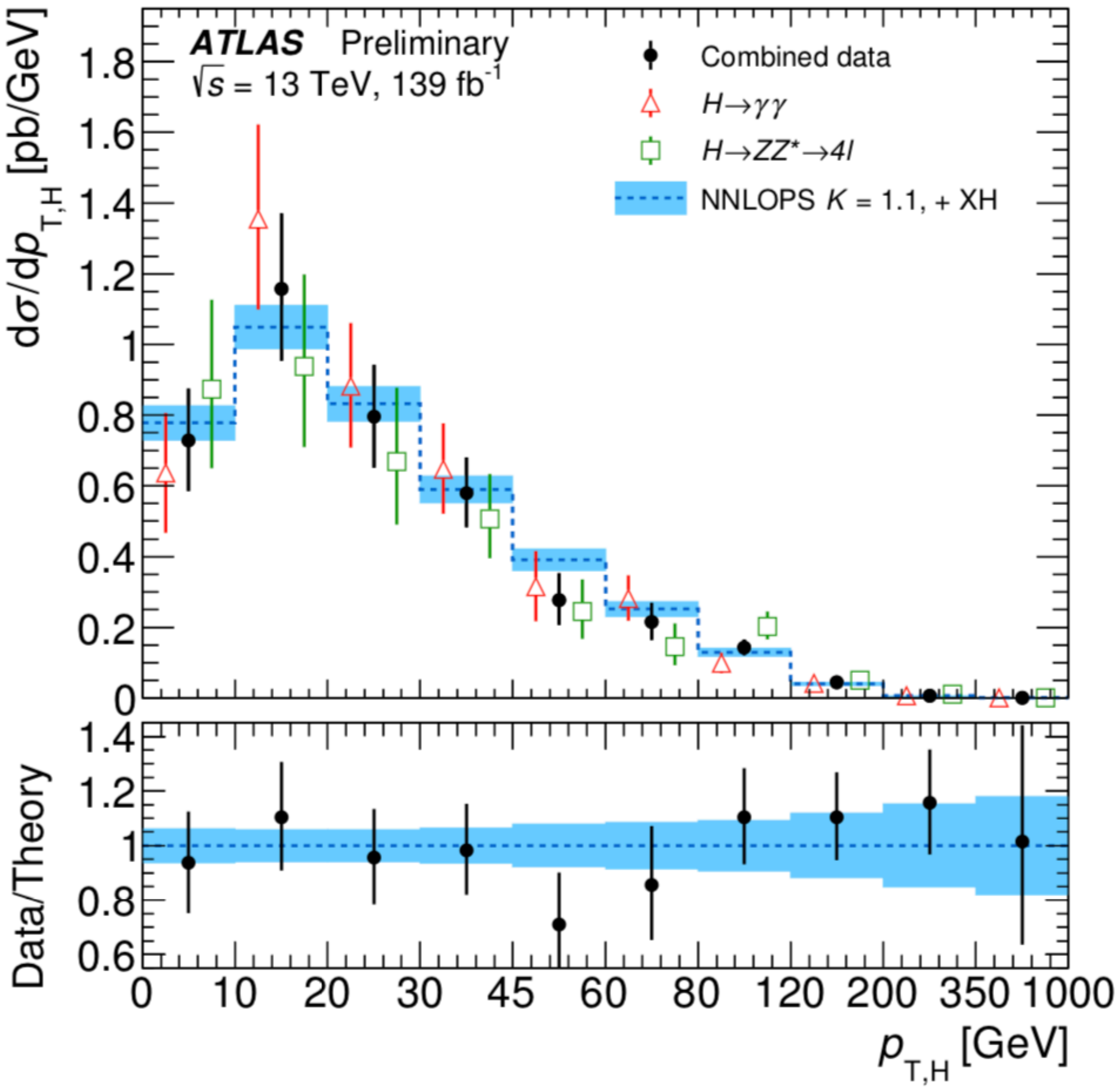


ATLAS-CONF-2019-032

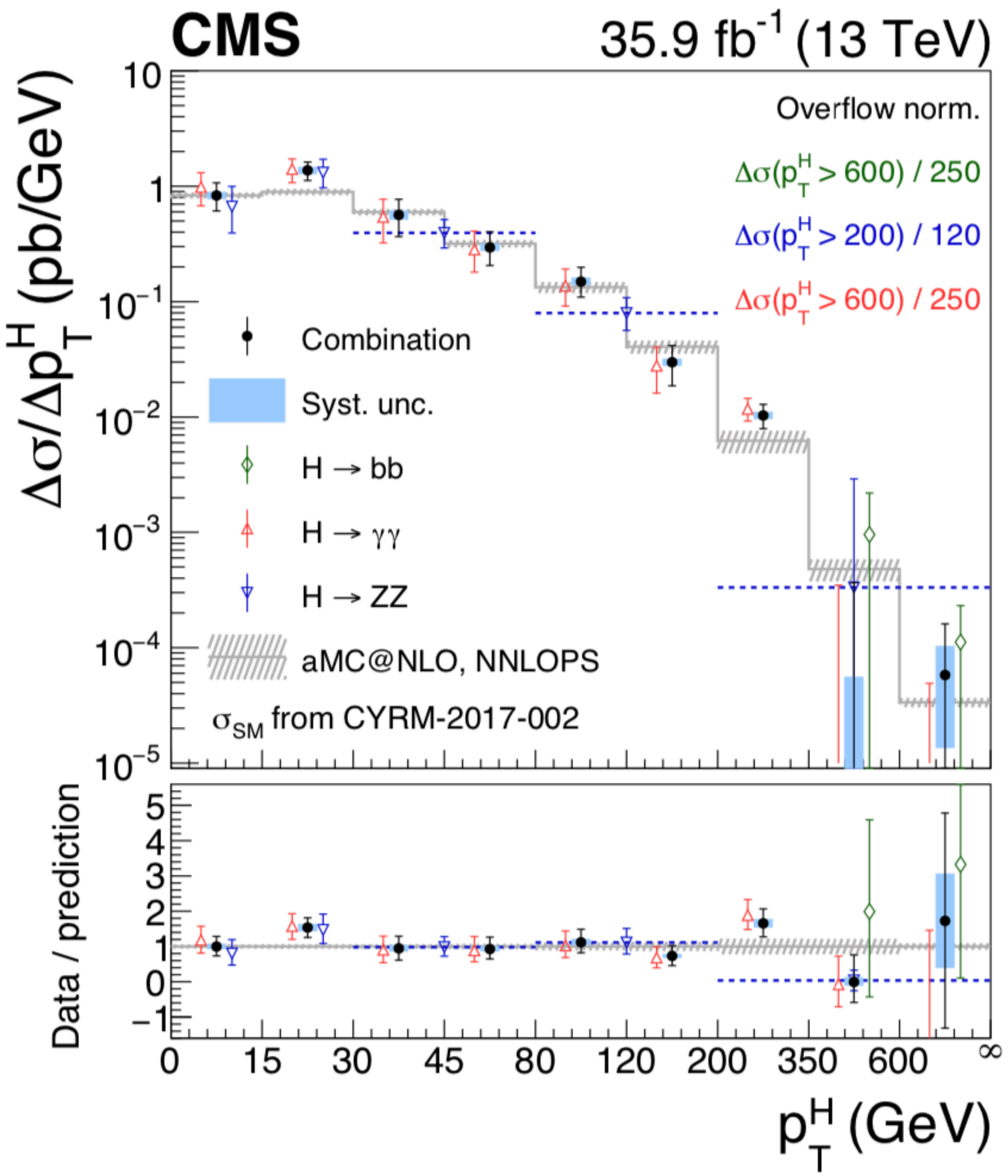
Higgs cross section measurements

- Differential cross-section measurements in **Higgs p_T,** Higgs rapidity and N_{jets}
  - Combination of H→γγ, ZZ (and bb) channels

ATLAS-CONF-2019-032



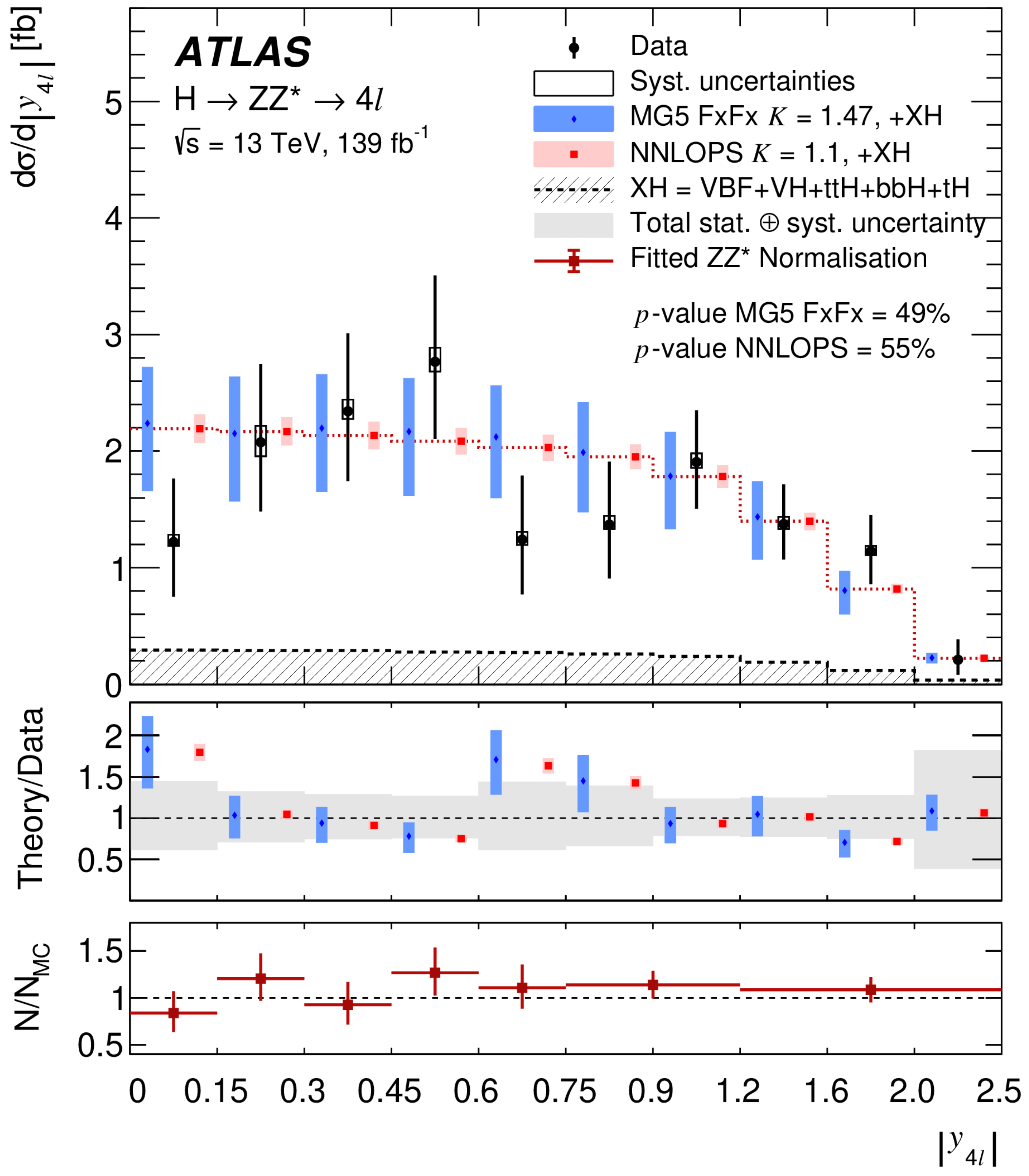
Phys. Lett. B 792 (2019) 369



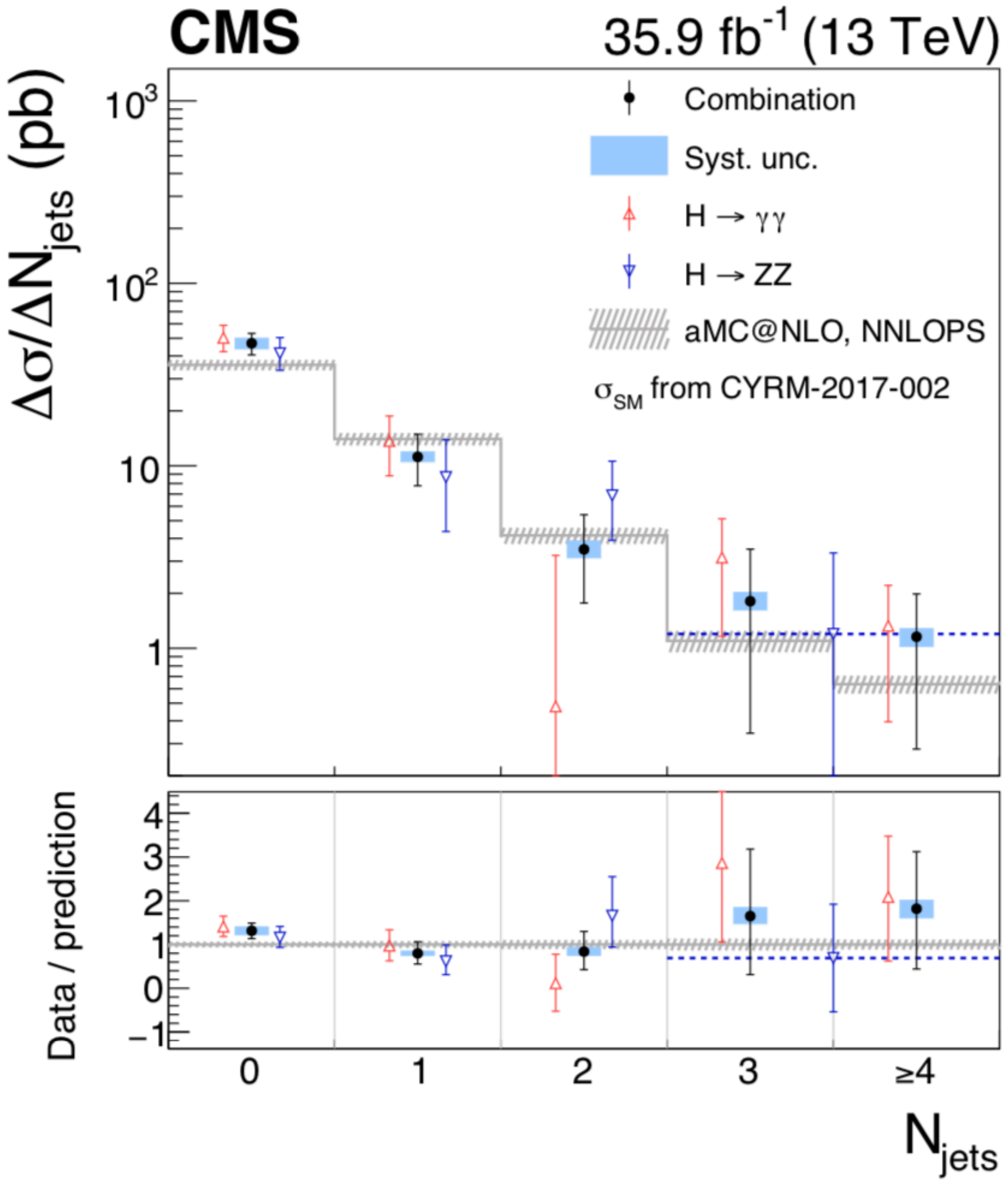
Higgs cross section measurements

- Differential cross-section measurements in Higgs p_T, **Higgs rapidity and N_{jets}**

Eur. Phys. J. C 80 (2020) 941

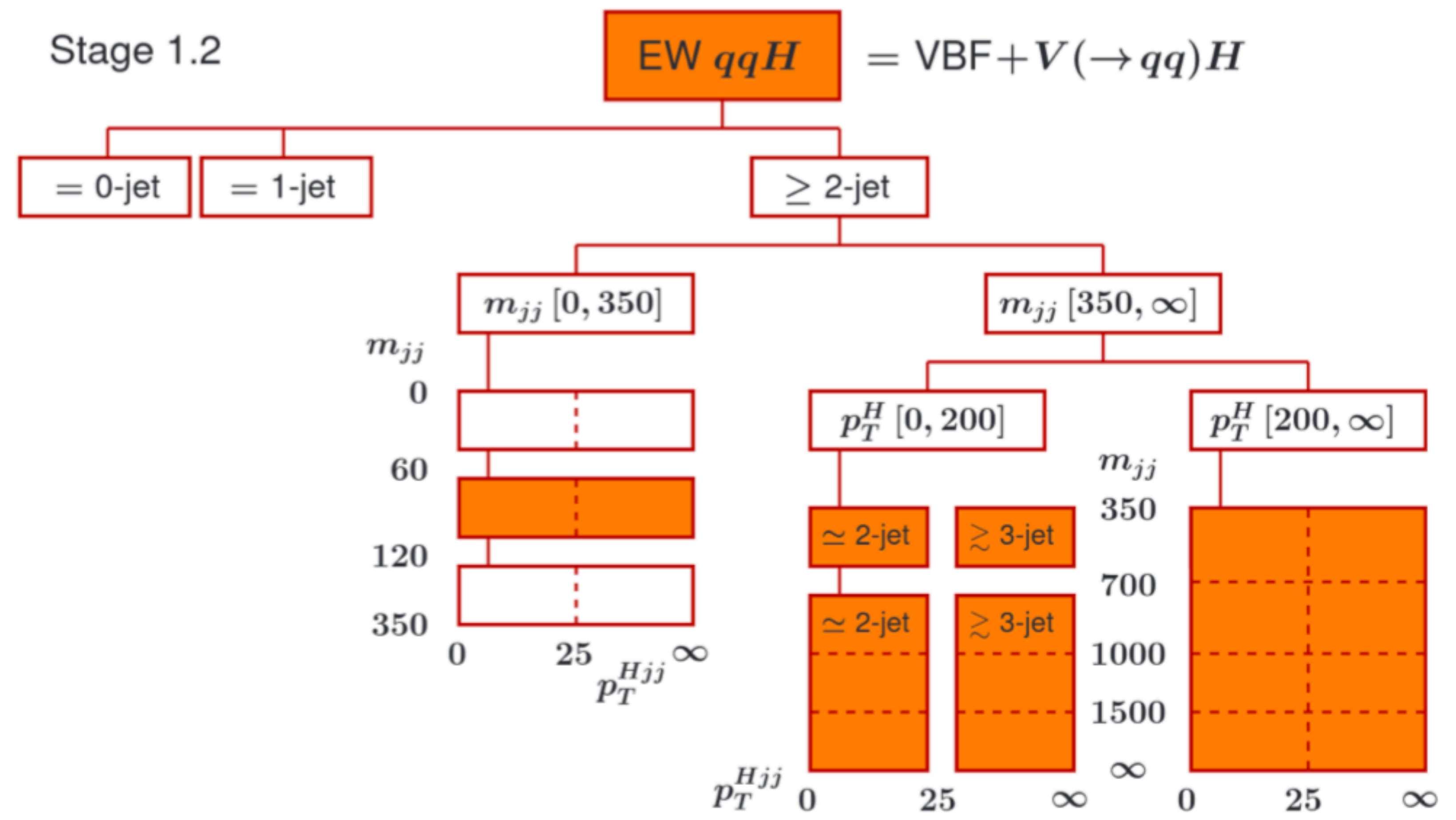


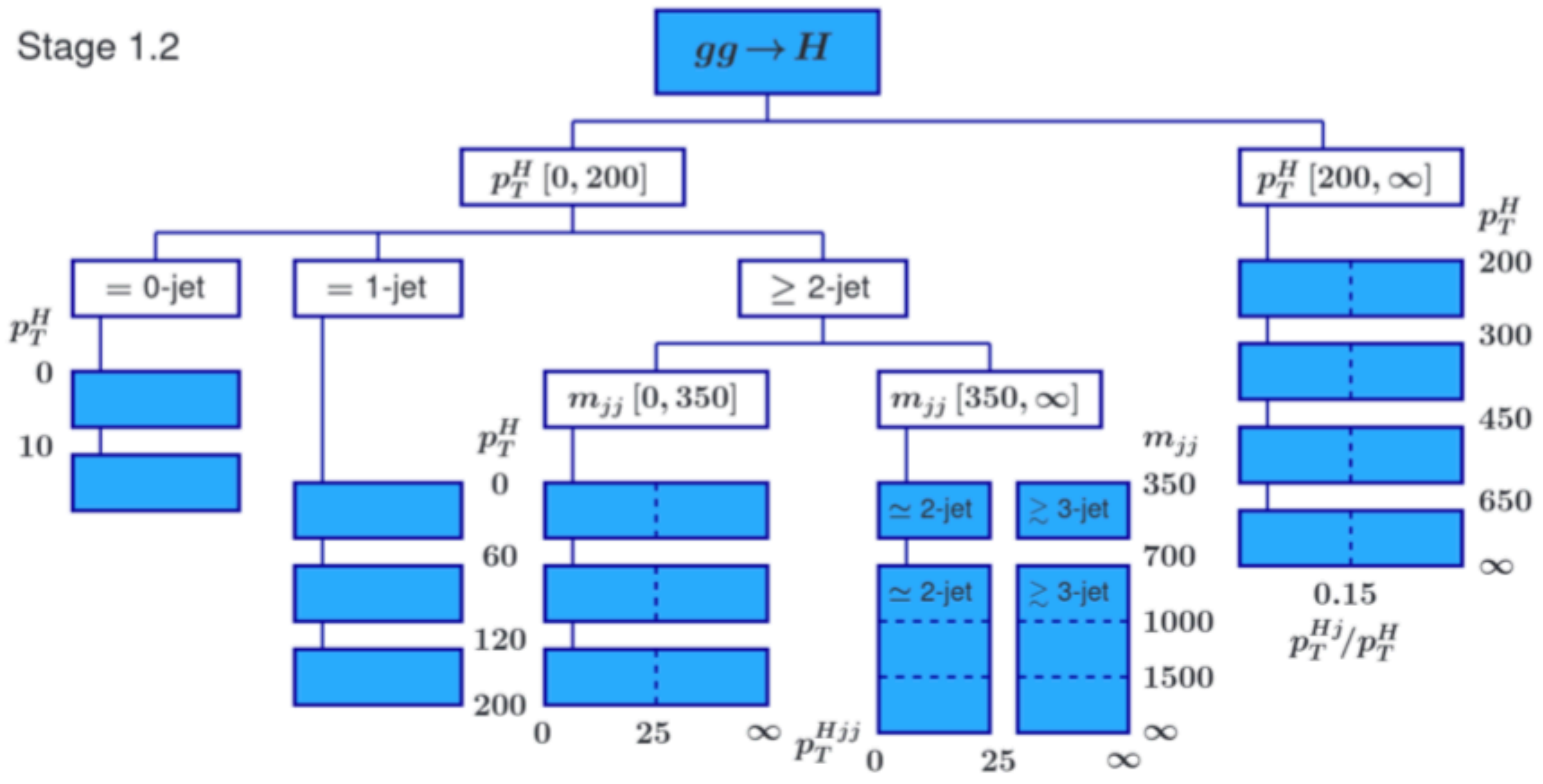
Phys. Lett. B 792 (2019) 369

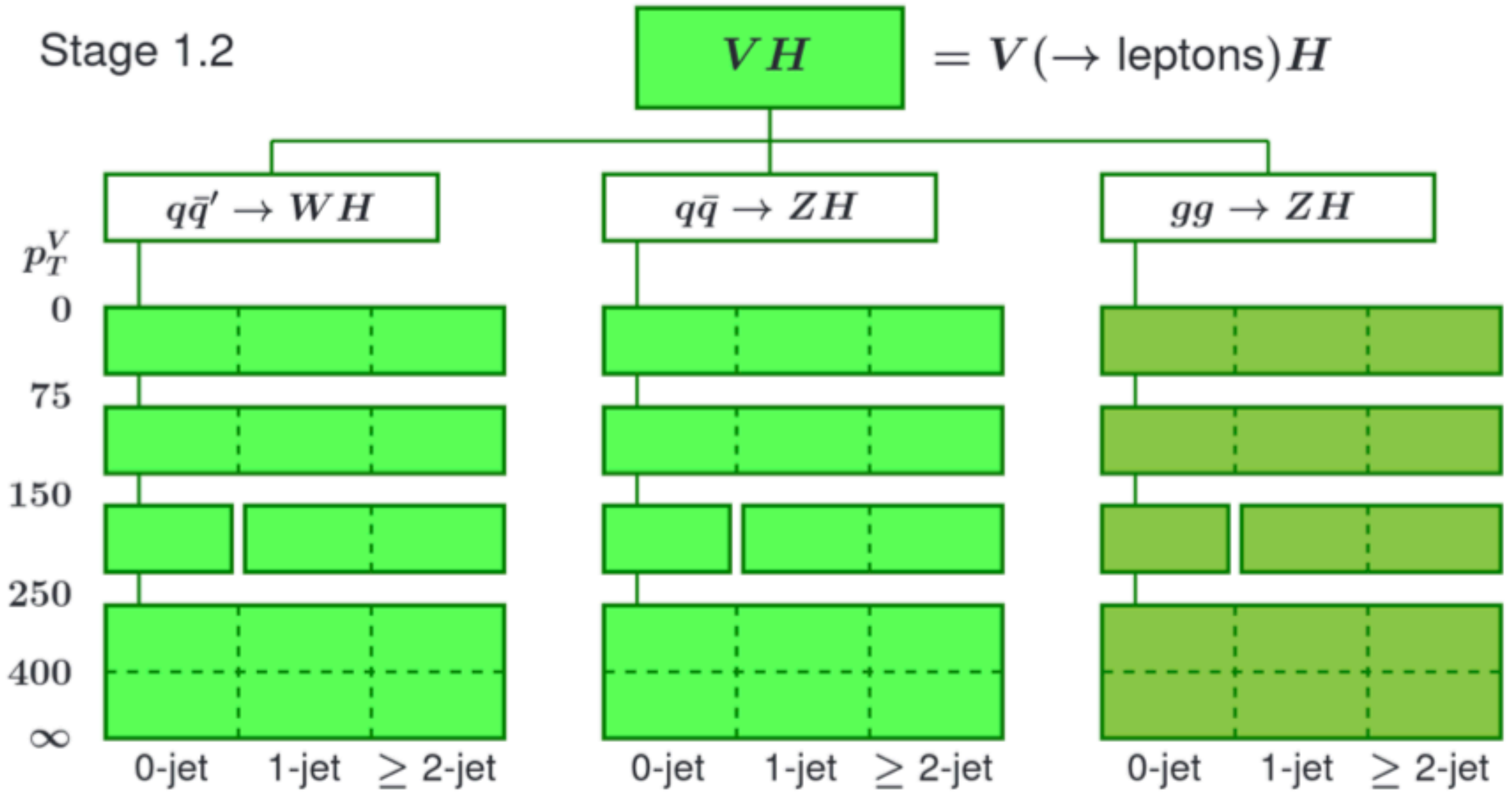


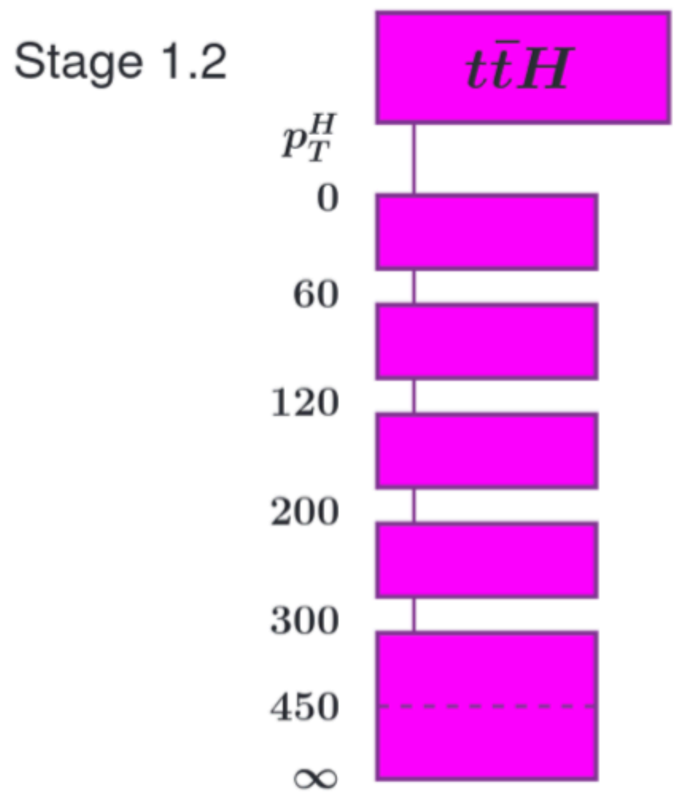
Simplified Template Cross-Sections (STXS)

- Measure cross sections in pre-defined kinematic bins per production mode template with the goal of:
  - Minimize model-dependent extrapolations
  - Maximize experimental sensitivity
  - Possible to isolate and probe certain classes of BSM effects
  - No fiducial phase space (except $|y_H| < 2.5$) → allows combining different decay channels







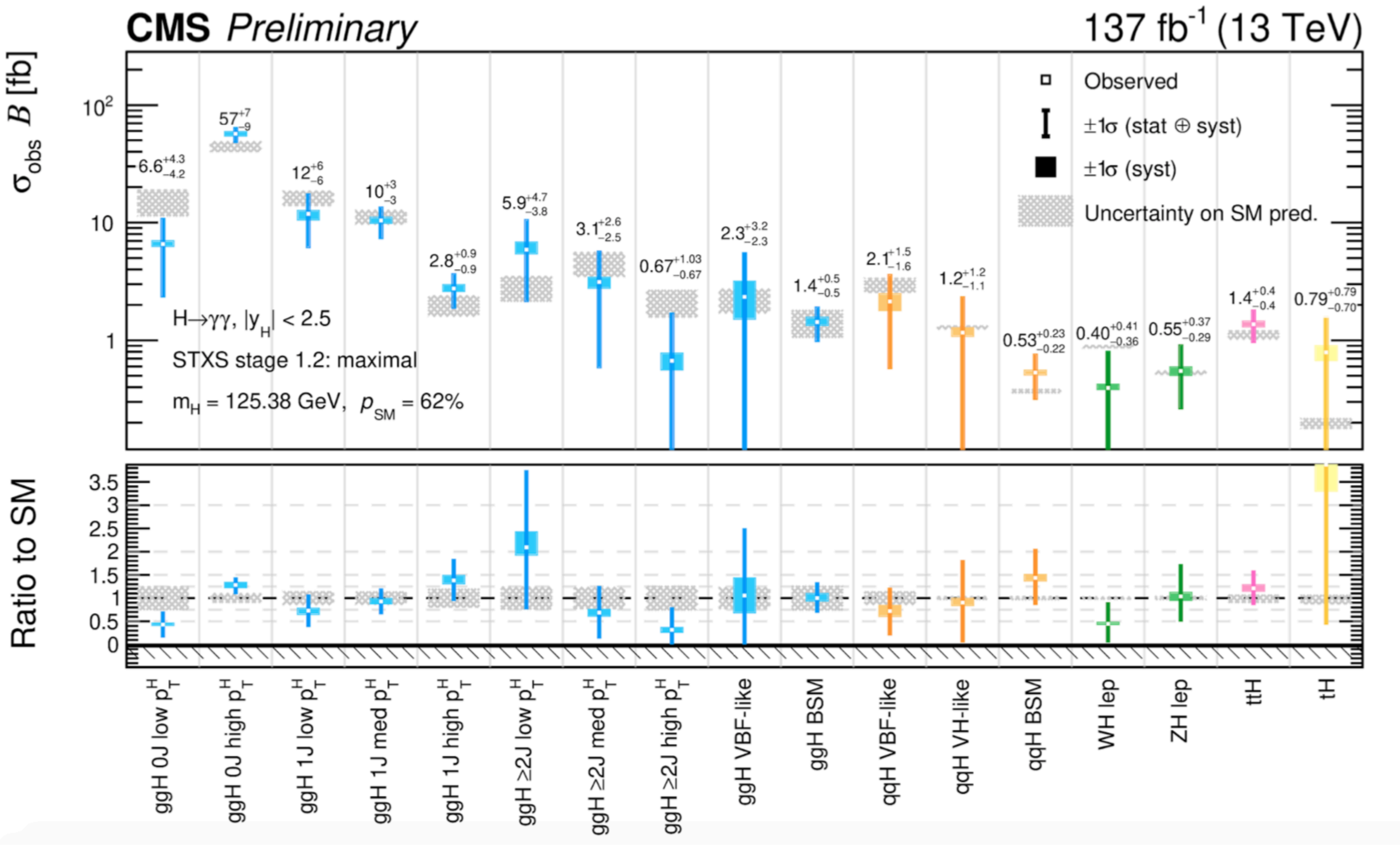


arXiv:1605.04692, arXiv:1906.02754, arXiv:2003.01700

Higgs STXS measurements

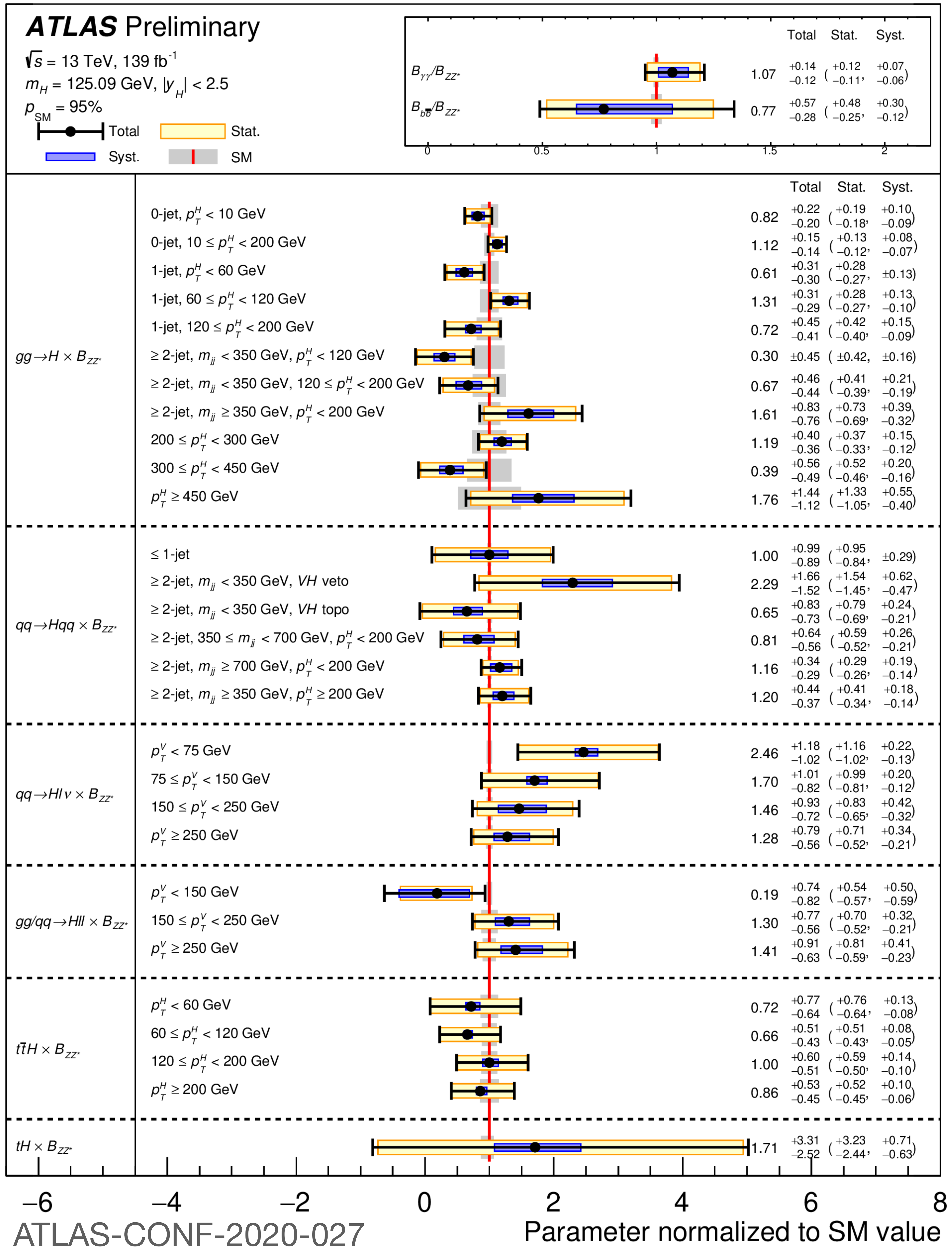
- Good agreement between data and SM so far, in particular in high-p_T BSM-sensitive bins

- CMS γγ



CMS-PAS-HIG-19-015

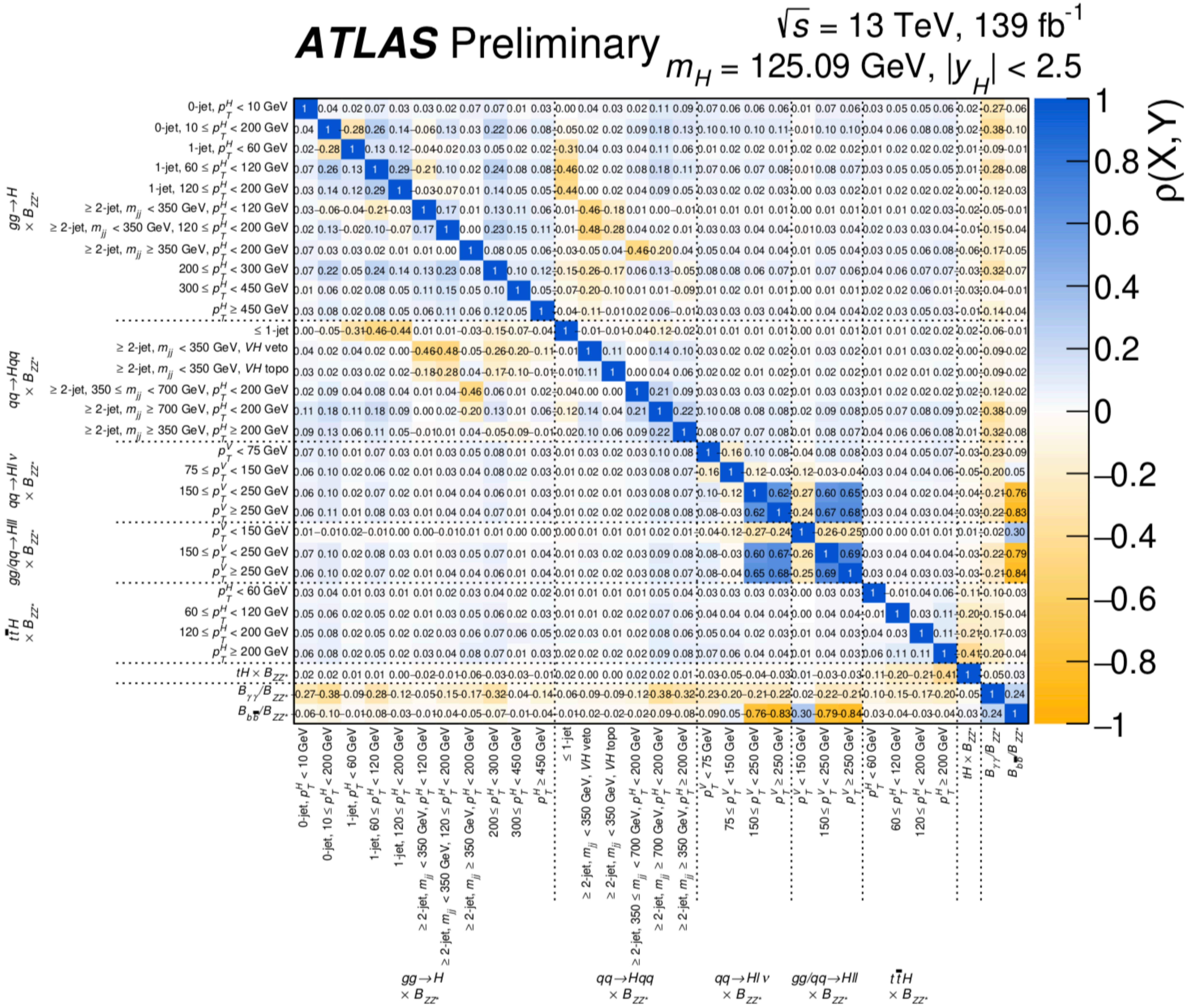
- ATLAS (combination)



ATLAS-CONF-2020-027

Higgs STXS measurements

- Do not forget about (quite spectacular!) correlation matrix



ATLAS-CONF-2020-027

Higgs coupling measurements - the kappa framework

- Parameterisations of Higgs boson production cross-sections and decay widths as a function of coupling strength modifiers using kappa framework
- Considering leading order contributions only
  - Other assumptions are typically made

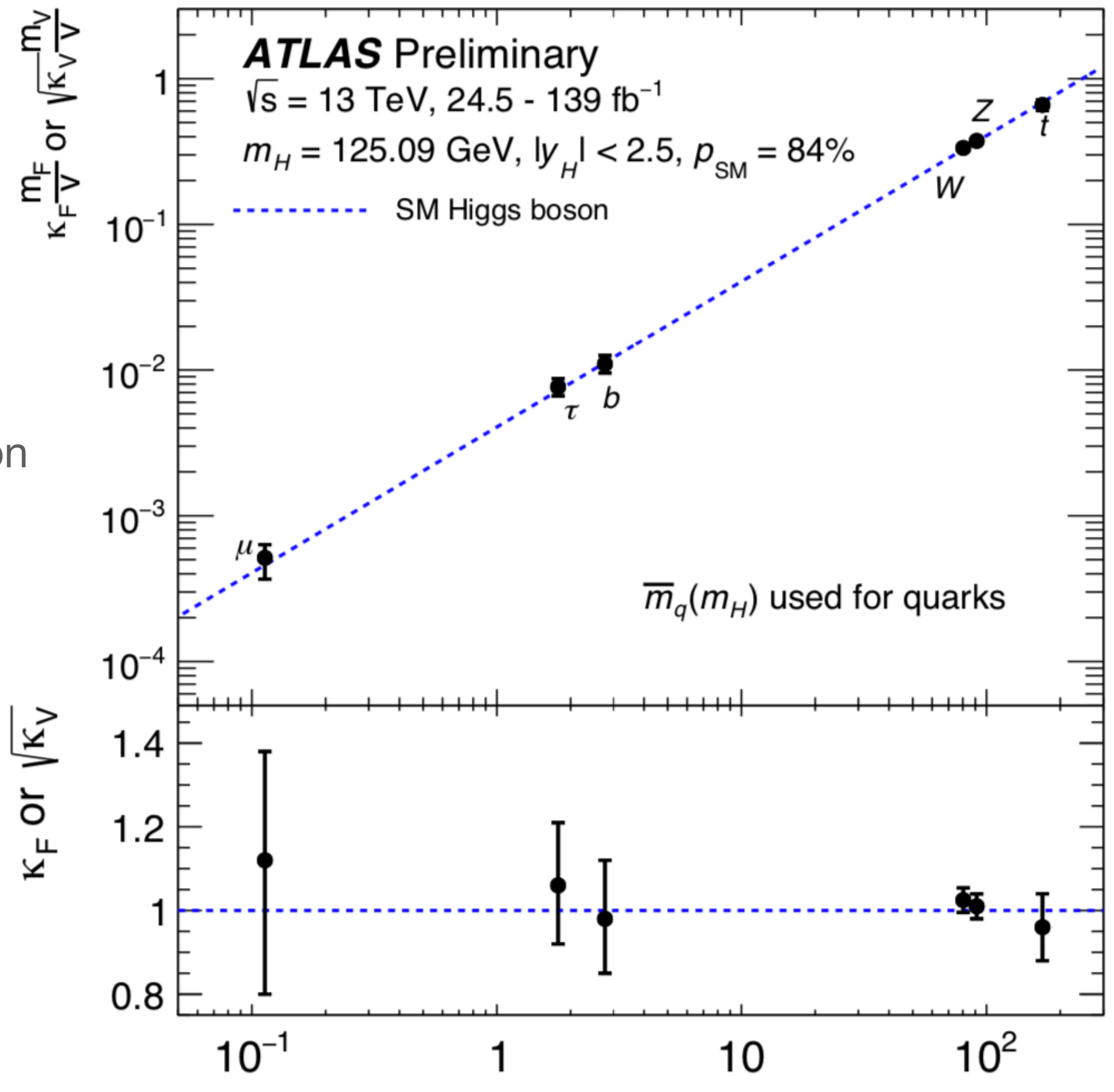
$$\kappa_j^2 = \frac{\sigma_j}{\sigma_j^{\mathrm{SM}}} \quad \text{or} \quad \kappa_j^2 = \frac{\Gamma_j}{\Gamma_j^{\mathrm{SM}}}$$

Production	Loops	Main interference	Effective modifier	Resolved modifier
$\sigma(\mathrm{ggF})$	✓	t–b	κ_g^2	$1.040\,\kappa_t^2 + 0.002\,\kappa_b^2 - 0.038\,\kappa_t\kappa_b - 0.005\,\kappa_t\kappa_c$
$\sigma(\mathrm{VBF})$	-	-	-	$0.733\,\kappa_W^2 + 0.267\,\kappa_Z^2$
$\sigma(qq/qg \to ZH)$	-	-	-	κ_Z^2
$\sigma(gg \to ZH)$	✓	t–Z	$\kappa_{(ggZH)}$	$2.456\,\kappa_Z^2 + 0.456\,\kappa_t^2 - 1.903\,\kappa_Z\kappa_t$ $- 0.011\,\kappa_Z\kappa_b + 0.003\,\kappa_t\kappa_b$
$\sigma(WH)$	-	-	-	κ_W^2
$\sigma(t\bar{t}H)$	-	-	-	κ_t^2
$\sigma(tHW)$	-	t–W	-	$2.909\,\kappa_t^2 + 2.310\,\kappa_W^2 - 4.220\,\kappa_t\kappa_W$
$\sigma(tHq)$	-	t–W	-	$2.633\,\kappa_t^2 + 3.578\,\kappa_W^2 - 5.211\,\kappa_t\kappa_W$
$\sigma(b\bar{b}H)$	-	-	-	κ_b^2
Partial decay width				
Γ^{bb}	-	-	-	κ_b^2
Γ^{WW}	-	-	-	κ_W^2
Γ^{gg}	✓	t–b	κ_g^2	$1.111\,\kappa_t^2 + 0.012\,\kappa_b^2 - 0.123\,\kappa_t\kappa_b$
$\Gamma^{\tau\tau}$	-	-	-	κ_τ^2
Γ^{ZZ}	-	-	-	κ_Z^2
Γ^{cc}	-	-	-	$\kappa_c^2\ (= \kappa_t^2)$
$\Gamma^{\gamma\gamma}$	✓	t–W	κ_γ^2	$1.589\,\kappa_W^2 + 0.072\,\kappa_t^2 - 0.674\,\kappa_W\kappa_t$ $+0.009\,\kappa_W\kappa_\tau + 0.008\,\kappa_W\kappa_b$ $-0.002\,\kappa_t\kappa_b - 0.002\,\kappa_t\kappa_\tau$
$\Gamma^{Z\gamma}$	✓	t–W	$\kappa_{(Z\gamma)}^2$	$1.118\,\kappa_W^2 - 0.125\,\kappa_W\kappa_t + 0.004\,\kappa_t^2 + 0.003\,\kappa_W\kappa_b$
Γ^{ss}	-	-	-	$\kappa_s^2\ (= \kappa_b^2)$
$\Gamma^{\mu\mu}$	-	-	-	κ_μ^2
Total width ($B_{\mathrm{i.}} = B_{\mathrm{u.}} = 0$)				
Γ_H	✓	-	κ_H^2	$0.581\,\kappa_b^2 + 0.215\,\kappa_W^2 + 0.082\,\kappa_g^2$ $+0.063\,\kappa_\tau^2 + 0.026\,\kappa_Z^2 + 0.029\,\kappa_c^2$ $+0.0023\,\kappa_\gamma^2 + 0.0015\,\kappa_{(Z\gamma)}^2$ $+0.0004\,\kappa_s^2 + 0.00022\,\kappa_\mu^2$

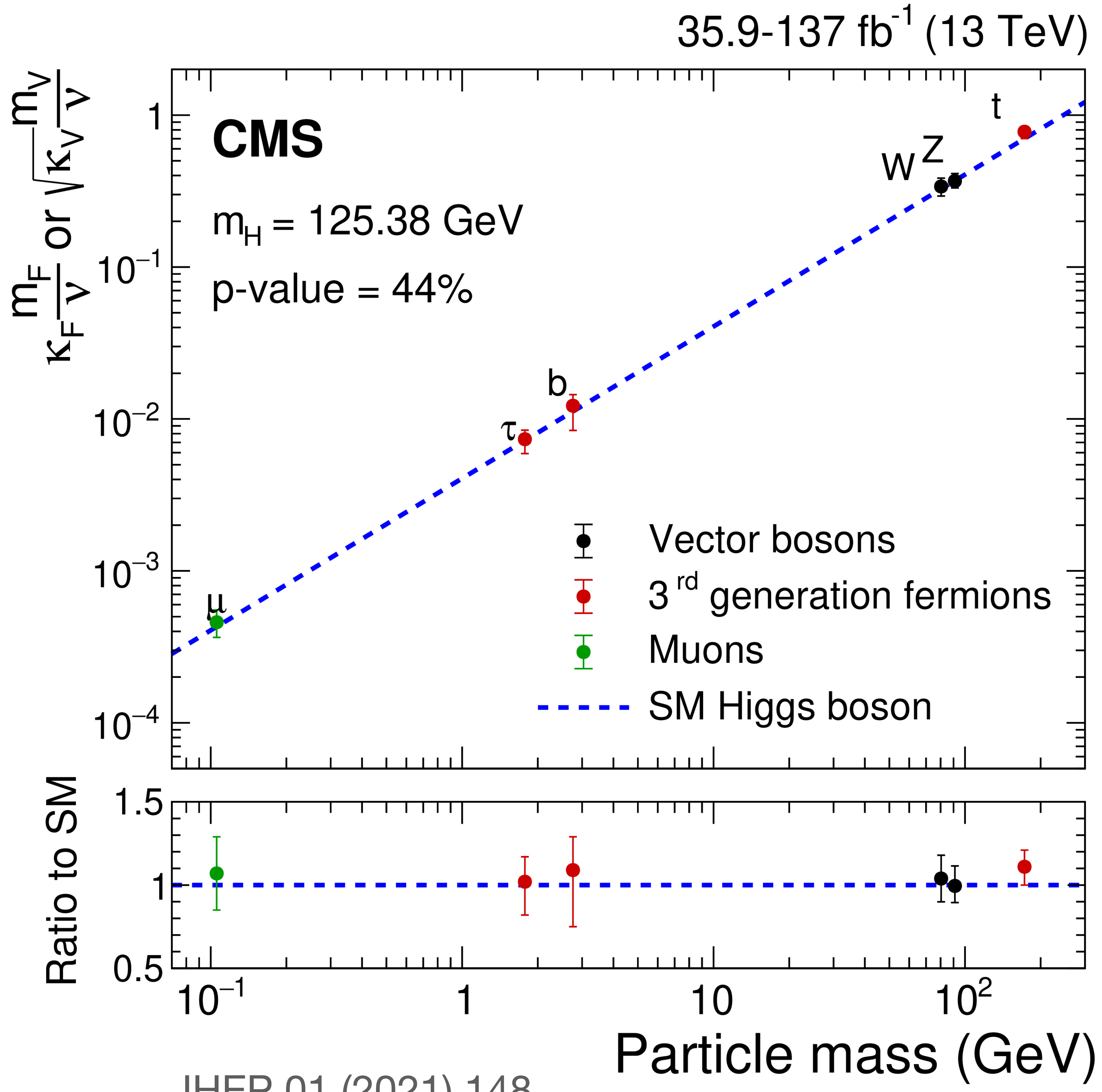
Higgs coupling measurements

- ATLAS and CMS have performed global fit of coupling modifiers (using kappa framework)
  - ~6% uncertainty on Higgs to vector boson couplings
  - ~10-15% uncertainty on Higgs to the 3rd generation fermion couplings

Footprint of SM Higgs boson: mass versus coupling correlation



ATLAS-CONF-2020-027



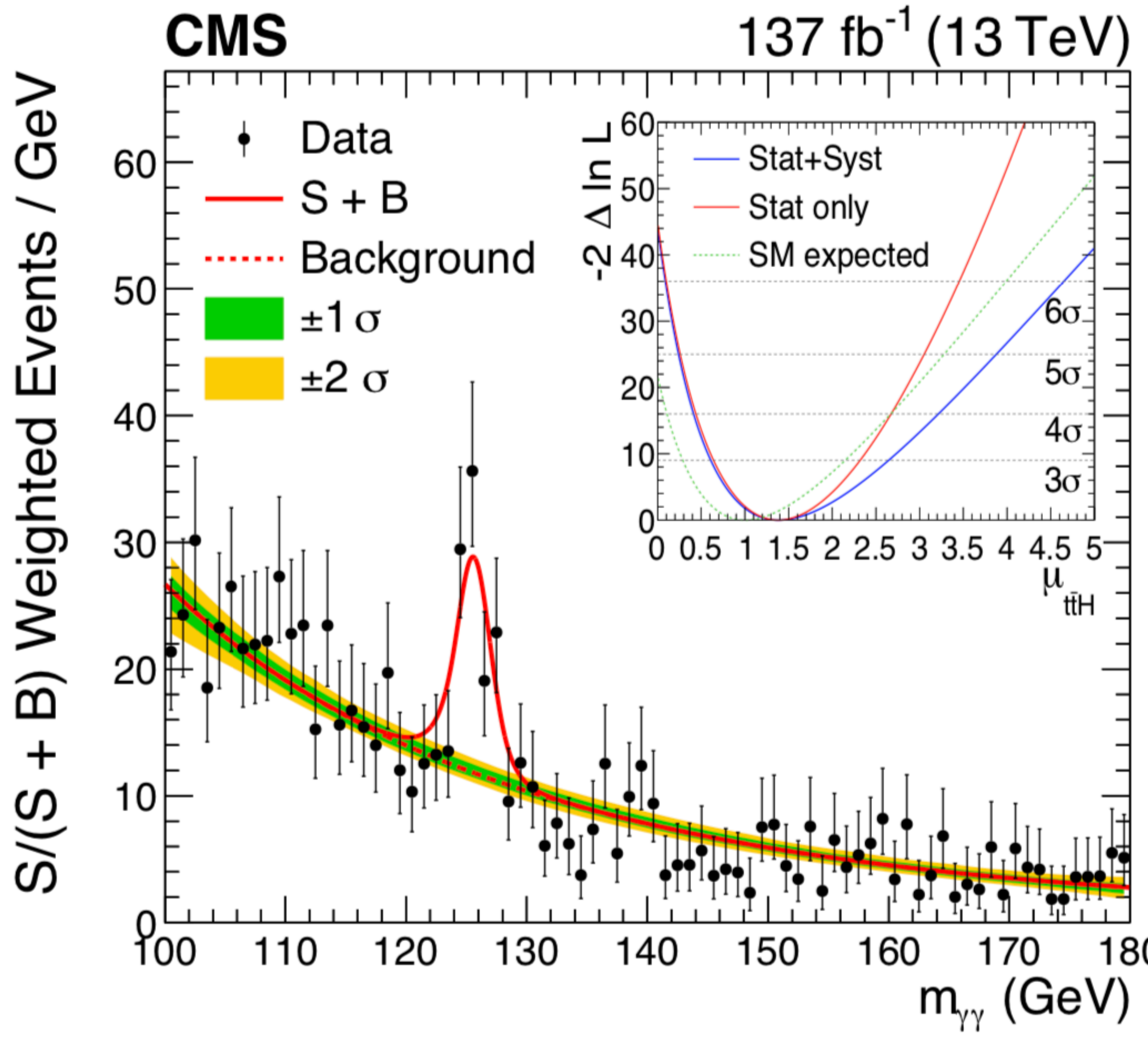
JHEP 01 (2021) 148

Measurements of CP structure of Higgs boson couplings

- With full Run 2 dataset, both ATLAS & CMS have observed **ttH in H→γγ** channel

PRL125 (2020) 061802 (ATLAS)
PRL125 (2020) 061801 (CMS)

  - This reaction is used to probe **CP mixing in top-Yukawa coupling**
  - The data disfavour **pure CP-odd** model of **Htt** coupling at **3.9σ** and **3.2σ** from ATLAS and CMS



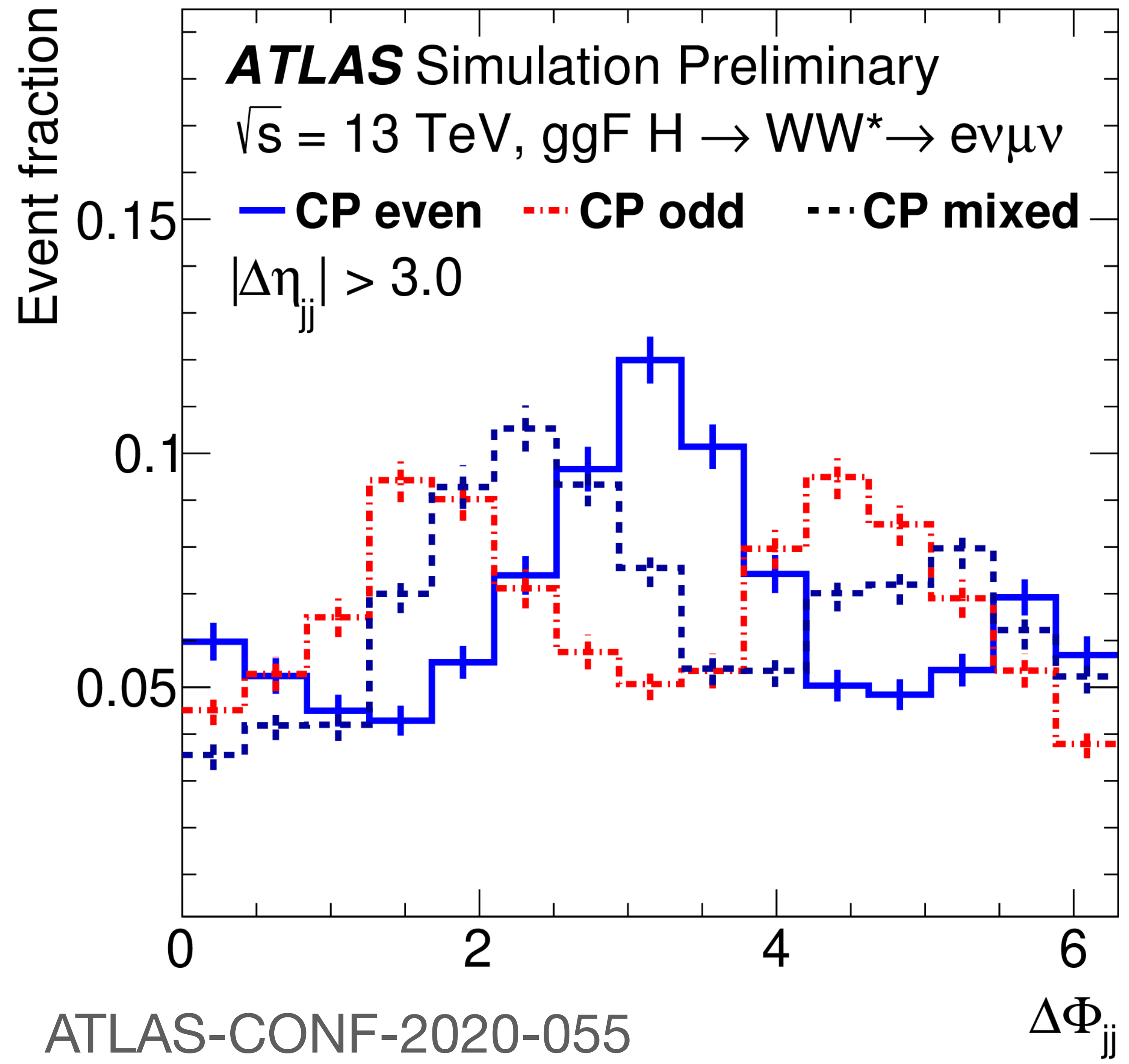
- **(H→WW)+jj** production is used by ATLAS to:
  - Constrain CP properties of the **effective Hgg vertex** (in ggF): ratio of CP-odd to CP-even coupling strength scale factors is measured to be **0.0 ±0.4(stat) ±0.3(syst)**
  - Access Higgs couplings to **longitudinally** and **transversely** polarised **W** and **Z** bosons in VBF process:

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

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

$$a_L = \frac{g_{HV_LV_L}}{g_{HVV}}, \quad a_T = \frac{g_{HV_TV_T}}{g_{HVV}}$$

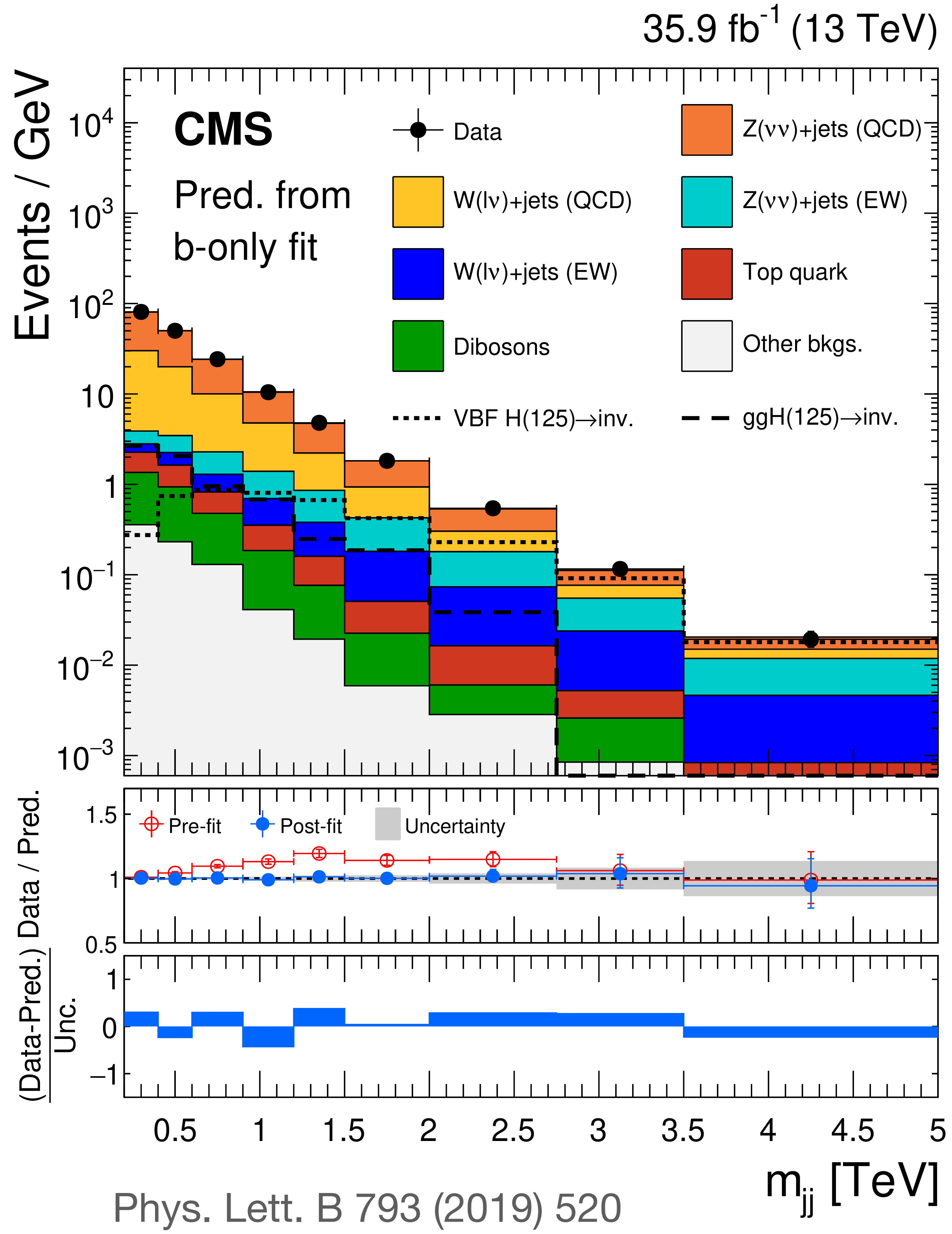
(results consistent with the SM predictions)



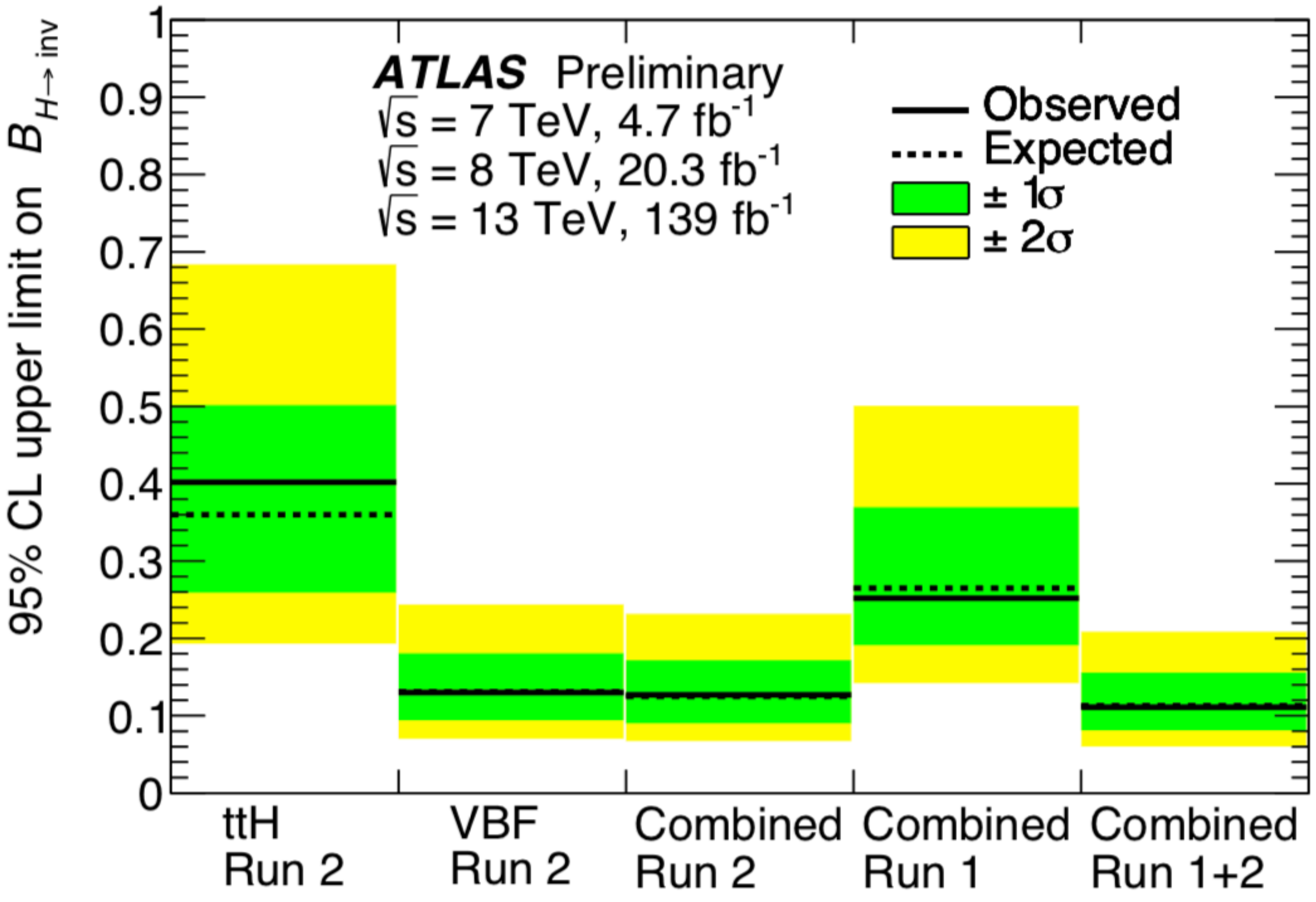
ATLAS-CONF-2020-055

Higgs to invisible searches

- Searches have been performed in VBF, ttH and VH channels in both ATLAS and CMS
  - Observed upper limit **B(H → inv.) = 0.11** (95% CL) from recent ATLAS combination



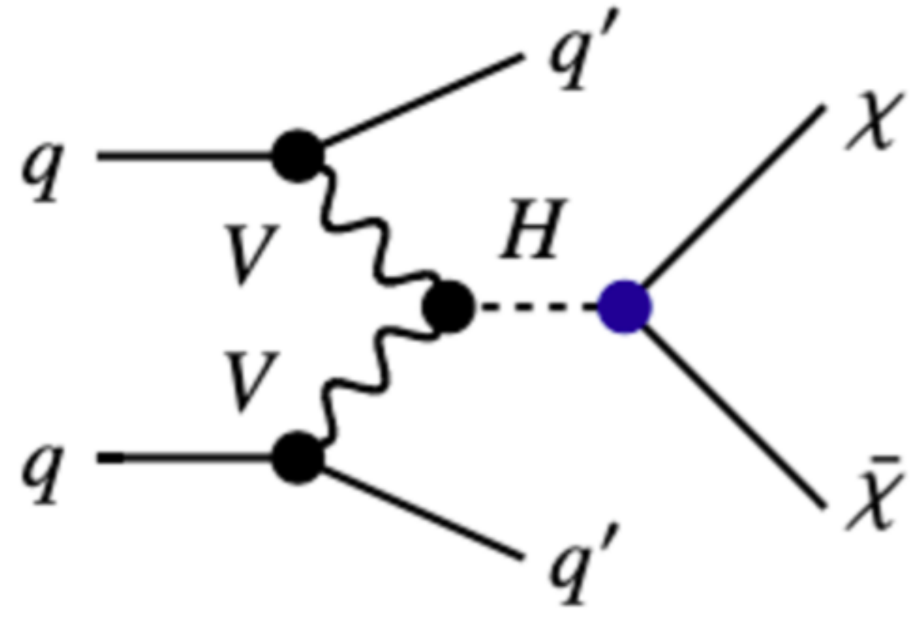
Phys. Lett. B 793 (2019) 520

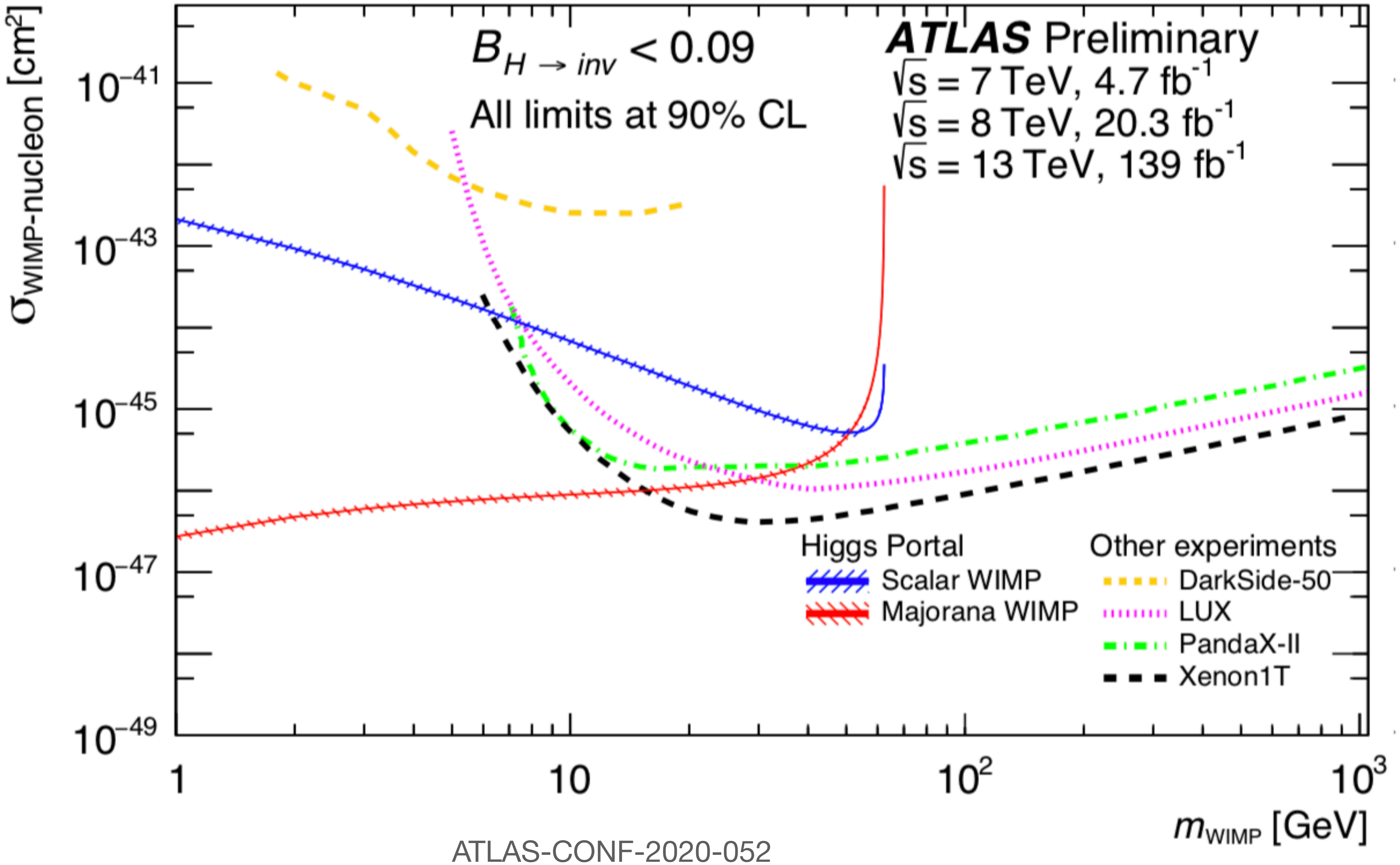


ATLAS-CONF-2020-052

Higgs to invisible searches

- Higgs to invisible is sensitive to BSM phenomena that can be recast in Dark Matter (DM) limits under certain assumptions (Higgs portal scenarios)
  - LHC provides the best limit for low-mass DM in model-specific scenarios



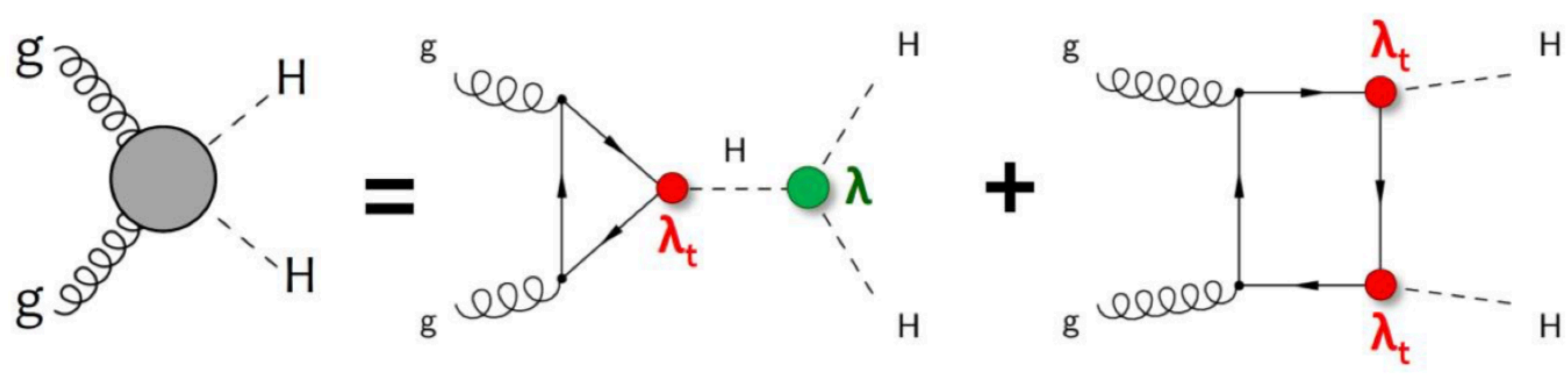


ATLAS-CONF-2020-052

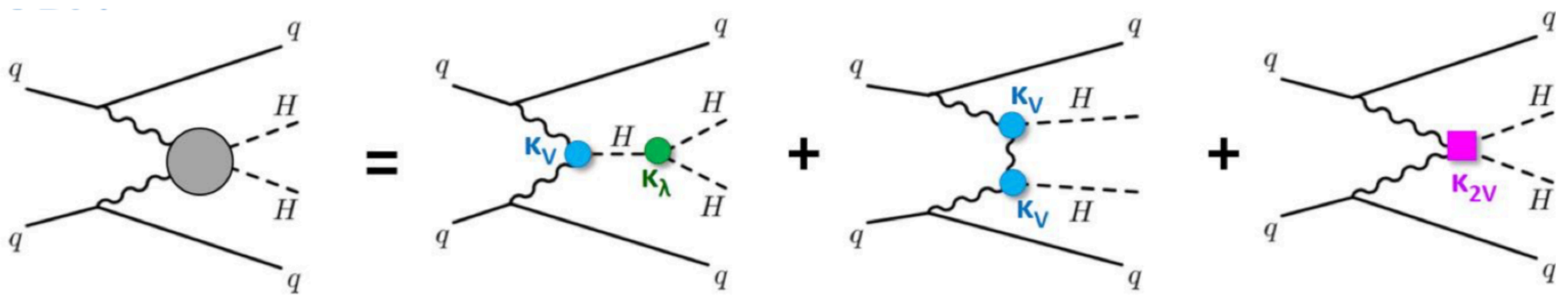
Di-Higgs production

- HH production at the LHC is dominated by the ggF process, followed by VBF production

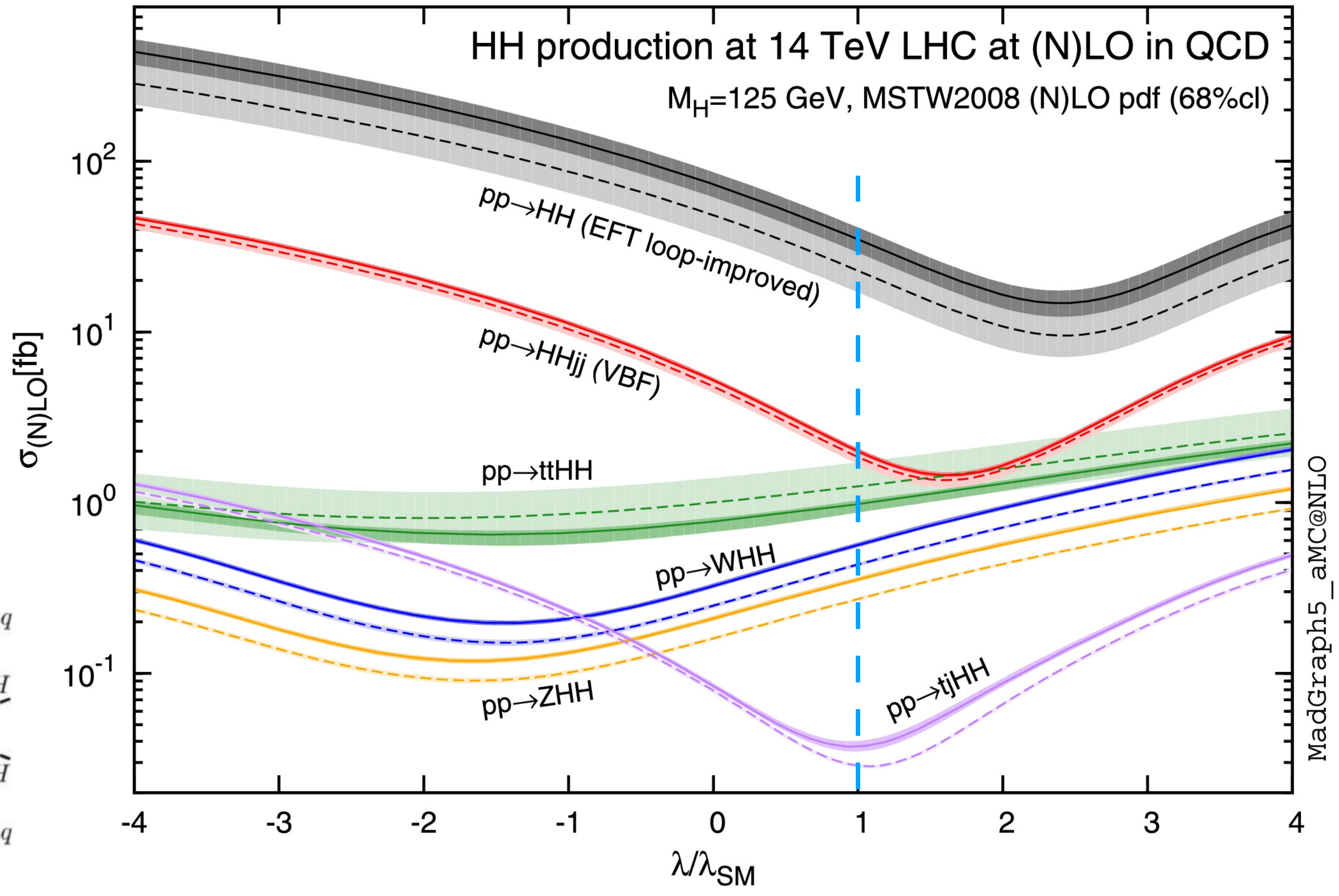
Diagrams from G. Petrucciani



Destructive interference leads to decrease in ggF cross section near SM value



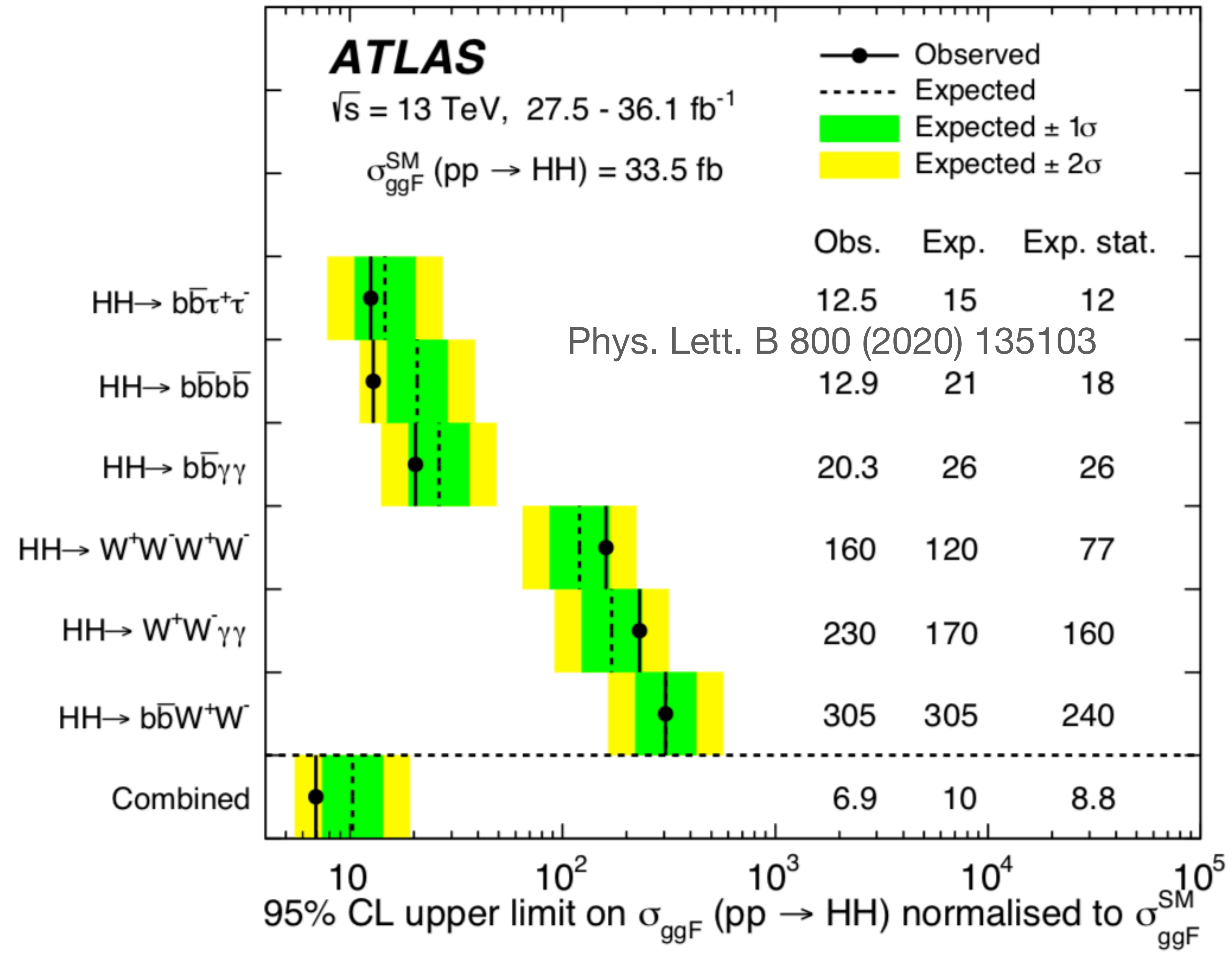
PLB 732 (2014) 142-149



VBF channel offers access to the **HHVV quartic coupling** (not present in ggF production).
Here also cancellations lead to decreasing cross section.

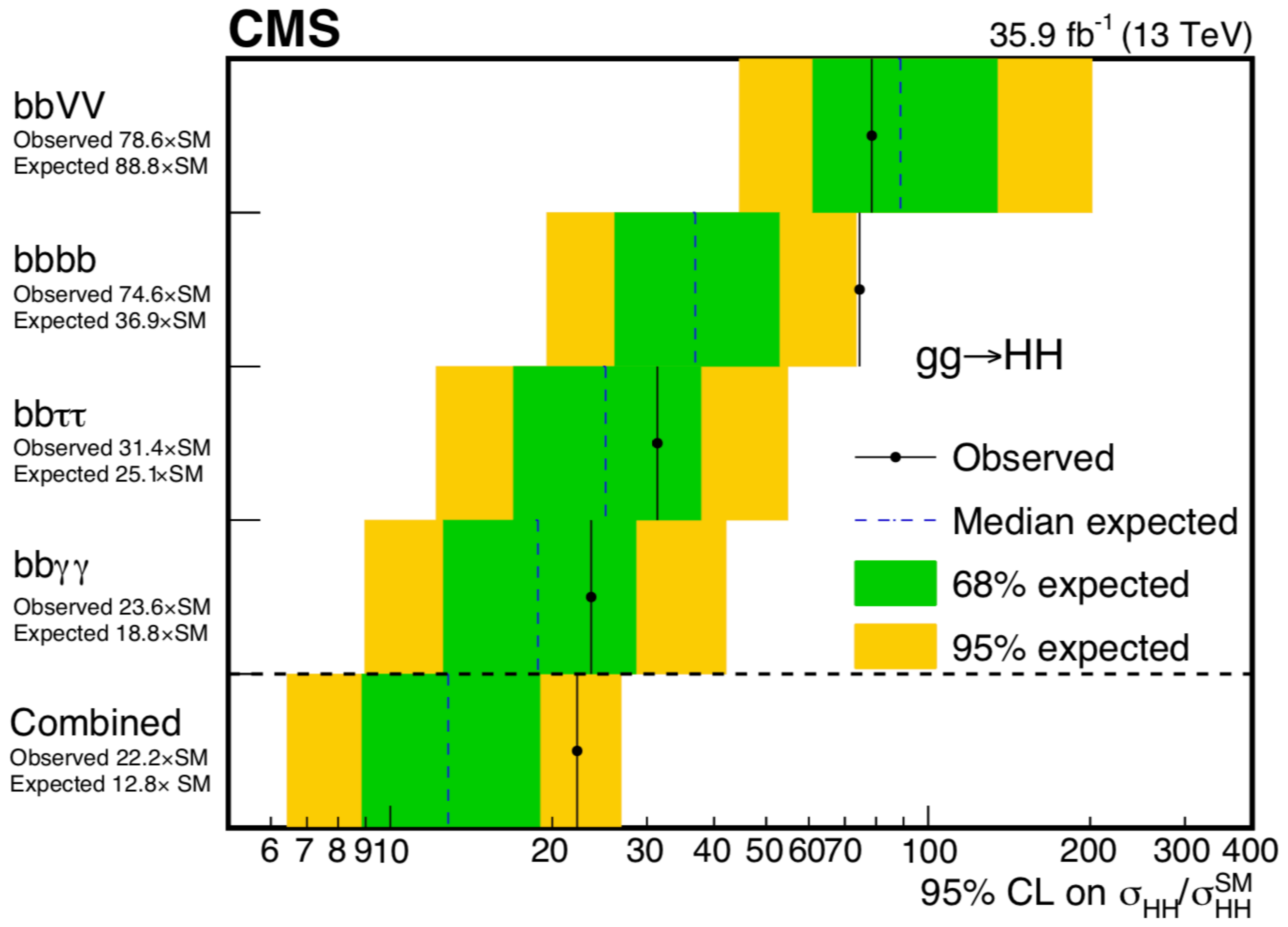
Search for di-Higgs production

- Early Run 2 results (36 fb^{-1}) focused on ggF production
- Limits on cross section and self-coupling were obtained
  - $\sigma_{HH}/\sigma_{HH}(SM)$: < 6.9 (ATLAS), < 22 (CMS)
  - **$\kappa_\lambda = \lambda/\lambda_{SM}$ ∈ [-5, 12]** (ATLAS), **[-12, 19]** (CMS)



Phys. Lett. B 800 (2020) 135103

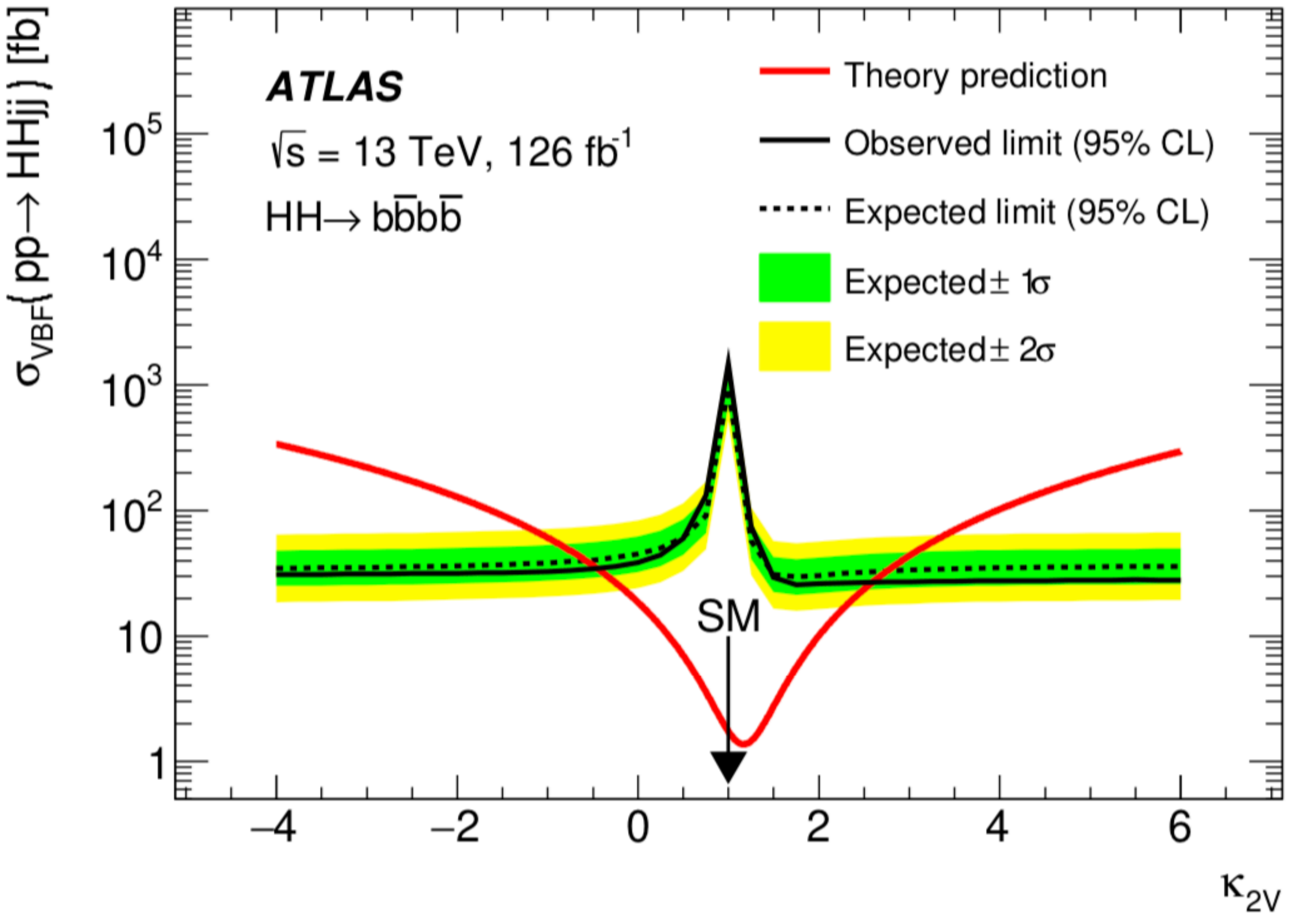
Phys. Rev. Lett. 122 (2019) 121803

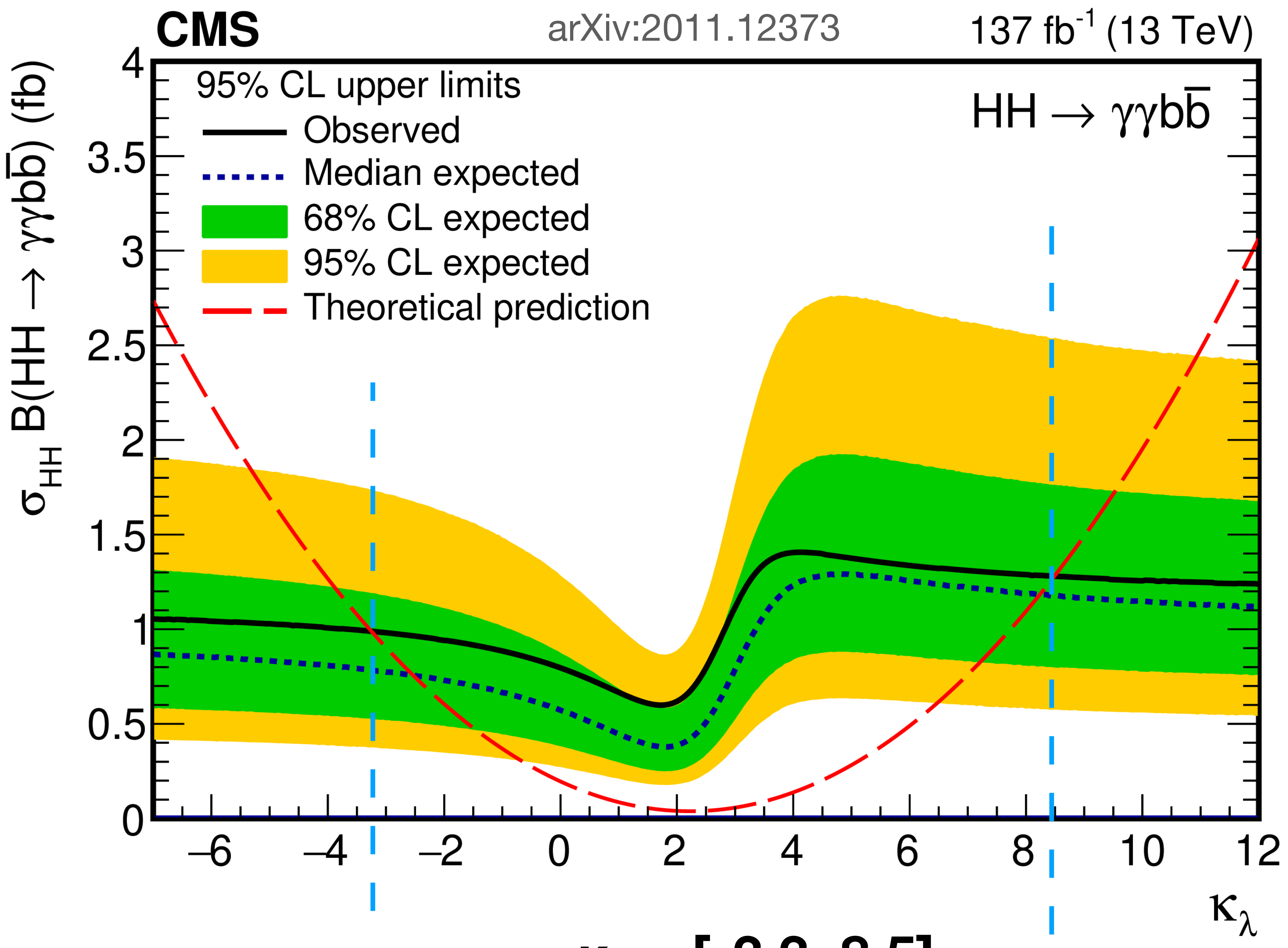


Search for di-Higgs production

- Recent HH searches with full Run 2 data
  - Constraints on κ_{2V} : **$-0.76 < \kappa_{2V} < 2.90$** (ATLAS bbbb), **$-1.3 < \kappa_{2V} < 3.5$** (CMS γγbb)
  - New CMS bbγγ result with full Run 2 luminosity:
    $\sigma_{HH} \times B(HH \rightarrow \gamma\gamma bb) <$ **7.7 (5.2) obs. (exp.) times SM prediction**

JHEP 07 (2020) 108

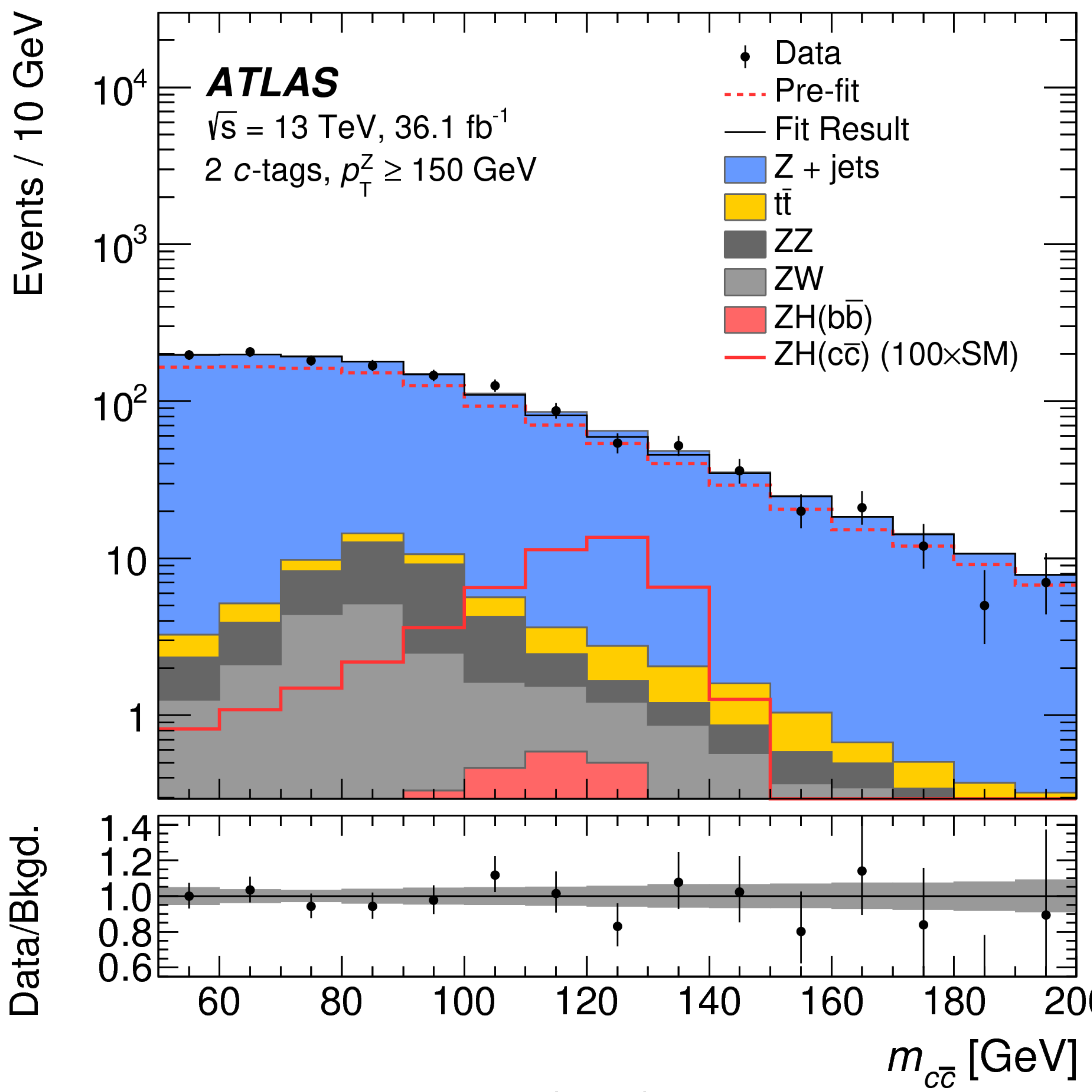




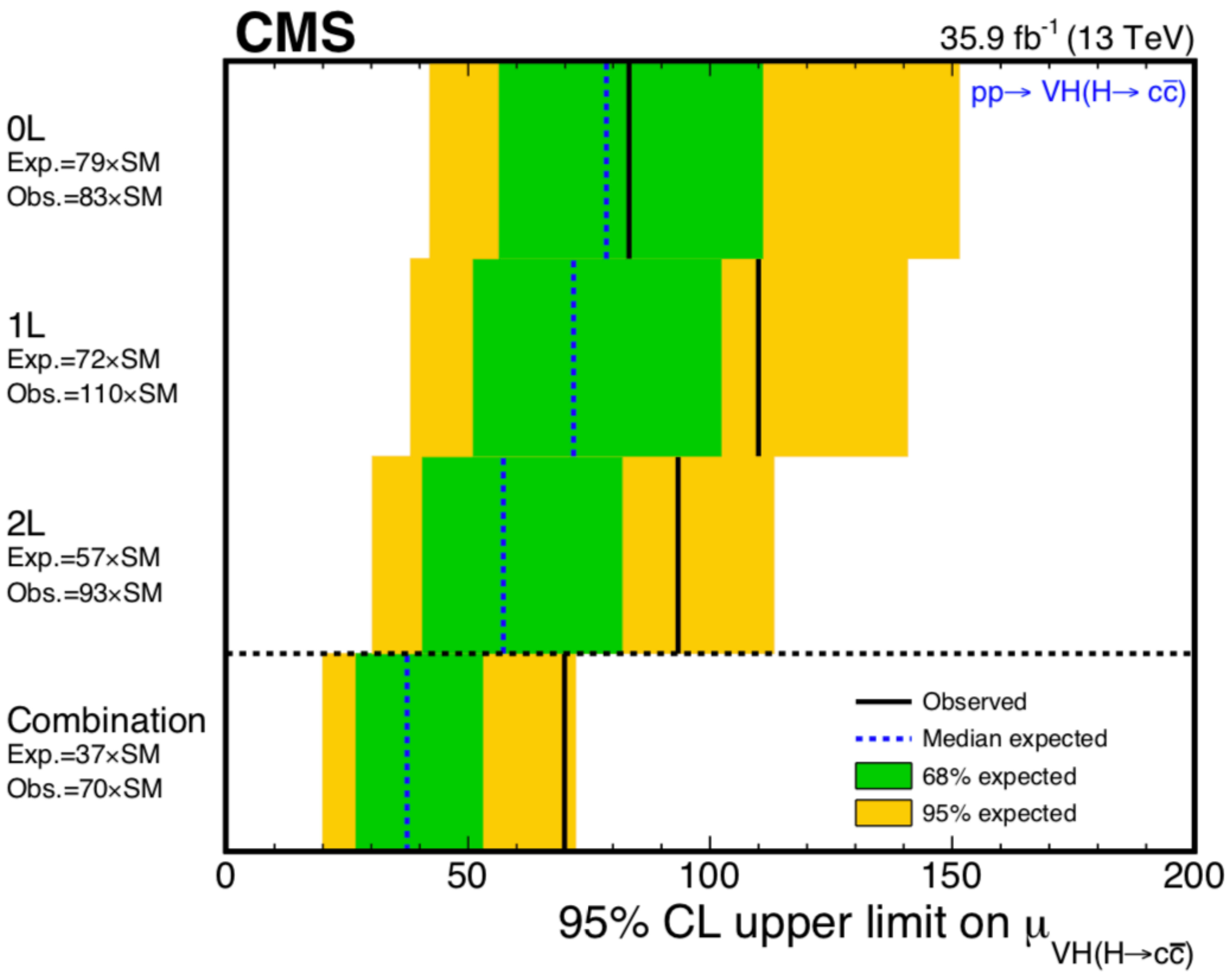
- **$\kappa_\lambda \in [-3.3, 8.5]$**

Search for H→cc decay

- Very challenging channel, large background from H→bb, c-tagging is critical
- Latest CMS search with 35.9 fb^{-1}: **σ/σ(SM) < 70 (37)** obs. (exp.)



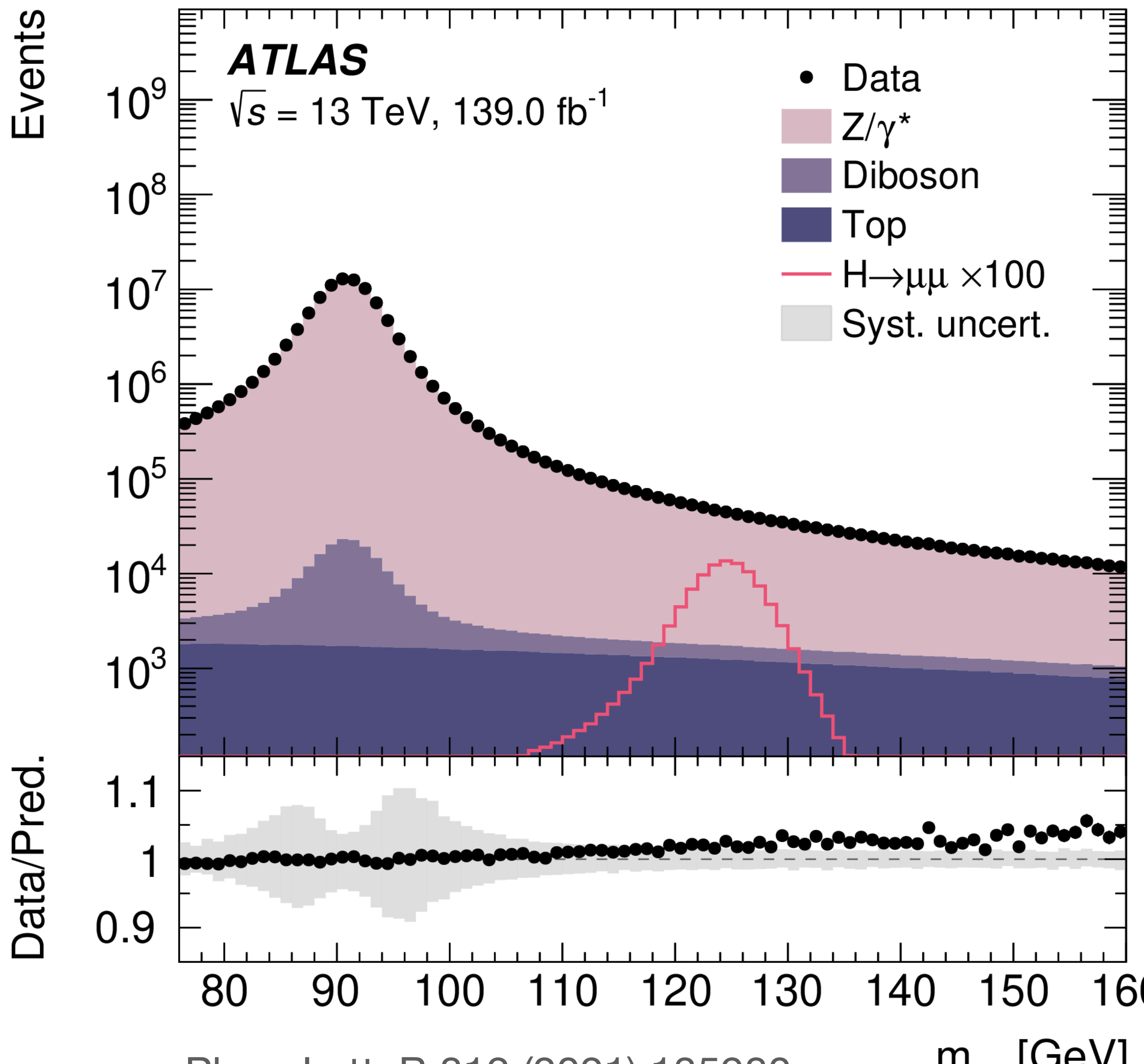
Phys. Rev. Lett. 120 (2018) 211802



JHEP 03 (2020) 131

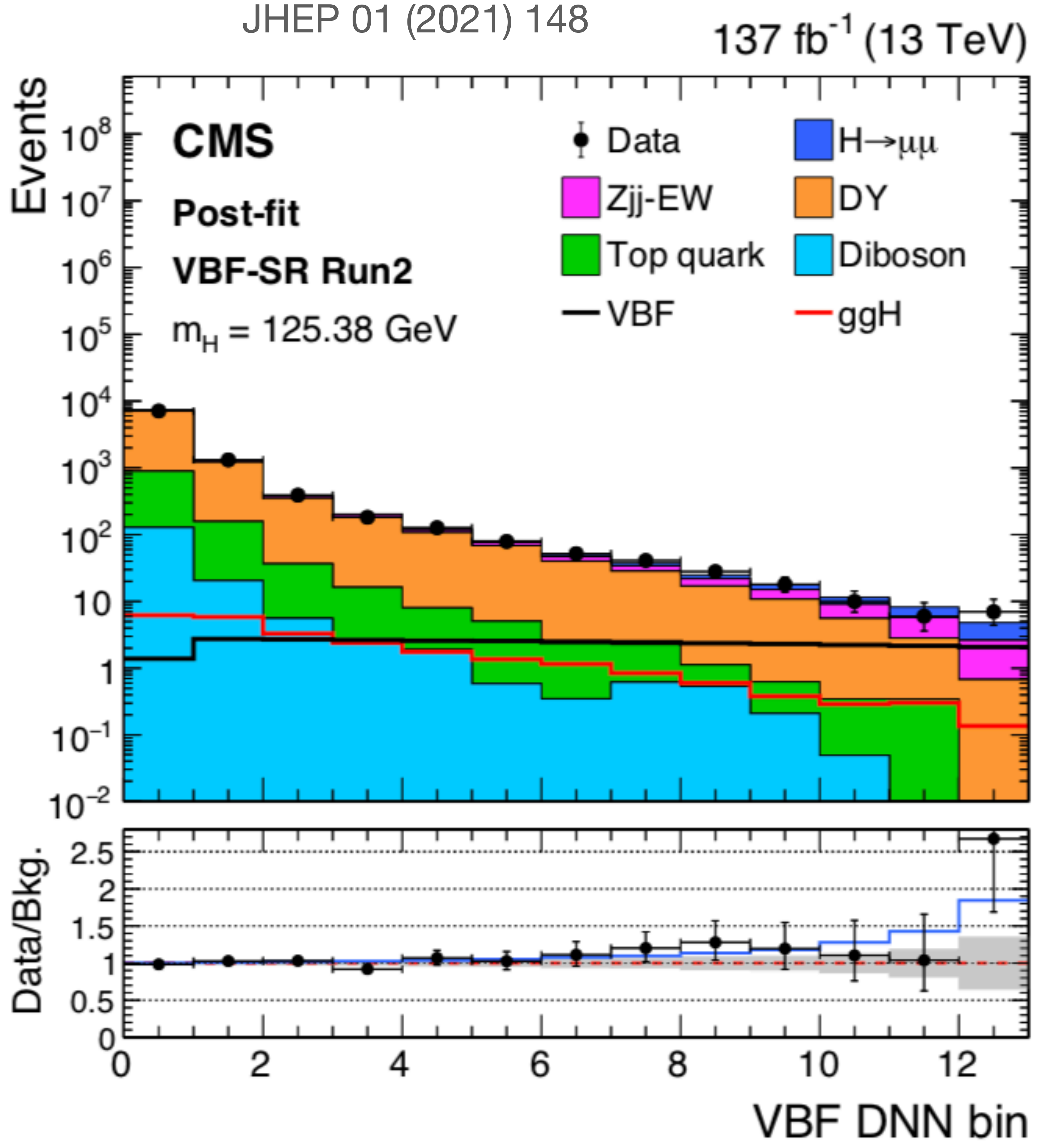
Evidence for H→μμ decay channel

- Very rare decay channel: **B(H→μμ) = 2.2 ×10^{-4}**
- Huge Drell-Yan background to "beat"
  - Signal extraction by topology of production mode
  - Use machine learning techniques to increase sensitivity



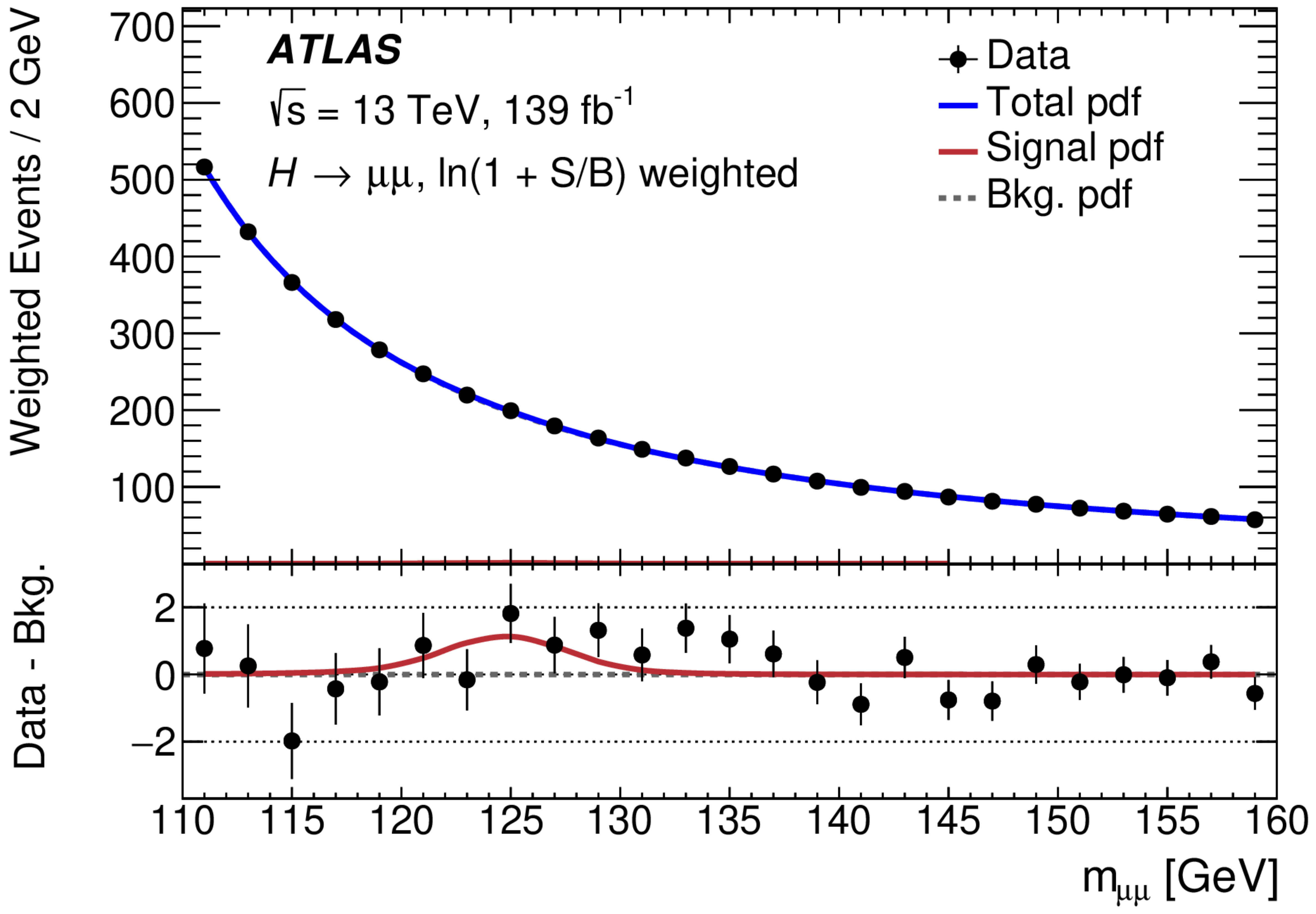
Phys. Lett. B 812 (2021) 135980

JHEP 01 (2021) 148

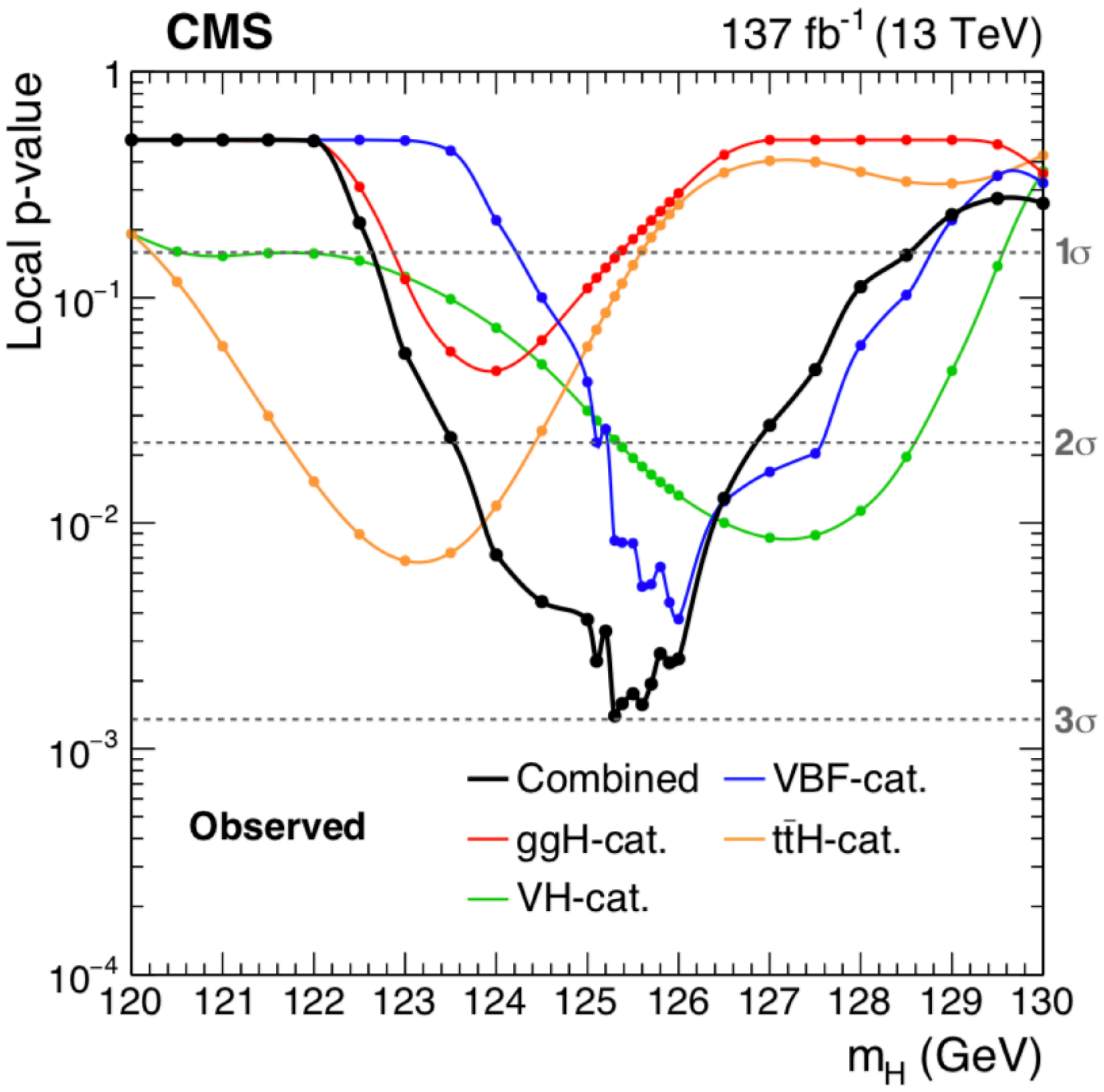


Evidence for H→μμ decay channel

- ATLAS result: **2.0σ** (1.7σ) obs. (exp.) significance, measured **μ = 1.2 ± 0.6**
- CMS result: **3.0σ** (2.5σ) obs. (exp.), **μ = 1.19 ±0.40 (stat) ±0.15 (syst)**



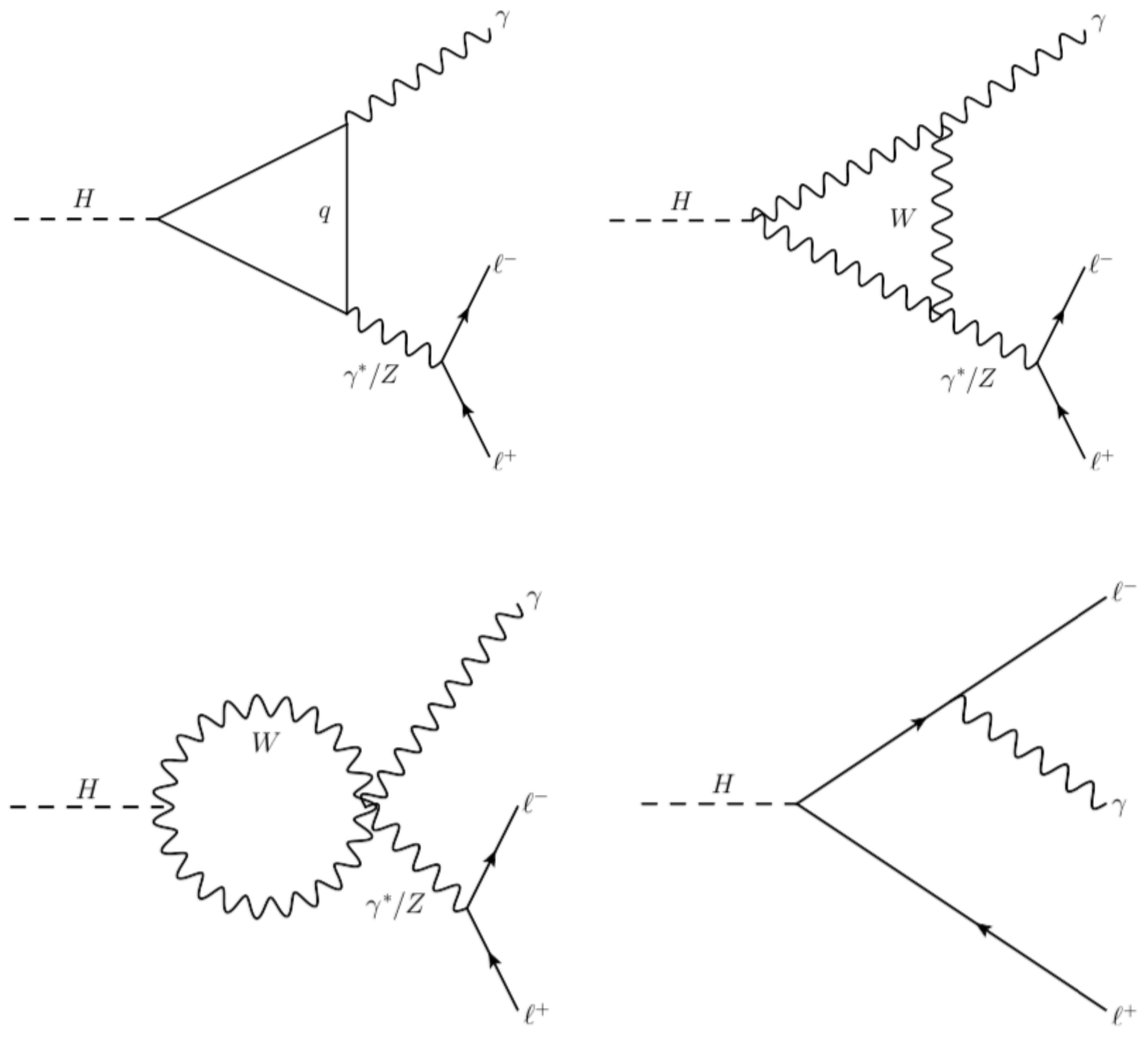
Phys. Lett. B 812 (2021) 135980

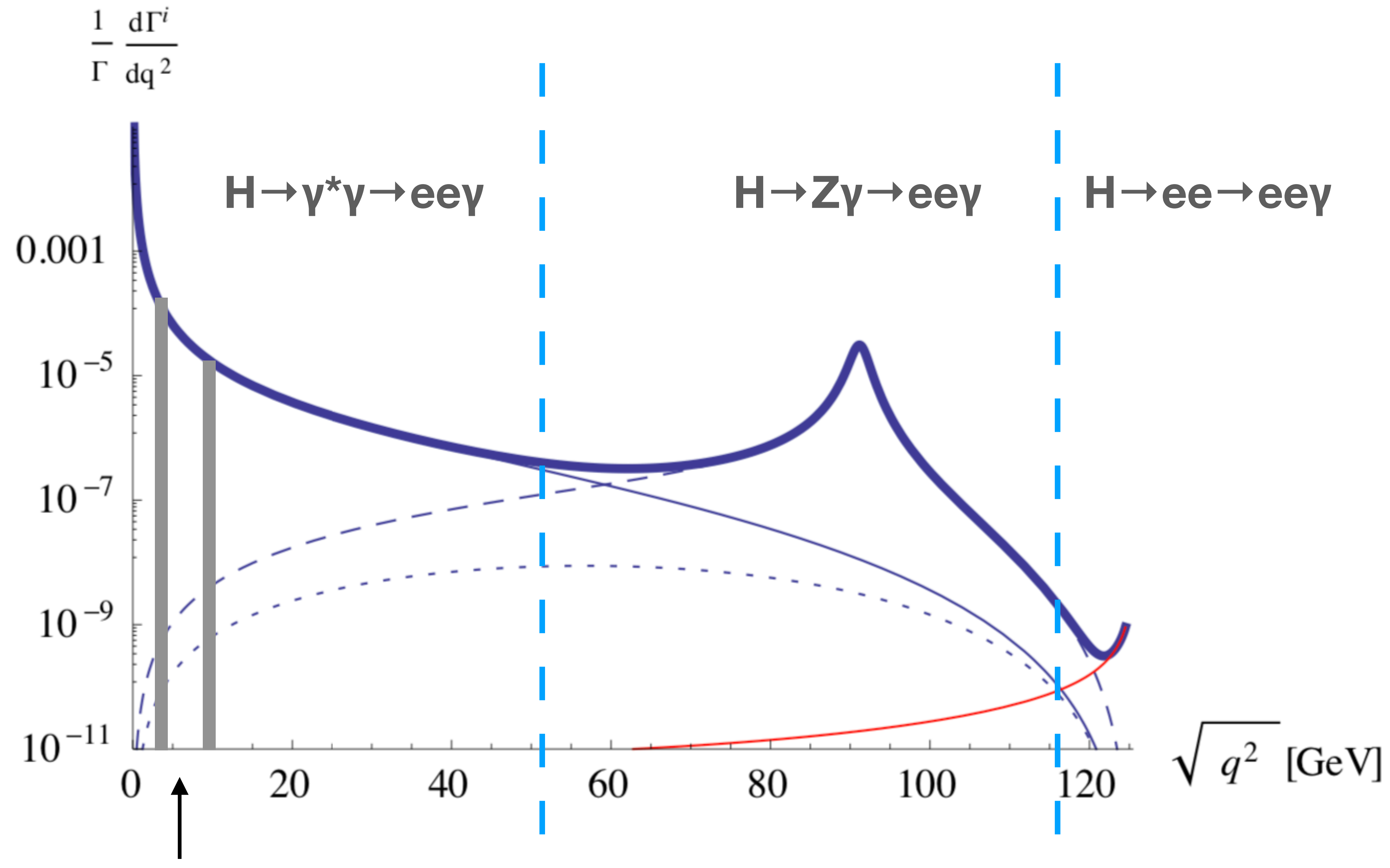


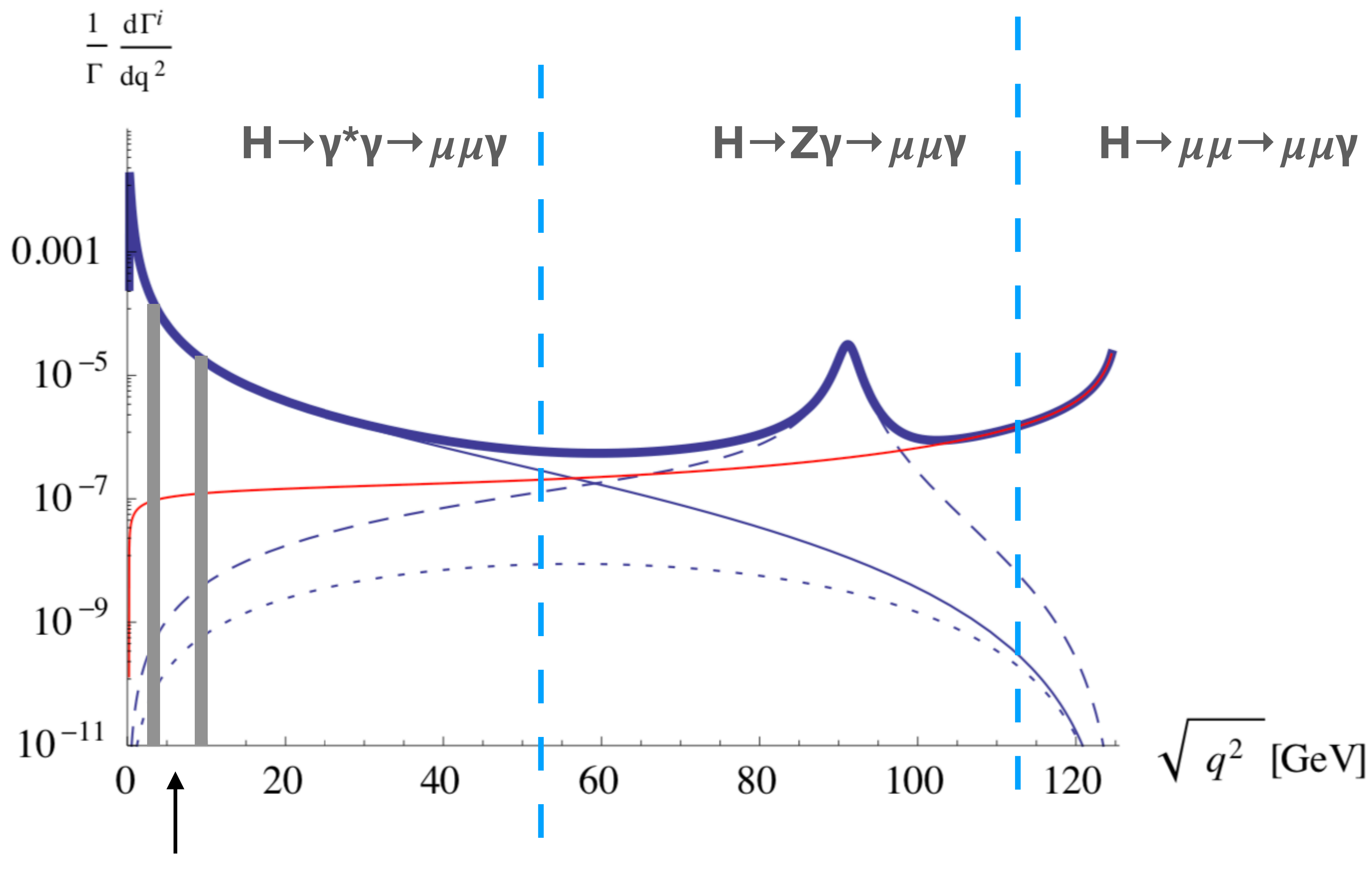
JHEP 01 (2021) 148

Search for H→llγ decays

- Very rare process
- Several processes contribute to the final state
  - BSM sensitivity through loops
- Diverse final state kinematics
  - Dedicated analyses are typically performed for each region of phase-space



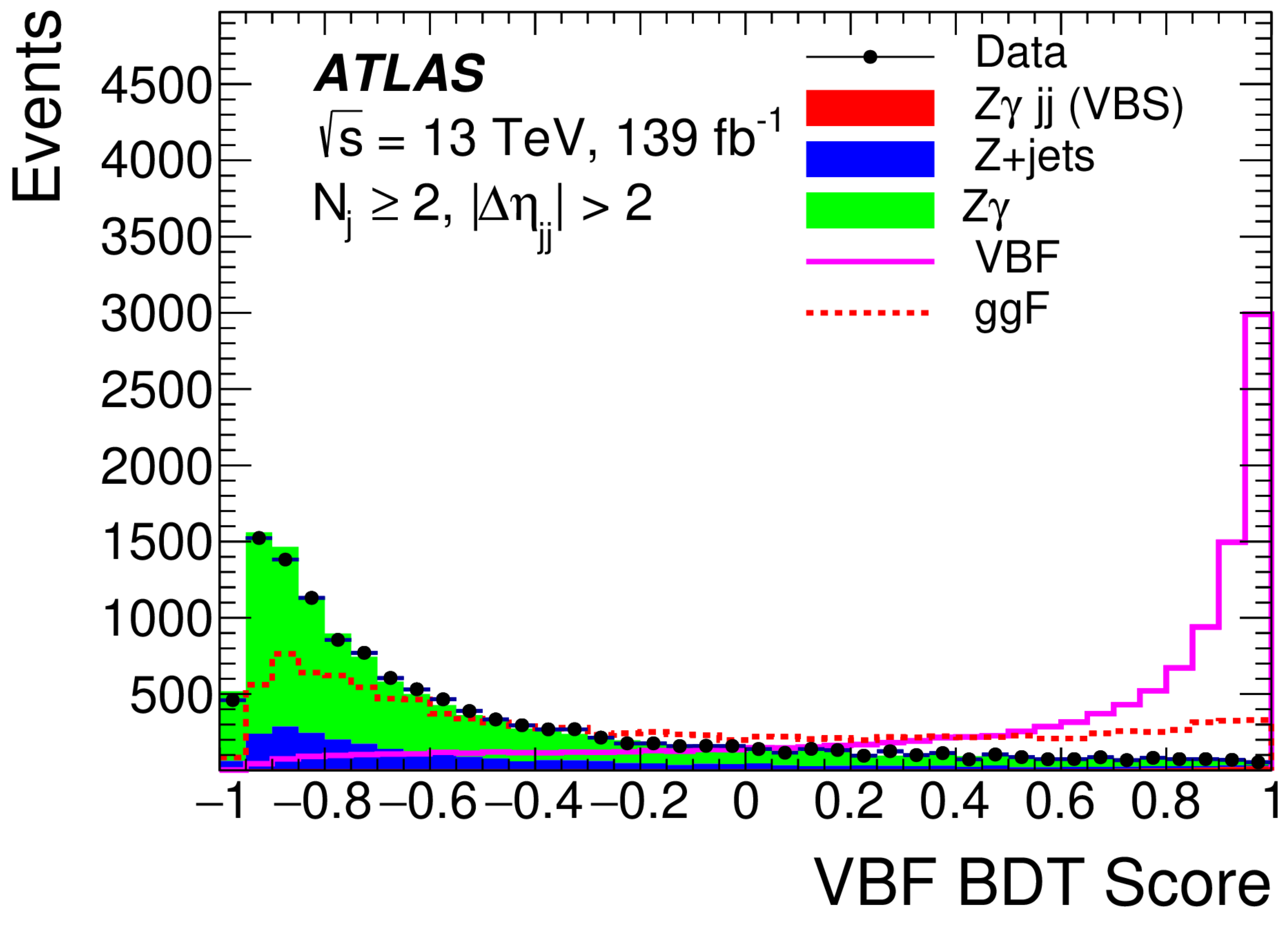


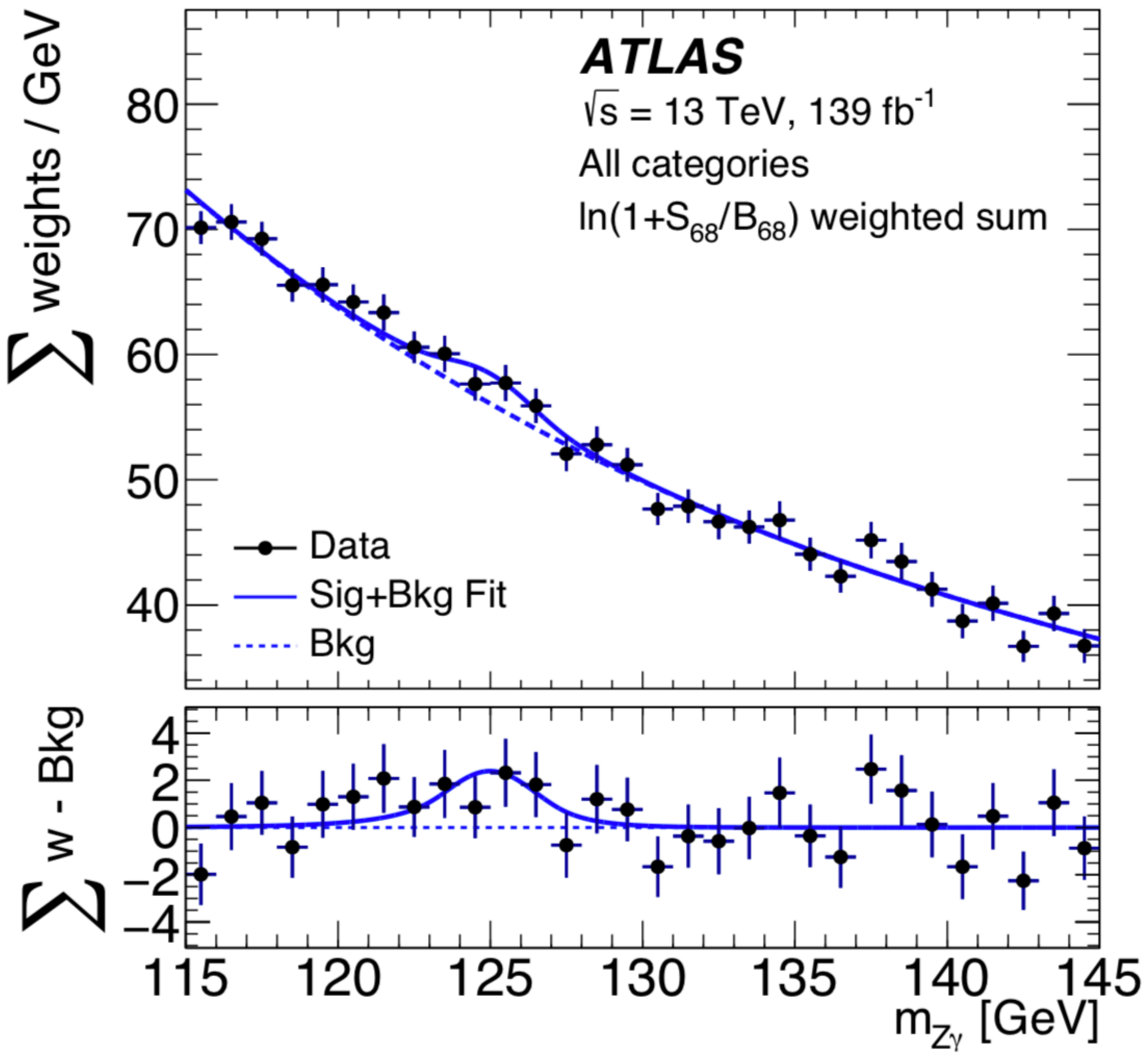


predictions from JHEP 05 (2013) 061

Search for H→Zγ decays

- Updated H→Zγ search with 139 fb^{-1} by ATLAS
  - Events categorised according to production modes
  - Additional BDT VBF categorisation to enhance sensitivity
- Observed (expected) significance is **2.2σ** (1.2σ)
  - Upper limit on $\sigma_H \times B(H\rightarrow Z\gamma)$: 3.6 times the SM prediction



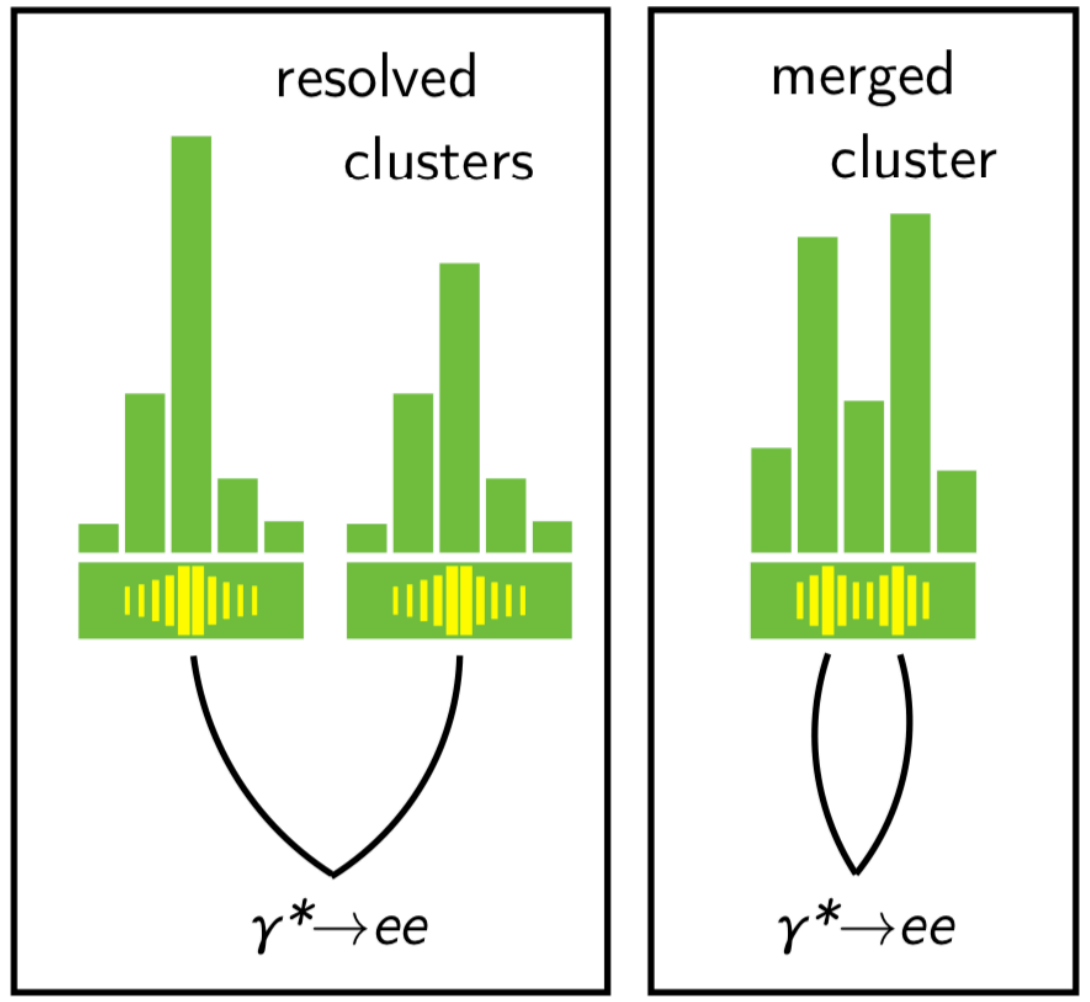


Category	Events	S_{68}	B_{68}	N_{68}	w_{68} [GeV]	S_{68}/B_{68} [10^{-2}]
VBF-enriched	194	2.7	16.7	17	3.7	16.2
High relative p_T	2276	7.6	108.5	118	3.7	7.0
High p_{Tt} ee	5567	9.9	474.7	498	3.8	2.1
Low p_{Tt} ee	76 679	34.5	6418.6	6505	4.1	0.5
High p_{Tt} $\mu\mu$	6979	12.0	634.4	632	3.9	1.9
Low p_{Tt} $\mu\mu$	100 876	43.5	8506.9	8491	4.0	0.5
Inclusive	192 571	110.2	16159.8	16261	4.0	0.7

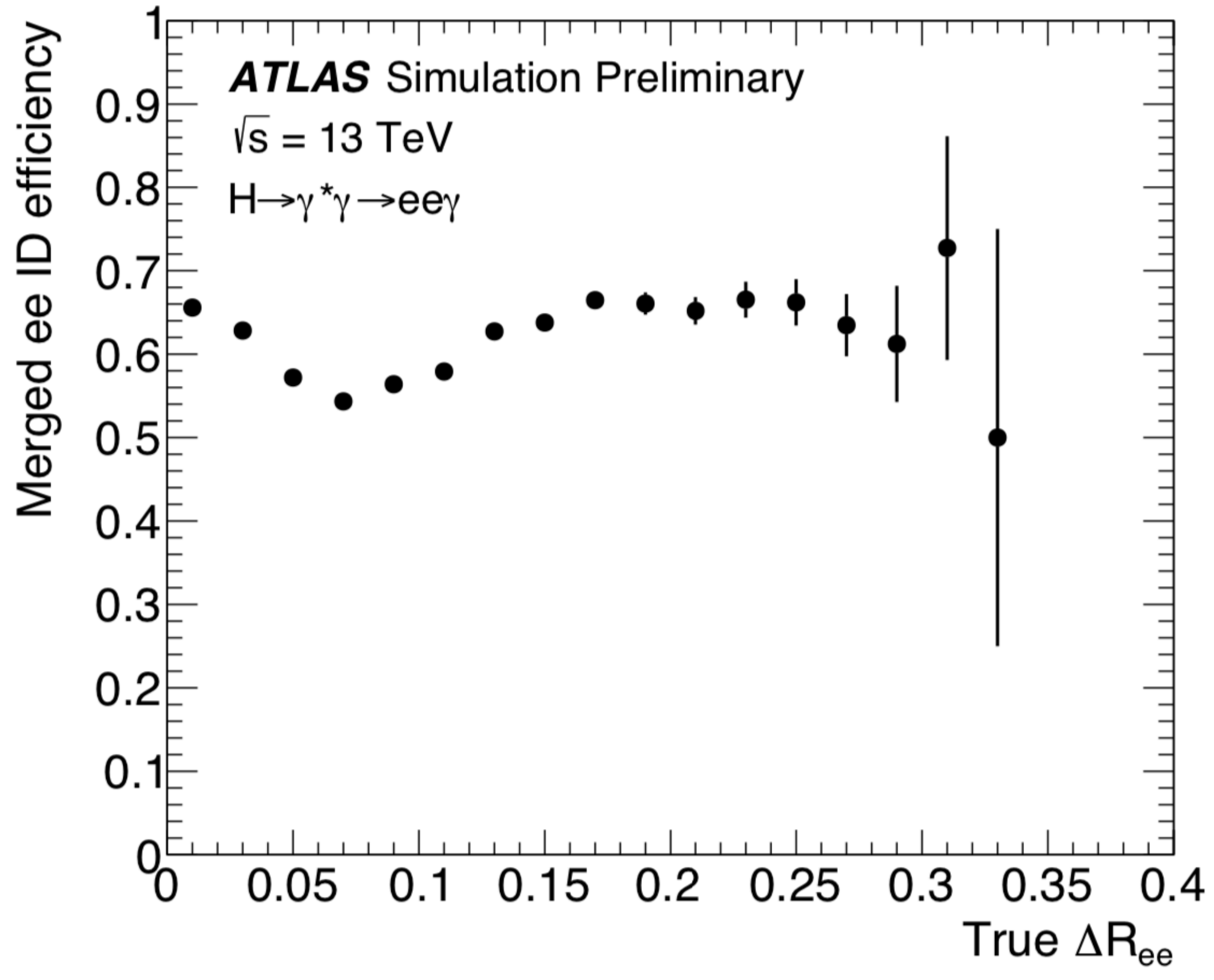
Phys. Lett. B 809 (2020) 135754

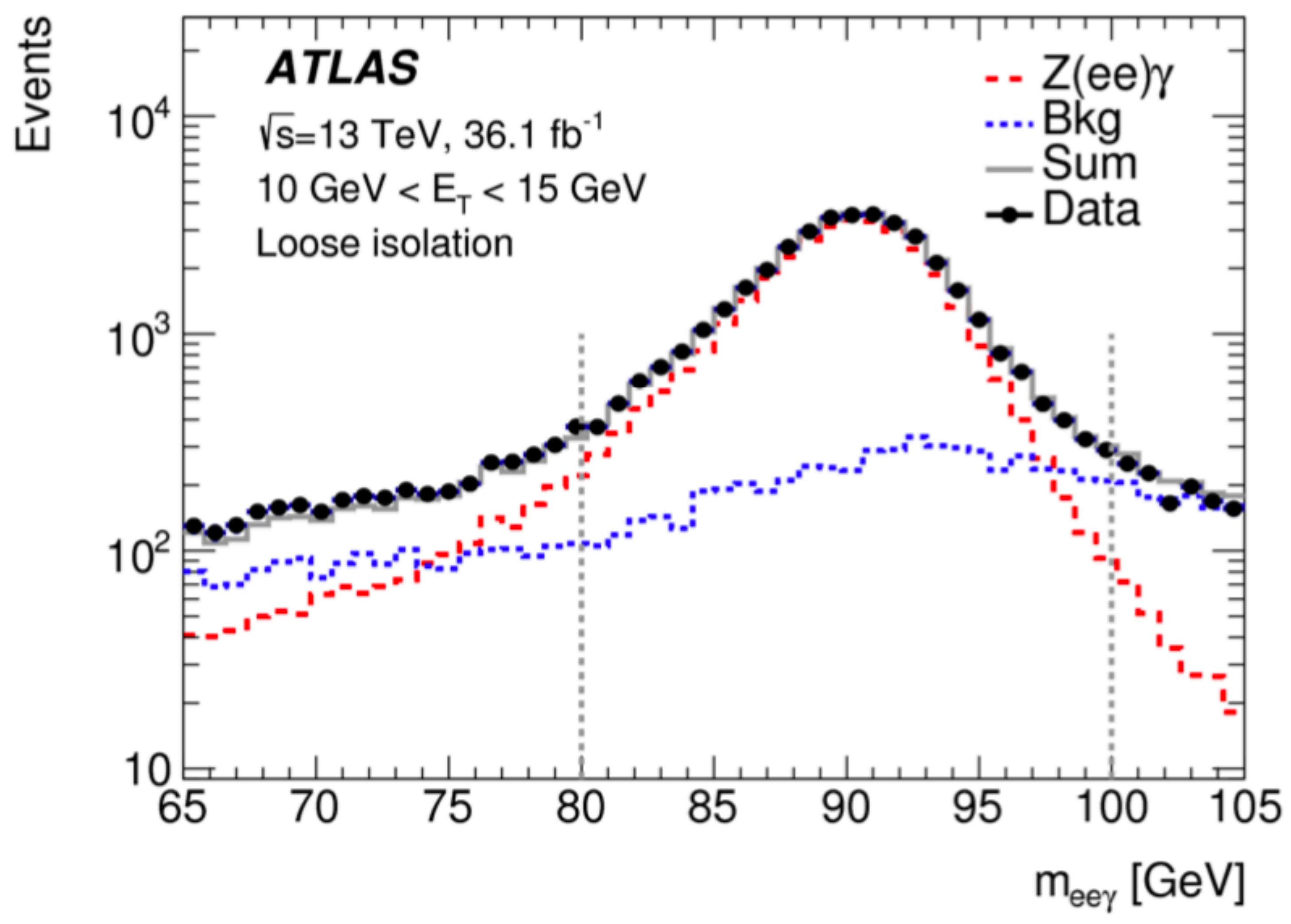
Evidence for H→llγ decays at low-m_{ll}

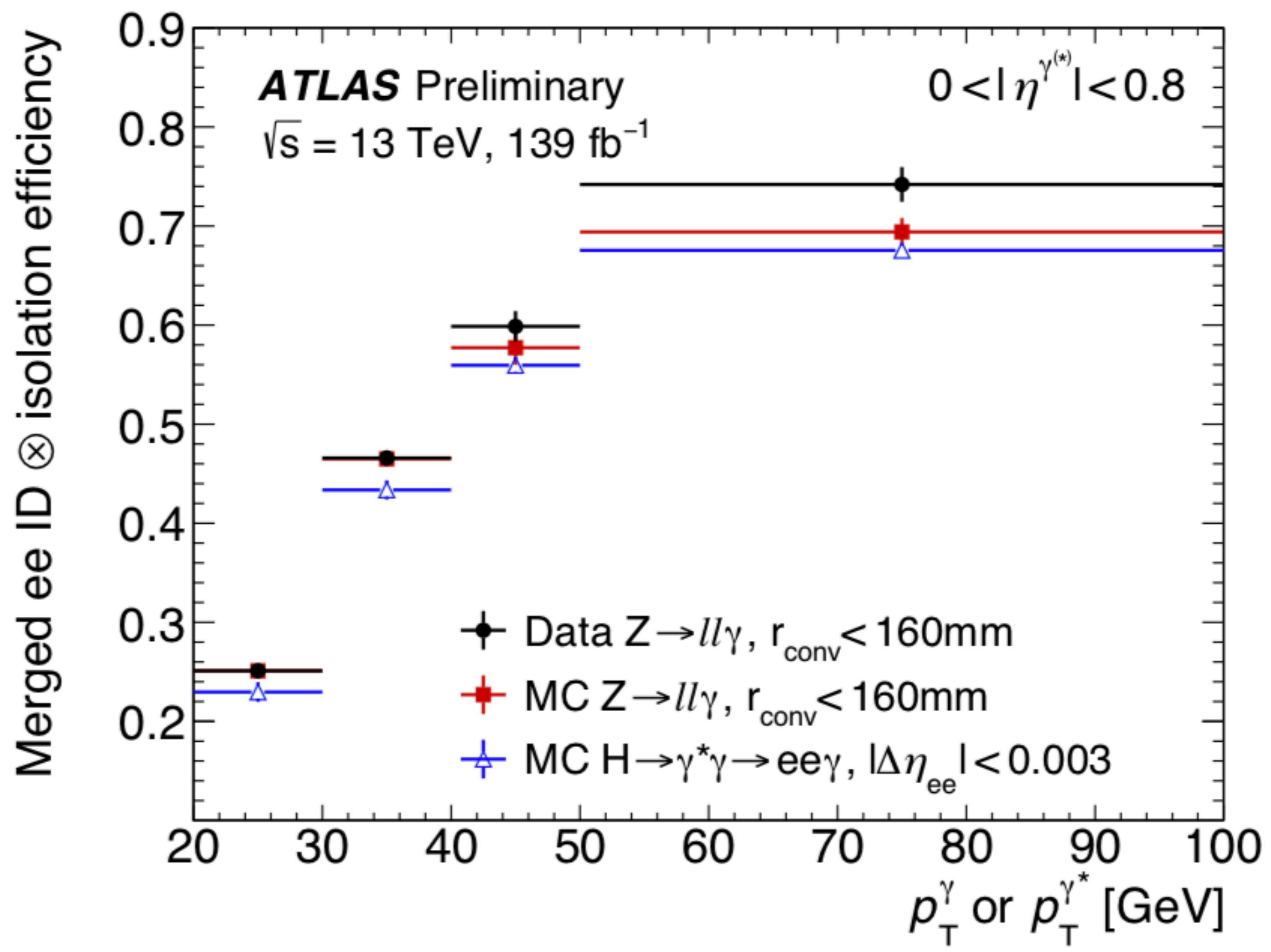
- New ATLAS analysis exploring m_{ll} < 30 GeV
    - Region dominated by H→γ*γ→llγ decay mechanism
    - B(H→eeγ) = **7.2 ×10^-5**, B(H→μμγ) = **3.4 ×10^-5**
- Due to the low-mass of the dilepton system leptons are often very collimated
    - Dedicated identification algorithms for merged-ee objects
    - Merged-ee ID efficiency is measured in data using radiative Z decays with early photon conversion



ATLAS-CONF-2021-002

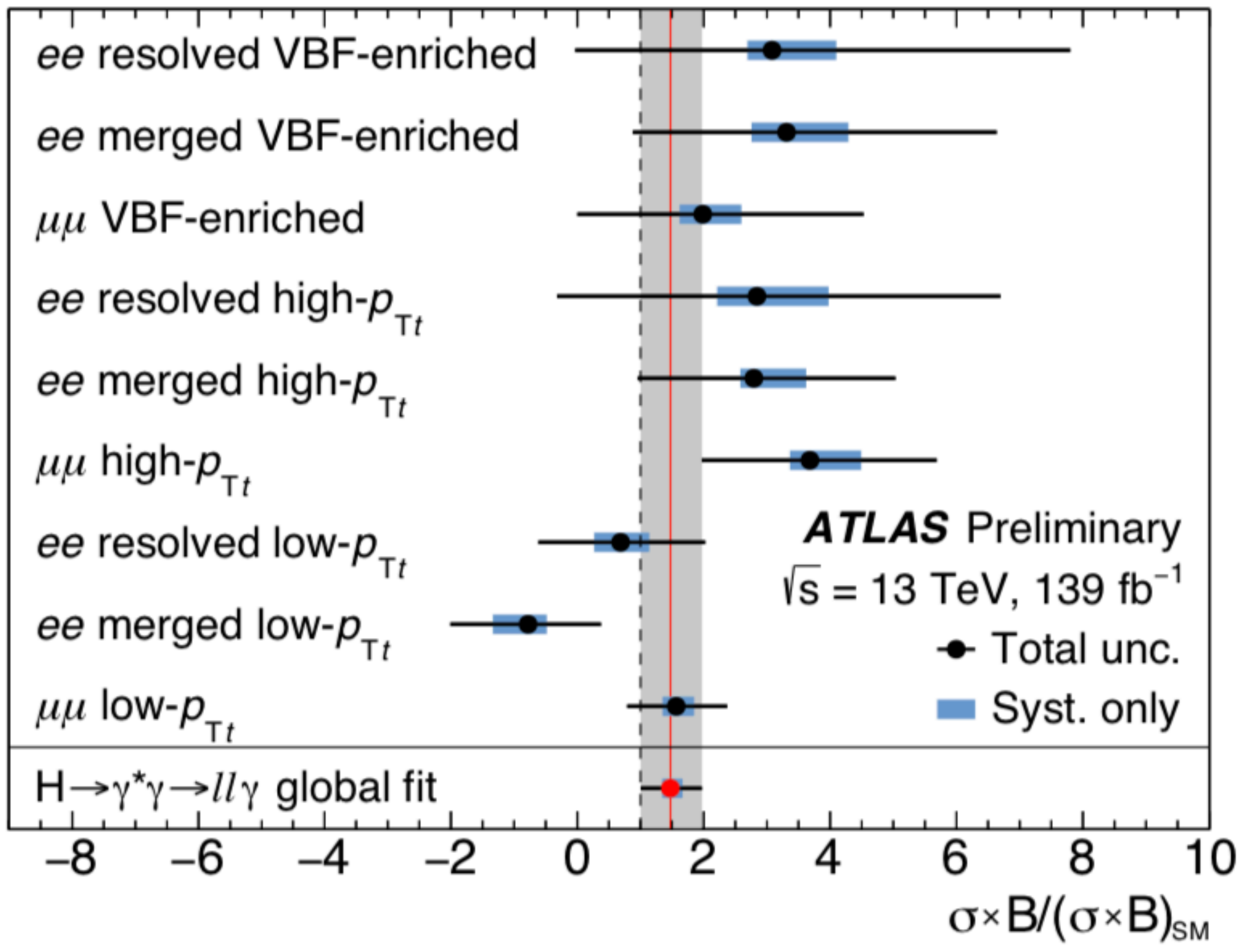


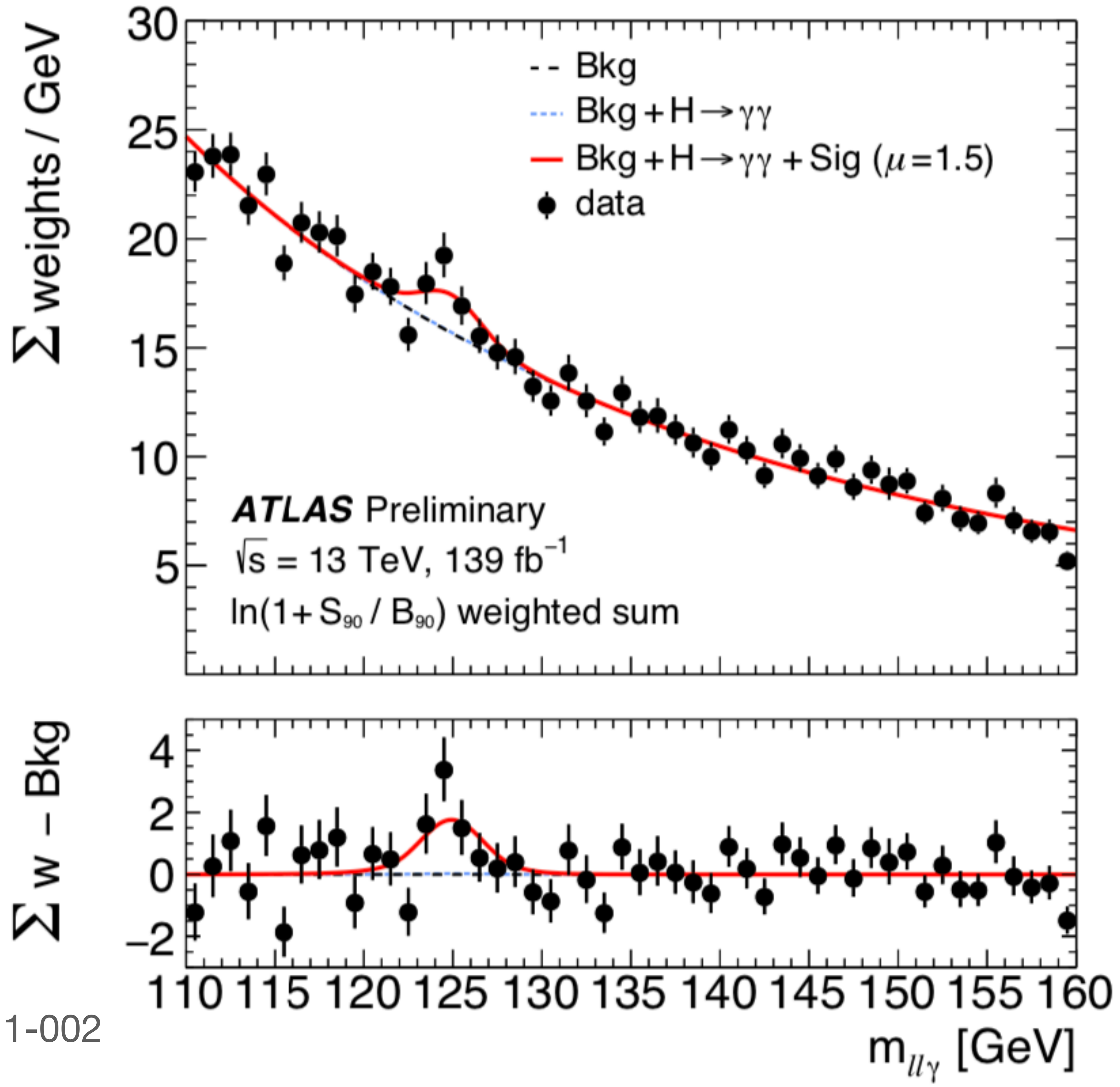




Evidence for H→llγ decays at low-m_{ll}

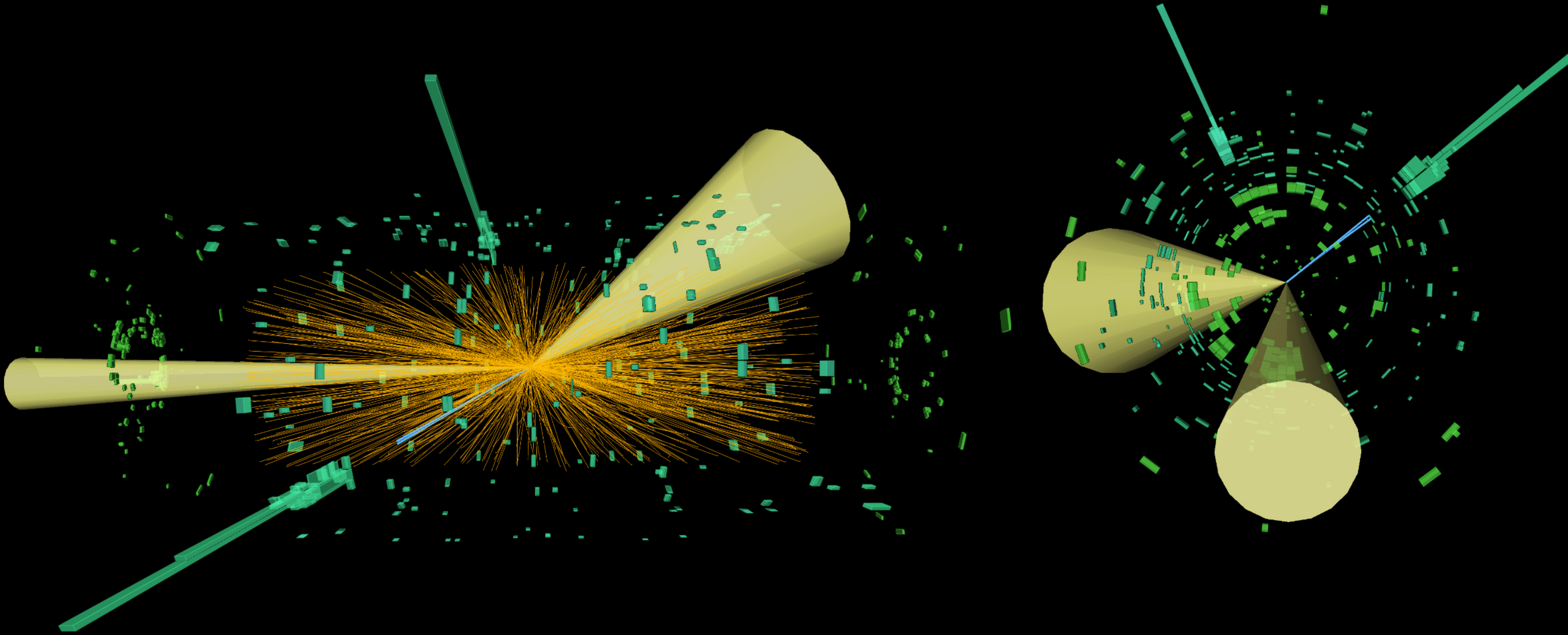
- Measured fiducial $\sigma_H \times B(H \rightarrow ll\gamma)$ ($m_{ll} < 30$ GeV): **8.7 ± 2.8 fb**
  - Corresponds to the signal strength **μ = 1.5 ±0.5**
- Significance above background-only hypothesis: **3.2σ** (2.1σ expected)
  - **First evidence for H→llγ decay**





ATLAS-CONF-2021-002

Evidence for $H \to ll\gamma$ decays at low-m_{ll}



ATLAS-CONF-2021-002

Event display of a candidate $H \to ee\gamma$ event from the ee-merged VBF-enriched category

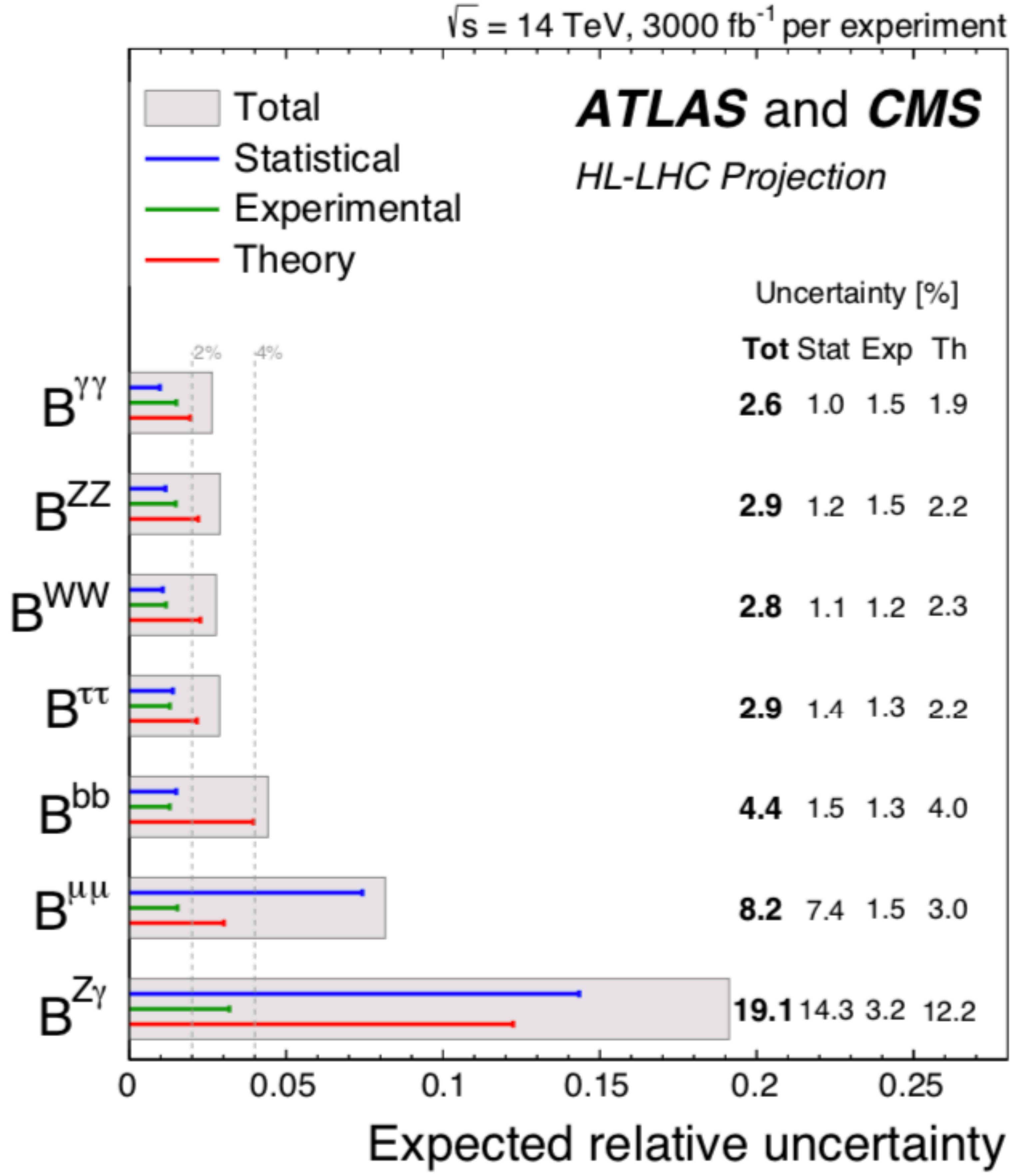
The High-Luminosity LHC

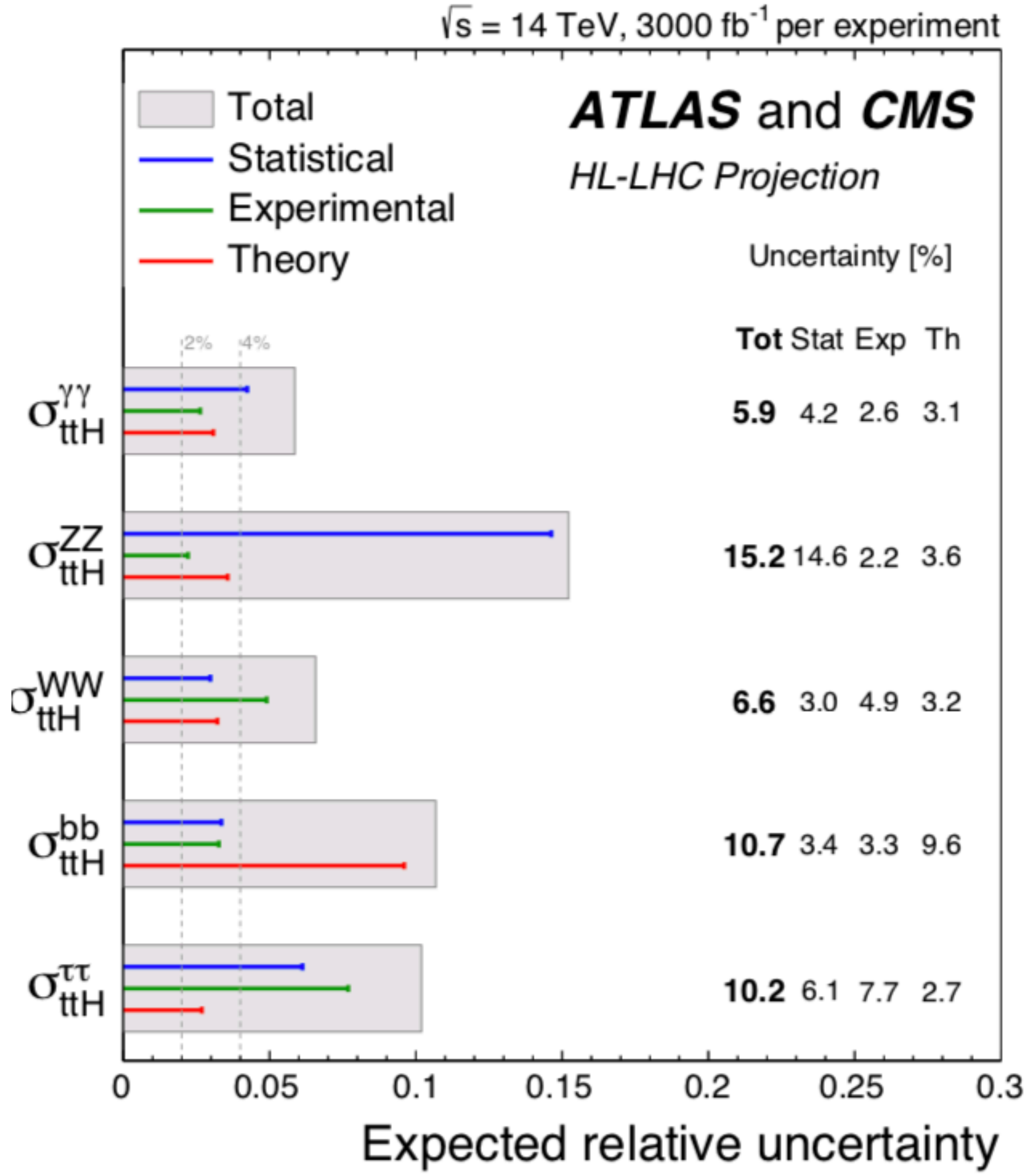
- 20 times more integrated luminosity than LHC Run 2
  - Up to 200 pp interactions per bunch crossing!
- Better detectors, larger acceptance, better triggers
- Improved theory and analysis methods

	2020 2021 2022 2023 2024 2025 2026 2027 2028 2029 2030 2031 2032 2033 2034					
	LHC		High-Luminosity LHC			
	LS2	Run 3	LS3	Run 4	LS4	Run 5
ATLAS and CMS		2×10^{34} 300 fb^{-1}	Detector Upgrade	$5\text{-}7 \times 10^{34}$ ~1000 fb^{-1}		$5\text{-}7 \times 10^{34}$ 3000 fb^{-1}

Prospects at High-Luminosity LHC (3000 fb^{-1})

- 3-8% precision of Higgs Br to W/Z, 3rd gen. fermions and muons
- Discovery of H→μμ and H→Zγ decays
- H→cc : σ/σ(SM) < 6 from ATLAS Run 2 result extrapolation

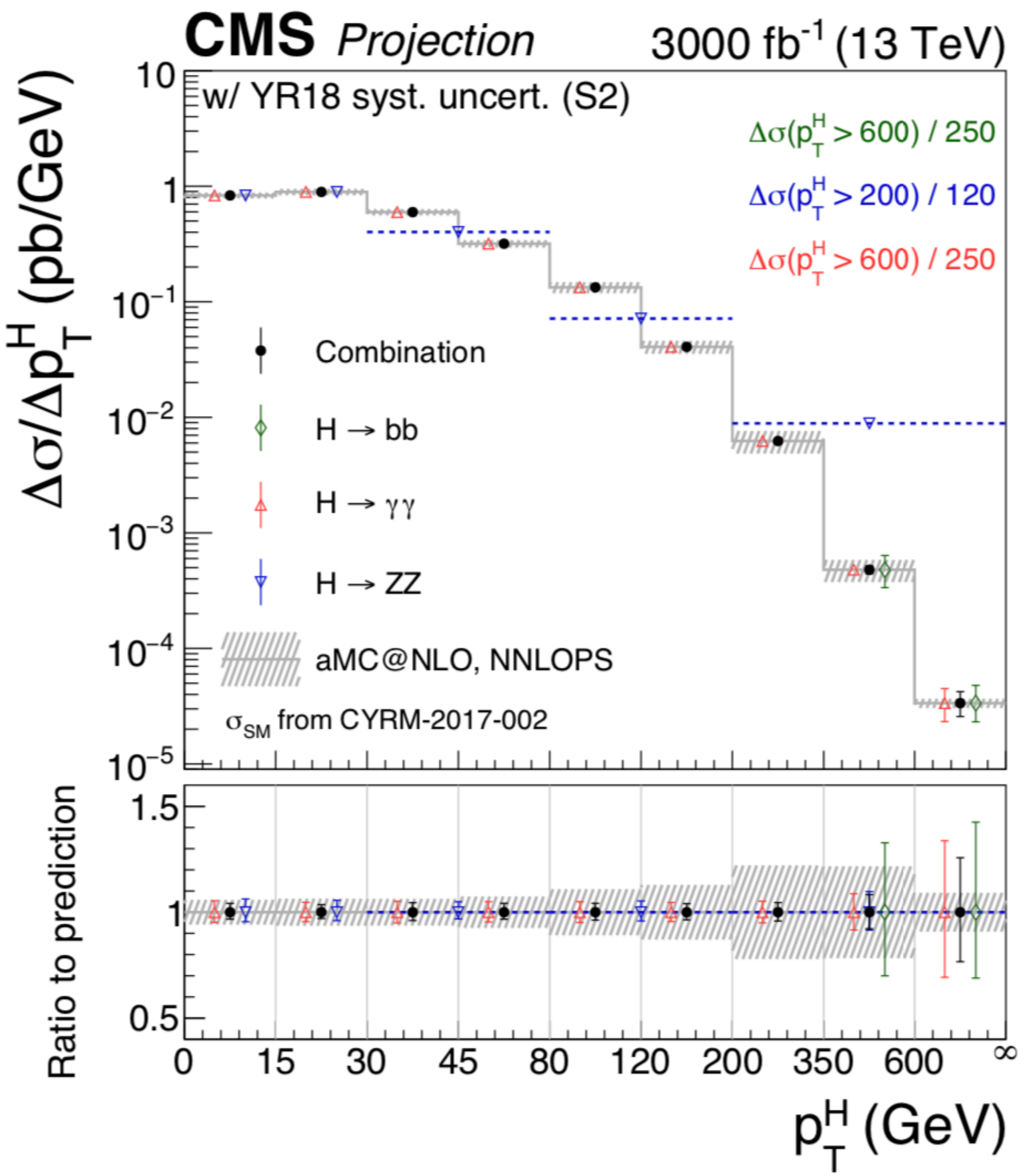


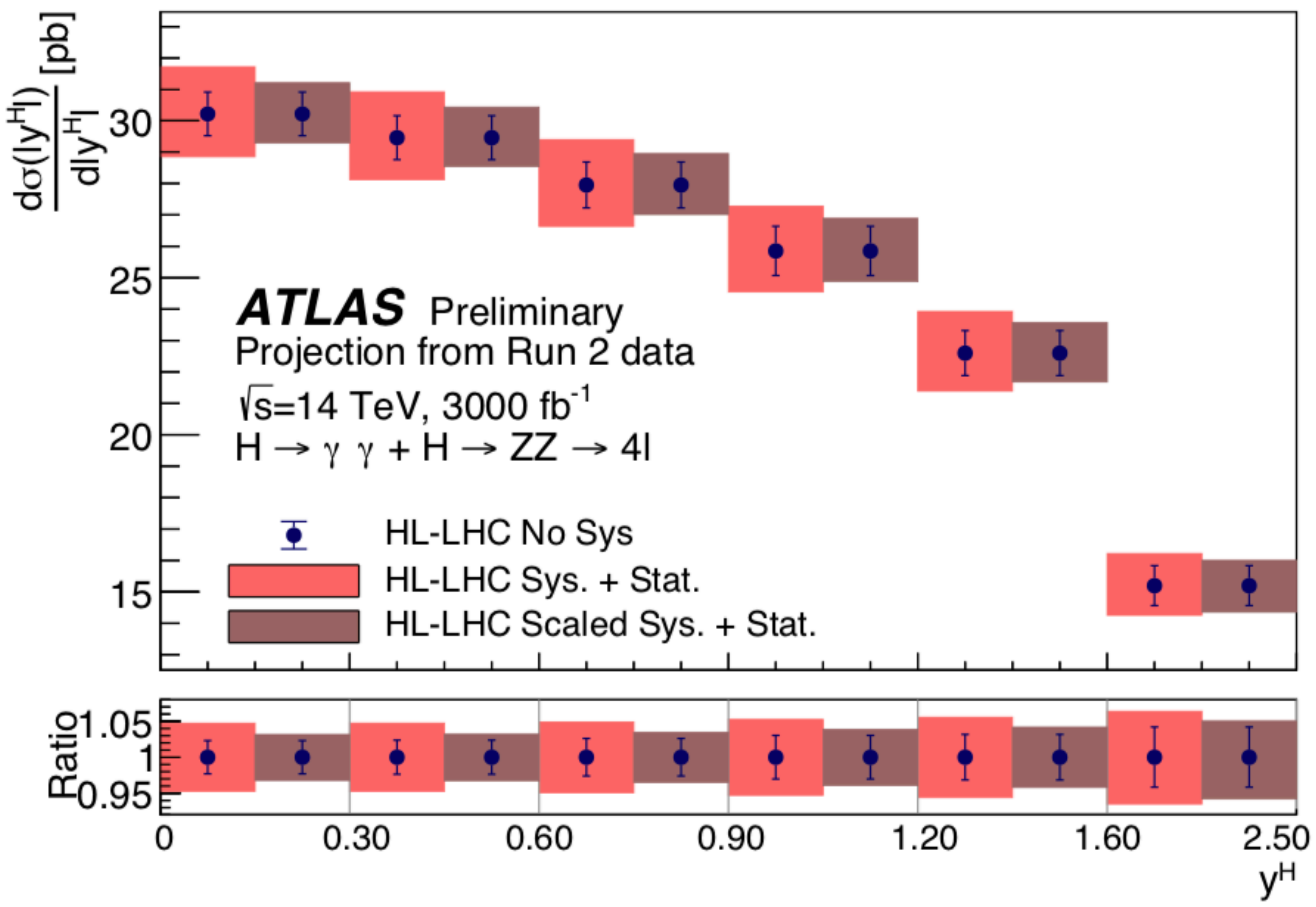


arXiv:1902.00134

Prospects at High-Luminosity LHC (3000 fb^{-1})

- Uncertainties in the Higgs p_T measurement at **high-p_T** can be reduced by a factor of 10 at HL-LHC w.r.t. current measurements

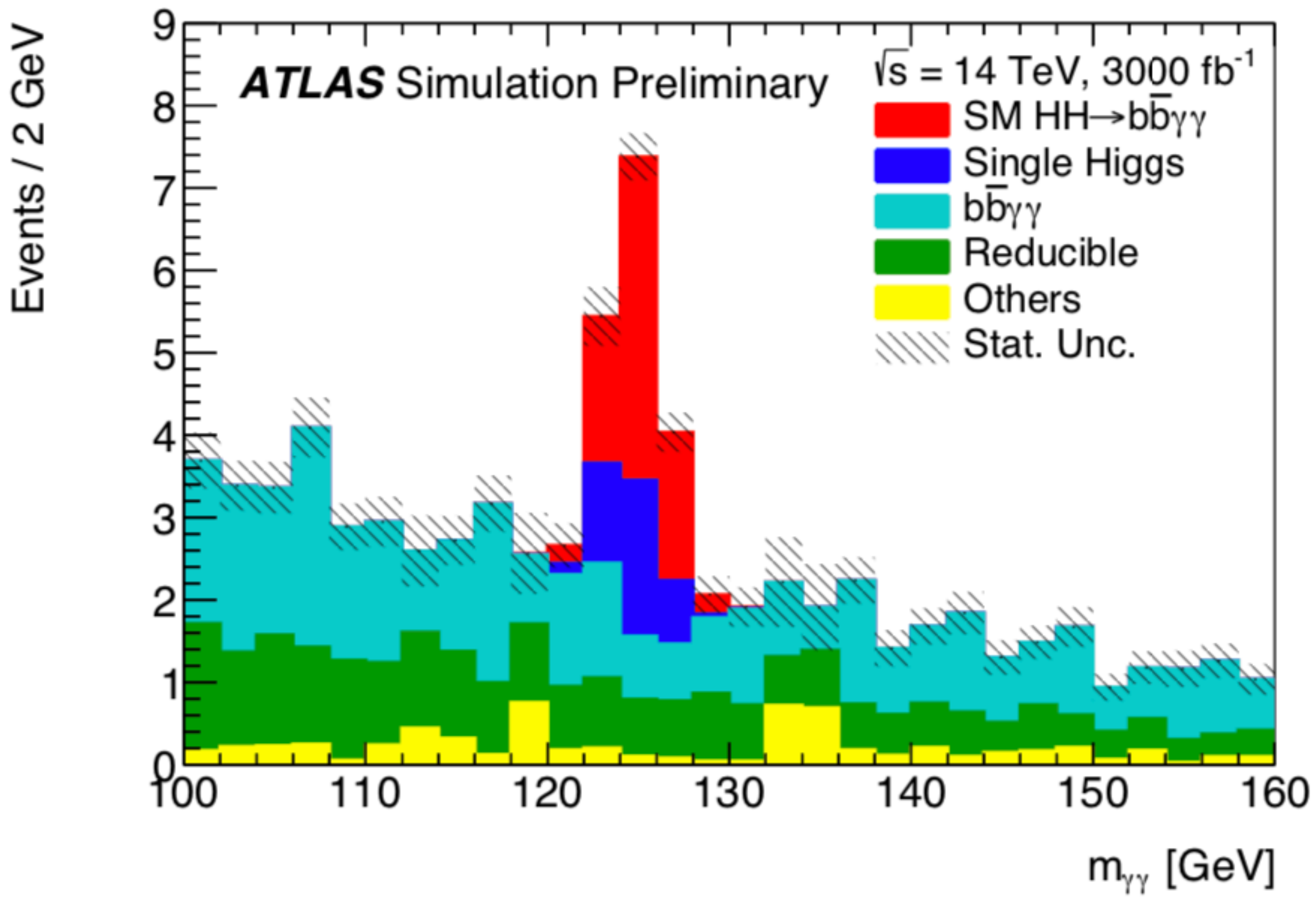


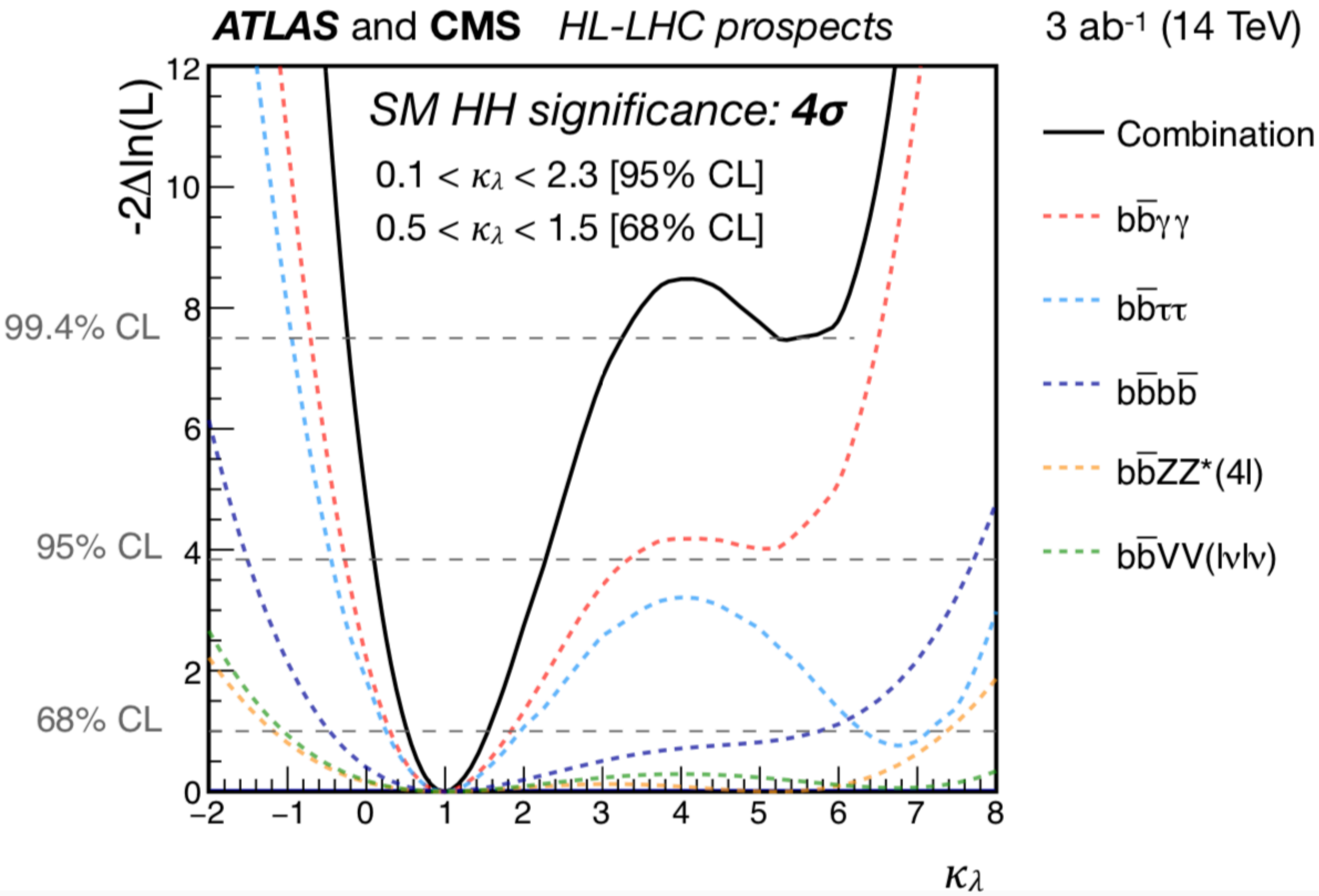


arXiv:1902.00134

Prospects at High-Luminosity LHC (3000 fb^{-1})

- At 95% CL, ATLAS+CMS is anticipated to exclude no Higgs trilinear coupling with full HL-LHC dataset





arXiv:1902.00134

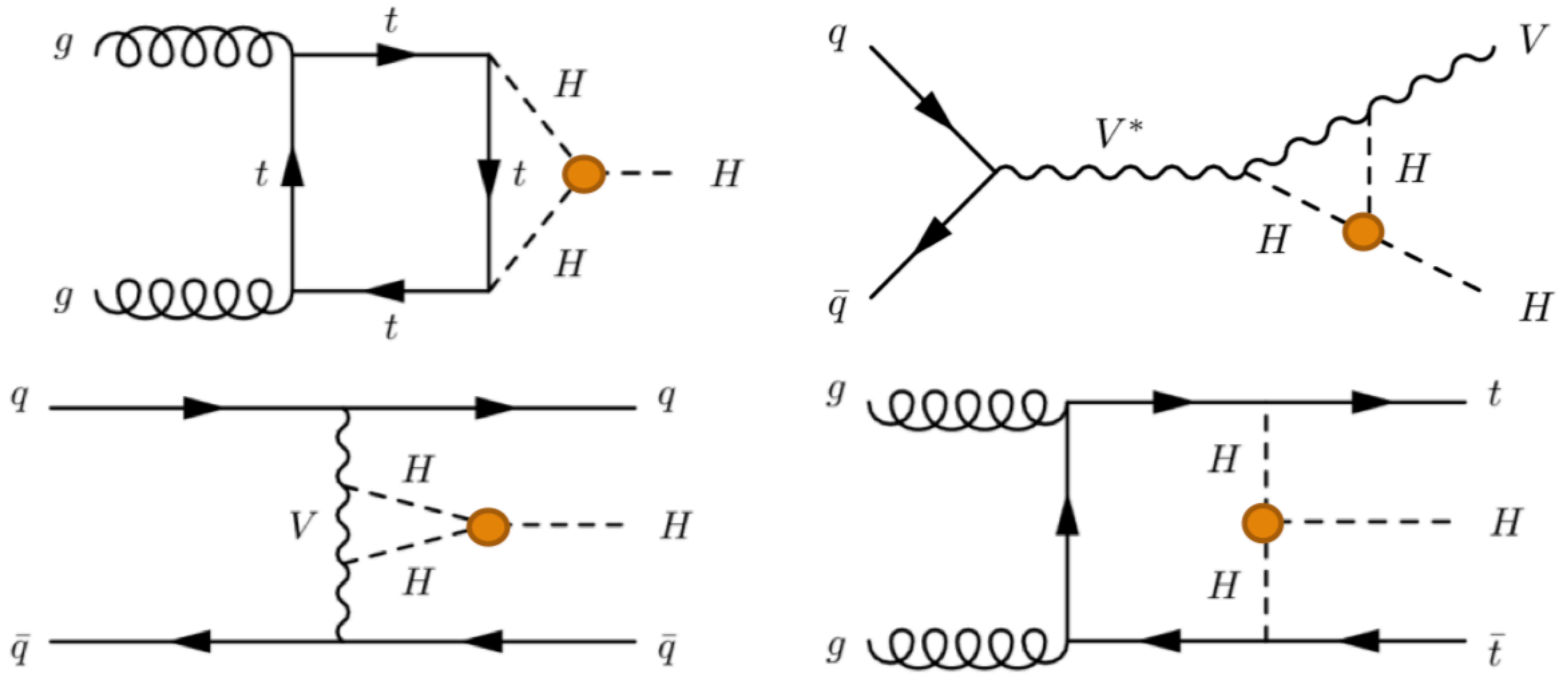
Summary

- ATLAS and CMS collaborations continue to probe the nature of the Higgs boson using full LHC Run 2 data at 13 TeV (~140 fb^{-1})
- Higgs physics at the LHC moves towards precision measurement era
- LHC starts to have sensitivity to Higgs couplings with 2nd generation fermion
- Other rare Higgs boson decays start to be accessible (e.g. $H \rightarrow ll\gamma$)
- ~5% of the LHC integrated luminosity has been achieved so far
    - HL-LHC will be able to precisely probe Higgs couplings with the 2nd generation fermion and be able to set strong constraints on Higgs self-coupling parameter
- Stay tuned for new measurements!

Backup

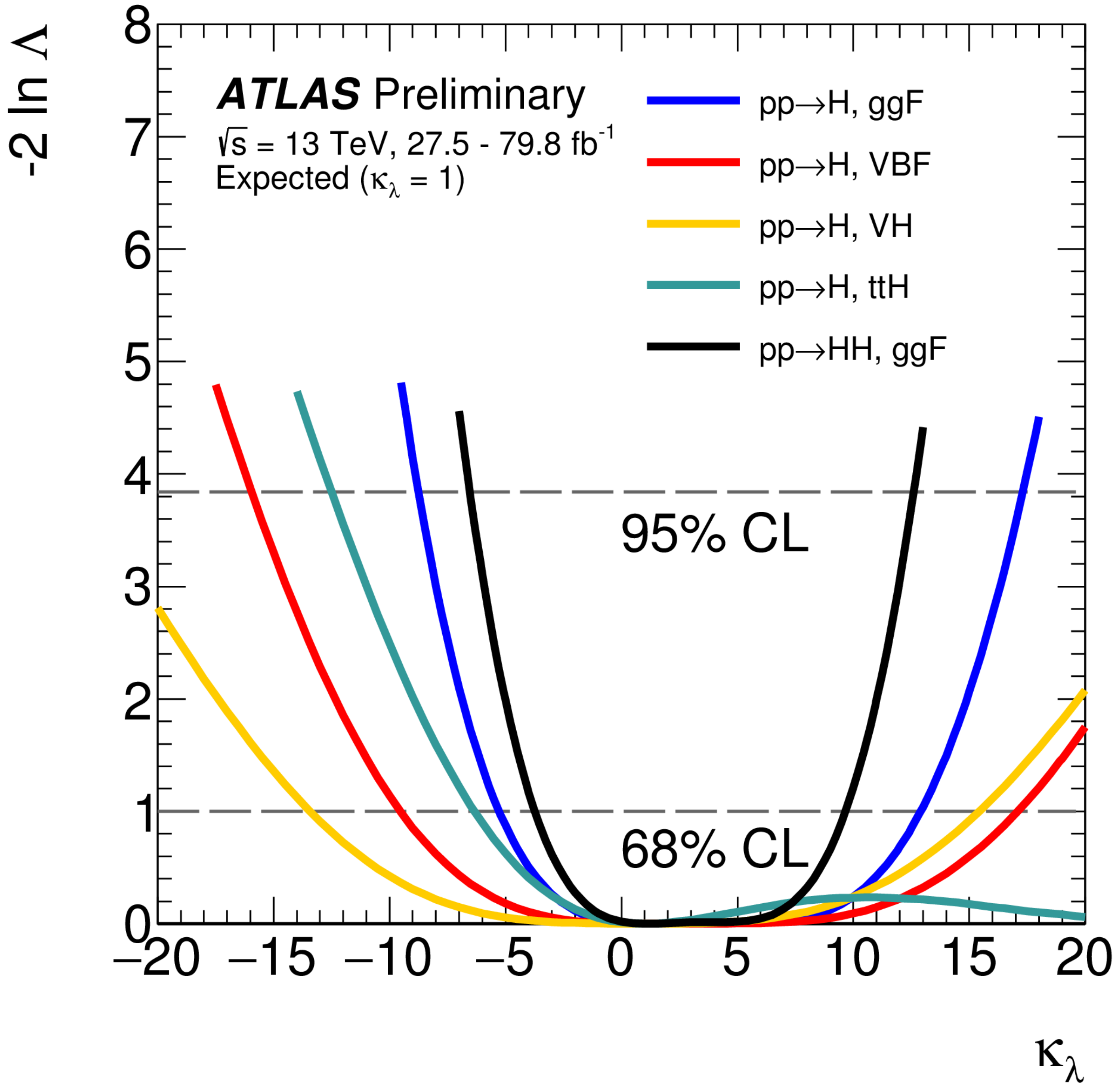
H self-coupling from single H production

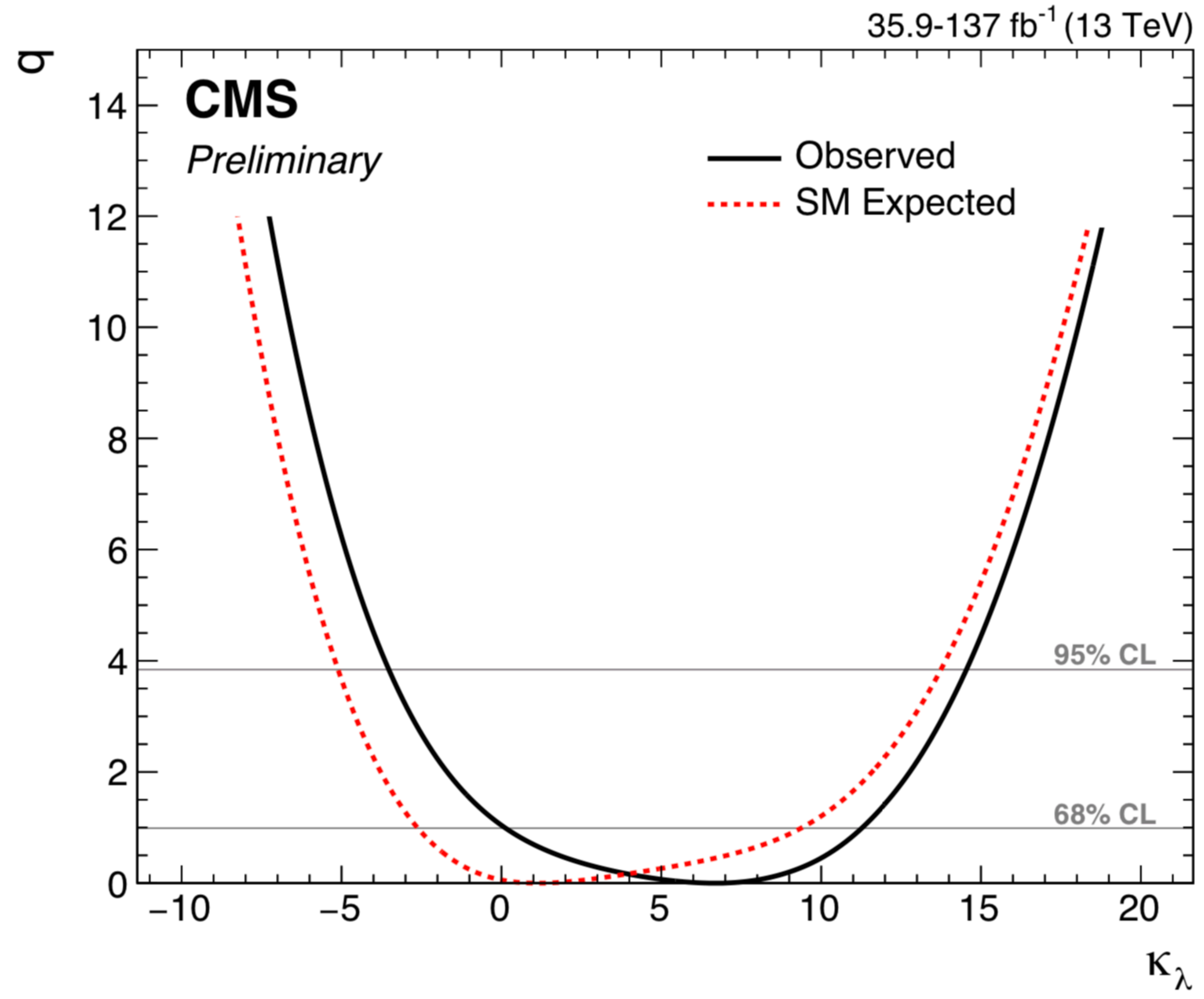
- Single H production sensitive to λ through NLO EW corrections
- ATLAS and CMS extracted limits on κ_λ as part of recent Higgs combinations



- This method achieves similar sensitivity to direct HH searches, but uses some assumptions

ATLAS-CONF-2019-049





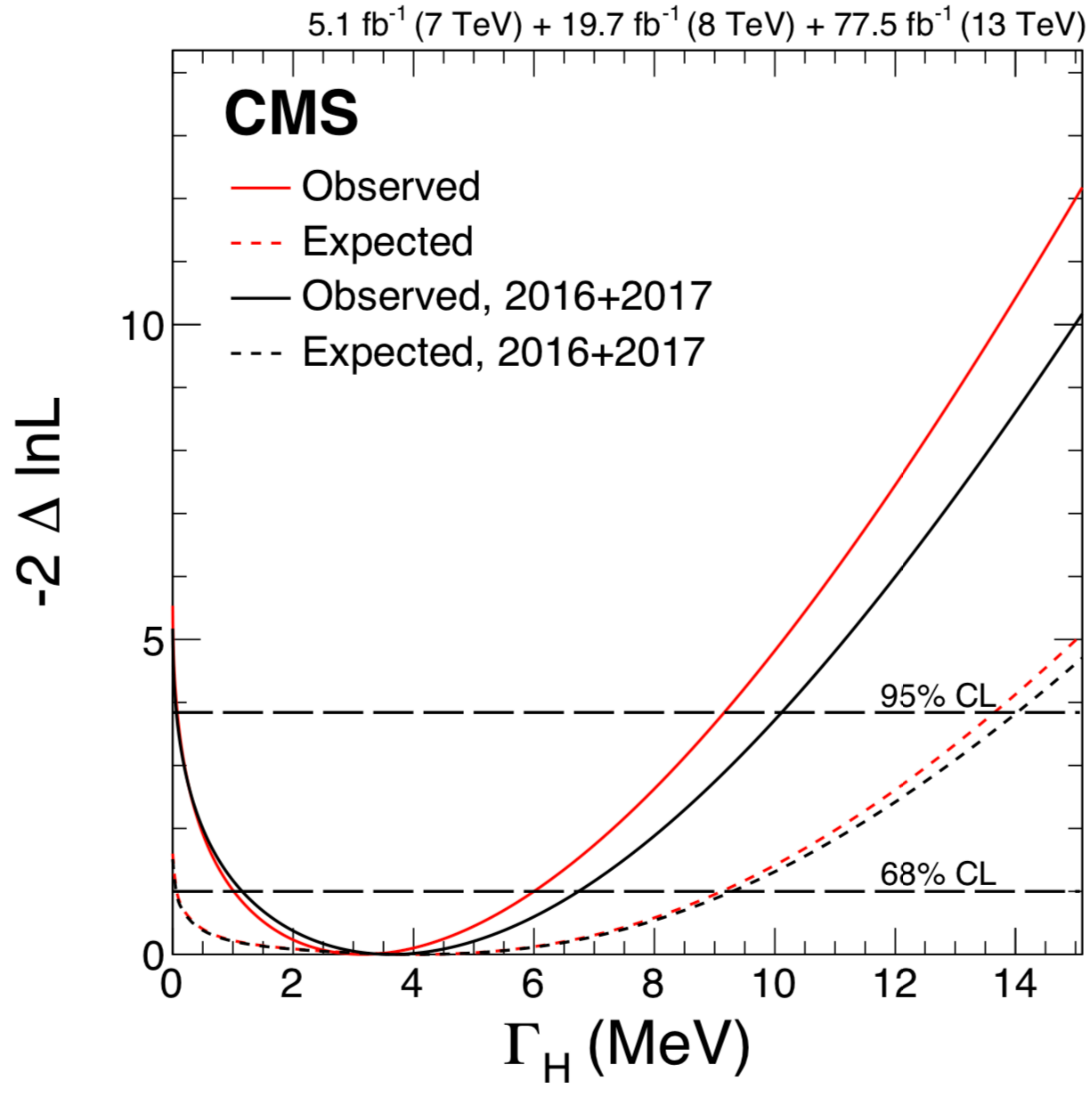
CMS-PAS-HIG-19-005

Constraints on Higgs boson width

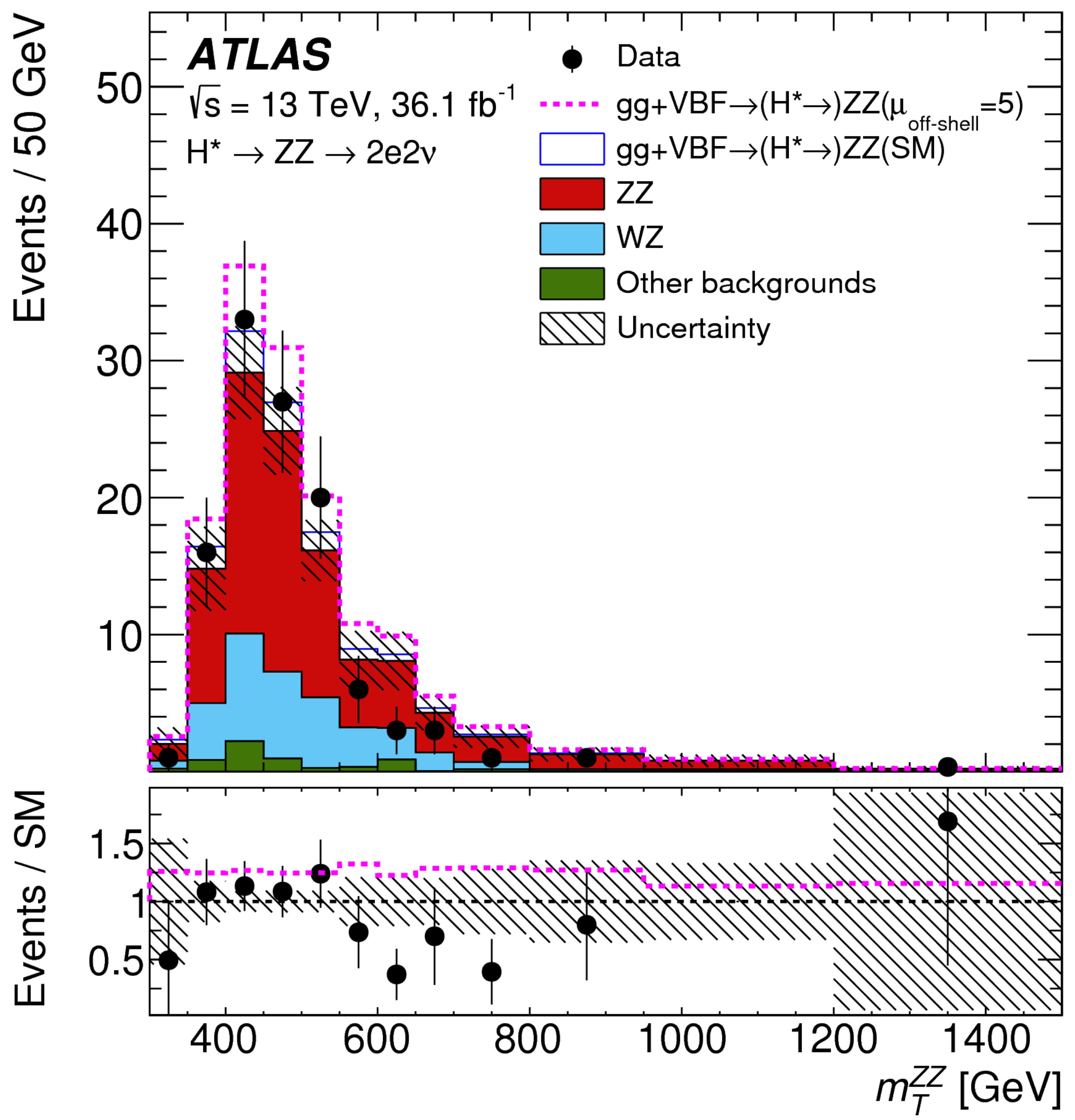
- Indirect measurement from off-shell production in H→ZZ channel
- Obs. limit on Higgs width:

$$\sigma^{\text{on-shell}}_{\text{vv}\to\text{H}\to4\ell} \propto \mu_{\text{vvH}} \quad \text{and} \quad \sigma^{\text{off-shell}}_{\text{vv}\to\text{H}\to4\ell} \propto \mu_{\text{vvH}}\,\Gamma_{\text{H}}.$$

  - ATLAS Run 2 (36.1fb^{-1}): **< 14.4 MeV**
  - CMS Run 1+2 (77 fb^{-1}): **[0.08, 9.16] MeV**
  - SM prediction: **4.1 MeV**



PRD 99 (2019) 112003



PLB 786 (2018) 223

HL-LHC projections:

CMS: $4.1^{+1.0}_{-1.1}$ MeV

ATLAS: $4.2^{+1.5}_{-2.1}$ MeV

arXiv:1902.00134