Experimental overview of EW and BSM physics at CMS and ATLAS

The 29th International Workshop on Weak Interactions and Neutrinos (WIN2023), SYSU (Zhuhai)

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on behalf of ATLAS and CMS collaborations

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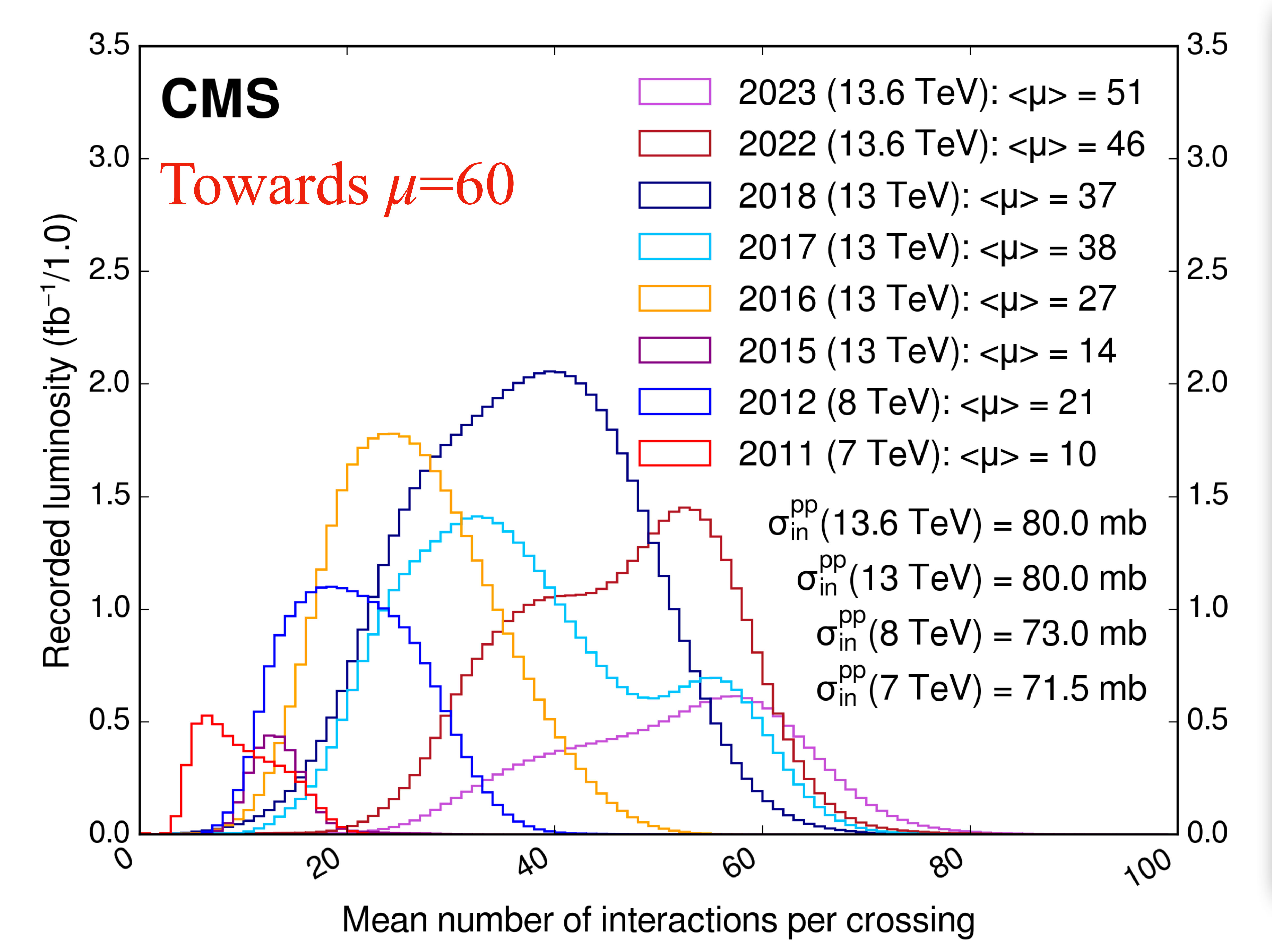
PEKING UNIVERSITY

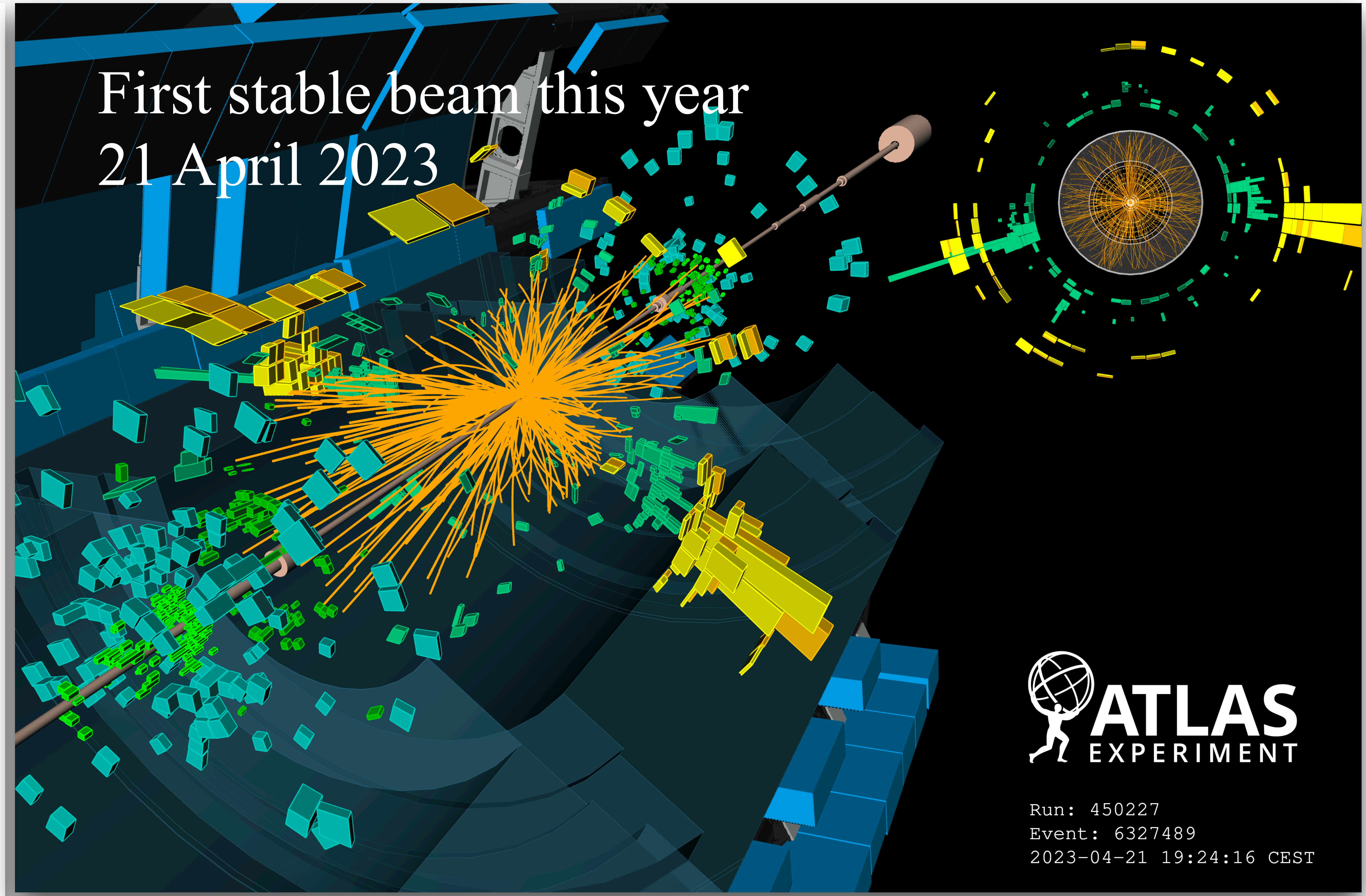
Introduction

- EW measurements and relevant BSM searches are of great interests for not only examining the Standard Model but also bridging to new physics
- These topics are very broad, while I will try to cover the recent highlights given the limited time
  - EW W/Z, VBS, multiple bosons
  - $t\bar{t}$, single top, mass
  - Higgs, rare decays
  - And the relevant BSM

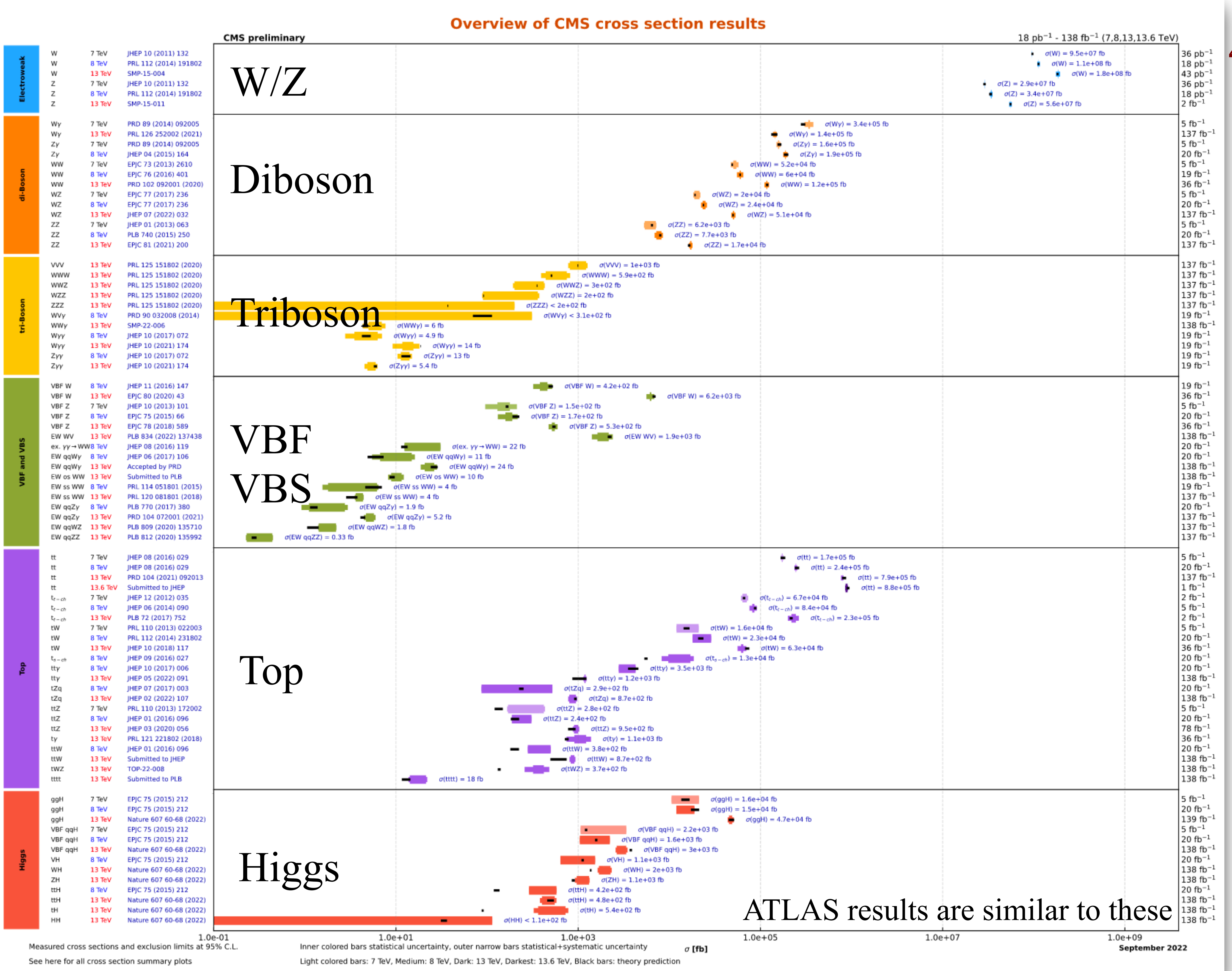
Data taking

- All of the physics results would not be possible without the excellent colliders and the well-operating detectors





- LHC is such a powerful machine, and ATLAS/CMS are high-performance detectors with excellent precisions
- The measured XS ranges over 10 orders of magnitude
- The Standard Model survives so well so far 🤔



$t\bar{t}$ productions

First LHC Run-3 paper submitted to a journal

$\sqrt{s}$	$\sigma_{t\bar{t}}$ (NNLO + NNLL)
13 TeV	$833.9^{+29.4}_{-36.6}$ pb (4.4%)
13.6 TeV	$923.6^{+32.1}_{-40.4}$ pb (4.4%)

(LHCPhysics)

~10% increase

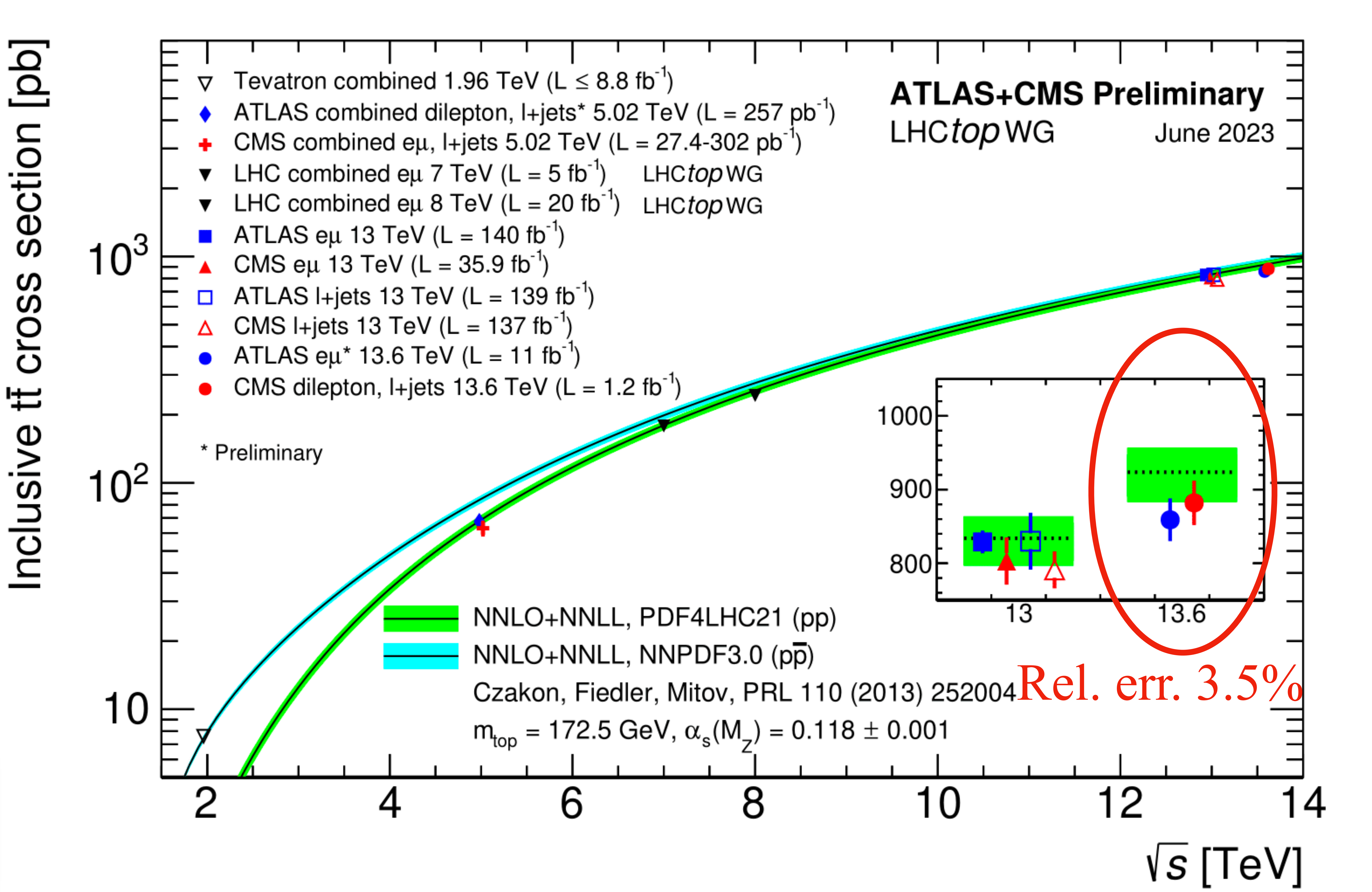
- Large produce rate at LHC: ~120M $t\bar{t}$ events @ 10Hz for 13 TeV
- New early Run3 $\sigma_{t\bar{t}}$ @ 13.6 TeV results

CMS 2303.10680, submitted to JHEP: 1/2L+jets, inclusive $\sigma_{t\bar{t}}$

$$\sigma(pp \to t\bar{t}) = 882 \pm 23\ (\text{stat+syst}) \pm 20\ (\text{lumi})\ \text{pb}$$

ATLAS-CONF-2023-006: eμ+jets, inclusive $\sigma_{t\bar{t}}$ and fiducial σ_Z

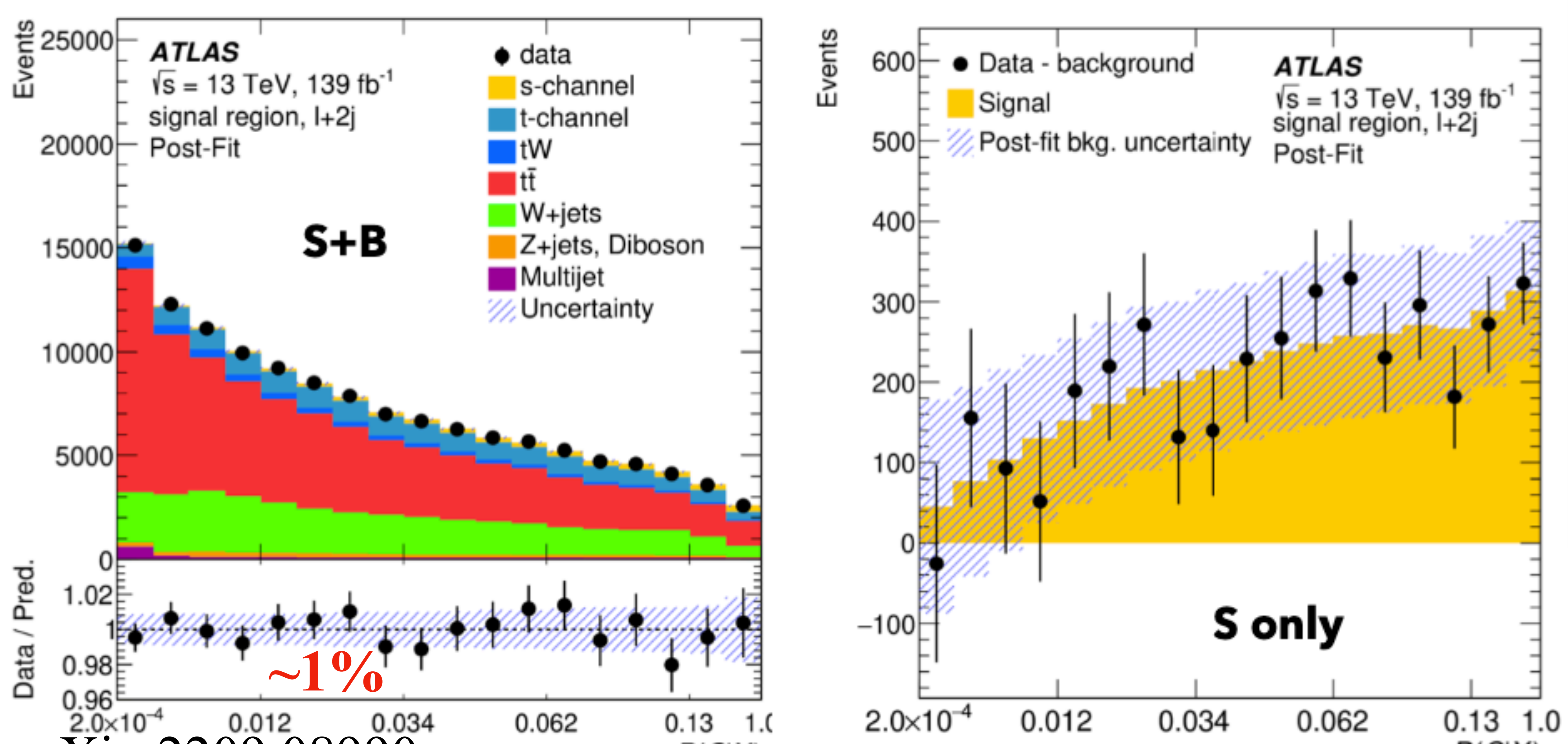
$$\sigma(pp \to t\bar{t}) = 859 \pm 4\ (\text{stat}) \pm 22\ (\text{syst}) \pm 19\ (\text{lumi})\ \text{pb}$$
$$\sigma(pp \to Z_{ll}^{fid.}) = 751 \pm 0.3\ (\text{stat}) \pm 15(\text{syst}) \pm 17\ (\text{lumi})\ \text{pb}$$
$$R_{t\bar{t}/Z} = 1.144 \pm 0.006\ (\text{stat}) \pm 0.022\ (\text{syst}) \pm 0.003\ (\text{lumi})$$



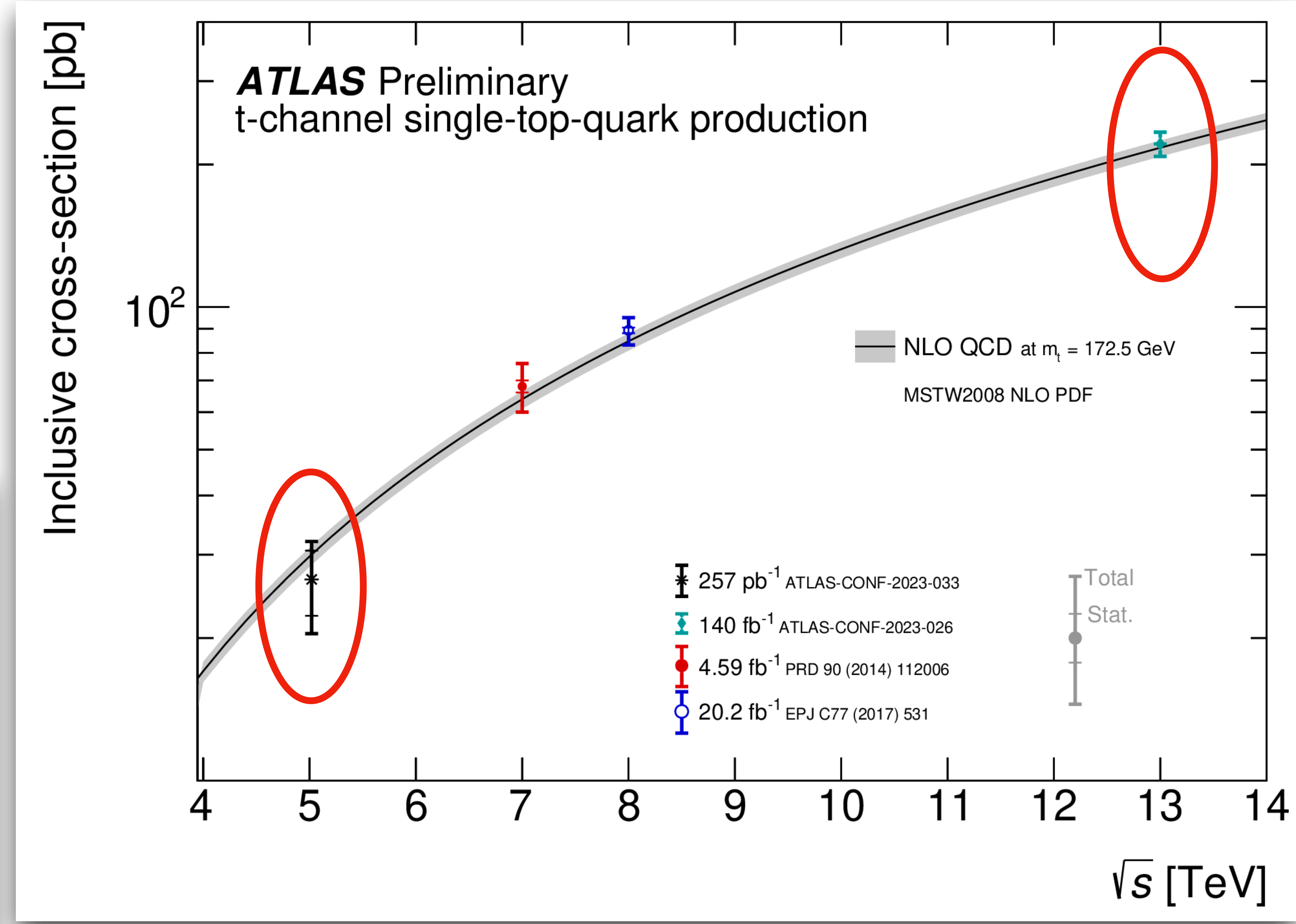
LHCTOPWGSummaryPlots

Single top productions

- Three leading production modes: t-channel (73%), tW (24%) and s-channel (3%) @ 13 TeV
- New t-channel results (1L) at 5 TeV & 13 TeV
- The challenging s-channel reached evidence with 3.3 (3.9) s.d. using 1L final state



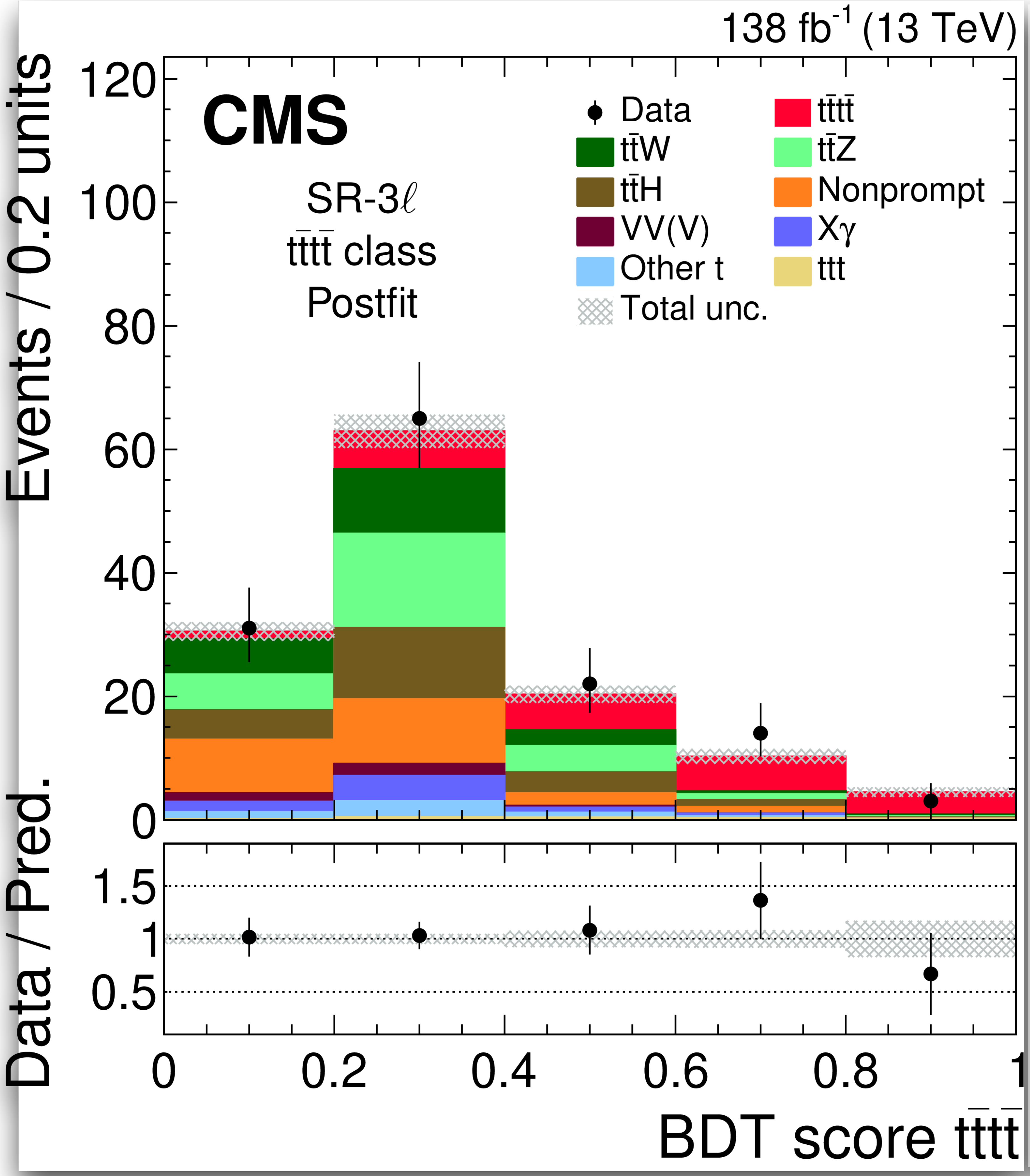
arXiv:2209.08990



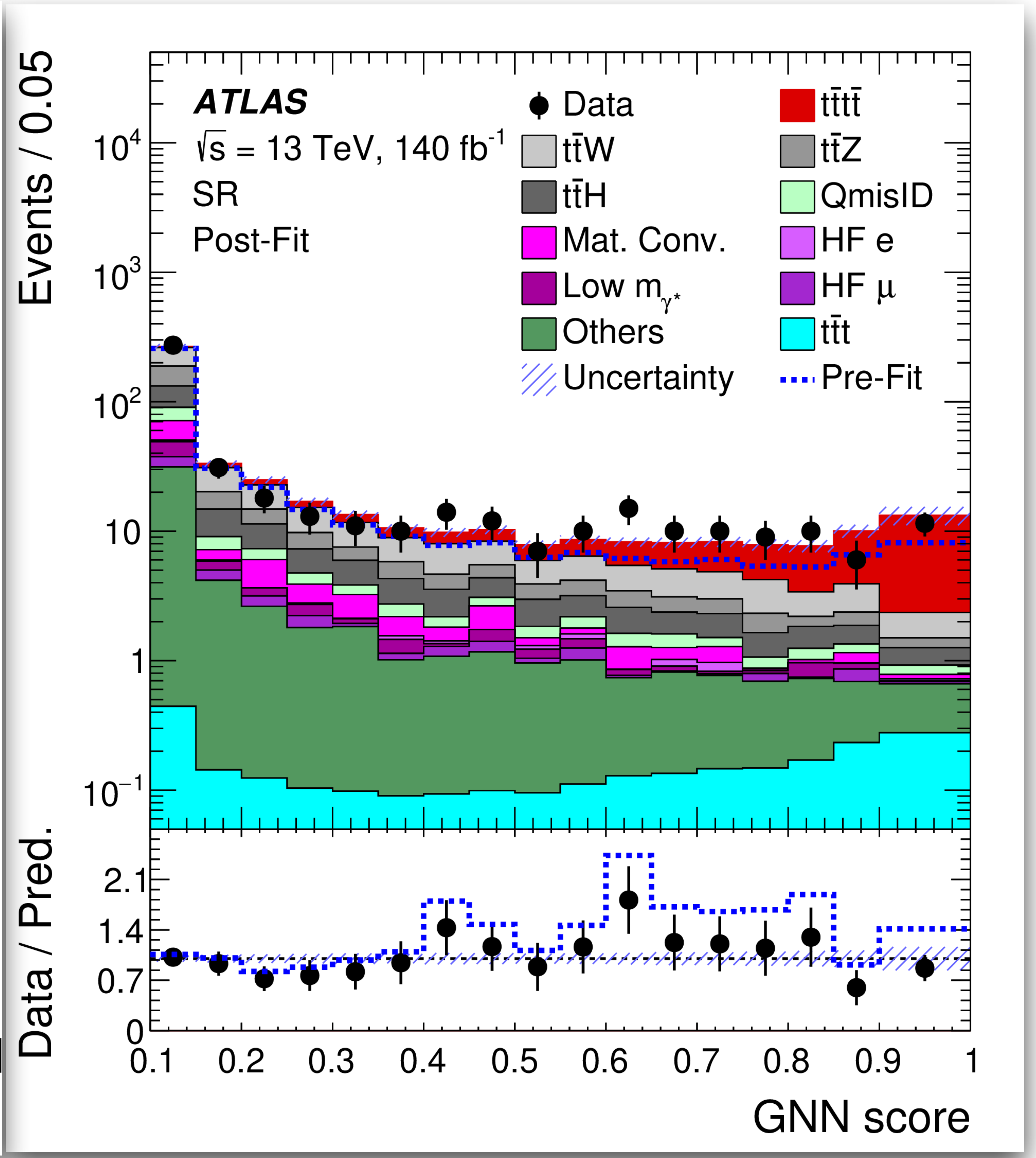
ATLAS-CONF-2023-033, ATLAS-CONF-2023-026
Observation at 5.02 TeV

Four-top production

- Rare production ~13 fb @ 13 TeV, but direct probe to top Yukawa and EFT couplings
- Observation is reached by both ATLAS with 6.1 (4.3) s.d. and CMS with 5.5 (4.9) s.d., using SS 2L and multiple leptons



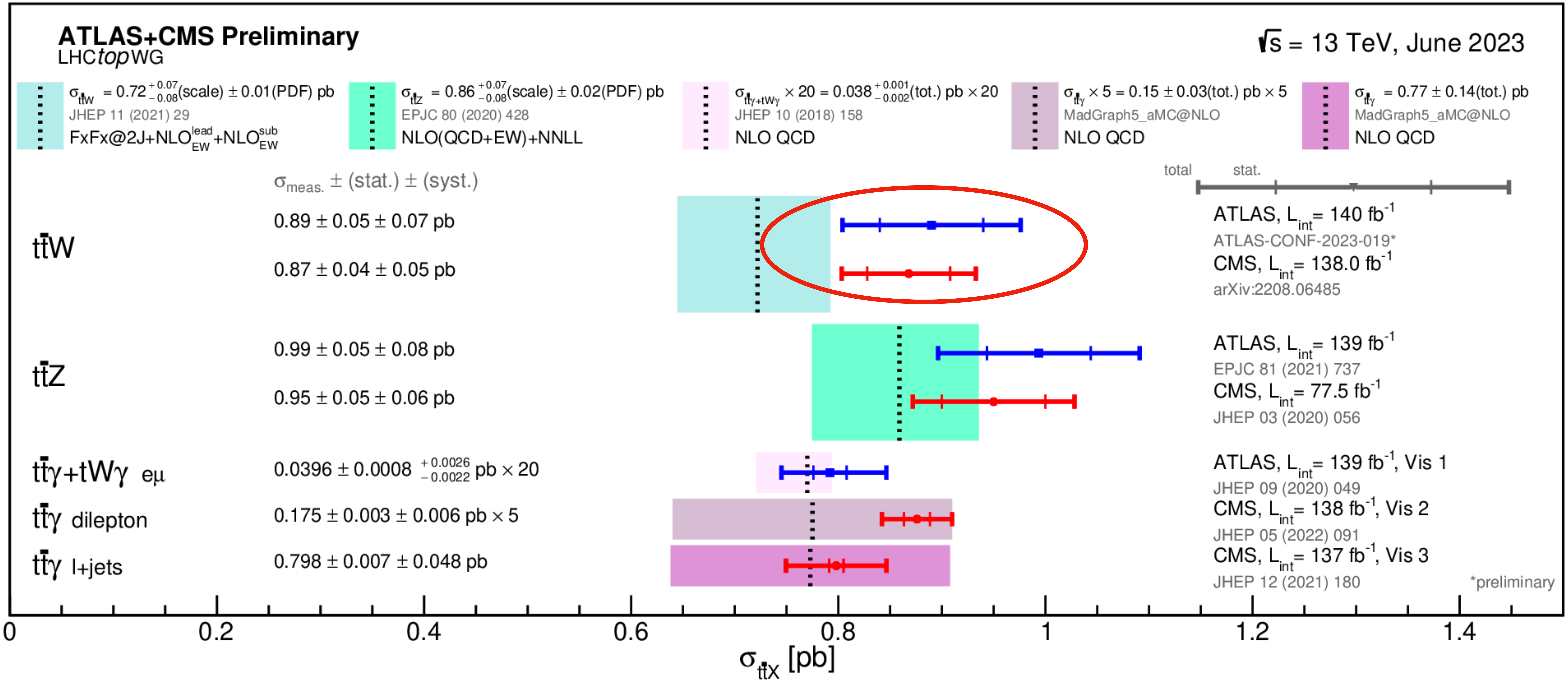
CMS 2305.13439, submitted to PLB



Eur. Phys. J. C 83 (2023) 496, 2303.15061

ttW

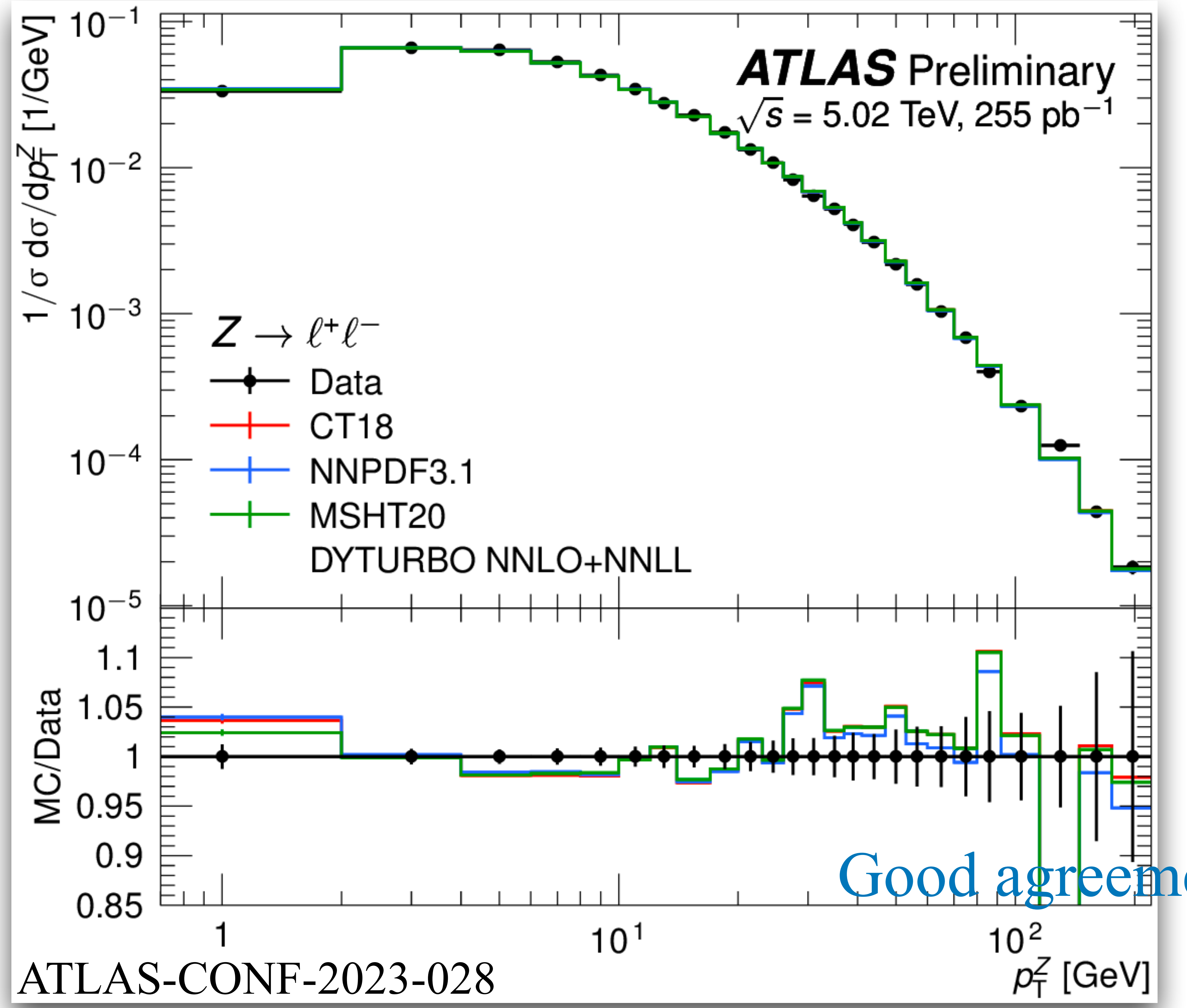
- ATLAS recently released a ttW measurement, slightly higher than the SM prediction, consistent with what CMS observed

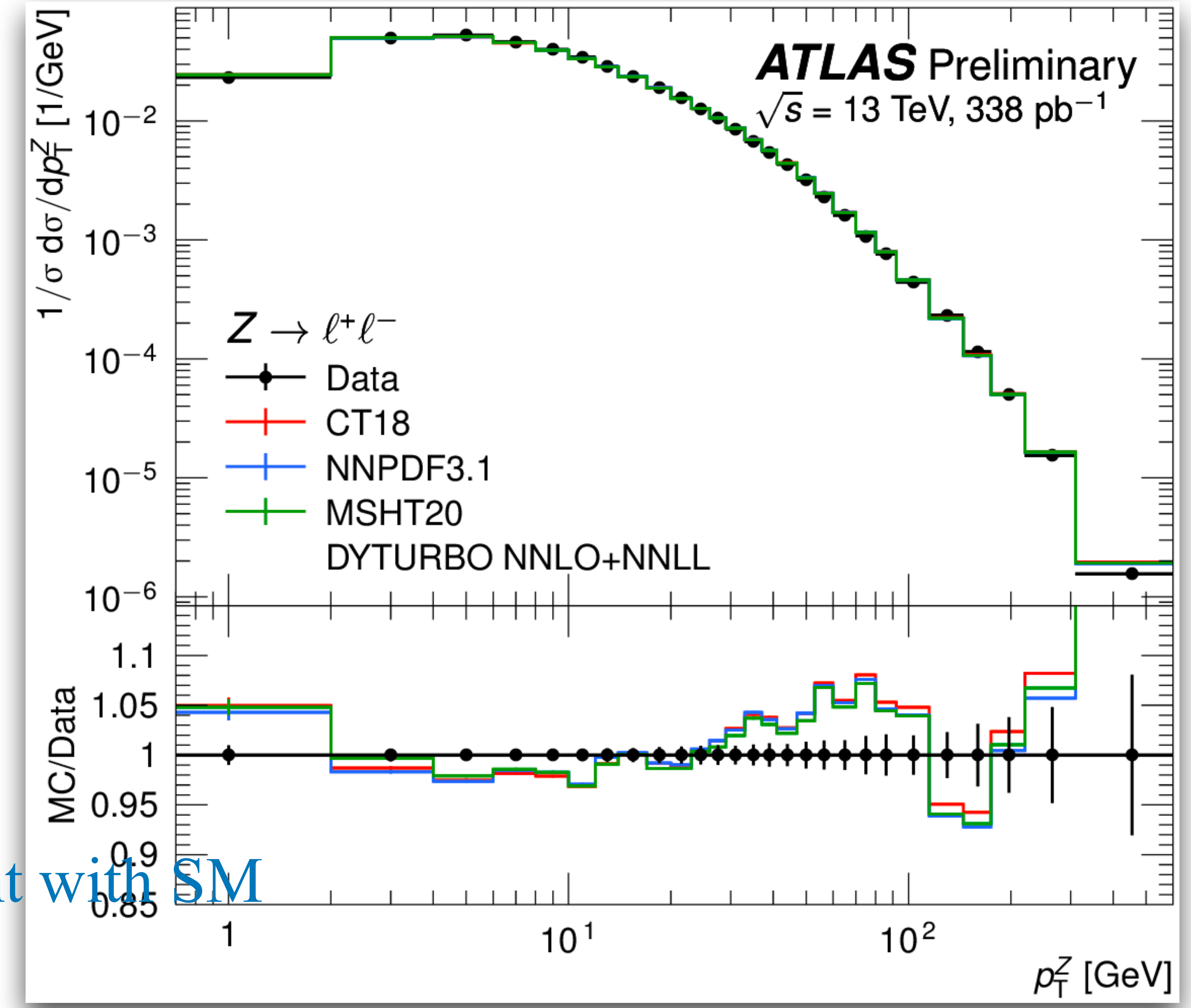


W/Z p_T spectra

- Transverse momentum of W/Z bosons are measured using reduced instantaneous luminosity (low-μ) for both 5.02 and 13 TeV

<μ> ~ 2 with respect to ~ 30 in full Run2

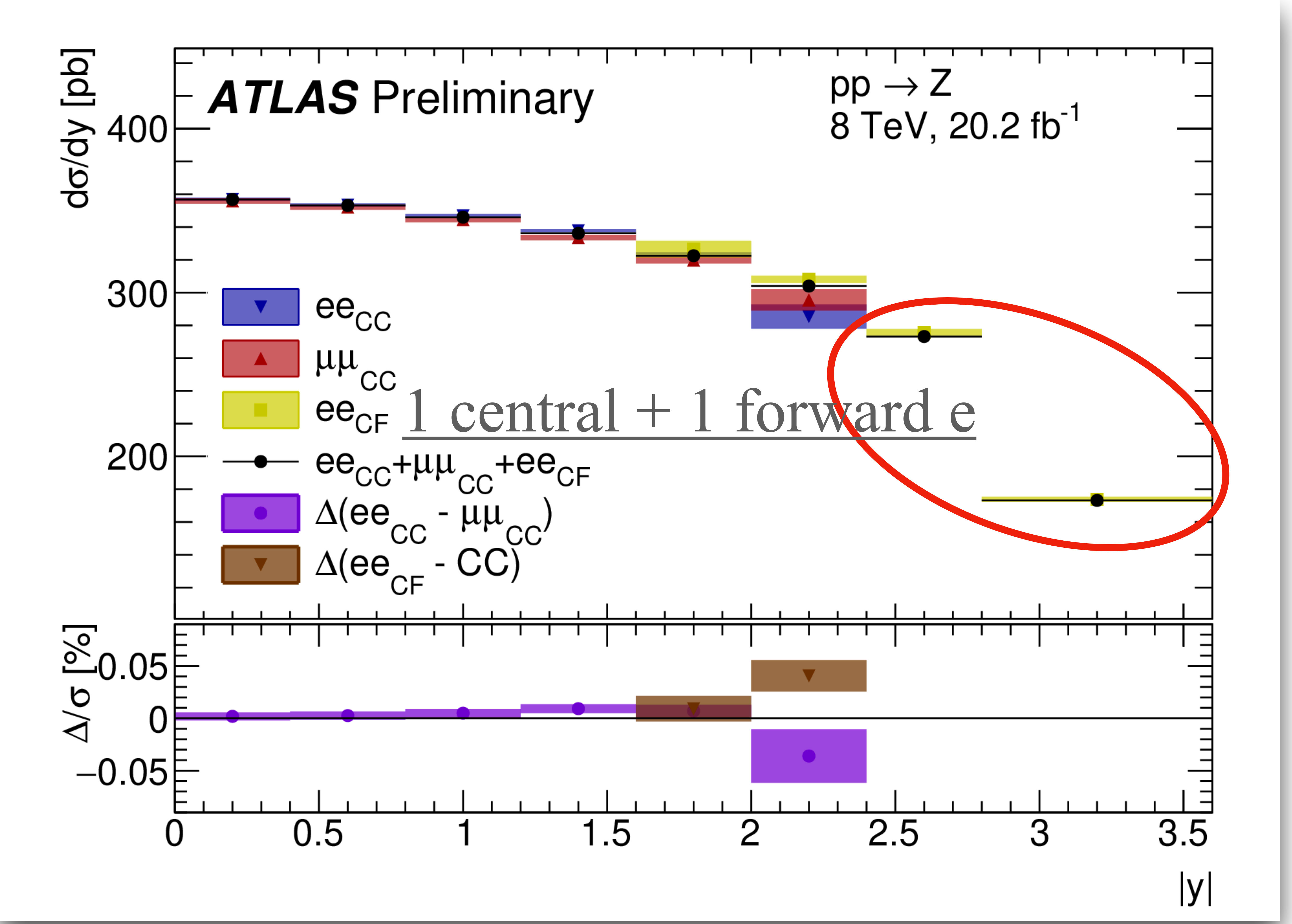


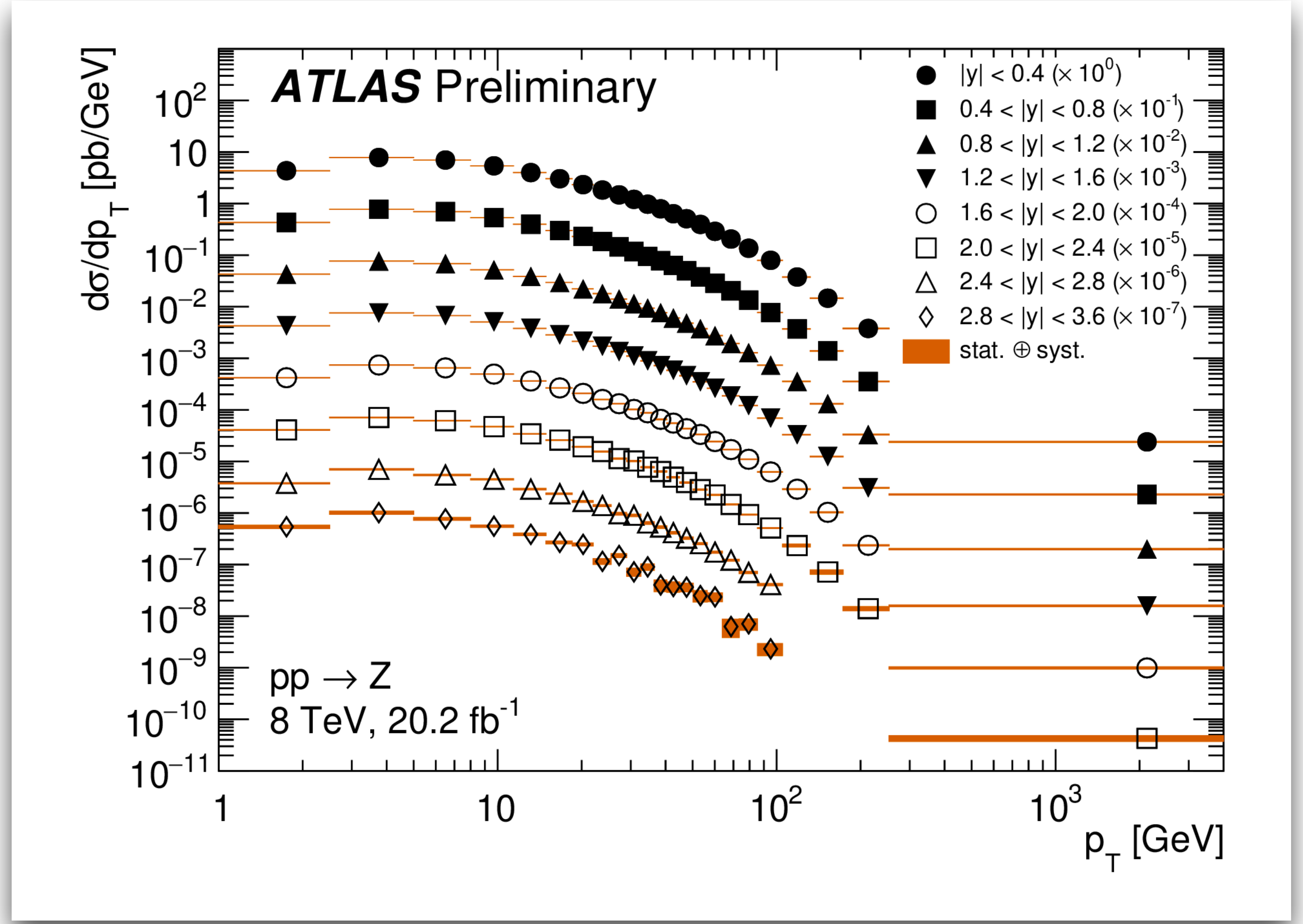


Good agreement with SM

Z p_T double differential XS

- New measurements on Z p_T in different rapidity regions are performed, with extended far forward region, by ATLAS

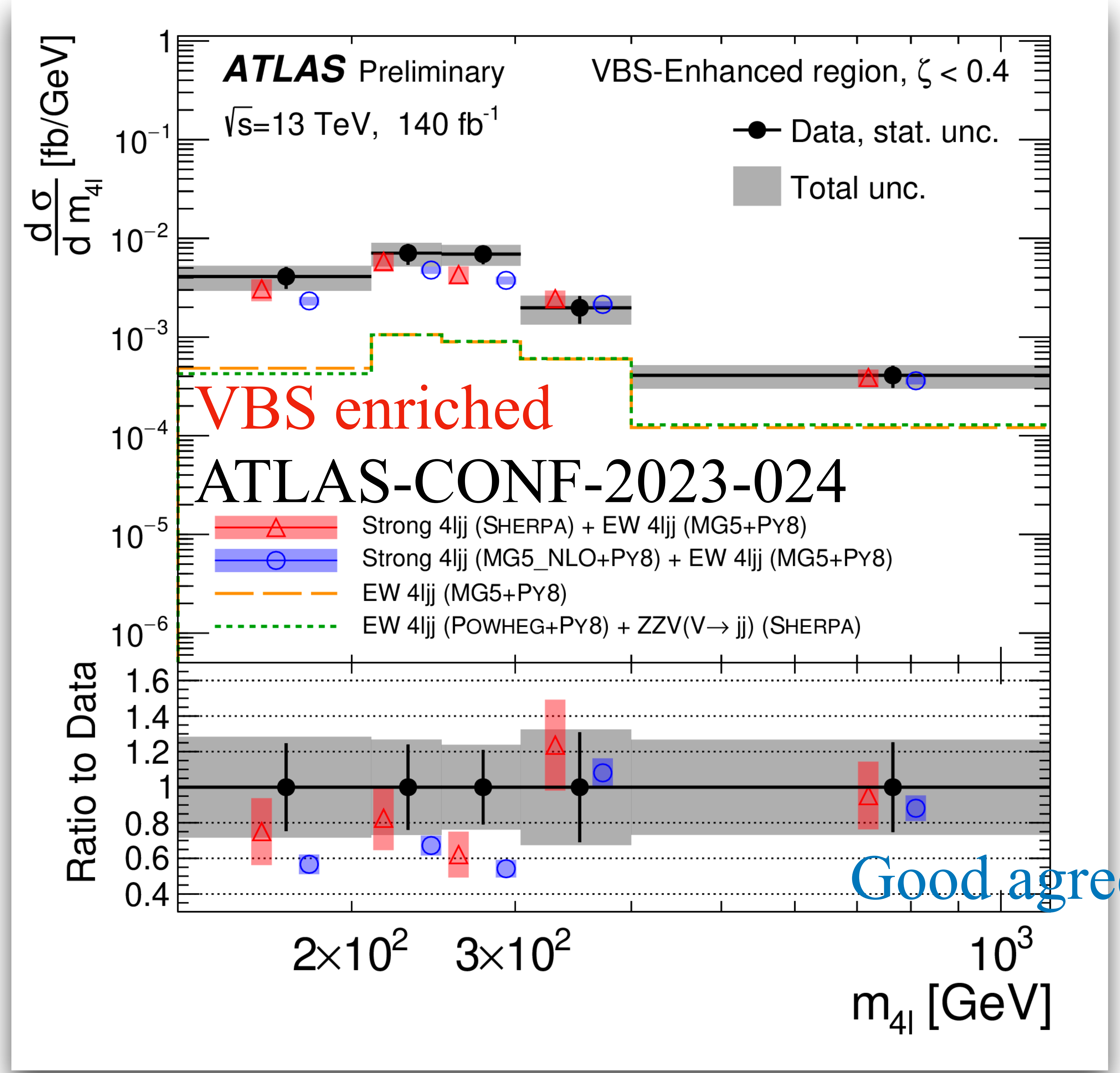


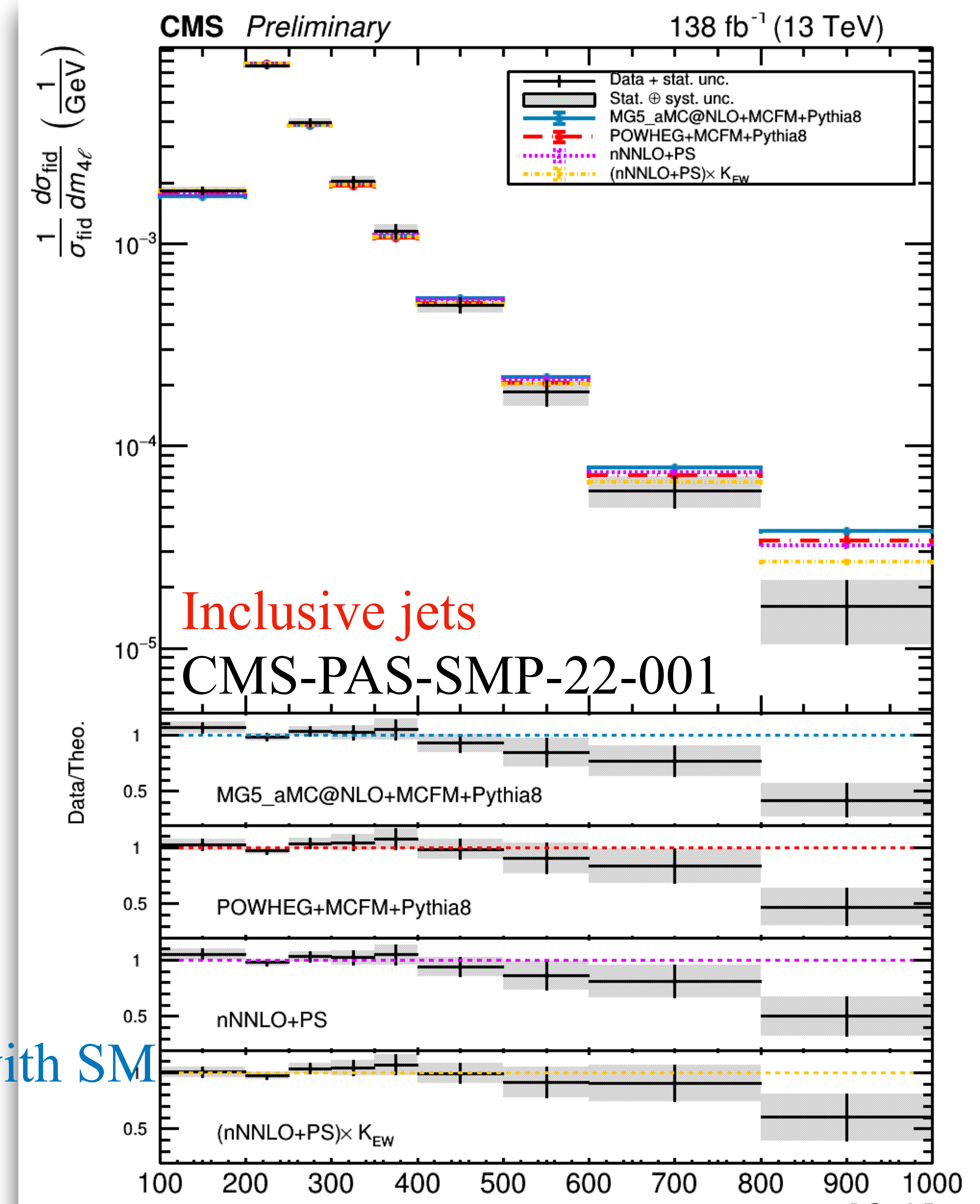


ATLAS-CONF-2023-013

ZZ differential XS

- ZZ(4L)+jets differential XS is measured



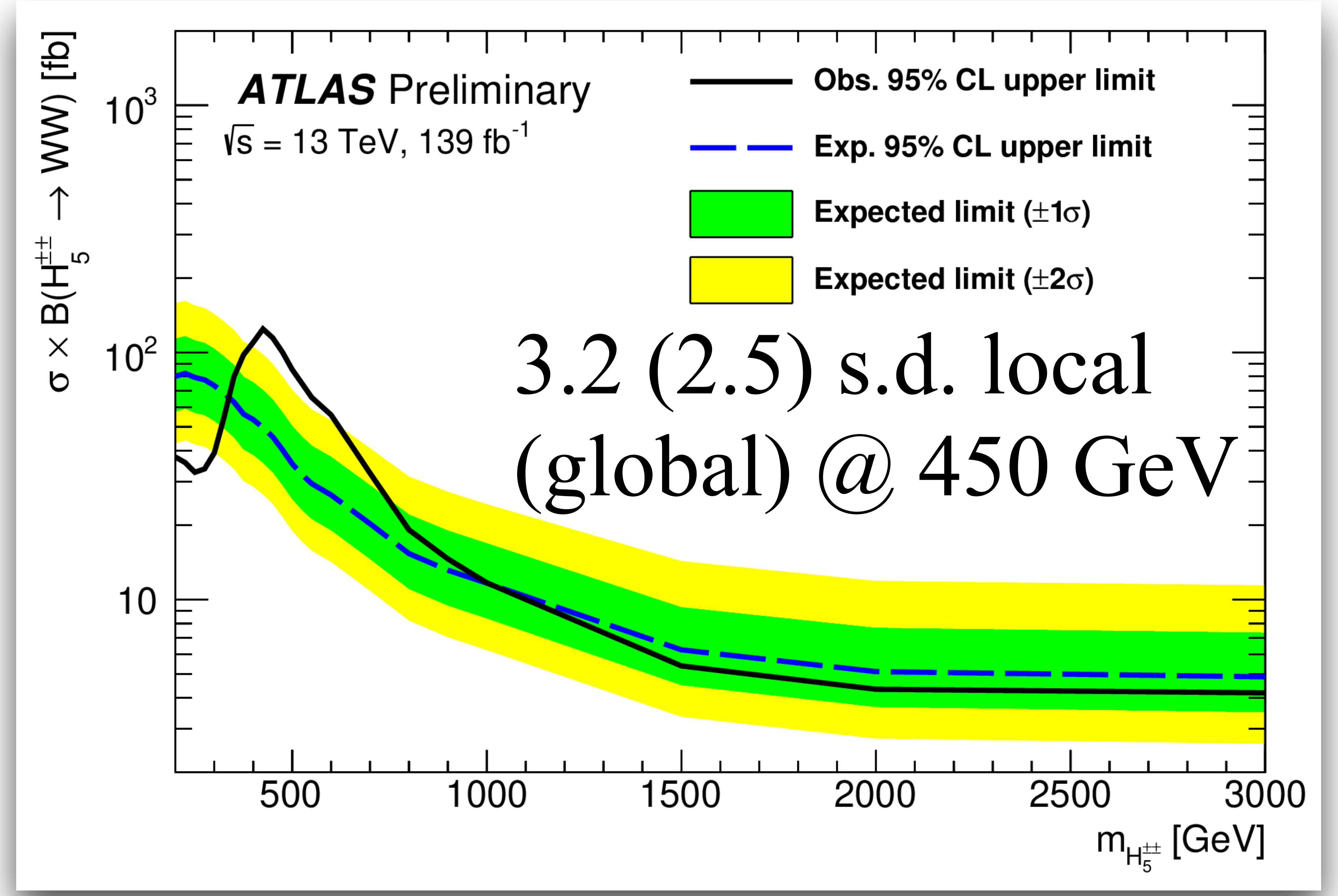


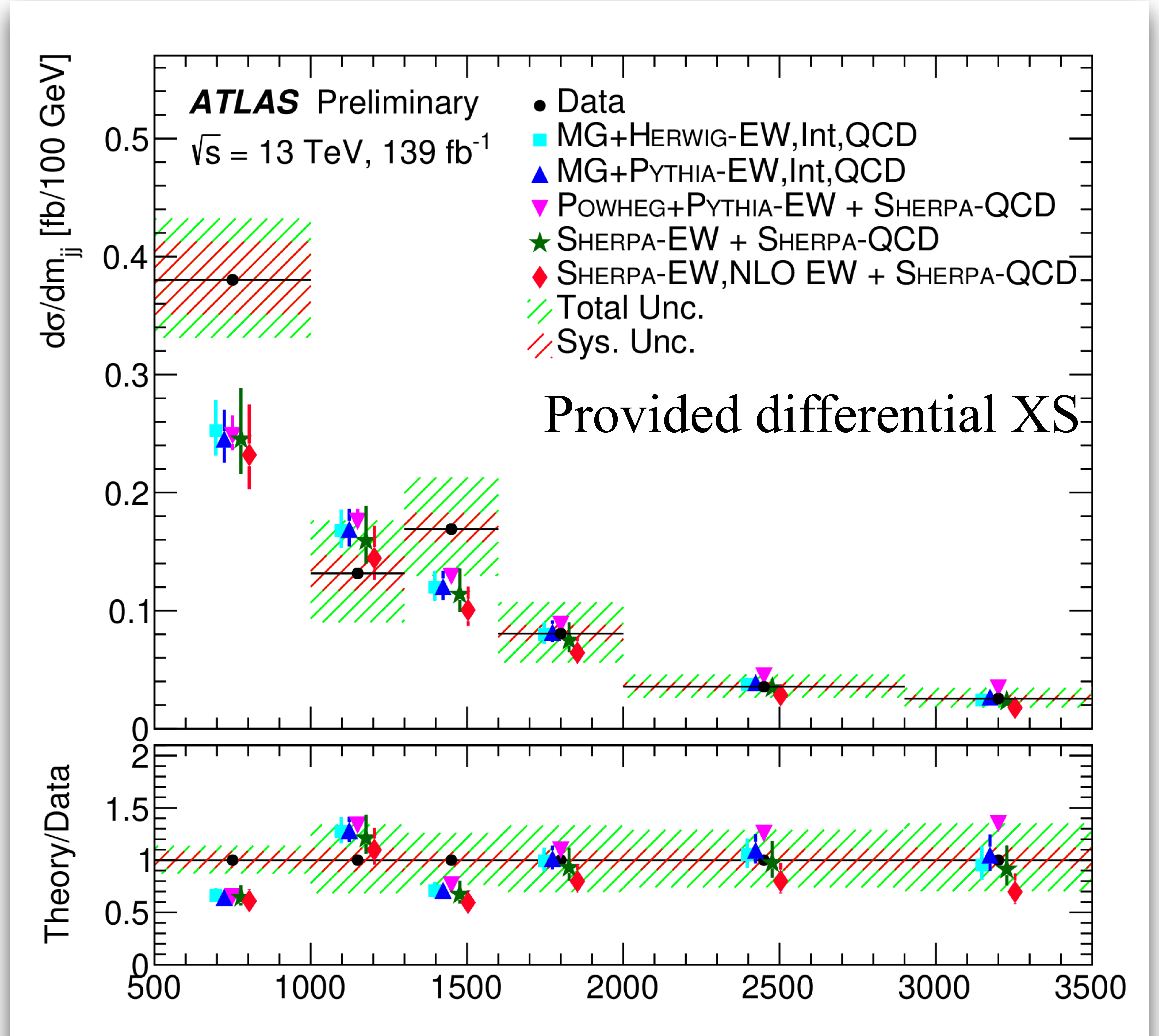
Good agreement with SM

EW corrections should mitigate high-tail diff

VBS ssWW

- Vector boson scattering same-signed WW production provides largest ratio of pure EWK to mixed QCD-EWK production
- Highly sensitive to gauge-boson self-couplings, EFTs and BSM (doubly-charged Higgs etc.)



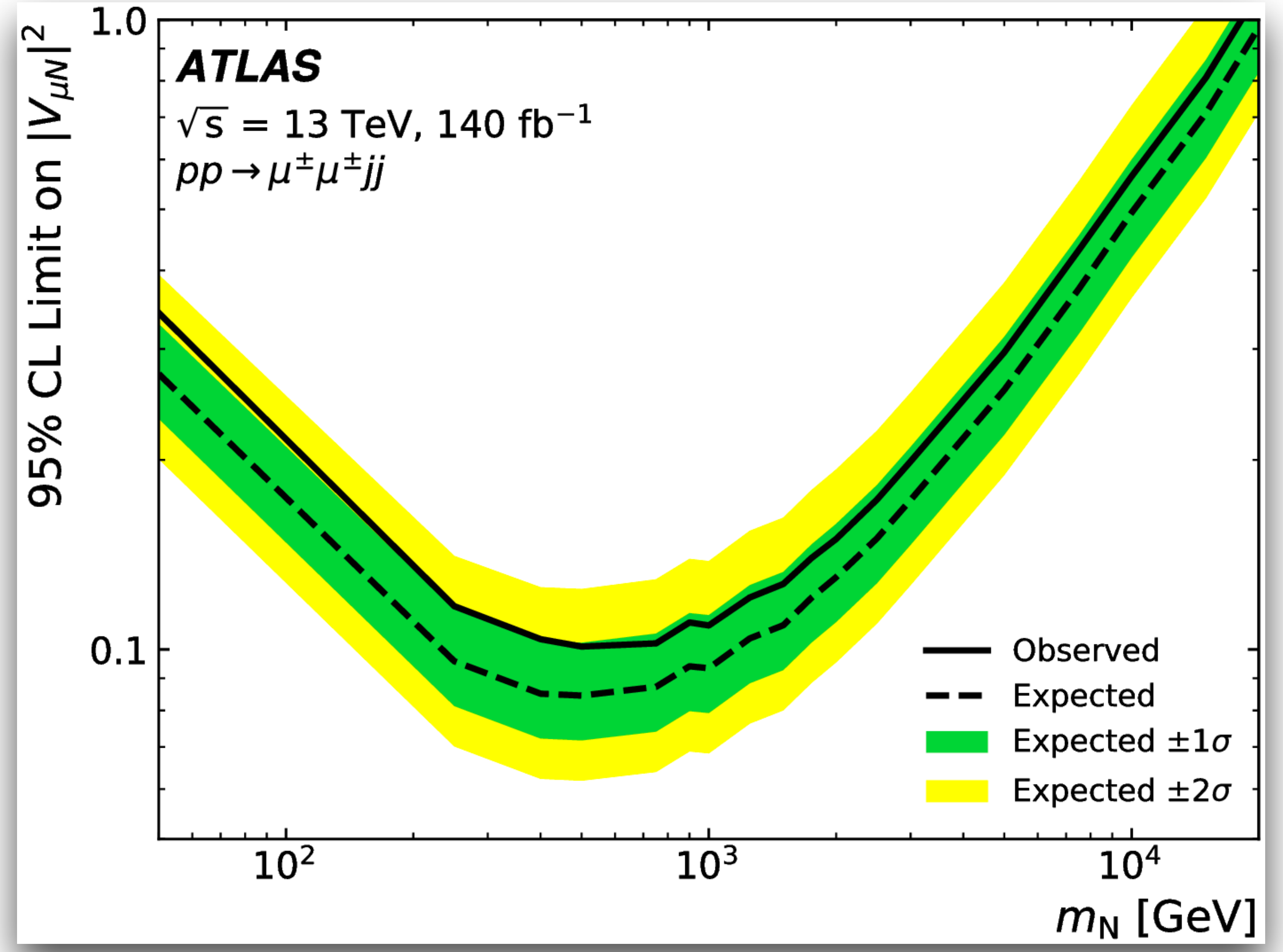


ATLAS-CONF-2023-023

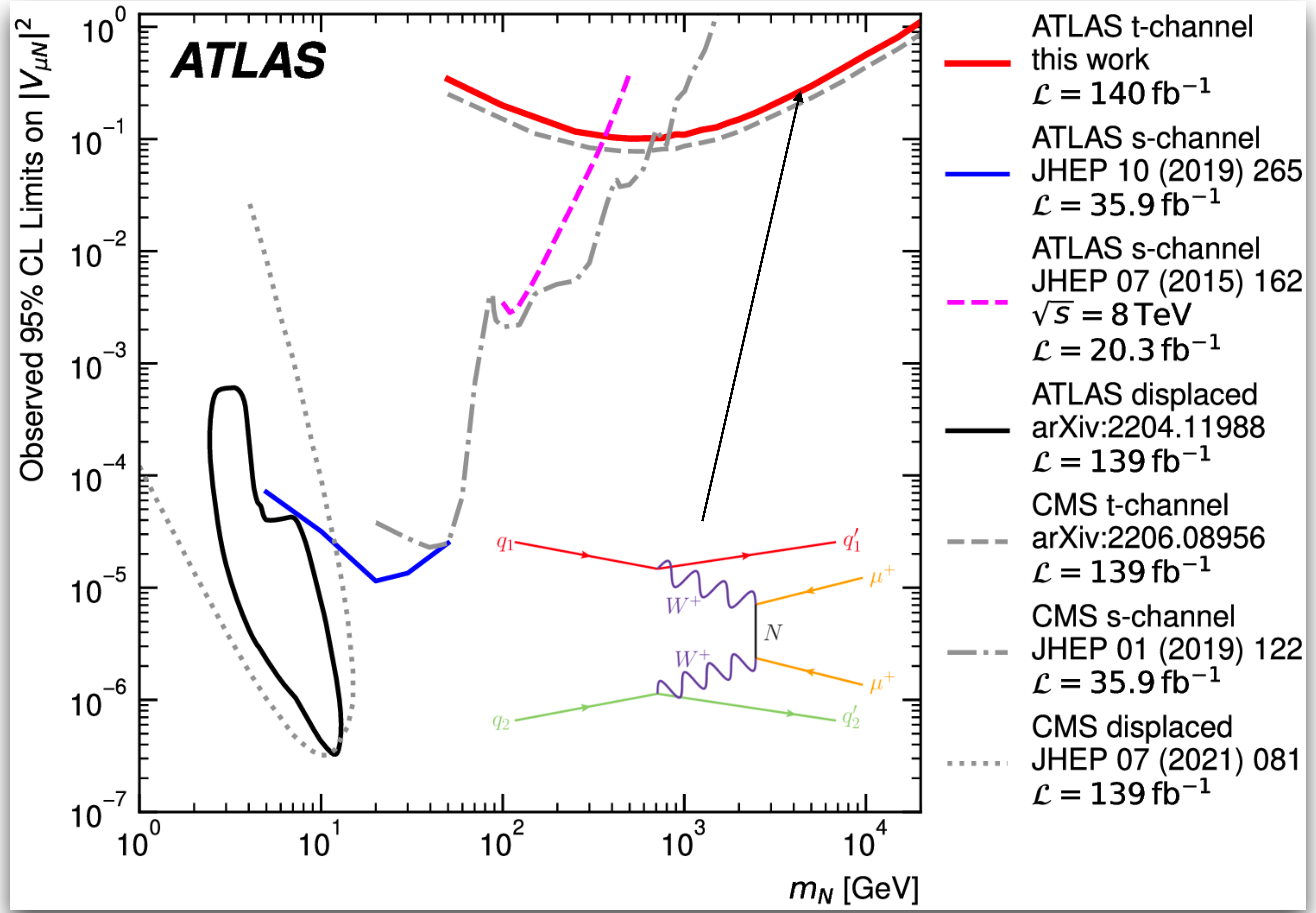
VBS ssWW for Majorana neutrinos

EXOT-2020-06

- Study the Majorana nature of neutrinos at colliders
- Set upper limits of the squared muon-neutrino-heavy-neutrino mass-mixing matrix element $|V_{\mu N}|^2$



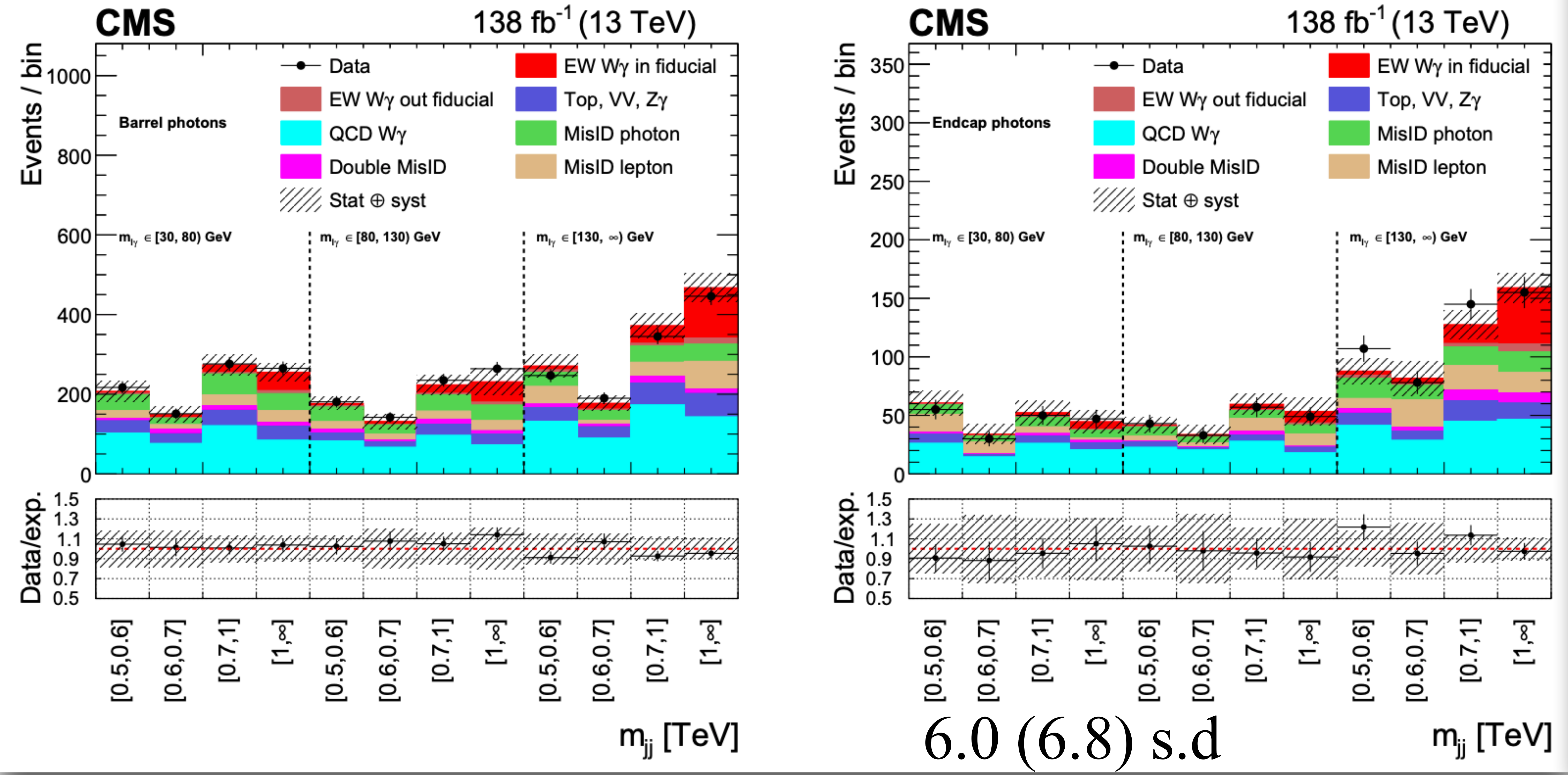
Assume no e, τ mixing with N



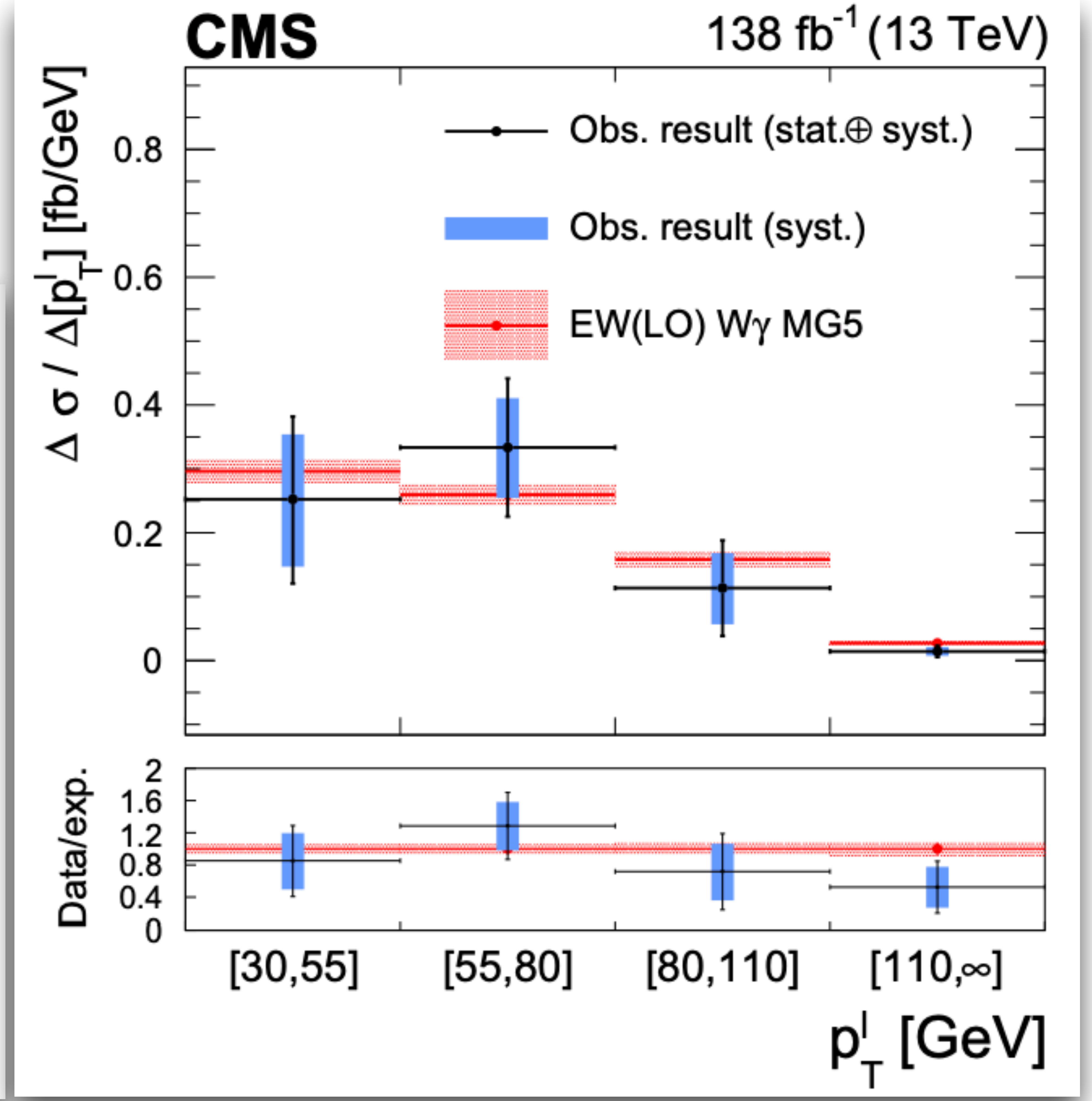
VBS $W\gamma$

arXiv:2212.12592 accepted by PRD

- First observation at 13 TeV
- Provide fiducial and differential XS
- Stringent limits on aQGCs: f_{M2-4} and f_{T6-7}



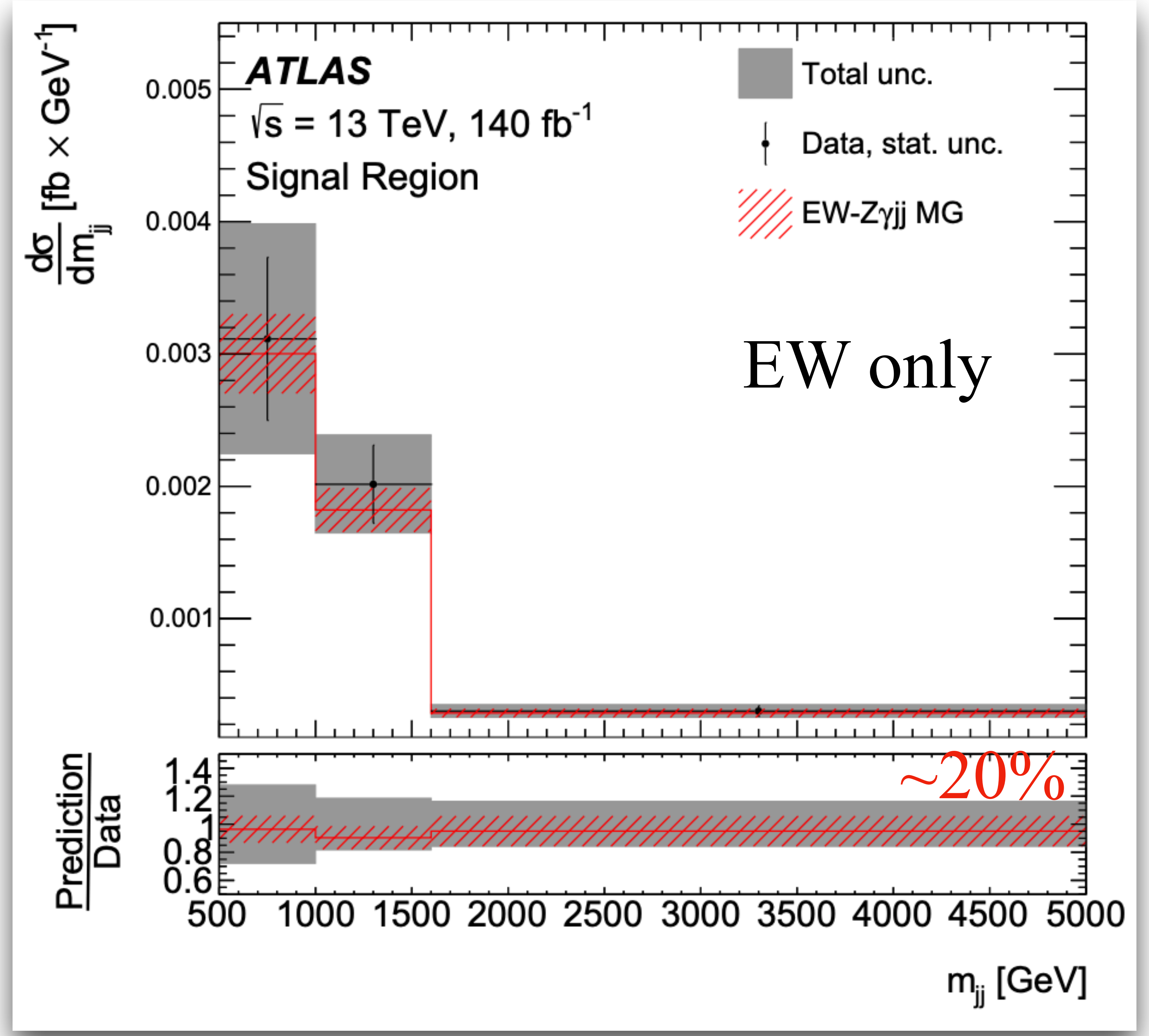
6.0 (6.8) s.d

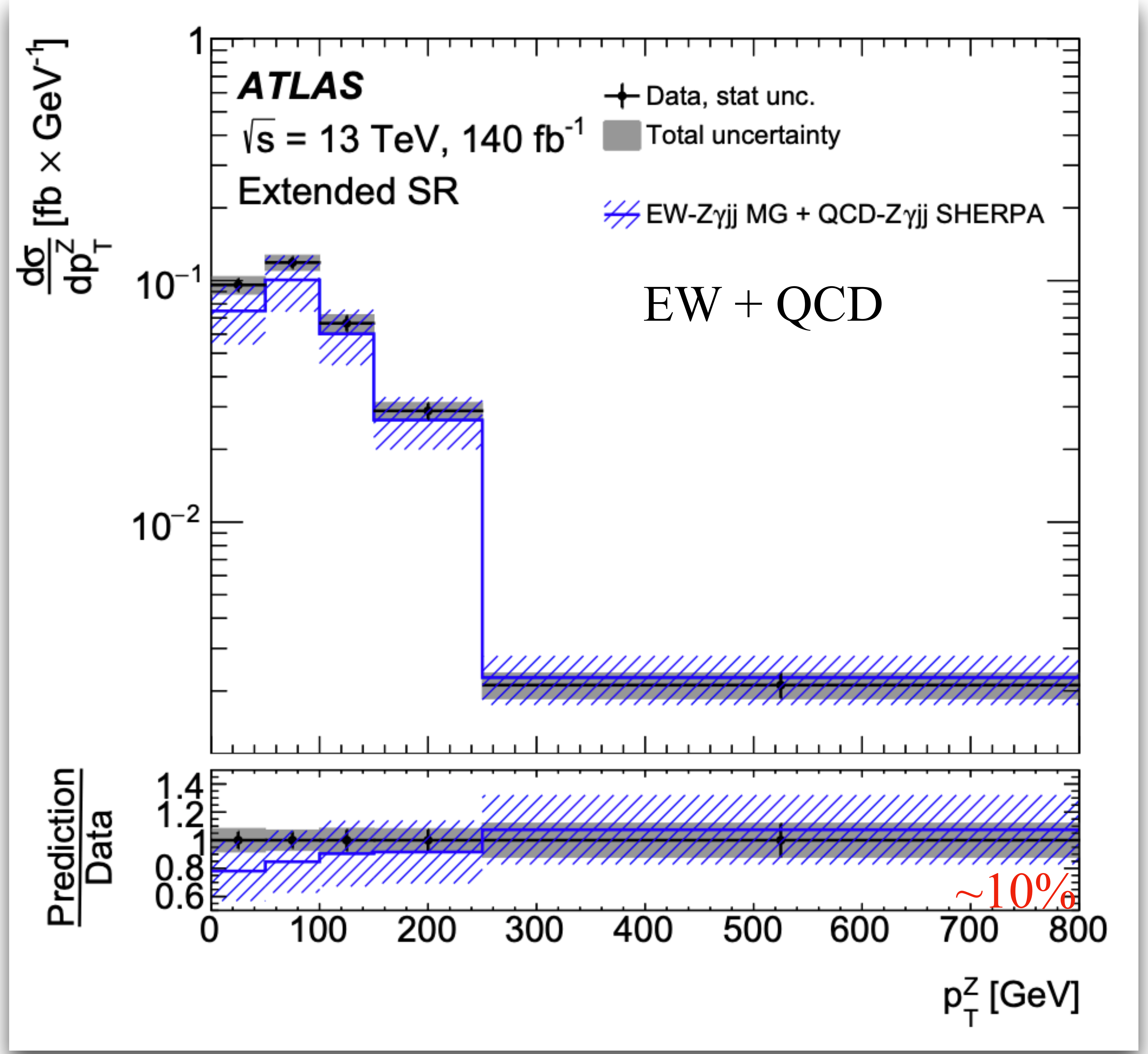


ATL-COM-PHYS-2023-282

VBS $Z\gamma$

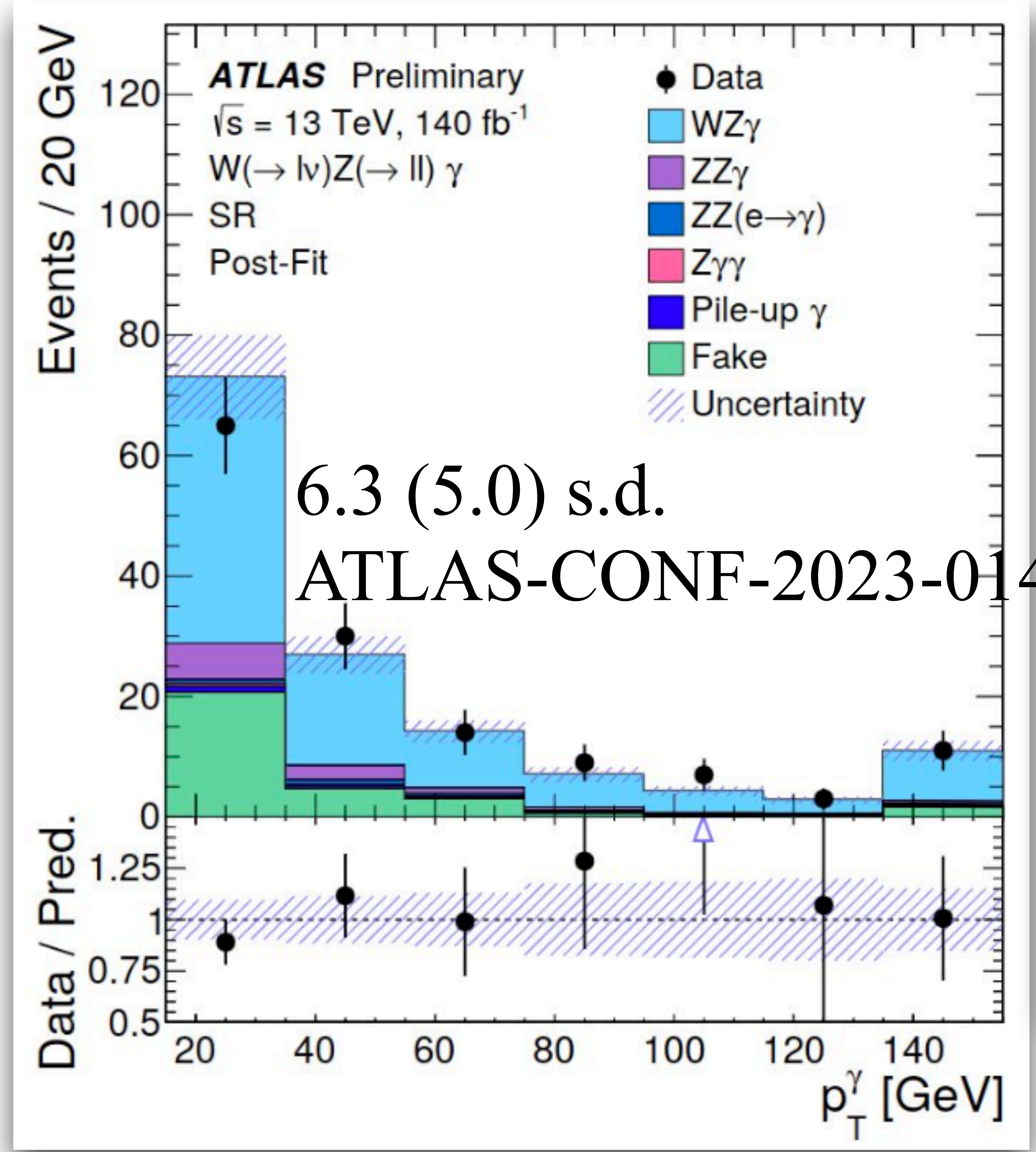
- Observation with >5 s.d.
- Provide fiducial and differential XS



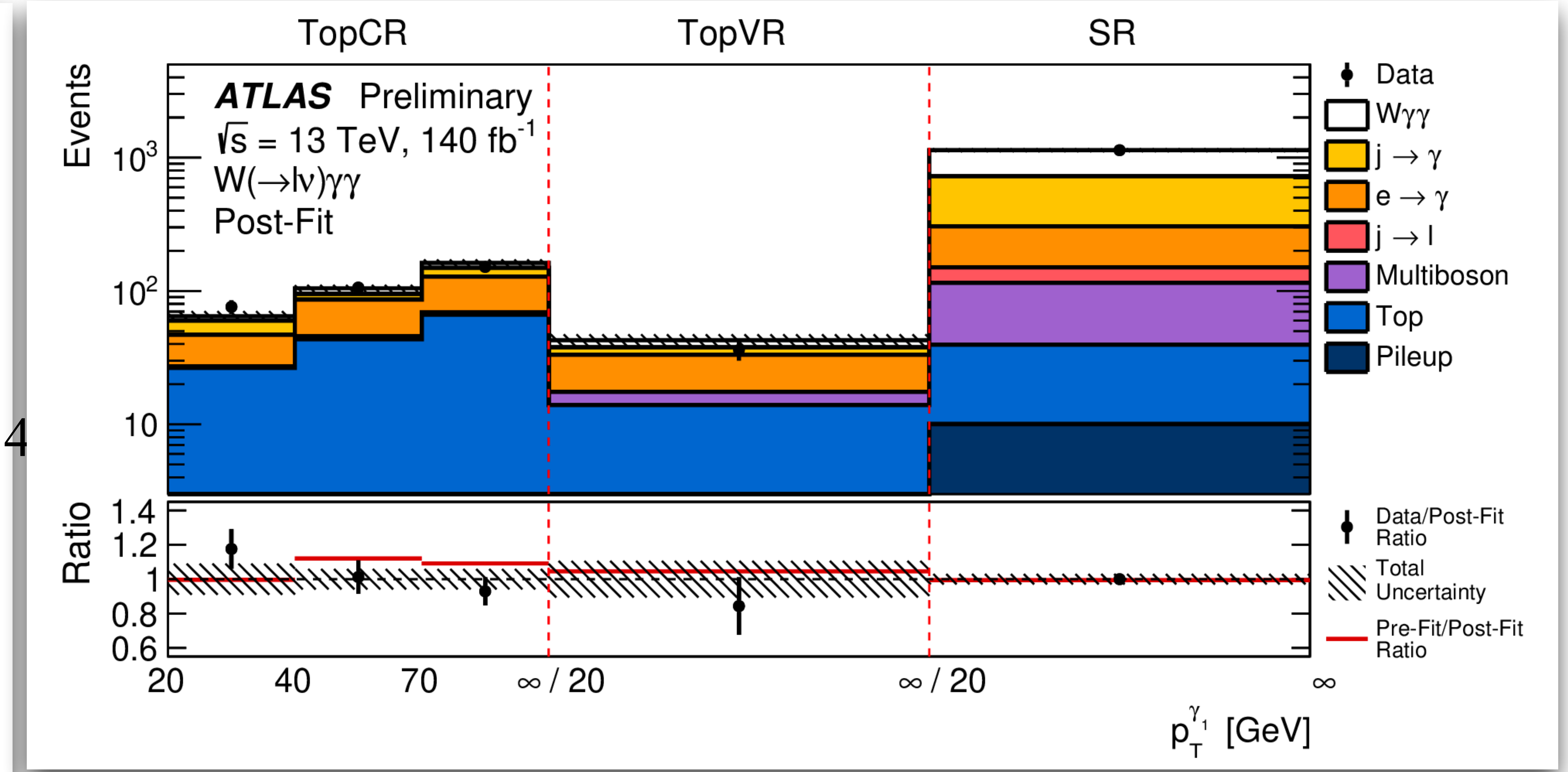


Triboson

- *WZγ* observation with 3L+*γ*
- *Wγγ* observation with 1L+*γγ*

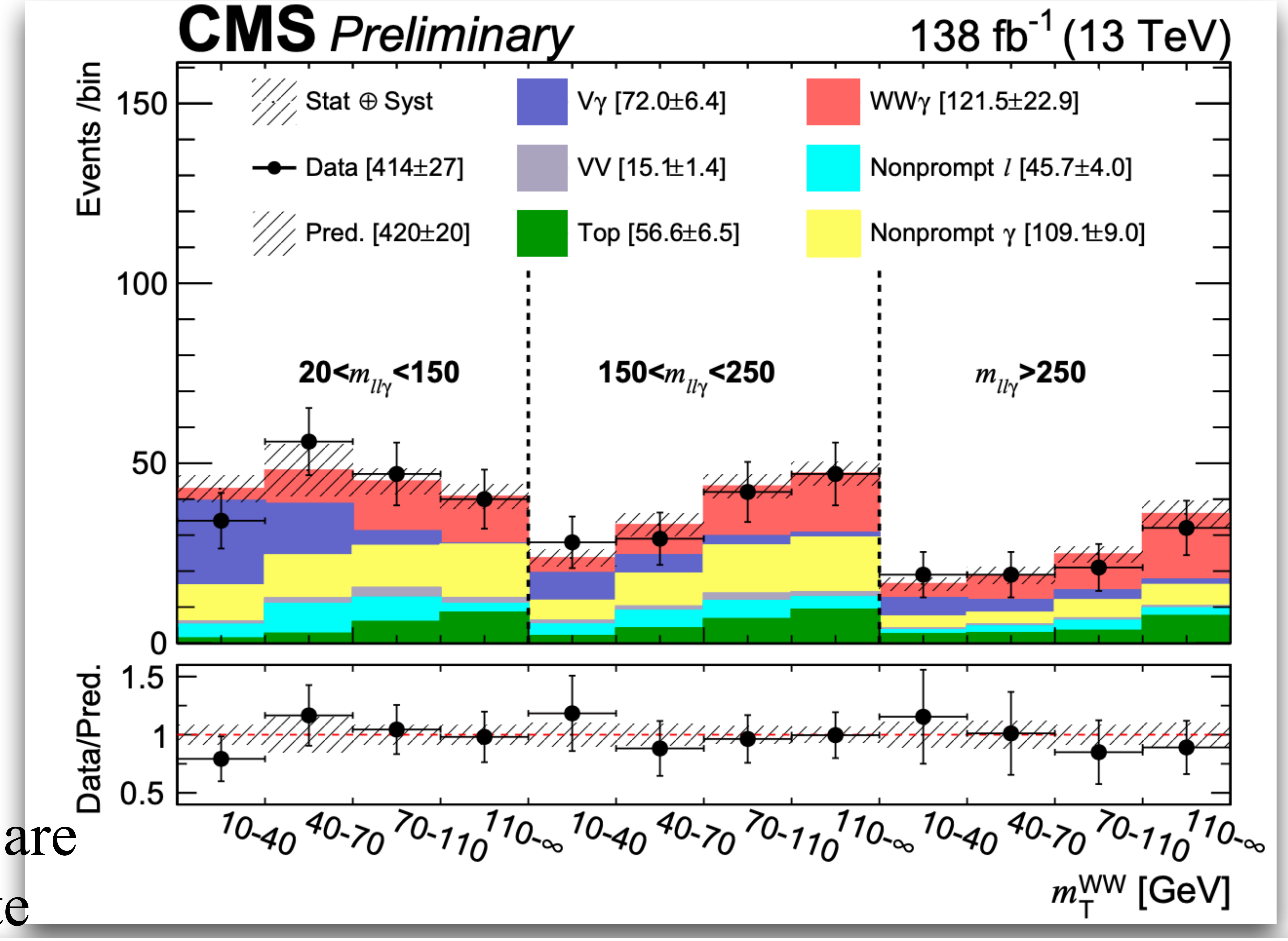


6.3 (5.0) s.d.
ATLAS-CONF-2023-014



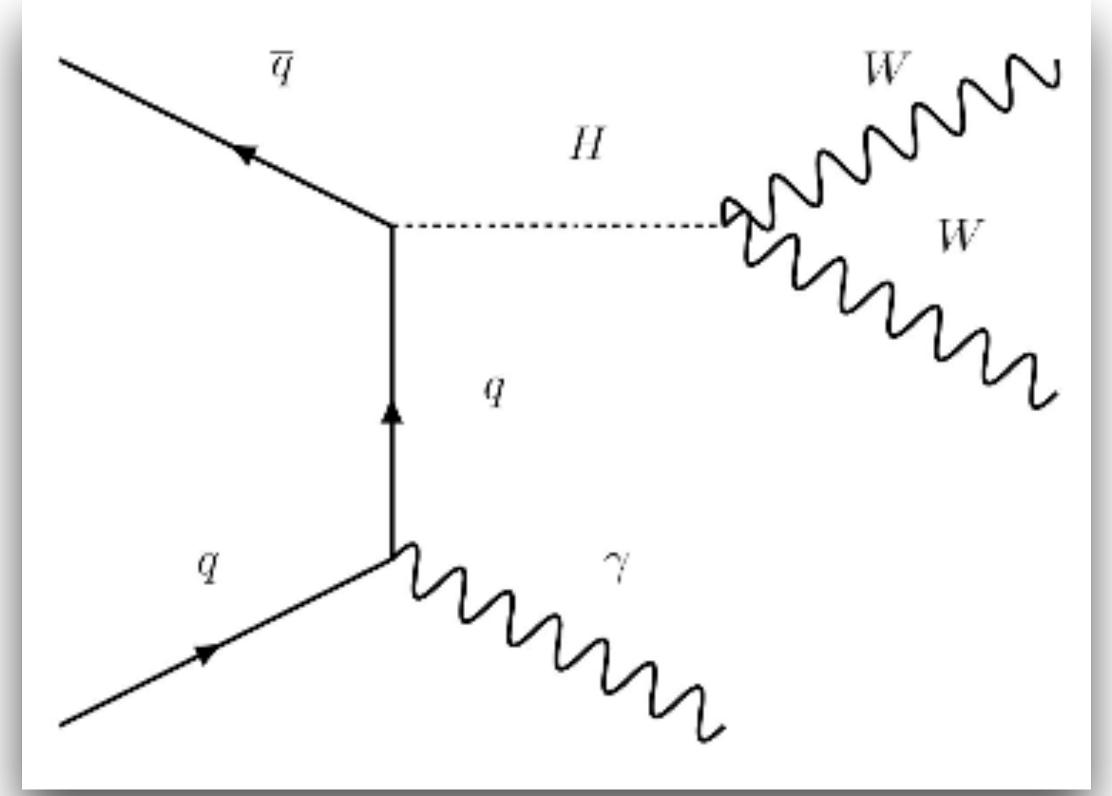
5.6 (5.6) s.d. ATLAS-CONF-2023-005

Triboson



- $WW\gamma$ observation with 5.6 (4.7) s.d.
- Also provide Higgs couplings to light quarks (uds) with further optimization based on Higgs
  - $\Delta\phi_{ll} < 2.5$
  - $\Delta R_{ll} < 2.3$
  - $\Delta R_{l\gamma} > 0.8$

Some of constraints are most stringent to date



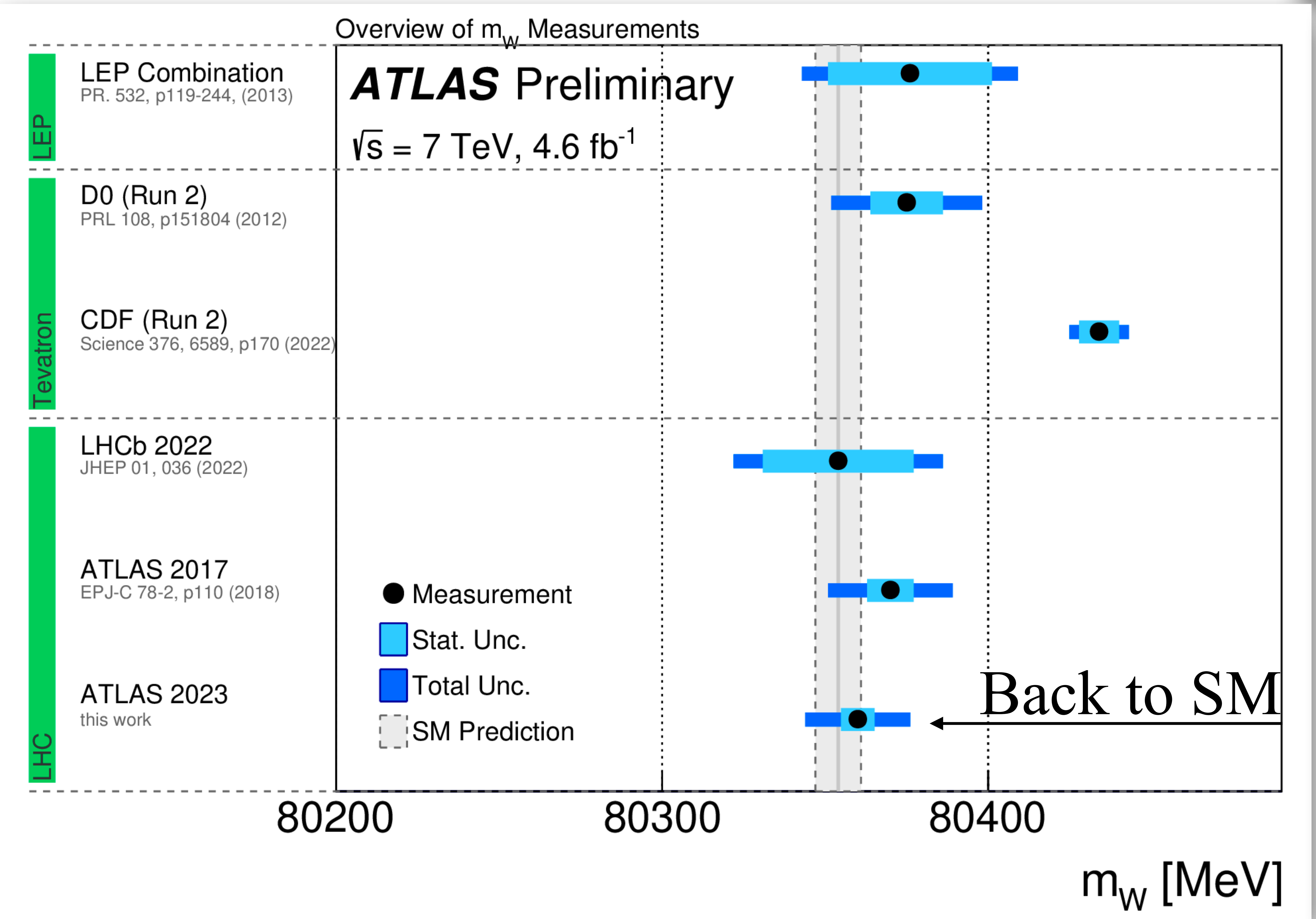
Process	σ_{up} pb exp.(obs.)	Yukawa couplings limits exp.(obs.)
$u\bar{u} \to H + \gamma \to e\mu\gamma$	0.067 (0.085)	$\lvert\kappa_u\rvert \leq 13000$ (16000)
$d\bar{d} \to H + \gamma \to e\mu\gamma$	0.058 (0.072)	$\lvert\kappa_d\rvert \leq 14000$ (17000)
$s\bar{s} \to H + \gamma \to e\mu\gamma$	0.049 (0.068)	$\lvert\kappa_s\rvert \leq 1300$ (1700)
$c\bar{c} \to H + \gamma \to e\mu\gamma$	0.067 (0.087)	$\lvert\kappa_c\rvert \leq 110(200)$

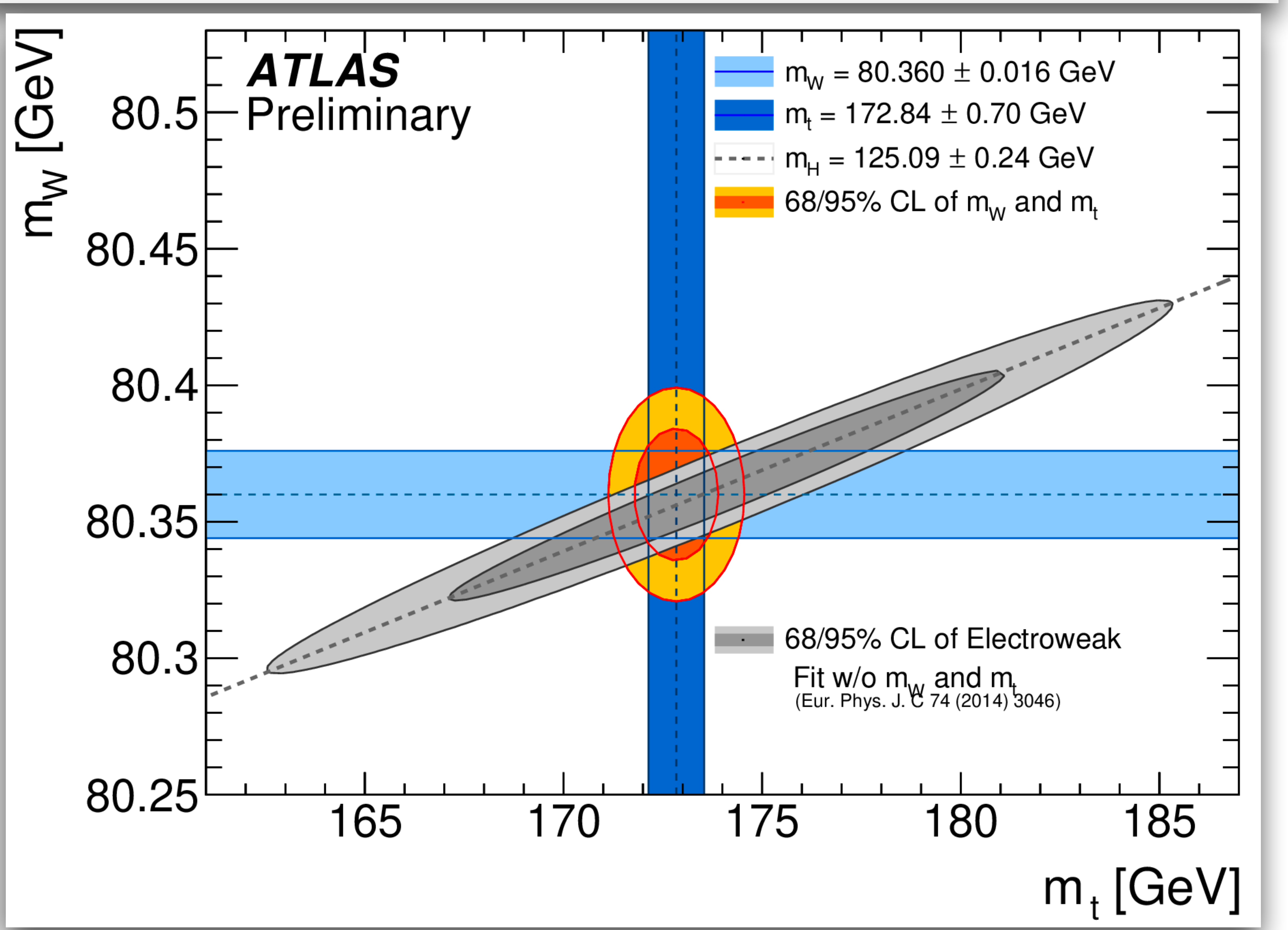
CMS-PAS-SMP-22-006

W mass

- W mass gives a very sensitive probe to new physics with model independence
- ATLAS W mass result came out with 7 TeV

$m_W = 80360 \pm 5(\text{stat.}) \pm 15(\text{syst.}) = 80360 \pm 16\,\text{MeV}$

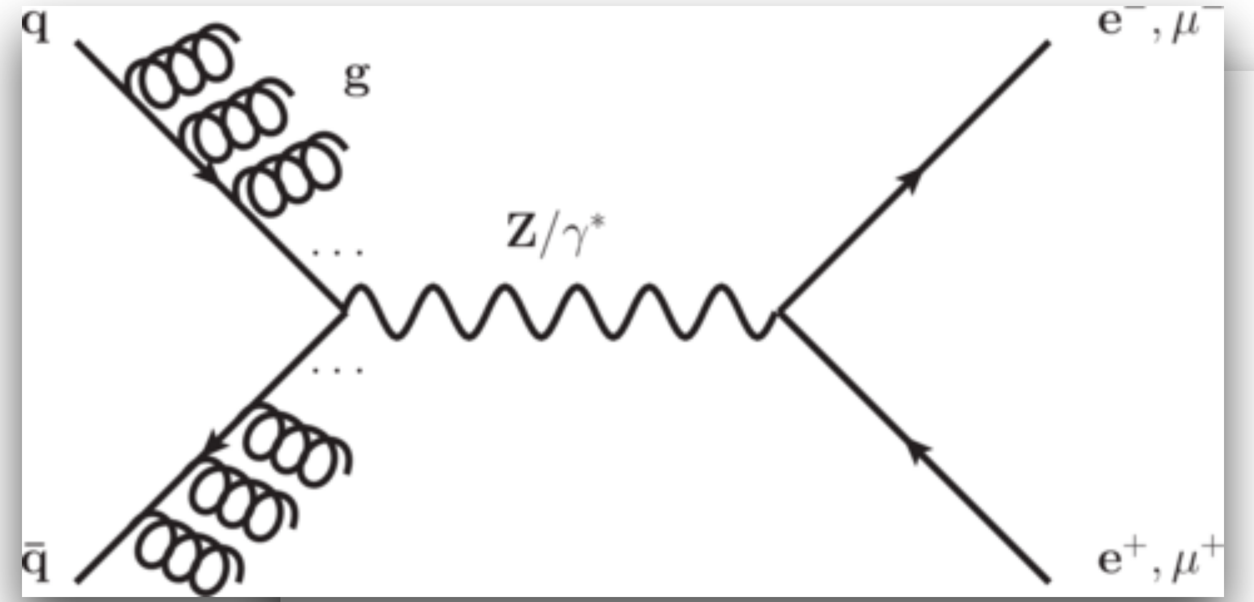


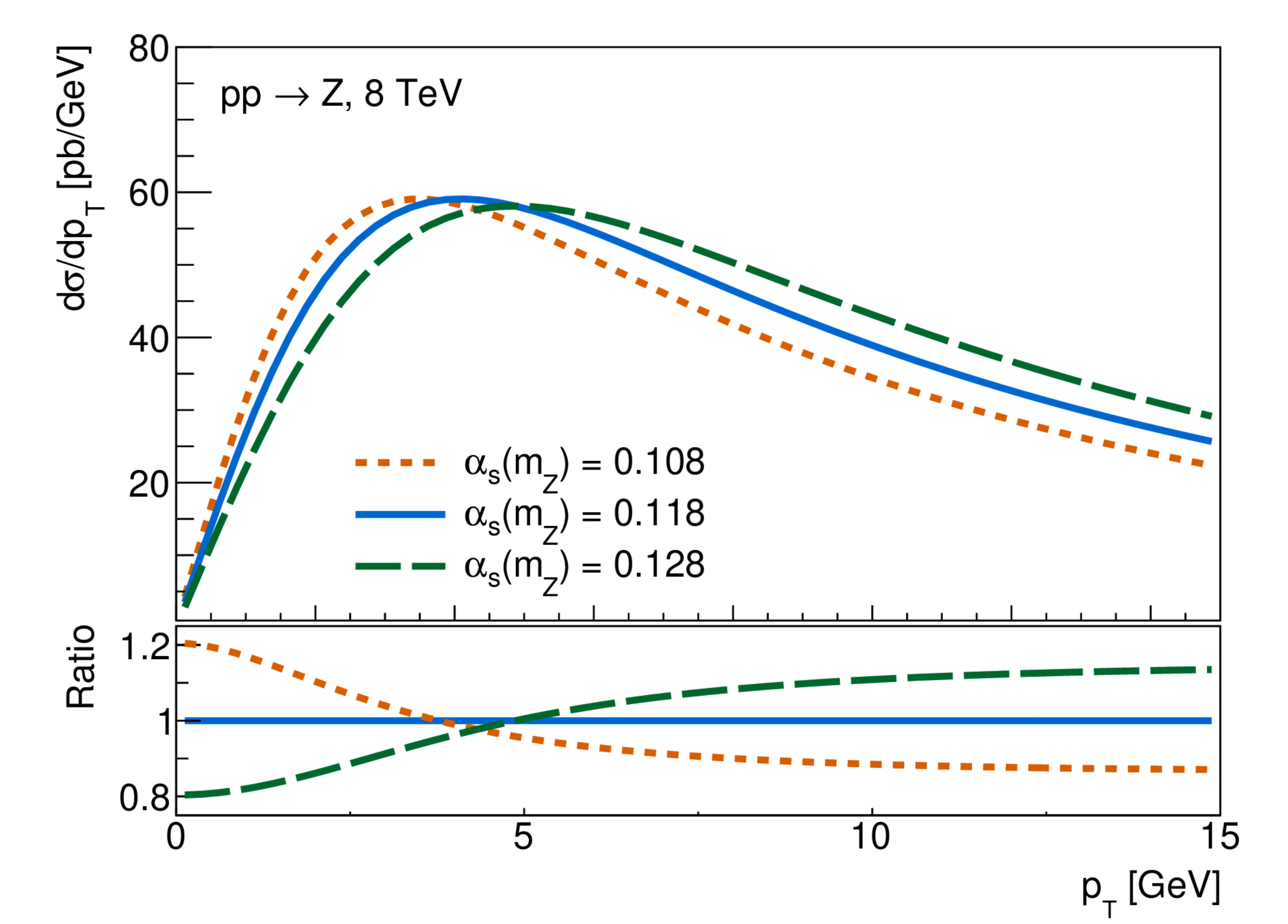


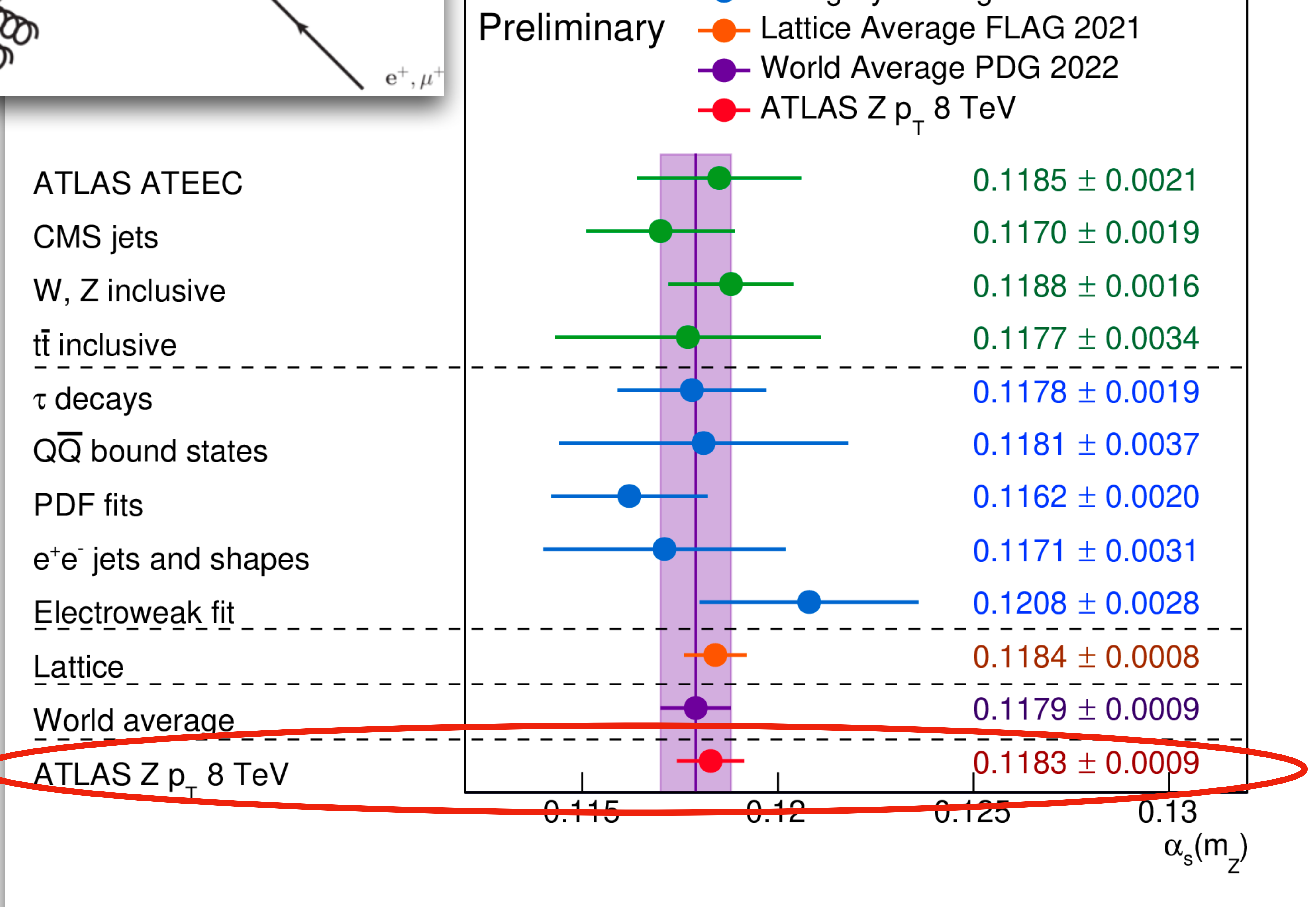
ATLAS-CONF-2023-004

α_S

- Most precise measurement of α_S to date, by ATLAS, using large-stat Zjets events with ISR







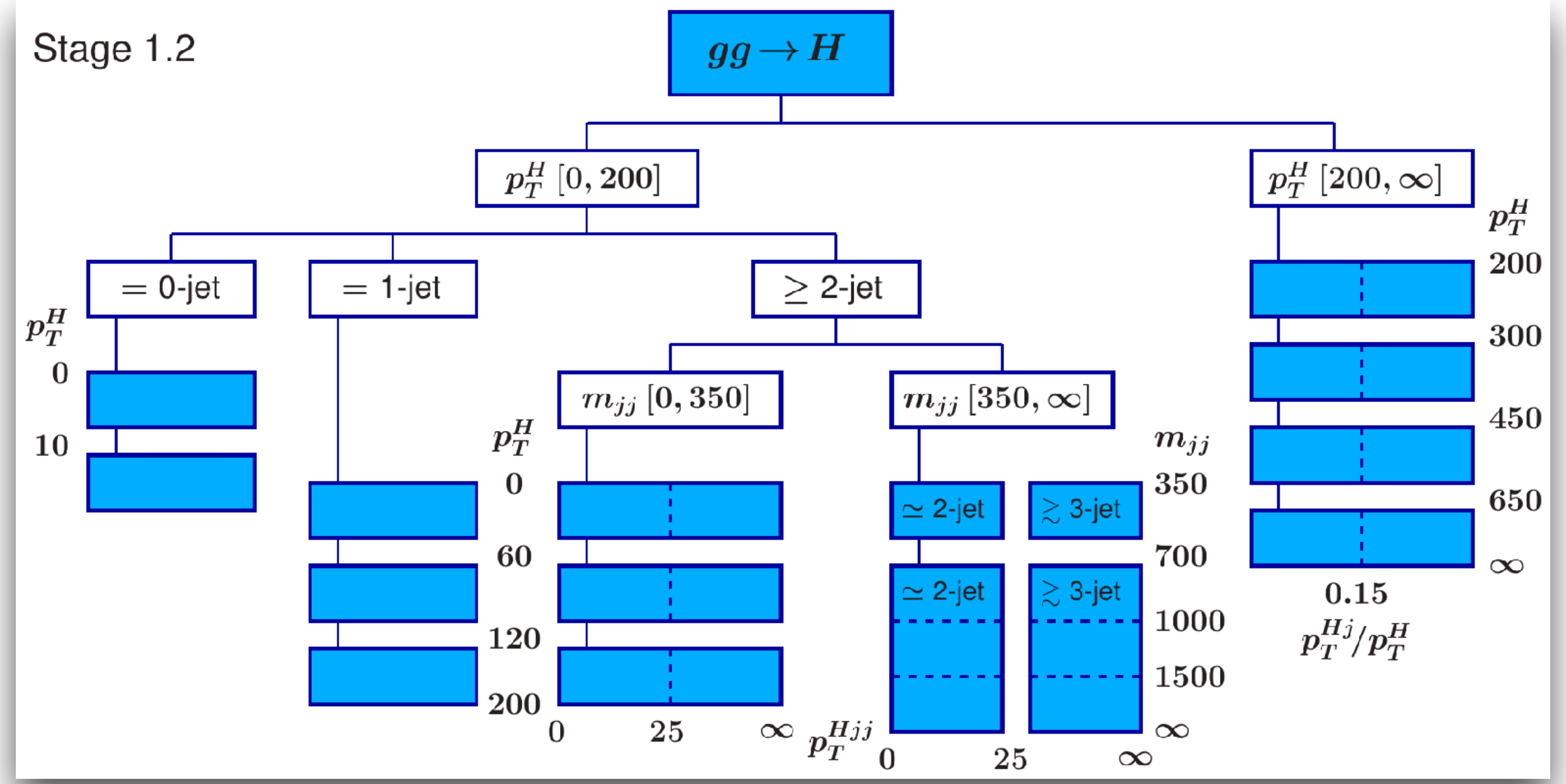
ATLAS-CONF-2023-015

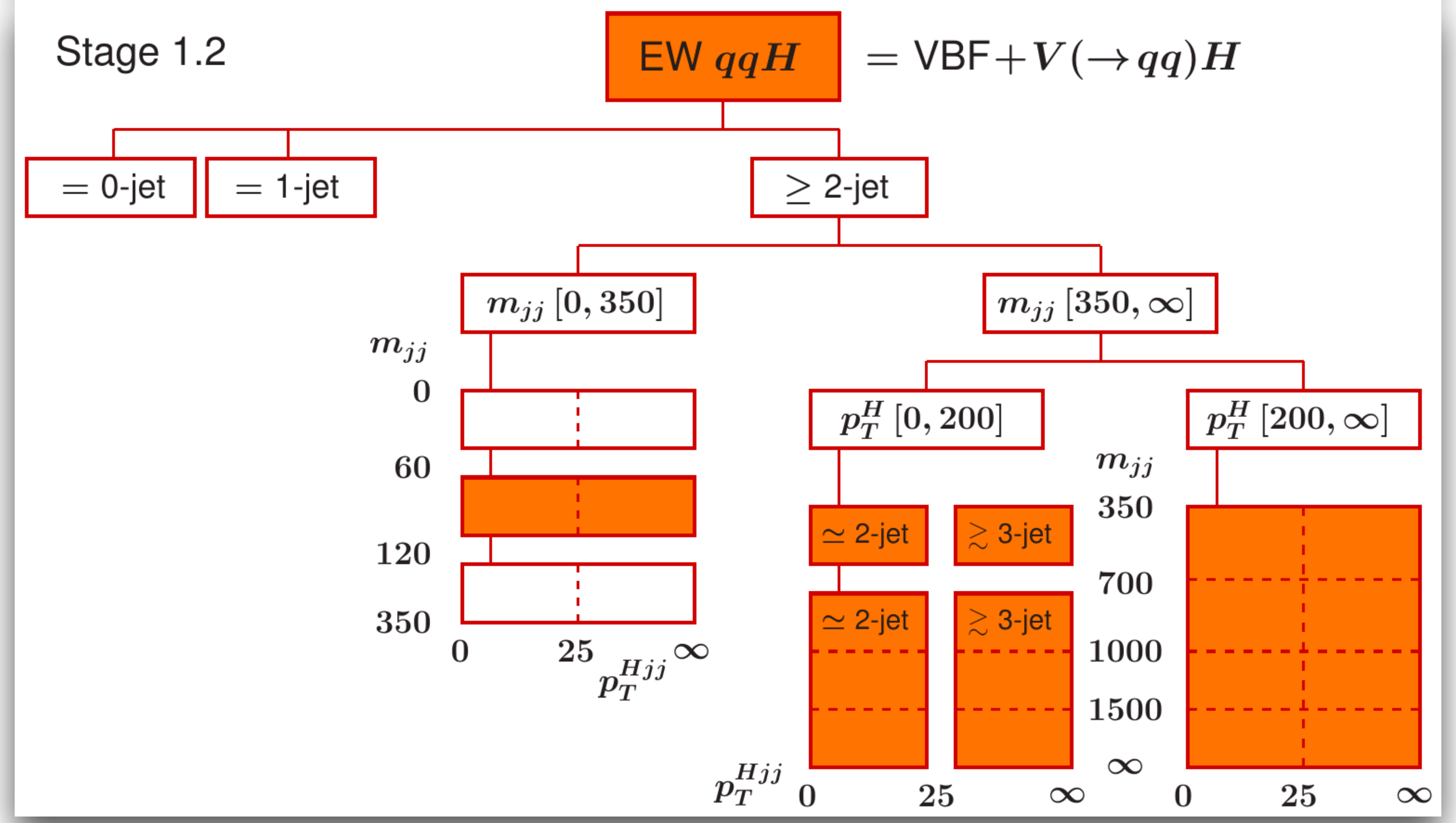
Higgs prod/decay

Higgs prod/decay

STXS

- The Simplified Template Cross Section (STXS) provides a pragmatic interface from the experimental accessibility to the theoretical handlers on SM and BSM phenomena, by using coarse kinematic bins
    - Balancing the experimental sensitivity (XS measurements with maximum sensitivities with deeply optimized cuts) and the model independence (differential XS measurements with fine kinematic bins using simple cuts)
- The experiments are reaching the precision for measuring STXS in Stage 1.2



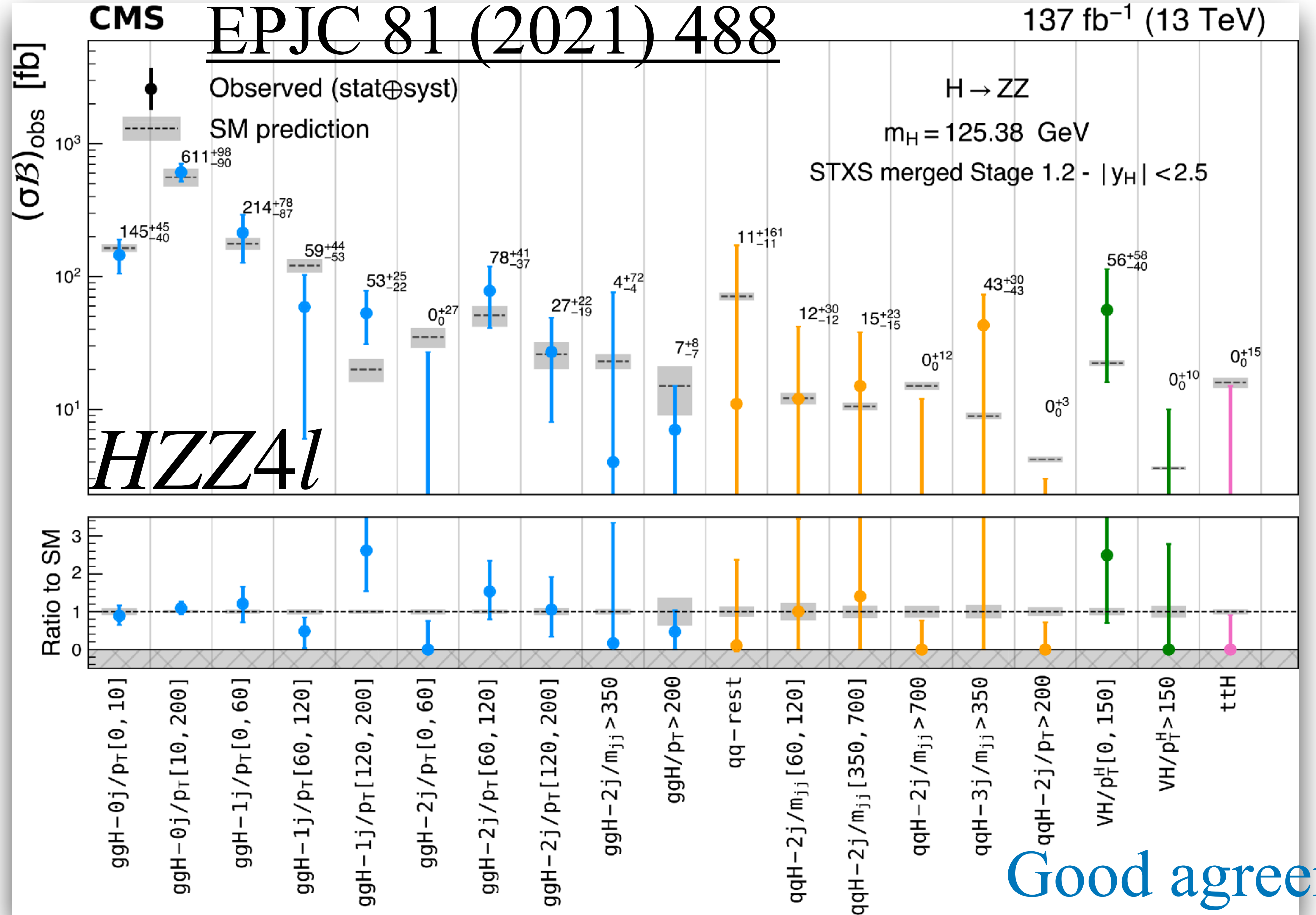


STXS in the "golden" channels

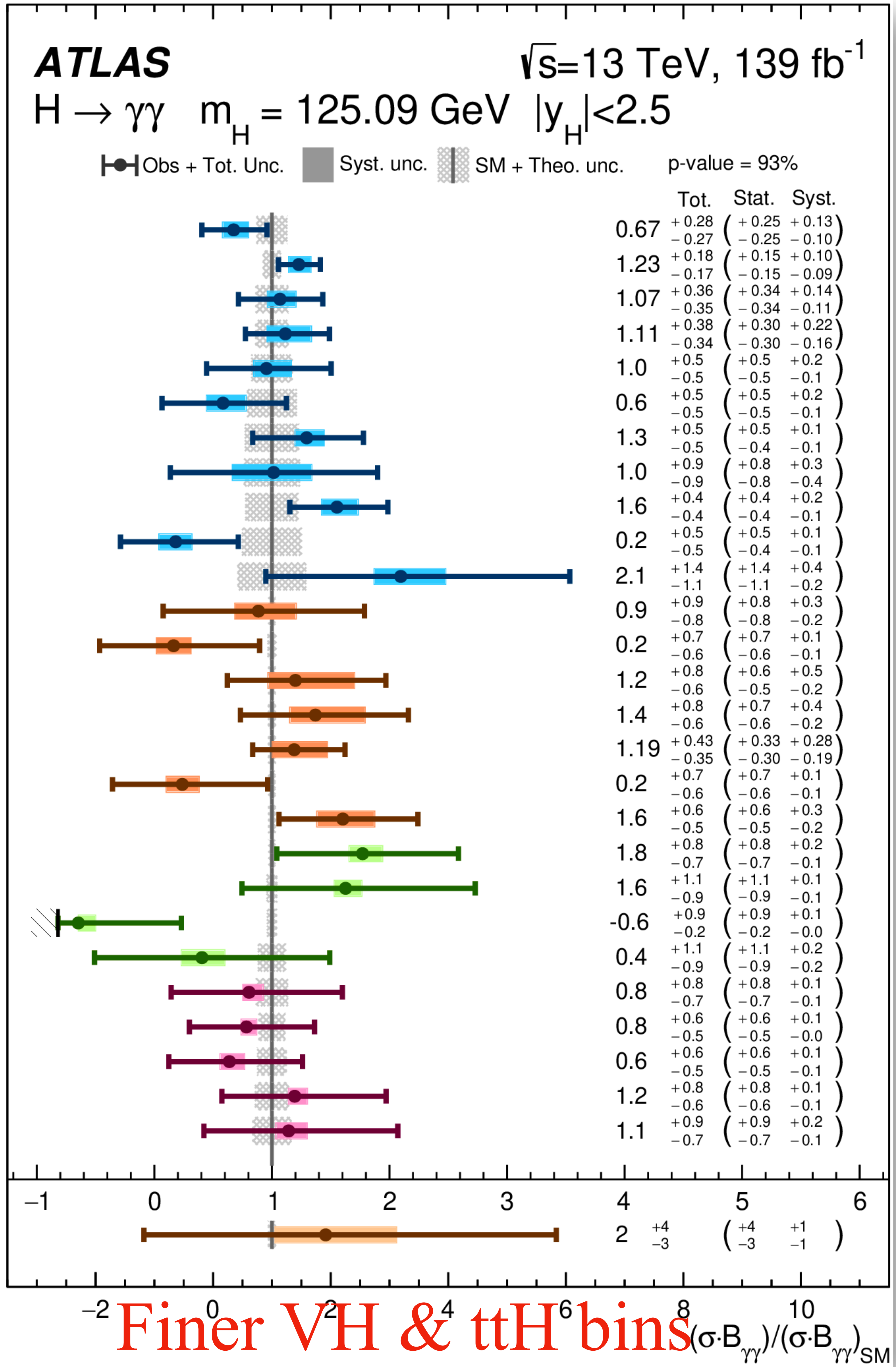
- *HZZ4l* and *Hγγ*, small BR, but high S/B, full m_H reconstruction with high resolution, providing slightly merged STXS Stage 1.2 measurements

EPJC 81 (2021) 488

HZZ4l



Hγγ
2207.00348

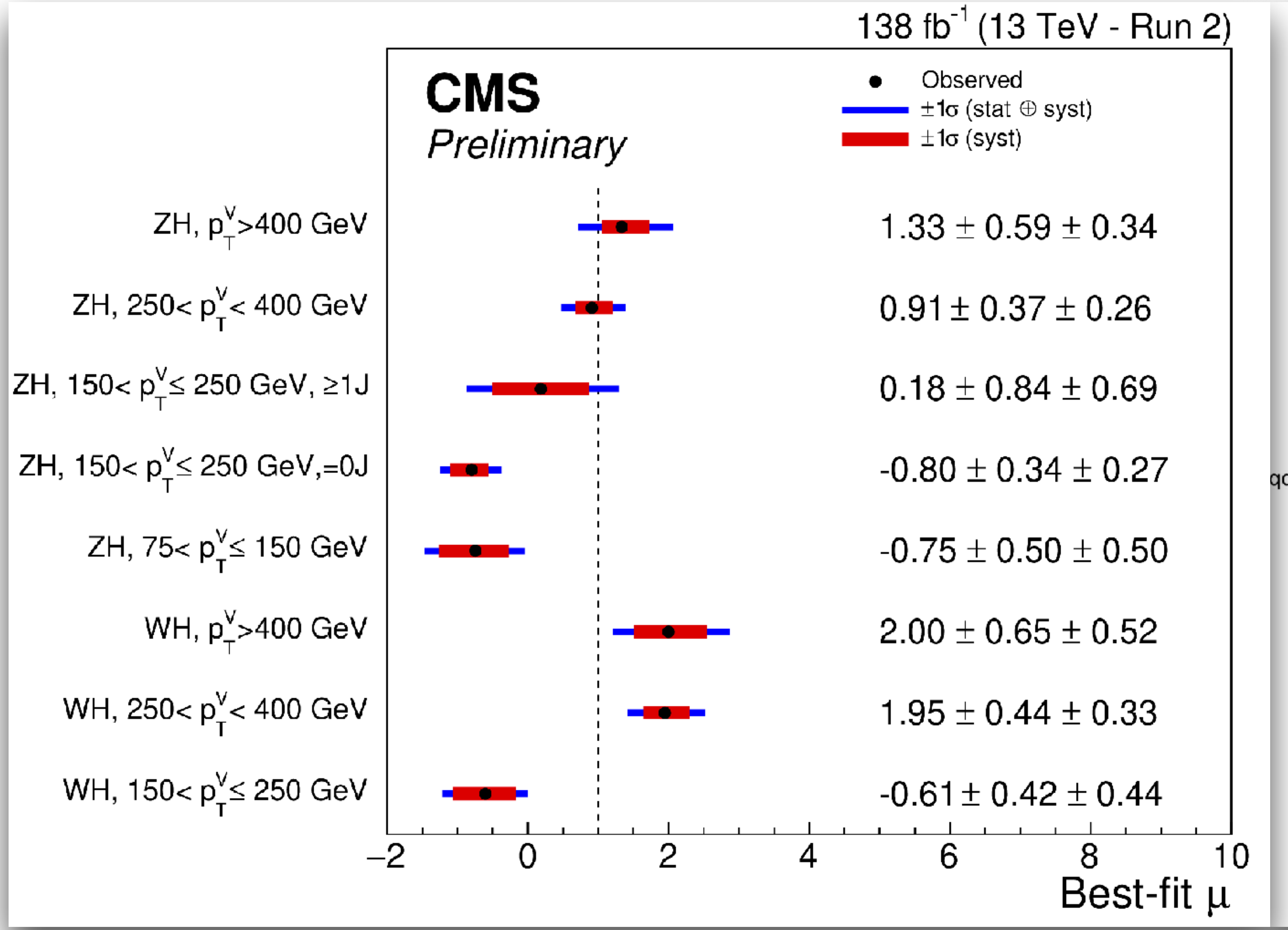


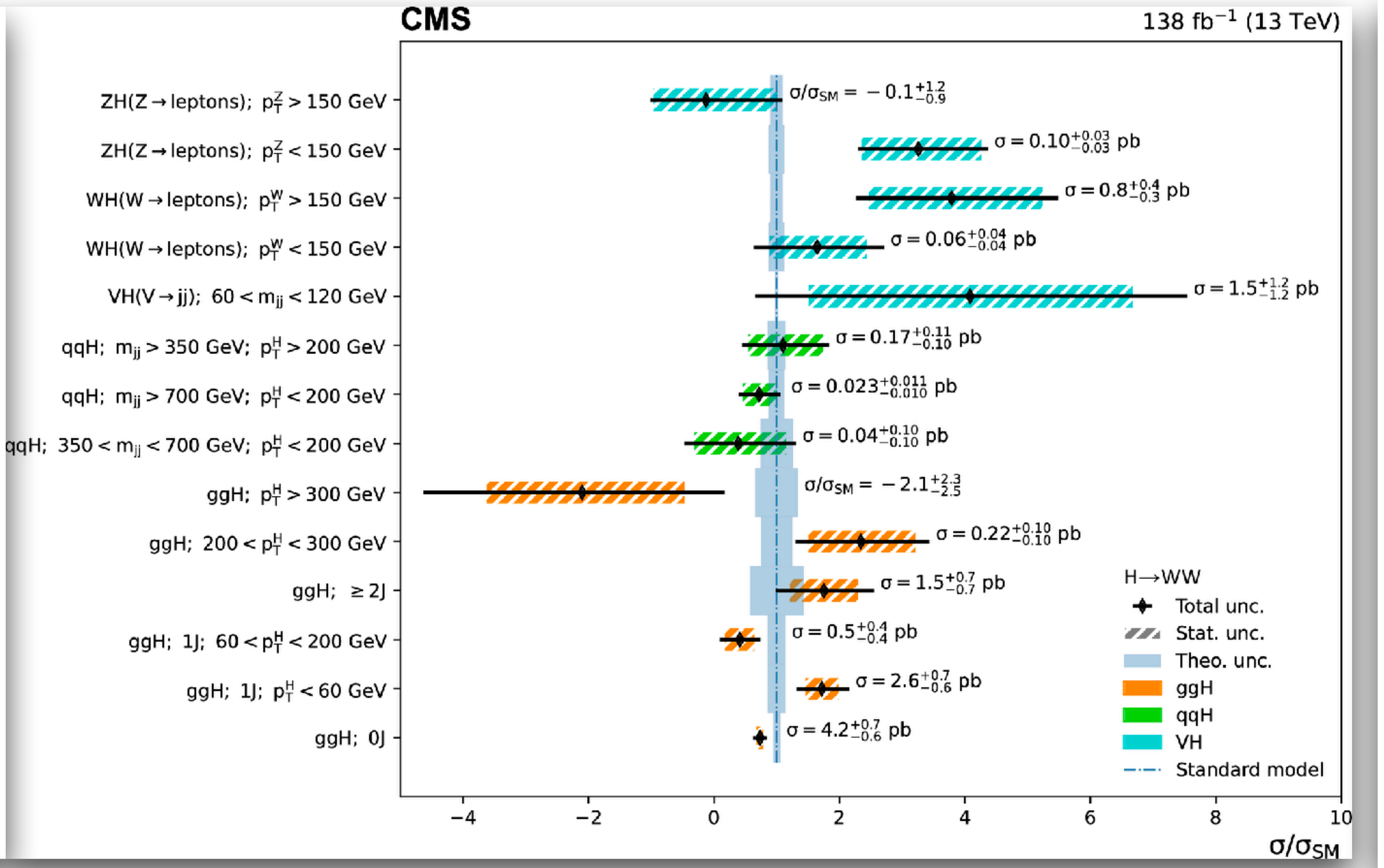
Good agreement with SM

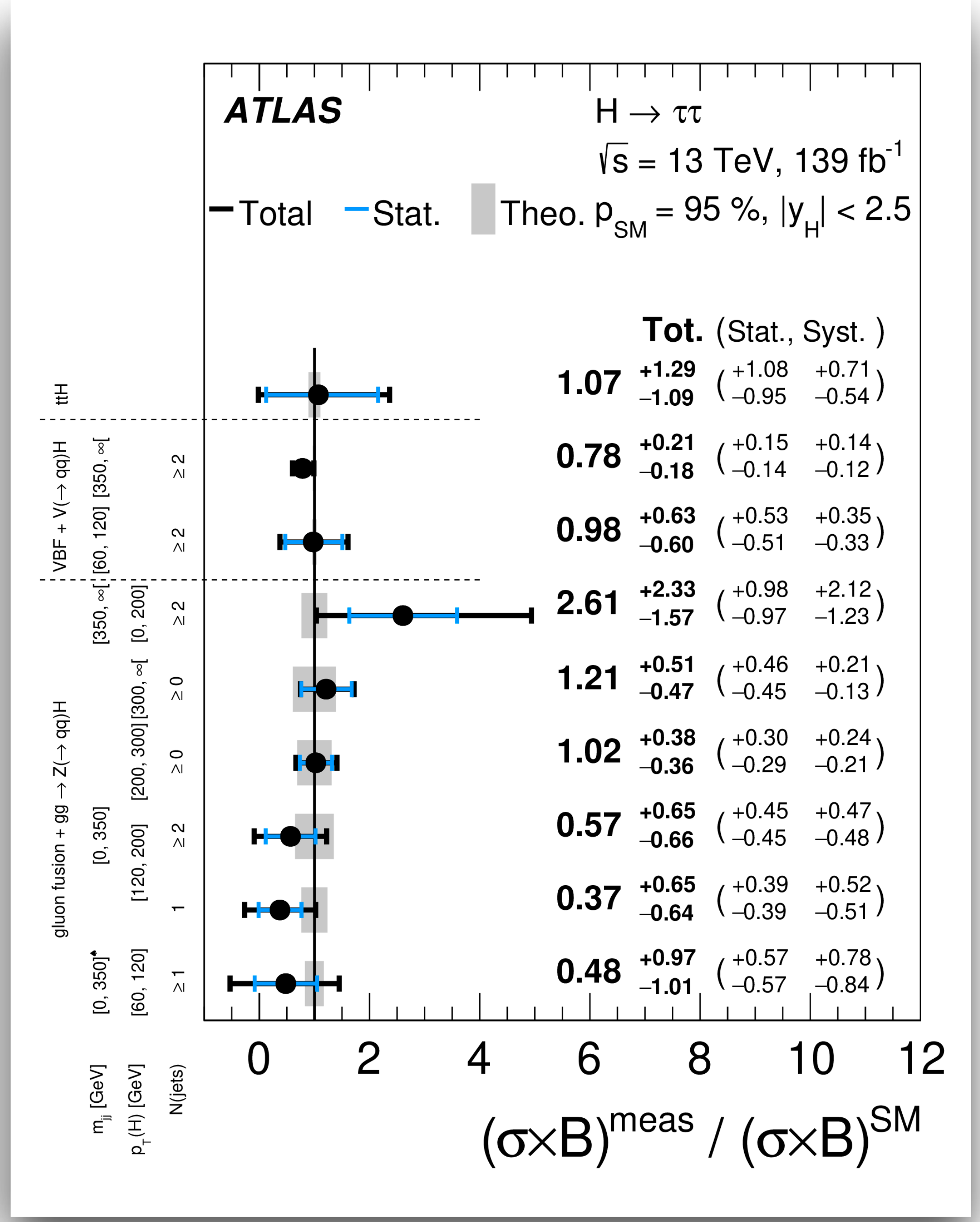
Finer VH & ttH bins

STXS in high-stats channels

- High-stats channels including *Hbb*, *HWW* and *Hττ* provide additional sensitivities in STXS
- The focuses are mainly on ggH, qqH and V(lep)H







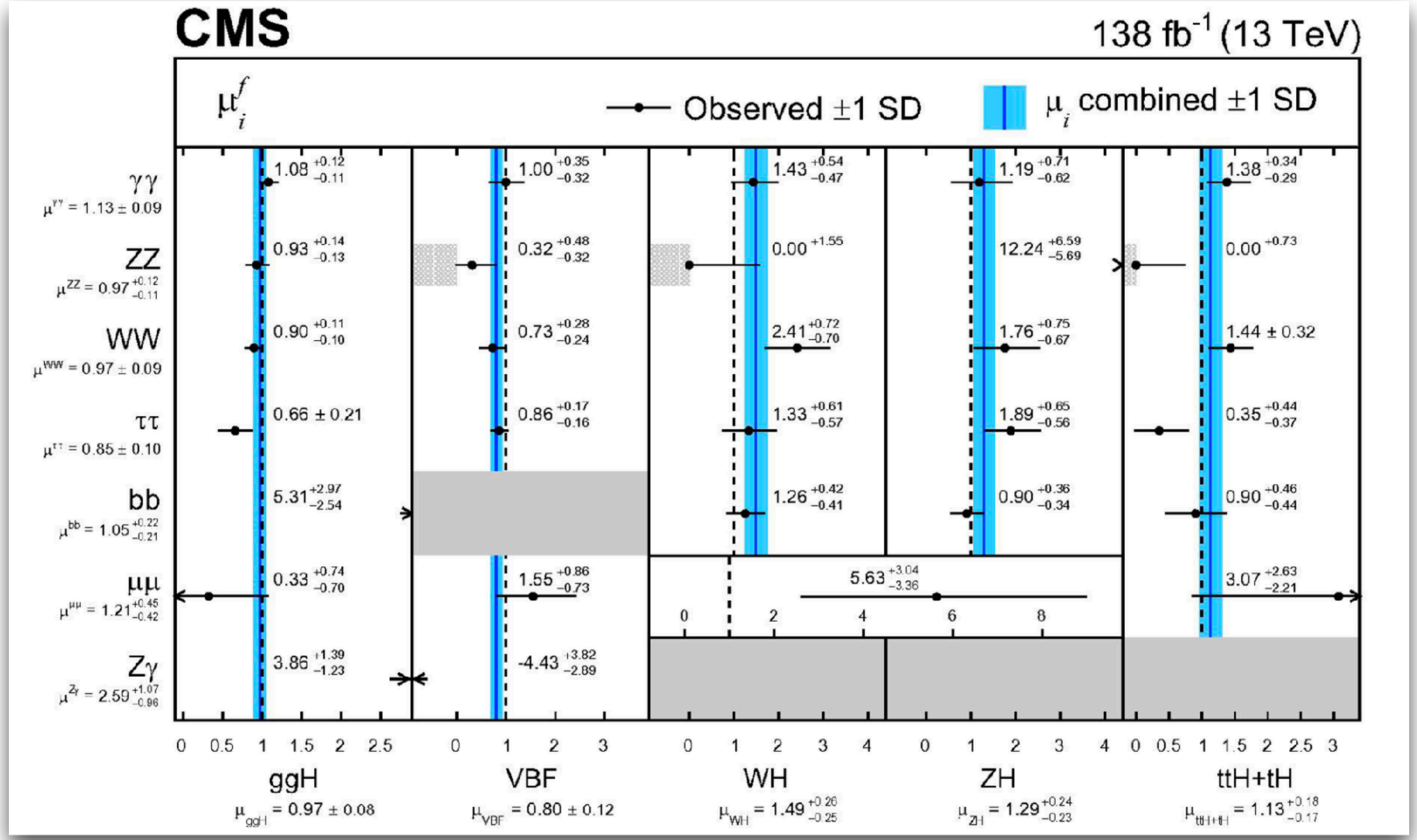
Hbb focuses on V(lep)H
CMS-PAS-HIG-20-001

HWW on ggH, qqH and V(lep)H
Accepted by Eur. Phys. J. C

Hττ focuses on ggH and qqH
JHEP 08 (2022) 175

Higgs combination

- At the 10th anniversary of the Higgs discovery, the "portrait" of the Higgs boson by CMS was published
  - A full combination of available experimental observables
  - A deep examination of the Higgs mechanism
- Results include inclusive signal strength μ, and a full breakdown from various couplings in the κ framework
- A good agreement with SM is observed at the current precision

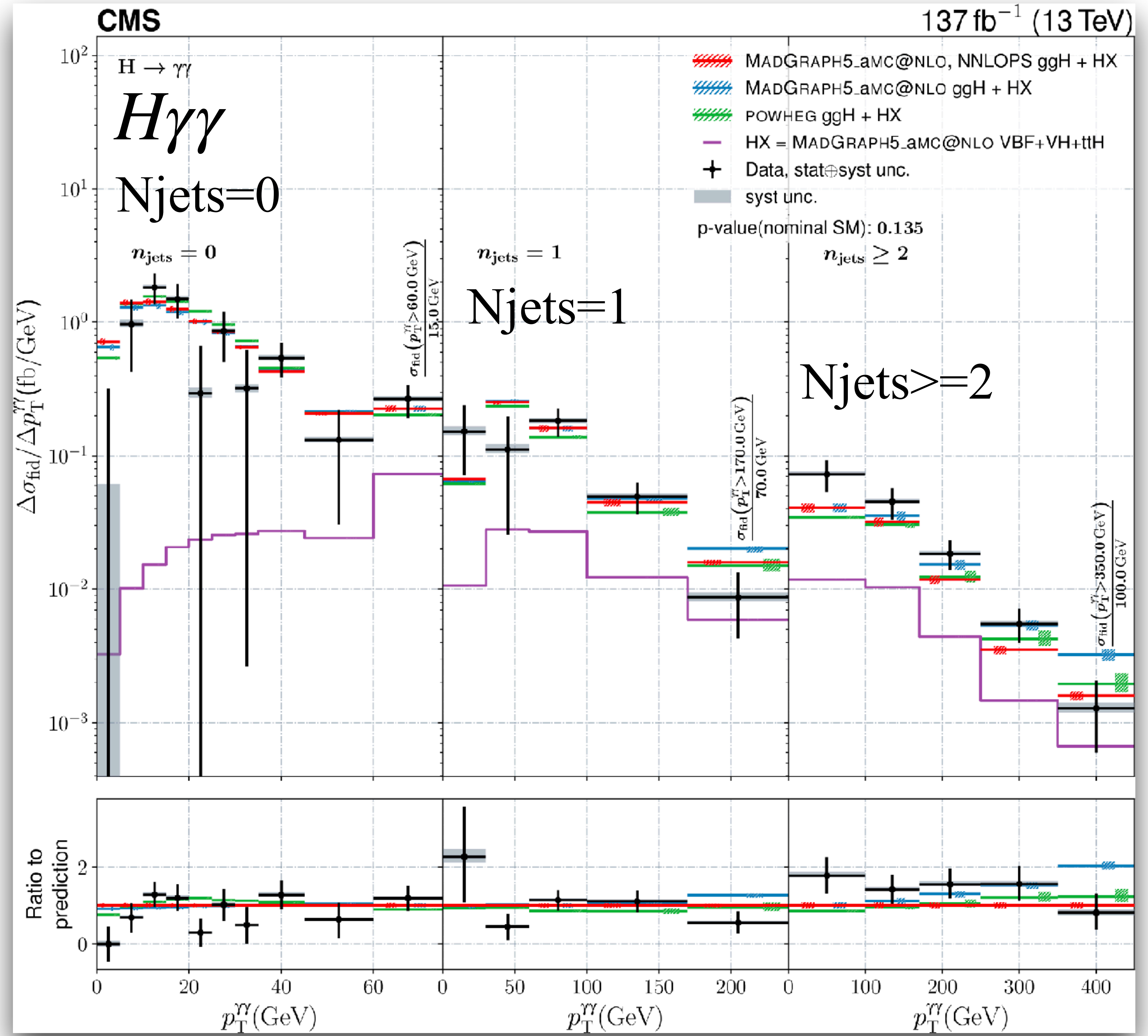


The signal strength μ's

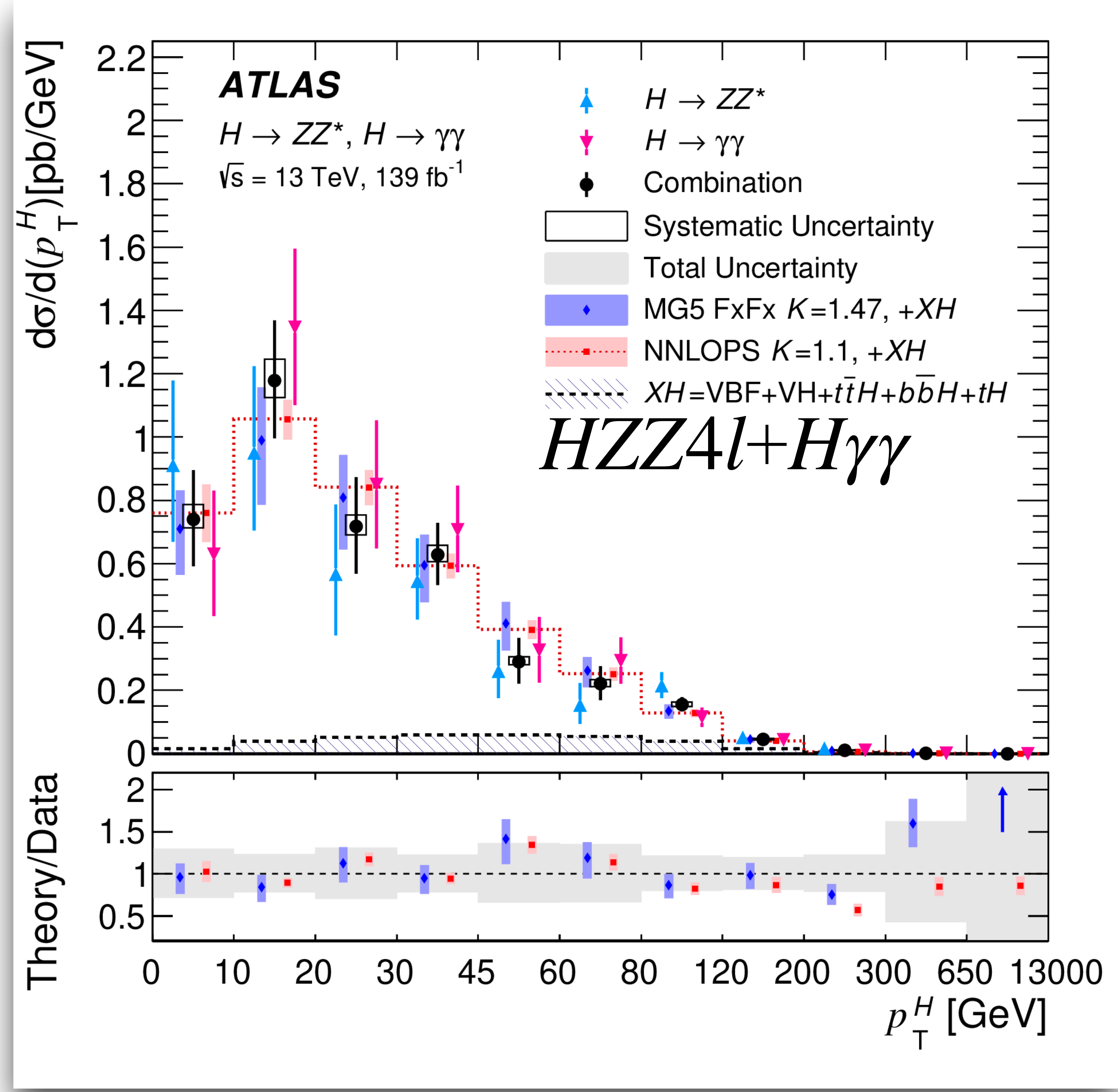
Nature 607 (2022) 60-68

Higgs differential XS

- Largely from *HZZ4l* and *Hγγ*
- Provide a big variety of unfolded kinematics with model independence



Hγγ Accepted by JHEP



HZZ4l+Hγγ JHEP 05 (2023) 028

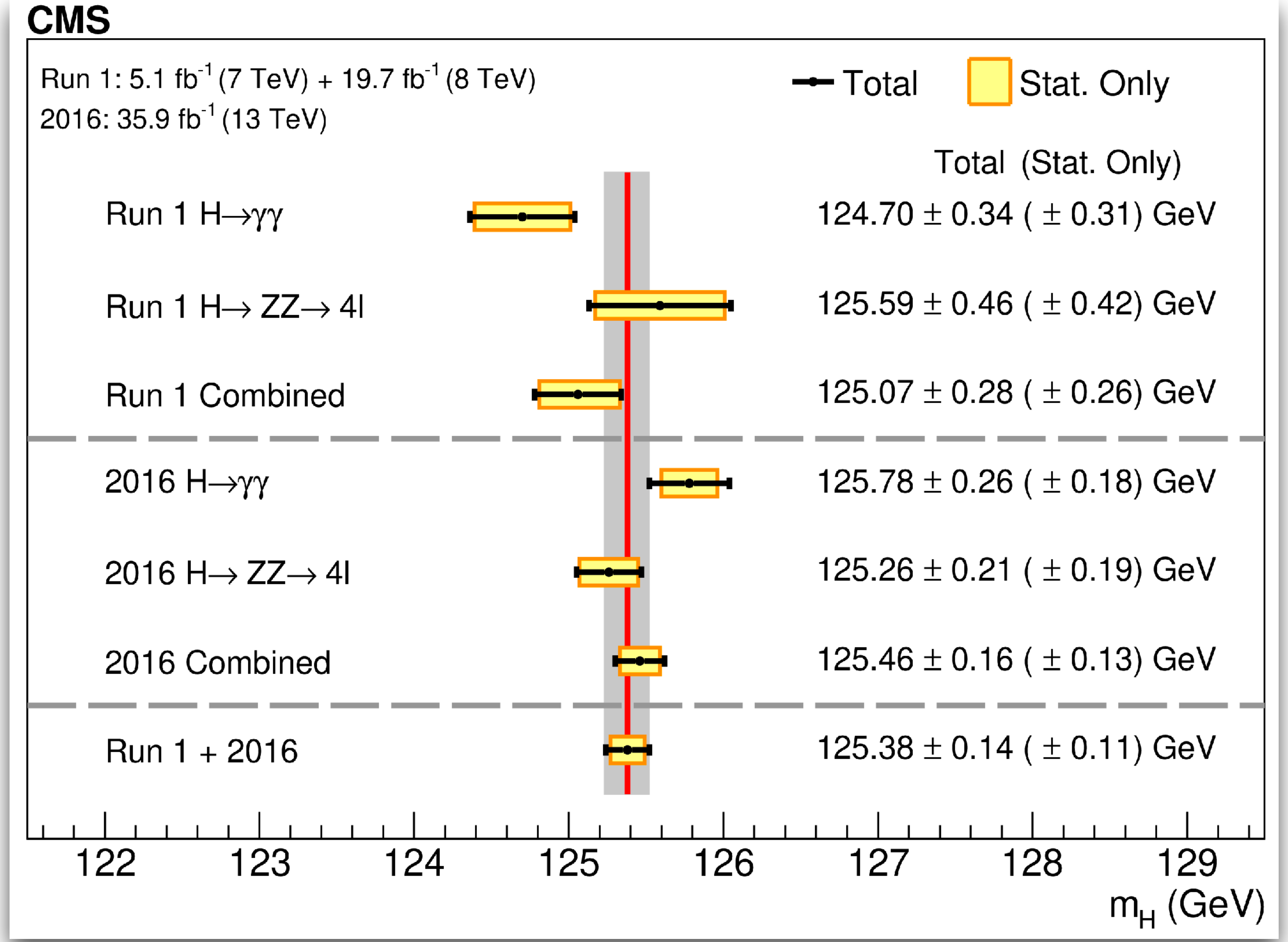
Higgs mass

- The mass is essential and determines many other properties (XS, BR etc.)
- Largely rely on *HZZ4l* and *Hγγ* thanks to their complete reconstruction of the final state and their excellent mass resolution (1-2%)

Run1 ATLAS+CMS:
$m_H = 125.09 \pm 0.24$ GeV
Phys. Rev. Lett. 114 (2015) 191803

Now CMS:
$m_H = 125.38 \pm 0.14$ GeV
Hγγ & *HZZ4l* with Run1+2016
Phys. Lett. B 805 (2020) 135425

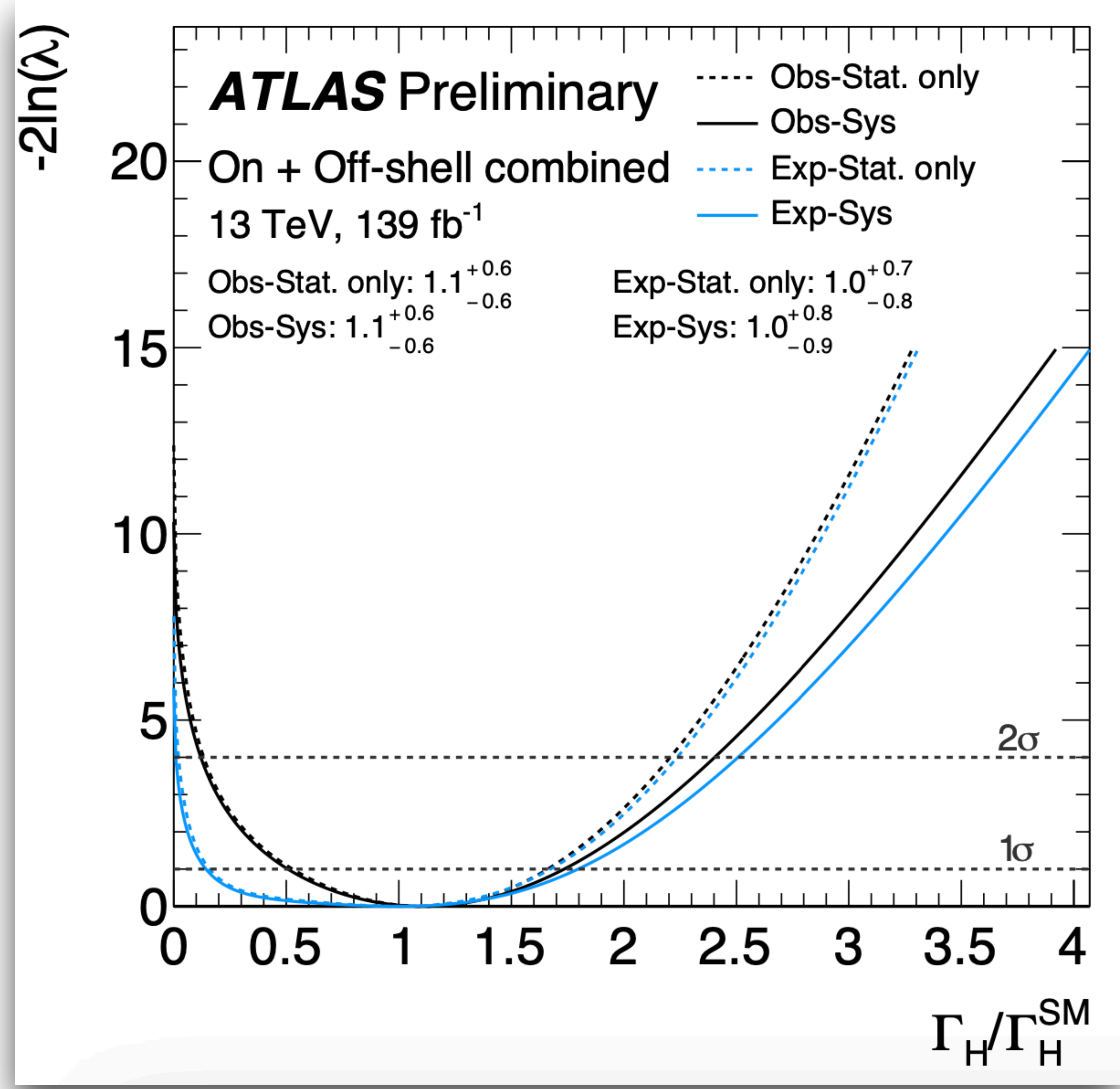
Now ATLAS:
$m_H = 124.94 \pm 0.18$ GeV
2207.00320 with Run1+Run2

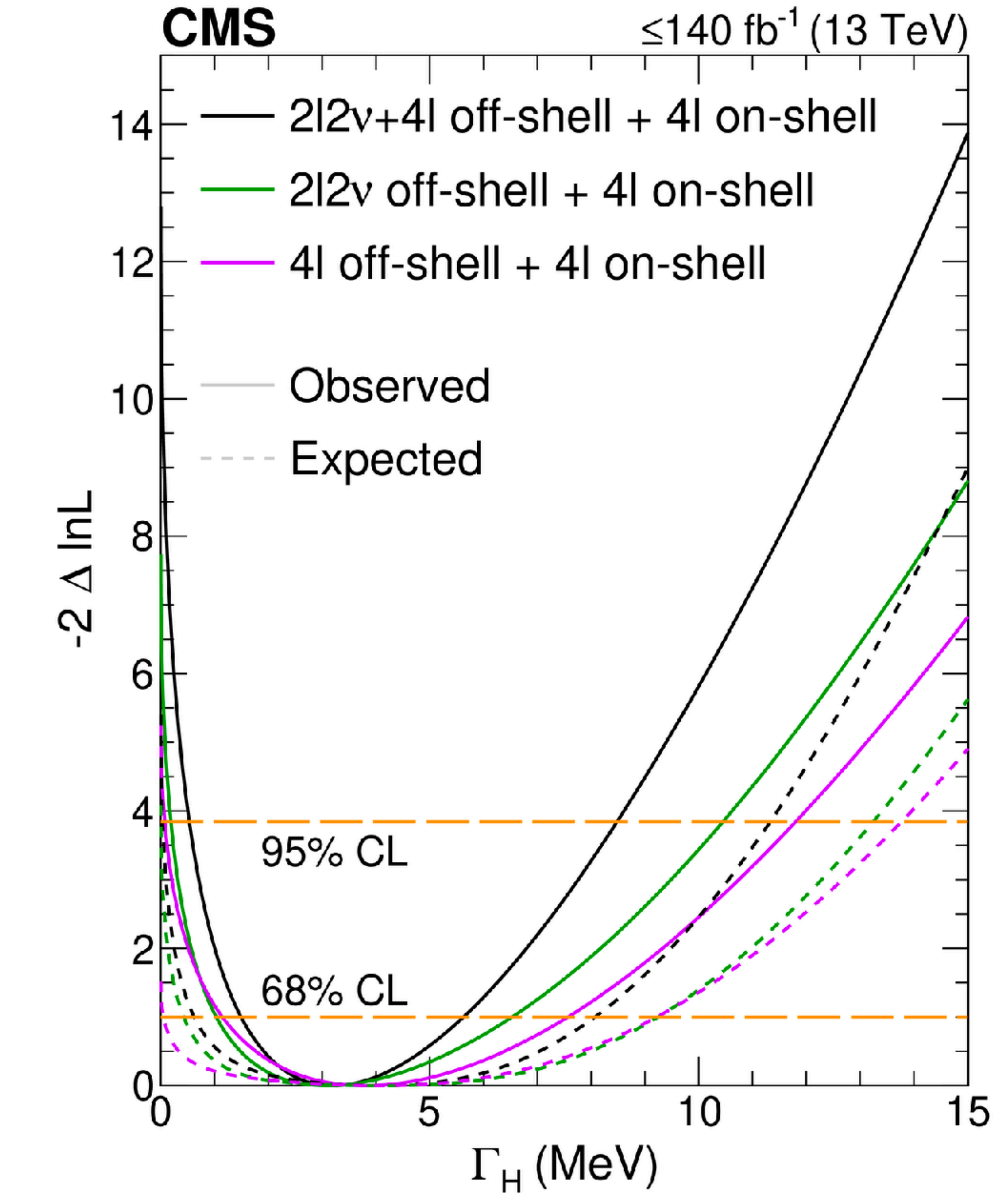


Higgs width

- Not quite possible to directly measure the width that is ~4.07 MeV, given the experimental resolution at ~O(1) GeV
- But can exploit the on-shell and off-shell production using *HZZ4l*

$$\frac{\sigma^{\text{on-shell}}_{gg\to H\to ZZ^*} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{m_H \Gamma_H}}{\sigma^{\text{off-shell}}_{gg\to H^*\to ZZ} \sim \dfrac{g^2_{ggH} g^2_{HZZ}}{(2m_Z)^2}}$$





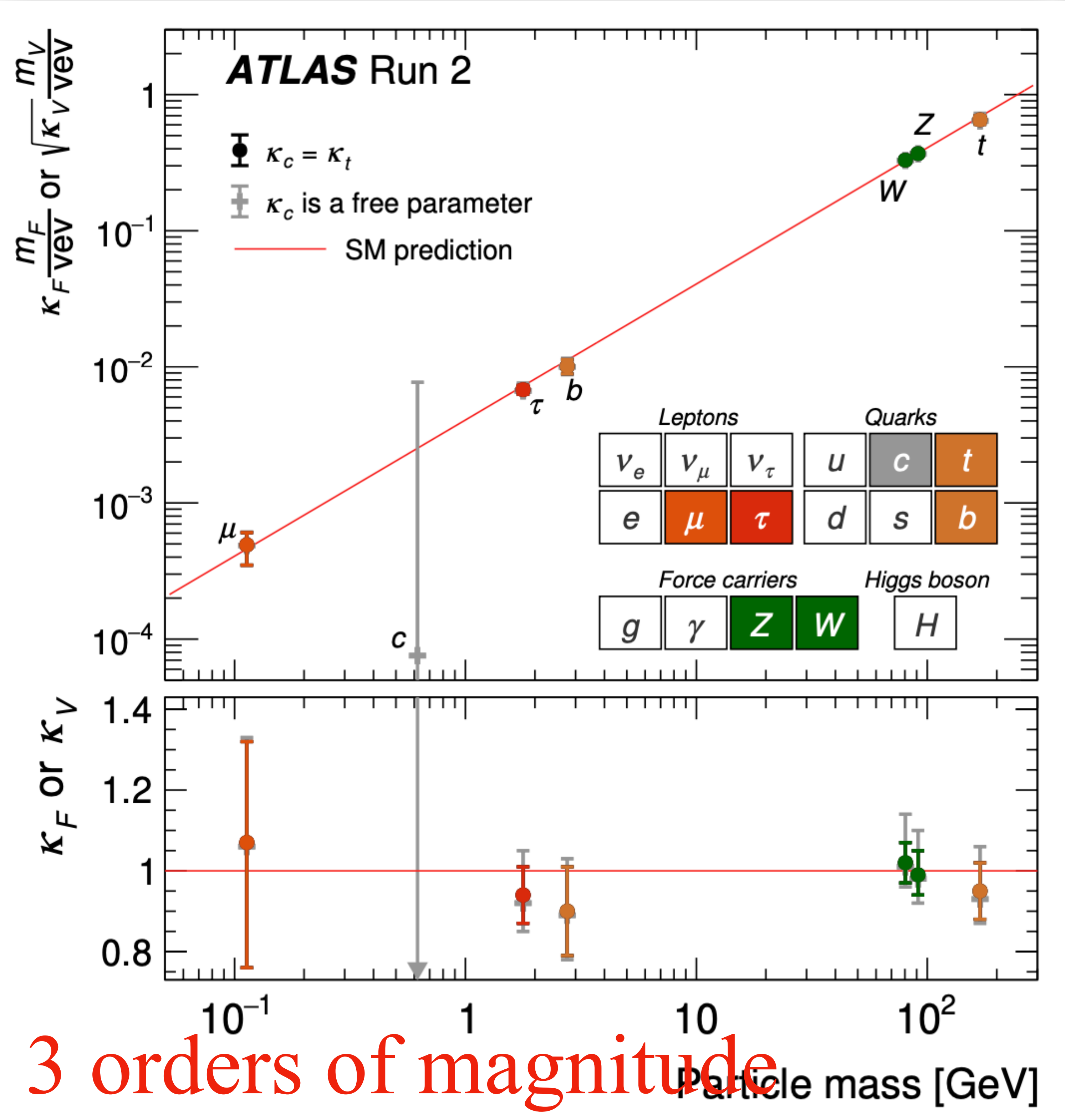
ATLAS $\Gamma = 4.6^{+2.6}_{-2.5}$ MeV
ATLAS-CONF-2022-068

CMS $\Gamma = 3.2^{+2.4}_{-1.7}$ MeV
Nat. Phys. 18 (2022) 1329

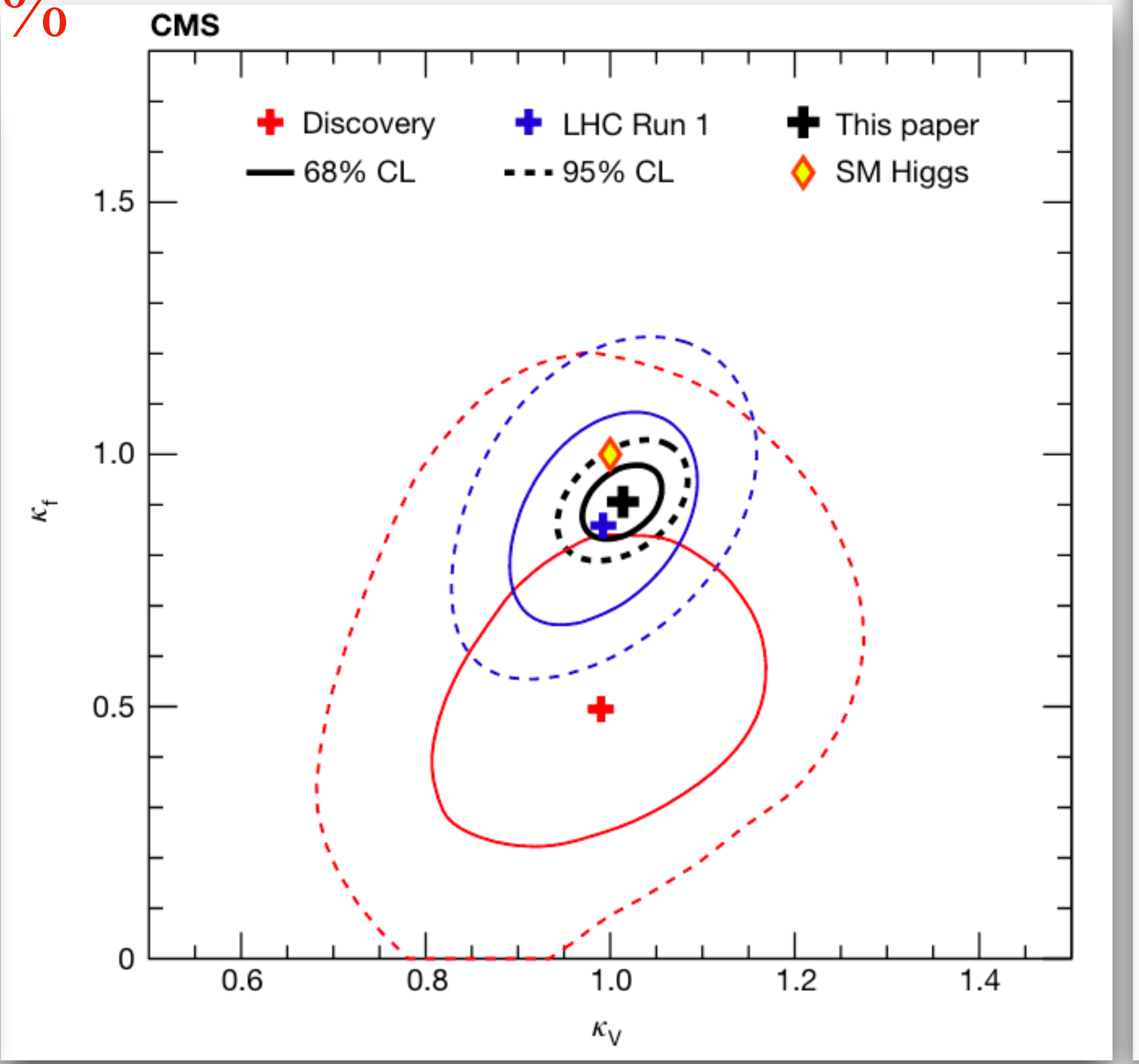
Higgs couplings

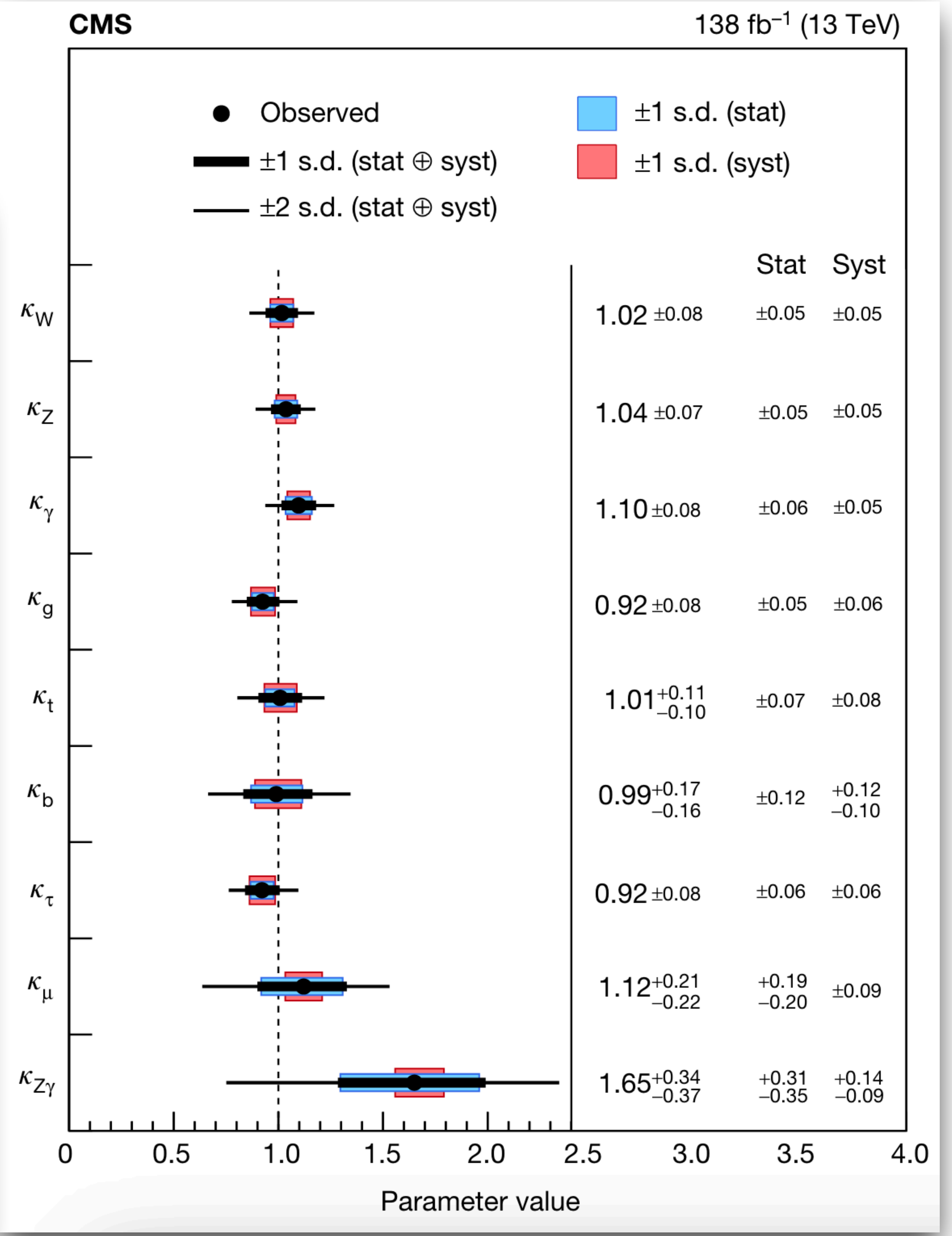
Nature 607 (2022) 52-59
Nature 607 (2022) 60-68

- The couplings measurements range over 3 orders of magnitude
- Couplings in the κ framework can be measured with a precision as good as < 10%



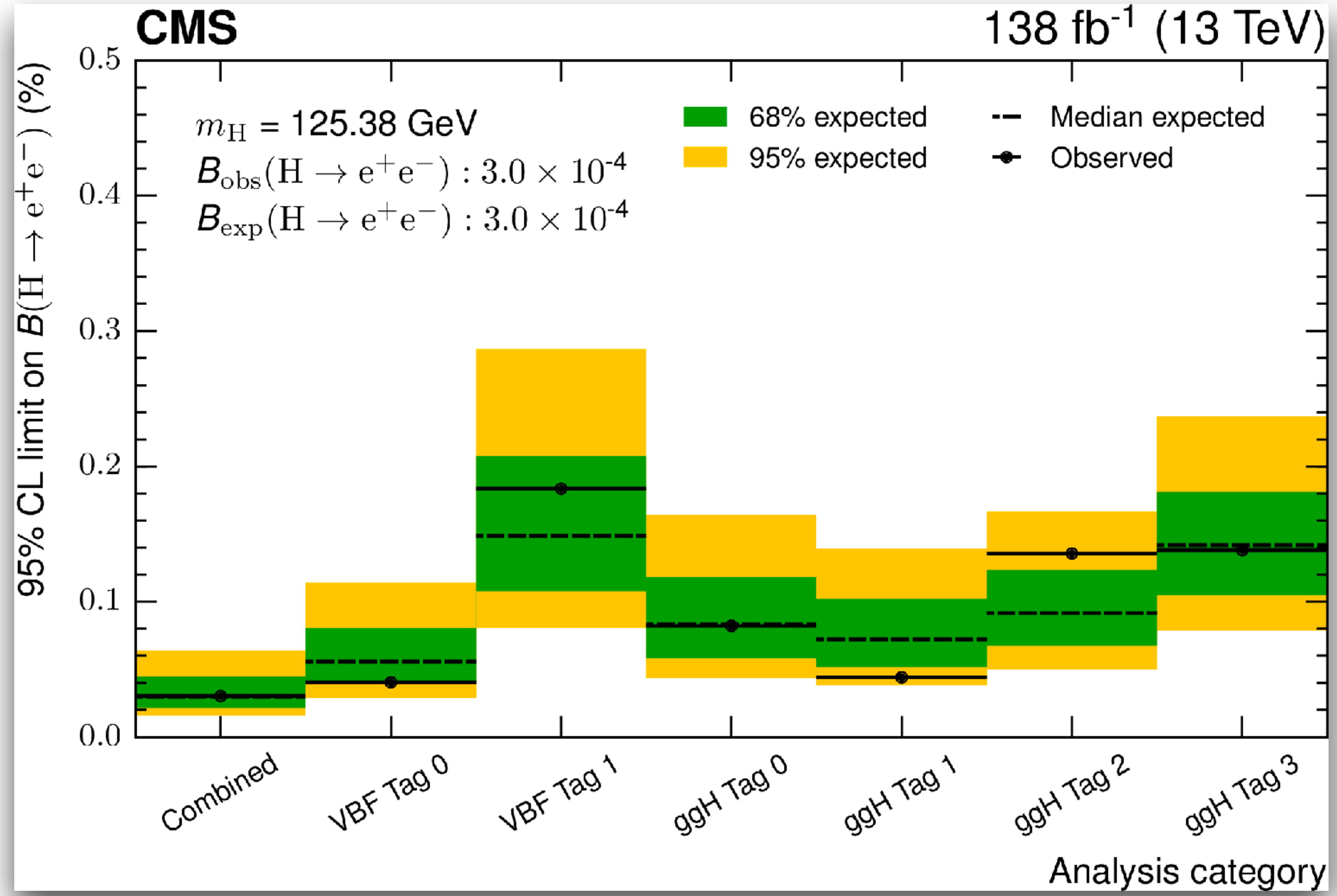
3 orders of magnitude

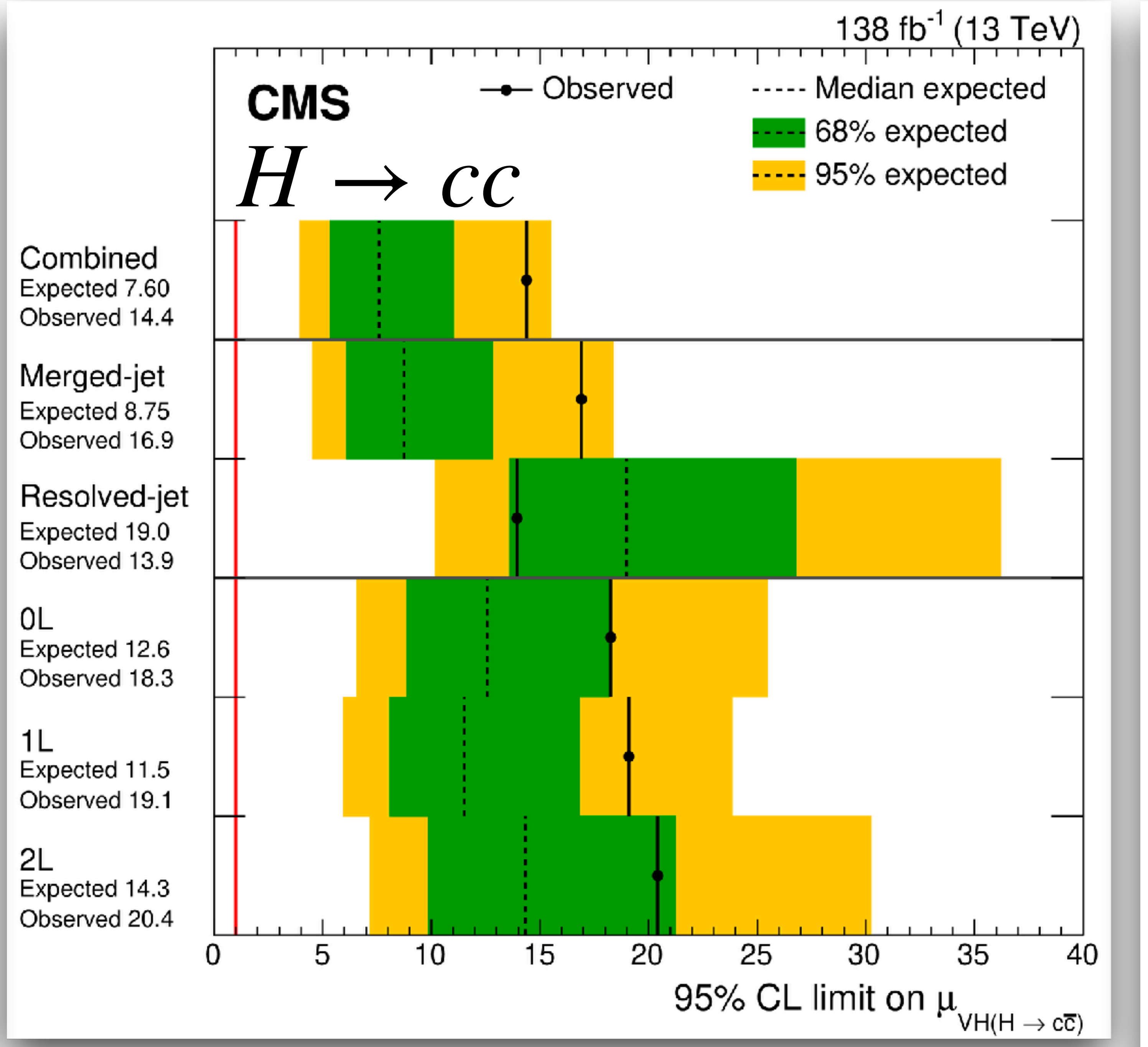


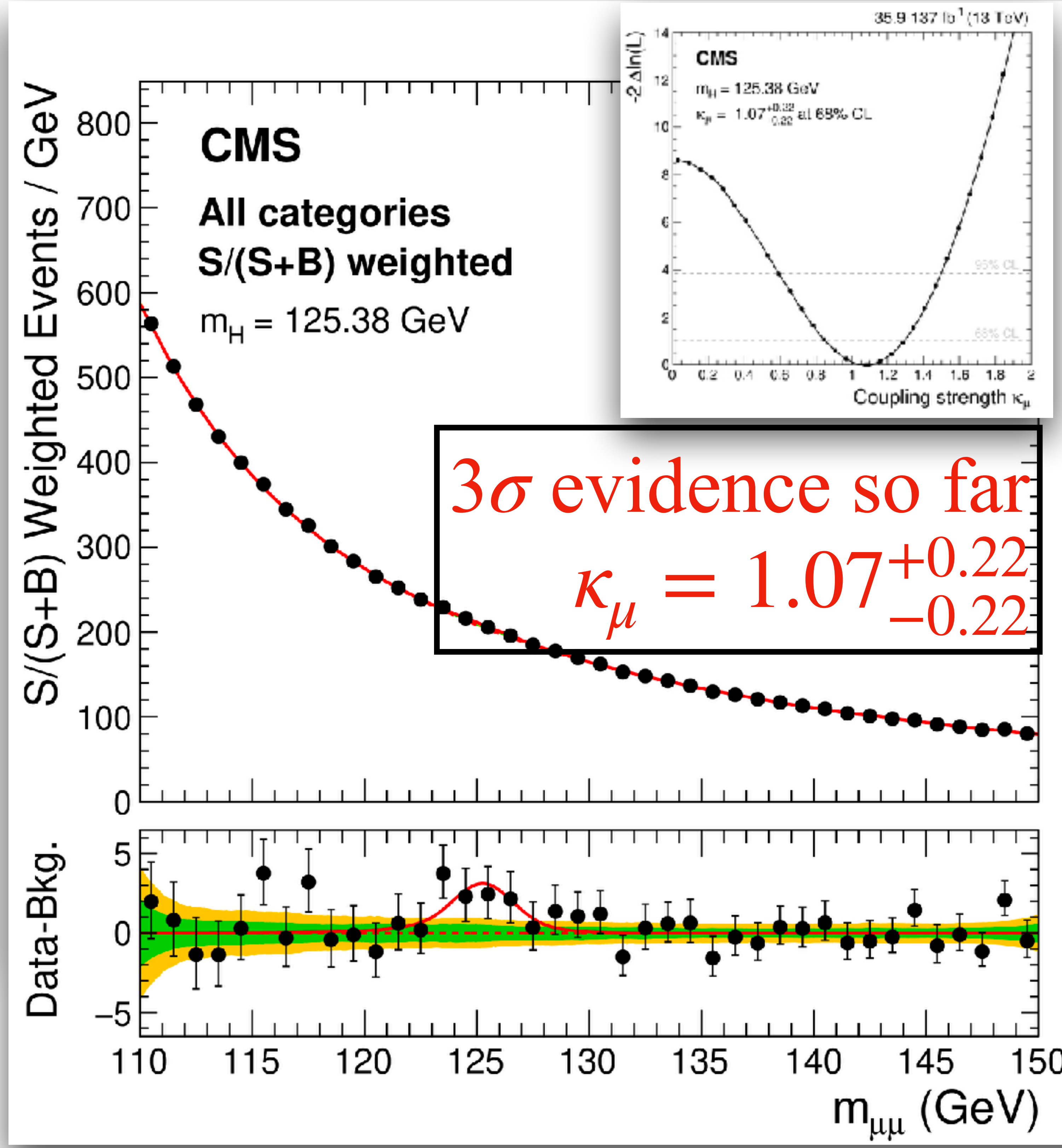


Couplings to lighter fermions

- Reaching out to the first and second generation fermions







$BR(H \to ee) < 3.0 \times 10^{-4} (3.0 \times 10^{-4})$ at 95% CL. Accepted by PLB

SM predicts $BR(H \to ee) = 10^{-9}$

$1.1 < |\kappa_c| < 5.5$ ($|\kappa_c| < 3.4$) at 95% CL. Accepted by PRL

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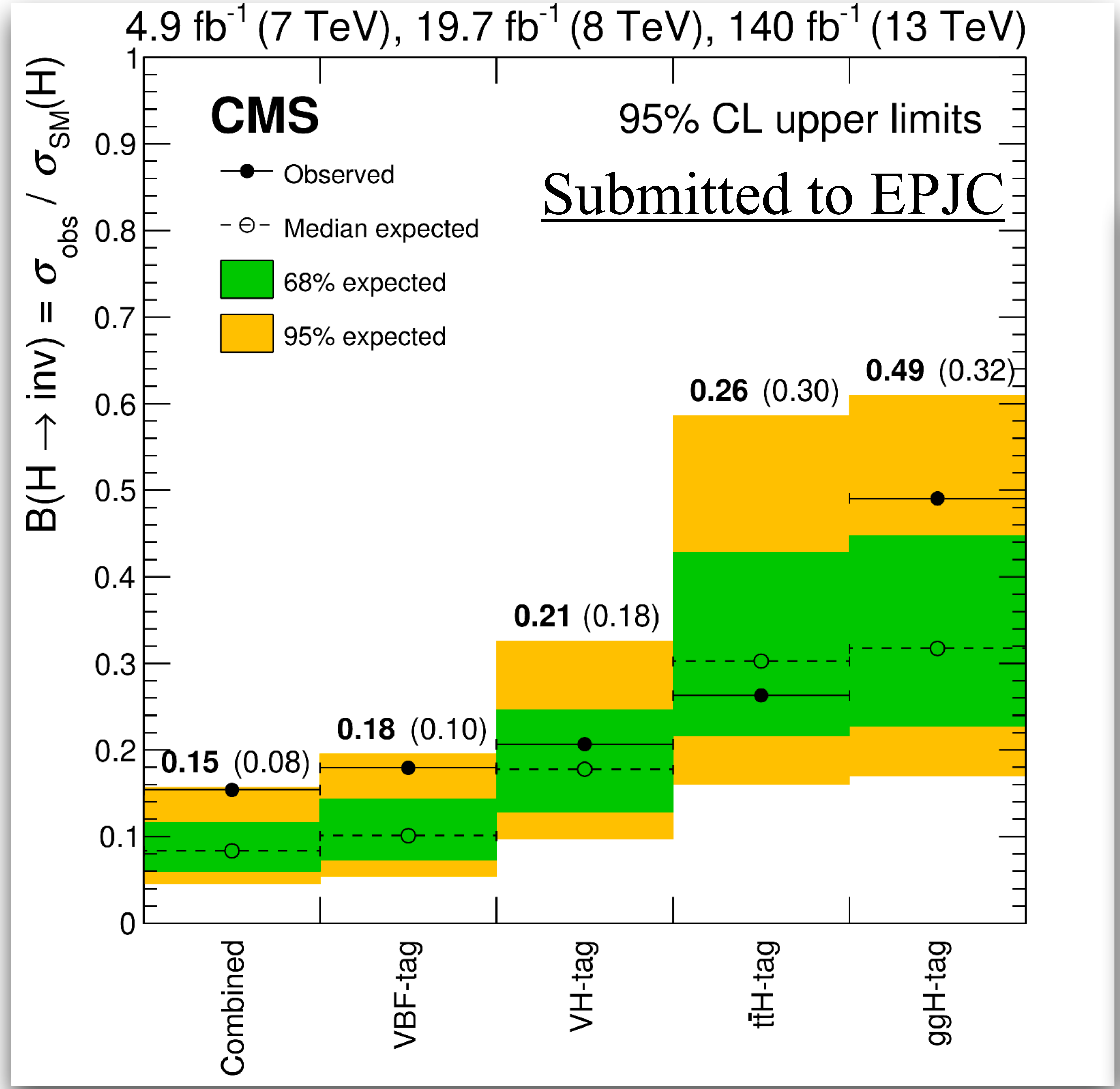
$H \rightarrow$ *invisible*

- Direct searches with MET

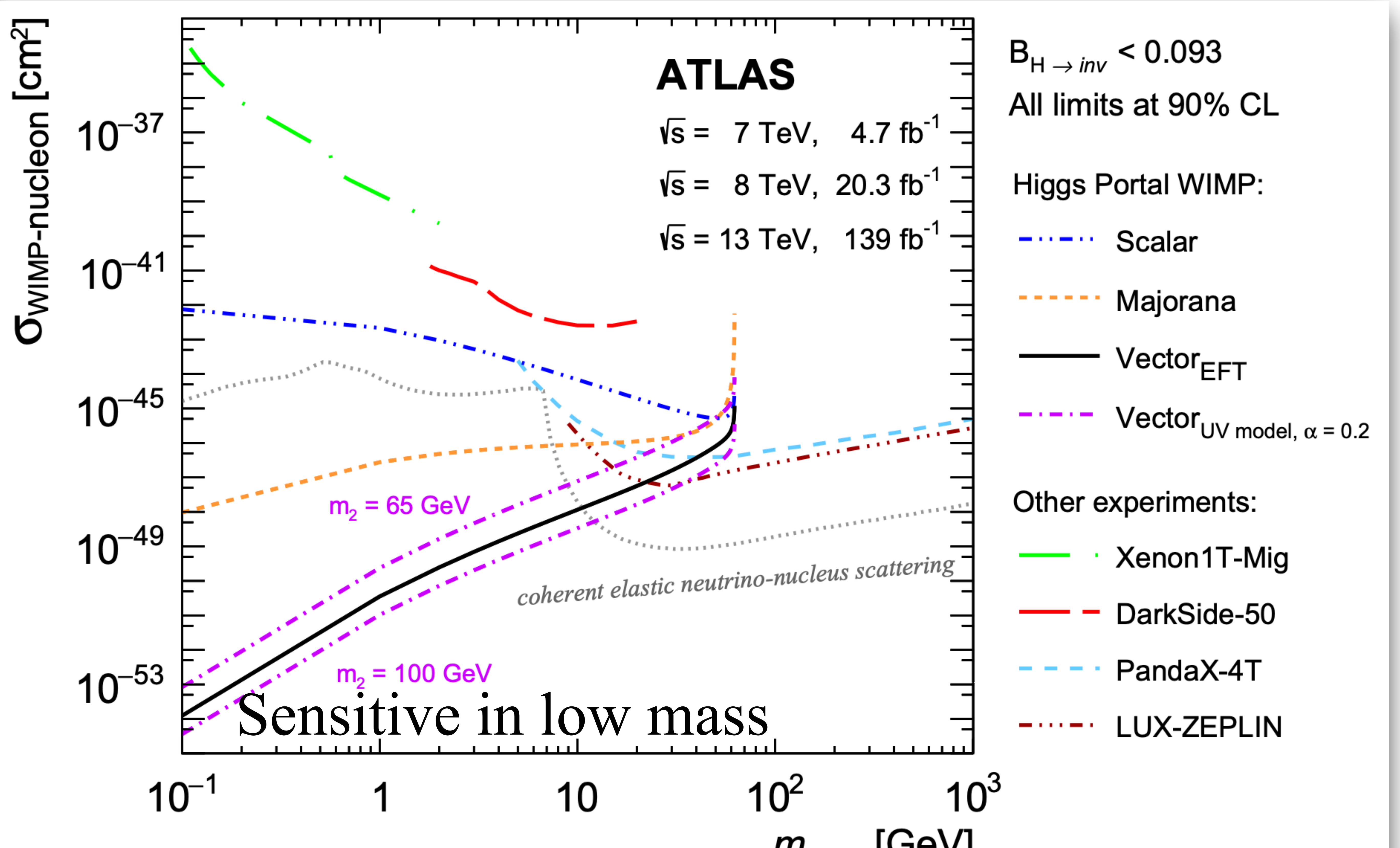
95% CL limit for H→ inv

ATLAS: 10.7% (7.7% exp.)

CMS: 15% (8% exp.)



Submitted to EPJC



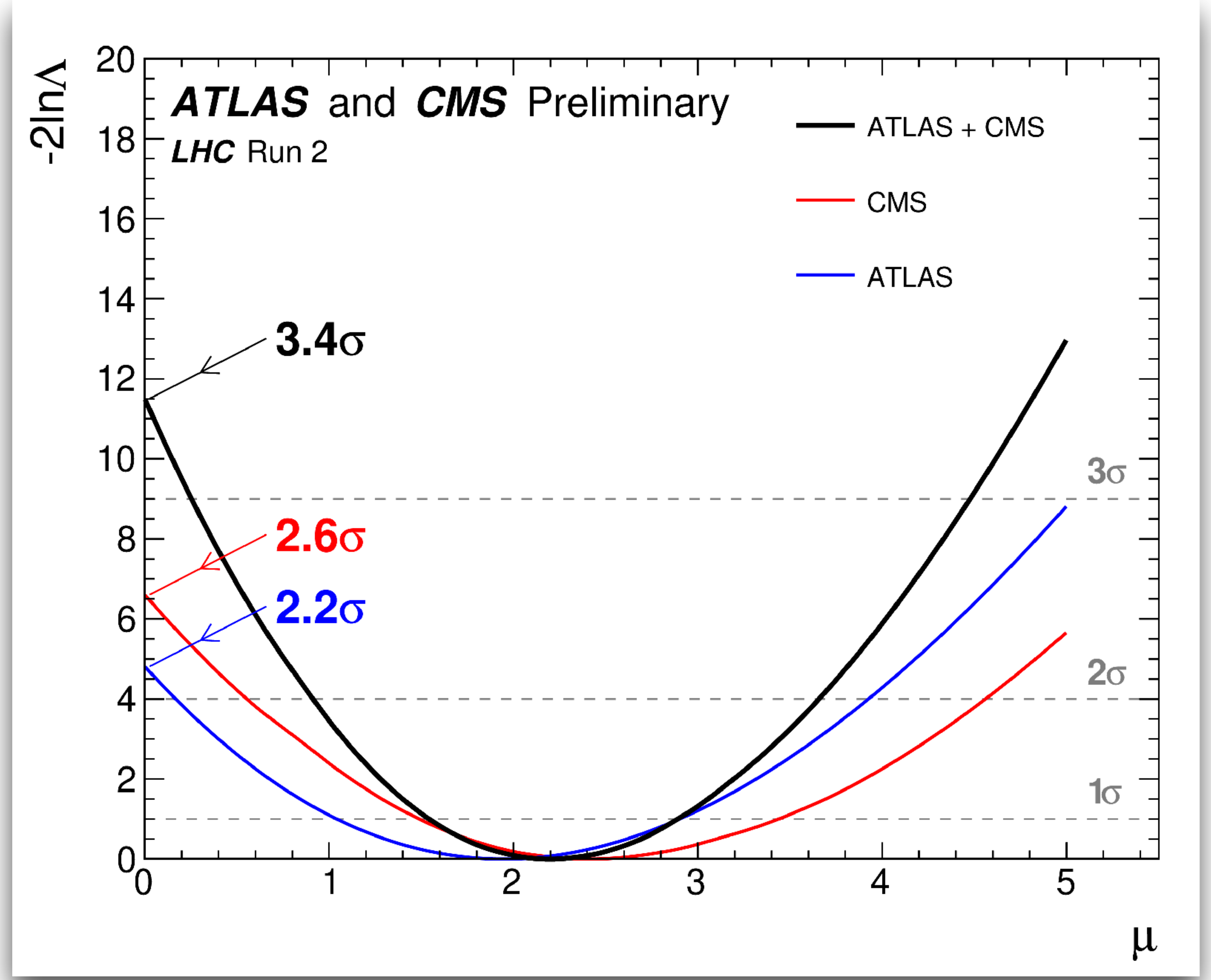
Sensitive in low mass

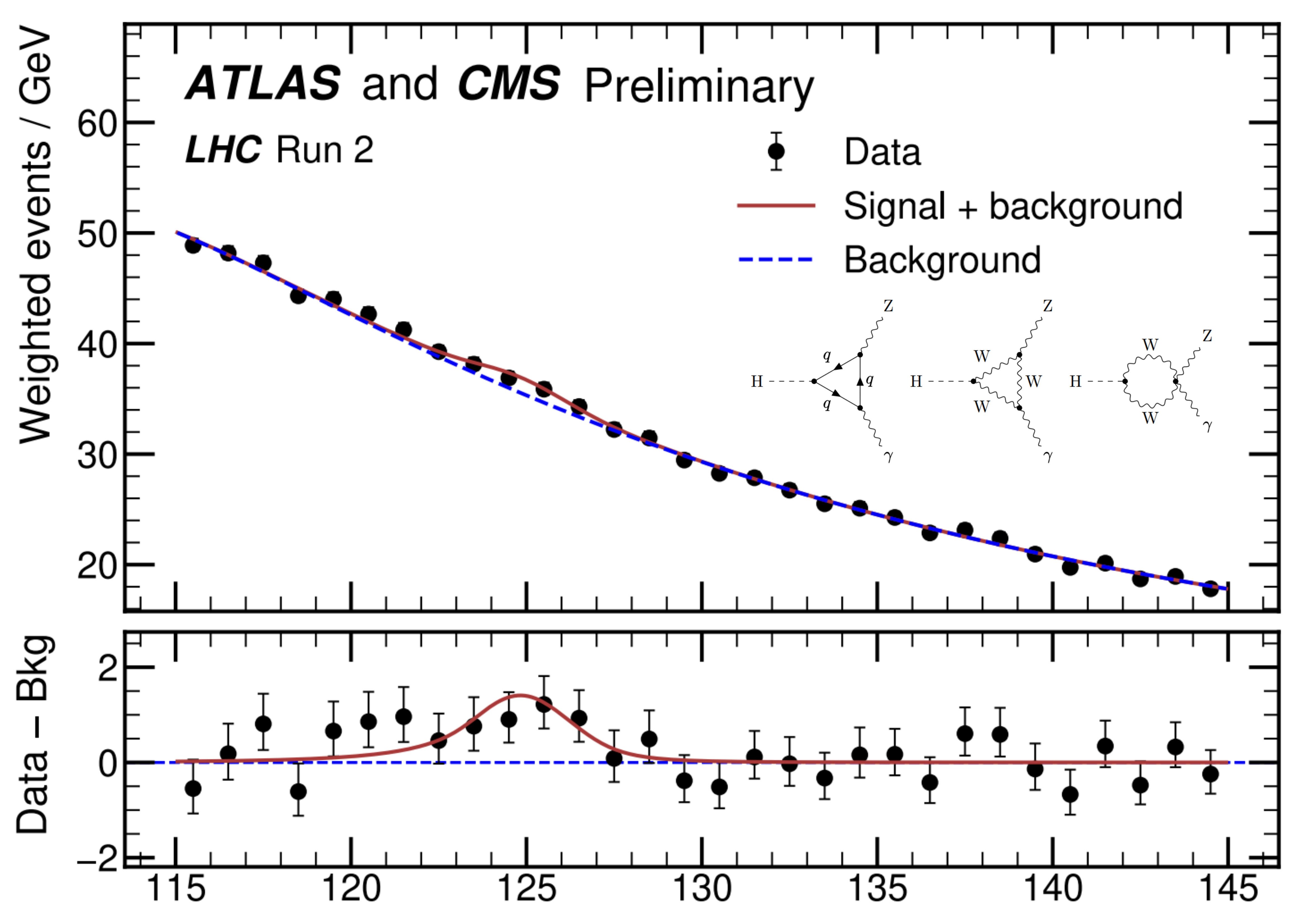
Physics Letters B 842 (2023) 137963

$H \to Z\gamma$ combined evidence

- $H \to Z\gamma$ with loop where new physics can hide
- New ATLAS and CMS results are combined for 3.4σ

	Observed (Expected)
ATLAS	2.2σ (1.2σ)
CMS	2.6σ (1.1σ)
Combination	3.4σ (1.6σ)

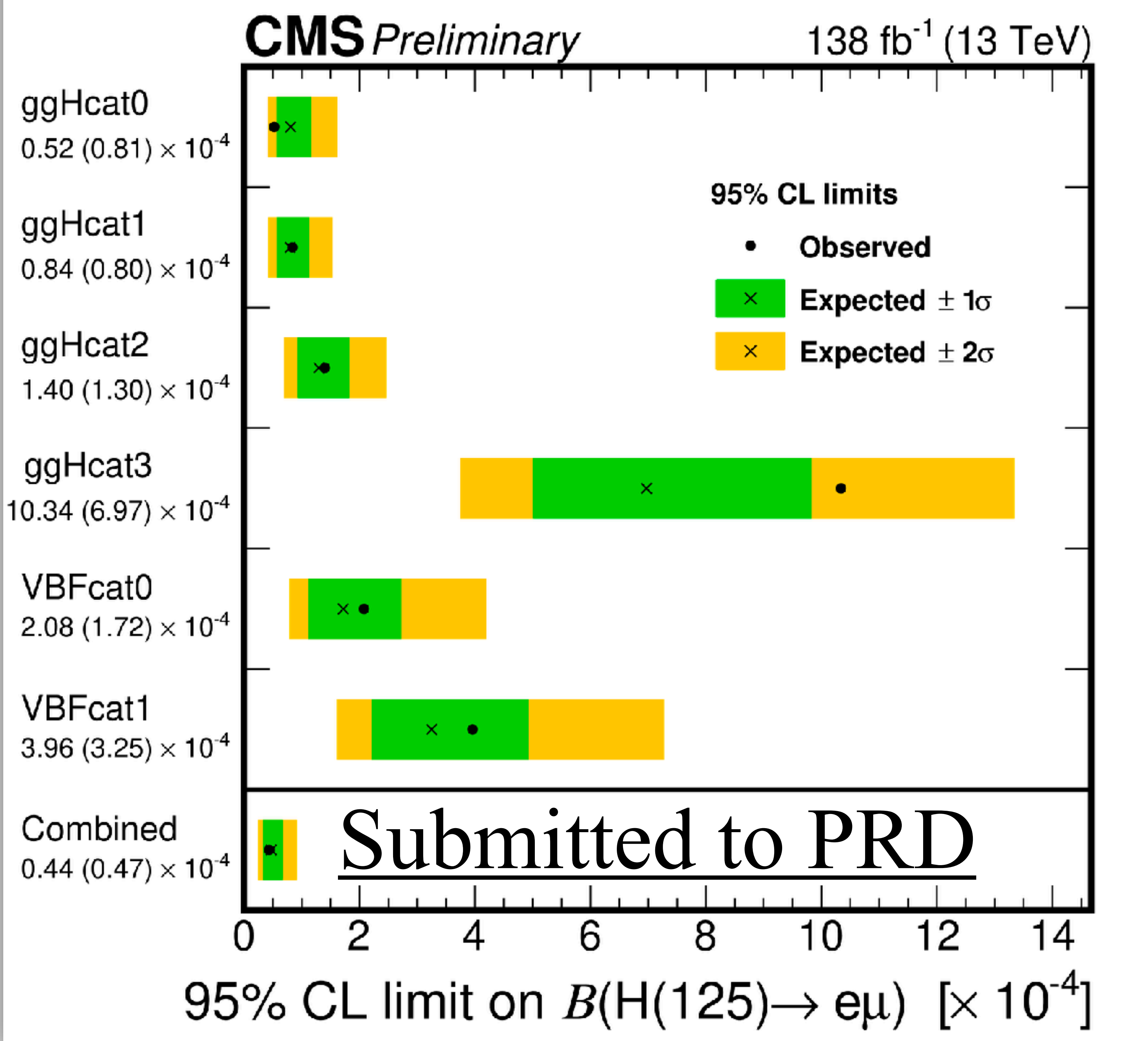




ATLAS-CONF-2023-025, CMS-PAS-HIG-23-002

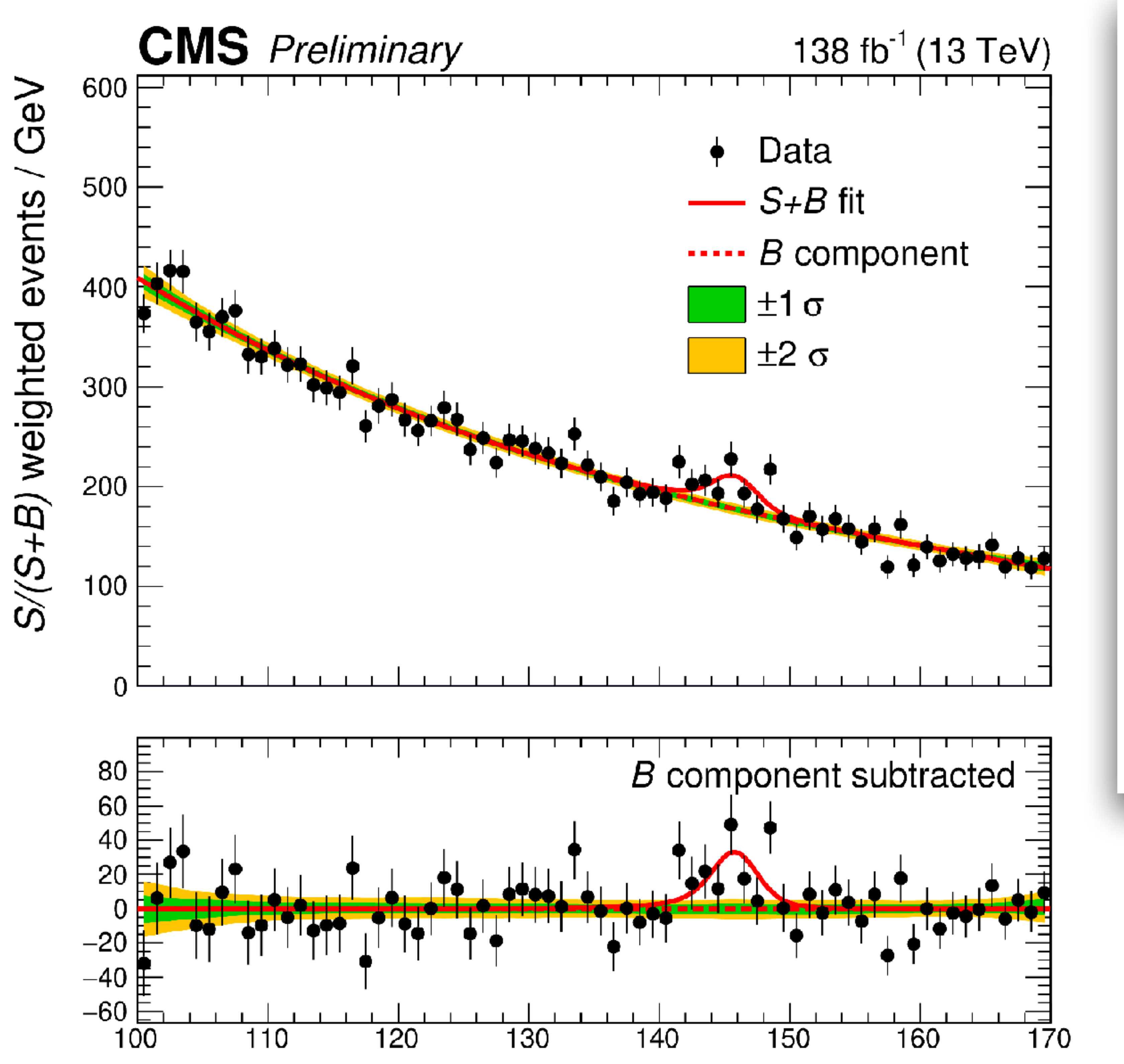
Higgs decays with lepton-flavor violation

- CMS searches for $H \to e\mu$ for SM H and scans the mass from 110 to 160 GeV for BSM H
- ATLAS searches for $H \to e\tau, \mu\tau$ decays

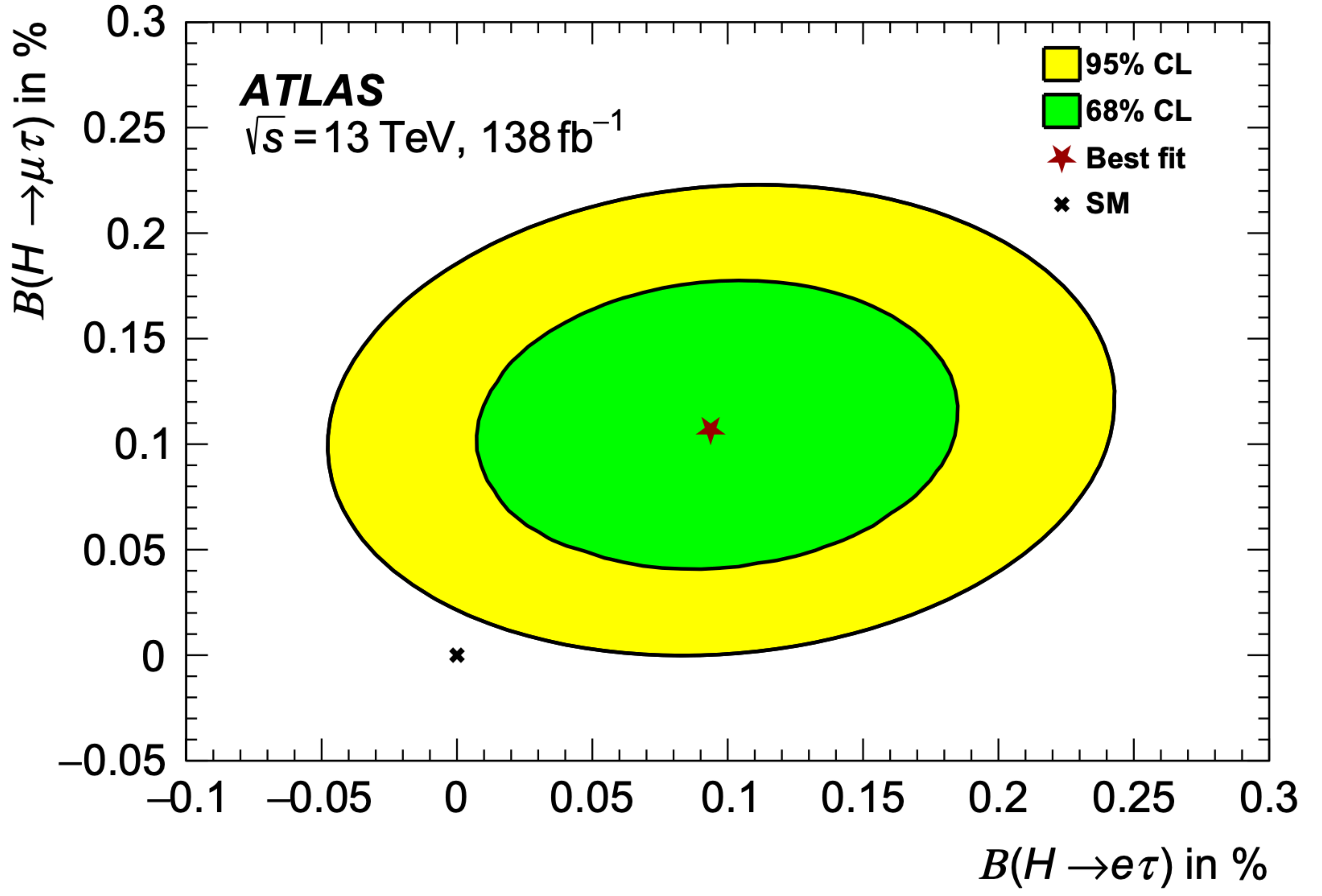


Submitted to PRD

$BR(H \to e\mu) < 4.4\ (4.7) \times 10^{-5}$ at 95% CL



Found small excess of 3.8σ (2.8σ) local (global) at 146 GeV



Simultaneous fit with 2 POIs

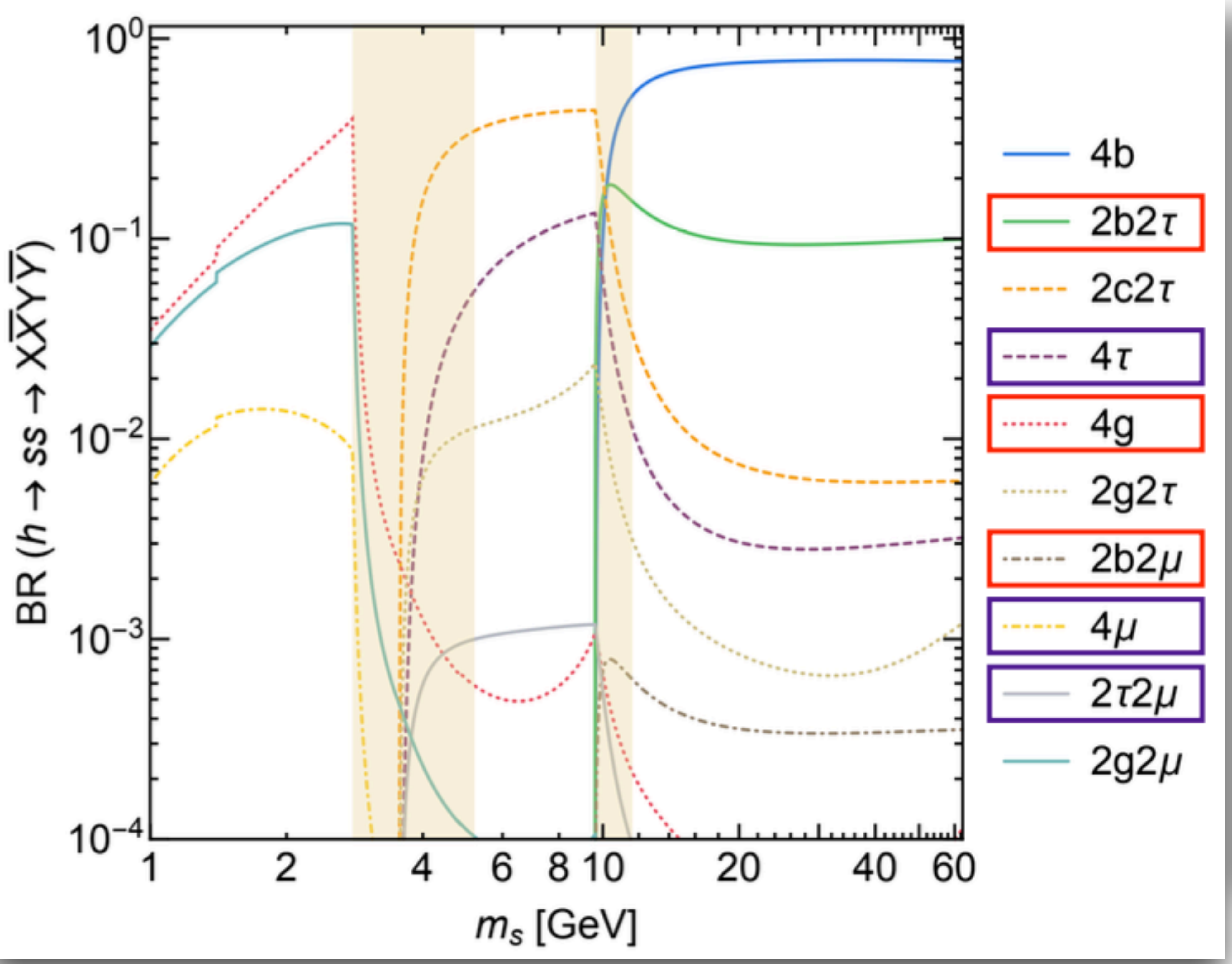
BR(H→eτ) < 0.20% (0.12% exp)

BR(H→μτ) < 0.18% (0.09% exp)

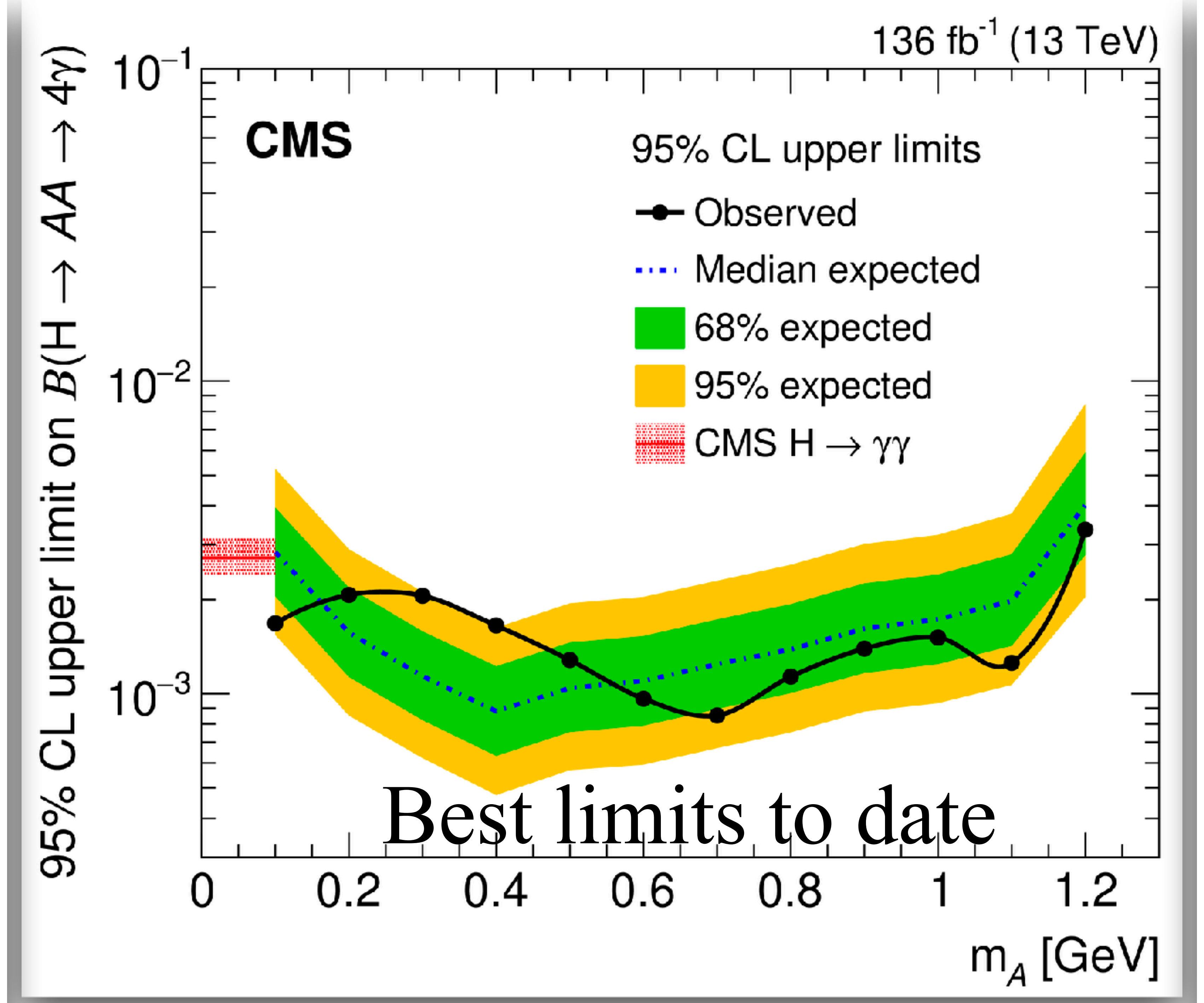
2302.05225

Higgs to pseudoscalars

- Copious BSM scenarios (2HDM, 2HDM+S, singlet, NMSSM, axion etc.) expect Higgs to decay to a pair of pseudoscalars and are extensively searched at CMS



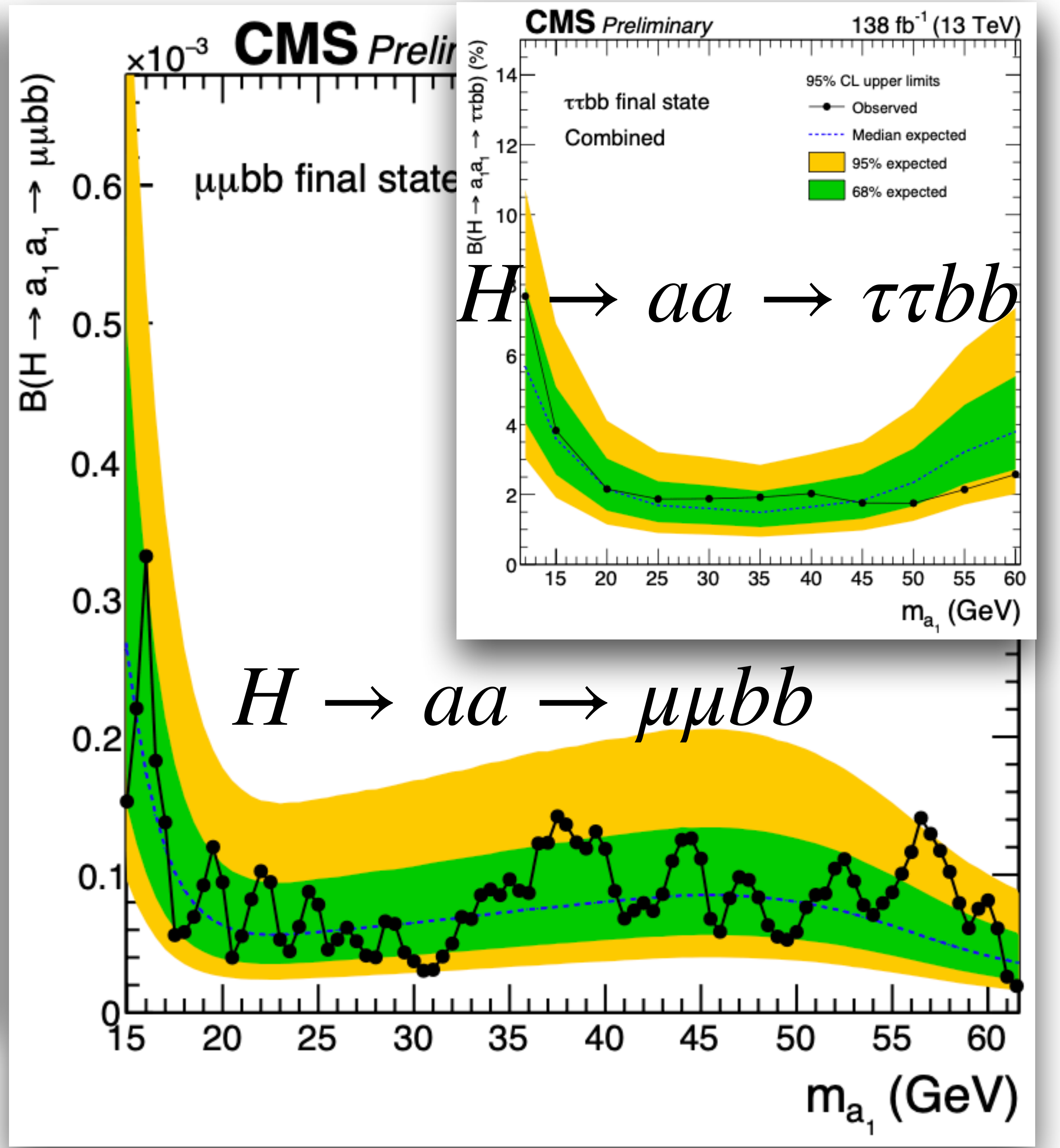
Channels sensitive in different mass ranges



$H \to aa \to 4\gamma$

First merged diphoton topology!

Accepted by PRL

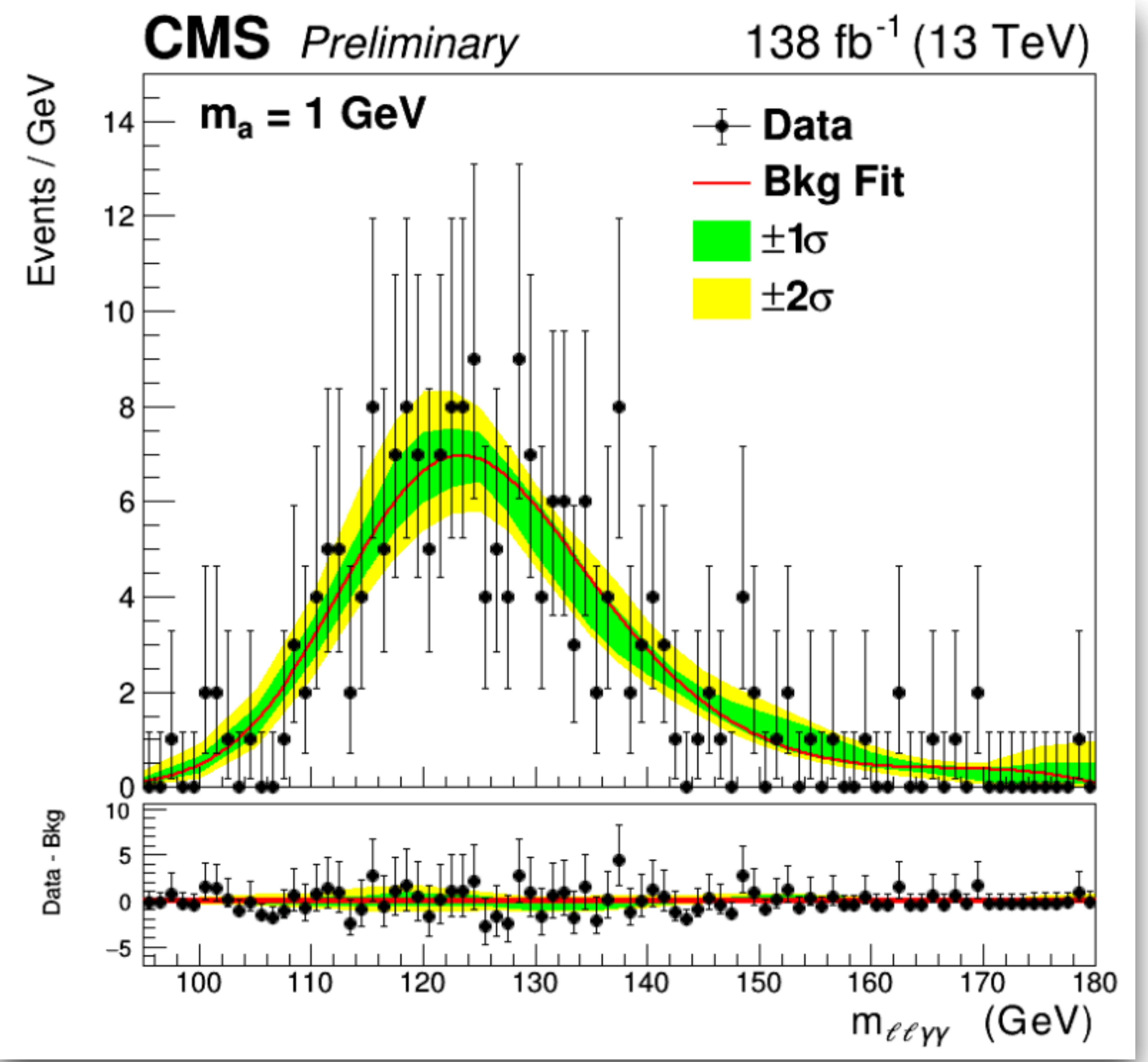


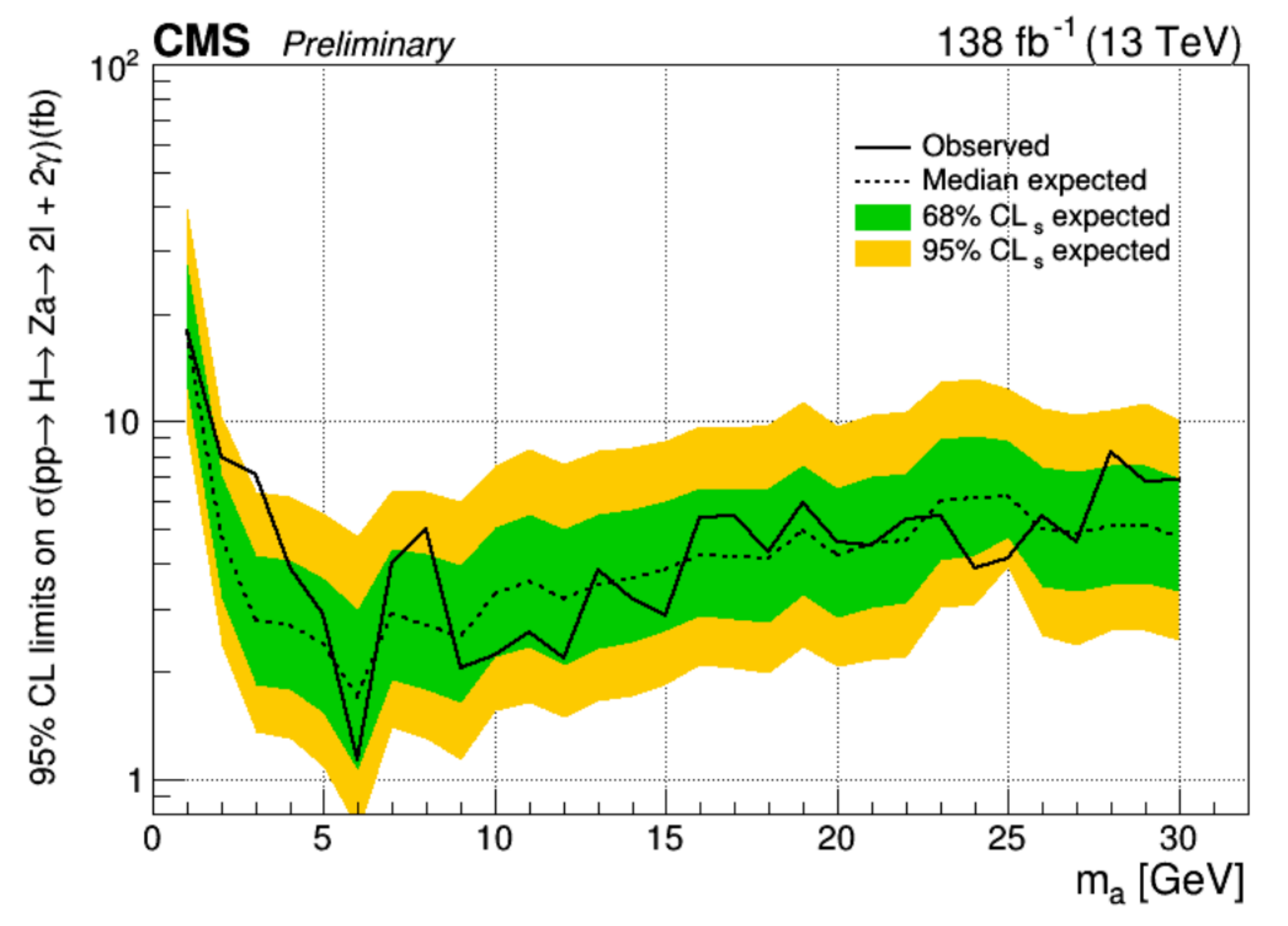
CMS-PAS-HIG-22-007

Higgs to pseudoscalars

- Instead of pairs, Higgs to Z+pseudoscalar is searched as well
- Unique signature with $ll\gamma\gamma$ classified with a BDT

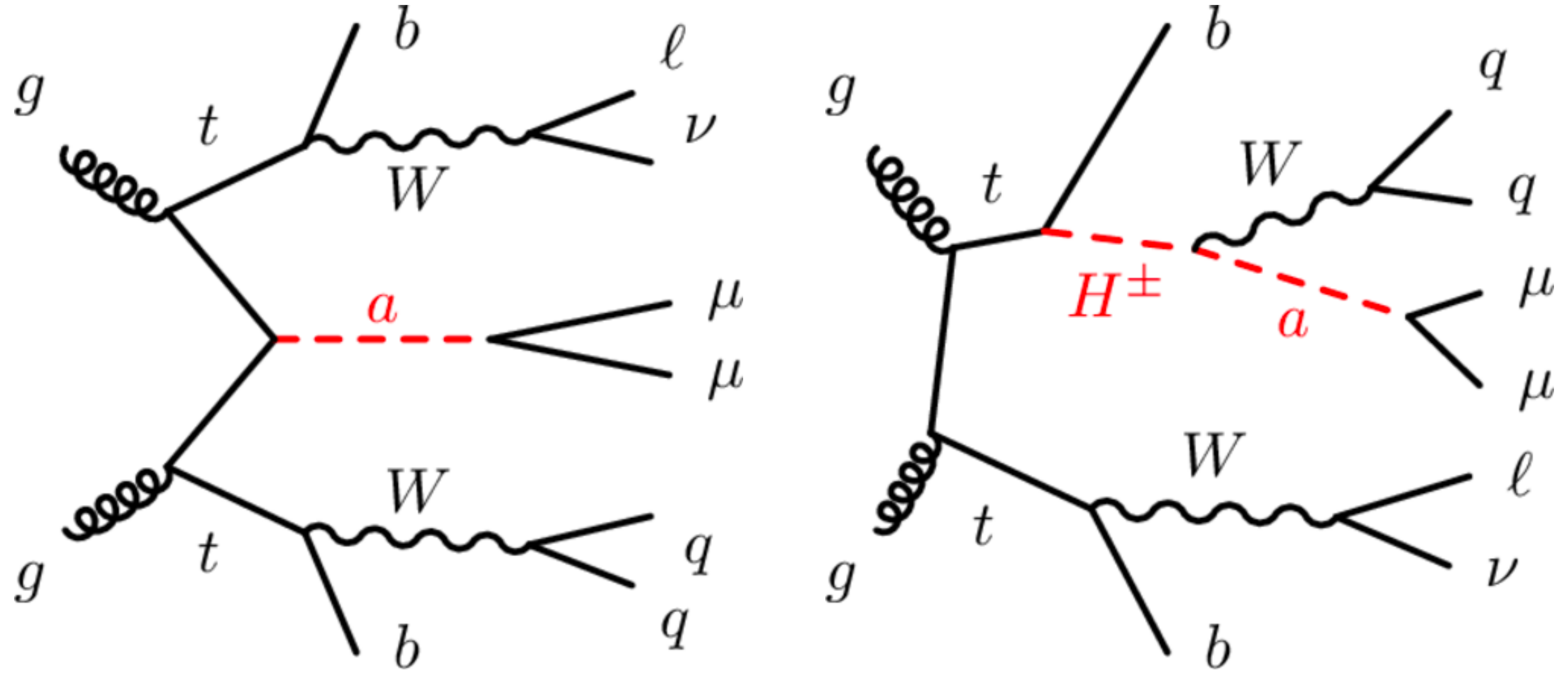
CMS-PAS-HIG-22-003

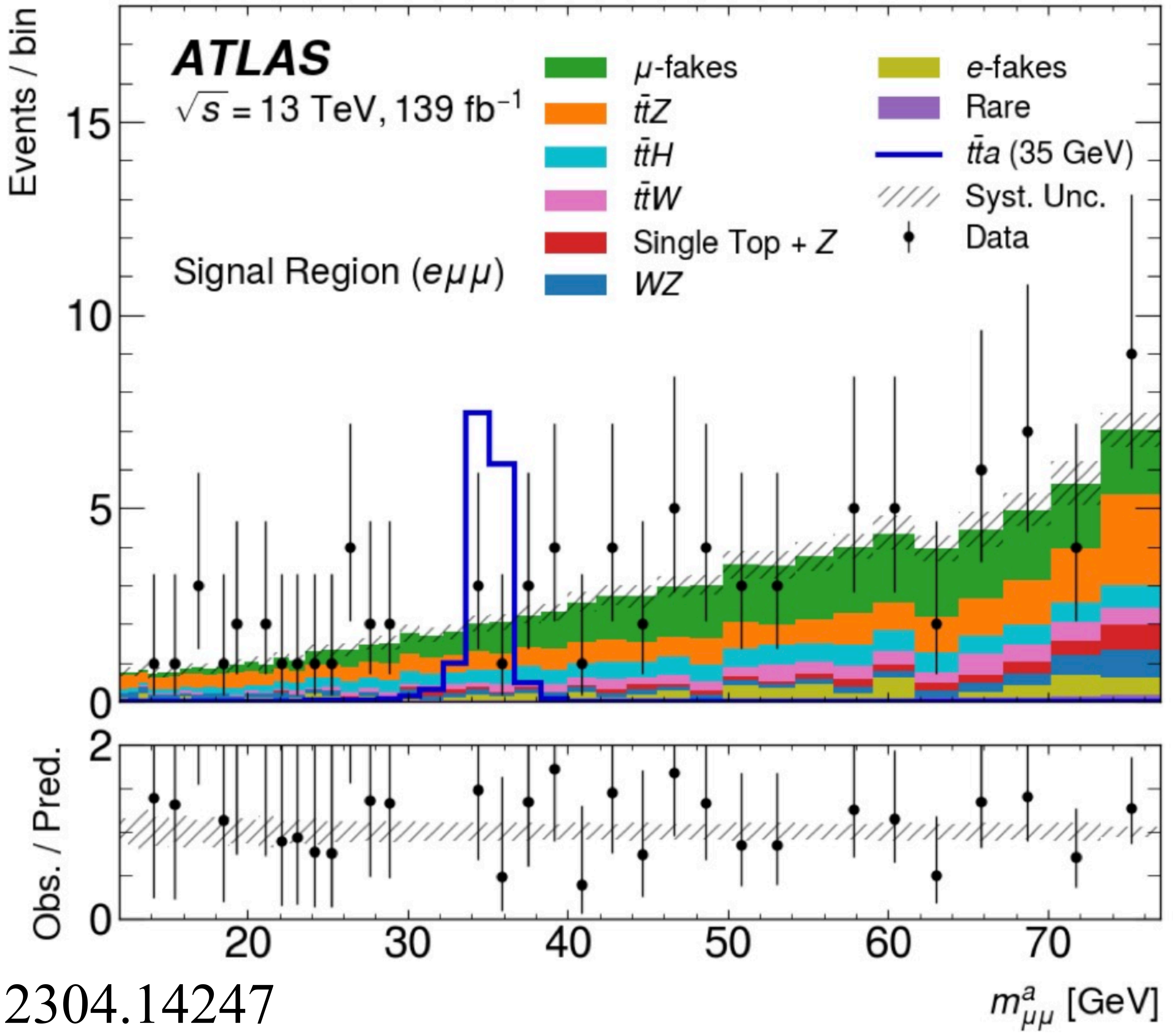




Top-associated pseudoscalar

- Motivated by the excess of γ-ray emissions from the galactic center (1-3 GeV), a search for a light scalar (tens of GeV) is performed by ATLAS
- Signal events with $e\mu\mu$ and $\mu\mu\mu$ are selected
- No significant excess is found in data



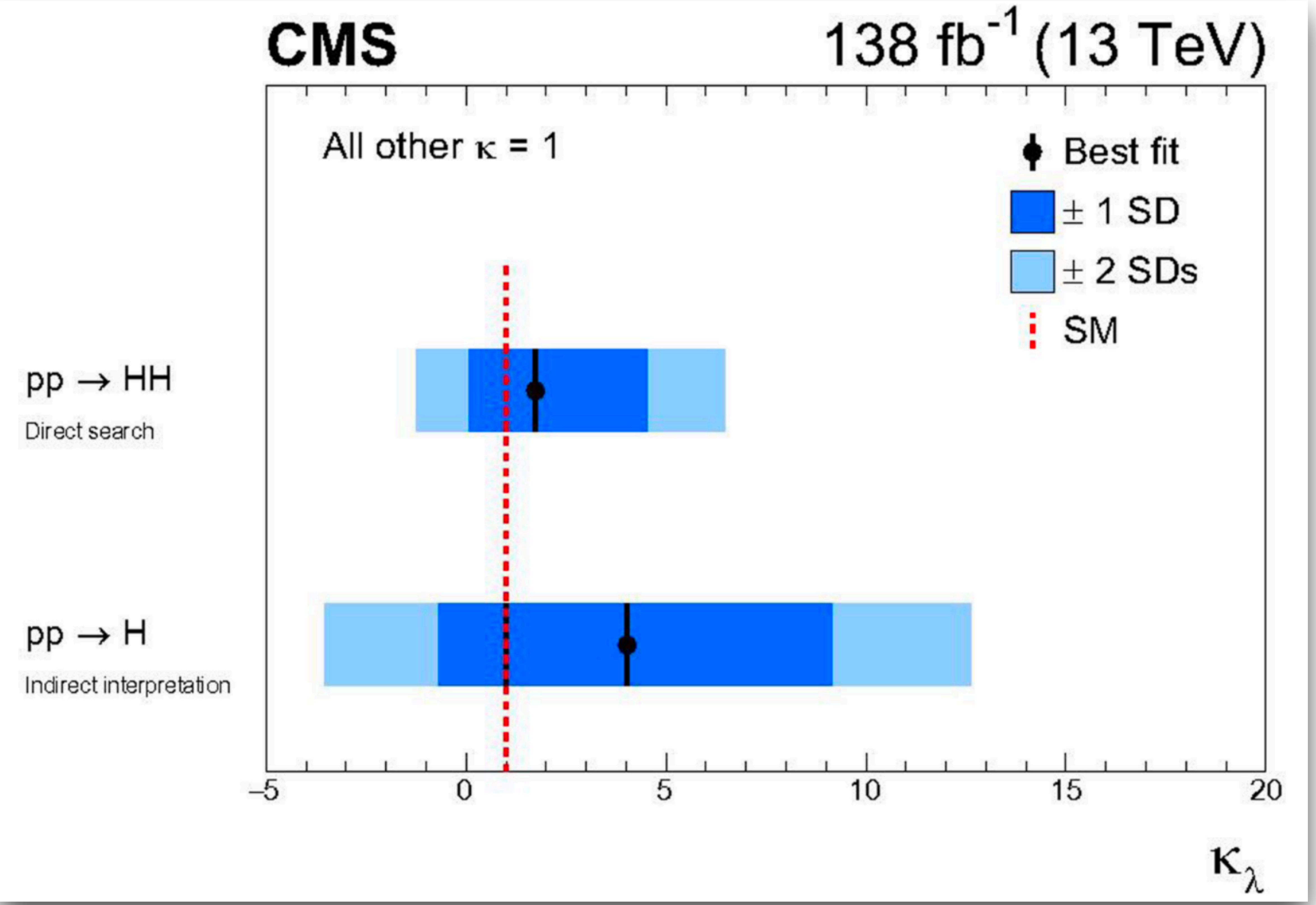


2304.14247

HH

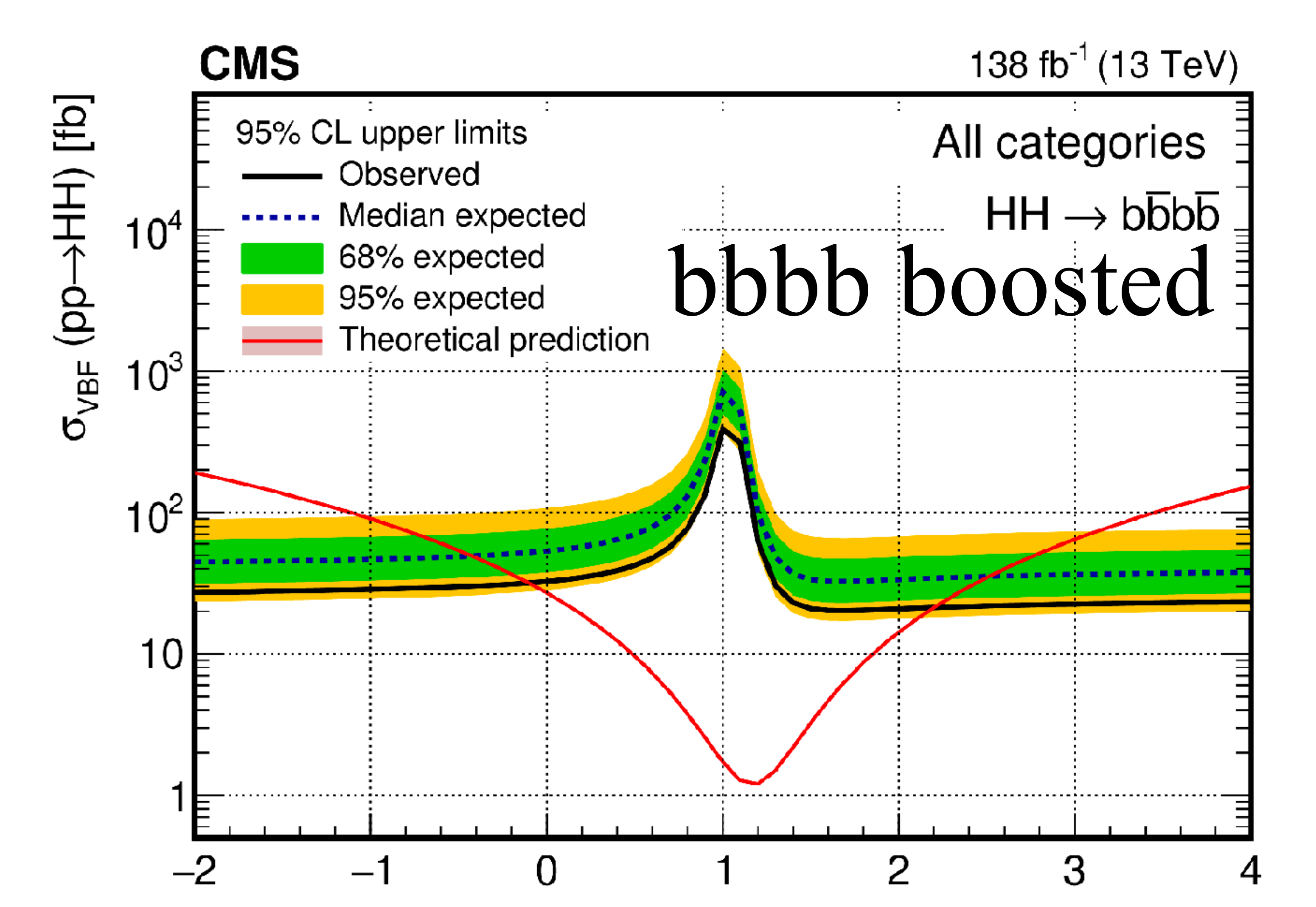
- The double Higgs processes (HH) provides a direct probe to the Higgs self-coupling and the four-boson coupling VVHH κ_{2V}, but very challenging as its XS is 3 orders of magnitude smaller than the single Higgs
- The HH sensitivity already surpassed the single Higgs in terms of Higgs self-coupling
- Both HH production and decays have been explored extensively
  - Production: ggH, VBF and VHH
  - Decays: $4b$, $bb\tau\tau$, $bb\gamma\gamma$, $bbWW$, $bbZZ$, $\tau\tau WW$, 4τ, $4W$, $WW\gamma\gamma$

Nature 607 (2022) 60-68

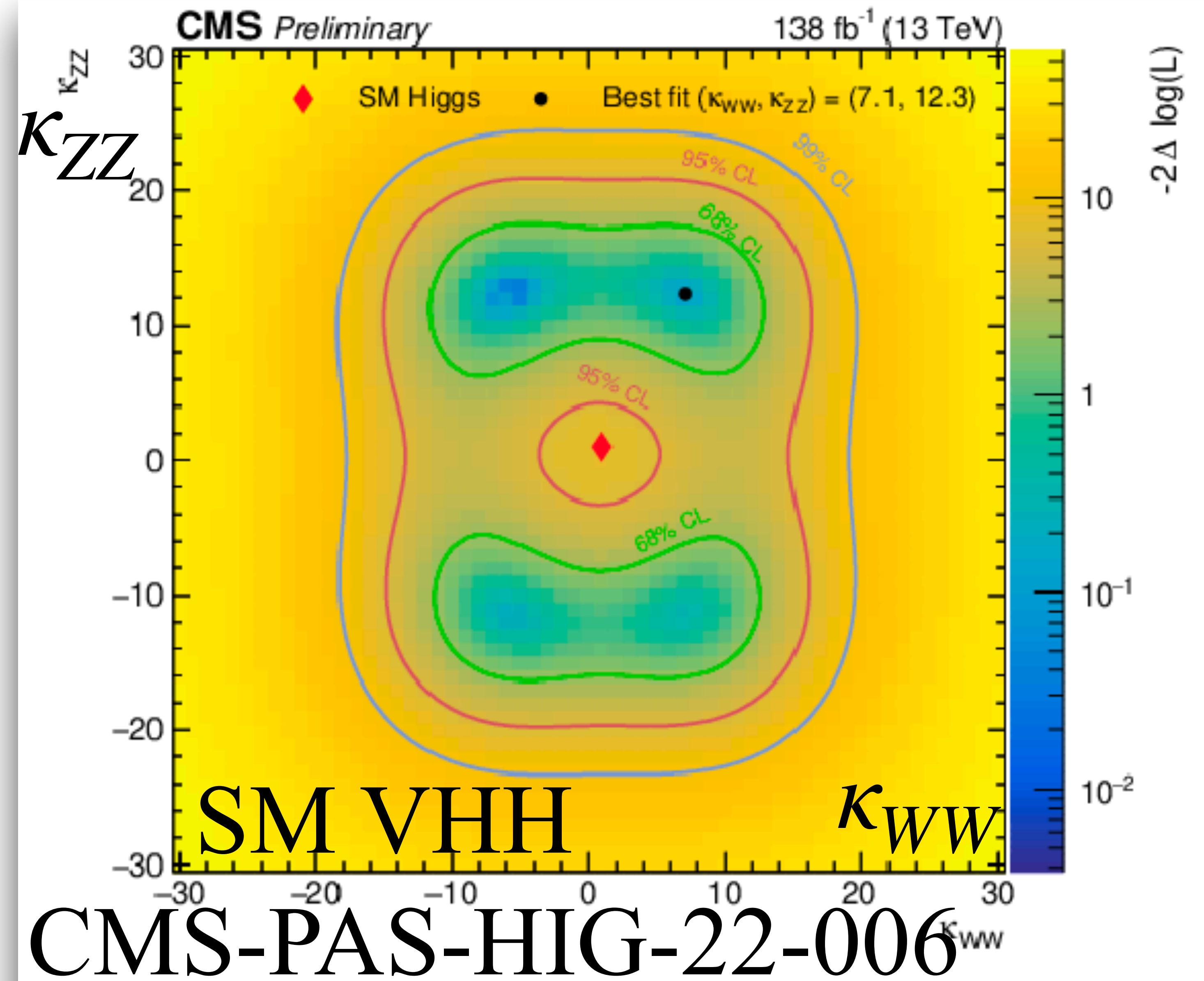


HH with 4b

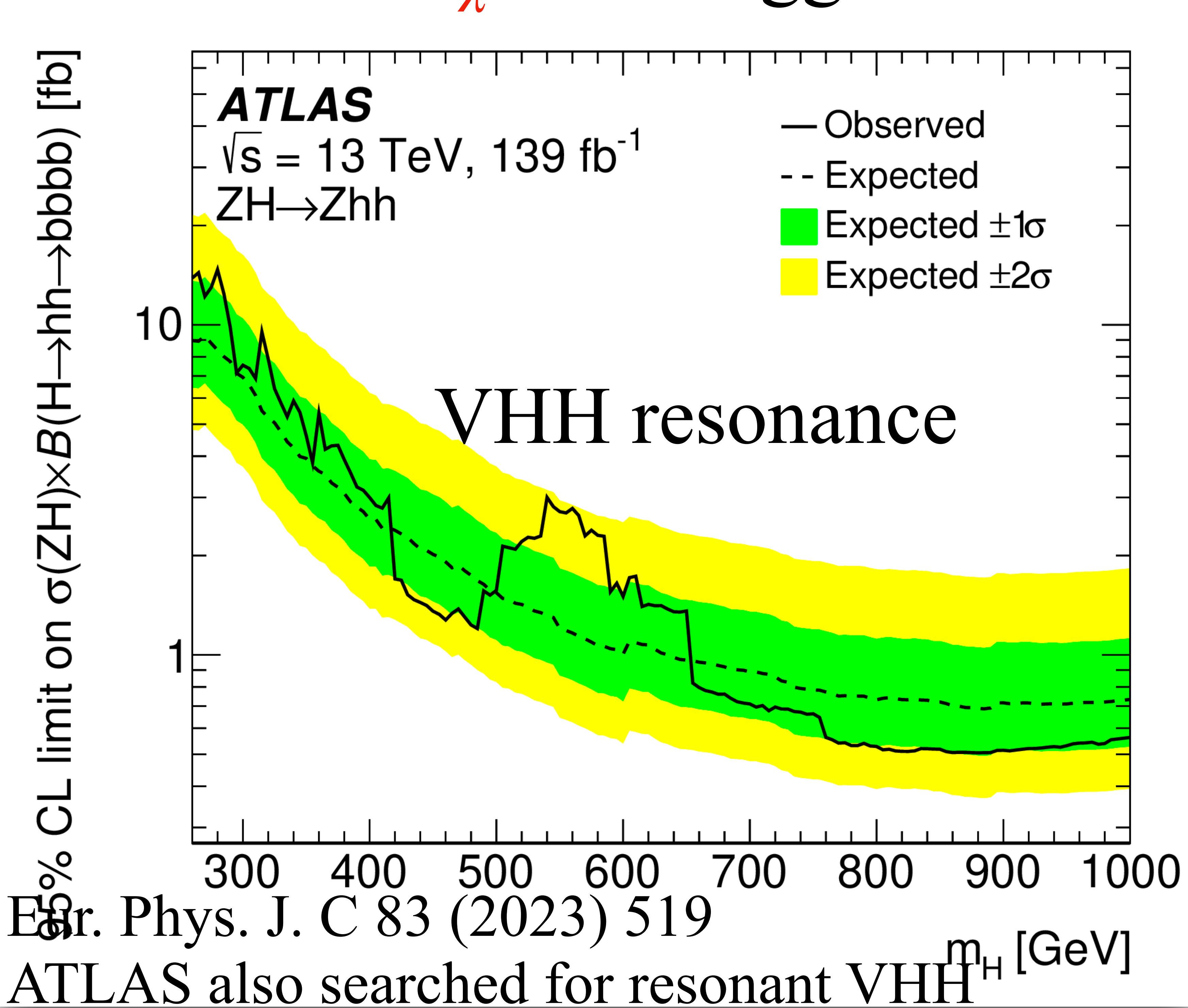
- Stats deliver in HH thanks to its largest BR among all; measure HH XS with an upper limits of 3.9 (7.8)xSM
- The boosted 4b excludes $\kappa_{2V} = 0$ for more than 5σ
- The VHH is also probed using 4b and provides unique probes to WWHH and ZZHH separately
  - Not sensitive to the κ_λ constraints in general, but way more sensitive in $\kappa_\lambda \sim 5$ than ggF
  - ATLAS also uses it for resonant searches



Phys. Rev. Lett. 129 (2022) 081802



CMS-PAS-HIG-22-006

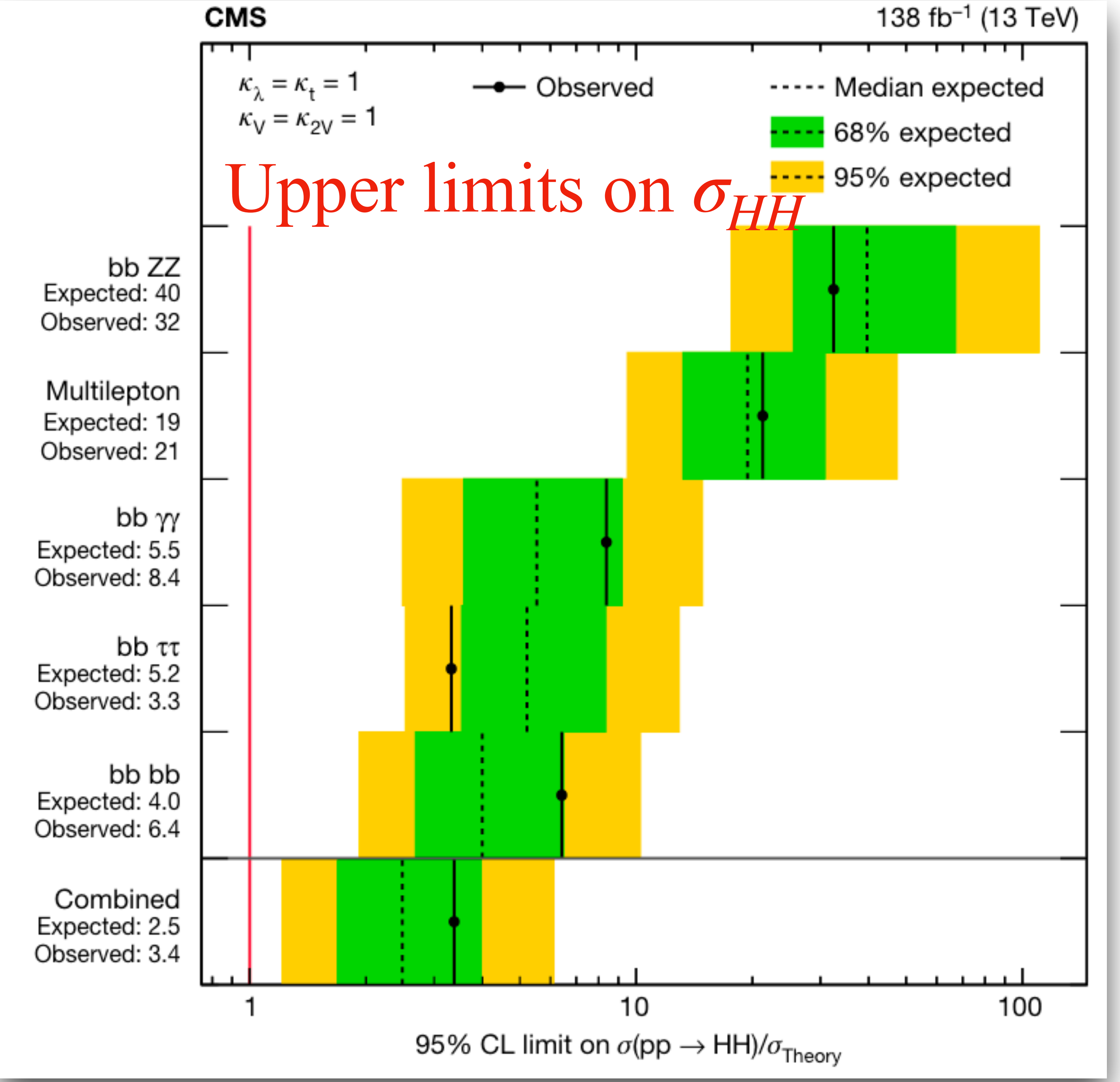


Eur. Phys. J. C 83 (2023) 519

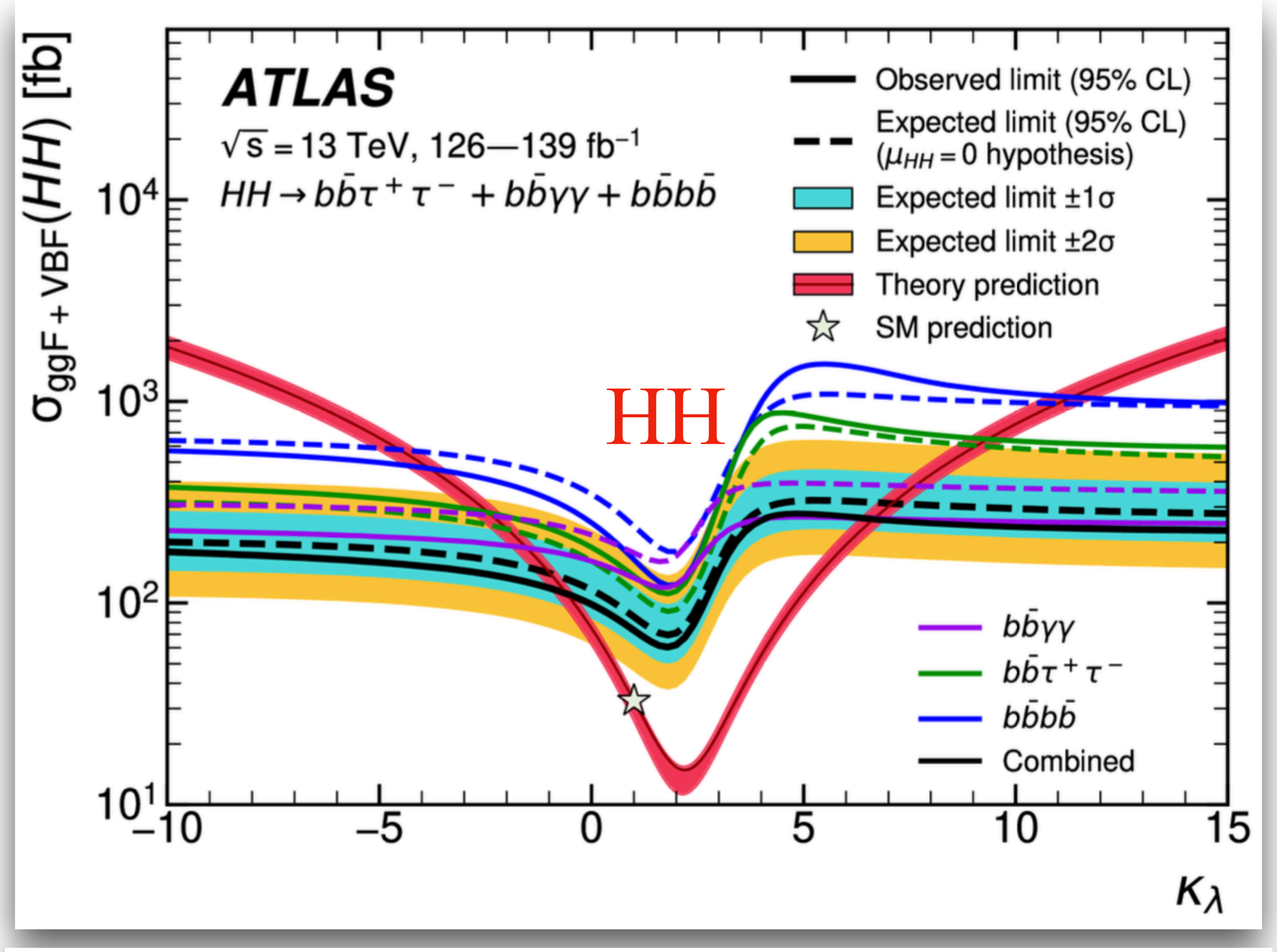
ATLAS also searched for resonant VHH

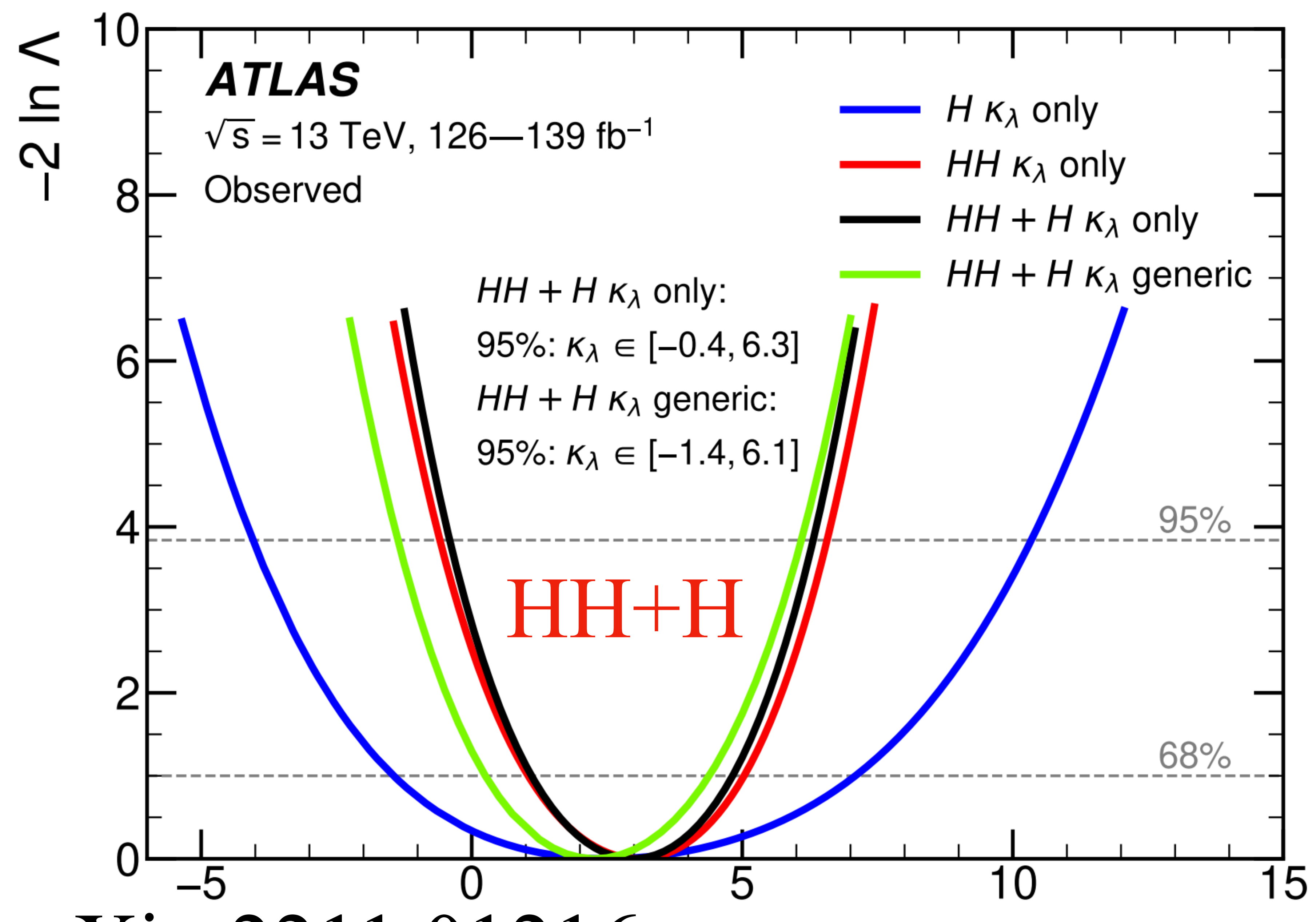
HH(+H) combined

- Still in the era of search, upper limits on HH XS get more stringent
- The combined H XS upper limit reaches 2-3 times of the SM prediction
- H is also introduced in the combination as κ_λ enters as EWK correction in H



Nature 607 (2022) 60-68





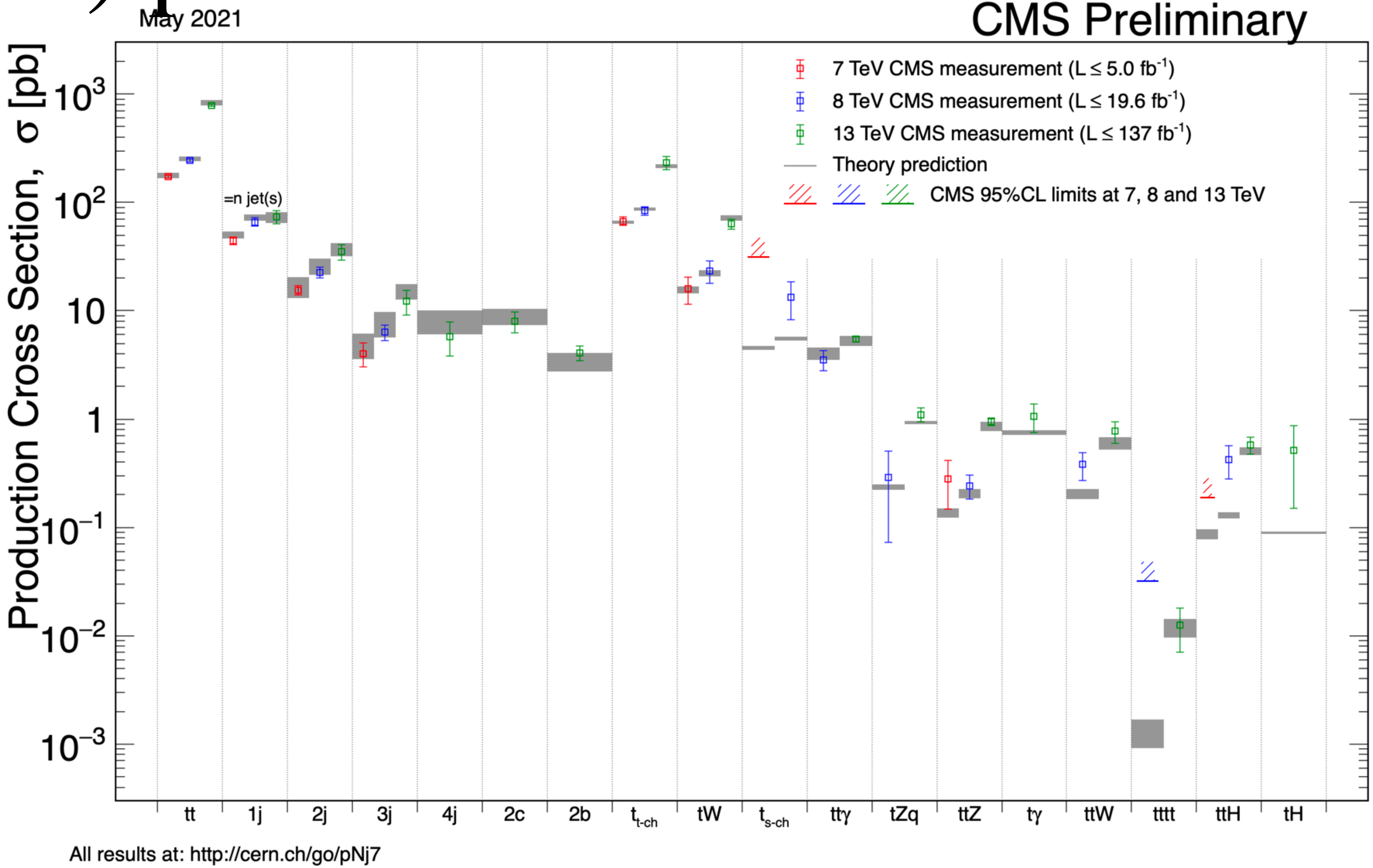
arXiv:2211.01216

Summary

- A brief review of the EW and relevant BSM studies at ATLAS and CMS
- Many improvements in precision beyond the increase brought by data statistics, while no obvious sign of BSM is found yet
- Run3 data taking is already well undergoing
- Look forward to more stringent examination to SM and more closer look for BSM effects

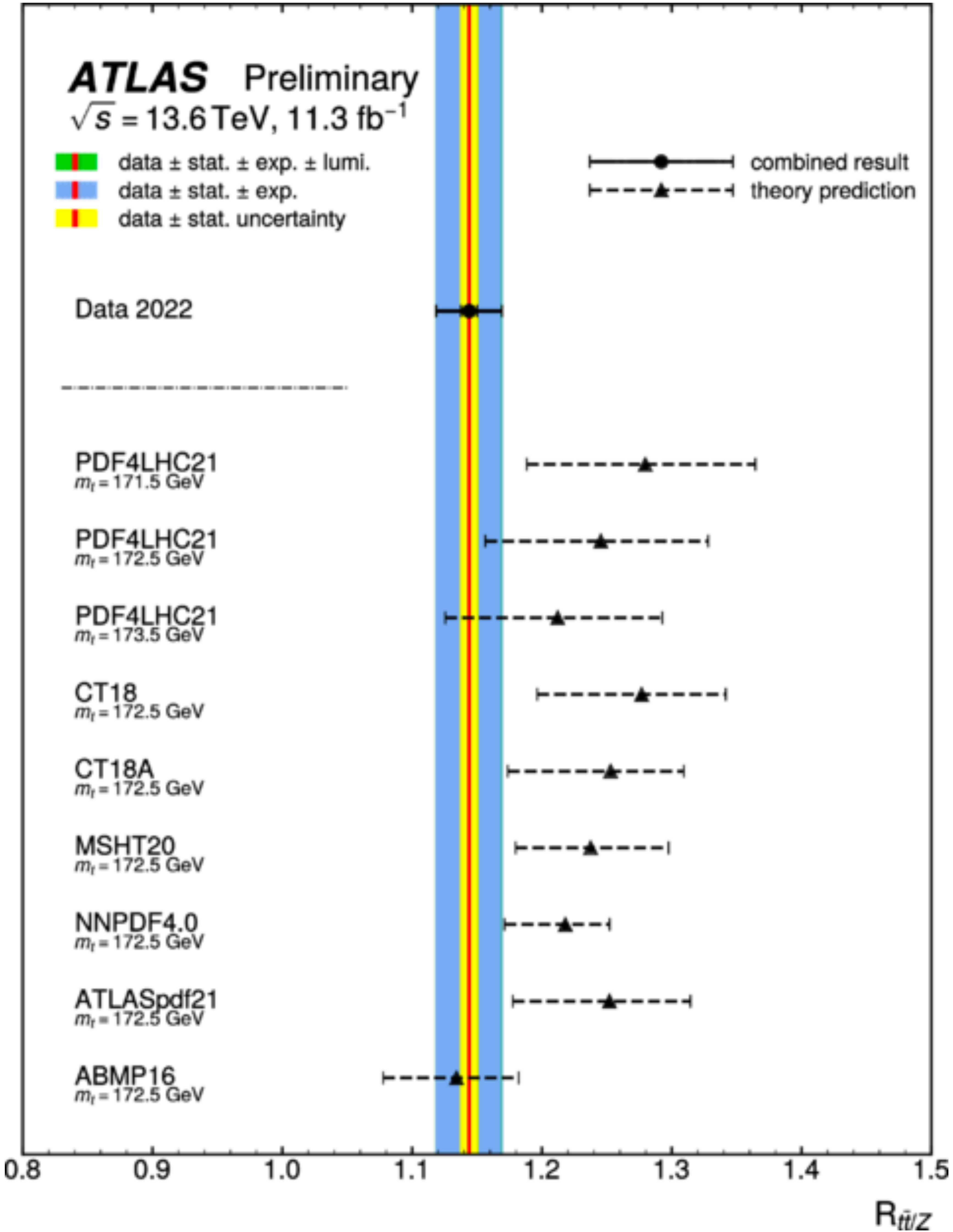
Backup slides

$t\bar{t}(+X)$ productions



$\sigma_{t\bar{t}}/\sigma_Z$

Sensitive to quark-gluon PDF ratio

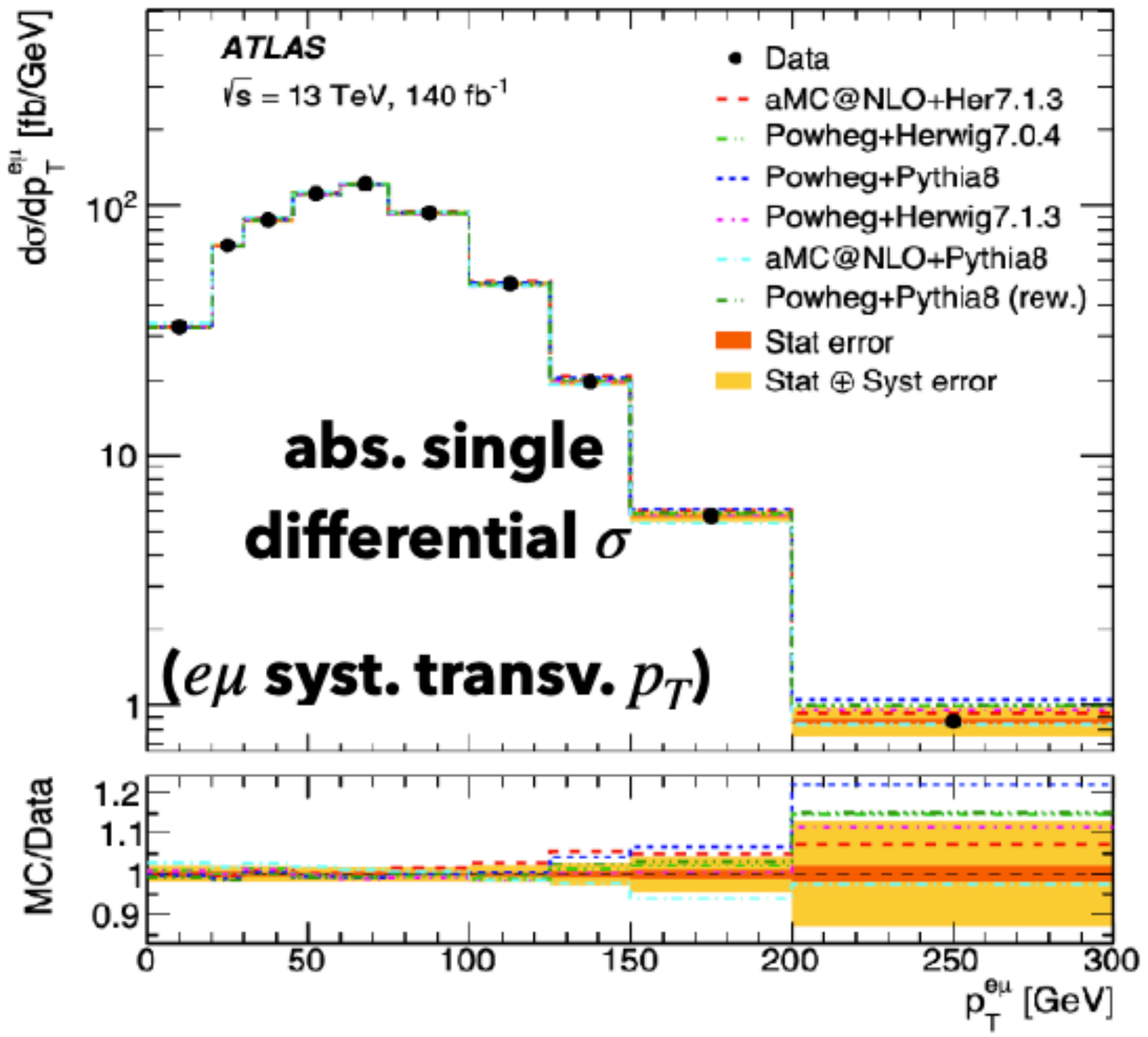


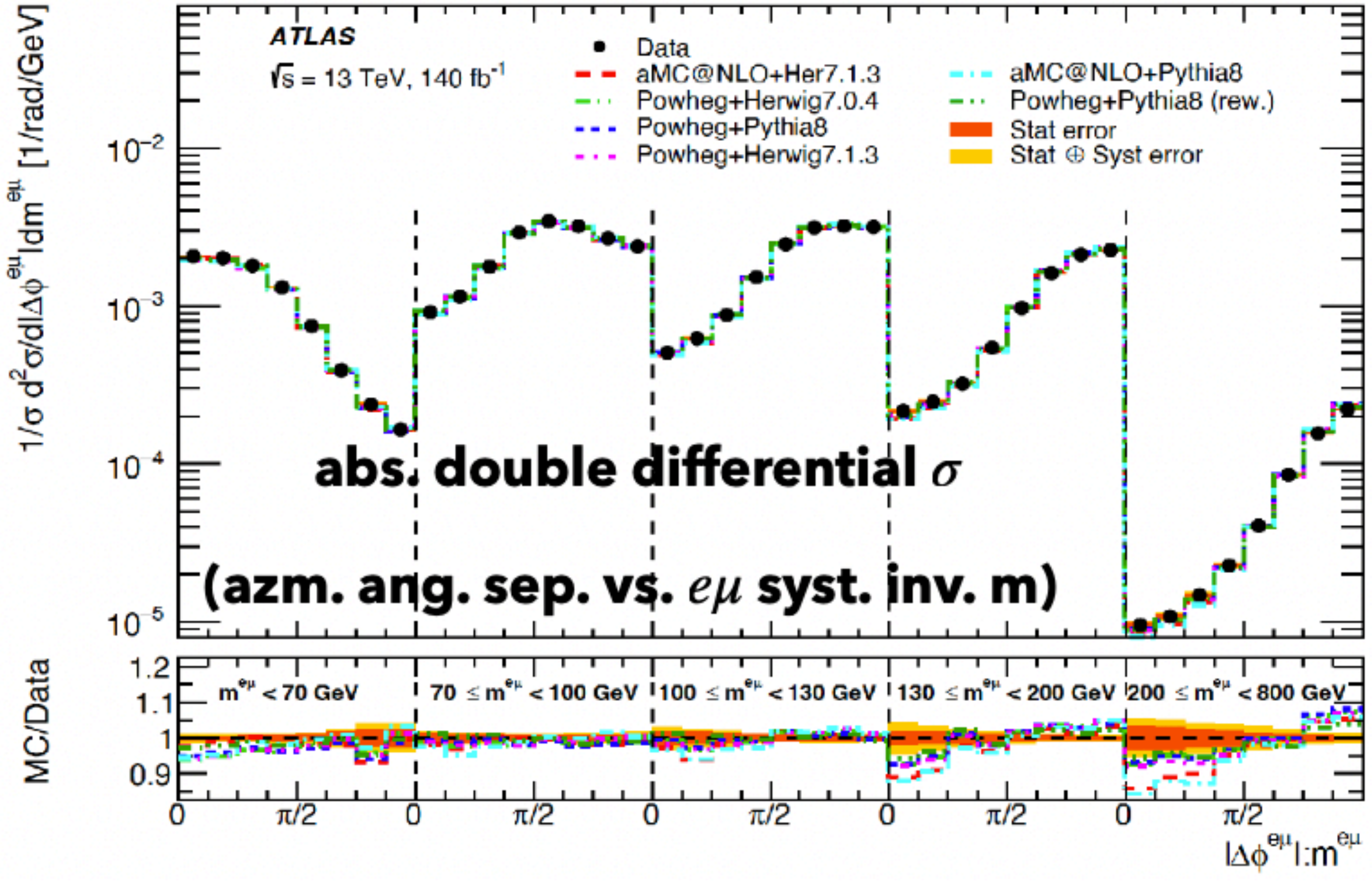
TOPQ-2018-26

inclusive & differential $t\bar{t}$

- Inclusive & single/double differential $\sigma_{t\bar{t}}$ ($e\mu$ final state)
- Inclusive: Most precise inclusive $\sigma_{t\bar{t}}$ @ 13 TeV! → impressive systematics (0.8% lumi!)
- Differential: Kinematic dists. of 8 variables → good agreement with predictions except tails, improved MC needed (NNLO/EW corrections, threshold effects)

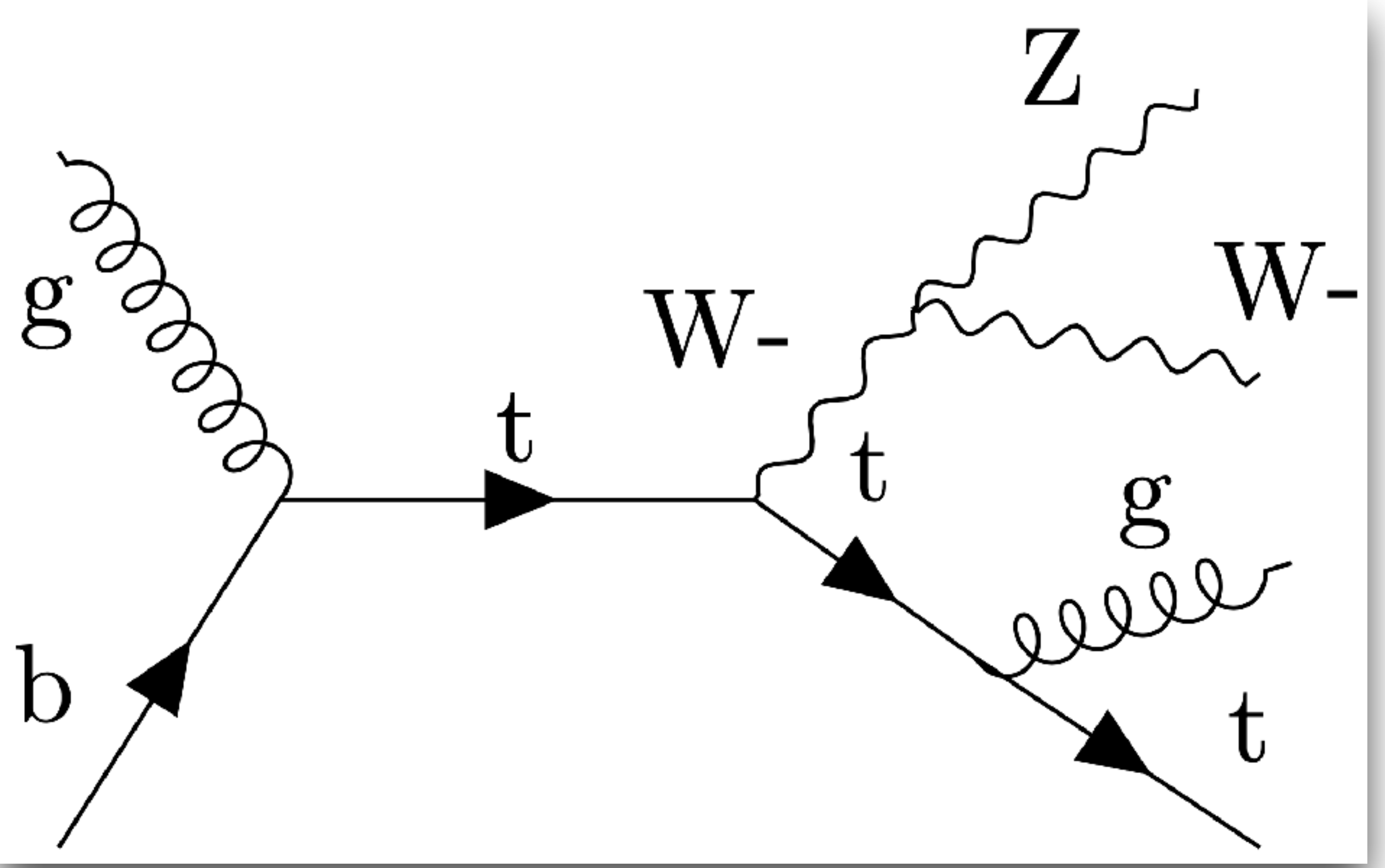
$$\sigma(pp \to t\bar{t}) = 829 \pm 1\ (\text{stat}) \pm 13\ (\text{syst}) \pm 8\ (\text{lumi}) \pm 2\ (\text{beam})\ \text{pb}$$

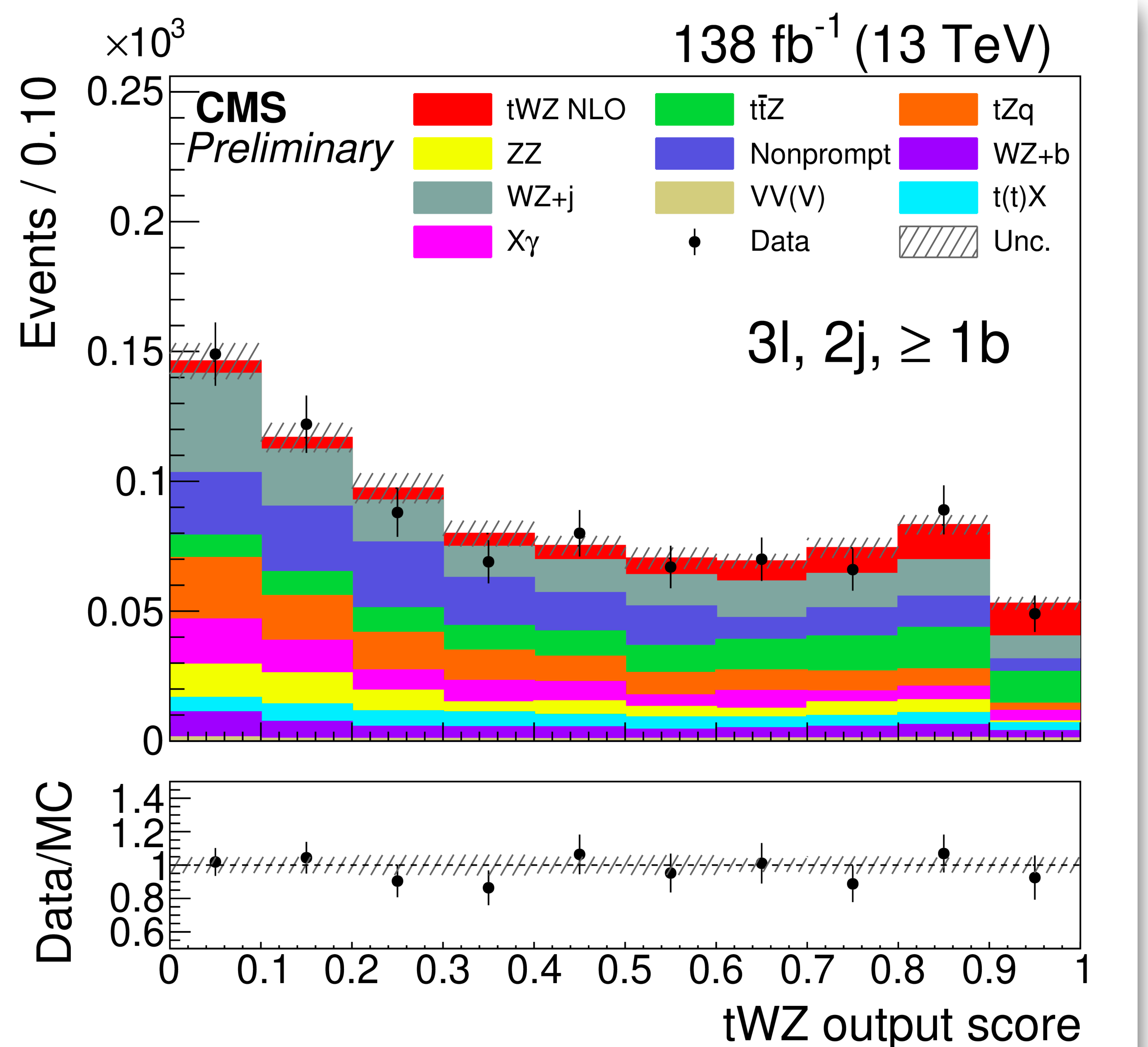




tWZ

- Rate production ~ 136 fb, sensitive to new physics, good probe of EFT
- Evidence with full Run2 data: 3.5 (1.4) s.d.

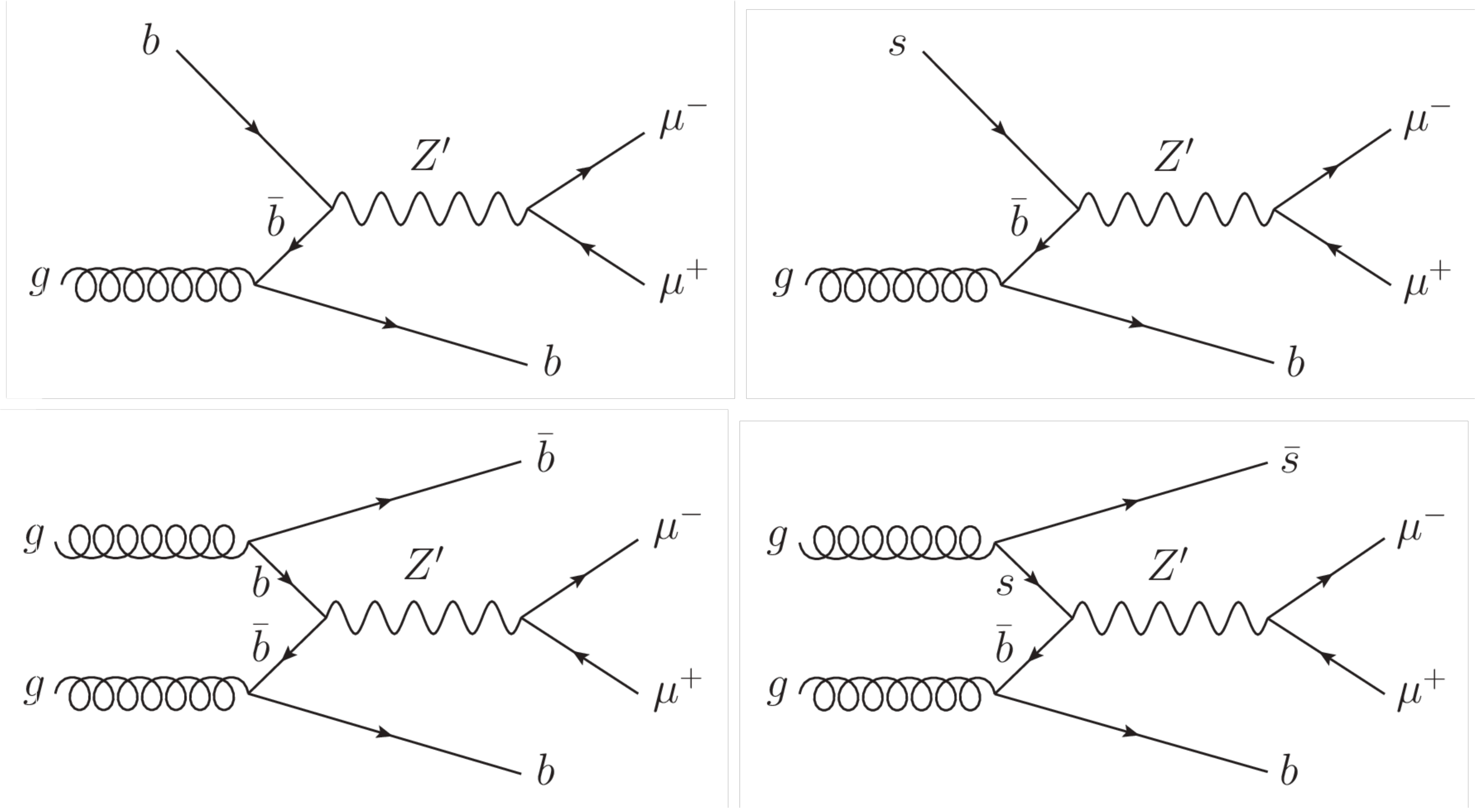


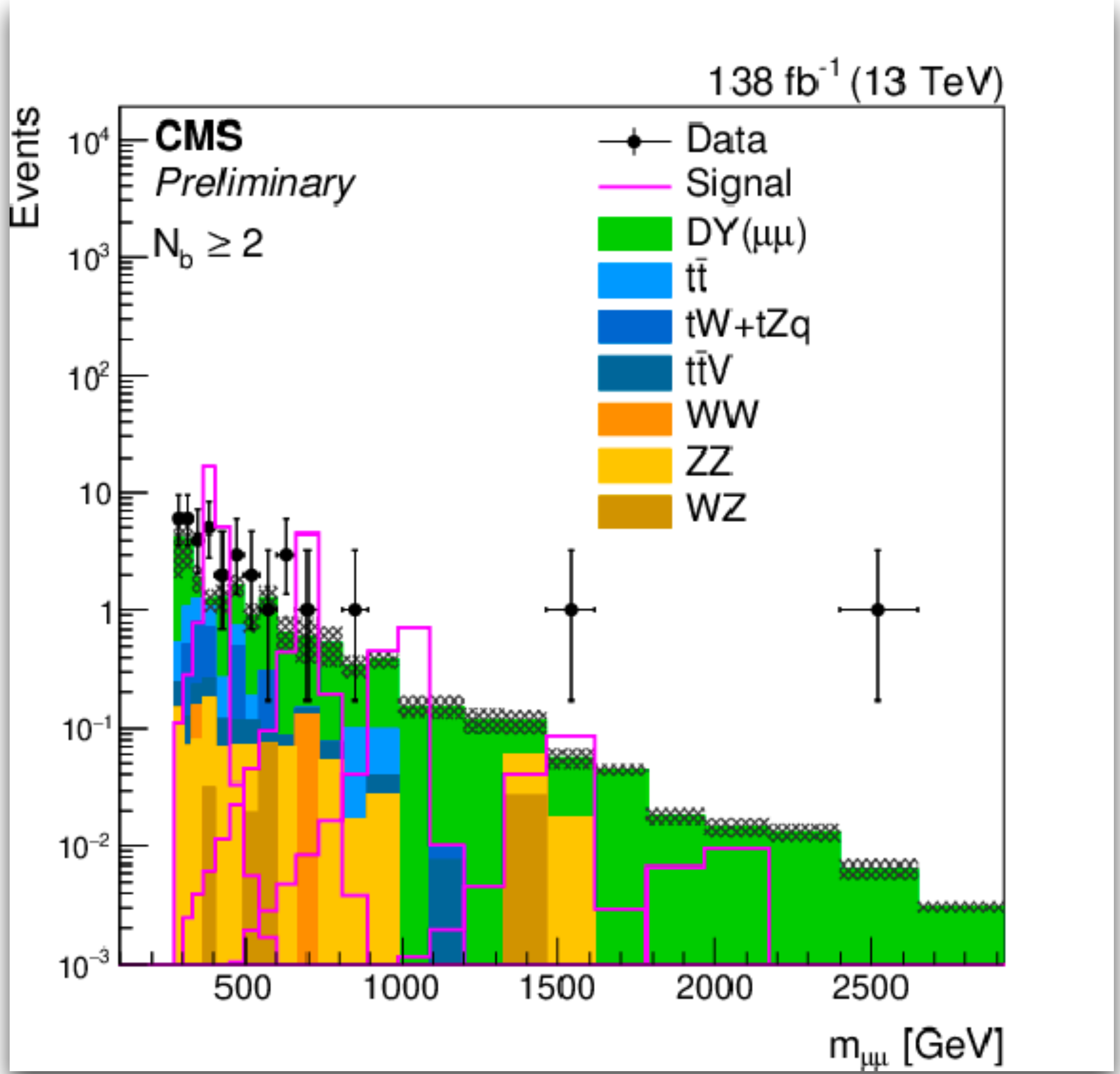


CMS-TOP-22-008

$X \to \mu\mu$ with b

- Search dimuon resonance associated with b-quarks
- Connection to LFUV models (Z')
- Constraints are set on specific Z' model, consistent with low-energy $b \to sll$ measurements

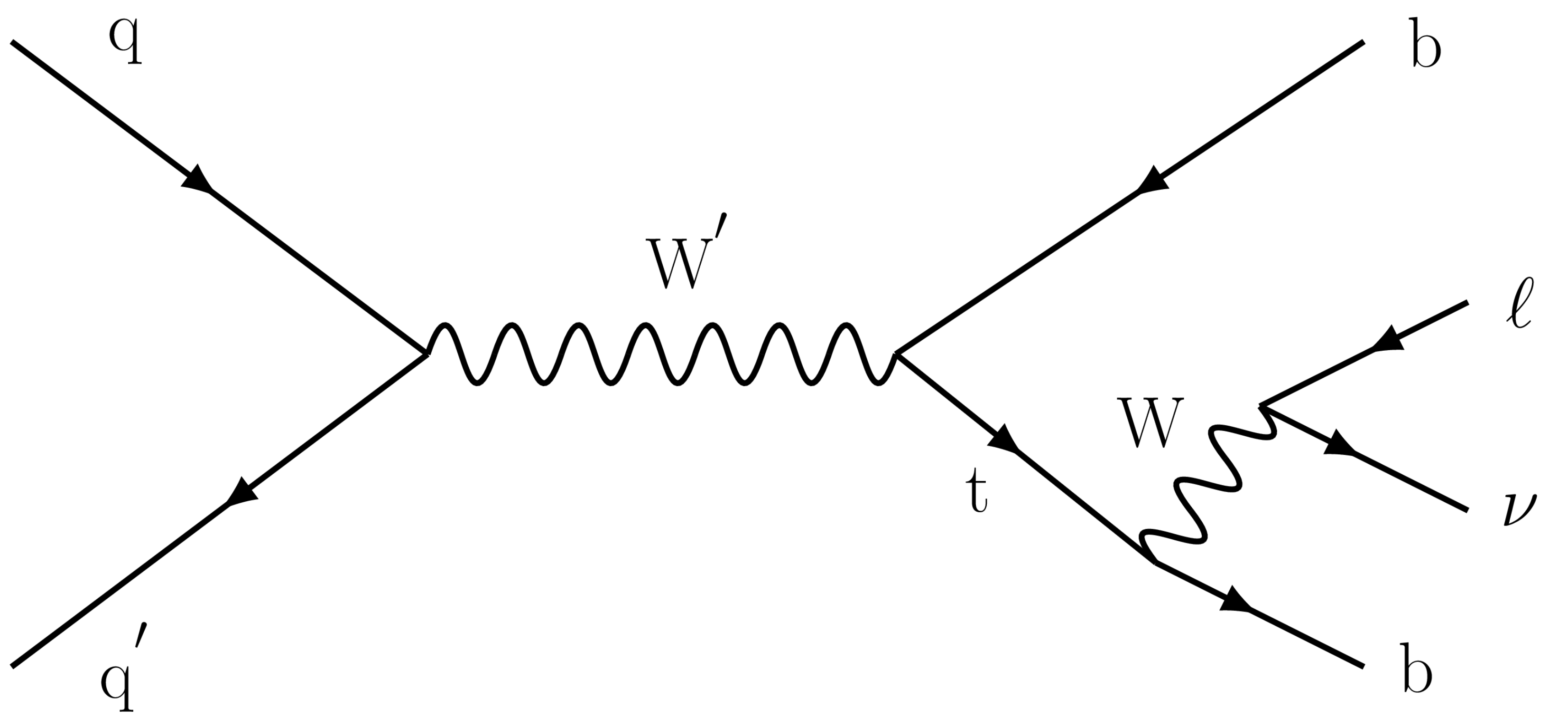


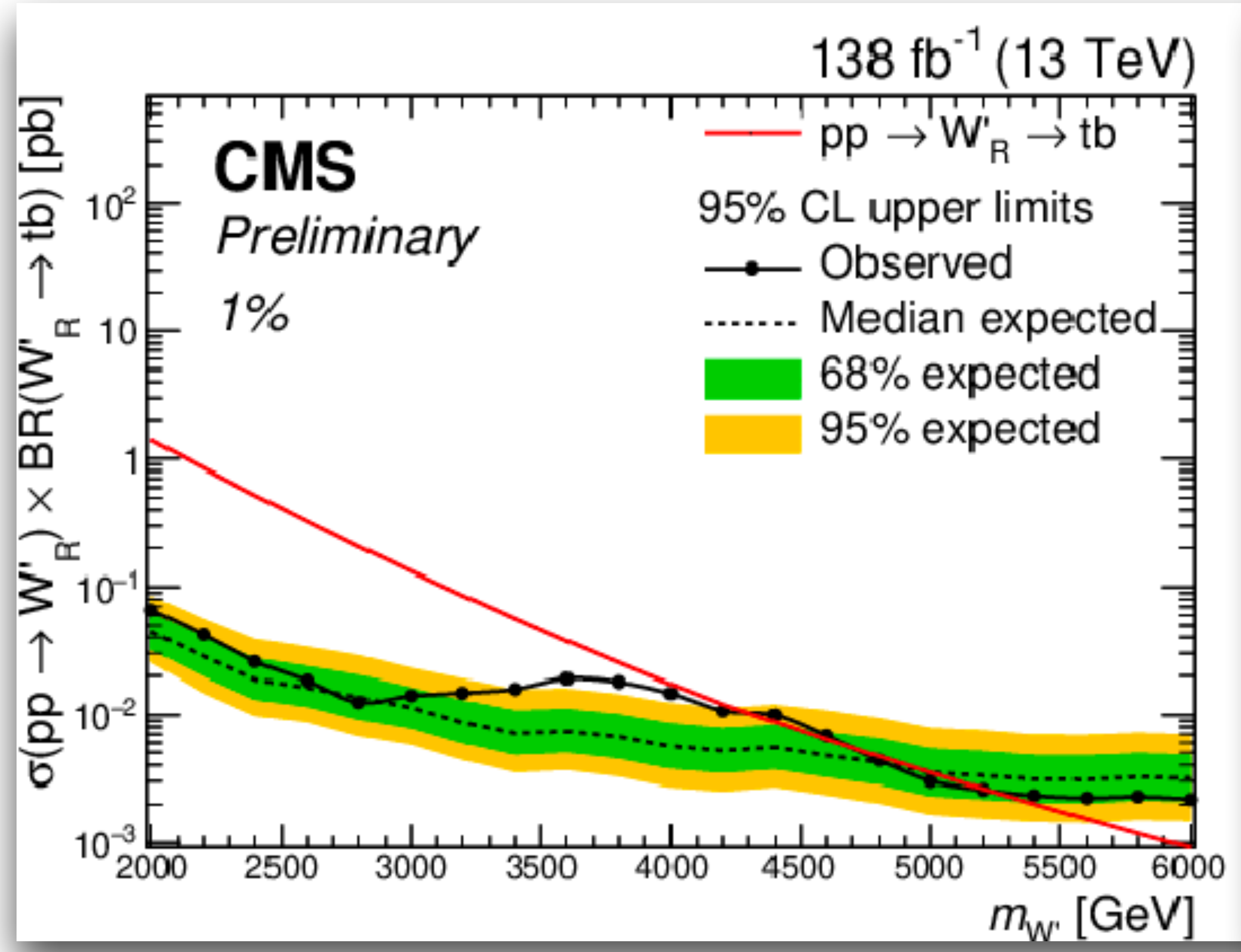


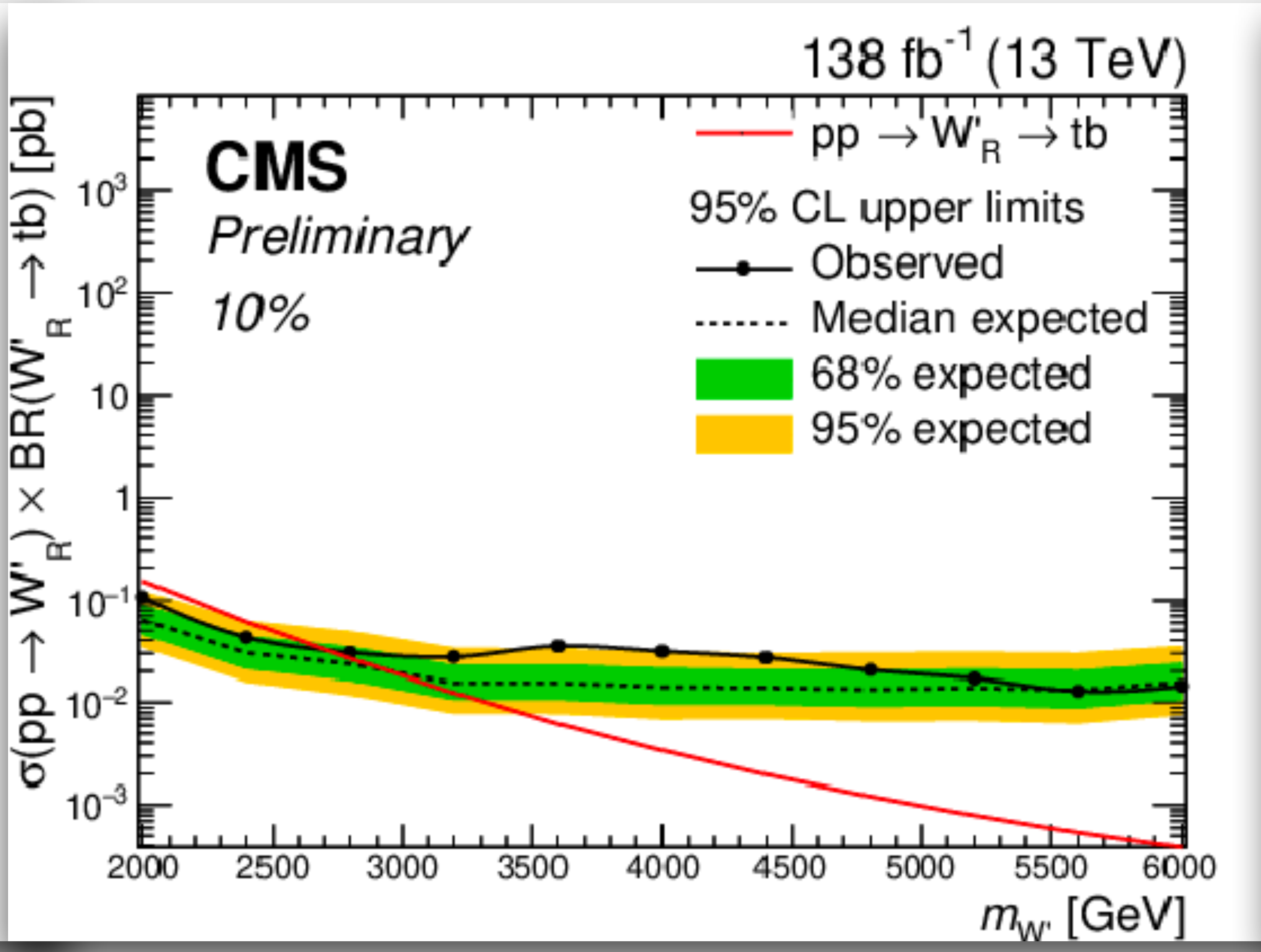
W’

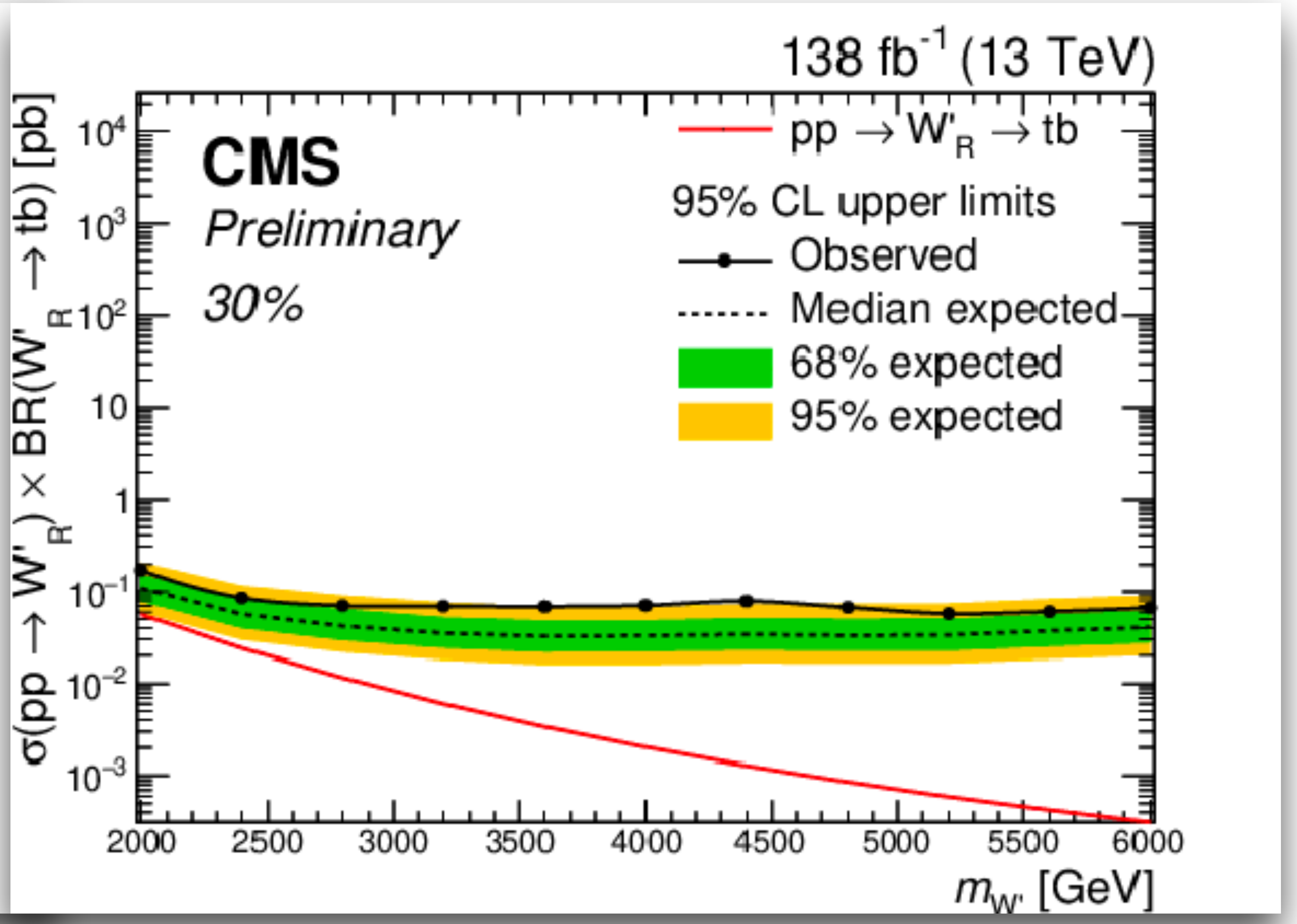
CMS-PAS-B2G-20-012

- New results of $W' \to tb$ is released by CMS
- Different width assumptions are tested
  - Width degrades the sensitive significantly









2.6 (2.0) s.d. @ 3.8 TeV