Experiment Summary: Top + SM

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Workshop for Tera-Scale Physics and Beyond, 23 Jun. 2023

v.3

Contents

- Top quark mass (ATLAS, CMS)
- 4 top (ATLAS, CMS)
- ttbb (CMS)
- ttW (ATLAS)
- Run 3 top measurements (ATLAS, CMS)
- W mass (ATLAS)
- α_s measurement from Z p_T (ATLAS)
- VBS (ATLAS, CMS)

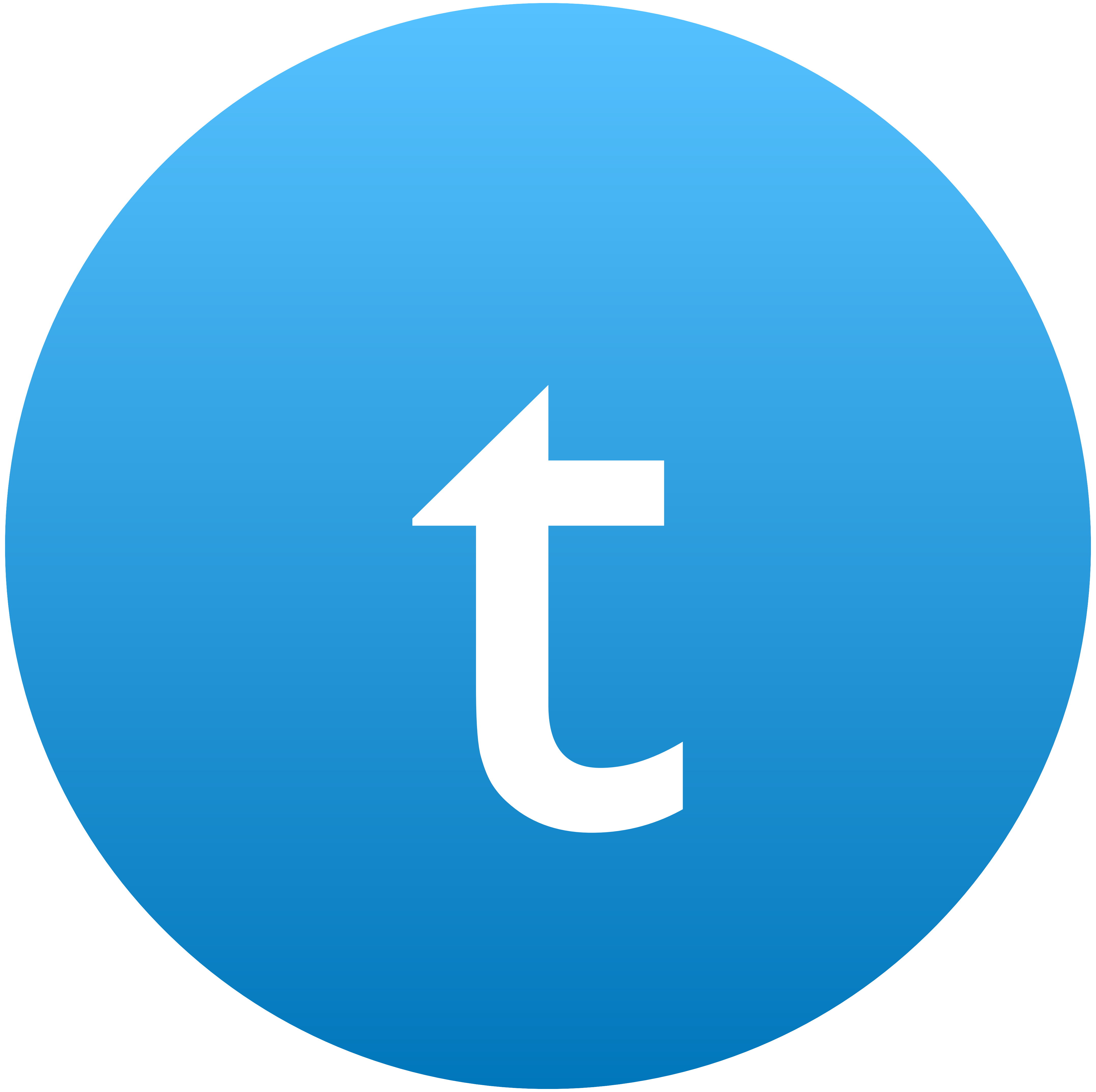
Top

SM

Top

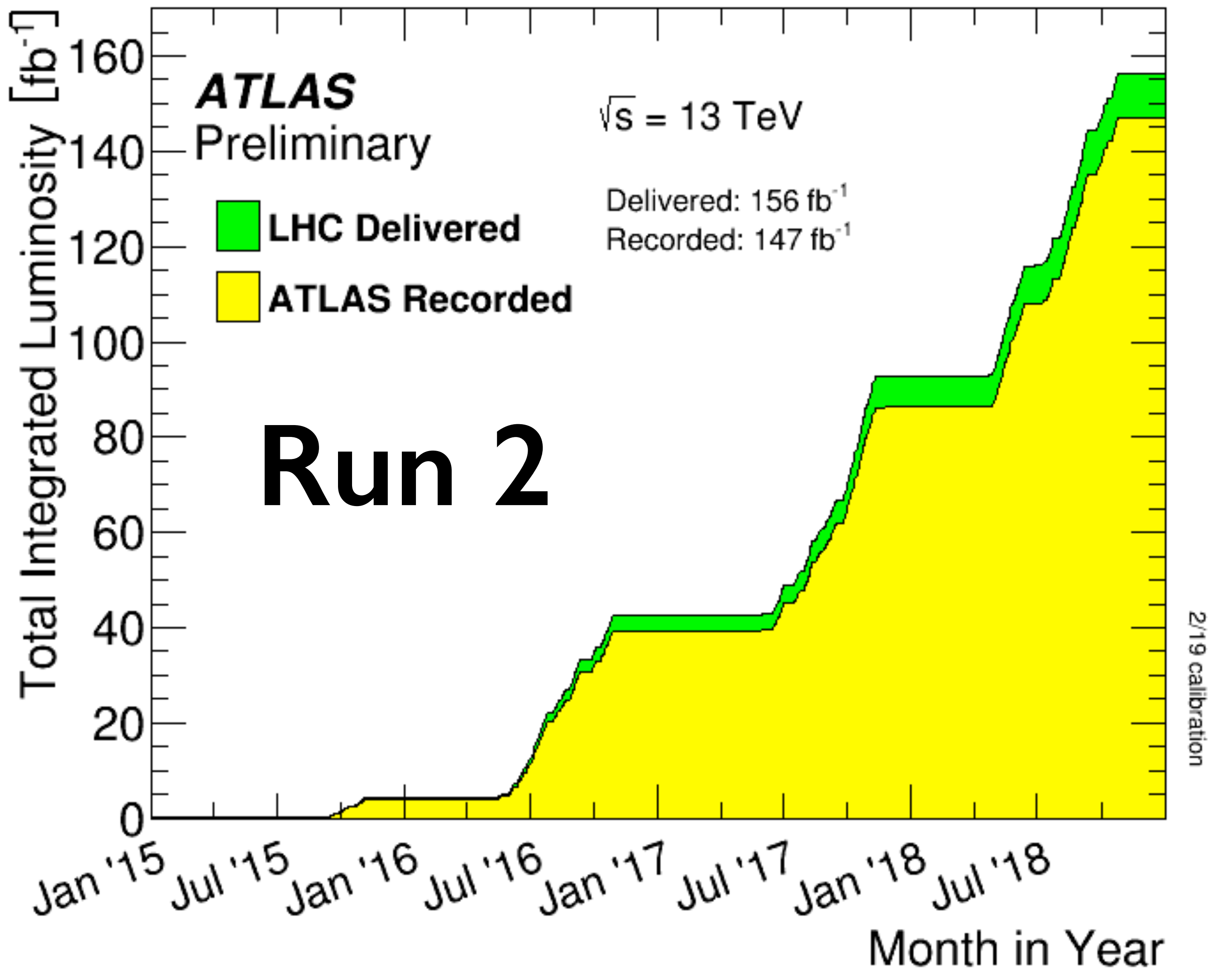
Top Quark

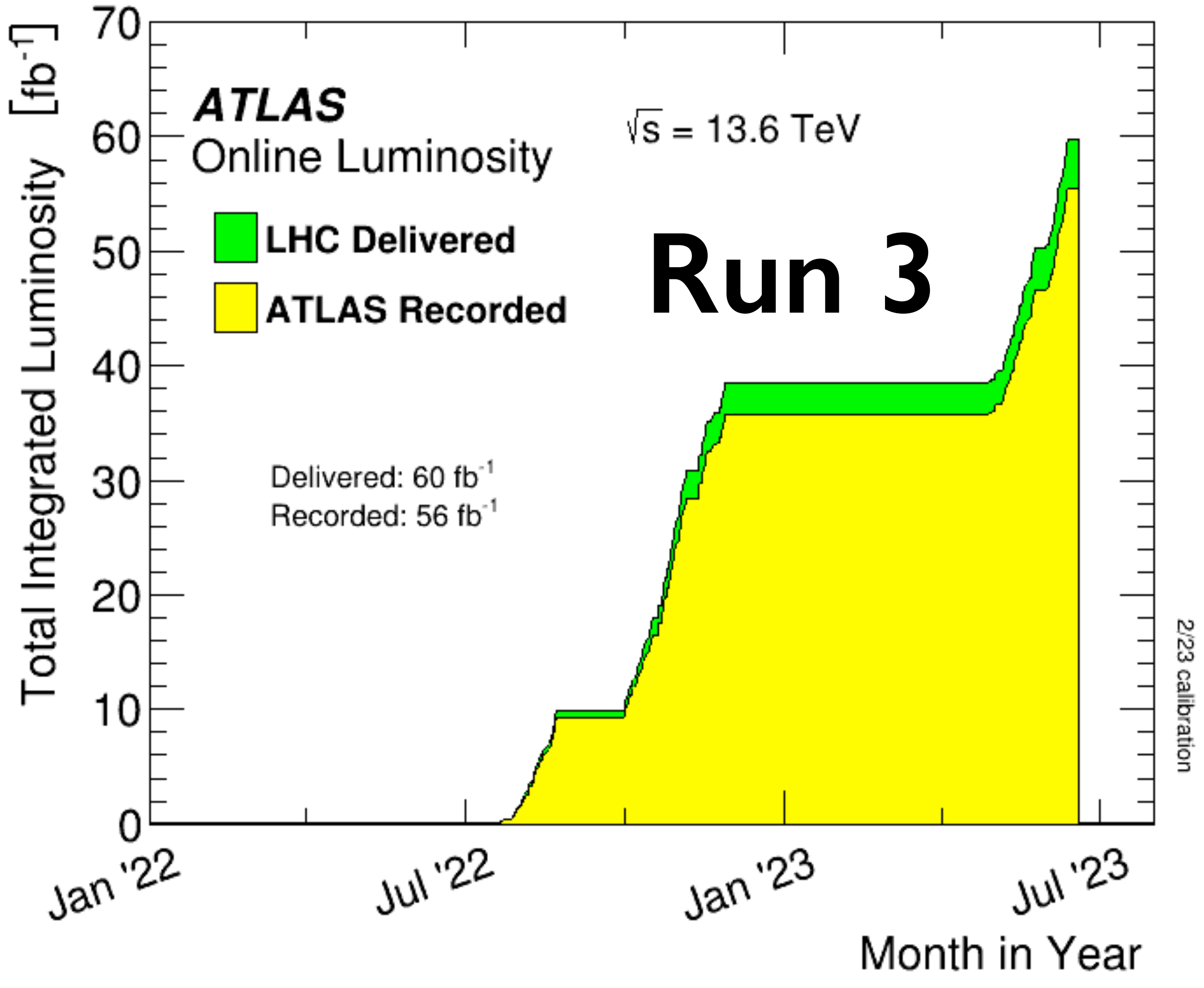
- Special place in the SM:
  - Heaviest elementary particle
  - Connection to Electroweak Symmetry Breaking with large Yukawa coupling ($\lambda \sim 1$)
- Unique quark:
  - Extremely short lifetime ($\tau \sim 10^{-25}$ s)
  - Decays before hadronisation
    - Allows to probe properties of bare quark
    - Almost exclusively to Wb



Top Precision Physics at the LHC

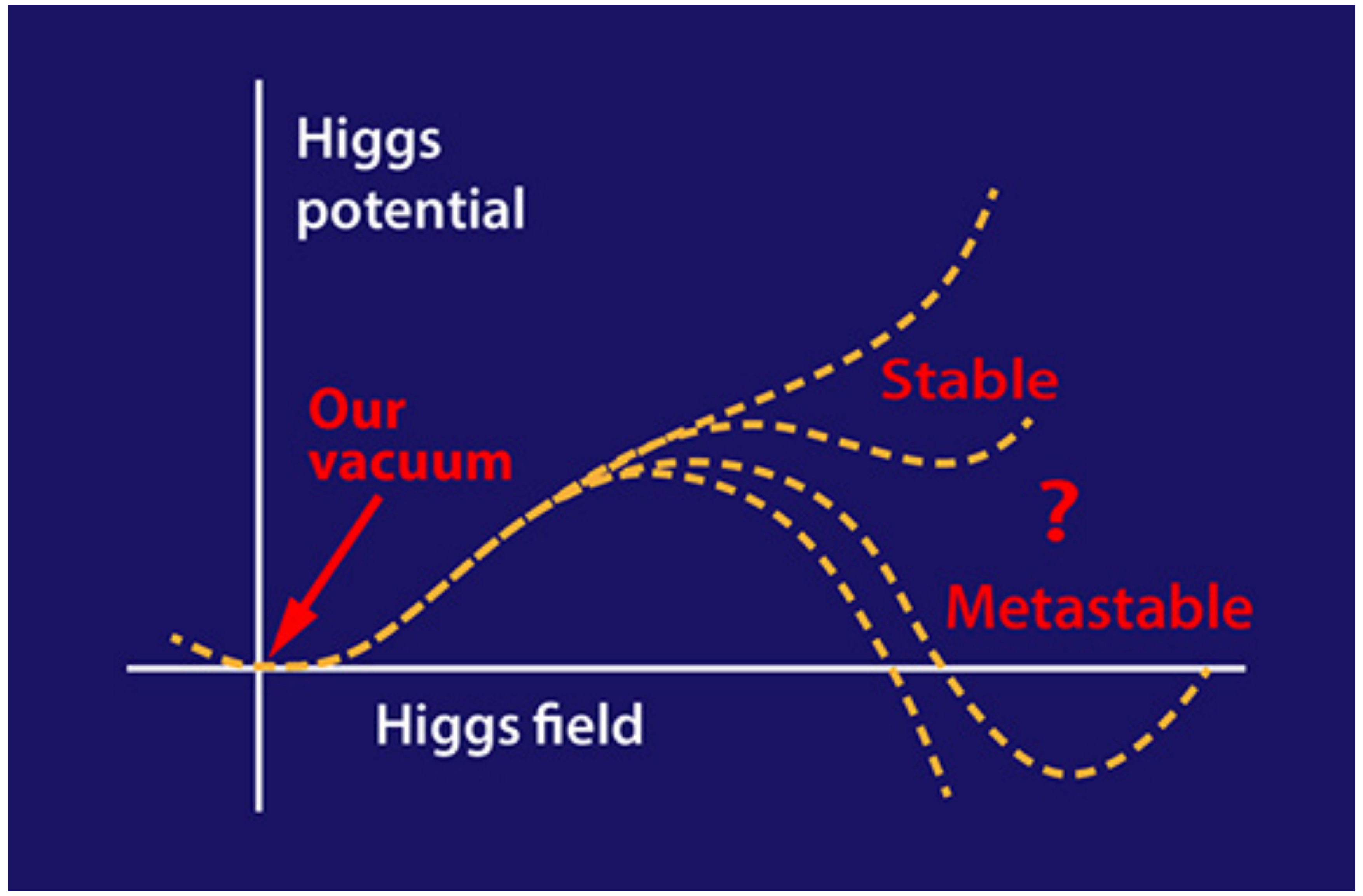
- LHC: top quark factory
  - ~120 million top quark pairs produced during Run 2 in each experiment
  - More to come in Run 3
- Allows for precision studies
  - Probe top quark properties, e.g. mass
  - Improve modelling — understand and control uncertainties
- Also can search for BSM effects



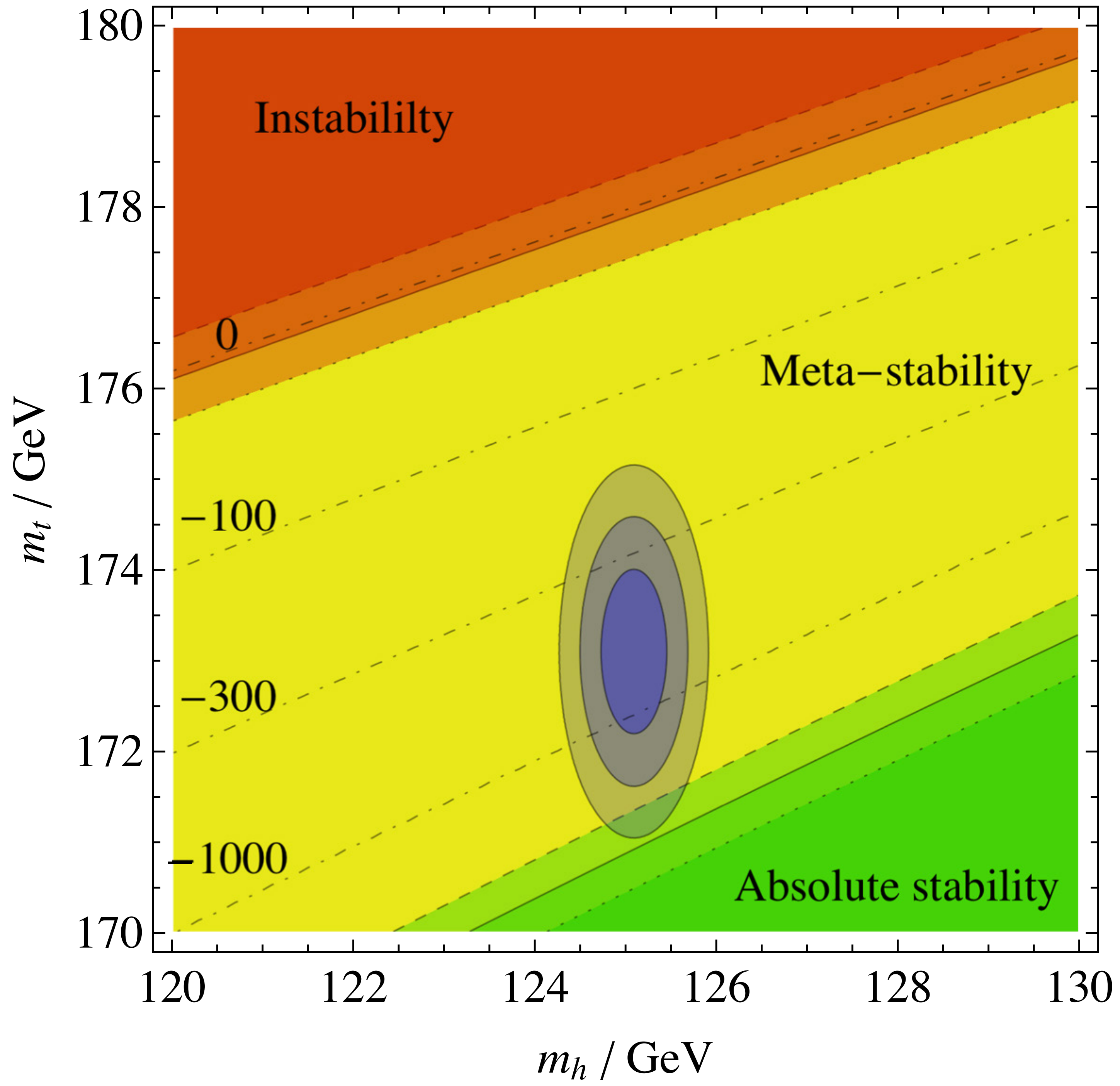


Top Quark Mass — Introduction

- Top quark mass (m_t) is a fundamental parameter of the SM
- m_t, m_W and m_H measurements can be compared to **EW fit predictions** to check **the validity of SM**
- m_t is crucial for **the stability of the electroweak vacuum** in the SM



APS/Alan Stonebraker, https://physics.aps.org/articles/v8/108



$m_h = 125.09 \pm 0.24,$

$m_t = 173.1 \pm 0.6,$

$\alpha_s(m_Z) = 0.1181 \pm 0.0011,$

Meta-stability preferred(?)

S. Chigusa, T. Moroi, and Y. Shoji, Phys. Rev. D 97, 116012 (2018)

Top Quark Mass — Direct and Indirect Measurements

Direct measurements (MC mass)

- From full or partial kinematic reconstruction of invariant mass of top decay products, comparison with MC calculations
- Theoretically not well defined

Indirect measurements (pole mass)

- From cross sections (inclusive or differential)
- Theoretically well defined

Relating the MC mass to a field theory mass is challenging because of hadronization and parton-shower dynamics, but the uncertainty reached a few hundred MeV.

PRL 117, 232001 (2016)

Top Quark Mass — Direct Measurement with l+jets

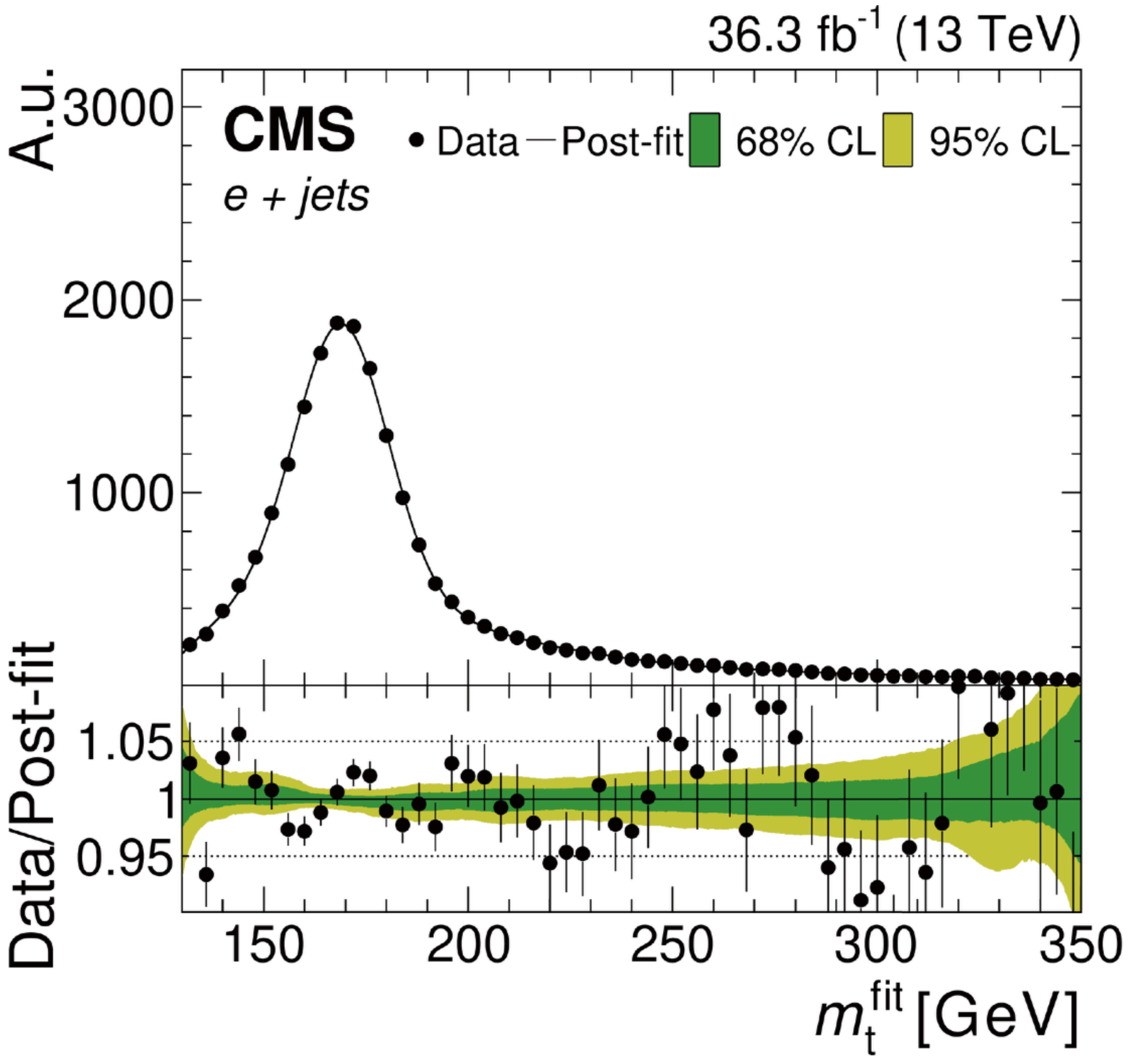
Unprecedented precision result by a fit of 5 observables

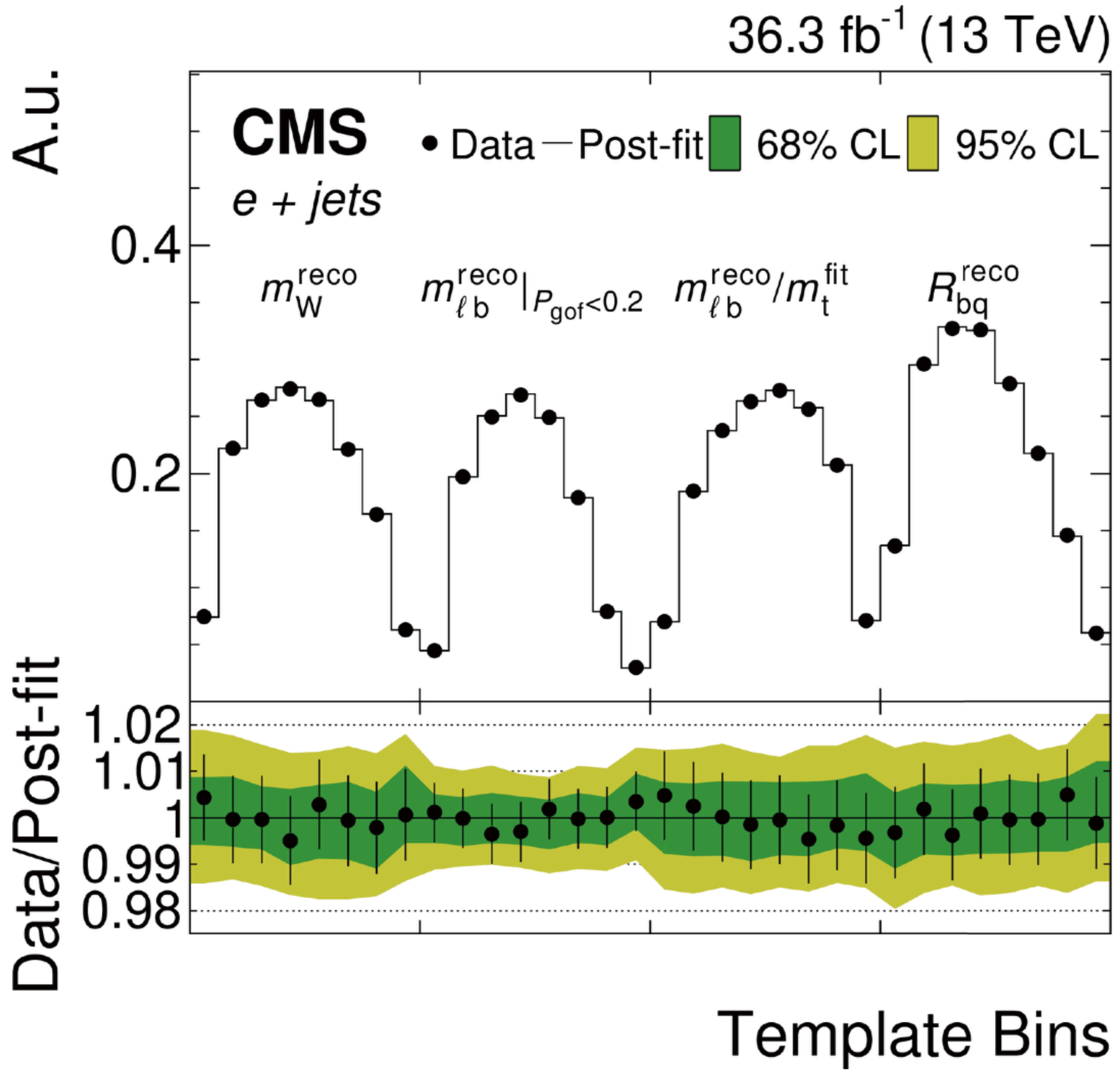
- m_t^{fit} and $m_{\ell b}^{\mathrm{reco}}$: sensitive to m_t
- m_W^{reco}, $m_{\ell b}^{\mathrm{reco}}/m_t^{\mathrm{fit}}$, and R_{bq}^{reco}: constraint of systematics

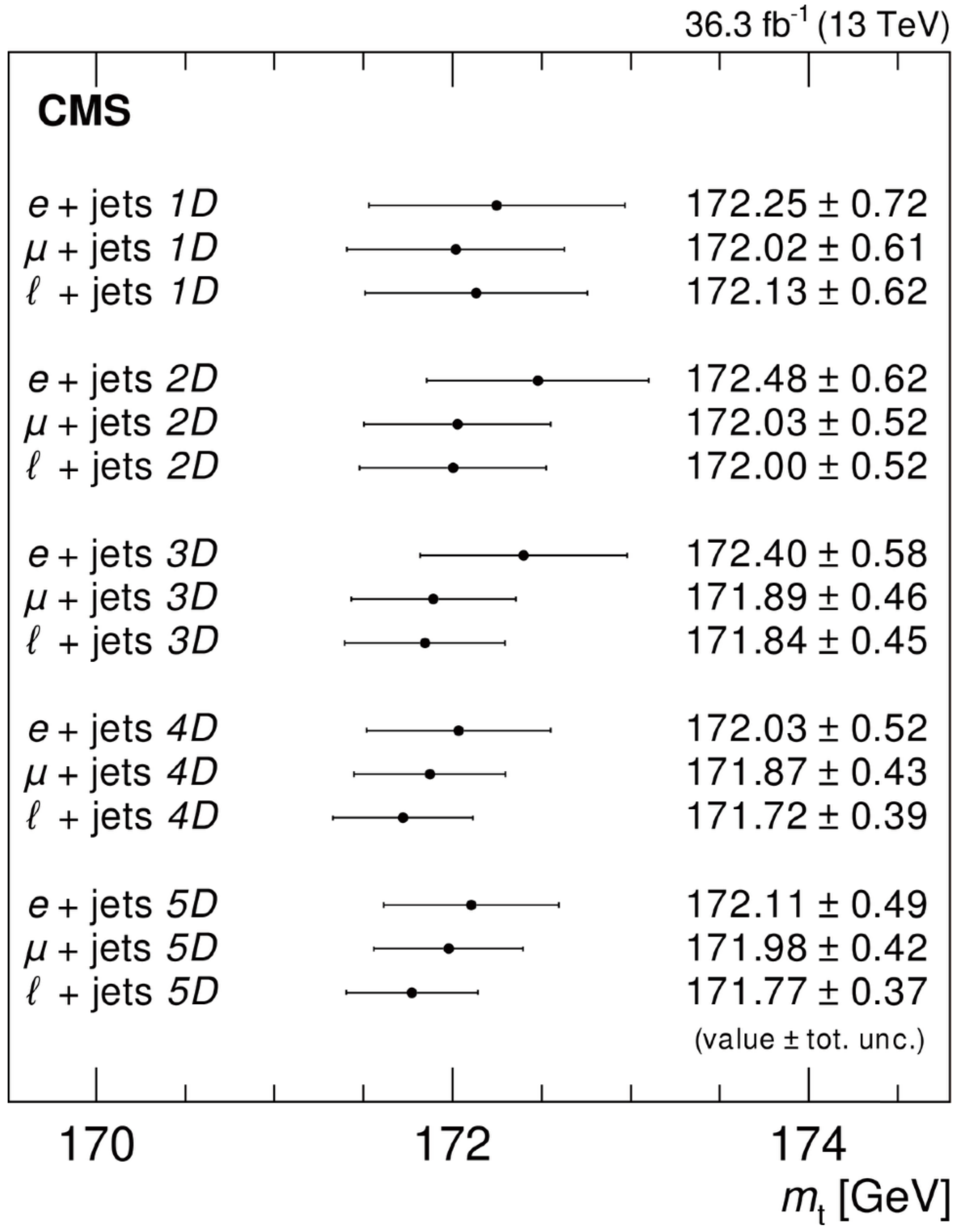
$$m_t^{\mathrm{MC}} = 171.77 \pm 0.37\ \mathrm{GeV}$$

arXiv:2302.01967

$$R_{bq}^{reco} = \frac{p_T^{b1} + p_T^{b2}}{p_T^{q1} + p_T^{q2}}$$







Syst. reduced

Top Quark Mass — Direct Measurement with Leptons

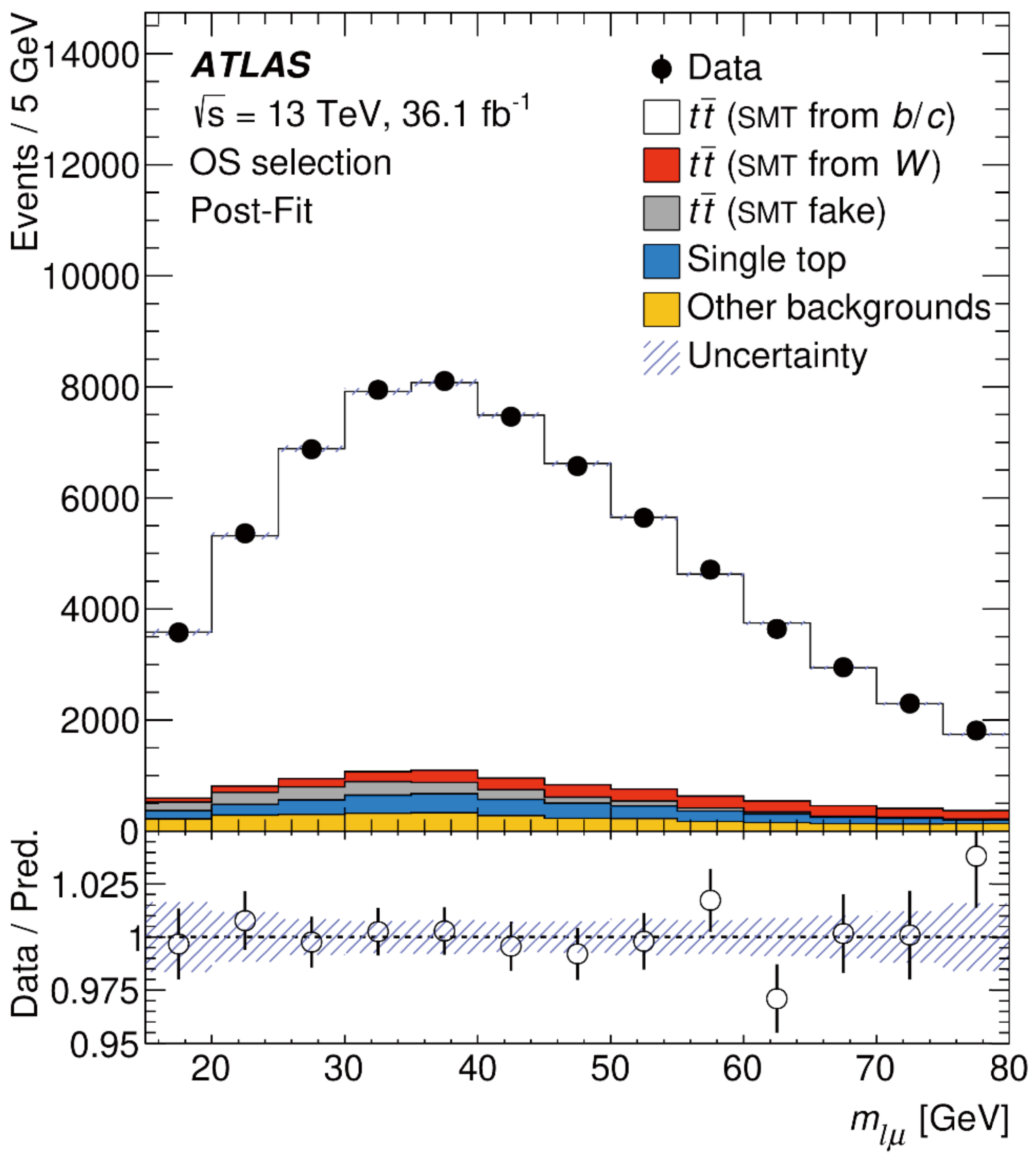
Top quark mass extracted from the invariant mass of prompt lepton and soft muon:

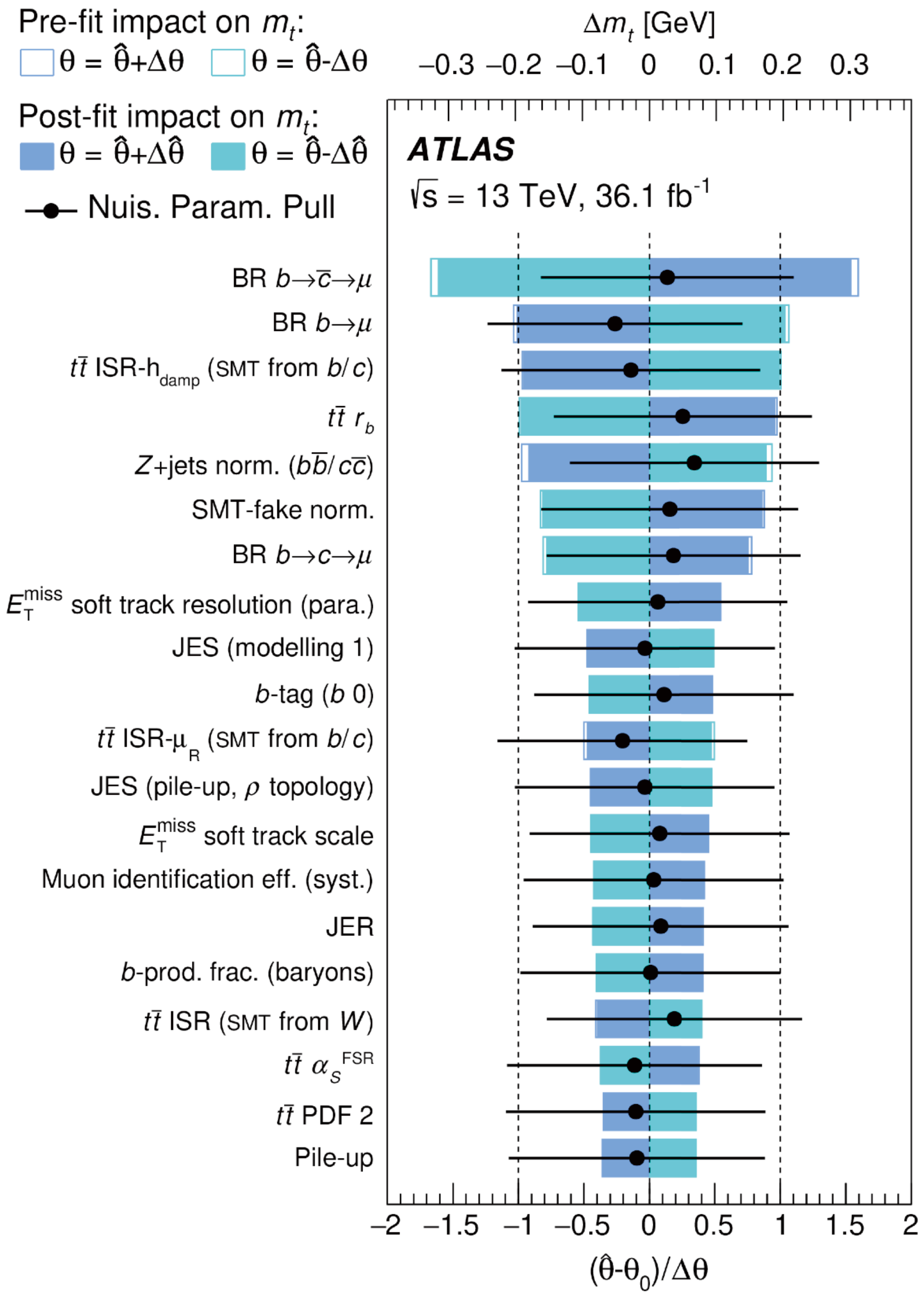
$$t \to Wb \to (\ \ell\ \nu\ )\ (\ X\ \mu\ \nu\ )$$

Only leptons!

Relatively small jet uncertainties

Dominant uncertainty from $b \to X\mu\nu$





$$m_t^{MC} = 174.41 \pm 0.39(\text{stat}) \pm 0.66(\text{syst}) \pm 0.25(\text{recoil})\ \text{GeV}$$
$$= 174.41 \pm 0.81\ \text{GeV}$$

arXiv:2209.00583

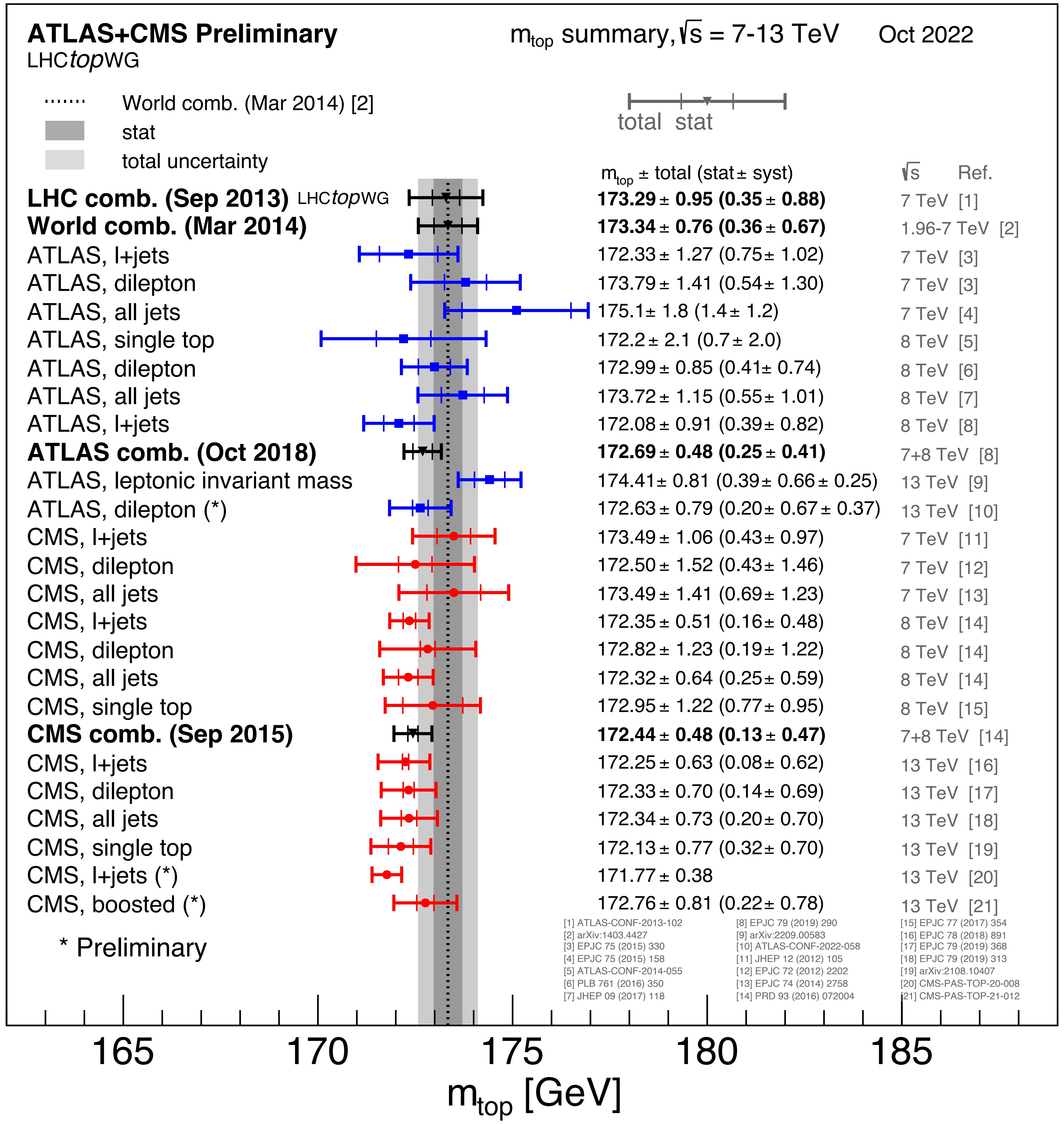
Top Quark Mass — Other Recent Measurements

- Direct measurement with template fit in dilepton channel (ATLAS)
  - $m_t^{\mathrm{MC}} = 172.21 \pm 0.80\ \mathrm{GeV}$ [ATLAS-CONF-2022-058]
- Direct measurement with boosted top in l+jets channel (CMS)
  - $m_t^{\mathrm{MC}} = 172.76 \pm 0.81\ \mathrm{GeV}$ [arXiv:2211.01456]
- Indirect measurement with differential cross section of tt+jet (CMS)
  - $m_t^{\mathrm{pole}} = 172.94 \pm 1.37\ \mathrm{GeV}$ for ABMP16NLO PDF [arXiv:2207.02270]

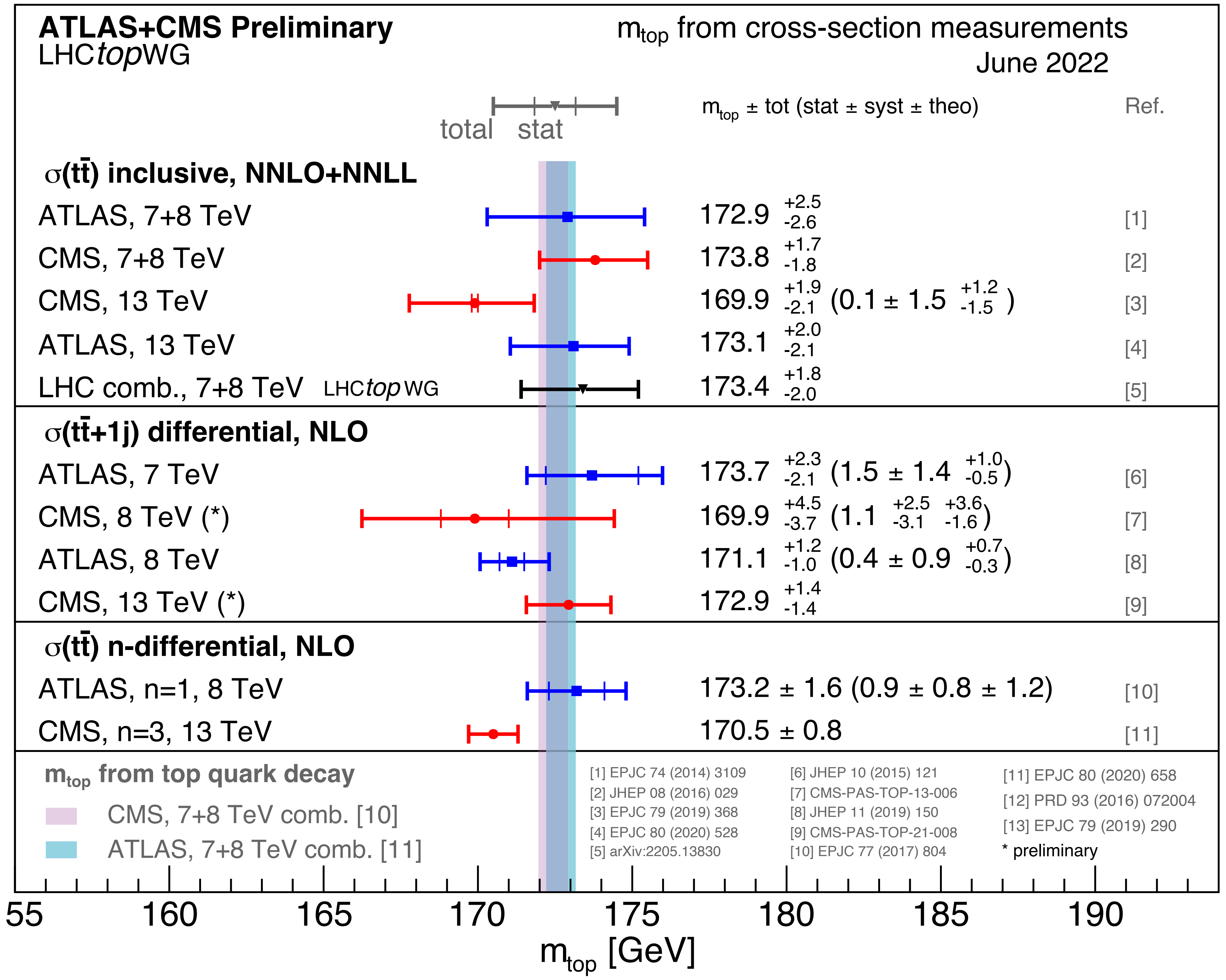
Various recent measurements with ~1 GeV precision

Top Quark Mass — Summary Plots LHCtopWG

Direct measurements (MC mass)



Indirect measurements (pole mass)



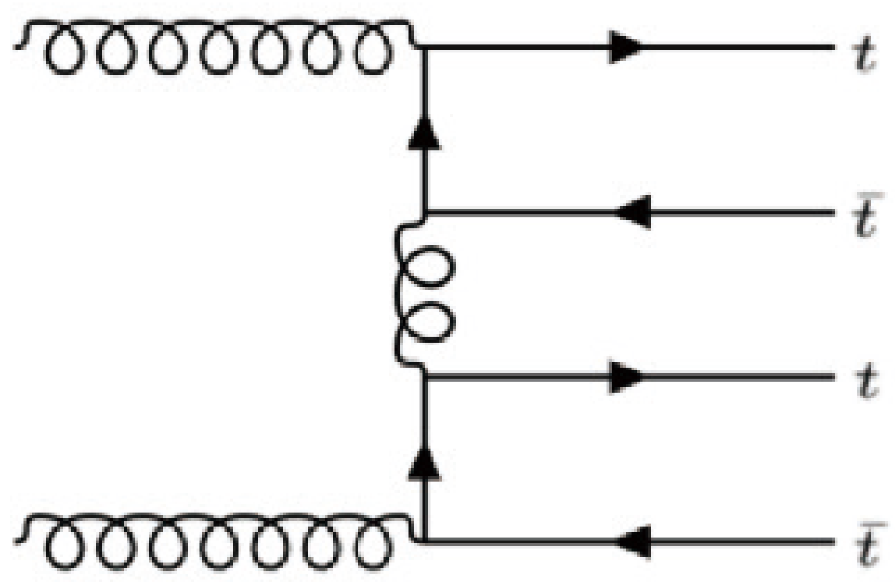
Recent results: relatively low m_t

Getting closer to the absolute stability?

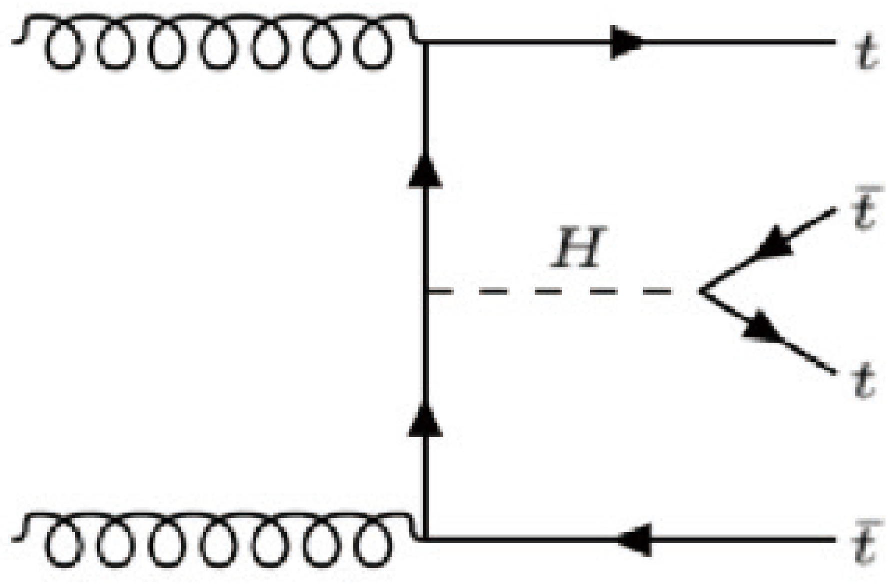
4 Top — Introduction

- Sensitive to top Yukawa coupling and potential BSM effects

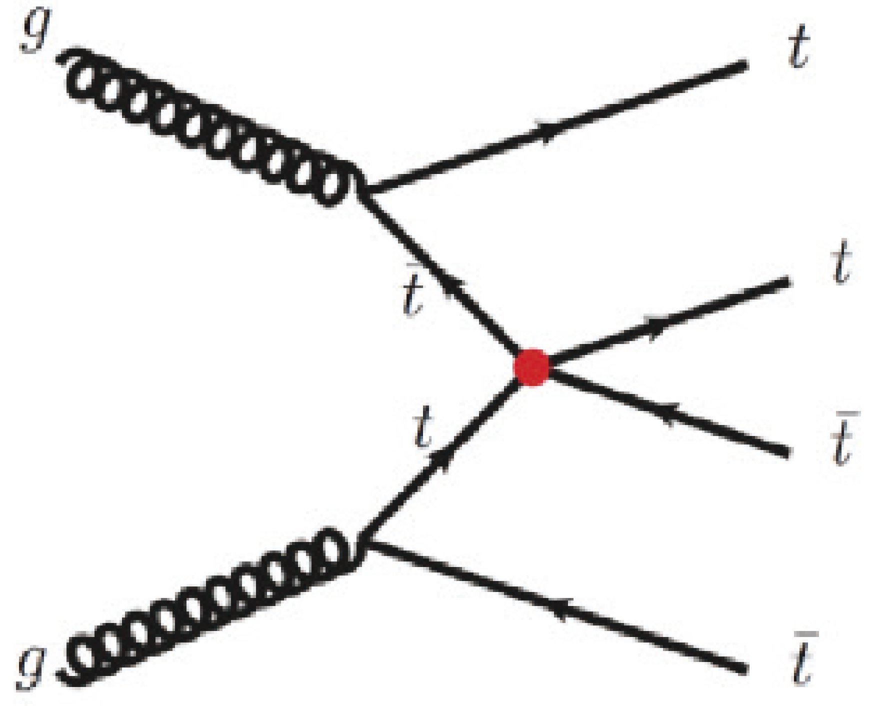
QCD



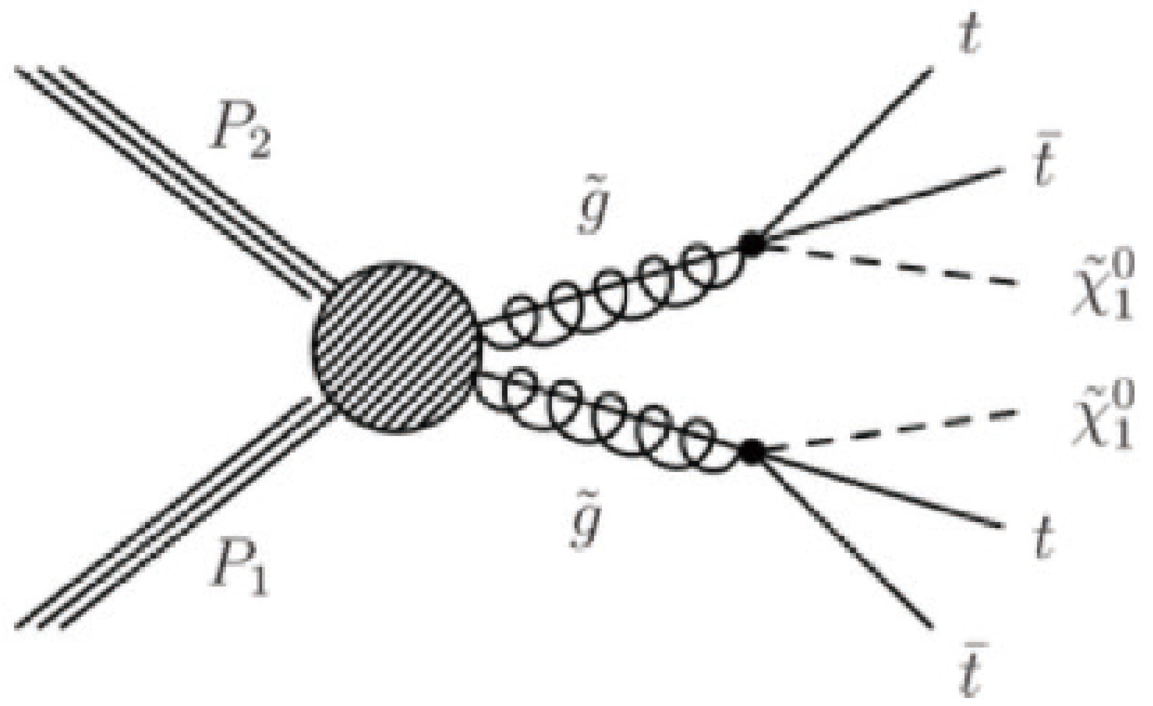
EWK



EFT four-fermion coupling



SUSY



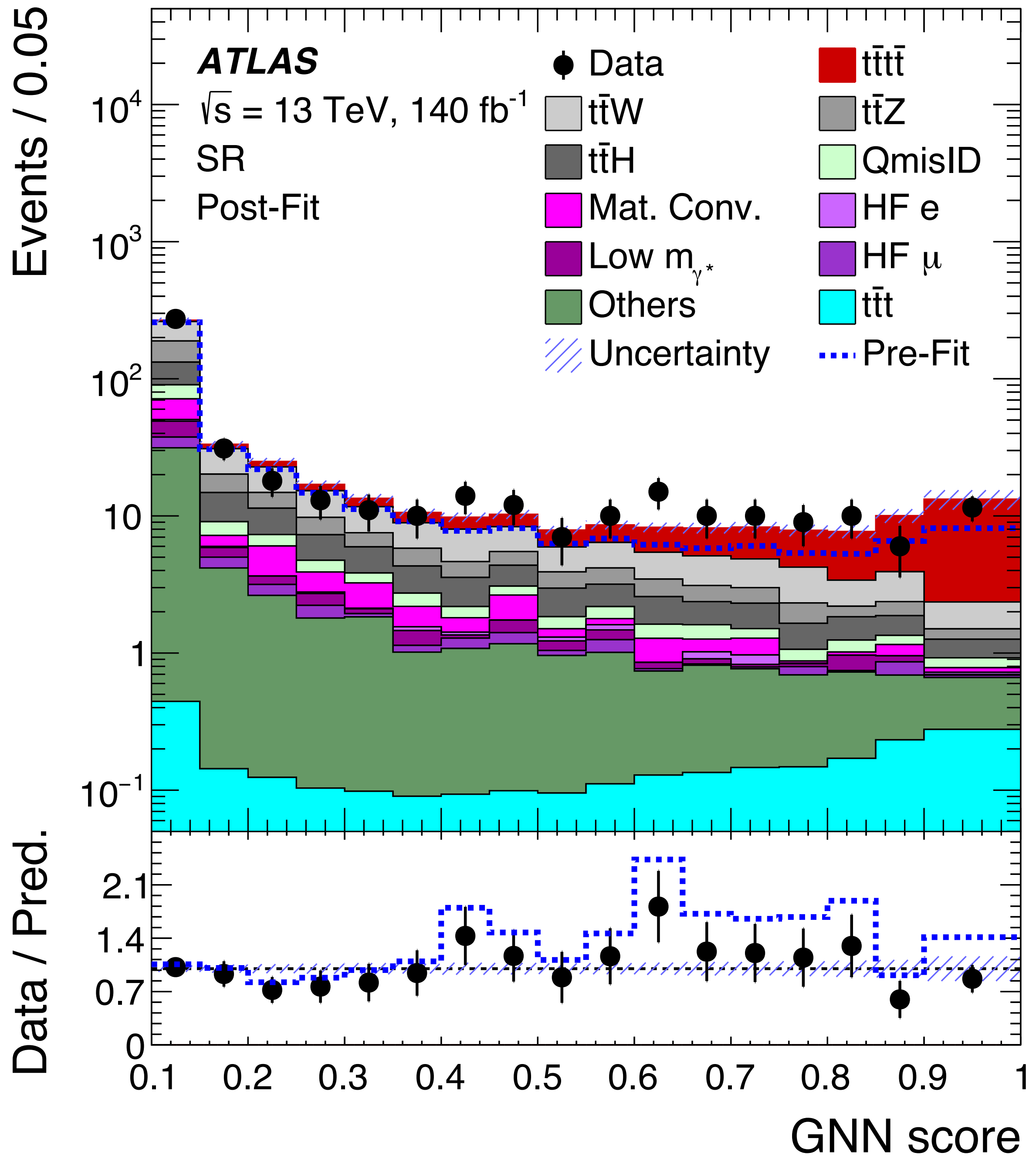
- $\sigma_{t\bar{t}t\bar{t}} = 13.4^{+1.0}_{-1.8}$ fb (NLO (QCD + EW) + NLL @13TeV) [arXiv:2212.03259]

Small cross section — no observation in previous analyses

4 Top — First Observation

ATLAS [arXiv:2303.15061]

Observed (expected): 6.1σ (4.3σ)

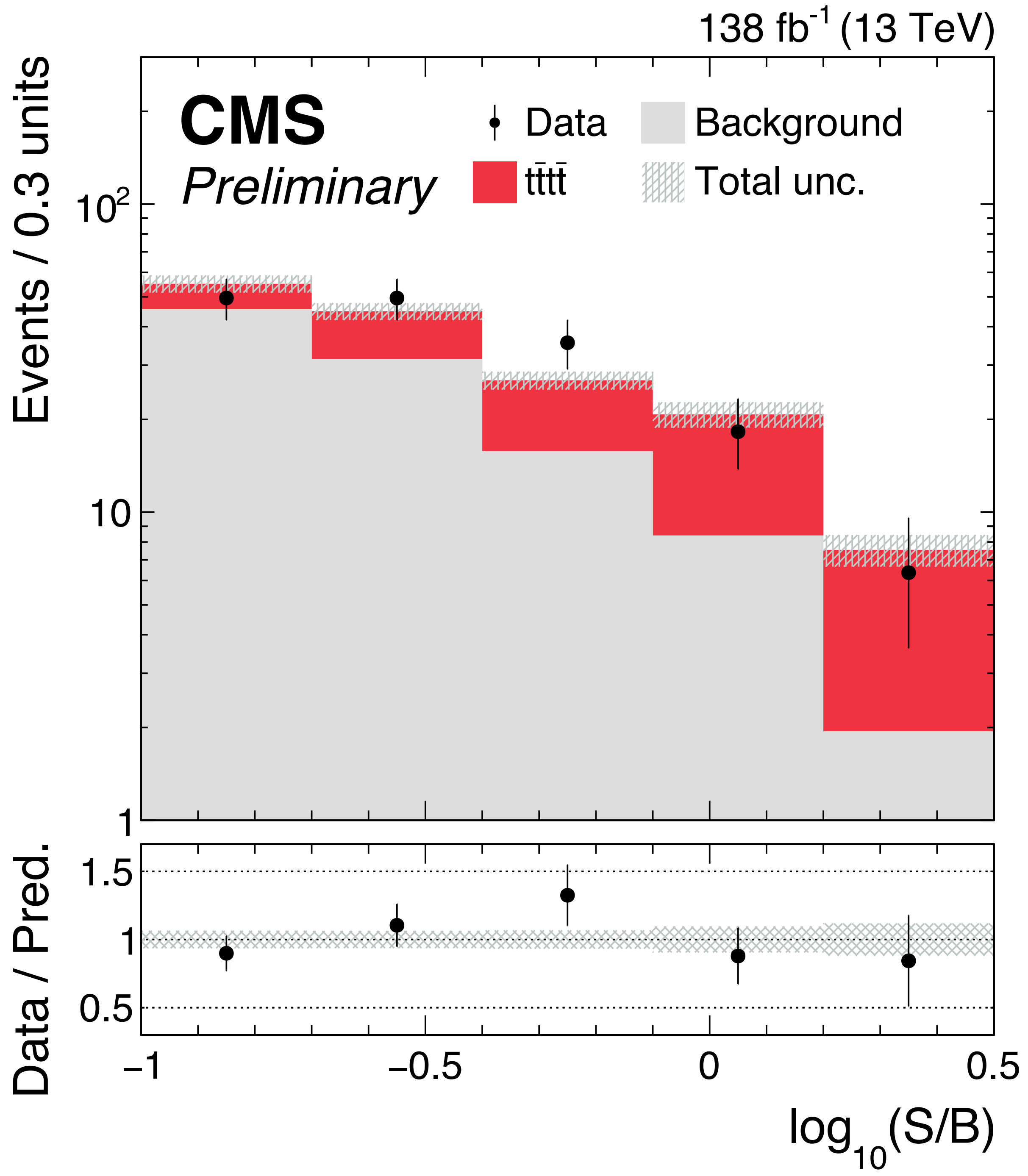


Looser event selection,
improved ttW estimation,
graph neural network
with nodes: reco objects

$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.5}\ \text{fb}$$

CMS [arXiv:2303.15061]

Observed (expected): 5.5σ (4.9σ)



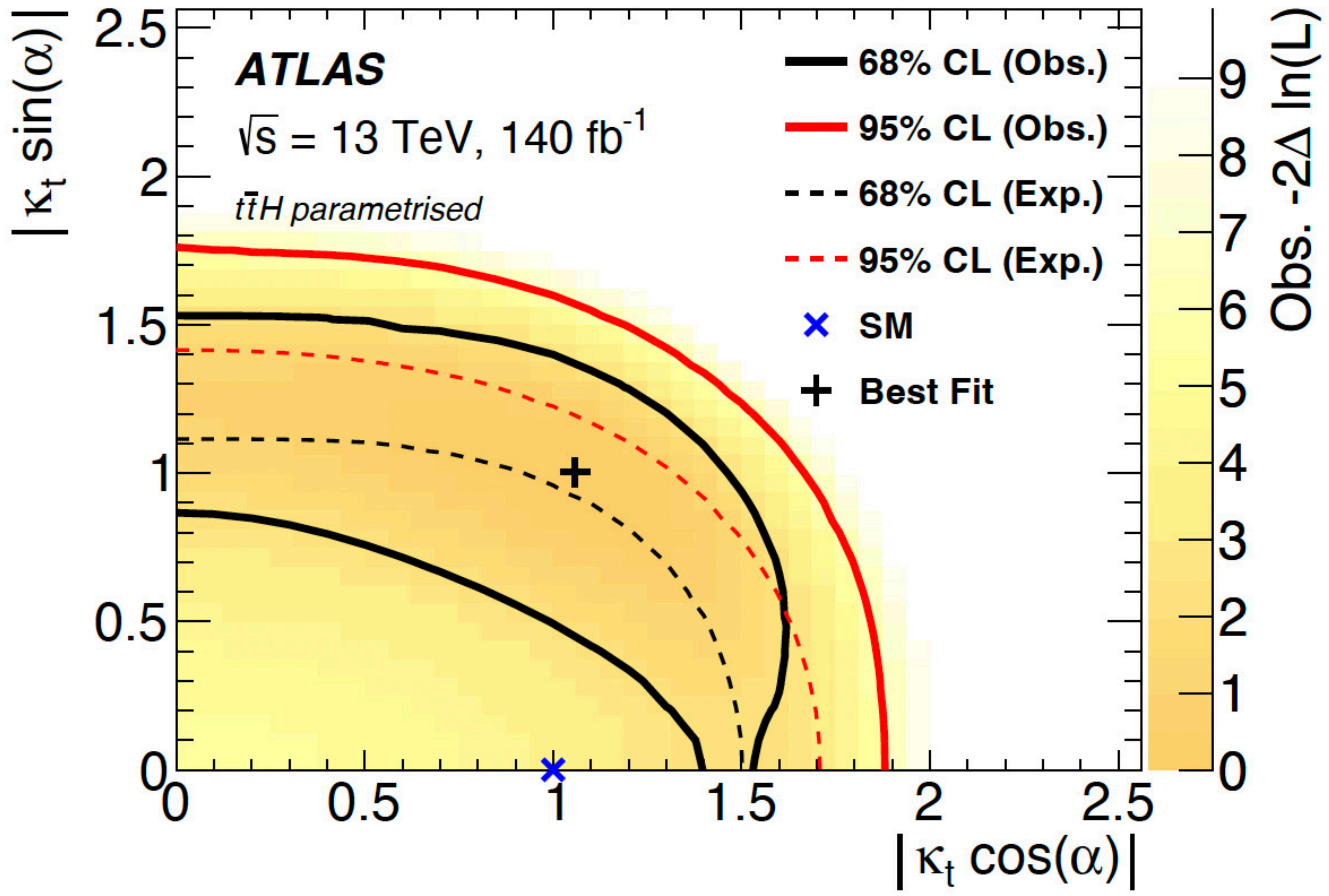
BDT lepton ID,
multiclassification
BDT for background
separation

$$\sigma_{t\bar{t}t\bar{t}} = 17.9^{+3.7}_{-3.5}(\text{stat})^{+2.4}_{-2.1}(\text{syst})\ \text{fb}$$

The measured cross section in agreement with the SM

4 Top — Interpretation

arXiv:2303.15061

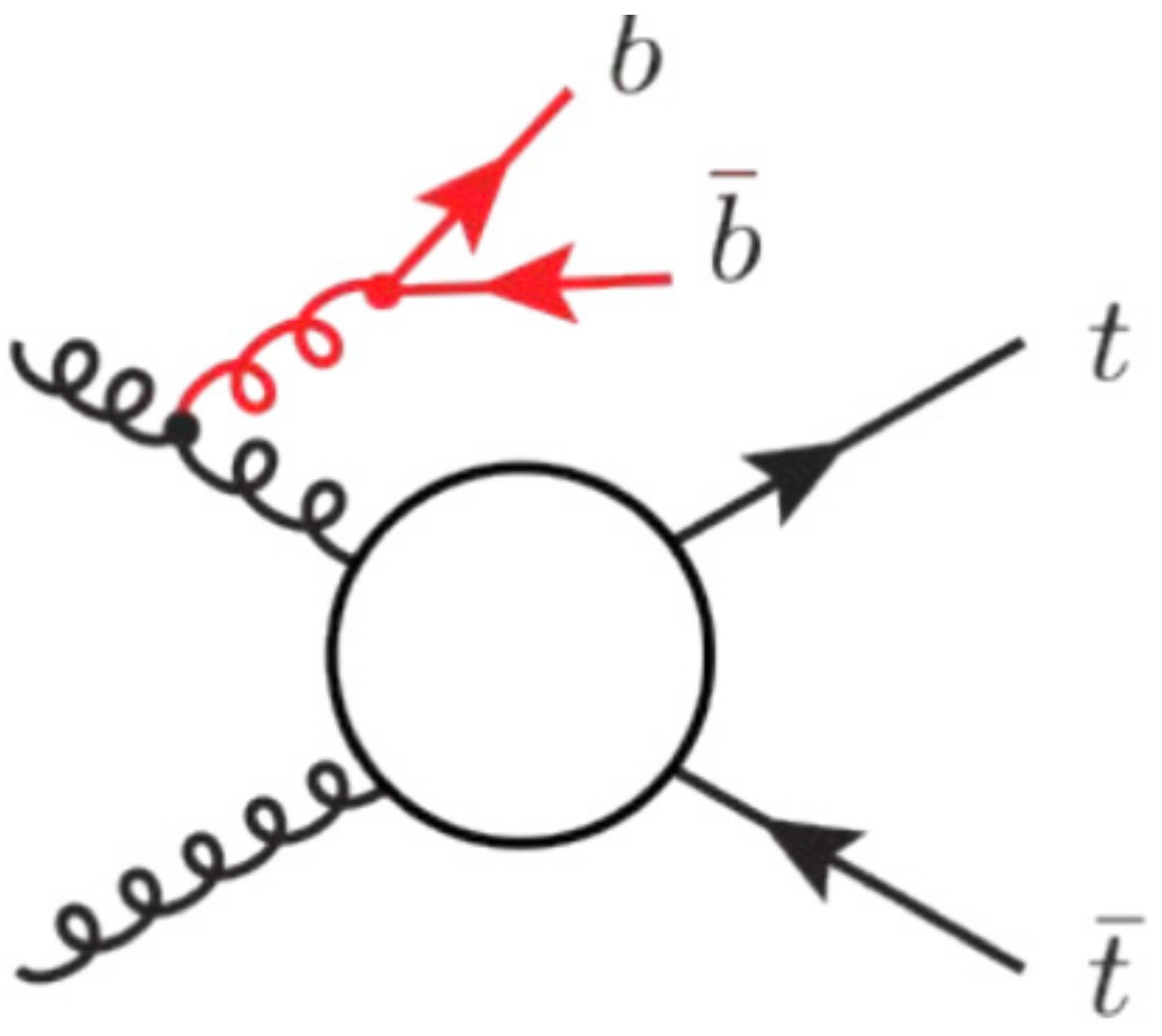


κ_t: top-Higgs Yukawa coupling strength parameter

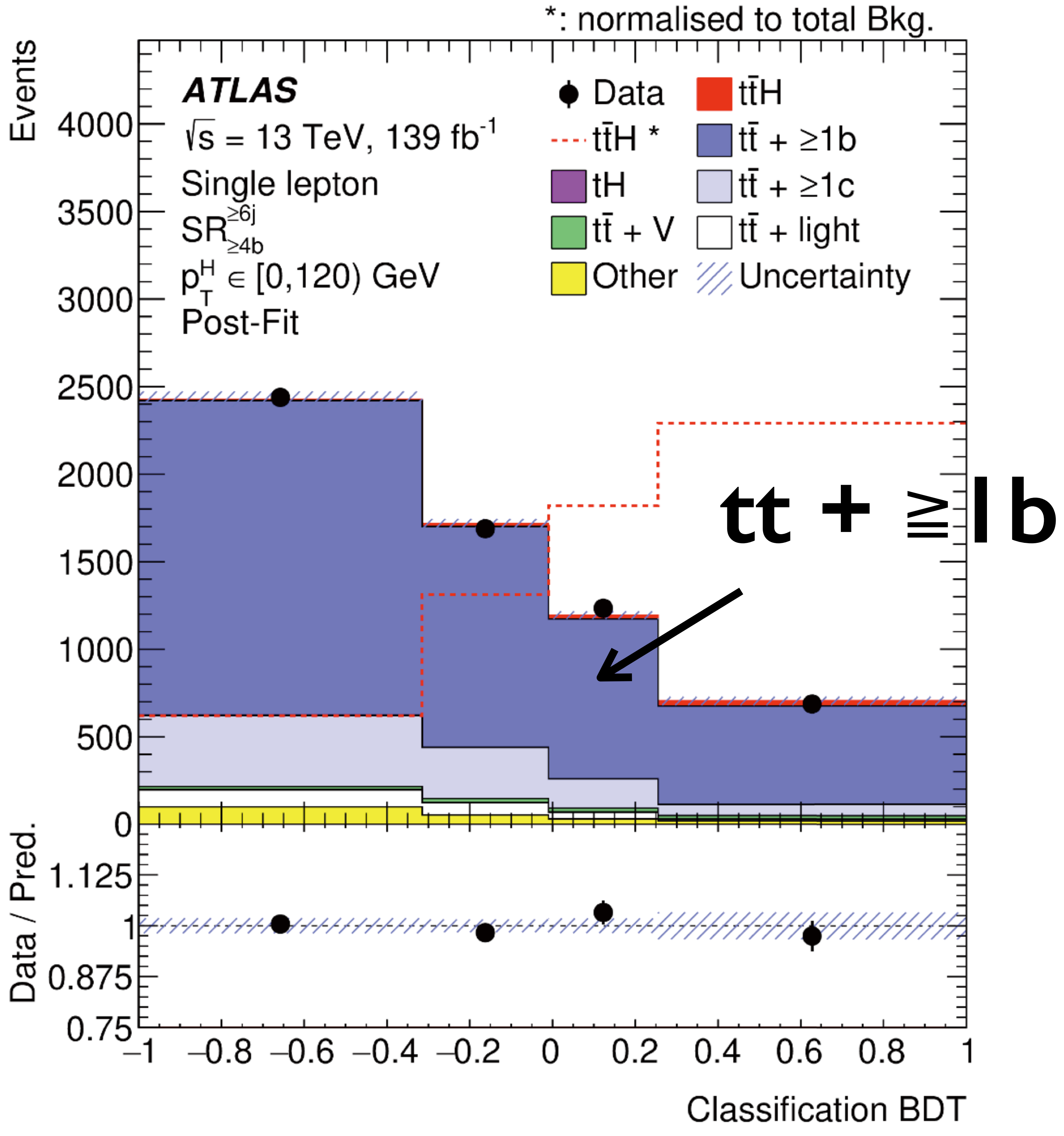
α: mixing angle between the CP-even and CP-odd components

Limits on EFT operators also shown in the preprint

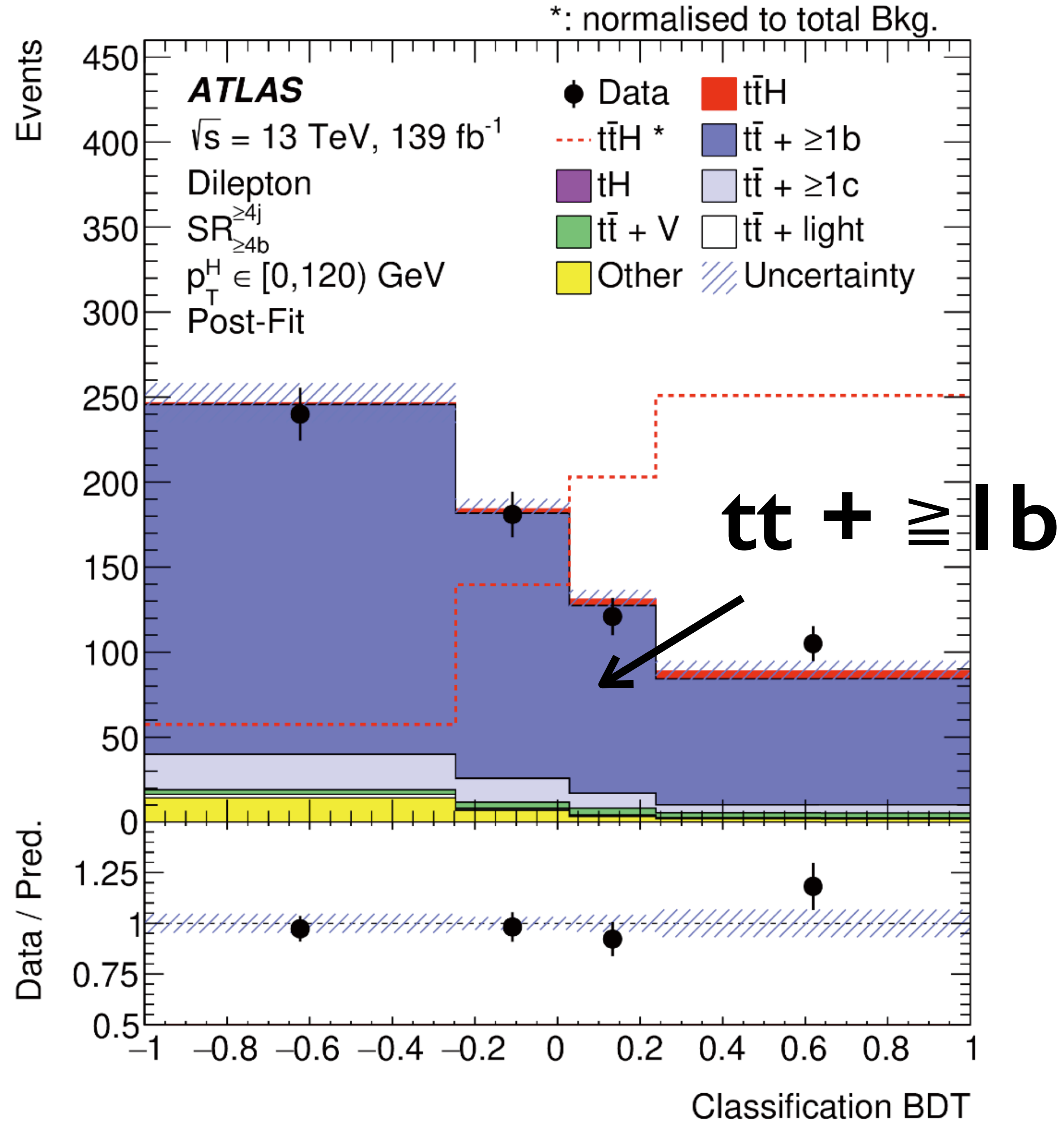
ttbb Production — Irreducible ttH Background



ttH, H→bb (single lepton)



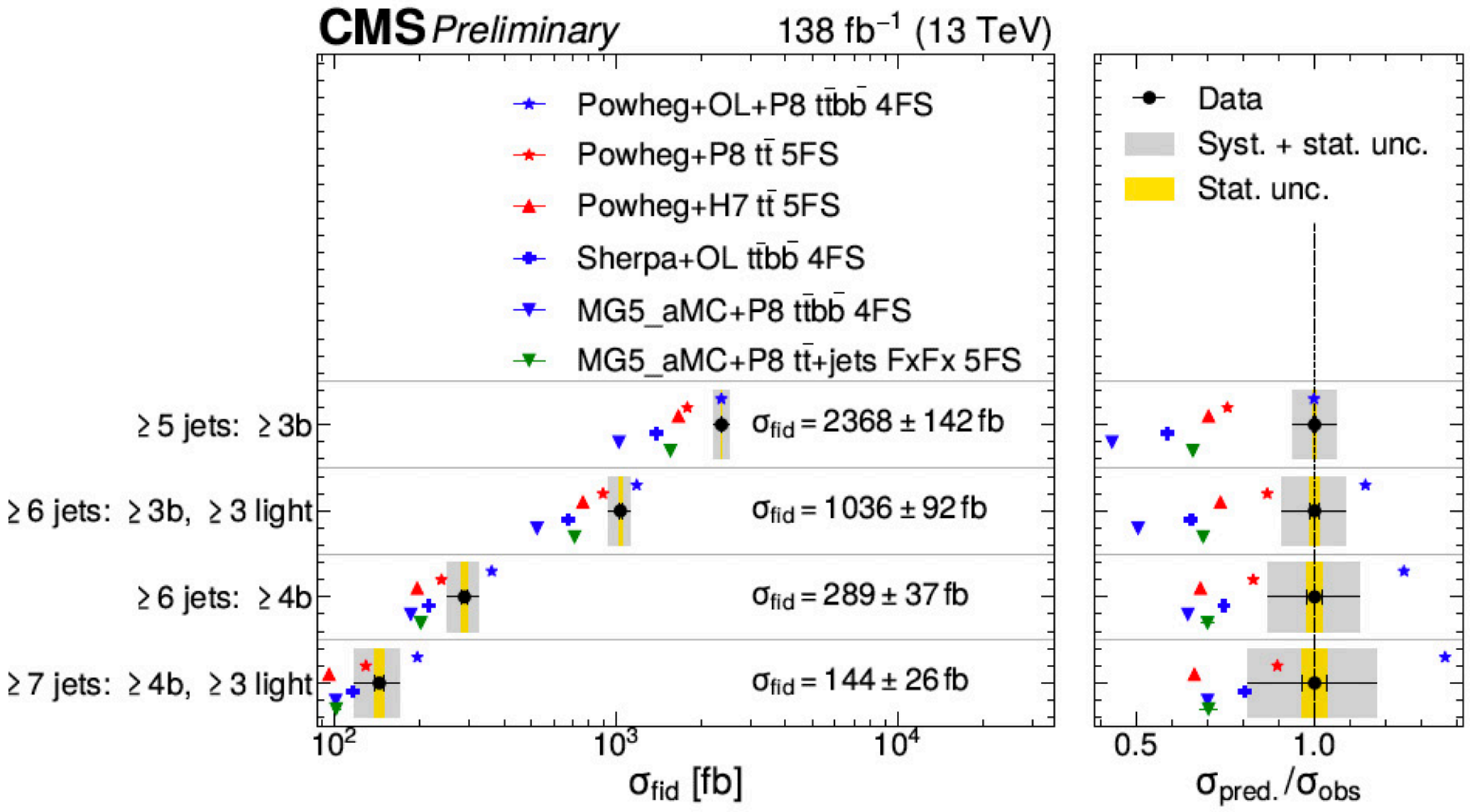
ttH, H→bb (di-lepton)



JHEP 06 (2022) 097

ttbb Production — Recent Results (Inclusive)

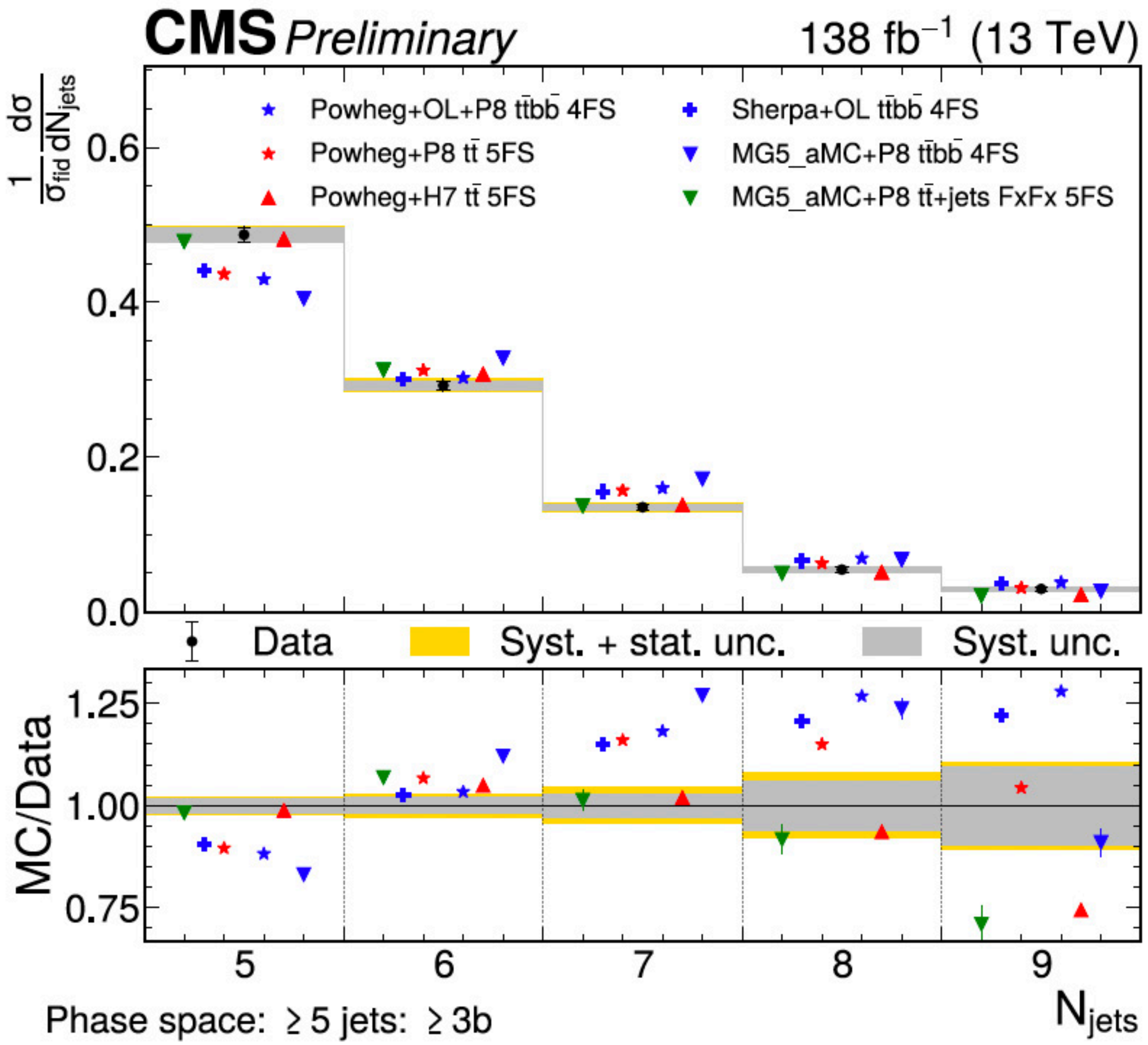
CMS-PAS-TOP-22-009



Higher than theoretical predictions (consistent with previous measurements)

ttbb Production — Recent Results (Differential)

CMS-PAS-TOP-22-009



and many other observables

Varying compatibility with theoretical predictions

ttW — Introduction

- Background for ttH and 4 top productions
- ttW observed for the first time in Run 1 and only with the full Run 2 dataset
  a precise inclusive measurement and the first differential measurements are obtainable

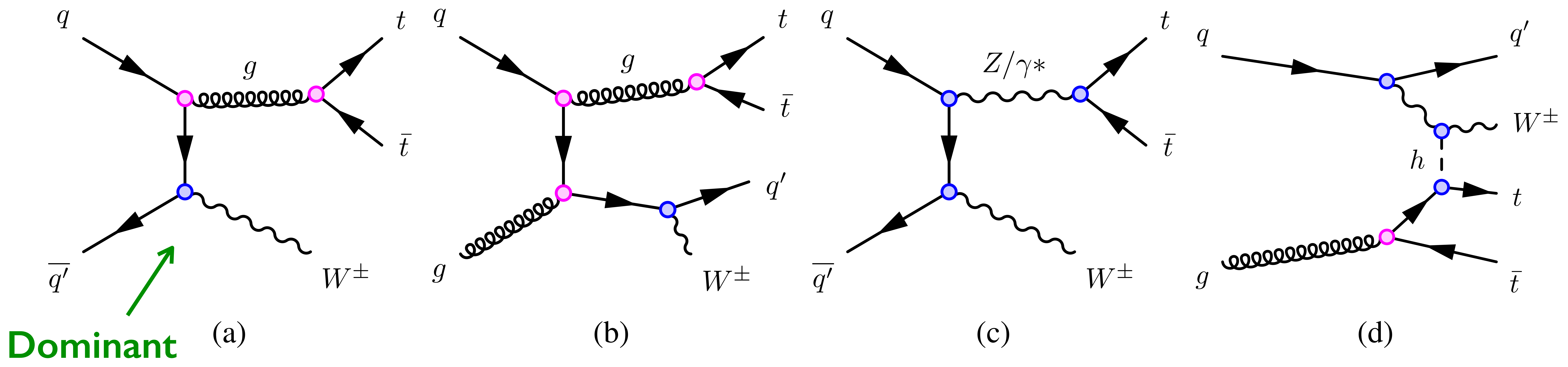
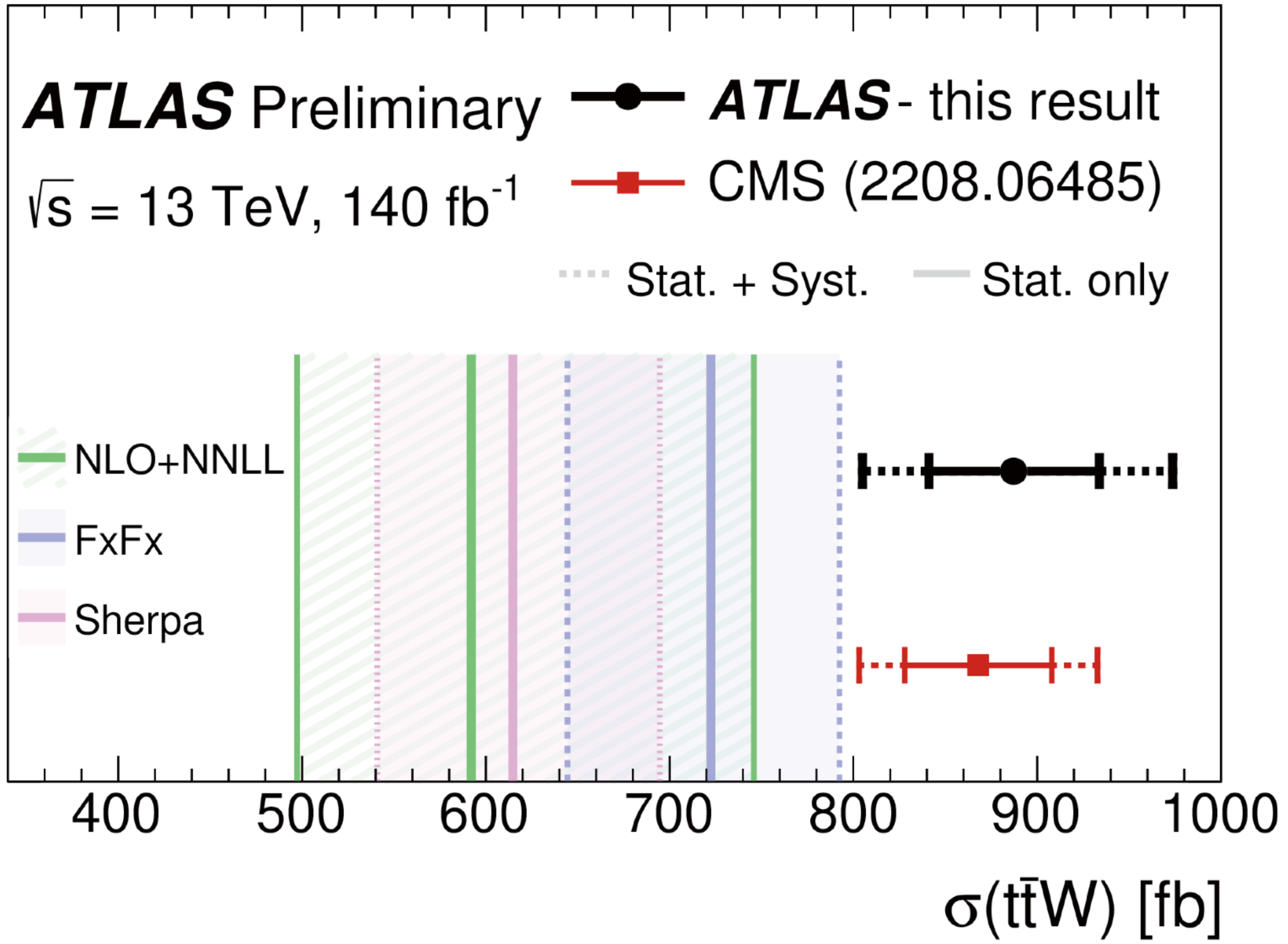


Figure 1: Signal diagrams for the dominant production modes of $t\bar{t}W$. (a) The LO contribution ($\alpha\alpha_s^2$), (b) a real emission diagram from the NLO QCD contribution ($\alpha\alpha_s^3$), (c) the tree-level EWK contribution (α^3), and (d) a representative diagram of the combined NLO QCD and EWK contributions ($\alpha^3\alpha_s$). The pink circles correspond to QCD couplings and the blue circles correspond to EWK couplings.

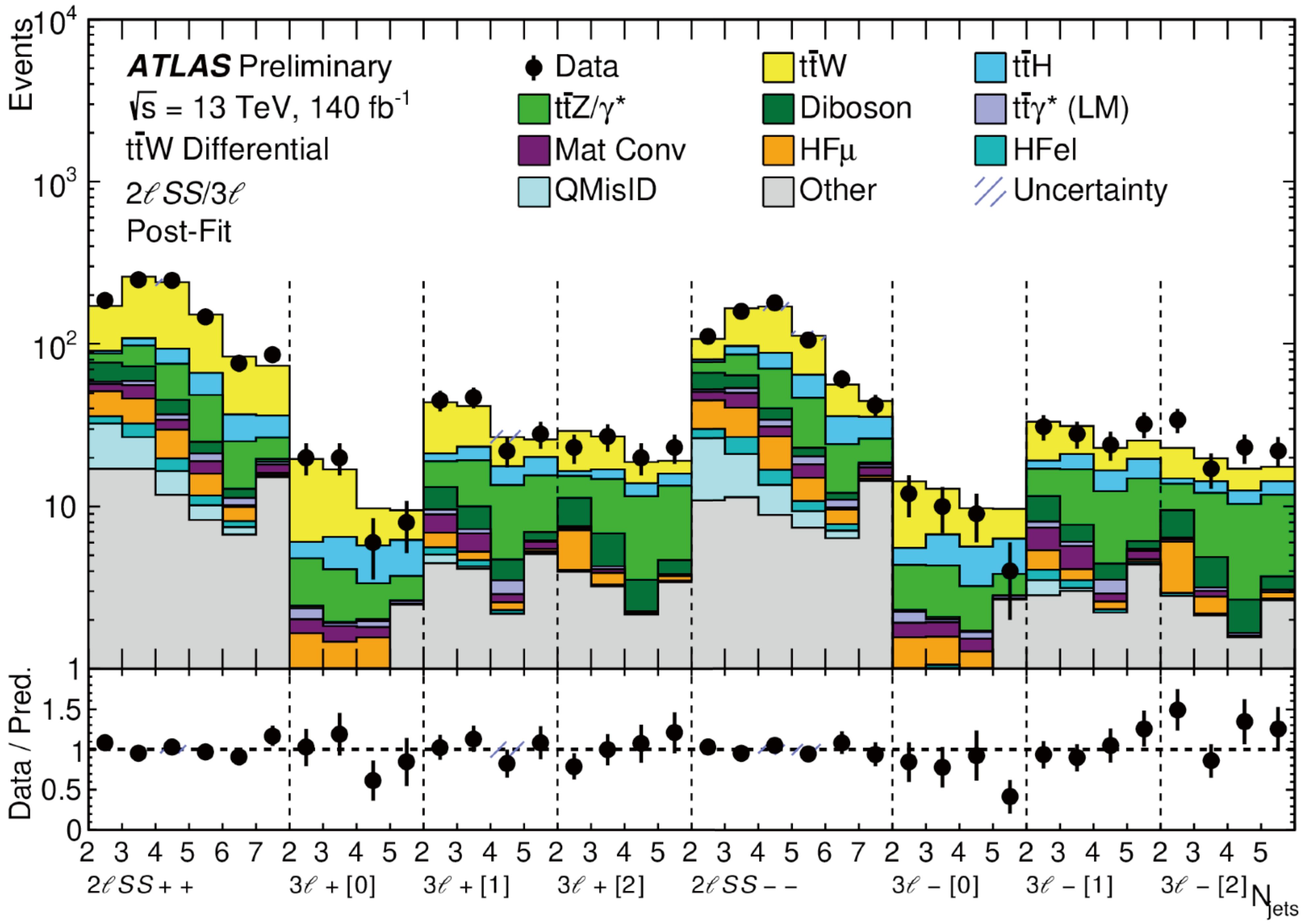
ttW — Recent Results

ATLAS-CONF-2023-019

Inclusive cross section higher than theoretical predictions



First differential measurement (7 variables)



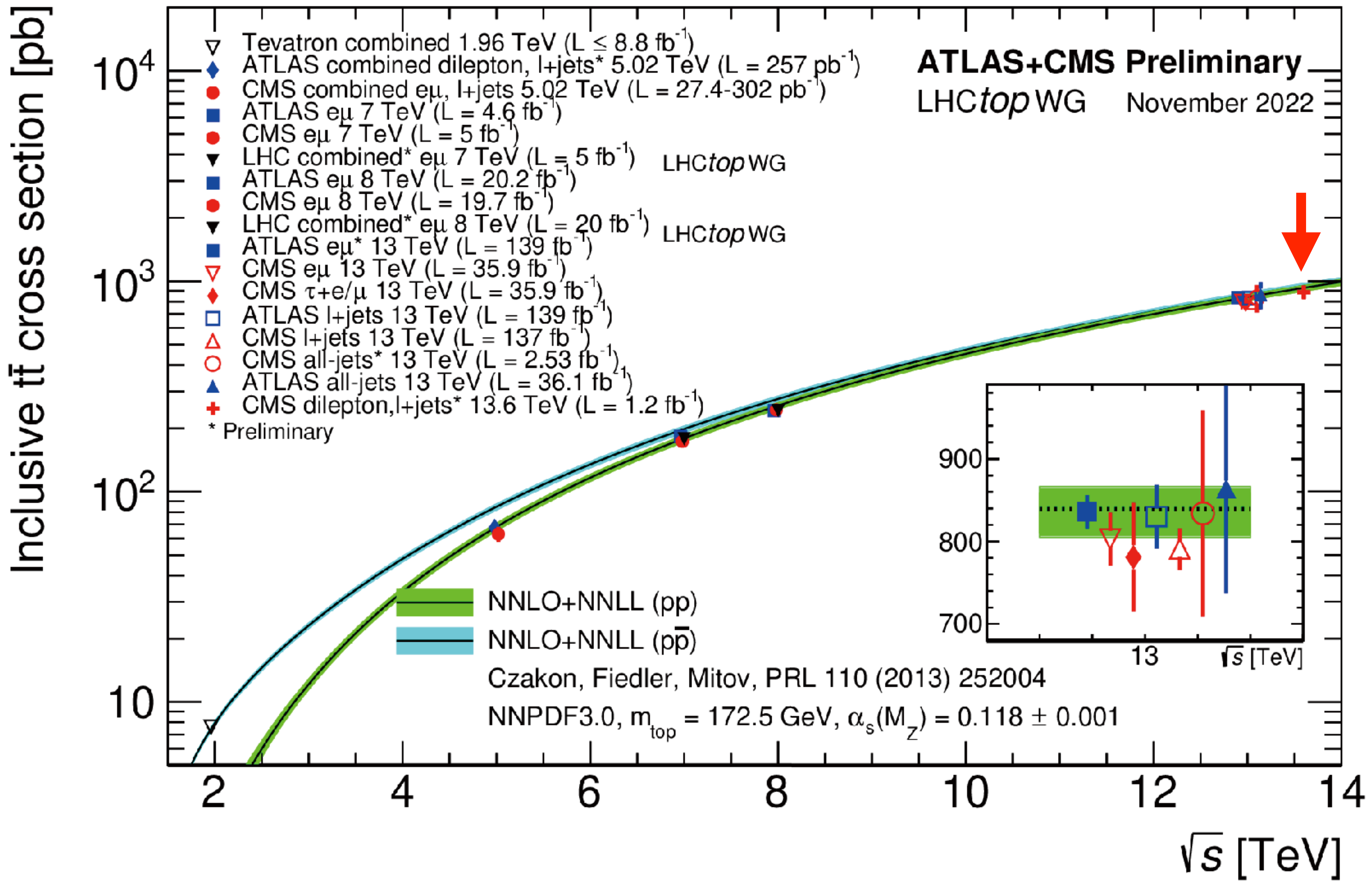
First Run 3 Top Measurements

CMS-TOP-22-012 (13.6 TeV, 1.21 fb^{-1})

$\sigma(t\bar{t})$ = 882 ± 23 (stat+syst) ± 20 (lumi) pb

ATLAS-CONF-2023-006 (13.6 TeV, 11.3 fb^{-1})

$\sigma(t\bar{t})$ = 859 ± 4 (stat) ± 22 (syst) ± 19 (lumi) pb



$\sqrt{s}$	$\sigma_{t\bar{t}}$ (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

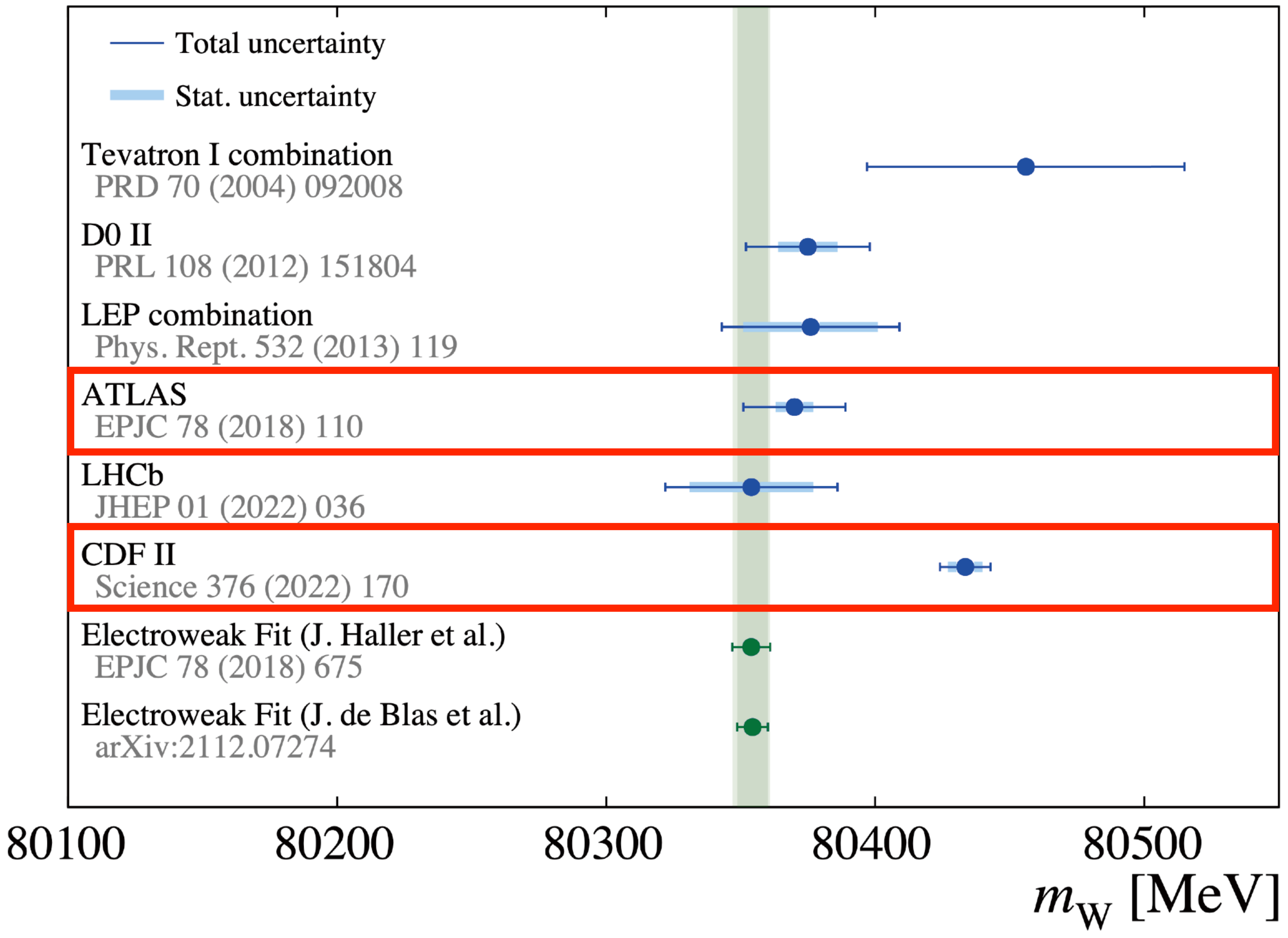
Experiment & theory agreement for 13.6 TeV!

SM

W Mass — Introduction

- In 2017, ATLAS published the LHC's first measurement of the W-boson mass: 80370 ± 19 MeV — the most precise single-experiment result, in agreement with the SM prediction and all other experimental results.

- Last year, the CDF Collaboration at Fermilab published an even more precise measurement of the W-boson mass: 80434 ± 9 MeV — deviated significantly from the SM prediction and from other experimental results.

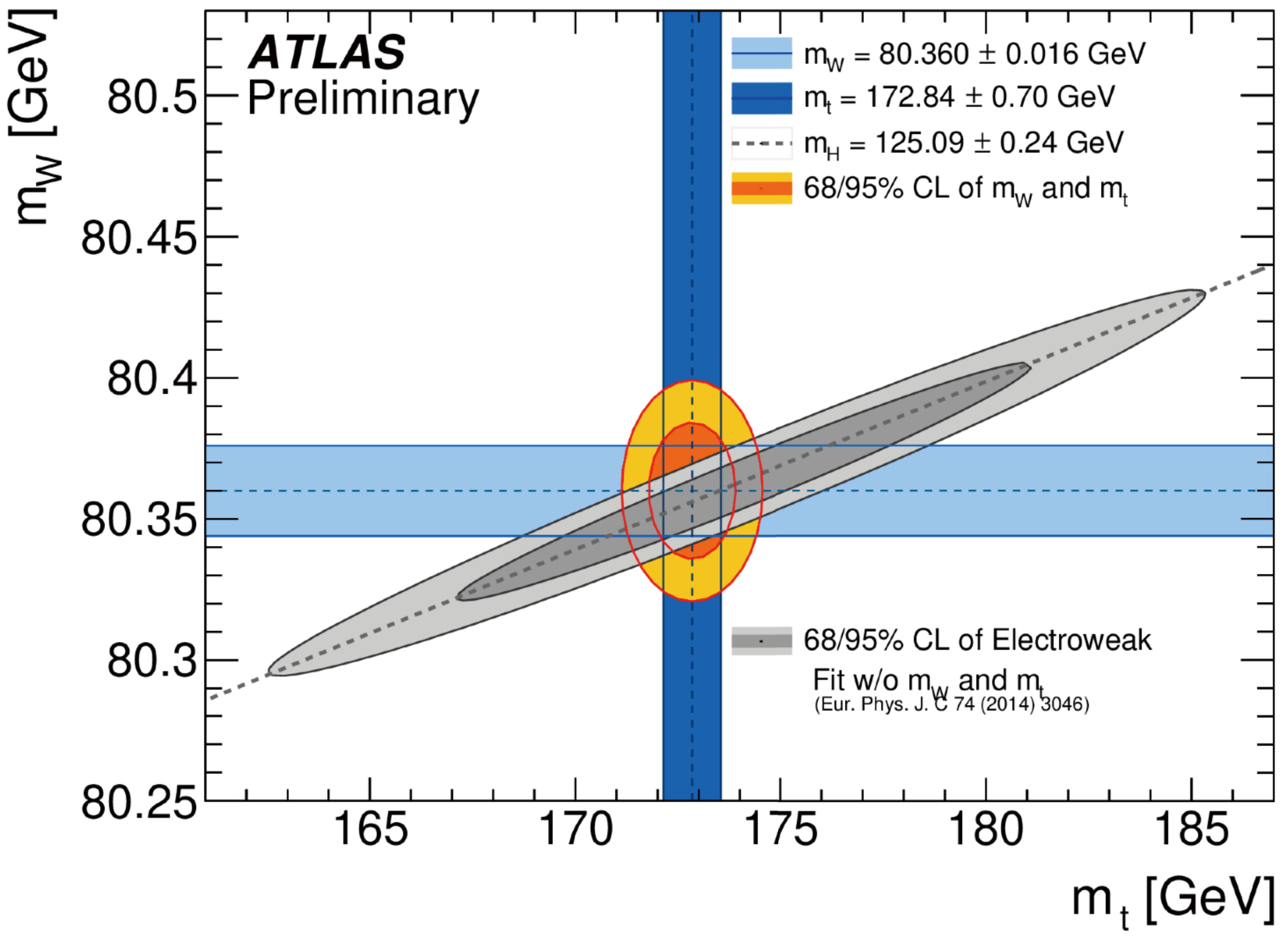


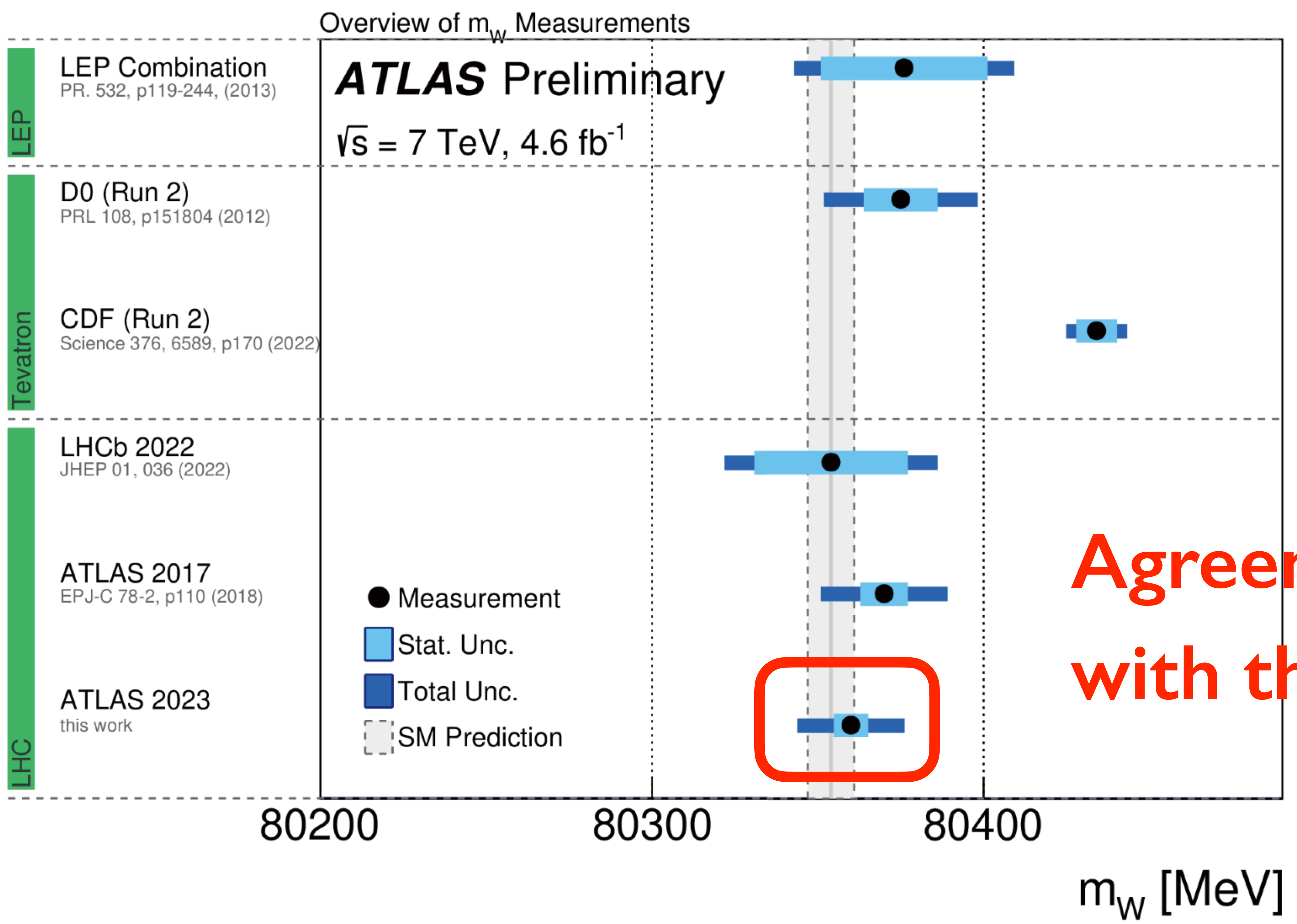
W Mass — Recent Result from ATLAS

Reanalysis of 7 TeV data — reduction of total uncertainty by 15 %
by updated PDFs (CT10NNLO→CT18NNLO), improvements in statistical analysis, …

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

ATLAS-CONF-2023-004





Agreement with the SM

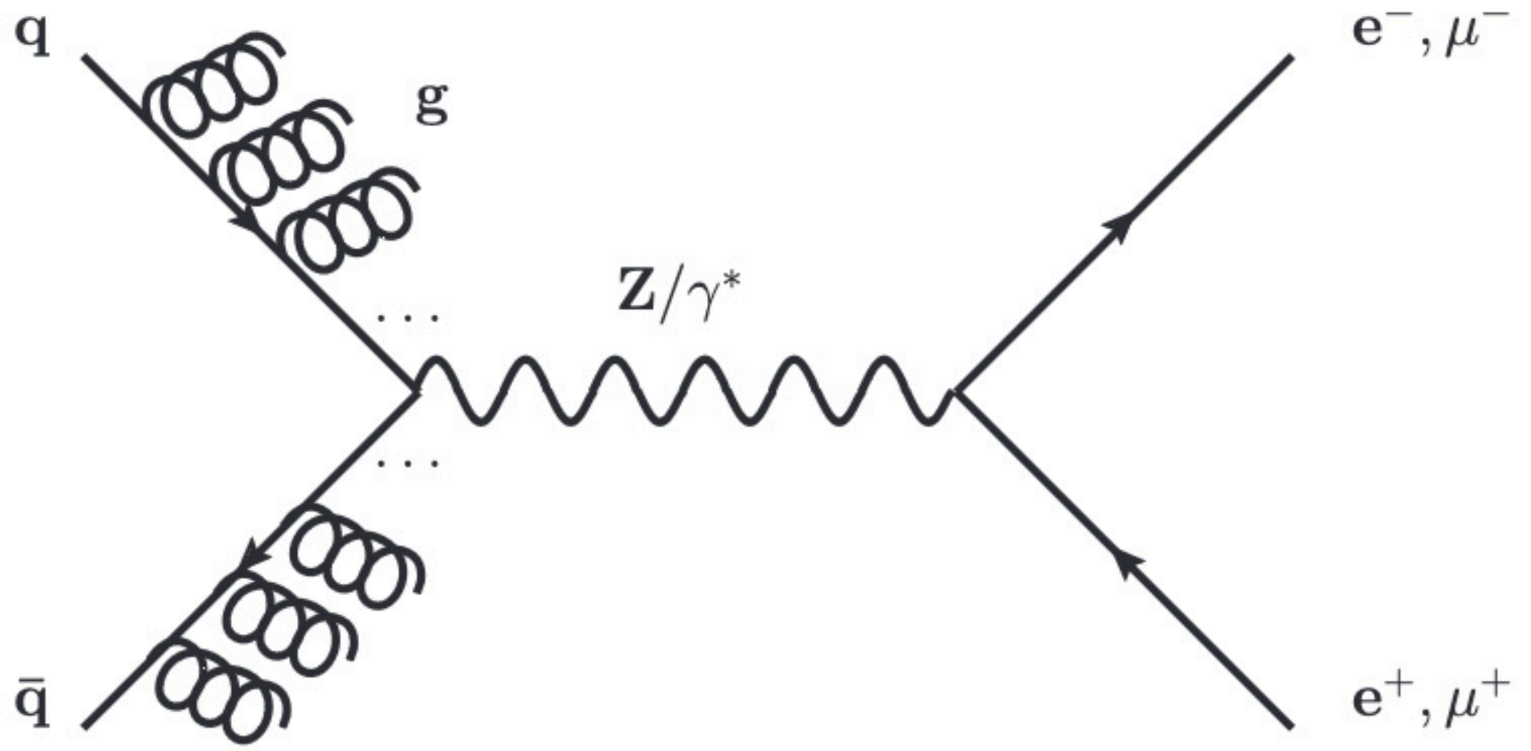
Awaiting a CMS result …

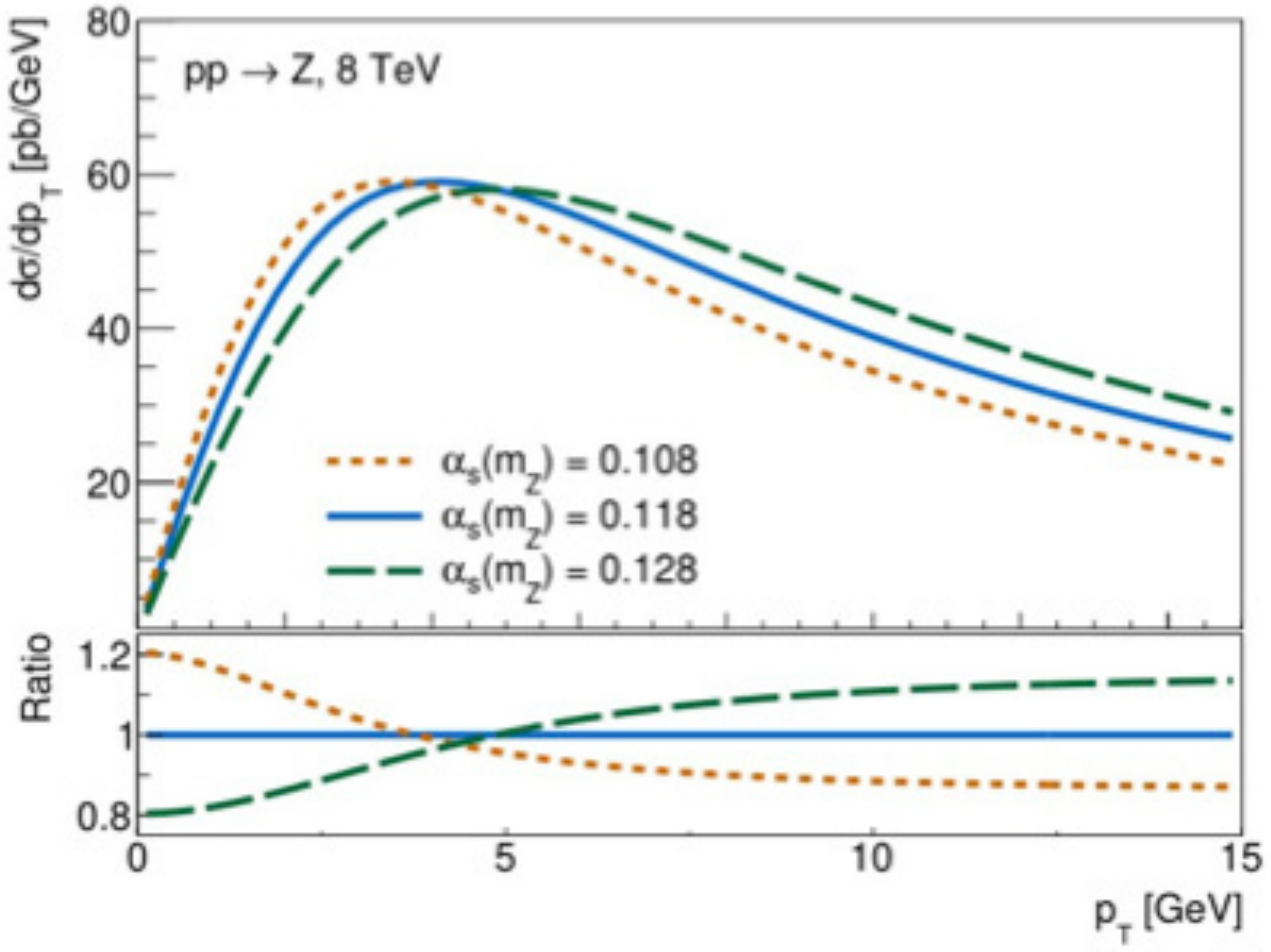
α_S Measurement from Z p_T

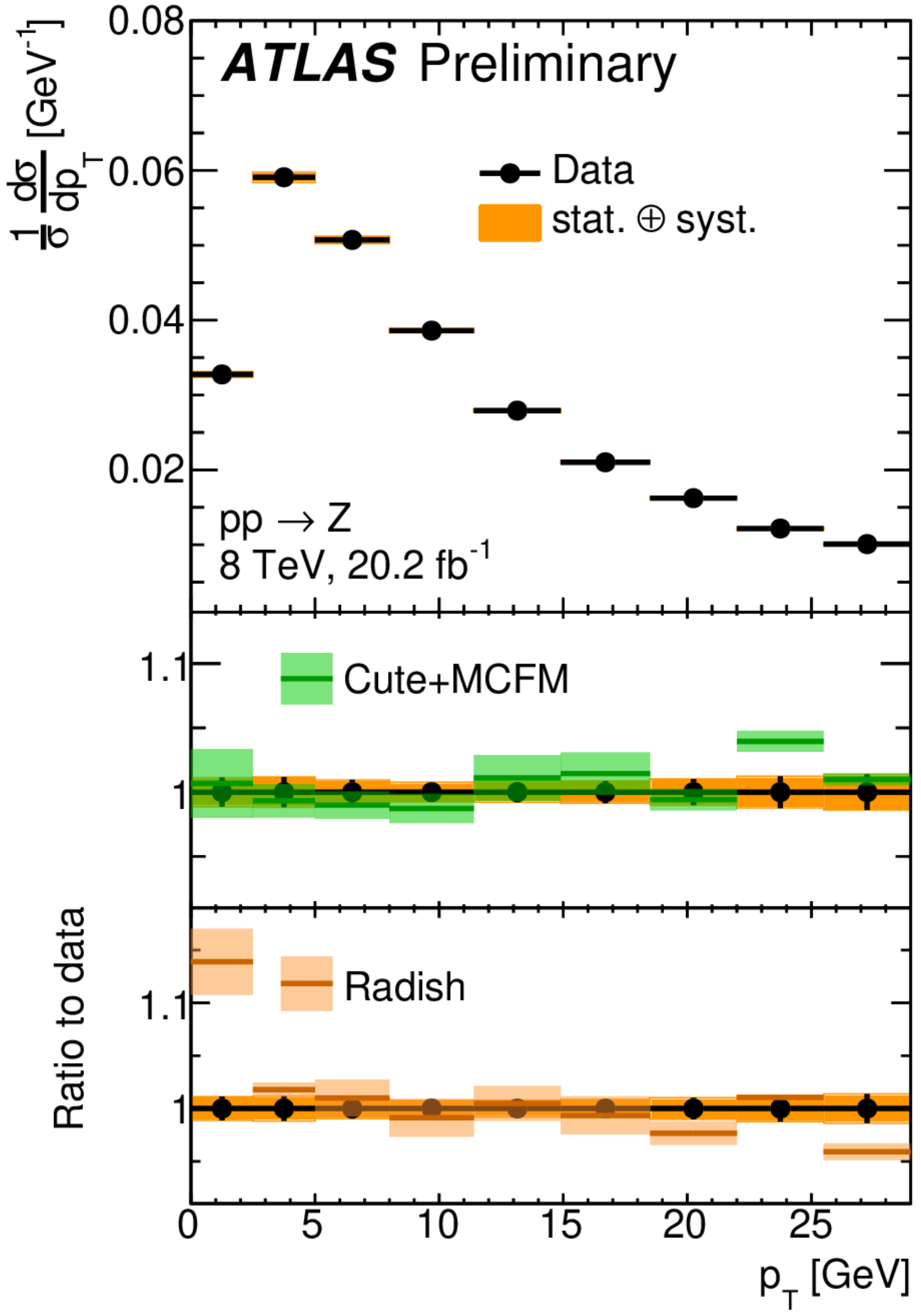
ATLAS-CONF-2023-013

The coupling constant of the strong interaction α_S is the least precisely known among the fundamental couplings

Z p_T distribution ("recoil of gluon emission") depends on α_S







Comparison with N4LL

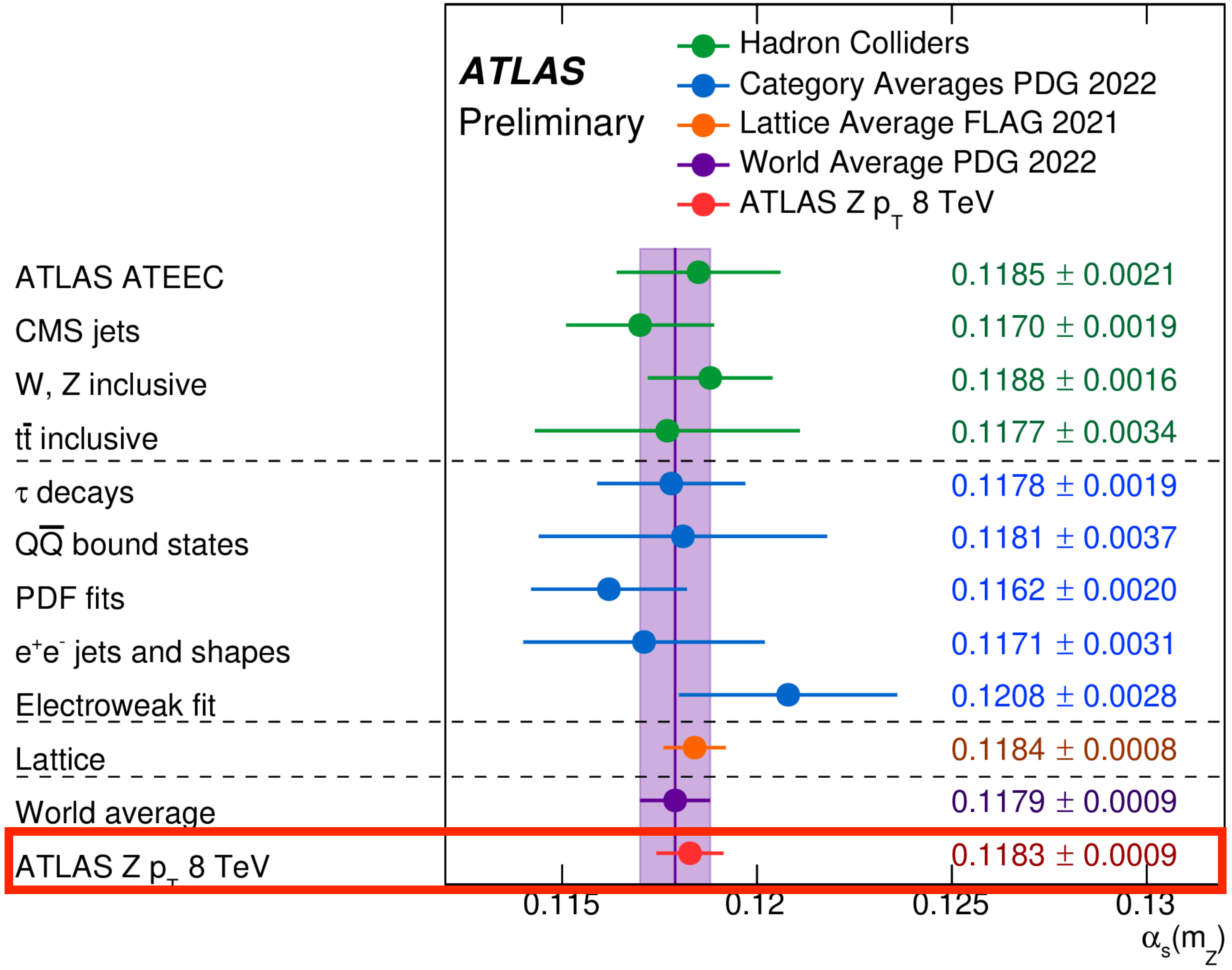
α_S Measurement from Z p_T

ATLAS-CONF-2023-015

Most precise experimental measurement on α_S,

and first time using N3LO+N4LL p_T(Z) predictions

Precision of α_S important to **reduce the associated theoretical uncertainty** which enters into all cross-section calculations for processes at the LHC

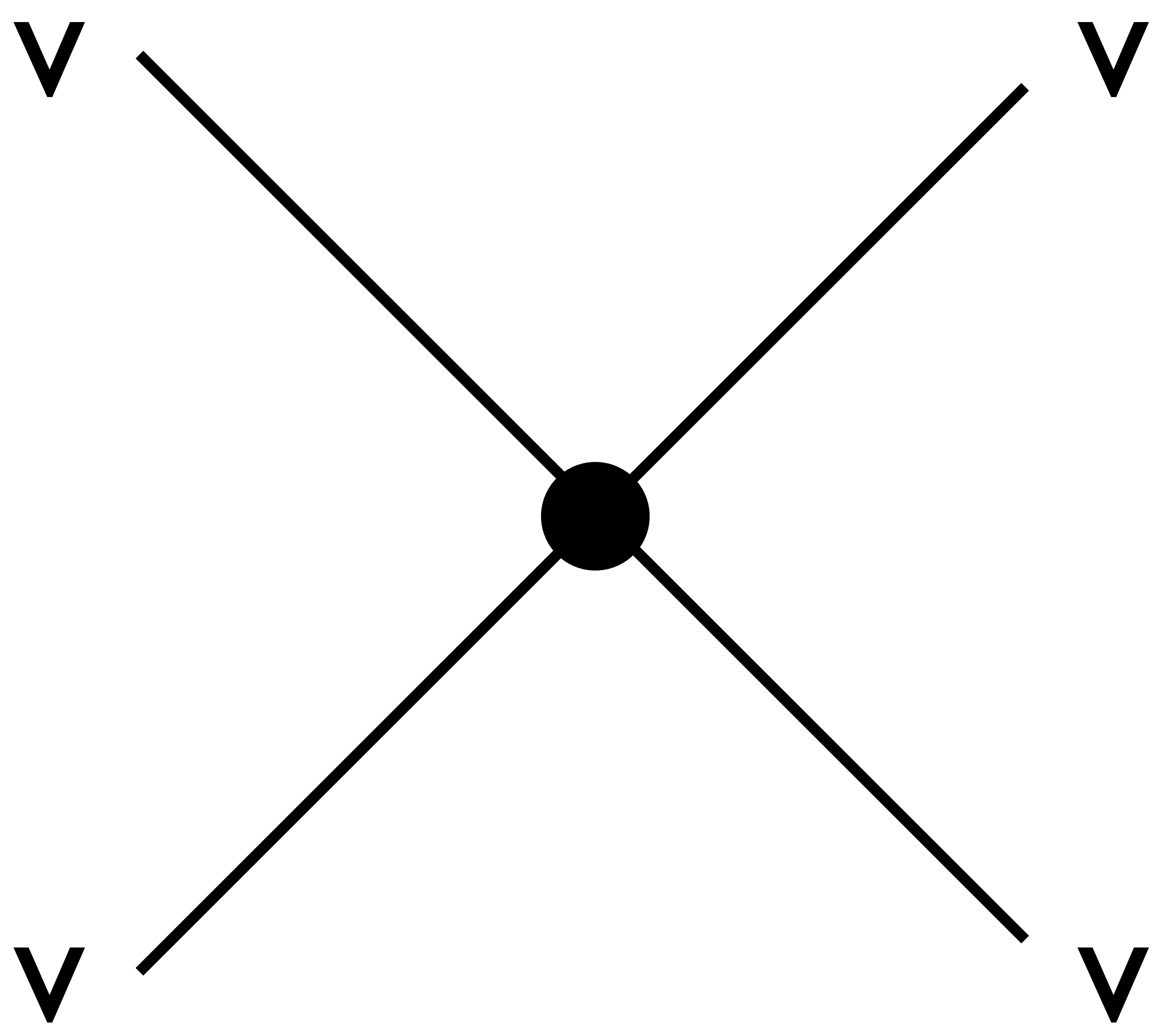


VBS — Introduction

Vector boson scattering (VBS),

VV→VV (V=W±/Z/γ), is crucial for

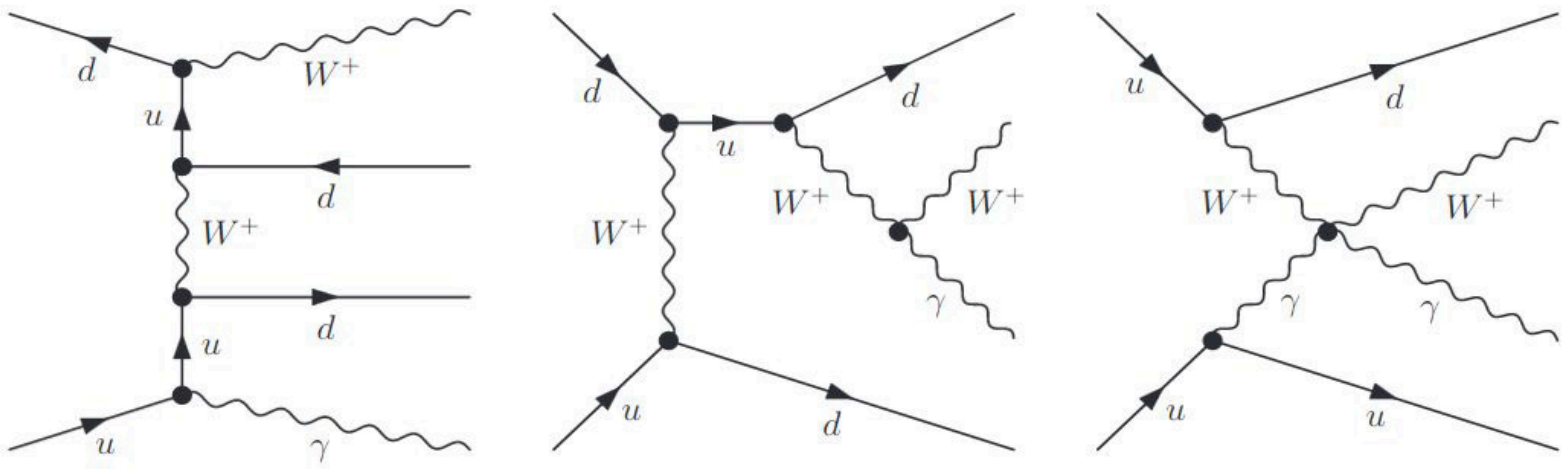
- understanding the nature of the electroweak symmetry-breaking mechanism in the SM
- searches for new physics processes, which may impact the scattering at high precision
- studies of the Higgs sector, as the Higgs mechanism impacts the scattering rate.



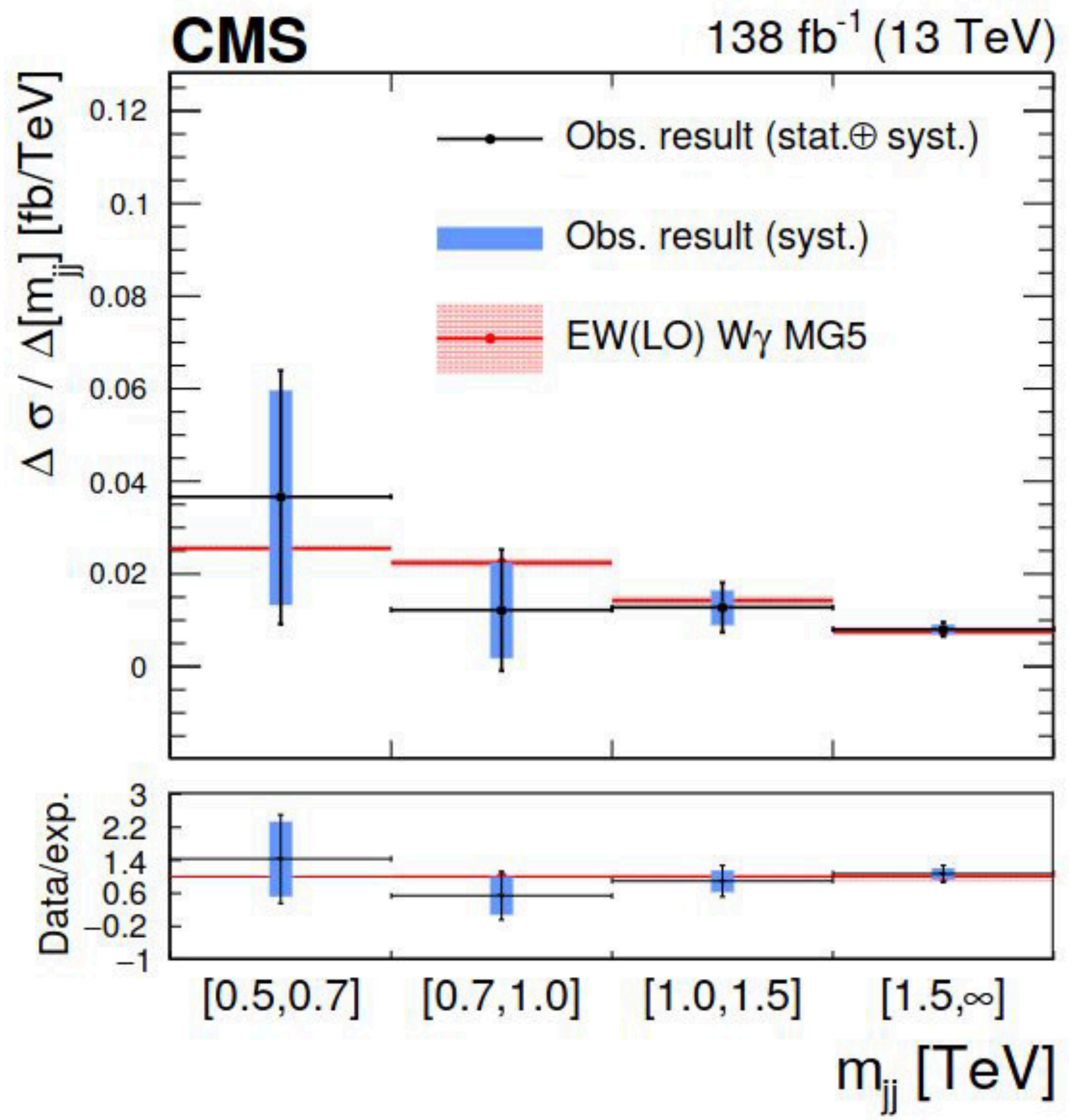
VBS — Recent Results from CMS

arXiv:2212.12592

Wγ: 6.0 (6.8)σ observed (expected)



$$\sigma^{\text{fid}}_{\text{EW}} = 23.5 \pm 2.8\,(\text{stat})^{+1.9}_{-1.7}\,(\text{theo})^{+3.5}_{-3.4}\,(\text{syst})\,\text{fb} = 23.5^{+4.9}_{-4.7}\,\text{fb}.$$



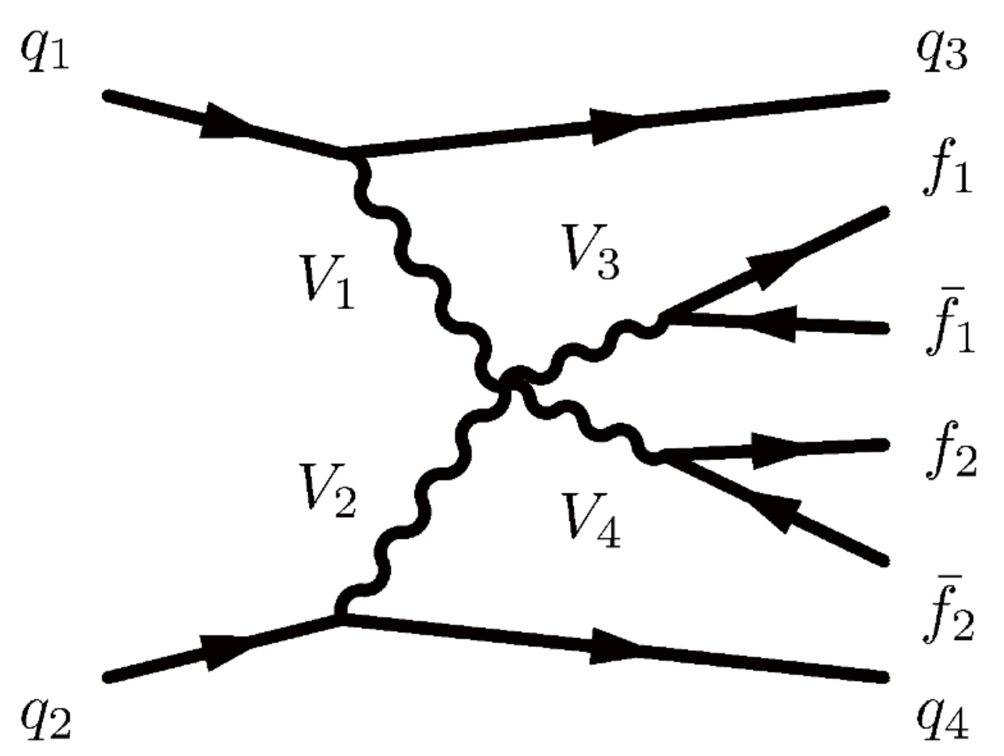
Fiducial and differential cross sections measured

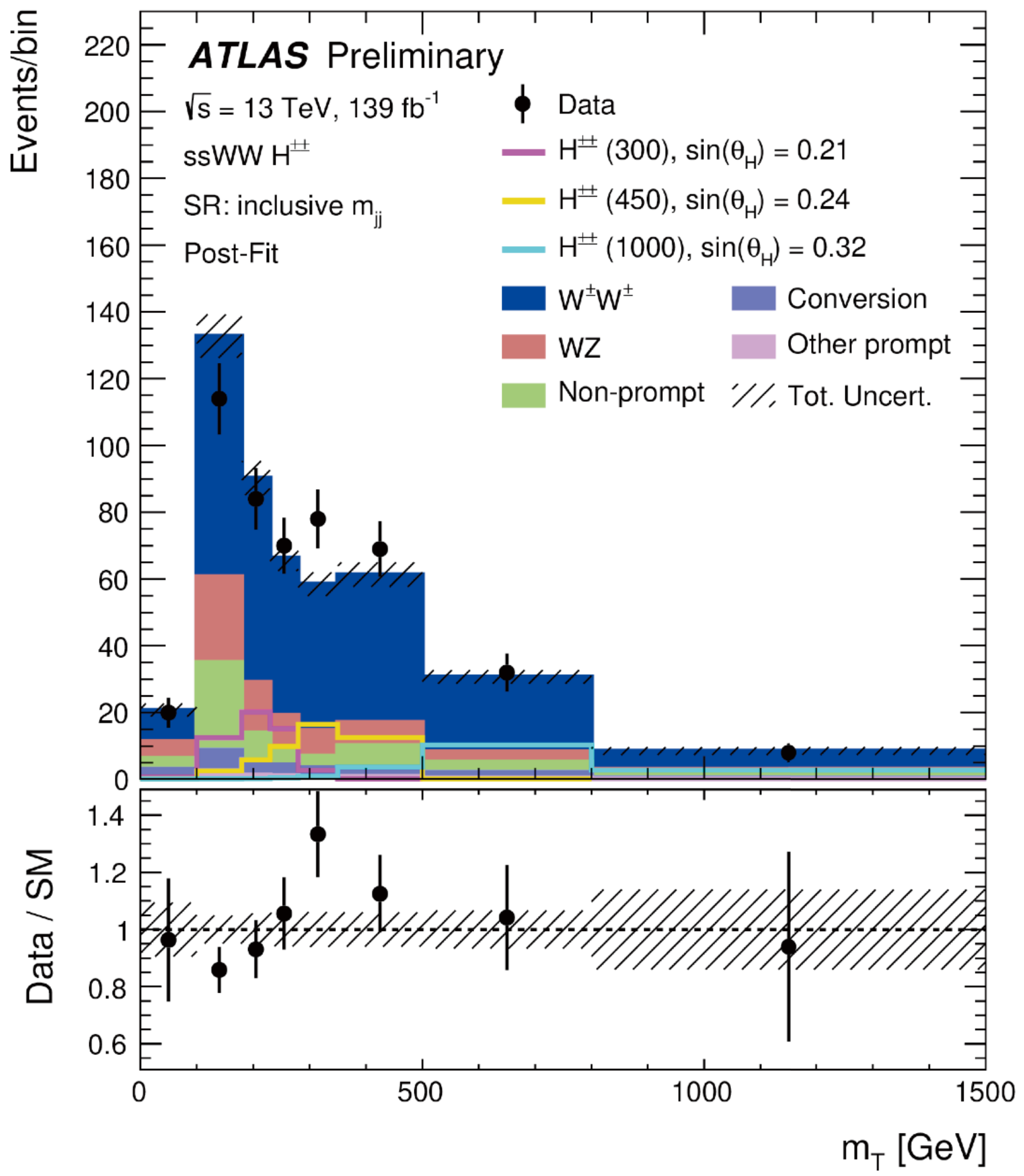
Stringent limits on anomalous quartic gauge couplings

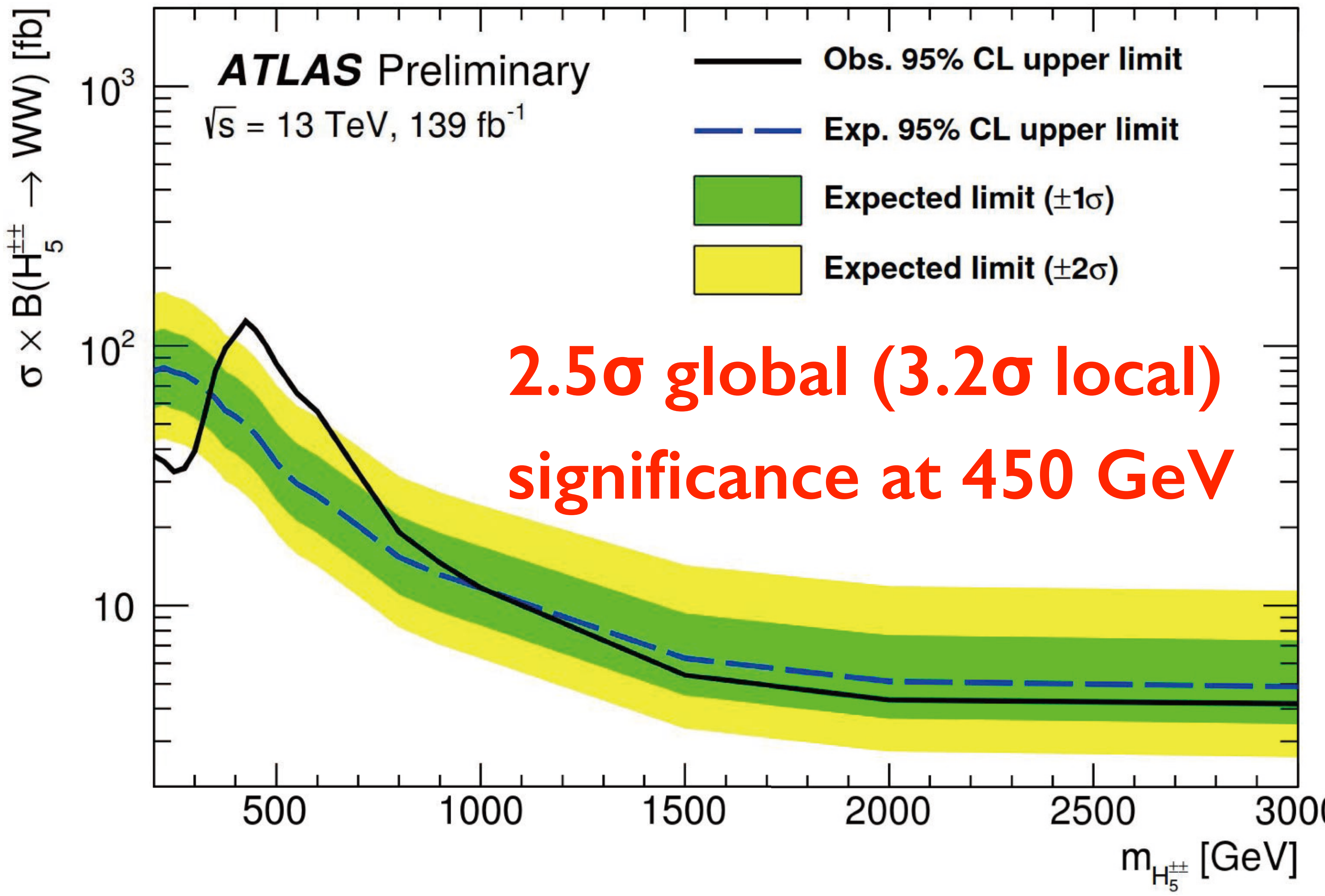
VBS — Recent Results from ATLAS

ATLAS showed new results on same-sign WW (below), ZZ (backup), and Zγ (backup).

- Fiducial and differential cross sections measured
- Searches for anomalous quartic gauge couplings and doubly charged Higgs (e.g. in GM model)







2.5σ global (3.2σ local) significance at 450 GeV

Summary

- Top quark mass new era: 0.4 GeV precision by single measurement
  Electroweak vacuum: closer to absolute stability(?)
- First tttt observation: new probe of top Yukawa coupling and new physics
- New ttbb and ttW measurements (most precise and differential)
- First Run 3 measurements for top quark pair production
- ATLAS results on W mass consistent with the SM
  — no convincing explanations on the deviation for CDF II result
- Most precise experimental measurement on α_S using Z p_T
- 2.5σ global (3.2σ local) significance at 450 GeV in same-sign WW

The Standard Model still reigns supreme! Stay tuned for Run 3 results!

Backup Slides

Interpretation of Top Quark MC Mass

TABLE I. Results of the calibration for $m_t^{\text{MC}} = 173$ GeV in PYTHIA, combining results from all Q sets and bin ranges. Shown are central values, perturbative and incompatibility uncertainties, and the total uncertainty, all in GeV.

$m_t^{\text{MC}} = 173$ GeV $(\tau_2^{e^+e^-})$					
Mass	Order	Central	Perturb.	Incompatibility	Total
$m_{t,1\,\text{GeV}}^{\text{MSR}}$	NLL	172.80	0.26	0.14	0.29
$m_{t,1\,\text{GeV}}^{\text{MSR}}$	NNLL	172.82	0.19	0.11	0.22
m_t^{pole}	NLL	172.10	0.34	0.16	0.38
m_t^{pole}	NNLL	172.43	0.18	0.22	0.28

PRL 117, 232001 (2016)

Getting Closer to Absolute Stability?

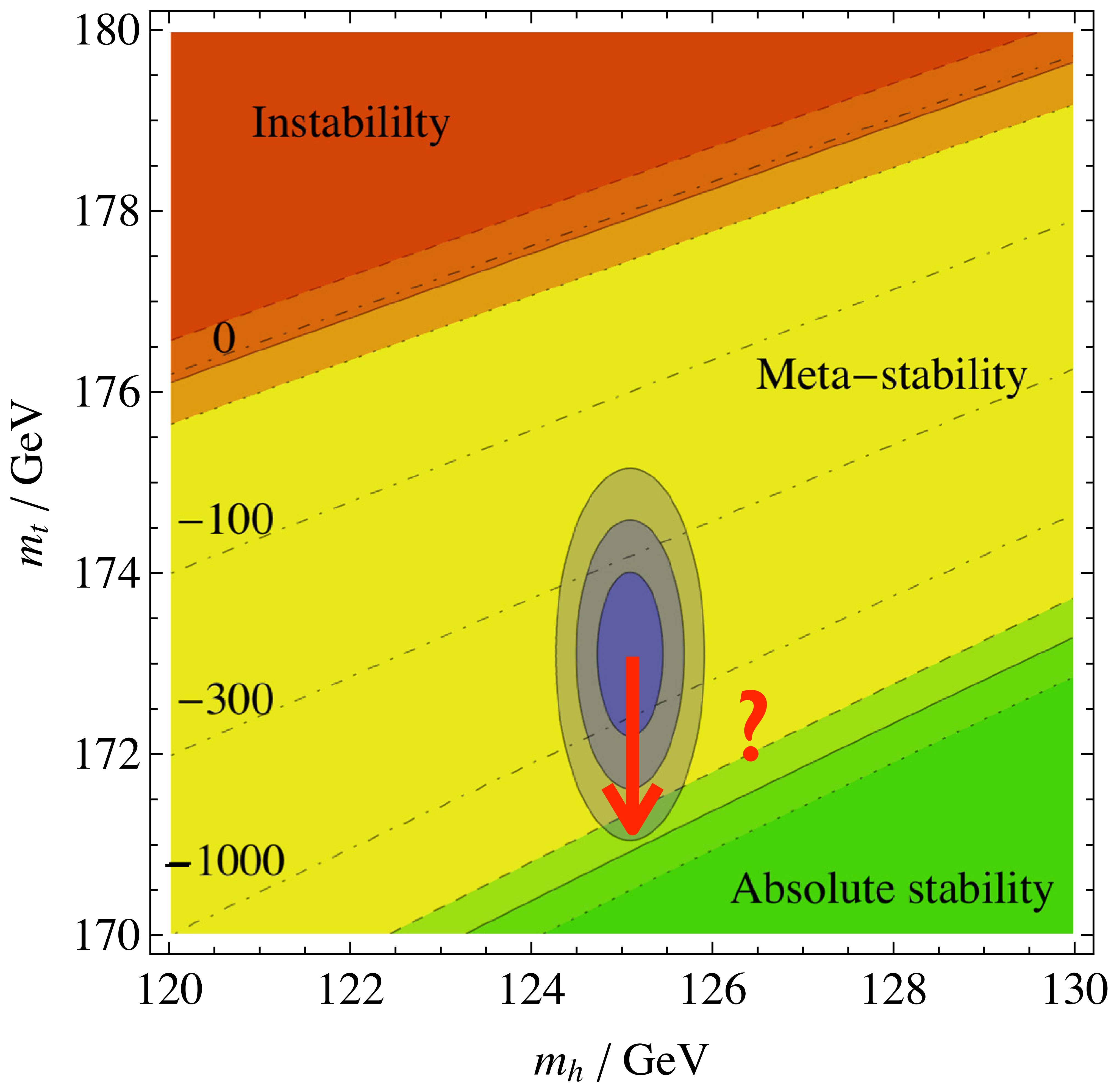
$m_t^{\mathrm{MC}} = 171.77 \pm 0.37\ \mathrm{GeV}$

arXiv:2302.01967

TABLE I. Results of the calibration for $m_t^{\mathrm{MC}} = 173$ GeV in PYTHIA, combining results from all Q sets and bin ranges. Shown are central values, perturbative and incompatibility uncertainties, and the total uncertainty, all in GeV.

$m_t^{\mathrm{MC}} = 173$ GeV $(\tau_2^{e^+e^-})$					
Mass	Order	Central	Perturb.	Incompatibility	Total
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	NLL	172.80	0.26	0.14	0.29
$m_{t,1\,\mathrm{GeV}}^{\mathrm{MSR}}$	NNLL	172.82	0.19	0.11	0.22
m_t^{pole}	NLL	172.10	0.34	0.16	0.38
m_t^{pole}	NNLL	172.43	0.18	0.22	0.28

PRL 117, 232001 (2016)



Vacuum Stability — Two Plots

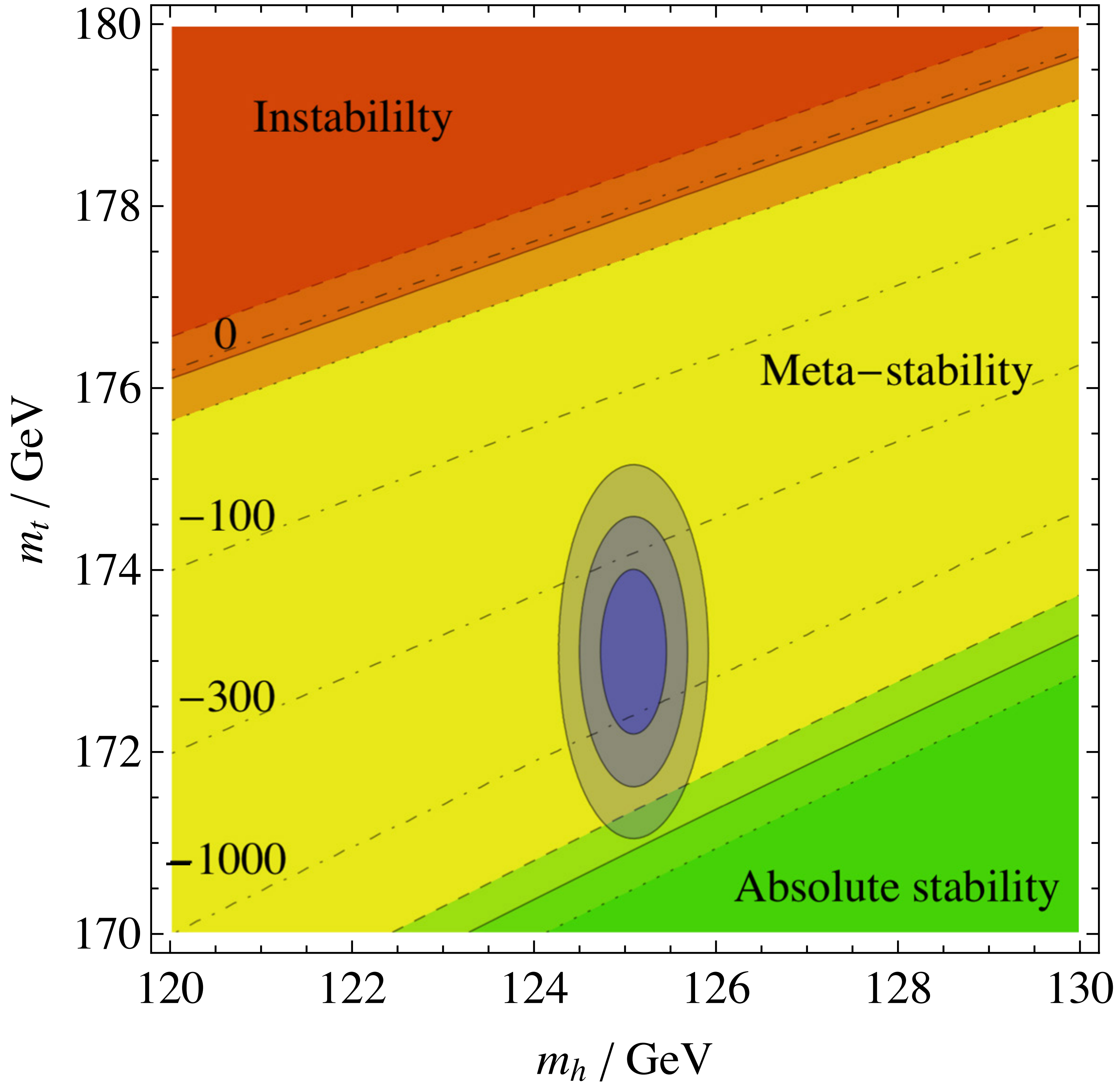
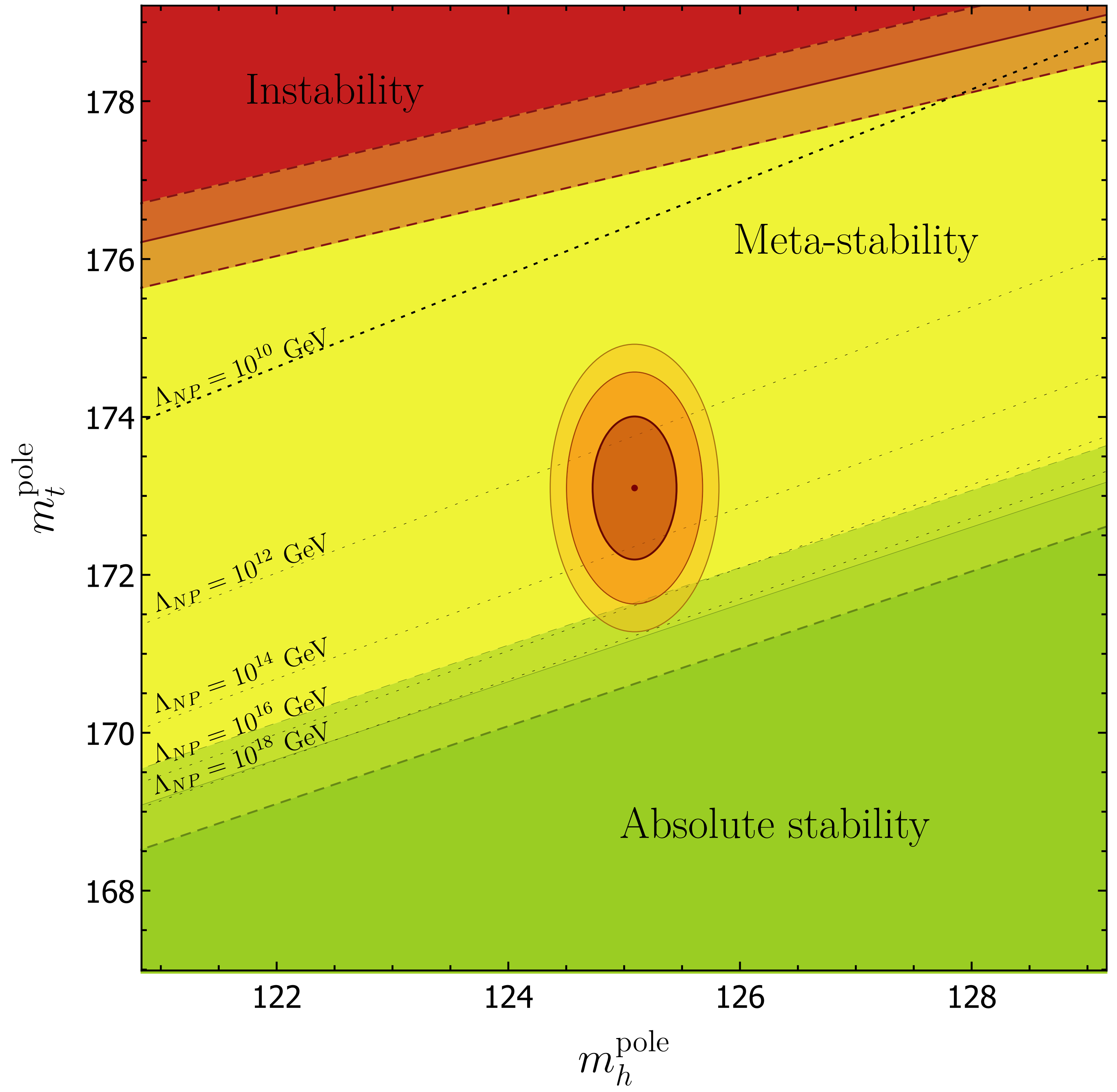


FIG. 3. The stability of the EW vacuum in the SM with a cutoff of the integration at $\bar{\phi}_C = M_{\mathrm{Pl}}$. The red region is unstable, the yellow region is metastable, and the green region is absolutely stable. The dashed, solid, and dotted lines correspond to $\alpha_s = 0.1192$, 0.1181, and 0.1170, respectively. The black dot-dashed lines indicate $\log_{10}[\gamma \times \mathrm{Gyr\,Gpc}^3] = 0, -100, -300$, and -1000 with the central value of α_s. The blue circles indicate 68, 95, and 99% C.L. constraints on the Higgs mass vs top mass plane assuming that their errors are independently Gaussian.

PRD 97, 116012 (2018)



PRD 97 (2018) 056006

Top Quark Mass — Direct Measurement with l+jets

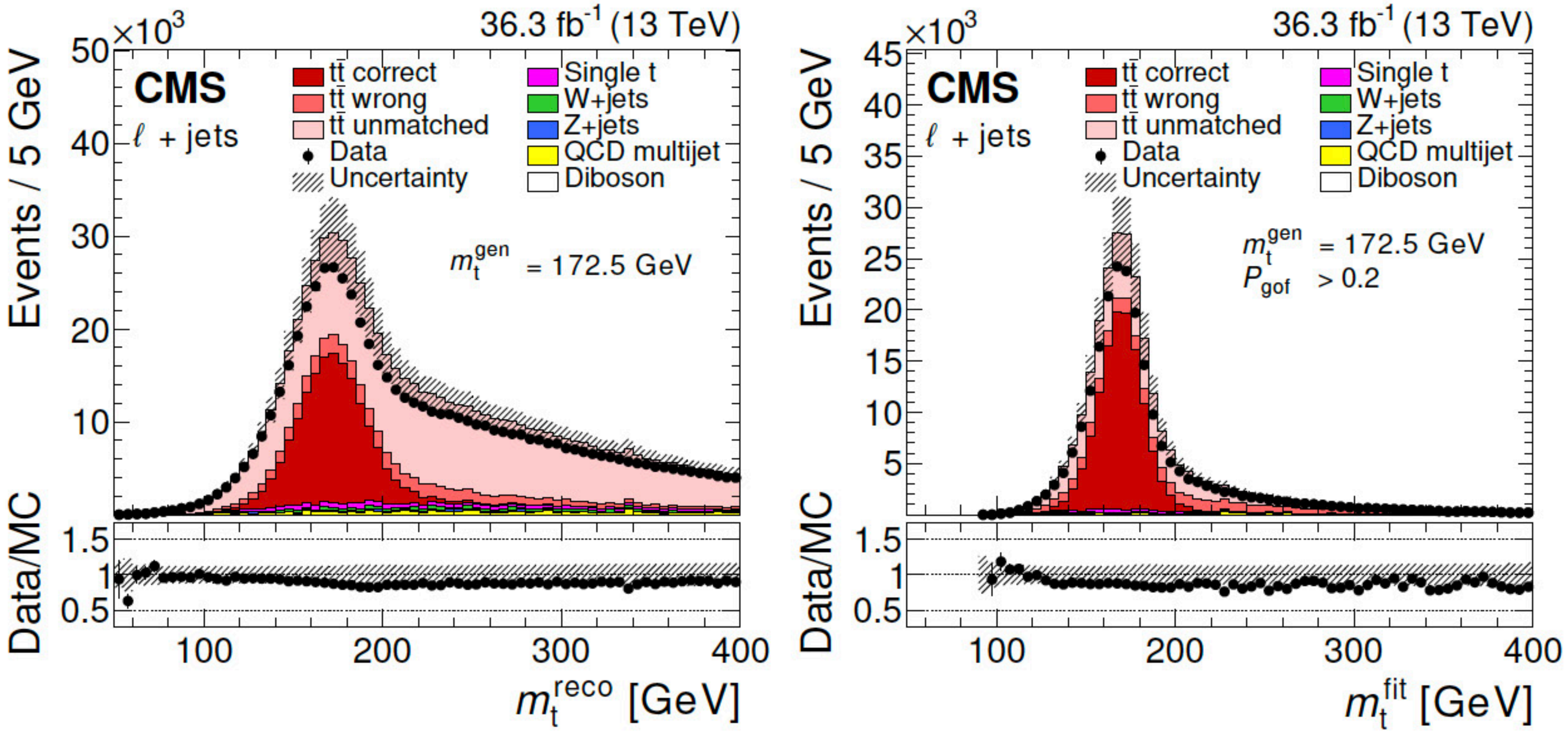


Figure 1: The top quark mass distribution before (left) and after (right) the $P_{gof} > 0.2$ selection and the kinematic fit. For the simulated $t\bar{t}$ events, the jet-parton assignments are classified as correct, wrong, and unmatched permutations, as described in the text. The uncertainty bands contain statistical uncertainties in the simulation, normalization uncertainties due to luminosity and cross section, jet energy correction uncertainties, and all uncertainties that are evaluated from event-based weights. A large part of the depicted uncertainties on the expected event yields are correlated. The lower panels show the ratio of data to the prediction. A value of $m_t^{gen} = 172.5\,\mathrm{GeV}$ is used in the simulation.

arXiv:2302.01967

m_t^{fit}: the invariant mass for hadronically decaying top quark after kinematic fit and requirement on goodness-of-fit for parton-jet assignment.

The kinematic fit constrains 4-momenta to the hypothesis that two heavy particles of equal mass are produced, each one decaying to a b quark and a W boson, with the invariant mass of the latter constrained to 80.4 GeV.

Top Quark Mass — Direct Measurement with l+jets

For most $t\bar{t}$ events, a low P_{gof} value is caused by assigning a wrong jet to the W boson candidate, while the two b-tagged jets are the correct candidates for the b quarks. Hence, m_{lb}^{reco} preserves a good m_t dependence and adds additional sensitivity to the measurement.

Additional observables are used in parallel for the mass extraction to constrain systematic uncertainties. In previous analyses by the CMS Collaboration in the lepton+jets channel [11, 13], the invariant mass of the two untagged jets before the kinematic fit m_{W}^{reco}, has been used together with m_{t}^{fit}, mainly to reduce the uncertainty in the jet energy scale and the jet modeling. Its distribution is shown in Fig. 2 (left). As m_{W}^{reco} is only sensitive to the energy scale and modeling of light flavor jets, two additional observables are employed to improve sensitivity to the scale and modeling of jets originating from b quarks. These are the ratio $m_{\ell b}^{reco}/m_{t}^{fit}$, and the ratio of the scalar sum of the transverse momenta of the two b-tagged jets (b1, b2), and the two non-b-tagged jets (q1, q2), $R_{bq}^{reco} = (p_{T}^{b1} + p_{T}^{b2})/(p_{T}^{q1} + p_{T}^{q2})$. Their distributions are shown in Fig. 3. While m_{t}^{fit} and m_{W}^{reco} have been used by the CMS Collaboration in previous analyses in the lepton+jets channel, $m_{\ell b}^{reco}$, $m_{\ell b}^{reco}/m_{t}^{fit}$, and R_{bq}^{reco} are new additions. However, R_{bq}^{reco} has been used in the lepton+jets channel by the ATLAS Collaboration [10, 53].

arXiv:2302.01967

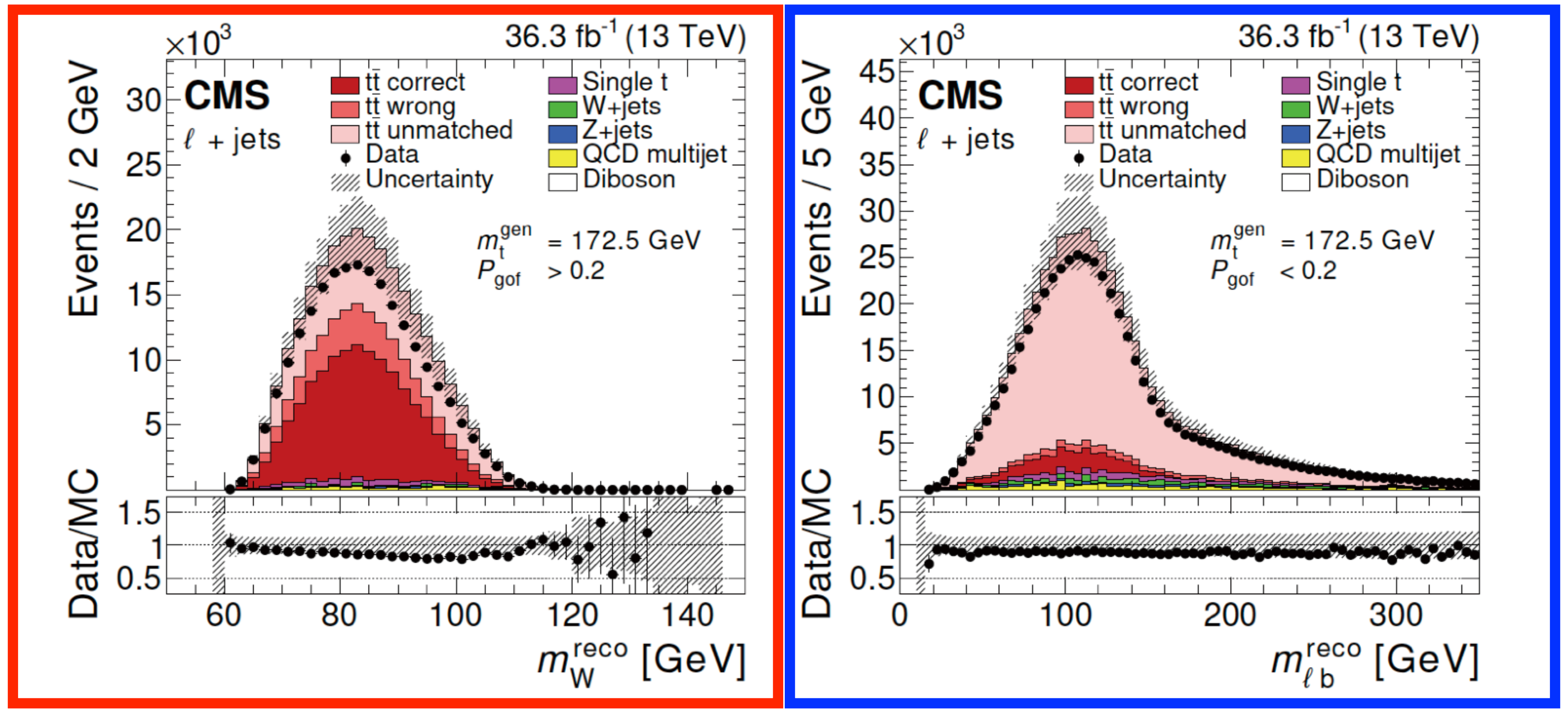


Figure 2: The distributions of the reconstructed W boson mass for the $P_{gof} > 0.2$ category (left) and of the invariant mass of the lepton and the jet assigned to the semileptonic decaying top quark for the $P_{gof} < 0.2$ category (right). The uncertainty bands contain statistical uncertainties in the simulation, normalization uncertainties due to luminosity and cross section, jet energy correction uncertainties, and all uncertainties that are evaluated from event-based weights. A large part of the depicted uncertainties on the expected event yields are correlated. The lower panels show the ratio of data to the prediction. A value of $m_{t}^{gen} = 172.5$ GeV is used in the simulation.

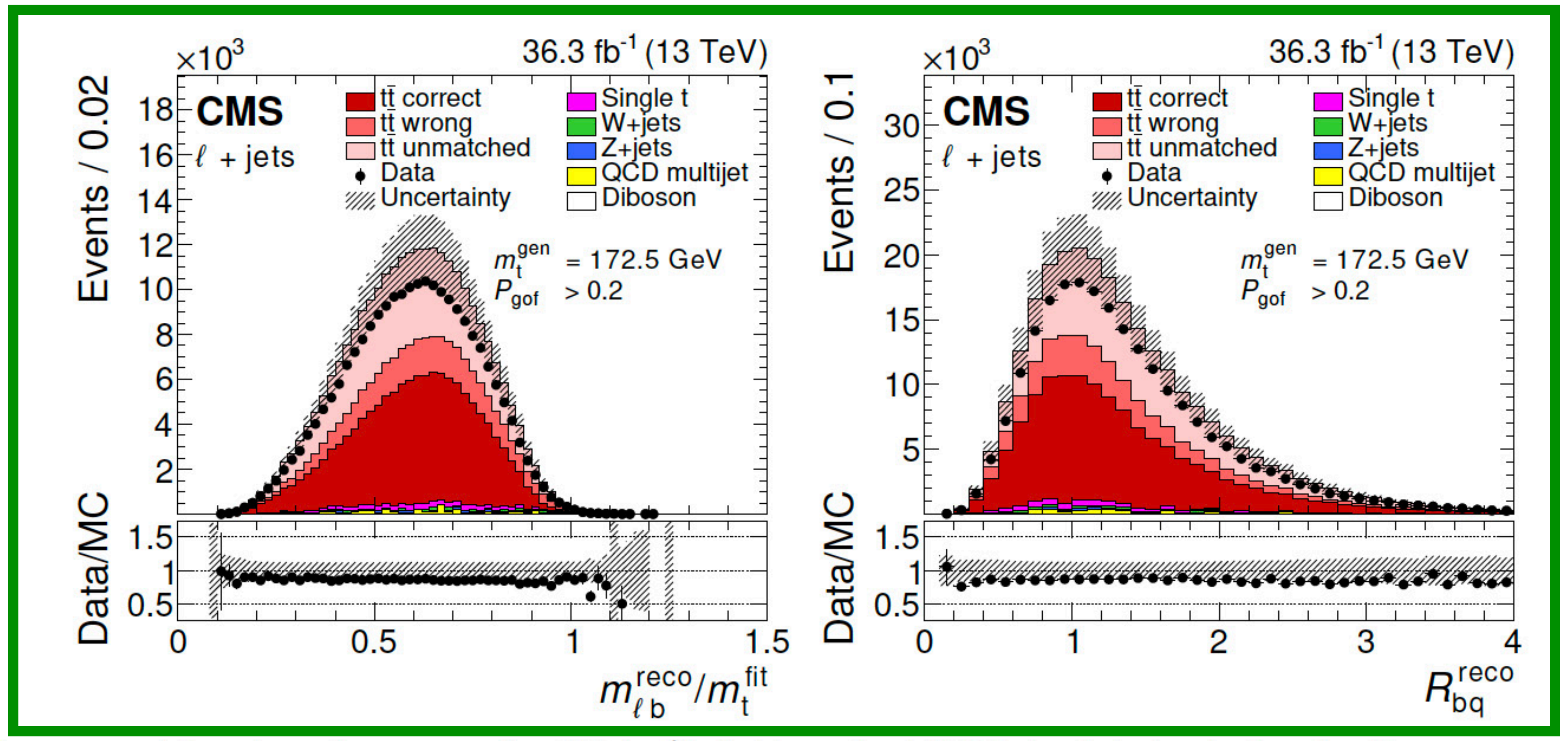


Figure 3: The distributions of $m_{\ell b}^{reco}/m_{t}^{fit}$ (left) and of R_{bq}^{reco} (right), both for the $P_{gof} > 0.2$ category. The uncertainty bands contain statistical uncertainties in the simulation, normalization uncertainties due to luminosity and cross section, jet energy correction uncertainties, and all uncertainties that are evaluated from event-based weights. A large part of the depicted uncertainties on the expected event yields are correlated. The lower panels show the ratio of data to the prediction. A value of $m_{t}^{gen} = 172.5$ GeV is used in the simulation.

Top Quark Mass — Direct Measurement with l+jets

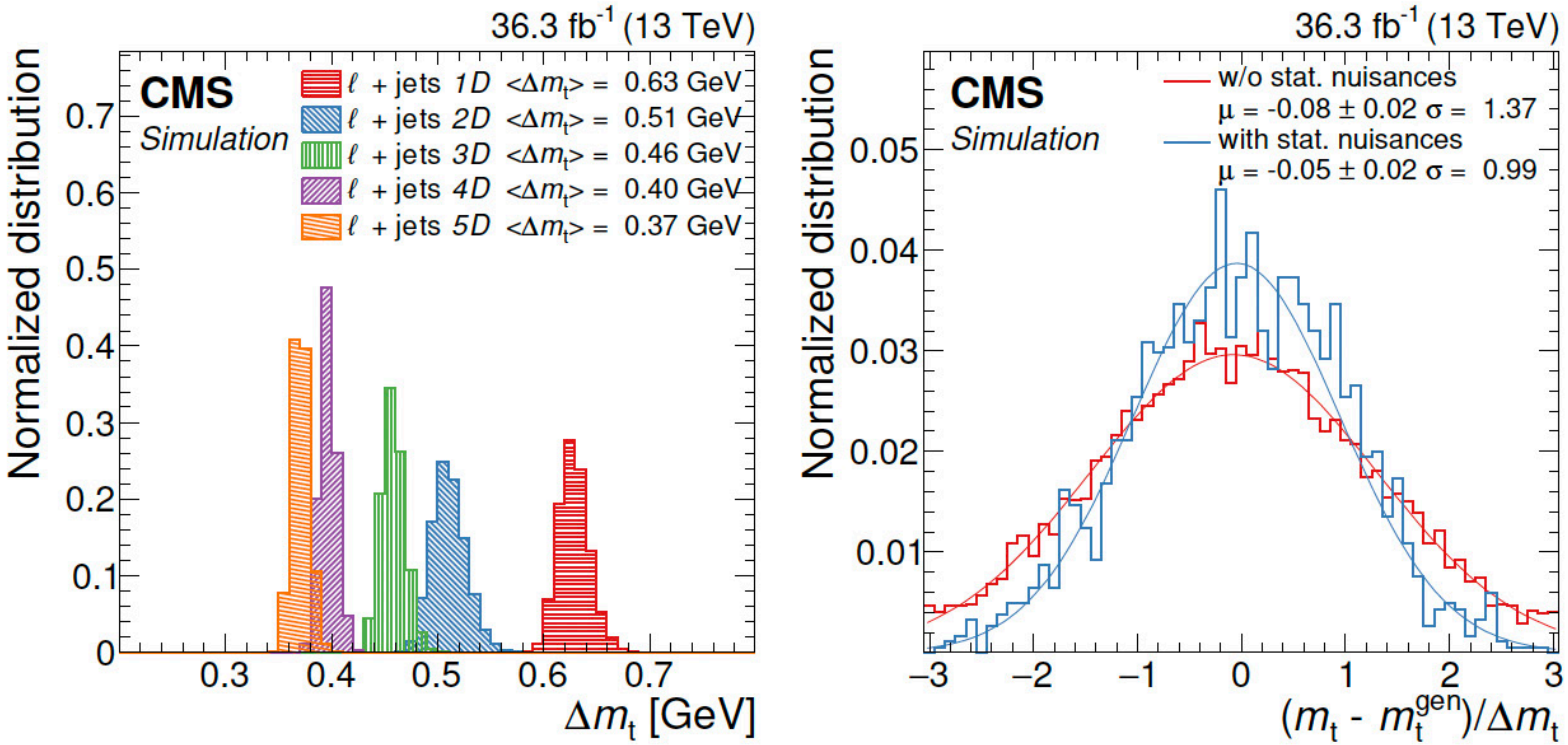
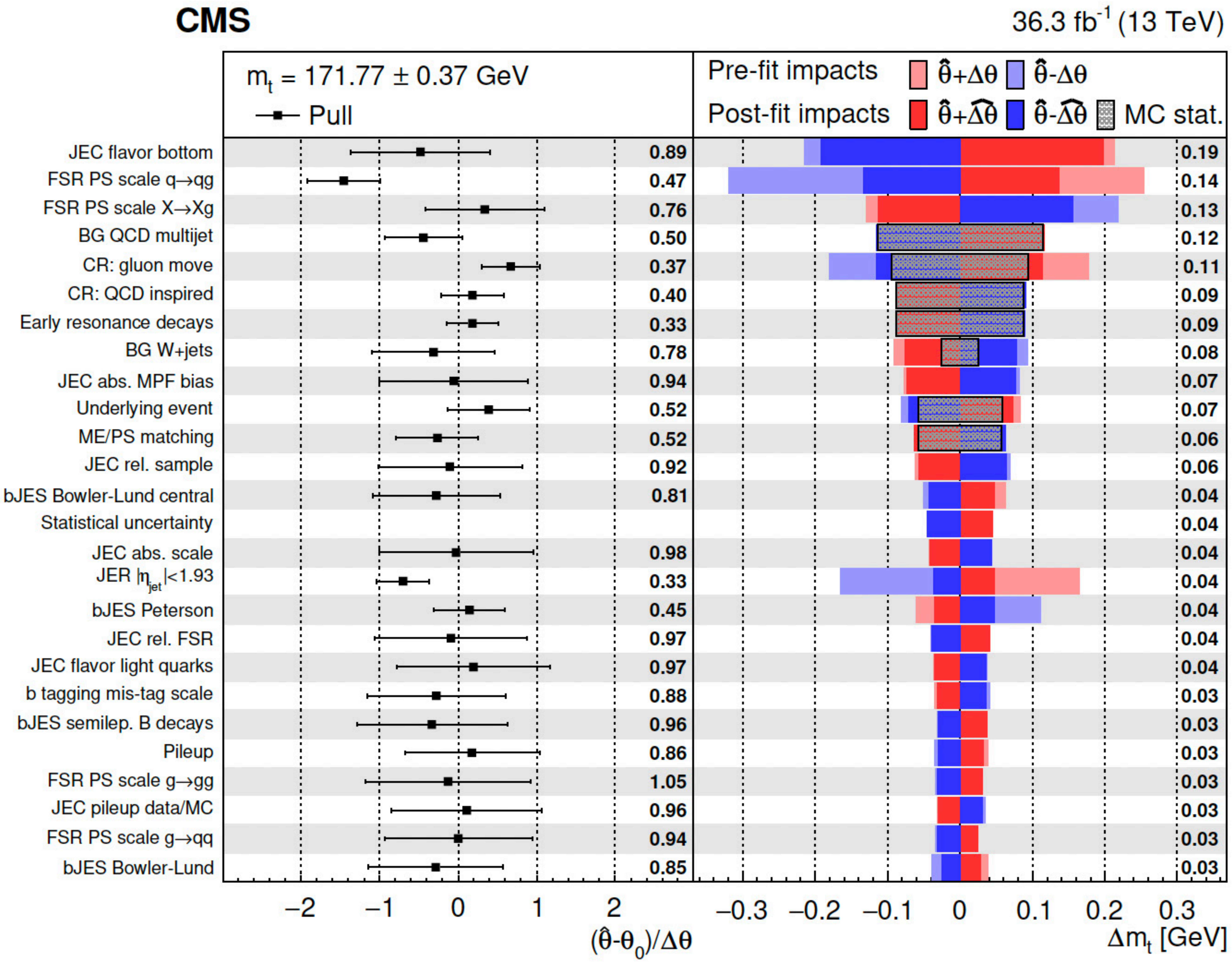


Figure 4: Left: Comparison of the expected total uncertainty in m_t in the combined lepton+jets channel and for the different observable-category sets defined in Table 1. Right: The difference between the measured and generated m_t values, divided by the uncertainty reported by the fit from pseudo-experiments without (red) or with (blue) the statistical nuisance parameters $\vec{\beta}$ and $\vec{\omega}$ in the *5D* ML fit. Also included in the legend are the μ and σ parameters of Gaussian functions (red and blue lines) fit to the histograms.

arXiv:2302.01967

Top Quark Mass — Direct Measurement with l+jets



Dominant uncertainties:

- Jet Energy Correction (JEC) flavor bottom
- Final State Radiation (FSR) Parton Shower (PS)
- Color Reconnection (CR)

arXiv:2302.01967

Top Quark Mass — “Recoil” Uncertainty

Gluon recoil schema in Phytia 8

arXiv:2209.00583

In the modelling of the parton shower of the b-quark from $t \to Wb$ with PYTHIA 8.2, there is the possibility to change the default gluon recoil scheme from recoiling against the b-quark (the nominal setting, referred to here as RTB), to recoiling against the W-boson (RECOILTOCOLOURED=OFF, referred to as RTW) [103]. Before PYTHIA version 8.160, the RTW was the only possibility, but it could give unphysical radiation patterns and it is now kept as an option to understand the effect this setting has in view of previous measurements. This setting changes the modelling of second and subsequent gluon emission from quarks produced by coloured resonance decays, such as the b-quark in a $t \to Wb$ process, but it has no impact for example on $Z \to b\bar{b}$ decays. A third recoil scheme has been recently made available via the USERHOOK

Top Quark Mass — Projections

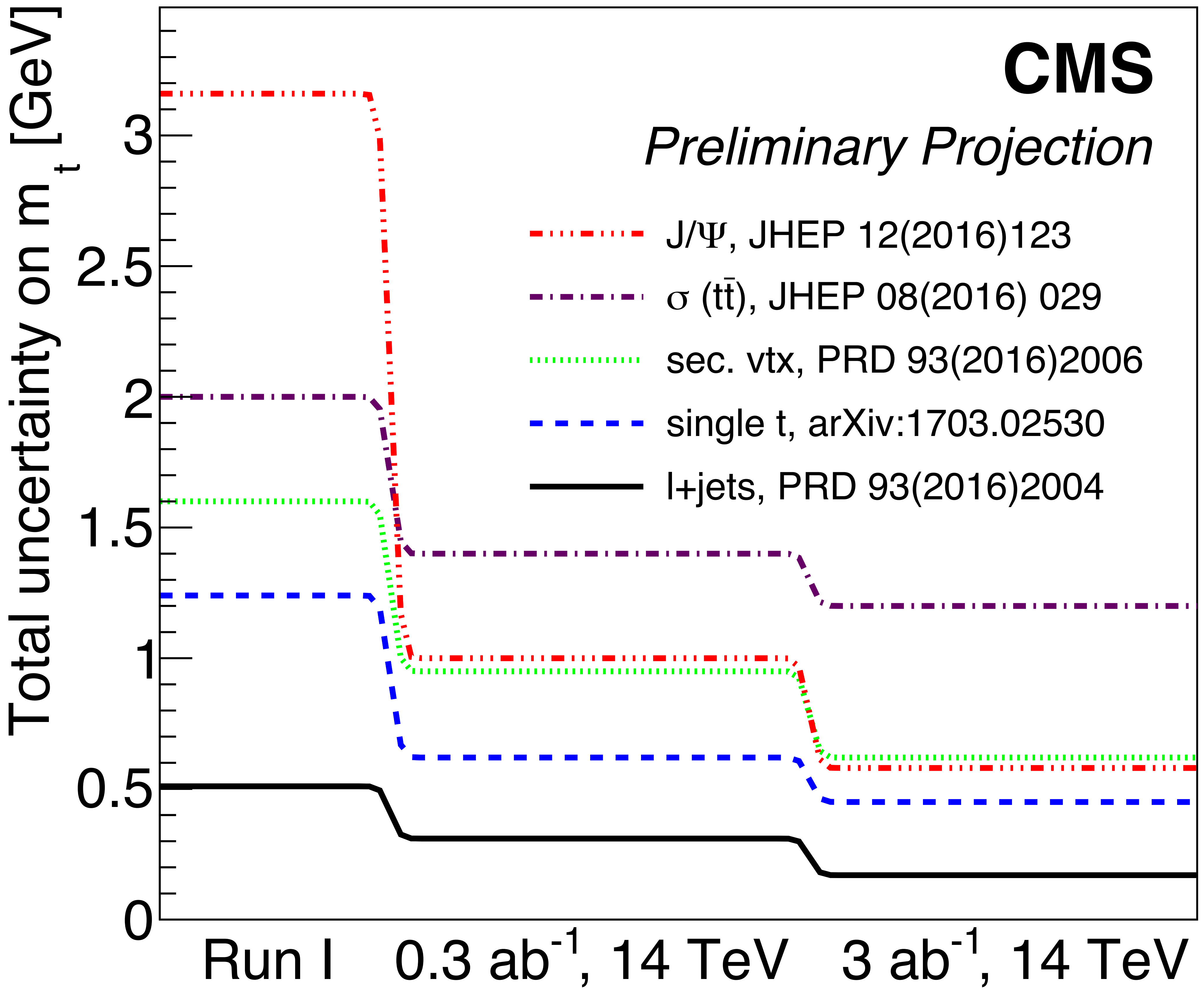


Figure 1: Total uncertainty on top quark mass (m_t) obtained with different measurement methods and their projections to the HL-LHC for running conditions foreseen after the phase II upgrade. The projections for $\sqrt{s} = 14$ TeV, with 0.3 ab^{-1} or 3 ab^{-1} of data, are based on m_t measurements performed at the LHC Run-1, assuming that an upgraded detector will maintain the same physics performance despite a severe pileup.

CMS-PAS-FTR-16-006

Jet Energy Scale Calibrations at ATLAS

Eur. Phys. J. C (2021) 81:689

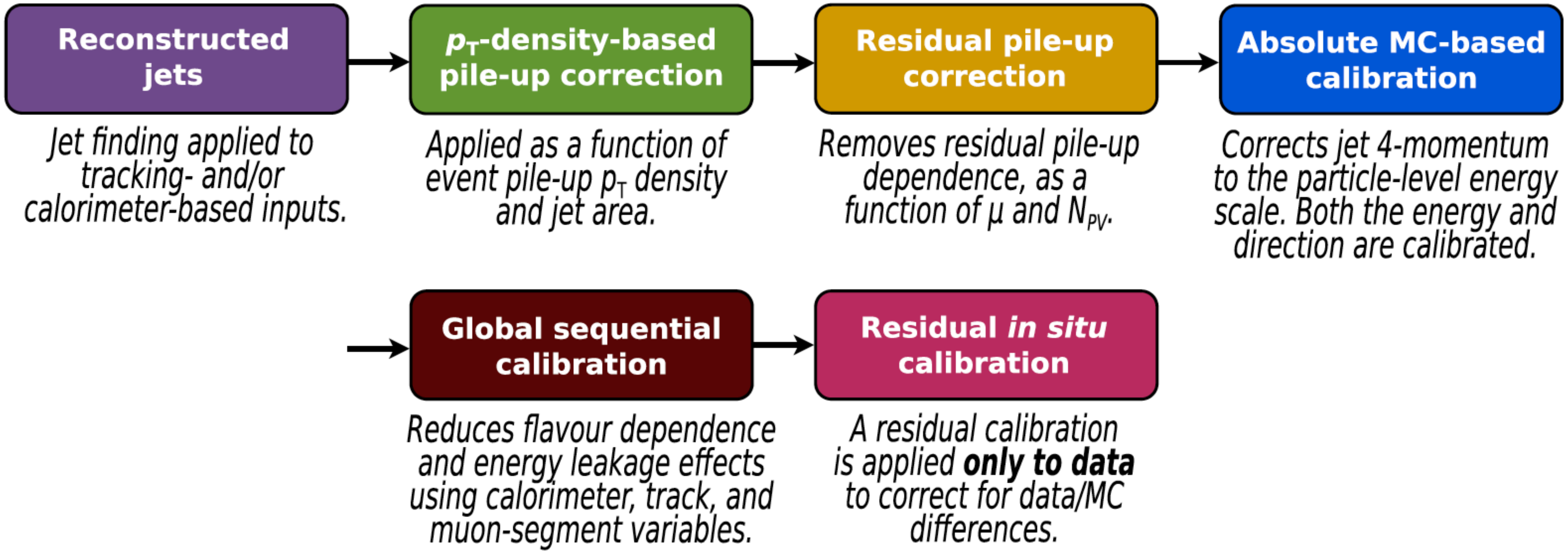


Fig. 2 Stages of jet energy scale calibrations. Each one is applied to the four-momentum of the jet

4 Top — Improvements in the Re-Analyses

arXiv:2303.15061 (ATLAS)

This paper presents a re-analysis of the 140 fb^{-1} data set at $\sqrt{s}$ = 13 TeV in the 2LSS/3L channel with the ATLAS detector and supersedes the result of Ref. [17]. Compared to the previous result that showed evidence for $t\bar{t}t\bar{t}$ production [17], this new measurement brings several improvements: an optimised selection with lower cuts on the leptons' and jets' transverse momenta; improved b-jet identification; a new data-driven estimation of the $t\bar{t}W$+jets background, one of the main backgrounds in this channel; a revised set of systematic uncertainties; an improved treatment of the $t\bar{t}t$ background and a more powerful multivariate discriminant to separate the signal from background. This paper also describes several

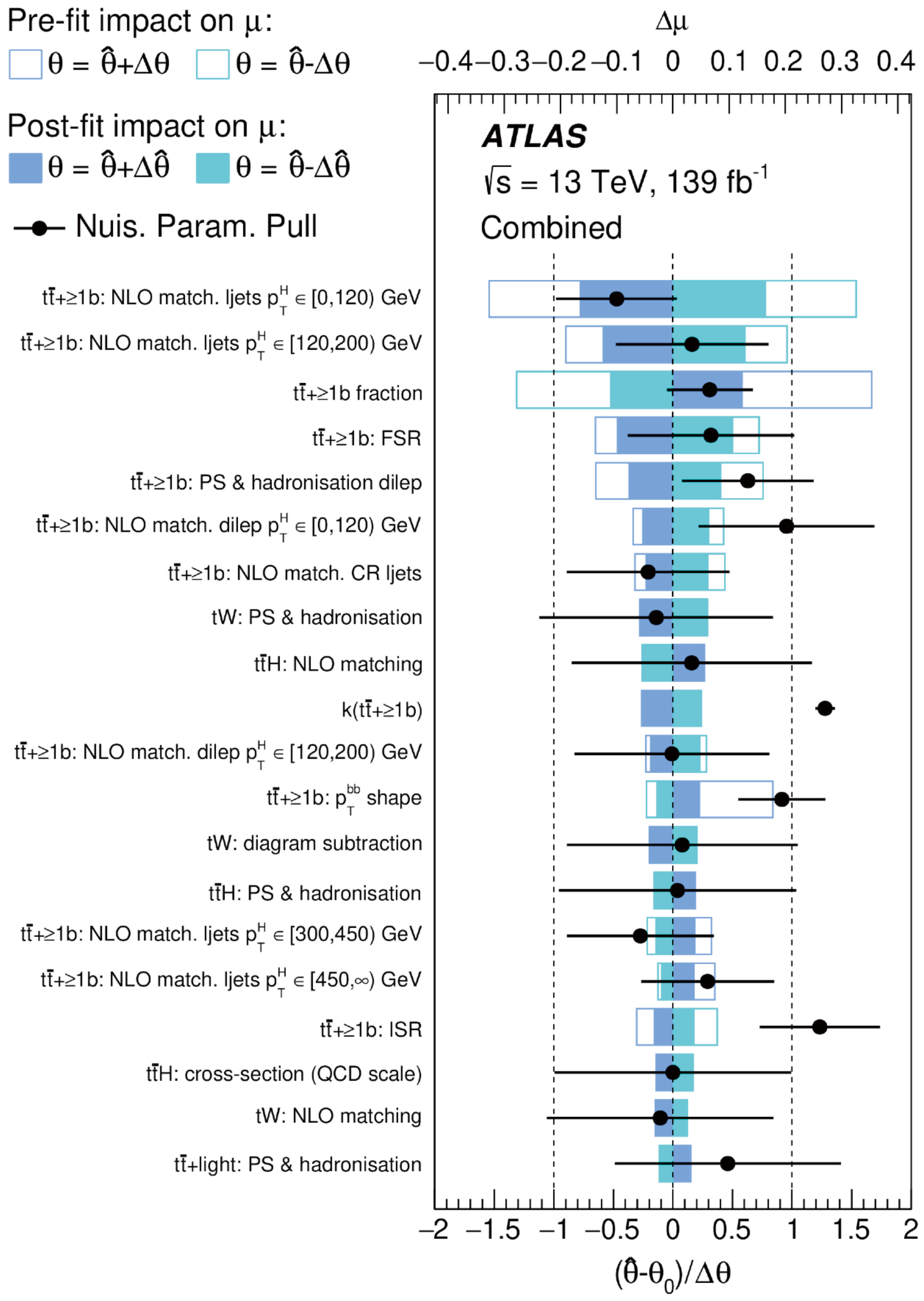
arXiv:2303.15061 (CMS)

from the same data set and found 2.6 (2.7) s.d. of observed (expected) significance. Notable improvements include the use of state-of-the-art machine learning techniques in the lepton identification, in the tagging of jets originating from the hadronization of a b quark, and in the discrimination between signal and background processes. The $\mathrm{t\bar{t}t\bar{t}}$ production cross section $\sigma(\mathrm{pp} \to \mathrm{t\bar{t}t\bar{t}})$ is extracted with a profile likelihood fit to optimized distributions that provide good signal-to-background discrimination.

ttbb — Background in the ttH(bb) Search

Uncertainty source	Description		Components
$t\bar{t}$ cross-section	$\pm 6\%$		$t\bar{t}$ + light
$t\bar{t} + \geq 1b$ normalisation	Free-floating		$t\bar{t} + \geq 1b$
$t\bar{t} + \geq 1c$ normalisation	$\pm 100\%$		$t\bar{t} + \geq 1c$
NLO matching	MADGRAPH5_AMC@NLO + PYTHIA 8 vs POWHEG BOX + PYTHIA 8		All
PS & hadronisation	POWHEG BOX + HERWIG 7 vs POWHEG BOX + PYTHIA 8		All
ISR	Varying α_s^{ISR} (PS), μ_r & μ_f (ME)	in POWHEG BOX RES + PYTHIA 8	$t\bar{t} + \geq 1b$
		in POWHEG BOX + PYTHIA 8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
FSR	Varying α_s^{FSR} (PS)	in POWHEG BOX RES + PYTHIA 8	$t\bar{t} + \geq 1b$
		in POWHEG BOX + PYTHIA 8	$t\bar{t} + \geq 1c$, $t\bar{t}$ + light
$t\bar{t} + \geq 1b$ fractions	POWHEG BOX + HERWIG 7 vs POWHEG BOX + PYTHIA 8		$t\bar{t} + 1b$, $t\bar{t} + \geq 2b$
p_T^{bb} shape	Shape mismodelling measured from data		$t\bar{t} + \geq 1b$

Table 3: Summary of the sources of systematic uncertainty for $t\bar{t}$ + jets modelling. The systematic uncertainties listed in the second section of the table are evaluated in such a way as to have no impact on the normalisation of the three $t\bar{t} + \geq 1b$, $t\bar{t} + \geq 1c$, and $t\bar{t}$ + light components in the phase-space selected in this analysis. The last column of the table indicates the $t\bar{t}$ + jets components to which a systematic uncertainty is assigned. All systematic uncertainty sources are treated as uncorrelated across the three components.

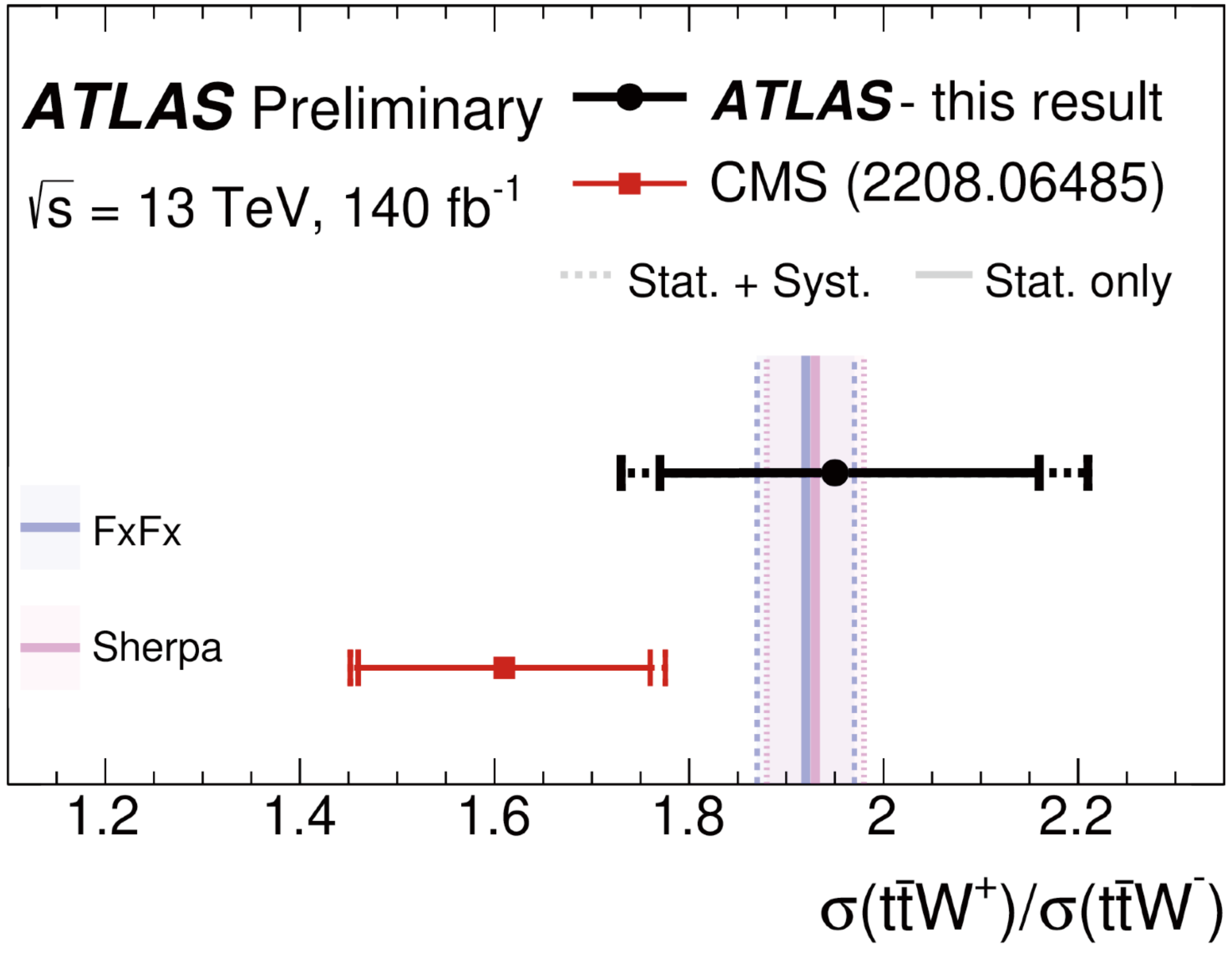


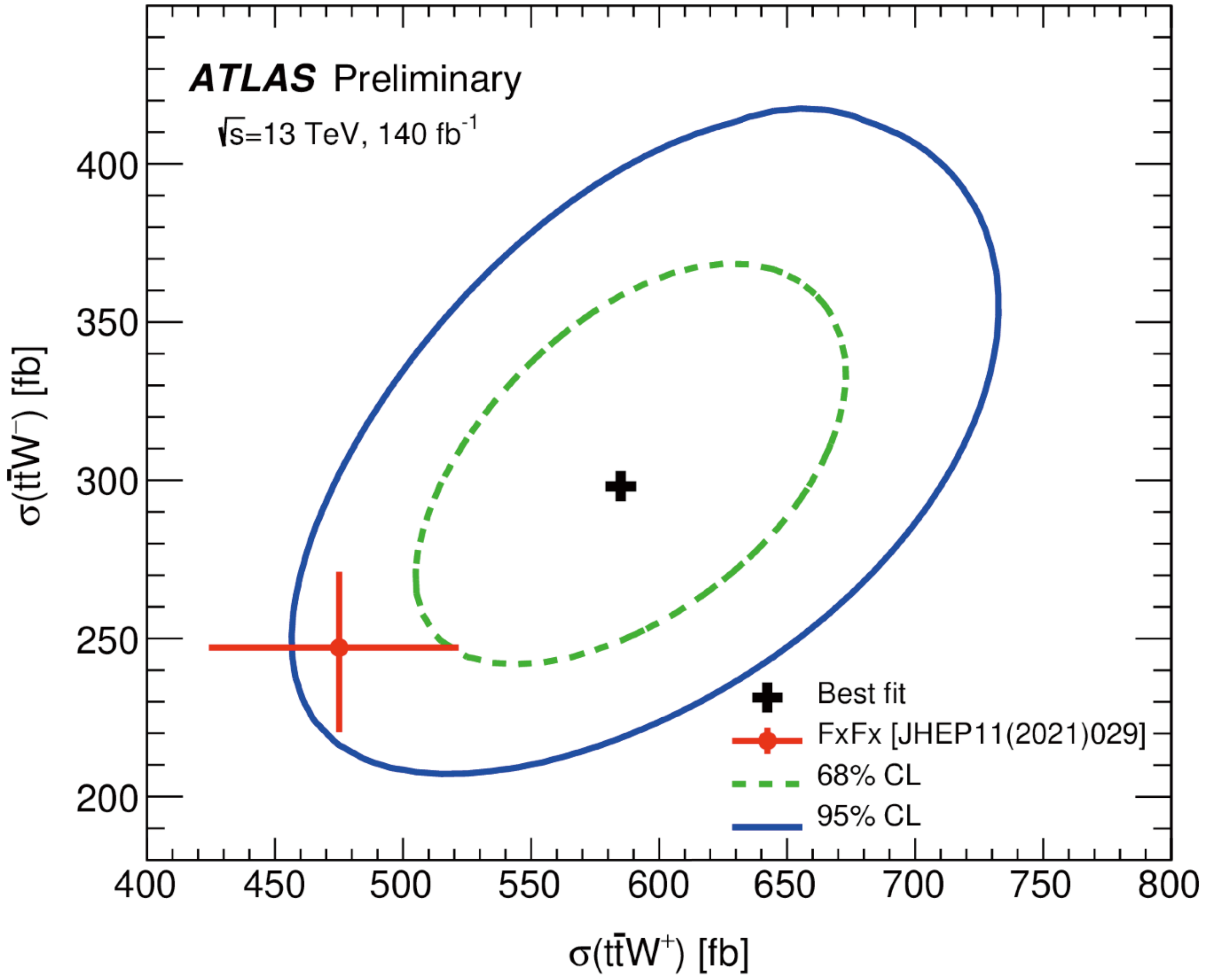
tt + ≧1b: no prior knowledge from theory or subsidiary measurements is assumed (normalisation)

https://arxiv.org/pdf/2111.06712.pdf

ttW — Recent Results (ttW$^+$ vs ttW$^-$)

ATLAS-CONF-2023-019



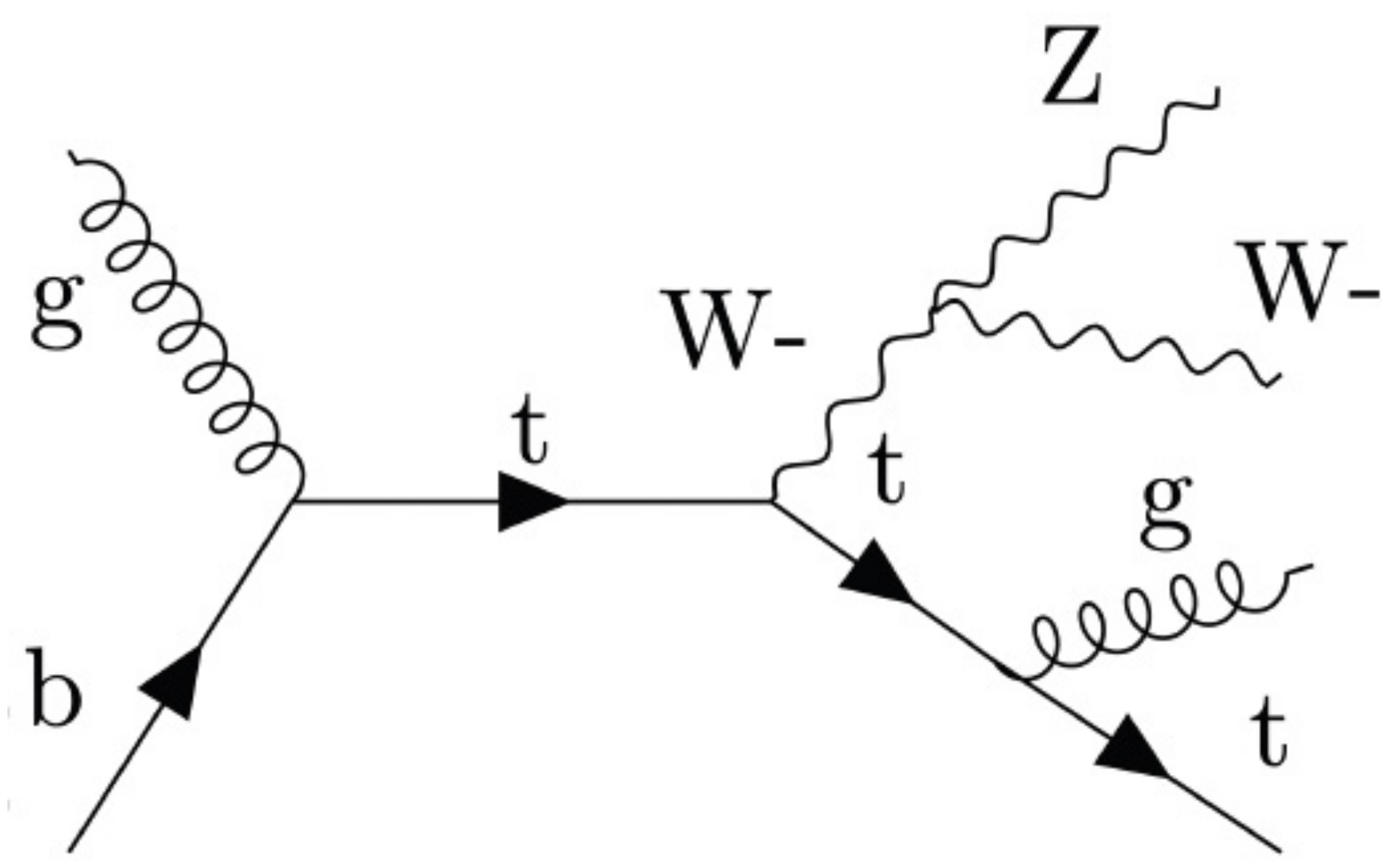


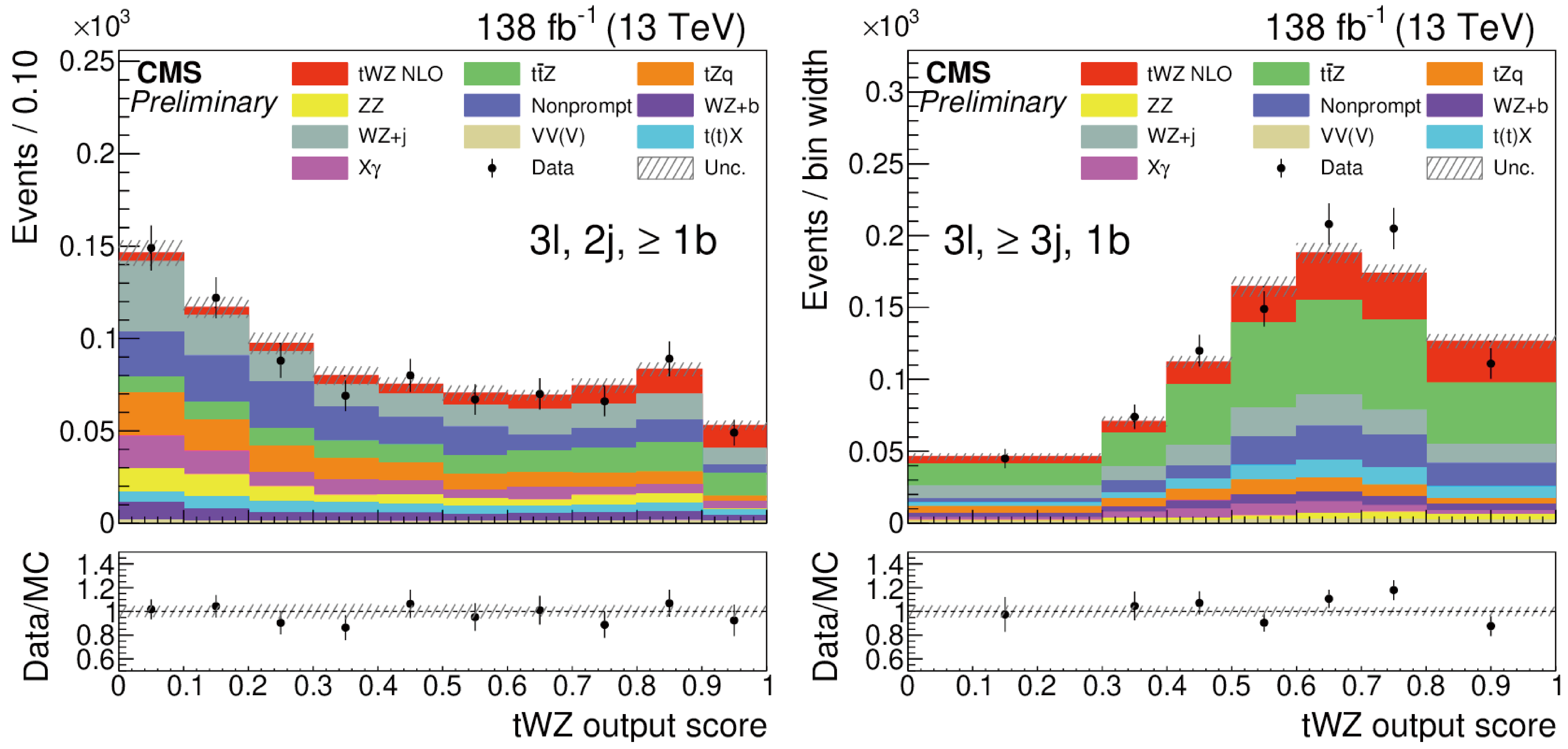
Agreement with theoretical predictions

First Evidence for tWZ

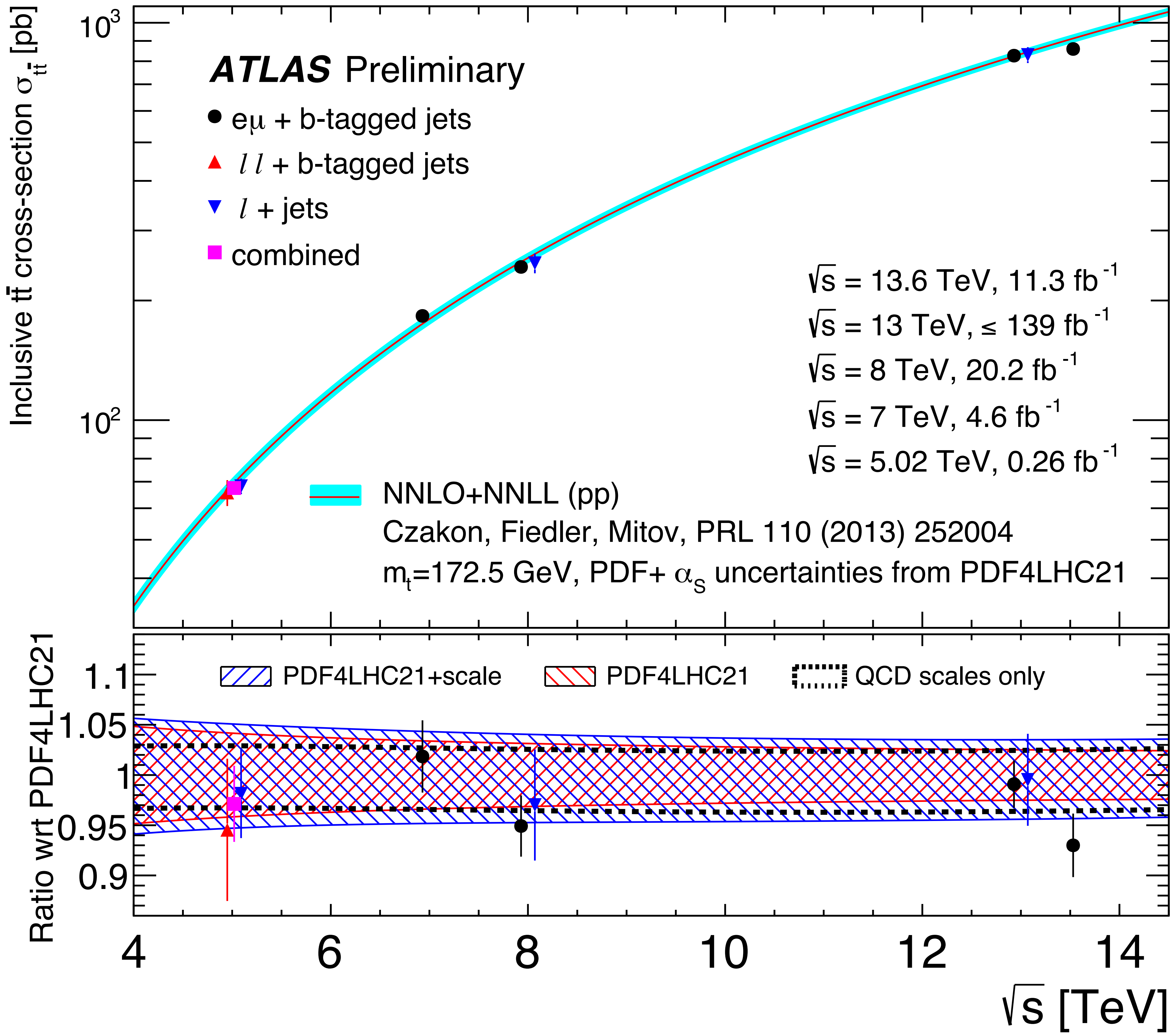
[CMS-PAS-TOP-22-008]

- Very rare process, new physics potential via modified interactions, good probe of EFT
- The measured cross section: 0.37 ± 0.05 (stat) ± 0.10 (syst) pb
- Observed (expected) significance: 3.5σ (1.4σ)





First Run 3 Top Measurements — ATLAS Plot



13.6 TeV: eμ channel

ATLAS-CONF-2023-006

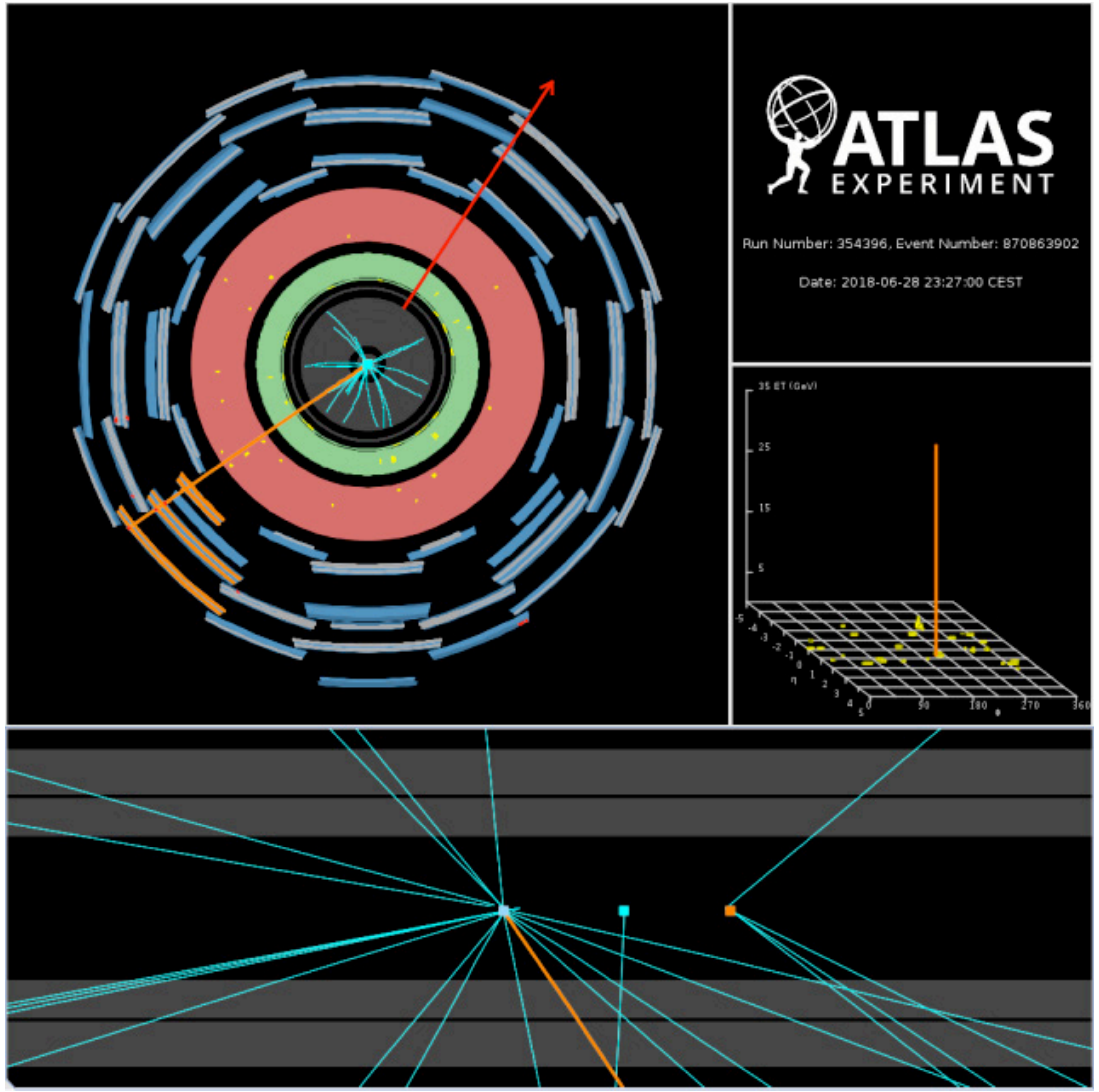
Figure 3: Comparison of the measured $t\bar{t}$ cross-sections at various centre-of-mass energies and the theory predictions using the PDF4LHC21 PDF set. The bottom panel shows the ratio of the measured values and three predictions that either contain only the uncertainties originating from the QCD scale variations (black), only the variations in the PDF uncertainties (red) or the total uncertainty in the prediction (blue).

W pT

ATLAS-CONF-2023-028

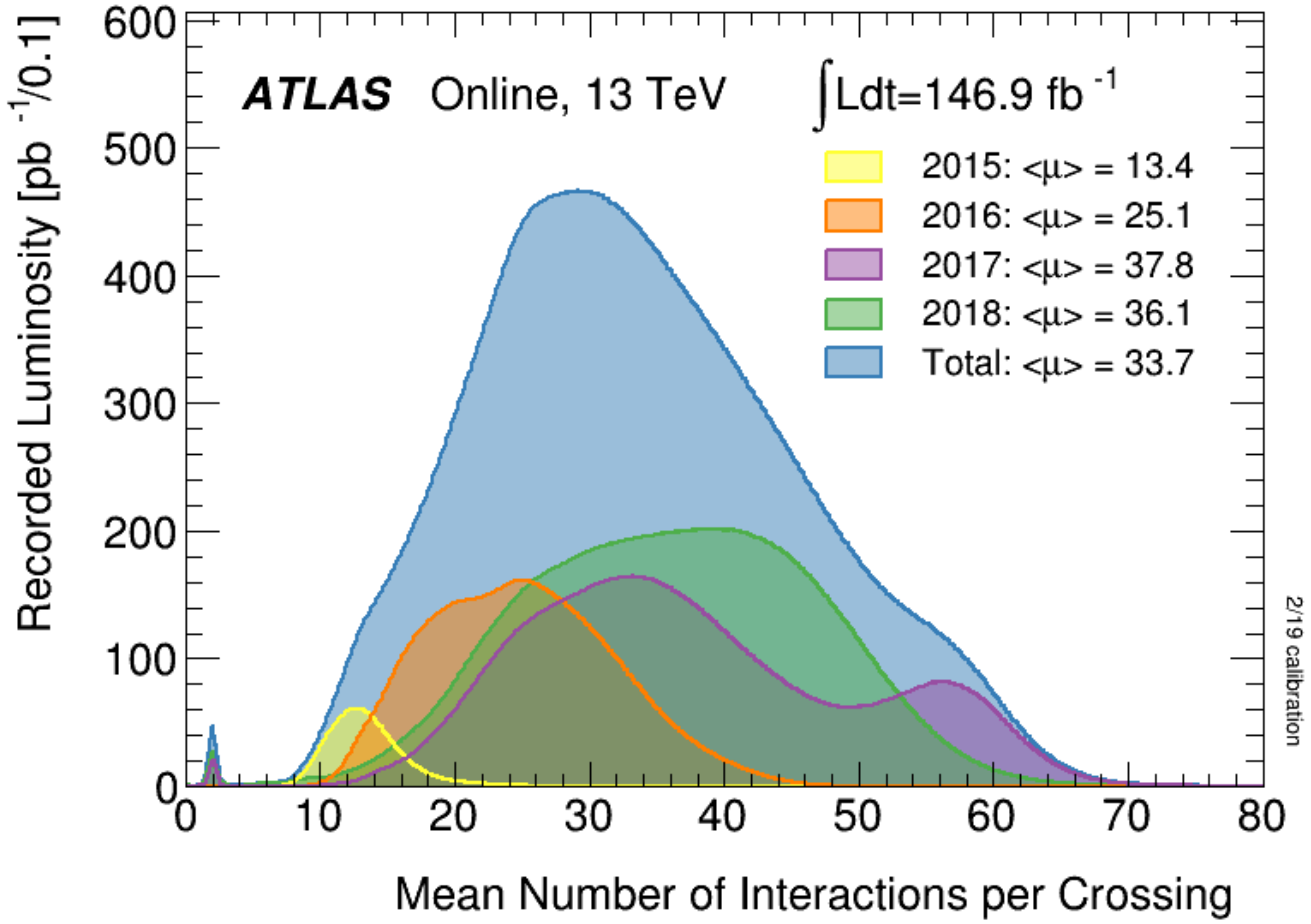
Event display for a W-boson candidate decays to one muon (orange line) and one neutrino (missing transverse momentum; red arrow).

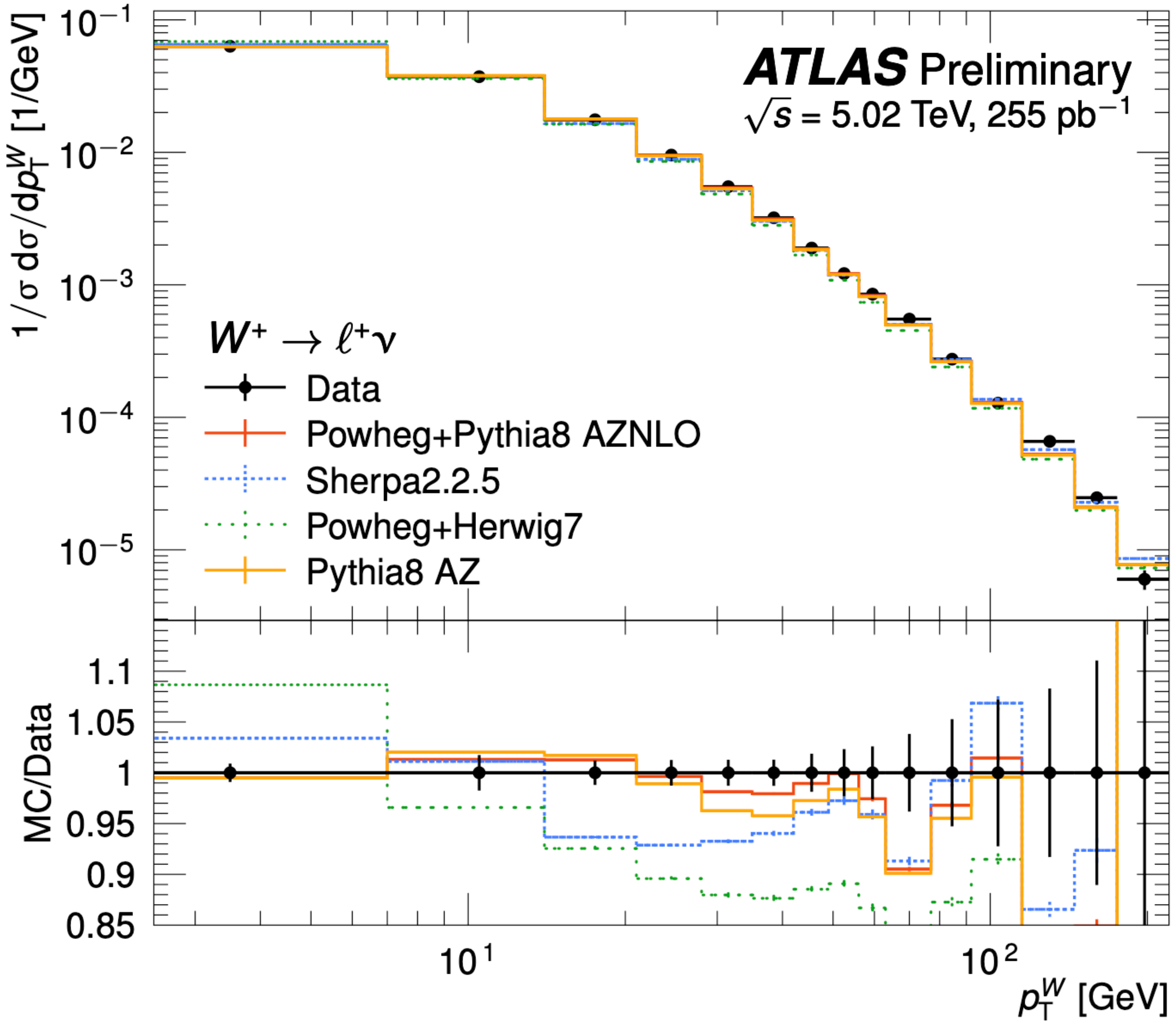
The W-boson is reconstructed in a beam crossing with two additionally reconstructed primary vertices.



W pT

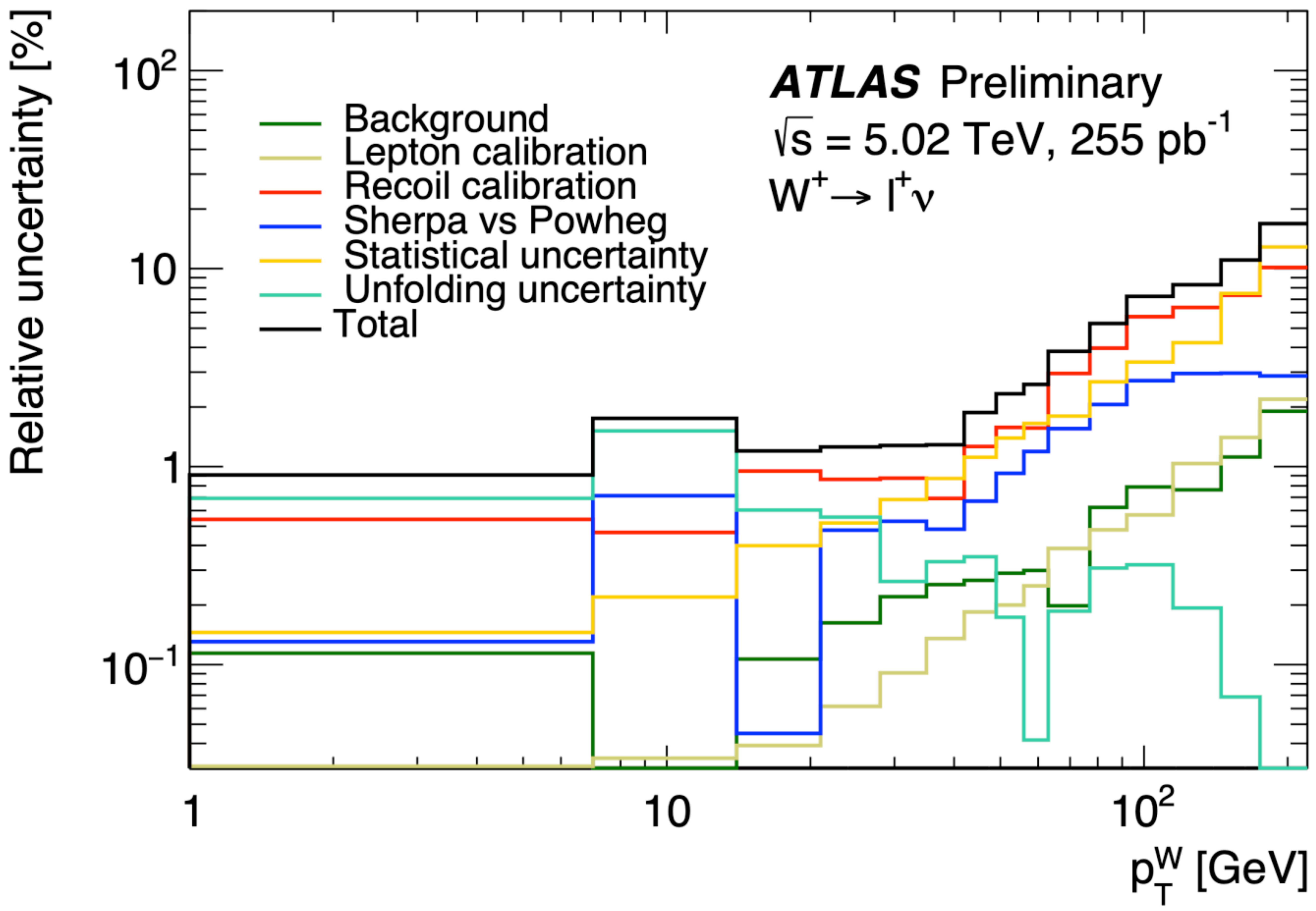
ATLAS-CONF-2023-028





The W+ boson transverse momentum spectrum at 5.02 TeV, compared to several predictions

W pT



Relative uncertainties for the W⁺ boson transverse momentum spectrum at 5.02 TeV

α_S Measurement from Z p_T ATLAS-CONF-2023-015

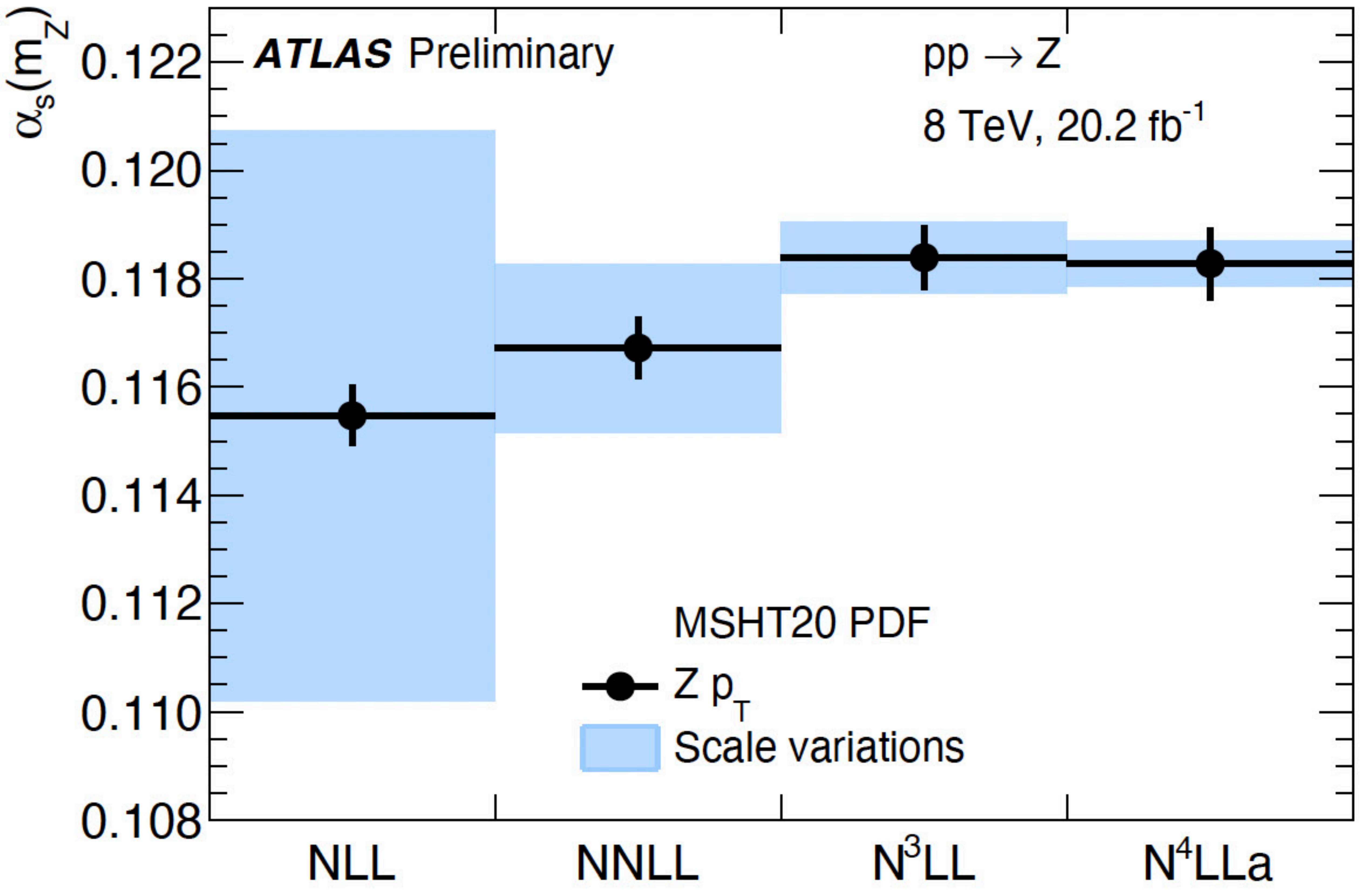
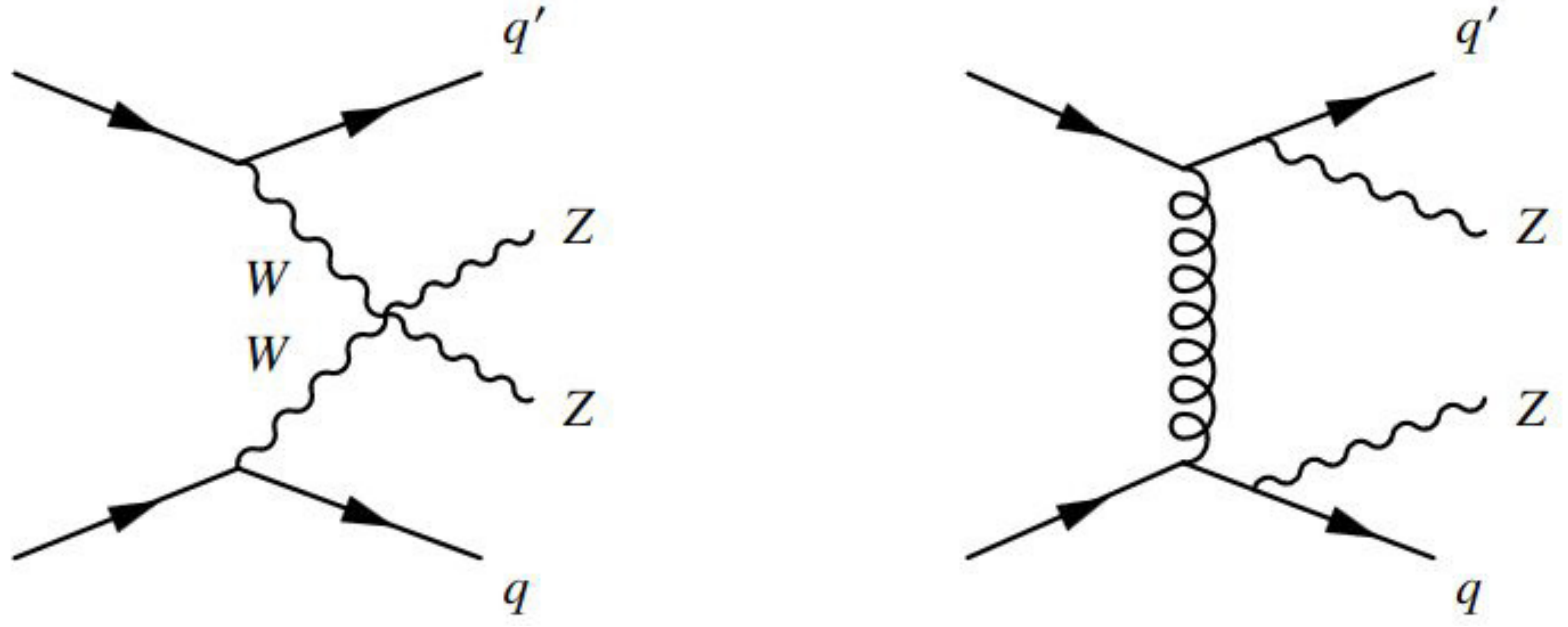


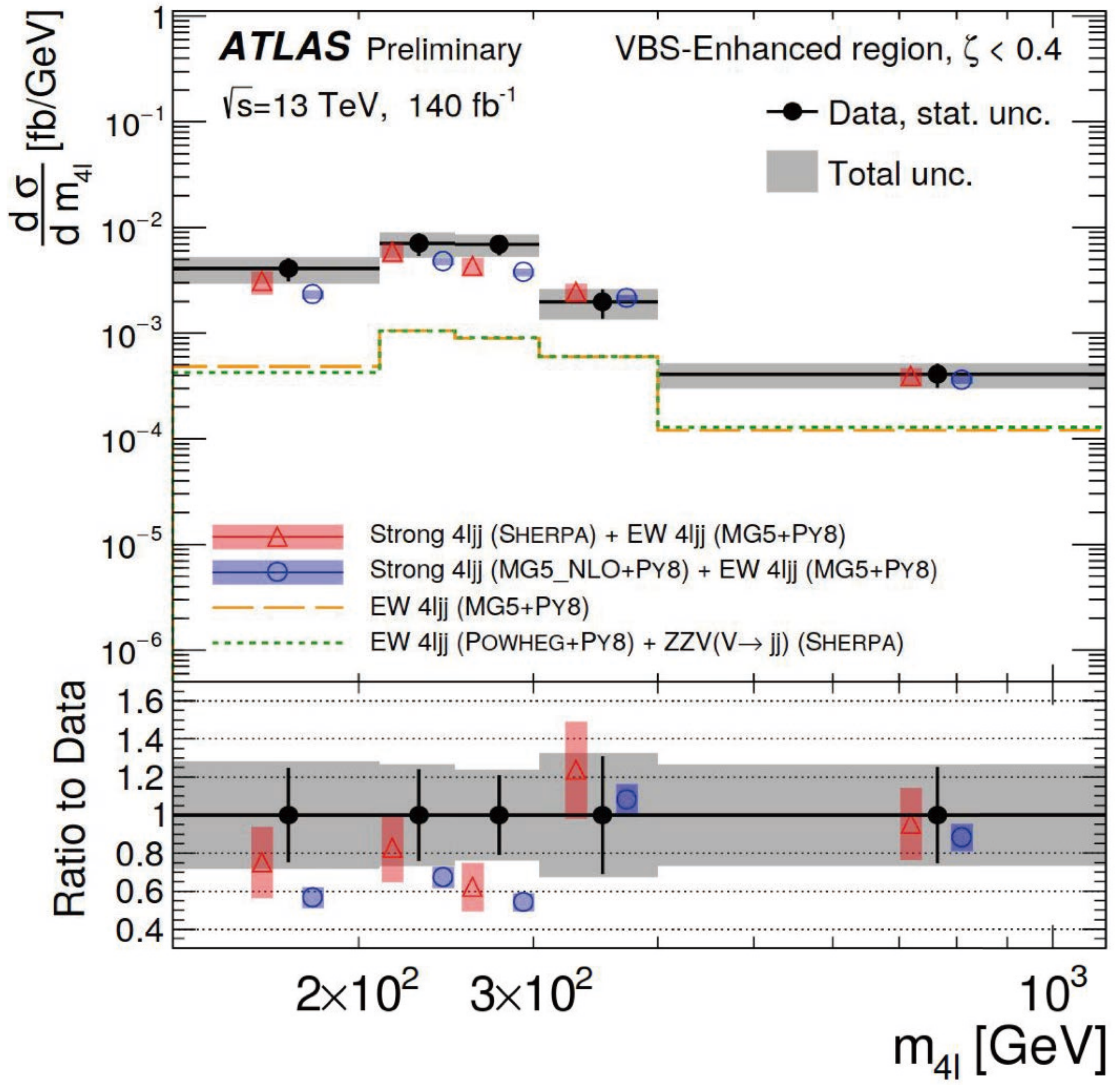
Figure 3: Determination of $\alpha_s(m_Z)$ at various different orders in the QCD perturbative expansion, using the MSHT20 PDF set. The filled area represents missing higher order uncertainties estimated through scale variations, the vertical error bars include experimental and PDF uncertainties.

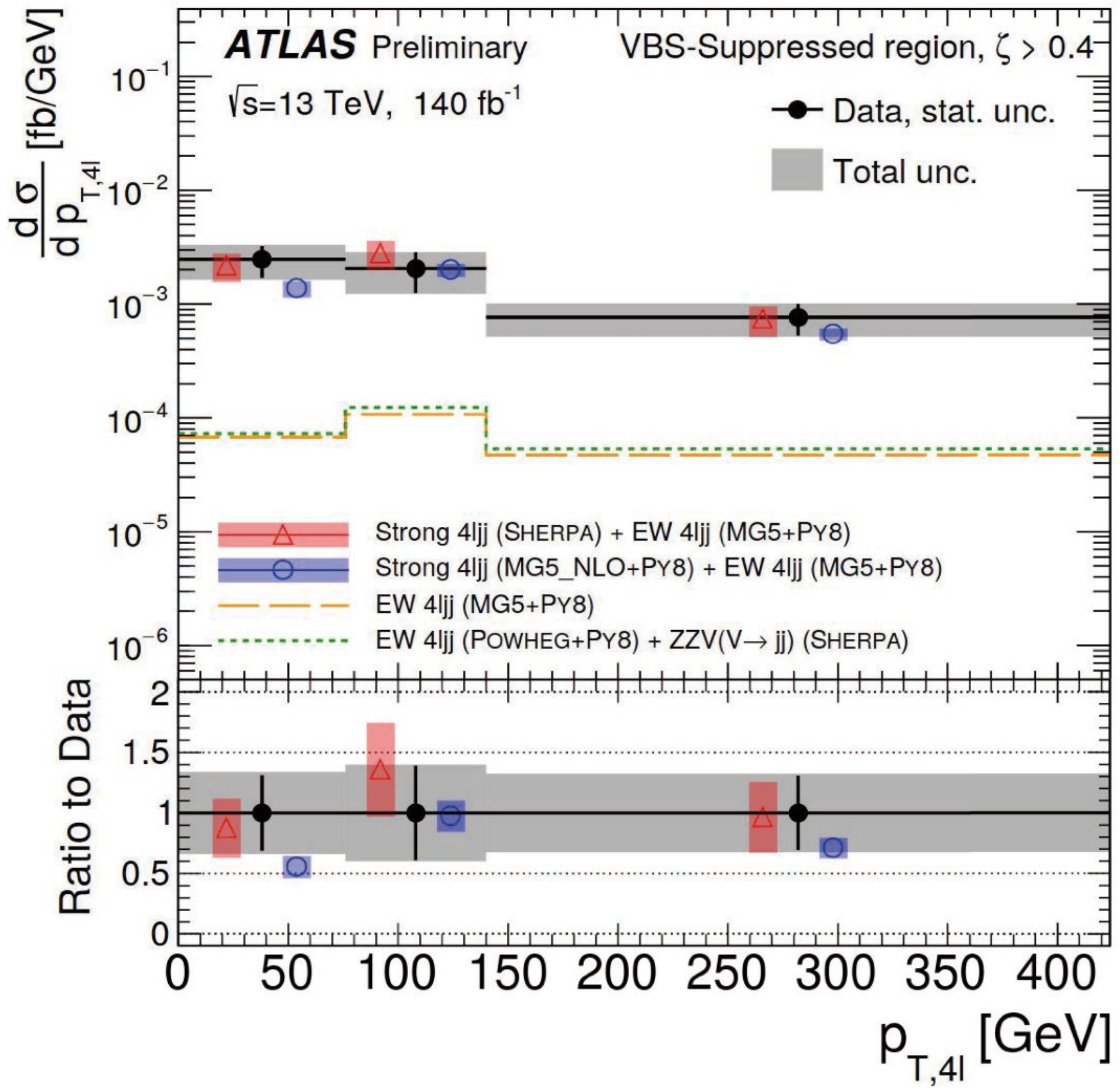
VBS — Recent Results on ZZ

arXiv:2305.19142

- Differential cross-section for both EW and inclusive productions
- Searches for dim-6 and dim-8 EFTs



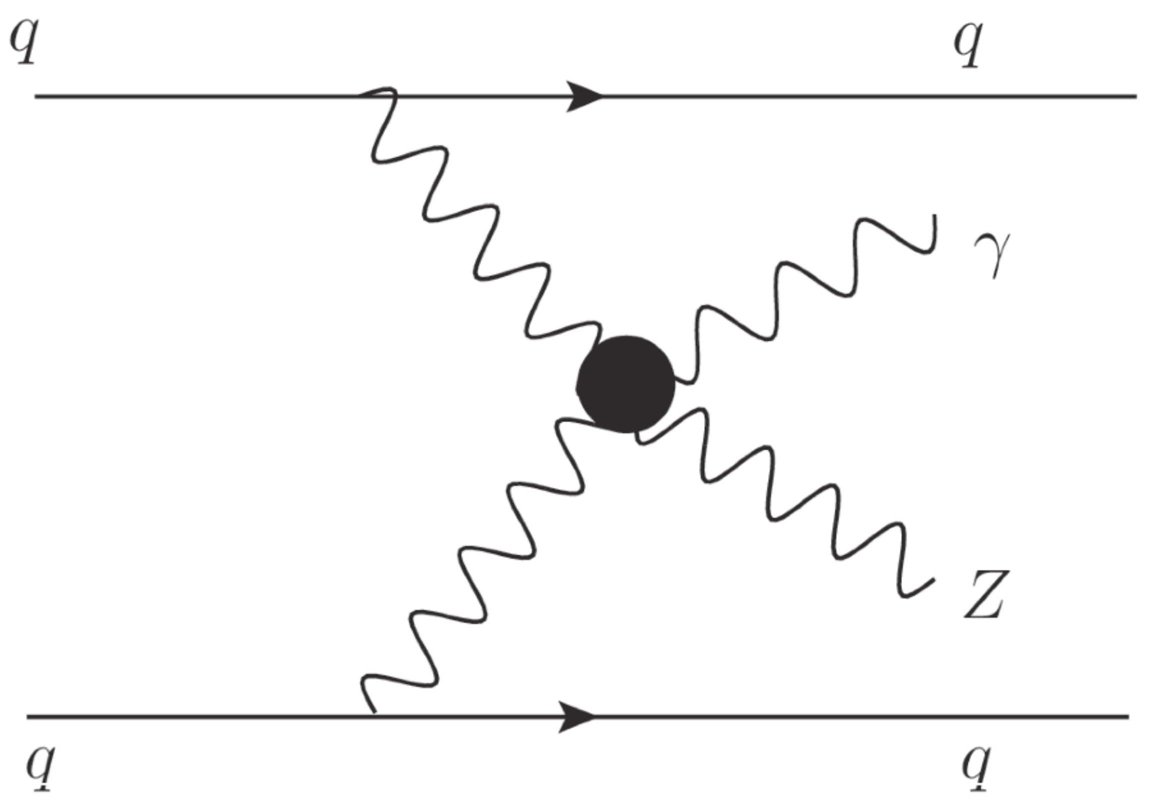


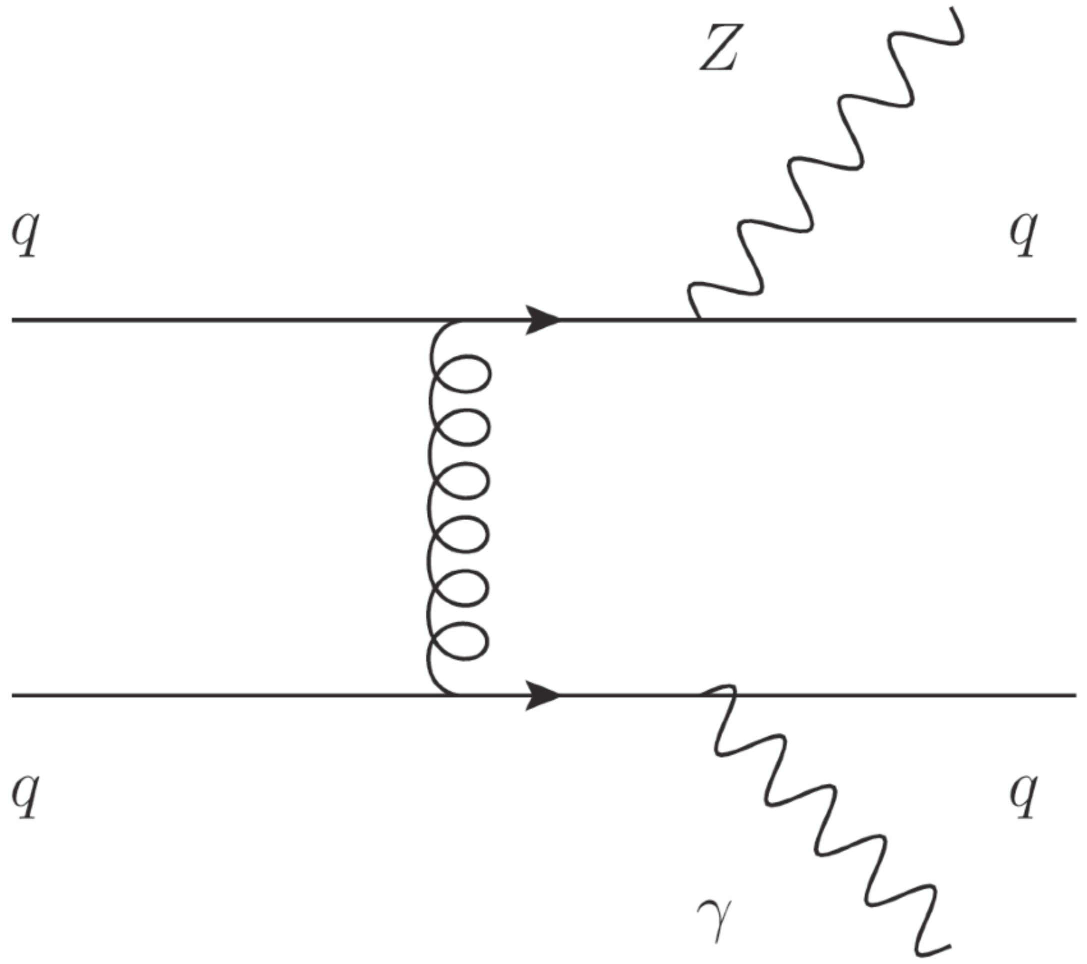


VBS — Recent Results on Zγ

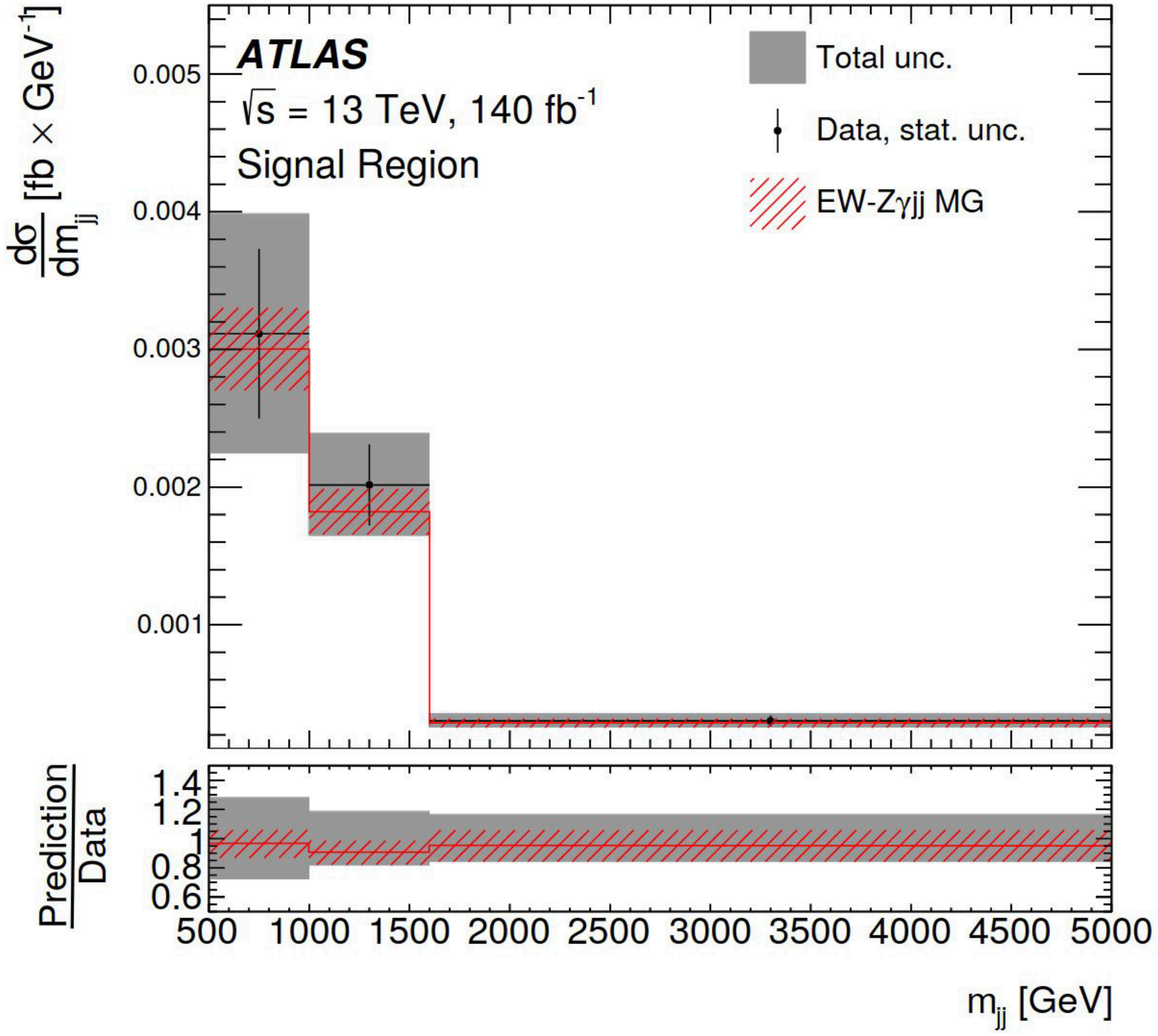
arXiv:2305.19142

Electroweak production of Zγ (Z→ee, μμ) in association with two jets, Fiducial and differential cross-sections, for both EW and EW+QCD.

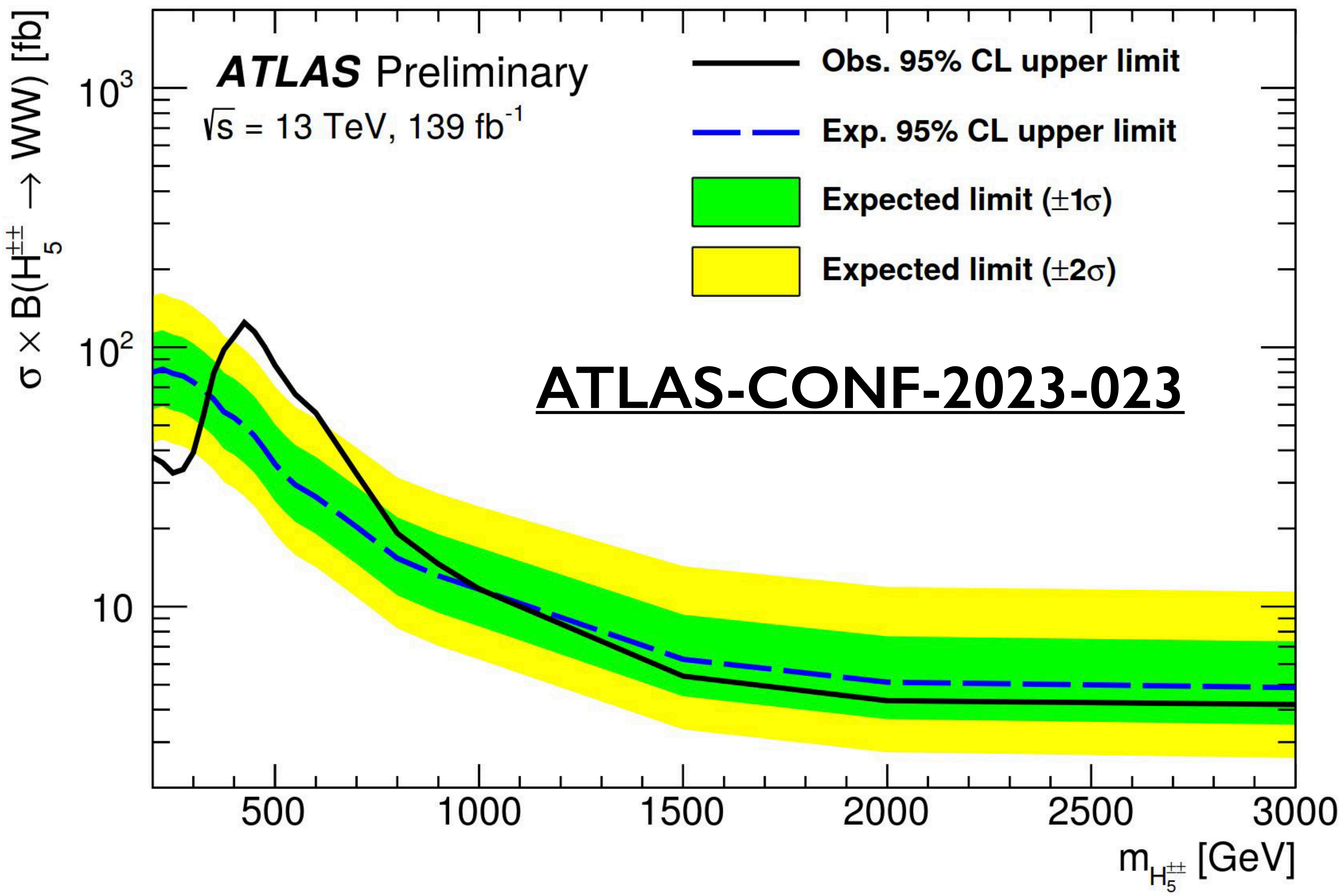


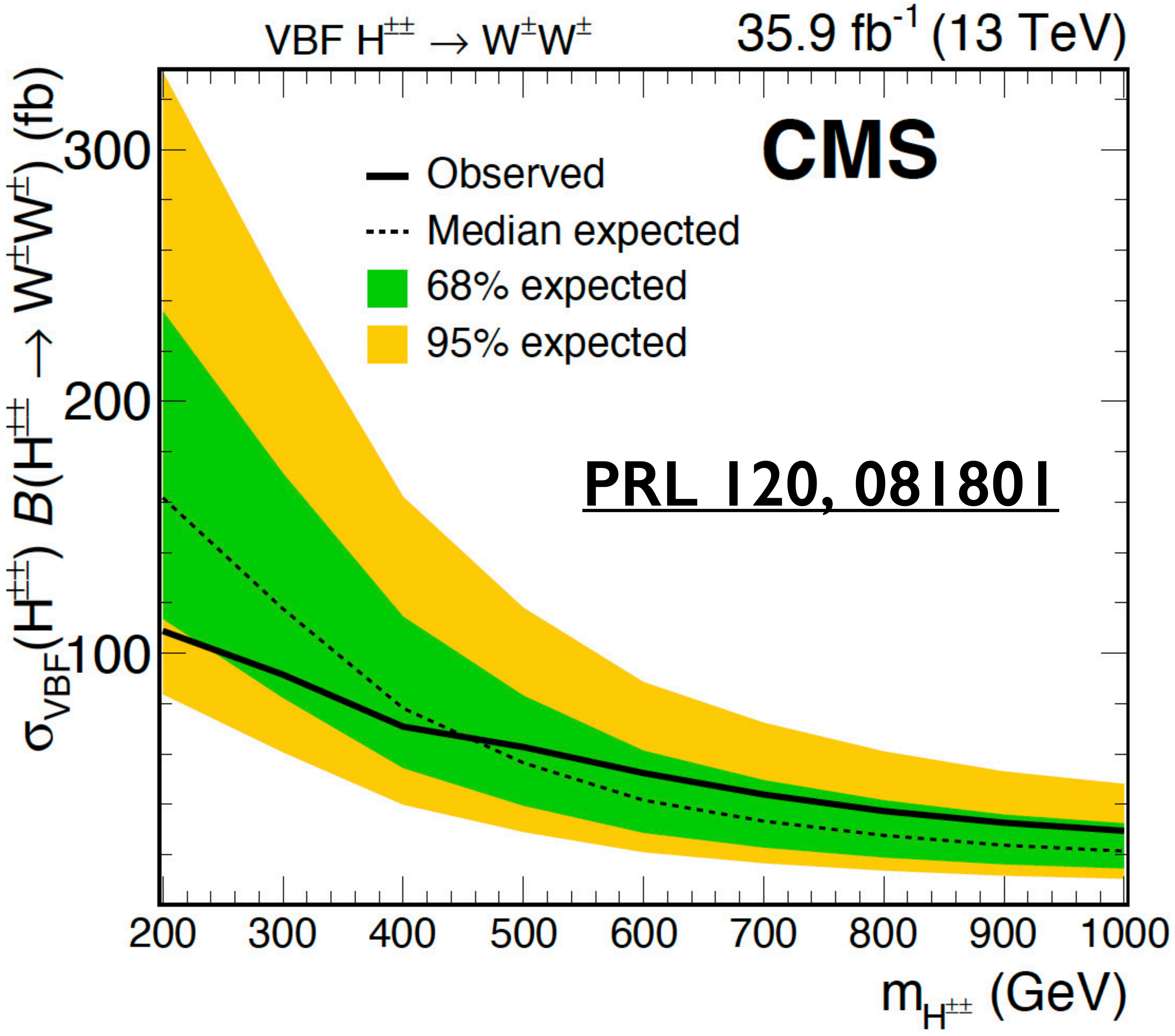


$$\mu_{\rm EW} = 1.02 \pm 0.09\,(\text{stat}) \pm 0.09\,(\text{syst}) = 1.02^{+0.13}_{-0.12}.$$



VBS — Same-Sign WW Comparison





No excess in CMS but ATLAS has slightly better sensitivity at 450 GeV