Electroweak physics - Experimental overview

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LeptonPhoton, Manchester, 10. 1. 2022

On behalf of ATLAS, CDF, CMS, D0, LHCb Collaborations

Outline

Single V-boson production

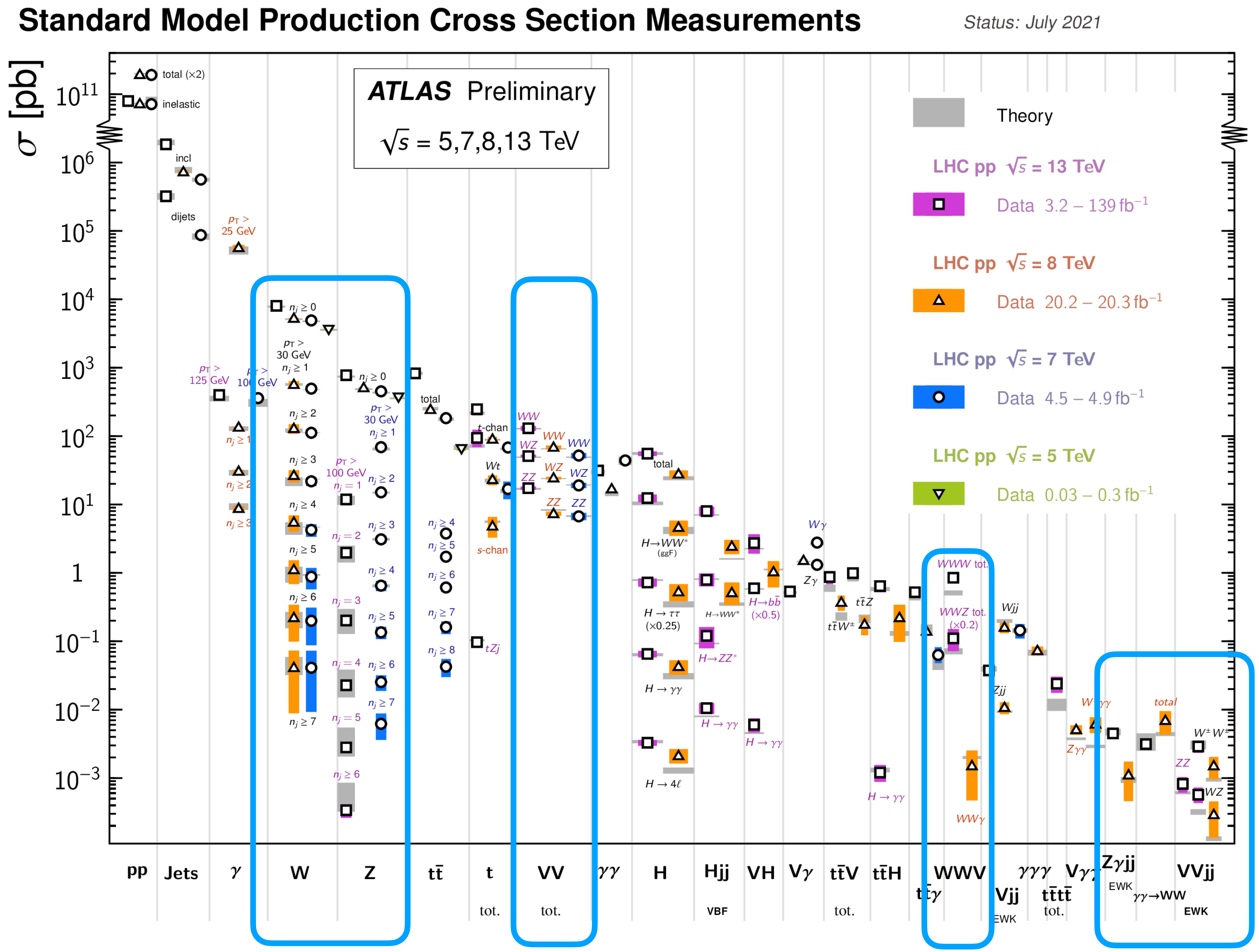
- Drell-Yan production
- Weak mixing angle
- W-mass
- Branching ratios to leptons

Diboson measurements

Electroweak production of bosons

- VBF/VBS processes

Triboson production



Drell-Yan

CMS-PAS-SMP-20-003

Drell-Yan process $q\bar{q} \to Z/\gamma^* \to \ell^+\ell^-$ is very important

- Many results from LHC experiments at different energies

Determination of electron/muon/tau/jet … performance

- Calibrating against m_Z precisely determined at LEP

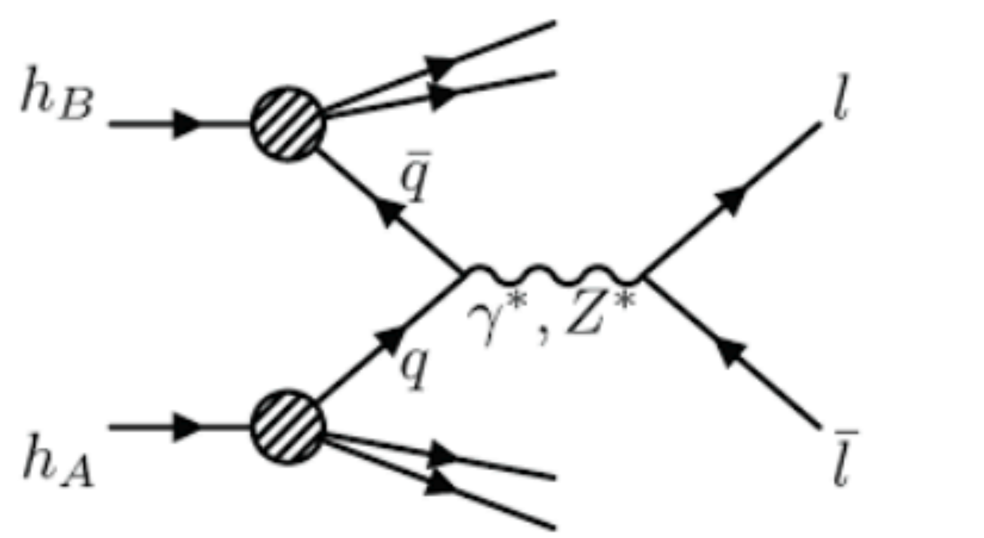
Testing theoretical predictions

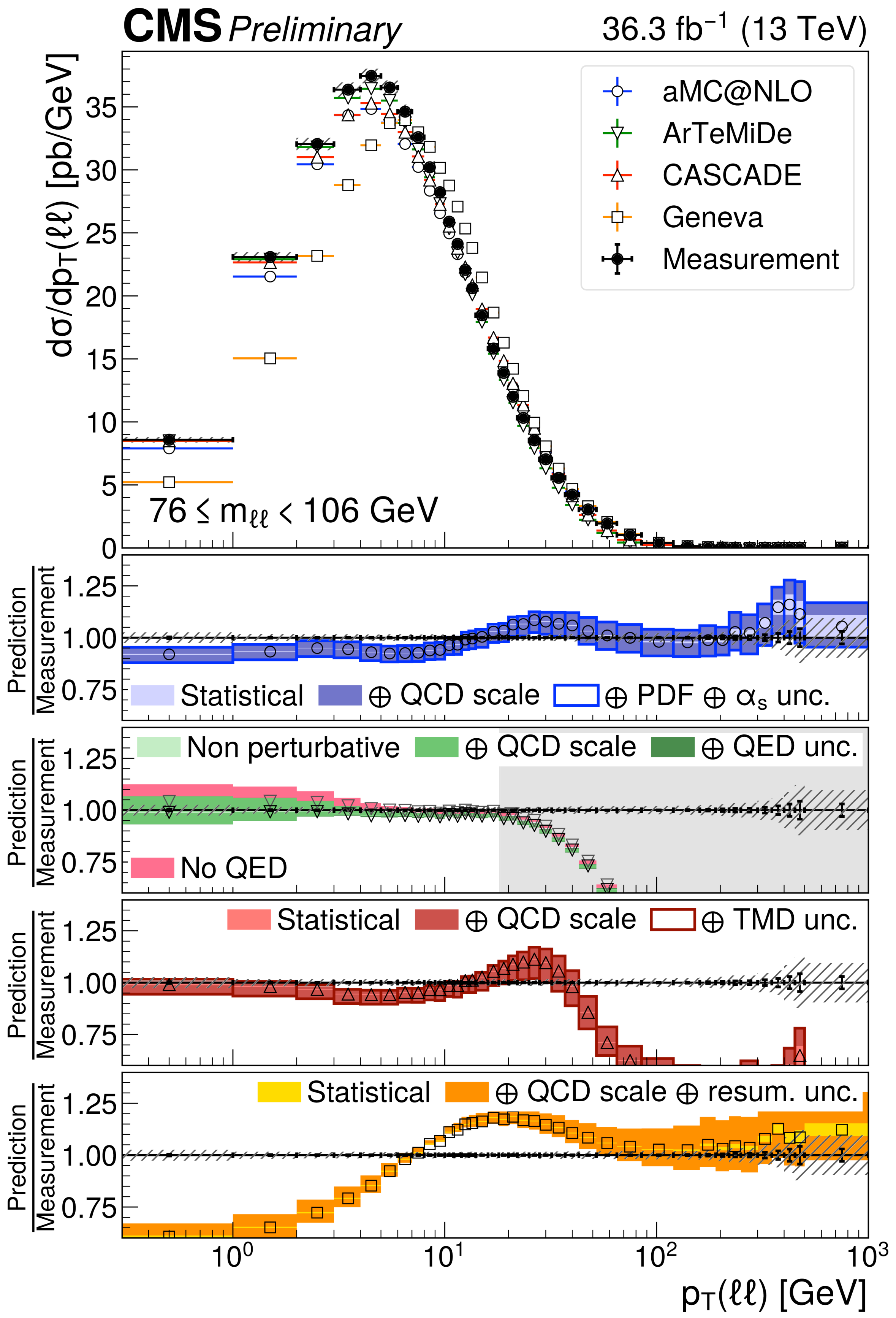
  - State-of-the art NLO/NNLO QCD calculations and parton showers
  - Soft-gluon resummation, PDF, extraction of EW parameters

CMS measurement of transverse lepton-pair momentum

- On-shell as well as off-shell productions for m_{ll}>50 GeV
- Inclusive and n_{jet}≥1, ratios normalised to Z-peak
- sensitivity to soft QCD initial state radiation at low-p_T, compared to TMD parton showers and hadronization predictions

Drell-Yan process



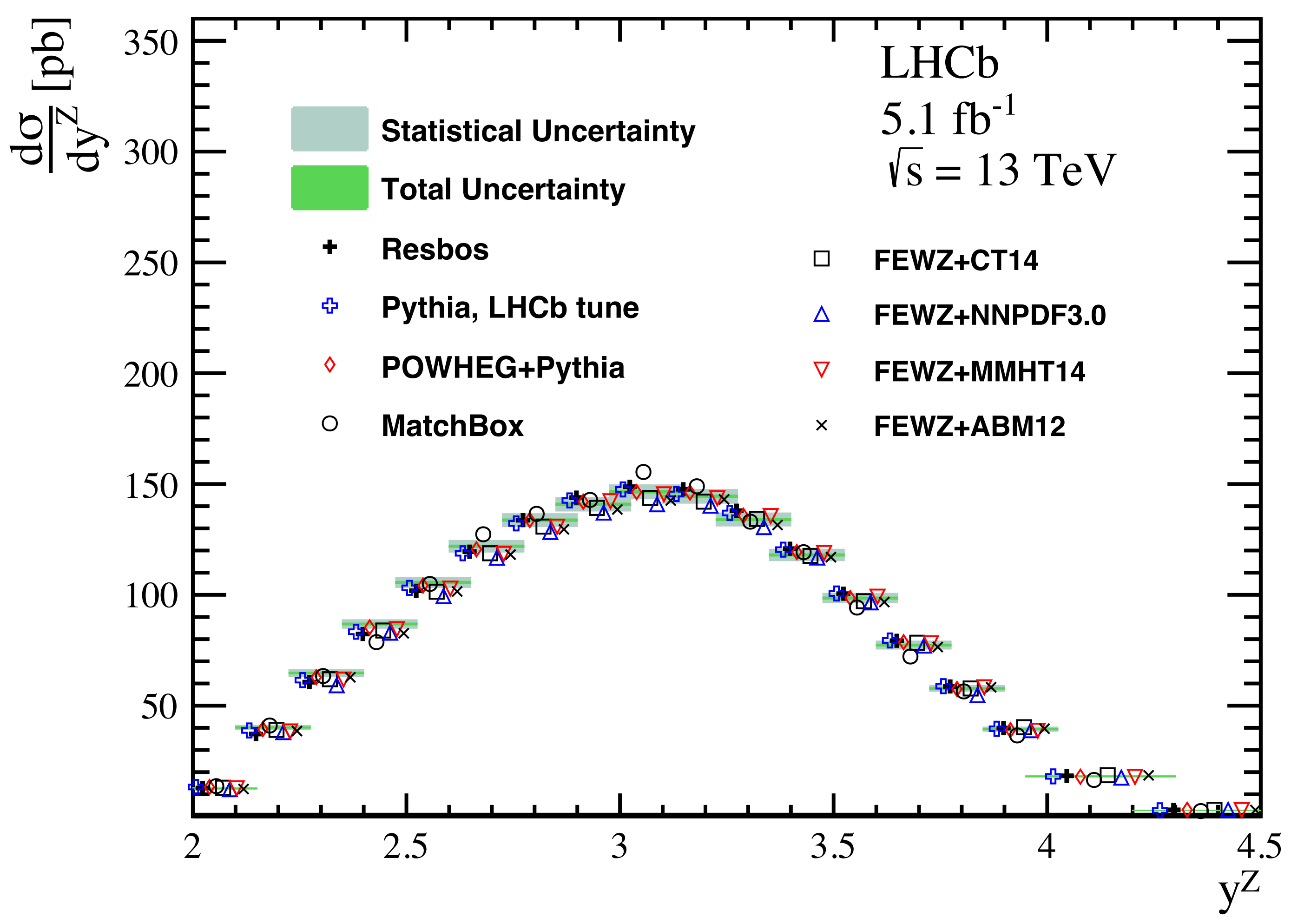


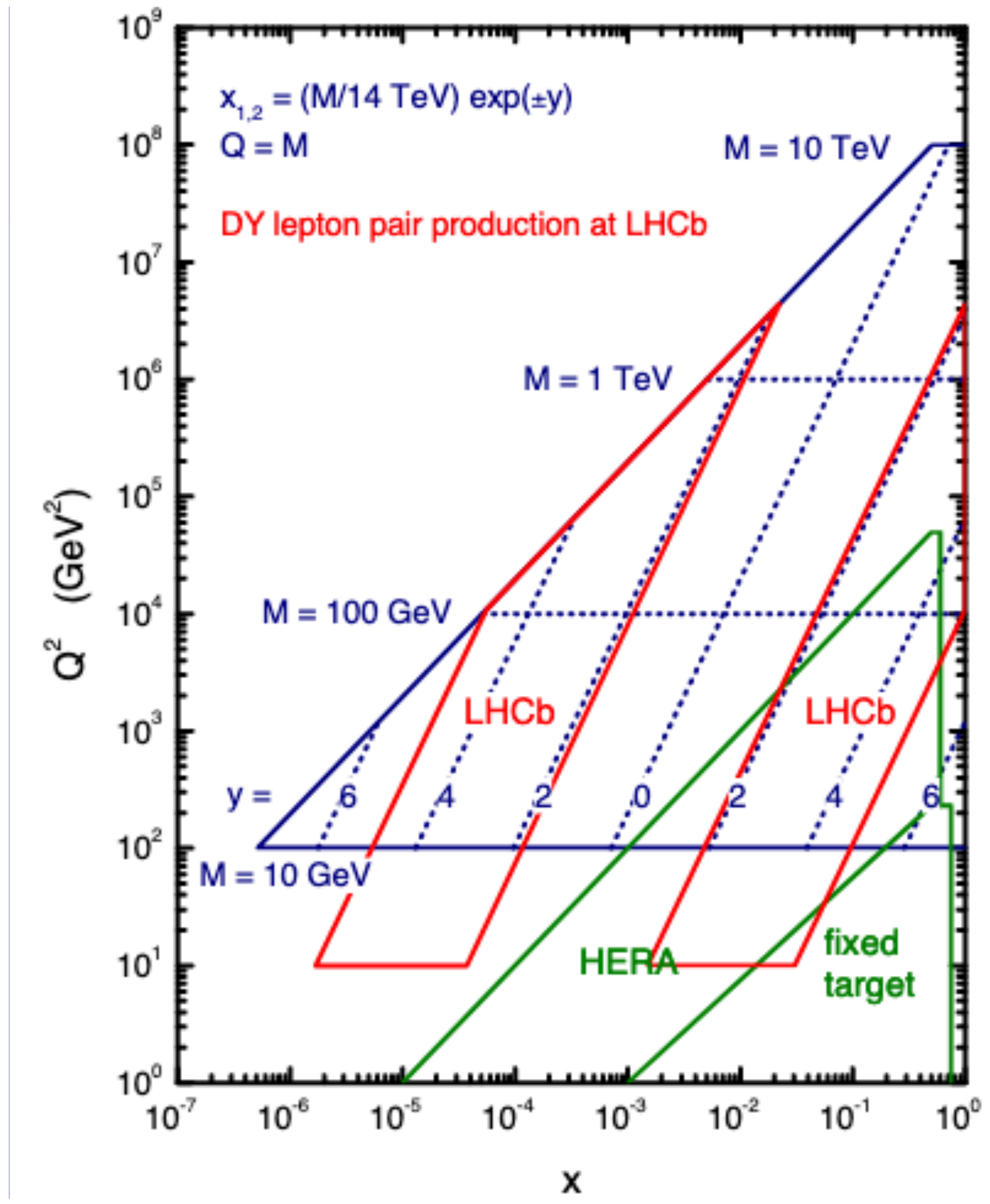
Forward Z boson production

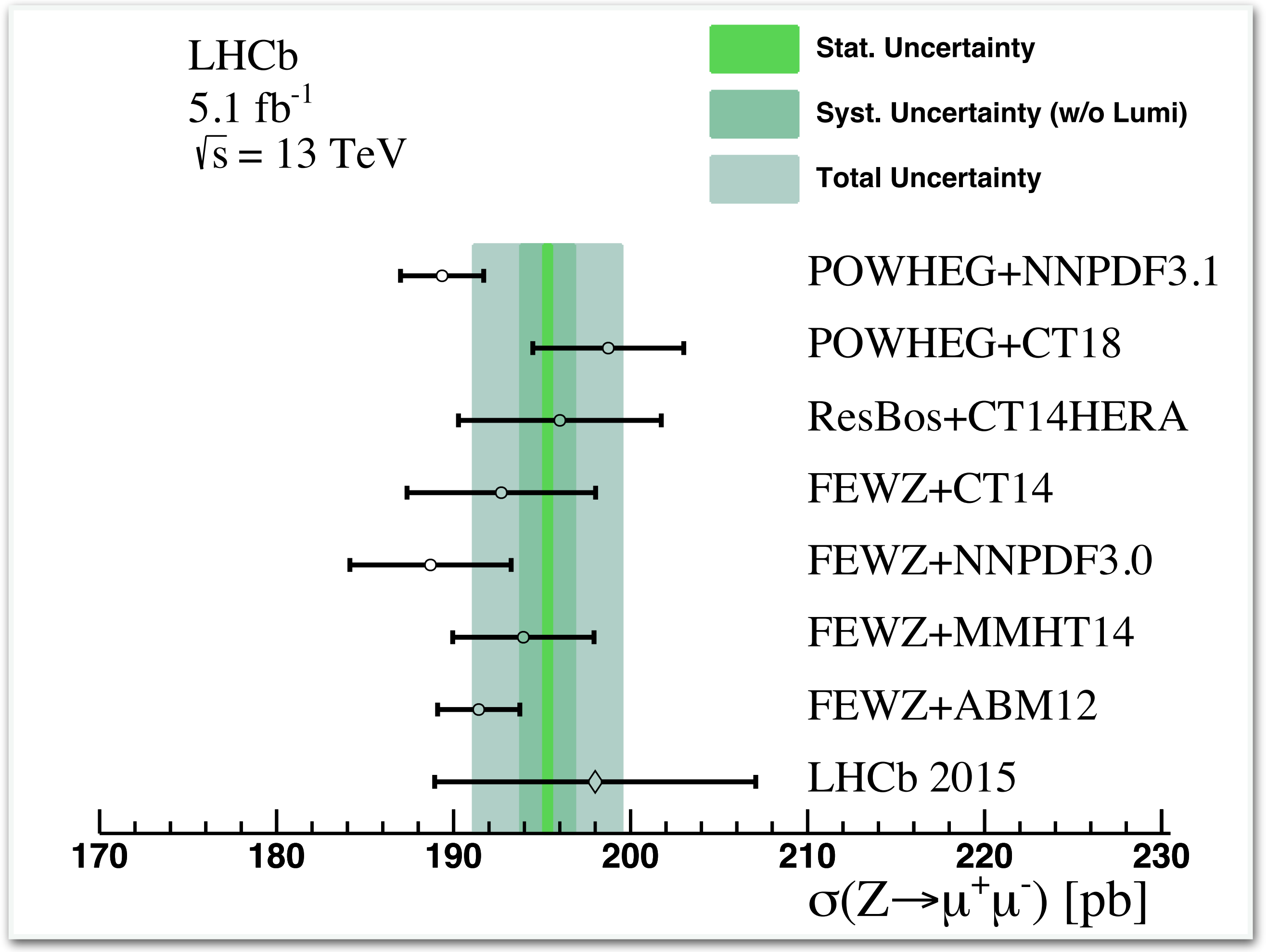
arXiv:2112.07458

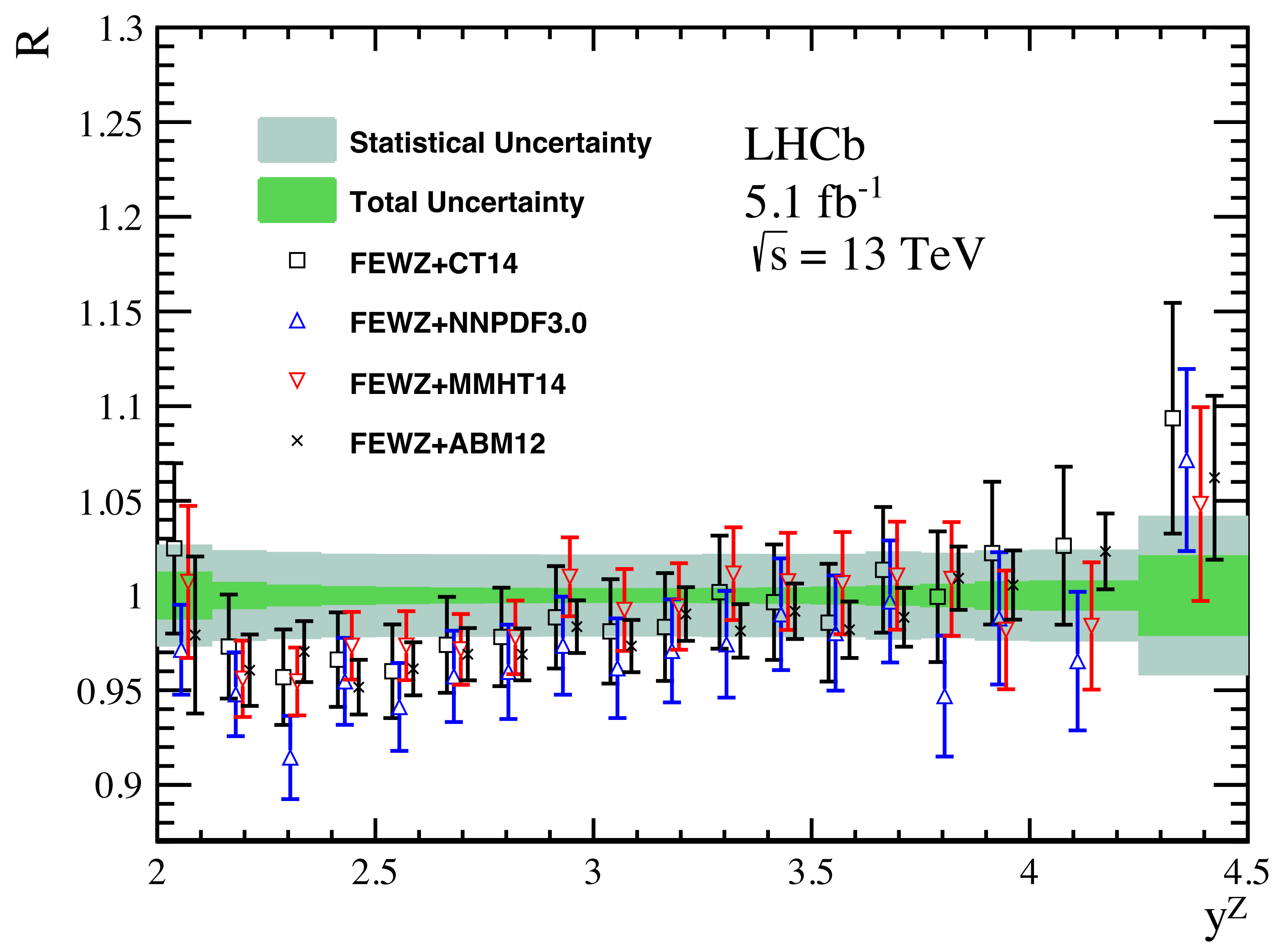
LHCb forward muons 2.0 < η < 4.5

- Unique complementary phase-space to other LHC experiments
- Transverse momentum and ϕ*
- Good modelling in general, but potential to constrain PDF at low and high-x









FB asymmetry and effective weak mixing angle

Forward-backward asymmetry in $q\bar{q} \to Z/\gamma* \to \ell^+\ell^-$ is sensitive to weak mixing angle

- $\sin^2\theta^f_{\text{eff}}$ determines relative strengths of vector and axial-vector couplings of Z to fermions, $M^2_W = M^2_Z \cos^2\theta^f_{\text{eff}}$
- Drell-Yan differential cross section, $\theta*$ - polar angle of ℓ^- in Collins-Soper frame

$$\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta*} = A((1+\cos^2\theta*) + A_4\cos\theta*)$$

- Experimentally measured $A_{\text{FB}} \equiv \frac{N_F - N_B}{N_F + N_B} = \frac{3}{8}A_4$

Different approaches by ATLAS and CMS to extract $\sin^2\theta^f_{\text{eff}}$

- ATLAS: from A_4 coefficients through effective linear dependence
- CMS: fit of $A_{FB}(m_{ll},y)$ using predictions obtained for different $\sin^2\theta^f_{\text{eff}}$

Status of $\sin^2 \theta^f_{\text{eff}}$

ATLAS: ATLAS-CONF-2018-037
CMS: EPJC 78 (2018) 701
LHCb: JHEP 1511(2015) 190
Tev: PRD 97 (2018) 112007

Current LHC measurements of $\sin^2 \theta^f_{\text{eff}}$ based only on Run 1 data

- Uncertainties dominated by PDFs and limited data sample
- ATLAS more precise than CMS thanks to additional category with one forward electron (only calorimeter measurement) which helps to constrain PDFs

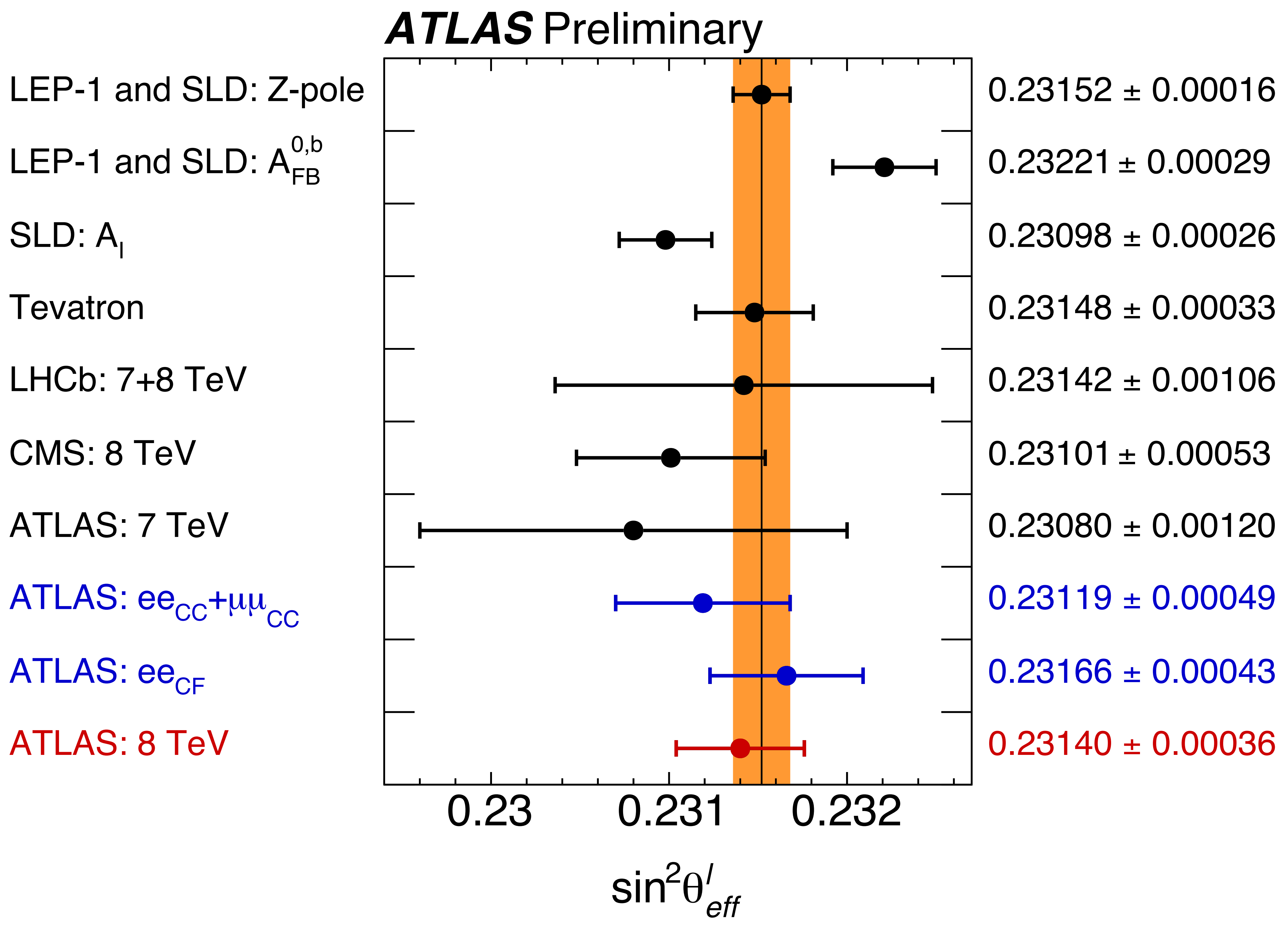
ATLAS (Run 1)

$\sin^2 \theta^f_{\text{eff}}$=0.23140 ± 0.00021 (stat) ± 0.00016 (syst) ± 0.00024 (PDF)

CMS (Run 1)

$\sin^2 \theta^f_{\text{eff}}$=0.23101 ± 0.00036 (stat) ± 0.00018 (syst) ± 0.00016 (theory) ± 0.00031 (PDF)

Tevatron combination is the most precise result from hadron collider



Expect improvement with Run 2 data and PDF using LHC Run 2 measurements

Measuring W mass at hadron colliders

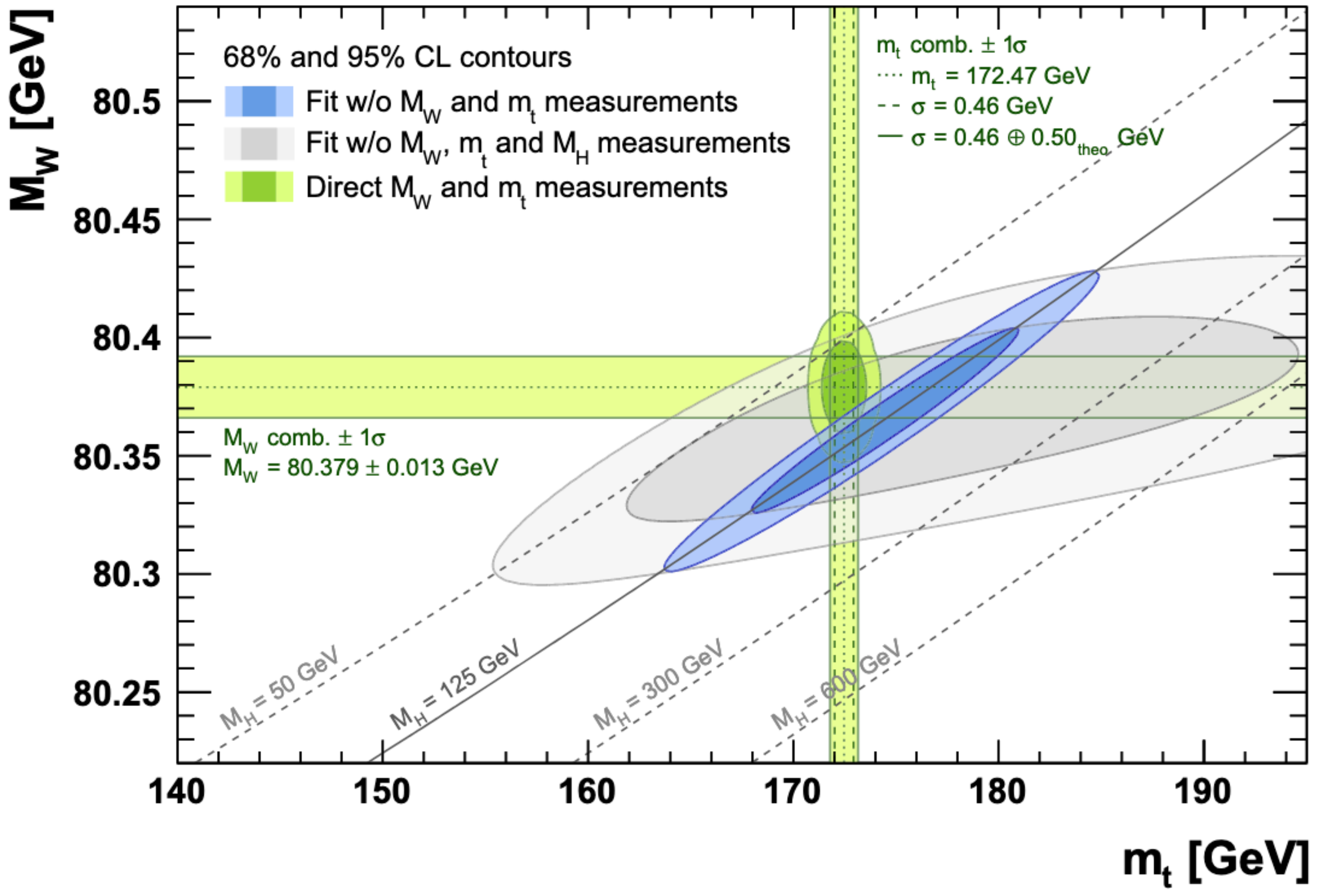
W boson mass is a fundamental parameter of SM

- Receives loop corrections (mainly higgs/top/BSM)

$$M_W^2\left(1-\frac{M_W^2}{M_Z^2}\right)=\frac{\pi\alpha}{\sqrt{2}G_F}(1+\Delta r)$$

Phys. Rev. D 42, 152

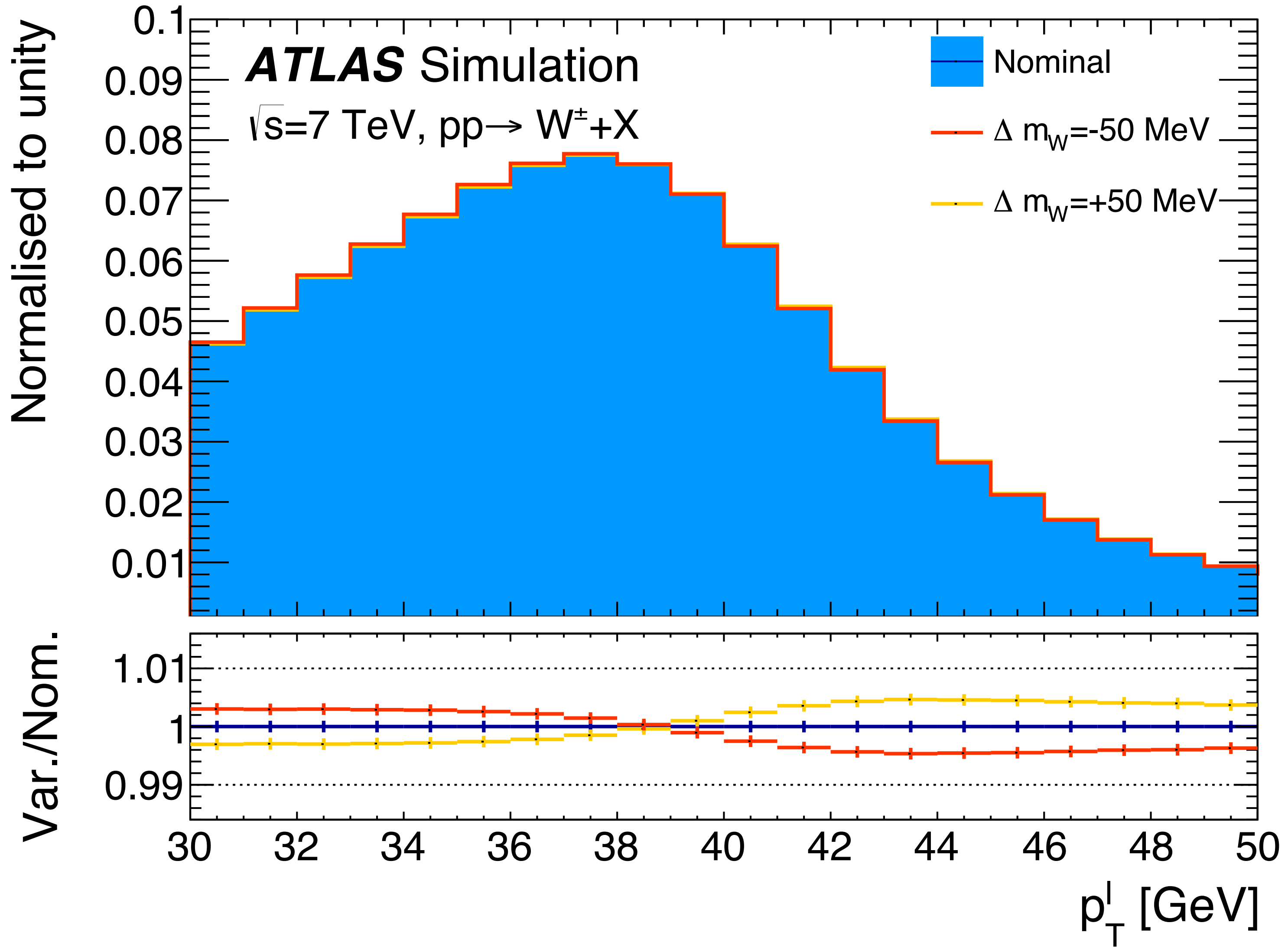
- Indirect global fit to EW parameters: 7 MeV uncertainty
- PDG average has precision of 12 MeV (twice larger than global fit)



EPJC 78 (2018) 675

Standard approach is to fit templates to p_T and m_T distributions in data (Jacobian peak $m_W/2$ or m_W)

- $p_T(l)$ experimentally more precise, but sensitive to theoretical modeling: W polarisation (PDFs) and $p_T(W)$ (QCD higher orders)



EPJC 78 (2018) 110

First LHC measurement from ATLAS

- $\Delta m_W = 7_{stat} \pm 11_{exp\ syst} \pm 14_{model} = 19$ MeV
- Dominated by theoretical uncertainties - 9 MeV (PDF), 8 MeV from $p_T(W)$
- Similar precision as Tevatron

CDF: $\Delta m_W = 12_{stat} \pm 10_{exp\ syst} \pm 12_{model} = 19$ MeV
D0: $\Delta m_W = 13_{stat} \pm 18_{exp\ syst} \pm 13_{model} = 26$ MeV

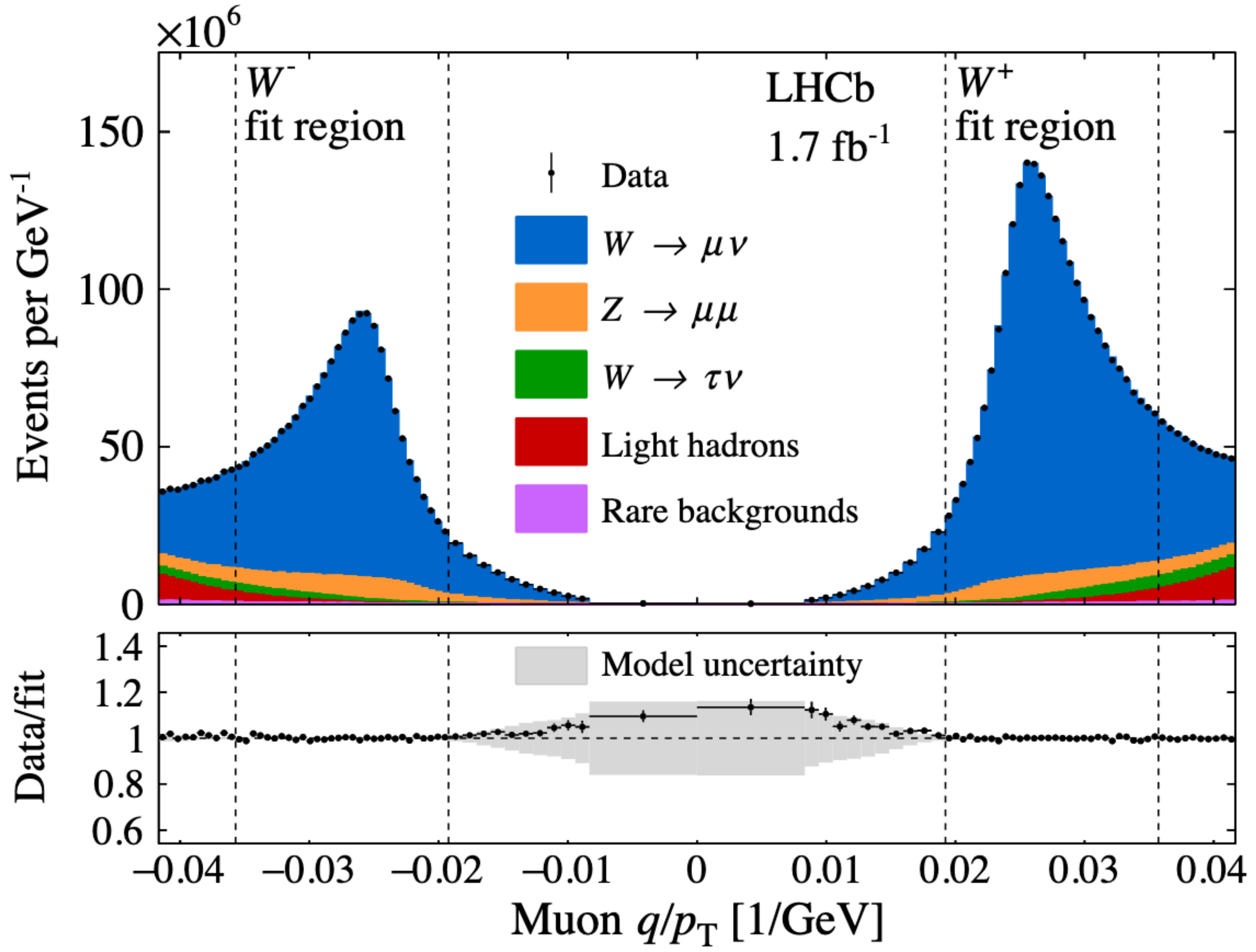
PRD 88 (2013) 052018

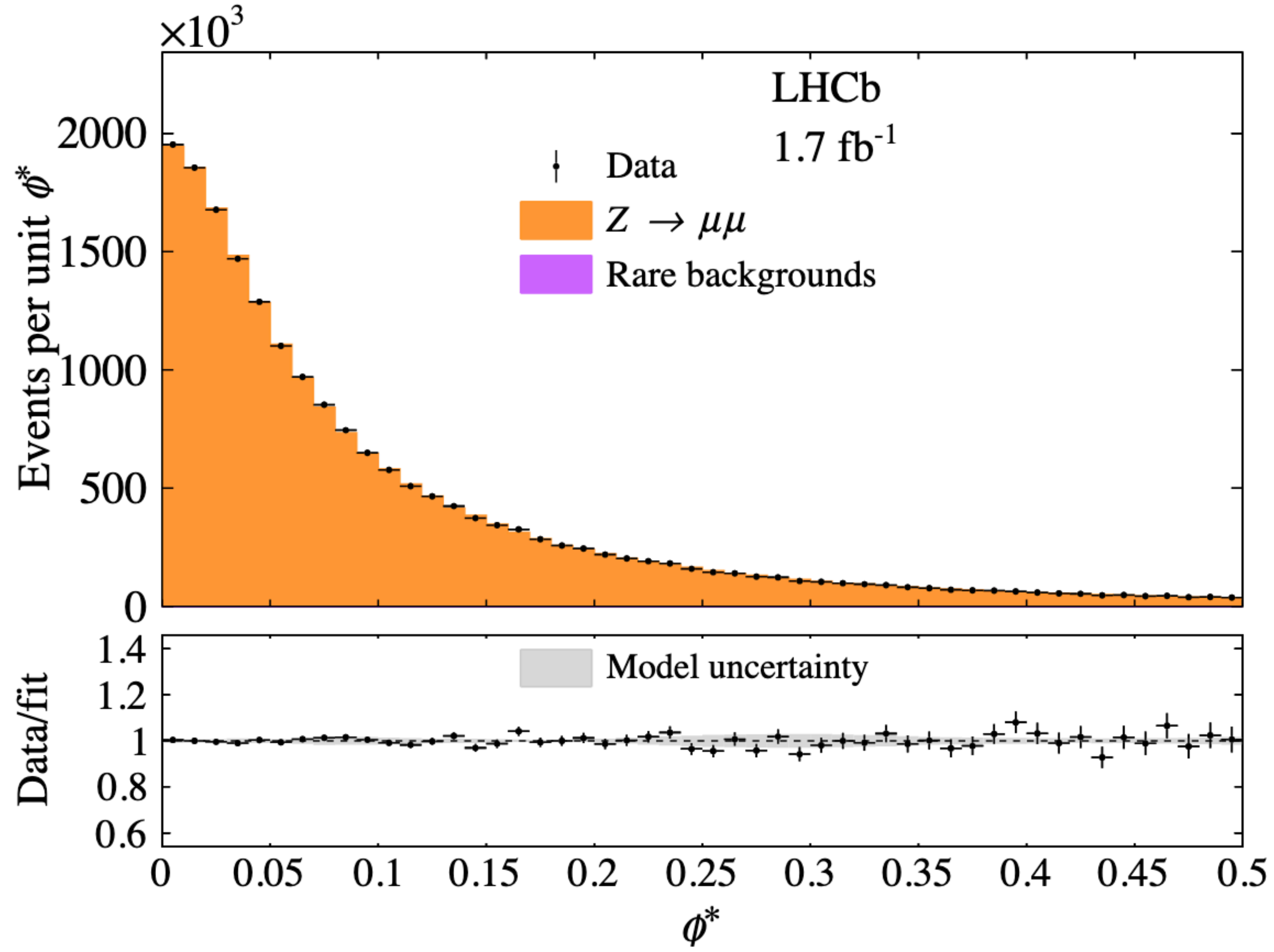
W mass at LHCb

arXiv:2109.01113

First W mass measurement at LHCb

- W→μν events from 1.7 fb^{-1}, only 1/3 of full Run2
- Simultaneous fit of q/p_T and ϕ* of W and Z
  (ϕ* proportional to Z p_T, but is angular measurement and so more precise)
- Constrain of uncertainties by in-situ Z→μμ measurement



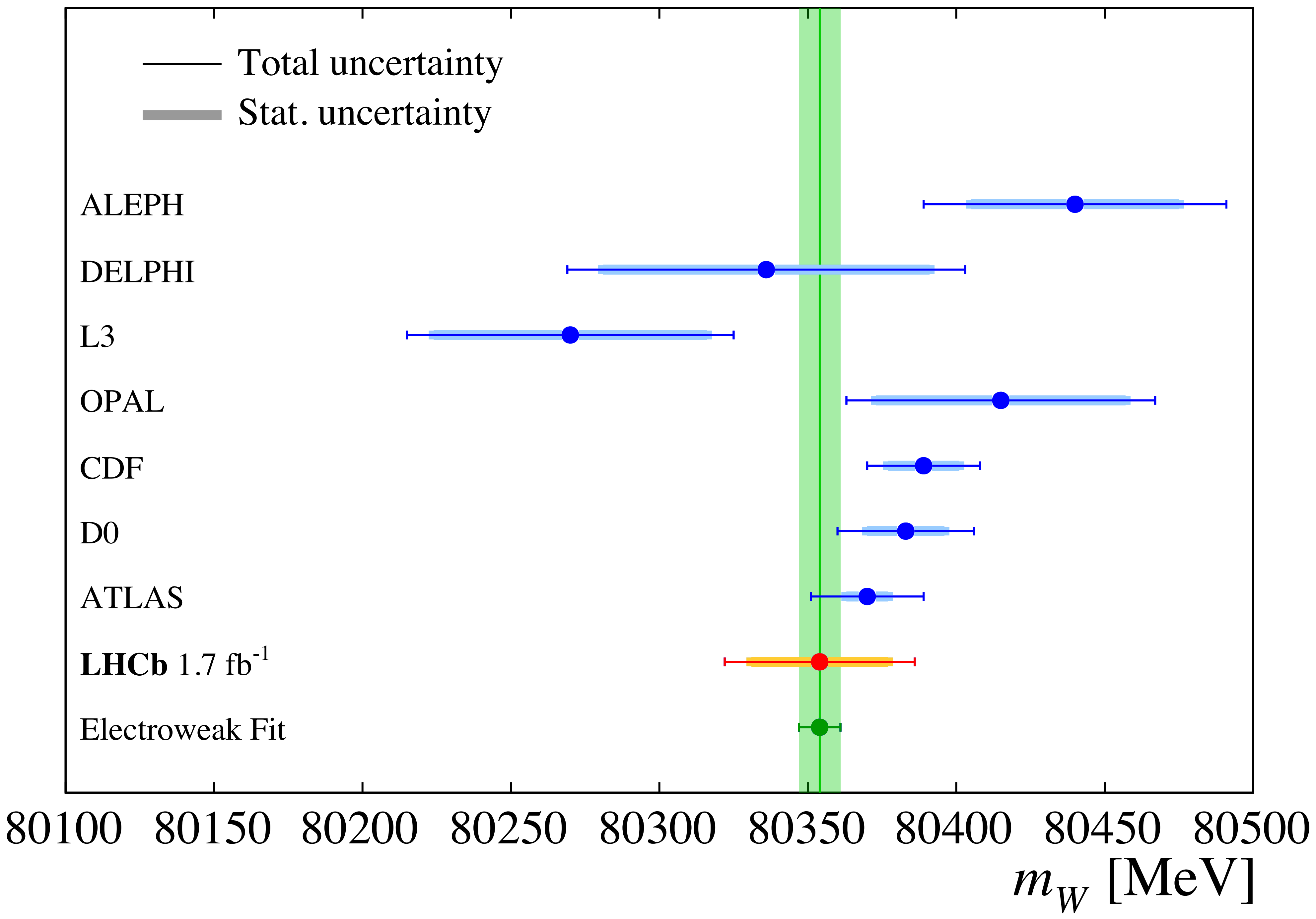


W mass at LHCb

LHCb-PAPER-2021-024

$$m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}\ \text{MeV}$$

$\Delta m_W \approx 32$ MeV



Pivotal measurement

- Larger uncertainties than ATLAS/Tevatron
- Systematic uncertainties from PDF, theory and experiment

- Expected LHCb precision < 20 MeV with full Run 1 and Run 2 datasets
  - Will employ 2D fits of q/p_T and η to reduce PDF uncertainties

Future combination

- Explores complementary region and can constrain PDF in future LHC+Tevatron combination

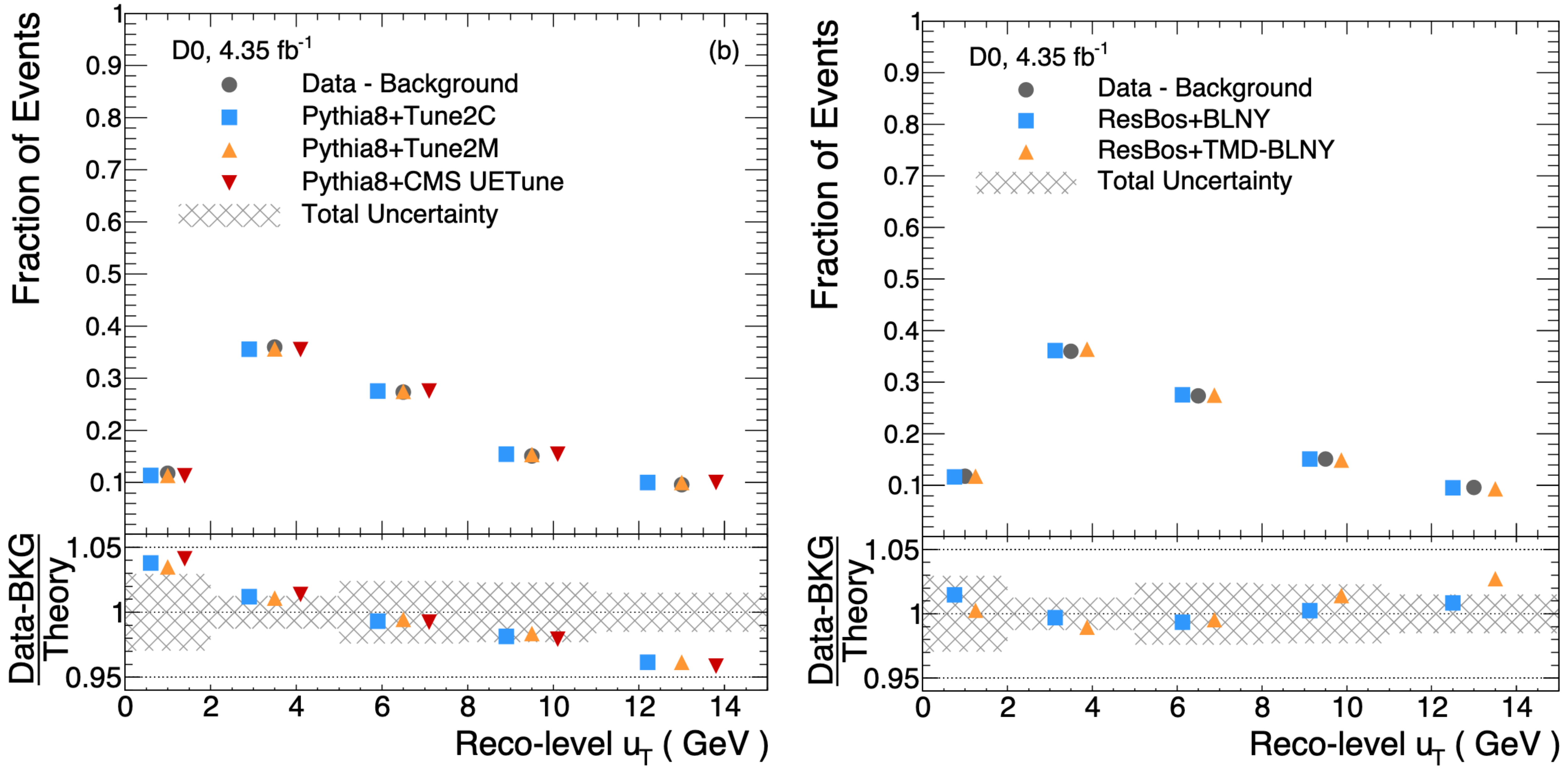
PRD 103 (2021) 012003

W measurements at Tevatron

FERMILAB-PUB-21-293-E

D0: First inclusive $p_T(W)$ using Tevatron Run II data

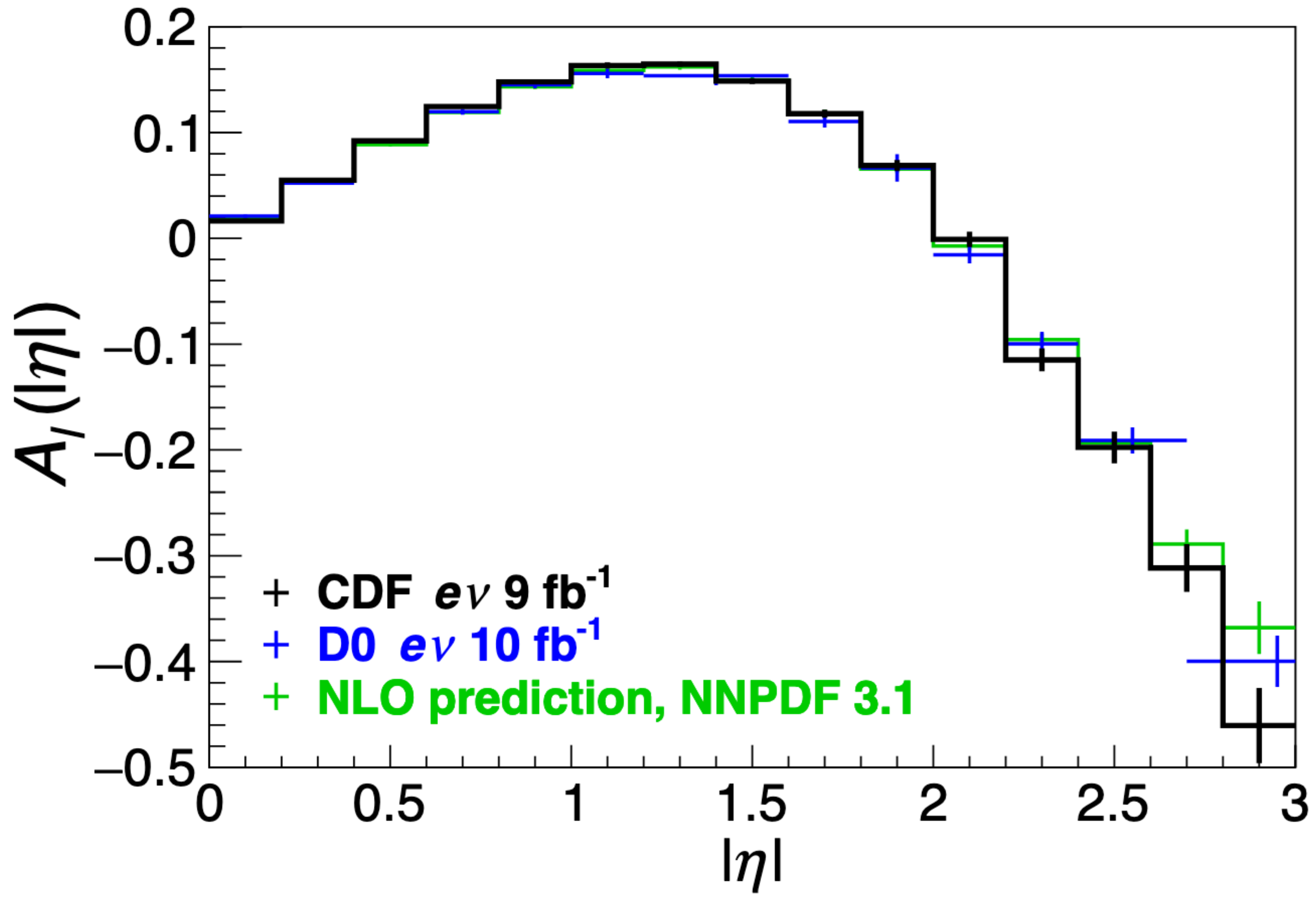
- Using hadronic recoil
- Provides additional information for evaluating resummation calculation for W boson when production dominated by valence quarks
- LHC measurements involve also s-quark



CDF: Charged-lepton asymmetry in W

- Full Tevatron dataset
- Sensitive to d/u valence quark ratio
- Improvements in global PDF expected

$$A_\ell = \frac{d\sigma_\ell^+/d\eta - d\sigma_\ell^-/d\eta}{d\sigma_\ell^+/d\eta + d\sigma_\ell^-/d\eta}$$



Resolved tension in W decays: R(τ/μ)

Nature 17, 813 (2021)

All charged leptons (e, μ, τ) couple to W boson with identical branching ratio

LEP reported 2.6σ tension between τ and e/μ

- BR of W to electrons and muons agree well

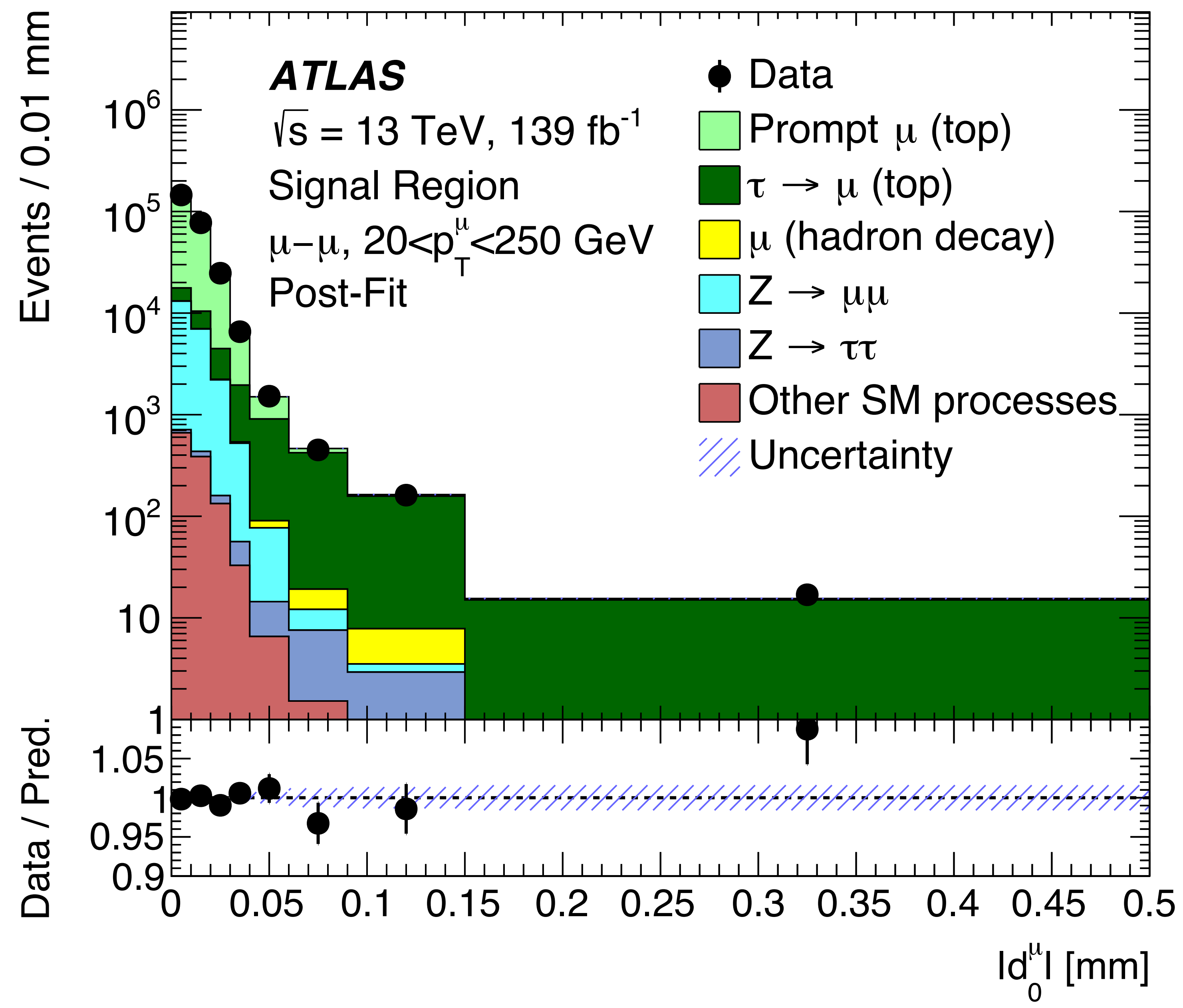
$$2\mathcal{B}(W \to \tau\bar{\nu}_\tau)/(\mathcal{B}(W \to e\bar{\nu}_e) + \mathcal{B}(W \to \mu\bar{\nu}_\mu)) = 1.066 \pm 0.025$$

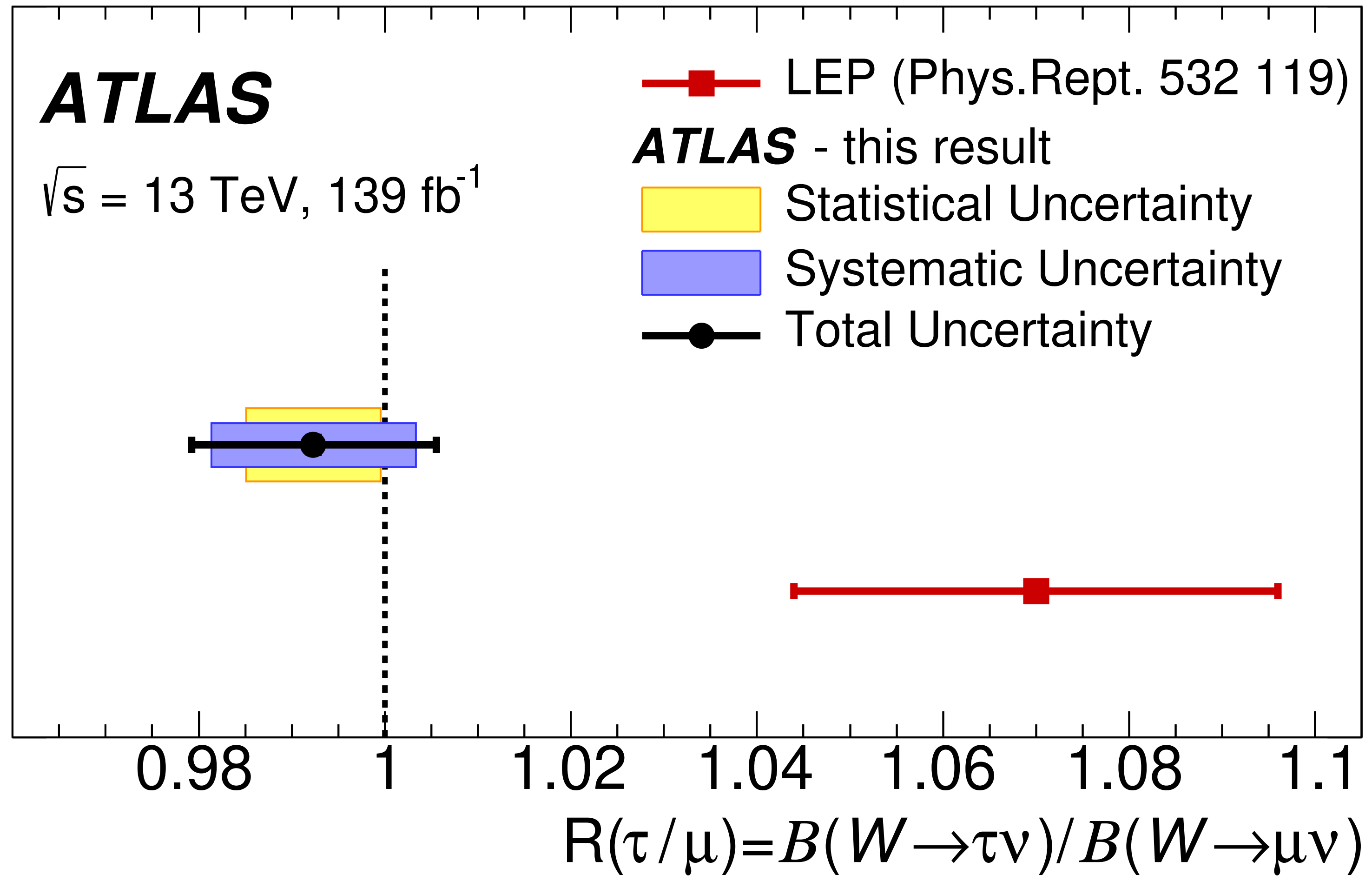
ATLAS measures W decays in $t\bar{t}$ events

- Muons classified to prompt W→ e/μ decays, τ-lepton decays and hadron decays fitted to muon transverse track impact parameter distribution d_0 and muon p_T

$$R(\tau/\mu) = 0.992 \pm 0.013\ [\pm 0.007\ (\text{stat}) \ \pm\ 0.011\ (\text{syst})]$$

- In agreement with SM, 2x more precise than LEP





W decay branching fractions

CMS-PAS-SMP-18-011

CMS uses $t\bar{t}$, tW, WW, $W+\text{jets}$ events to study W decay BR

- Trailing lepton p_T used to discriminate between prompt W → e/μ decays and τ-lepton in ee, μμ, eμ

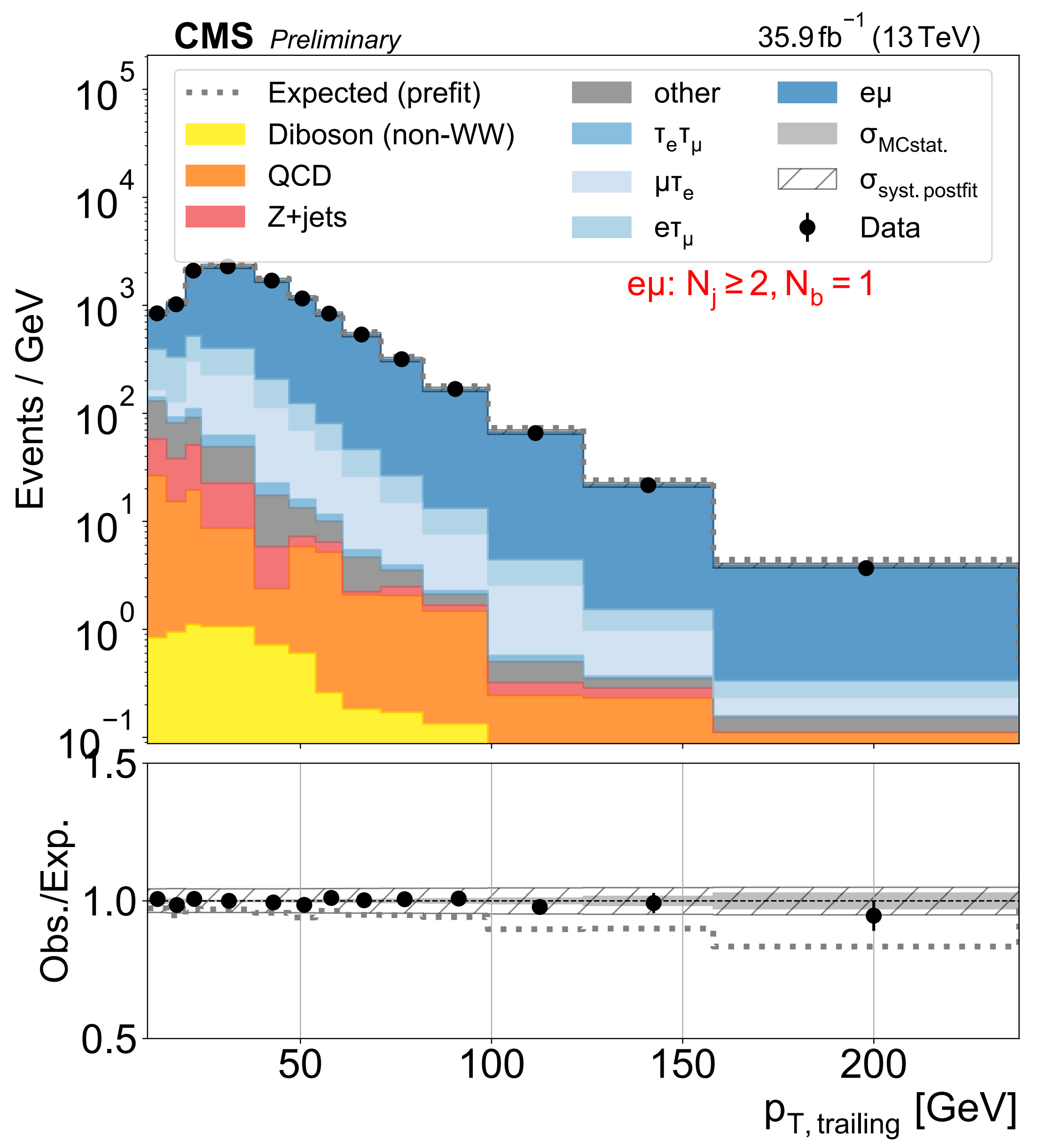
Measured BR of individual lepton flavours

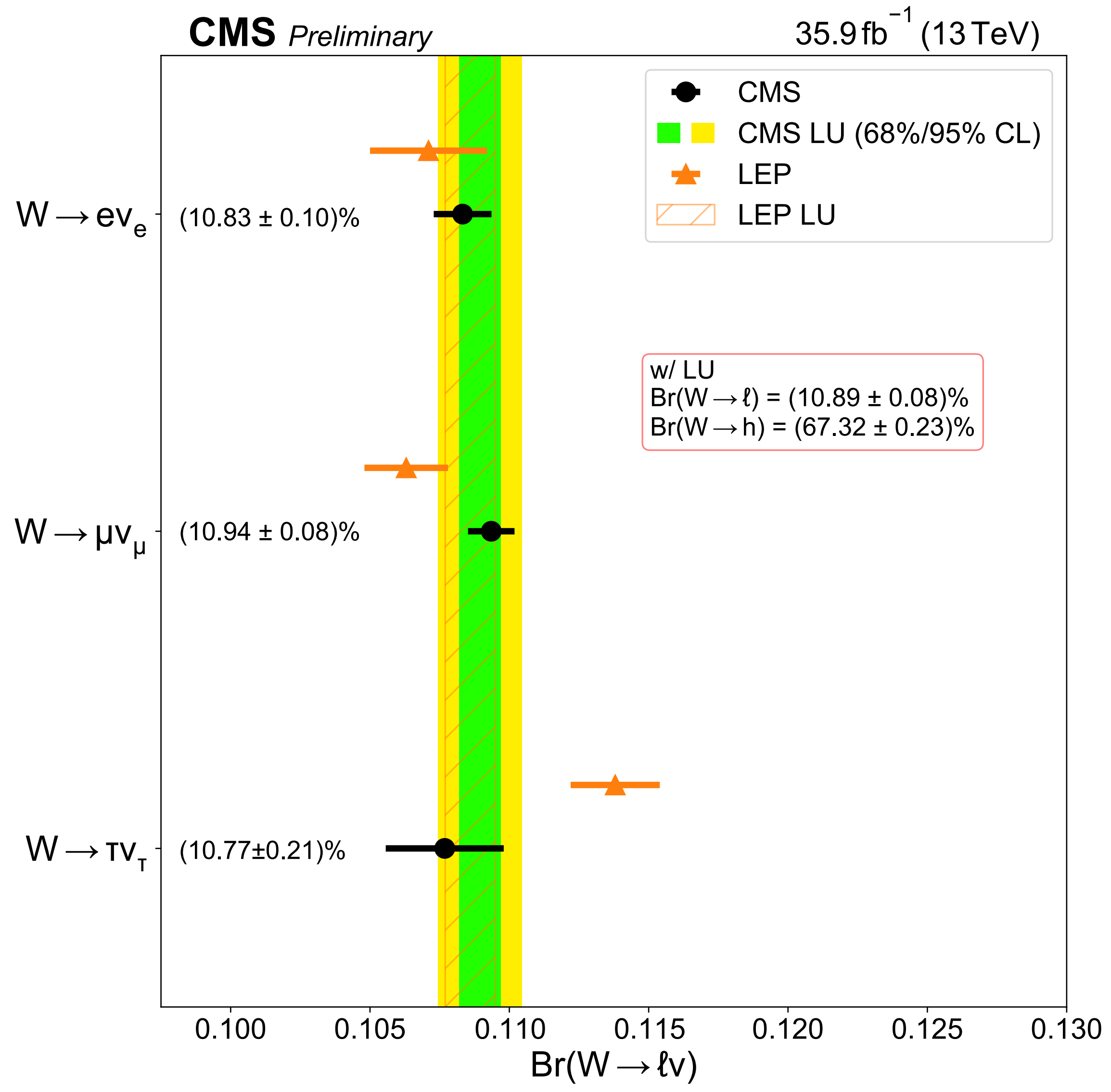
- While systematic uncertainties comparable to LEP, factor of 3-10 statistically more precise
- Assuming lepton universality BR(W →leptons) = $(10.89 \pm 0.01 \pm 0.08)\%$

	CMS	LEP
$\mathcal{B}(\mathrm{W} \to \mathrm{e}\bar{\nu}_\mathrm{e})$	$(10.83 \pm 0.01 \pm 0.10)\%$	$(10.71 \pm 0.14 \pm 0.07)\ \%$
$\mathcal{B}(\mathrm{W} \to \mu\bar{\nu}_\mu)$	$(10.94 \pm 0.01 \pm 0.08)\%$	$(10.63 \pm 0.13 \pm 0.07)\ \%$
$\mathcal{B}(\mathrm{W} \to \tau\bar{\nu}_\tau)$	$(10.77 \pm 0.05 \pm 0.21)\%$	$(11.38 \pm 0.17 \pm 0.11)\ \%$
$\mathcal{B}(\mathrm{W} \to \mathrm{h})$	$(67.46 \pm 0.04 \pm 0.28)\%$	–

	CMS	LEP	ATLAS
$R_{\mu/\mathrm{e}} = \mathcal{B}(\mathrm{W} \to \mu\bar{\nu}_\mu)/\mathcal{B}(\mathrm{W} \to \mathrm{e}\bar{\nu}_\mathrm{e})$	1.009 ± 0.009	0.993 ± 0.019	**1.003±0.010**
$R_{\tau/\mathrm{e}} = \mathcal{B}(\mathrm{W} \to \tau\bar{\nu}_\tau)/\mathcal{B}(\mathrm{W} \to \mathrm{e}\bar{\nu}_\mathrm{e})$	0.994 ± 0.021	1.063 ± 0.027	–
$R_{\tau/\mu} = \mathcal{B}(\mathrm{W} \to \tau\bar{\nu}_\tau)/\mathcal{B}(\mathrm{W} \to \mu\bar{\nu}_\mu)$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013
$R_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	–

ATLAS: EPC 77 (2017) 367





Lepton universality at high-mass DY

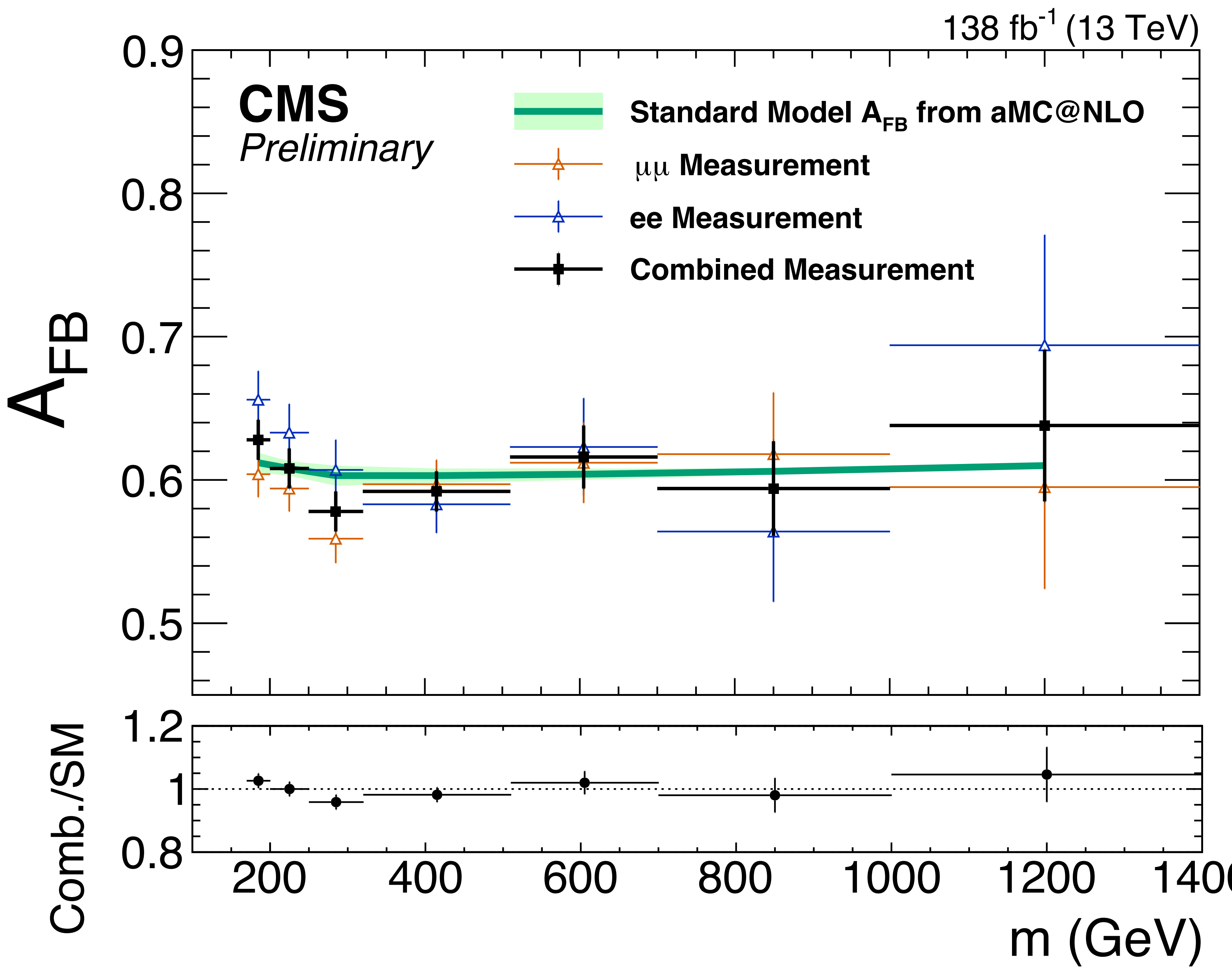
CMS A_{FB} measurement for m_{ll}>170 GeV

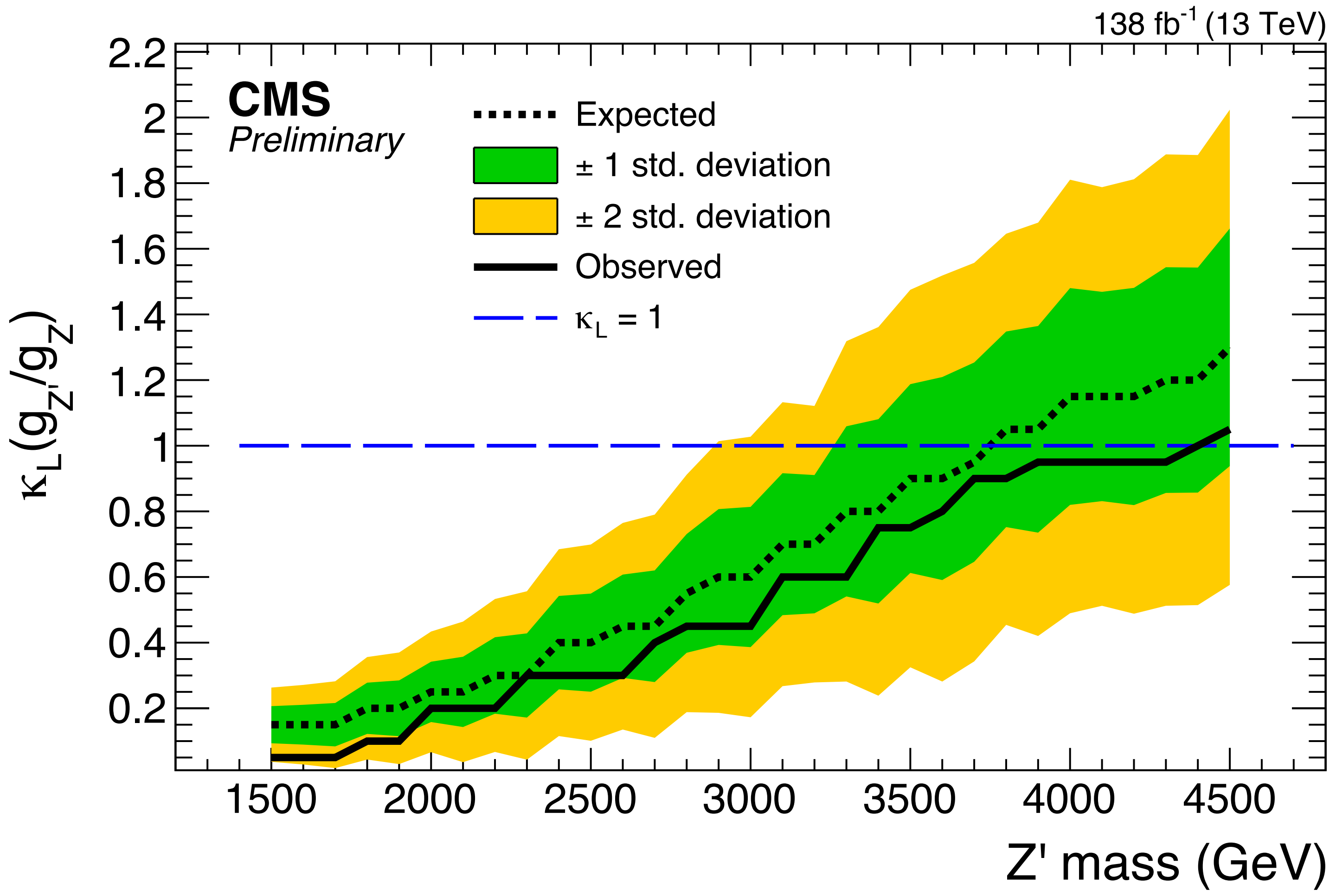
CMS-PAS-SMP-21-002

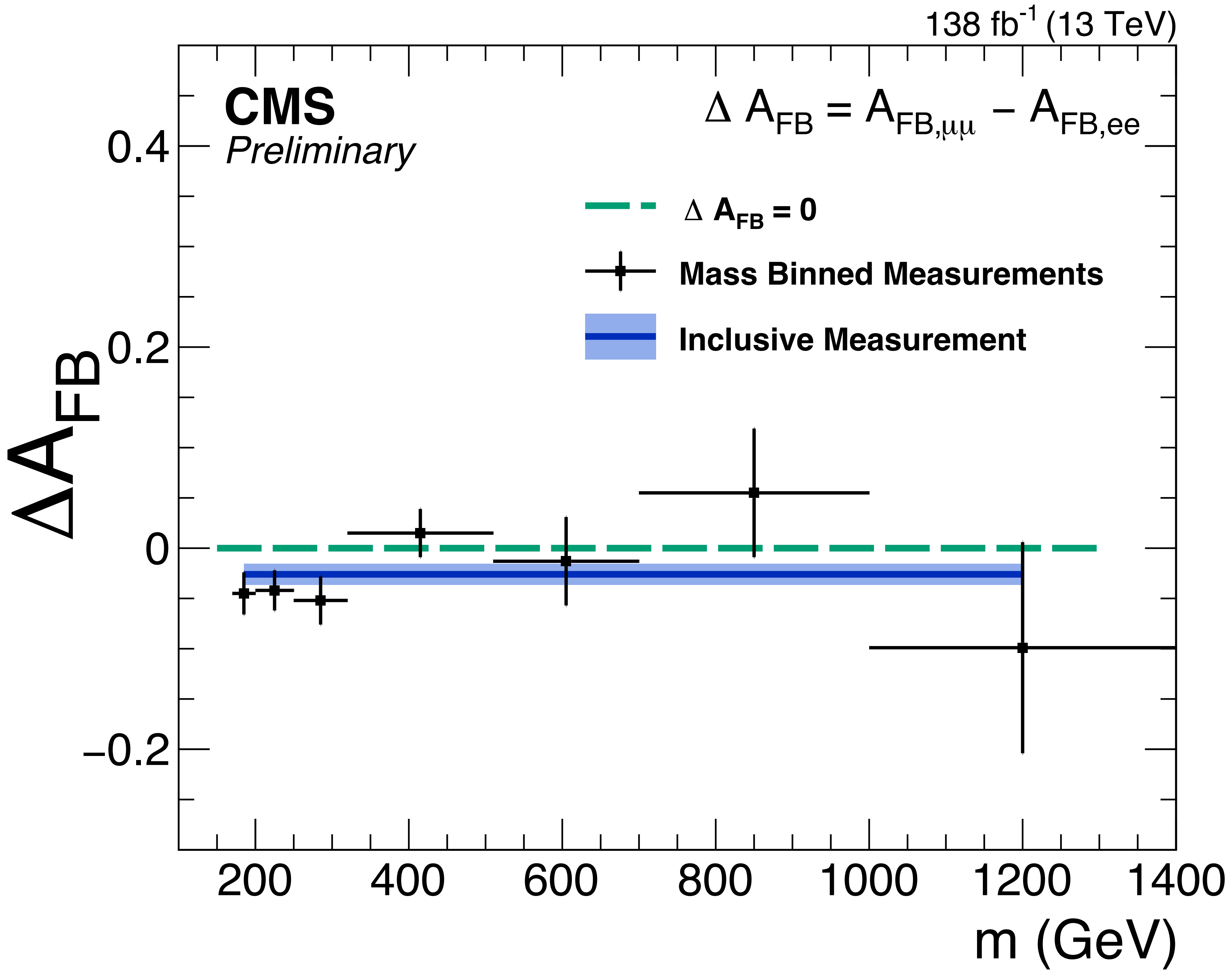
- A_{FB} non-zero and positive above Z-peak due to γ^*/Z interference
- Sensitive to BSM through interference with heavy vector boson

A_{FB} for ee and μμ allows to test lepton universality

- In the inclusive ΔA_{FB}, e/μ are found to deviate at 2.4σ







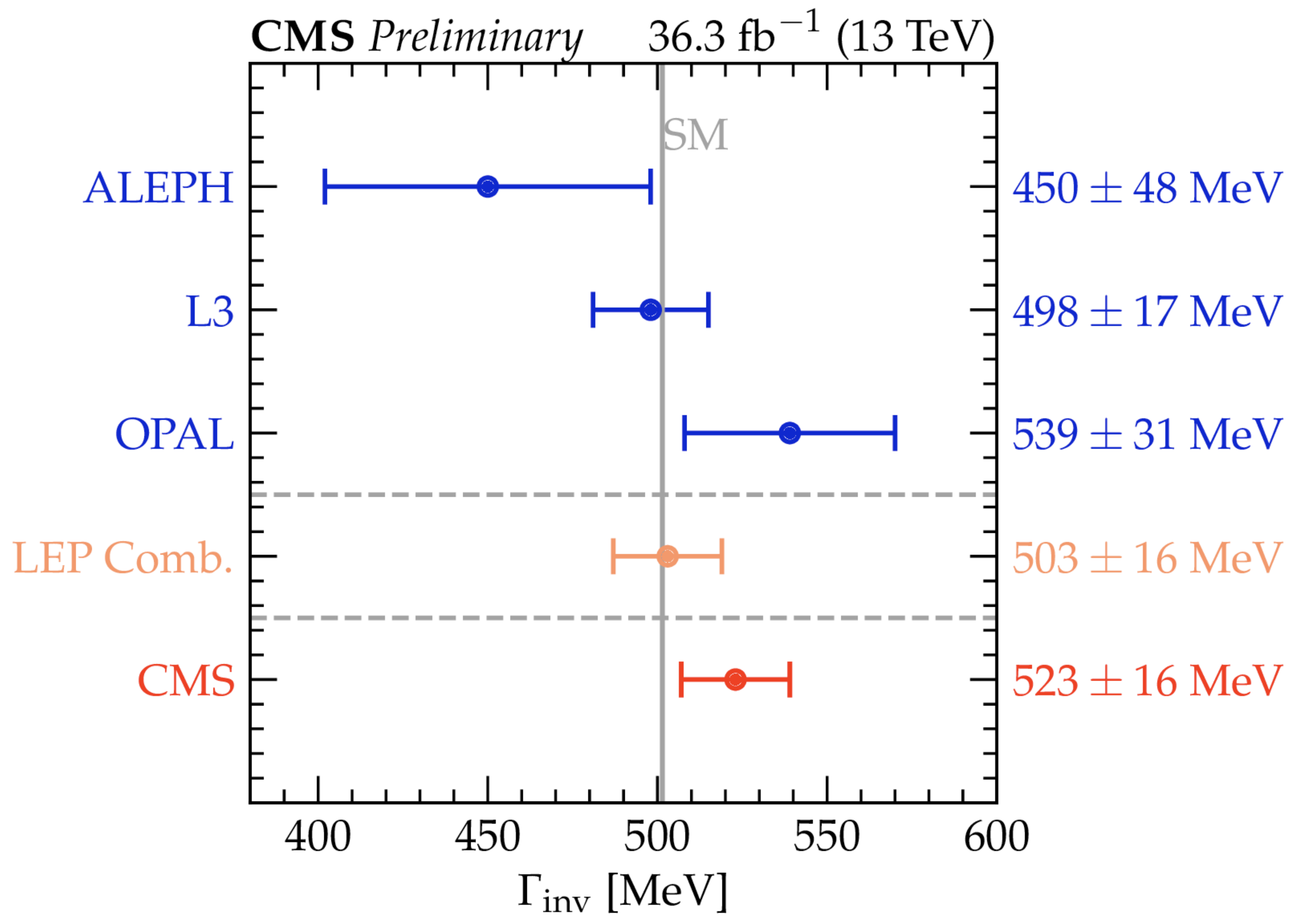
Z invisible width at CMS

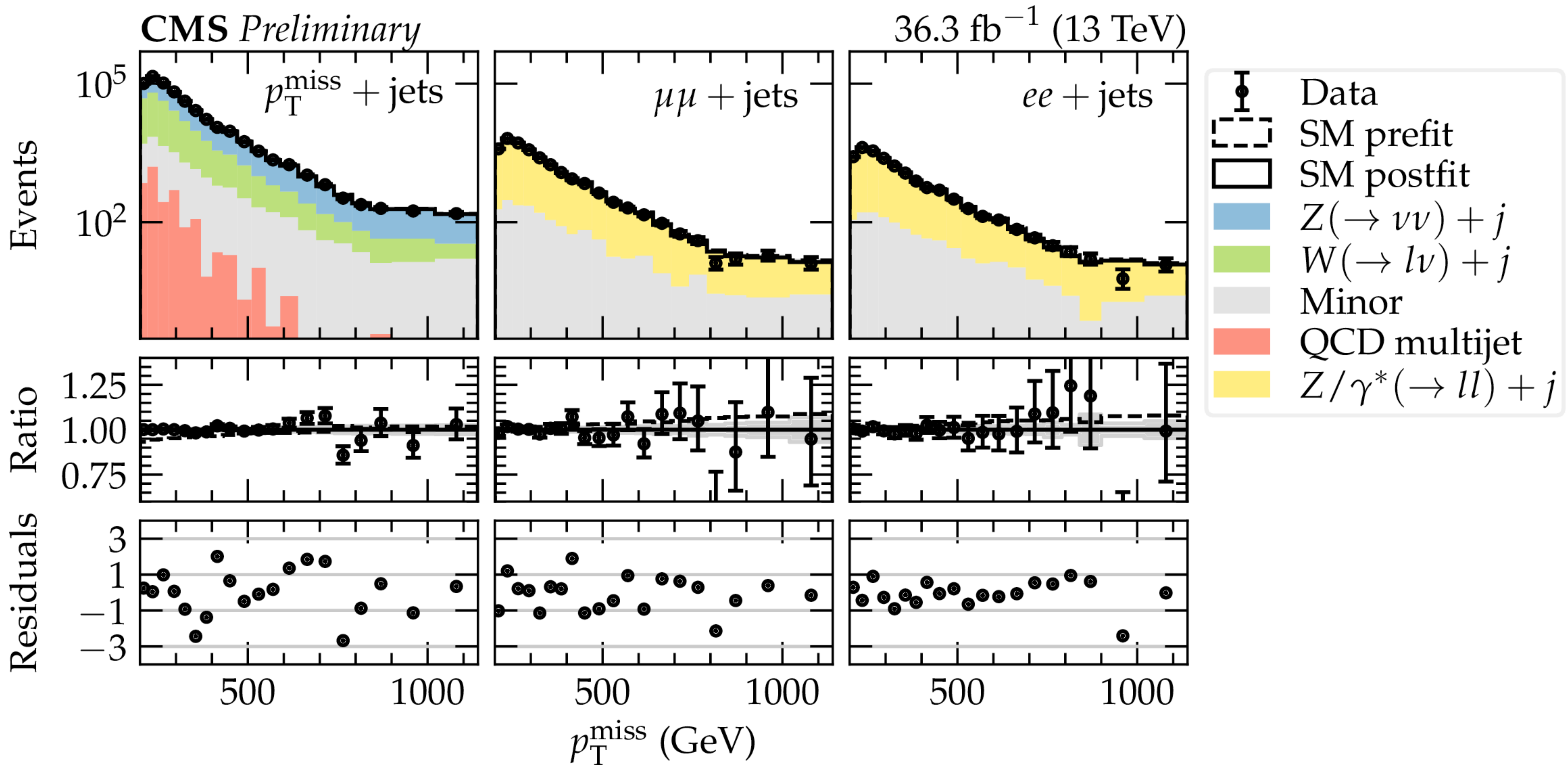
SMP-18-014

First measurement of Z invisible width at hadron collider

- Sensitive to number of neutrinos coupling to Z boson
- Ratio σ(Z→νν) / σ(Z→ll) interpreted as Γ_{inv}
- Largest background W→lν estimated using a control region

Competitive precision with LEP direct measurements





Diboson and triboson measurements

All diboson production mechanisms have been measured by ATLAS and CMS

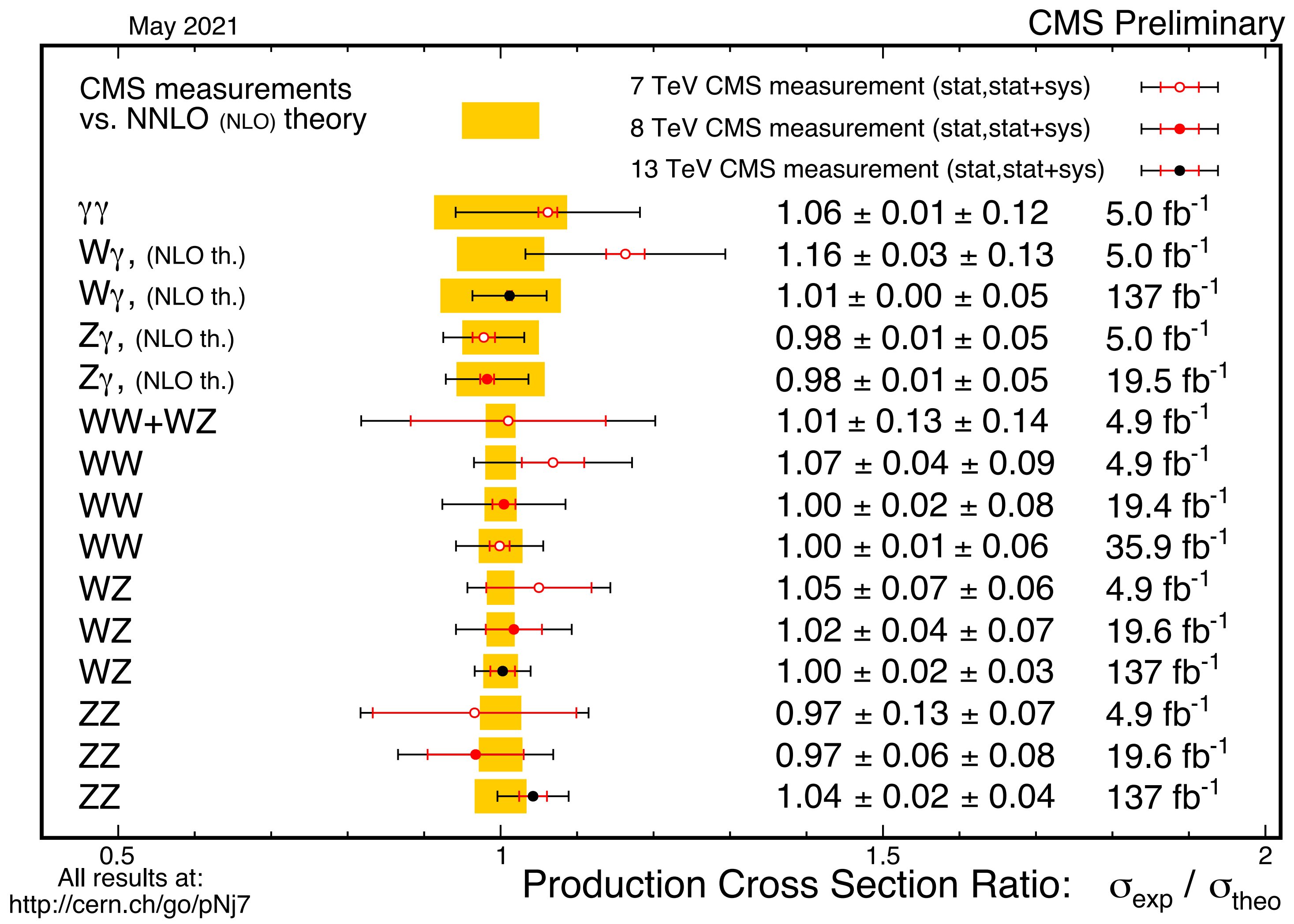
- Different decay modes of the vector bosons
- Mostly 13 TeV data, but some measurement still in progres with full Run 2 data
- Precision with Run 2 dataset is limited by systematic uncertainties
- In agreement with state-of-the-art theoretical calculations (see ATLAS and CMS summaries)

Many triboson processes studied

- Low cross section require use of hadronic decays of massive gauge bosons
- First observation of the 3 massive gauge boson process at the LHC

not measured
8TeV
13 TeV

Diboson		Triboson	
Wγ	ATLAS@7TeV CMS	γγγ	ATLAS
Zγ	ATLAS(llγ, ννγ) CMS@8TeV(llγ, ννγ)	Zγγ	ATLAS@8TeV CMS
WW	ATLAS(incl, ≥1j) CMS	Wγγ	ATLAS@8TeV CMS
WZ	ATLAS CMS	WWγ	ATLAS CMS
ZZ	ATLAS (4l,2l2ν, CMS(4l,4l+jets)	WZγ	ATLAS (WVγ) CMS (WVγ)
		ZZγ	
		WWW	ATLAS CMS
		WWZ	ATLAS (WVV)
		WZZ	ATLAS (WVV)
		ZZZ	



results at lower $\sqrt{s}$ not shown, adapted from P. Sommer

BSM representation using EFT

Characterise deviations from SM using SM Effective Field Theory (SMEFT)

$$\mathcal{L}_{\text{SMEFT}} \approx \mathcal{L}_{\text{SM}}^{(4)} + \sum_i \frac{c_i^{(6)}}{\Lambda^2} \mathcal{O}_i^{(6)} + \sum_j \frac{c_j^{(8)}}{\Lambda^4} \mathcal{O}_j^{(8)}$$

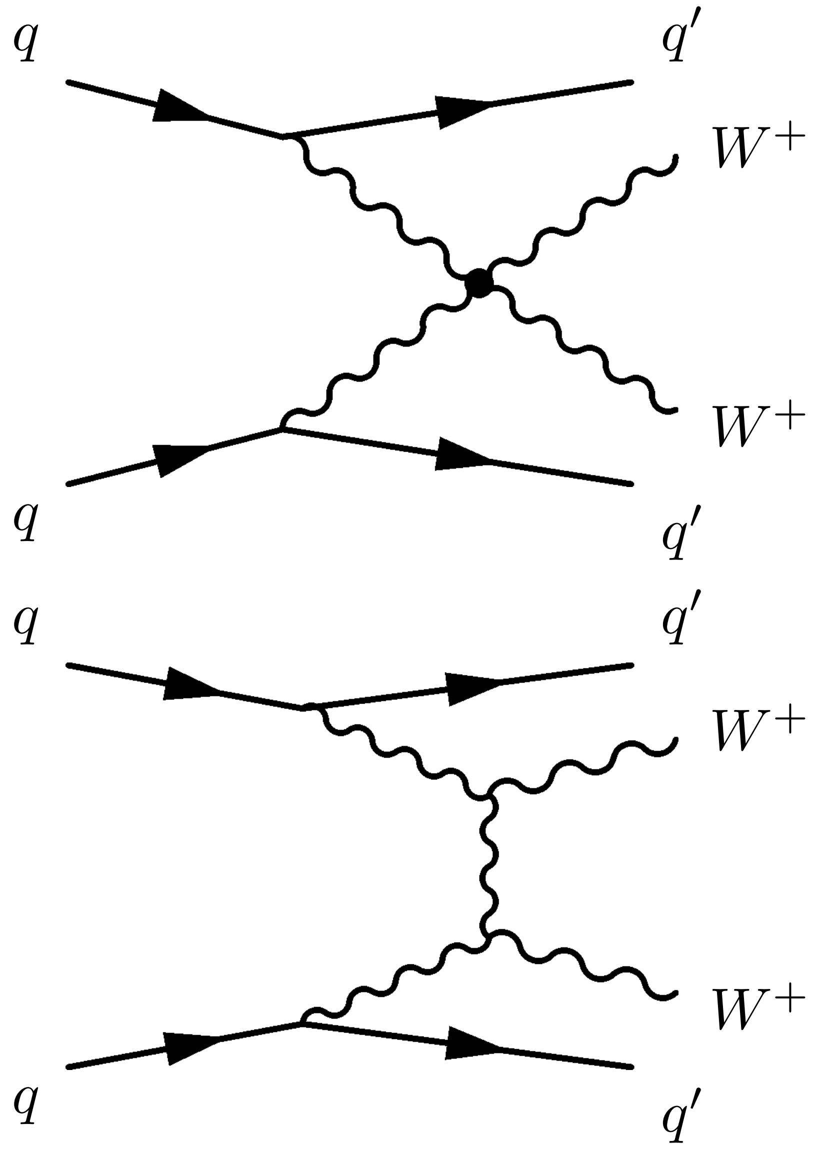
- Expansion in terms of scale of new physics 1/Λ
- Typically constrain one Wilson coefficient at a time in single measurement

First attempts of global SMEFT interpretations using dim6 operators

- ATLAS: Combined interpretation of WW, WZ, 4l, EW Zjj measurements or H→WW* and WW processes, see ATL-PHYS-PUB-2021-022, ATL-PHYS-PUB-2021-010

VBS processes - laboratory to test SM EW symmetry breaking

- Leading divergence (due to V_L) cancellation between TGC and QGC contributions
- Higgs diagrams needed to avoid violation of unitarity
- Dim-8 operators can modify VVjj production via aQGC
- Experiments should use same unitarisation procedure allowing reinterpretation/combination (clipping, …)

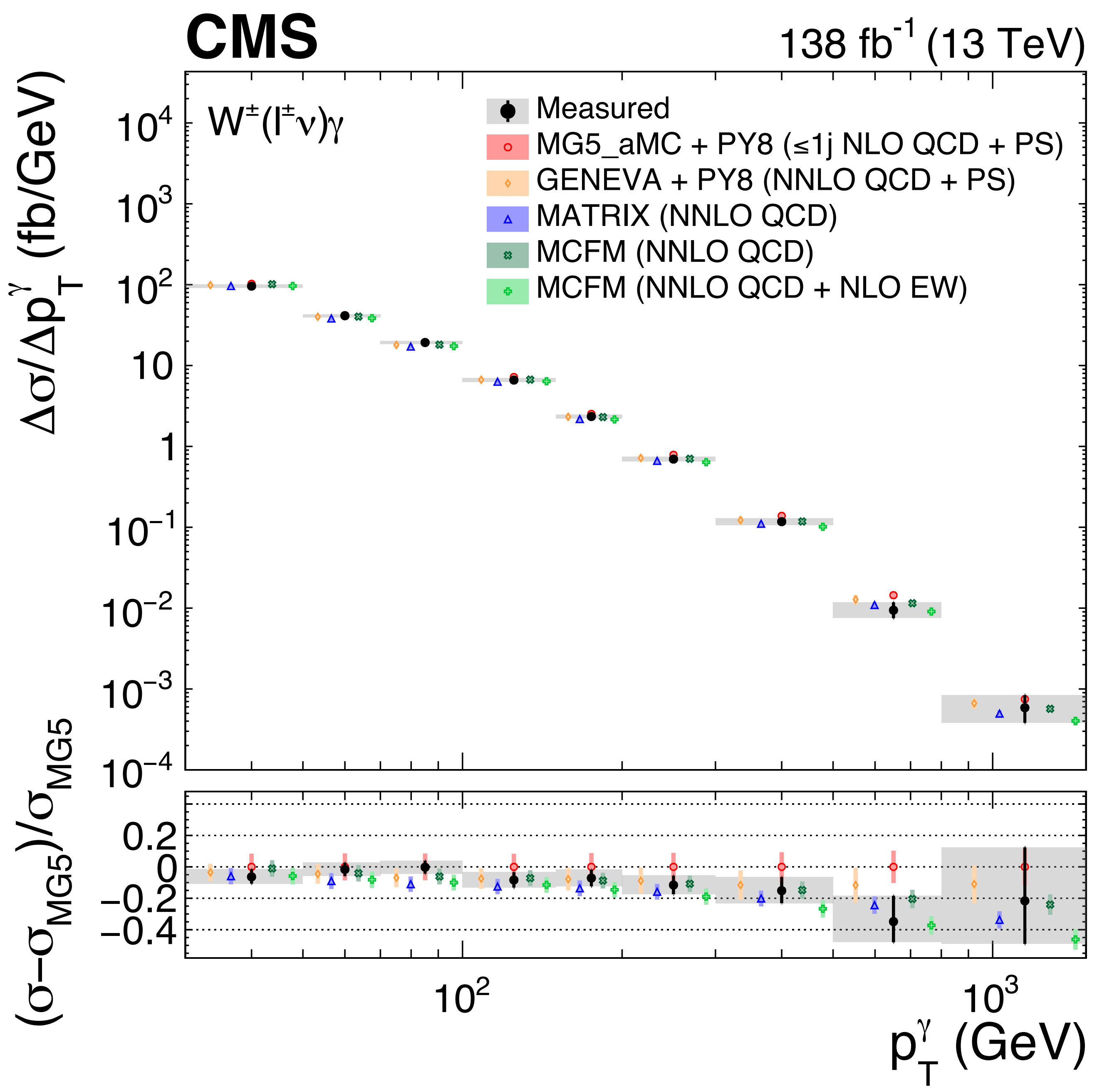


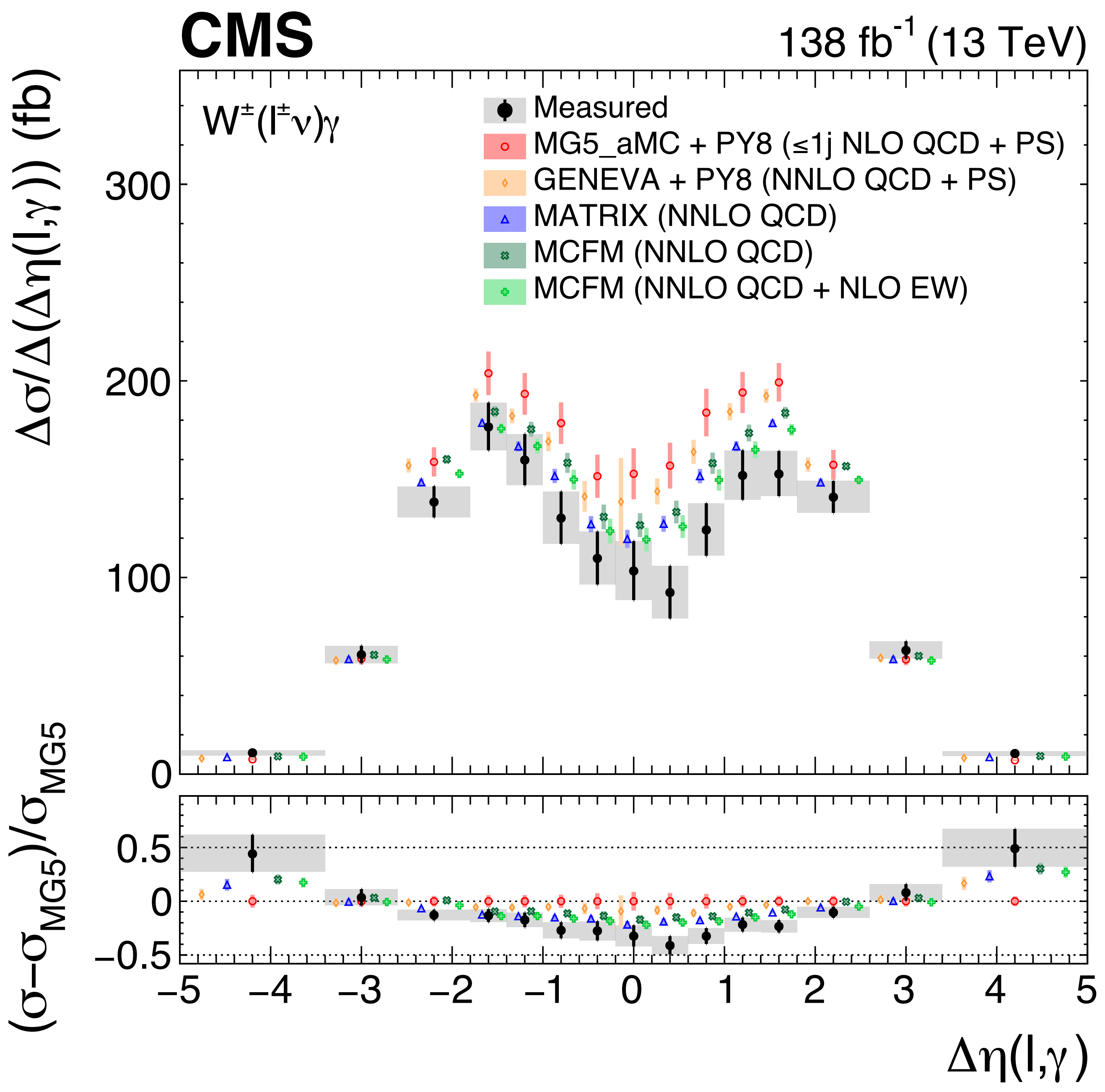
Wγ measurement

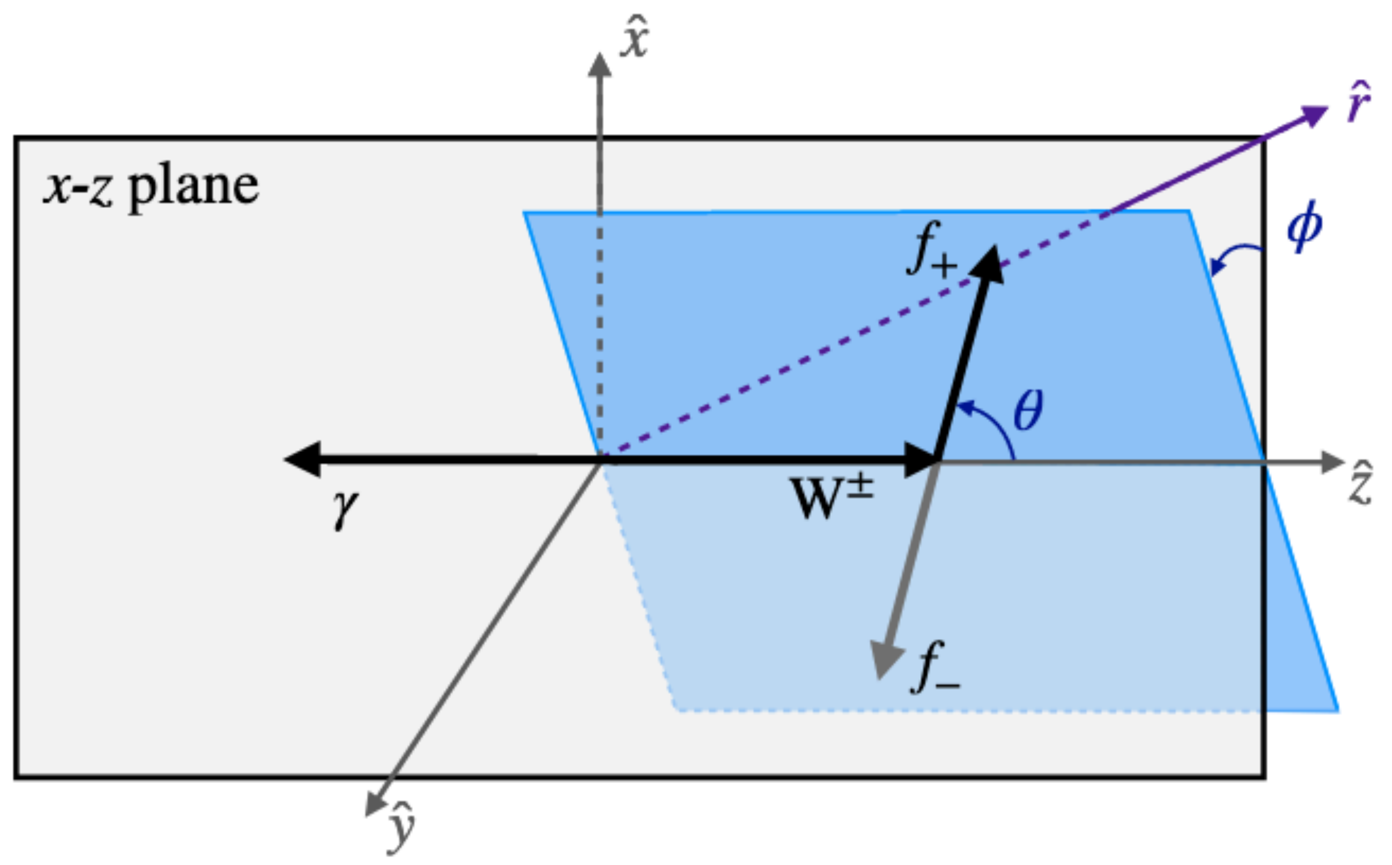
PRL 126 (2021) 252002
SMP-20-005

Full Run 2 measurement of Wγ by CMS

- Previous result only at 7TeV, inclusive and differential cross section measurements, jet observables
- Radiation-zero due to destructive interference of LO diagrams
  - observed in rapidity difference between lepton/γ, sensitive to BSM contributions
- ϕ variable defined in the Wγ rest frame increases sensitivity for EFT constraints
  - enhancement of interference between SM and BSM differentially, which is zero for inclusive observable (linear term resurrection)





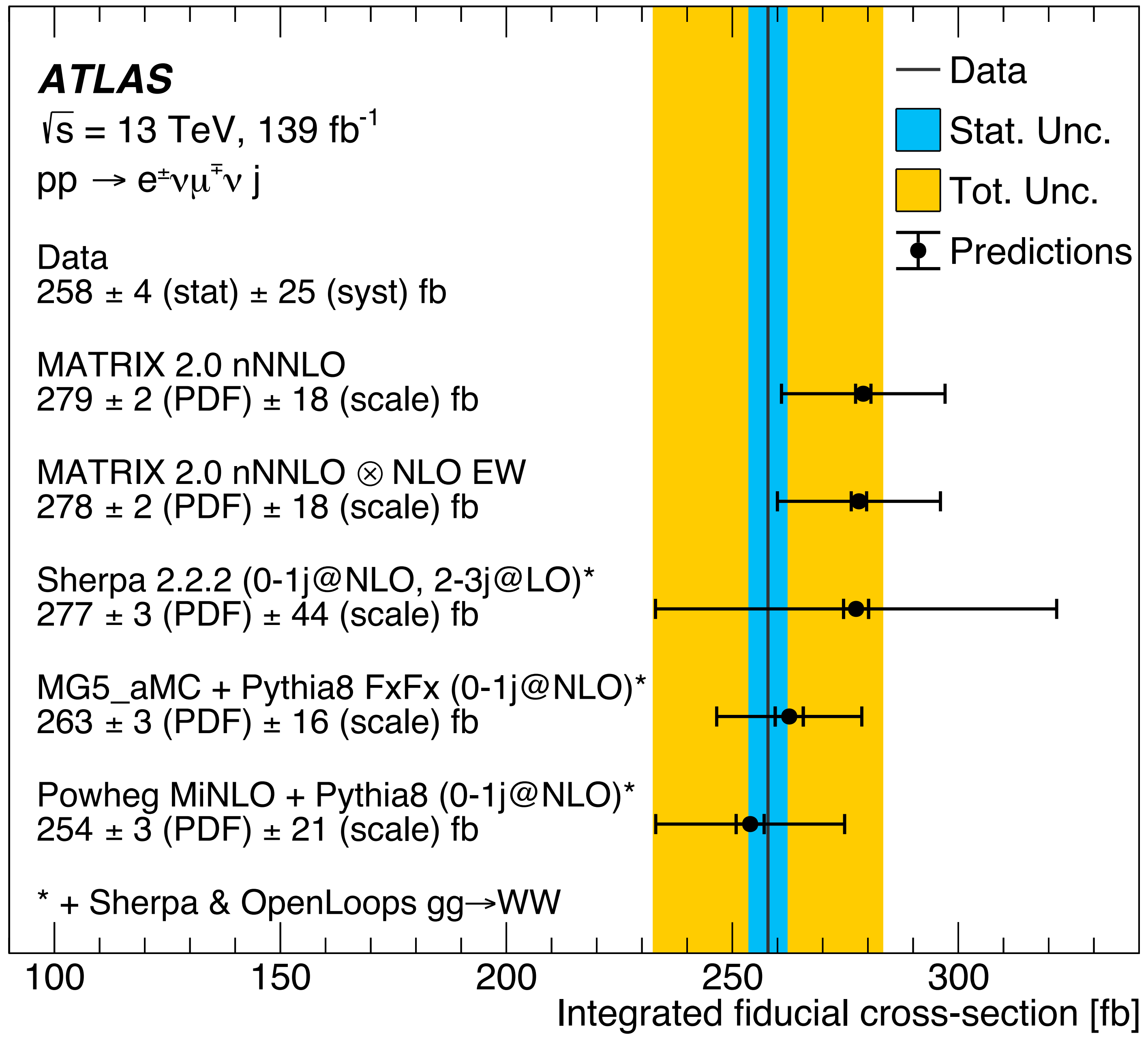


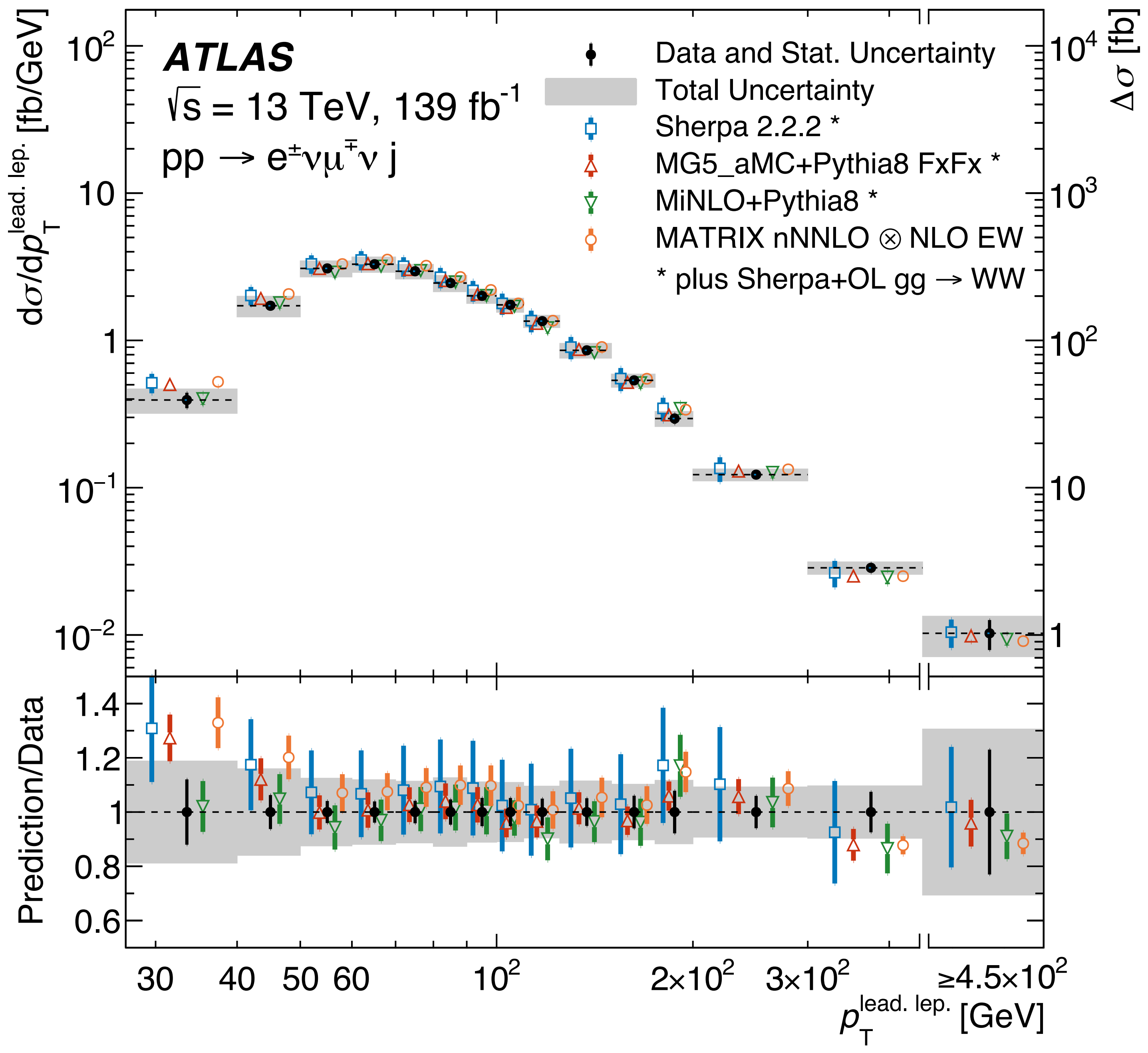
WW+≥1jet in ATLAS

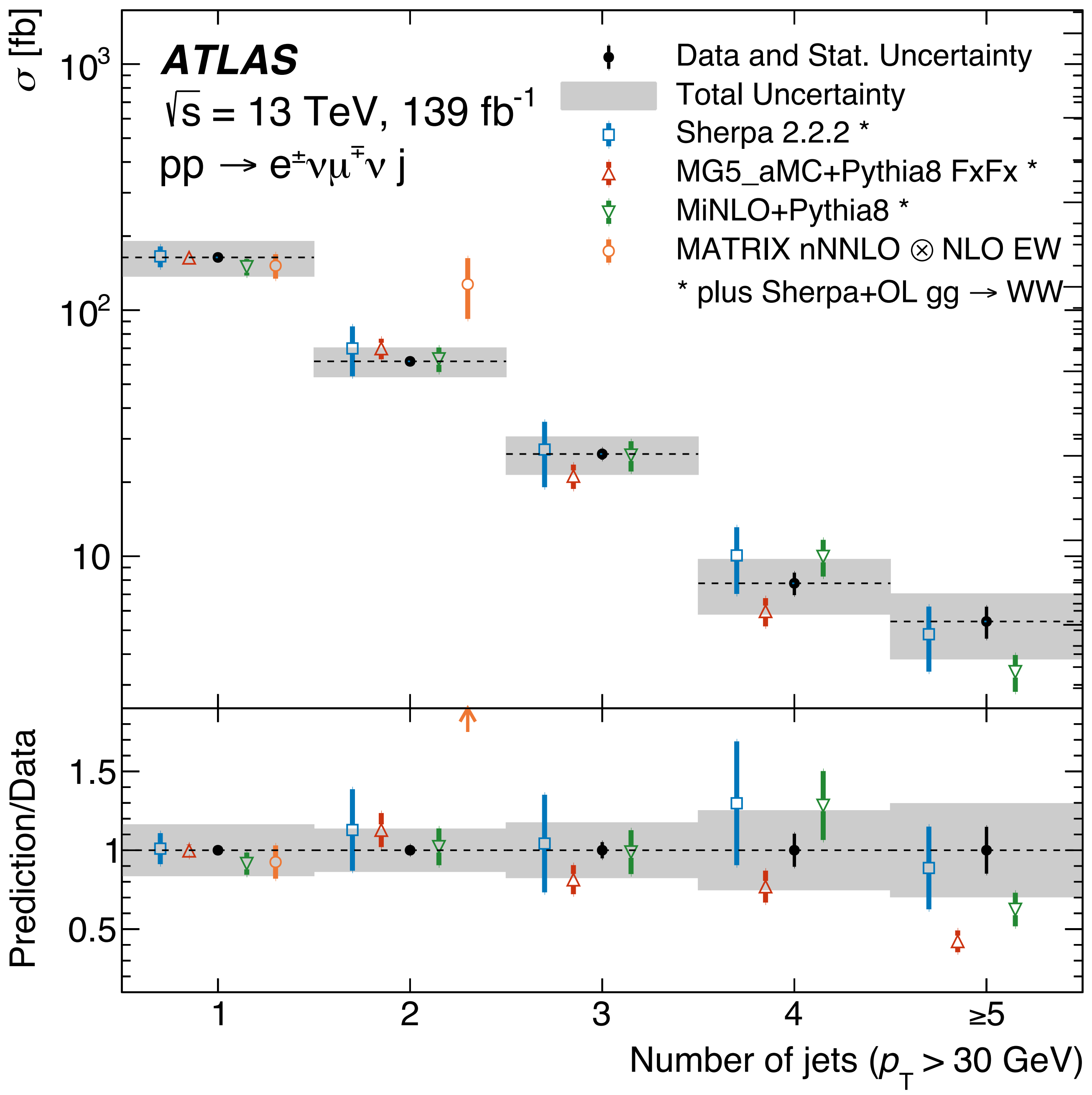
JHEP 06 (2021) 003

Probing QCD higher order contributions in WW production: $pp \rightarrow e^{\pm}\nu\mu^{\mp}\bar{\nu}j$

- Precision differential measurement of lepton and jet observables with full Run 2
- Data driven top background estimate, which is large after b-jet veto
- NLO theoretical prediction model well previously unexplored phase-space up to 5 jets





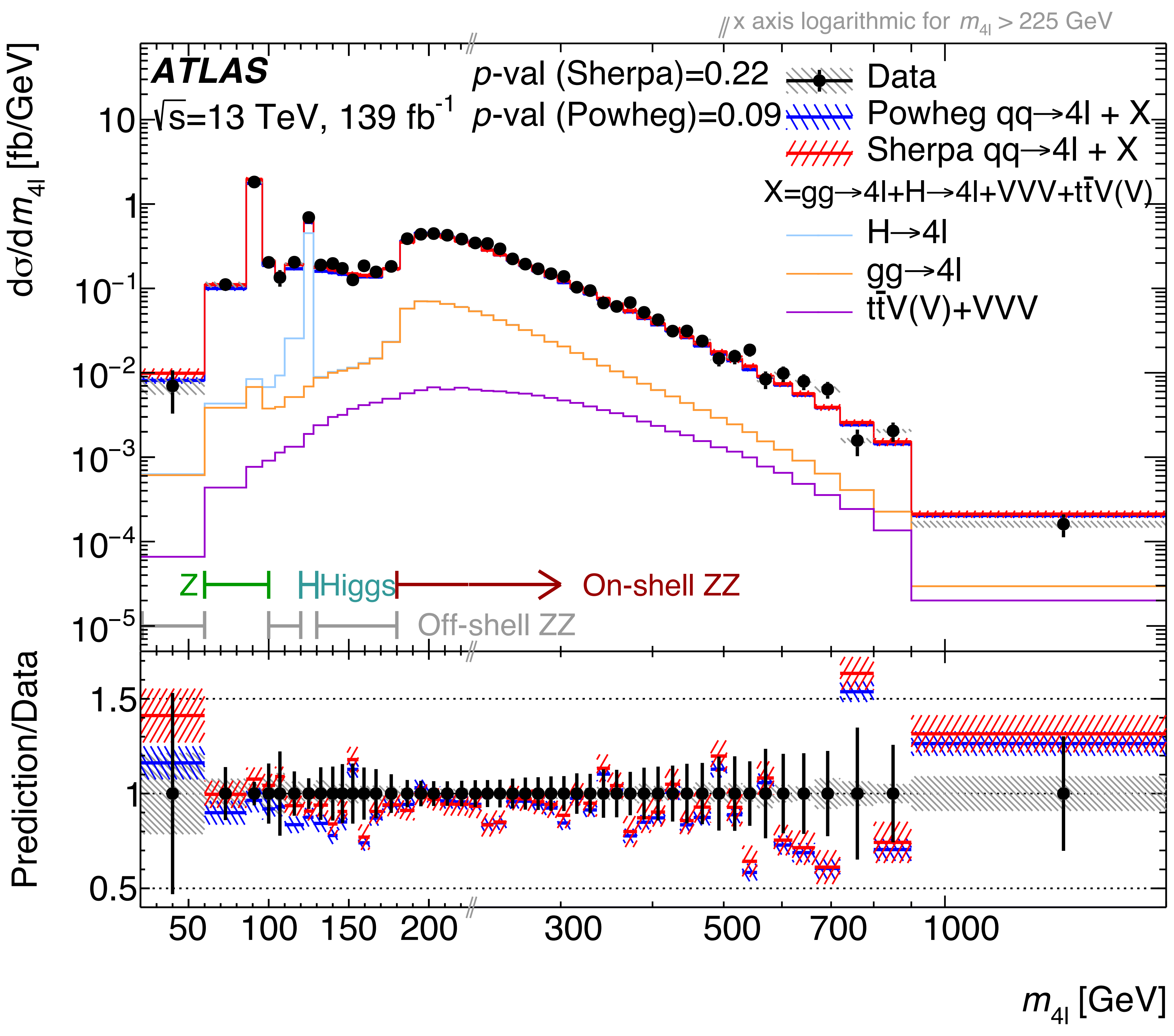


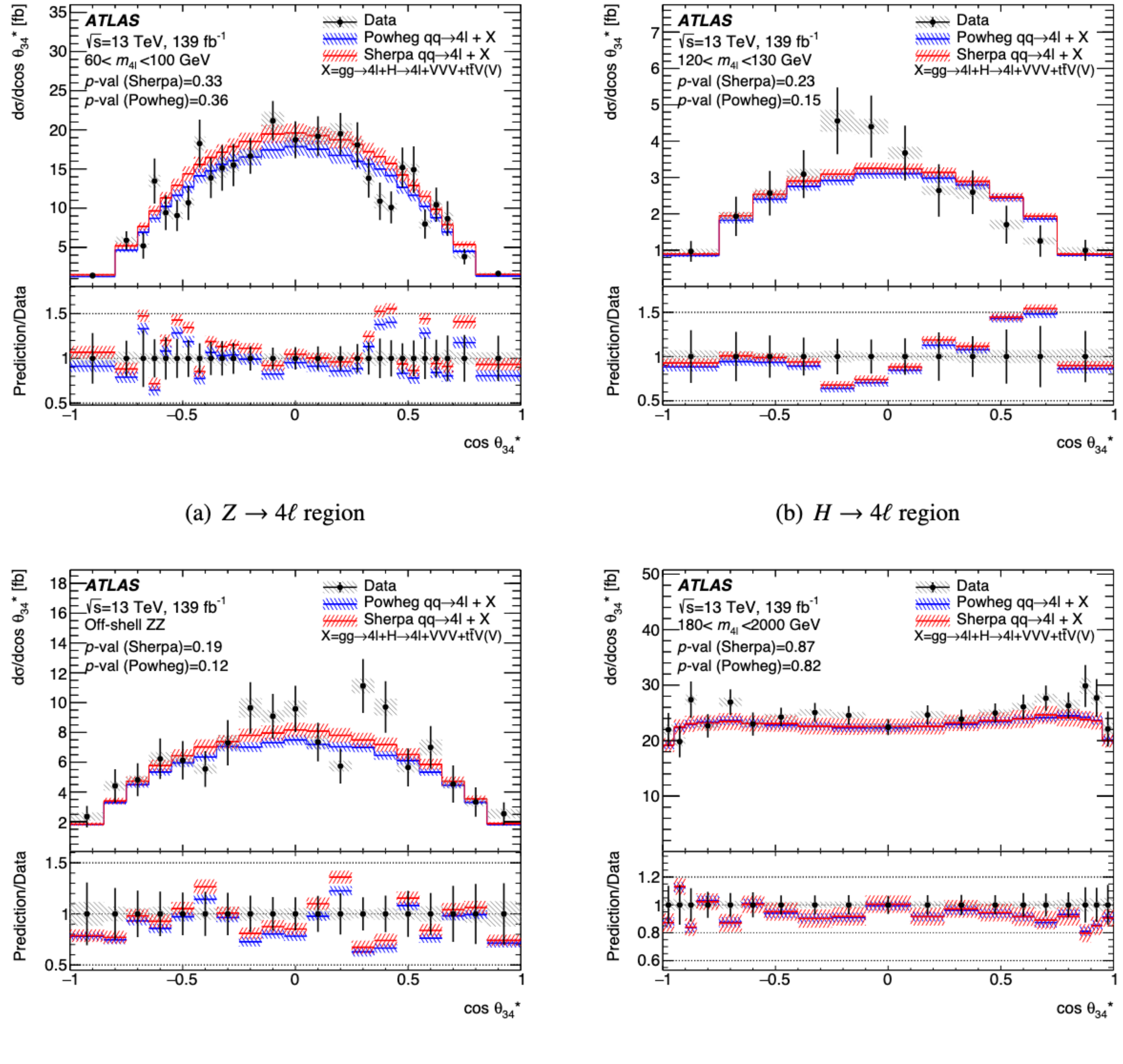
4-lepton production

JHEP 07 (2021) 005

Differential measurement of 4l production in ATLAS

- $Z \to 4l$, $H \to 4l$, on-shell ZZ and off-shell regions
- Many variables measured including angular correlation
- Statistically limited even with full Run 2





(a) $Z \to 4\ell$ region

(b) $H \to 4\ell$ region

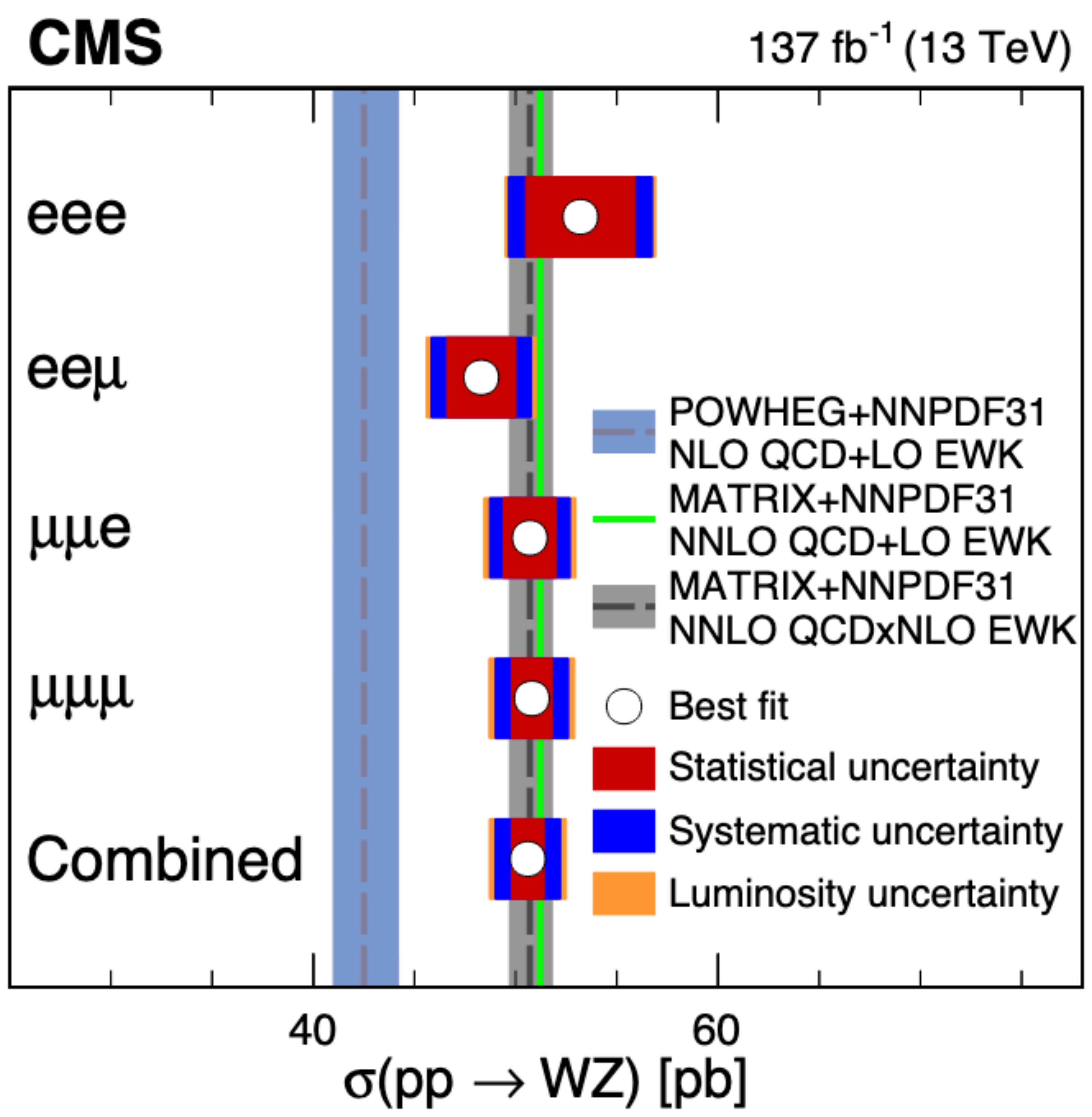
(c) Off-shell ZZ region

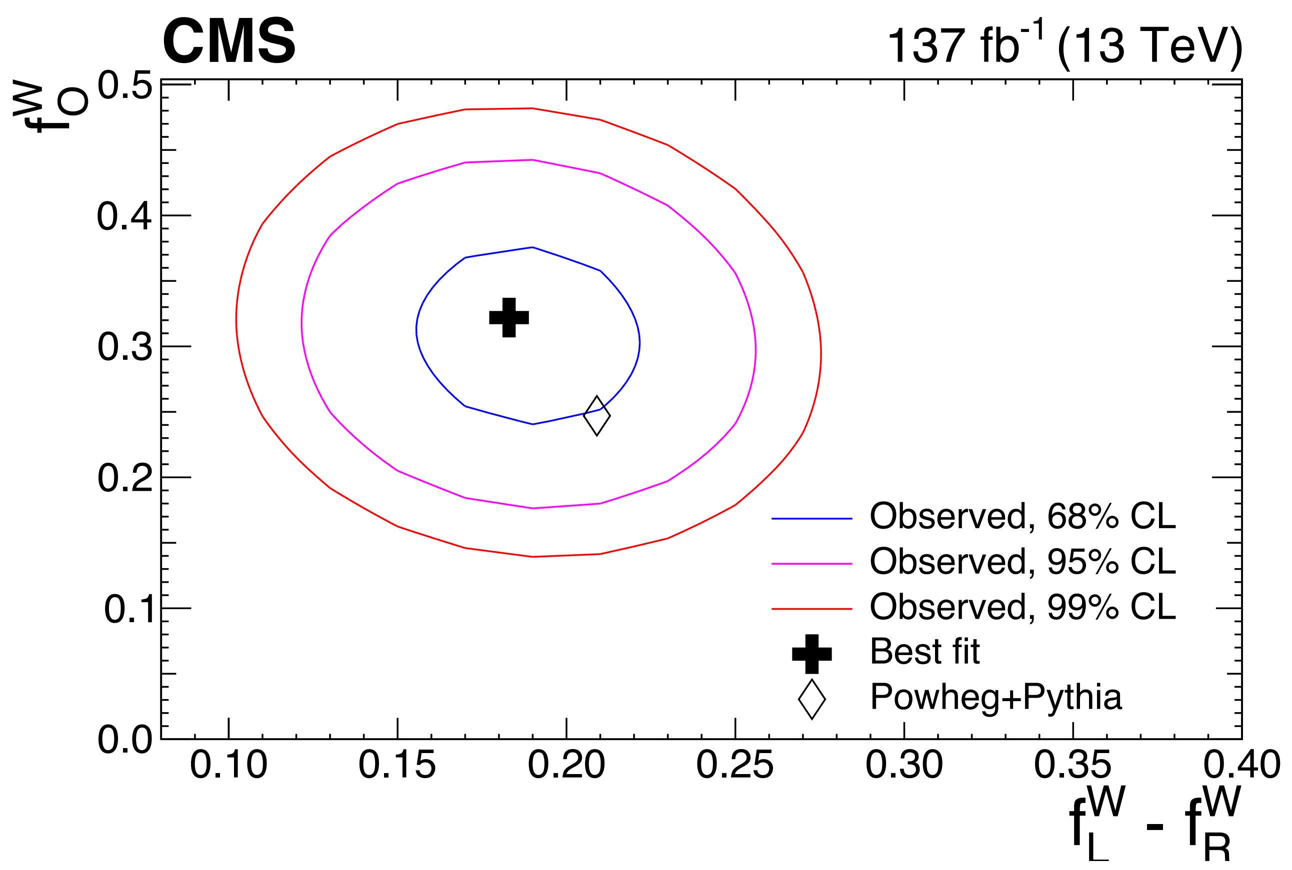
(d) On-shell ZZ region

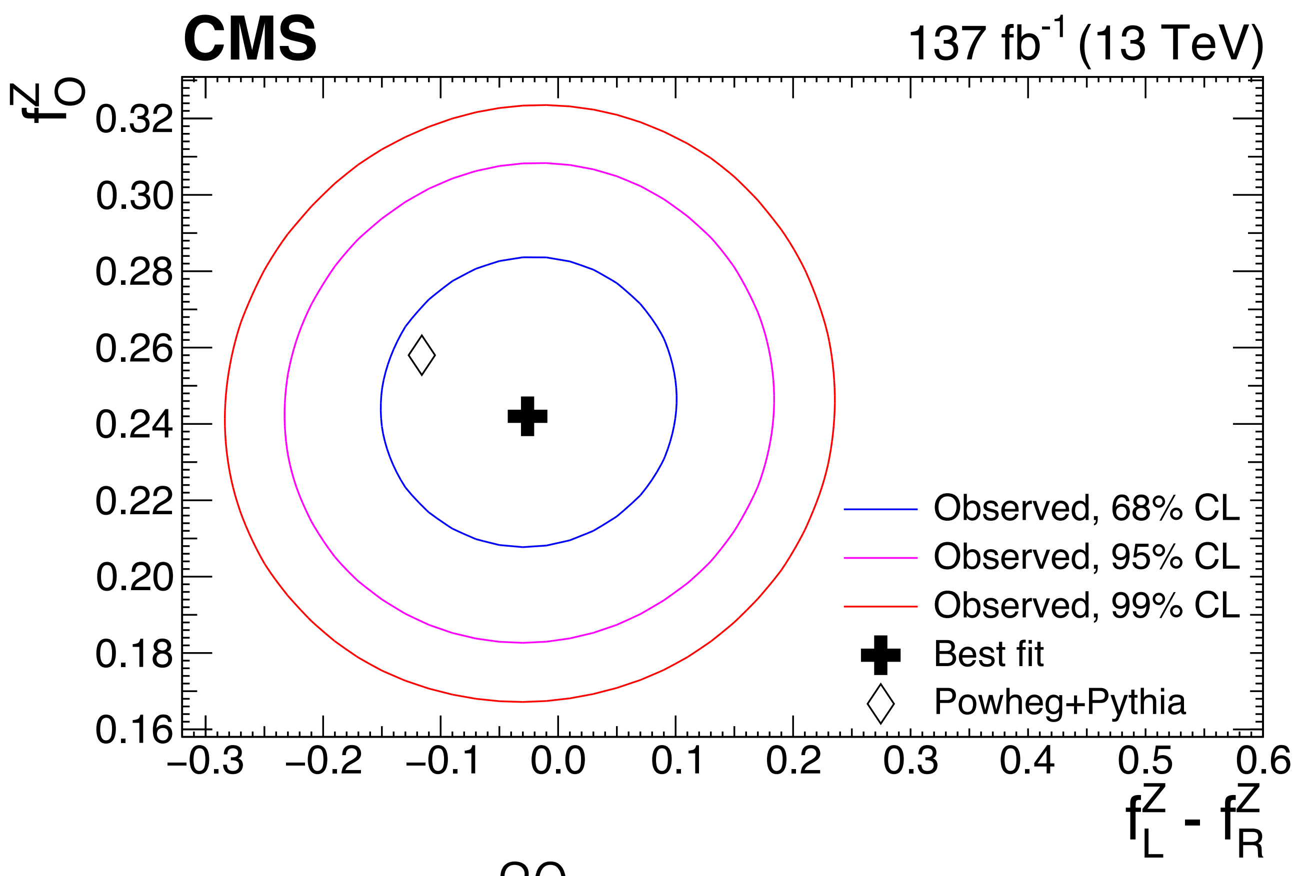
WZ cross section and polarisation CMS-PAS-SMP-20-014

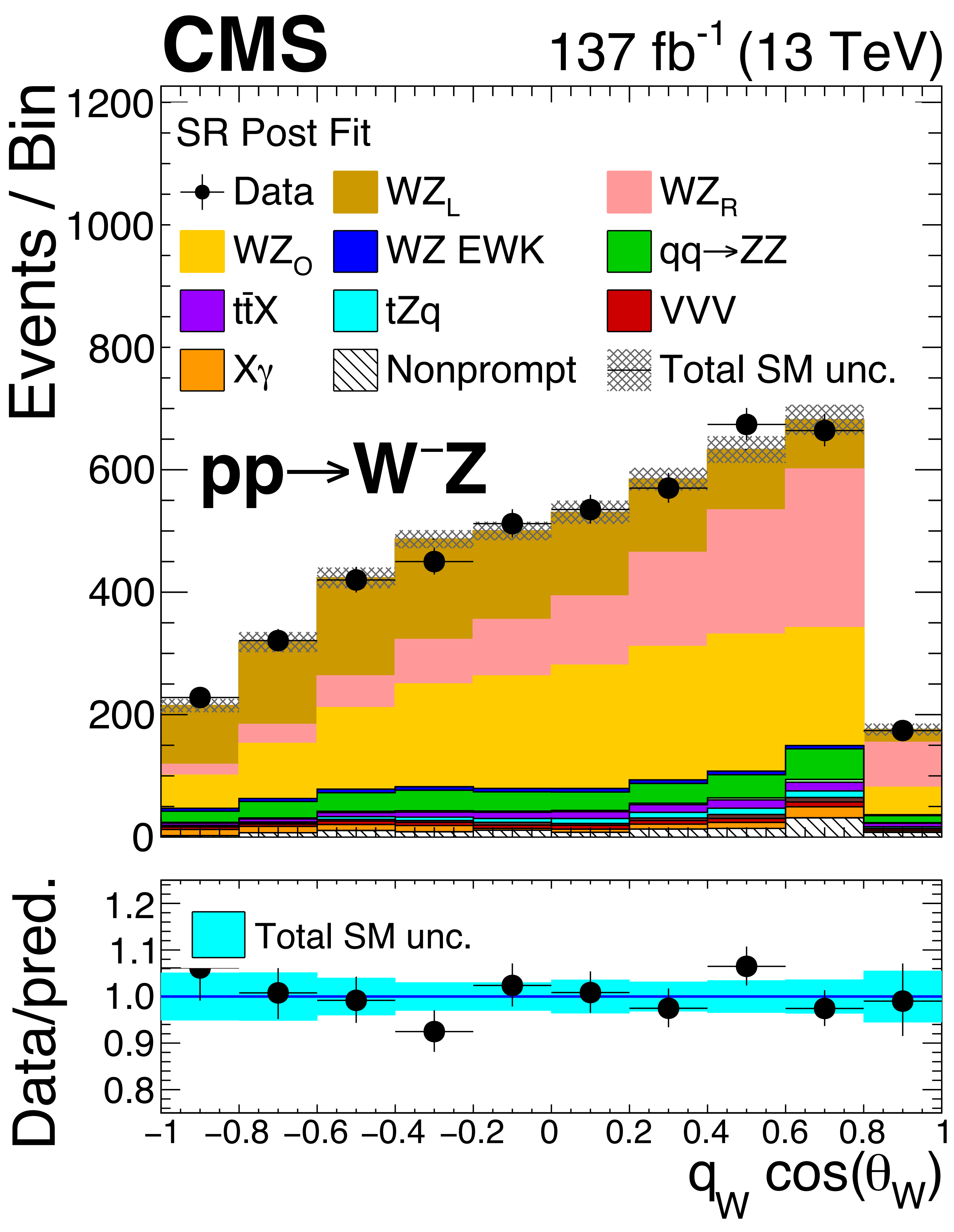
Full Run 2 measurement of WZ by CMS

- Improved precision compared to ATLAS/CMS measurement using smaller dataset
- Differential cross section measurement, charged asymmetry and (single-boson) polarisation
- Longitudinal polarisation from additional degree of freedom introduced by Higgs mechanism
- NNLO QCD gives better description









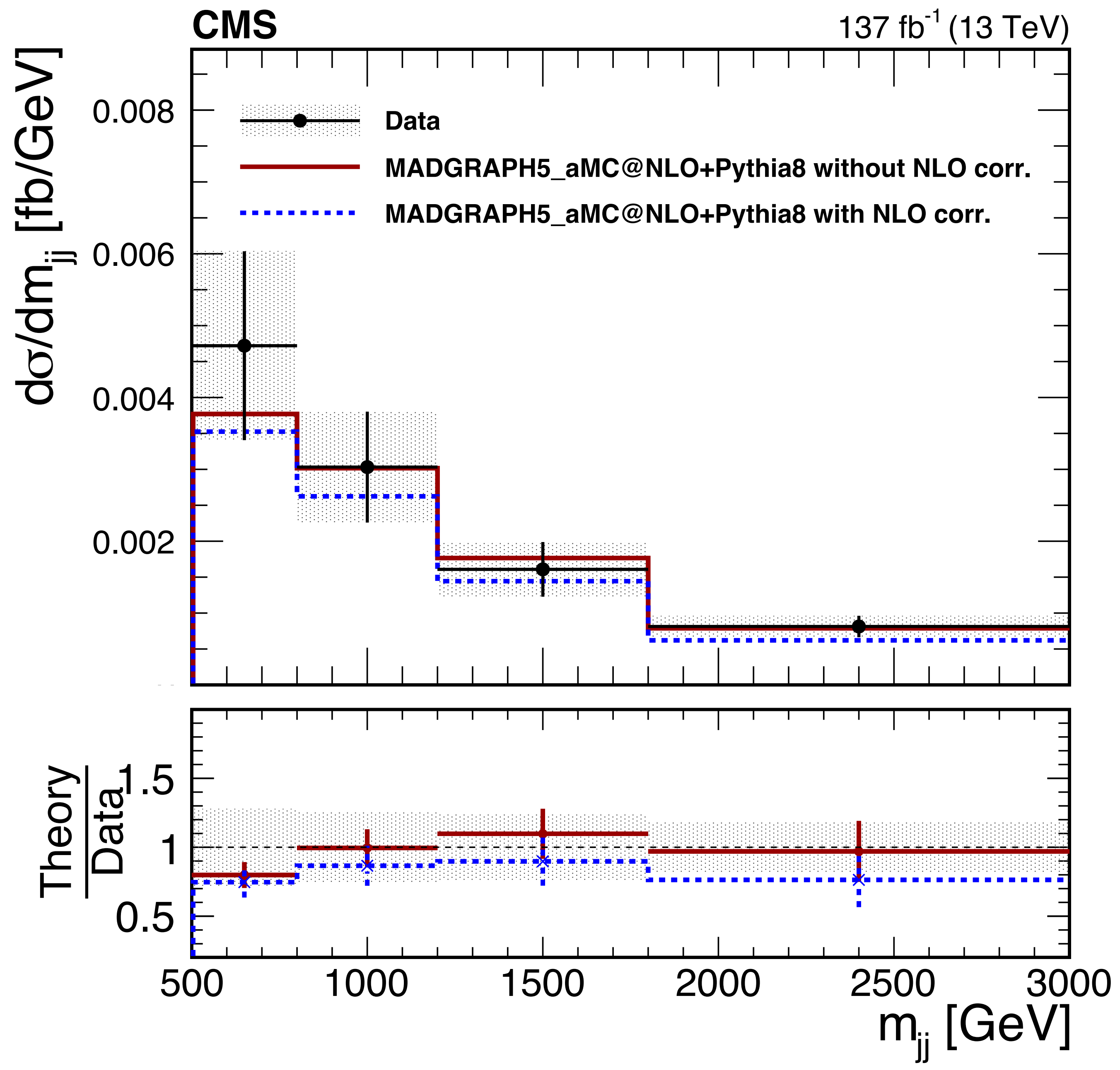
VBS WW and WZ

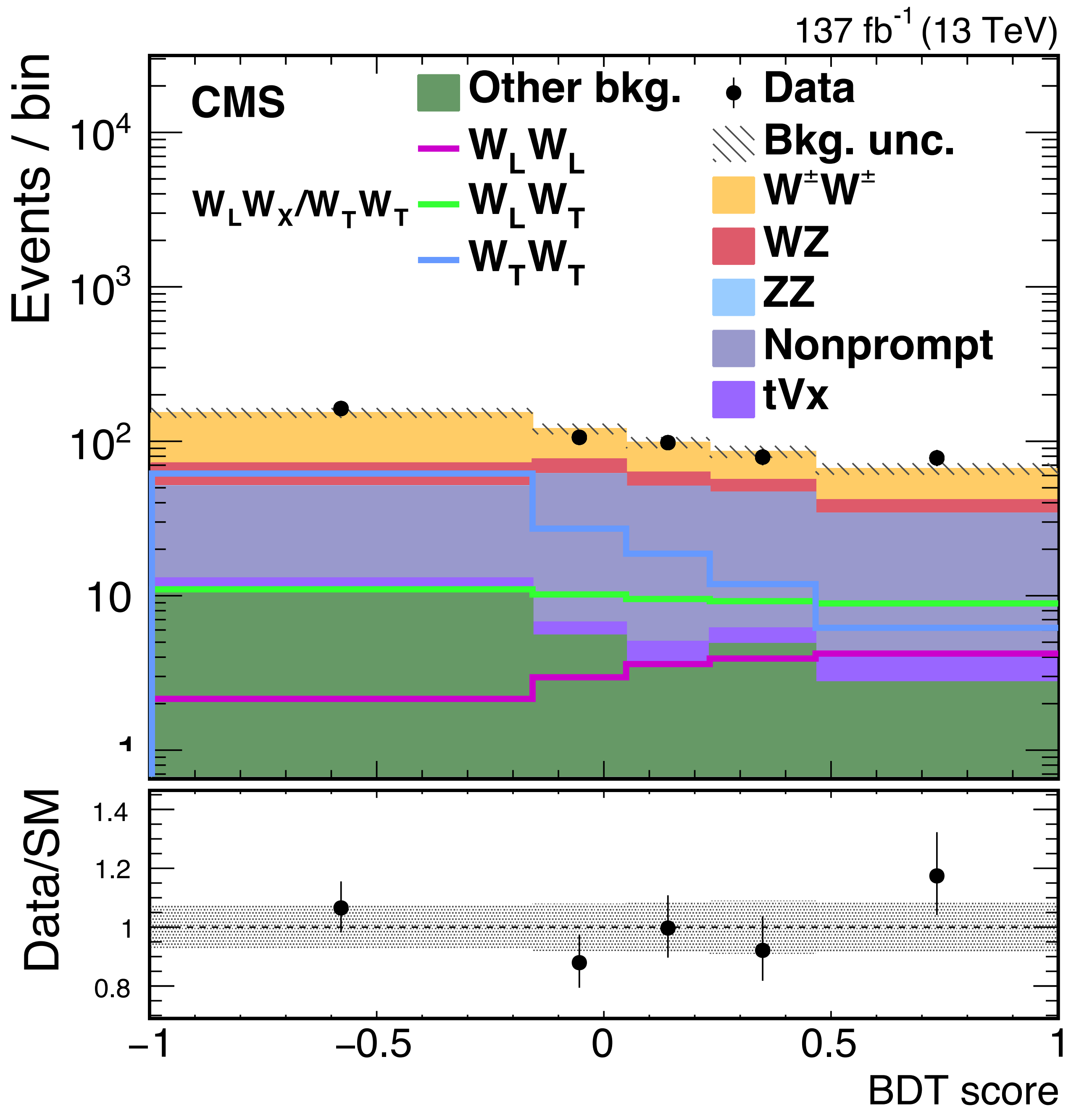
Same-sign electroweak $W^{\pm}W^{\pm}jj$ and WZjj productions observed by ATLAS/CMS with early Run2

- processes well understood at NLO EW and NLO QCD arXiv:2106.01393

Update with full Run 2 and first measurement of $W^{\pm}W^{\pm}jj$ polarisation fractions by CMS

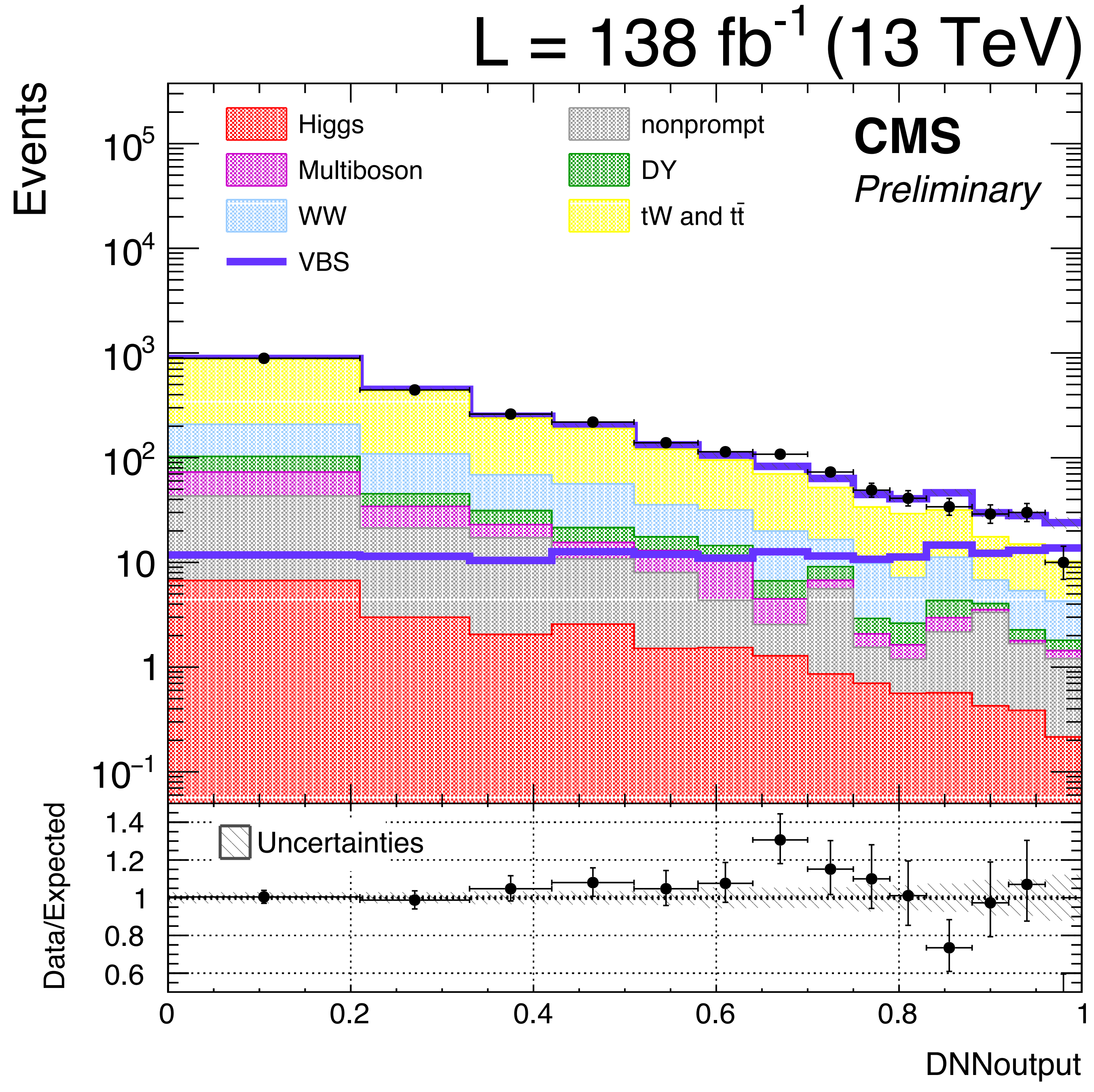
- Significance for W_LW_X of 2.3σ (3.1σ exp.)
  evidence for W_LW_L possible at HL-LHC, see FTR-21-001





Opposite-sign W^+W^-jj production observed by CMS with Run 2

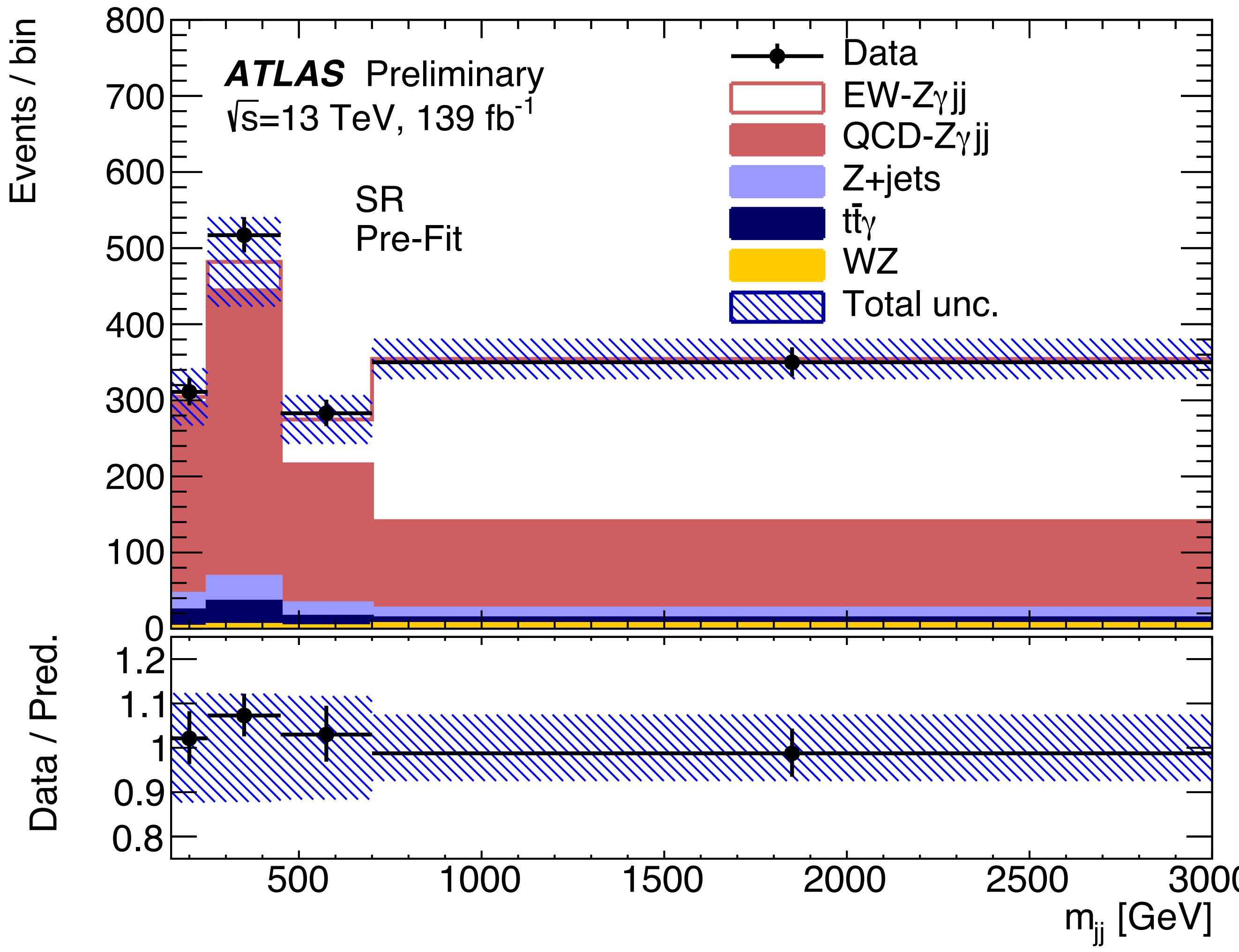
- Significance 5.6σ (5.2 exp.)

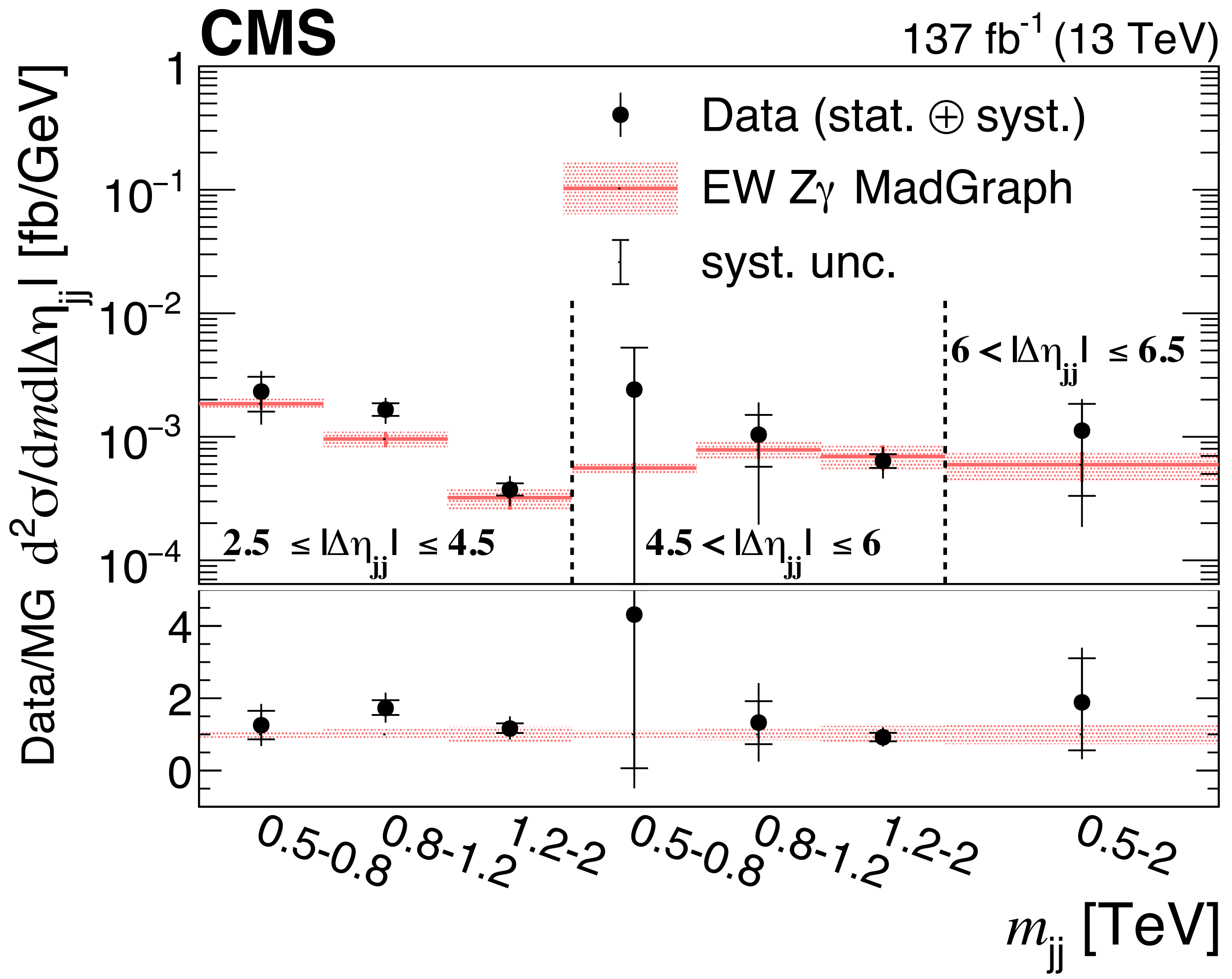


VBS Zγ

ATLAS/CMS cross section measurement of EW production Z(->ll)γ

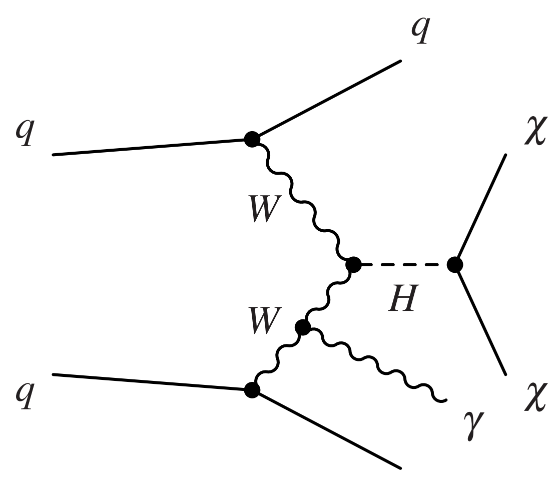
- Single and double differential distribution measured (m_{jj}, $\Delta\eta_{jj}$)
- Most stringent limit to date on the aQGC parameters F_{T9}/Λ^4 by CMS

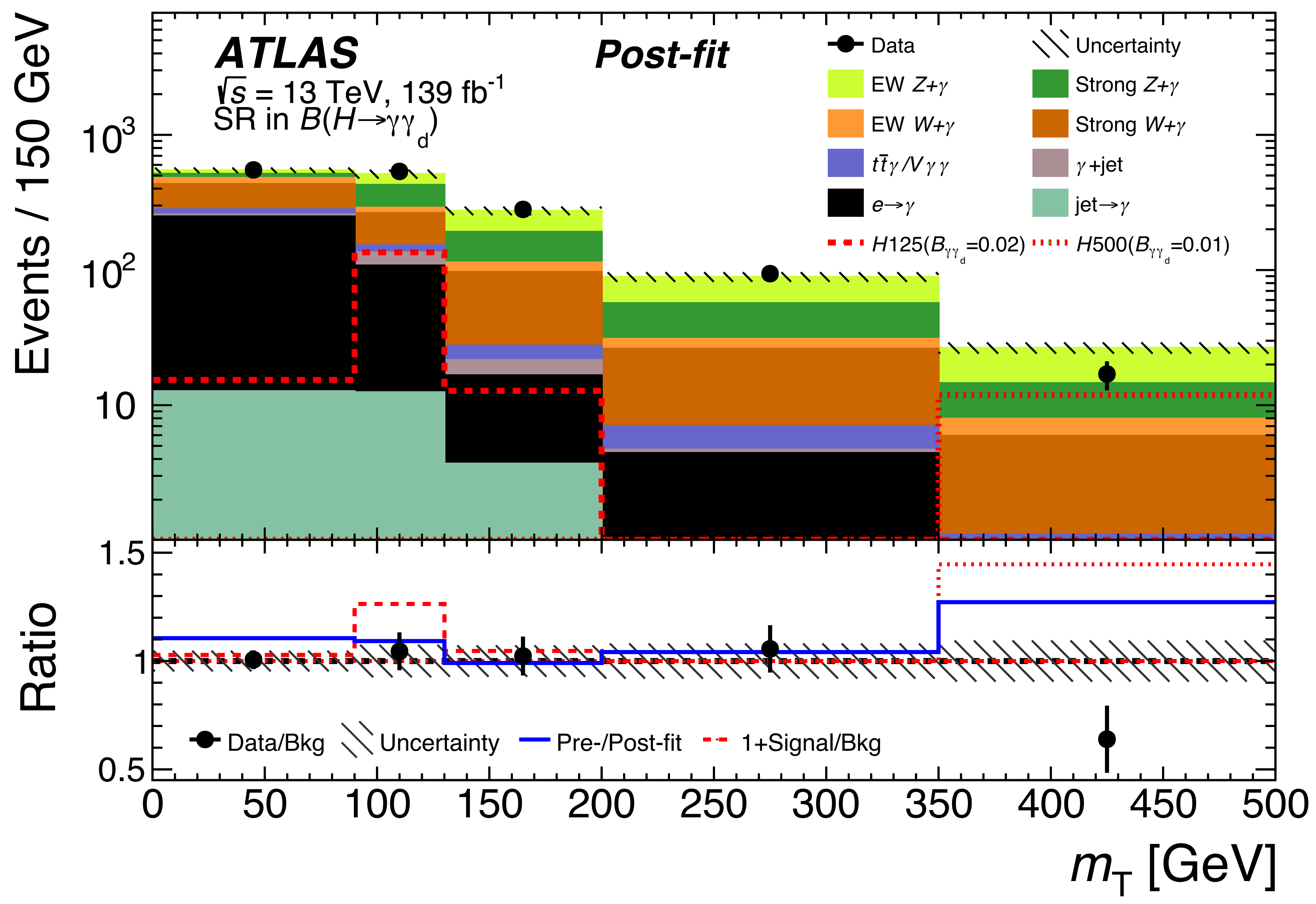




First ATLAS observation of EW production of Z(→νν)γ

- Limits on branching ratio of Higgs to invisible particles
- Best limits on Higgs branching ratio o $\gamma\gamma_D$ (dark photon) at m_H=125 GeV





Photon-induced W+W- and γγ

PLB 816 (2021) 136190
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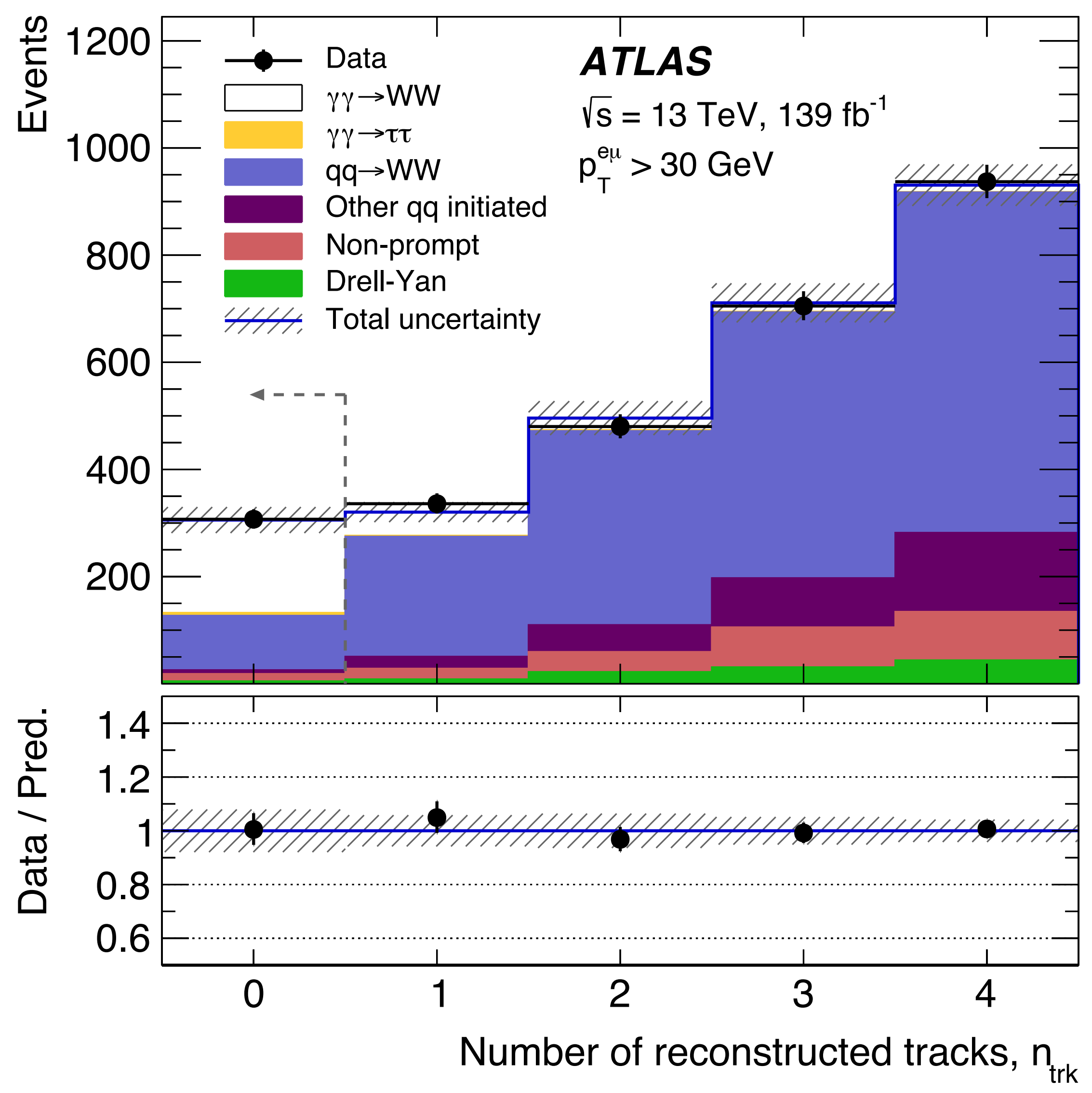
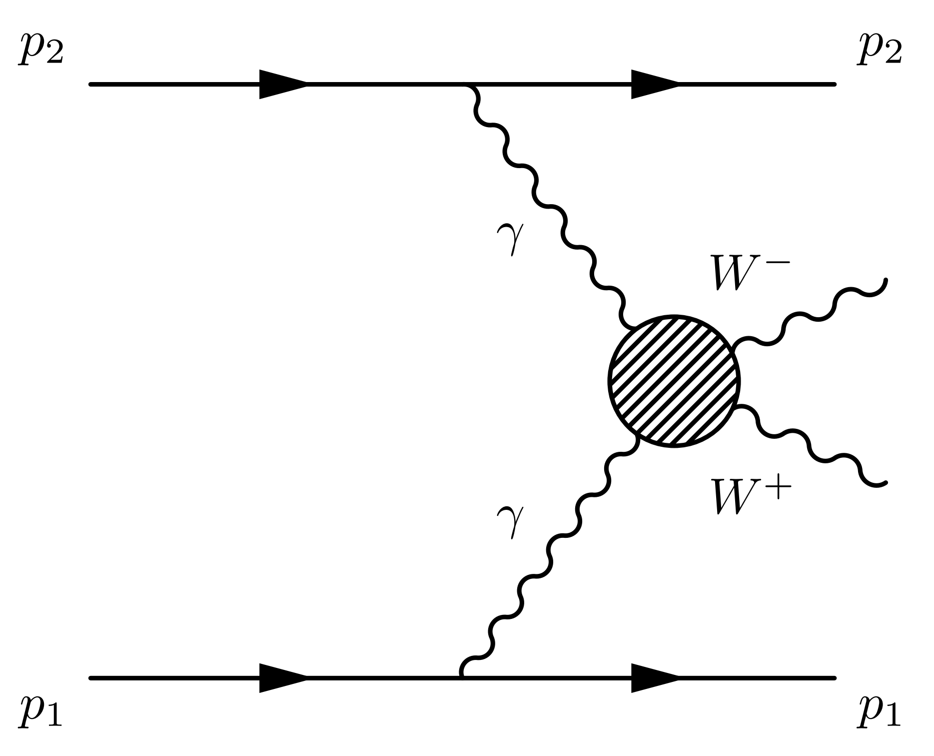
LHC as a photon-photon collider to test electroweak physics

Observation of photon-induced WW process in ATLAS

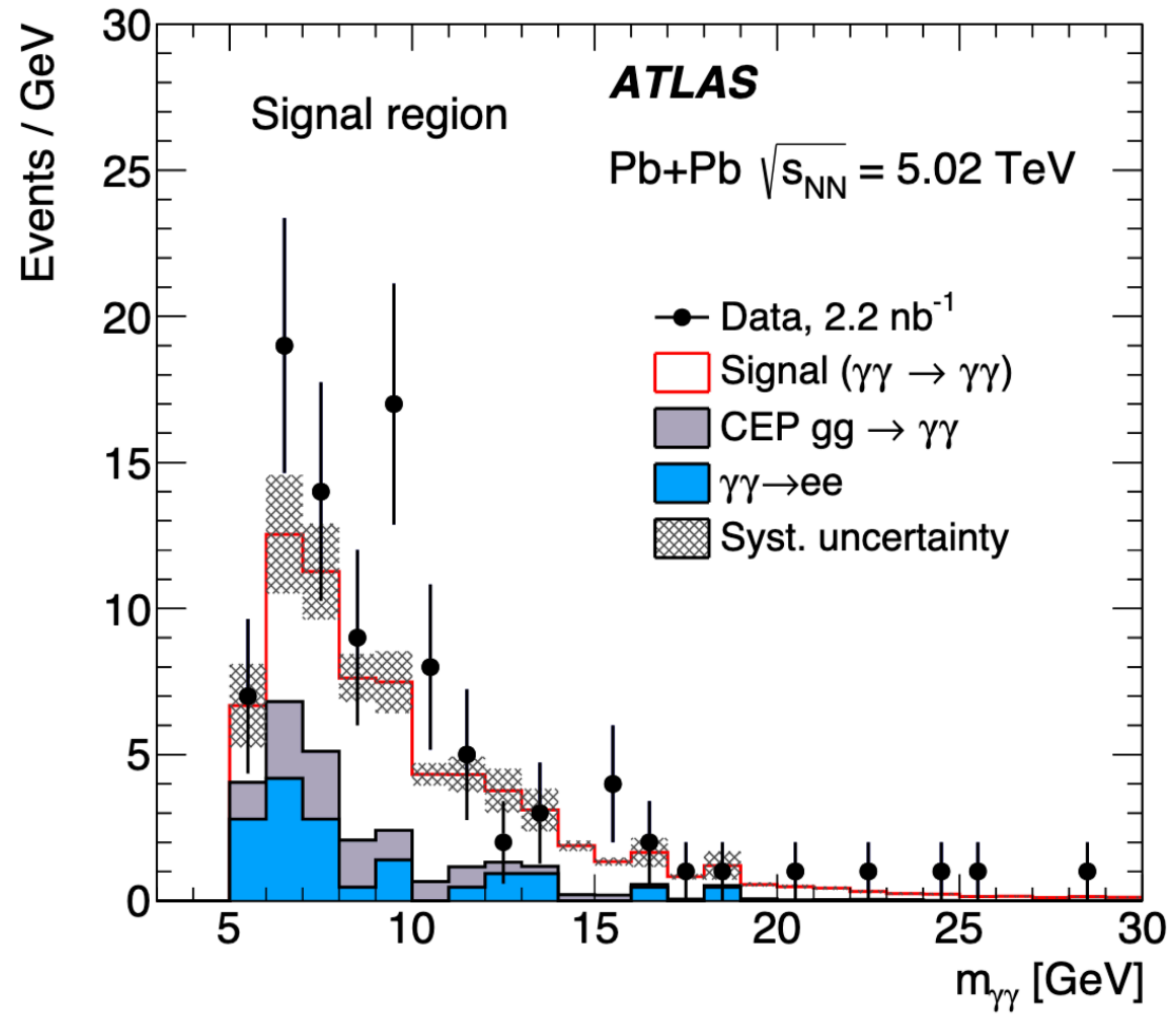
- Signal selected by requirement 0 tracks associated with reconstructed vertex (except selected eμ)

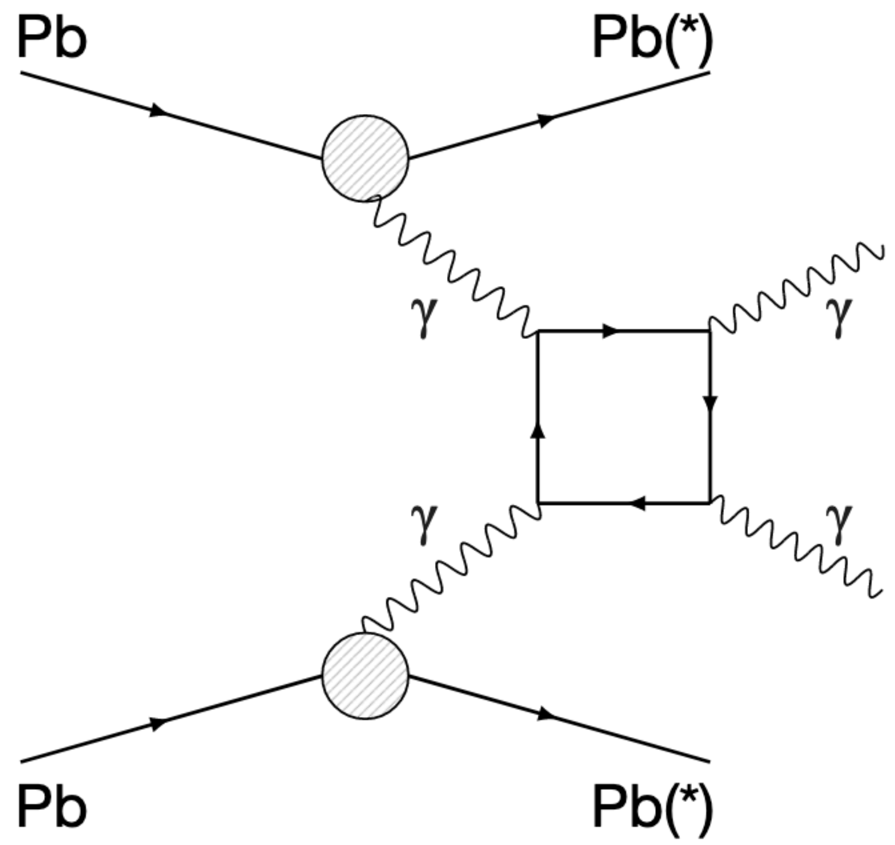




Measurement of light-by-light scattering in PbPb collisions

- Slight access, consistent within 2σ with SM





Forward proton tagging in ATLAS/CMS

- Ongoing effort to use dedicated detectors installed ~220 m from the interaction point to detect scattered protons

Wγγ and Zγγ

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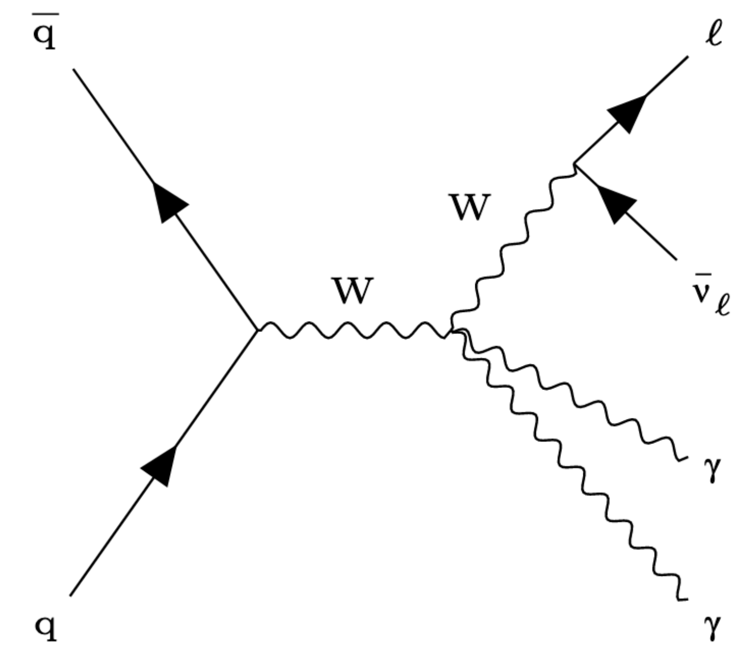
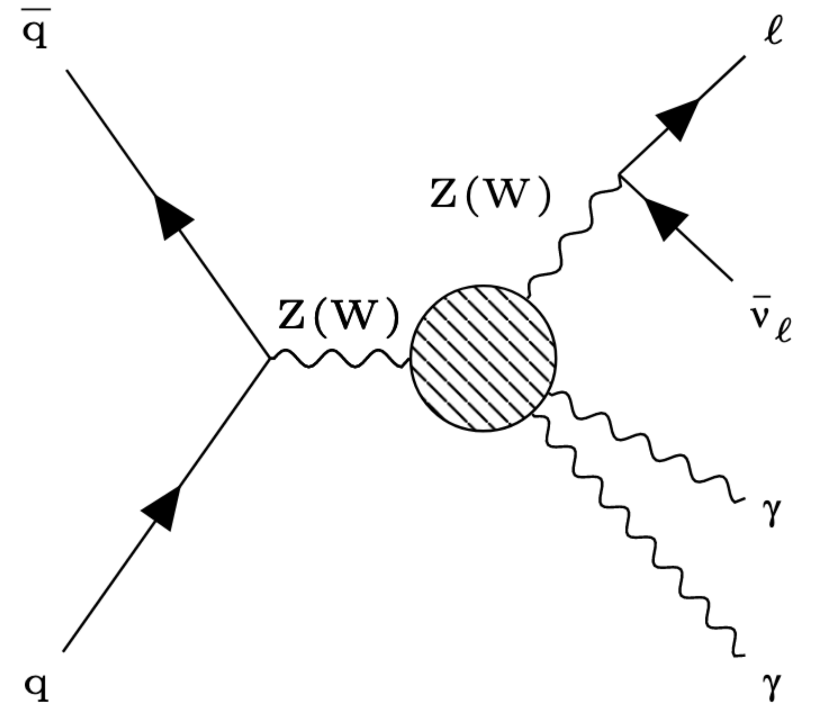
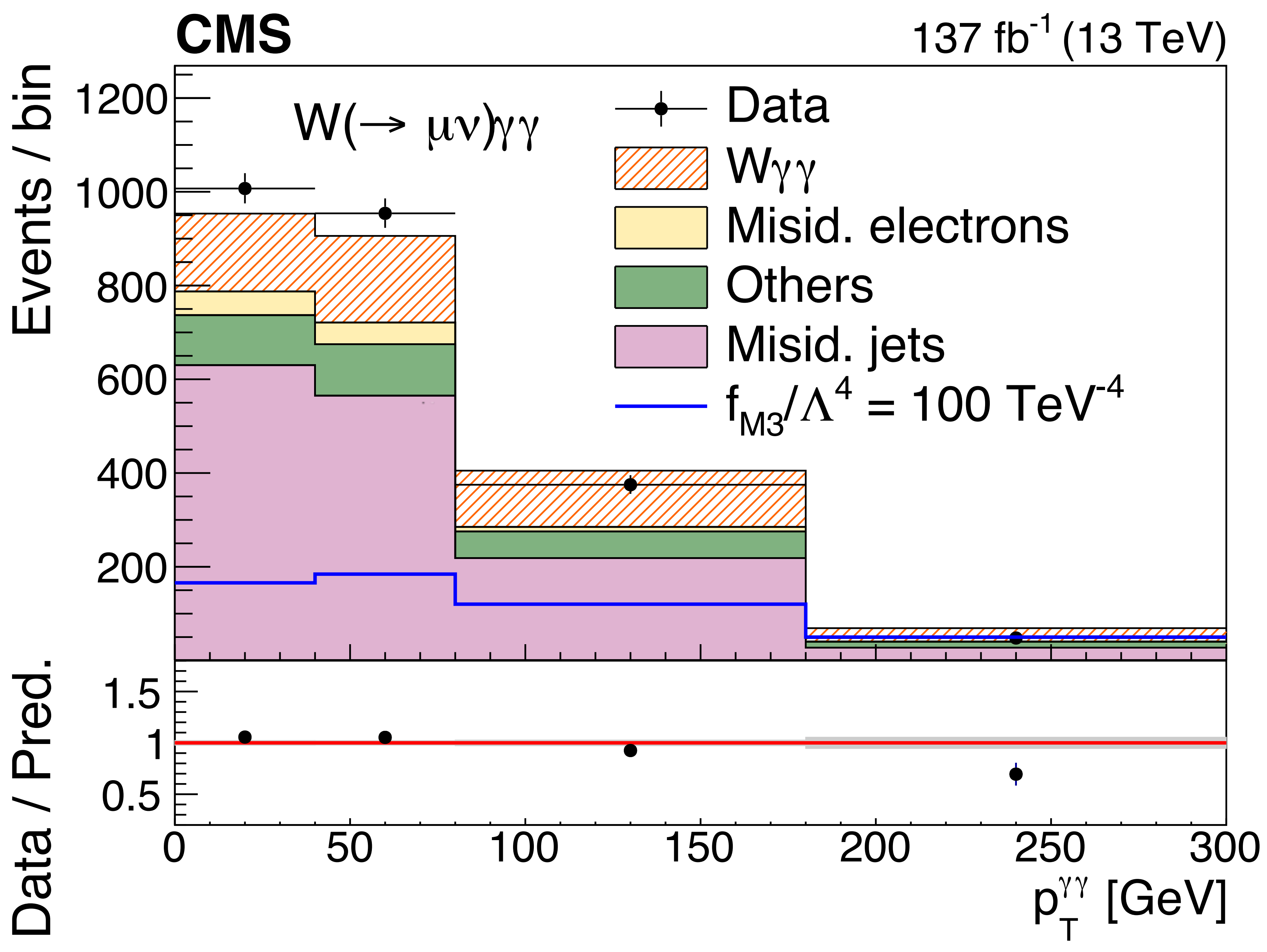
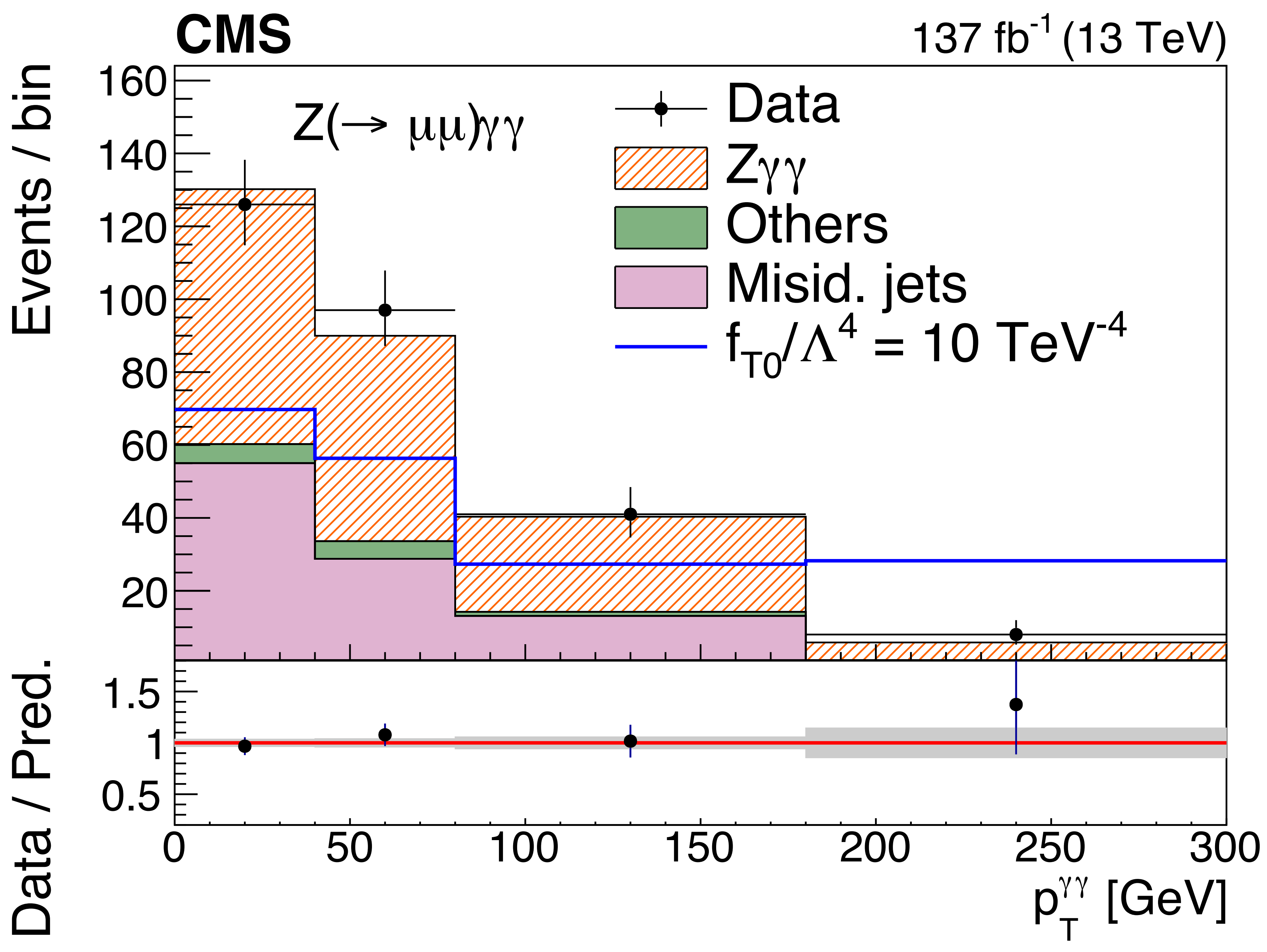
New result on Vγγ by CMS

- Previous measurements only at 8 TeV
- Experimental limitations are the photon reconstruction (efficiency) and background (jet faking photons)
- Background only hypothesis reject with 3.1σ and 4.8σ significance
- Measurement compatible with SM, limits on aQGC







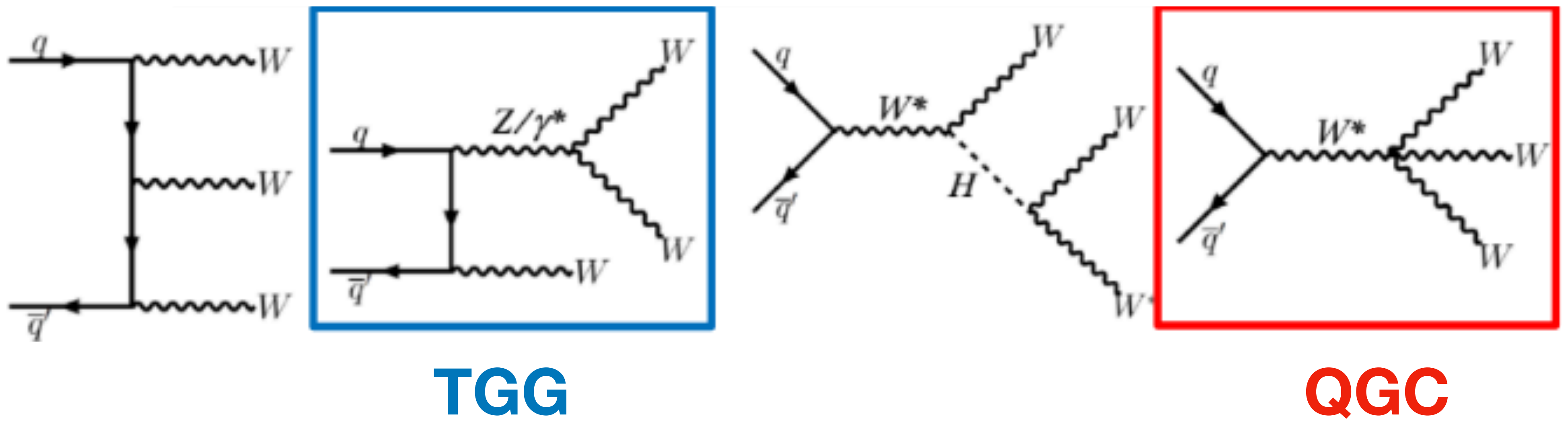


WWW in ATLAS

ATLAS-CONF-2021-039

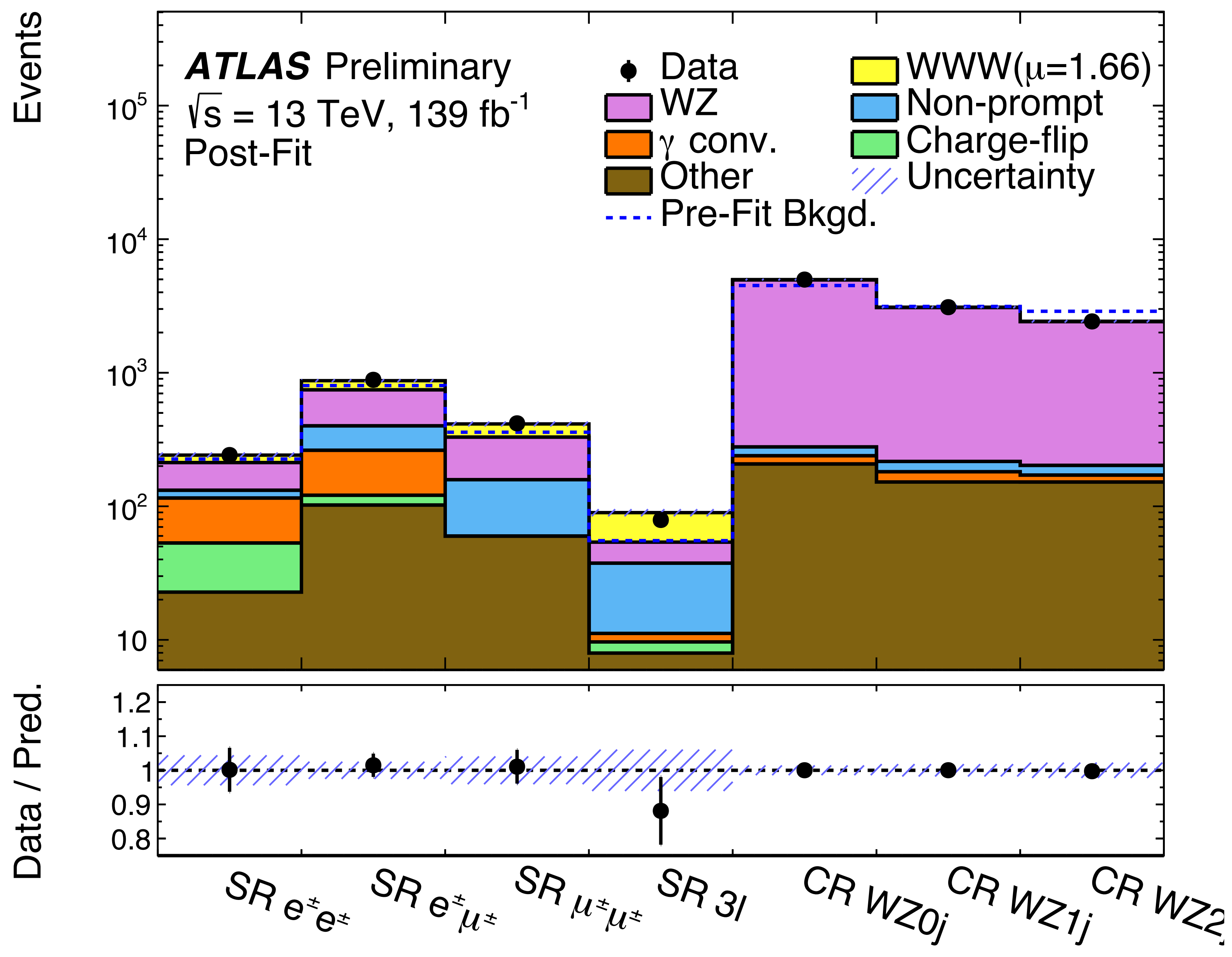
Observation of three massive gauge bosons at the LHC

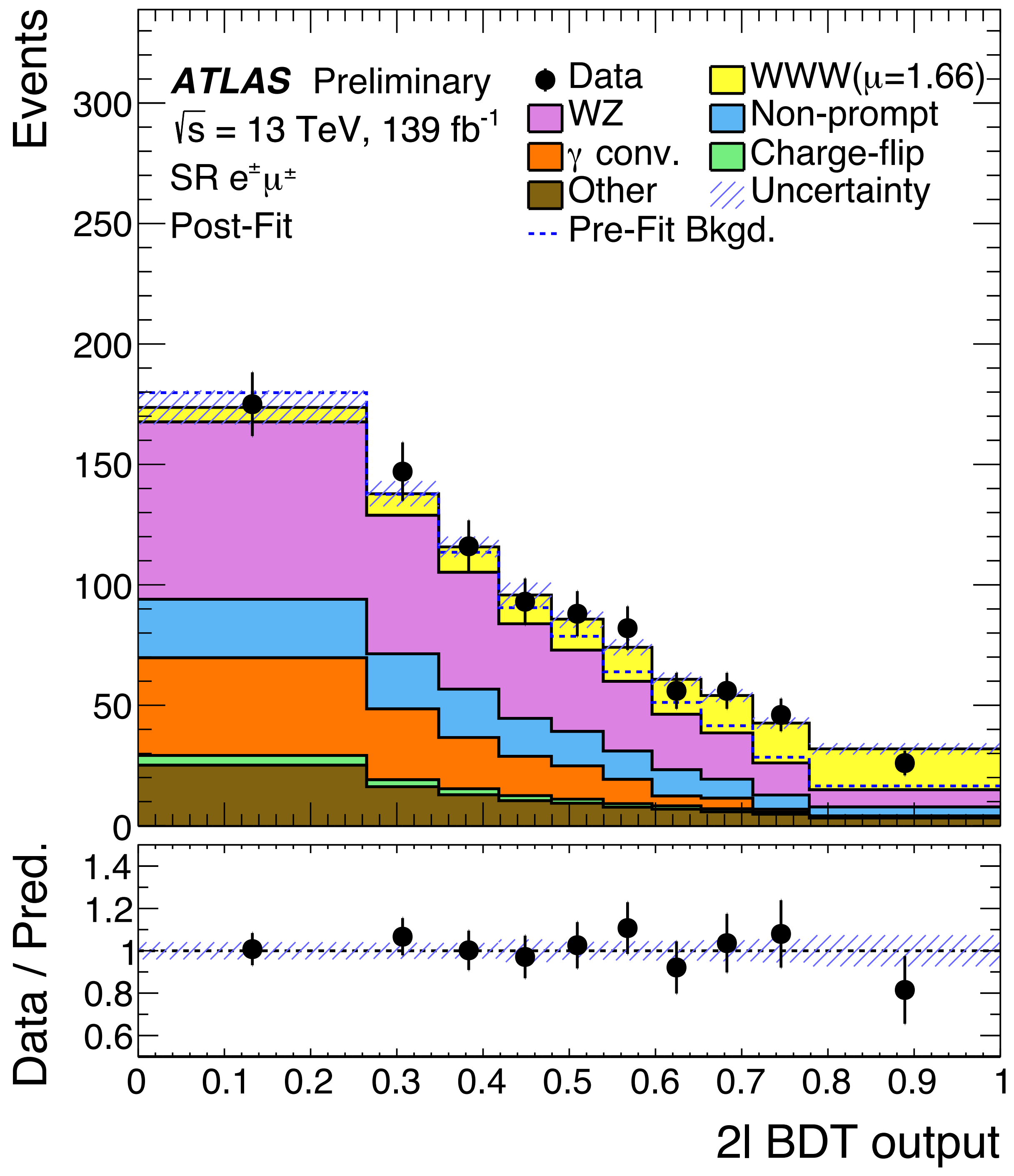
- Combination of WWW and WH→WWW*
- Leptonic and semi-leptonic decays - 2 and 3 lepton signal categories, using BDT to enhance sensitivity
- Systematic uncertainties dominated by the non-prompt background and prompt background modelling



Measured total WWW cross section

- Observed significance 8.2σ
- Signal strength = 1.66 ± 0.28
- About 2.4σ tensions between measured and predicted cross sections





Summary

EW precision parameters with full Run 2 data still to come

Diboson cross section all measured and in good agreement with state-of-the art predictions

- Precision measurements and improvements in the tails

First observation of three heavy gauge bosons at the LHC

Many VBS/VBF processes observed

- More precise measurement will benefit from Run 3 dataset and HL-LHC

No significant deviation from Standard Model observed

- Ongoing effort to constrain EFT operators, ensure publishing data in a format to allow combination and re-interpretation

Backup

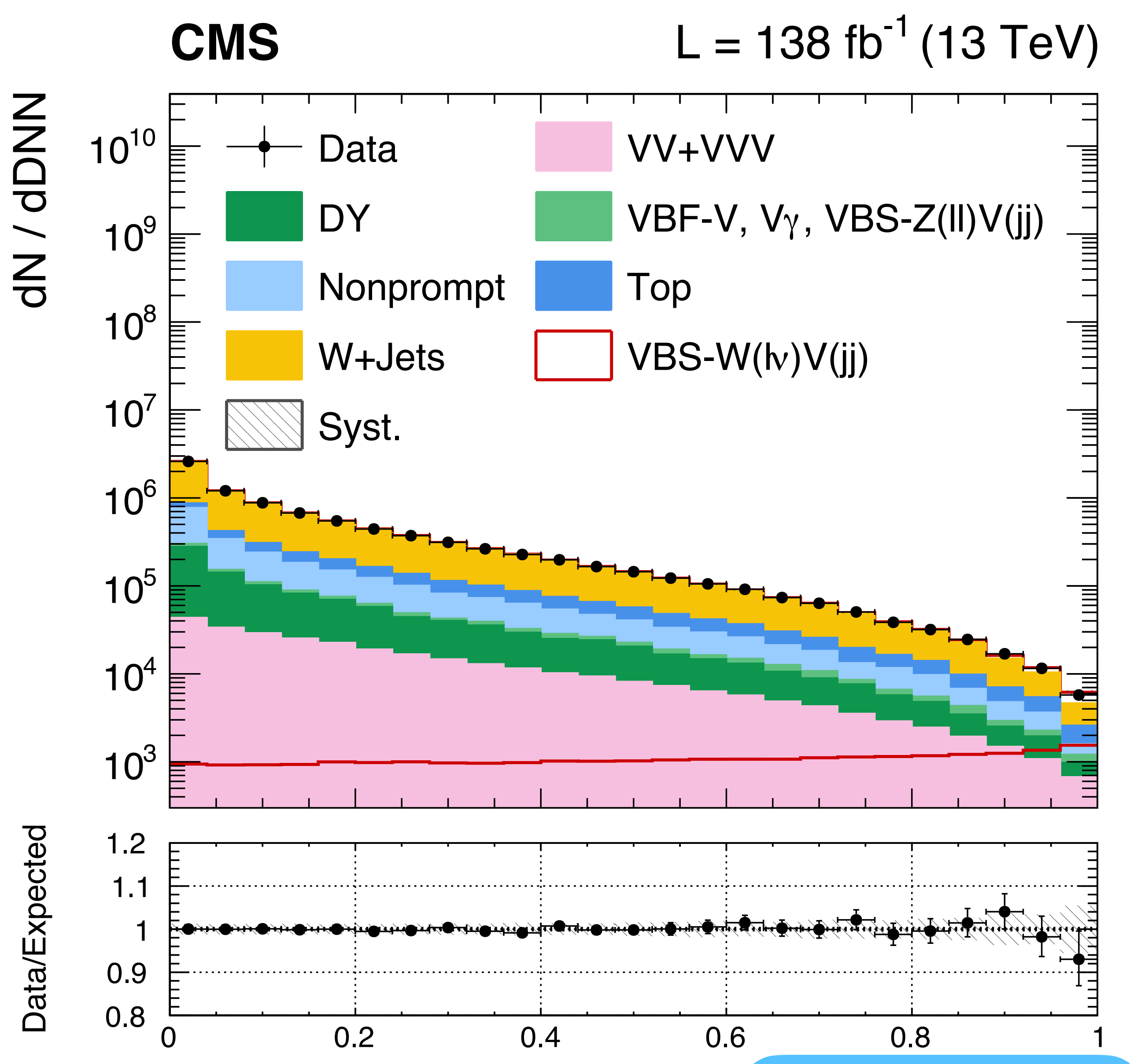
Search for semi-leptonic VBS WV

Measurement in semi-leptonic WV decays, WV(→lνjj)jj

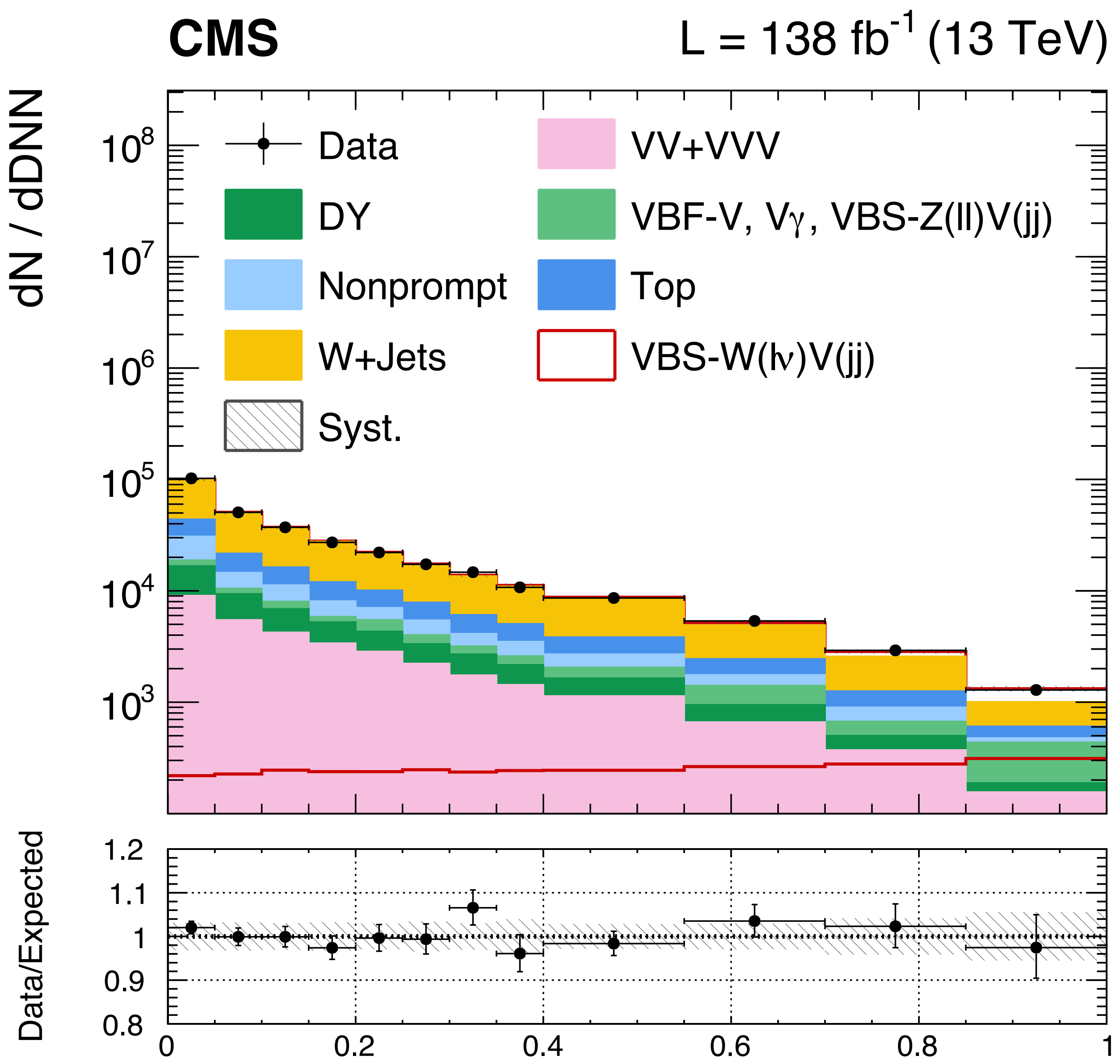
arXiv:2112.0525

- Large backgrounds from W+jet and top quark
- Separated using DNN classifier, resolved and boosted categories
- Background-only hypothesis rejected with 4.4σ (5.1σ expected)

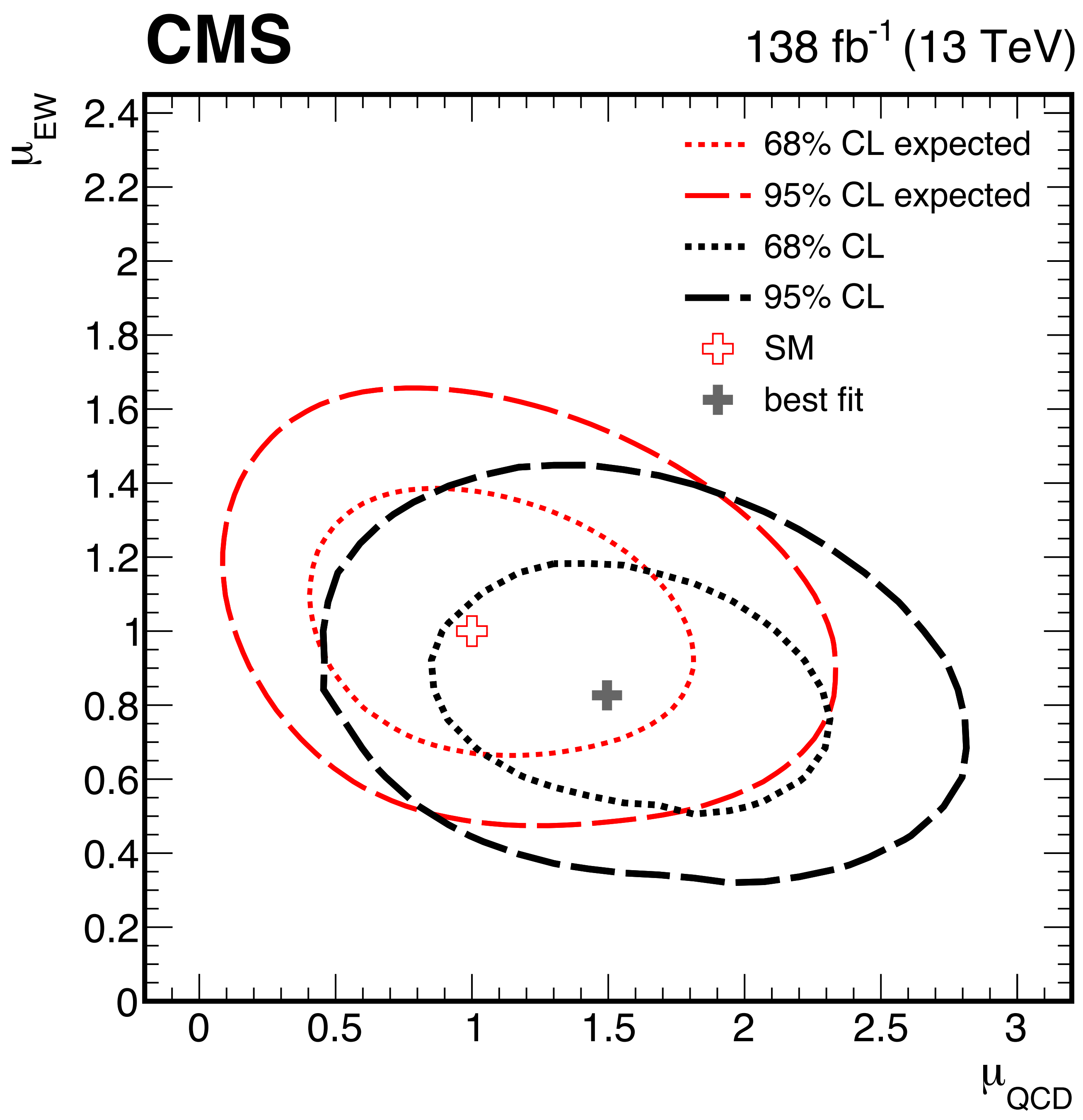
Previous results using 35 fb^{-1} data by ATLAS and CMS



DNN resolved



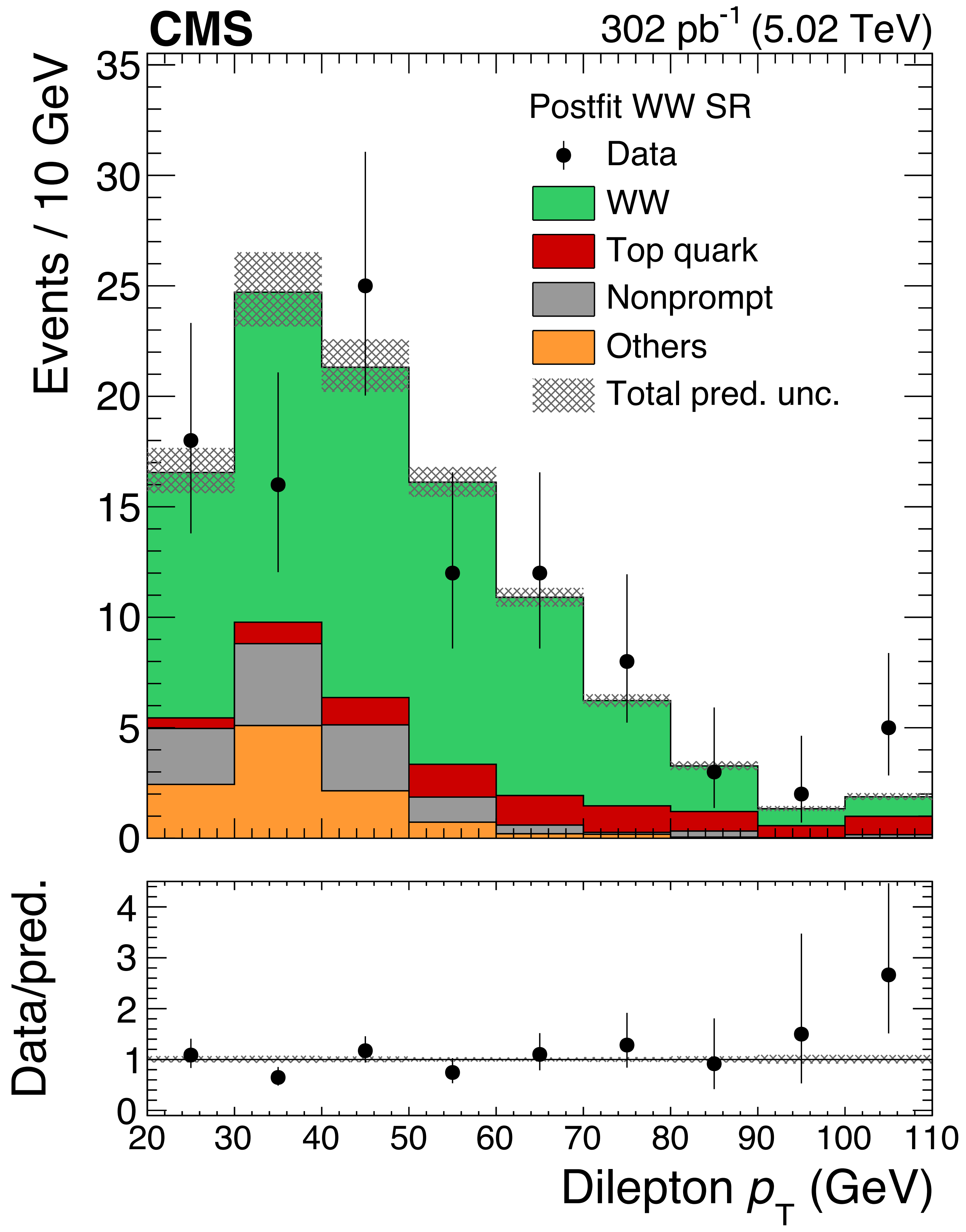
DNN boosted

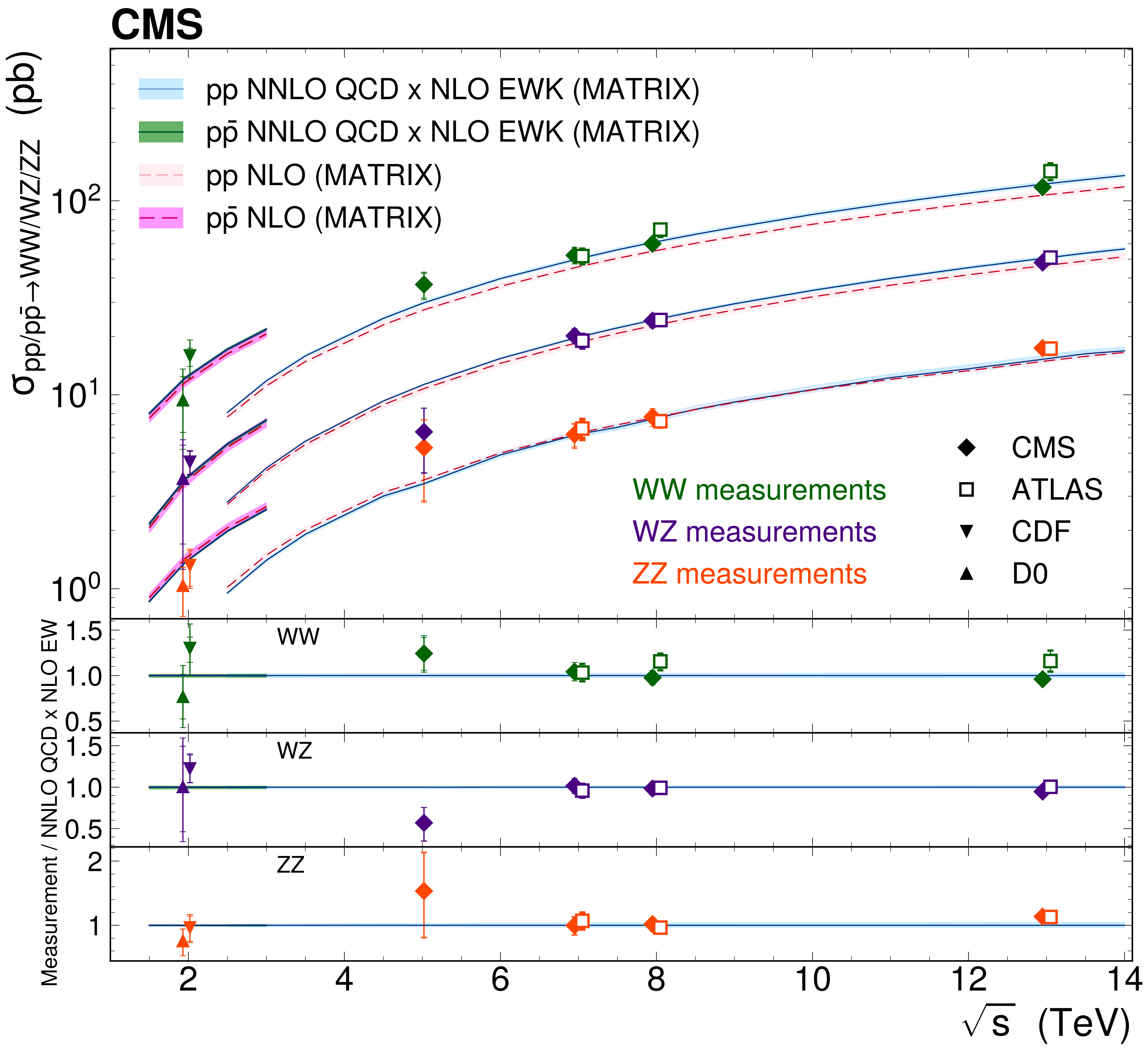


Dibosons at lower energy

CMS measusured WW, WZ, ZZ cross section at 5.02 TeV

- Good agreement seen for $\sqrt{s}$ evolution, smaller statistical precision



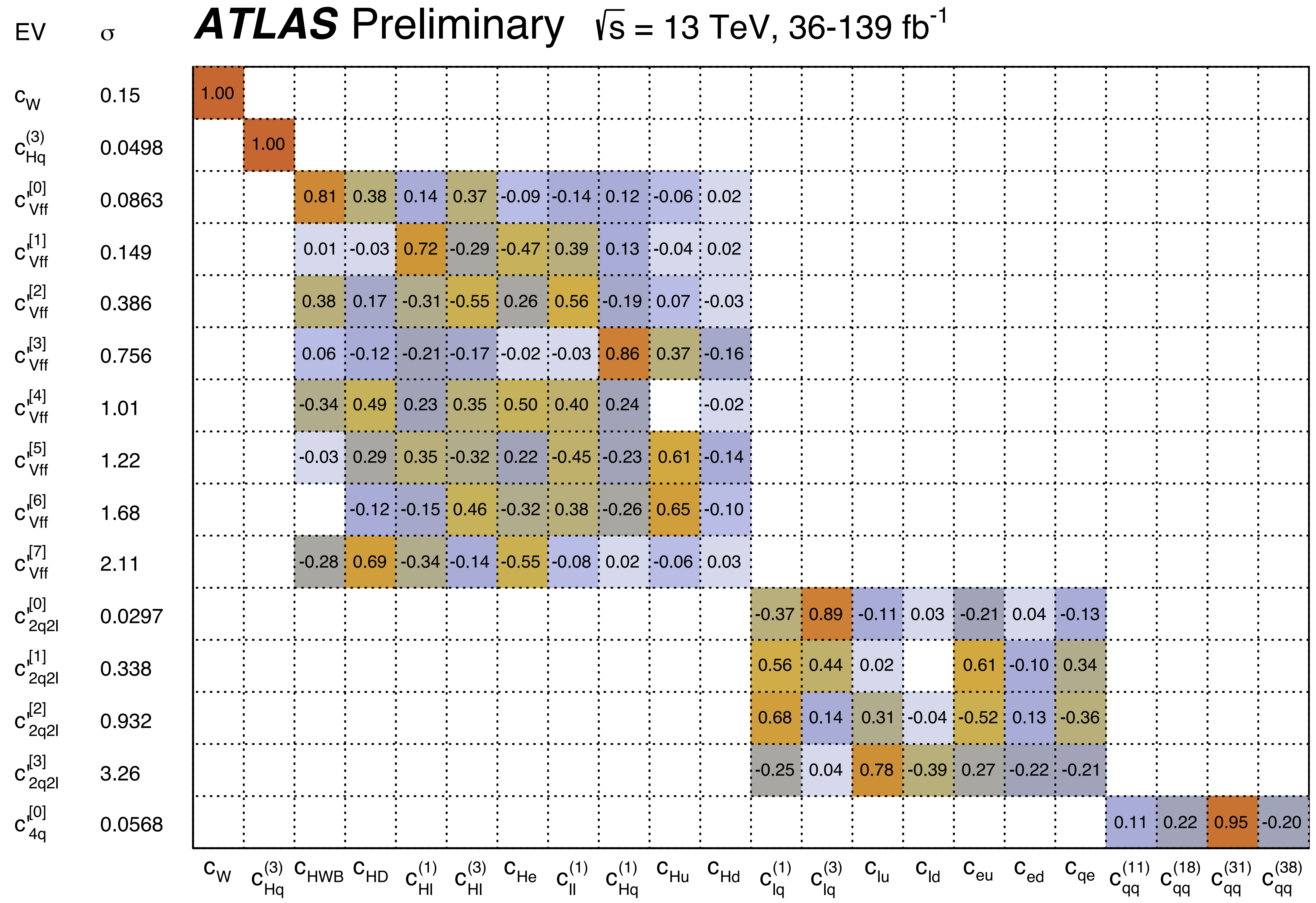


Global SMEFT combination

ATL-PHYS-PUB-2021-022

- Simultaneous constrains of multiple Wilson coefficients achieved by complementarity of WW, WZ, 4l, EW Zjj measurements
  - Limited information prevents constraining all coefficients
  - Sensitivity directions determined using eigenvalue decomposition of the covariant matrix in space of Wilson coefficients

$$\sigma = \frac{1}{\sqrt{\lambda}}$$ Expected uncertainty of eigenvector



- Limits are set on linear combination of Wilson coefficients

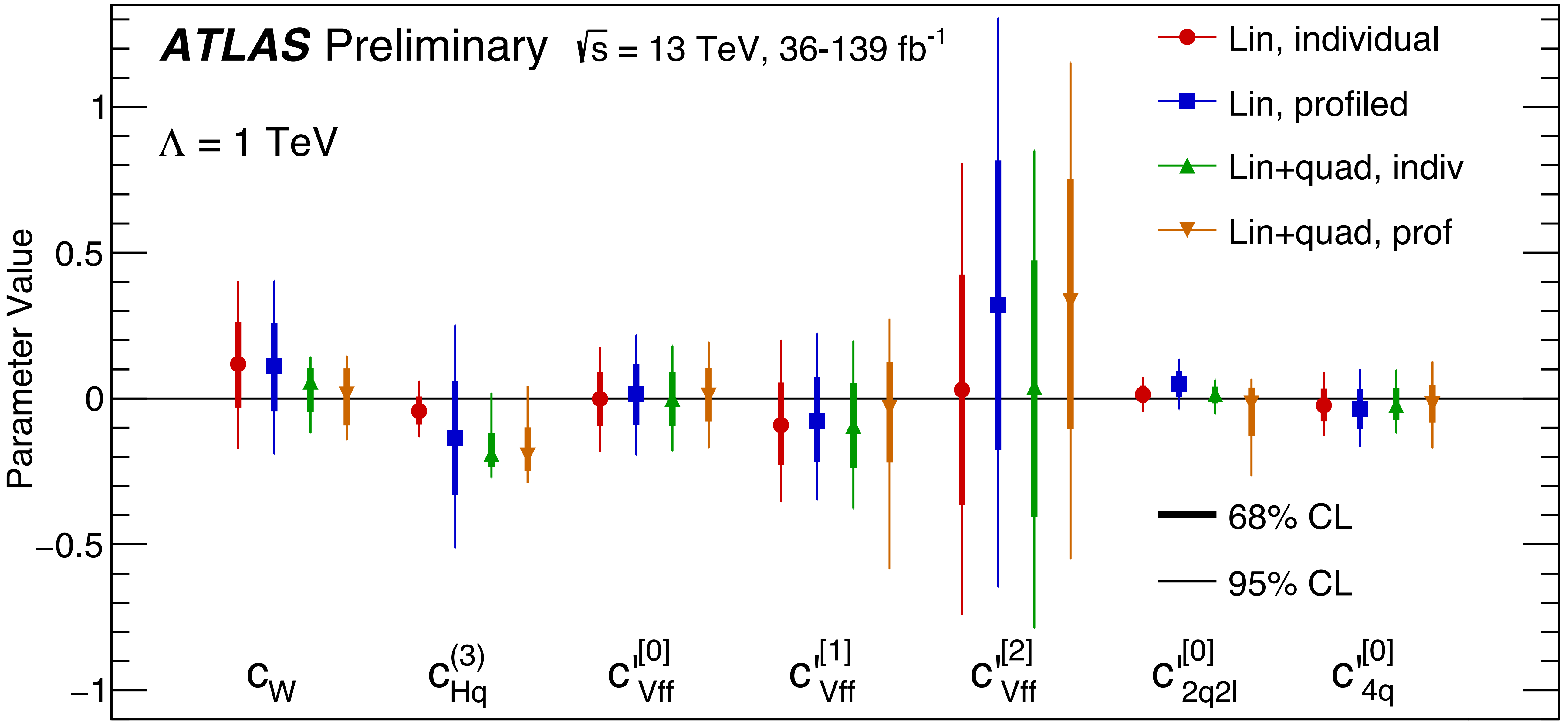
Global SMEFT combination

ATL-PHYS-PUB-2021-022

$$\sigma \propto |\mathcal{M}_{\mathrm{SMEFT}}|^2$$

$$= |\mathcal{M}_{\mathrm{SM}}|^2 + \sum_i \frac{c_i^{(6)}}{\Lambda^2} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)}\mathcal{M}_{\mathrm{SM}}^*\right) + \sum_i \frac{\left(c_i^{(6)}\right)^2}{\Lambda^4}\left|\mathcal{M}_i^{(6)}\right|^2 + \sum_{i<j} \frac{c_i^{(6)} c_j^{(6)}}{\Lambda^4} 2\mathrm{Re}\left(\mathcal{M}_i^{(6)}\mathcal{M}_j^{(6)*}\right)$$

linear quadratic cross



$c'^{[0]}_{Vff} \approx 0.81c_{HWB} + 0.38c_{HD} + 0.13c^{(1)}_{Hl} + 0.37c^{(3)}_{Hl} - 0.14c^{(1)}_{ll} + 0.12c^{(1)}_{Hq}$

$c'^{[1]}_{Vff} \approx 0.73c^{(1)}_{Hl} - 0.28c^{(3)}_{Hl} - 0.48c_{He} + 0.38c^{(1)}_{ll} + 0.13c^{(1)}_{Hq}$

$c'^{[2]}_{Vff} \approx 0.37c_{HWB} + 0.17c_{HD} - 0.31c^{(1)}_{Hl} - 0.53c^{(3)}_{Hl} + 0.25c_{He} + 0.59c^{(1)}_{ll} - 0.21c^{(1)}_{Hq}$

$c'^{[0]}_{2q2l} \approx -0.37c^{(1)}_{lq} + 0.89c^{(3)}_{lq} - 0.11c_{lu} - 0.21c_{eu} - 0.13c_{qe}$

$c'^{[0]}_{4q} \approx 0.11c^{(11)}_{qq} + 0.22c^{(18)}_{qq} + 0.95c^{(31)}_{qq} - 0.2c^{(38)}_{qq}$