Latest highlights by ATLAS
Precision measurements and simulations

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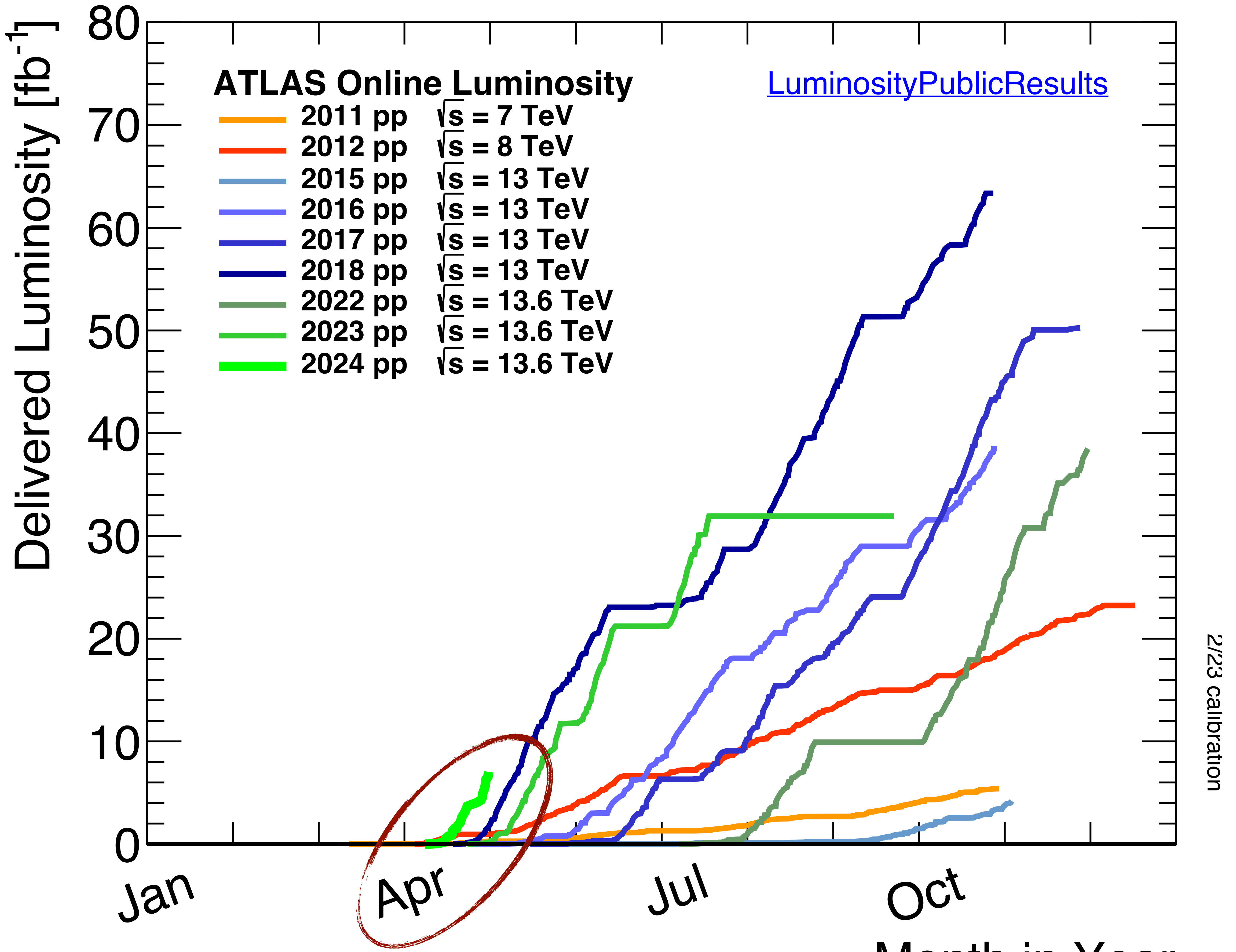
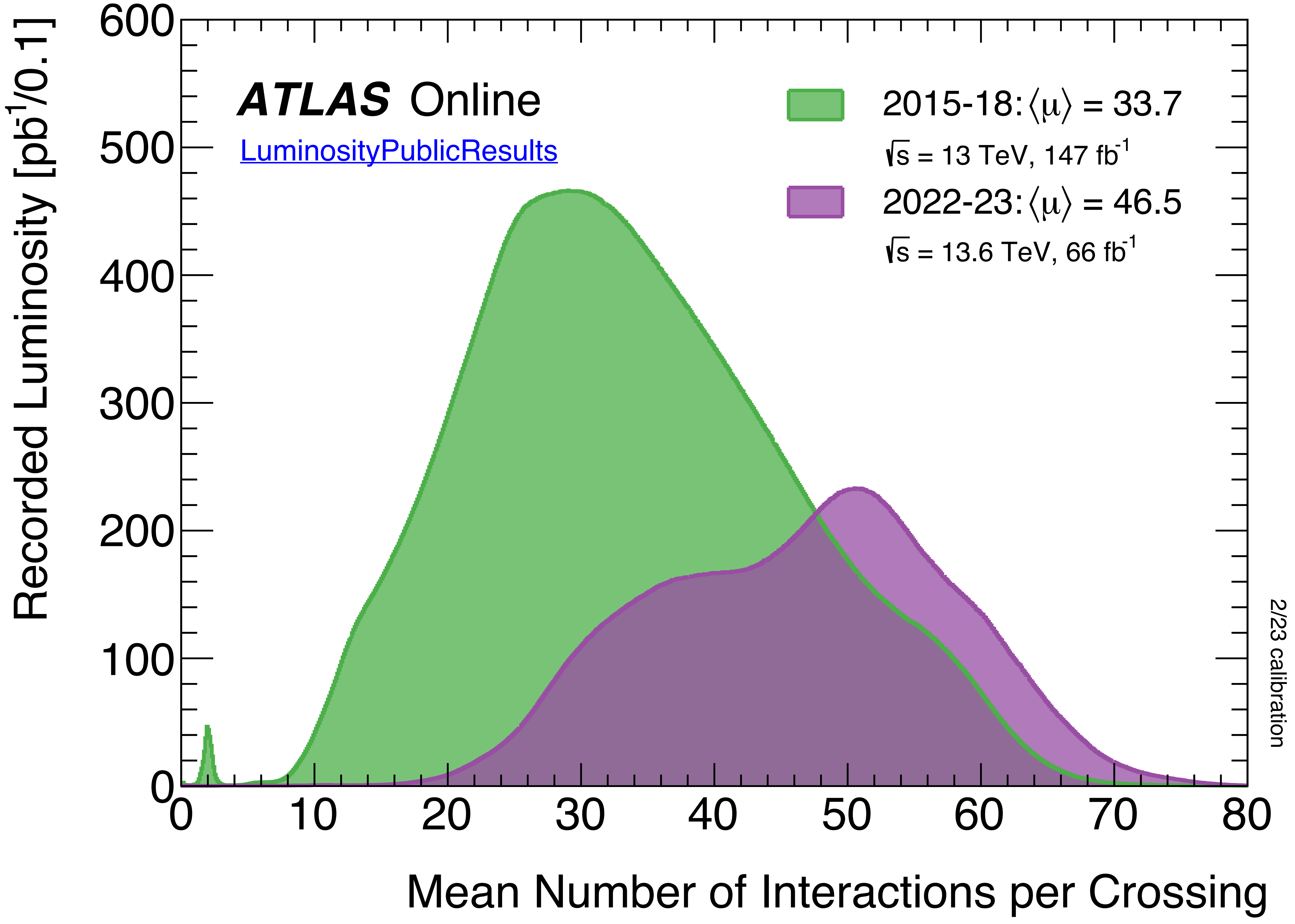
ATLAS EXPERIMENT
"YOU ARE WELCOME HERE!"

ATLAS data taking performance

- Final ATLAS integrated luminosity for Run 2 *pp* collisions at 13 TeV: 140.1±1.2 fb^{-1} (**0.83% precision**)*
  - Very well understood detector performance and calibrations— crucial for precision measurements
- Run 3 data taking at 13.6 TeV underway— about 70 fb^{-1} collected so far
  - Expected to continue through 2025 with a total integrated luminosity of ~250 fb^{-1}
  - Higher pileup than in Run 2, but comparable detector performance thanks to upgrades (e.g. NSW)

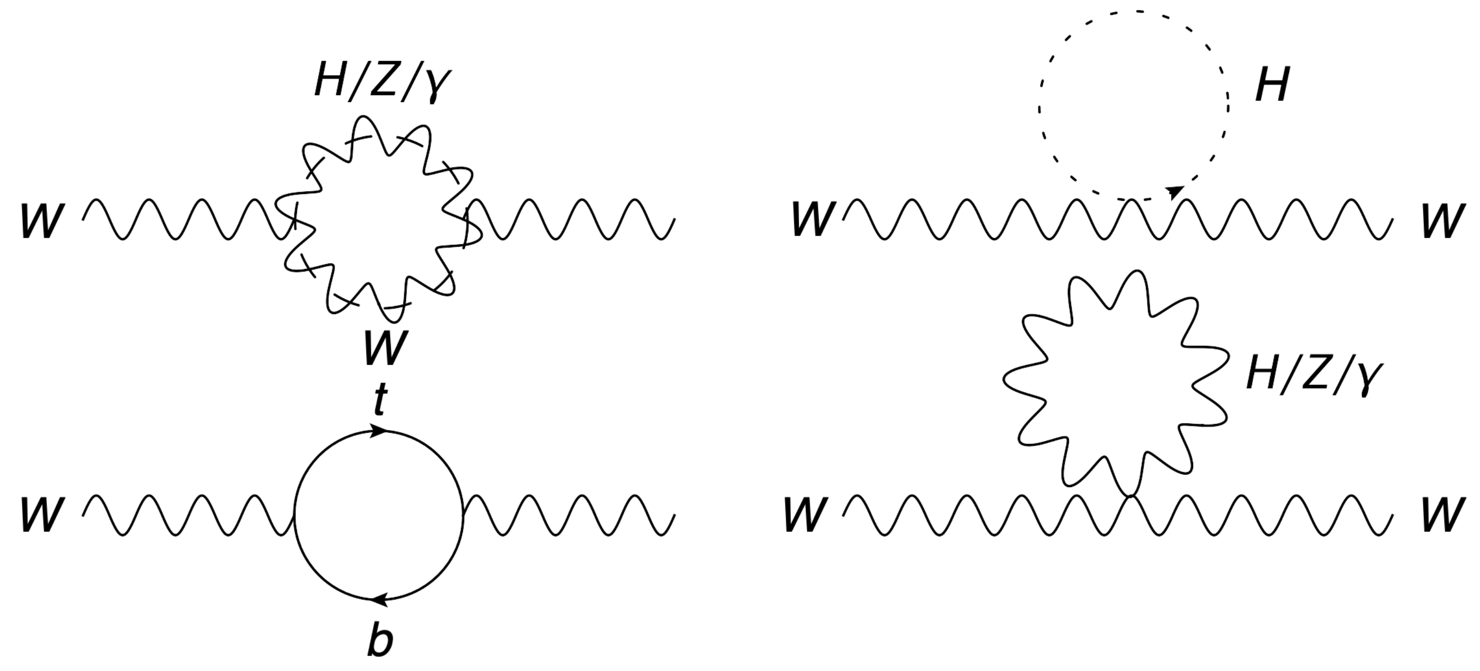


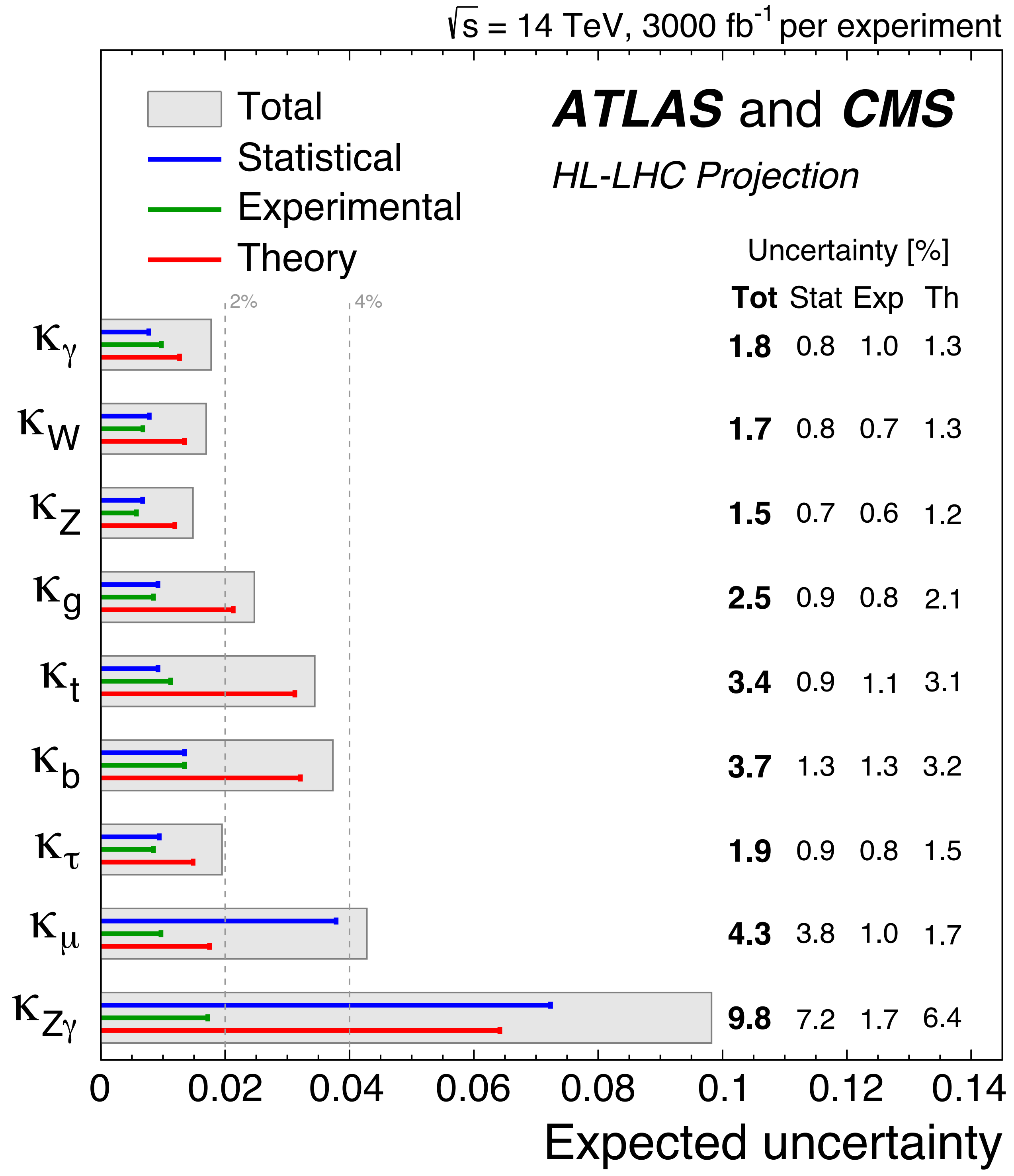


*: Eur. Phys. J. C 83 (2023) 982

Why precision measurements?

- Precision measurements play a major role in the search for New Physics (NP) at the LHC and HL-LHC
  - Direct sensitivity to New Physics (e.g. electroweak parameters via loop corrections)
  - Input to simulations and PDF fits— indirectly improves sensitivity to NP
- Substantial improvements in the precision of *pp* collision simulations needed to unlock the discovery potential of the HL-LHC
  - E.g. theory uncertainty (sig. & bkg.) expected to be dominant for Higgs production and decay measurements even though they have already been halved in the projections





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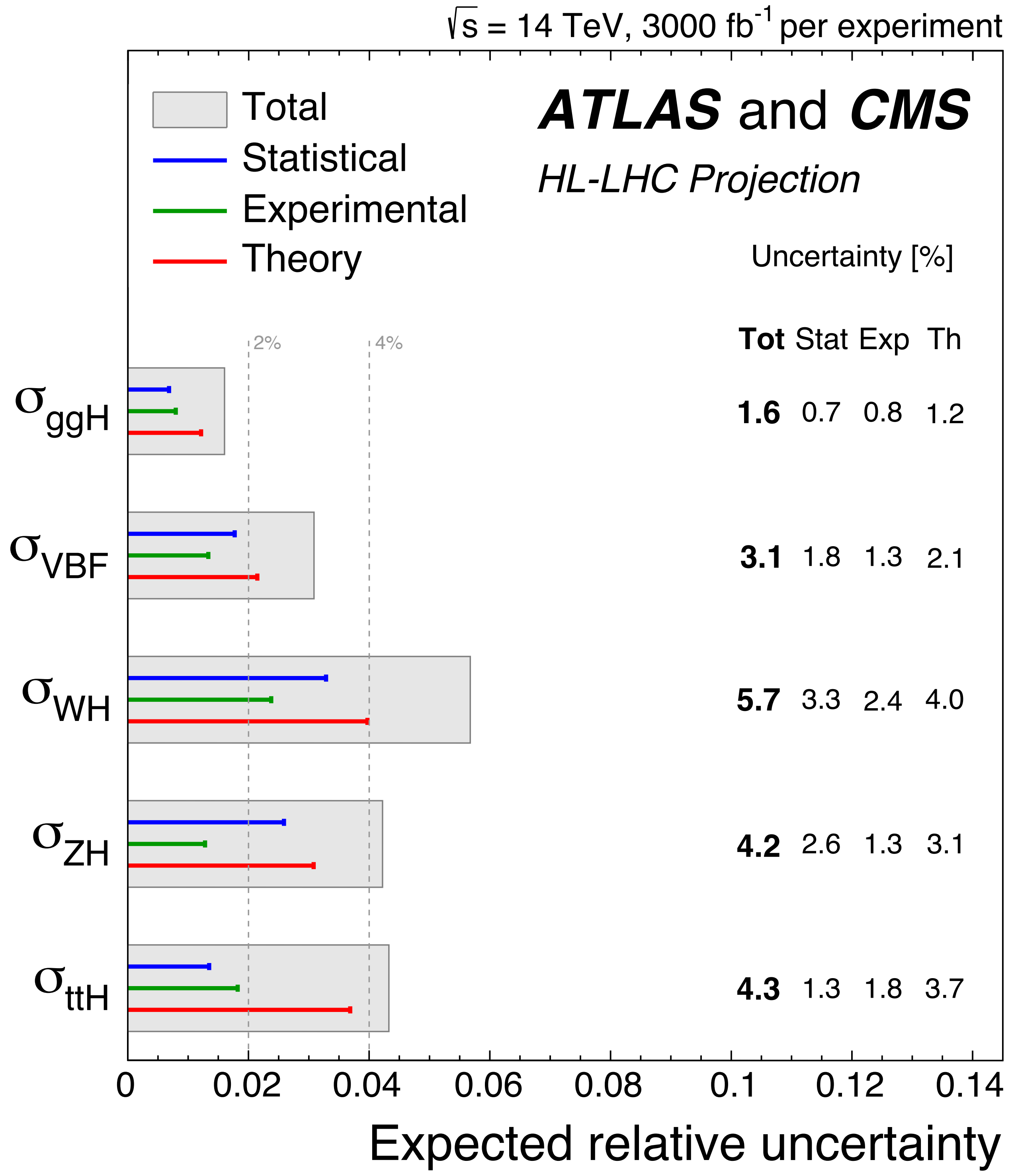
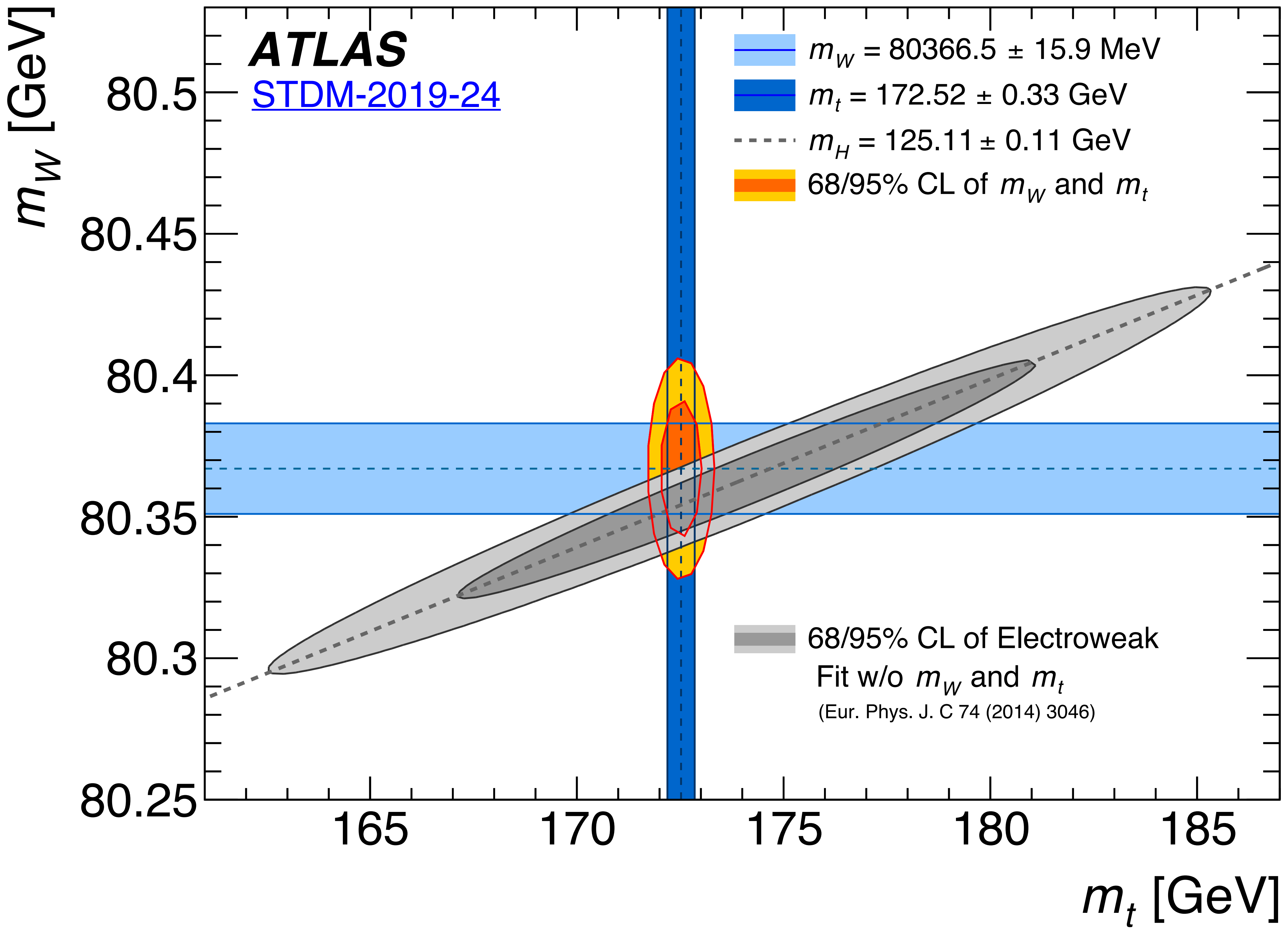
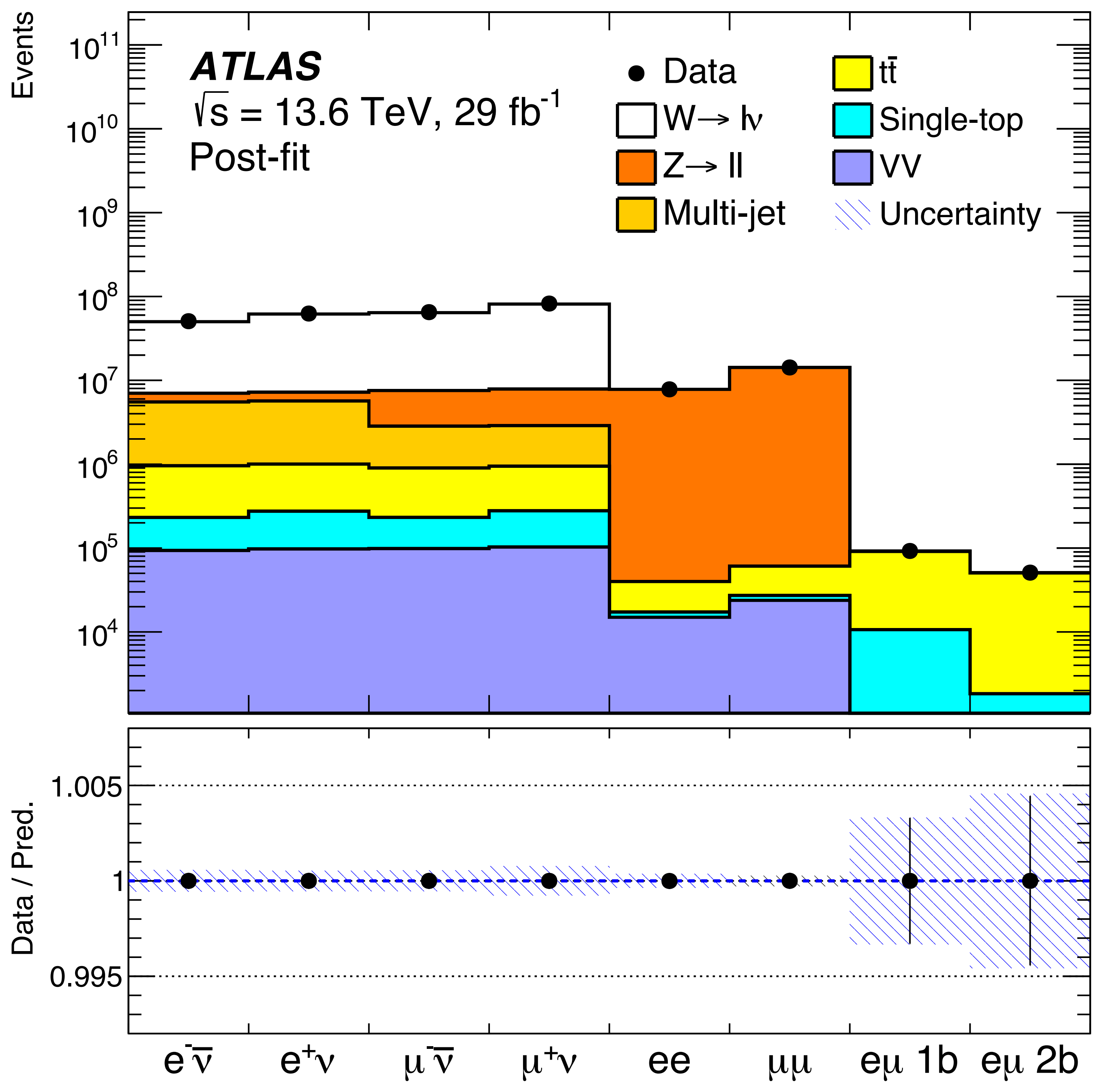


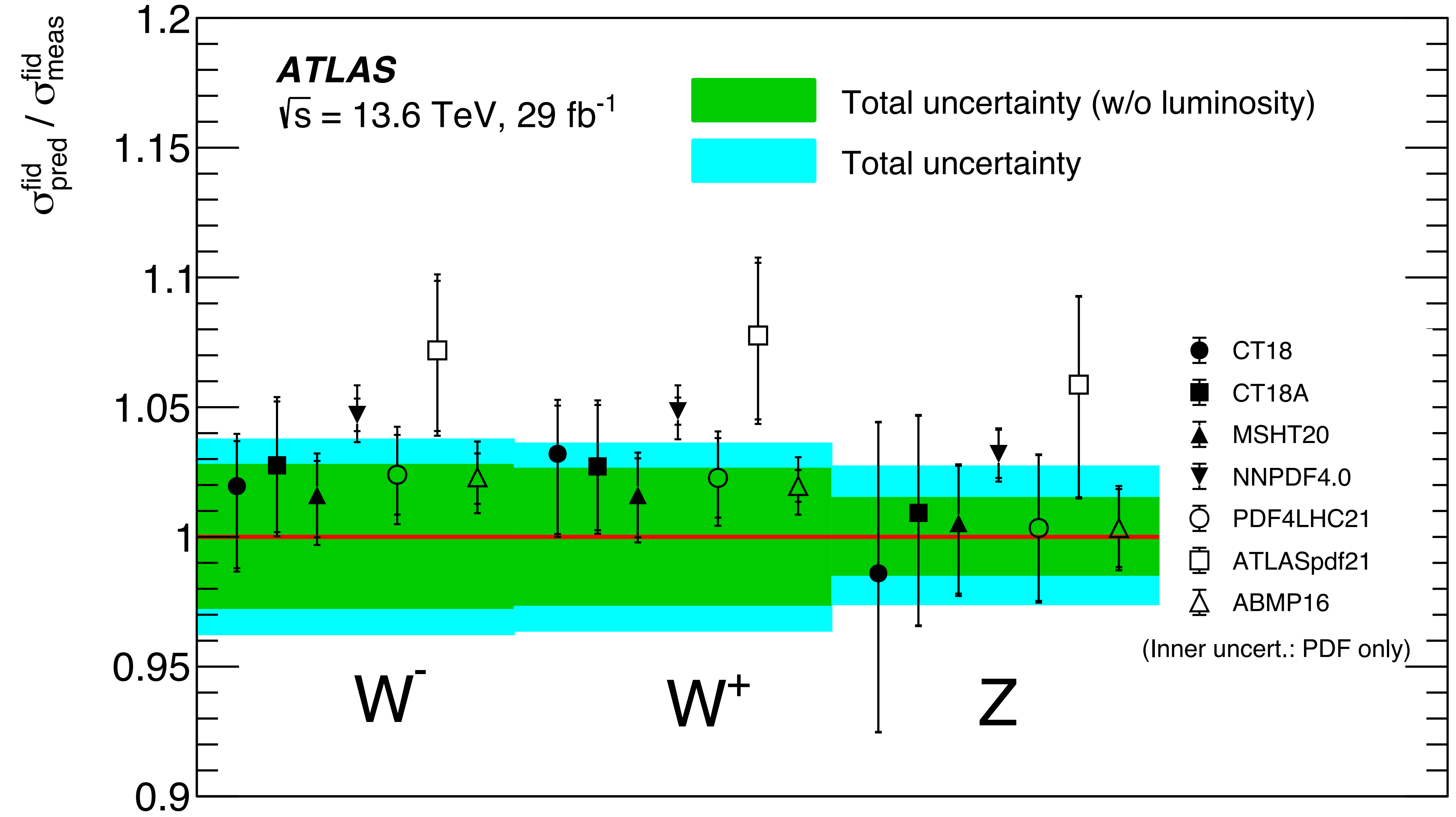


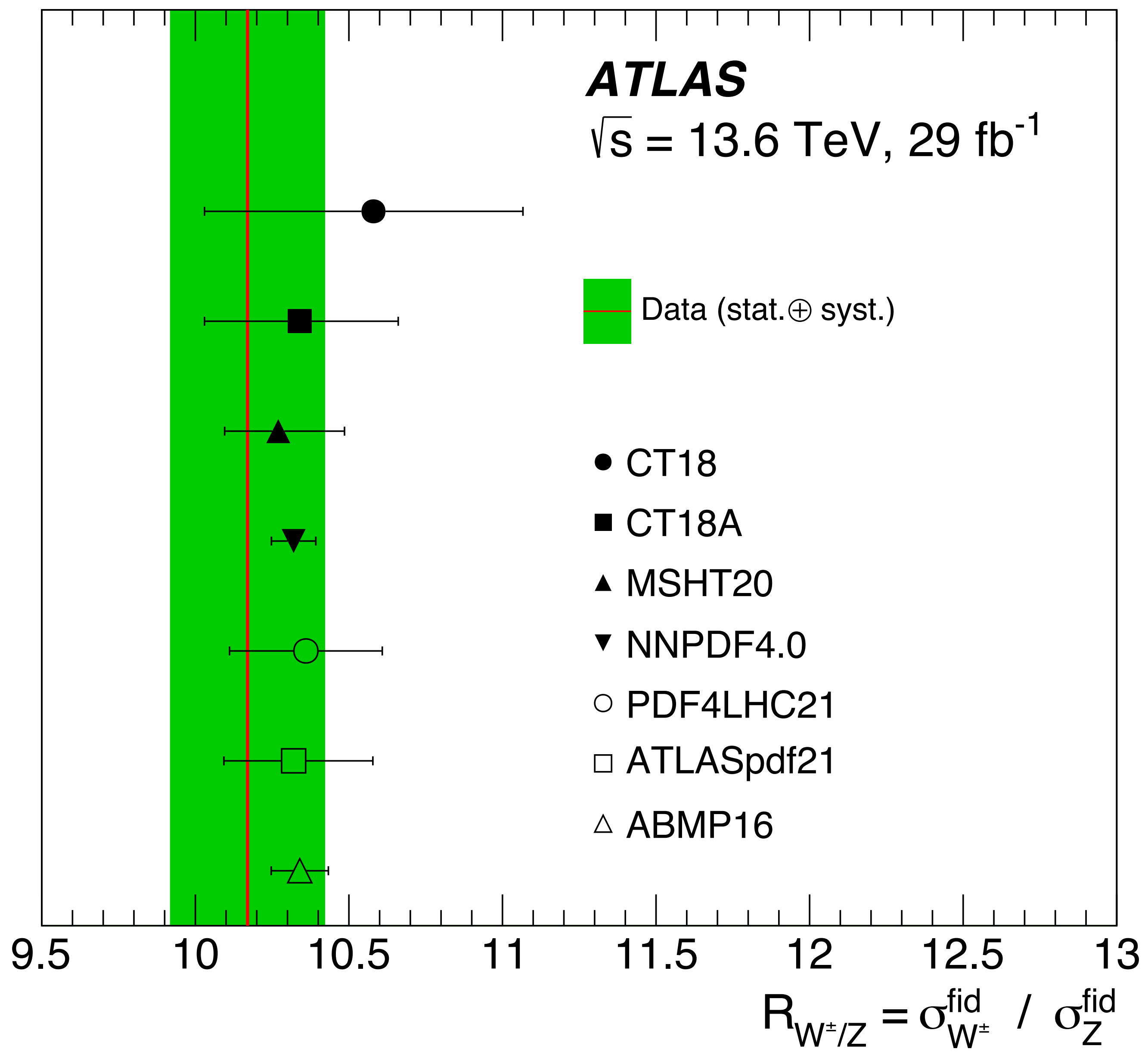
Run 3 Highlights

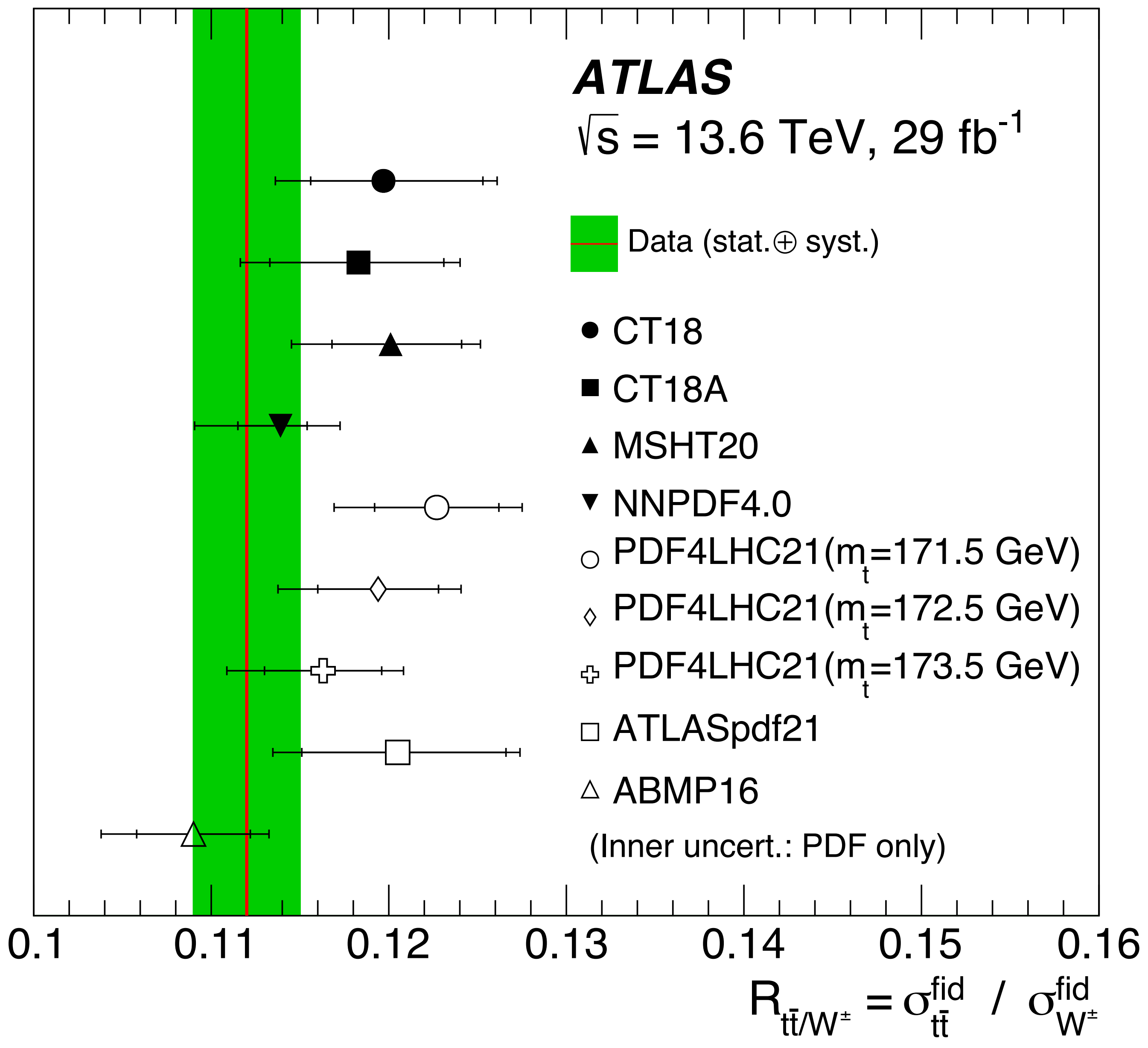
W and Z cross section at 13.6 TeV STDM-2023-16

- Simultaneous measurement of W and Z cross section and their ratios
  - σ_{W+}, σ_{W-}, σ_{Z}, $\sigma_{W+} / \sigma_{W-}$, $\sigma_{W\pm} / \sigma_{Z}$
- Using 29 fb^{-1} of the 2022 data taking; 2023 / 2024 data not included
- For the first time also provided the $t\bar{t}/W^{\pm}$ cross section ratio*
- Cross sections extracted with a likelihood fit (systematics profiled)
- Dominated by experimental uncertainties (lepton ID, multi-jet, luminosity)
- Generally good agreement with predictions for most PDFs







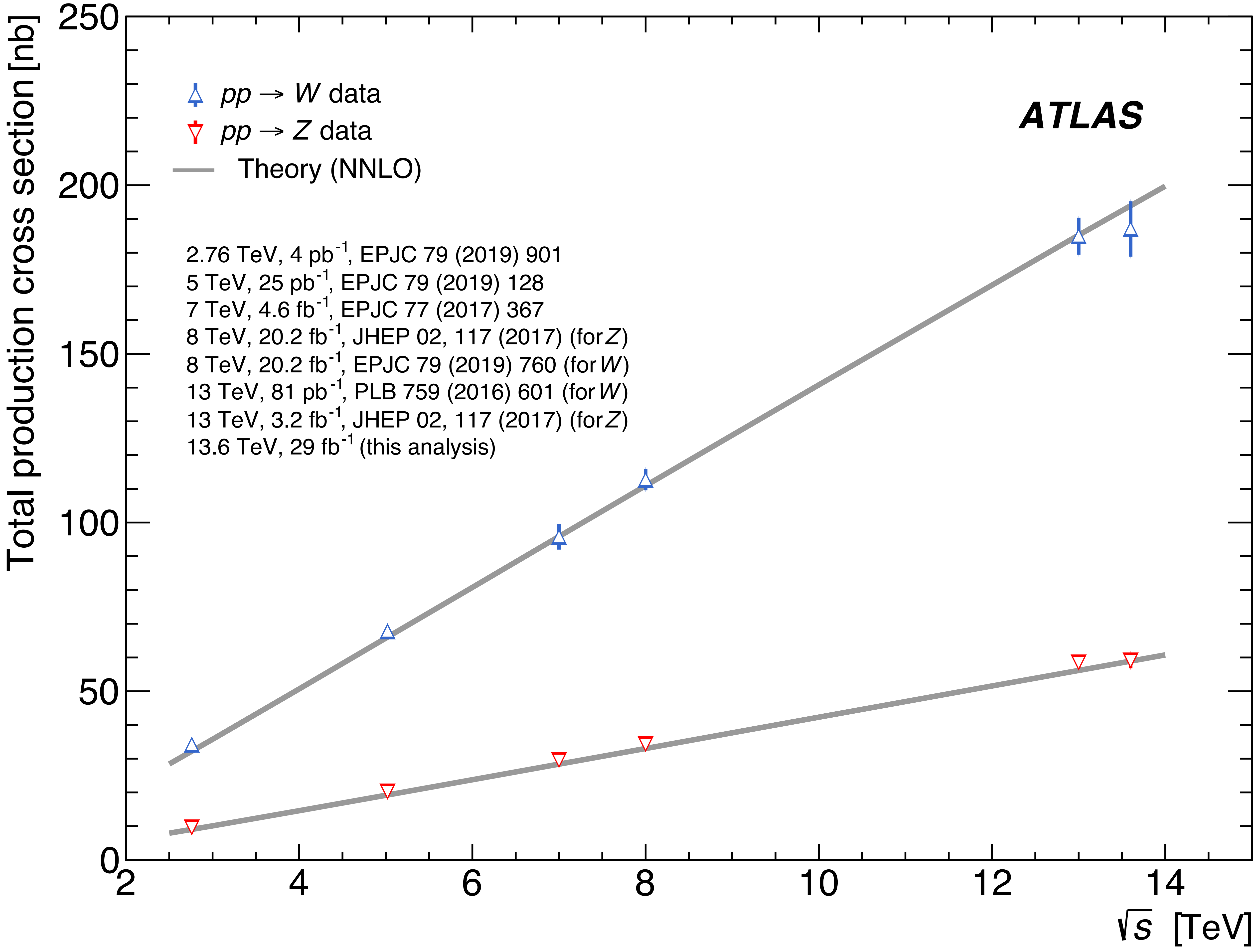


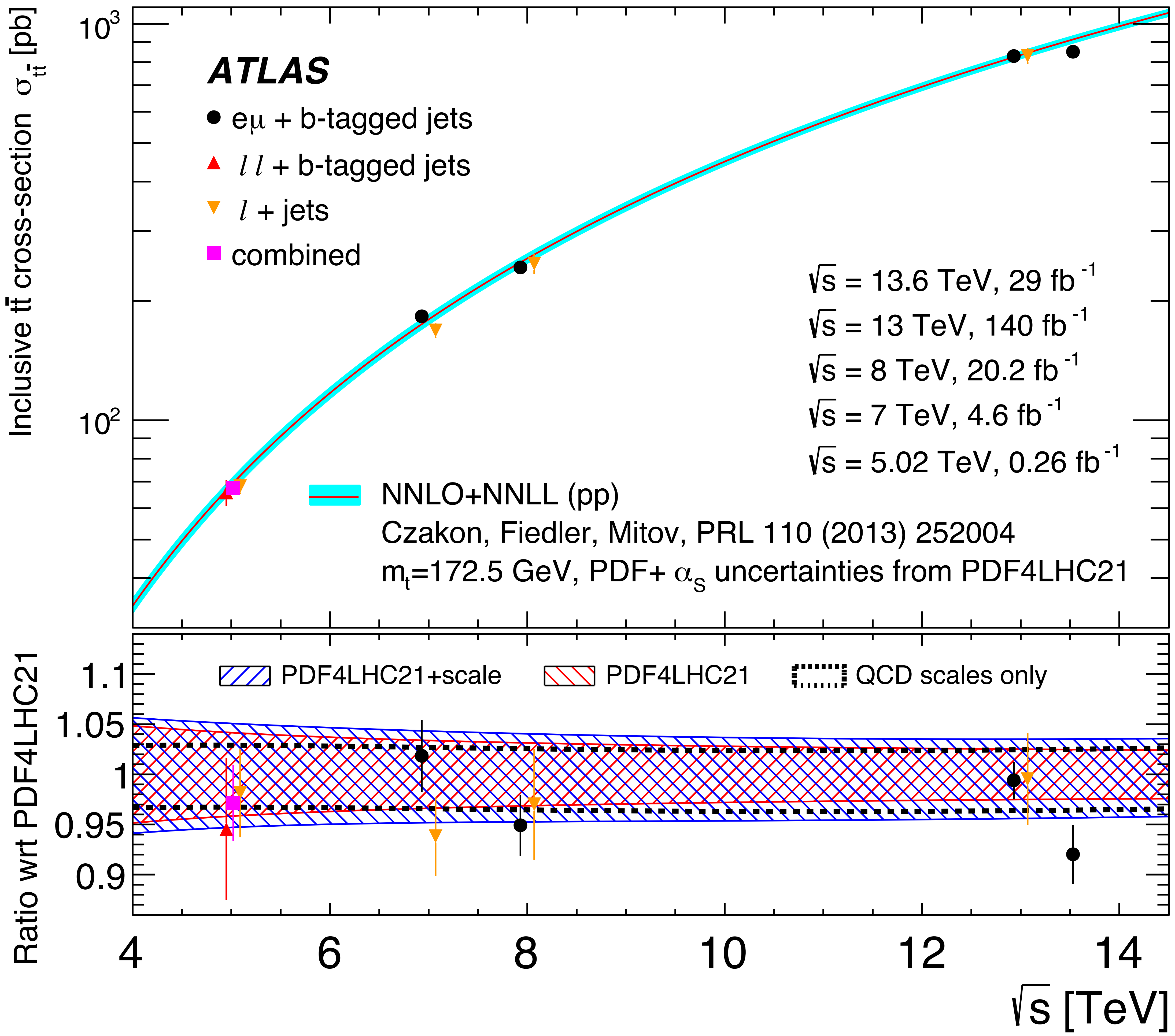
*: Phys. Let. B 848 (2024) 138376

W, Z, and $t\bar{t}$ cross section evolution

STDM-2023-16

- Good agreement with NNLO and NNLO+NNLL predictions from 2.76 TeV to 13.6 TeV
- Precision can be improved in the future with consolidated lepton and luminosity calibrations
- Important first look into the 13.6 TeV data, validating the detector performance

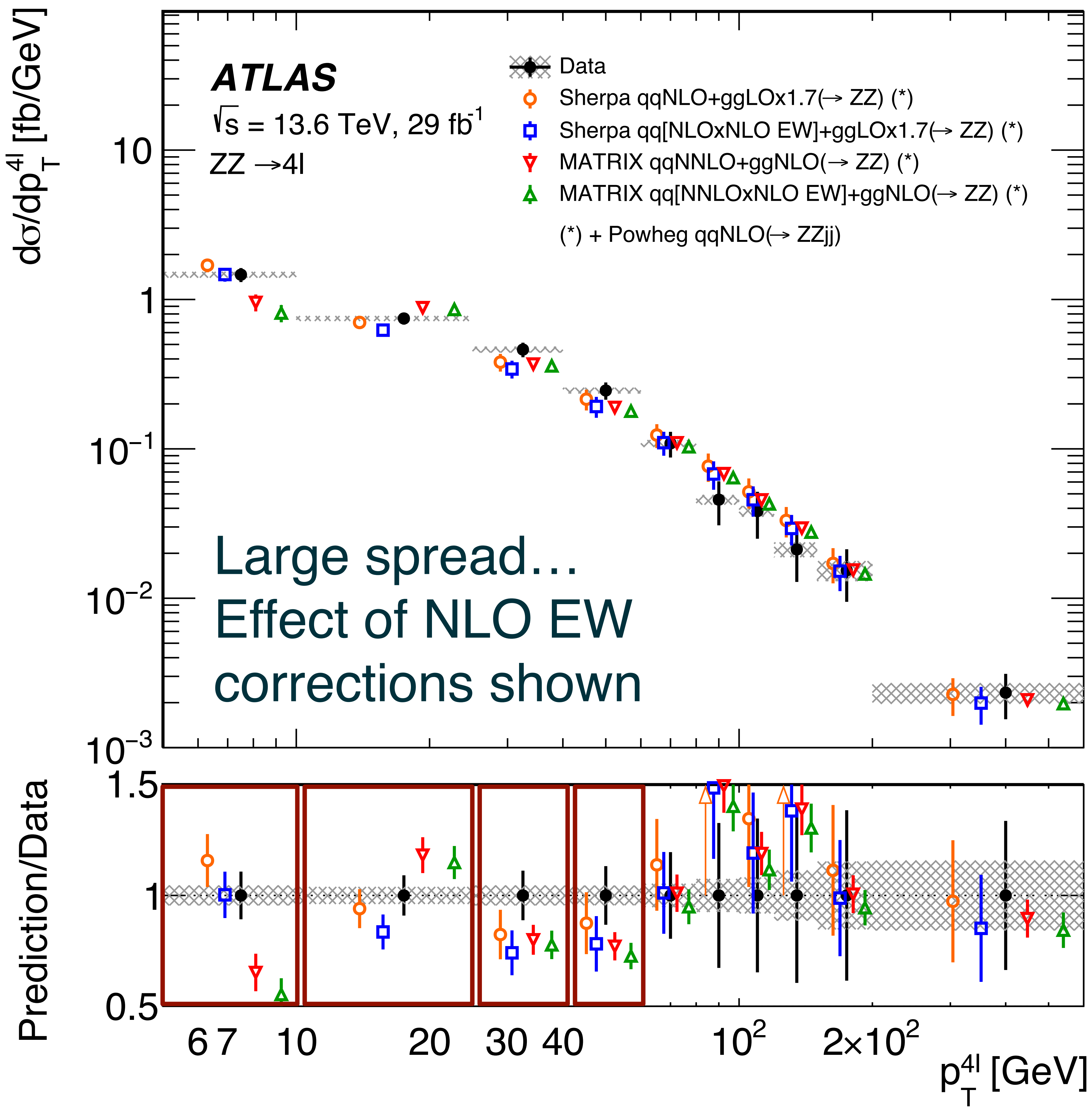




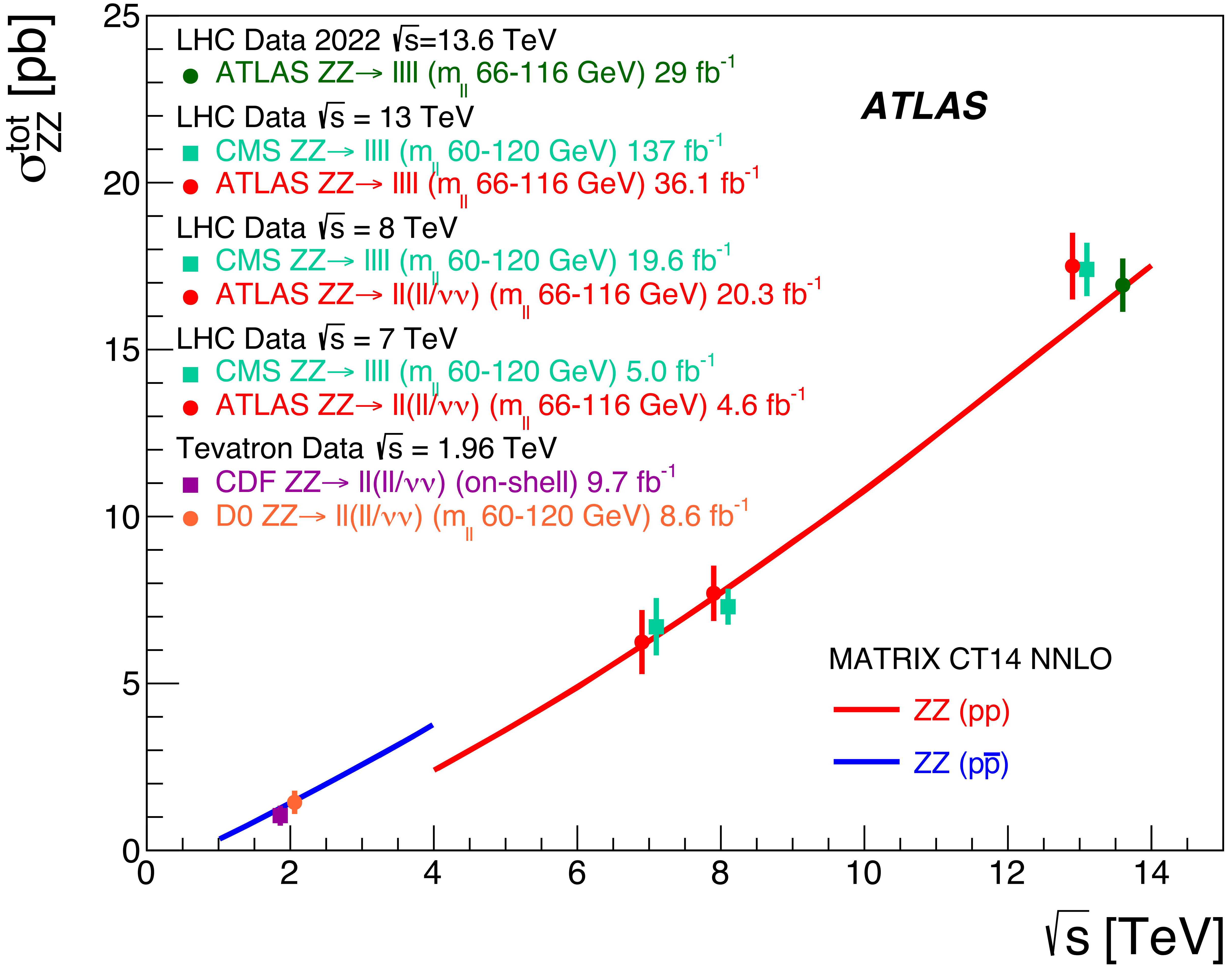
Measurement of ZZ cross-section at 13.6 TeV

STDM-2022-17

- The four-lepton final state used: ZZ→4ℓ
- Measurement dominated by data statistical uncertainty and lepton efficiency calibrations
- Iterative bayesian unfolding for **fiducial differential cross sections** m(4ℓ) and p_T(4ℓ)
- Extrapolated to the **total phase space** with a requirement of 66 < m_Z < 116 GeV

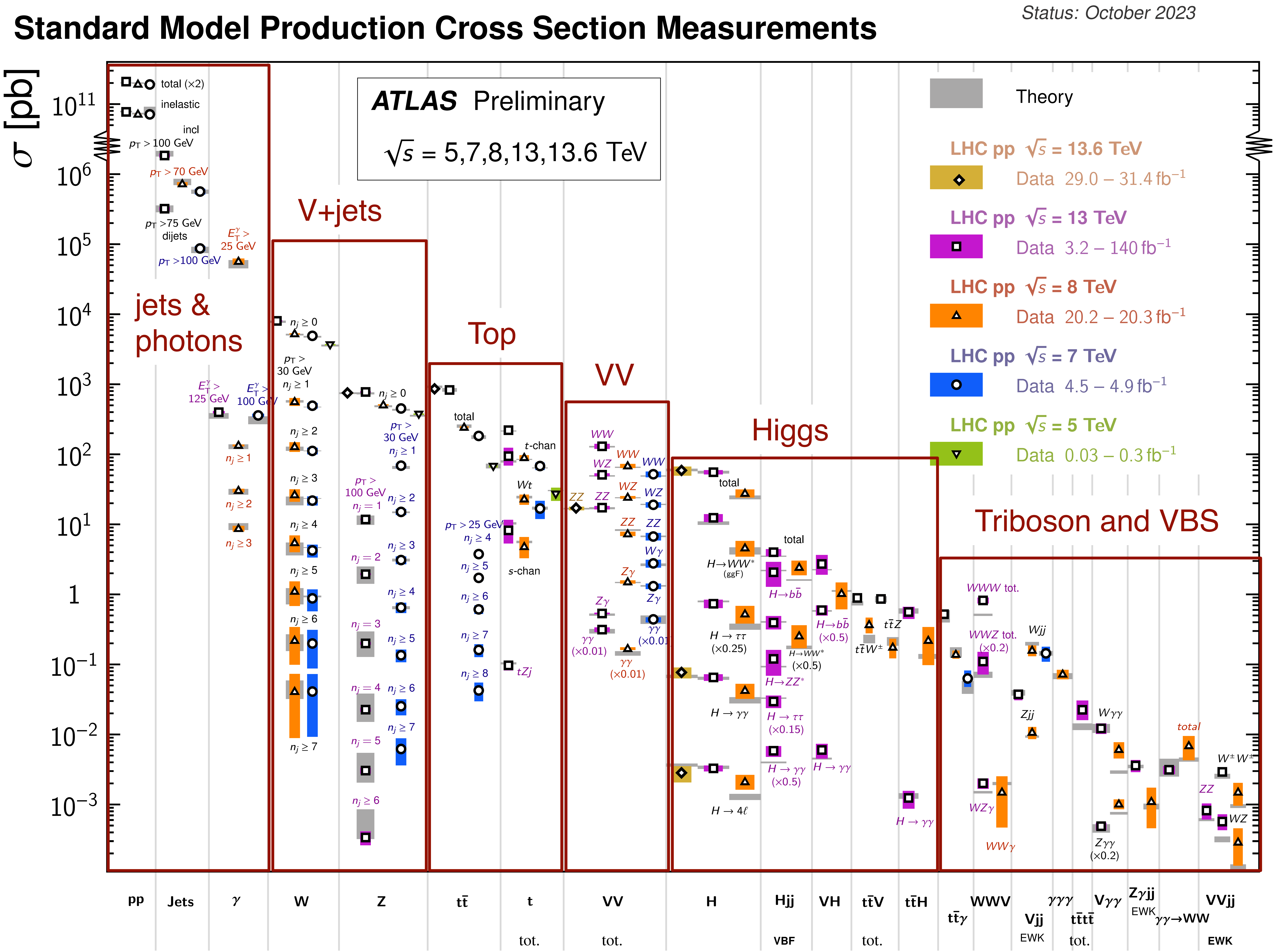


Large spread…
Effect of NLO EW corrections shown



Run 1 & Run 2 Highlights

Measuring SM processes across ~10 orders of magnitude..

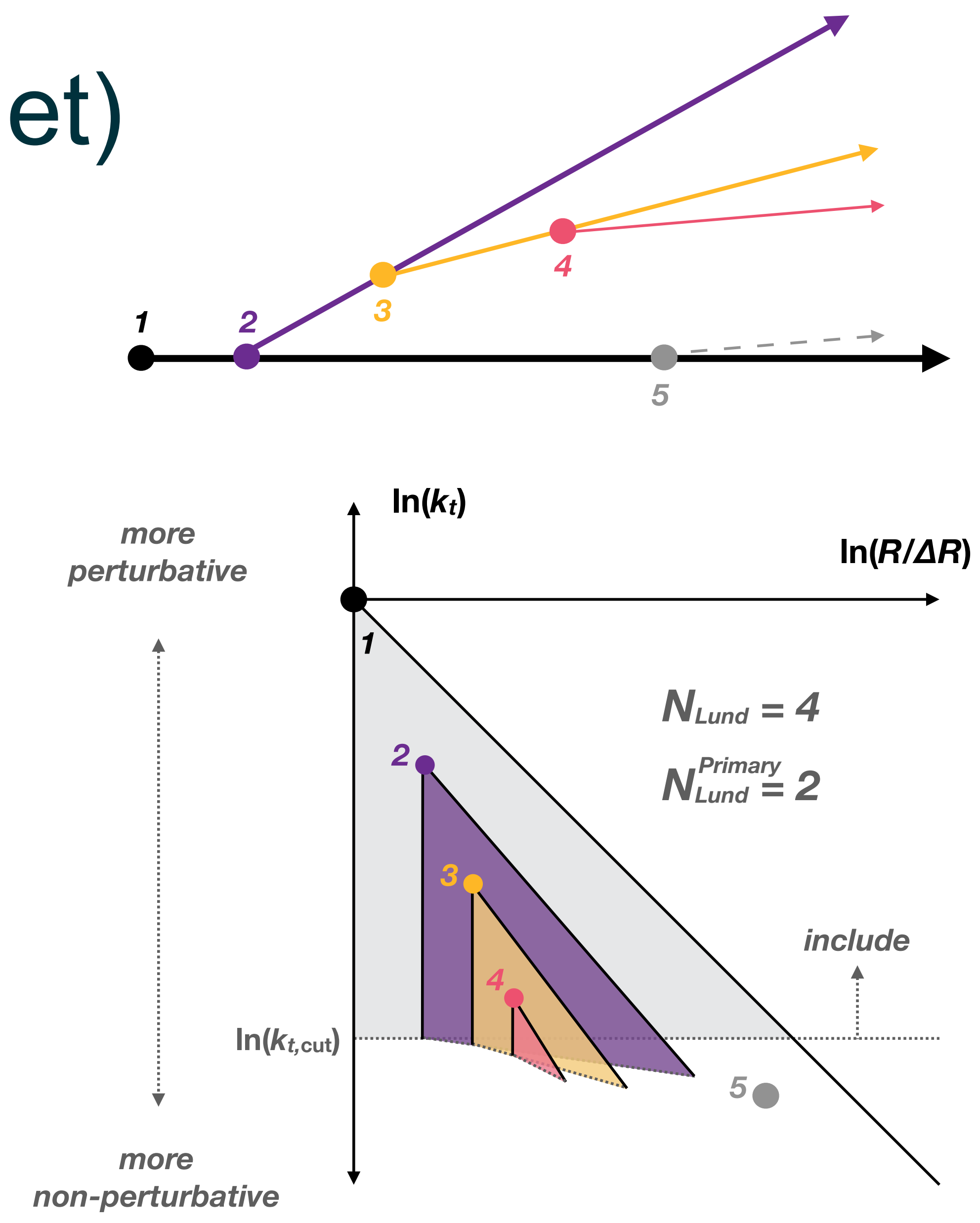


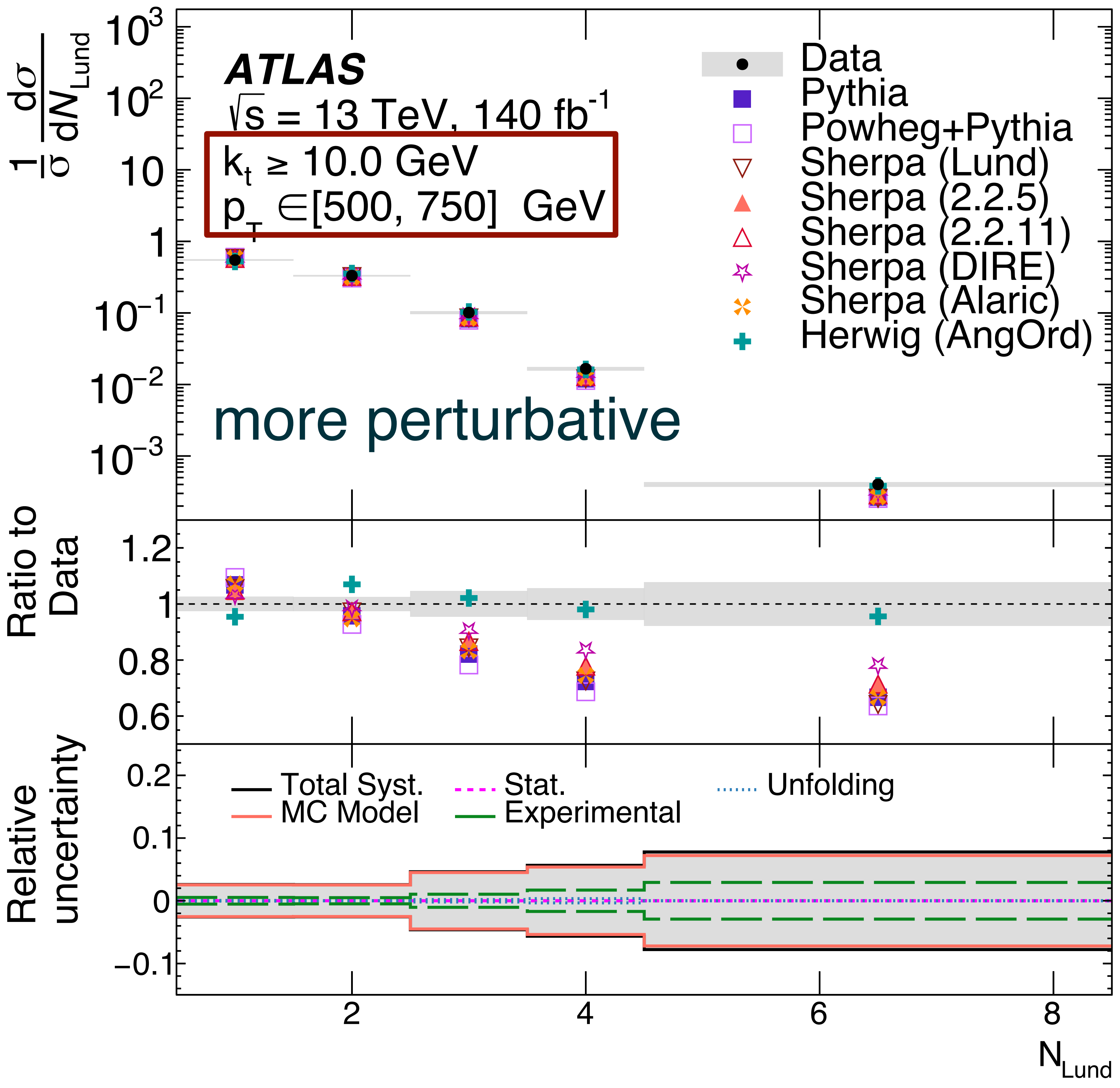
Multi-jet measurements

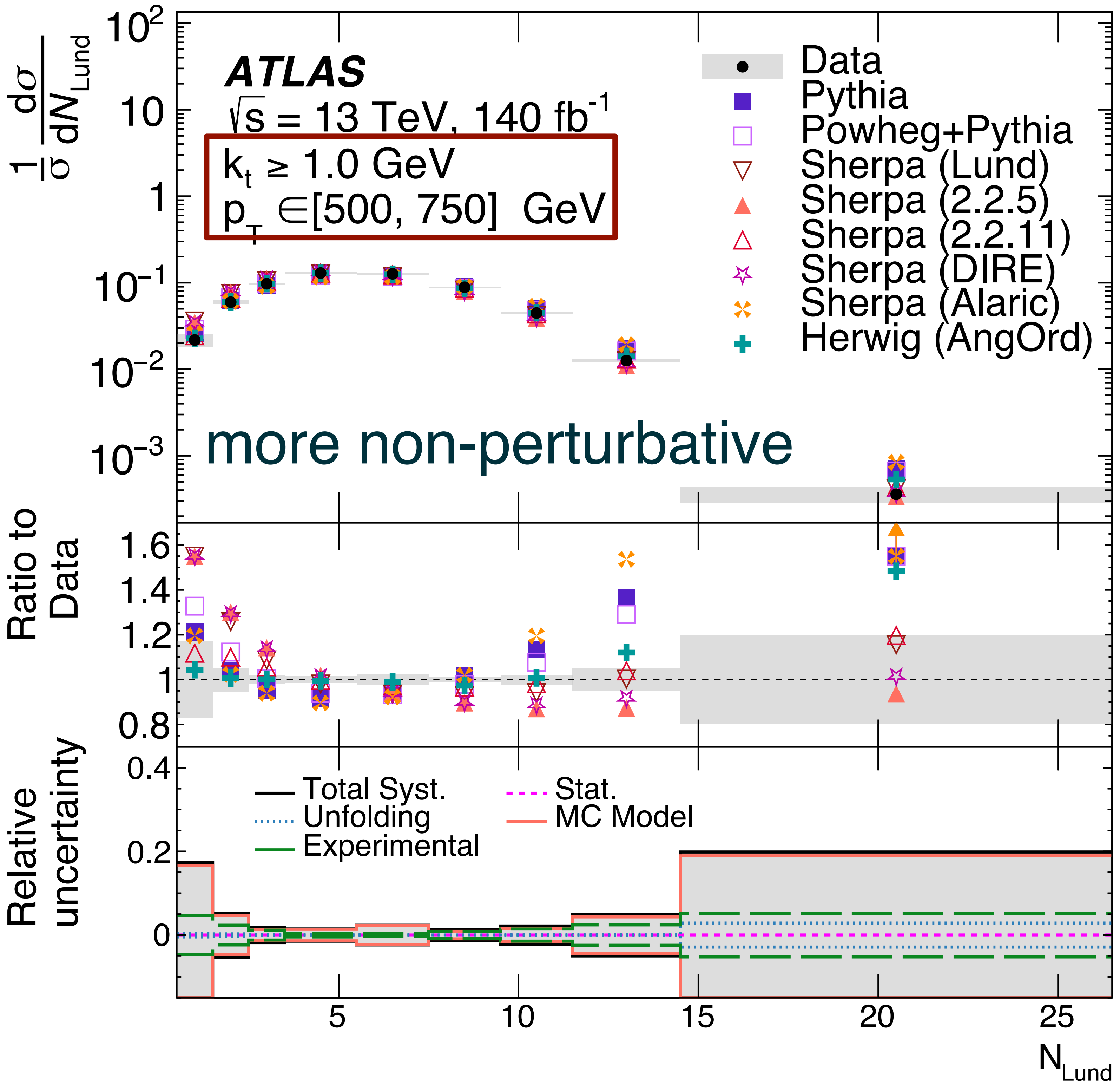
Lund jet multiplicities in the Run 2 multi-jet dataset

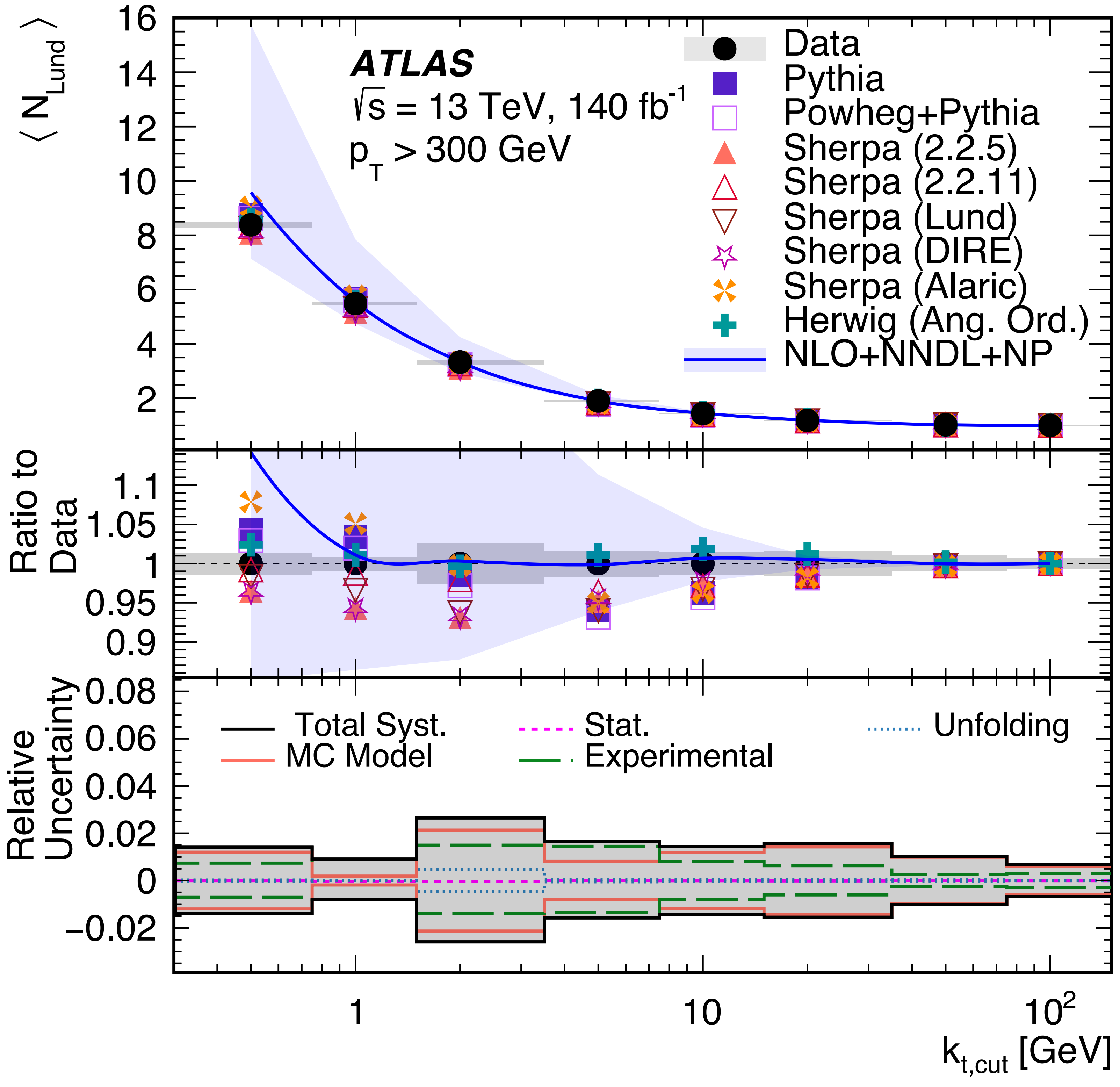
STDM-2023-07

- Measure number of emissions above a specified energy (k_T [GeV]) for a jet with p_T(jet)
  - Reclustering jet constituents with the **Cambridge-Aachen** (C/A) algorithm
- Sensitive to higher-order effects in parton showers; important for NLL showers
- Comparisons with NLO+NNDL+NP analytical calculations (JHEP 04 (2023) 104)
- Herwig gives the best overall description of multiplicities; Sherpa best when non-perturbative emissions allowed



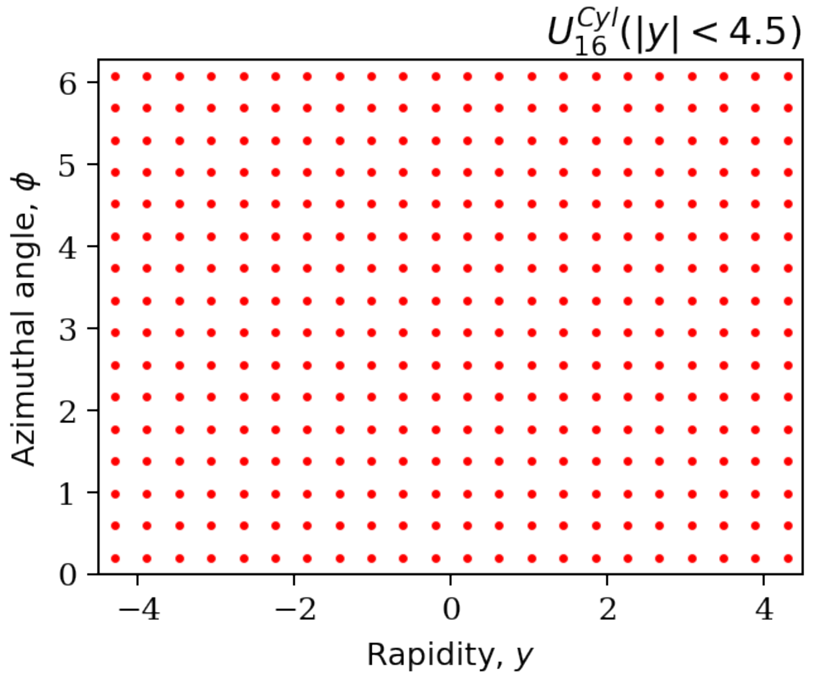


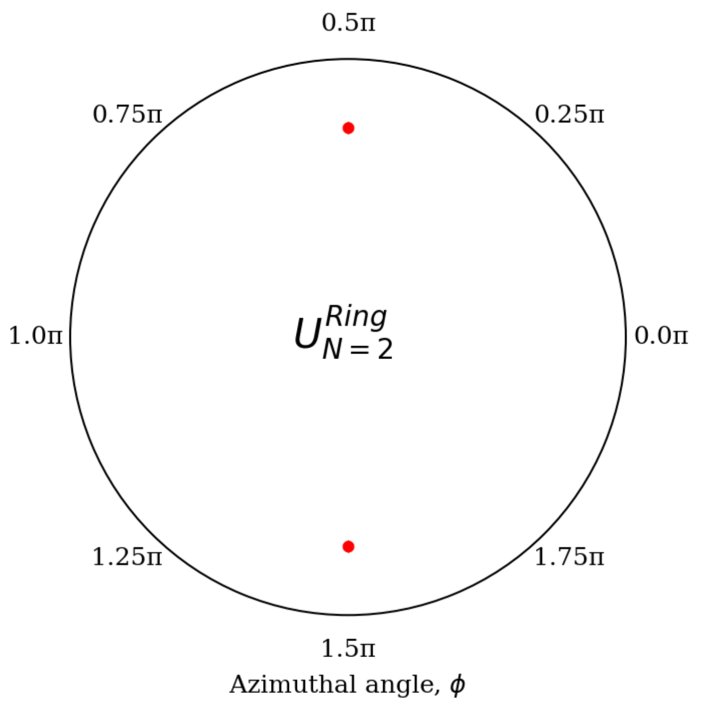


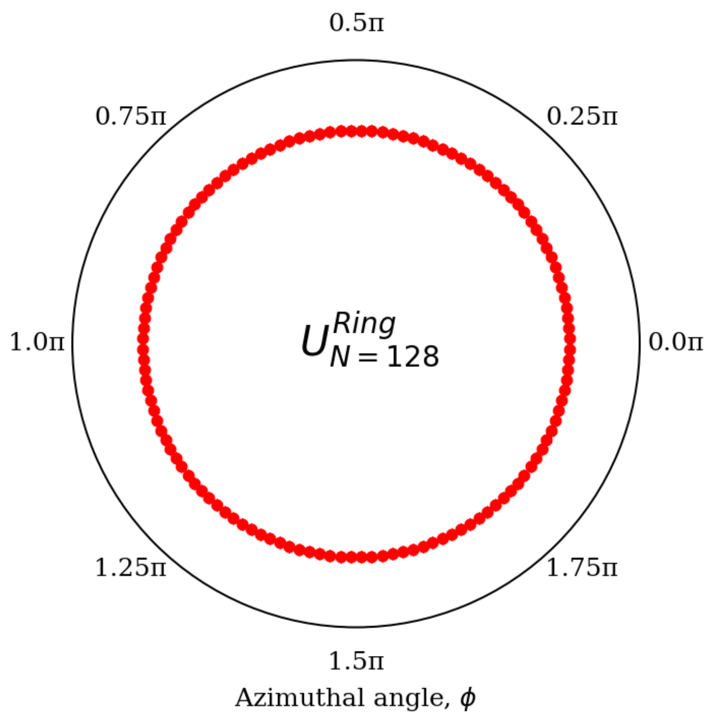


Measurements of multi-jet event isotropies w/ optimal transport STDM-2020-20

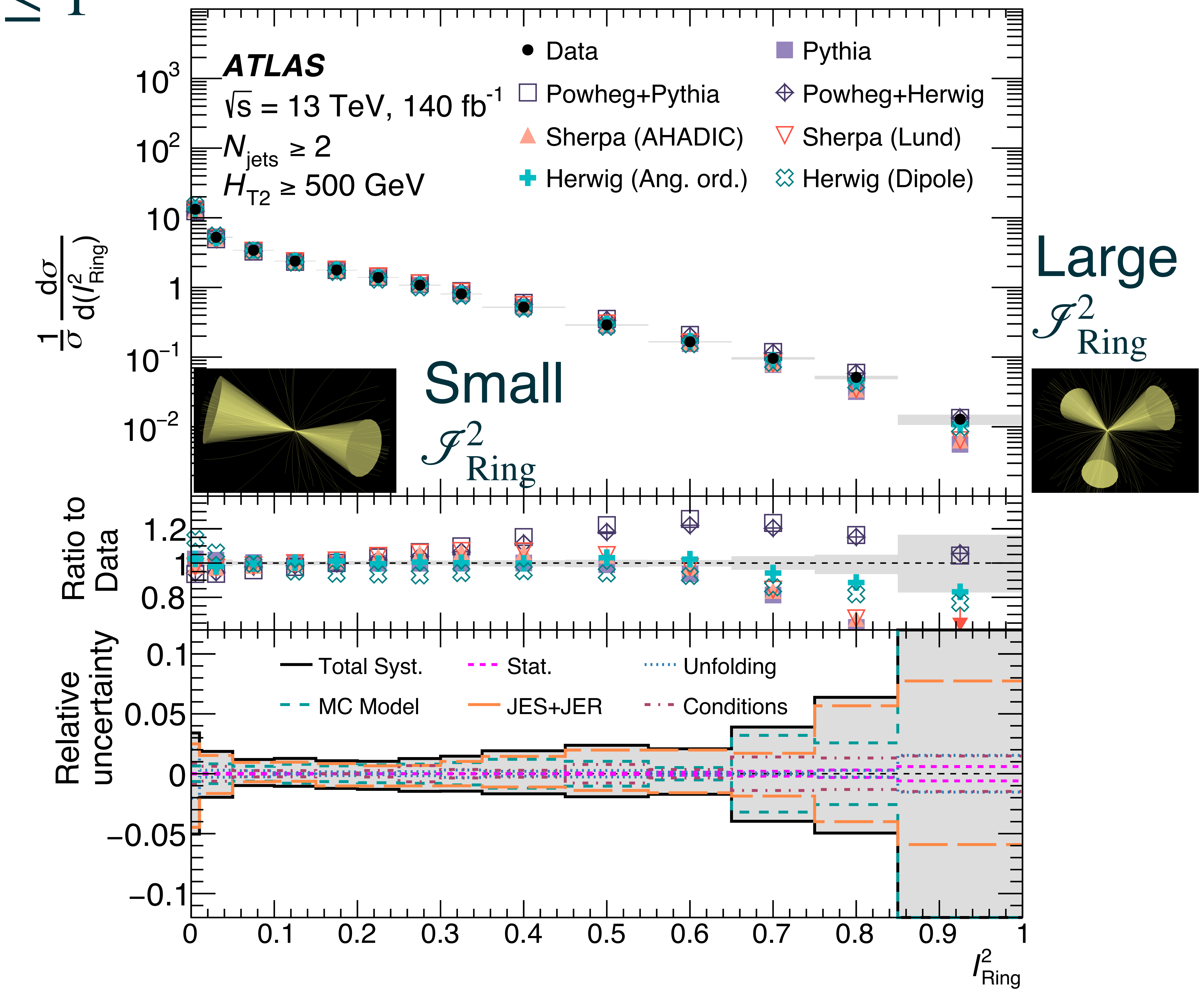
- Family of observables which characterize the event topology and/or energy flow in collider events
  - Unified through a geometric language JHEP07 (2020) 006
- Event isotropies— how far is a collider event $\mathscr{E}$ from a symmetric radiation pattern $\mathscr{U}$, $\mathscr{I} = \mathrm{EDM}(\mathscr{E}, \mathscr{U})$
  - Earth mover's distance EDM— minimal amount of work to rearrange one event $\mathscr{E}$ into another $\mathscr{E}'$
  - Completely isotropic: $\mathscr{I} = 0$ and in general $0 \leq \mathscr{I} \leq 1$







$\mathcal{I}$	$\mathcal{I}$ binning	N_{jet} binning	H_{T2} binning [GeV]
$\mathcal{I}^{N=16}_{\text{Cyl}}$	0.0, 0.65, 0.7, 0.75, 0.775, 0.8, 0.825, 0.85, 0.875, 1.0	2+, 3+, 4+, 5+	400+, 500+, 1000+, 1500+
$\mathcal{I}^{N=2}_{\text{Ring}}$	0.0, 0.01, 0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.45, 0.55, 0.65, 0.75, 0.85, 1.0	2+, 3+, 4+, 5+	400+, 500+, 1000+, 1500+
$\mathcal{I}^{N=128}_{\text{Ring}}$	0.0, 0.040, 0.065, 0.09, 0.115, 0.14, 0.165, 0.190, 0.215, 0.240, 0.270, 0.320, 0.370, 0.420, 0.470, 0.520, 0.570, 0.620, 0.670, 0.720, 0.770, 0.820, 0.870, 1.0	2+, 3+, 4+, 5+	400+, 500+, 1000+, 1500+



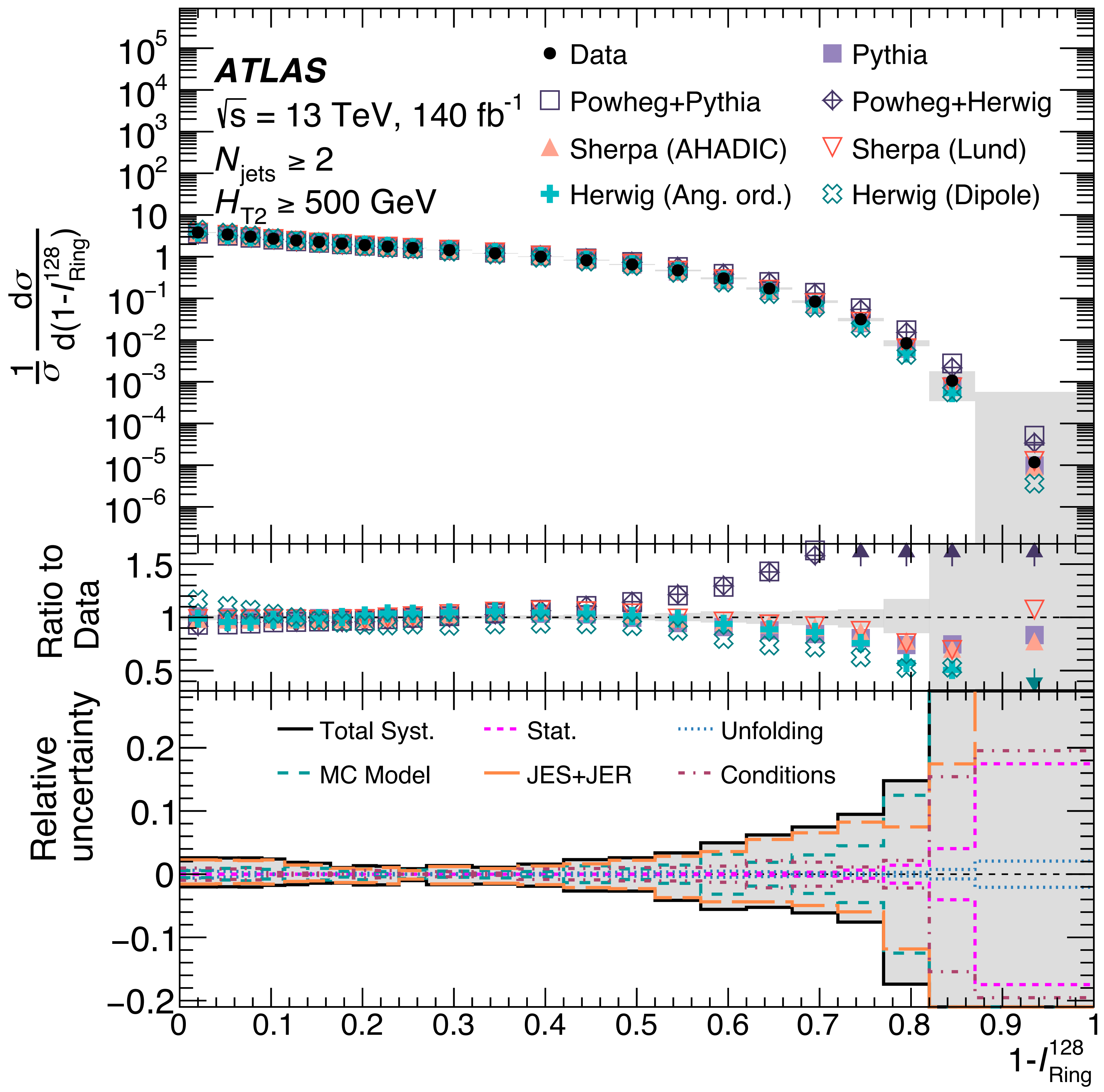
Small $\mathcal{I}^2_{\text{Ring}}$

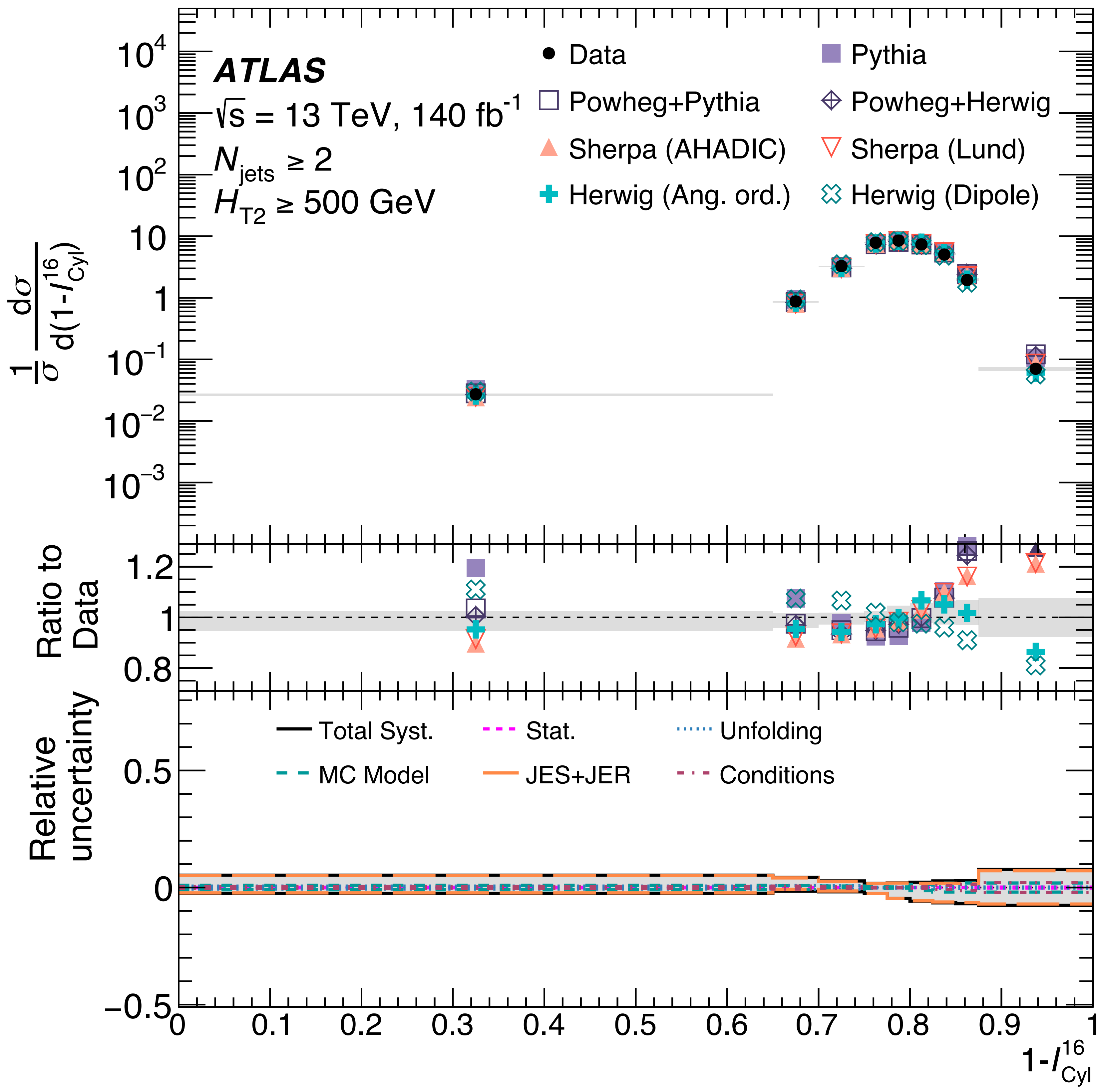
Large $\mathcal{I}^2_{\text{Ring}}$

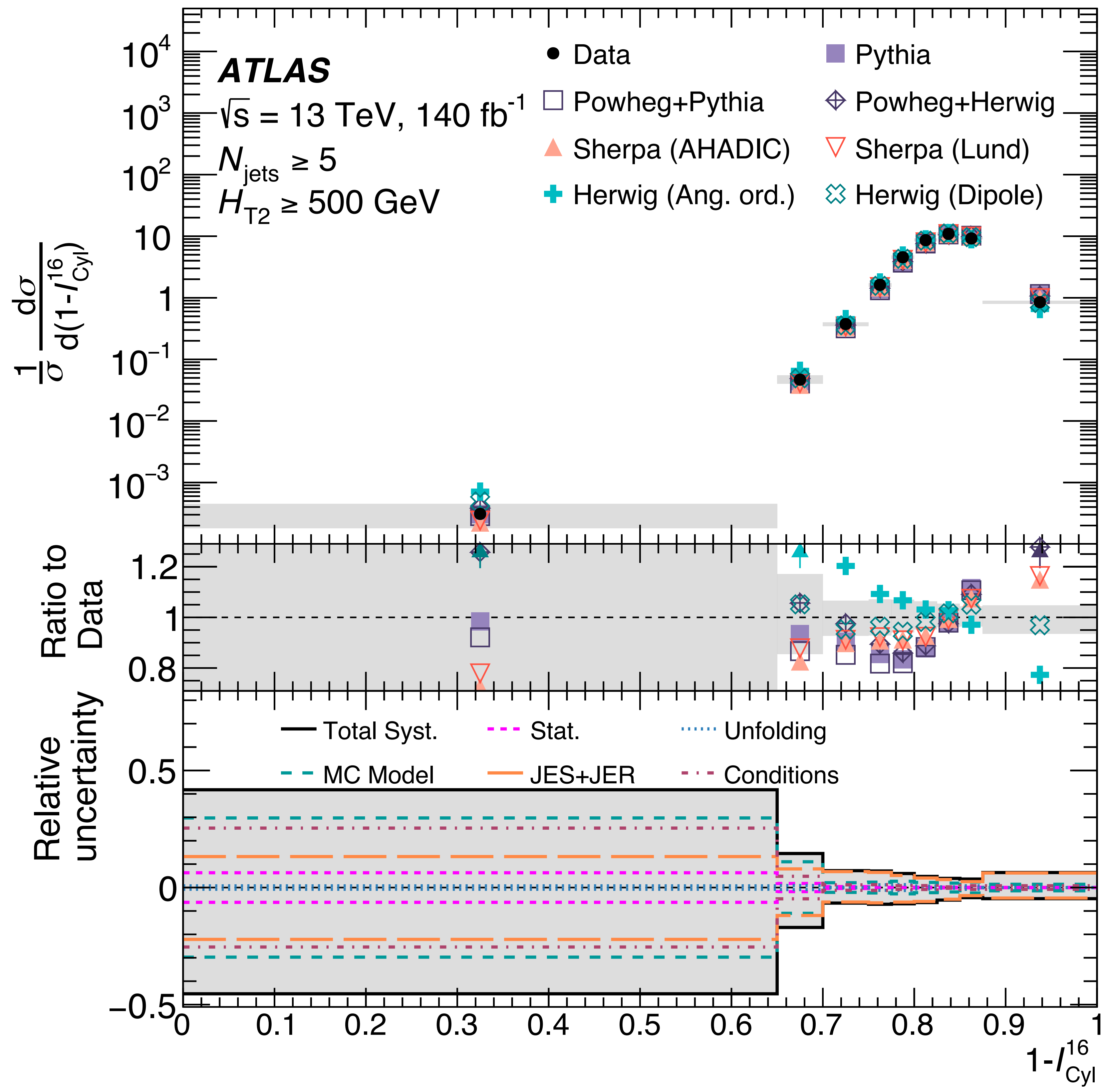
Event isotropies: more results

STDM-2020-20

- Powheg+Pythia/Herwig (NLO ME) significantly overestimates the isotropic multi-jet events ($\mathscr{I}^{128} = 0$)
- Relatively large differences between Herwig Dipole and Herwig Angular Ordered predictions
- No significant differences observed between the cluster and Lund string hadronisation models







Precision W/Z measurements

W boson mass re-analysis at 7 TeV

STDM-2019-24

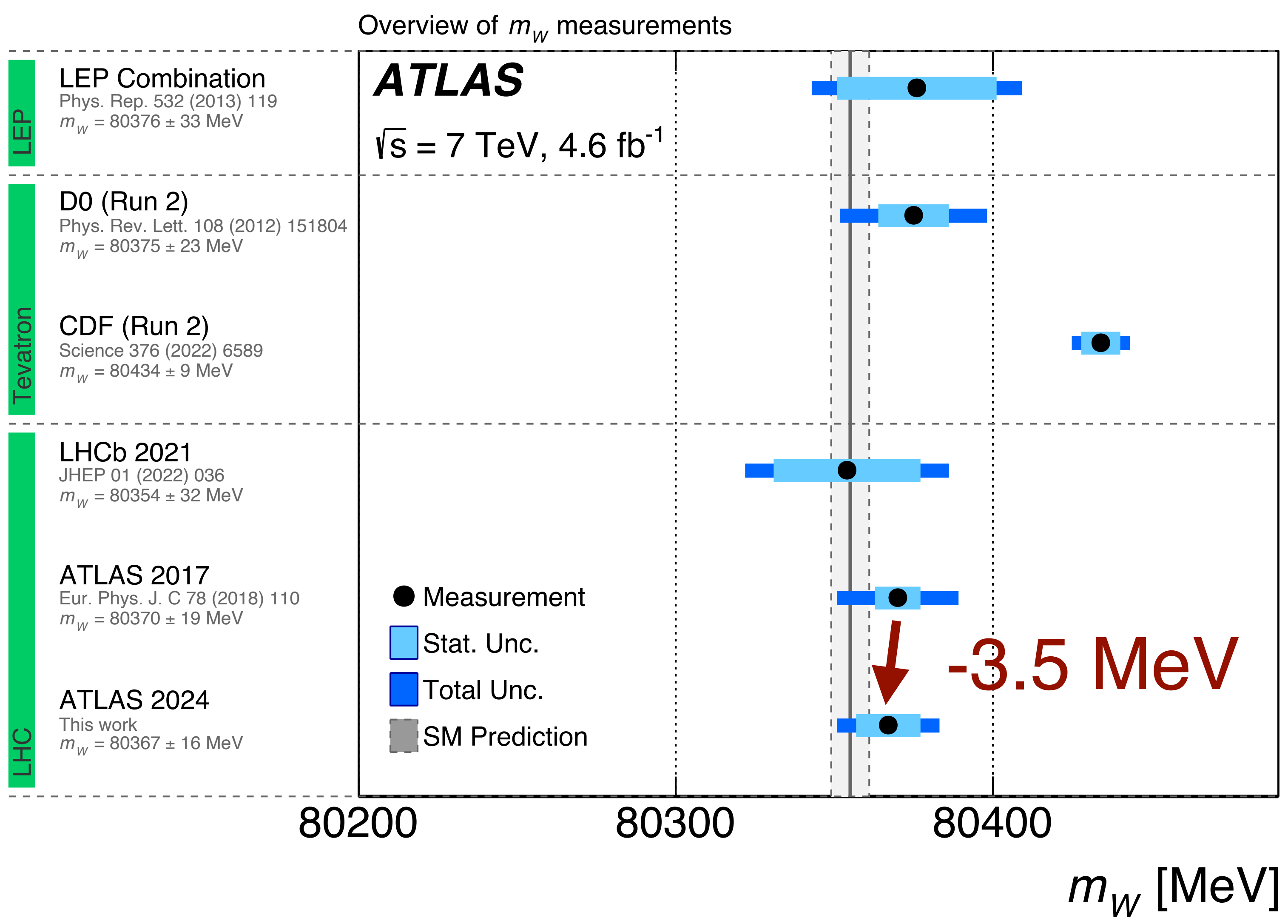
- Using the ~4 fb^{-1} of 2011 proton-proton collision data at 7 TeV (average pileup ~9)
- Several updates in comparison with the result published in 2018 using the same dataset:
  - Measure W boson width Γ_W along with the mass m_W (nominally either Γ_W or m_W is fixed to SM)
  - New baseline PDF (CT18 from CT10nnlo)
  - Mass and width extracted with a profile likelihood fit (theory / experimental unc. profiled)
- $m_W = 80366.5 \pm 9.8\,(\text{stat.}) \pm 12.5\,(\text{syst.})\,\text{MeV} = 80366.5 \pm 15.9\,\text{MeV}$ (0.02% precision)
- $\Gamma_W = 2195.8 \pm 32.0\,(\text{stat.}) \pm 34.1\,(\text{syst.})\,\text{MeV} = 2195.8 \pm 46.8\,\text{MeV}$ (2.1% precision)

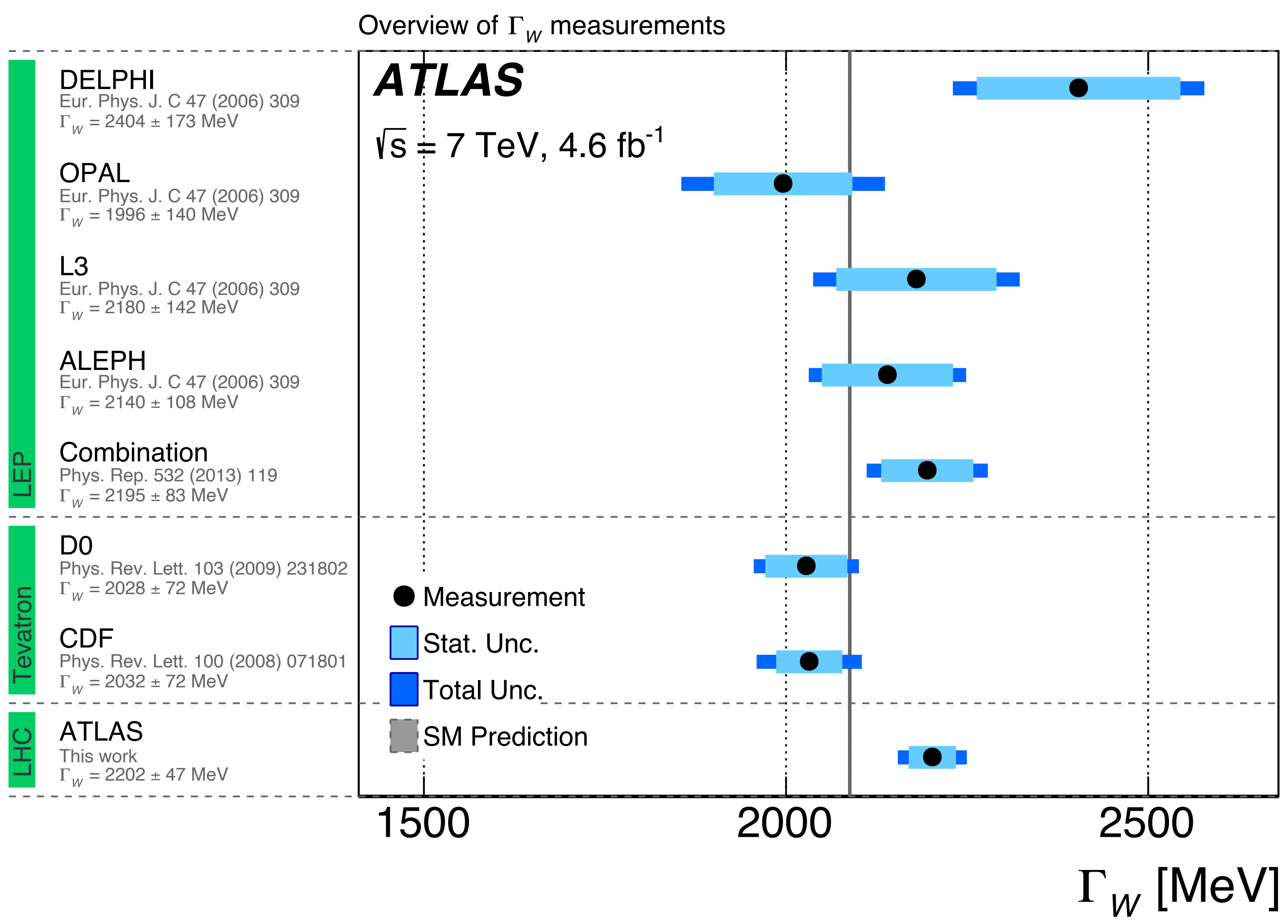
m_W

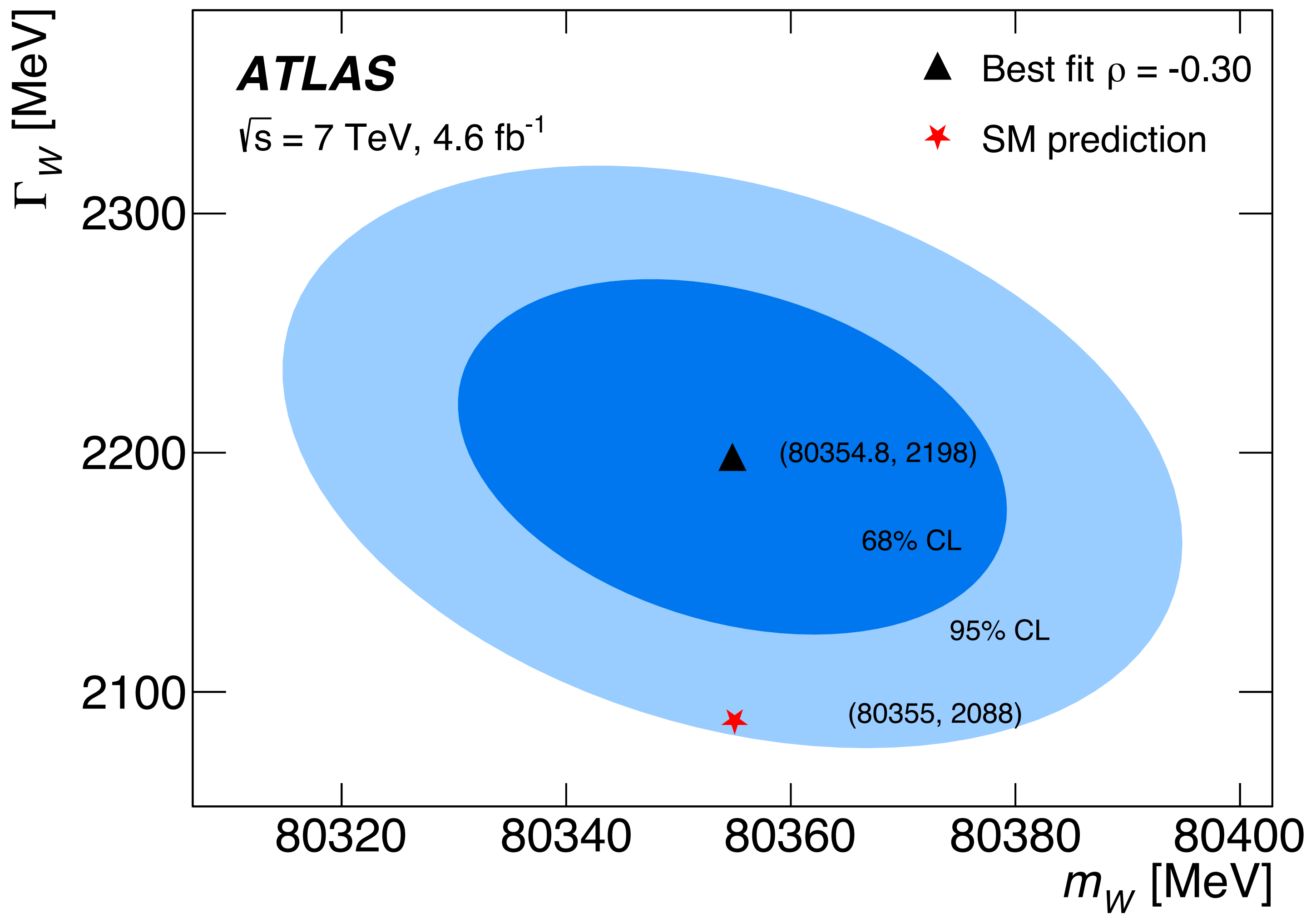
Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	Γ_W	PS
p_T^ℓ	16.2	11.1	11.8	4.9	3.5	1.7	5.6	5.9	5.4	0.9	1.1	0.1	1.5
m_T	24.4	11.4	21.6	11.7	4.7	4.1	4.9	6.7	6.0	11.4	2.5	0.2	7.0
Combined	15.9	9.8	12.5	5.7	3.7	2.0	5.4	6.0	5.4	2.3	1.3	0.1	2.3

Γ_W

Unc. [MeV]	Total	Stat.	Syst.	PDF	A_i	Backg.	EW	e	μ	u_T	Lumi	m_W	PS
p_T^ℓ	72	27	66	21	14	10	5	13	12	12	10	6	55
m_T	48	36	32	5	7	10	3	13	9	18	9	6	12
Combined	47	32	34	7	8	9	3	13	9	17	9	6	18



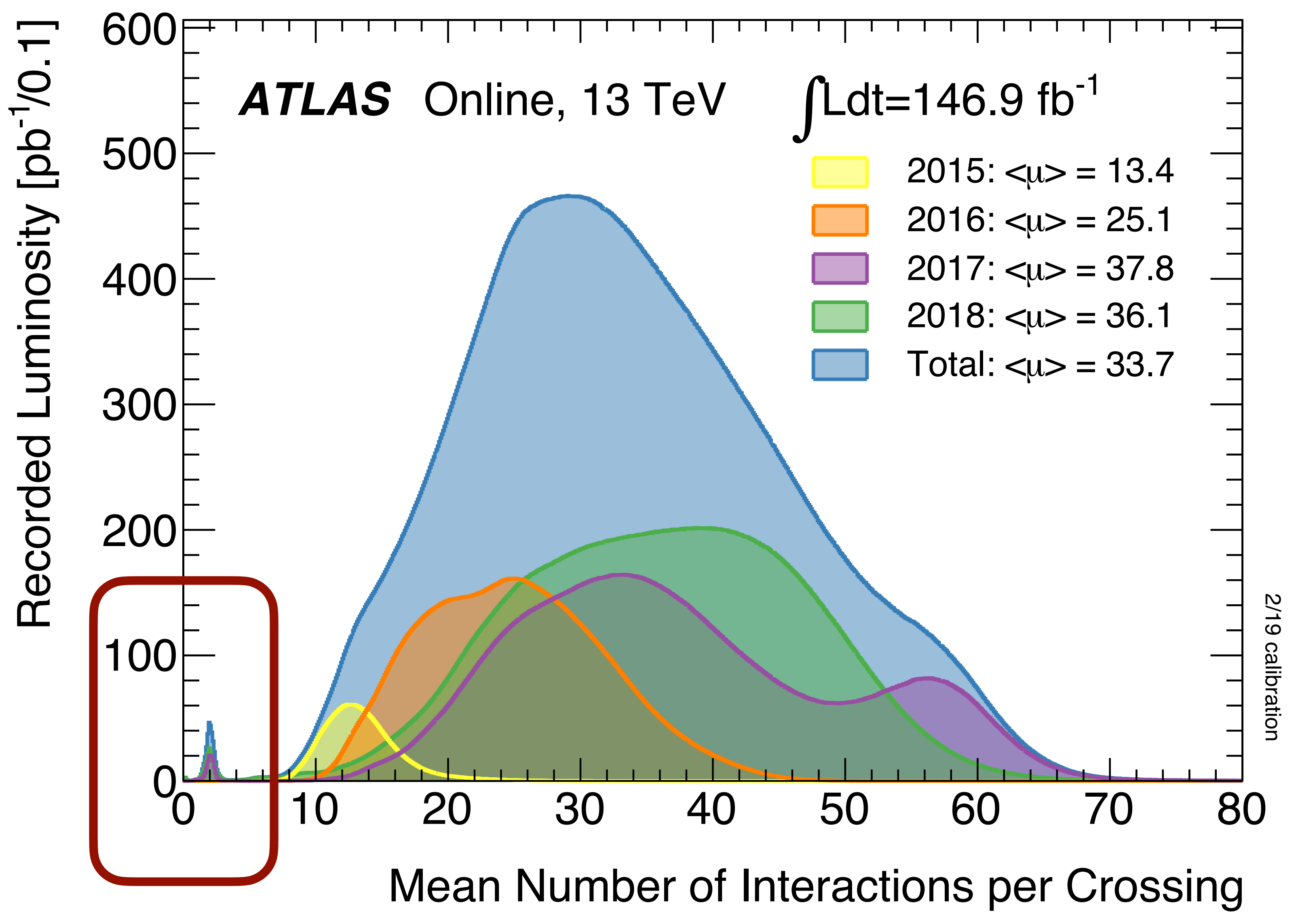


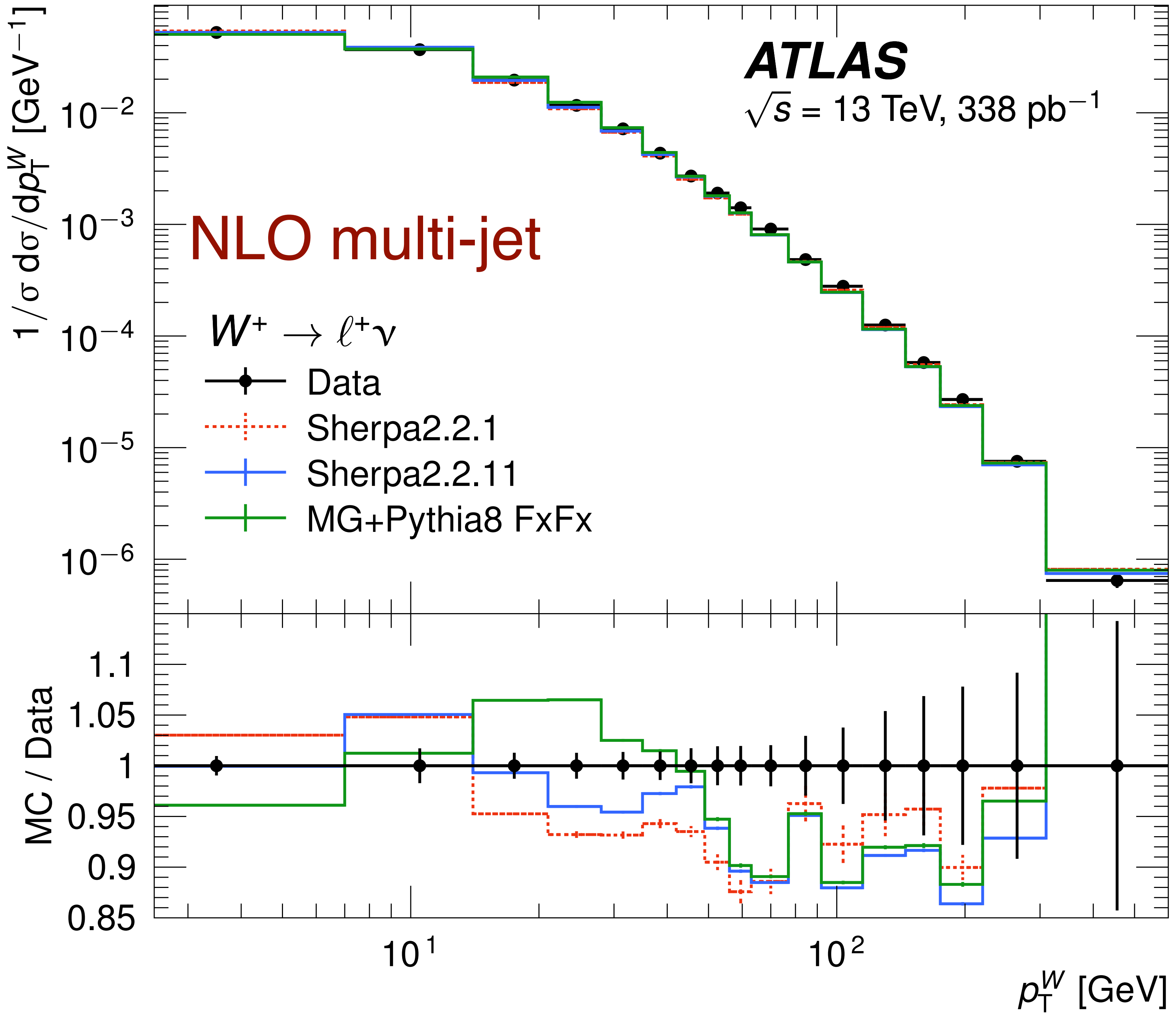


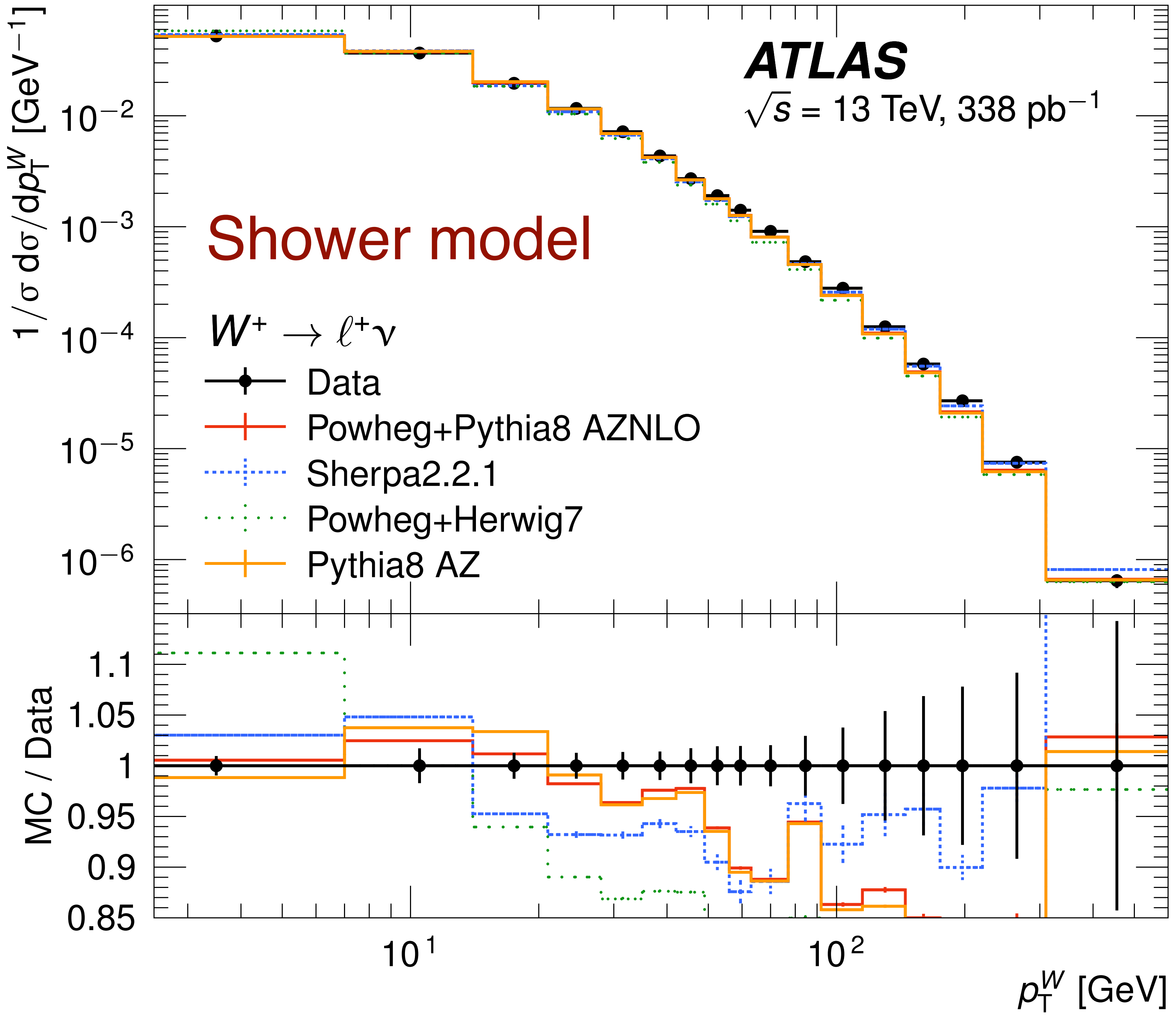
$p_T(V)$ @ 5.02 and 13.0 TeV

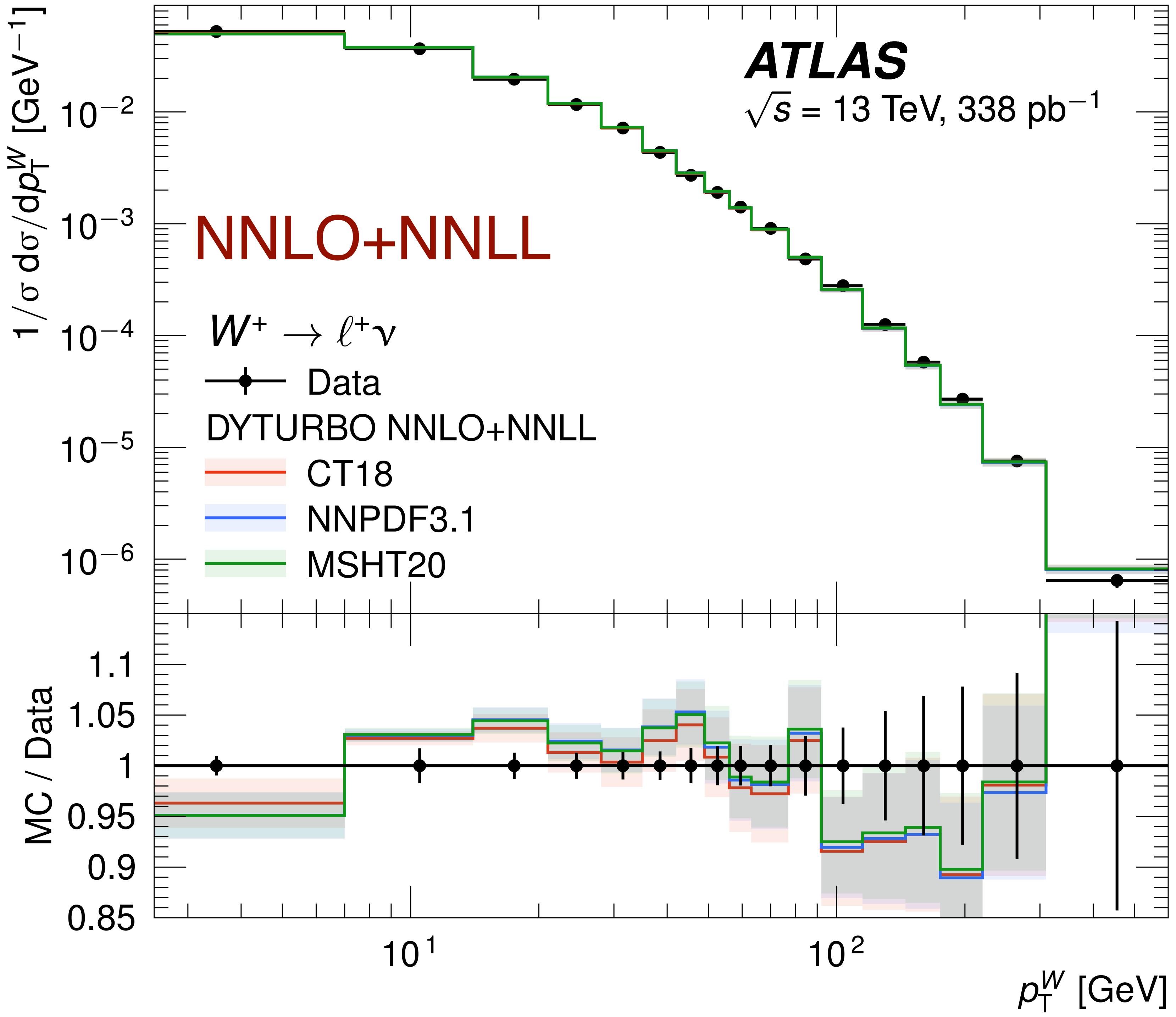
STDM-2018-17

- Using the **low-pileup data** with <μ> ~ 2 taken in 2017 and 2018
  - 255 pb^{-1} at 5.02 TeV and 338 pb^{-1} at 13.0 TeV
  - About 6M *Z* and 500k *W*-bosons after selection
- Uses the **hadronic recoil** to access $p_T(W)$
  - Calibrated with $p_T(Z)$— $p_T(\ell\ell)$ vs hadronic recoil
- $p_T(W)$ measurement can reduce the modeling uncertainty and theory assumptions in the m(W) measurements
- Compare to different generators / tunes / PDFs / …





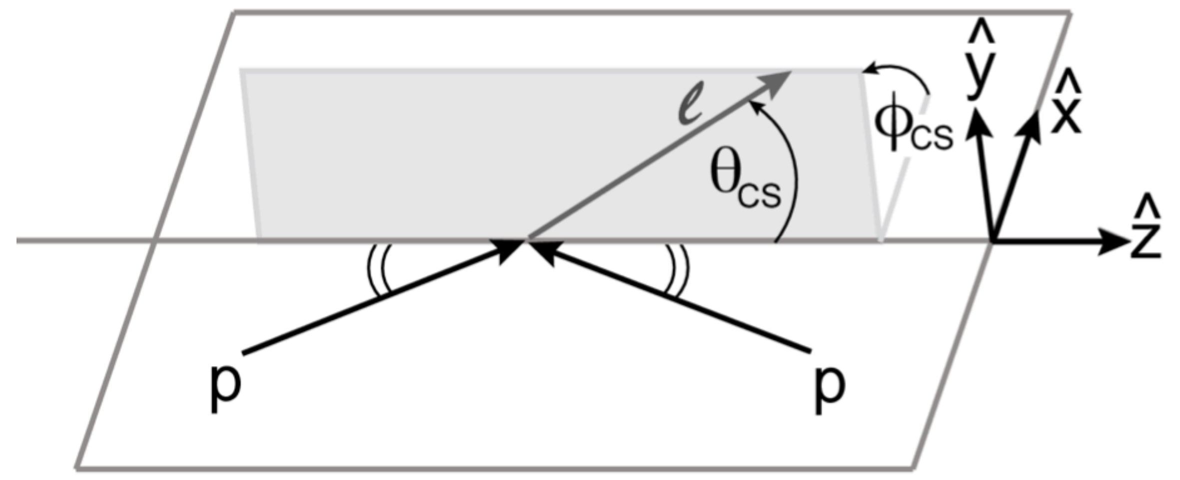


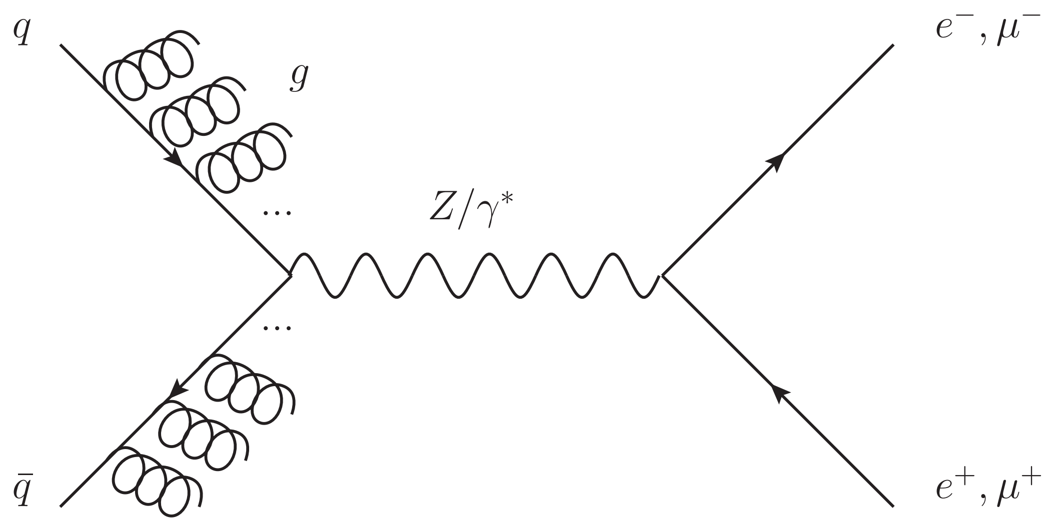


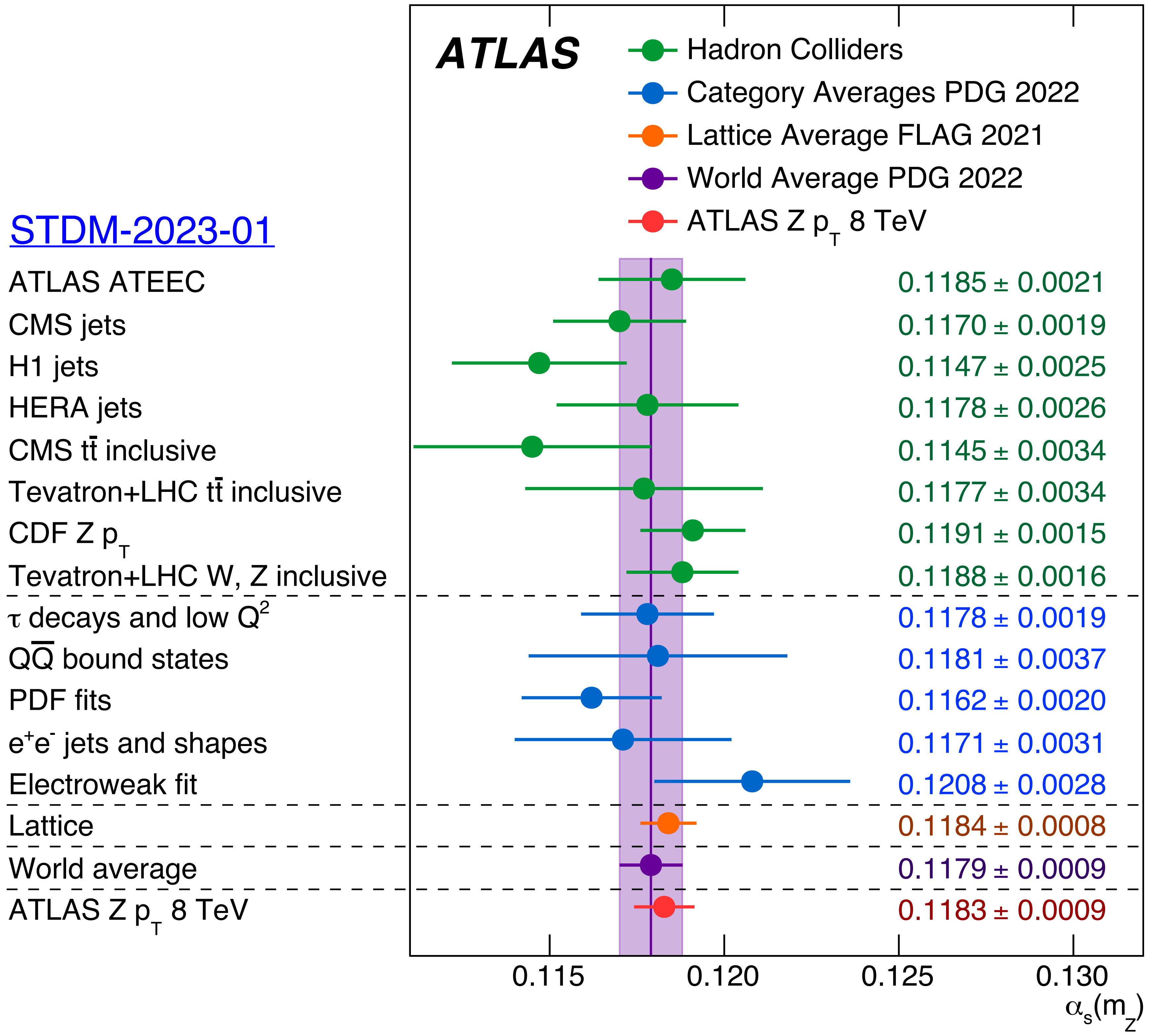
$p_T(Z)$ @ 8 TeV and α_S determination

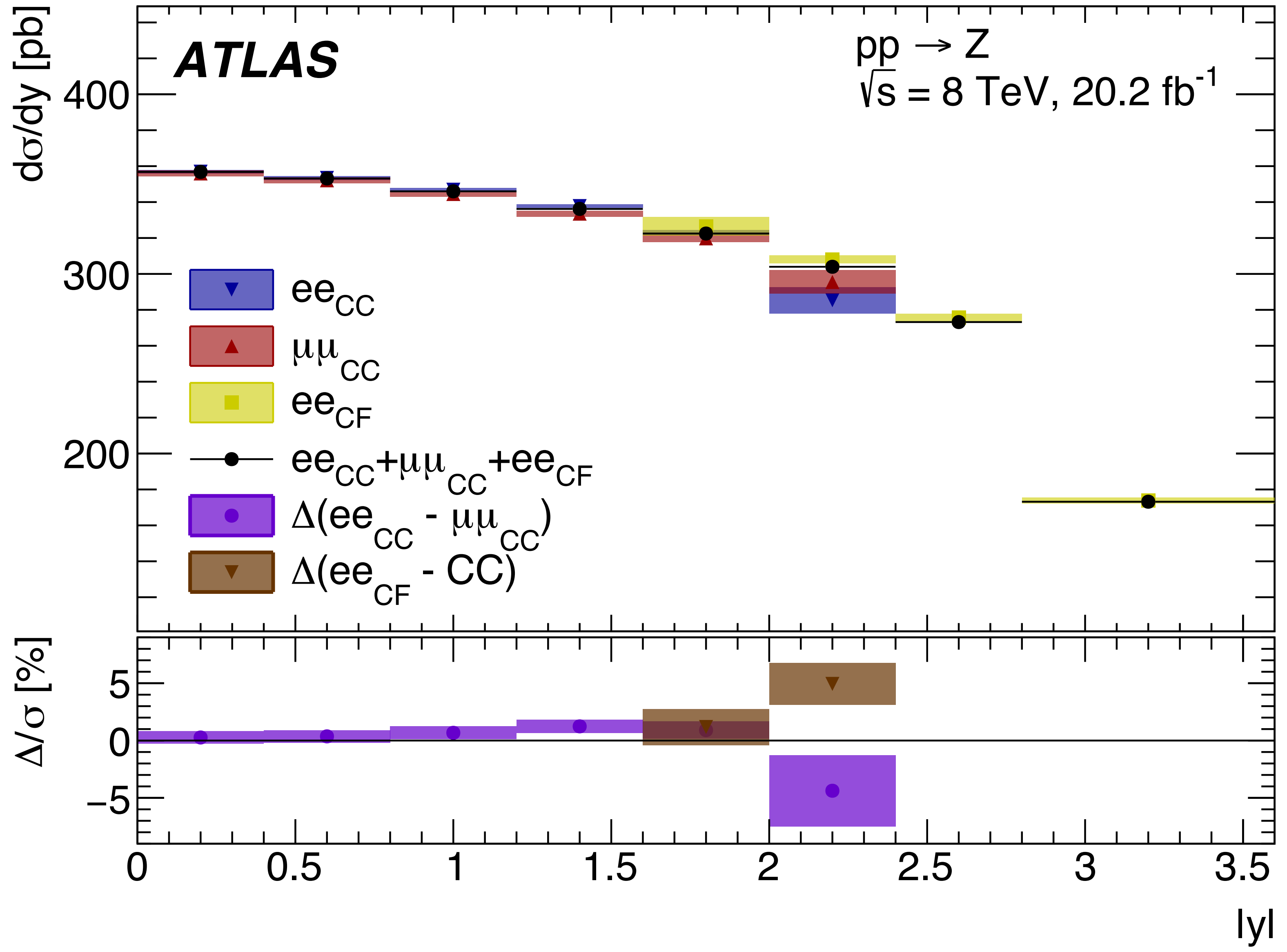
Eur. Phys. J. C 84 (2024) 315

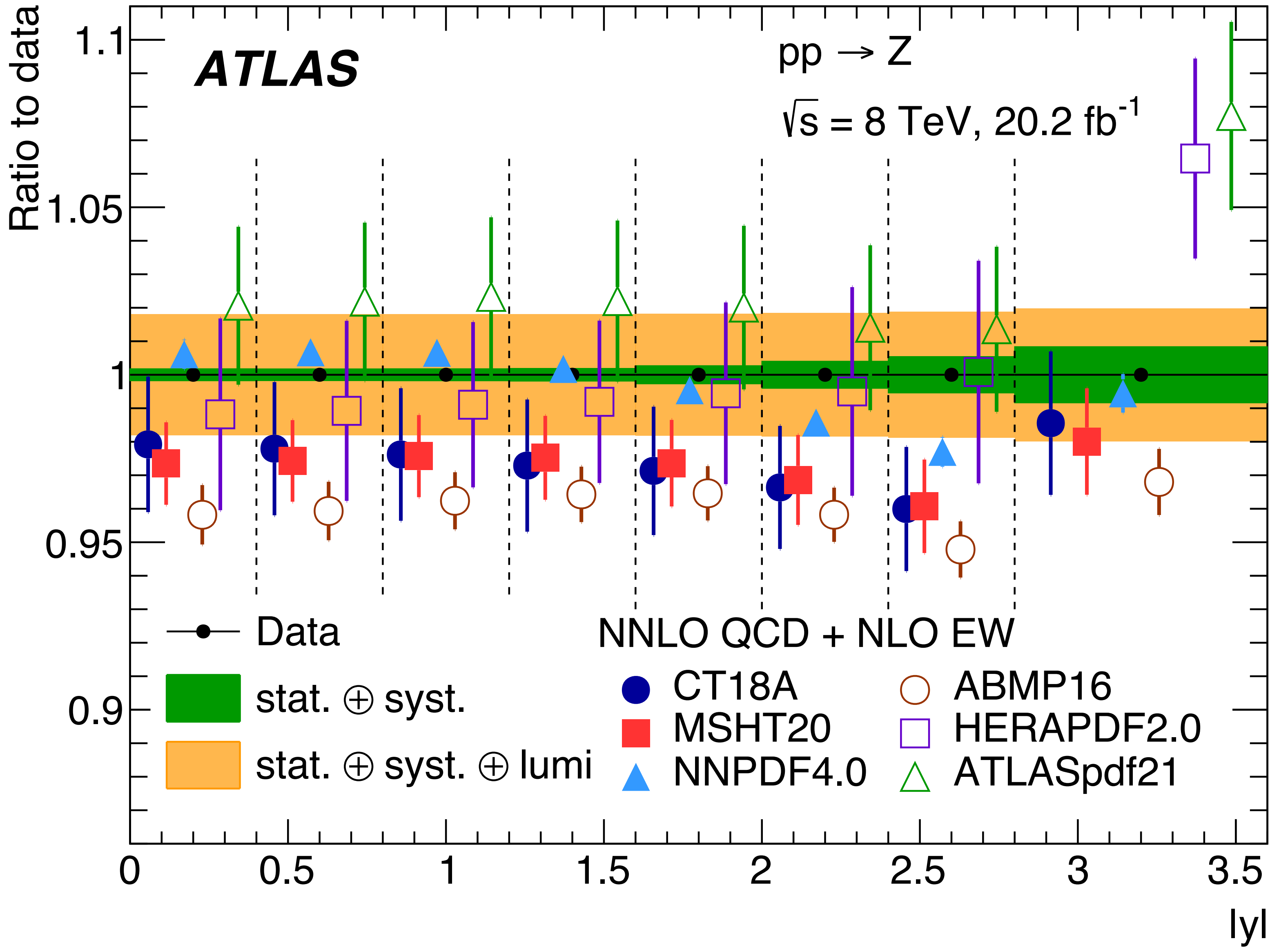
- 22,528 4D detector-level bins in ($p_T(Z)$, $y(Z)$, $\cos\theta$, ϕ)
- Extrapolated to full decay phase space by measuring the angular coefficients and $d^2\sigma/(dp_T dy)$
- Extract α_S with approximate **N³LO+N⁴LL** $p_T(Z)$ predictions
  - With small enough scale uncertainty $p_T(Z)$ shape sensitive to α_S due to soft gluon radiation from initial-state quarks

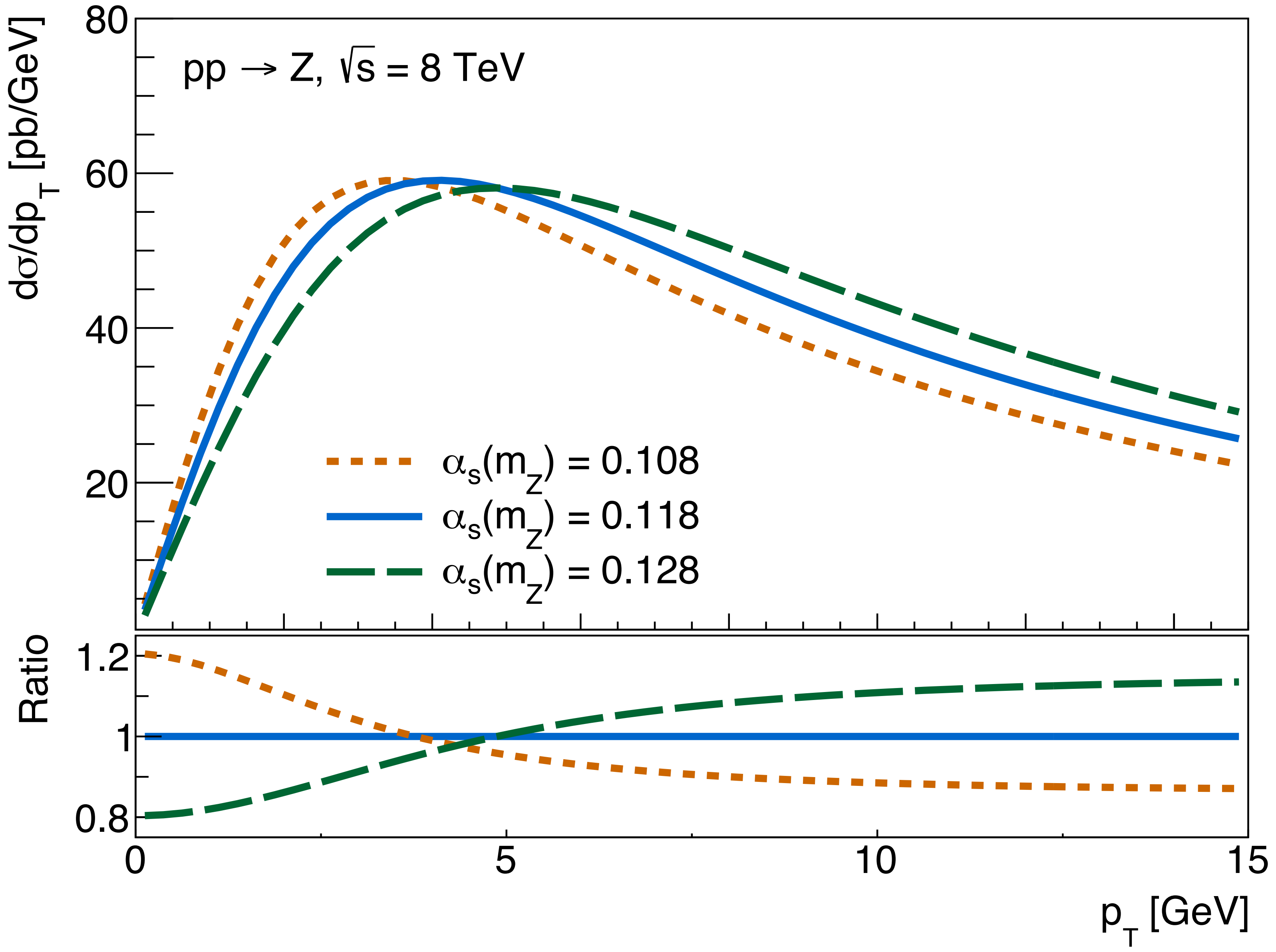












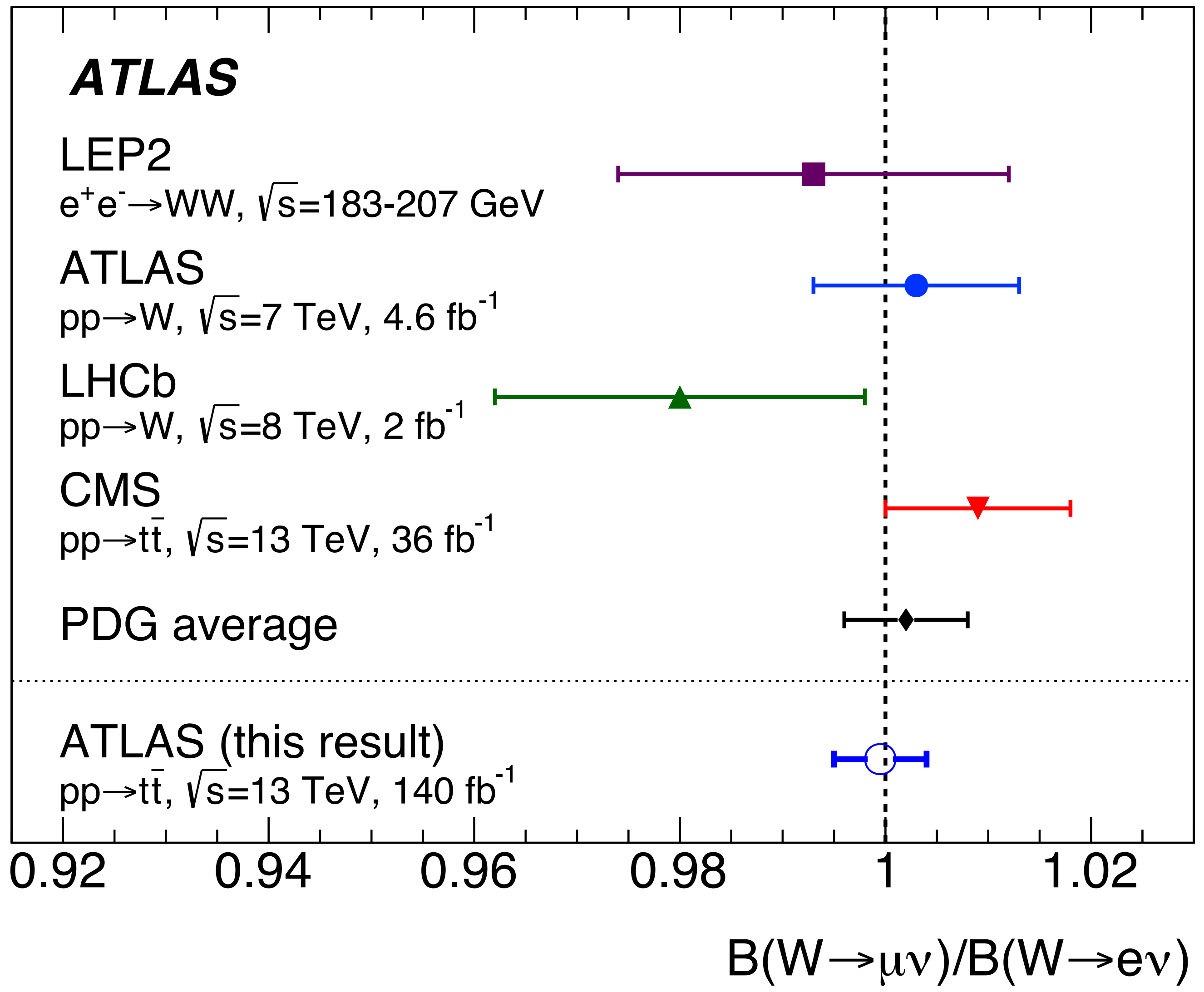
Lepton flavor universality in W decays (full Run 2)

TOPQ-2023-28

- Measure ratio $R_W^{\mu/e} = B(W \to \mu\nu)/B(W \to e\nu)$
- However, a direct measurement would be limited by the lepton efficiency uncertainties; instead:

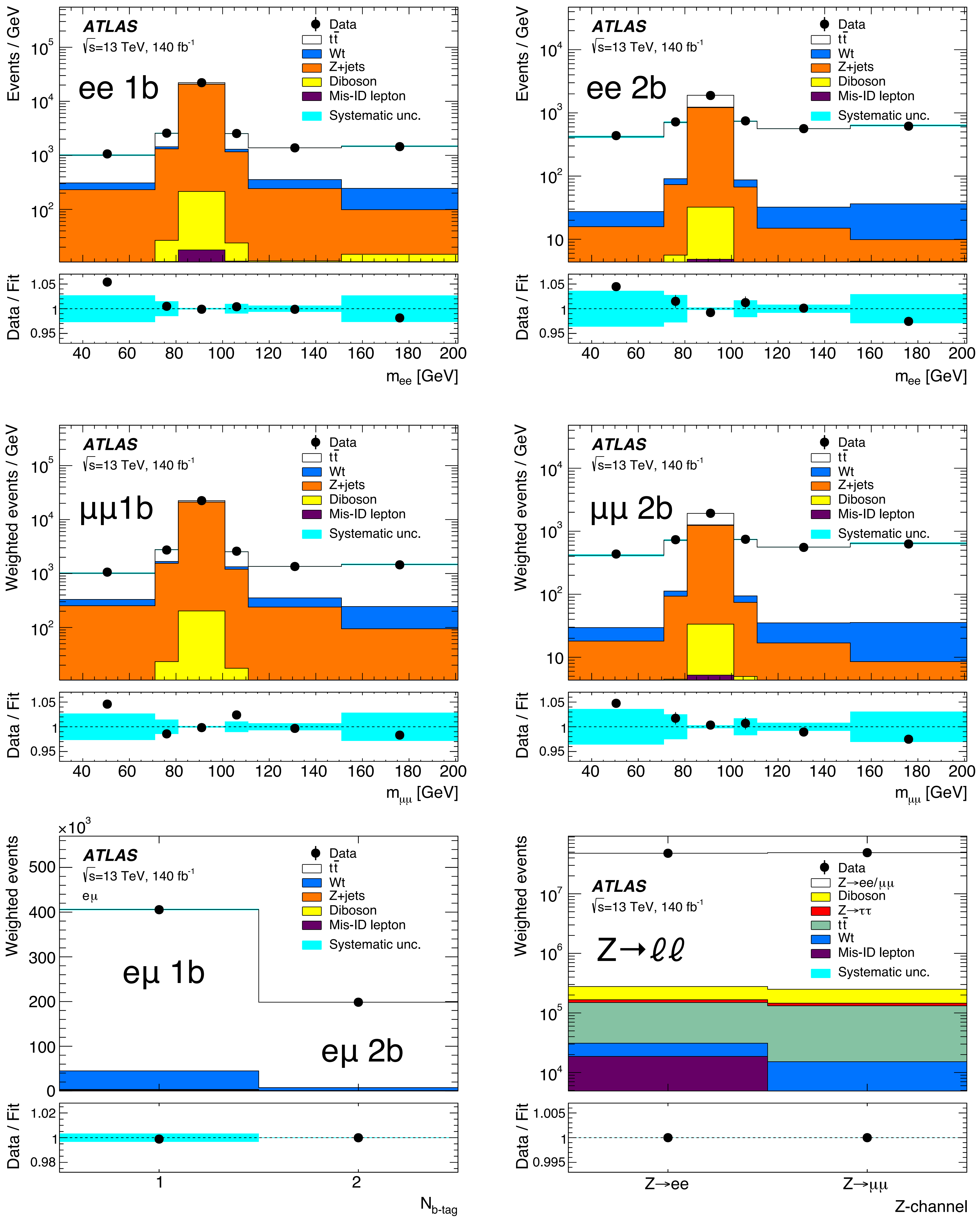
$$\boxed{R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{B(W \to \mu\nu)}{B(W \to e\nu)}\sqrt{\frac{B(Z \to ee)}{B(Z \to \mu\mu)}}}$$

- Extracted w/ a likelihood fit (28 bins in the right plots)
- Obtain $R_W^{\mu/e}$ by multiplying $R_{WZ}^{\mu/e}$ with the best independent value of $R_Z^{\mu\mu/ee} = 1.0009 \pm 0.0028^{\text{LEP + SLD}}$



$$\boxed{R_W^{\mu/e} = 0.9995 \pm 0.0045}$$

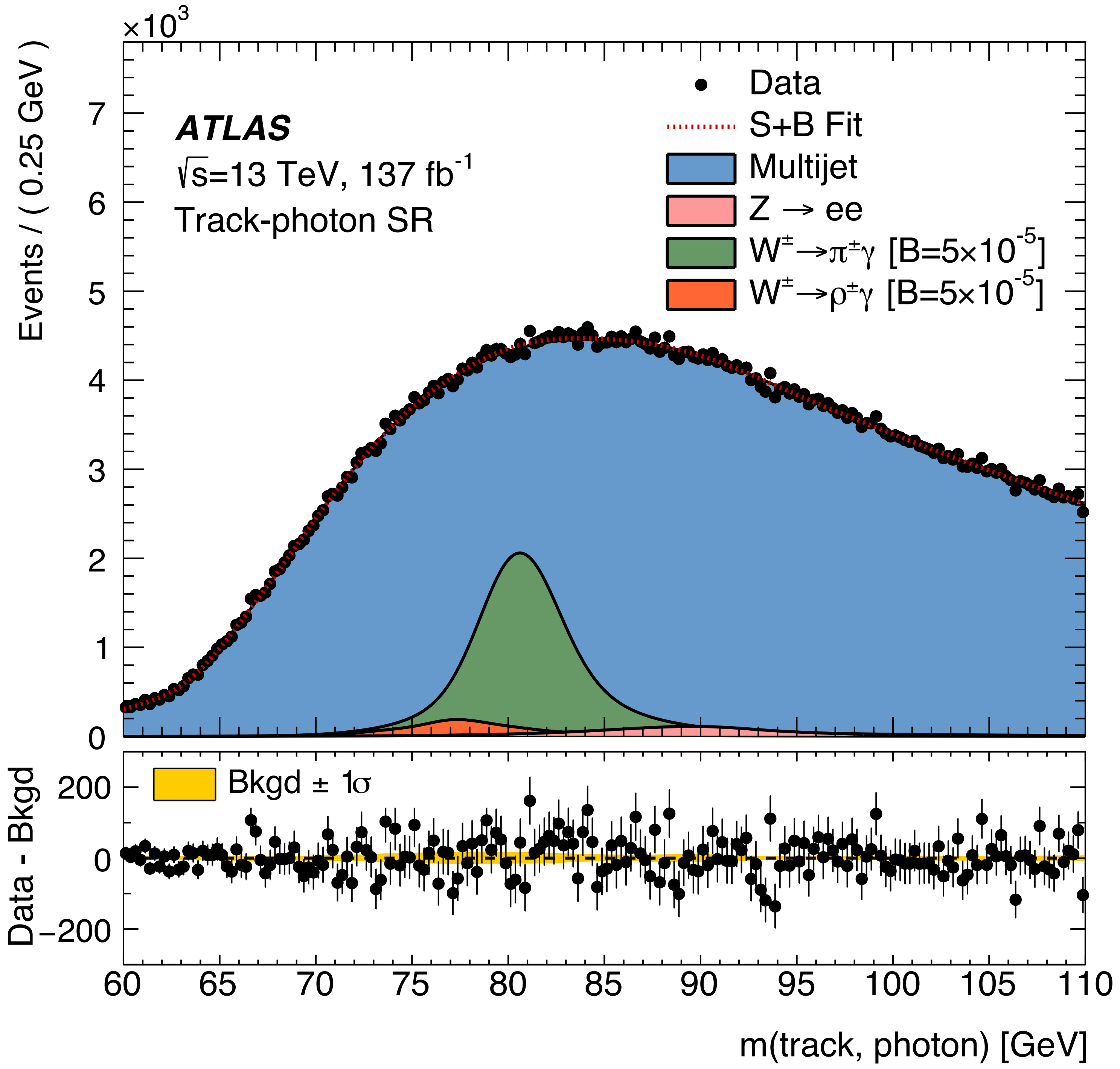
Single most precise measurement; no sign of lepton non-universality

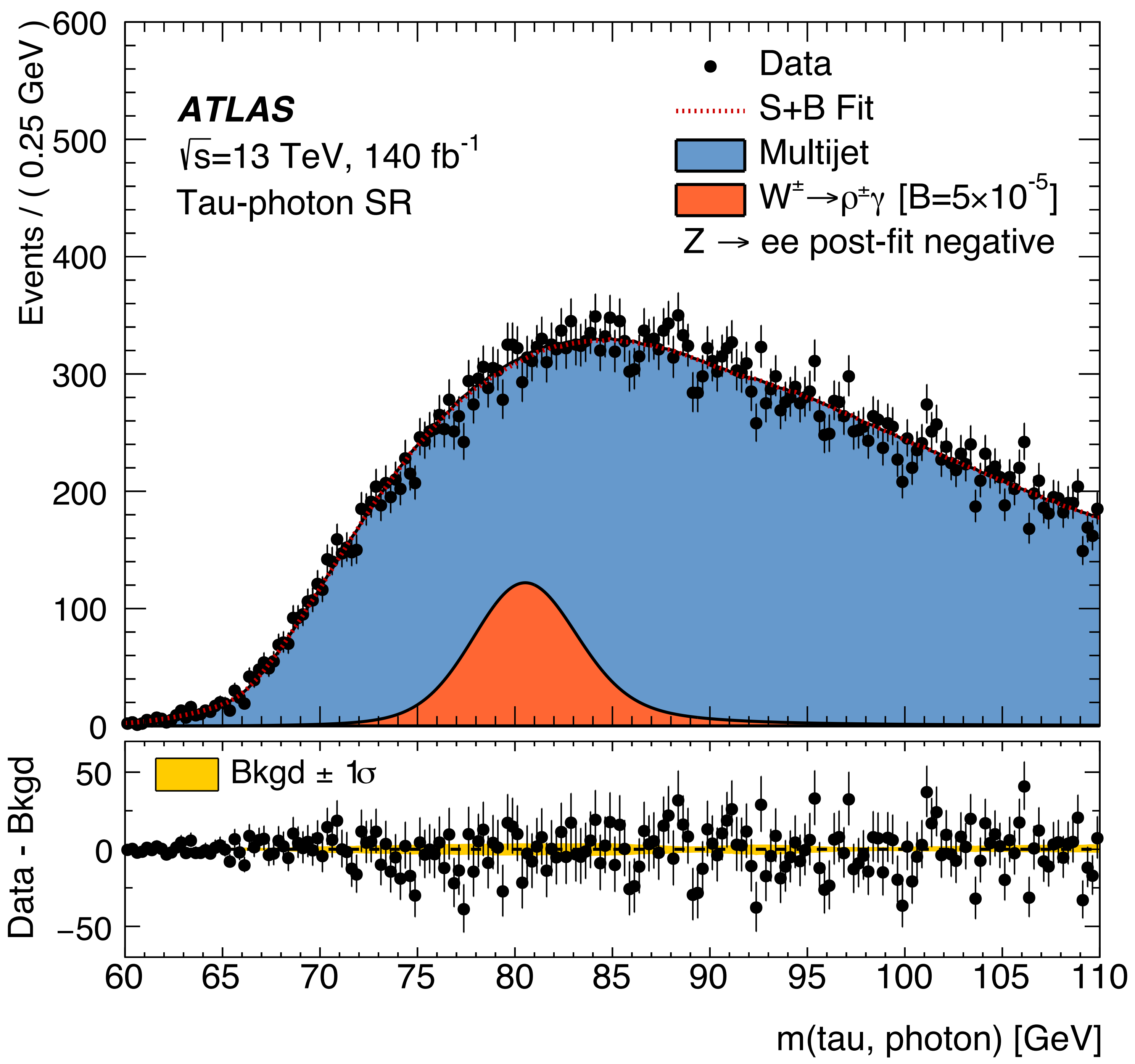


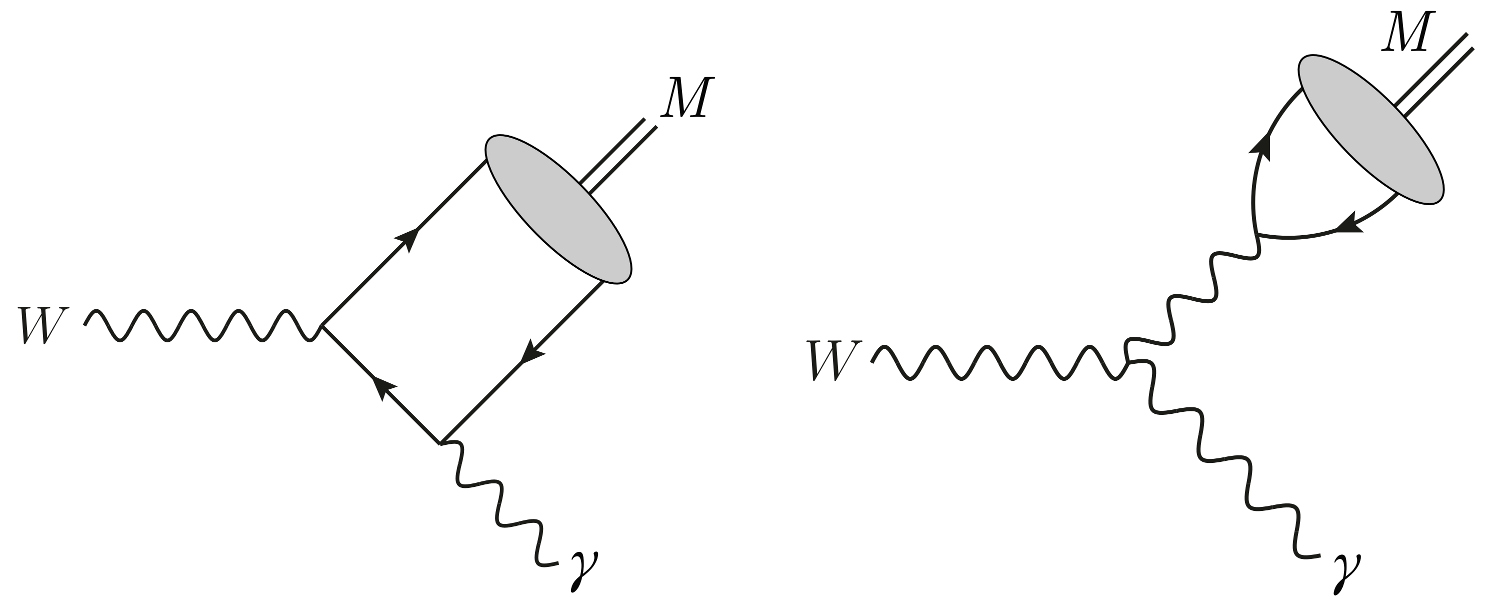
Search for exclusive hadronic W boson decays (full Run 2)

STDM-2019-20

- No exclusive hadronic decay mode of any boson has yet been observed
  - Potentially sensitive to exclusive had. W boson decays at the HL-LHC (not enough data in Run 2 + Run 3)
- Probe W boson coupling to different generations of quarks; testbed for QCD factorization
- Possible new channels for the direct measurement of the W boson mass
- Two final states experimentally probed with dedicated triggers for the track + photon final state:
  - Track + photon (sensitive to $W \to \pi/K + \gamma$)
  - Tau + photon (sensitive to $W \to \rho(\to \pi\pi^0) + \gamma$)







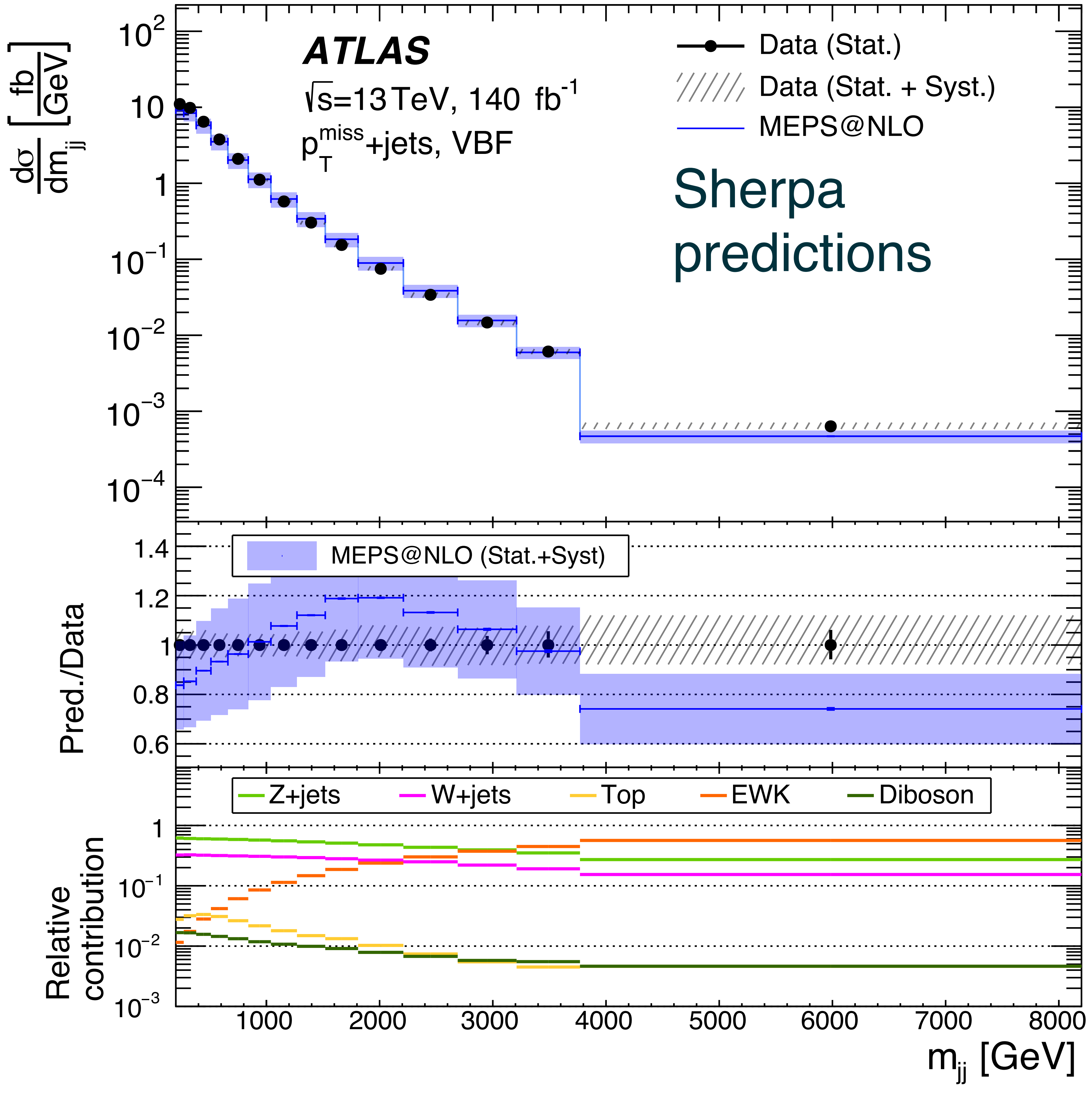
	95% CL upper limits	
Branching fraction	Expected $\times 10^{-6}$	Observed $\times 10^{-6}$
$\mathcal{B}(W^{\pm} \to \pi^{\pm}\gamma)$	$1.2^{+0.5}_{-0.3}$	1.9
$\mathcal{B}(W^{\pm} \to K^{\pm}\gamma)$	$1.1^{+0.4}_{-0.3}$	1.7
$\mathcal{B}(W^{\pm} \to \rho^{\pm}\gamma)$	$6.0^{+2.3}_{-1.7}$	5.2

V+jets measurements (including V+HF)

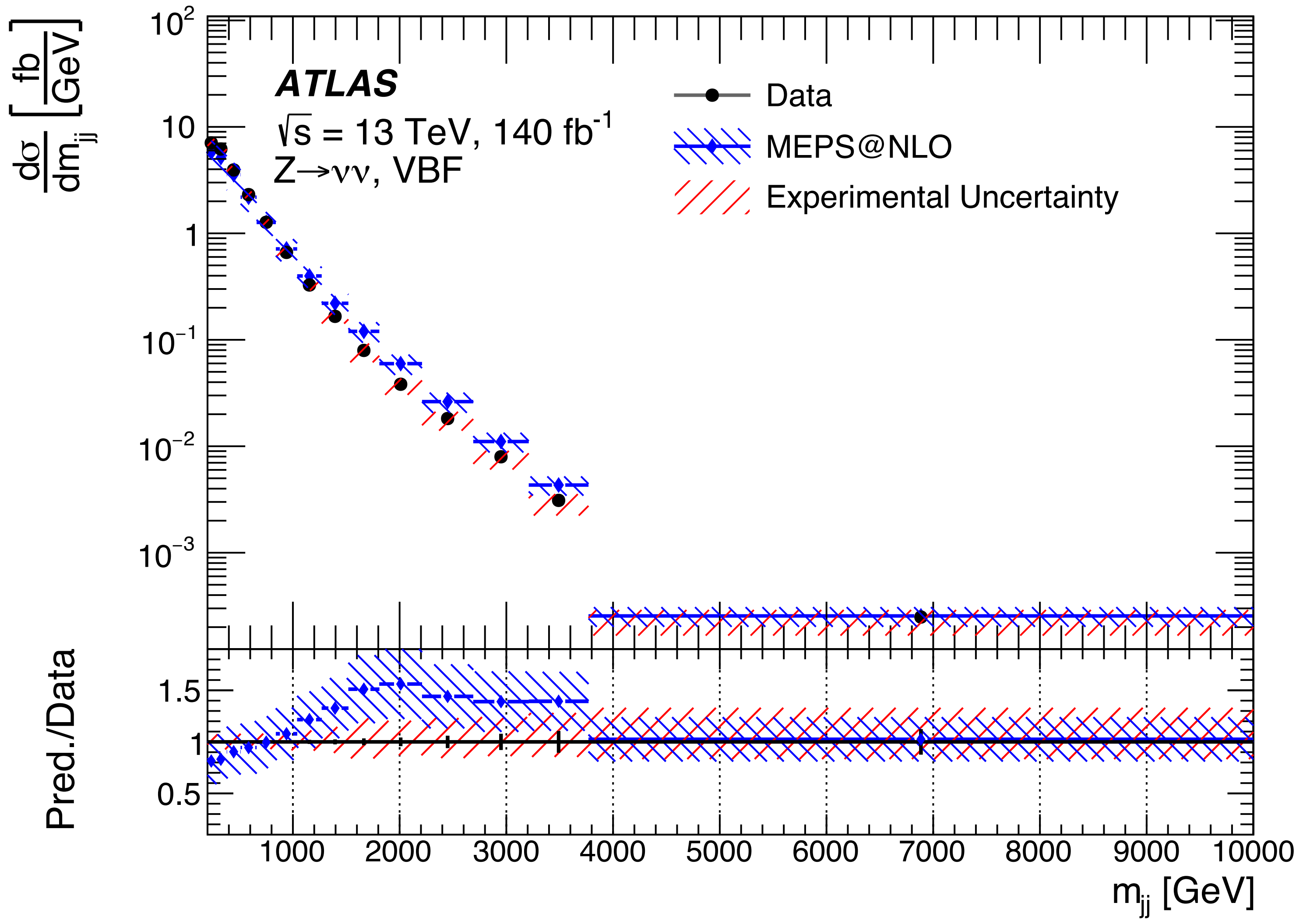
Measurement of MET + jets (Full Run 2)

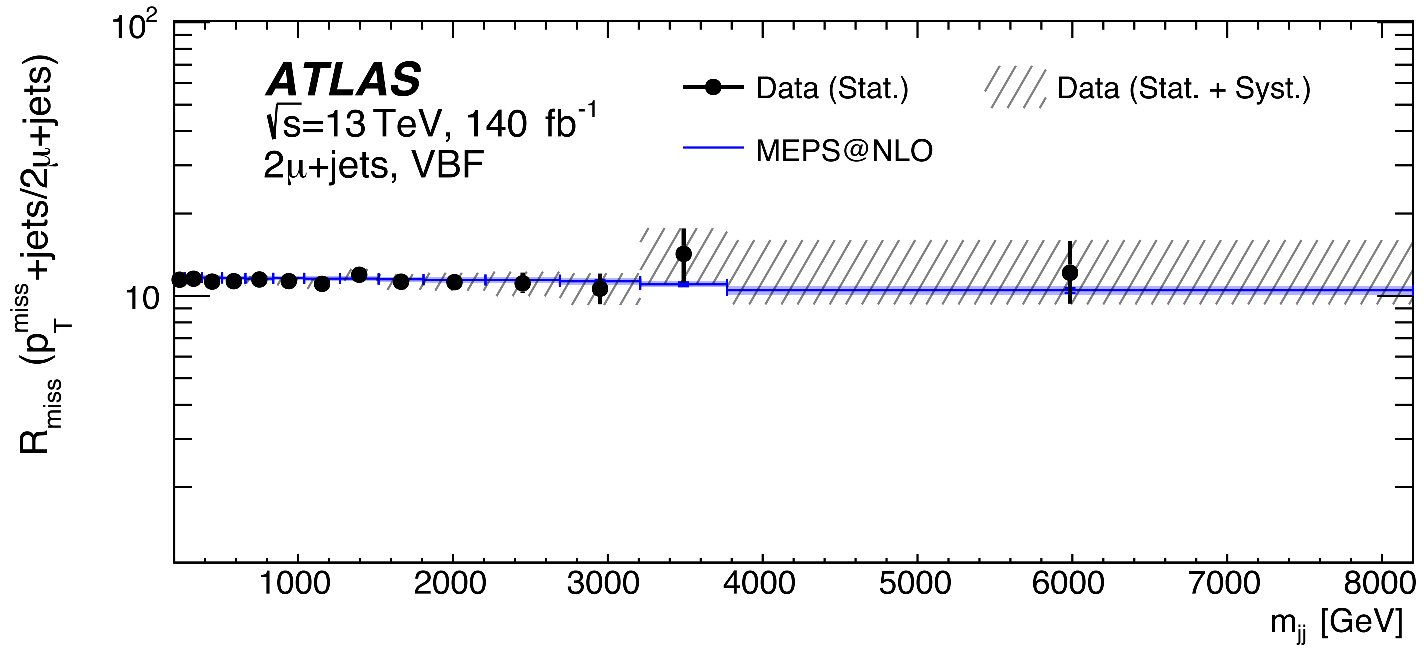
STDM-2018-55

- Model independent measurement of differential cross sections for the $p_{\mathrm{T}}^{\mathrm{miss}}$ + jets final state
  - Explicit measurement of $Z \rightarrow \nu\nu$ + jets also made to ease the comparisons with the SM predictions
- Auxiliary measurements: hadronic recoil $p_{\mathrm{T}}^{\mathrm{recoil}}$ together with isolated leptons and photos
  - Enables cross section ratio measurements where systematic uncertainties cancel out
- Inclusive ≥ 1 jet phase-space and VBF phase space (2 jets with large m_{jj}) probed

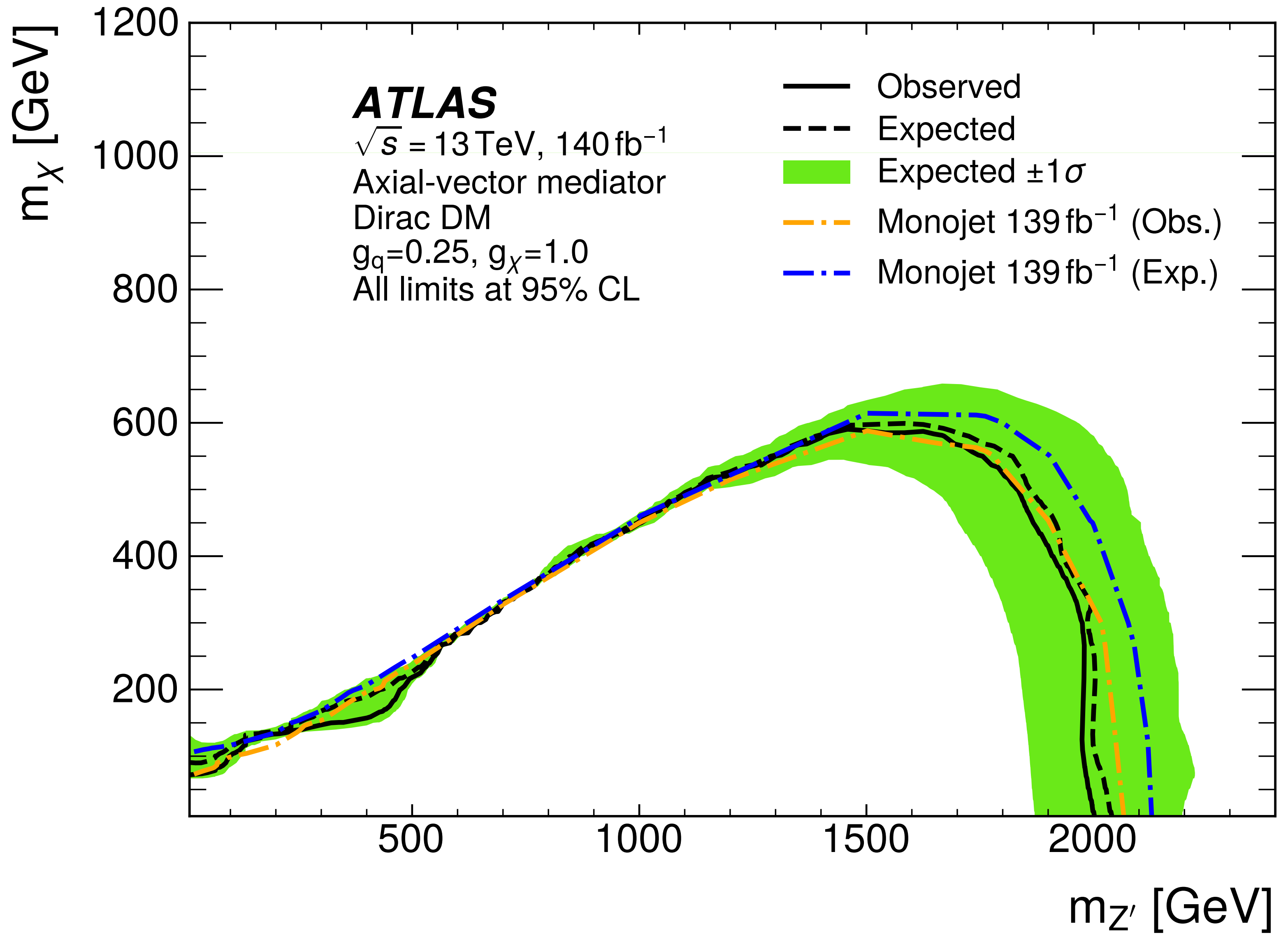


Sherpa predictions





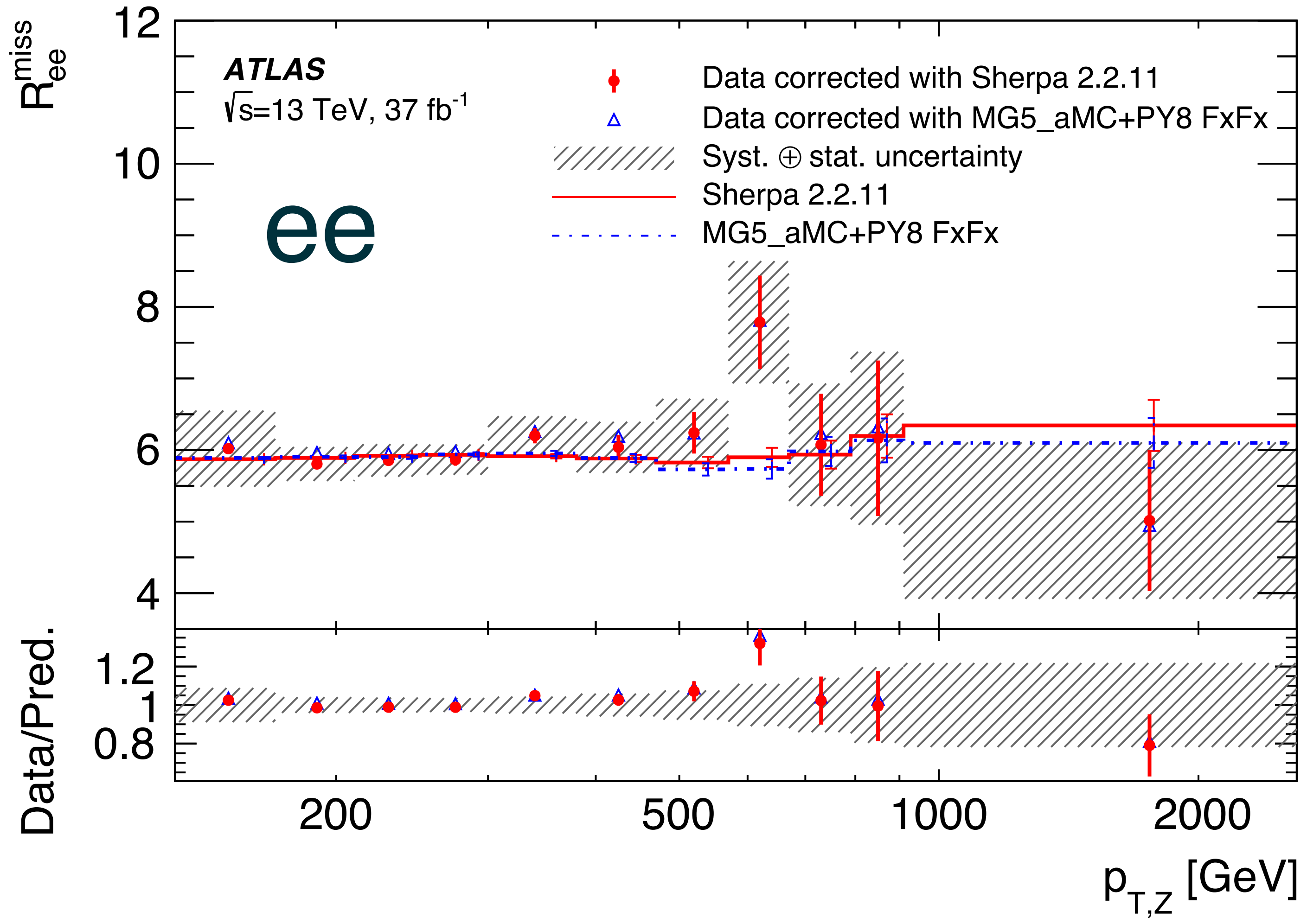
Data can also be used to set limits on Dark Matter BSM models. Comparable sensitivity to direct searches!

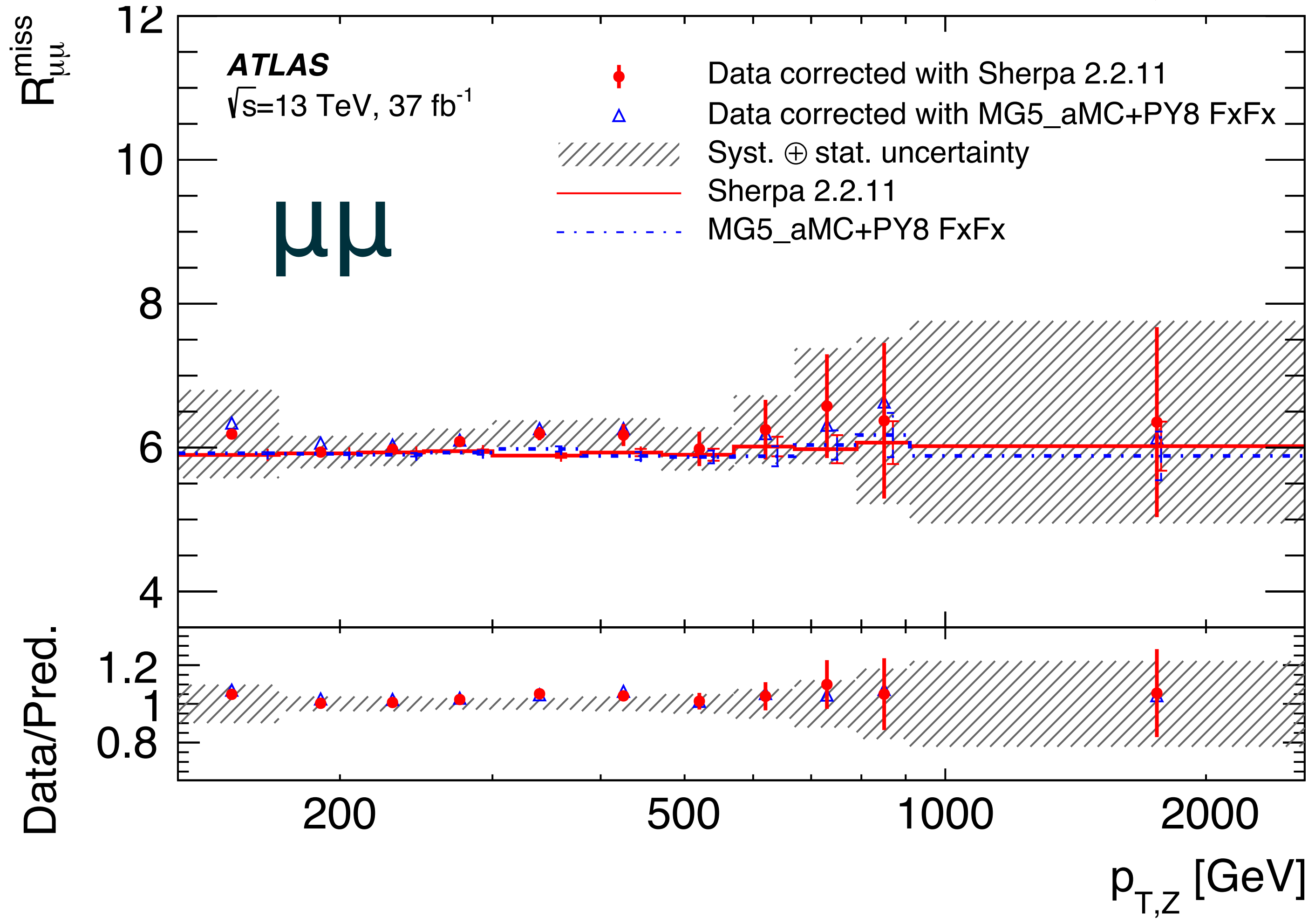


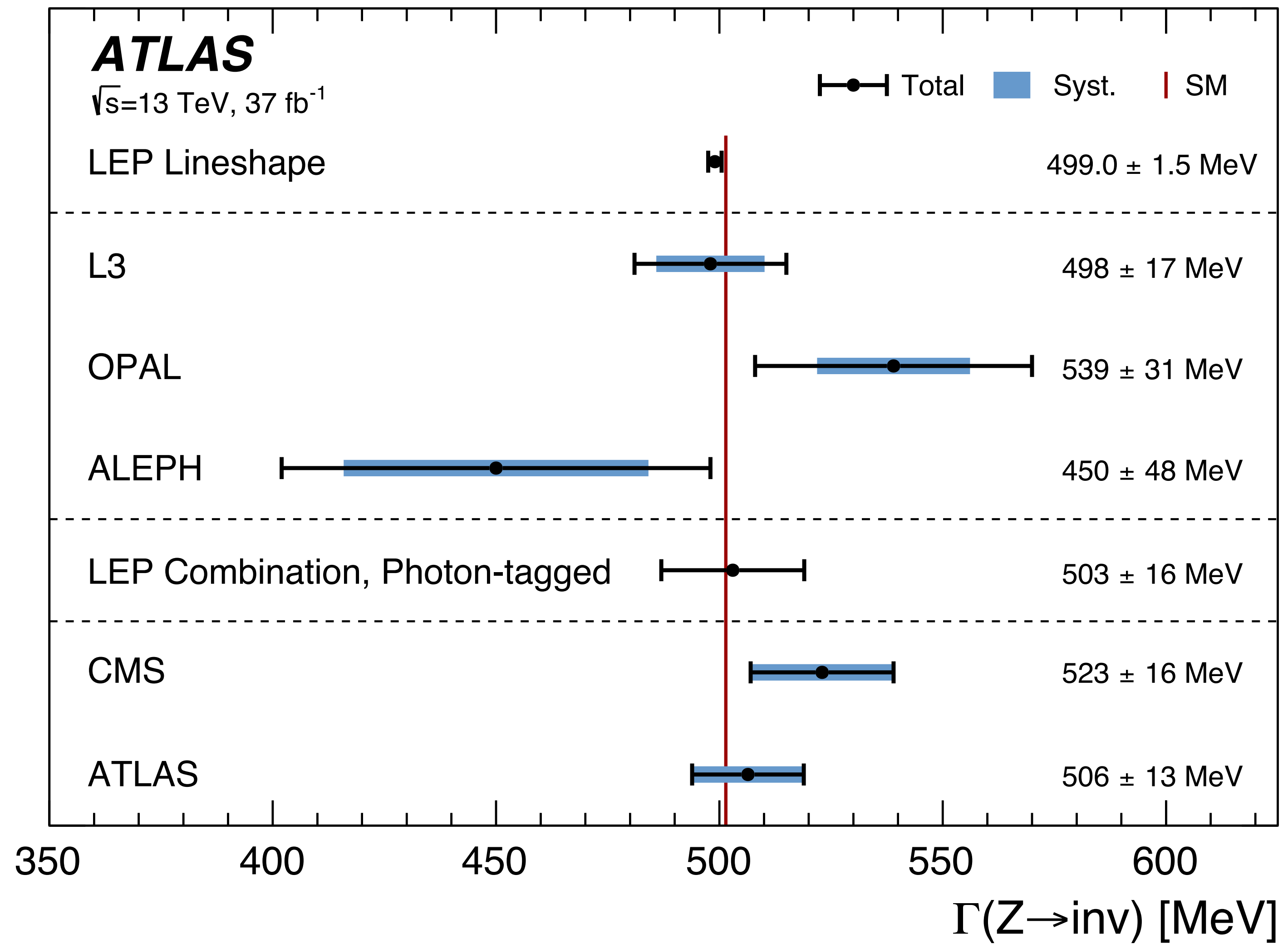
Measurement Z boson invisible width (2015 + 2016 data)

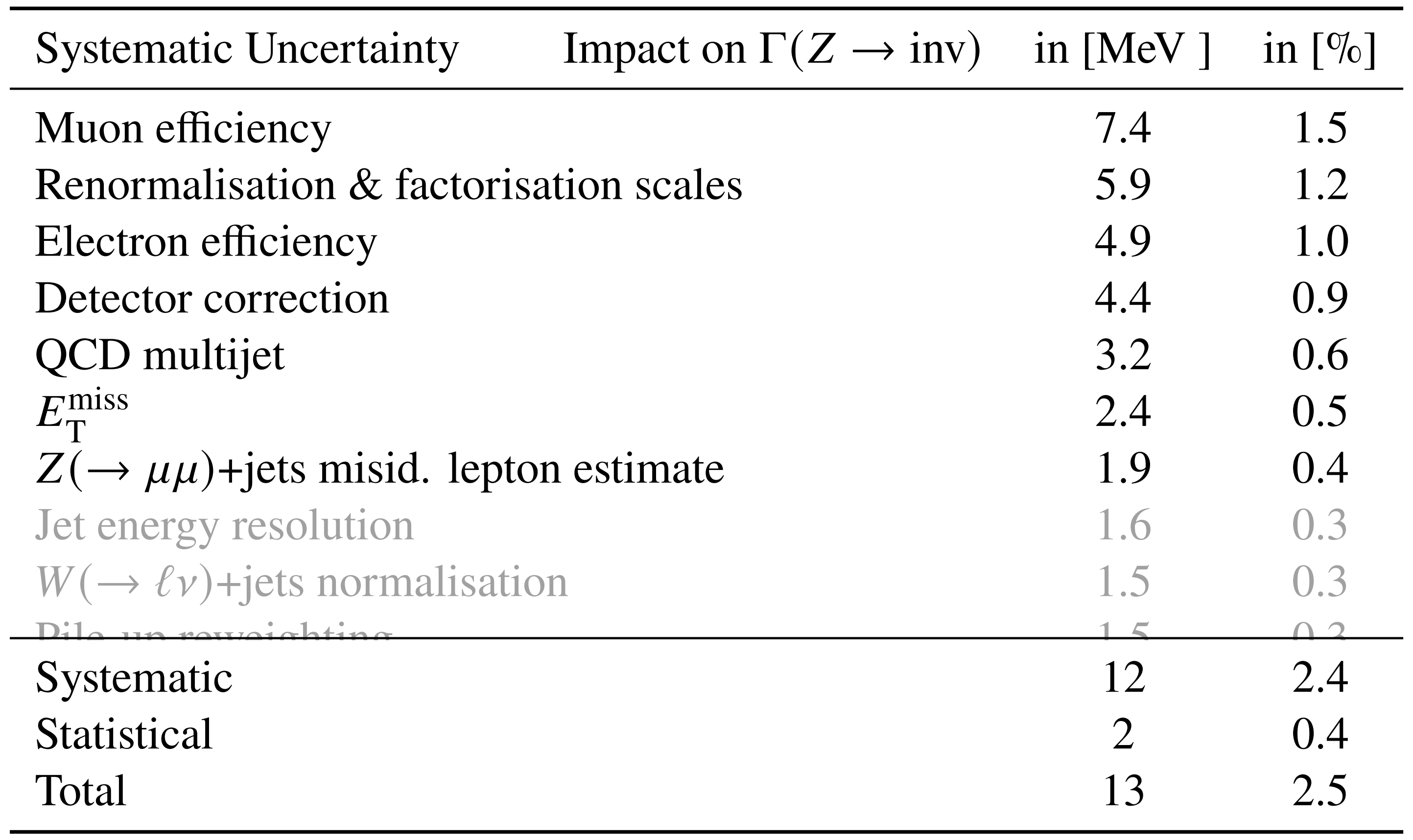
STDM-2019-01

- Z boson invisible width $\Gamma(Z \to \mathrm{inv})$ related to the number of lepton generations and potential BSM effects
- Measurement performed with partial Run 2 data— measure the ratio of $p_{\mathrm{T}}^{\mathrm{miss}}$ + jets vs $Z \to \ell\ell$ + jets
  - The ratio R^{miss} can be determined very precisely as most systematic uncertainties cancel out
- $\Gamma(Z \to \mathrm{inv})$ is determined by multiplying R^{miss} with the independent value of $\Gamma(Z \to \ell\ell)$ from LEP

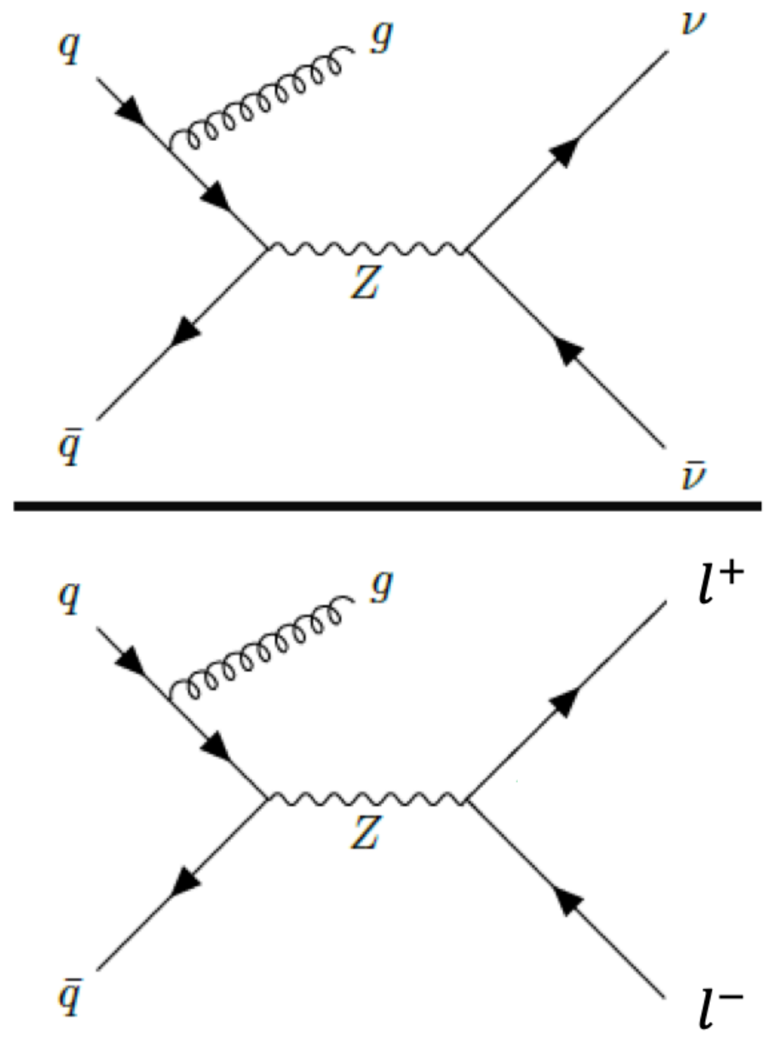








Systematic Uncertainty	Impact on $\Gamma(Z \to \mathrm{inv})$ in [MeV]	in [%]
Muon efficiency	7.4	1.5
Renormalisation & factorisation scales	5.9	1.2
Electron efficiency	4.9	1.0
Detector correction	4.4	0.9
QCD multijet	3.2	0.6
$E_{\mathrm{T}}^{\mathrm{miss}}$	2.4	0.5
$Z(\to \mu\mu)$+jets misid. lepton estimate	1.9	0.4
Jet energy resolution	1.6	0.3
$W(\to \ell\nu)$+jets normalisation	1.5	0.3
Pile-up reweighting	1.5	0.3
Systematic	12	2.4
Statistical	2	0.4
Total	13	2.5



$$R^{\mathrm{miss}} = \frac{\Gamma(Z \to \mathrm{inv})}{\Gamma(Z \to \ell\ell)}$$

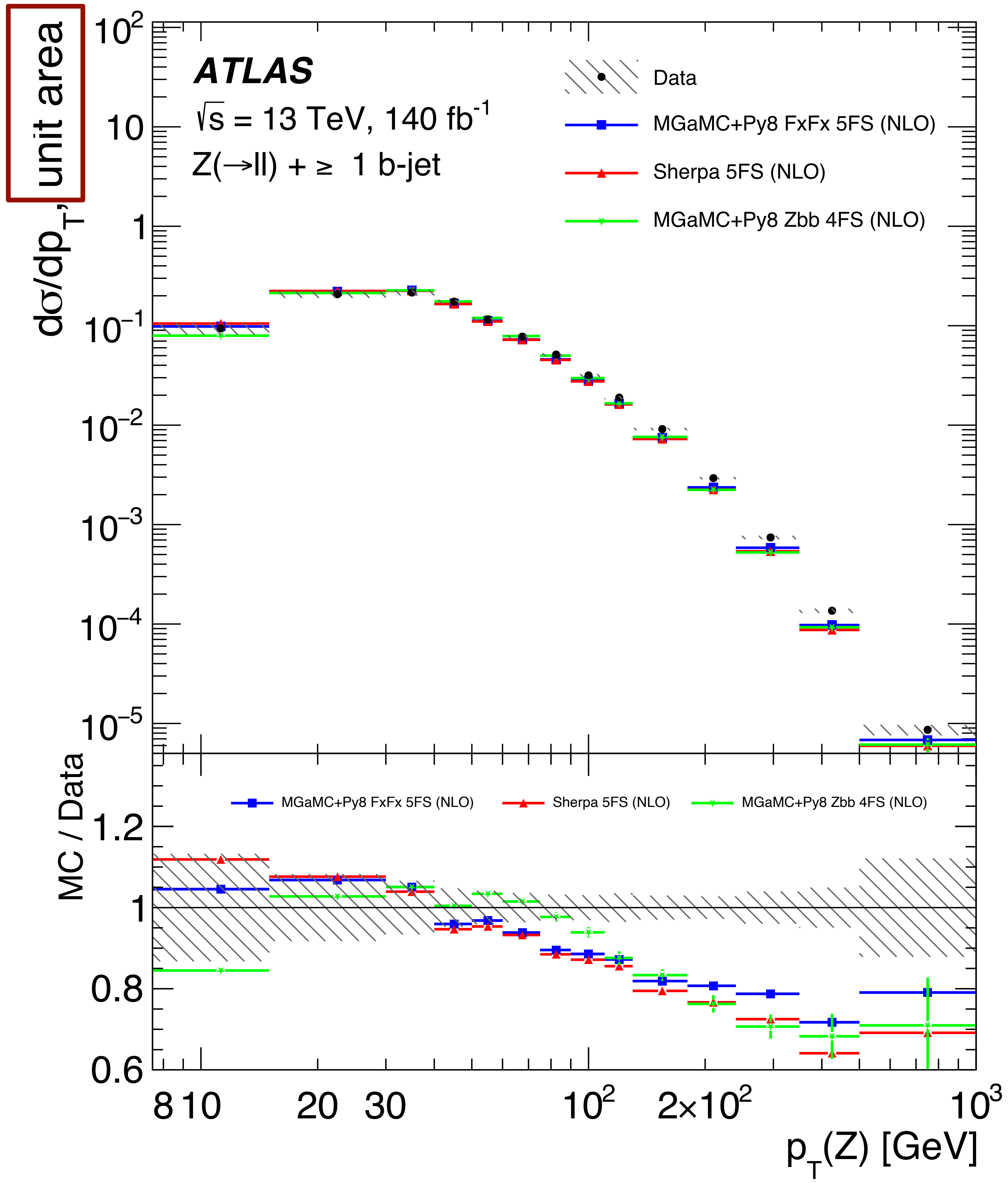
$$\Gamma(Z \to \mathrm{inv}) = 506 \pm 2\,(\mathrm{stat.}) \pm 12\,(\mathrm{syst.})\,\mathrm{MeV}$$

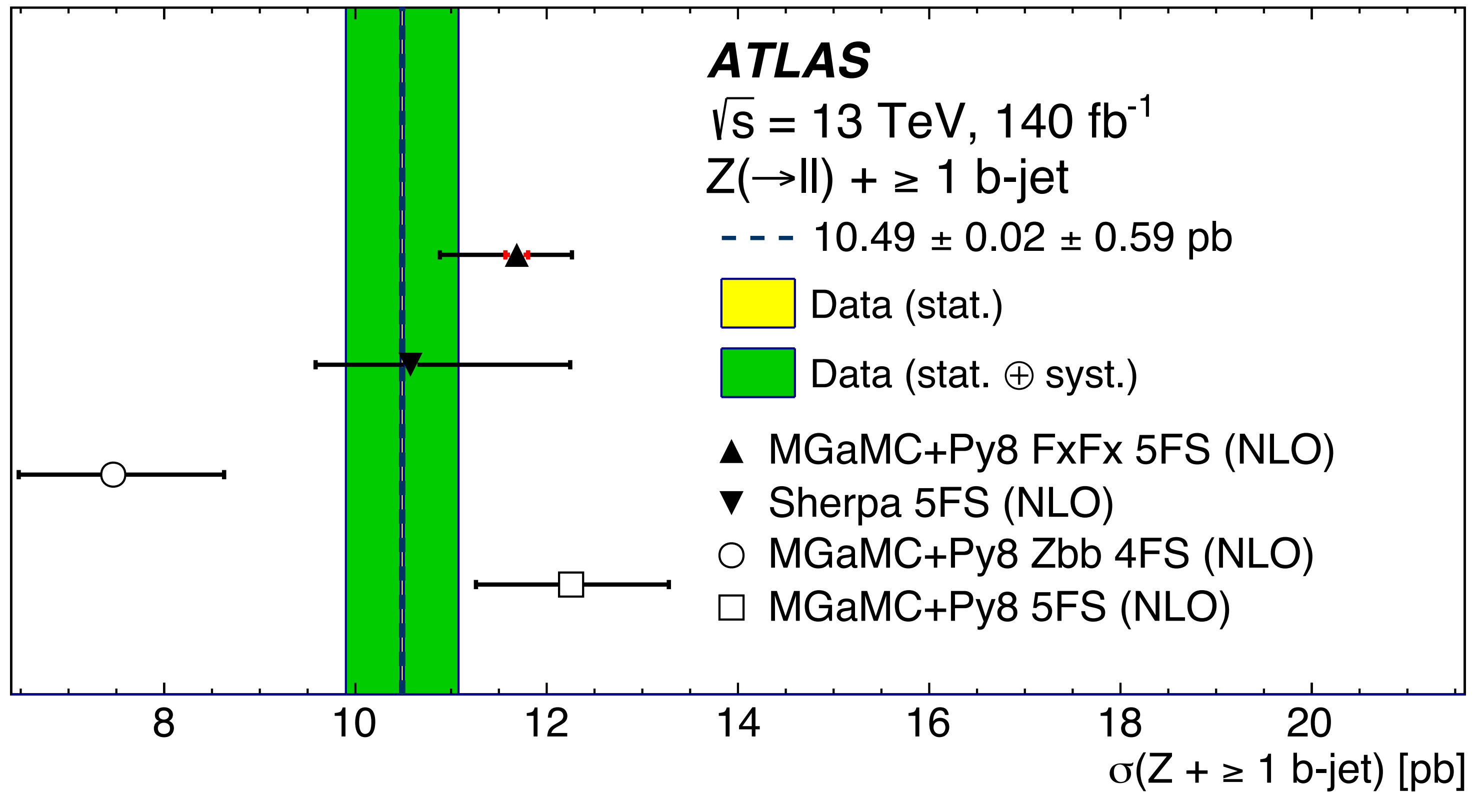
Most precise single “recoil based” measurement; dominated by systematic uncertainties in lepton efficiencies.

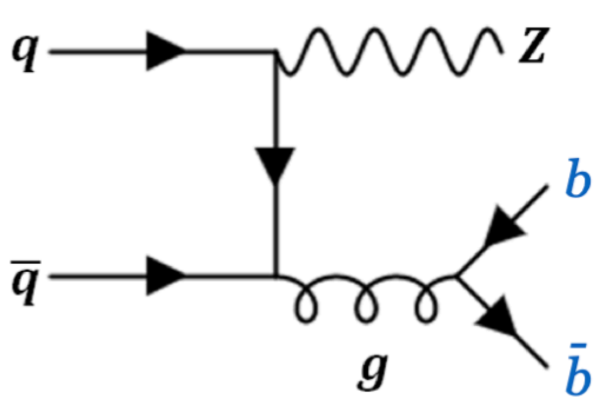
Z+HF jets measurement (Full Run 2)

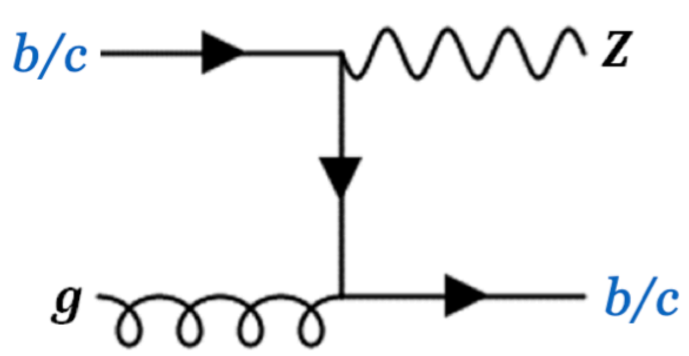
STDM-2018-43

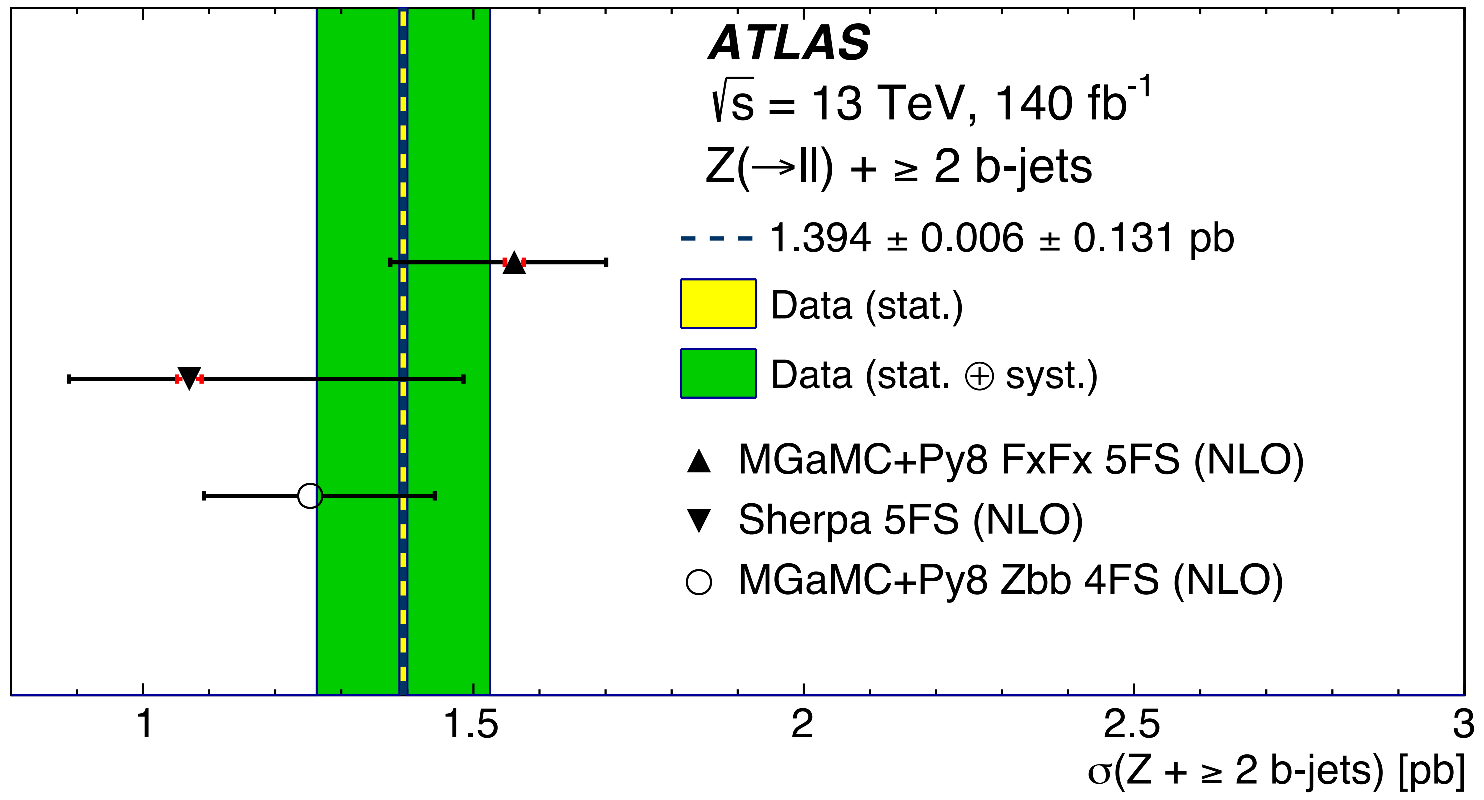
- Measurement performed with “particle flow” jets using ML-based flavor tagging (FTAG) algorithms
- Events split into ≥1b-jet, ≥2b-jet, and ≥1c-jet regions; corresponding FTAG uncertainties: 3.6%, 5.7%, 10%
- Very important for MC tuning as V+HF are major background in many searches (e.g. H→bb/cc)
  - Sensitive to pQCD, PDFs (strange, charm, bottom), different Flavor Number Schemes in simulations
- Differential cross sections measured for many variables:
  - pT(Z), pT(jet), ΔR(Z,b), Δϕ(b,b), m(b,b), x_F(c-jet)

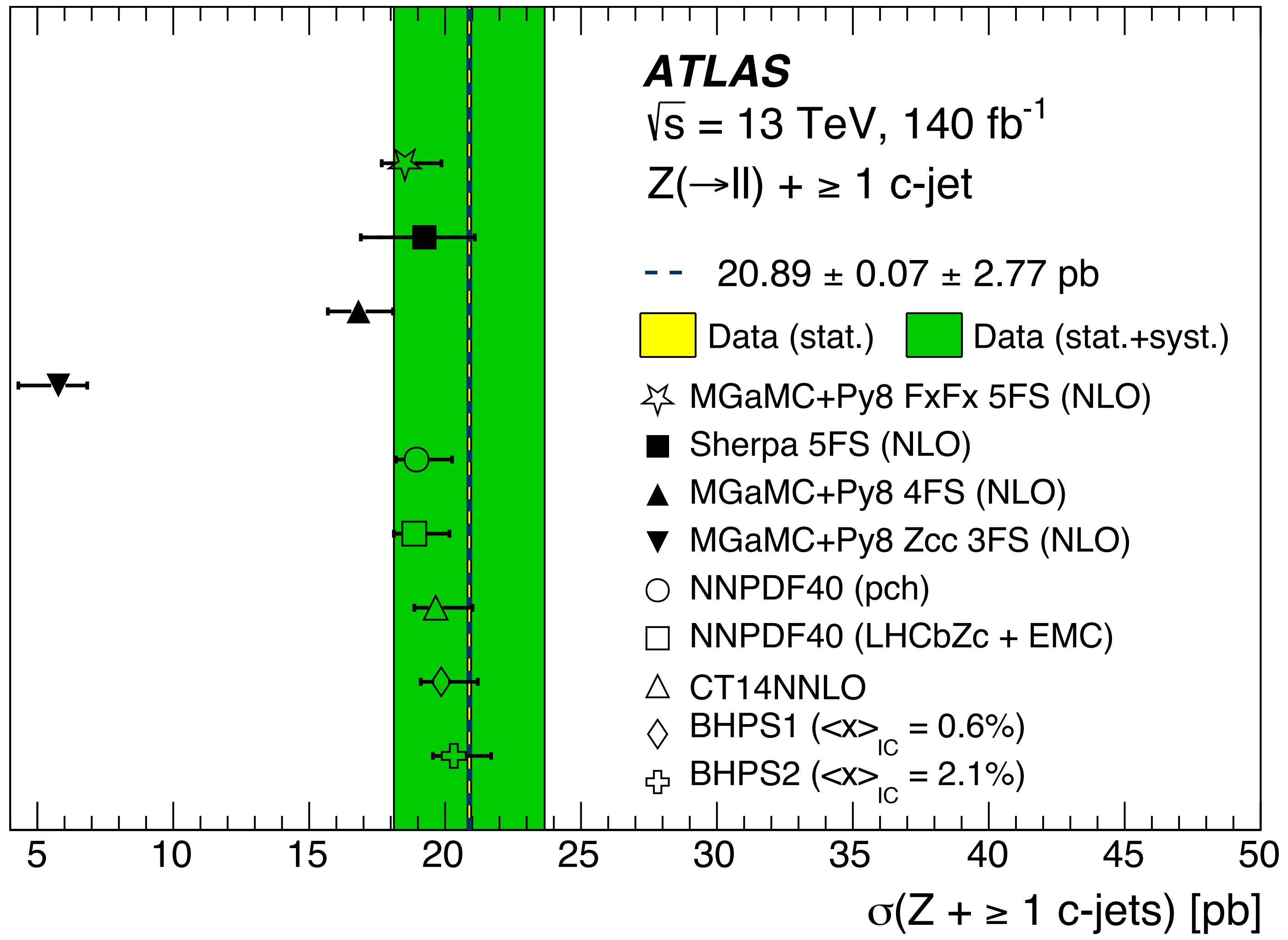






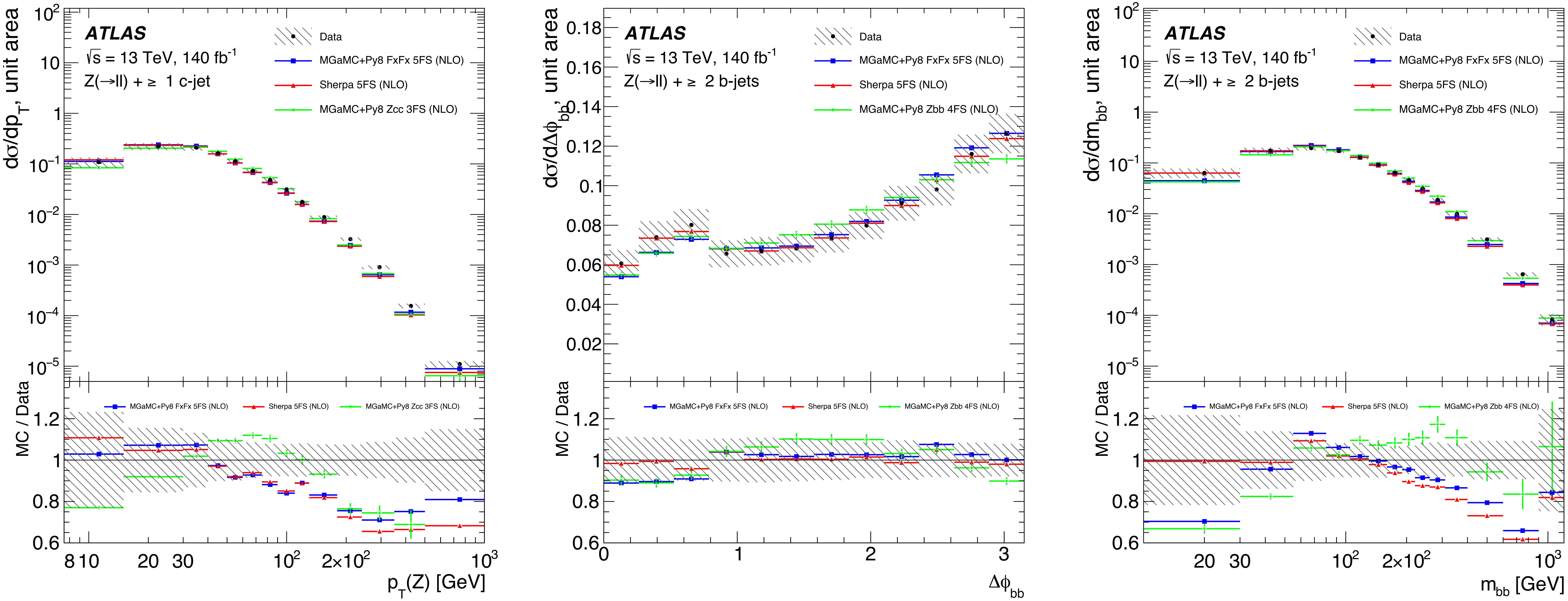






Z+HF jets measurement: more results STDM-2018-43

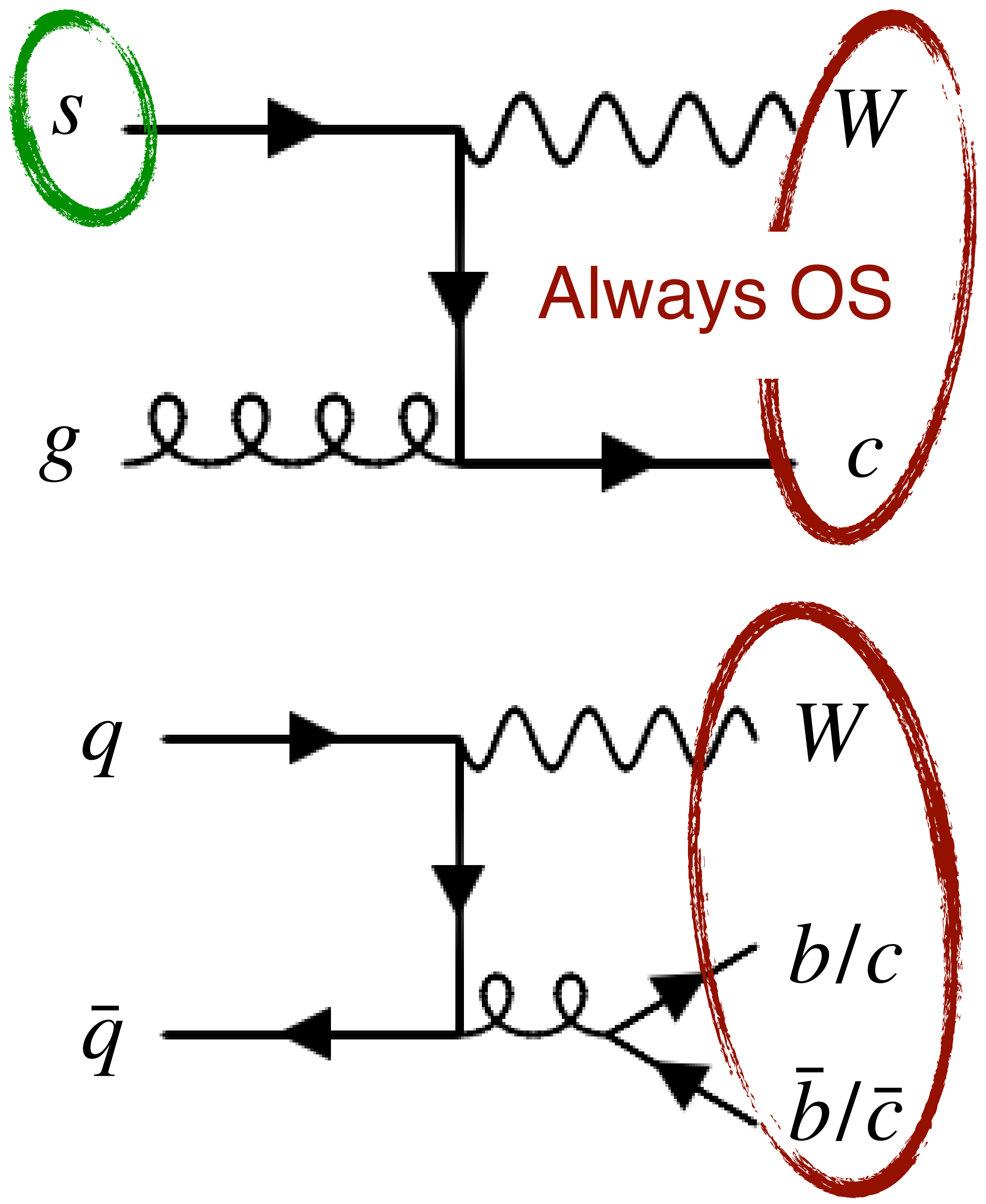
- NLO multi-jet merged simulations generally describe the data well in the bulk of the phase-space
- However, some issues observed e.g.: $p_T(Z)$ modeling and low $\Delta R(bb)$ / $m(bb)$
- Currently we need to be very careful in designing our searches for new physics in a way to not be sensitive to these effects— e.g. in-situ fit $p_T(Z)$ shape; de-correlate uncertainties across $\Delta R(bb)$, etc.
  - Generally reduces sensitivity; will not be good enough for HL-LHC with 10x larger statistics



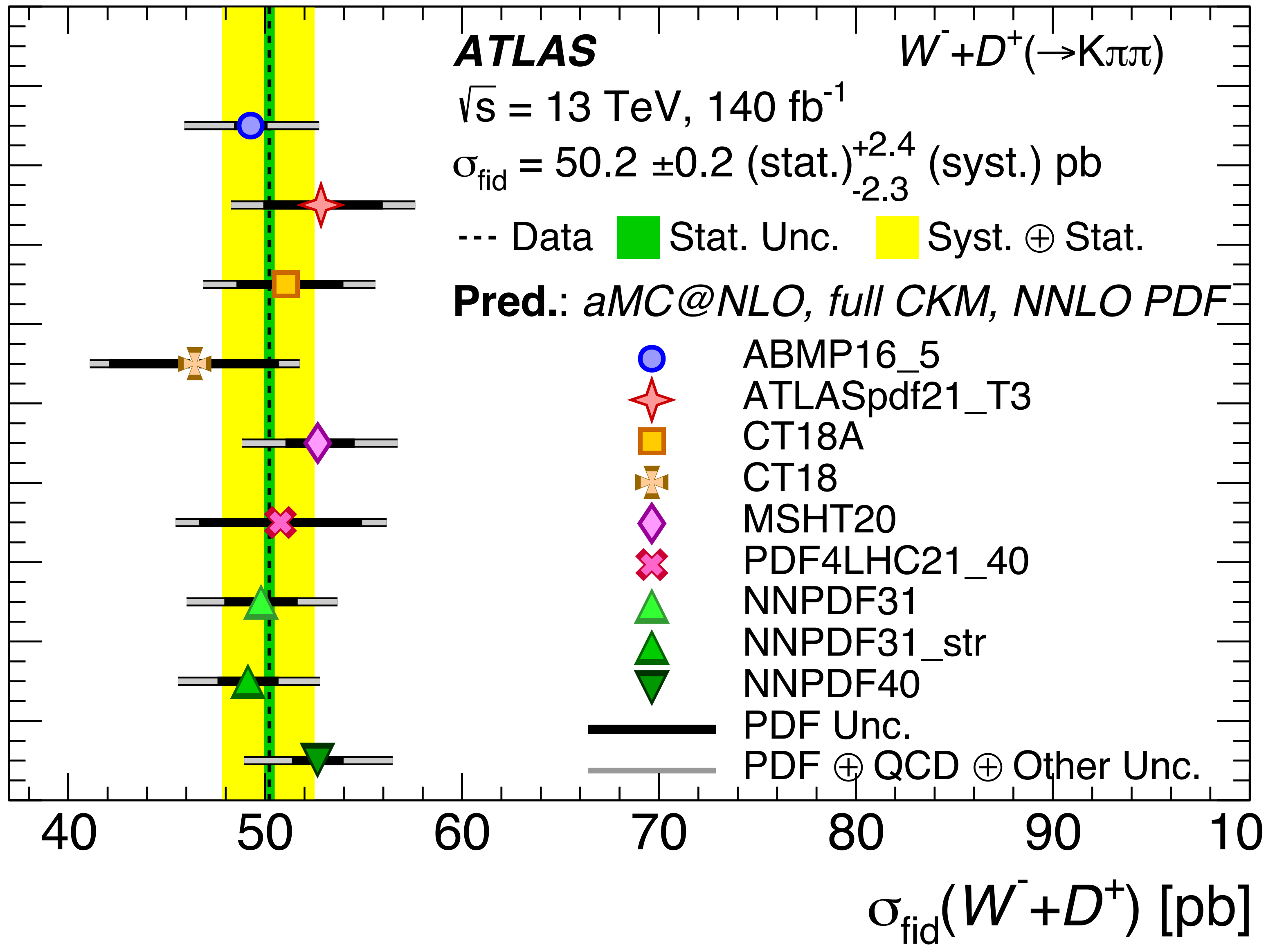
W+D(*) measurement (Full Run 2)

Phys. Rev. D 108 (2023) 032012

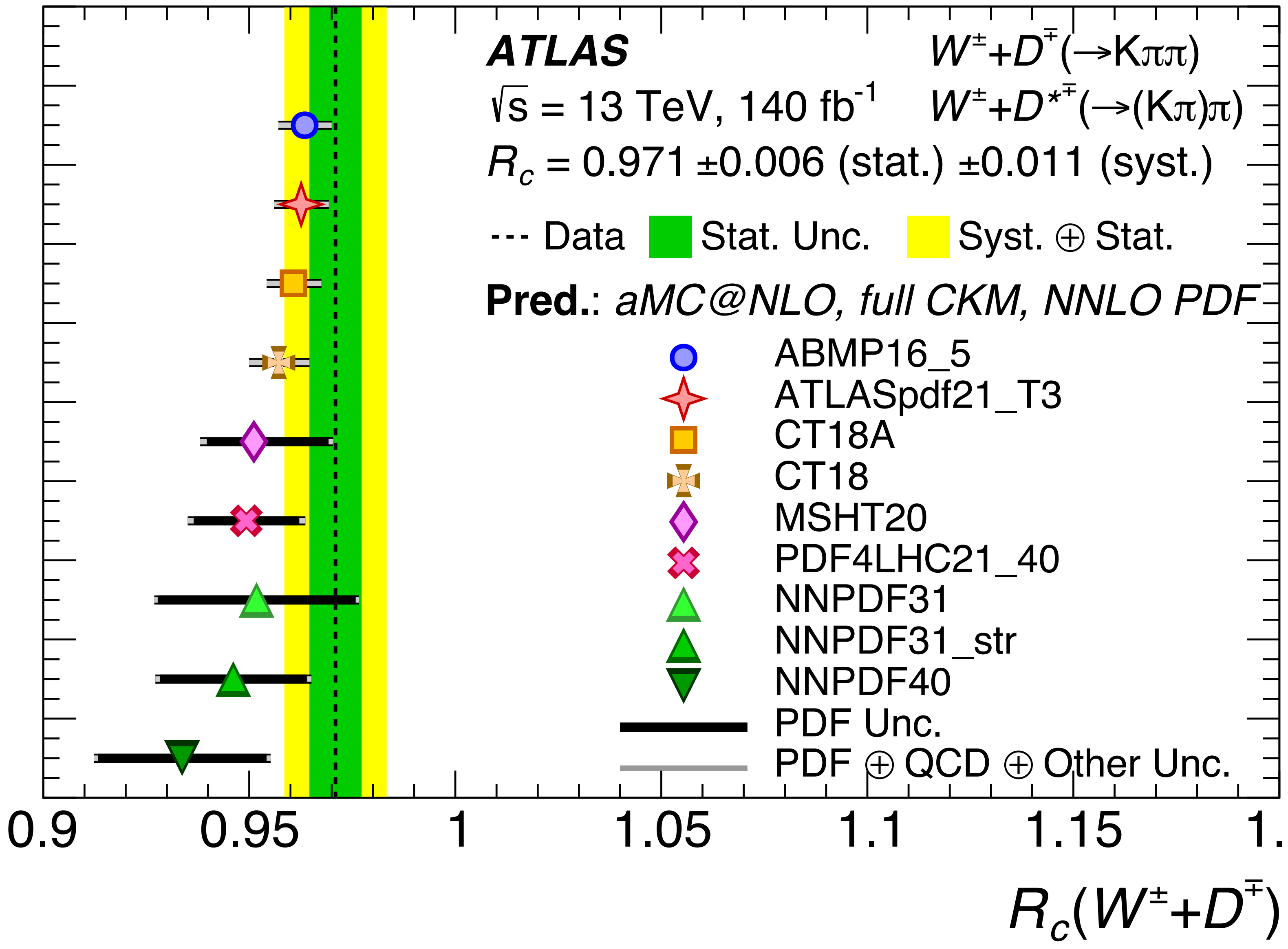
- Measurement performed without jets; c-quarks tagged by explicitly reconstructing the D-mesons:
- Two hadronic decay modes used: $D^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$ and $D^{*\pm} \rightarrow D^{0}\pi^{\pm} \rightarrow K^{\mp}\pi^{\pm}\pi^{\pm}$
- No systematic uncertainties due to jet reconstruction / flavor tagging, but larger statistical uncertainty
- Statistically remove the gluon splitting contribution $g \rightarrow c\bar{c}$ with the “OS-SS” subtraction
  - Precise measurement of the $sg \rightarrow Wc$ process; always has OS charge between $D^{*\pm}$ and $W^{\mp} \rightarrow \ell^{\mp}\nu$
- Provide differential cross section of p_T(D) for MC modeling and |η(ℓ)| for PDF fits; sensitive to s-quark PDF



Cross sections measured for:
W+D-, W-D+
W+D*-, W-D*+

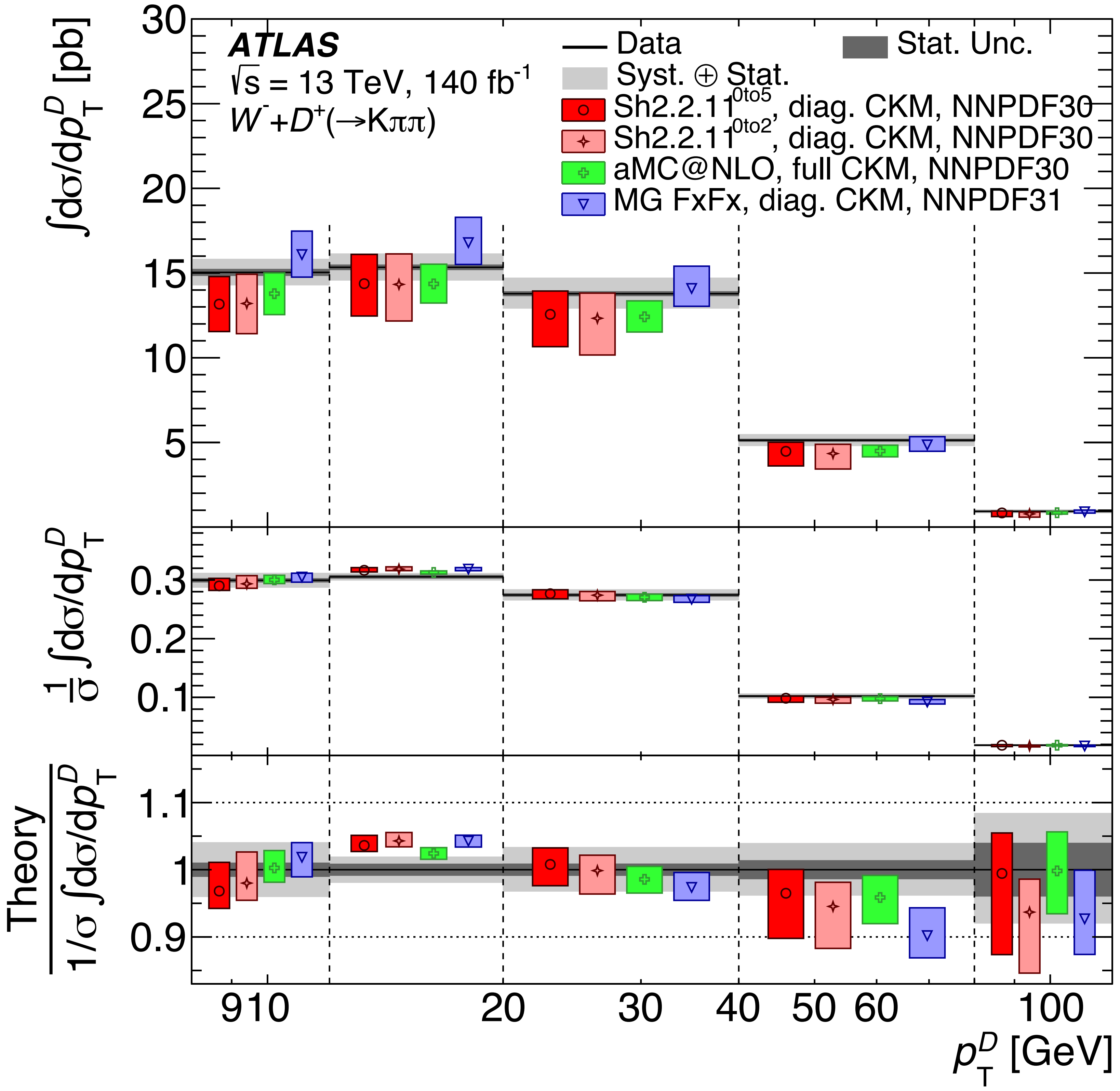


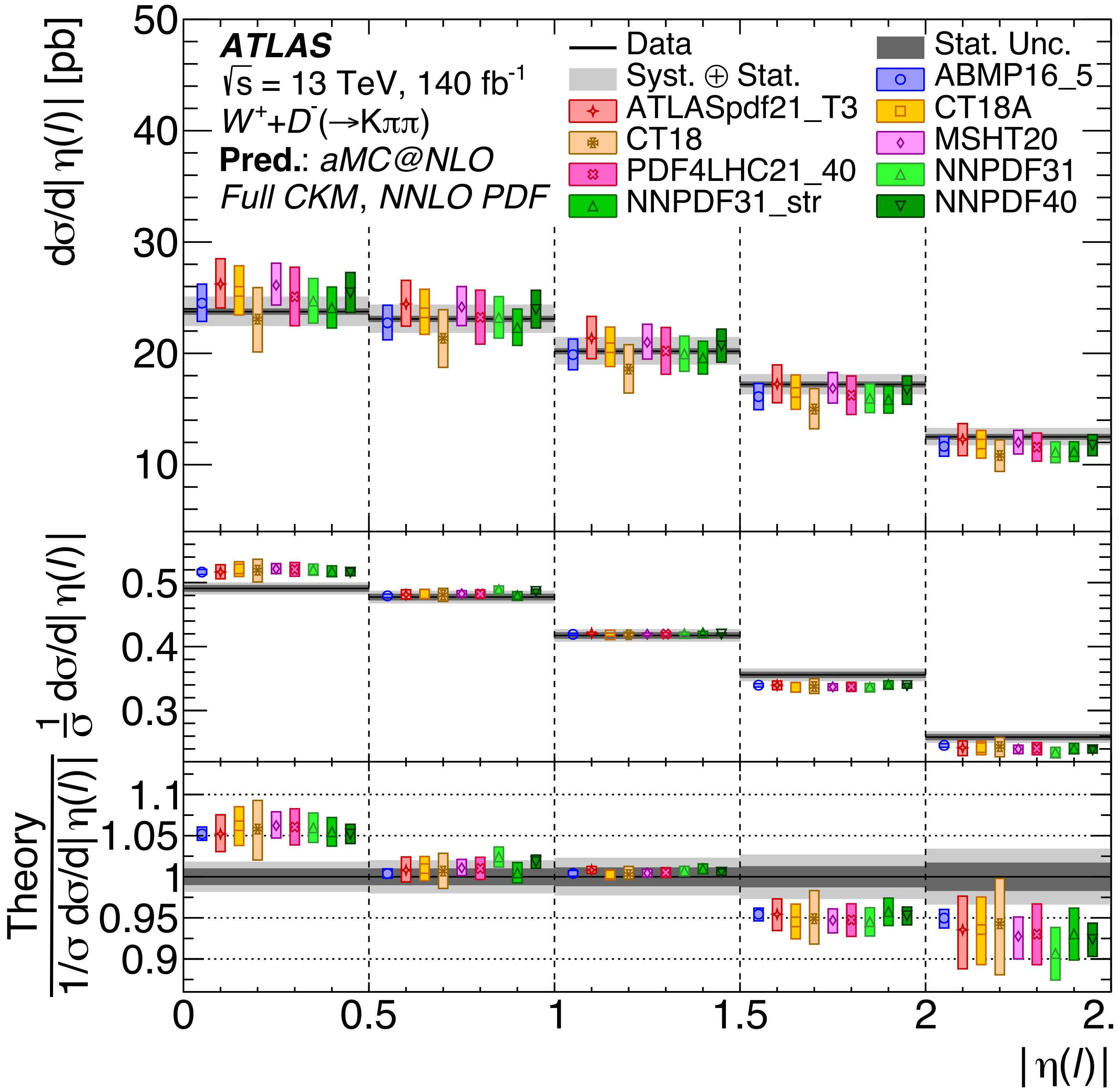
Cross section ratio Rc measured with 1% precision; compatible with NLO predictions; no large s-sbar asymmetry



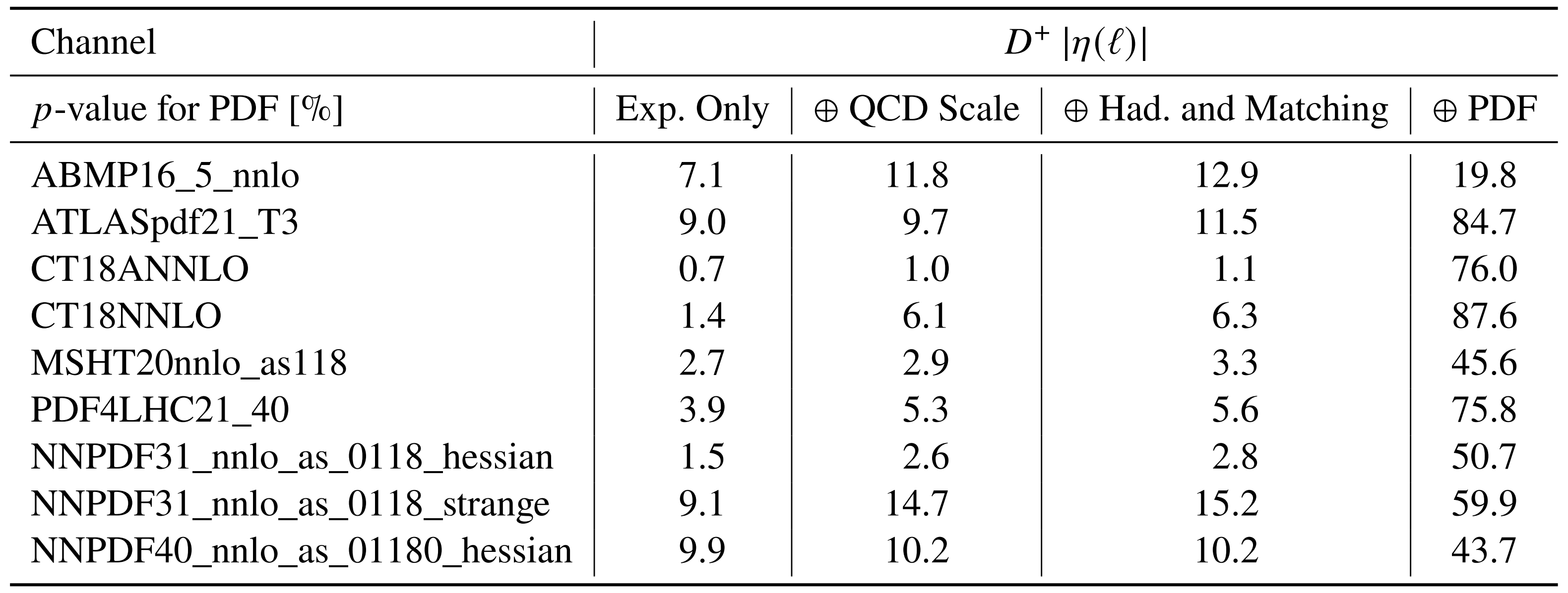
W+D(*) measurement: more results

- Differential **p_T(D) cross section** compared to multi-jet merged simulations
  - Some shape differences visible, but mostly covered by the theory uncertainties
- aMC@NLO at NLO precision w/ a massive c-quark created with different **PDF sets for |η(ℓ)| comparison**
  - Central values of NNLO PDFs generally do not match the data; but PDF uncertainties cover the difference
  - NLO PDFs perform better— more consistent setup with the ME prediction?
- However, at the moment difficult to include in PDF fits due to a lack of a NNLO W+D(*) calculation
  - At the moment would need to parameterize the parton-level ↔ particle-level relation (large uncertainties?)



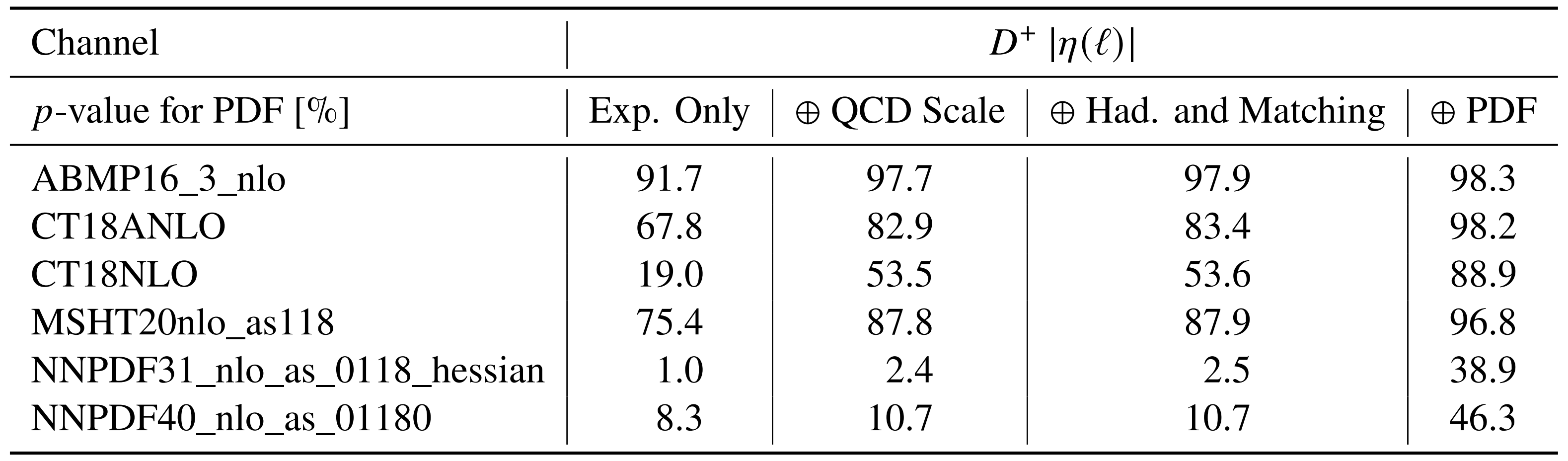


NNLO PDFs



Channel	D^+ $\|\eta(\ell)\|$			
p-value for PDF [%]	Exp. Only	⊕ QCD Scale	⊕ Had. and Matching	⊕ PDF
ABMP16_5_nnlo	7.1	11.8	12.9	19.8
ATLASpdf21_T3	9.0	9.7	11.5	84.7
CT18ANNLO	0.7	1.0	1.1	76.0
CT18NNLO	1.4	6.1	6.3	87.6
MSHT20nnlo_as118	2.7	2.9	3.3	45.6
PDF4LHC21_40	3.9	5.3	5.6	75.8
NNPDF31_nnlo_as_0118_hessian	1.5	2.6	2.8	50.7
NNPDF31_nnlo_as_0118_strange	9.1	14.7	15.2	59.9
NNPDF40_nnlo_as_01180_hessian	9.9	10.2	10.2	43.7

NLO PDFs



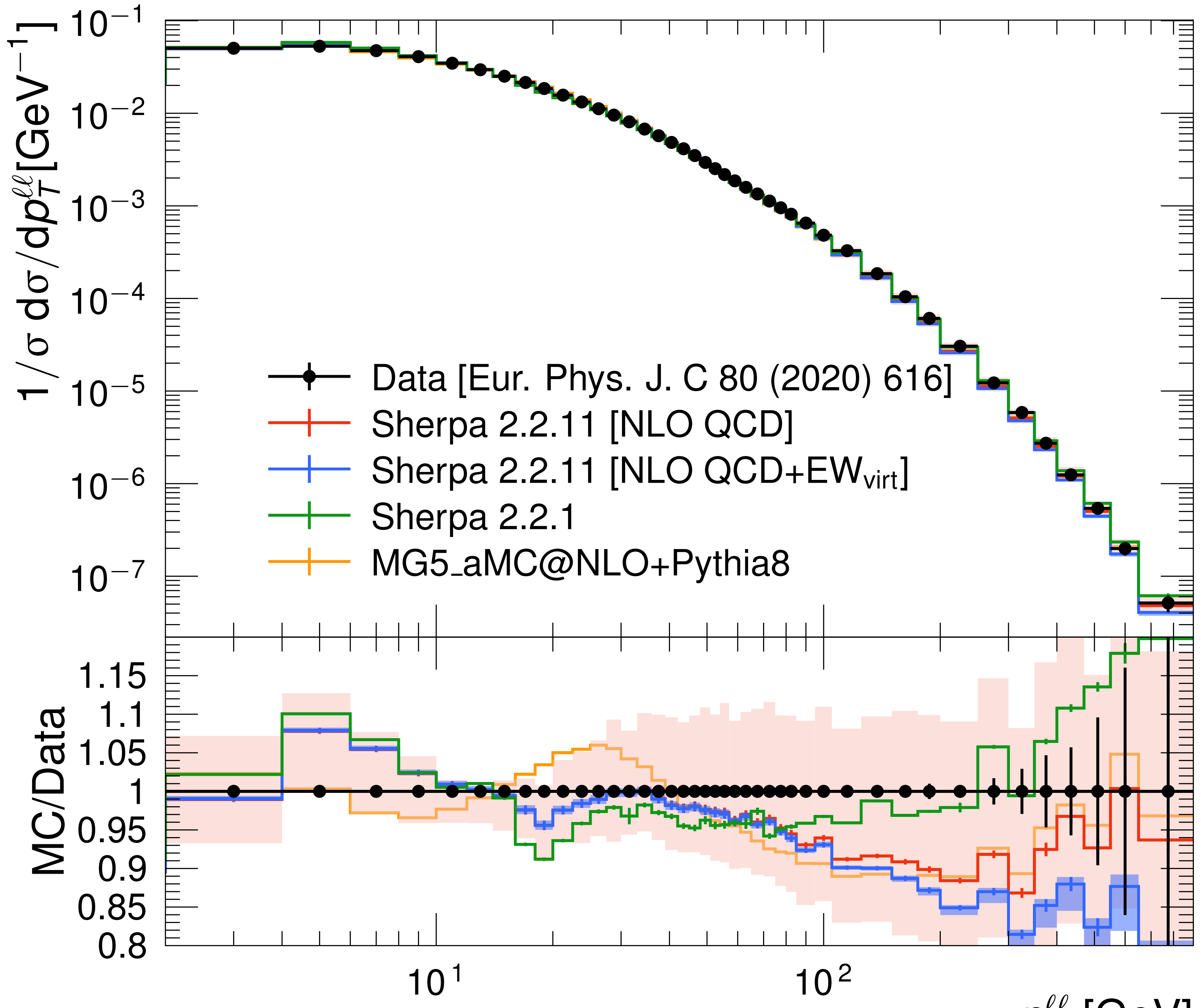
Channel	D^+ $\|\eta(\ell)\|$			
p-value for PDF [%]	Exp. Only	⊕ QCD Scale	⊕ Had. and Matching	⊕ PDF
ABMP16_3_nlo	91.7	97.7	97.9	98.3
CT18ANLO	67.8	82.9	83.4	98.2
CT18NLO	19.0	53.5	53.6	88.9
MSHT20nlo_as118	75.4	87.8	87.9	96.8
NNPDF31_nlo_as_0118_hessian	1.0	2.4	2.5	38.9
NNPDF40_nlo_as_01180	8.3	10.7	10.7	46.3

Discussion

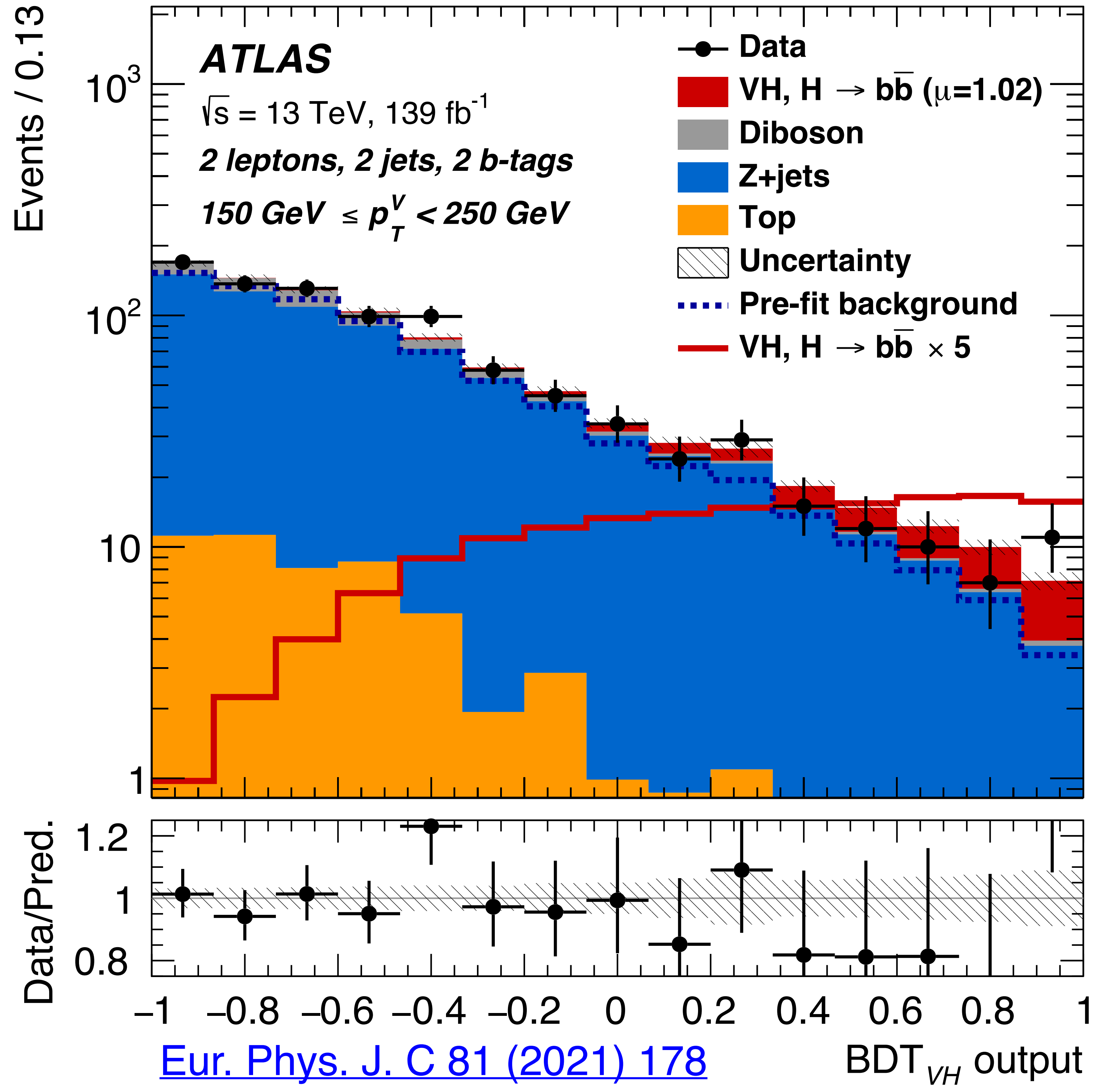
QCD scale uncertainty (missing higher order effects)

QCD scale uncertainties

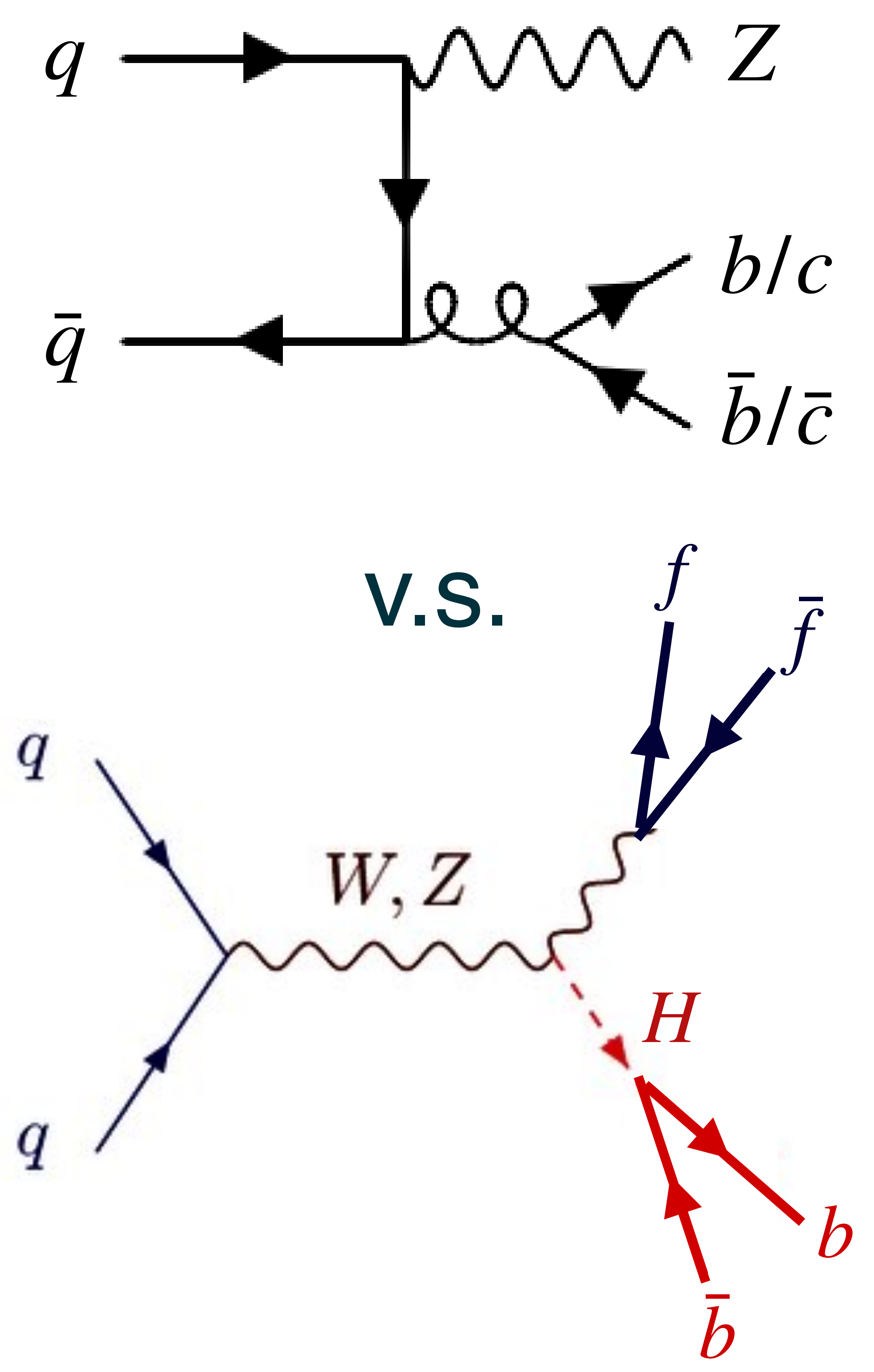
- Scale uncertainty in multi-jet merged samples estimated with the 7-point variations: [μR, μF] × [0.5, 2.0]
- **From theory**: any curve within the scale uncertainty “envelope” is valid
  - Typically 10-30% relative uncertainty per bin for V+HF processes (e.g. Z+bb)
- However, faithfully applying this uncertainty would significantly reduce sensitivity in many searches..
- Typically we extract background normalziation from data (in CRs) and profile / reduce scale uncertainty
  - Assuming that the scale uncertainty is correlated across all bins (**not known from theory**)
- Danger of underestimating the uncertainty; need to add additional ad-hoc uncertainties to be conservative



JHEP 08 (2022) 089



Eur. Phys. J. C 81 (2021) 178

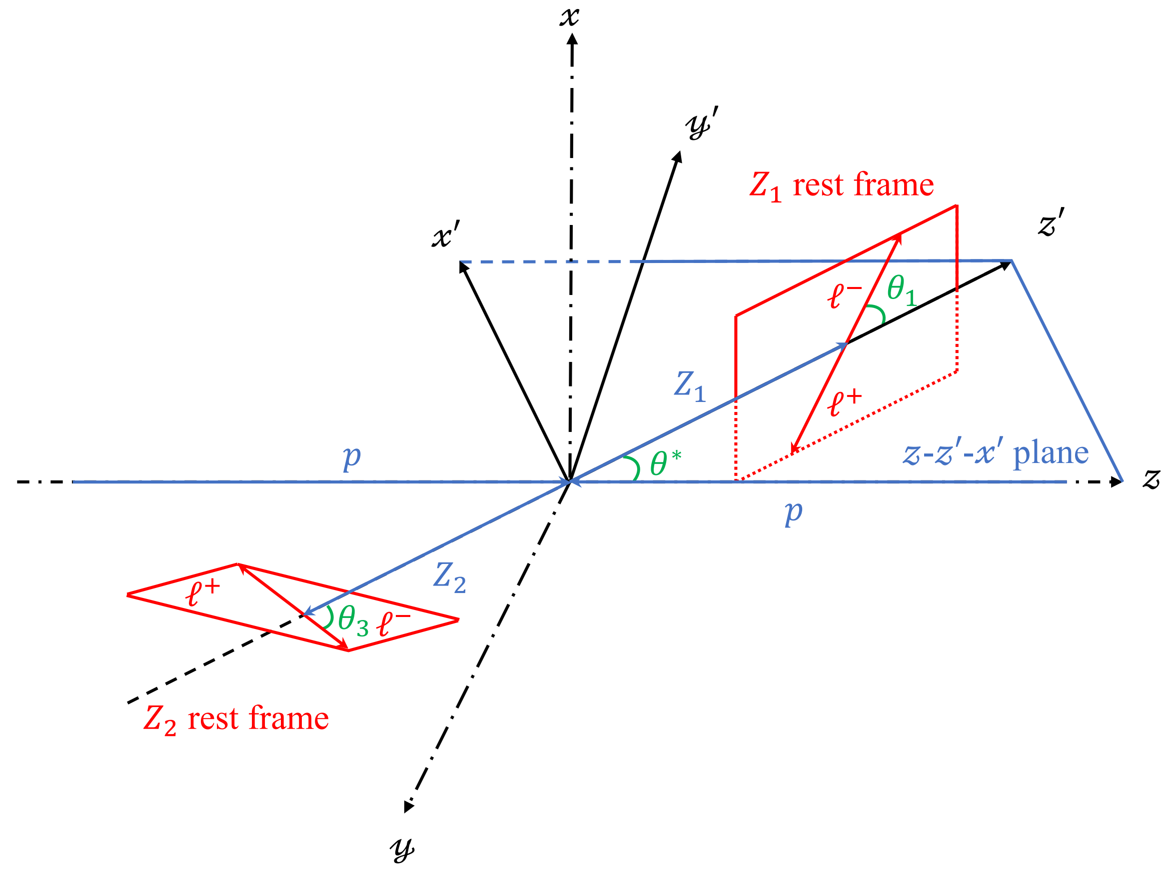


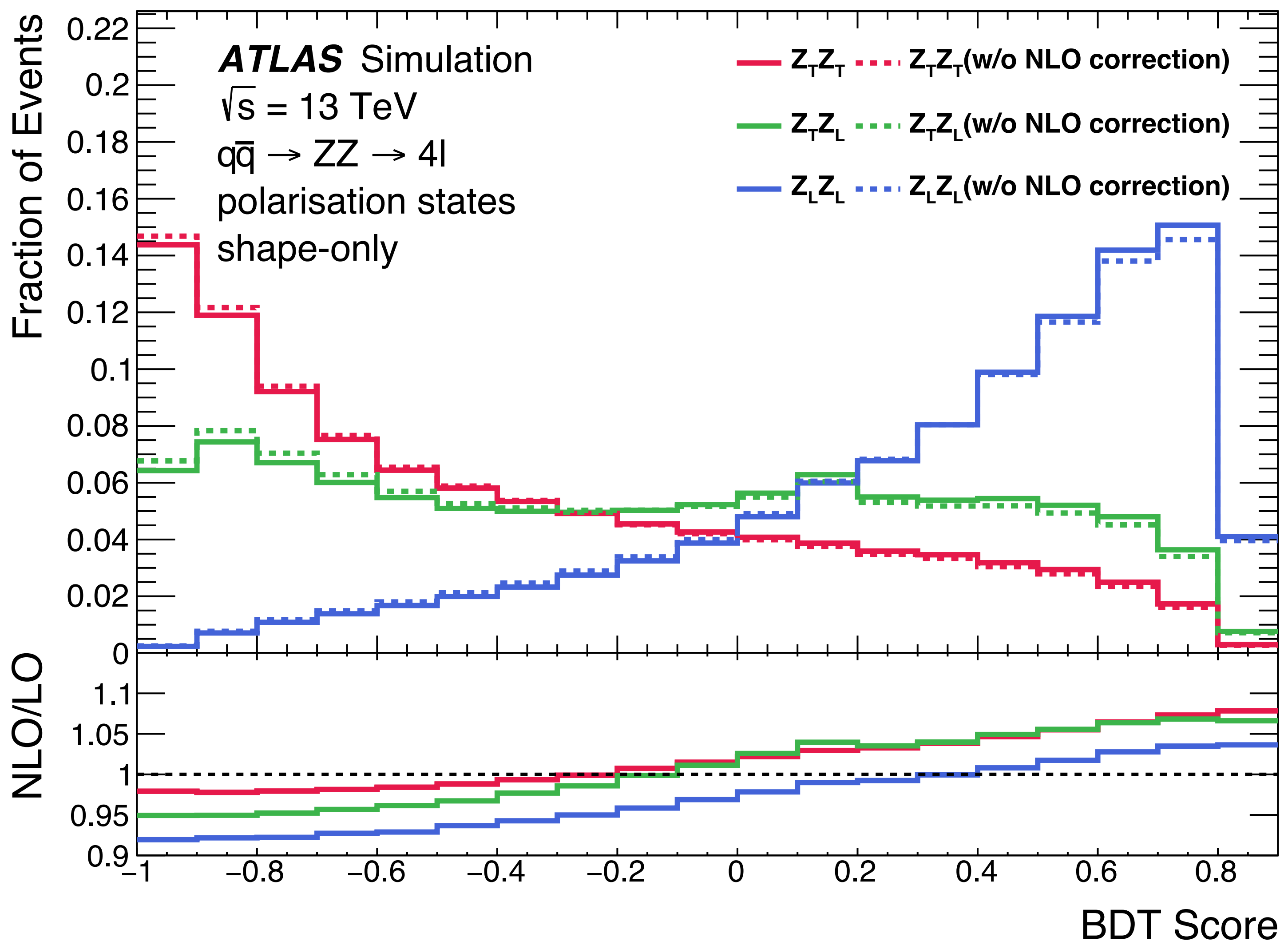
Multiboson measurements (including VBS)

ZZ polarization in Full Run 2

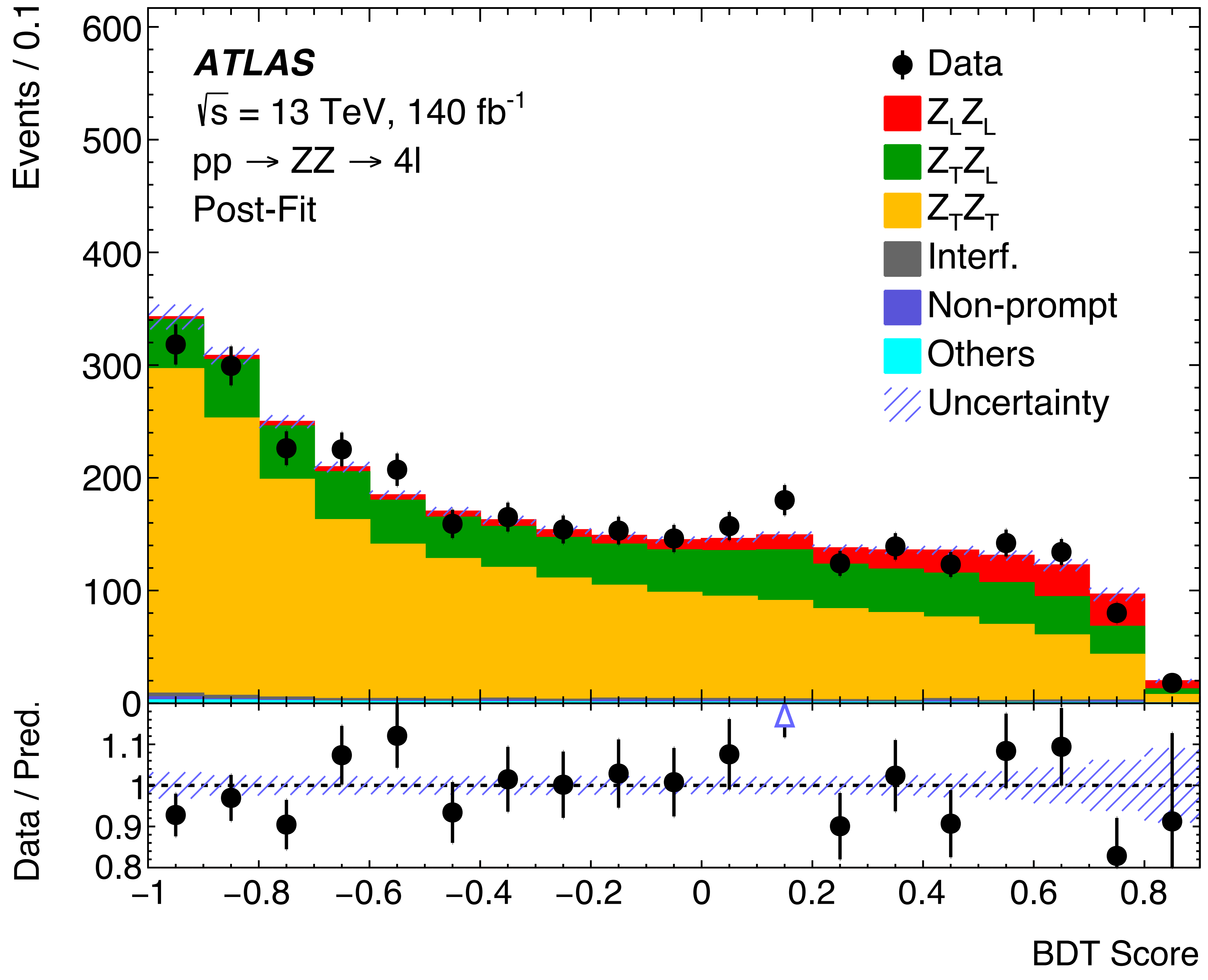
JHEP 12 (2023) 107

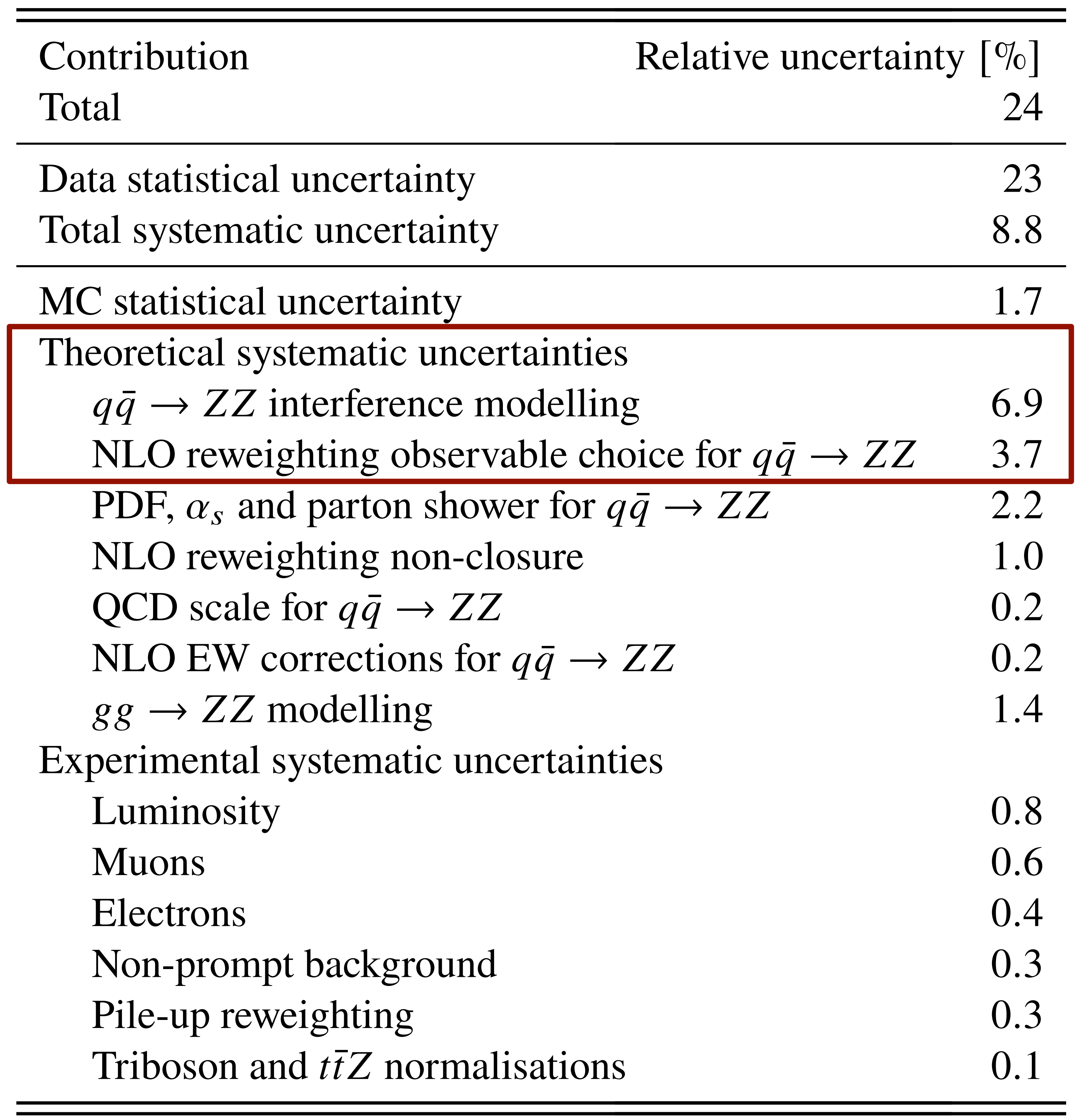
- Select ZZ via the four lepton final state ZZ→4ℓ
- Define angular variables sensitive to different polarization states: Z_TZ_T, Z_TZ_L, Z_LZ_L
- Construct a multi-variate discriminant using boosted decision trees (BDT) to extract the Z_LZ_L component
- MC template fit to the data yields a **4.3σ significance** for the Z_LZ_L component
  - Fiducial cross section of 2.45 ± 0.60 fb, compatible with the NLO predictions (MoCaNLO)





Stat. Uncertainty is dominant; followed by theory uncertainties in qq→ZZ modeling (NLO reweight and interference effects)





Contribution	Relative uncertainty [%]
Total	24
Data statistical uncertainty	23
Total systematic uncertainty	8.8
MC statistical uncertainty	1.7
Theoretical systematic uncertainties	
$q\bar{q} \to ZZ$ interference modelling	6.9
NLO reweighting observable choice for $q\bar{q} \to ZZ$	3.7
PDF, α_s and parton shower for $q\bar{q} \to ZZ$	2.2
NLO reweighting non-closure	1.0
QCD scale for $q\bar{q} \to ZZ$	0.2
NLO EW corrections for $q\bar{q} \to ZZ$	0.2
$gg \to ZZ$ modelling	1.4
Experimental systematic uncertainties	
Luminosity	0.8
Muons	0.6
Electrons	0.4
Non-prompt background	0.3
Pile-up reweighting	0.3
Triboson and $t\bar{t}Z$ normalisations	0.1

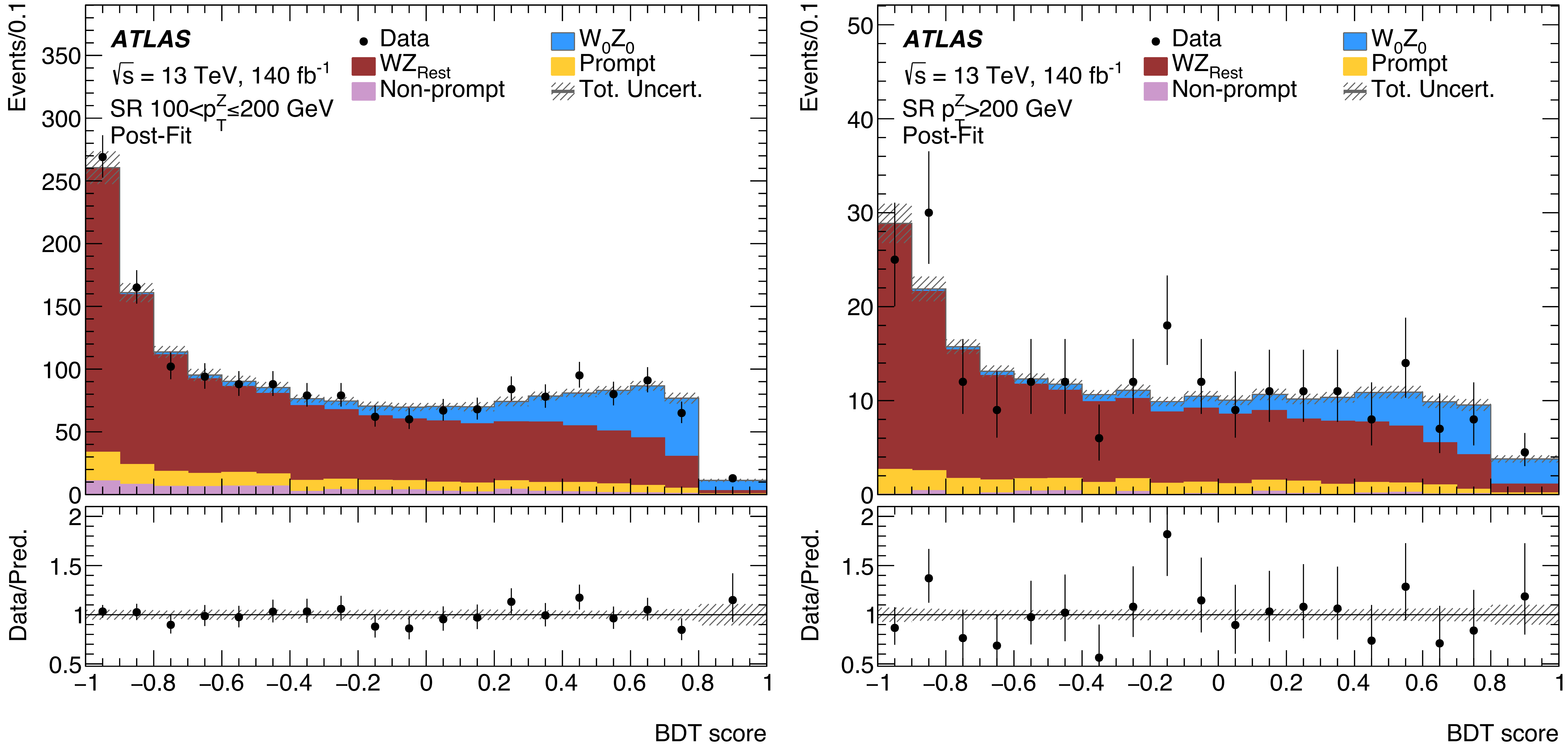
WZ polarization energy dependence (Full Run 2)

STDM-2020-01

- Select WZ via the leptonic final states
- BDT trained to separate the polarization states
- Measure the fraction of polarization states vs $p_T(Z)$

BDT variables

Training variable	Definition
$\Delta Y(\ell_W Z)$	Rapidity difference between the W lepton and Z boson
p_T^{WZ}	Transverse momentum of the WZ system
$p_T(\ell_W)$	Transverse momentum of the W lepton
$p_T(\ell_2^Z)$	Transverse momentum of the subleading Z lepton
E_T^{miss}	Missing transverse momentum
$\cos\theta_{\ell_Z}$	Cosine of the angle of the Z lepton in the WZ rest frame w.r.t the z-axis
$\cos\theta_{\ell_W}$	Cosine of the angle of the W lepton in the WZ rest frame w.r.t. the z-axis

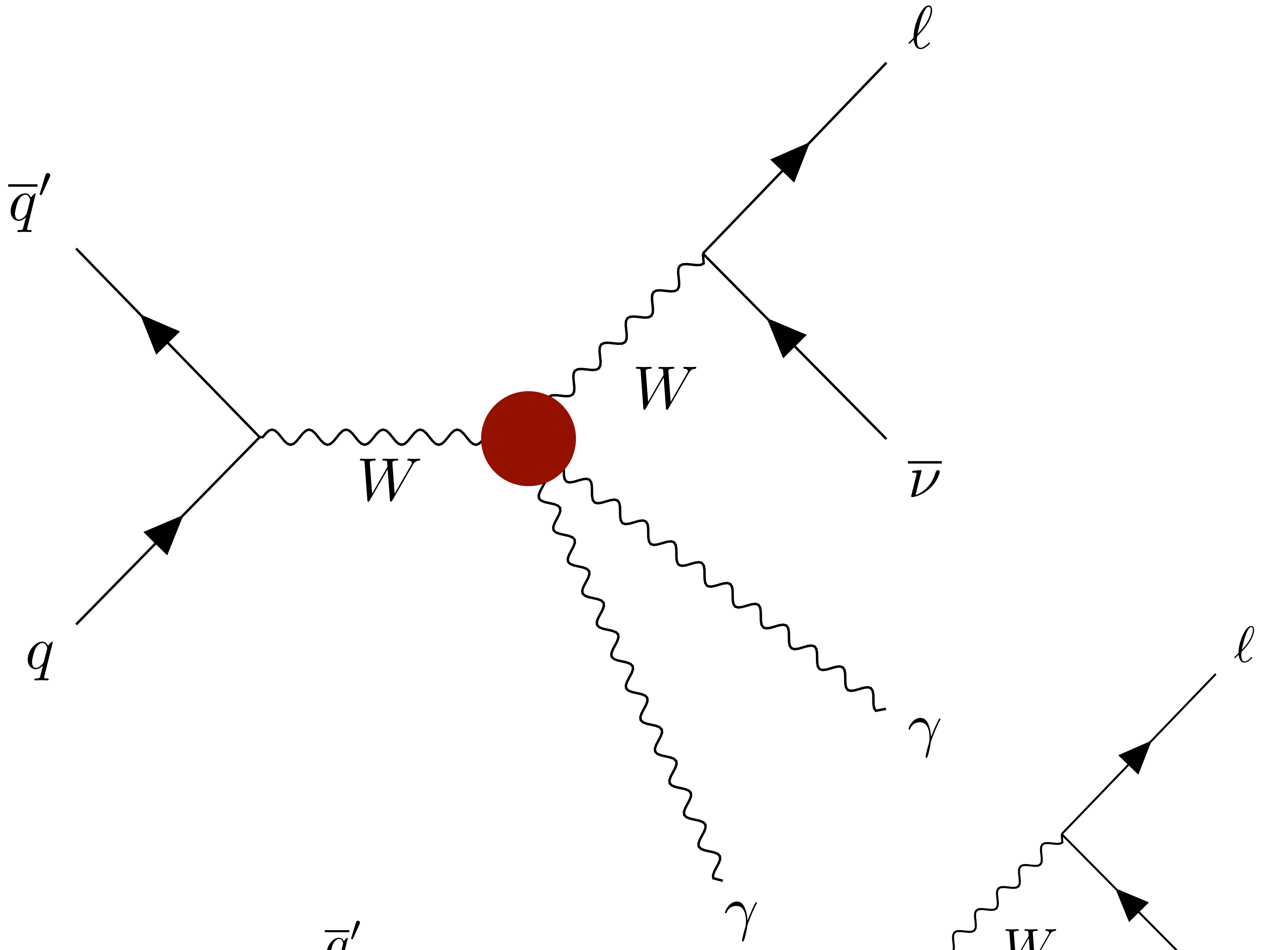


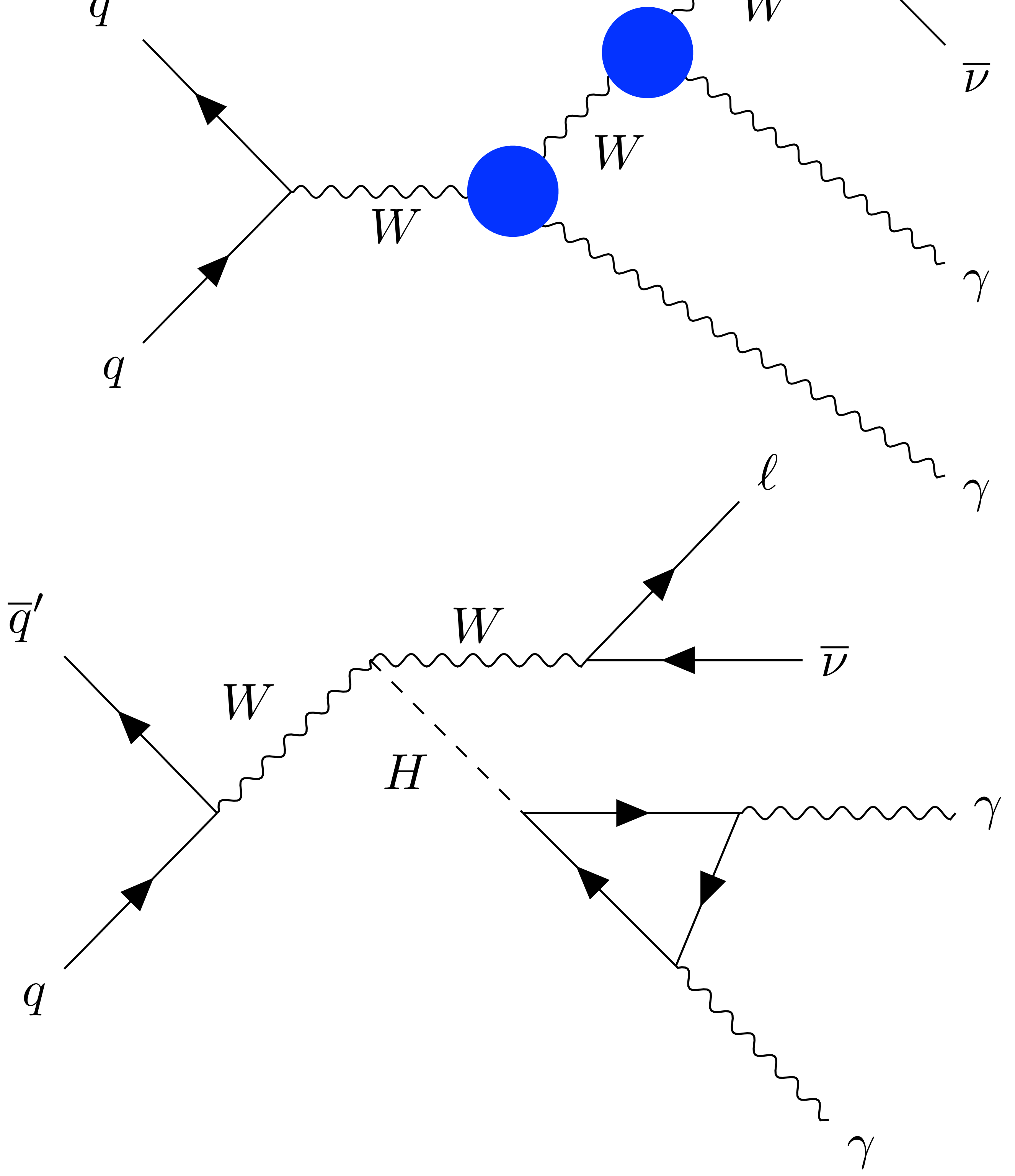
- More than 5σ sensitivity to the fully longitudinally polarized state at 100 GeV < $p_T(Z)$ < 200 GeV
- Lower sensitivity at $p_T(Z)$ > 200 GeV
- Consistent with SM predictions (2302.03324) at 1σ level
- Dominated by statistical uncertainties; followed by modeling uncertainties

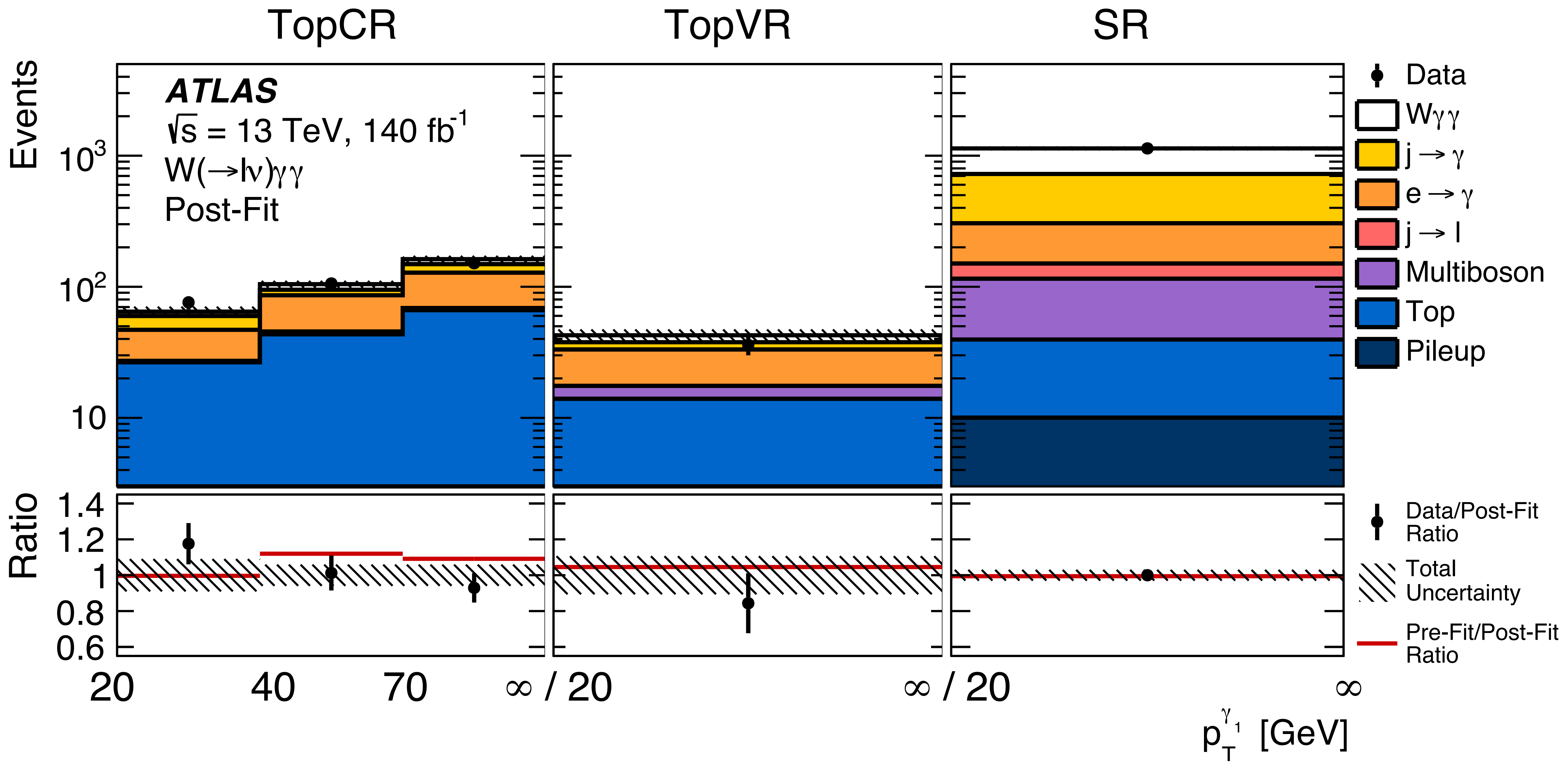
	Measurement			**Prediction**	
	100 < p_T^Z ≤ 200 GeV	**p_T^Z > 200 GeV**		**100 < p_T^Z ≤ 200 GeV**	**p_T^Z > 200 GeV**
f_{00}	$0.19 \pm^{0.03}_{0.03}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	$0.13 \pm^{0.09}_{0.08}$ (stat) $\pm^{0.02}_{0.02}$ (syst)	f_{00}	0.152 ± 0.006	0.234 ± 0.007
f_{0T+T0}	$0.18 \pm^{0.07}_{0.08}$ (stat) $\pm^{0.05}_{0.06}$ (syst)	$0.23 \pm^{0.17}_{0.18}$ (stat) $\pm^{0.06}_{0.10}$ (syst)	f_{0T}	0.120 ± 0.002	0.062 ± 0.002
f_{TT}	$0.63 \pm^{0.05}_{0.05}$ (stat) $\pm^{0.04}_{0.04}$ (syst)	$0.64 \pm^{0.12}_{0.12}$ (stat) $\pm^{0.06}_{0.06}$ (syst)	f_{T0}	0.109 ± 0.001	0.058 ± 0.001
f_{00} obs (exp) sig.	5.2 (4.3) σ	1.6 (2.5) σ	f_{TT}	0.619 ± 0.007	0.646 ± 0.008

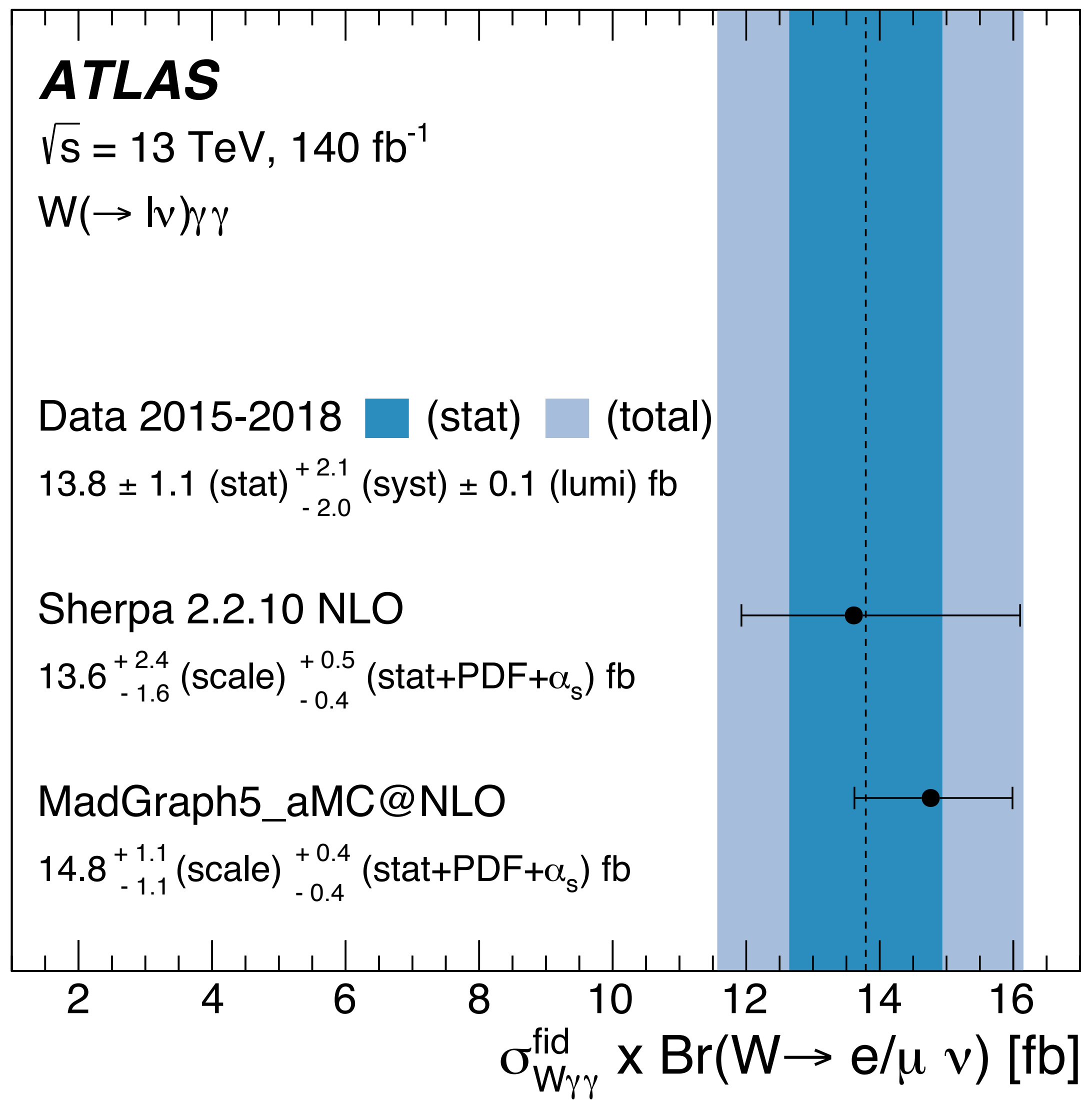
Observation of triboson Wɣɣ production (Full Run 2) Phys. Lett. B 848 (2024) 138400

- Selected with two isolated photons, an isolated lepton, and MET
- Sensitive to quartic and triple gauge couplings (WWɣɣ, WWɣ)
- Background from other multiboson processes (including WH(→ɣɣ))
- Wɣɣ process observed with 5.6σ sensitivity
- Good agreement with simulations (Sherpa NLO, aMC@NLO)
- Dominated by statistical uncertainties and fake background estimation





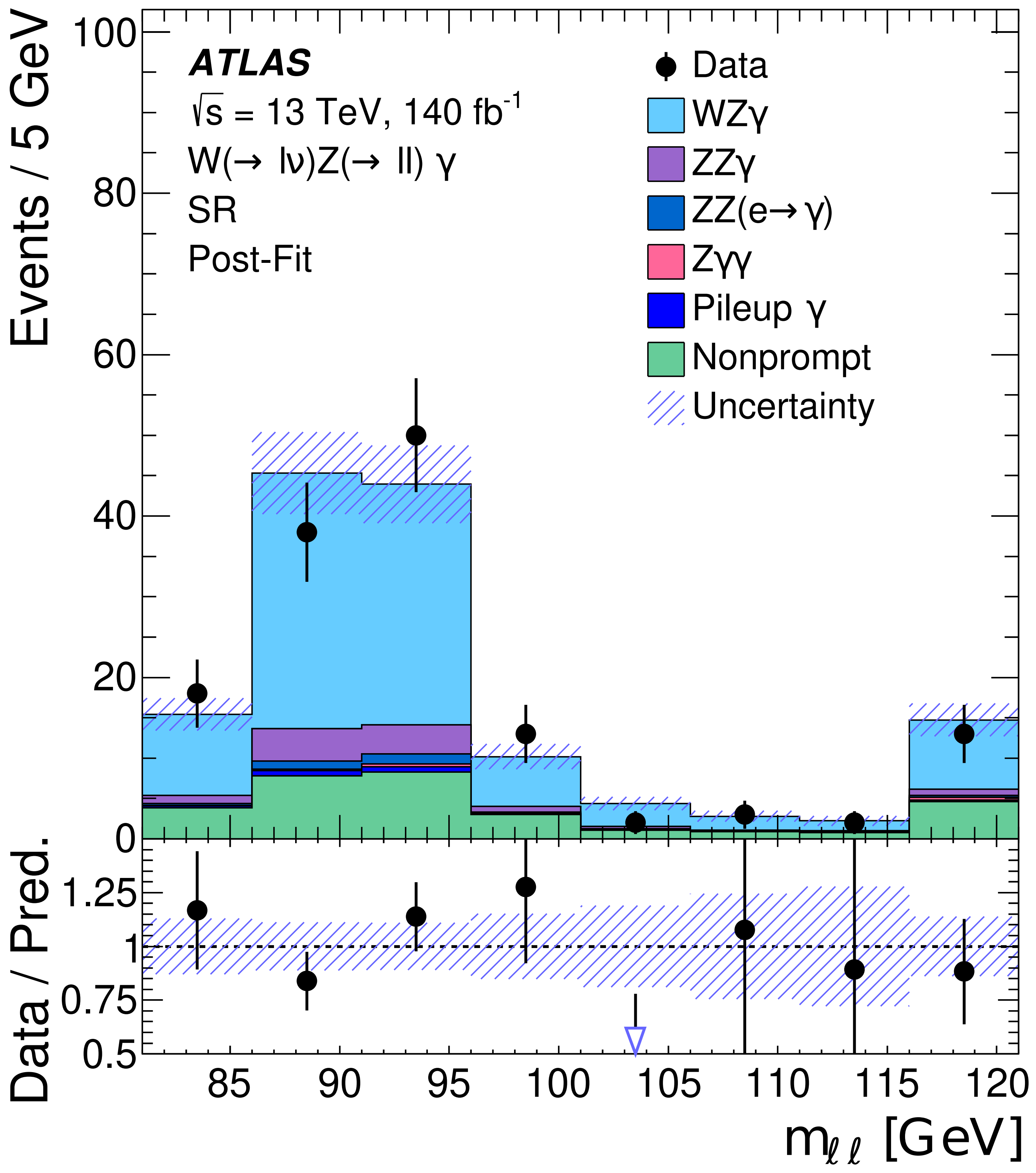


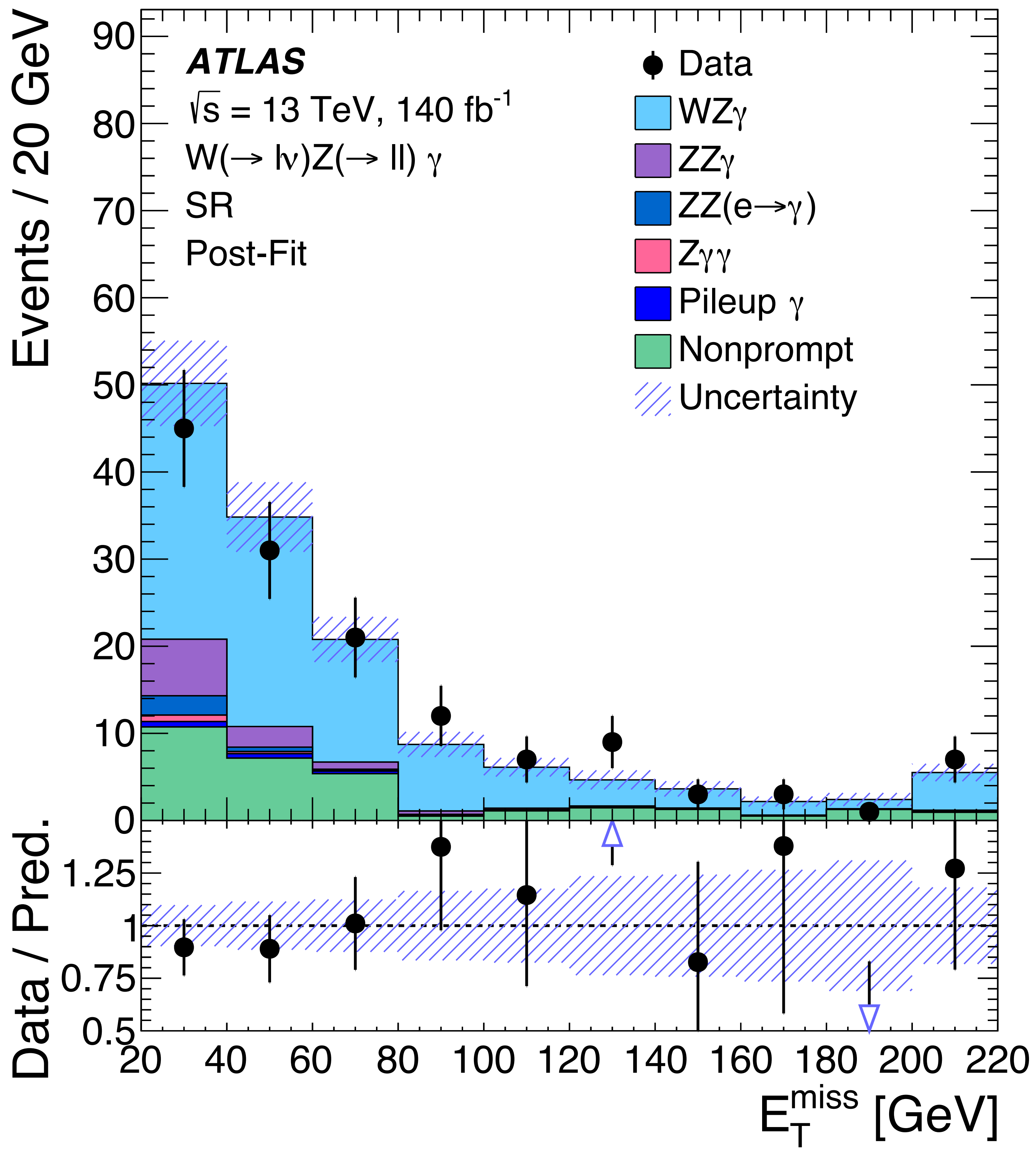


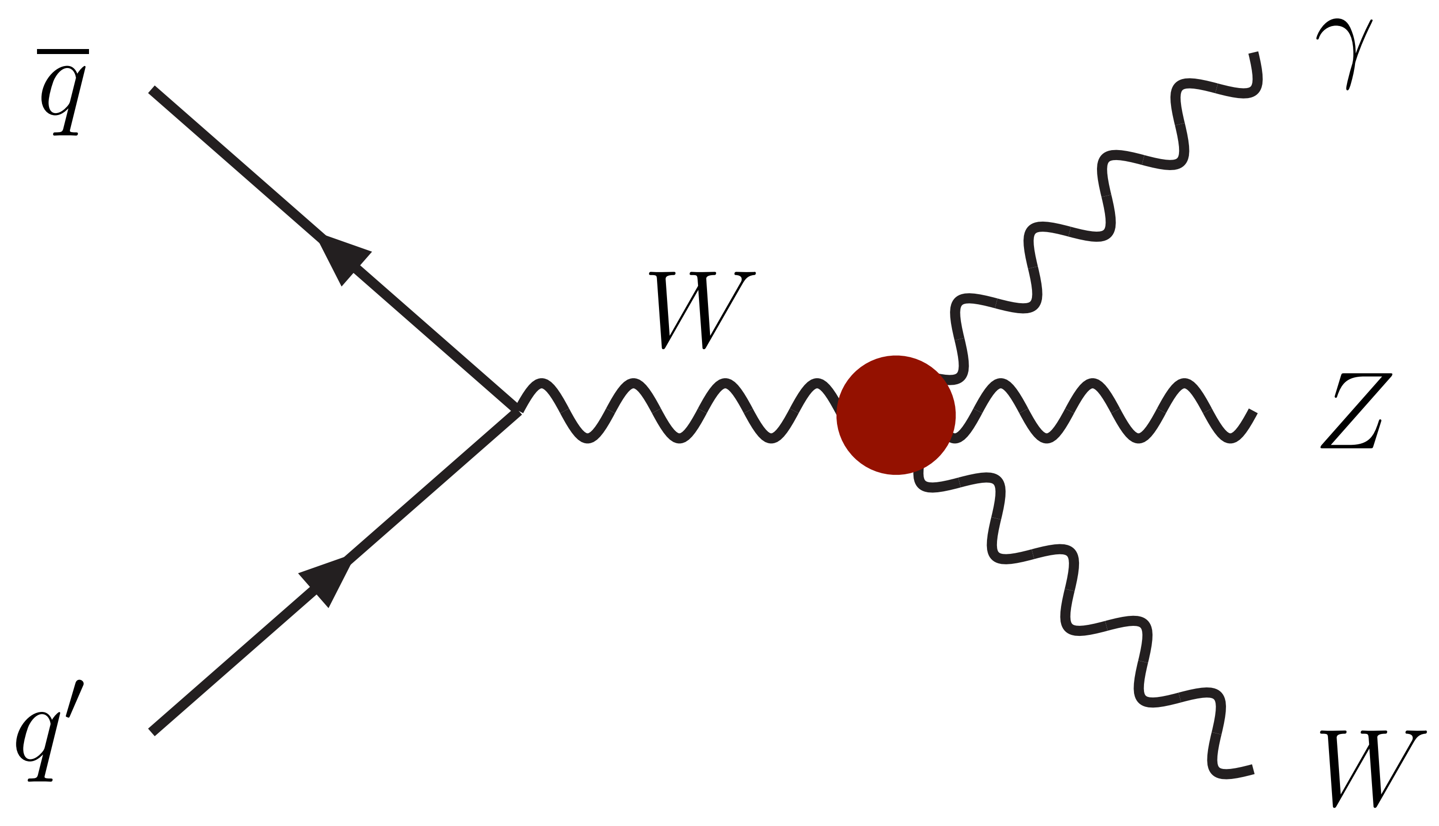
Observation of triboson WZɣ production

Phys. Rev. Lett. 132 (2024) 021802

- Selected with two leptons from Z→ℓℓ, isolated photon, lepton + MET
- Sensitive to quartic gauge coupling WWZɣ
- Background from other multiboson processes and fakes
- WZɣ process observed with 6.3σ sensitivity
  - Consistent with SM predictions at 1.5σ level (NLO Sherpa prediction)
- Dominated by statistical uncertainties

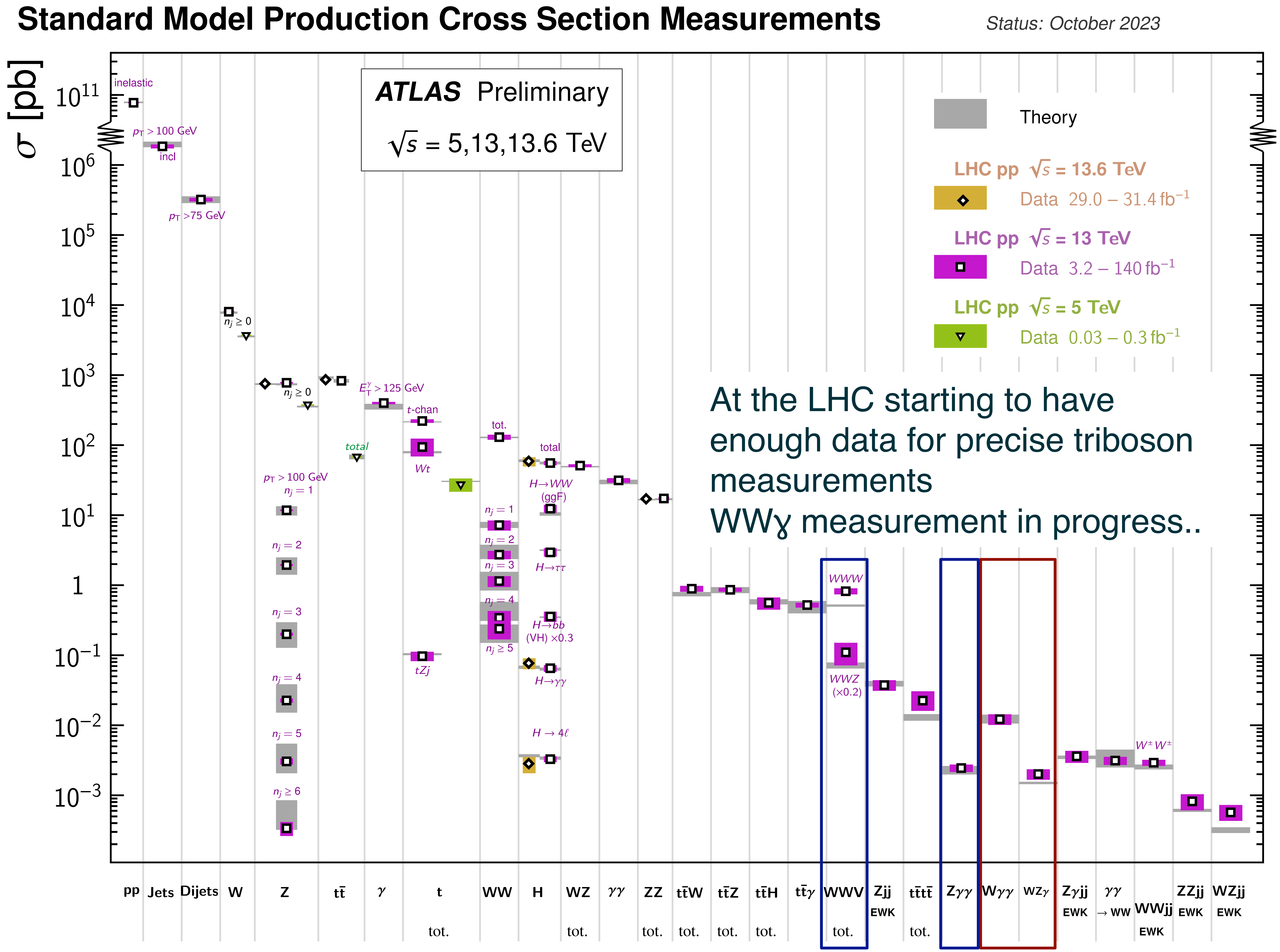






	SR definition
Lepton veto	no additional leptons with $p_T^{\ell_4} > 10$ GeV
Z-leptons assignment	smallest $\|m_{\ell\ell} - m_Z\|$
ΔR	$\Delta R(\ell,\gamma) > 0.4$, $\Delta R(\mu,e) > 0.2$
$ZZ(e \to \gamma)$ rejection	$\|m(e_W,\gamma) - m_Z\| > 10$ GeV
Missing p_T	$E_T^{miss} > 20$ GeV
Z candidate mass	$m_{\ell\ell} > 81$ GeV

Triboson summary

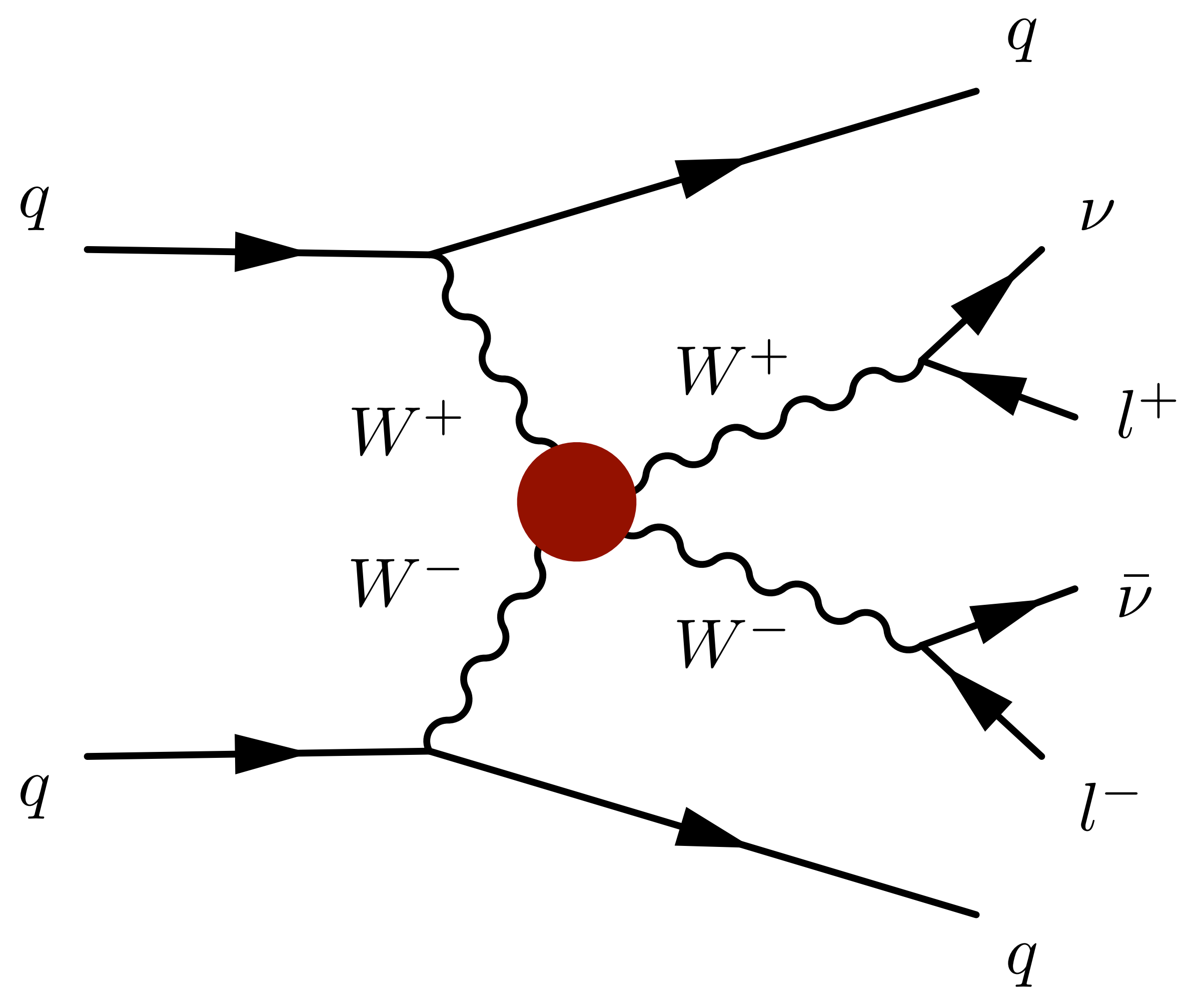


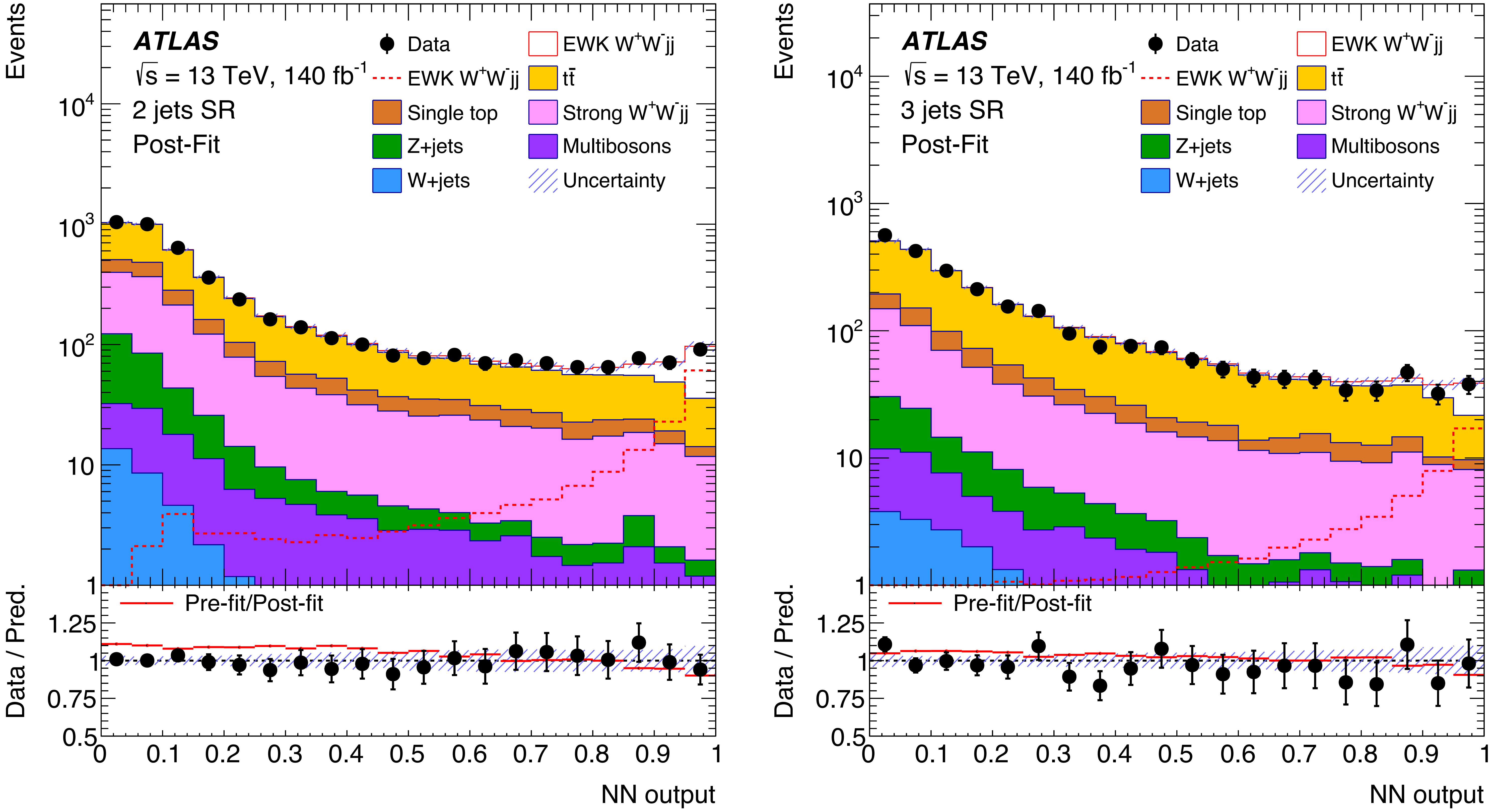
At the LHC starting to have enough data for precise triboson measurements
WWɣ measurement in progress..

Observation of EW opposite sign W+W-jj production

STDM-2022-06

- Select with OS electron / muon pair, b-jet veto, and typical VBS selection
- Backgrounds from ttbar and strong WWjj production
- Split into two-jet and three-jet regions for better signal / background separation
  - Neural network trained to extract the EW W+W-jj component
- Dominated by statistical uncertainty; followed by top background modeling
- Signal simulated with Powheg+Pythia at NLO QCD
- Signal observed with 7.1σ (6.2σ expected); fiducial cross section: 2.7 ± 0.5 fb



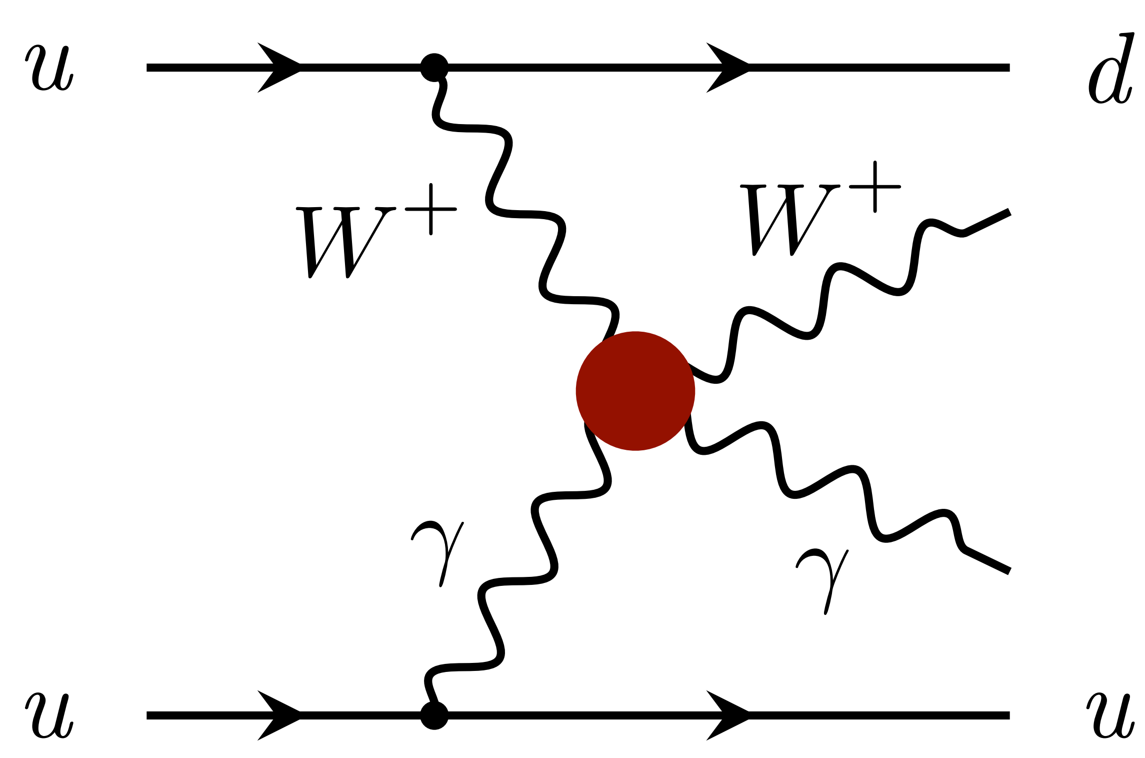


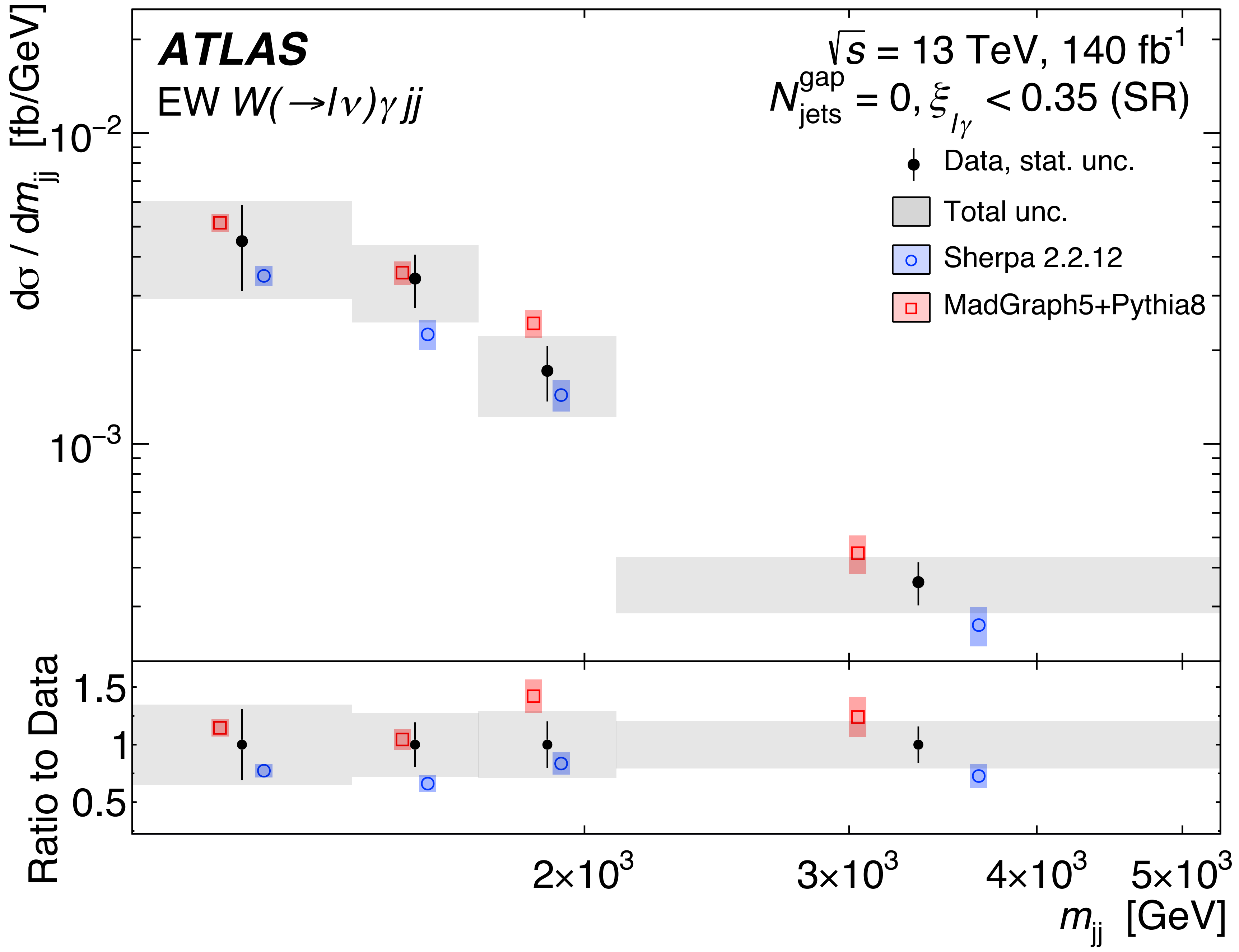
Sources	$\frac{\sqrt{(\Delta\mu)^2-(\Delta\mu')^2}}{\mu}$ [%]
MC statistical uncertainty	7.7
Top quark theoretical uncertainties	6.3
Signal theoretical uncertainties	5.8
Jet experimental uncertainties	4.9
Strong W^+W^-jj theoretical uncertainties	1.3
Luminosity	0.8
Misidentified lepton uncertainty	0.5
b-tagging	0.4
Lepton experimental uncertainties	0.1
Others	0.3
Data statistical uncertainty	12.3
Top quark normalisation uncertainty	4.9
Strong W^+W^-jj normalisation uncertainty	2.2
Total uncertainty	18.5

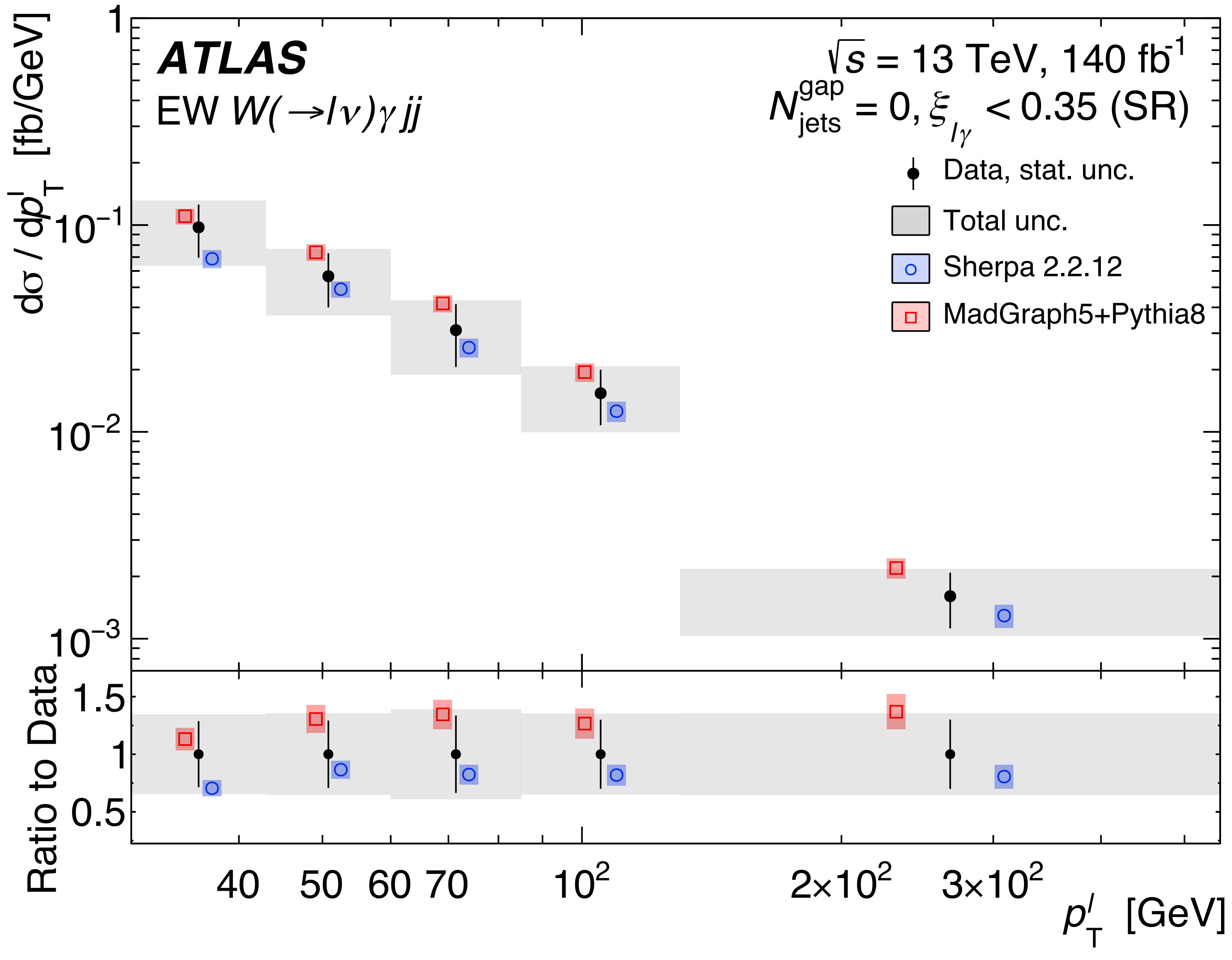
Measurement of VBS Wɣjj process (Full Run 2)

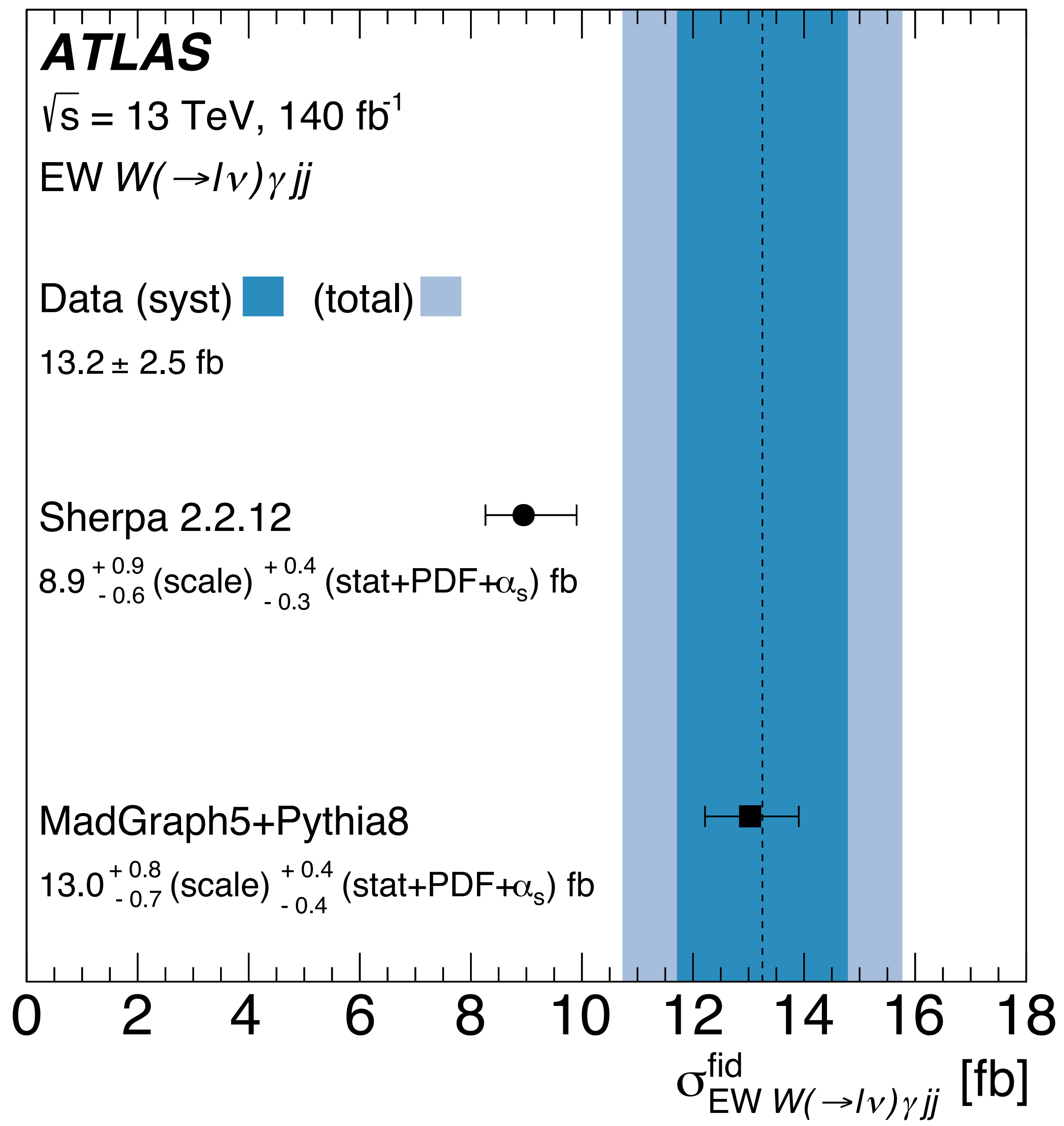
STDM-2018-31

- Clean experimental signature with lepton + MET and an isolated photon
- Typical VBS-enhanced event selection performed
  - Neural network trained to separate EW component from strong production
- Differential cross section measurement for EW Wɣjj process:
  - m(jj), pT(jj), **Δ**ϕ(jj), pT(ℓ), **Δ**ϕ(ℓɣ), m(ℓɣ)
- Sherpa and aMC@NLO predictions (LO QCD) generally agree well with the data
  - Sherpa slightly underestimates the total fiducial cross section





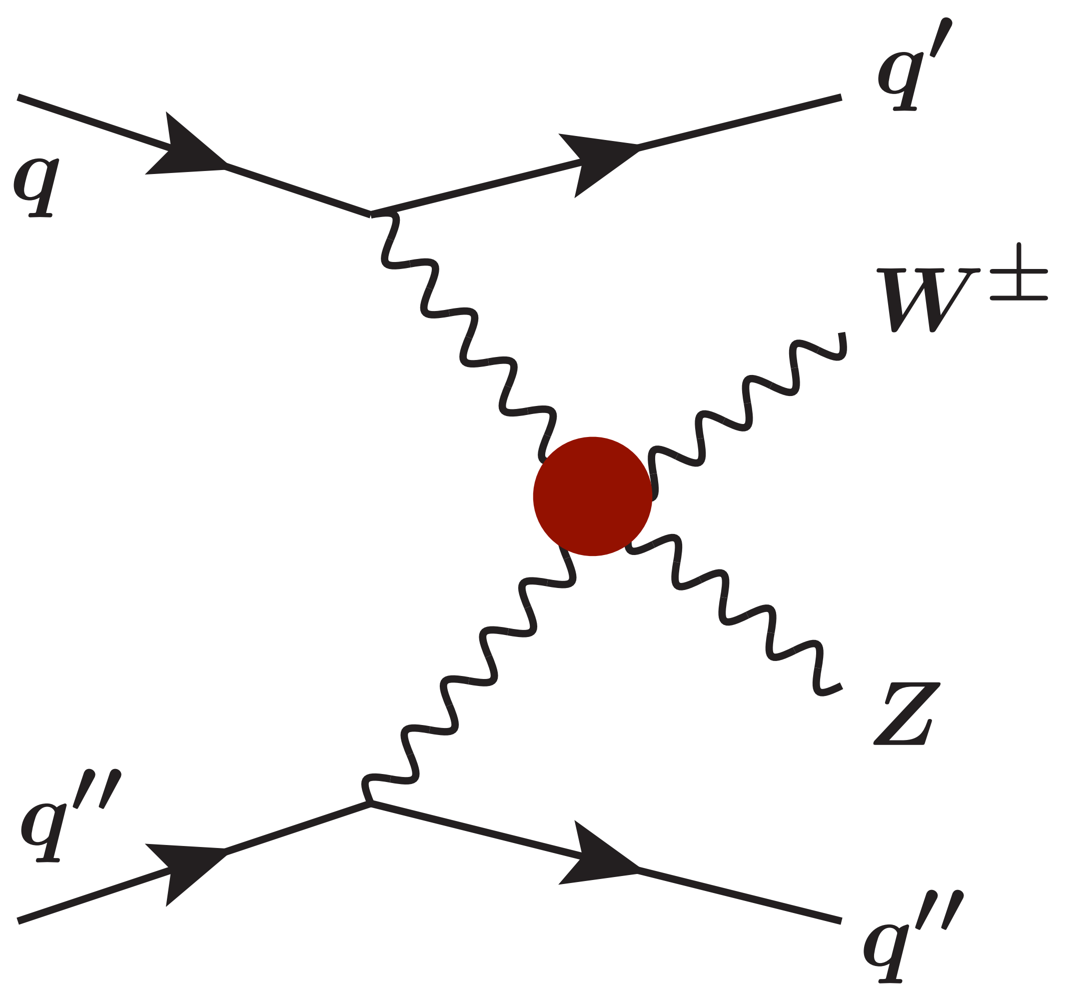


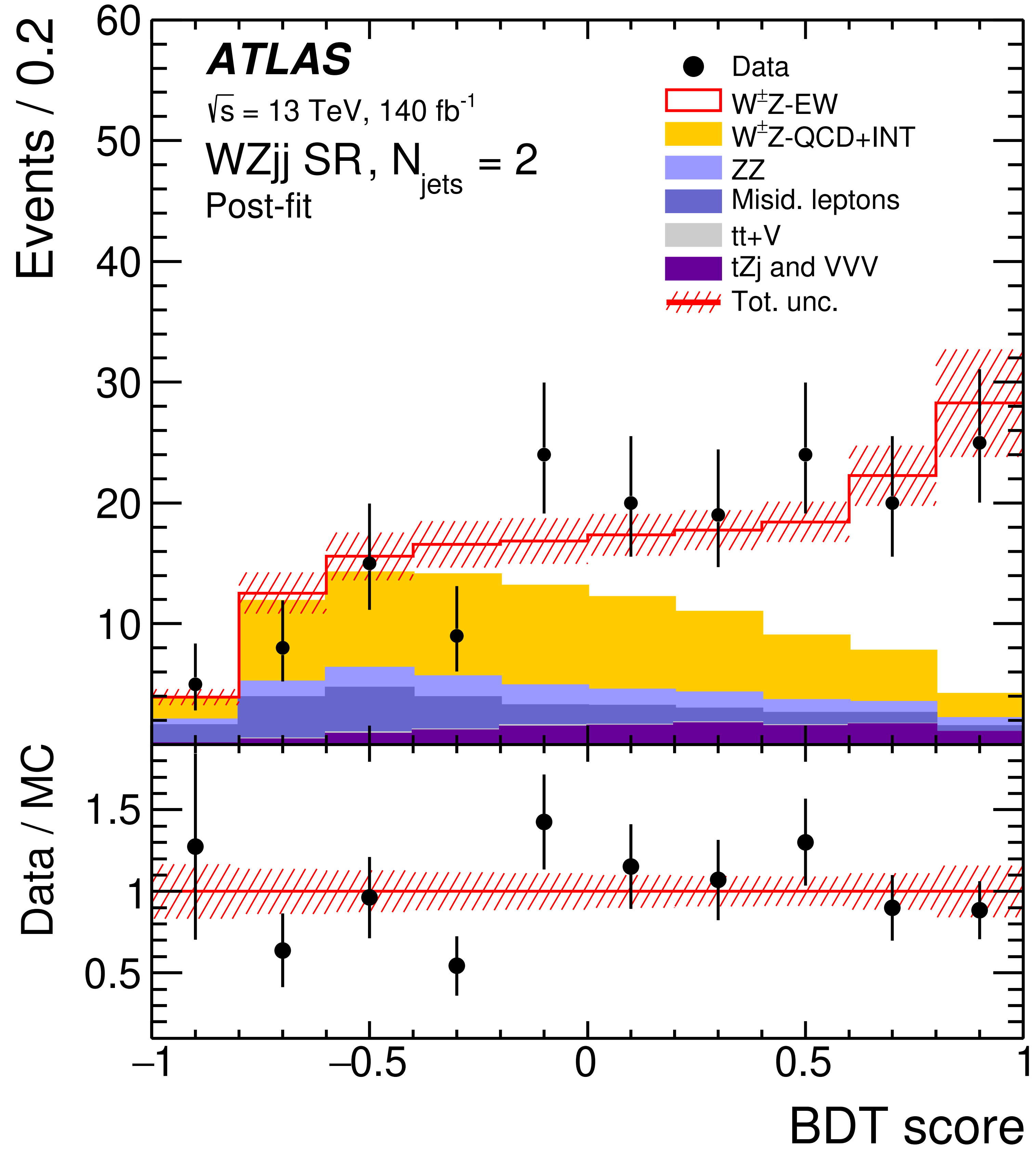


Measurement of VBS WZjj process (Full Run 2)

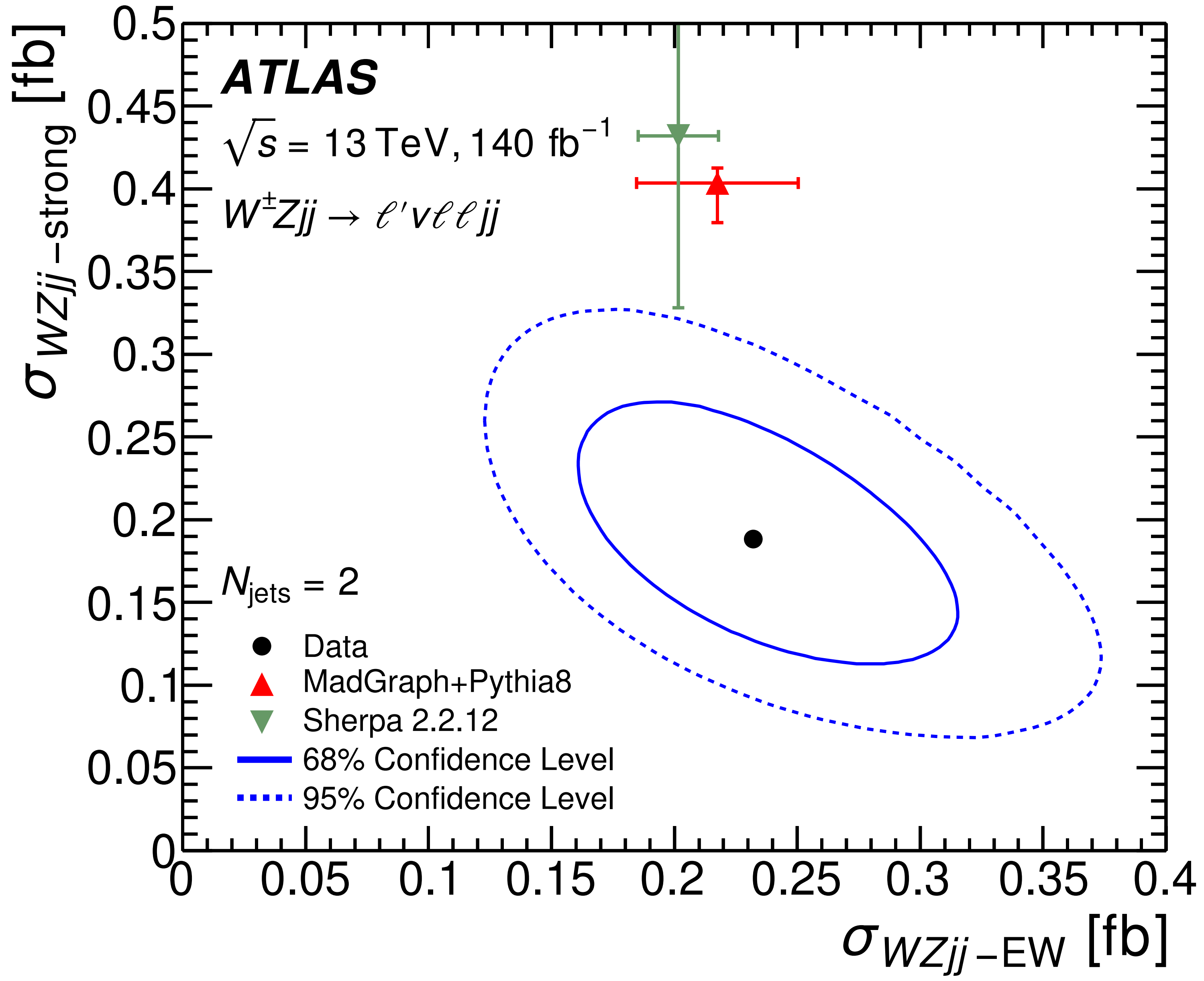
STDM-2018-35

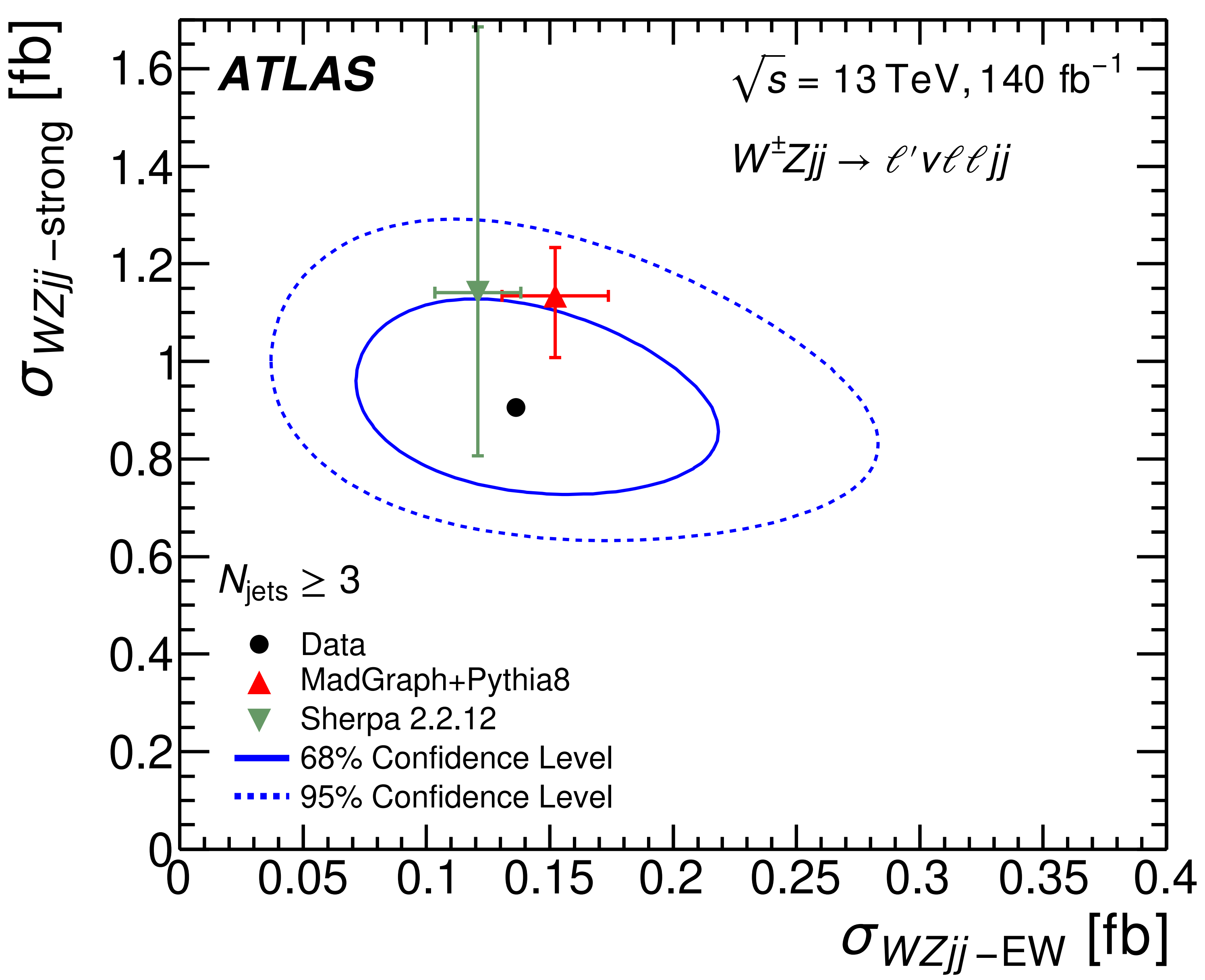
- Selected with two leptons from Z→ℓℓ, lepton + MET, and VBS selection
- Split into two-jet and three-jet regions for better signal / background separation
- Backgrounds from strong WZjj production and ZZ+jets
  - Boosted decision tree trained to extract the EW WZjj component
- Predictions made with aMC@NLO+Pythia8 and Sherpa
  - LO QCD for the EW component and NLO QCD for the strong component





Measured EW WZjj cross section agrees with predictions; strong WZjj cross section measurement below predictions Overall ~1.8σ tension.

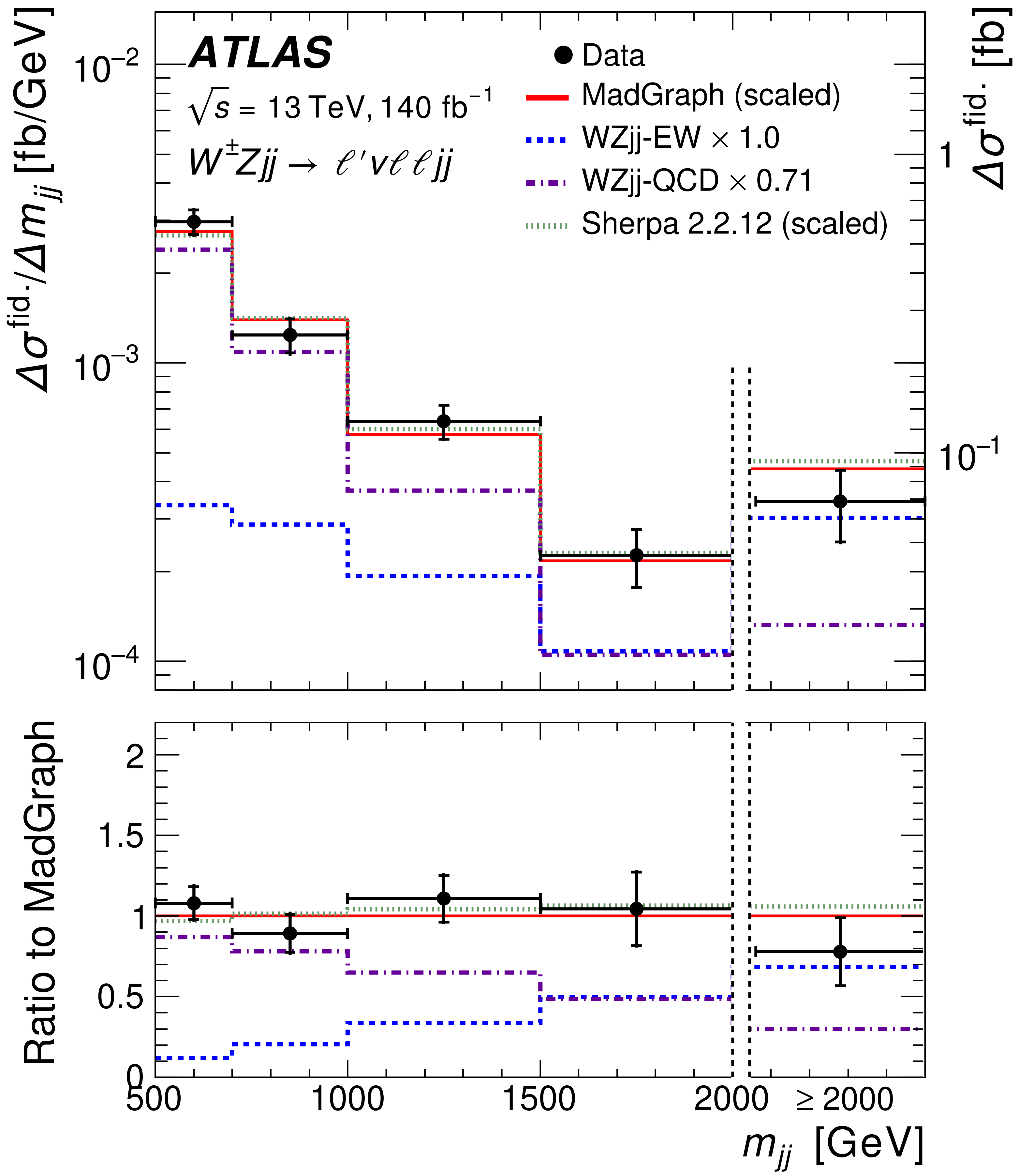


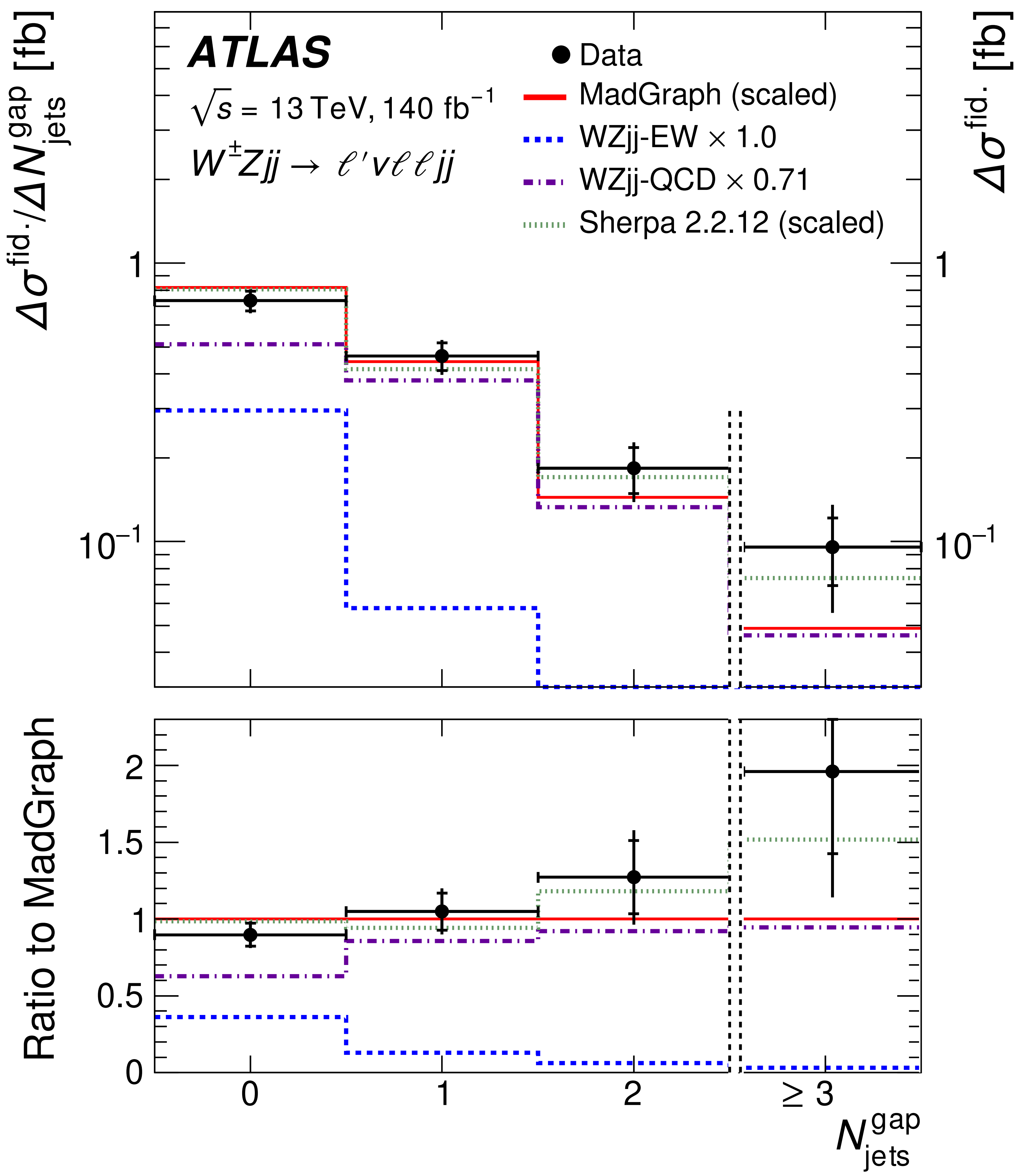


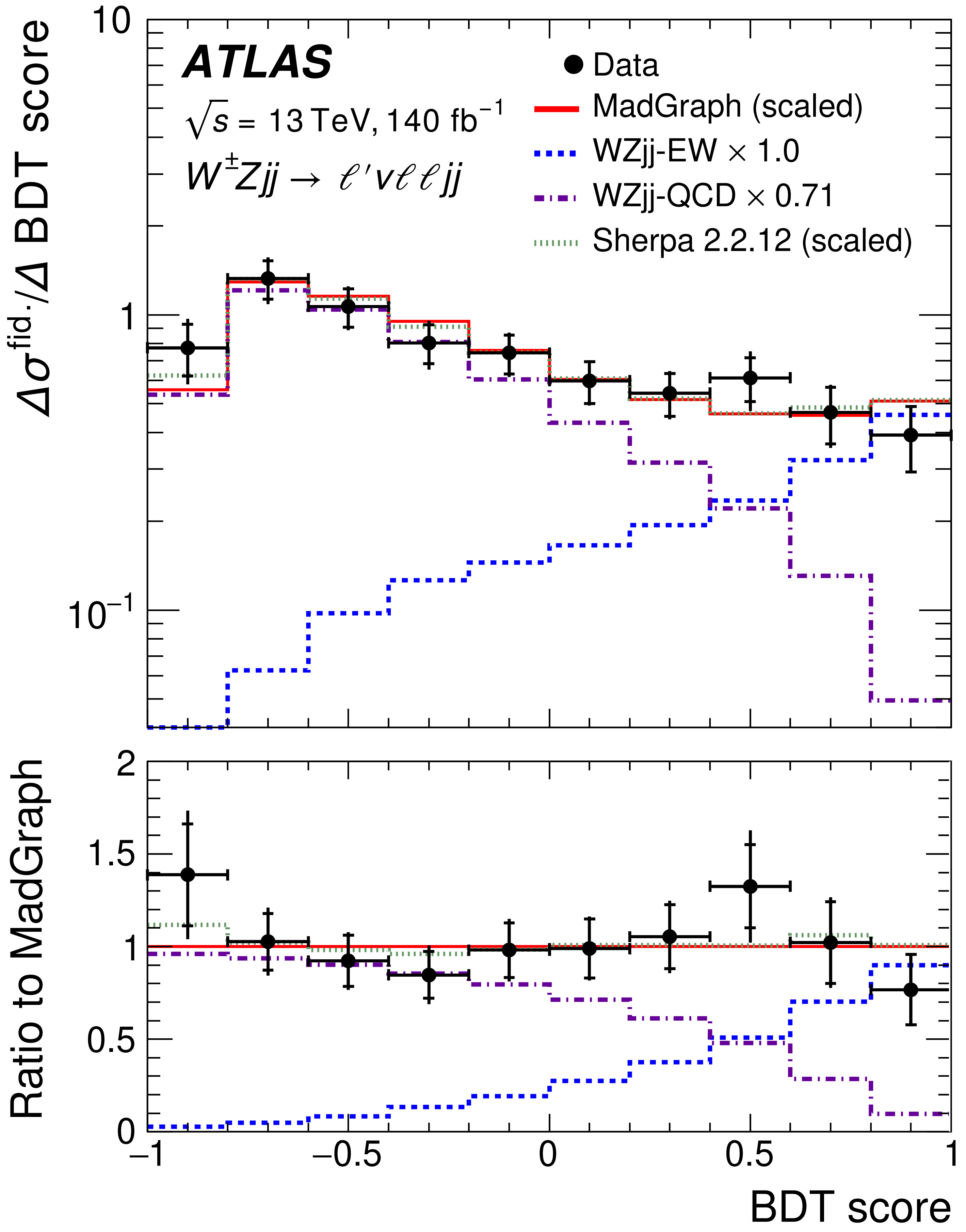
VBS WZjj process: more results

STDM-2018-35

- Differential cross section measurements provided (including the BDT score)
- Generally good agreement with predictions after correcting the overall cross sections
  - Strong WZjj component rescaled to match the observed fiducial cross sections
- Measurement dominated by statistical uncertainties, followed by jet experimental uncertainties







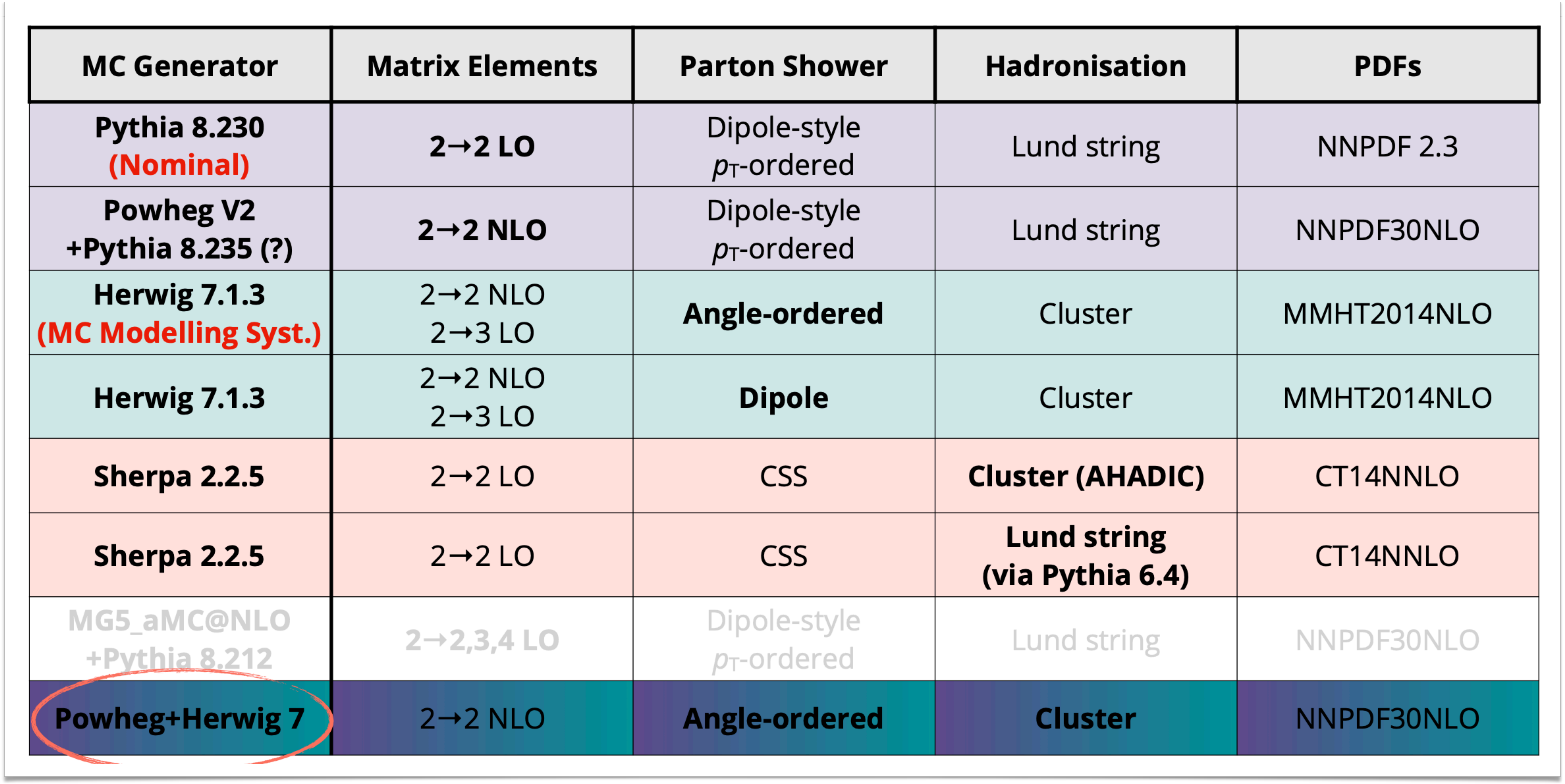
Summary and conclusions

Summary

- LHC gives us a remarkable opportunity for precision measurements across many SM processes
- Stringent measurements of EW parameters surpassing LEP / Tevatron precision
- Observation of new processes that were inaccessible before the LHC
- Important tests of perturbative and non-perturbative QCD
- More and more advanced experimental methods used in precision measurements
  - E.g. machine learning classification to increase the signal / background separation
- Need to work with the theory community to improve the Monte Carlo simulations in time for HL-LHC
  - Theory uncertainties (e.g. PDF or background modeling) will pose a bottleneck otherwise

Backup

Event Isotropies MJ samples



MC Generator	Matrix Elements	Parton Shower	Hadronisation	PDFs
Pythia 8.230 **(Nominal)**	**2→2 LO**	Dipole-style p_{T}-ordered	Lund string	NNPDF 2.3
Powheg V2 **+Pythia 8.235 (?)**	**2→2 NLO**	Dipole-style p_{T}-ordered	Lund string	NNPDF30NLO
Herwig 7.1.3 **(MC Modelling Syst.)**	2→2 NLO 2→3 LO	**Angle-ordered**	Cluster	MMHT2014NLO
Herwig 7.1.3	2→2 NLO 2→3 LO	**Dipole**	Cluster	MMHT2014NLO
Sherpa 2.2.5	2→2 LO	CSS	**Cluster (AHADIC)**	CT14NNLO
Sherpa 2.2.5	2→2 LO	CSS	**Lund string** **(via Pythia 6.4)**	CT14NNLO
MG5_aMC@NLO **+Pythia 8.212**	**2→2,3,4 LO**	Dipole-style p_{T}-ordered	Lund string	NNPDF30NLO
Powheg+Herwig 7	2→2 NLO	**Angle-ordered**	**Cluster**	NNPDF30NLO

Sherpa2.2.1 vs Sherpa2.2.11 pT(V) modeling

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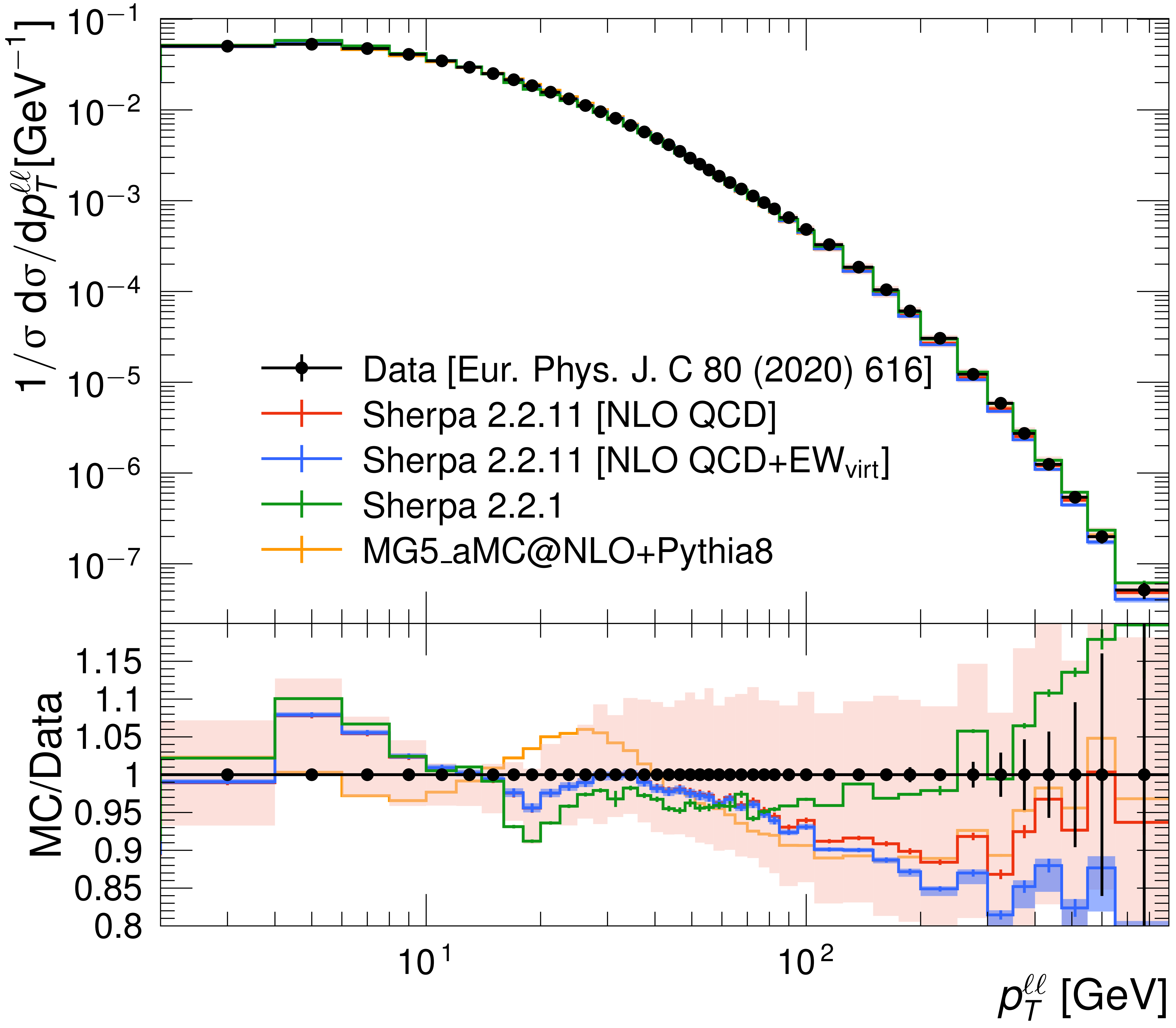

Configuration	SHERPA 2.2.1	SHERPA 2.2.11
Generator version	SHERPA 2.2.1	SHERPA 2.2.11
PDF set	NNPDF3.0NNLO	NNPDF3.0NNLO
EW input scheme	Effective	$\sin^2\theta_{\mathrm{eff}}$
QCD accuracy	0–2j@NLO+3,4j@LO	0–2j@NLO+3,4,5j@LO
NLO EW$_{\mathrm{virt}}$ corrections	No	Yes
Subtraction scheme	Default	Modified Catani–Seymour
Special treatment for unordered histories	No	Yes
Scale for H-events	STRICT_METS	H'_{T}
Gluon colour/spin exact matching	Yes	No
Core process for K-factor	$2 \rightarrow 4$	$2 \rightarrow 2$
Phase-space strategy	Sliced in $\max(H_{\mathrm{T}}, p_{\mathrm{T}}^{V})$	Analytic enhancement

Strong coupling constant from TEECs in multijet events

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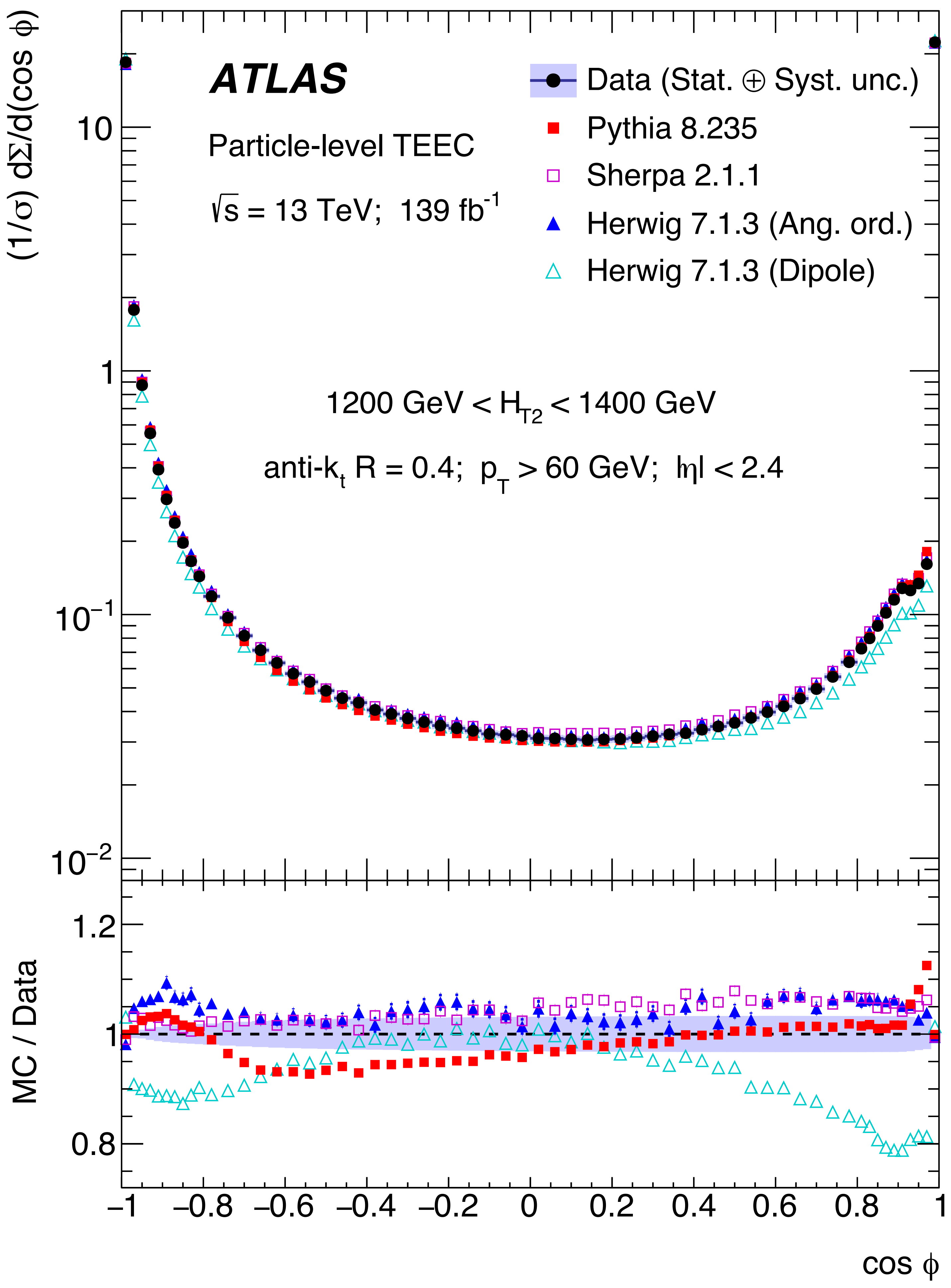
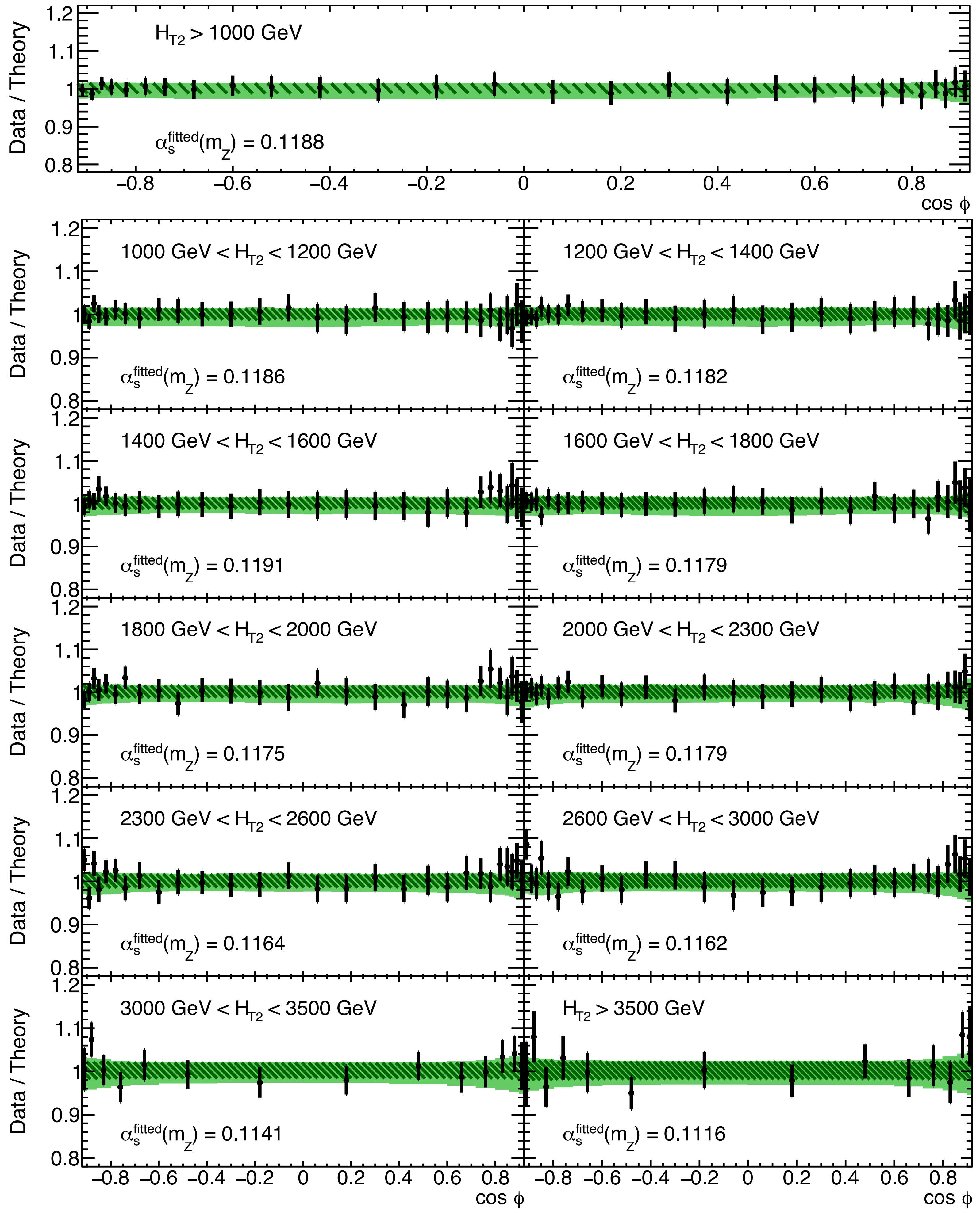
- ATLAS measurement of the strong coupling from Energy-Energy Correlations in jet events
- Predictions for the TEEC function are calculated from the NNLO 3-jet x-secs: PRL 129, 119901 (2022)

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}=\frac{1}{\sigma}\sum_{i,j}^{\text{jets}}\int d\sigma_{pp\to\text{jets}}\,\frac{E_{\mathrm{T}i}E_{\mathrm{T}j}}{E_{\mathrm{T}}^{2}}\,\delta(\cos\Delta\varphi_{ij}-\cos\phi)$$





ATLAS
Particle-level TEEC
√s = 13 TeV; 139 fb⁻¹
anti-k_t R = 0.4
p_T > 60 GeV
|η| < 2.4

$\mu_{R,F}=\hat{H}_T$
NNLO pQCD
MMHT 2014 (NNLO)
Exp. unc.
Non-scale unc.
Theo. unc.