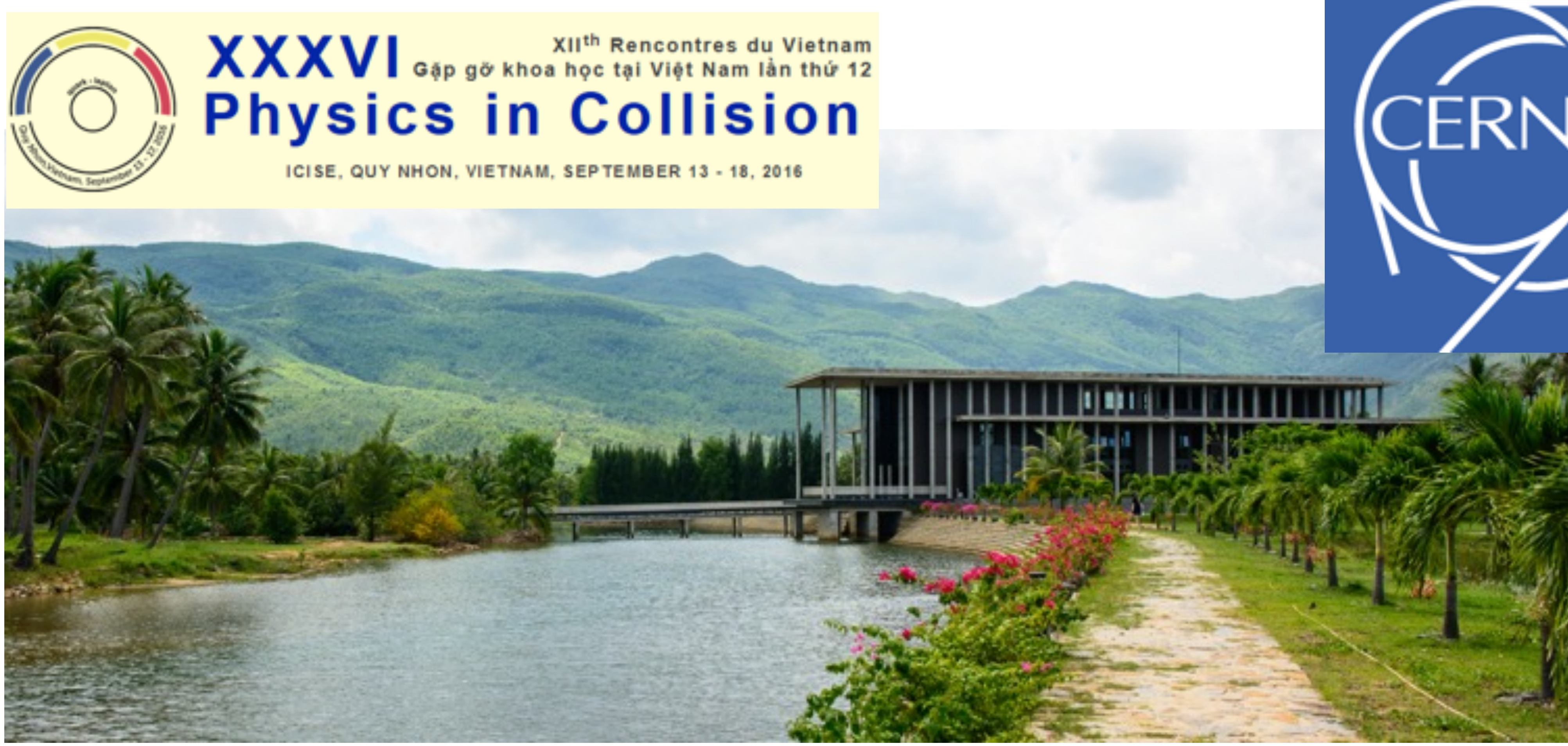
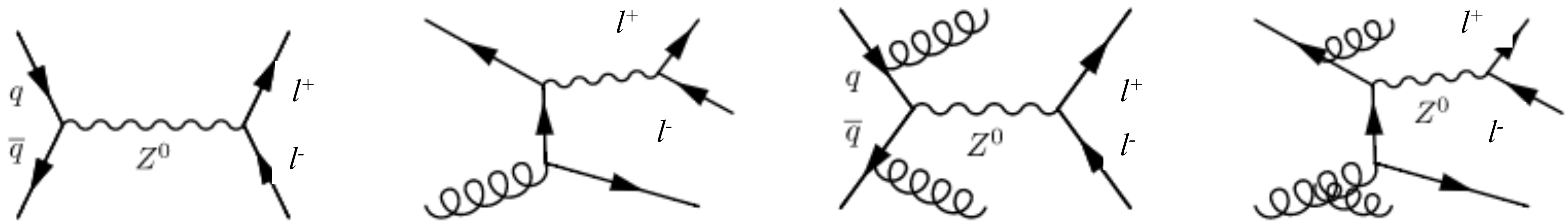
W and Z precise measurements at 13 TeV with the ATLAS and CMS experiments

XXXVI Physics in Collisions, Quy Nhon, September 2016

Kristof Schmieden, on behalf of the ATLAS & CMS collaborations



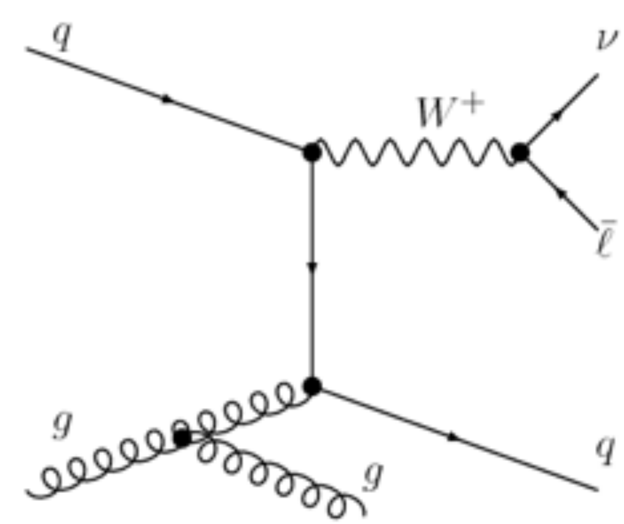
Motivation



(a) Leading Order (b) Next to leading order (c) Parton shower (d) Next to leading + parton shower

$p_T(ll) \sim 0$ $p_T(ll) > 0$

- Probes perturbative QCD
- Non perturbative effects / soft gluon resummation
- Parton shower effects
- Behavior of different MC modeling approaches



Precision measurements at hadron colliders?

- Precise measurements using weak gauge Bosons:
  - **Huge statistic, clean signature**

  - Experimental uncertainties: ~1% (sometimes better!)
    - excellent calibration and control of systematics
    - low pileup environment preferable!

- Luminosity uncertainty:
  - 2% - 3% => most precise measurements are ratios

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Achieved precision in inclusive x-section measurement:

total

Phys. Lett. B 759 (2016) 601

CMS-PAS-SMP-15-011

- 13 TeV: $\sigma(Z \rightarrow ll)$ = 1870pb ± 0.1% (stat) ± 1.9% (syst) ± 2.7% (lumi)
- 13 TeV: $\sigma(Z \rightarrow ll)$ = 779pb ± 0.4% (stat) ± 0.8% (syst) ± 2.1% (lumi)

fiducial!

total

Eur. Phys. J. C 76(5), 1-61 (2016)

Eur. Phys. J. C 75 (2015) 147

- 8 TeV: $\sigma(Z \rightarrow ll)$ = 1138pb ± 0.07% (exp) ± 2.2% (theo) ± 2.6% (lumi)
- 8 TeV: $\sigma(Z \rightarrow ll)$ = 537.10pb ± 0.03% (stat) ± 0.45% (syst) ± 2.8% (lumi)

fiducial!

(update: 1.9%)

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fiducial!

(update: 1.9%)

- Differential measurements: 10s - 100s of bins stat. unc. dominating!

At present: **most precise measurements released from 8 TeV data!**
precision of 8 TeV run might no be reached any time soon with 13 TeV data

Overview

- **13 TeV analyses:**
  - Single boson cross section measurements
  - Ratio measurements
  - Associated jets

- **Recent highlights from 8 TeV data:**
  - Z-Boson transverse momentum measurement
  - Drell-Yan x-section measurements
  - Study of Angular coefficients in pp $\rightarrow Z/\gamma^* \rightarrow$ ll

Naturally this represents a selection of few of the many results from the ATLAS and CMS collaborations. For a complete list, please refer to the collaboration websites:

ATLAS physics results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/StandardModelPublicResults

CMS physics results: https://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/SMP/index.html

Results at $\sqrt{s}$ = 13 TeV

Typical Selection of W,Z Events

ATLAS

- Data collected during 2015
  - √s = 13 TeV, 81 pb^{-1}
- Fiducial Volume, ee and μμ channels

$p_T > 25\,\mathrm{GeV}$
$|\eta| < 2.5$

W: $E_T^{miss} > 25\,\mathrm{GeV}$, $m_T > 50\,\mathrm{GeV}$

Z: $66\,\mathrm{GeV} < m_Z < 116\,\mathrm{GeV}$

- Signal Simulation:
  - Powheg + Pythia8
- Backgrounds:
  - EW & ttbar from MC
  - QCD multijet: data-driven

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CMS

- Data collected during 2015
  - √s = 13 TeV, 2.3 fb^{-1}
- Fiducial volume of μμ channel

$p_T > 25\,\mathrm{GeV}$
$|\eta| < 2.4$

W: $m_T > 50\,\mathrm{GeV}$

Z: $60\,\mathrm{GeV} < m_Z < 120\,\mathrm{GeV}$

- Signal Simulation:
  - MG5_aMC@NLO + Pythia8
- Backgrounds:
  - EW & ttbar from MC
  - QCD multijet: data-driven

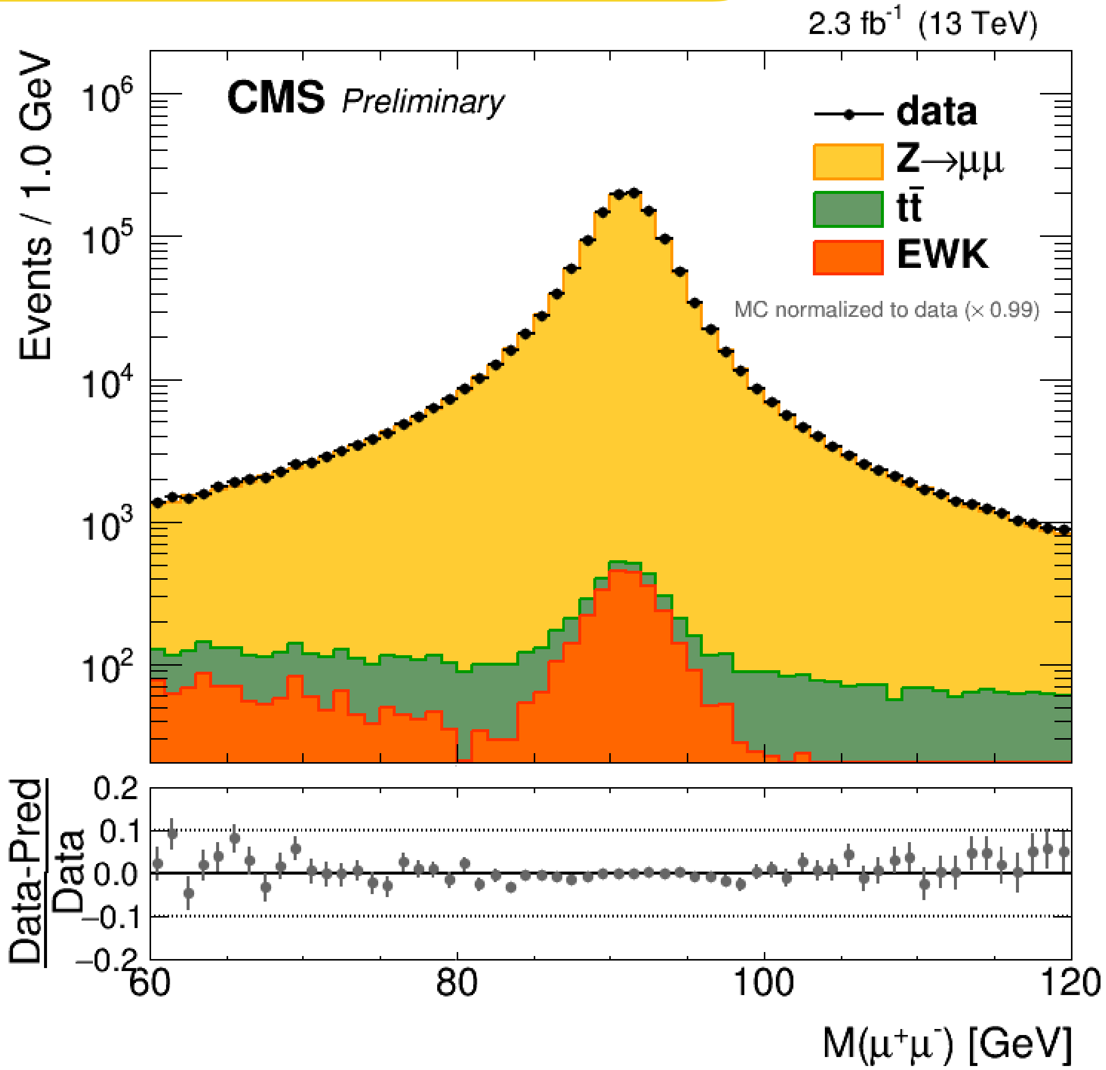
CMS-PAS-SMP-15-011

Measured distributions

- **Control distributions**: invariant mass (transverse mass)
  - Signal process, Electroweak and top backgrounds simulated
  - Multijet background estimated from data (negligible in Z analysis)

Simulation and measurement agree very well!

CMS-PAS-SMP-15-011



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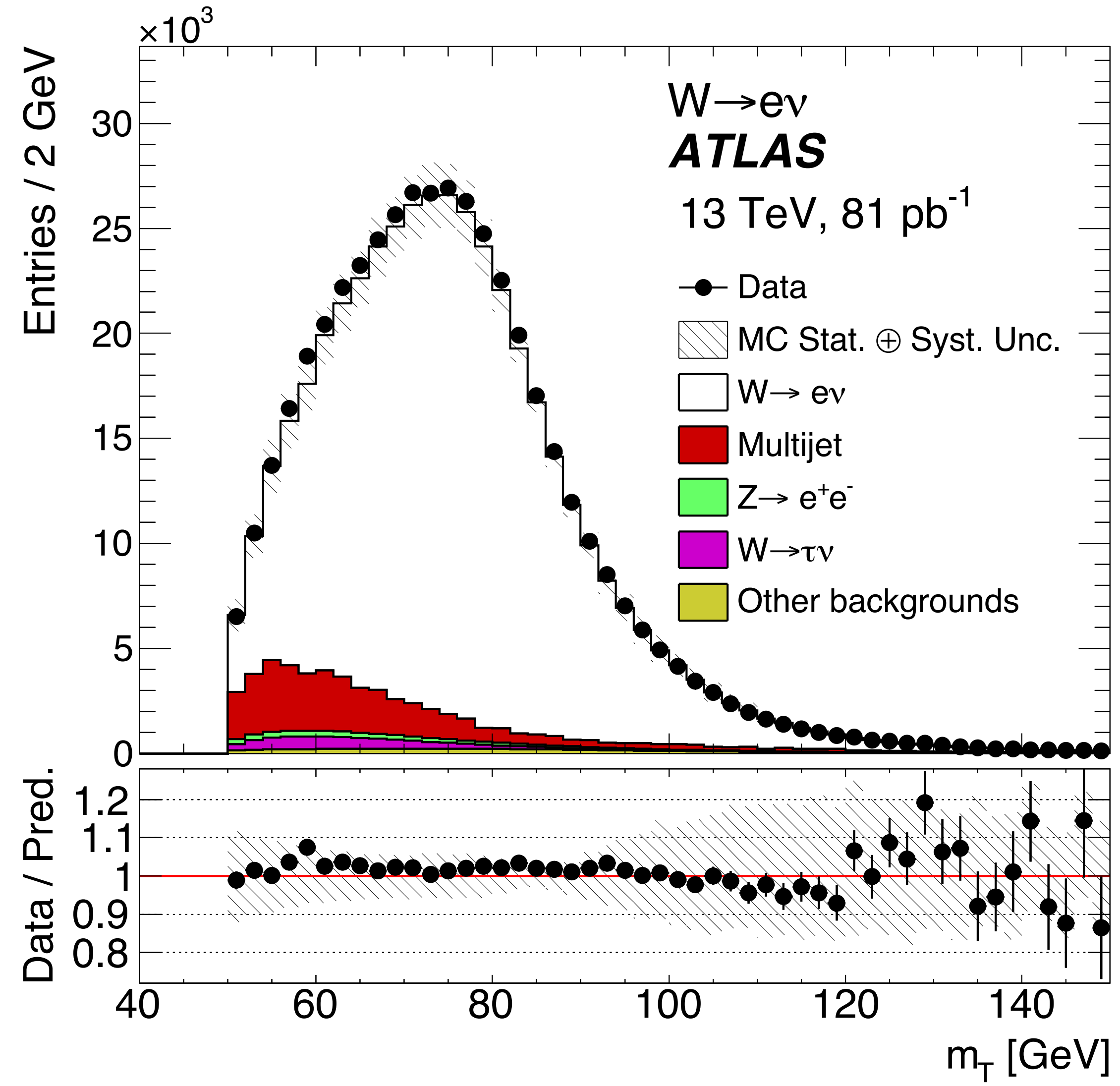


Systematic uncertainties

- Main sources:
  - Jet energy scale (W only)
    - Propagated to uncertainty on MET
  - Lepton reco & id (W & Z)
  - Lepton isolation (Z)

- Uncertainty estimation:
  - Calibration derived from the data
    - Largely based on 2012 calibration
    - Uncertainties are derived in calibration
  - Efficiency scale factors account for data / simulation discrepancy. Varied within uncertainties.

ATLAS

$\delta C/C$ [%]	$Z \to e^+e^-$	$W^+ \to e^+\nu$	$W^- \to e^-\bar{\nu}$	$Z \to \mu^+\mu^-$	$W^+ \to \mu^+\nu$	$W^- \to \mu^-\bar{\nu}$
Lepton trigger	0.1	0.3	0.3	0.2	0.6	0.6
Lepton reconstruction, identification	0.9	0.5	0.6	0.9	0.4	0.4
Lepton isolation	0.3	0.1	0.1	0.5	0.3	0.3
Lepton scale and resolution	0.2	0.4	0.4	0.1	0.1	0.1
Charge identification	0.1	0.1	0.1	–	–	–
JES and JER	–	1.7	1.7	–	1.6	1.7
$E_{\mathrm{T}}^{\mathrm{miss}}$	–	0.1	0.1	–	0.1	0.1
Pile-up modelling	< 0.1	0.4	0.3	< 0.1	0.2	0.2
PDF	0.1	0.1	0.1	< 0.1	0.1	0.1
Total	1.0	1.9	1.9	1.1	1.8	1.8

CMS: Z -> μμ

Lepton reco. & id. [%]	1.3
Bkg. subtraction / modeling [%]	0.1
Total experimental [%]	1.3
PDF [%]	0.7
QCD corrections [%]	1.1
EW corrections [%]	0.4
Theoretical Uncertainty [%]	1.4
Lumi [%]	2.7
Total [%]	3.3

Results - Differential Distributions

CMS-PAS-SMP-15-011

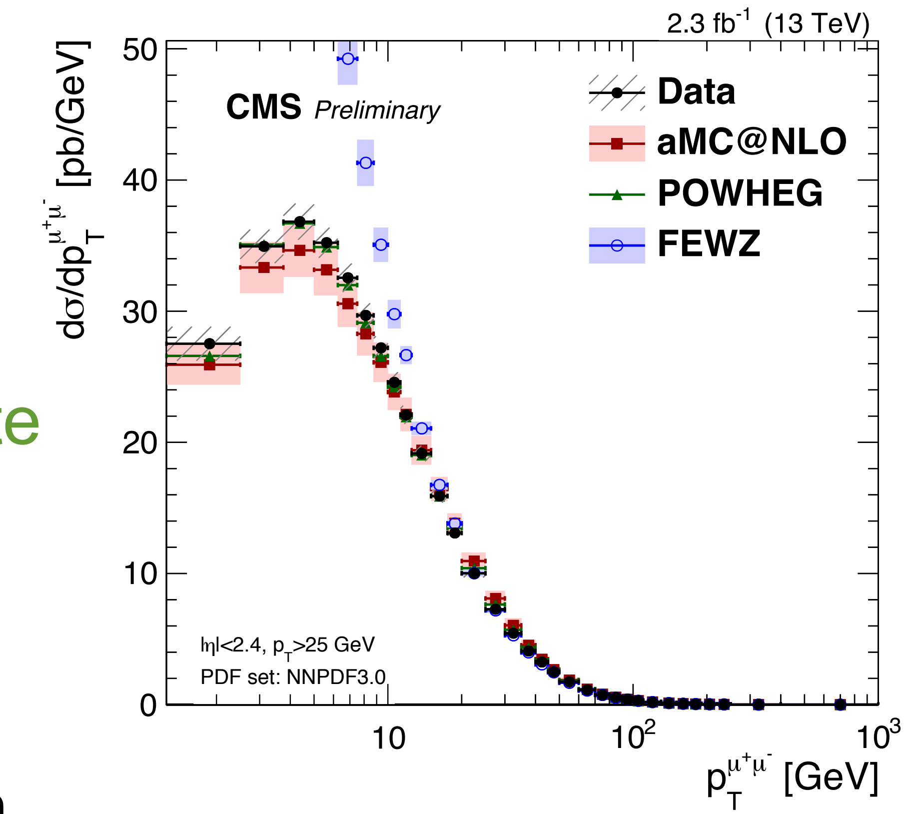
- Low range dominated by:

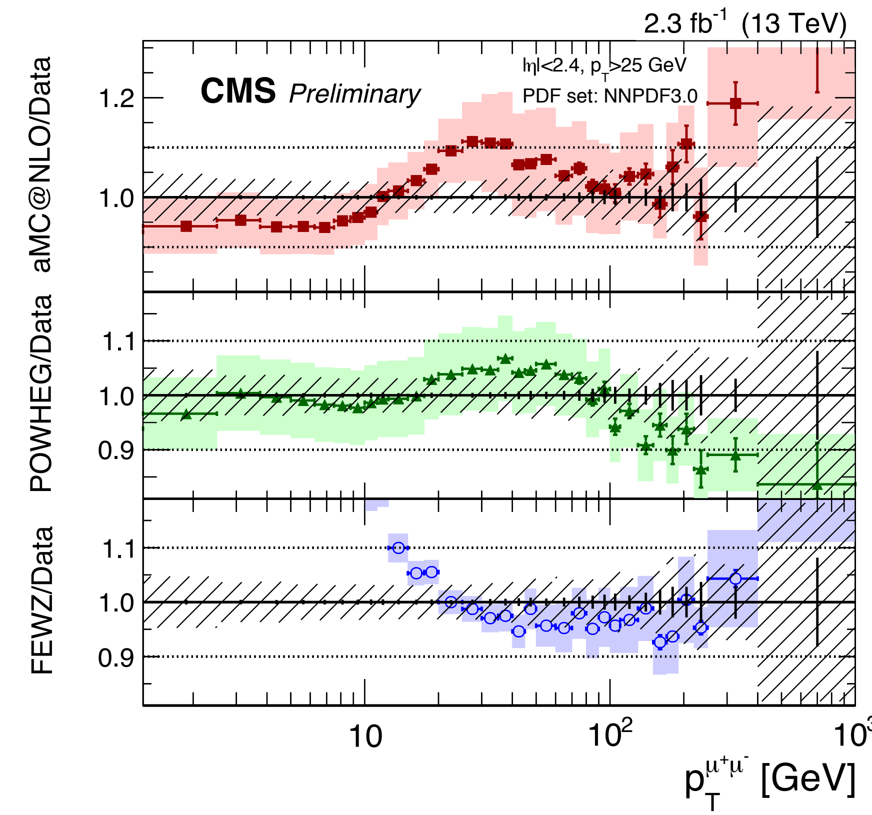
  Non perturbative effects
  Soft gluon resummation

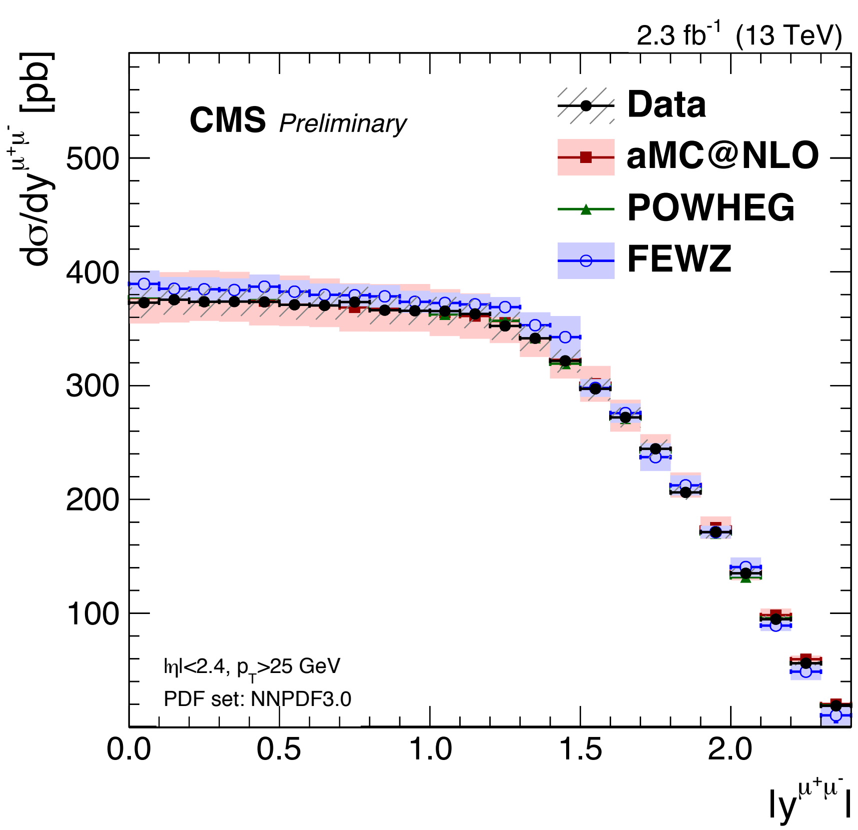
  FEWZ doesn't calculate that

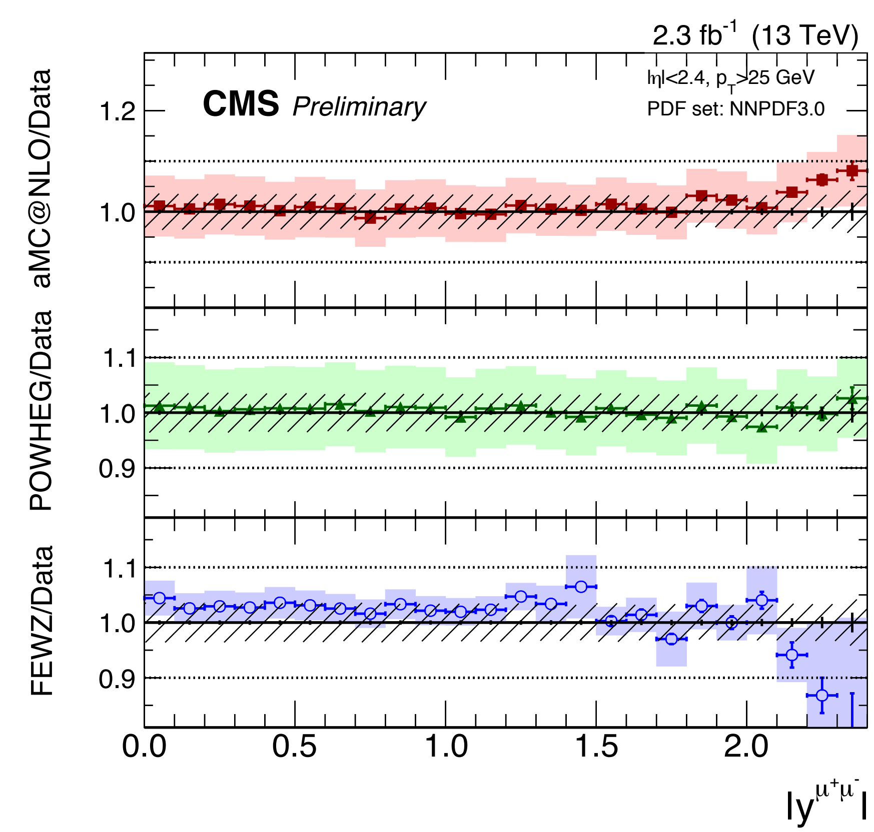
- High pT range:
  dominated by hard parton emission

- Rapidity spectrum well described
  small deviations at large |Y|









Results - Ratios and impact on PDFs

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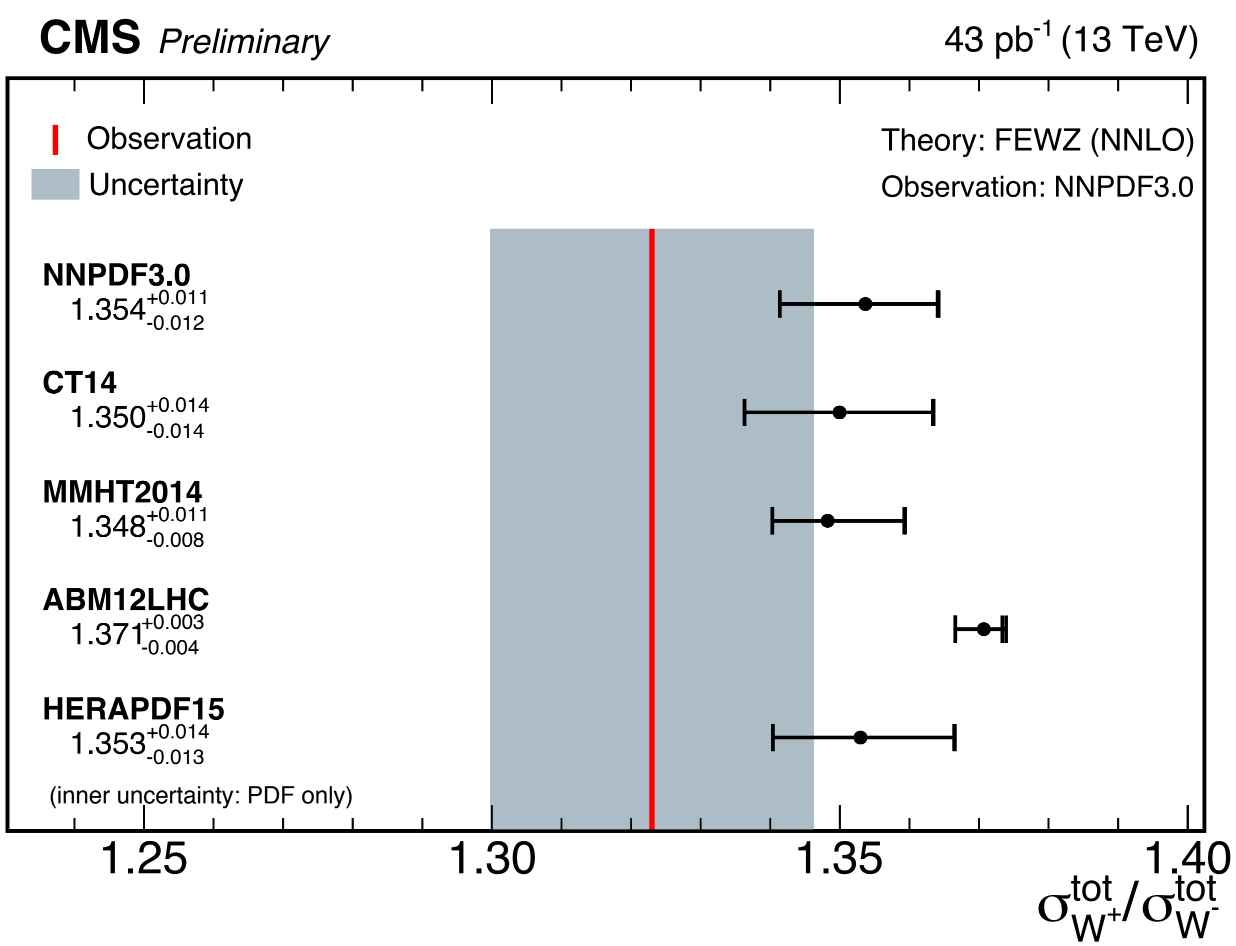
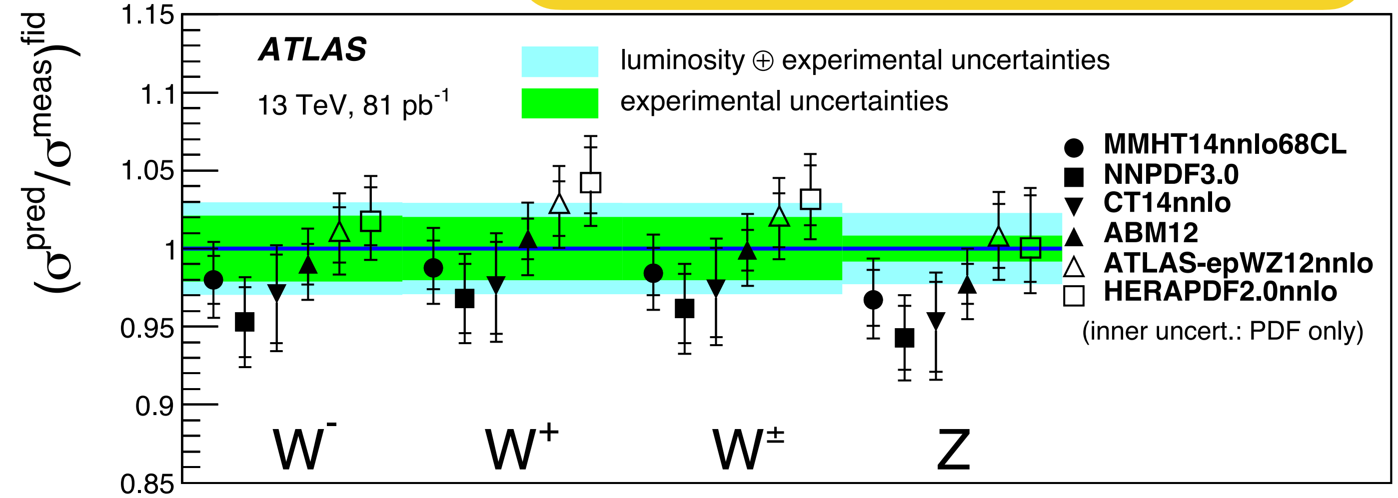
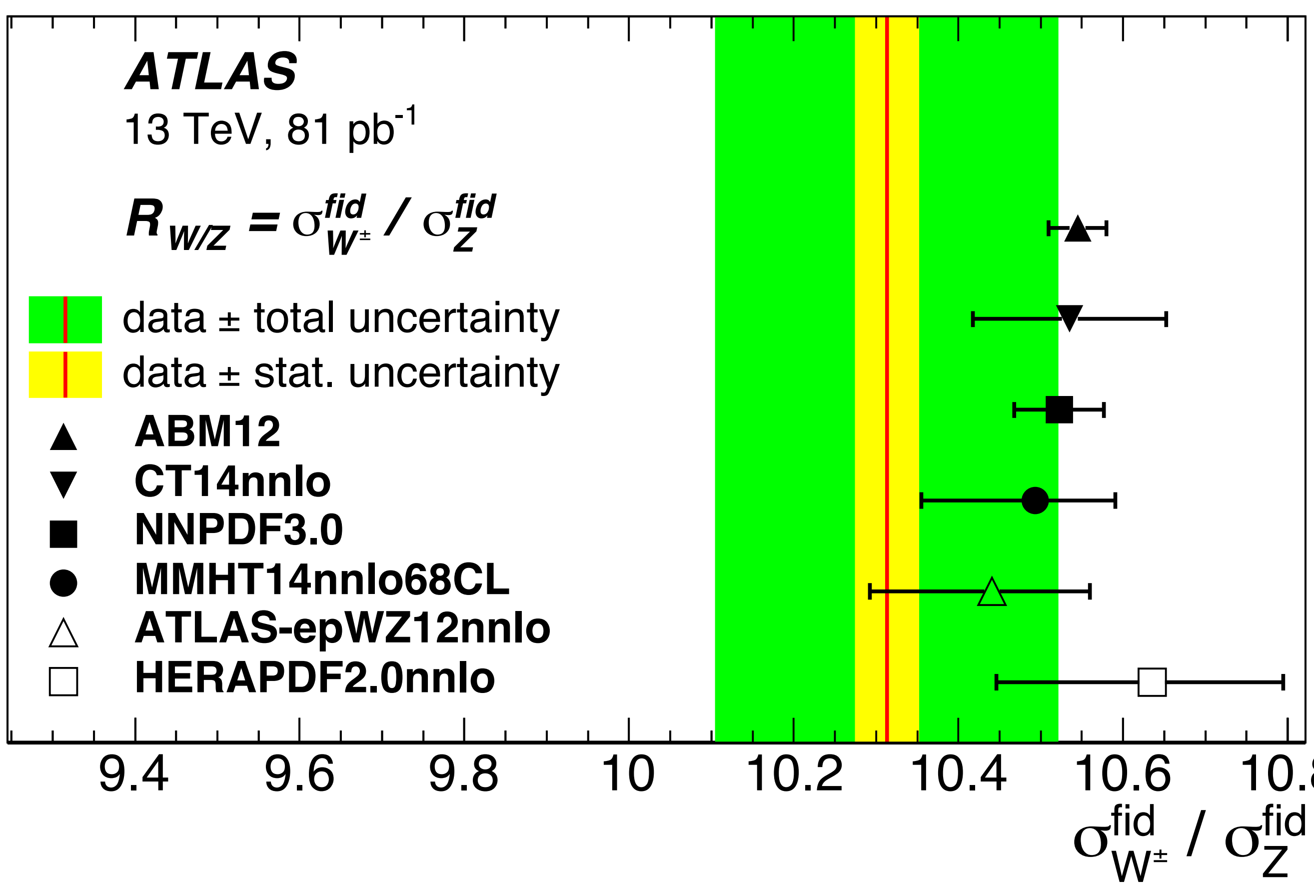
CMS-PAS-SMP-15-004

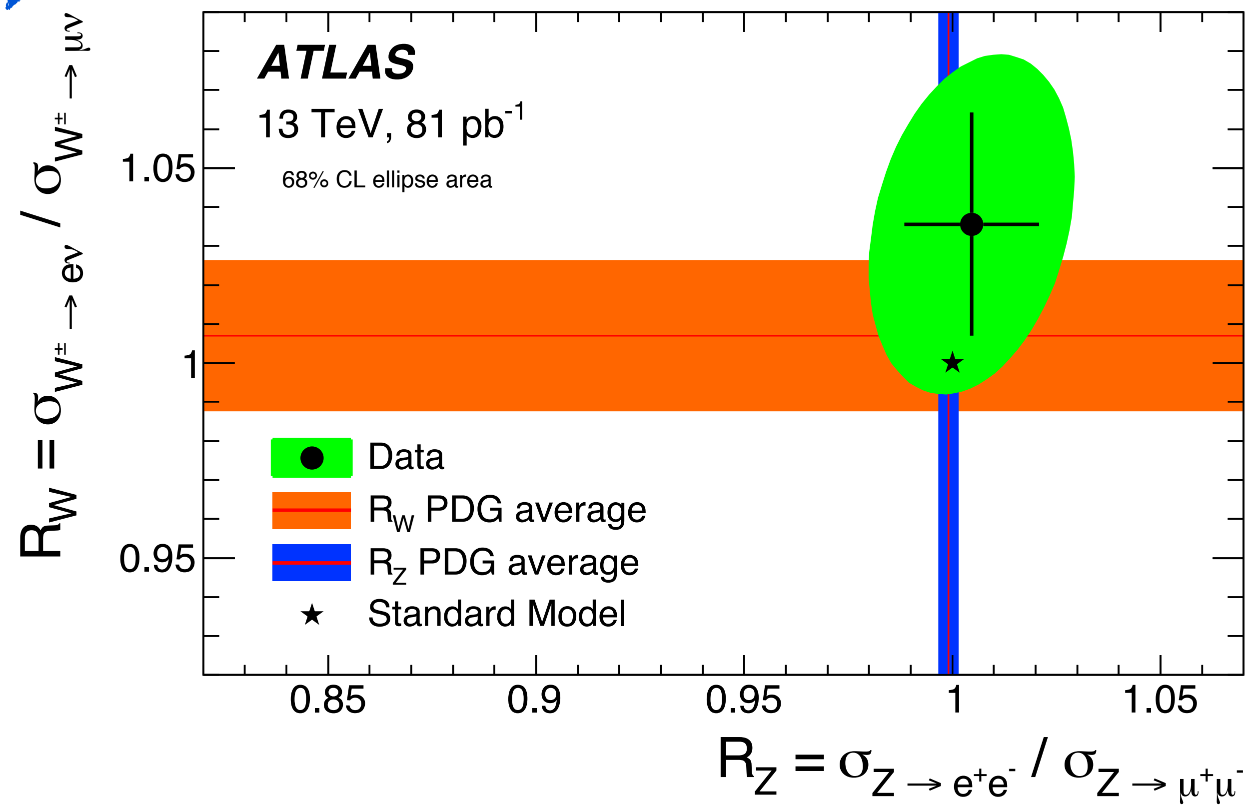


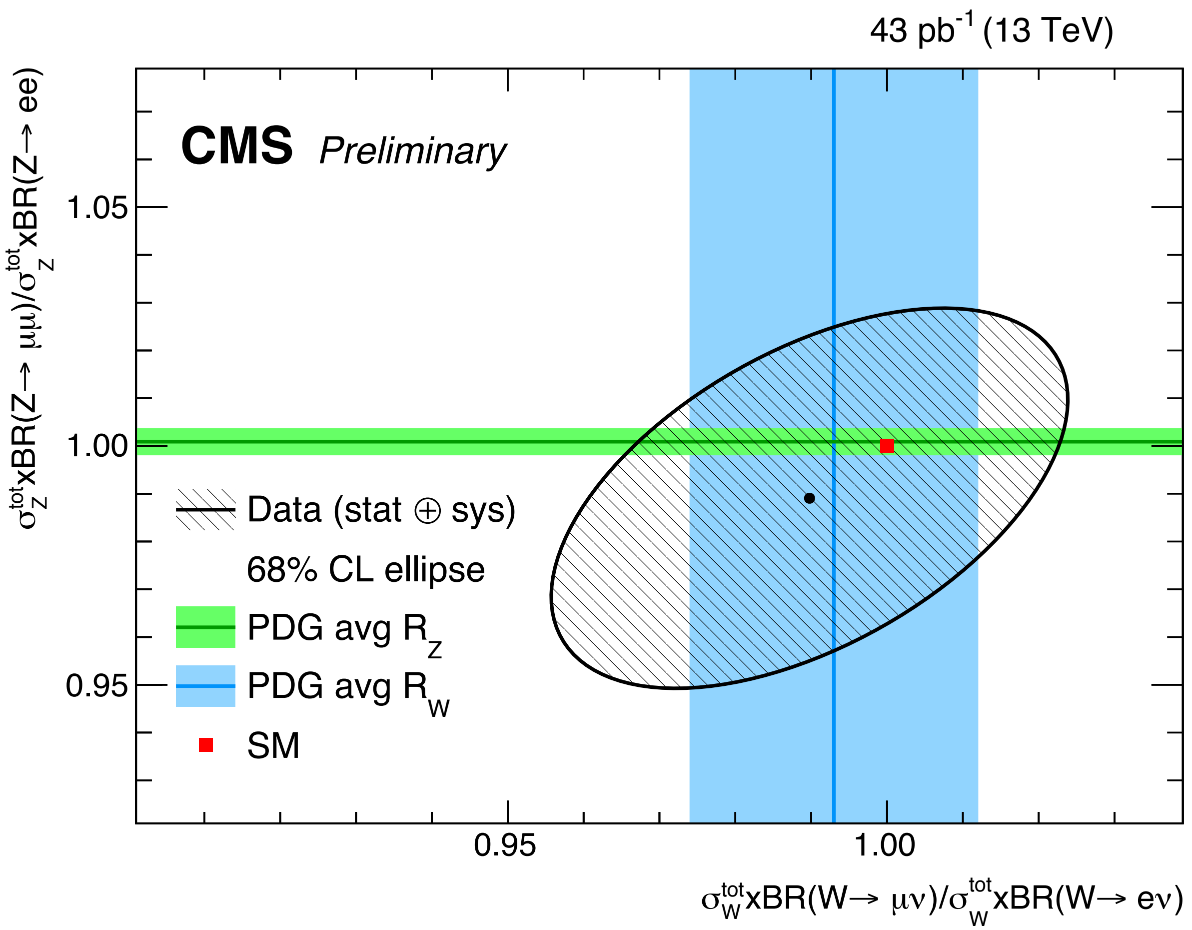




- Luminosity uncertainty cancels in ratios!
- Sensitivity to PDFs
  - Predictions and measurement disagree systematically by ~ 1 standard deviation

Results - Lepton Universality





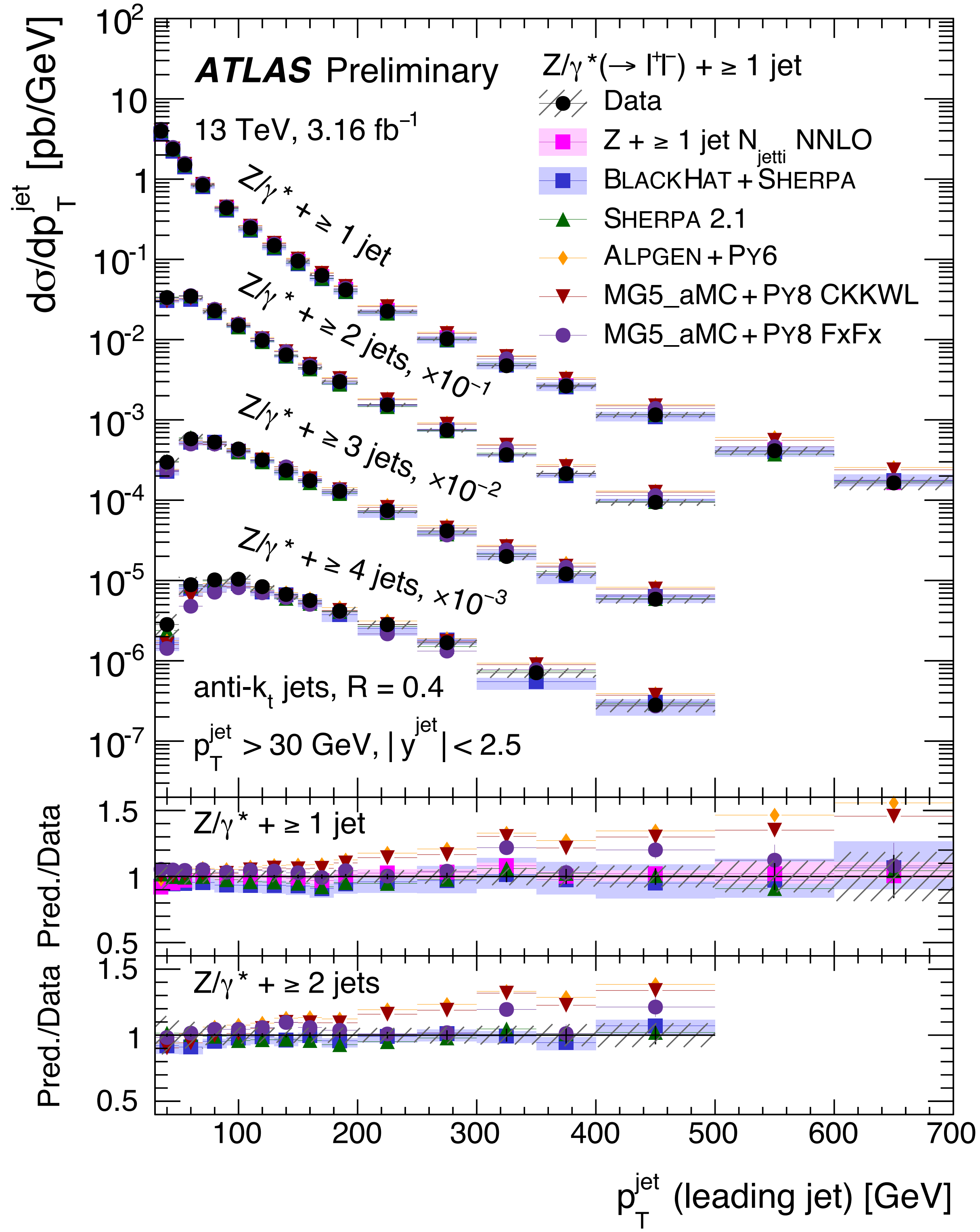
- Ratio of cross sections in different lepton final states
- W,Z: 2 independent processes
- Precise test of lepton universality

In agreement with standard model predictions

Z + jet cross section measurements

- Sensitive to
  - Parton shower, matrix element & PS matching
- Standard Z selection + requirement on jets
- Jet definition:
  - Anti-k_t algorithm, radius 0.4
  - p_T > 30 GeV && |y| < 2.5 (2.4)
  - Jets overlapping with leptons are removed
- Measurement differentially in several variables, compared to various simulations
- Very sensitive probe of different MC approaches, tuning, …
- Alpgen + Py6 & MG5_aMC + Py8 CKKWL
  - discrepancy for large jet pT (> 200 GeV)

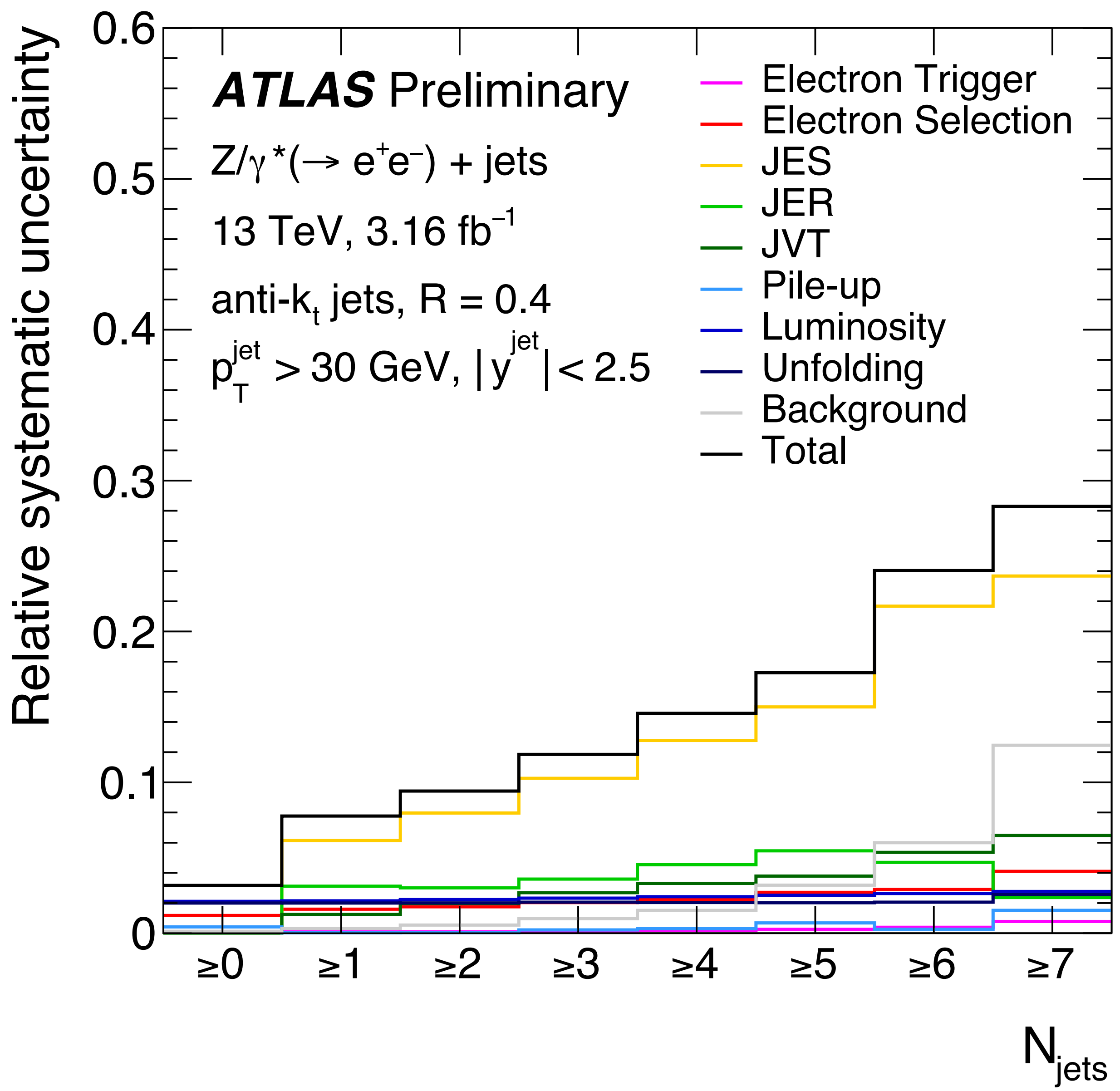
ATLAS-CONF-2016-046



Z + jet cross section measurements: Systematics

- Systematics dominated by
  - Jet Energy Scale

- Other large contributions depend on variable of interest
  - Jet energy resolution, Luminosity, Background, …

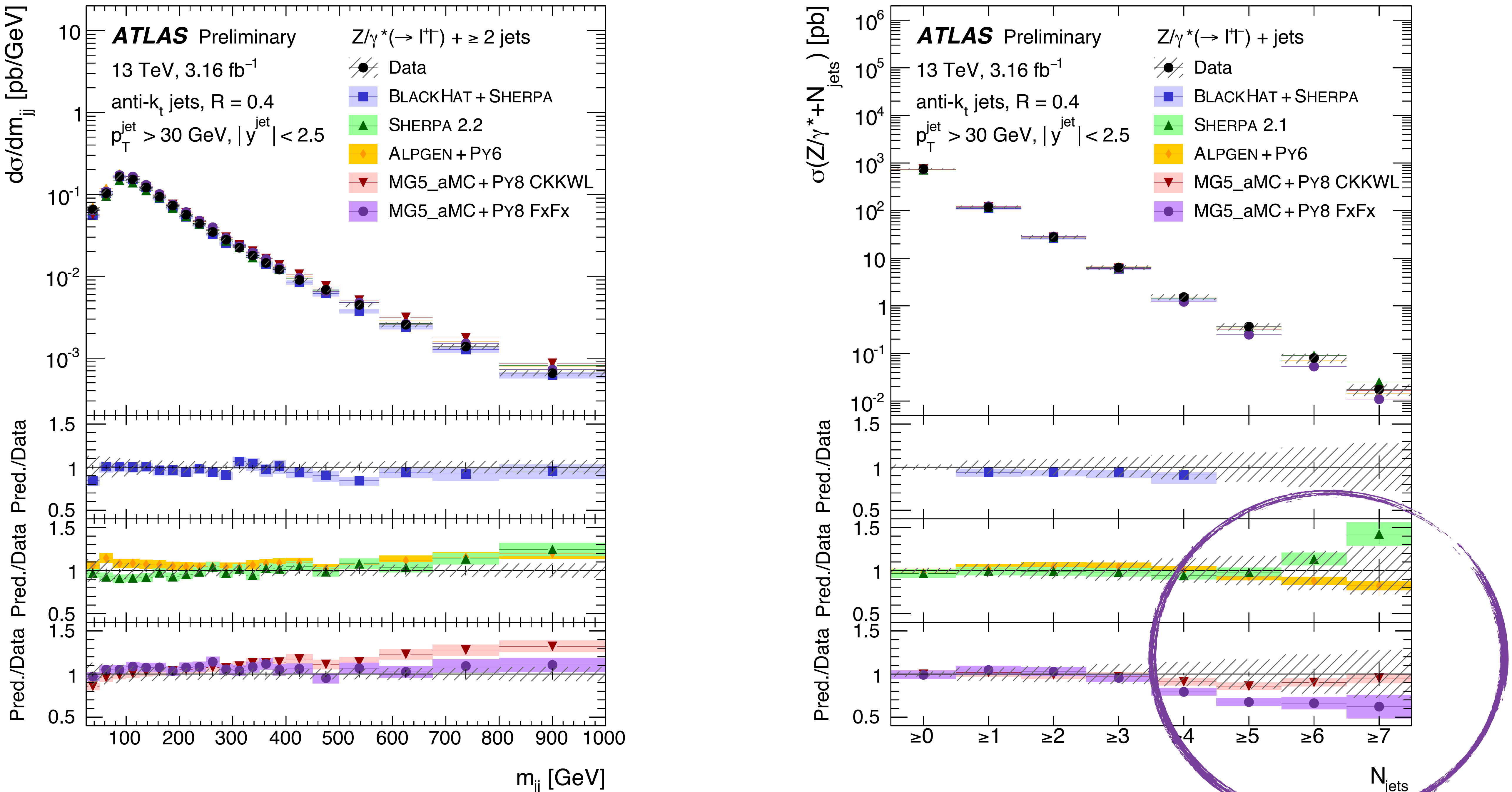


Z + jet cross section measurements

ATLAS-CONF-2016-046

- Z + jet measurement vs. number of jets

  - Some deviations from measurement observed for high jet multiplicities
  - Different generators describe different features well

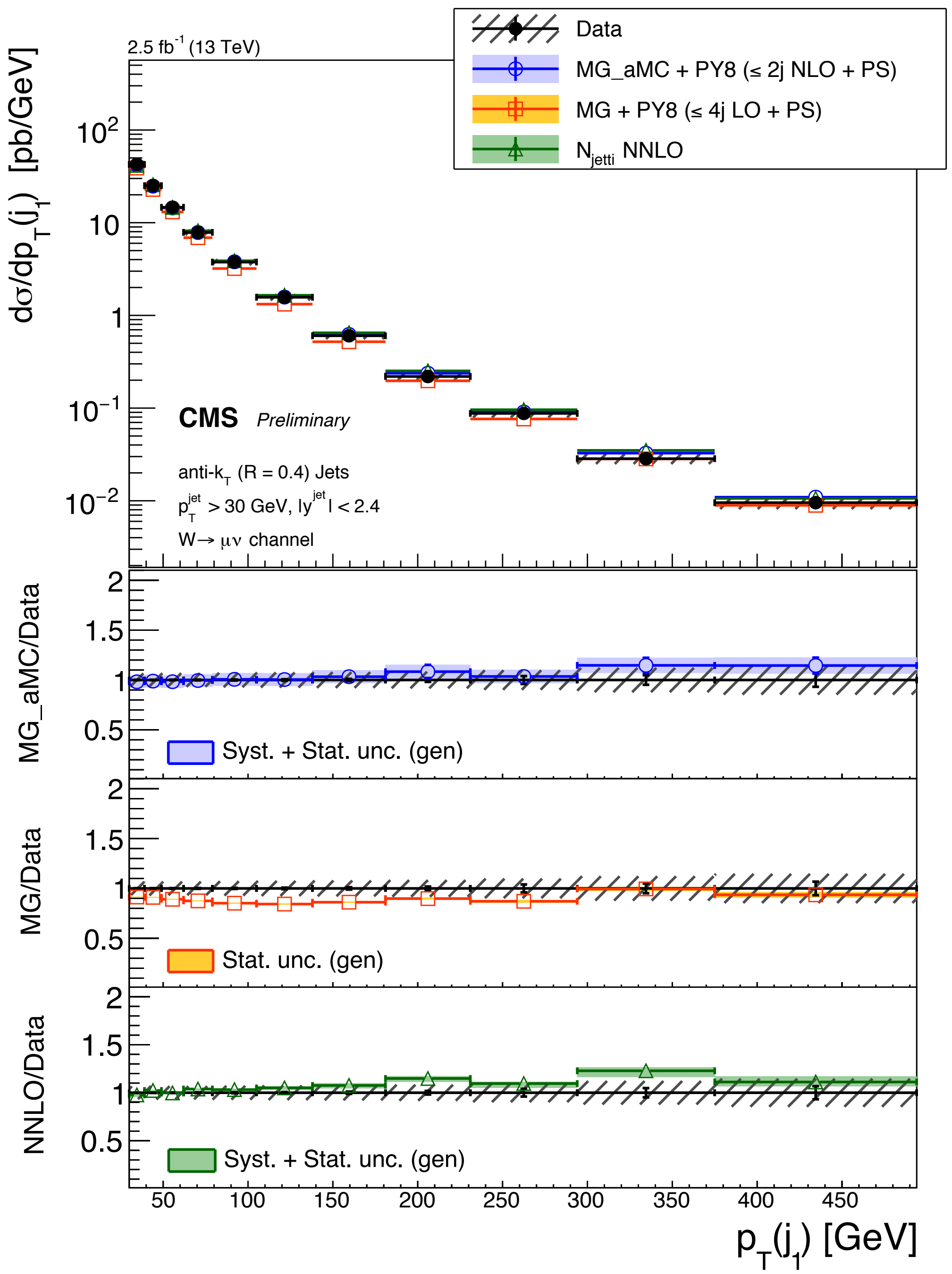


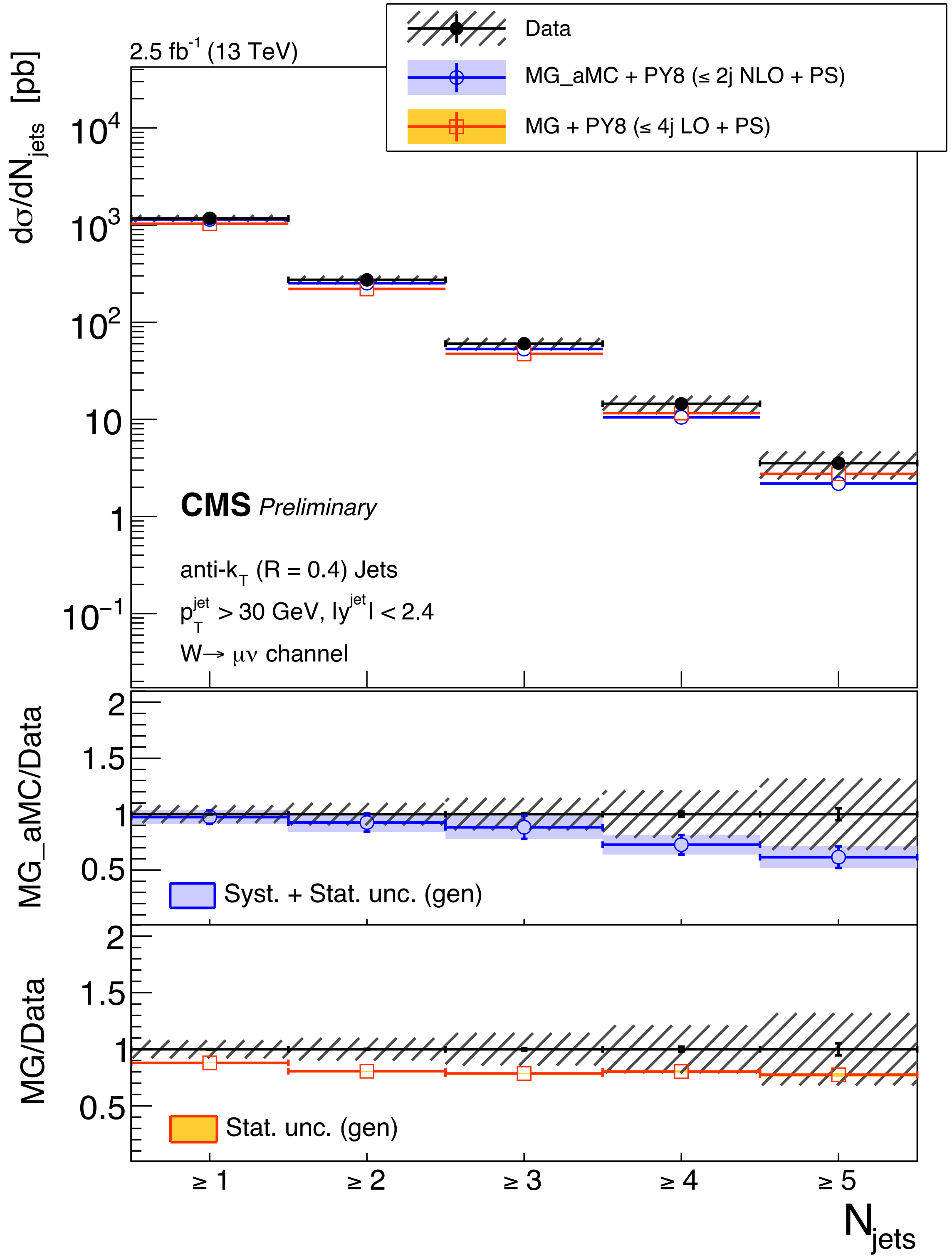
W + jet cross section measurements

- Same observables of interest as for Z+jet measurement

CMS-PAS-SMP-16-005

- Systematic uncertainties: similar to Z analysis
  - Dominant uncertainty: **jet energy scale**





Selected precision results from 8 TeV data set

Measurement of p_{T}^{ll} and ϕ_{η}^{*}

ATLAS

- Data collected during 2012
  - √s = 8 TeV, 20.3 fb^{-1}
- Fiducial Volume (ee and μμ channels)

$$p_{\mathrm{T}} > 20\,\mathrm{GeV}$$
$$|\eta| < 2.4$$

- MC signal:
  - POWHEG+PYTHIA
- Backgrounds:
  - EW & ttbar from MC
  - QCD multijet: data-driven

Eur. Phys. J. C 76(5), 1-61 (2016)

CMS

- Data collected during 2012
  - √s = 8 TeV,18.4 pb^{-1} (W,Z p_T)
  - √s = 8 TeV,19.7 fb^{-1} (φ*)
- Fiducial volume of ee (μμ) channels

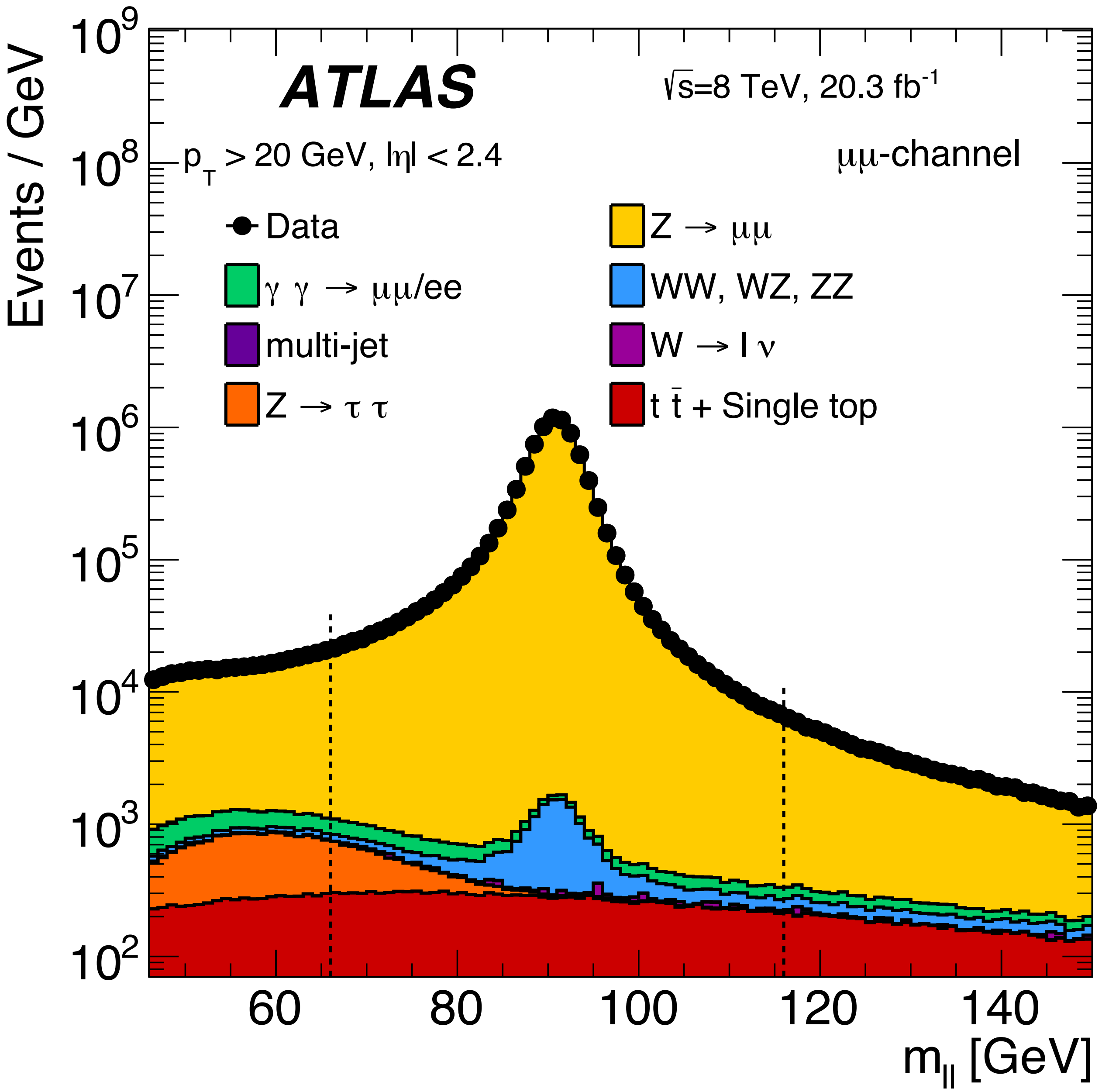
$$p_T > 25(20)\ \mathrm{GeV}$$
$$|\eta| < 2.5(2.1)$$

- MC signal:
  - POWHEG+PYTHIA
- Backgrounds:
  - EW & ttbar from MC
  - QCD multijet: data-driven

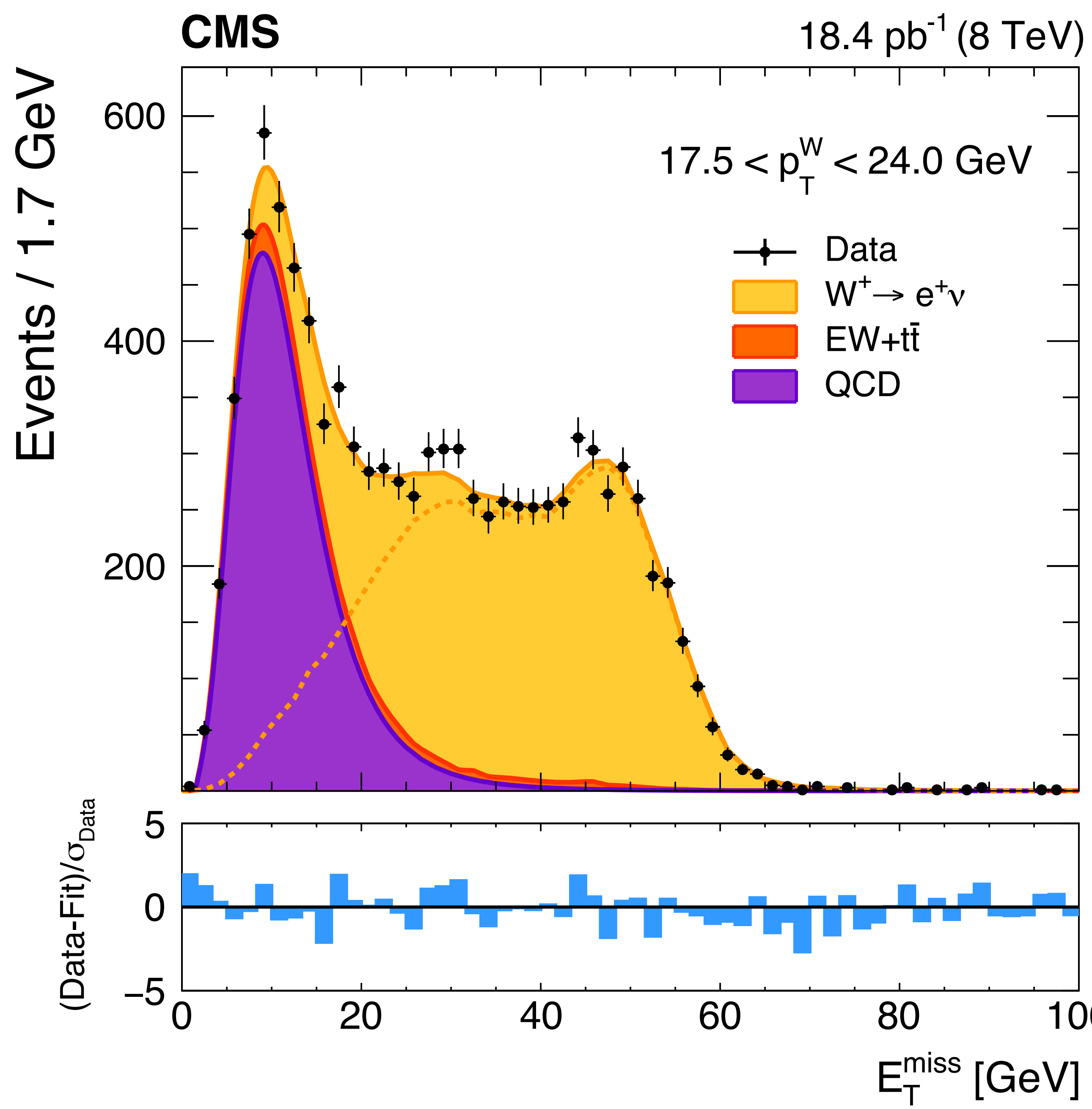
arXiv:1606.05864,
CMS-PAS-SMP-15-002

Measurement of p_T^{ll} and ϕ^*_η

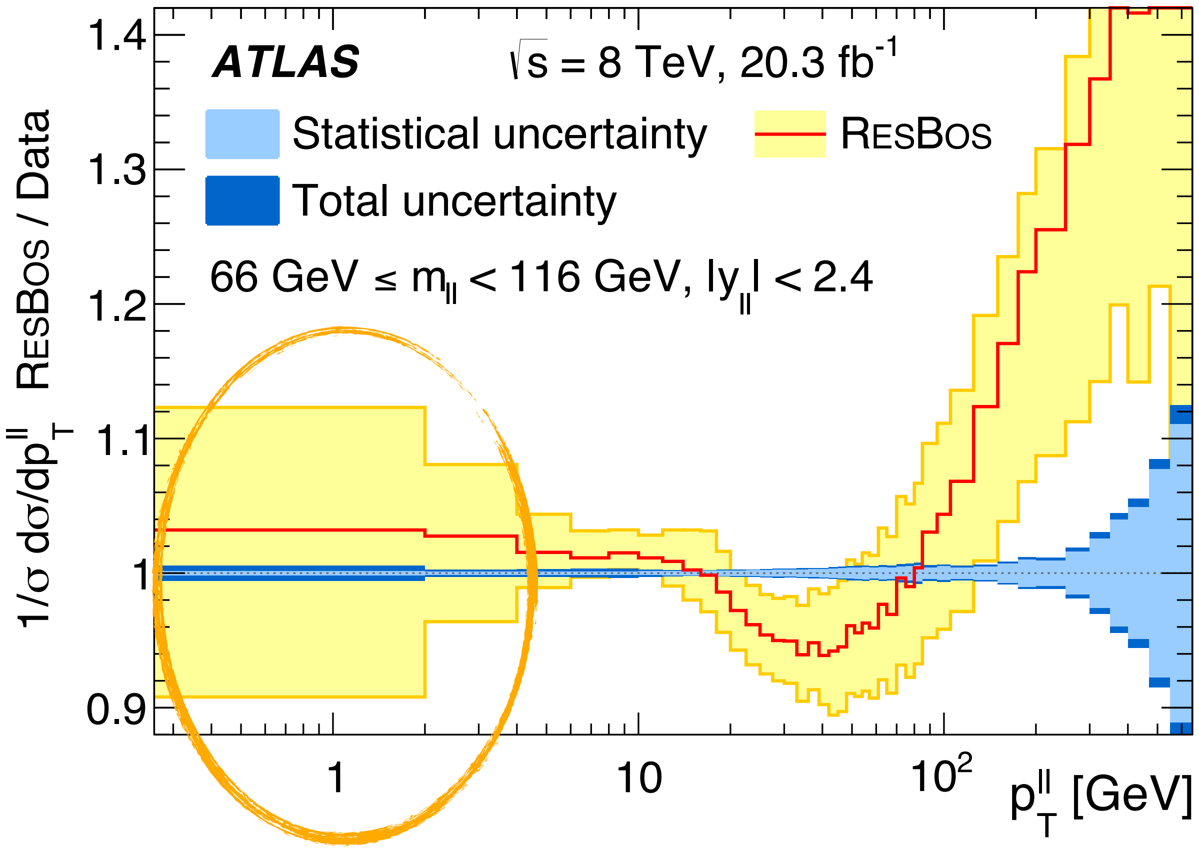
ATLA Z - Selection, muon channel

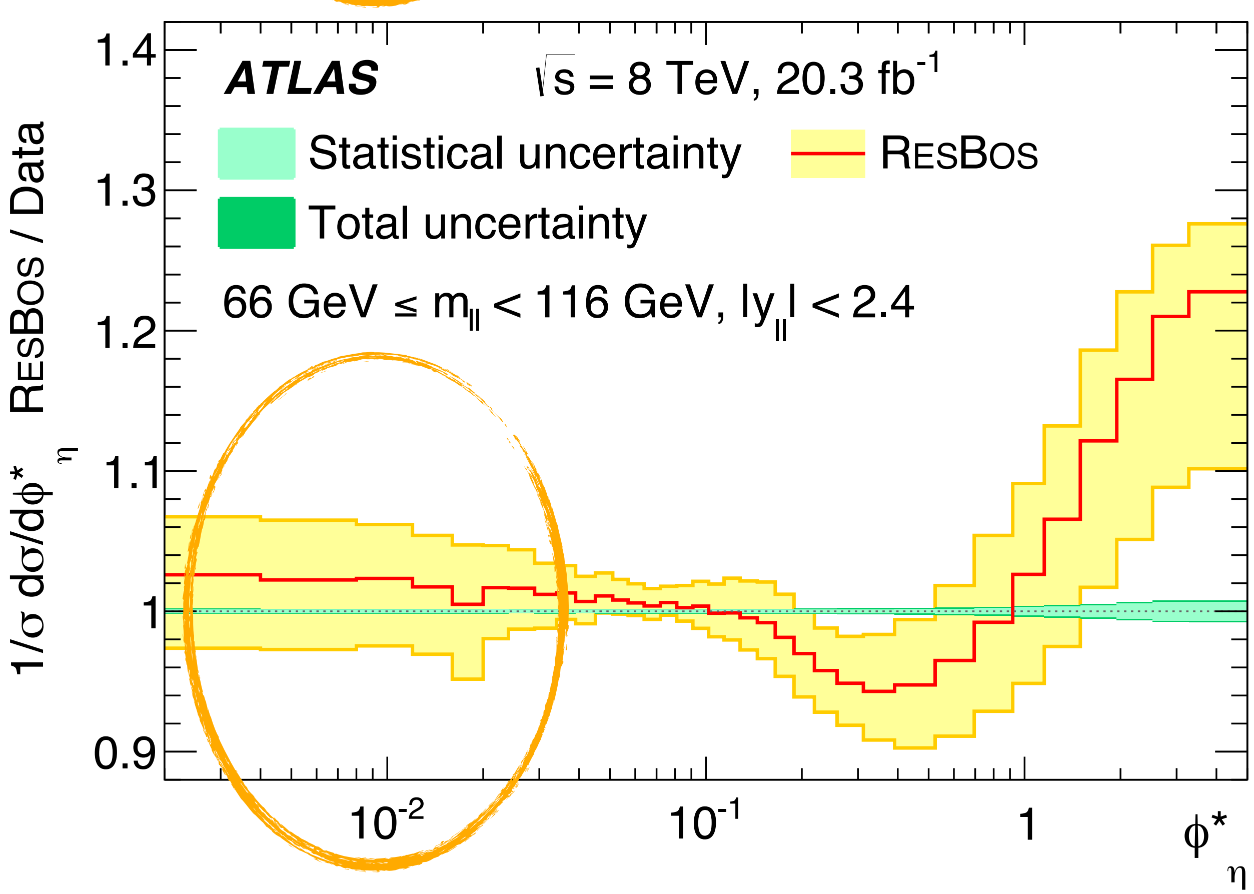


CMS W - Selection, muon channel



Measurement of p_{T}^{ll} and ϕ_{η}^{*}





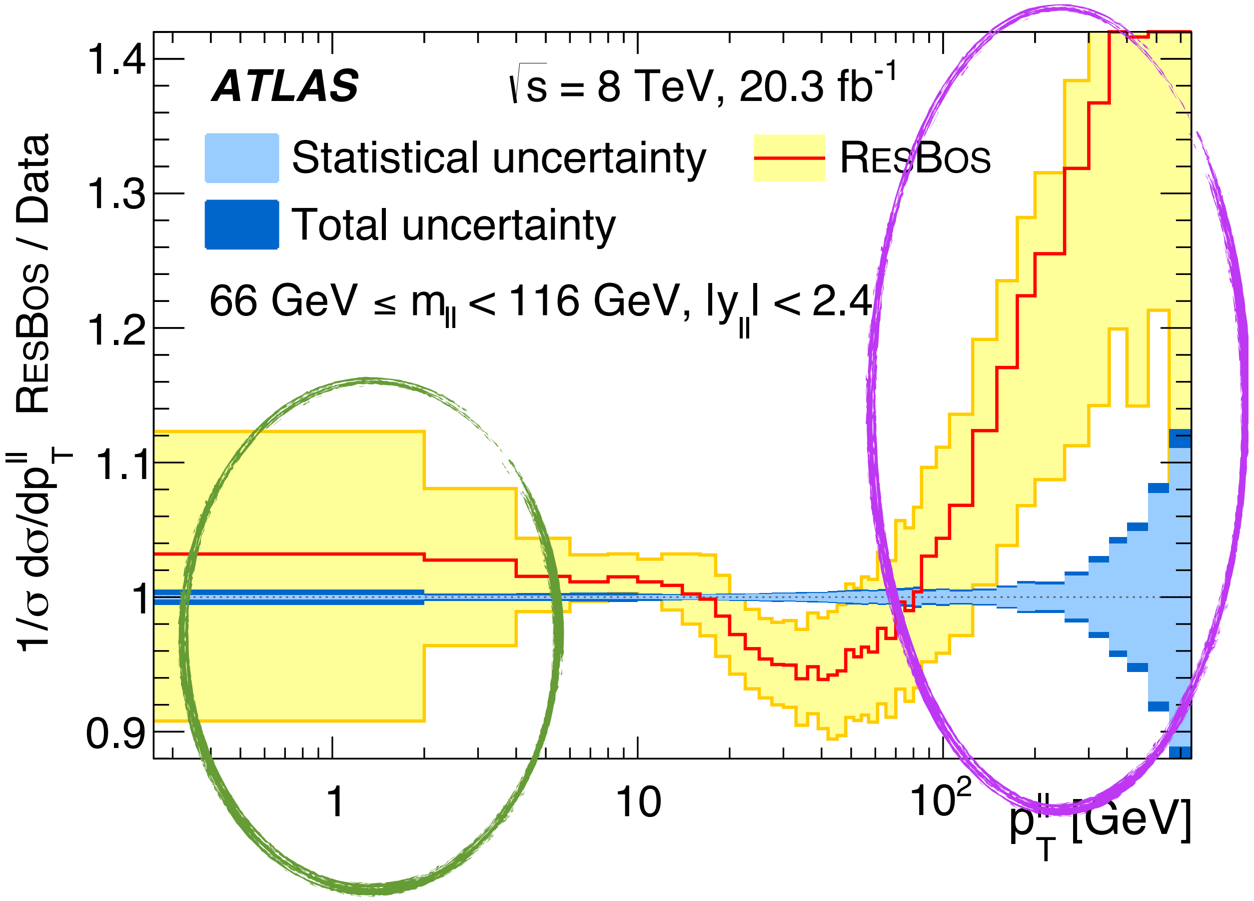
azimuthal angle between the two leptons

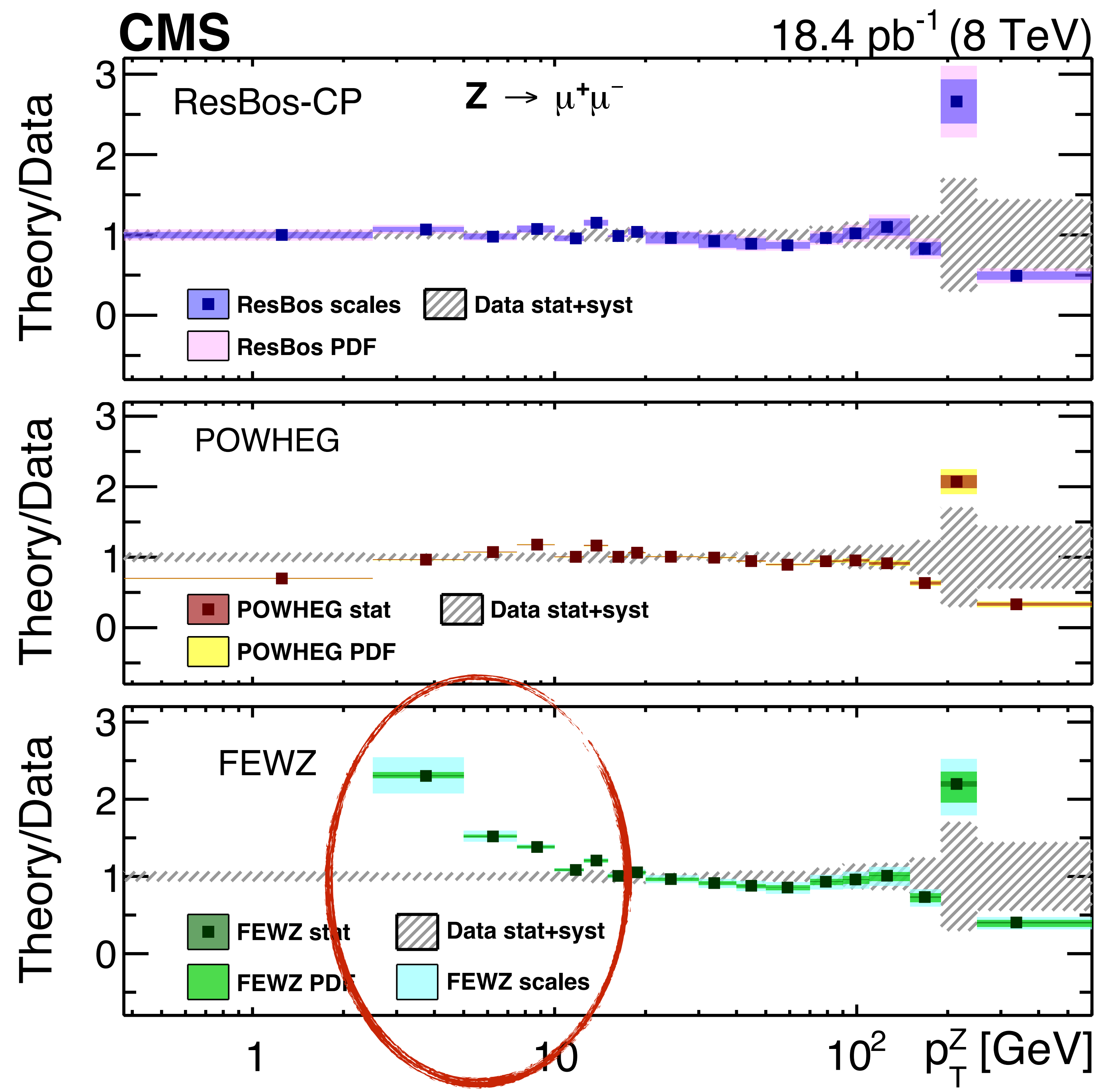
$$\phi_{\eta}^{*} = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\cdot\sin(\theta_{\eta}^{*})$$

$$\theta_{\eta}^{*} = \arccos\left(\tanh\left(\frac{\eta^{-} - \eta^{+}}{2}\right)\right)$$

- Depends only on measured angles
  - Better resolution compared to momentum measurements
- $\sqrt{2}m_Z\phi_{\eta}^{*} \approx p_{\mathrm{T}}^{ll}$
- x-axes in Plots are aligned

Measurement of p_{T}^{ll} and ϕ^*_η

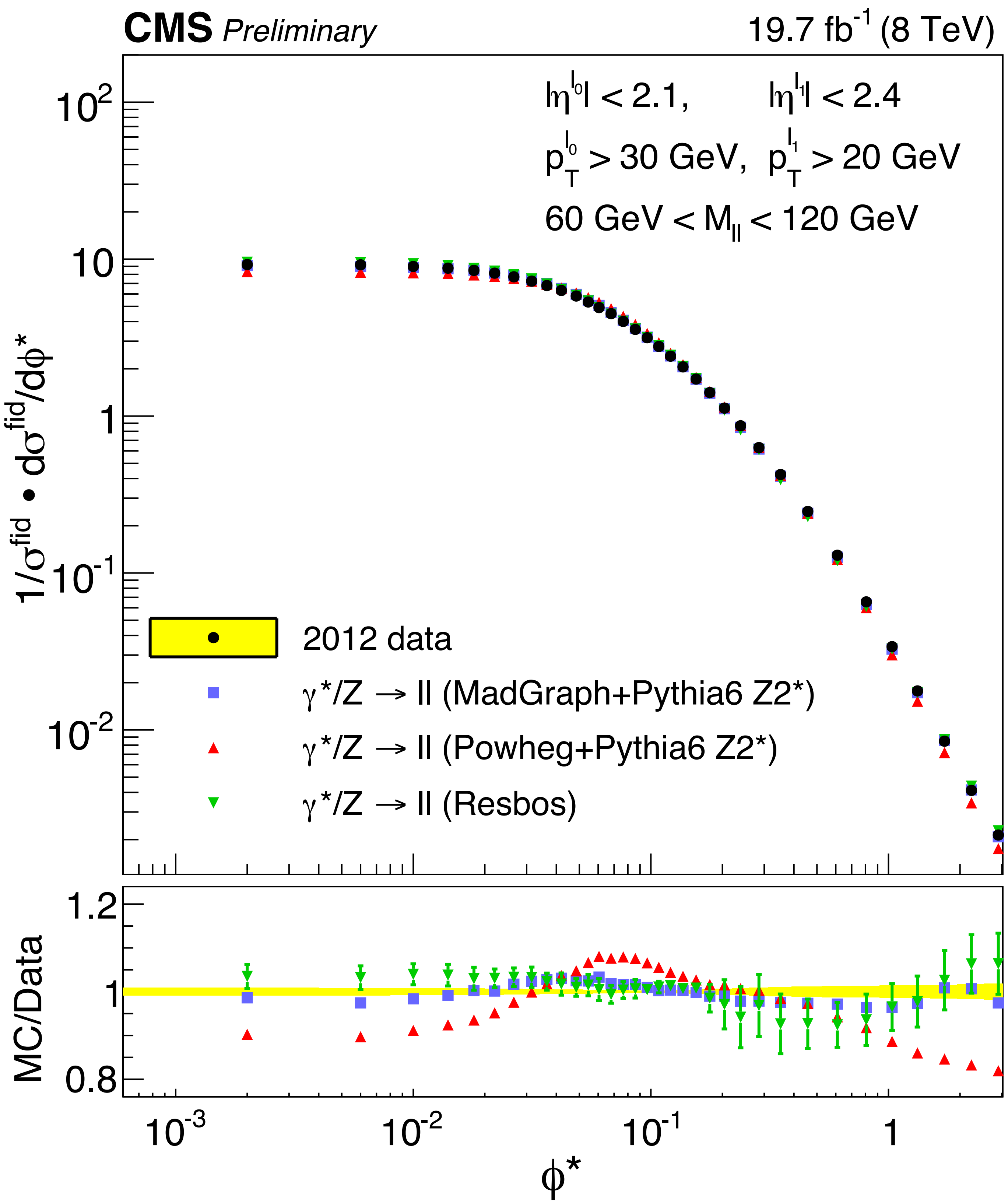




- Low range dominated by:
  - Non perturbative effects
  - Soft gluon resummation
    - ResBos predictions agree with data
- High range dominated by:
  - Emission of hard partons
    - ResBos predictions not consistent with data

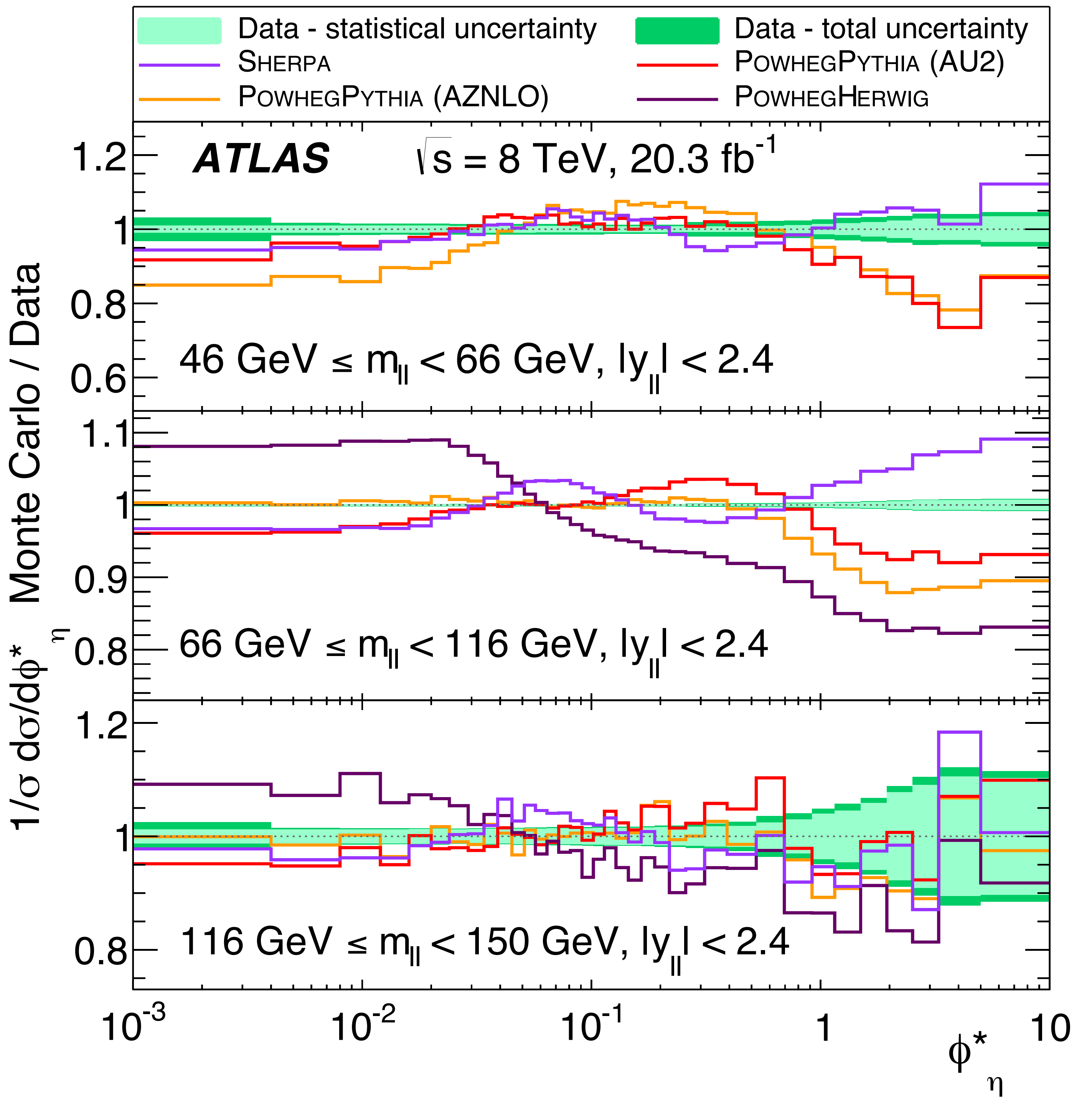
Comparison to different ME generators

CMS-PAS-SMP-15-002



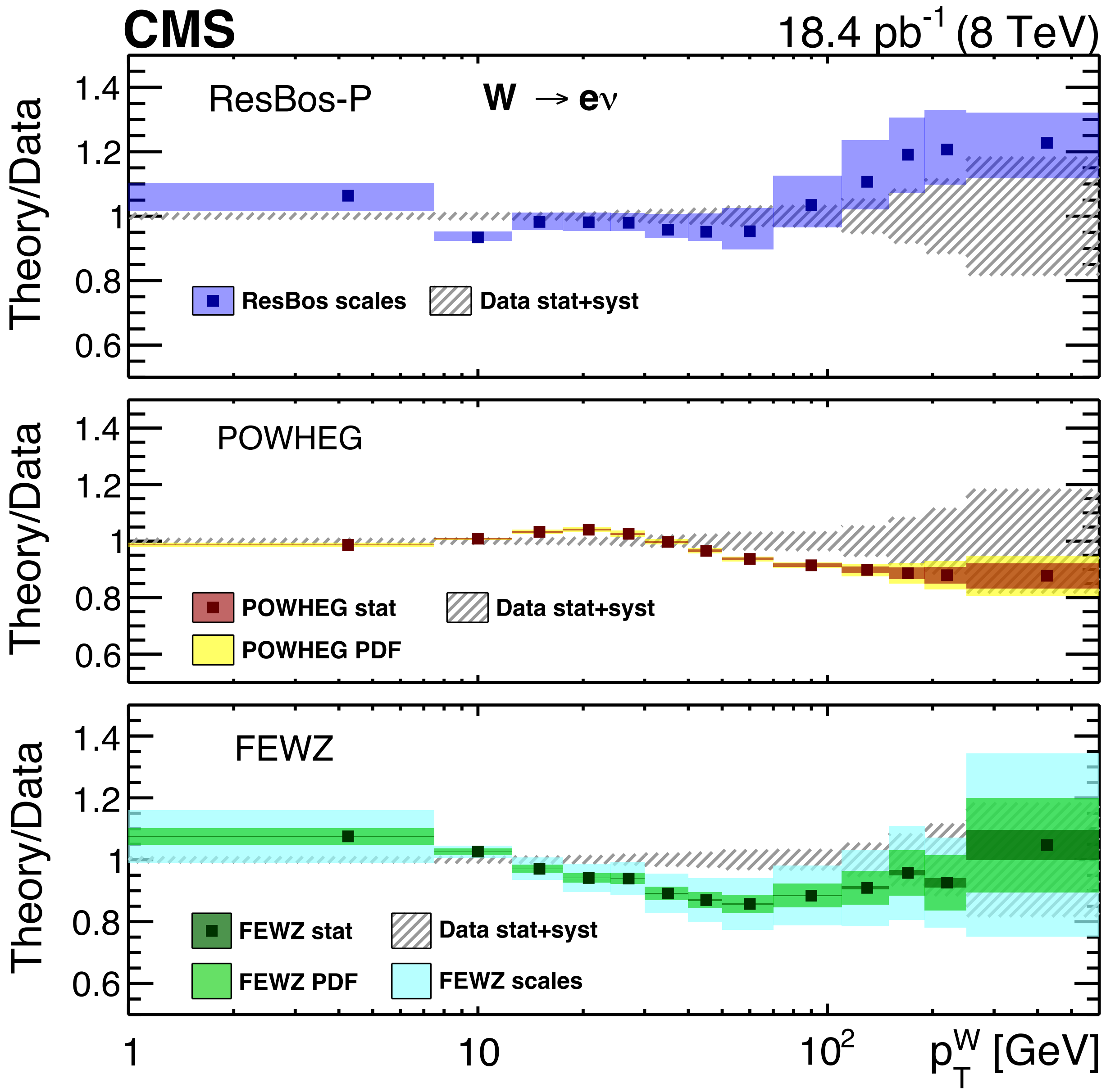
- Powheg:
  - Disagreement with measurement
  - most pronounced in low / high phi* region
- Resbos:
  - Uses resummation technique
  - Optimized for describing low momentum tail
- Madgraph:
  - Describes high momentum tail very well

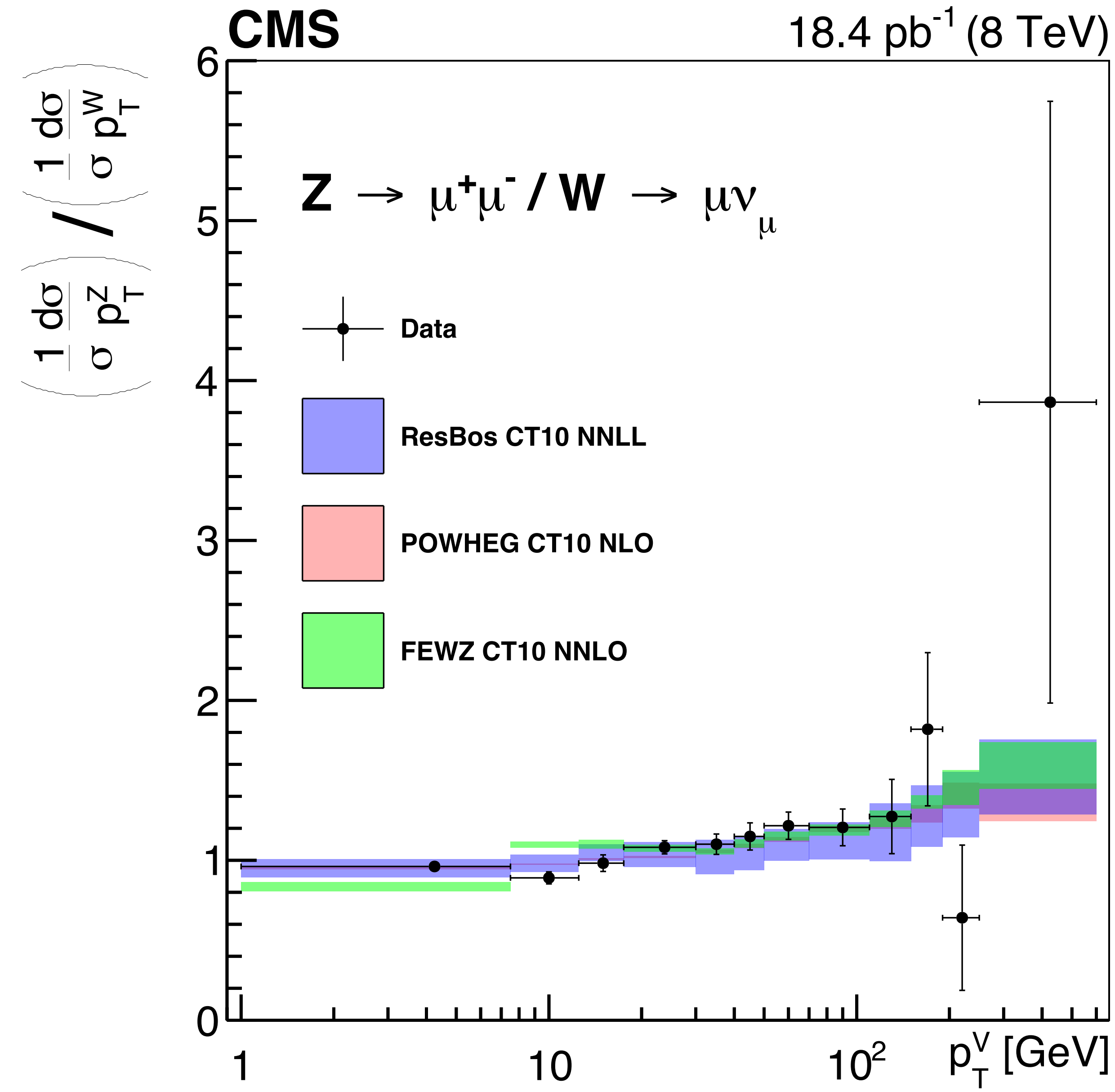
Comparison to parton-shower Simulations



- Comparison in 3 regions of m_{ll}
- 2 individual Pythia tunes:
  - AZNLO done on 7 TeV data at Z-peak
  - AU2
- Significant disagreement between simulation & data in peak region
- Also significant disagreement between PowHeg and Sherpa
  - Particularly for large φ^* values

W Boson pT measurement





- Resbos and Powheg show deviation from measurement at high p_T
- FEWZ shows some disagreement in mid p_T range

Ratio of Z / W p_T well modeled by all generators!

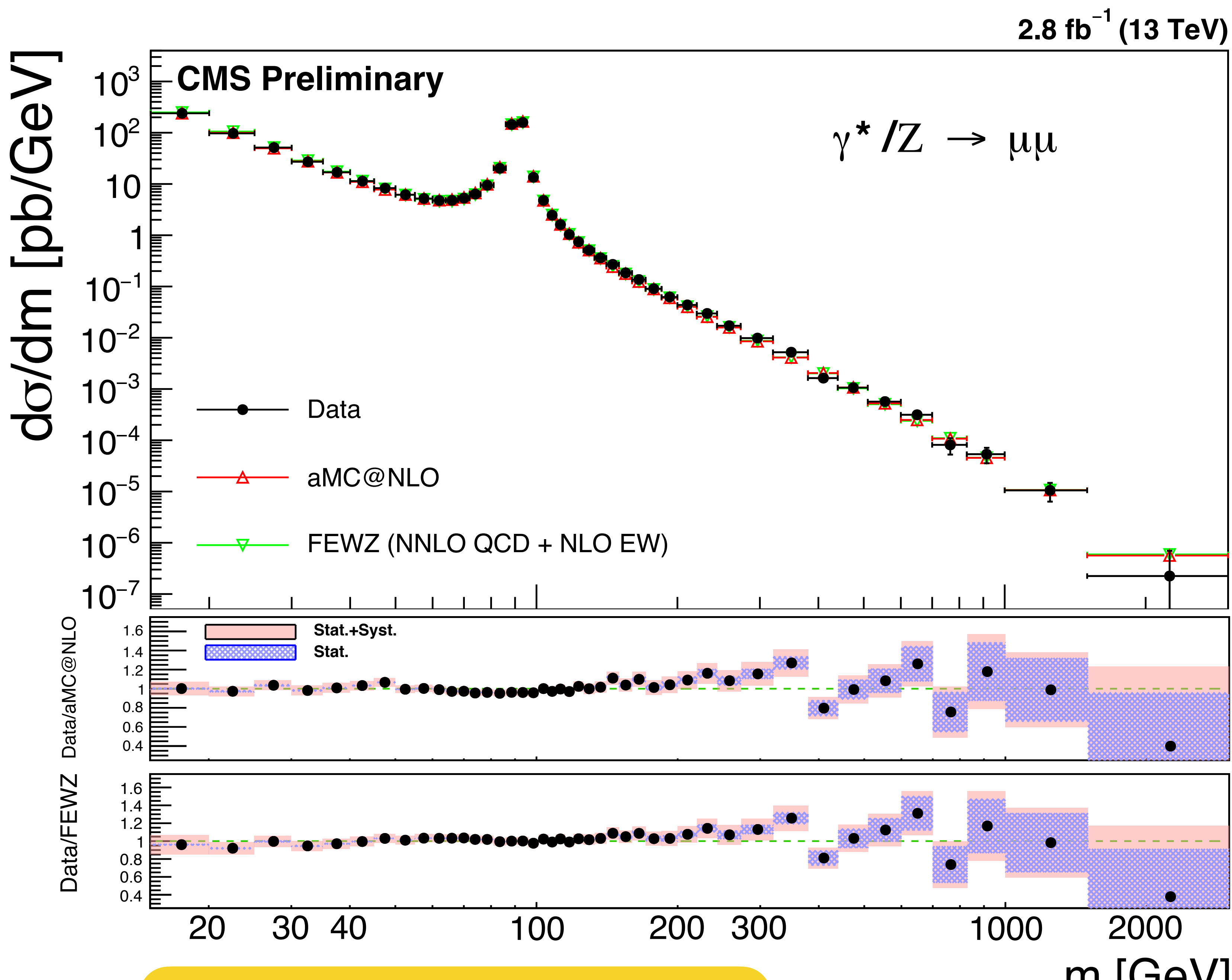
Drell - Yan cross section measurements

Drell-Yan measurements $pp \to l^+l^- + X$

13 TeV

- Comparison to predictions from:
  - **aMC@NLO:** provides automated PS matching to ME, NLO accuracy
  - **FEWZ:** full spin correlation, NNLO QCD accuracy, NLO EWK

- Statistically limited at large invariant masses
- Uncertainties > 20% @ 500 GeV
- More precise measurement with 8 TeV dataset



CMS-PAS-SMP-16-009

Drell-Yan measurements @ 8 TeV

- Uncertainties at few % level, compared to 20% at 13 TeV analysis

Agreement with SM over 3 orders of magnitude in mass!

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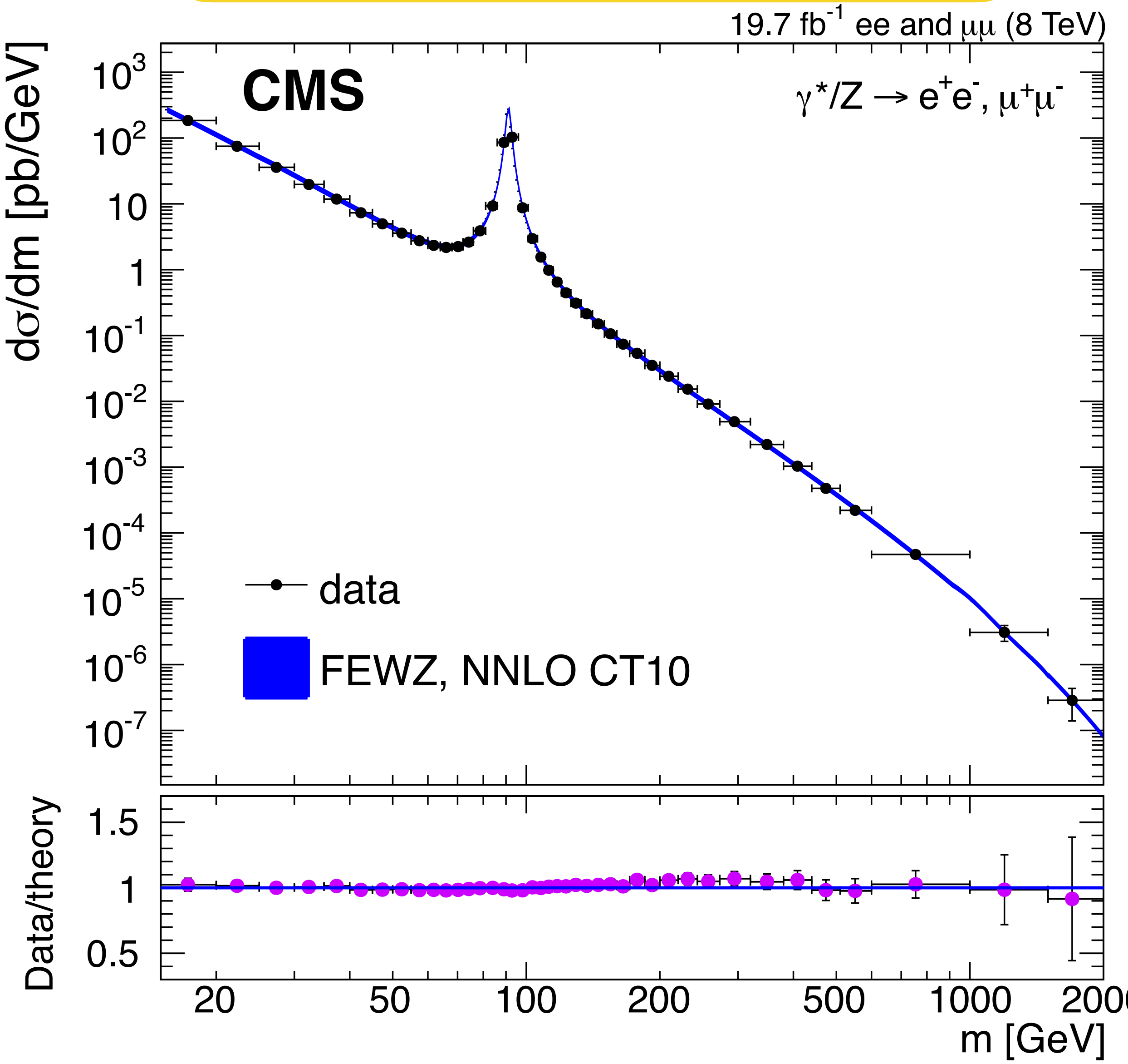
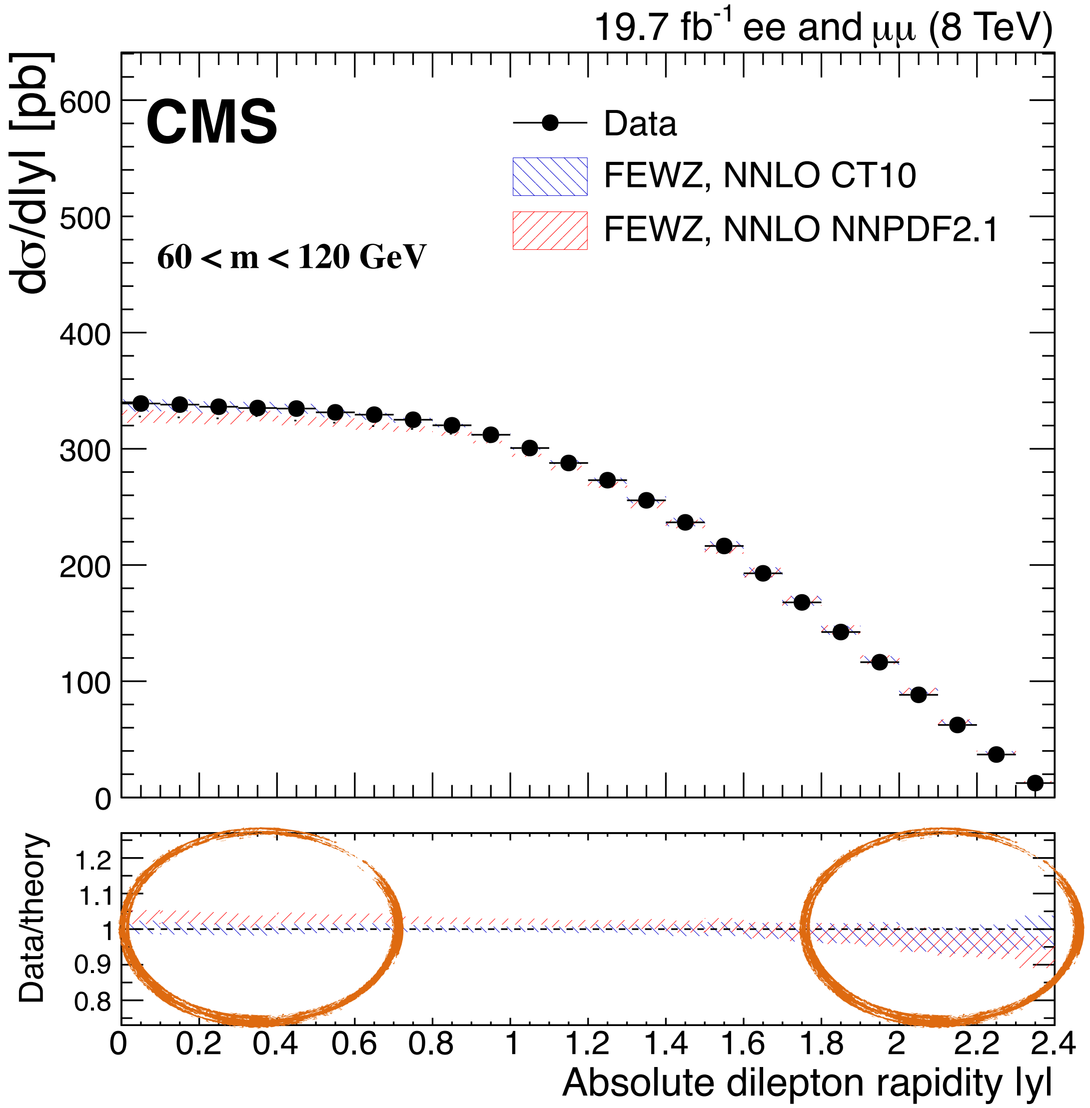


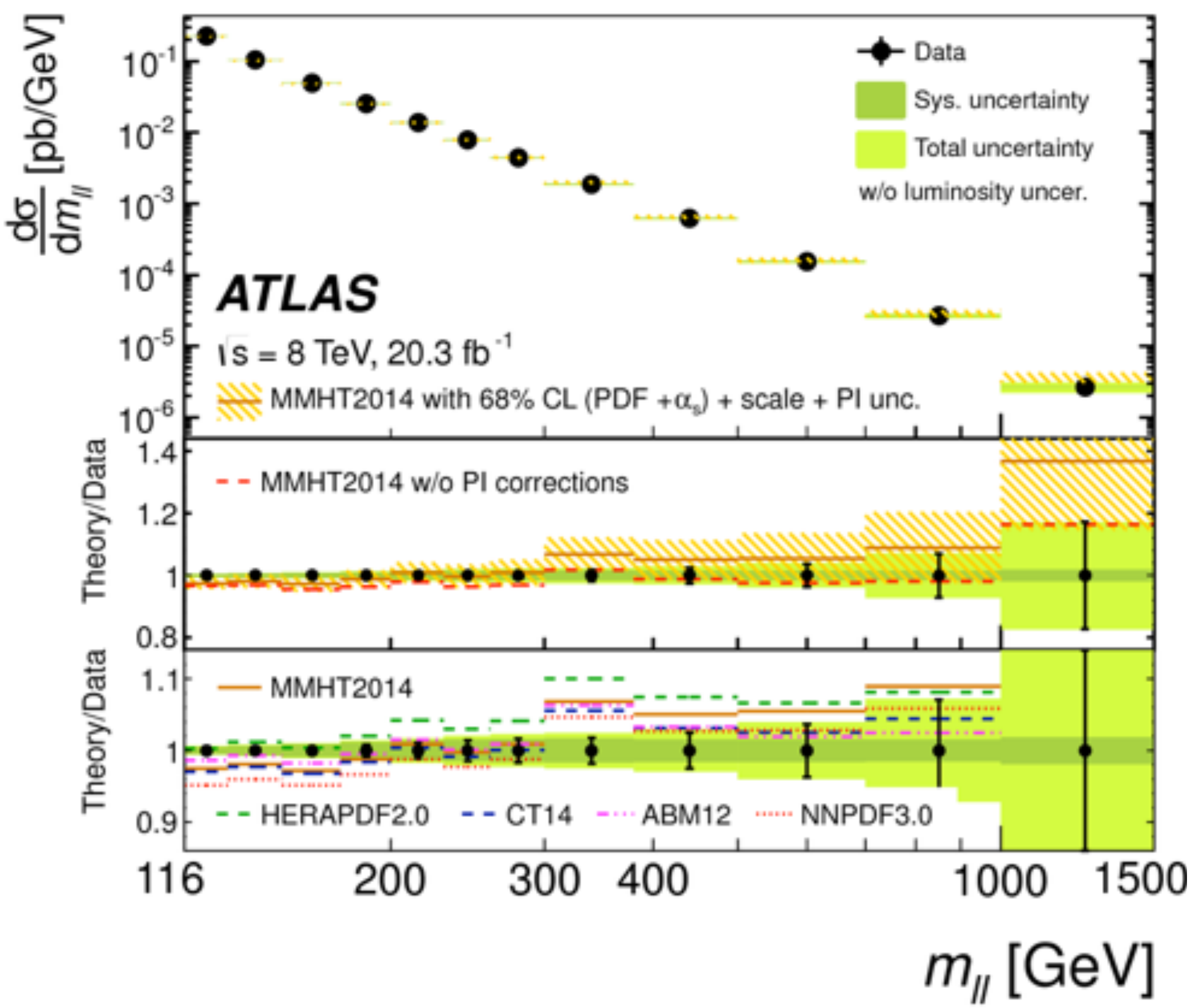


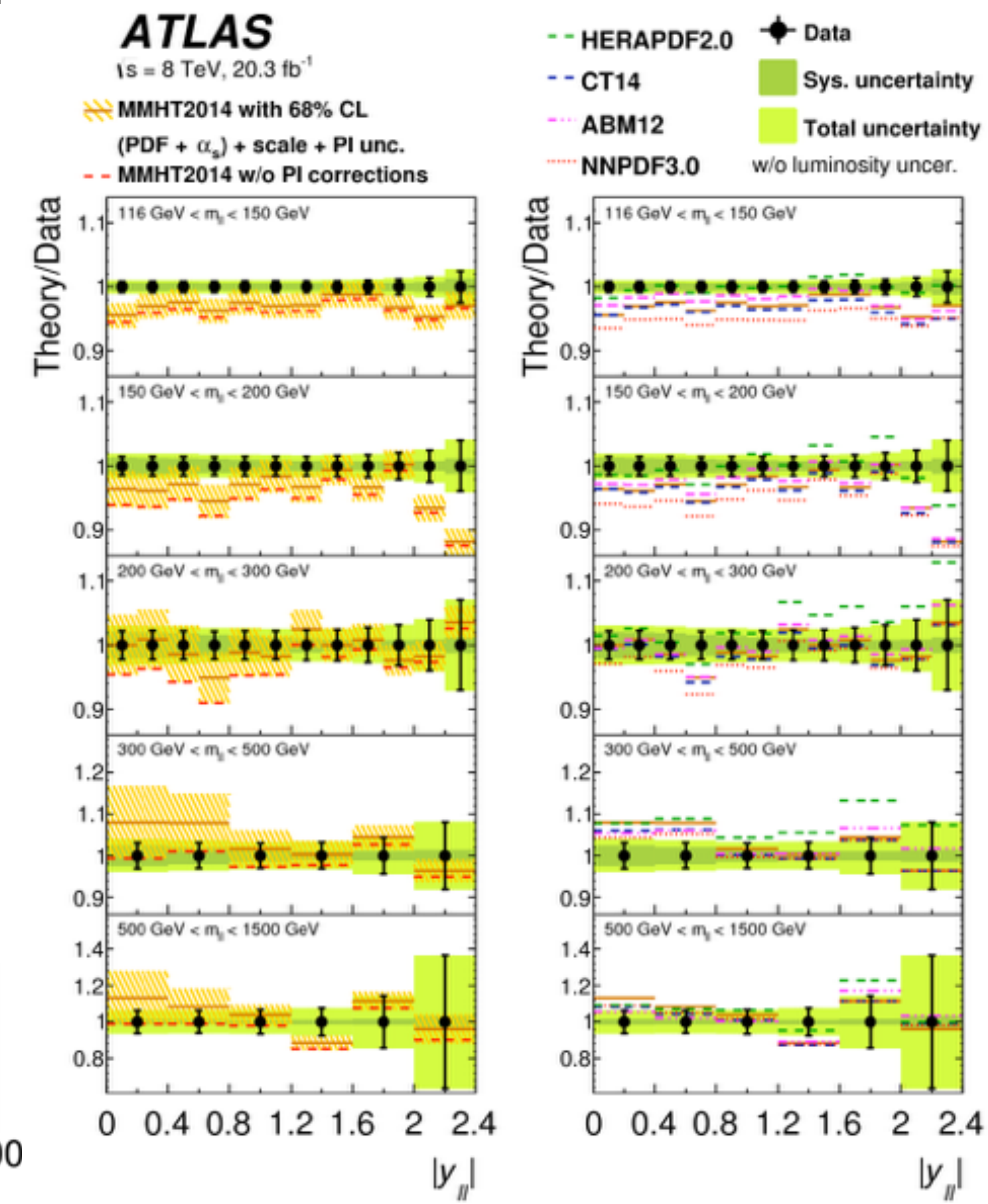
- Impact of PDFs becomes visible

High mass DY measurement @ 8 TeV

[JHEP 08 (2016) 009]

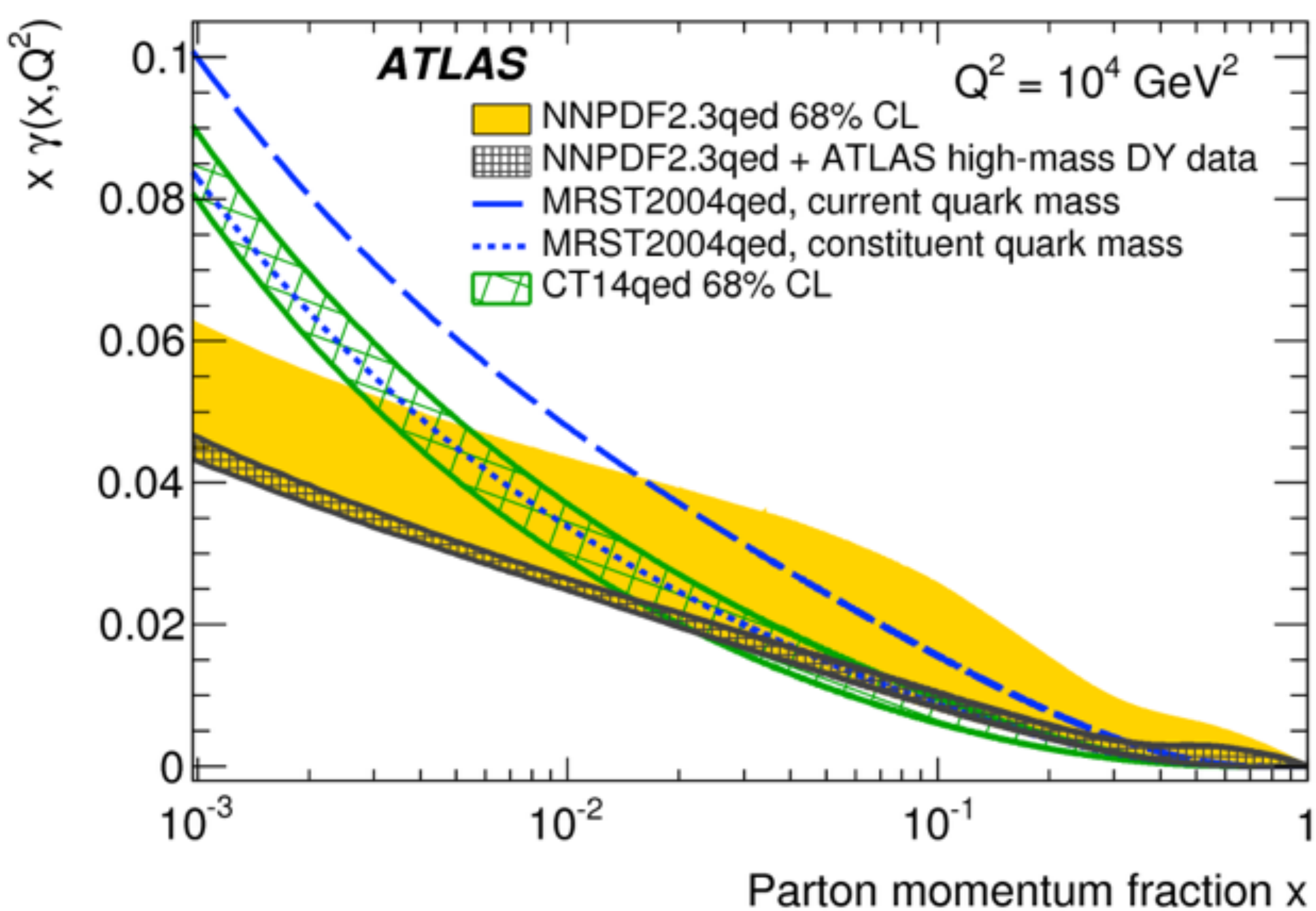
- Only masses above Z-peak considered
  - Comparison to various PDFs
  - Rapidity distribution very sensitive
    - Significant deviations observed





Impact on PDF fits

- High mass Drell-Yan data included in NNPDF2.3
  - **Significant constraint of photon PDF**



Angular Coefficients A_i

A bit of Theory

Differential cross section for

$$pp \to Z/\gamma^* + X \to l^+ l^- + X$$

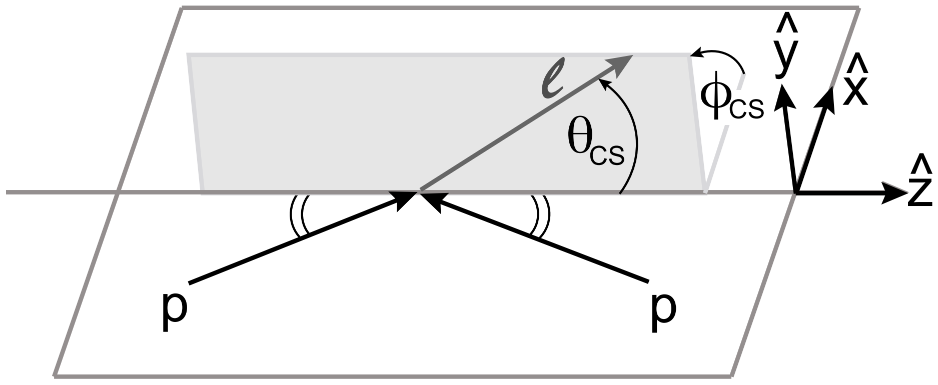
$$\frac{d\sigma}{dp_T^Z \, dy^Z \, dm^Z \, d\cos\theta \, d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^Z \, dy^Z \, dm^Z}$$

$$\Big\{(1+\cos^2\theta) + \frac{1}{2} A_0 (1 - 3\cos^2\theta) + A_1 \sin 2\theta \cos\phi$$
$$+ \frac{1}{2} A_2 \sin^2\theta \cos 2\phi + A_3 \sin\theta \cos\phi + A_4 \cos\theta$$
$$+ A_5 \sin^2\theta \sin 2\phi + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \Big\}$$

Angular distributions parametrized by coefficients $\mathbf{A_i}$

- Test QCD predictions to all orders of α_s
- Includes Spin-correlations of all particles

Angles in **Collins-Soper** Frame:



- Rest frame of di-lepton system
- z-axis bisecting directions of incoming proton momenta
- Direction of z-axis defined by longitudinal boost of di-lepton system

- Sensitive to various SM parameters

A bit of Theory

Orthogonal polynomials used to parametrize angular distribution:

$$\langle P(\cos\theta,\phi)\rangle = \frac{\int P(\cos\theta,\phi)\,d\sigma(\cos\theta,\phi)\,d\cos\theta\,d\phi}{\int d\sigma(\cos\theta,\phi)\,d\cos\theta\,d\phi}$$

Ai are neither input to theory calculations, nor simulations!

$< 1 + \cos^2\theta >$ normalization of unpolarized cross section, also applied to all other P

$< \frac{1}{2}(1-3\cos^2\theta) >= \frac{3}{20}(A_0 - \frac{2}{3})$ longitudinal polarization

$< \sin 2\theta \cos\phi >= \frac{1}{5}A_1$ interference term: longitudinal / transverse

$< \sin^2\theta \cos 2\phi >= \frac{1}{10}A_2$ transverse polarization

$< \sin\theta \cos\phi >= \frac{1}{4}A_3$ product of v-a couplings, sensitive to Weinberg angle

$< \cos\theta >= \frac{1}{4}A_4$ 8/3 * forward backward asymmetry A_{FB}, sensitive to Weinberg angle non-zero already at LO $q\bar{q} \to Z/\gamma^* \to l^+l^-$

$< \sin^2\theta \sin 2\phi >= \frac{1}{5}A_5$

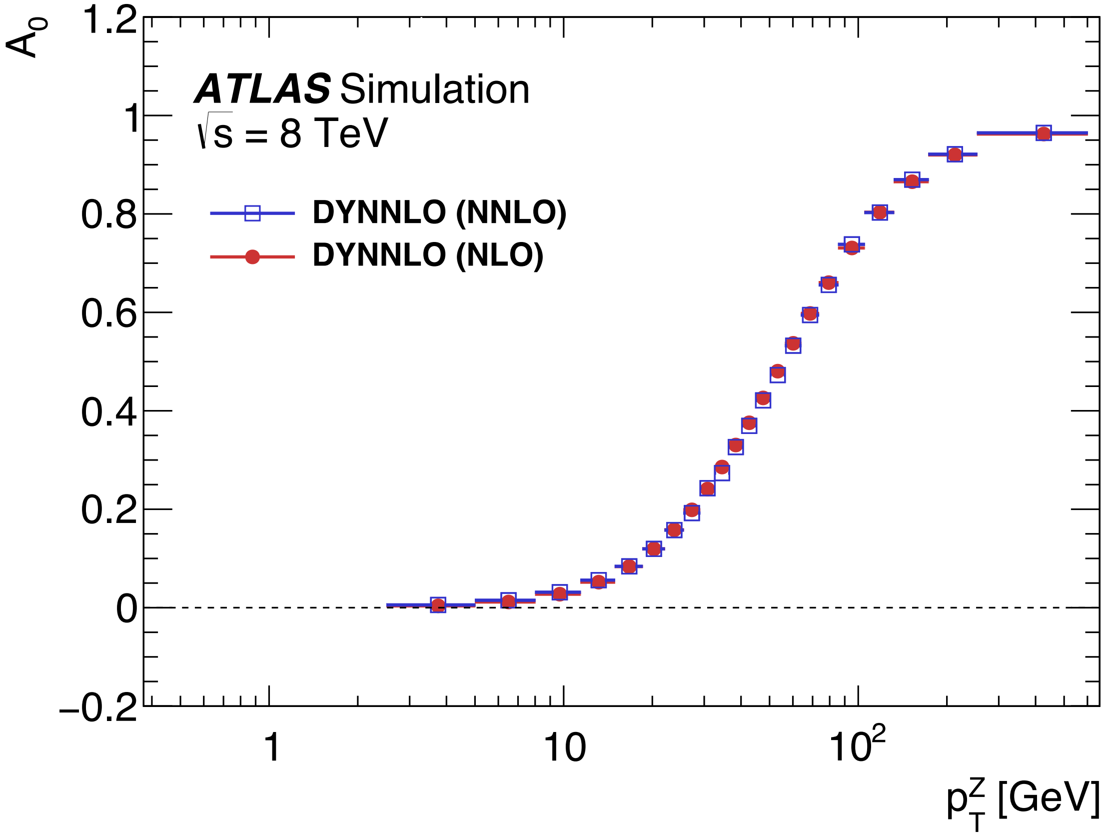
$< \sin 2\theta \sin\phi >= \frac{1}{5}A_6$

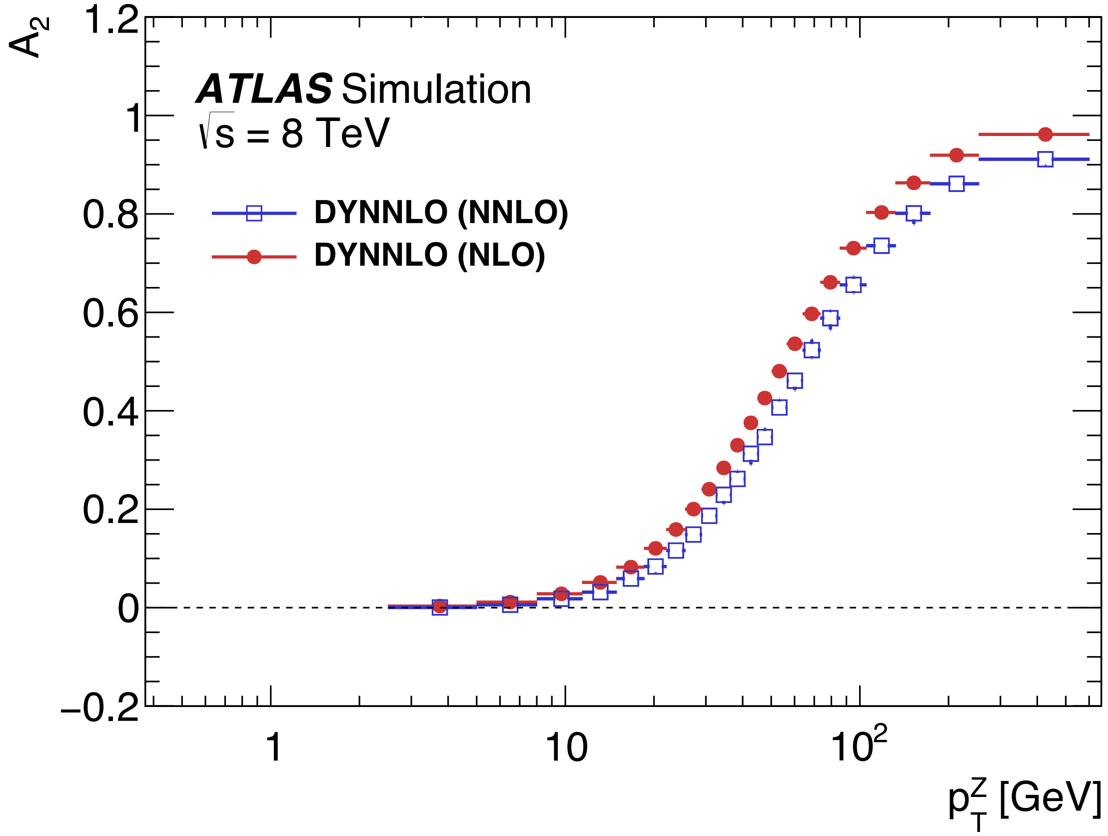
$< \sin\theta \sin\phi >= \frac{1}{4}A_7$

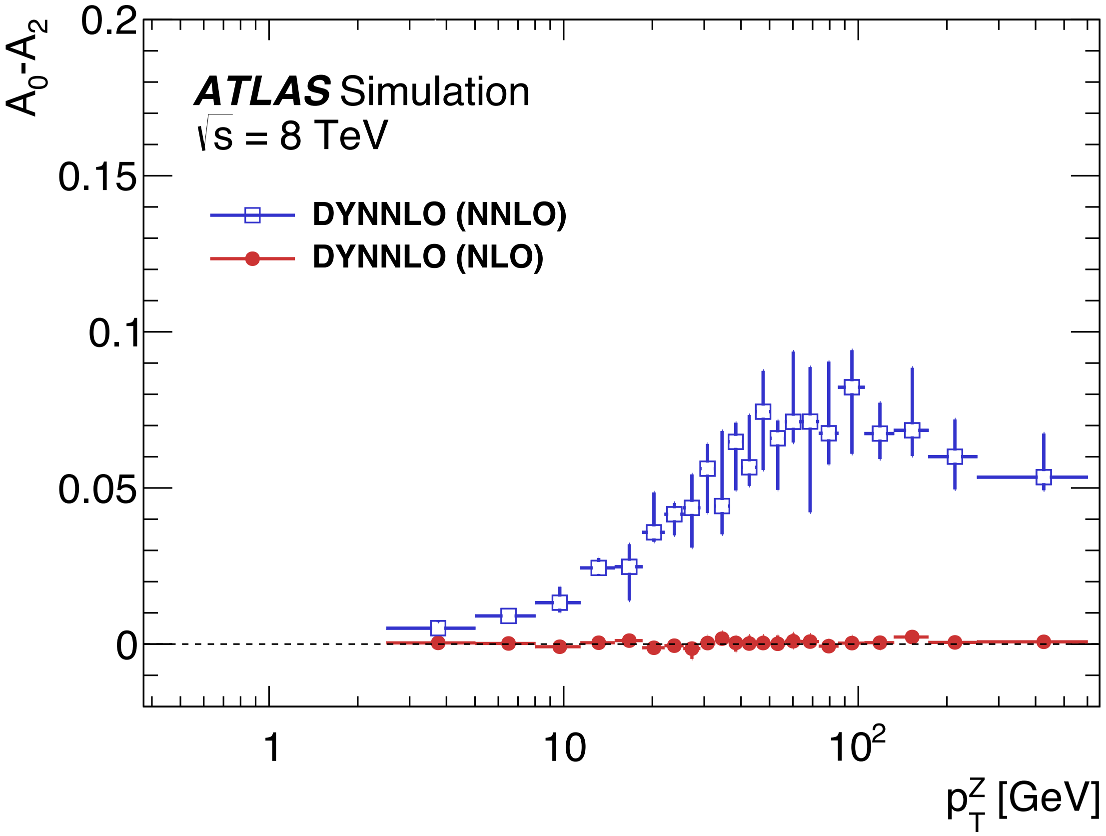
Predicted to be 0 @ NLO
Non zero contributions @ NNLO for large $p_T(Z)$

Measured by ATLAS - Set to 0 in CMS analysis

Impact of higher order QCD corrections







- A_0-A_2: Sensitive to the Spin of the Gluon (Lam-Tung relation)
  - exactly 0 @ NLO
  - A2 changed 10% @ NNLO

The Measurement - Lepton Selection

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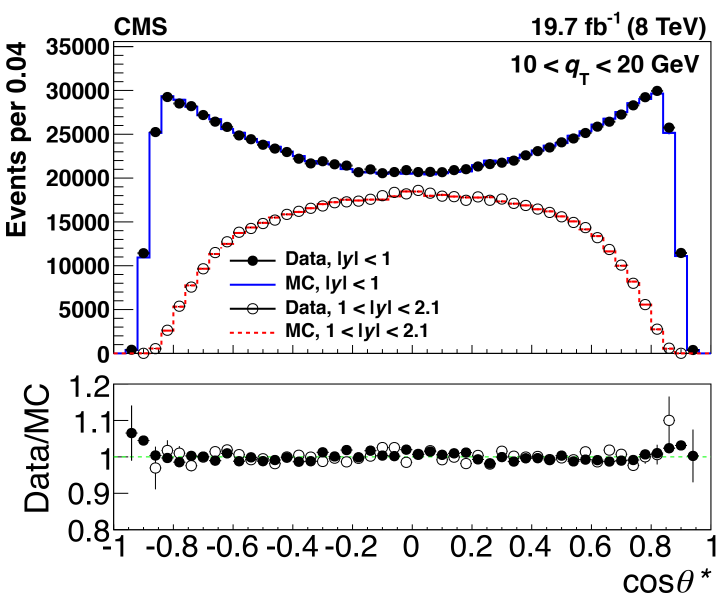
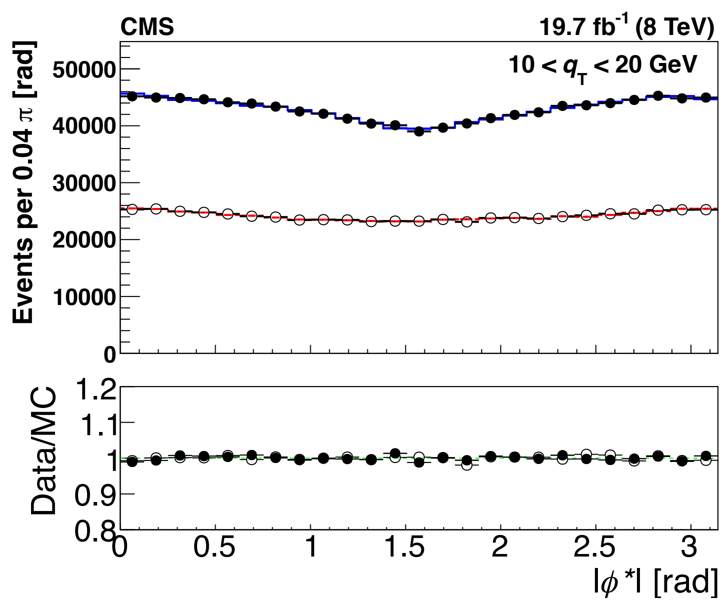
CMS

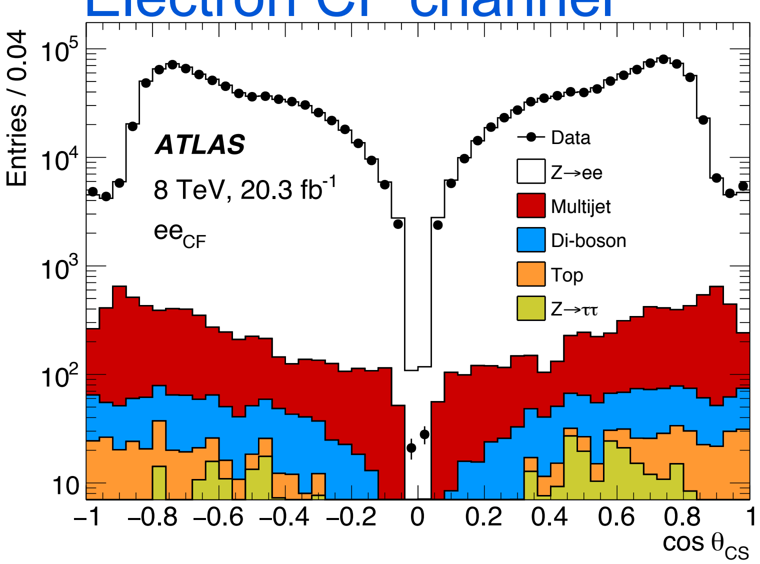
- √s = 8 TeV, 19.7 fb^{-1}
- Fiducial Volume: (muons only)

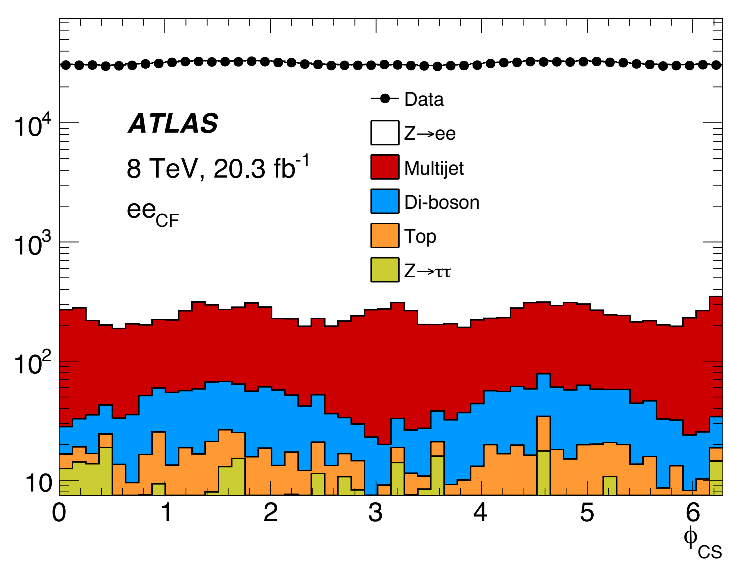
$$p_T > 25(10)\,\mathrm{GeV} \quad |\eta| > 2.1(2.4)$$





Electron CF channel





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ATLAS

- √s = 8 TeV, 20.3 fb^{-1}
- Measurement performed in 3 independent channels:
  - Muons
  - Electrons: central central
  - Electrons: central-forward
- Fiducial Volume:
  - CC & μμ: $p_T > 25\,\mathrm{GeV} \quad |\eta| < 2.4$
  - CF: $p_T > 20\,\mathrm{GeV} \quad 2.5 < |\eta| < 4.9$
  - OS di-leptons $80 < m_{ll} < 100\,\mathrm{GeV}$

Analysis strategy

- Angular distributions **sculpted by fiducial acceptance**

- Polynomials are „folded" into reconstruction space
  - Simulation used to model acceptance, efficiencies & resolution
  - 3D folding in cosθ,φ, p^{ll}_T

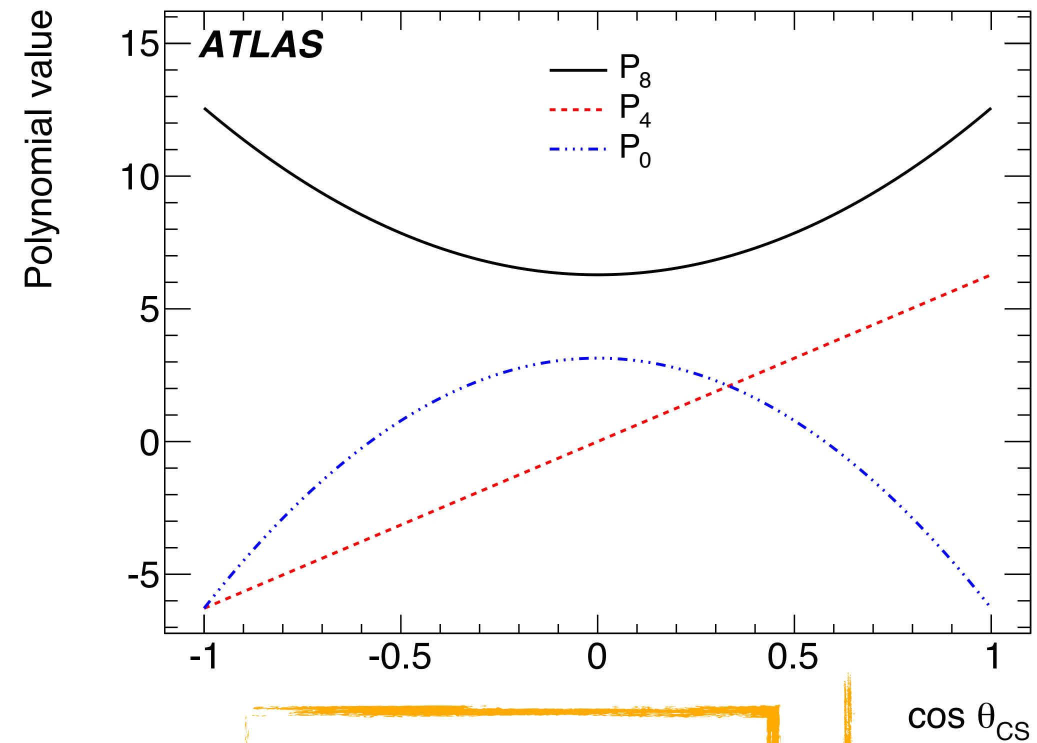
- Folded polynomials (templates) fitted to measured angular distributions

- Angular coefficients A_i normalize the templates relative to each other
  - A_i extracted from fit

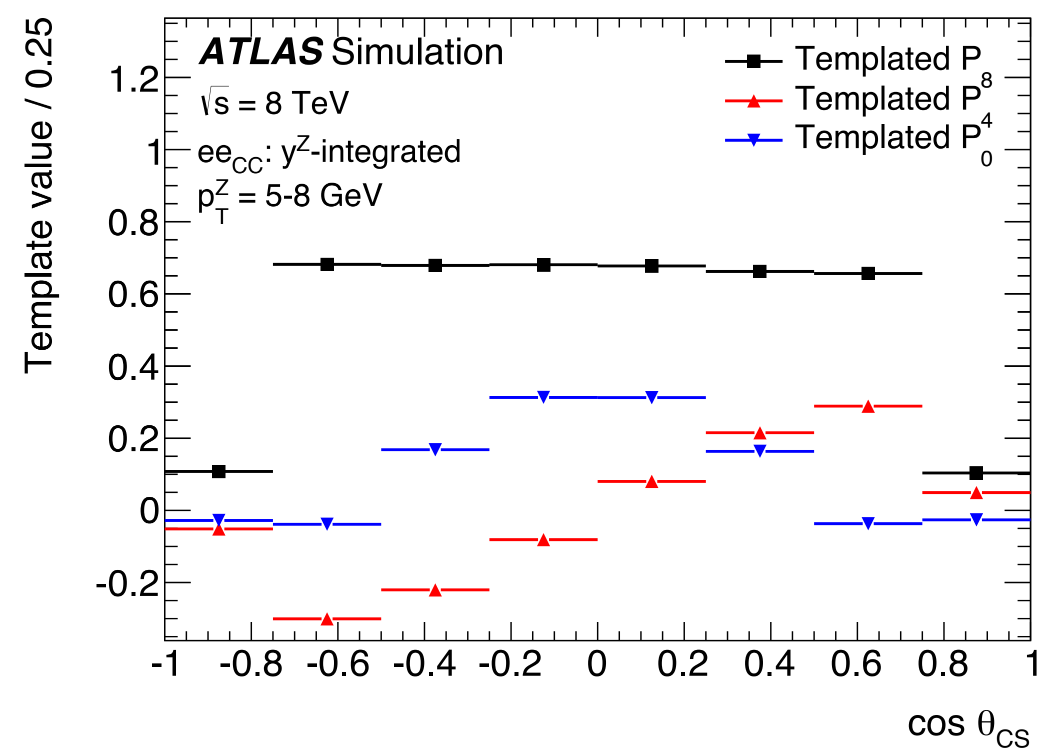
- Overall normalization done in $p_T(Z)$

- Fit implemented as maximum likelihood fit

  - Nuisance parameter for each systematic uncertainty incorporated
  - Background templates included

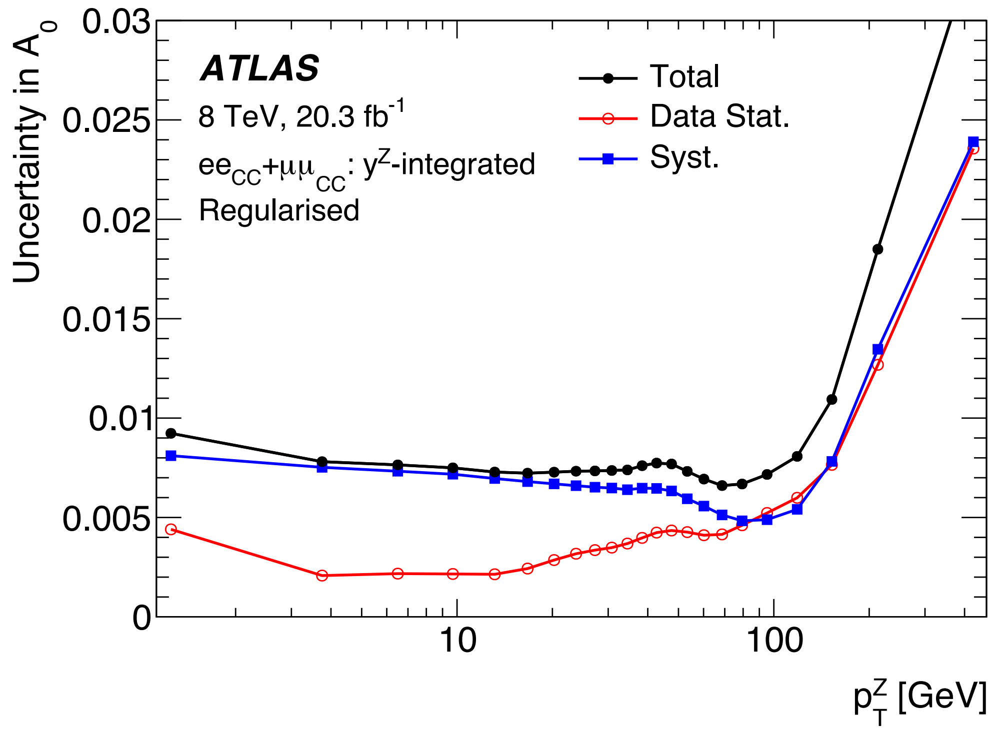


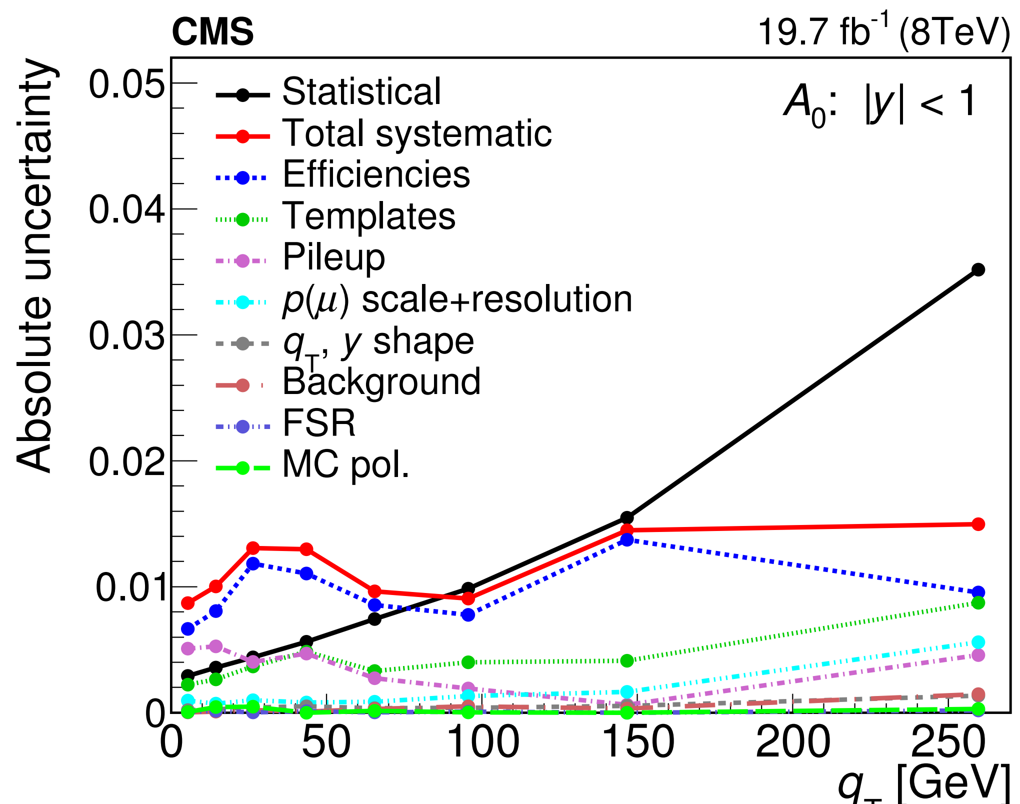
folding with detector effect



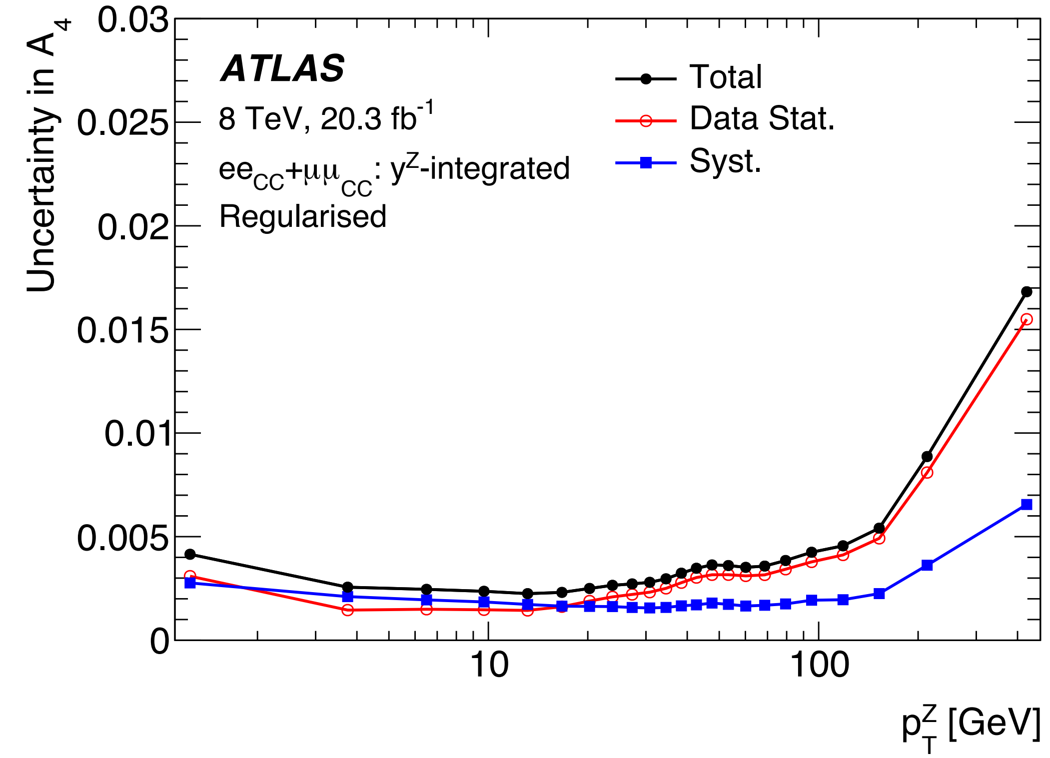
A glance at Uncertainties

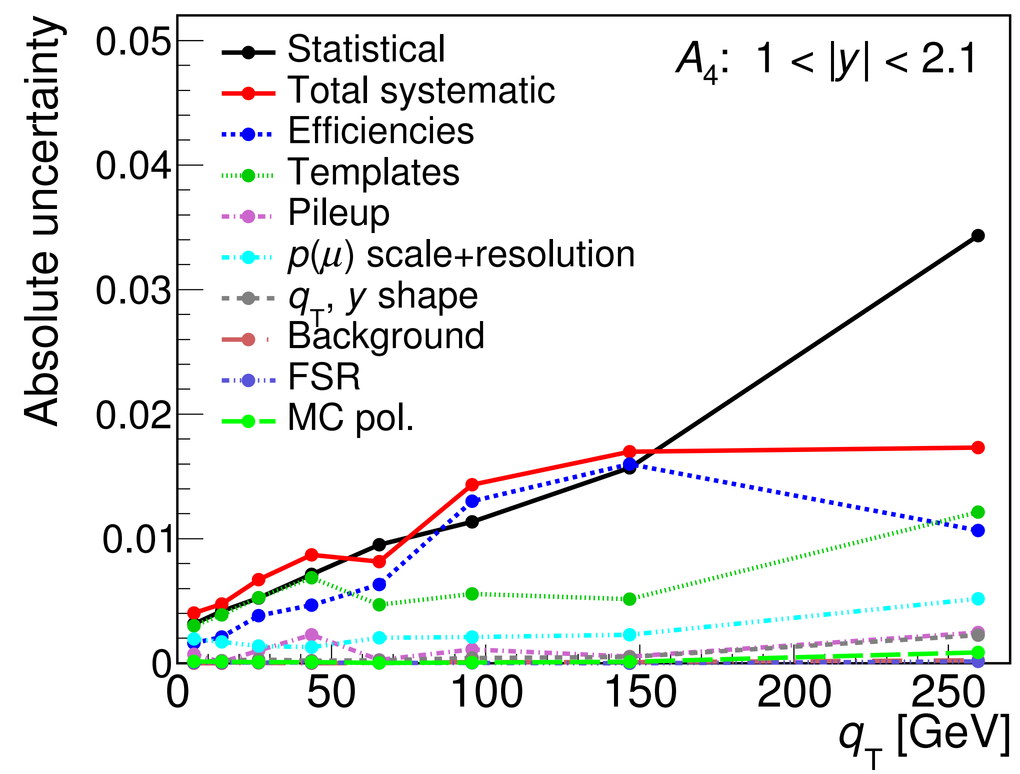
- Breakdown of systematic uncertainties



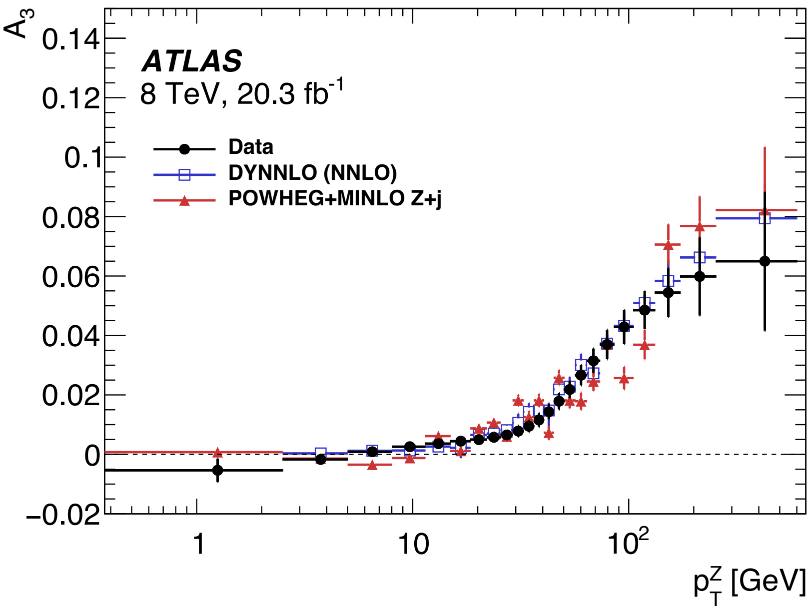


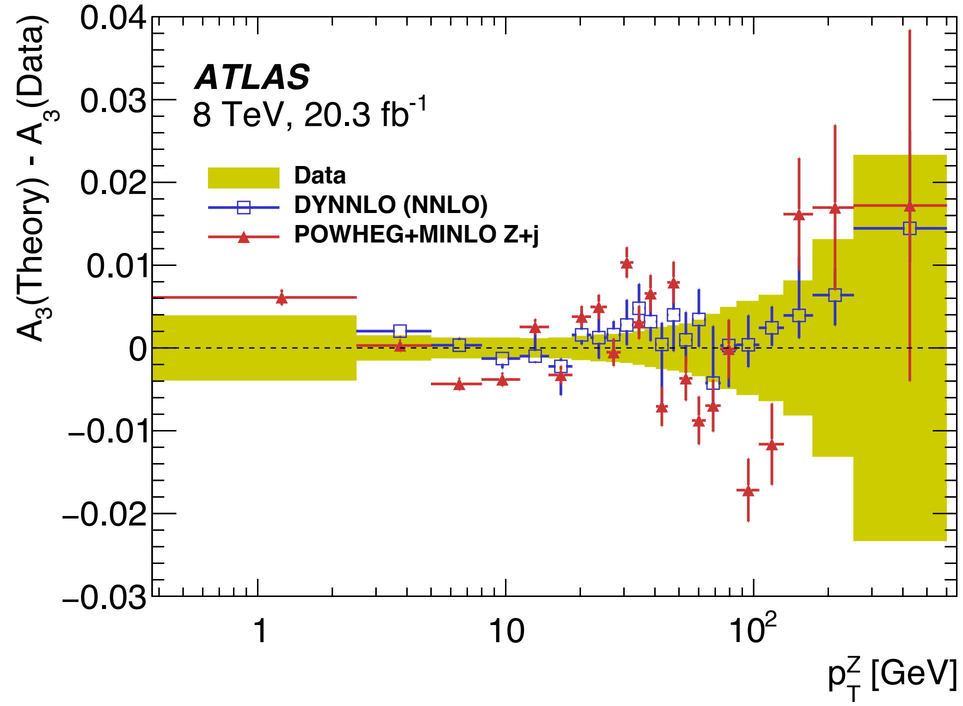
- Total uncertainties
  - Very similar shape for all A_i

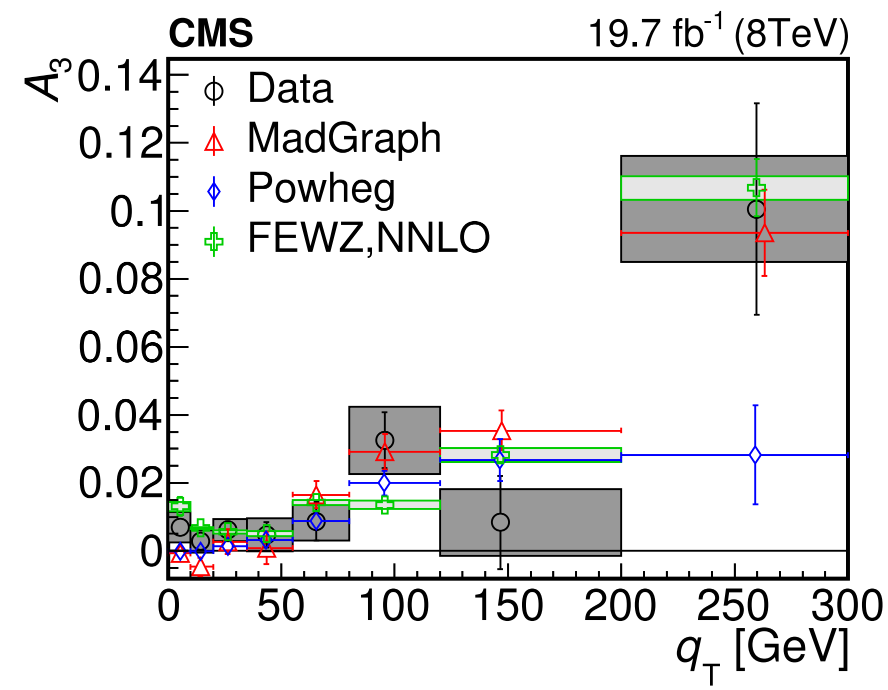


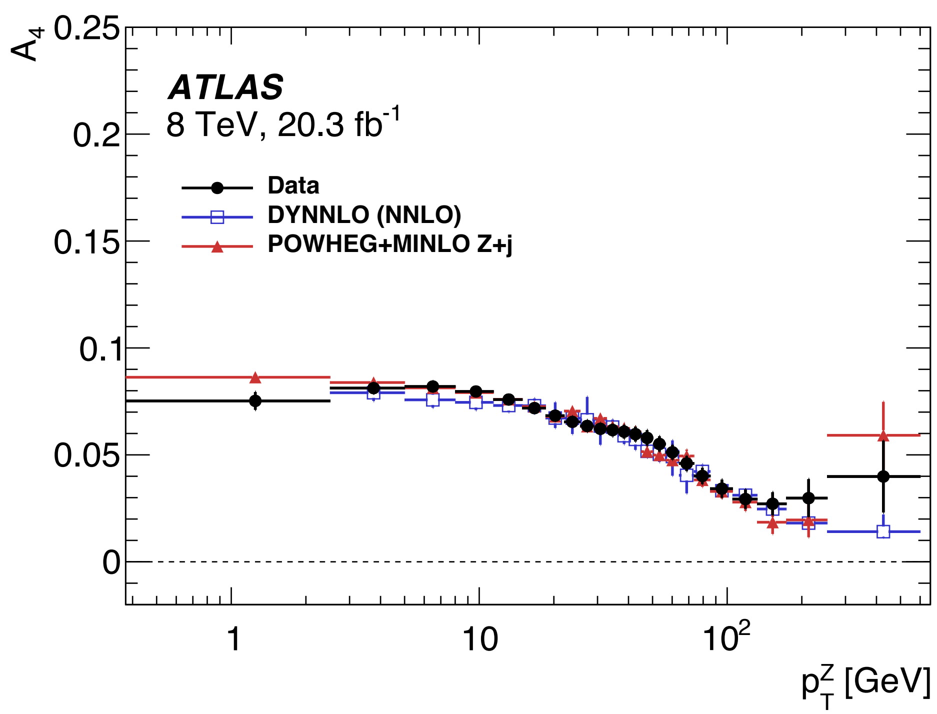


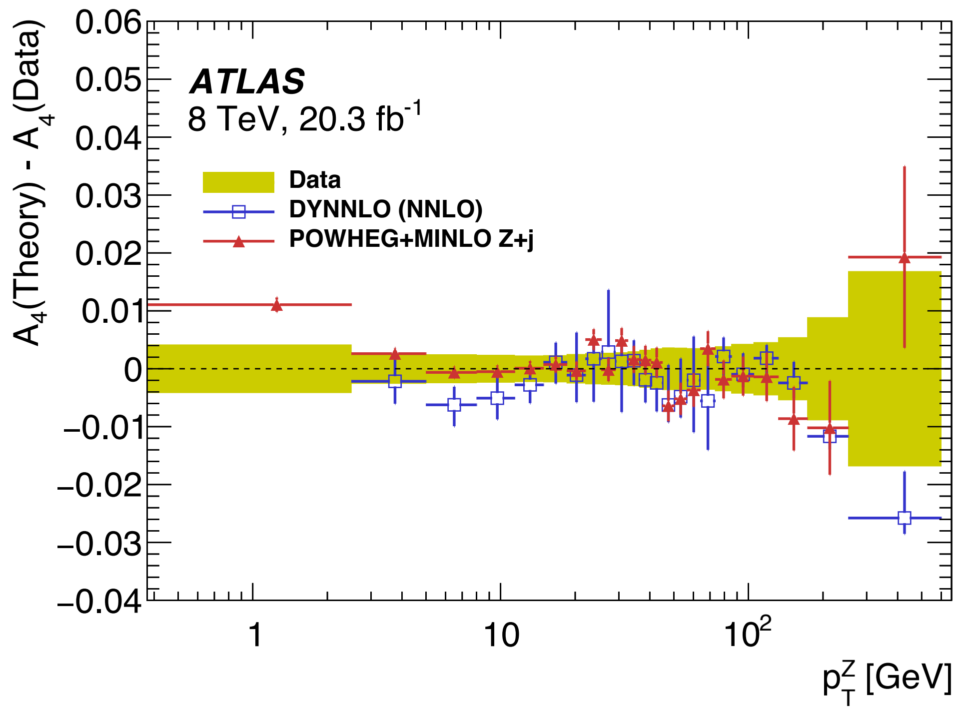
Measurement Results





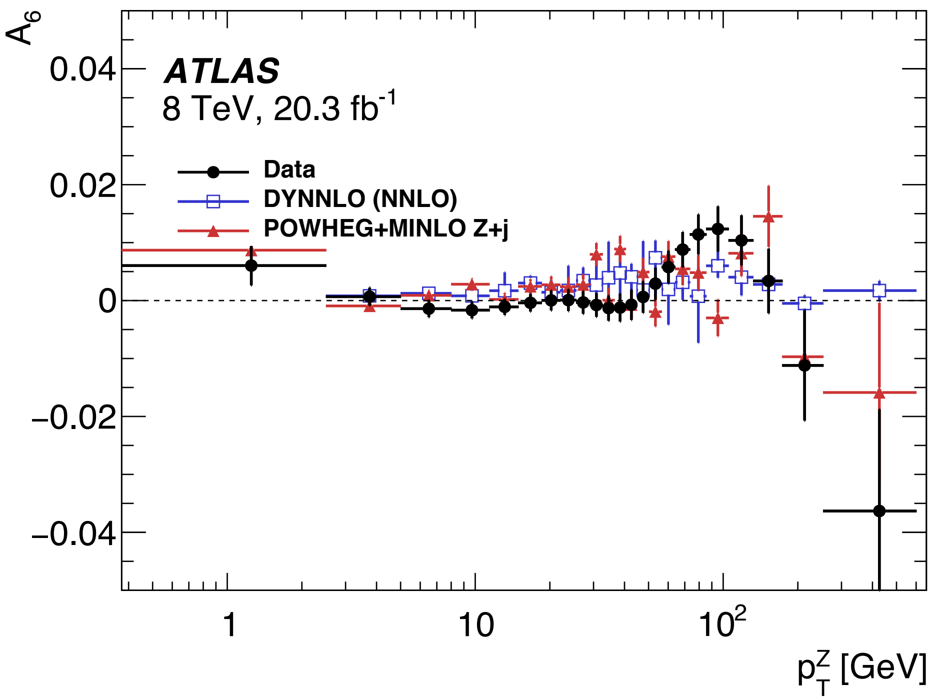


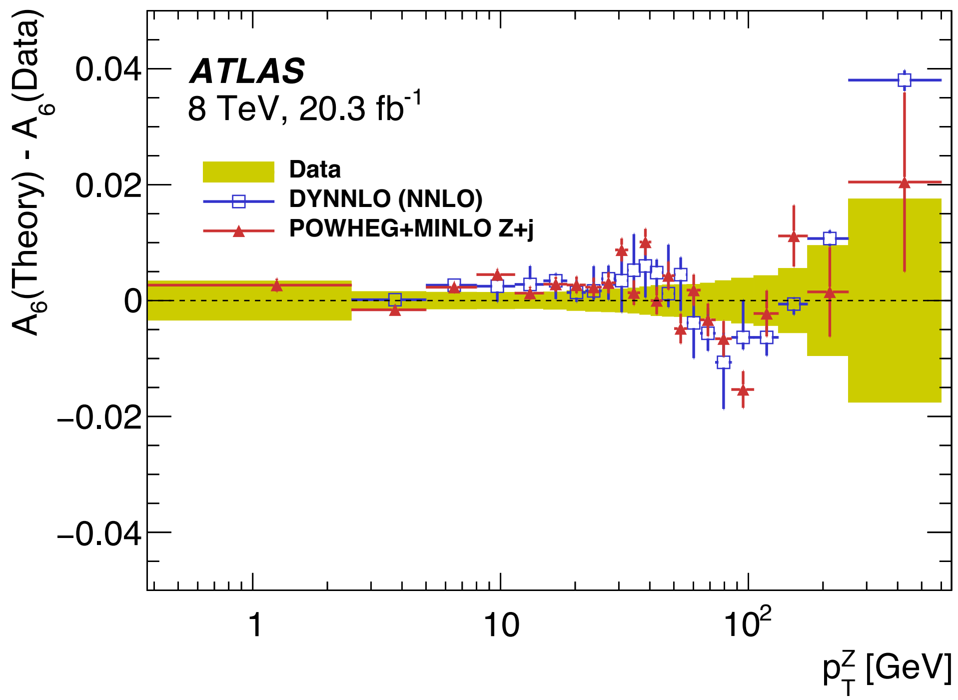


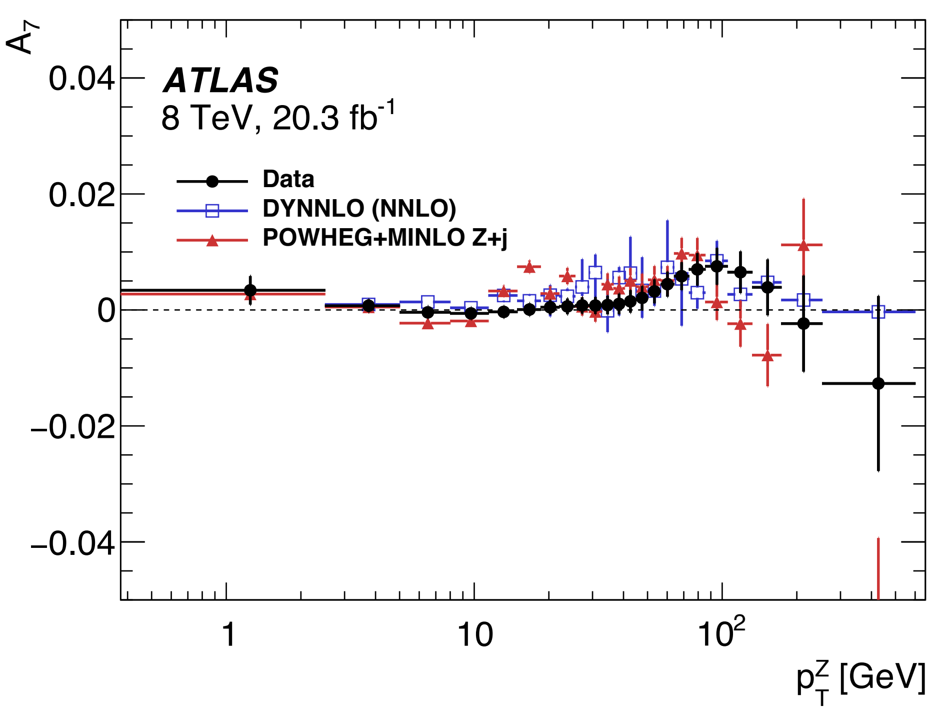


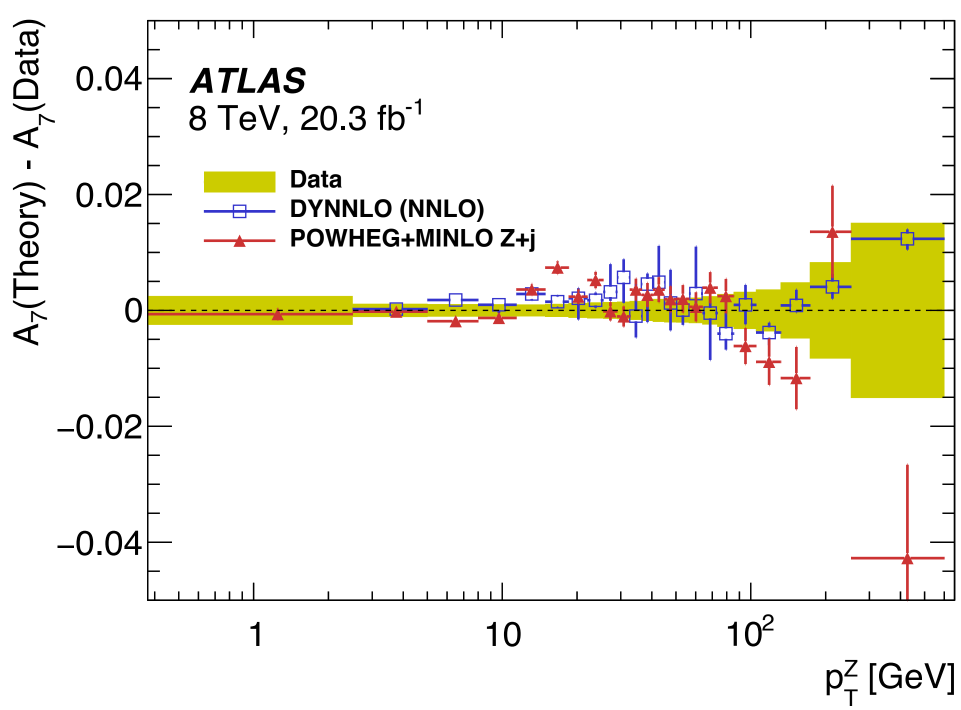
- $A_{3,4}$ well described by fixed order simulations
- Those are sensitive to the Weinberg angle

Measurement Results



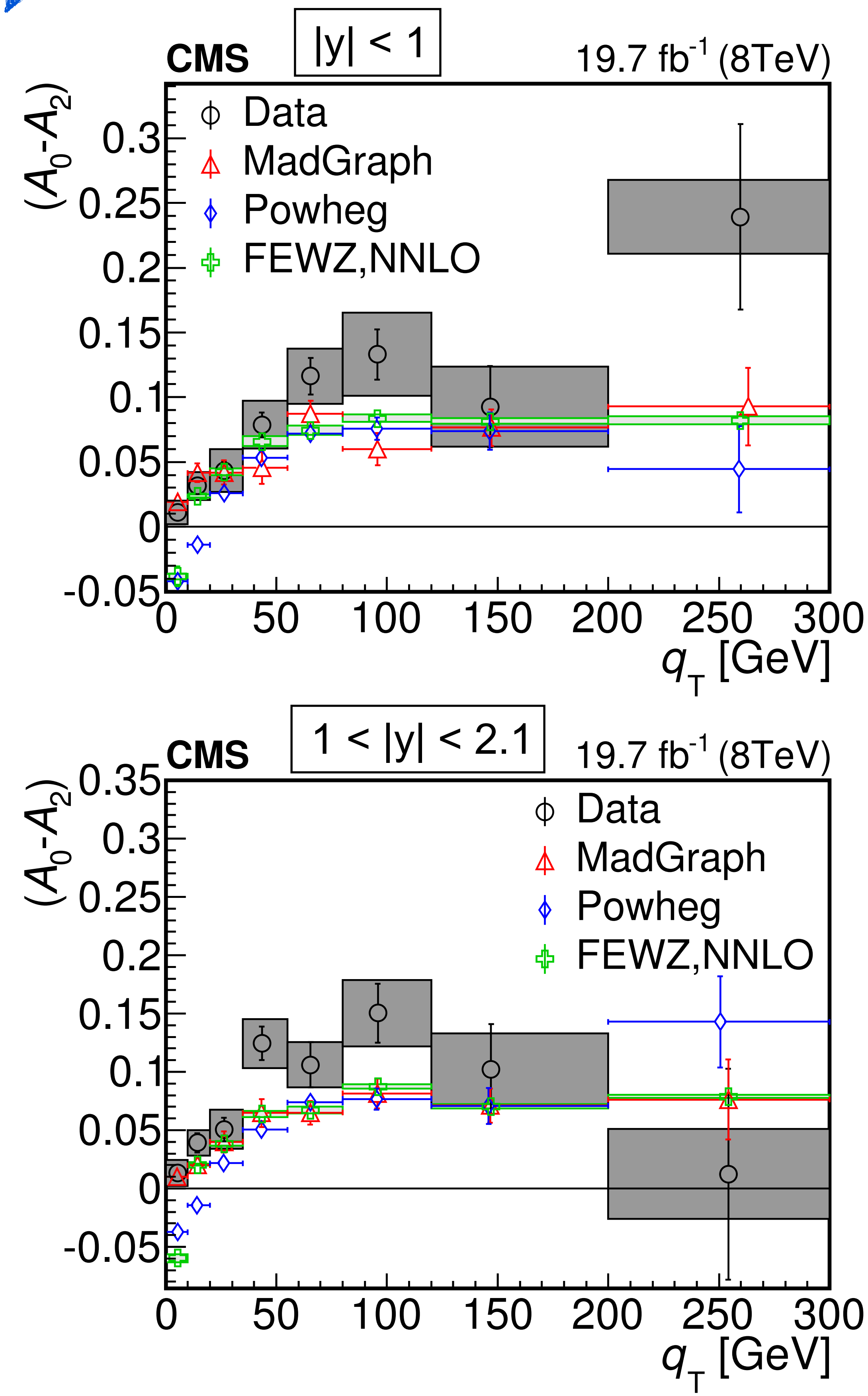






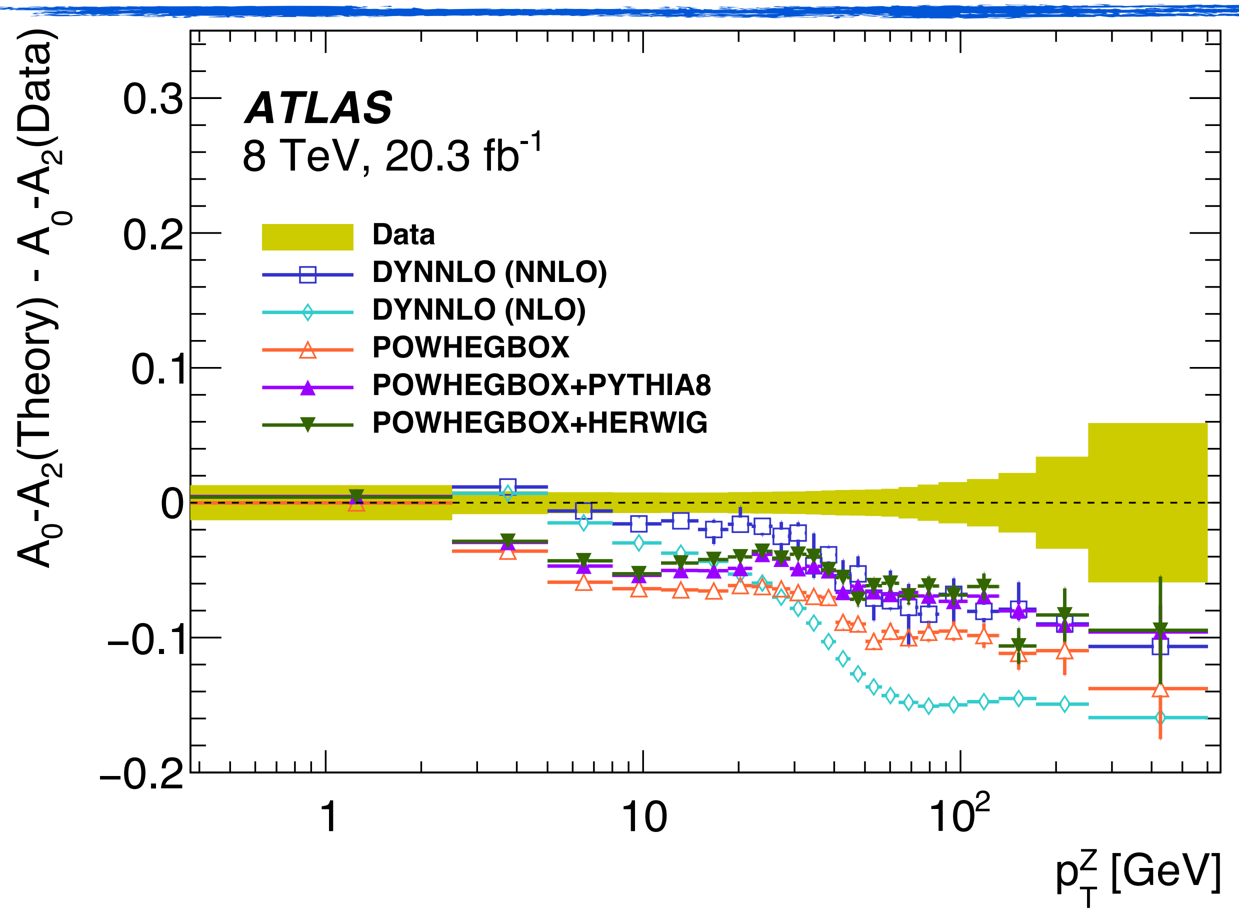
- Equal to 0 @ NLO
- Higher order effects become visible
- Small discrepancy between measurement and simulation:
  - Limitations of current simulations

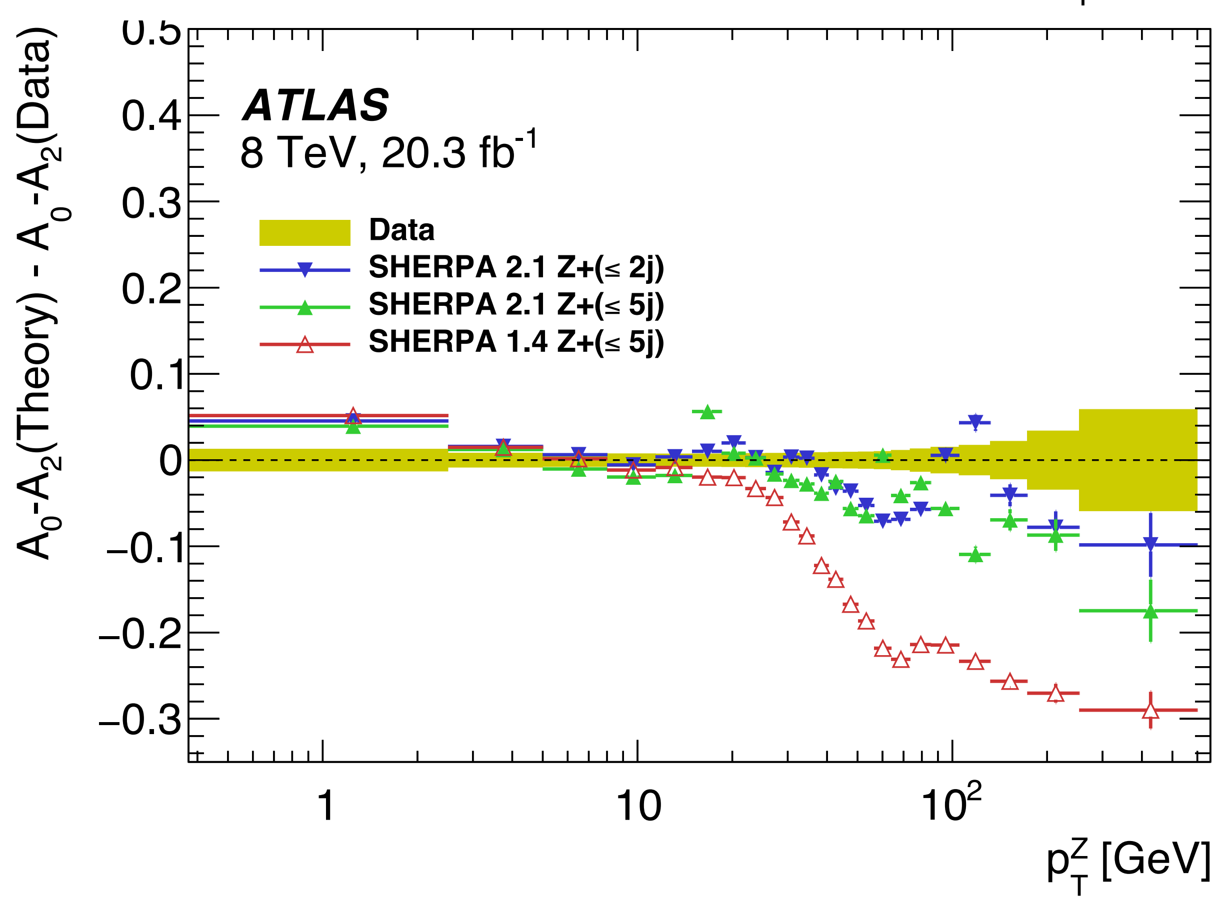
Comparison of various Generators



- A0 - A2 (↗ Lam-Tung relation)
- Compatible results in different rapidity regions
- Significant differences between simulations

Comparison of various Generators





- Significant differences between simulations!
- Sherpa & PowHegBox show statistical unc. only
- DYNNLO gives best description of measured A_0
- No generator describes A0-A2
  - (Best: Sherpa 2.1)
- Improvement from Sherpa 1.4 to 2.1

Conclusions & Outlook

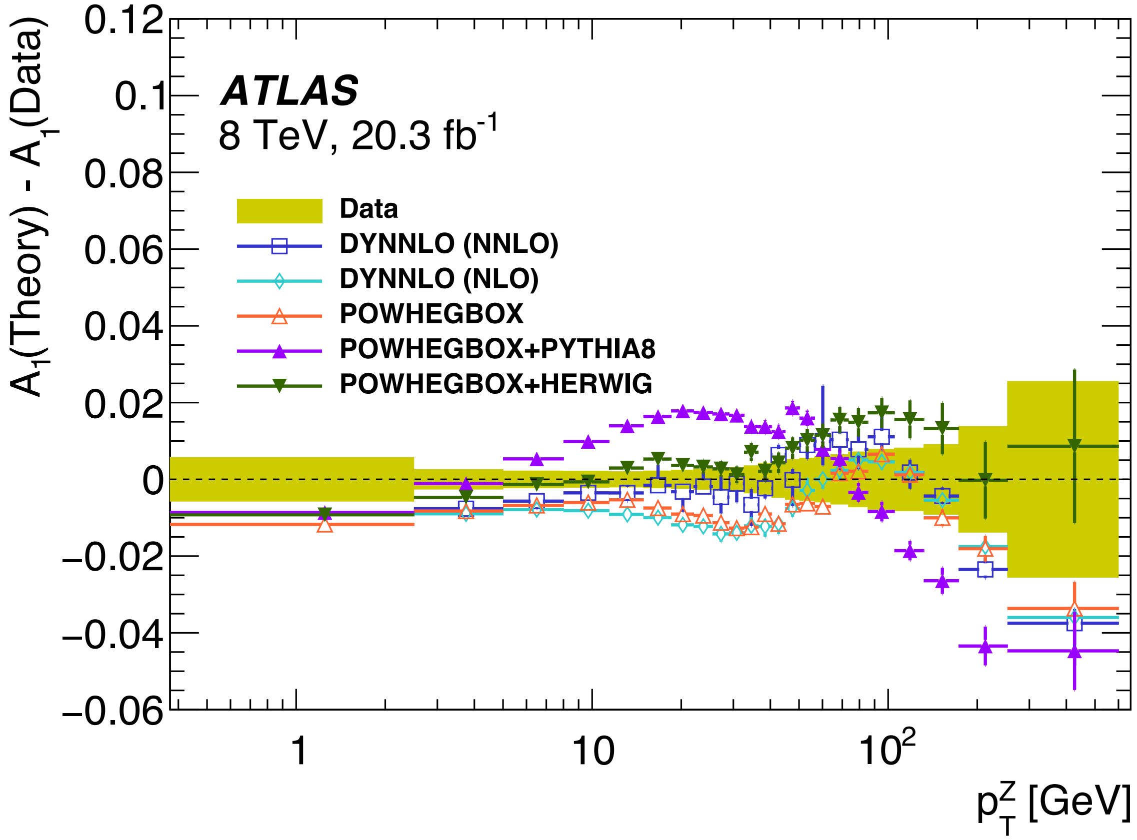
Conclusions & Outlook

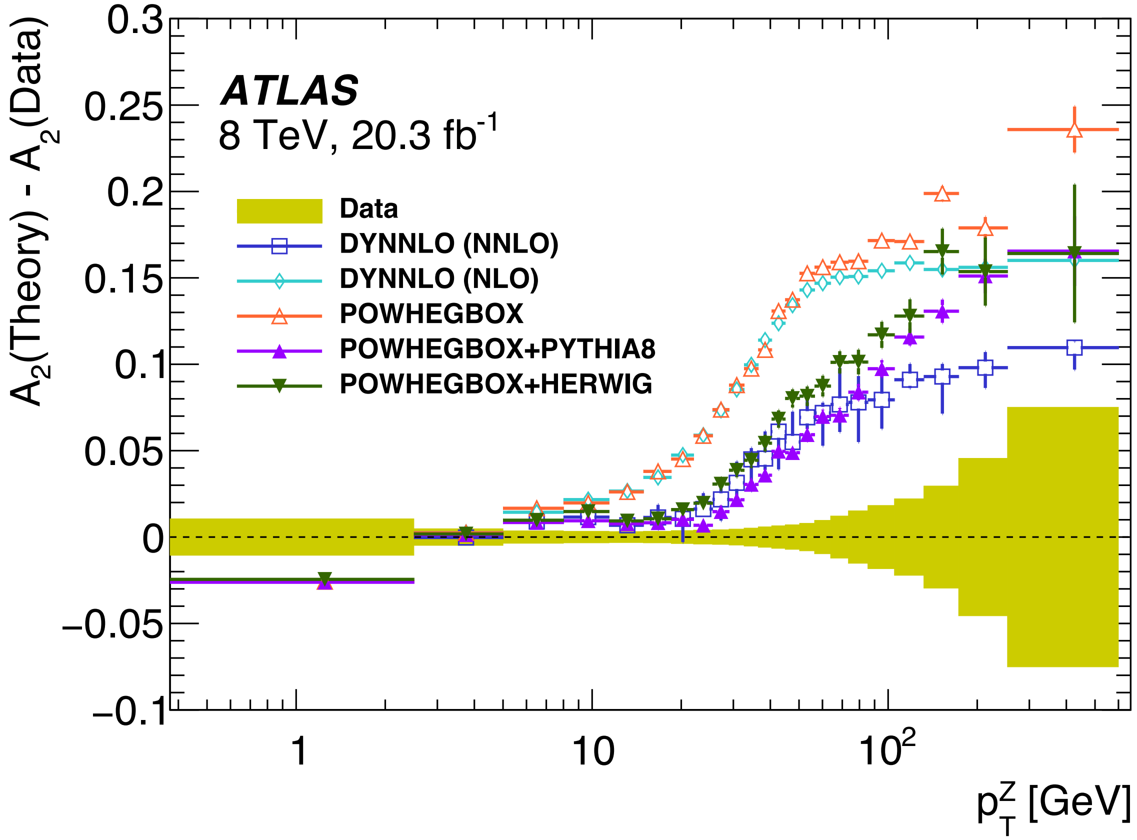
- Study of weak vector bosons provide a wealth of information
  - Partonshower modeling
  - Higher order matrix element calculations
  - PDFs, alpha_s, weak mixing angle, new physics
- 13 TeV results have been provided by ATLAS and CMS in short time!
  - First precise results appearing
    - Inclusive and differential cross section, V+jets
- Precision domain dominated by study of 8 TeV data (2012)
  - Differential measurements with %-level uncertainties!
  - Very sensitive tools!
- Several further measurements in progress
  - Addition of heavy flavor jets
  - Multidifferential x-section measurements
    - Large impact on PDFs expected!

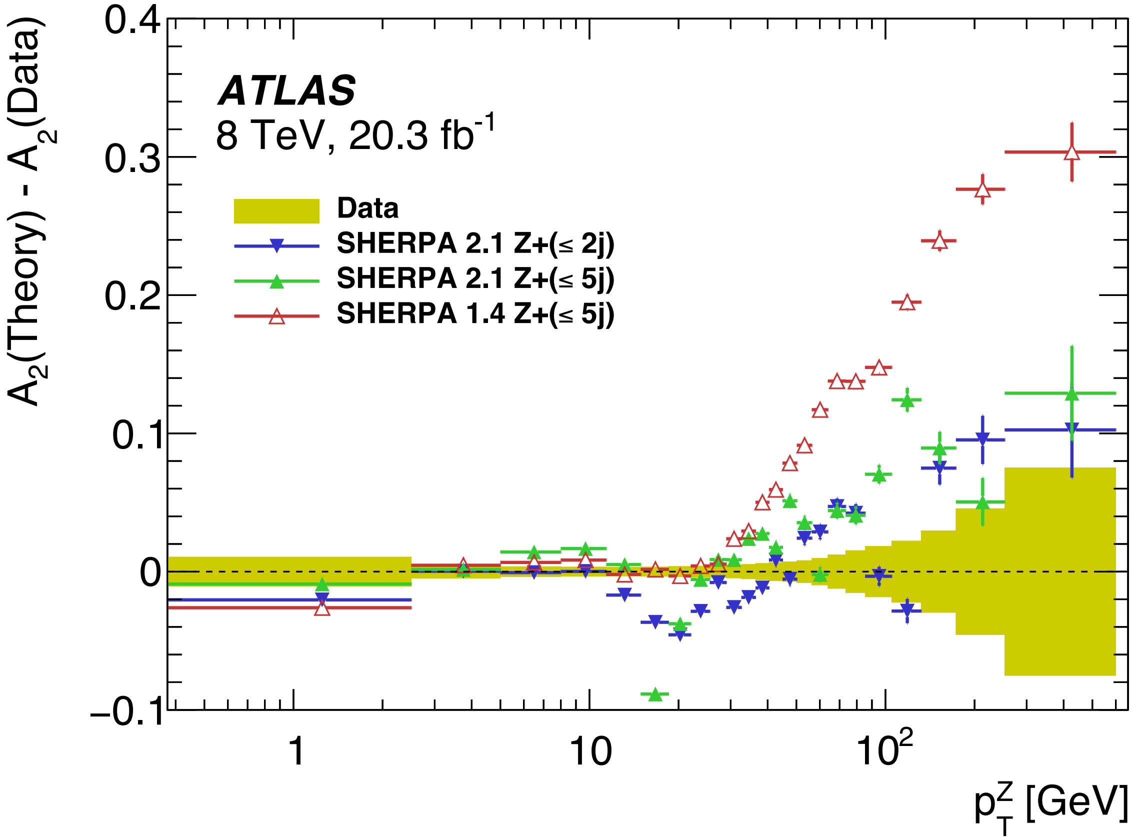
Stay tuned for what still is to come :-)

BACKUP

Z Polarisation measurement - results



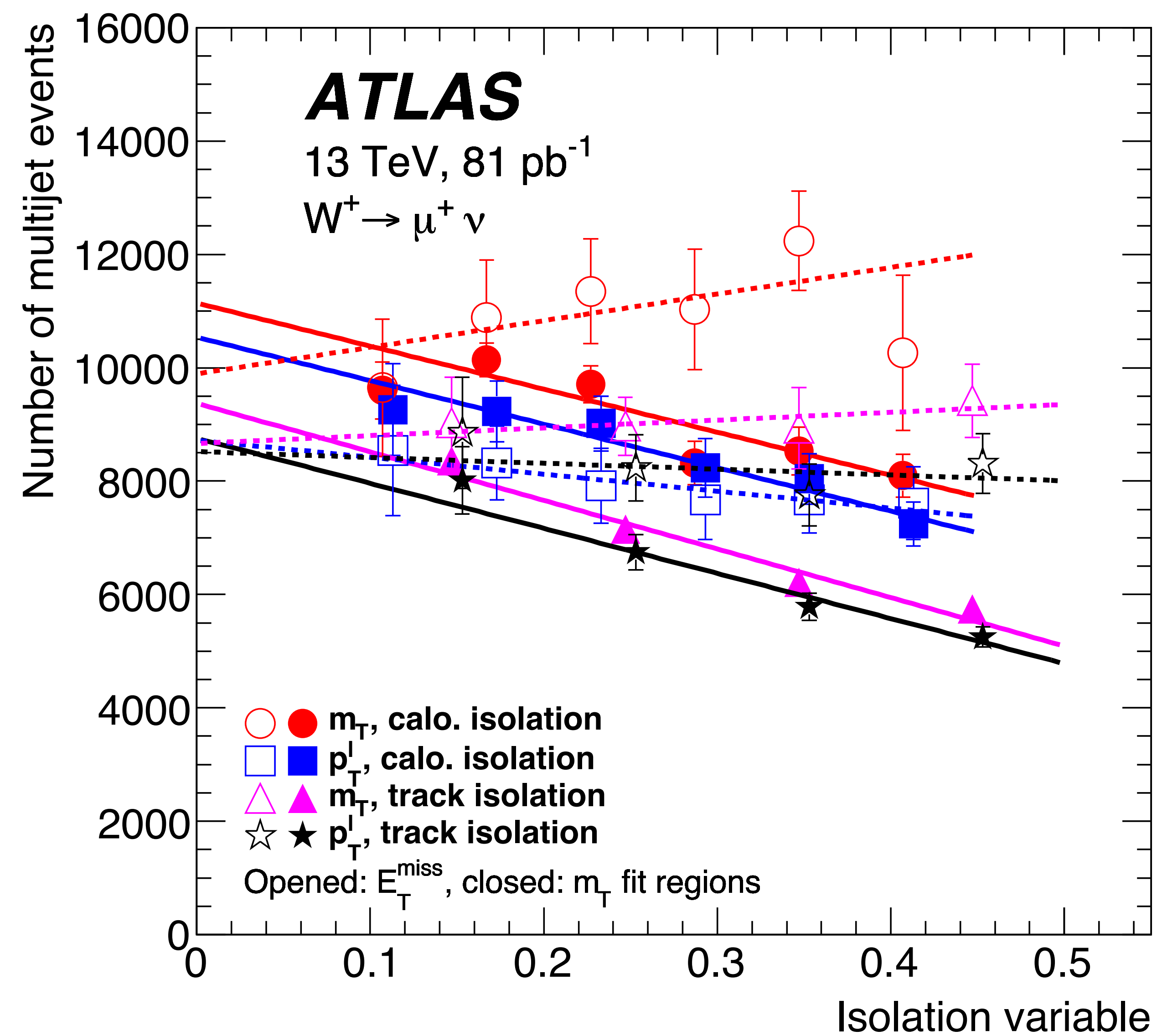




Multijet Background estimation in detail

- MJ fit regions:
  - full event selection removing **mT** or **MET** requirement

- MJ enriched samples in fit region:
  - Mutually exclusive isolation cuts
    - Statistically independent sample
  - Similar samples for signal and other backgrounds created from simulation
  - Normalization of MJ sample and Signal template extracted in ML fit
  - Linear extrapolation to signal region

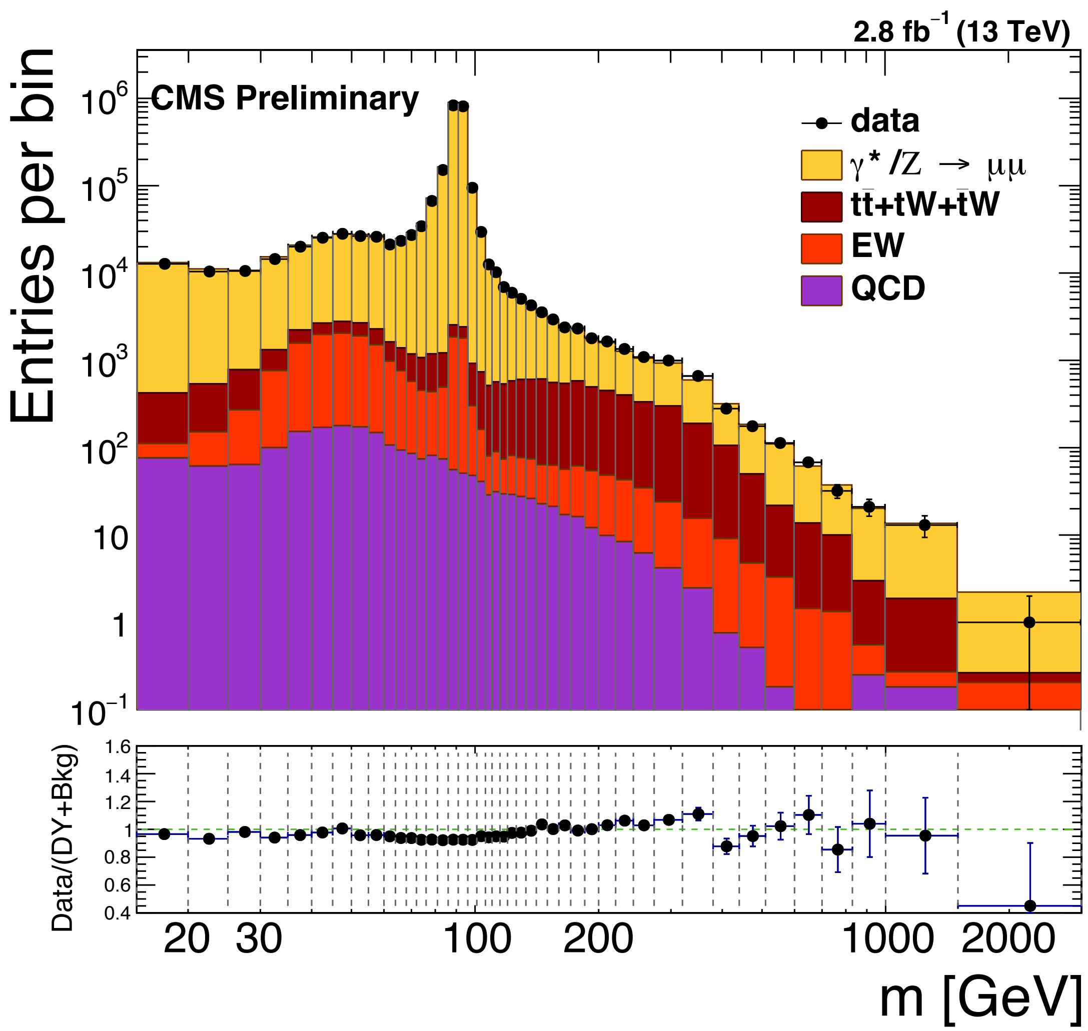


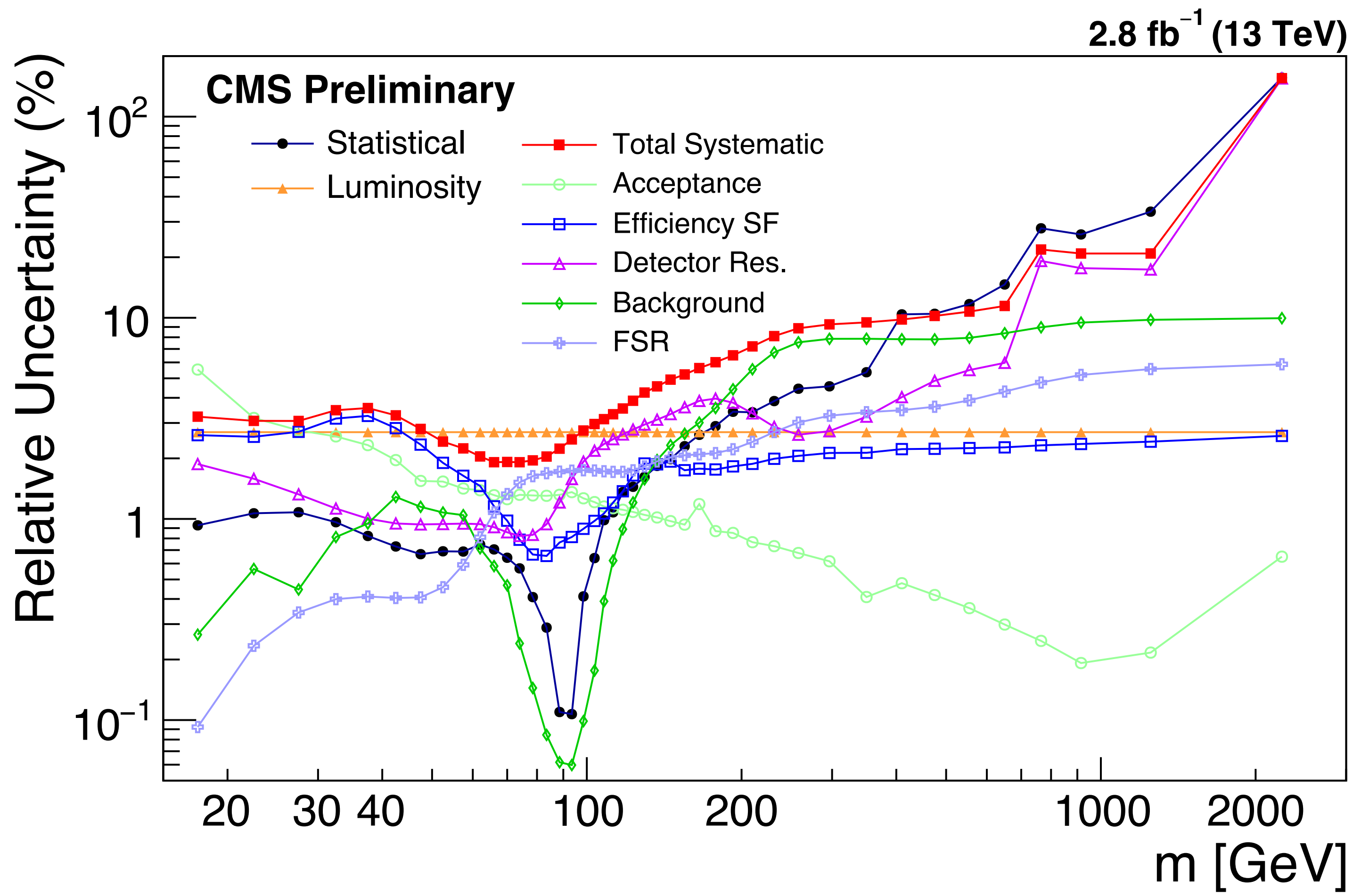
- Average of all MJ estimations used as central value (4% μ channel, 10% e channel)
- 0.5 * difference between average and single estimations used as uncertainty
  - (20%-30%)

Drell-Yan Measurements - low & high masses

CMS-PAS-SMP-16-009

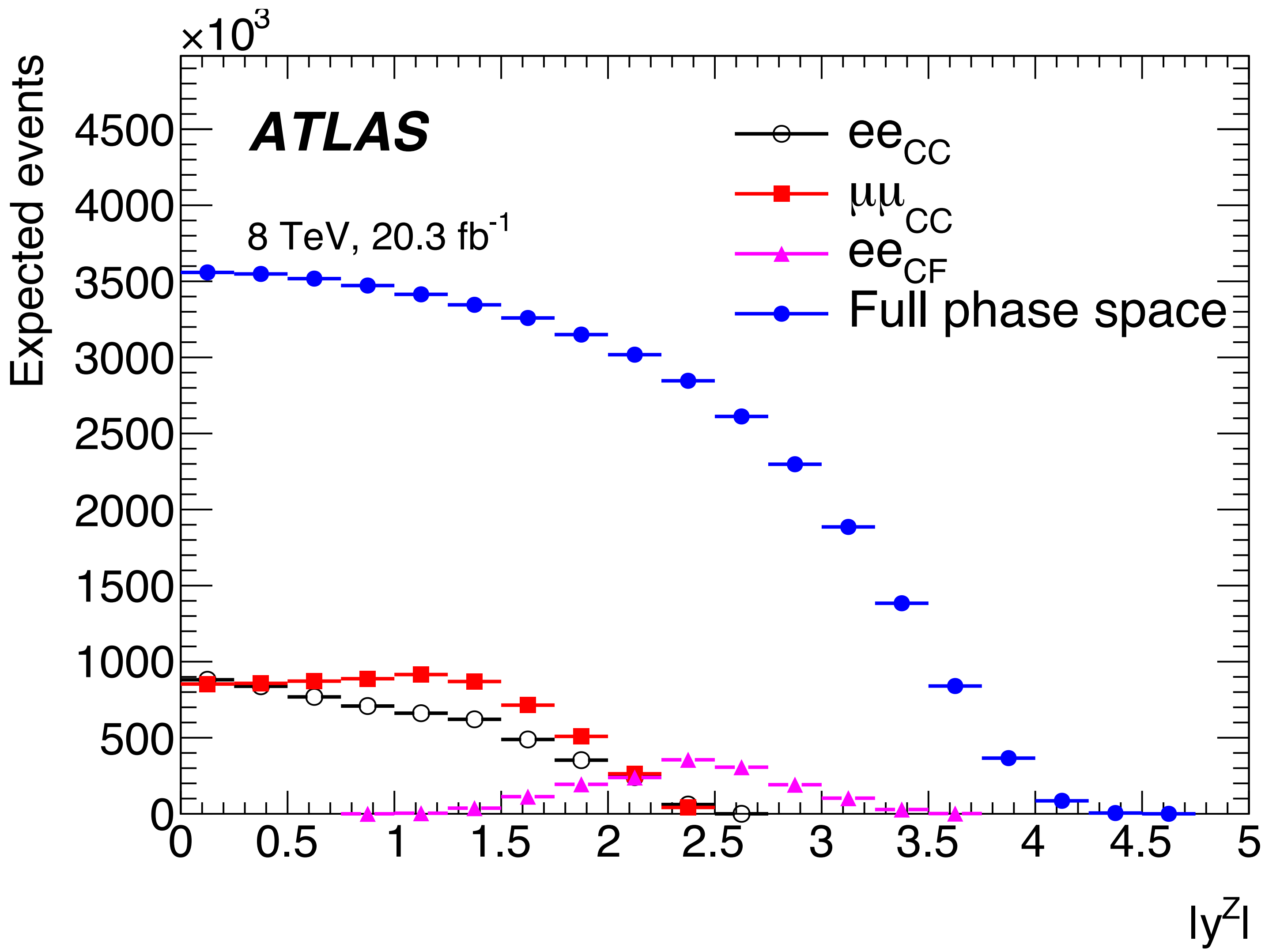
- Reaction: pp → $\mu^+\mu^-$ + X
  - Large statistics allow to go to high invariant masses
  - Sensitivity to new physics





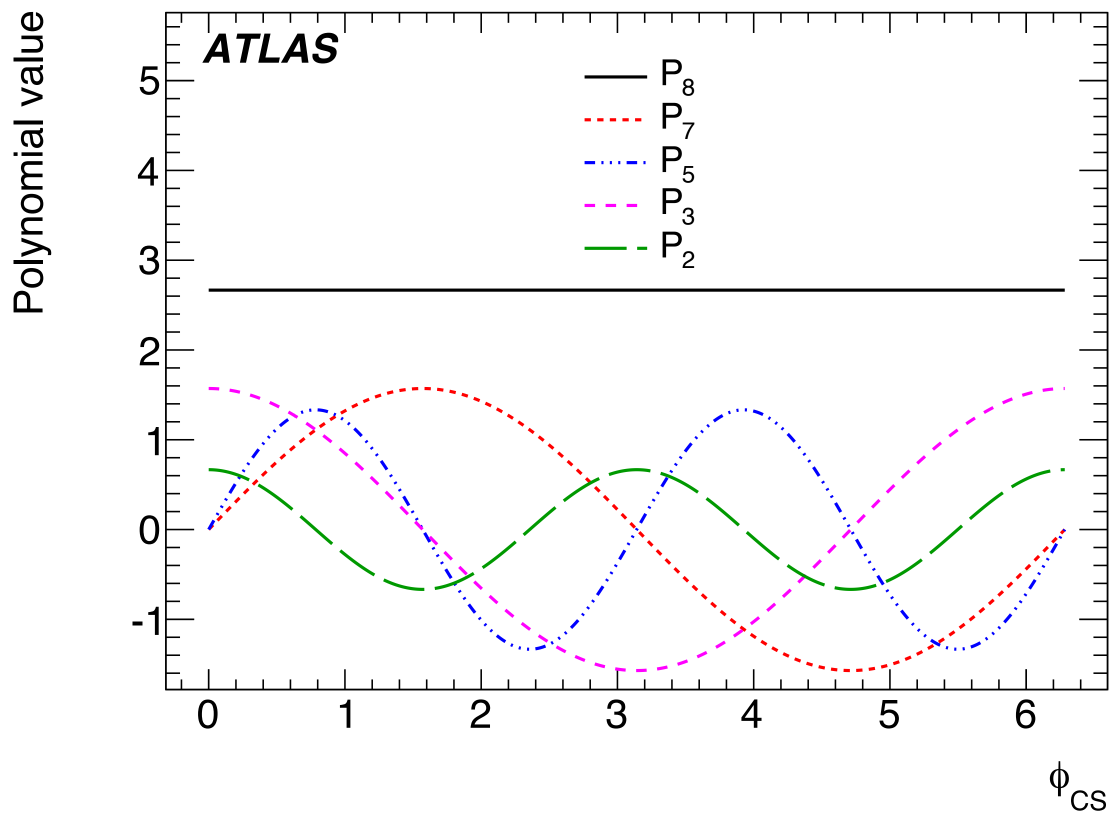
Z Polarisation measurement

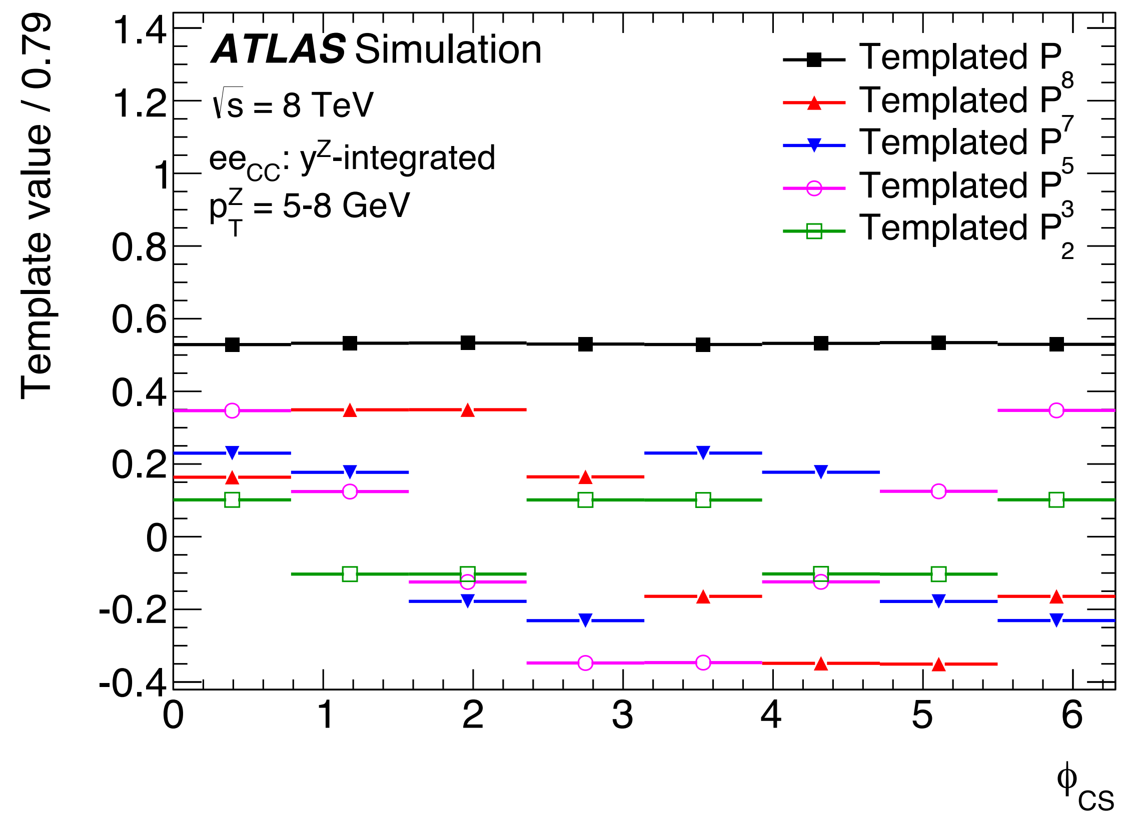
Analysis Acceptance * Efficiency for 3 considered channels



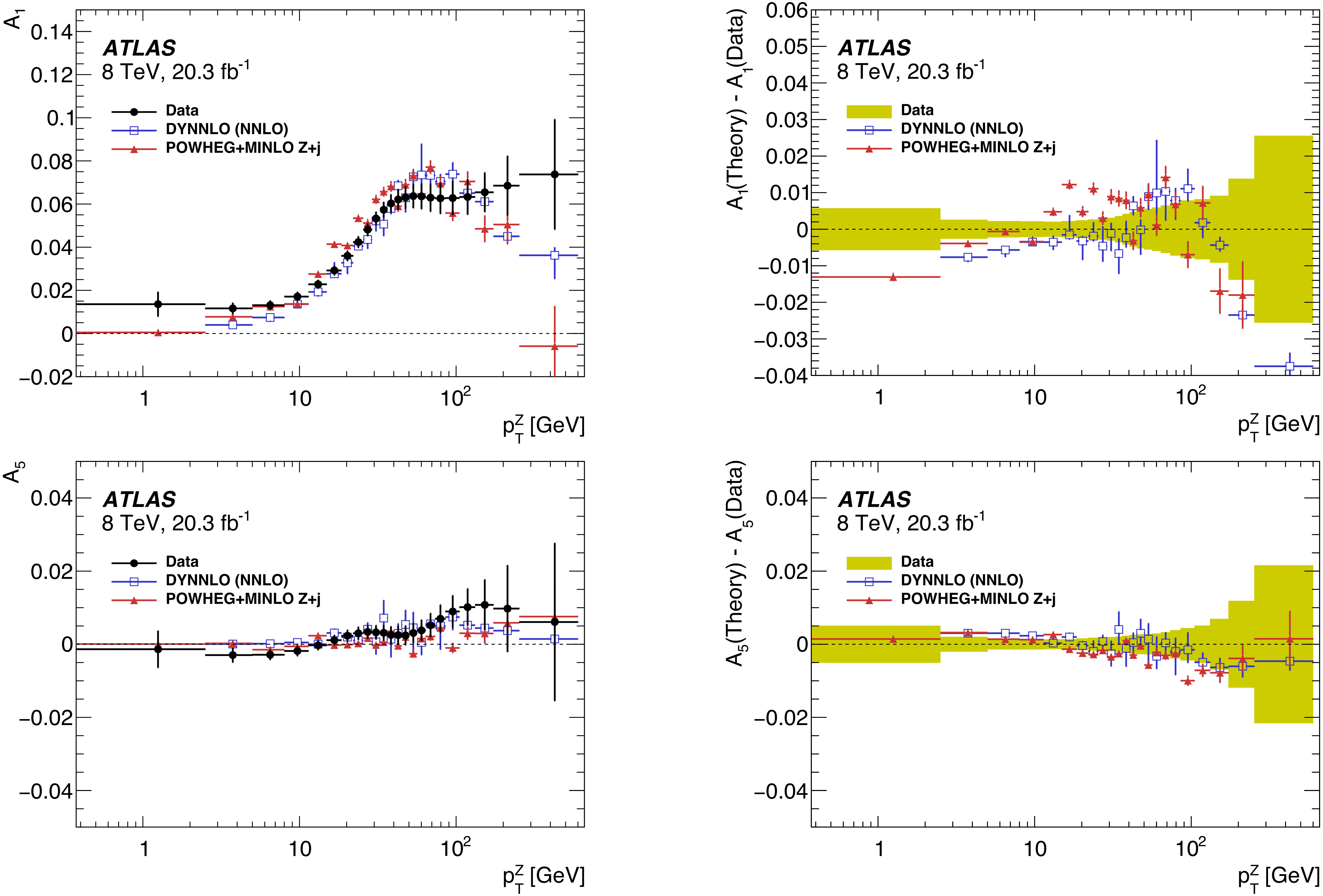
Z Polarisation measurement

- Folding of phi projected polynomials

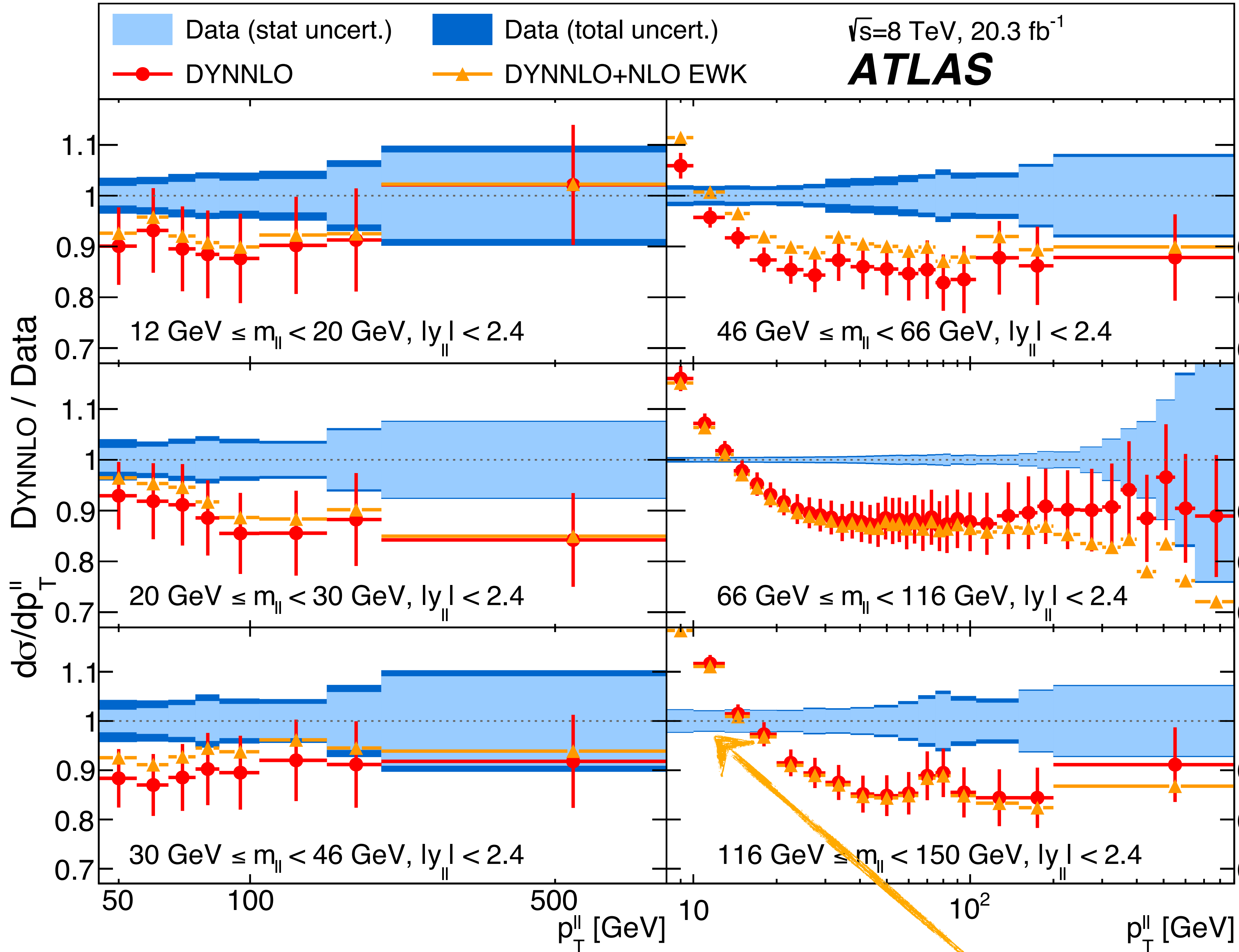




Z Polarisation measurement



Electroweak corrections

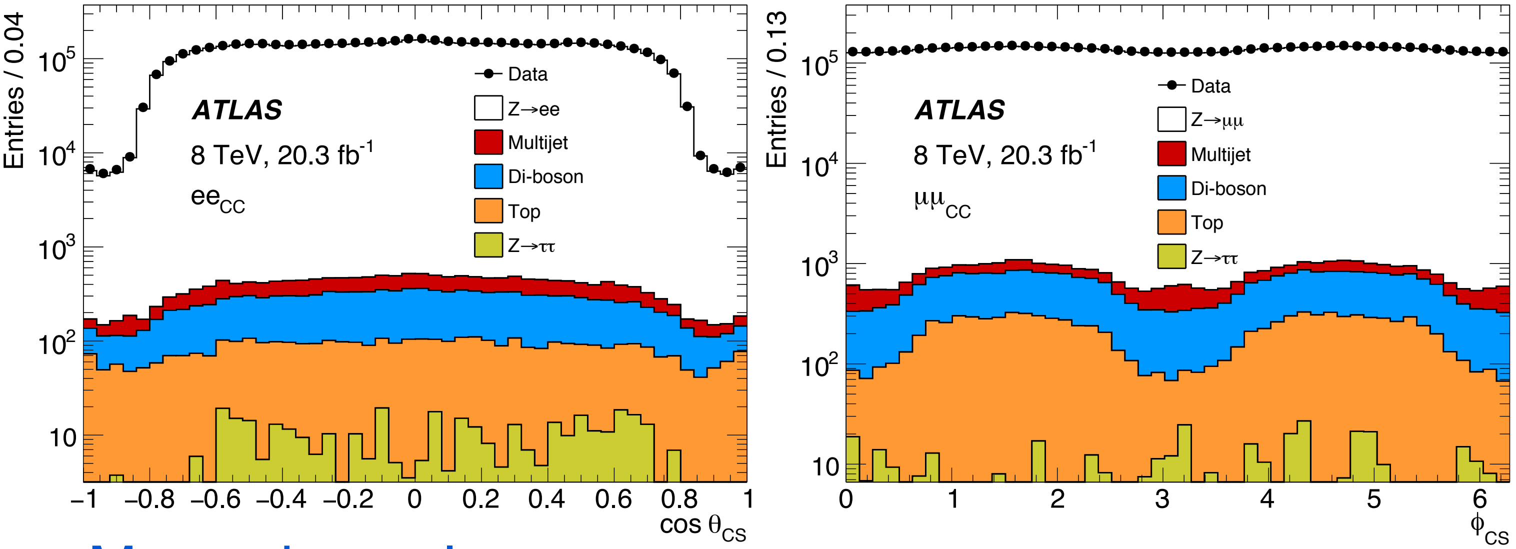


- Predictions low by ~15% in all m_{ll} bins
- No significant impact of NLO EWK corrections

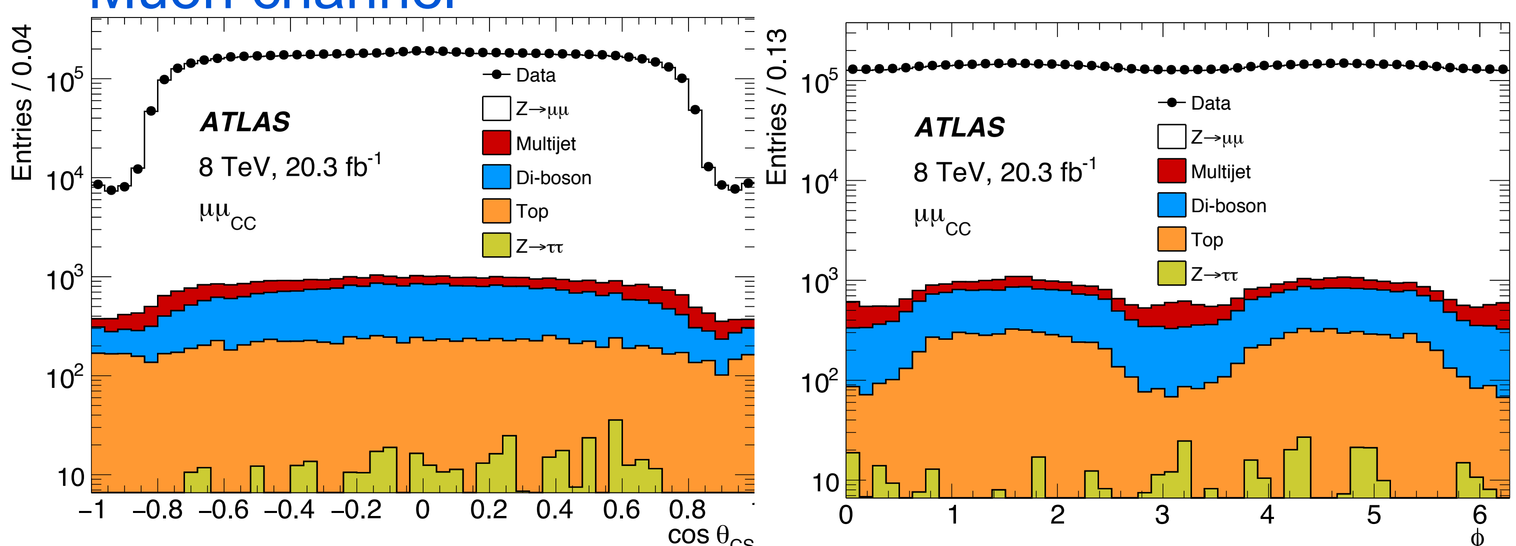
Expected due to soft-gluon emissions

The Measurement - Lepton Selection

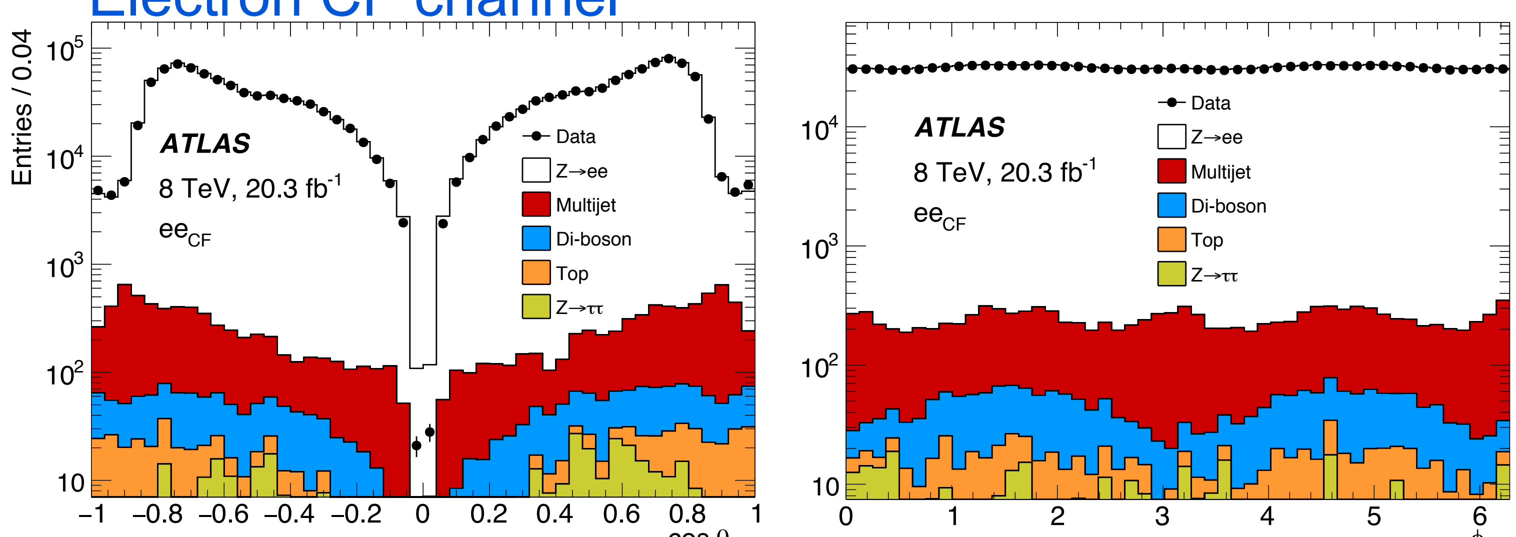
Electron CC channel



Muon channel



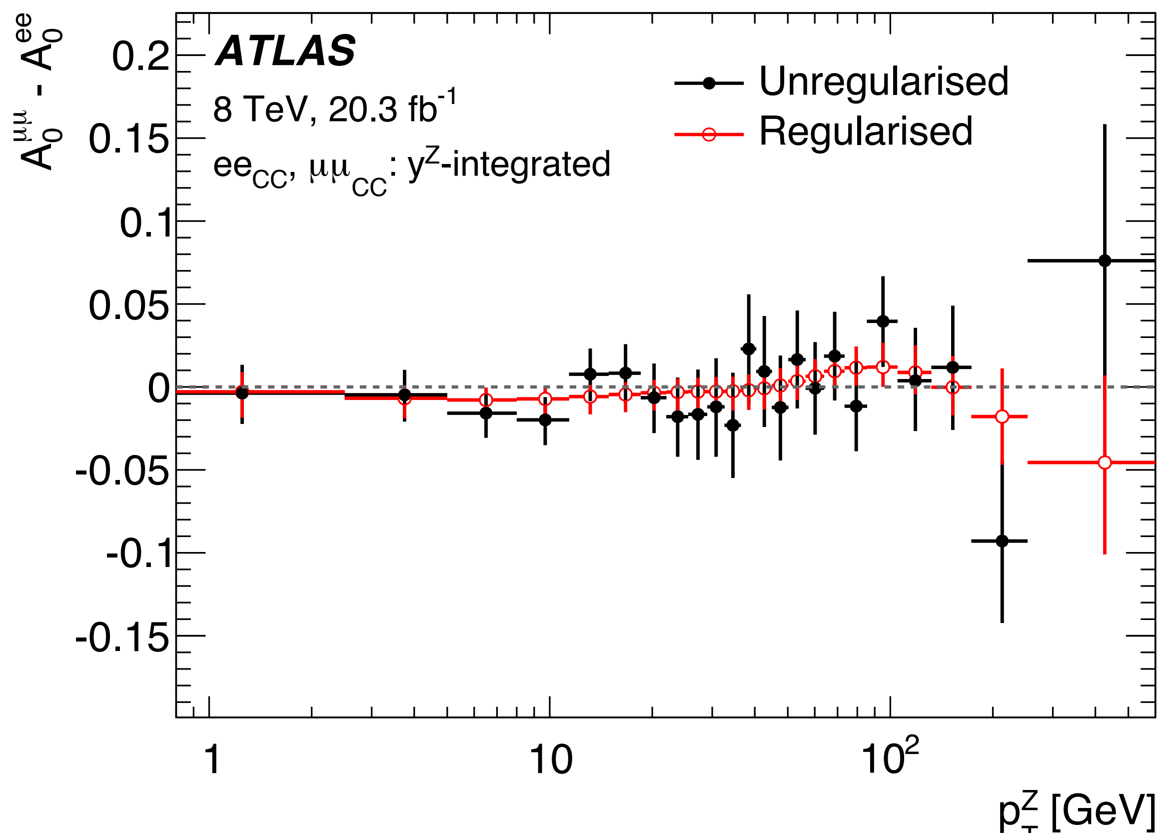
Electron CF channel

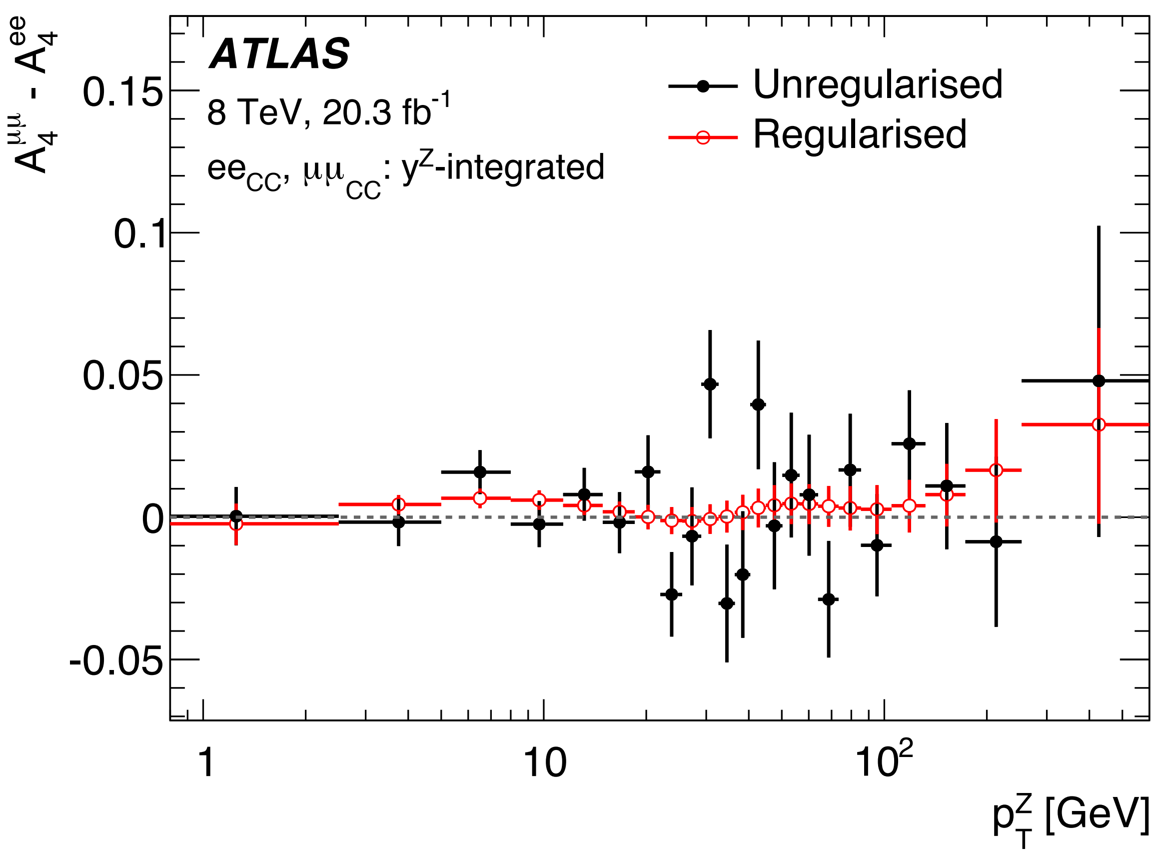


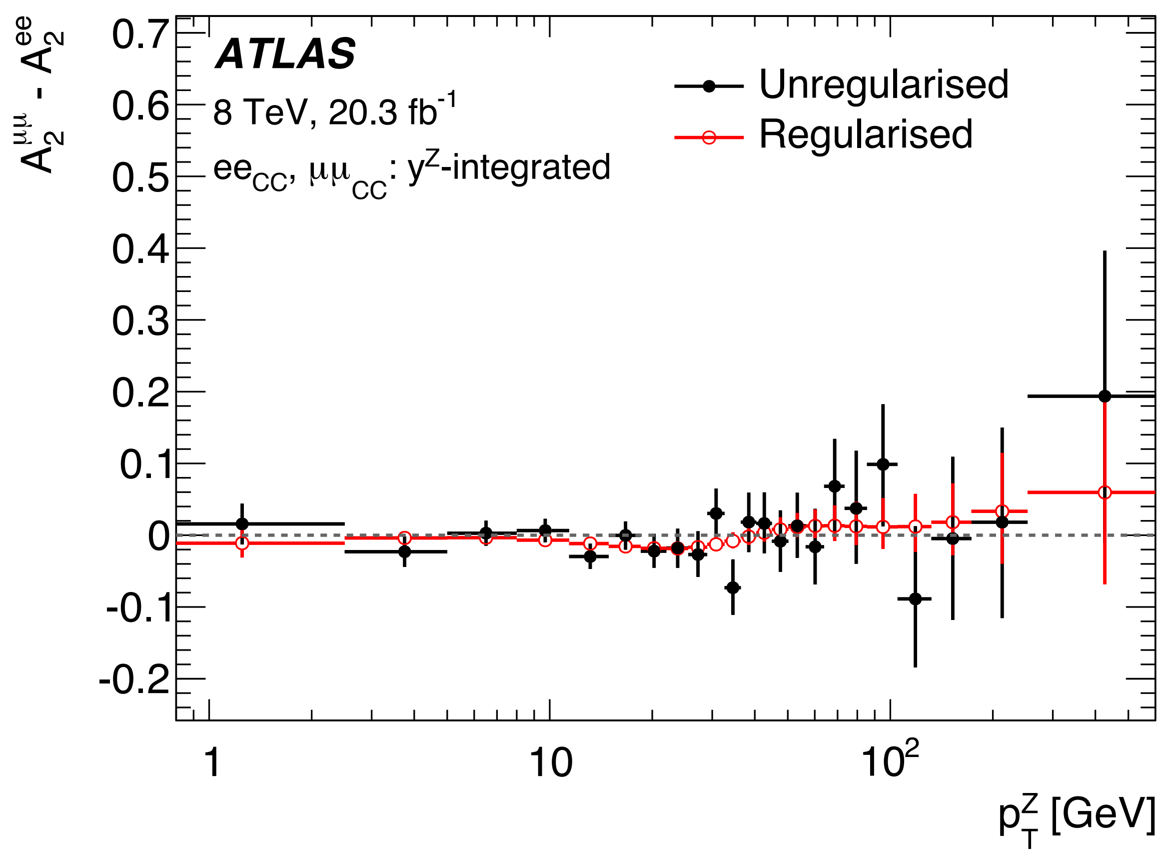
- Data collected during 2012
  - $\sqrt{s}$ = 8 TeV, 20.3 fb^{-1}
- Measurement performed in 3 independent channels:
  - Muons
  - Electrons: central central
  - Electrons: central-forward
- Fiducial Volume:
  - CC & μμ: $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ $|\eta| < 2.4$
  - CF: $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ $2.5 < |\eta| < 4.9$
  - OS di-leptons $80 < m_{ll} < 100\,\mathrm{GeV}$
- Backgrounds:
  - EW & ttbar from simulation
  - QCD multi-jet: data driven
- Signal simulation:
  - POWHEG + Pythia

Measurement Results - Compatibility ee / μμ

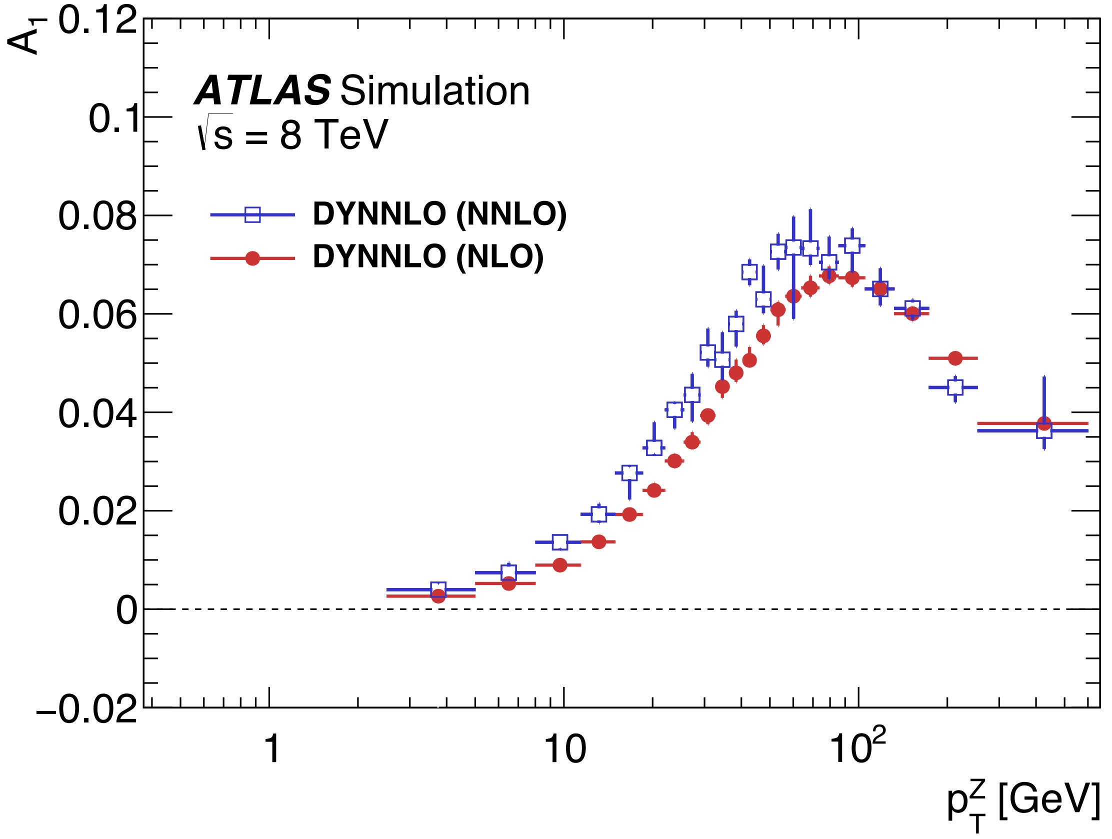
- Electron and Muon channels give consistent results
    - Similar for all A_i
- Regularization:
    - Smooth fluctuations in results & uncertainties
    - Increase correlation between bins

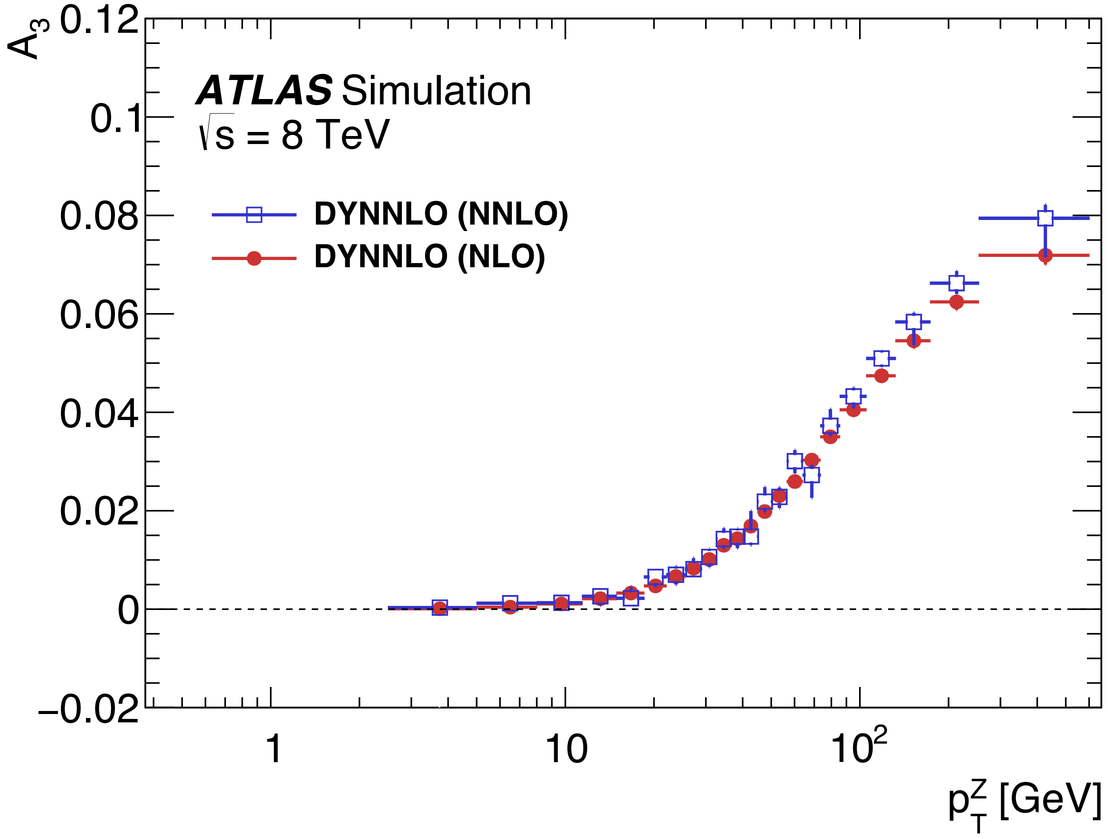


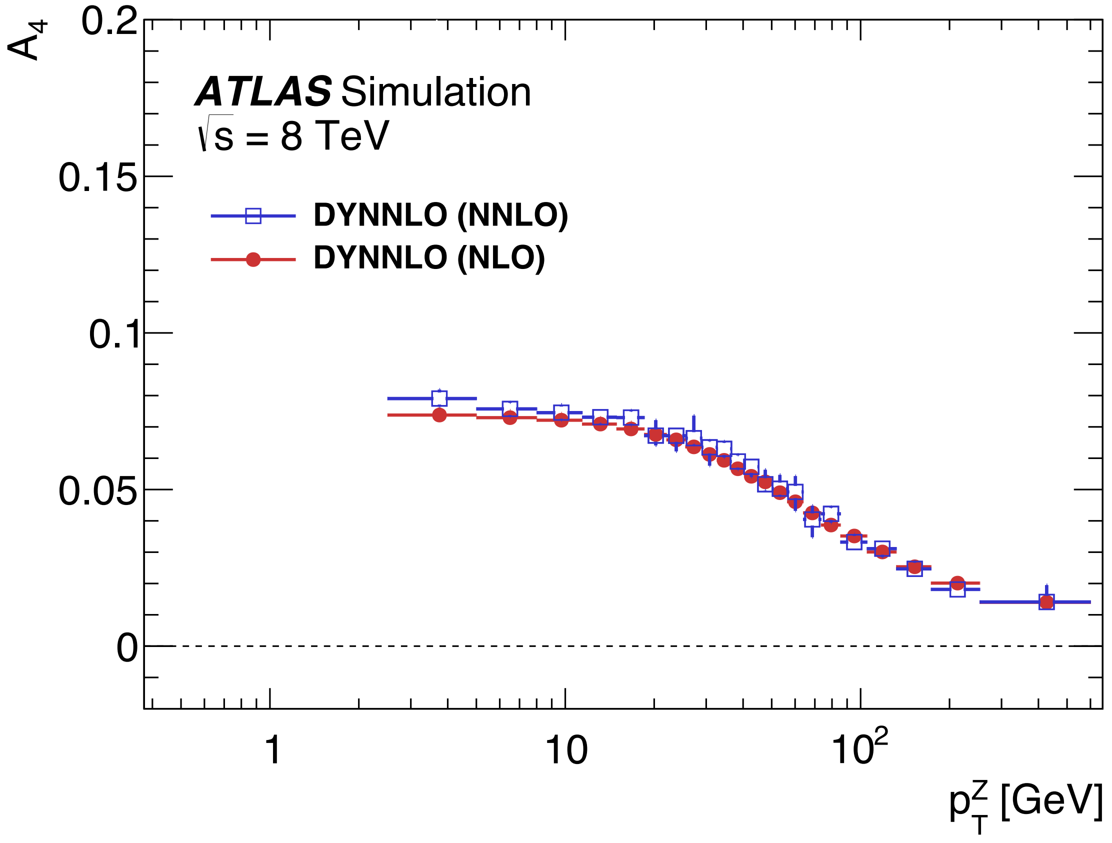




Impact of higher order QCD corrections

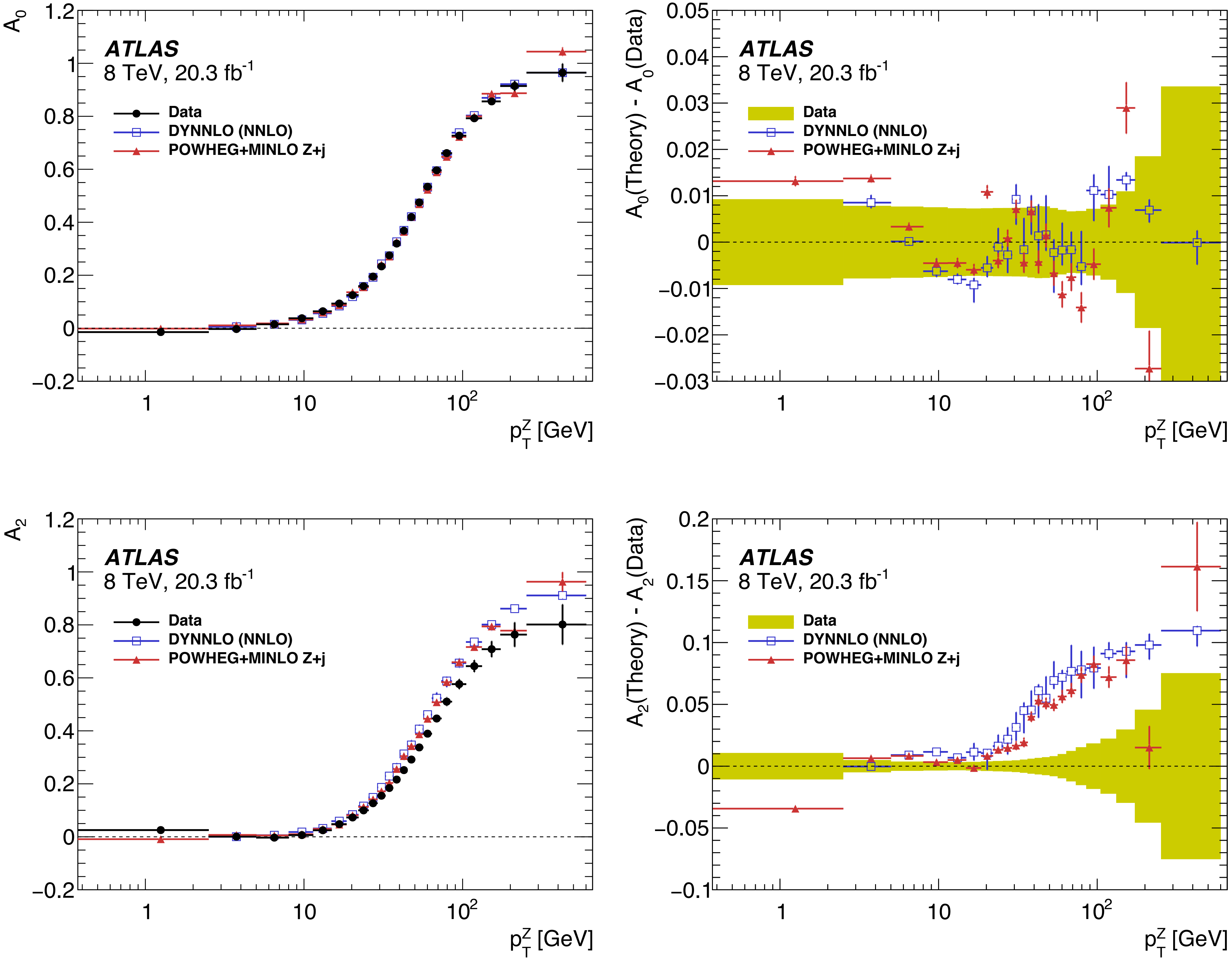






- Only small impact in $A_{1,3,4}$
- No sensitivity with current measurement

Measurement Results



- A_0 well described by fixed order calculations
- A_2 predicted too high for large p^Z_T

▸ A_0 - A_2 predictions also off w.r.t. measurement

▸ Impact of higher order effects not covered in simulation