Precision measurements with W and Z/γ^* bosons with the ATLAS detector

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on behalf of the ATLAS Collaboration

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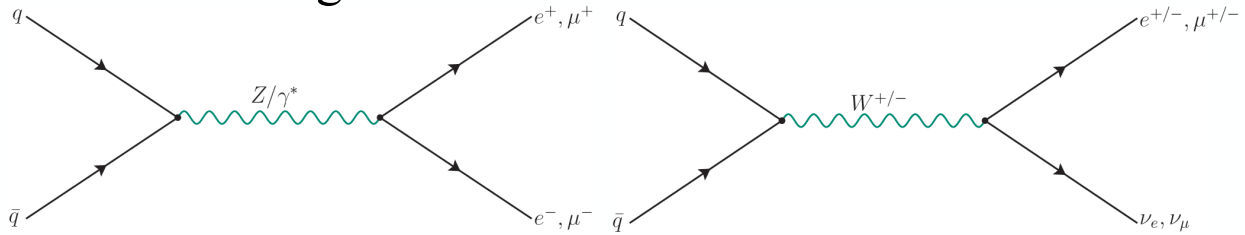
W and *Z* production in Drell-Yan processes

- Drell-Yan di-lepton production of *W* and *Z* bosons offer clear signature, large statistics, and small background



- Benchmark for understanding of pQCD processes
  - Predictions at NNLO QCD with NLO EW corrections
  - Validation of Matrix Element (ME) + Parton Shower (PS) montecarlos
- Constraints on parton distribution functions (PDFs)
- High precision SM tests and extraction of SM parameters

- Double differential high-mass Drell-Yan cross section — JHEP 08 (2016) 009
- Study of the transverse momentum and ϕ^*_η distributions of DY lepton pairs — EPJC 76(5), 1-61 (2016)
- Measurement of angular coefficients in Z-boson production — JHEP 08 (2016) 159

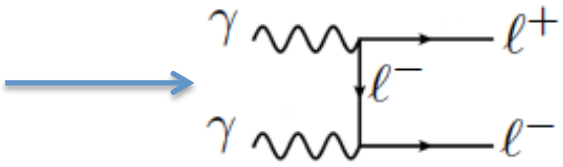
All measurements performed with 20.3 fb^{-1} of *pp* collisions data at 8 TeV (RUN I)

Double-differential high-mass Drell-Yan cross section at 8 TeV

JHEP 08 (2016) 009
arXiv:1606.01736

Study of high-mass Drell-Yan processes at 8 TeV

- Different sensitivity to u-type, d-type and anti-quarks for on-shell (Z) and off-shell (γ^* dominated)
- Sensitive to the photon PDF through the photon-induced (PI) process $\gamma\gamma \rightarrow l^+l^-$



- Sensitivity to New Physics, and bkgd to dilepton resonant-states searches at high mass

- Measurement of double-differential cross sections:

$\frac{d^2\sigma}{dm_{ll}d|y_{ll}|}$ allows to constrain PDFs at large x: $\left(x_{1,2} = \frac{m_{ll}}{\sqrt{s}} e^{\pm y_{ll}}\right)$

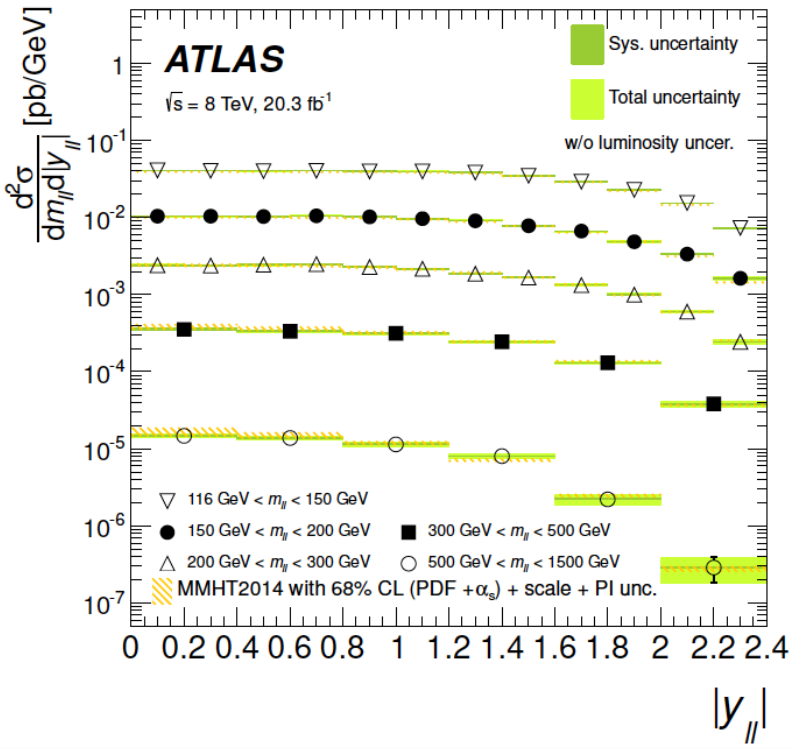
$\frac{d^2\sigma}{dm_{ll}d|\Delta\eta_{ll}|}$ helps to disentangle PDF, EW, and PI contributions

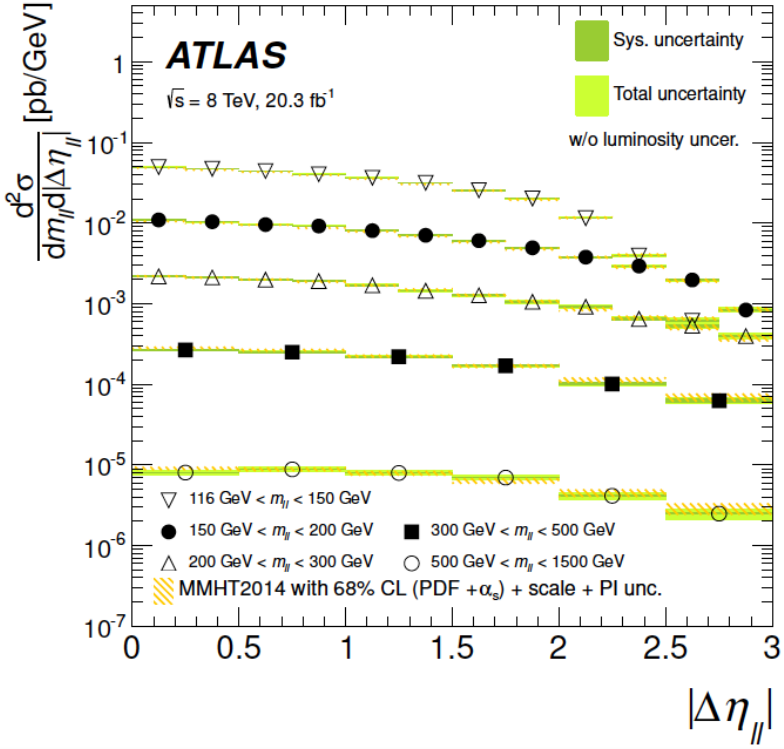
- Use 20.3 fb^{-1} of data at $\sqrt{s}$=8 TeV
- Measure $Z/\gamma^* \rightarrow \mu\mu$ and $Z/\gamma^* \rightarrow ee$
- Fiducial phase space at Born level:
  - Mass range $116 < m_{ll} < 1500$ GeV
  - $p_T > 40$ GeV (leading lepton)
  - $p_T > 30$ GeV (subleading lepton)
  - $\eta < 2.5$

High Mass Drell-Yan at 8 TeV

Dominant background
- top (*tt* and *Wt*) & di-boson production estimated from MC
- QCD multi-jet estimated with data-driven methods

Systematic uncertainties between 0.5 and ~3% (not including luminosity uncert.) increasing with m_{ll}
- Background estimate
- Electron energy scale
- Muon reco. efficiency and momentum scale calibration





- Good agreement between data and predicted results
  - Combined fiducial cross section at Born level compared to NNLO pQCD calculations
  - Theoretical predictions from FEWZ 3.1 using MMHT14 PDF set

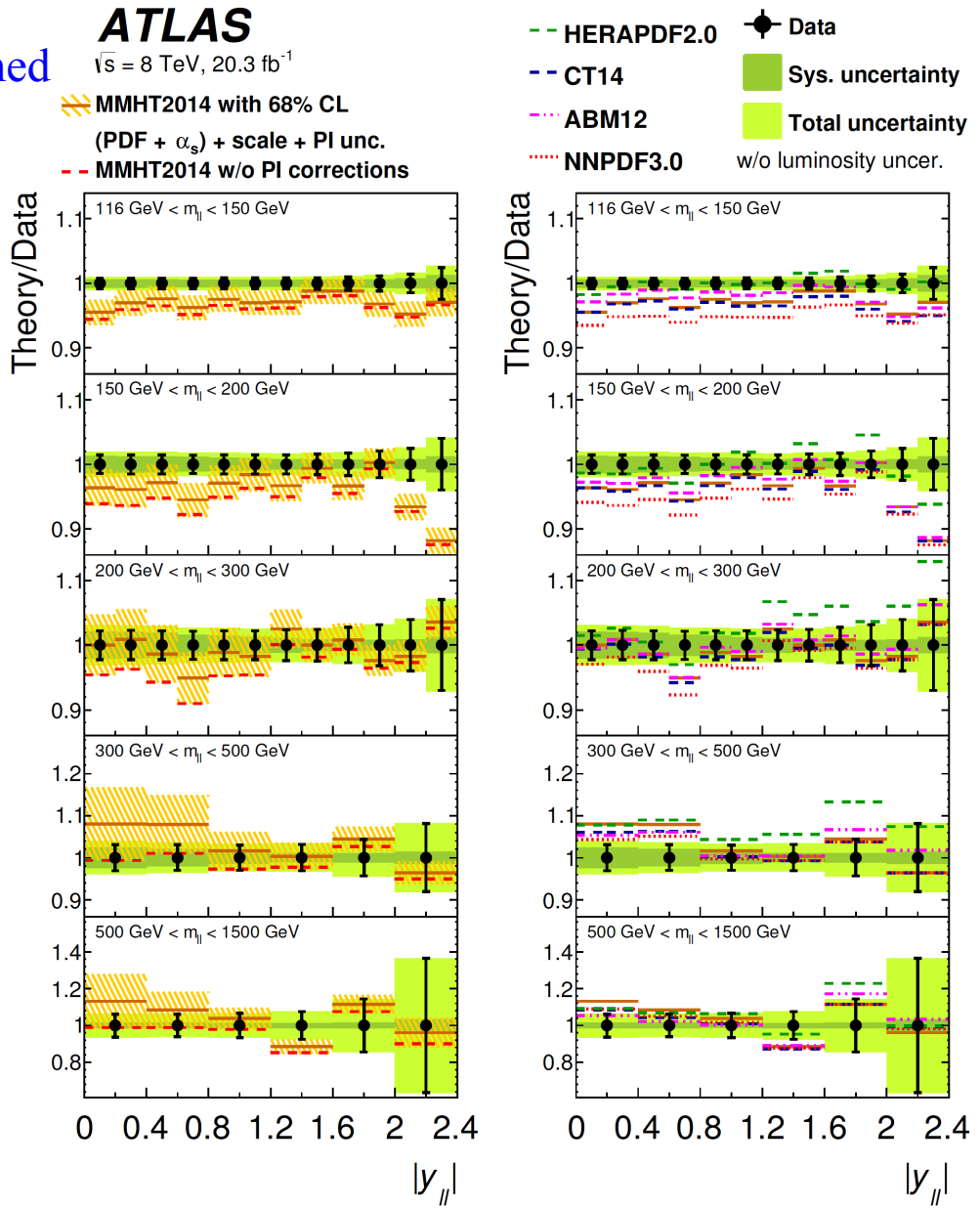
High Mass Drell-Yan at 8 TeV

- Ratio of theoretical calculations to combined double-differential cross section

- Comparison to PDF sets:
  - MMHT2014, CT14, HERAPDF2.0, NNPDF3.0, ABM12
  - ABM12 seems favored

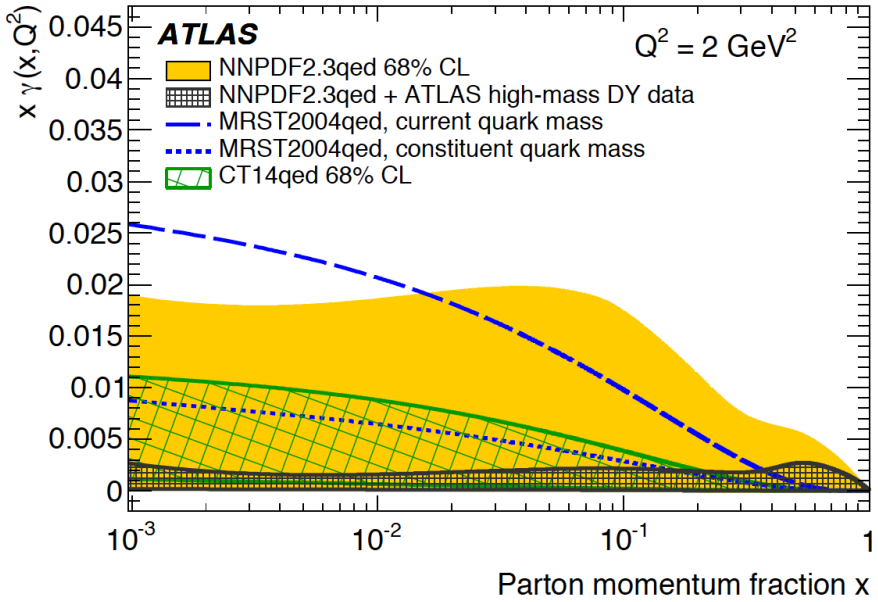
- Contribution of PI process included, estimated at LO using photon PDF
  - 1% at low mass, but reaches 15% at high mass
- Theory uncertainties larger than experimental ones
  - PDF uncert. for $m_{ll} < 200$ GeV
  - PI uncert. for $m_{ll} > 200$ GeV

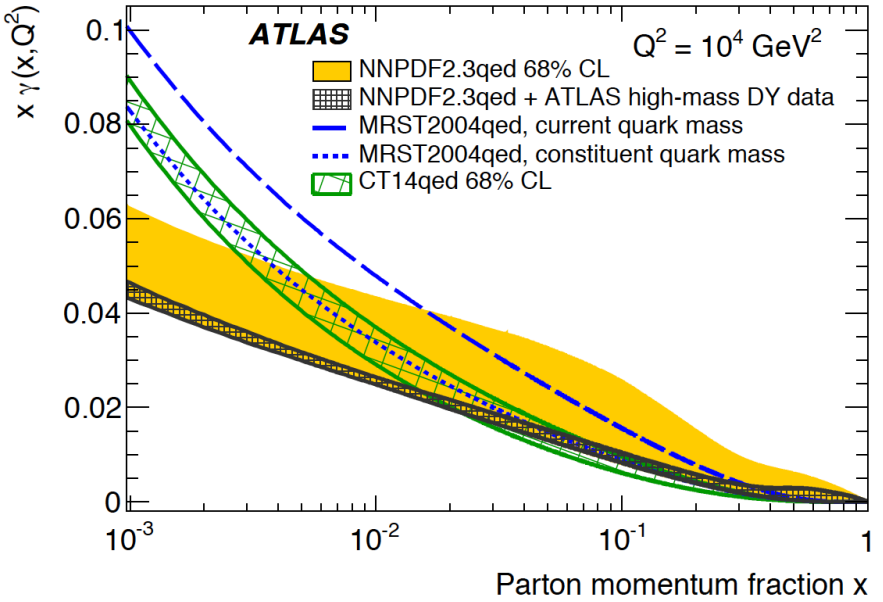
==> potential for significant constraints of proton and photon PDFs



High Mass Drell-Yan at 8 TeV

Impact of the measured cross sections on photon PDF sets





- Inclusion of $d^2\sigma/dm_{ll}d|y_{ll}|$ and $d^2\sigma/dm_{ll}d|\Delta\eta_{ll}|$ data into PDF fits
  - Bayesan reweighting used for MC replica representing NNPDF2.3qed photon PDF based on χ^2 minimization (replicas not describing well get smaller weight assigned)
- Shaded area indicates new PDF after inclusion of the data
- Strong sensitivity to the photon PDF ==> Large reduction of the uncertainty
  - largest sensitivity at small $|y_{ll}|$ and large $|\Delta\eta_{ll}|$

Measurement of the transverse momentum and ϕ^*_η distributions of Drell-Yan lepton pairs

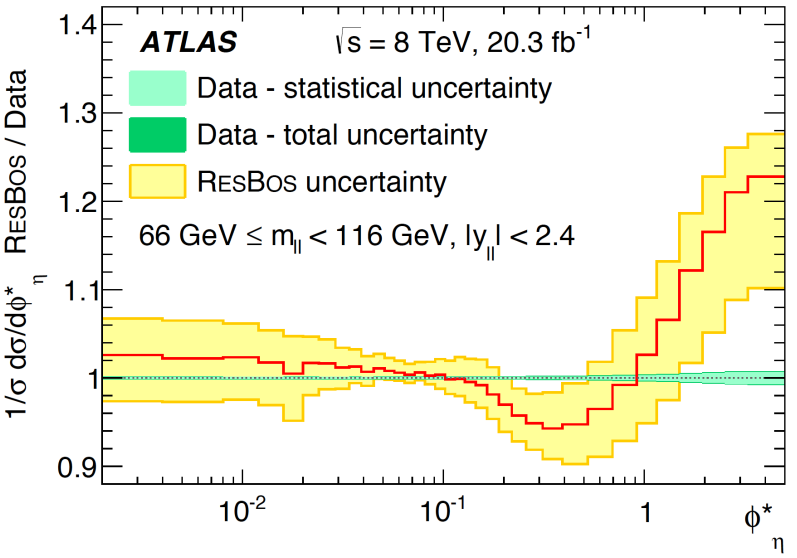
Eur. Phys. J. C 76(5), 1-61 (2016)
arXiv:1512.02192

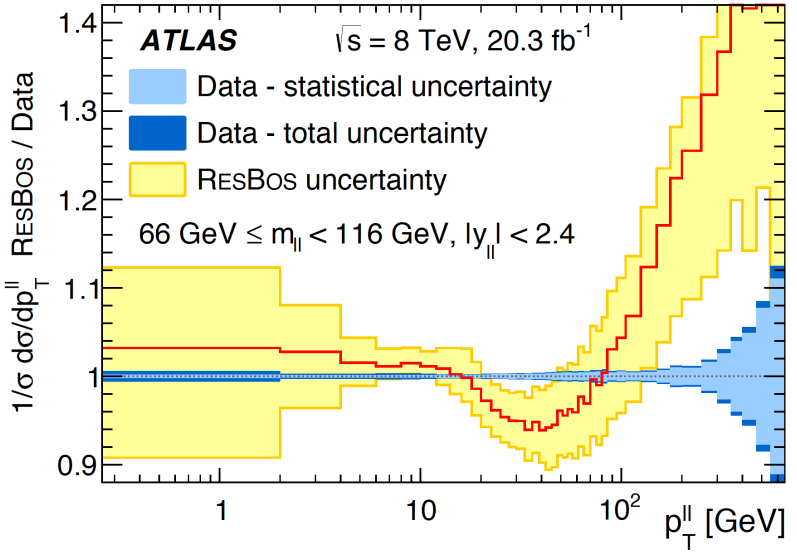
Measurement of p_T & ϕ_η^* @ 8 TeV

Motivations:

- p_T^Z data provides a test for pQCD (NNLO), resummed (NNLO+NNLL), and PS models
- Alternative variable: $\phi^* = \tan\left(\frac{\pi - \Delta\phi}{2}\right) \cdot \sin\left(\theta_\eta^*\right)$
  - where $\cos\left(\theta_\eta^*\right) = \tanh\left(\eta^- - \eta^+\right)/2$
  - ϕ_η^* depend only on the directions of leptons
  - Get rid of momentum calibration uncertainties
- Three l^+l^- mass regions explored, with boundaries: [46, 66, 116, 150 GeV]

x-axis aligned according to $\sqrt{2}M_z\phi^* \approx p_T$





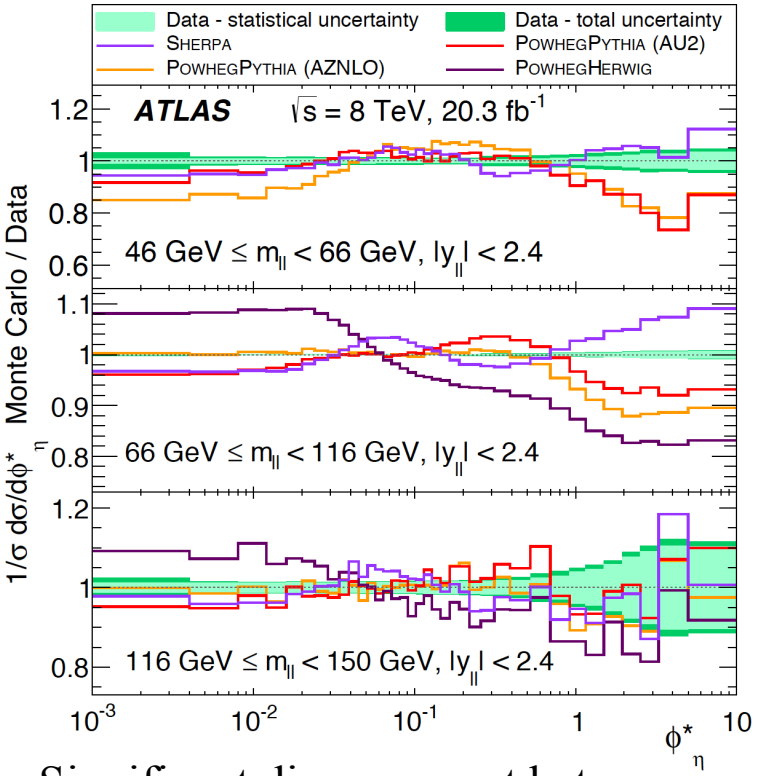
Data at the Z peak compared to ResBos:

- Typical accuracy for $p_T < 30$ GeV: 0.3-0.4%
  - can be used to reduce uncertainties on p_T modeling
- Good agreement at low values
  - non-perturbative effects; soft-gluon emission
- Disagreement at high p_T and ϕ_η^* values
  - emission of hard partons not well reproduced

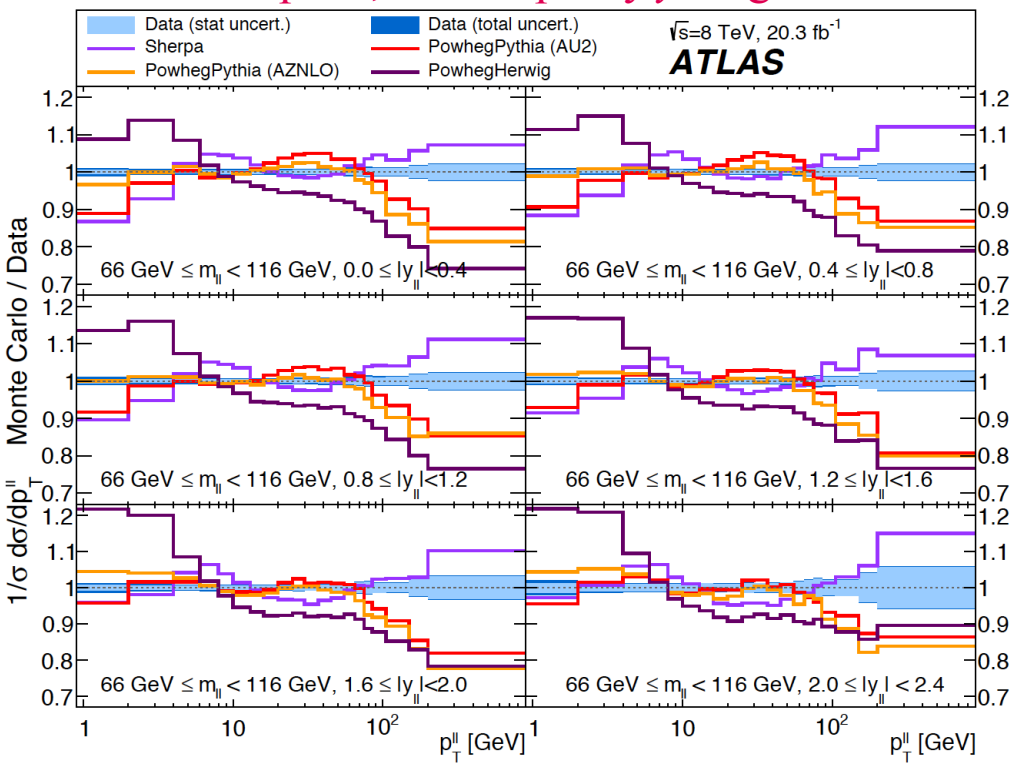
p_T & ϕ_η^* @ 8 TeV: comparison to parton shower approaches

MC generators used: Sherpa; POWHEG + HERWIG; POWHEG + PYTHIA

MC/Data ratio of $(1/\sigma)\, d\sigma/d\phi_\eta^*$ for the 3 mass regions



MC/Data ratio of $(1/\sigma)\, d\sigma/dp_T^{ll}$ at the Z-peak, for 6 rapidity y^{ll} regions



- Significant disagreement between simulation and data in the *Z*-peak region
- Large differences between Sherpa and POWHEG, in particular for large ϕ*

- Agreement not better than 10% for $5 < p_T^{ll} < 100$ GeV
- Best descritpion of data provided by POWHEG+PYTHIA

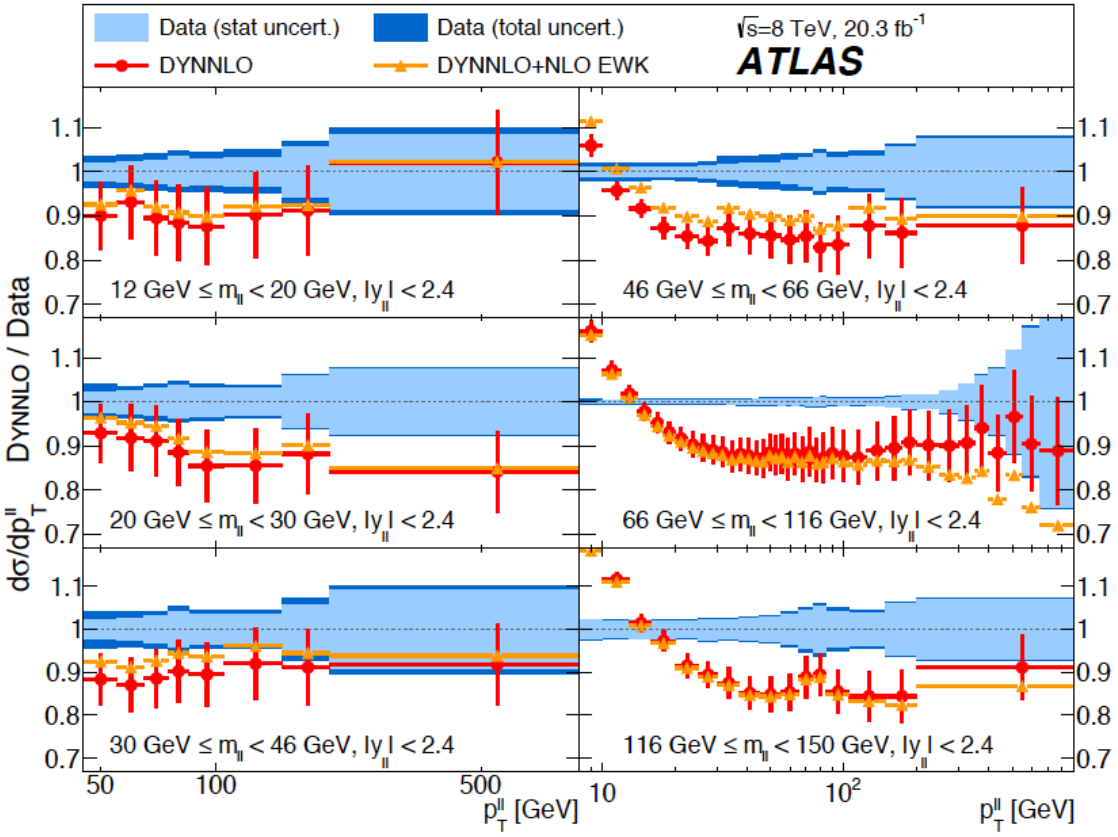
p_T & ϕ_η* @ 8 TeV: comparison to fixed order QCD

Born-level data compared to:

- DYNNLO
- DYNNLO + NLO EW

MC/Data ratio of $(1/\sigma)\, d\sigma/dp_T^{ll}$

(analysis extended at very low m^{ll} regions for y^{ll} <2.4)



- Predictions are not expected to describe the low p_T^{ll} region
  - soft-gluon emissions become important
- For $p_T^{ll} > 30$ GeV:
  - DYNNLO reproduce reasonably well the shape of data
    - systematically ~15% below
  - NLO EW corrections have a very limited impact
  - Recent calculations based on Z+jet @NNLO show improvement

Measurement of angular coefficients in *Z*-boson production

JHEP 08 (2016) 159
arXiv:1606.00689

Angular coefficients in Z-boson production

Motivations:

- Spin correlation between initial quarks and decay leptons
- Probe fixed-order QCD predictions
- Probe parton-shower approach
- Ingredient for future precision EW measurements

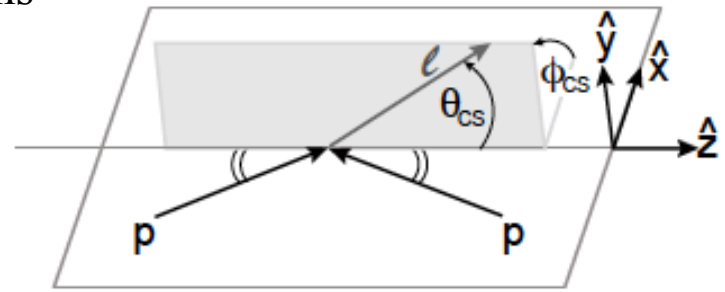
- 5-dimension differential cross section decomposed as a sum of harmonic polynomials $P_i(\cos\theta,\phi)$ times polarization coefficients $A_{0\text{-}7}(p_T^Z, y^Z, m^Z)$.

Unpolarized cross section

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

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

Angles defined in the Collins-Soper Frame



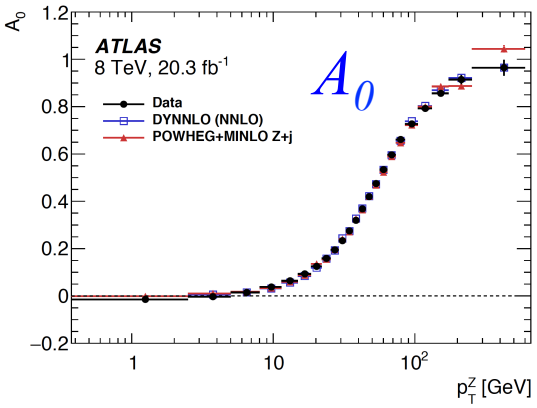
- A_0 Transverse polarization
- A_2 Longitudinal polarization
- A_1 interference between T and L polarizations
- A_3 and A_4 sensitive to the Weinberg angle

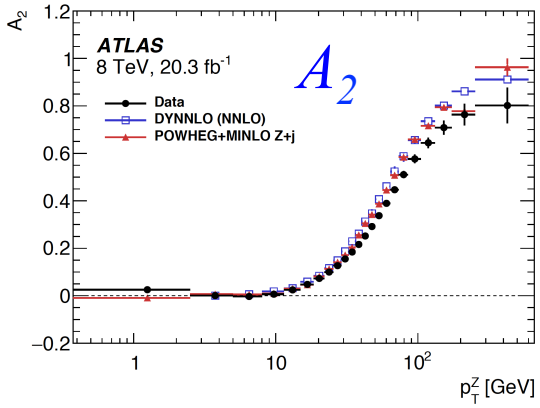
- LO: only A_4 different from zero
- NLO: A_0--A_4 non zero,
  - $A_0 = A_2$ (Lam-Tung relation)
- NNLO: also A_5, A_6, A_7 slightly different from zero at large p_T^Z
  - $A_0 \neq A_2$

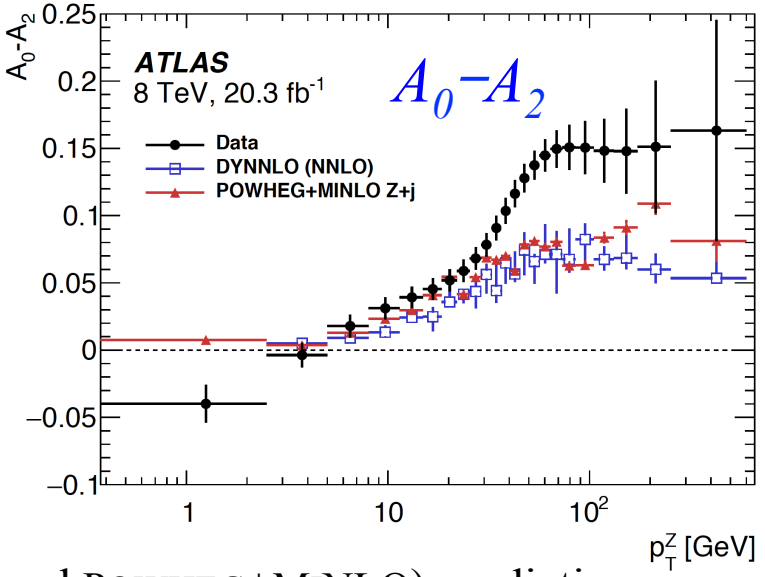
Angular coefficients in Z-boson production: results

- Use 20.3 fb^{-1} of *pp* collisions at 8 TeV
- 3 independent channels:
  - Muons (CC), electrons (CC), electrons (CF) (CC=central-central. CF=central-forward)
  - $80 < m_{ll} < 100$ GeV. Results in three y^Z bin, and y^Z-integrated

- A_i extracted by fitting *templates* of the $P_i(\cos\theta,\phi)$ to the reconstructed angular distributions
- Templates obtained from MC by sculpting the angular distributions according to fiducial acceptance and reconstruction efficiencies

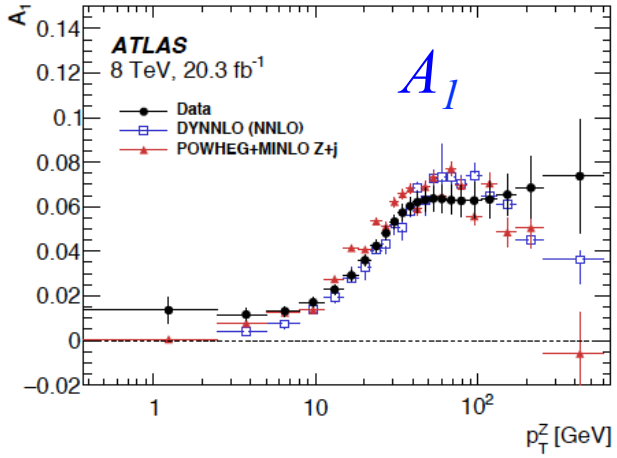


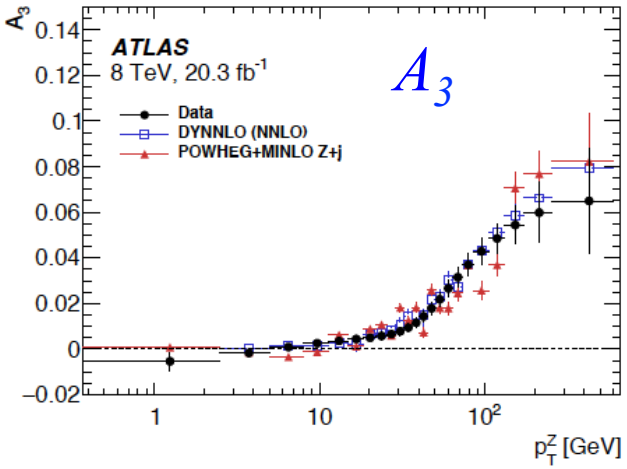


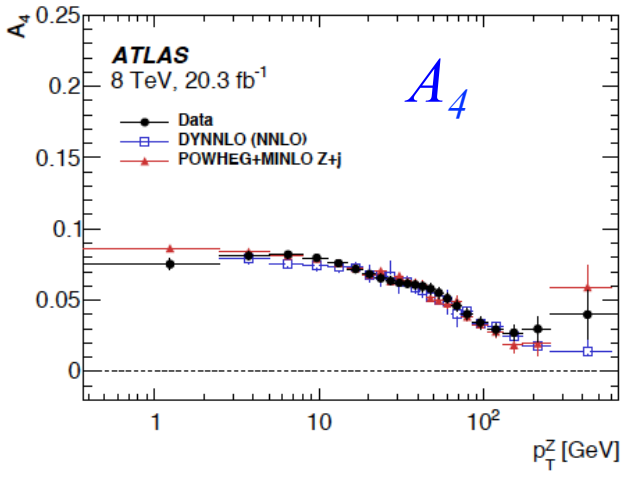


- Data compared to NNLO pQCD with PS (DYNNLO and POWHEG+MINLO) predictions
- Deviations between data and predictions in A_2 (and A_0-A_2) explained by higher-order QCD effects missing in the calculations
- A_0-A_2 different from 0, as expected from theory already at NNLO

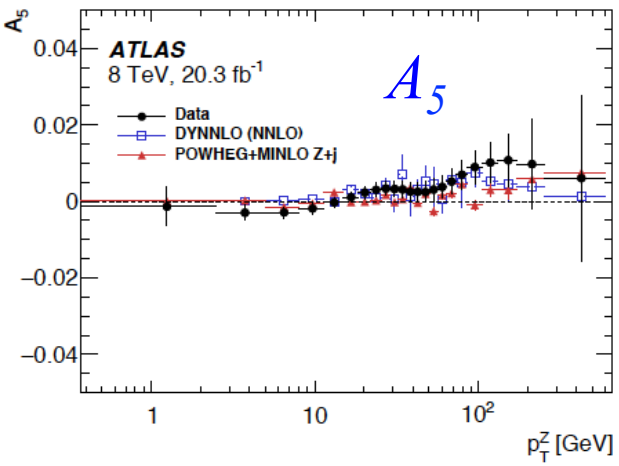
Angular coefficients in Z-boson production: results

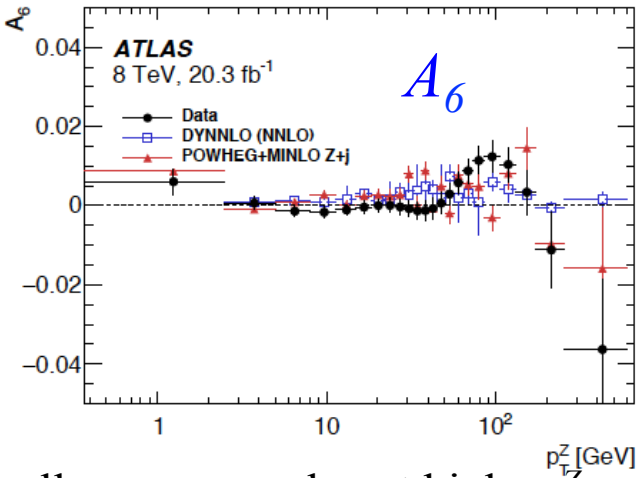


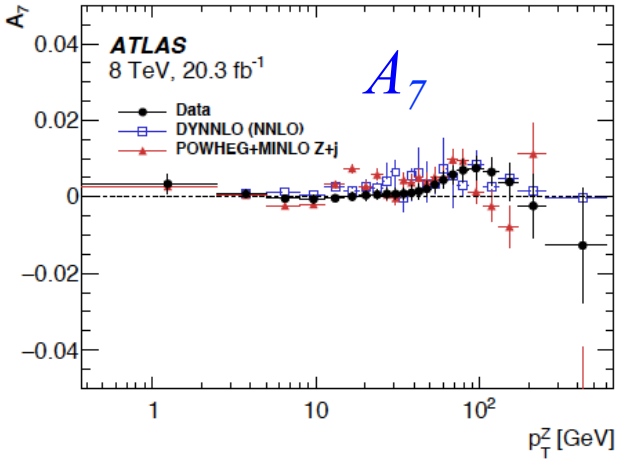




- General data-theory agreement



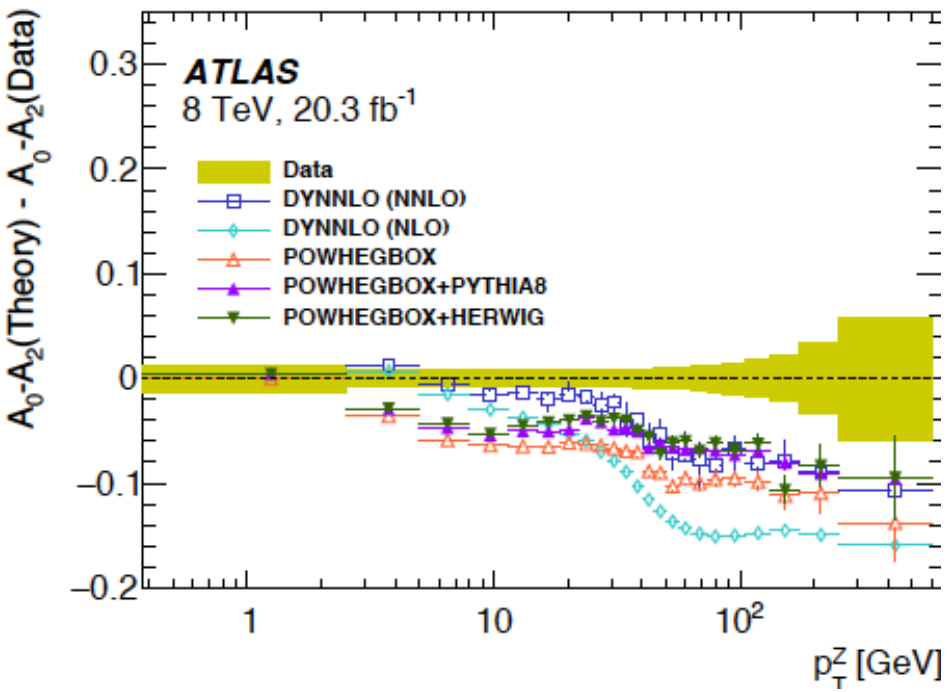


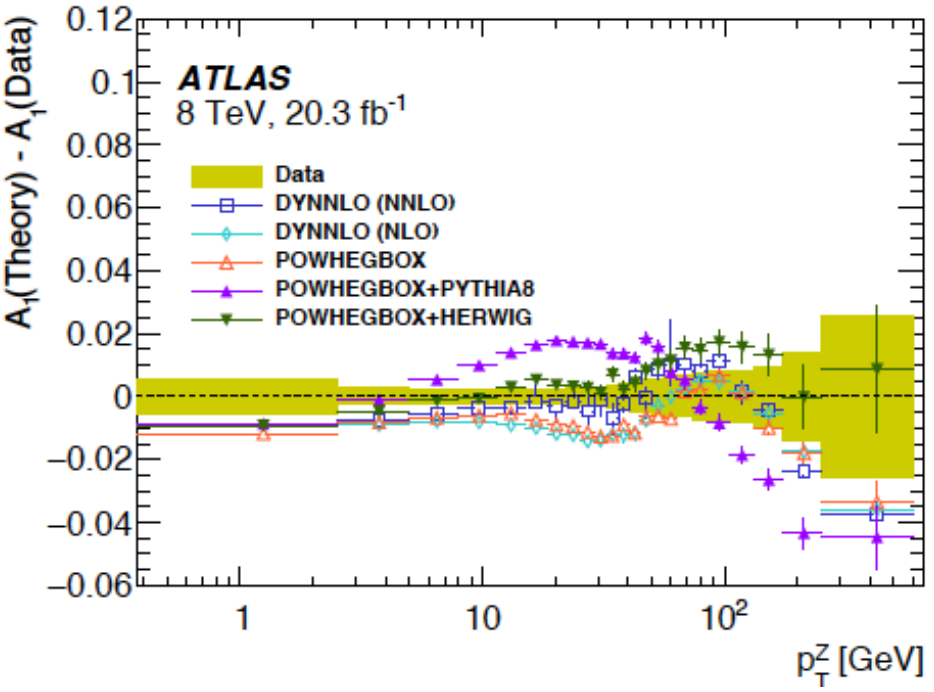


- $A_{5,6,7}$ seems to tend to a small non-zero value at high p_T^Z as expected, but the experimental sensitivity is not enough, yet.

Angular coefficients in Z-boson production: results

- Study of the effects of various PS generators





- Adding a PS simulation to POWHEG brings the simulation closer to data and DYNNLO @ NNLO, for A_0, A_2 and A_0-A_2.
  - Consistent with the assumption that the PS models emulates higher-order effects.
- No generators however describes A_0-A_2.

- Inconsistency between PYTHIA 8 and HERWIG for A_1 over most of p_T^Z range.
  - probe different parton-shower models and matching schemes

Summary

- Measurement of Drell-Yan processes at LHC allows to probe many aspects of QCD in both perturbative and non-perturbative regime
- A few recent results obtained with RUN-I data (at $\sqrt{s}$ =8 TeV) have been shown.

- Double differential high-mass Drell-Yan cross sections
  - Experimental precision better than 1% at lower explored mass regions
  - Data potential to constraint the proton PDFs; Large impact of data on photon PDF
- Precise measurement of p_T^Z and ϕ^* in $Z \rightarrow l^+l^-$
  - Stringent tests of resummation and pQCD calculations
- Precision measurement of the full set of angular coefficients in Z-boson production
  - DYNNLO in agreement with measured coefficients (with exception of A_2 and $A_0 - A_2$)
  - MC generators show different description of data

- Most analysis are going to be updated with the additional data collected at 13 TeV

Summary

- Measurement of Drell-Yan processes at LHC allows to probe many aspects of QCD in both perturbative and non-perturbative regime
- A few recent results obtained with RUN-I data (at $\sqrt{s}$ =8 TeV) have been shown.

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Stay Tuned!
Thank you

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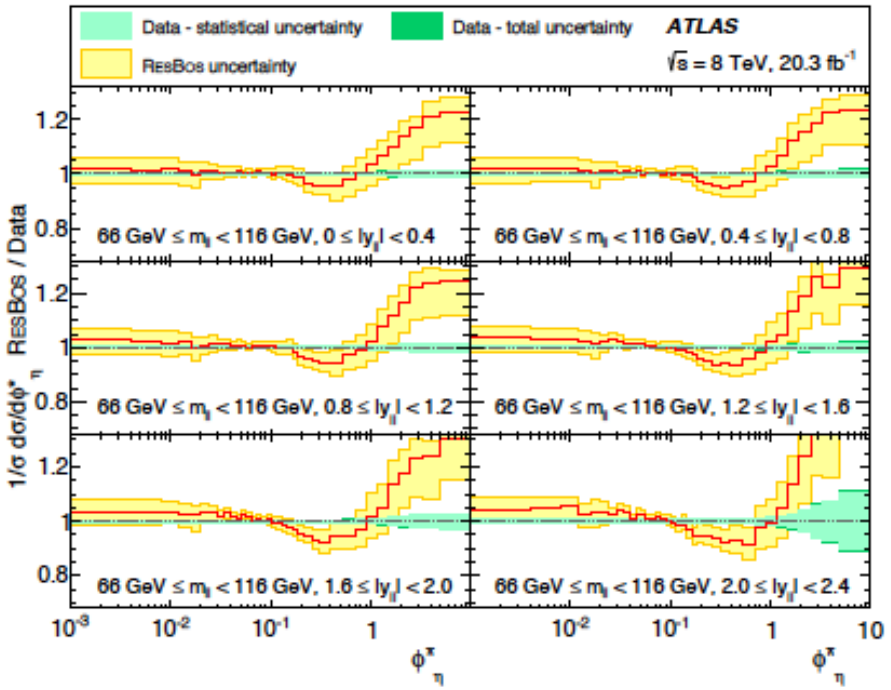
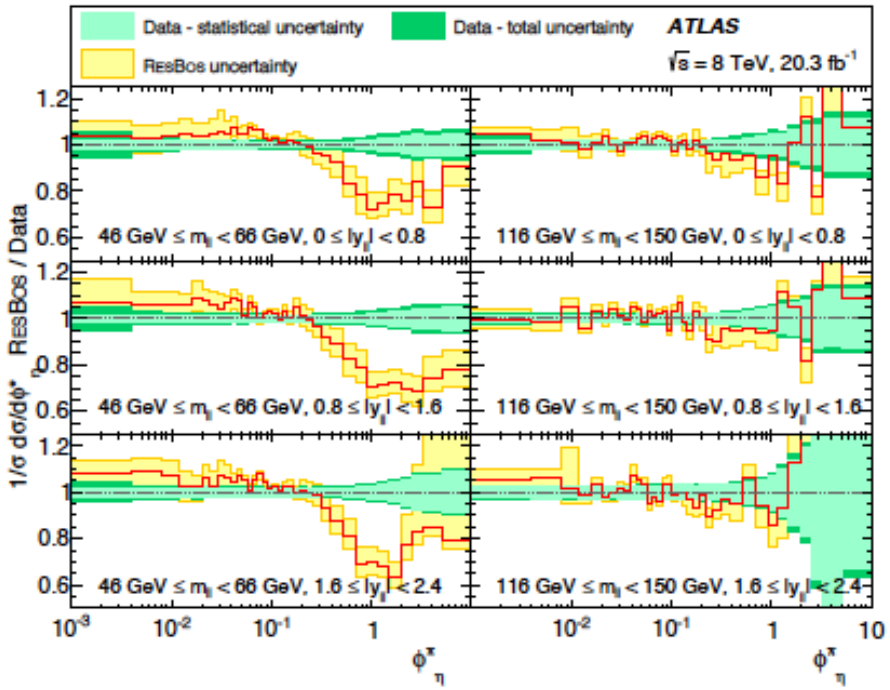
BACKUP
slides

Drell-Yan transverse distributions

at Z-mass peak



below Z-peak above Z-peak



Good agreement with ResBos at low ϕ^* values for all $|y_{ll}|$ and m_{ll} bins

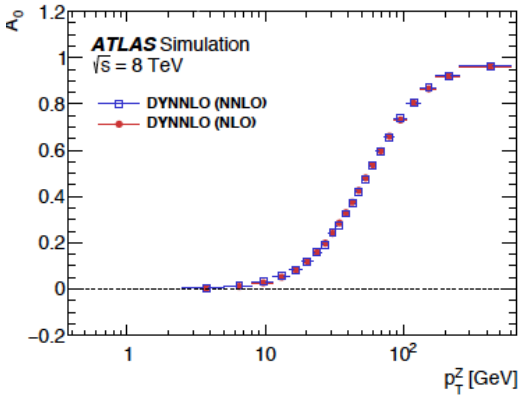
Consistent for above Z-peak region

In Z-peak region disagreement for $\phi^* \geq 2$

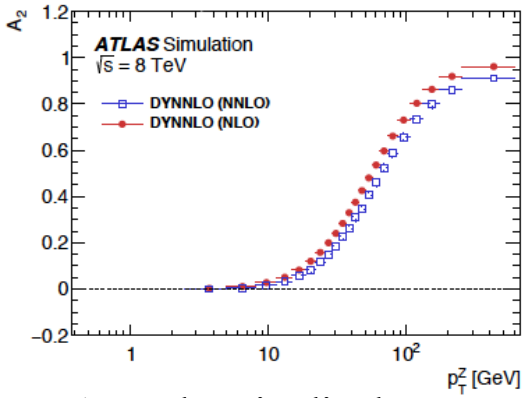
Below Z-peak region disagreement for $\phi^* \geq 0.4$

Lack of NNLO QCD corrections for the γ^* and Z/γ^* interference

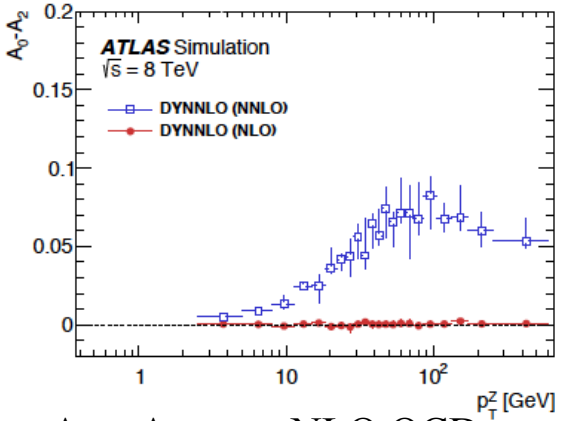
Predictions on angular coefficients : Impact of higher order QCD corrections



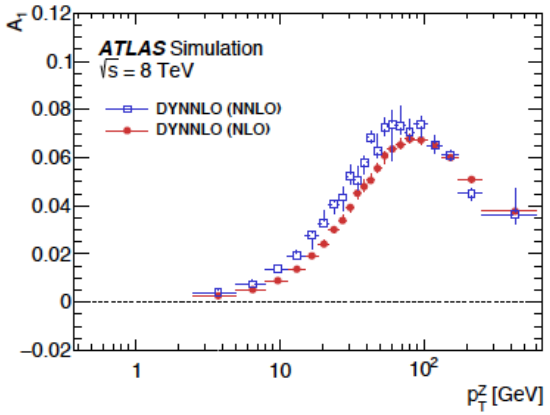
A_0 : transverse polarization



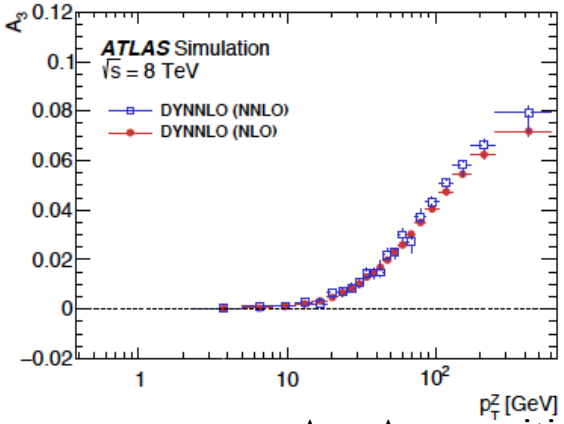
A_2 -> longitudinal polarization

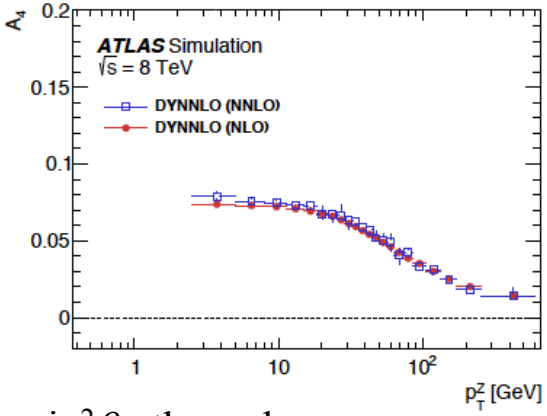


$A_0 = A_2$ up to NLO QCD (Lam-Tung relation)
- $A_0 > A_2$ at higher orders



A_1 : interference between transverse and logitudinal polarization





A_3 e A_4 : sensitive to $\sin^2\theta_W$ through V-A couplings to fermions

- $A_{5,6,7}$ – arise from gluon loops, slightly different from zero at NNLO for large p_T^Z

Study of $W^{\pm} \to l\nu$ and $Z/\gamma^* \to l^+l^-$ inclusive production at 13 TeV

Phys. Lett. B 759 (2016) 601
arXiv:1603.09222

Inclusive production of $W^{\pm} \to l\nu$ and $Z/\gamma^* \to l^+l^-$

- First integrated cross section measurements at $\sqrt{s}$=13 TeV:
  - Based on 81 pb^{-1}
  - $W \to \mu\nu$, $W \to e\nu$: ~900k selected events
  - $Z \to \mu\mu$, $Z \to ee$: ~80k selected events
  - Combination of e and μ channels
  - Comparison with NNLO pQCD, with NLO EW effects included
  - Complementary to ep DIS data from HERA

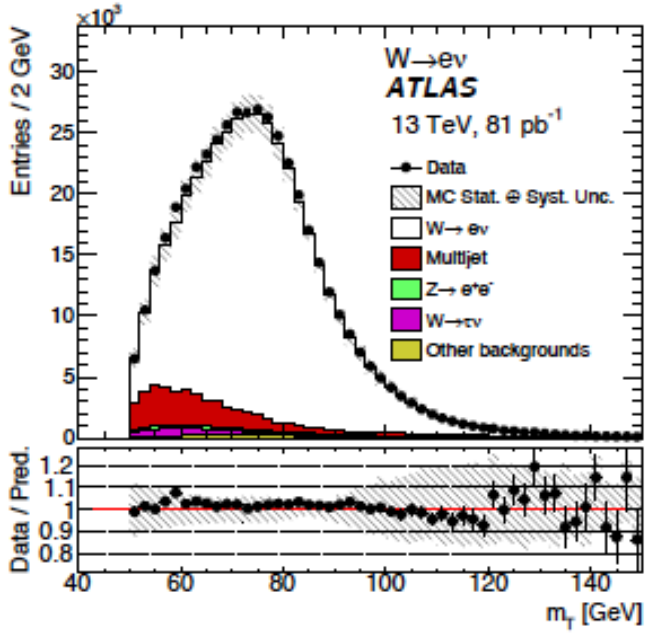
Fiducial volume

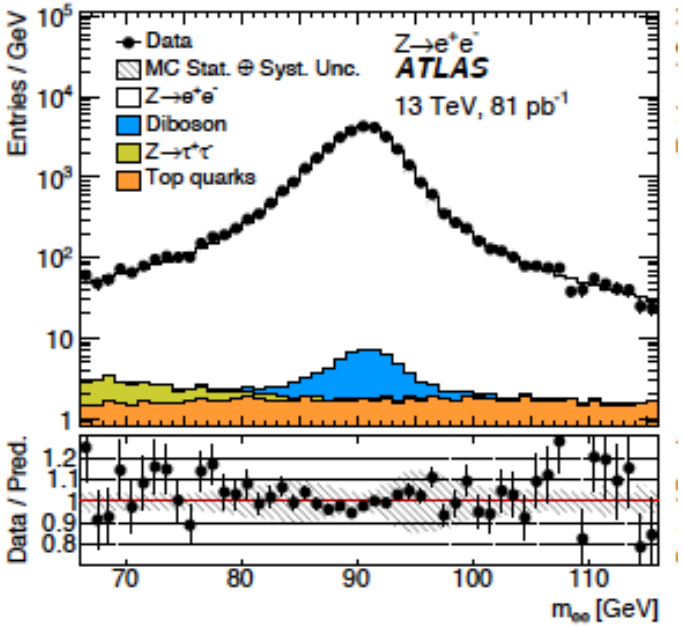
$W \to \mu\nu, e\nu$: $m_T^W > 50\text{GeV}$

$Z \to \mu\mu, ee$: $66\text{GeV} < m_{ll} < 116\text{GeV}$

$p_T^{l,\nu} > 25\,GeV$, $|\eta_l| < 2.5$

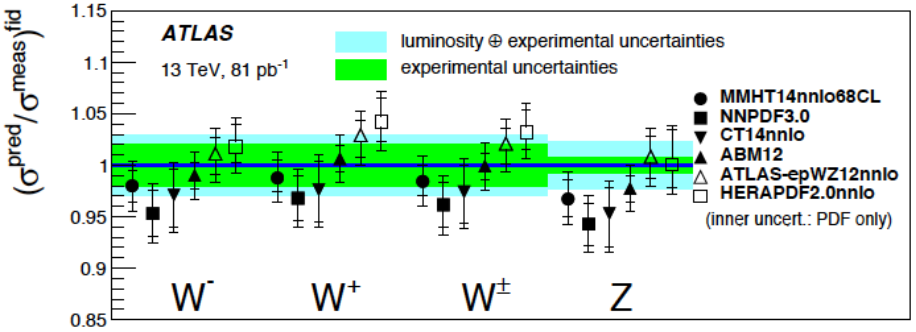
- QCD multi-jet bkgd from data-driven approach
- Other bkgds (mainly EW processes) from MC
- Measure fiducial cross sections
- Extract total cross sections, and ratios of cross sections





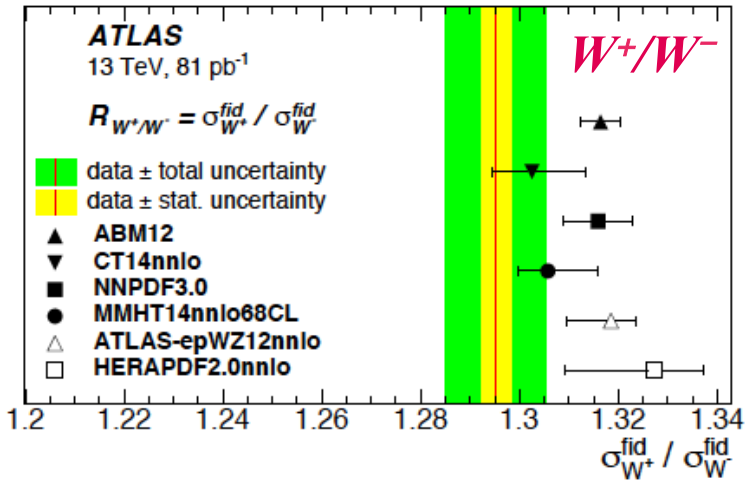
W and *Z* cross sections and ratios

- Ratio of the predicted to measured fiducial cross section for the combined electron and muon channels using various PDFs

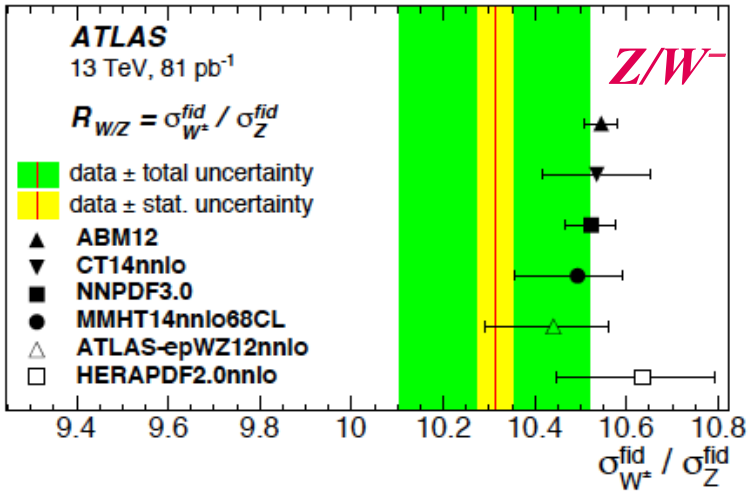


- Improved precision for W and Z:
  - 3% and 1% + 2.1% of luminosity
- The measurements agree well with the predictions

Ratios of fiducial cross sections

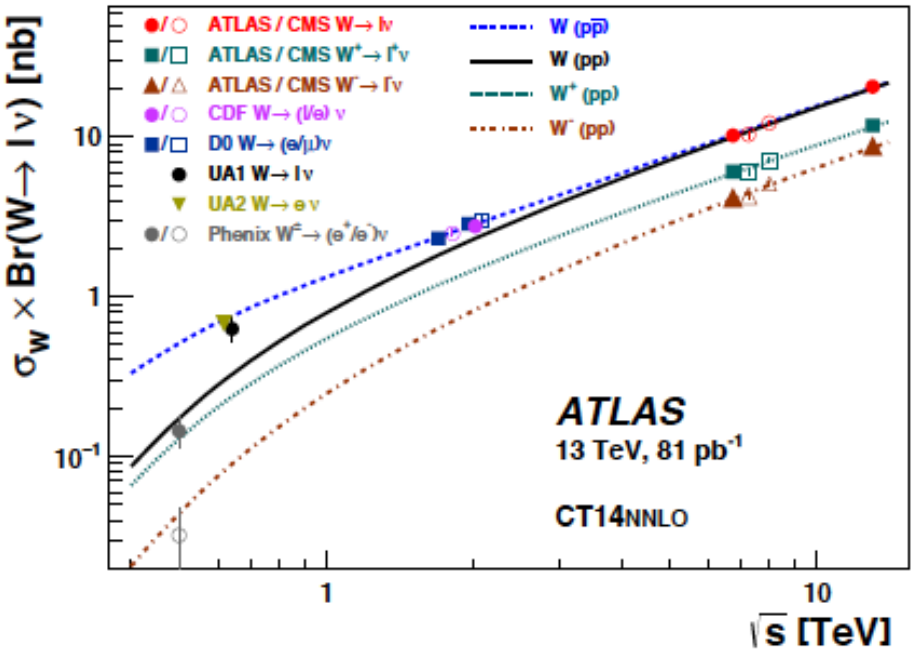


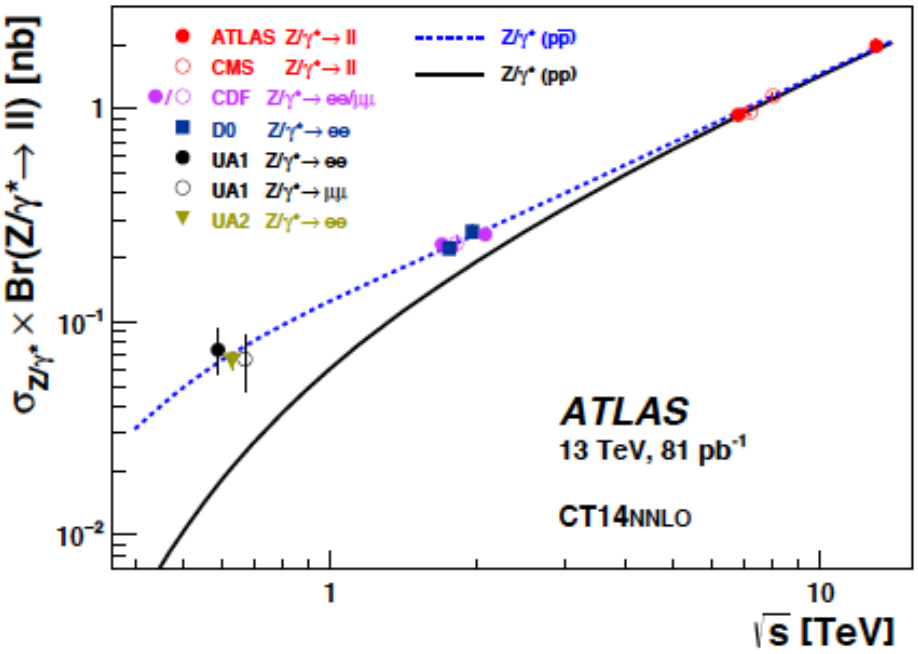
- Sensitive to the low-x $u_v - d_v$ PDFs



- Sensitive to the strange-quark PDF

W and Z cross sections *vs* $\sqrt{s}$





- The measured values of $\sigma \times BF$ compared to the theoretical predictions based on NNLO pQCD calculations
  - Good agreement between data and theory
  - Cross section increase following the expectations (about twice than values at 7 TeV)