Defiducialization: Providing Experimental Measurements for Accurate Fixed-Order Predictions

DIS2021, 14.04.2021, S. Glazov

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Motivation

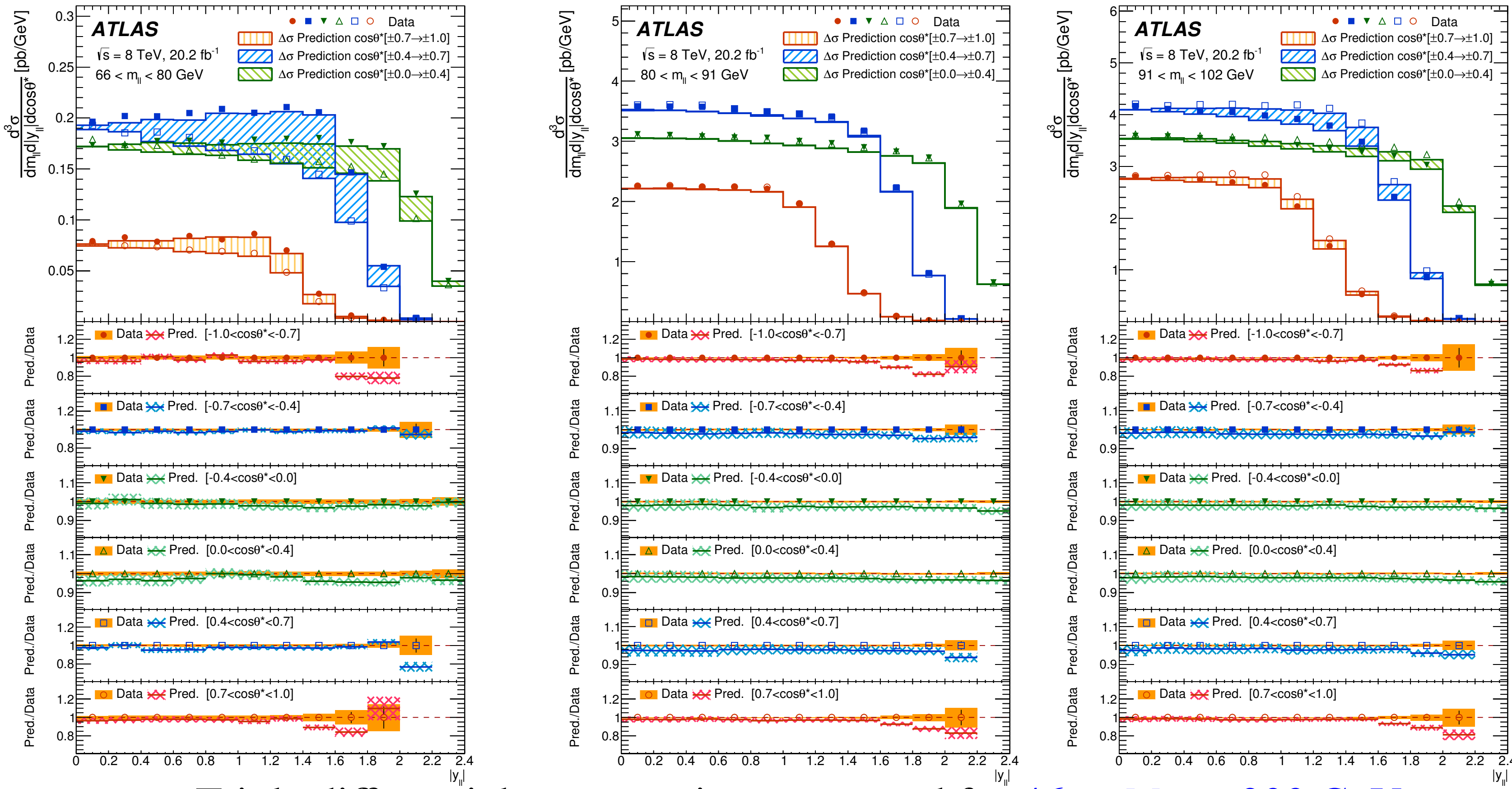
- Presize determination of PDFs requires both accurate data and theory.
- Experimental measurements in fiducial phase space (e.g. $p_T^\ell > 20$ GeV, $|\eta^\ell| < 2.4$) of W, Z production reaches $< 0.5\%$ accuracy
- NNLO theoretical predictions differ as much as 1% for fiducial phase space while they agree significantly better for full phase space (see e.g. arXiv:2104.02400).
- Fixed order predictions may be not optimal for fiducial predictions since the boson p_T distribution is not modeled well.

$\rightarrow$ comparing data to fixed oprder predictions in full phase space may provide more accurate constraints on PDFs.

Possibile experimental improvements

- Perform measurements directly in the full phase space (e.g. ATLAS JHEP08(2016)159).
- Isolate regions with low acceptance, compare to NNLO only high acceptance bins (2 next slides).
- Defiducialization: correct fiducial measurement differential in the boson p_T to the full phase space.

Triple differential cross section $d^3\sigma/dM_{\ell\ell}d|y_{\ell\ell}|d\cos\theta^*$



- Triple differential cross section, measured for $46 < M_{\ell\ell} < 200$ GeV range, for CC and CF topology.
- Simultaneous sensitivity to PDFs and $\sin^2\theta_W$, care needed for pure PDF interpretation.

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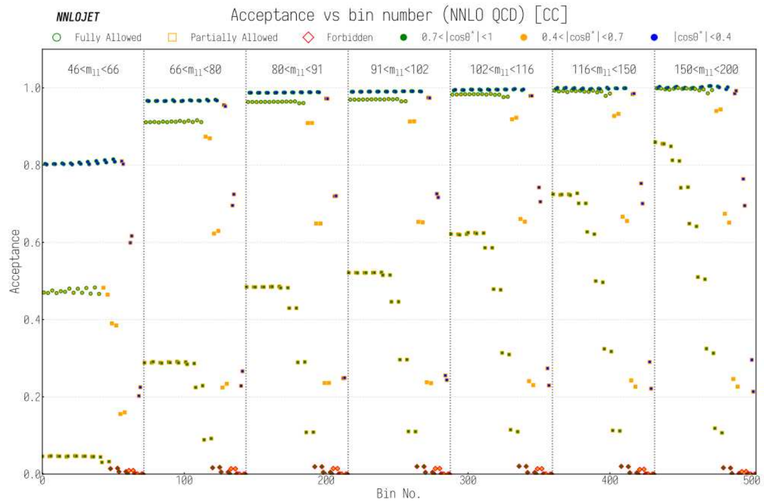
Acceptance for Z3D



- Acceptance, $A = \sigma_{fid}/\sigma_{tot}$ calculated using NNLOjet program at NNLO ($n_{jet} = 0$) shows strong variation vs $|\cos\theta_{CS}|$, $|y_{\ell\ell}|$ and $M_{\ell\ell}$ ("bin number $= 72i_M + 12i_y + i_{\cos\theta^*}$).
- More than 50% of bins at low $|\cos\theta^*|$ and $M_{\ell\ell} > 66$ GeV have $A > 95\%$.
- Restricting cross section data to these bins (which are also more accurate experimentally) allows to mitigate effect of fiducial cuts.
- Other bins can be converted to FBA.

D. Walker, PhD thesis

Only bins with $A > 95\%$ used in MSHT20 fit (arXiv:2012.04684), improving χ^2/dof for the NNLO fit.

Defiducialization: Formalism I

$$\frac{\mathrm{d}^5\sigma}{\mathrm{d}p_T\mathrm{d}y_{\ell\ell}\mathrm{d}m_{\ell\ell}\mathrm{d}\cos\theta\mathrm{d}\phi} = \frac{3}{16\pi}\frac{\mathrm{d}^3\sigma^{U+L}}{\mathrm{d}p_T\mathrm{d}y_{\ell\ell}\mathrm{d}m_{\ell\ell}}\sum_{i=0}^{8} P_i(\cos\theta,\phi)$$

- Factorization of the Z boson production and decay, according to its polarisation.
- The kinematics of the final state leptons is fully determined for given $y_{\ell\ell}, M_{\ell\ell}, p_T$, polarisation.
- The polarisation can be computed at fixed order for given $y_{\ell\ell}, M_{\ell\ell}, p_T$, thus acceptance $A(p_T, y_{\ell\ell}, m_{\ell\ell})$ can be determined with high accuracy (at NNLO for Z+jet using NNLOJET).
- Electroweak corrections break the factorisation, however they are small at the Z peak.

Formalism II

For a measurement differential in p_T and $y_{\ell\ell}$, one can first perform correction to the full phase space and then integrate in p_T.

→ Compare

$$\sigma_{\text{full,theory}} = \int \frac{d\sigma_{\text{theory}}}{dp_T} dp_T \quad \text{vs} \quad \sigma_{\text{full,data}} = \int \frac{d\sigma_{\text{data}}}{dp_T} \frac{1}{A(p_T)} dp_T \,,$$

instead of fiducial cross sections

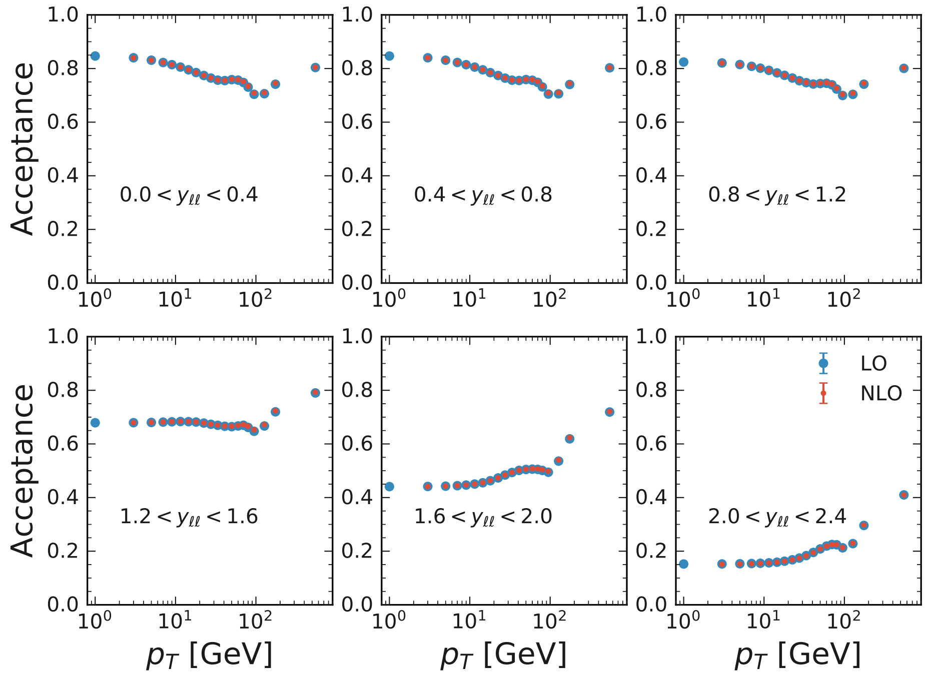
$$\sigma_{\text{fidu,theory}} = \int \frac{d\sigma_{\text{theory}}}{dp_T} A(p_T) dp_T \quad \text{vs} \quad \sigma_{\text{fidu,data}} = \int \frac{d\sigma_{\text{data}}}{dp_T} dp_T \,.$$

Both approaches require accurate modeling of $A(p_T)$, however the first approach does not required accurate modeling of the p_T distribution.

Input data

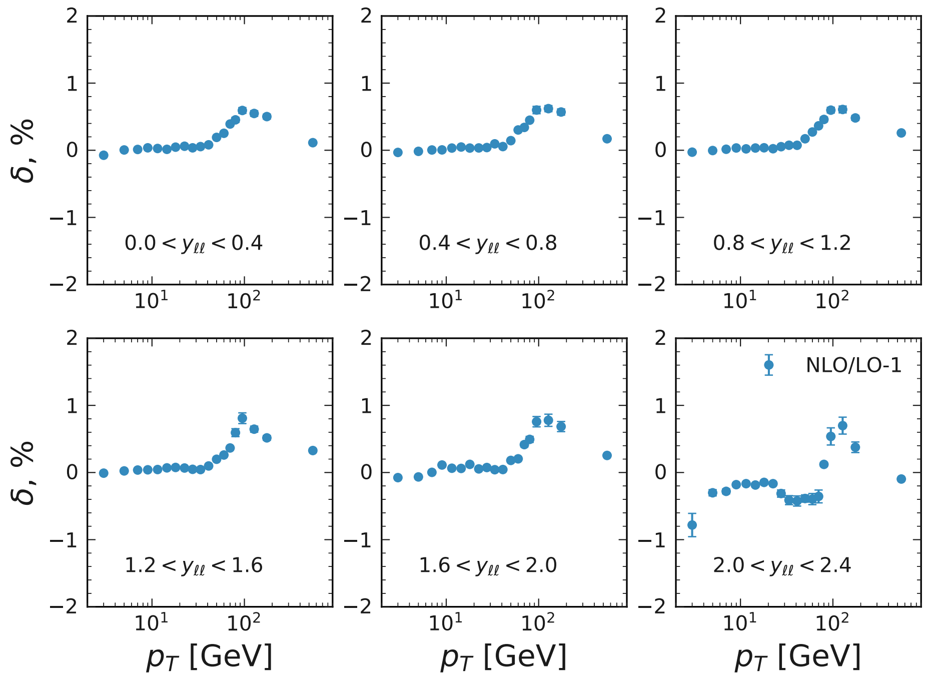
- ATLAS Z p_T measurement at $\sqrt{s}$ = 8 TeV: EPJC76 (2016) 292.
- For the Z peak, the measurement is differential in p_T and $y_{\ell\ell}$
- Binning in $y_{\ell\ell}$ is rather fine: 0.4 between 0 and 2.4. Binning in p_T starts with narrow 2 GeV bins, 20 bins in total up to 900 GeV
- Measurement is performed in the fiducial phase space defined by $p_T^\ell > 20$ GeV and $|\eta^\ell| < 2.4$ cuts.
- All data tables are from HEPDATA, data are rescaled by 20.3/20.2 to account luminosity update. Luminosity uncertainty is 1.9%.

Acceptance vs p_T



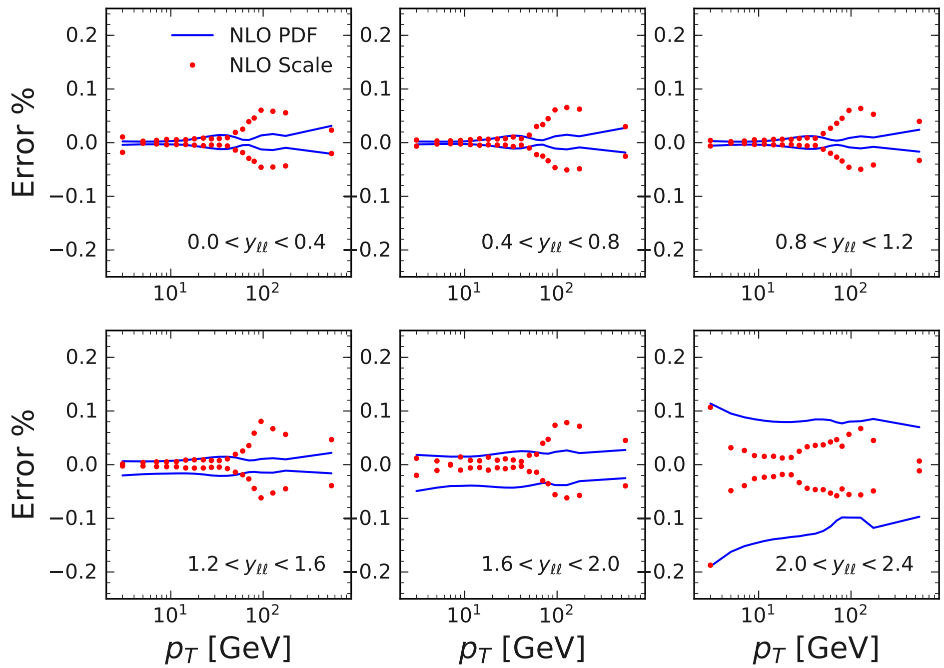
- Compute acceptance correction using MCFM v6.8, interfaced to APPLGRID using Z+jet predictions with $p_T^{\rm jet} > 1$ GeV
- Perform calculations at LO ($O(\alpha_S)$) and NLO ($O(\alpha_S^2)$), use CT14NNLO set.
- Stat. errors for LO are negligible, small for NLO (20000 CPU hours).

NLO/LO correction for the acceptance



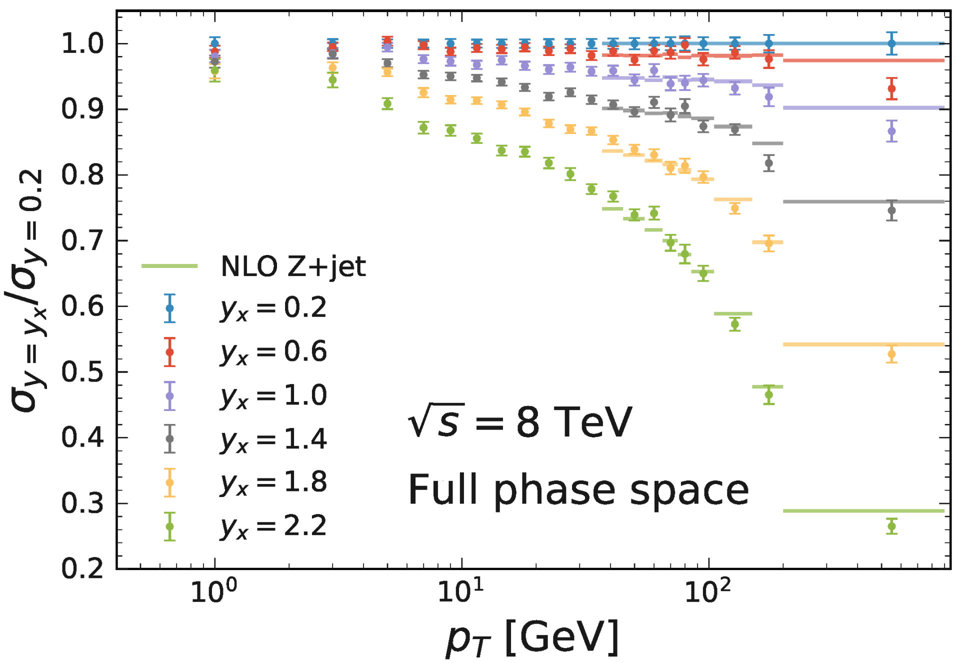
- Compare LO and NLO caluclations in terms of δ = NLO/LO − 1.
- Small correction < 1%: main effect on acceptance is from A_0 for which the leading $q\bar{q}$ and $q(\bar{q})g$ diagrams are already present at LO.
- For bin $0 < p_T < 2$ GeV, acceptance is determined as $Acc(0) = Acc(0)_{\mathrm{LO}} \frac{Acc(1)_{\mathrm{NLO}}}{Acc(1)_{\mathrm{LO}}}$

Acceptance PDF and scale uncertainties



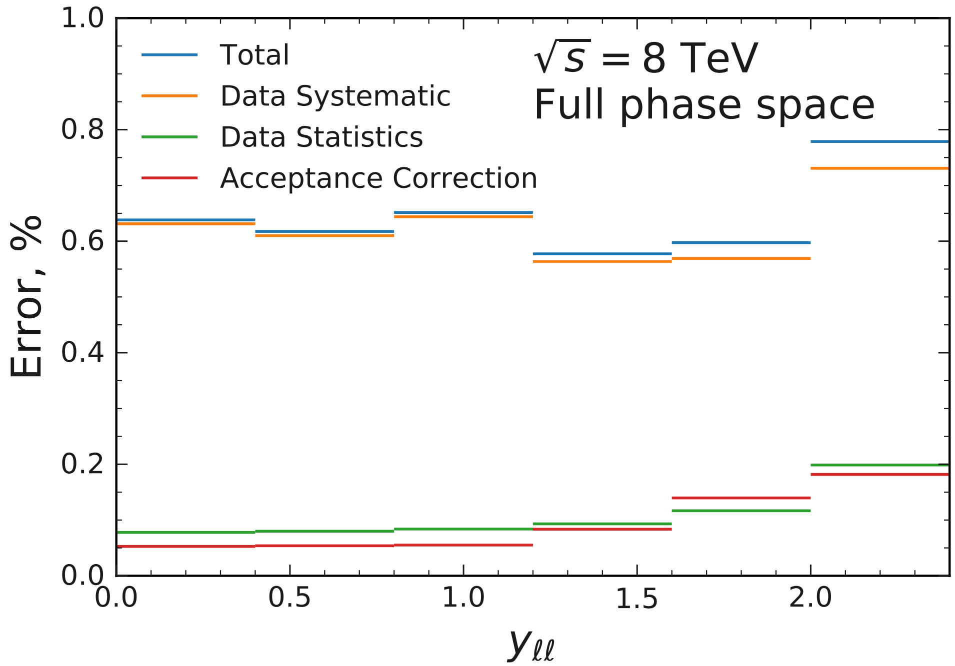
- PDF uncertainty from CT18ANNLO PDF set
- Scale uncertainty from the envelope method
- It is verified, that for most of PDFs central values of the acceptance are within the PDF error band.

Full phase-space data vs p_T



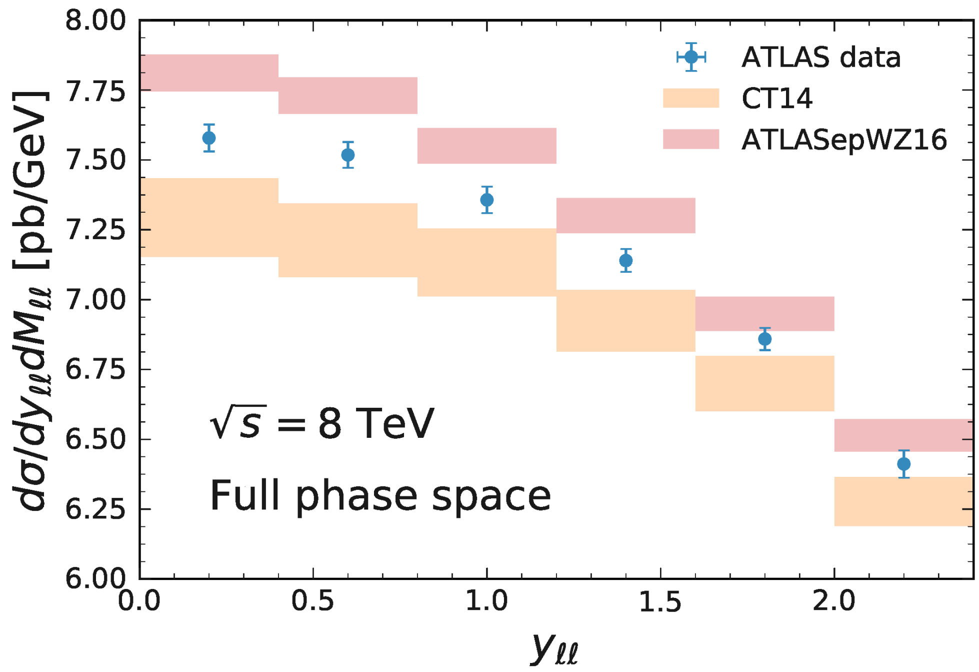
- Given smallness of the uncertainties of the acceptance correction, correct the measurement to full phase space.
- Compare ratios of p_T distribution for different $y_{\ell\ell}$ bins to $0 < y_{\ell\ell} < 0.4$ bin between data and NLO prediction. Reasonable agreement for $p_T > 35$ GeV.

Decomposition of uncertainties for y_Z in full phase space



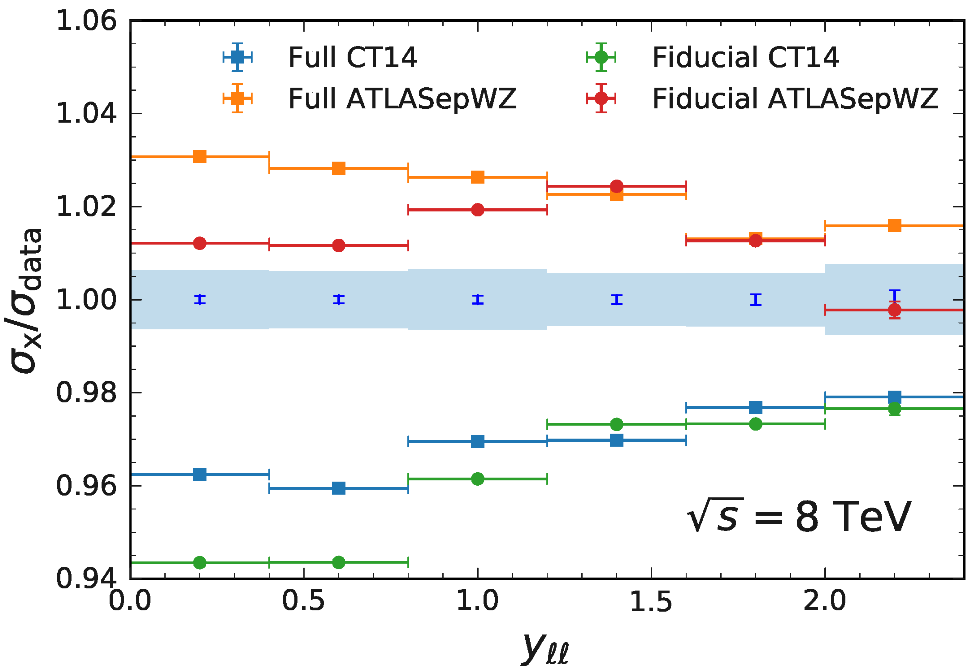
- Integrate full acceptace p_T distributions to obtain full phase space $y_{\ell\ell}$.
- Statistical uncertainties are propagated by sum in quadrature, correlated systemtic – linearly.
- Extrapolation uncertainties are similar to stat., approaching max 0.2% for highest y.

Data vs CT14 and ATLASepWZ16



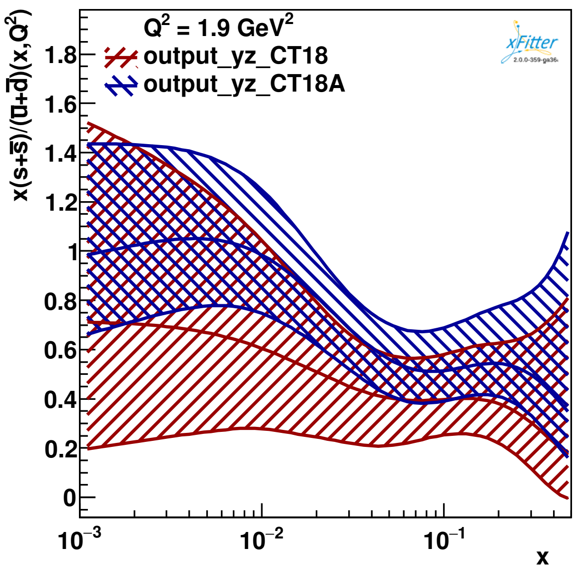
- Compare full phase space $y_{\ell\ell}$ between data and NNLO ($O(\alpha_S)$) predictions for inclusive Z production computed using MCFM v9.
- Predictions based on CT14 (ATLASepWZ16) undershoot (overshoot) the data.
- Difference in uncertainties since only EIG set is used for ATLASepWZ16 based prediction.

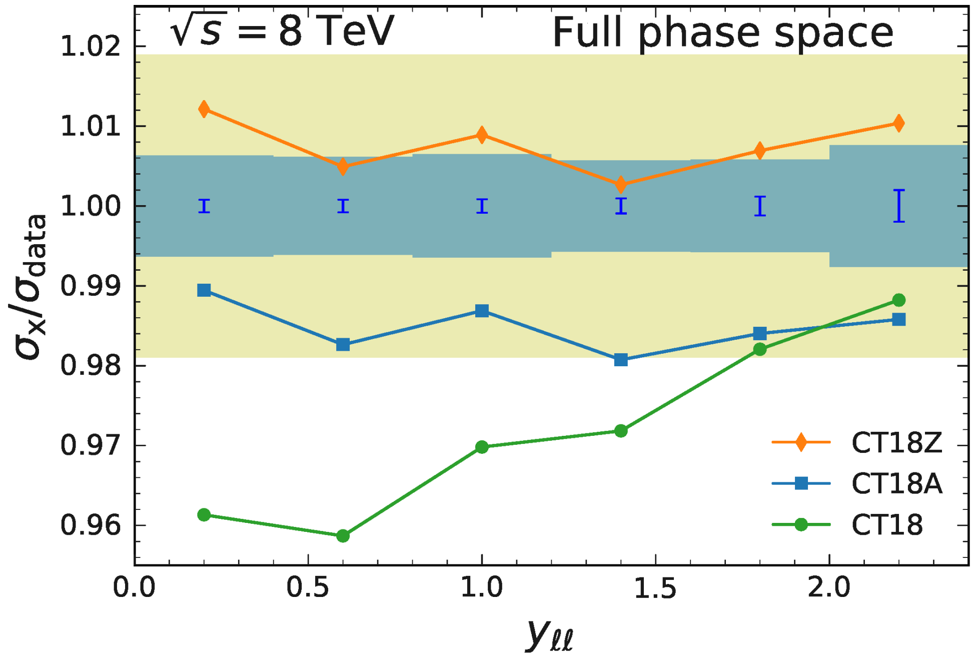
Full and fiducial cross sections vs predictions



- The differences are easier to see using ratios. It is also interesting to compare ratios of the fiducial measurements to the fiducial predictions, for the same data.
- For CT14, full phase space ratio is closer to unity. At low y the difference between full and fiduical ratios is as large as 2%: $\rightarrow$ sizable impact of fiducial correction.

Data vs CT18x predictions



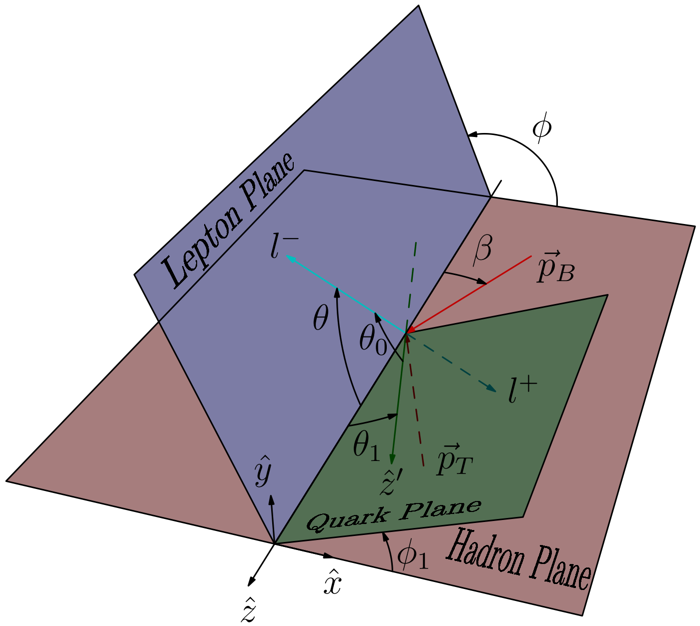


- Compare full phase space data to NNLO predictions based on CT18x PDF sets. CT18A and CT18Z use ATLAS 7TeV W, Z measurement leading to increased strange-quark sea distribution.
- CT18A and CT18Z provide better description of the 8TeV data.

Summary

- Proposal to use measured in data p_T distribution and acceptance calculated at fixed order QCD to correct to the full phase space.
- Tested using ATLAS $\sqrt{s} = 8$ TeV measurement differential in p_T and $y_{\ell\ell}$.
- Acceptance correction uncertainties are subleading vs experimental.
- There is a significant up to 2% difference for comparisons between data to NNLO theory predictions when doing them in full vs fiducial phase space.
- Full phase space comparisons show improved agreement between data and predictions based on CT14 PDF set
- The best agreement is with CT18A, CT18Z PDF sets which have unsupressed strange-quark distribution for $x < 0.01$.

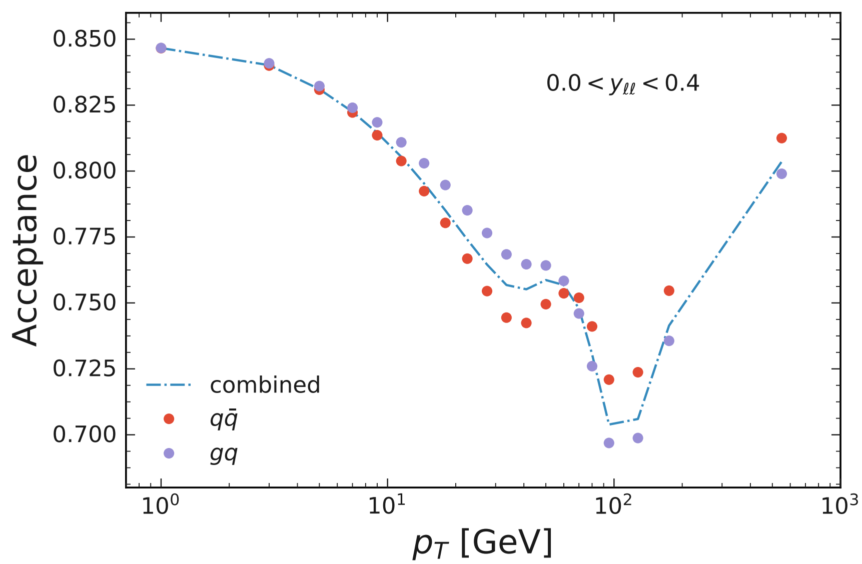
Polarisation vs p_T



- For $q\bar{q} \to \gamma^*/Z \to \ell^+\ell^-$ process, for massless spin 1/2 quarks and leptons, $d\sigma/d\cos\theta_0 = 1 + \cos^2\theta_0 + A_4 \cos\theta_0$ where the $\hat{z}'$ axis is along $q\bar{q}$ direction.
- Due to radiation, $\hat{z}'$ is misaligned vs $\hat{z}$ in Collins-Soper (or lab) rest frame by θ_1.
- Using $\cos\theta_0 = \cos\theta\cos\theta_1 + \sin\theta\sin\theta_1\cos(\phi - \phi_1)$ and $A_0 = \overline{\sin^2\theta_1}$
- Generically, $0 \le A_0 \le 1$ and $A_0 \sim p_T^2/M_{\ell\ell}$ for small p_T and ~ 1 for large.

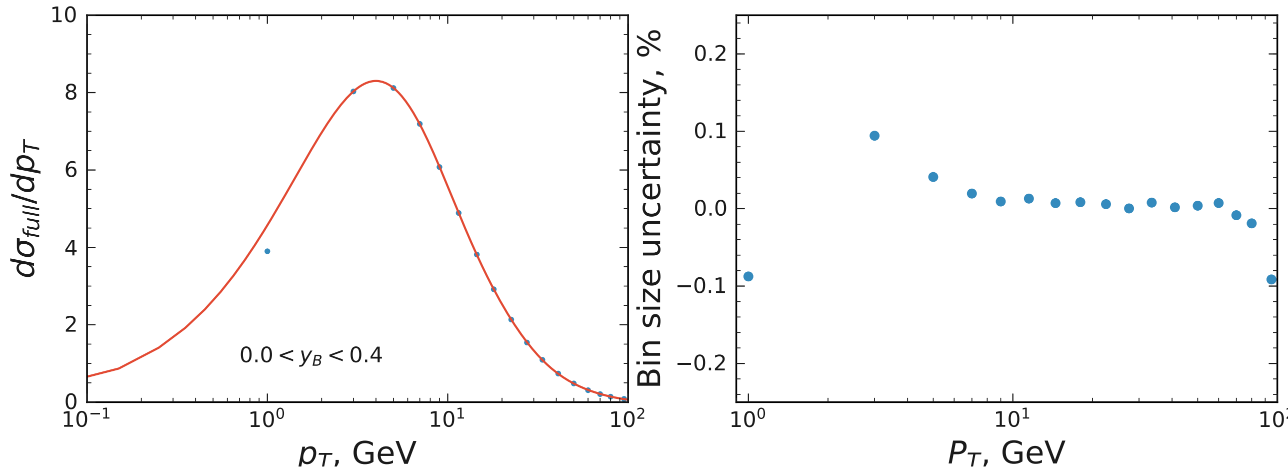
arXiv:1511.08932

Acceptance for $q\bar{q}$ and qg



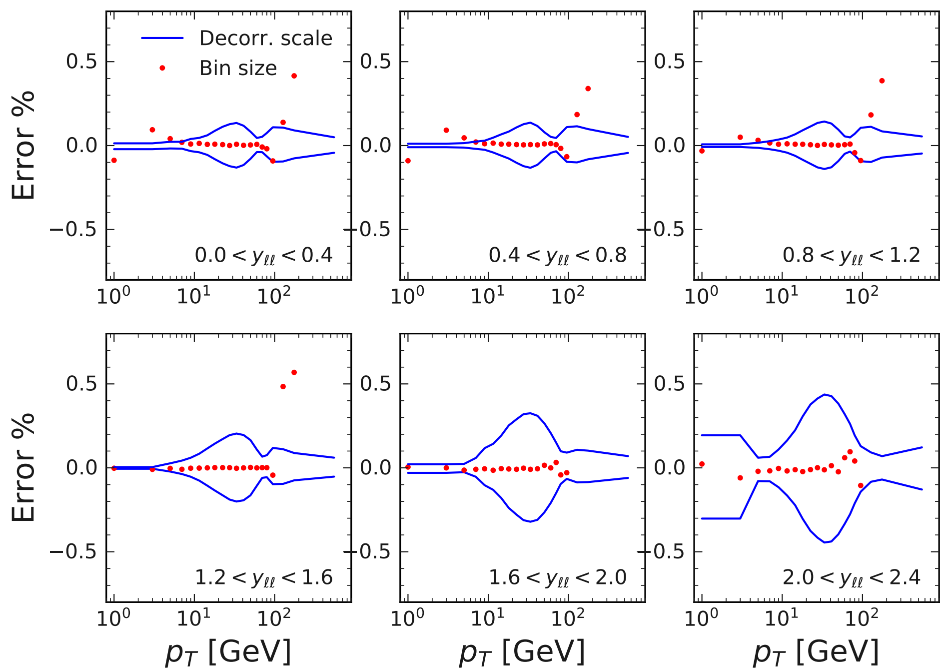
- Using APPLGRID, separate $q\bar{q}$ and qg contributions, corresponding to extreme values of $\sin^2\theta_1$.
- Higher order corrections may have different structure for these two contributions, to be concervative treat scale variations as uncorrelated.

Bin size effects



- Acceptance varies as much as 0.7% per 2 GeV for low p_T bins where fixed order and data p_T distributions disagree strongly $\rightarrow$ potential uncertainty from variation within bin, bin size effect.
- Estimated by reweighting fixed order to data.
- Data corrected to full phase space, fitted by $p_T \sum_i A_i \exp(-B_i p_T)$
- LO theory re-weighted in 0.1 GeV bins, full variation of acceptance is taken as uncertainty.

Decorrelated scale and bin-size effect uncertainties



- Decorrelation of scale variations for $q\bar{q}$ and qg subprocesses lead to visible increase of uncertainties, up to 0.5%. It would be interesting to check this with higher order calculations (NNLOJET).
- Bin size effects are 0.1% for low P_T and become sizable at high p_T, but remain small vs data statistics.