Procedure for improved data to fixed order QCD comparison

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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
- Fixed order predictions may be not optimal for fiducial predictions since the boson p_T distribution is not modeled well.

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

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

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

instead of fiducial cross sections

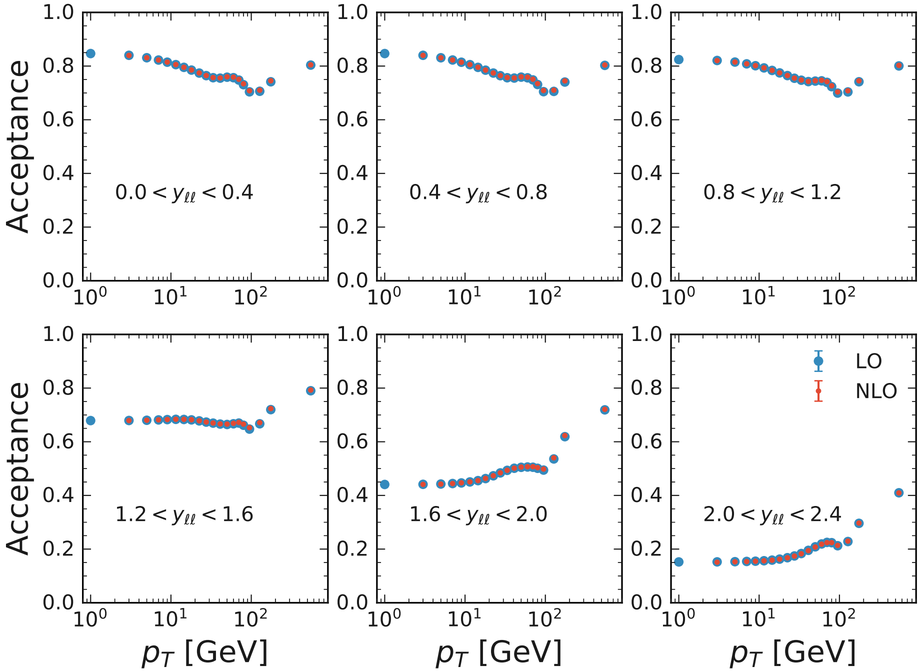
$$\sigma_{\text{fidu,theory}} = \int \frac{\mathrm{d}\sigma_{\text{theory}}}{\mathrm{d}p_T}A(p_T)\mathrm{d}p_T \quad \text{vs} \quad \sigma_{\text{fidu,data}} = \int \frac{\mathrm{d}\sigma_{\text{data}}}{\mathrm{d}p_T}\mathrm{d}p_T\,.$$

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

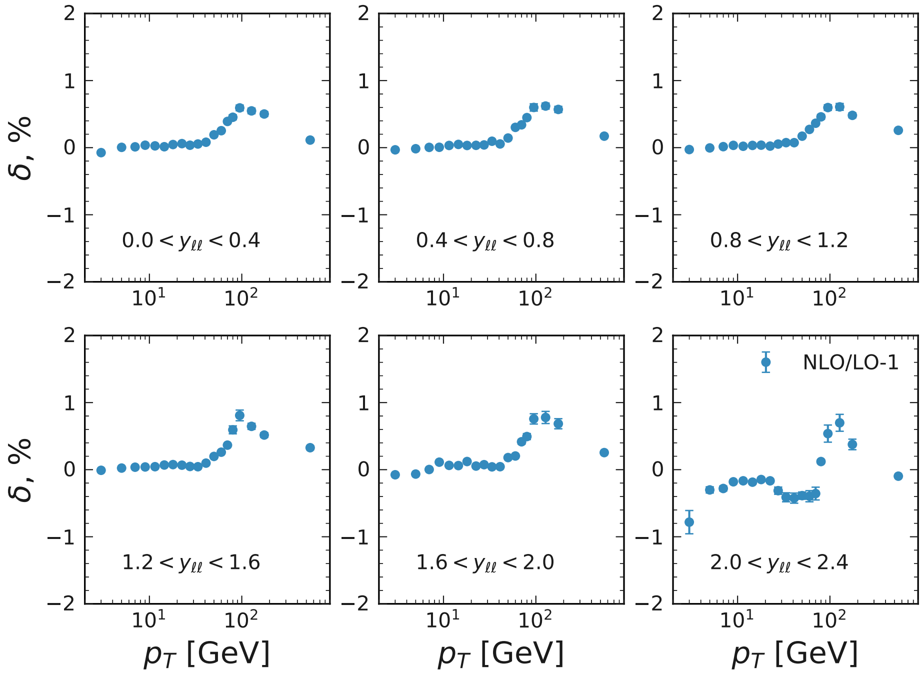
- ATLAS Z p_T measurement at $\sqrt{s} = 8$ TeV: EPJC76 (2016) 292.
- For the Z peak, the measurement is differential in p_T and $y_{\ell\ell}$
- Binning in $y_{\ell\ell}$ is rather fine: 0.4 between 0 and 2.4. Binning in p_T starts with narrow 2 GeV bins, 20 bins in total up to 900 GeV
- Measurement 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



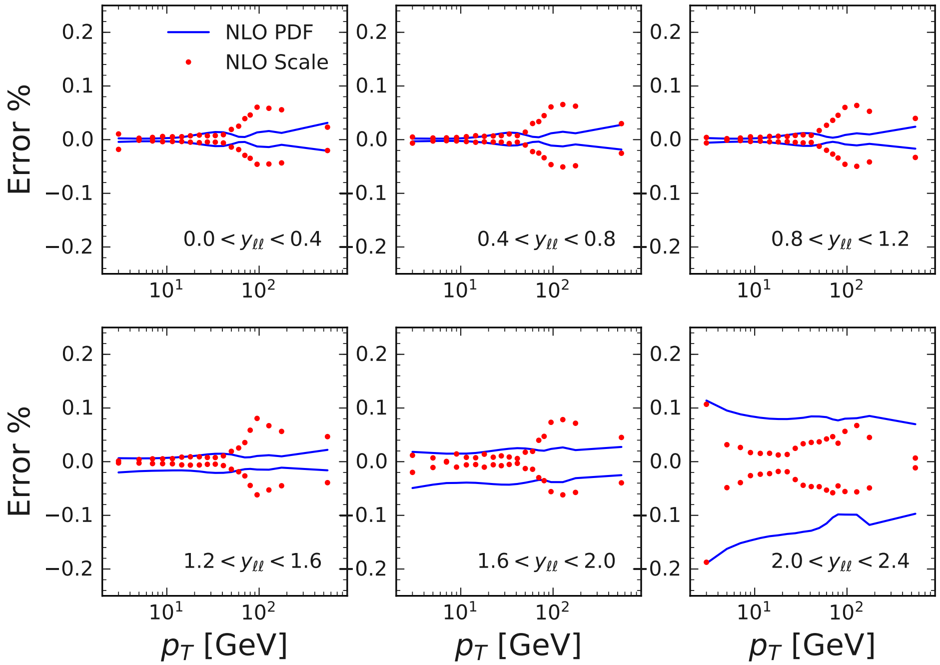
- Compute acceptance correction using MCFM v6.8, interfaced to APPLGRID using Z+jet predictions with $p_T^{\text{jet}} > 1$ GeV
- Perform calculations at LO ($O(\alpha_S)$) and NLO ($O(\alpha_S^2)$), use CT14NNLO set.
- Stat. errors for LO are negligible, small for NLO (20000 CPU hours).

NLO/LO correction for the acceptance



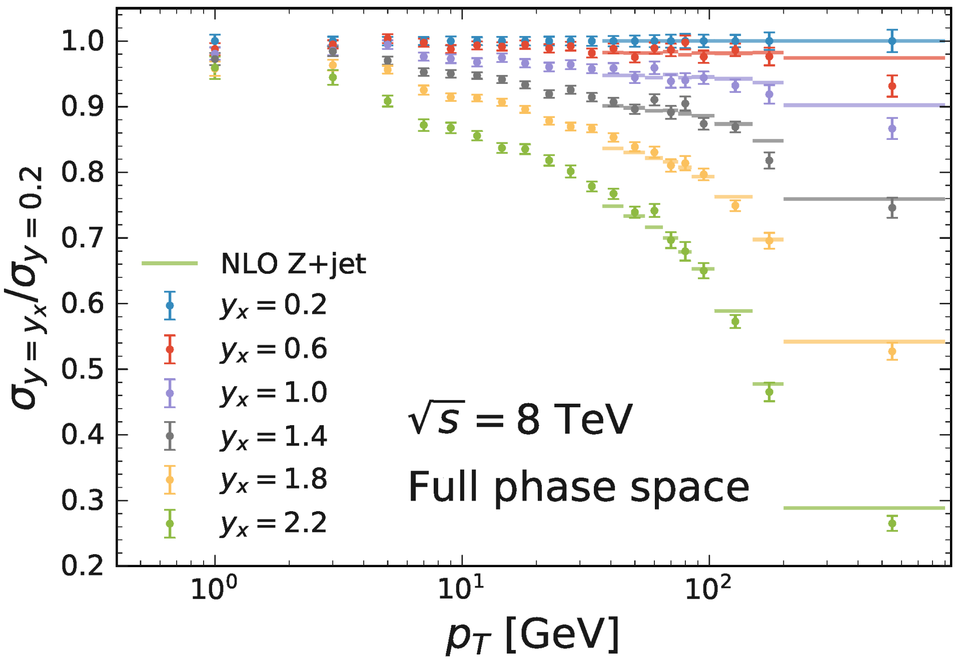
- Compare LO and NLO caluclations in terms of δ = NLO/LO − 1.
- Small correction $< 1\%$: main effect on acceptance is from A_0 for which the leading $q\bar{q}$ and $q(\bar{q})g$ diagrams are already present at LO.
- For bin $0 < p_T < 2$ GeV, acceptance is determined as $Acc(0) = Acc(0)_{\mathrm{LO}}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

Acceptance PDF and scale uncertainties



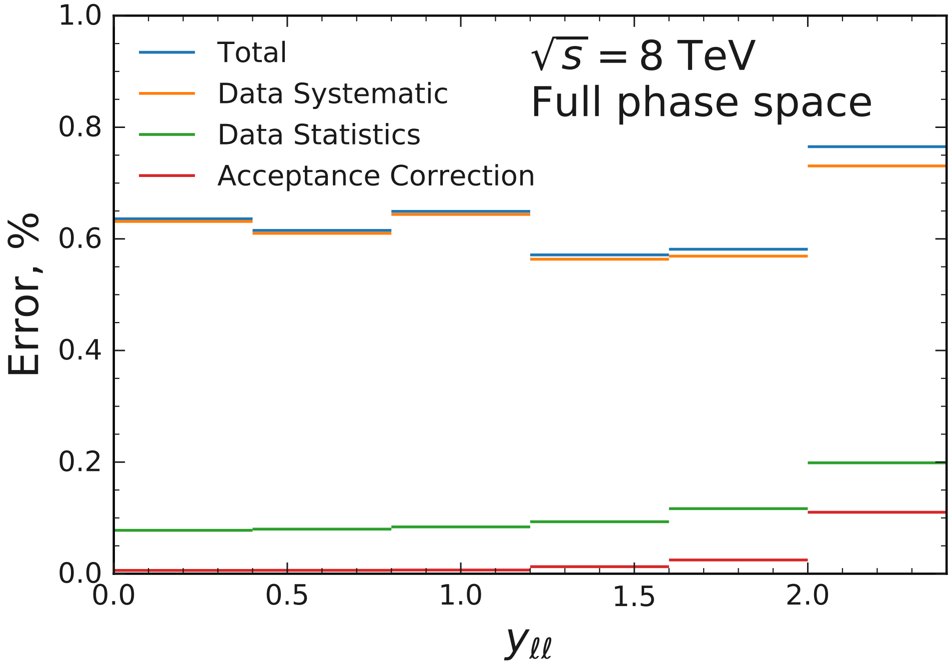
- PDF uncertainty from CT18ANNLO PDF set
- Scale uncertainty from the envelope method
- It is verified, that for most of PDFs central values of the acceptance are within the PDF error band.

Full phase-space data vs p_T



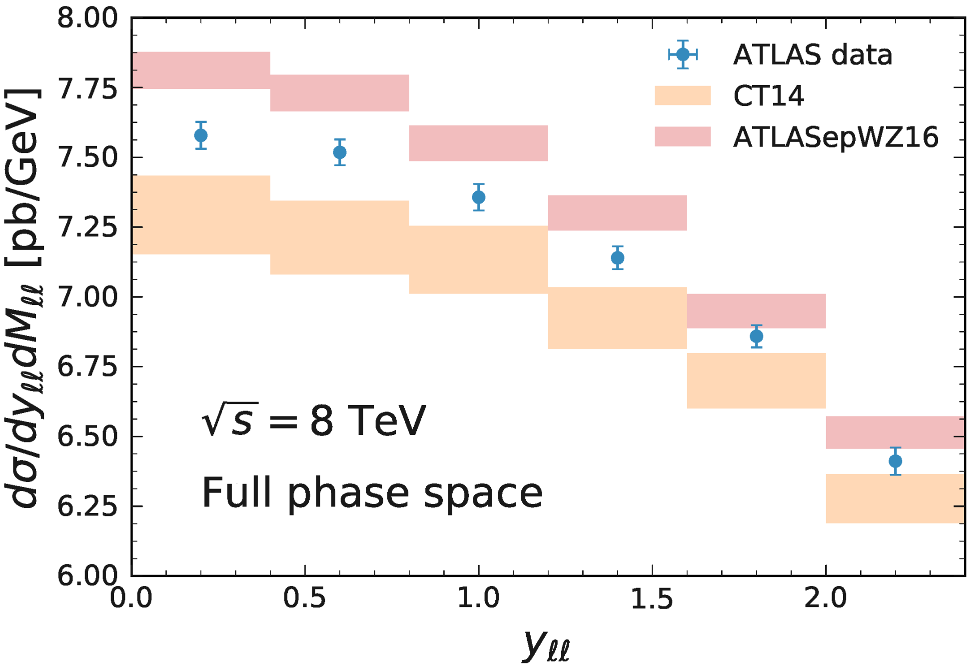
- Given smallness of the uncertainties of the acceptance correction, correct the measurement to full phase space.
- Compare ratios of p_T distribution for different $y_{\ell\ell}$ bins to $0 < y_{\ell\ell} < 0.4$ bin between data and NLO prediction. Reasonable agreement for $p_T > 35$ GeV.

Decomposition of uncertainties for y_Z in full phase space



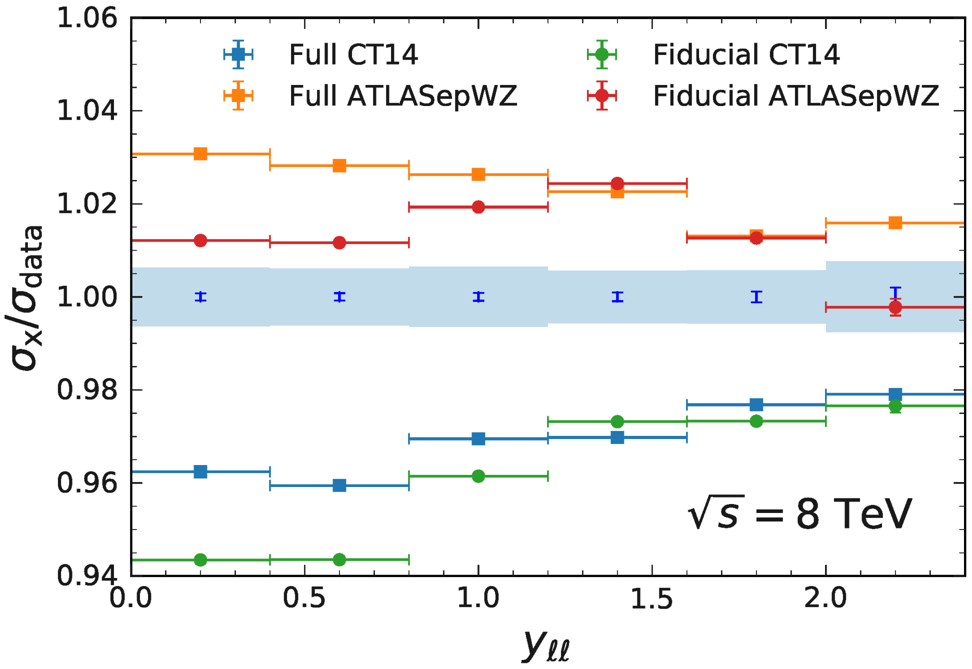
- Integrate full acceptace p_T distributions to obtain full phase space $y_{\ell\ell}$.
- Statistical uncertainties are propagated by sum in quadrature, correlated systemtic – linearly.
- Extrapolation uncertainties are subleading for all bins, approaching max 0.1% for highest y.

Data vs CT14 and ATLASepWZ16



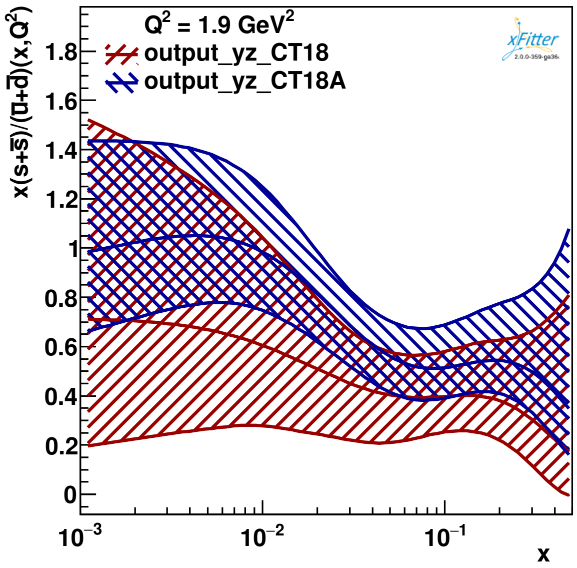
- Compare full phase space $y_{\ell\ell}$ between data and NNLO ($O(\alpha_S)$) predictions for inclusive Z production computed using MCFM v9.
- Predictions based on CT14 (ATLASepWZ16) undershoot (overshoot) the data.
- Difference in uncertainties since only EIG set is used for ATLASepWZ16 based prediction.

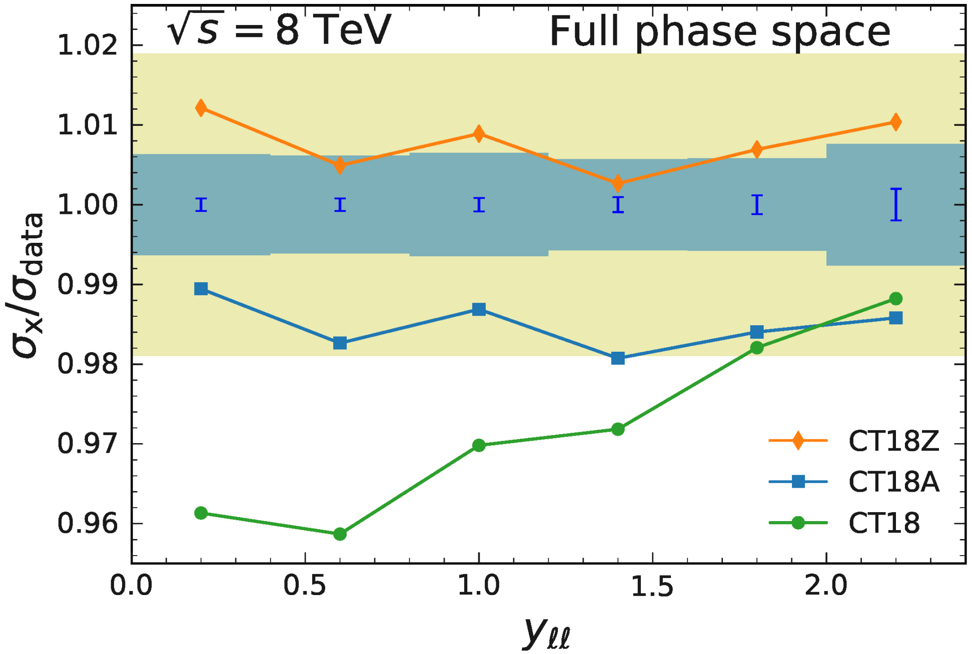
Full and fiducial cross sections vs predictions



- 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%: → sizable impact of fiducial correction.

Data vs CT18? predictions





- Compare full phase space data to NNLO predictions based on CT18? 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 $x < 0.01$.

Possible follow up in xFitter

- More detailed study of the relevant effects e.g. what has higher impact on the acceptance: p_T boost vs change of polarisation.
- Include CMS data at 8, 13 TeV.
- Extension to W production
- Full analysis of strange PDF constraints: requires knowledge of correlations in y_Z (ATLAS internal input needed).
- Analysis of full phase space p_T distribution (e.g. extraction of α_S).