Updates on the low-μ W-mass analysis

DESY SM group meeting

January 27, 2025

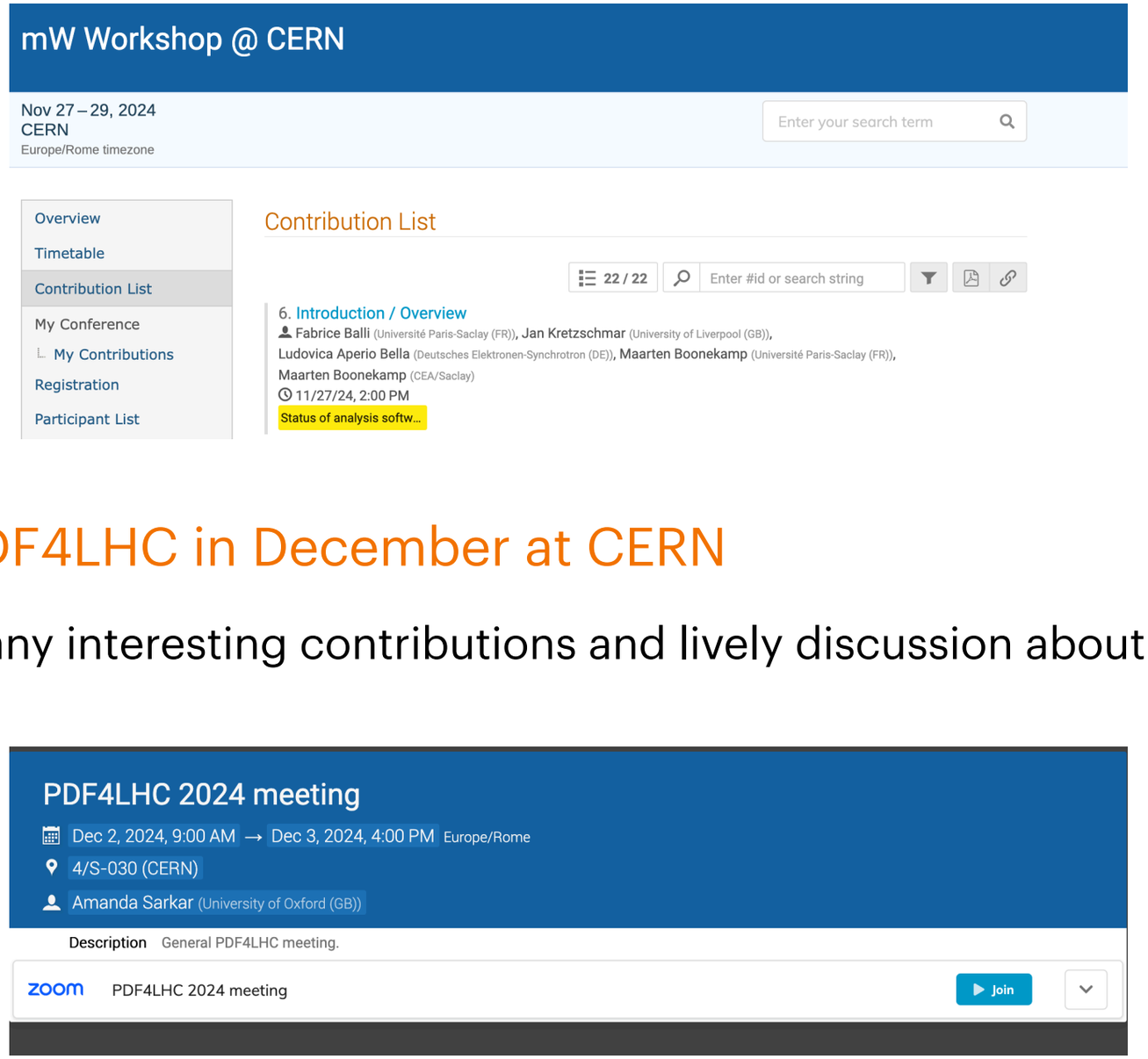
LAB, F. Dattola

Christmas *intermezzo*

News on *W* - mass (and related)

Last *W*-mass workshop at CERN before the Christmas break

… new workshop coming up in March/April



PDF4LHC in December at CERN

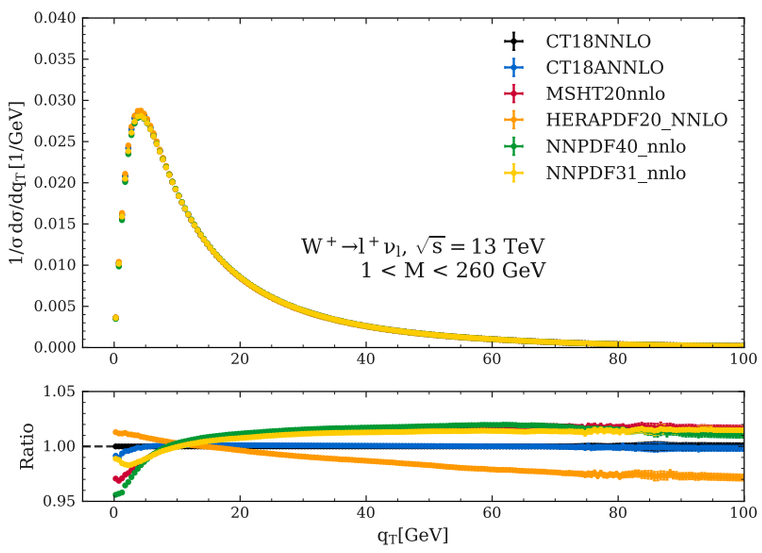
Many interesting contributions and lively discussion about the way beyond NNLO

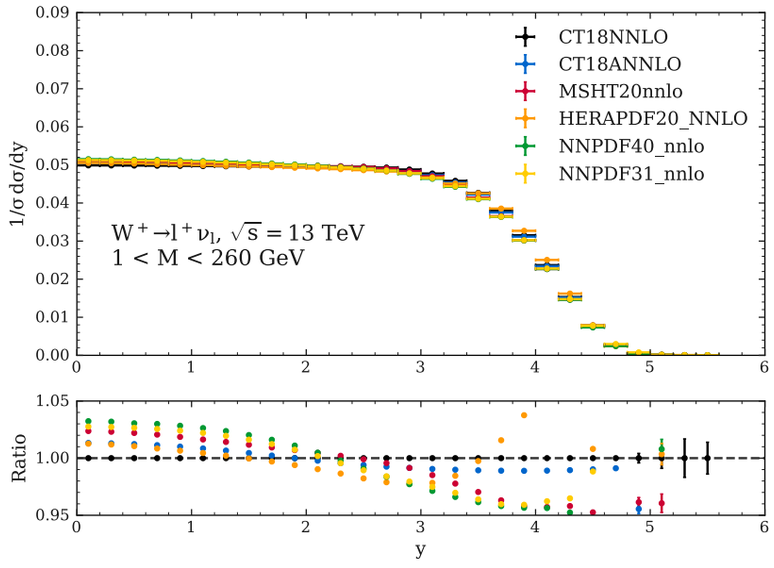
QCD modelling with DYTurbo

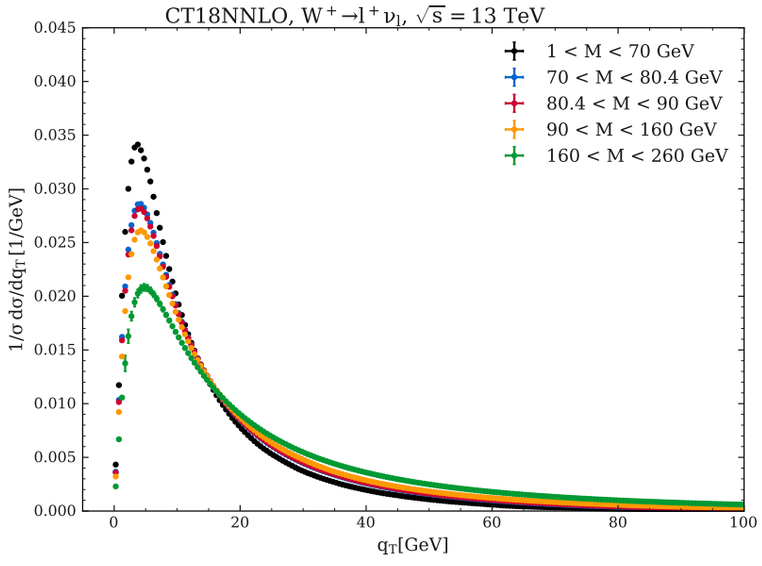
Full phase-space boson (p_{T}, y, M) predictions

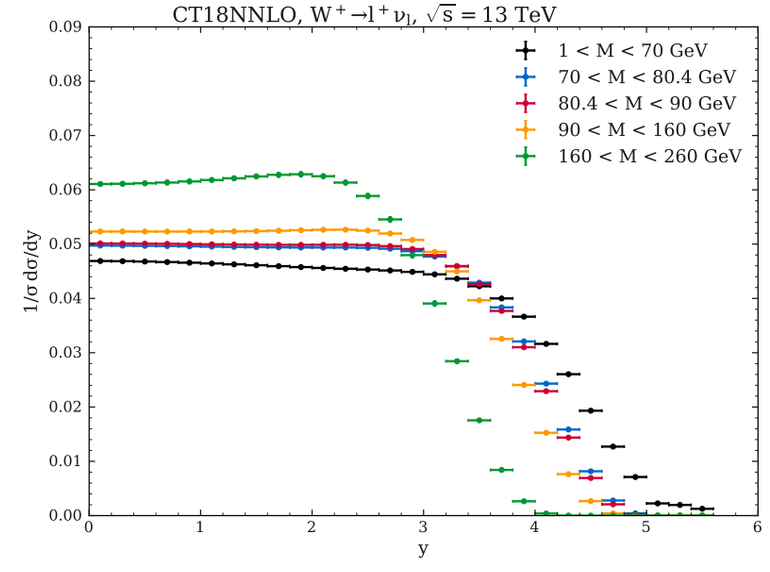
- **Status of predictions:**

> $W^{\pm}$ **baseline** NNLO+NNLL predictions $(g_1 = 0.5, \alpha_S = 0.0118)$ **inclusive in M and in mass bins** ready for all PDF sets at 5, 13 TeV. ✓







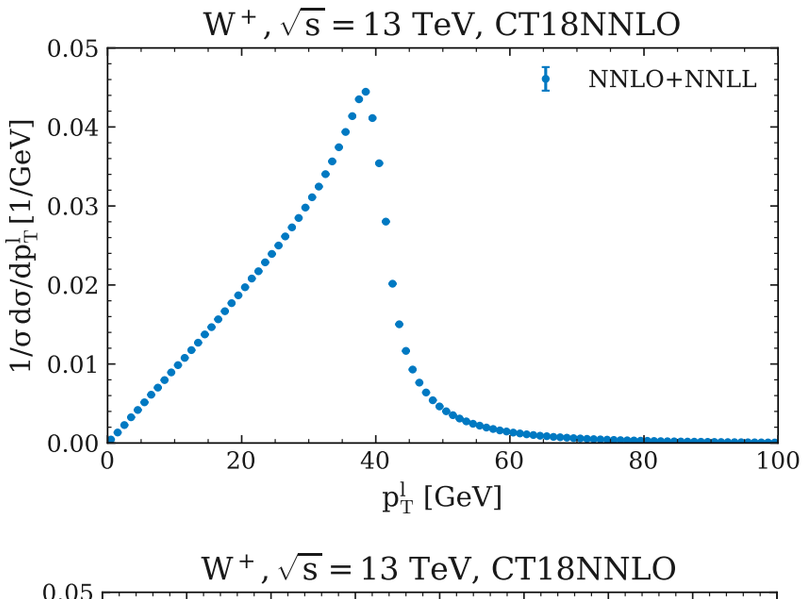


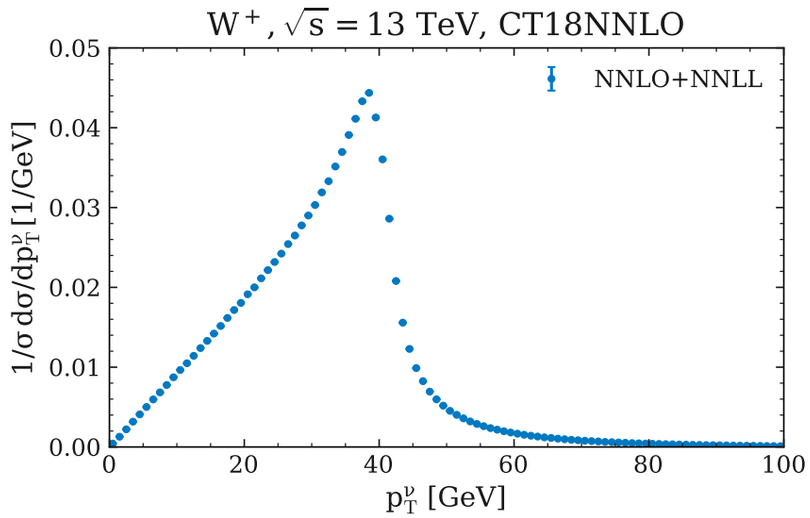
QCD modelling with DYTurbo

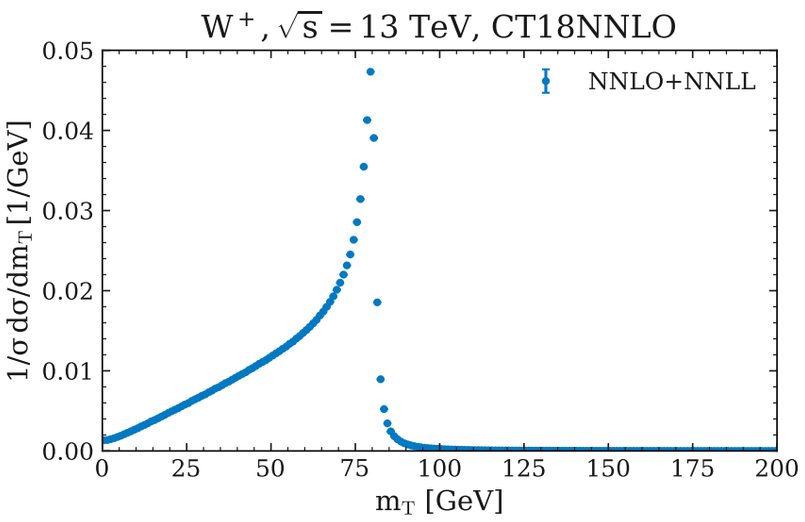
Full phase-space boson (p_{T}, y, M) predictions

- **Status of predictions:**

> Predictions of **final-state kinematic observables**, i.e. p_{T}^{l}, p_{T}^{ν}, $\mathrm{m_T}$, produced at NNLO+NNLL (with $g_1 = 0.5, \alpha_S = 0.0118$) for W^+ at 13 TeV with CT18NNLO ✓







- Quadrature rules for BORN(RES) and CT terms.
- VEGAS MC integration for VJ term.

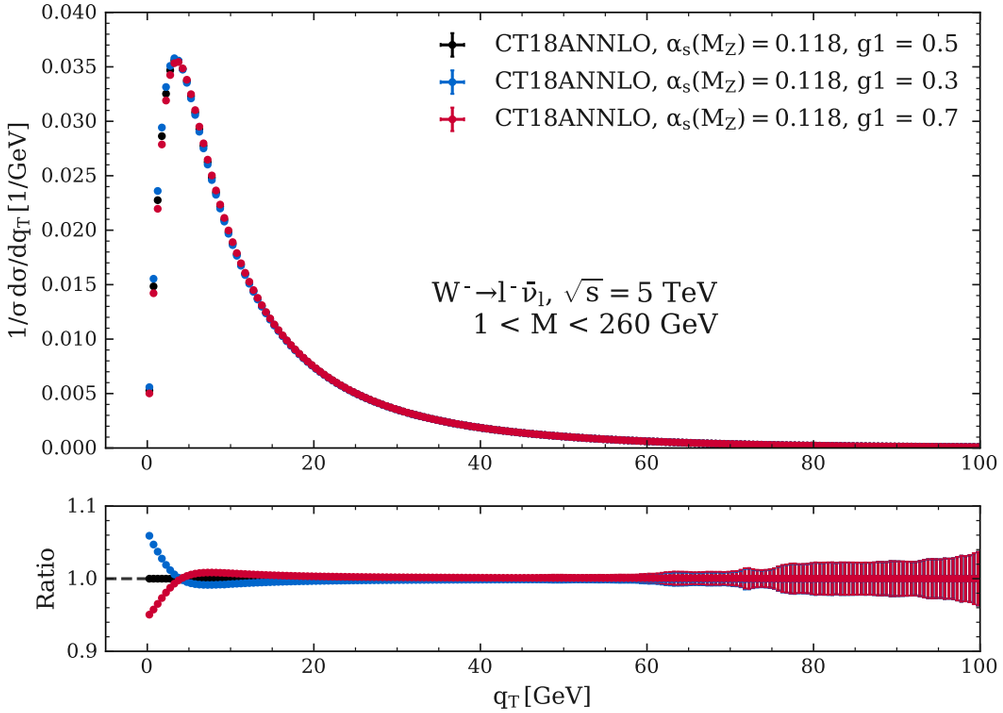
QCD modelling with DYTurbo

Full phase-space boson (p_{T}, y, M) predictions

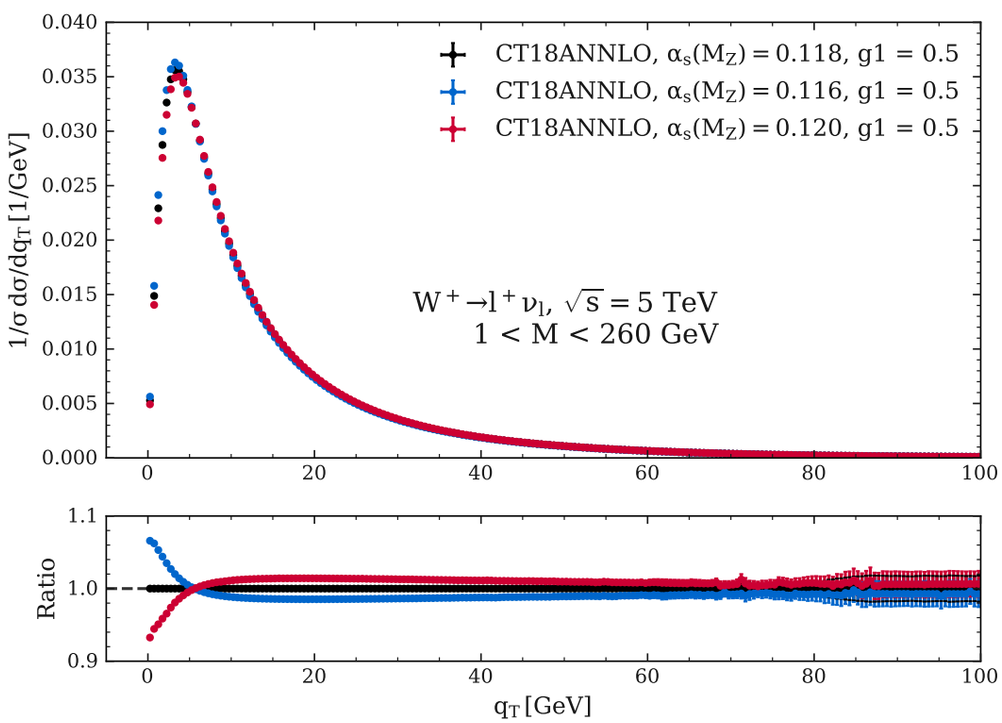
- **Status of predictions:**

  > $W^{\pm}$ NNLO+NNLL predictions with g_1, α_s **variations** inclusive in M and in mass bins ready for all PDF sets at 5, 13 TeV. ✓

$g_1 = 0.5 \pm 0.2$



$\alpha_s(M_Z) = 0.118 \pm 0.002$



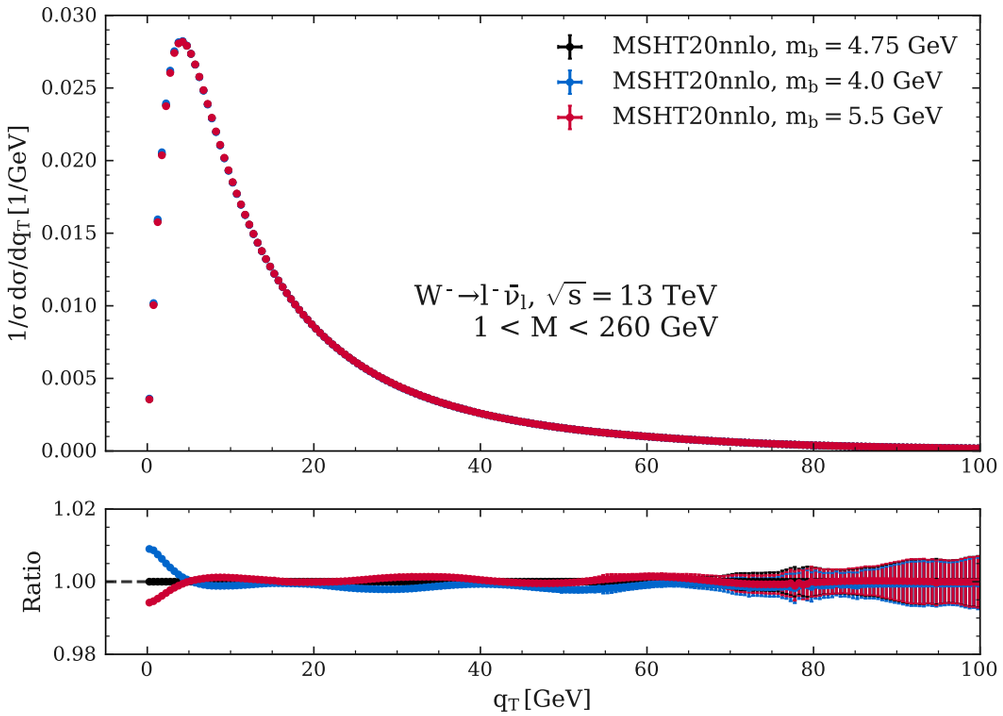
QCD modelling with DYTurbo

Full phase-space boson (p_{T}, y, M) predictions

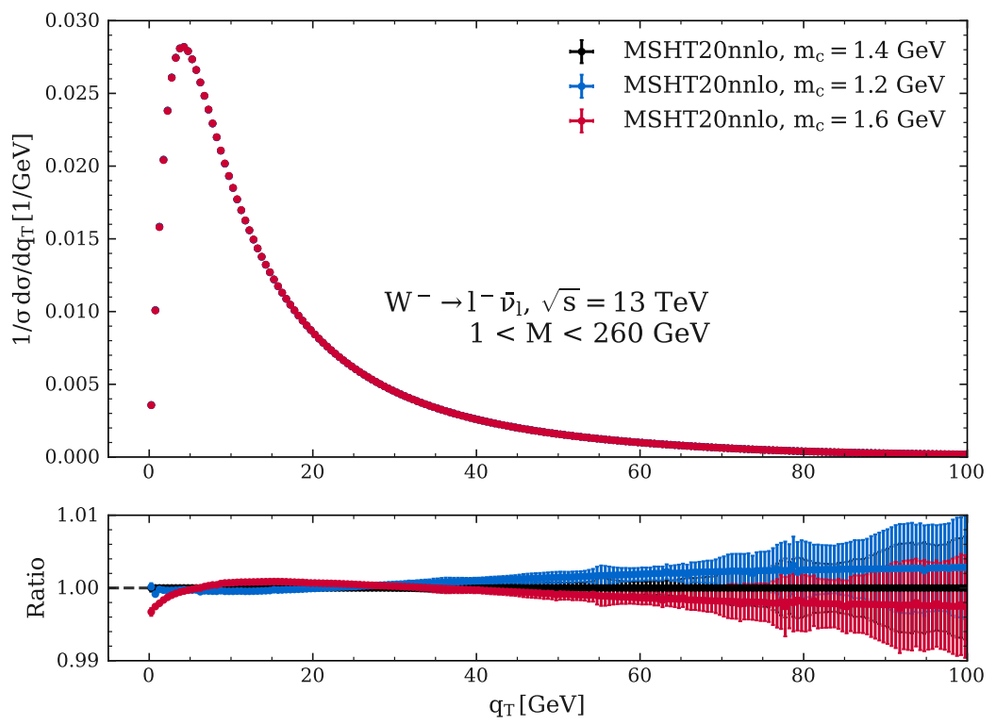
- **Status of predictions:**

  > $W^{\pm}$ NNLO+NNLL predictions with m_b, m_c **variations** inclusive in M and in mass bins ready for all PDF sets at 5, 13 TeV. ✓

$m_b = 4.75 \pm 0.75\,\mathrm{GeV}$



$m_c = 1.4 \pm 0.2\,\mathrm{GeV}$



QCD modelling with DYTurbo

$A_i\,(p_{\mathrm{T}}, y, M)$ predictions

- Angular distributions of *W*, *Z* decay leptons are determined by the boson polarisation state.
- Polarisation is induced at orders above tree level by initial-state QCD interactions.
- A_i's ≡ boson helicity cross-sections / boson unpolarised cross section.

$$\frac{d\sigma}{dp_T^2 dy dm d\cos\theta d\phi} = \frac{3}{16\pi}\frac{d\sigma}{dp_T^2 dy dm} \times [(1+\cos^2\theta) + A_0\frac{1}{2}(1-3\cos^2\theta)$$
$$+ A_1 \sin 2\theta \cos\phi$$
$$+ A_2 \frac{1}{2}\sin^2\theta \cos 2\phi$$
$$+ A_3 \sin\theta \cos\phi$$
$$+ A_4 \cos\theta$$
$$+ A_5 \sin^2\theta \sin 2\phi$$
$$+ A_6 \sin 2\theta \sin\phi$$
$$+ A_7 \sin\theta \sin\phi]$$

> A_i's $\to 0$ when $p_{\mathrm{T}} \to 0$, except for A_4.

> A_5 - A_7 only at $\mathcal{O}(\alpha_s^2)$, small contribution.

θ, ϕ polar and azimuthal angles of the lepton in the boson rest frame.

QCD modelling with DYTurbo

$A_i\,(p_{\mathrm{T}}, y, M)$ predictions

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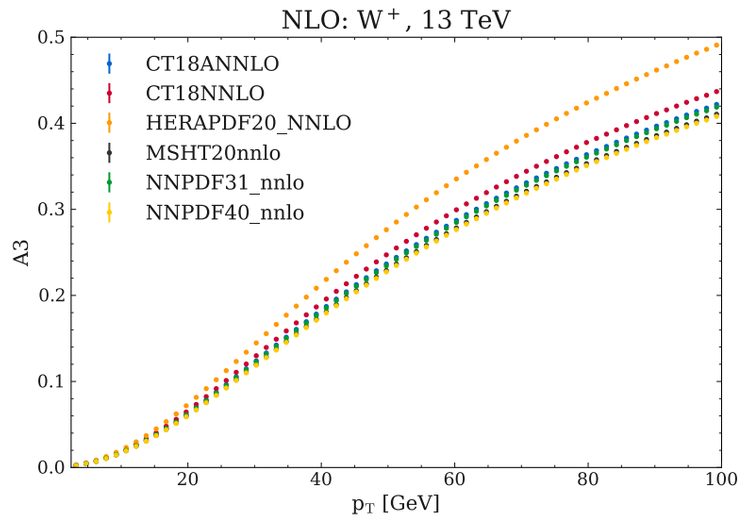
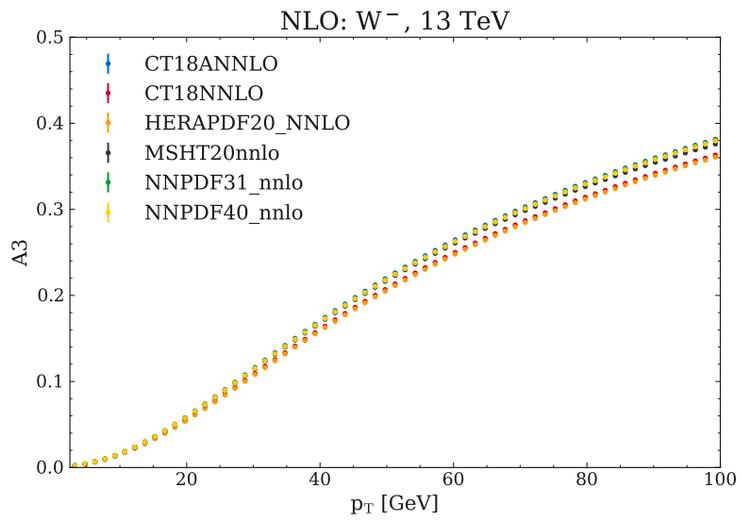
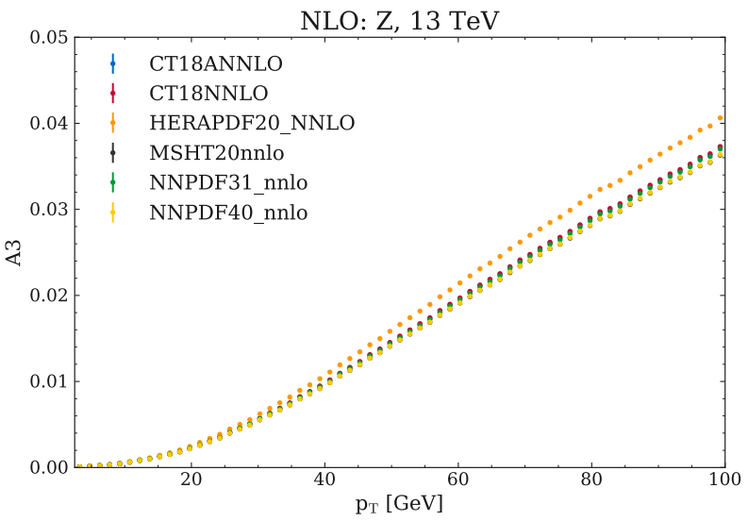
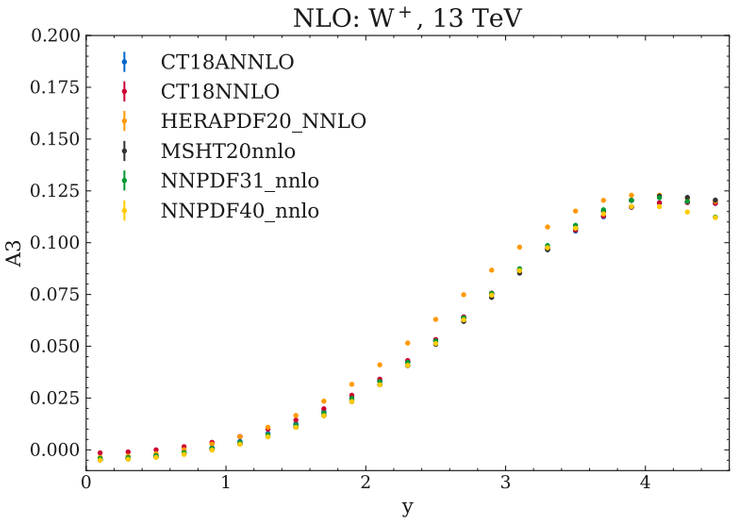
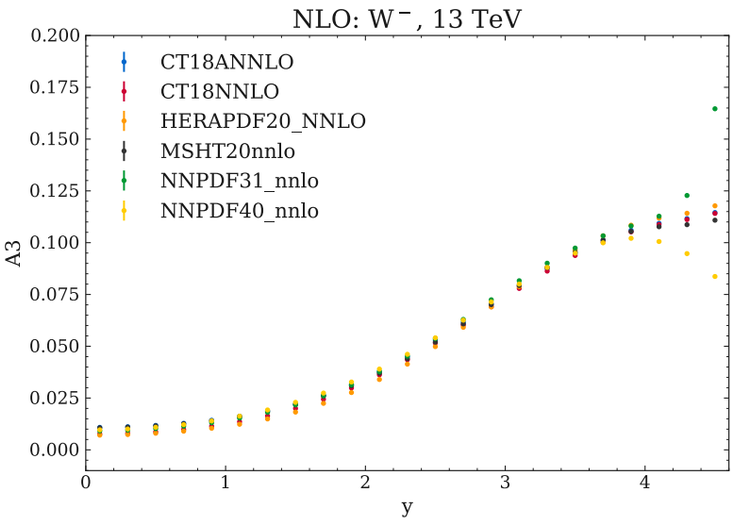
> Predictions of A_is for Z, $W^{\pm}$ **at NLO** inclusive in M ready for all PDF sets at 5, 13 TeV. ✓

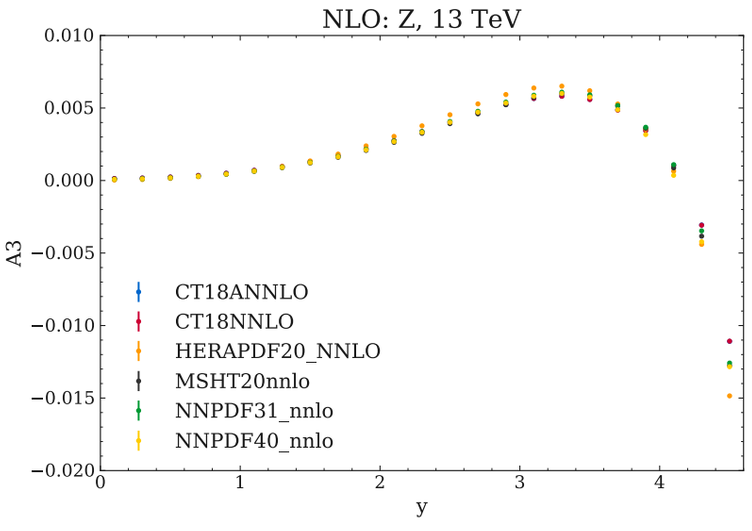












QCD modelling with DYTurbo

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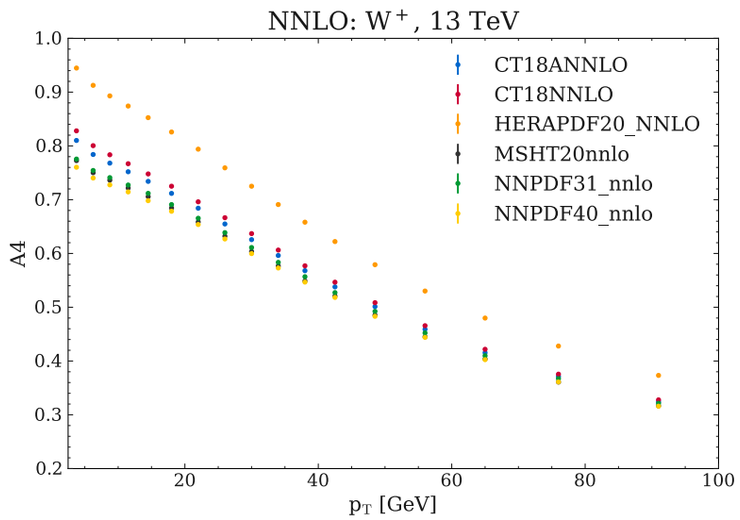
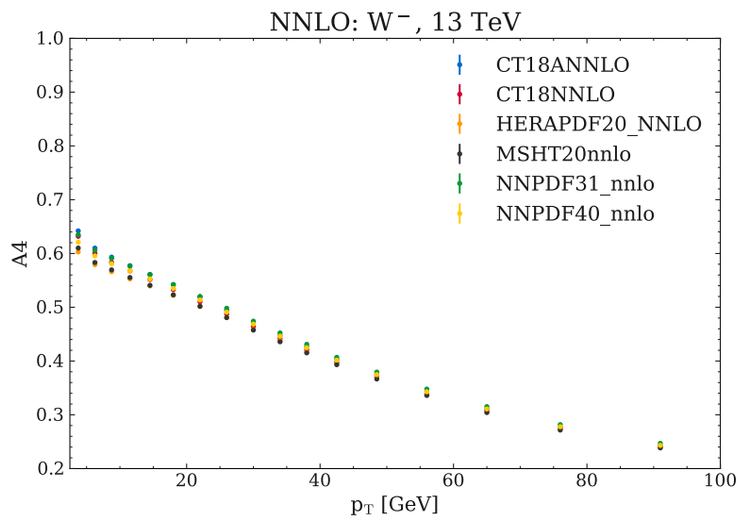
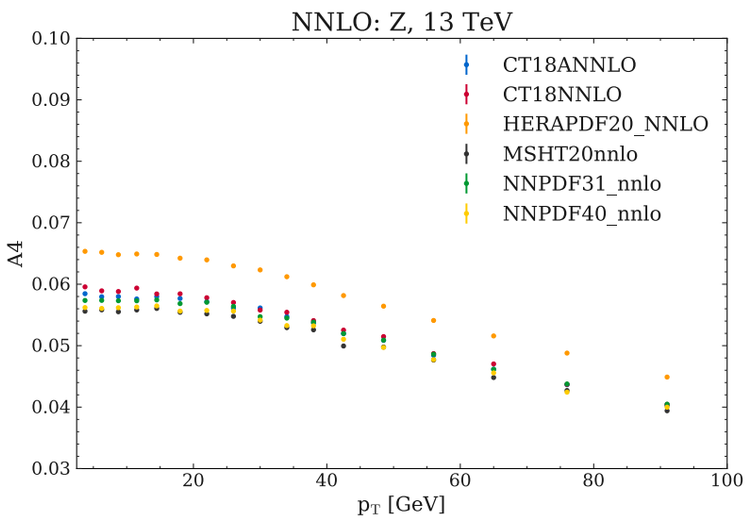
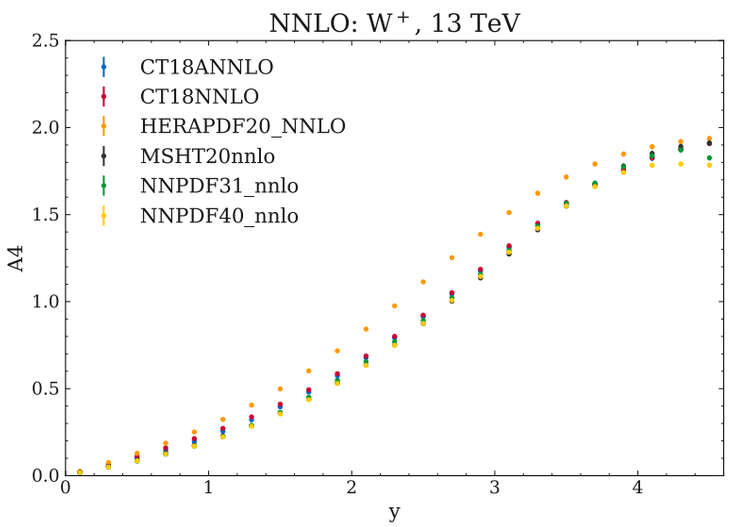
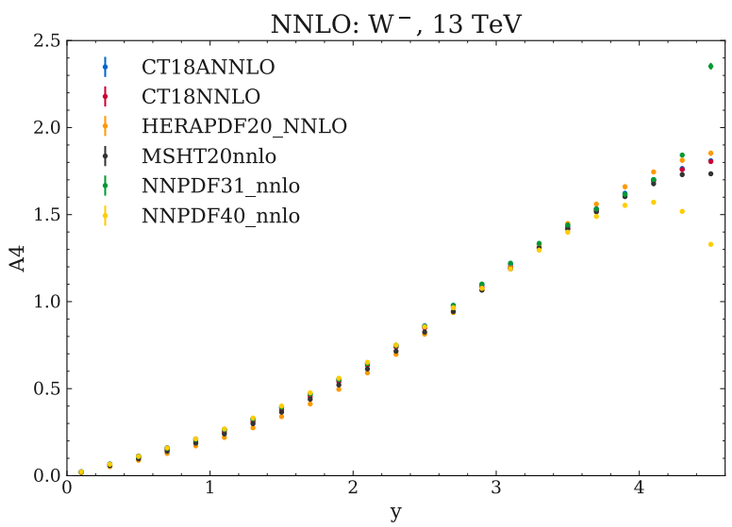
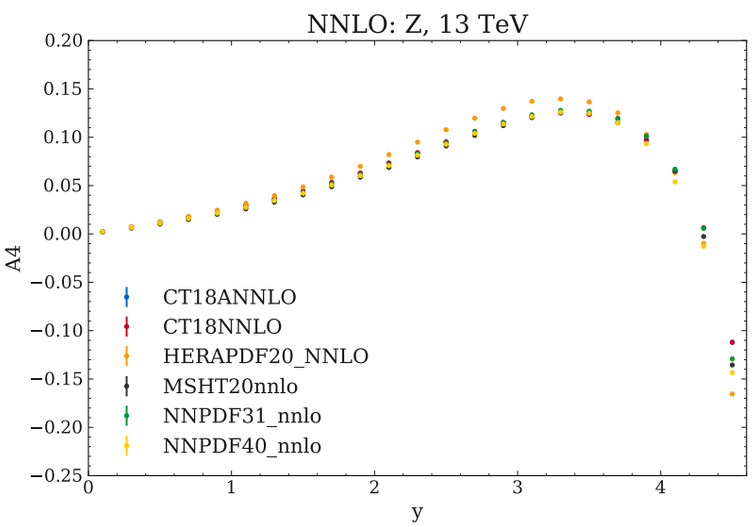












QCD modelling with DYTurbo

TMD fits: extraction of non-perturbative parameters from Drell-Yan data

- **Goal: build a full-analytical resummation model where theory is already precise before m(W) fit.**

- **Achieve the best understanding and control over the underlying non-perturbative (NP) QCD,** which is related to the intrinsic momentum of partons and can be described by TMD PDFs.

  - DYTurbo parametrises the **NP transverse modes** in TMDs with a form factor.

$$S_{\mathrm{NP}}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{\ell\ell}^2}{Q_0^2}\right] \quad \begin{cases} g_j(b) = \dfrac{g\,b^2}{\sqrt{1+\lambda\,b^2}} + \mathrm{sign}(q)\left(1-\exp\left[-|q|\,b^4\right]\right) \\ g_K(b) = g_0\left(1-\exp\left[-\dfrac{C_F\alpha_s(b_0/b_*)b^2}{\pi g_0\, b_{\mathrm{lim}}^2}\right]\right) \end{cases}$$

- S_{NP} includes 6 parameters which can be fitted to data or varied to assess an uncertainty.
  - g_1 and q representing the leading quadratic and quartic terms, dominant at $p_{\mathrm{T}} \sim$ 4–10 GeV.
  - λ controlling the transition from Gaussian (quadratic) to exponential (linear).
  - g_0 controlling the very high b (very small p_{T}) behaviour.
  - b_{lim} freezing the scale of α_S and Q_0 defining the starting scale of the TMD evolution.

- **Extract and constrain g_0, g_1, q, λ fitting DY data to state-of-the-art QCD predictions.**
  - **Interfacing DYTurbo to xFitter we can profile simultaneously PDF and NP QCD uncertainties.**

QCD modelling with DYTurbo

TMD fits: extraction of non-perturbative parameters from Drell-Yan data

- **Which DY data?**

  - **Primarily data from ATLAS DY measurements**

    - **8 TeV Z - p_{T} data** in y bins, fitted up to $p_{\mathrm{T}}^{Z} \leq 29$ GeV: provide **most stringent constraints** on NP parameters.
    - **13 TeV low-mass DY** $p_{\mathrm{T}}(\mu\mu)$ data in M bins, fitted up to $p_{\mathrm{T}}^{\mu\mu} \leq 10$ GeV: **expand NP sensitivity**.

      (5 and 13 TeV W and Z - p_{T} data measured at low μ will also be included as a cross-check)

  - **But also data from fixed-target DY measurements:** help to better constrain g_0.

    - $p_{\mathrm{T}}(\mu\mu)$ data from Fermilab-E288: $p\,N(\mathrm{Pt}) \rightarrow \mu^{+}\mu^{-}\,\mathrm{X}$ at √s = 19.4 / 23.8 / 27.4 GeV
    - $p_{\mathrm{T}}(\mu\mu)$ data from Fermilab-E605: $p\,N(\mathrm{Cu}) \rightarrow \mu^{+}\mu^{-}\,\mathrm{X}$ at √s = 38.8 GeV
    - $p_{\mathrm{T}}(\mu\mu)$ data from Fermilab-E772: $pd \rightarrow \mu^{+}\mu^{-}\,X$ at √s = 38.8 GeV

  - **And data from Tevatron:** help to constrain valence PDFs at high-x, no HF-initiated processes.

    - Z - p_{T} data from CDF at 1.96 TeV, p_{T} bins of 0.5 GeV fitted up to $p_{\mathrm{T}}^{Z} \leq 30$ GeV: sensitive to g_1 through the position of the Sudakov peak.

QCD modelling with DYTurbo

TMD fits: extraction of non-perturbative parameters from Drell-Yan data

- **Fit setup:**
  - DYTurbo 1.4 interfaced to xFitter.
  - DYTurbo predictions at N3LO (N2lO for lmDY) + N3LL, including EW kFactors and mixed QCDxQED corrections a LL.
  - Build a χ^2 including:
    - nuisance parameters (NPs) for experimental uncertainties $\equiv \beta_{j,\mathrm{exp}}$
    - NPs coupled with PDF-uncertainty eigenvectors and profiled in the fit. $\equiv \beta_{k,\mathrm{th}}$
    - **Four free fit parameters** corresponding to g_0, g_1, q, λ .
- χ^2 numerically minimised with CERES.

$$\chi^2(\beta_{\mathrm{exp}}, \beta_{\mathrm{th}}) = \sum_{i=1}^{N_{\mathrm{data}}} \frac{\left(\sigma_i^{\mathrm{exp}} + \sum_j \Gamma_{ij}^{\mathrm{exp}} \beta_{j,\mathrm{exp}} - \sigma_i^{\mathrm{th}} - \sum_k \Gamma_{ik}^{\mathrm{th}} \beta_{k,\mathrm{th}}\right)^2}{\Delta_i^2} + \sum_j \beta_{j,\mathrm{exp}}^2 + \sum_k \beta_{k,\mathrm{th}}^2$$

QCD modelling with DYTurbo

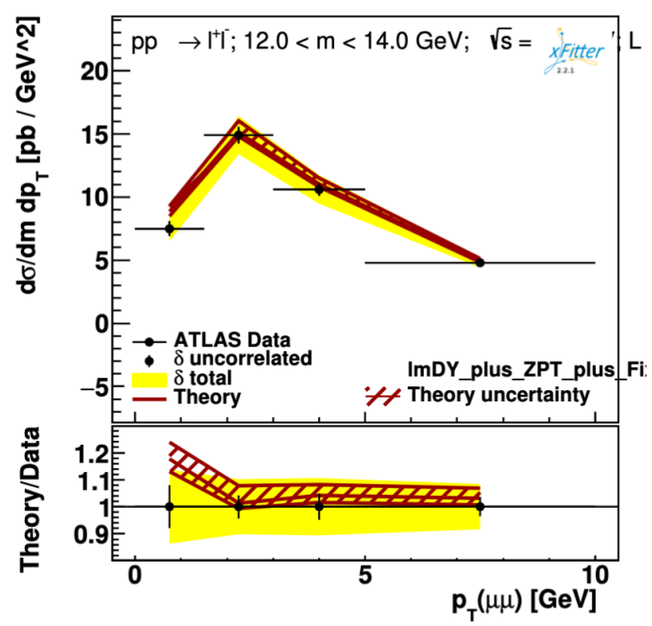
TMD fits: extraction of non-perturbative parameters from Drell-Yan data

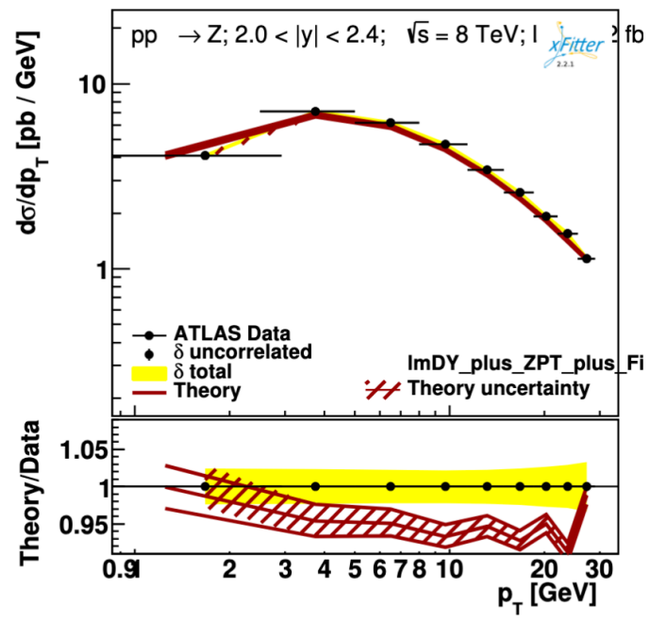
- **(Preliminary) fit results:**

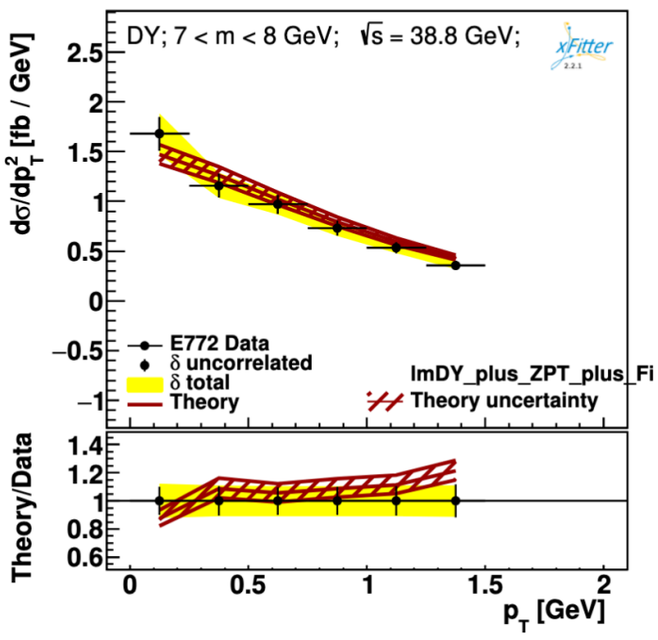
```
  Partial chi2s
Dataset    1      2.46( +0.25)     4  ATLAS lmDY pT 13 TeV 12.0-14.0 GeV
Dataset    2      9.89( -0.35)     4  ATLAS lmDY pT 13 TeV 14.0-17.0 GeV
Dataset    3     20.09( -0.44)     4  ATLAS lmDY pT 13 TeV 17.0-22.0 GeV
Dataset    4      6.82( -0.36)     4  ATLAS lmDY pT 13 TeV 22.0-28.0 GeV
Dataset    5      1.06( -0.30)     4  ATLAS lmDY pT 13 TeV 28.0-36.0 GeV
Dataset    6      6.70( -0.20)     4  ATLAS lmDY pT 13 TeV 36.0-46.0 GeV
Dataset    7      3.59( -0.30)     4  ATLAS lmDY pT 13 TeV 46.0-56.0 GeV
Dataset    8      2.33( -0.38)     9  ATLAS Z pT 8 TeV 0.0-0.4
Dataset    9      1.84( -0.40)     9  ATLAS Z pT 8 TeV 0.4-0.8
Dataset   10      3.08( -0.44)     9  ATLAS Z pT 8 TeV 0.8-1.2
Dataset   11      1.13( -0.42)     9  ATLAS Z pT 8 TeV 1.2-1.6
Dataset   12      2.04( -0.41)     9  ATLAS Z pT 8 TeV 1.6-2.0
Dataset   13      0.77( -0.45)     9  ATLAS Z pT 8 TeV 2.0-2.4
Dataset   14      1.70( -0.48)     9  ATLAS Z pT 8 TeV 2.4-2.8
Dataset   15      5.47( -0.45)     9  ATLAS Z pT 8 TeV 2.8-3.6
Dataset   16      2.64( +0.30)     4  E288 200 GeV M 4-5 GeV
Dataset   17      8.43( +0.83)     5  E288 200 GeV M 5-6 GeV
Dataset   18      3.65( +1.19)     6  E288 200 GeV M 6-7 GeV
Dataset   19      2.88( +2.62)     7  E288 200 GeV M 7-8 GeV
Dataset   20      3.06( +5.24)     8  E288 200 GeV M 8-9 GeV
Dataset   21      1.94( +8.37)     9  E288 300 GeV M 11-12 GeV
Dataset   22      8.34( +0.27)     4  E288 300 GeV M 4-5 GeV
Dataset   23      6.54( +0.78)     5  E288 300 GeV M 5-6 GeV
Dataset   24      2.02( +1.13)     6  E288 300 GeV M 6-7 GeV
Dataset   25      2.02( +1.15)     7  E288 300 GeV M 7-8 GeV
Dataset   26      7.69( +1.08)     8  E288 300 GeV M 8-9 GeV
Dataset   27     40.56( -3.91)    10  E288 400 GeV M 10-11 GeV
Dataset   28      8.96( +1.68)    10  E288 400 GeV M 11-12 GeV
Dataset   29      6.11( +2.59)    10  E288 400 GeV M 12-13 GeV
Dataset   30      3.62( +4.59)    10  E288 400 GeV M 13-14 GeV
Dataset   31      5.75( +1.05)     5  E288 400 GeV M 5-6 GeV
Dataset   32     13.07( +1.24)     6  E288 400 GeV M 6-7 GeV
Dataset   33     10.48( +1.48)     7  E288 400 GeV M 7-8 GeV
Dataset   34     10.25( +1.44)     8  E288 400 GeV M 8-9 GeV
Dataset   35     71.64( -6.11)    10  E288 400 GeV M 9-10 GeV
Dataset   36      7.51( -0.48)     7  E605 M 7-8 GeV
Dataset   37     10.92( +0.52)     8  E605 M 8-9 GeV
Dataset   38     10.61( +1.16)    11  E605 M 10.5-11.5 GeV
Dataset   39     20.37( +0.20)    12  E605 M 11.5-13.5 GeV
Dataset   40     21.68( +1.87)    14  E605 M 13.5-18 GeV
Dataset   41      1.47( +0.75)     4  E772 M 5-6 GeV
Dataset   42      3.89( +1.45)     5  E772 M 6-7 GeV
Dataset   43      4.84( +0.74)     6  E772 M 7-8 GeV
Dataset   44      7.13( +0.65)     6  E772 M 8-9 GeV
Dataset   45     11.66( +2.55)     8  E772 M 11-12 GeV
Dataset   46     11.76( +3.58)     8  E772 M 12-13 GeV
Dataset   47      5.54( +3.14)     6  E772 M 13-14 GeV
Dataset   48      1.25( +0.37)     6  E772 M 14-15 GeV
Dataset   49      3.43( -0.67)    55  CDF ZPT 1.96 TEV

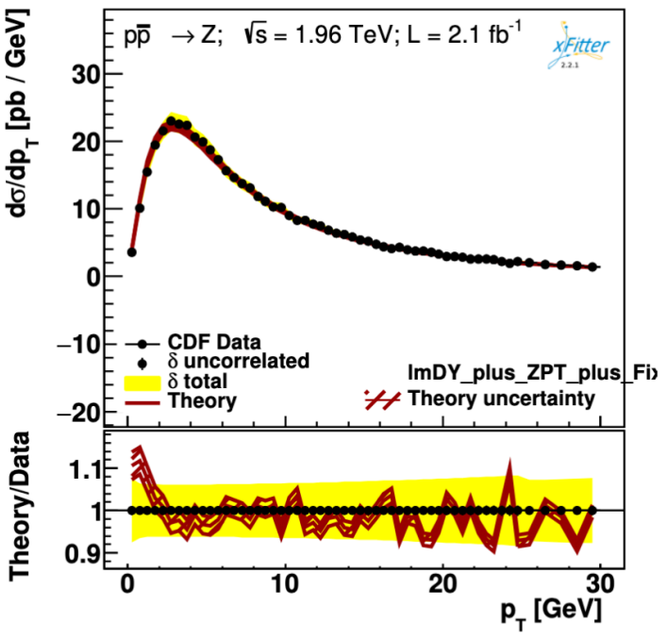
 Correlated Chi2    316.75875586412513
 Log penalty Chi2    37.735584781810601
 Systematic shifts          247
```

- χ^2/dof at minimum = 765/397









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Dataset   15      5.47( -0.45)     9  ATLAS Z pT 8 TeV 2.8-3.6
Dataset   16      2.64( +0.30)     4  E288 200 GeV M 4-5 GeV
Dataset   17      8.43( +0.83)     5  E288 200 GeV M 5-6 GeV
Dataset   18      3.65( +1.19)     6  E288 200 GeV M 6-7 GeV
Dataset   19      2.88( +2.62)     7  E288 200 GeV M 7-8 GeV
Dataset   20      3.06( +5.24)     8  E288 200 GeV M 8-9 GeV
Dataset   21      1.94( +8.37)     9  E288 300 GeV M 11-12 GeV
Dataset   22      8.34( +0.27)     4  E288 300 GeV M 4-5 GeV
Dataset   23      6.54( +0.78)     5  E288 300 GeV M 5-6 GeV
Dataset   24      2.02( +1.13)     6  E288 300 GeV M 6-7 GeV
Dataset   25      2.02( +1.15)     7  E288 300 GeV M 7-8 GeV
Dataset   26      7.69( +1.08)     8  E288 300 GeV M 8-9 GeV
Dataset   27     40.56( -3.91)    10  E288 400 GeV M 10-11 GeV
Dataset   28      8.96( +1.68)    10  E288 400 GeV M 11-12 GeV
Dataset   29      6.11( +2.59)    10  E288 400 GeV M 12-13 GeV
Dataset   30      3.62( +4.59)    10  E288 400 GeV M 13-14 GeV
Dataset   31      5.75( +1.05)     5  E288 400 GeV M 5-6 GeV
Dataset   32     13.07( +1.24)     6  E288 400 GeV M 6-7 GeV
Dataset   33     10.48( +1.48)     7  E288 400 GeV M 7-8 GeV
Dataset   34     10.25( +1.44)     8  E288 400 GeV M 8-9 GeV
Dataset   35     71.64( -6.11)    10  E288 400 GeV M 9-10 GeV
Dataset   36      7.51( -0.48)     7  E605 M 7-8 GeV
Dataset   37     10.92( +0.52)     8  E605 M 8-9 GeV
Dataset   38     10.61( +1.16)    11  E605 M 10.5-11.5 GeV
Dataset   39     20.37( +0.20)    12  E605 M 11.5-13.5 GeV
Dataset   40     21.68( +1.87)    14  E605 M 13.5-18 GeV
Dataset   41      1.47( +0.75)     4  E772 M 5-6 GeV
Dataset   42      3.89( +1.45)     5  E772 M 6-7 GeV
Dataset   43      4.84( +0.74)     6  E772 M 7-8 GeV
Dataset   44      7.13( +0.65)     6  E772 M 8-9 GeV
Dataset   45     11.66( +2.55)     8  E772 M 11-12 GeV
Dataset   46     11.76( +3.58)     8  E772 M 12-13 GeV
Dataset   47      5.54( +3.14)     6  E772 M 13-14 GeV
Dataset   48      1.25( +0.37)     6  E772 M 14-15 GeV
Dataset   49      3.43( -0.67)    55  CDF ZPT 1.96 TEV

 Correlated Chi2    316.75875586412513
 Log penalty Chi2    37.735584781810601
 Systematic shifts          247
```

- χ^2/dof at minimum = 765/397
- **Estimated values of the NP parameters:**
  - $g_0 = 0.508 \pm 0.053\ \text{GeV}^2$
  - $g_1 = 0.612 \pm 0.039\ \text{GeV}^2$
  - $\lambda = 2.501 \pm 0.416\ \text{GeV}^2$
  - $q = 0.003 \pm 0.001\ \text{GeV}^4$
- **Correlation matrix:**

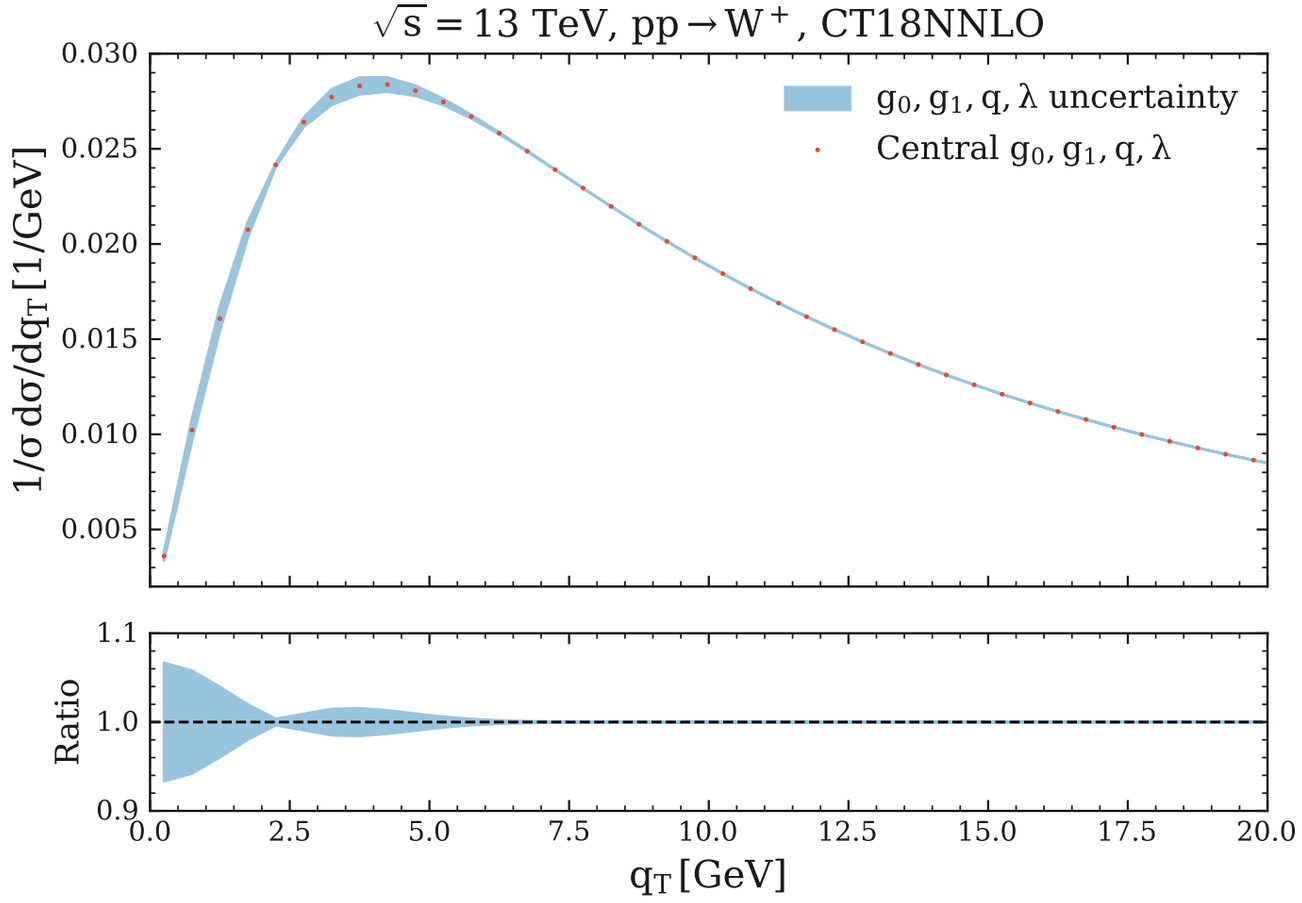
$$\begin{array}{c} \\ g_0 \\ g_1 \\ \lambda \\ q \end{array} \begin{array}{c} \begin{array}{cccc} g_0 & g_1 & \lambda & q \end{array} \\ \begin{pmatrix} 1 & 0.1148 & 0.3419 & -0.8067 \\ 0.1148 & 1 & 0.8876 & -0.001803 \\ 0.3419 & 0.8876 & 1 & -0.007184 \\ -0.8067 & -0.001803 & -0.007184 & 1 \end{pmatrix} \end{array}$$

QCD modelling with DYTurbo

TMD fits: extraction of non-perturbative parameters from Drell-Yan data

- **(Preliminary) fit results:**

  - Diagonalise covariance matrix to derive 4 eigenvectors of independent g_0, g_1, λ, q variations.
  - Compute p_{T} of W^+ at NNLO+NNLL at 13 TeV with central g_0, g_1, λ, q values and eigenvariations.
  - Sum in quadrature to derive a "TMD" uncertainty band: $\delta\sigma(\mathrm{TMD}) = \frac{1}{2}\sqrt{\sum_{\mathrm{i}} \left(\sigma_{+\mathrm{eig_i}} - \sigma_{-\mathrm{eig_i}}\right)^2}$



QCD modelling with DYTurbo

TMD fits: extraction of non-perturbative parameters from Drell-Yan data

- **Next steps:**

  - Improve predictions, i.e. add N3LO corrections for the predictions of low-mass DY data, try other aN3LO PDF sets (aN3LO NNPDF4.0).
  - Validate and refine estimation of post-fit uncertainties, i.e. Minuit + Hesse on top of CERES.
  - Estimate correlation between TMD NP parameters and PDF uncertainties and propagate again the uncertainties to p_{T}^{W} and also to the predicted p_{T}^{l}.
  - Study alternative parametrisations for the NP form factor.
  - Study fit dependence on modelling variations involving heavy-flavours and PDF evolutions, which can lead to differences in particular in g_1 and q.
  - **... and much more to come :)**