Recent studies for m(*W*) QCD modelling

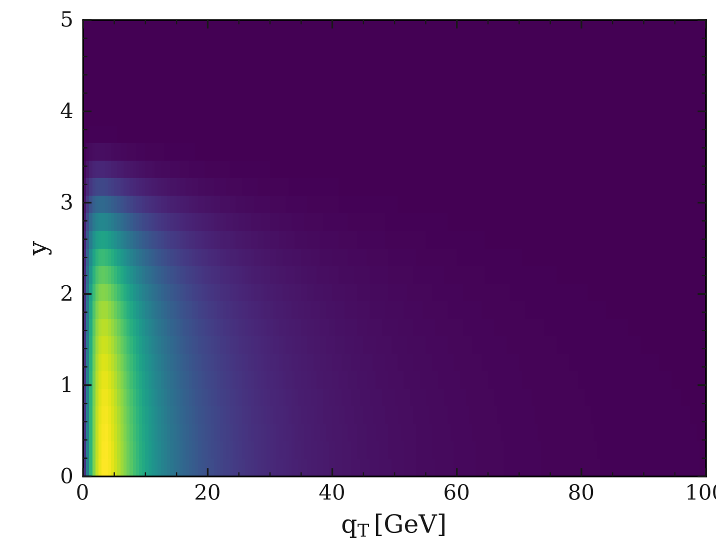
DESY SM group meeting

September 23, 2024

LAB, F. Dattola

QCD modelling reweighting procedure

(p_T, y, M) predictions with DYTurbo



- Compute 2D (p_T, y) full PHSP distributions in mass (M) bins.
- For each y bin compute predictions in p_T at **NNLO+NNLL**:

> relying on analytical resummation of large logs to all orders in α_s

$$\mathrm{d}\sigma^{V}_{\mathrm{NNLO+NNLL}} = \mathrm{d}\sigma^{\mathrm{res}}_{\mathrm{NNLL}} - \mathrm{d}\sigma^{\mathrm{CT(res)}}_{\mathrm{NLO}} + \mathrm{d}\sigma^{V+\mathrm{jet}}_{\mathrm{NLO}}$$

$$\mathrm{d}\sigma^{\mathrm{res}}_{\mathrm{NNLL}} = \mathrm{d}\hat{\sigma}_{\mathrm{LO}} \times H^V \times S_{\mathrm{NP}} \times \exp\{G_{\mathrm{NNLL}}(\alpha_s, L)\}$$ → Perturbative Sudakov Form Factor $S(b)$

> including non-perturbative QCD effects in $S(b)$ via

$$S_{\mathrm{NP}}(b) = \exp\left[-g_j(b) - g_K(b)\log\frac{m_{ll}^2}{Q_0^2}\right]$$

$$g_j(b) = \frac{g\,b^2}{\sqrt{1+\lambda\,b^2}} + \mathrm{sign}(q)\left(1 - \exp\left[-|q|\,b^4\right]\right)$$

$$g_K(b) = g_0\left(1 - \exp\left[-\frac{C_F\alpha_s(b_0/b_*)b^2}{\pi g_0\,b_{\mathrm{lim}}^2}\right]\right)$$

with a prescription to avoid Landau pole in *b* space, $b_*^2 = \dfrac{b^2}{1 + b^2/b_{\mathrm{lim}}^2}$

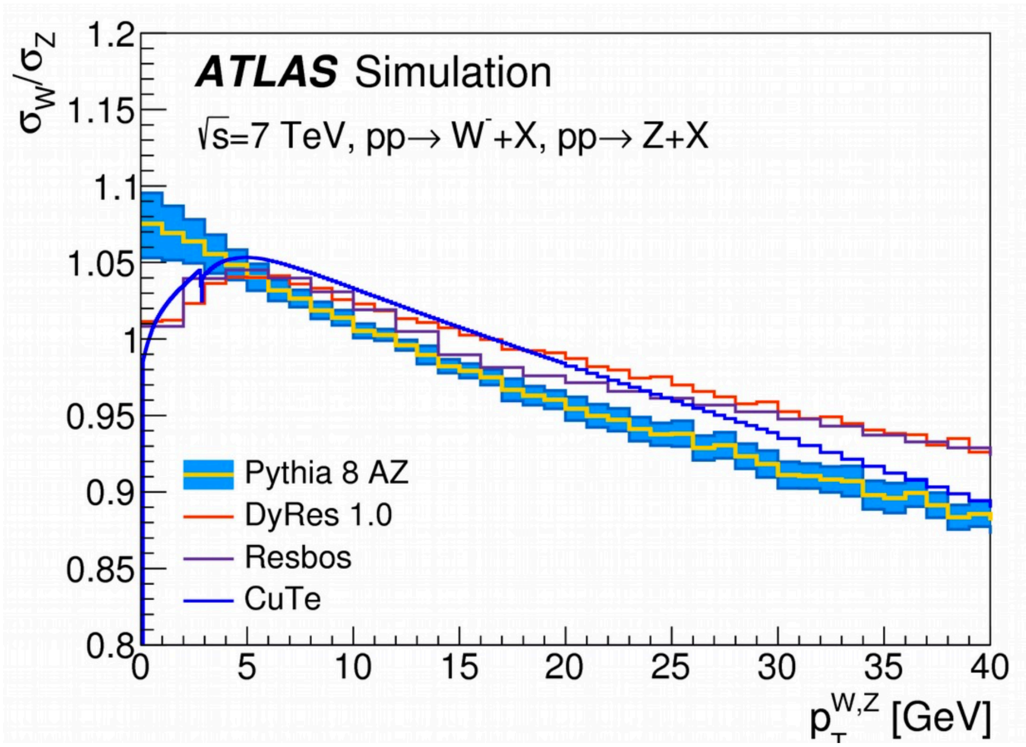
$pT(W)/pT(Z)$

Why care about $pT(W)/pT(Z)$?

- QCD modelling of boson transverse momentum distribution can be validated studying the predicted differential cross-section ratio

$$R_{W/Z}(p_{\mathrm{T}}) = \left(\frac{1}{\sigma_W} \cdot \frac{\mathrm{d}\sigma_W(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}\right)\left(\frac{1}{\sigma_Z} \cdot \frac{\mathrm{d}\sigma_Z(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}\right)^{-1}$$

- For the *W*-mass at 7 TeV MiNLO and NNLL **analytic resummed predictions** (i.e., DYRes, RESBOS, CuTe) **were discarded** in favour of PYTHIA 8 AZ **based on findings related to *p*T(*W*)/*p*T(*Z*):**
  - Unexpected **turnover** of ratio at *p*T ~ 5 GeV (DYRes, RESBOS, CuTe) **vs monotonic falling** (PYTHIA 8 AZ)



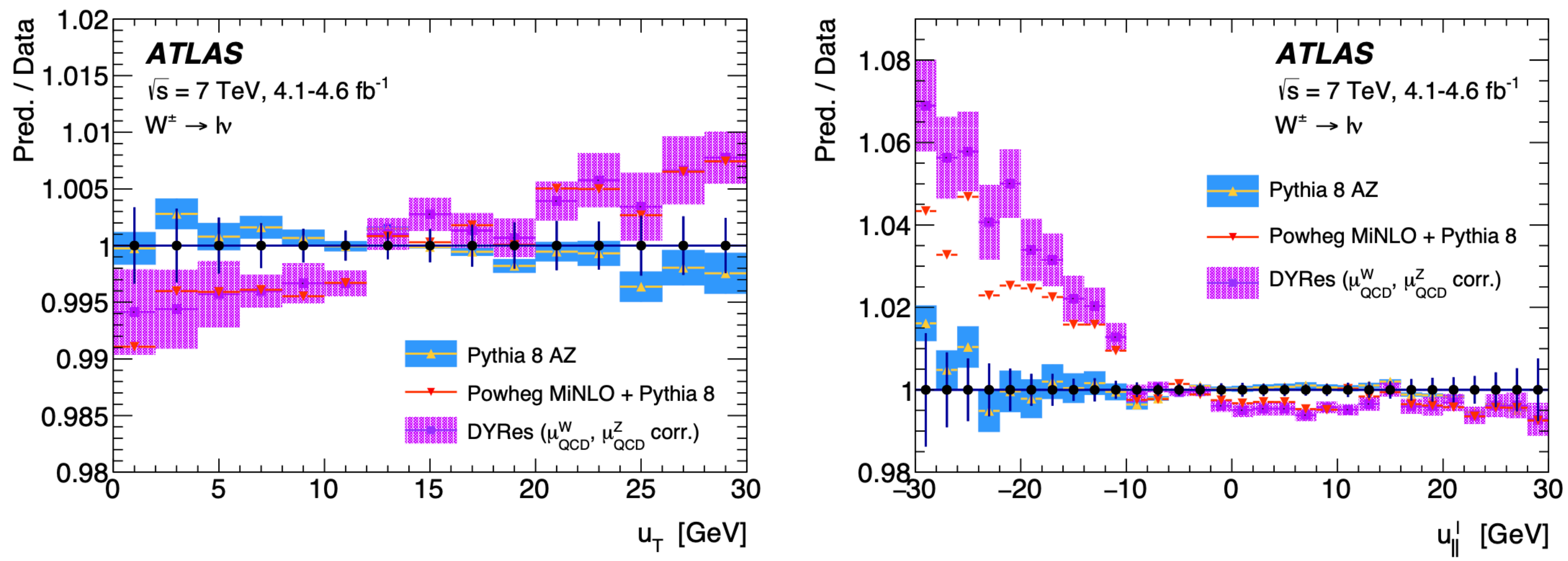
pT(*W*)/pT(*Z*)

Why care about *p*T(*W*)/*p*T(*Z*) ?

- QCD modelling of boson transverse momentum distribution can be validated studying the predicted differential cross-section ratio

$$R_{W/Z}(p_{\mathrm{T}}) = \left(\frac{1}{\sigma_W} \cdot \frac{\mathrm{d}\sigma_W(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}\right)\left(\frac{1}{\sigma_Z} \cdot \frac{\mathrm{d}\sigma_Z(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}\right)^{-1}$$

- For the *W*-mass at 7 TeV MiNLO and NNLL **analytic resummed predictions** (i.e., DYRes, RESBOS, CuTe) **were discarded** in favour of PYTHIA 8 AZ **based on findings related to *p*T(*W*)/*p*T(*Z*):**
  - MiNNLO and NNLL **analytic resummed predictions disfavoured by recoil** distribution in data



(reweighting pTW by the product of pTZ from PYTHIA 8 AZ and *RW*/*Z*(*p*T) from DYRes, MiNLO+PYTHIA)

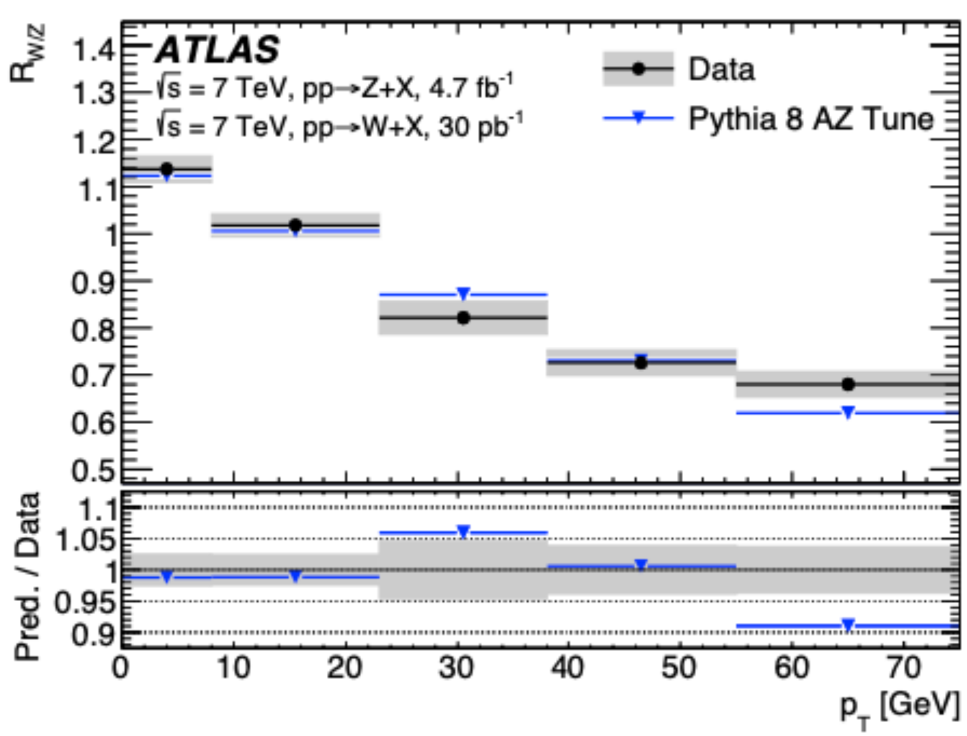
*p*T(*W*)/*p*T(*Z*)

Why care about *p*T(*W*)/*p*T(*Z*) ?

- QCD modelling of boson transverse momentum distribution can be validated studying the predicted differential cross-section ratio

$$R_{W/Z}(p_{\mathrm{T}}) = \left(\frac{1}{\sigma_W} \cdot \frac{\mathrm{d}\sigma_W(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}\right)\left(\frac{1}{\sigma_Z} \cdot \frac{\mathrm{d}\sigma_Z(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}\right)^{-1}$$

- For the *W*-mass at 7 TeV MiNLO and NNLL **analytic resummed predictions** (i.e., DYRes, RESBOS, CuTe) **were discarded** in favour of PYTHIA 8 AZ **based on findings related to *p*T(*W*)/*p*T(*Z*):**
  - Ratio predicted by **PYTHIA 8 AZ in good agreement with data** for *p*T < 30 GeV



pT(*W*)/pT(*Z*) with DYTurbo

DYTurbo setup

- Studies performed using DYTurbo tag v1.4.beta
- All *W*, *Z* predictions are **NNLO(+NNLL)** computed in pT bins of 0.5 GeV.
- No kinematical selection cuts on the leptons besides invariant mass cuts:
  - 80 < M(ll) < 100 GeV and M(lν) > 50 GeV.
- Central value of the scales $\mu_F = \mu_R = \mu_{RES} = M$.
- All predictions are computed using **CT18NNLO** as PDF set.
- We compare
  - **VFN forward evolution** of the PDFs from $Q_0 \to b_0/b \sim p_\mathrm{T}$ with LHAPDF;
  - **FFN iterative backward evolution** of the PDFs from $\mu_F \to b_0/b \sim p_\mathrm{T}$.

(Always switching off b and c PDFs below the corresponding thresholds.)

pT(*W*)/pT(*Z*) with DYTurbo

DYTurbo setup

- Studies performed using DYTurbo tag v1.4.beta
- All *W*, *Z* predictions are **NNLO(+NNLL)** computed in pT bins of 0.5 GeV.
- No kinematical selection cuts on the leptons besides invariant mass cuts:
  - 80 < M(ll) < 100 GeV and M(lv) > 50 GeV.
- Central value of the scales $\mu_F = \mu_R = \mu_{RES}$ = M.
- All predictions are computed using **CT18NNLO** as PDF set.
- We compare
  - **VFN forward evolution** c
  - **FFN iterative backward** e

There exit several *flavour number schemes* that incorporate the heavy quark effects under different assumptions. Depending on the relation between the mass of a heavy quark m_q and the scale at which we probe the PDF, Q, we can identify two limiting cases:

$m_q \ll Q$ In this case we can simply treat the heavy quark as another massless proton, so that it is perturbatively generated by the DGLAP evolution. **~ VFN**

$m_q \gtrsim Q$ The heavy quark can be considered as a purely final state that does not participate in the evolution (since there is no energy to produce it). This then allows to consider fully the mass effects in the matrix elements of the final state. **~ FFN**

$pT(W)/pT(Z)$ with DYTurbo

Effect of heavy-flavour initiated processes

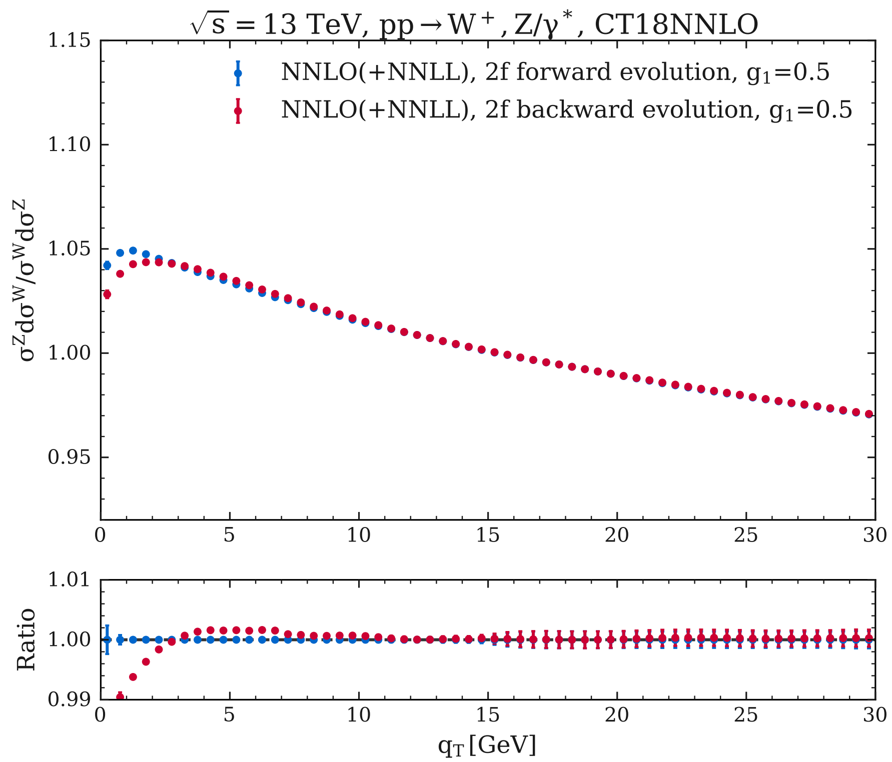
- Heavy-flavour-initiated (HFI) production introduce differences between Z and W.
- HFI production results in a **harder boson *pT* spectrum**, however c, b quarks contribute differently to W and Z production:
  - for example, at 7 TeV, $cc \to Z$ ($bb \to Z$) are 6% (3%) of Z production, $cs \to W$ is ~20% of W production.

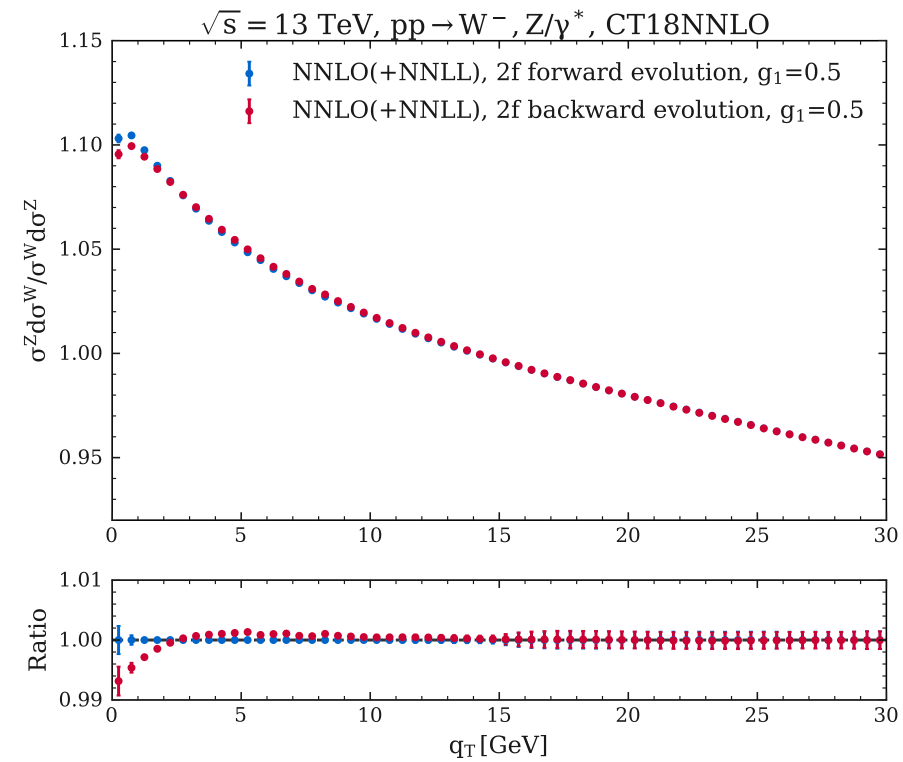
→ Disentangle HFI effects studying **$pT(W)/pT(Z)$ for different allowed initial state flavours:**

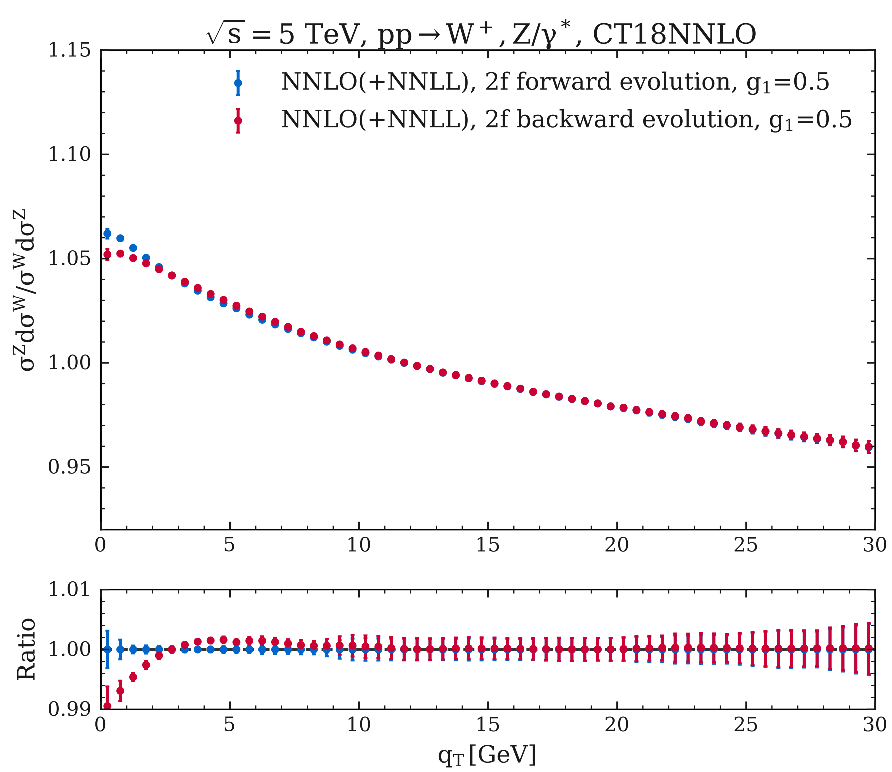
- 2 flavours → keep only $uu \to Z$, $dd \to Z$ and $ud \to W$ couplings;
- 3 flavours → add $ss \to Z$ and $us \to W$;
- 4 flavours → add $cc \to Z$ and $cs \to W$, $cd \to W$;
- 5 flavours → add $bb \to Z$ and $ub \to W$, $cb \to W$.

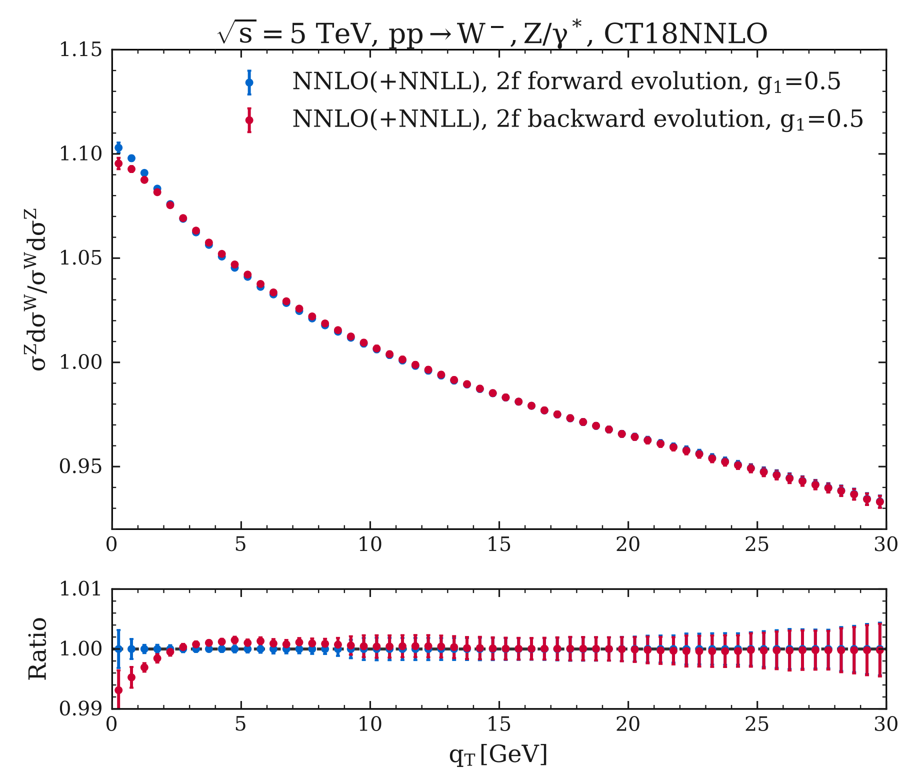
pT(W)/pT(Z) with DYTurbo

2 flavours: VFN forward vs FFN backward PDF evolution



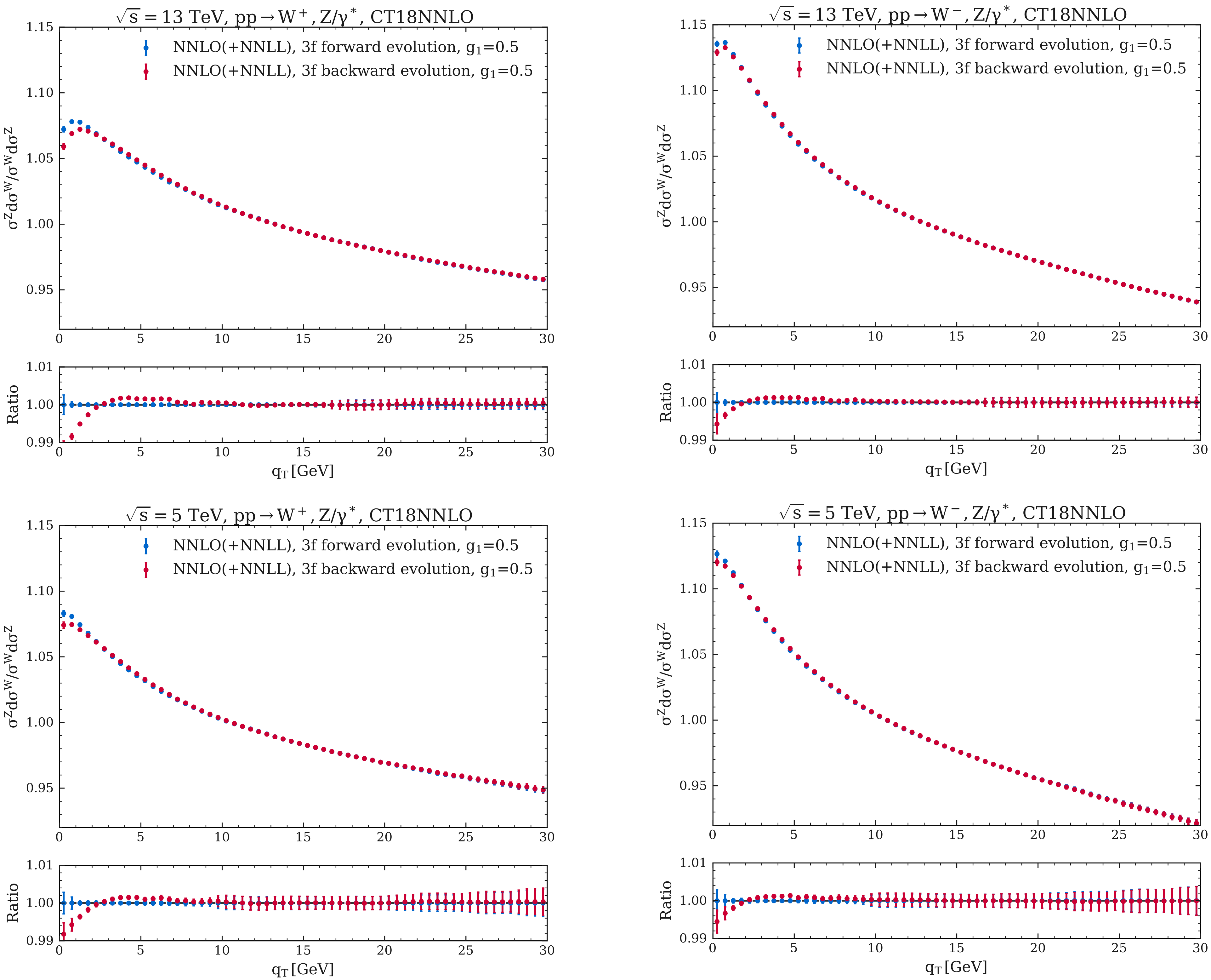






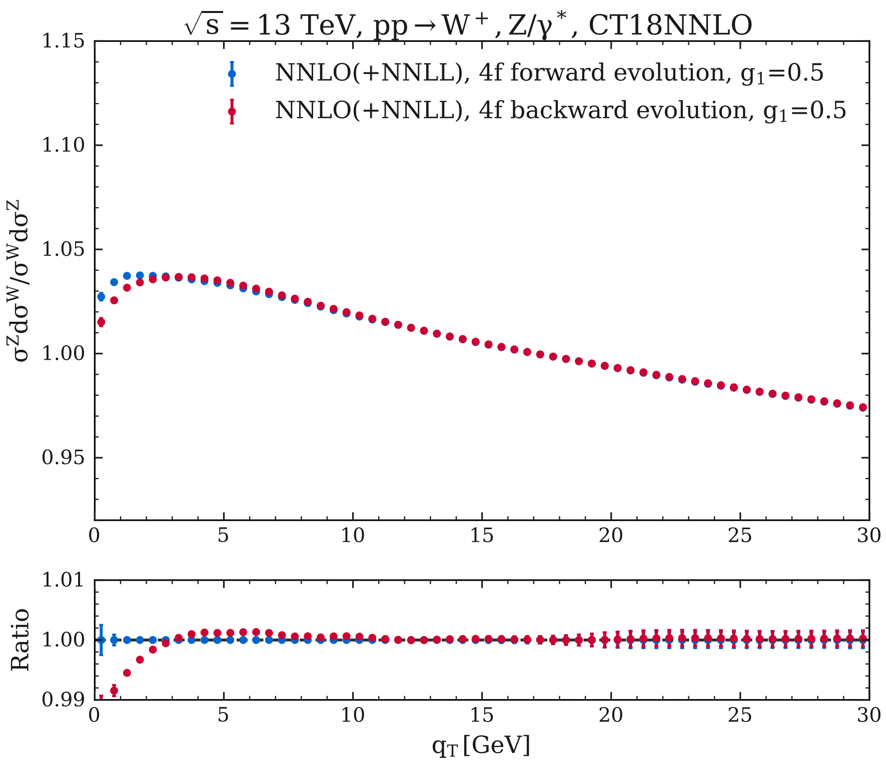
pT(W)/pT(Z) with DYTurbo

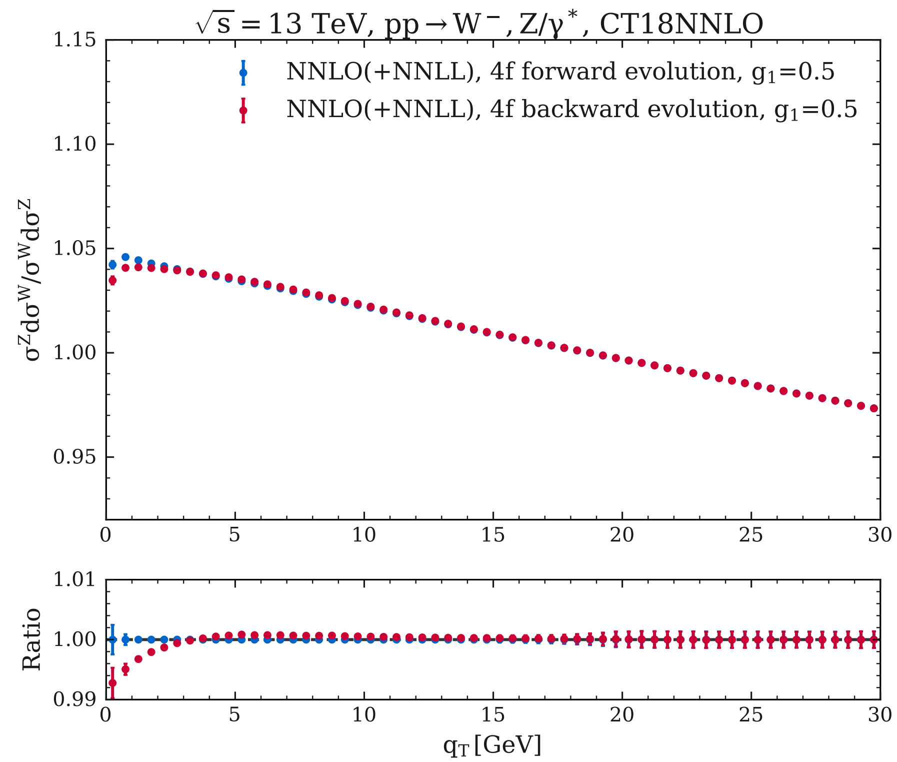
3 flavours: VFN forward vs FFN backward PDF evolution

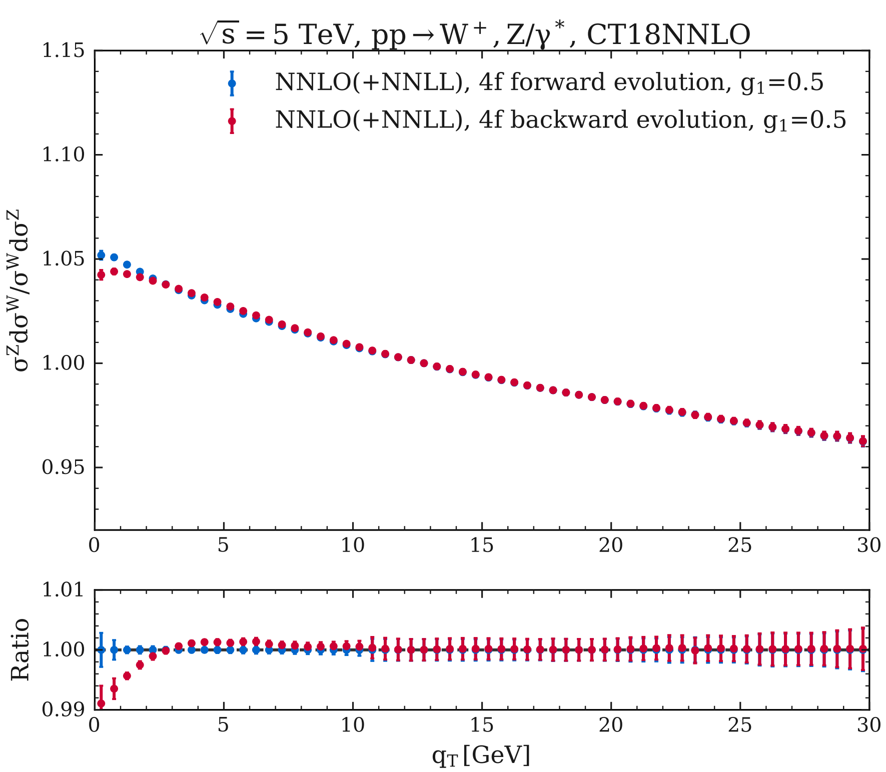


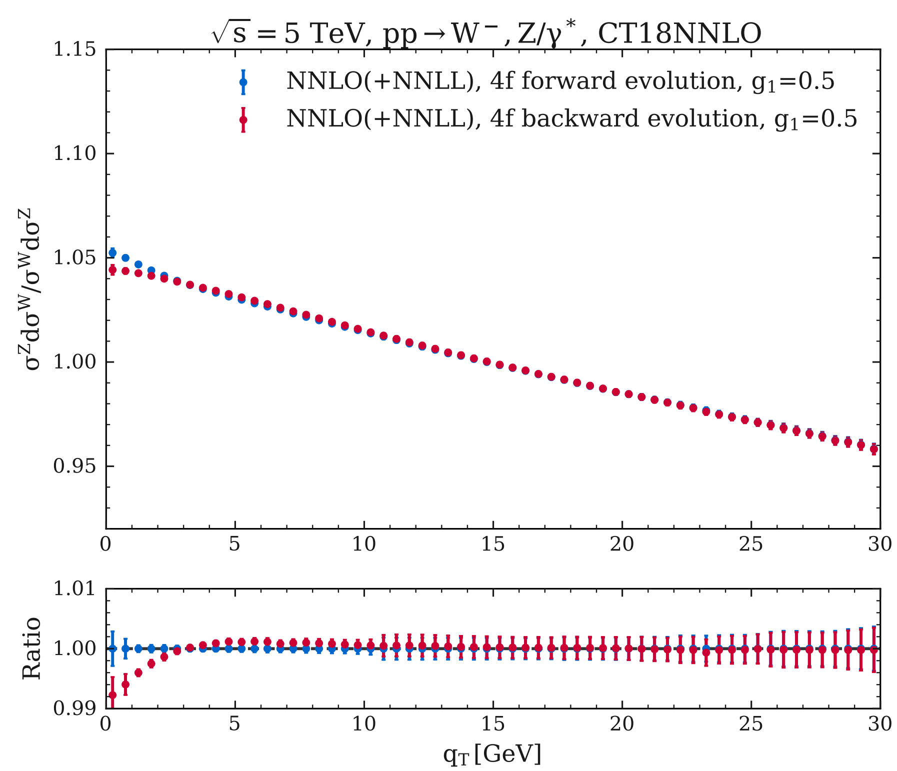
*p*T(*W*)/*p*T(*Z*) with DYTurbo

4 flavours: VFN forward vs FFN backward PDF evolution



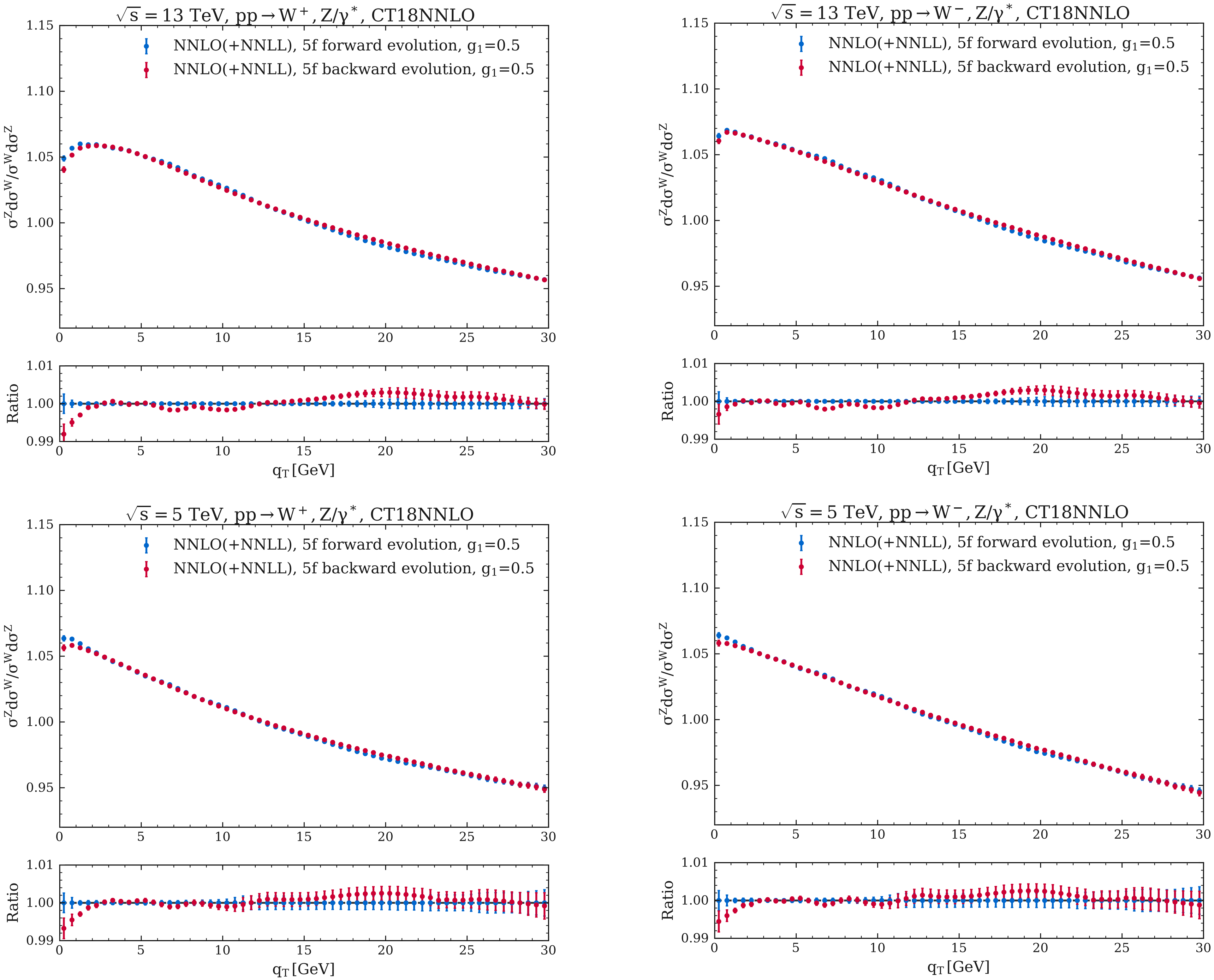






$pT(W)/pT(Z)$ with DYTurbo

5 flavours: VFN forward vs FFN backward PDF evolution



$pT(W)/pT(Z)$ with DYTurbo

Effect of non-perturbative form factor (FF)

- Check $pT(W)/pT(Z)$ with 5 flavours for **different values of g_1 in the non-perturbative FF:**
    - $g_1 = 0, 0.5, 1, 1.5\ \mathrm{GeV}^2$;

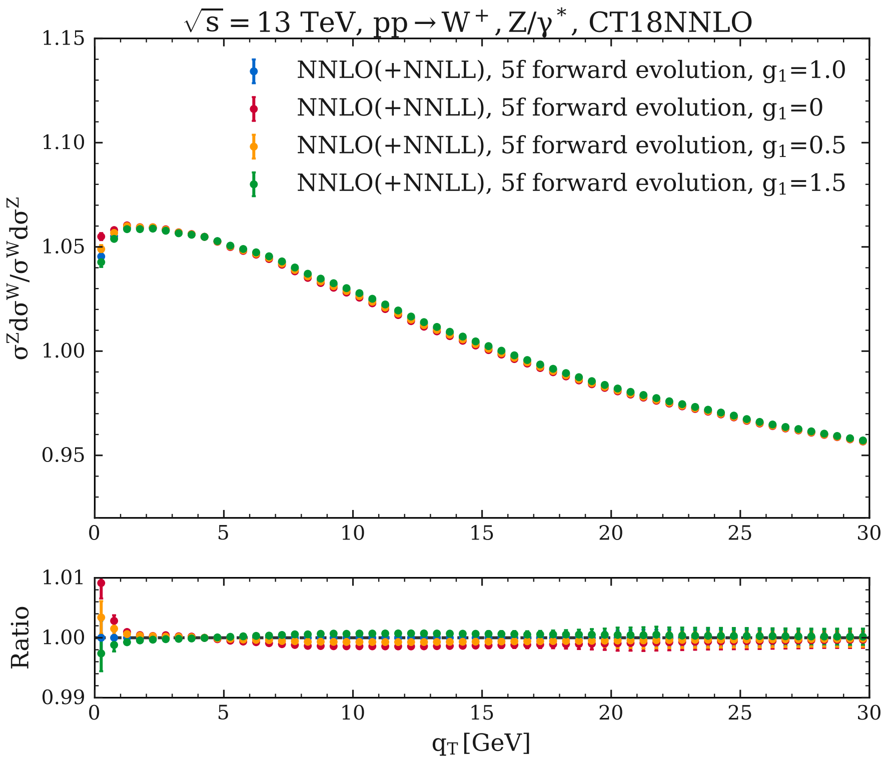
  comparing

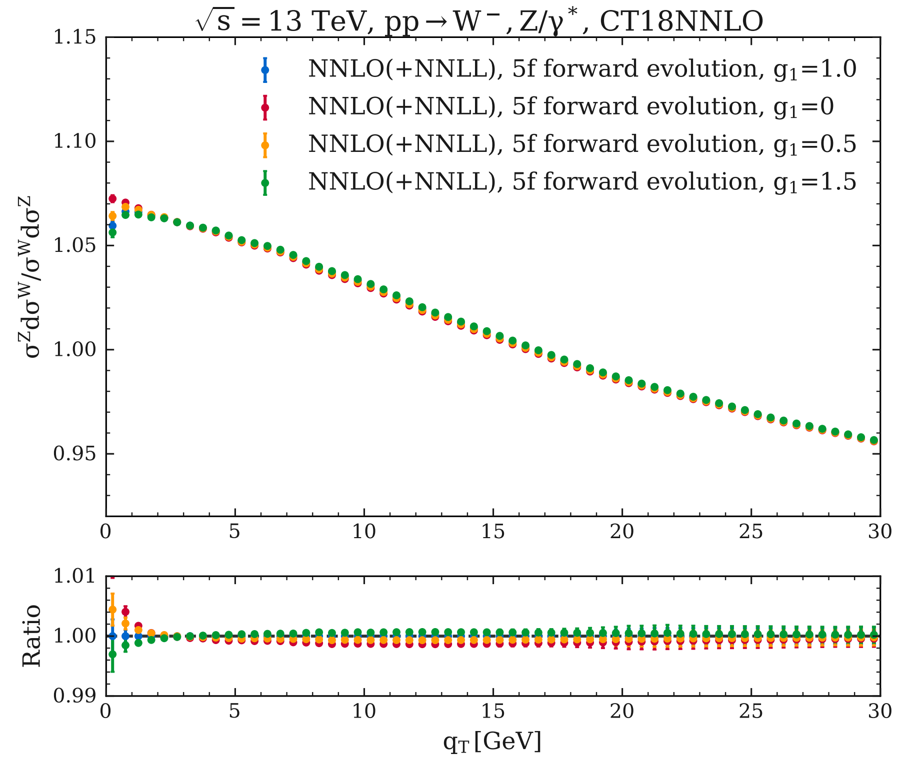
    - **VFN forward evolution vs FFN iterative backward evolution** of the PDFs.

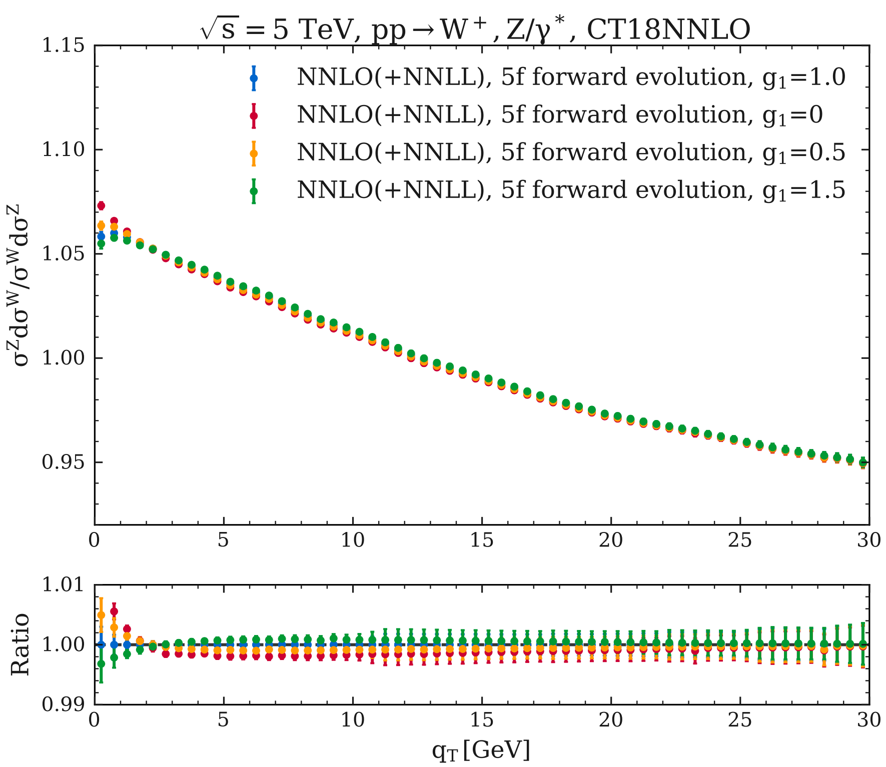
(Always switching off b and c PDFs below the corresponding thresholds.)

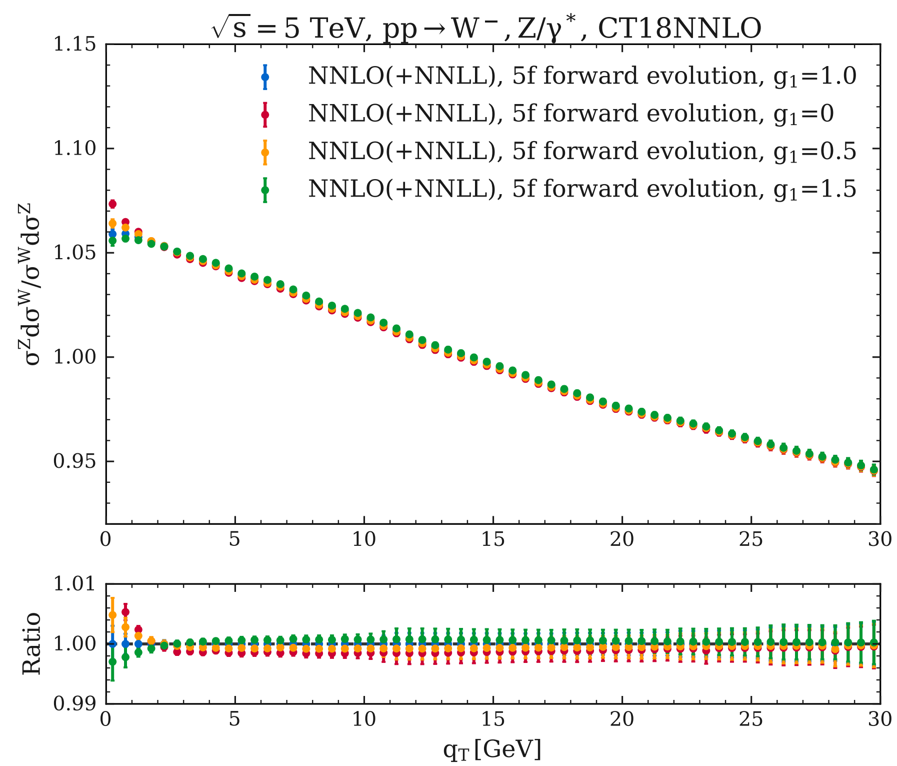
pT(W)/pT(Z) with DYTurbo

5 flavours, VFN forward PDF evolution: $g_1 = 0, 0.5, 1, 1.5\ \mathrm{GeV}^2$



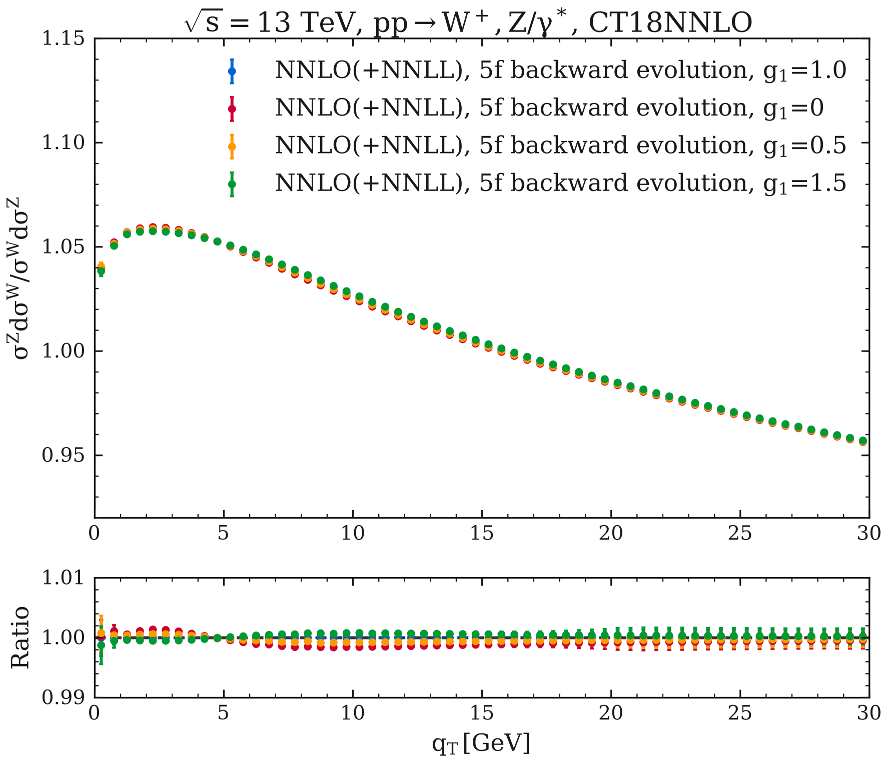


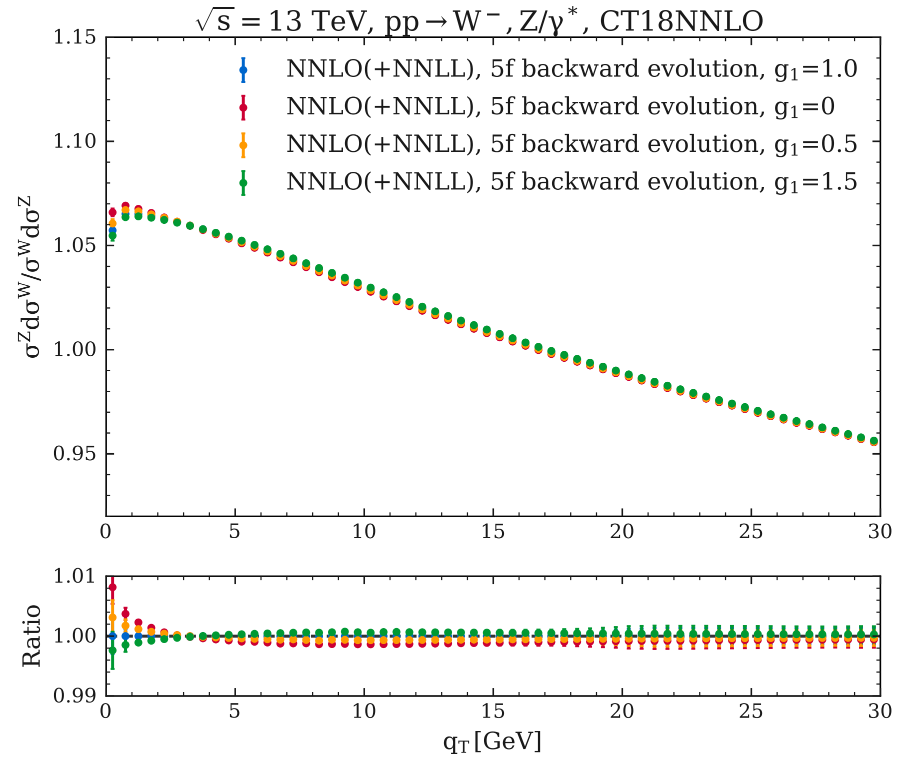


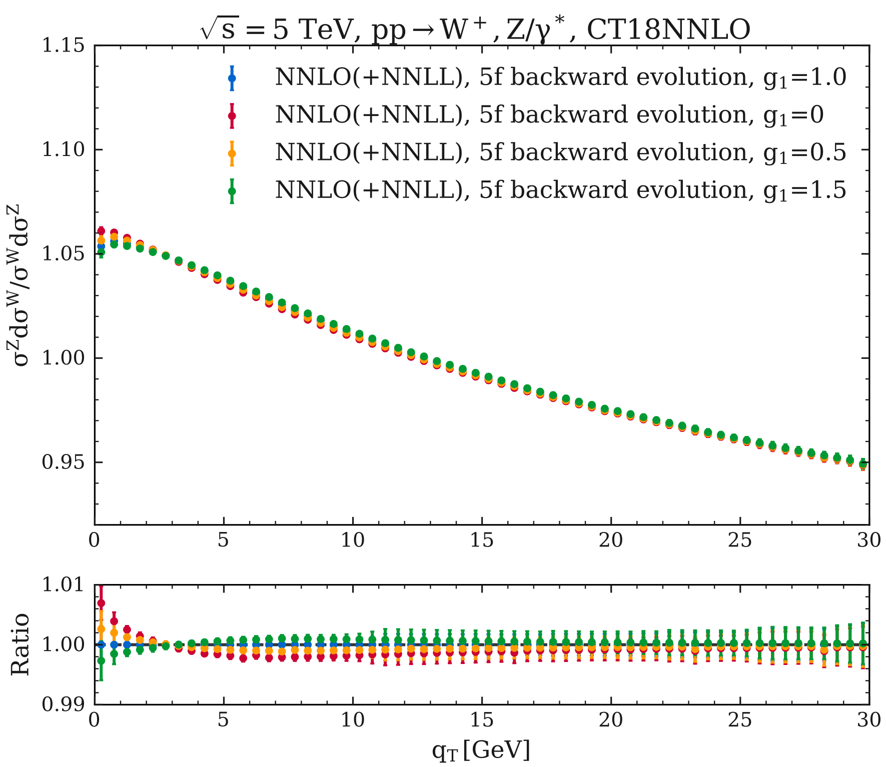


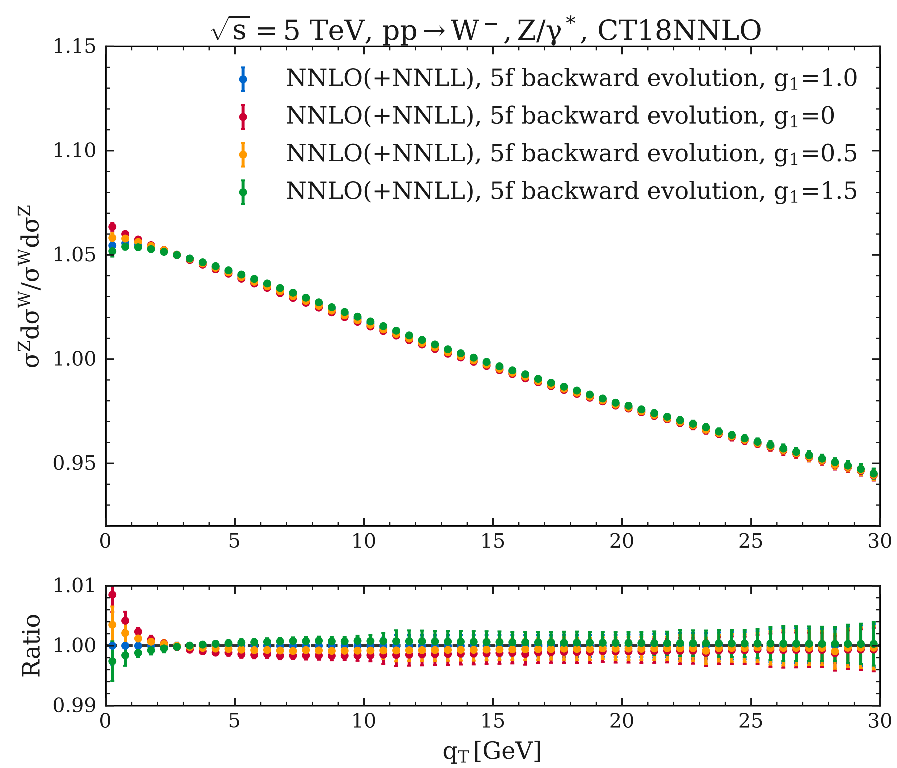
pT(W)/pT(Z) with DYTurbo

5 flavours, FFN backward PDF evolution: $g_1 = 0, 0.5, 1, 1.5\ \mathrm{GeV}^2$









$pT(W)/pT(Z)$ with DYTurbo

5-flavour ratios with PDF and scale uncertainties

- Check $pT(W)/pT(Z)$ with 5 flavour couplings accounting for **PDF and scale uncertainties**.

- **Uncertainty on $pT(W)/pT(Z)$ due to PDFs is computed at NNLO(+NNLL)** using CT18NNLO Hessian eigenvectors (90% CL):

$$\delta R_{W/Z}(\mathrm{PDF}) = \frac{1}{2}\sqrt{\sum_{\mathrm{i}} \left(\mathrm{R}_{+\mathrm{i}} - \mathrm{R}_{-\mathrm{i}}\right)^2}$$

- **Uncertainty on $pT(W)/pT(Z)$ due to missing higher-order terms also at NNLO(+NNLL)** performing independent variation of μ_F, μ_R, μ_{RES} in the range $M/2 \leq \{\mu_F, \mu_R, \mu_{RES}\} \leq 2M$ with the constraints $0.5 \leq \{\mu_F/\mu_R, \mu_{RES}/\mu_R, \mu_{RES}/\mu_F\} \leq 2$ and taking the envelope.

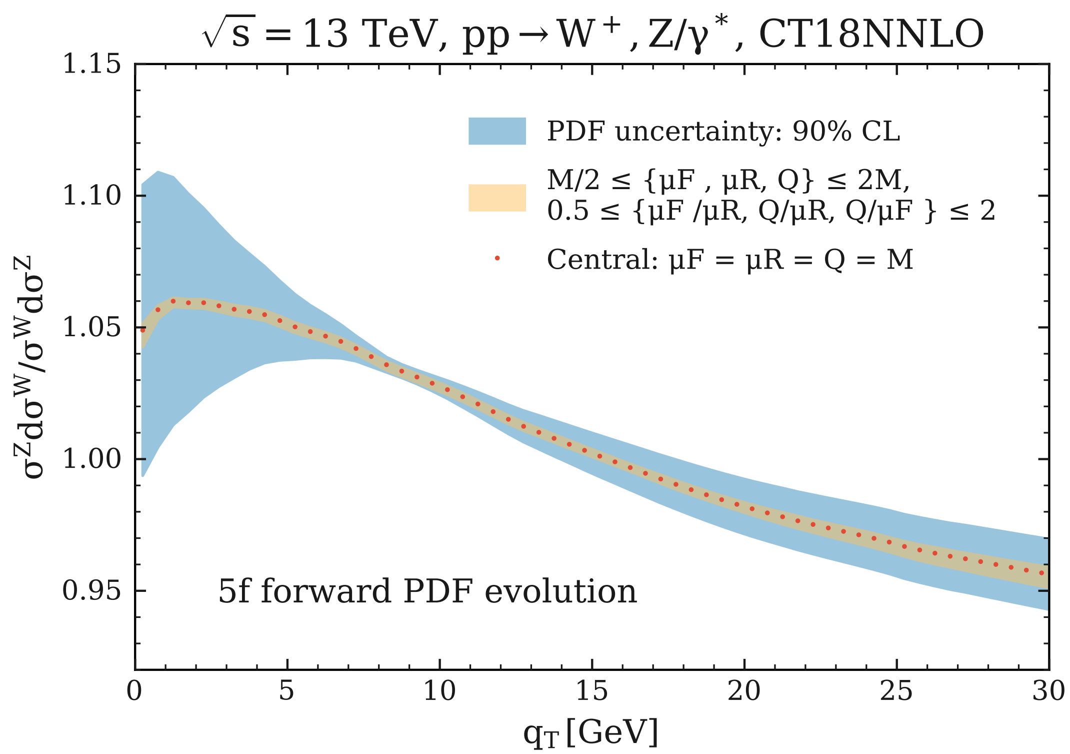
- We compare results obtained with

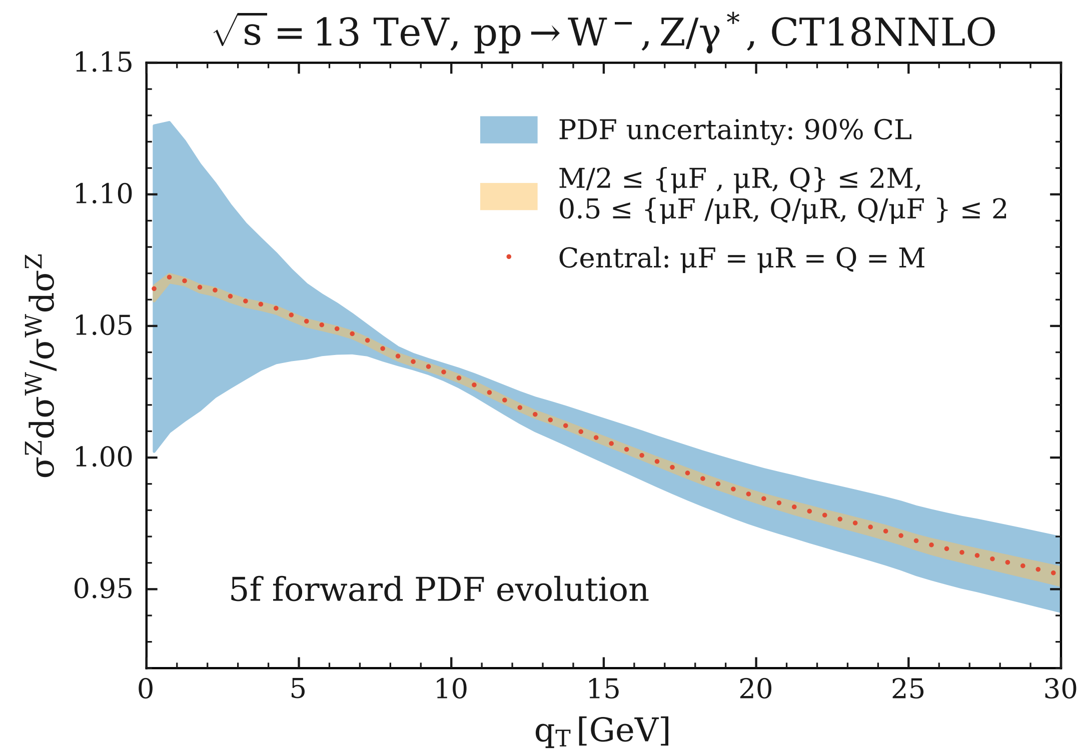
  - **VFN forward evolution vs FFN iterative backward evolution** of the PDFs.

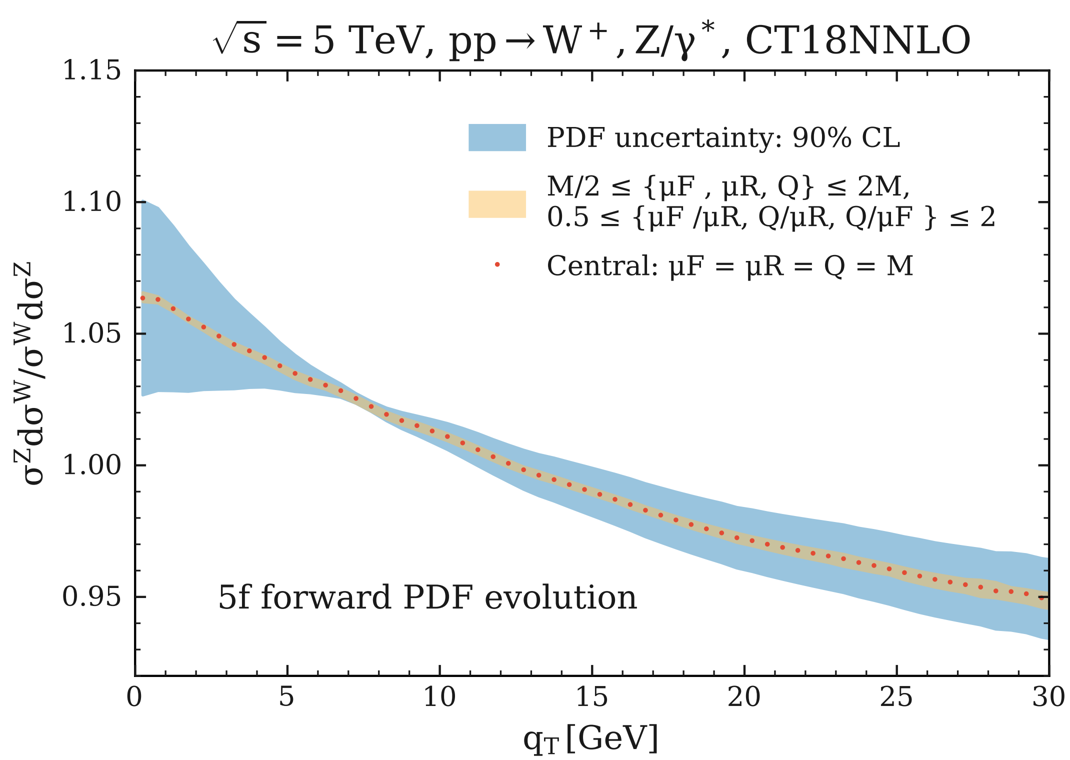
(Always switching off b and c PDFs below the corresponding thresholds.)

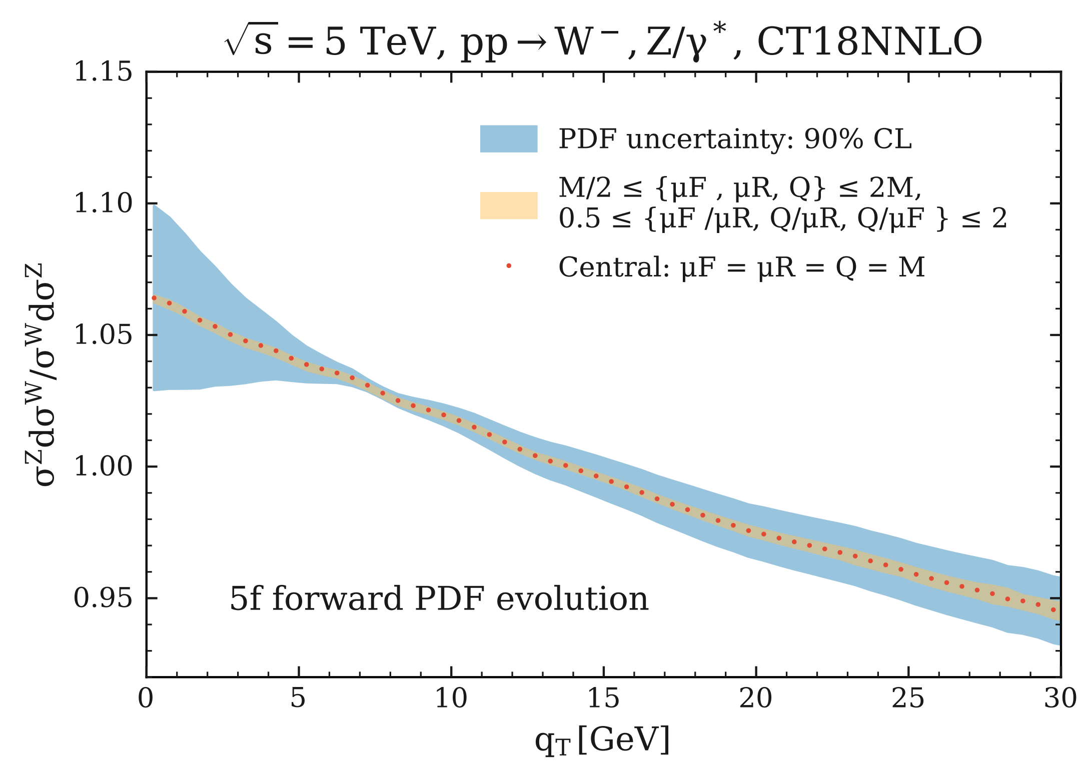
pT(W)/pT(Z) with DYTurbo

5-flavour ratios with PDF and scale uncertainties: VFN forward evolution



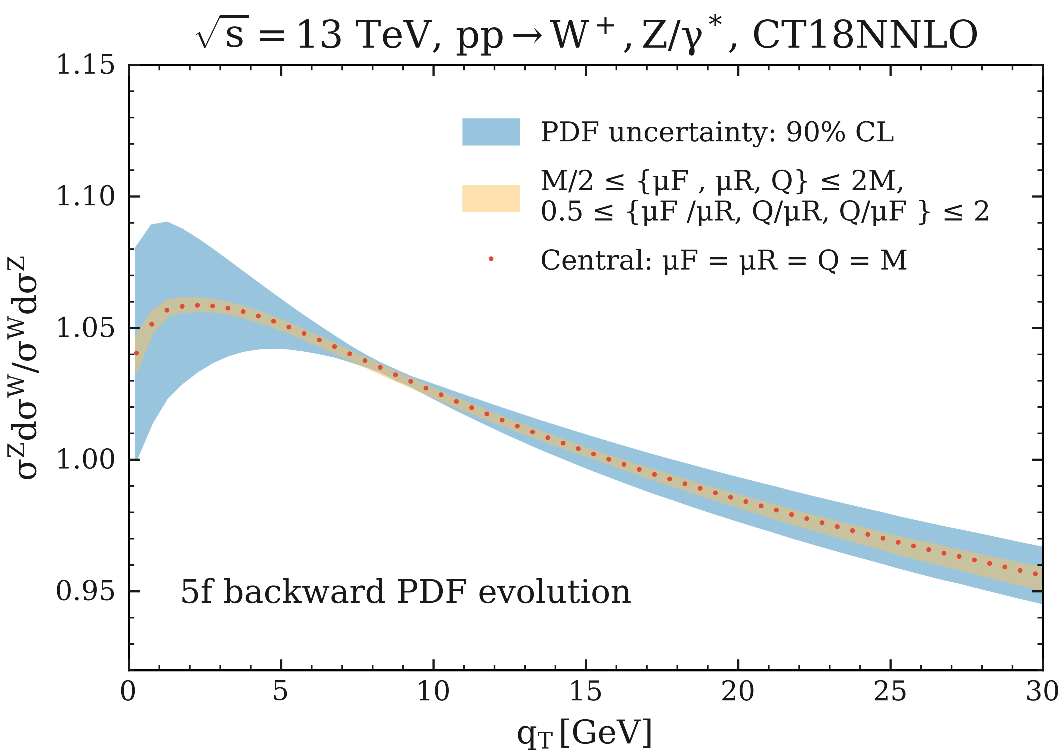


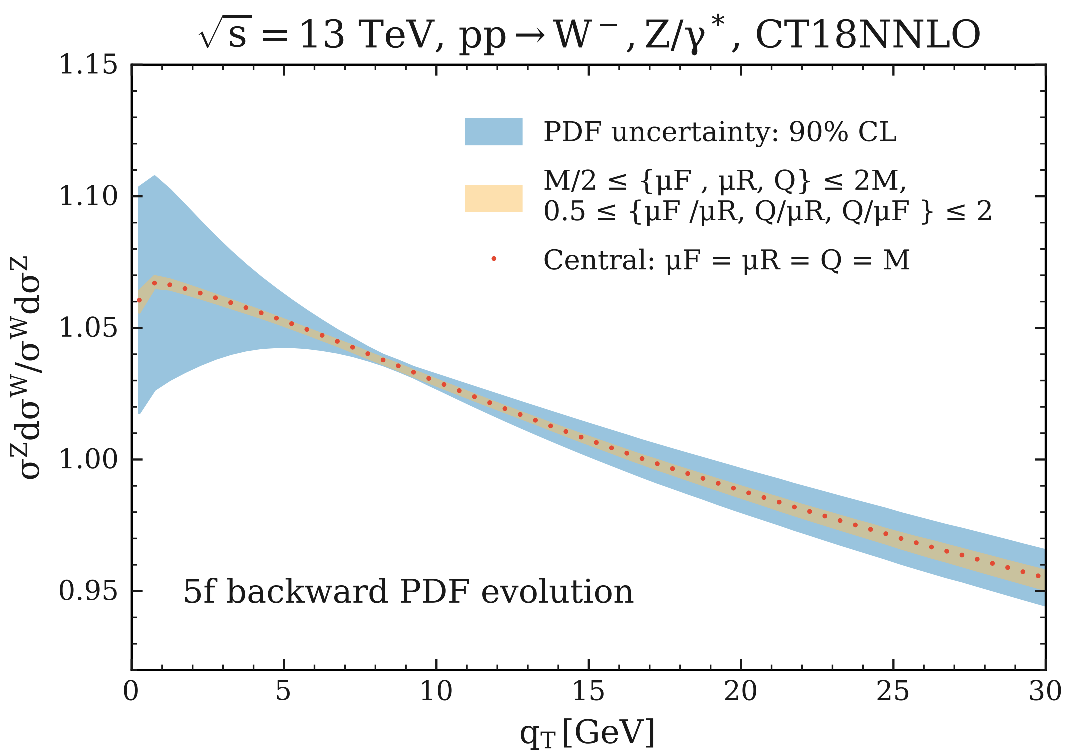


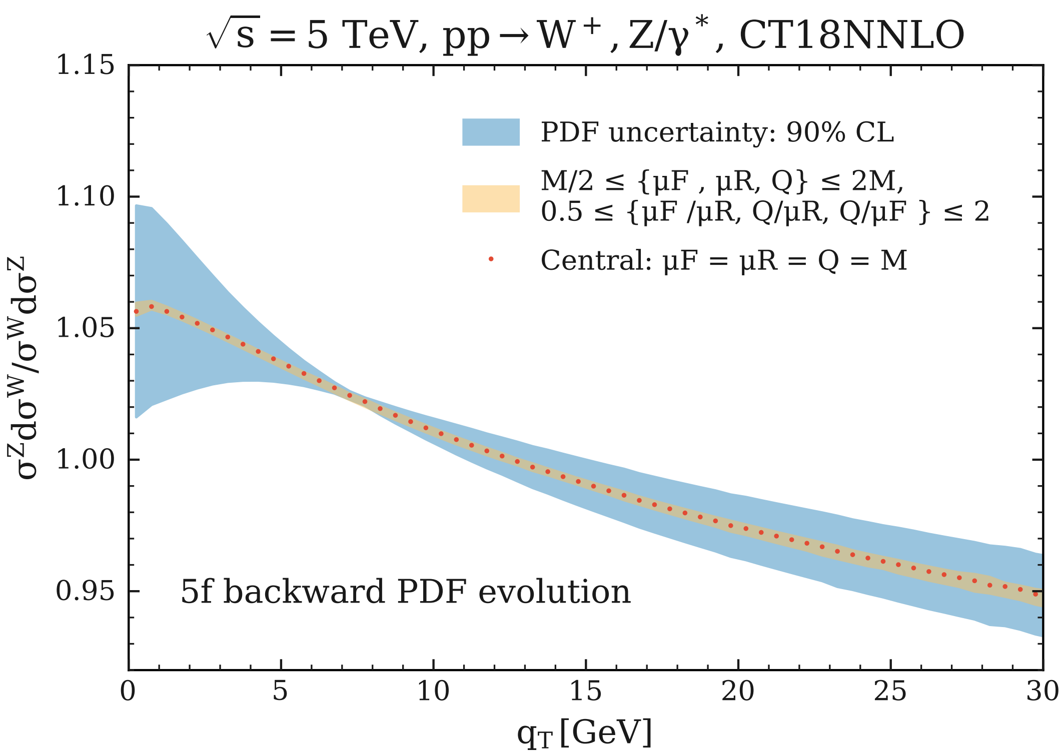


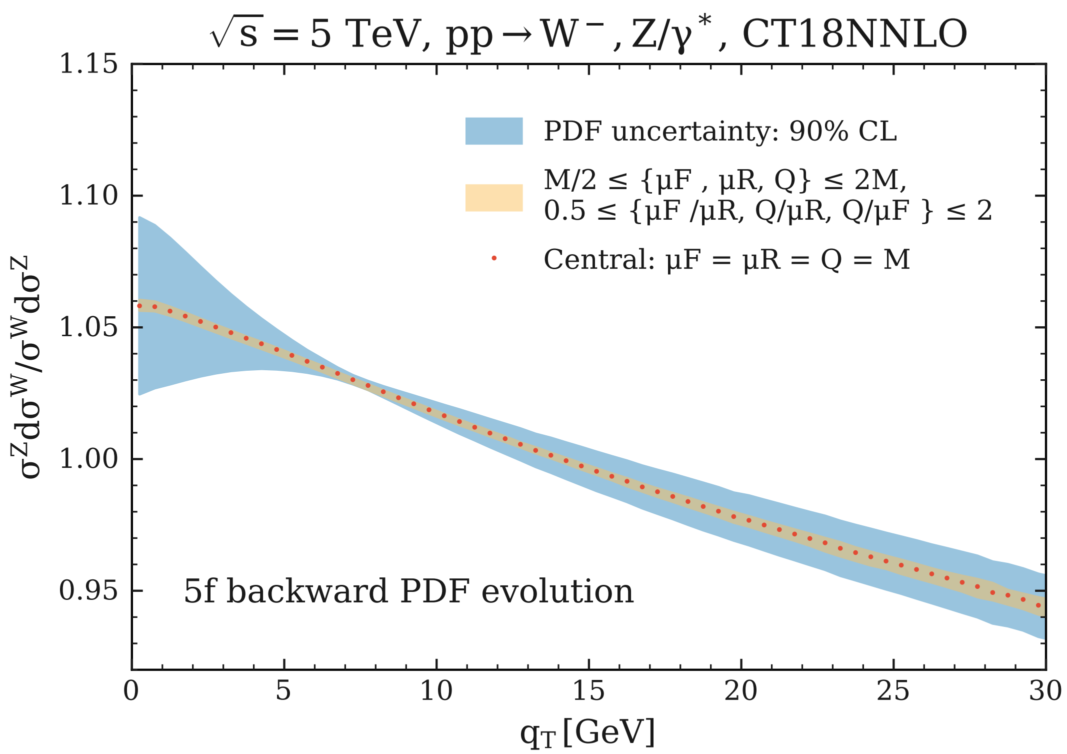
pT(W)/pT(Z) with DYTurbo

5-flavour ratios with PDF and scale uncertainties: FFN backward evolution





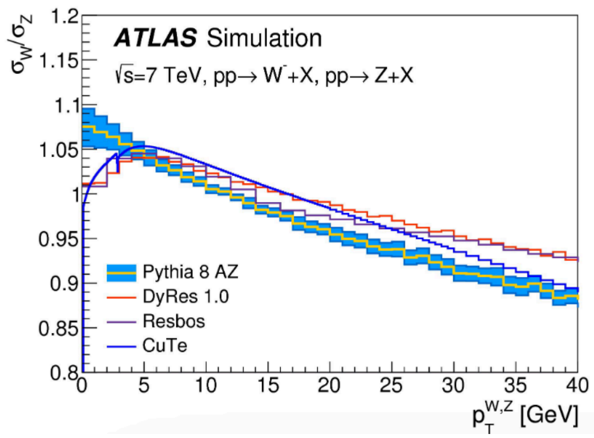


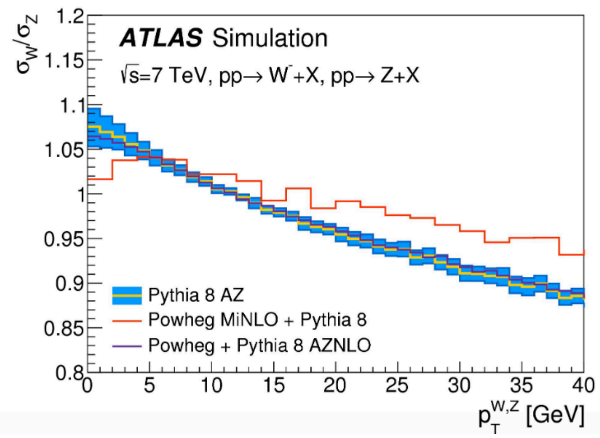


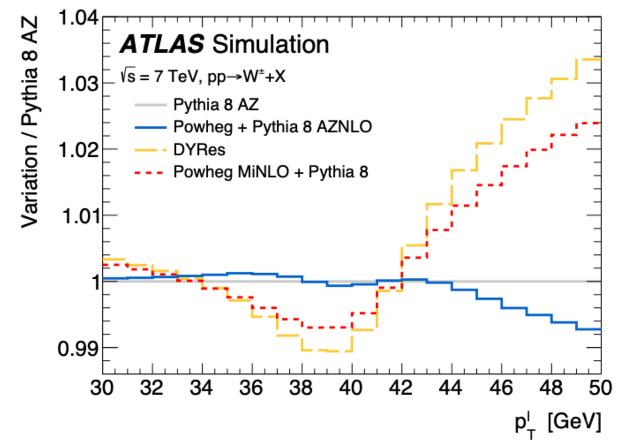
pT(*W*)/pT(*Z*) with DYTurbo

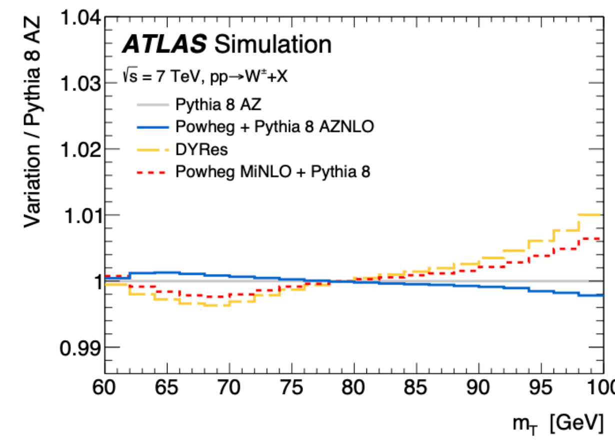
Next checks

- Check ***pT(W)/pT(Z)* at NNLO(+NNLL) with DYTurbo against other predictions**, e.g. Powheg MiNNLO+Pythia8 (MiNNLOPS).

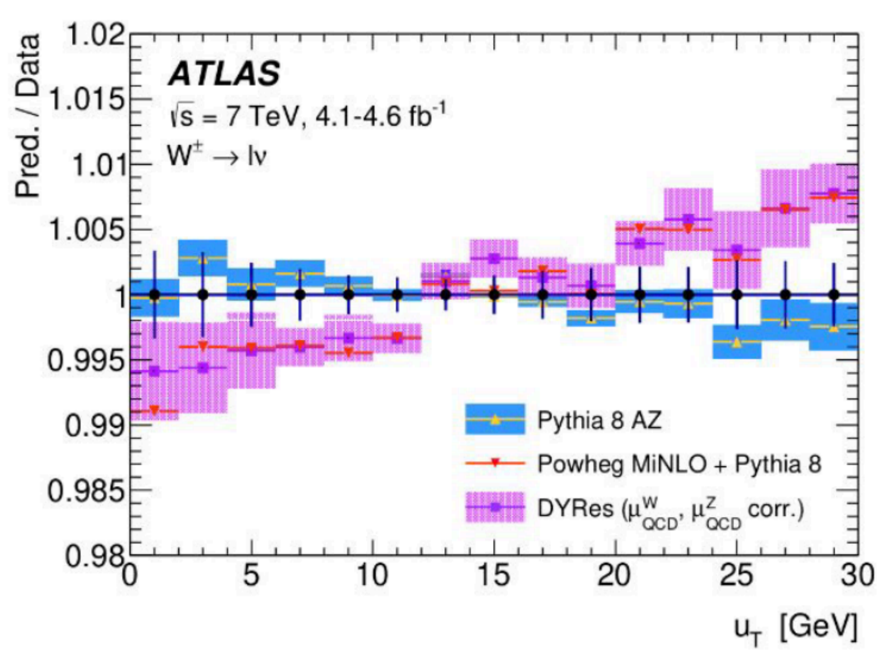








- Reweight detector-level distributions and check against data: **data-driven checks** with recoil.



... a brief detour into *Ai's*

Status of Ai production

Physics	2D Ai(pT,Y)	3D Ai(pT,Y,M)
NLO		
`NNPDF40_nnlo`	W+ 5TeV (NLO) ; W- 5TeV (NLO) W+ 13TeV (NLO); W- 13TeV (NLO)	
`NNPDF31_nnlo`	W+ 5TeV (NLO) ; W- 5TeV (NLO) W+ 13TeV (NLO); W- 13TeV (NLO)	
`CT18ANNLO`	W+ 5TeV (NLO) ; W- 5TeV (NLO) W+ 13TeV (NLO); W- 13TeV (NLO)	
`CT18NNLO`	W+ 5TeV (NLO) ; W- 5TeV (NLO) W+ 13TeV (NLO); W- 13TeV (NLO)	
`MSHT20nnlo`	W+ 5TeV (NLO) ; W- 5TeV (NLO) W+ 13TeV (NLO); W- 13TeV (NLO)	
`HERAPDF20_NNLO`	W+ 5TeV (NLO) ; W- 5TeV (NLO) W+ 13TeV (NLO); W- 13TeV (NLO)	
NNLO		
`NNPDF40_nnlo`		
`NNPDF31_nnlo`		
`CT18ANNLO`		
`CT18NNLO`		
`MSHT20nnlo`		
`HERAPDF20_NNLO`		

- 2D Ai(pT, Y) at **NLO completed for *W+/-* and *Z***: missing maps will be linked to the table.
- 2D Ai(pT, Y) at **NNLO almost completed for *W+/-*** (only HERAPDF still running) **in good progress for *Z***.

A huge thanks to Fra' who's sharing with me the production :)