DYTurbo interface for xFitter

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xFitter workshop – 10th March 2022

DYTurbo project

- Optimised version of DYNNLO, DYqT, DYRes with improvements in

Software	Numerical integration
Code profiling	Quadrature with interpolating functions
Loop vectorisation	Factorisation of integrals
Hoisting	Analytic integration
Loop unrolling	
Multi-threading	

- The main application is the measurement of the W mass at the LHC, Other applications: PDF fits including qt-resummation for cross-section predictions, $\sin^2\theta_W$, $\alpha_s(m_Z)$
- A few active developers (SC, Giancarlo Ferrera, Leandro Cieri, Manuel Der) and several users helping with testing, scripts, etc…
- Widely used in ATLAS, CMS, LHCb, primary usage are W,Z NNLO predictions

DYTurbo project

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Fast predictions for Drell-Yan processes including qt-resummation

Installation instructions

Download the source code

- dyturbo-1.1.tar.gz

- Public code available on HEPForge (https://dyturbo.hepforge.org/)
- Original reference”
  - “DYTurbo: Fast predictions for Drell-Yan processes” Eur.Phys.J.C 80 (2020) 3, 251
- Recent developments:
  - “Drell–Yan lepton-pair production: q_T resummation at N3LL accuracy and fiducial cross sections at N3LO”, Phys.Rev.D 104 (2021) 11, L111503
  - “Fiducial perturbative power corrections within the q_T subtraction formalism”, arXiv:2111.14509

Drell-Yan cross section

- DYTurbo can compute the DY cross section at

Fixed order
with qt-subtraction

$$d\sigma^{V}_{(N)NLO} = d\sigma^{virt}_{(N)NLO} - d\sigma^{CT(FO)}_{(N)LO} + d\sigma^{V+jet}_{(N)LO}$$

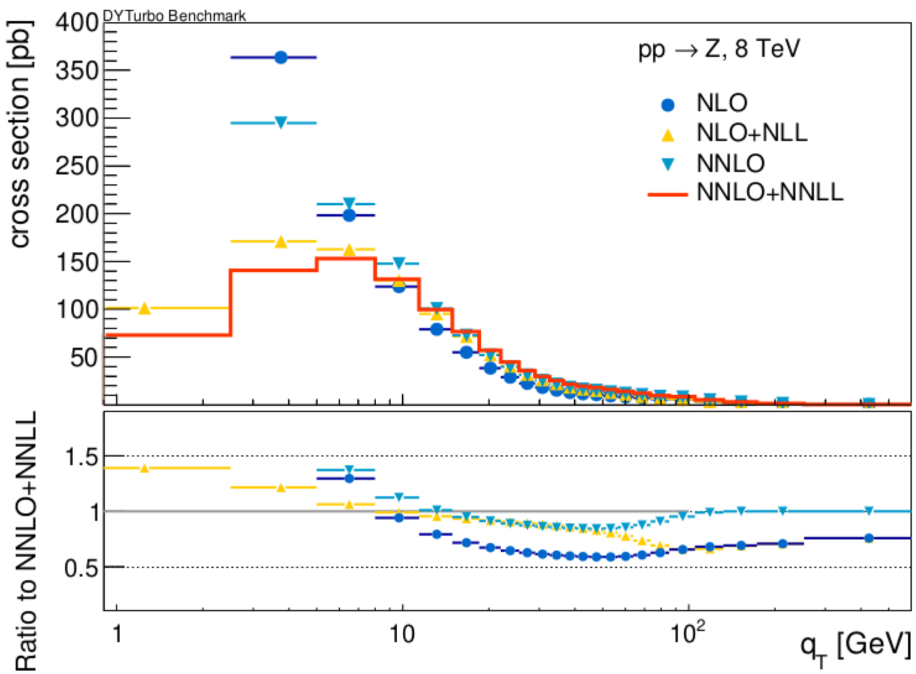
Fast predictions already implemented with NNLOJET + APPLfast

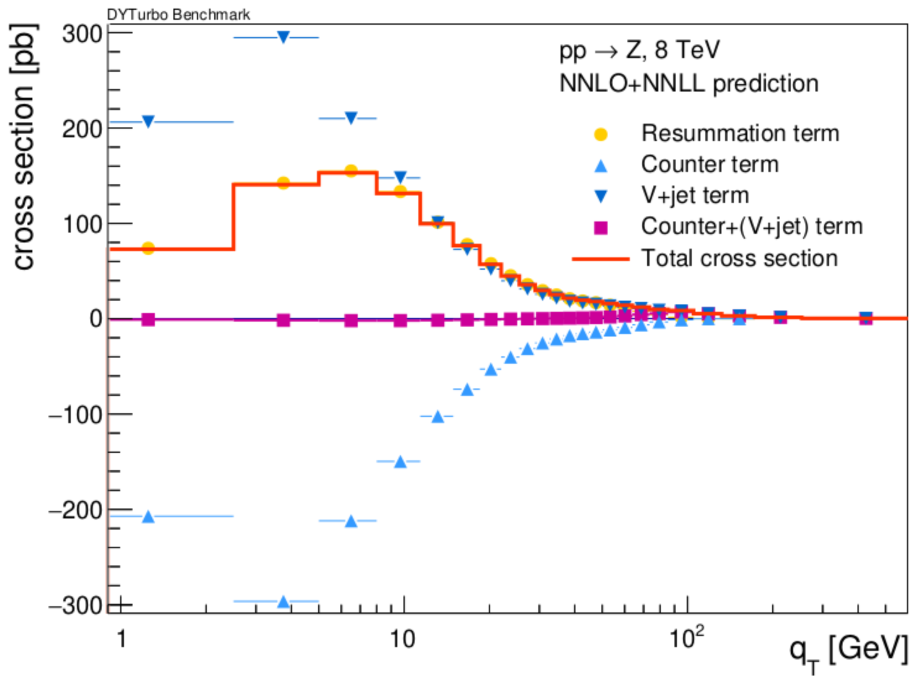
Fixed order
+qt-resummation

$$d\sigma^{V}_{(N)NLO+(N)NLL} = d\sigma^{res}_{(N)NLL} - d\sigma^{CT(res)}_{(N)LO} + d\sigma^{V+jet}_{(N)LO}$$

Main motivation for DYTurbo

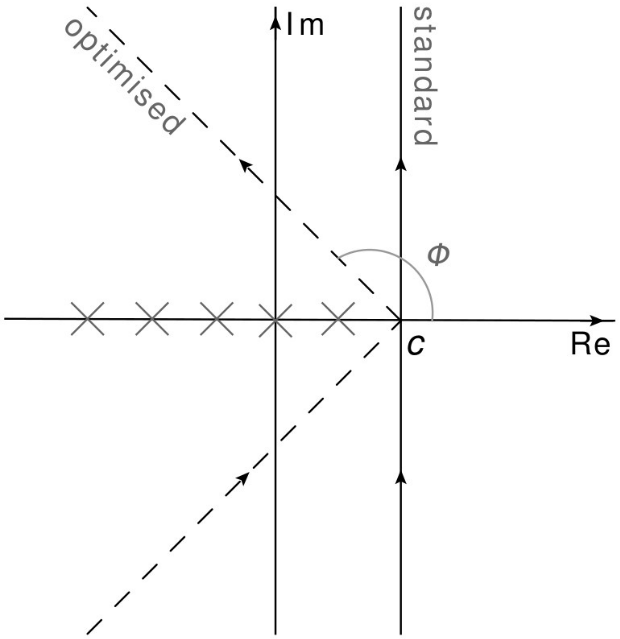
b-space CdFG resummation formalism





Numerical integration improvements

- Fast x-space to Mellin-space integral transform of PDFs based on Gauss-Legendre quadrature, coefficients in Mellin space evaluated through their large-N expansion



- Acceptance corrections evaluated by factorising the integration over lepton-decay angular variables in the LO cross section

$$\sigma_{LO} = a + b\cos(\theta) + c\cos^2(\theta) \rightarrow a\,\theta_0 + b\,\theta_1 + c\,\theta_2$$

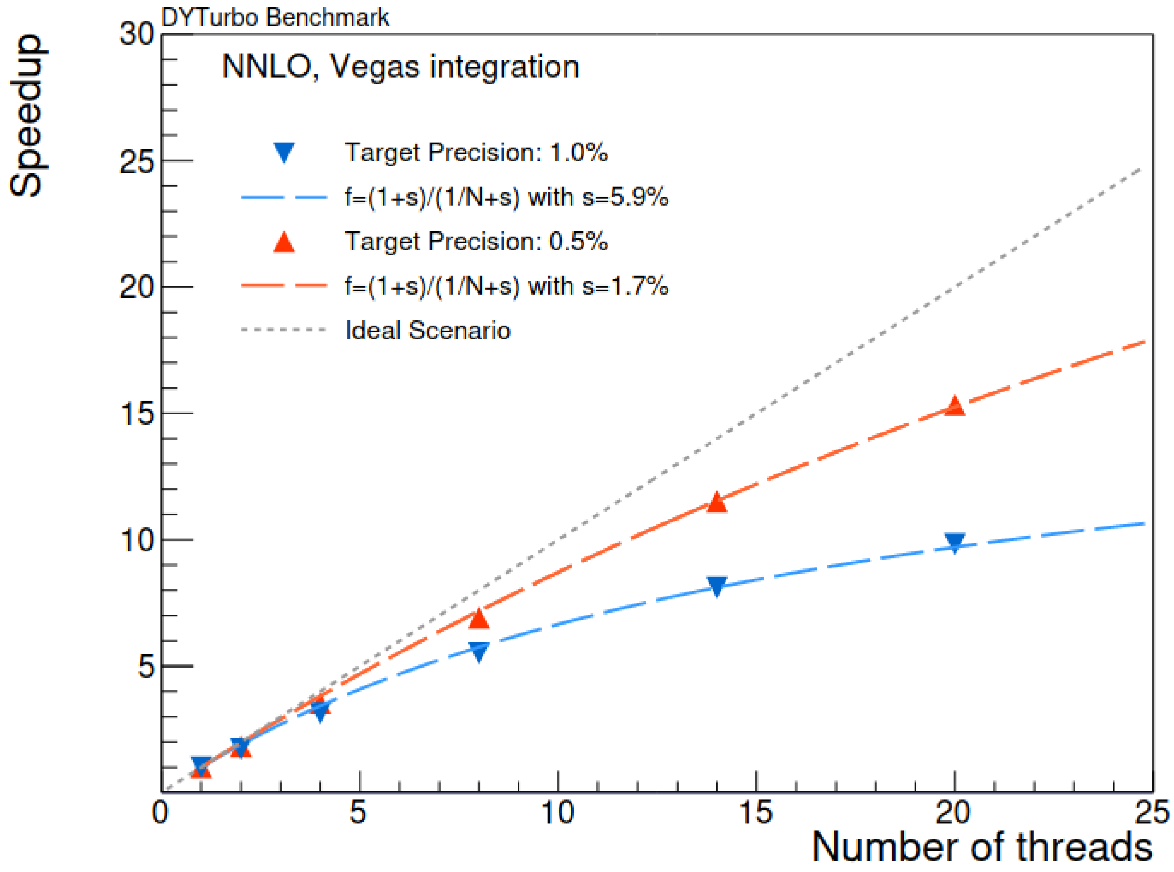
- Analytic integration over

$$\begin{cases} \theta_0 = \int \mathrm{d}\Omega\, \Theta_K\,, \theta_1 = \int \mathrm{d}\Omega\, \Theta_K\, \cos\theta_\ell\,, \\ \theta_2 = \int \mathrm{d}\Omega\, \Theta_K\, \cos^2\theta_\ell \end{cases}$$

$$\int \mathrm{d}x\, x J_0(x) = x J_1(x) \quad \Rightarrow \quad \int_{q_\mathrm{T}^0}^{q_\mathrm{T}^1} \mathrm{d}q_\mathrm{T}\, 2q_\mathrm{T}\, \mathcal{W}(q_\mathrm{T}, m) = \frac{m^2}{s}\int_0^\infty \mathrm{d}b\, \frac{1}{2}\left[q_\mathrm{T}^1 J_1(bq_\mathrm{T}^1) - q_\mathrm{T}^0 J_1(bq_\mathrm{T}^0)\right]\, \tilde{\mathcal{W}}(b, m)$$

Multithreading time performance

- Measured the performance of the multi-threading implementation

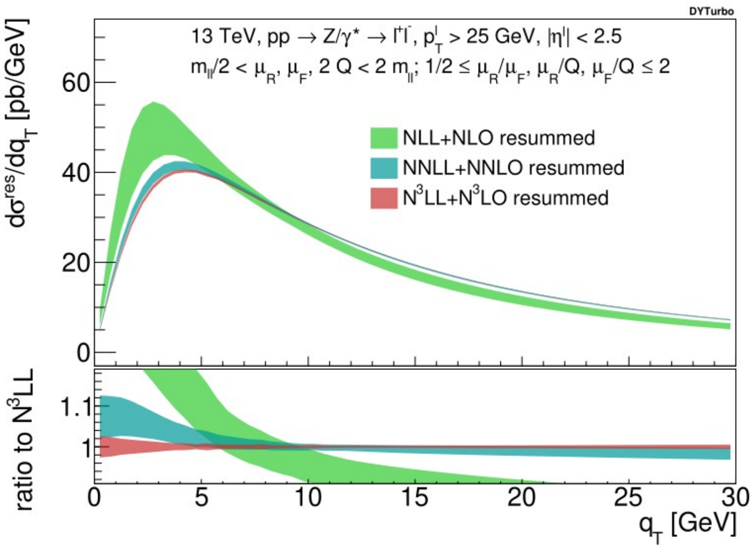


Good efficiency (~ 1) thanks to small overhead

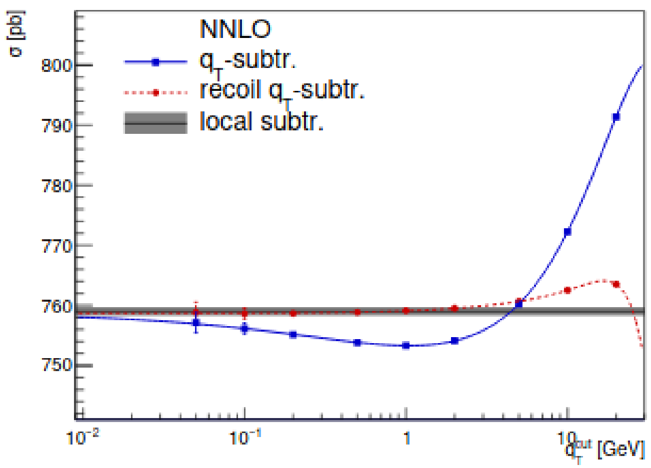
s ~ 2-5% is the nonparallelisable fraction

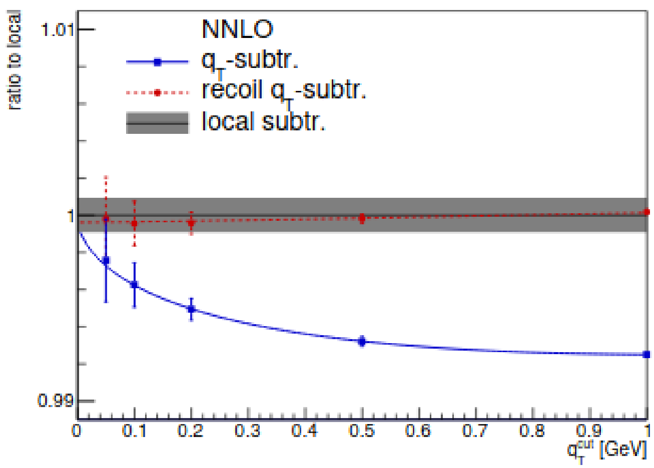
Larger gain from multi-threading when the required precision is higher

Recent DYTurbo results



- N3LL q_T resummation
- Fiducial power corrections
- N3LO fiducial cross sections (depend on the availability of external V+jet NNLO predictions)





Order	N^3LO
q_T subtr. ($q_T^{cut} = 4$ GeV)	747.1 ± 0.7 pb
recoil q_T subtr.	745.7 ± 0.7 pb

xFitter interface

- DYTurbo-xFitter interface developed in two xFitter branches:
  - dyturbo-reaction
  - alphas-scan
- yaml settings currently include scales and non-perturbative parameters

```
# DYTurbo:
order: 2     # Perturbative order in QCD: 0 for LL, 1 for NLL+NLO, 2 for NNLL+NNLO, 3 for NNNLL+NNLO
muR: 1.      # Renormalization scale
muF: 1.      # Factorization scale
muRes: 1.    # Resummation scale
g1: 1        # Universal Gaussian non-perturbative form factor
g2: 0        # Q-dependent Gaussian non-perturbative form factor
g3: 0        # x-dependent Gaussian non-perturbative form factor
Q0: 1        # Reference scale at which the g2 contribution is zero
```

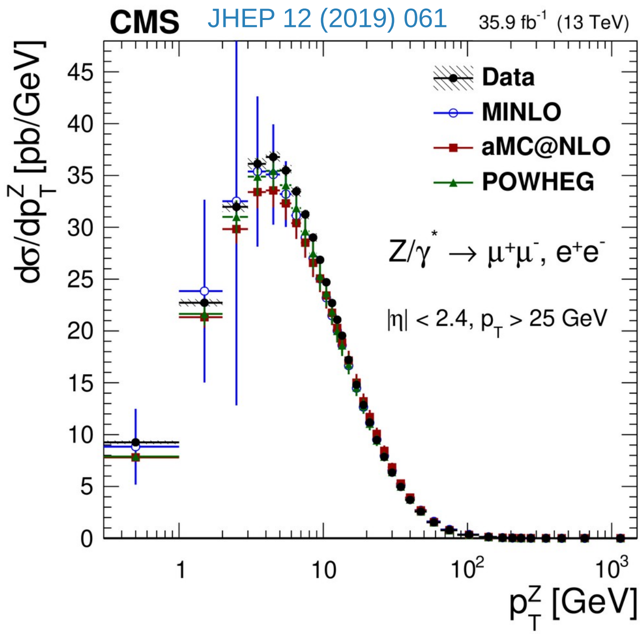
- Two main operational modes for Z/γ*
  - Full-lepton phase space cross sections in p_T,y,m: DYTurbo can provide the full fixed order or resummed prediction
  - Fiducial phase space cross sections in p_T,y,m: include V+jet APPLgrid, DYTurbo computes the rest
- Lepton variables (for W) are possible, but currently rather slow

Measure $\alpha_s(m_Z)$ from semi-inclusive DY

Desirable features for a measurement of $\alpha_s(m_Z)$ [PDG]

- Large observable's sensitivity to $\alpha_s(m_Z)$ compared to the experimental precision
- High accuracy of the theory prediction
- Small size of non-perturbative QCD effects

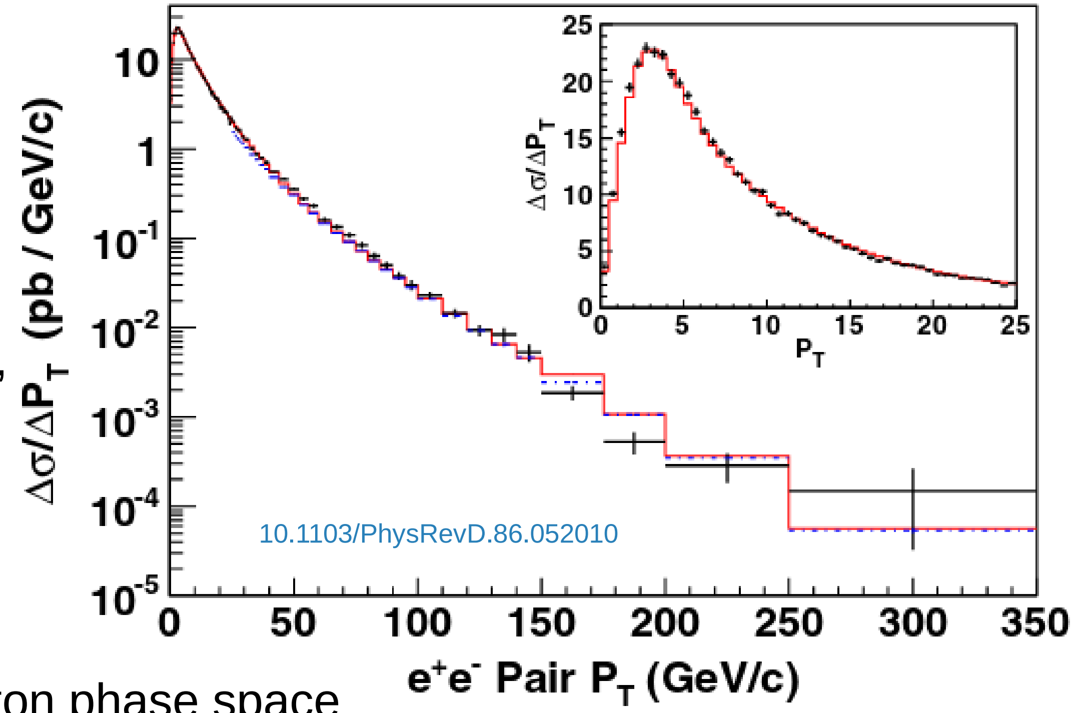
- Measuring $\Lambda_{\overline{MS}}$ from semi-inclusive (radiation inhibited) DY cross sections was first proposed in Nucl. Phys. B 349 (1991) 635-654 (Catani, Marchesini, Webber), in the context of Monte Carlo parton showers
- Here we consider as semi-inclusive observable the Z p_T distribution in the Sudakov region



- Inclusive observables benefit from higher theory accuracy and smaller non-pQCD effects, but usually smaller experimental sensitivity to $\alpha_s(m_Z)$
- Exclusive observables have higher experimental sensitivity, but generally larger theory uncertainties
- Semi-inclusive observables may take benefits from both categories

CDF measurement of Z-boson p_T

- The CDF measurement of Z-boson p_T in full-lepton phase space is an ideal candidate for testing the $\alpha_s(m_Z)$ extraction, and the xFitter-DYTurbo interface



- The measurement is extrapolated to full-lepton phase space using measured angular coefficients

$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma}{dp_T dydm} \sum_i A_i(y, p_T, m) P_i(\cos\theta, \phi)$$

- $p\bar{p}$ collisions

→ reduced contribution from heavy-flavour-initiated production compared to pp collisions

$b\bar{b}$ → Z: 0.4%
$c\bar{c}$ → Z: 1.3%

Theory predictions

- Theory predictions evaluted with DYTurbo: public code implementing CdFG qt-resummation in b-space

$$\frac{d\hat{\sigma}_{F\,ab}}{dq_T^2} = \frac{d\hat{\sigma}^{(\mathrm{res.})}_{F\,ab}}{dq_T^2} + \frac{d\hat{\sigma}^{(\mathrm{fin.})}_{F\,ab}}{dq_T^2}$$

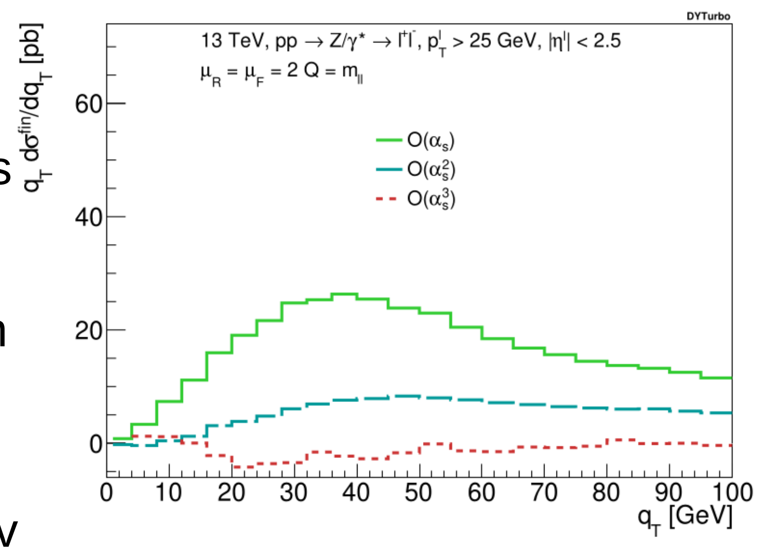
$$\frac{d\hat{\sigma}^{(\mathrm{res.})}_{V}}{dq_T^2}(q_T, M) = \frac{M^2}{\hat{s}} \int_0^\infty db\, \frac{b}{2}\, J_0(bq_T)\, \mathcal{W}^V(b, M)$$

perturbative Sudakov form factor

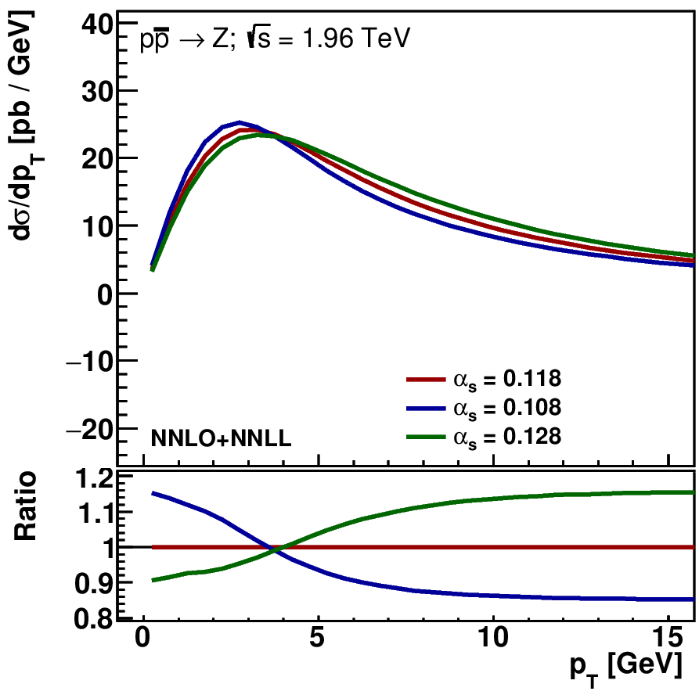
$$\mathcal{W}_N^V(b, M) = \mathcal{H}_N^V(\alpha_S) \times \exp\{\mathcal{G}(\alpha_S, L)_N\},\ L = log(M^2 b^2)$$

Sensitivity to α_s

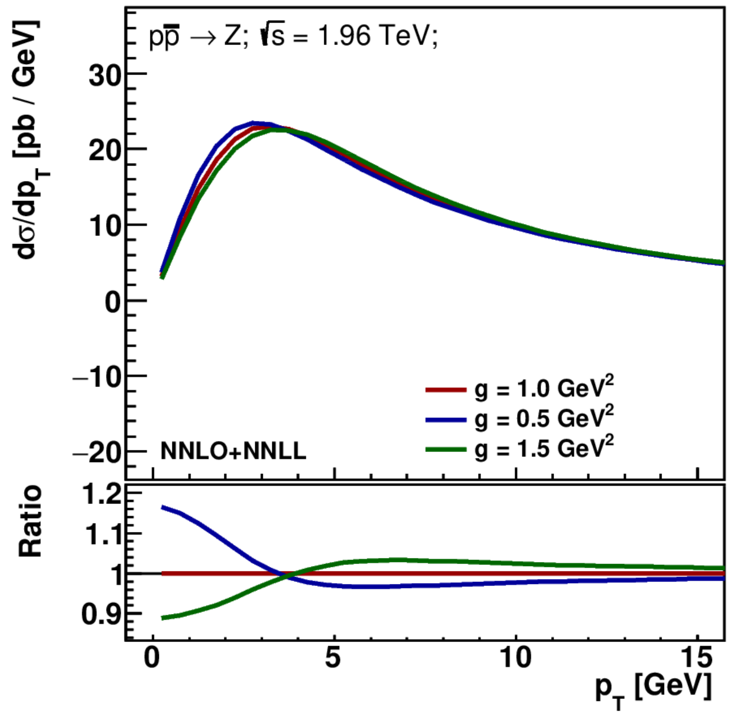
- N3LL accuracy in the Sudakov, N3LO accuracy in the hard coefficient H
- NNLO accuracy in the matching to fixed order at large p_T → missing $O(\alpha_s^3)$ terms have permille or subpermille effects in the region $p_T < 30$ GeV
- Consistent 4-loop running of α_s in all parts of the calculation
- PDFs evaluated at the hard scale and evolved with FFN 5F
- Non-perturbative effects modelled with a Gaussian Sudakov form factor governed by a parameter g



Sensitivity to $\alpha_s(m_Z)$



- The sensitivity of the Z-boson p_T distribution to $\alpha_s(m_Z)$ mainly comes from the position of the Sudakov peak
- Typical recoil scale: $\langle p_T \rangle \sim 10$ GeV



- The sensitivity of the Z-boson p_T distribution to the non-perturbative parameter g also comes from the position of the Sudakov peak
- The scale of the non-perturbative smearing is given by the primordial $\langle k_T \rangle$: $g \sim 0.6\ \mathrm{GeV}^2 \rightarrow \langle k_T \rangle \sim 1.5$ GeV

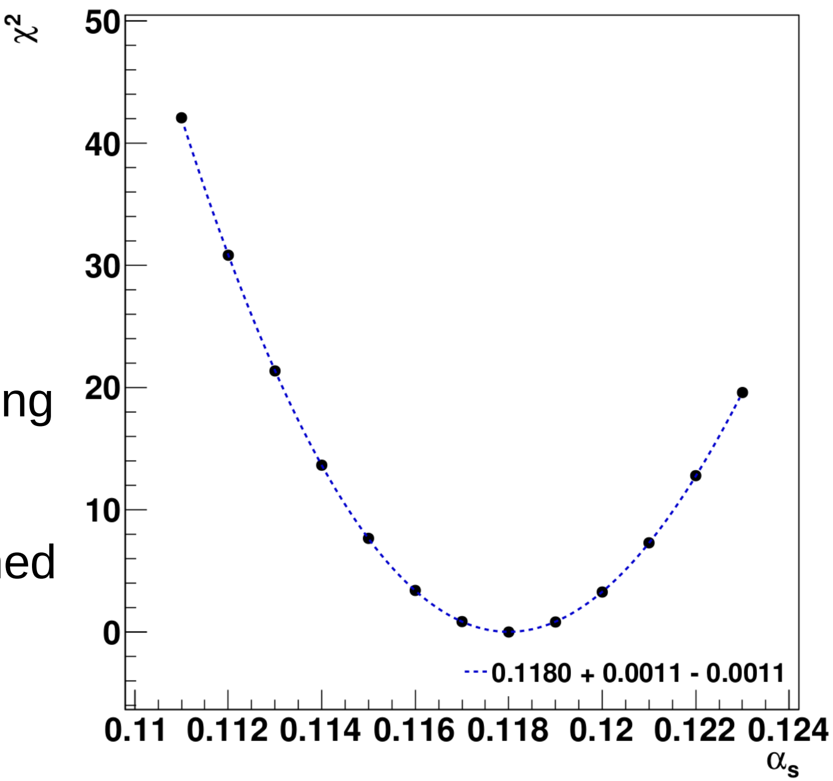
→ Possible to disentangle α_s, and g, thanks to their different scale

Methodology for the $\alpha_s(m_Z)$ determination

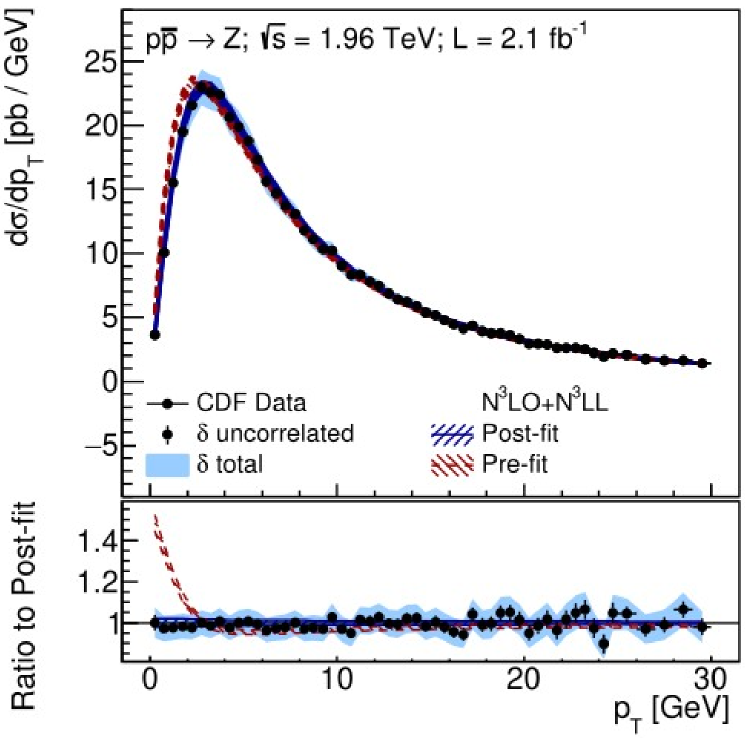
- DYTurbo interfaced to xFitter
- Evaluate $\chi^2(\alpha_s)$ with α_s variations as provided in LHAPDF
- Include experimental ($\beta_{j,\mathrm{exp}}$) and PDF ($\beta_{k,\mathrm{th}}$) uncertainties in the χ^2

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

- At each value of $\alpha_s(m_Z)$ the $\beta_{k,\mathrm{th}}$ terms explore the PDF space to find the best fit to the Z p_T data → equivalent to including the new dataset in the PDF without refitting, using profiling/reweighting Eur.Phys.J.C 75 (2015) 9, 458
- The non-perturbative form factor is added as unconstrained nuisance parameter ($\beta = 0$) i.e. left free in the fit
- Fit the region of Z p_T < 30 GeV



Fit results

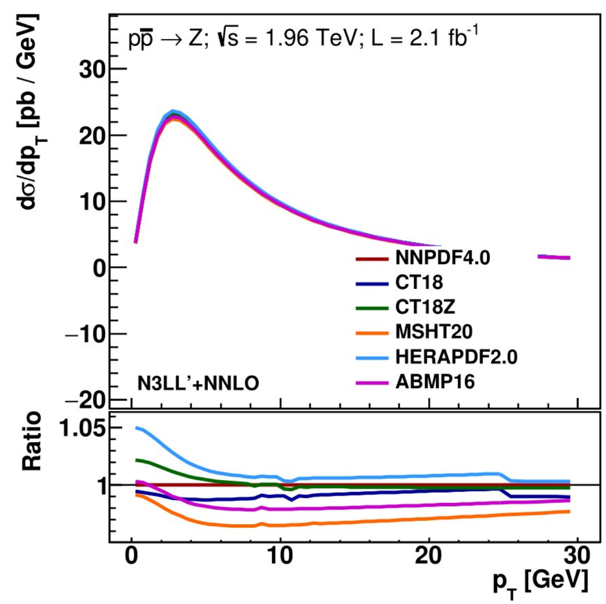


- Simultaneous fit of $\alpha_s(m_Z)$ and g

$$\alpha_s = 0.1187 \pm 0.0007 \text{ (exp. stat)} \pm 0.0002 \text{ (exp. syst)} \pm 0.0004 \text{ (PDF)}$$

$$g = 0.66 \pm 0.05 \text{ (GeV}^2\text{)}$$

	NNPDF4.0	CT18	CT18Z	MSHT20	HERAPDF2.0	ABMP16
$\alpha_s(m_Z)$	0.1187	0.1186	0.1192	0.1178	0.1185	0.1178
PDF unc.	0.0004	0.0006	0.0005	0.0004	0.0004	0.0002
g (GeV^2)	0.66	0.69	0.69	0.72	0.74	0.72
χ^2/dof	41/55	40/55	40/55	40/55	40/55	41/55

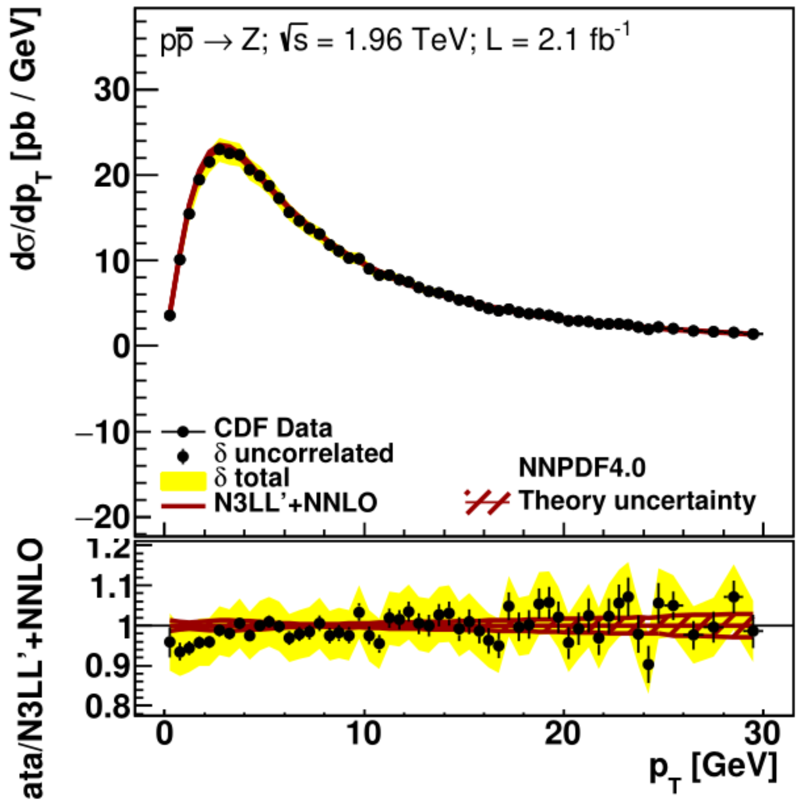


$$\alpha_s = 0.1185 \pm 0.0007 \text{ (PDF envelope)}$$

QCD scale variations

- Predictions depend on three QCD scales: renormalisation, factorisation, and resummation
- Uncertainty from the envelope of all possible combinations of $m_{ll}/2 < \mu_R, \mu_F, \mu_{RES} < 2m_{ll}$ with $0.5 < \mu_R/\mu_F, \mu_R/\mu_{RES}, \mu_F/\mu_{RES} < 2$

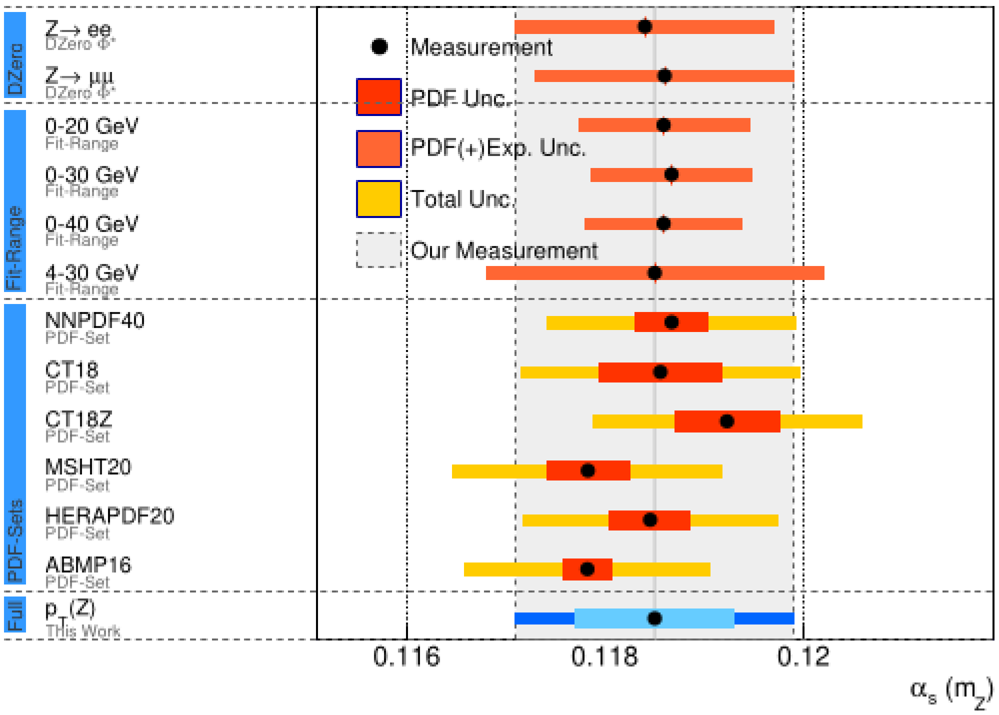
μ_R	μ_F	μ_{RES}	$\alpha_s(m_Z)$	g(GeV^2)	χ^2
1	1	1	0.1187	0.66	41.2
1	1	2	0.1178	0.81	39.1
1	1	0.5	0.1193	0.68	41.3
1	2	1	0.1189	0.66	40.2
1	2	2	0.1178	0.81	39.5
1	0.5	1	0.1187	0.66	41.4
1	0.5	0.5	0.1193	0.69	41.5
2	1	1	0.1190	0.67	41.3
2	1	2	0.1188	0.68	40.8
2	2	1	0.1189	0.67	41.1
2	2	2	0.1188	0.67	40.5
0.5	1	1	0.1177	0.80	40.3
0.5	1	0.5	0.1187	0.64	40.4
0.5	0.5	1	0.1177	0.79	40.0
0.5	0.5	0.5	0.1187	0.64	40.6

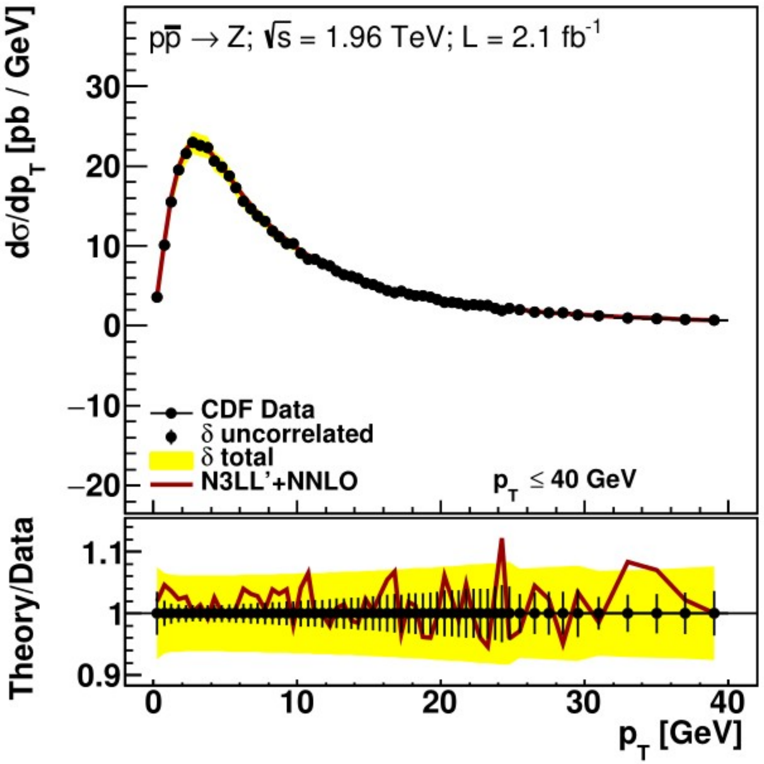


$\delta\alpha_s = + 0.0007 - 0.0010$

$\delta g = + 0.15 - 0.02$ (GeV^2)

Fit range stability





- Remarkable stability with respect to variations of the fit range
- Confirms negligible effect of missing $O(\alpha_s^3)$ corrections in the matching to fixed order, and goodness of the NP model

	$p_T < 20$ GeV	$p_T < 30$ GeV	$p_T < 40$ GeV
$\alpha_s(m_Z)$	0.1186	0.1187	0.1186
fit unc.	0.0009	0.0008	0.0008
χ^2/dof	27/38	41/53	47/58

	$0 < p_T < 30$ GeV	$2 < p_T < 30$ GeV	$4 < p_T < 30$ GeV
$\alpha_s(m_Z)$	0.1187	0.1187	0.1185
fit unc.	0.0008	0.0008	0.0015
χ^2/dof	41/53	41/49	38/45

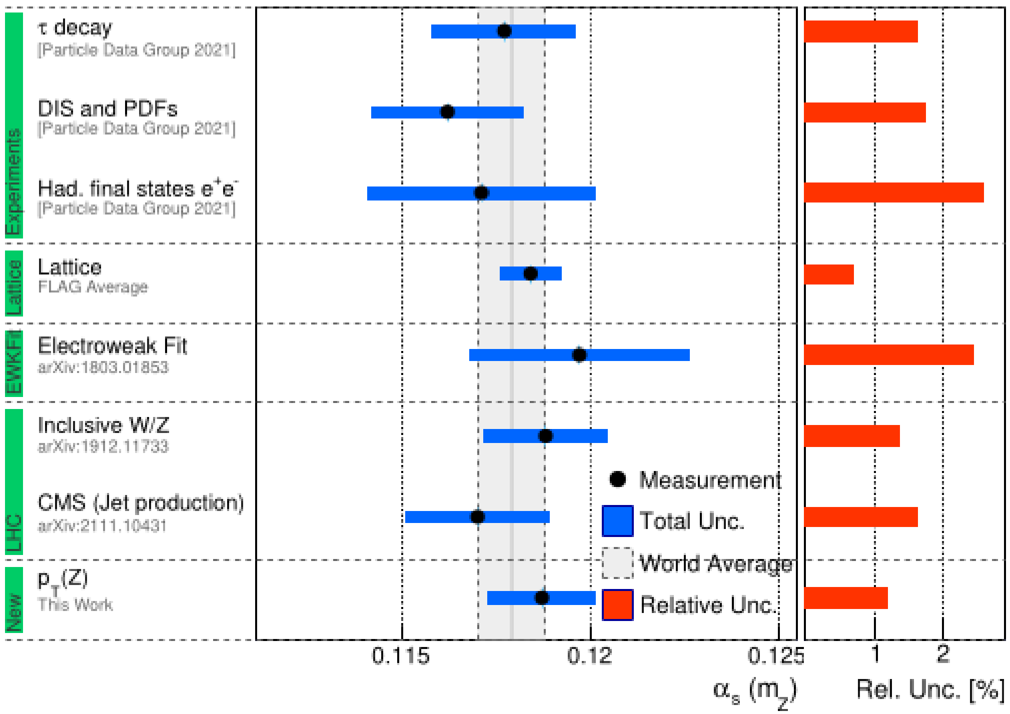
Result

$\alpha_s = 0.1185 +0.0014 -0.0015$

Breakdown of uncertainties

	$\delta\alpha_s(m_Z,+)$	$\delta\alpha_s(m_Z,-)$
Exp. unc.	+0.0007	–0.0007
PDF unc.	+0.0008	–0.0008
Scale var.	+0.0007	–0.0010
Theory unc.	+0.0007	–0.0004

- Measurement in agreement with the world average
- Uncertainty comparable to other determinations
- 1.2% rel. unc.: best collider measurement, second after lattice QCD average
- First N3LO $\alpha_s(m_Z)$ at hadron colliders



Summary

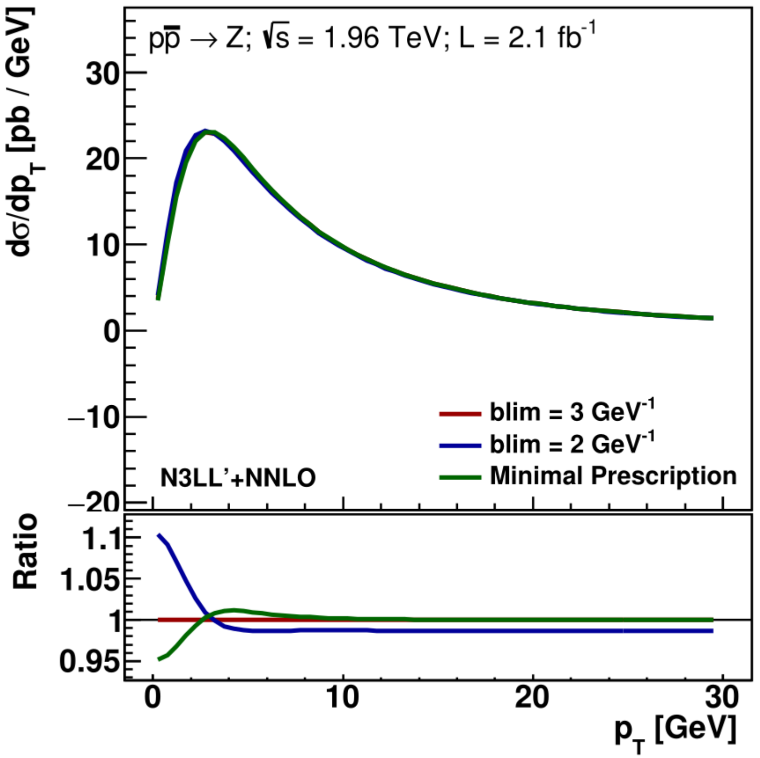
- DYTurbo interface is working, and was tested to determine α_s from Tevatron Z p_T
- Plan to add a few additional yaml settings
- Not yet tested the possibility to explicitly fit non perturbative parameters, but the functionality should be there (profiling was tested)
- Currently using the BLNY parametrisation, but in principle it should be possible to use arbitrary TMD functions in b space, controlled by xFitter
- Cross sections as functions of p_T,m,y without cuts on the leptons can be calculated relatively fast (~1 min). Fiducial cross sections are slower, and need a V+jet applgrid. With a sufficiently large number of cores it should be possible to test actual fits on a small number of datasets
- Lepton p_T and lepton η are possible, but currently rather slow, would need to optimise the phase space generation to make them fast

BACKUP

Theory uncertainties

- Alternative fits with blim = 2 and with the minimal prescription:
  $\delta\alpha_s$ = +0.0006 – 0.0004
  δg = +0.21 -0.13

- Alternative fit with VFN PDF evolution:
  $\delta\alpha_s$ = – 0.0002



QED ISR correction

- QED ISR estimated with Pythia 8, and applied as a multiplicative correction

- Correction to the Z-boson p_T at the level of 1%
- Effect on $\alpha_s(m_Z)$: $\Delta\alpha_s = -0.0006$
- Comparable to corrections obtained with QED qt-resummation