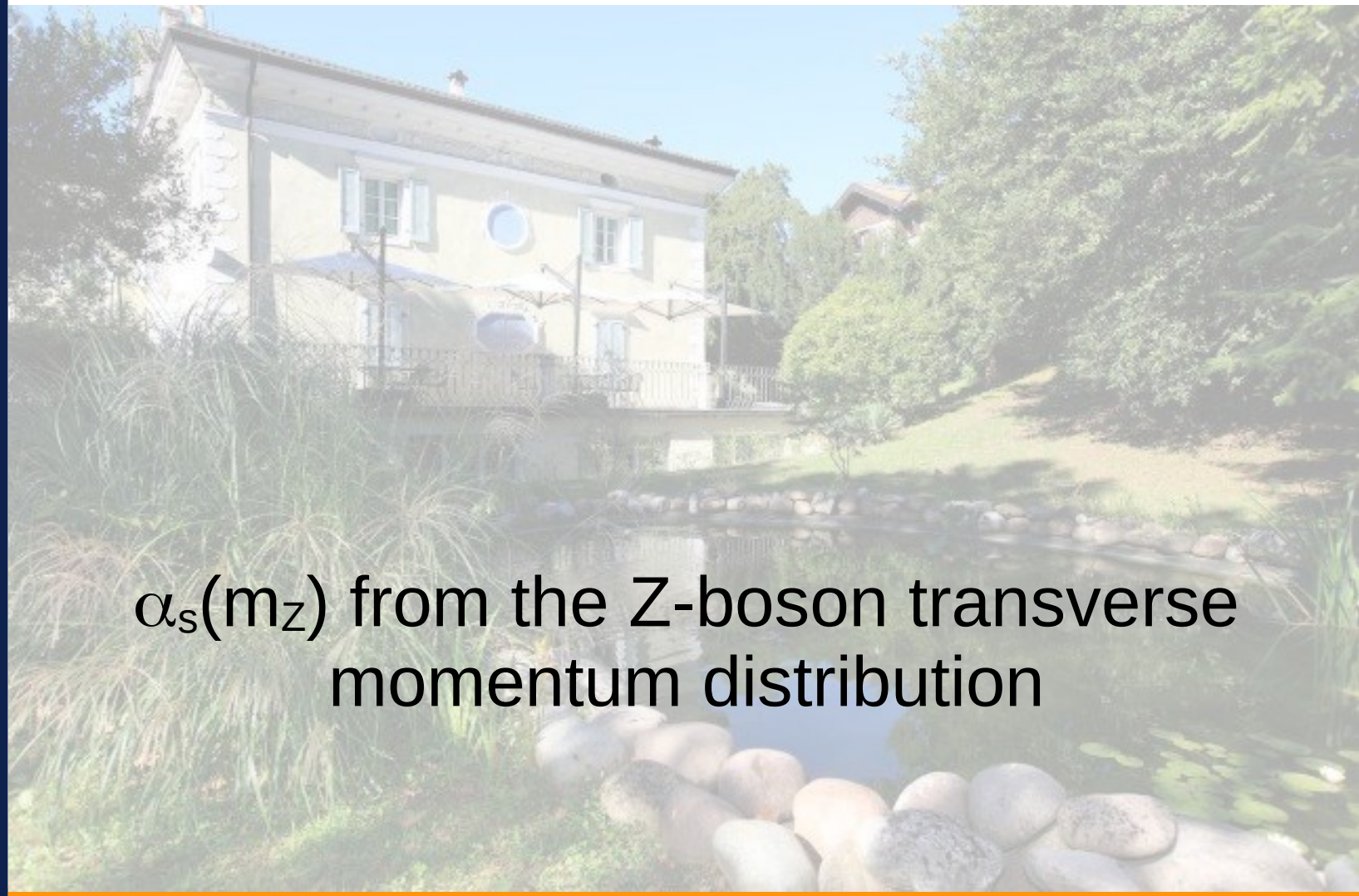


$\alpha_s(m_Z)$ from the Z-boson transverse momentum distribution

Stefano Camarda

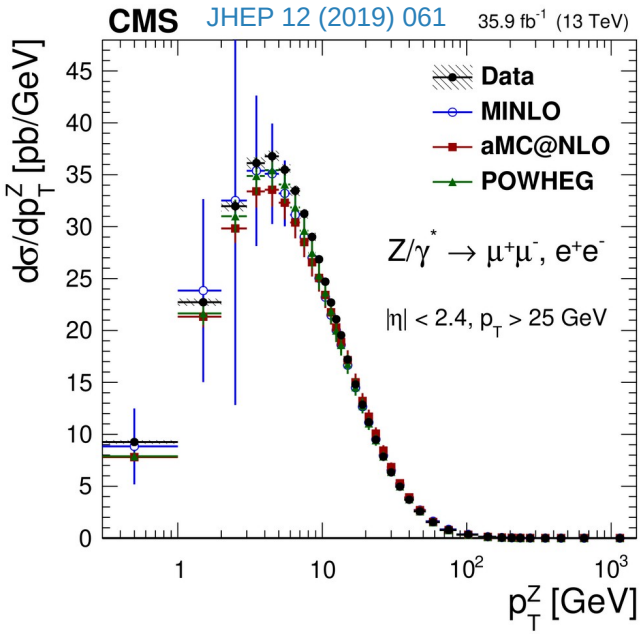
alphas-2022
ECT* Trento, Italy
3rd February 2022

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

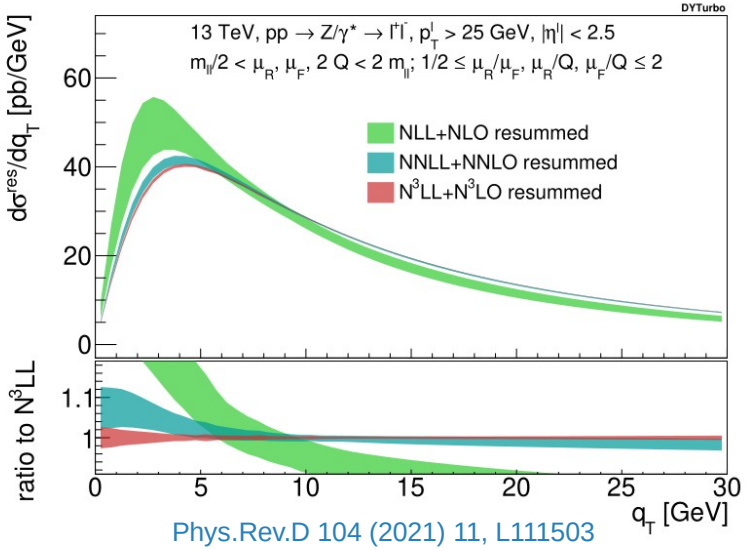
- Measuring $\Lambda_{\overline{MS}}$ from semi-inclusive (radiation inhibited) DY cross sections was first proposed in Nucl. Phys. B 349 (1991) 635-654 (Catani, Marchesini, Webber), in the context of Monte Carlo parton showers
- Here we consider as semi-inclusive observable the Z p_T distribution in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

Measure $\alpha_s(m_Z)$ from the Z p_T distribution

- In particular the Z p_T distribution benefits from:
  - Very precise measurements and high experimental sensitivity to $\alpha_s(m_Z)$
  - High order theory predictions based on analytic qt-resummation



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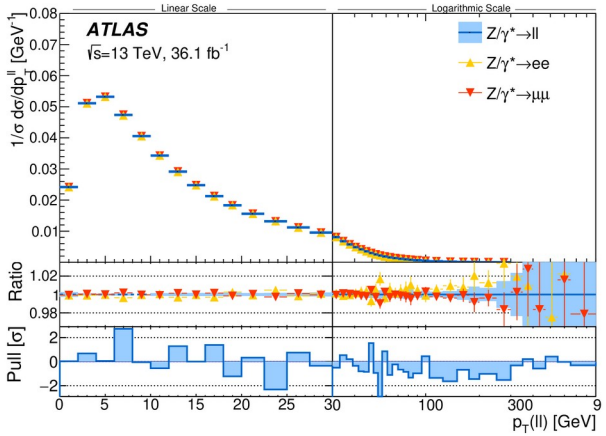

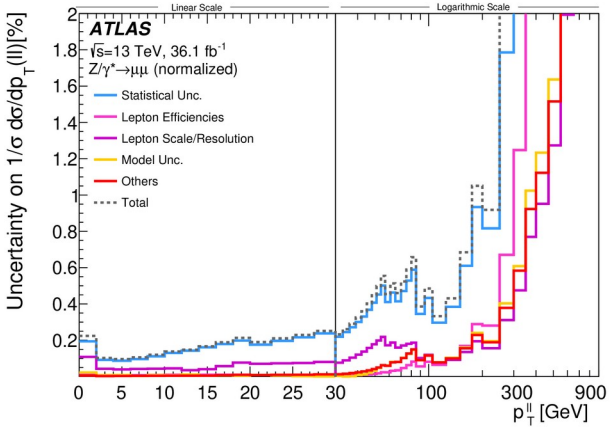

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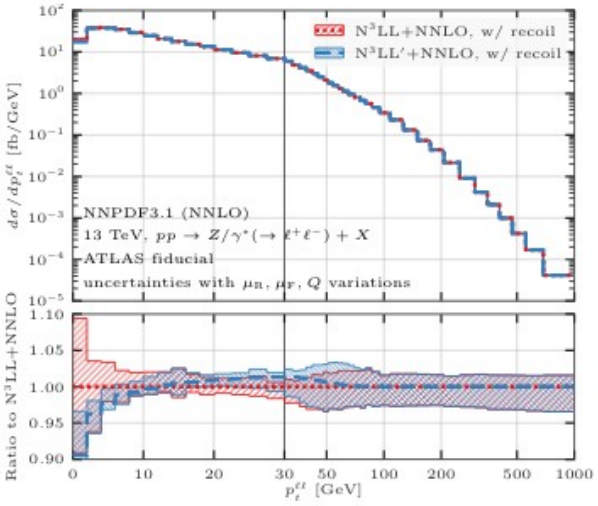

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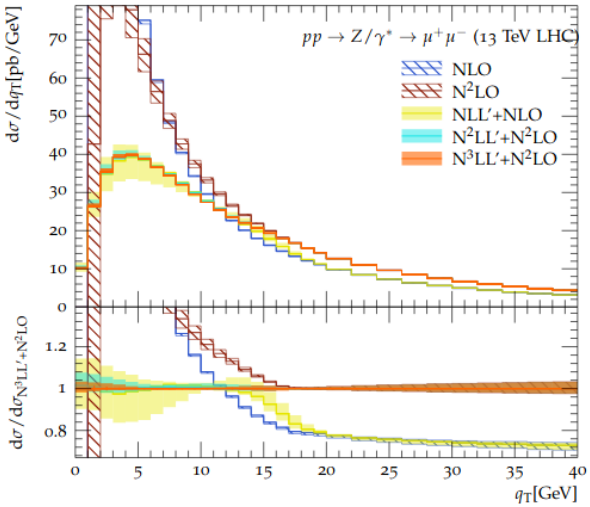
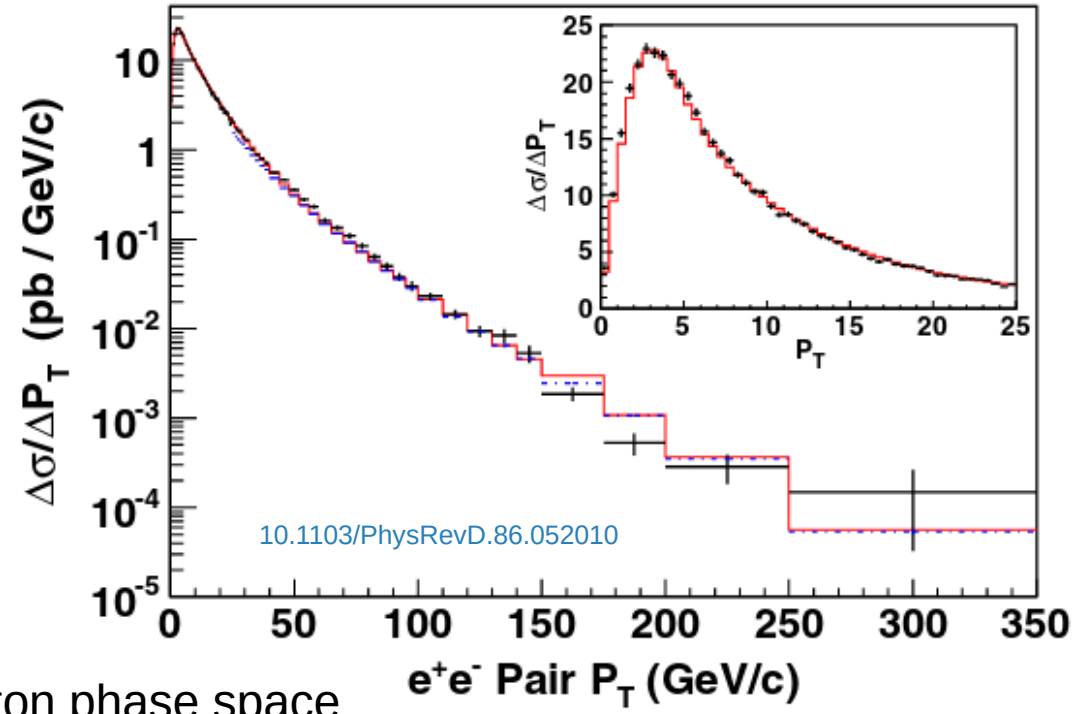


CDF measurement of Z-boson p_T

- The CDF measurement of Z-boson p_T in full-lepton phase space is an ideal candidate for the determination of $\alpha_s(m_Z)$ with analytic predictions



- The measurement is extrapolated to full-lepton phase space with the angular coefficients method

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

→ allows fast analytic predictions

→ avoid theoretical uncertainties on Z polarisation

- $p\bar{p}$ collisions

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

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

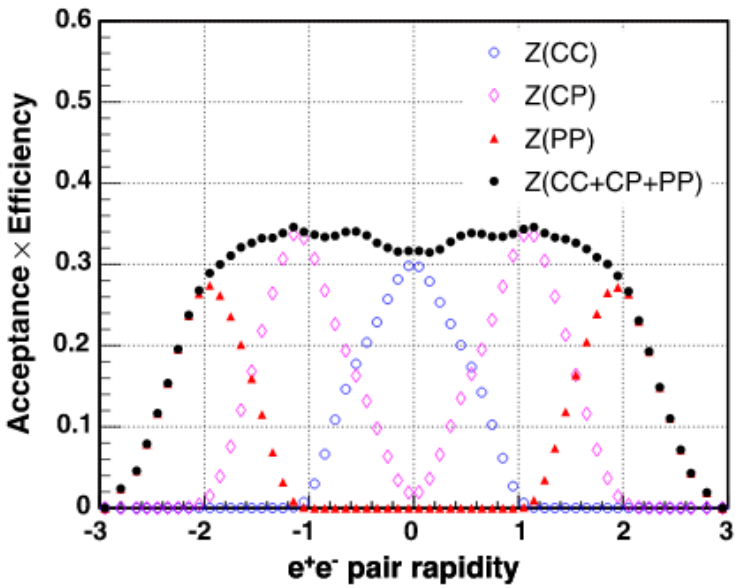
CDF measurement of Z p_T

- Measurement performed in the electron channel, with CC, CF, FF kinematic configurations

  → small extrapolation to full rapidity range:

  $|\eta^e| < 2.8$ → $y_{max} \sim 3.1$

- Low pileup data with good electron resolution



$$\sigma/E = 14\%/\sqrt{E_T}$$

Central → σ = 0.9 GeV at E_T = 45 GeV

$$\sigma/E = 16\%/\sqrt{E} \oplus 1\%$$

Forward → σ = 1.1 GeV at E_T = 45 GeV

→ allows fine p_T bins (0.5 GeV) with relatively small bin-to-bin correlations

Theory predictions

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

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

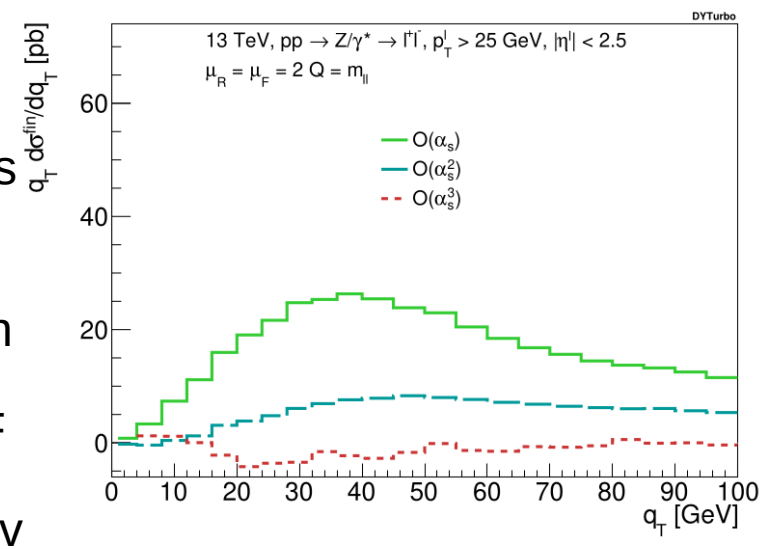
$$\frac{d\hat{\sigma}_V^{(\mathrm{res.})}}{dq_T^2}(q_T, M) = \frac{M^2}{\hat{s}} \int_0^\infty db\, \frac{b}{2}\, J_0(bq_T)\, \mathcal{W}^V(b, M)$$

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

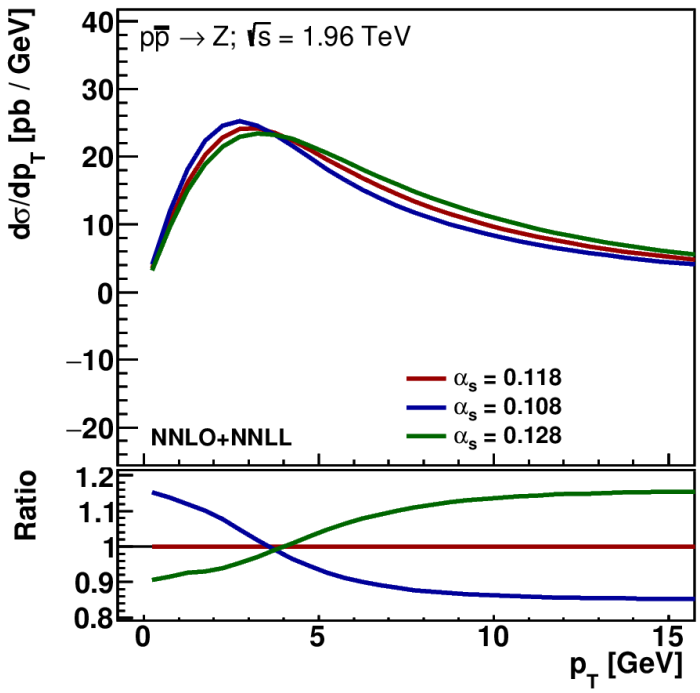
perturbative Sudakov form factor

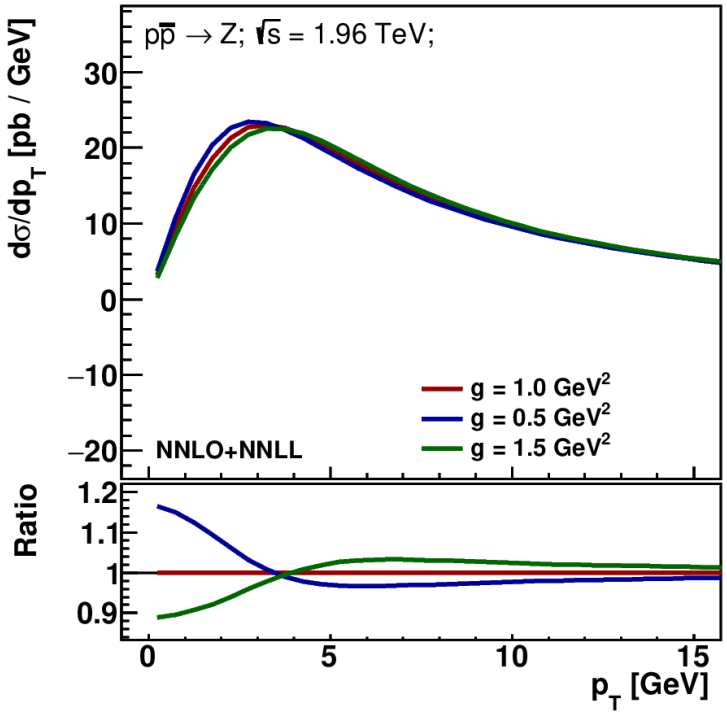
Sensitivity to α_s

- 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 $\langle k_T \rangle$: $g \sim 0.6$ GeV^2 $\rightarrow$ $\langle k_T \rangle \sim 1.5$ GeV

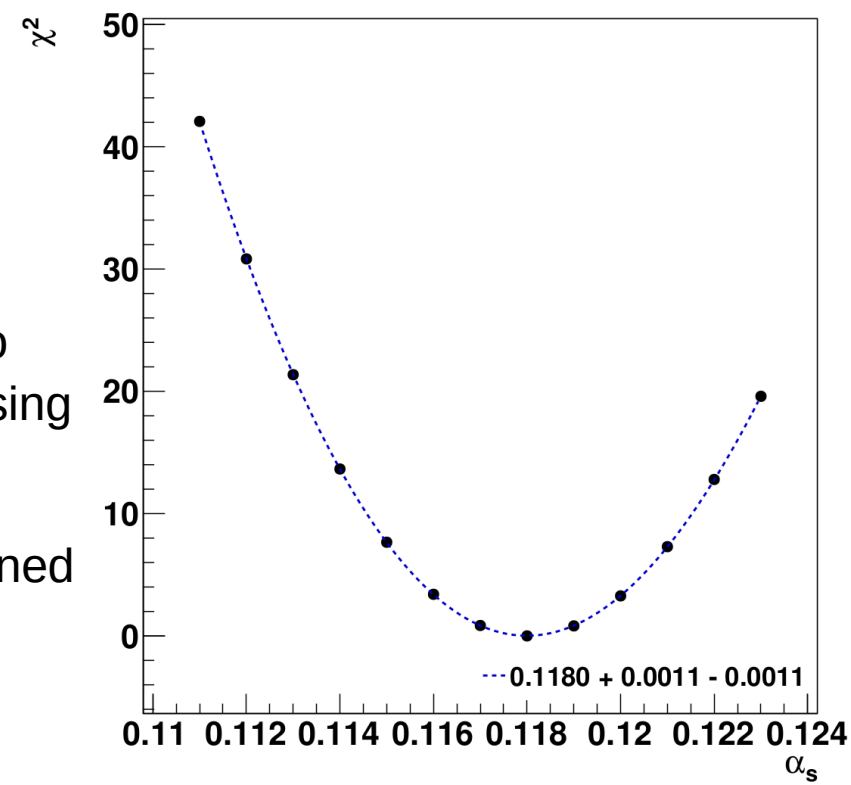
$\rightarrow$ Possible to disentangle α_s, and g, thanks to their different scale

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 ($\beta_{j,exp}$) and PDF ($\beta_{k,th}$) uncertainties in the χ^2

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

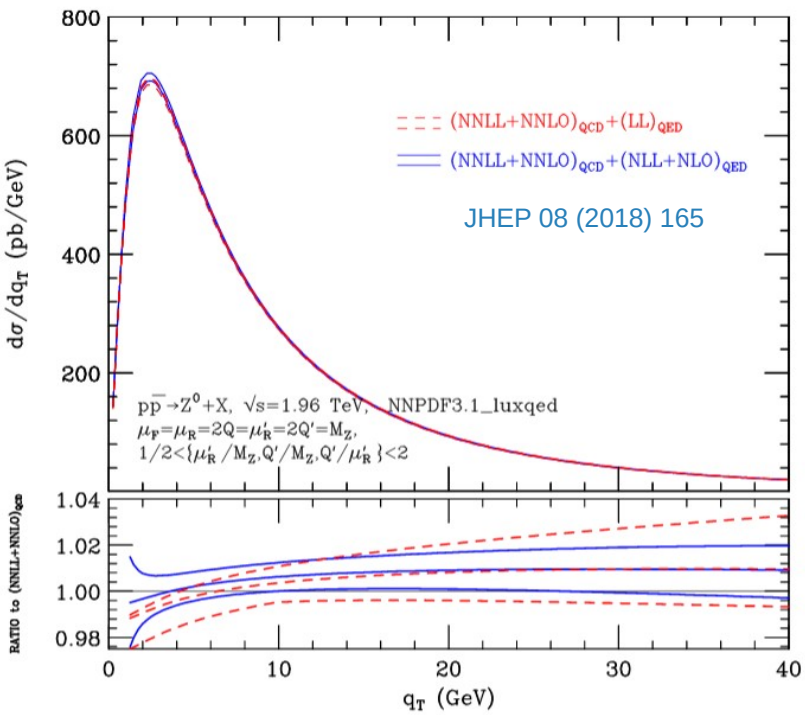
- At each value of $\alpha_s(m_Z)$ the $\beta_{k,th}$ terms explore the PDF space to find the best fit to the Z p_T data → equivalent to including the new dataset in the PDF without refitting, using profiling/reweighting Eur.Phys.J.C 75 (2015) 9, 458
- The non-perturbative form factor is added as unconstrained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

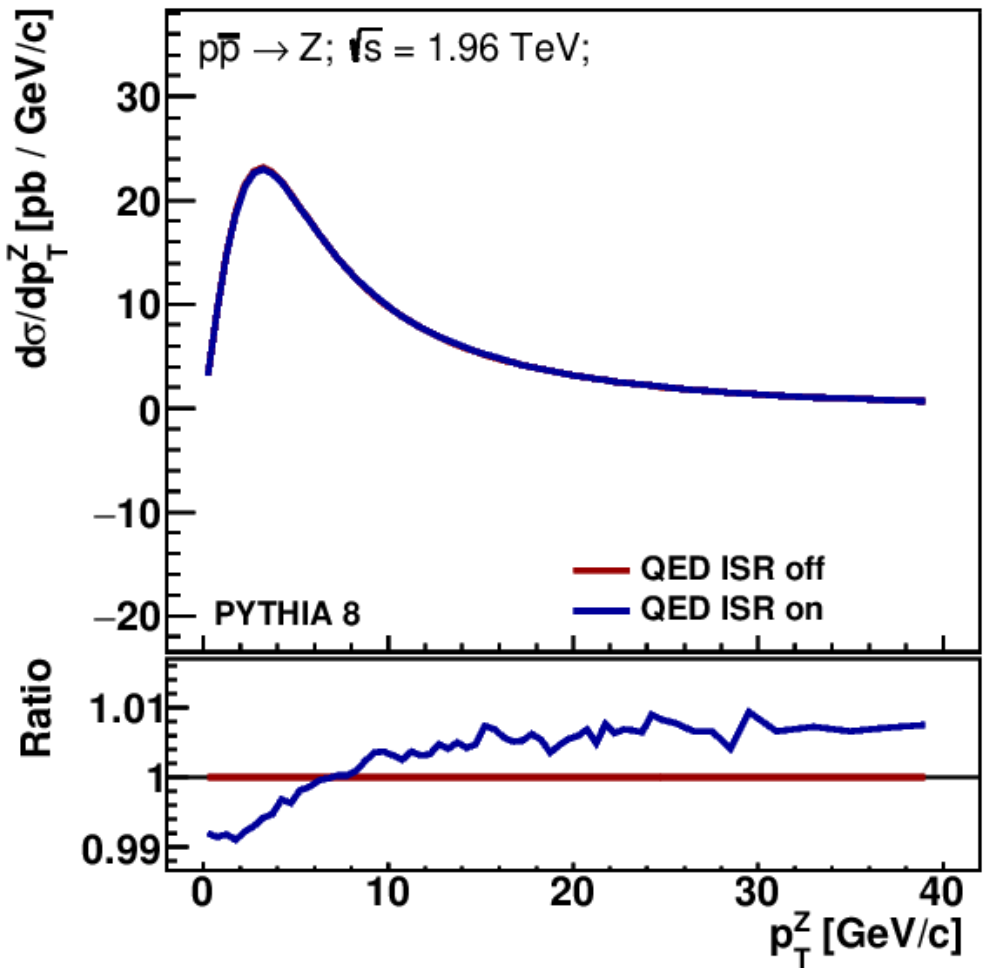


QED ISR correction

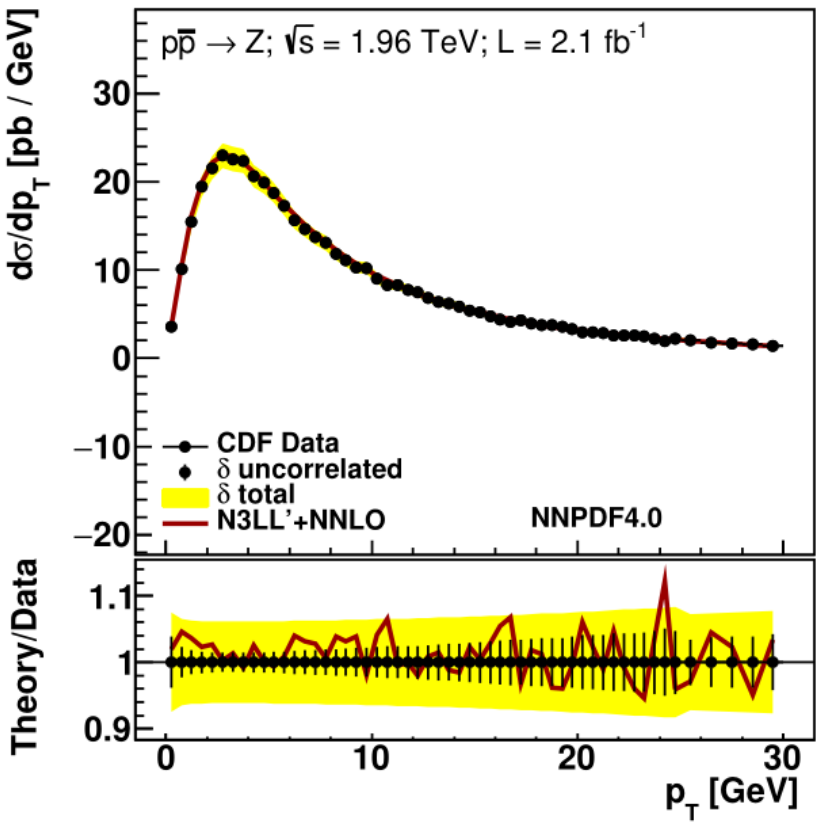
- QED ISR estimated with Pythia 8, and applied as a multiplicative correction

- Correction to the Z-boson p_T at the level of 1%
- Effect on $\alpha_s(m_Z)$: $\Delta\alpha_s = -0.0004$
- Comparable to corrections obtained with QED qt-resummation





Fit results

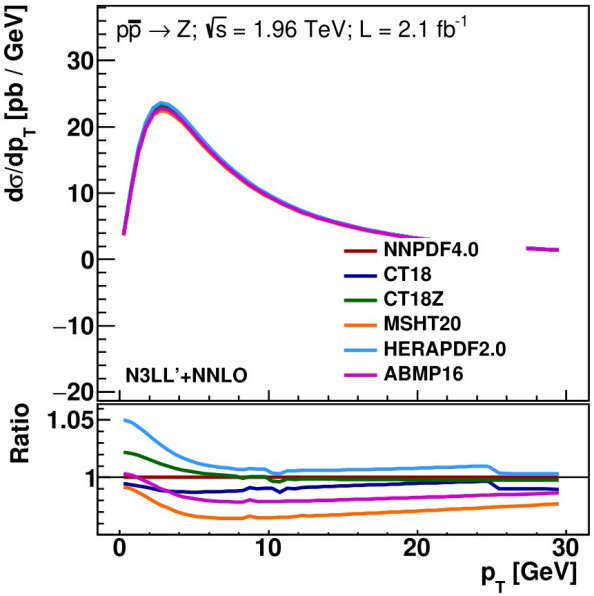


- Simultaneous fit of $\alpha_s(m_Z)$ and g

$\alpha_s = 0.1187$
±0.0007 (exp. stat)
±0.0002 (exp. syst)
±0.0004 (PDF)

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

	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

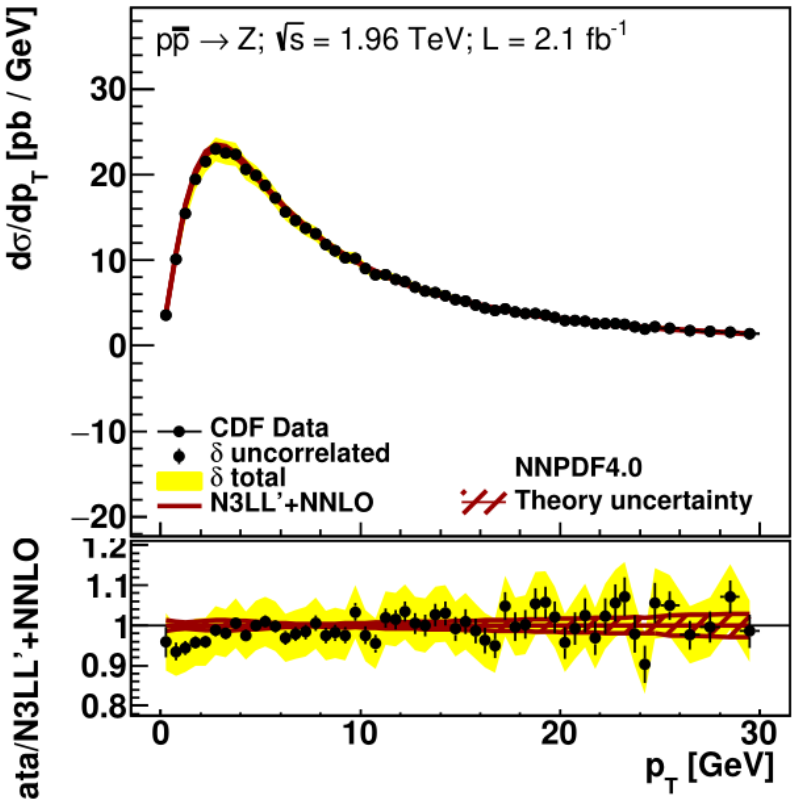


$\delta\alpha_s = +0.0006 - 0.0009$ (PDF envelope)

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

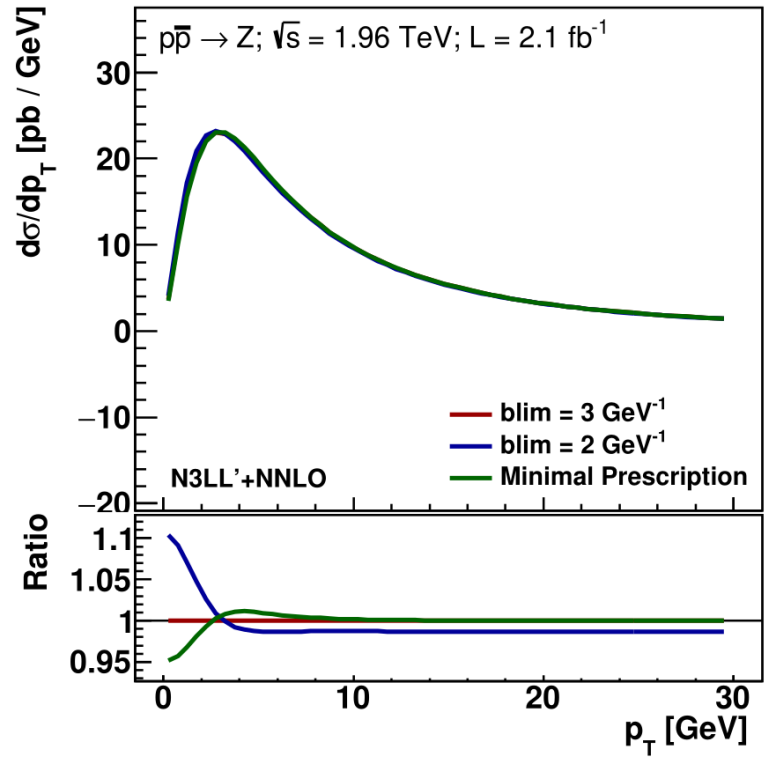


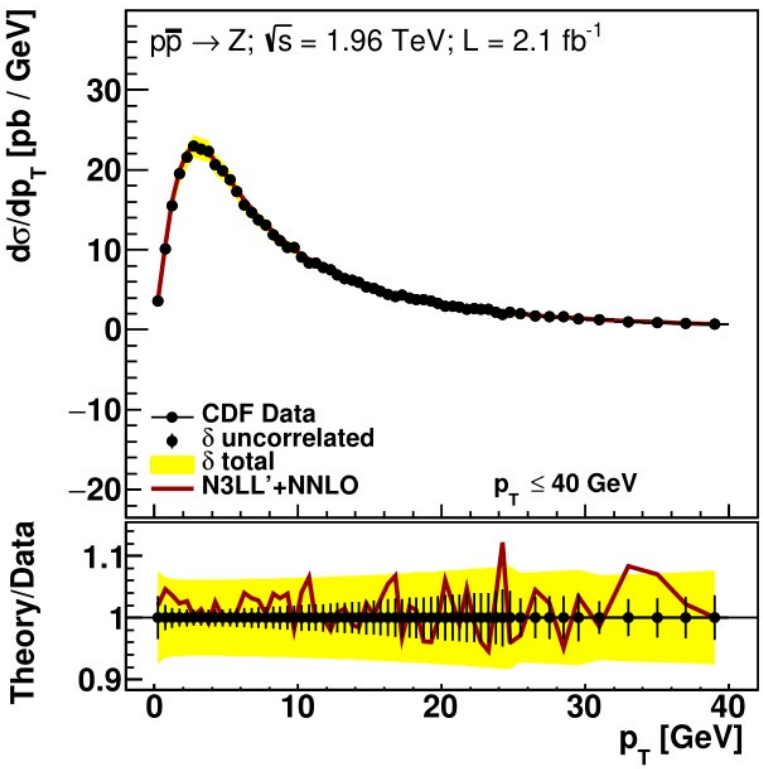
$\delta\alpha_s = +0.0007 - 0.0010$

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

Theory uncertainties

- Alternative fits with blim = 2 and with the minimal prescription:
  $\delta\alpha_s = +0.0006 - 0.0004$
  $\delta g = +0.21 -0.13$
- Alternative fit with VFN PDF evolution:
  $\delta\alpha_s = - 0.0002$





	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	27/40	41/55	47/60

- 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

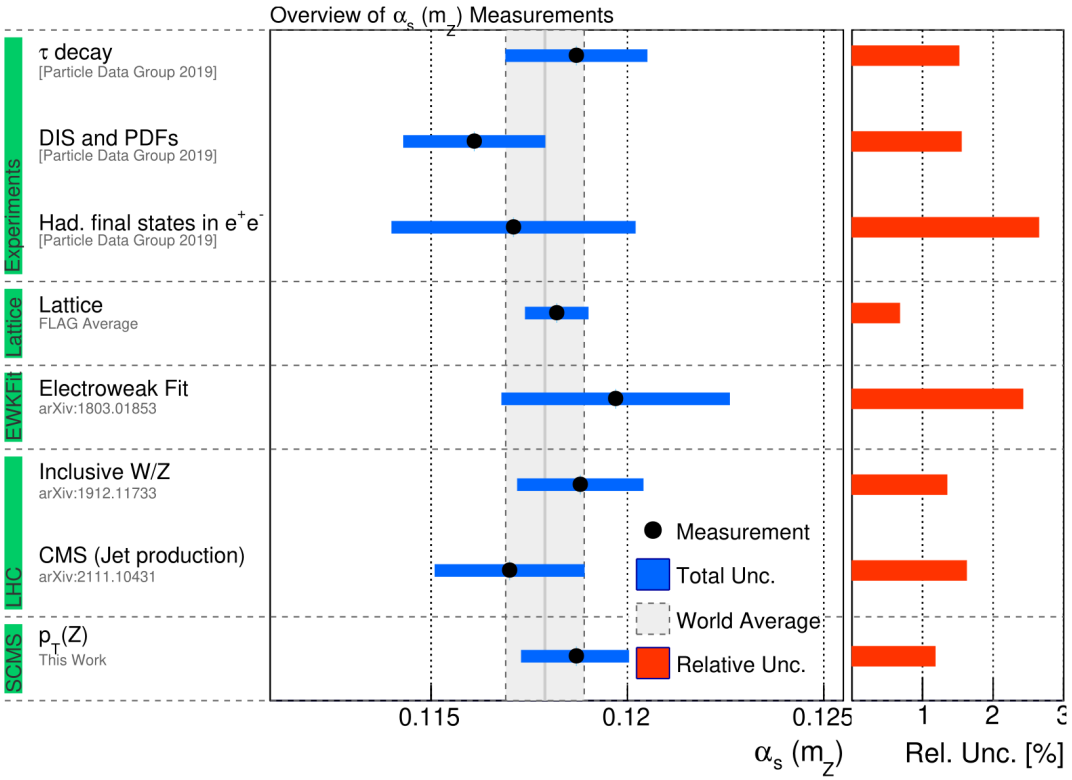
Result

$\alpha_s = 0.1187\ ^{+0.0013}_{-0.0016}$

Breakdown of uncertainties

	$\delta\alpha_s(m_Z,+)$	$\delta\alpha_s(m_Z,-)$
Exp. unc.	+0.0007	–0.0007
PDF unc.	+0.0007	–0.0009
Scale var.	+0.0007	–0.0010
Theory unc.	+0.0007	–0.0004

- Measurement in agreement with the world average
- Uncertainty comparable to other determinations



Summary and conclusions

- Preliminary measurement of $\alpha_s(m_Z)$ by fitting the CDF Z p_T distribution in the Sudakov region $p_T < 30$ GeV yields $\alpha_s = 0.1187\ ^{+0.0013}_{-0.0016}$
- The α_s determination is performed consistently at N3LO, and the characteristic scale of the measurement is related to $\langle p_T \rangle \sim 10$ GeV,
- Measurement based on a semi-inclusive observable, which has different features than other inclusive or exclusive observables used at hadron colliders
- The low Z p_T observable is not included in any PDF fit, and there is no reason to do so (small sensitivity to collinear PDFs, not predictable in fixed order pQCD)
- Conservative approach for PDF uncertainties, including envelope of 6 different PDF sets
- Simple but effective non pQCD model based on Gaussian form factor, with conservative uncertainties related to the Landau pole prescription

CREDITS

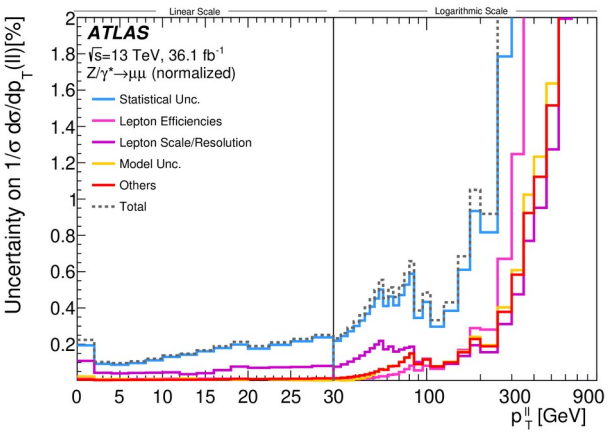
$\alpha_s(m_Z)$ from Z p_T: M. Schott, A. Glazov, G. Ferrera

DYTurbo: M. Boonekamp, G. Bozzi, S. Catani, L. Cieri, J. Cuth, G. Ferrera, D. de Florian, A. Glazov, M. Grazzini, M. G. Vincter, M. Schott

Prospects and wishlist for high (permille) precision

Experimental wishlist

- LHC measurement of Z p_T are significantly more precise than Tevatron, likely to reach a few 10^{-4} experimental uncertainty on $\alpha_s(m_Z)$ with Run 2 and Run 3 data samples
- The main experimental limitation will be the lepton momentum/energy scale, currently known at ~ 10^{-3}. Improving to 10^{-4} will help to reach high precision on $\alpha_s(m_Z)$
- Measurements of DY p_T at high mass will bring further sensitivity to $\alpha_s(m_Z)$, but resolution may be a limiting factor
- Precise measurements of DY p_T at low and intermediate mass will help reducing the non perturbative uncertainties

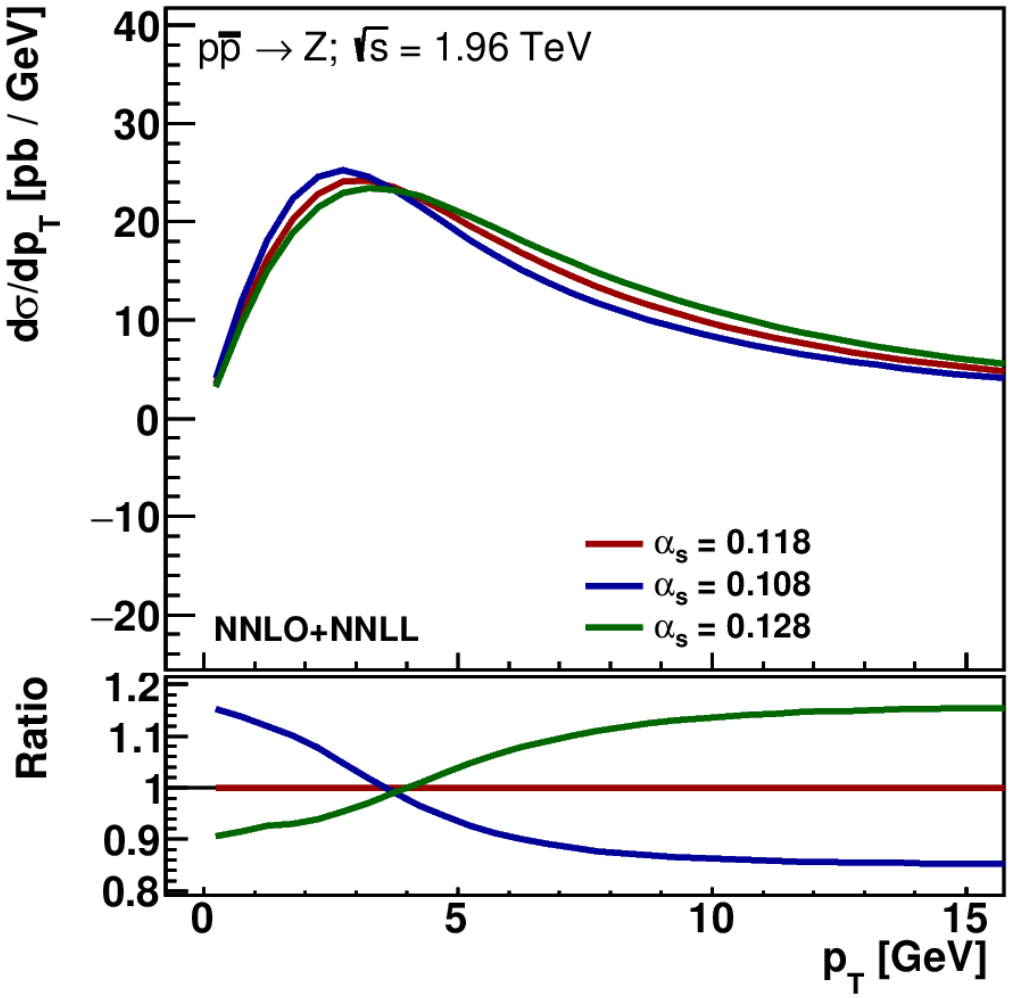


Theory wishlist

- N4LL ingredients (5-loop cusp, 4-loop RAD)
- N4LL' ingredients (N3LO PDFs, N4LO TMD, 4-loop quark form factor,…)
- Improved heavy-flavour treatment (massive corrections, VFN)
- Joint qt/small-x resummation
- QED/QCD qt-resummation
- First-principle understanding of non-perturbative corrections (effective coupling, renormalon, lattice)
- Public code for Z+jet at NNLO

Prospects to reach subpercent precision in the next 10 years mostly rely on theory developments

BACKUP

Measure $\alpha_s(m_Z)$ from the Z p_T distribution

- The recoil of Z bosons produced in hadron collisions is mainly due to QCD initial-state radiation
- The Sudakov factor is responsible for the existence of a Sudakov peak in the Z-boson transverse-momentum distribution, at transverse-momentum values of approximately 4 GeV
- The position of the peak is sensitive to the value of the strong-coupling constant