Determination of the strong-coupling constant from the Z-boson transverse-momentum distribution

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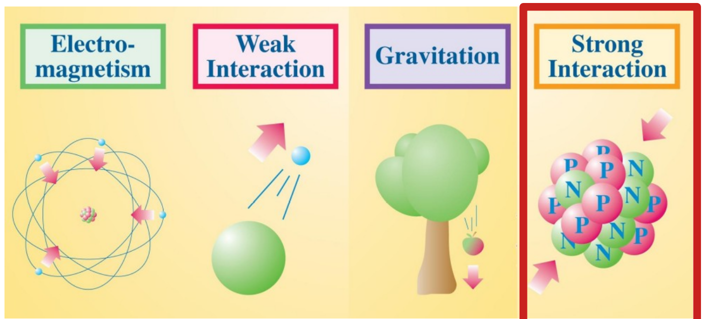
The strong-coupling strength $\alpha_s(m_Z)$

The strong coupling is the least known fundamental force of nature

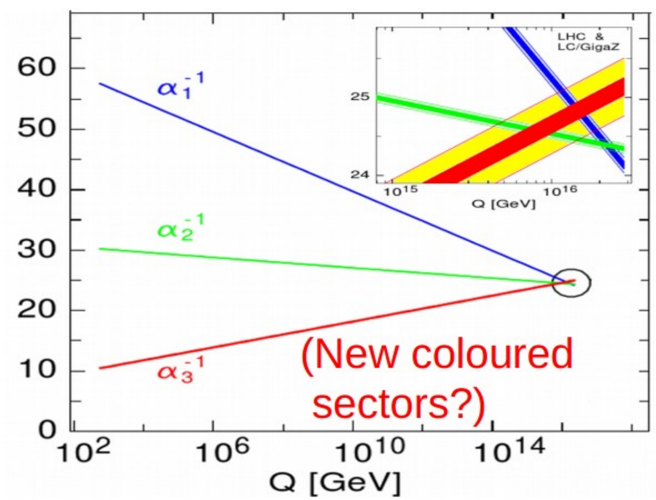


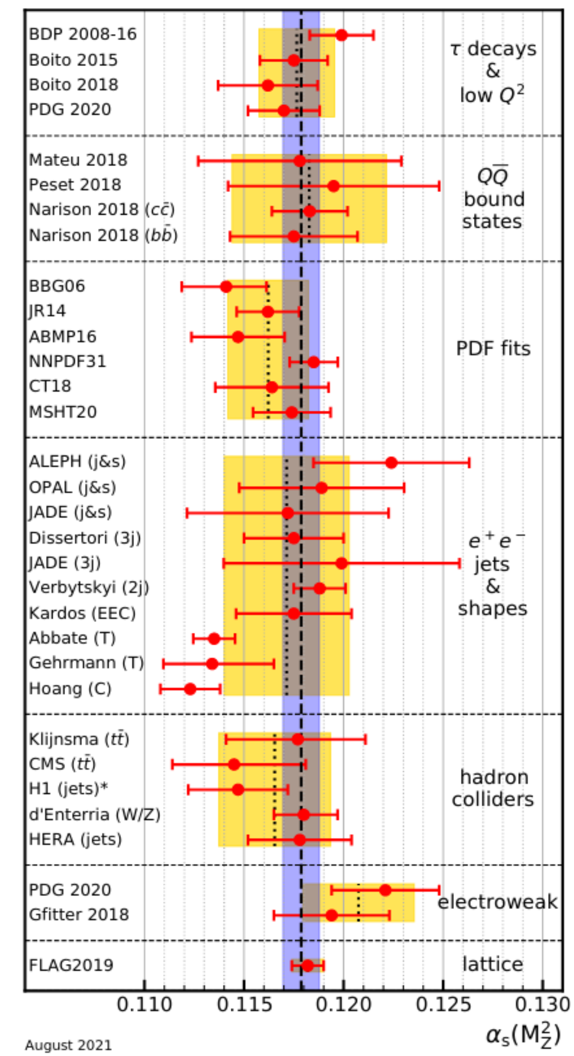
	Electro-magnetism	Weak Interaction	Gravitation	Strong Interaction
Relative uncertainty	10^{-10}	10^{-7}	10^{-5}	10^{-2}

World average:
$\alpha_s(m_Z) = 0.1179 \pm 0.0009$

- Single free parameter of QCD in the $m_q \rightarrow 0$ limit
- Conventionally determined at the reference scale $Q = m_Z$
- Decreases ("runs") as $\alpha_s \sim \ln(Q^2/\Lambda^2)^{-1}$

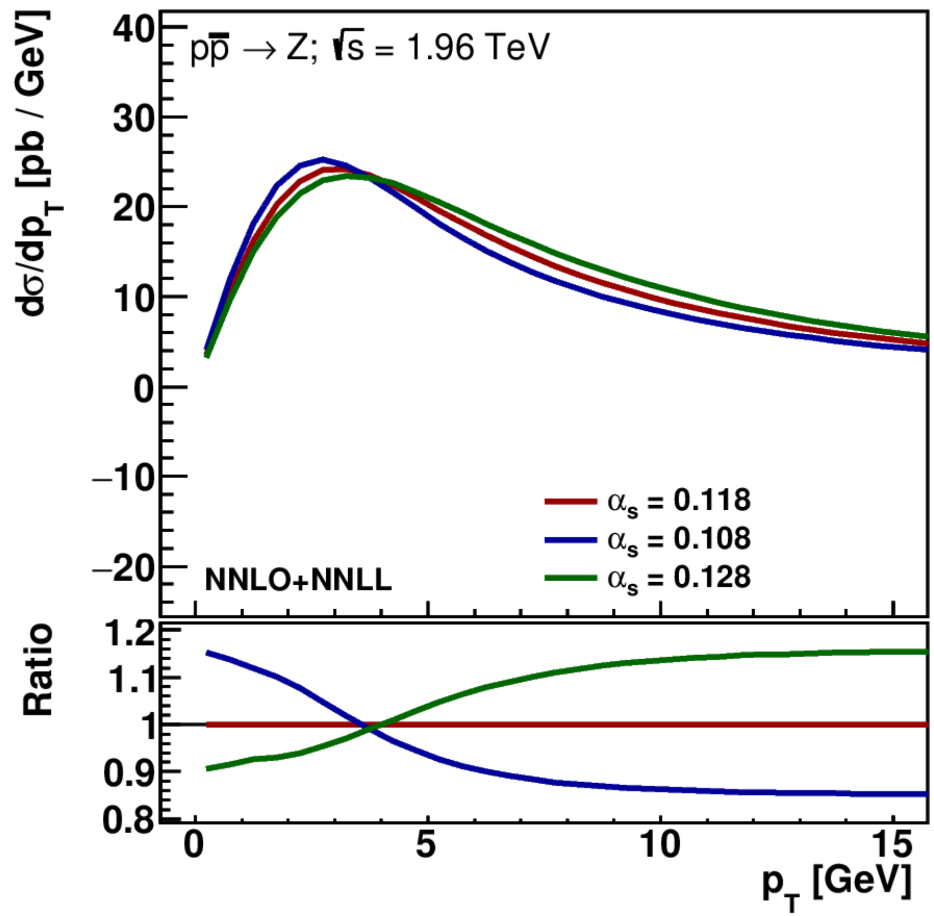
- Impacts physics at the Planck scale: EW vacuum stability, GUT
- Is among the dominant uncertainties of several precision measurements at colliders
  - Higgs couplings at the LHC
  - EW precision observables at e+e- colliders





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

- The recoil of Z bosons produced in hadron collisions is mostly due to QCD initial-state radiation
- The Sudakov factor is responsible for the existence of a peak in the Z-boson p_T distribution, at values of approximately 4 GeV
- The position of the peak is sensitive to $\alpha_s(m_Z)$
- Methodology first tested in proton-antiproton collisions (Tevatron), application to proton-proton (LHC) is more challenging, but could lead to substantially smaller uncertainties



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

- 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

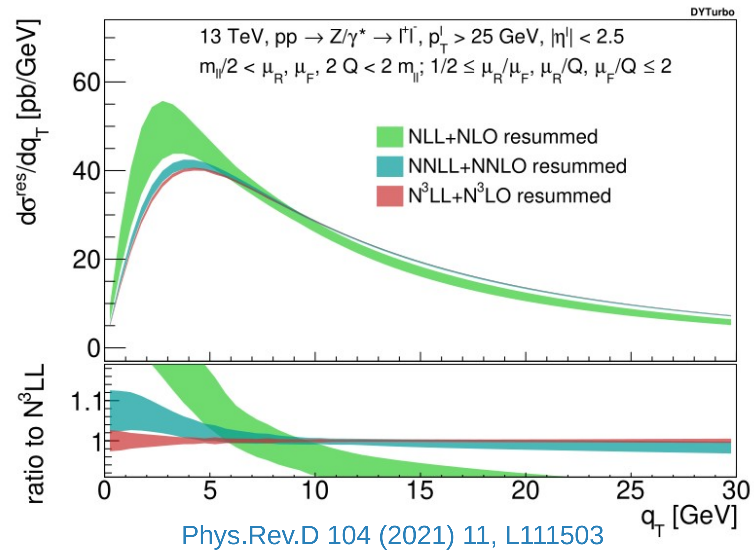
Exclusive observables

Inclusive observables

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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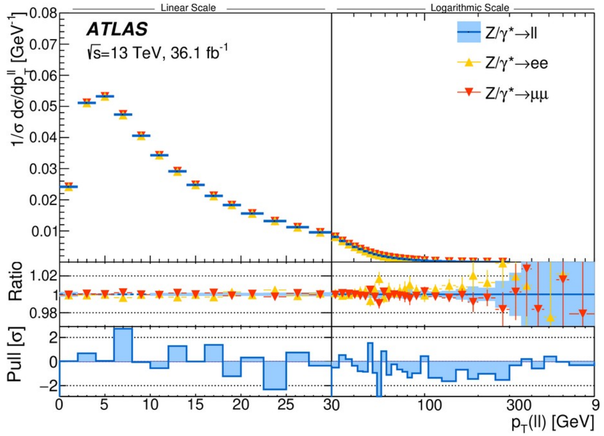

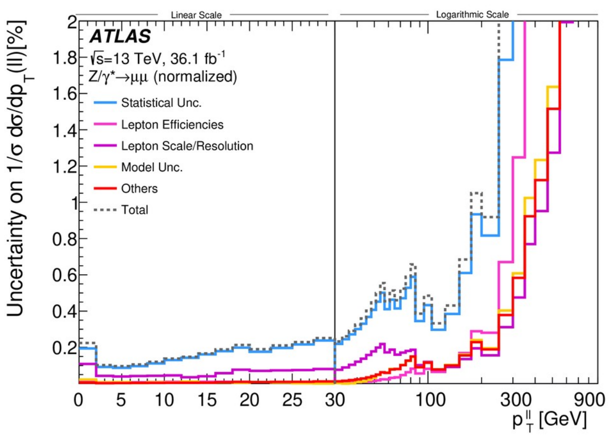

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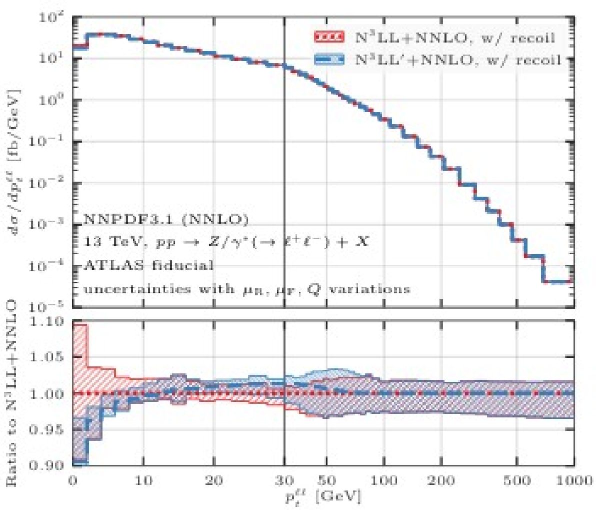

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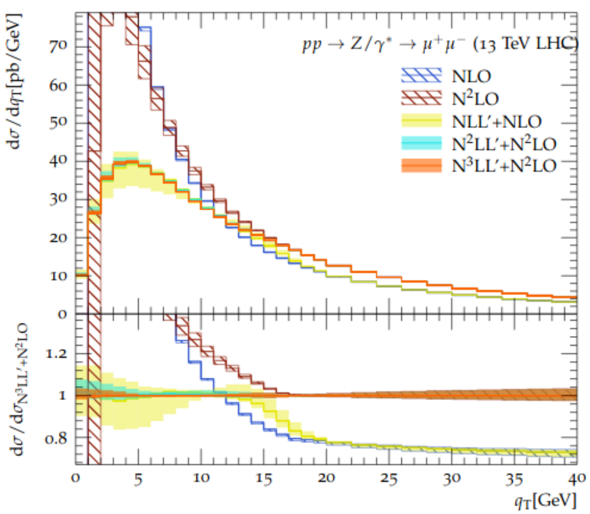
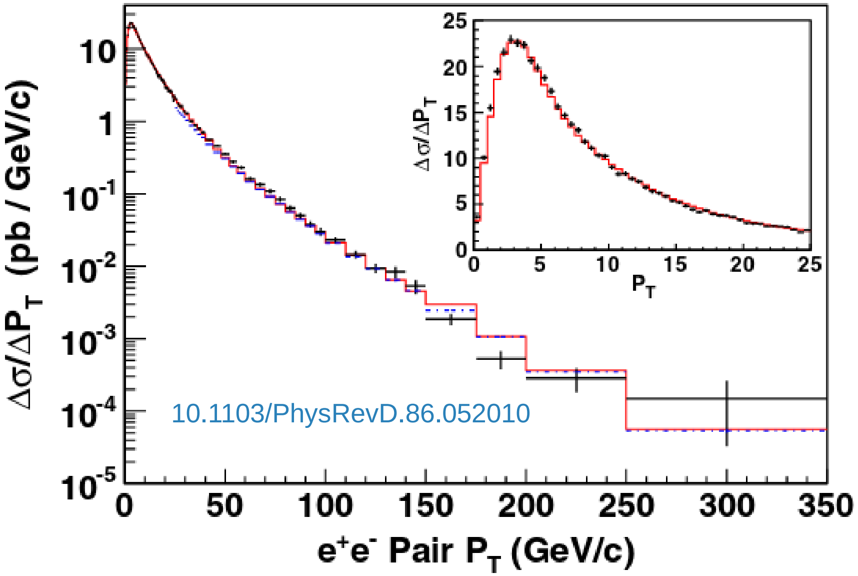


CDF measurement of Z-boson p_T

- 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

  → allows fast analytic predictions and avoid theoretical uncertainties on Z polarisation



- $p\bar{p}$ collisions

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

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

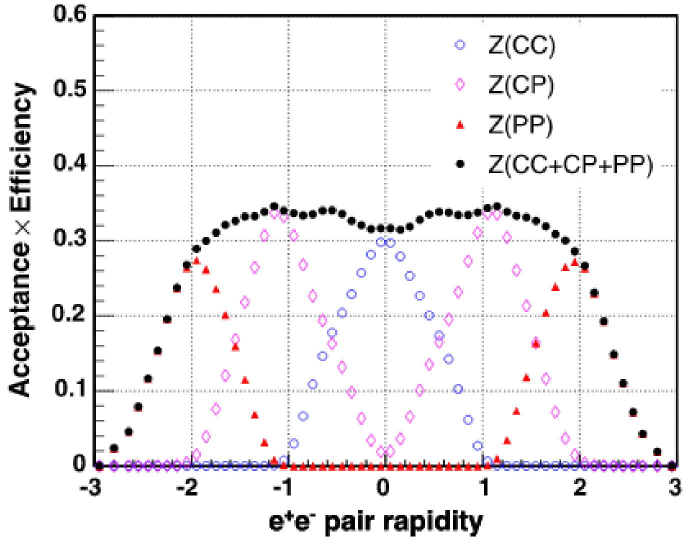
$$\frac{d\sigma}{dpdq} = \frac{d^3\sigma}{dp_T\,dy\,dm}\sum_i A_i(y, p_T, m)P_i(\cos\theta, \phi)$$

- 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, 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 i

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

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https://dyturbo.hepforge.org/

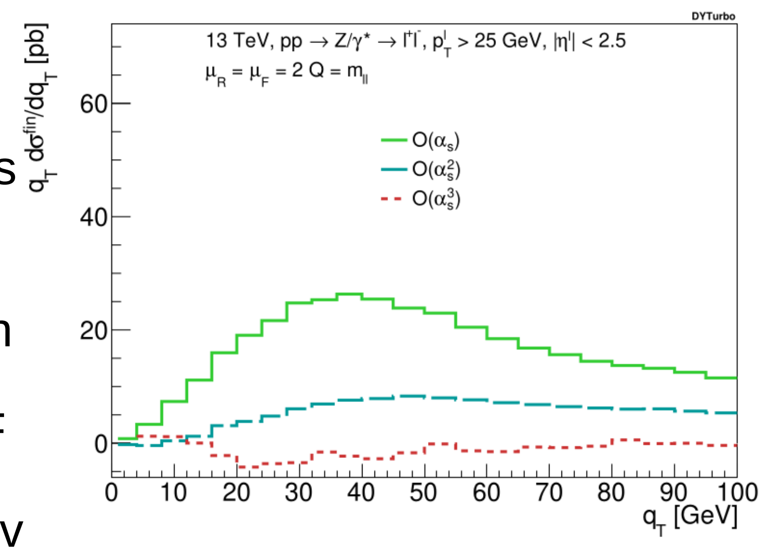
$$\frac{d\hat{\sigma}^{(\text{res.})}_{V}}{dq_T^2}(q_T, M) = \frac{M^2}{\hat{s}} \int_0^\infty db\, \frac{b}{2}\, J_0(bq_T)\, \mathcal{W}^V(b, M)$$

perturbative Sudakov form factor

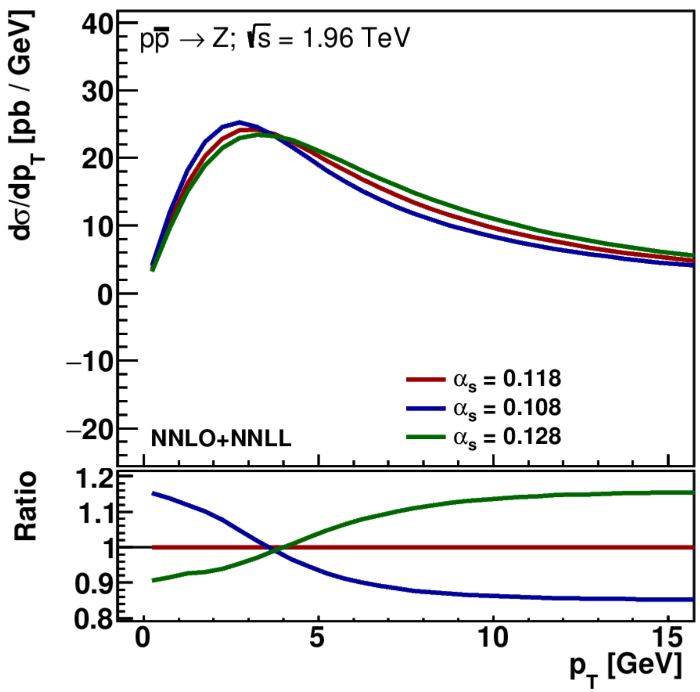
$$\mathcal{W}_N^V(b, M) = \mathcal{H}_N^V(\alpha_S) \times \exp\{\mathcal{G}(\boxed{\alpha_S}, L)_N\},\ L = log(M^2 b^2)$$

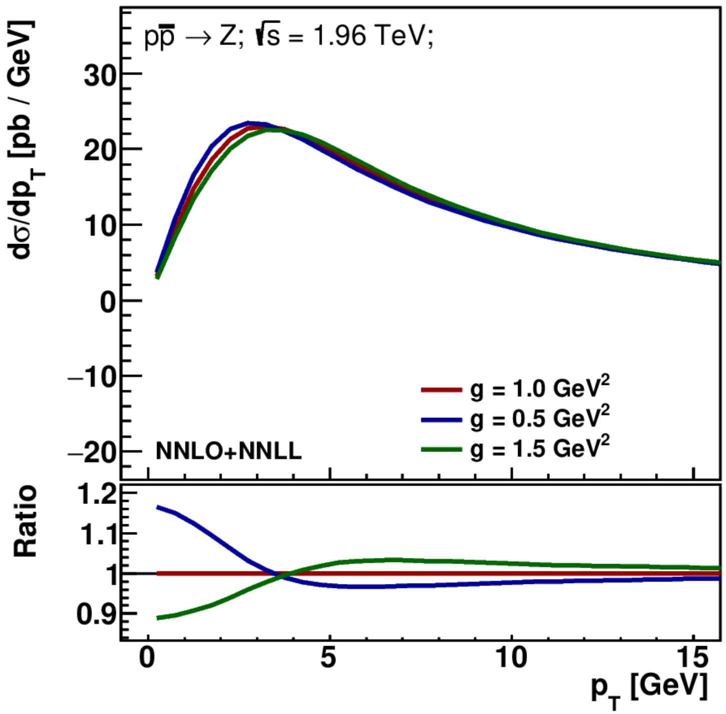
Sensitivity to α_s

- 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 ~ 0.6 GeV^2 → $\langle k_T \rangle \sim 1.5$ GeV

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

Methodology for the $\alpha_s(m_Z)$ determination

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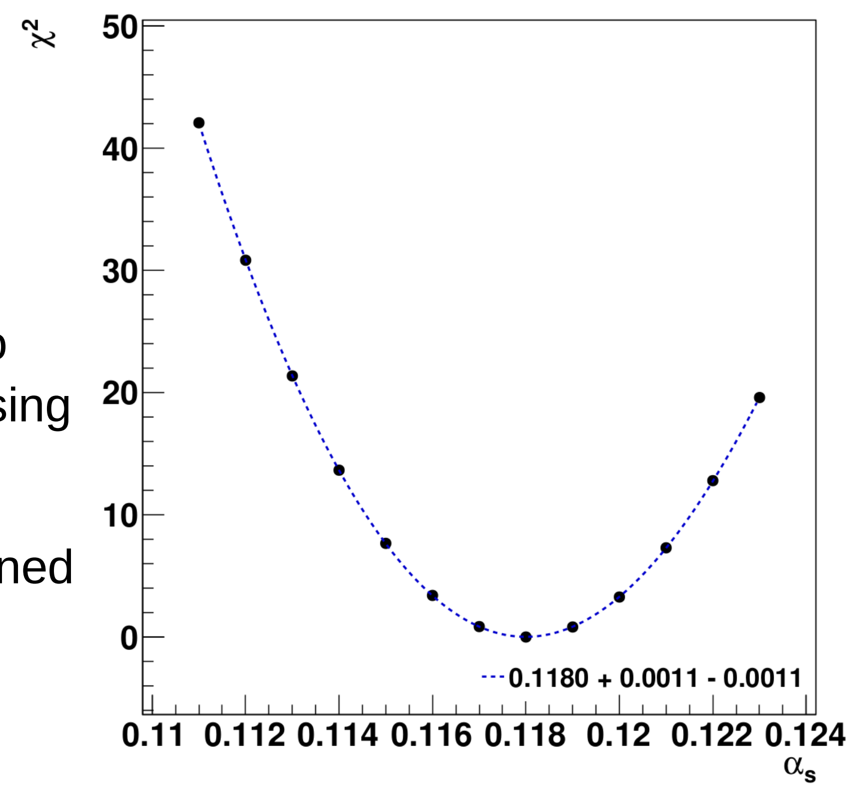
https://www.xfitter.org/xFitter/

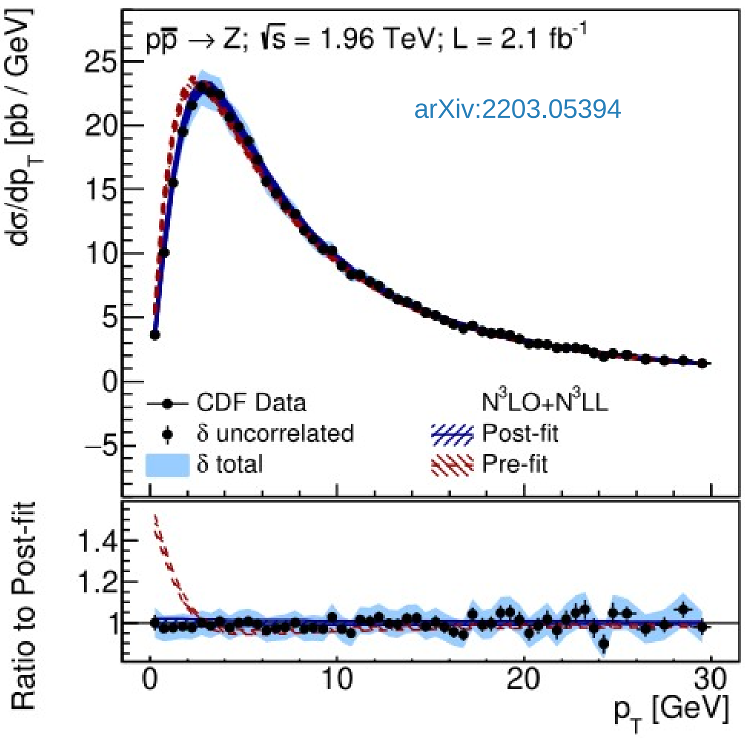
- DYTurbo interfaced to xFitter
- Evaluate $\chi^2(\alpha_s)$ with α_s variations as provided in LHAPDF
- Include experimental ($\beta_{j,\mathrm{exp}}$) and PDF ($\beta_{k,\mathrm{th}}$) uncertainties in the χ^2

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



- 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

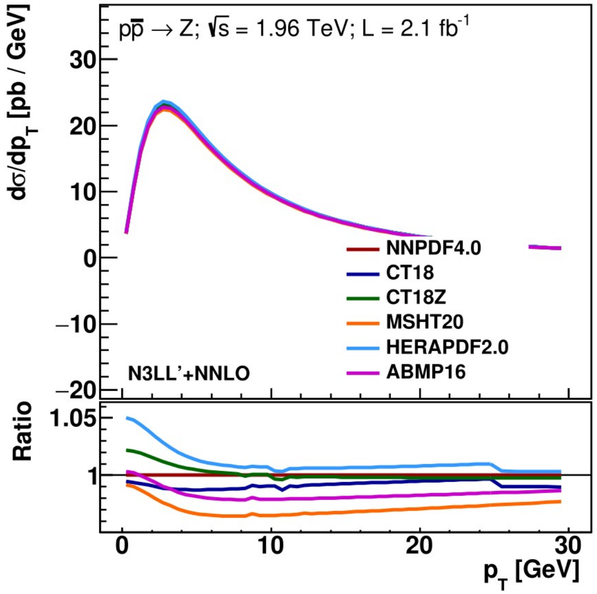


- Simultaneous fit of $\alpha_s(m_Z)$ and g

α_s = 0.1187
±0.0007 (exp. stat)
±0.0002 (exp. syst)
±0.0004 (PDF)

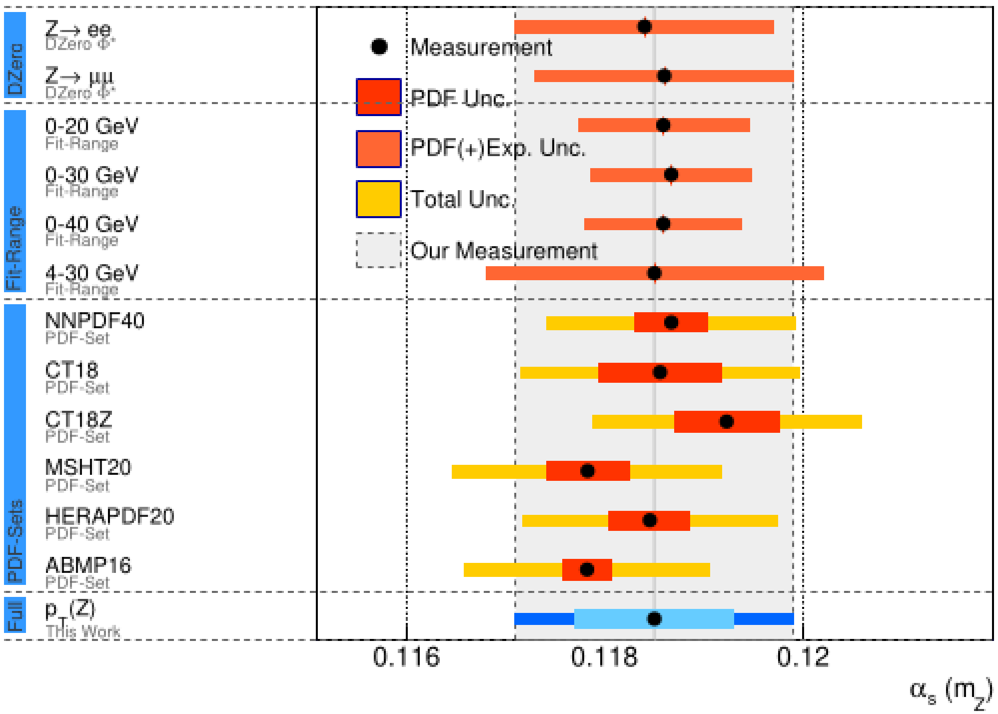
g = 0.66 ± 0.05 (GeV^2)

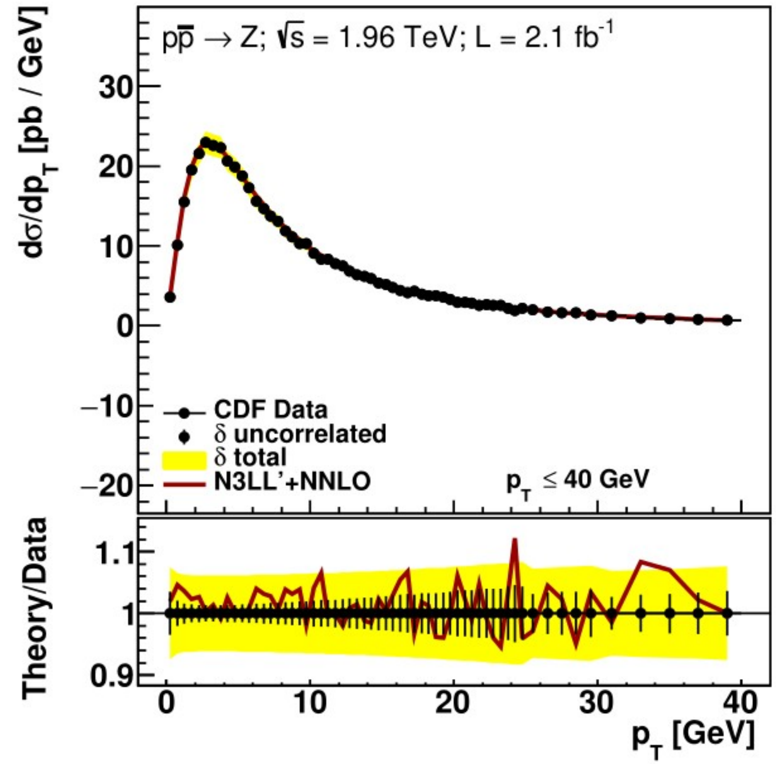
	NNPDF4.0	CT18	CT18Z	MSHT20	HERAPDF2.0	ABMP16
$\alpha_s(m_Z)$	0.1187	0.1186	0.1192	0.1178	0.1185	0.1178
PDF unc.	0.0004	0.0006	0.0005	0.0004	0.0004	0.0002
g (GeV^2)	0.66	0.69	0.69	0.72	0.74	0.72
χ^2/dof	41/53	40/53	40/53	40/53	40/53	41/53



α_s = 0.1185 ± 0.0007 (PDF envelope)

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

$\alpha_s = 0.1185 + 0.0014 - 0.0015$

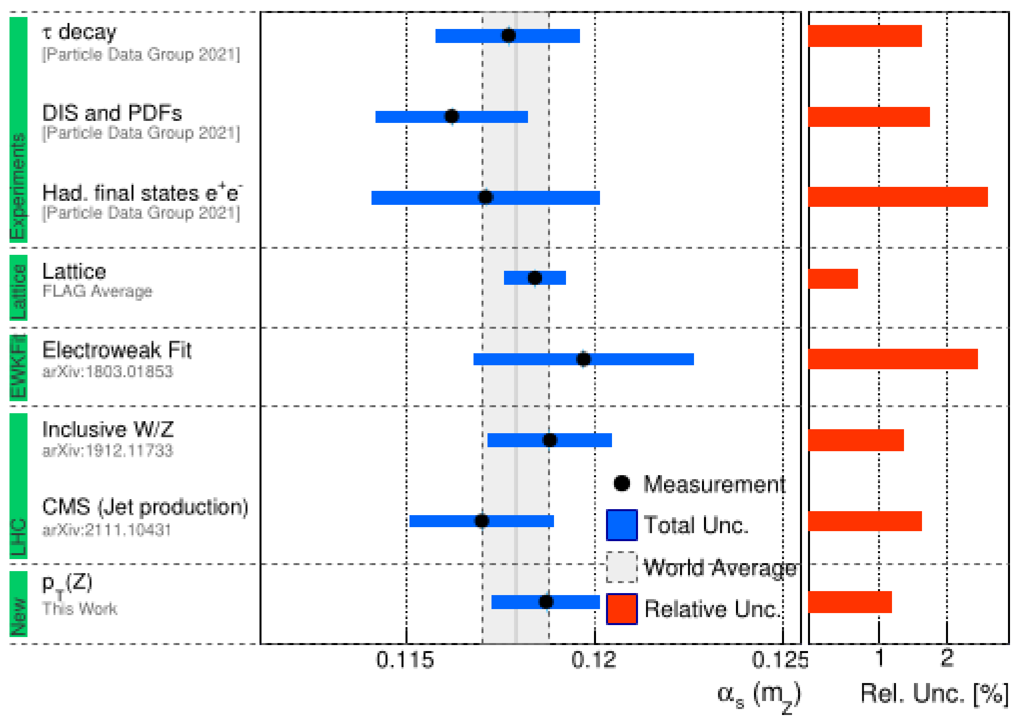
Breakdown of uncertainties

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

- Alternative fits with different prescriptions for the Landau pole
  $\delta\alpha_s = +0.0006 - 0.0004$
  $\delta g = +0.21 -0.13$
- Alternative fit with VFN PDF evolution
  $\delta\alpha_s = - 0.0002$

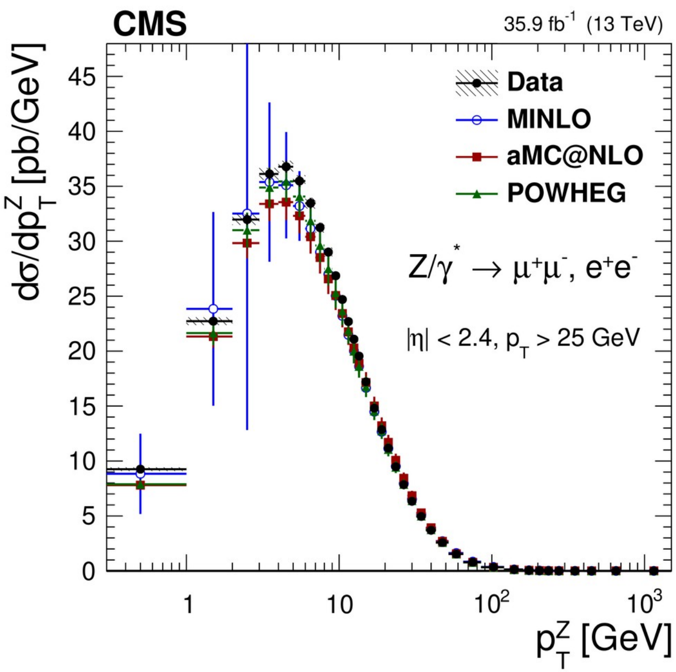
- Measurement in agreement with the world average
- Uncertainty comparable to other determinations
- 1.2% rel. unc.: best collider measurement, second after lattice QCD average
- First N3LO $\alpha_s(m_Z)$ at hadron colliders

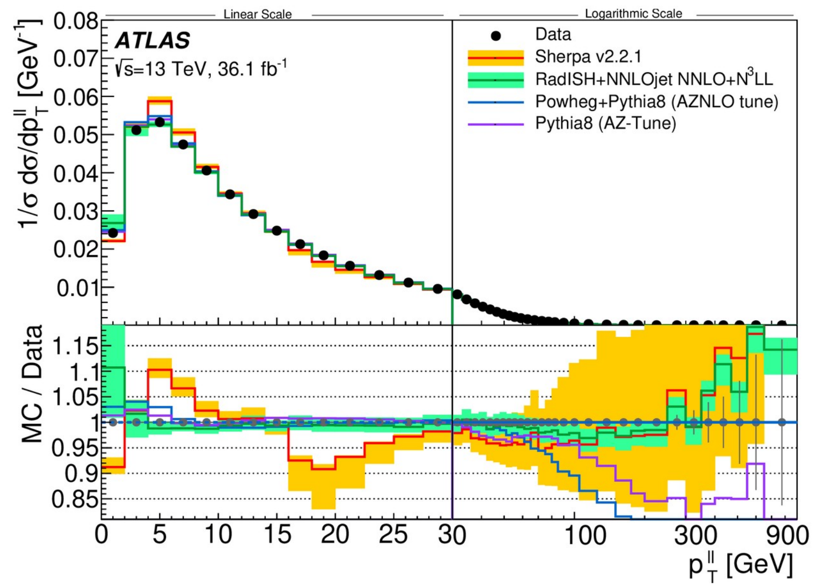
arXiv:2203.05394



$\alpha_s(m_Z)$ from the Z p_T distribution at the LHC

- LHC measurement of Z p_T are significantly more precise than Tevatron:
  - ATLAS 7 TeV data yields 0.2% experimental uncertainties on α_s (estimated from MC tuning)
  - 3 times smaller uncertainties with 8 TeV ATLAS/CMS
  - Likely to reach a few 10^{-4} relative uncertainty on α_s with full Run 2 LHC data sample





- Several additional theory challenges at the LHC
  - Significant heavy flavour initiated production
  - Small-x resummation
  - Larger gluon PDF uncertainty

Summary and conclusions

- The strong-coupling constant is a fundamental parameter of the SM, improving its knowledge has far-reaching implications in the quest for new phenomena
- A large variety of $\alpha_s(m_Z)$ determinations are currently being pursued, leading to a much improved overall understanding of QCD. Some of the most clean determinations are likely to reach subpercent uncertainty in the near future
- A new methodology based on the Z p_T distribution provided a measurement of $\alpha_s(m_Z)$ with precision comparable to other determinations. The same methodology applied to LHC data has the potential to provide an even more precise determination

BACKUP

The strong-coupling constant - Motivation

ggF cross section at N³LO QCD

$\sqrt{s}$	σ	δ(theory)		δ(PDF)	$\delta(\alpha_s)$	
13 TeV	48.61 pb	$^{+2.08\text{pb}}_{-3.15\text{pb}}$	$\left(^{+4.27\%}_{-6.49\%}\right)$	± 0.89 pb ($\pm 1.85\%$)	$^{+1.24\text{pb}}_{-1.26\text{pb}}$	$\left(^{+2.59\%}_{-2.62\%}\right)$
14 TeV	54.72 pb	$^{+2.35\text{pb}}_{-3.54\text{pb}}$	$\left(^{+4.28\%}_{-6.46\%}\right)$	± 1.00 pb ($\pm 1.85\%$)	$^{+1.40\text{pb}}_{-1.41\text{pb}}$	$\left(^{+2.60\%}_{-2.62\%}\right)$
27 TeV	146.65 pb	$^{+6.65\text{pb}}_{-9.44\text{pb}}$	$\left(^{+4.53\%}_{-6.43\%}\right)$	± 2.81 pb ($\pm 1.95\%$)	$^{+3.88\text{pb}}_{-3.82\text{pb}}$	$\left(^{+2.69\%}_{-2.64\%}\right)$

[HE/HL-LHC Yellow Report '19]

- The strong-coupling constant is among the dominant uncertainties of several precision measurements at colliders
  - Higgs couplings at the LHC
  - EWPO at e+e- colliders

Msbar mass error budget (from threshold scan)

$(\delta M_t^{\text{SD-low}})^{\text{exp}}$	$(\delta M_t^{\text{SD-low}})^{\text{theo}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\text{conversion}}$	$(\delta\overline{m}_t(\overline{m}_t))^{\alpha_s}$
40 MeV	50 MeV	7 – 23 MeV	70 MeV

$\Rightarrow$ improvement in α_s crucial $\delta\alpha_s(M_Z) = 0.001$

Quantity	FCC-ee	future param.unc.	Main source
Γ_Z [MeV]	0.1	0.1	$\delta\alpha_s$
R_b [10^{-5}]	6	< 1	$\delta\alpha_s$
R_ℓ [10^{-3}]	1	1.3	$\delta\alpha_s$

Sven Heinemeyer – 1st FCC physics workshop, CERN, 17.01.2017

Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	± 3.7	-6.2 +7.4	-2.61 +0.32
ttH	0.611	± 3.0	± 8.9	-9.3 +5.9

Partial width	intr. QCD	para. m_q	para. α_s
$H \to b\bar{b}$	$\sim 0.2\%$	1.4%	0.4%
$H \to c\bar{c}$	$\sim 0.2\%$	4.0%	0.4%
$H \to gg$	$\sim 3\%$	$< 0.2\%$	3.7%

State-of-the-art for the strong coupling $\alpha_s(m_Z)$

- PDG approach: set selection criteria (NNLO QCD, published result, standard theory uncertainty) and treat all measurements democratically with unweighted pre-averages

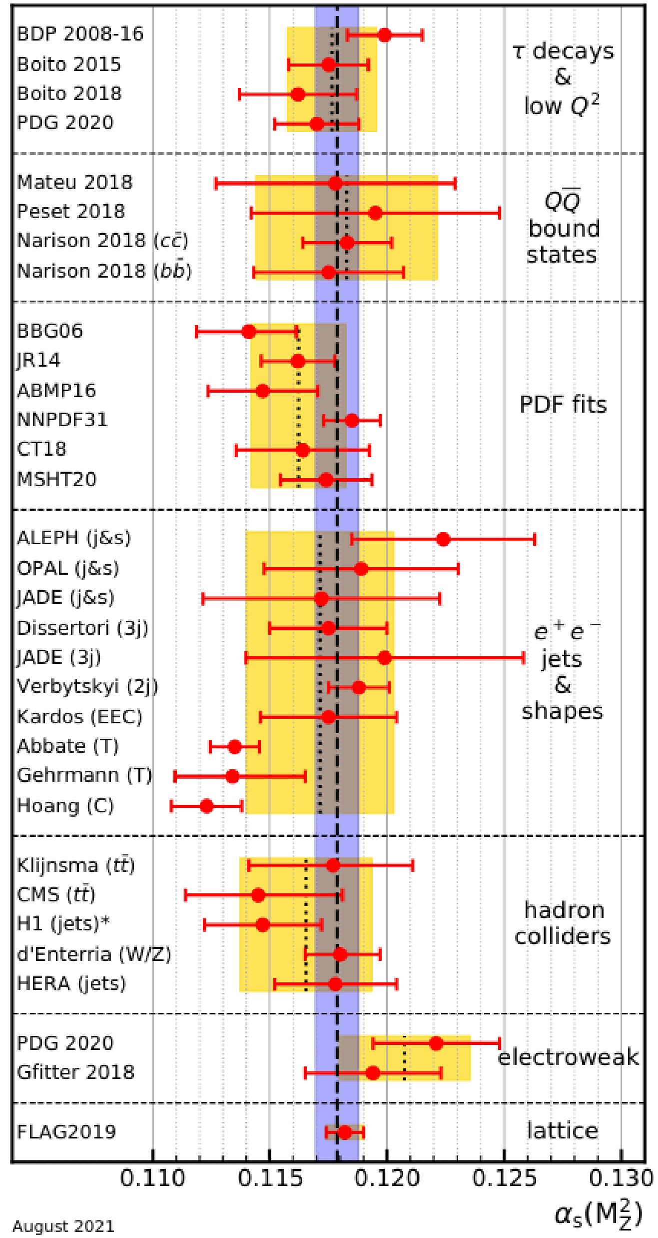
  → Test of QCD, unbiased result, but total uncertainty affected by unresolved tensions

- Critical view: select a smaller set of *clean* $\alpha_s(m_Z)$ measurements to achieve better precision:

  [...] *one should select few theoretically simplest processes for measuring αs and consider all other ways as tests of the theory (G. Altarelli)*

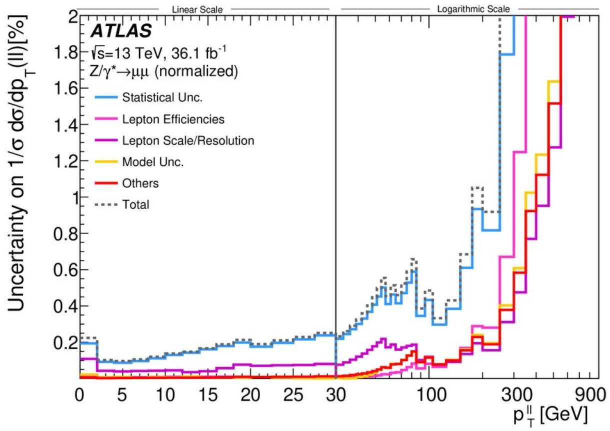
  Desirable features of a clean $\alpha_s(m_Z)$ measurement

  - Large observable's sensitivity to α_s as compared to the experimental precision
  - High (perturbative) accuracy of the perturbative prediction
  - Small size of non-perturbative effects
  - The scale at which the measurement is performed



Prospects for $\alpha_s(m_Z)$ at 0.1% from Z p_T

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

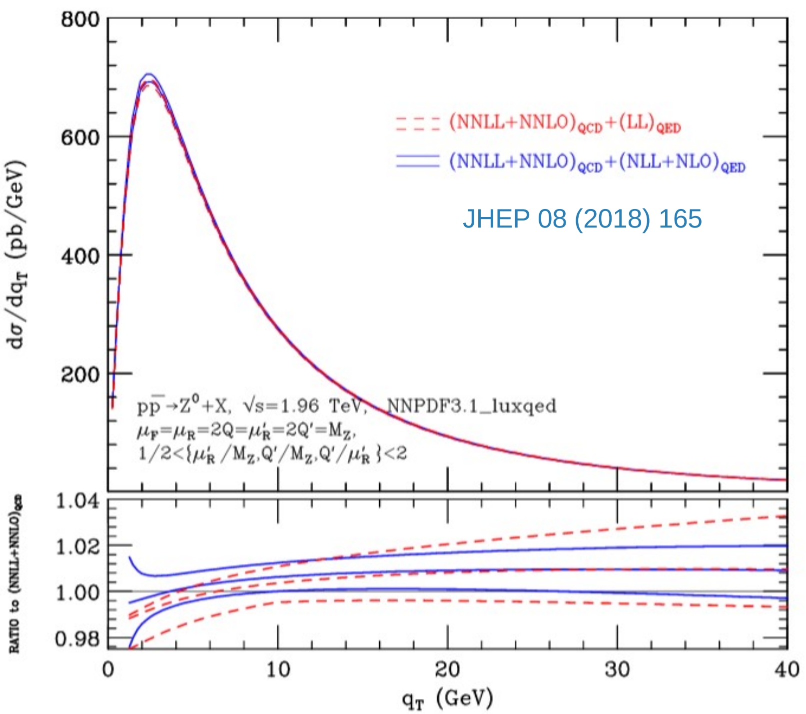
- N4LL ingredients (5-loop cusp, 4-loop RAD)
- N4LL' ingredients (N3LO PDFs, N4LO TMD, 4-loop quark form factor,…)
- Improved heavy-flavour treatment (massive corrections, VFN)
- Joint qt/small-x resummation
- QED/QCD qt-resummation
- First-principle understanding of non-perturbative corrections

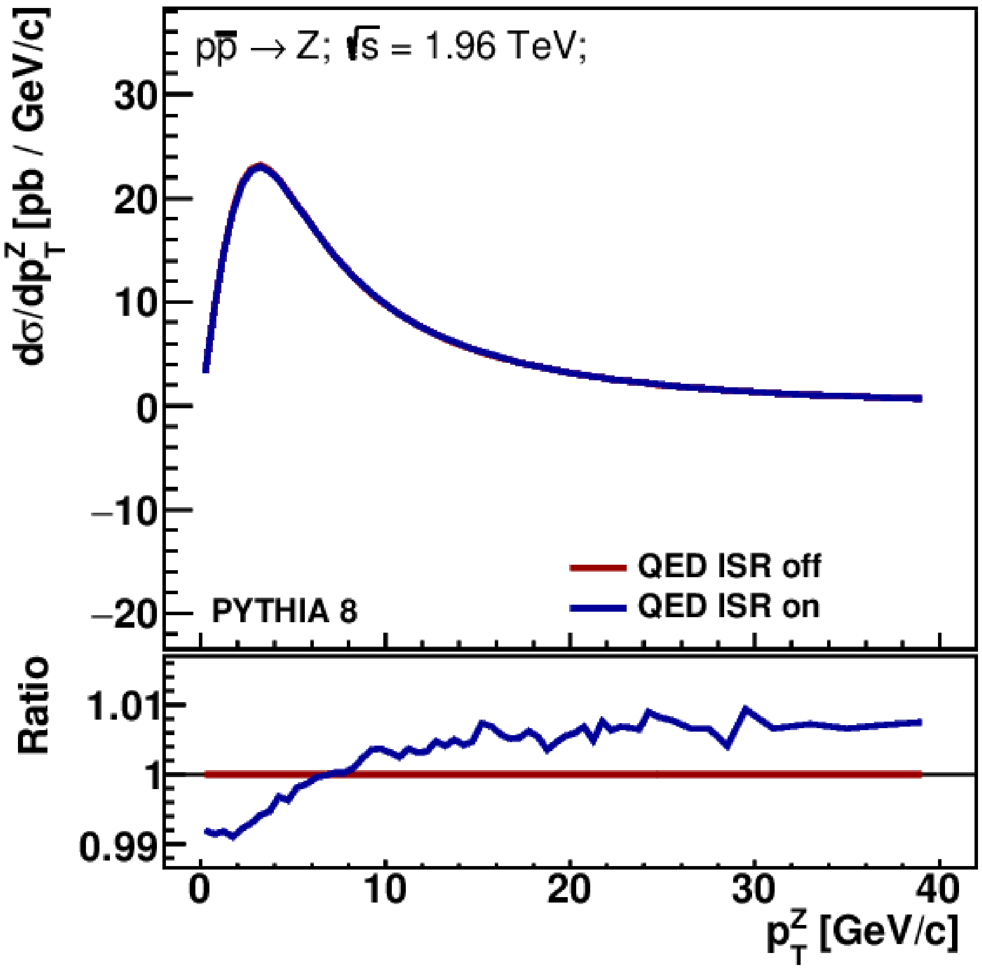
Prospects to reach subpercent precision in the next 10 years mostly rely on theory developments

QED ISR correction

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

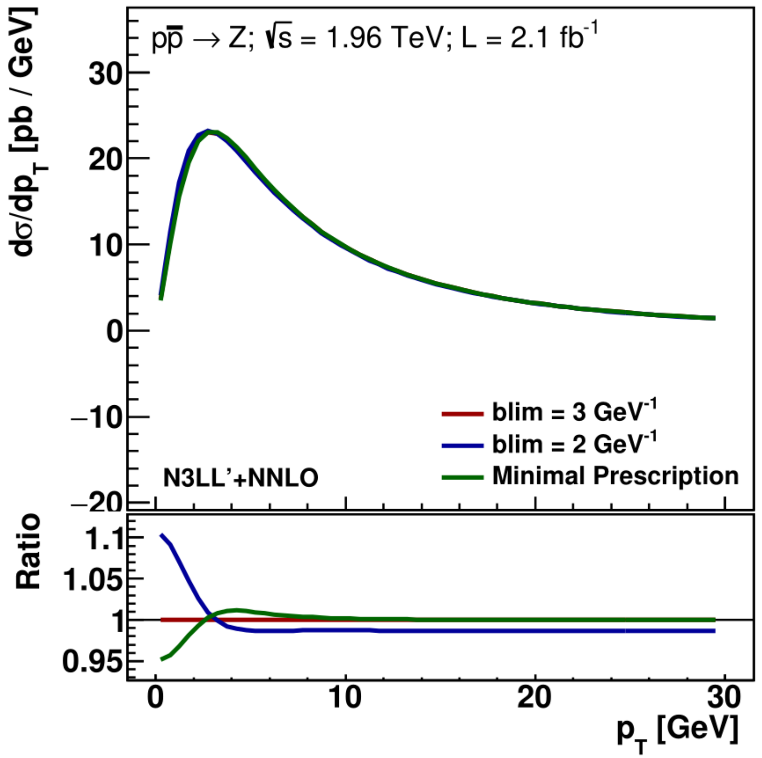
- Correction to the Z-boson p_T at the level of 1%
- Effect on $\alpha_s(m_Z)$: $\Delta\alpha_s = -0.0004$
- Comparable to corrections obtained with QED qt-resummation





Theory uncertainties

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

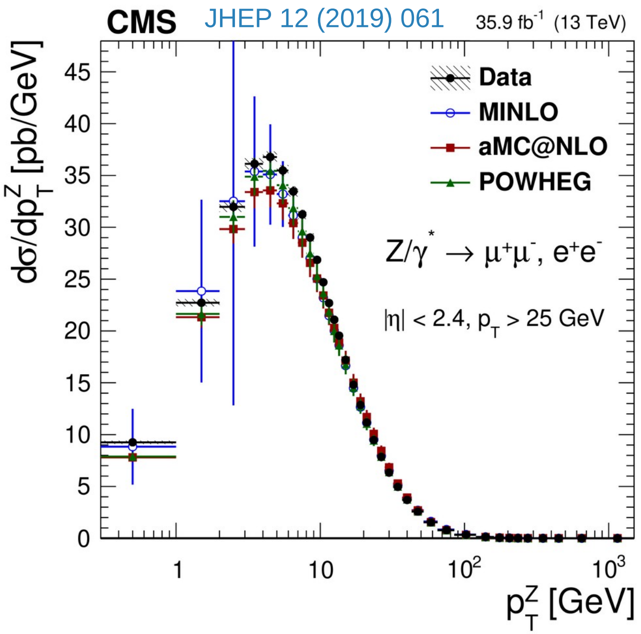


Measure $\alpha_s(m_Z)$ from semi-inclusive DY

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