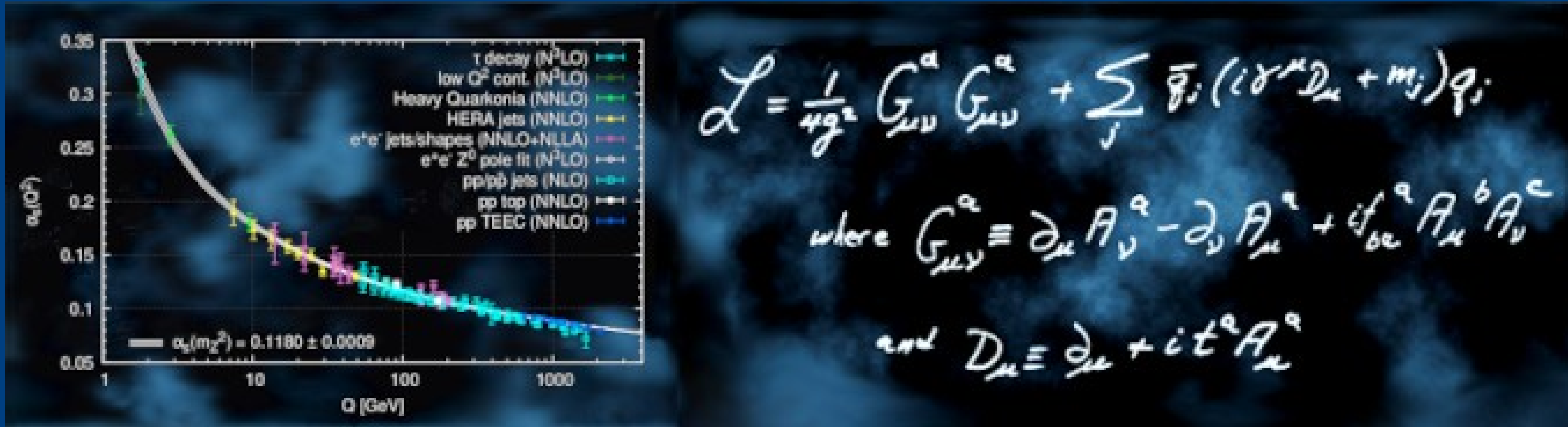


Overview of current α_s extractions

Extracting α_s at EIC & Future Colliders

Stony Brook Univ., 5th May 2025

David d'Enterria (CERN)

<u>Foreword</u>: *Mostly covering α_s extractions from the PDG'24 (other more recent extractions will be shown during this workshop), plus future perspectives from:*

The strong coupling constant: State of the art and the decade ahead

arXiv:2203.08271 [hep-ph]

Introduction: QCD coupling α_s

- Determines strength of the strong interaction among quarks & gluons.
- Single free parameter of QCD in the $m_q = 0$ limit. Running via RGE.
- Determined at a ref. scale ($Q=m_Z$), decreases as $\alpha_s \approx \ln(Q^2/\Lambda^2)^{-1}$; $\Lambda \approx 0.2$ GeV

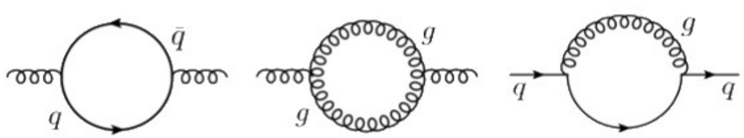
$$\frac{\partial \alpha_s}{\partial \log Q^2} = \beta(\alpha_s) = -\alpha_s^2(\beta_0 + \beta_1\alpha_s + \beta_2\alpha_s^2 + \mathcal{O}(\alpha_s^3))$$

- The solution at three-loop precision

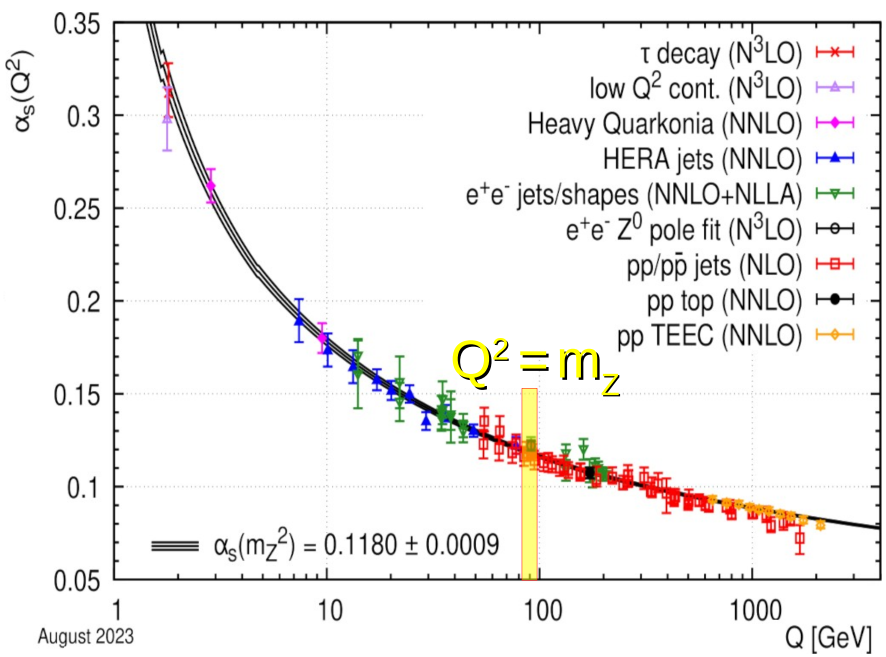
$$\frac{\alpha_s}{4\pi}(Q^2) = \frac{1}{\beta_0 x}\left[1 - \frac{\beta_1}{\beta_0^2}\frac{\log x}{x} + \frac{\beta_1^2}{\beta_0^4 x^2}\left(\log^2 x - \log x - 1 + \frac{\beta_2\beta_0}{\beta_1^2}\right)\right]; \quad x = \log\left(\frac{Q^2}{\Lambda^2}\right)$$

$\Lambda \approx 0.2$ GeV

Standard Model with n_f quark flavours:



$$\left.\begin{aligned} \beta_0 &= 11 - \frac{2}{3}n_f \\ \beta_1 &= 102 - \frac{38}{3}n_f \\ \beta_2 &= \frac{2857}{2} - \frac{5033}{18}n_f - \frac{325}{54}n_f^2 \end{aligned}\right\}$$



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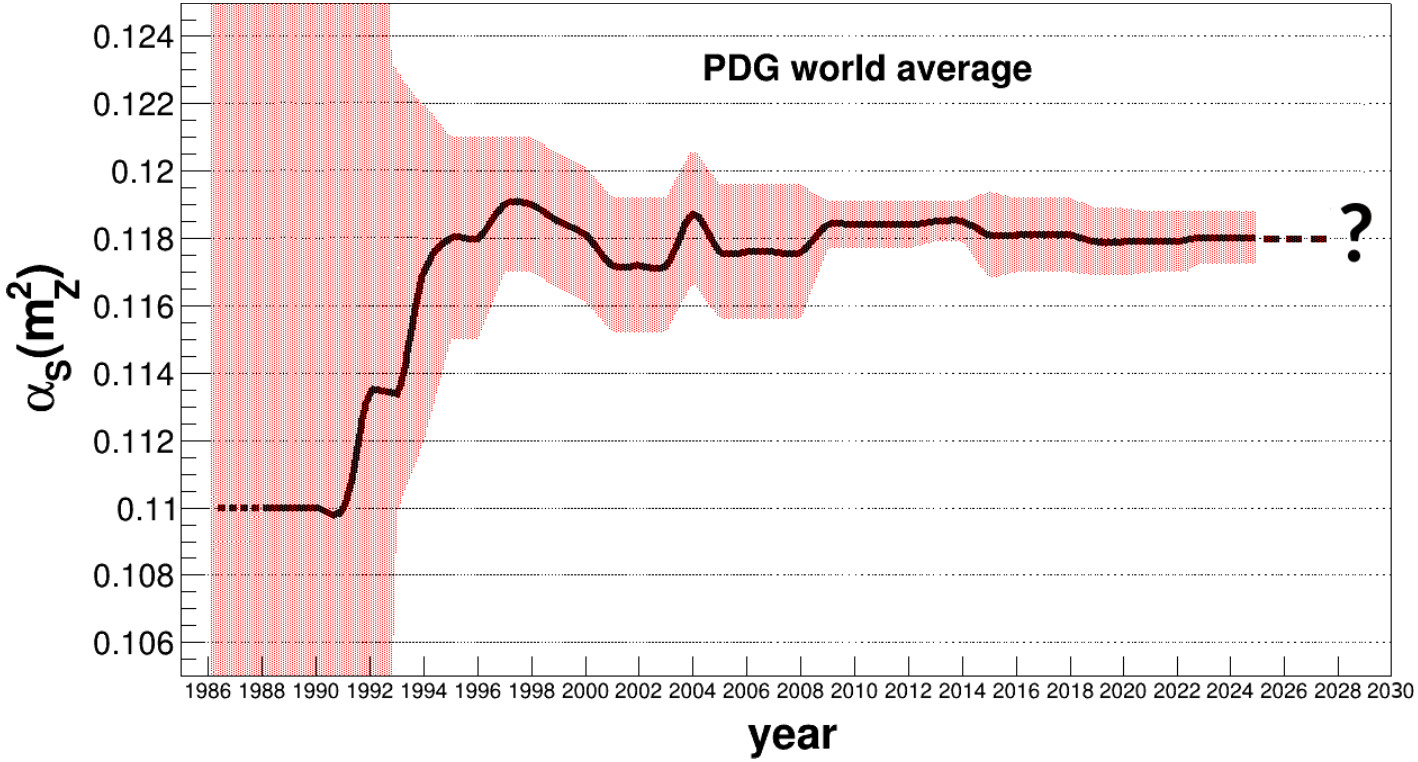
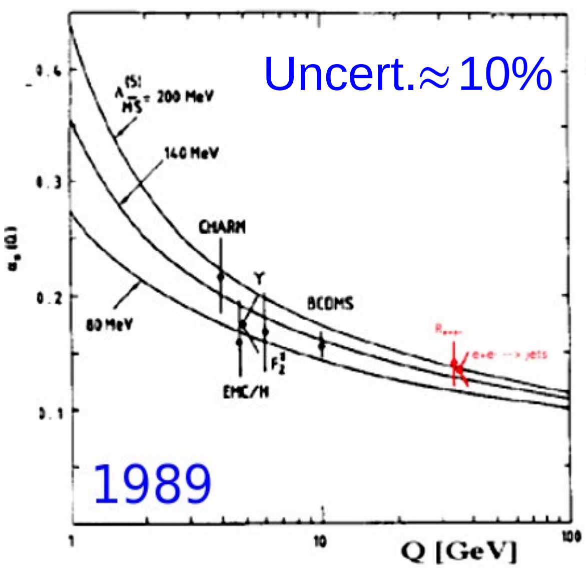


➧ 1986: First PDG world-average with ~100% uncertainty.

➧ 2025: Where are we 40 yrs later? How EIC/future-colliders will improve it?

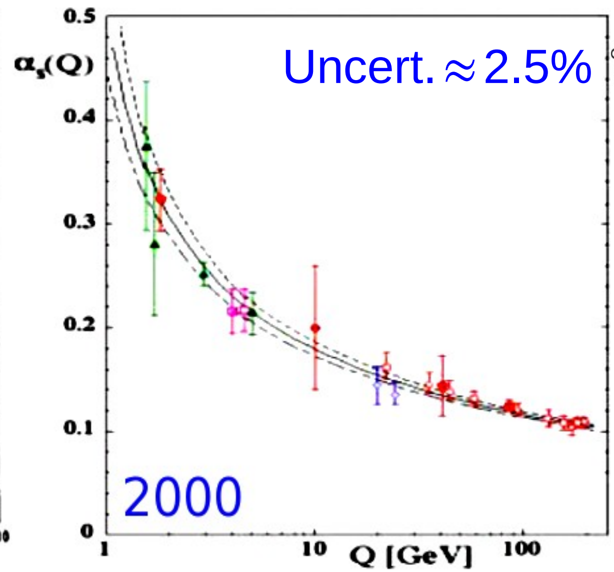
Motivation: QCD coupling α_s

- Determines strength of the strong interaction among quarks & gluons.
- Single free parameter of QCD in the $m_q = 0$ limit.
- Determined at a ref. scale ($Q=m_Z$), decreases as $\alpha_s \approx \ln(Q^2/\Lambda^2)^{-1}$, $\Lambda \approx 0.2$ GeV



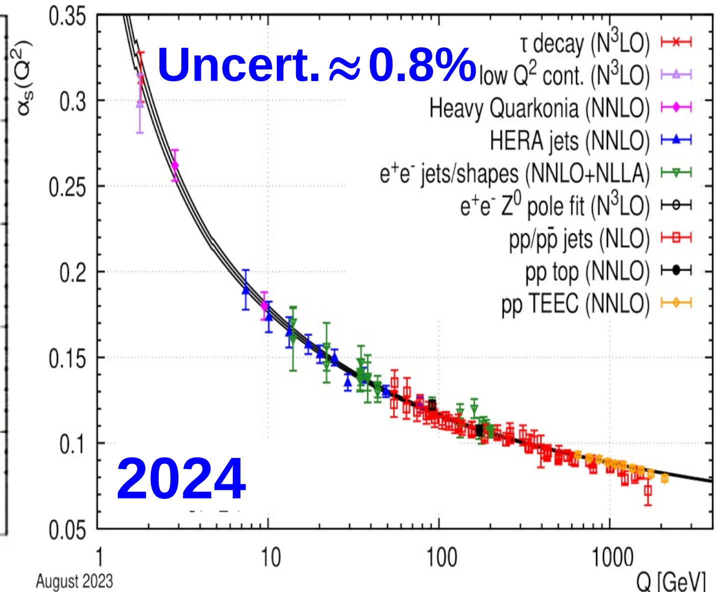
$\alpha_S(M_Z) = 0.110^{+0.006}_{-0.008}$ (NLO)

G. Altarelli, Ann. Rev. Nucl. Part. Sci. 39, 1989



$\alpha_S(M_Z) = 0.1184 \pm 0.0031$ (NNLO)

S. B. , J. Phys. G 26, 2000



$\alpha_S(m_Z^2) = 0.1180 \pm 0.0009$

➧ Least precisely known of all interaction couplings !

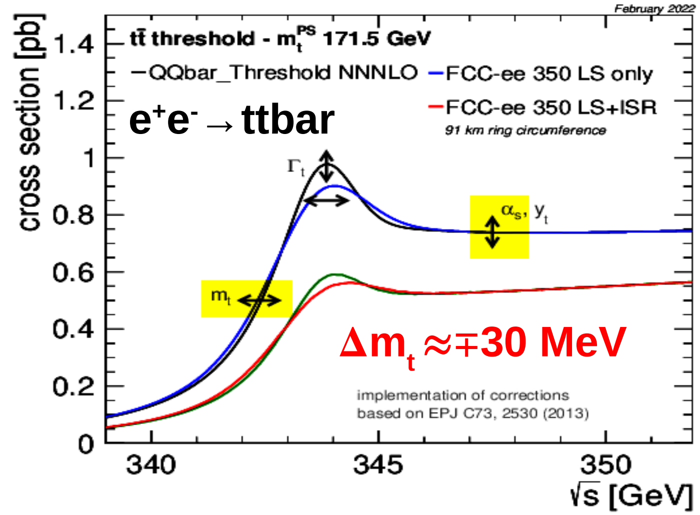
$\delta\alpha \approx 10^{-10} \ll \delta G_F \approx 10^{-7} \ll \delta G \approx 10^{-5} \ll \delta\alpha_s \approx 10^{-3}$

Motivation: α_s impact beyond QCD

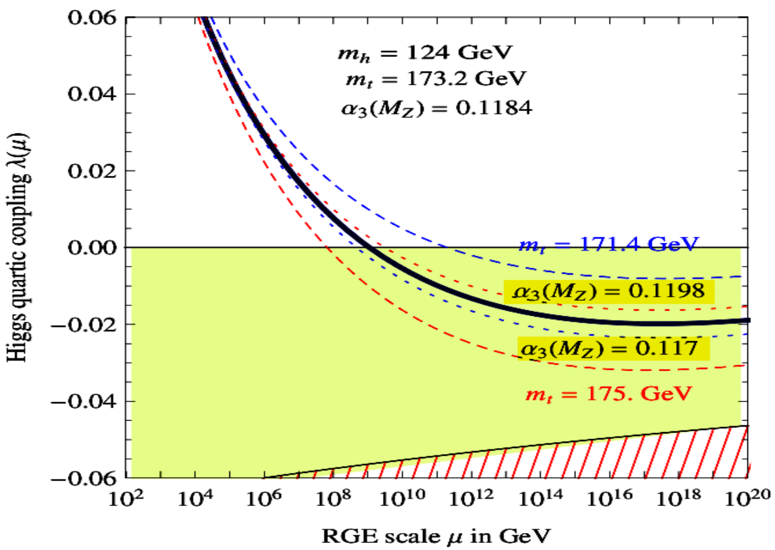
- Precision calculations of Higgs hadronic x-sections/decays, top mass, EWPO..

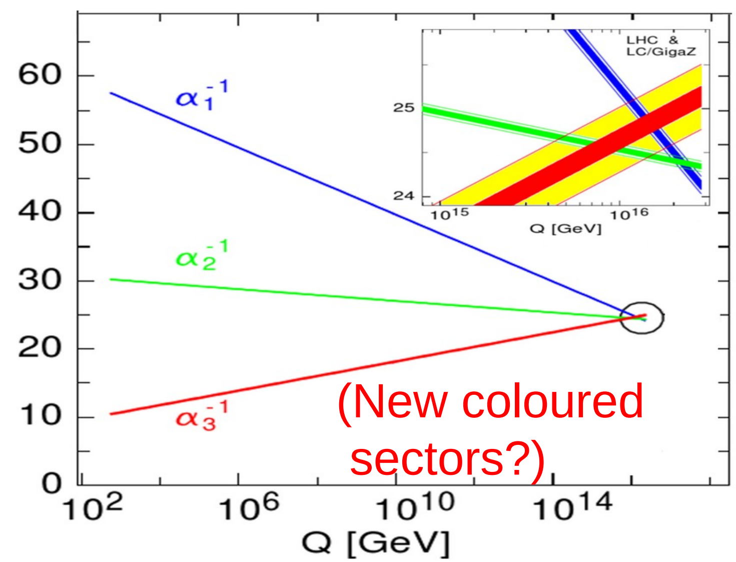
Process	σ (pb)	$\delta\alpha_s(\%)$	PDF $+\alpha_s(\%)$	Scale(%)
ggH	49.87	± 3.7	-6.2 +7.4	-2.61 +0.32
ttH	0.611	± 3.0	± 8.9	-9.3 +5.9

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%



- Impacts physics approaching Planck scale: EW vacuum stability, GUT

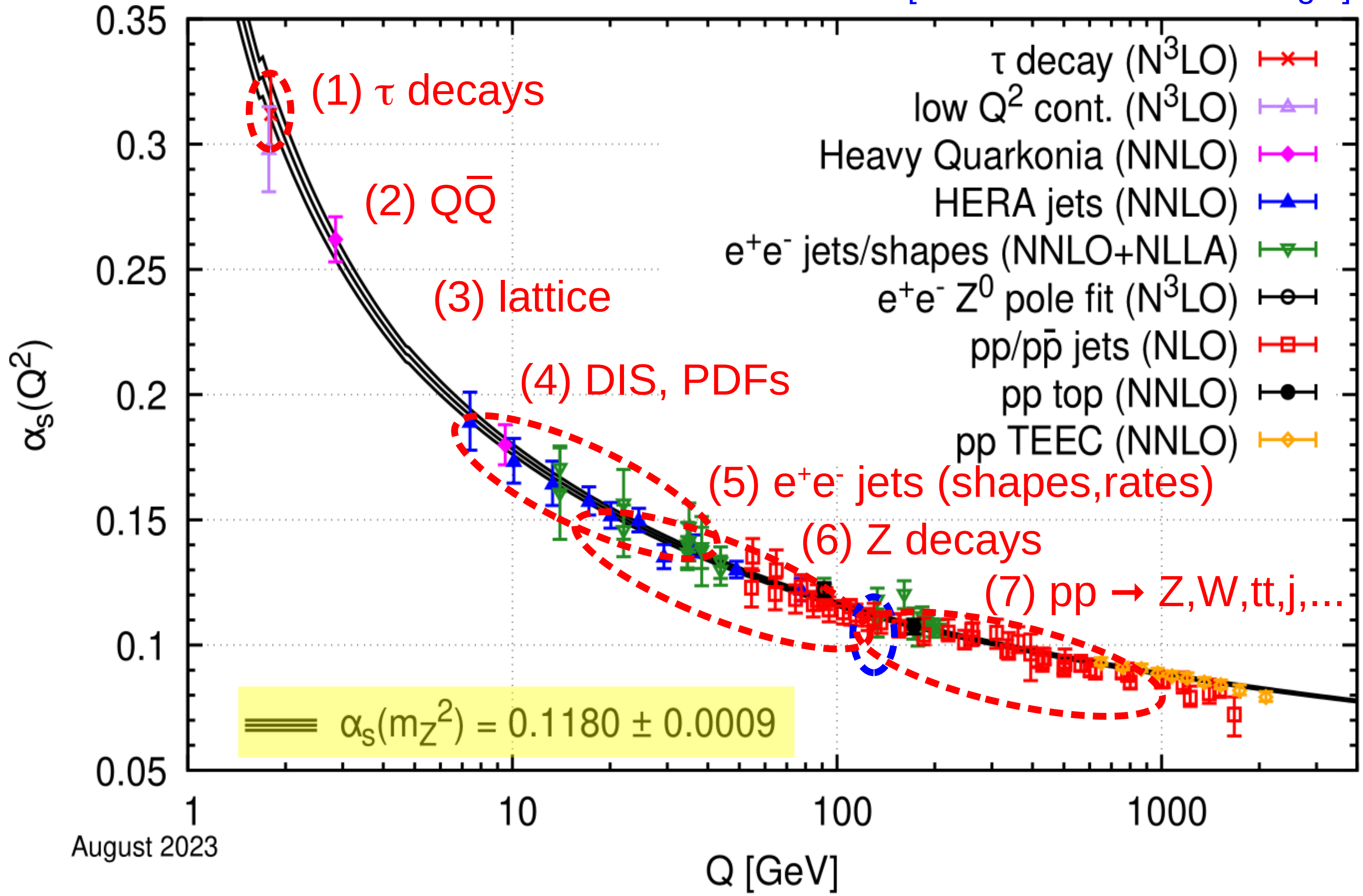




World α_s determination (PDG 2024)

- Determined today by comparing 7 experimental observables to pQCD NNLO,N^{3}LO predictions, plus global average at the Z pole scale:

[Huston/Rabbertz/Zanderighi]



World-average α_s (PDG 2024)

- χ^2-based average of (unweighted) pre-averages from 7 categories of observables:

  $\alpha_s(M_z) = 0.1180 \pm 0.0009$ (±0.8%)

  Hadronic tau decay (5 values):

  $\alpha_s(M_z) = 0.1173 \pm 0.0017$ (±1.4%)

  Quarkonia properties (6 values):

  $\alpha_s(M_z) = 0.1181 \pm 0.037$ (±3.3%)

  DIS & PDFs fits (7 values):

  $\alpha_s(M_z) = 0.1161 \pm 0.0022$ (±1.9%)

  $e^+e^- \rightarrow$ hadrons final states (7 values):

  $\alpha_s(M_z) = 0.1189 \pm 0.0037$ (±3.1%)

  Hadron collider measurements (7 values):

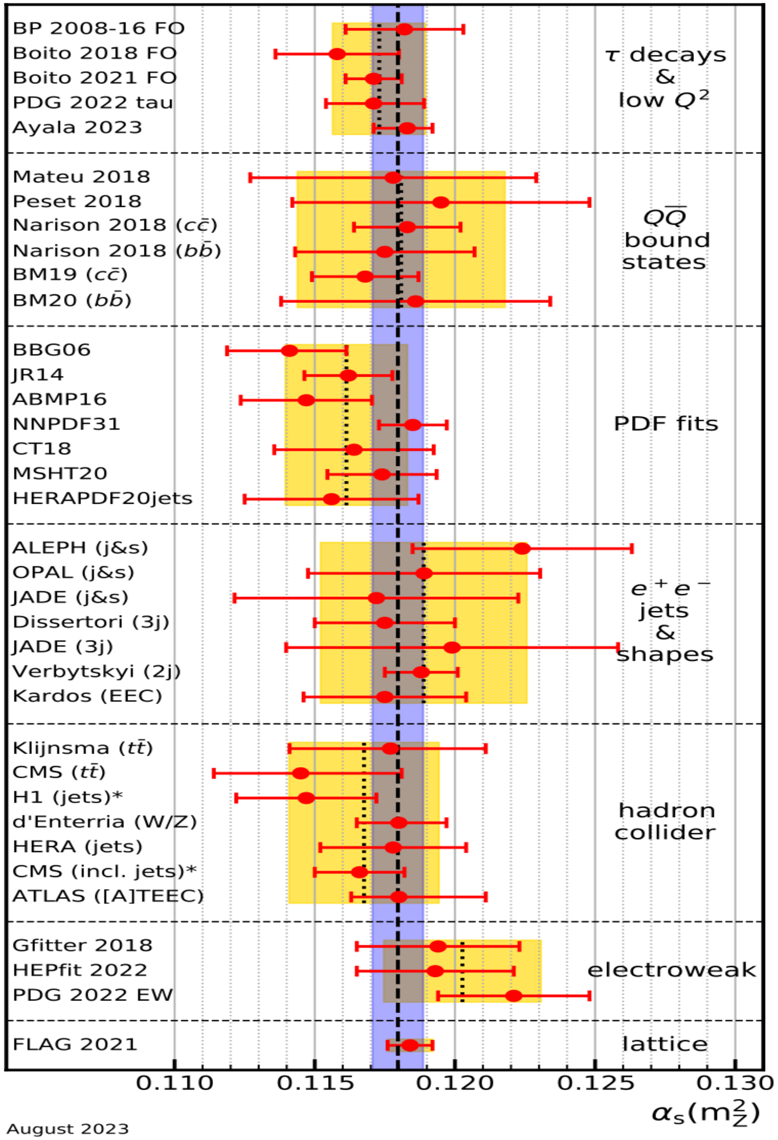
  $\alpha_s(M_z) = 0.1168 \pm 0.0027$ (±2.3%)

  Electroweak precision fits (3 values):

  $\alpha_s(M_z) = 0.1203 \pm 0.0028$ (±2.3%)

  Lattice QCD (1 FLAG average value):

  $\alpha_s(M_z) = 0.1184 \pm 0.0008$ (±0.7%)



(1) α_s from lattice QCD

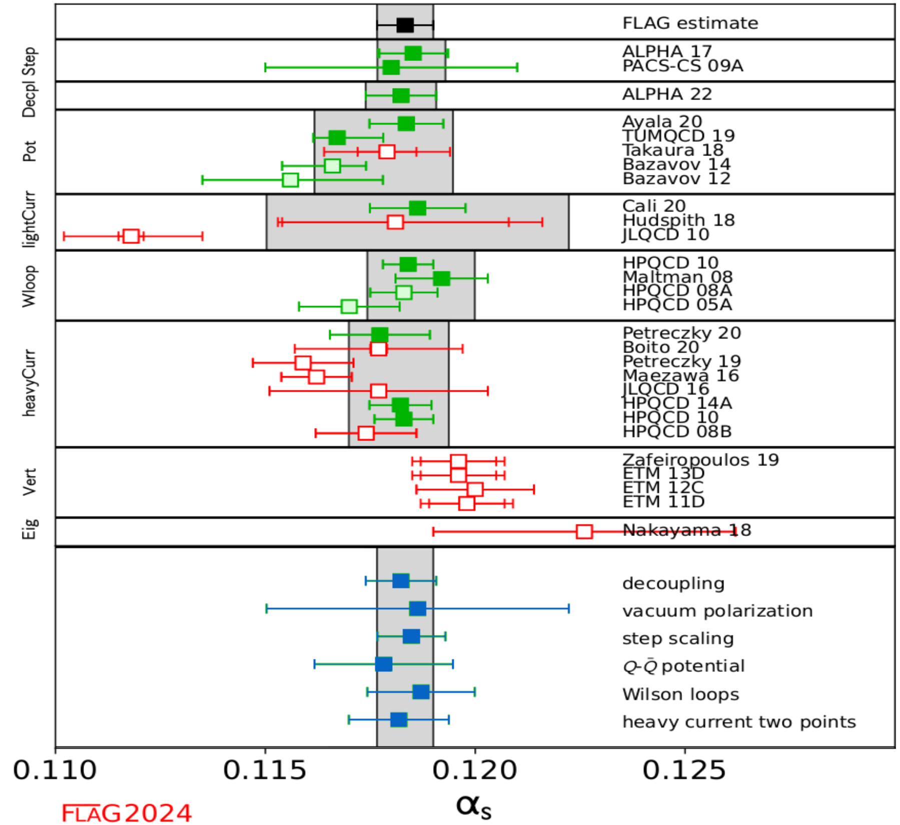
- Comparison of short-distance quantities (QCD static energy/force, light-q & heavy-Q currents, quarkonium,..) computed at $N^{2,3}LO$ in pQCD to lattice data with m_{had}, f_{had} fixed to exp. data:

$$K^{\mathrm{NP}} = K^{\mathrm{PT}} = \sum_{i=0}^{n} c_i \alpha_s^i$$

- Community-agreed (FLAG) criteria based on: large μ scale for pQCD part, well-defined continuum limit, latt. size/spacing: $L/a \gg \mu/\Lambda_{QCD}$, peer-reviewed results.

- Current uncertainties driven mostly by pQCD truncation & matching, and continuum limit (lattice spacing & computing statistics).

[FLAG Collab. http://flag.unibe.ch]



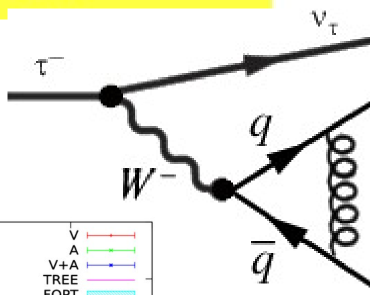
$\alpha_s = 0.1184 \pm 0.0008$ (±0.7%)

➧ Future prospects:

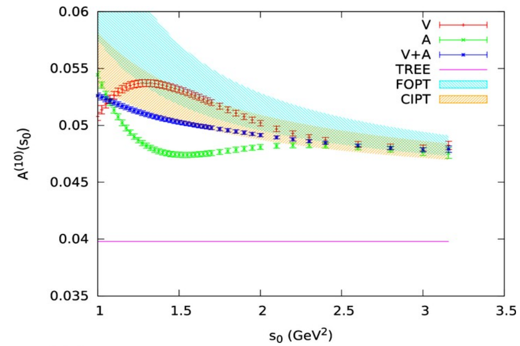
– Uncertainty in α_s halved with reduced latt. spacing, $N^{3,4}LO$ pQCD, active charm quark, extension of step-scaling method to more observables.

(2) α_s from hadronic τ-lepton decays

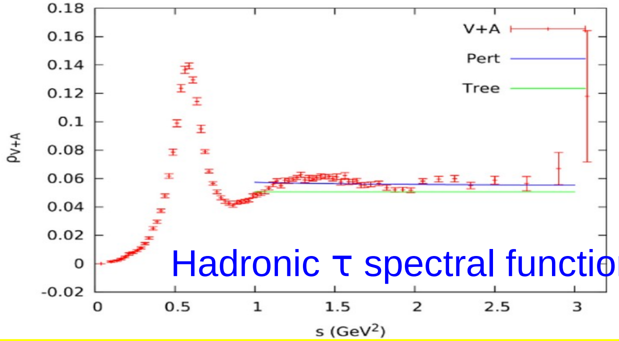
- Computed at N^{3}LO: $R_\tau \equiv \frac{\Gamma(\tau^- \to \nu_\tau + \text{hadrons})}{\Gamma(\tau^- \to \nu_\tau e^- \bar{\nu}_e)} = S_{\rm EW} N_C (1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5) + \delta_{\rm np})$



- Experimentally: $R_{\tau,\rm exp}$ = 3.6355 ± 0.0081 (±0.22%)
- Theoretically:
  - "Historical" diffs. in pQCD approaches. FOPT vs. CIPT OPE truncations (matching to npQCD spectral functions):
  - Reconciled via IR renormalon-free gluon condensate?
  - (CIPT not in PDG for now)



- Uncertainty driven today by:
  - non-pQCD corrections (duality violations): Note: $(\Lambda/m_\tau)^2$ ~ 2%



- Future prospects:
  - N^{4}LO corrections.
  - Better spectral functions needed: BELLE-II, STCF. Longer future: $\mathcal{O}(10^{12})$ Z→ττ at FCC-ee(90)
  - Reconciling FOPT vs. CIPT?

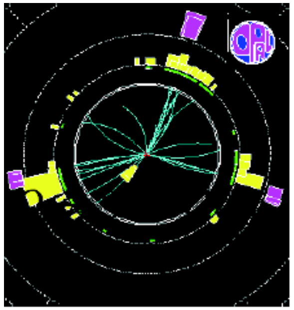
α_s = 0.1173 ± 0.0017 (±1.4%)

(3) α_s from e^+e^- event shapes & jet rates

- Computed at N^{2,3}LO+N^{2}LL accuracy.
- Experimentally (LEP):
  Thrust, C-parameter, jet shapes
  3-jet x-sections

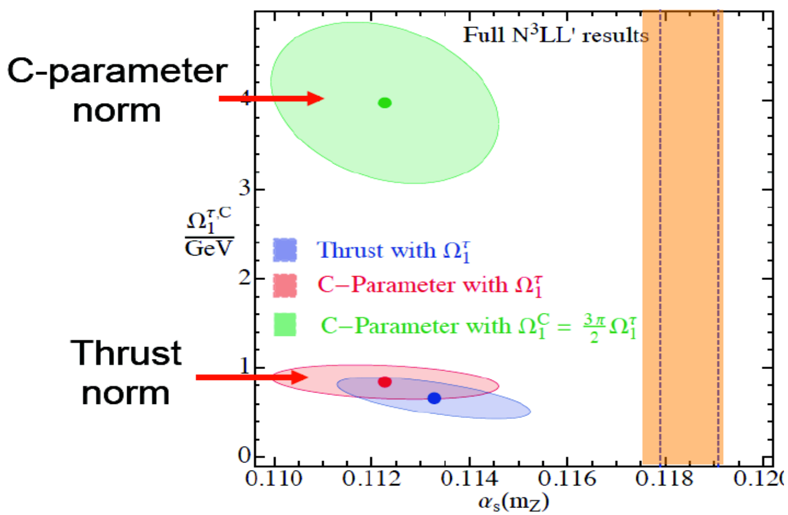
$$\tau = 1 - \max_{\hat{n}} \frac{\sum |\vec{p}_i \cdot \hat{n}|}{\sum |\vec{p}_i|}$$

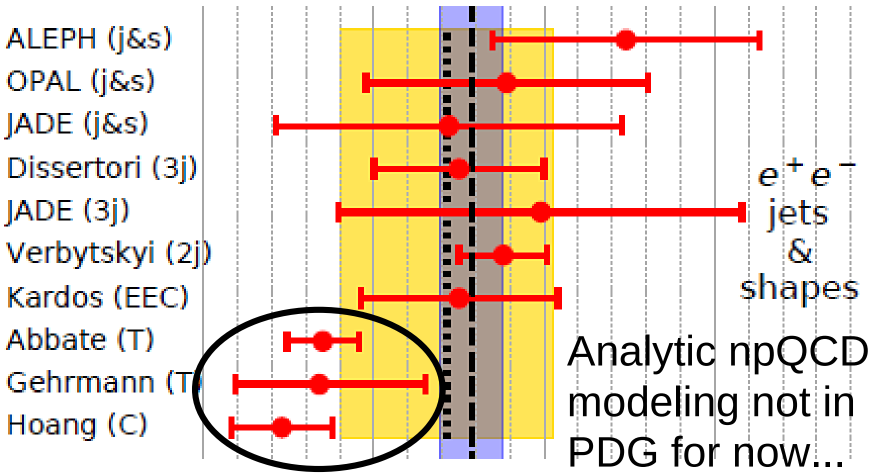
$$C = \frac{3}{2} \frac{\sum_{i,j} |\vec{p}_i||\vec{p}_j| \sin^2\theta_{ij}}{\left(\sum_i |\vec{p}_i|\right)^2}$$



OPAL 3 jet event

- Results sensitive to non-pQCD (hadronization) corrections.
  - Accounted for via MCs or analytically:





- Impact of power corrections & NNLL resummations in the 2-jet limit?
- Uncertainty of mass-scheme to extend evt. shapes to massive hadrons?

$\alpha_s(M_z)$= 0.1171 ± 0.0031 (±2.6%)

↓

$\alpha_s(M_z)$ = 0.1189 ± 0.0037 (±3.1%)

(3) α_s from e^+e^- event shapes & jet rates

- Computed at $N^{2,3}LO+N^2LL$ accuracy.
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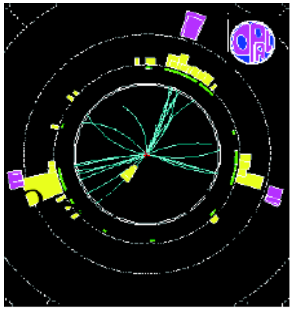
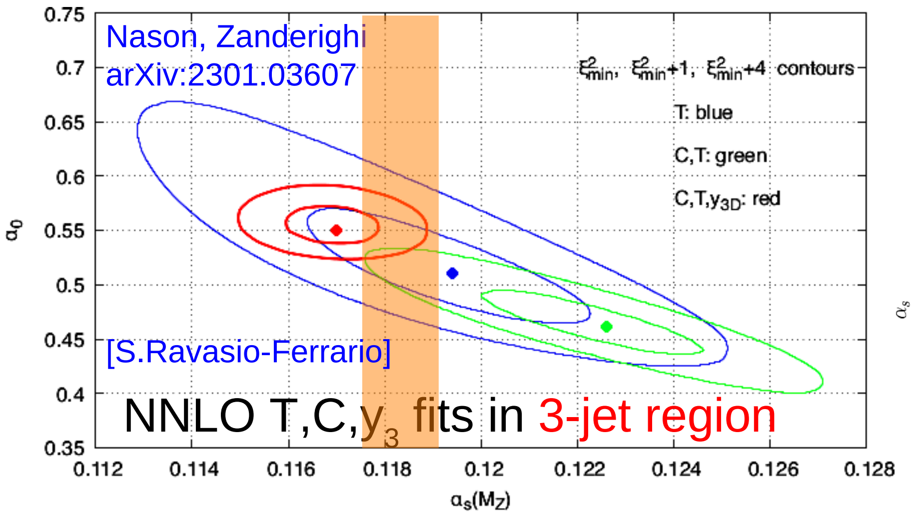
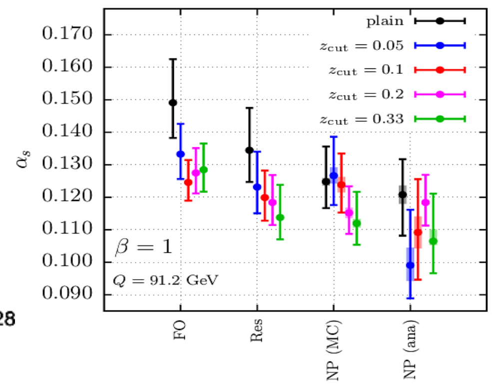


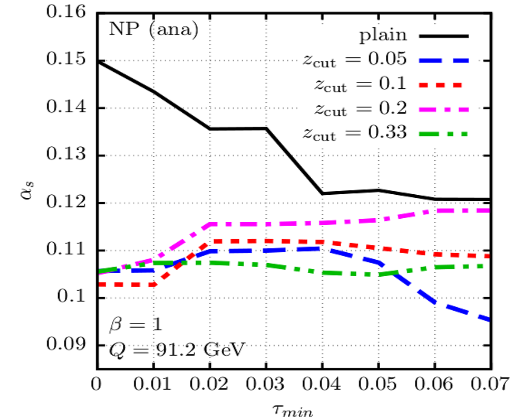
OPAL 3 jet event

- Results sensitive to non-pQCD (hadronization) corrections.
  - ➧ Improved evt-shape power-corrs:



➧ Modern jet substructure techniques: “Soft drop” can help reduce non-pQCD corrections for thrust:





➧ Future prospects:

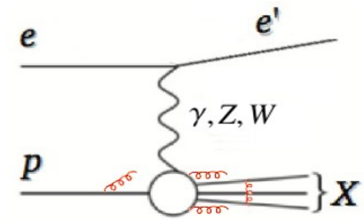
– Better power-corrs for shapes, ($N^{2,3}LL$) resummation for rates. Grooming?

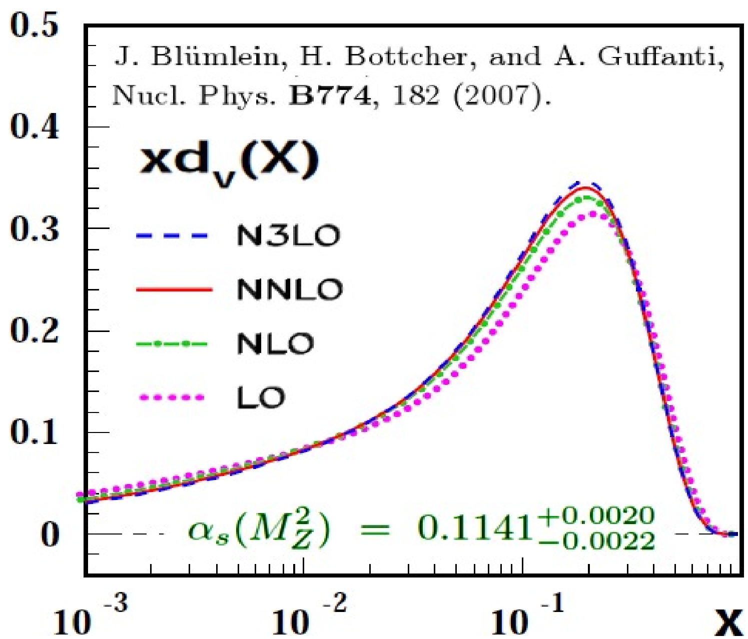
– New e^+e^- data at lower-√s (Belle-II) & higher-√s (Higgs factories) needed.

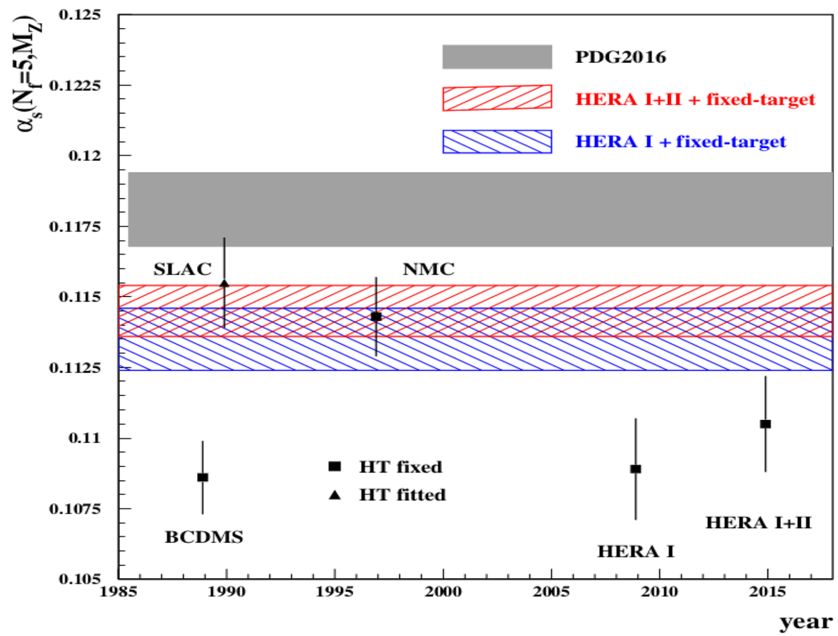
(4) α_s from DIS struct. functions

- N[2,3]LO analysis of (non)singlet struct. functions (BBG, JR14) (and NNLO global PDF AMBP fit) tend to give "lowish" $\alpha_s(M_Z) \approx 0.1150$

$$F_2(x,Q^2) = x \sum_{n=0}^{\infty} \frac{\alpha_s^n(\mu_R^2)}{(2\pi)^n} \sum_{i=q,g} \int_x^1 \frac{dz}{z} C_{2,i}^{(n)}(z,Q^2,\mu_R^2,\mu_F^2)\, f_{i/p}\left(\frac{x}{z},\mu_F^2\right) + \mathcal{O}\left(\frac{\Lambda^2}{Q^2}\right)$$





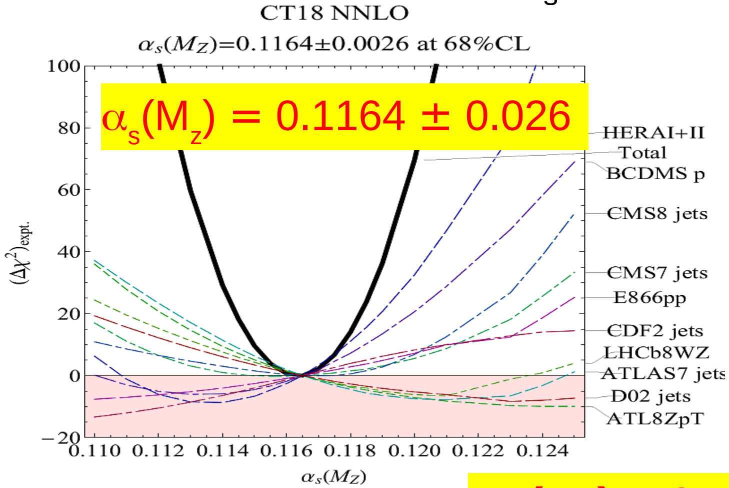


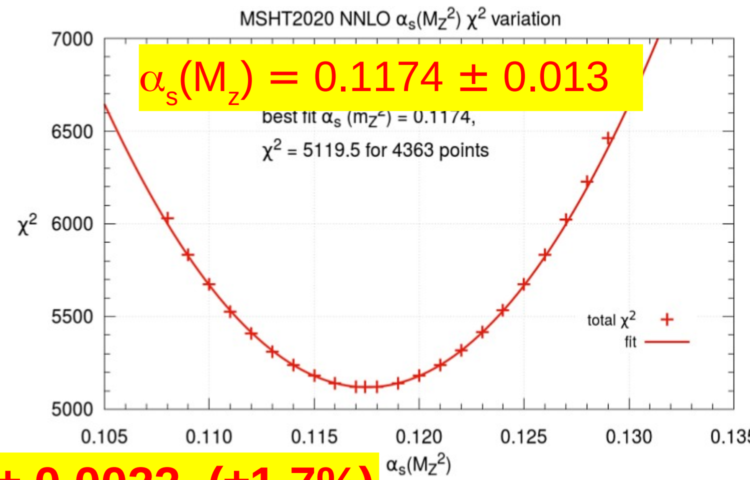
- Neglect of singlet contribs. for x>0.3 in NS fits? Size of higher-order corrs.?

➧ Future prospects: New high-precision $F_2(x,Q^2)$ at EIC.

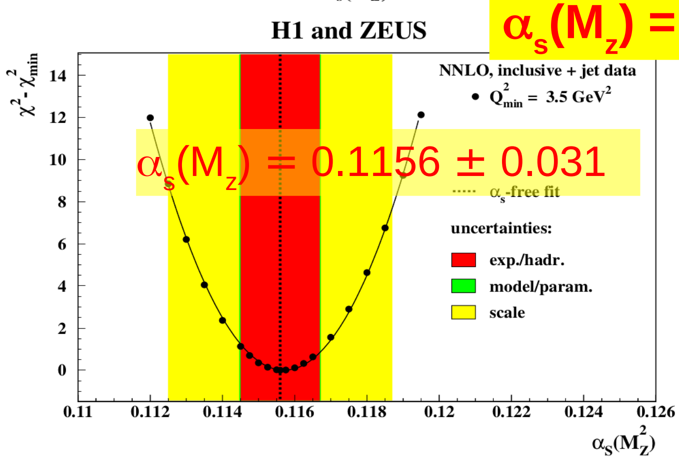
(4) α_s extraction from global-PDF fits

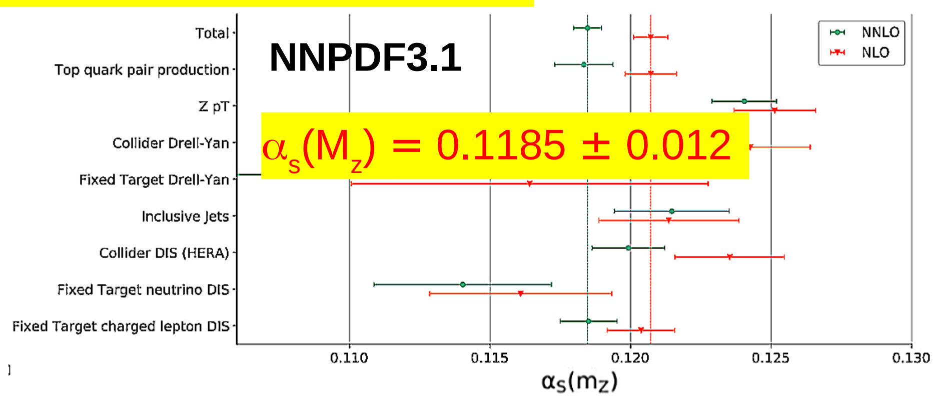
- NNLO PDF fits extract α_s by leaving it float in the global fit (PDF+α_s fit):





$\alpha_s(M_z)$ = 0.1161 ± 0.0022 (±1.7%)



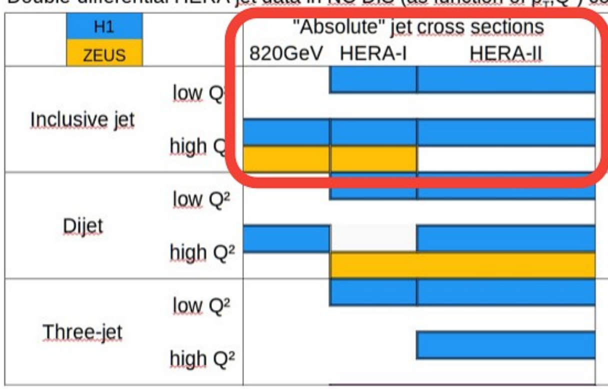


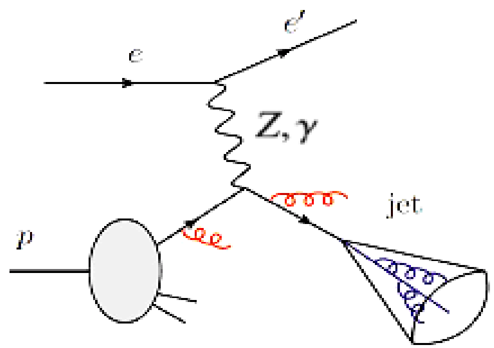
- Diffs. across fits: Tolerance factors, weights on specific data sets, parametriz. biases
- Theory uncertainties (size of missing HO corrections)? Full N^{3}LO upcoming.
- <u>Future</u> prospects: New high-precision (polarized) PDF(x,Q^2) at EIC.

(5) α_s from hadron colliders: HERA jet x-sections

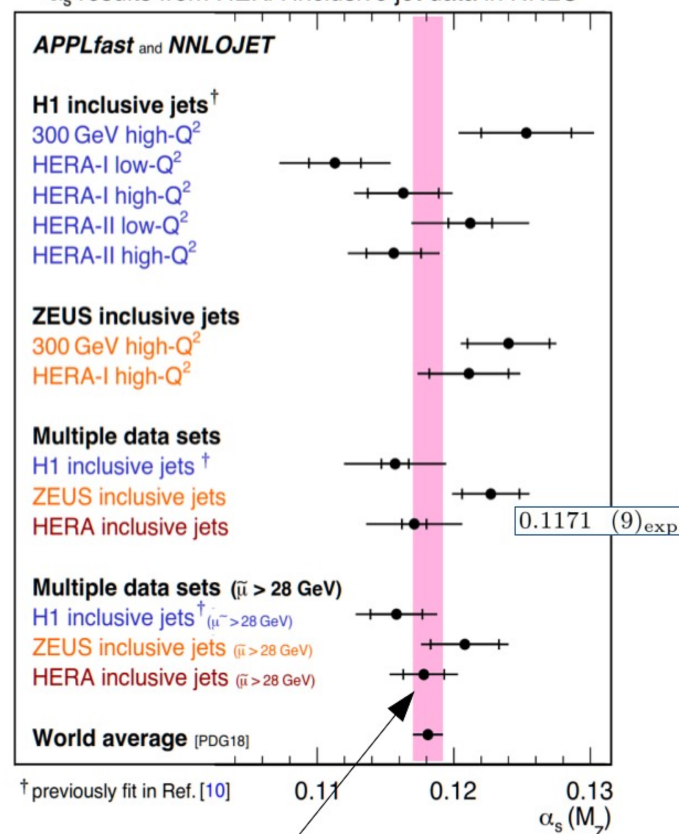
- DIS HERA jet x-sections employed for α_s extractions via NNLOjet:

Double-differential HERA jet data in NC DIS (as function of p_T,Q^2) commonly used for α_s determinations





α_s results from HERA inclusive jet data in NNLO



- α_s from inclusive jet cross sections in NC DIS
- NNLO pQCD w/ non-pert. hadronisation corrections
- H1 and ZEUS consistent
- Sizeable scale uncertainties (MHOU) since data are at comparably low scales
- Highest precision obtained in fit to data with μ > 28 GeV

$$\alpha_s(M_Z) = 0.1178\,(15)_{\rm exp}\,(21)_{\rm th}$$

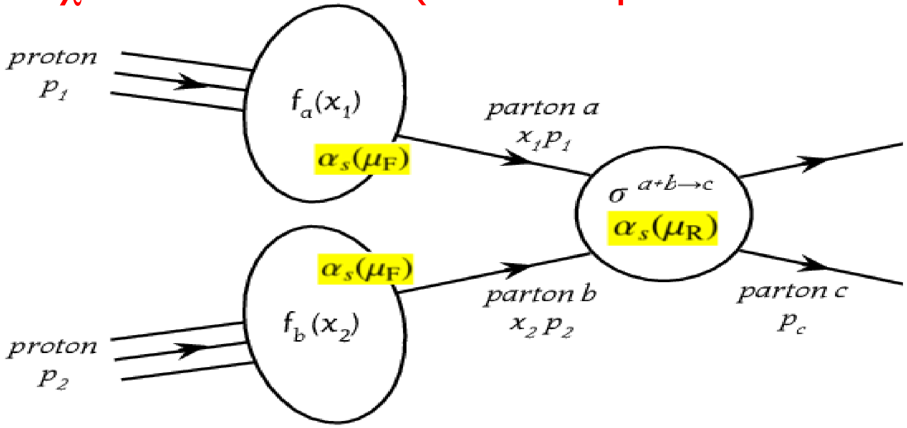
- Largest uncertainty from missing HO corrs.

➧ <u>Future</u> prospects: NNLO jet x-sections-based extractions at EIC

(5) α_s extraction from LHC pQCD x-sections

- Method: (1) Compare σ(exp) to σ(NNLO) for varying PDFs+α_s
  (2) Extract α_s via χ^2 minimization (extra requiremnt: redo partial PDF fit)

Note:
Gluon & α_s strongly (anti)correlated at high (low) x.



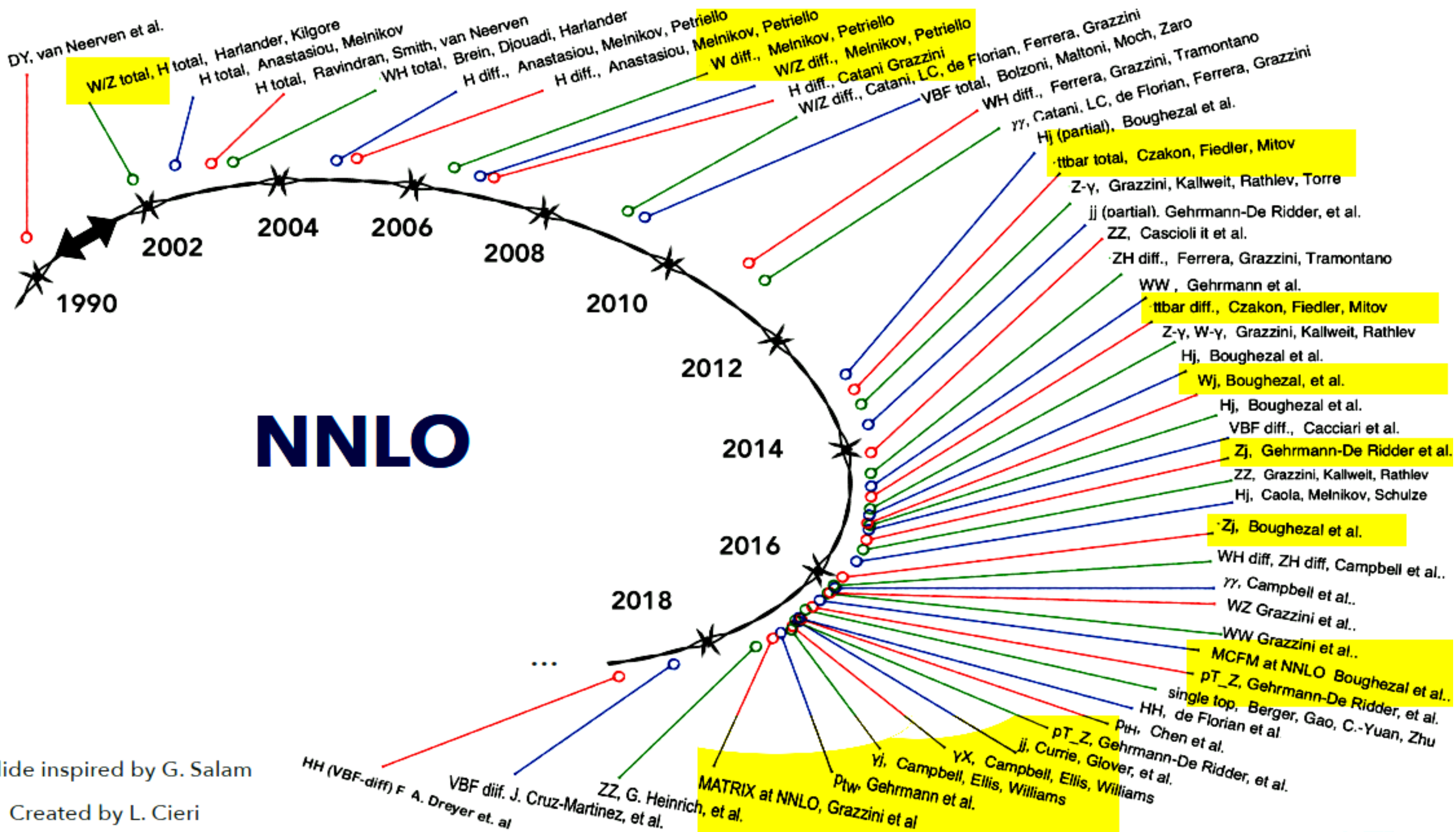
$$\sigma(pp\to X) = \sum_{\text{partons}} \int\int dx_1 dx_2\, f_1(x_1,\alpha_s(\mu_F))\, f_2(x_2,\alpha_s(\mu_F))\left[\hat\sigma_{LO} + \alpha_s(\mu_R)\hat\sigma_{NLO} + \alpha_s^2(\mu_R)\hat\sigma_{NNLO} + \dots\right]$$

pQCD accuracy: $\mathcal{O}$(50%) $\mathcal{O}$(20%) $\mathcal{O}$(2–5%)

- Global requirement:
  – x-section NOT incorporated/incorporable in global-PDF fits (avoid “double counting”)
- Theory requirements:
  – NNLO prediction: Few % scale uncertainty
  – Low non-pQCD & parametric (e.g. m_q) uncertainties & controlled EW corrections
- Exp. requirements:
  – Few % stat. uncertainty: Process with large cross sections (say σ≳100 pb).
  – Few % syst. uncertainties: Ratios (luminosity & other syst. cancel out) better?

(5) α_s extraction from LHC pQCD x-sections

- Increasing number of NNLO processes, but: not yet in global-PDF-fits, large x-sections, small EW/non-pQCD corrections, small exp. uncerts,...:

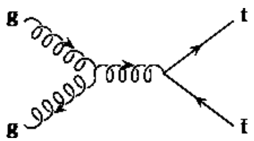


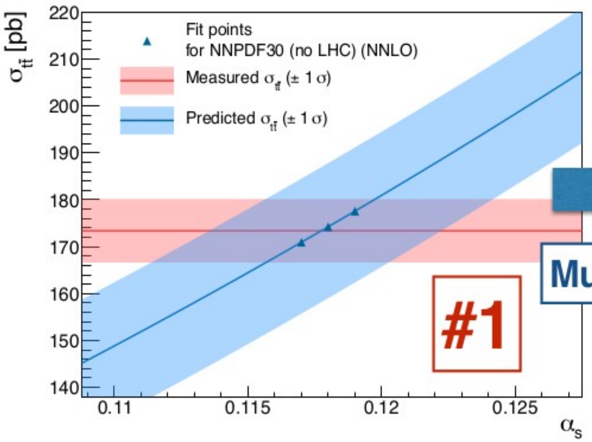
- First ones tried: σ_{tot}(ttbar), σ_{tot}(W,Z), $d\sigma/dp_T$(Z, low p_T),...

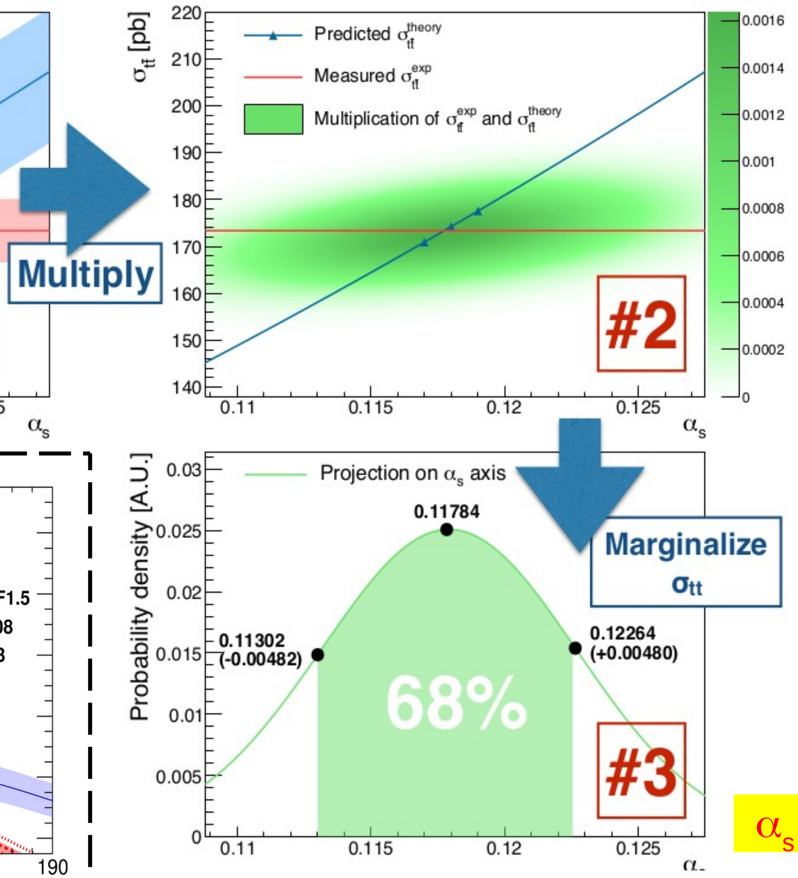
- Not yet tried at NNLO: Ratios $R_{32}(p_T) = \sigma(3j)/\sigma(2j)$, $\sigma(Z+j)/\sigma(Z)$, $\sigma(W+j)/\sigma(W)$,…
  Note: Different TH prescriptions exist to construct "correct" NNLO R_X ratios...

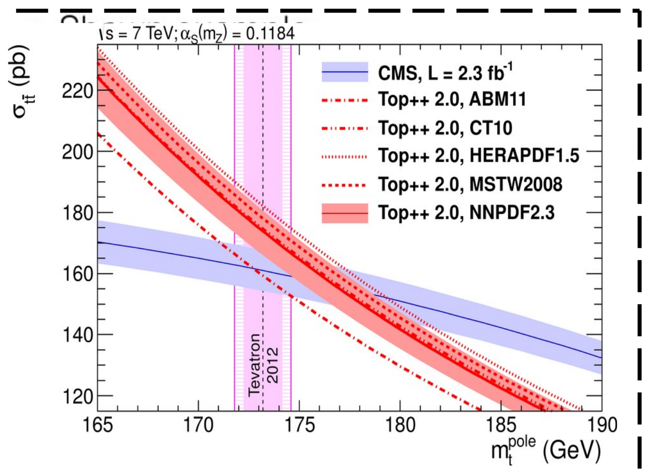
(5) α_s from inclusive LHC ttbar x-sections

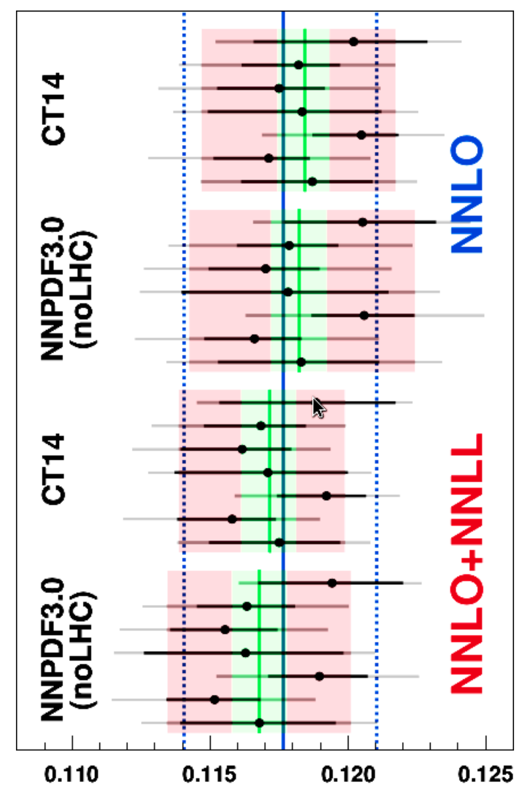
- Compare σ(exp,ttbar) to σ(NNLO,ttbar) for diff. PDFs+α_s
  + Advantages: Direct LO sensitivity to α_s (via gg→ttbar)
  – Disadvantages: $\mathcal{O}$(5%) exp/th. uncertainties, dependence on m_{top}
- First tried by CMS (pp @ 7TeV). Extended to 8 LHC data sets by Klijnsma et al.





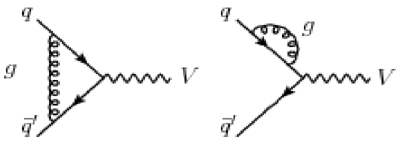






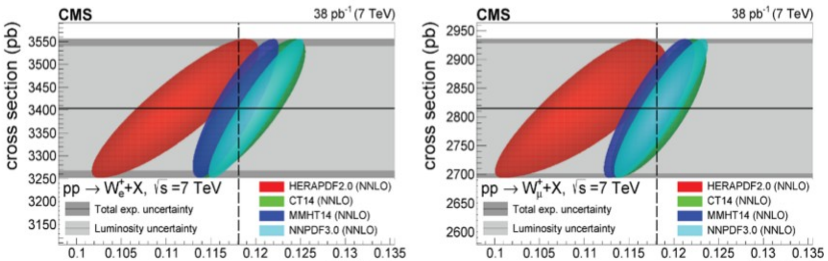
α_s = 0.1177 ± 0.0035 (±3.0%)

(5) α_s from inclusive LHC W, Z x-sections

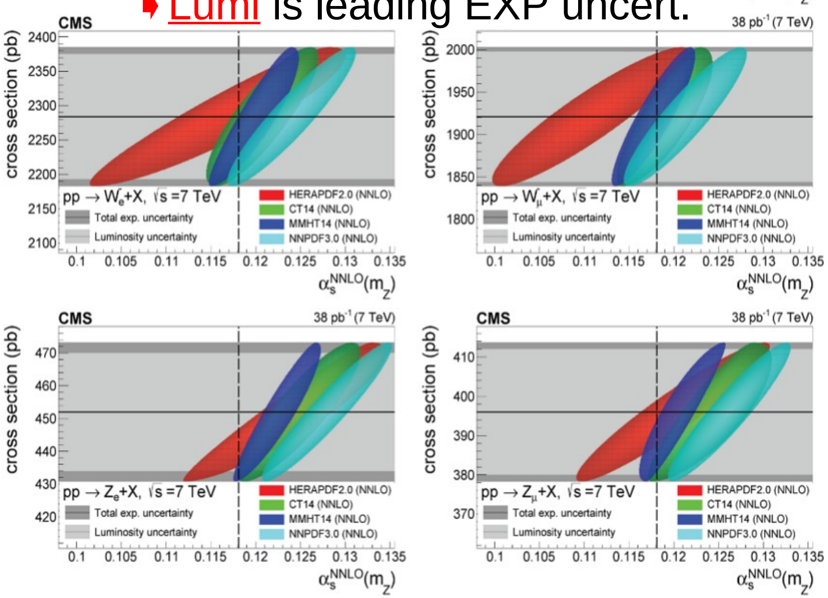


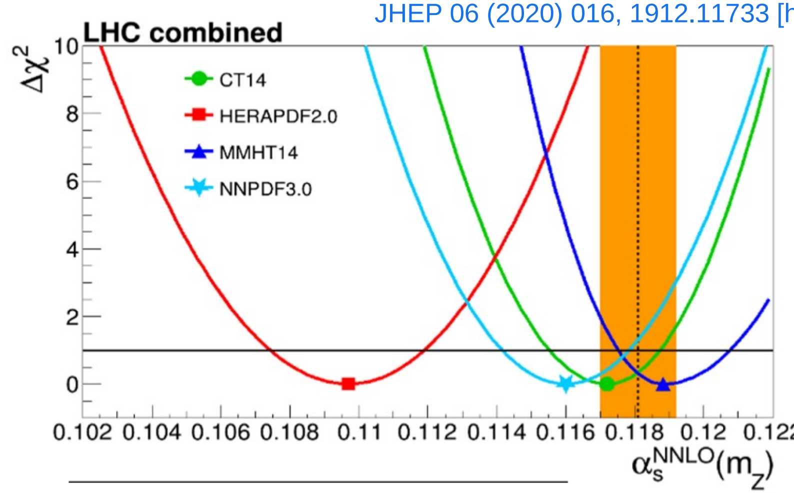
- Compare σ(exp;W,Z) to σ(NNLO;W,Z) for diff. PDFs+α_s
  + Advantages: $\mathcal{O}$(1–2%) exp/th. uncertainties
  – Disadvantages: No LO sensitivity to α_s (only via K_{NnLO}~1.3)
- First tried by CMS (pp @ 7,8 TeV). Extended to 28 LHC data sets by DdE&Poldaru

JHEP 06 (2020) 016, 1912.11733 [hep-ph]



➧ Lumi is leading EXP uncert.





PDF	$\alpha_s(m_Z)$
CT14	$0.1172^{+0.0015}_{-0.0017}$
MMHT14	$0.1188^{+0.0019}_{-0.0013}$
HERAPDF2.0	$0.1097^{+0.0022}_{-0.0023}$
NNPDF3.0	0.1160 ± 0.0018

α_s = 0.1180 ± 0.0016 (±1.3%)

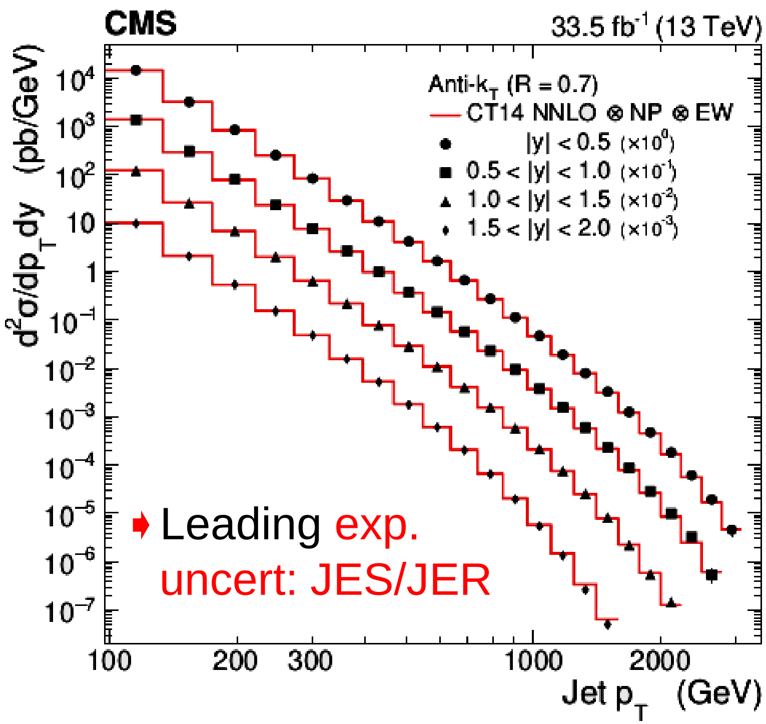
➧ Future: Add past-2020 data sets + redo (partial) aN³LO PDF fit.

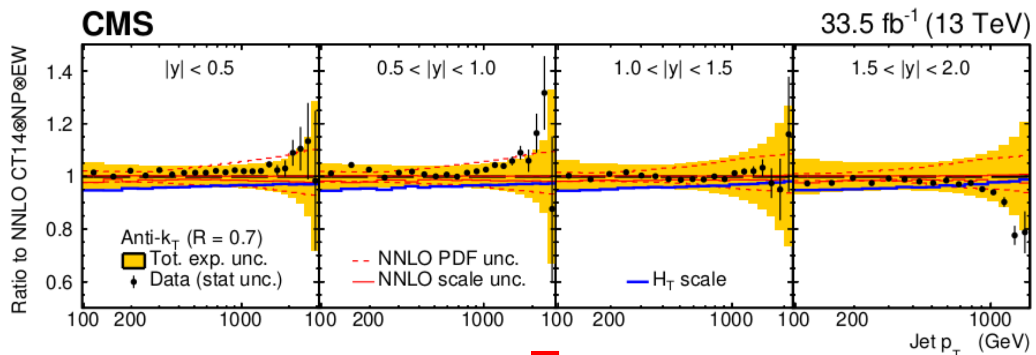
(5) α_s from inclusive jet x-sections (CMS)

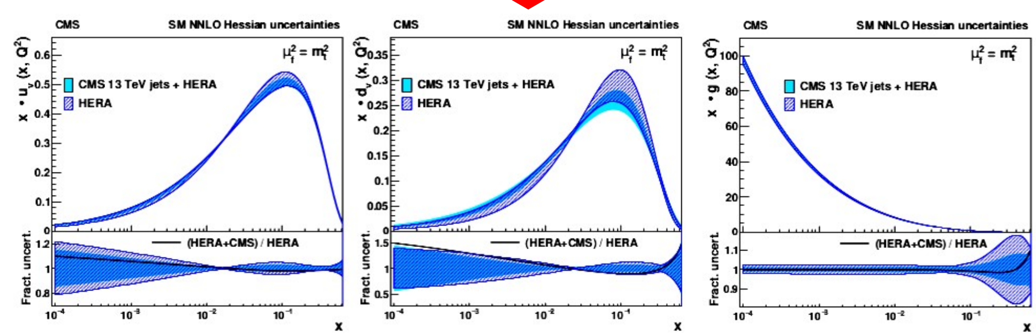
- Combined xFitter NNLO fit of PDF+α_s of incl. jet $d^2\sigma/dydp_T$ + HERA DIS data

  + Advantages: Correlation of gluon PDF & α_s accounted for.

- CMS 13 TeV [arXiv:2111.10431] HERAPDF-like analysis:







- Extraction with small (mostly fit) uncertainty: $\alpha_s = 0.1166 \pm 0.0017$ (±1.5%)

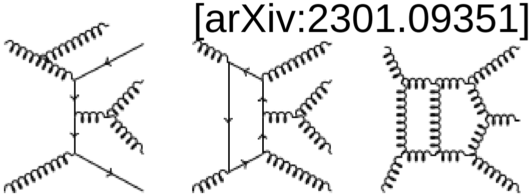
  ➧ Multiple jet spectra incorporated into upcoming full global-PDF fits. (overall tolerance will decrease α_s sensitivity?)

(5) α_s from EEC in multijet events (ATLAS)

■ Multijet energy-energy correlations available at NNLO
+ Advantages: Small exp. uncertainties (JES/JER). PDF uncertainties subleading.

- Use multi-jets transverse energy–energy correlations (***TEEC***) and their associated azimuthal asymmetries (***ATEEC***) to perform the measurement

[arXiv:2301.09351]



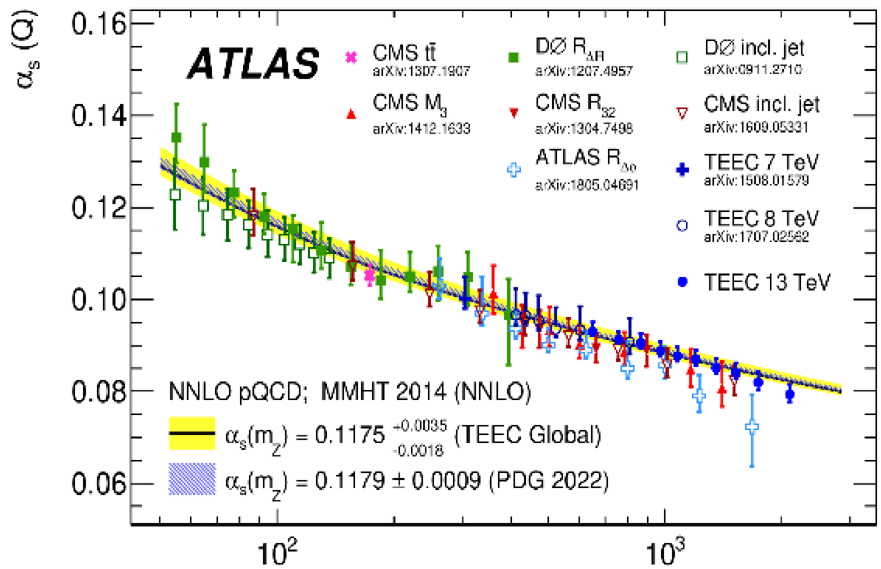
NNLO diagrams contributing to $gg \to$ jjj

- The TEEC function is defined as the transverse-energy-weighted distribution of the azimuthal differences between jet pairs in the final state

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi - \cos\varphi_{ij})$$

Also use associated azimuthal asymmetries (ATEEC) to cancel uncertainties symmetric in cos(φ)

$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$



$\alpha_s = 0.1175^{+0.0035}_{-0.0018}$ (±1.5–3.0%)

- Large theoretical improvement from NNLO correction to gg→3-jet production in pp collisions
  - reduction of theoretical uncertainty by a factor of 3

(TH scale still leading uncertainty)

■ RGE running of QCD coupling tested up to scales Q≈H_T/2≈ 2 TeV

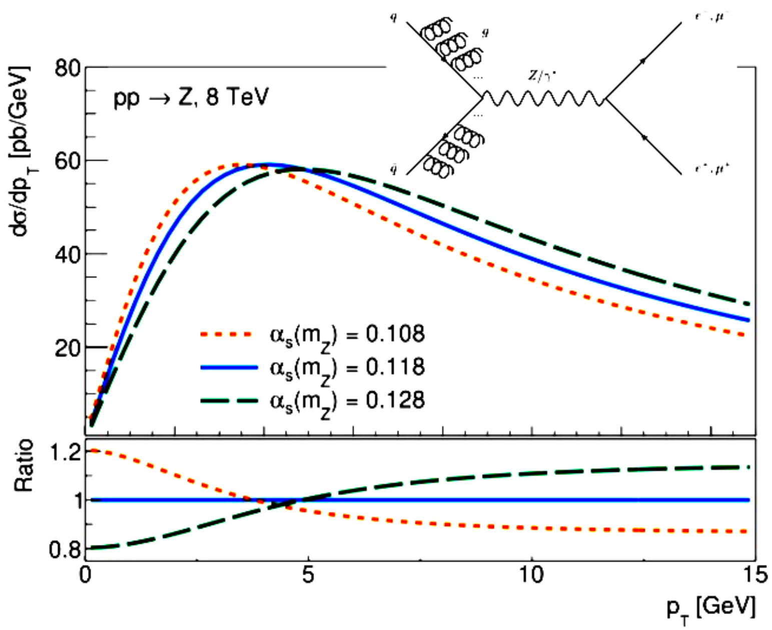
(5) α_s from Z boson $d\sigma/dp_T$ recoil (ATLAS)

(not yet in PDG)

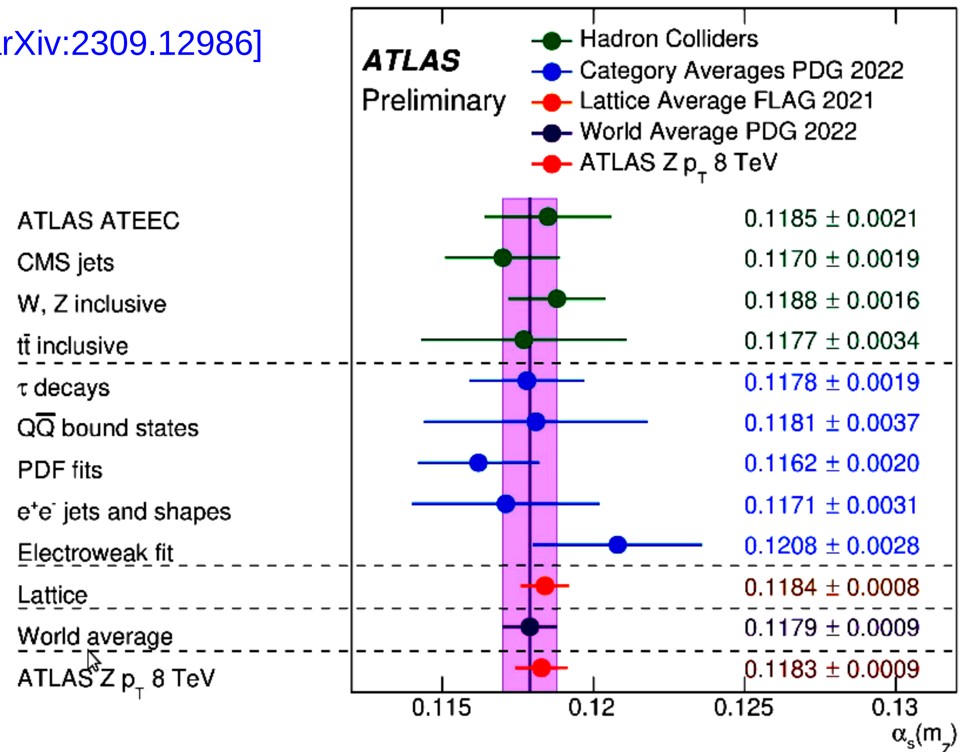
- Differential Z boson x-sections available at $N^{2,3}LO+N^{3,4}LL$
- Method: Compare $d\sigma/dp_T$(exp) to $d\sigma/dp_T(N^nLO+N^nLL)$ for diff. PDFs/α_s: Extract α_s

  \+ Advantages: $\mathcal{O}$(<1%) exp. uncertainties, direct sensitity to α_s (ISR gluon)

  – Disadvantages: Sensitivity to npQCD effects, resummation, HF PDFs



[arXiv:2309.12986]



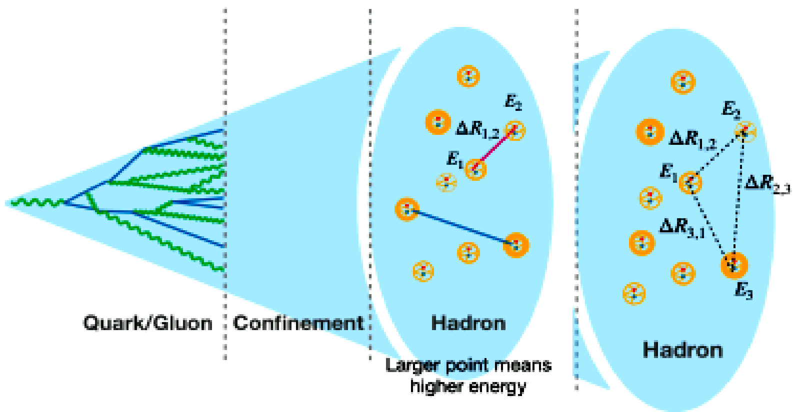
- Extraction with "aggressive" ±0.75% uncertainty:
  - Just one approx-N^3LO PDF fit used
  - Gaussian npQCD model under good control?

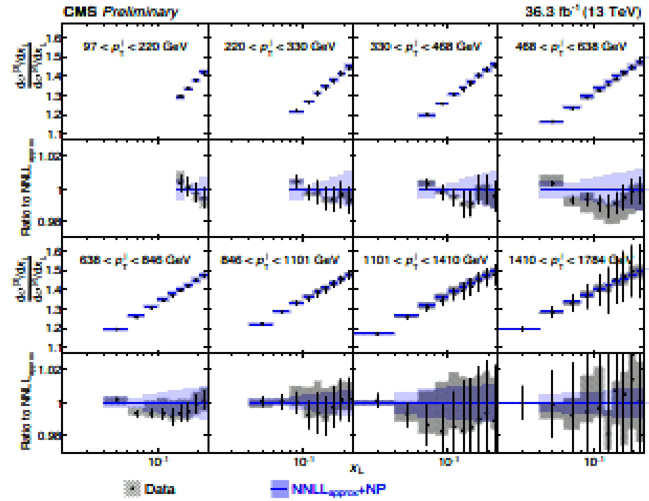
α_s = 0.11828 ± 0.00088 (±0.75%)

(5) α_s from energy correlations inside jets (CMS)

(NLO, not in PDG)

- 3-,2-particle jet substructure energy correlators (E3C and E2C) as a function of ang. separation (x_L) known at NLO+NNLL. Advantages: Insensitive to PDFs. Uncorrelated with other extractions

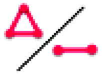




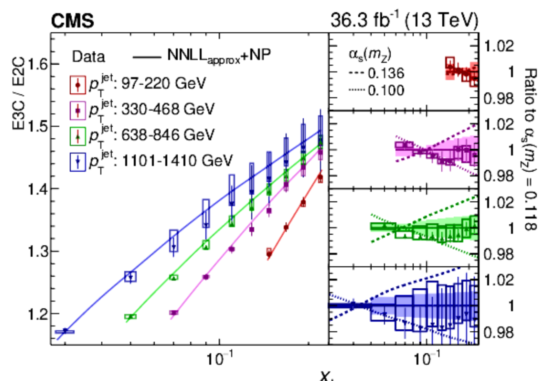
SMP-22-015

Unfolded E3C/E2C

- In QFT at LL, E3C/E2C is linear function of α_S:



$$\propto \alpha_S(Q)\ln x_L + O(\alpha_s^2)$$



$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050} \;(<4.1\,\%\ \text{rel.})$$

PRL133 (2024) 071903, arXiv:2402.13864

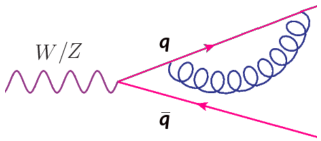
- New & most precise α_s extraction from jet substructure so far.

Does E3C/E2C $\propto \alpha_s$ hold at N^nLL? NNLO theory soon?

(6) α_s from Z boson hadronic decays

- Z-boson decays known at N[3]LO, no NP uncerts. (but only ~4% sensitivity to α_s):

$$R_l^0 \equiv \frac{\Gamma(Z\to \mathrm{h})}{\Gamma(Z\to l)} = R_Z^{\mathrm{EW}} N_C \left(1 + \sum_{n=1}^{4} c_n \left(\frac{\alpha_s}{\pi}\right)^n + \mathcal{O}(\alpha_s^5)\right) + \delta_{\mathrm{m}} + \delta_{\mathrm{np}}$$

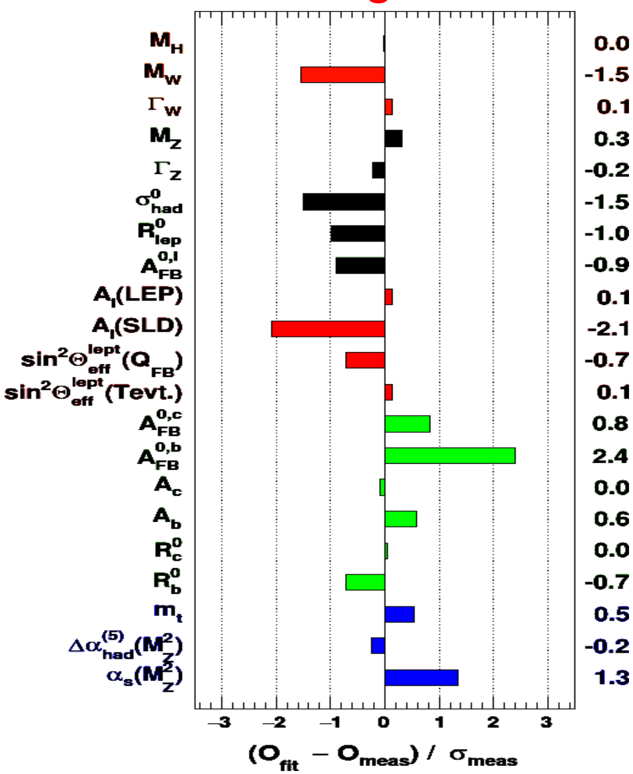


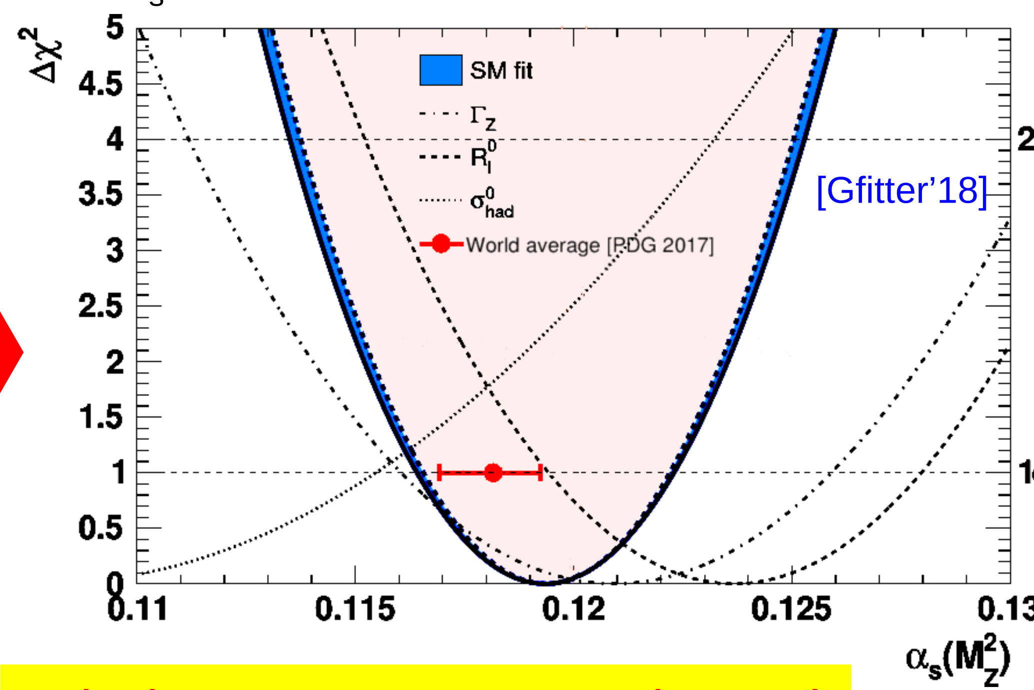
- Extraction from three Z-peak pseudo-observables (LEP, SLC):

$$R_\ell^0 = \frac{\Gamma_{\mathrm{had}}}{\Gamma_\ell},\quad \sigma^0_{\mathrm{had}} = \frac{12\pi}{m_Z}\frac{\Gamma_e\Gamma_{\mathrm{had}}}{\Gamma_Z^2},\quad \sigma^0_\ell = \frac{12\pi}{m_Z}\frac{\Gamma_\ell^2}{\Gamma_Z^2}$$

$\alpha_s(M_Z) = 0.1221 \pm 0.0027$ (±2.3%)

- Also from the global EW fit leaving α_s as single free parameter:





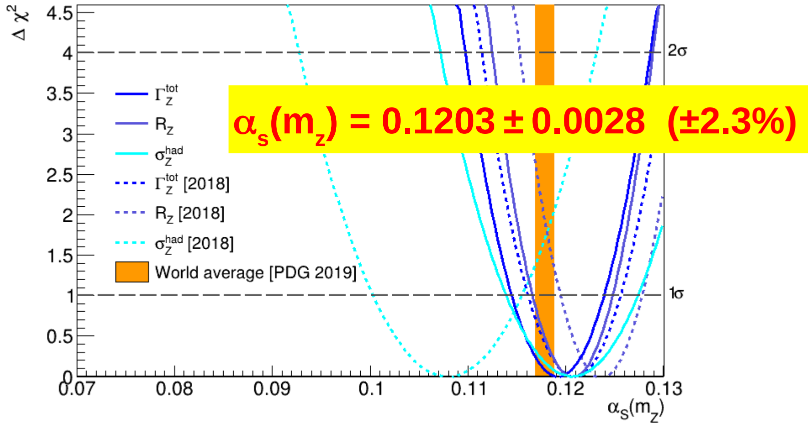
$\alpha_s(M_Z) = 0.1203 \pm 0.0028$ (±2.3%)

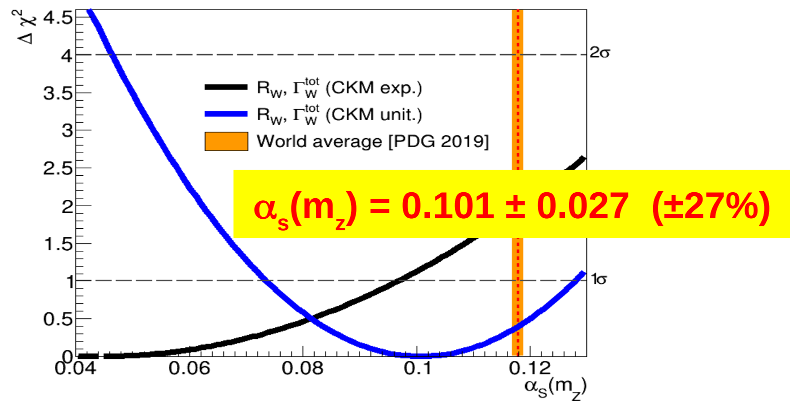
(6) α_s from EW bosons hadronic decays

- Updated Z,W-based $\alpha_s(m_z)$ extractions:

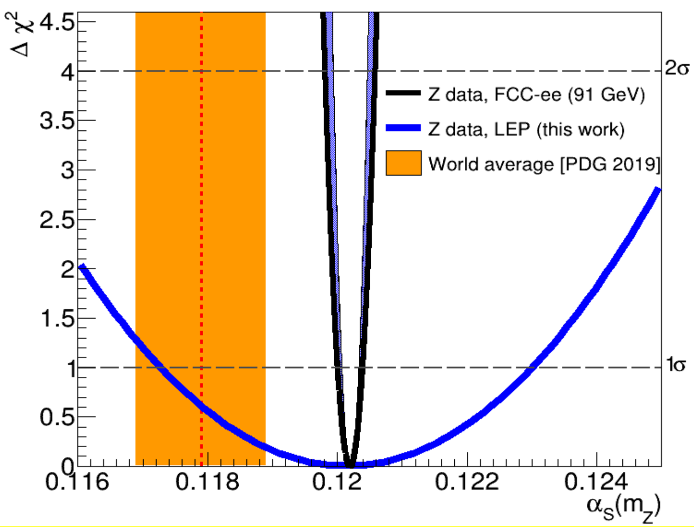
[DdE&Jacobsen, 2005.04545 [hep-ph]]

New fit with HO EW corrs. + corrected Z LEP data. New N^{3}LO fit to Γ_W, R_W



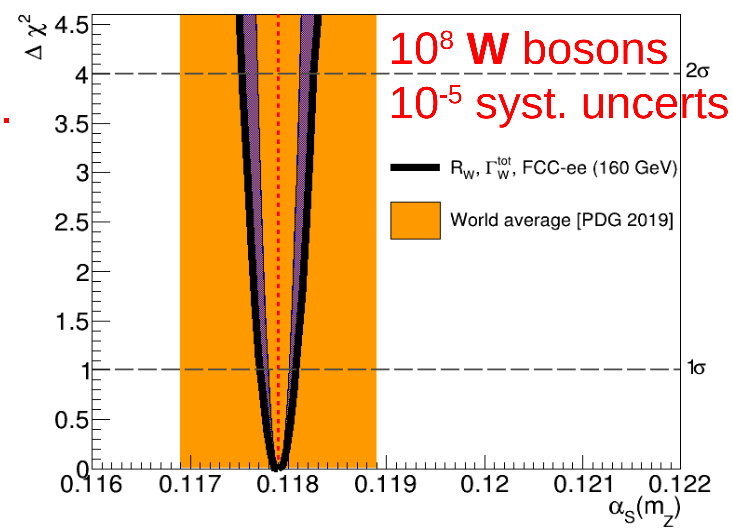


- Future: Permil uncertainty possible only with a machine such as FCC-ee



10^{12} **Z** bosons
10^{-5} syst. uncerts.

Strong SM "stress test"



$\alpha_s(m_z)$ = ***0.12030 ± 0.00028*** ±0.2% (tot), ±0.1% (exp)

$\alpha_s(m_z)$ = ***0.11790 ± 0.00023*** ±0.2% (tot), ±0.1% (exp)

Summary: Current & future α_s precision

- Well-defined exp./th. path towards $\alpha_s(m_z)$ permil precision in coming years

Method	Relative $\alpha_S(m_Z^2)$ uncertainty: Current — theory & exp. uncertainties sources	Near (long-term) future — theory & experimental progress
(1) Lattice	0.7%	≈ 0.3% (0.1%)
	Finite lattice spacing & stats.	Reduced latt. spacing. Add more observables
	$N^{2,3}$LO pQCD truncation	Add $N^{3,4}$LO, active charm (QED effects)
		Higher renorm. scale via step-scaling to more observ.
(2) τ decays	1.6%	< 1.%
	N^3LO CIPT vs. FOPT diffs.	Add N^4LO terms. Solve CIPT–FOPT diffs.
	Limited τ spectral data	Improved τ spectral functions at Belle II
(3) $Q\overline{Q}$ bound states	3.3%	≈ 1.5%
	$N^{2,3}$LO pQCD truncation	Add $N^{3,4}$LO & more $(c\bar{c})$, $(b\bar{b})$ bound states
	$m_{c,b}$ uncertainties	Combined $m_{c,b} + \alpha_S$ fits
(4) DIS & PDF fits	1.7%	≈ 1% (0.2%)
	$N^{2,(3)}$LO PDF (SF) fits	N^3LO fits. Add new SF fits: $F_2^{p,d}$, g_i (EIC)
	Span of PDF-based results	Better corr. matrices. More PDF data (LHeC/FCC-eh)
(5) e^+e^- jets & evt shapes	2.6%	≈ 1.5% (< 1%)
	NNLO+$N^{(1,2,3)}$LL truncation	Add $N^{2,3}$LO+N^3LL, power corrections
	Different NP analytical & PS corrs.	Improved NP corrs. via: NNLL PS, grooming
	Limited datasets w/ old detectors	New improved data at B factories (FCC-ee)
(6) Electroweak fits	2.3%	(≈ 0.1%)
	N^3LO truncation	N^4LO, reduced param. uncerts. ($m_{W,Z}$, α, CKM)
	Small LEP+SLD datasets	Add W boson. Tera-Z, Oku-W datasets (FCC-ee)
(7) Hadron colliders	2.4%	≈ 1.5%
	NNLO(+NNLL) truncation, PDF uncerts.	N^3LO+NNLL (for color-singlets), improved PDFs
	Limited data sets ($t\bar{t}$, W, Z, e-p jets)	Add more datasets: Z p_T, p-p jets, σ_i/σ_j ratios,...
World average	0.8%	≈ 0.4% (0.1%)

Summary: α_s wish-list for the next ~10 years

- **Theoretical needs to approach (0.1%) precision:**

(1) Lattice QCD: Sufficient dedicated computing resources & person-power:

- Develop pQCD $N^{3,4}LO$ theory for observables in a finite space-time volume
- Extend higher renormalization scales via step-scaling to more observables

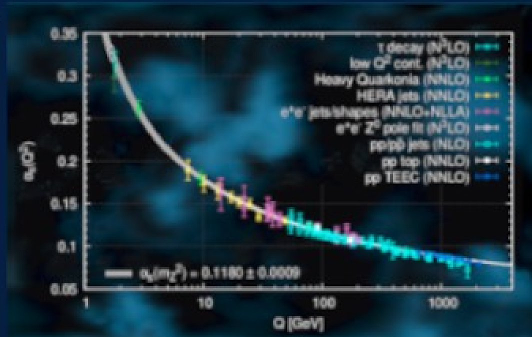
(2) Other phenomenology efforts:

- N^4LO for tau decays. Completion of hadronic τ decay renormalon analysis
- Advanced power corrections for e^+e^- event shapes & resummation for jet rates
- NNLL accuracy parton showers matched to NNLO:
  NNLO(+NNLL) MCs for complex final states in e^+e^-, e-p, p-p
- Differential NNLO predictions for LHC & HERA multi-jet observables,…
- Z, W hadronic decays at N^4LO & mixed QCD+EW needed for longer term.

- **Experimental needs to approach (0.1%) precision:**

(3) Extension of $N^{2,3}LO$ hadron-collider- and/or PDF-based extractions via:

- LHC: Add new precision observables & datasets (TEECC, Z p_T, σ_i/σ_j ratios,...)
  Improved treatment of exp. correl. matrices uncertainties among measurements
- EIC: New DIS measurements (also LHeC/FCC-eh): $F_2^{p,d}(x,Q^2)$, $PDF_{pol}(x,Q^2)$, Bj.SR
- FCC: Hadronic Z (and W) decays is the only non-lattice method known that
  can reach permil precision: Tera-Z machine needed.



$$\mathcal{L} = \frac{1}{4g^2} G^a_{\mu\nu} G^a_{\mu\nu} + \sum_j \bar{q}_j (i\gamma^\mu D_\mu + m_j) q_j$$

$$\text{where } G^a_{\mu\nu} \equiv \partial_\mu A^a_\nu - \partial_\nu A^a_\mu + i f^a_{bc} A^b_\mu A^c_\nu$$

$$\text{and } D_\mu \equiv \partial_\mu + i t^a A^a_\mu$$

alphas-2025: Workshop on precision measurements of the QCD coupling constant

https://indico.cern.ch/e/alphas2025

14–19 Dec 2025
Europe/Andorra timezone

Enter your search term

- Overview
- Participant List
- Venue (CNRS Centre Paul Langevin, Aussois)
- Accomodation & Costs

Support

alphas-conf-organizers...

The "alphas-2025: Workshop on precision measurements of the strong coupling constant" will be held at the **CNRS Paul Langevin Center in Aussois (Savoie)** in **the third week of December 2025 (Sun. 14th to Friday 19th).**

The workshop aims at exploring in depth the current status and upcoming prospects in the determination of the QCD coupling constant $\alpha_S(m_Z)$ from the key observables where high-precision experimental measurements and theoretical calculations are (or will be) available: (i) lattice QCD, (ii) hadronic decays of tau leptons, (iii) deep-inelastic electron-proton scattering and global parton densities analyses, (iv) QCD corrections to electroweak precision observables, and analysis of (v) hadronic final states in high energy particle collisions (e^+e^-, ep, and pp).

Previous meetings:

- alpha_s(2024), ECT*, Trento
- alpha_s(2022), ECT*, Trento
- alpha_s(2019), ECT*, Trento
- alpha_s(2015), CERN, Geneva
- alpha_s(2011), MPI, Munich

Starts 14 Dec 2025, 18:00
Ends 19 Dec 2025, 14:00
Europe/Andorra

David d'Enterria
Giulia Zanderighi
Stefan Kluth

Backup slides

Where LHC has made/can make an impact?

- Average of pre-averages from 7 categories of observables:

  $\alpha_s(M_z) = 0.1179 \pm 0.0009$ (±0.8%)

  Hadronic tau decay (4 values):

  $\alpha_s(M_z) = 0.1178 \pm 0.0019$ (±1.6%)

  Quarkonia properties (4 values):

  $\alpha_s(M_z) = 0.1181 \pm 0.037$ (±3.3%)

  DIS & PDFs fits (6 values):

  $\alpha_s(M_z) = 0.1162 \pm 0.0020$ (±1.7%)

  $e^+e^- \rightarrow$ hadrons final states (10 values):

  $\alpha_s(M_z) = 0.1171 \pm 0.0031$ (±2.6%)

  Hadron collider measurements (5 values):

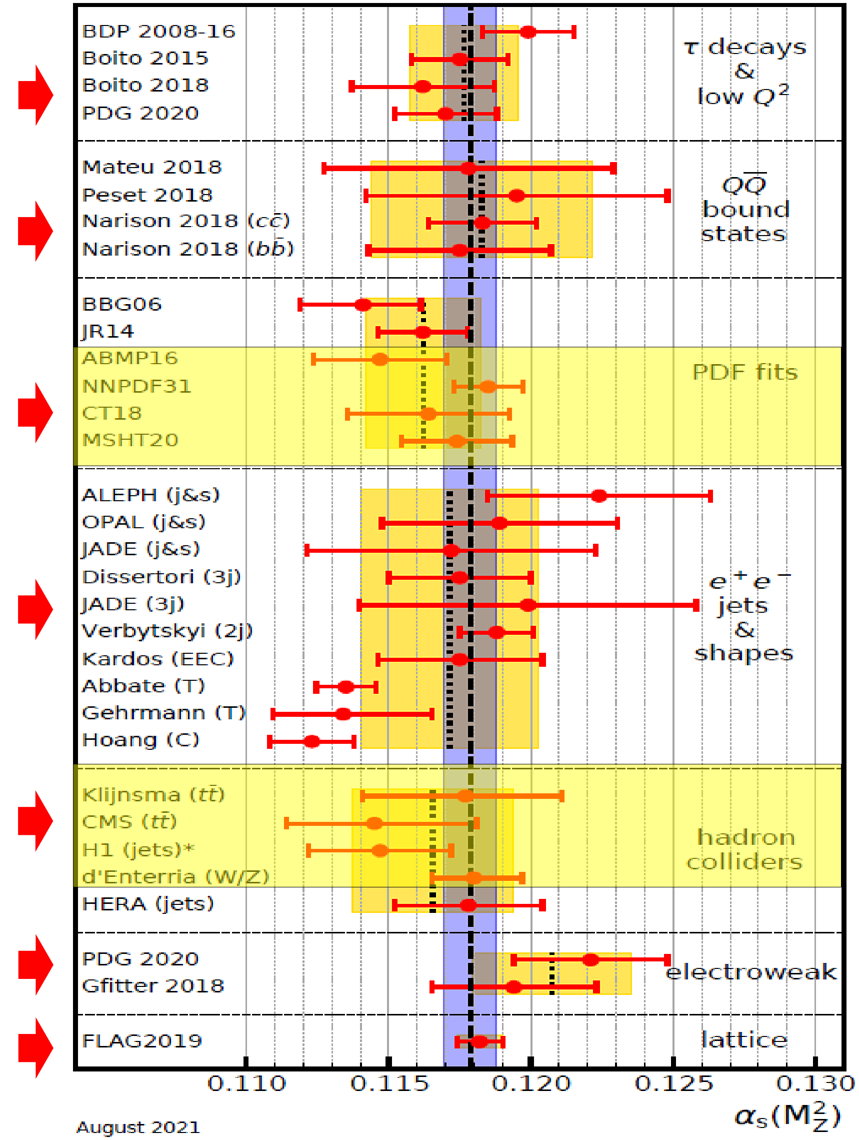
  $\alpha_s(M_z) = 0.1165 \pm 0.0028$ (±2.4%)

  Electroweak precision fits (2 values):

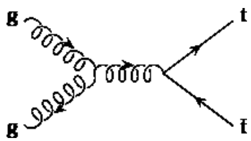
  $\alpha_s(M_z) = 0.1208 \pm 0.0028$ (±2.3%)

  Lattice QCD (1 FLAG value):

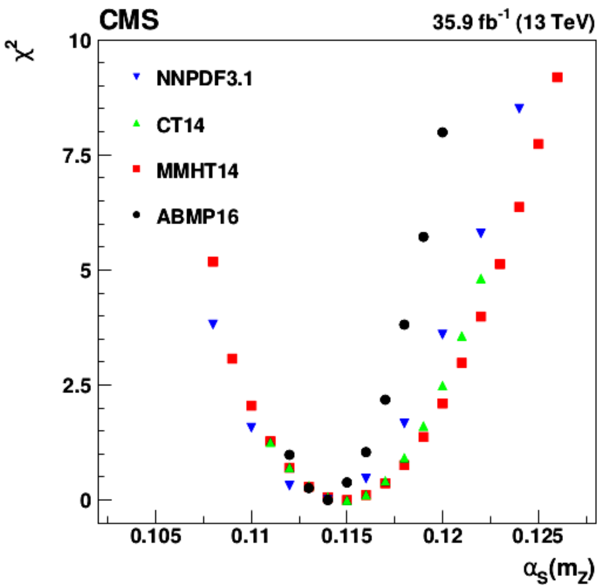
  $\alpha_s(M_z) = 0.1182 \pm 0.0008$ (±0.7%)

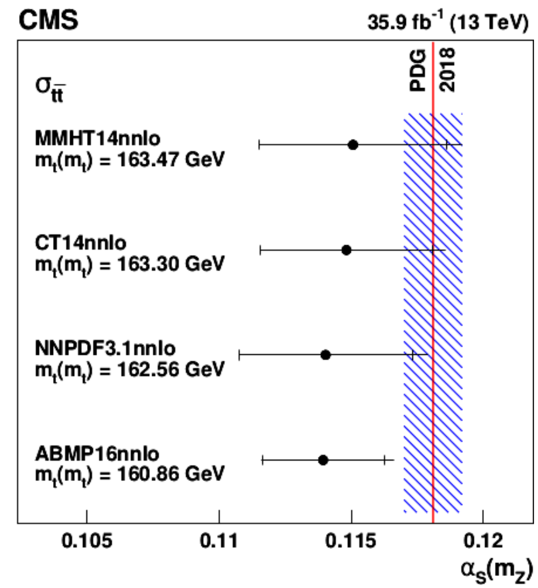


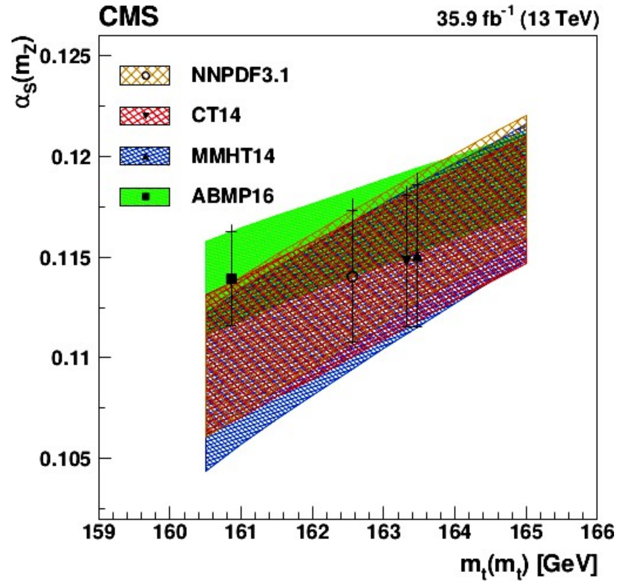
(5) α_s from inclusive ttbar x-sections (CMS)



- Compare σ(exp,ttbar) to σ(NNLO,ttbar) for diff. PDFs+α_s
  + Advantages: Direct LO sensitivity to α_s (via gg → ttbar)
  – Disadvantages: $\mathcal{O}$(5%) exp/th. uncertainties, dependence on m_{top}
- Latest extraction from CMS: pp @ 13 TeV [1812.10505 [hep-ex]]







➧ Lumi is leading EXP uncert.

α_s = 0.1145 ± 0.0033 (±2.9%)

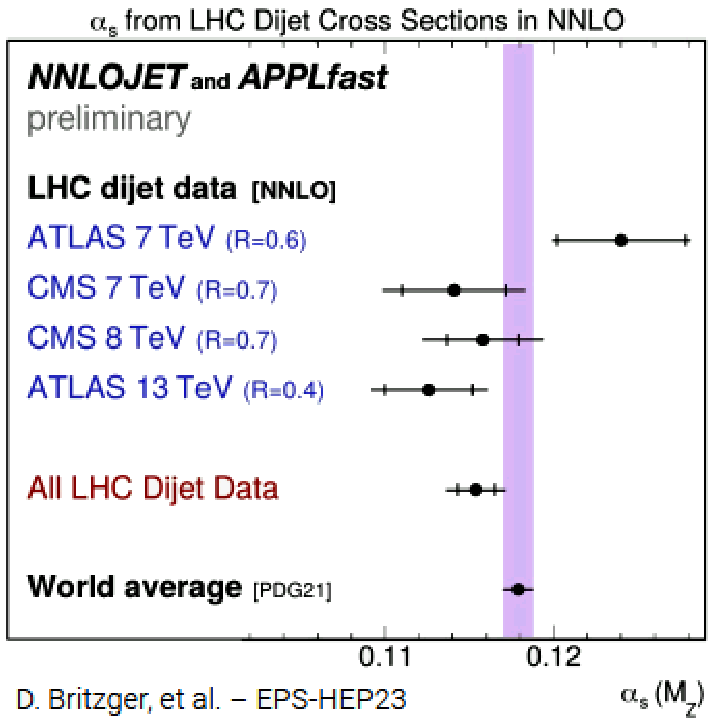
Extraction with ~3% uncert. from σ(exp) & PDF. Correlation of α_s & g(x,Q^2) & m_{top}

- Future: ±3% compressible? Worth adding all data sets (past 2018) + redo fit?

(5) α_s from inclusive jet x-sections (LHC)

■ Compare dijet $d\sigma/dp_T$(exp) to $d\sigma/dp_T$(NNLO) for diff. PDFs+α_s

- $\alpha_s(m_Z)$ from LHC dijet data in NNLO pQCD
  (MSbar, n_f=5, massless, m_Z=91.1876 GeV)
- Fit to all dijet data χ^2/ndf = 379.0/(351-1)
- Reasonable agreement of data sets
- Use NNPDF3.1 as central PDF
  (other PDF result in a bit larger α_s value, but smaller χ^2)
- Uncertainties include
  - experimental
  - non-perturbative corrections
  - PDF (replicas/eigenvectors)
  - PDFset, PDFα_s, PDFμ_0
  - Scale



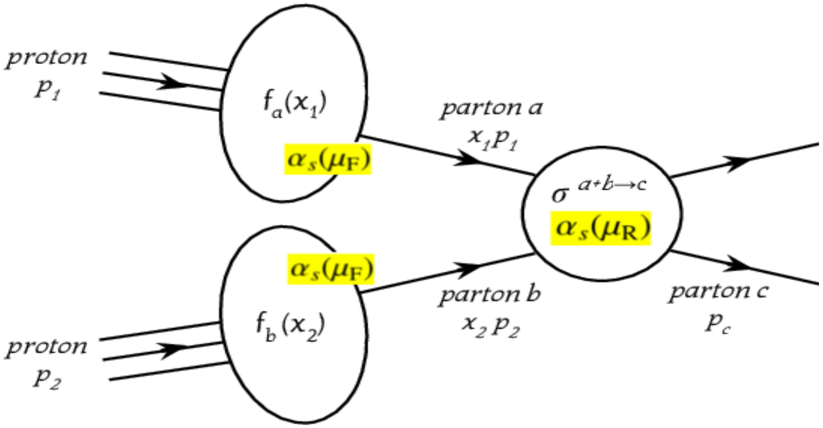
α_s = 0.1145 ± 0.0020 (±1.7%)

➧ Preliminary extraction (NNPDF3.1 based) with small (±1.7%) uncertainty.
Does this uncertainty cover the extractions from other PDF sets?

(3) α_s extraction from global-PDF fits

- Perform a common global-PDF fit + α_s extraction:

  Note: gluon & α_s strongly (anti)correlated at high (low) x.



$$\sigma(pp \to X) = \sum_{\text{partons}} \int\int dx_1 dx_2\, f_1(x_1, \alpha_s(\mu_F))\, f_2(x_2, \alpha_s(\mu_F)) \left[\hat{\sigma}_{\rm LO} + \alpha_s(\mu_R)\hat{\sigma}_{\rm NLO} + \alpha_s^2(\mu_R)\hat{\sigma}_{\rm NNLO} + \ldots\right]$$

pQCD accuracy: $\mathcal{O}$(50%) $\mathcal{O}$(20%) $\mathcal{O}$(2–5%)

- Theory requirements:
  – NNLO prediction: Few % scale uncertainty
  – Low non-pQCD & controlled EW (and mixed QCD⊗EW) corrections

- Exp. requirements:
  – Ideally, full correlation matrices across observables needed for proper uncertainties propagation.

α_s from φ correlations in multijet events (CMS)

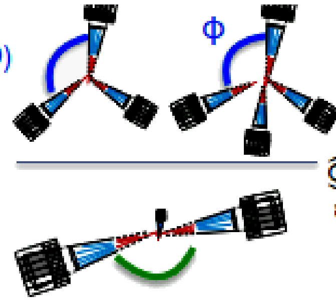
- Azimuthal-correlation observable (available at NLO so far only)
- Preliminary result from CMS [SMP-22-005]:

PRELIMINARY

Topologies with at least 3 jets ($\sim \alpha_s^3$) (LO)

$$R_{\Delta\phi}(p_T) = \frac{\sum_{i=1}^{N_{\text{jet}}(p_T)} N_{\text{nbr}}^{(i)}(\Delta\phi, p_{T\min}^{\text{nbr}})}{N_{\text{jet}}(p_T)}$$

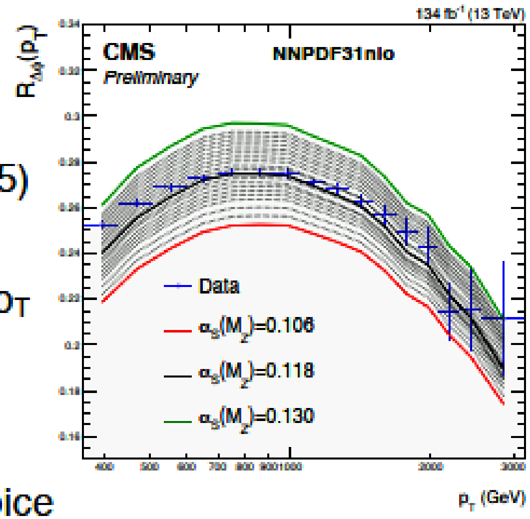
Inclusive jets ($\sim \alpha_s^2$) (LO)

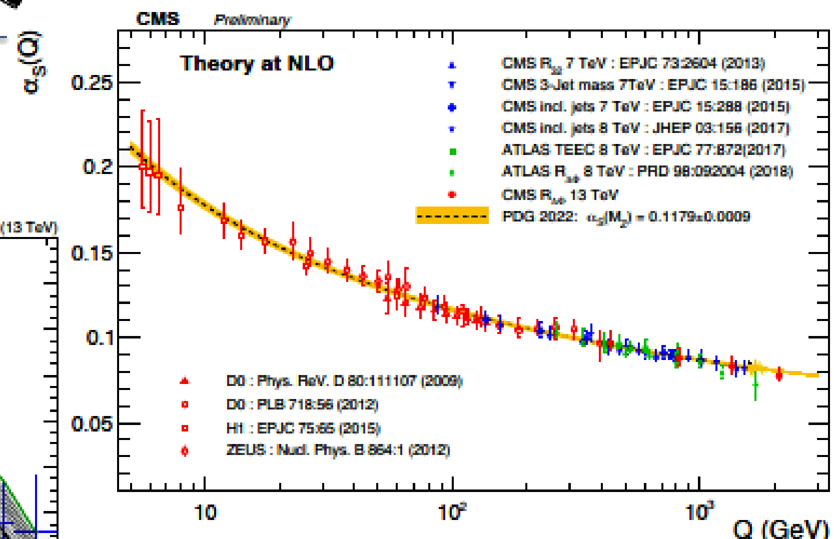


Measurement

13 TeV, 2016-2018 data, AK7 (p_T>360 GeV; |η| < 2.5)

- Sensitive to α_s
- Performed in different p_T ranges → running
- Dominated by scale uncertainty, spread in results due to PDF choice



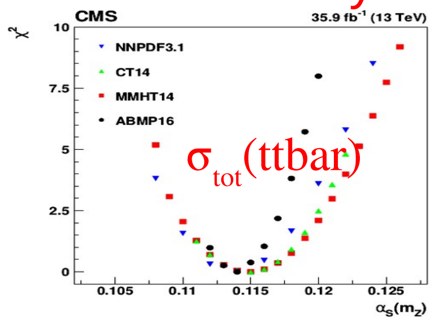


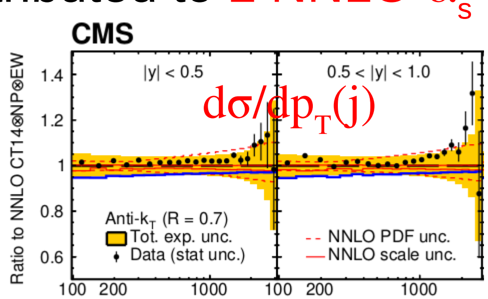
$\alpha_s = 0.1175^{+0.0117}_{-0.0074}$ (<10%)

- Not a precise extraction yet, but RGE running tested up to $Q \approx H_T/2 \approx 2$ TeV. Testing α_s running to Q→10 TeV is key for LHC physics programme.

Summary: CMS past/future impact on α_s

- CMS has directly contributed to 2 NNLO α_s values in PDG:



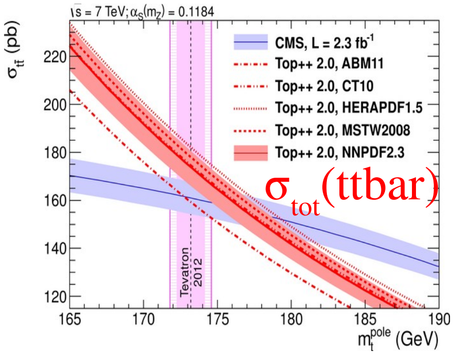


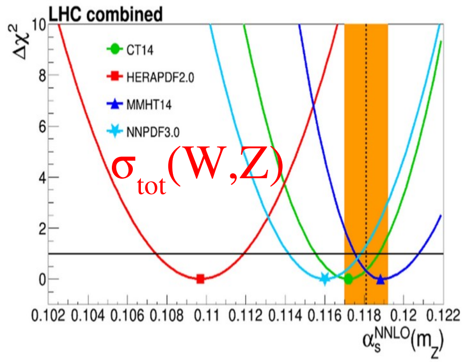
$\alpha_s = 0.1145 \pm 0.0033$ (±2.9%)

$\alpha_s = 0.1170 \pm 0.0019$ (±1.6%)

➧ Lumi/JES/JER leading EXP uncerts.

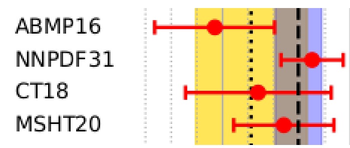
- CMS has indirectly contributed to 2+1 α_s NNLO values in the PDG:





$\alpha_s = 0.1177 \pm 0.0035$ (±3.0%)

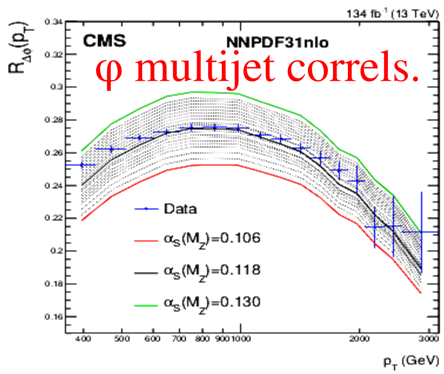
$\alpha_s = 0.1180 \pm 0.0016$ (±1.3%)

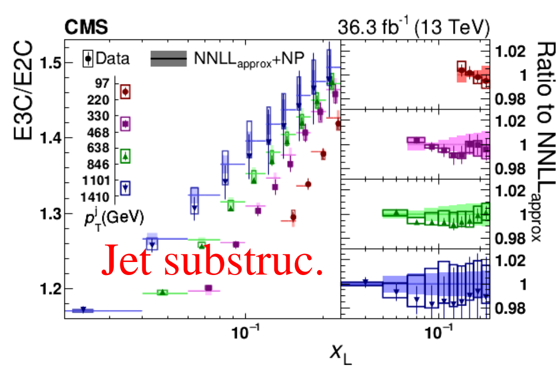


$\alpha_s = 0.1161 \pm 0.0022$ (±1.6%)

➧ Lumi is often lead EXP unc.

- New NLO observables studied by CMS (theory needs NNLO upgrade):

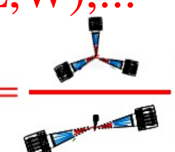




- New NNLO ratios to be studied, to reach ±1%?

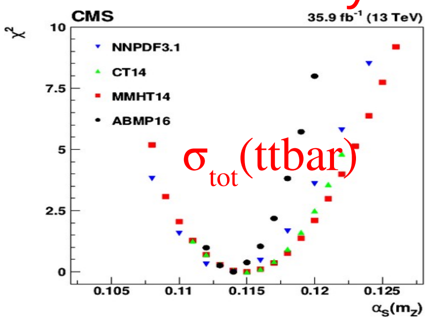
$R_{32}(p_T^{min})=\sigma(3j)/\sigma(2j)$,

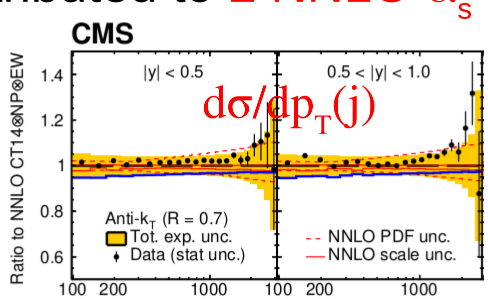
$\sigma(Z,W+j)/\sigma(Z,W)$,...

$R_{32}(p_T^{min}) = \sigma(3j)/\sigma(2j) =$  $\propto \alpha_s$

Summary: CMS past/future impact on α_s

- CMS has directly contributed to 2 NNLO α_s values in PDG:



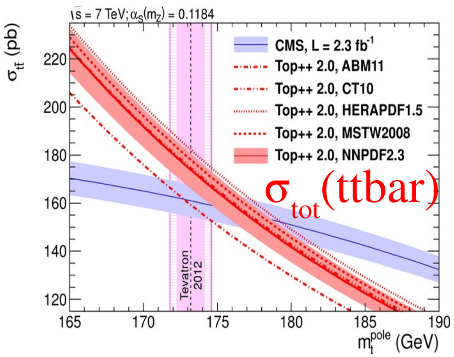


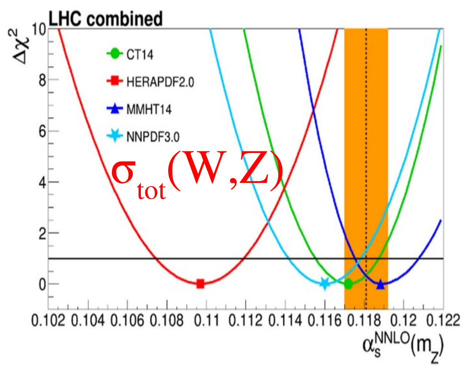
α_s = 0.1145 ± 0.0033 (±2.9%)

α_s = 0.1170 ± 0.0019 (±1.6%)

➧ Lumi/JES/JER leading EXP uncerts.

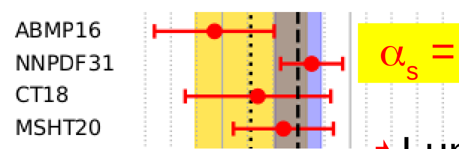
- CMS has indirectly contributed to 2+1 α_s NNLO values in the PDG:





α_s = 0.1177 ± 0.0035 (±3.0%)

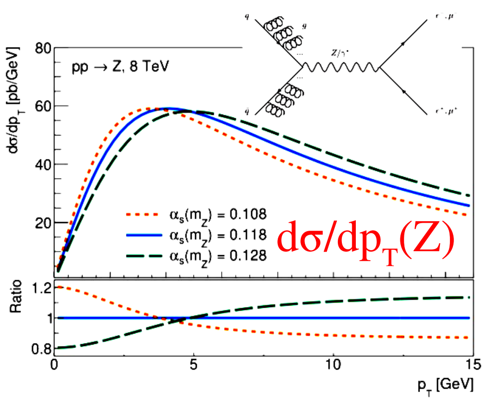
α_s = 0.1180 ± 0.0016 (±1.3%)

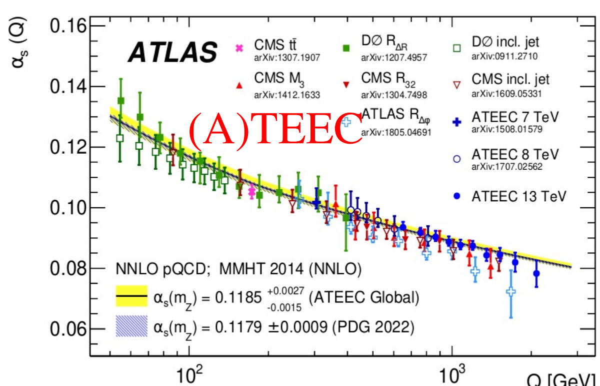


α_s = 0.1161 ± 0.0022 (±1.6%)

➧ Lumi is often lead EXP unc.

- New NNLO observables studied by ATLAS:





α_s = 0.11828 ± 0.00088 (±0.7%!?)

α_s = $0.1175^{+0.0035}_{-0.0018}$ (±1.5–3.0%)

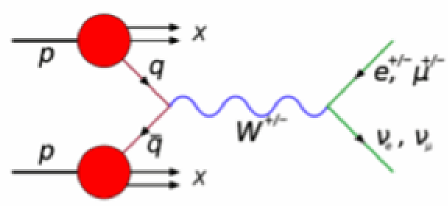
α_s from inclusive σ(W,Z) in hadronic collisions

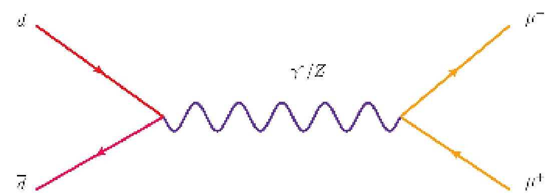
- Method: Calculate inclusive $W^{\pm}$ and Z production cross sections at NNLO and compare them to the LHC experimental data.

$$\sigma_{\rm pp\to W,Z+X} = \iint dx_1 dx_2\, f_1(x_1,\mu_F) f_2(x_2,\mu_F)\; \left[\hat{\sigma}_{\rm LO} + \alpha_s(\mu_R)\hat{\sigma}_{\rm NLO} + \alpha_s^2(\mu_R)\hat{\sigma}_{\rm NNLO} + \cdots\right.$$

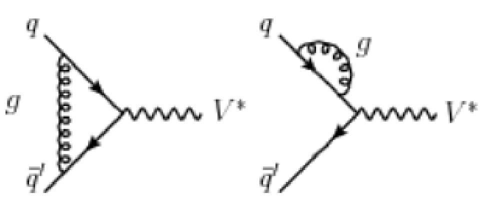
- The α_s dependency of the cross section comes from higher order effects (virtual & real parton emissions).

LO diagrams:

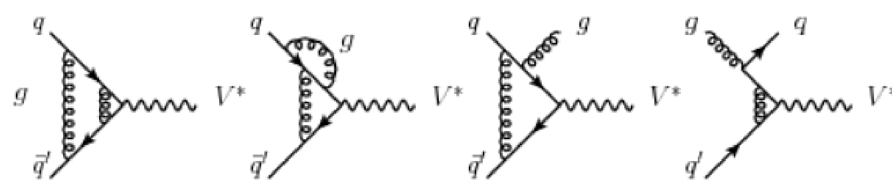




NLO diagrams:



NNLO diagrams:



Fiducial cross sections:	CDF	D0	LHCb	ATLAS	CMS
NNLO/LO ratio	1.35	1.35	1.29	1.22	1.33

Experimental data & NNLO computations

A total of 28 different experimental setups considered

$\sqrt{s}$ (TeV)	7	8	13	Total
ATLAS	3	1	3	7
LHCb	3	5	1	9
CMS	6	6	0	12

- The 28 systems represent a total of ∼20 000 jobs, taking into account all PDF eigenvalues (101 NNPDF + (56+7) CT14 + (29+14+7) HERA + (51+7) MMHT), and 5 or 7 α_s values (0.115, 0.116, 0.117, 0.118, 0.119, 0.120, and 0.121).
- All these computations are done at the CERN computer cluster with hundreds of jobs in parallel.
- Running at NNLO is slow. Using the longest 2-week queue we get 0.2–0.6% numerical accuracy, comparable to ~1% diffs. to alternative NNLO calculators: FEWZ, DYNNLO (impact on final α_s result assessed at the end)

Exp. & theor. uncertainties. χ^2/ndf data-theory

- Experimental & theoretical uncertainties and their correlations:

Source	Uncertainty	Degree of correlation
Experimental:		
Luminosity	2–4% (CMS), 2–3% (ATLAS), 1–4% (LHCb), 3–6% (CDF, D0)	fully correlated per exp. at each $\sqrt{s}$
Systematic	1–3% (CMS), 0.3–2% (ATLAS), 0.6–2% (LHCb), 2–3% (CDF, D0)	partially correlated within each exp.
c.m. energy	0.9–1.3% (LHCb)	fully correlated at each $\sqrt{s}$
Statistical	0.3–2.5% (CMS), $<$ 0.4% (ATLAS), 0.2–0.5% (LHCb), 0.4–2.6% (CDF, D0)	uncorrelated
Theoretical:		
PDF	1–4%	partially correlated within PDF set
Scales	0.4–1.2%	partially correlated among all calculations
Numerical	0.2–0.6%	uncorrelated

Table 4. Typical ATLAS, CMS, LHCb and Tevatron experimental and theoretical uncertainties in the $W^{\pm}$ and Z boson production cross sections, and their degree of correlation

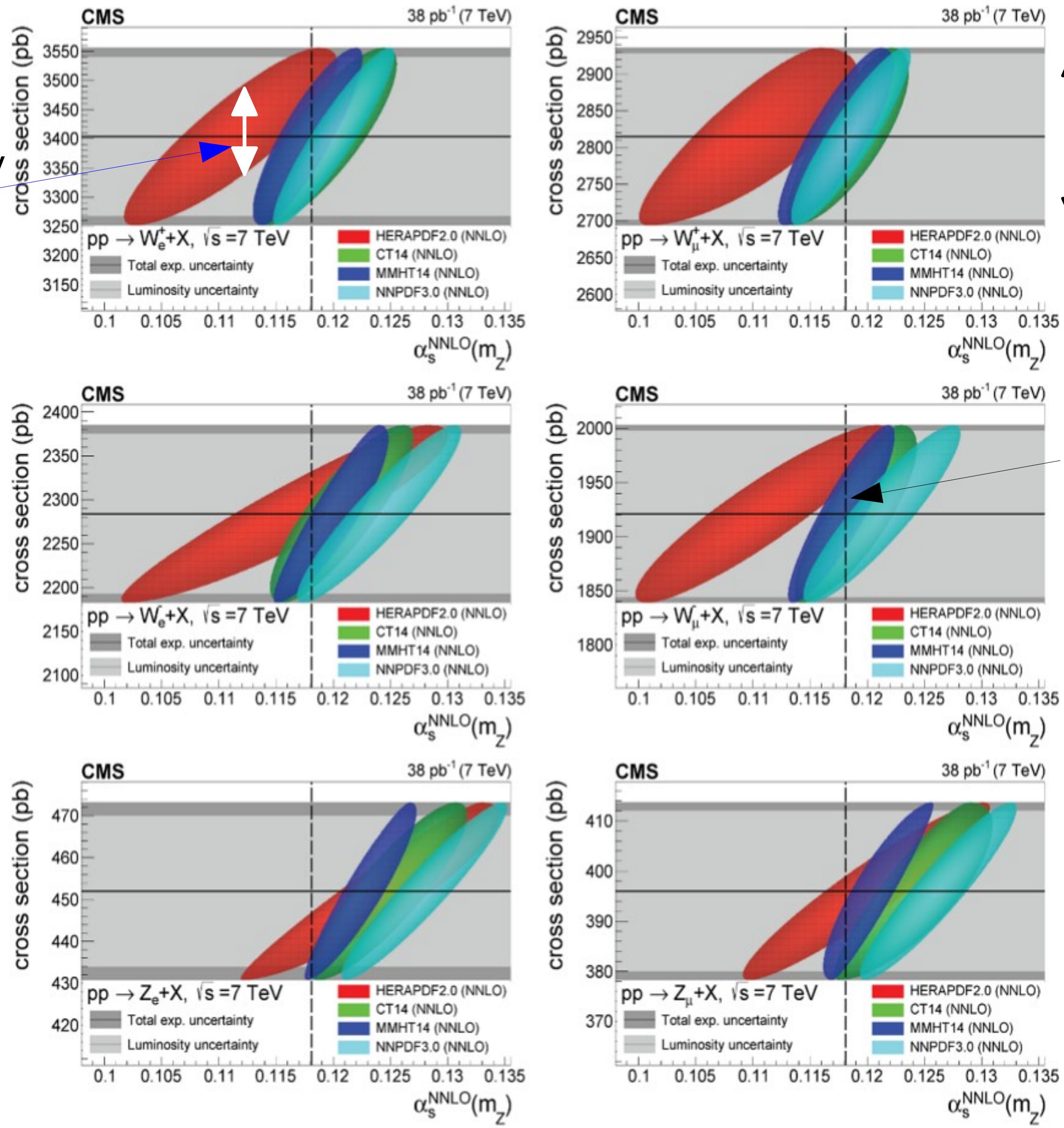
- NNLO-data for default α_s=0.118: Goodness-of-fit ~1 for CT14/MMHT14
  ~2 for HERAPDF2.0/NNPDF3.0

	CT14	HERAPDF2.0	MMHT14	NNPDF3.0
χ^2/ndf (symmetrized to the largest PDF uncertainty value)	15.8/27	21.8/27	15.7/27	58.8/27
χ^2/ndf (symmetrized to the smallest PDF uncertainty value)	26.3/27	60.4/27	22.7/27	58.8/27

Table 11. Overall goodness-of-fit per number of degrees of freedom, χ^2/ndf, among the 28 LHC experimental measurements of W^+, W^-, and Z boson cross sections and the corresponding theoretical predictions obtained with the four different PDF sets for their default $\alpha_s(m_Z) = 0.118$ value. The first (second) row lists the results obtained symmetrizing the PDF uncertainties of the cross sections obtained with the CT14, HERAPDF2.0, and MMHT14 sets to the largest (smallest) of their respective values.

$\sigma_{NNLO}(W,Z)$ versus $\alpha_s(m_Z)$ for CMS data

Theory uncertainty (mostly PDF)



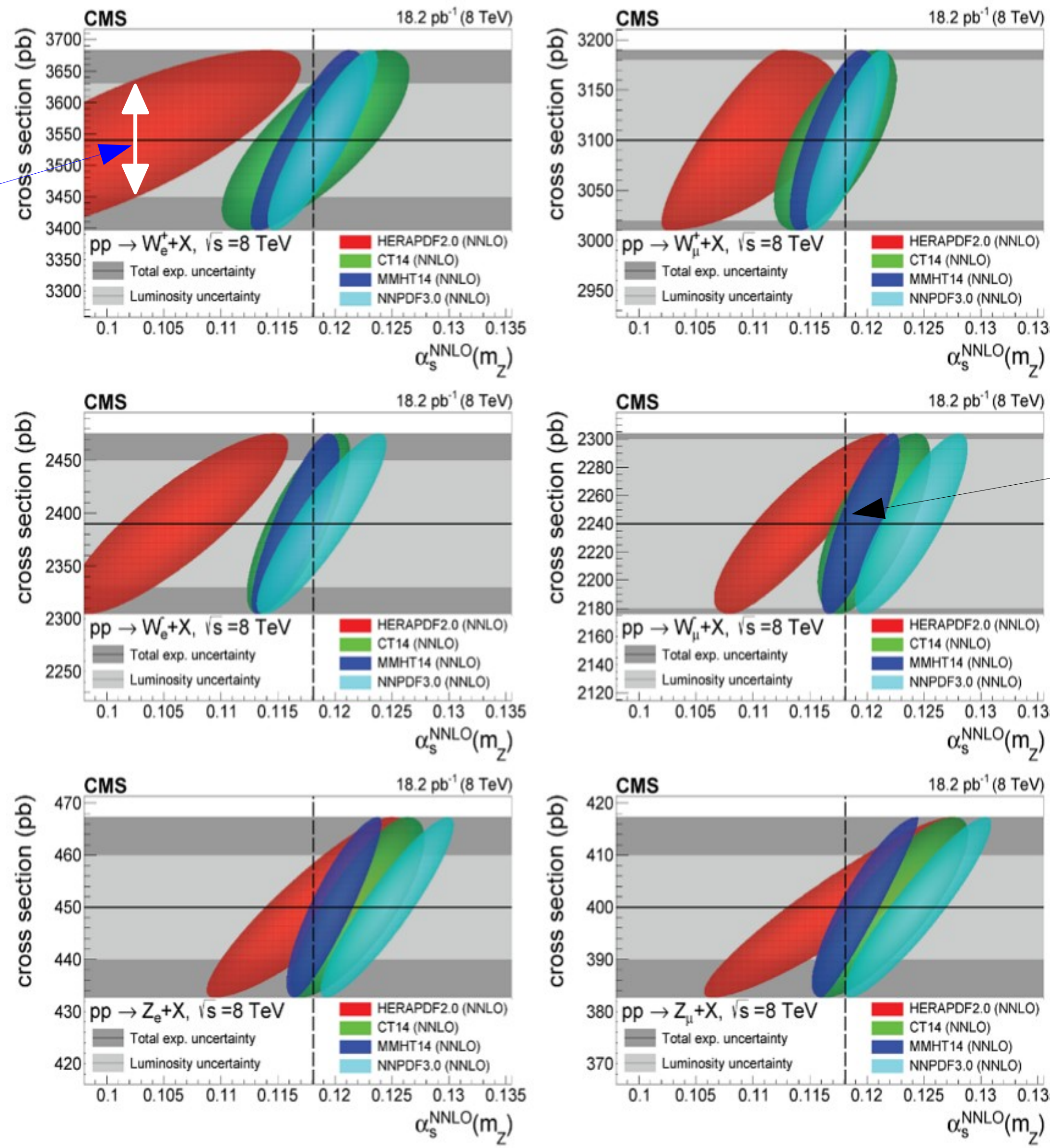
Exp. uncertainty (mostly lumi)

Crossing-line point indicates “perfect match” of exp-theory x-sections for the default $\alpha_s(m_Z)$=0.118 of all PDF sets

1σ ellipses are Joint Probability Density Functions (product of data & theory uncertainties)

σ_{NNLO}(W,Z) versus $\alpha_s(m_Z)$ for CMS data

Theory uncertainty (mostly PDF)

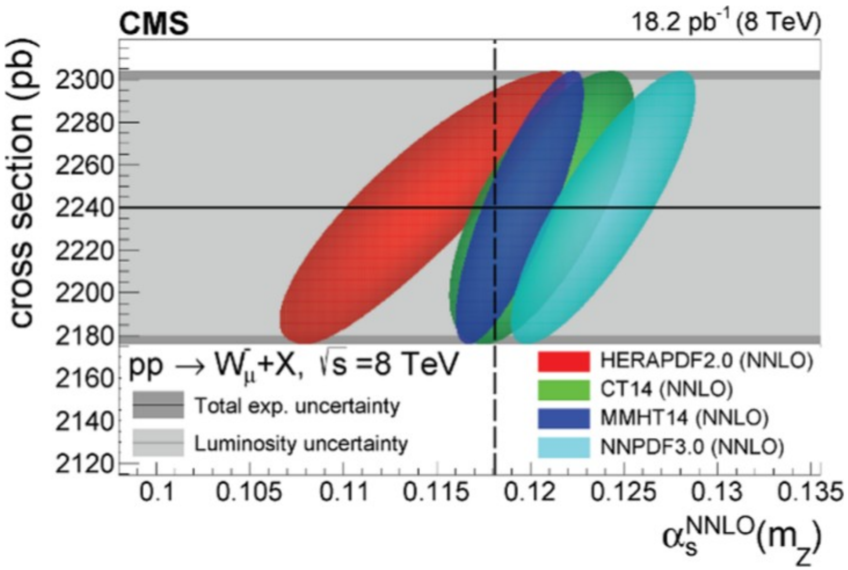


Exp. uncertainty (mostly lumi)

Crossing line point indicates “perfect match” of exp-theory x-sections for the default $\alpha_s(m_Z)$=0.118 of all PDF sets

1σ ellipses are Joint Probability Density Functions (product of data & theory uncertainties)

$\sigma_{NNLO}(W,Z)$ versus $\alpha_s(m_Z)$ for LHC data: Global trends



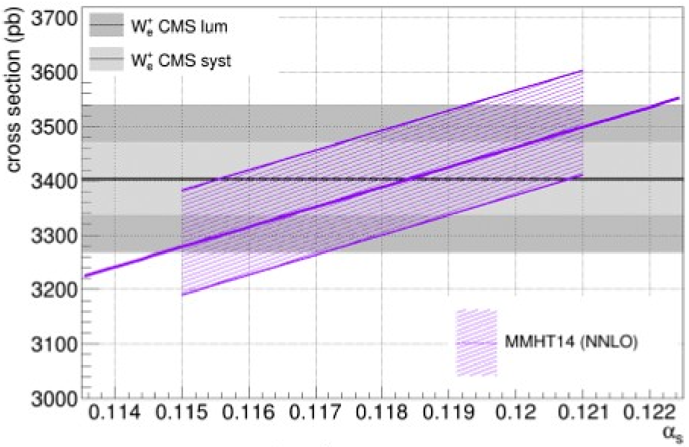
- Theory consistent with data within uncertainties but not systematically for the same $\alpha_s(m_Z)$ value (in particular, HERAPDF2.0 results do not always overlap with any of the others within the 1 std.-dev. region)

- For a fixed $\alpha_s(m_Z)$ value, HERAPDF2.0 (NNPDF3.0) predict larger (smaller) x-sections: HERAPDF2.0 (NNPDF3.0) prefer systematically smaller (larger) $\alpha_s(m_Z)$. MMHT14 and CT14 predictions are in between (and less scattered).

- HERAPDF2.0 (MMHT14) always has the smallest (largest) slope, i.e. HERAPDF2.0 (MMHT14) x-sections are the least (most) sensitive to α_s variations.

Preferred $\alpha_s(m_Z)$ per measurement & propag. uncertainty

- The α_s value for each setup is determined by the intersection point of the fitted theoretical line with the experimental value.



- Each σ uncertainty δ_i propagates into α_s as δ_i/k:
- To motivate this, one can construct a marginalized posterior by multiplying the theoretical and experimental probability densities and integrating over σ:

$$P(\alpha_s) = \int f_{exp}(\sigma) \cdot f_{th}(\sigma|\alpha_s) d\sigma.$$

- Using this the variance of α_s from this single system considering all uncertainty sources δ_i is given by (k is the slope of the fitted line):

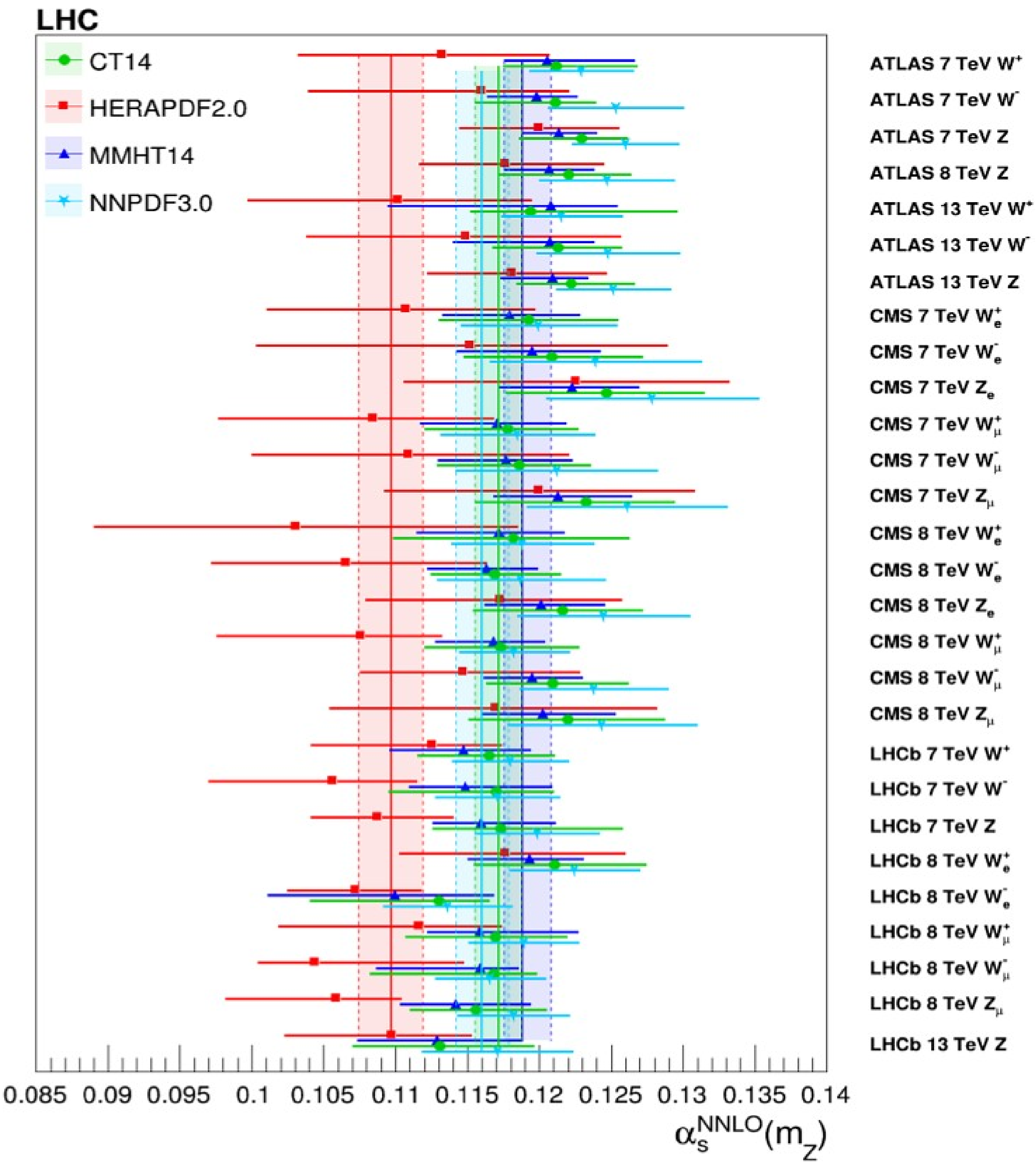
$$\mathrm{var}(\alpha_s) = \frac{1}{k} \sum_i \mathrm{var}(\delta_i).$$

Combination of α_s extractions per data-set & PDF-set

- Results are combined using Convino[1] (Neyman χ^2 prescription), taking into account correlations and asymmetric PDF uncertainties (method equivalent to BLUE for symmetric uncertainties).
- 6 uncertainty sources for each estimate considered: EXP: statistical, luminosity, systematic; TH: NNLO scale, PDF, and numerical.
- Uncertainty correlations:
  1. Luminosity at the same $\sqrt{s}$: 1 within one detector, 0. between detectors. 0 between different $\sqrt{s}$.
  2. Stat. uncert.: fully uncorrelated.
  3. Syst. uncert.: see next slide.
  4. TH scale uncert.: partially correlated.
  5. PDF uncertainty: partially correlated within each PDF set (see slides later).
  6. TH Numerical error: fully uncorrelated.

[1] J. Kieseler, Eur. Phys. J. C 77 (2017) 792

Combined 28 α_s extractions & average α_s per PDF



PDF	$\alpha_s(m_Z)$
CT14	$0.1172^{+0.0015}_{-0.0017}$
HERAPDF2.0	$0.1097^{+0.0022}_{-0.0023}$
MMHT14	$0.1188^{+0.0019}_{-0.0013}$
NNPDF3.0	0.1160 ± 0.0018

- CT14, MMHT14 and NNPDF3.0 scatter around $\alpha_s(m_Z)$=0.117–0.119 world average with ~1% propag. uncertainties.
- HERAPDF2.0 is systematically below, $\alpha_s(m_Z)$~0.110, and ~2% propag. uncertainty

$\alpha_s(m_Z)$ robustness wrt. exp./theor. ingredients

- Stability of extracted $\alpha_s(m_Z)$ values per PDF cross-checked by varying key exp. & theor. ingredients & uncertainties:

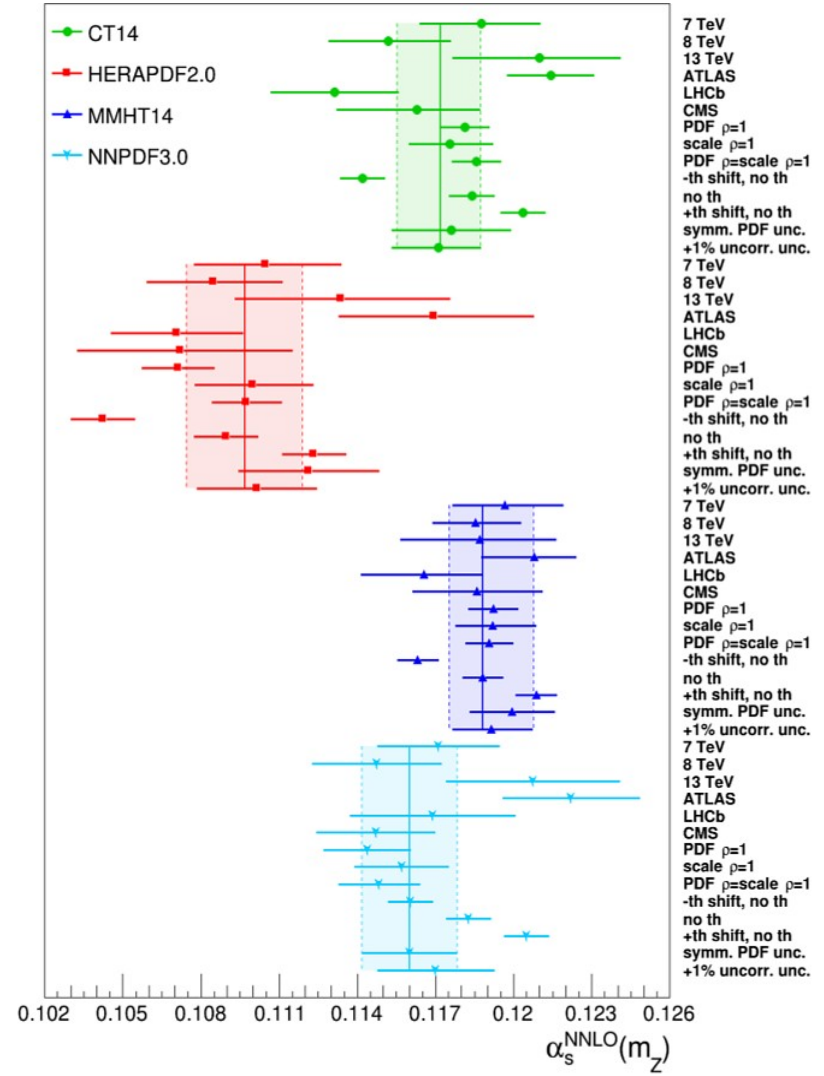
(i) Data subsets: ATLAS/CMS/LHCb or 7, 8, 13 TeV

(ii) Varying ρ=0–1 correlation of PDF/scale uncerts.

(iii) $\pm 1\sigma$ TH shift of central values prior to combination

(iv) Adding $\pm$1% TH uncert. (diffs. among NNLO calc.)

PDF	$\alpha_s(m_Z)$	$\alpha_s(m_Z)$	$\alpha_s(m_Z)$
	[7 TeV data]	[8 TeV data]	[13 TeV data]
CT14	$0.1188^{+0.0022}_{-0.0024}$	$0.1152^{+0.0024}_{-0.0023}$	$0.1210^{+0.0031}_{-0.0033}$
HERAPDF2.0	$0.1105^{+0.0029}_{-0.0028}$	$0.1085^{+0.0027}_{-0.0025}$	$0.1134^{+0.0042}_{-0.0041}$
MMHT14	$0.1197^{+0.0022}_{-0.0020}$	0.1186 ± 0.0017	$0.1187^{+0.0029}_{-0.0030}$
NNPDF3.0	0.1171 ± 0.0023	0.1147 ± 0.025	0.1207 ± 0.0033
	[ATLAS data]	[LHCb data]	[CMS data] [28]
CT14	0.1214 ± 0.0017	0.1131 ± 0.0024	$0.1163^{+0.0024}_{-0.0031}$
HERAPDF2.0	$0.1170^{+0.0038}_{-0.0037}$	0.1071 ± 0.0021	$0.1072^{+0.0043}_{-0.0040}$
MMHT14	$0.1208^{+0.0016}_{-0.0020}$	$0.1166^{+0.0023}_{-0.0024}$	0.1186 ± 0.0025
NNPDF3.0	0.1222 ± 0.0026	0.1169 ± 0.0032	0.1147 ± 0.0023
	[PDF corr. = 1]	[scale corr. = 1]	[PDF corr. = scale corr. = 1]
CT14	0.1181 ± 0.0010	$0.1176^{+0.0017}_{-0.0016}$	0.1186 ± 0.0009
HERAPDF2.0	0.1071 ± 0.0014	$0.1100^{+0.0023}_{-0.0022}$	0.1098 ± 0.0013
MMHT14	0.1192 ± 0.0009	$0.1192^{+0.0016}_{-0.0014}$	0.1191 ± 0.0009
NNPDF3.0	0.1144 ± 0.0017	0.1157 ± 0.0018	0.1148 ± 0.0016
	[− th. shift, comb. w/o th. unc.]	[comb. w/o th. unc.]	[+ th. shift, comb. w/o th. unc.]
CT14	0.1142 ± 0.0009	0.1184 ± 0.0009	0.1203 ± 0.0009
HERAPDF2.0	0.1042 ± 0.0012	0.1090 ± 0.0012	0.1123 ± 0.00012
MMHT14	0.1163 ± 0.0008	0.1188 ± 0.0008	0.1209 ± 0.0008
NNPDF3.0	0.1160 ± 0.0009	0.1183 ± 0.0009	0.1205 ± 0.0009
	[symm. PDF uncert.]	[+1% uncorr. uncert.]	Largest differences
CT14	0.1176 ± 0.0023	$0.1171^{+0.0016}_{-0.0018}$	(+0.0042, −0.0041)
HERAPDF2.0	0.1121 ± 0.0027	0.1101 ± 0.0023	(+0.0073, −0.0026)
MMHT14	0.1200 ± 0.0016	$0.1191^{+0.0016}_{-0.0015}$	(+0.0020, −0.0022)
NNPDF3.0	0.1160 ± 0.0018	0.1170 ± 0.0022	(+0.0062, −0.0016)



Final combined α_s extractions per PDF set

- Final $\alpha_s(m_Z)$ values per PDF with break-down of uncertainties & χ^2/ndf:

PDF	$\alpha_s(m_Z)$	δ (stat)	δ (lumi)	δ (syst)	δ(PDF)	δ(scale)	δ (num)	χ^2/ndf
CT14	$0.1172^{+0.0015}_{-0.0017}$	0.0003	0.0005	0.0006	$^{+0.0011}_{-0.0013}$	0.0006	0.0003	23.5/27
HERAPDF2.0	$0.1097^{+0.0022}_{-0.0023}$	0.0004	0.0009	0.0009	$^{+0.0015}_{-0.0016}$	0.0007	0.0005	27.0/27
MMHT14	$0.1188^{+0.0019}_{-0.0013}$	0.0002	0.0008	0.0003	$^{+0.0015}_{-0.0007}$	0.0007	0.0002	19.3/27
NNPDF3.0	0.1160 ± 0.0018	0.0006	0.0004	0.0005	0.0013	0.0006	0.0007	56.9/27

- Preferred $\alpha_s(m_Z)$=0.1188±0.0016 extraction from MMHT14:
  1) Largest sensitivity (slope) of σ(W,Z) to α_s
  2) Better χ^2/ndf~1 of combined α_s values.
  3) Lowest (symm.) propag. uncert.
  4) Most robust wrt. analysis variations