α_s — present status and perspectives

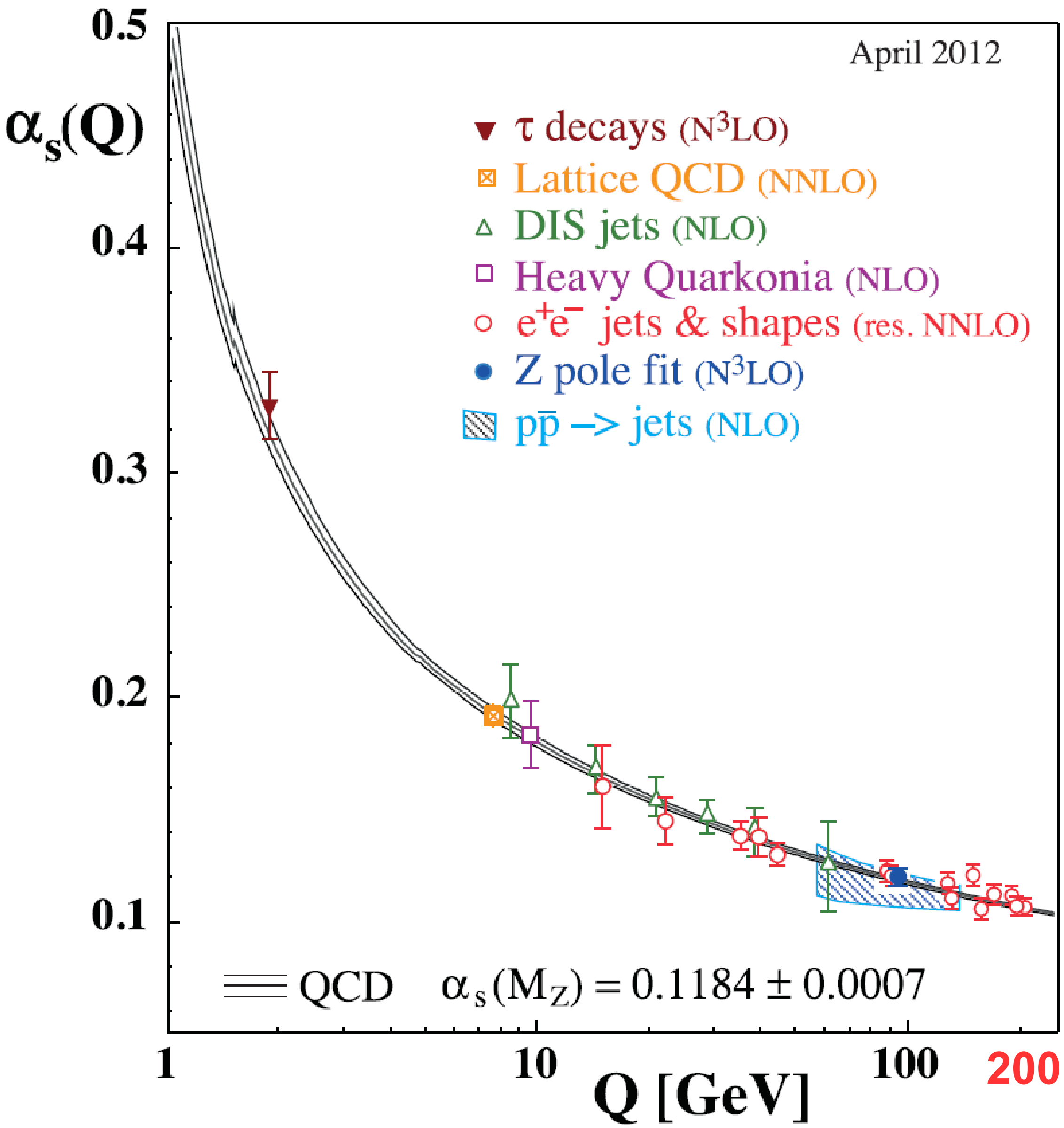
Klaus Rabbertz (KIT)

Outline

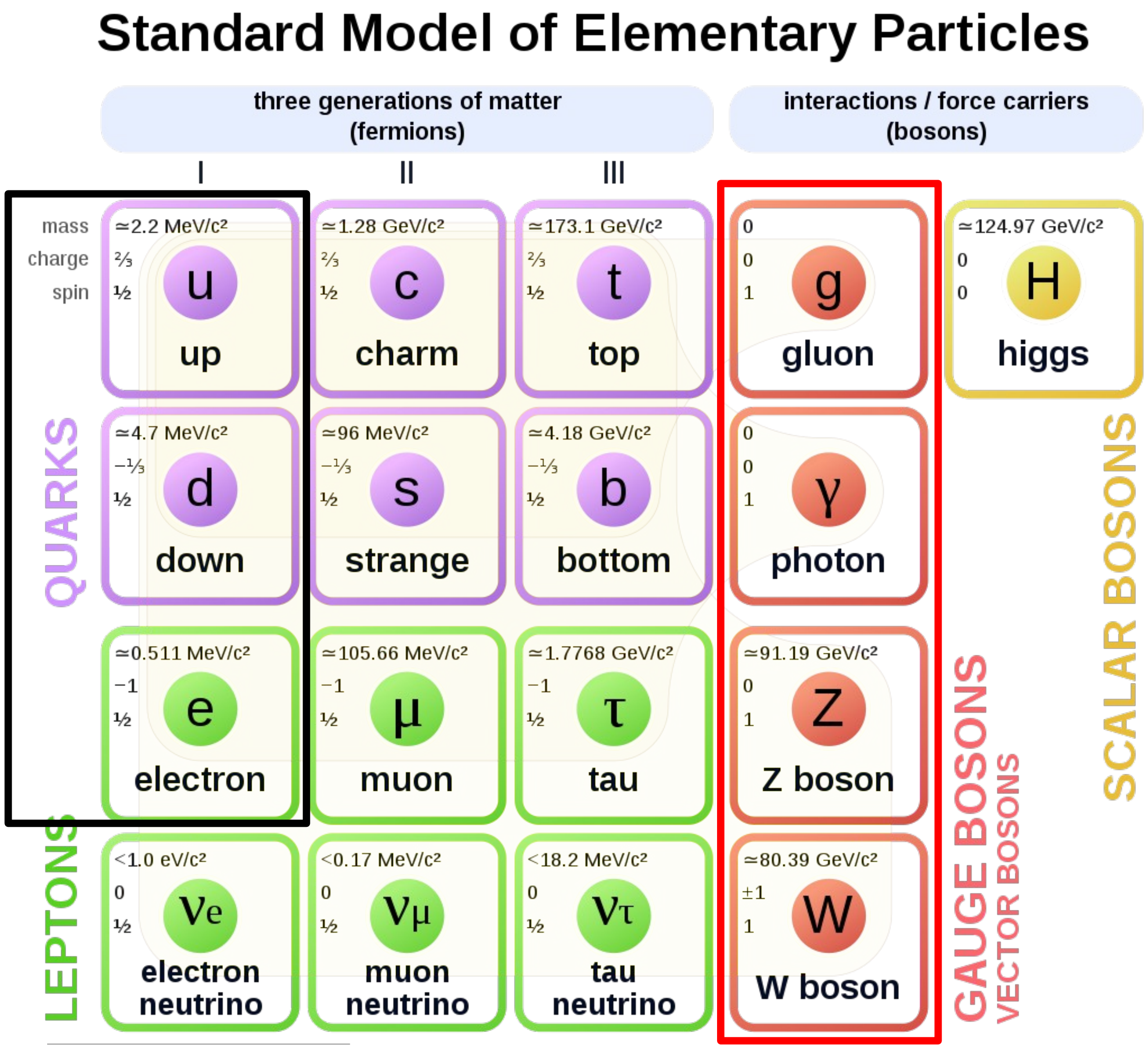
- **Motivation**
- **PDG averages**
- **PDG update 2023**
- **LHC news**
- **EIC & LHC perspectives**
- **Summary & outlook**

2012: No LHC results yet

PDG2012



Solid matter …

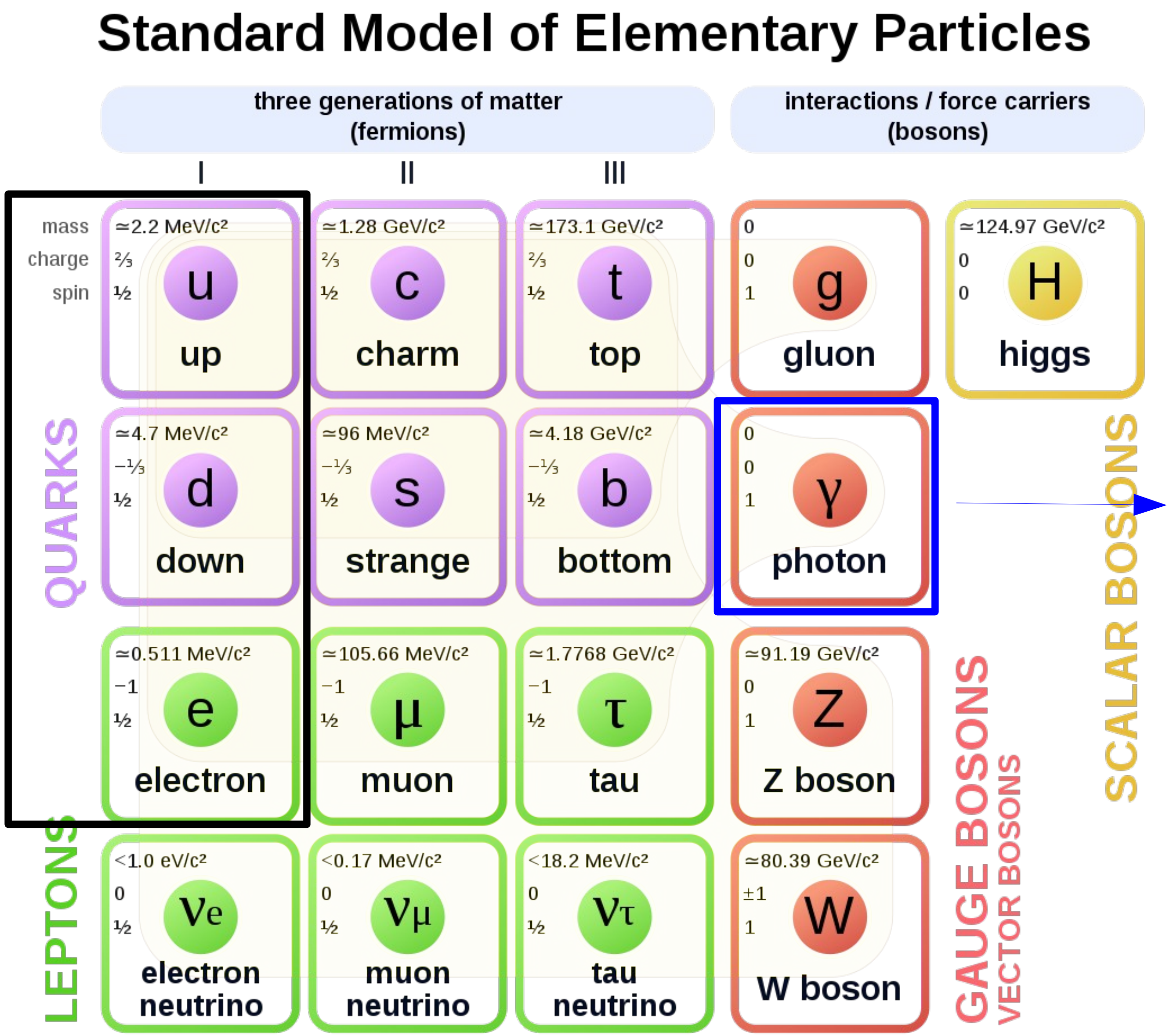


Cush, Wikipedia.

… and three fundamental interactions. (no gravity)

Standard Model of Particle Physics

Solid matter
...



Cush, Wikipedia.

Electromagnetic interaction (magnets, electricity, ...)

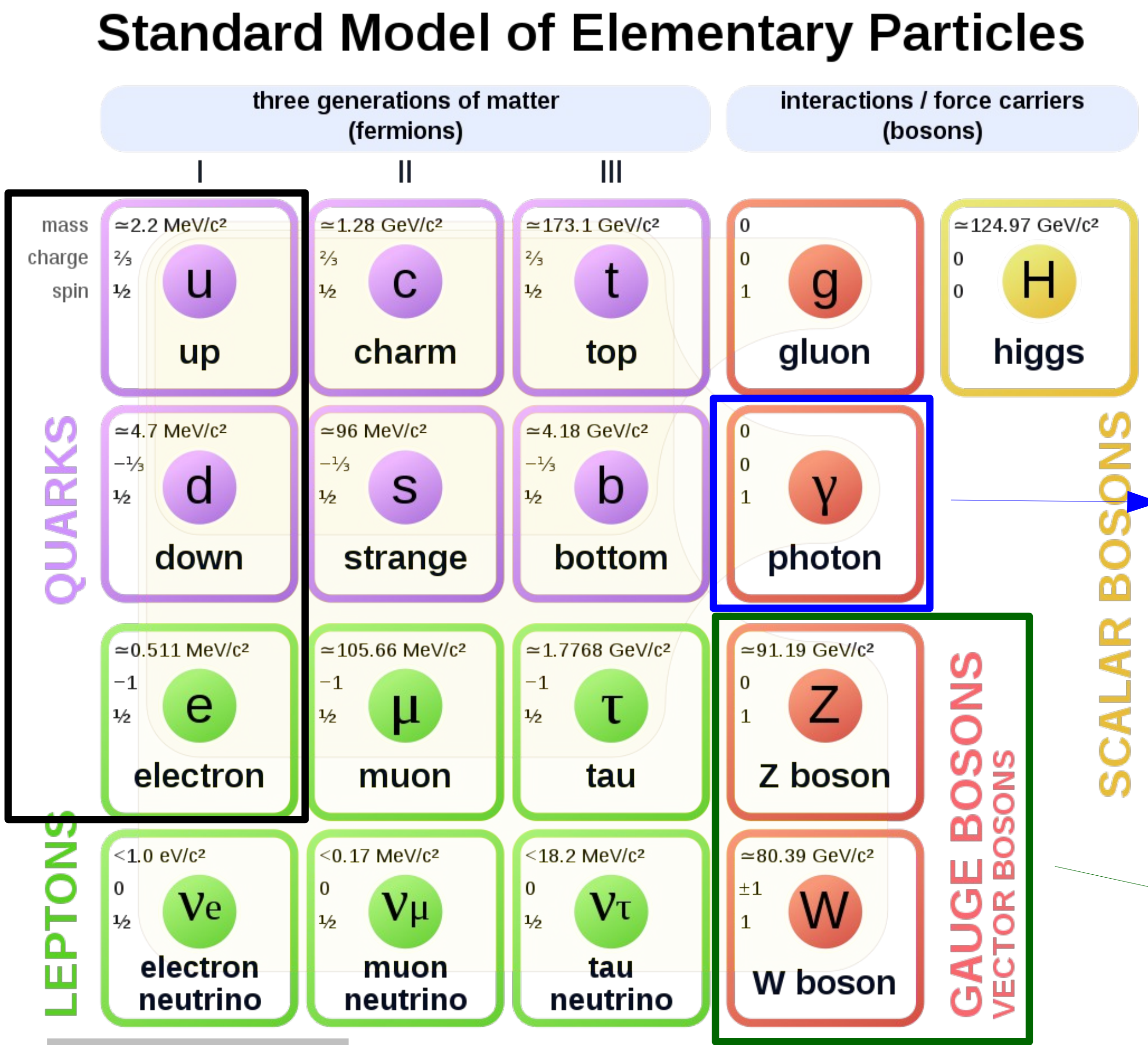
$\alpha \approx 1/137$

$\Delta\alpha/\alpha = 0.15 \cdot 10^{-9}$

… and three fundamental interactions. (no gravity)

Standard Model of Particle Physics

Solid matter ...



Cush, Wikipedia.

Electromagnetic interaction (magnets, electricity, ...)

$\alpha \approx 1/137$

$\Delta\alpha/\alpha = 0.15 \cdot 10^{-9}$

Weak interaction (β decays, sun, ...)

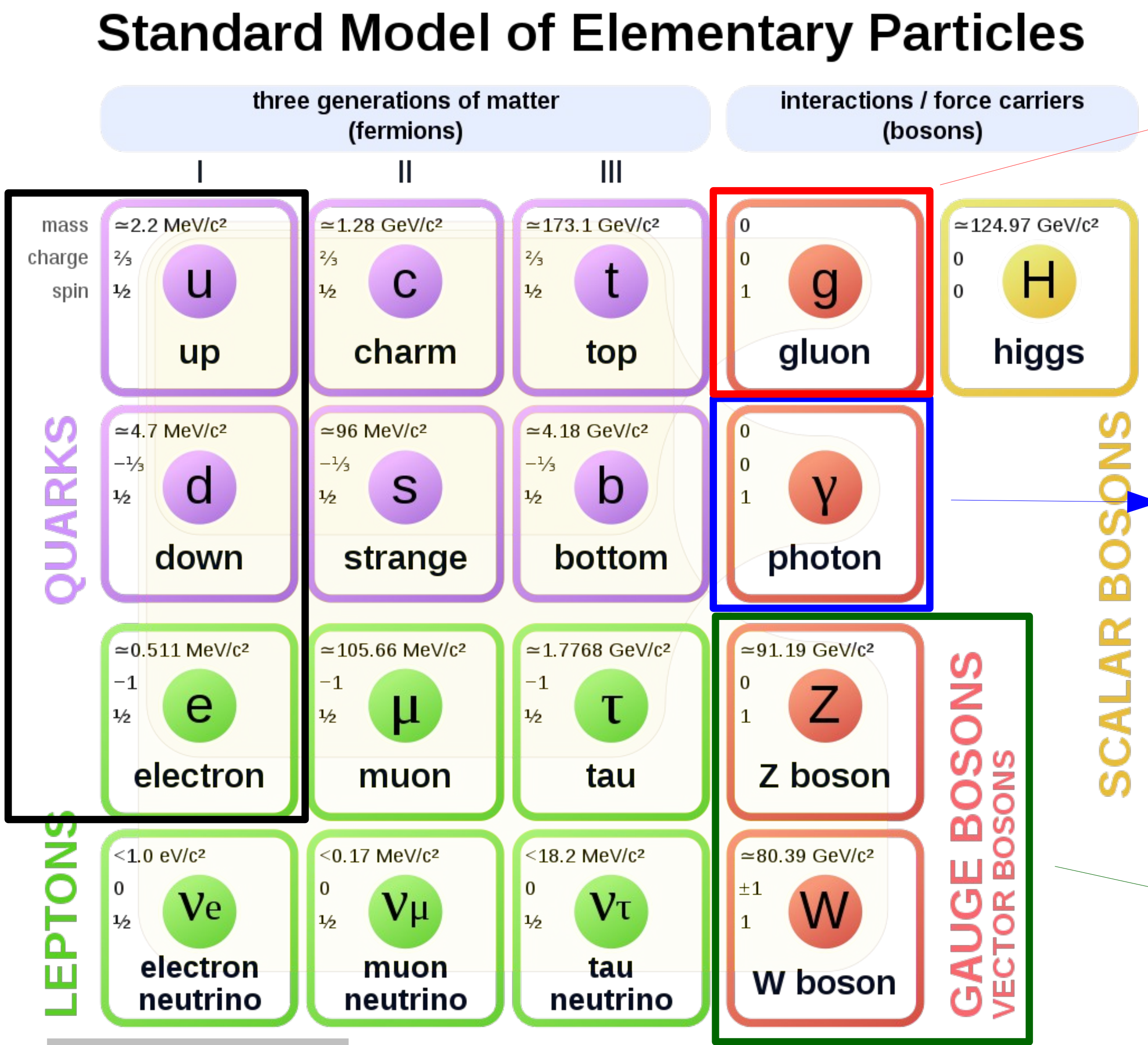
$G_F \approx 1.17 \cdot 10^{-5}/\mathrm{GeV}^2$

$\Delta G_F/G_F = 0.51 \cdot 10^{-6}$

… and three fundamental interactions. (no gravity)

Standard Model of Particle Physics

Solid matter ...



Cush, Wikipedia.

Strong interaction (nuclear forces, ...)

$\alpha_s \approx 0.118$

$\Delta\alpha_s/\alpha_s = 0.76 \cdot 10^{-2}$

Electromagnetic interaction (magnets, electricity, ...)

$\alpha \approx 1/137$

$\Delta\alpha/\alpha = 0.15 \cdot 10^{-9}$

Weak interaction (β decays, sun, ...)

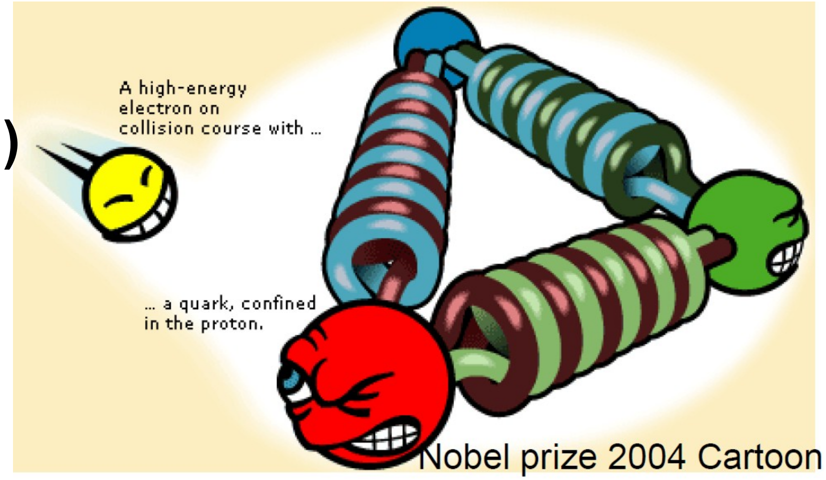
$G_F \approx 1.17 \cdot 10^{-5}/\mathrm{GeV}^2$

$\Delta G_F/G_F = 0.51 \cdot 10^{-6}$

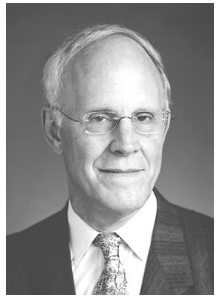
… and three fundamental interactions. (no gravity)

QCD and asymptotic freedom

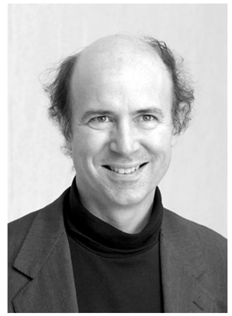
Nobel prize 2004



Nobel prize 2004 Cartoon


D. Gross


D. Politzer


F. Wilczek

nobelprize.org

- **Theory:**
  - **Renormalisation group equation (RGE)**
  - **Solution of 1-loop equation**
  - **Running coupling constant**

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \alpha_s(\mu^2)\beta_0 \ln\left(\frac{Q^2}{\mu^2}\right)}$$

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)}$$

- **'Strong' coupling weak for $Q^2 \to \infty$, i.e. small distances**
- **Asymptotic freedom**
- **Perturbative methods usable**

$$\beta_0 = \frac{33 - 2 \cdot N_f}{12\pi}$$

Physik Journal 3 (2004) Nr. 12

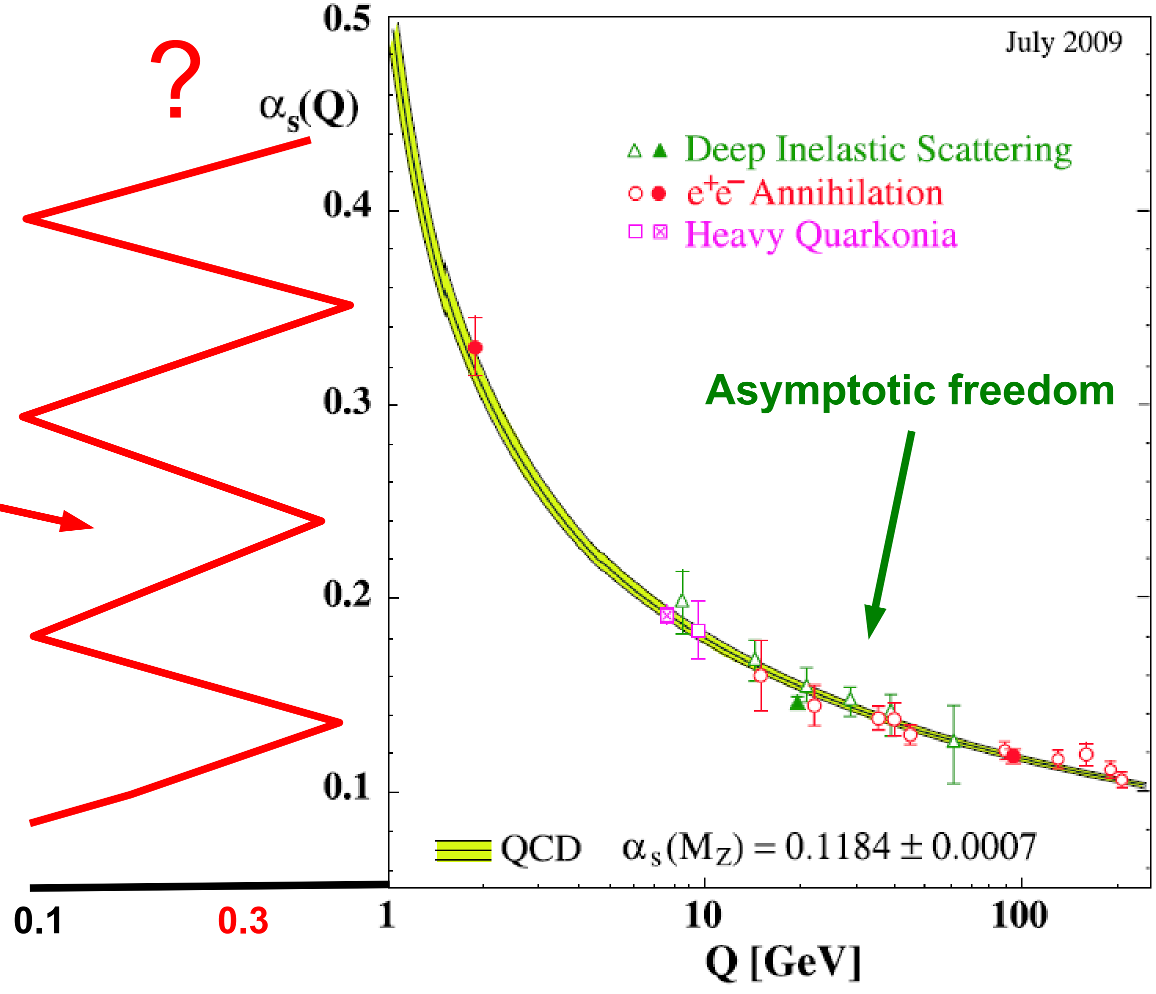
- **What happens at large distances?**
  - **$Q^2 \to 0$?**
  - **Cannot be answered here!**
    For $Q^2 \to \Lambda^2$ perturbation theory not applicable anymore!

Running coupling constant

$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)}$$

with Λ typically ≈ 200 – 300 MeV

pre-LHC



S. Bethke, EPJC 64 (2009).

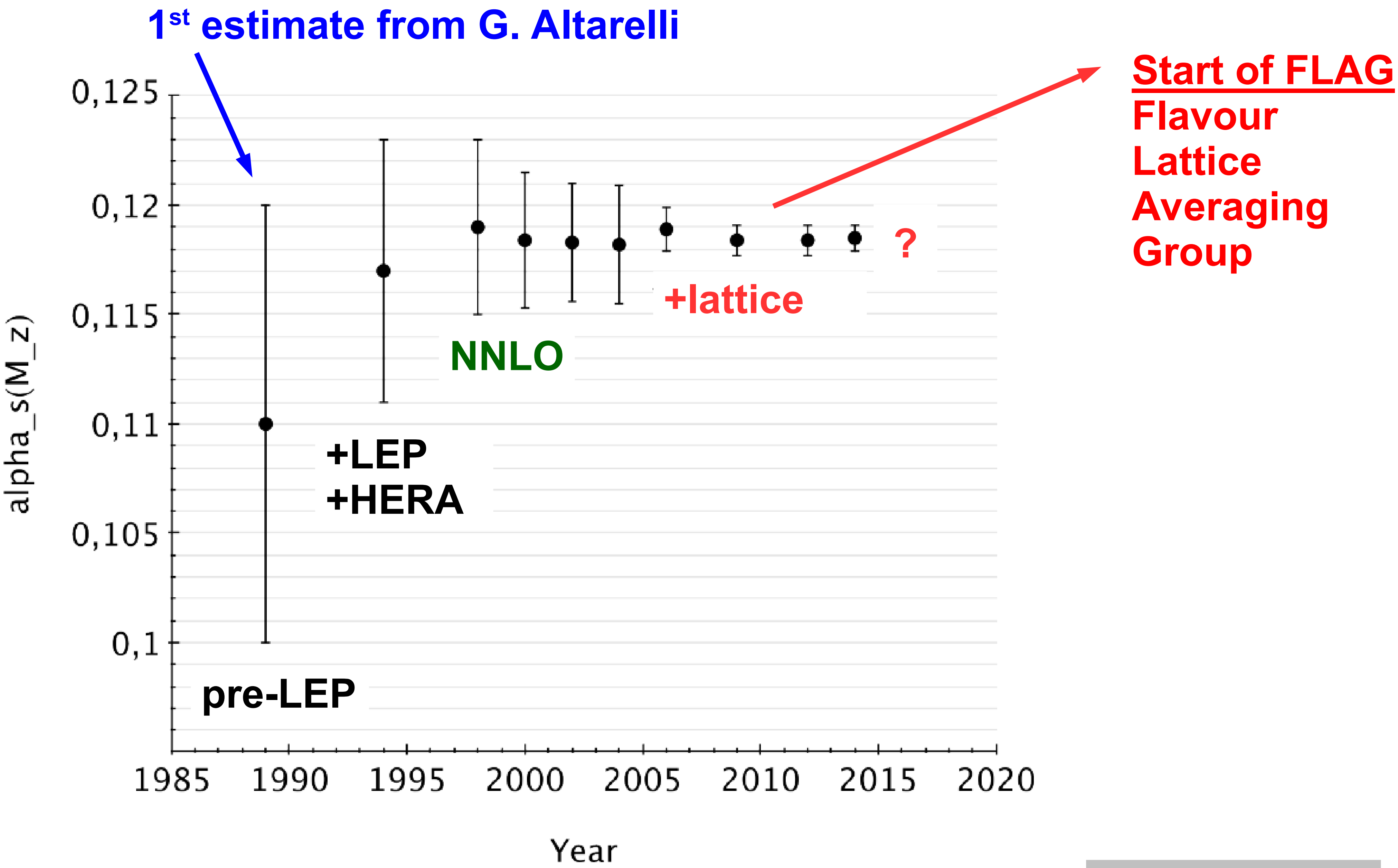
QCD potential grows linearly with larger distances:

$$V = \sigma \cdot r \approx 1\mathrm{GeV/fm} \cdot r$$

→ No free quarks (or gluons)
→ Confinement

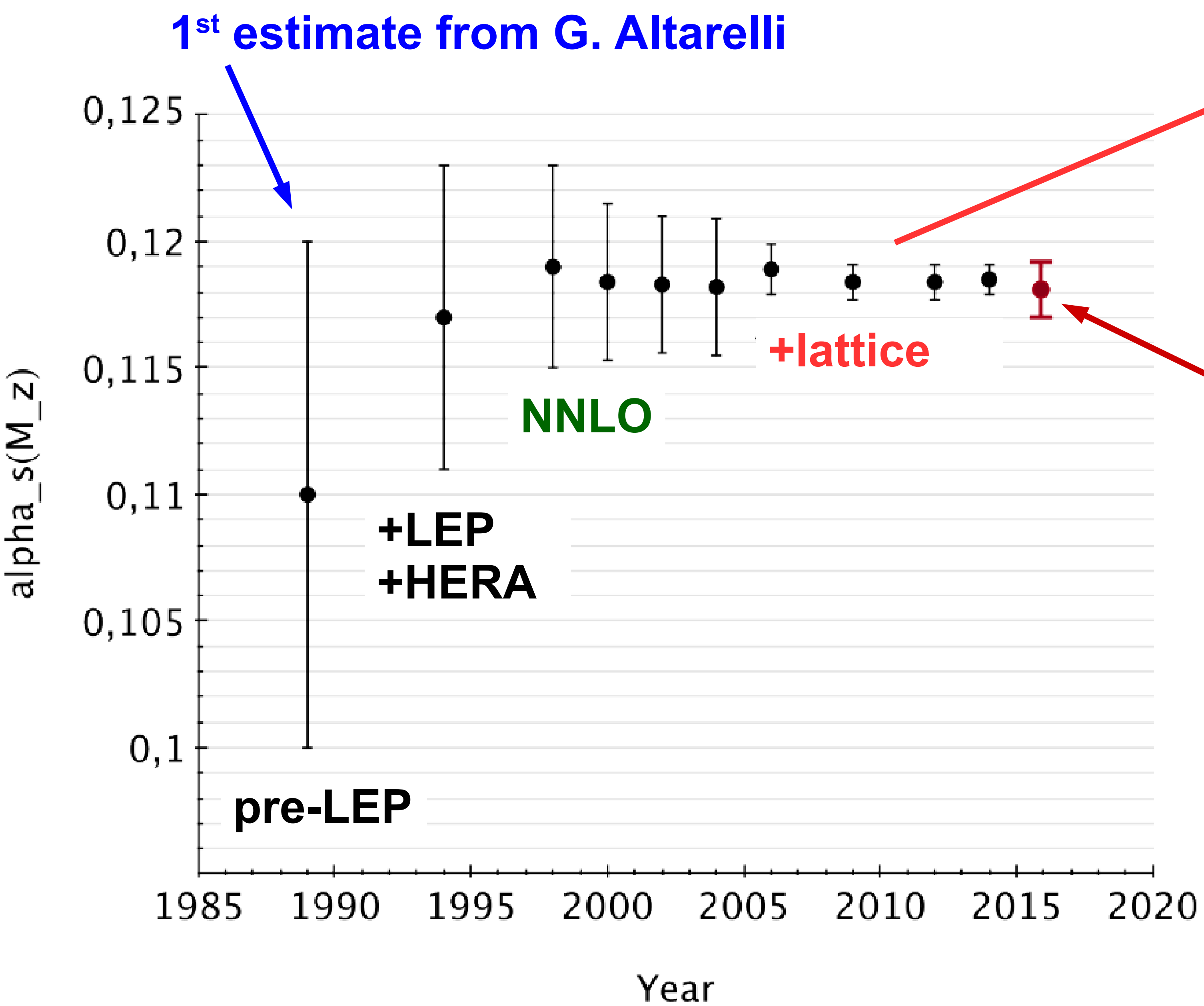
PDG averages

$\alpha_s(M_Z)$ world average versus time



S. Bethke, arXiv:1907.01435.

$\alpha_s(M_Z)$ world average versus time



Start of FLAG
Flavour Lattice Averaging Group

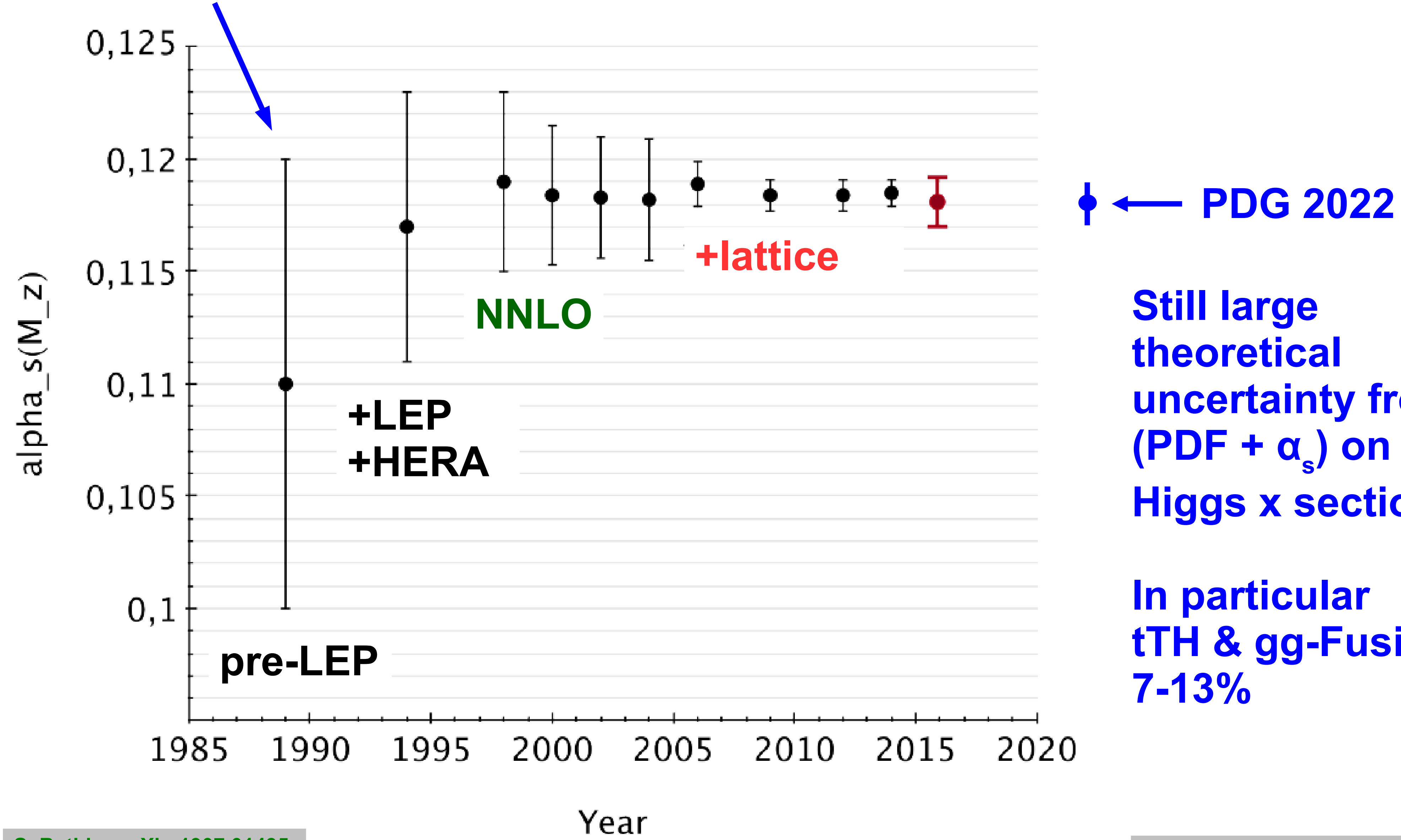
PDG 2016

More careful validation of lattice methods & uncertainties

S. Bethke, arXiv:1907.01435.

$\alpha_s(M_Z)$ world average versus time

1st estimate from G. Altarelli



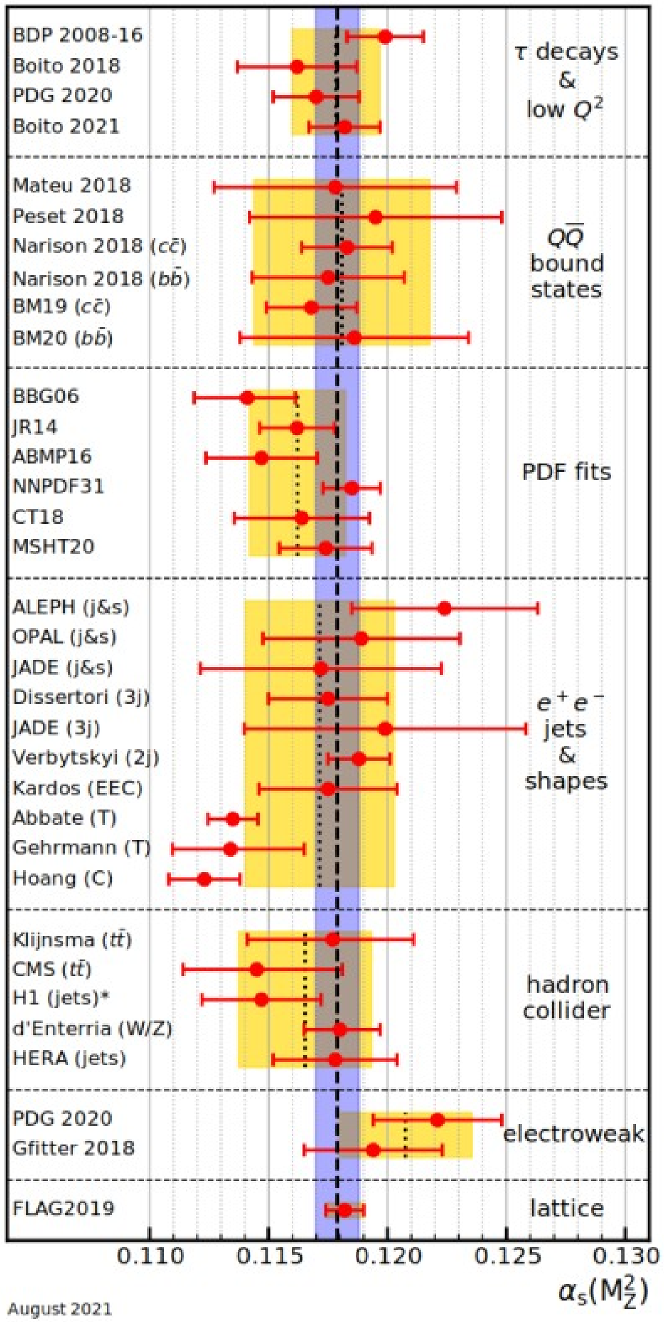
Still large theoretical uncertainty from (PDF + α_s) on Higgs x sections

In particular tTH & gg-Fusion: 7-13%

S. Bethke, arXiv:1907.01435.

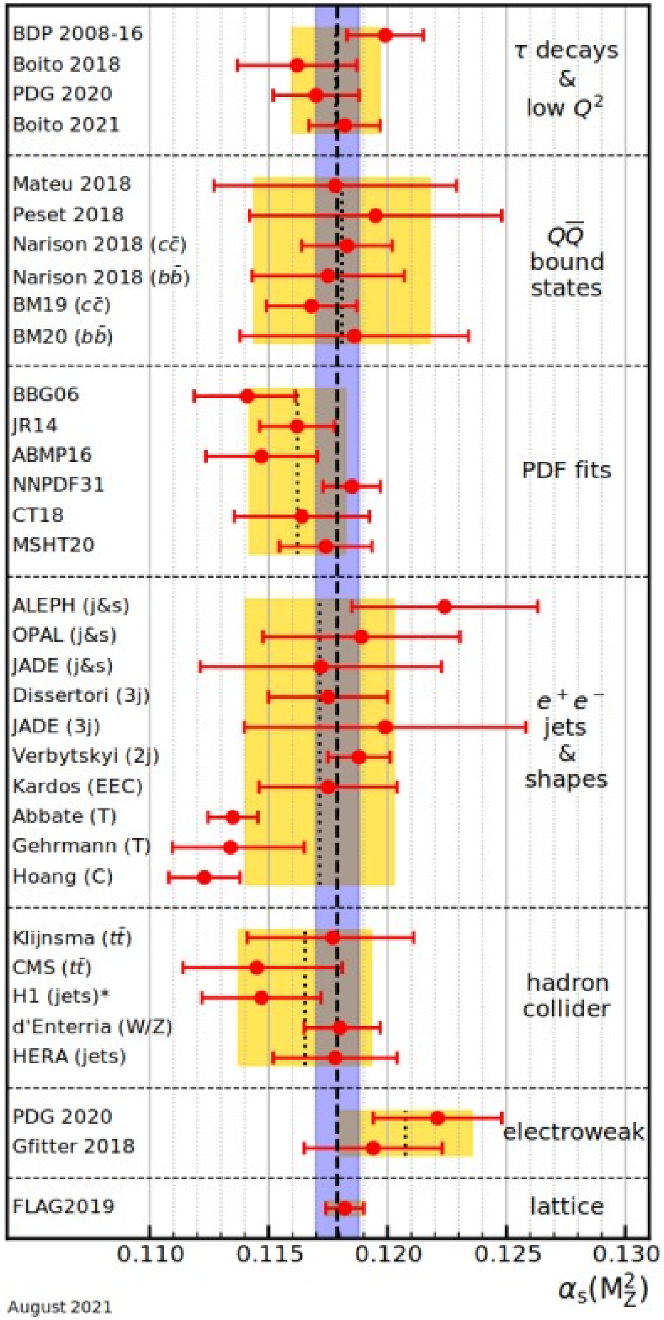
CERN YR, LHC Higgs xs WG.

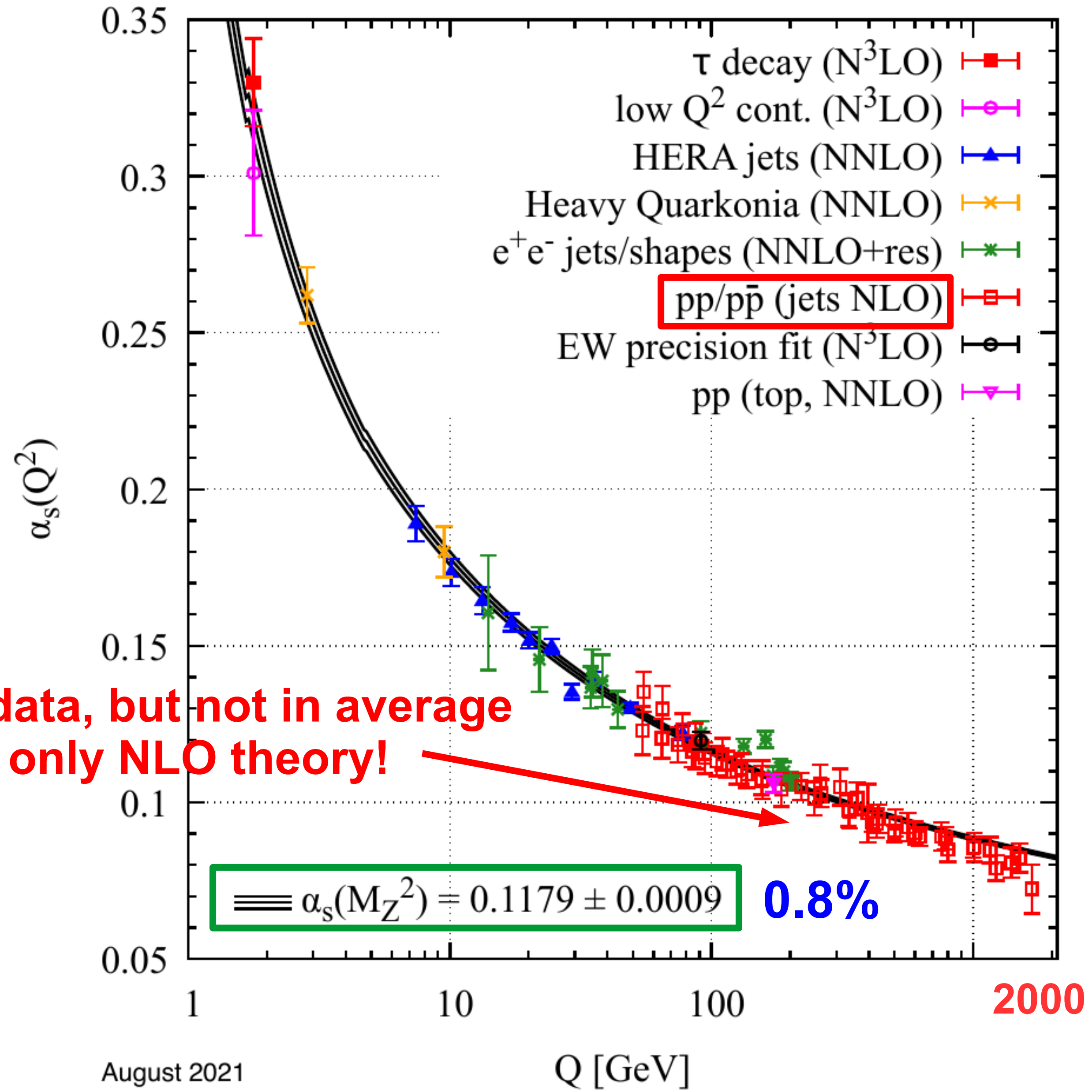
PDG α_s averaging in 6 groups



- τ hadronic decay widths & spectral functions
- heavy quarkonia decays
- global fits of proton structure & α_s
- event shapes & jet rates in e^+e^-
- observables from hh collisions & DIS
- electroweak fits
- FLAG average from lattice calculations

PDG α_s average 2022





LHC data, but not in average since only NLO theory!

0.8%

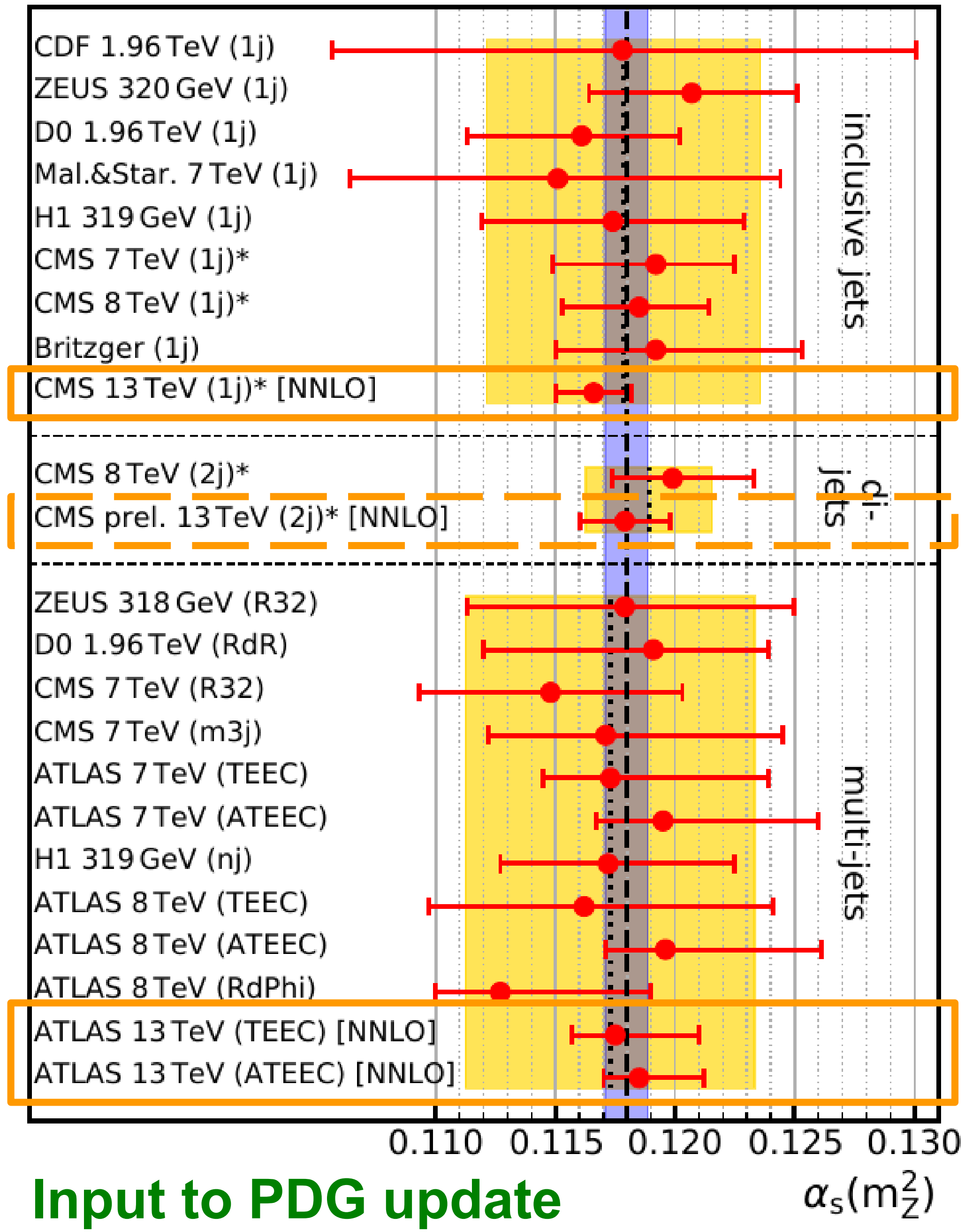
2000

PDG, PTEP (2022) 083C01.

PDG´92: 2.4%

PDG update 2023

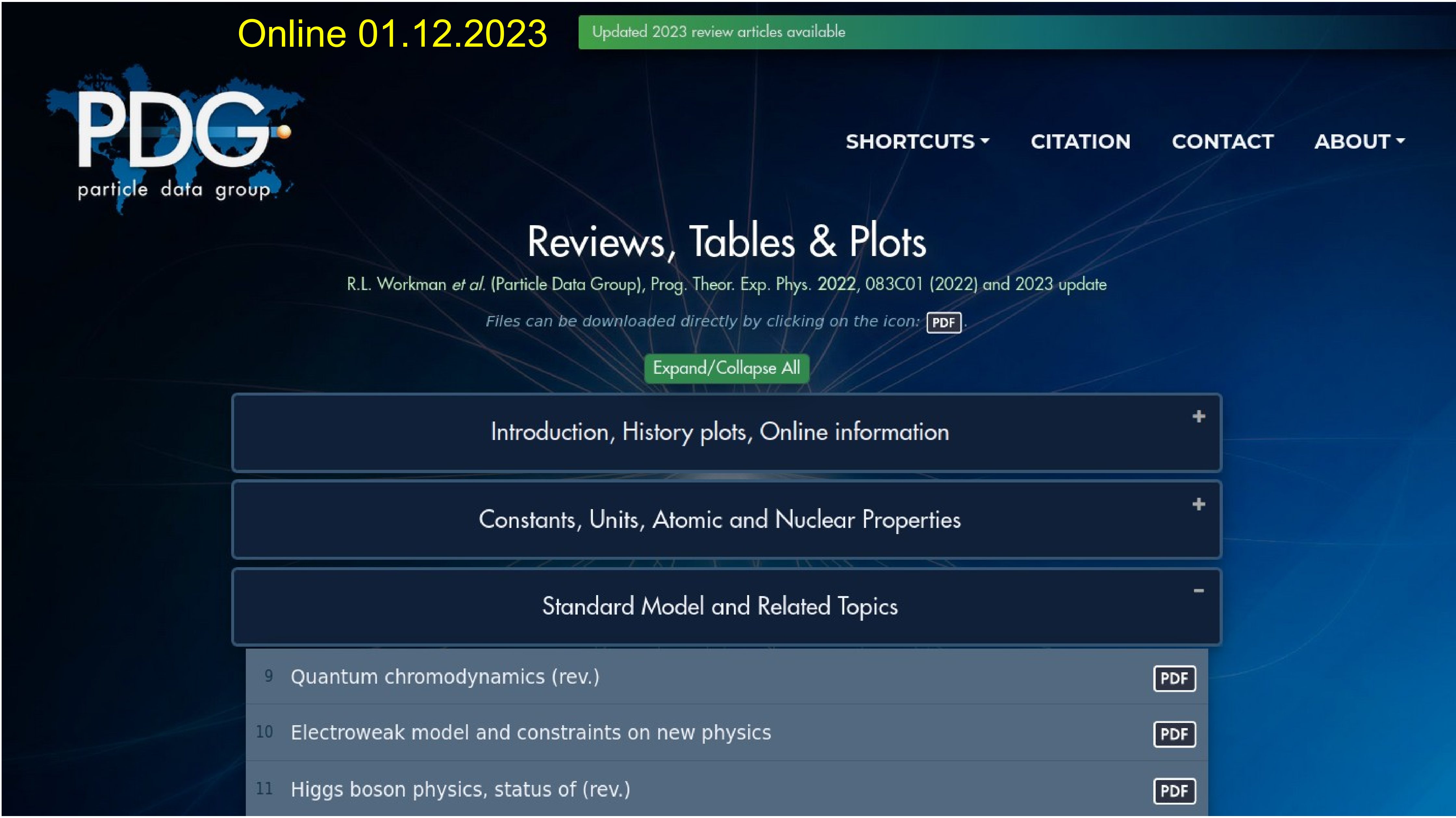
$\alpha_s(m^2_Z)$ from jet data



2023: new at NNLO!

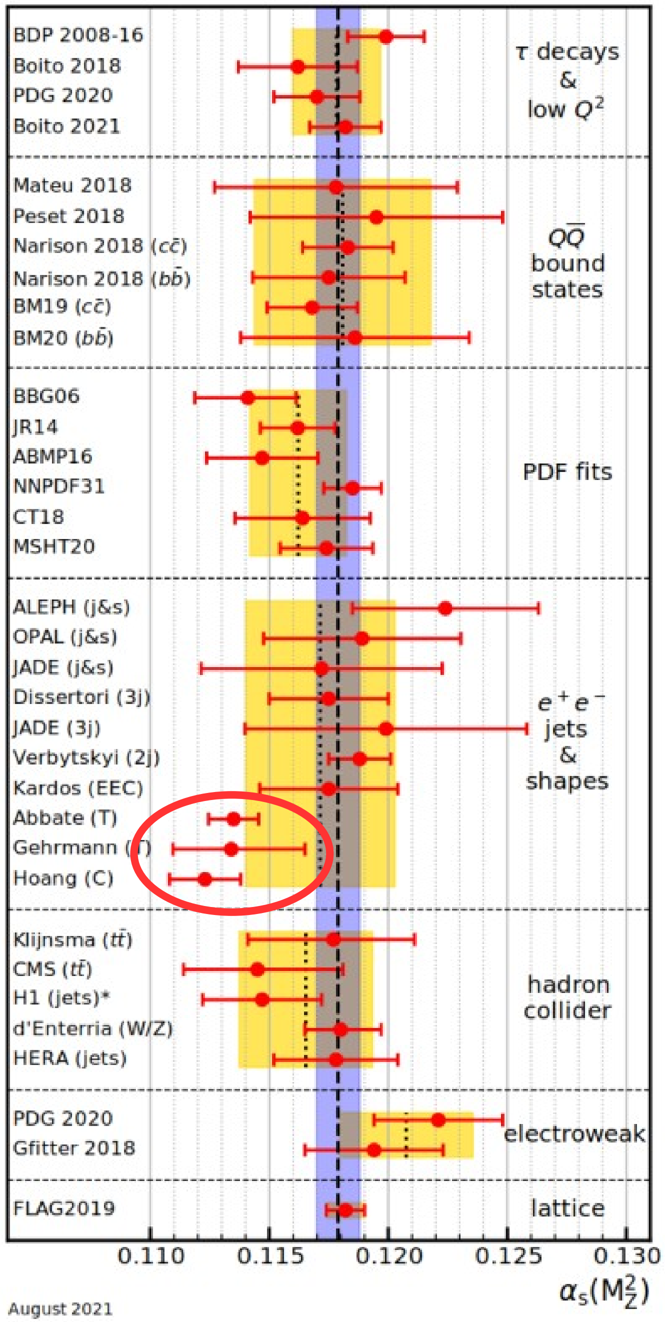
Input to PDG update

PDG 2023 online updates



https://pdg.lbl.gov/2023/reviews/contents_sports.html

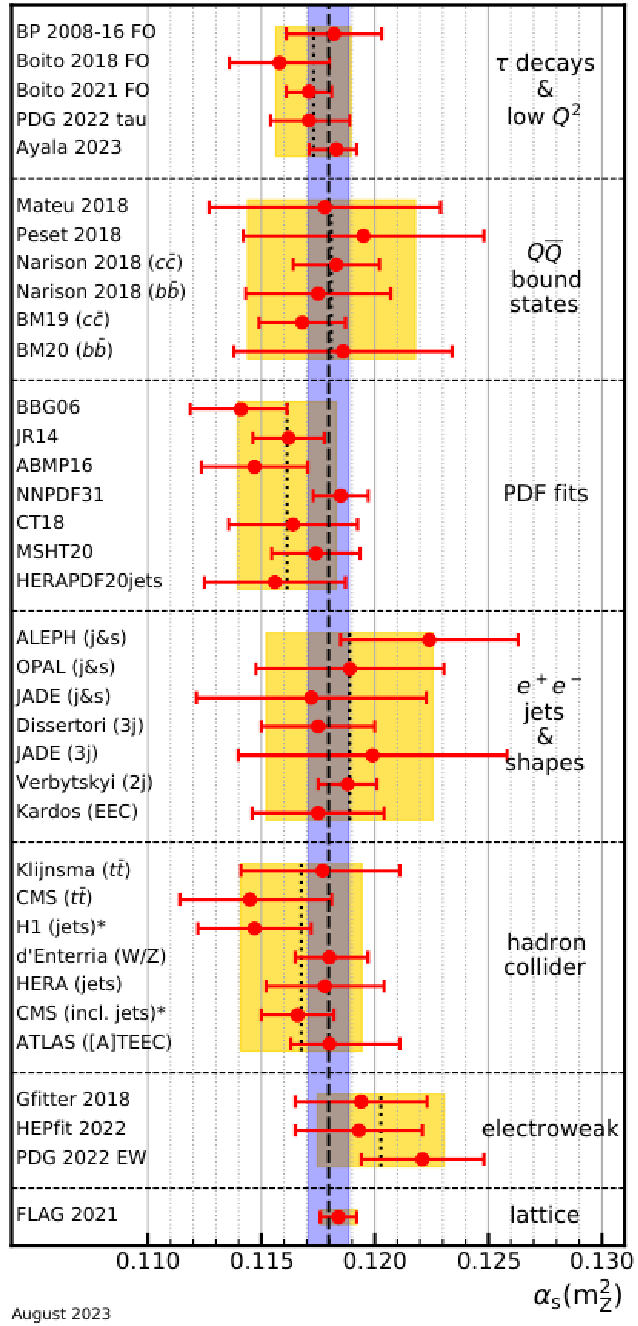
PDG α_s average 2022 → 2023



- remove CIPT → red. uncertainty
- add result, update result
- add 1 result

2022 → 2023

- remove results with analytic hadronisation corrections
- add 3 results
- add 1 result
- update FLAG result



Most prominent changes

- τ decay widths
  - two perturbative calculations used, both valid
    - fixed-order perturbation theory (FOPT)
    - contour-improved perturbation theory (CIPT)
  - finite difference between the two, $\alpha_s^{CIPT} > \alpha_s^{FOPT}$, started long debate;
→ included in uncertainty estimate
  - now found that CIPT cannot be combined with standard OPE to estimate non-perturbative effects → removed for now
- e^+e^- event shapes (thrust, C parameter)
  - analytical hadronisation corrections possible
  - but outliers with respect to MC estimated hadronisation corrections
  - now found that use of analytical model based on 2-jet configuration needs modification for 3-jet limit where α_s was extracted → removed for now

See QCD review at PDG2023 online for details and references.

PDG 2023 α_s averages

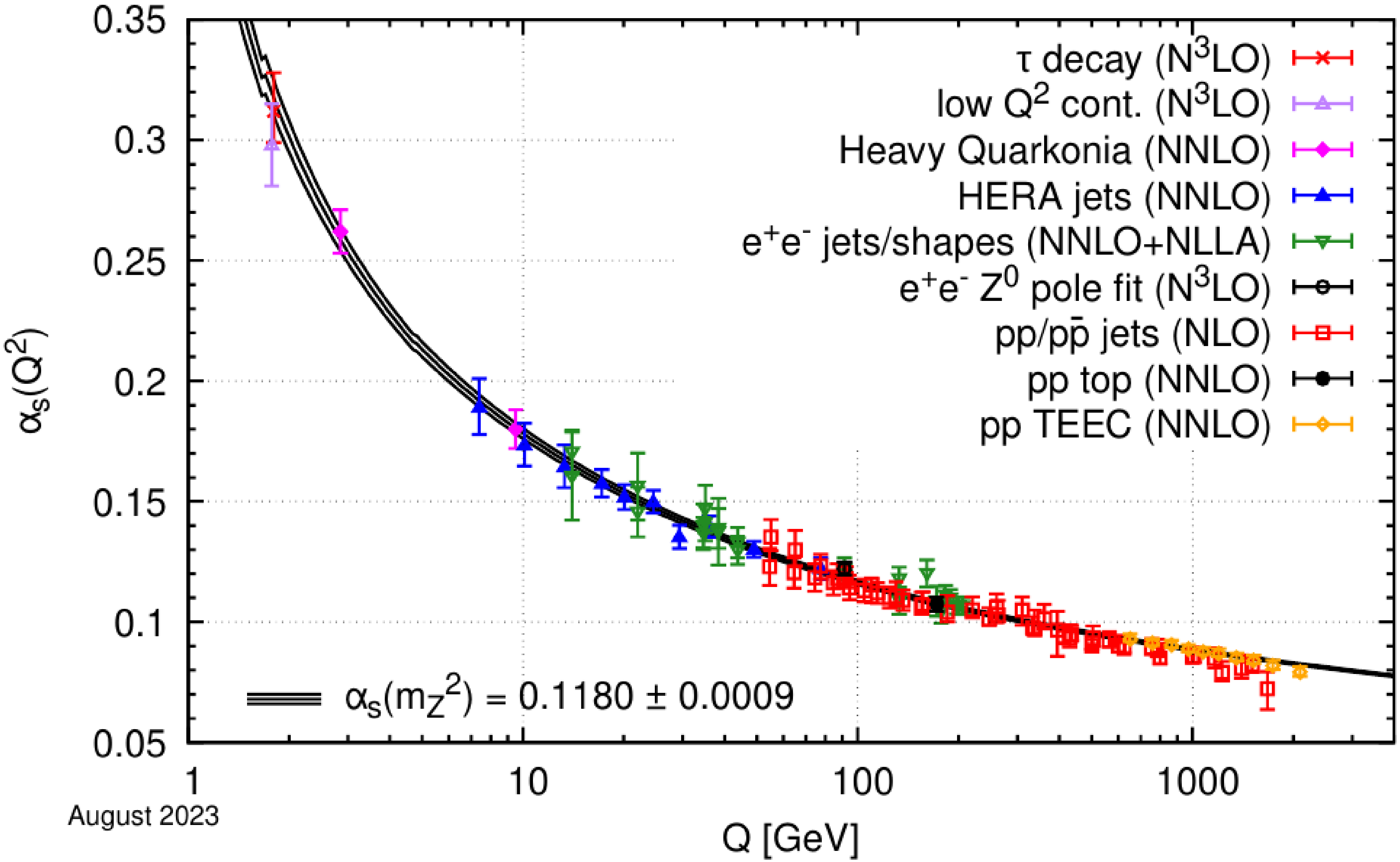
averages per sub-field	unweighted
τ decays & low Q^2	0.1173 ± 0.0017
$Q\bar{Q}$ bound states	0.1181 ± 0.0037
PDF fits	0.1161 ± 0.0022
e^+e^- jets & shapes	0.1189 ± 0.0037
hadron colliders	0.1168 ± 0.0027
electroweak	0.1203 ± 0.0028
PDG 2023 (without lattice)	0.1175 ± 0.0010

Final average including lattice (FLAG2021):

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

rel. uncertainty: 0.76%

PDG 2023 α_s running



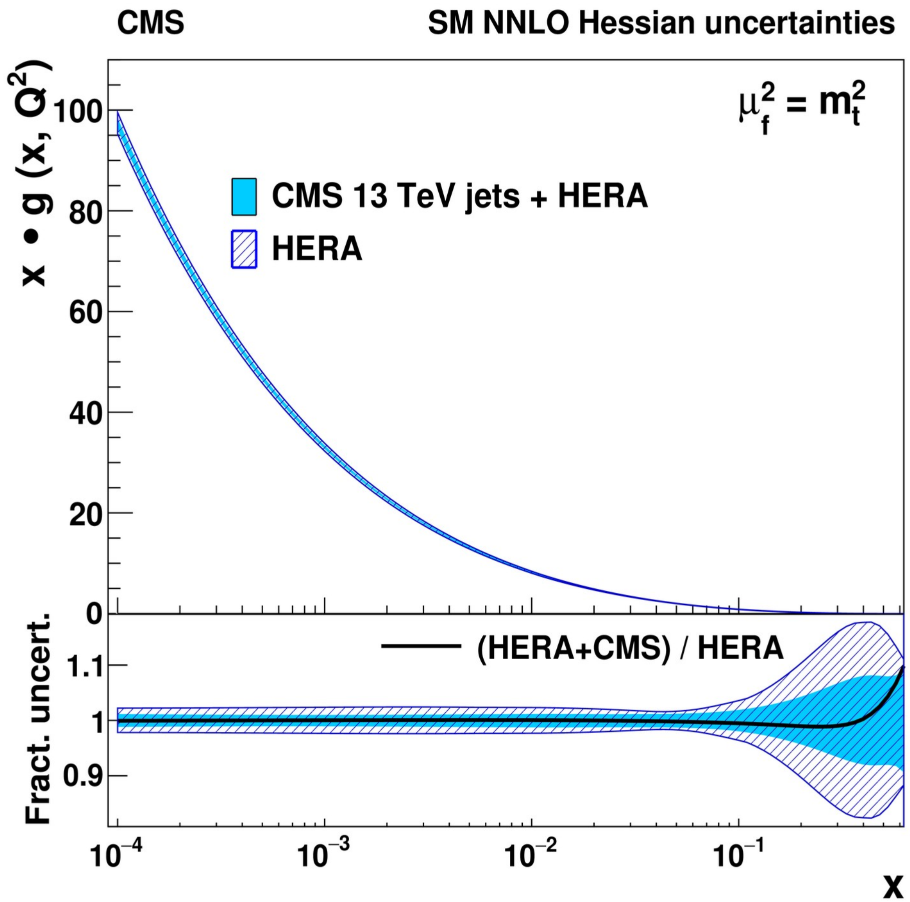
LHC news

Inclusive jets: α_s & PDFs

Simultaneous fit of α_s & PDFs possible combining HERA DIS & CMS jet data using xFitter Tool

CMS result for $\alpha_s(M_Z)$ at NNLO: $\alpha_s(m_Z^2) = 0.1166 \pm 0.0016(\text{fitall}) \pm 0.0004(\text{scl})$

Reduced uncertainties of gluon PDF



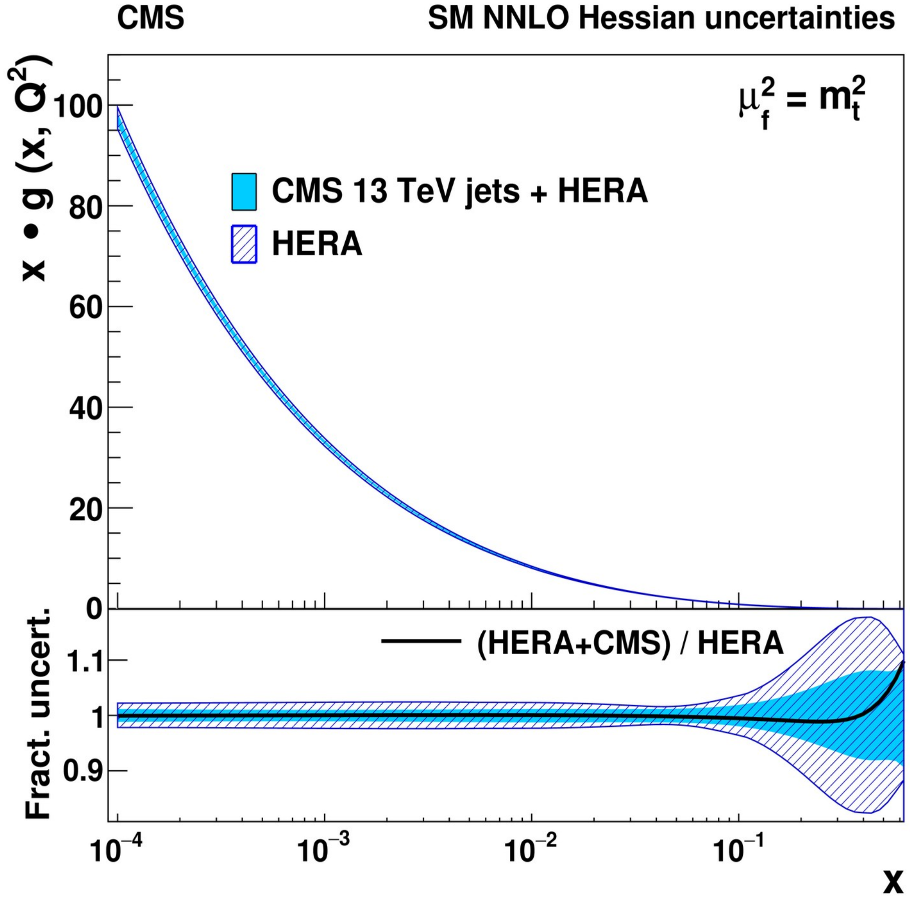
CMS, JHEP02 (2922) 142 & JHEP12 (2922) 035.

Inclusive jets: α_s & PDFs

Simultaneous fit of α_s & PDFs possible combining HERA DIS & CMS jet data using xFitter Tool

CMS result for $\alpha_s(M_Z)$ at NNLO: $\alpha_s(m_Z^2) = 0.1166 \pm 0.0016(\text{fitall}) \pm 0.0004(\text{scl})$

Reduced uncertainties of gluon PDF



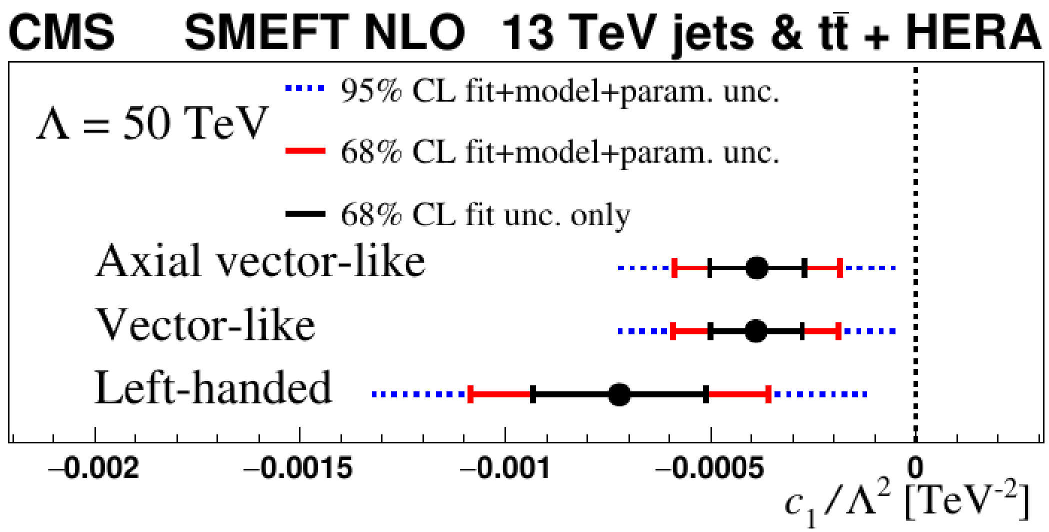
CMS, JHEP02 (2922) 142 & JHEP12 (2922) 035.

Also NLO fit of α_s & PDFs & CI

Data compatible with SM → exclusion limits

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \frac{2\pi}{\Lambda^2} \sum_{n\in\{1,3,5\}} c_n O_n.$$

EFT

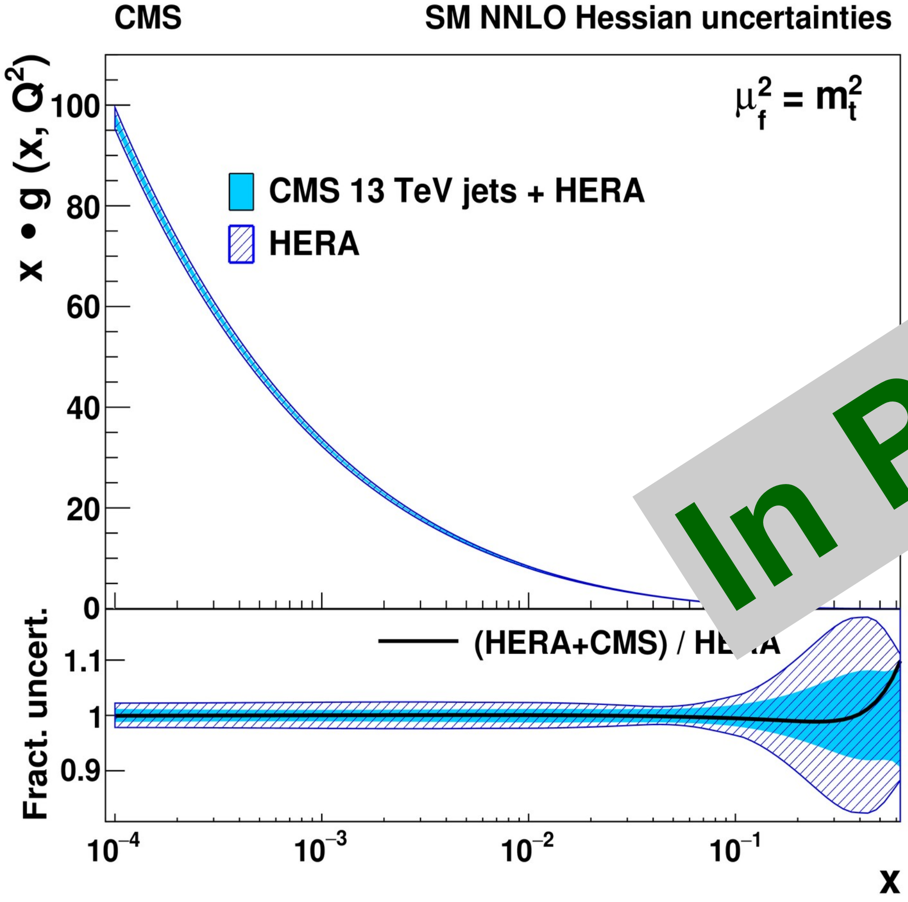


Inclusive jets: α_s & PDFs

Simultaneous fit of α_s & PDFs possible combining HERA DIS & CMS jet data using xFitter Tool

CMS result for $\alpha_s(M_Z)$ at NNLO: $\alpha_s(m_Z^2) = 0.1166 \pm 0.0016(\text{fitall}) \pm 0.0004(\text{scl})$

Reduced uncertainties of gluon PDF



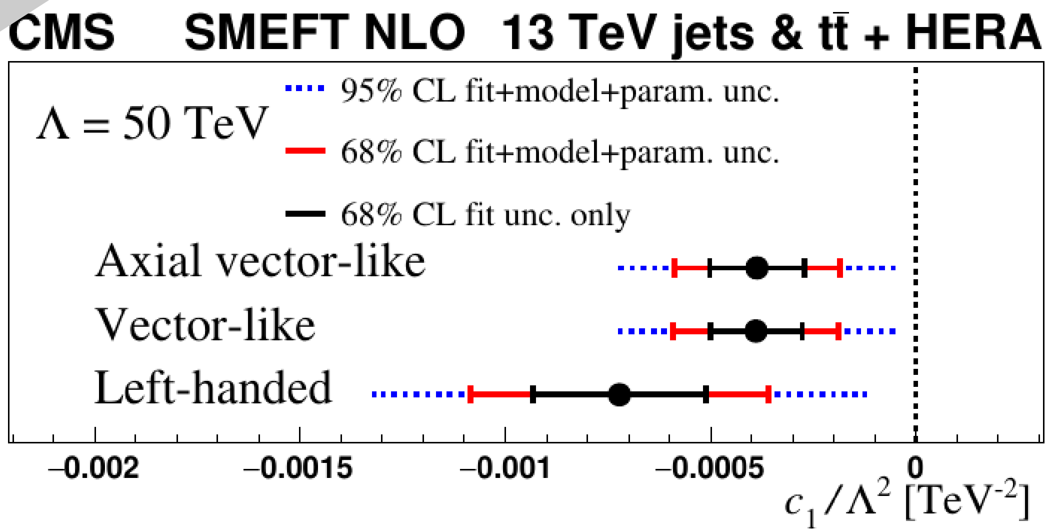
Also NLO fit of … & PDFs & CI

Data comp… …h SM → exclusion limits

$$\ldots\mathcal{L}_{\mathrm{SM}} + \frac{2\pi}{\Lambda^2} \sum_{n\in\{1,3,5\}} c_n O_n.$$

EFT

In PDG 2023



CMS, JHEP02 (2922) 142 & JHEP12 (2922) 035.

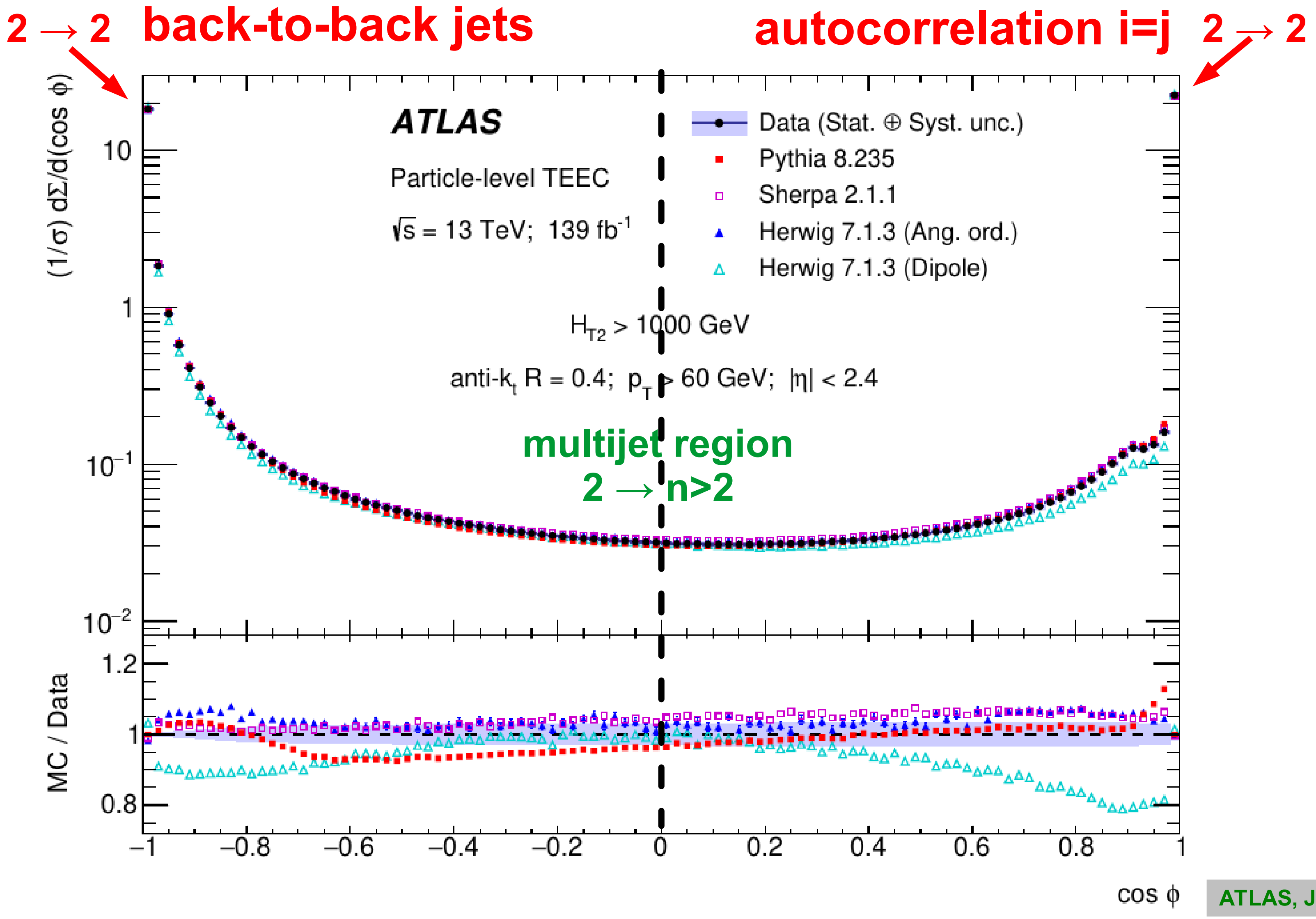
Transverse energy-energy correlation

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

$$\mathrm{TEEC} \propto \alpha_s$$

Normalised

Multiple bins in H_T



ATLAS, JHEP 07 (2023) 085.

Transverse energy-energy correlation

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

Asymmtry

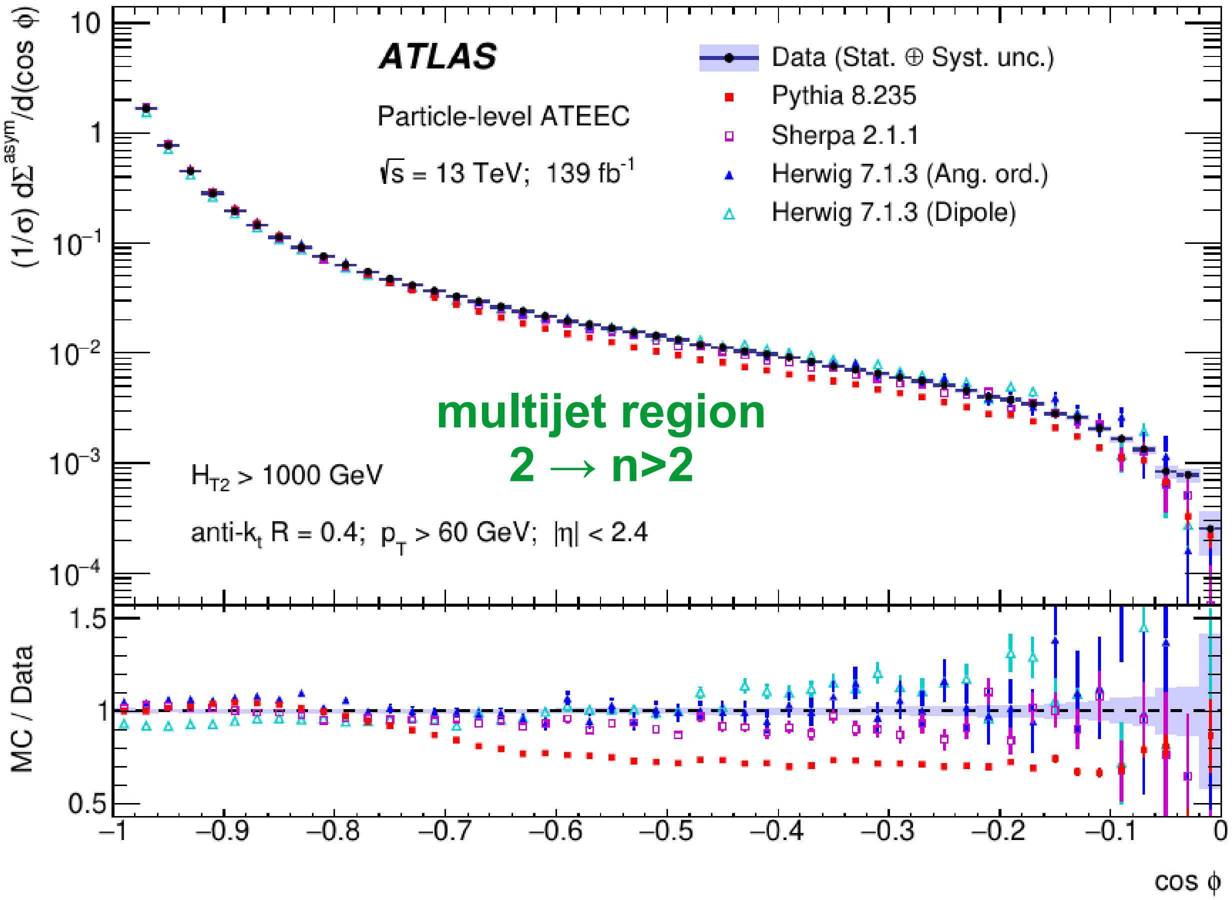
$$\text{ATEEC} \propto \alpha_s$$

NNLO

$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\ (\text{exp.})^{+0.0034}_{-0.0017}\ (\text{theo.})$$

$$\alpha_s(m_Z) = 0.1185 \pm 0.0009\ (\text{exp.})^{+0.0025}_{-0.0012}\ (\text{theo.})$$

Normalised



ATLAS, JHEP 07 (2023) 085.

Transverse energy-energy correlation

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

Asymmtry

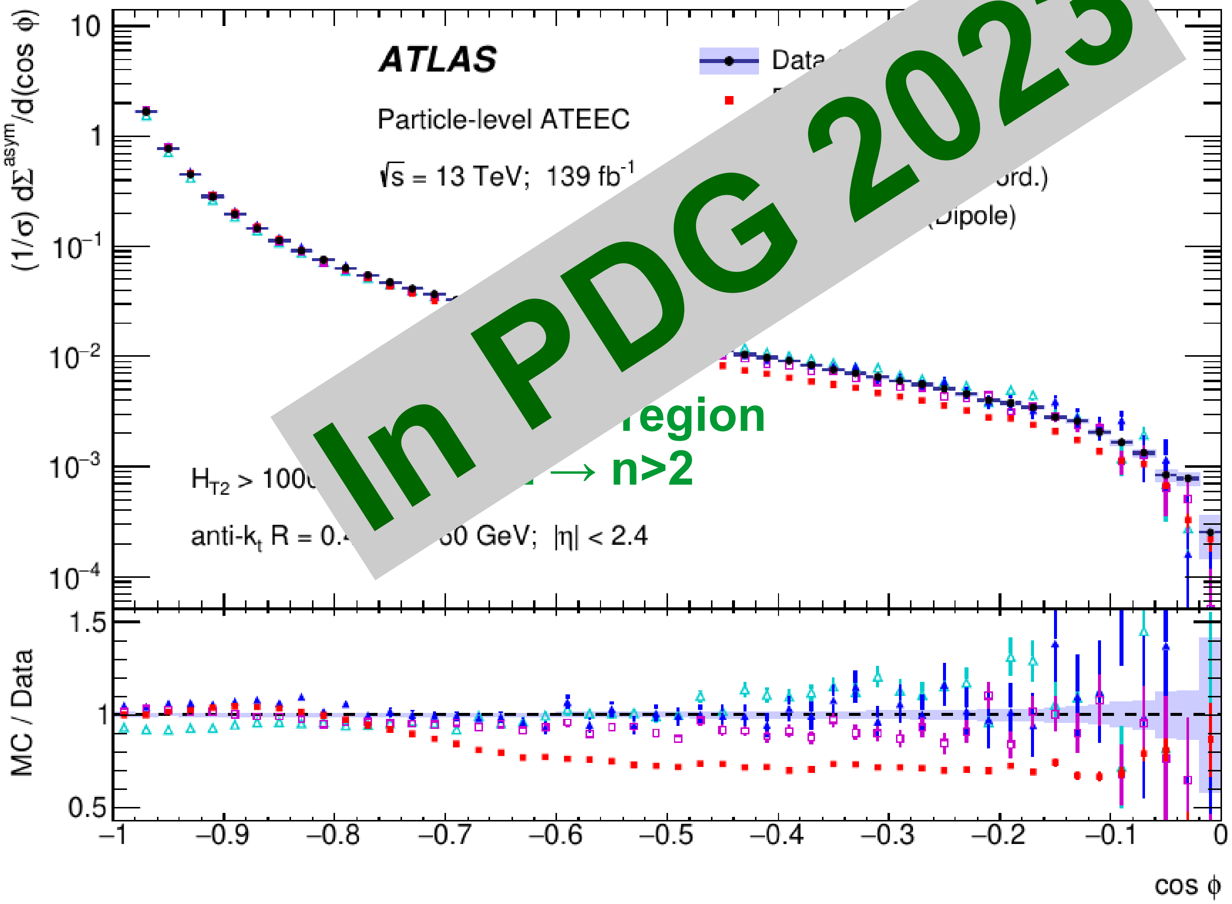
$$\text{ATEEC} \propto \alpha_s$$

NNLO

$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\ (\text{exp.})^{+0.0034}_{-0.0017}\ (\text{theo.})$$

$$\alpha_s(m_Z) = 0.1185 \pm 0.0009\ (\text{exp.})^{+0.0025}_{-0.0012}\ (\text{theo.})$$

Normalised



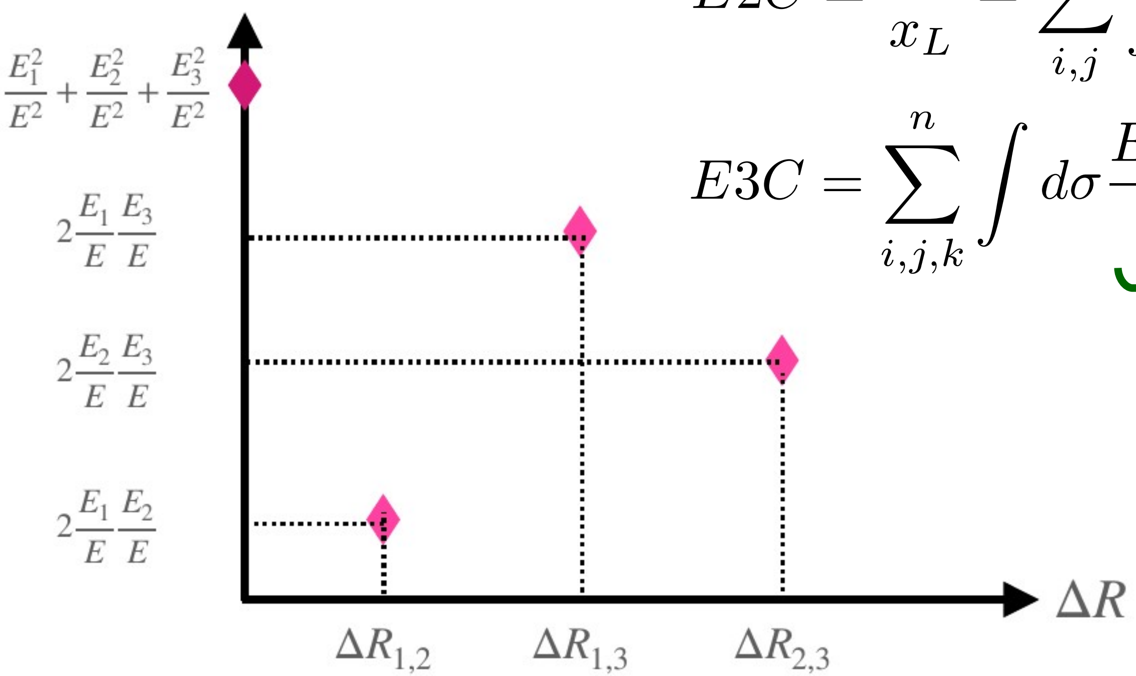
ATLAS, JHEP 07 (2023) 085.

Jet substructure variable representing correlations of energy flow inside jets

- **measure 2- and 3-point energy correlators**
- **multiple entries, i.e. for each pair or triple inside jet**

$$E2C = \frac{\sigma}{x_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E_{\text{jet}}^2} \delta\left(x_L - \Delta R_{ij}\right)$$

$$E3C = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E_{\text{jet}}^3} \delta\left(x_L - \max\left\{\Delta R_{ij}, \Delta R_{jk}, \Delta R_{ki}\right\}\right)$$



distance → x-axis

weight → y-axis

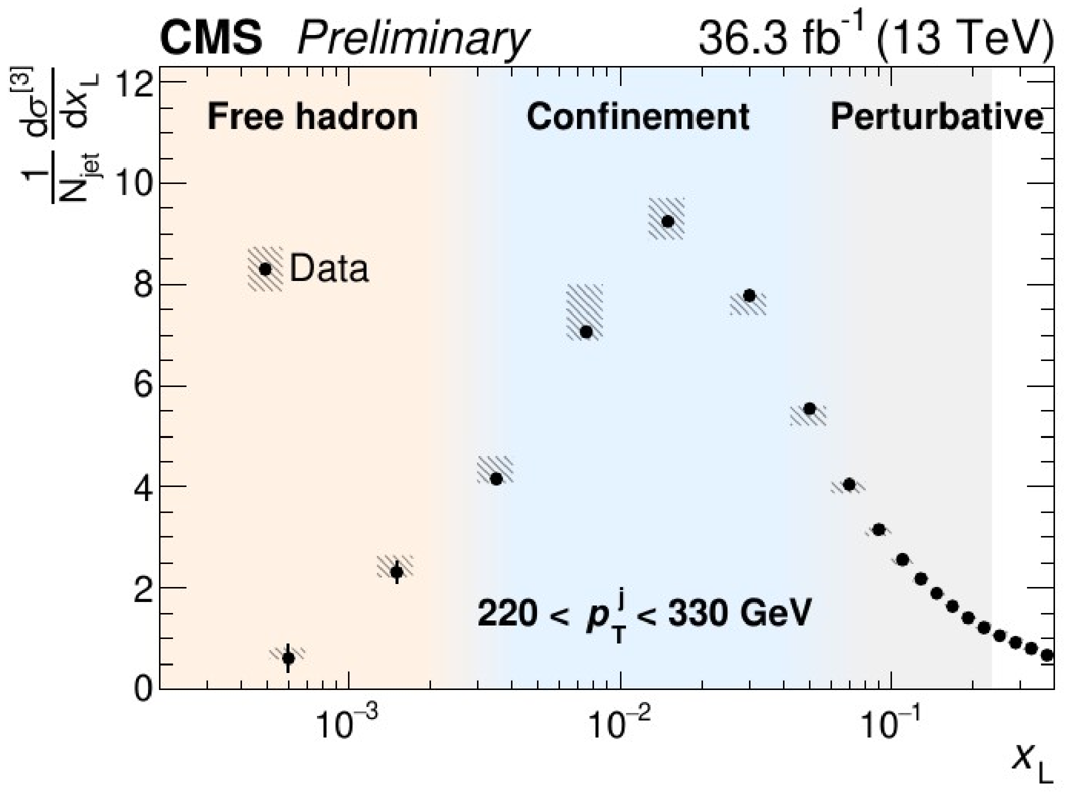
Yulei Ye

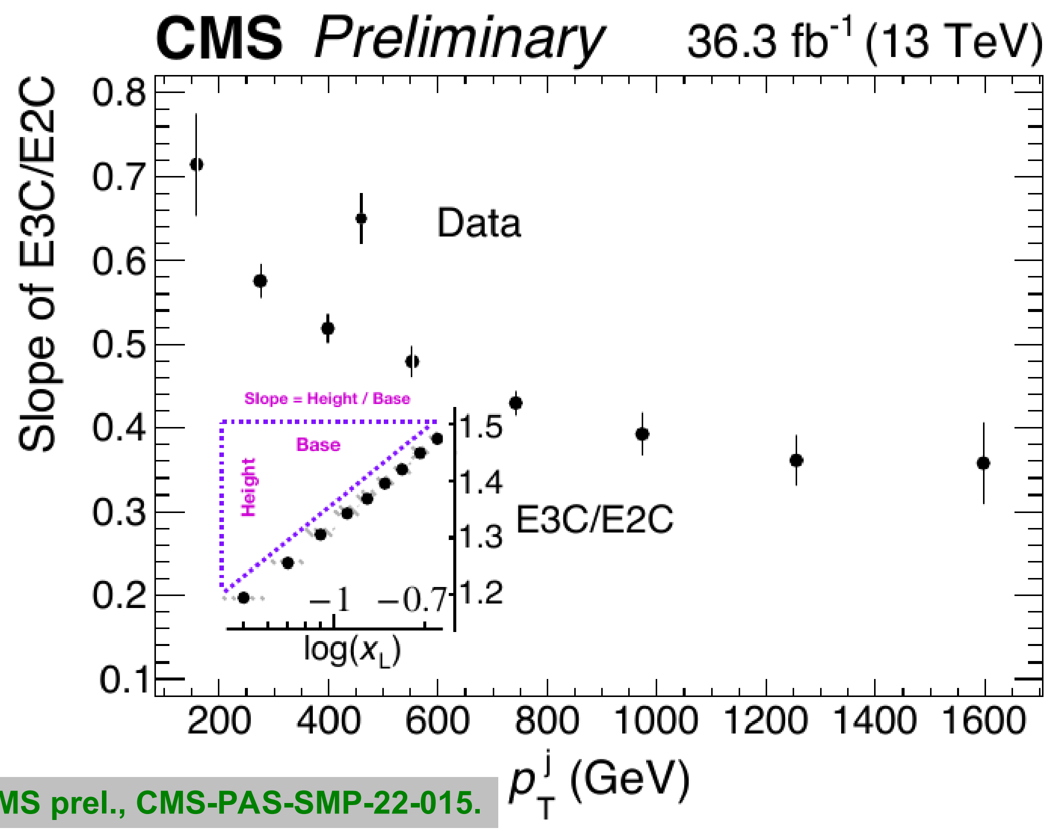
$3 * 3 = 9$ pairs

Chen et al., arXiv:2004.11381; Lee et al., arXiv:2205.0314; Chen et al., arXiv:2307.07510.

N-point E-E correlators in jets

Unfolded data distribution of E3C





Ratio of E3C/E2C

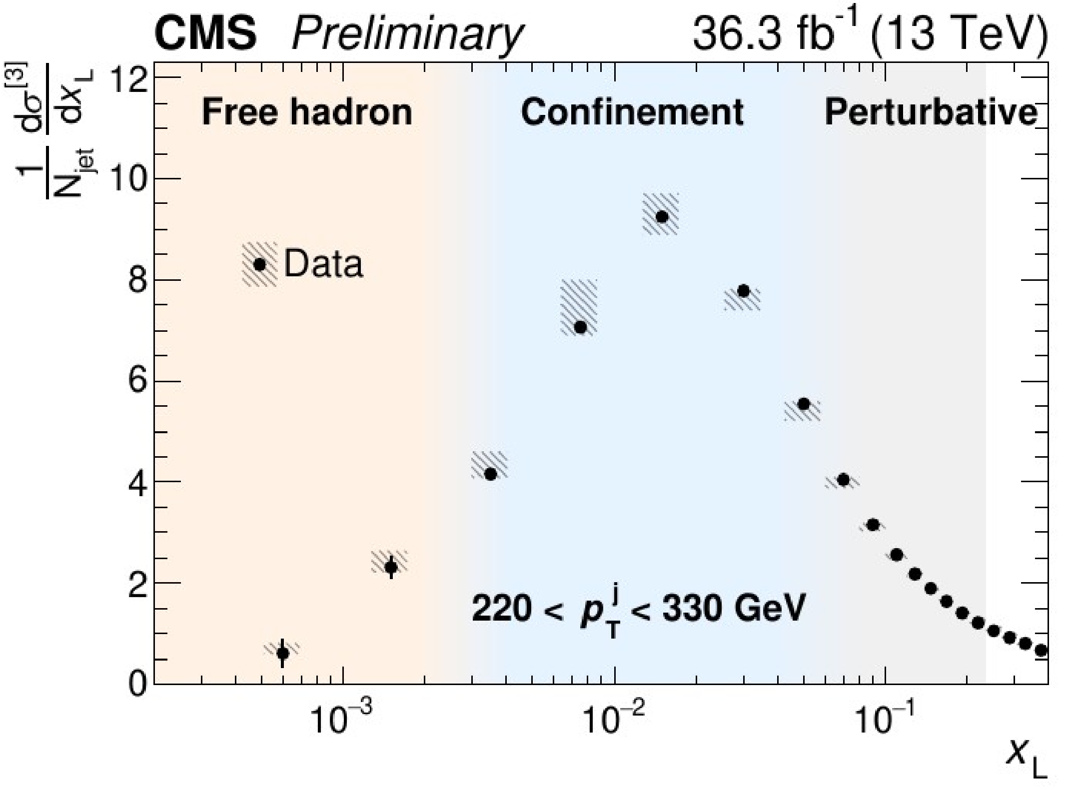
$$\propto \alpha_s(Q) \ln R + \mathcal{O}(\alpha_s^2)$$

$$\alpha_s(M_Z) = 0.1229^{+0.0040}_{-0.0050}$$

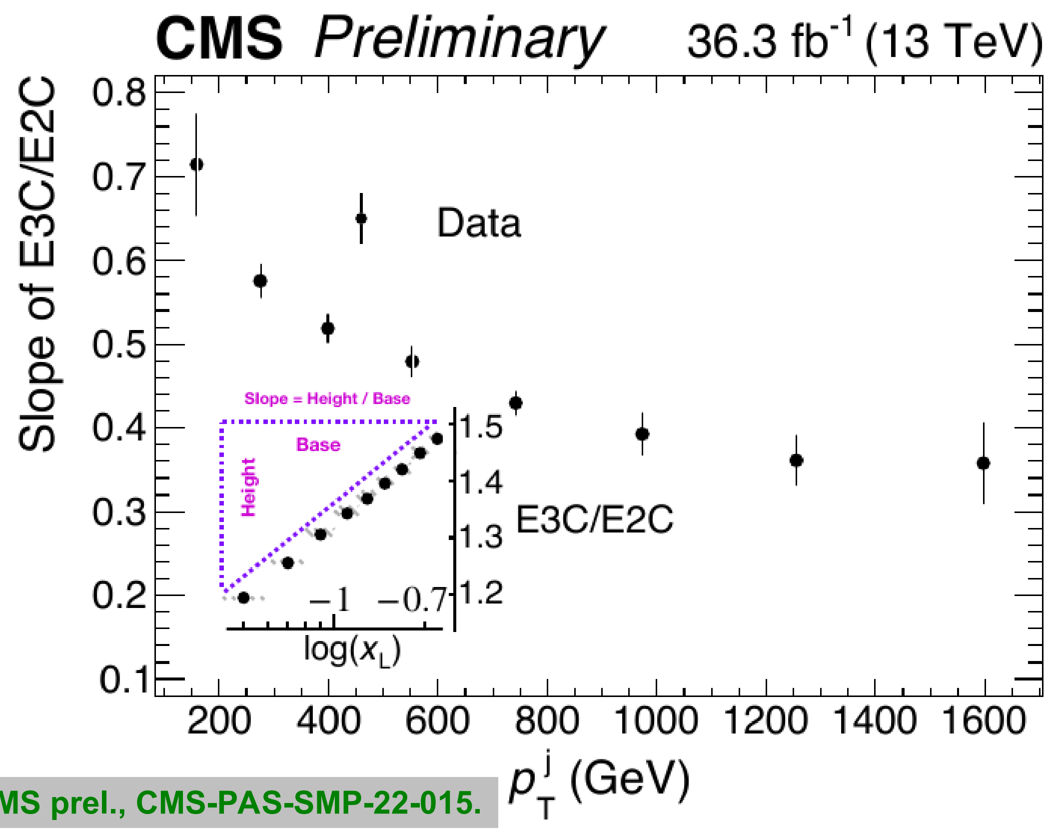
NLO

CMS prel., CMS-PAS-SMP-22-015.

Unfolded data distribution of E3C



E2C also studied by ALICE and STAR
→ study at EIC, see talk by B. Jacak



Ratio of E3C/E2C

$$\propto \alpha_s(Q)\ln R + \mathcal{O}(\alpha_s^2)$$

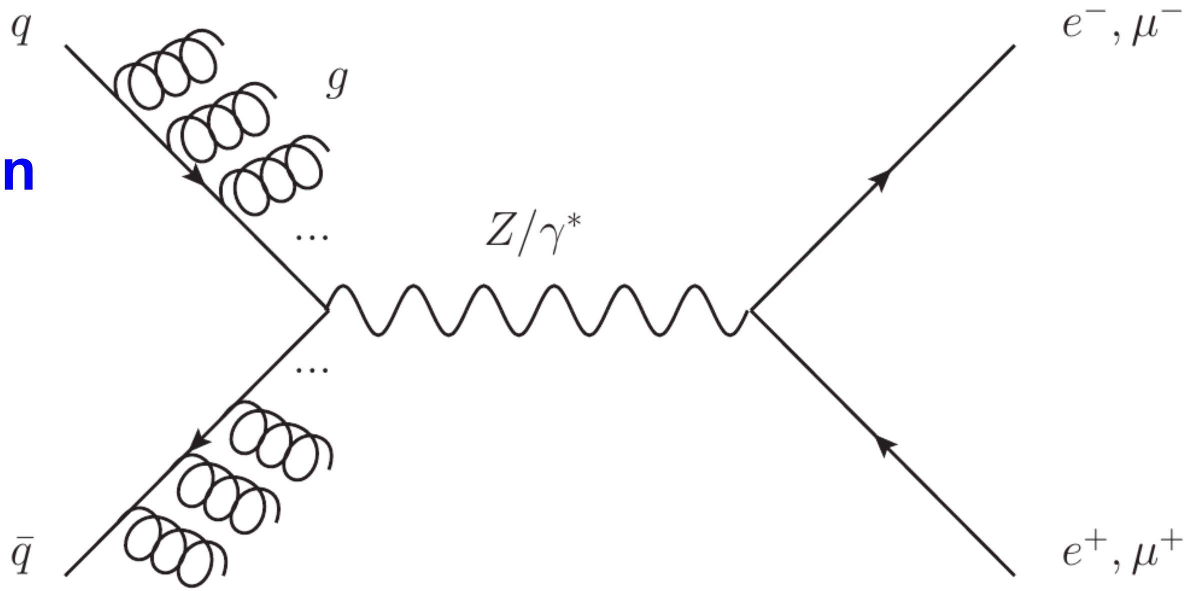
$$\alpha_s(M_Z) = 0.1229^{+0.0040}_{-0.0050}$$

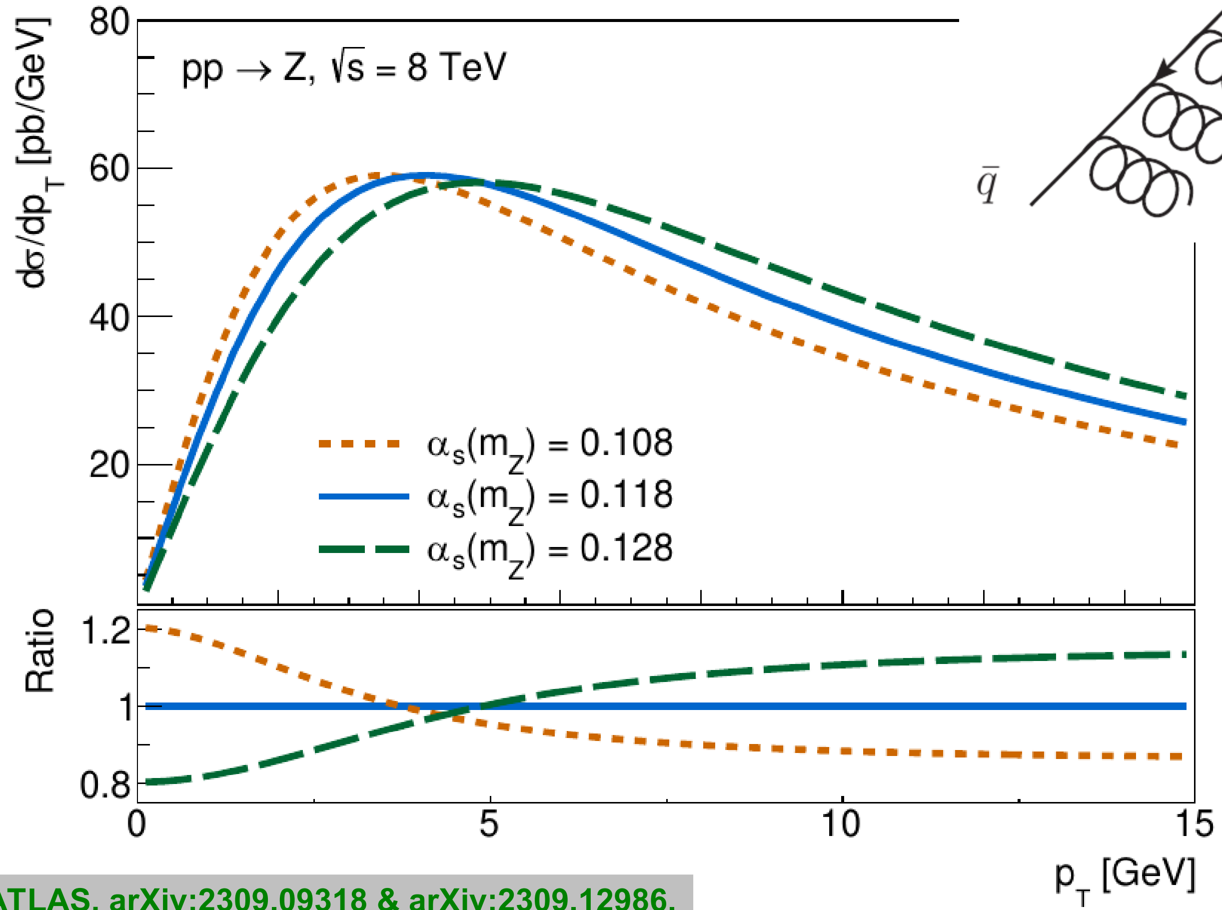
NLO

CMS prel., CMS-PAS-SMP-22-015.

Sudakov peak of Z p_T

Multiple gluon emissions in initial state require resummation to predict shape of Z pT distribution



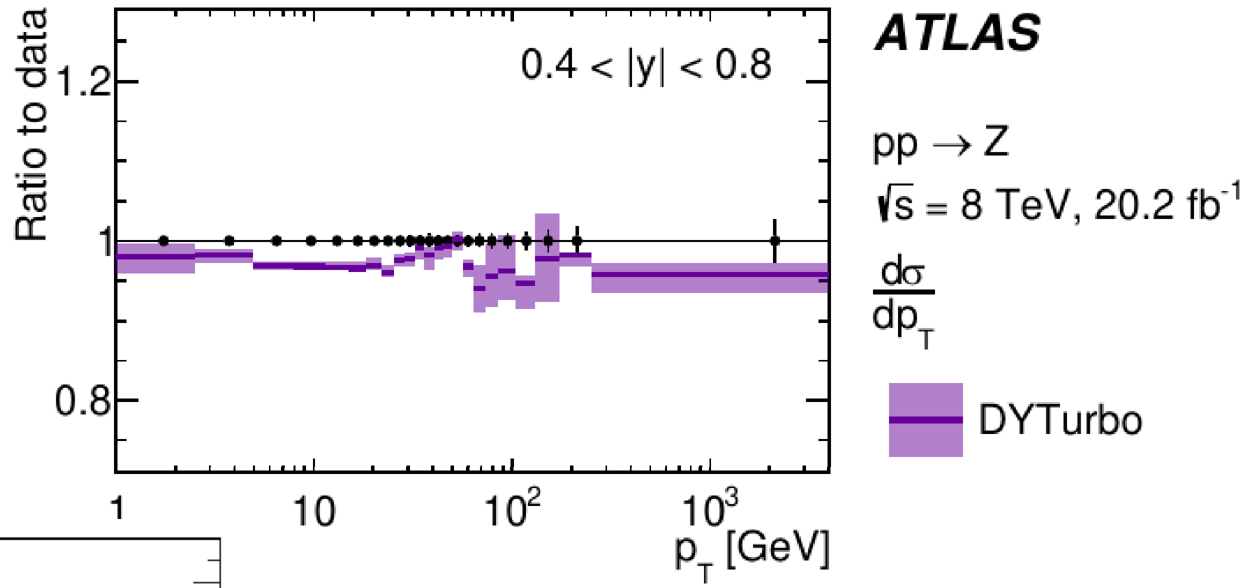


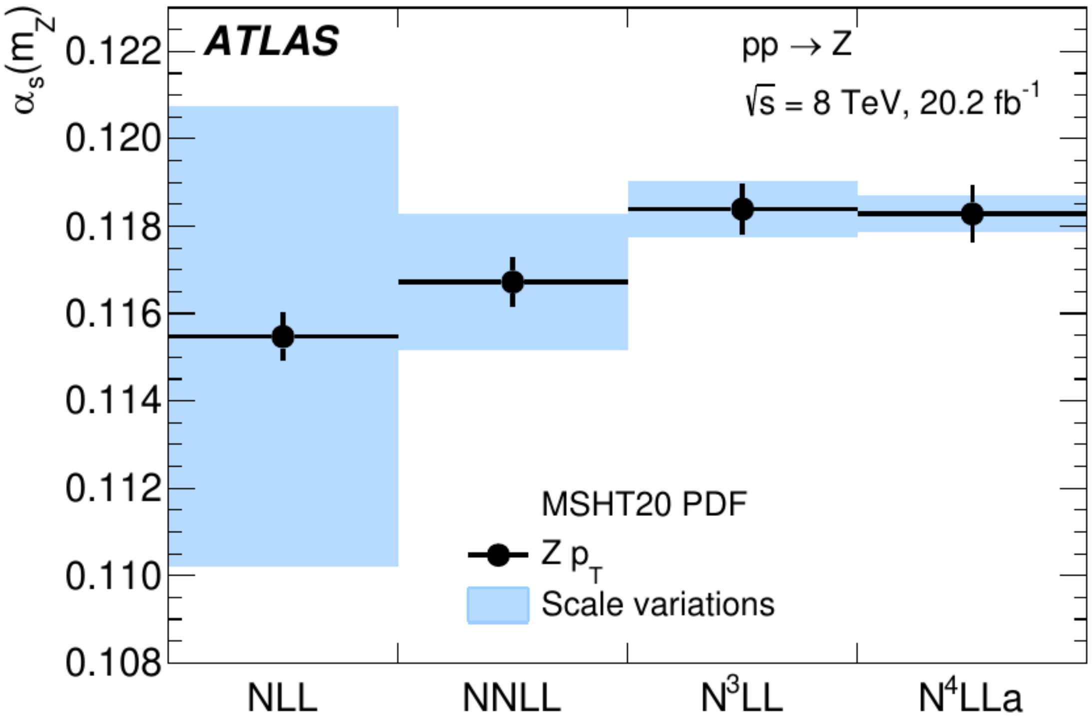
Sensitivity to α_s

ATLAS, arXiv:2309.09318 & arXiv:2309.12986.

Sudakov peak of Z p_T

Ratio to data of DYTurbo resummed+matched fixed-order prediction





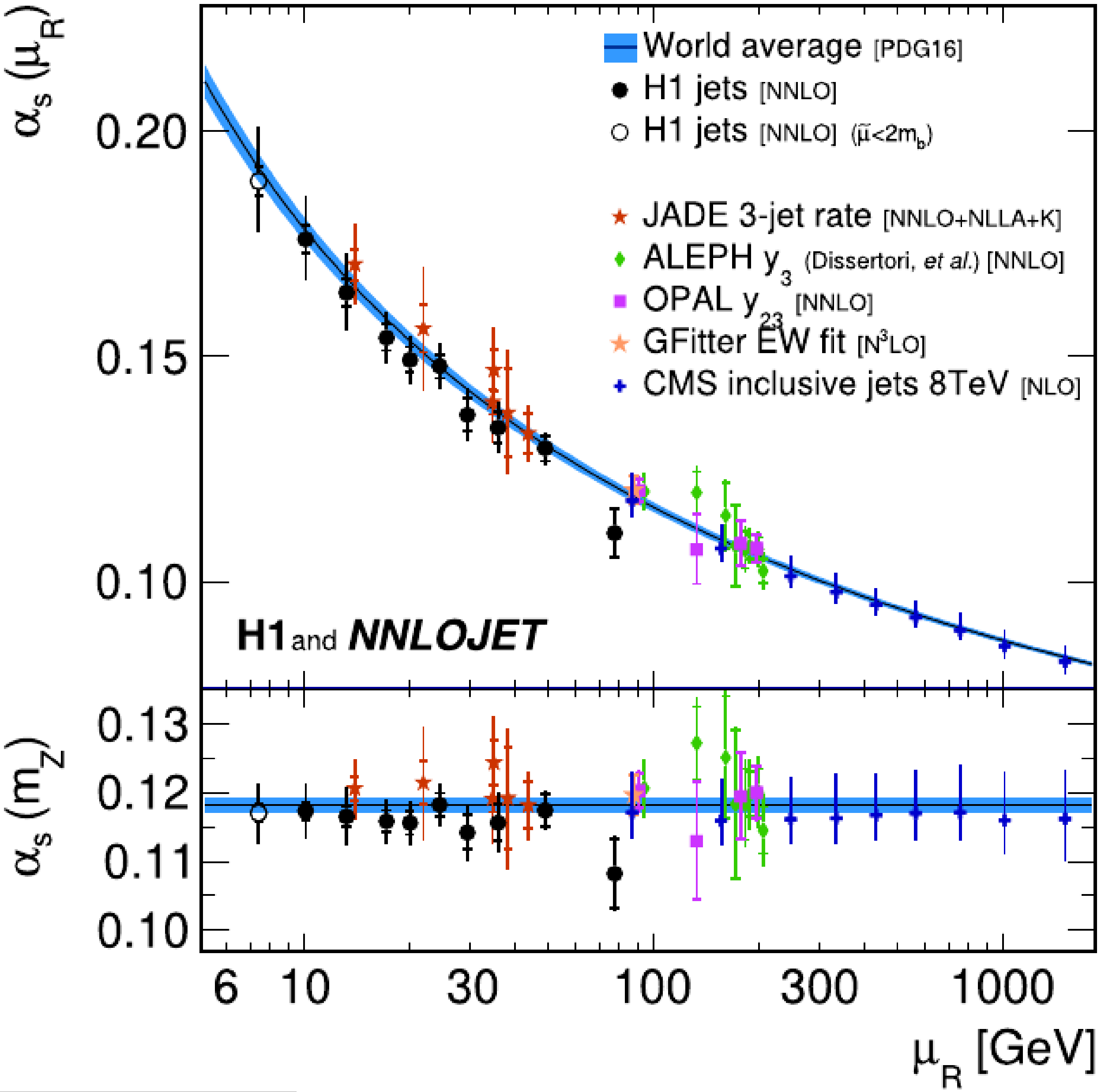
Series of α_s extractions with increasing precision

$$\alpha_s(M_Z) = 0.1183 \pm 0.0009$$

Size of uncertainty stimulated discussion ...

ATLAS, arXiv:2309.09318 & arXiv:2309.12986.

EIC & LHC perspectives



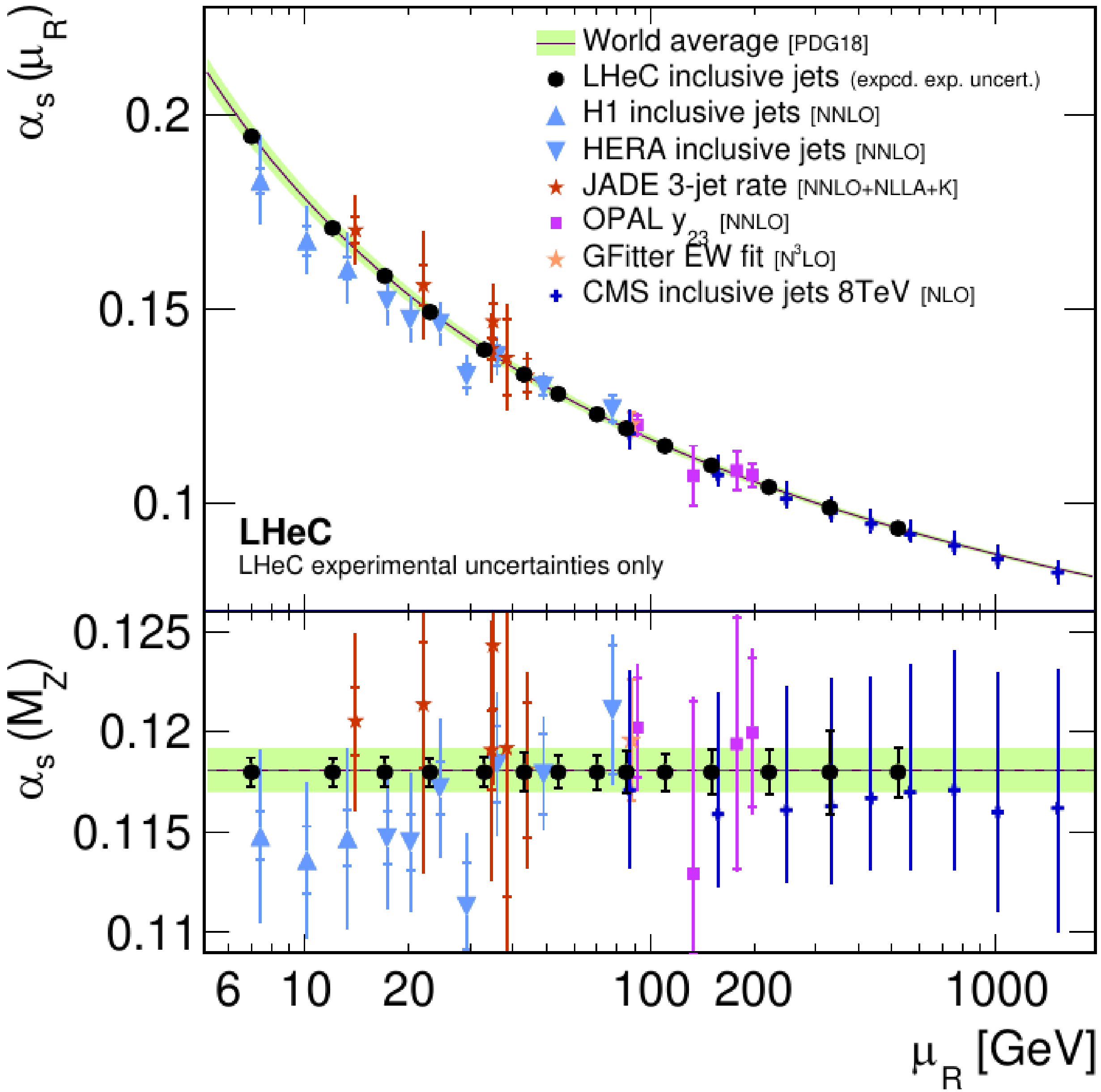
Combined fit of PDF+α_s to DIS and jet data now at NNLO

$$\alpha_s(M_Z) = 0.1147 \pm 0.0012$$
$$\pm 0.0023(\mathrm{MHO})$$

In PDG 2021

H1, EPJC81 (2021) 738.

DIS & structure functions



Combined fit of PDF+α_s possible to DIS data alone (NNLO)

$$\Delta\alpha_s(M_Z) = \pm 0.00022(\text{exp} + \text{PDF})$$

and to jet data in addition (NNLO)

$$\Delta\alpha_s(M_Z) = \pm 0.00018(\text{exp} + \text{PDF})$$

Also big impact on global PDF fits (ABM, CT, …) & N3LO NS structure function → Snowmass report 2021

LheC & FCC-eh study, arXiv:2007.14491.

Projections from Snowmass 2013

Still at LHC:

Only jets probe running α_s at highest scales

< 1% uncertainty at M_Z challenging ...

Need NNLO and improved PDFs (gluon) plus some experimental optimization

Method	Current relative precision	Future relative precision	
e^+e^- evt shapes	expt ~ 1% (LEP) thry ~ 1–3% (NNLO+up to N^{3}LL, n.p. signif.) [27]	< 1% possible (ILC/TLEP) ~ 1% (control n.p. via Q^2-dep.)	~1%
e^+e^- jet rates	expt ~ 2% (LEP) thry ~ 1% (NNLO, n.p. moderate) [28]	< 1% possible (ILC/TLEP) ~ 0.5% (NLL missing)	
precision EW	expt ~ 3% (R_Z, LEP) thry ~ 0.5% (N^{3}LO, n.p. small) [9,29]	0.1% (TLEP [10]), 0.5% (ILC [11]) ~ 0.3% (N^{4}LO feasible, ~ 10 yrs)	<1%
τ decays	expt ~ 0.5% (LEP, B-factories) thry ~ 2% (N^{3}LO, n.p. small) [8]	< 0.2% possible (ILC/TLEP) ~ 1% (N^{4}LO feasible, ~ 10 yrs)	
ep colliders	~ 1–2% (pdf fit dependent) [30,31], (mostly theory, NNLO) [32,33]	0.1% (LHeC + HERA [23]) ~ 0.5% (at least N^{3}LO required)	<1%
hadron colliders	~ 4% (Tev. jets), ~ 3% (LHC $t\bar{t}$) (NLO jets, NNLO $t\bar{t}$, gluon uncert.) [17,21,34]	< 1% challenging (NNLO jets imminent [22])	~1%
lattice	~ 0.5% (Wilson loops, correlators, ...) (limited by accuracy of pert. th.) [35–37]	~ 0.3% (~ 5 yrs [38])	<0.5%

Snowmass QCD Report, arXiv:1310.5189.

Snowmass 2021

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

Snowmass 2021 arXiv:2203.08271

Two goals for α_s:

1. Measure the running of $\alpha_s(Q)$ up to the highest scales possible

→ looked after $\alpha_s(Q)$!

2. Measure $\alpha_s(M_Z)$ as precisely as possible

→ find phase space with small uncertainties:

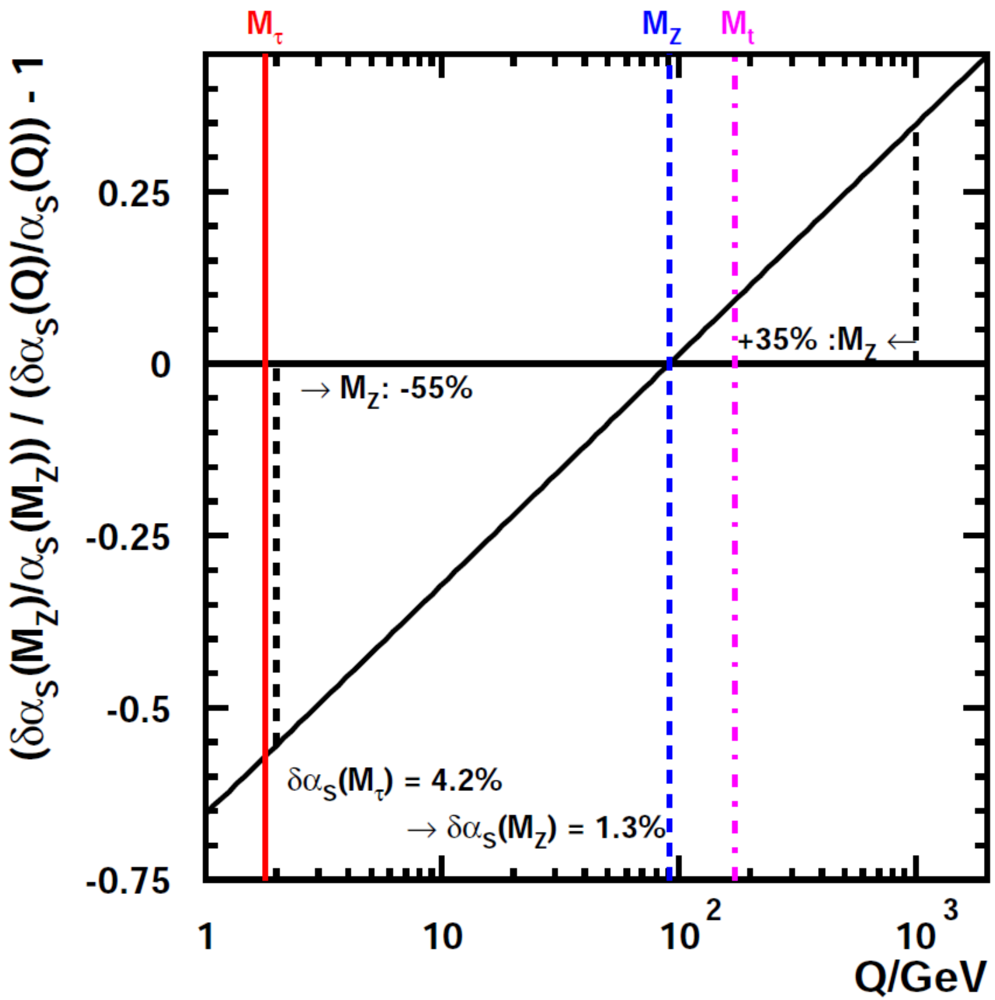
20 – 200 GeV, central rapidity

Better in:
- JEC uncertainty
- PDF uncertainty
- Evolution to M_Z

Worse in: NP effects

Incredibly shrinking error →

← Uncomfortably growing error



Summary & Outlook

- LHC at 7, 8, and 13 TeV enabled to test $\alpha_s(Q)$ up to Q ~ 2 TeV
- LHC results reached $\Delta\alpha_s(M_Z)$ ~ 0.5% experimentally
- LHC theory uncertainty still leads to $\Delta\alpha_s(M_Z)$ ~ 1.5% in total (except one)
- Theory at full N3LO desperately needed
- Lattice gauge reached $\Delta\alpha_s(M_Z)$ ~ 0.6%, has potential for permille level
- With N3LO great potential for $\Delta\alpha_s(M_Z) < 0.5\%$ from DIS, structure functions and jets at EIC (& LHeC)

Backup Slides

New LHC results

Exp.	$\sqrt{s}$ / TeV	Lumi / fb^{-1}	Theory	Obs.	$\alpha_s(M_Z)$	$\Delta\alpha_s$ exp	$\Delta\alpha_s$ oth	$\Delta\alpha_s$ scale	Ref.
CMS	13	33.5	NNLO	Jet pT	0.1166	14 (NP)	7	4	JHEP12(2022) 035
ATLAS	13	139	NNLO	TEEC	0.1175	6	12	+32 -11	JHEP07(2023)085
ATLAS	13	139	NNLO	ATEEC	0.1185	9	12	+22 -2	JHEP07(2023)085
CMS	13	36.3	NNLO	2D m_{jj}	0.1201	12 (NP)	9	8	SMP-21-008
CMS	13	36.3	NNLO	3D m_{jj}	0.1201	10 (NP)	10	5	SMP-21-008
ATLAS	8	20.2	N4LLa + FO	Z pT	0.1183	4	7	4	arXiv:2309.12986