Latest results on the strong coupling at the LHC

Seminar at the
Department of Physics
University of Oxford

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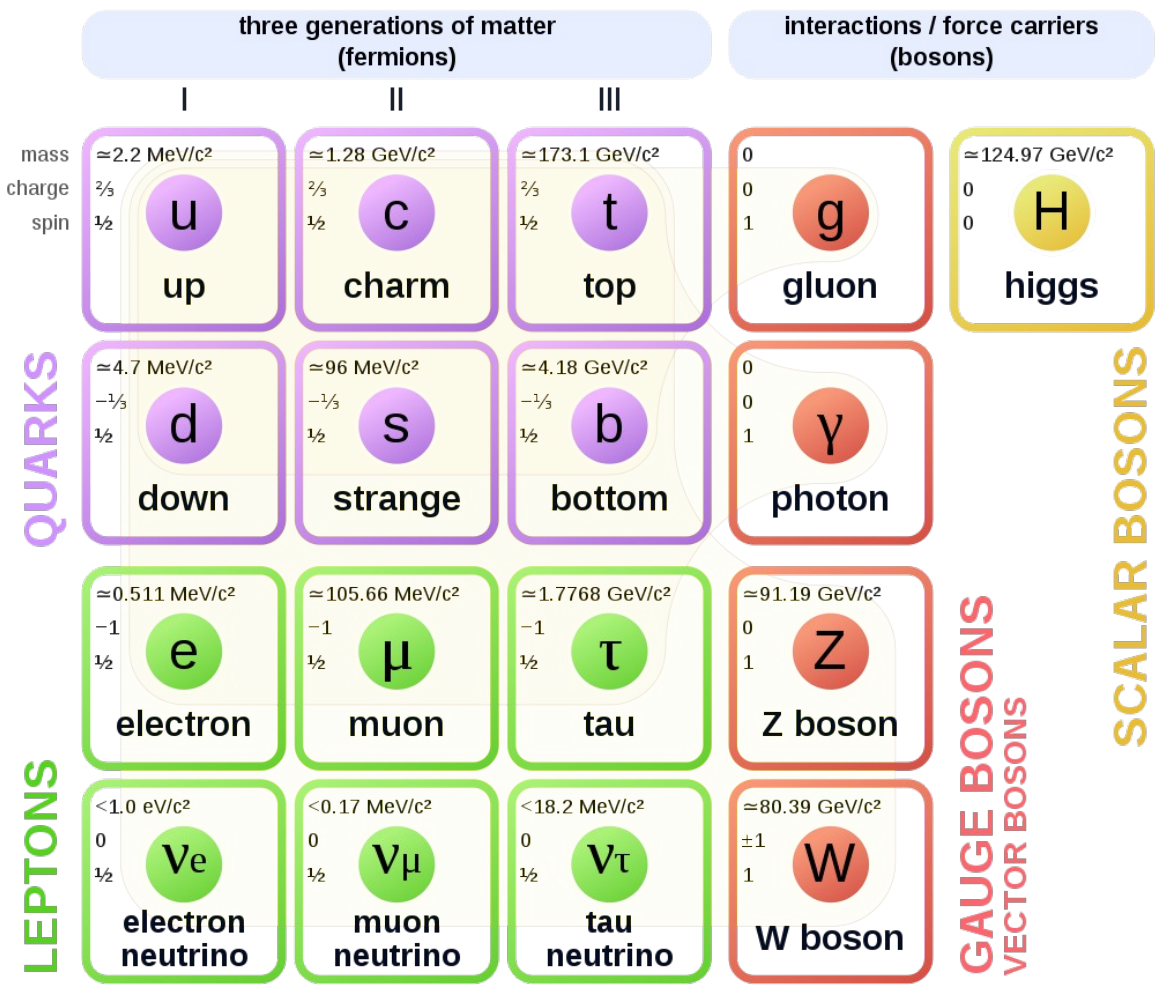
Outline

- Motivation
- Status of α_s
- New results from LHC
  - Jet cross sections
  - Normalised distributions
  - Ratio observables
- Outlook

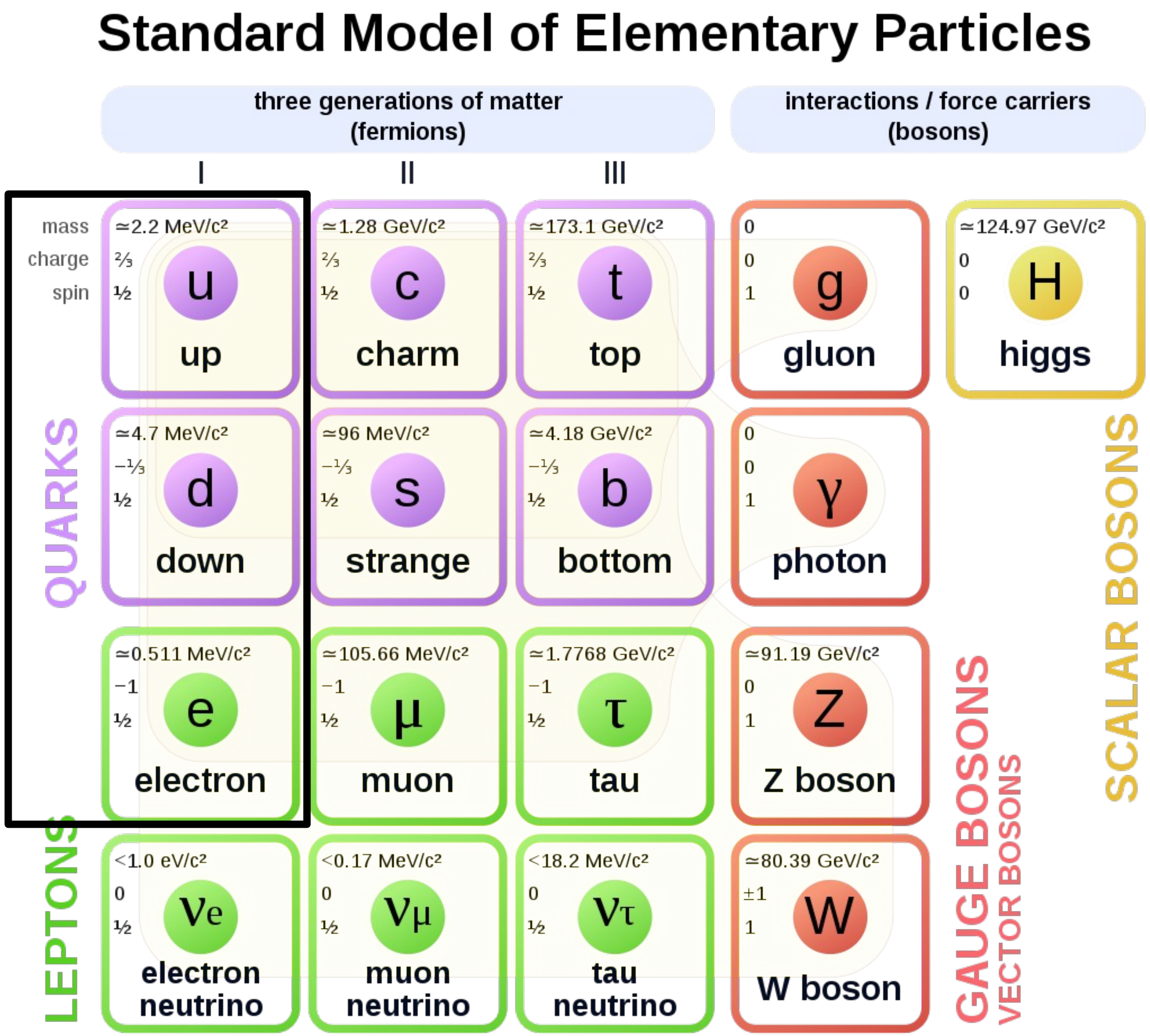
Standard Model of Elementary Particles



Cush, Wikipedia.

Solid matter

...



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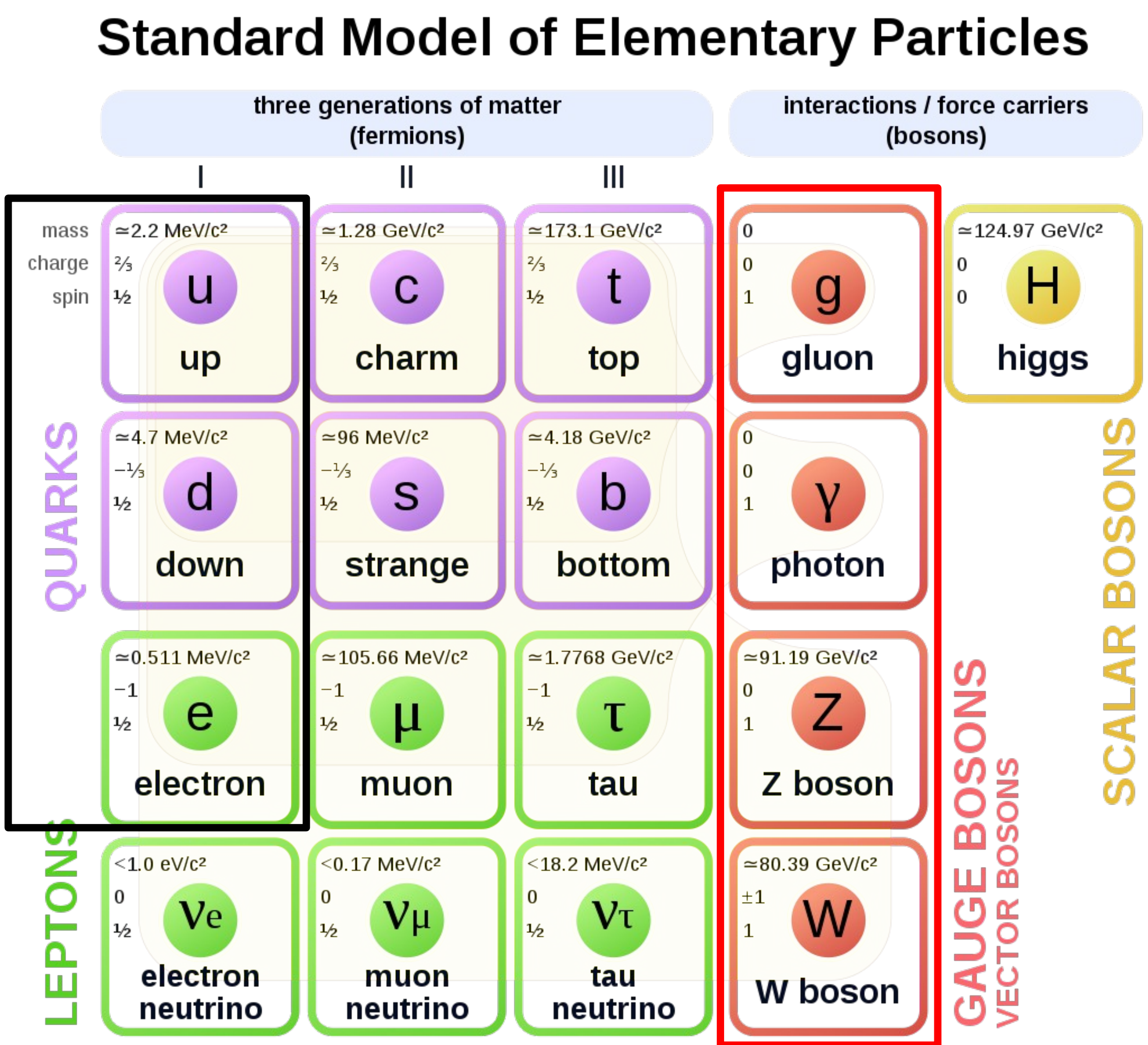
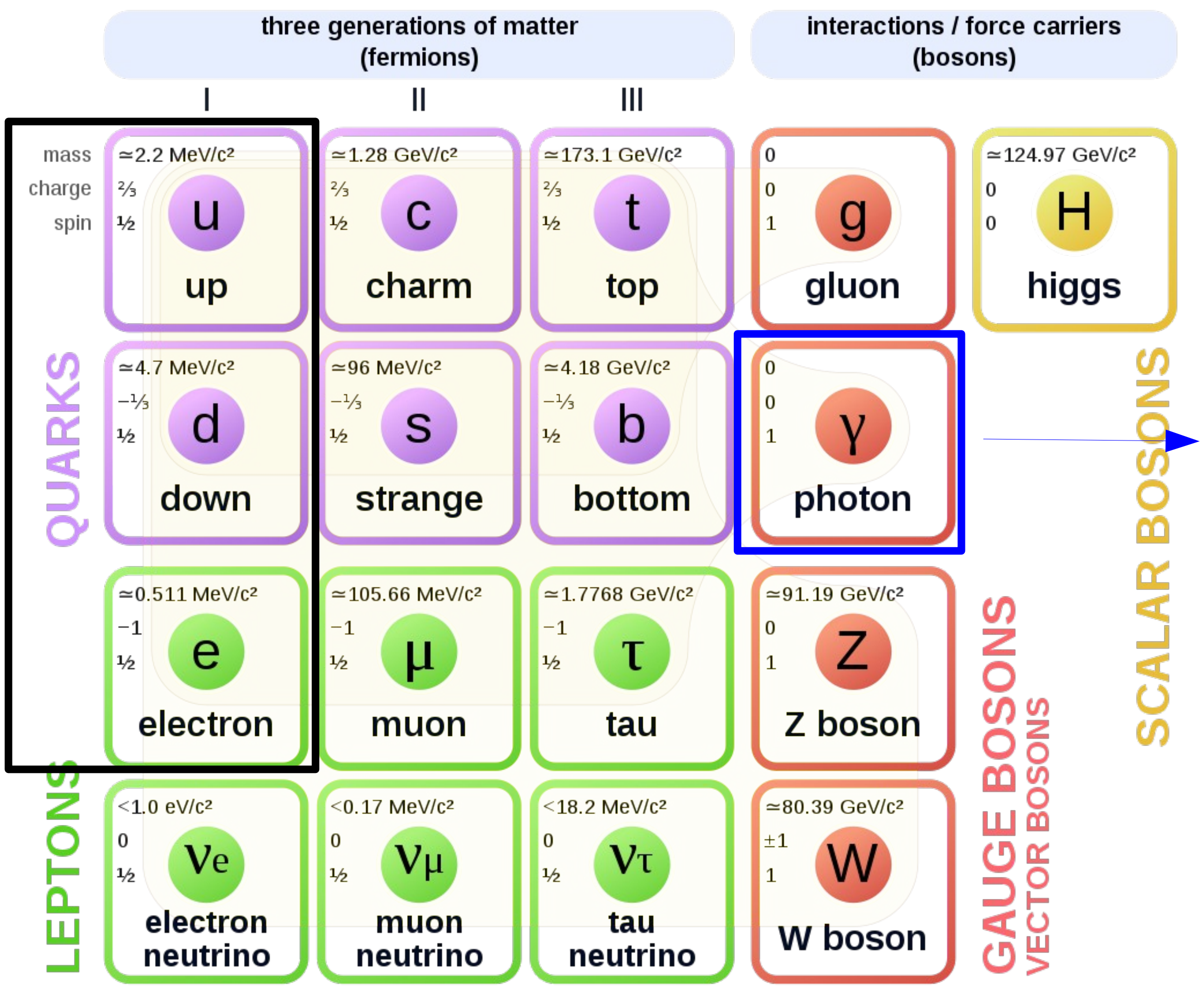


Cush, Wikipedia.

… and three fundamental interactions. (no gravity)

Solid matter ...

Standard Model of Elementary Particles



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Electromagnetic interaction (magnets, electricity, ...)

$\alpha \approx 1/137$

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

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Standard Model of Particle Physics

Solid matter
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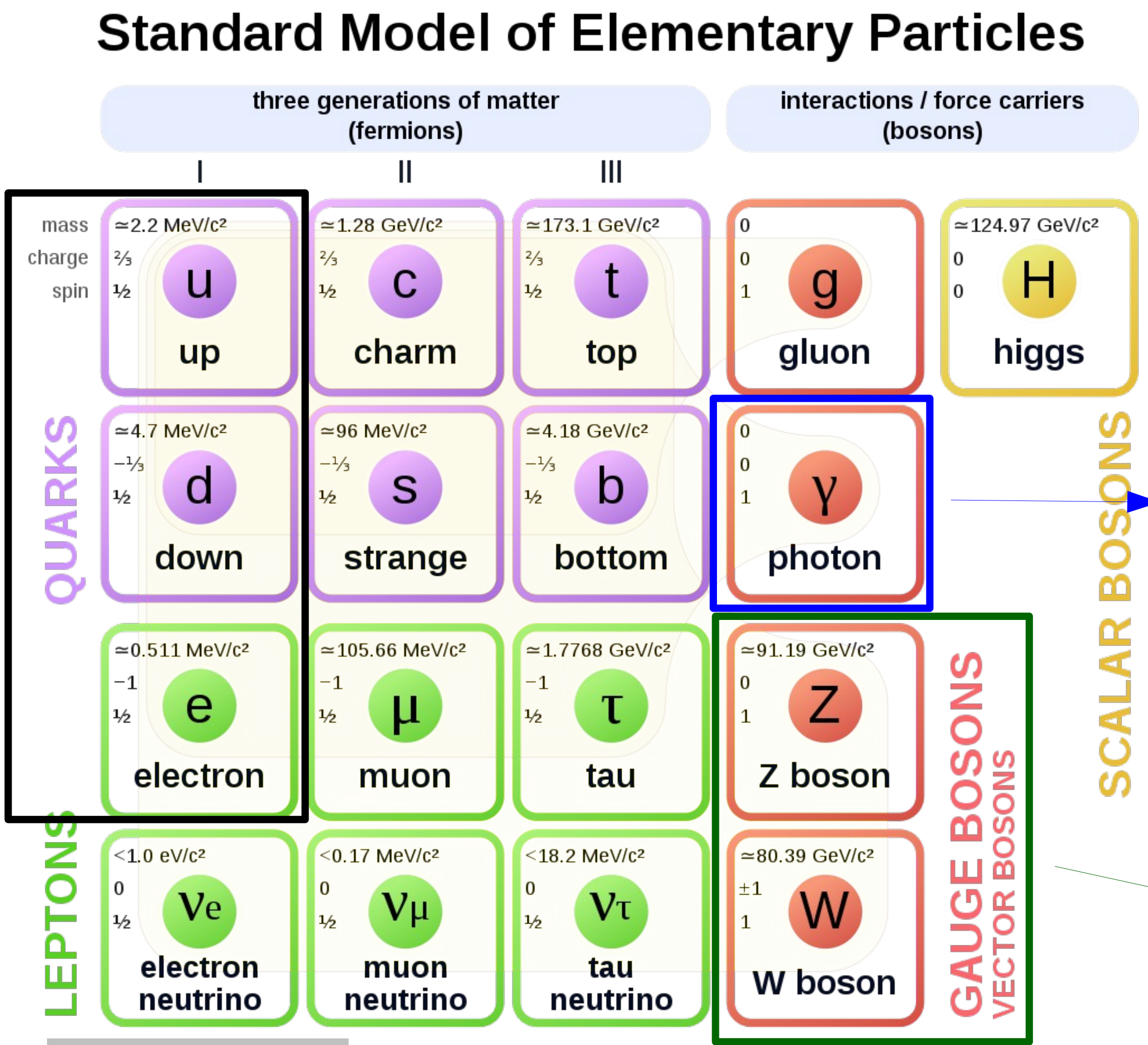

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Weak interaction (β decays, sun, ...)

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

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

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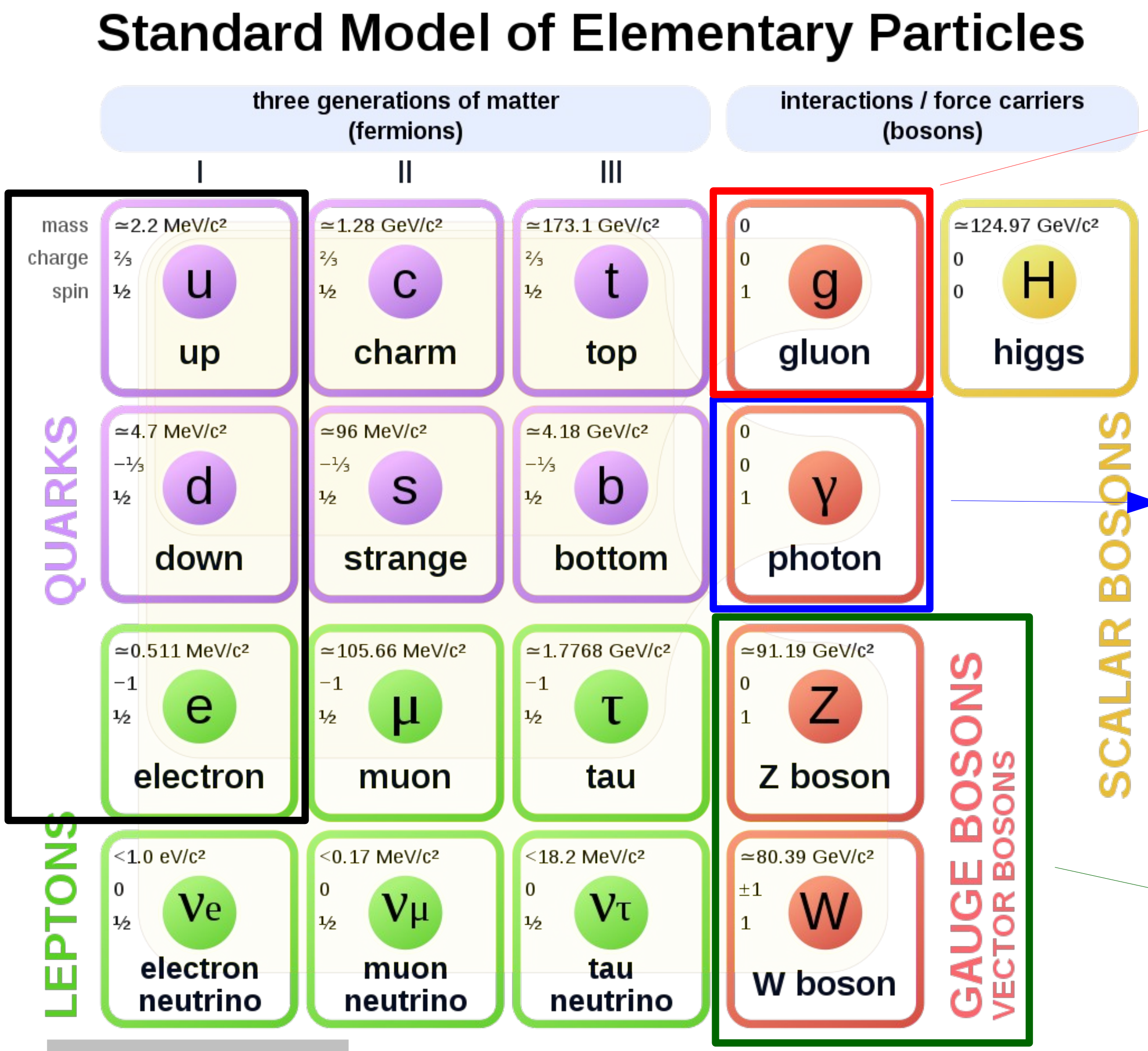

Cush, Wikipedia.

Strong interaction (nuclear forces, ...)

$\alpha_s \approx 0.118$

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

Electromagnetic interaction (magnets, electricity, ...)

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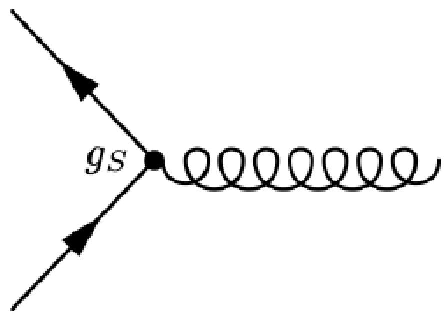
QCD Lagrangian

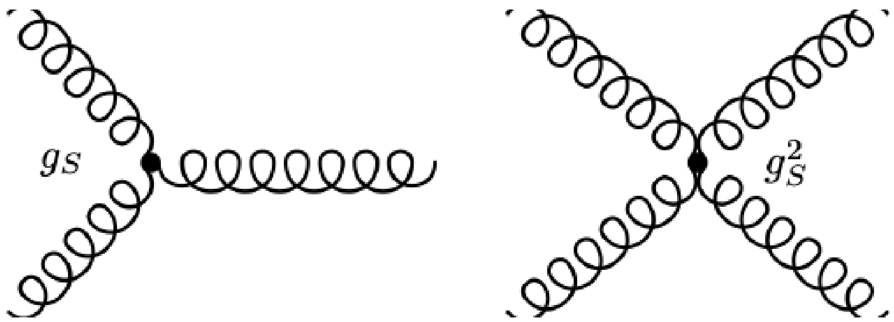
- **Invariance under local $SU(3)_c$ transformations**
  - **Three color charges a = 1, 2, 3 → Red, Green, Blue (as analogue to electric charge in QED)**
  - **Eight vector fields (gluons) $\mathcal{A}_\mu^A$ carry color charge and color anti-charge**
  - **The gluons are massless**
    → exact symmetry
    → in principal infinite range of strong force

$$\mathcal{G}_{\mu\nu}^A = \partial_\mu \mathcal{A}_\nu^A - \partial_\nu \mathcal{A}_\mu^A - g_s f^{ABC} \mathcal{A}_\mu^B \mathcal{A}_\nu^C$$

  - **Non-zero commutator leads to gluon self-interactions via triple and quartic gauge couplings**



quark-gluon interaction



gluon self-interaction

Beta functions

- **In (renormalisable) QFT the beta function encodes the dependence of the coupling parameter g on the energy (or distance) scale μ:**

$$\alpha_i := \frac{g_i^2}{4\pi} \qquad \beta(g) = \frac{\partial g}{\partial \log(\mu^2)}$$

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- **Beta function of QED (1-loop):** $\beta(\alpha) = \frac{1}{3\pi}\alpha^2$
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  - **The coupling decreases with larger distances**
    - **Infinite range, Coulomb potential:** $V(r) \propto \frac{1}{r}$

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- **Beta function of QCD (1-loop):** $\beta(\alpha_s) = -\left(\frac{11N_C - 2N_f}{12\pi}\right)\alpha_s^2$
  - **The coupling decreases with energy scale, if** $N_C = 3, \quad N_f \leq 16$
    - **Asymptotic freedom**
  - **The coupling increases with larger distances**
    - **Confinement, string potential:** $V(r) \approx \sigma \cdot r$ **with tension** $\sigma \approx 1\,\mathrm{GeV/fm}$

QCD and asymptotic freedom

Nobel prize 2004

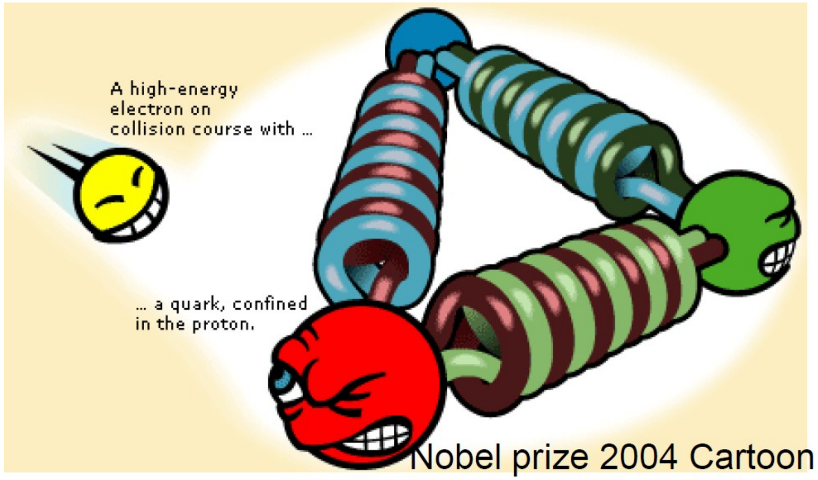
- **Theory:**
  - **Renormalisation group equation (RGE)**
  - **Solution of 1-loop equation**
  - **Running coupling constant**

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

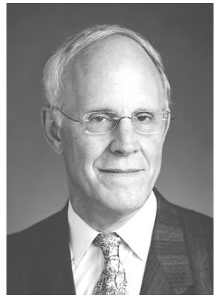
$$\alpha_s(Q^2) = \frac{1}{\beta_0 \ln\left(\frac{Q^2}{\Lambda^2}\right)}$$

- **Towards small distances, $Q^2 \to \infty$**
  - **"Strong" coupling becomes weak**
  - **Perturbative methods usable**
  - **Asymptotic freedom**

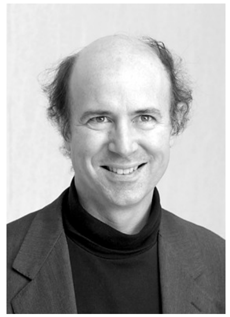
Physik Journal 3 (2004) Nr. 12



Nobel prize 2004 Cartoon


D. Gross


D. Politzer


F. Wilczek

nobelprize.org

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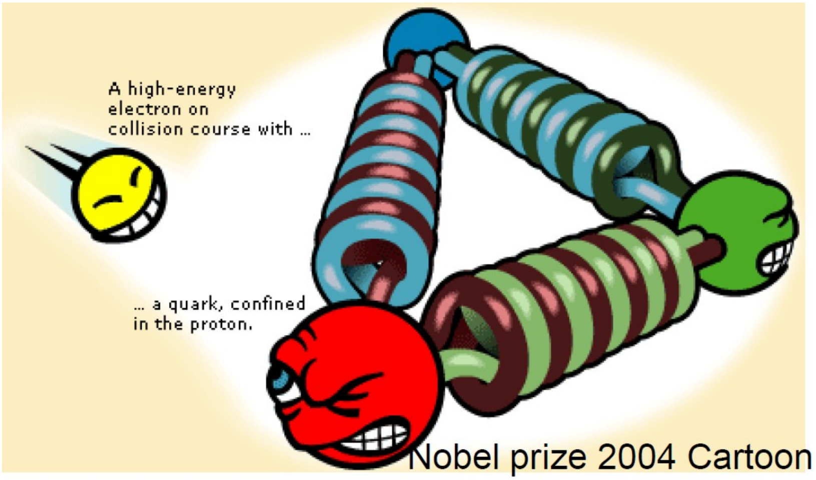

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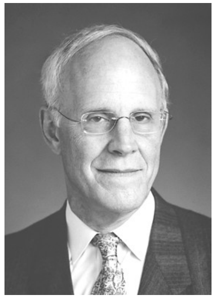
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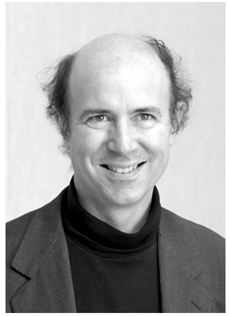

F. Wilczek

nobelprize.org

- **Towards large distances, $Q^2 \to 0$**
  - **Strong coupling, confinement**
  - **Perturbative methods not usable for $Q^2 \to \Lambda^2$**
  - **Lattice gauge theory**

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

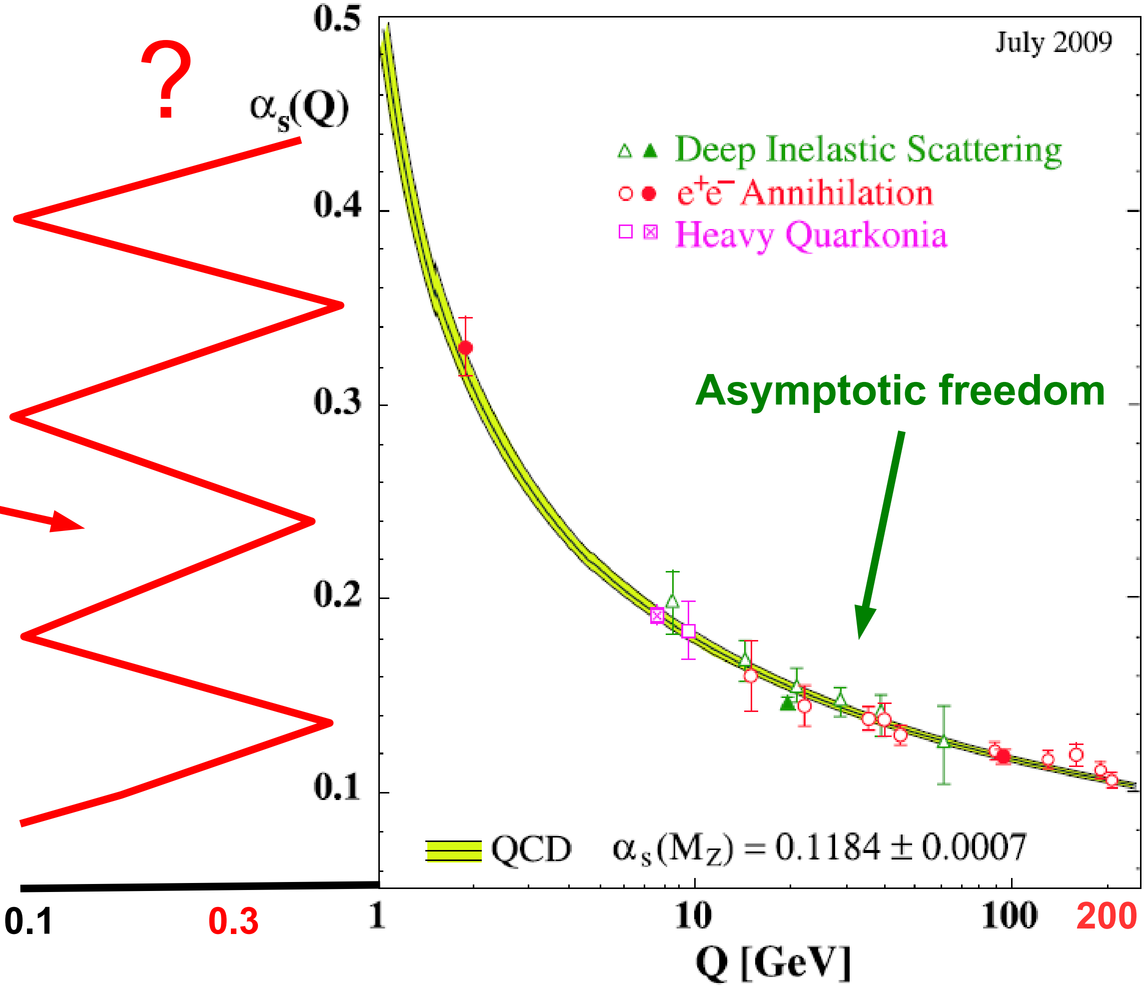
Non-perturbative regime

QCD potential grows linearly with larger distances:

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

→ No free quarks (or gluons)
→ Confinement

pre-LHC

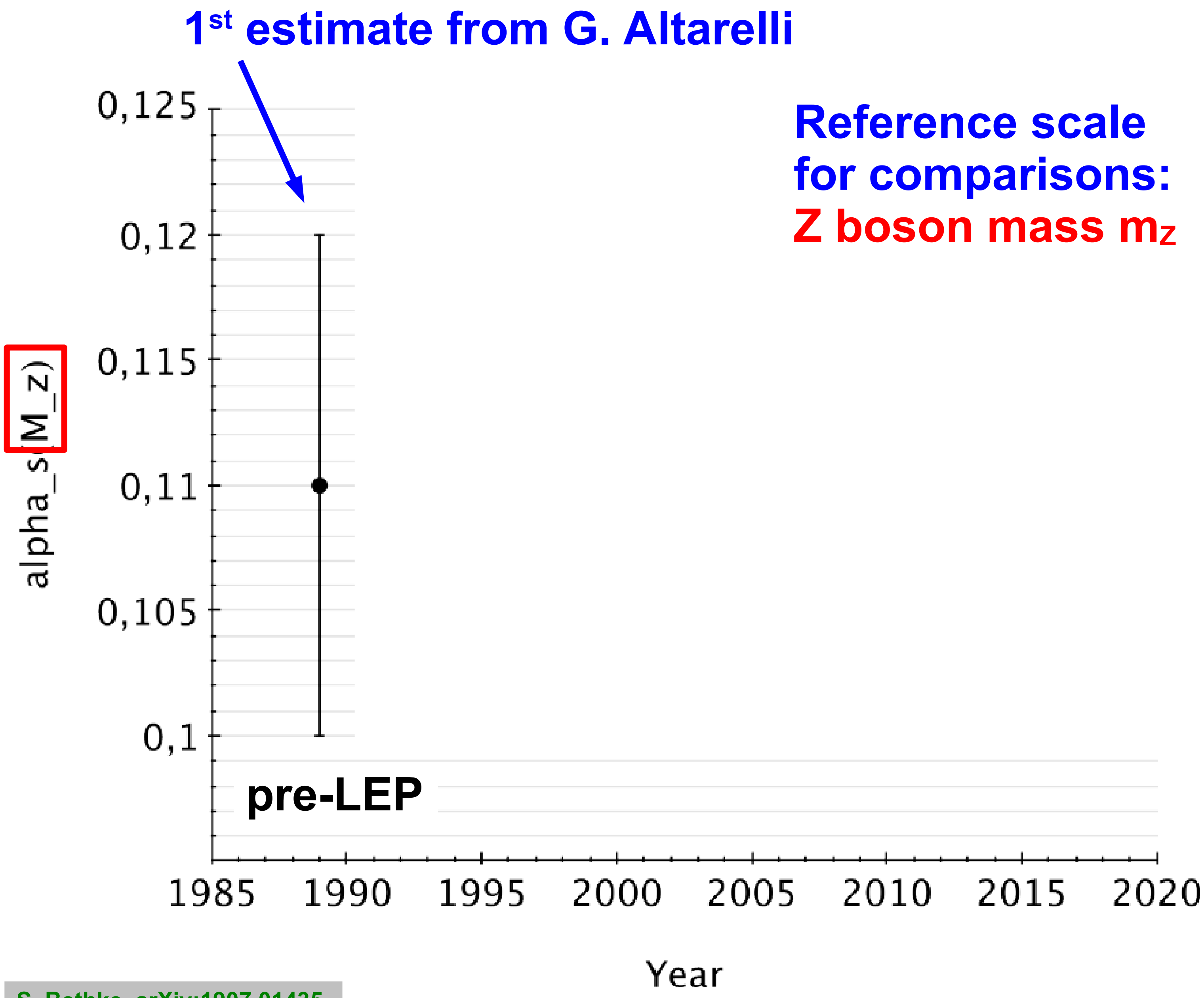


S. Bethke, EPJC 64 (2009).

Status of α_s in PDG review

Particle Data Group
https://pdg.lbl.gov

$\alpha_s(m_Z)$ average versus time



Reference scale for comparisons:
Z boson mass m_Z

S. Bethke, arXiv:1907.01435.

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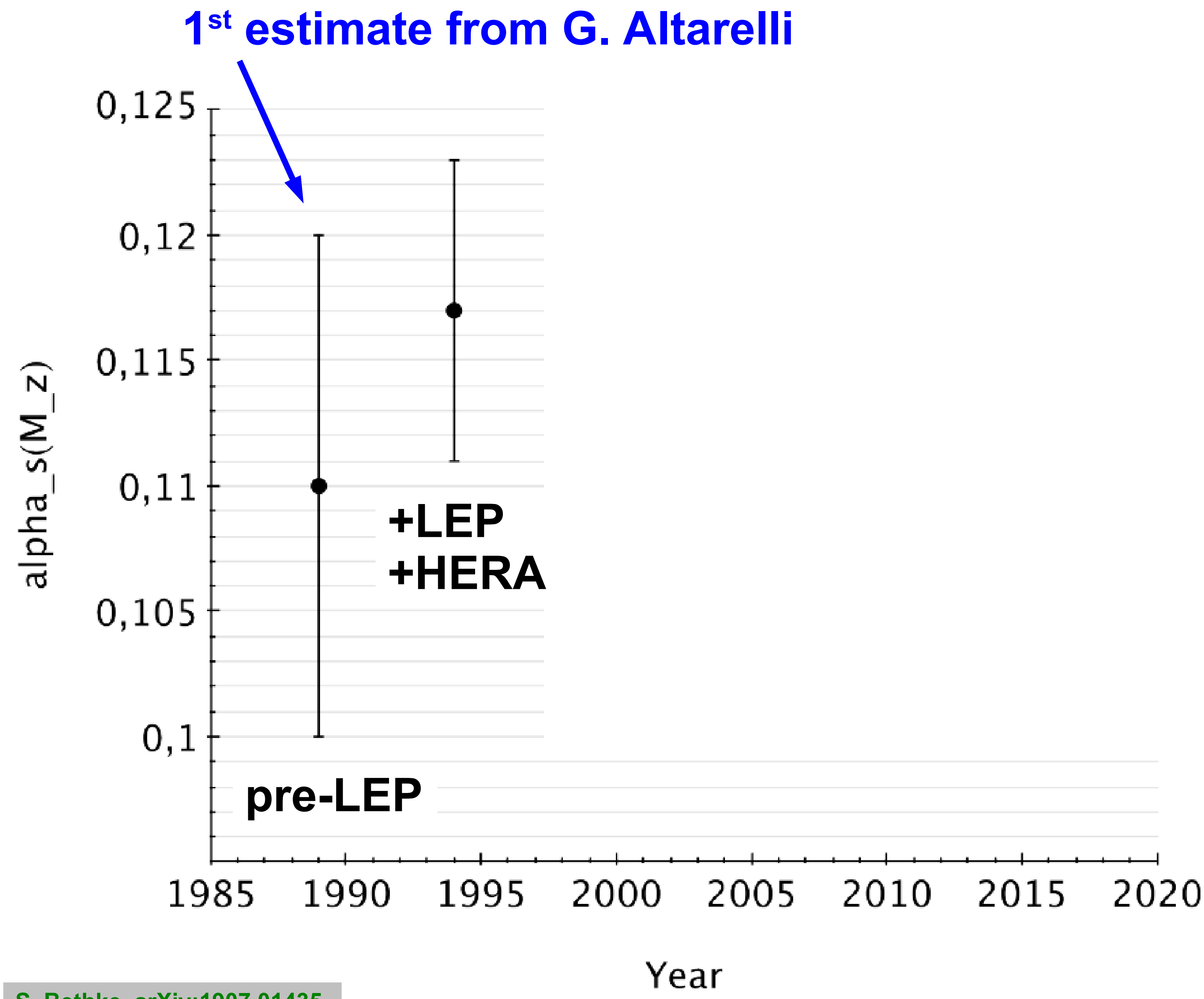

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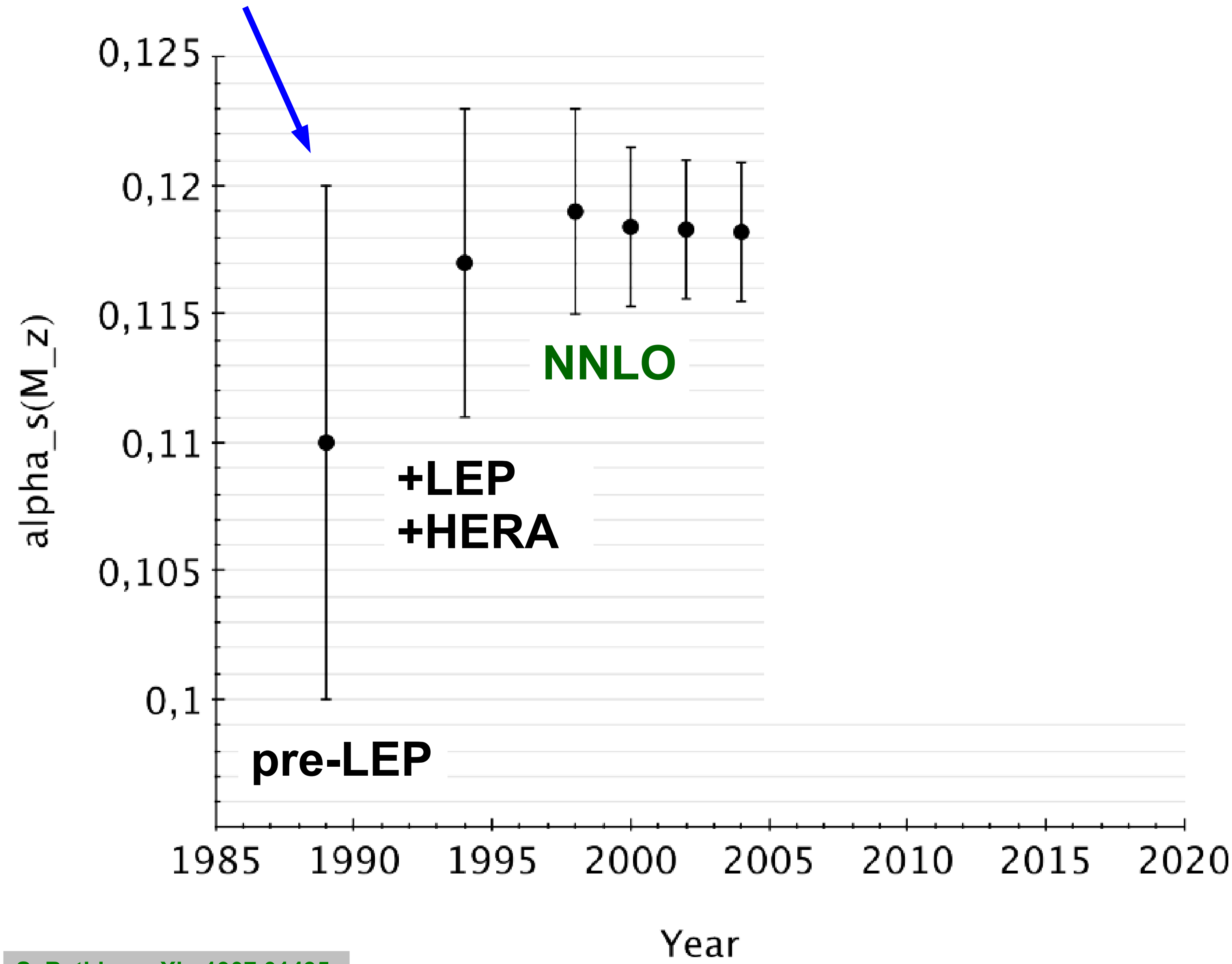
$\alpha_s(m_Z)$ average versus time

1st estimate from G. Altarelli



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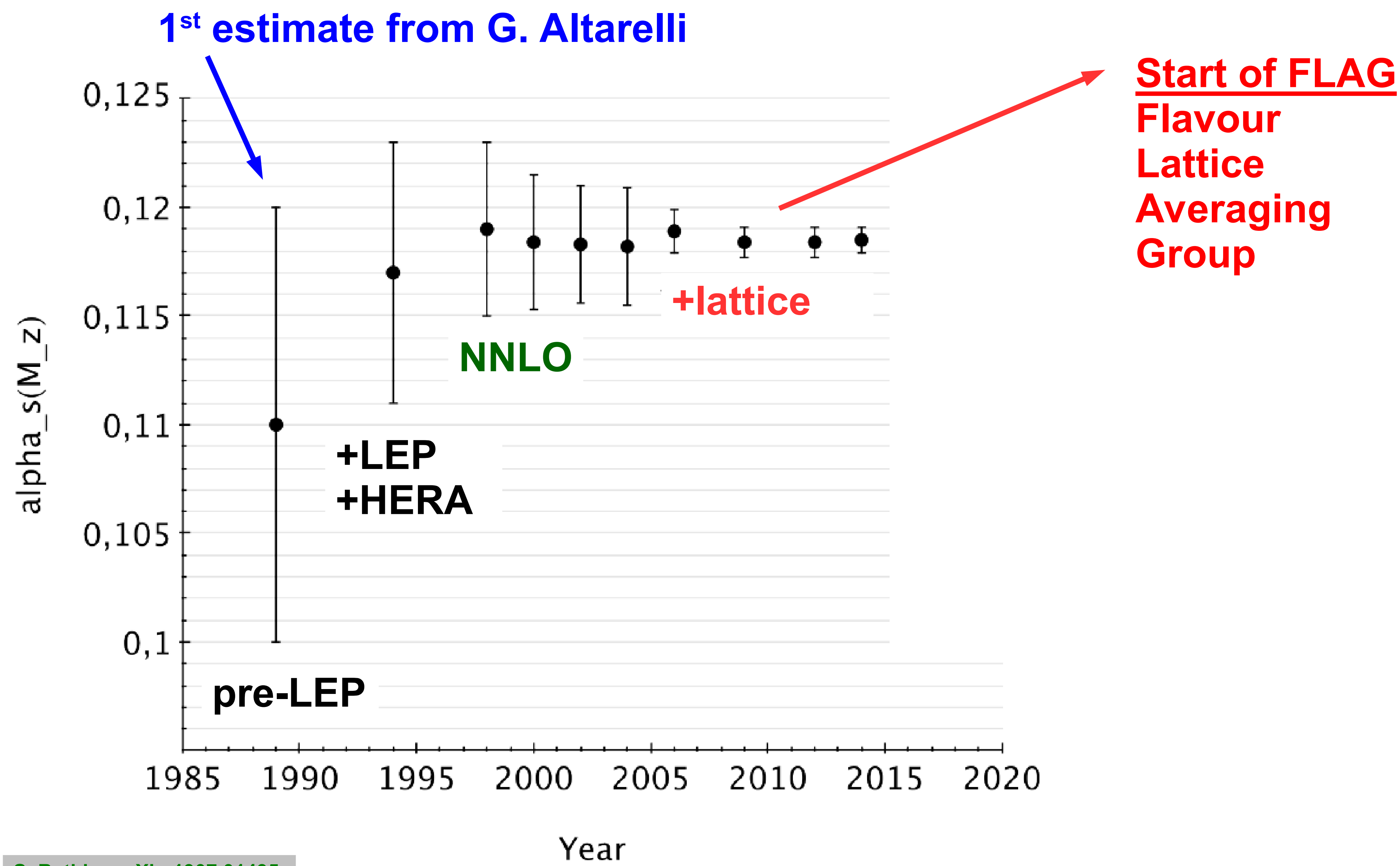

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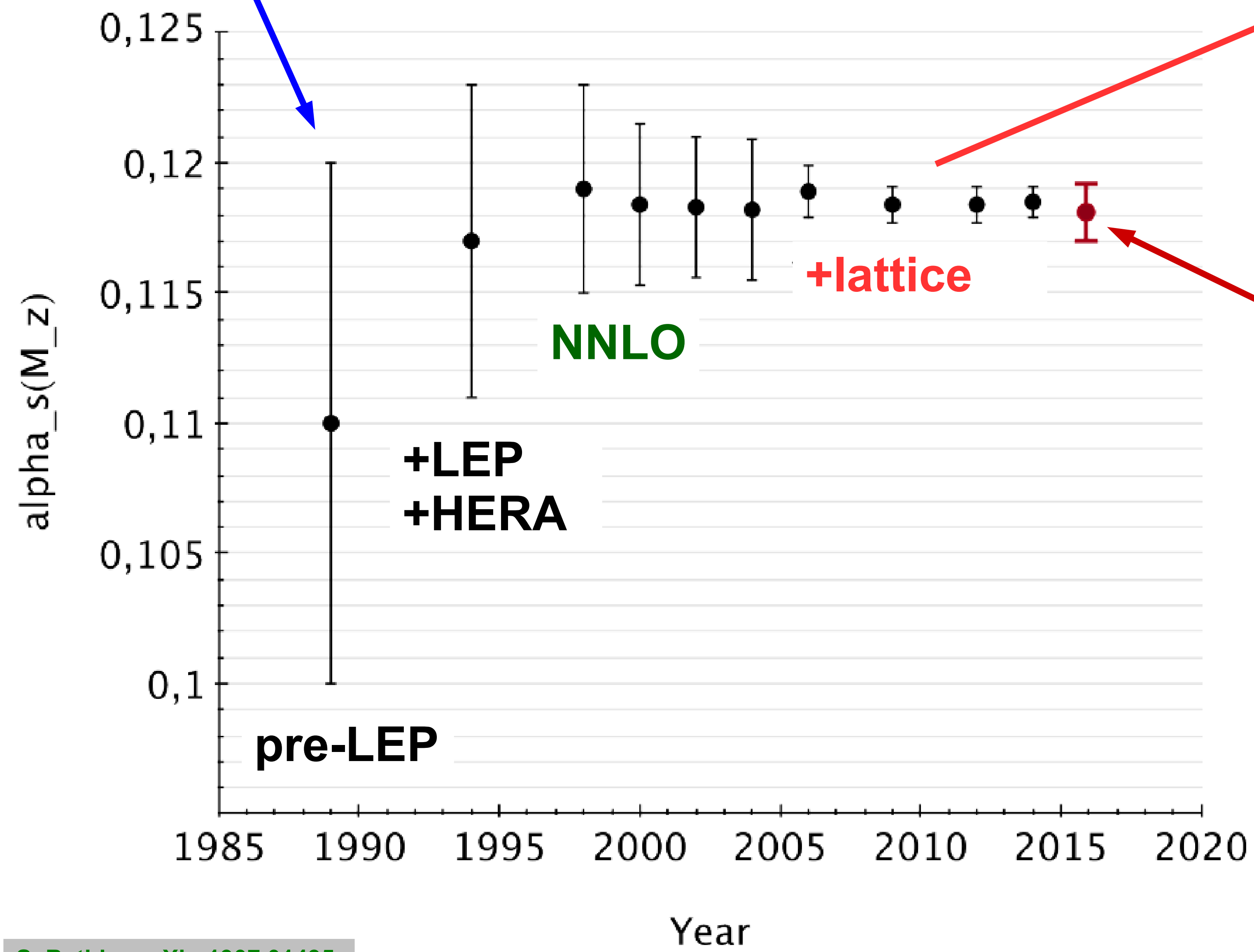

Start of FLAG
Flavour
Lattice
Averaging
Group

PDG 2016

More careful validation of lattice methods & uncertainties

S. Bethke, arXiv:1907.01435.

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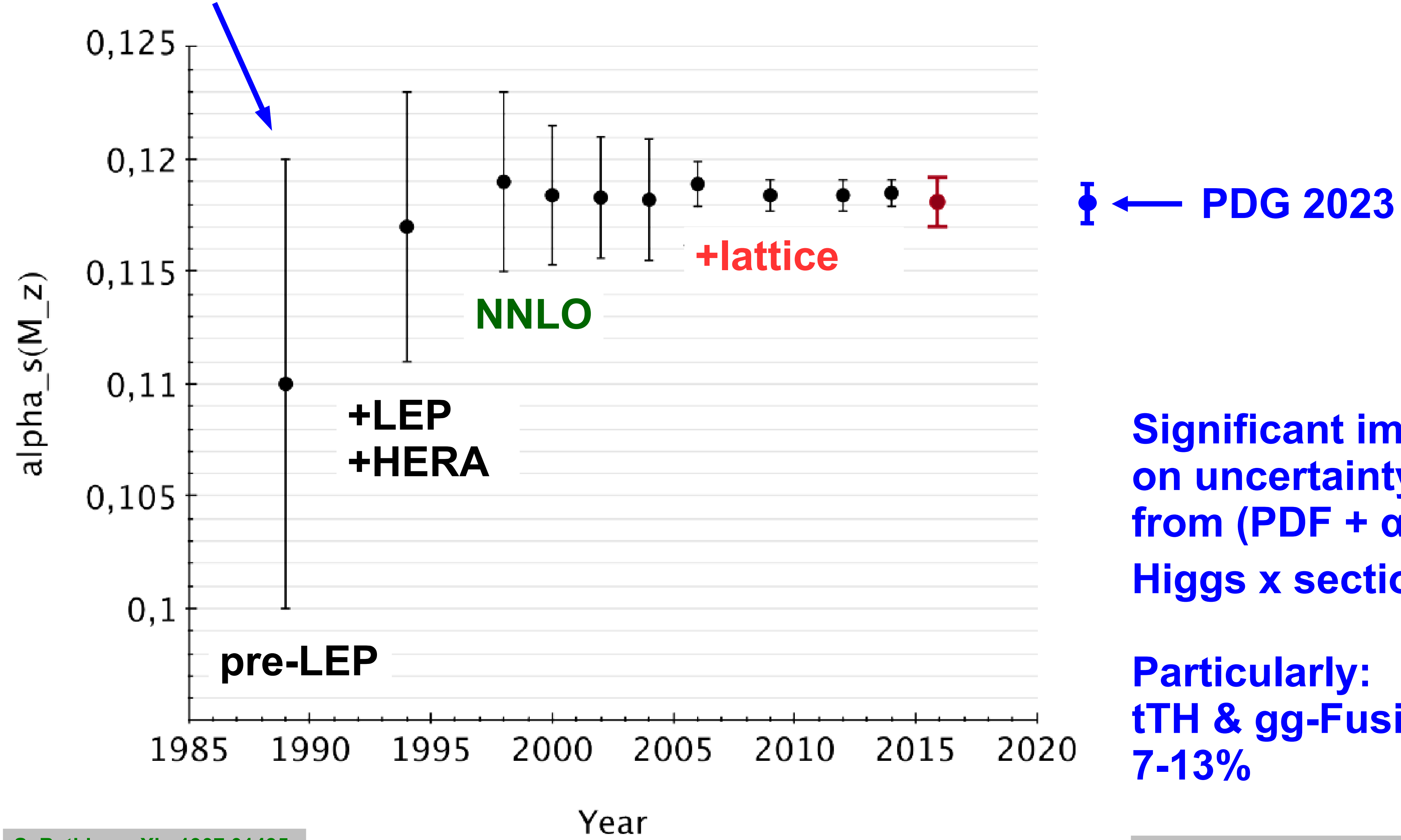
1st estimate from G. Altarelli



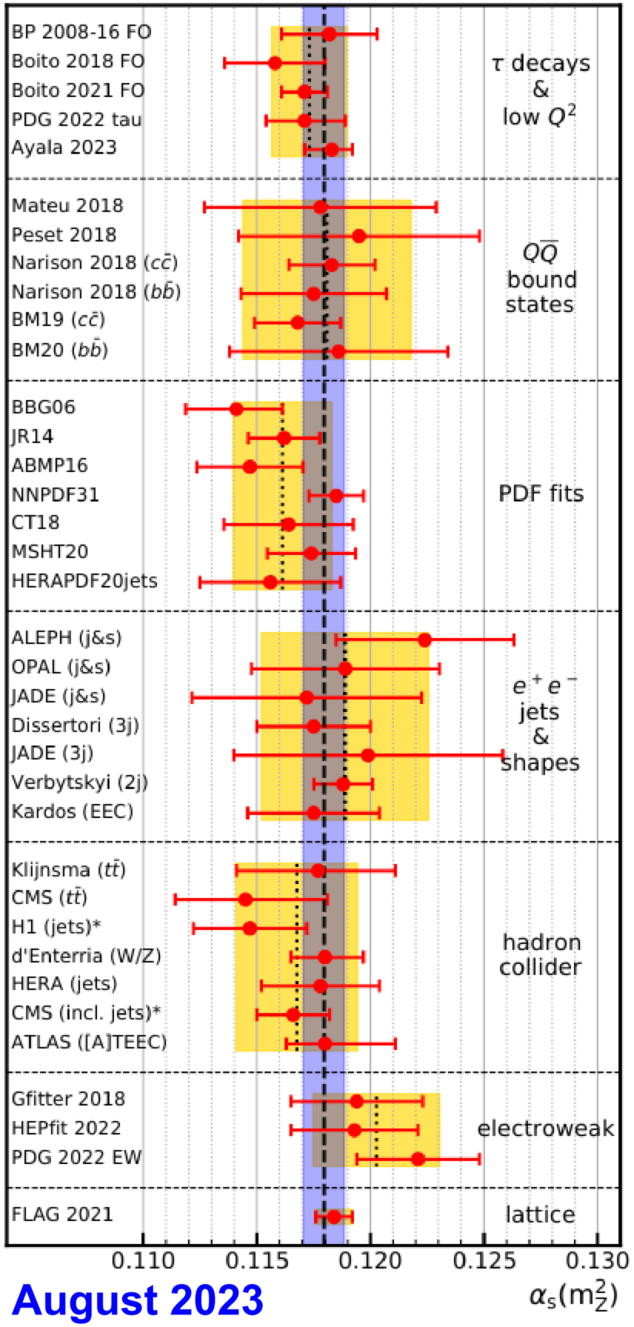
Significant impact on uncertainty from (PDF + α_s) on Higgs x sections:

Particularly:
tTH & gg-Fusion:
7-13%

S. Bethke, arXiv:1907.01435.

CERN YR, LHC Higgs xs WG.

PDG α_s averaging in 6 groups



August 2023

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, PRD (2024) 110, 3, 030001.

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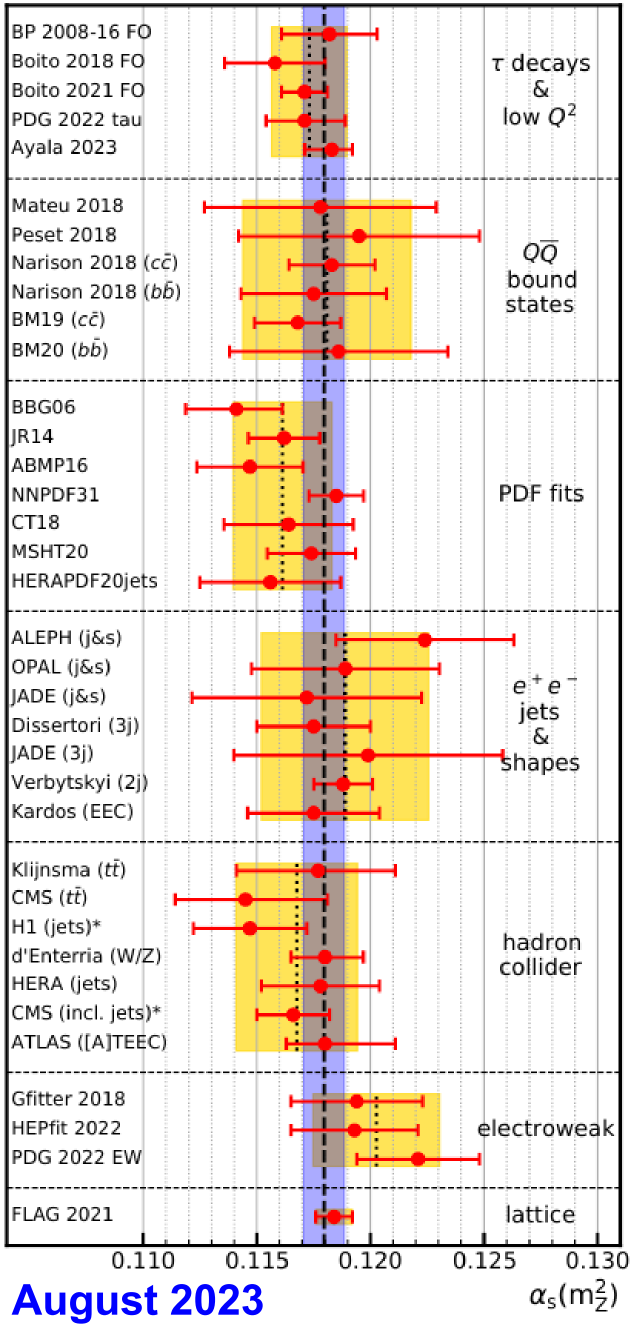


August 2023

- **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**

partially also input here

PDG, PRD (2024) 110, 3, 030001.

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

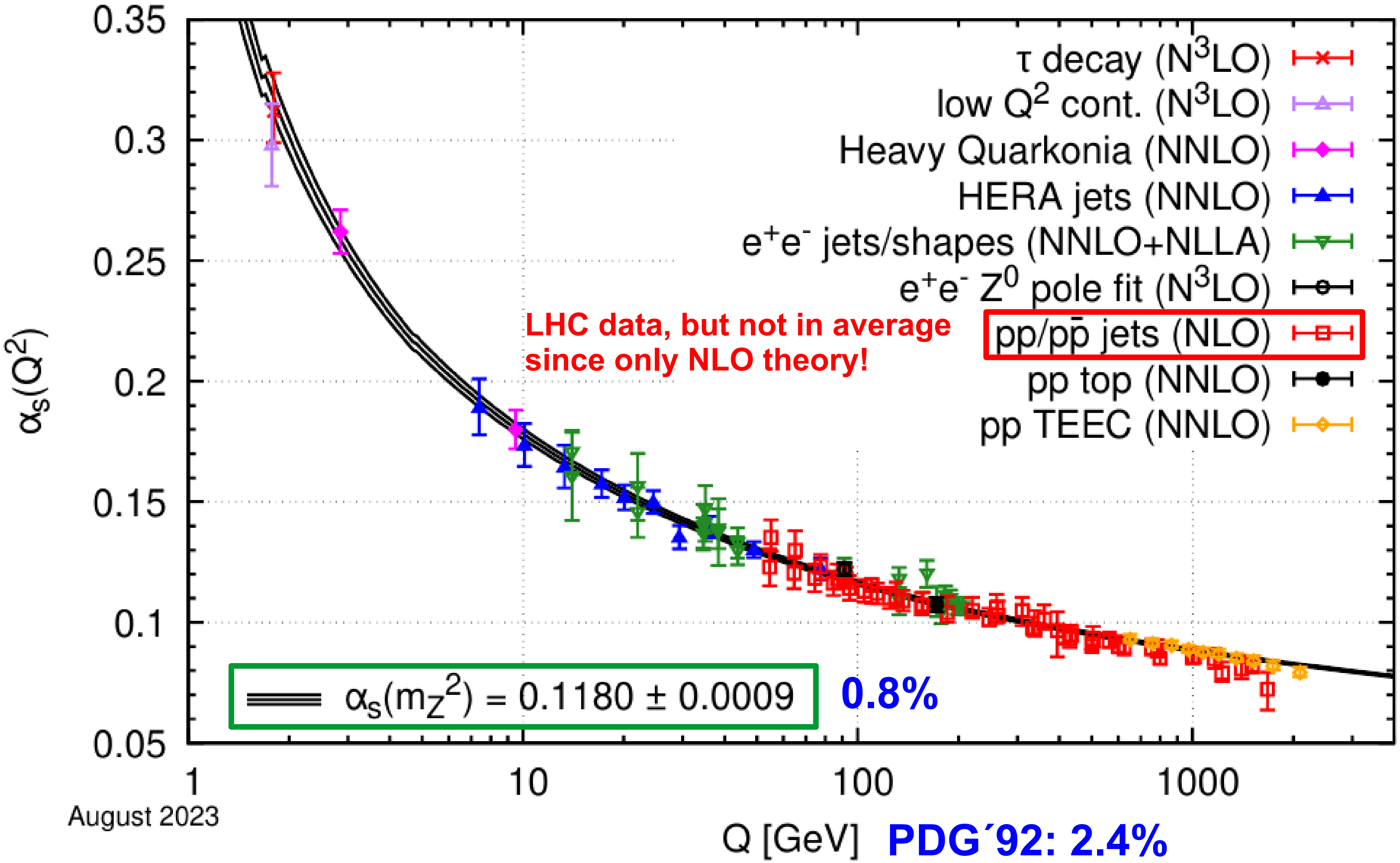
Final average including lattice (FLAG2021):

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

rel. uncertainty: 0.8%

PDG, PRD (2024) 110, 3, 030001.

PDG 2023 α_s running

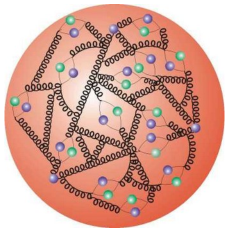


PDG, PRD (2024) 110, 3, 030001.

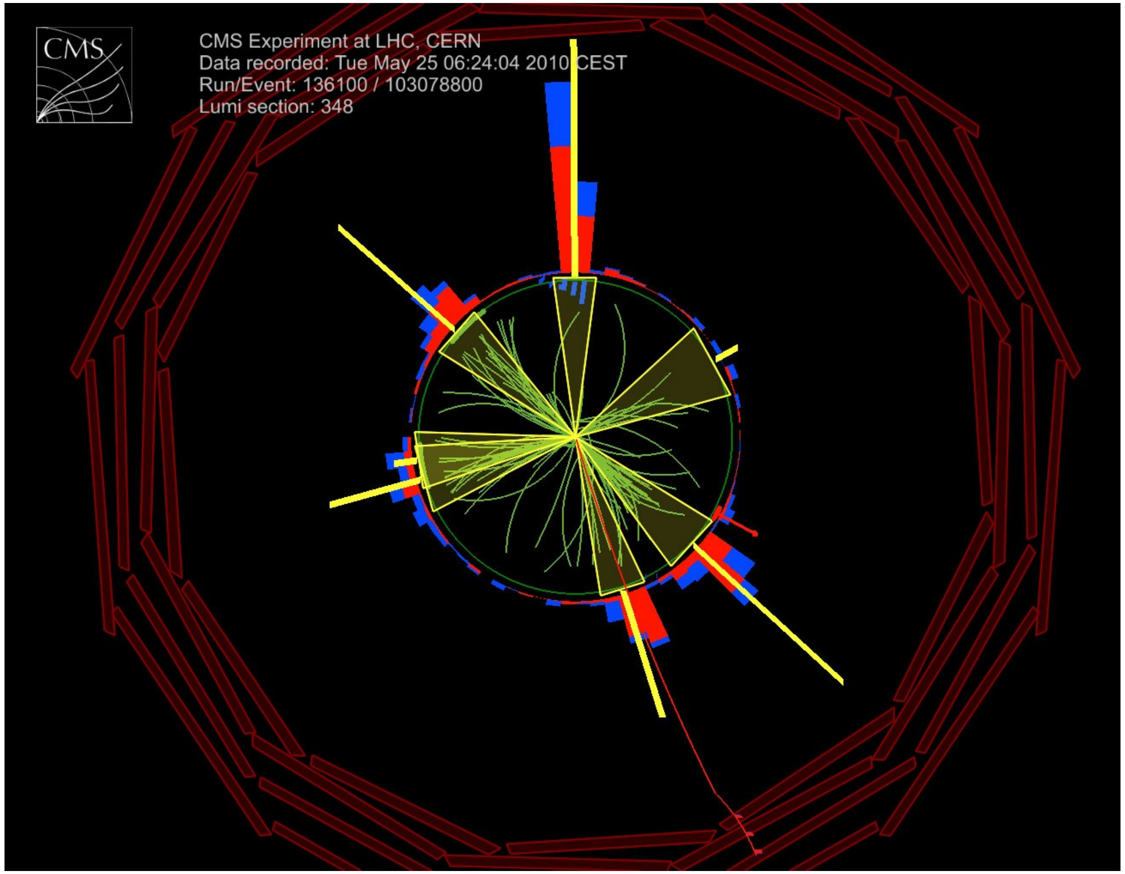
New results from LHC

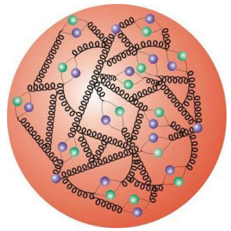
Jets

Large transverse momenta



Proton



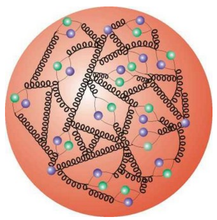


Proton

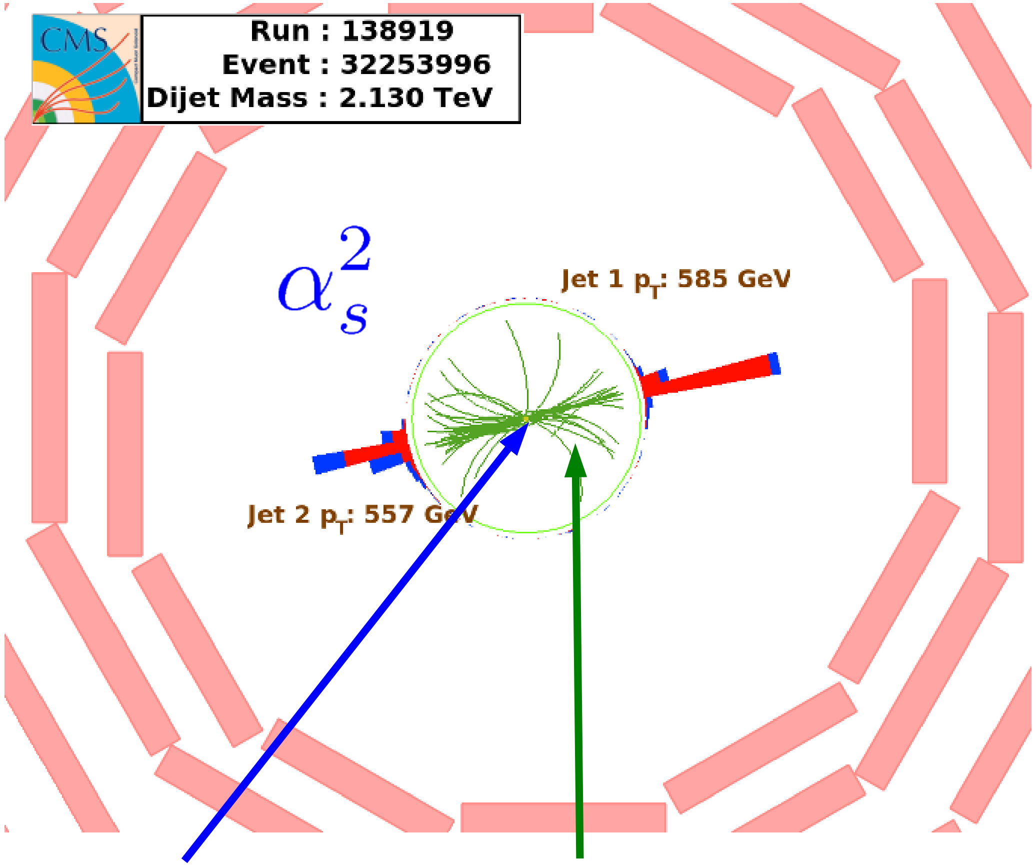
Jets at the LHC

Abundant production of jets:

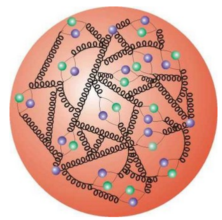
- Highest reach ever in energy scale Q to determine the strong coupling
- Learn about hard QCD, the proton structure, non-perturbative effects, and electroweak effects at high Q



Proton Structure (PDF)



Matrix Element   Hadrons

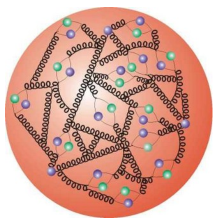


Proton Structure (PDF)

Jets at the LHC

<u>Abundant production of jets:</u>

➔ Extract $\alpha_s(m_Z)$, the least precisely known fundamental constant!



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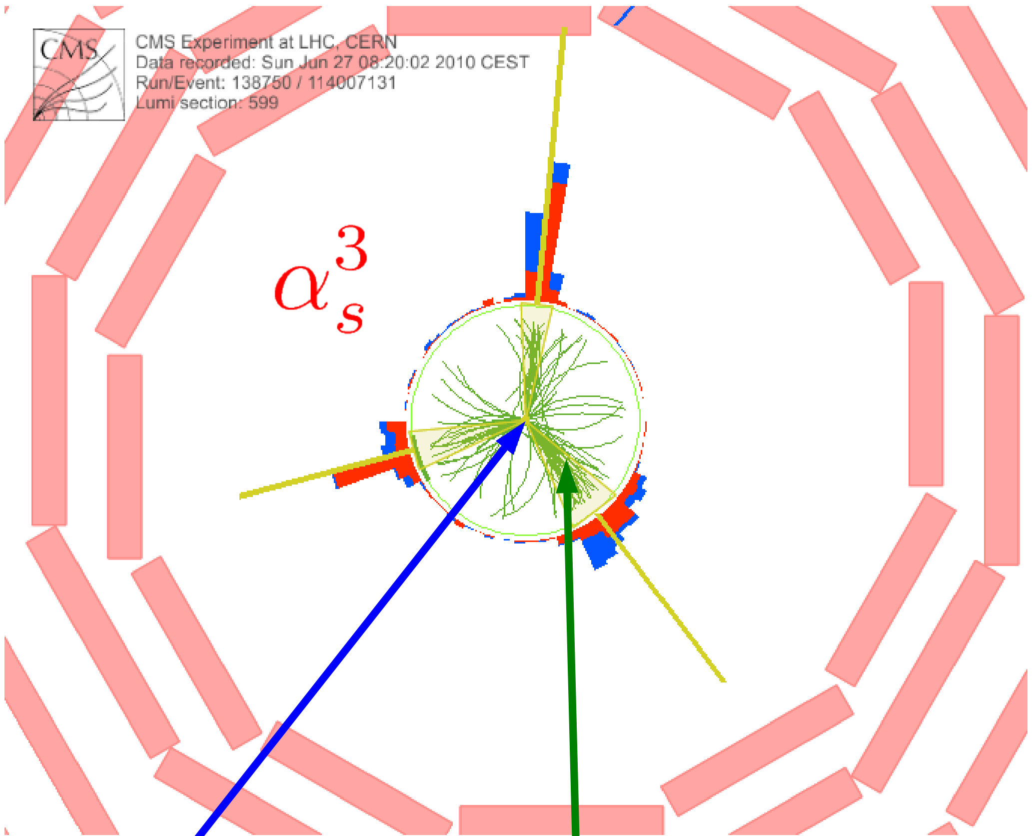

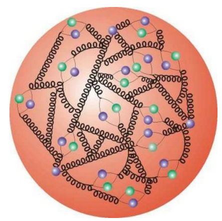

Proton Structure (PDF)

Matrix Element Hadrons

Jet cross sections ~ α_s^{2+n}

- Counting jets or jet events in bins of e.g. momentum and rapidity
- Useful for i.a.:
  - Determination of $\alpha_s(m_Z)$
  - Test of running of $\alpha_s(Q)$
  - Multi-parameter fit of $\alpha_s(m_Z)$ & PDFs
  - Multi-parameter fit including EFT parameters

Jet cross sections ~ α_s^{2+n}

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  - **Test of running of $\alpha_s(Q)$**
  - **Multi-parameter fit of $\alpha_s(m_Z)$ & PDFs**
  - **Multi-parameter fit including EFT parameters**
- **Subject to many/all systematic uncertainties:**
  - **Jet energy calibration (JEC) & resolution (JER)**
  - **Luminosity**
  - **Missing higher orders**

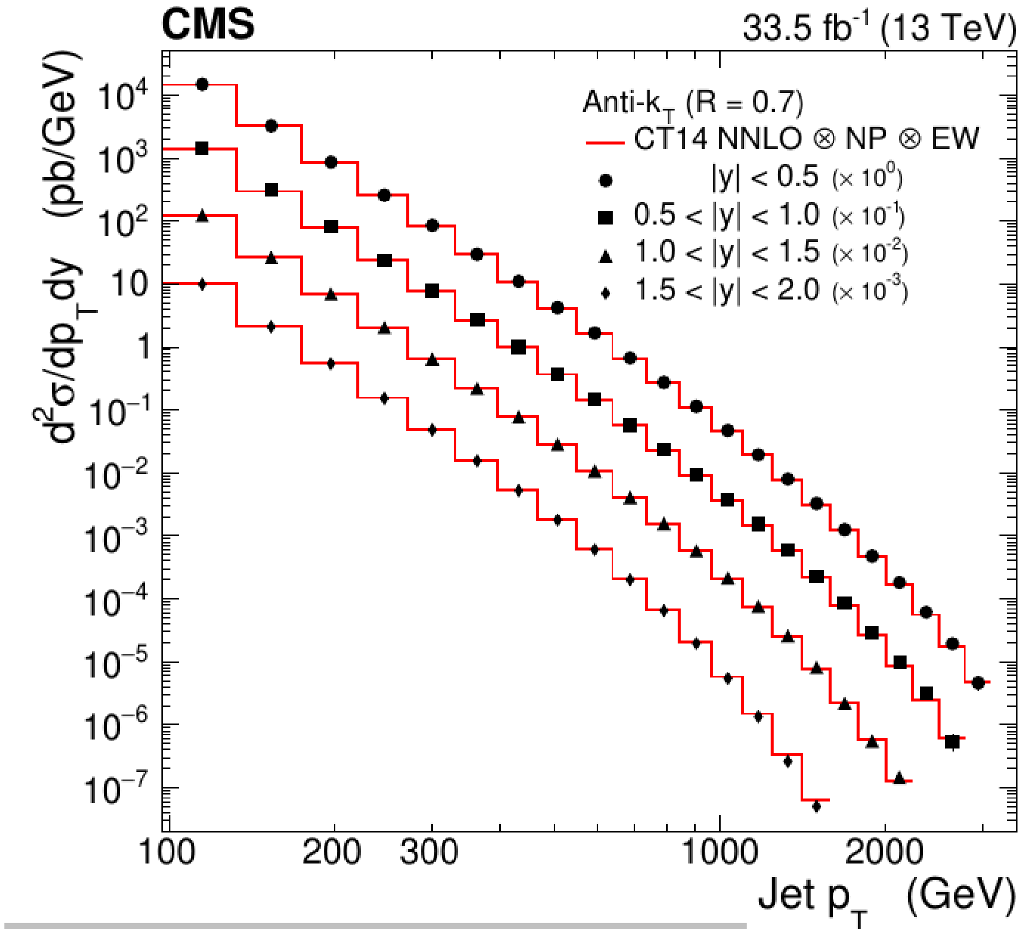
  … to name a few

Inclusive jets: α_s & PDFs

Jet counting in bins of jet transverse momentum and rapidity
Comparison of unfolded measurement with theory:

NNLO x nonperturbative x electroweak correction

(NNLO in leading-color (LC) approximation; subleading effects small)

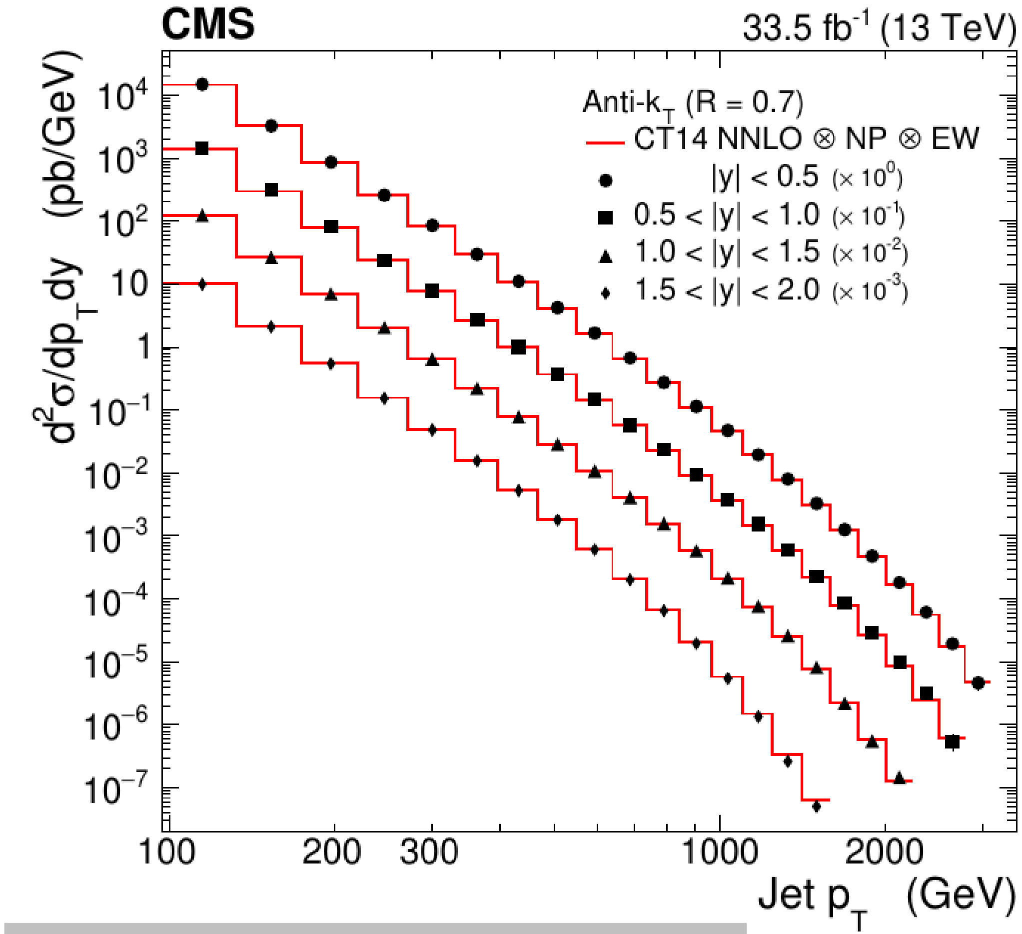


CMS, JHEP02 (2022) 142 & JHEP12 (2022) 035.

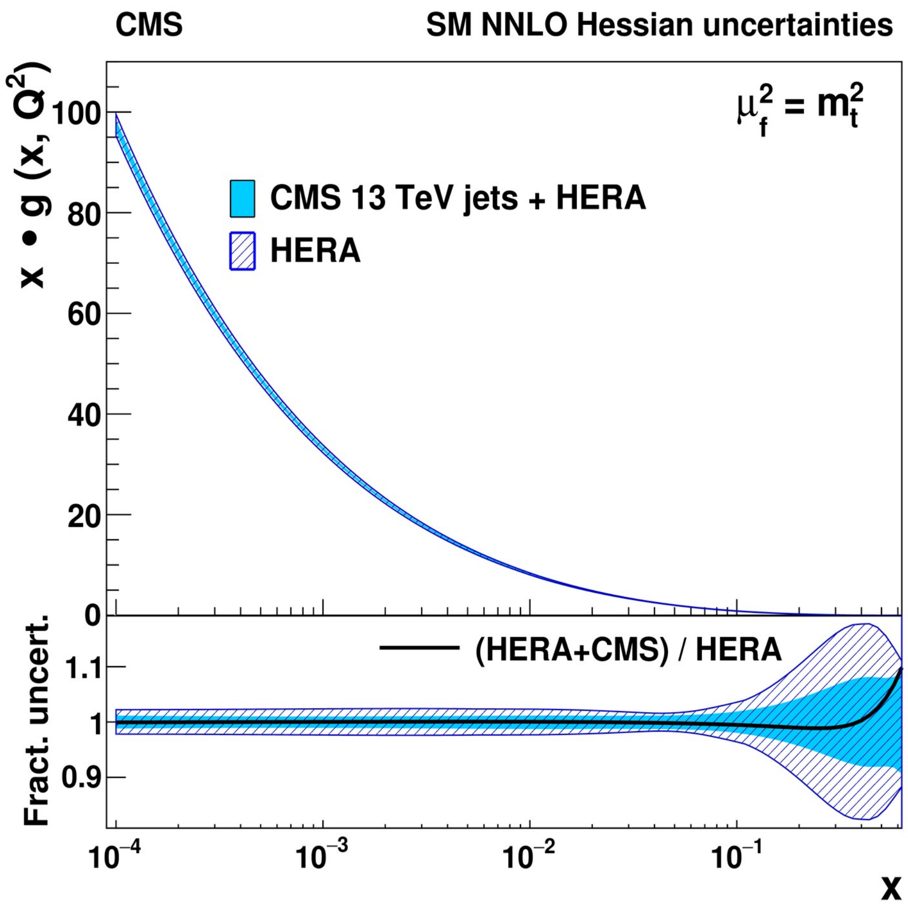
Inclusive jets: α_s & PDFs

First determination of $\alpha_s(m_Z)$ from jets at NNLO-LC:

$$\alpha_s(m_Z^2) = 0.1166 \pm 0.0016(\mathrm{fitall}) \pm 0.0004(\mathrm{scl})$$



Simultaneous fit with PDFs → reduced uncertainties of gluon



CMS, JHEP02 (2022) 142 & JHEP12 (2022) 035.

Jet event counting in bins of dijet mass or average transverse momentum (x) and

rapidity separation

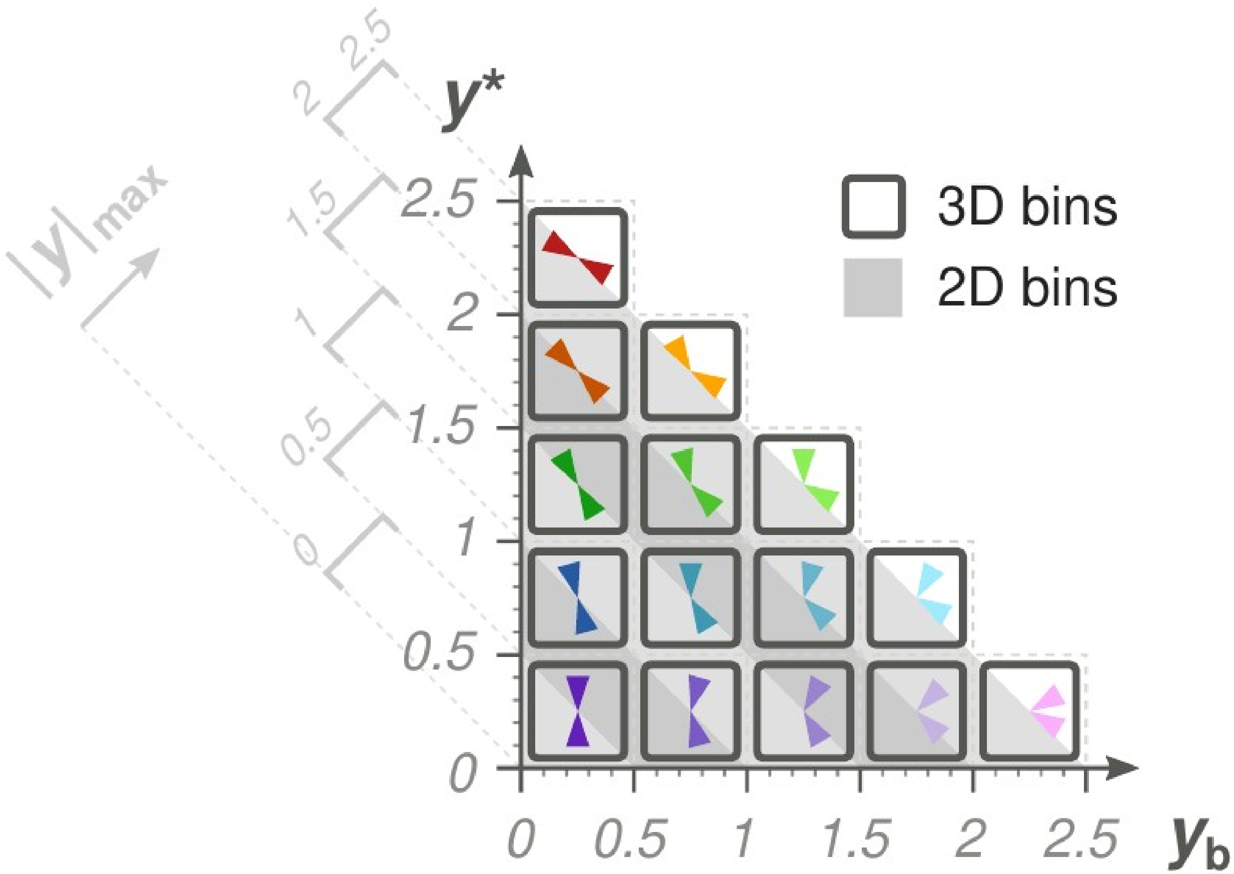
$$y^* = \frac{1}{2}|y_1 - y_2|$$

boost of dijet system

$$y_b = \frac{1}{2}|y_1 + y_2|$$

$$\frac{\mathrm{d}^3\sigma}{\mathrm{d}y^*\mathrm{d}y_\mathrm{b}\mathrm{d}x} = \frac{1}{\varepsilon\,\mathcal{L}_\mathrm{int}}\,\frac{N}{\Delta y^*\Delta y_\mathrm{b}\Delta x}.$$

Illustration of dijet event topologies



Alternativ 2D binning in maximum rapidity of $|y_1|,|y_2|$

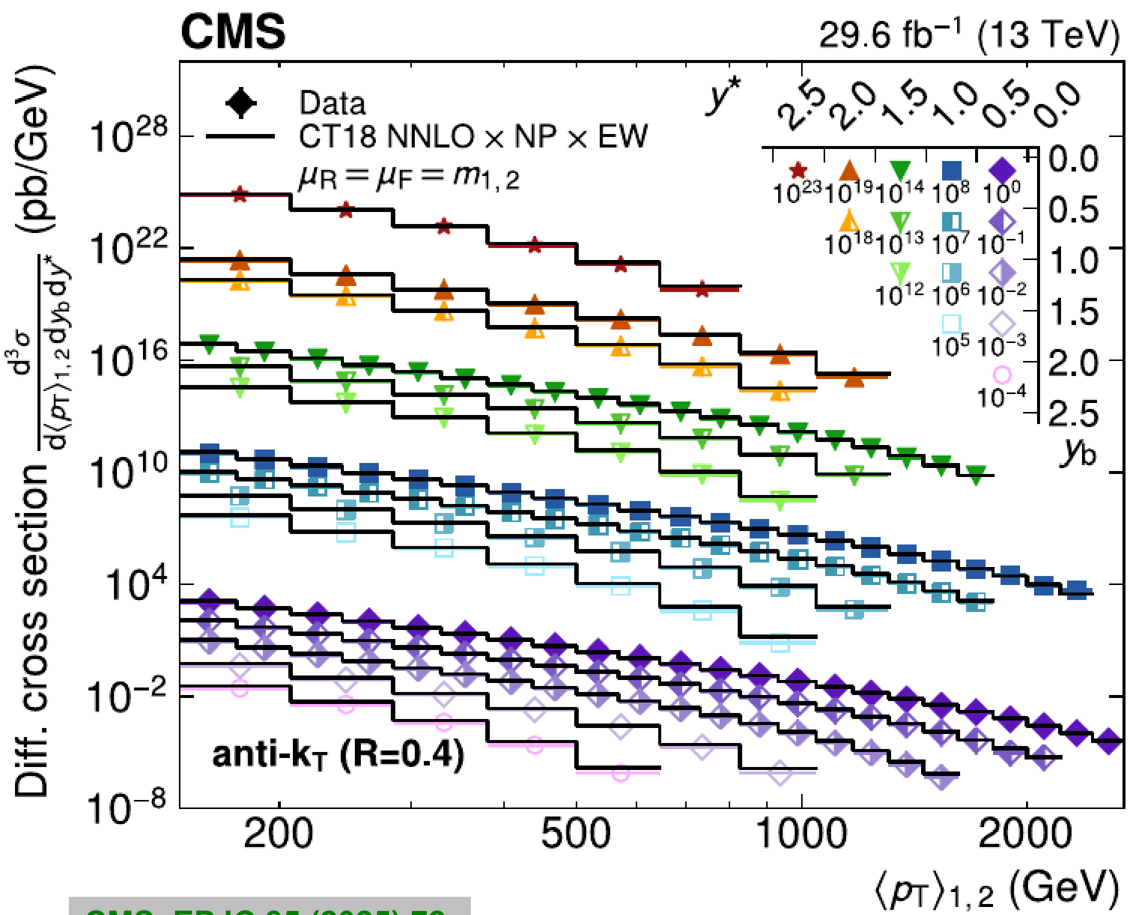
CMS, EPJC 85 (2025) 72.

Jet event counting in bins of x, y^*, y_b

Comparison of unfolded measurement with theory:

NNLO x nonperturbative x electroweak correction

(Impact of subleading-color corrections up to few %)



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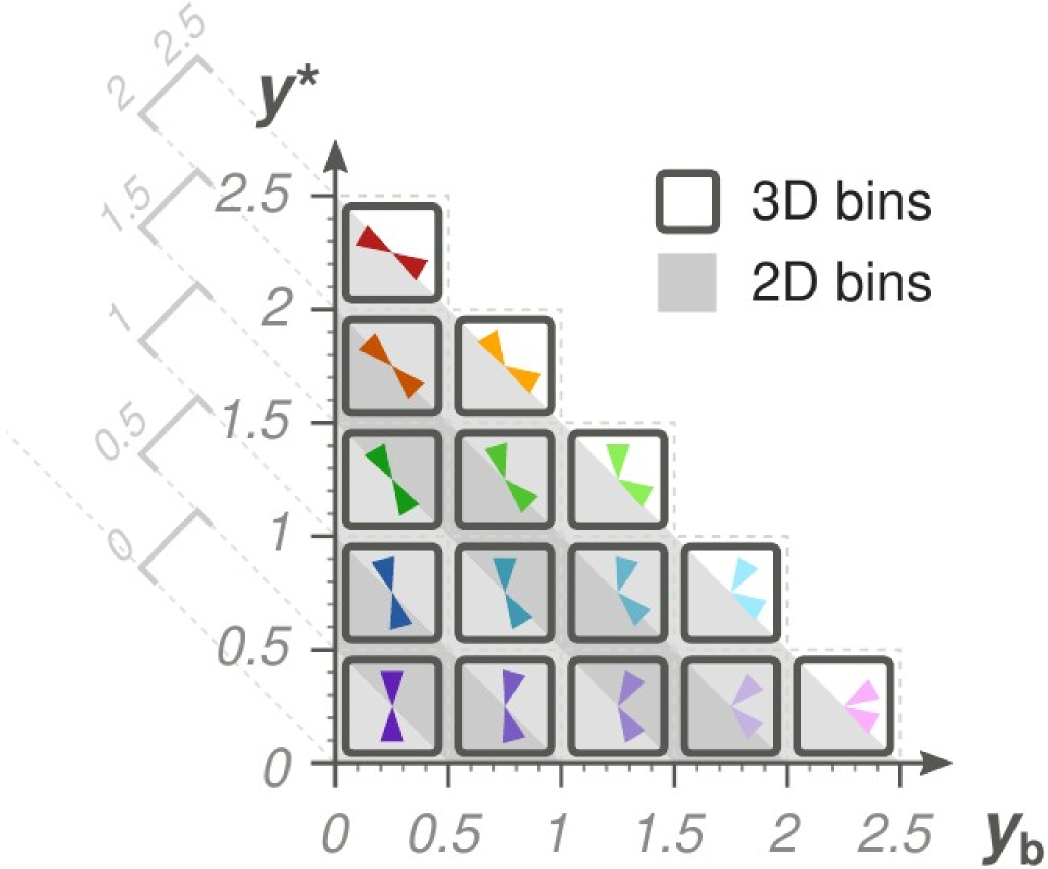


CMS, EPJC 85 (2025) 72.

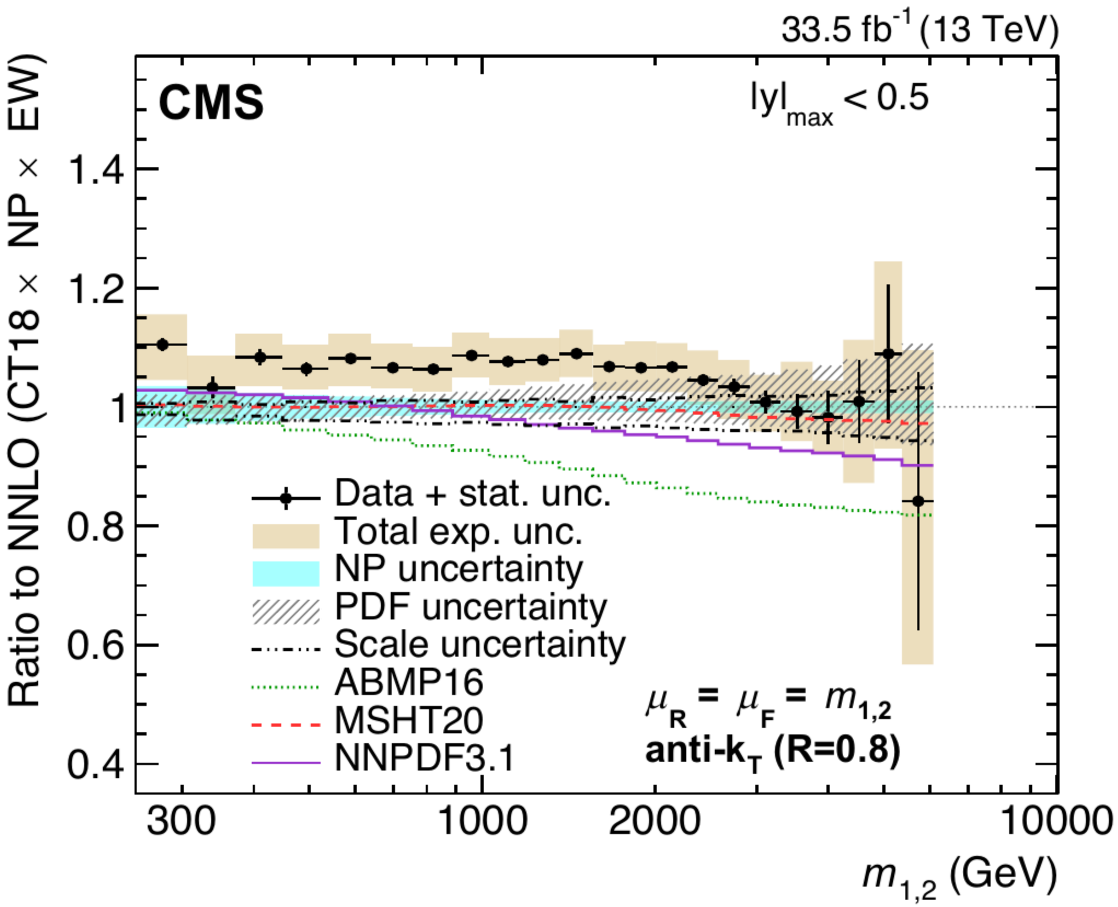
Double/triple-differential dijets

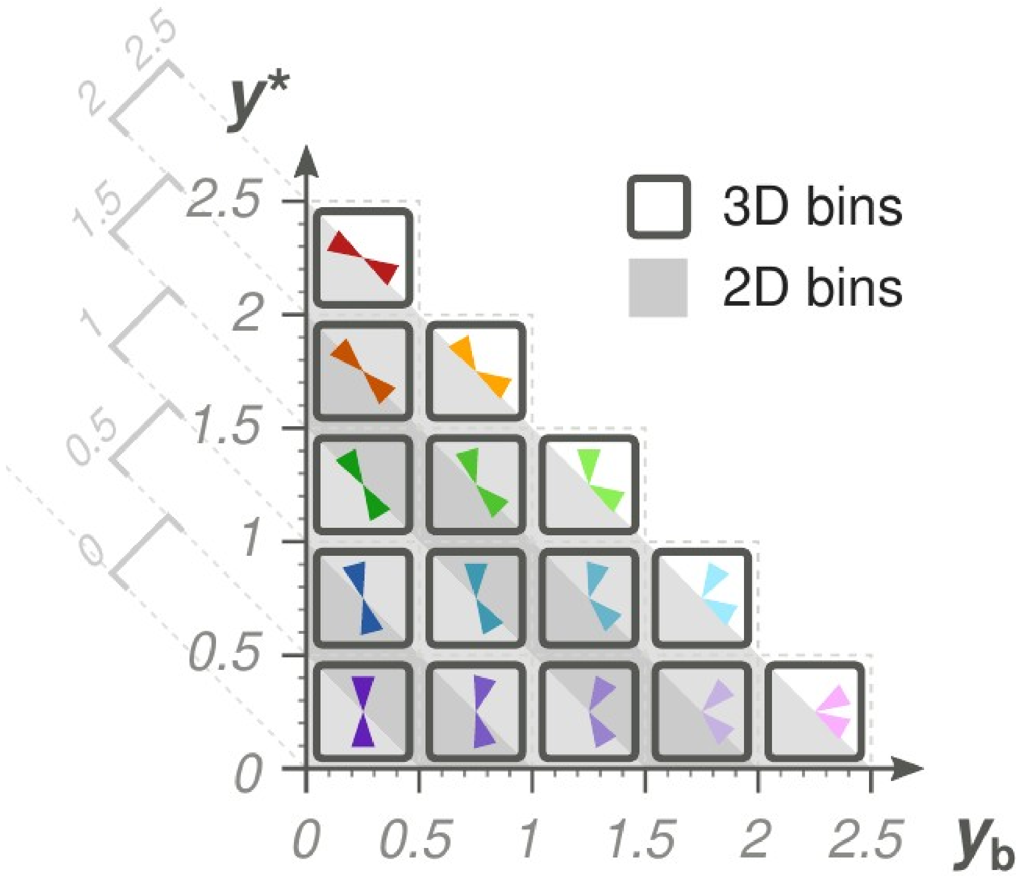
Determine $\alpha_s(m_Z)$ + PDFs

Example of ratio data / theory

2D $\alpha_s(m_Z) = 0.1179 \pm 0.0017(\text{fitall}) \pm 0.0008(\text{scl})$

3D $\alpha_s(m_Z) = 0.1181 \pm 0.0019(\text{fitall}) \pm 0.0009(\text{scl})$





CMS, EPJC 85 (2025) 72.

Combining jet datasets → $\alpha_s(Q)$

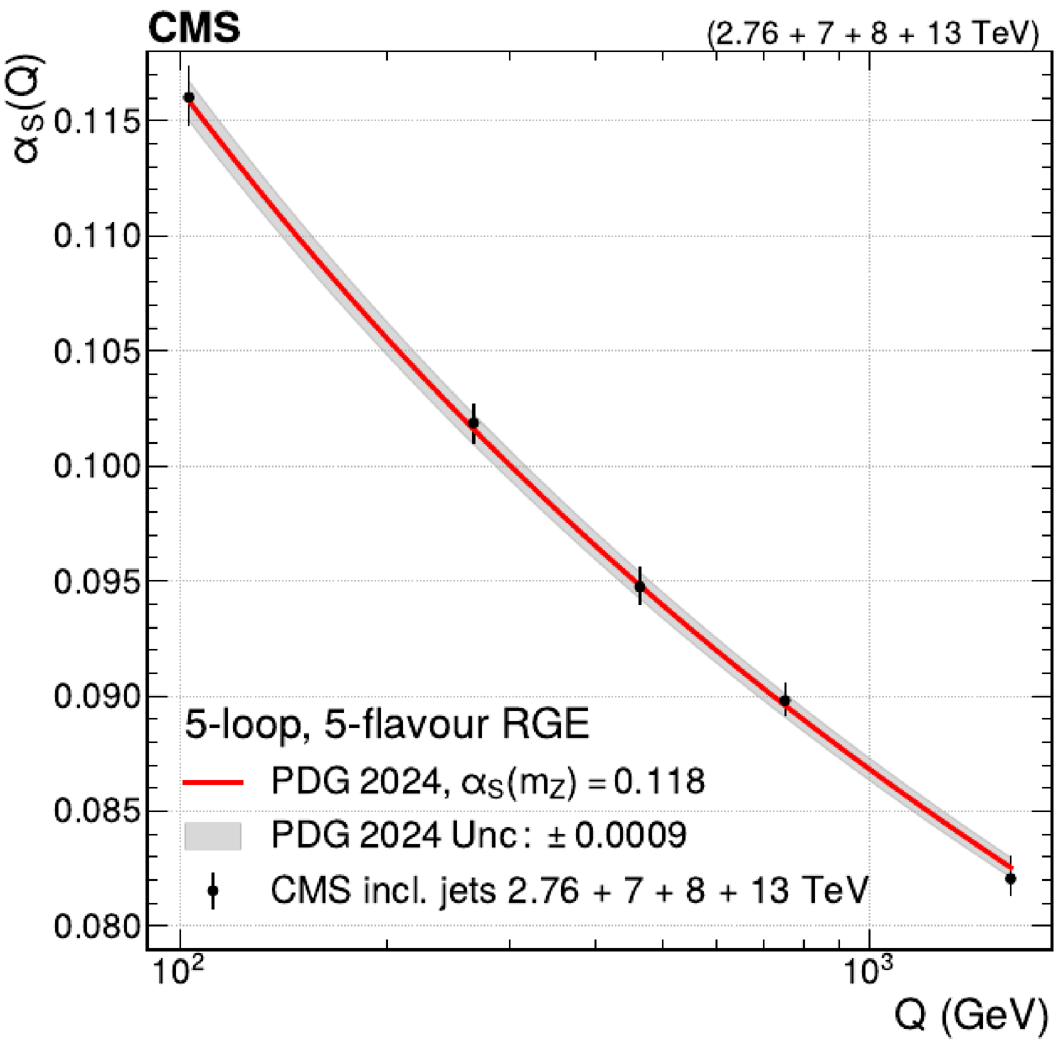
- Up to now: Fit of whole dataset → $\alpha_s(m_Z)$ & PDFs (running used implicitly)
- New QCD analysis from CMS
  - Combination of multiple datasets (→ table)
  - Subdivide into ranges of jet p_T
  - Multi-parameter fit of $\alpha_s(m_Z)$ & PDFs in each range separately
- Uncertainty correlations vs. E_{cms} studied and varied
  - Some correlation in JEC among cms energies, insignificant in JER
  - MHOU (scale variation) fully correlated

$\sqrt{s}$ [TeV]	$\mathcal{L}$ [fb^{-1}]	N_p	p_T [GeV]	$\|y\|$
2.76	0.0054	80	74–592	0.0–3.0
7	5.0	130	114–2116	0.0–2.5
8	20	165	74–1784	0.0–3.0
13	33.5	78	97–3103	0.0–2.0

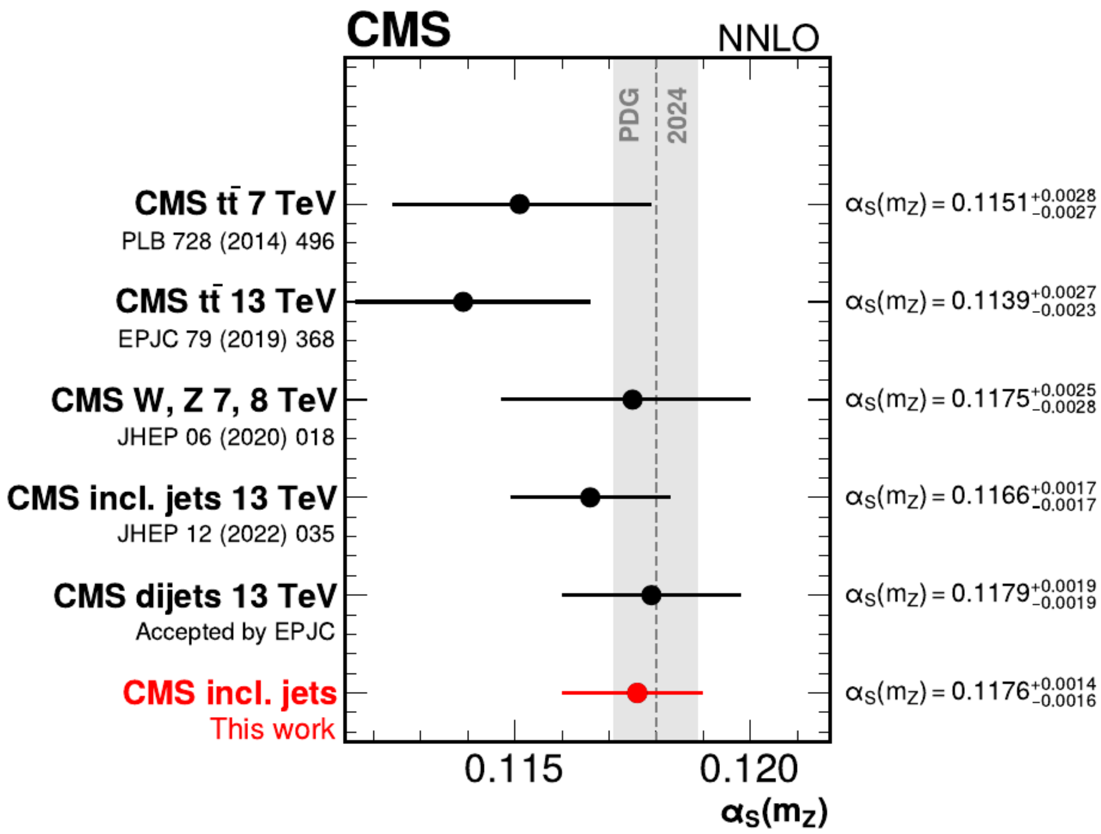
CMS, arXiv:2412.16665.

Combining inclusive jet datasets

Running of $\alpha_s(Q)$ in five ranges of jet p_T



Comparison of $\alpha_s(m_Z)$ from all jet data to previous CMS results at NNLO



No discrepancies observed!

CMS, arXiv:2412.16665.

Combining dijet datasets → $\alpha_s(Q)$

- **New α_s extraction from all dijet data of ATLAS & CMS**
  - **Combination of multiple datasets (→ table), in 2nd step also HERA dijets**
  - **Subdivide into ranges of relevant scale Q**
  - **Complete NNLO predictions**
  - **Simultaneous fit of one $\alpha_s(Q)$ per each range (with PDF variations as nuisance parameters at starting scale μ_0 = 90 GeV)**
- **Uncertainty correlations**
  - **Experimental ones assumed negligible**
  - **MHOU (scale variation) fully correlated**

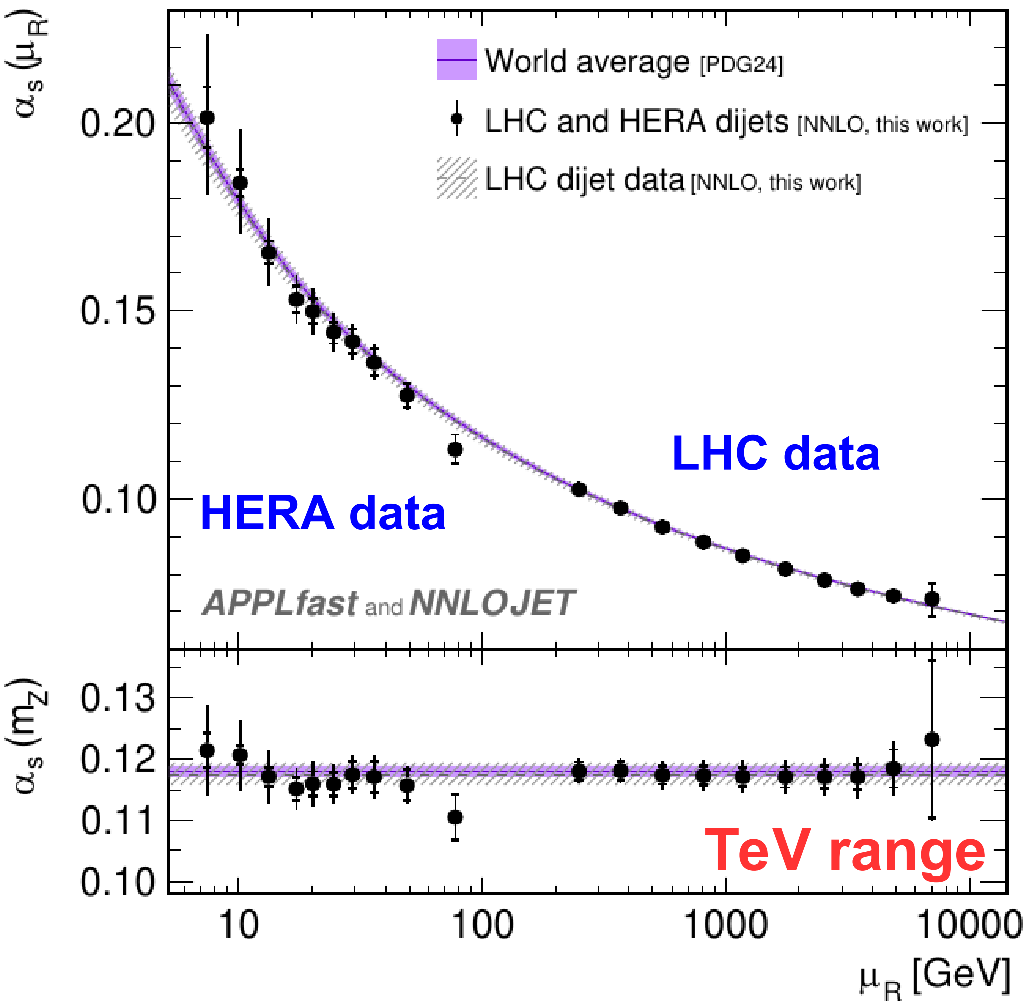
Data	$\sqrt{s}$ [TeV]	dσ	R	$\mathcal{L}$
ATLAS [10]	7	$\frac{d^2\sigma}{dm_{jj}dy^*}$	0.6	$4.5\,\mathrm{fb}^{-1} \pm 1.8\,\%$
CMS [12]	7	$\frac{d^2\sigma}{dm_{jj}dy_{max}}$	0.7	$5.0\,\mathrm{fb}^{-1} \pm 2.2\,\%$
CMS [13]	8	$\frac{d^3\sigma}{d\langle p_T\rangle_{1,2}dy^*dy_b}$	0.7	$19.7\,\mathrm{fb}^{-1} \pm 2.6\,\%$
ATLAS [11]	13	$\frac{d^2\sigma}{dm_{jj}dy^*}$	0.4	$3.2\,\mathrm{fb}^{-1} \pm 2.1\,\%$
CMS [14]	13	$\frac{d^2\sigma}{dm_{jj}dy_{max}}$	0.8	$33.5\,\mathrm{fb}^{-1} \pm 1.2\,\%$
CMS [14]	13	$\frac{d^3\sigma}{dm_{jj}dy^*dy_b}$	0.8	$29.6\,\mathrm{fb}^{-1} \pm 1.2\,\%$

Ahmahdova, KR, et al., arXiv:2412.21165.

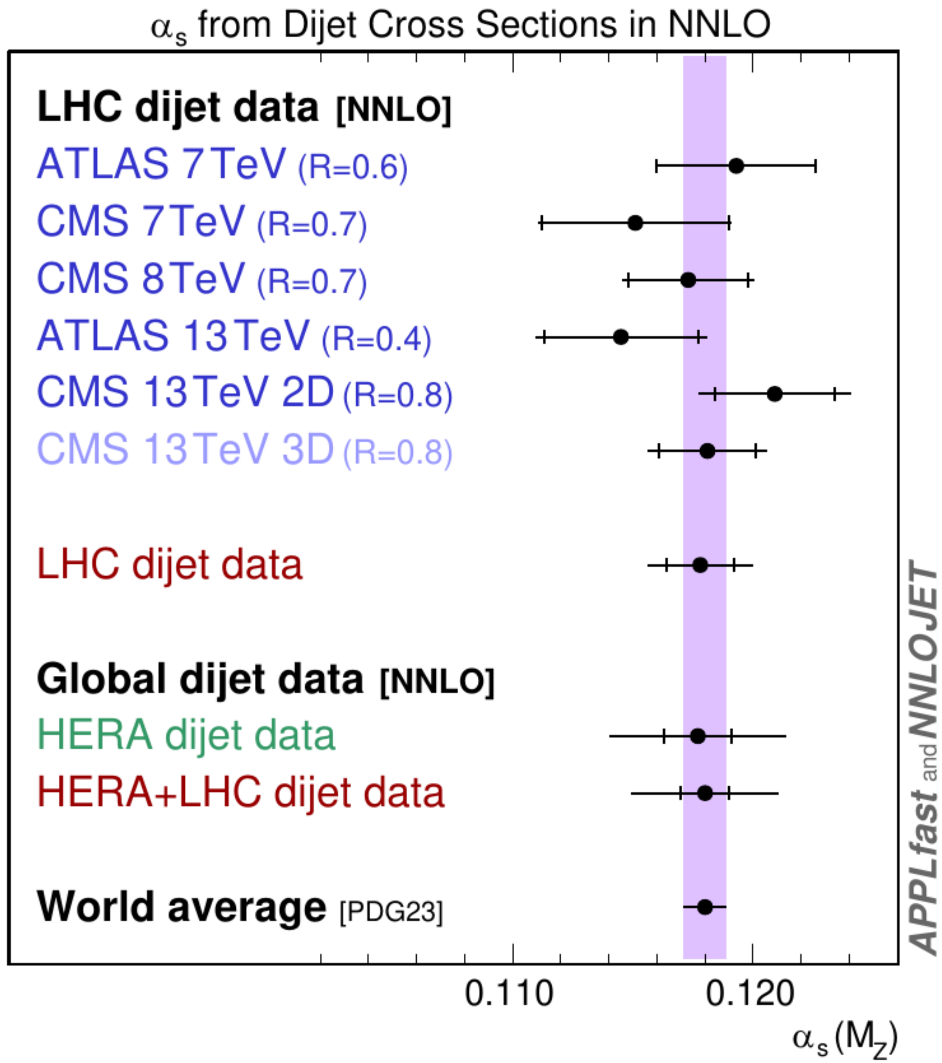
Combining dijet datasets → $\alpha_s(Q)$

From LHC dijet data $\alpha_s(m_Z^2) = 0.1178 \pm 0.0014(\text{fitall}) \pm 0.0017(\text{scl})$

α_s(Q) from HERA & LHC dijet data



α_s fit results per dataset



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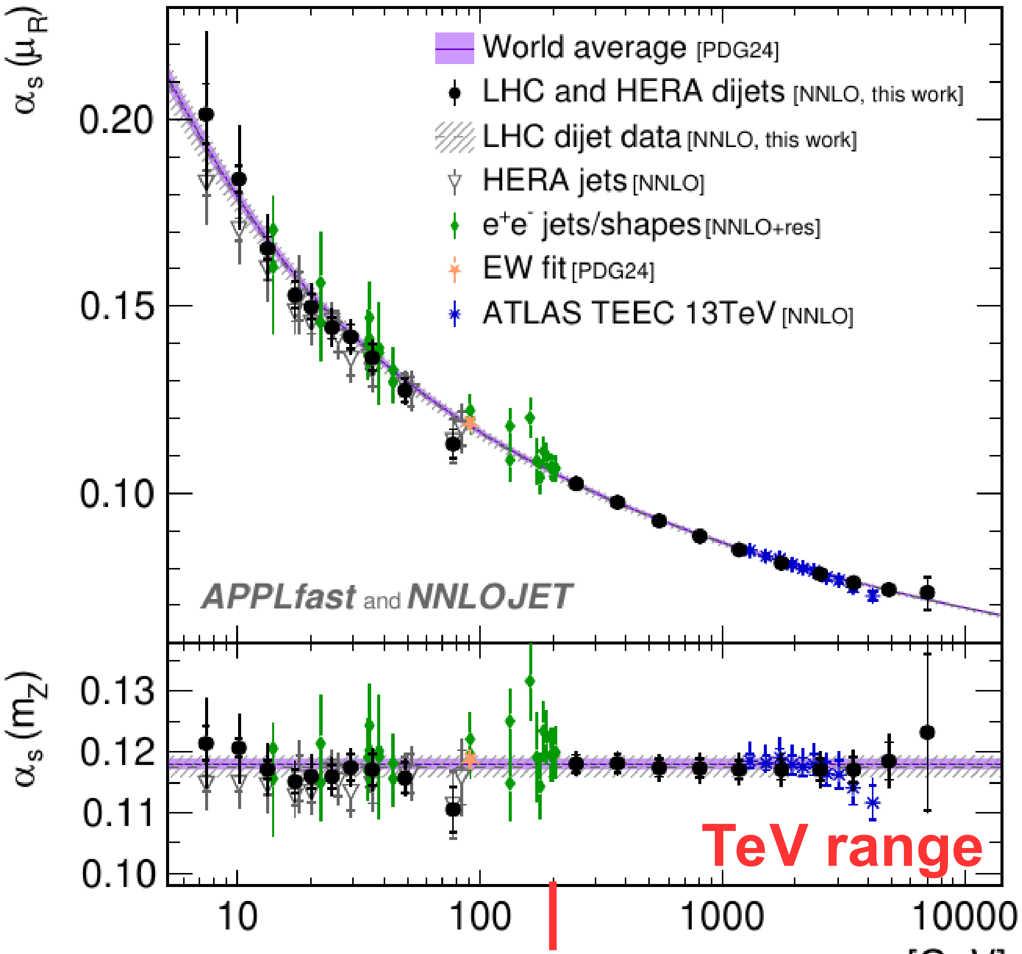
Comparison to selected other data



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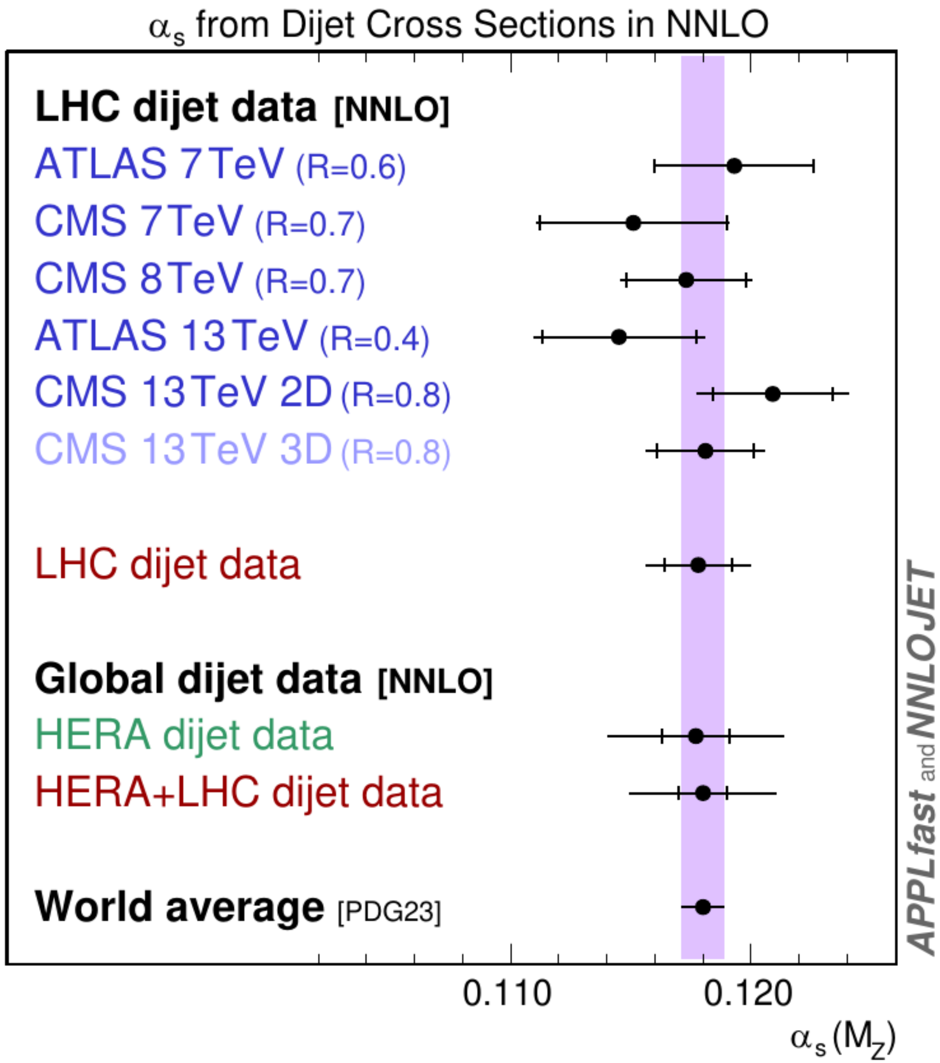
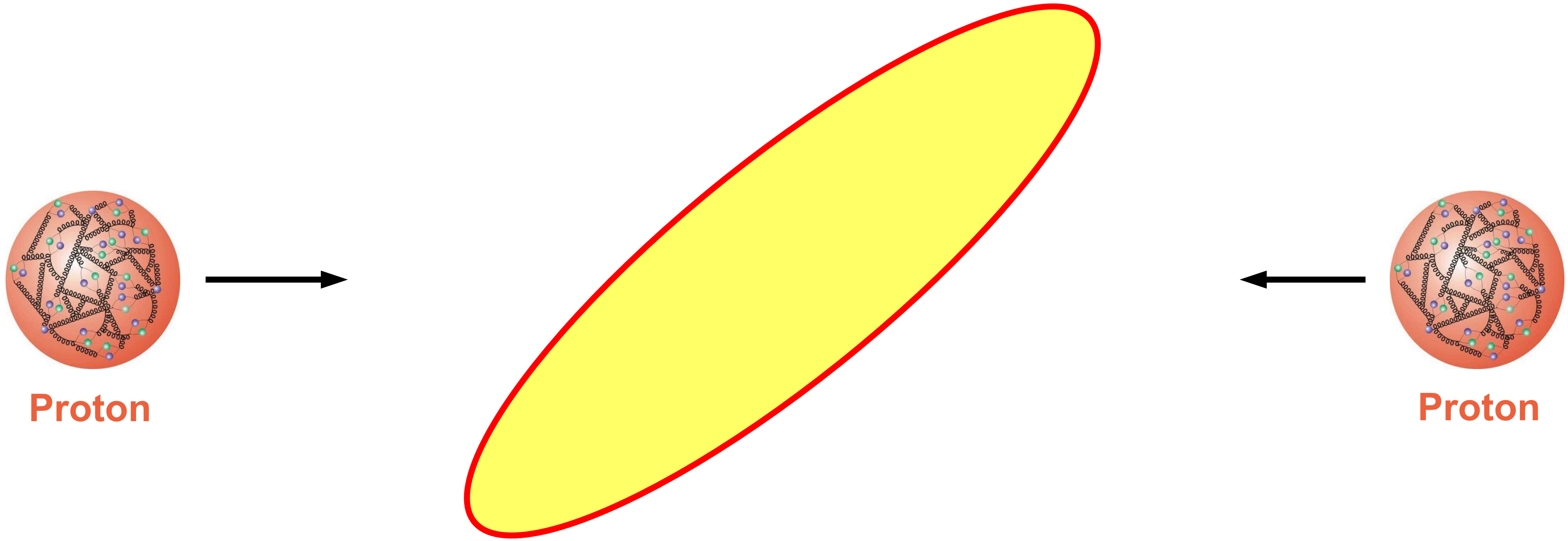


Ahmahdova, KR, et al., arXiv:2412.21165.

Normalised distributions

Energy flow



Normalised distributions

- Analysing the energy flow within an event in bins of some momentum scale and a suitable observable
- Often so-called “event shapes” like thrust or energy-energy correlations
- Go back to definitions suggested for e^+e^- collisions; for pp only transverse momenta used
- Useful for i.a.:
  - Determination of $\alpha_s(m_Z)$ & test of running of $\alpha_s(Q)$
  - MC generator comparison & tuning
  - Search for new physics

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  - Search for new physics
- Independent of luminosity
- Reduced sensitivity to other systematic effects
- Often multi-scale problem → more complicated scale dependence
- Can contain transition region from perturbative to nonperturbative QCD

Transverse energy-energy correlation

- Example of an event shape: energy-energy correlation (EEC)
  - Goes back to definition in e^+e^- — Basham, Brown, Ellis, Love, PRL41 (1978) 1585; PRD 19 (1979) 2018.
  - Here specialised to pp collisions → only transverse momenta (TEEC)
  - Measures E_T weighted azimuthal differences:

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

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Transverse jet energy weights

Measure of pairwise azimuthal distance between jets i,j

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Normalisation to no. of events N

Sum over all events in sample

Normalisation to E_T sum per event

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Normalisation to no. of events N

Sum over all events in sample

Normalisation to E_T sum per event

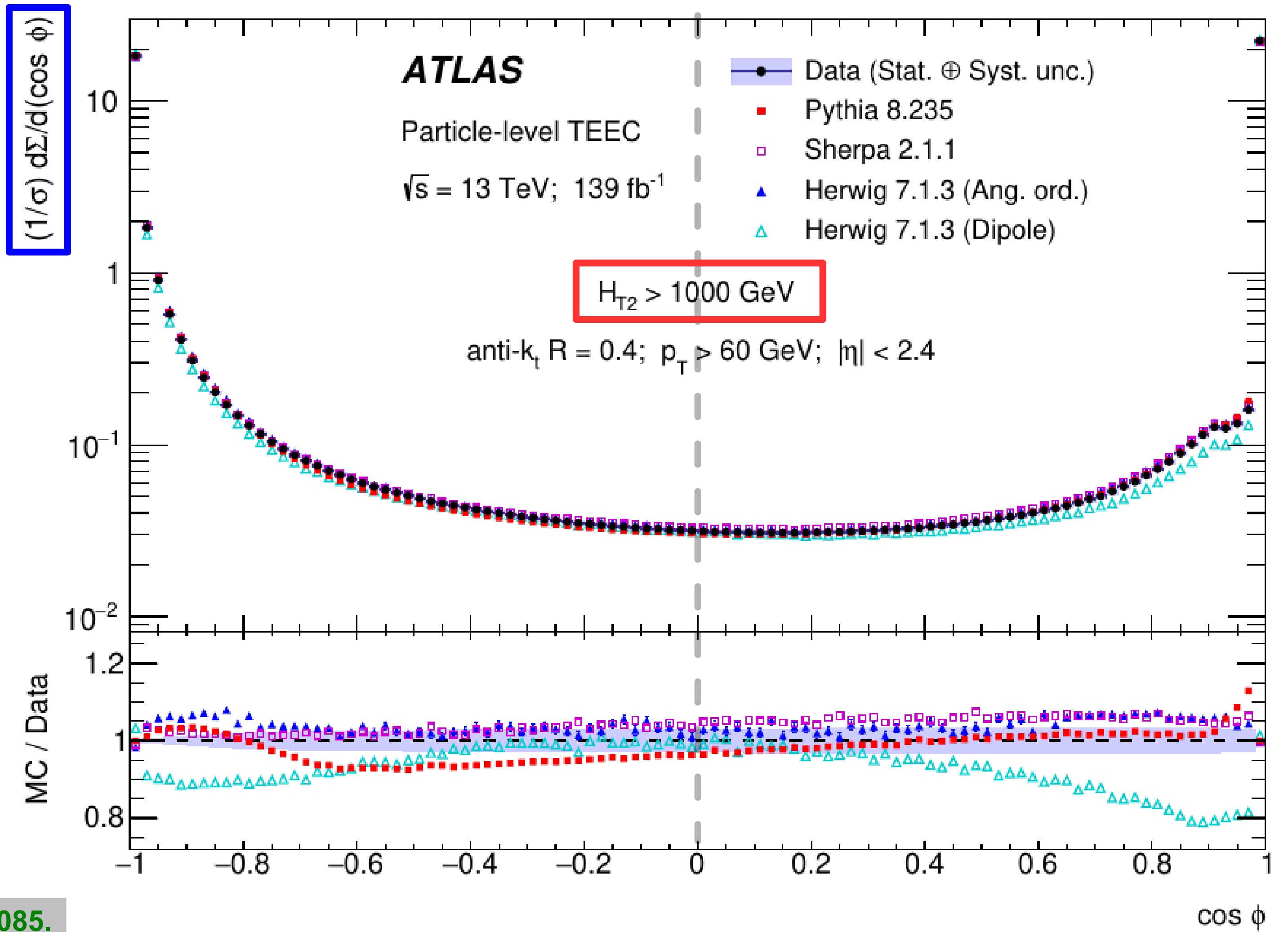
Additional binning in e.g. transverse energy sum H_T → scale Q

Transverse energy-energy correlation

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

Event shape: $\mathrm{TEEC} \propto \alpha_s$

Normalised



Multiple bins in H_T

ATLAS, JHEP 07 (2023) 085.

Transverse energy-energy correlation

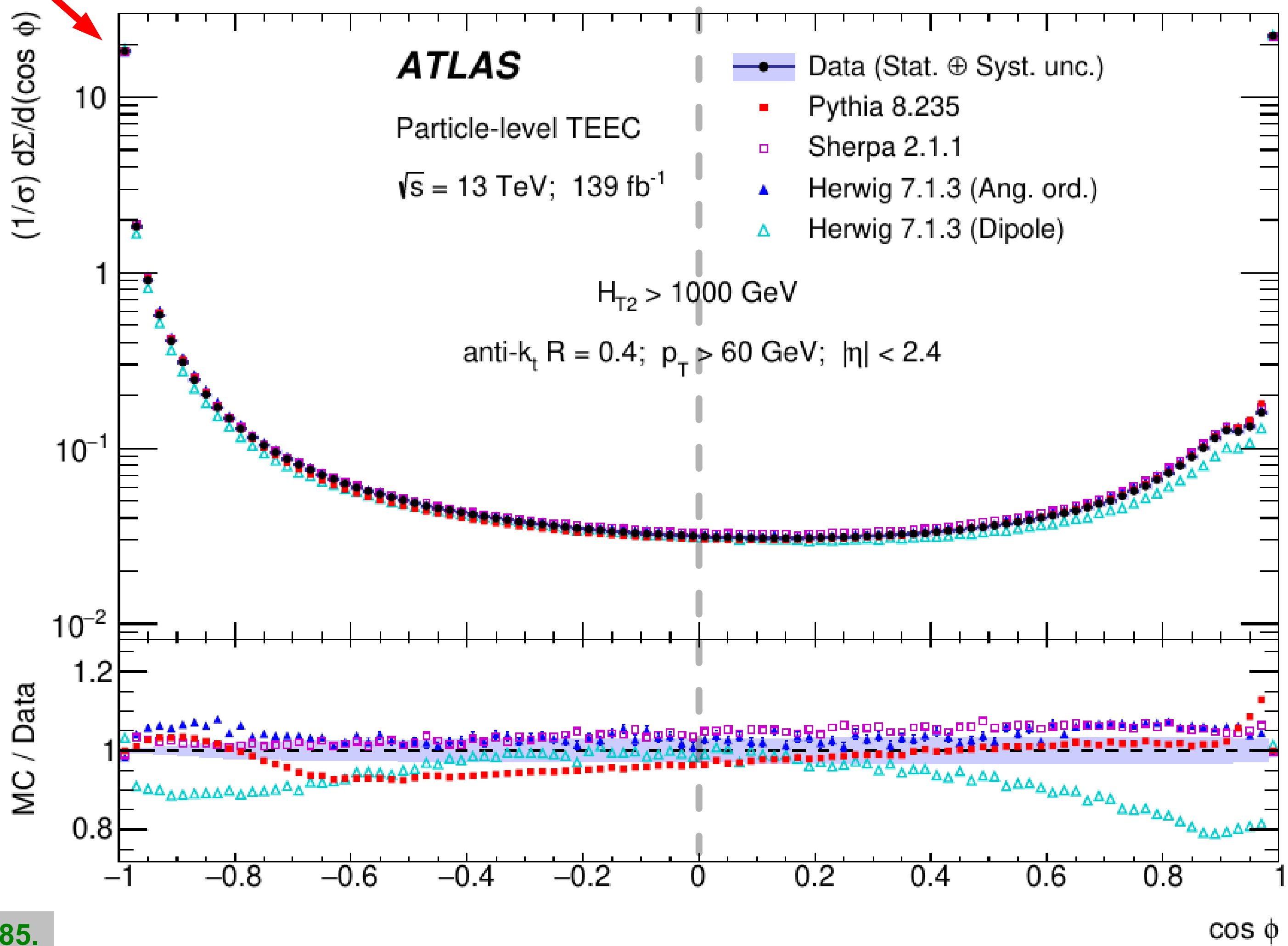
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

Event shape: $\mathrm{TEEC} \propto \alpha_s$

$2 \rightarrow 2$ back-to-back jets

autocorrelation i=j $2 \rightarrow 2$

Normalised



Multiple bins in H_T

ATLAS, JHEP 07 (2023) 085.

Transverse energy-energy correlation

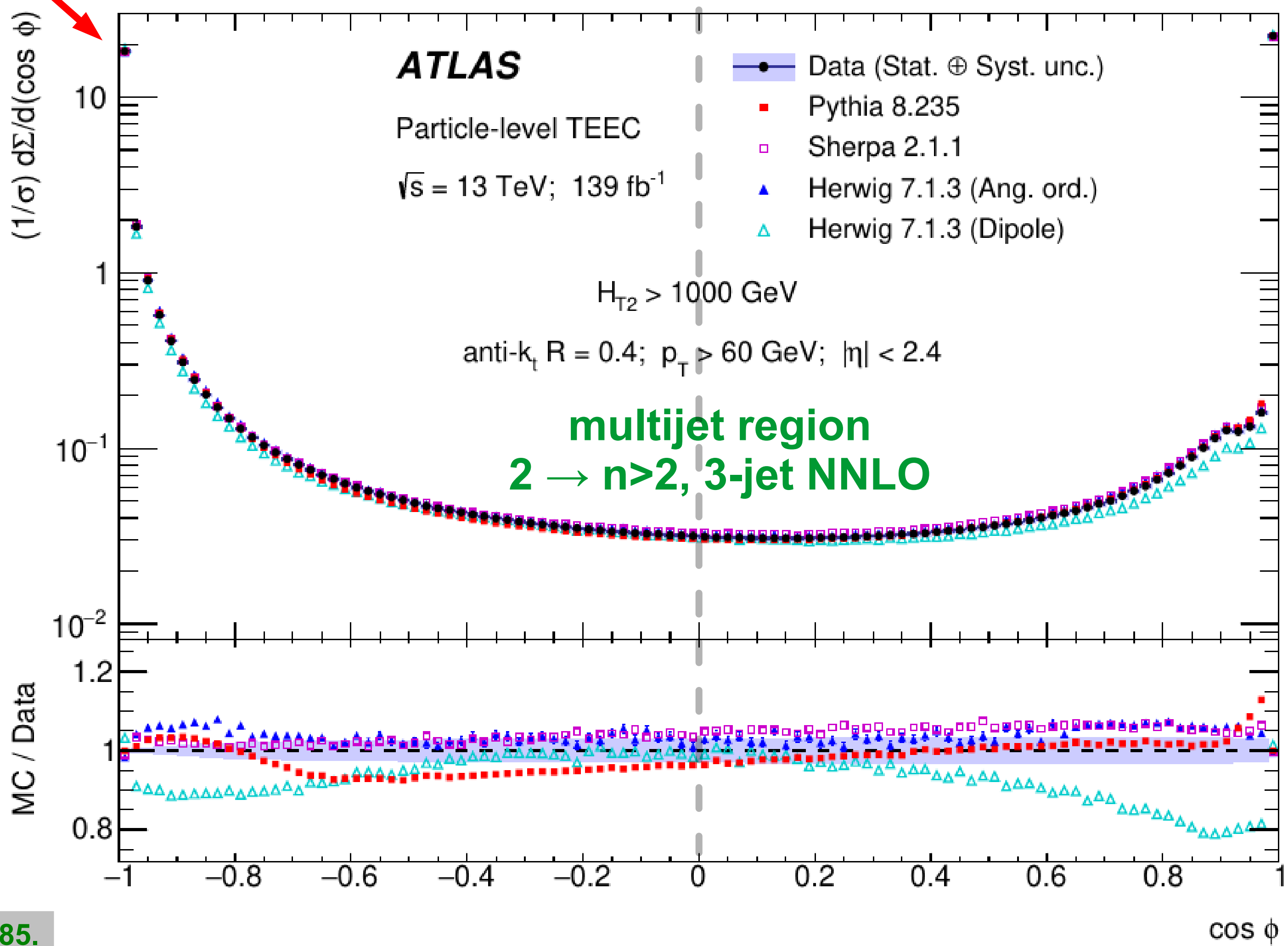
$$\frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi} = \frac{1}{N}\sum_{A=1}^{N}\sum_{ij}\frac{E^A_{\mathrm{T}i}E^A_{\mathrm{T}j}}{\left(\sum_k E^A_{\mathrm{T}k}\right)^2}\delta(\cos\phi - \cos\phi_{ij})$$

Event shape: $\mathrm{TEEC} \propto \alpha_s$

2 → 2 back-to-back jets

autocorrelation i=j 2 → 2

Normalised



Multiple bins in H_T

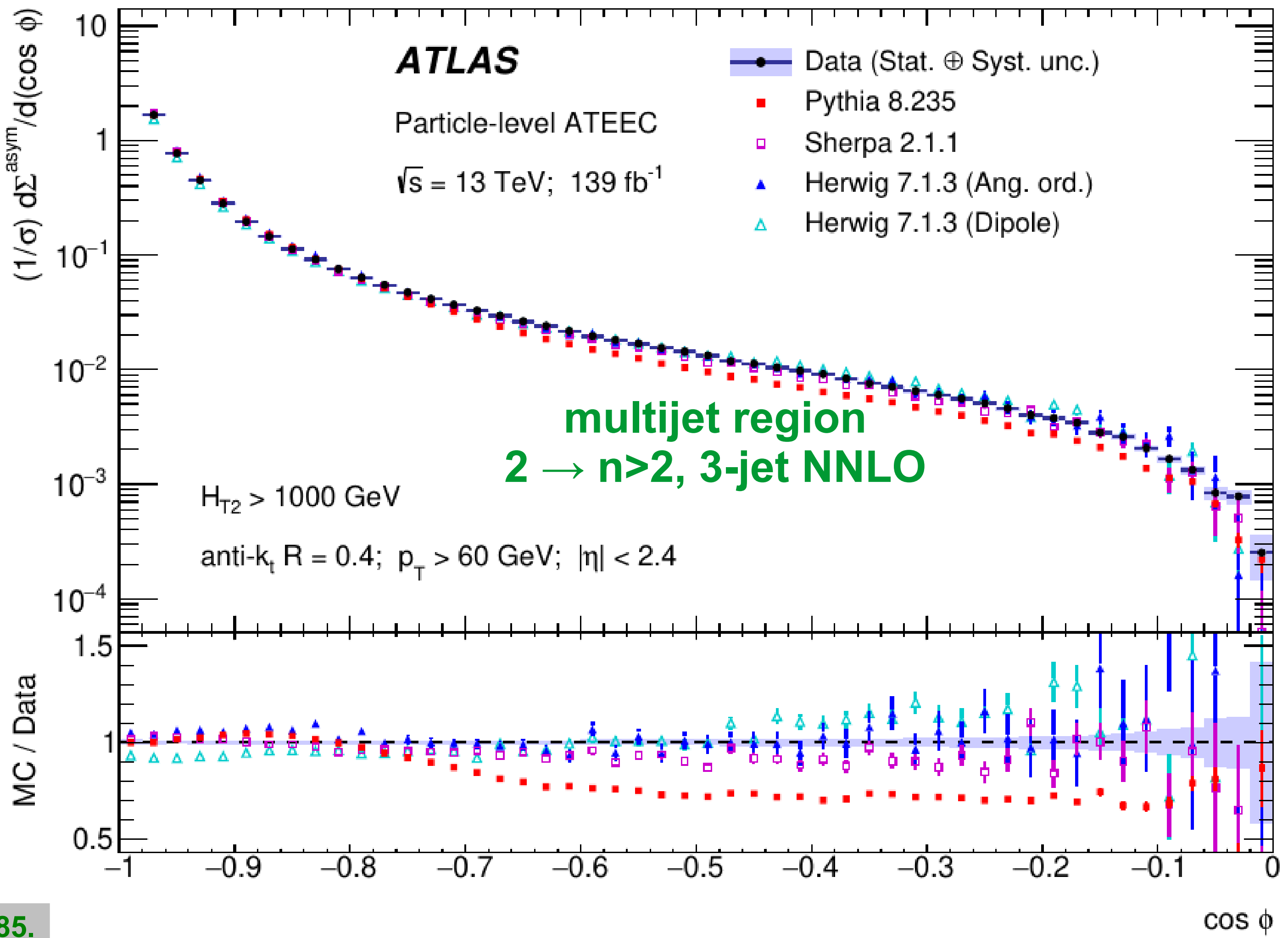
ATLAS, JHEP 07 (2023) 085.

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

Event shape: $\mathrm{ATEEC} \propto \alpha_s$

Asymmtry

Normalised



Multiple bins in H_T

ATLAS, JHEP 07 (2023) 085.

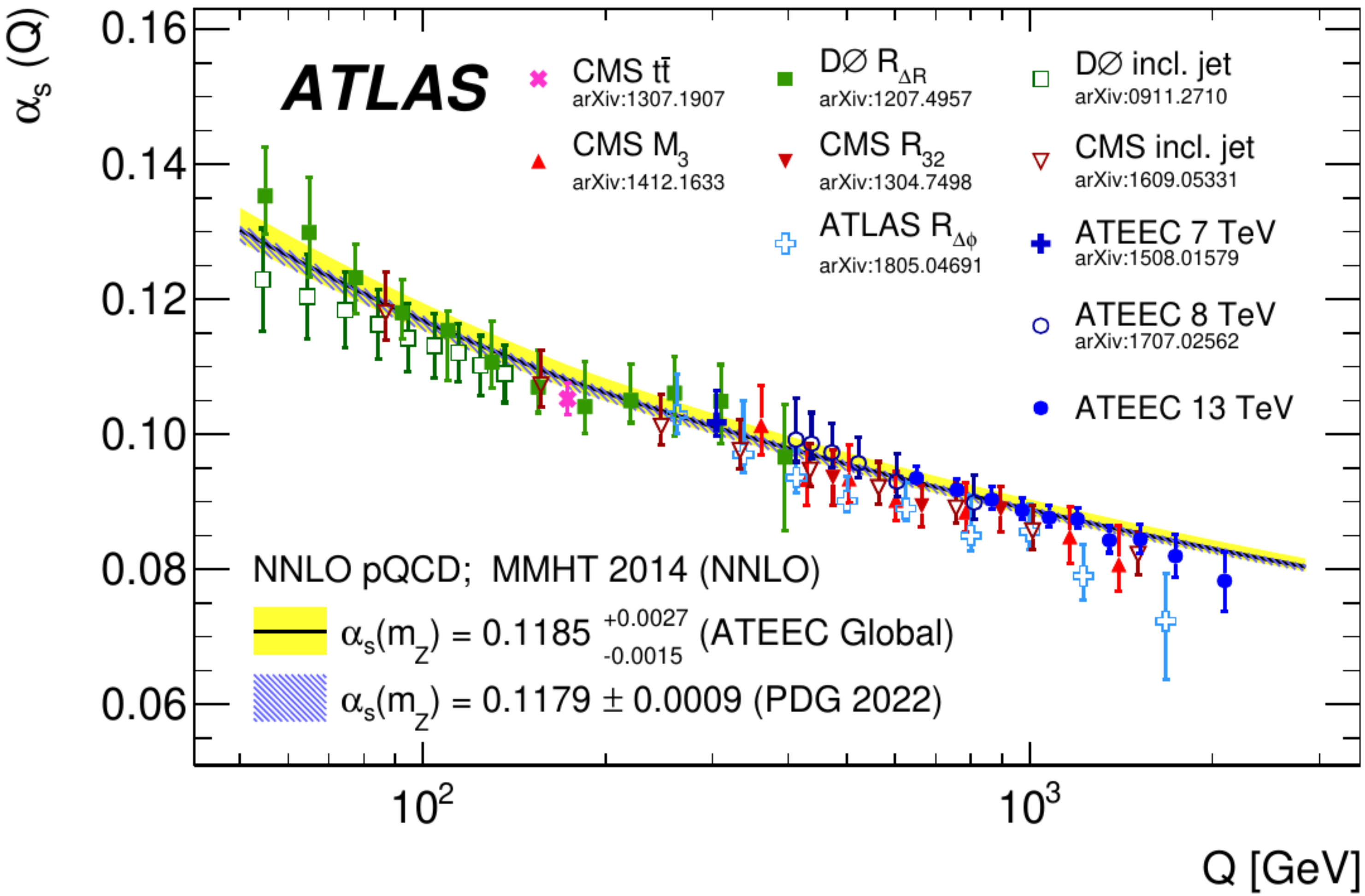
Transverse energy-energy correlation

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

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

Remark:
Reduction in MHO uncertainty smaller than maybe anticipated

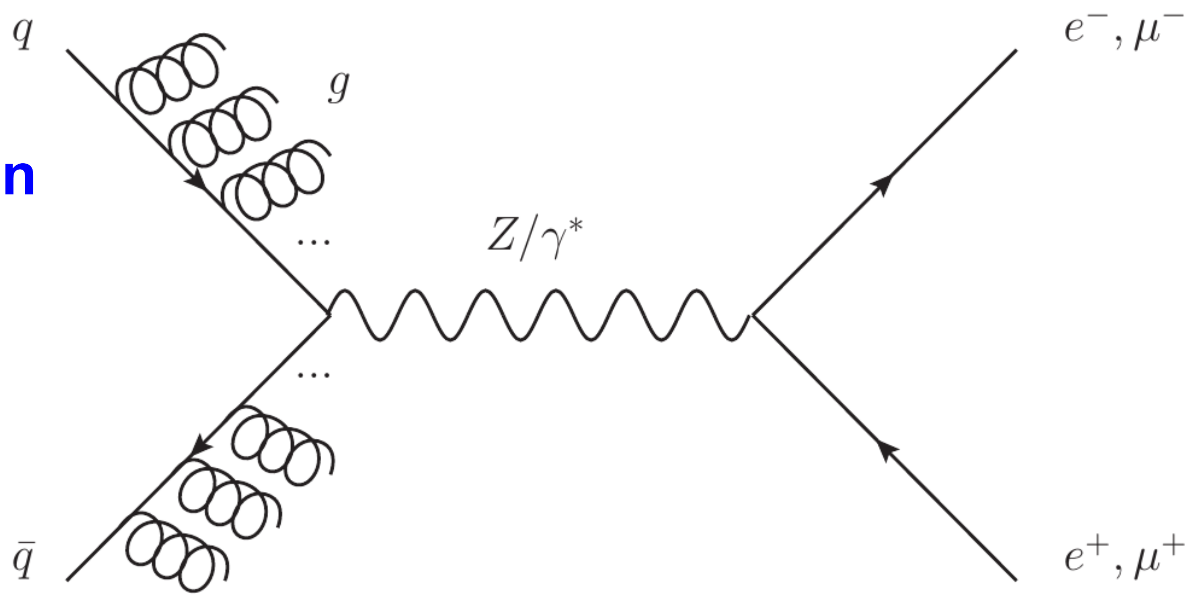
First "running" points from pp observable at NNLO

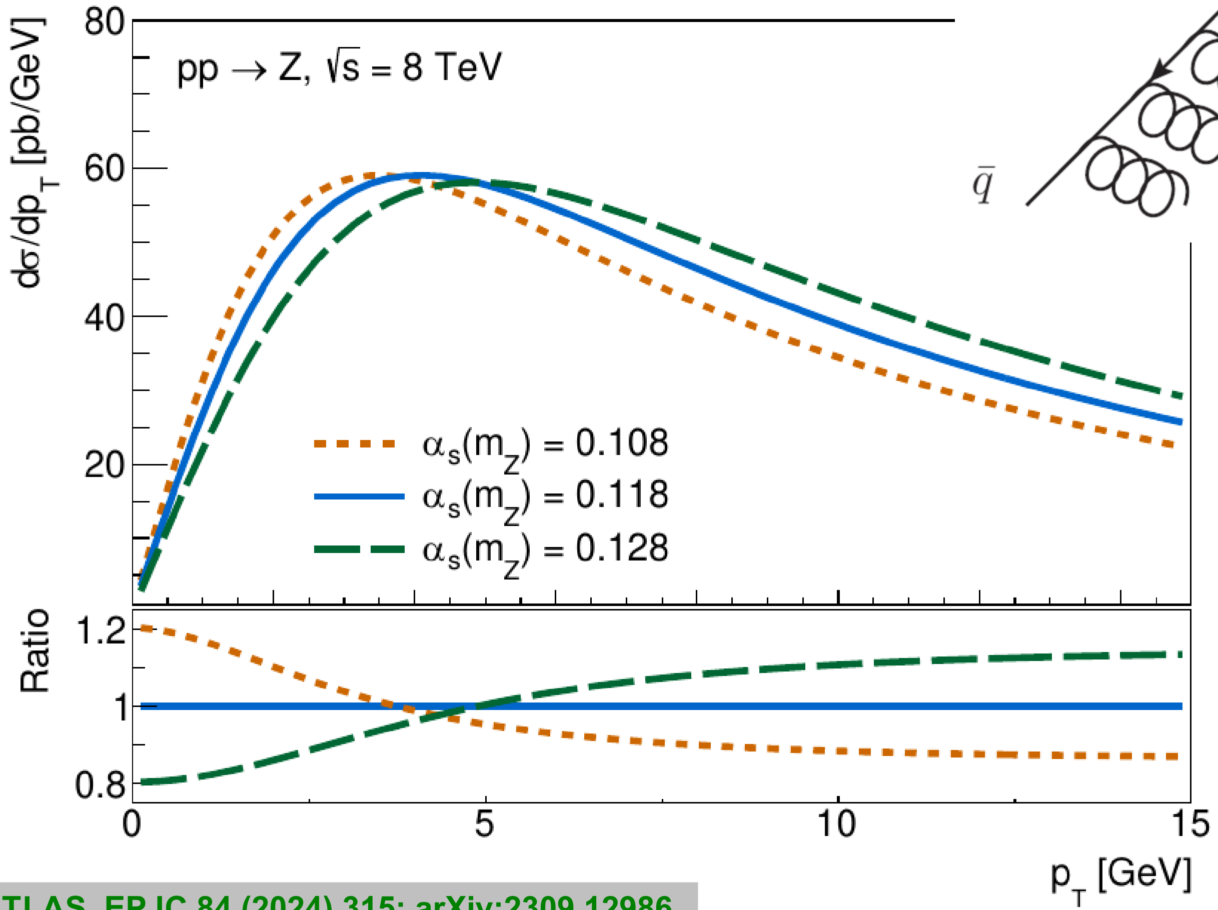


ATLAS, JHEP 07 (2023) 085.

Sudakov peak of DY Z p_T

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





Sensitivity to α_s

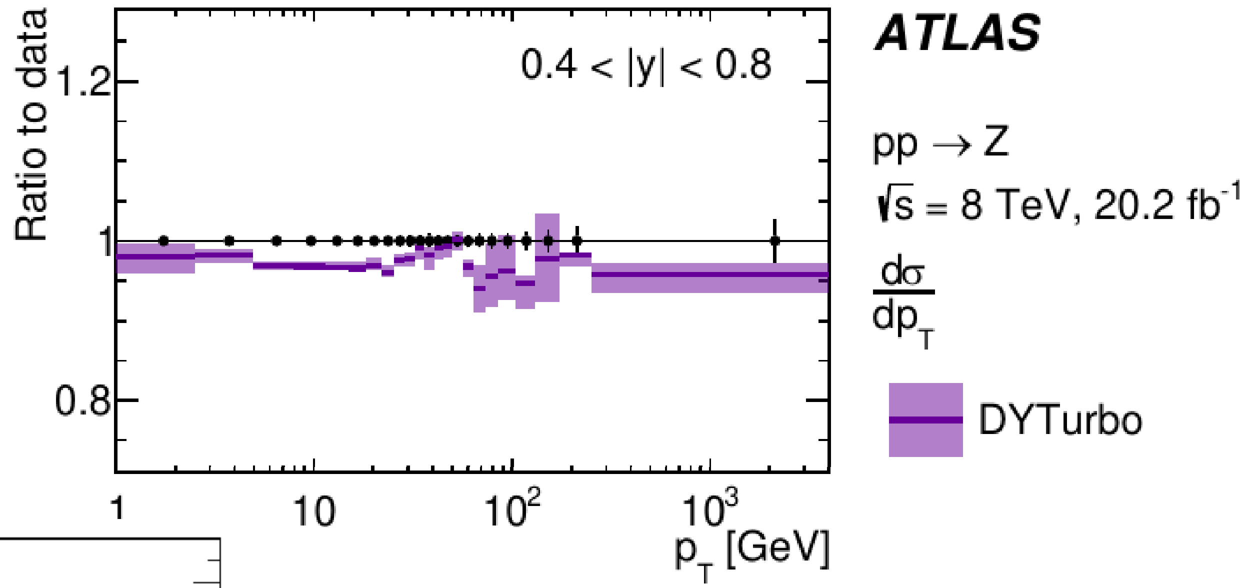
Novel idea pursued by ATLAS (and CDF)

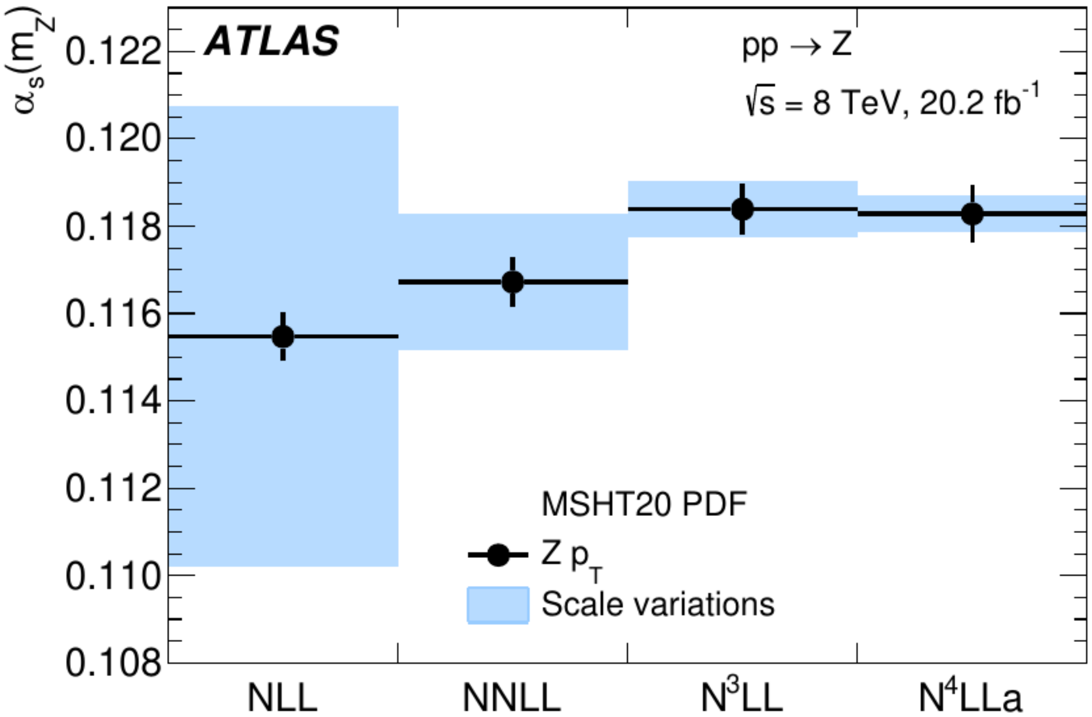
ATLAS data published!

ATLAS, EPJC 84 (2024) 315; arXiv:2309.12986.

Sudakov peak of DY Z p_T

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





Series of α_s extractions with increasing precision

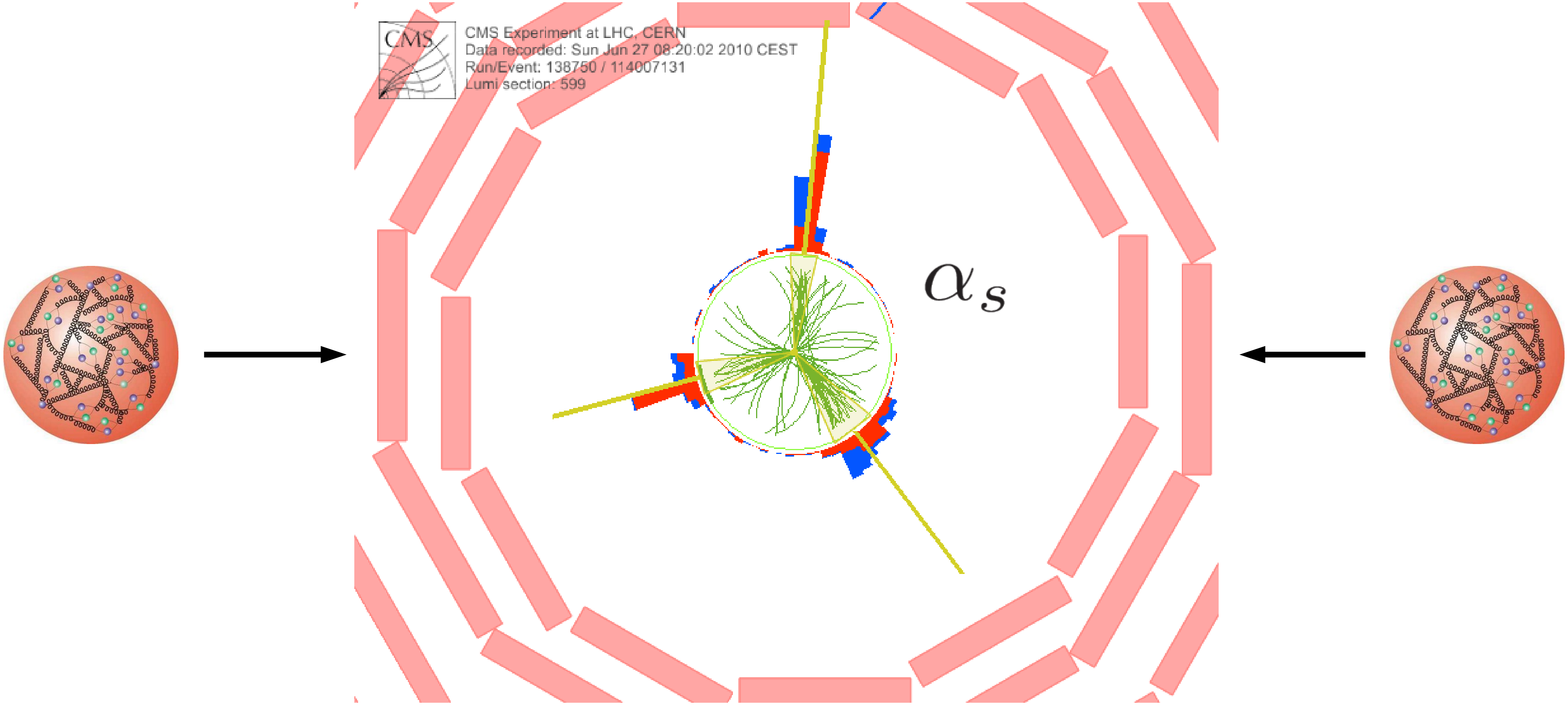
$$\alpha_s(M_Z) = 0.1183 \pm 0.0009$$

Most precise single determination (except Lattice), but so far not accepted by journal. Stimulated discussion notably on theory uncertainty.

ATLAS, EPJC 84 (2024) 315; arXiv:2309.12986.

Ratio observables

Higher multiplicity



Ratio observables

- Aim to reduce or eliminate impact of systematic effects
- Useful for i.a.:
  - Determination of $\alpha_s(m_Z)$ & test of running of $\alpha_s(Q)$
  - MC generator comparison & tuning
  - Investigation of jet size R dependence
  - Search for new physics

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  - Investigation of jet size R dependence
  - Search for new physics
- Often independent of luminosity
- Reduced or eliminated sensitivity to systematic effects
- Correlations between numerator & denominator
- Often multi-scale problem → more complicated scale dependence
- Also reduced sensitivity to desired effect

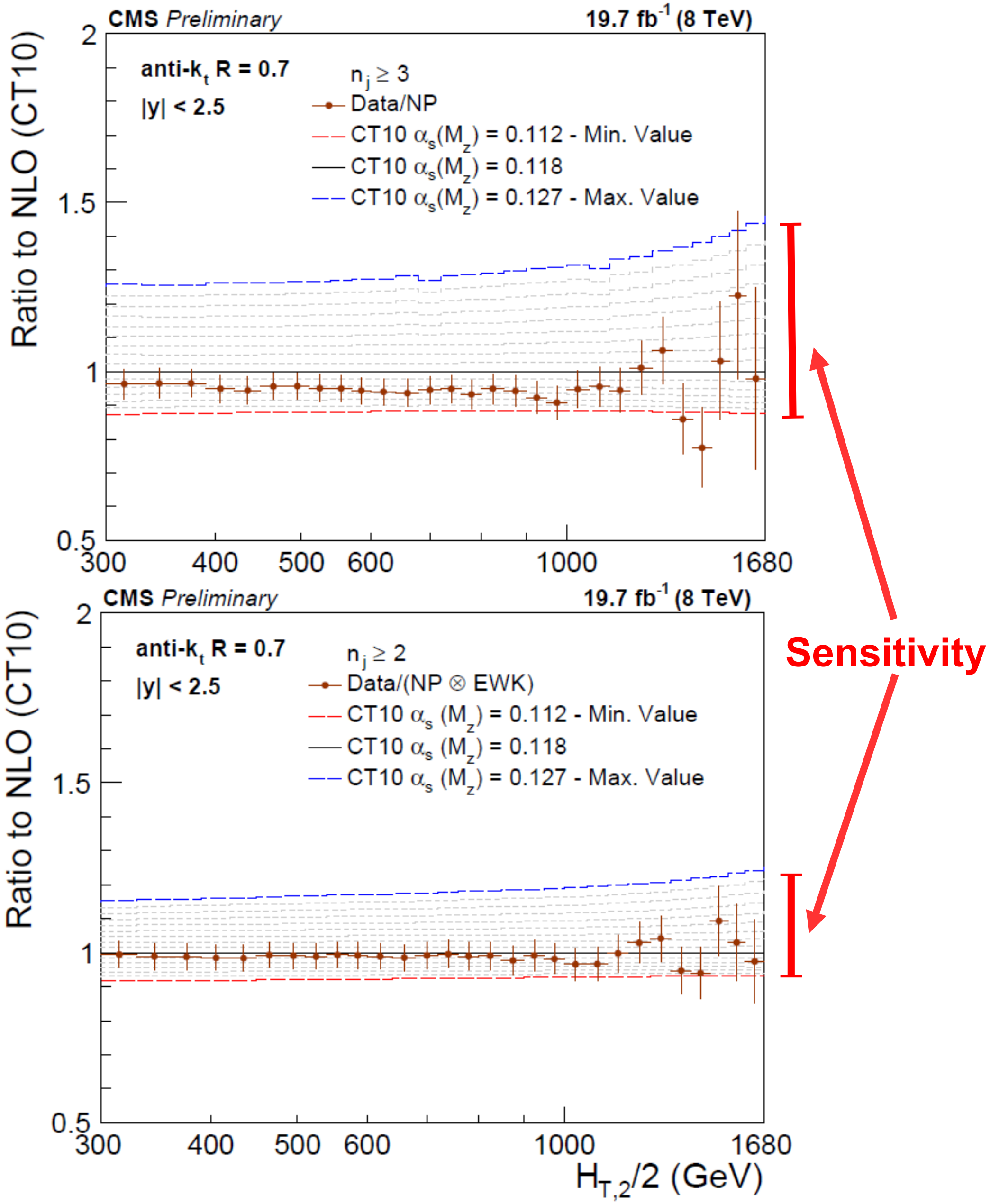
Sensitivity vs. systematic effects

Inclusive 3-jet cross section

$$\sigma_{3\mathrm{j}} \propto \alpha_s^3$$

Inclusive 2-jet cross section

$$\sigma_{2\mathrm{j}} \propto \alpha_s^2$$



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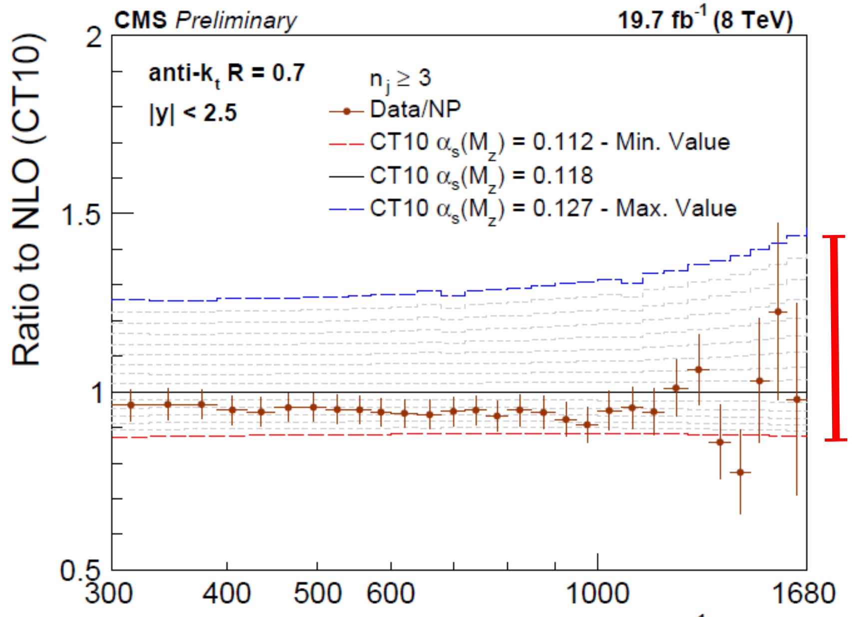

Inclusive 2-jet cross section

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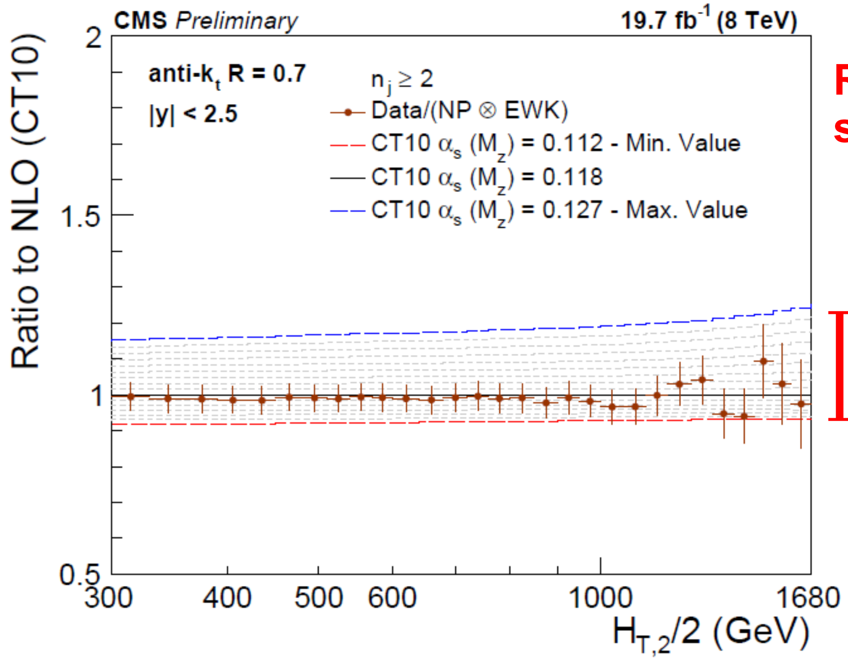
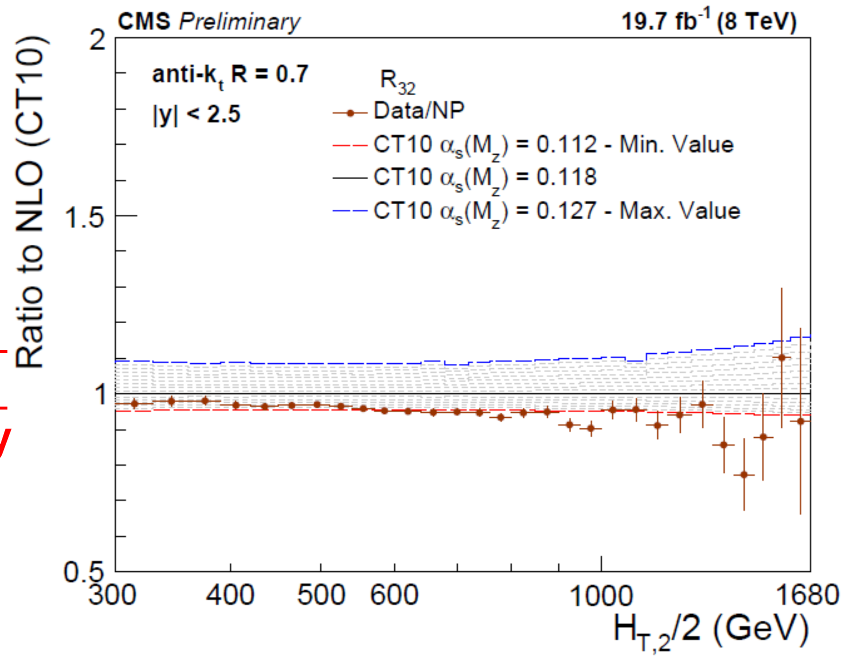


Reduced sensitivity

Inclusive 3-jet to inclusive 2-jet cross section ratio

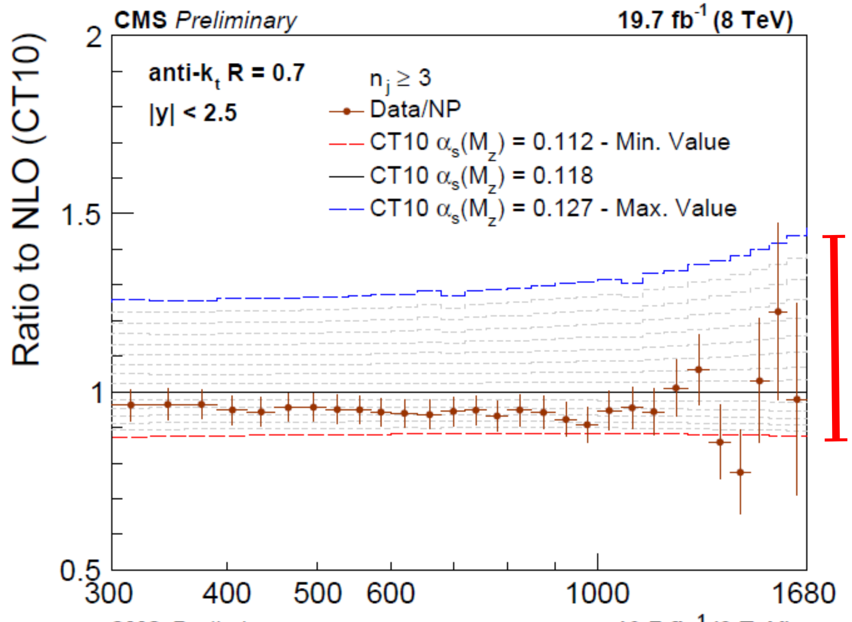
$$R_{3/2} \propto \alpha_s$$



Sensitivity vs. systematic effects

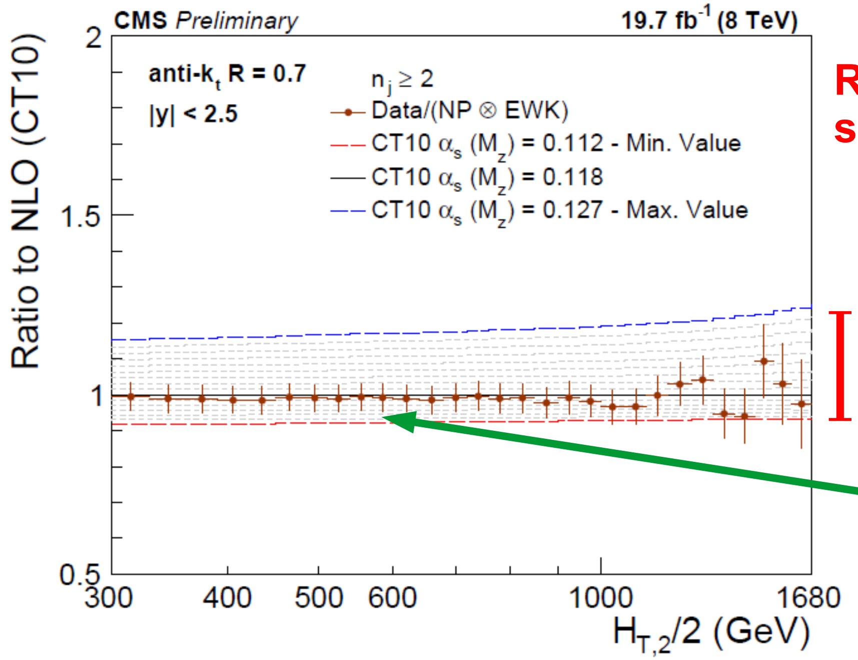
Inclusive 3-jet cross section

$$\sigma_{3j} \propto \alpha_s^3$$



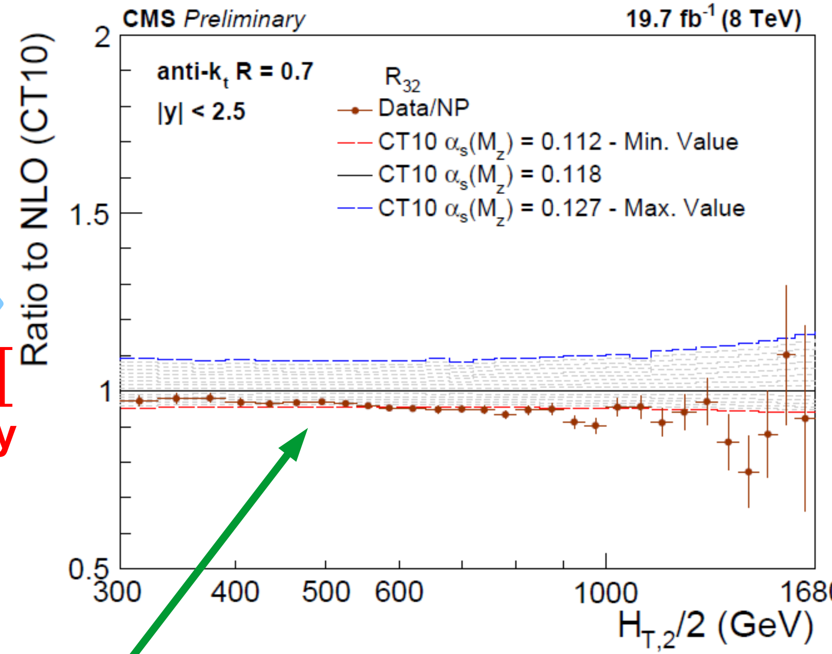
Inclusive 2-jet cross section

$$\sigma_{2j} \propto \alpha_s^2$$



Inclusive 3-jet to inclusive 2-jet cross section ratio

$$R_{3/2} \propto \alpha_s$$

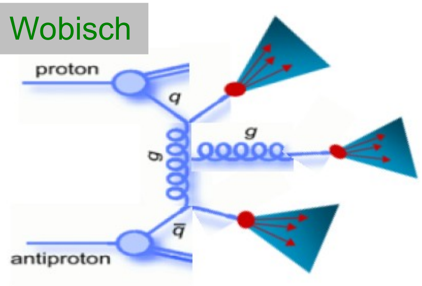


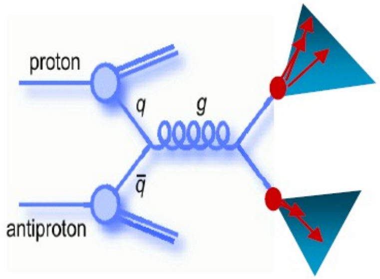
Reduced sensitivity

Much reduced systematic uncertainty

M. Wobisch

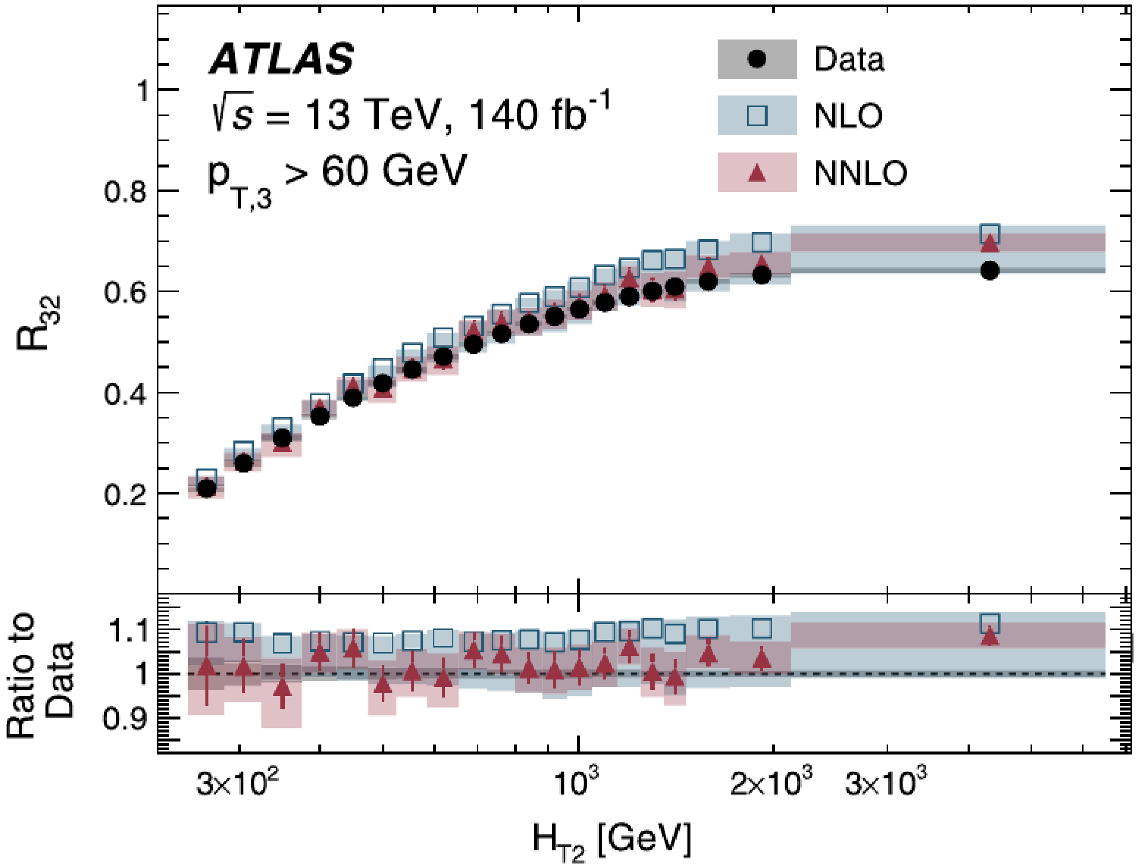
$R_{3/2}$





$\Leftrightarrow$ α_s

$$\frac{\sigma_{3+\text{jet}}}{\sigma_{2+\text{jet}}} \propto \alpha_s^1$$



Nice measurement from ATLAS: $R_{3/2}$, $R_{4/2}$, $R_{4/3}$, $R_{5/4}$

First comparison of $R_{3/2}$ vs. NNLO

But no α_s fit (yet).

ATLAS, PRD 110 (2024) 072019.

Multijet azimuthal correlation

- Ratio observable differential in jet p_T, where:
  - Numerator counts no. of neighbouring jets with minimal p_T within azimuthal distance $2\pi/3 < \Delta\Phi < 7\pi/8$ → enforces ≥ 3-jet configuration
  - Denominator counts all jets in p_T bin

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

$$R_{\Delta\phi}(p_T) \propto \alpha_s$$

CMS, EPJC 84 (2024) 842.

  - Requires 3-jet NNLO
  - Similar observables previously used by
    - D0: $R_{\Delta R}(p_T)$ D0, PLB 718 (2012) 56.
    - ATLAS: $R_{\Delta\phi}(H_T)$ ATLAS, PRD 98 (2018) 092044.

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$$R_{\Delta\phi}(p_T) \propto \alpha_s$$

CMS, EPJC 84 (2024) 842.

  - Nice feature: Equivalent definition with 2D quantity $N(p_T,n)$ counting neighbouring jets

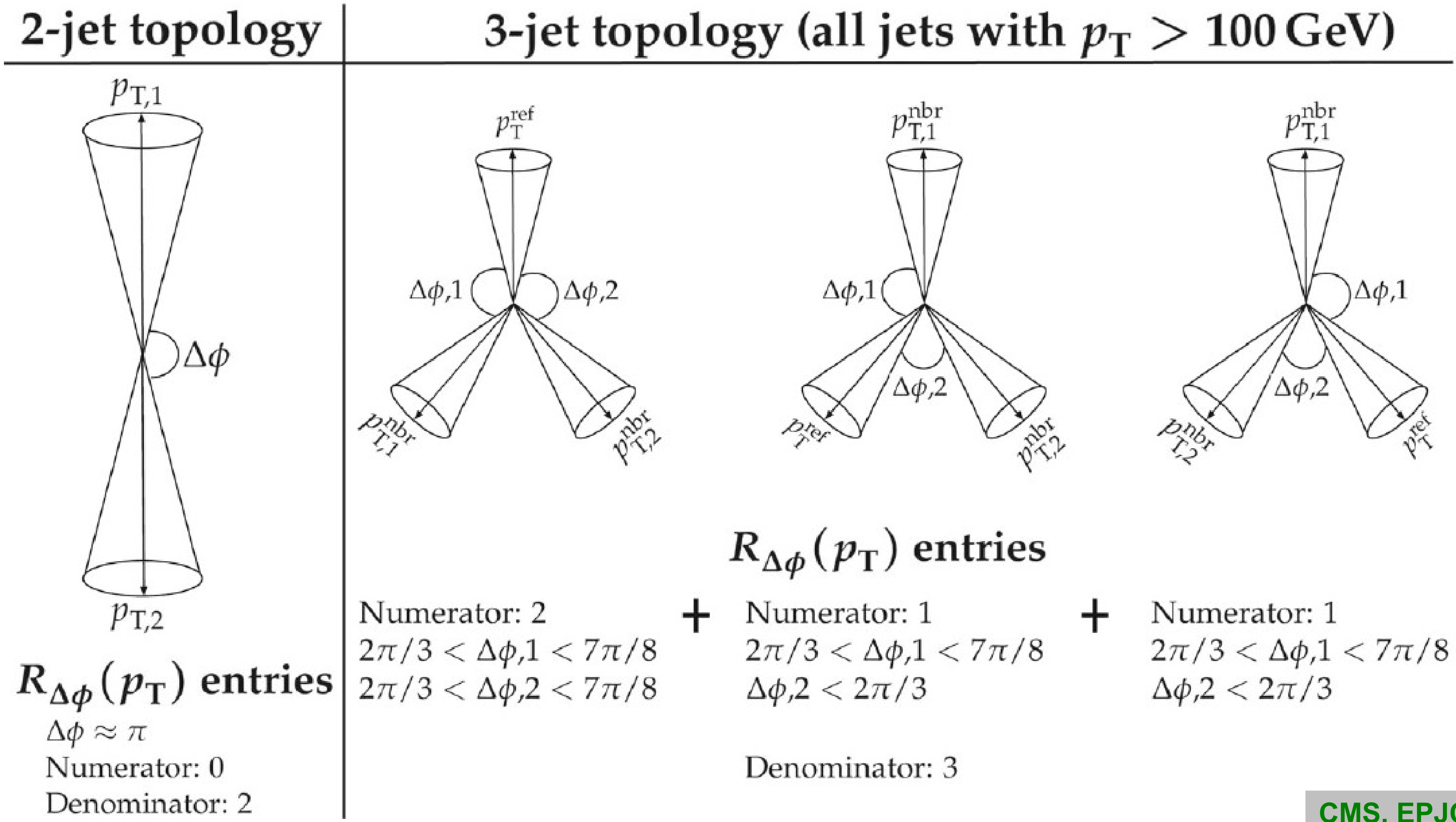
$$R_{\Delta\phi}(p_{\mathrm{T}}) = \frac{\sum_n n N(p_{\mathrm{T}}, n)}{\sum_n N(p_{\mathrm{T}}, n)}$$

  - enables unfolding accounting for all correlations

Multijet azimuthal correlation

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

Example configurations
(on request)



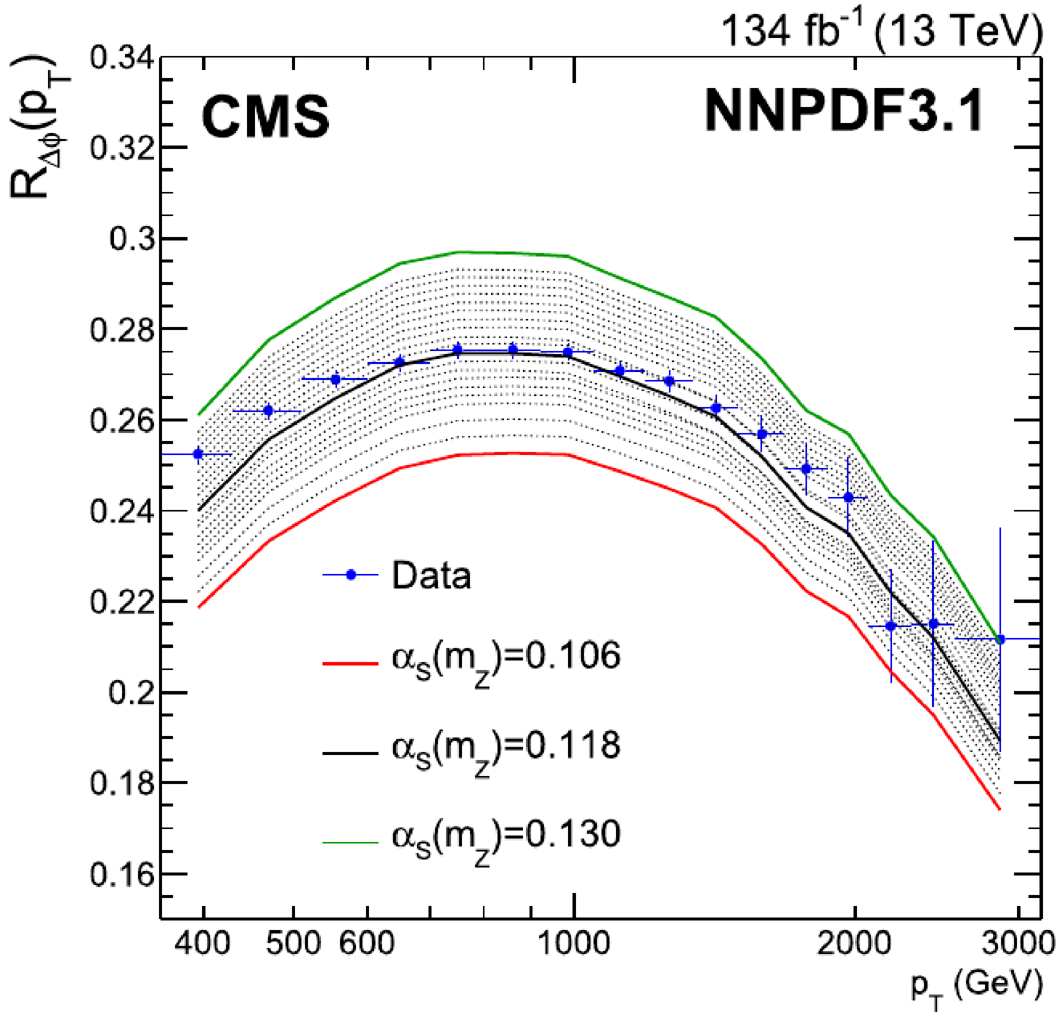
CMS, EPJC 84 (2024) 842.

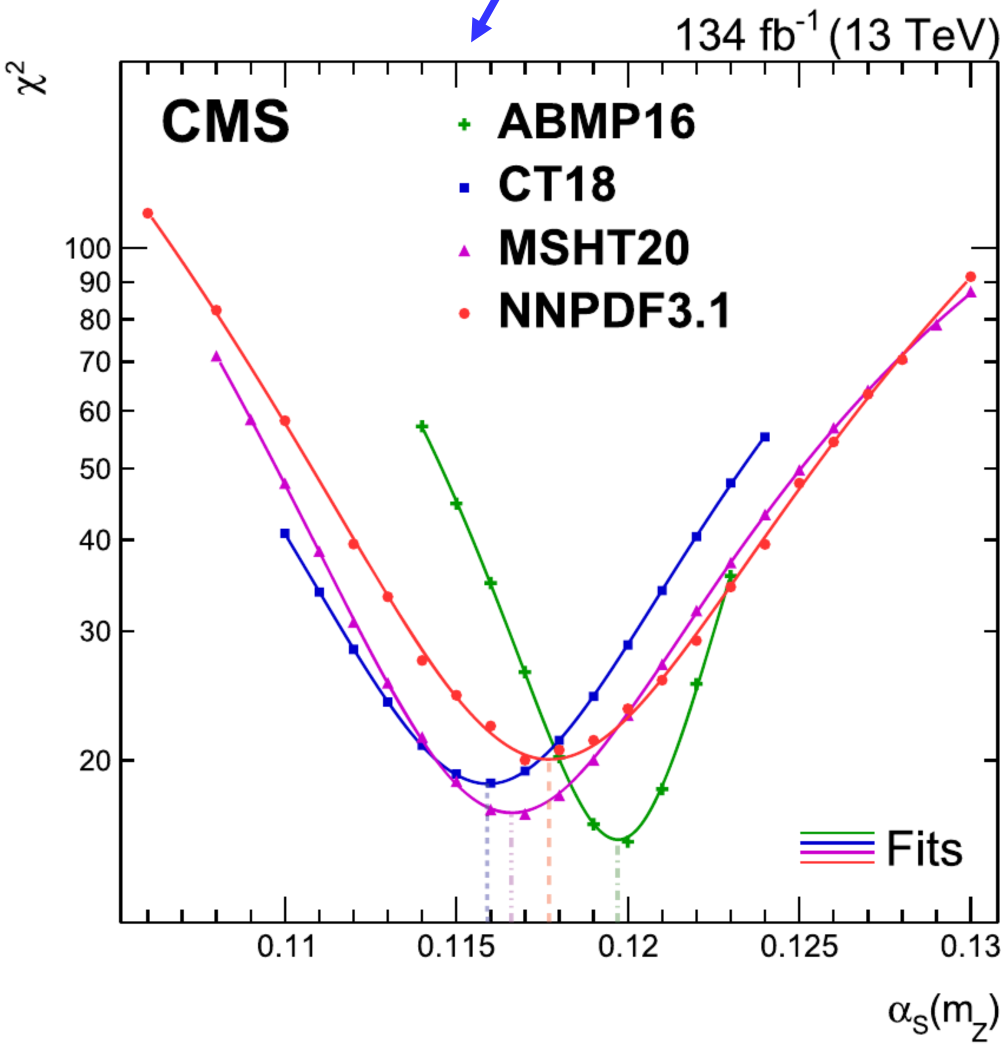
Good sensitivity, but

So far only NLO → huge MHO uncertainty

Significant PDF dependence

$$\alpha_s(m_Z) = 0.1177 \pm 0.0028(\text{all})^{+0.0114}_{-0.0068}(\text{scl})$$





CMS, EPJC 84 (2024) 842.

N-point E-E correlators in jets

Jet substructure variable representing correlations of energy flow inside jets

- **2-point energy correlators**

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

- **multiple entries, e.g. n=3 → 9 pairs inside jet**

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

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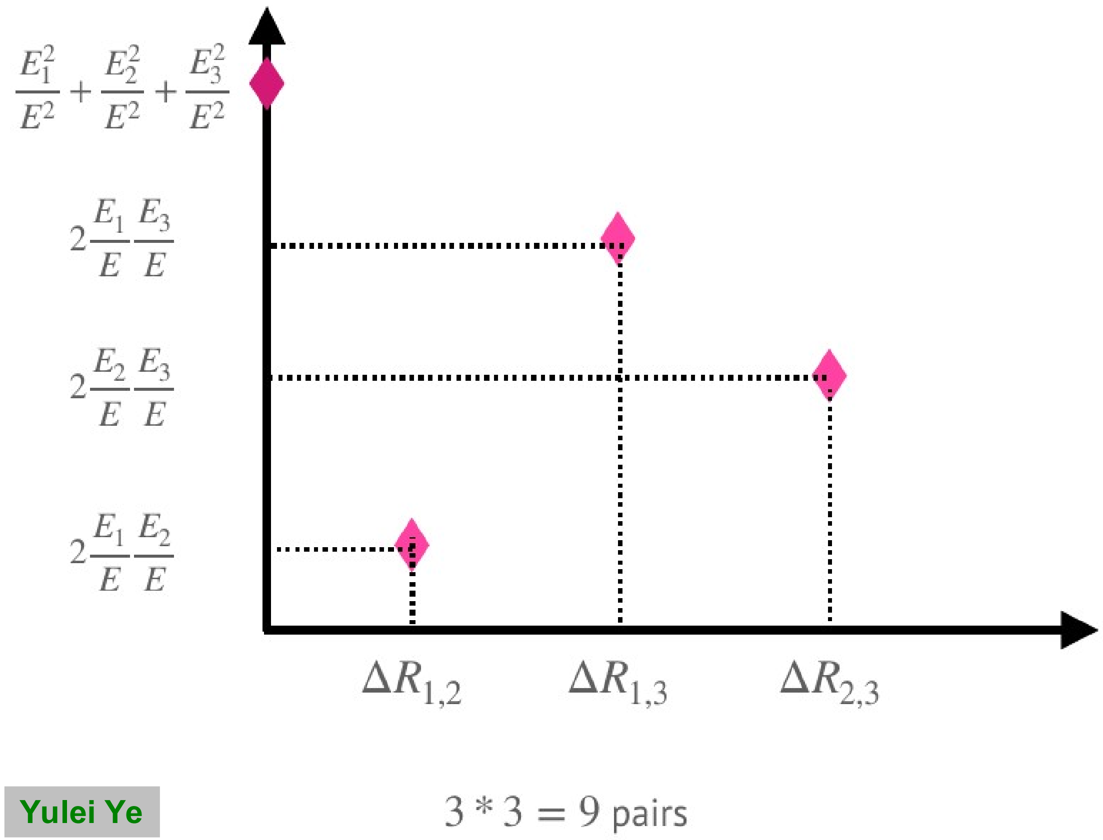
weight distance

- **multiple entries, e.g. n=3 → 9 pairs inside jet**



$$x_L = \Delta R_{ij} = \sqrt{(\Delta\eta_{ij})^2 + (\Delta\phi_{ij})^2}$$

Yulei Ye

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

Jet substructure variable representing correlations of energy flow inside jets

- **3-point energy correlators**

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

- **e.g. n=3 → 27 triplets inside jet**

$$x_L = \max \Delta R_{ij}, \Delta R_{jk}, \Delta R_{ki}$$

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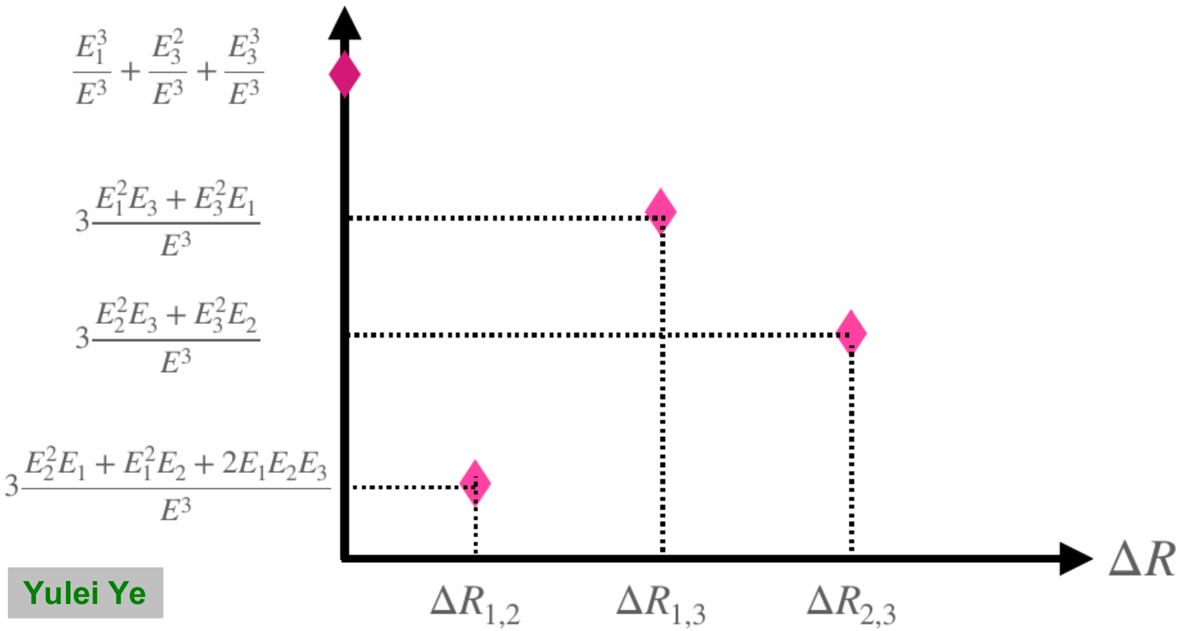


Chen et al., arXiv:2004.11381;
Lee et al., arXiv:2205.0314;
Chen et al., arXiv:2307.07510.

Data analysis details

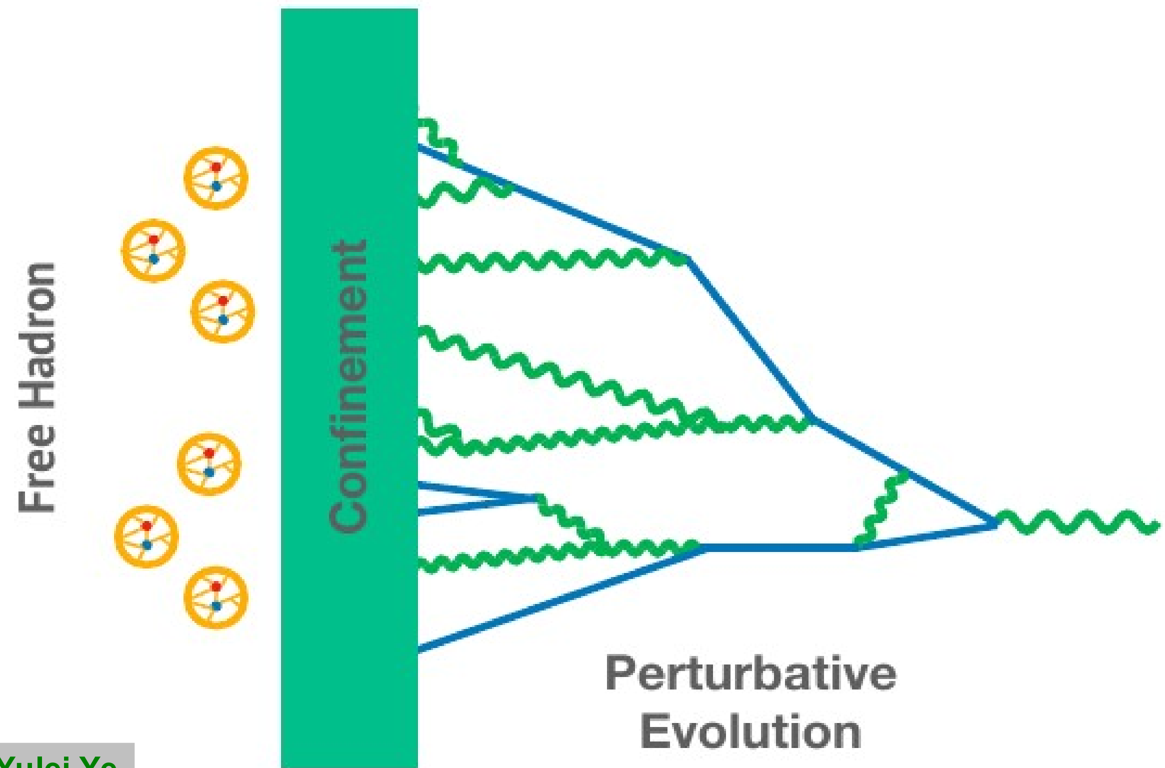
- 2016 data comprising 36.3 fb^{-1}
- Series of single jet triggers with lowest p_T threshold 60 GeV
- Dijet event selection with:
  - Anti-kT jets R=0.4
  - p_T > 97 GeV, |η| < 2.1 → good momentum resolution
  - |ΔΦ| > 2 → back-to-back jets
  - Only two leading jets used
- All particle candidates with p_T > 1 GeV used for E2C & E3C
- Iterative unfolding with early stopping (D'Agostini)
  - Jet matching efficiency 99%
  - For particle candidates more problematic

→ largest uncertainty on EEC from MC modelling!

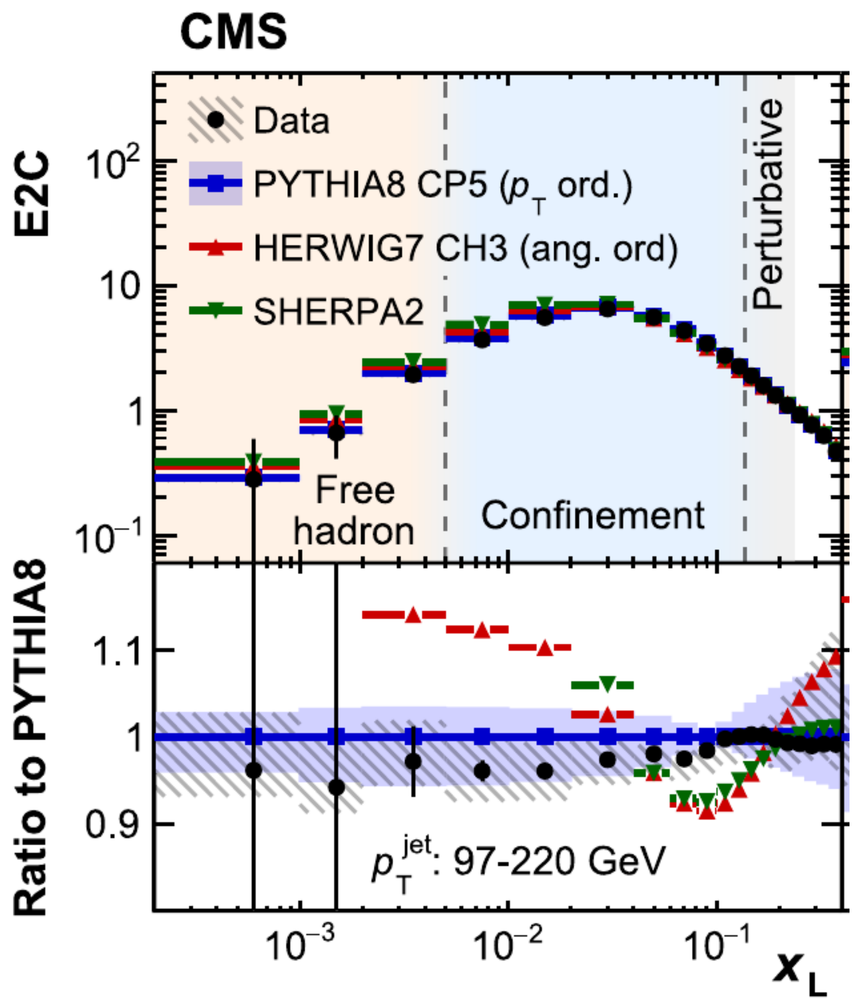
E2C and confinement

As ΔR goes smaller: perturbative region → confinement → free hadron

Transition depends on jet p_T bin, dashed lines move to the left with p_T up



Yulei Ye



CMS, PRL 133 (2024) 071903.

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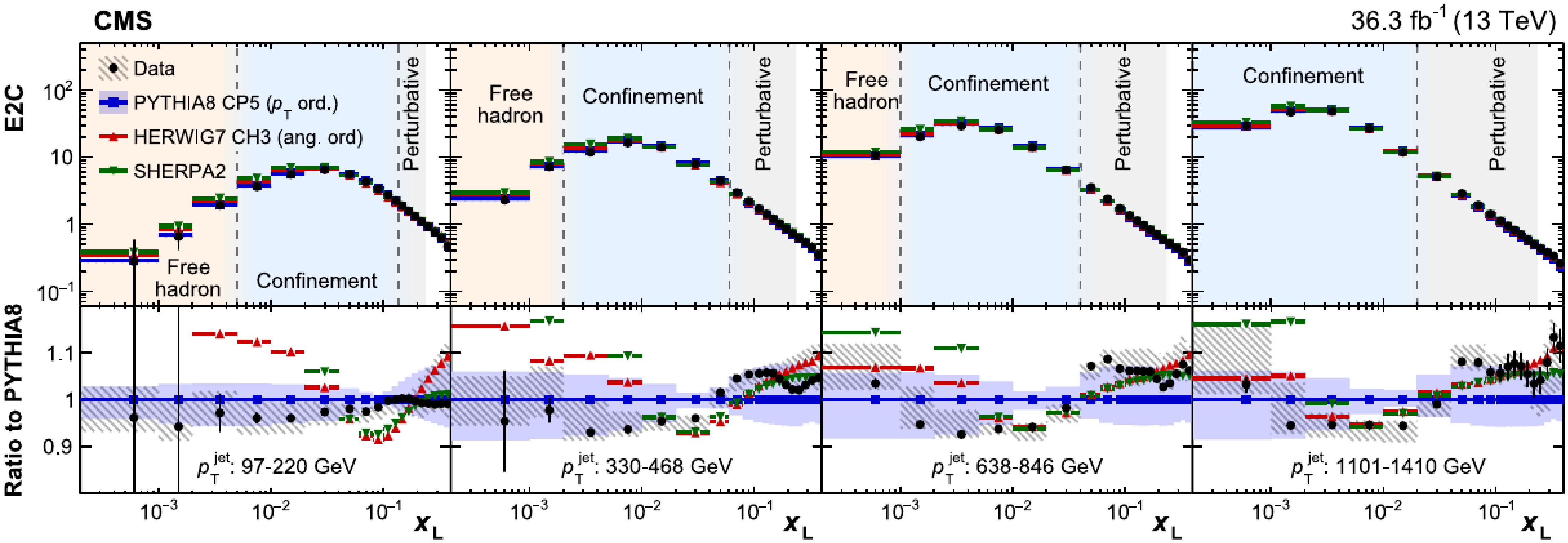
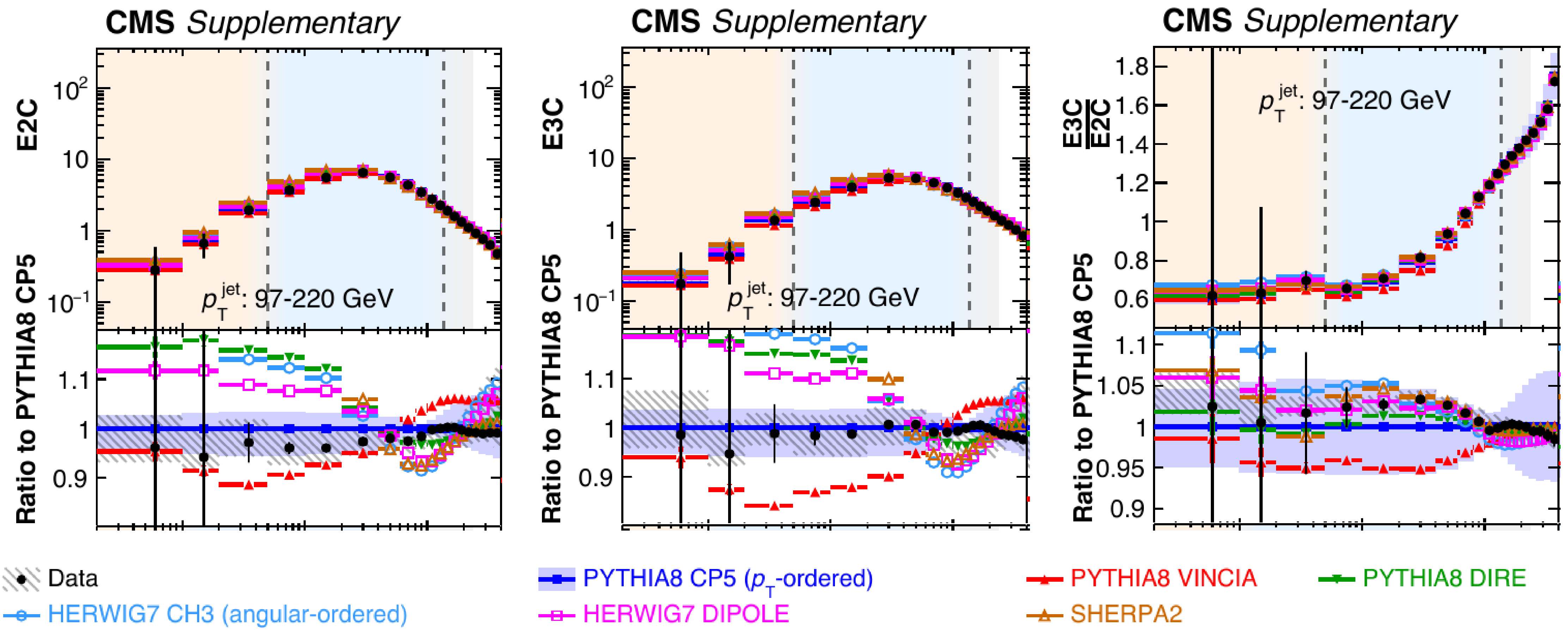


CMS, PRL 133 (2024) 071903.

Comparison to PS MC

Example of lowest p_T bin out of eight → 1784 GeV

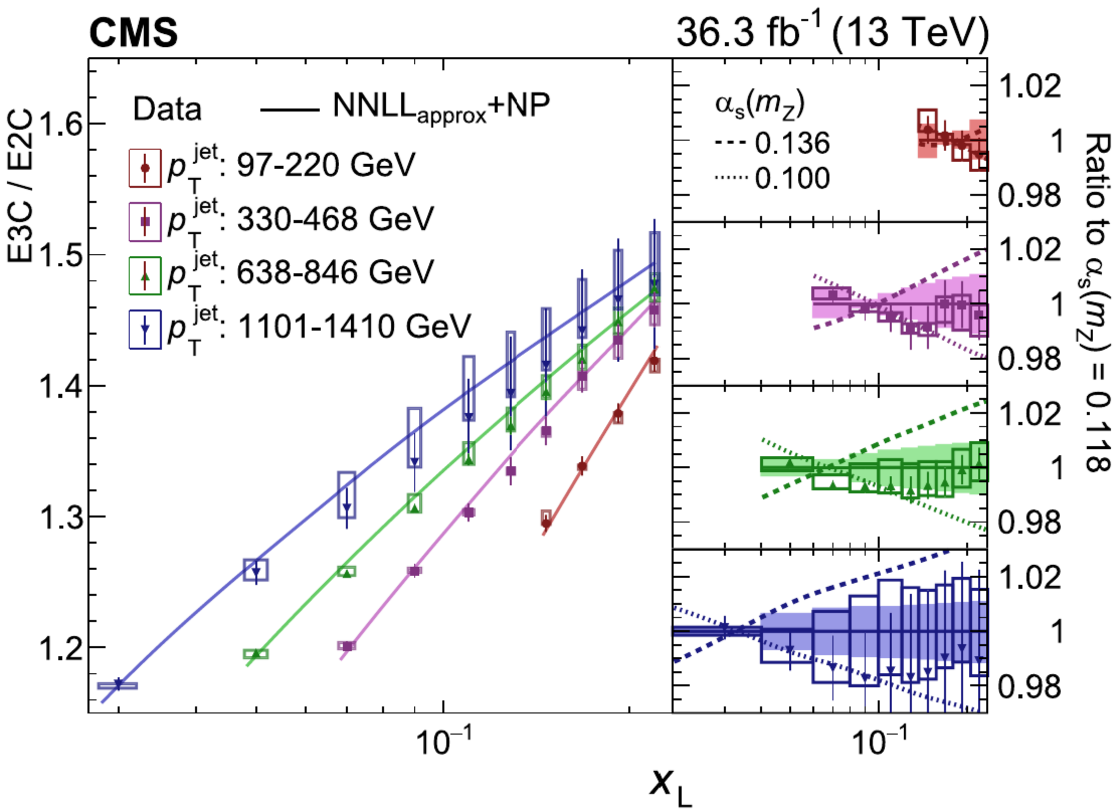
E2C **E3C** **E3C/E2C**



From uncertainty to interesting new observable to study vs. PS models

Perturbative region

- **Focus on perturbative region:**
  - **Comparison to NLO+NNLL$_{approx}$**
  - **Use ratio E2C / E3C →** $\propto \alpha_s(Q) \ln R + \mathcal{O}(\alpha_s^2)$
  - **Effects of e.g. gluon vs. quark jet expected to cancel → α_s(Q) (NLO)**



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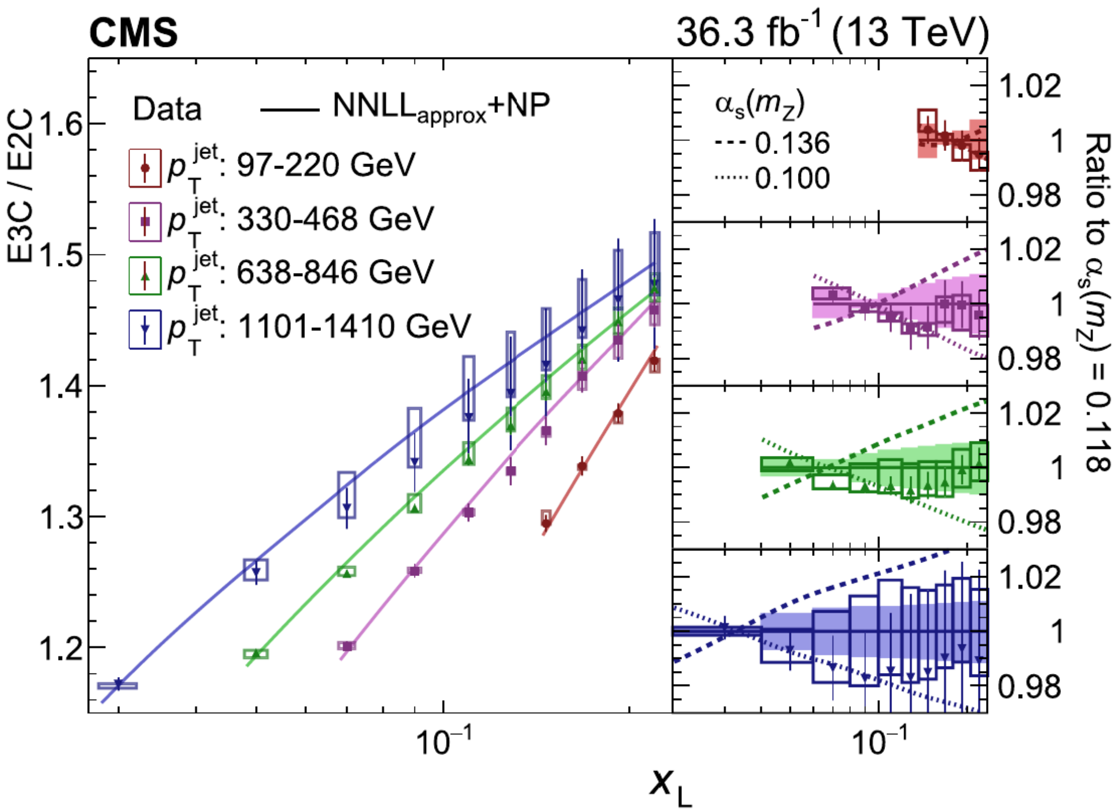

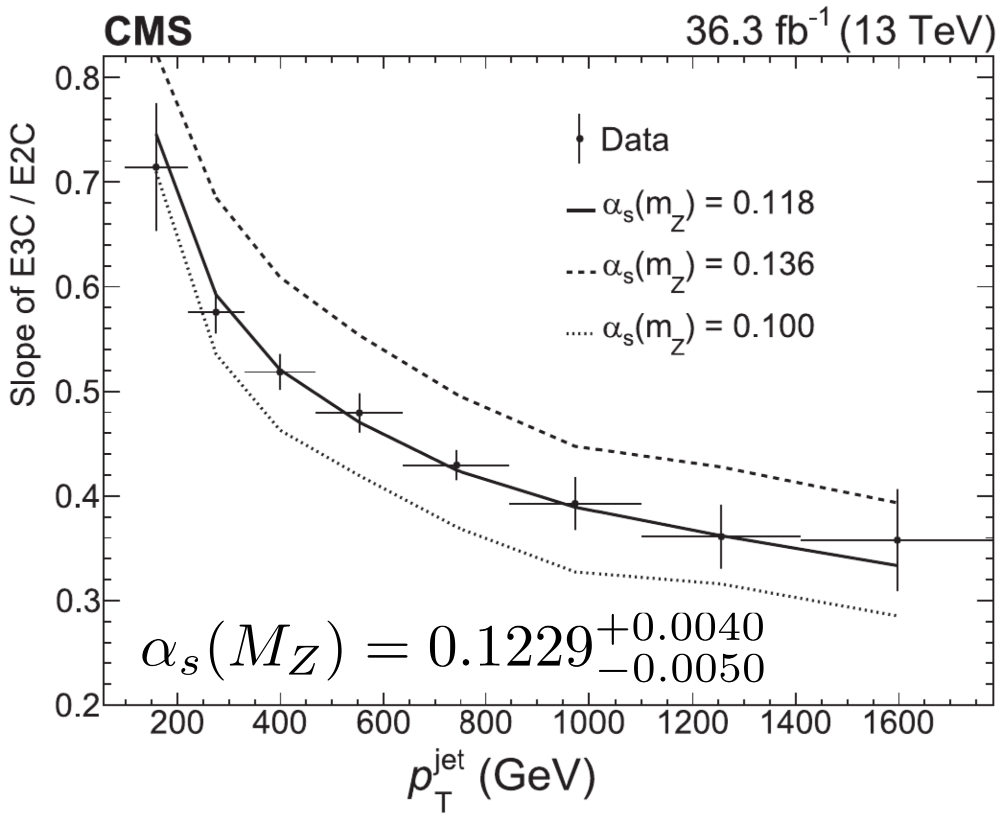

Summary & Outlook

- LHC at 7, 8, and 13 TeV enabled to test $\alpha_s(Q)$ up to Q ~ 7 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 (mostly)
- Still more theory understanding required
- Novel ideas like energy-energy correlators in jets (or Z p_T) very promising, need some more experience

Thank you for your attention!

Thank you very much to the organisers for the invitation to this very special place