The most precise determination of α_S from jets and the illustration of its running

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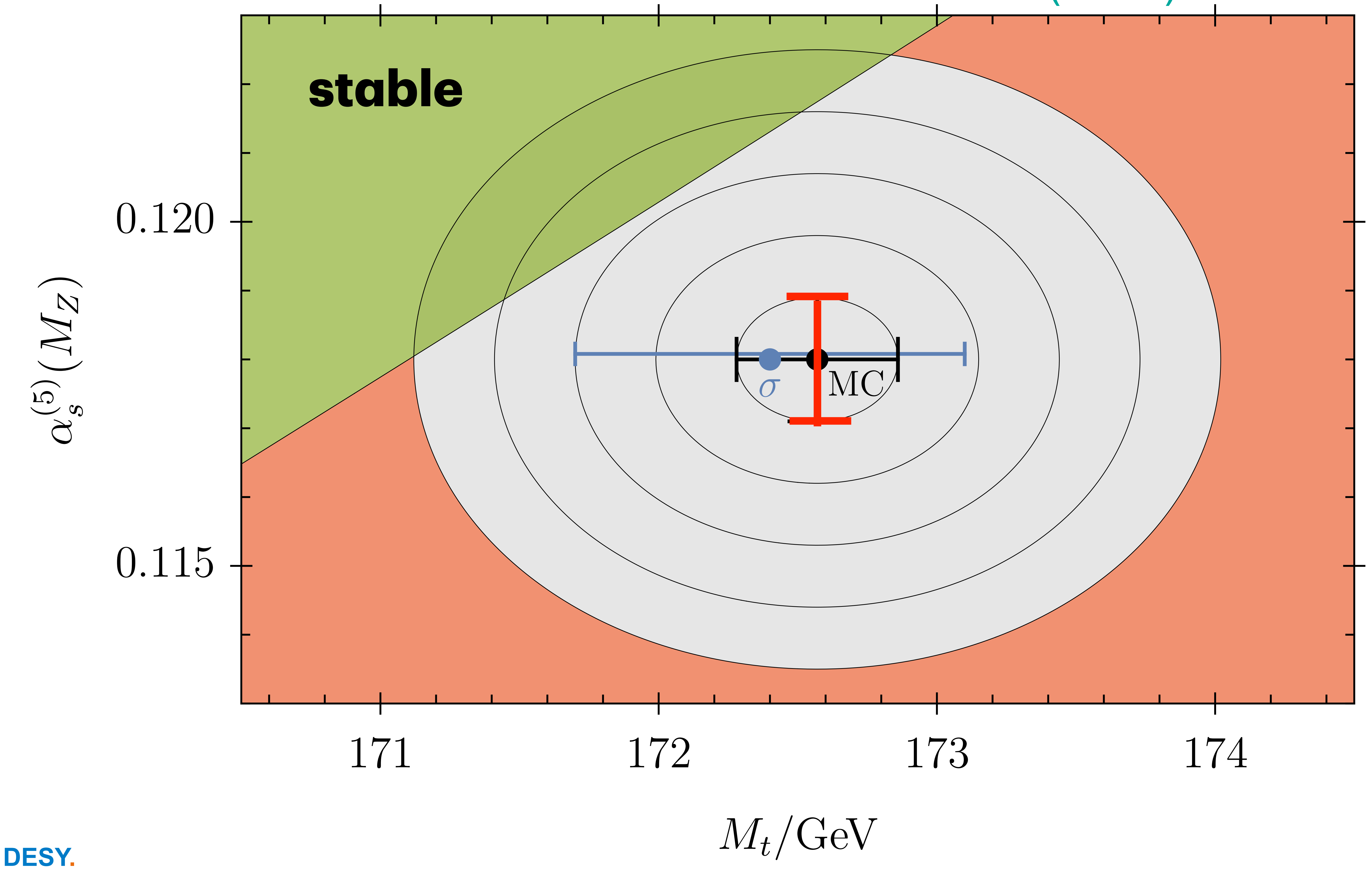
EPS25, Marsille, 6.07.2025

Motivation: Why is it important to precisely extract α_S?

- Single free parameter of QCD in the $m_q \to 0$ limit
- Impact EW vacuum stability at the Planck scale, dependent on $\mathbf{m_H}$, $\alpha_S(\mathbf{m_Z})$, $\mathbf{m_t}$

PRD 110 (2024) 115017



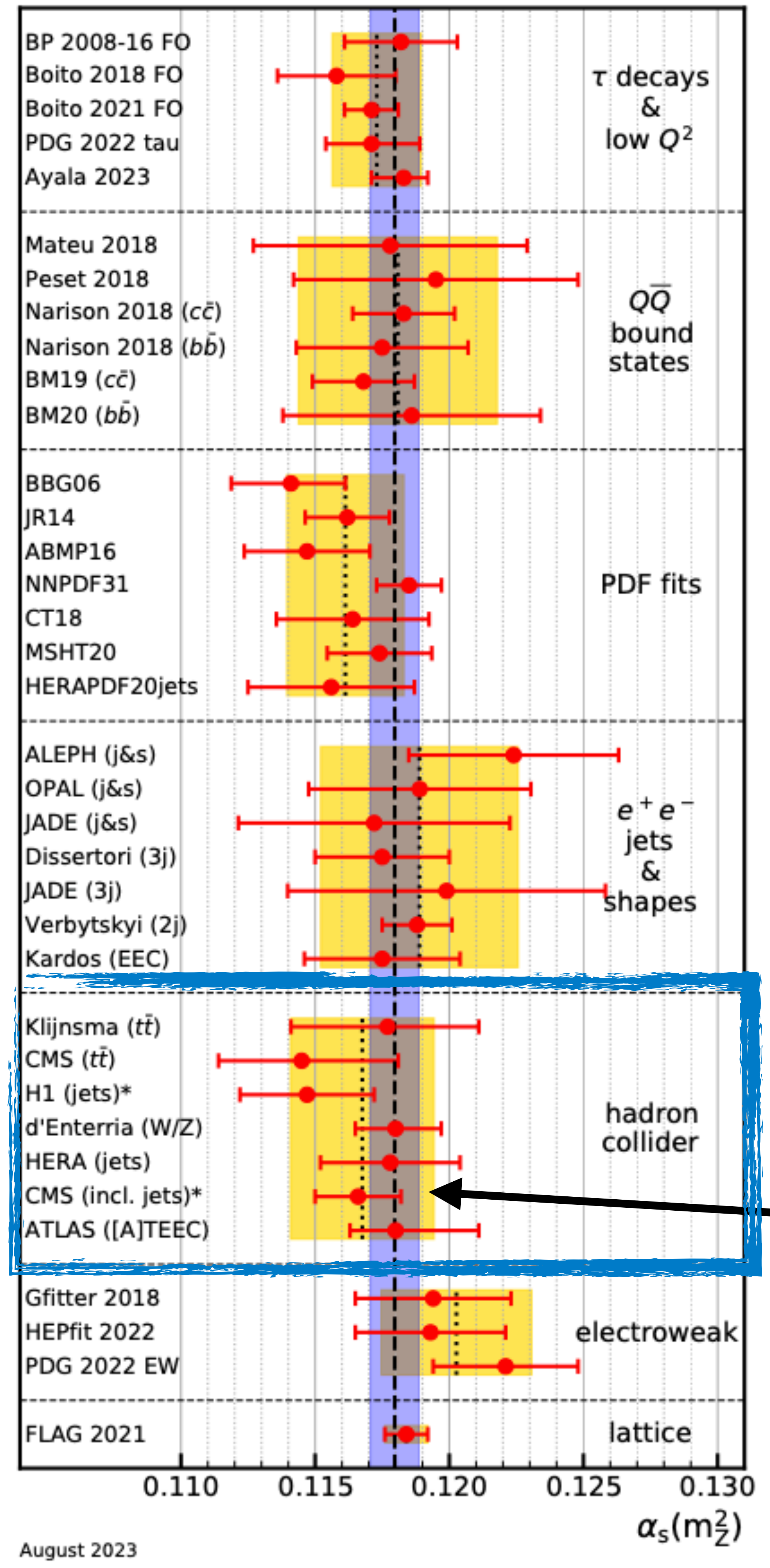
In PRD 110 (2024) 115017: Establishment of SM vacuum stability at 5σ demands improvement on m_t and α_S by a factor of 2-3

→ Precise determination on $\alpha_S(m_Z)$ impact the EWK vacuum stability

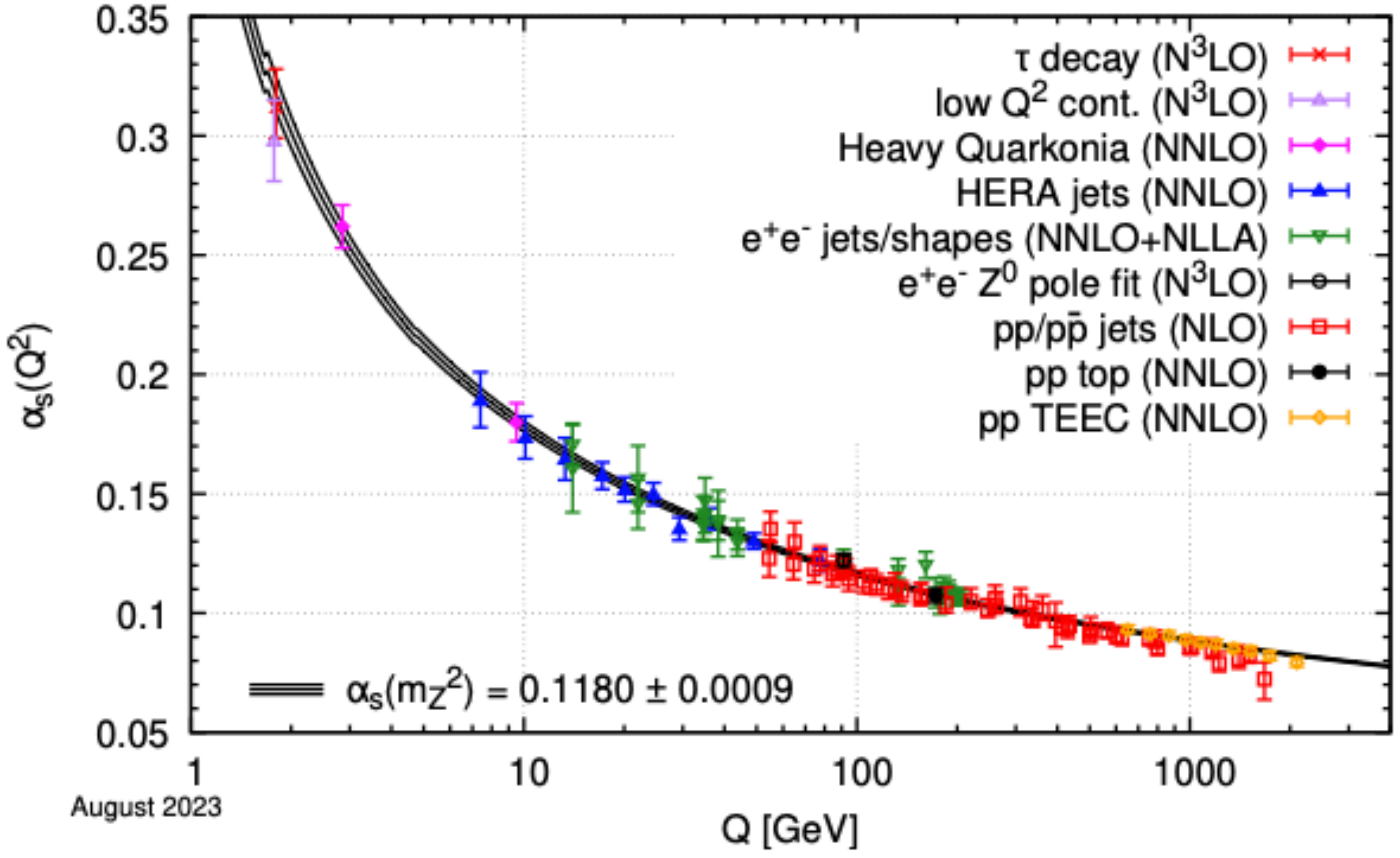
The state of the art of the strong coupling

QCD PDG Review 2024

Summary of $\alpha_S(m_Z)$



Running of α_S with Q



How can we improve these results?

CMS inclusive jets at 13 TeV was the most precise determination of $\alpha_S(m_Z)$ from jets

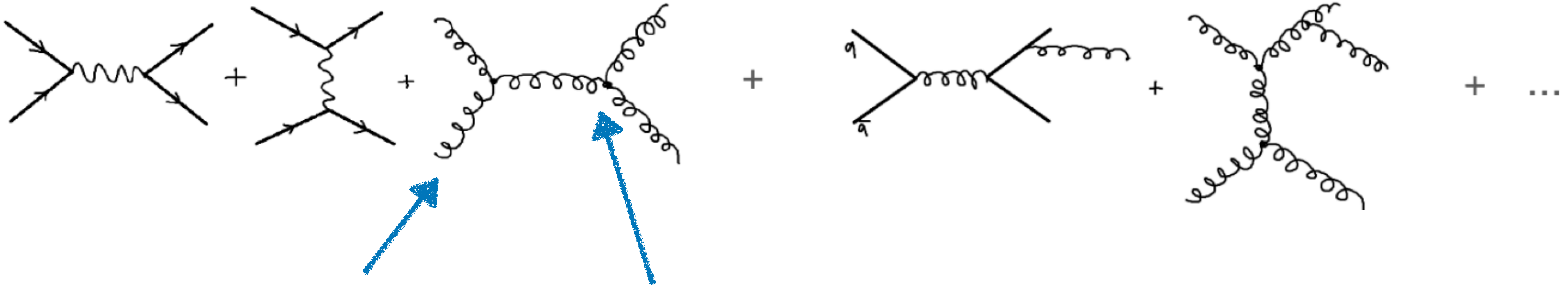
$$\alpha_S(m_Z) = 0.1166 \pm 0.0017$$ JHEP 12 (2022) 035

$$(= 0.0014_{fit} \pm 0.0007_{model} \pm 0.0004_{scale} \pm 0.0001_{param})$$

Dominant uncertainty from experimental data

Jets as a probe of QCD

Probe of QCD dynamics, PDFs and $\alpha_S(m_Z)$



Each line is sensitive to PDFs

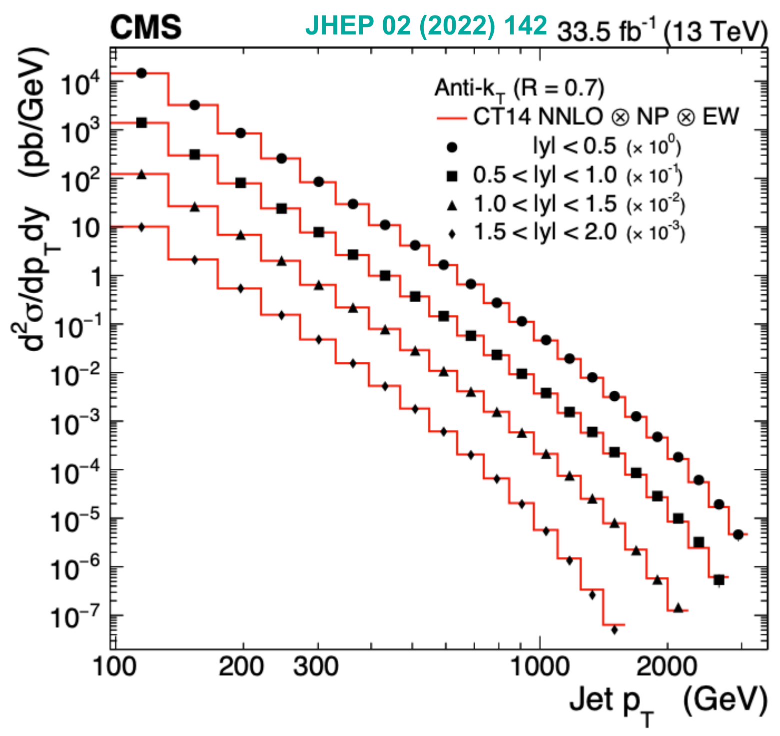
Each vertex is sensitive to $\alpha_S(m_Z)$

Combination of CMS inclusive jet measurements

- CMS inclusive jet production cross-section measurements at $\sqrt{s}$ of 2.76, 7, 8, 13 TeV
- EPJC 76 (2016) 265, PRD 87 (2013)112002, JHEP 03 (2017) 156, JHEP 02 (2022) 142
- Jet clustered with anti-k_T (R=0.7)
- **QCD analysis** combining **CMS inclusive jet measurements**

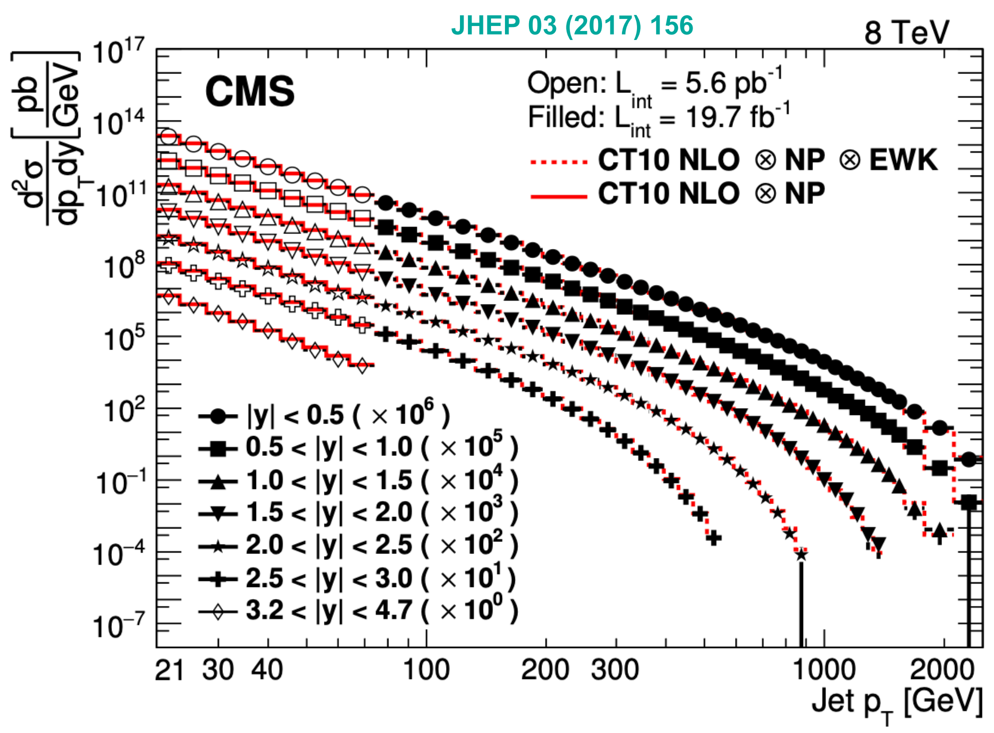
$\sqrt{s}$	Ndp
13 TeV	78
8 TeV	168
7 TeV	130
2.76 TeV	81

13 TeV



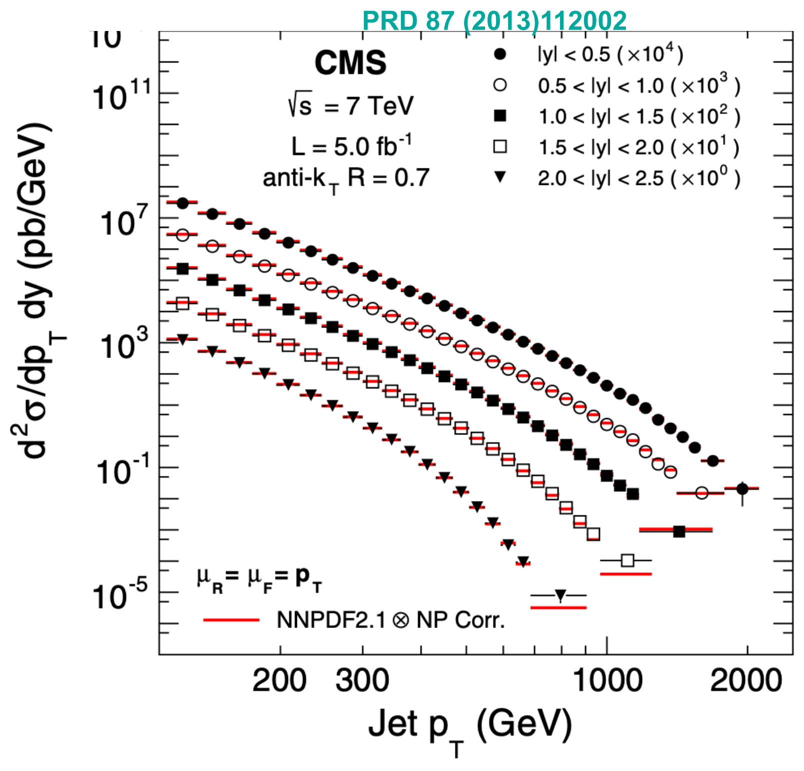
+

8 TeV



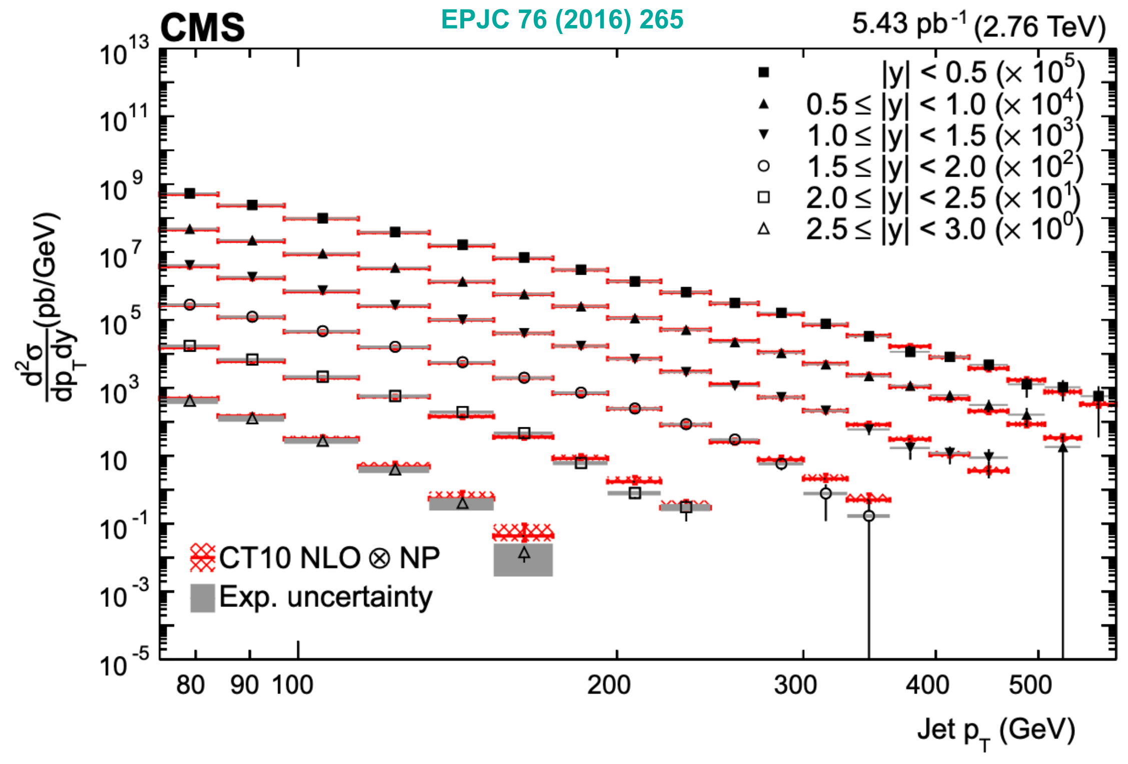
+

7 TeV



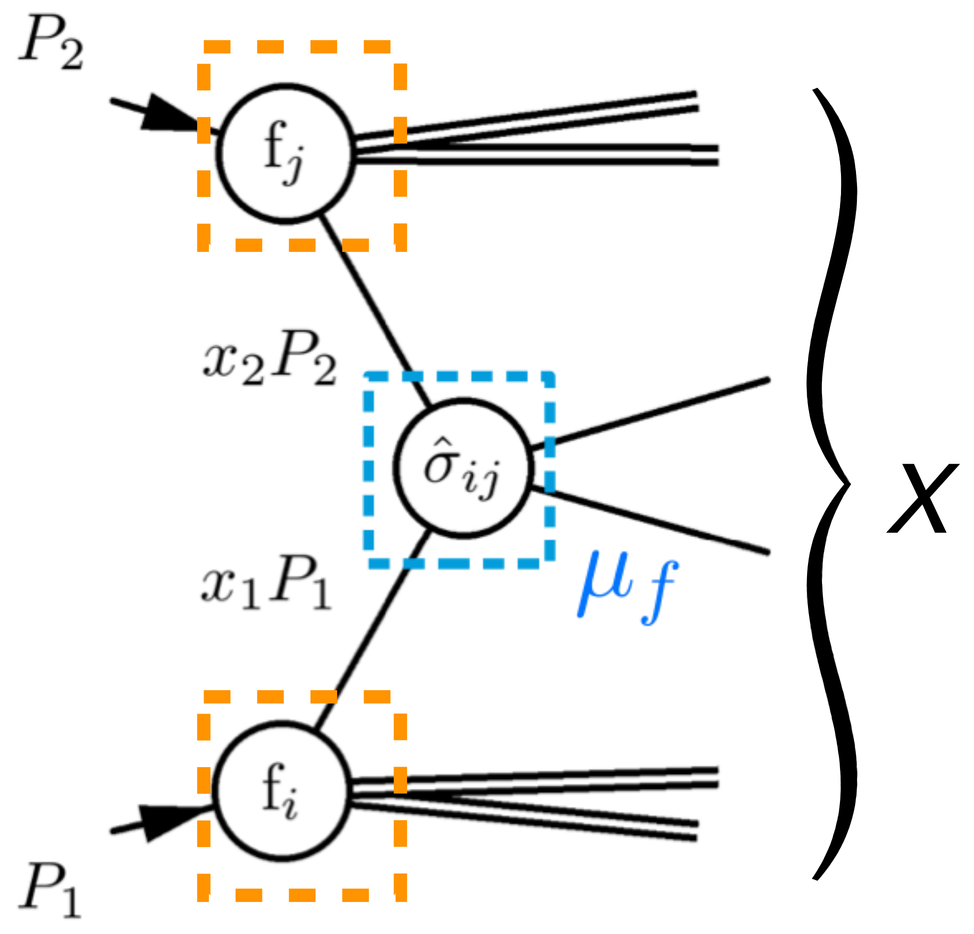
+

2.76 TeV



Combine inclusive jet measurements to extract a more precise $\alpha_S(m_Z)$

Extraction of α_S at LHC



DGLAP eq.   Exp. measurements

PDFs $f_i(\mu, x)$

Partonic cross section (pQCD)

Non perturbative corrections

$$\sigma_{pp\to X} = \int dx_1 \int dx_2 \sum_{ij} f_i(x_1, \mu_f)\, f_j(x_2, \mu_f)\, \hat{\sigma}_{ij}(x_1, x_2, \alpha_S(\mu_R), \mu_r, \mu_f) + \mathcal{O}\left(\frac{\Lambda^2_{QCD}}{Q^2}\right)$$

Methods to extract $\alpha_S(m_Z)$:

- Profiling varying PDFs+α_S series (predefined PDF from global PDF sets)
- Simultaneous fit of α_S and PDFs → Correlation between PDFs and α_S considered

NB: To disentangle x_1 and x_2, LHC data can not be used alone to extract PDFs

Need to add inclusive lepton-proton DIS data (HERA, EPJ C75(2015) 580)

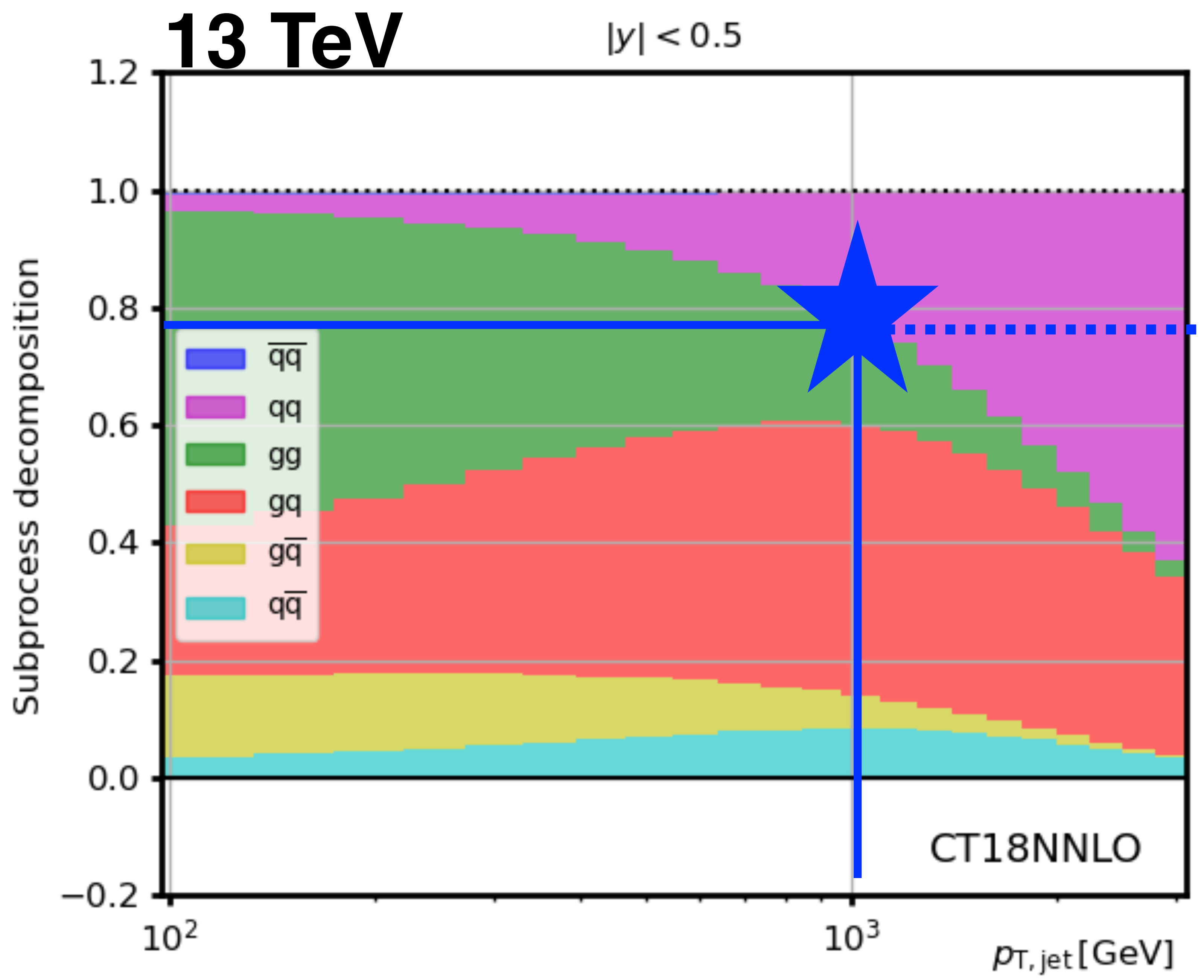
Simultaneous fit of PDFs and α_S at NNLO to reduce bias of α_S from PDFs

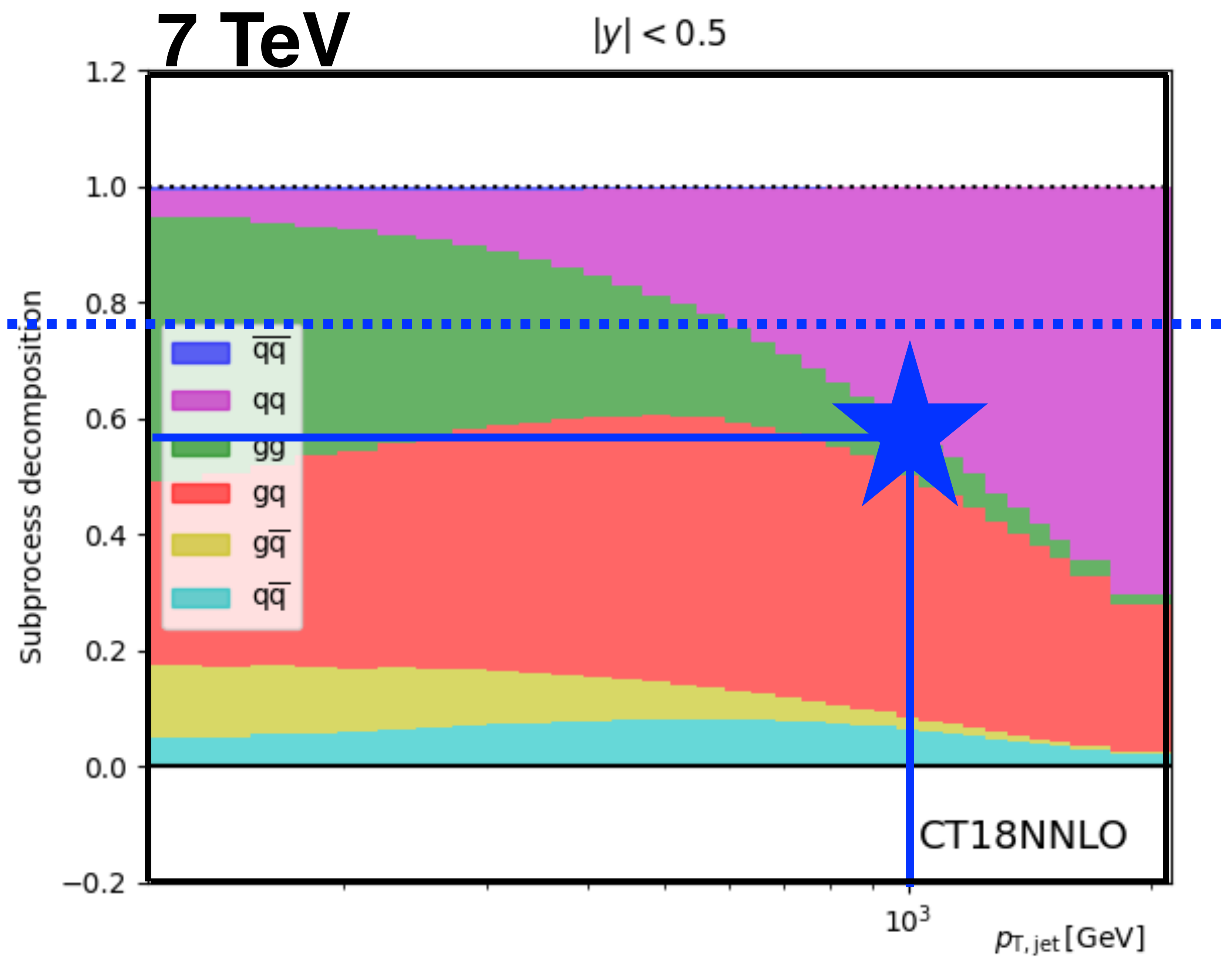
Inclusive jet productions and PDF sensitivity

Inclusive jets at different $\sqrt{s}$ probe different p_T and y regions

→ **Probe different PDF distributions**

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





Figures produced using the fastNLO program and the fastNLO interpolation grids EPJC 82 (2022) 10 930, arXiv:1208.3641, arXiv:0609285

Lowering $\sqrt{s}$, more qq contirubtion at high p_T

How to improve further $\alpha_S(m_Z)$ precision?

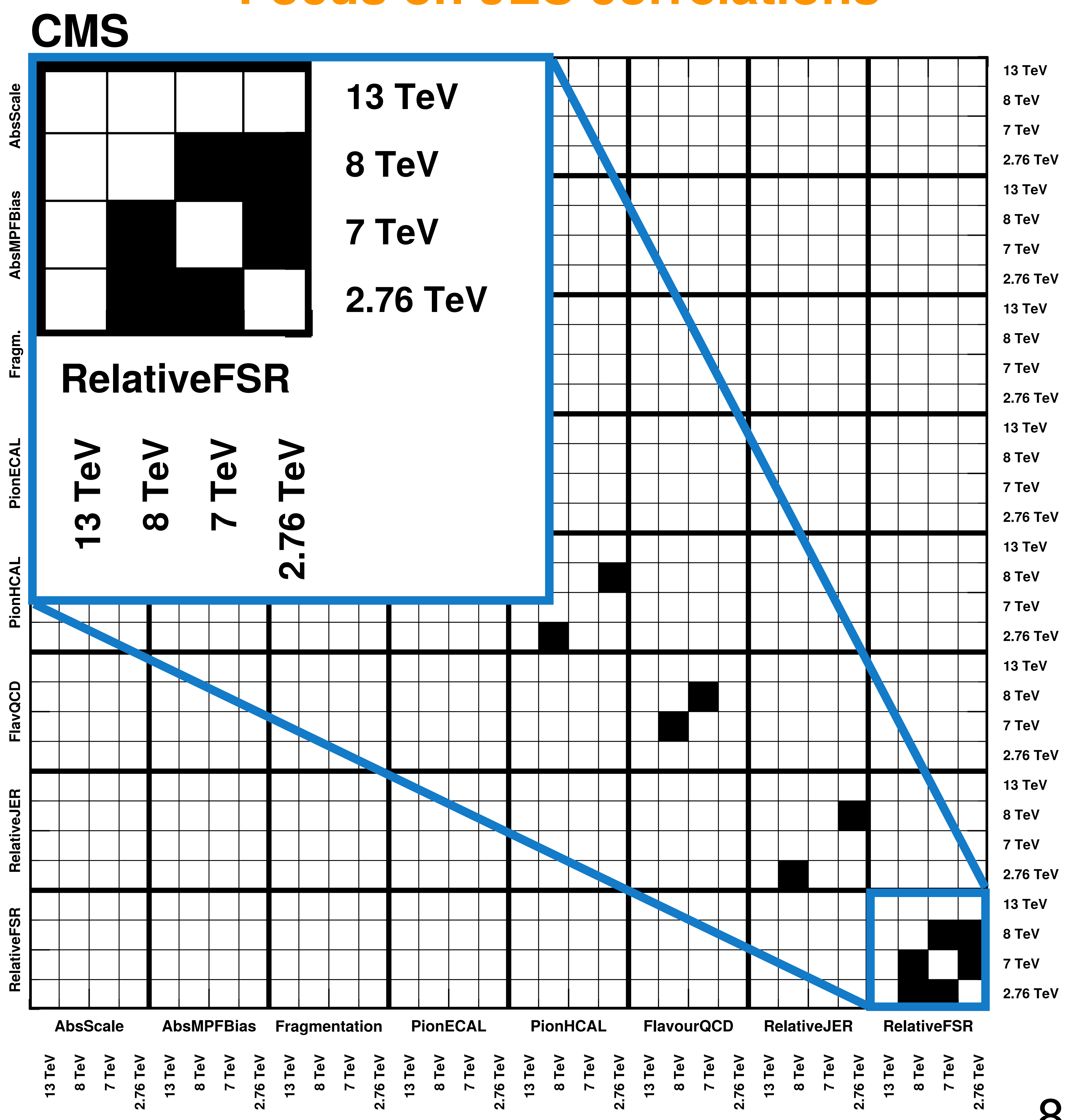
Correlation across the measurements investigated in this analysis **for the first time**

- Improved precision on $\alpha_S(m_Z)$
- Useful input for global PDF fitters

JES dominant uncertainty

Data	# unc	# JES
13 TeV	30	22/30
8 TeV	28	24/28
7 TeV	25	20/25
2.76 TeV	25	22/25

Focus on JES correlations



Theory predictions for inclusive jet production

Fixed-order perturbative QCD theory predictions (NNLOJET) PRL 118, 072002 (2017), JHEP 10 (2018) 155, arXiv:1801.06415, leading color approximation

- Full interpolation grids at NNLO computed with APPLfast, available in ploughshare (EPJC 82 (2022) 930)
- Fully accounts for dependence on PDFs and α_S; QCD scales are set to $\mu_{R,F} = p_T^{jet}$
- Readable via FastNLO Toolkit interface in the xFitter release v2.2.0

Fixed-order predictions corrected by:

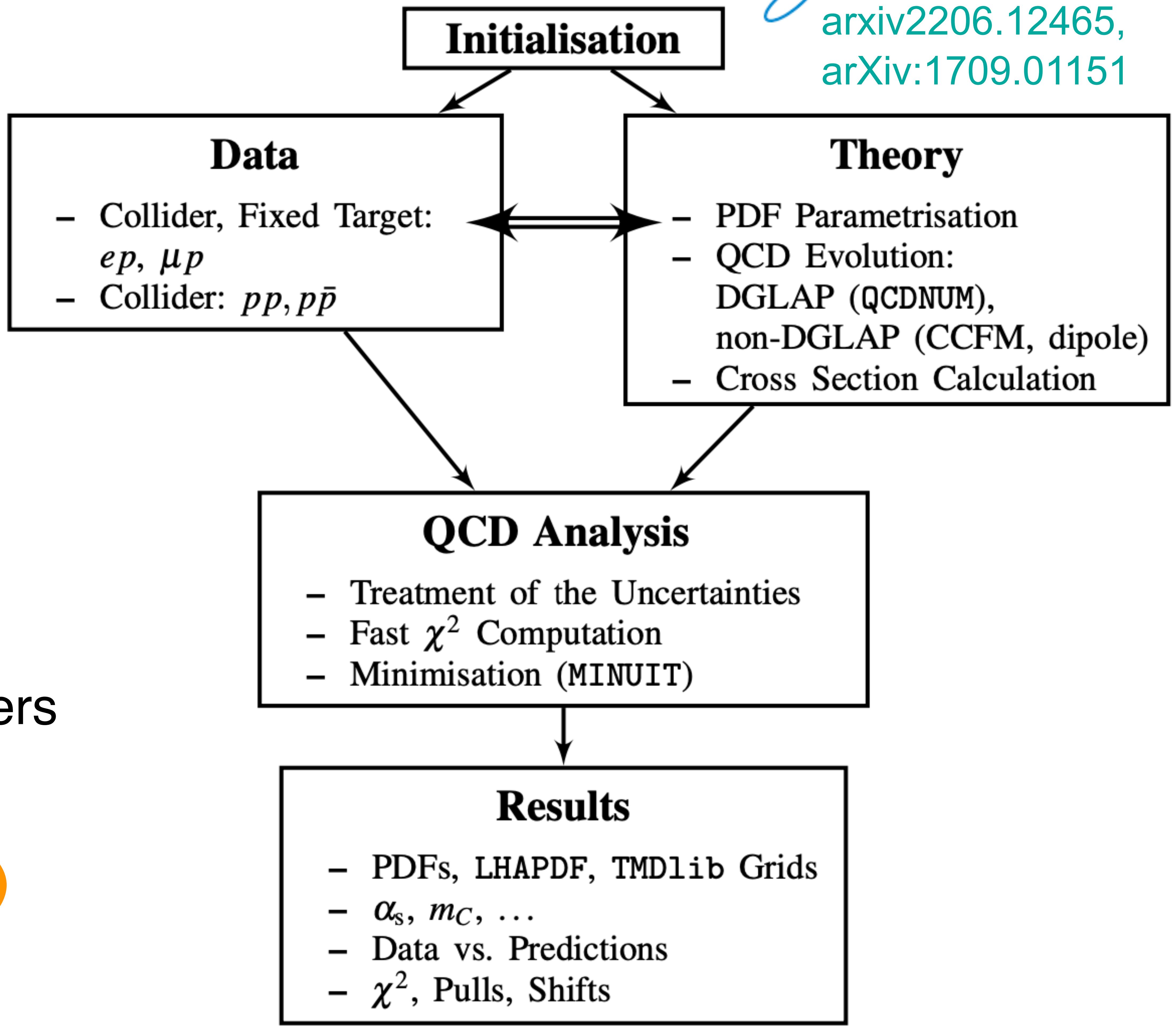
- Effects of hadronisation and underlying event → Non-perturbative corrections
- Virtual *W*, *Z* contributions at NLO electroweak → EW corrections

The QCD analysis: extraction of PDFs and α_S

arxiv2206.12465,
arXiv:1709.01151

- **Parametrise PDFs** at a starting scale
- **Evolve PDFs** to the scales of the measured data
  - DGLAP evolution
- **Compute theory predictions**
- **Compare theory with data via χ^2**
  - Systematic uncertainties included as nuisance parameters
- **Minimise the χ^2 w.r.t. the fitted parameters (PDFs, α_S)**

Same approach as HERAPDF2.0



PDF parametrisation at starting scale $Q_0^2 = 1.9$ GeV^2

Parametrisation from JHEP 02 (2022) 142 (13 TeV jet analysis) used as a starting parametrisation

At $\mu_0^2 = 1.9$ GeV^2, parameterised PDFs are:

- gluon distribution: $xg(x)$
- valence distributions: $xu_v(x)$ and $xd_v(x)$
- antiquark distributions: $x\bar{U}(x)$ and $x\bar{D}(x)$

$$xg(x) = A_g x^{B_g}(1-x)^{C_g}(1 + D_g x + E_g x^2)$$

$$xu_v(x) = A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1 + E_{u_v} x^2)$$

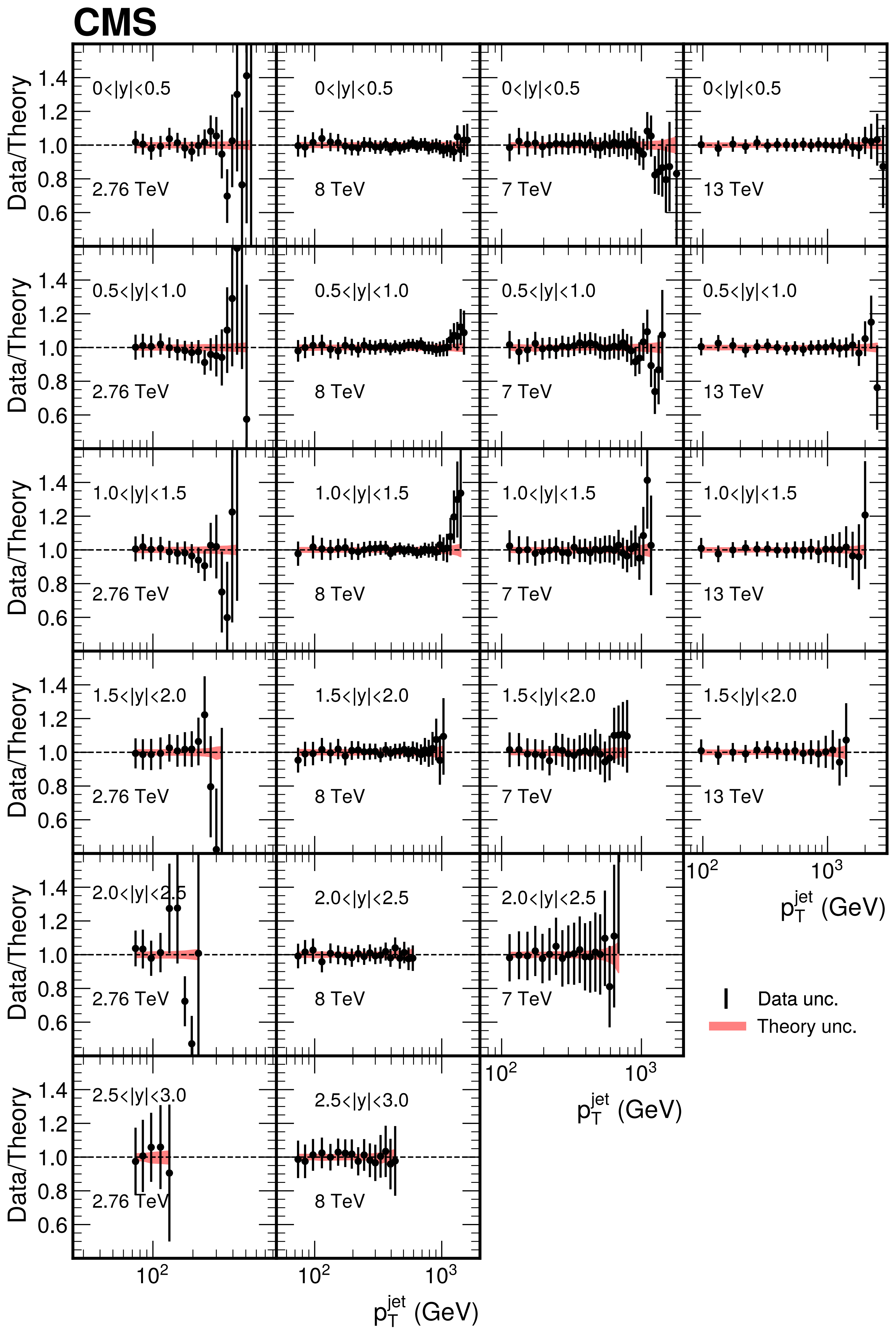
$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}$$

$$x\bar{u}(x) = A_{\bar{u}} x^{B_{\bar{u}}}(1-x)^{C_{\bar{u}}}(1 + D_{\bar{u}} x)$$

$$x\bar{d}(x) = A_{\bar{d}} x^{B_{\bar{d}}}(1-x)^{C_{\bar{d}}}(1 + E_{\bar{d}} x^2)$$

- $x\bar{U}(x) = x\bar{u}(x)$ and $x\bar{D}(x) = x\bar{d}(x) + x\bar{s}(x)$
- $B_{\bar{U}} = B_{\bar{D}}$ and $A_{\bar{U}} = A_{\bar{D}}(1 - f_s)$ with the strangeness fraction $f_s = x\bar{s}/(x\bar{d} + x\bar{s}) = 0.4$
- Thorne-Roberts general mass variable flavour scheme PRD 57 (1998) 6871, PRD 73 (2006) 054019, PRD 86 (2012) 074017

Data/Theory agreement for all data sets at one glance



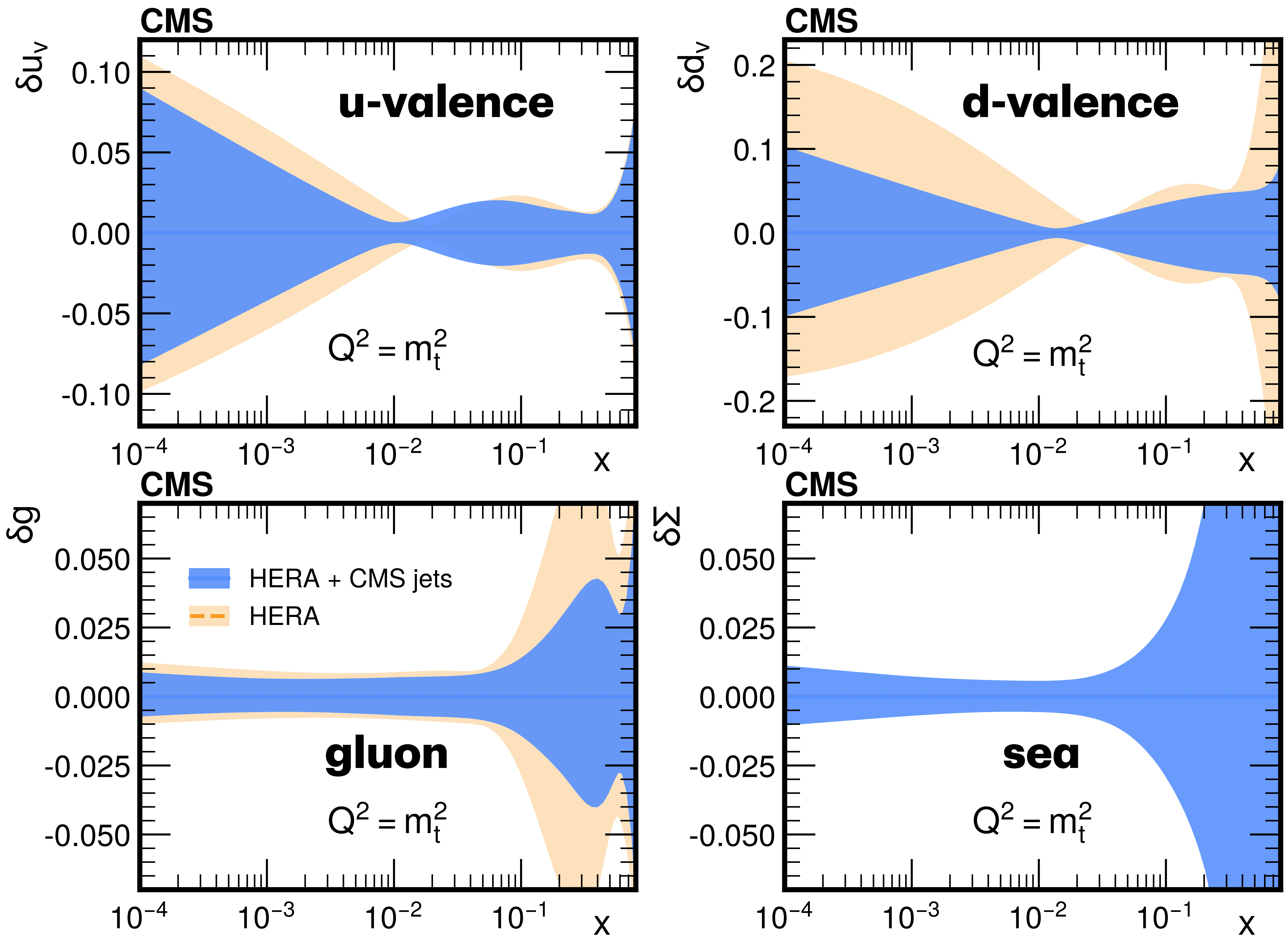
After simultaneous fit of PDFs and $\alpha_S(m_Z)$

Dataset	Partial χ^2/N_{dp}
HERA I+II neutral current	1036/935
HERA I+II charged current	112/81
CMS jets 2.76 TeV	63/80
CMS jets 7 TeV	81/130
CMS jets 8 TeV	206/165
CMS jets 13 TeV	77/78
Correlated χ^2	125
Total χ^2/N_{dof}	1680/1453

- Somewhat high χ^2 for HERA data known, in agreement with the detailed study in EPJC 75 (2015) 12, 580
- CMS jet data consistent with each other $\chi^2/\mathrm{ndp} = 427/453$

Results of PDFs: comparison with HERA-only

CMS jets + HERA DIS data compared to **only-HERA fit**



PDF uncertainties at 68% CL

Adding jet data leads to significant improvement in PDF precision especially in:

- gluon (expected)
- d-valence (jet data at lower $\sqrt{s}$)

Final result: $\alpha_S(m_Z)$ and uncertainty sources

$$\alpha_S(\mathbf{m_Z}) = 0.1176^{+0.0014}_{-0.0016}$$

- **Fit uncertainty:**

  Statistical and experimental uncertainty $^{+0.0009}_{-0.0009}$

- **Scale uncertainty:**

  Envelope of 7-point variations of μ_r, μ_f $^{+0.0009}_{-0.0012}$

- **Model uncertainty:**

  Fixed parameters varied within uncertainties $^{+0.0006}_{-0.0004}$

Parameter	Central value	Lower limit	Upper limit
m_b	4.50 GeV	4.25 GeV	4.75 GeV
m_c	1.47 GeV	1.41 GeV	1.53 GeV
Q^2_{min}	10 GeV^2	7.5 GeV^2	12.5 GeV^2
Q^2_0	1.9 GeV^2	1.7 GeV^2	2.1 GeV^2
f_s	0.40	0.32	0.48

- **Parameterisation uncertainty:**

  Add / remove new parameters to the PDFs, one at a time $^{+0}_{<-0.0001}$

**Fit, Model and Missing Higher order added in quadrature, while PDF parametrisation added linearly*

Comparison with other CMS measurements

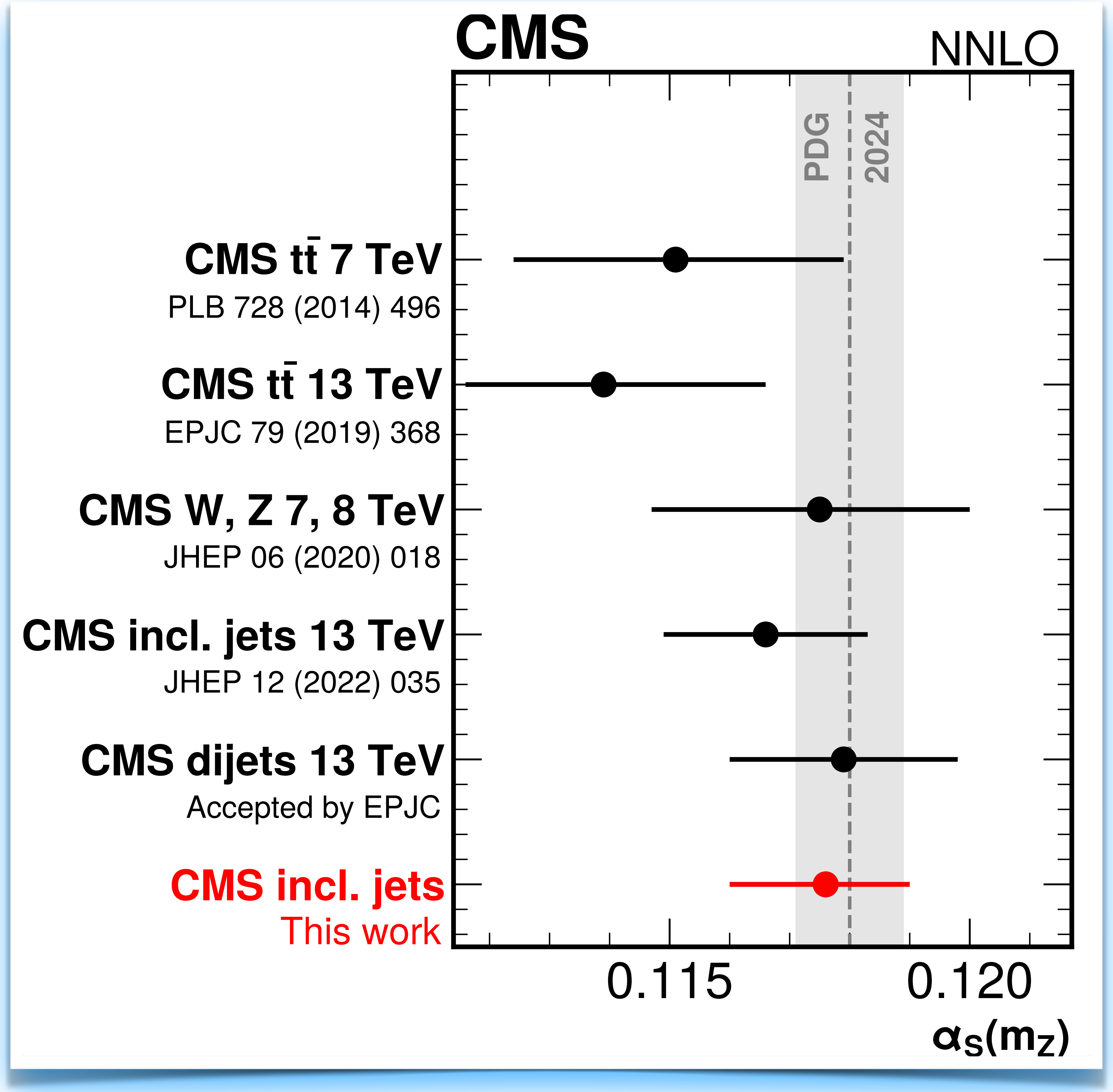
$$\alpha_S(m_Z) = 0.11759 \,{}^{+0.00093}_{-0.00094}\,(\text{fit})\,{}^{+0.00091}_{-0.0012}\,(\text{scale})\,{}^{+0.00059}_{-0.00043}\,(\text{model})\,{}^{+0}_{-0.00004}\,(\text{param})$$

$$= 0.1176^{+0.0014}_{-0.0016}$$

Most precise value obtained from jets, to date

Dominant contribution from scale uncertainty:

missing higher order contributions

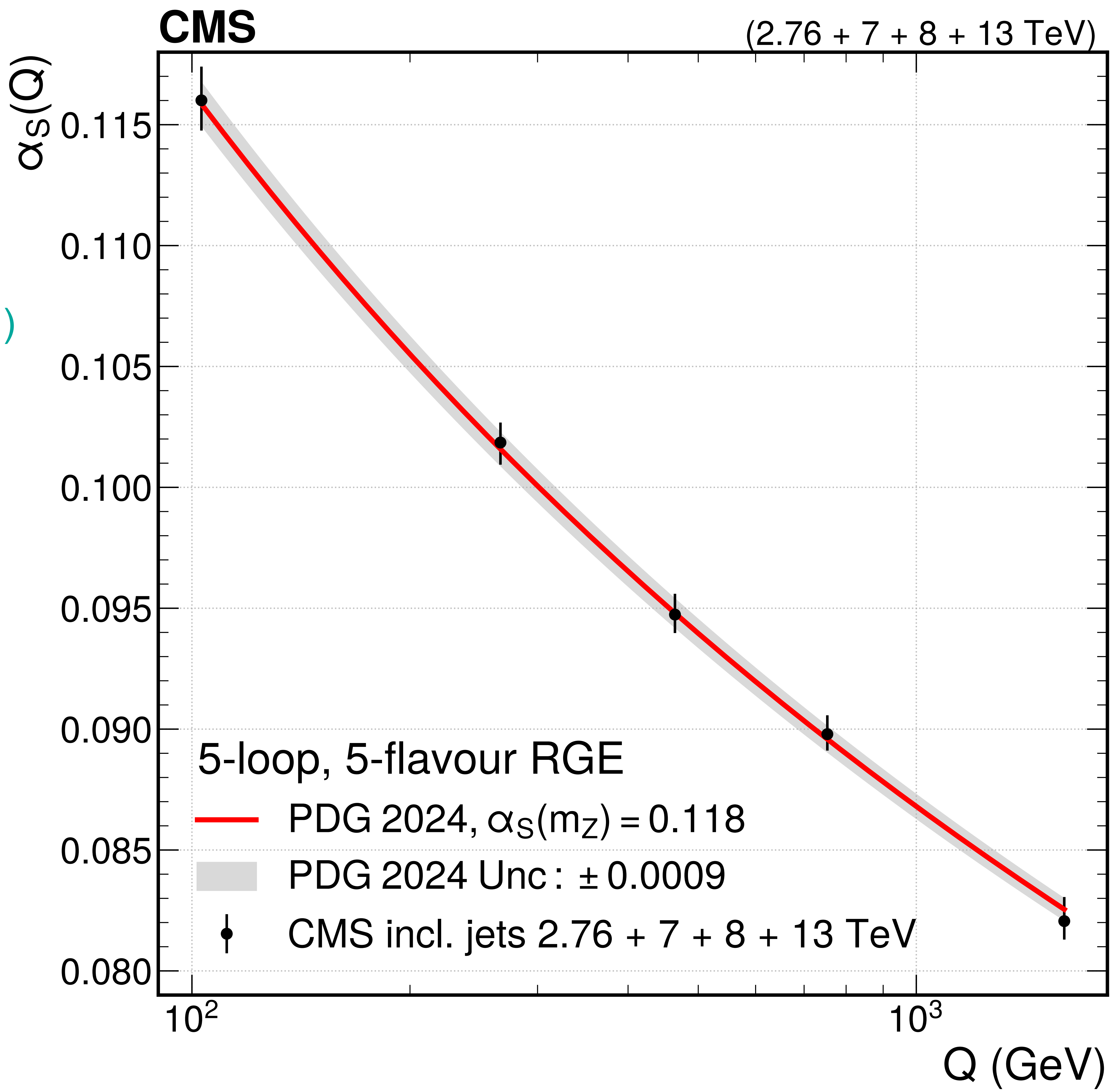


**Fit, Model and Scale added in quadrature, while PDF parametrisation added linearly*

Extraction of α_S running at NNLO

Divide CMS jet data into 5 independent p_T ranges

- Fit PDFs and $\alpha_S(m_Z)$ simultaneously
- Define the center of gravity Q of each p_T range
- Evolve $\alpha_s(m_Z)$ to Q with CRunDec package (arXiv:1703.03751)



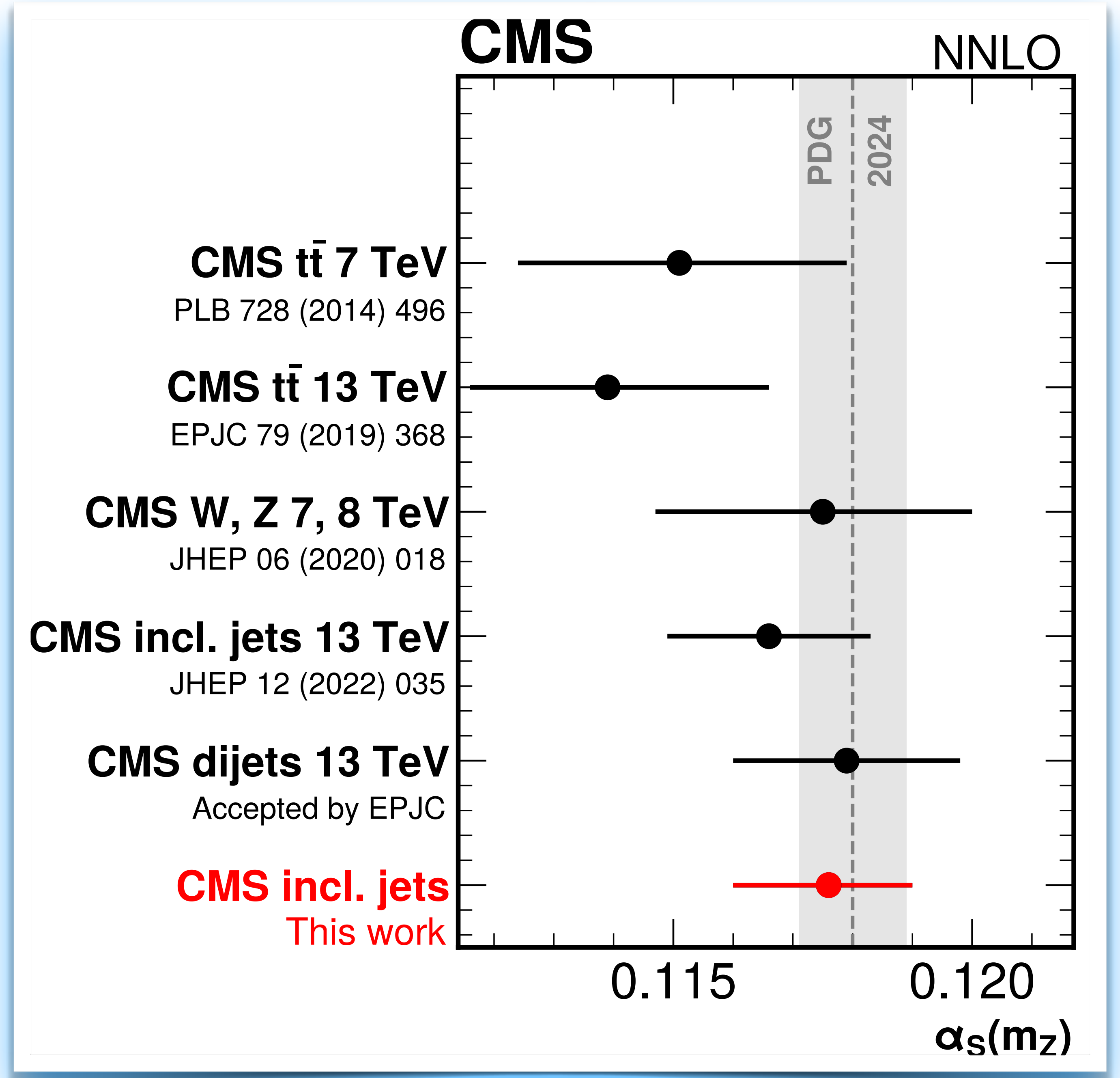
→ **Running probed up to 1.6 TeV**

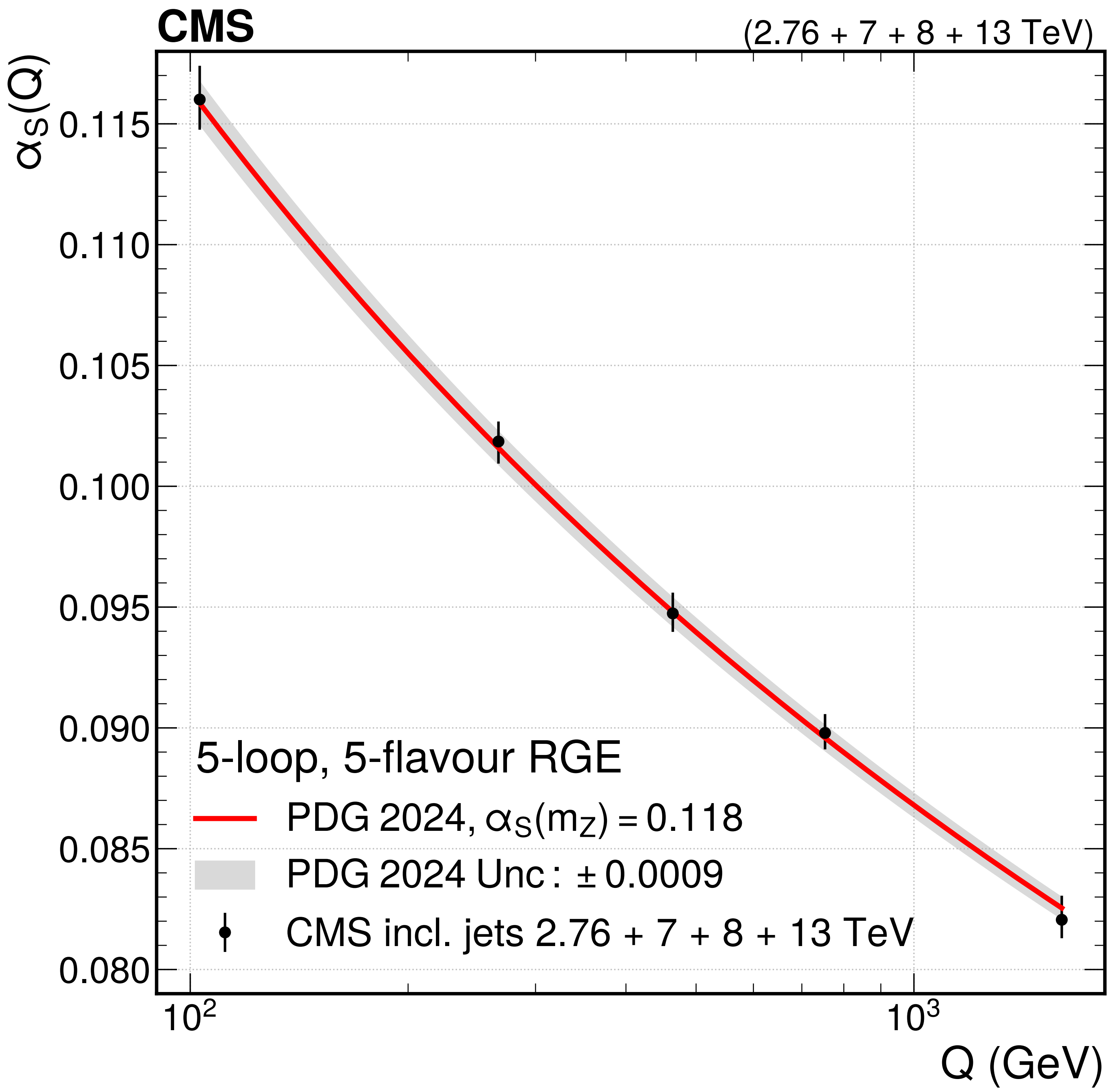
→ **Good agreement in the entire range**

Summary and conclusions

Combination of CMS inclusive jet measurements at $\sqrt{s} = 2.76,\ 7,\ 8,\ 13\ \mathrm{TeV}$

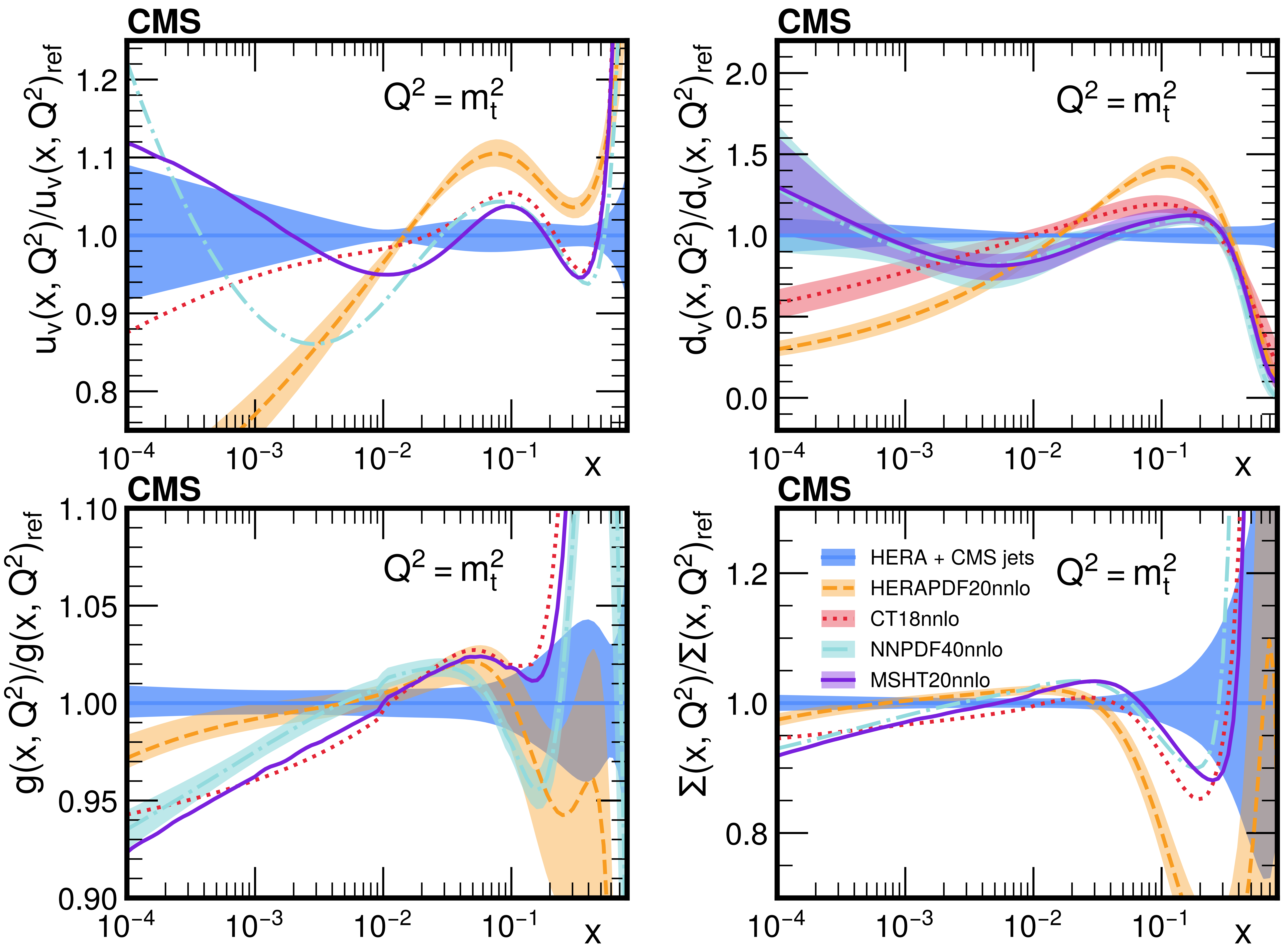
- Study of **systematics correlation among CMS jet data** → input for global PDF fitters
- **Most precise determination of $\alpha_S(m_Z)$ from jets**
- **Running of α_S** probed up to energy scale of **1.6 TeV** at NNLO





Thank you

Backup



CMS
$Q^2 = m_t^2$
$u_v(x, Q^2)/u_v(x, Q^2)_{ref}$
x
CMS
$Q^2 = m_t^2$
$d_v(x, Q^2)/d_v(x, Q^2)_{ref}$
x
CMS
$Q^2 = m_t^2$
$g(x, Q^2)/g(x, Q^2)_{ref}$
x
CMS
HERA + CMS jets
HERAPDF20nnlo
CT18nnlo
NNPDF40nnlo
MSHT20nnlo
$Q^2 = m_t^2$
$\Sigma(x, Q^2)/\Sigma(x, Q^2)_{ref}$
x