

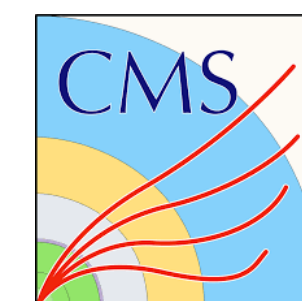
Determination of the strong coupling and its running from measurements of inclusive jet production in CMS

SMP-24-007 published in PLB 868 (2025) 139651

... and some prospects on Z pT in CMS

Valentina Guglielmi, on behalf of CMS collaboration

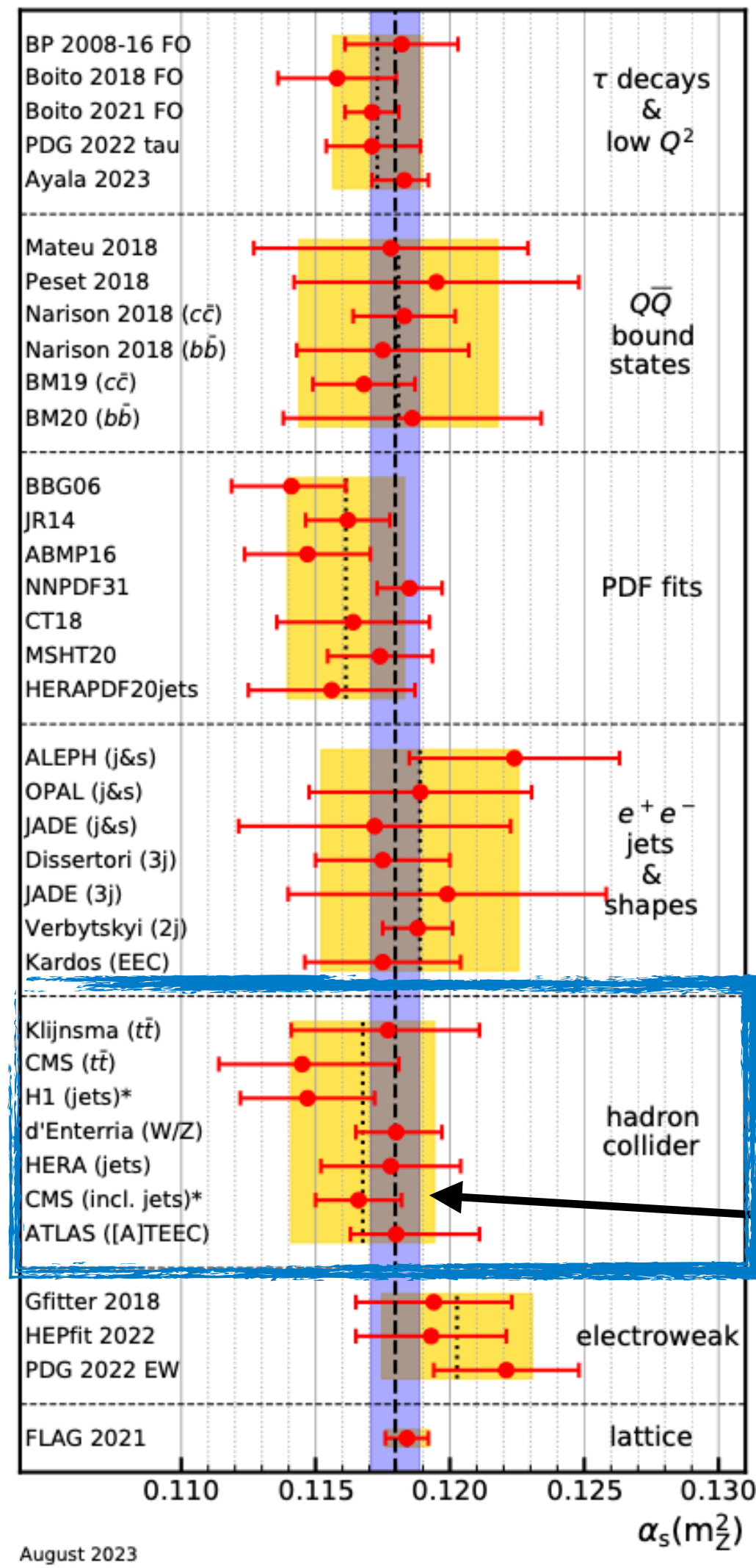
α_S workshop, Aussois, 16.12.2025



**Universität
Zürich^{UZH}**

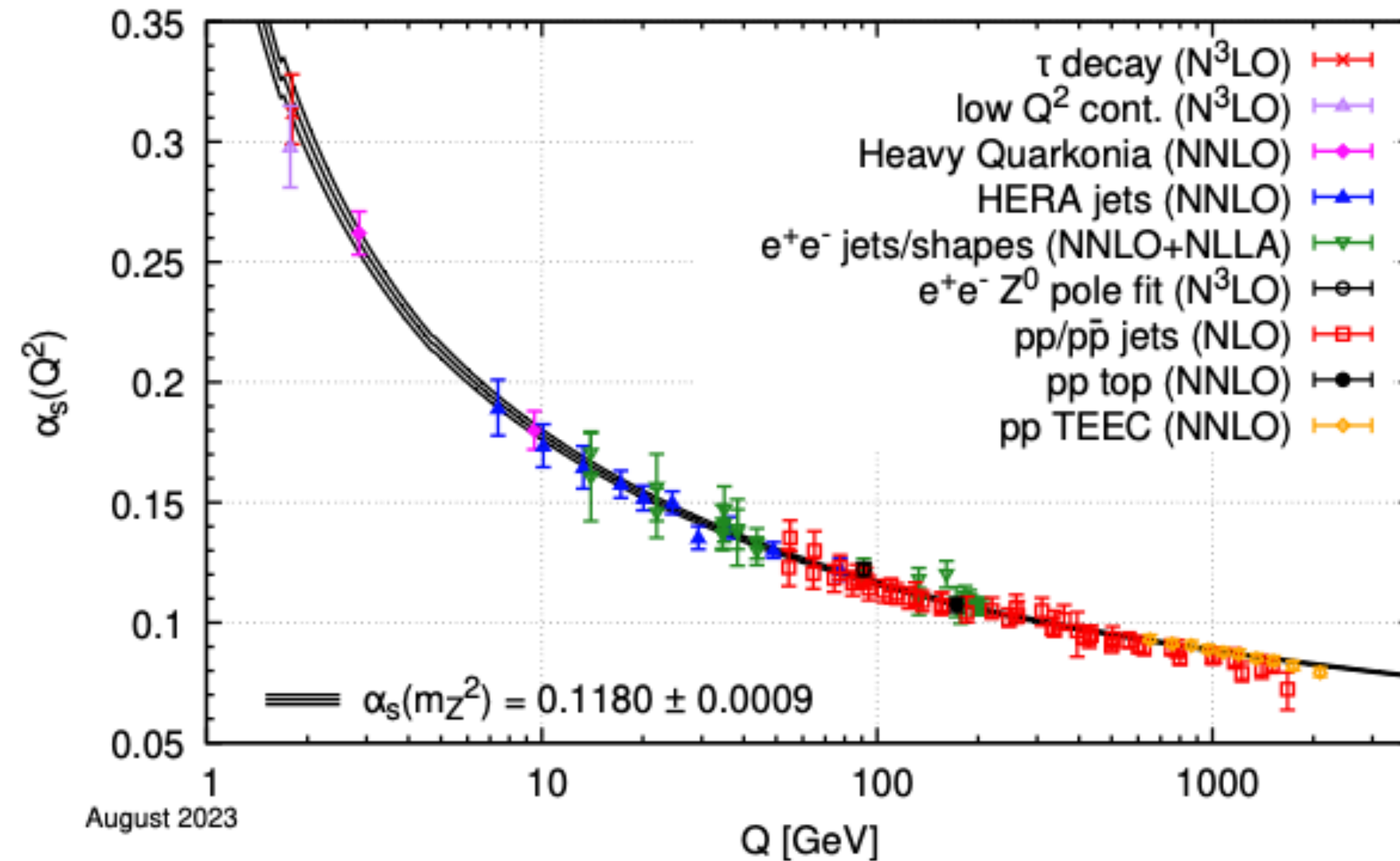
The state of the art (2023!) of the strong coupling

Summary of $\alpha_S(m_Z)$



Running of α_S with Q

[QCD PDG Review 2024](#)



How can we improve these results?

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

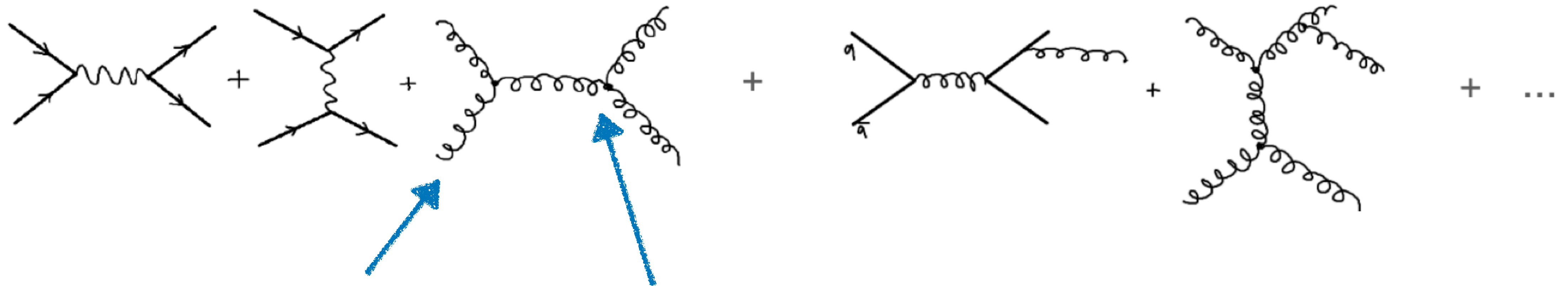
$$\alpha_S(m_Z) = 0.1166 \pm 0.0017 \quad \text{JHEP 12 (2022) 035}$$

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

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

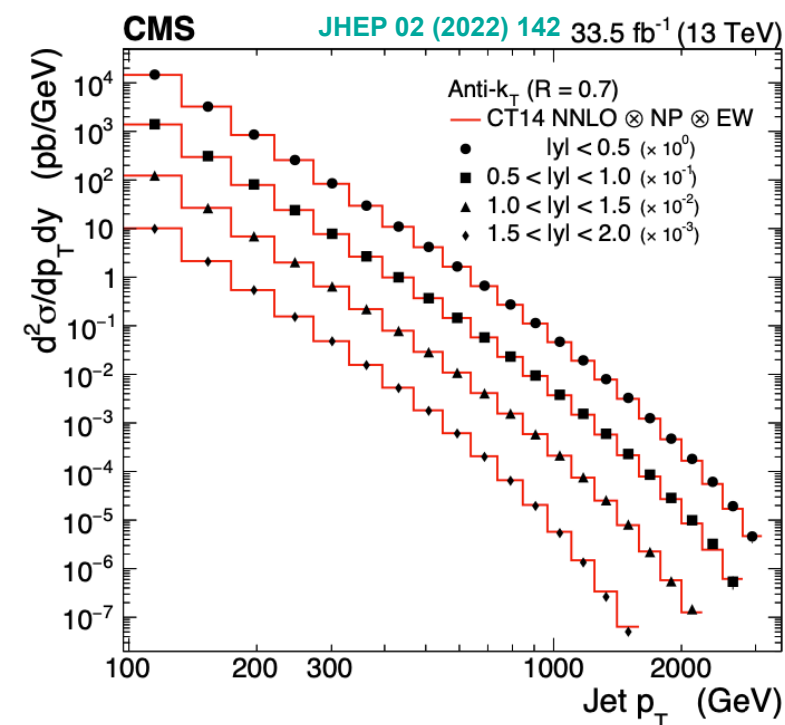
Each vertex is sensitive to $\alpha_S(m_Z)$

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**

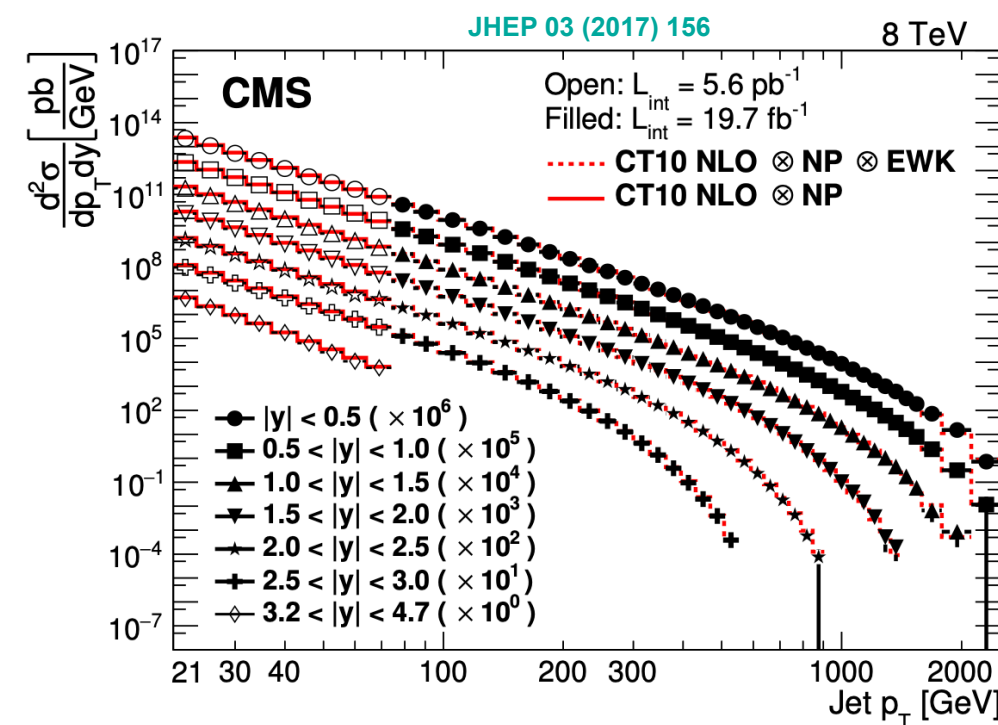
\sqrt{s}	Ndp
13 TeV	78
8 TeV	168
7 TeV	130
2.76 TeV	81

13 TeV



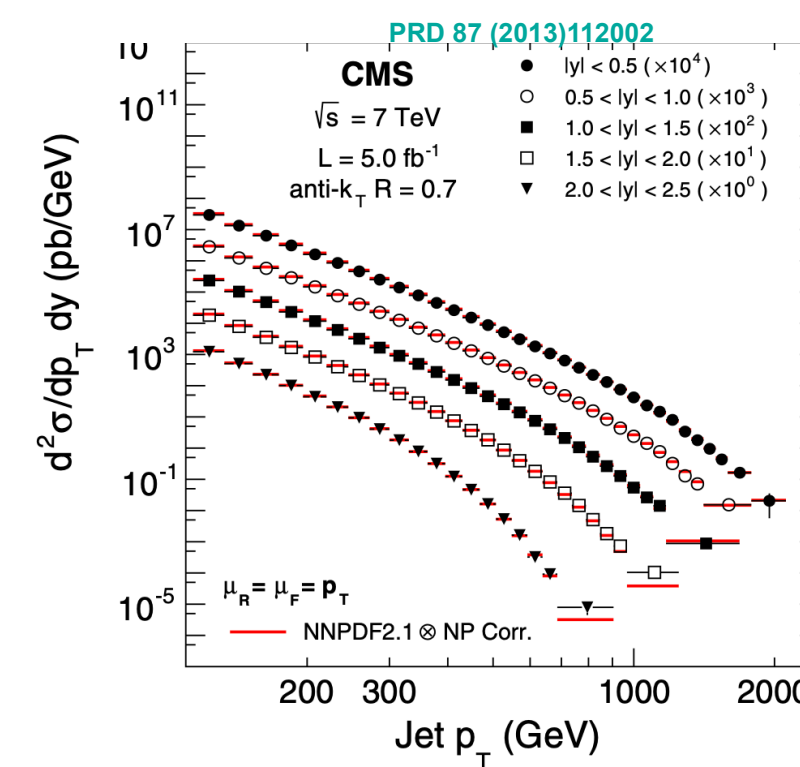
+

8 TeV



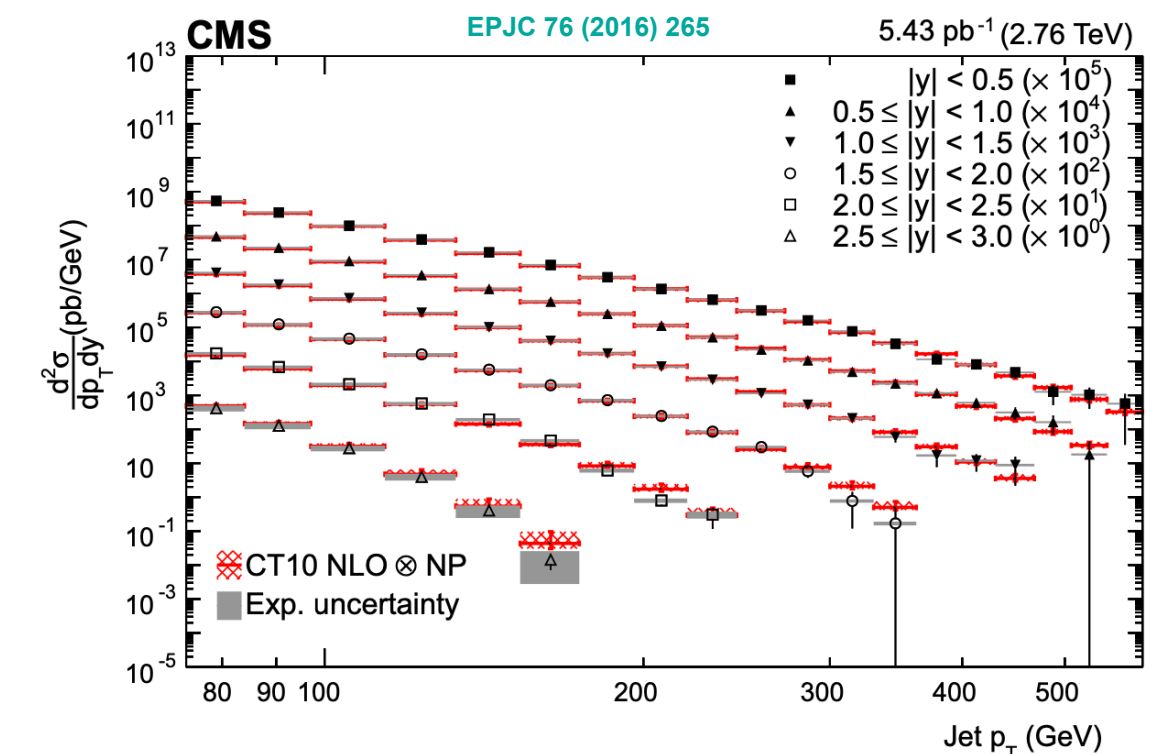
+

7 TeV



+

2.76 TeV



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

Extraction of α_S at LHC

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

DGLAP eq. Exp. measurements
PDFs $f_i(\mu, x)$ Partonic cross section (pQCD) Non perturbative corrections

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)

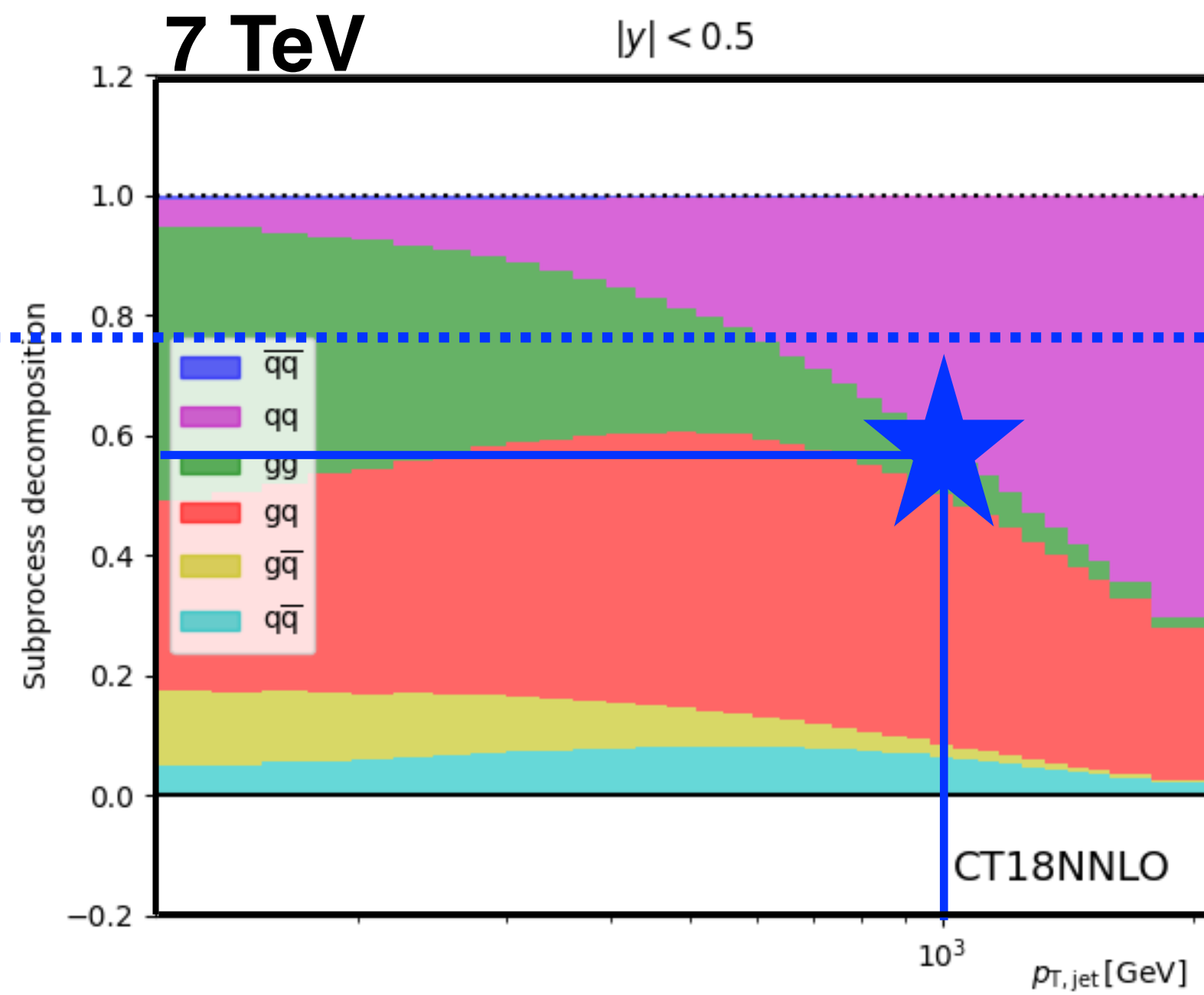
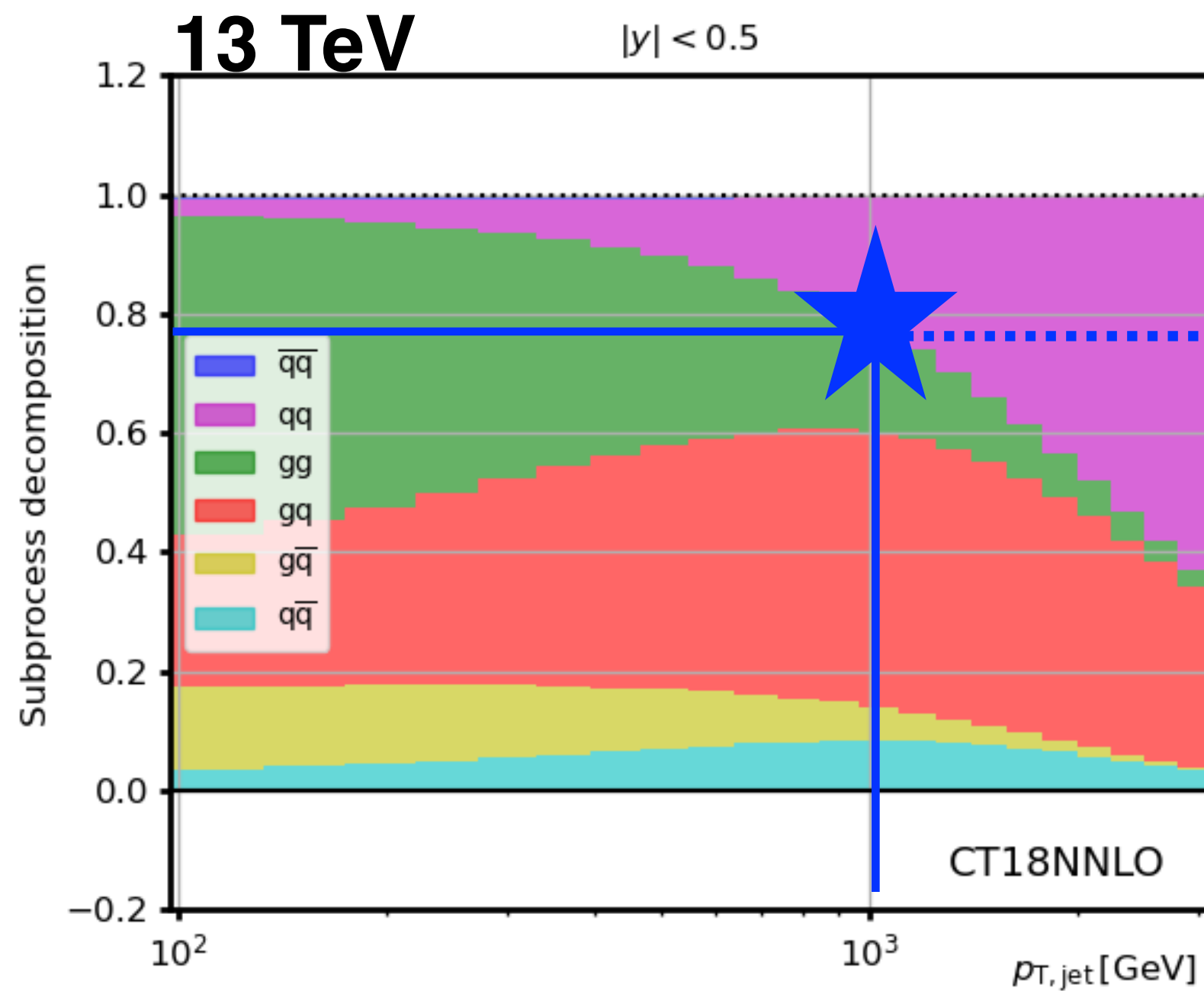
Simultaneous fit of PDFs and α_S at NNLO to reduce bias of α_S from PDFs

Inclusive jet productions and PDF sensitivity

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

→ Probe different PDF distributions

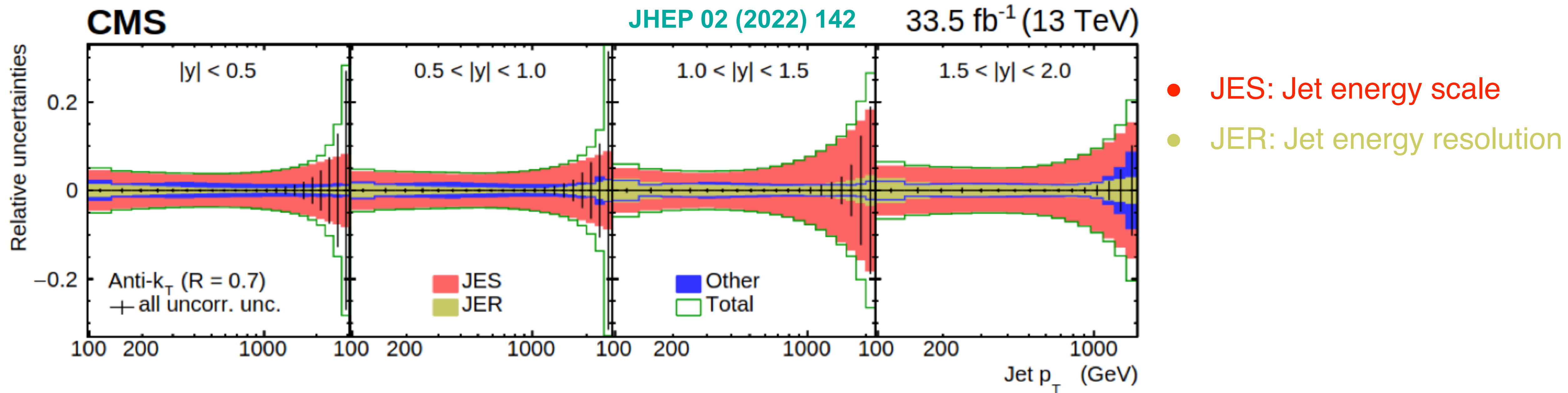
\sqrt{s} [TeV]	\mathcal{L} [fb ⁻¹]	p_T [GeV]	$ y $
2.76	0.0054	74–592	0.0–3.0
7	5.0	114–2116	0.0–2.5
8	20	74–1784	0.0–3.0
13	33.5	97–3103	0.0–2.0



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 contribution at high p_T

Reanalysis of systematics



- JER uncertainties are treated as uncorrelated across the measurements at different \sqrt{s}
- Within each individual measurement, JER decorrelated across $|y|$ for 2.76, 7.8 TeV to account for residual $|y|$ dependence in these datasets
- An additional uncorrelated component of 1.5% is assigned to the JER uncertainty in 2.76 TeV, to take into account a statistical contribution to the JER uncertainty

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 colour 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:

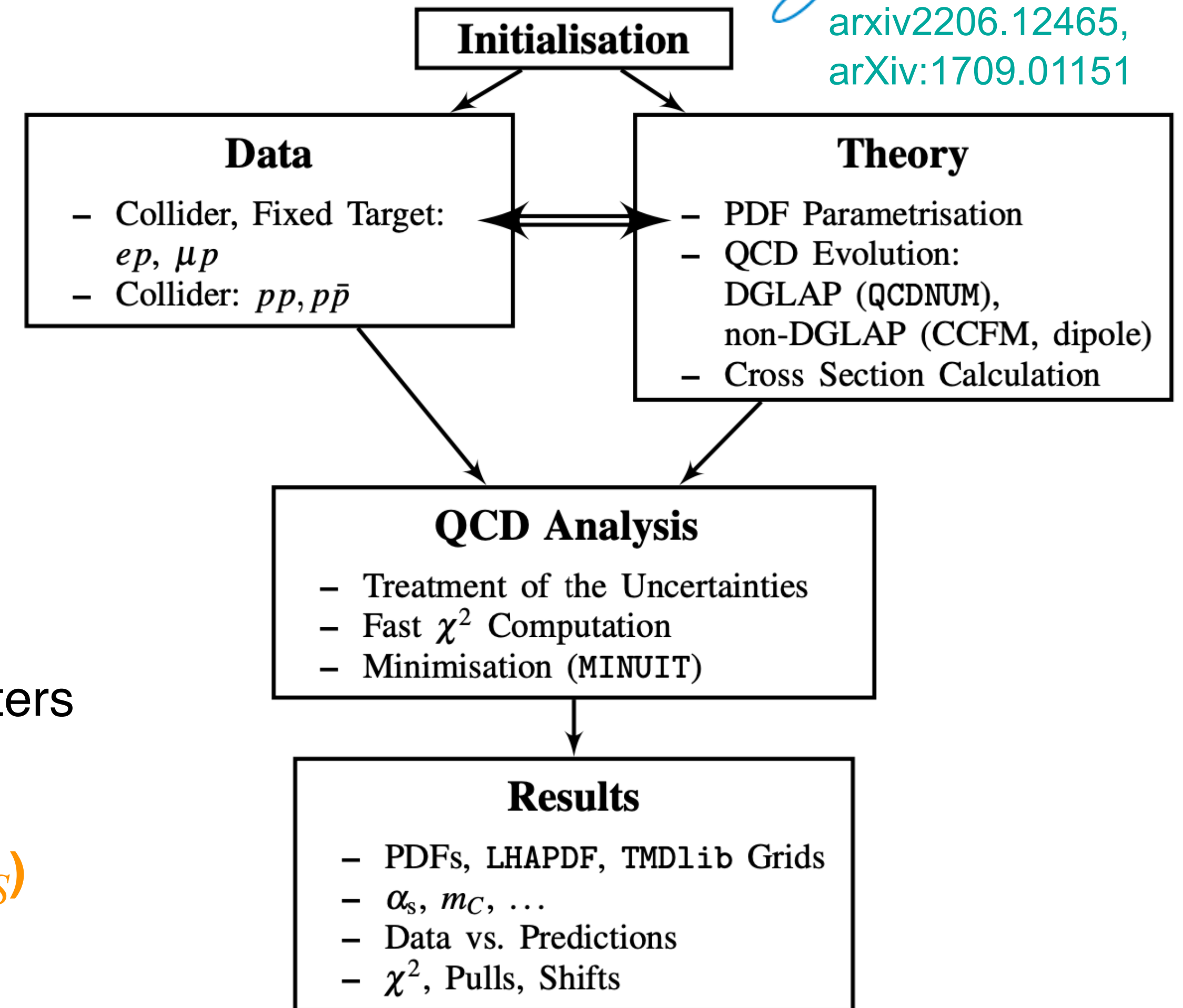
- Effects of hadronization and underlying event → Non-perturbative corrections
- Virtual W , Z contributions at NLO electroweak → EW corrections

The QCD analysis: extraction of PDFs and α_S



- **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 $Q_0^2 = 1.9 \text{ GeV}^2$

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

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

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

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

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

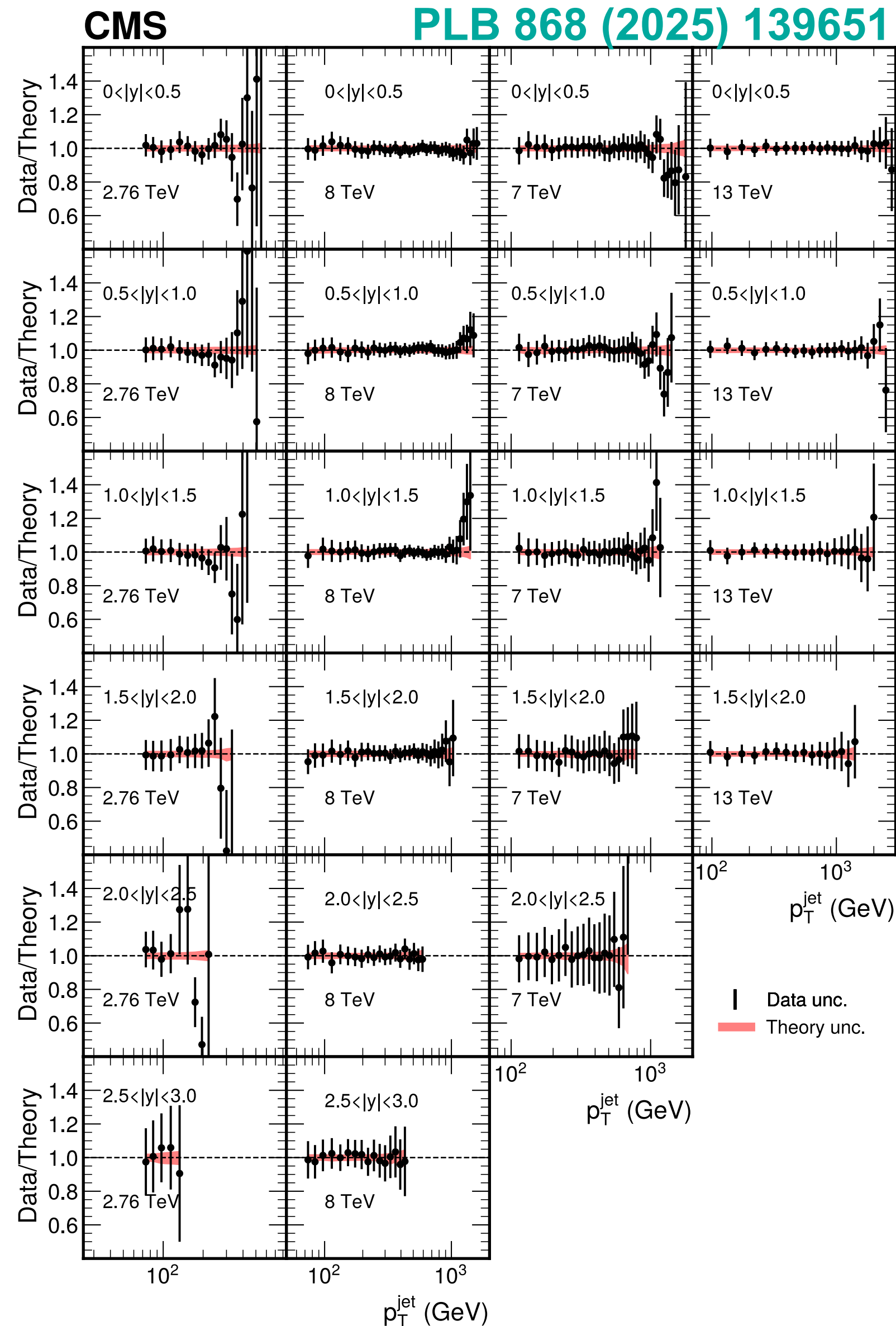
$$xd_v(x) = A_{d_v} x^{B_{d_v}} (1-x)^{C_{d_v}}$$

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

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

- $x\bar{U}(x) = x\bar{u}(x)$ 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



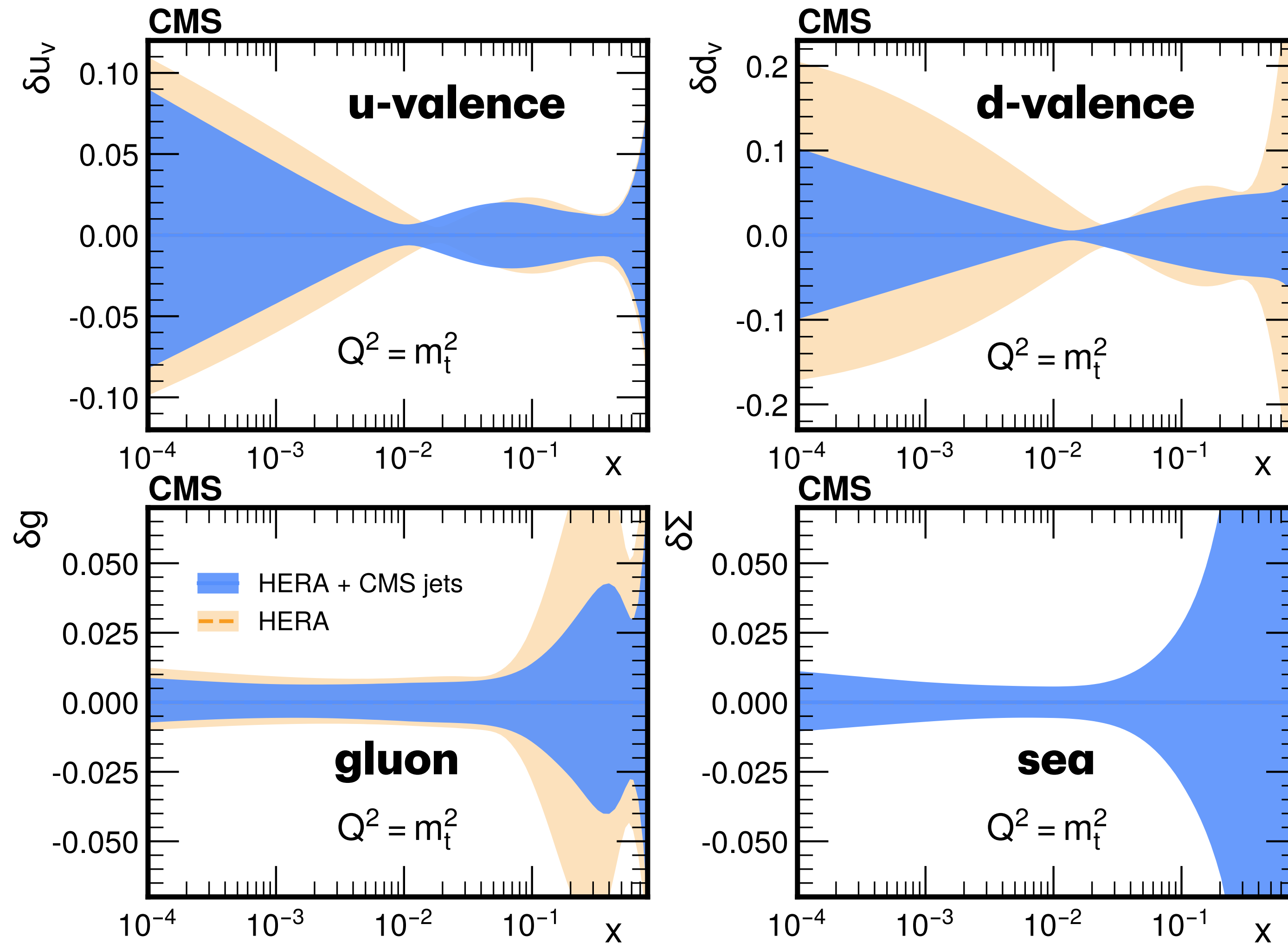
After simultaneous fit of PDFs and $\alpha_s(m_Z)$

Dataset	Partial χ^2 / N_{dof}
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 $\chi^2 / \text{ndf} = 427/453$

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

- **Parameterisation uncertainty:**

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



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_{\min}^2	10 GeV ²	7.5 GeV ²	12.5 GeV ²
Q_0^2	1.9 GeV ²	1.7 GeV ²	2.1 GeV ²
f_s	0.40	0.32	0.48

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

Comparison with other CMS measurements

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

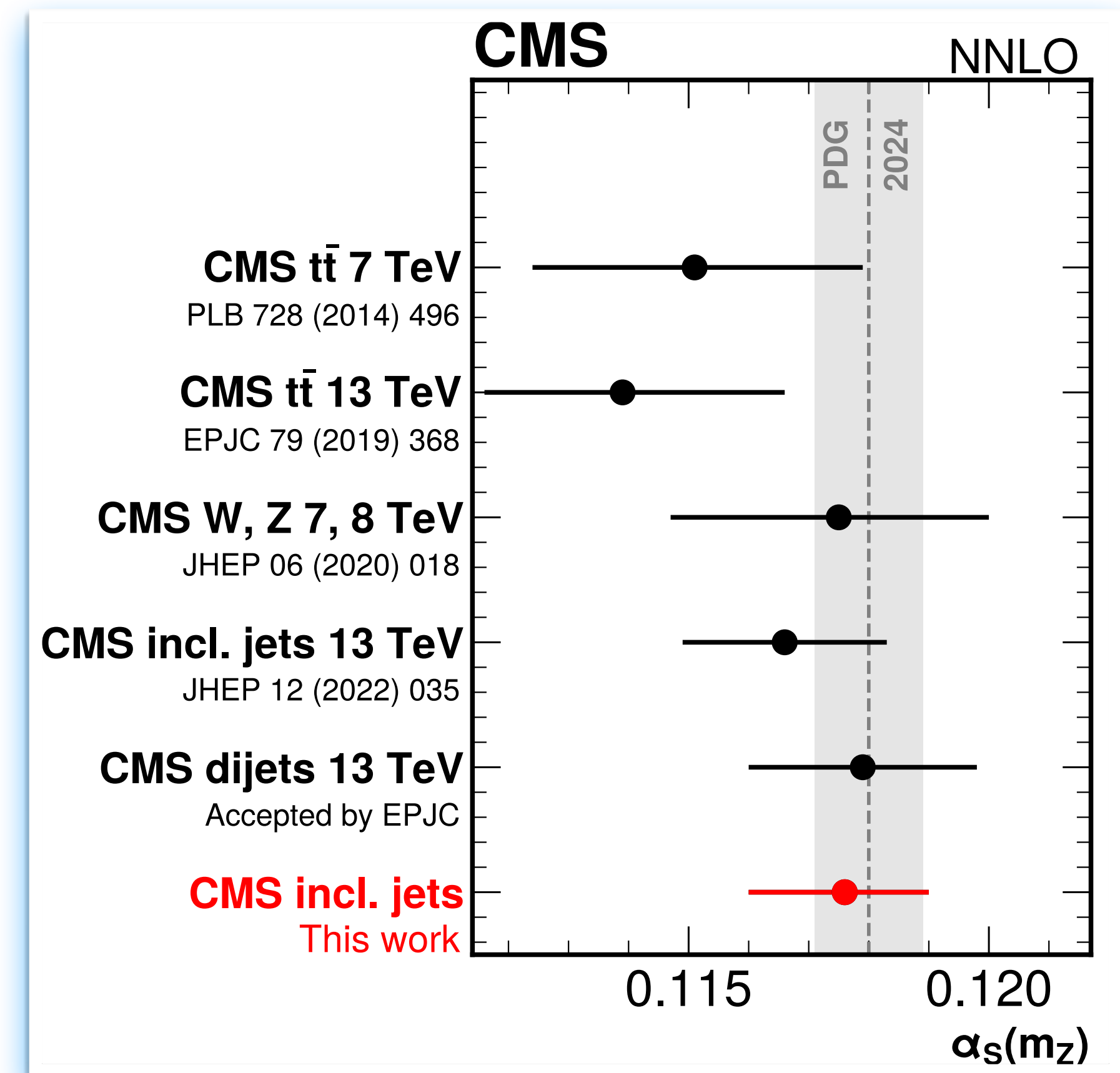
$$= 0.1176^{+0.0014}_{-0.0016}$$

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Most precise value obtained from jets at the LHC

*Dominant contribution from scale uncertainty:
missing higher order contributions*

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



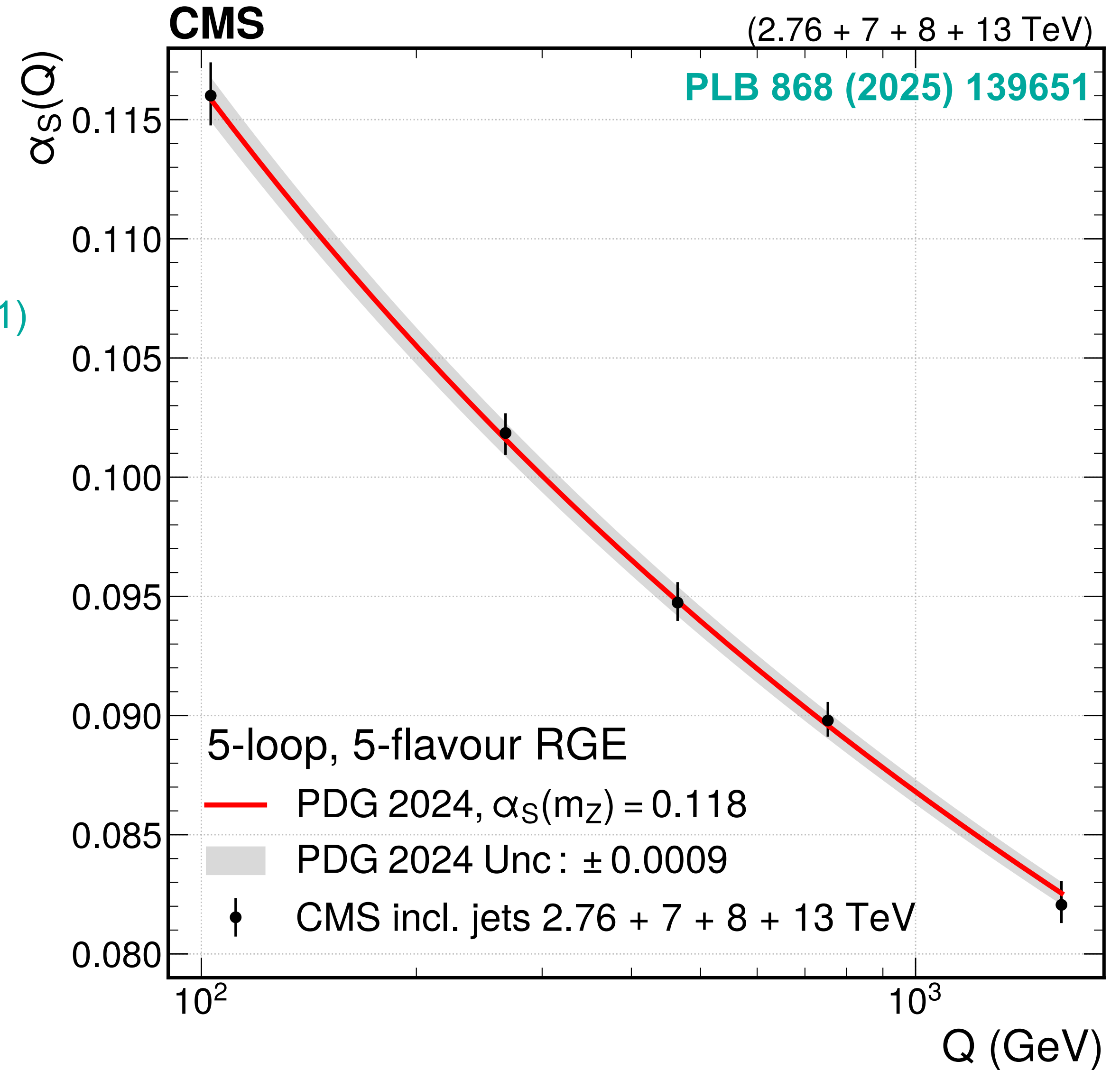
Extraction of α_s running at NNLO

Divide CMS jet data into 5 independent p_T ranges

- Fit PDFs and $\alpha_s(m_Z)$ simultaneously
- Define the centre of gravity Q of each p_T range
- Evolve $\alpha_s(m_Z)$ to Q with CRunDec package ([arXiv:1703.03751](https://arxiv.org/abs/1703.03751))

→ Running probed up to 1.6 TeV

→ Good agreement in the entire range



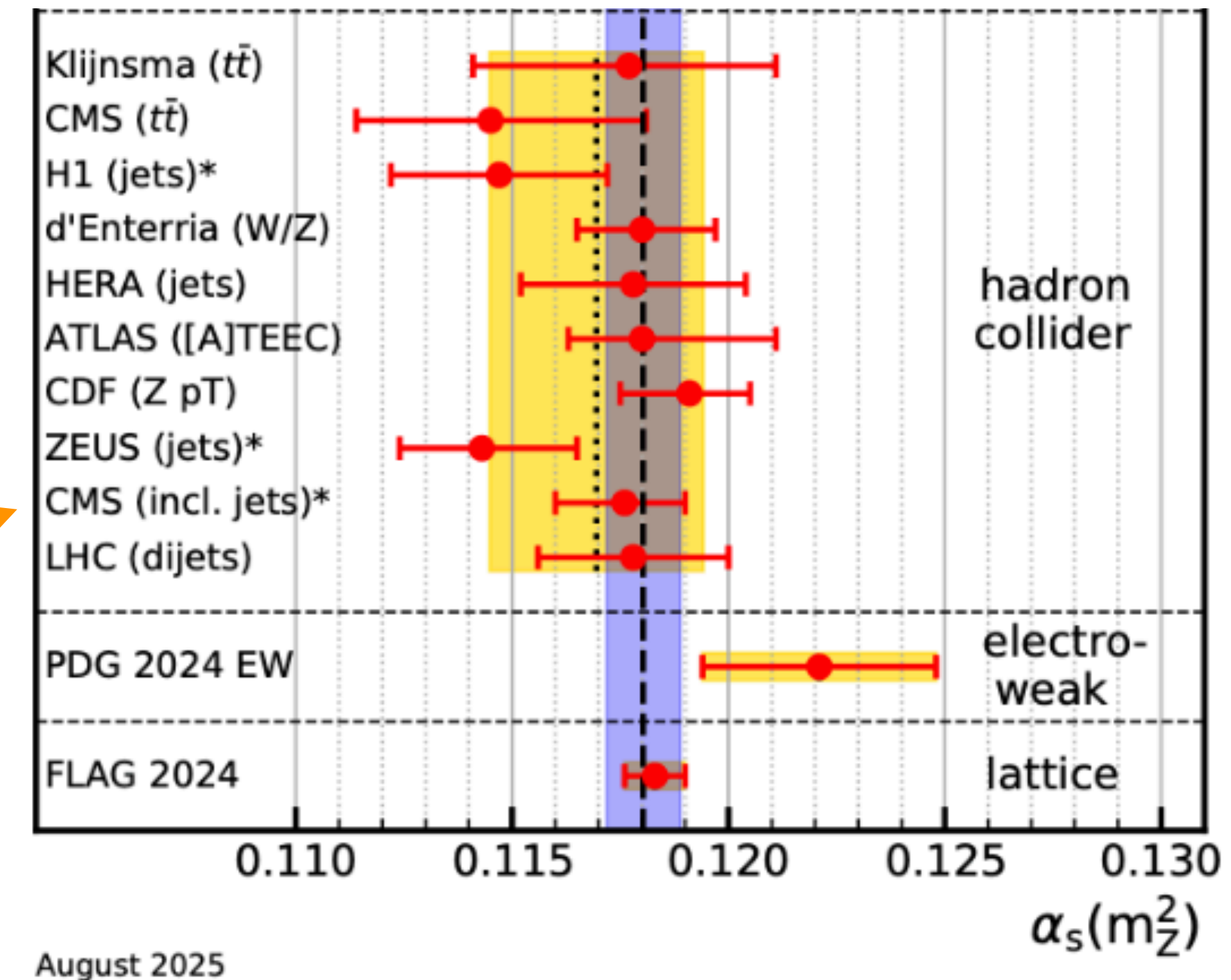
Summary...

Combination of CMS inclusive jet measurements at

$$\sqrt{s} = 2.76, 7, 8, 13 \text{ TeV}$$

- **Reanalysis of systematics uncertainties**
→ input for global PDF fitters
- **Study of systematics correlation among CMS jet data**
→ input for global PDF fitters
- **Most precise determination of $\alpha_S(m_Z)$ from jets:**
$$\alpha_S(m_Z) = 0.1176^{+0.0014}_{-0.0016}$$
- **Running of α_S probed up to energy scale of 1.6 TeV at NNLO**

[QCD PDG Review 2025](#)



... and prospects

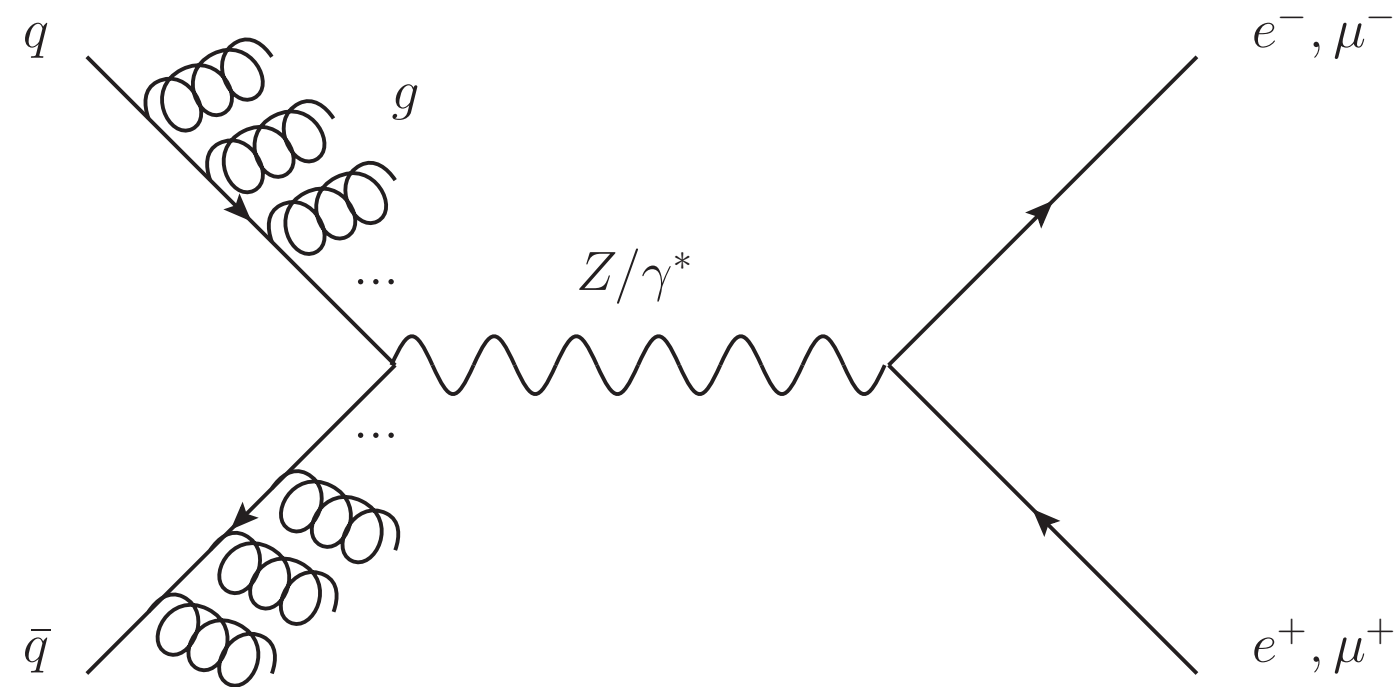
- Currently, a very good candidate to determine $\alpha_s(m_Z)$ is from the p_T distribution of the Z boson
 - Very clean experimental signature
 - High experimental sensitivity
 - Fast analytic predictions
- ATLAS $Z p_T$: [arxiv:2309.12986](https://arxiv.org/abs/2309.12986)
- Recent paper from theory (T. Cridge, G. Marinelli, F. J. Tackmann): [arxiv:2506.13874](https://arxiv.org/abs/2506.13874)

$\alpha_s(m_Z)$ from $Z p_T$:

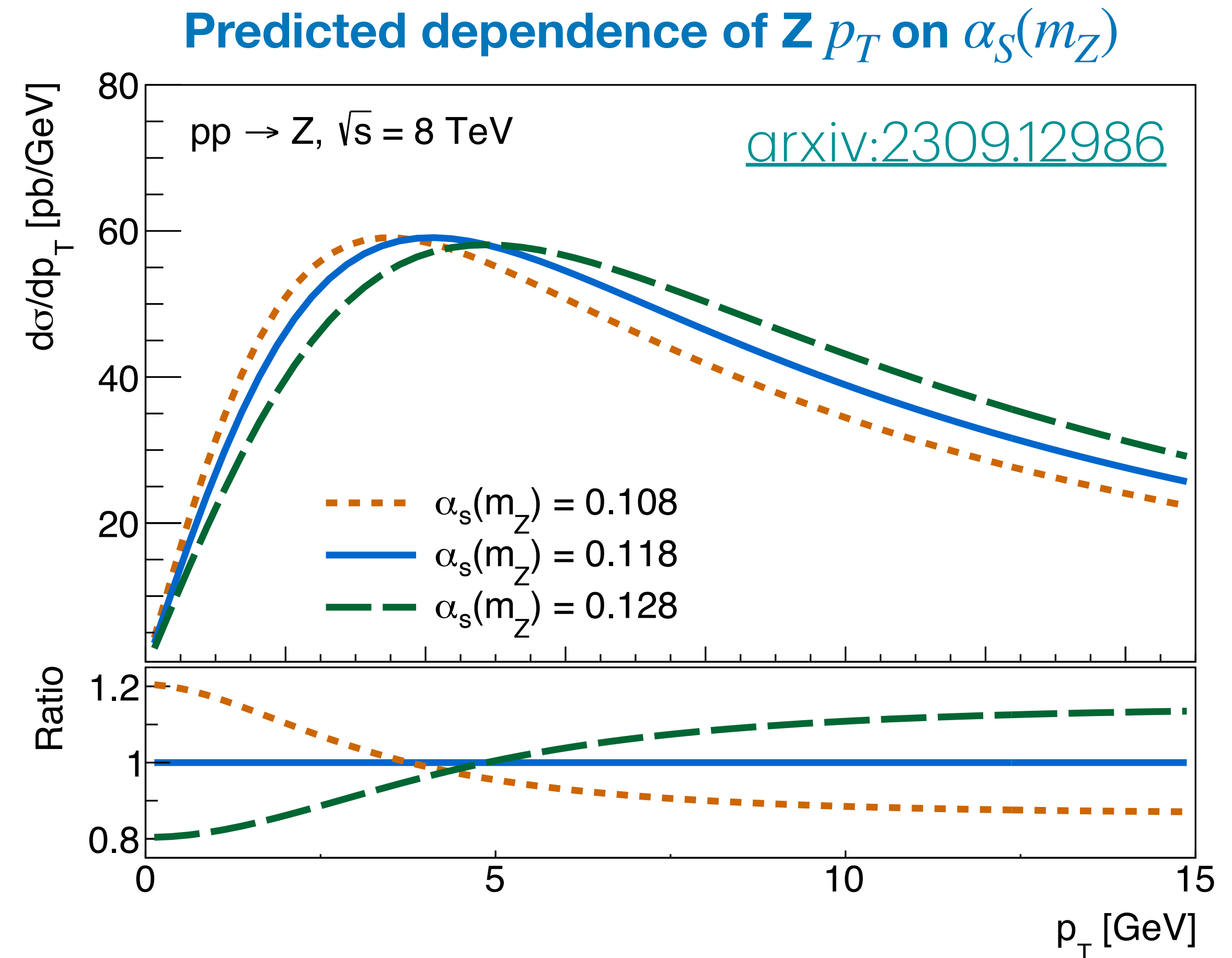
WIP in CMS !

Sensitivity of $Z p_T$ to $\alpha_s(m_Z)$

- Z bosons produced boosted at LHC by recoil against QCD ISR

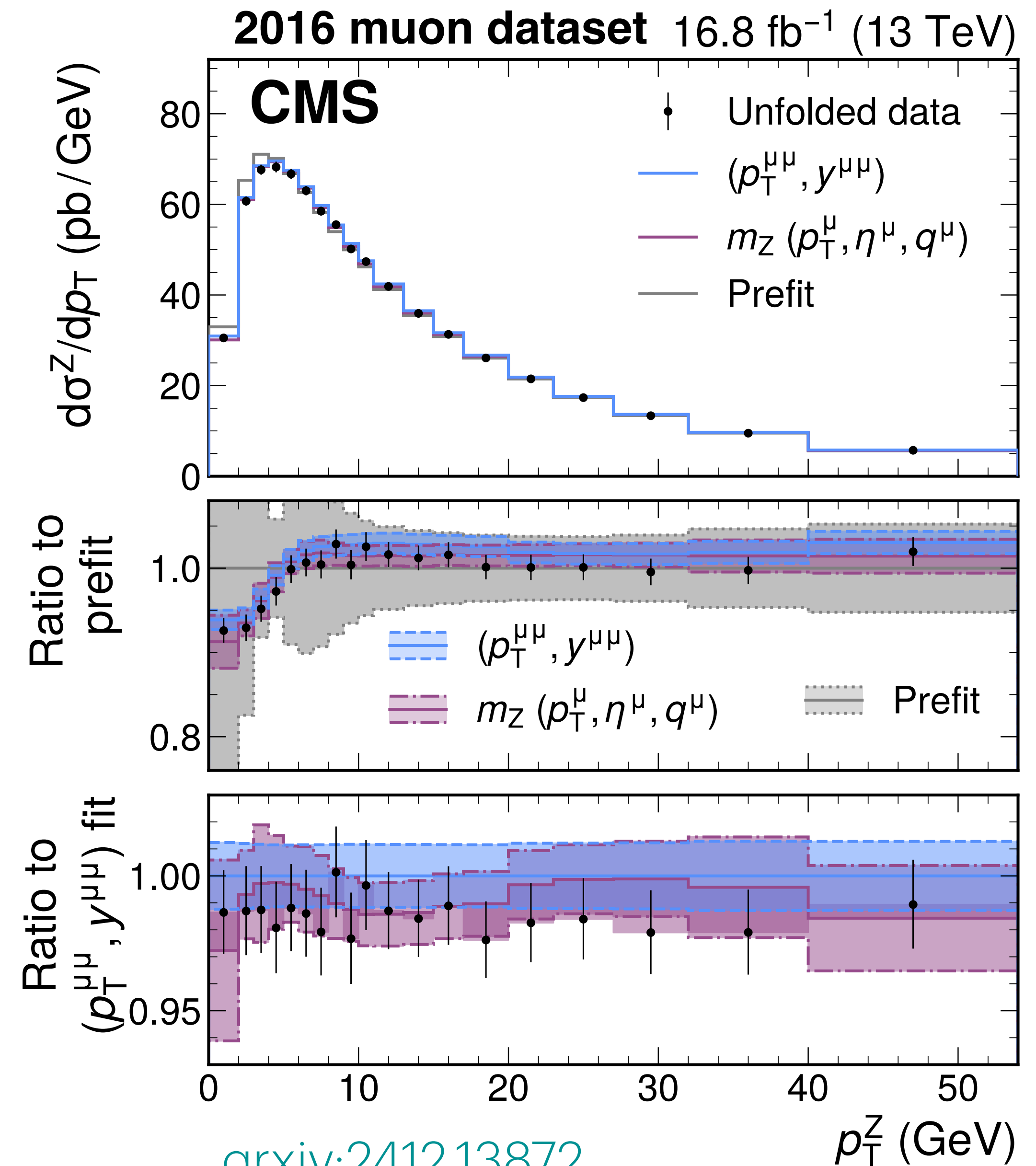


- Sudakov factor responsible for the existence of a peak in the $Z p_T$ distribution around 4 GeV
- **Linear sensitivity to $\alpha_s(m_Z)$**
- **Semi-inclusive** (radiation inhibited) observable, requires resummation



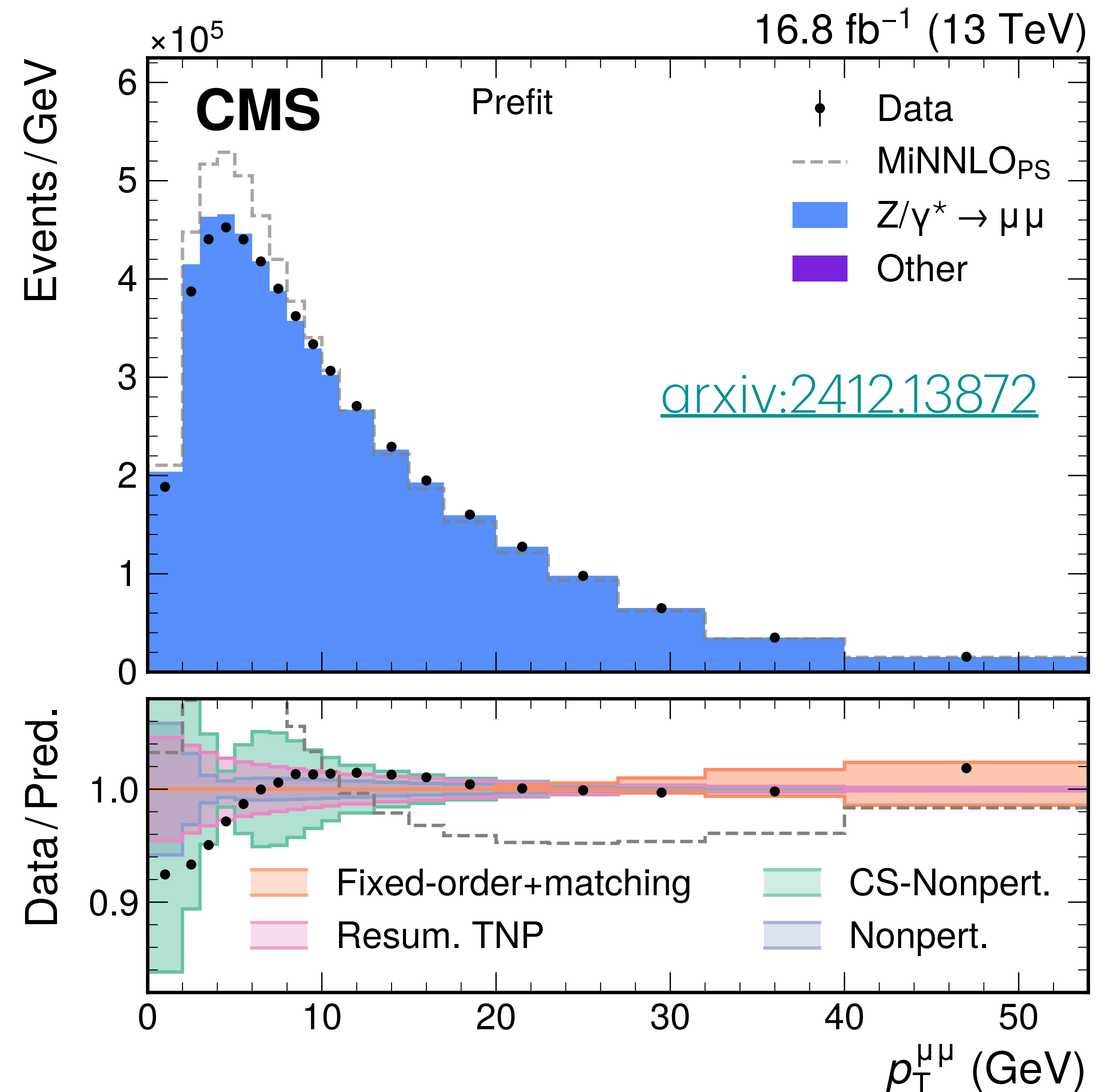
CMS $\alpha_s(m_Z)$ from Z p_T : input data

- In the CMS publication of m_W ([arxiv:2412.13872](https://arxiv.org/abs/2412.13872)), m_Z and W-like were validation components of m_W analysis itself, and $\alpha_s(m_Z)$ was treated as nuisance parameter
- The CMS framework of m_W has all ingredients (theory predictions, experimental setup, datasets) to extract $\alpha_s(m_Z)$ from Drell-Yan



CMS $\alpha_s(m_Z)$ from Z p_T : starting from m_W theoretical model

- QED: ISR simulated with PYTHIA8, FSR simulated with PHOTOS
- QCD POWHEG-MiNNLO for NNLO, corrected with resummation at N3LL from SCETLib matched to fixed order at NNLO from DYTurbo
- Nonperturbative effects (e.g. residual transverse motion of the partons inside the proton): phenomenological models ([arxiv:2411.16004](https://arxiv.org/abs/2411.16004))
- Fixed-order + matching unc.
- Perturbative unc. in the resummed prediction using TNP ([arxiv:2411.18606](https://arxiv.org/abs/2411.18606))
- Collins--Soper (CS) kernel nonperturbative unc.
- Other nonperturbative unc.



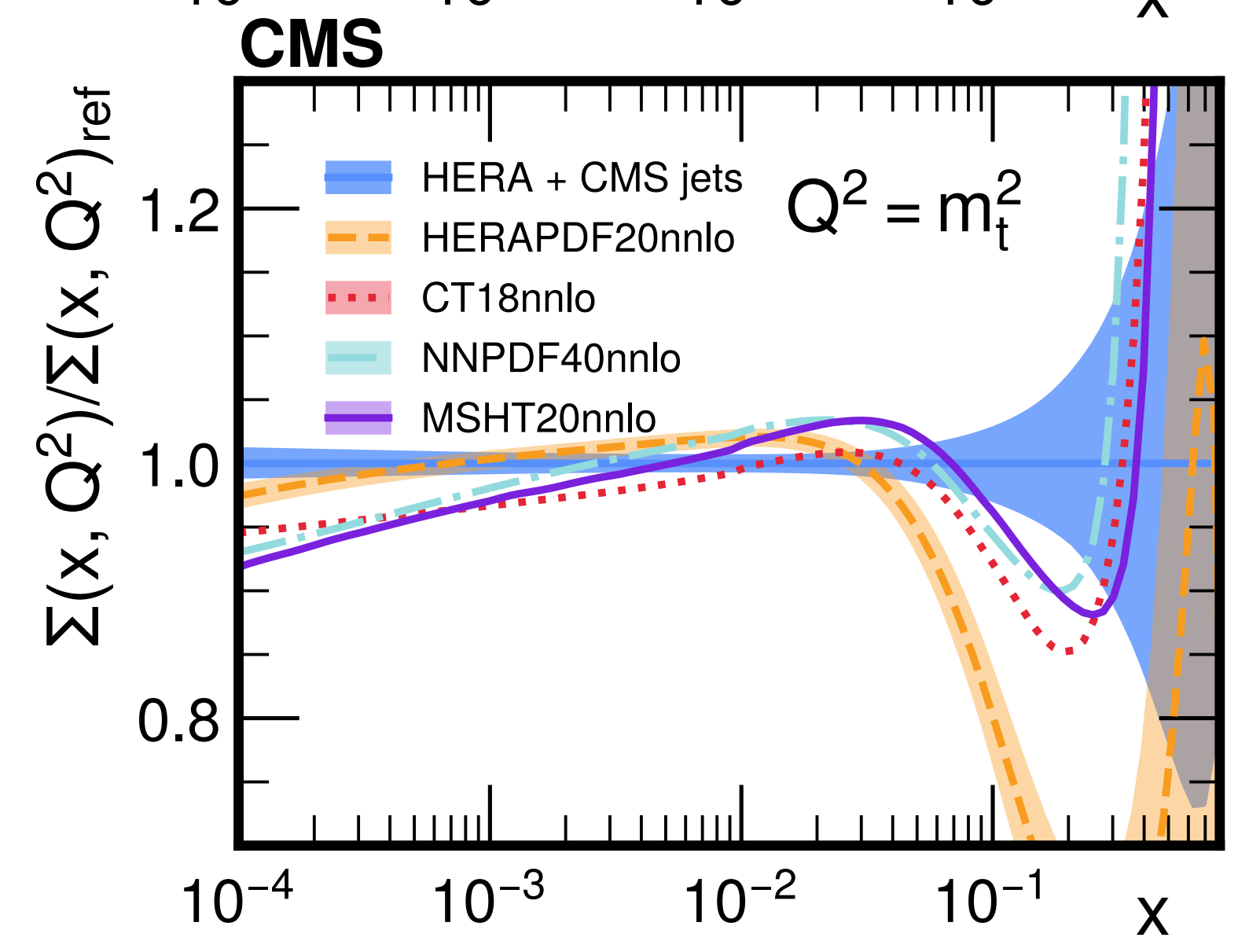
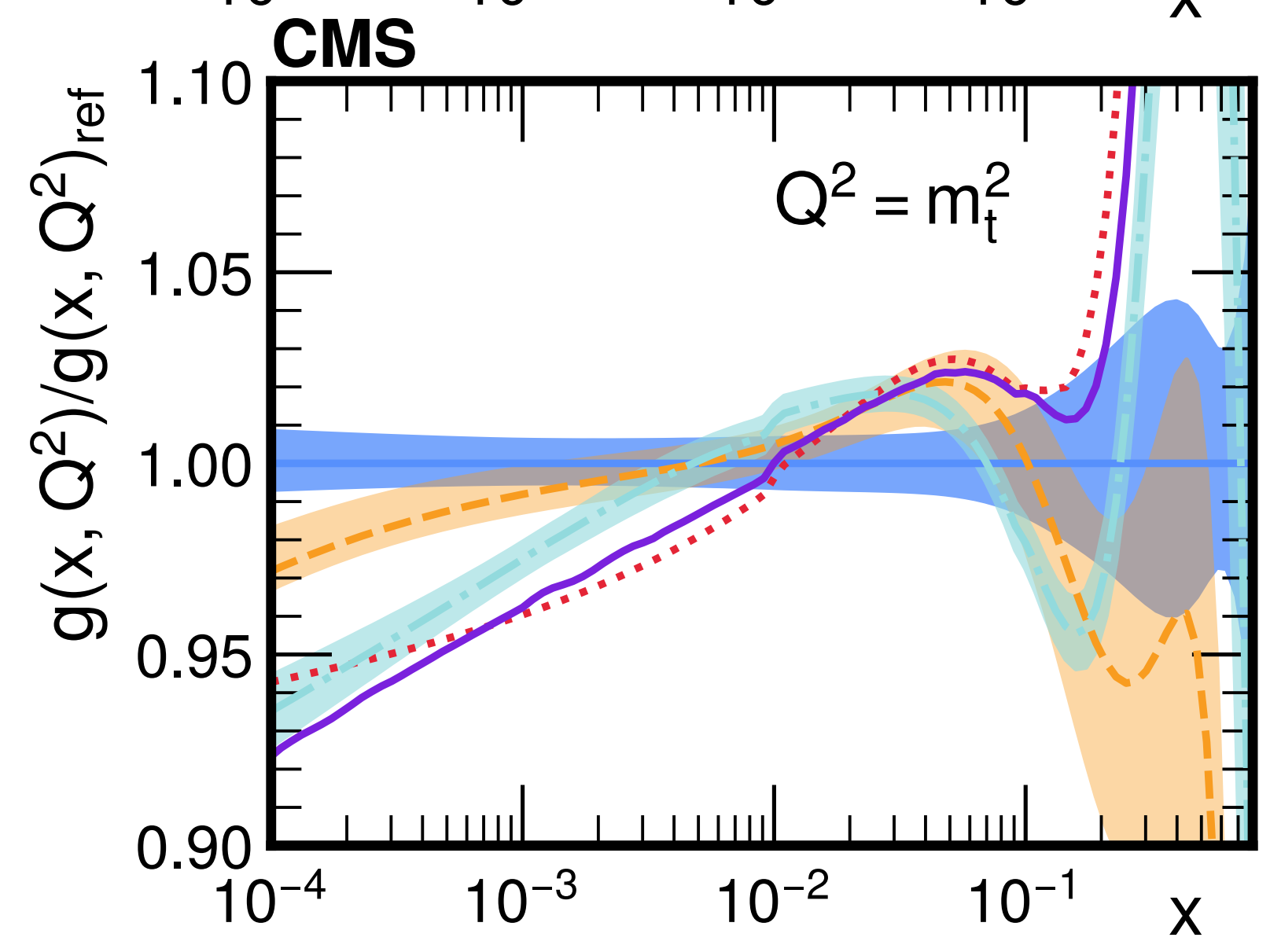
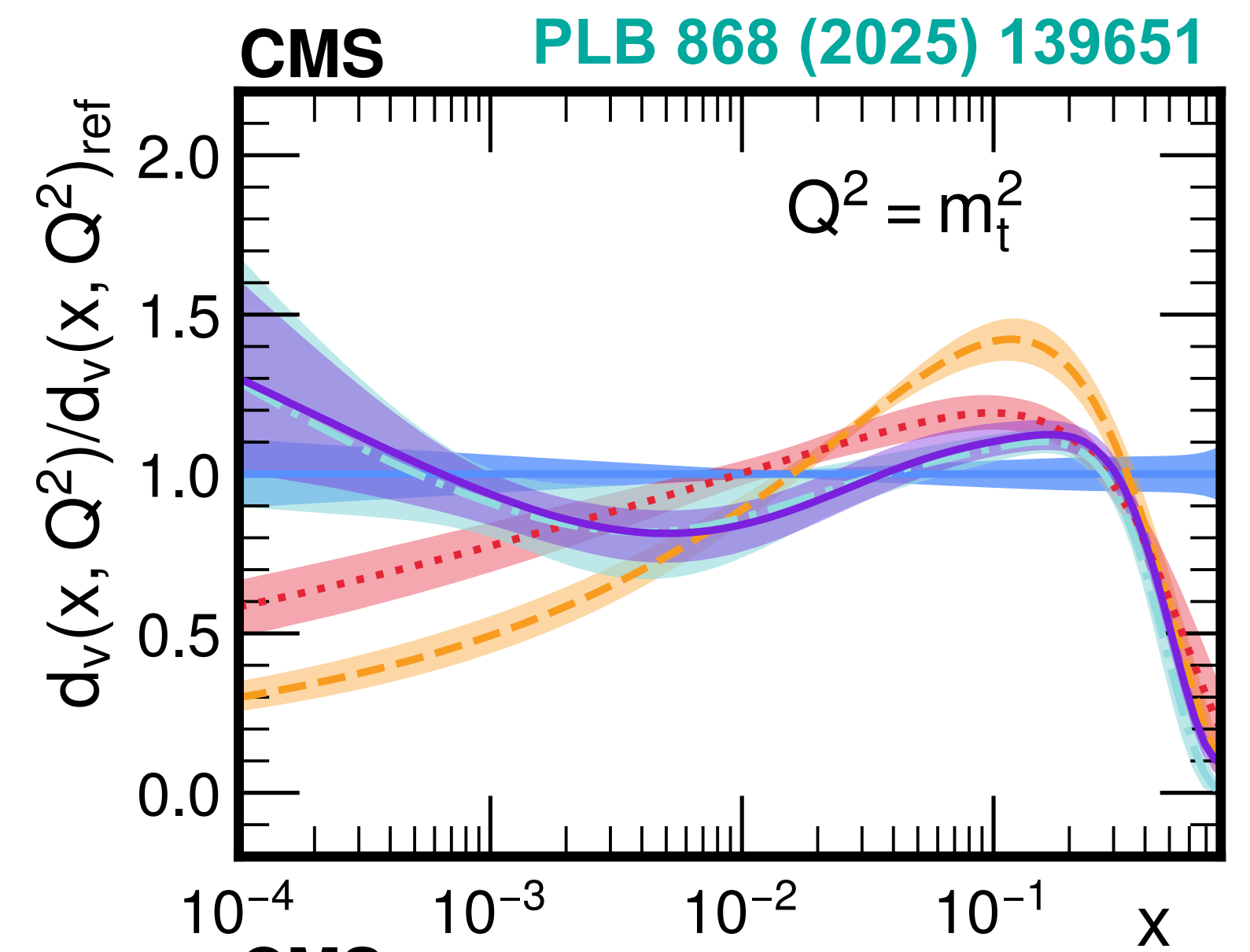
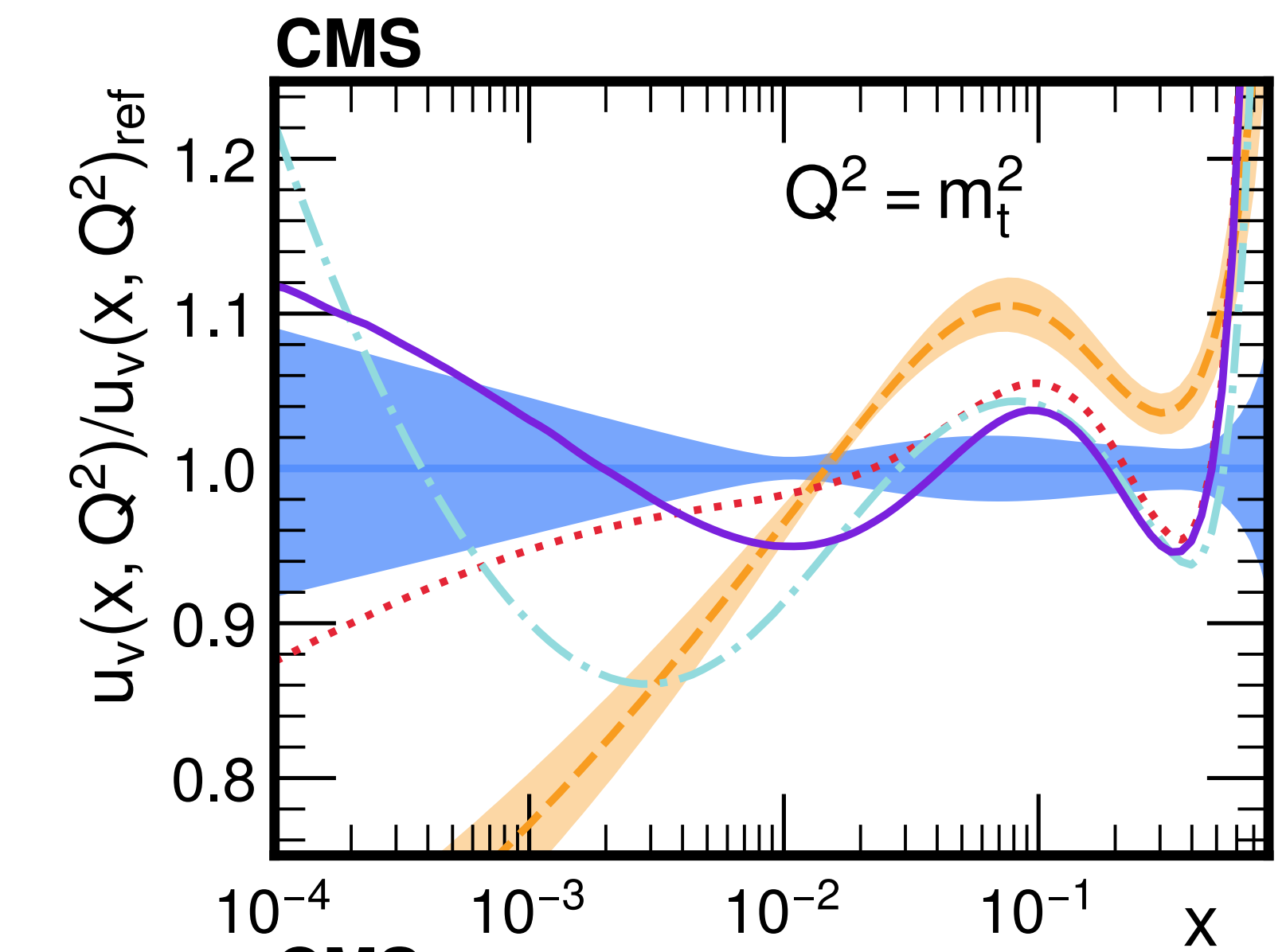
Conclusions

- Combination of CMS inclusive jets at $\sqrt{s} = 2.76, 7, 8, 13$ TeV
 - Most precise determination of $\alpha_S(m_Z)$ from jets at the LHC
 - Running of α_S probed up to energy scale of 1.6 TeV at NNLO
 - Reanalysis of systematics and study of correlations among CMS jet data → inputs for global PDF fits
- Next step:
 - We have all the ingredients to extract $\alpha_S(m_Z)$ from $Z p_T$ using the same framework of m_W analysis

Stay tuned!

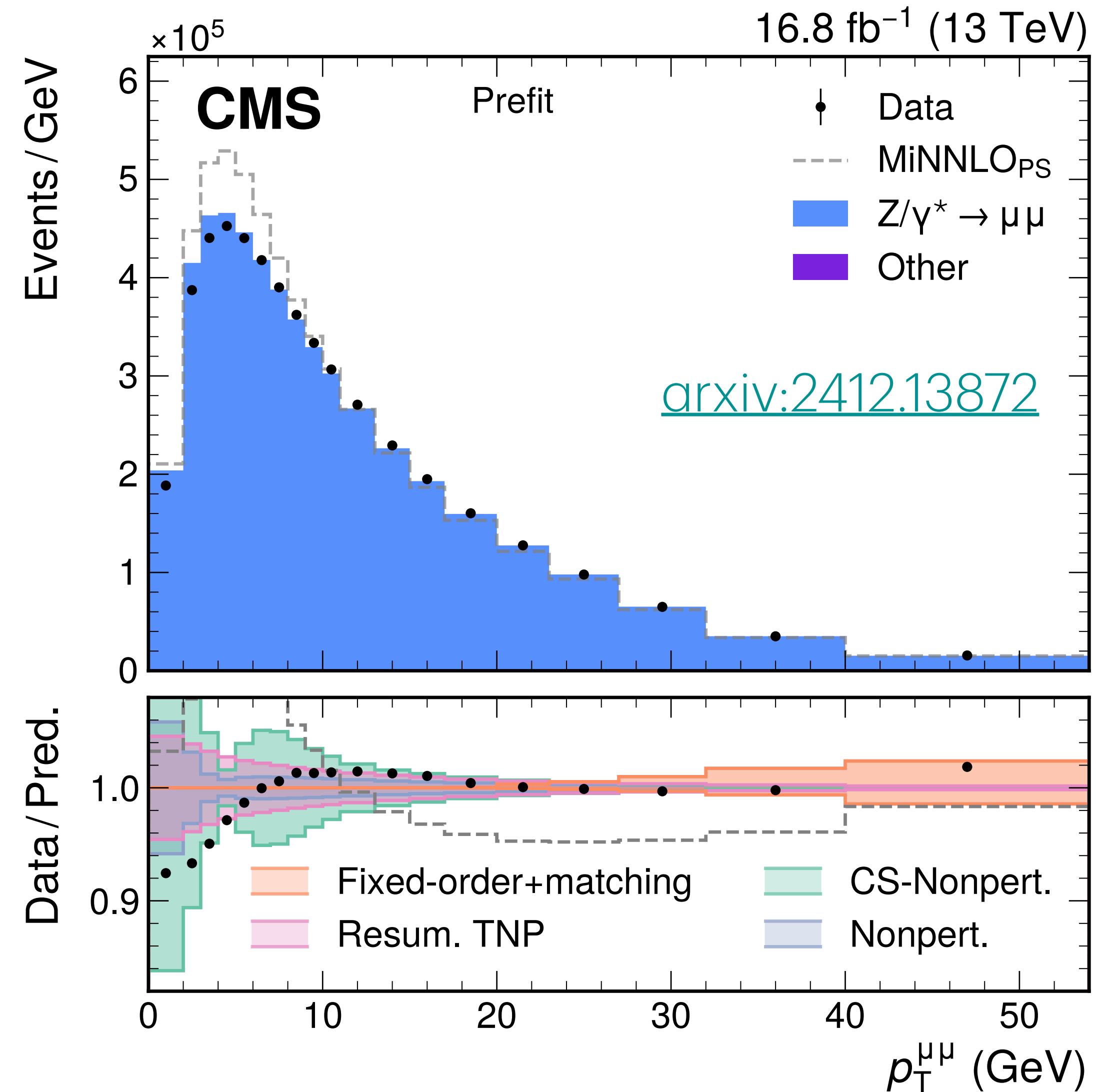
Thank you

Backup



Boson pT Modelling Uncertainties: Non-perturbative effects

- **Empirical model inspired by TMD PDFs** ~Gaussian smearing of parton momentum, with additional freedom to account for possible x and flavour dependence
- **The associated parameters cannot be predicted a priori**, but need to be determined from data (or lattice calculations)
- Initial values are somewhat arbitrary, with large uncertainties applied -> intended to be constrained from data



Boson pT Modeling Uncertainties: Non-perturbative effects

- **CS kernel** is related to matching of non-perturbative model to resummation and is “universal” (fully correlated between W and Z)
- The rest of the NP model is taken as decorrelated between W^+ , W^- and Z , and with an additional y -dependent term for the degree of smearing to account for possible x and flavour dependence

