α_S determinations at the LHC

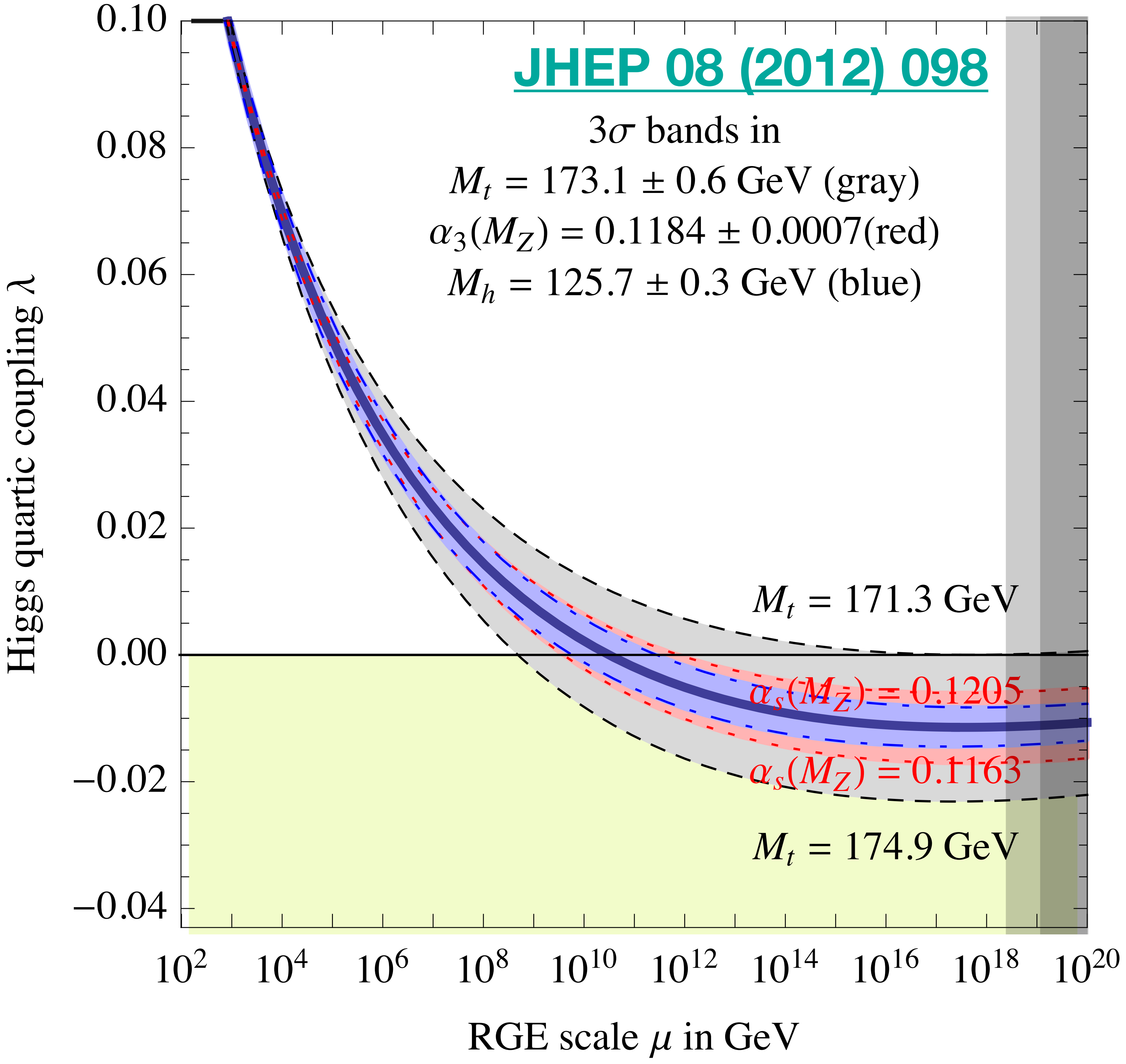
Valentina Guglielmi

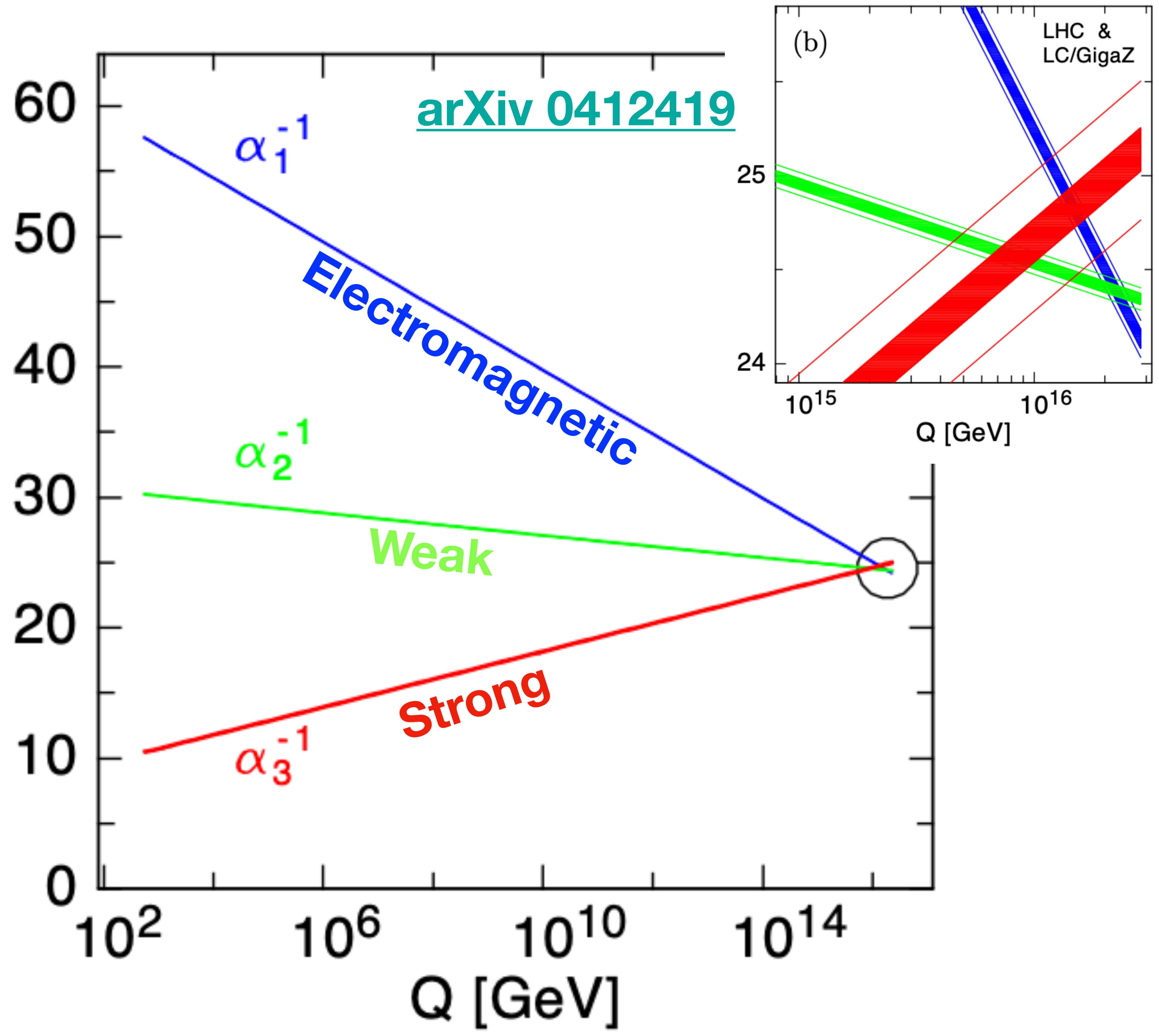
QCD@LHC2024, Freiburg, 7.10.2024

HELMHOLTZ

Motivation

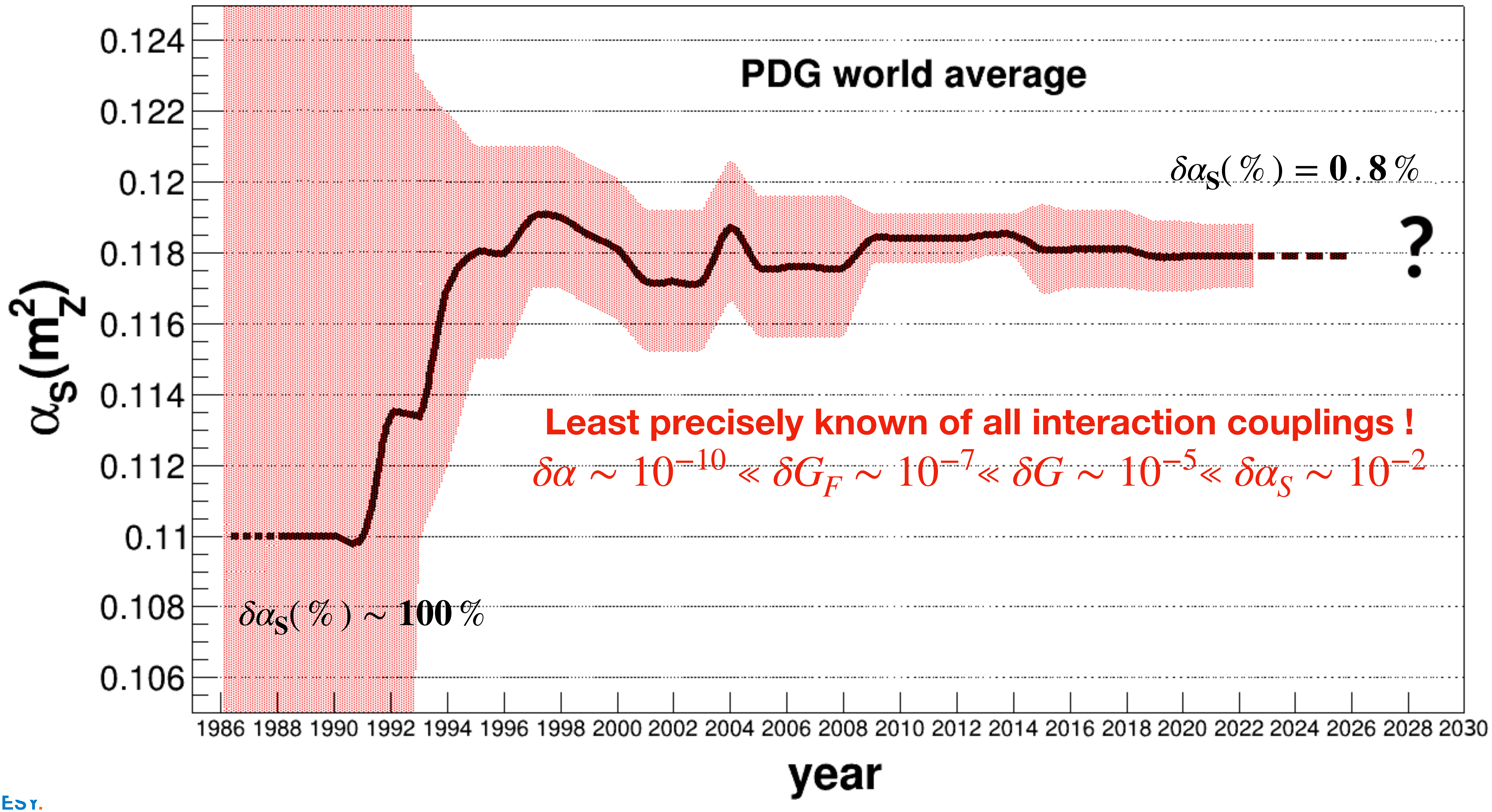
- Single free parameter of QCD in the $m_q \rightarrow 0$ limit
- Impact physics at the Planck scale: EW vacuum stability, GUT
- α_S is among the major uncertainties of many precision measurements: Higgs couplings at the LHC





The strong coupling constant $\alpha_S(m_Z)$ in the years

arXiv:2203.08271



$\delta\alpha_S(\%) = \mathbf{0.8}\,\%$

$\delta\alpha_S(\%) \sim \mathbf{100}\,\%$

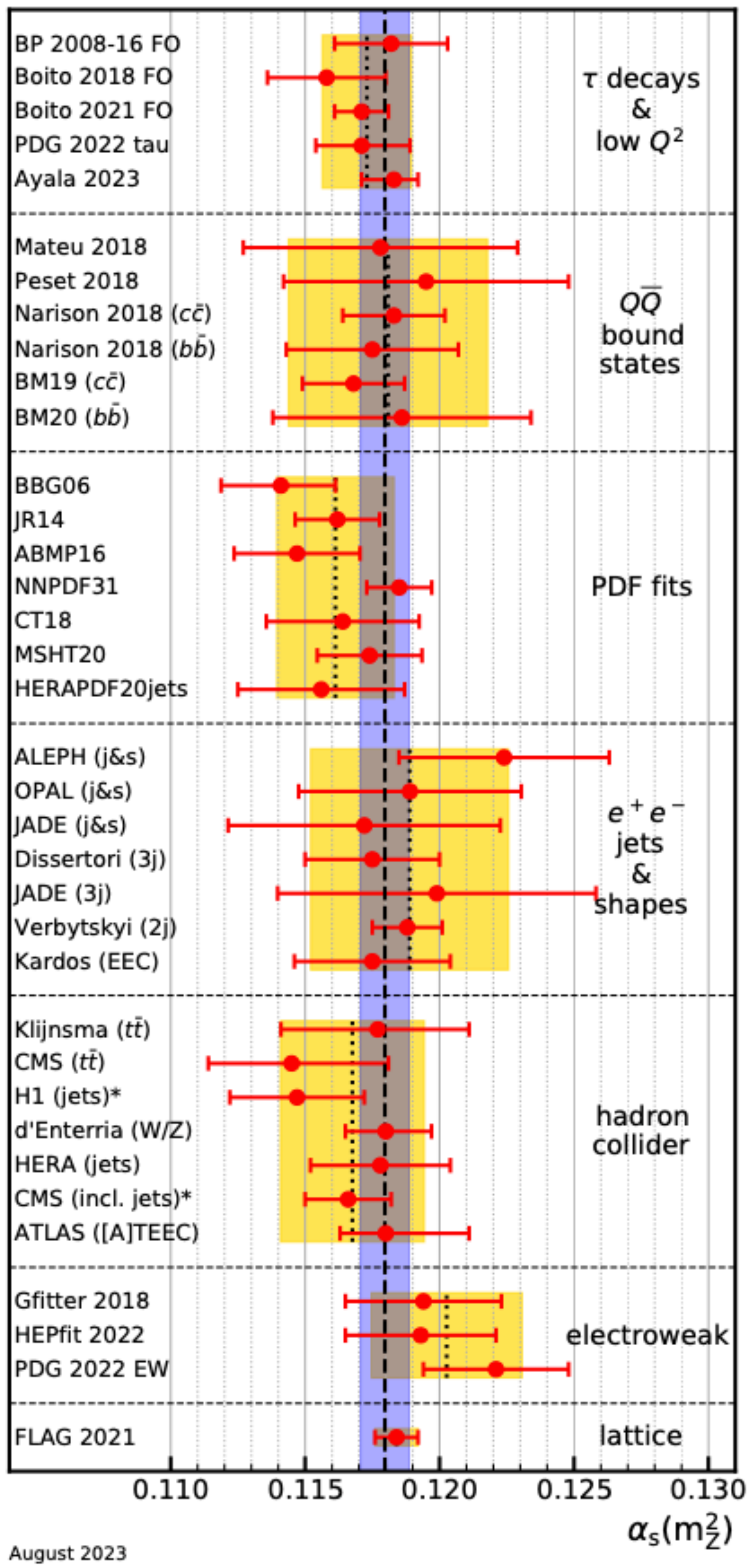
Least precisely known of all interaction couplings !

$\delta\alpha \sim 10^{-10} \ll \delta G_F \sim 10^{-7} \ll \delta G \sim 10^{-5} \ll \delta\alpha_S \sim 10^{-2}$

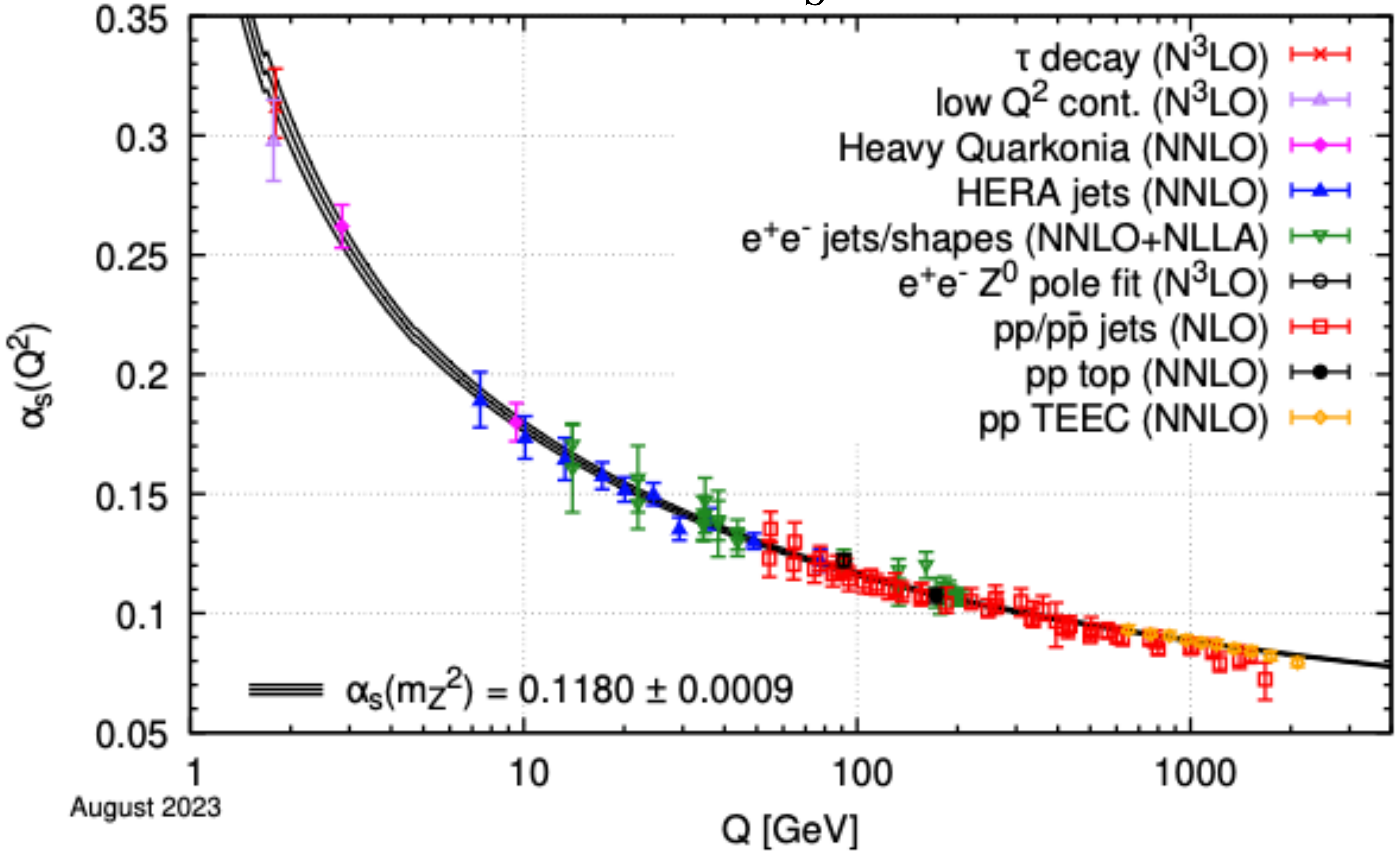
The state of the art

QCD PDG Review 2024

Summary of $\alpha_S(m_Z)$



Running of α_S with Q



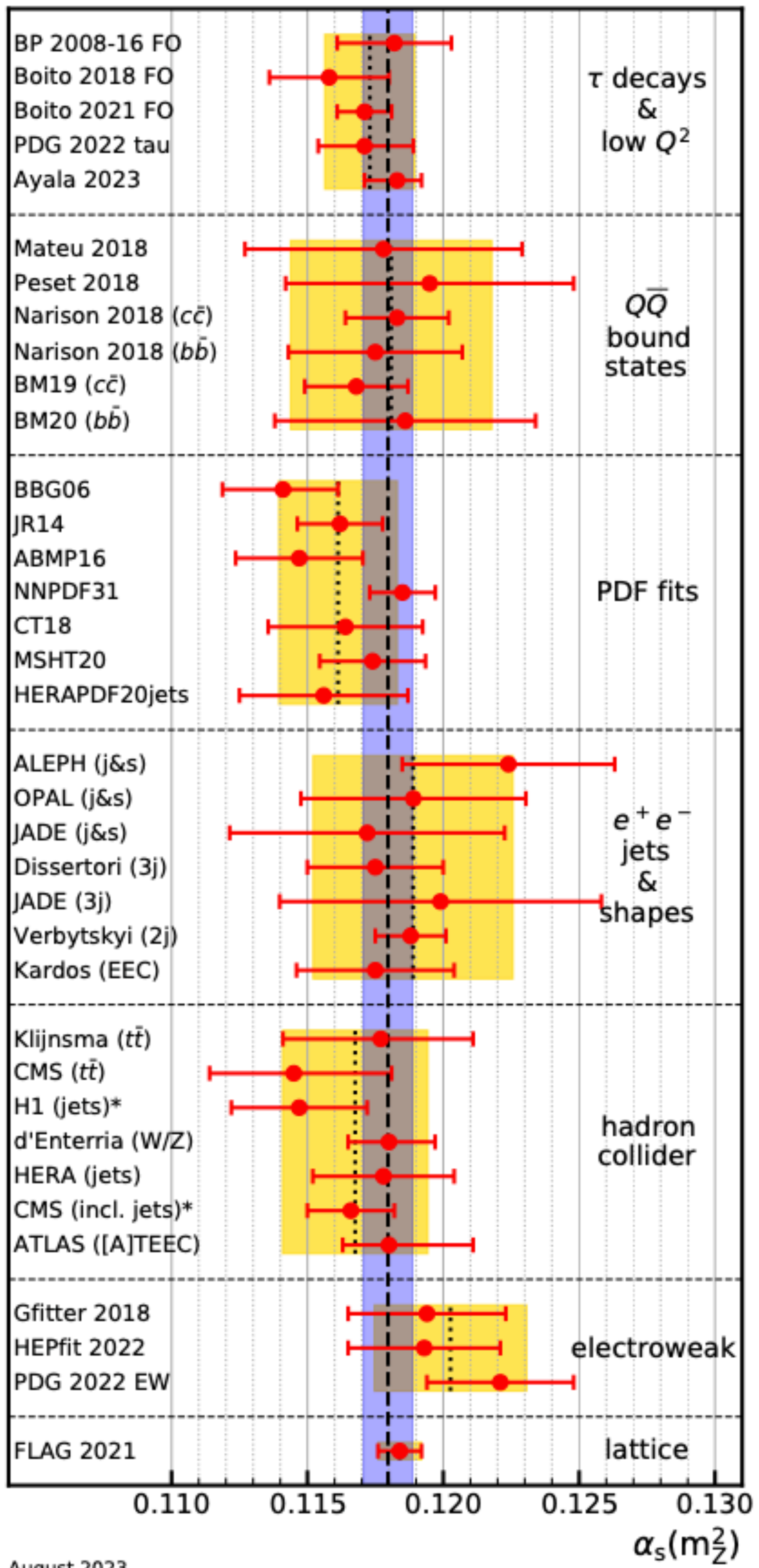
← **World average (PDG 2024):** $\alpha_S(m_Z) = 0.118 \pm 0.0009$

→ α_S **“runs” as** $\approx \ln(Q^2/L^2)$ **at LO,** $L \approx 0.2$ GeV

The state of the art of $\alpha_S(m_Z)$

Category	$\alpha_S(m_Z)$	Unc.	Rel. Unc.
Tau decays and low Q2	0.1173	0.0017	1.5%
$Q\bar{Q}$ bound states	0.1181	0.0037	3.1%
PDF fits	0.1161	0.0022	1.9%
e^+e^- jets and shapes	0.1189	0.0037	3.1%
Hadron colliders	0.1168	0.0027	2.3%
EW boson decays	0.1203	0.0028	2.3%
Lattice QCD	0.1184	0.0008	0.7%
PDG 24 World Average	0,118	0.0009	0.8%

- **7 PDG categories**
- Currently, most precise determinations from lattice QCD and tau decays



August 2023

Where LHC has made/can make an impact?

Category	$\alpha_S(m_Z)$	Unc.	Rel. Unc.
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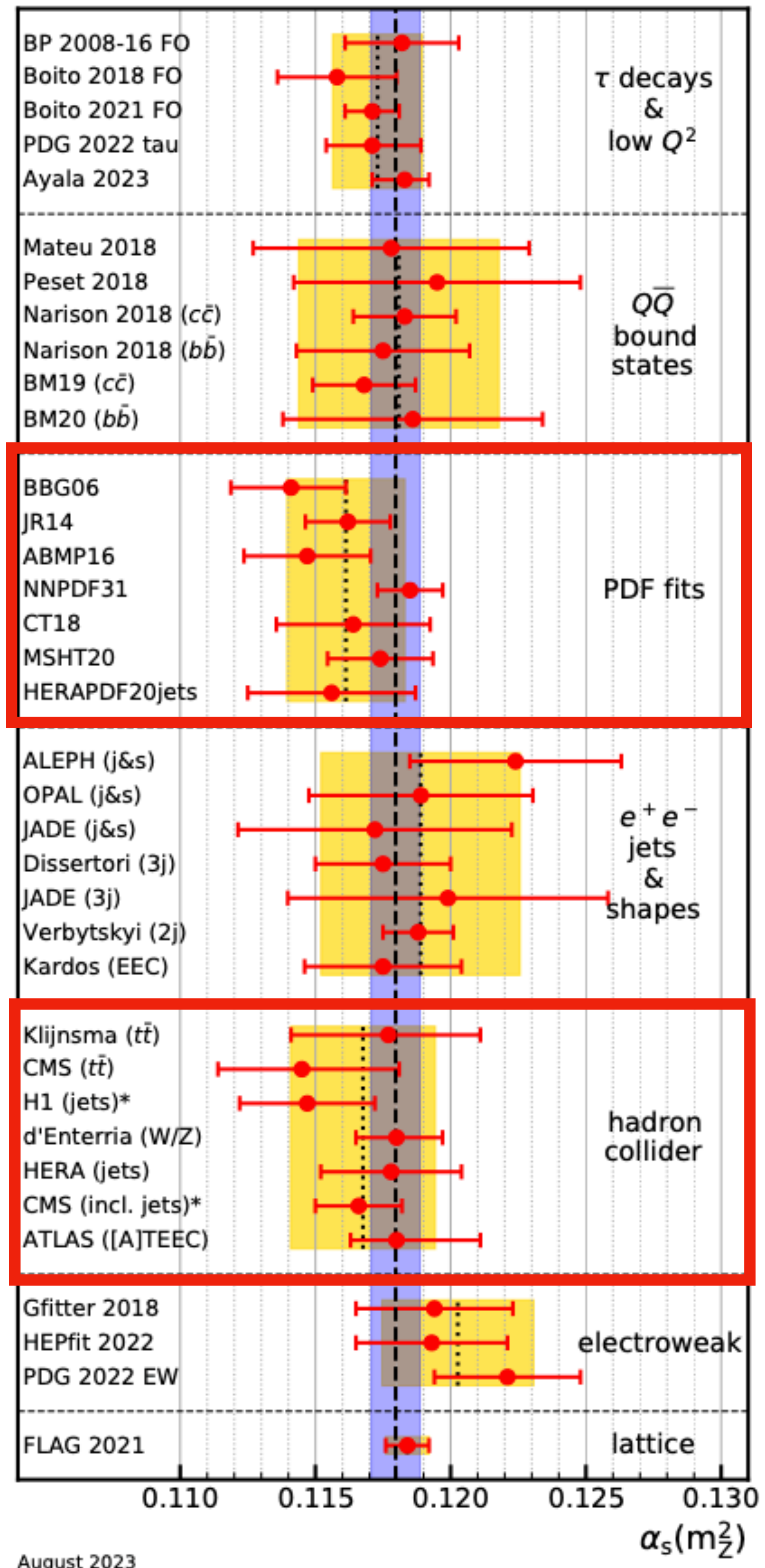


August 2023

How to extract α_S at LHC?

$$\boxed{\sigma_{pp\to X}} = \sum_{ij} \boxed{f_i(x_1,\mu_F^2)\times f_j(x_2,\mu_F^2)} \otimes \boxed{\hat{\sigma}_{ij}(x_1,x_2,\alpha_S(\mu_R),\frac{Q^2}{\mu_R},\frac{Q^2}{\mu_F})} + O(\frac{\Lambda^2_{QCD}}{Q^2})$$

Data $\sigma(exp)$

PDFs $f_i(\mu, x)$

DGLAP eq.

Exp. measurements

Partonic XS (pQCD)

need to be corrected by non perturbative effects

Two methods to compare $\sigma(\mathrm{exp})$ to $\sigma(\mathrm{pQCD})$:

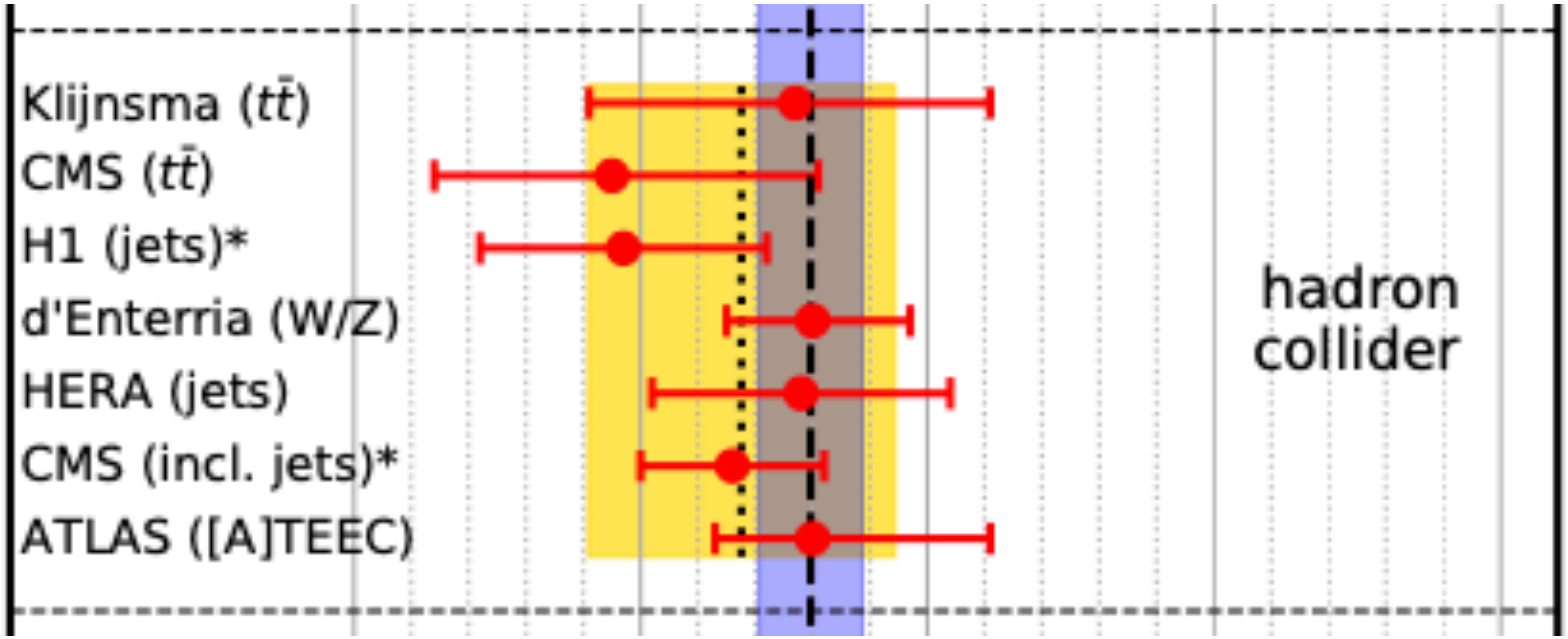
- **Profiling α_S using varying PDF+α_S** (predefined PDF from global PDF)
- **Simultaneous fit of α_S and PDFs**
  - Correlation between PDFs and α_S took into account
  - Reduced bias
  - BUT time consuming

Determinations of $\alpha_S(m_Z)$ at the LHC

Desirable features:

- Experimental precision
- High accuracy of theory prediction → NNLO, N3LO
- Small non perturbative QCD effects

Canonical observables used for $\alpha_S(m_Z)$@NNLO:



New observable: Z p_T

→ **Inclusive $t\bar{t}$ cross-sections**

→ **Inclusive W/Z cross-sections**

→ **Jet cross-sections**

Outlook

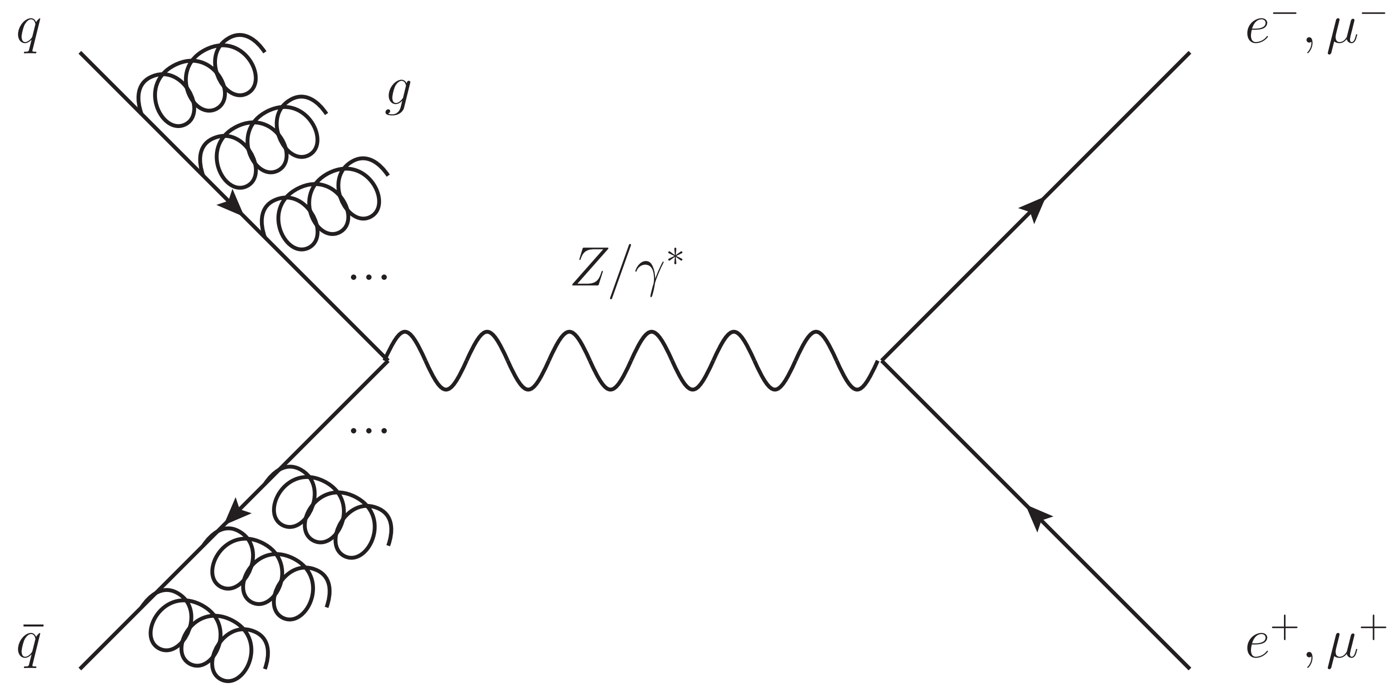
Today I will focus on most recent measurements (not yet in PDG), special focus at $\geq$ NNLO

- ATLAS Z pT @8TeV: arXiv2309.12986, *submitted to Nat. Phys.*
- ATLAS (A)TEEC @13TeV: JHEP 07 (2023) 085
- ATLAS cross-section ratios @13TeV: arXiv2405.20206, *submitted to PRD*
- @NLO: CMS azimuthal correlation $R_{\Delta\phi}$ @13TeV: EPJC 84 842 (2024)
- @NNLL$_{\mathrm{approx}}$: CMS energy correlators @13TeV: PRL 133 071903 (2024)
- CMS dijets @13TeV: arXiv312.16669, *submitted to the EPJC*
- CMS Inclusive jets @13 TeV: JHEP 02 (2022) 142 + Addendum (Nov. 2022)
- **CMS Inclusive jets @2.76, 7, 8, 13 TeV** NEW! CMS-PAS-SMP-24-007

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

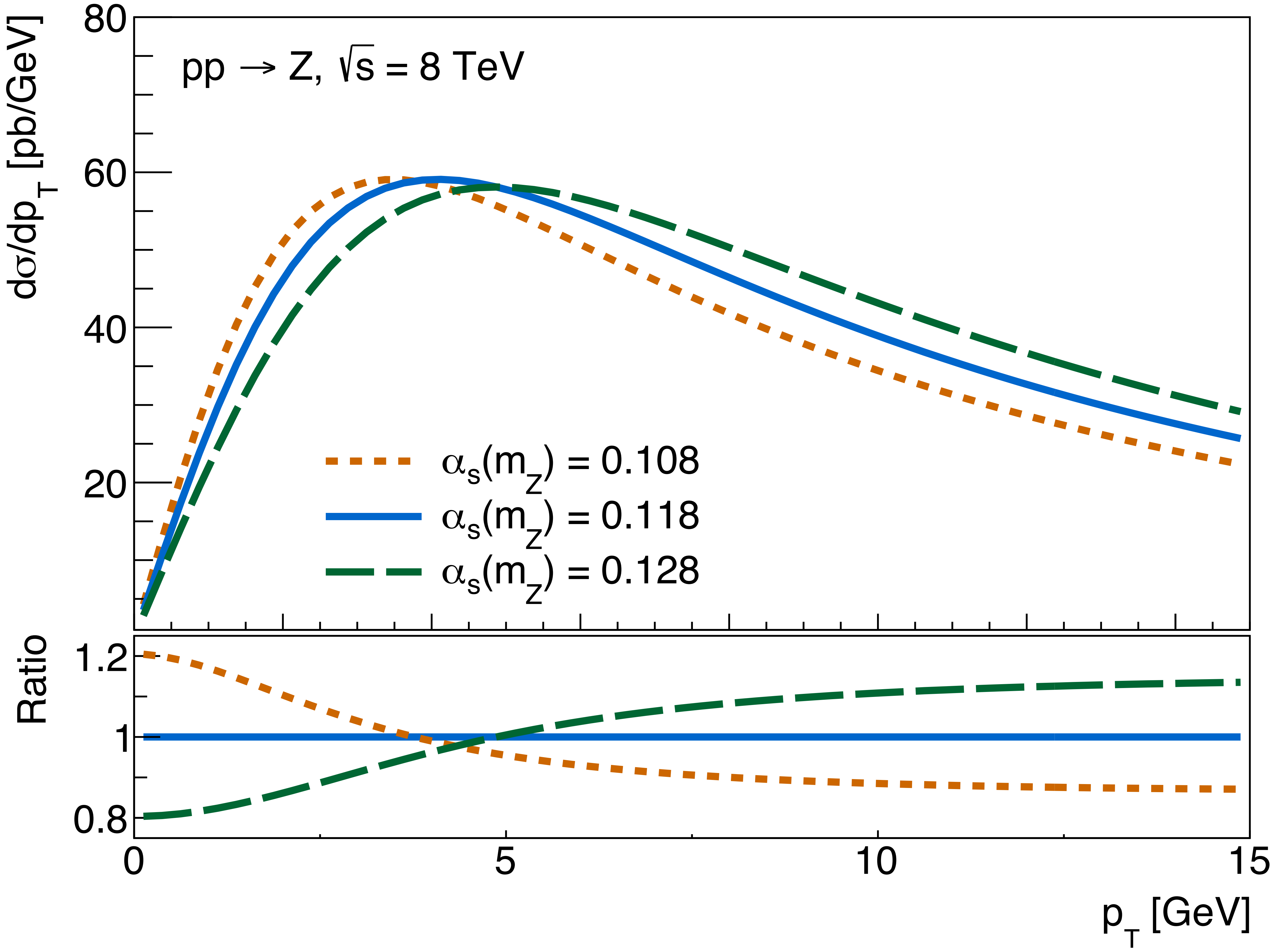
More details in parallel talk of O. Kuprash, this afternoon

- 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

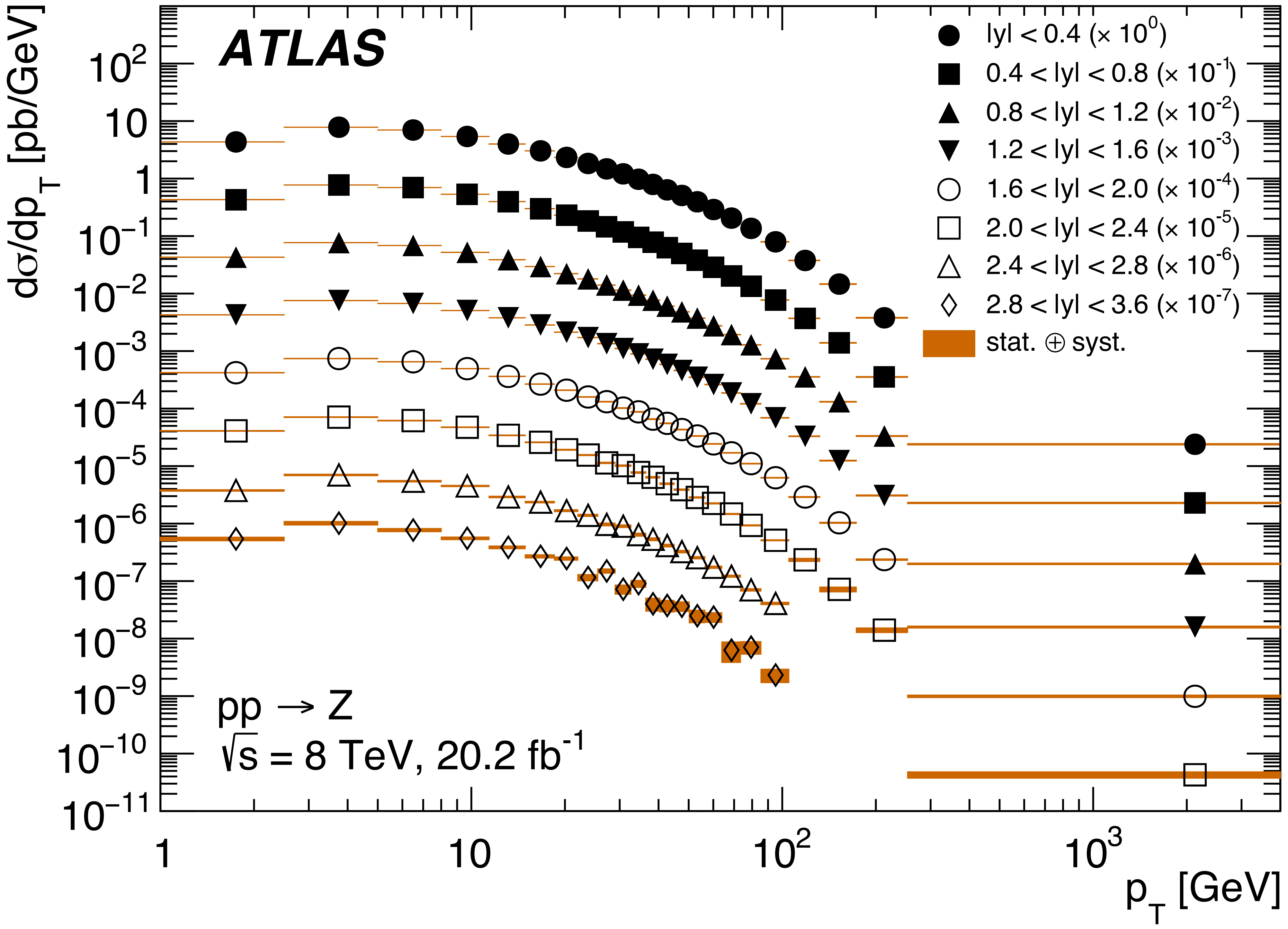
Predicted dependence of Z p_T on $\alpha_S(m_Z)$

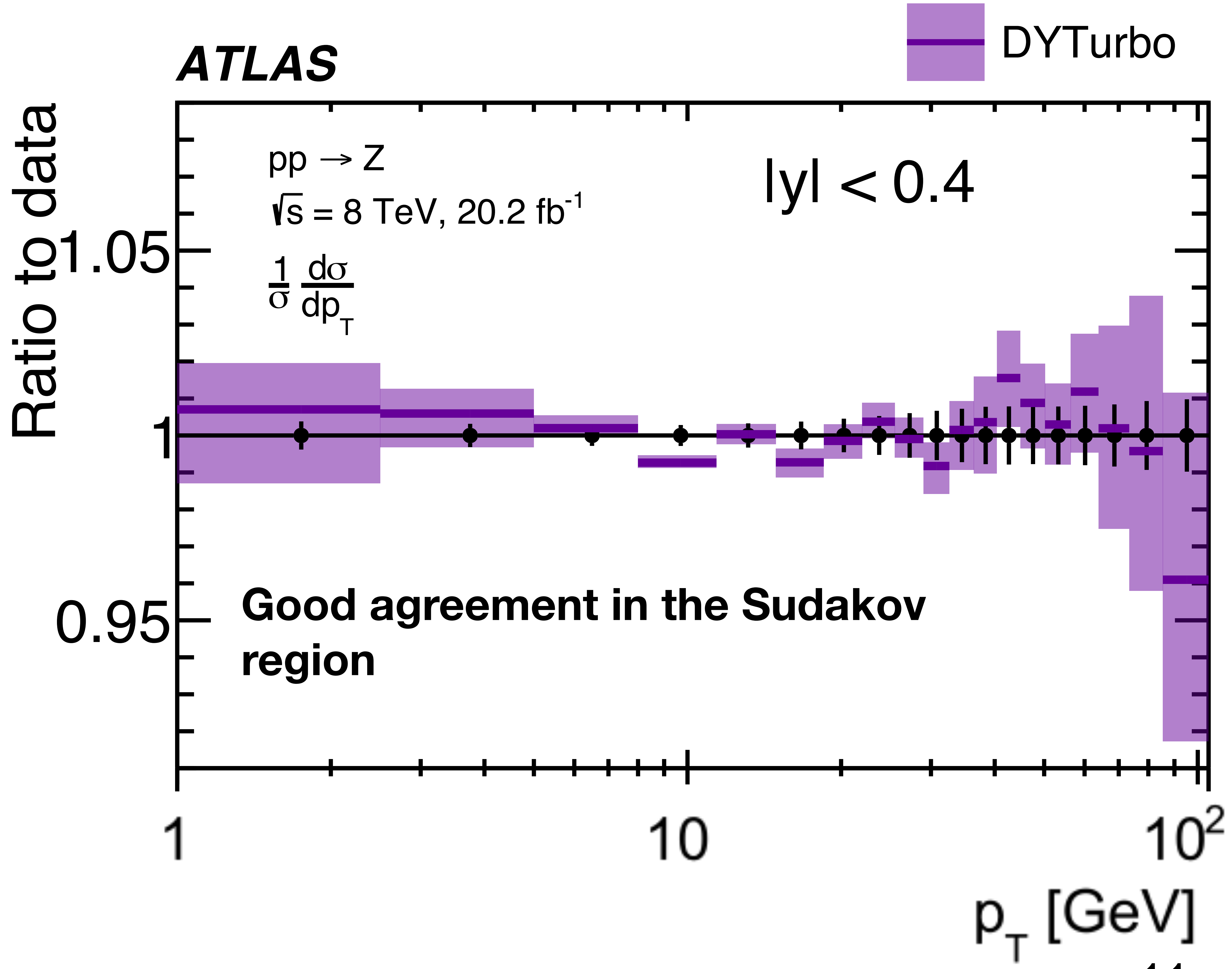


ATLAS cross-section measurement at 8 TeV EPJC 84 (2024) 315

Cross-sections in $p_T - \mathrm{y}$ in **full lepton phase space:**

- Clean experimental signature
- High experimental sensitivity
- Fast analytic predictions (at $\mathrm{N^4LLa + N^3LO}$)



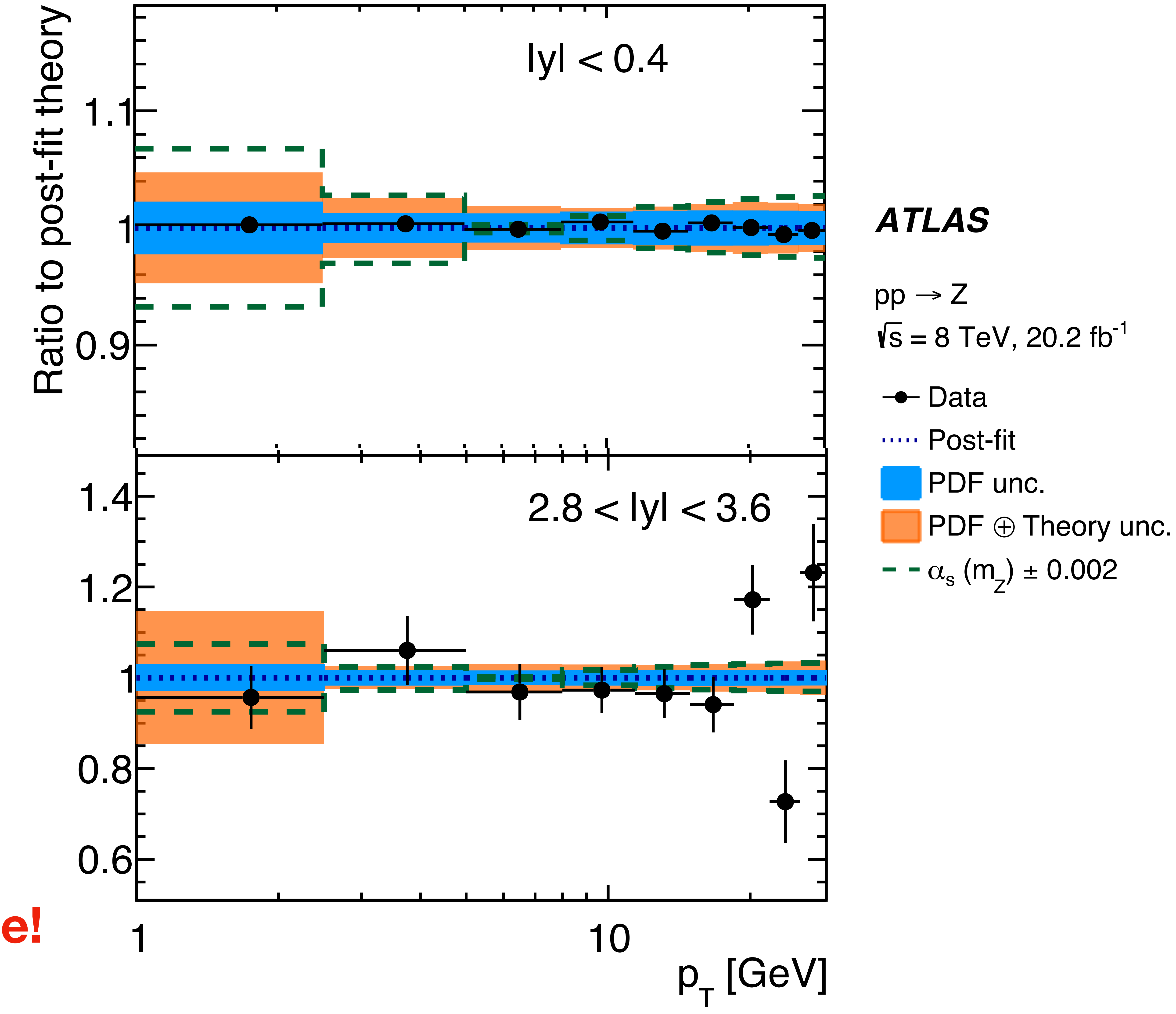


Good agreement in the Sudakov region

Extraction of $\alpha_S(m_Z)$ from ATLAS Z p_T at 8 TeV

MSHT20aN3LO PDF set used to extract $\alpha_S(m_Z)$

Summary of the uncertainties in units of 10^{-3}		
Experimental uncertainty	± 0.44	
PDF uncertainty	± 0.51	
Scale variation uncertainties	± 0.42	
Matching to fixed order	0	-0.08
Non-perturbative model	$+0.12$	-0.20
Flavour model	$+0.40$	-0.29
QED ISR	± 0.14	
N^4LL approximation	± 0.04	
Total	$+0.91$	-0.88



Final result: $\alpha_S(m_Z) = 0.1183 \pm 0.0009$

Most precise experimental measurement to date!

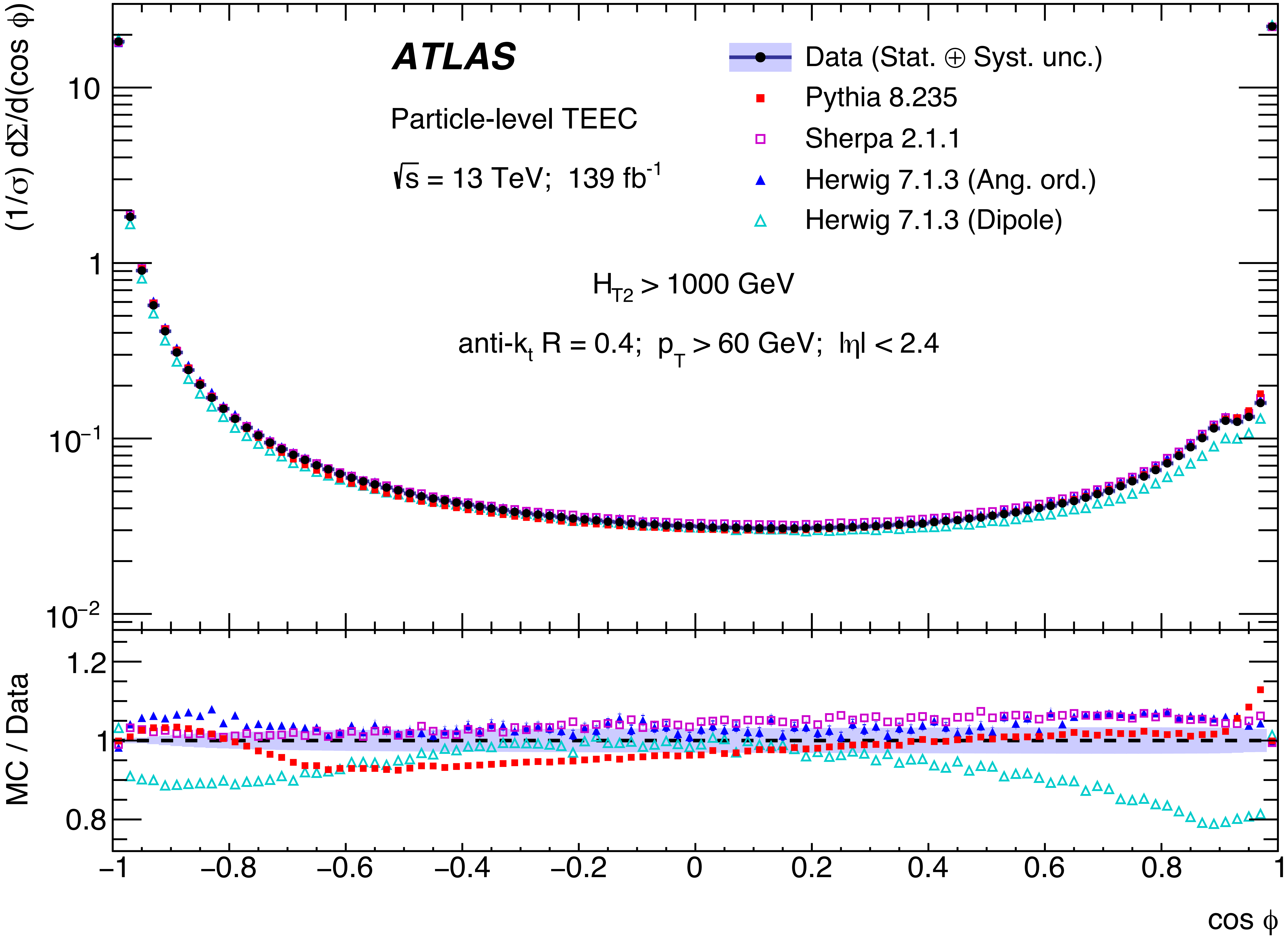
ATLAS TEEC measurement at 13 TeV

More details in parallel talk of A. Ziaka, this afternoon

- **Transverse energy-energy correlations (TEEC):** tranverse-energy-weigthed distribution of ϕ differences between final-state jet pairs
- **Sensitive to gluon radiation and to $\alpha_S(m_Z)$**

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

Measured as a function of $cos\phi$ in 10 bins of H_{T2} ($\mathrm{H_{T2} = p_T^{jet1} + p_T^{jet2}}$)



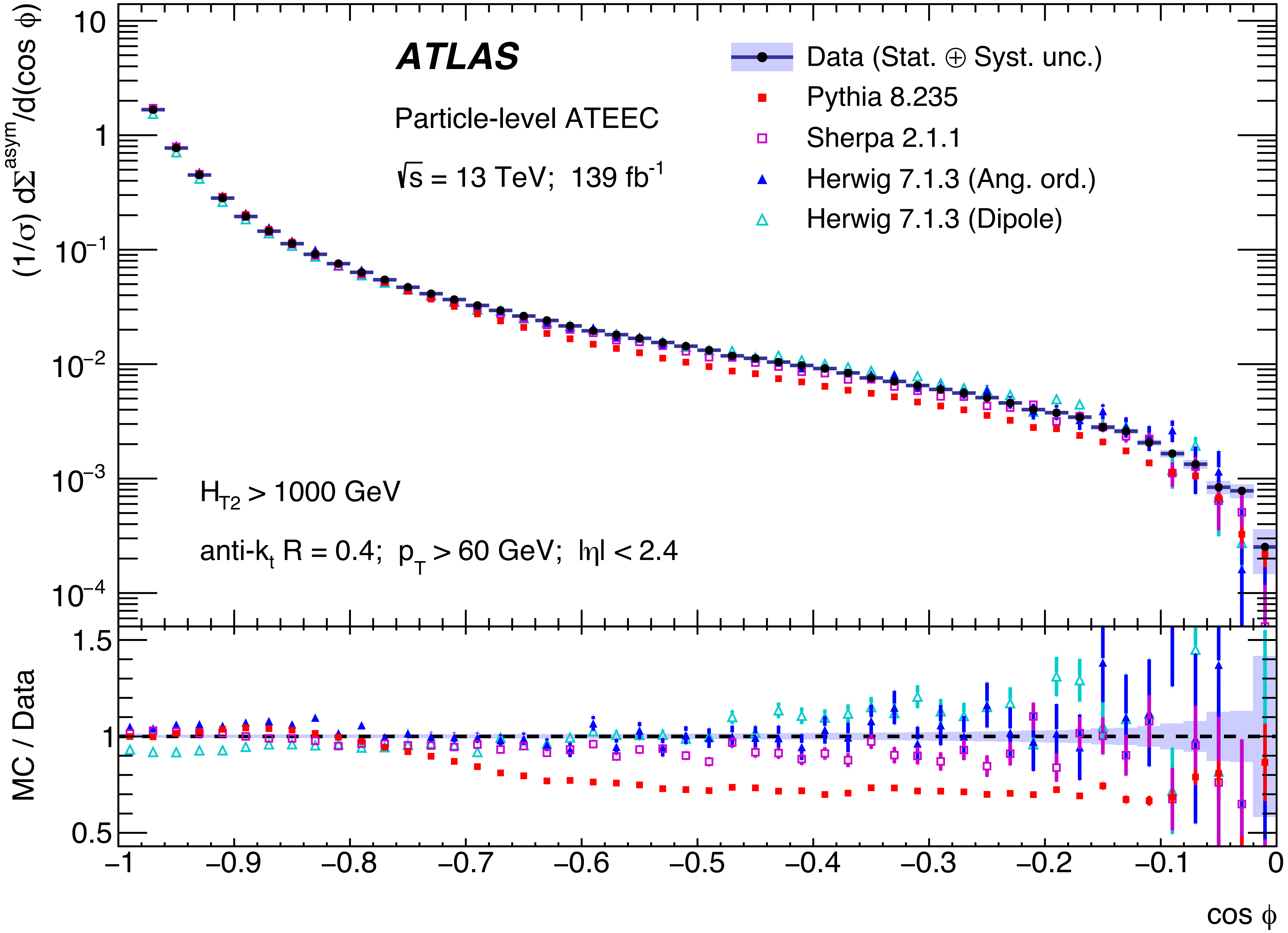
ATLAS ATEEC measurement at 13 TeV

More details in parallel talk of A. Ziaka, this afternoon

- **Its asymmetry (ATEEC):** forward-backward difference of TEEC → uncertainties symmetric in cosϕ cancelled out
- **Sensitive to gluon radiation and to $\alpha_S(m_Z)$**

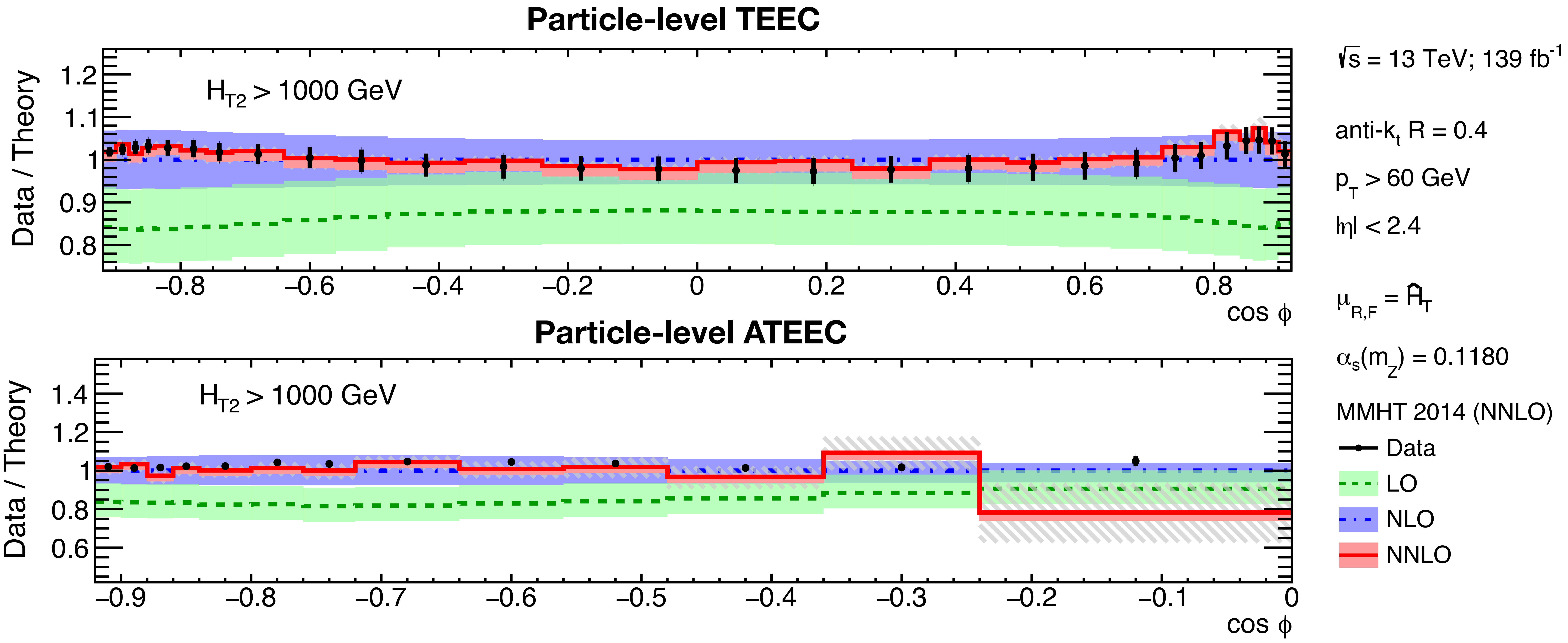
$$\frac{1}{\sigma}\frac{d\Sigma^{asym}}{d\cos\phi} = \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d\cos\phi}\bigg|_{\pi-\phi}$$

Measured as a function of $cos\phi$ in 10 bins of H_{T2} ($\mathrm{H_{T2}} = \mathrm{p_T^{jet1}} + \mathrm{p_T^{jet2}}$)



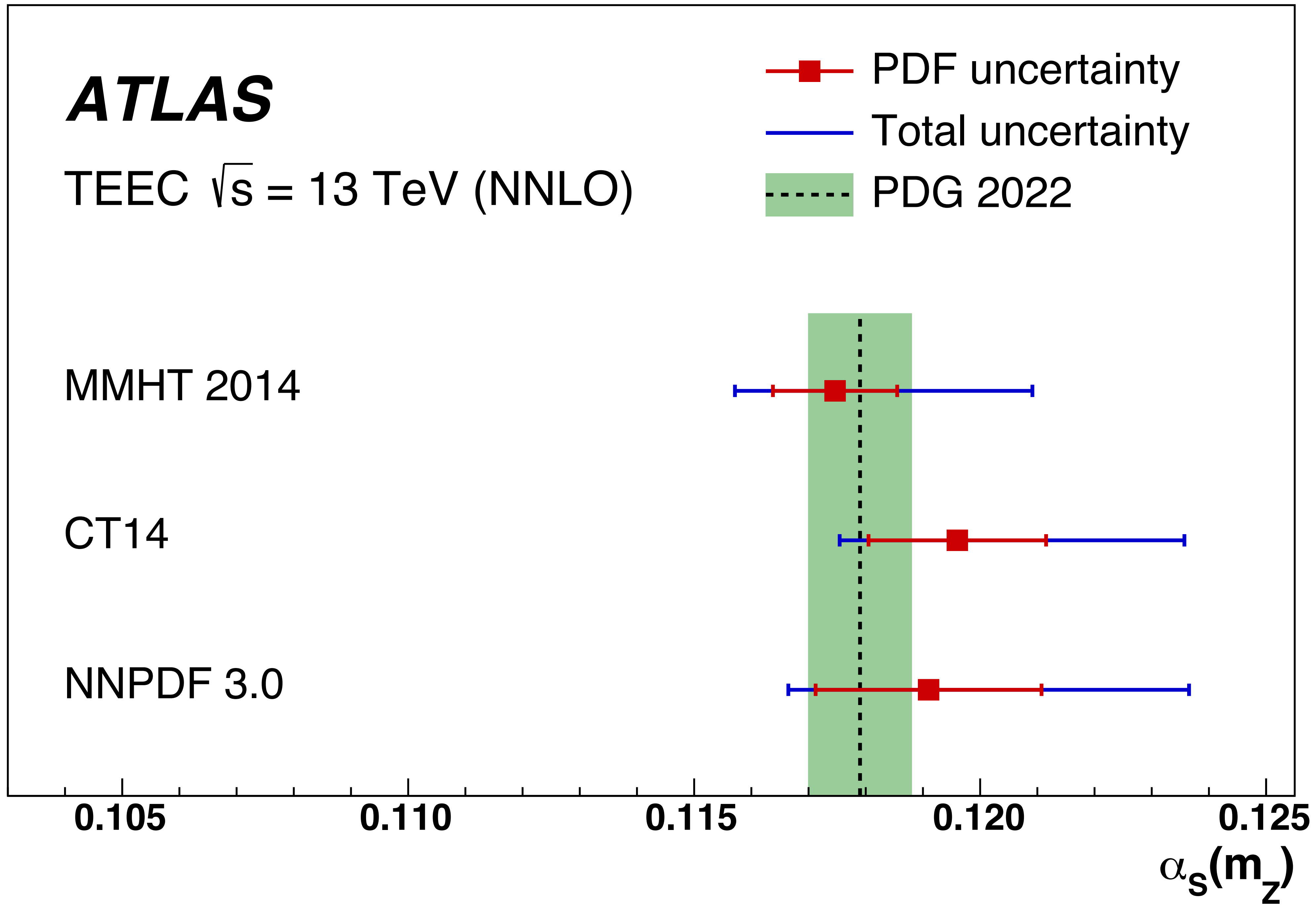
Fixed order pQCD for (A)TEEC

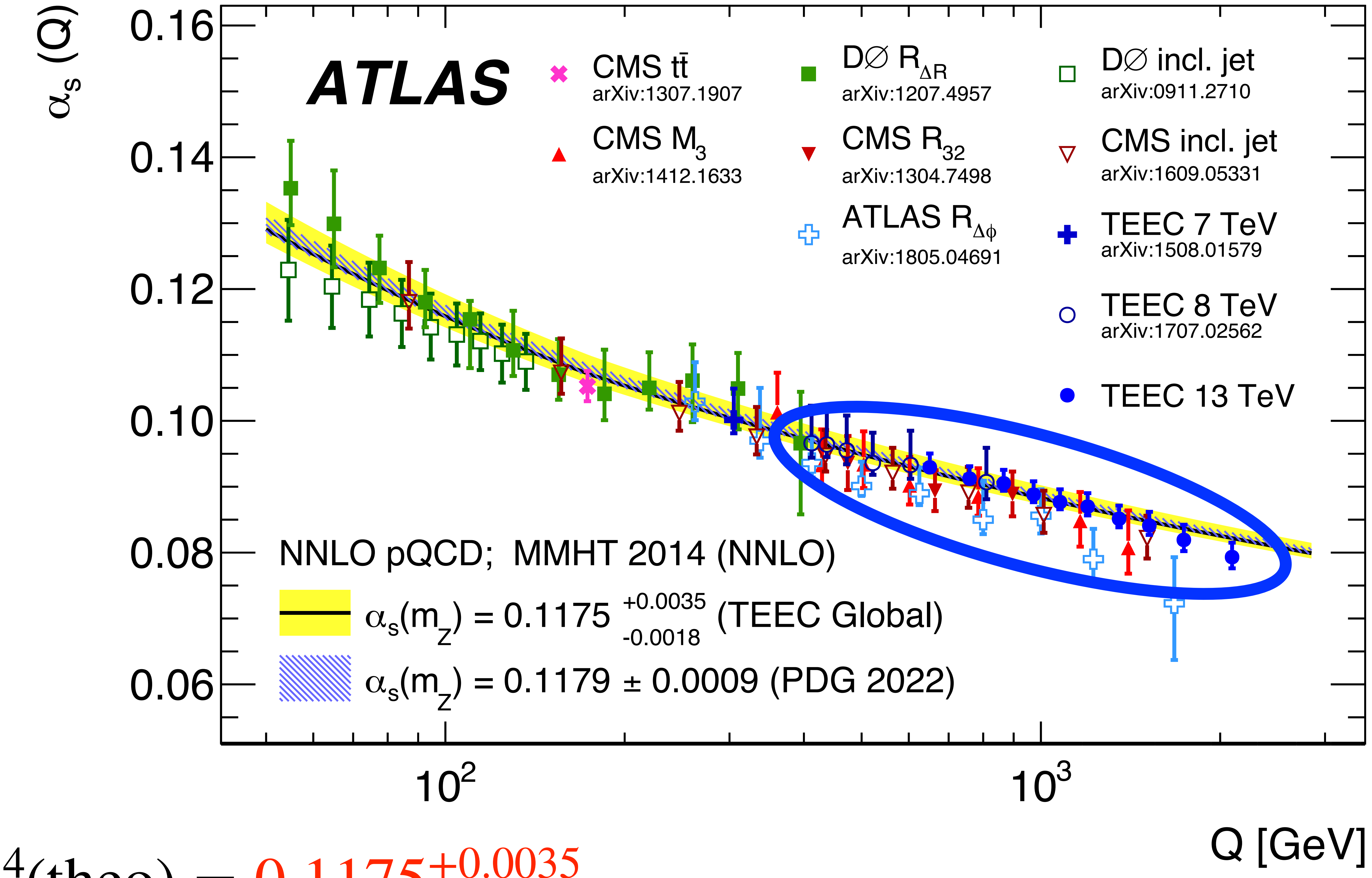
- Extraction of $\alpha_S(m_Z)$ at NNLO using prediction of 3-jet production
- Improved agreement with data and scale uncertainty reduced by factor of 3 w.r.t. NLO



Extraction of $\alpha_S(m_Z)$ from (A)TEEC

- Determined value of $\alpha_S(m_Z)$ in agreement with PDG world average
- Agreement with the RGE predictions up to ~2TeV





$$\textbf{TEEC:}\quad \alpha_S(m_Z) = 0.1175 \pm 0.0006(\text{exp})^{+0.0034}_{-0.0017}(\text{theo}) = 0.1175^{+0.0035}_{-0.0018}$$

$$\textbf{ATEEC:}\ \alpha_S(m_Z) = 0.1185 \pm 0.0009(\text{exp})^{+0.0025}_{-0.0012}(\text{theo}) = 0.1185^{+0.0027}_{-0.0015}$$

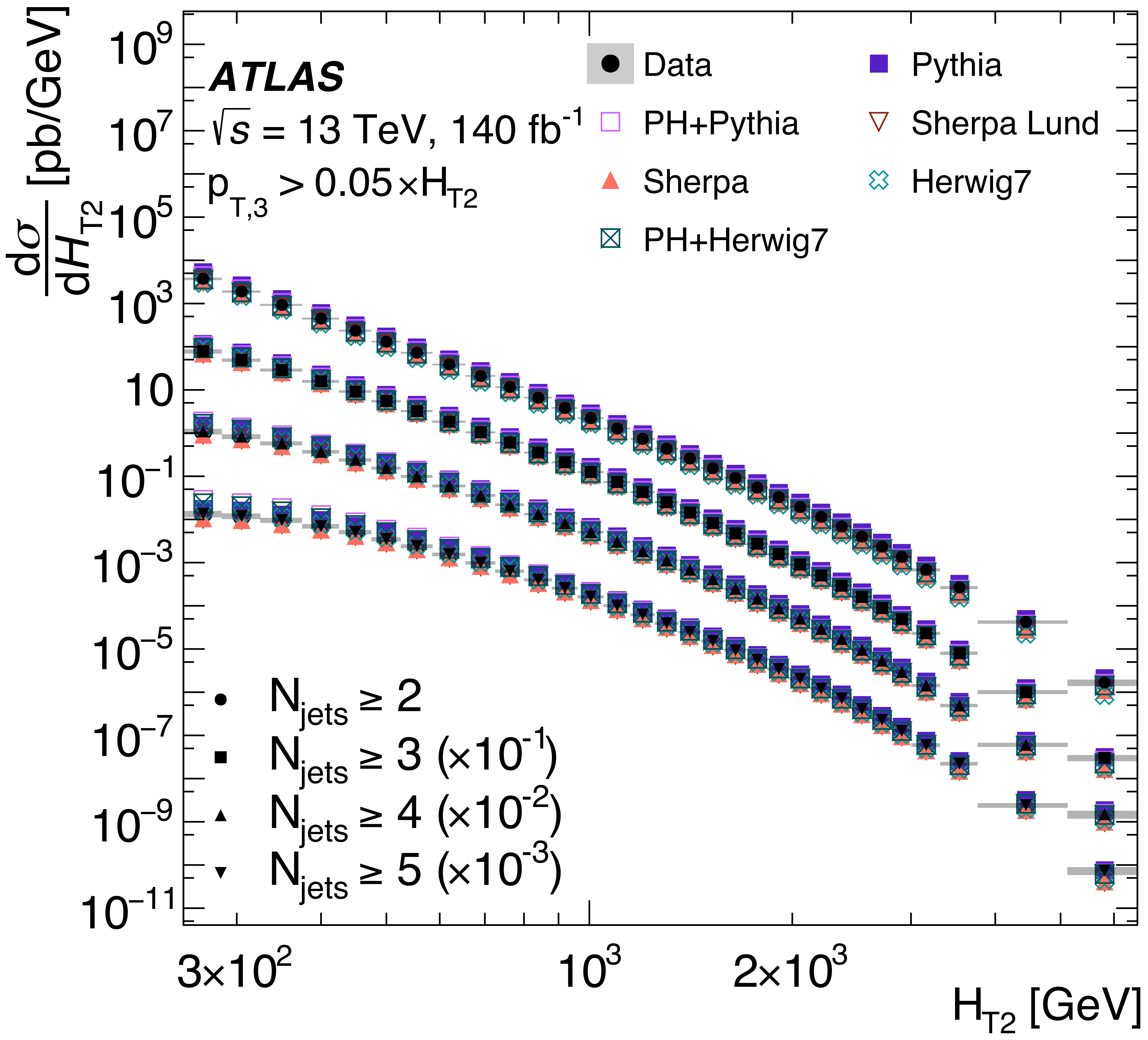
Dominant contribution is still the scale uncertainty

ATLAS cross-section ratios

More details in parallel talk of A. Ziaka, this afternoon

- **Measurement:**
  - Differential cross sections of multijet events
  - Ratios of inclusive jet-multiplicity bins (R_{32}, R_{42}, R_{43})
  - e.g. R_{32} = 3–jet/2–jet

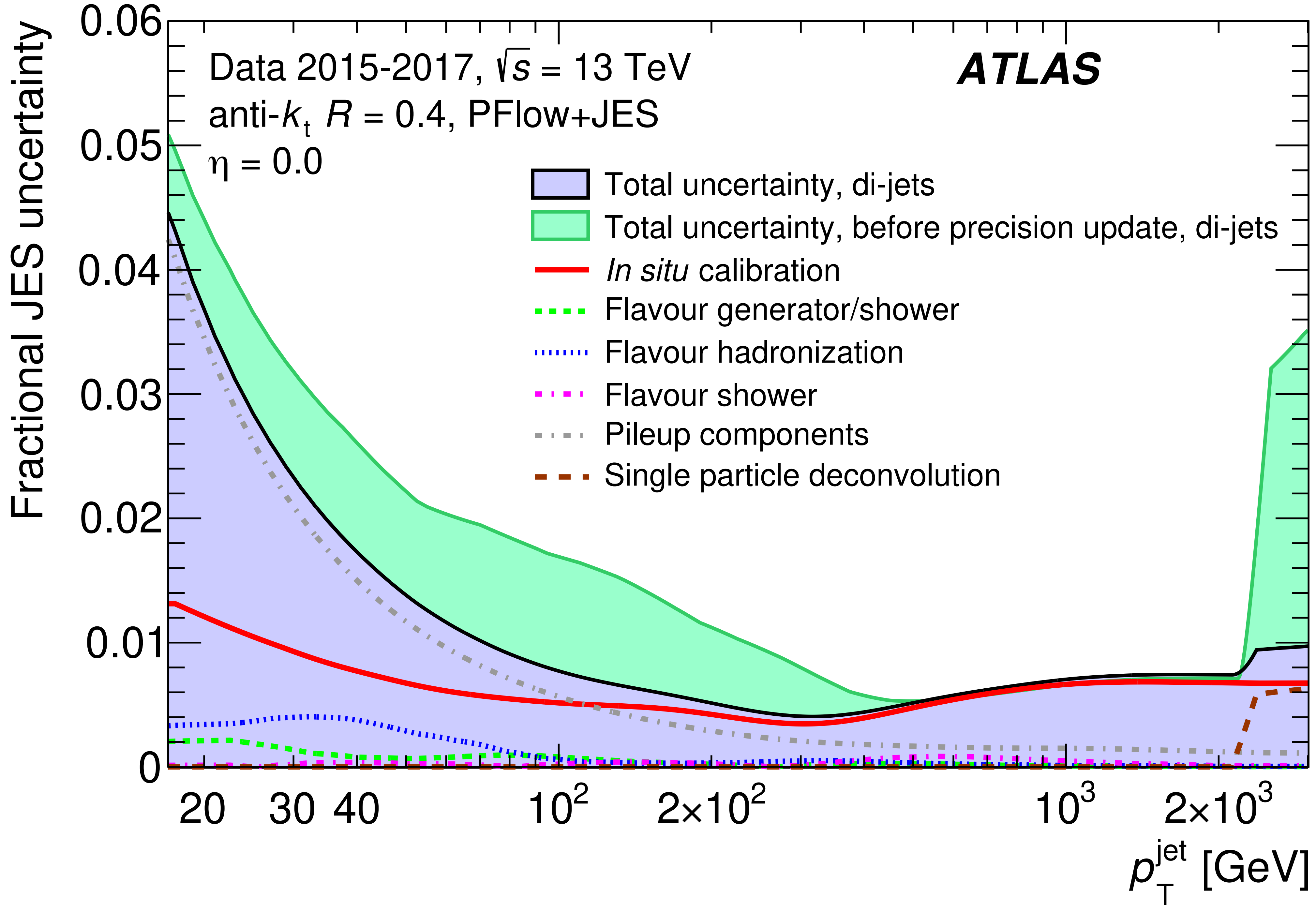
- **Variable sensitive to** $\alpha_S(m_Z)$
  - $H_{T2} = p_T^{jet1} + p_T^{jet2}$ (p_T^{jet3} sensitive to resummation effects)
  - p_T^{Nincl} : inclusive jet p_T in bins of multiplicity



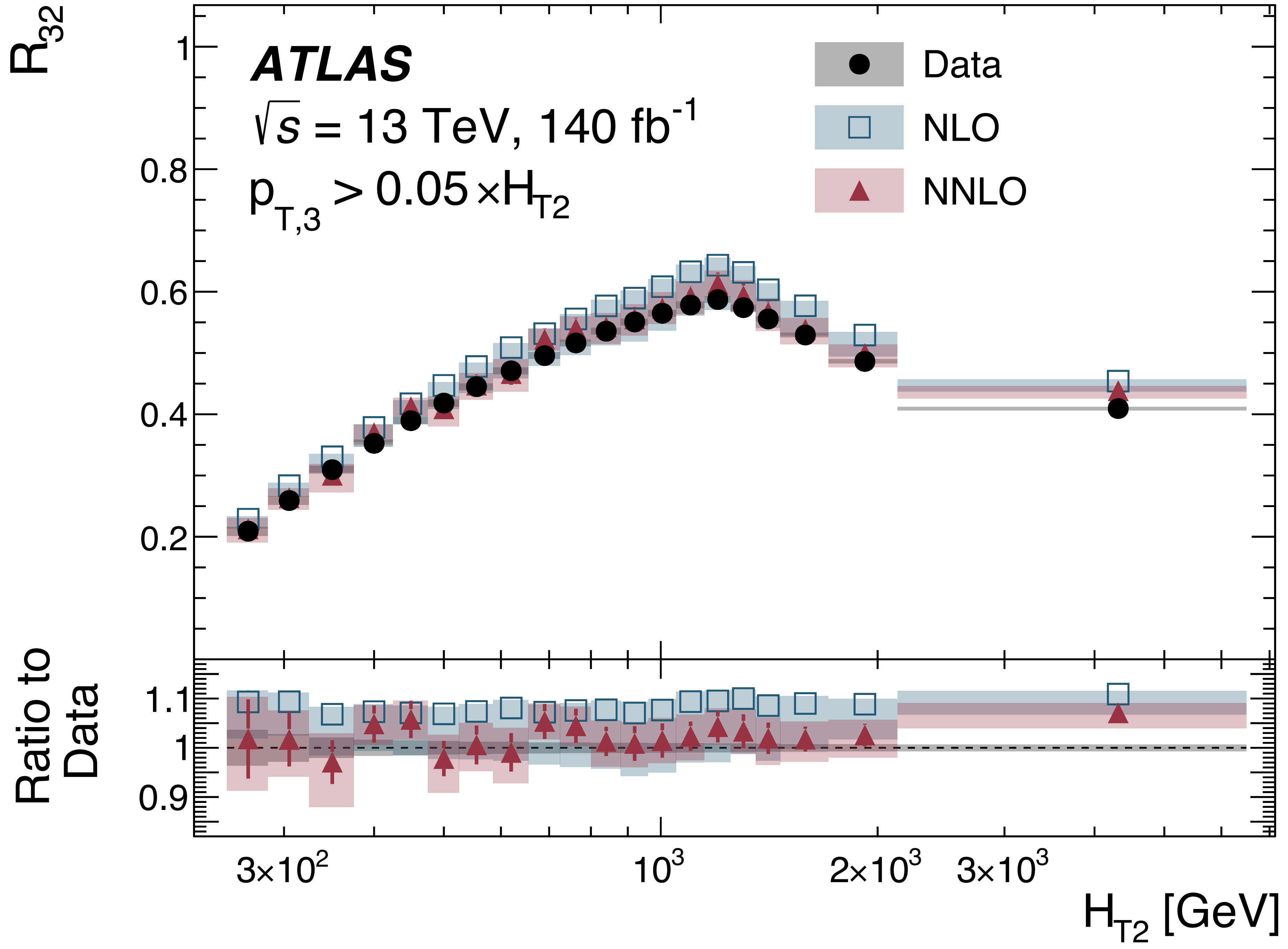
ATLAS cross-section ratios More details in parallel talk of A. Ziaka, this afternoon

- **Jet energy scale calibration** dominant uncertainty
  → Significantly improved (especially at higher p_T)
- **Theoretical predictions available at NNLO**
  → Good agreement data and theory

→ All ingredients to extract $\alpha_S(m_Z)$



R_{32} = 3–jet/2–jet

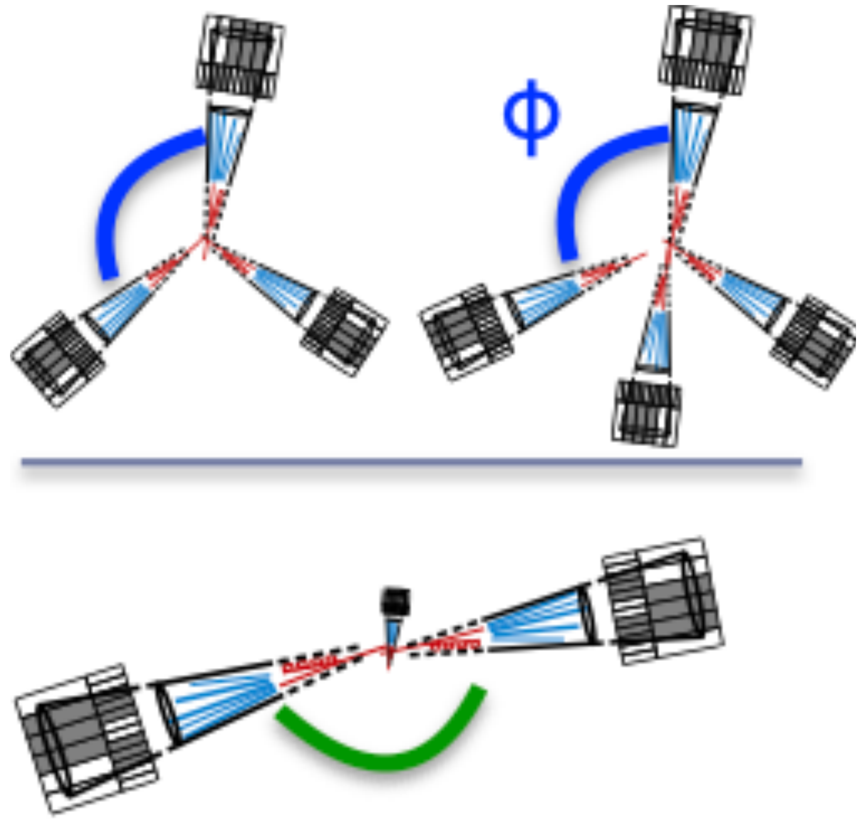


CMS $\alpha_S(m_Z)$ at NLO: azimuthal correlations at 13 TeV

More details in parallel talk of A. Ziaka, this afternoon

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

$R_{\Delta\phi}(p_T) =$



$\propto \frac{\alpha_S^3}{\alpha_S^2}$

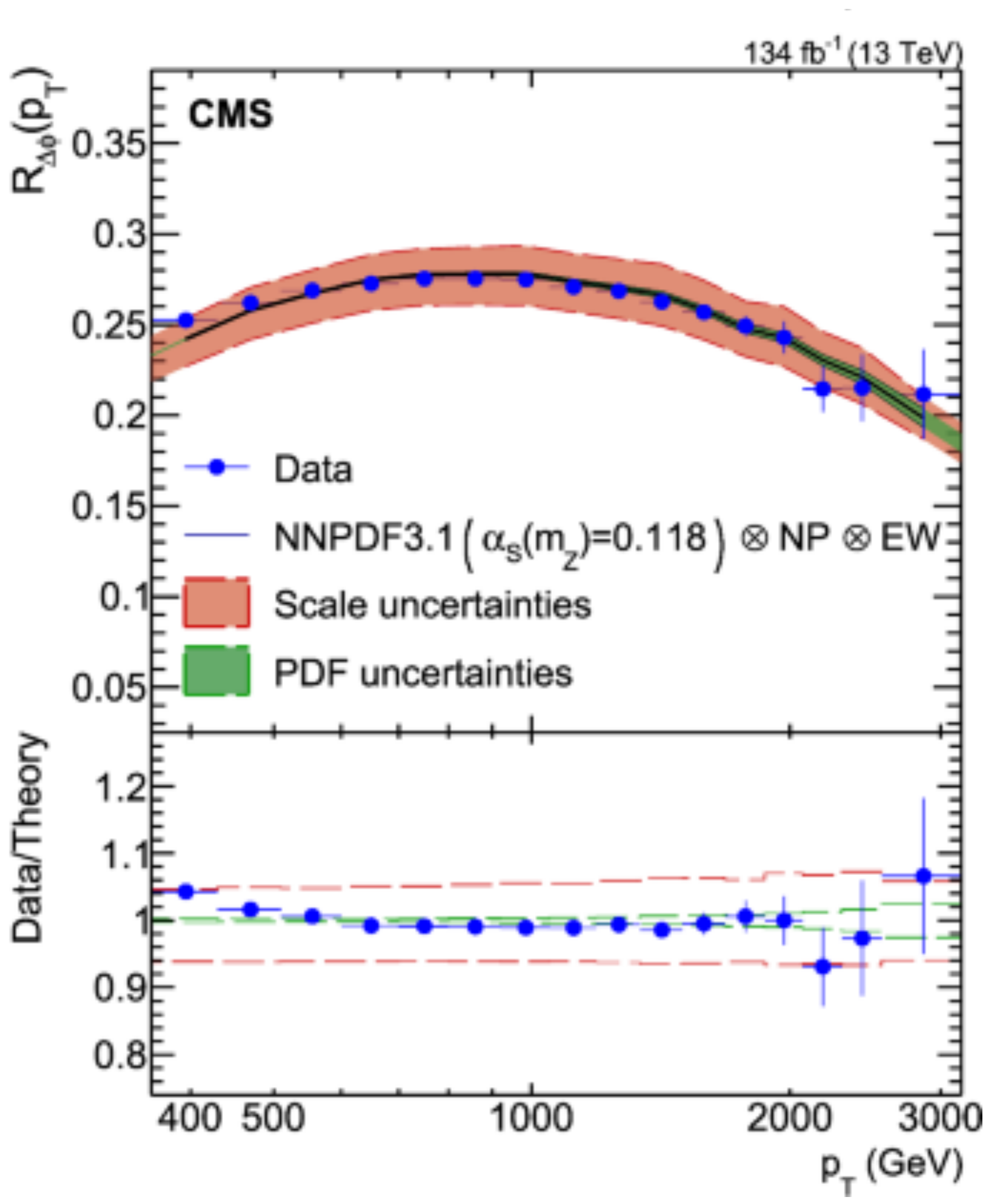
Inclusive jets ($\sim \alpha_s^2$) (LO)

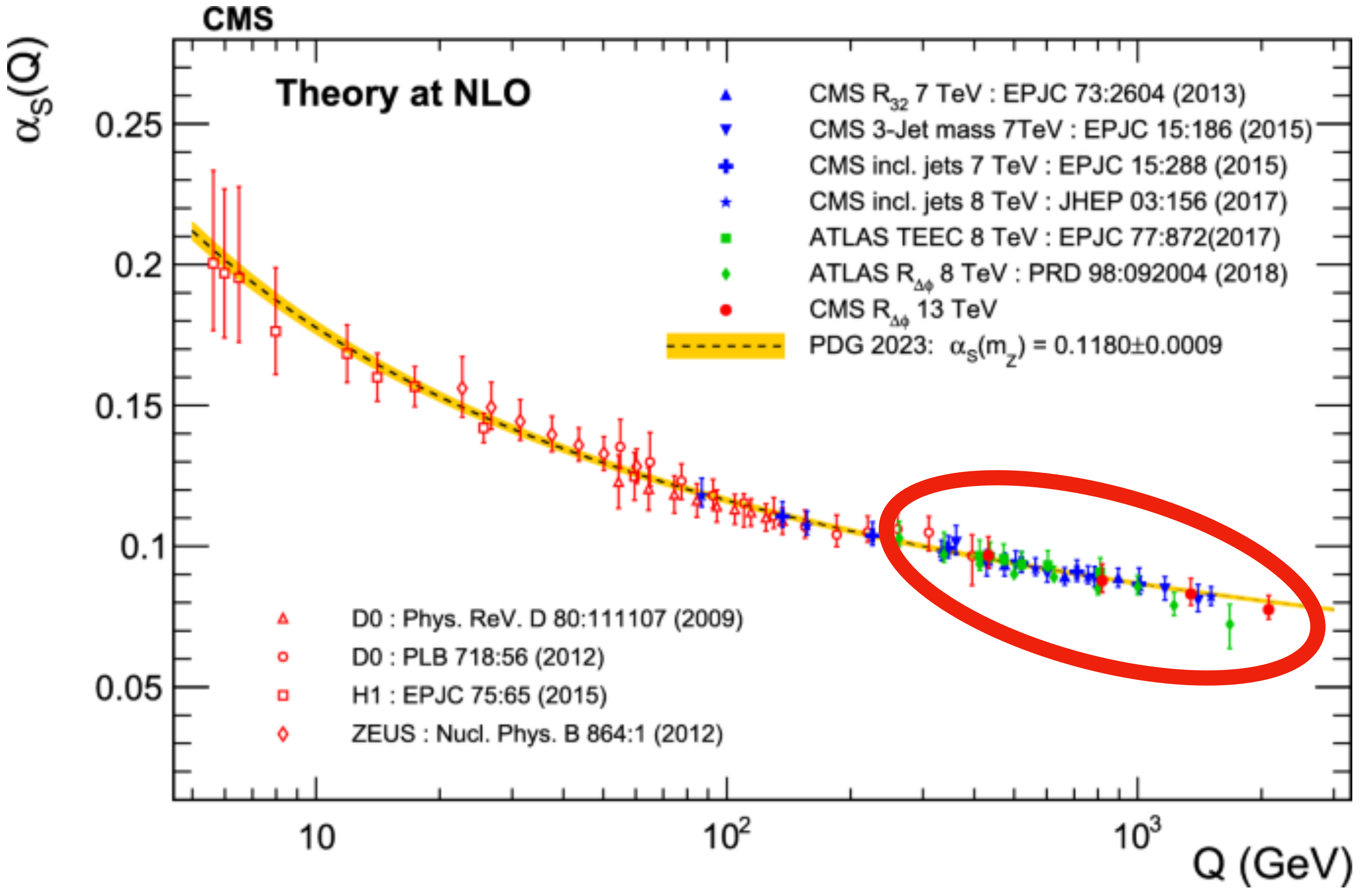
- Sensitivity to $\alpha_S(m_Z)$
- Cancellation of systematic effects, e.g. luminosity
- Reduction of theoretical uncertainties, e.g. NP

Final result: $\alpha_S(m_Z) = 0.117^{+0.0117}_{-0.0074}$

Scale unc. dominant

PDF unc. reduced in the ratio

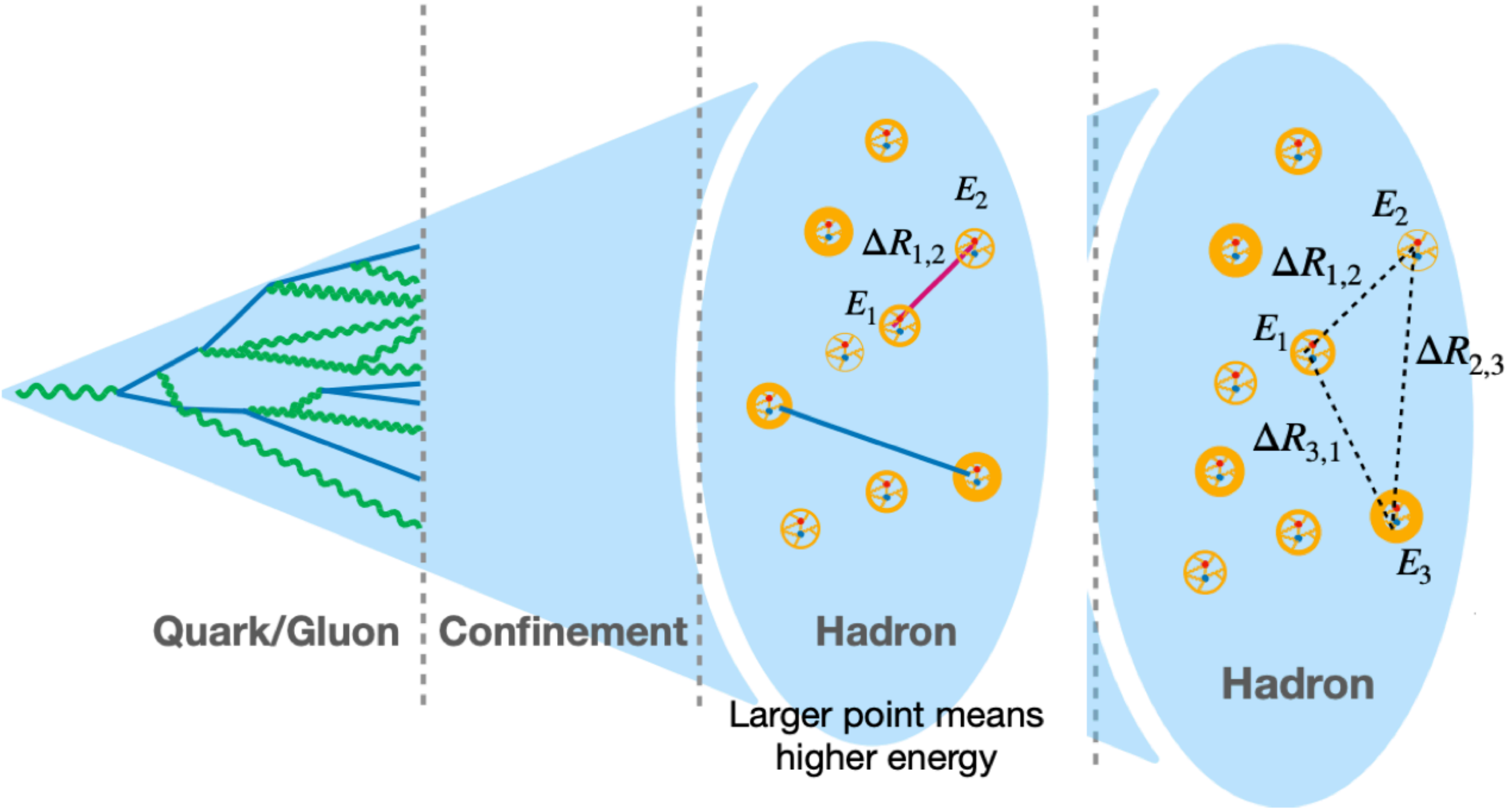




Running of α_S up to 2 TeV

CMS $\alpha_S(m_Z)$ at NNLL$_{approx}$: energy corellators at 13 TeV

More details in parallel talk of O. Kuprash, this afternoon



Energy-weighted distances between two (E2C) or three particles (E3C)

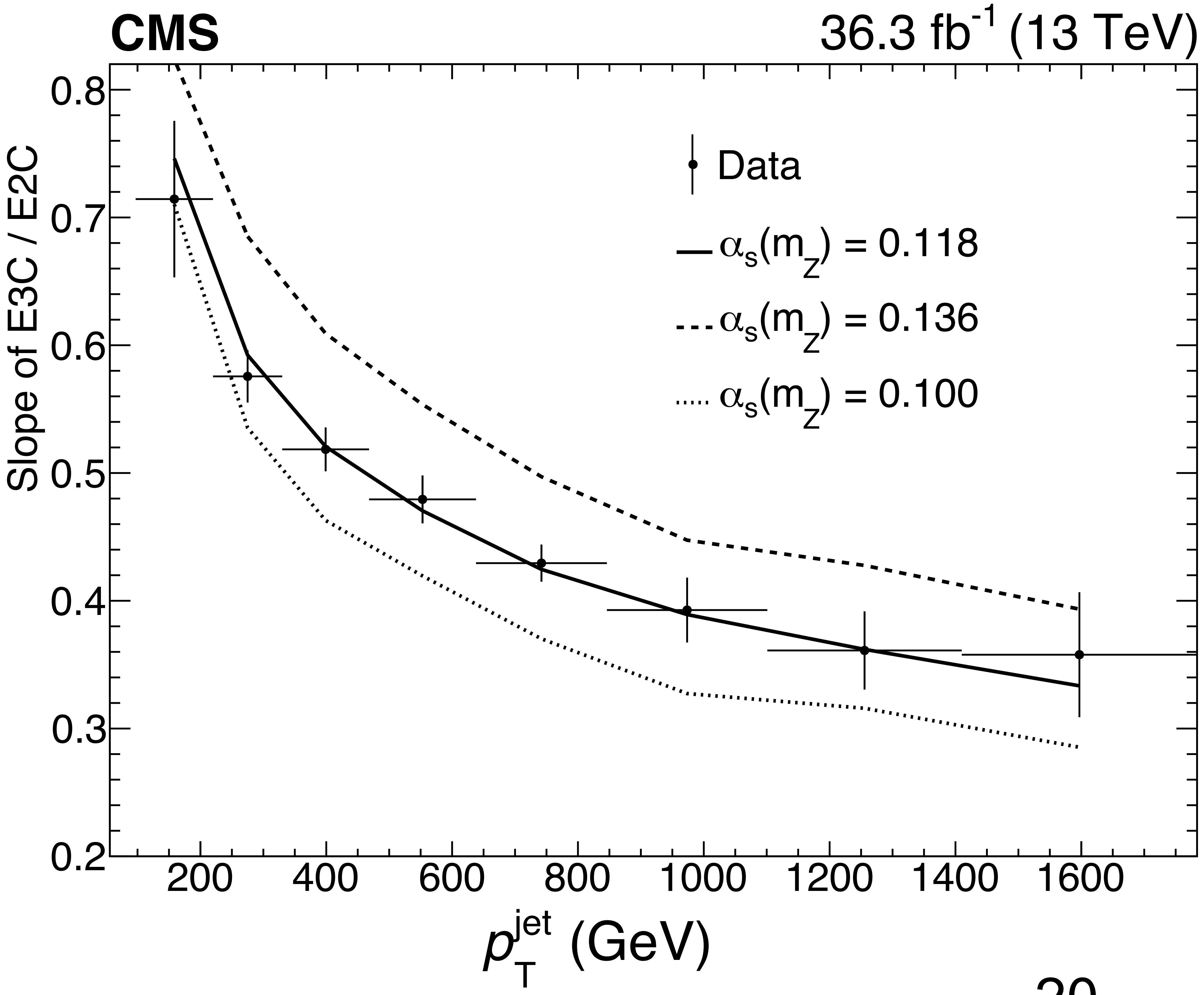
$$E3C/E2C \text{ (at LL)} \propto \alpha_S(\mathrm{Q})\ \ \ln \mathrm{x_L} + \mathrm{O}(\alpha_S^2)$$

Probe confinement and asymptotic freedom of α_S

Fit data to NLO+NNLL$_{approx}$ with different $\alpha_s(m_Z)$

$$\boxed{\alpha_S(m_Z) = 0.1229^{+0.0040}_{-0.0050} \ (<4.1\ \%\ \mathrm{rel})}$$

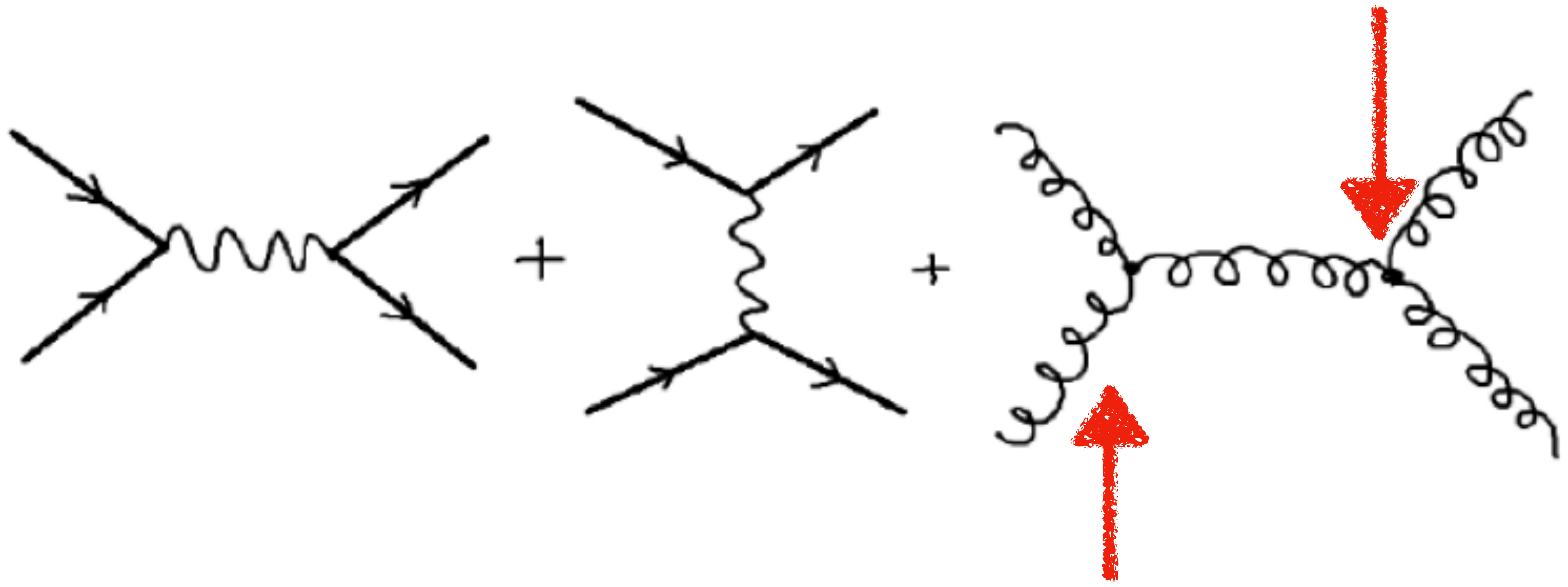
Most precise $\alpha_s(m_Z)$ from substructure



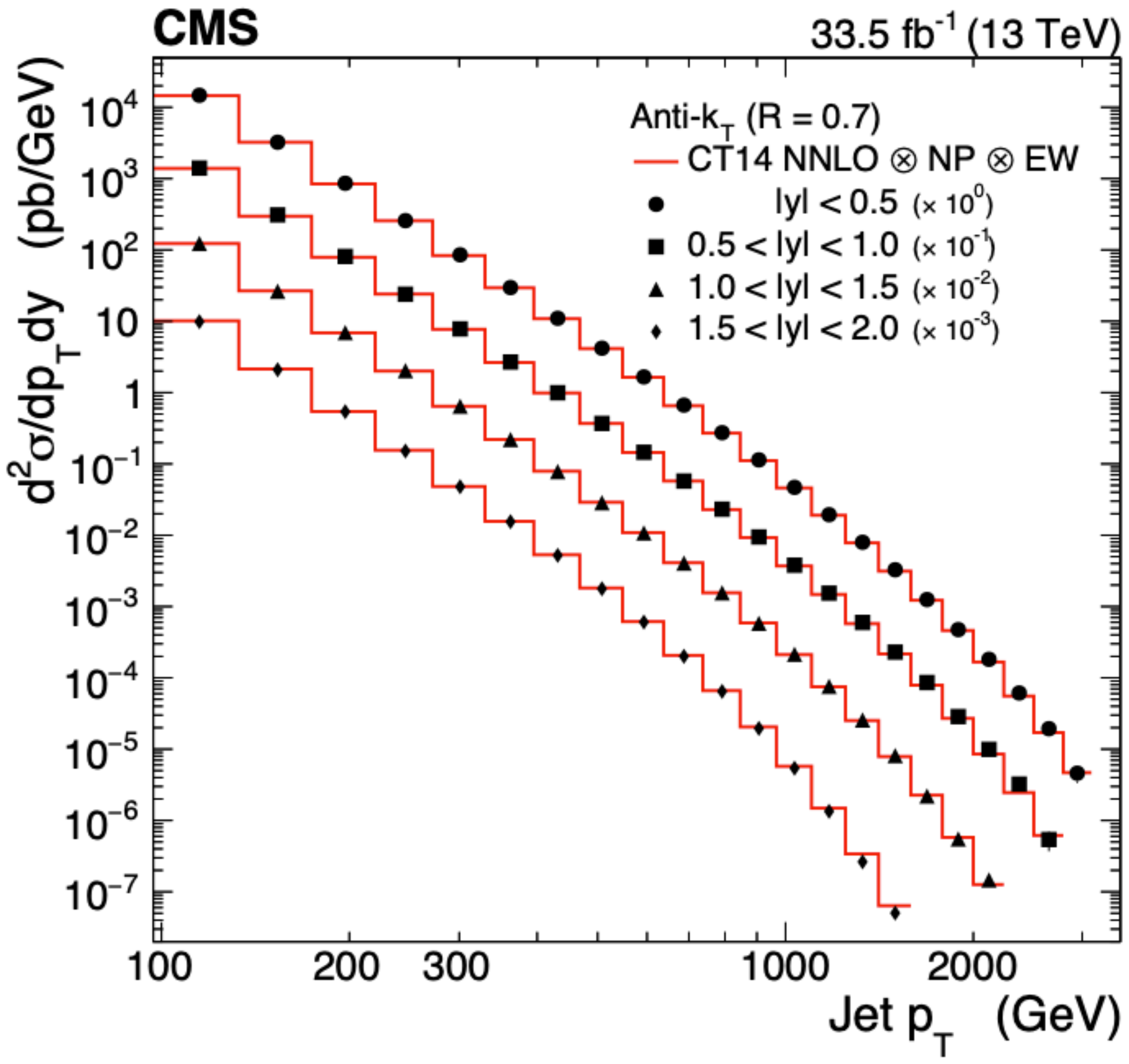
CMS Inclusive jet measurement at 13 TeV

- **Inclusive jets sensitive at PDFs and $\alpha_S(m_Z)$ at LO**
- Data compared to **NNLO QCD** corrected by real non-perturbative and virtual electroweak effects

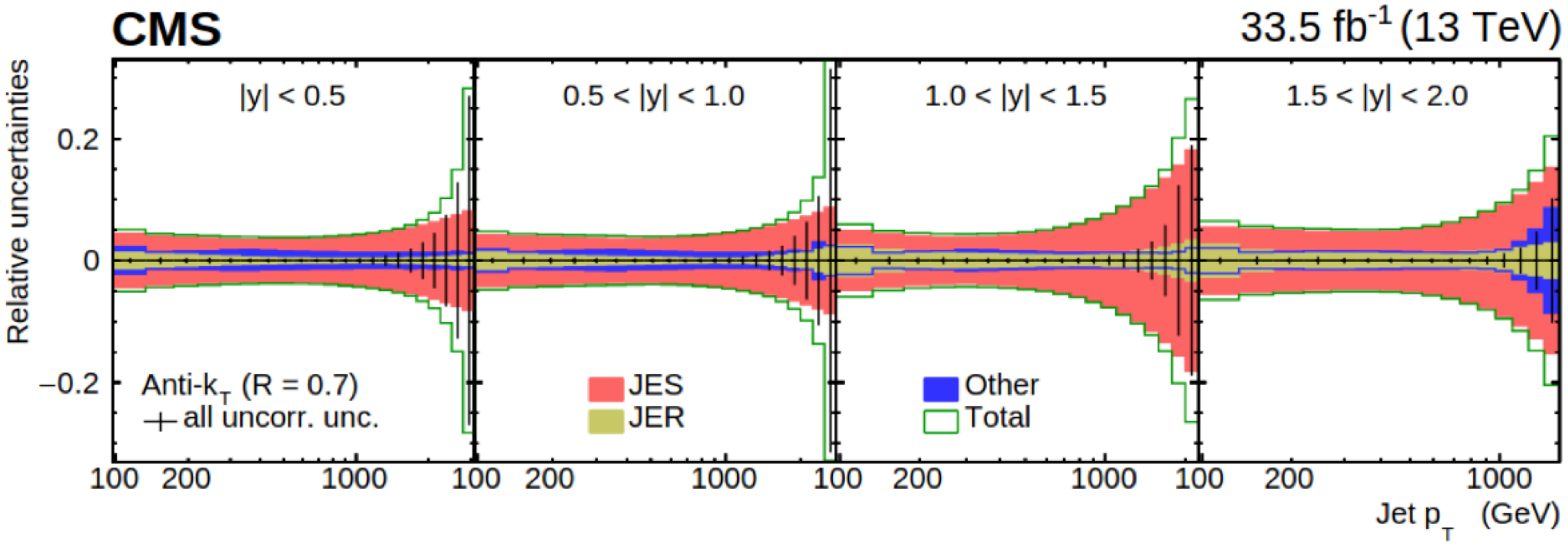
Each vertex sensitive to $\alpha_S(m_Z)$



Each line sensitive to PDFs



$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{jets}^{eff}}{L_{eff} * \Delta p_T * \Delta y}$$



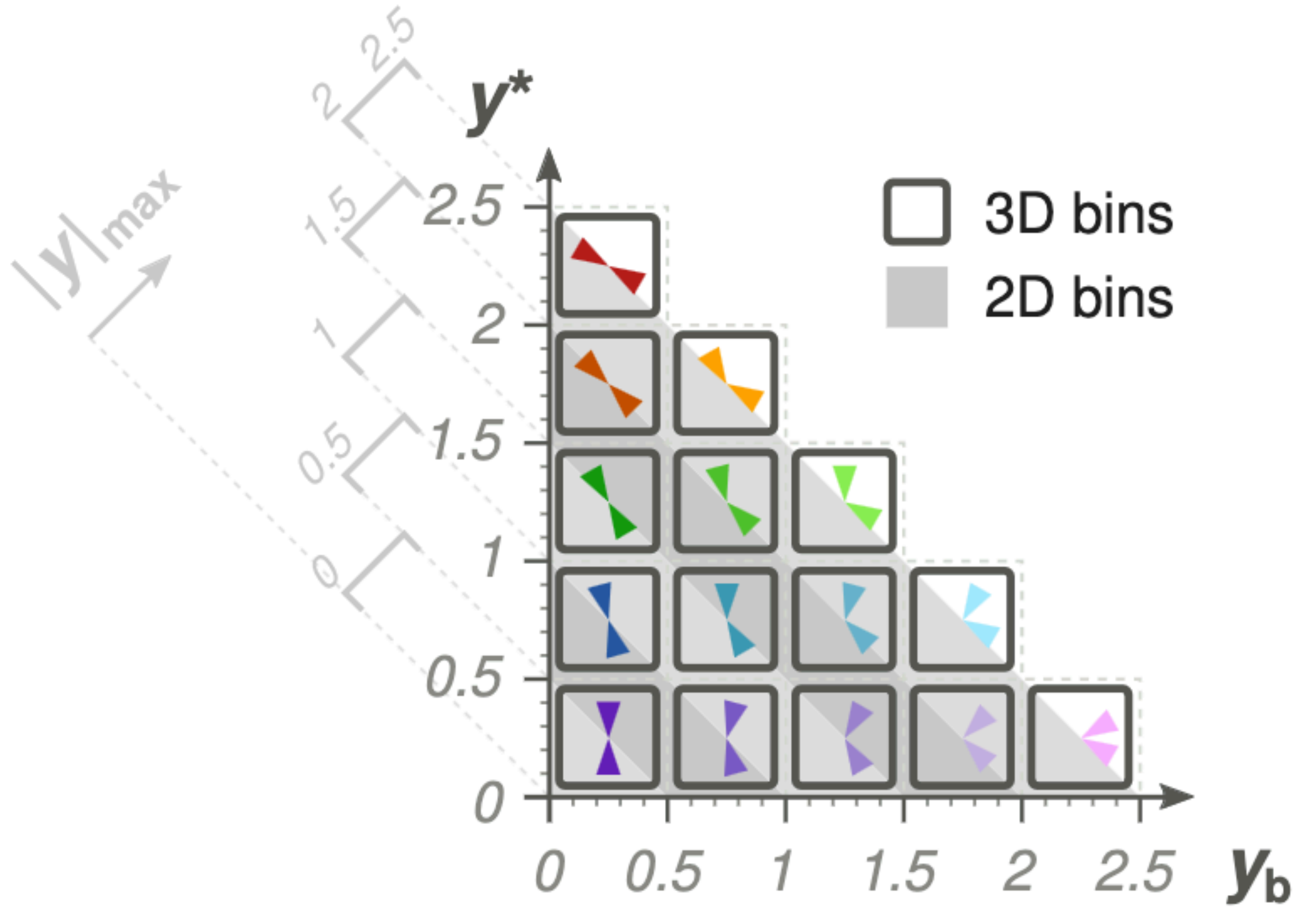
Experimental uncertainty dominated by JES

CMS dijet production at 13 TeV

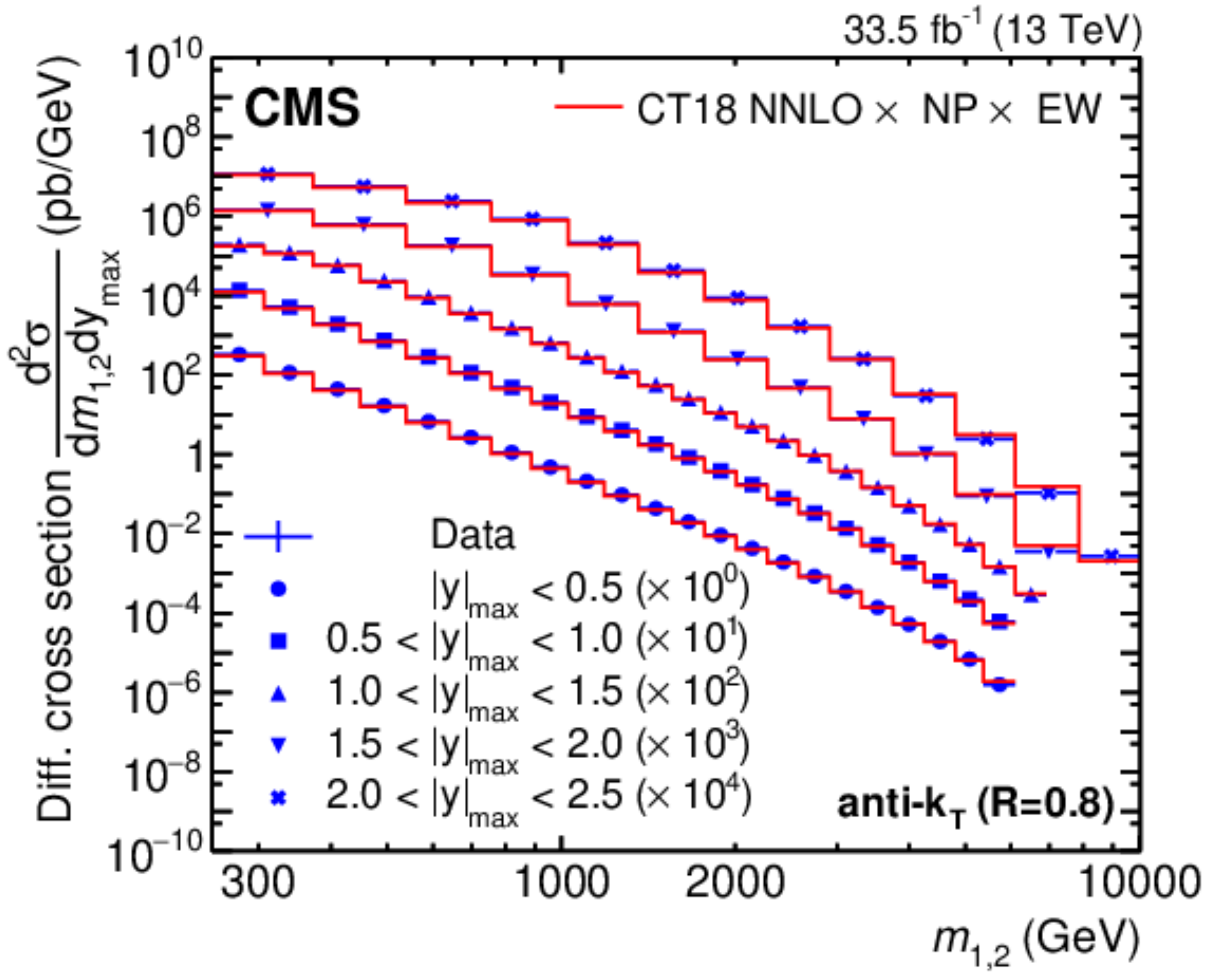
More details in parallel talk of A. Ziaka, this afternoon

- **2-D cross sections:** vs rapidity of the outermost jet $|y_{max}|$ and dijet invariant mass m_{12}
- **3-D cross sections:** vs $m_{12}/<p_T>_{1,2}$, rapidity separation $y^* = \frac{1}{2}|y_1 - y_2|$ and boost $y_b = \frac{1}{2}|y_1 + y_2|$

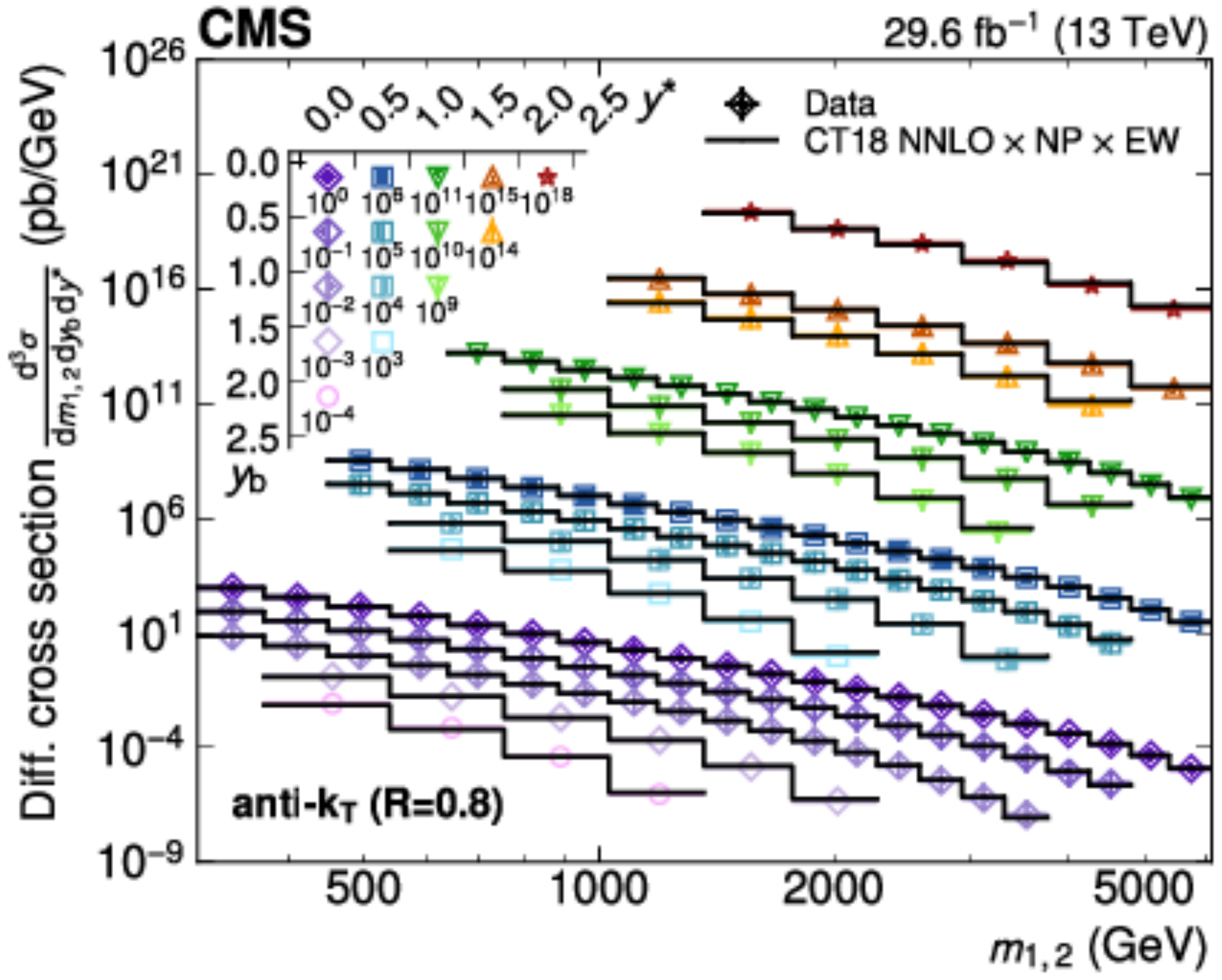
→ Idea: probe x_1 and x_2 using different event topologies



2-D cross section



3-D cross section



Data compared to **NNLO QCD** corrected by non-perturbative and electroweak effects

Method: simultaneous fit of $\alpha_S(m_Z)$ and PDFs

Simultaneous fit → Reduced dependence of $\alpha_S(m_Z)$ from PDFs

PDFs cannot be extracted with only LHC data

→ **Inclusive lepton-proton DIS data (HERA, EPJ C75(2015) no. 12, 580)**

- **Parametrise PDFs at a starting scale** →

Small-x limit

High-x limit

$$xf(x) = A_f x^{B_f} (1-x)^{C_f} (1 + D_f x + E_f x^2)$$

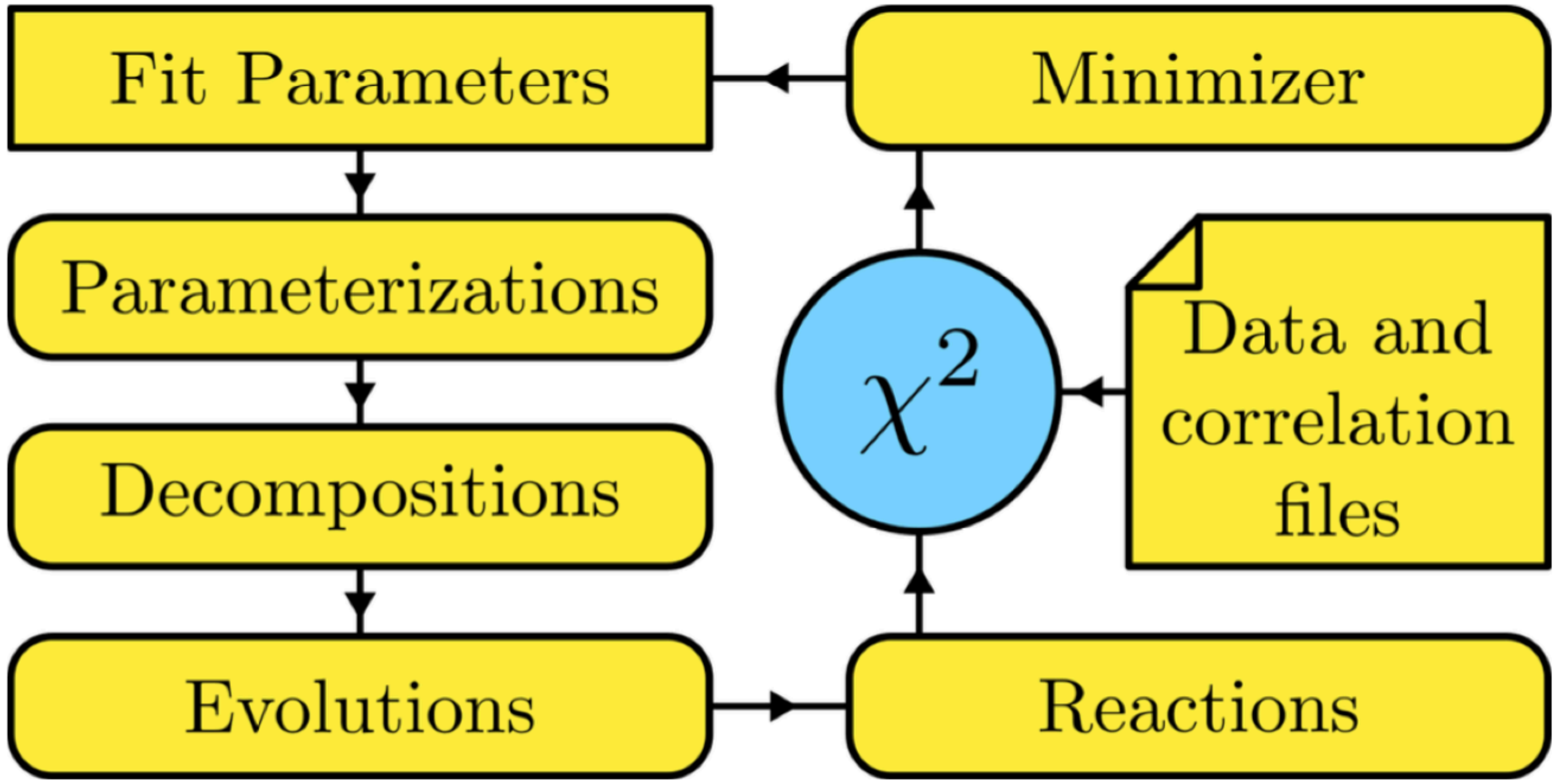
Normalization

Shape

- **Evolve PDFs at the scale of the measured data with DGLAP evolution**
- **Compute theory predictions:**
  - DIS at NNLO with different mass schemes
  - For jets using interpolation grids
- **Compare theory with data using χ^2**

Same approach as HERAPDF2.0

xFitter framework



Fit Parameters

Minimizer

Parameterizations

χ^2

Data and correlation files

Decompositions

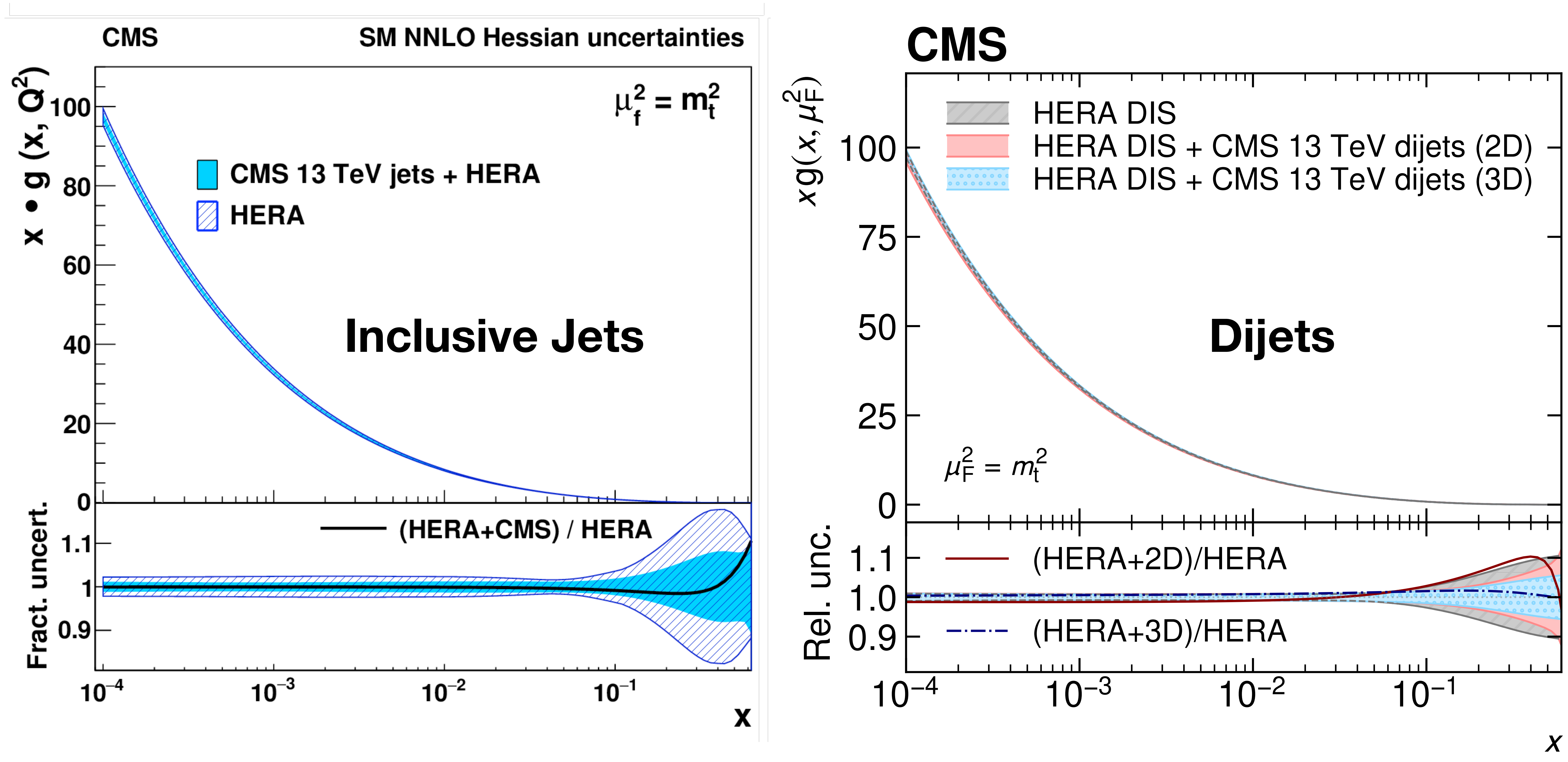
Evolutions

Reactions

CMS $\alpha_S(m_Z)$ from jet production at 13 TeV

- **Simultaneous fit of PDFs and α_s at NNLO**
- Hera+jets fits compared to HERA-only fit

Gluon distribution



Inclusive jets result:

$$\alpha_S(m_Z) = 0.1166 \pm 0.0017$$

Dijets 2-D result:

$$\alpha_S(m_Z) = 0.1179 \pm 0.0019$$

Dijets 3-D result:

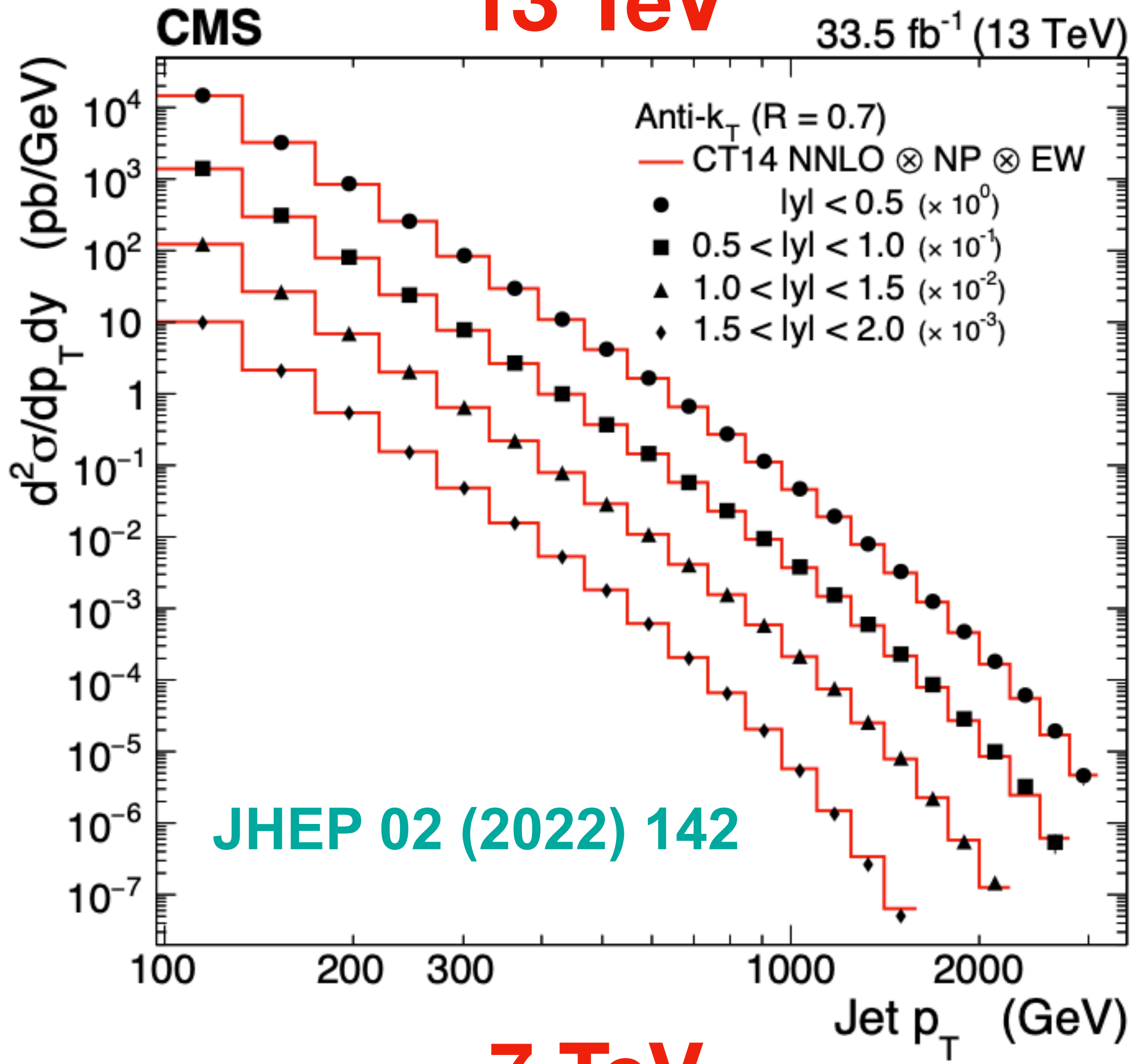
$$\alpha_S(m_Z) = 0.1181 \pm 0.0022$$

Inclusive jets and dijets dominated by fit uncertainty: experimental + PDF

Inclusive jets at CMS

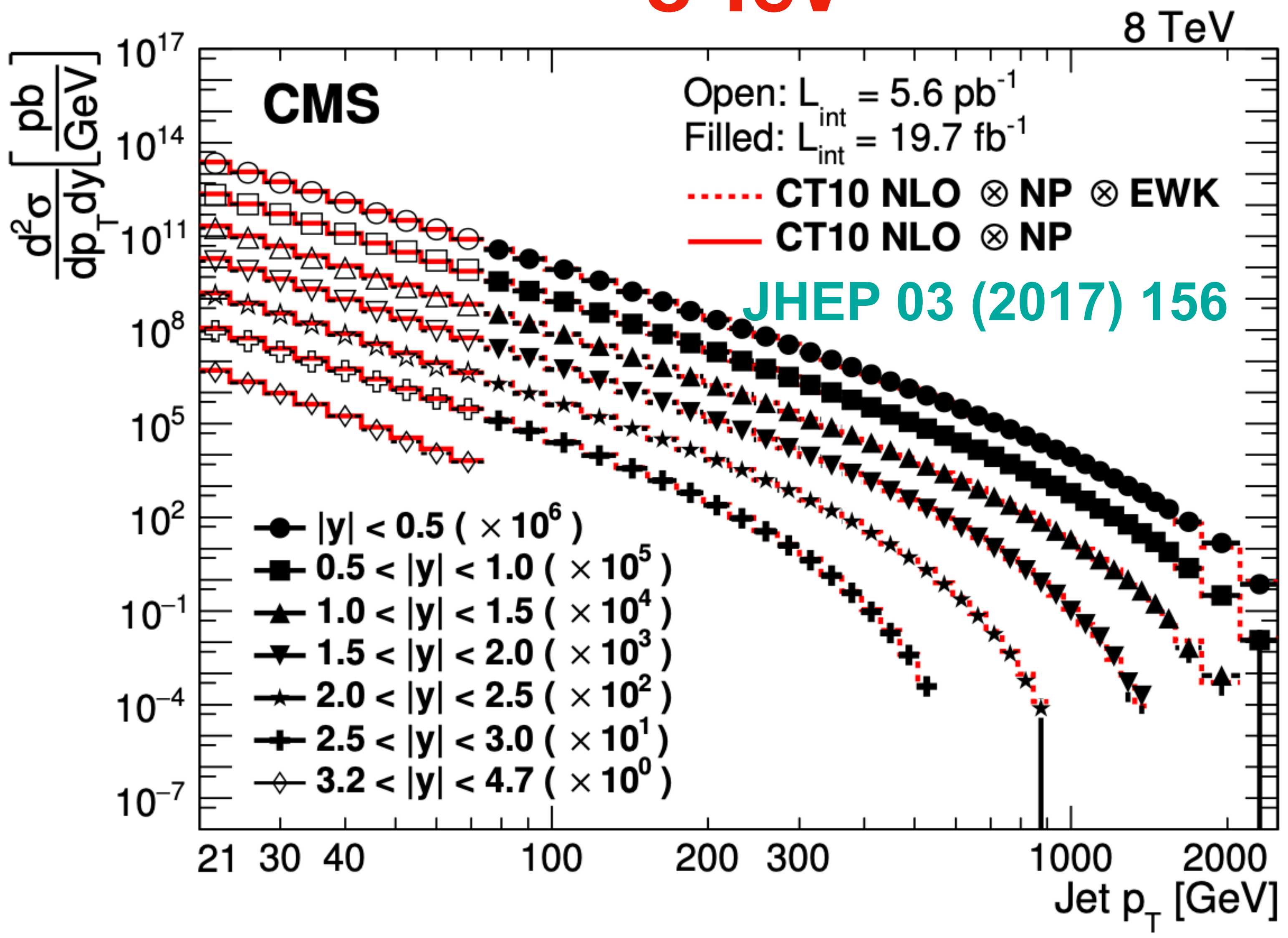
NEW! More details in parallel talk of O. Kuprash, this afternoon

13 TeV



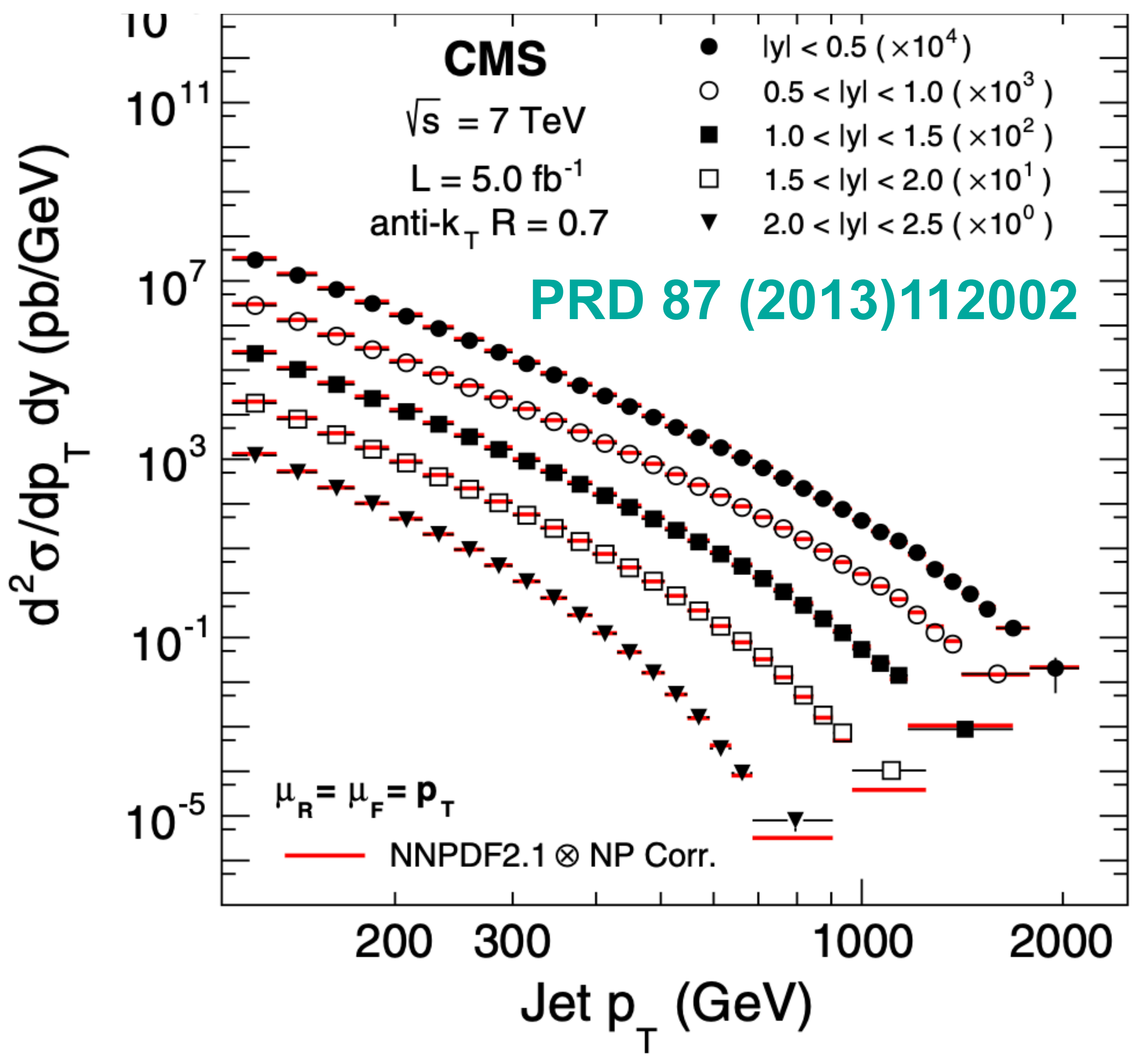
JHEP 02 (2022) 142

8 TeV



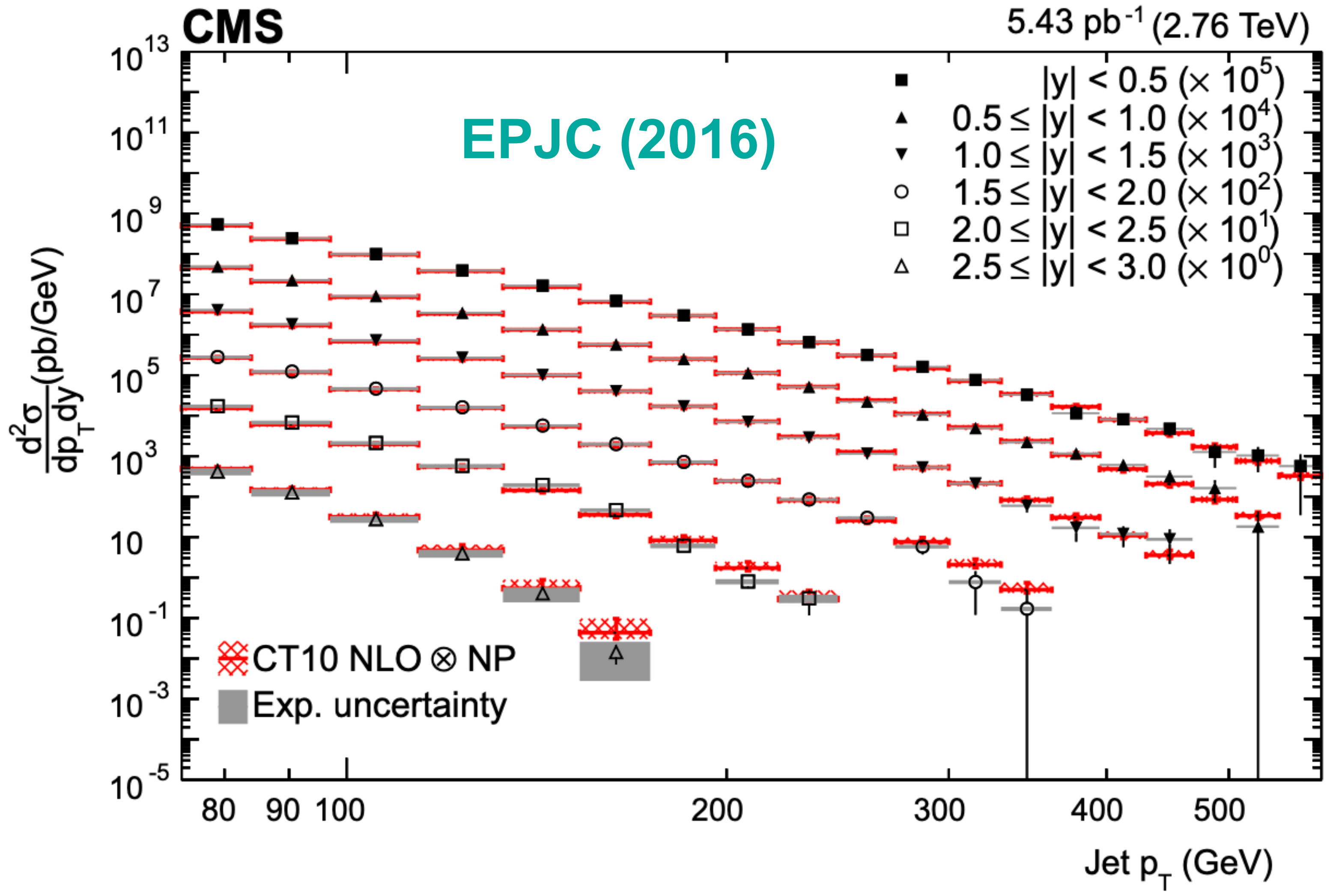
JHEP 03 (2017) 156

7 TeV



PRD 87 (2013)112002

2.76 TeV



EPJC (2016)

- **Inclusive jets at 2.76, 7, 8, 13 TeV**
- **Simultaneous fit of PDF and $\alpha_S(m_Z)$ at NNLO**
- Jet clustered with **anti-kT (R=0.7)**

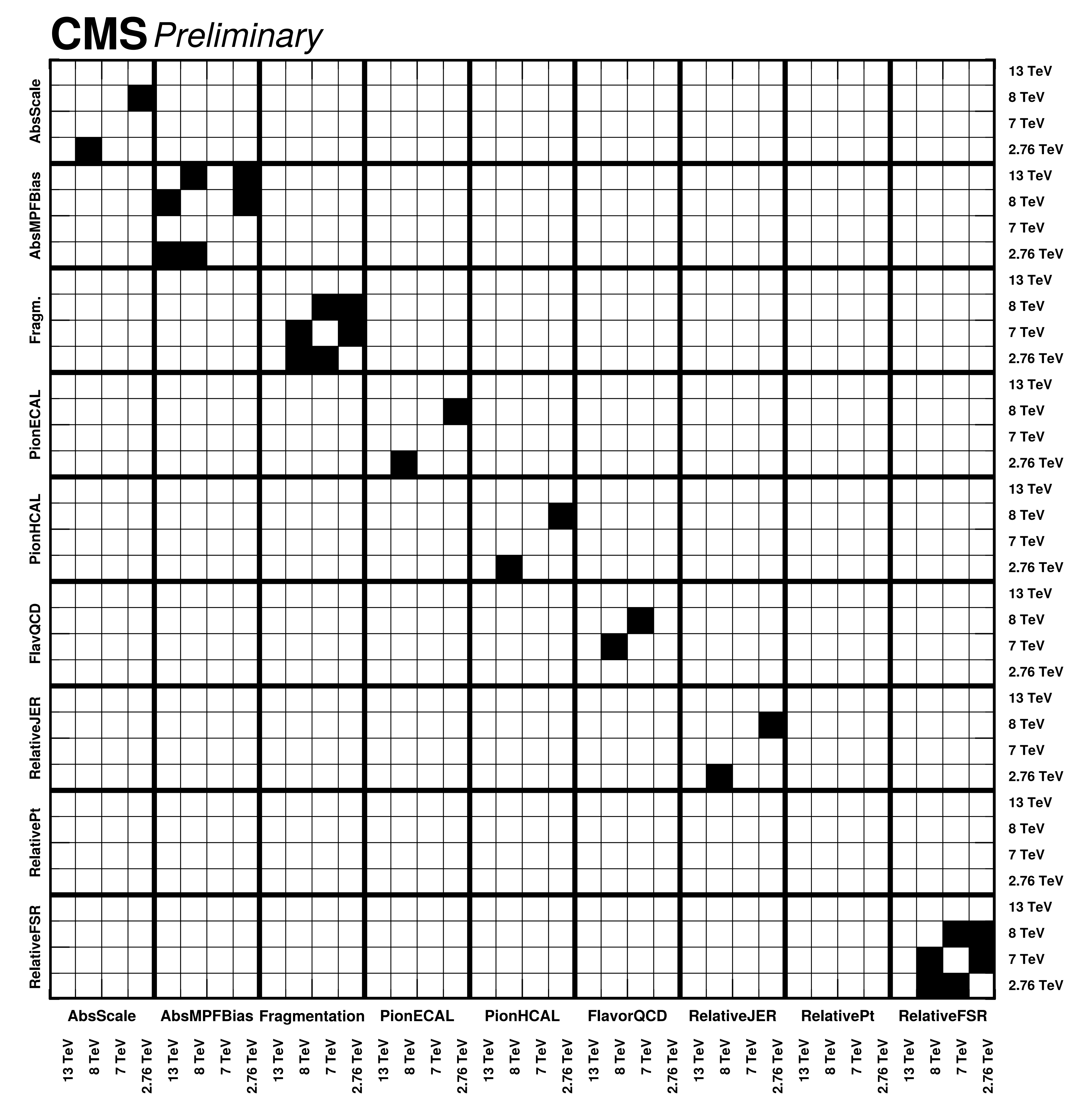
	|y|	pT	Ndata
13 TeV	|y|<2.0	97 < pT < 3103	78
8 TeV	|y|<3.0	74 < pT < 1784	168
7 TeV	|y|<2.5	114 < pT < 2116	130
2.76 TeV	|y|<3.0	74 < pT < 592	81

Using all measurements crucial to probe different PDF distributions

Correlation of uncertainties in CMS jet data

- **Correlation within a dataset investigated during the measurements or individual QCD interpretation**
- **Correlation between the individual measurements**
  - Global PDF fitters treat the different measurements uncorrelated
  - Here, correlation among CMS inclusive jets is investigated
  - JES dominant uncertainty → focus on JES correlations

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



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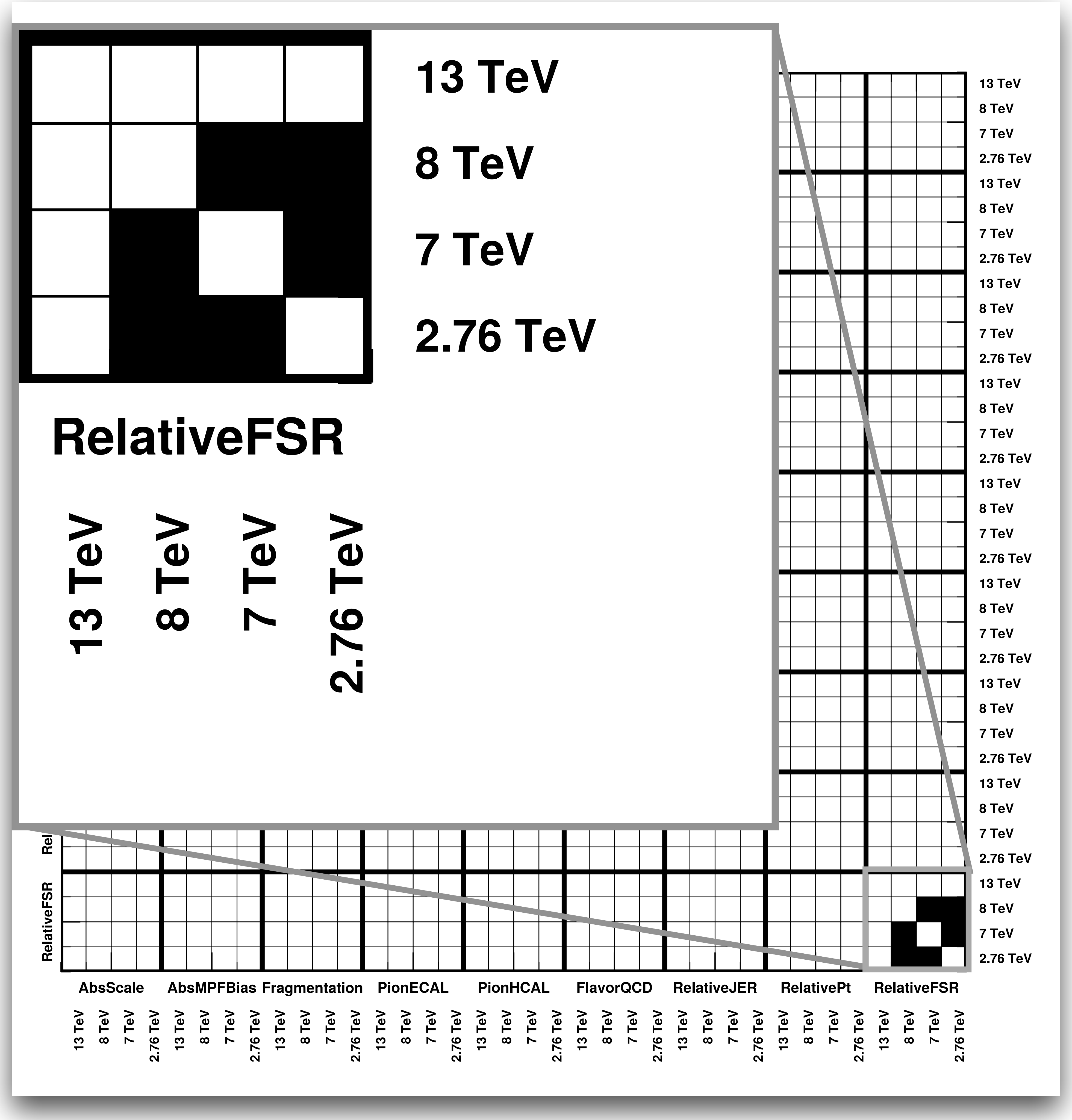
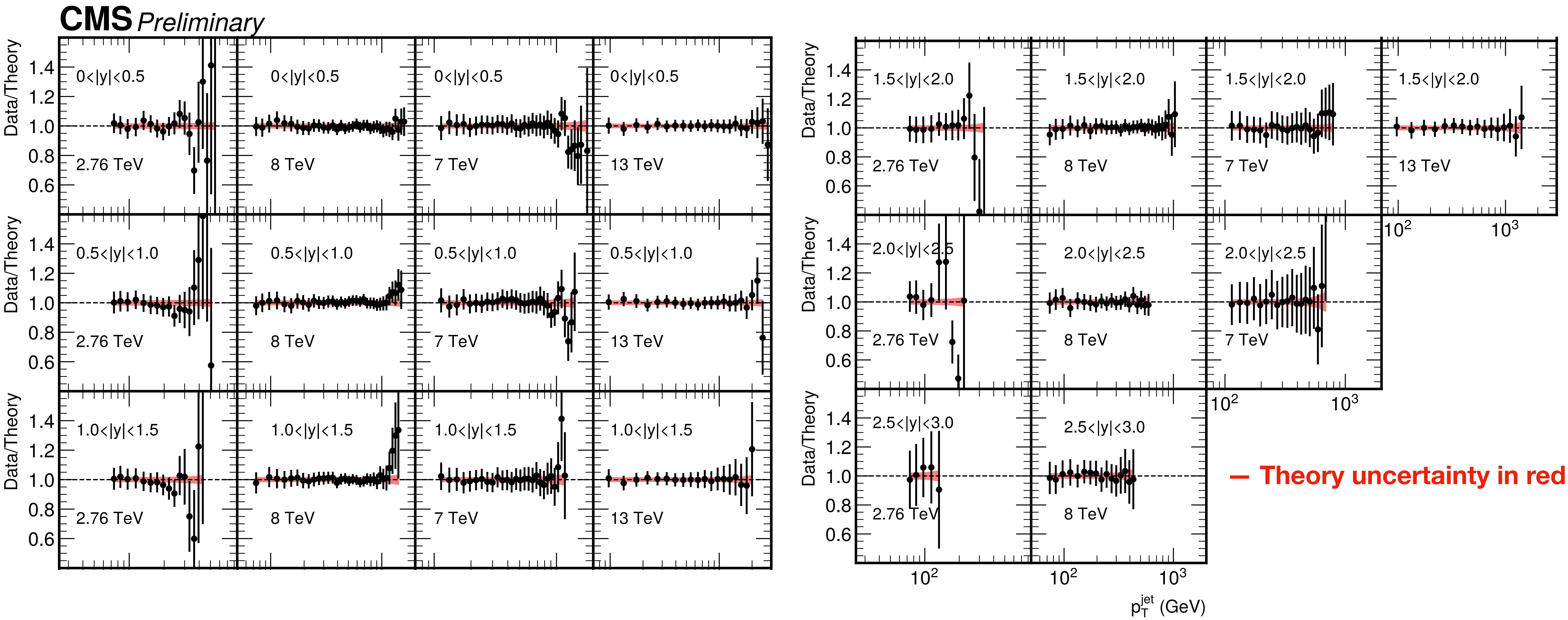


Data/Theory agreement for all data sets at one glance

Data/theory comparison after simultaneous fit of PDFs and $\alpha_S(m_Z)$

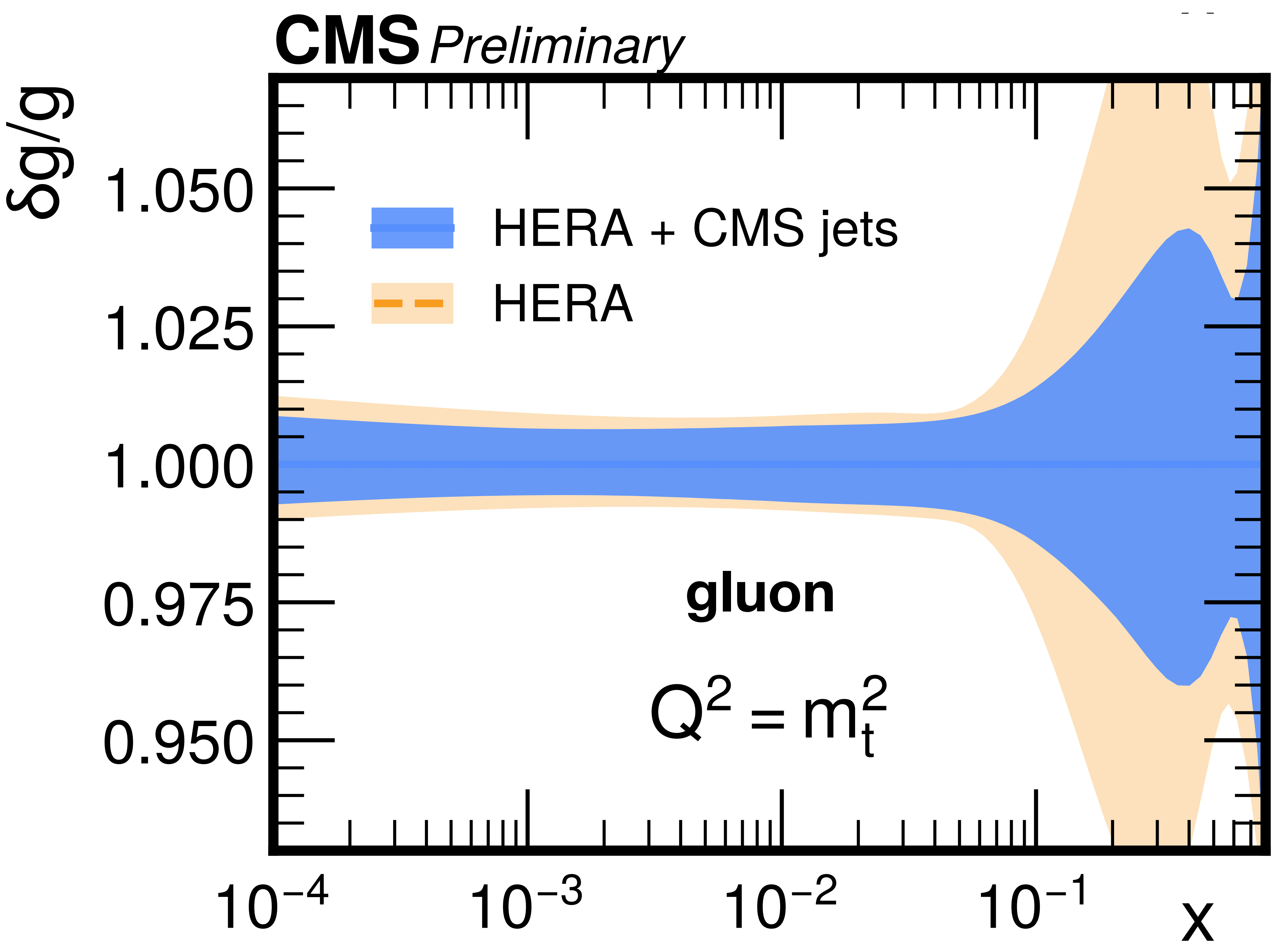


— Theory uncertainty in red

Good agreement data/theory

Final result: PDFs and $\alpha_S(m_Z)$

CMS All inclusive jets + HERA DIS data, compared to only-HERA fit



$$\alpha_\mathbf{S}(\mathbf{m_Z}) = 0.11759$$

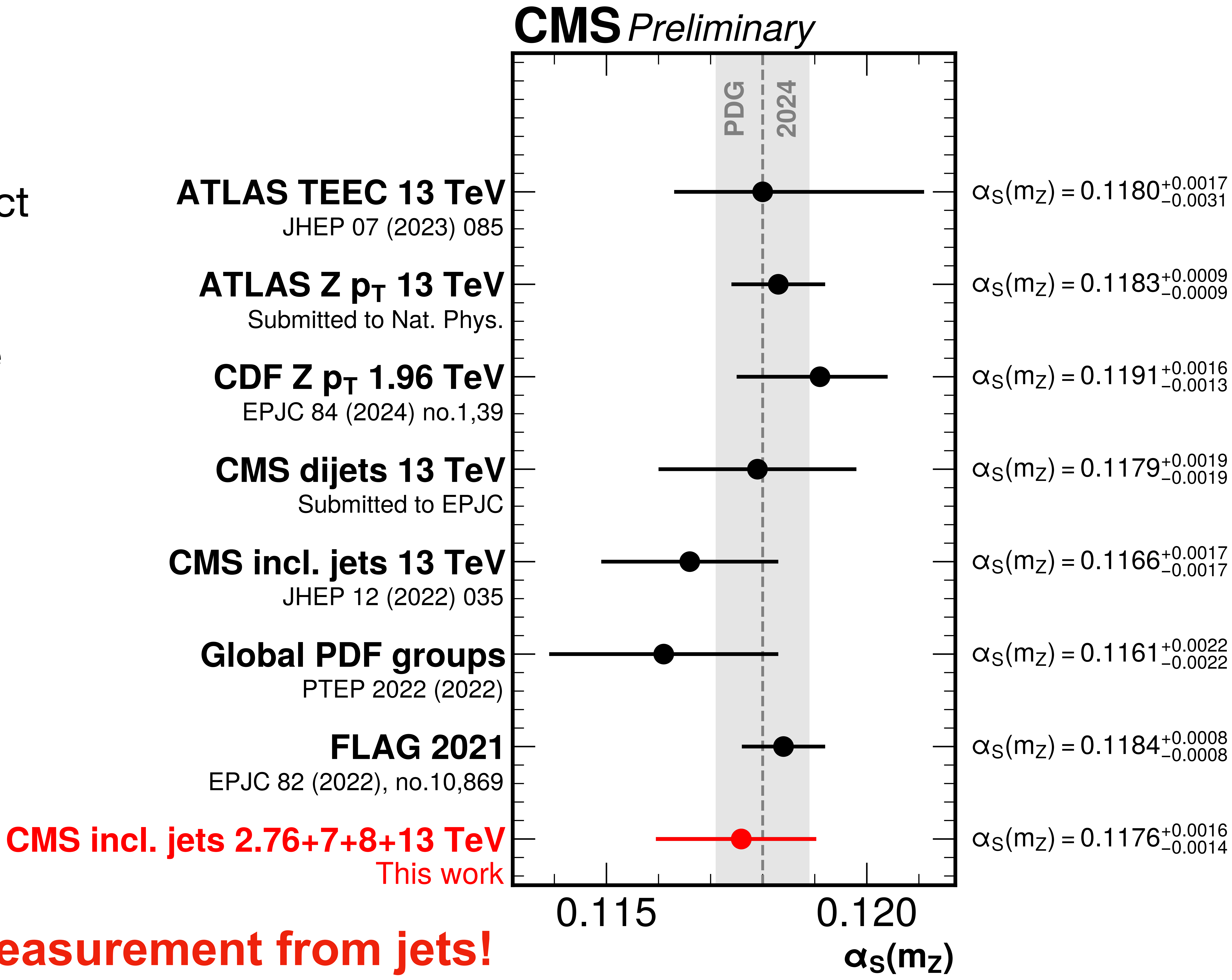
- **Fit unc:** $^{+0.00093}_{-0.00094}$ → Experimental and PDFs
- **Scale unc:** $^{+0.00091}_{-0.0012}$ → Missing higher order contributions (μ_F, μ_R)
- **Model unc:** $^{+0.00059}_{-0.00043}$ → Varied fixed parameters e.g. Q^2_{min}, m_b, m_c…
- **Param unc:** $^{+0}_{-0.00004}$ → Parametrisation choice

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

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

Comparison $\alpha_S(m_Z)$

- Improvement of uncertainty respect Inclusive jets and dijets at 13 TeV
- Dominant contribution is the scale uncertainty

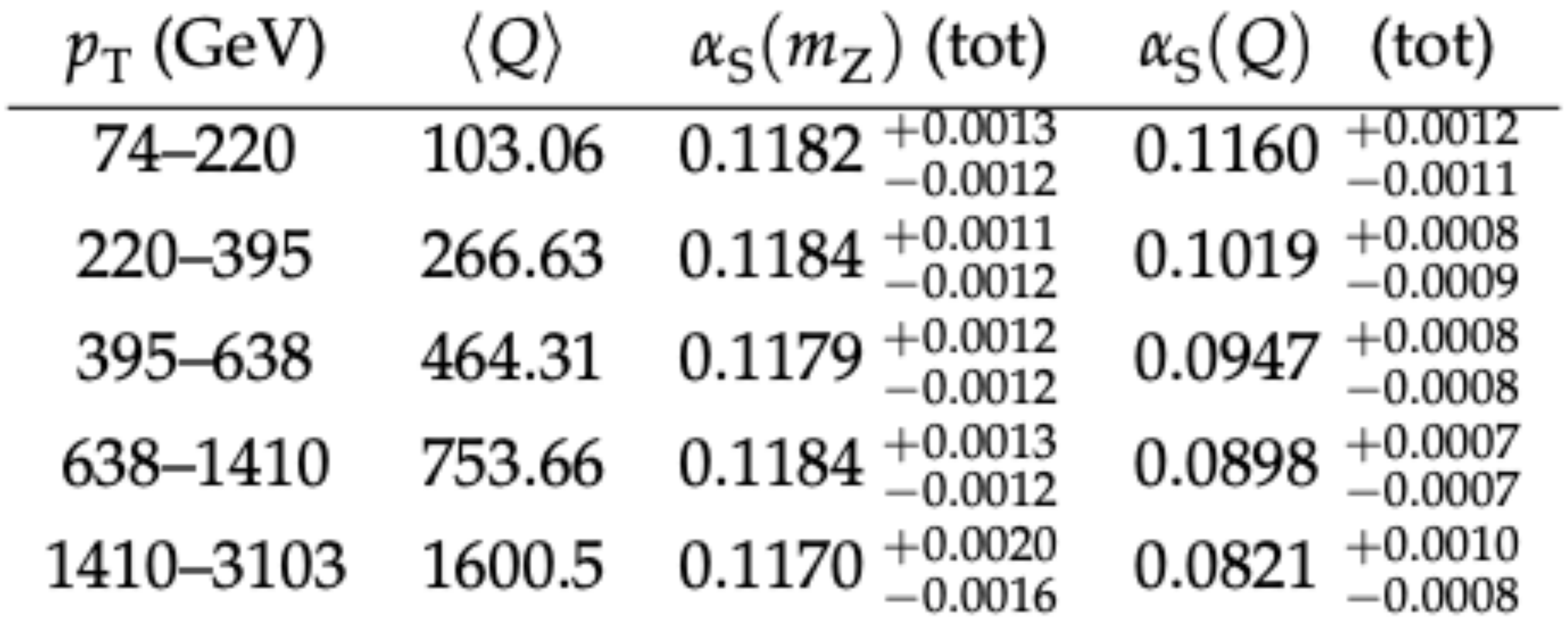


Most precise measurement from jets!

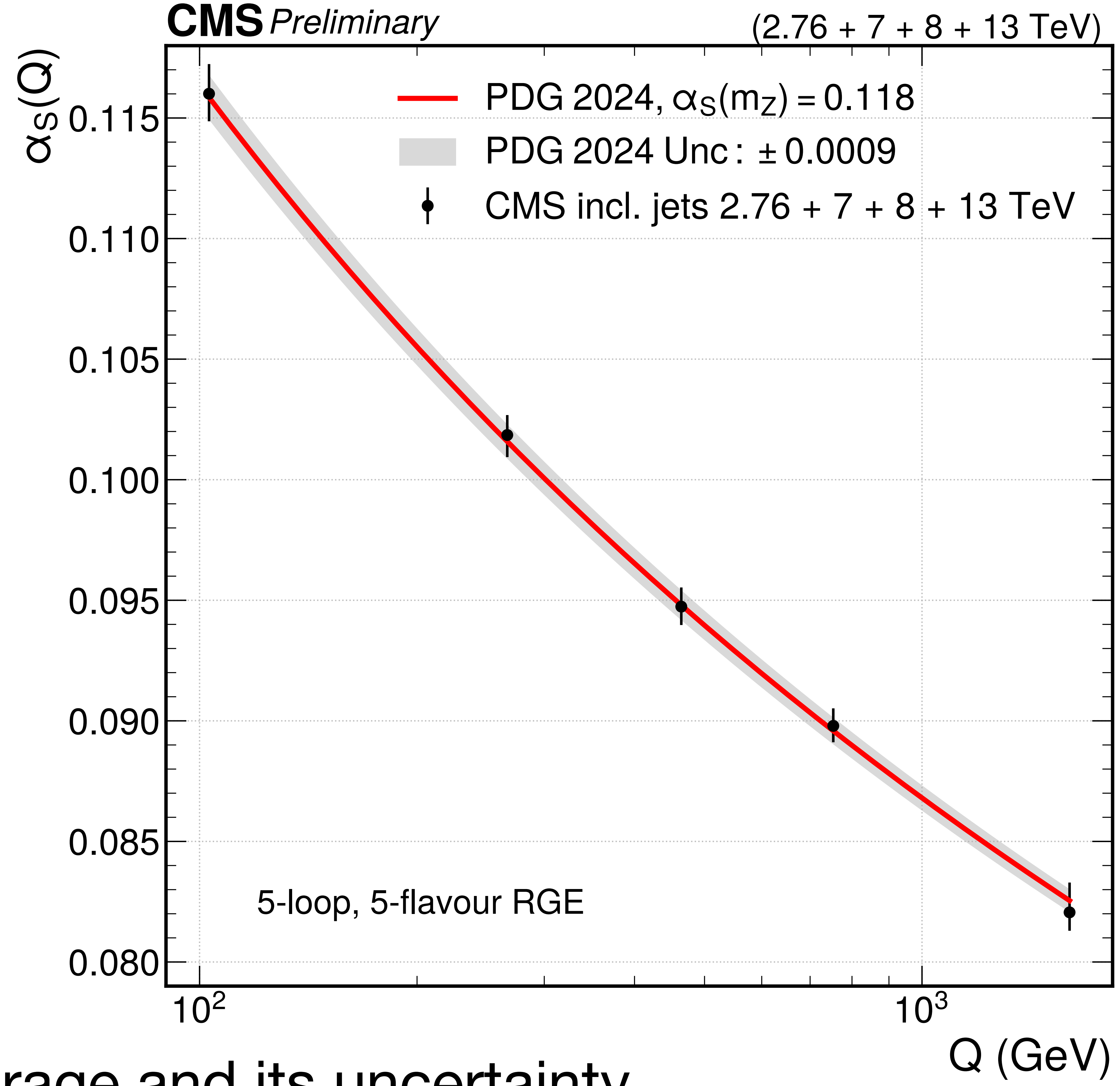
Extraction of α_S running

Divide CMS data into 5 independent p_T ranges

- In each p_T range, fit PDFs and $\alpha_S(m_Z)$ simultaneously
- Define the center of gravity of each p_T range $< Q >$
- Evolve $\alpha_s(m_Z)$ to $< Q >$ (**CRunDec package**)



p_T (GeV)	$\langle Q \rangle$	$\alpha_S(m_Z)$ (tot)	$\alpha_S(Q)$ (tot)
74–220	103.06	$0.1182\,^{+0.0013}_{-0.0012}$	$0.1160\,^{+0.0012}_{-0.0011}$
220–395	266.63	$0.1184\,^{+0.0011}_{-0.0012}$	$0.1019\,^{+0.0008}_{-0.0009}$
395–638	464.31	$0.1179\,^{+0.0012}_{-0.0012}$	$0.0947\,^{+0.0008}_{-0.0008}$
638–1410	753.66	$0.1184\,^{+0.0013}_{-0.0012}$	$0.0898\,^{+0.0007}_{-0.0007}$
1410–3103	1600.5	$0.1170\,^{+0.0020}_{-0.0016}$	$0.0821\,^{+0.0010}_{-0.0008}$



$\alpha_S(Q)$ in the five p_T ranges are compared to the world average and its uncertainty

→ **Running probed up to 1.6 TeV**

→ **Good agreement in the entire range**

Summary and conclusions

- The strong coupling constant is a key parameter of QCD

- Various methods/observables to determine α_S

- Recent determinations at the LHC achieved %-level

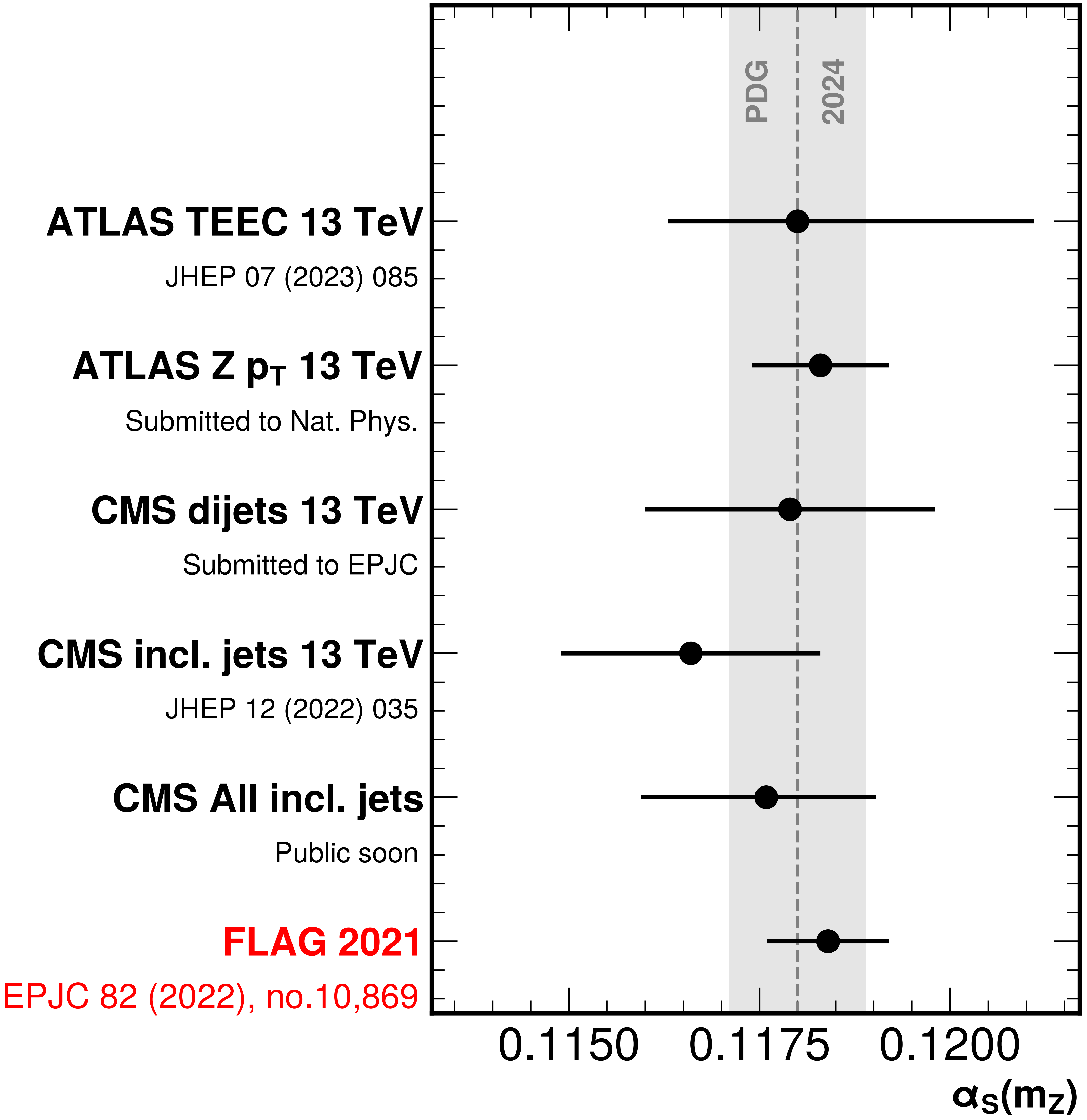
→ Impact the PDG world average

- **Z p_T most precise:** experimentally accurate, further improvement in theory

- **How to improve further the precision of $\alpha_S(m_Z)$?**

  - Push theory predictions: NNLO → N3LO

  - Observables that can reduce uncertainty: e.g. $R_{\Delta\phi}$

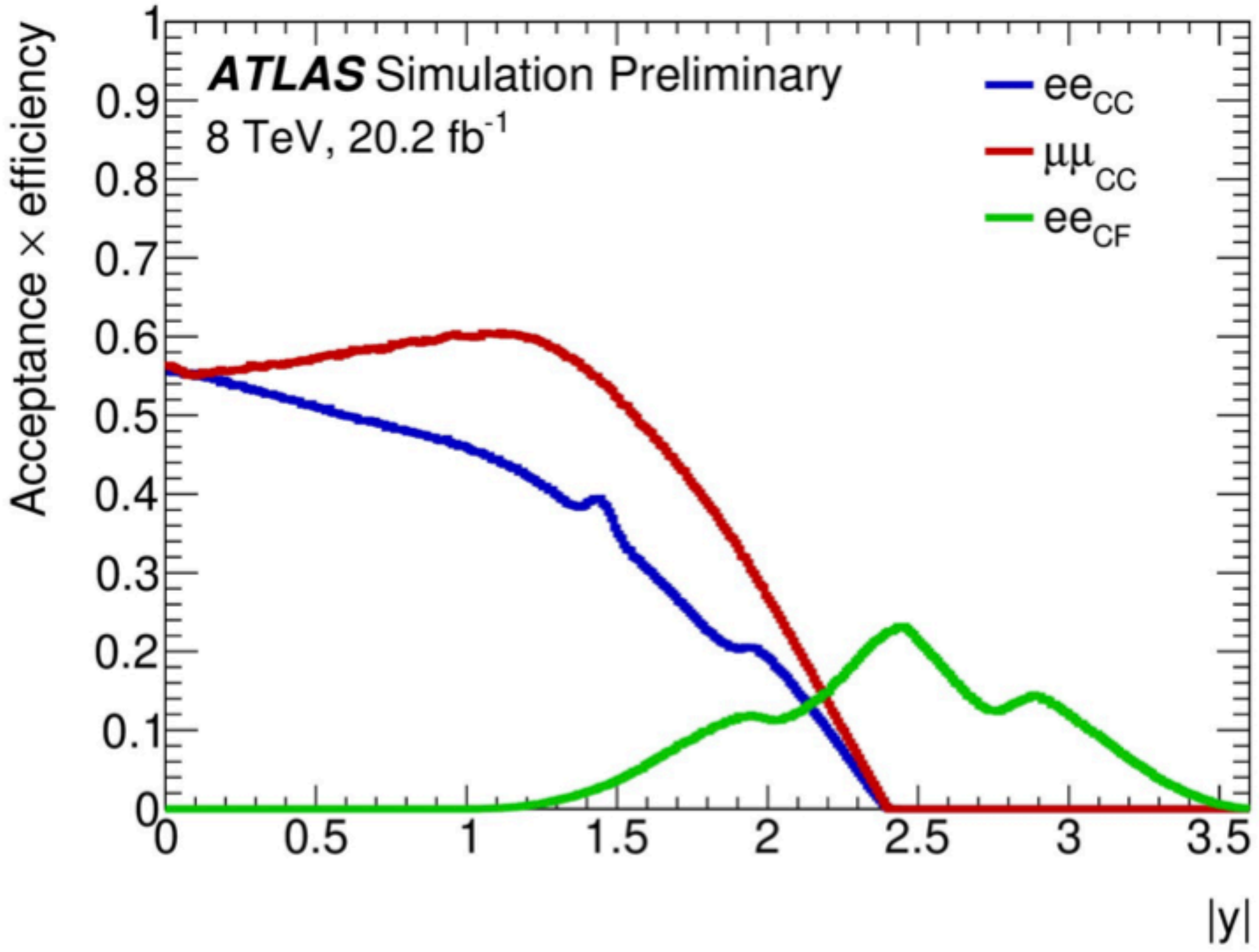


Thank you

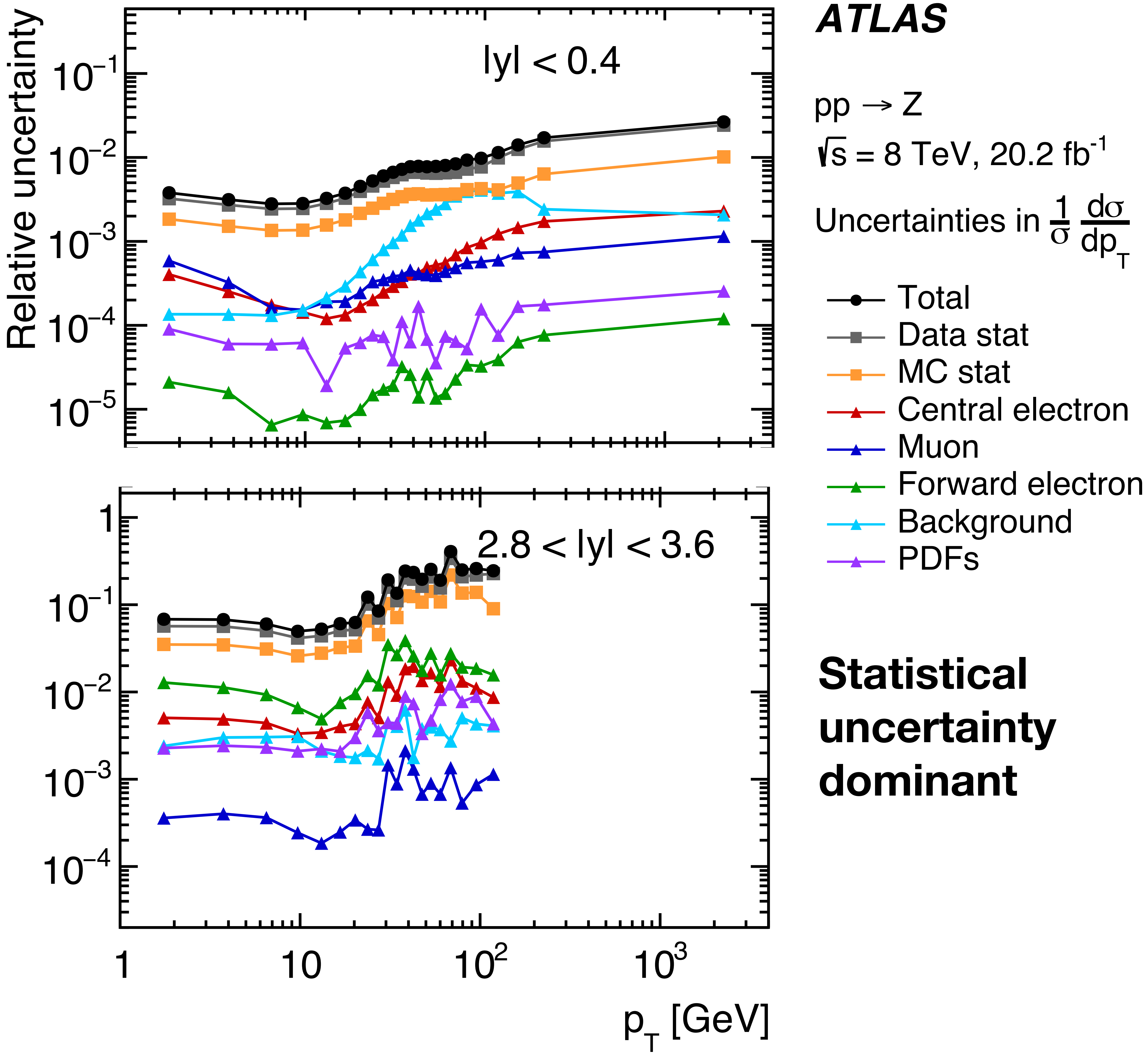
Backup

ATLAS cross-section measurement at 8 TeV

- Three channels: eeCC, $\mu\mu$CC, eeCF:
- Central ee/$\mu\mu$ with $p_T > 25$ GeV, $|\eta| < 2.4$, forward electron with $p_T > 20$ GeV, $2.5 < |\eta| < 4.9$
- $80 < m_{ll} < 100$ GeV
- Double differential p_T, y cross section, $|y| < 3.6$

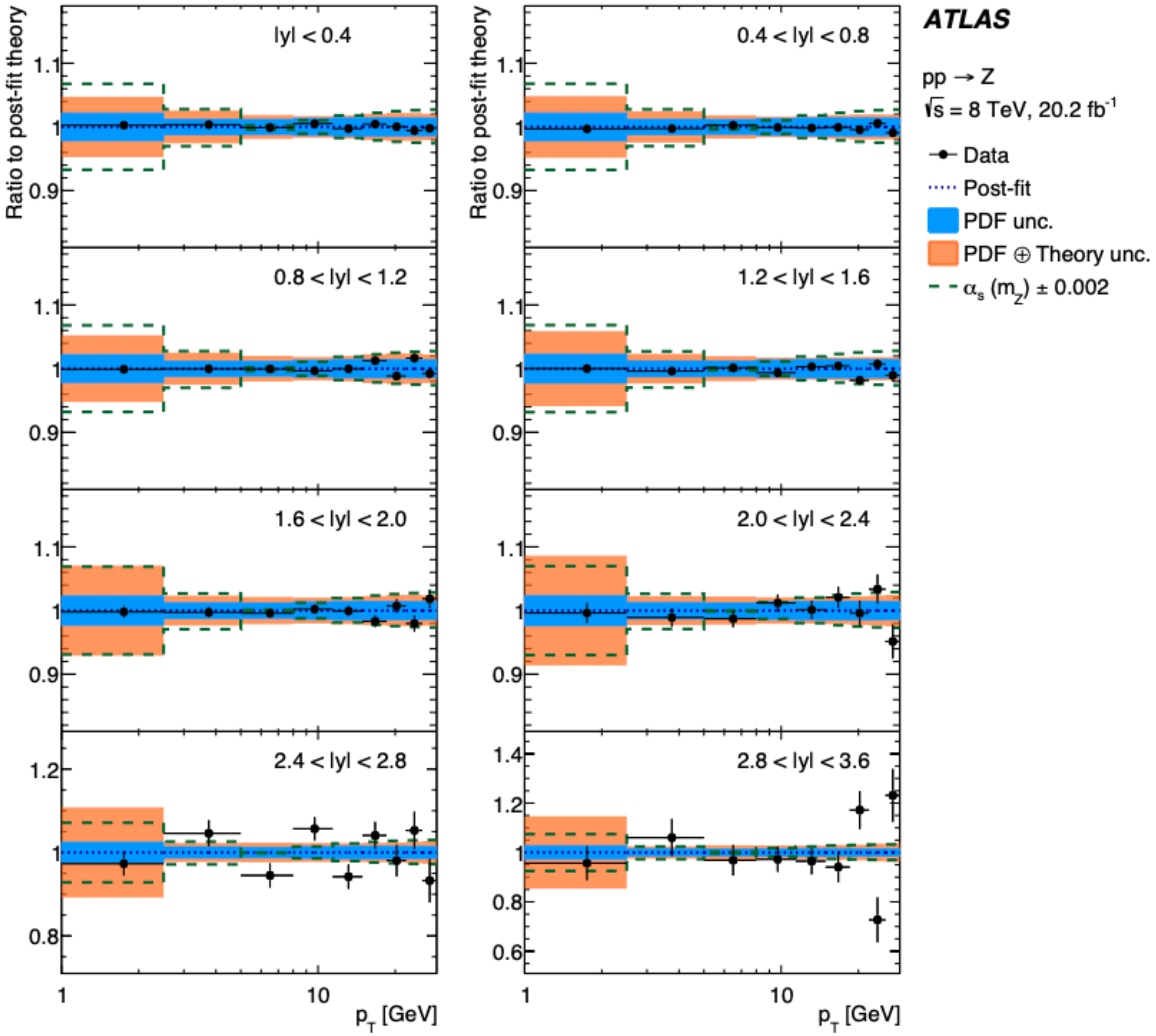


Breakdown of uncertainty

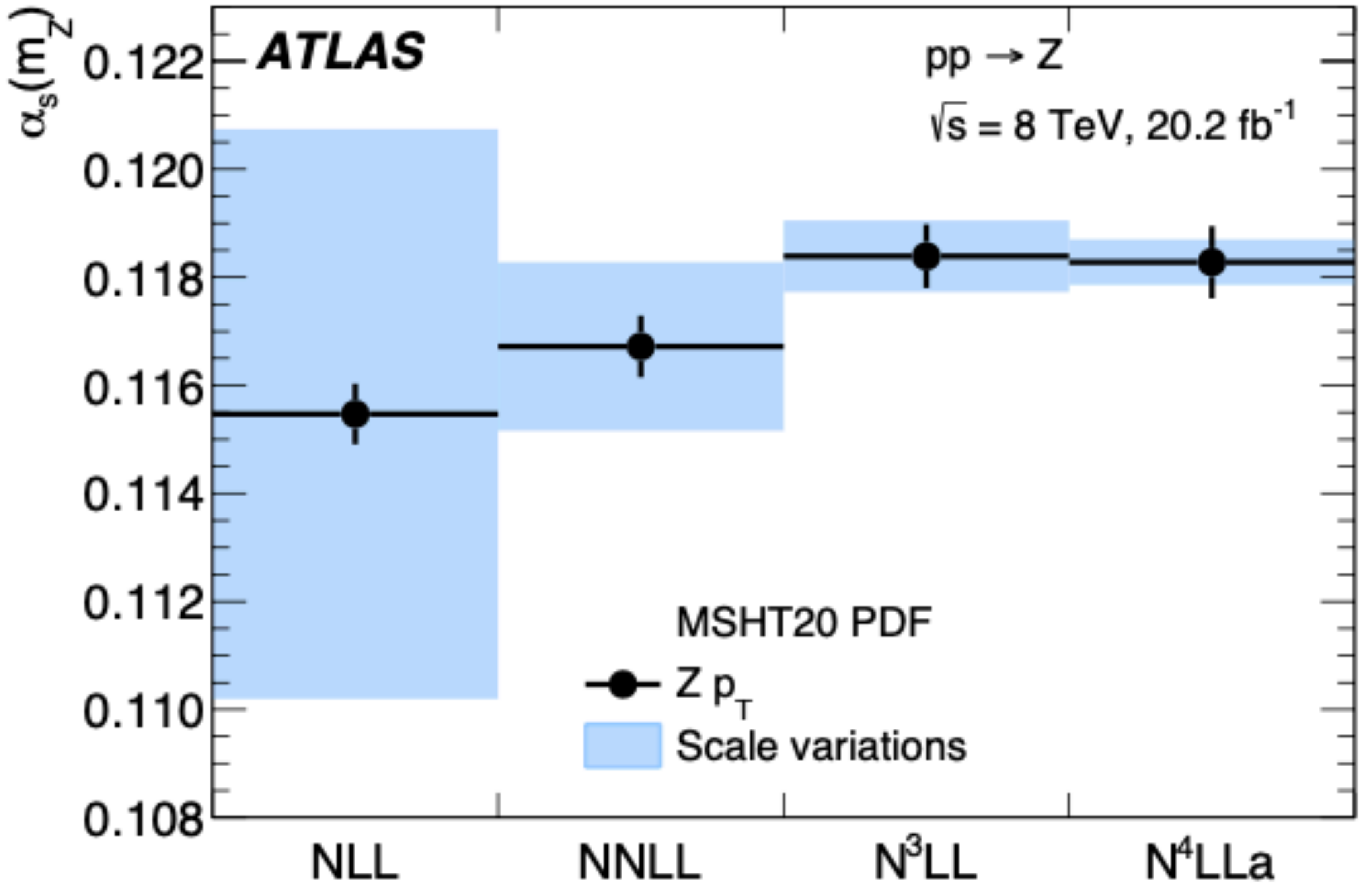


Statistical uncertainty dominant

ATLAS Z p_T: nominal results



- Experimental sensitivity evaluated with pseudodata: $\Delta\alpha_S/\alpha_S$ = 0.05%
- Postfit χ^2/dof = 82/72
- Determination performed at lower orders demonstrating convergence of the perturbative series



ATLAS Z p_T: theory uncertainties

Summary of the uncertainties in units of 10^{-3}

Experimental uncertainty	±0.44	
PDF uncertainty	±0.51	
Scale variation uncertainties	±0.42	
Matching to fixed order	0	−0.08
Non-perturbative model	+0.12	−0.20
Flavour model	+0.40	−0.29
QED ISR	±0.14	
N^{4}LL approximation	±0.04	
Total	+0.91	−0.88

- Scale: 14 indipendent variations (μ_R, μ_F, Q)
- QED ISR uncertainty from half the LL corrections, validated at NLL
- Matching uncertainty estimated by removing the unitarity constraint (canonical logarithms)
- Uncertainty of the N4LL approximation one order of magnitude smaller than missing higher order uncertainties from scale variations
- Flavour model: effect of charm- and bottom-quark masses and threshold

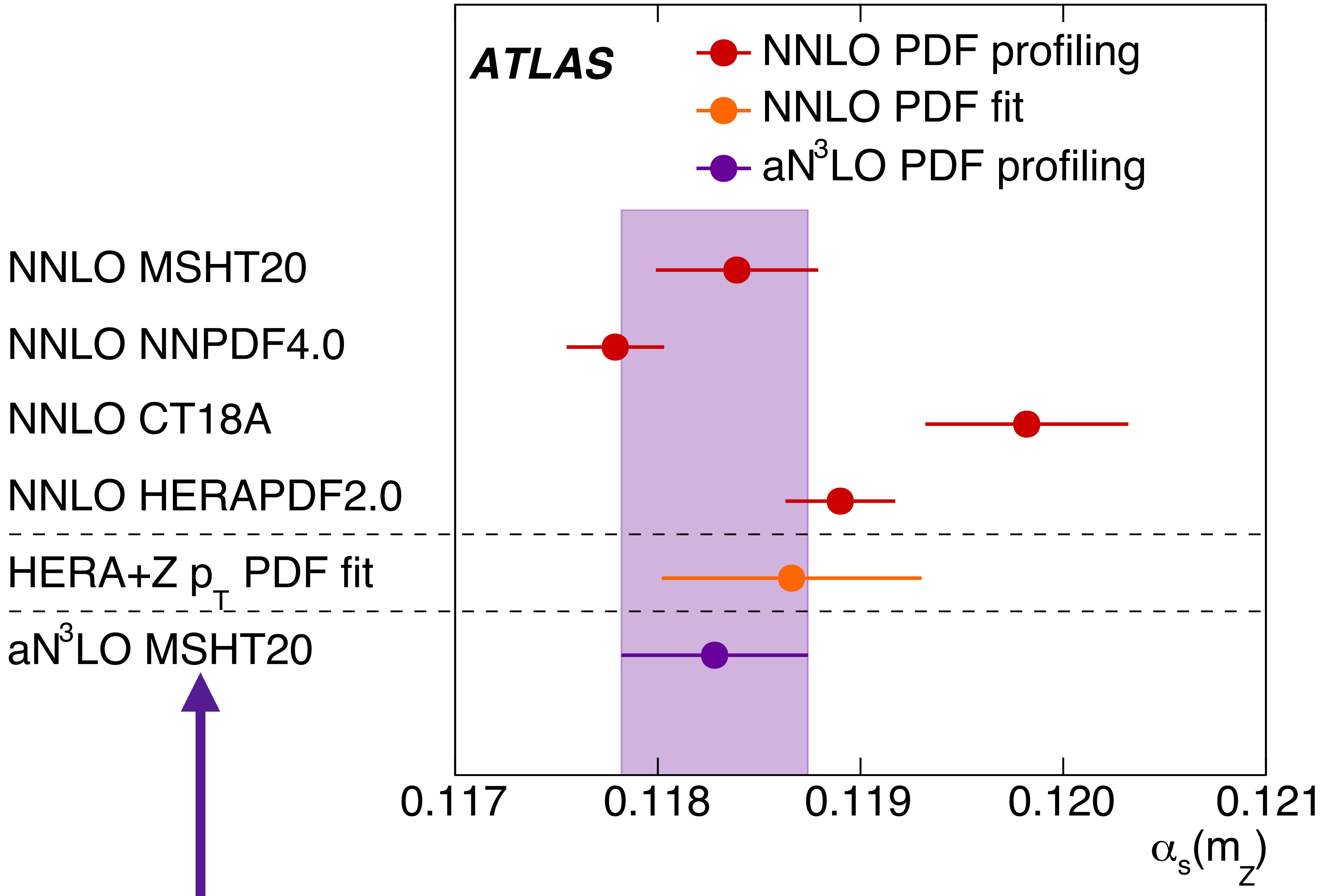
ATLAS Z p_T: fit and profiling

- At N4LL+N3LO only one N3LO PDF set is available: MSHT20an3lo

- Different PDF sets studied at N3LL+N3LO: spread of NNLO PDFs is ±0.00102, driven by NNPDF4.0-CT18A difference (with CT14 the spread would be a factor of 2 smaller)

- Adding HERA data to the fit (counted twice), the spread is reduced to ±0.00016, around a central value of 0.11804

ATLAS Z p_T: fit and profiling



Final result: $\alpha_S(m_Z) = 0.1183 \pm 0.0009$

Final result compared to:

- NNLO PDF profiling
- NNLO PDF fit

PDF set	$\alpha_s(m_Z)$	PDF uncertainty	g [GeV^2]	q [GeV^4]
MSHT20 [37]	0.11839	0.00040	0.44	−0.07
NNPDF4.0 [84]	0.11779	0.00024	0.50	−0.08
CT18A [29]	0.11982	0.00050	0.36	−0.03
HERAPDF2.0 [65]	0.11890	0.00027	0.40	−0.04

- NNLO PDF spread is ±0.00102
- Adding HERA data to the fit (counted twice), the spread is reduced to ±0.00016, around a central value of 0.11804

CMS Inclusive jets: comparison with 13 TeV

13 TeV

$$\alpha_S(m_Z) = 0.1166 \pm 0.0014_{fit} \pm 0.0004_{scale} \pm 0.0007_{model} \pm 0.0001_{param}$$

$$= 0.1166 \pm 0.0017$$

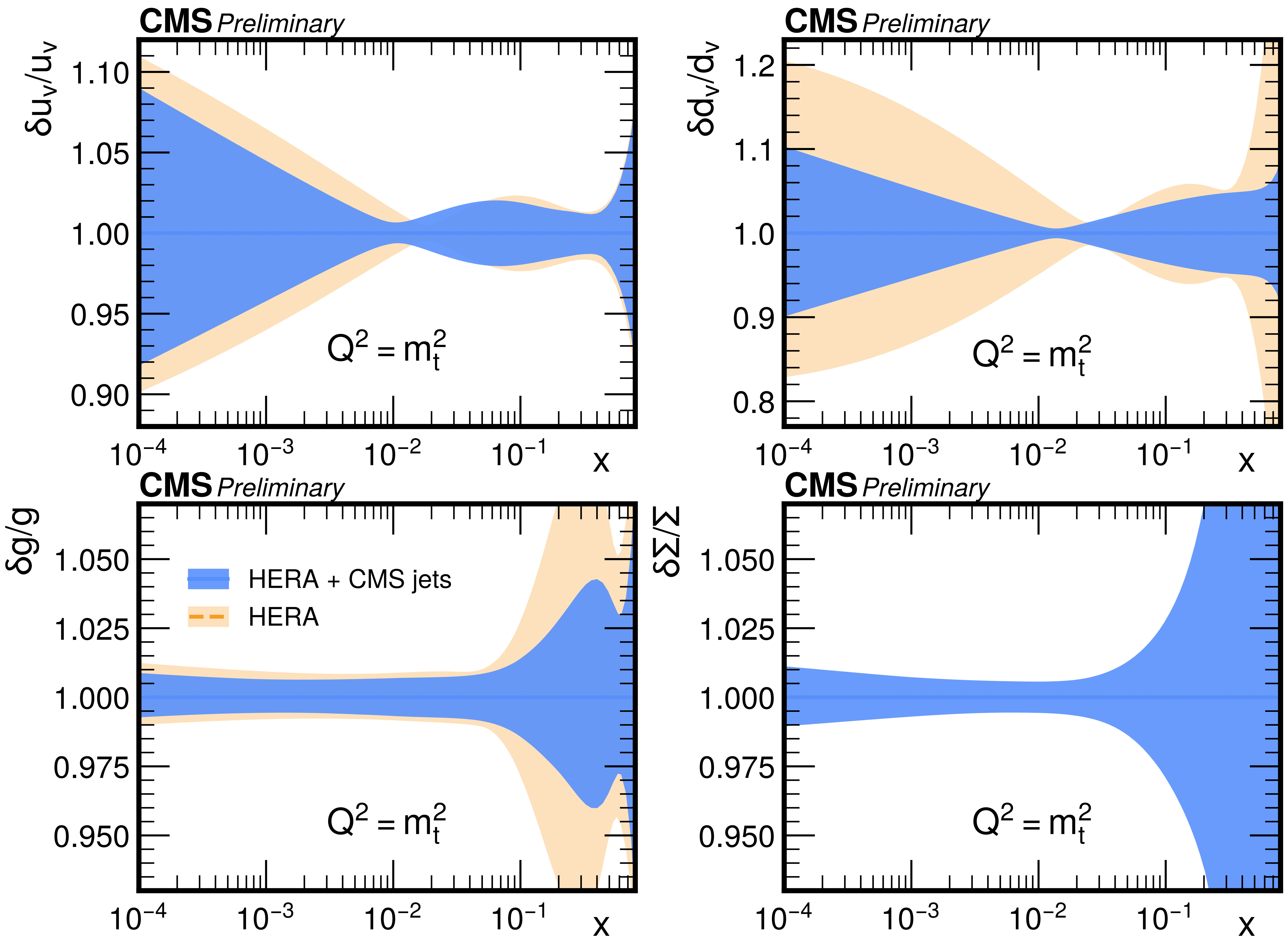
All jets

$$\alpha_S(m_Z) = 0.1176 \ {}^{+0.0009}_{-0.0009}\ (\text{fit})\ {}^{+0.0009}_{-0.0010}\ (\text{scale})\ {}^{+0.0006}_{-0.0004}\ (\text{model})\ {}^{+0}_{-0.00004}\ (\text{param})$$

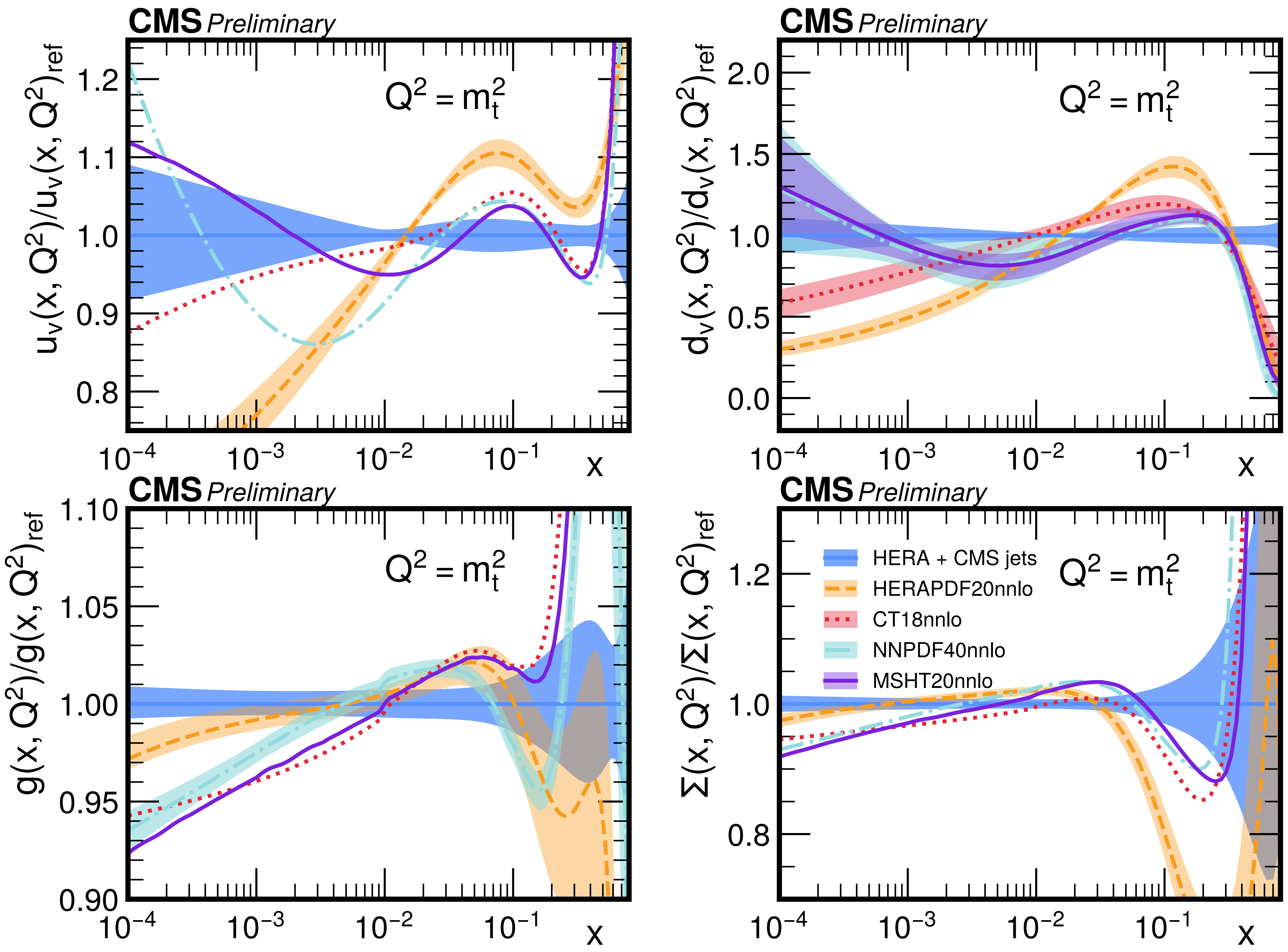
$$= 0.1176^{+0.0014}_{-0.0016}$$

- **Fit uncertainty reduced of ~37%**
- **Model and parametrisation similar order of magnitude**
- **Scale uncertainty dominant contribution considering all jets**

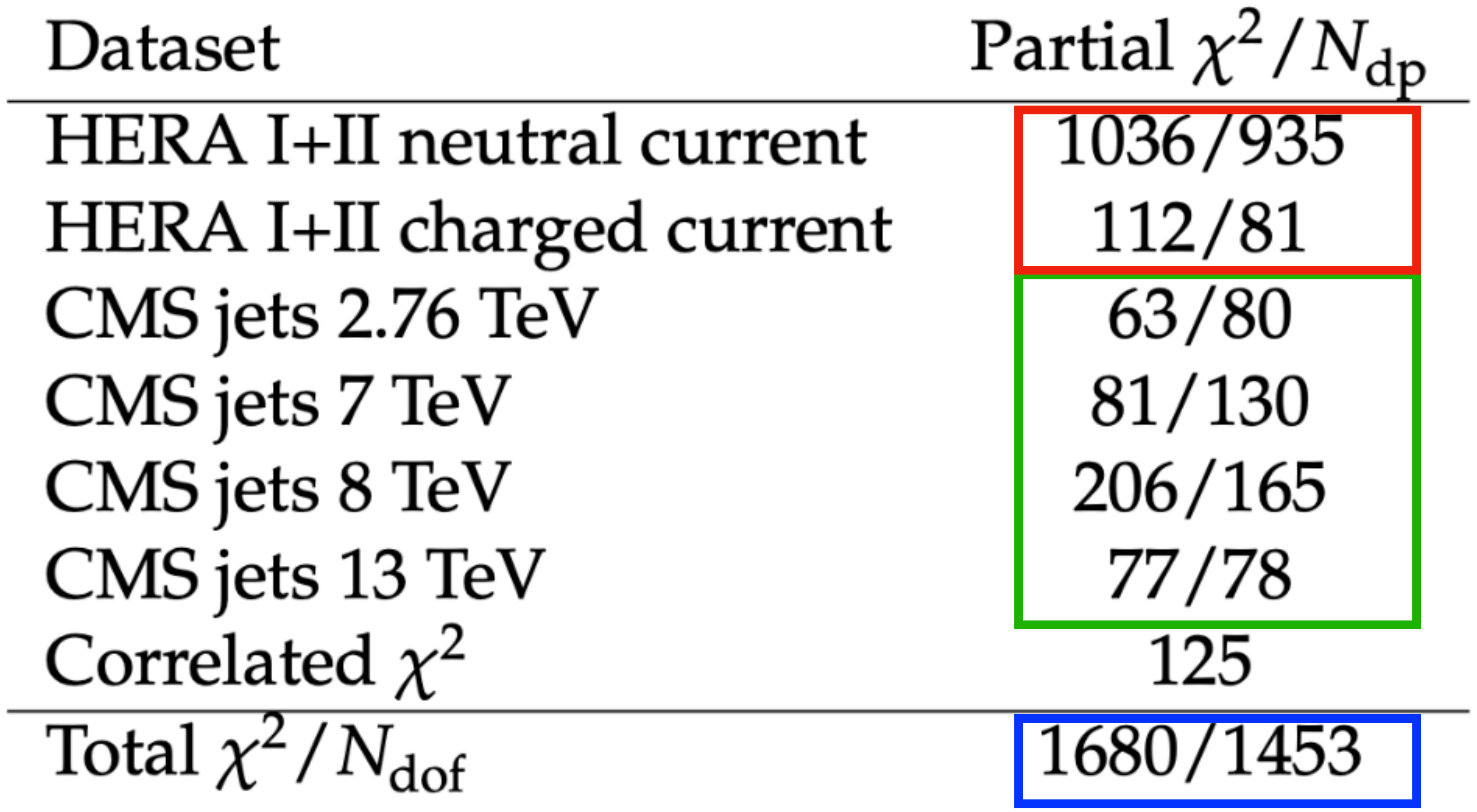
CMS Inclusive jets: comparison with HERA-only fit



CMS Inclusive jets: comparison with global PDF fitters



Results: χ^2 per measurement



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 arxiv1506.06042
- CMS jet data consistent with each other: $\chi^2/\mathrm{ndp} = 427/453$

PDF parametrisation

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 $x\bar{D}(x)$

$$
\begin{aligned}
xg(x) &= A_g x^{B_g}(1-x)^{C_g}(1 + D_g x + E_g x^2), \\
xu_v(x) &= A_{u_v} x^{B_{u_v}}(1-x)^{C_{u_v}}(1 + E_{u_v} x^2), \\
xd_v(x) &= A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}, \\
x\overline{U}(x) &= A_{\overline{U}} x^{B_{\overline{U}}}(1-x)^{C_{\overline{U}}}(1 + D_{\overline{U}} x), \\
x\overline{D}(x) &= A_{\overline{D}} x^{B_{\overline{D}}}(1-x)^{C_{\overline{D}}}(1 + E_{\overline{D}} x^2).
\end{aligned}
$$

- $x\bar{U}(x) = x\bar{u}(x)$ 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 $f_s = x\bar{s}/(x\bar{d} + x\bar{s}) = 0.4$

Parametrisation uncertainty

Parametrisation scan: Add D and E parameters (where missing) one by one until no further improvement in the ***bayesian information criterion***

$$\mathbf{BIC} = \mathbf{k} \times \mathbf{log(N)} + \chi^2$$

where $\mathrm{N} = \mathrm{dof} + \mathrm{k}$

k free parameters in the fit

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

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

$$xd_v(x) = A_{d_v} x^{B_{d_v}}(1-x)^{C_{d_v}}(1+D_{d_v} x + E_{d_v} x^2)$$

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

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

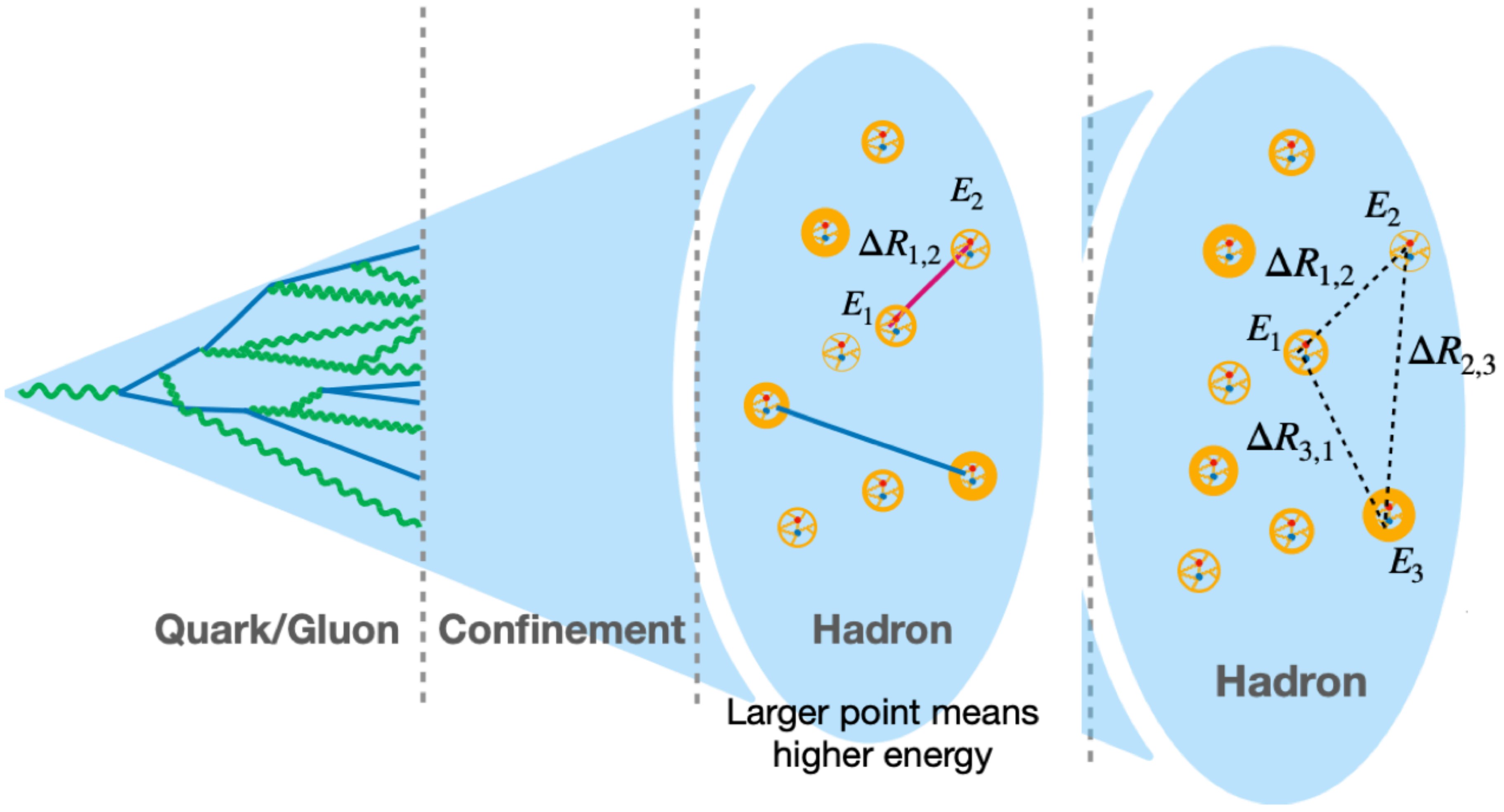
No improvement in the BIC

Improvement in the BIC

PDF parametrisation uncertainties taken as the envelope between all the other PDF parametrisations and the nominal one (i.e. between nominal and nominal+Ddv)

CMS $\alpha_S(m_Z)$ at NNLL$_{approx}$: energy corellators at 13 TeV

More details parallel talk from O. Kuprash



$$E3C/E2C \text{ (at LL)} \propto \alpha_S(Q)\ \ln x_L + O(\alpha_S^2)$$

$$E2C = \frac{d\sigma}{dx_L} = \sum_{i,j}^{n} d\sigma \boxed{\frac{E_iE_j}{E^2}} \delta(x_L - \Delta R_{i,j})$$

$$E3C = \frac{d\sigma}{dx_L} = \sum_{i,j,k}^{n} d\sigma \boxed{\frac{E_iE_jE_k}{E^2}} \times\ \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$

ΔR: angular distance

x_L: maximum ΔR

- **Large weight: energetic**
- **Low weight: soft**

→ "mapping" of parton stages in jet formation

Datasets and trigger strategy:

- $L = 36.3\ fb^{-1}$ (2016)
- Leading jets with $p_T^{HLT} > 60$ GeV, jets ak4

Phase space selection:

- Exactly two jets
- $|\eta| < 2.1,\ 97 < p_T^{jet} < 1784$ GeV (8 bins)
- $p_T^{particle} > 1$GeV

- **D'Agostini unfolding in 3D** (x_L, p_T^{jet}, energy weight)

CMS $\alpha_S(m_Z)$ at NNLL$_{approx}$: energy corellators at 13 TeV

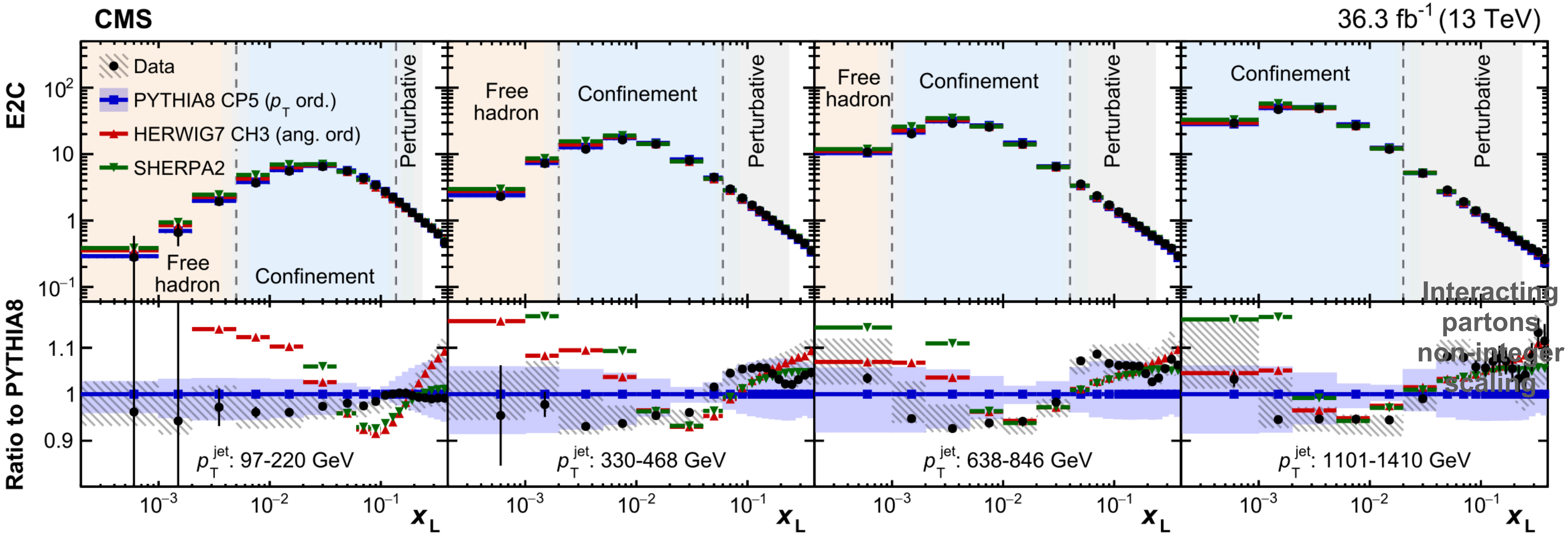


FIG. 1. Measured (unfolded) and simulated E2C x_L distributions, in four p_T bins. The lower panels show the ratios to the PYTHIA8 reference. The data statistical (bars) and systematic (boxes) uncertainties are also shown, as is the PYTHIA8 uncertainty (blue band).

time

47

CMS $\alpha_S(m_Z)$ at NNLL$_{approx}$: energy corellators at 13 TeV

Unfolded $\frac{E3C}{E2C}$ vs MC simulations → Slope of $\frac{E3C}{E2C}$ sensitive to α_s

Benefit of ratio:

- Suppressed ambiguity in jet quark/gluon composition
- Reduced uncertainty
  - Exp. syst: ~8% → ~3%
  - Data/MC difference ~10% → ~3%

$$\alpha_S(m_z) = 0.1229^{+0.0014}_{-0.0012}\,(\text{stat})\,{}^{+0.0030}_{-0.0033}(\text{theo})\,{}^{+0.0023}_{-0.0036}(\text{exp})$$

Largest sources:

- Renormalisation scale
- Energy scales of jet constituents

Chi2 definition

γ sensitivity of a measurement to a given error source

μ^i measurement

$$\chi^2_{\mathrm{exp}}(\boldsymbol{m},\boldsymbol{b}) = \sum_i \frac{\left[m^i - \sum_\alpha \gamma^i_\alpha \mu^i b_\alpha - \mu^i\right]^2}{\left(\delta_{i,\mathrm{stat}}\,\mu^i\right)^2 + \left(\delta_{i,\mathrm{uncor}}\,\mu^i\right)^2} + \sum_\alpha b_\alpha^2$$

m fitted model parameters

PDFs and α_S

Statistical uncertainty

uncorrelated error sources

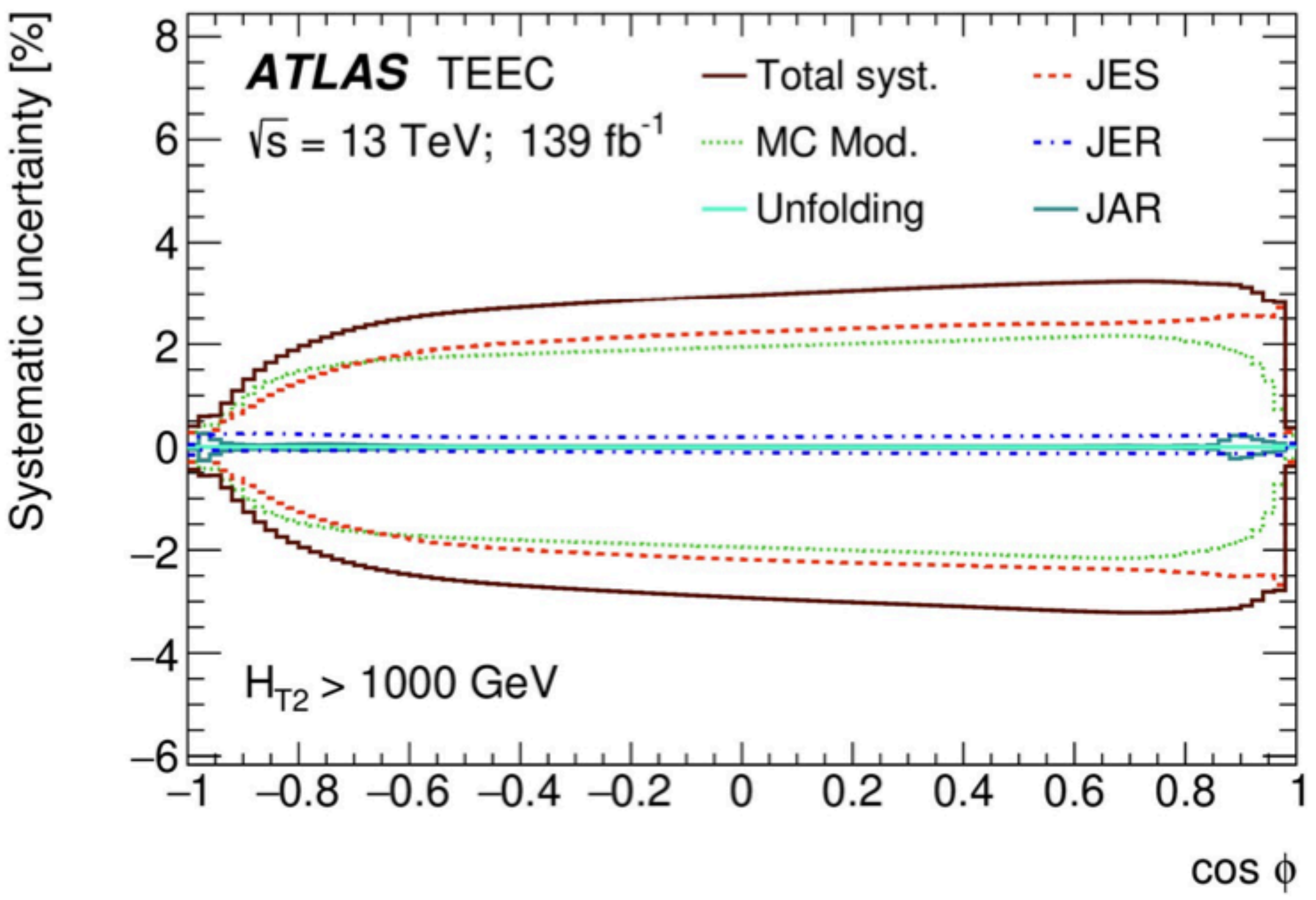
b nuisance parameters for correlated error sources

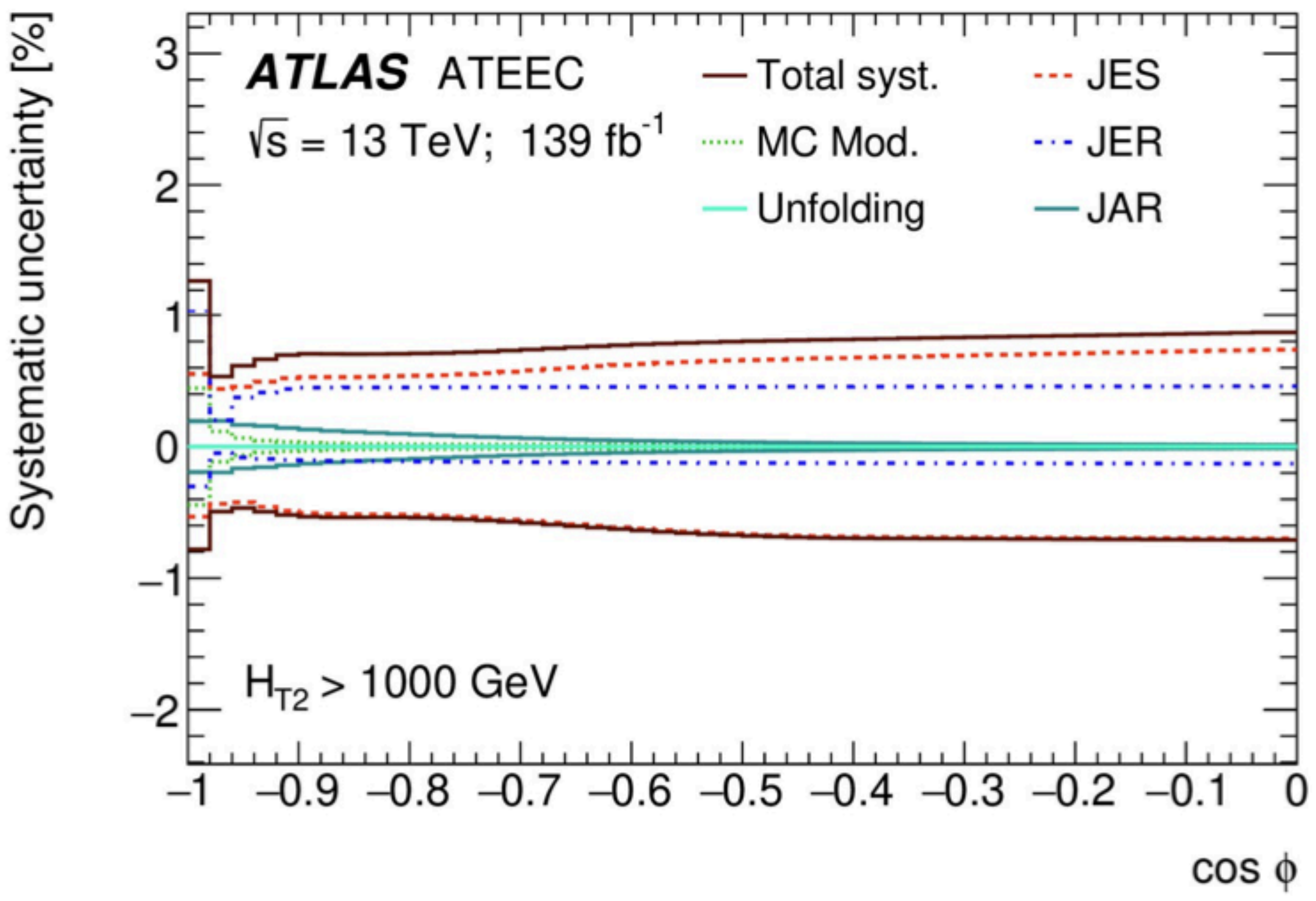
Systematic uncertainties

- In the limit where stat and syst uncertainties are gaussian → equivalent to a profile likelihood minimisation
- PDFs and α_S minimised with MINUIT, uncertainties computed asymmetrically with Pumplin method (CTEQ)
- Systematic uncertainties minimised analytically with matrix inversion

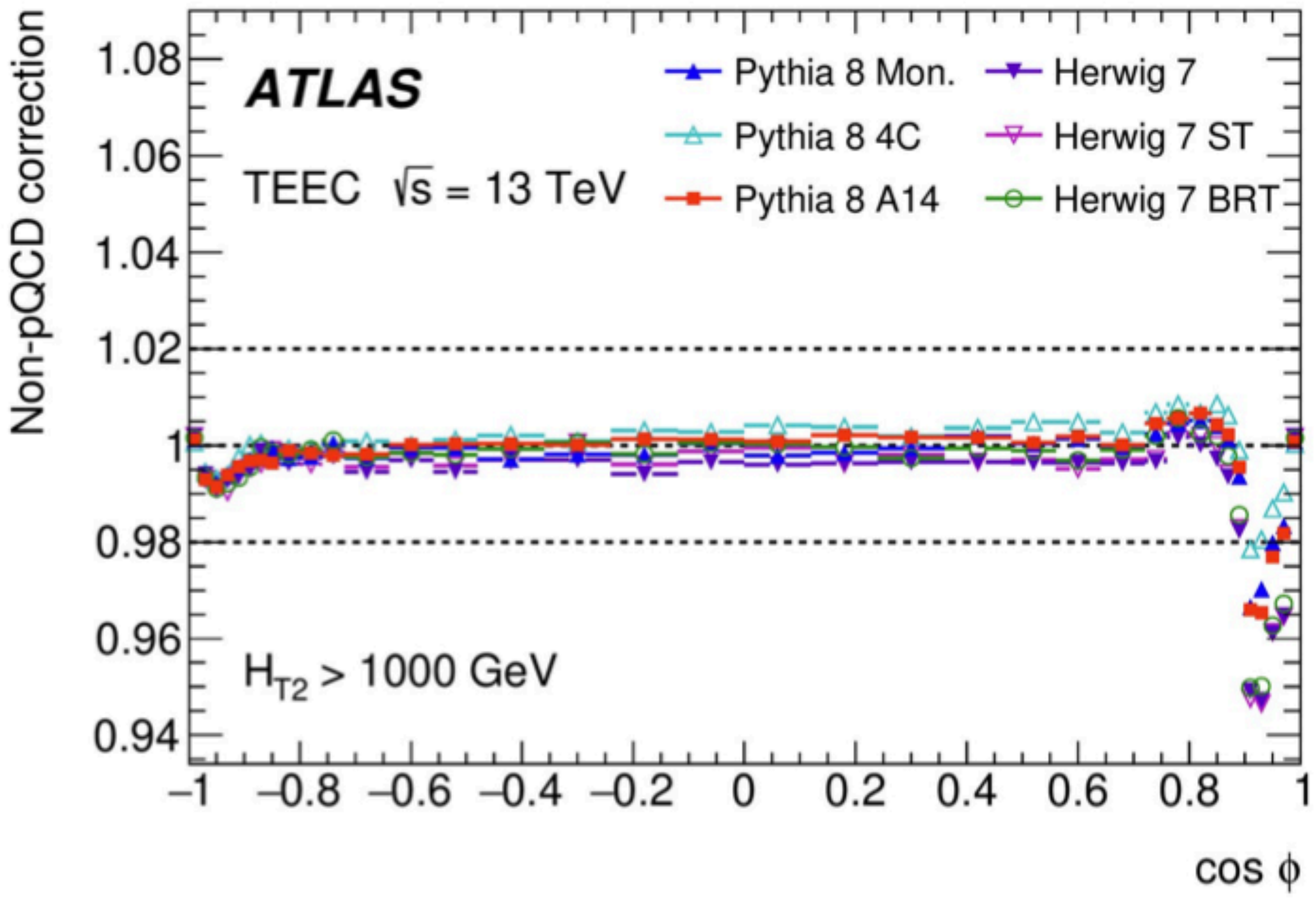
Correlations of systematic uncertainties within/across data sets is the key aspect
(*advantage of a fit within experiment*)

ATLAS (A)TEEC measurement

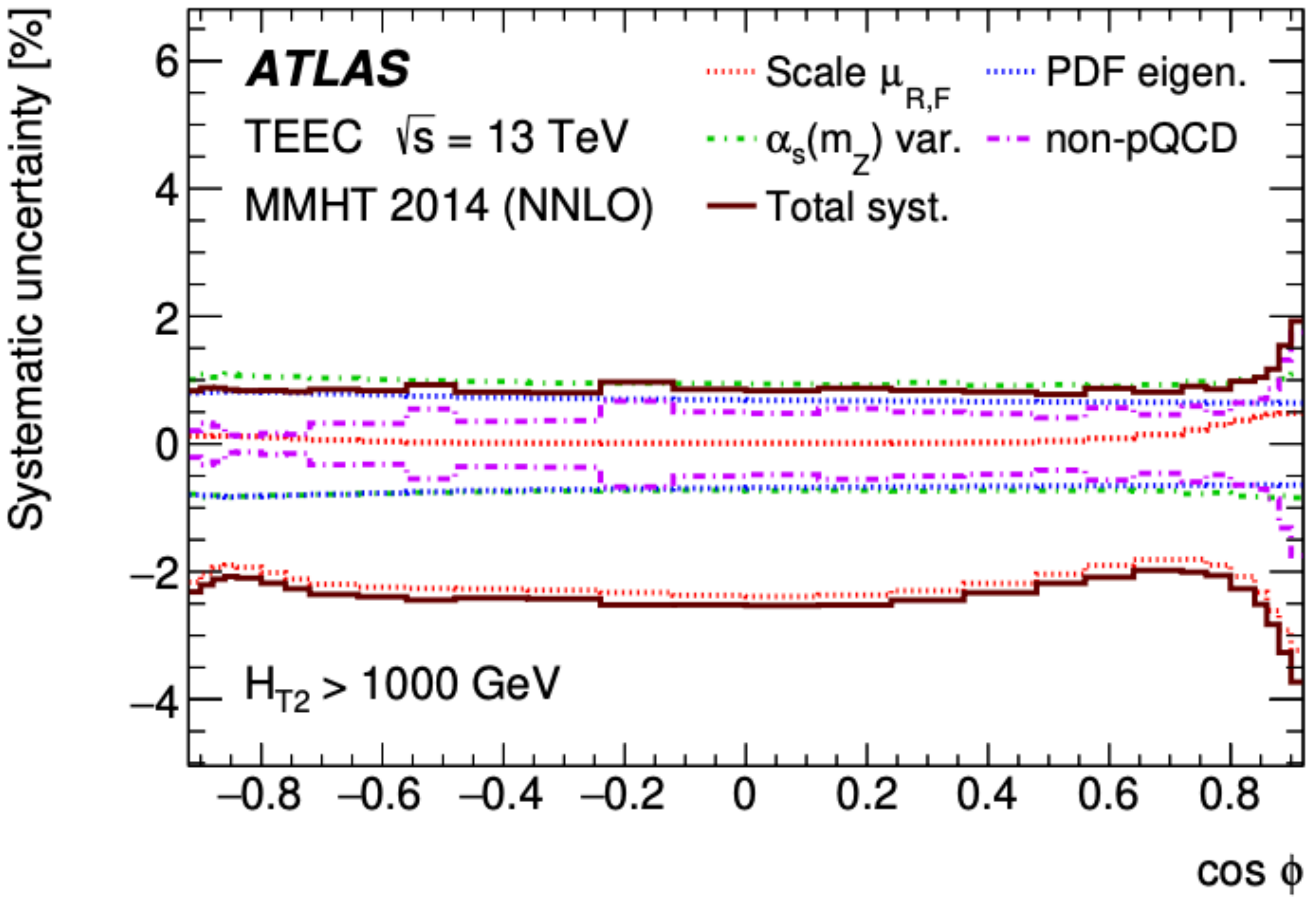


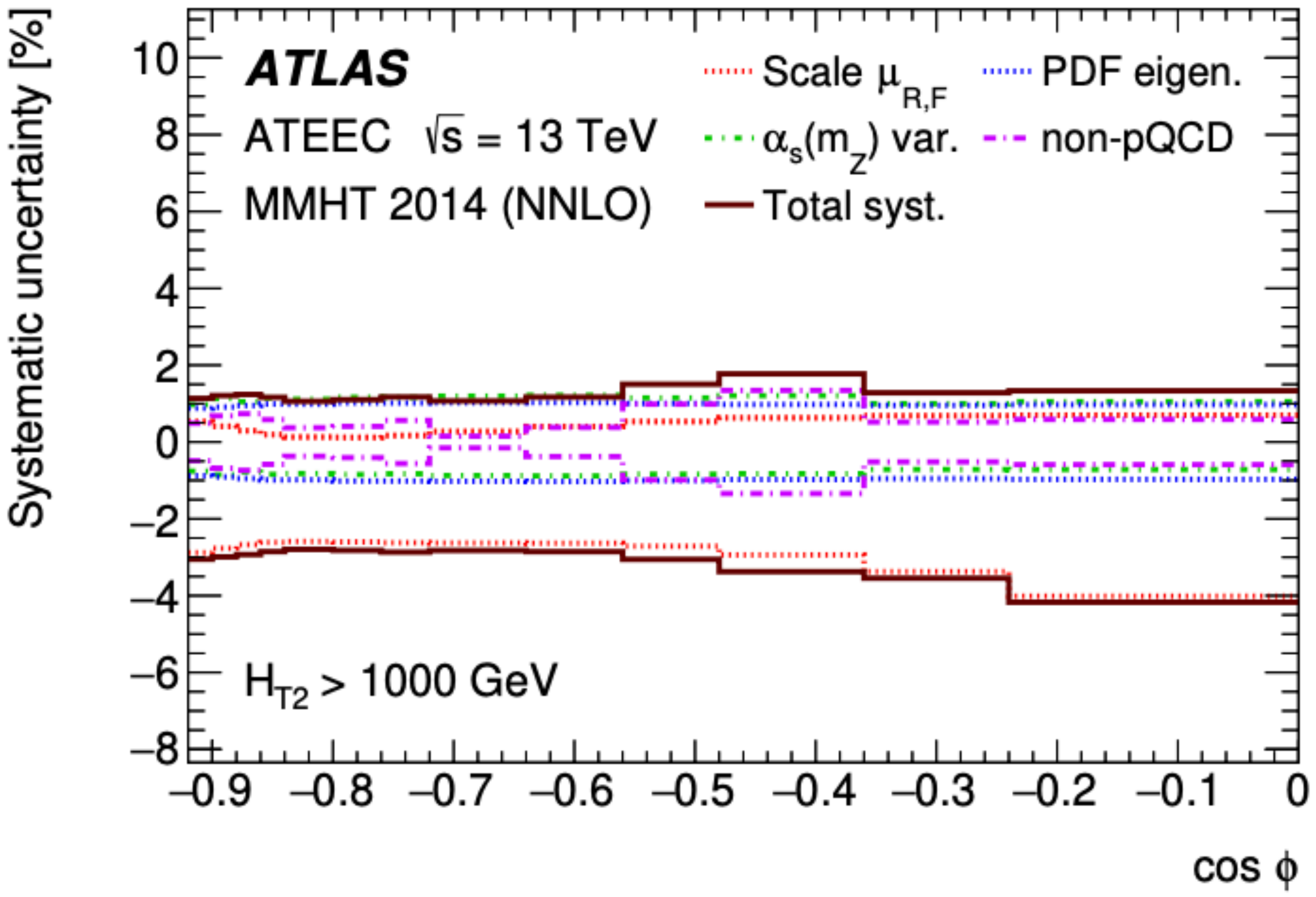


- Full Run 2 dataset: 139 fb-1
- Anti-kT calibrated PF jets with $p_T > 60$ GeV and $|\eta| < 2.4$
- Experimental uncertainties dominated by jet modeling and JES/JER
- Small size of parton-to-particle corrections, except in the collinear region



ATLAS (A)TEEC measurement





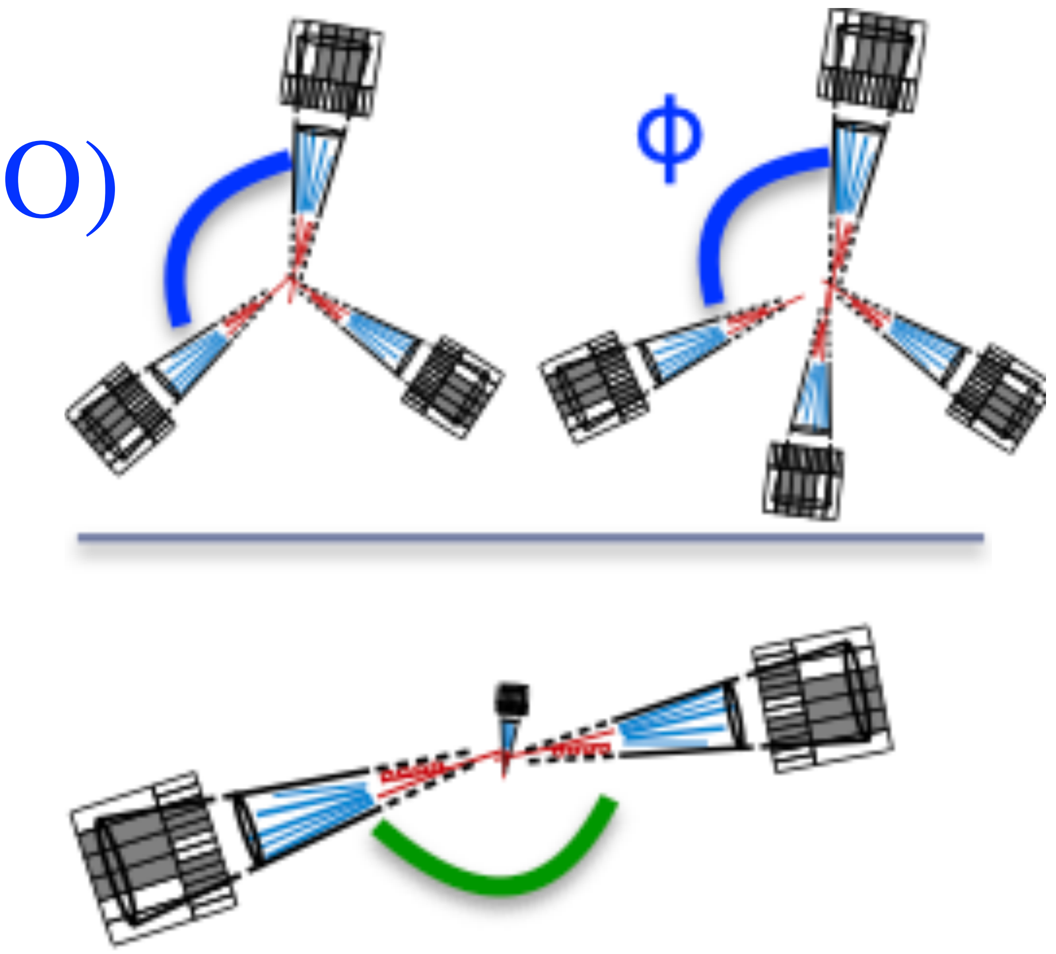
- Scale: envelope of 6 variations (μ_R, μ_F), still dominant contribution
- PDF: computed with PDF replicas/eigenvectors
- NP: envelope of different generators and tunes

CMS $\alpha_S(m_Z)$ at NLO: azimuthal correlations at 13 TeV

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

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

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



$$\propto \frac{\alpha_S^3}{\alpha_S^2}$$

N_{nbr}: # neighbouring jets

$p_{T\,min}^{nbr}$: minimum p_T that neighbouring jets need to exceed

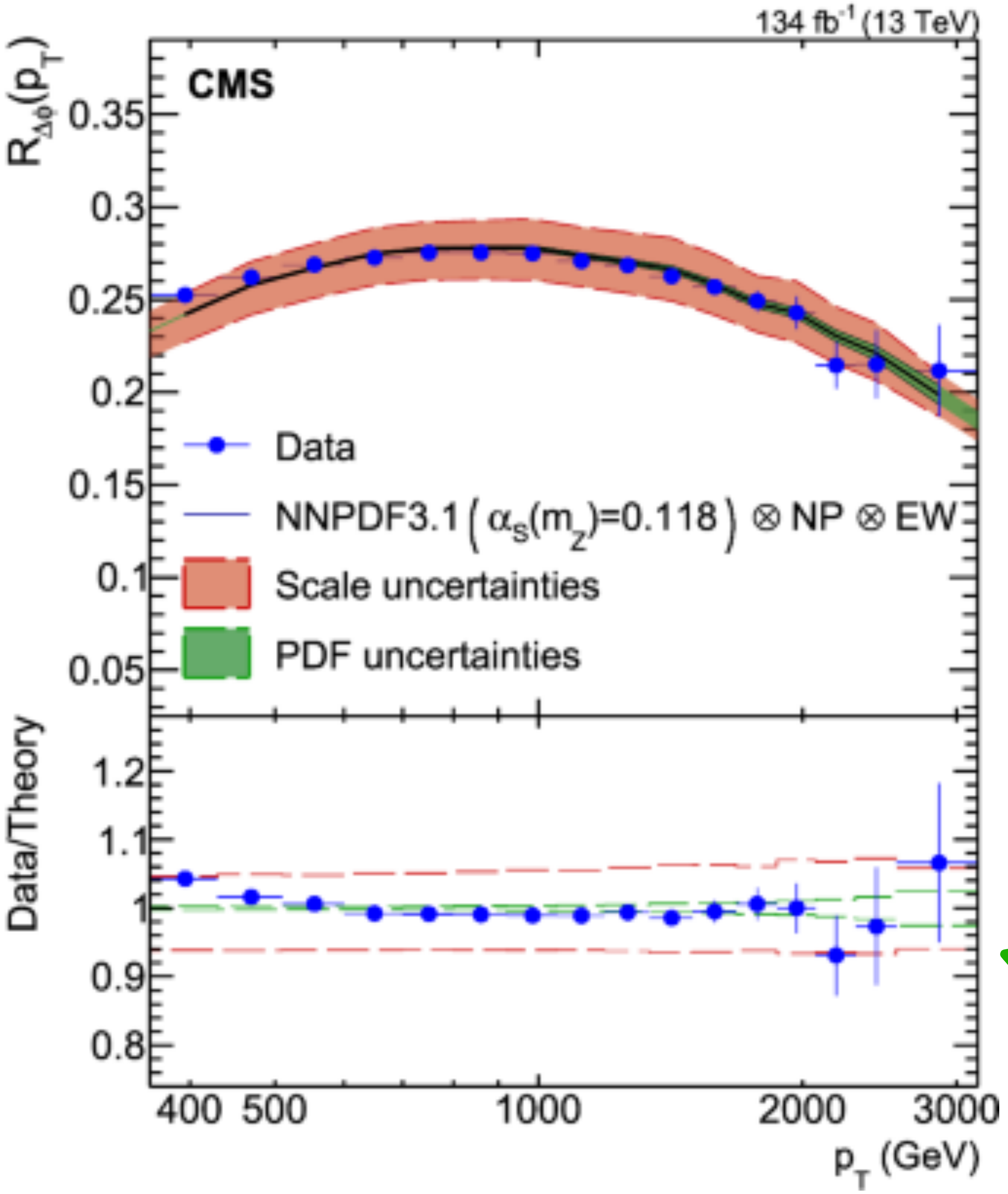
$\Delta\phi$: azimuthal angle separation

- **Datasets and trigger strategy**
  - $L = 134\ fb^{-1}$ (2016-2018), leading jets with $p_T^{HLT} > 40$ GeV, jets ak7
- **Phase space selection:**
  - $p_{T\,min}^{nbr} > 100$ GeV and $\frac{2\pi}{3} < \Delta\phi < \frac{7\pi}{8}$

Results of azimuthal correlations among jets

NEW!

SMP-22-005



- Unfolded results vs QCD predictions (NLOJet++ × fastNLO) using different PDFs

- **Unfolded observable:**

$$R_{\Delta\phi}(p_T) = \frac{\sum_{n=0}^{\infty} nN(p_T, n)}{\sum_{n=0}^{\infty} N(p_T, n)}$$

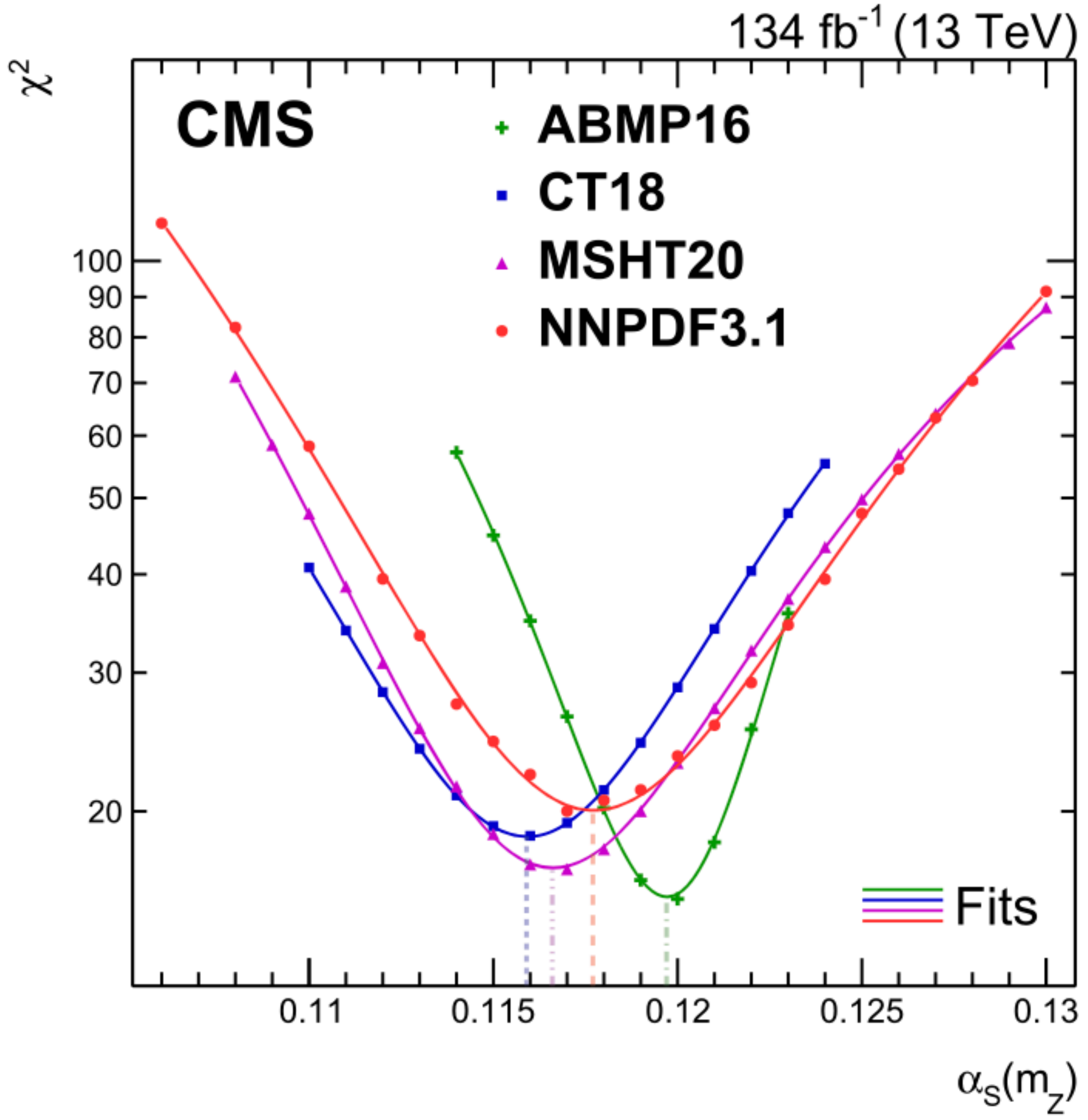
Scales $\mu_r = \mu_f = \hat{H}_T/2$ **;**

($\hat{H}$ **= sum of parton energies)**

Scale uncertainty dominant

PDF uncertainty reduced in the ratio

CMS $\alpha_S(m_Z)$ at NLO: azimuthal correlations at 13 TeV



- **Using different PDFs: Sensitivity to $\alpha_S(m_Z)$**

NLO PDF set	$\alpha_S(m_Z)$	Exp.	NP	PDF	EW	Scale	χ^2/n_{dof}
ABMP16	0.1197	0.0008	0.0007	0.0007	0.0002	$^{+0.0043}_{-0.0042}$	16/16
CT18	0.1159	0.0013	0.0009	0.0014	0.0002	$^{+0.0099}_{-0.0067}$	19/16
MSHT20	0.1166	0.0013	0.0008	0.0010	0.0003	$^{+0.0112}_{-0.0063}$	17/16
NNPDF3.1	0.1177	0.0013	0.0011	0.0010	0.0003	$^{+0.0114}_{-0.0068}$	20/16

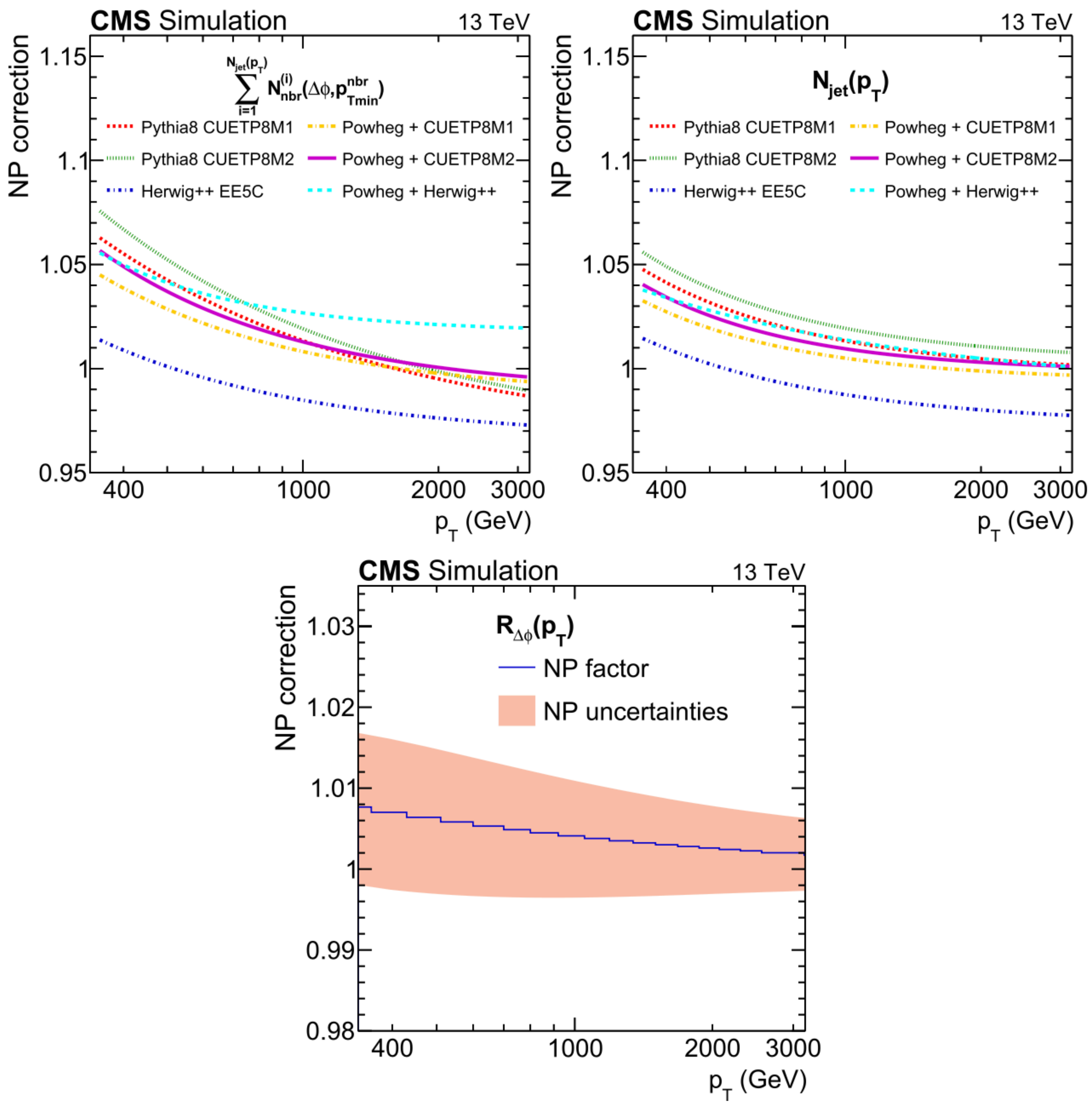
- **Spread in results due to PDF choice:**

  ±0.0020 (PDF choice)

Final result: $\alpha_S(m_Z) = 0.117^{+0.0117}_{-0.0074}$

$^{+0.0114}_{-0.0068}\ (scale)\ \pm 0.0013\ (exp) \pm 0.0011\ (NP)\ \pm 0.0010\ (PDF) \pm 0.0003\ (EW) \pm 0.0020\ (PDF\ choice)$

CMS $\alpha_S(m_Z)$ at NLO: azimuthal correlations at 13 TeV, NP and EW



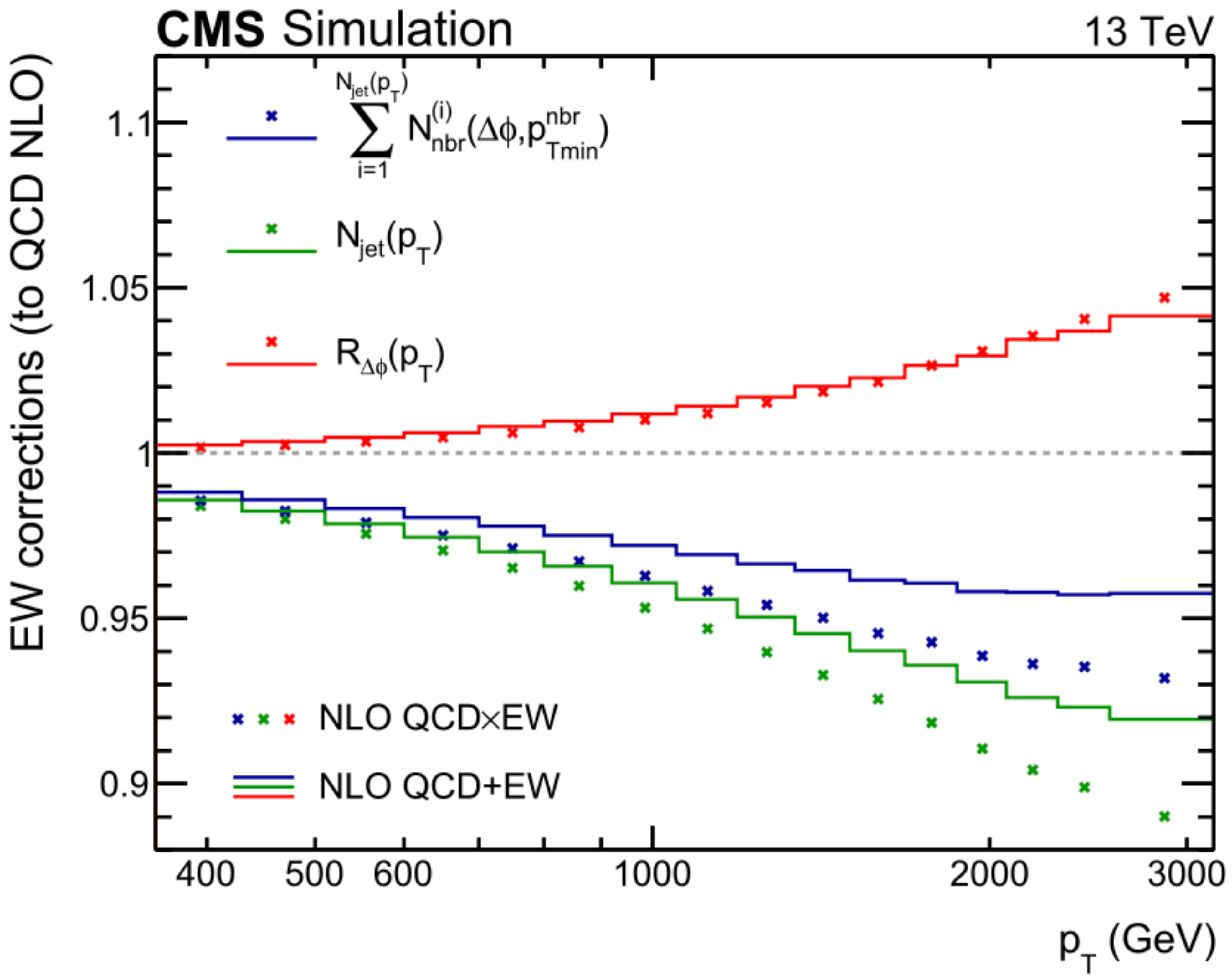


Fig. 7 Electroweak corrections for the numerator (blue) and denominator (green) of Eq. (1), and for the $R_{\Delta\phi}(p_T)$ ratio itself (red). The solid lines correspond to the additive combination of NLO EW corrections to the QCD process (NLO QCD + EW), and the markers represent the multiplicative combination (NLO QCD × EW)

Multi-differential 2-jet production

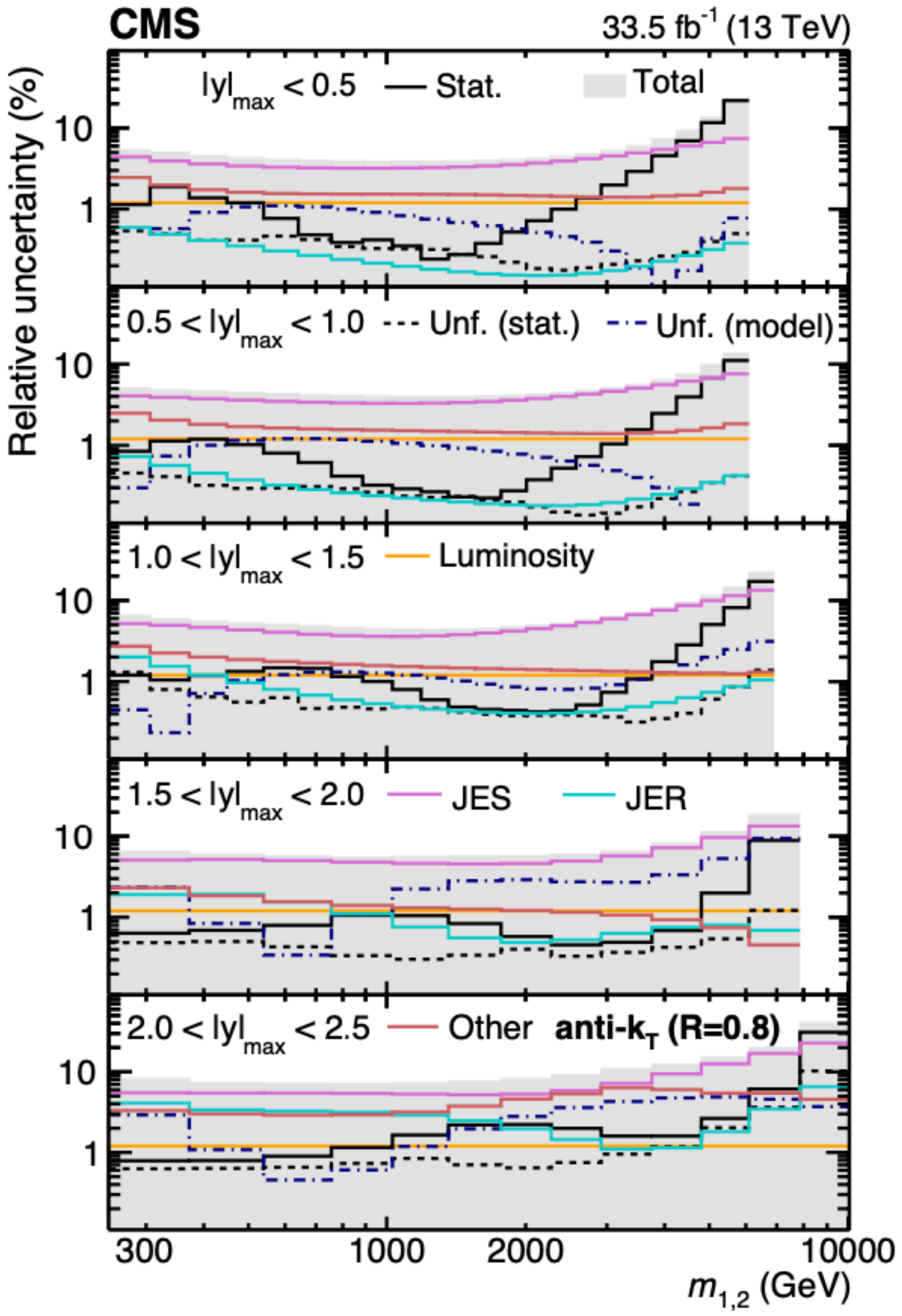
Datasets and trigger strategy

- $L \sim 35\ fb^{-1}$ (2016)
- Single-jet (di-jets) HLT selections $p_T^{HLT} > 40$ for 2-D (3-D)
- jets ak4 and ak8

Event Selection

- Dijet system

Experimental dominant contribution: JES, JER, luminosity



Dijets

2D

$$\begin{aligned}\alpha_S(m_Z) &= 0.1179 \pm 0.0015\,(\text{fit}) \pm 0.0008\,(\text{scale}) \pm 0.0008\,(\text{model}) \pm 0.0001\,(\text{param.})\\ &= 0.1179 \pm 0.0019\,(\text{total}),\end{aligned}$$

3D

$$\begin{aligned}\alpha_S(m_Z) &= 0.1181 \pm 0.0013\,(\text{fit}) \pm 0.0009\,(\text{scale}) \pm 0.0006\,(\text{model}) \pm 0.0002\,(\text{param.})\\ &= 0.1181 \pm 0.0022\,(\text{total}),\end{aligned}$$

$\alpha_S(m_Z)$ from inclusive LHC $t\bar{t}$ x-sections

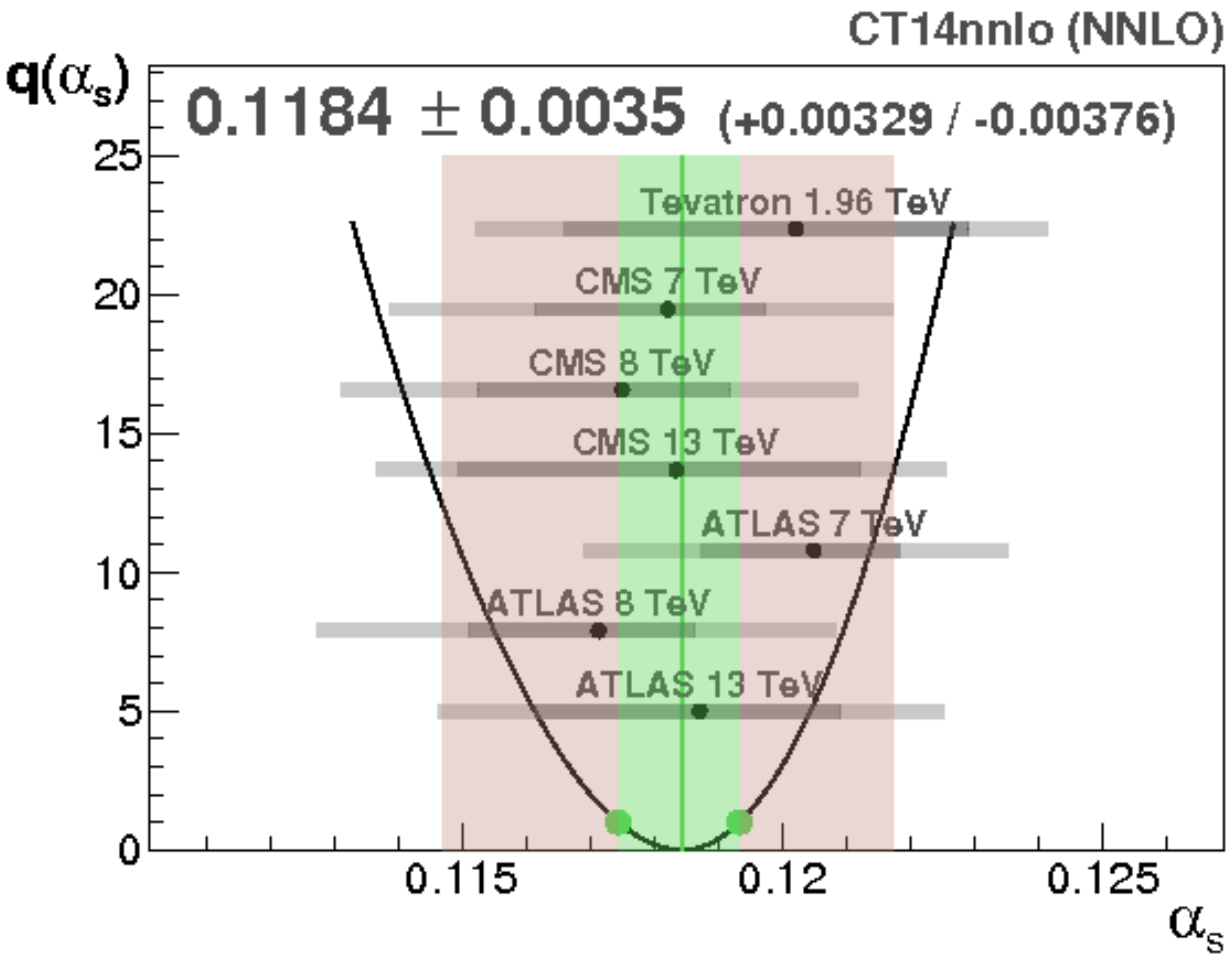
Compare $\sigma(exp, t\bar{t})$ to $\sigma(NNLO, t\bar{t})$ for diff PDFs and α_S

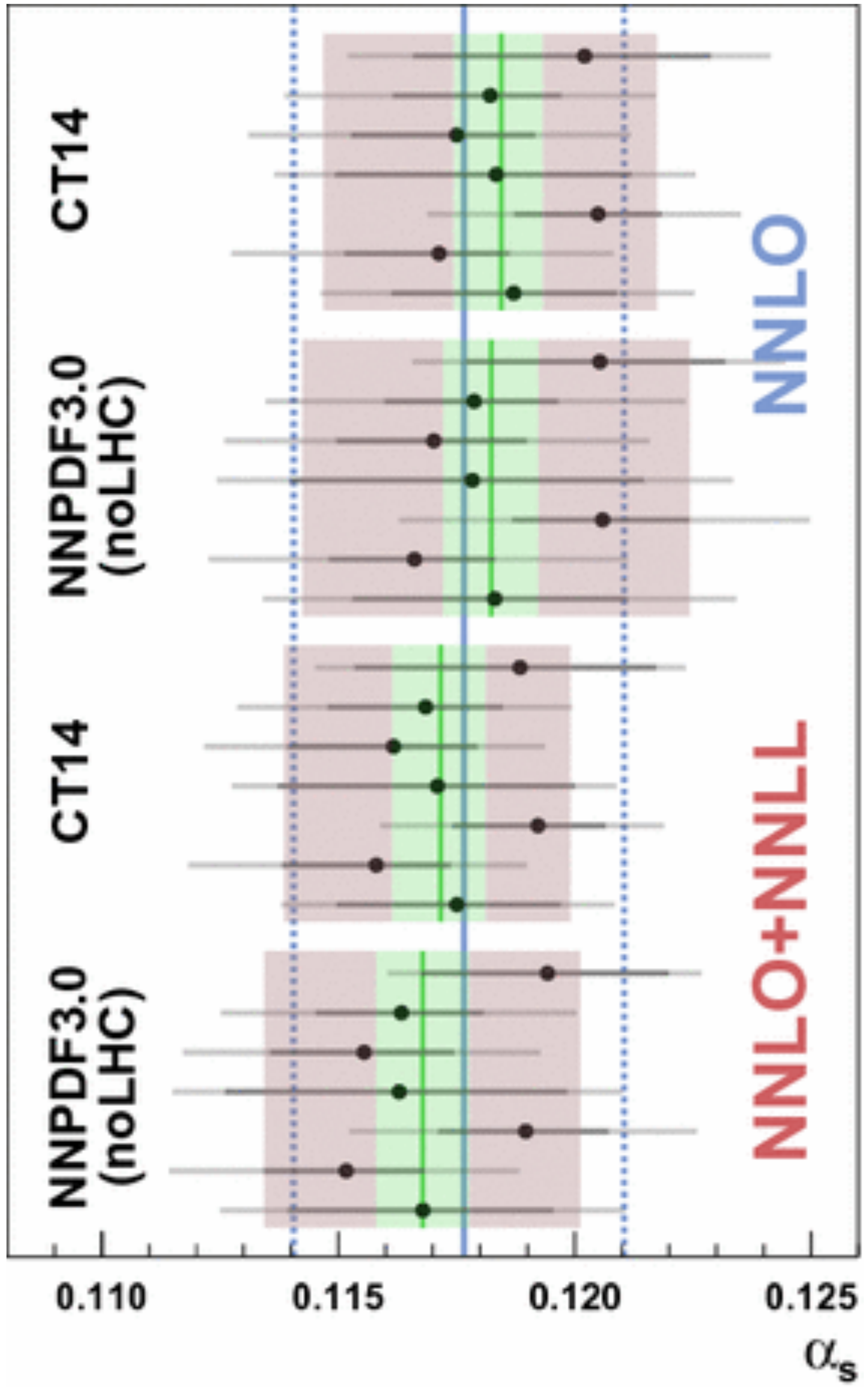
- Pro: Direct sensitivity to α_S at LO (via $gg \to t\bar{t}$)
- Cons: α_S, m_{top}, $g(x)$ correlated in $\sigma(t\bar{t})$

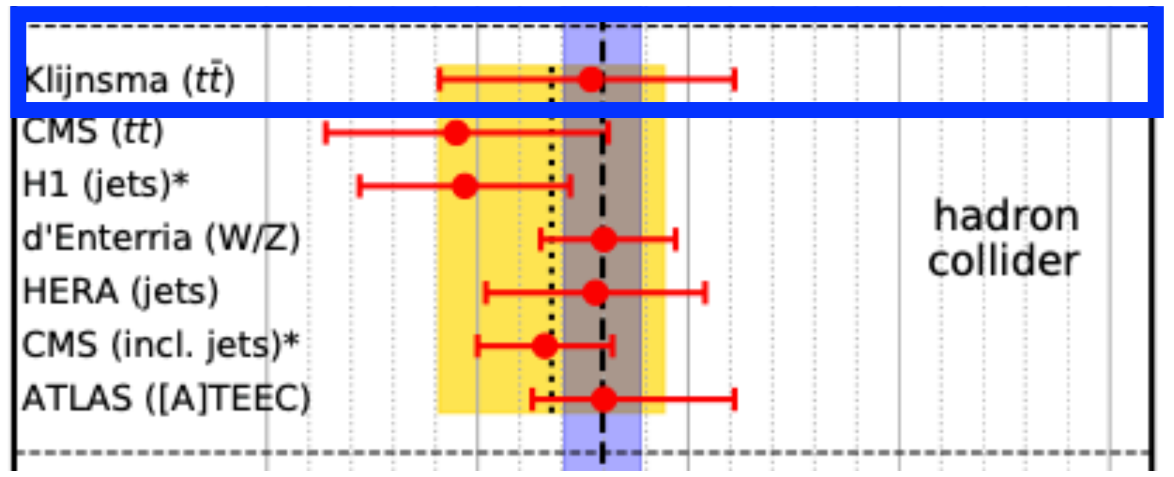
→ **only one parameter can be extracted from inclusive cross sections**

Combined extraction from LHC: from Klinjisma et al. EPJC 77, 778 (2017)

Procedure extends to 7 LHC data sets and combined $\alpha_S(m_Z)$ extracted



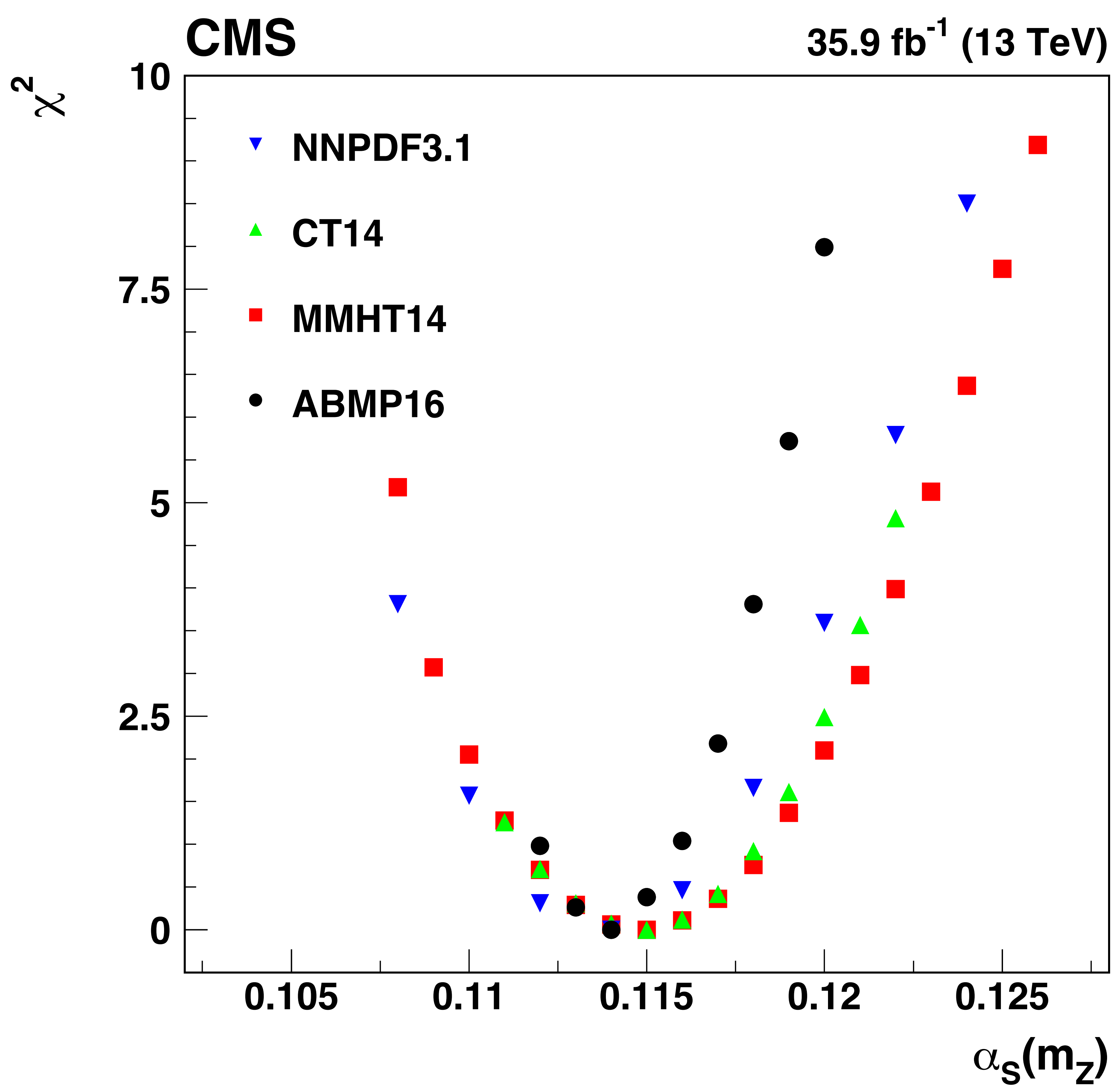


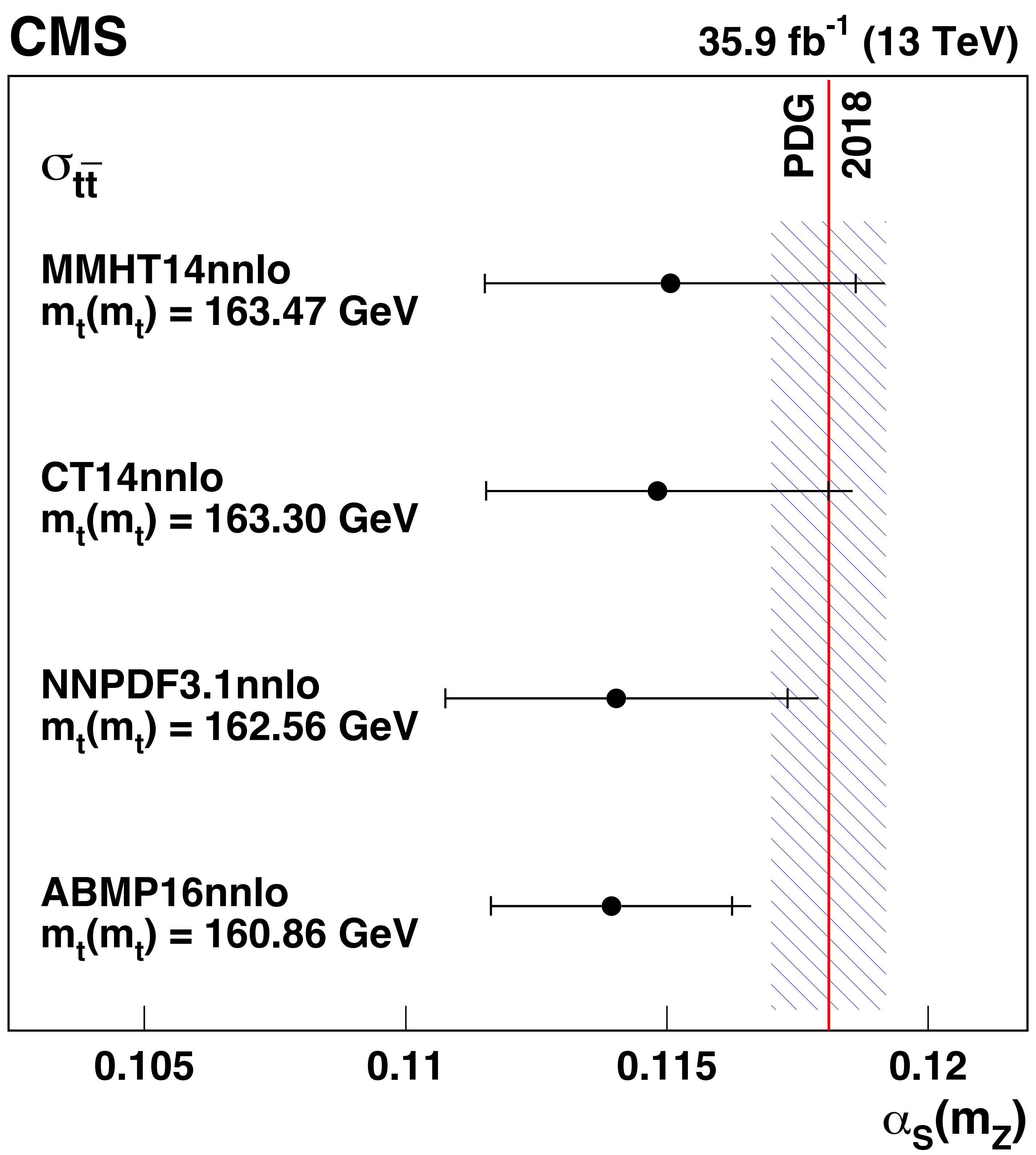


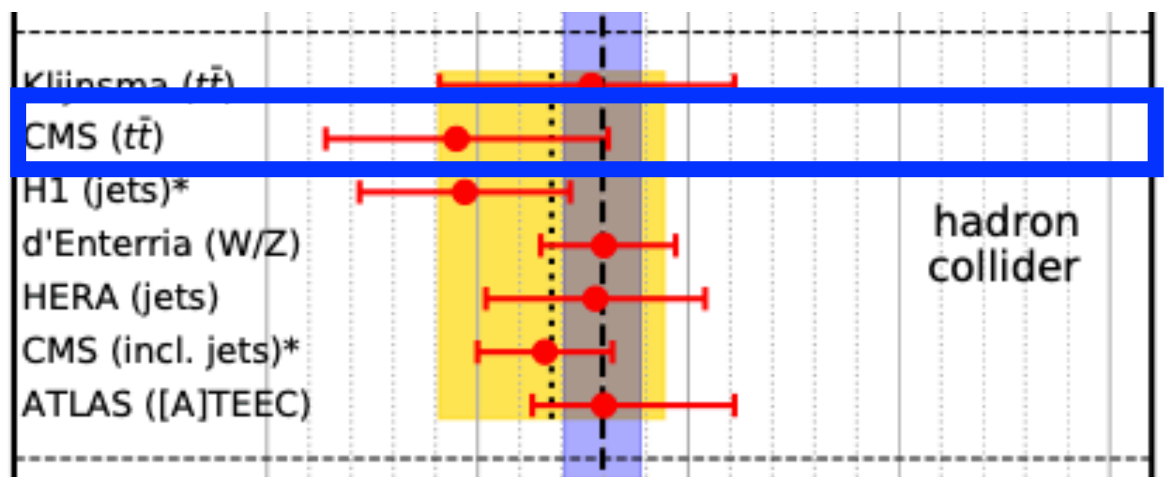
$$\alpha_S(m_Z) = 0.1177^{+0.0034}_{-0.0036}$$

Largest unc. > missing higher orders and PDFs

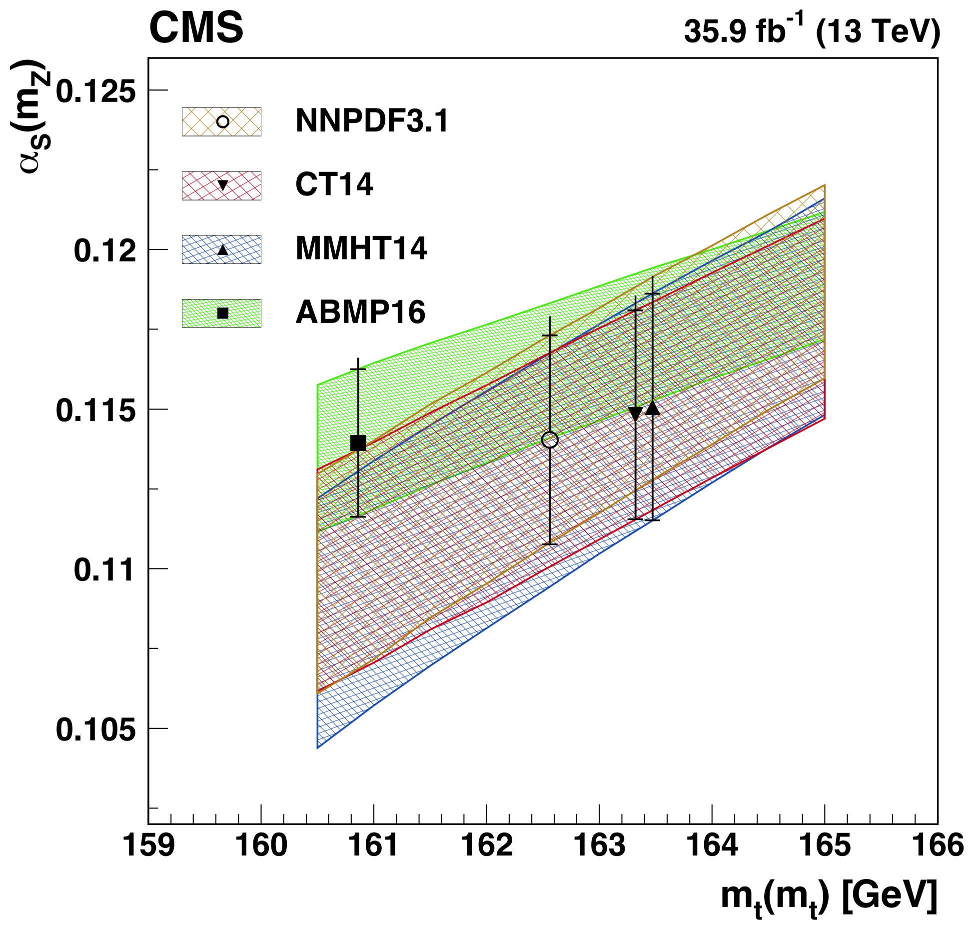
Latest extraction from CMS@13TeV EPJC 79 (2019) 368







$$\alpha_S(m_Z) = 0.1145^{+0.0036}_{-0.0031}$$



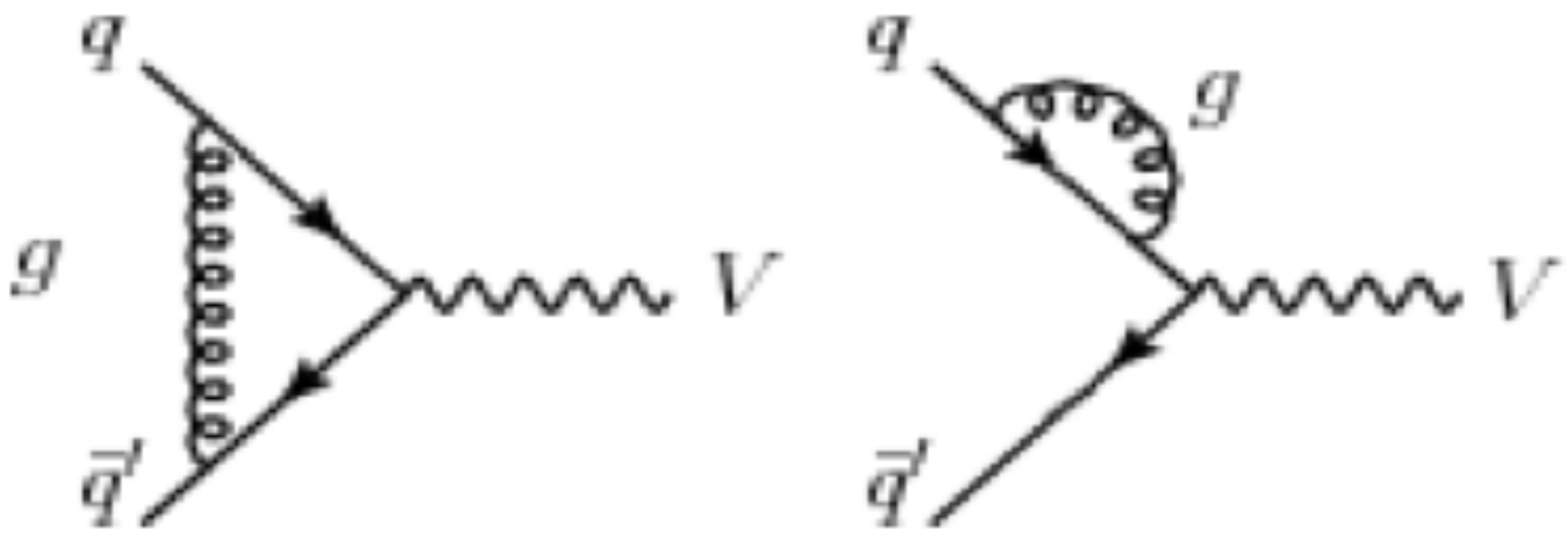
PDF set	$\alpha_S(m_Z)$
ABMP16	$0.1139 \pm 0.0023\,(\text{fit + PDF})\,^{+0.0014}_{-0.0001}\,(\text{scale})$
NNPDF3.1	$0.1140 \pm 0.0033\,(\text{fit + PDF})\,^{+0.0021}_{-0.0002}\,(\text{scale})$
CT14	$0.1148 \pm 0.0032\,(\text{fit + PDF})\,^{+0.0018}_{-0.0002}\,(\text{scale})$
MMHT14	$0.1151 \pm 0.0035\,(\text{fit + PDF})\,^{+0.0020}_{-0.0002}\,(\text{scale})$

~3% uncertainty dominated by luminosity and **PDF correlation of $\alpha_S(m_Z)$, $g(x)$ and m_{top}**

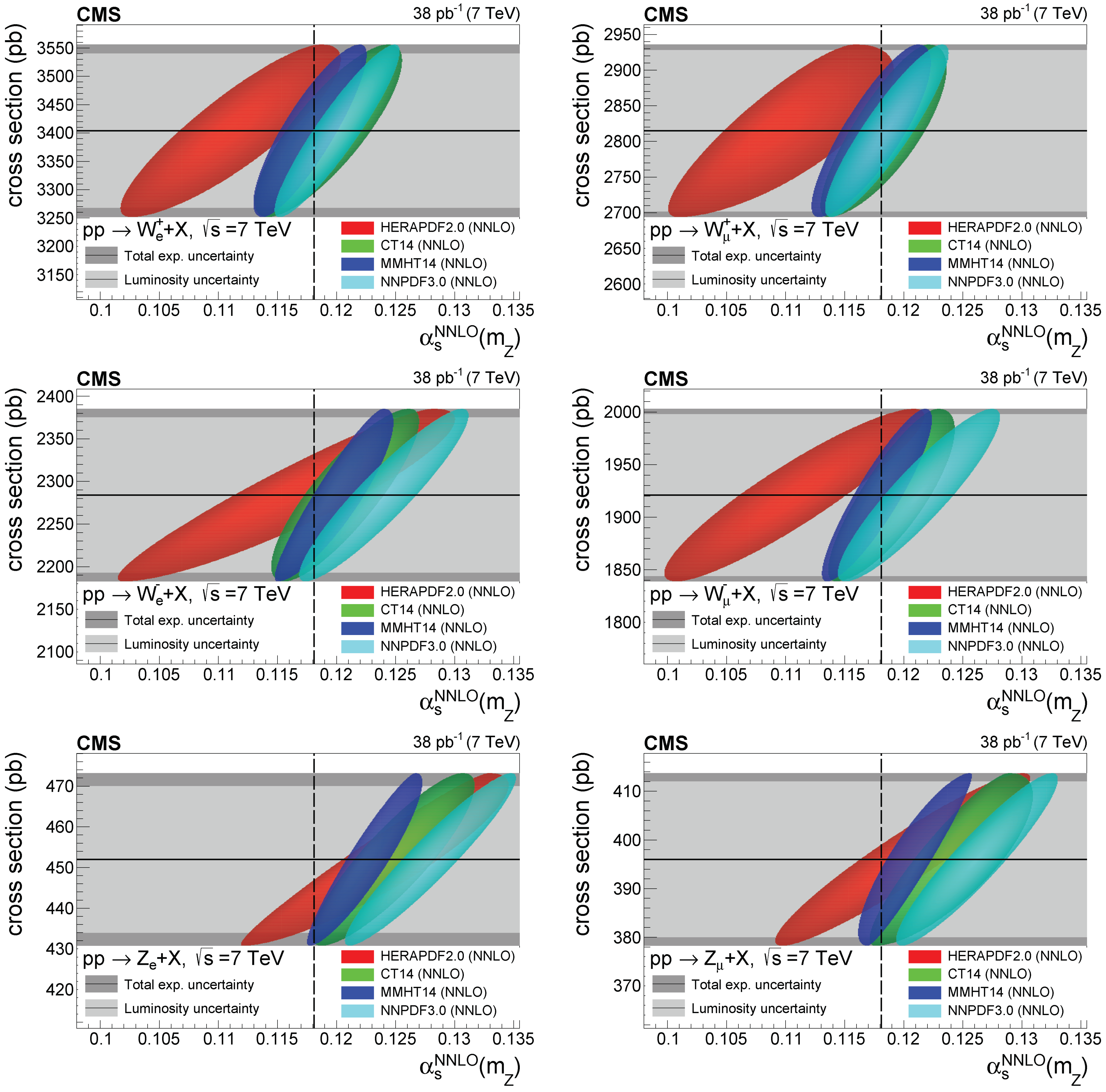
$\alpha_S(m_Z)$ from inclusive LHC W, Z x-scetions

Compare $\sigma(exp, W, Z)$ to $\sigma(NNLO, W, Z)$ for different PDFs and α_S

- **Pro:** O(1-2%) exp/th uncertainties
- **Cons:** No LO sensitivity to $\alpha_S(m_Z)$ (only via k_{NNLO}~1.3)



First extraction from CMS@7,8 TeV JHEP06 (2020) 018



CMS @7TeV: $(W_e^+, W_\mu^+, W_e^-, W_\mu^-, Z_e, Z_\mu)$

CMS @8TeV: $(W_e^+, W_\mu^+, W_e^-, W_\mu^-, Z_e, Z_\mu$

Four different PDF sets:

- HERAPDF2.0
- CT14
- MMHT14
- NNPDF3.1

Combined extraction from LHC JHEP 06 (2020) 016

Extended to 29 LHC data sets by D. D'enterria and A. Poldaru

CMS @7TeV: $(W_e^+, W_\mu^+, W_e^-, W_\mu^-, Z_e, Z_\mu)$

CMS @8TeV: $(W_e^+, W_\mu^+, W_e^-, W_\mu^-, Z_e, Z_\mu)$

ATLAS @7TeV: (W^+, W^-, Z)

ATLAS @8TeV: (Z)

ATLAS @13TeV: (W^+, W^-, Z)

LHCb @7TeV: (W^+, W^-, Z)

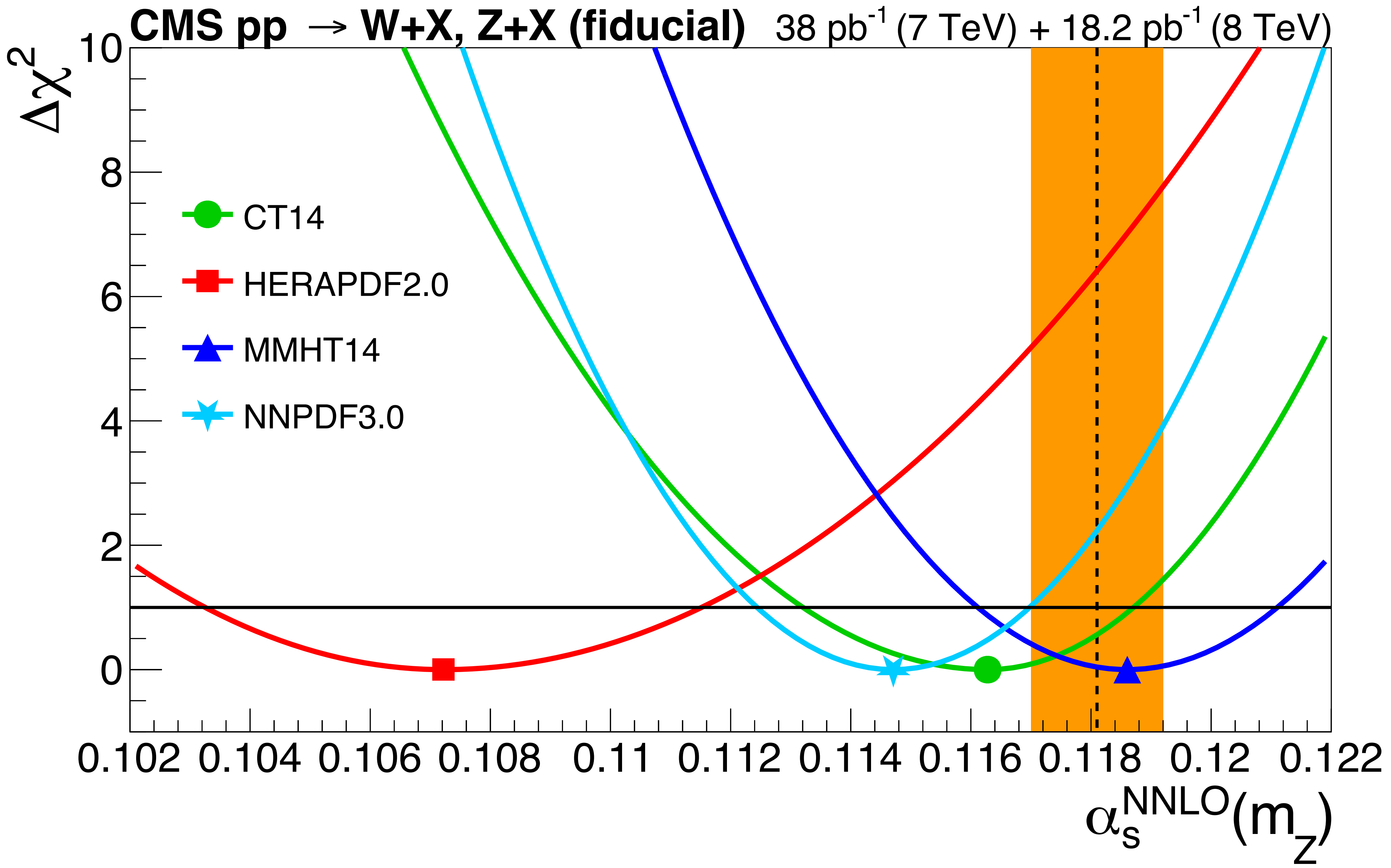
LHCb @8TeV: $(W_e^+, W_\mu^+, W_e^-, W_\mu^-, Z_\mu)$

LHCb @13TeV: (Z)

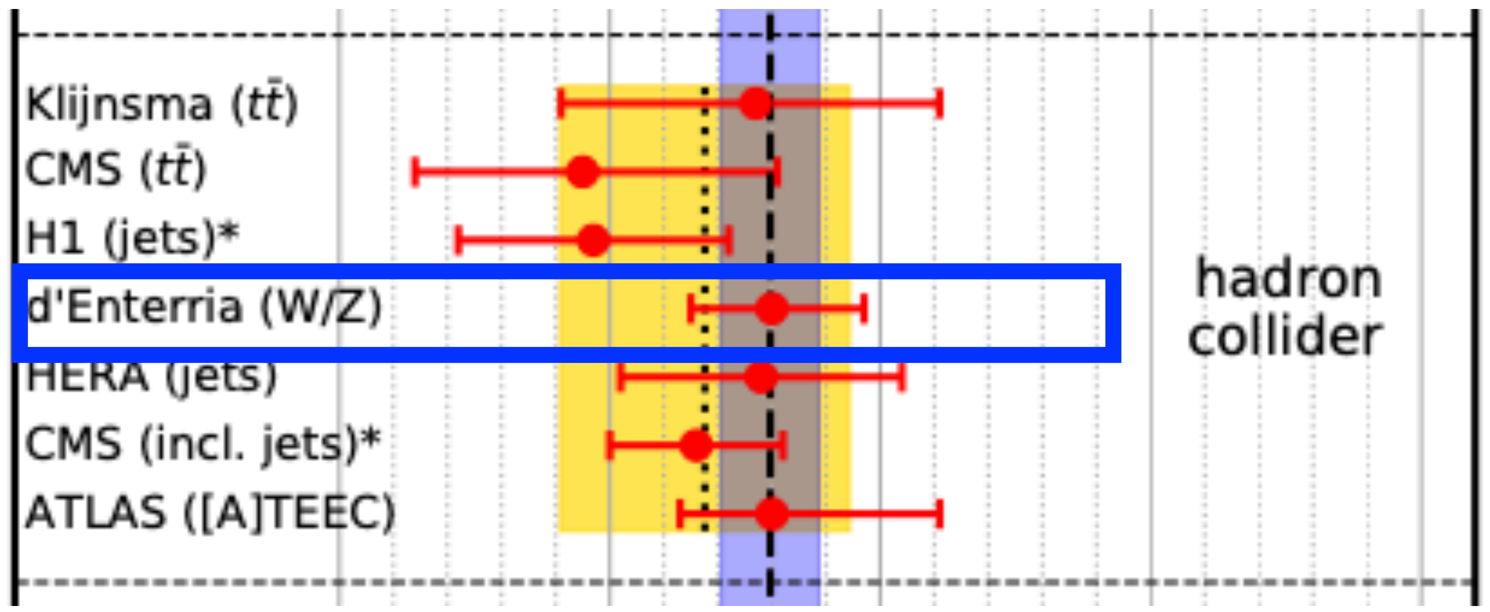
$\alpha_S(m_Z)$ from inclusive LHC W, Z x-scetions

JHEP 06 (2020) 016

- Measurement dominated by PDF and luminosity uncertainties
- Advantage wrt to global PDF fits → single out the sensitivity to as(mZ) of inclusive DY cross sections, which is an experimentally and theoretically clean signature
- The analysis could be upgraded to N3LO in the near future



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



$$\alpha_S(m_Z) = 0.1180^{+0.0017}_{-0.0015}$$

Motivation

- Single free parameter of QCD in the $m_q \to 0$ limit
- Impact physics at the Planck scale: EW vacuum stability, GUT
- α_S is among the major uncertainties of many precision measurements: Higgs couplings at the LHC