Measurements involving jets and extraction of fundamental SM parameters in CMS

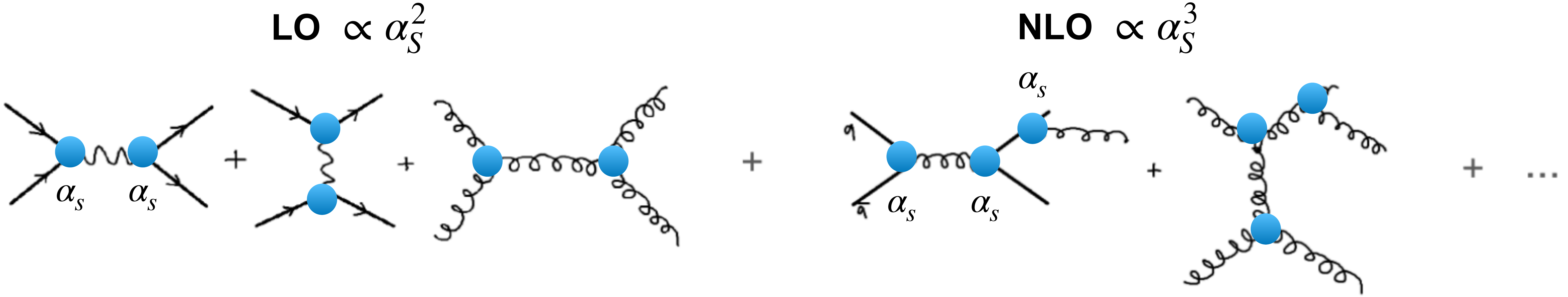
Valentina Guglielmi on behalf of CMS collaboration

QCD@LHC 2023, Durham, 6.9.2023

HELMHOLTZ

Jets as a probe of QCD

- **Test of QCD model:** **sensitive to α_S and PDFs**



- Extract α_s
- Improve PDF precision

Jets production at LHC

- **Recent CMS measurements at $\sqrt{s} = 13$ TeV:**

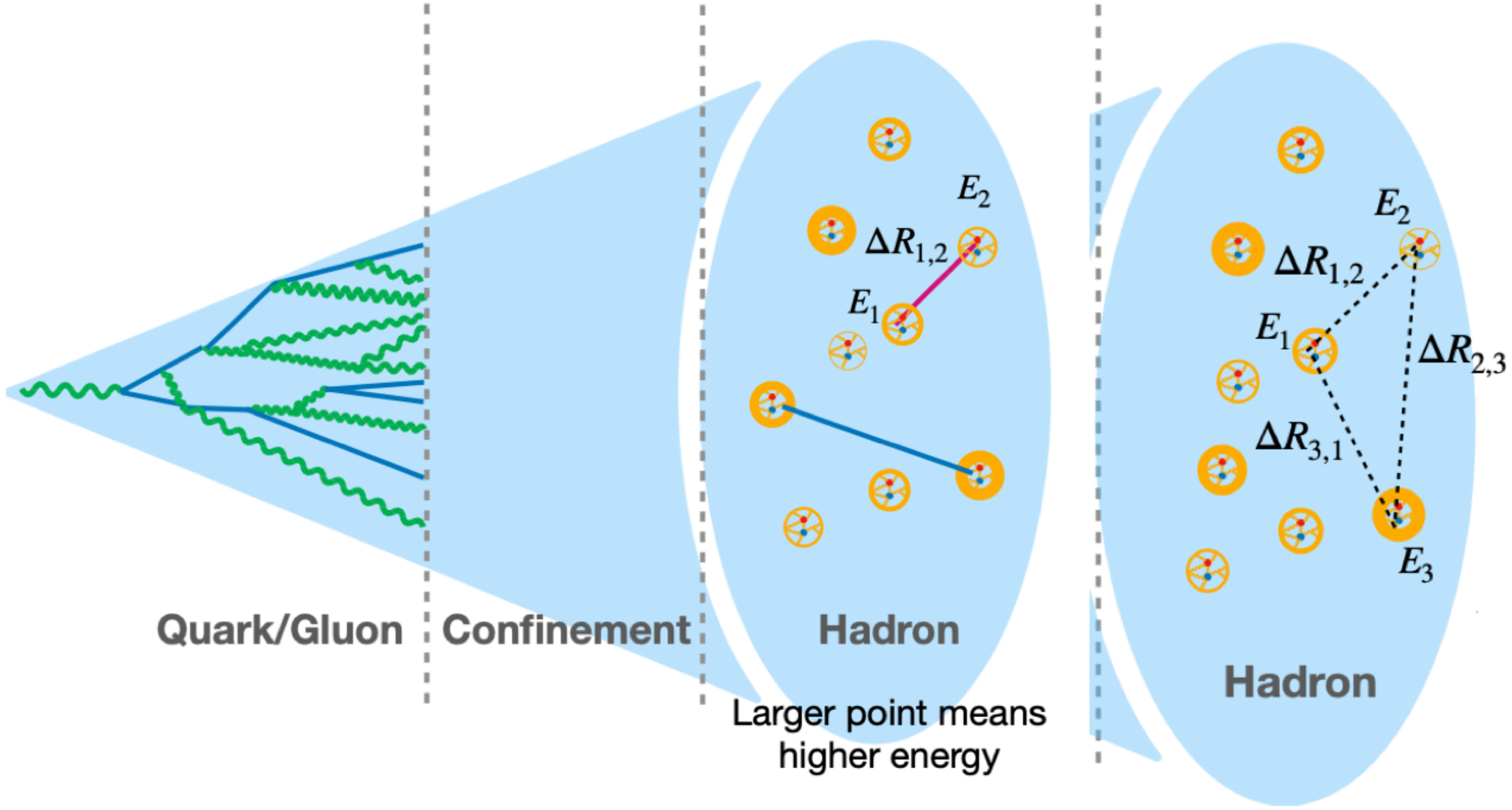
  - **Substructure**
    - **Energy correlators:** CMS-PAS-SMP-22-015
    - **Lund Jet plane:** CMS-PAS-SMP-22-007

  - **High energy jets**
    - **Azimuthal correlations:** CMS-PAS-SMP-22-005
    - **Inclusive jets:** JHEP 02 (2022) 142 + Addendum (Nov. 2022)
    - **Multi-differential dijets:** CMS-PAS-SMP-21-008

- Jets reconstructed using **anti-k_T** algorithm using $\Delta R = 0.8$ or (ak8) or 0.7 (ak7) or 0.4 (ak4) and **unfolded** to particle level

Measurement of energy correlators inside jets

NEW! SMP-22-015 CMS



- **Energy flow within a jet: jet energy correlators**

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

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

ΔR: angular distance
x_L: maximum ΔR

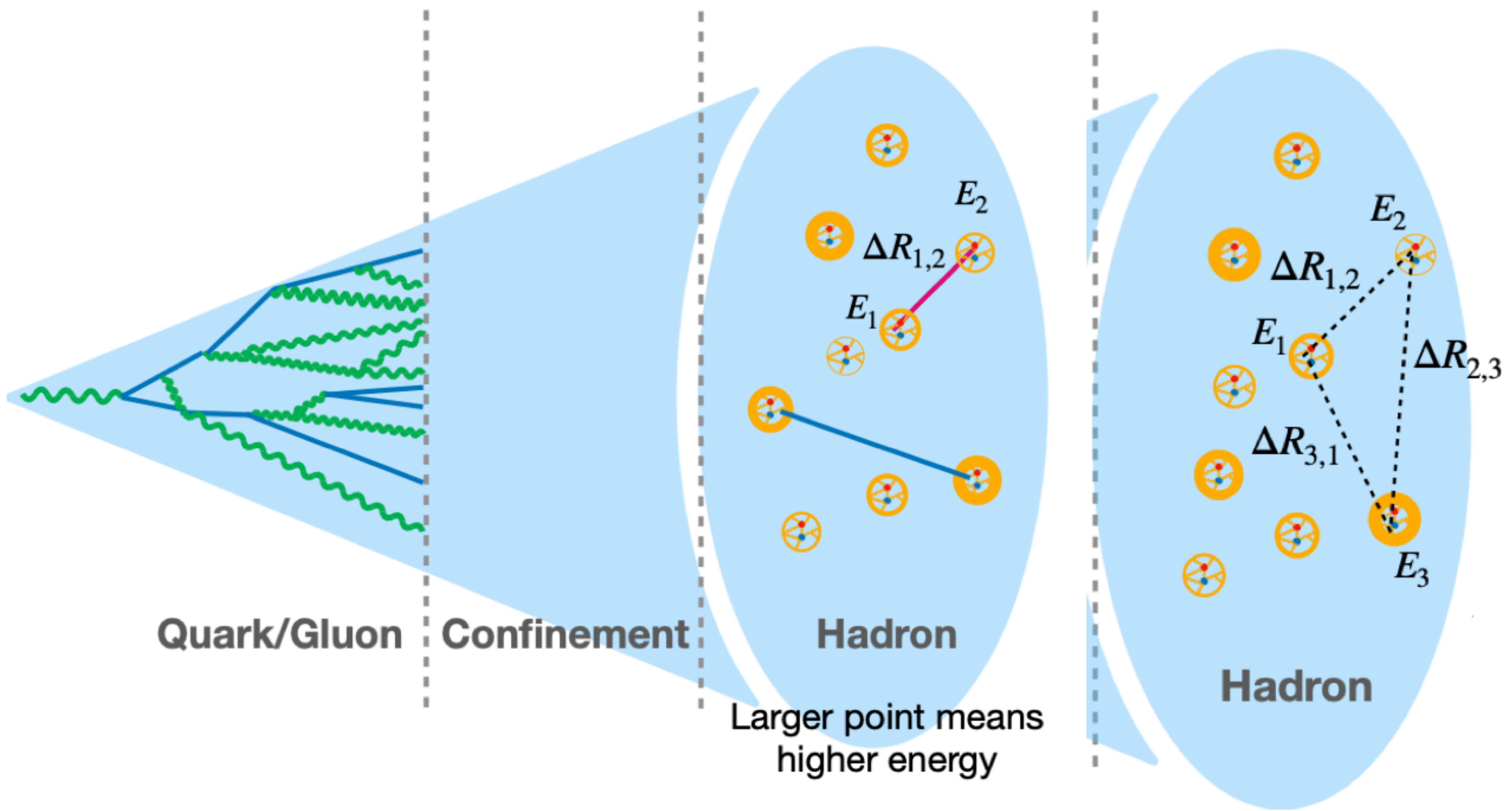
- **Large weight: energetic**
- **Low weight: soft**

→ "mapping" of parton stages in jet formation

Measurement of energy correlators inside jets → α_s

NEW!

SMP-22-015



- Theory calculations at **NLL, NNLL**$_{approx}$

Chen, Moult, Zhang, and Zhu, [arXiv:2004.11381]
Lee, Meçaj, and Moult, [arXiv:2205.03414]
Chen, Gao, Li, Xu, Zhang, and Zhu, [arXiv:2307.07510]

- **Energy flow within a jet: jet energy correlators**

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

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

- **Novel method to extract α_S:**

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

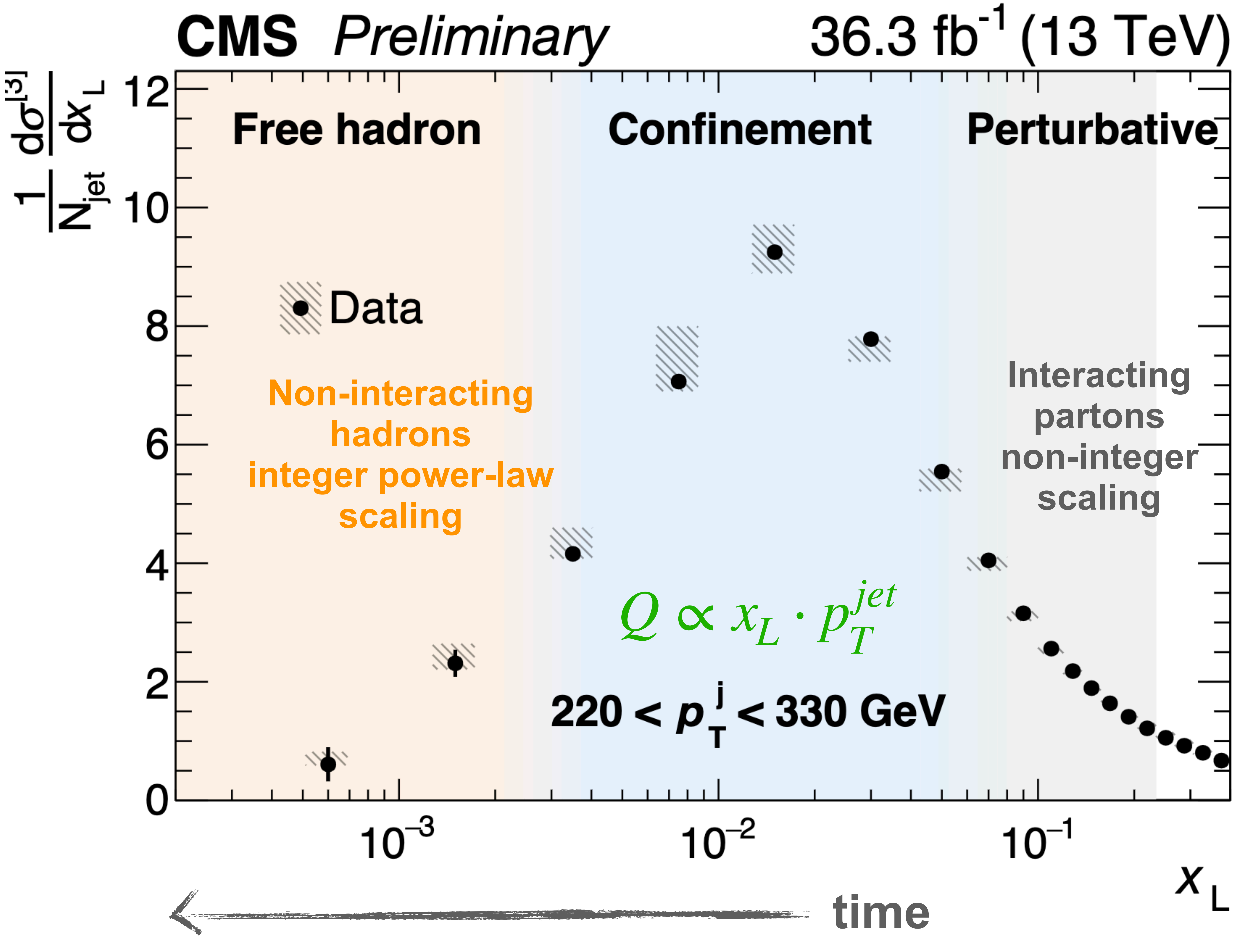
PRD 102, 054012 (2020)

Illustration of partonic time evolution

NEW! SMP-22-015

- **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)
  - $p_T^{particle} > 1\text{GeV}$
- Detector to particle level:
  D'Agostini unfolding in 3D (x_L, p_T^{jet}, energy weight)

Unfolded E3C in one p_T^{jet} bin



Energy correlator ratio

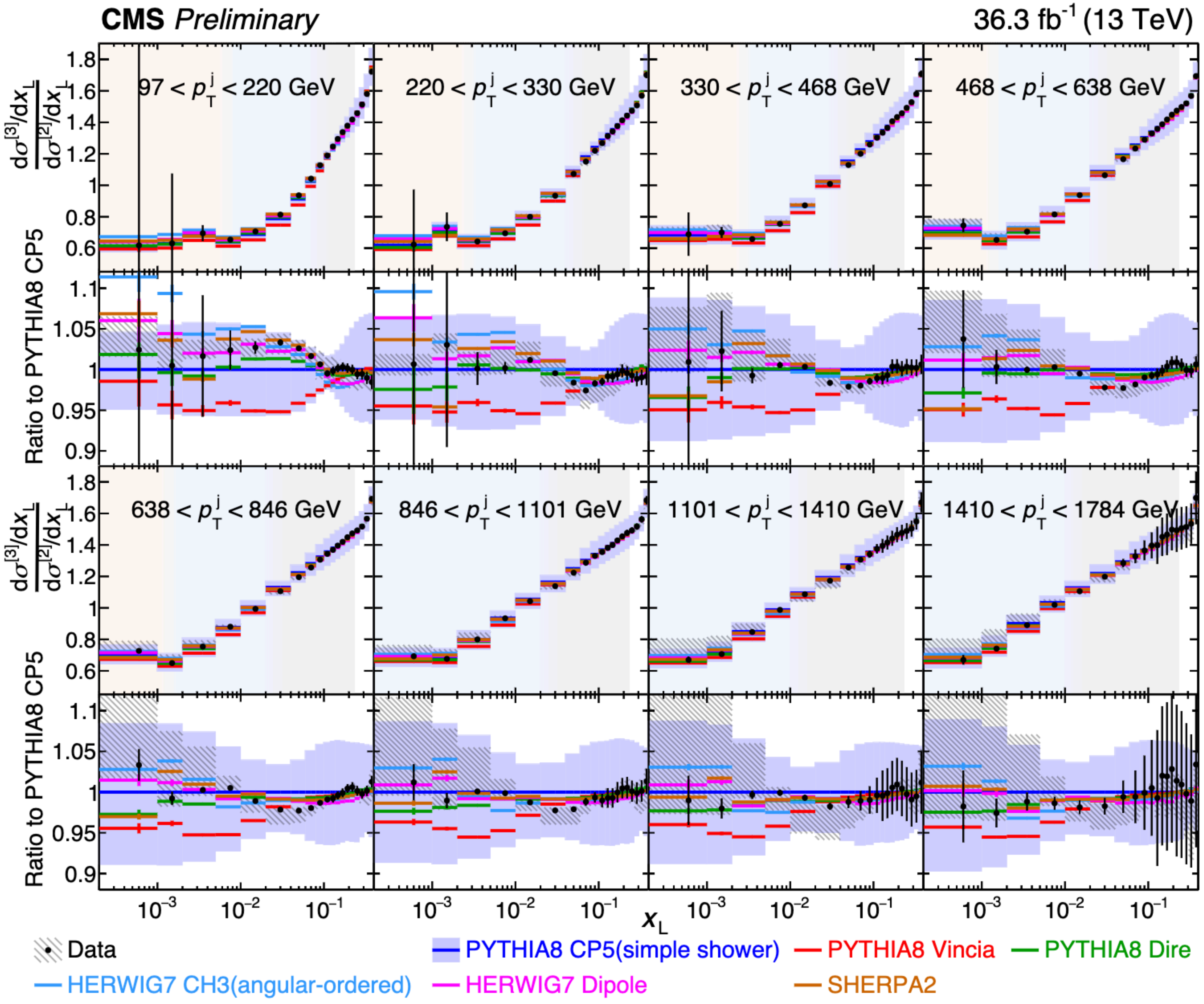
NEW!

SMP-22-015

- Unfolded $\frac{E3C}{E2C}$ vs MC simulations

- **Benefit of ratio:**
    - Suppressed ambiguity in jet quark/gluon composition
    - Reduced uncertainty

→ Slope of $\frac{E3C}{E2C}$, sensitive to α_s, vs p_T^j

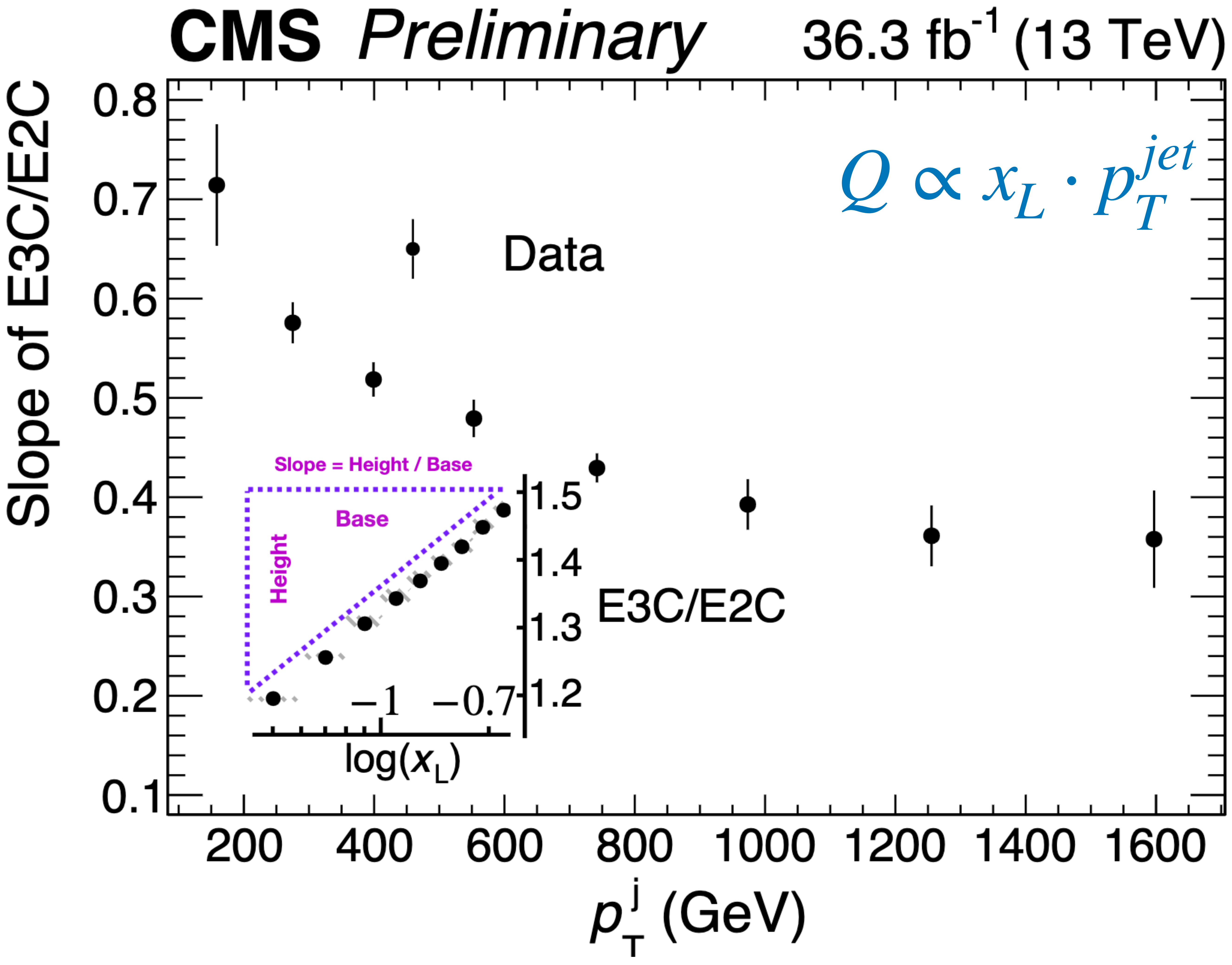


Energy correlator results

NEW! SMP-22-015

- **Running of α_s**
  - $\frac{E3C}{E2C} \propto \alpha_S(Q)\ \ln x_L + O(\alpha_S^2)$: **ratio slope proportional to $\alpha_s(Q^2)$**

Observation of running of α_s probing relatively low scales



Energy correlator results

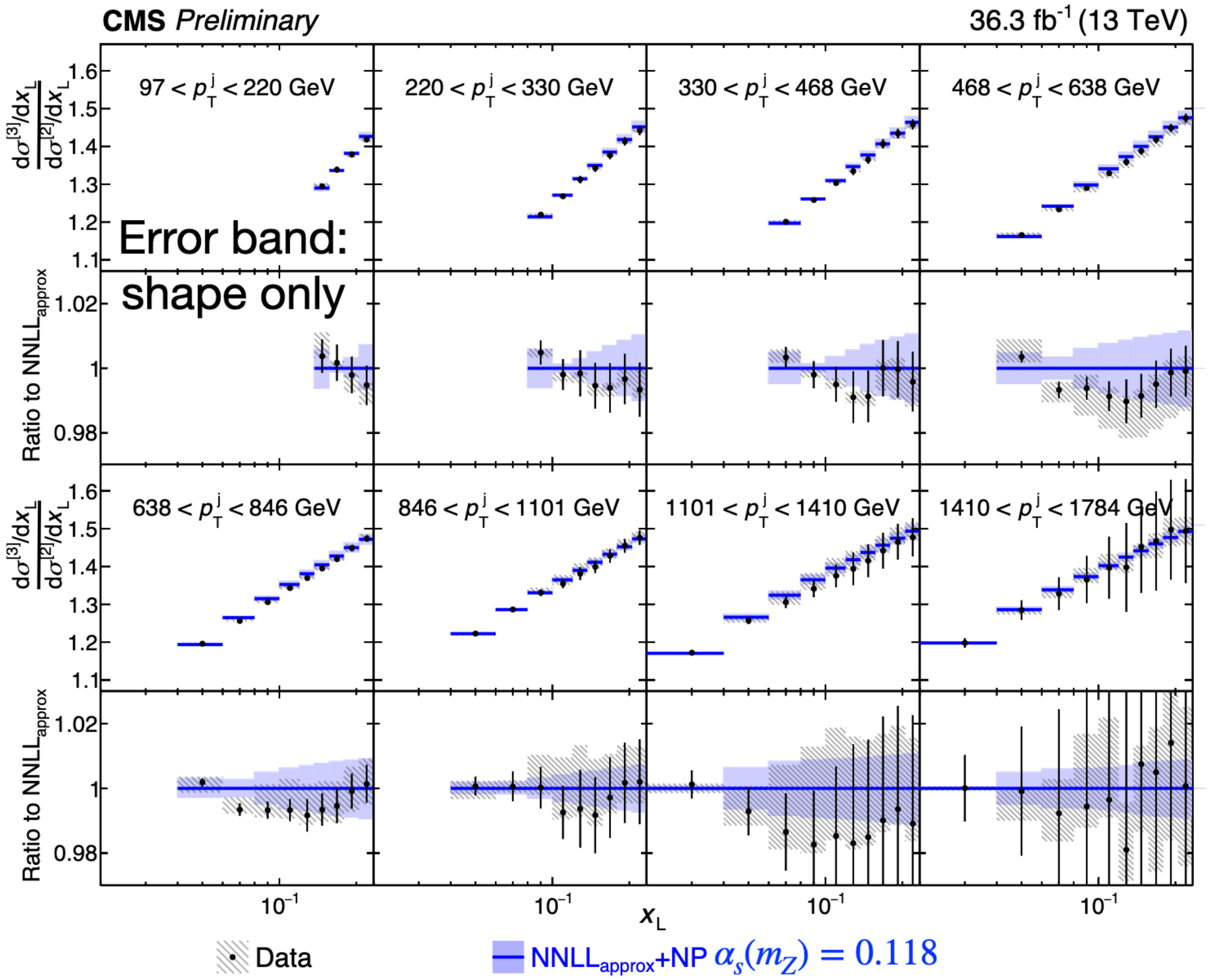
NEW!

SMP-22-015

- **Unfolded E3C/E2C vs NNLL$_{approx}$**
  - **Fit data to NNLL$_{approx}$ with different $\alpha_s(m_Z)$**

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

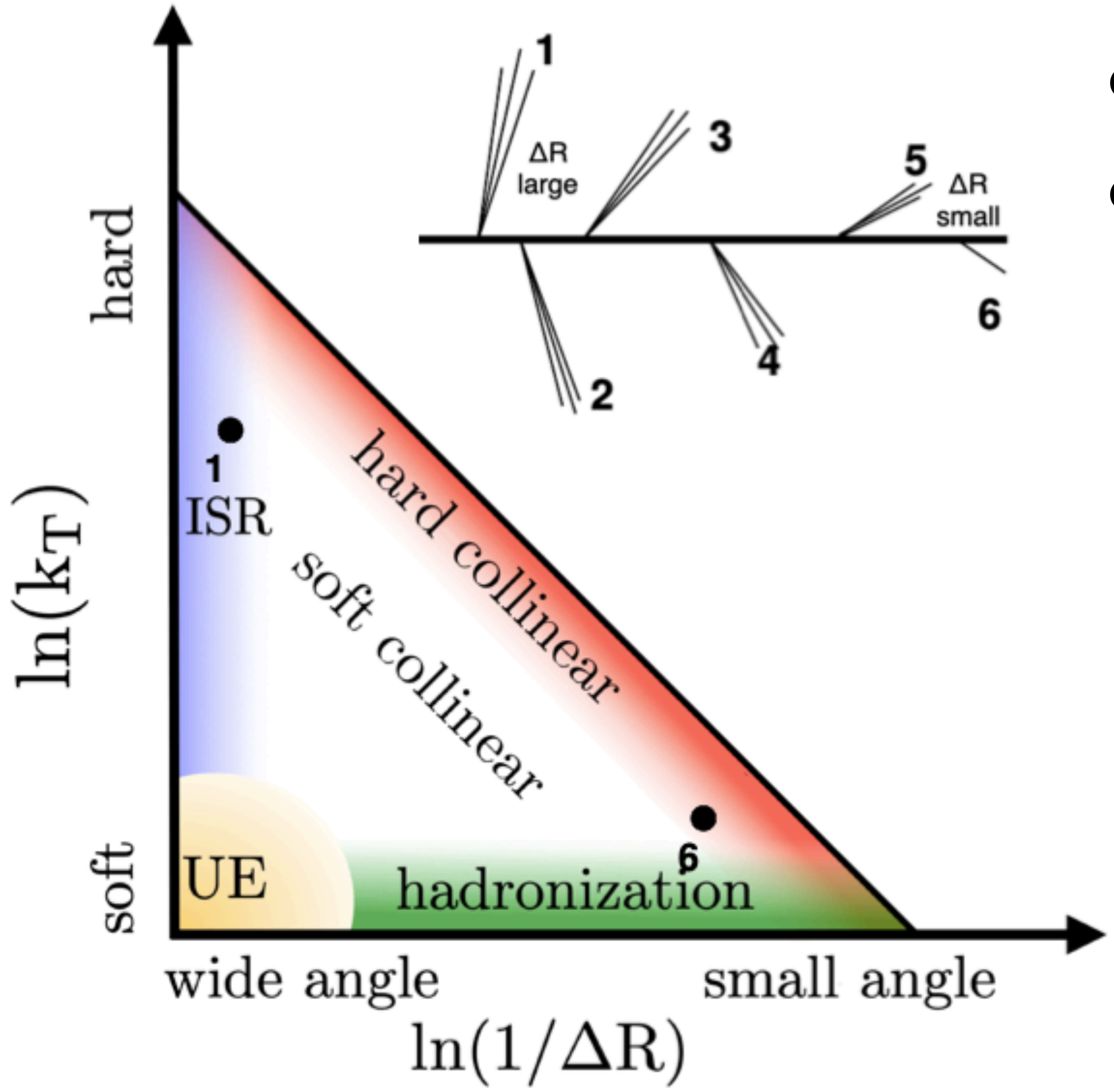
Most precise $\alpha_s(M_Z)$ from substructure



Measurement of Lund Jet Plane

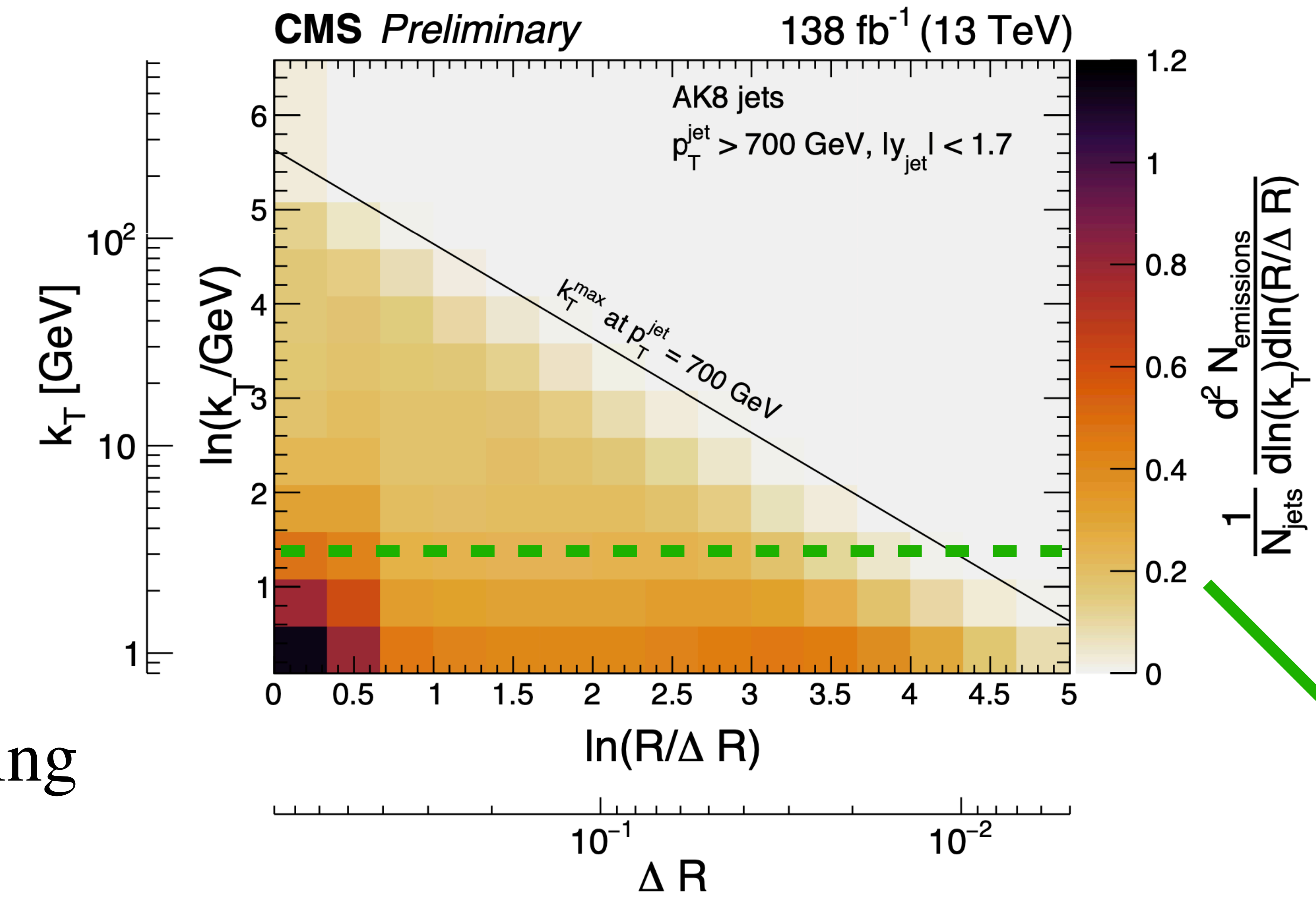
NEW!

SMP-22-007



- ΔR : splitting angle of branching
- k_T : relative p_T of emission

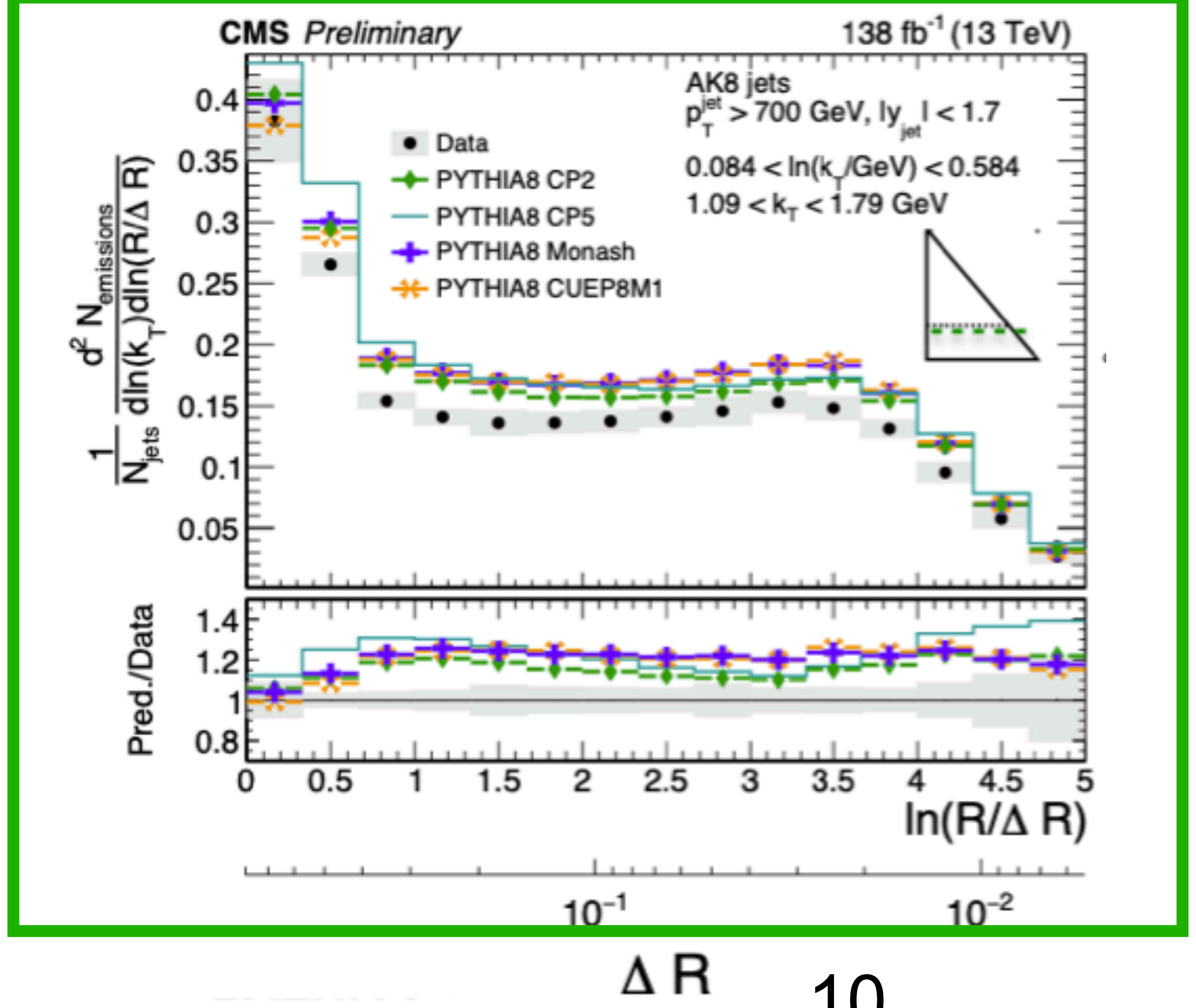
- **Lund Jet Plane** JHEP12 064 (2018) **factorises QCD effects** in jets
- Jet as **soft emissions around hard core** (quark/gluon origin)



- **Primary Lund jet plane density**

$$\frac{1}{N_{\text{jets}}}\frac{d^2N_{\text{emissions}}}{d\ln(k_T)\,d\ln(R/\Delta R)} \approx \frac{2}{\pi}C_R\alpha_S(k_T).$$

In the soft and collinear limit of pQCD



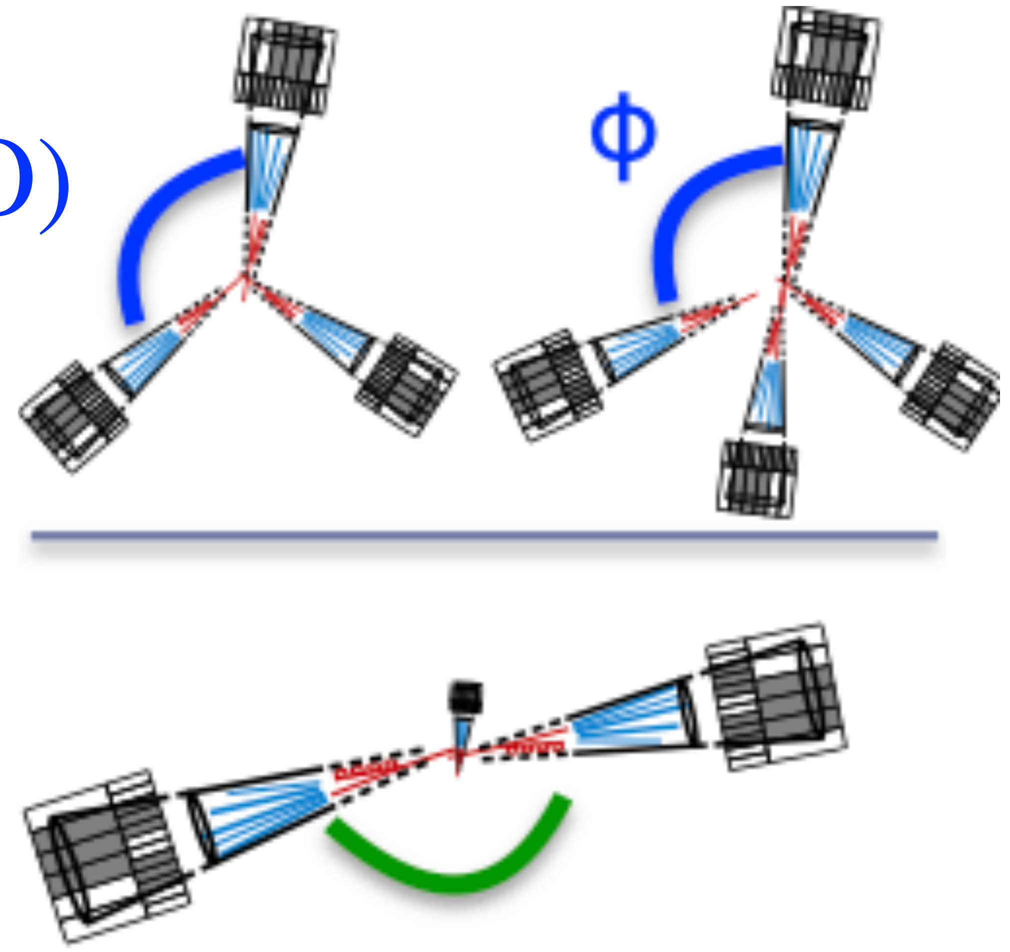
- **Comparison to various MC predictions** (diff. Tunes, diff. PS) → **benchmark next generation of parton showers** with resummation beyond LL accuracy

Measurement of azimuthal correlations among jets

NEW! SMP-22-005

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

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



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

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

N_{nbr}: # neighbouring jets

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

$\Delta\phi$: azimuthal angle separation

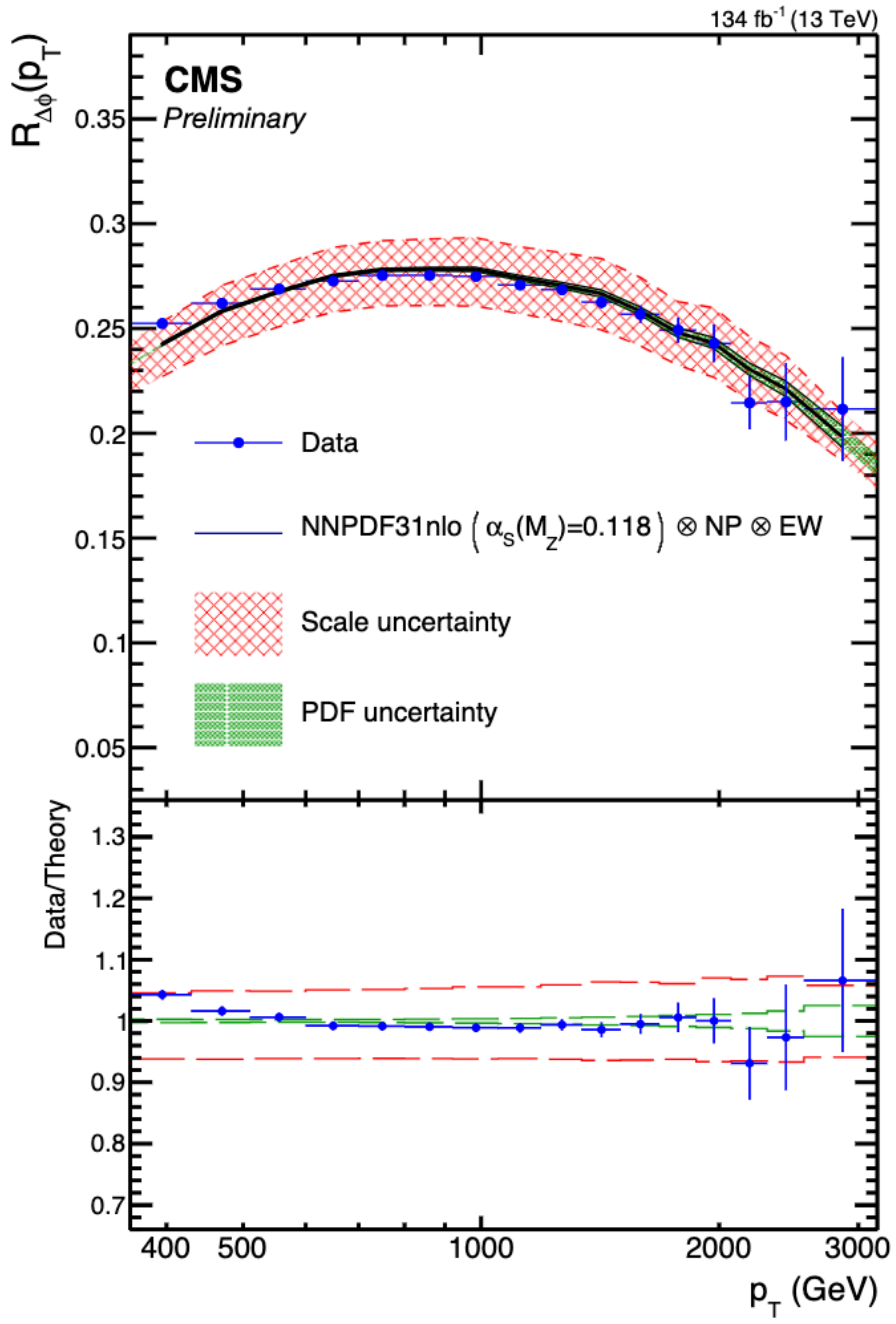
- **Datasets and trigger strategy**
  - $L = 134\ fb^{-1}$ (2016-2018), leading jets with $p_T^{HLT} > 40$ GeV, jets ak7

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

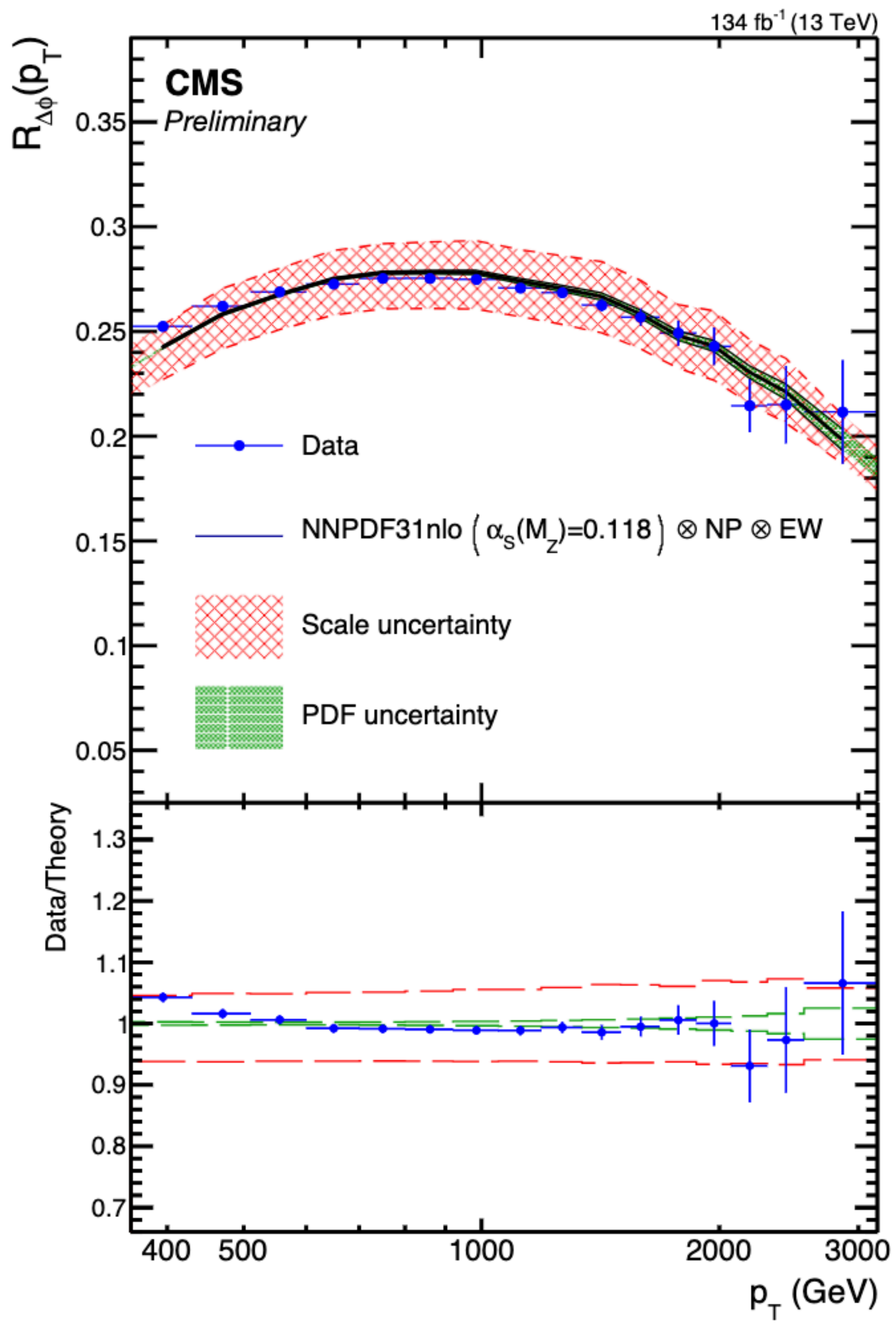
($\hat{H}$ **= sum of parton energies)**

Scale uncertainty dominant

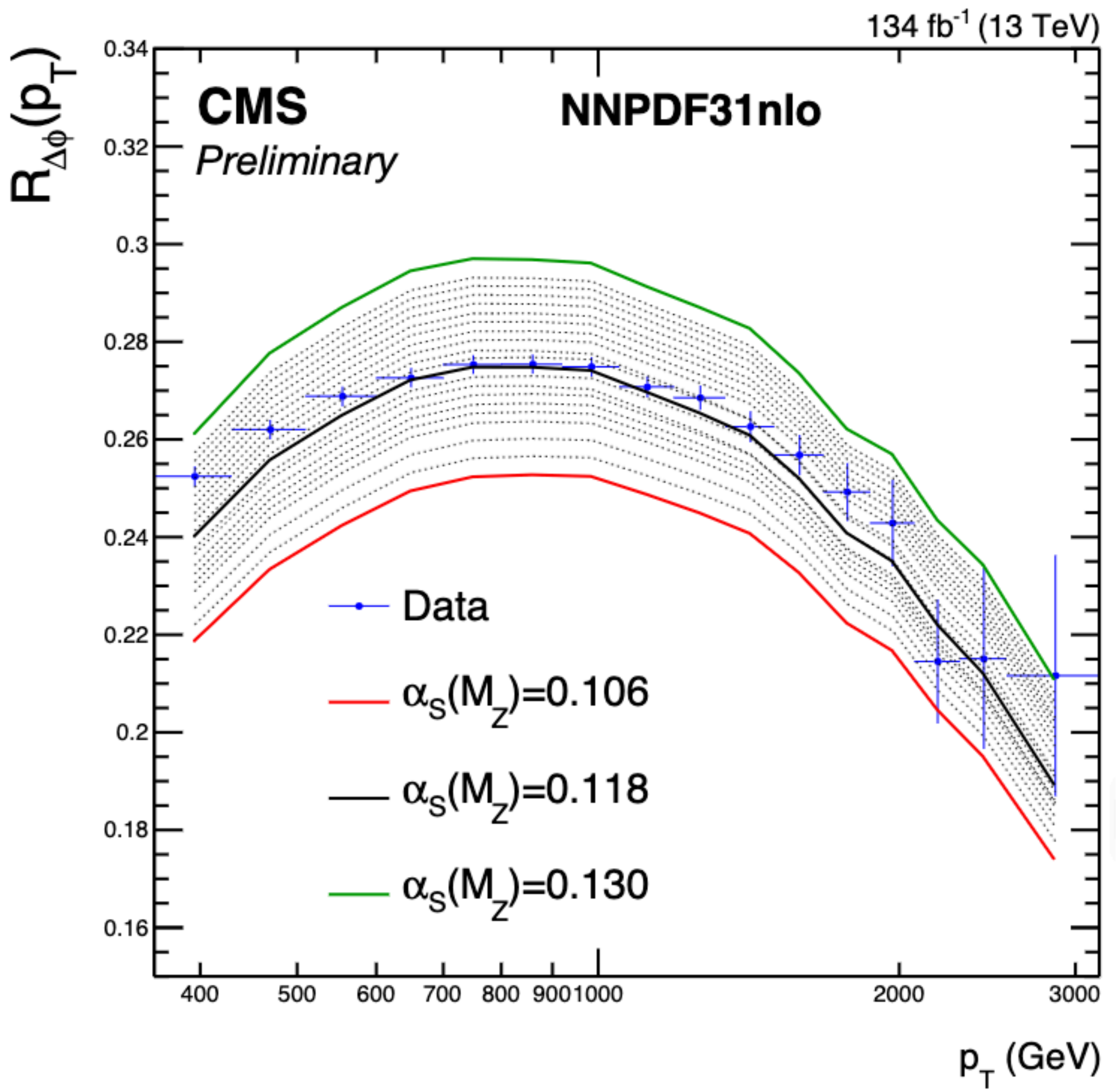
PDF uncertainty reduced in the ratio

Results azimuthal correlations among jets

NEW! SMP-22-005

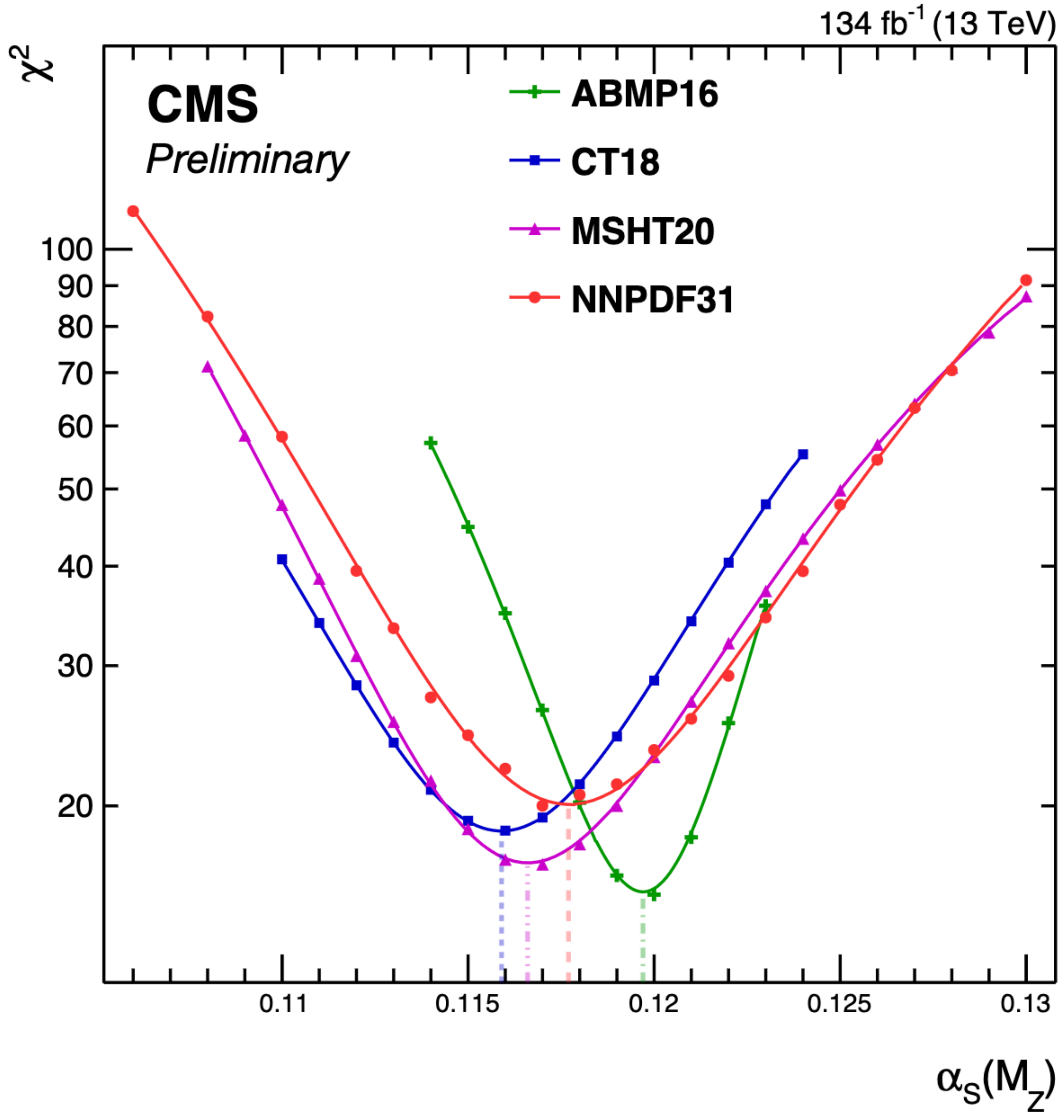


- **Sensitivity to $\alpha_S(m_Z)$**



Results of azimuthal correlations among jets

NEW! SMP-22-005



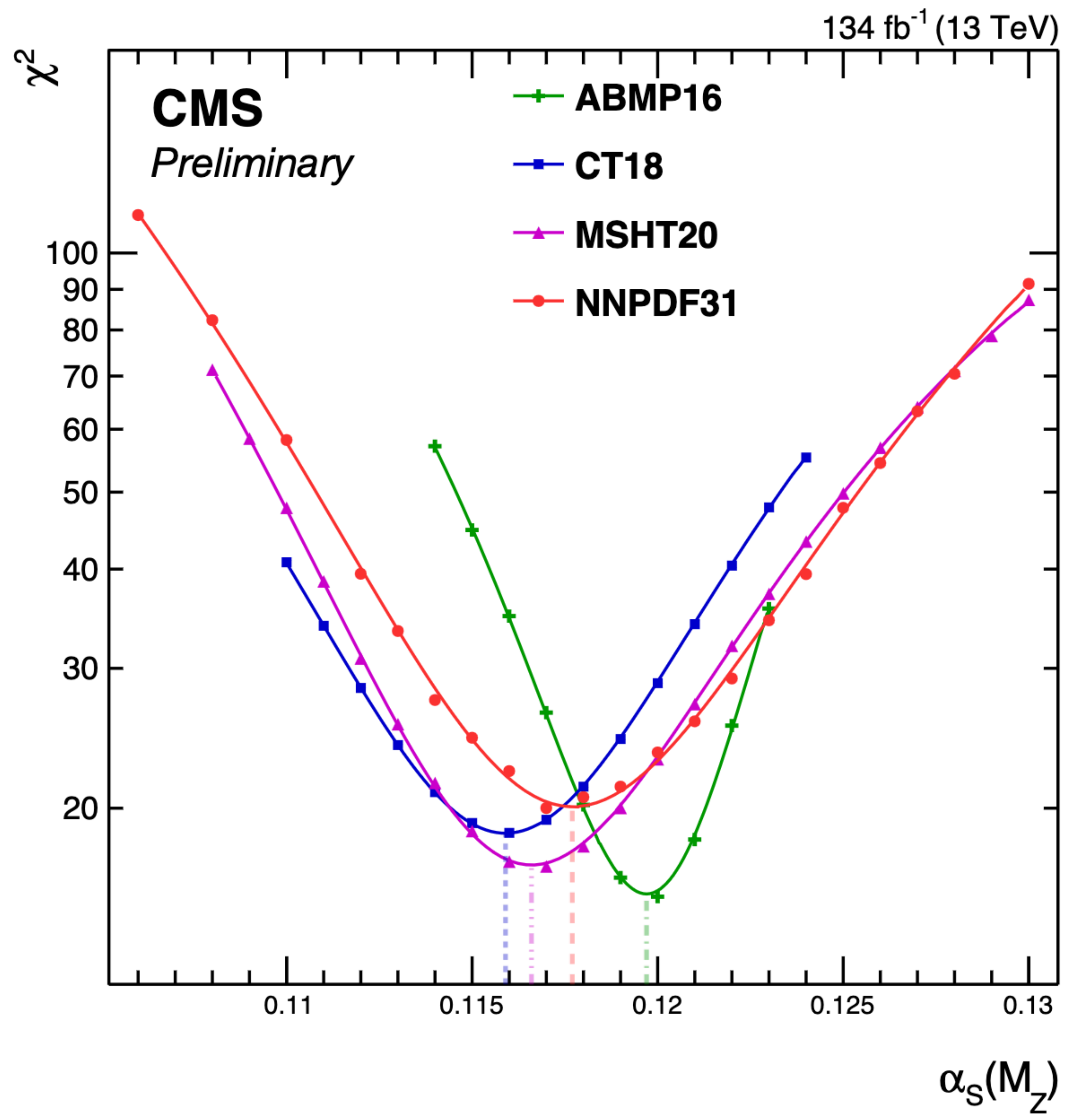
- **Using different PDFs: Sensitivity to $\alpha_S(m_Z)$**

PDF set	$\alpha_S(M_Z)$	Exp	NP	PDF	EW	Scale
ABMP16	0.1197	0.0008	0.0007	0.0007	0.0002	$^{+0.0043}_{-0.0042}$
CT18	0.1159	0.0013	0.0009	0.0014	0.0002	$^{+0.0099}_{-0.0067}$
MSHT20	0.1166	0.0013	0.0008	0.0010	0.0003	$^{+0.0112}_{-0.0063}$
NNPDF31	0.1177	0.0013	0.0011	0.0010	0.0003	$^{+0.0114}_{-0.0068}$

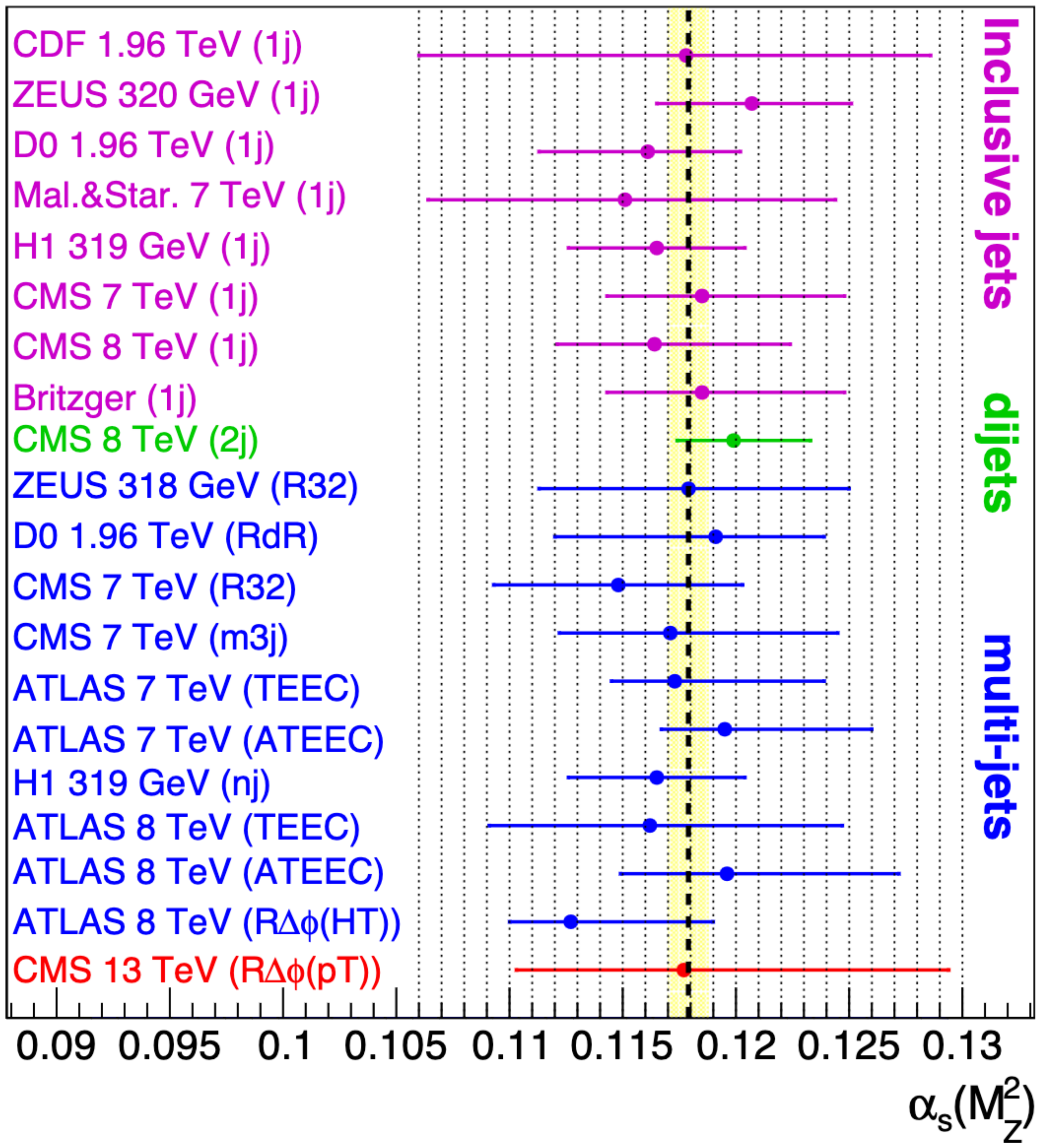
- **Spread in results due to PDF choice:**
  ± 0.0020 (PDF choice)

Results of azimuthal correlations among jets

NEW! **SMP-22-005**



Summary of NLO results:



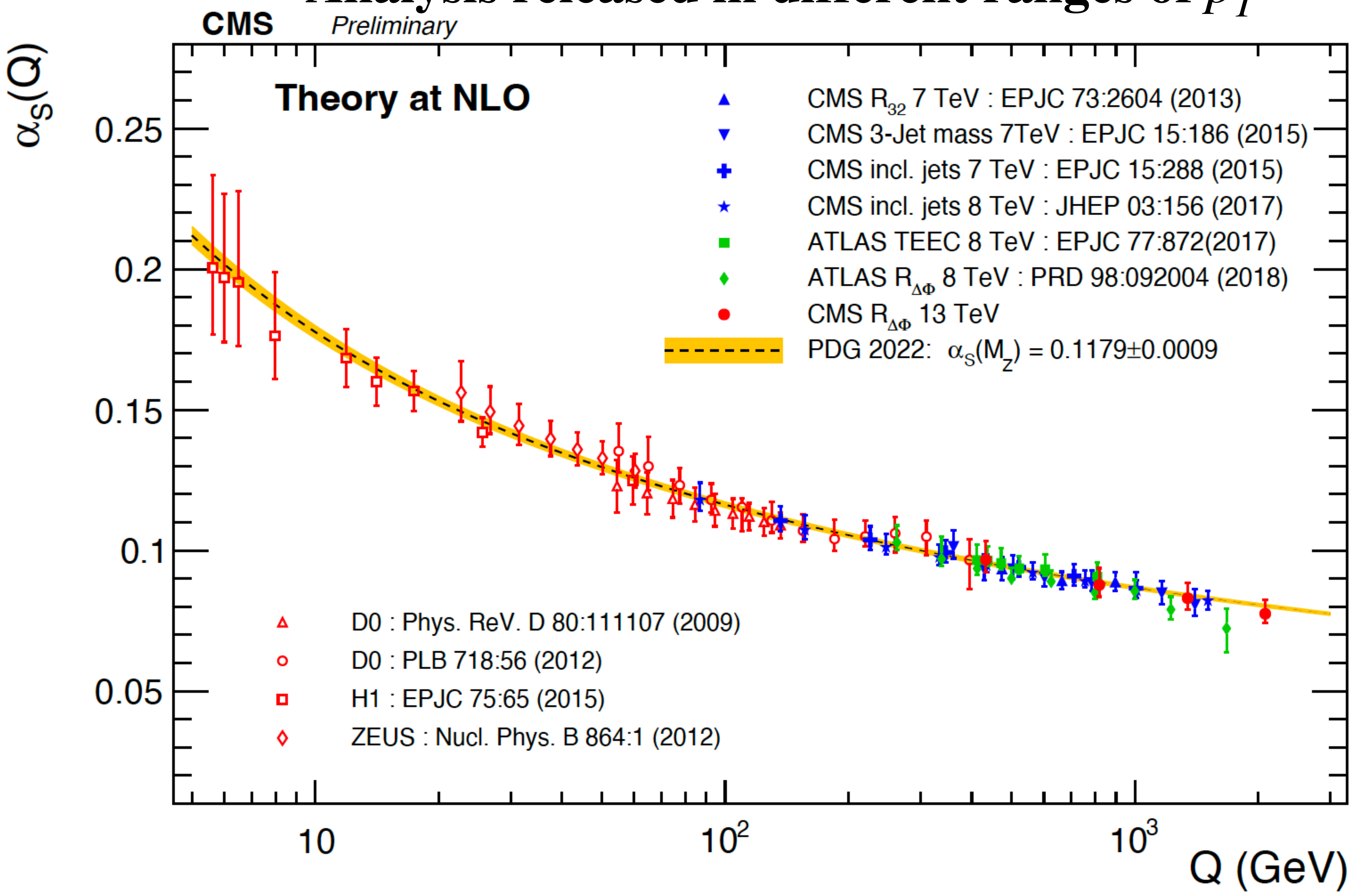
Final result: $\alpha_S(m_Z) = 0.117^{+0.0117}_{-0.0074}$

Azimuthal correlations among jets: running of α_s

NEW!

SMP-22-005

Analysis released in different ranges of p_T



Running of α_S demonstrated up to 2 TeV !

Inclusive jet production

12/2022 (addendum)
JHEP 02 (2022) 142 [Addendum]

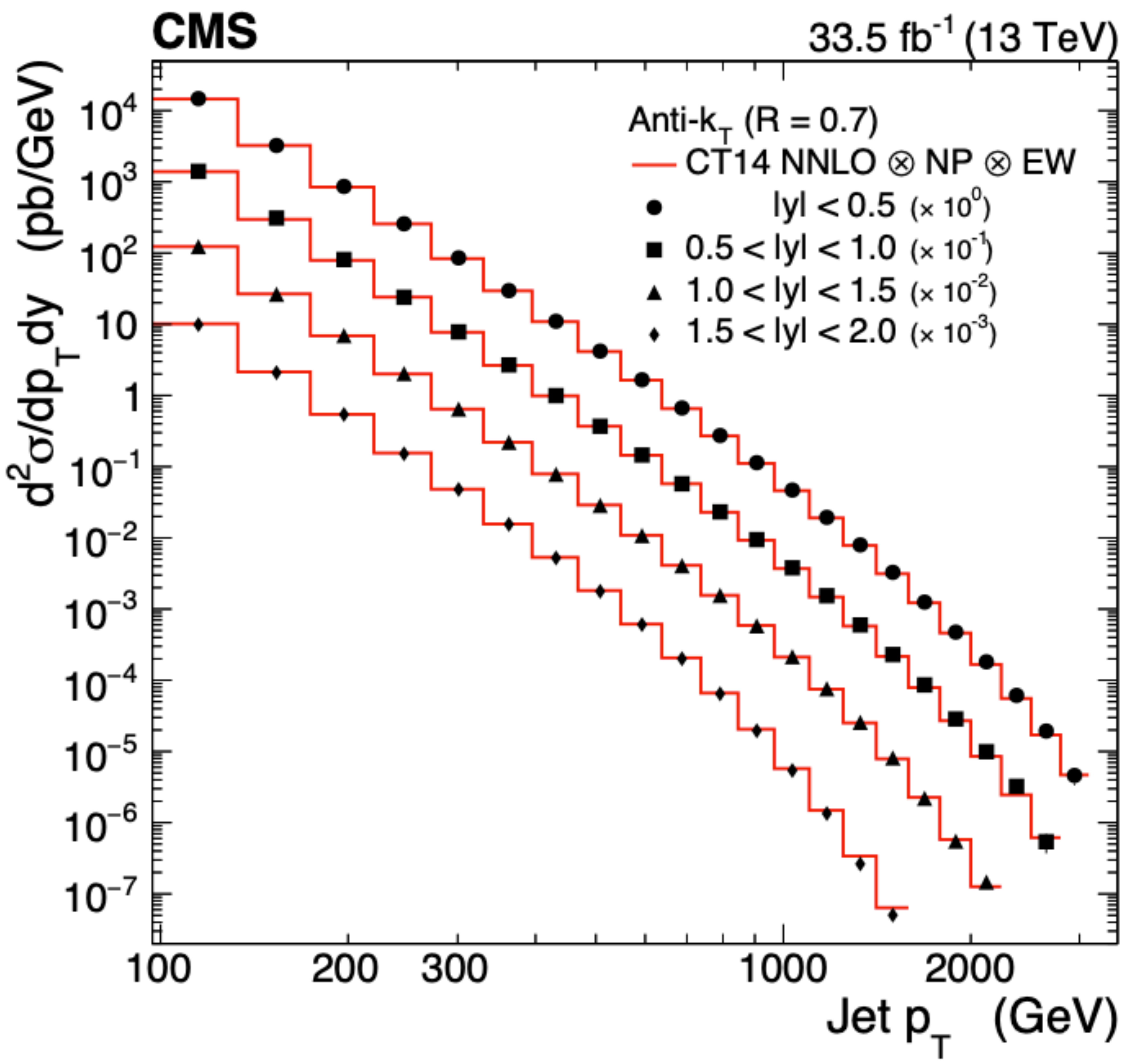
- **Cross section measurement of inclusive jets**
  - For each jet of each event, p_T and y are measured

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

- **Datasets and trigger strategy:**
  - $L \sim 35\ fb^{-1}$ (2016), leading jets with $p_T^{HLT} >$ 40 GeV, jets ak4 and ak7

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

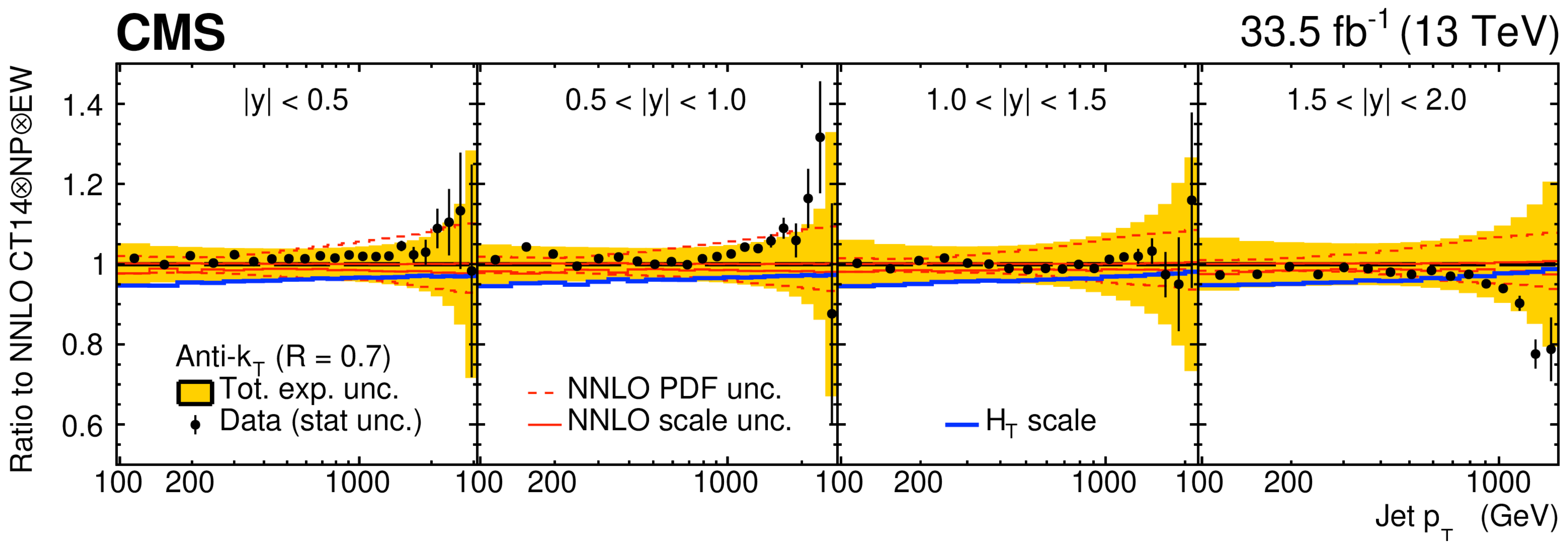
- **Addendum** with **NNLO interpolation grids**



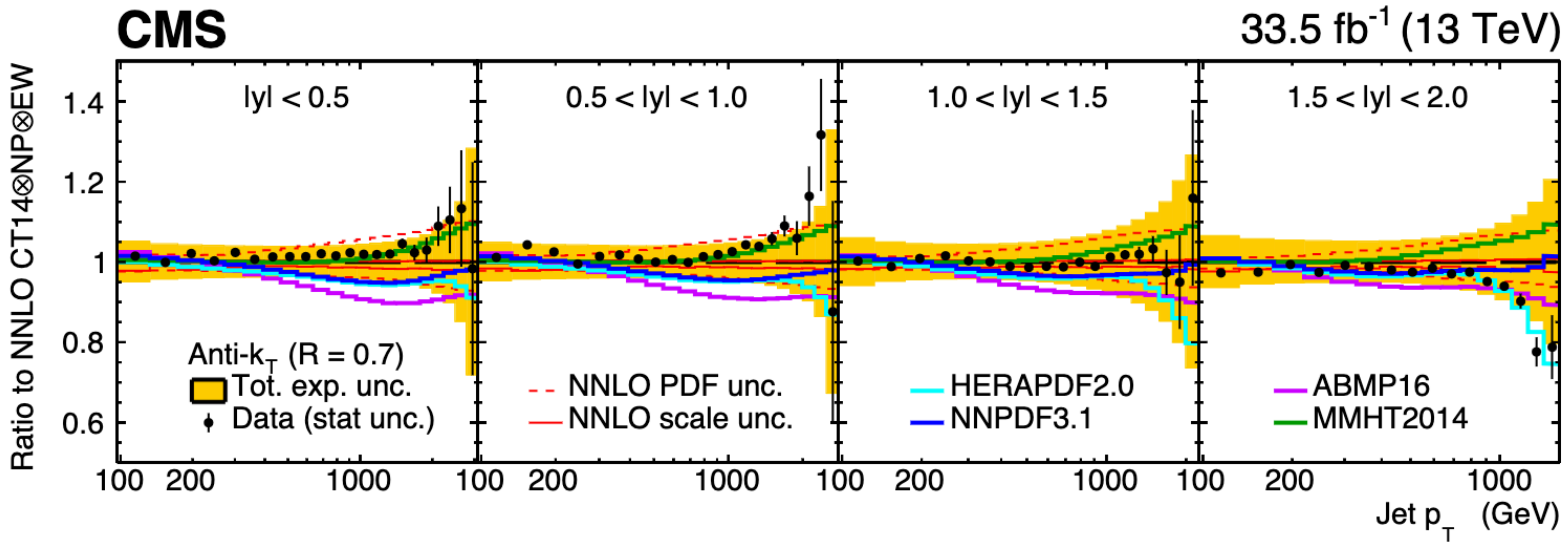
Inclusive jet production in details

12/2022 (addendum)
JHEP 02 (2022) 142 [Addendum]

Data vs NNLO



Predictions with different PDFs

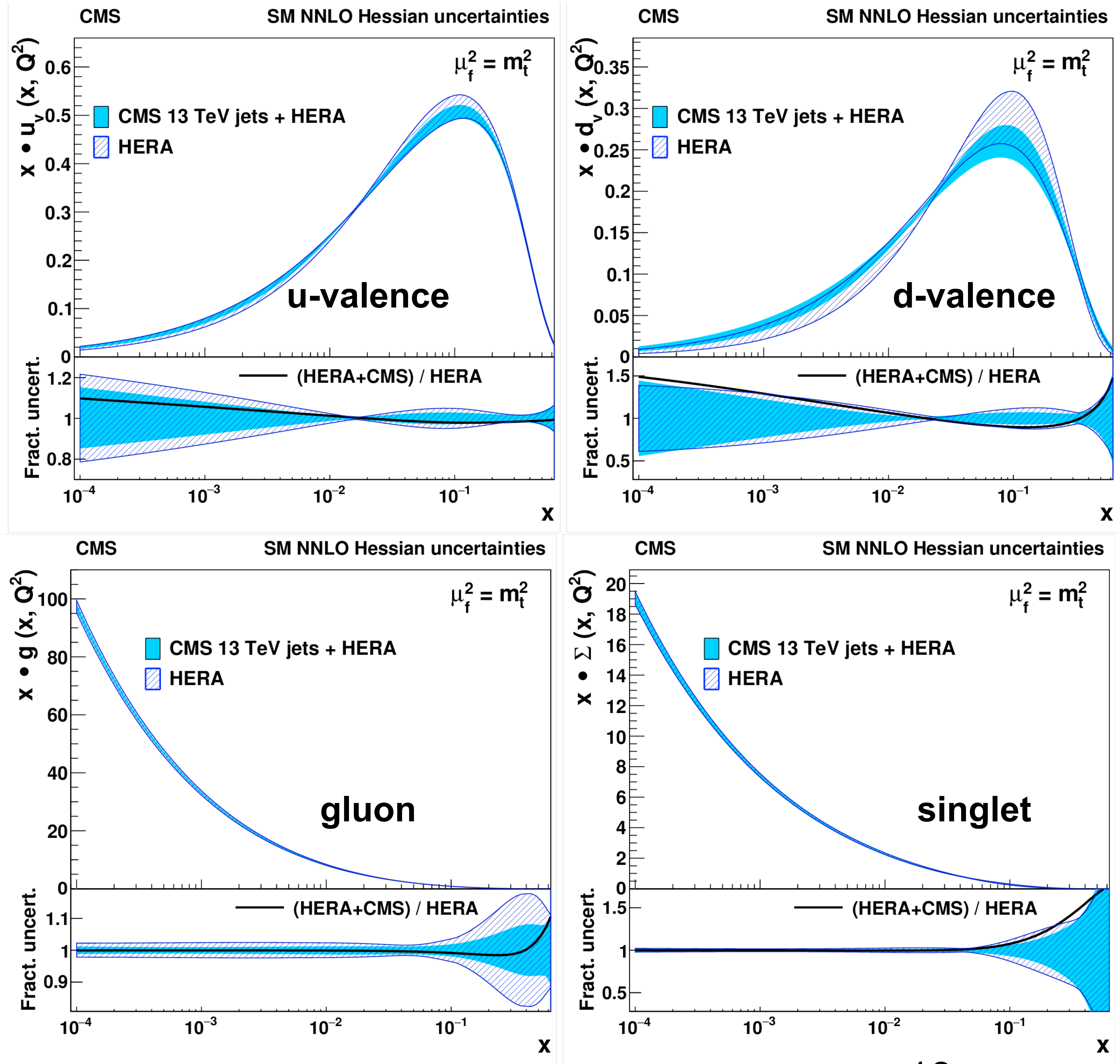


PDFs dominate theory uncertainty → PDFs can be constrained using these data!

QCD FIT @ NNLO (xFitter)

12/2022 (addendum)
JHEP 02 (2022) 142 [Addendum]

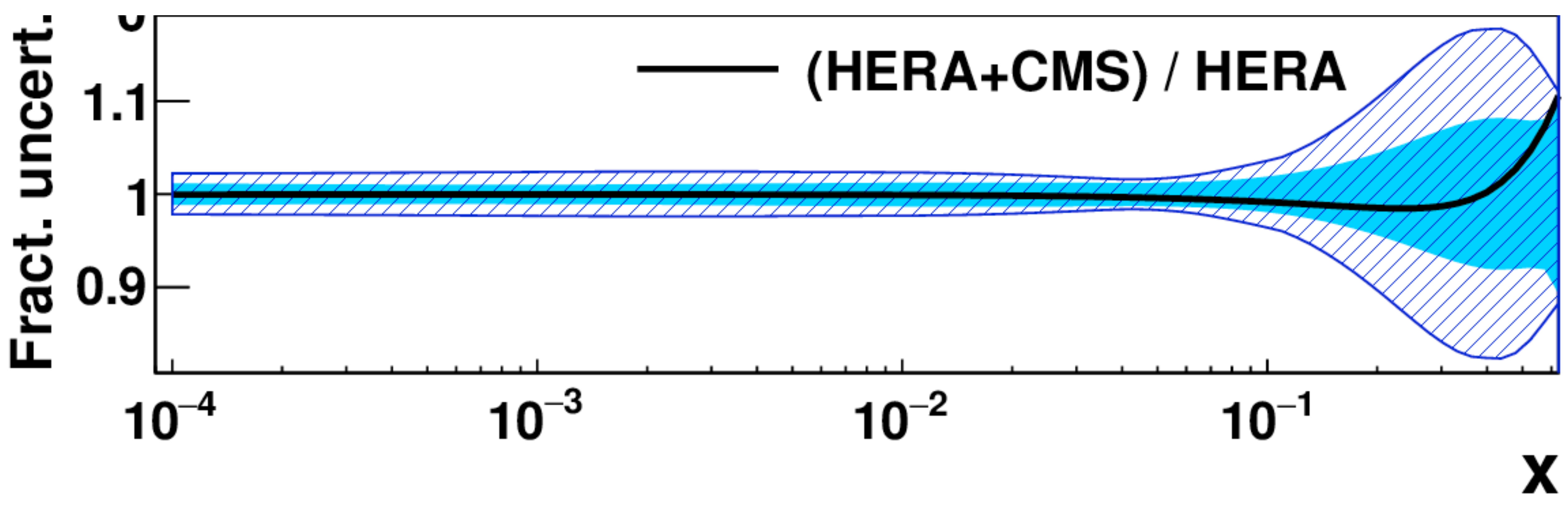
- **Simultaneous fit at NNLO: PDFs and α_s**
- **Datasets:**
  - *ep* inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  - CMS inclusive jets at 13 TeV [arXiv:2111.10431]
- **NNLO fast grids NNLOJet+applFast**



QCD FIT @ NNLO results

12/2022 (addendum)
JHEP 02 (2022) 142 [Addendum]

- **Improved precision of gluon** PDF at high x

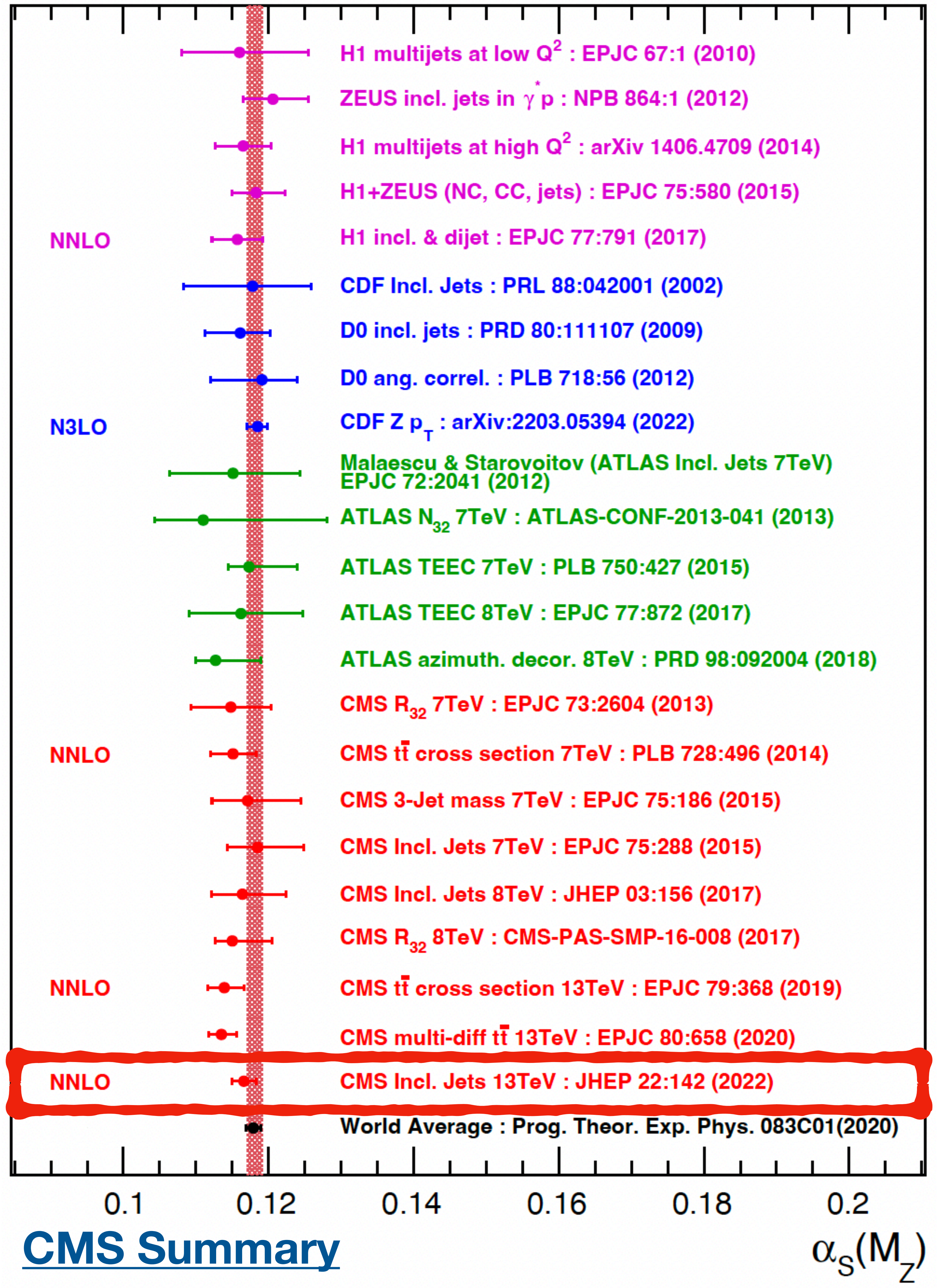


- **Precision extraction of α_s at percent-level**

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

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

Summary of NNLO results:

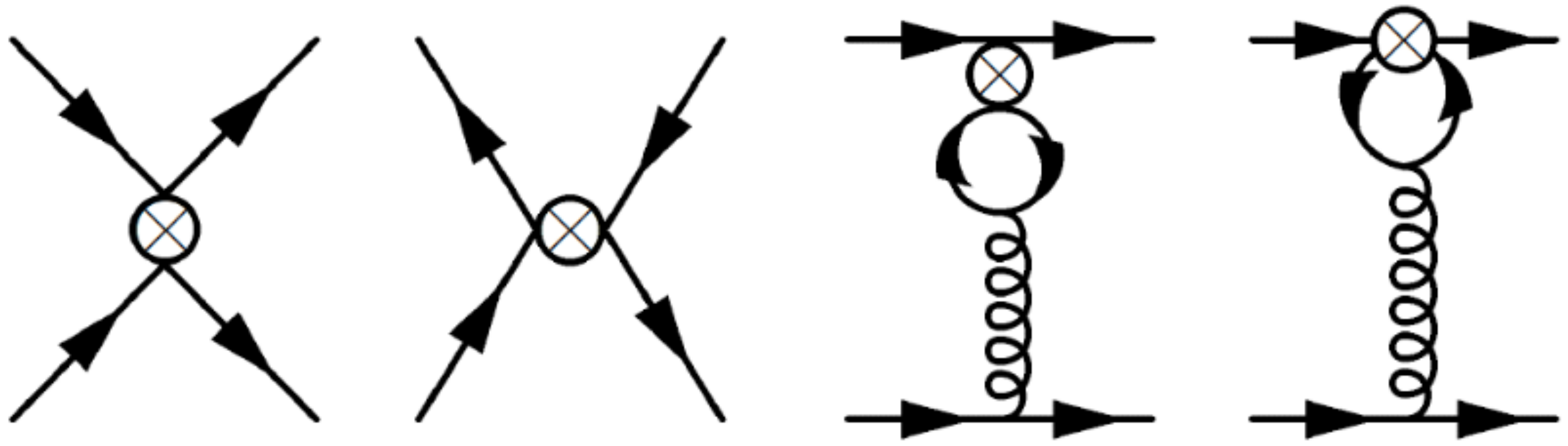


CMS Summary

World Average: $\alpha_S(m_Z) = 0.1179 \pm 0.0009$

Jets as a probe of new physics

- **Probe BSM: New phenomena** described in **Effective Field Theory (EFT):**
  - 4-quark "contact interactions" (CI)



$$L_{SMEFT} = L_{SM} + \frac{4\pi}{2\Lambda^2} \sum_n c_n O_n$$

c_n: Wilson Coefficient
O_n: dimension-6 operators
Λ: energy scale of new physics

- Check BSM effects are not absorbed into PDFs→ **fit PDFs simultaneously with** c_n

SMEFT FIT @ NLO (xFitter)

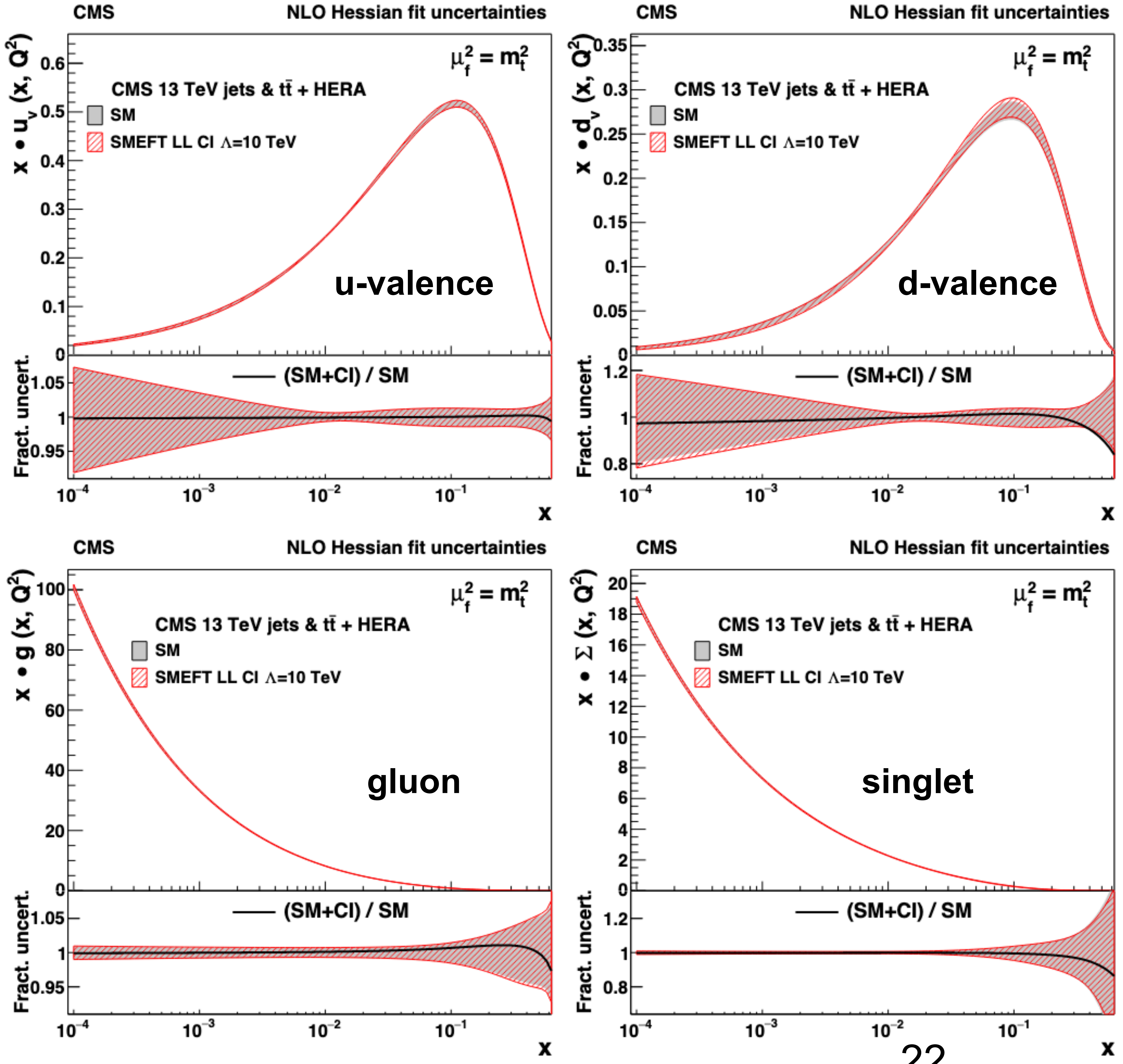
12/2022 (addendum)
JHEP 02 (2022) 142 [Addendum]

PDFs in SMEFT and SM fits agree

- **Simultaneous fit at NLO: c_1 + PDFs + $\alpha_s(m_Z)$ + m_t^{pole}**

- **Datasets:**
  - *ep* inclusive DIS cross sections (HERA) [arXiv:1506.06042]
  - CMS inclusive jets at 13 TeV [arXiv:2111.10431]
  - CMS 3-D $t\bar{t}$ cross sections [arXiv:1904.05237]:

- **Predictions for jet x-sections: QCD NLO+NLL + EFT 4-quark CI (LL, VV, A-V models)**



SMEFT FIT @ NLO results

12/2022 (addendum)
JHEP 02 (2022) 142 [Addendum]

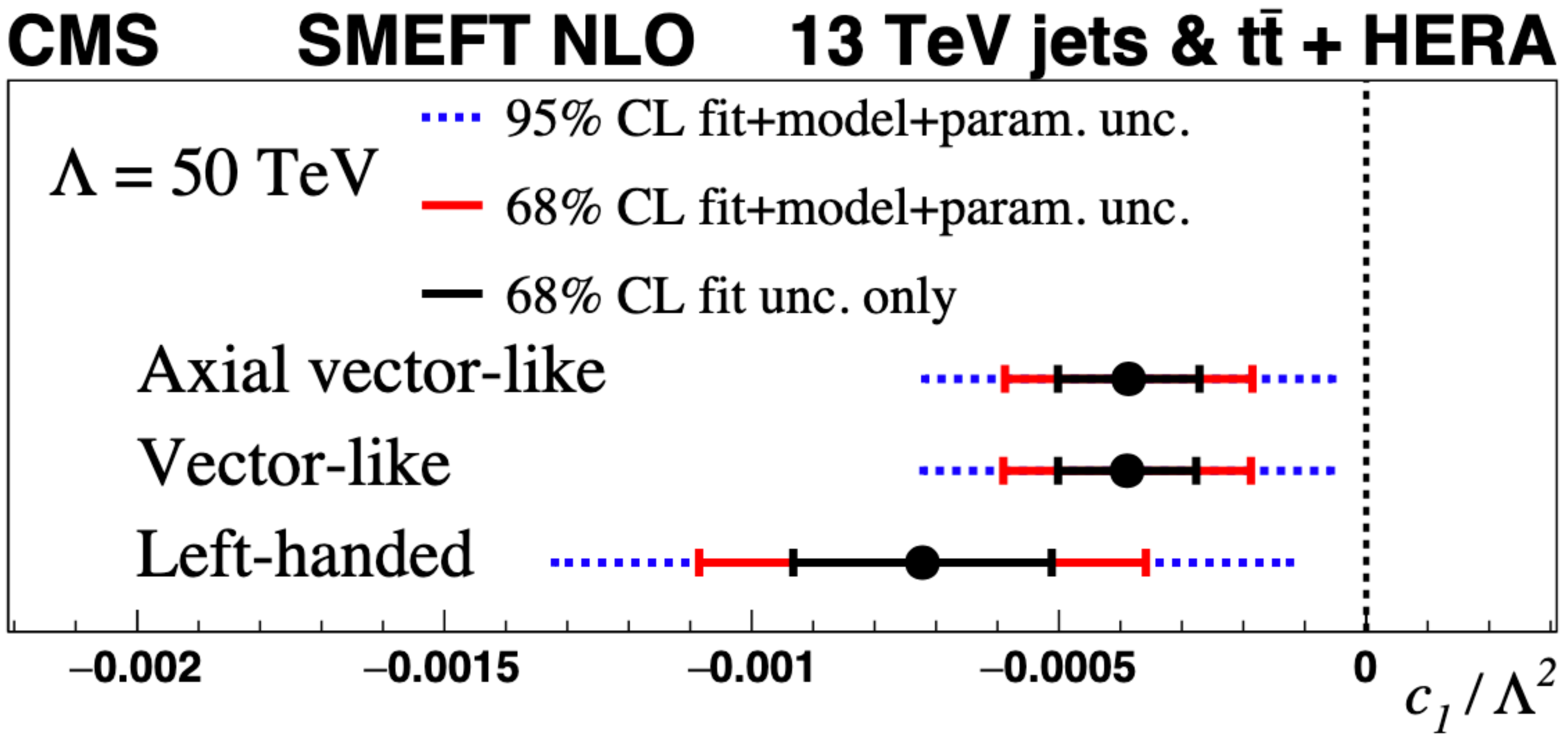
- Results in SMEFT and SM fits agree

  - **QCD parameters agree with SM fit:**

    - $\alpha_S(m_Z) = 0.1187 \pm 0.0033$
    - $m_t^{pole} = 170.4 \pm 0.7$ GeV

  - **CI parameters ($\Lambda_{NP} = 10$ TeV):**

    - $c_1^L = -0.07 \pm 0.02_{exp} \pm 0.01_{mod+par}$



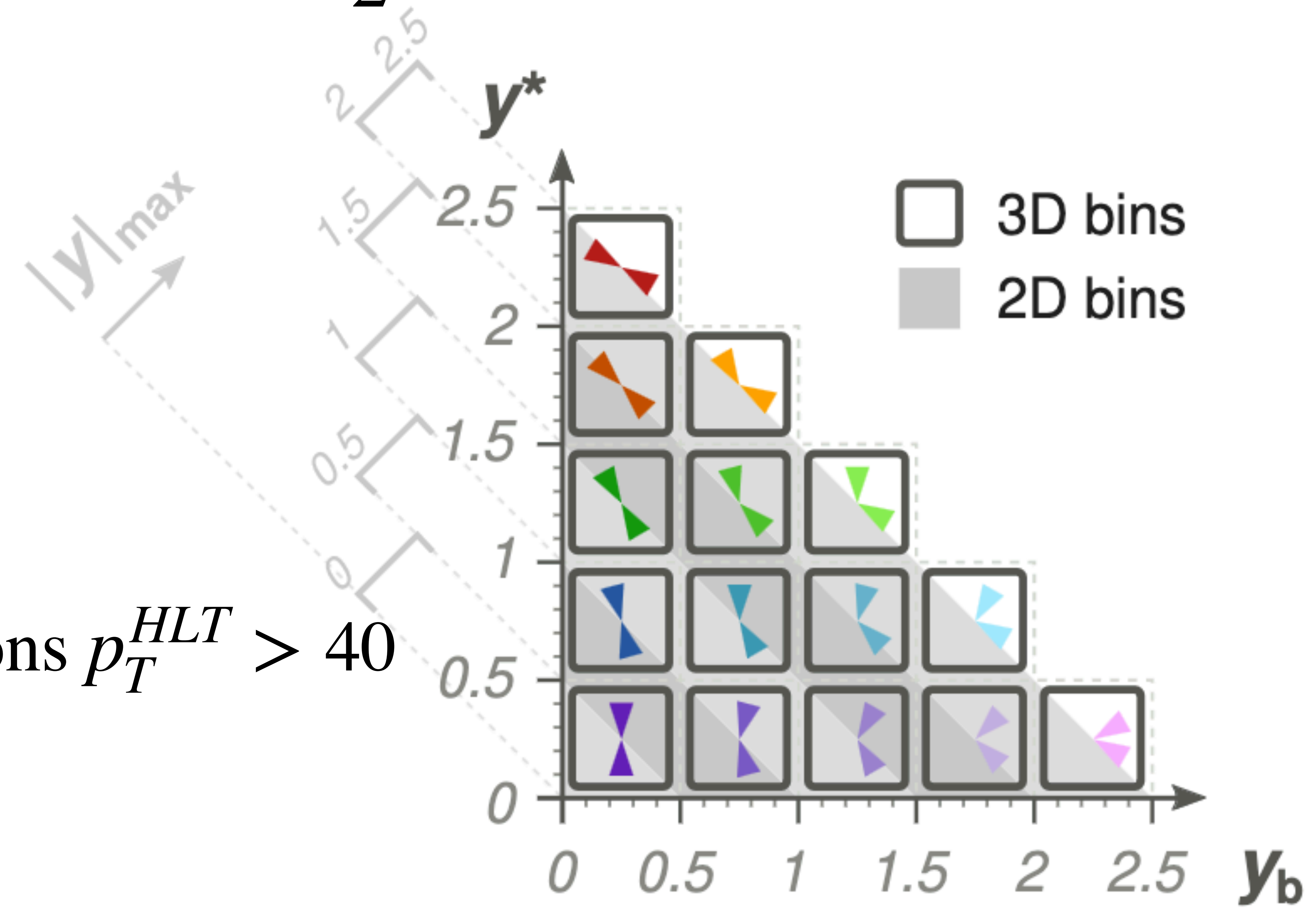
Correspond to 95% exclusion limits for Λ ($c_1 = -1$):

LL : $\Lambda > 24$ TeV
V: $\Lambda > 32$ TeV
AV: $\Lambda > 31$ TeV

Multi-differential 2-jet production

NEW! SMP-21-008

- **2-D cross sections** vs rapidity of the outermost jet $|y_{max}|$ and di-jet invariant mass m_{12}
- **3-D cross sections:** vs m_{12} or $< p_T >_{1,2}$, 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

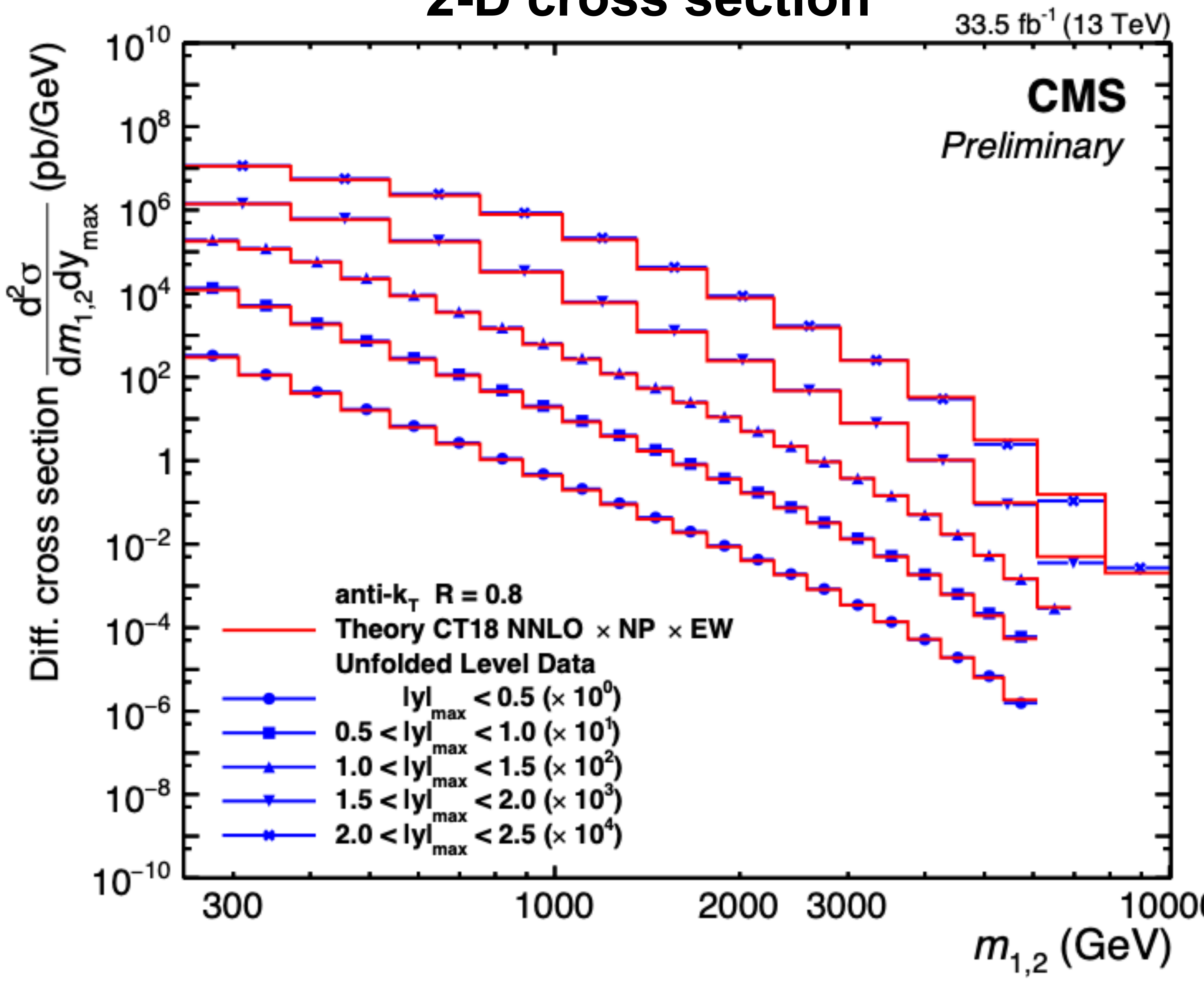
- **Datasets and trigger strategy**
  - $L \sim 35\ fb^{-1}$ (2016), single-jet (di-jets) HLT selections $p_T^{HLT} > 40$ for 2-D (3-D), jets ak4 and ak8

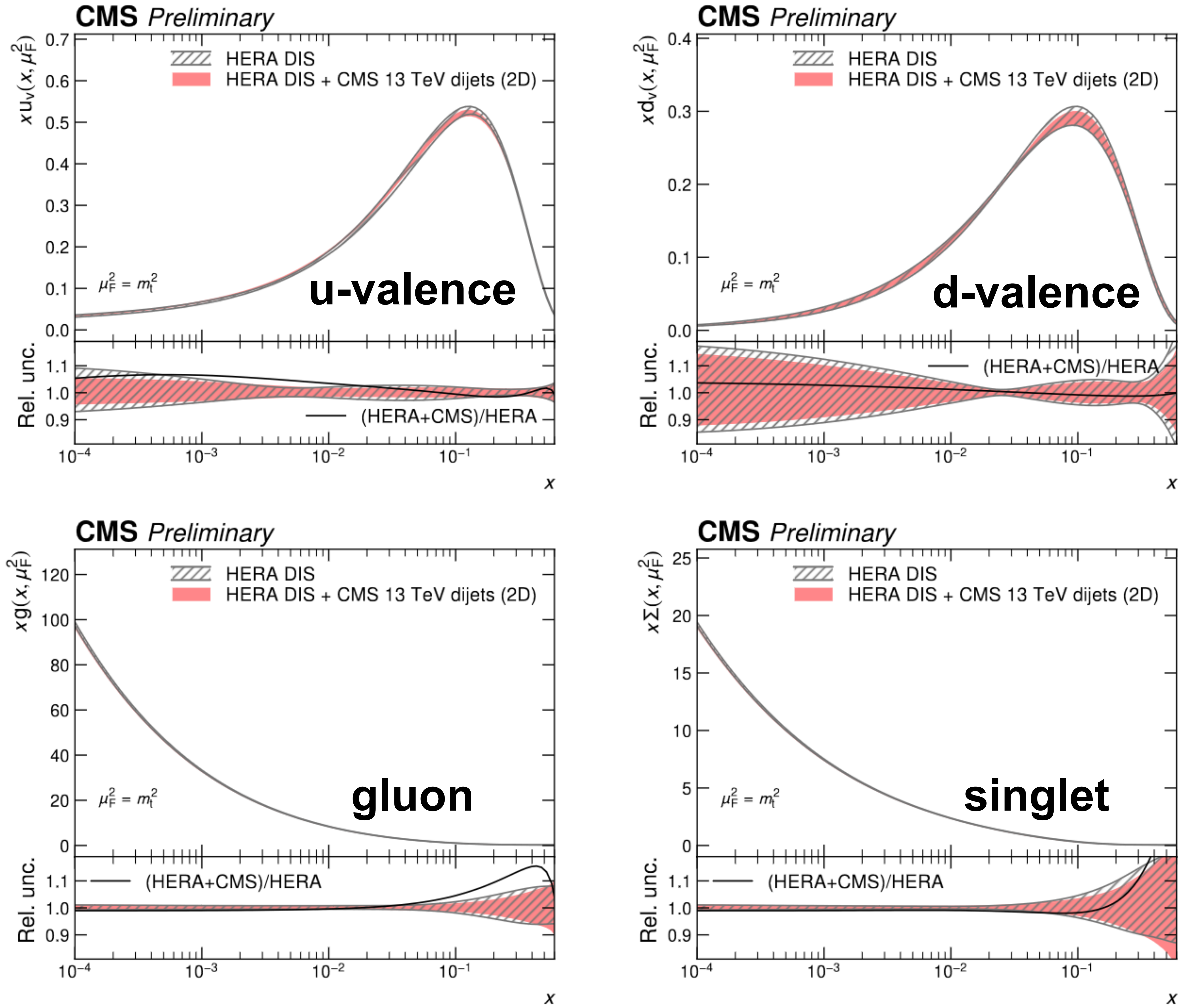
- **Event Selection**
  - Dijet system

Results of multi-differential 2-jet production

NEW! **SMP-21-008**

2-D cross section





- Data compared to **NNLO QCD** corrected by non-perturbative and electroweak effect
- **Simultaneous fit** using interpolation grids **at NNLO**: PDFs and α_s

- **Preliminary 2-D (similar results with 3-D)**

$$\alpha_S(m_Z) = 0.1201 \pm 0.0021$$

$$0.0012_{fit} \pm 0.0008_{model} \pm 0.0008_{scale} \pm 0.0005_{param}$$

Summary and Conclusions

- **Presented recent and new CMS measurements at $\sqrt{s} = 13$ TeV:**
  - **Substructure**
    - **Energy correlators** → Running α_s at low energy scale, most precise measurement of $\alpha_s(M_Z)$ in substructure measurement at NNLL
    - **Lund Jet Plane** → benchmark next generation of parton showers with resummation beyond LL accuracy
  - **High energy jets**
    - **Azimuthal correlations** → First demonstration of running of α_S up to 2 TeV at NLO
    - **Inclusive jets** → Most precise measurement of $\alpha_s(m_Z)$ to date in CMS at NNLO, Full SMEFT fit at NLO
    - **Multi-differential dijets** → Disentanglement of x_1 and x_2 using different event topologies, extract $\alpha_s(m_Z)$

Thank you

Backup