Energy correlator measurements at the ATLAS and CMS

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on behalf of ATLAS and CMS

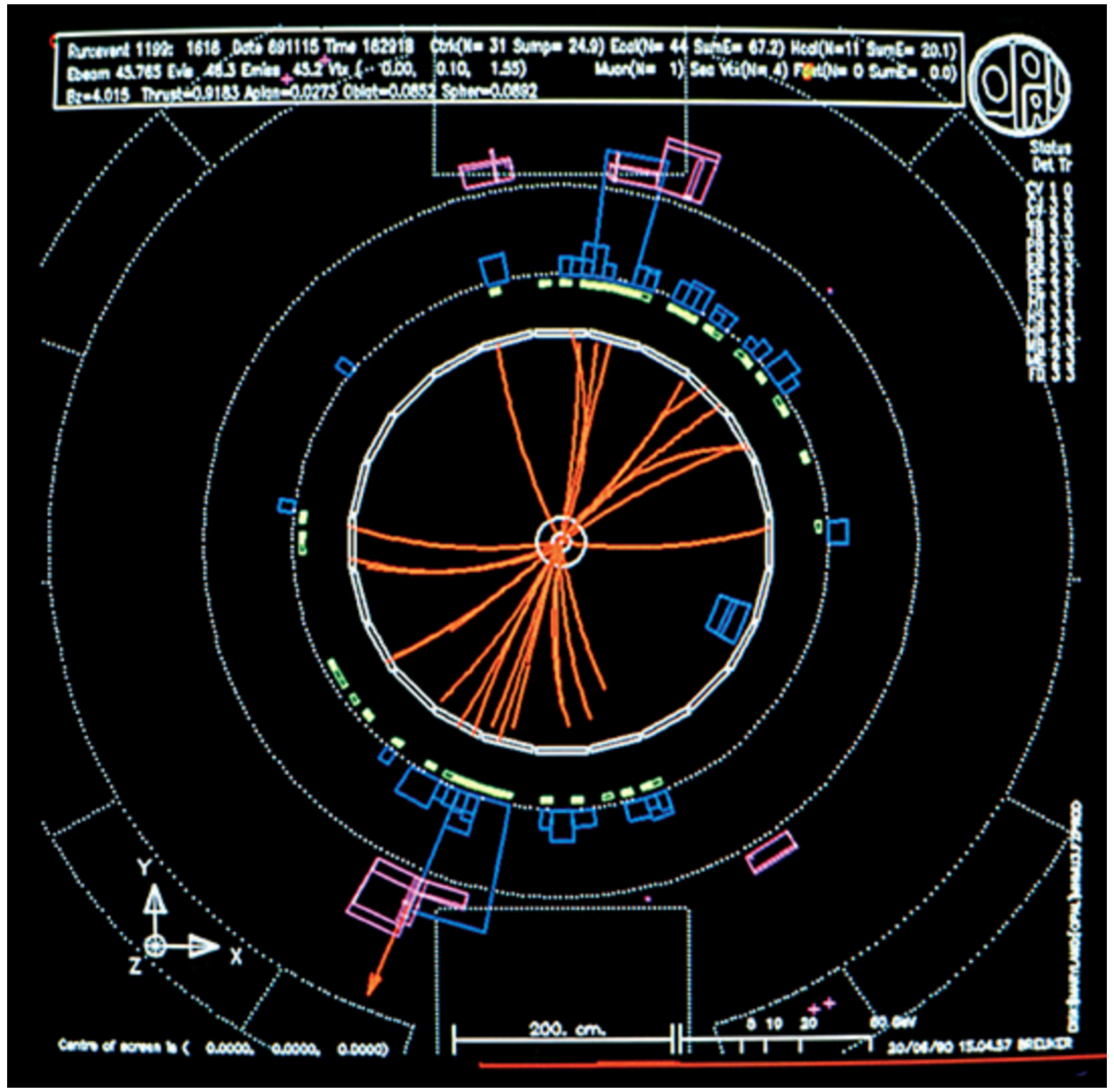
LHC-EW General meeting, 2024.07.10

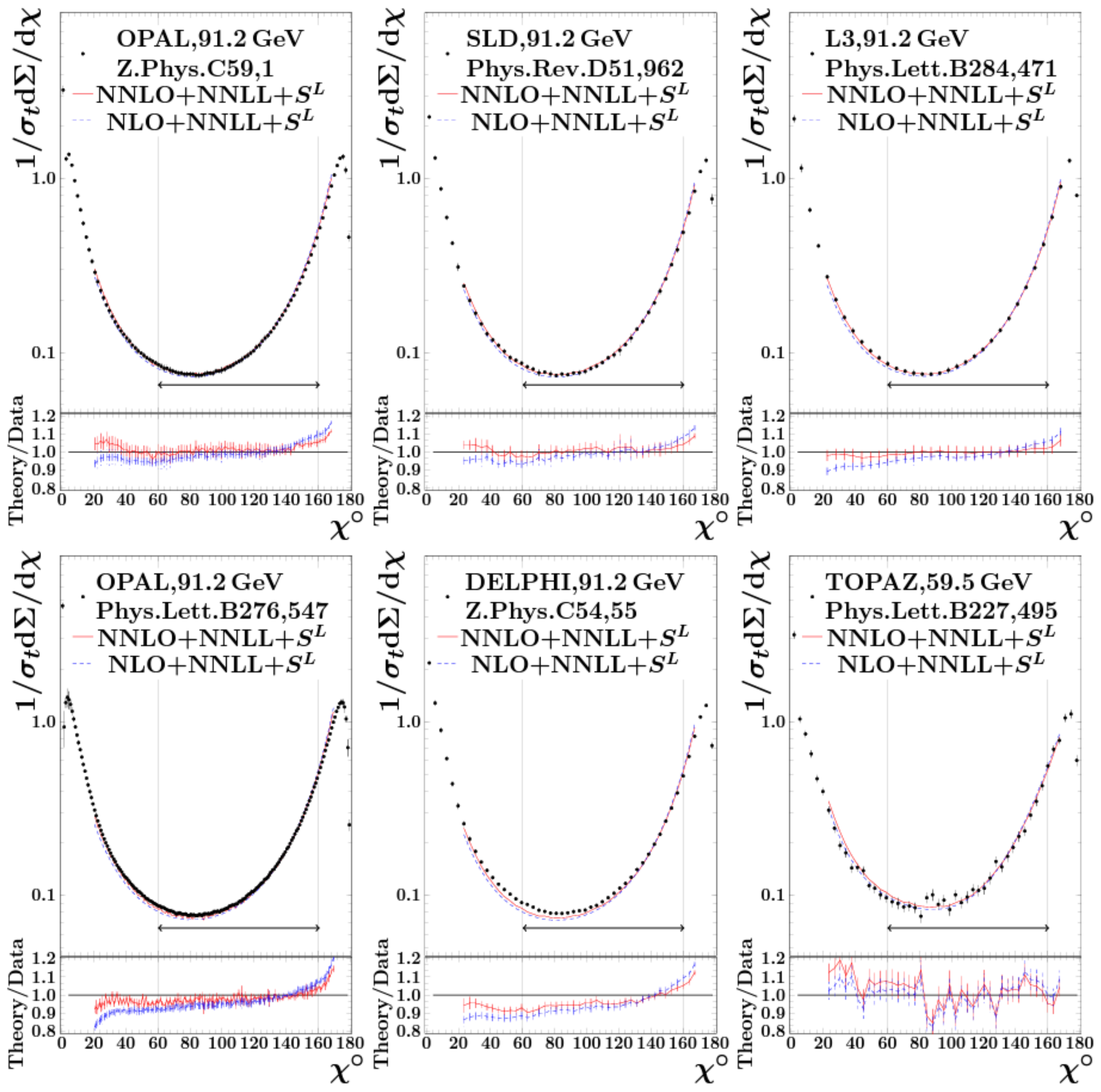
Energy-energy correlator at e^+e^-

EEC: event shape observable proposed for e^+e^- experiment in 1978 [PRL 41 (1978) 1585]

$$\frac{1}{\sigma_\mathrm{t}}\frac{\mathrm{d}\Sigma(\chi)}{\mathrm{d}\cos\chi} \equiv \frac{1}{\sigma_\mathrm{t}}\int \sum_{i,j}\frac{E_iE_j}{Q^2}\,\mathrm{d}\sigma_{e^+e^-\to ij+X}\,\delta(\cos\chi-\cos\theta_{ij})\,,$$

All particles · Energy weight · Azimuthal distance





Widely measured at e^+e^-

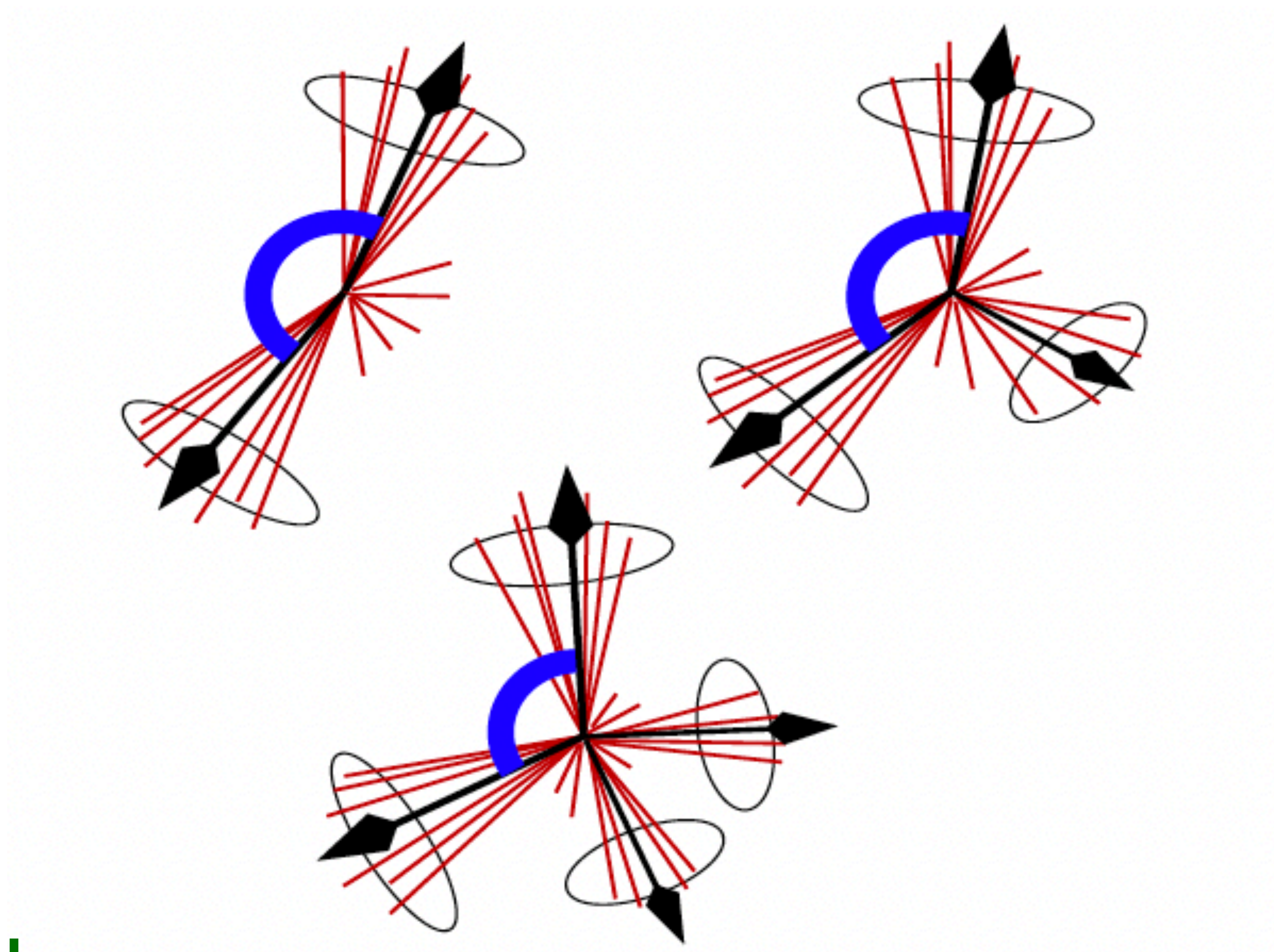
Extract αS at NNLO+NNLL ~ 2% precision [arXiv:1804.09146].

Energy-energy correlator at LHC

Adaptions for hadron collider

Transverse EEC (TEEC)
***PLB* 141 (1984) 447**

Angular correlation between jets in an event



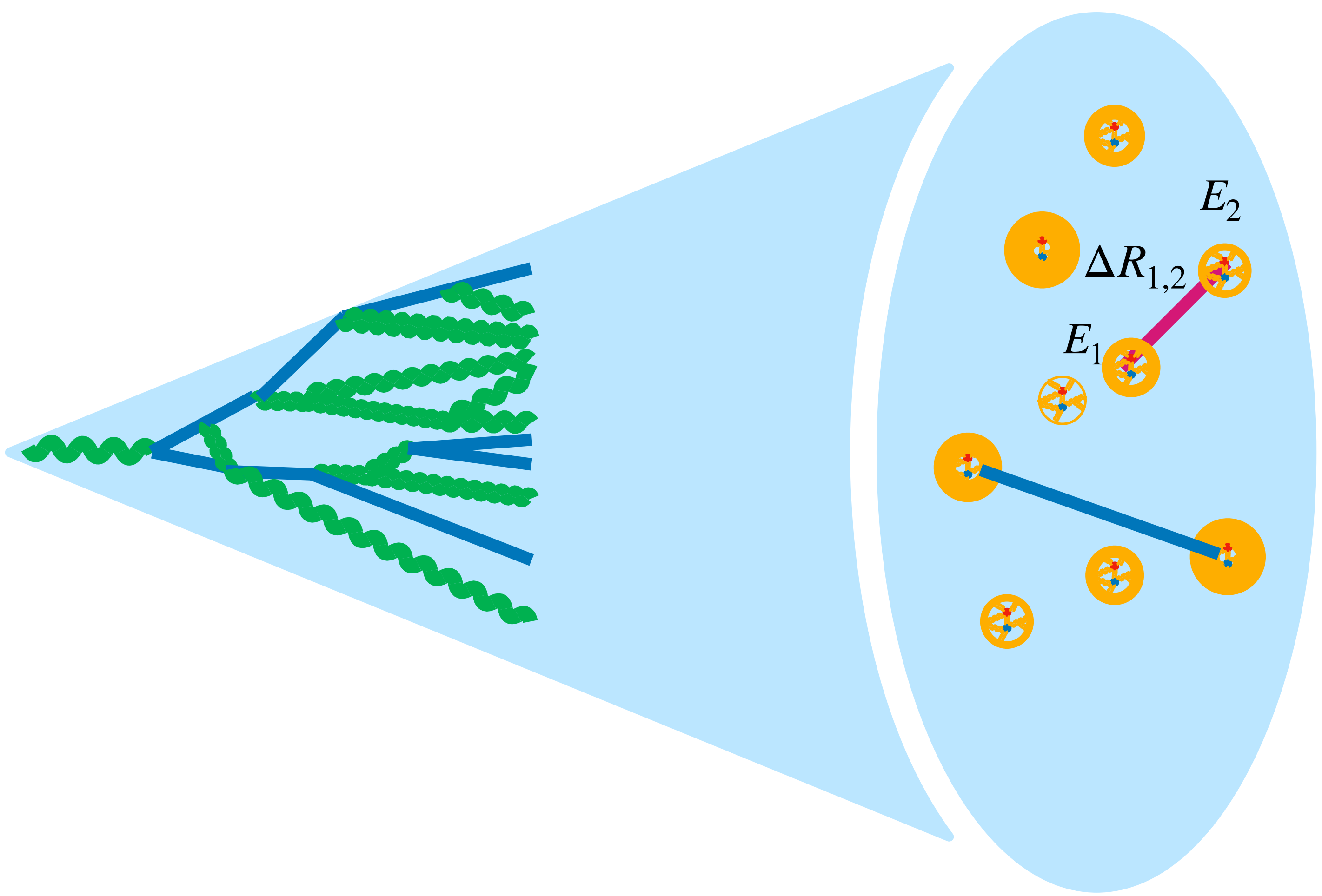
All jets

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

Transverse energy weight

EEC inside jets
arXiv:2004.11381

Angular correlation between particles in a jet



All particles inside a jet

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

ΔR

Energy-energy correlator at LHC

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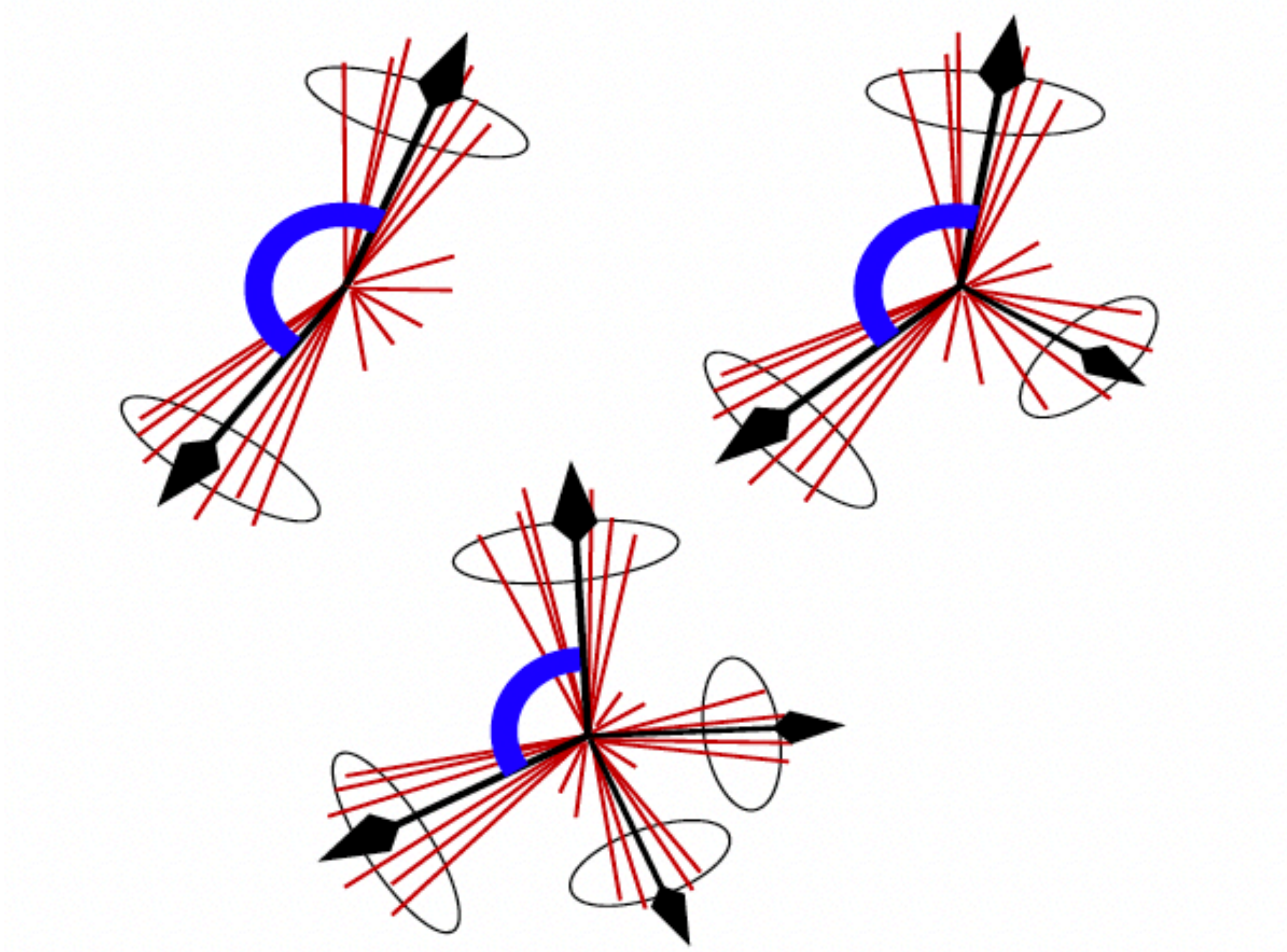
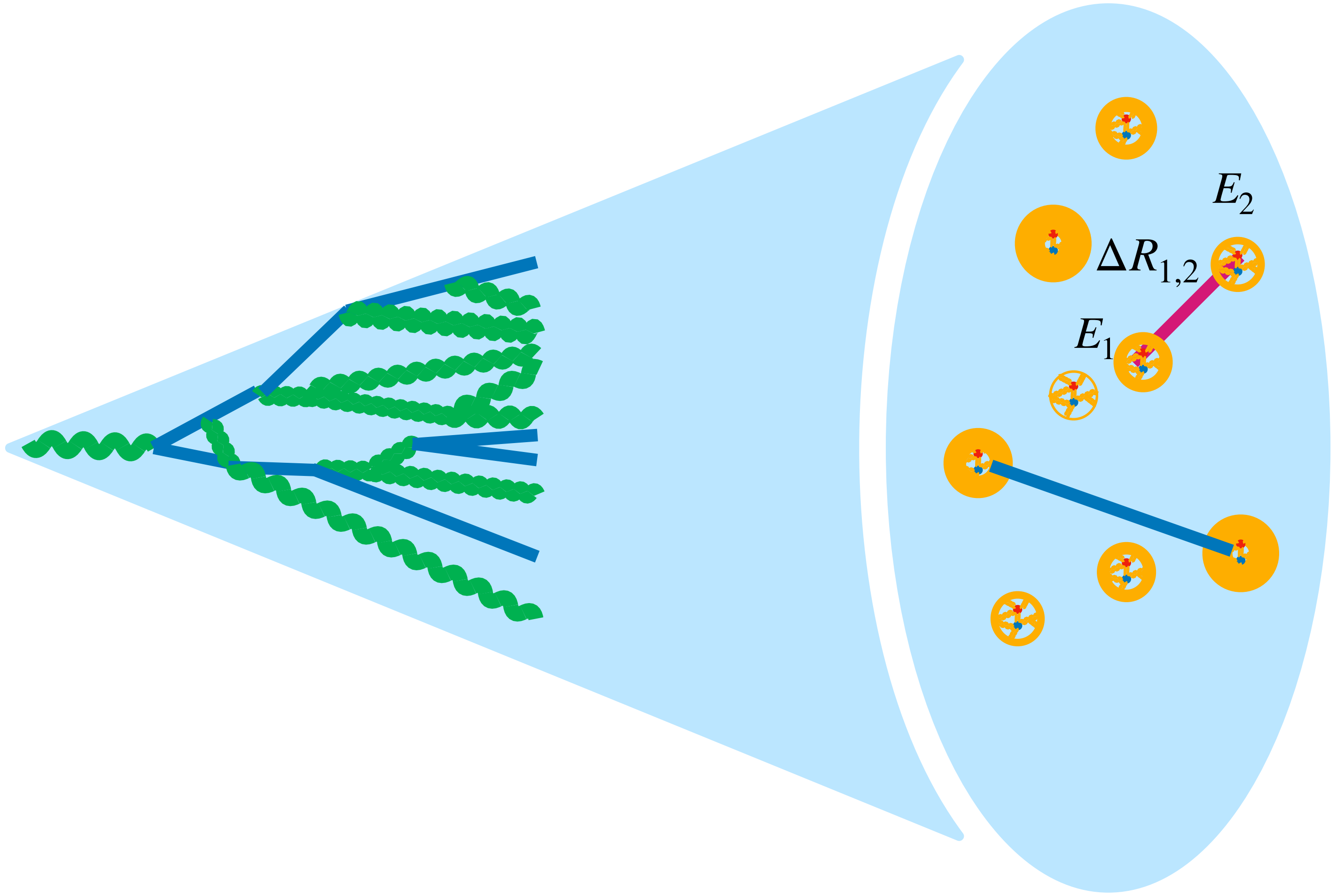


Energy scale Q ~ **O (TeV)**

Fixed order QCD dominant
NNLO pQCD available [JHEP 03 (2023) 129]

EEC inside jets
arXiv:2004.11381

Angular correlation between particles in a jet



Energy scale Q ~ pT * ΔR ~ **O (10 GeV)**

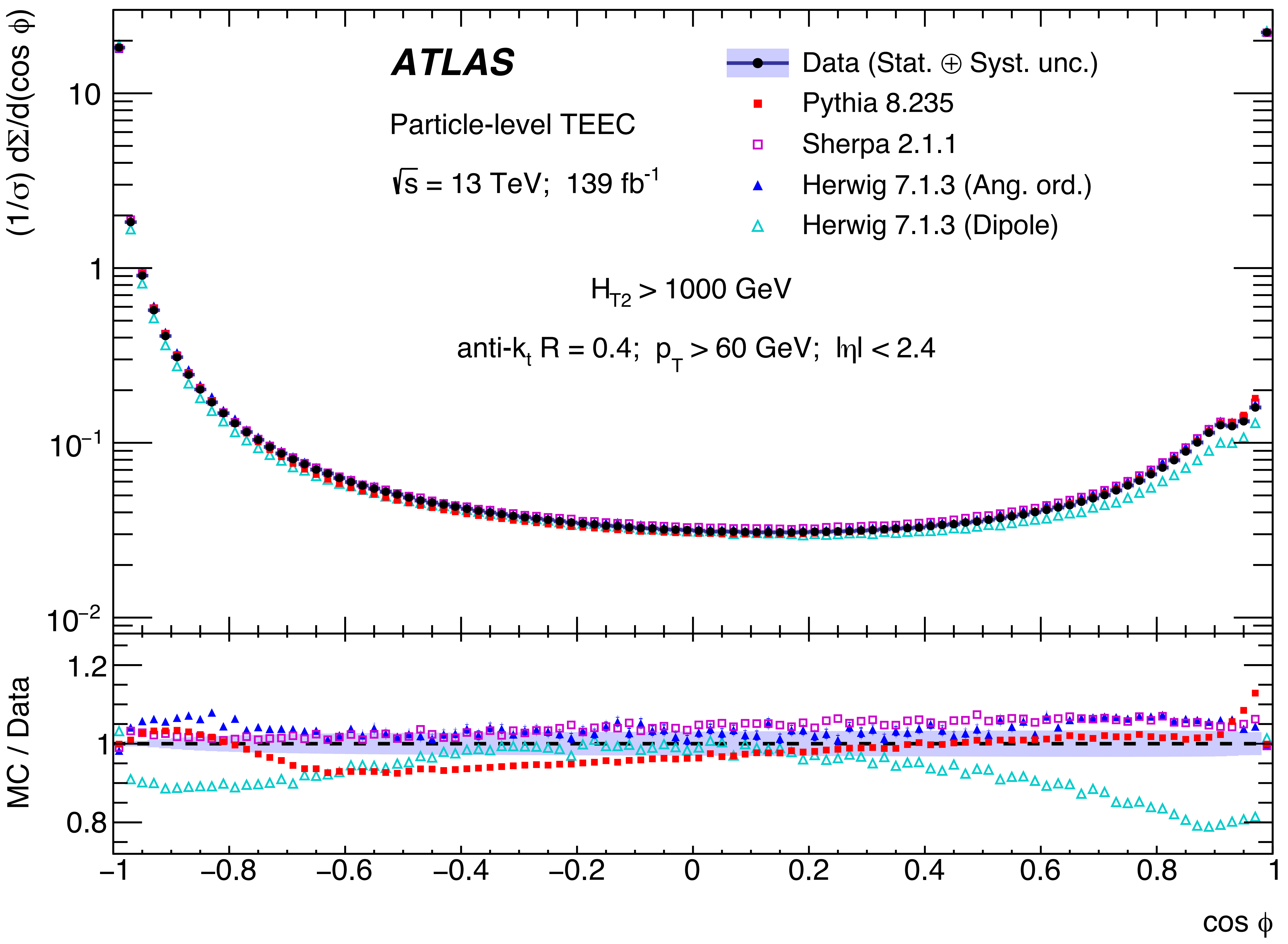
Collinear QCD dominant
NLO+NNLL$_{approx}$, arXiv:2307.07510

Measurement of TEEC

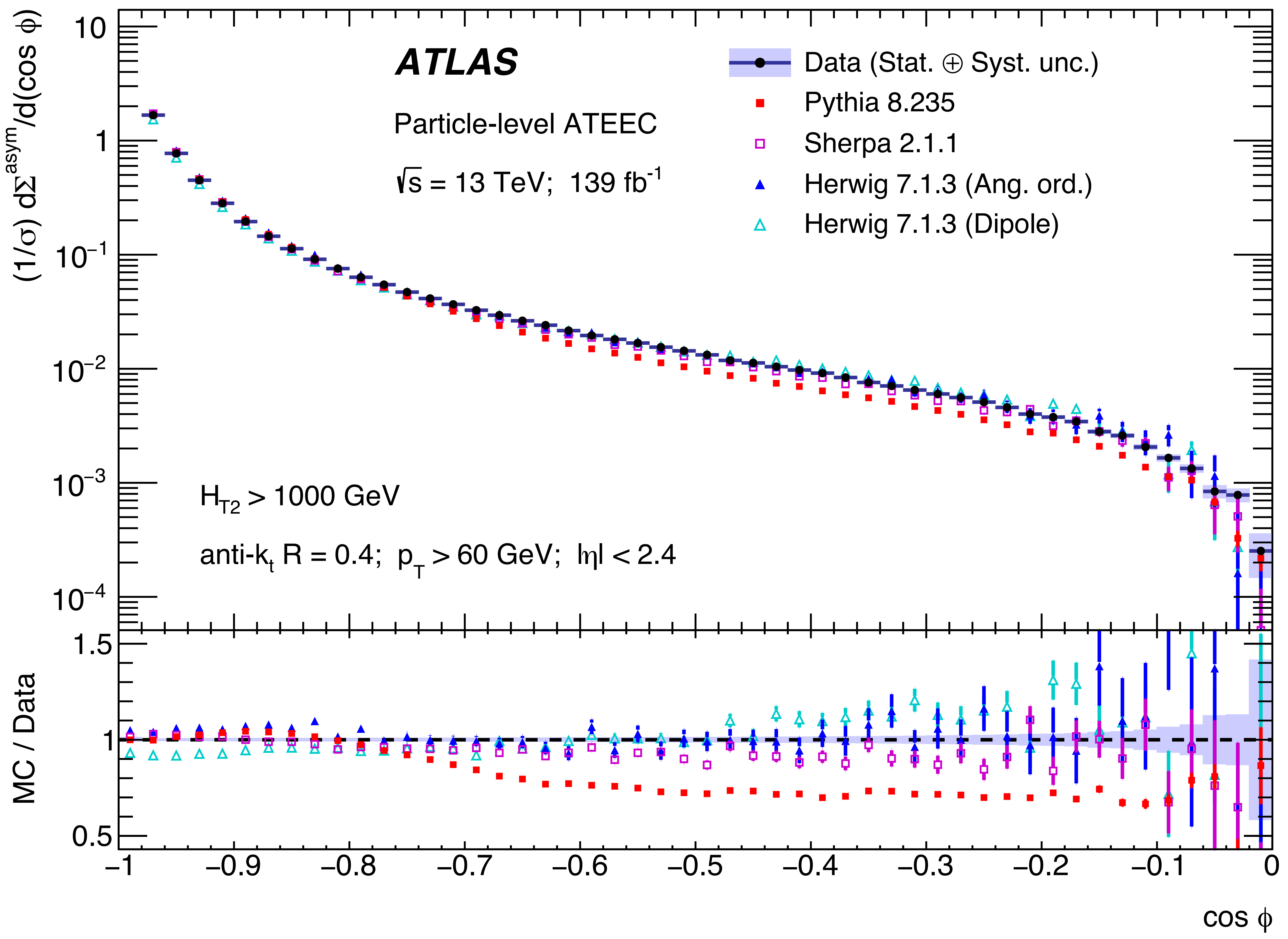
ATLAS, JHEP 07 (2023) 85

Anti-kt jets, R = 0.4
HT= pT1+pT2: [1, 3.5] TeV

TEEC



ATEEC $\frac{1}{\sigma}\frac{d\Sigma^{\mathrm{asym}}}{d(\cos\phi)} \equiv \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\Big|_{\phi} - \frac{1}{\sigma}\frac{d\Sigma}{d(\cos\phi)}\Big|_{\pi-\phi}$



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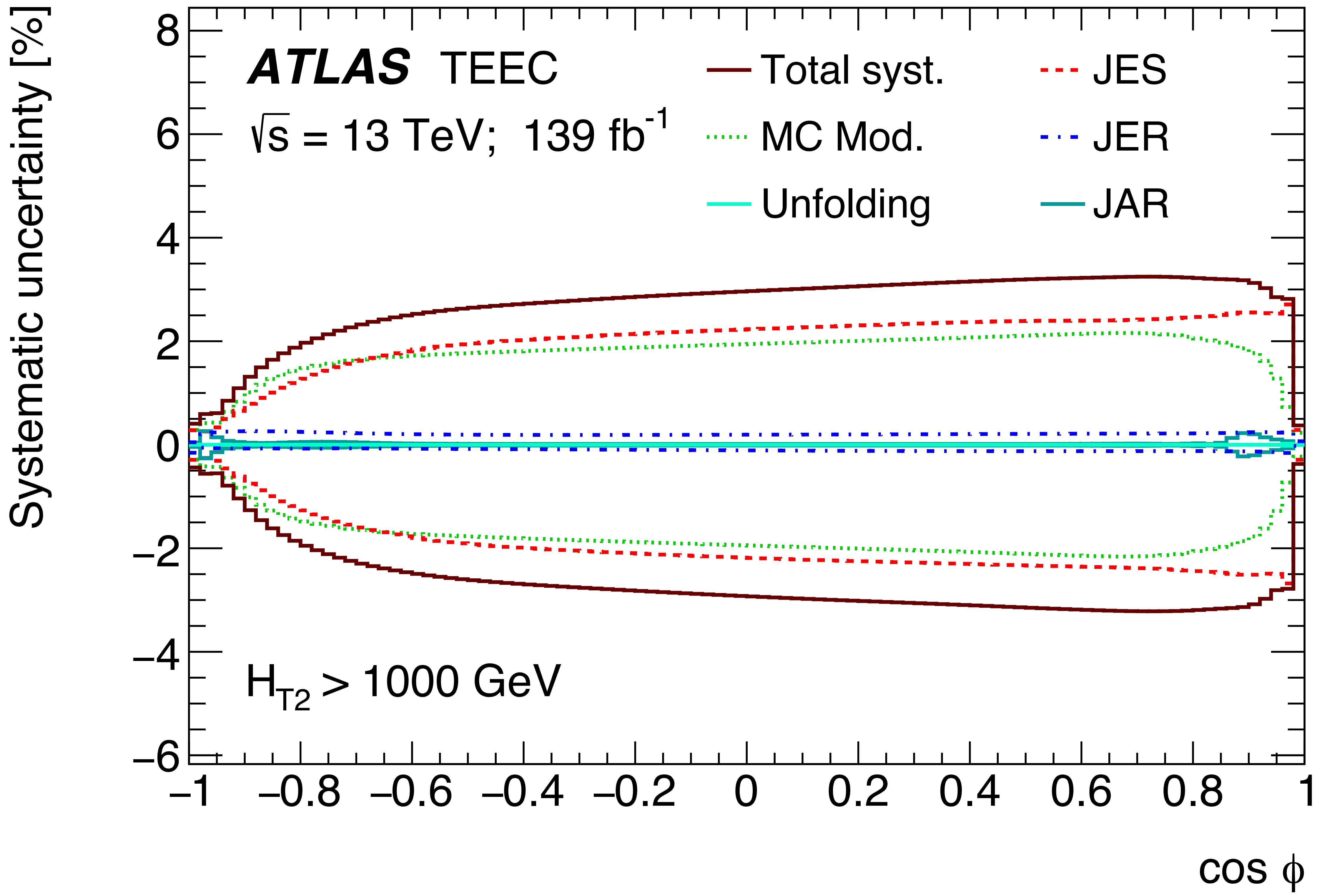
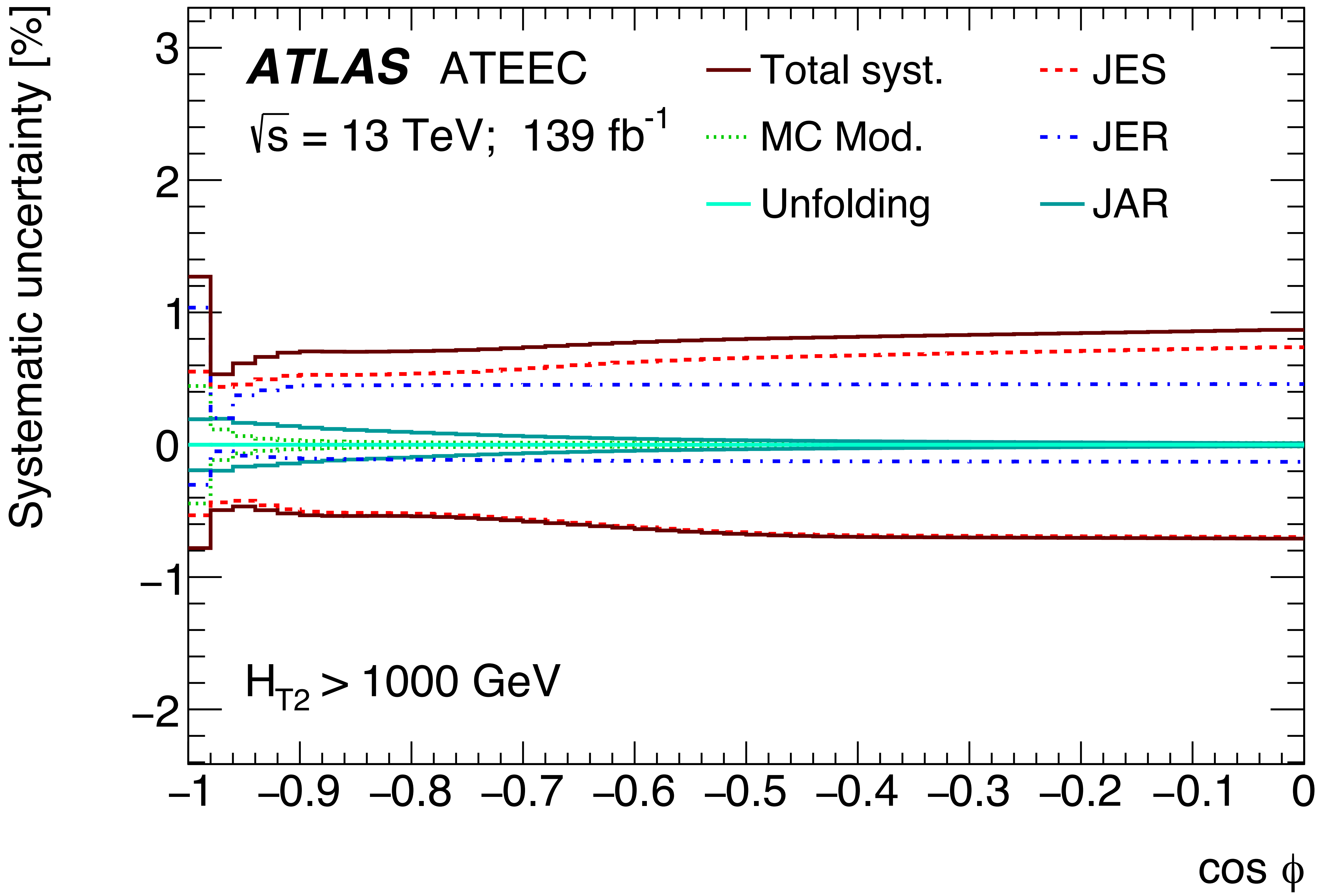
TEEC Uncertainty

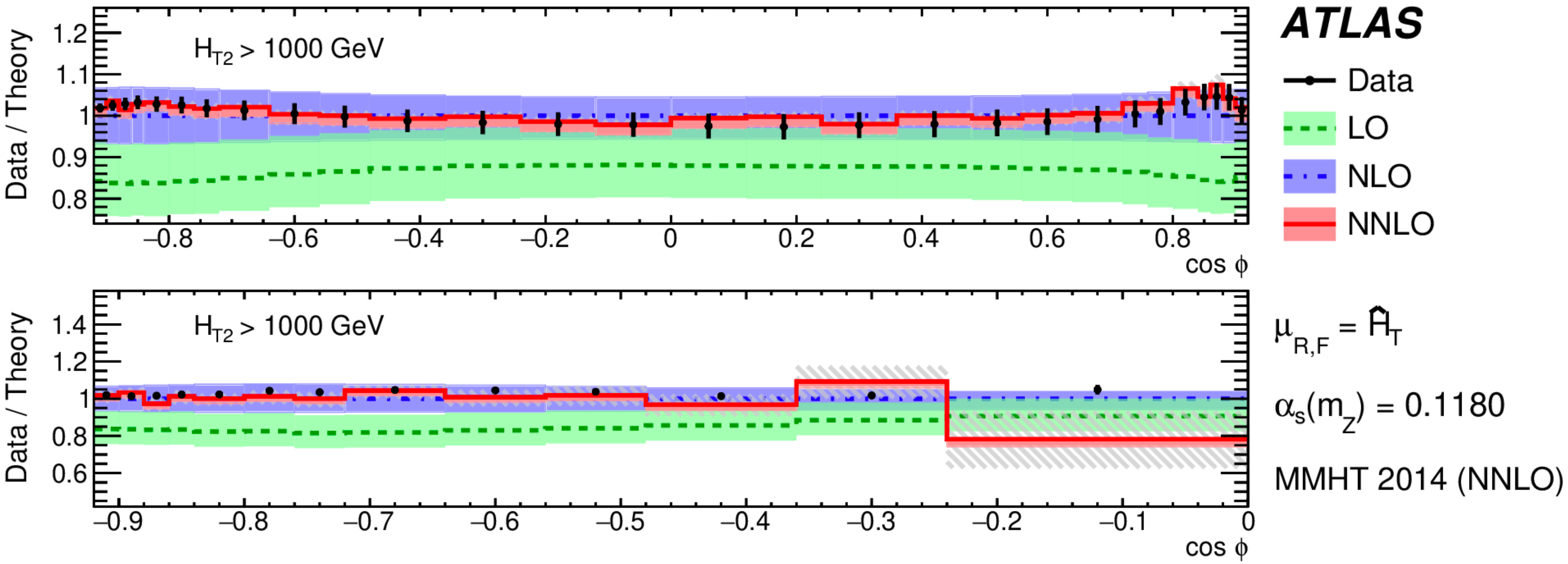


ATEEC Uncertainty



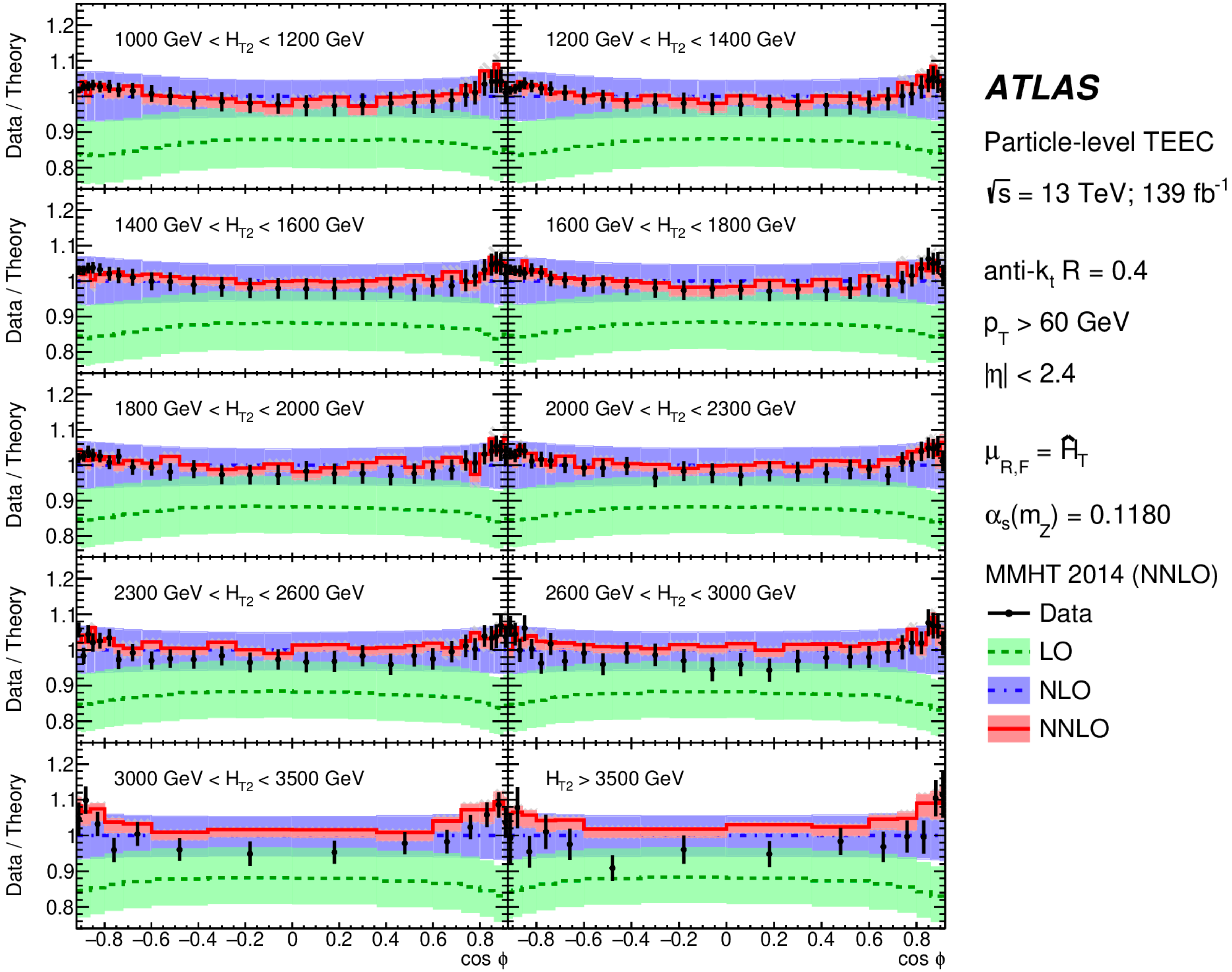
(A)TEEC compared to theory

A leap of uncertainty reduction from LO to NNLO
Prediction avoid collinear and back-to-back regions $|\cos\varphi| < 0.92$
Excellent agreement

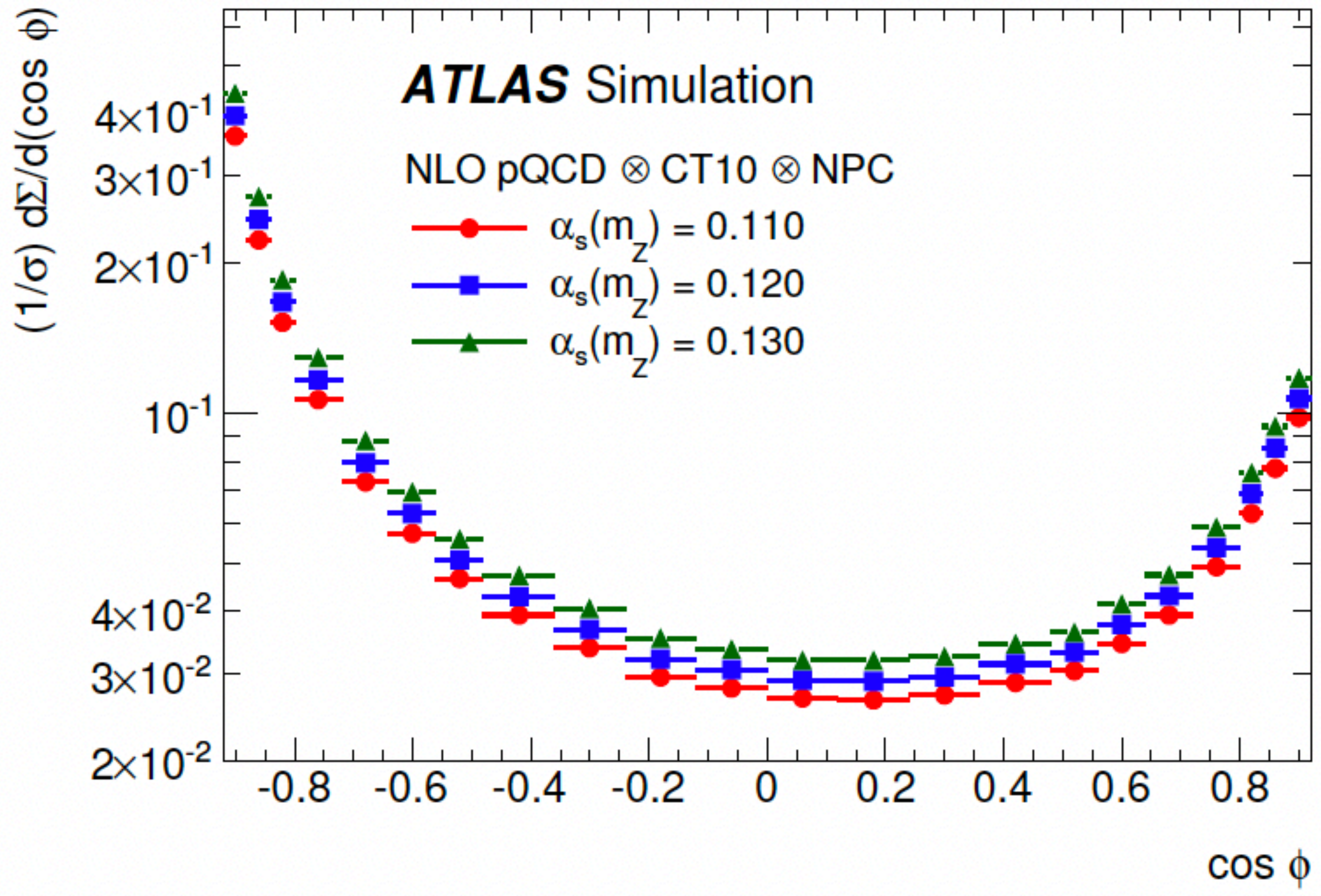


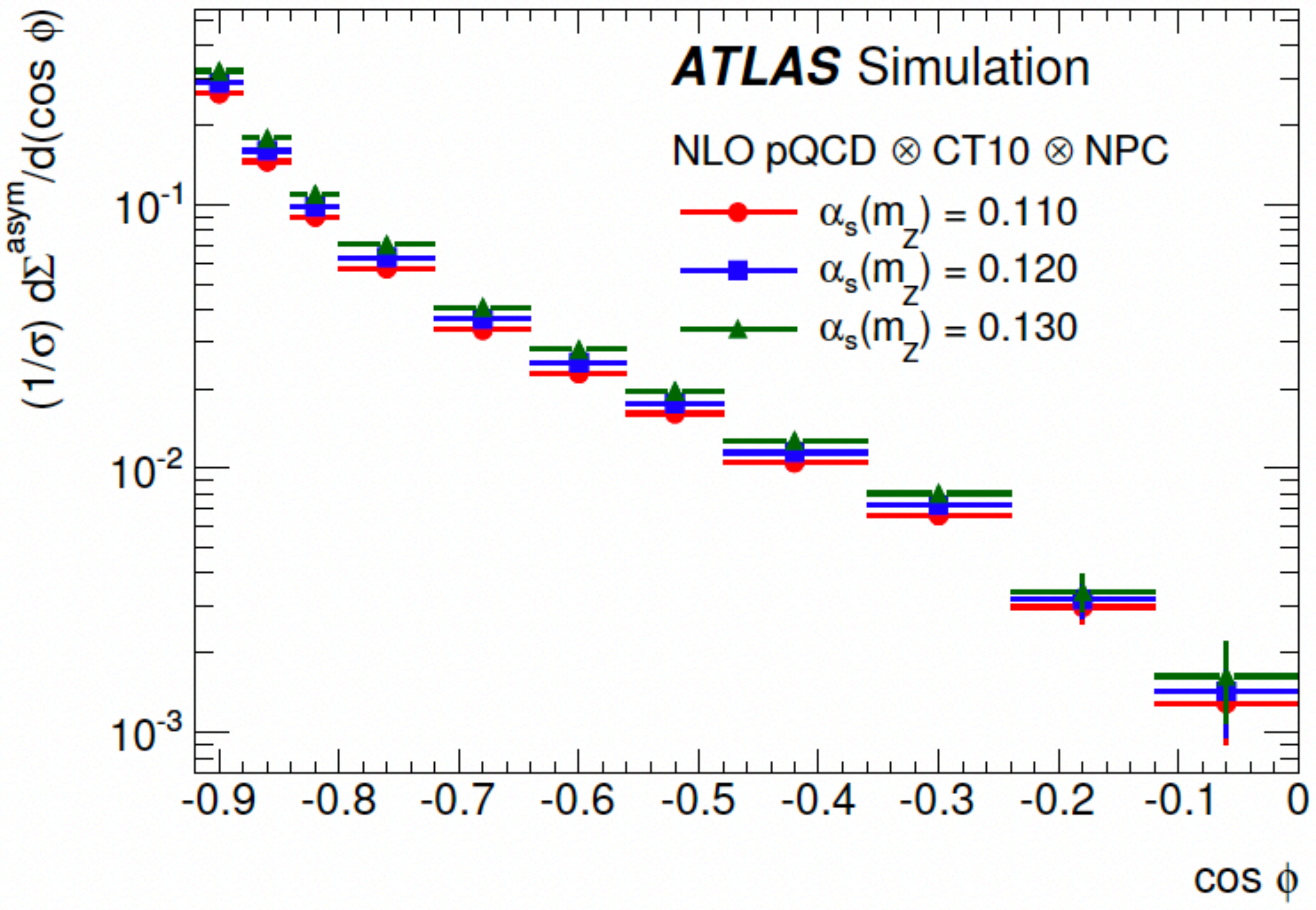
(A)TEEC compared to theory

Comparison in multiple HT regions
[1, 3.5] TeV



α_S extraction from TEEC

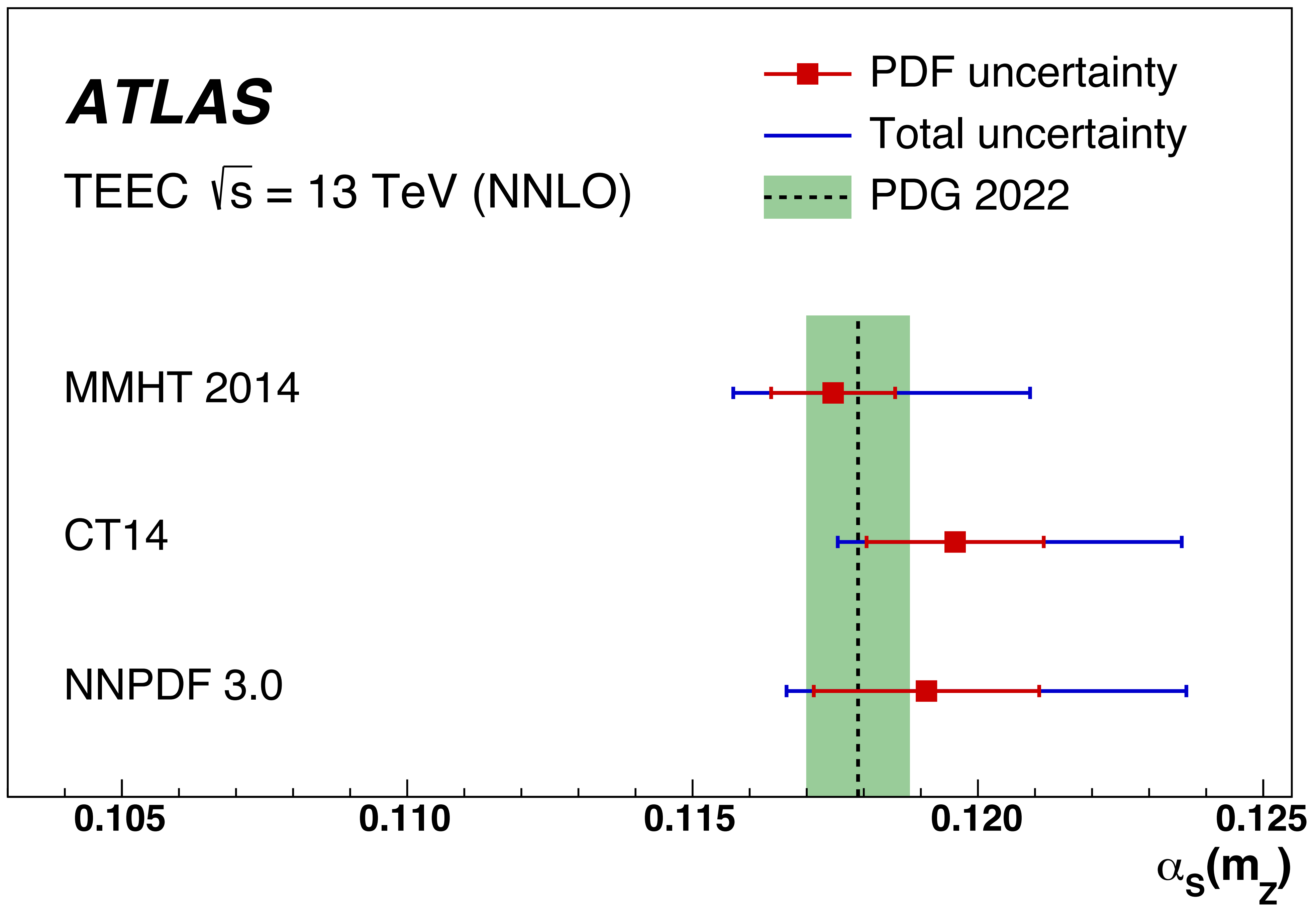


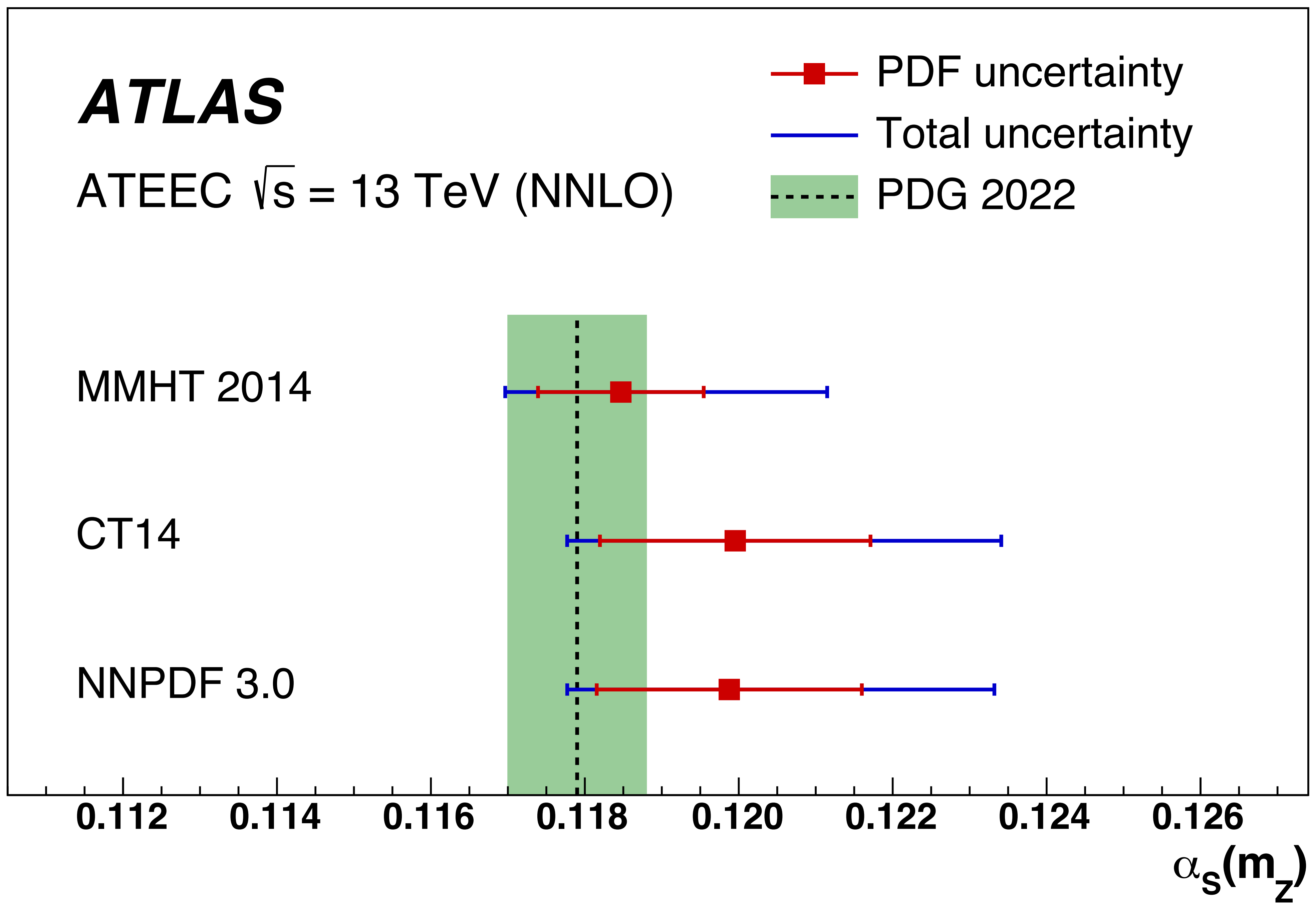


$$\alpha_s(m_Z) = 0.1175 \pm 0.0006\,(\text{exp.})^{+0.0034}_{-0.0017}\,(\text{theo.})$$

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

α_S extraction from TEEC





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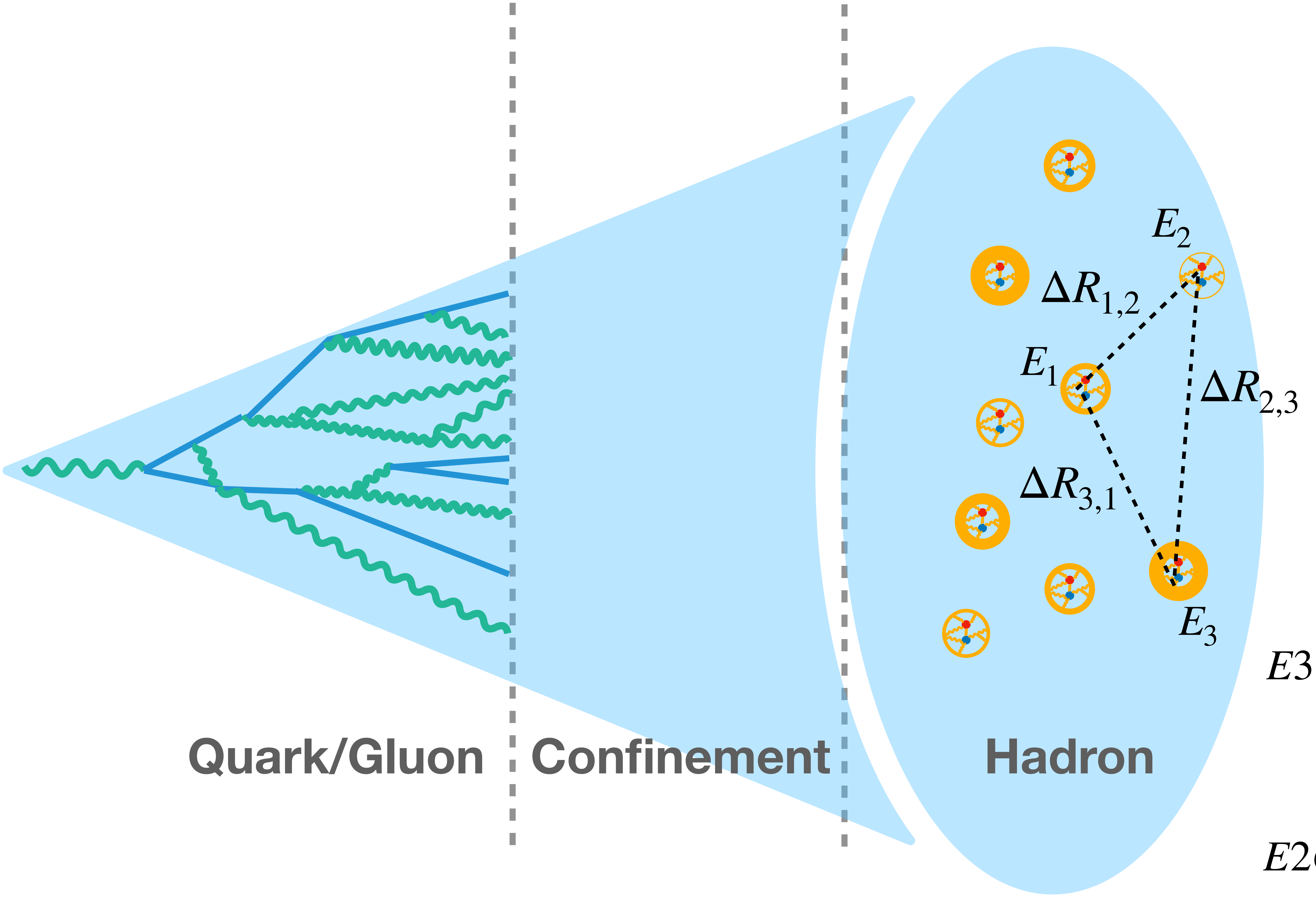
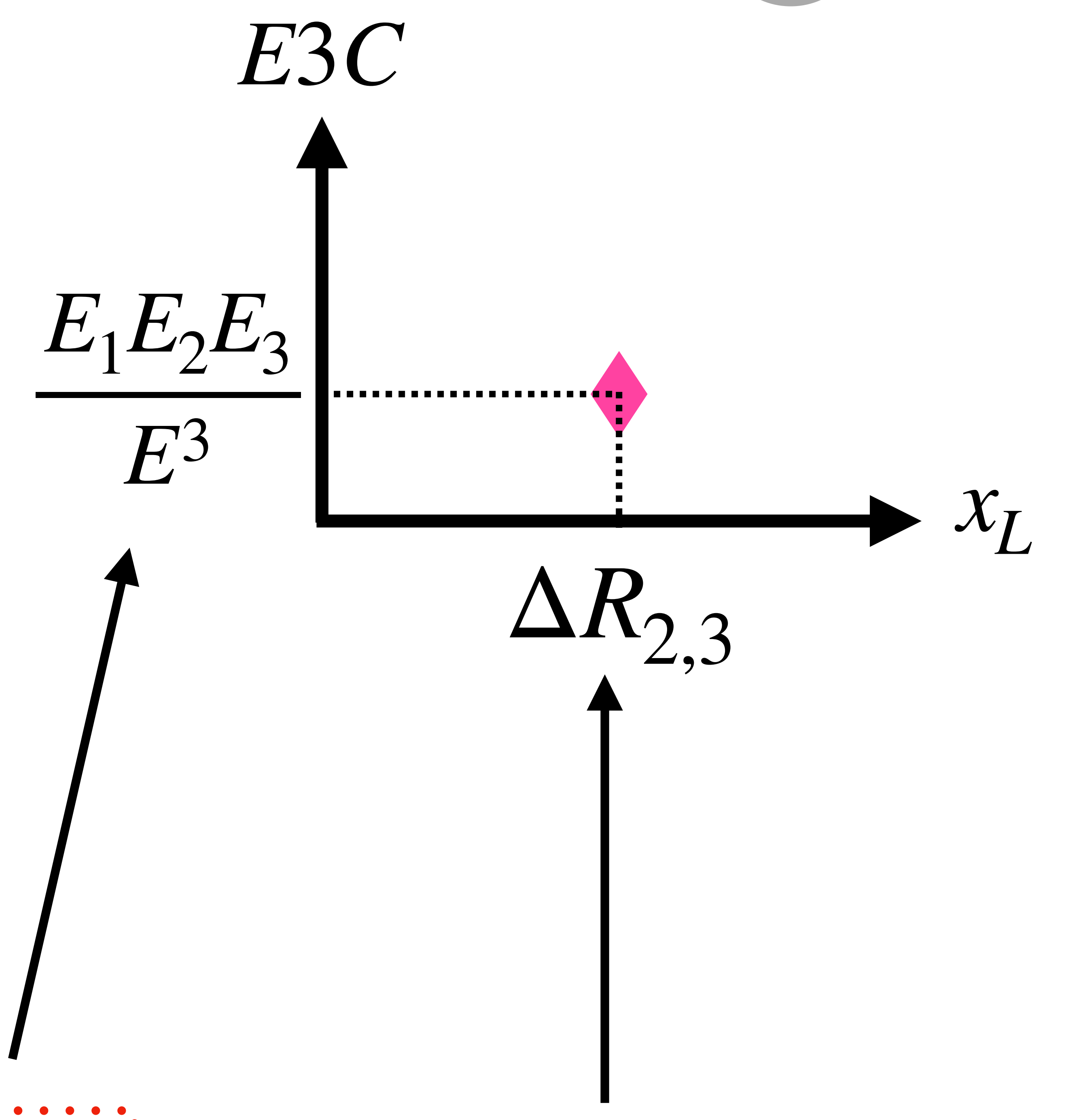
Highest energy scale in αs extraction
Highest precision in beyond TeV scale

Energy correlators in jets: E2C & E3C





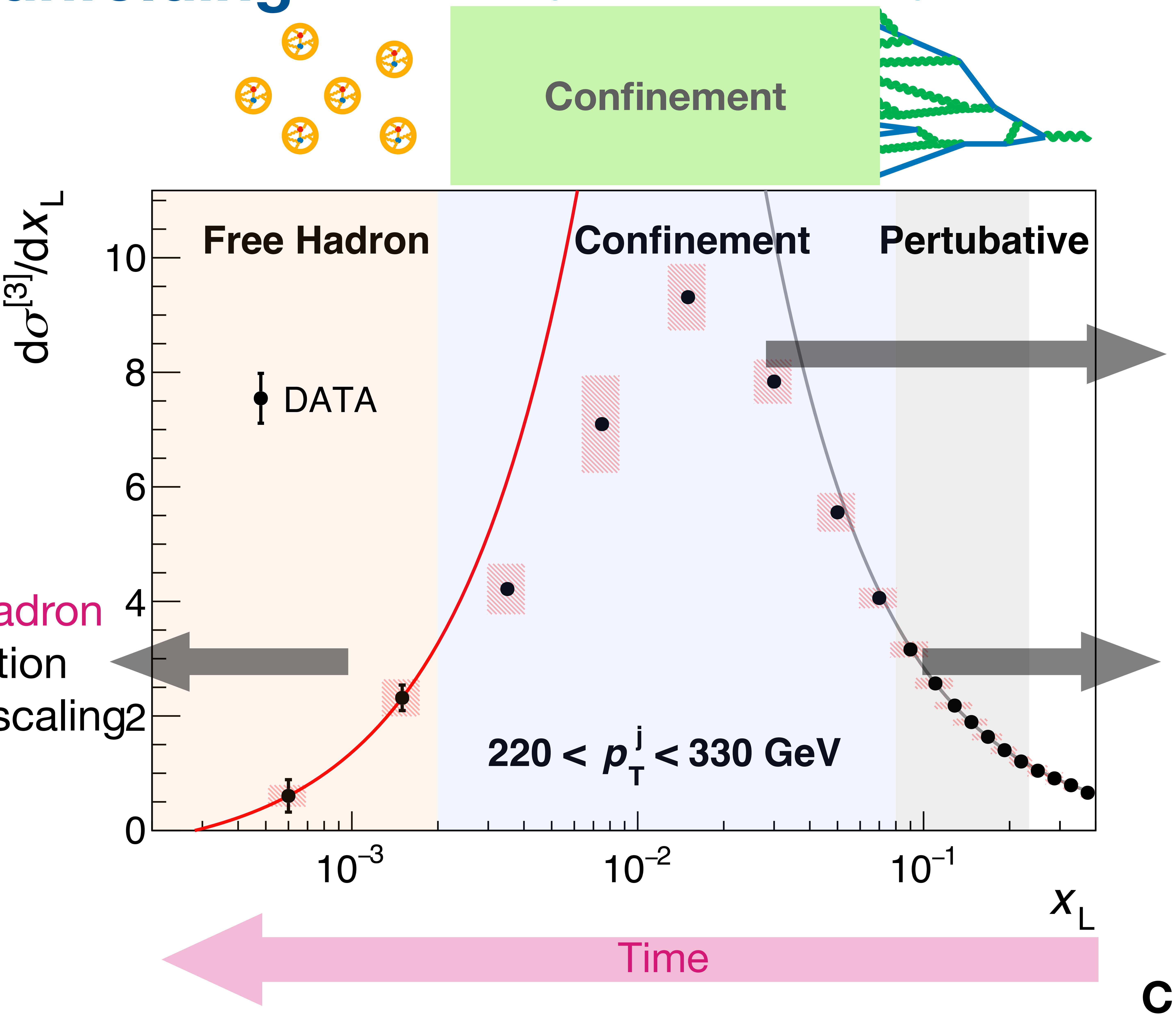
$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_i E_j E_k}{E^3} \delta(x_L - \max(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$

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

Jet substructure observable, sensitive to jet formation

E3C after unfolding

Using all neutral & charged hadrons > 1GeV in a jet



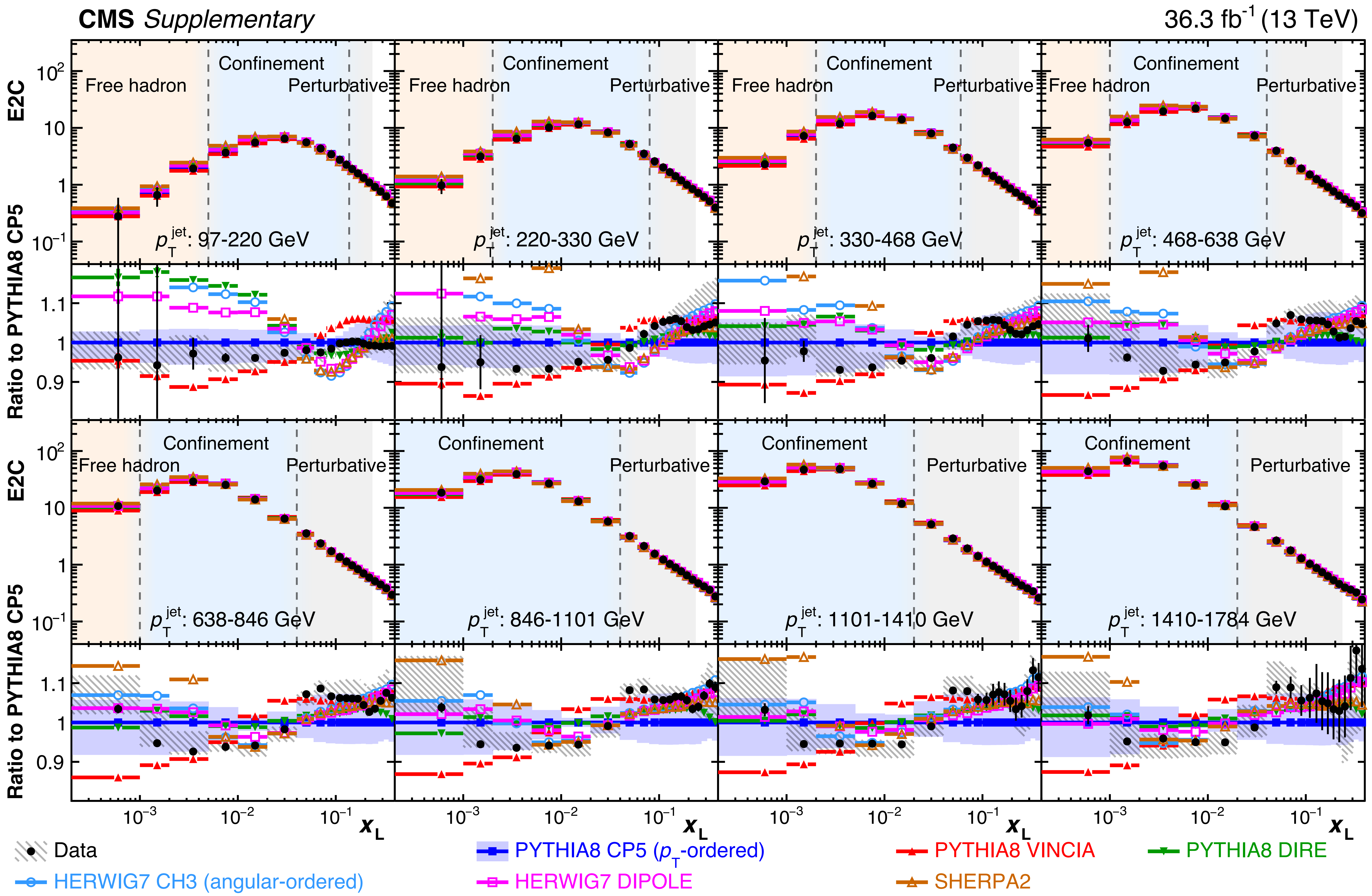
Phase transition
from parton to hadron

Non-interacting hadron
random distribution
integer power-law scaling

Interacting partons
non-integer scaling

CMS, arXiv:2402.13864

Unfolded E2C vs MC



97 ~ 1784 GeV

Data vs various parton shower model, difference ~ 10%

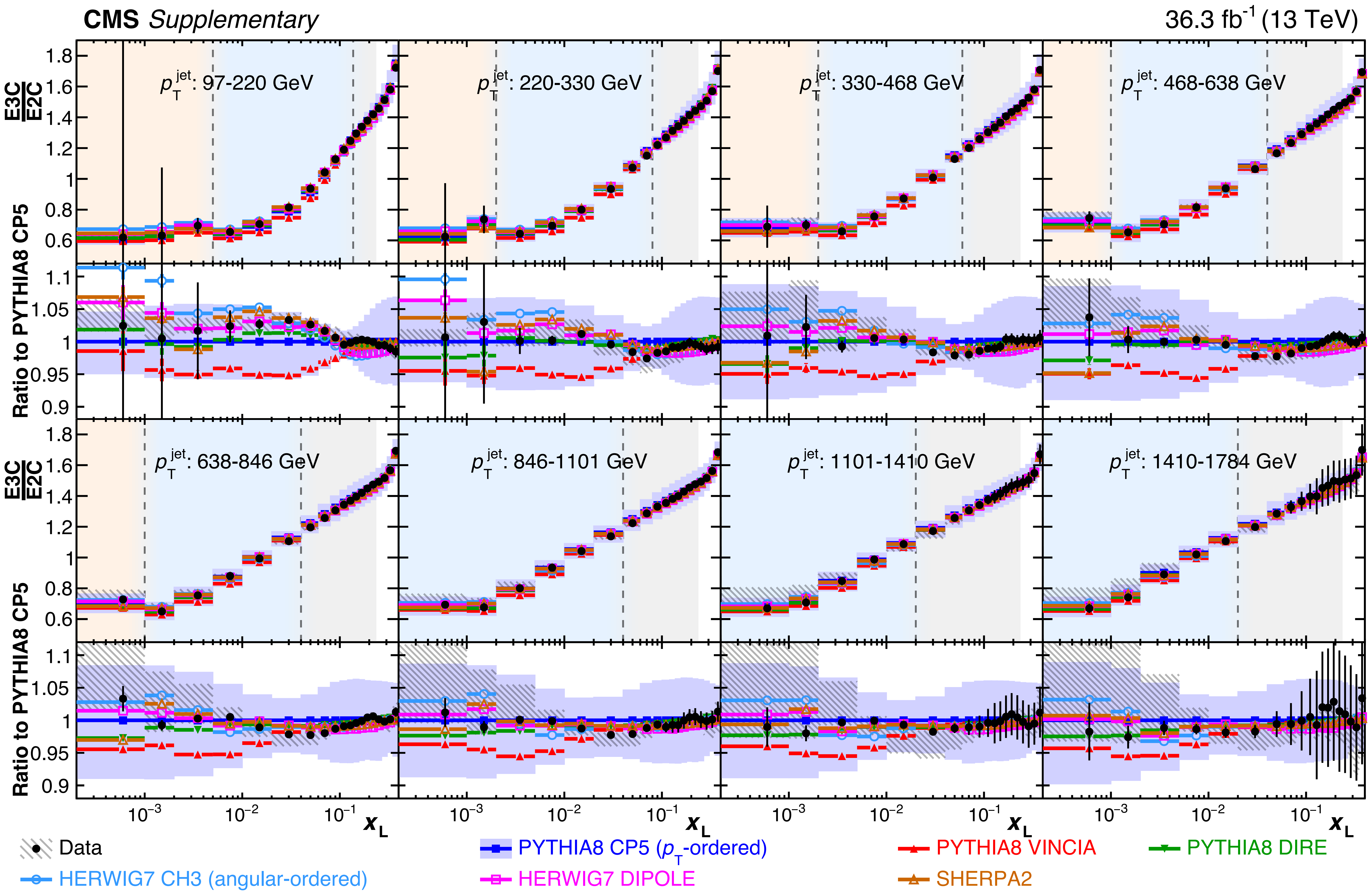
No model match data well in all p_t^{jet} region

: Data stat error

: Exp systematic

: Theo systematic

E3C/E2C



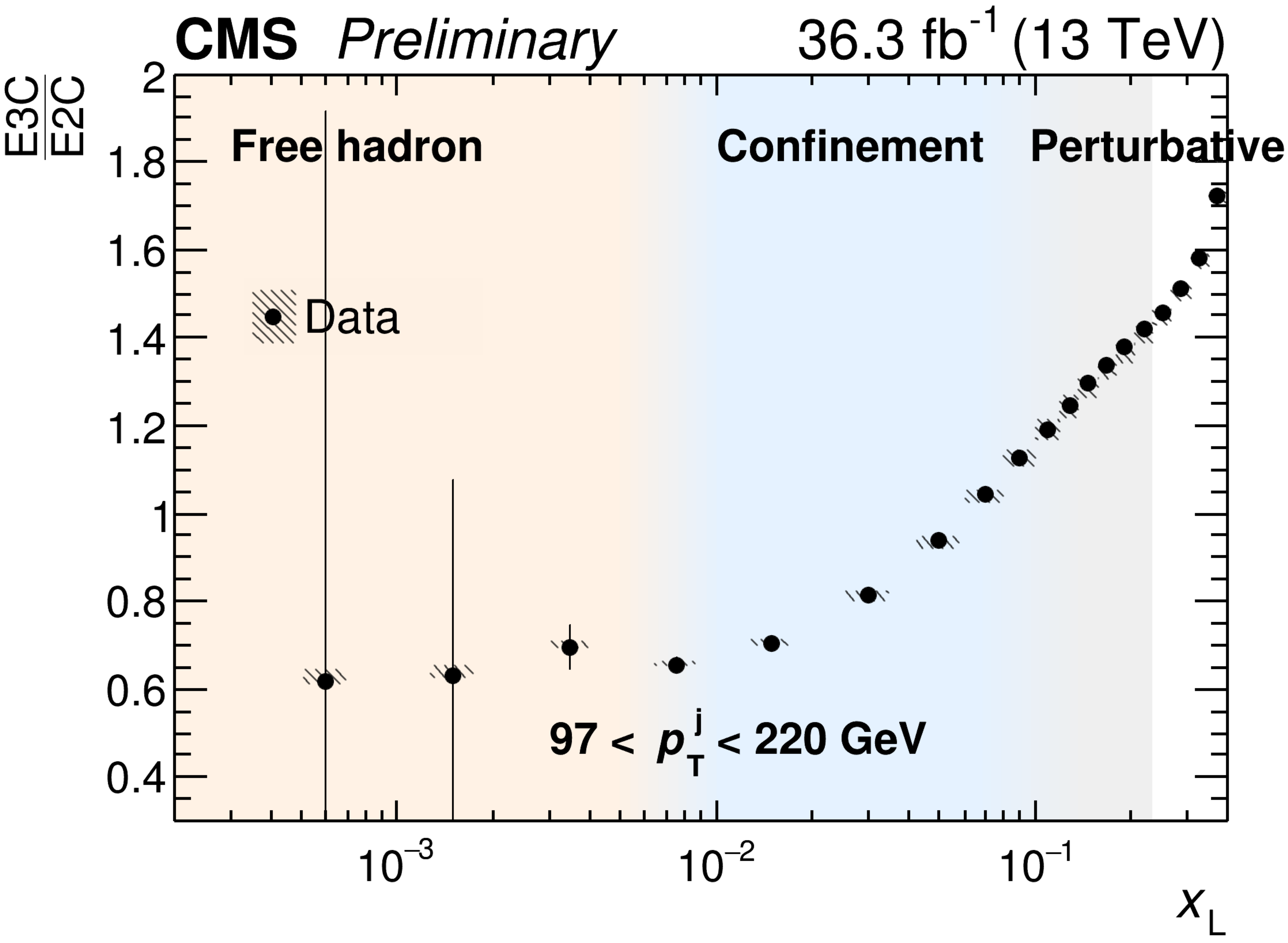
Benefit of taking ratio

- Data MC difference: ~ 10% => ~ 3%
- Exp sys: ~ 8% => ~ 3%

All models agree well

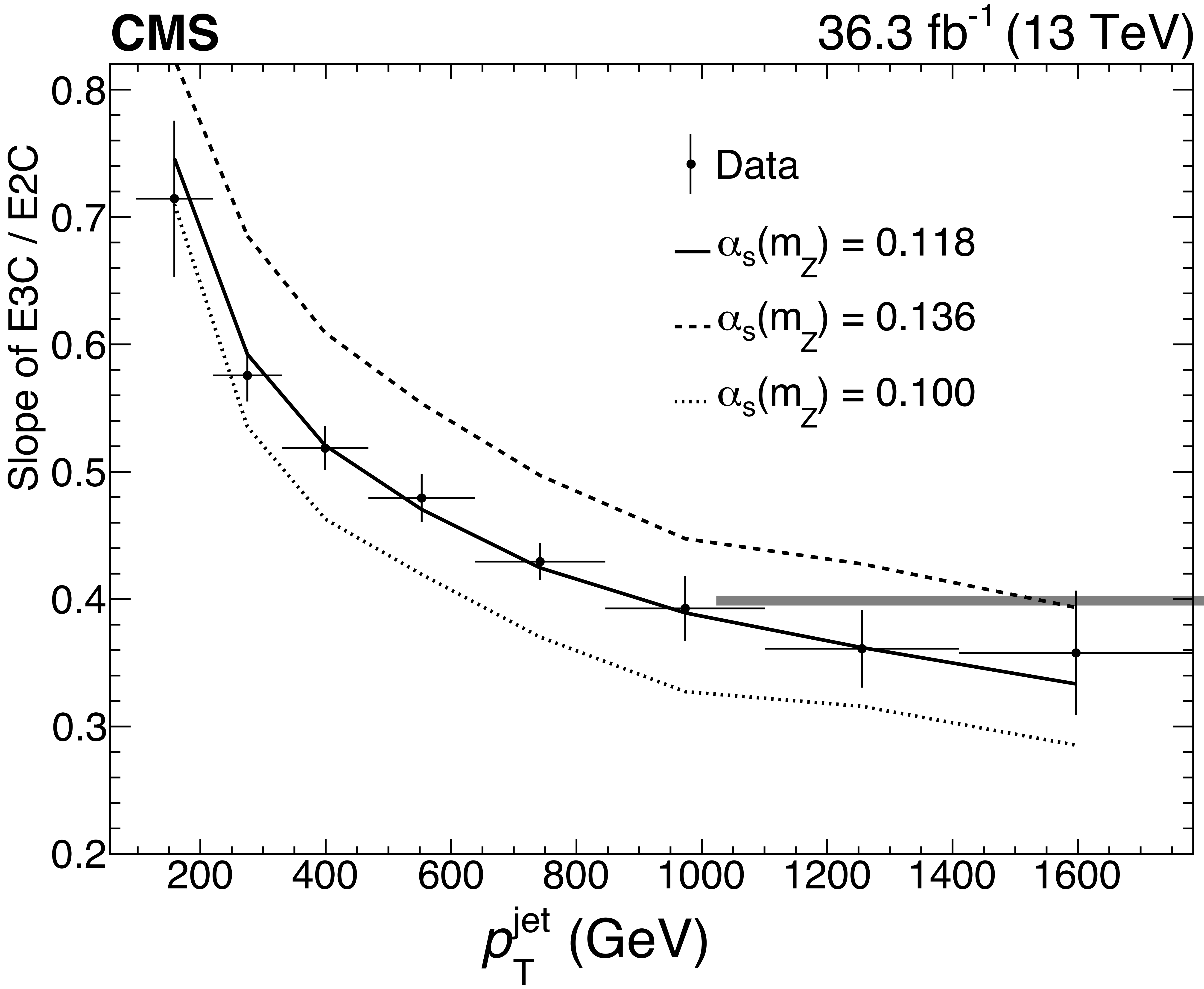
p_T^{jet} ↑ , Slope~αs ↓

E3C/E2C



Animated E3C/E2C in multiple pT regions

Direct observation of asymptotic freedom



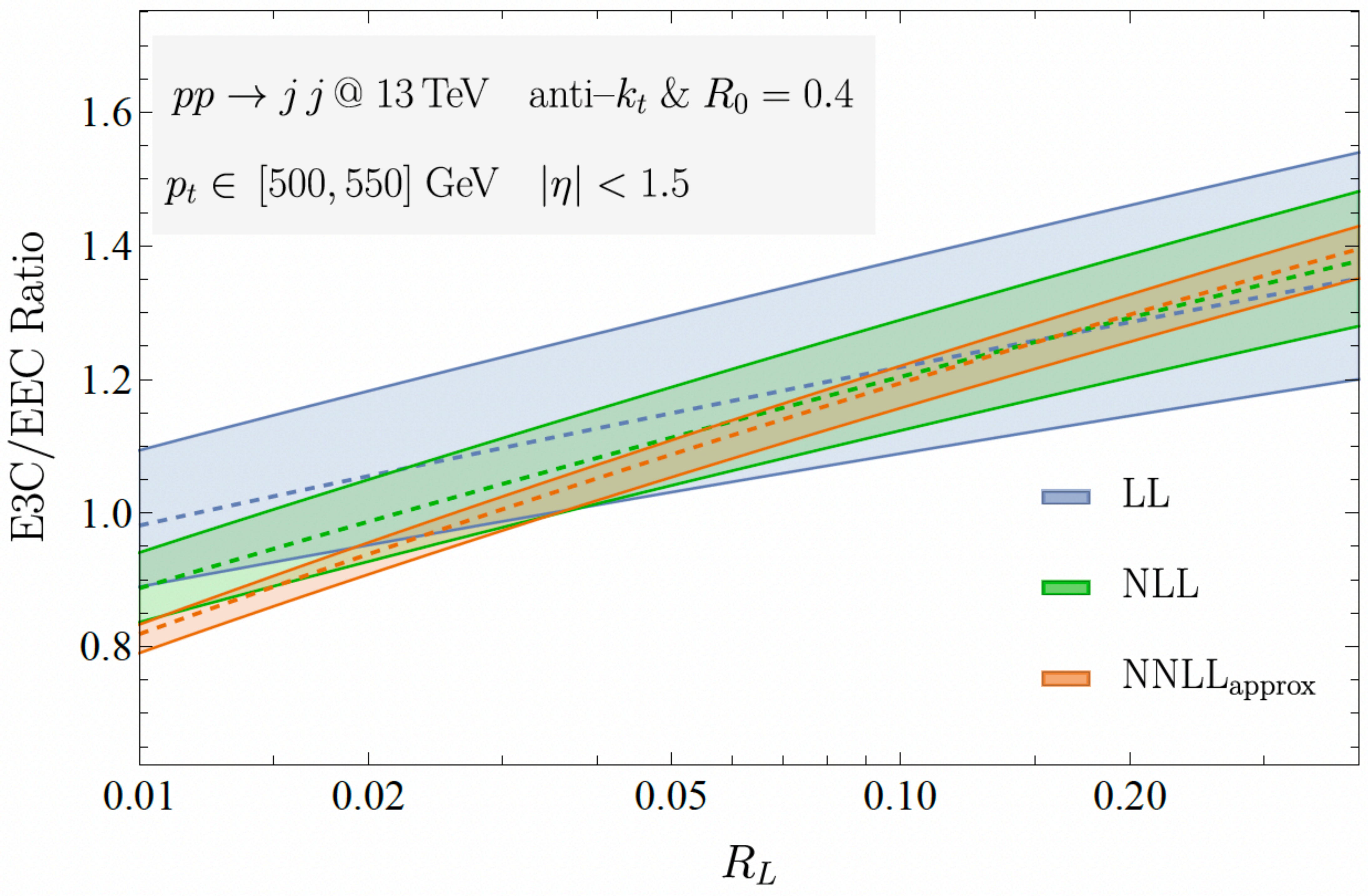
$p_T^{jet} \uparrow \; Q \uparrow$

Slope $\downarrow$ $\alpha_s(Q) \downarrow$

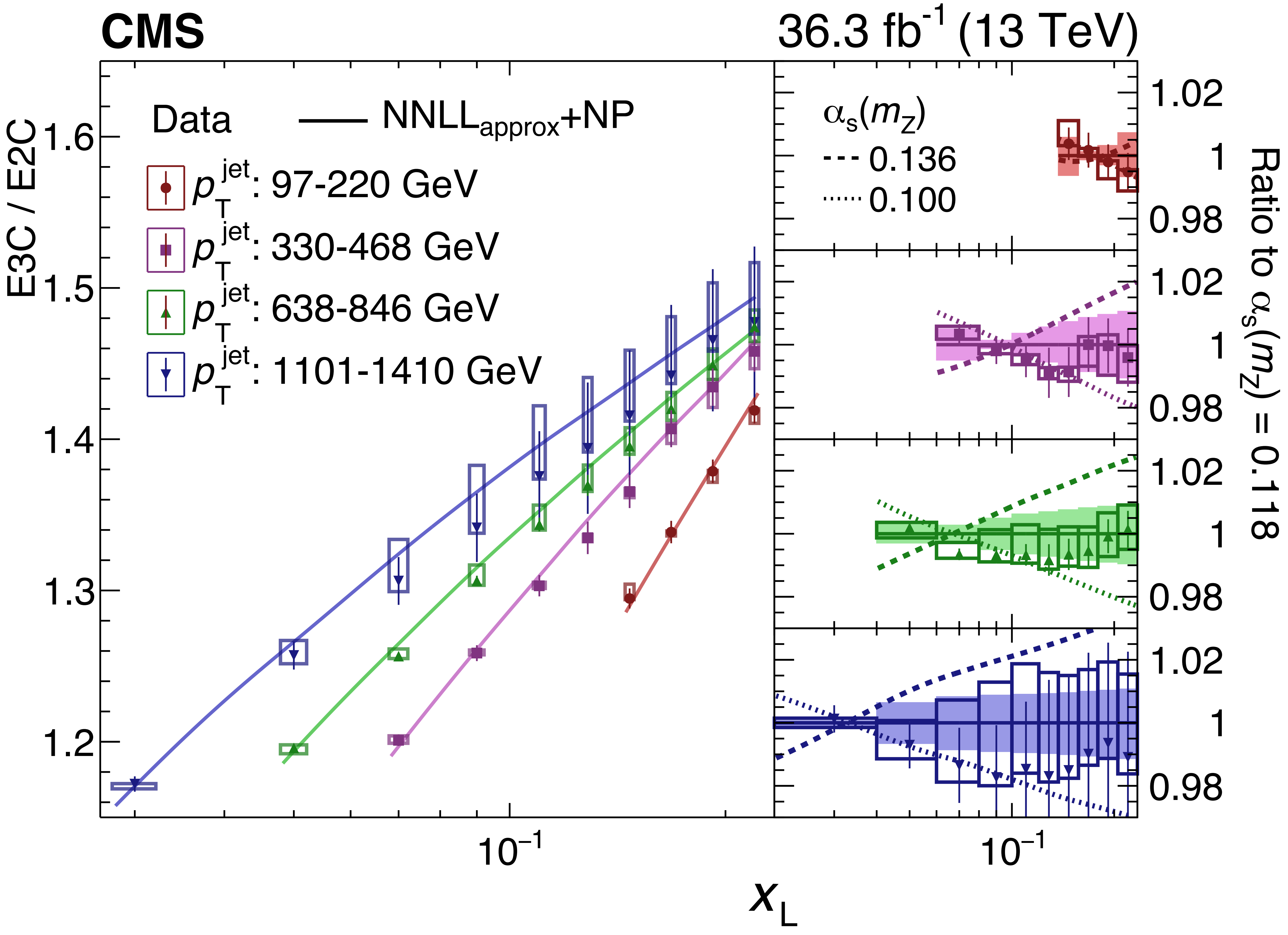
Data point: slope fitted in a p_T^{jet} region

Unfolded E3C/E2C vs NNLL$_{approx}$

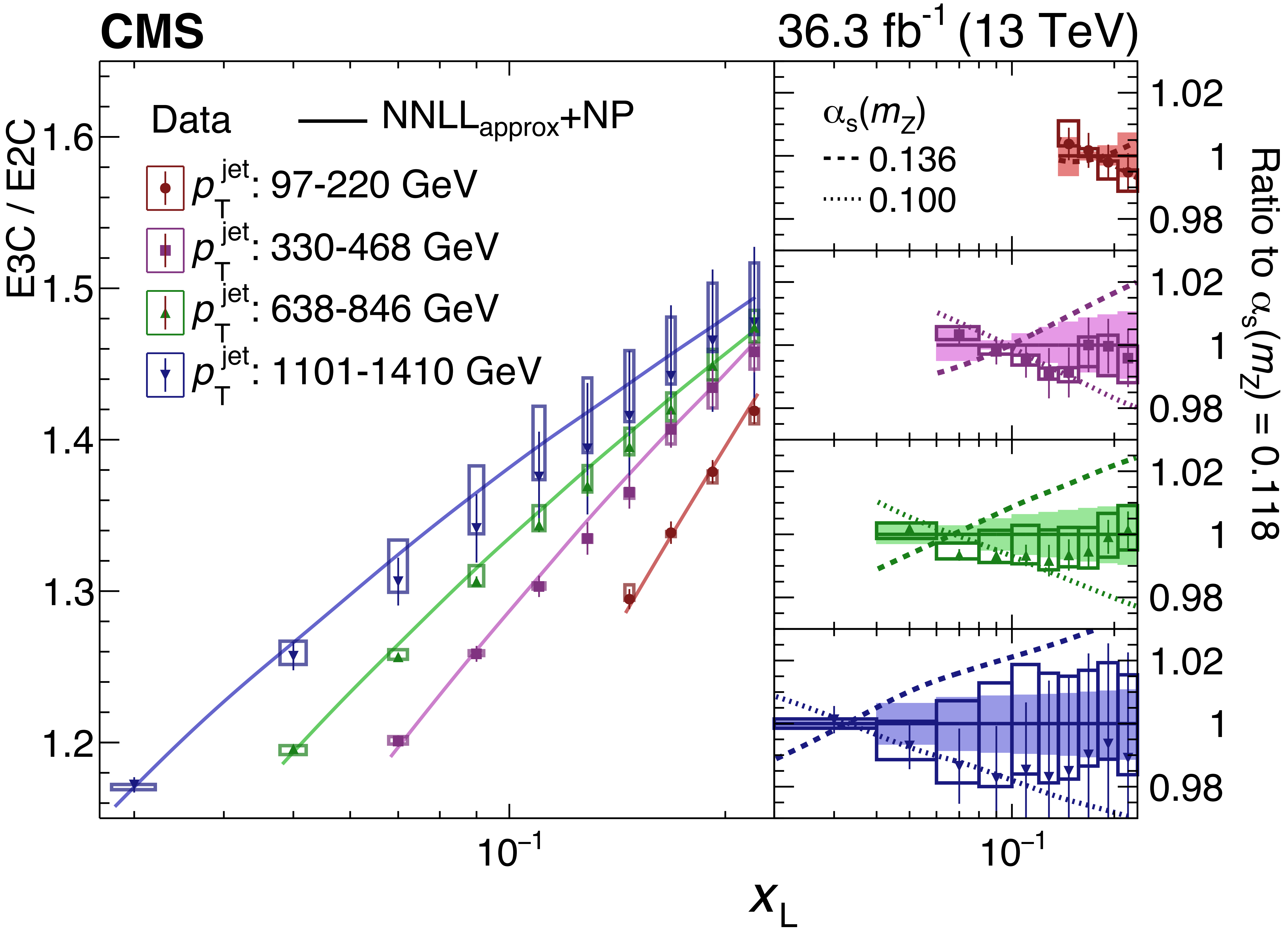
Theoretical uncertainty from LL->NNLL



Data agrees with NNLL$_{approx}$ within uncertainty



Unfolded E3C/E2C vs NNLL$_{approx}$



$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

$$= 0.1229^{+0.0014(stat.)+0.0030(theo.)+0.0023(exp.)}_{-0.0012(stat.)-0.0033(theo.)-0.0036(exp.)}$$

major source

QCD scale of NNLL$_{approx}$

Neutral hadron energy scale

Uncertainty ~ 4%,
Q~ O(10) GeV, collinear regime
Most precise from jet substructure to date

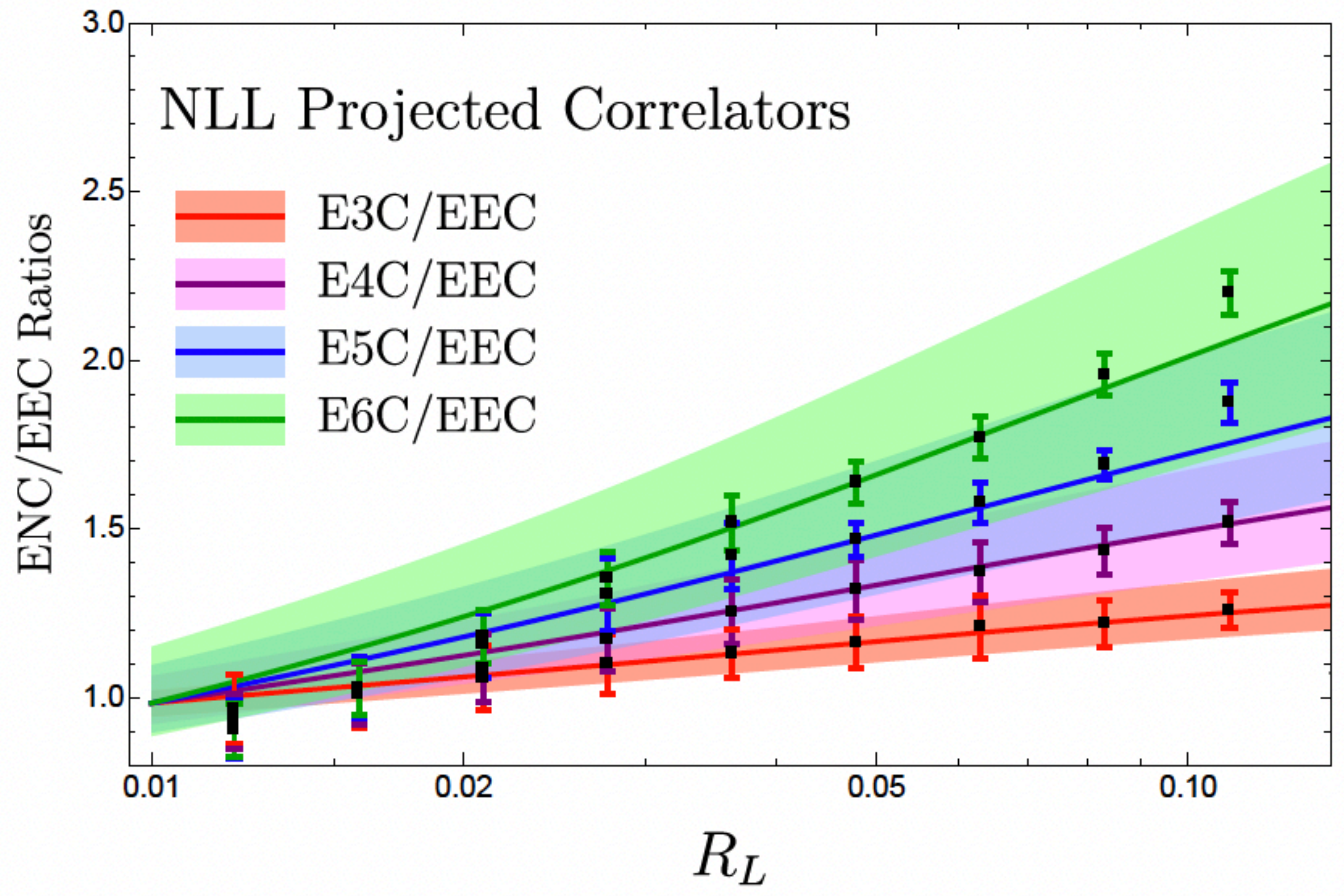
Summary

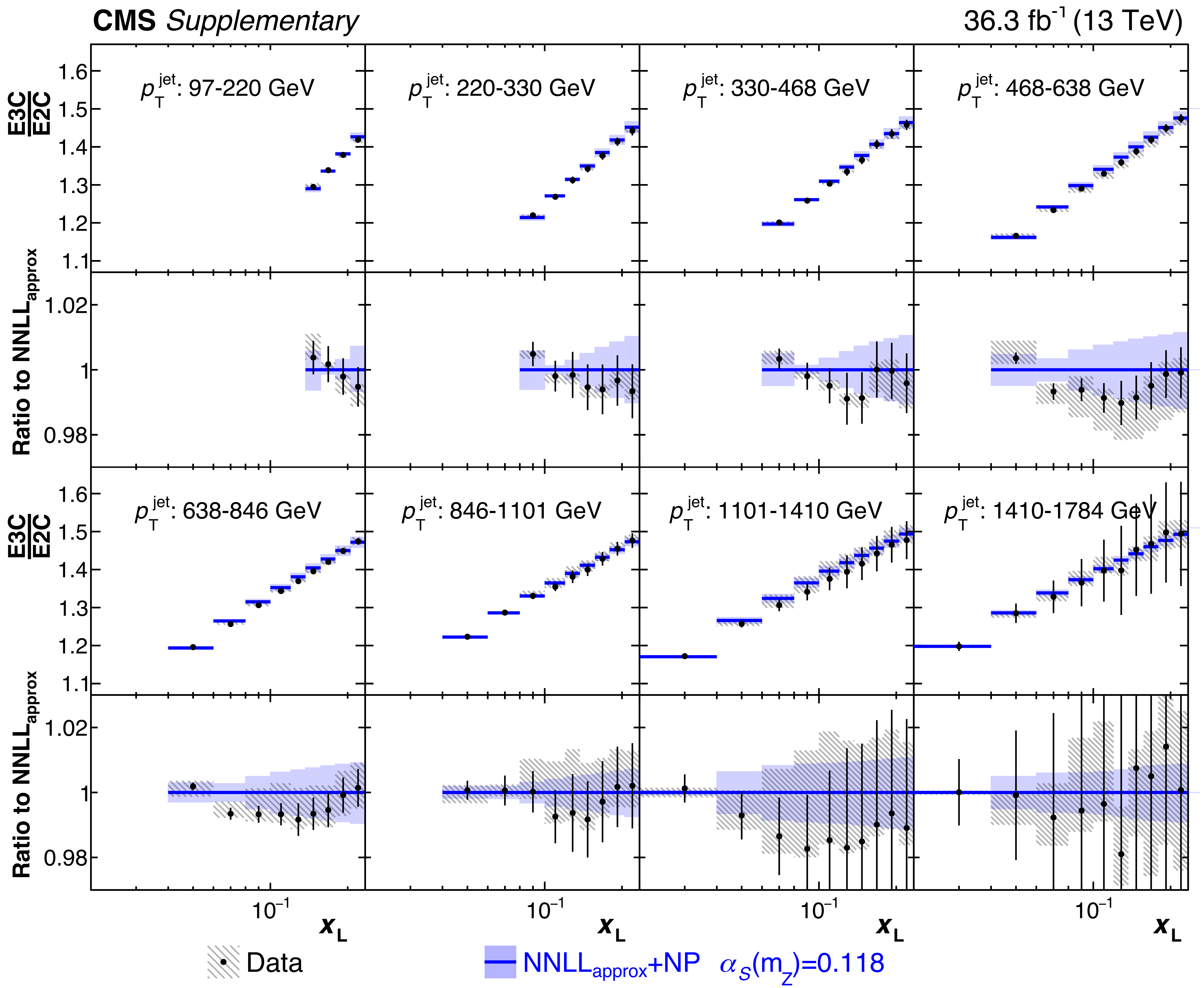
- Energy correlators revive at hadron colliders
    - Different definition adaptation concentrate on complementary phase spaces
- High precision experimental measurements on energy correlators
    - TEEC: high Q, jet correlation
    - E2C and E3C: collinear, jet substructure
- High precision α_S determination from both methods
    - Both theoretical uncertainty dominant

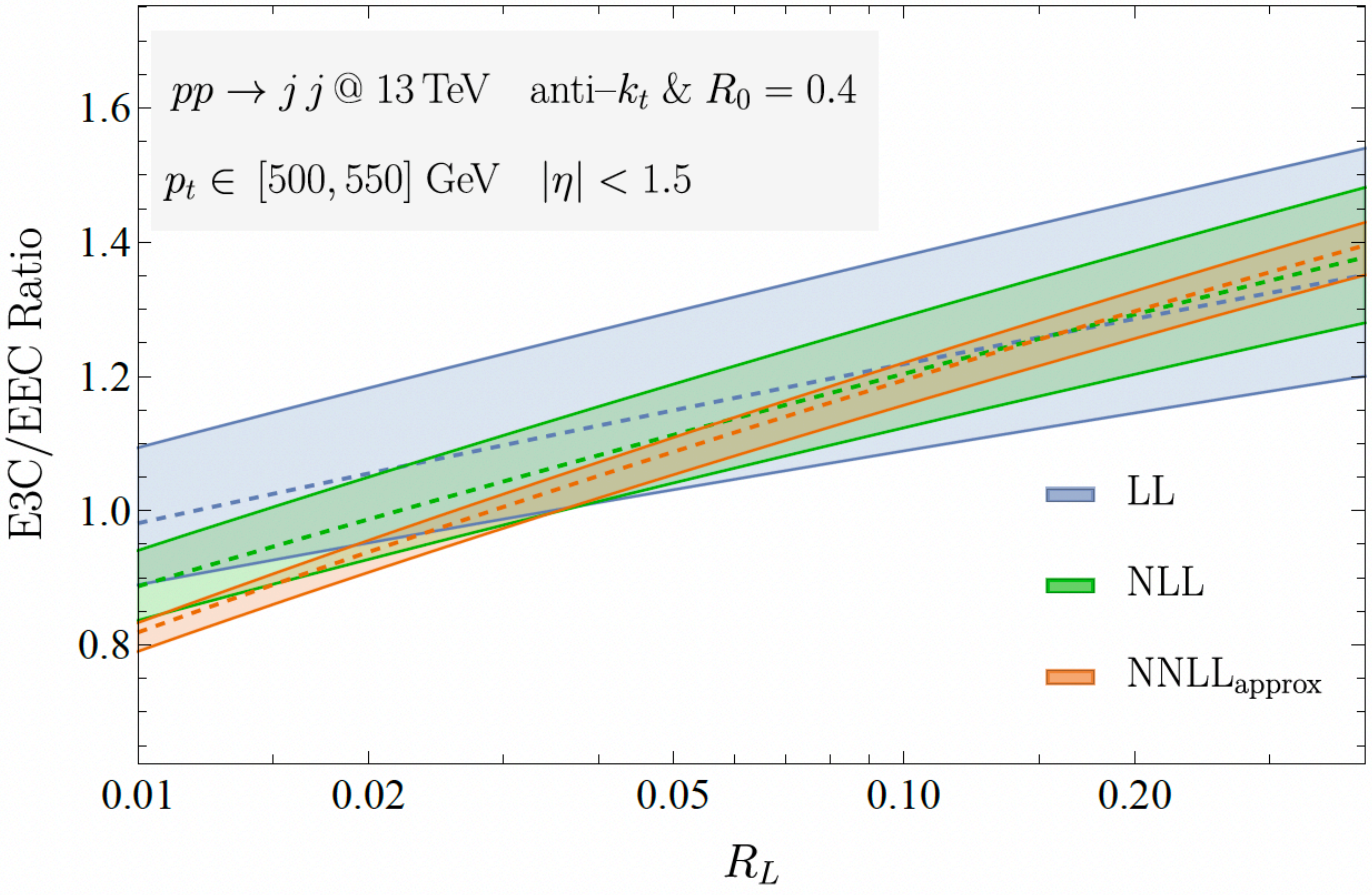
From Ian Moult

Improving the α_s measurement

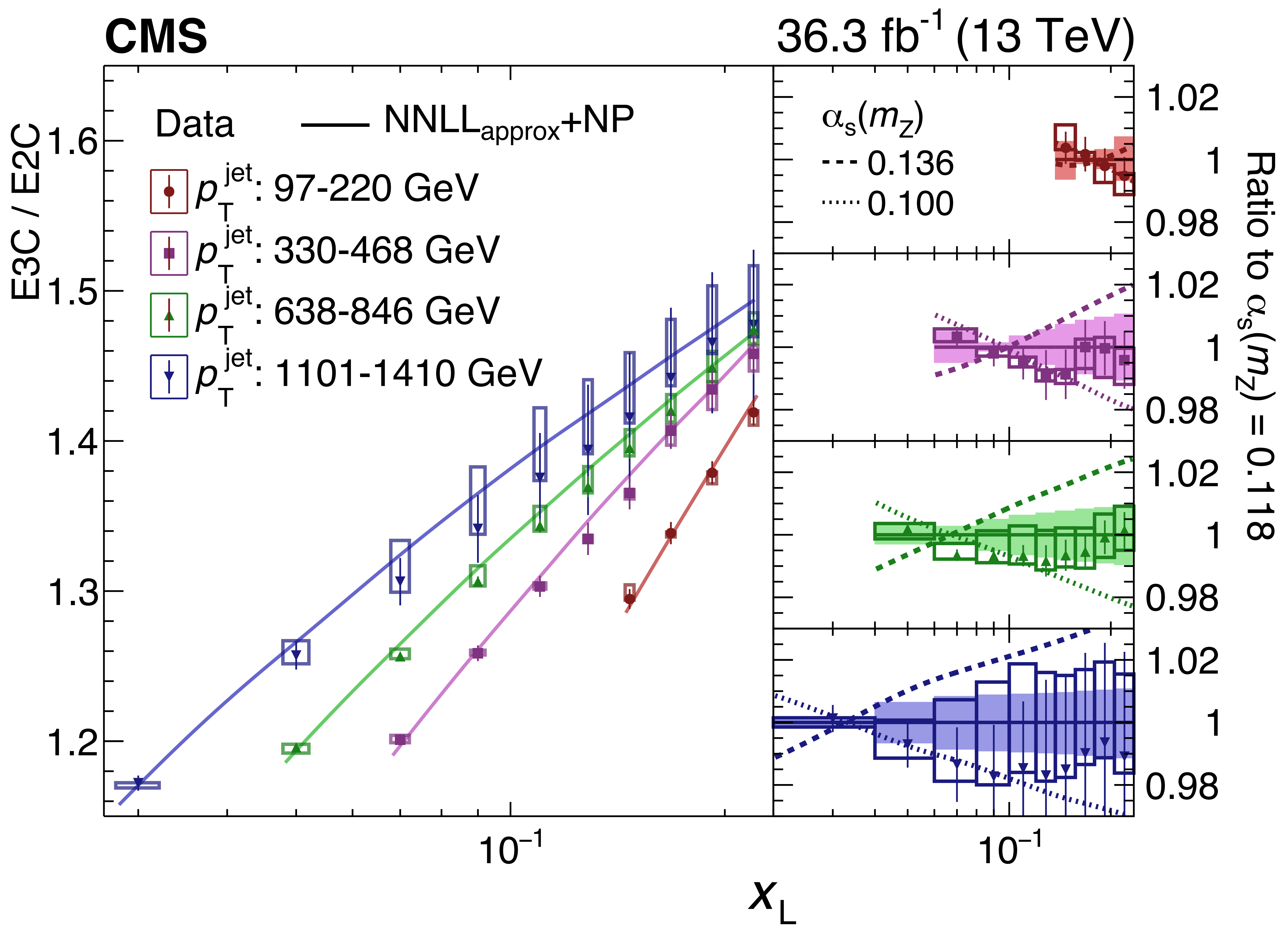
- Measure on tracks.
- Measure the higher point ratios to over constrain α_s from quark gluon fractions.
- Go to highest possible energy.




CMS Supplementary
36.3 fb^-1 (13 TeV)
p_T^jet: 97-220 GeV
p_T^jet: 220-330 GeV
p_T^jet: 330-468 GeV
p_T^jet: 468-638 GeV
p_T^jet: 638-846 GeV
p_T^jet: 846-1101 GeV
p_T^jet: 1101-1410 GeV
p_T^jet: 1410-1784 GeV
E3C/E2C
Ratio to NNLL_approx
x_L
Data
NNLL_approx+NP α_S(m_Z)=0.118


$pp \to j\,j$ @ 13 TeV anti–k_t & $R_0 = 0.4$
$p_t \in [500, 550]$ GeV $|\eta| < 1.5$
E3C/EEC Ratio
1.6
1.4
1.2
1.0
0.8
0.01
0.02
0.05
0.10
0.20
R_L
LL
NLL
$\text{NNLL}_{\text{approx}}$

Unfolded E3C/E2C vs NNLL$_{approx}$



Analytical predictions

- NNLL$_{approx}$: Parton level E3C/E2C
  - NLO+NNLLapprox — Chen, Gao, Li, Xu, Zhang, and Zhu, arXiv:2307.07510
- Same phase space as the analysis

Hadronization factors

- Bin by bin factor
  - average of Pythia&Herwig
- E2C, E3C: 5 - 40%
- E3C/E2C: 3%

Theo sys:

(shape only, no normalization effect)

- QCD scale of $\mathrm{NNLL}_{\mathrm{approx}}$ prediction
- Hadronization factors
- QCD scale in hard scattering
- Underlying event + parton shower tune
- PDF