Energy correlator measurements at the CMS experiment

PRL 133 (2024), 071903

Meng Xiao (Zhejiang University)

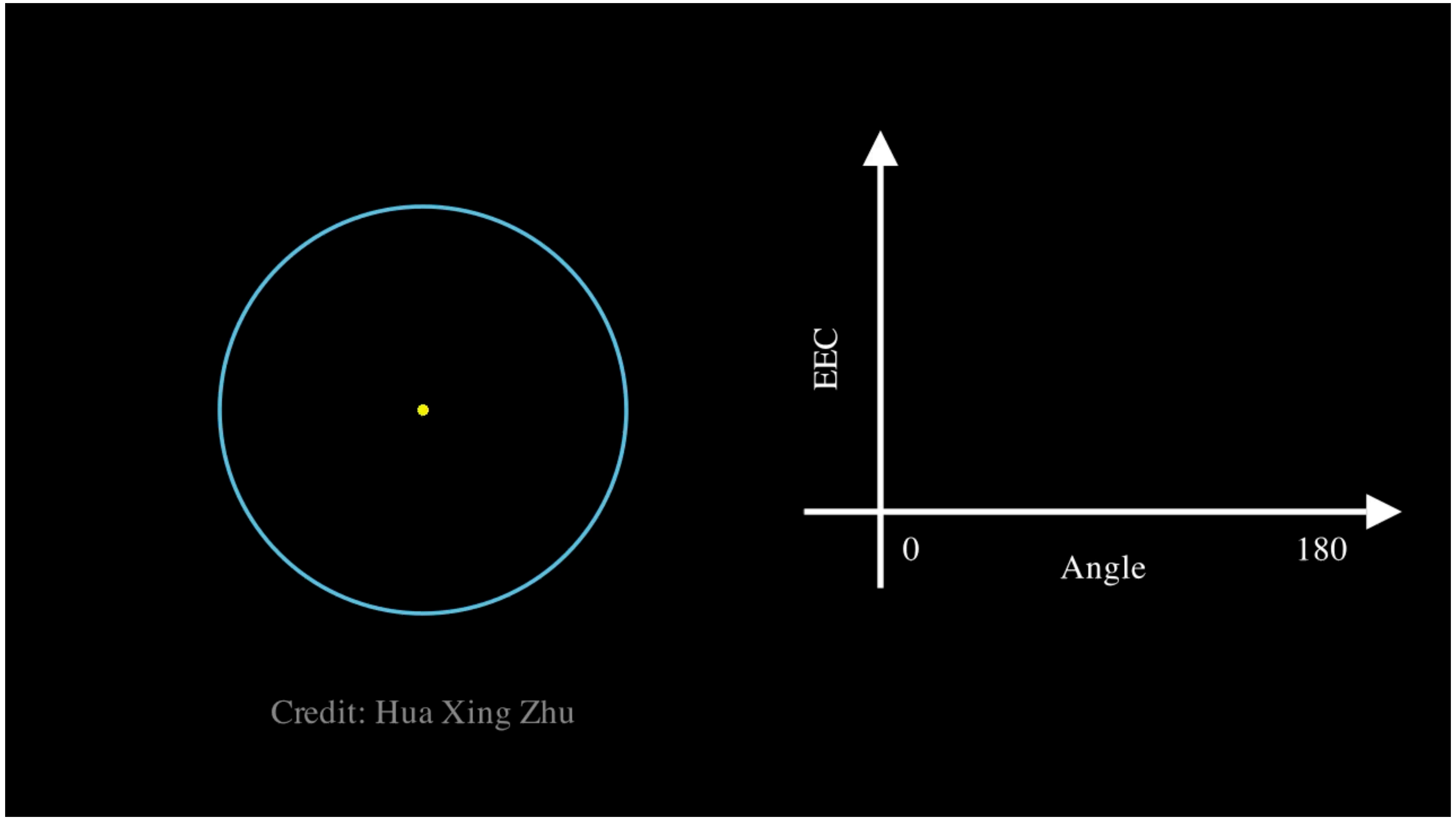
West lake workshop on nuclear physics, 2024.10.19

Energy-energy correlator: history at e^+e^-

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

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

All particles Energy weight Azimuthal distance



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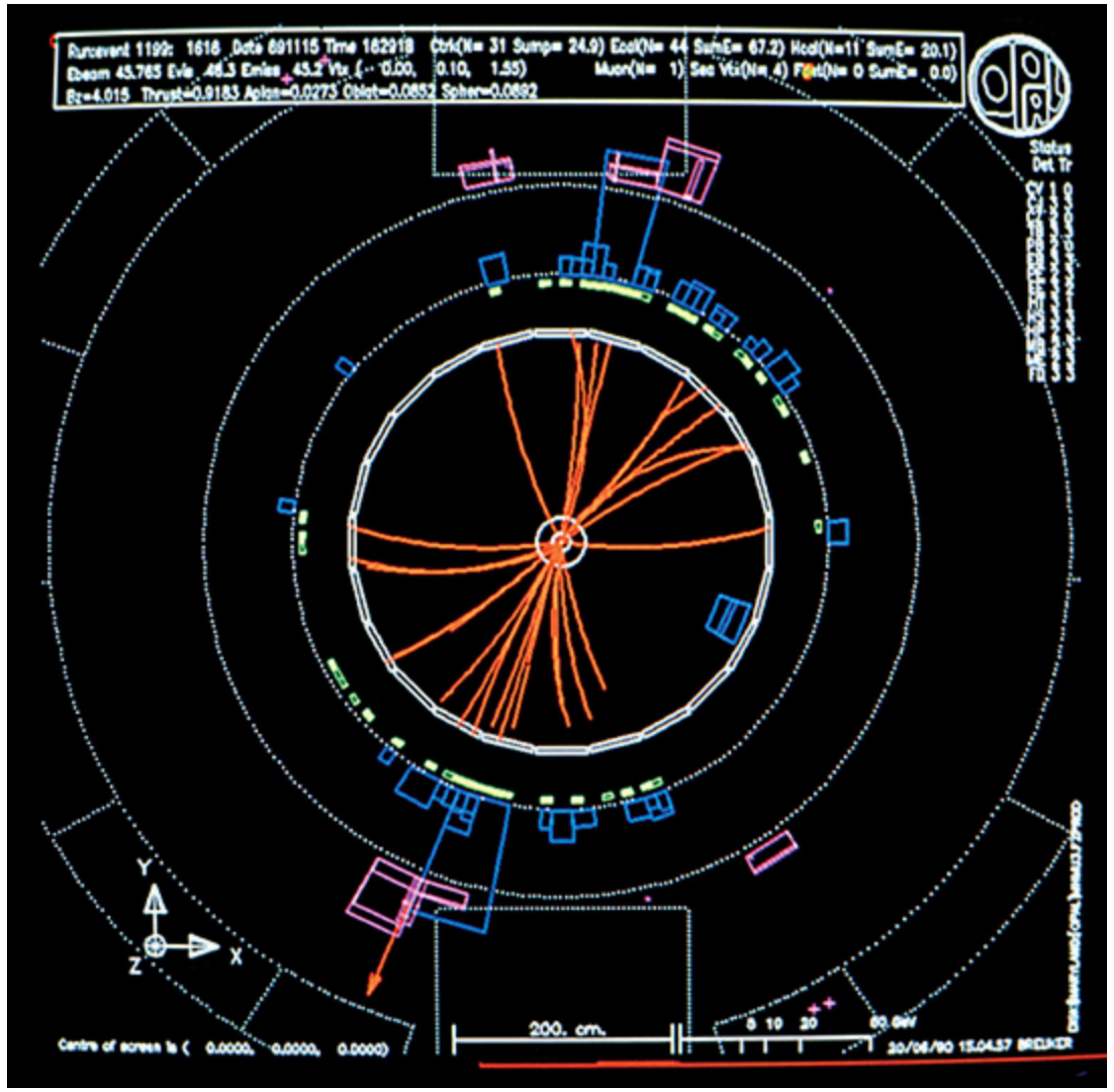
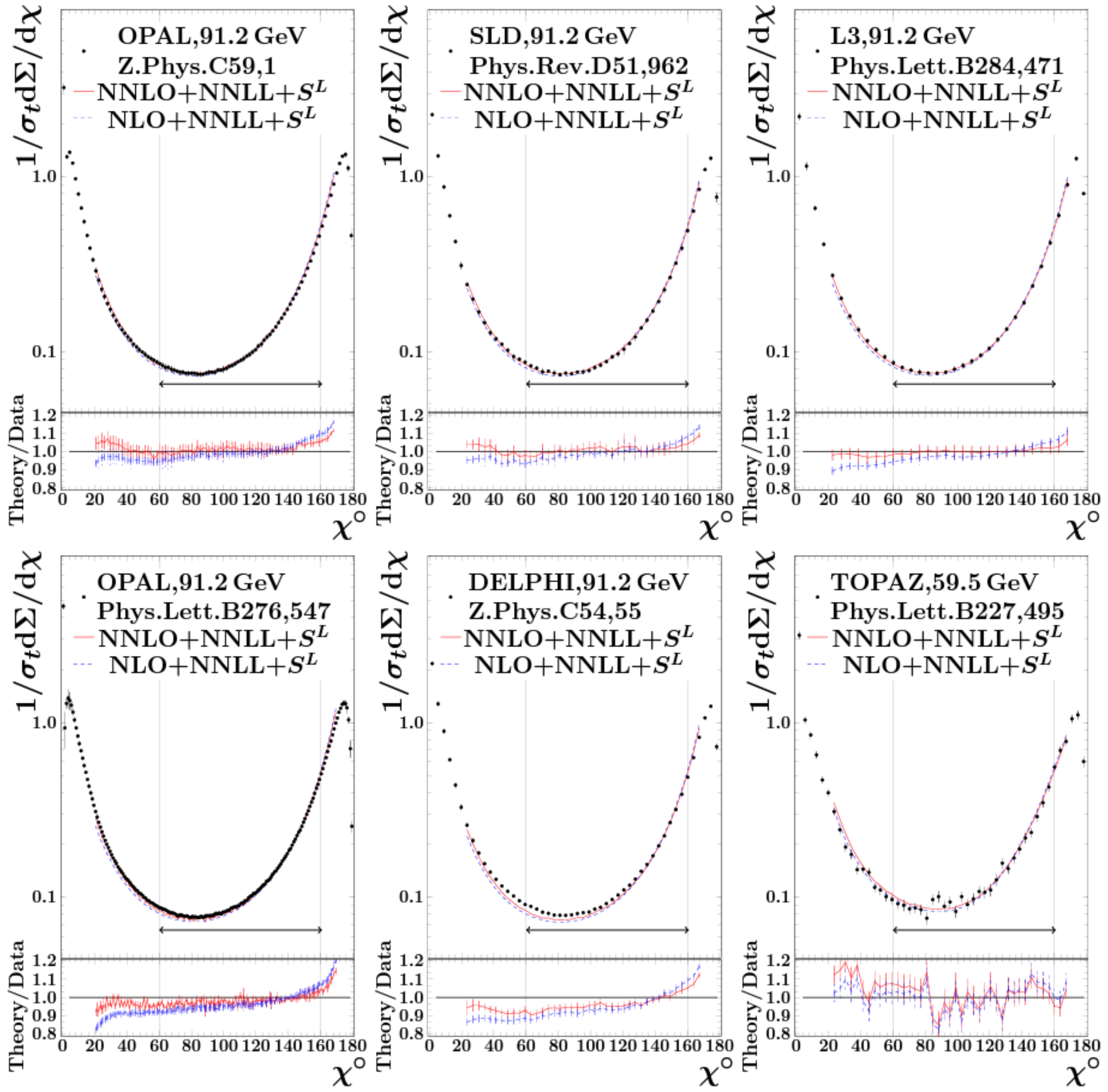




Widely measured at e^+e^-

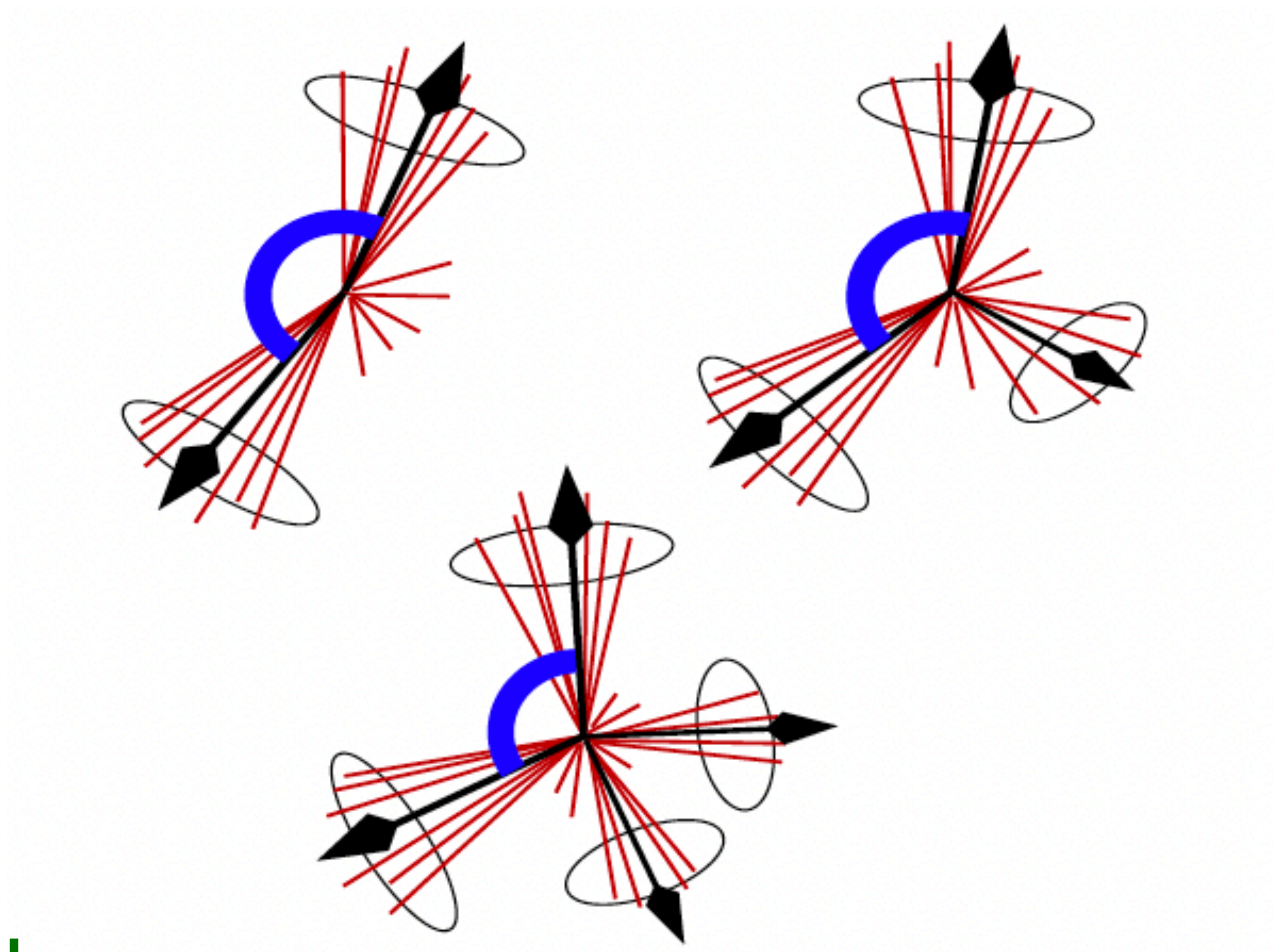
Extract α_S at NNLO+NNLL ~ 2% precision [arXiv:1804.09146].

Energy-energy correlator at LHC

Adaptions for hadron collider

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

Angular correlation between jets in an event



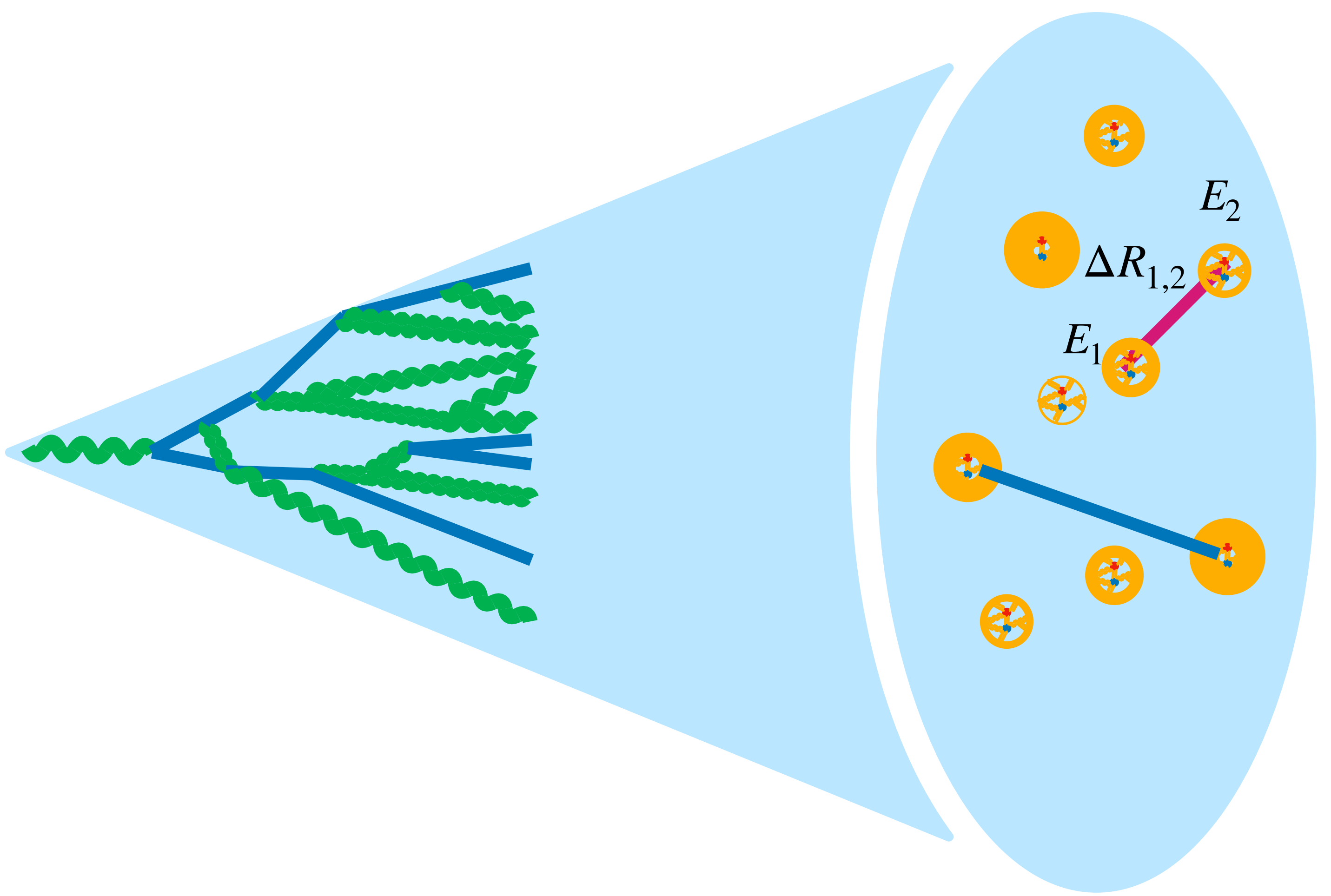
All jets

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

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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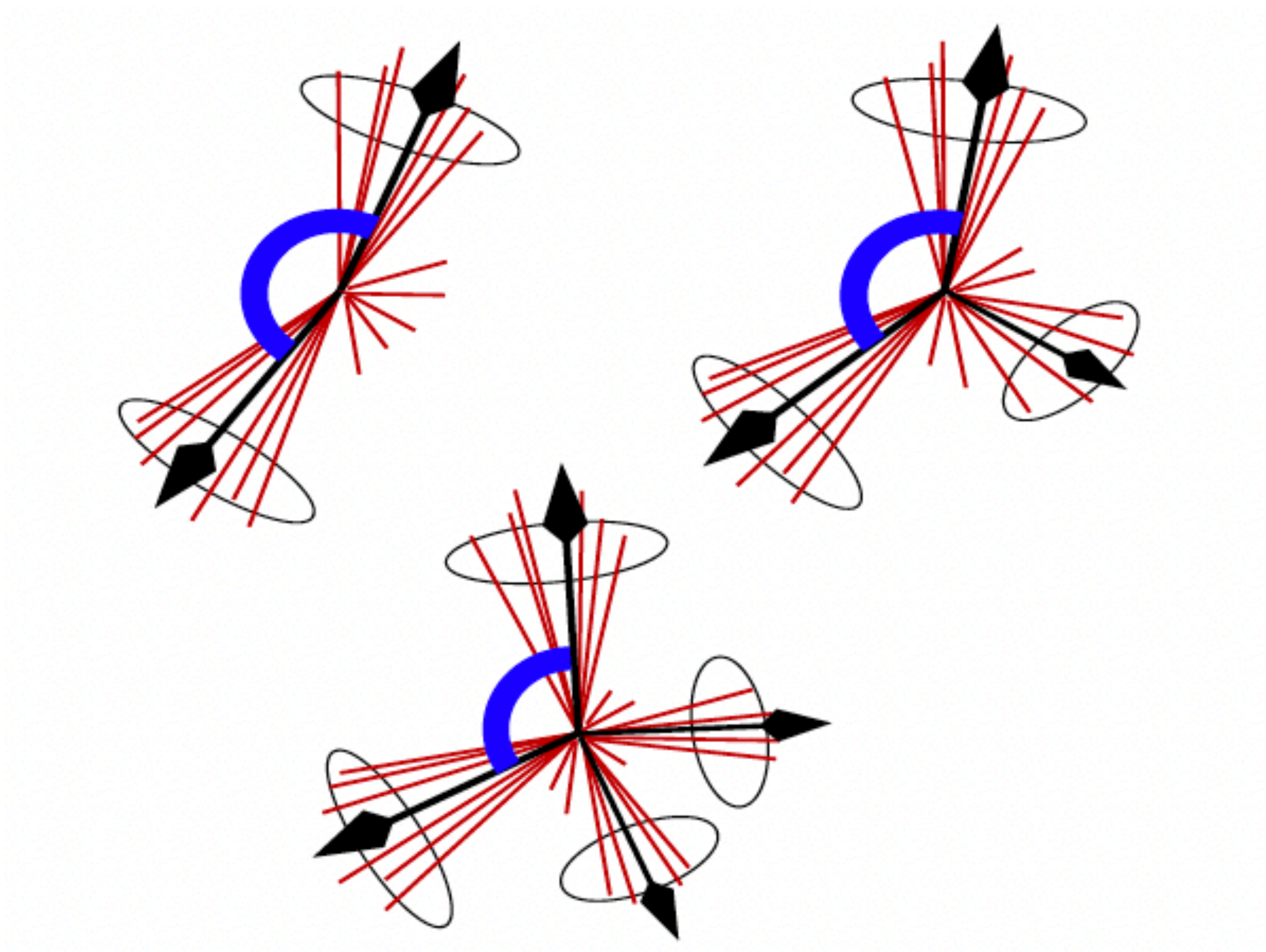
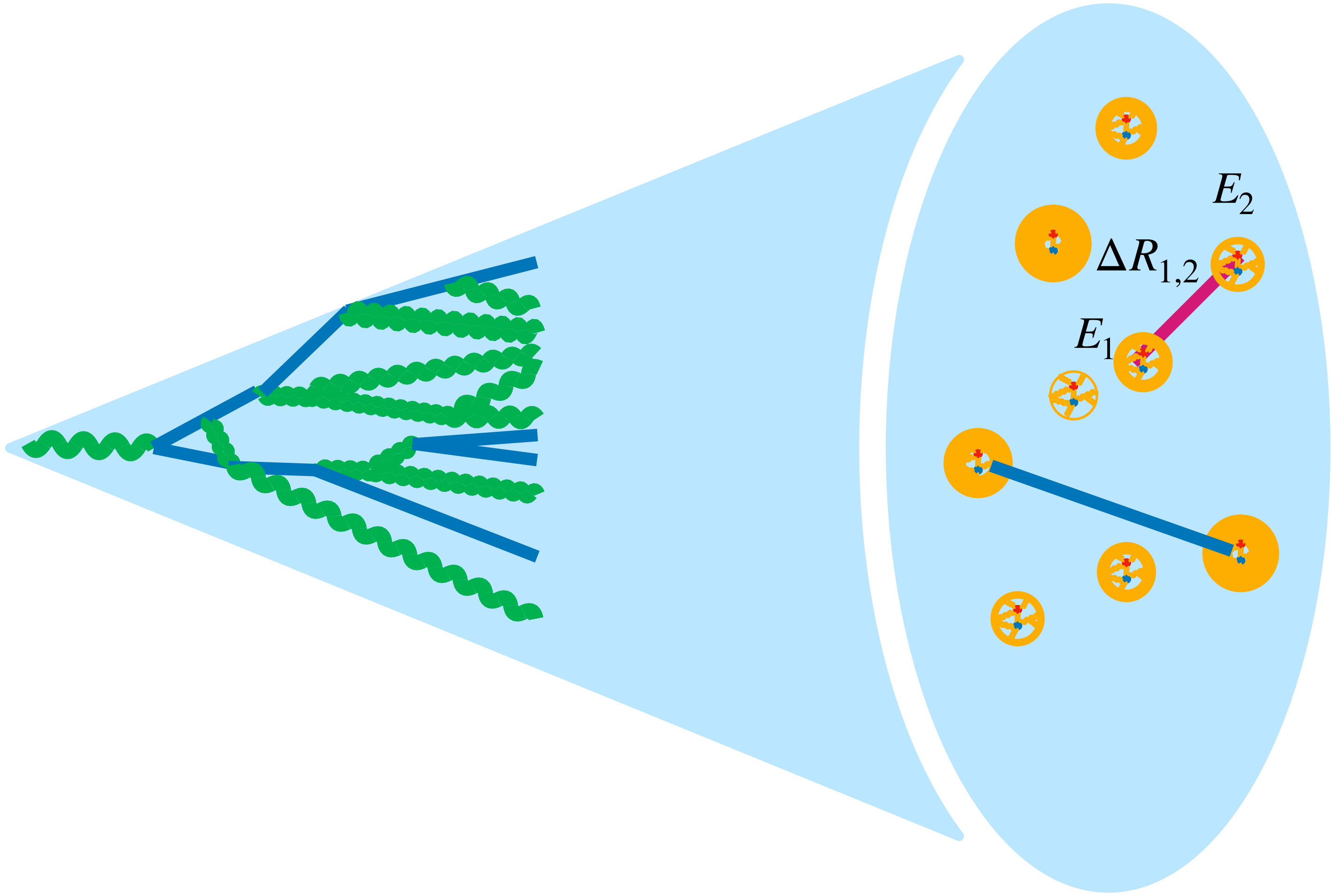


Energy scale Q ~ **O (TeV)**

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

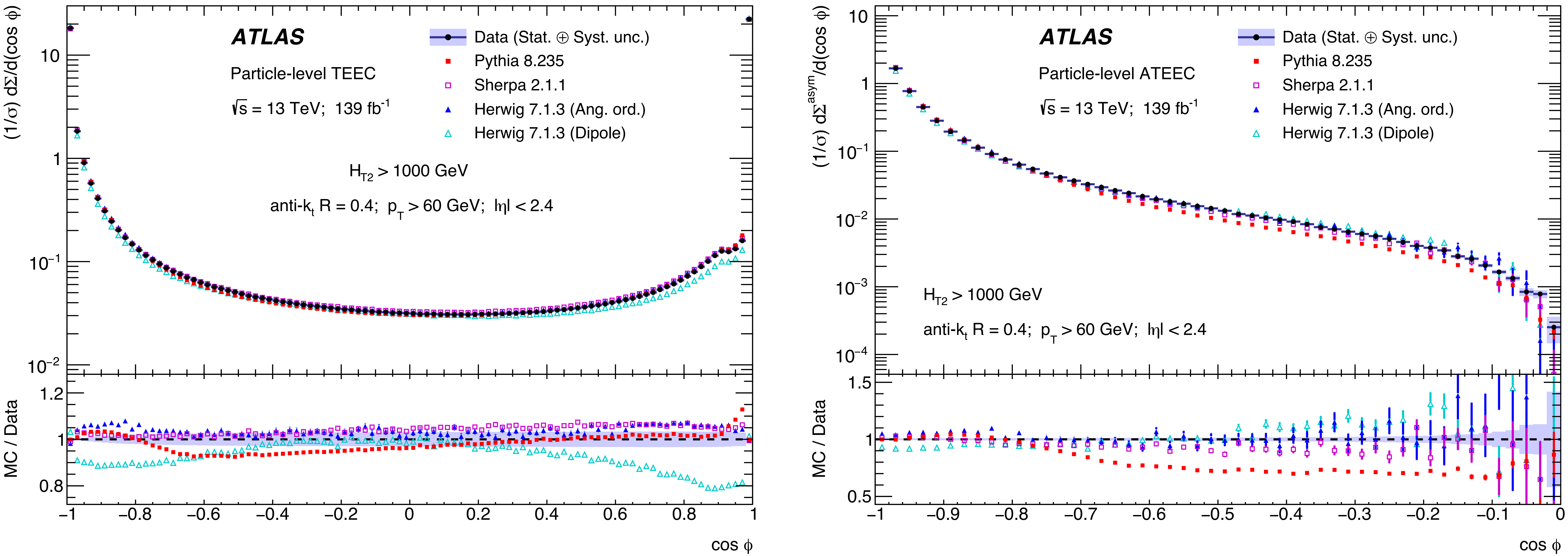
Measurement of TEEC

ATLAS, JHEP 07 (2023) 85

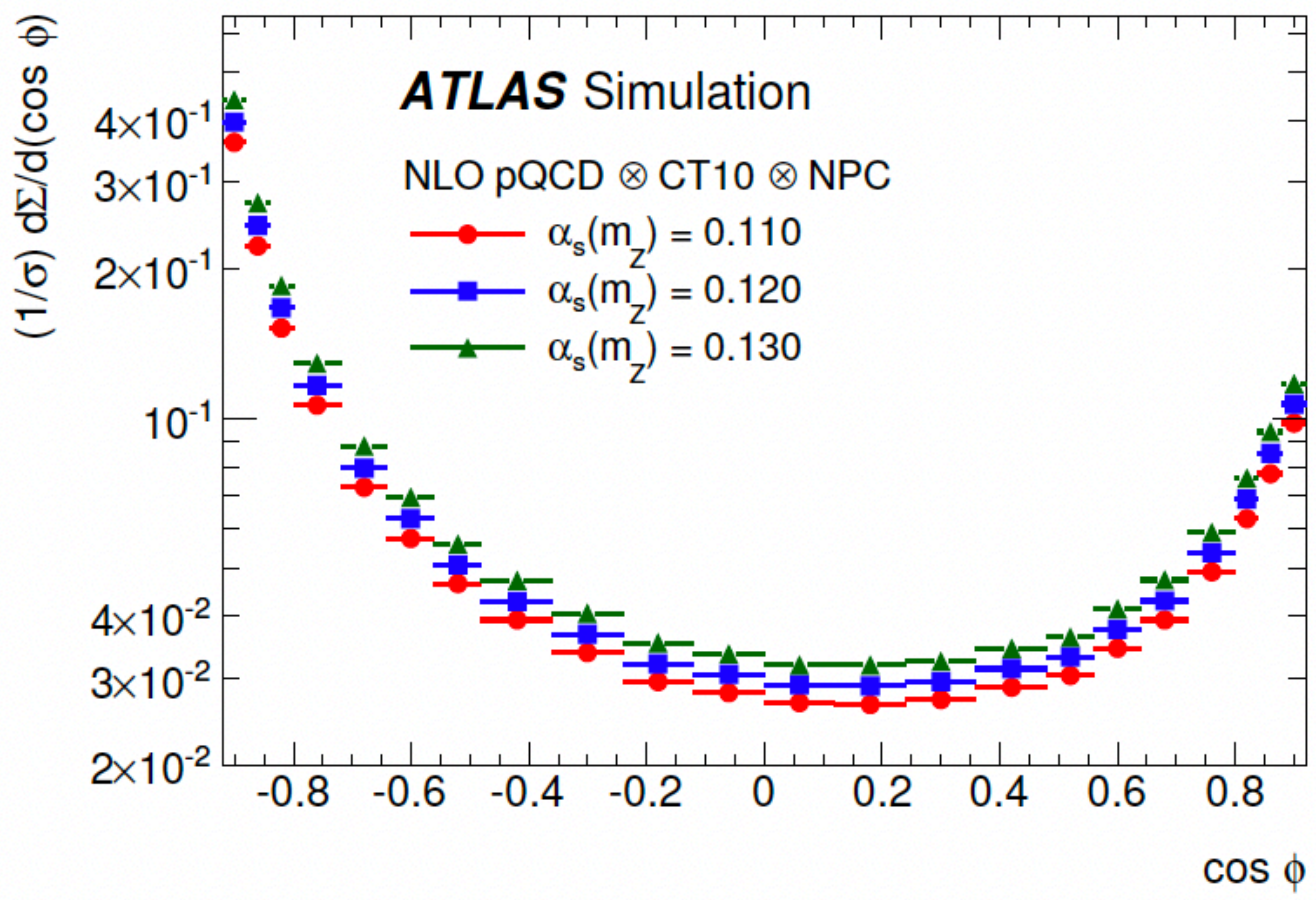
Anti-kt jets, R = 0.4
HT= pT1+pT2: [1, 3.5] TeV

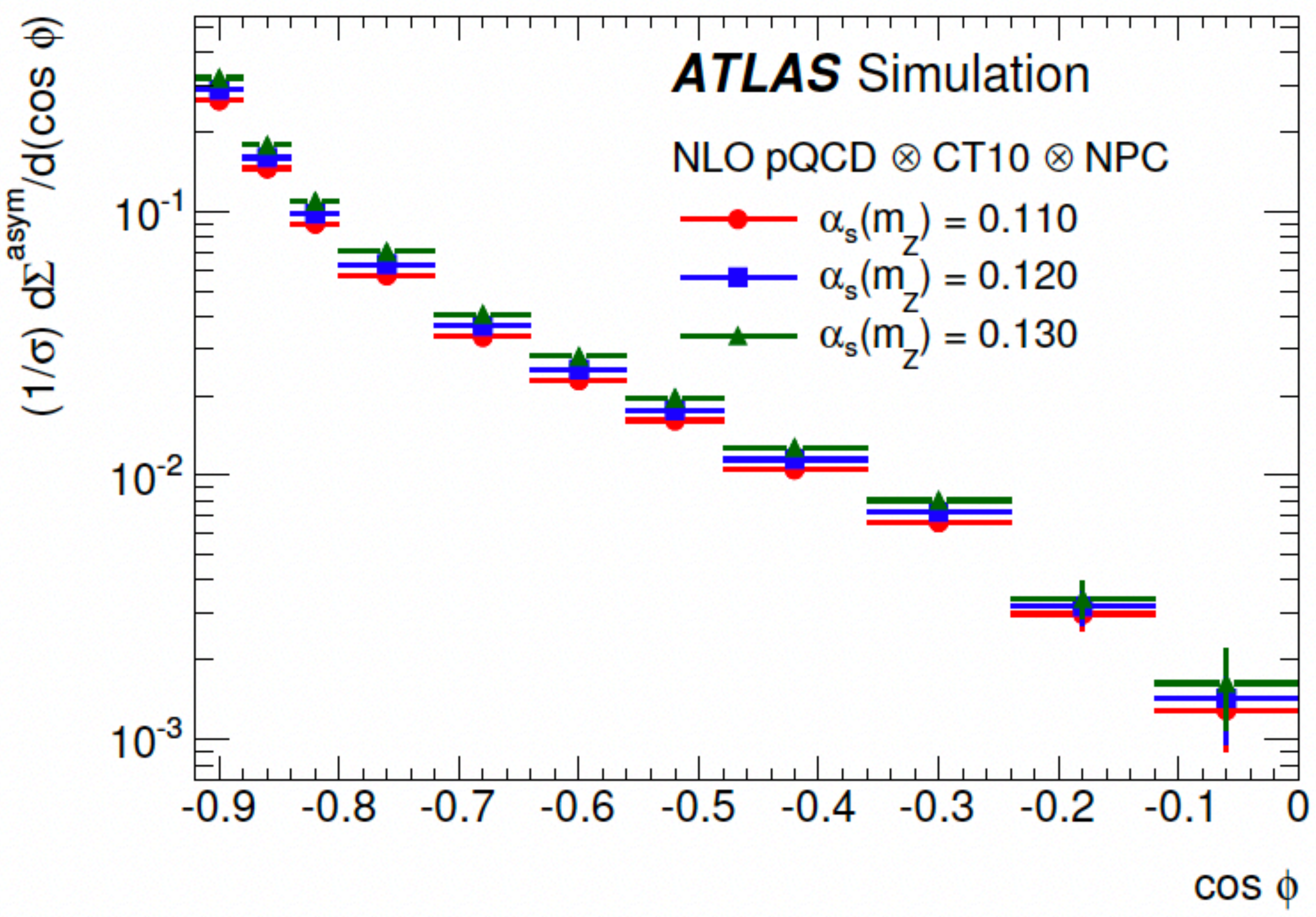
TEEC

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



α_S extraction from TEEC





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

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

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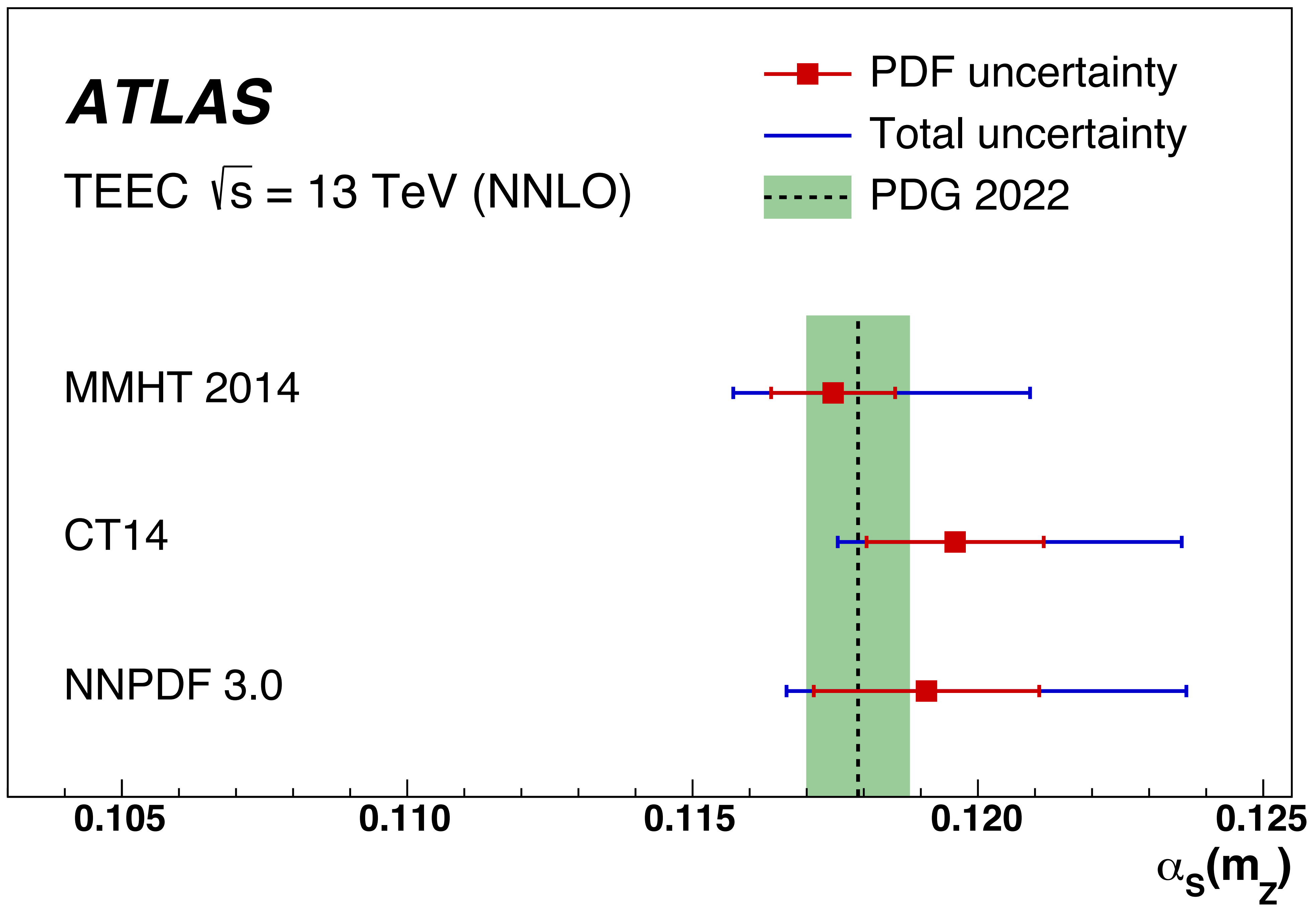

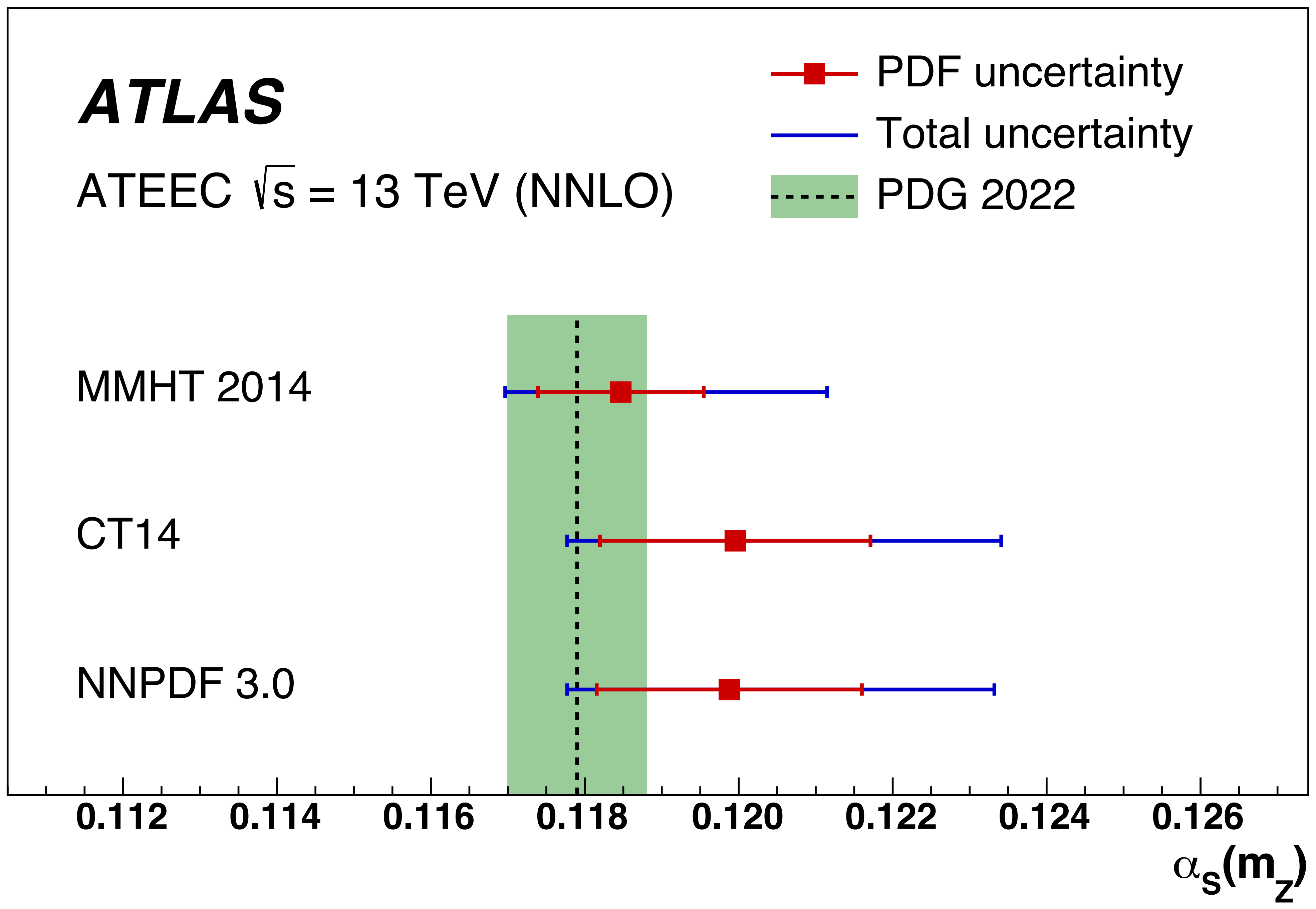

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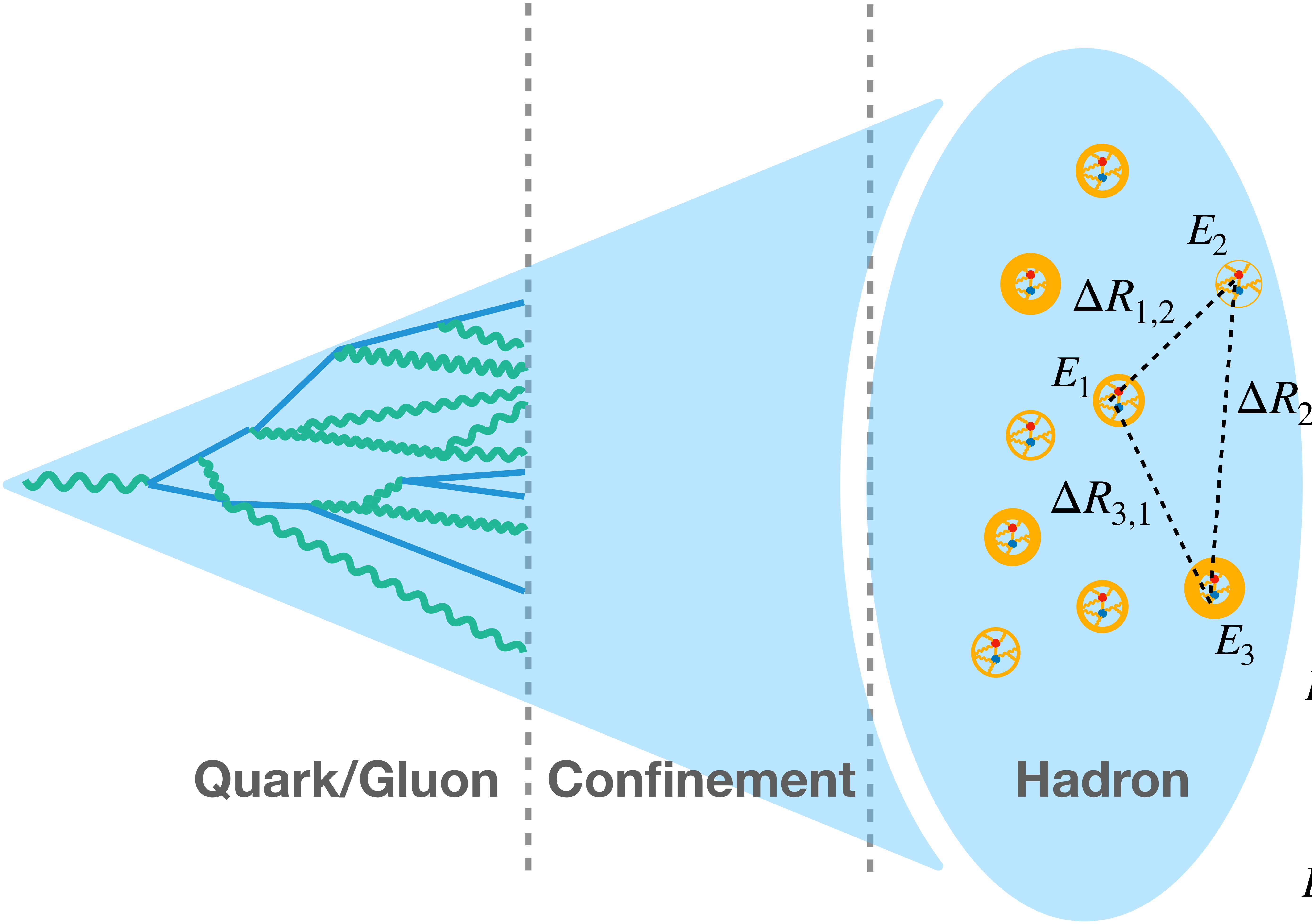
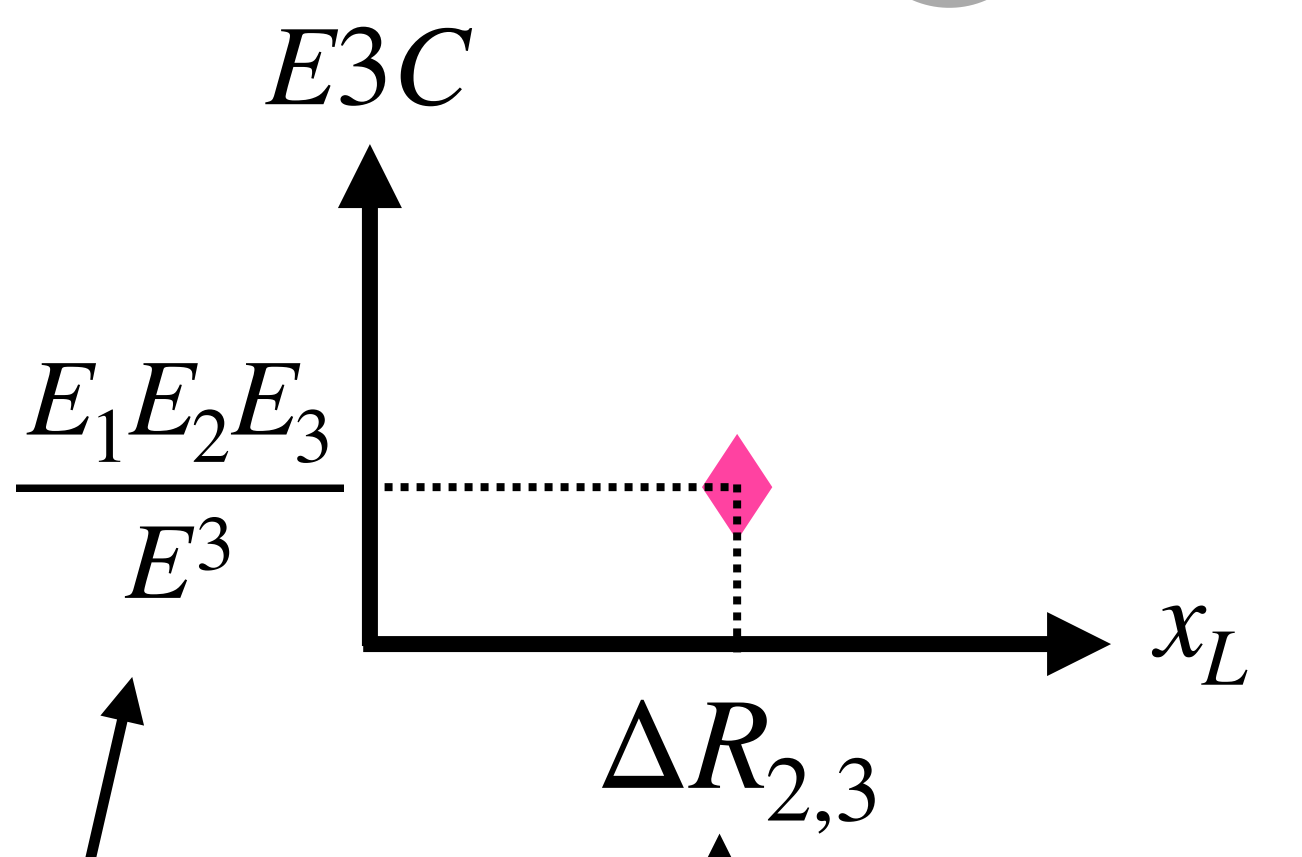
Highest energy scale in α_S extraction
Highest precision in beyond TeV scale

Energy correlators in jets: E2C & E3C



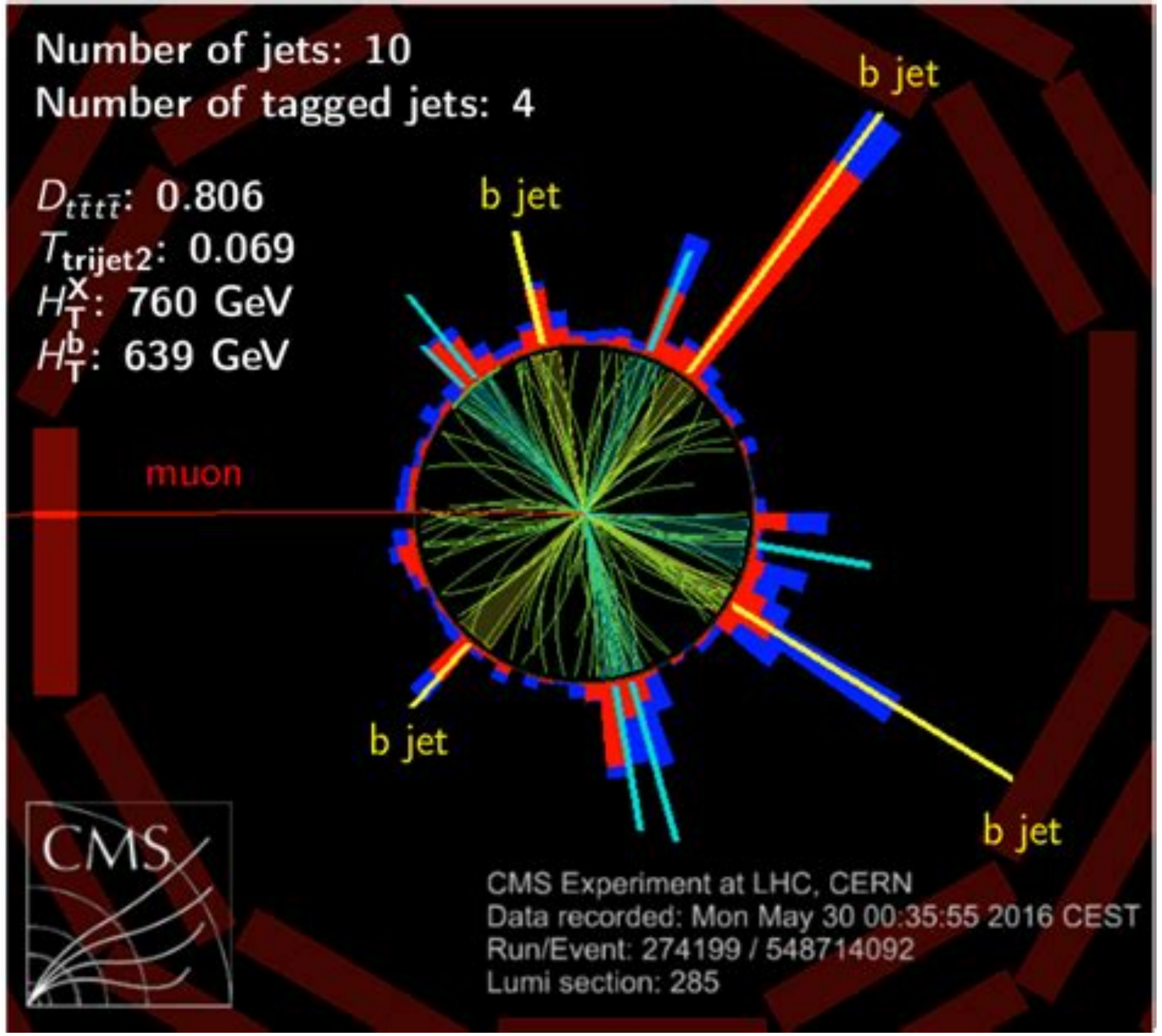


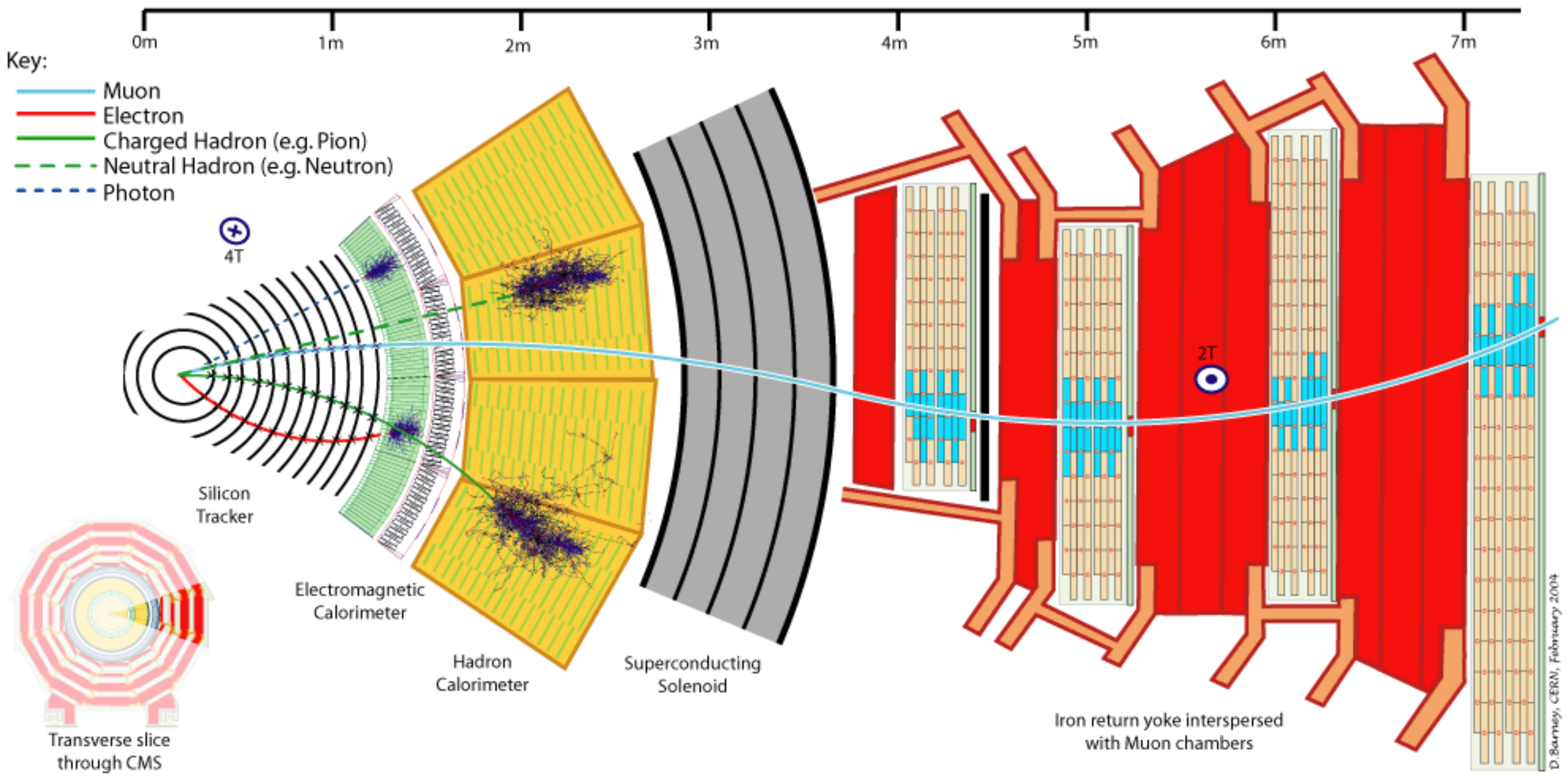
$$E3C = \frac{d\sigma^{[3]}}{dx_L} = \sum_{i,j,k}^{n} \int d\sigma \frac{E_iE_jE_k}{E^3} \delta(x_L - \mathrm{max}(\Delta R_{i,j}, \Delta R_{i,k}, \Delta R_{j,k}))$$

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

Jet substructure observable, sensitive to jet formation

Jets at the CMS



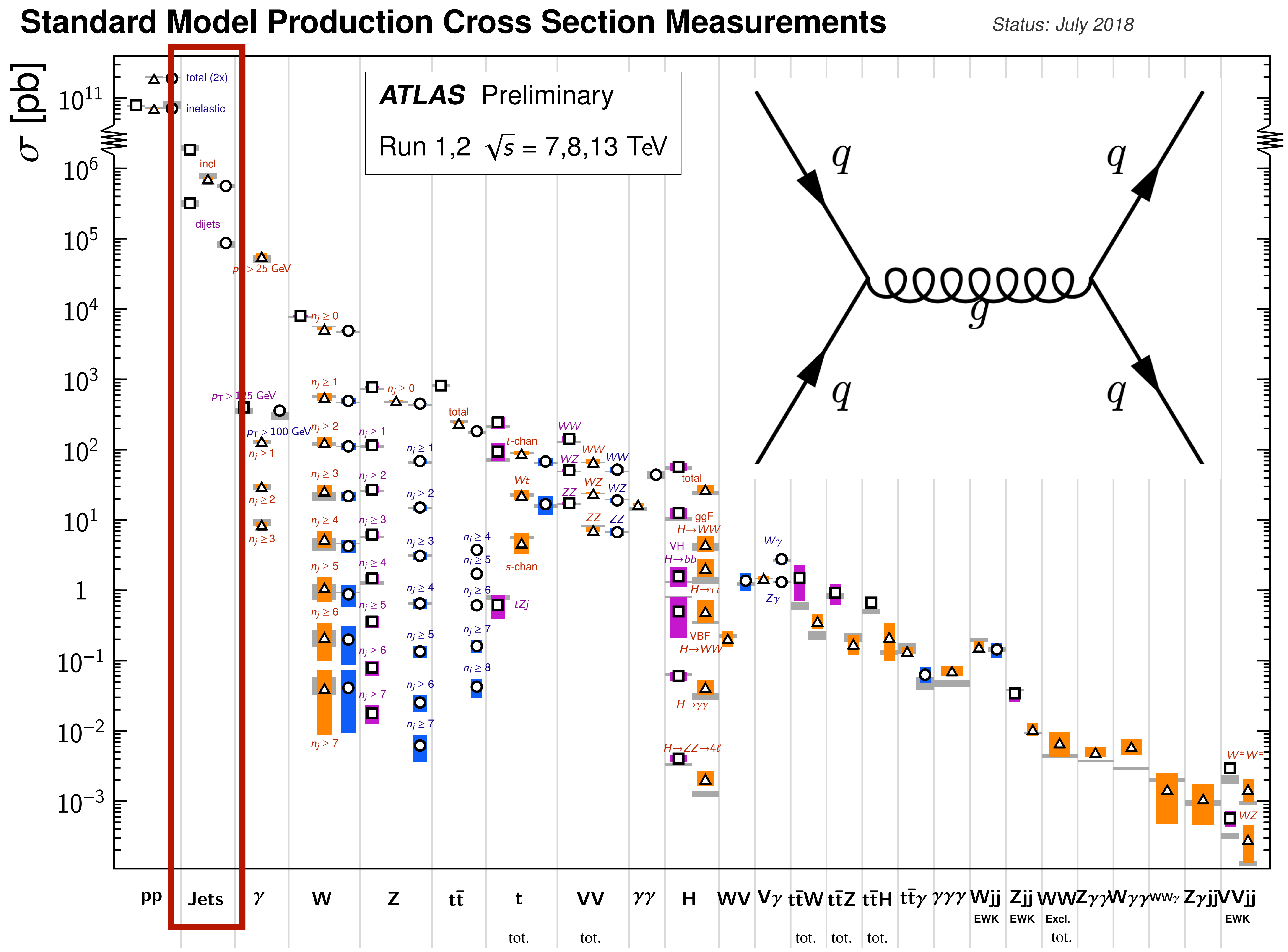


No particle ID at CMS, only see

Jet <=

- Charged hadrons
- Neutral hadrons
- Photons

Measurement in nutshell



Dijet events in central region $|\eta| < 2.1$

- Large cross section

anti-kT with R = 0.4

Probe energy scale dependency

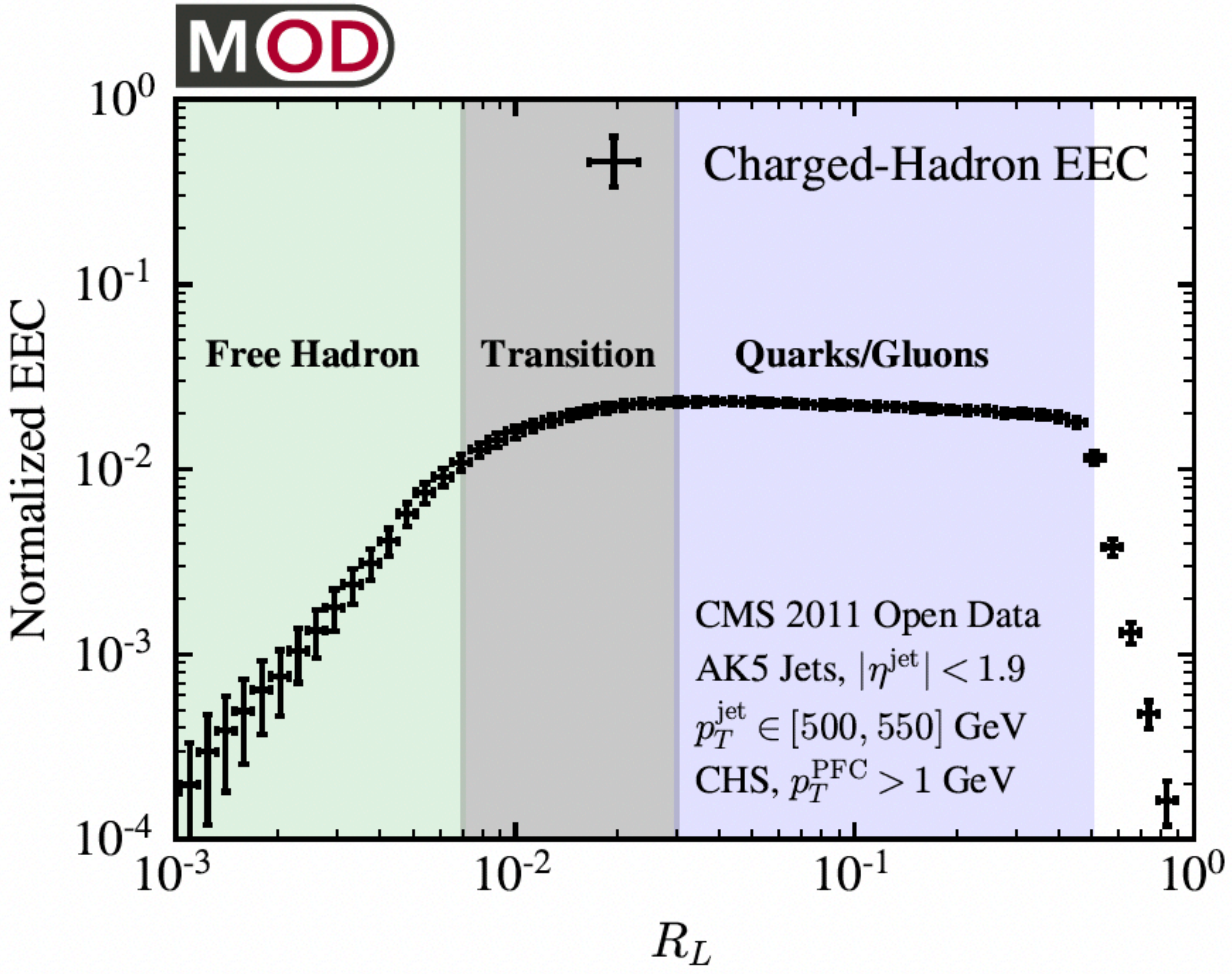
- 8 p_T^{jet} region in 97 ~ 1784 GeV

Neutral & charged & photon with p_T > 1 GeV

- All particles included

EEC reconstructed from open data

arXiv: 2201.07800



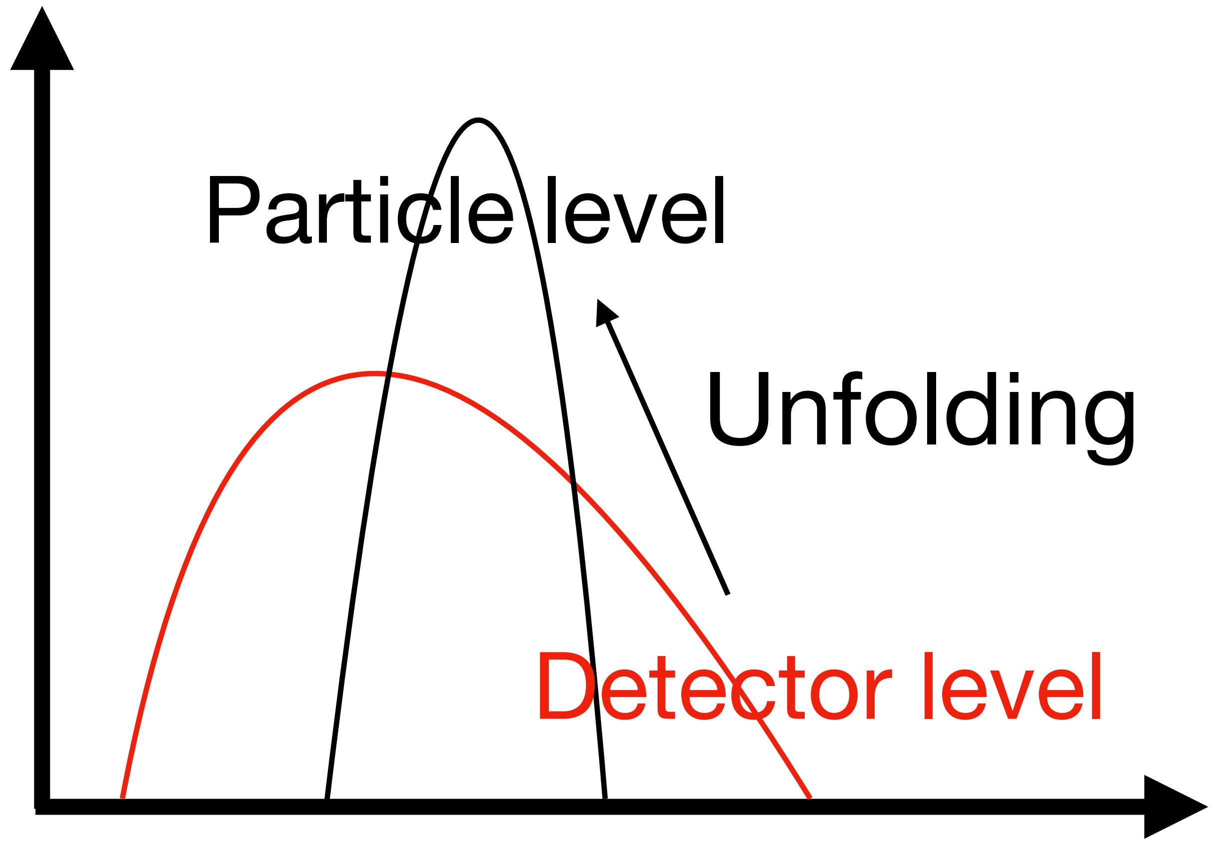
Theorists could do it too!

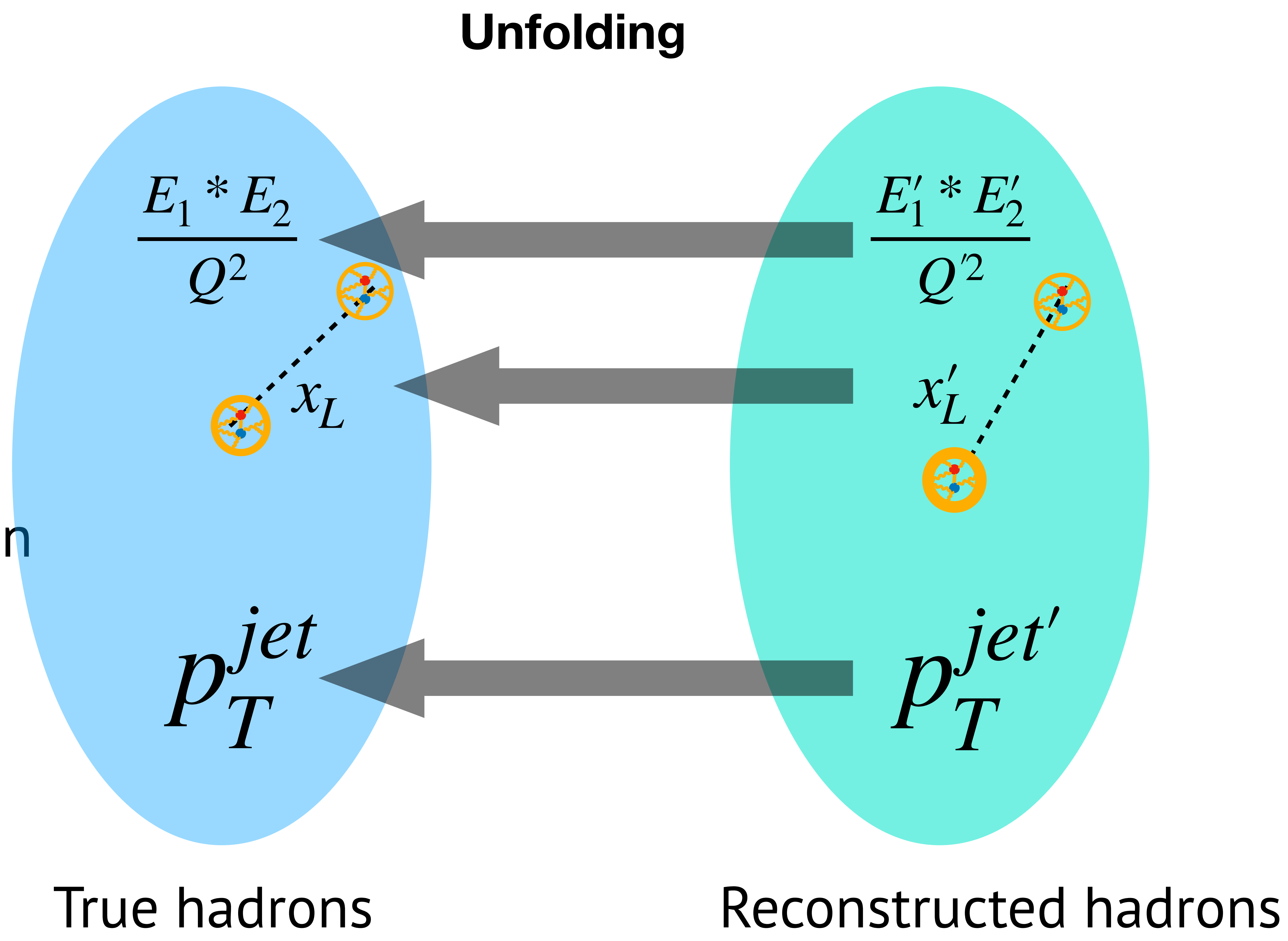
Extra experimental steps: unfolding

Unfolding: detector hadron -> true hadron

Unfold jet constituents:

- p_T^{jet}, x_L and energy weight, 3D unfolding
- $10 * 22 * 20 = 4400$ bins
- 4400x4400 migration matrix and regularization





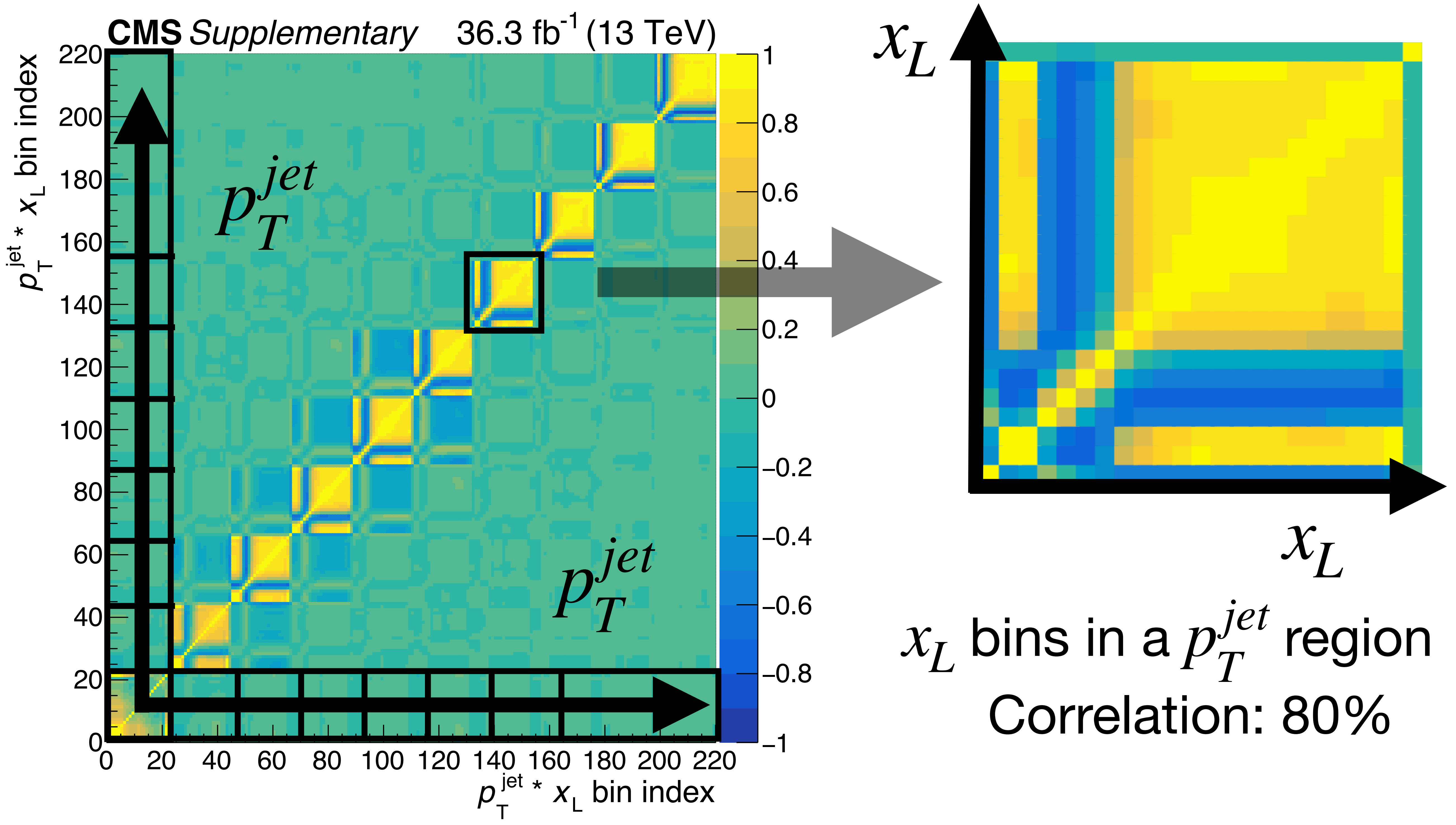
Extra experimental steps: statistical correlations

Multi entry distribution for every jet, statistical correlation important

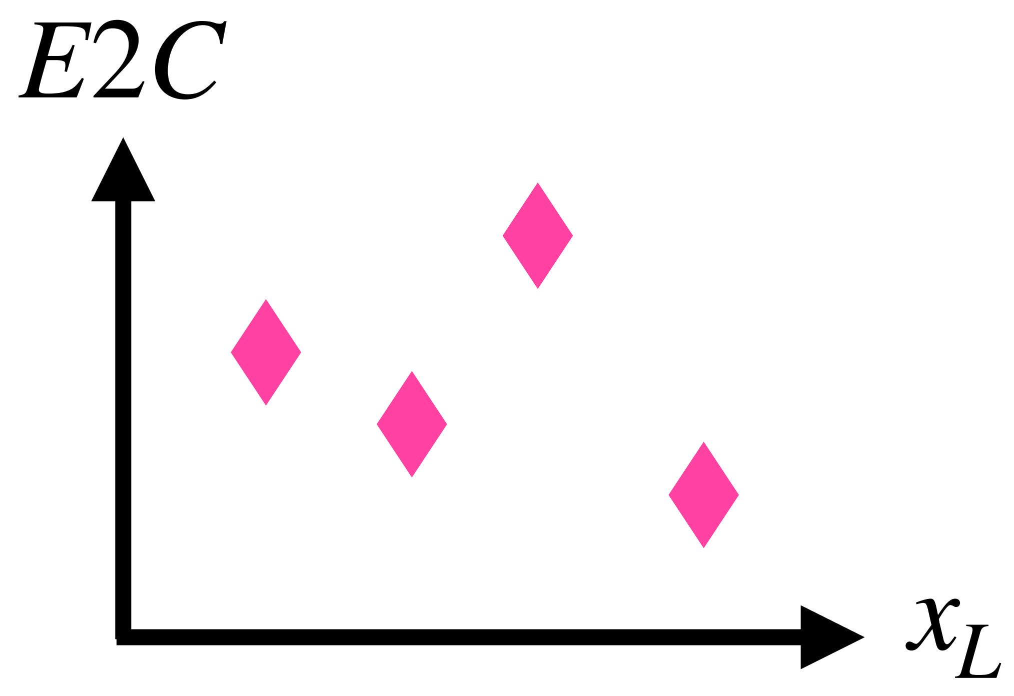
Detector level => Unfolding => Normalization

Independent statistics for E2C, E3C

E2C correlation matrix



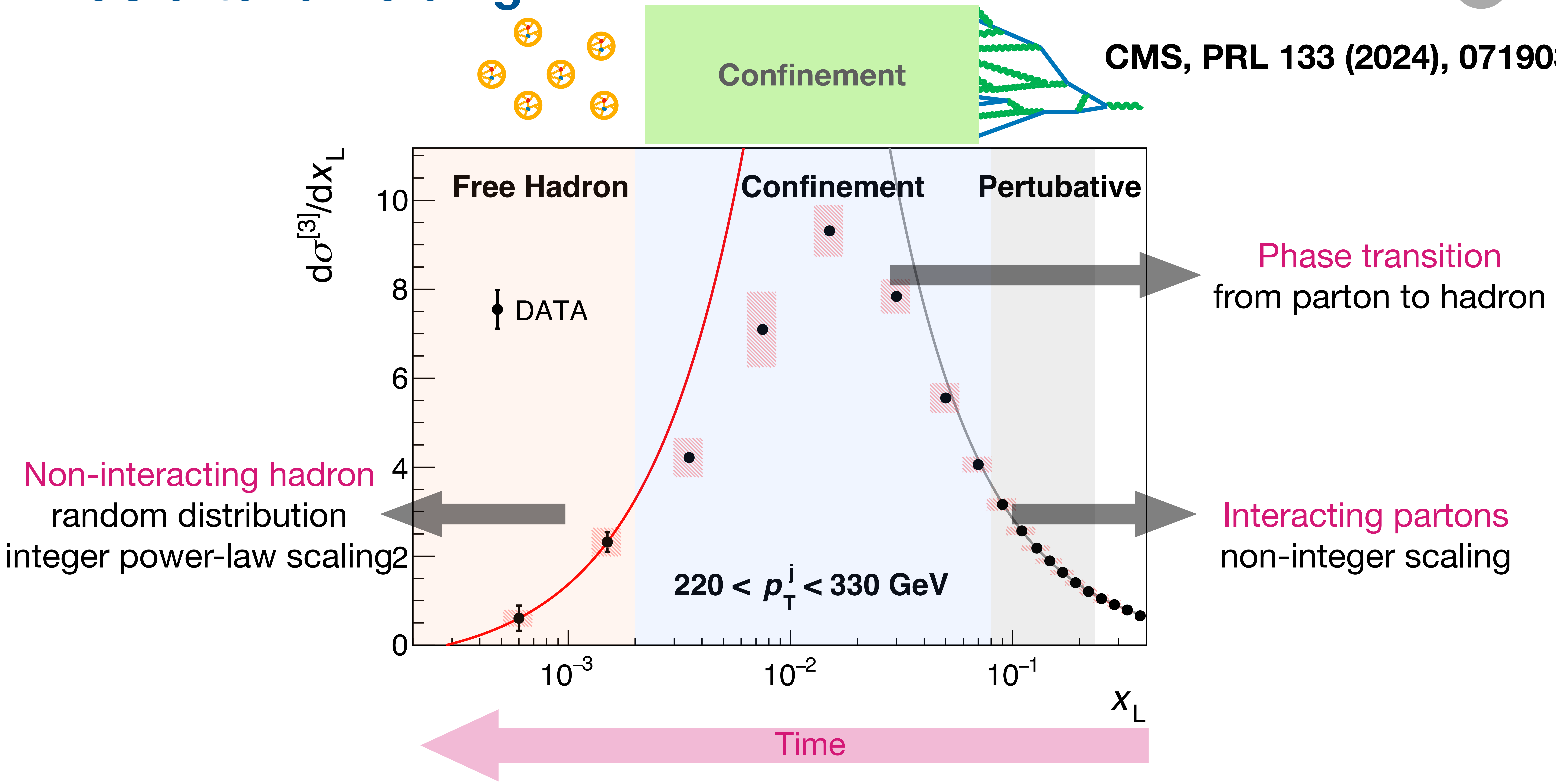
x_L bins in a p_T^{jet} region
Correlation: 80%



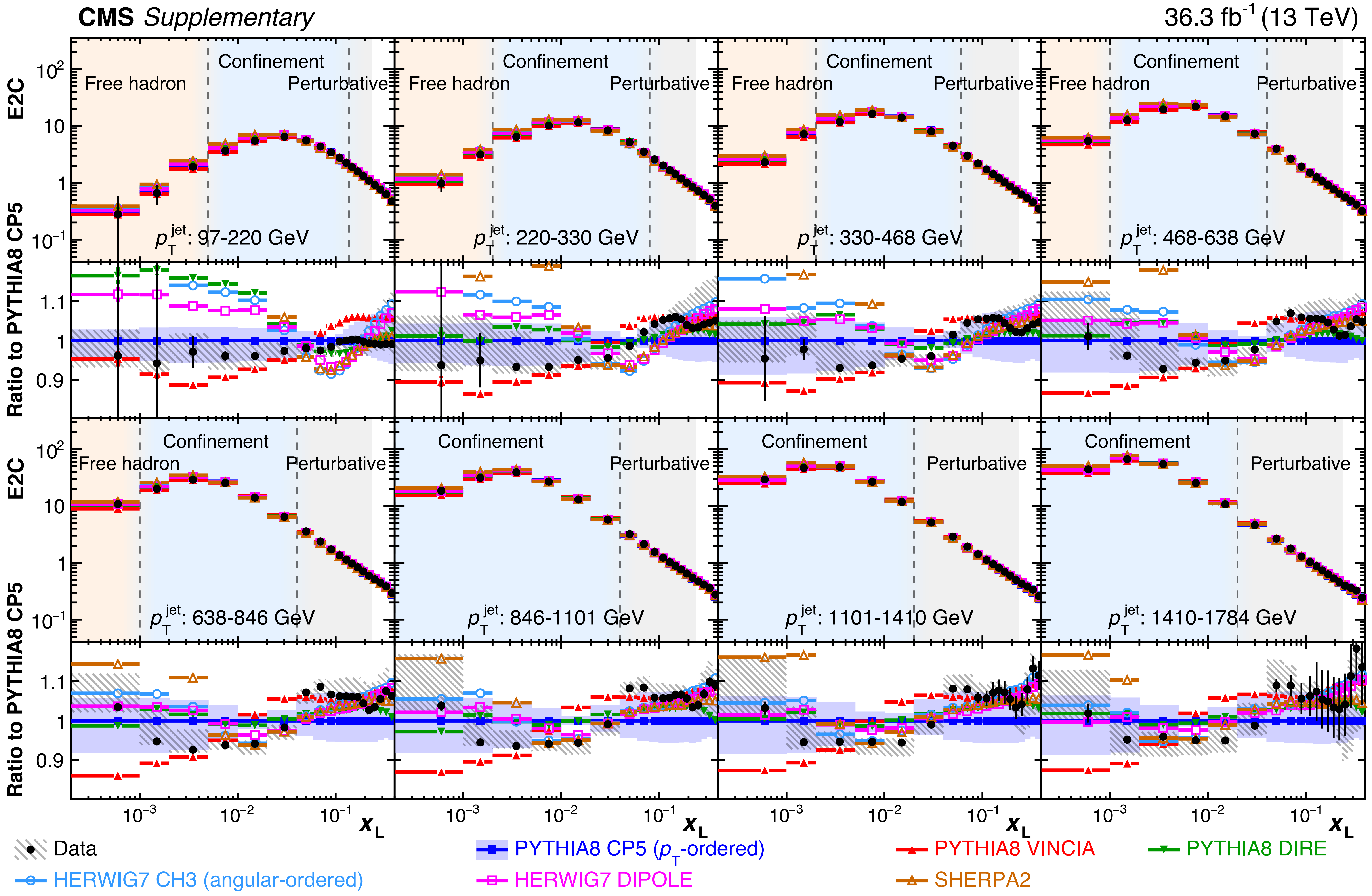
E3C after unfolding

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

CMS, PRL 133 (2024), 071903



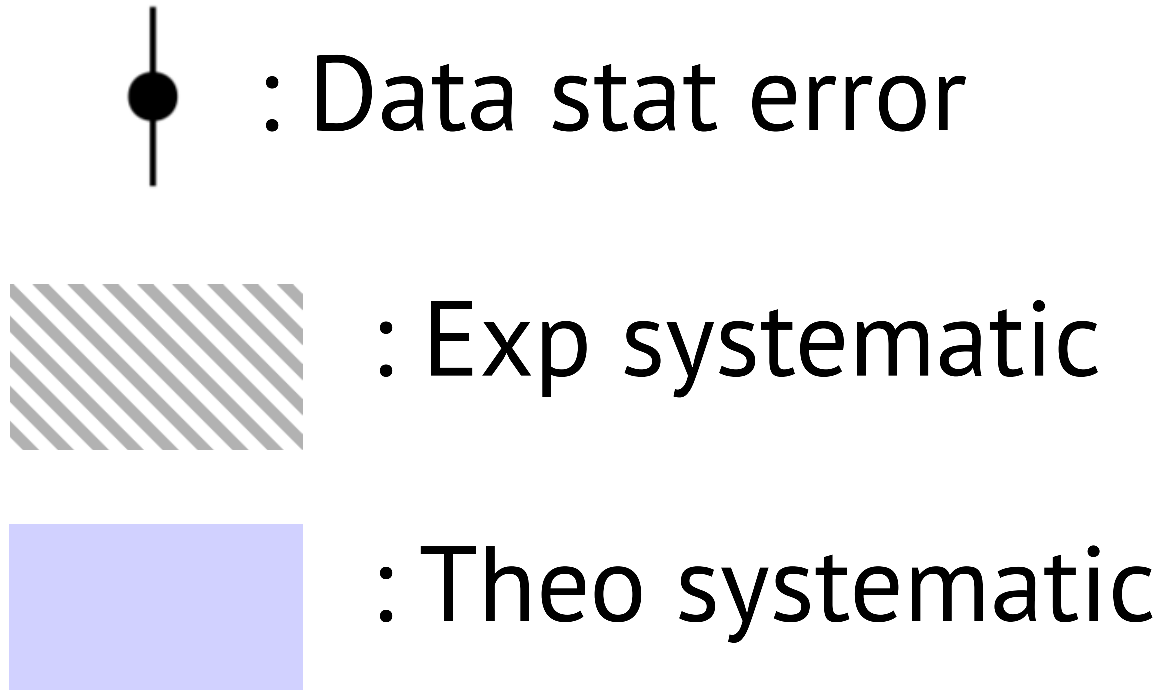
Unfolded E2C vs MC



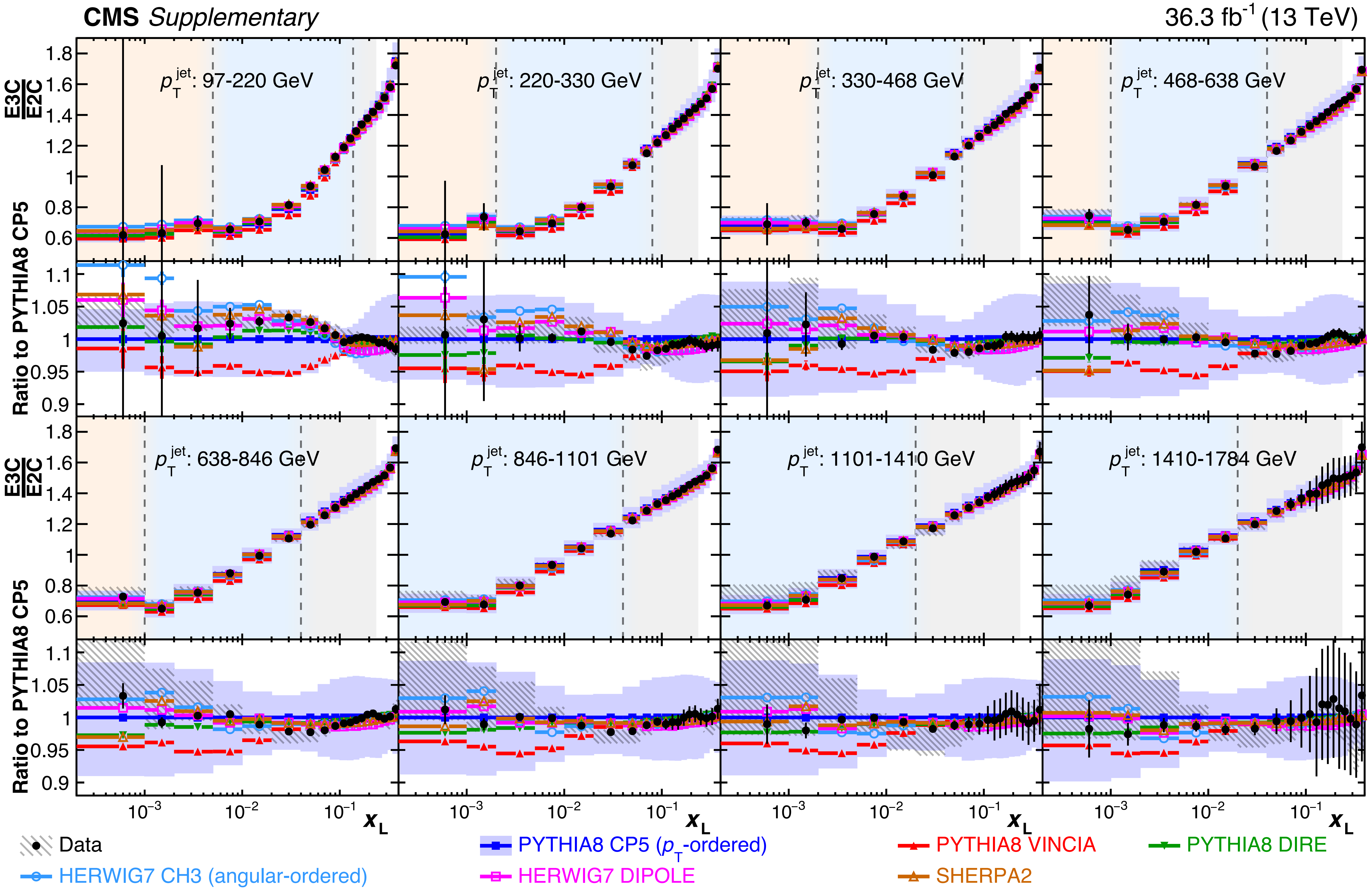
97 ~ 1784 GeV

Data vs various parton shower model, difference ~ 10%

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



E3C/E2C



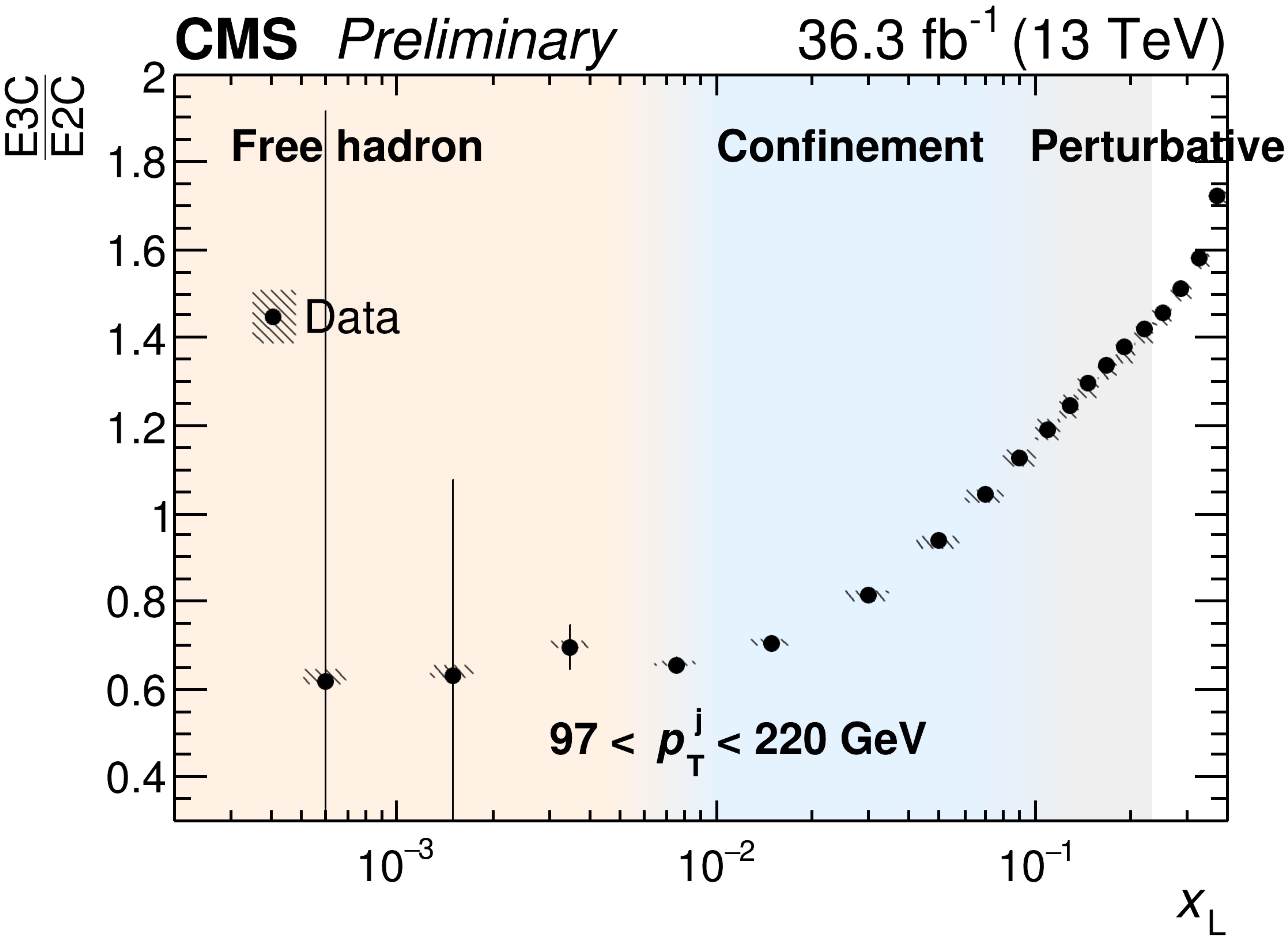
Benefit of taking ratio

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

All models agree well

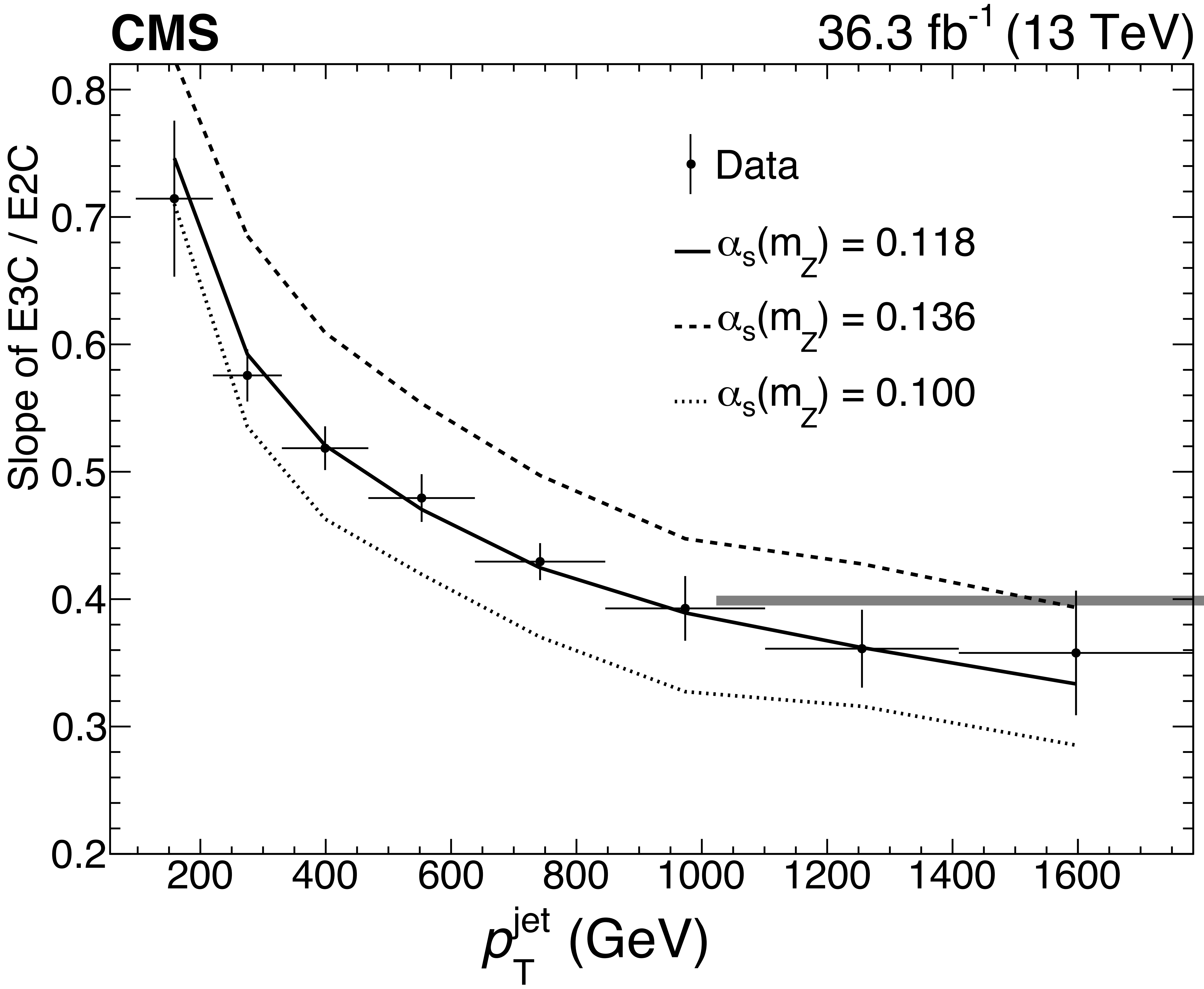
p_T^{jet} ↑ , Slope~αs ↓

E3C/E2C



Animated E3C/E2C in multiple pT regions

Direct observation of asymptotic freedom



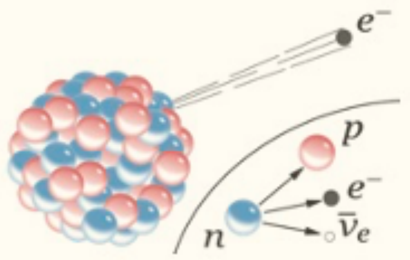
$p_T^{jet} \uparrow$ $Q \uparrow$

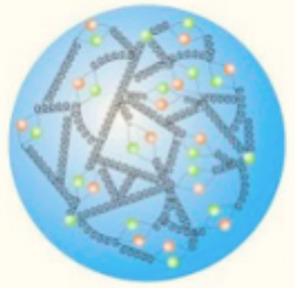
Slope $\downarrow$ $\alpha_s(Q) \downarrow$

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

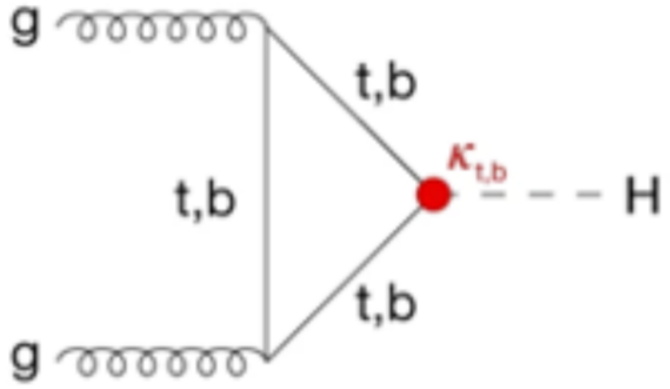
Extraction of α_S

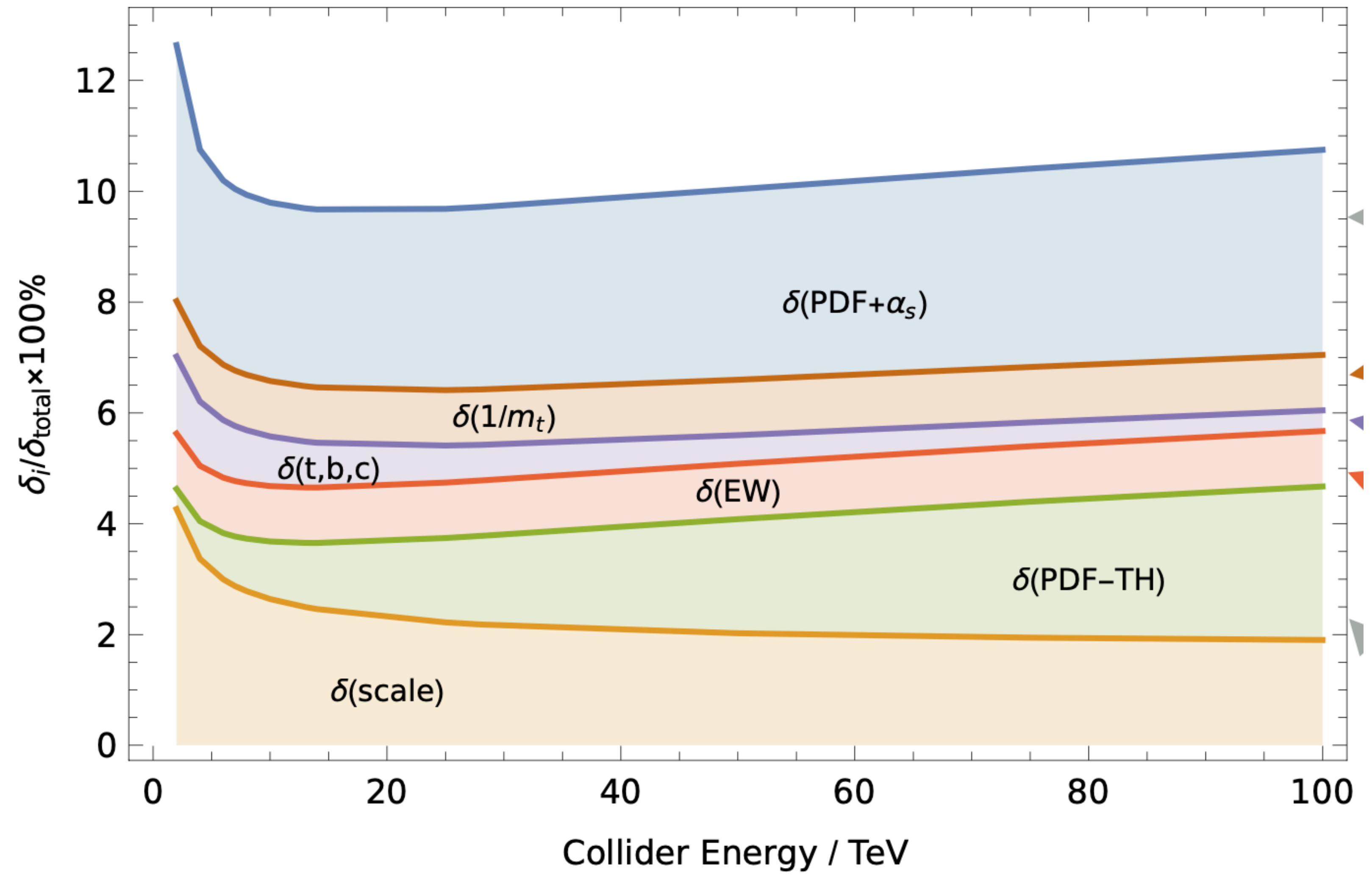
电磁相互作用	弱相互作用	引力	强相互作用
$\frac{\delta\alpha}{\alpha} \simeq 10^{-10}$	$\frac{\delta G_F}{G_F} \simeq 10^{-8}$	$\frac{\delta G_N}{G_N} \simeq 10^{-5}$	$\frac{\delta\alpha_S}{\alpha_S} \simeq 0.01$





An important uncertainty source of LHC theoretical calculations





Current status of α_S

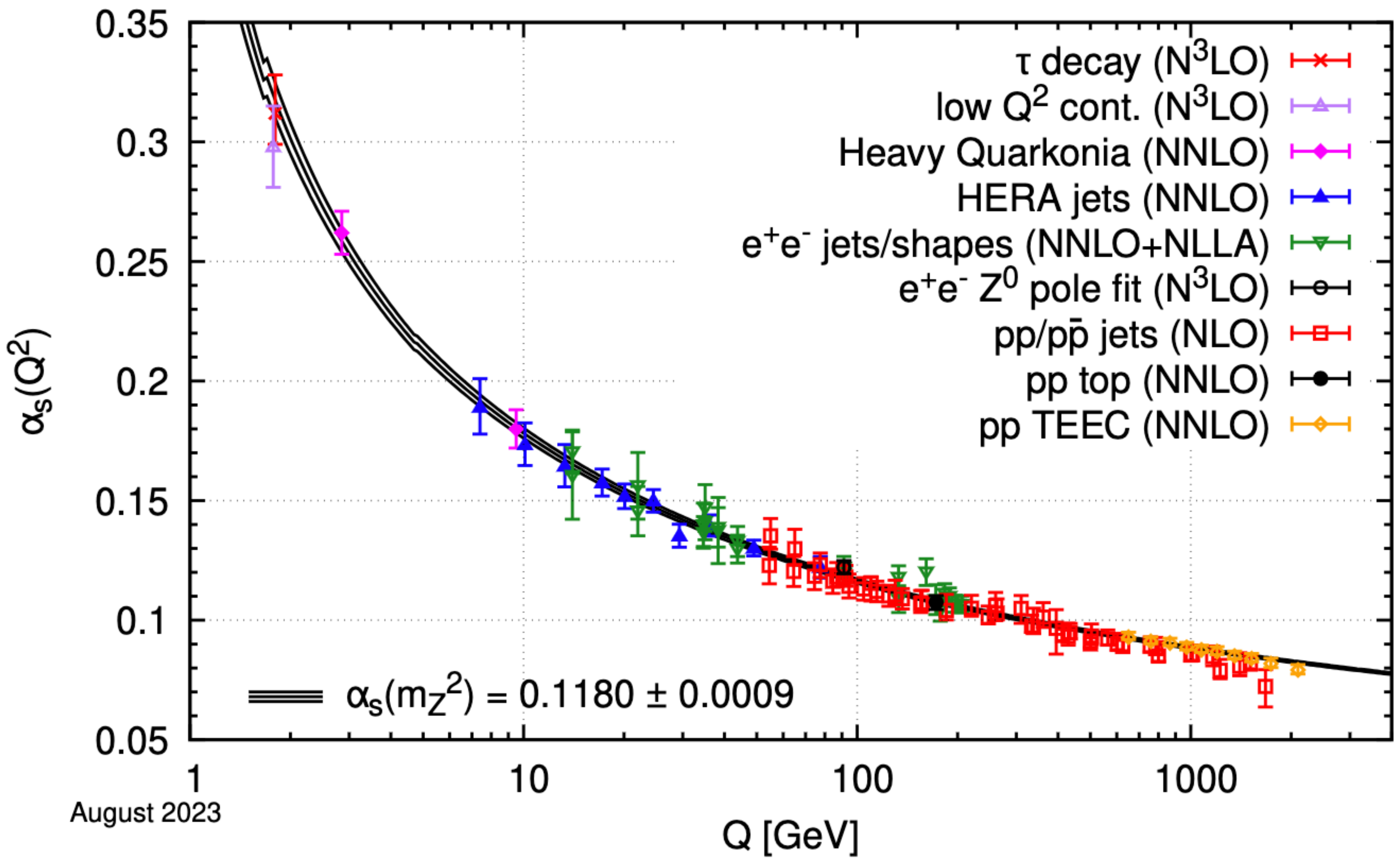
World average: $\alpha_S(m_Z) = 0.1180 \pm 0.0009$

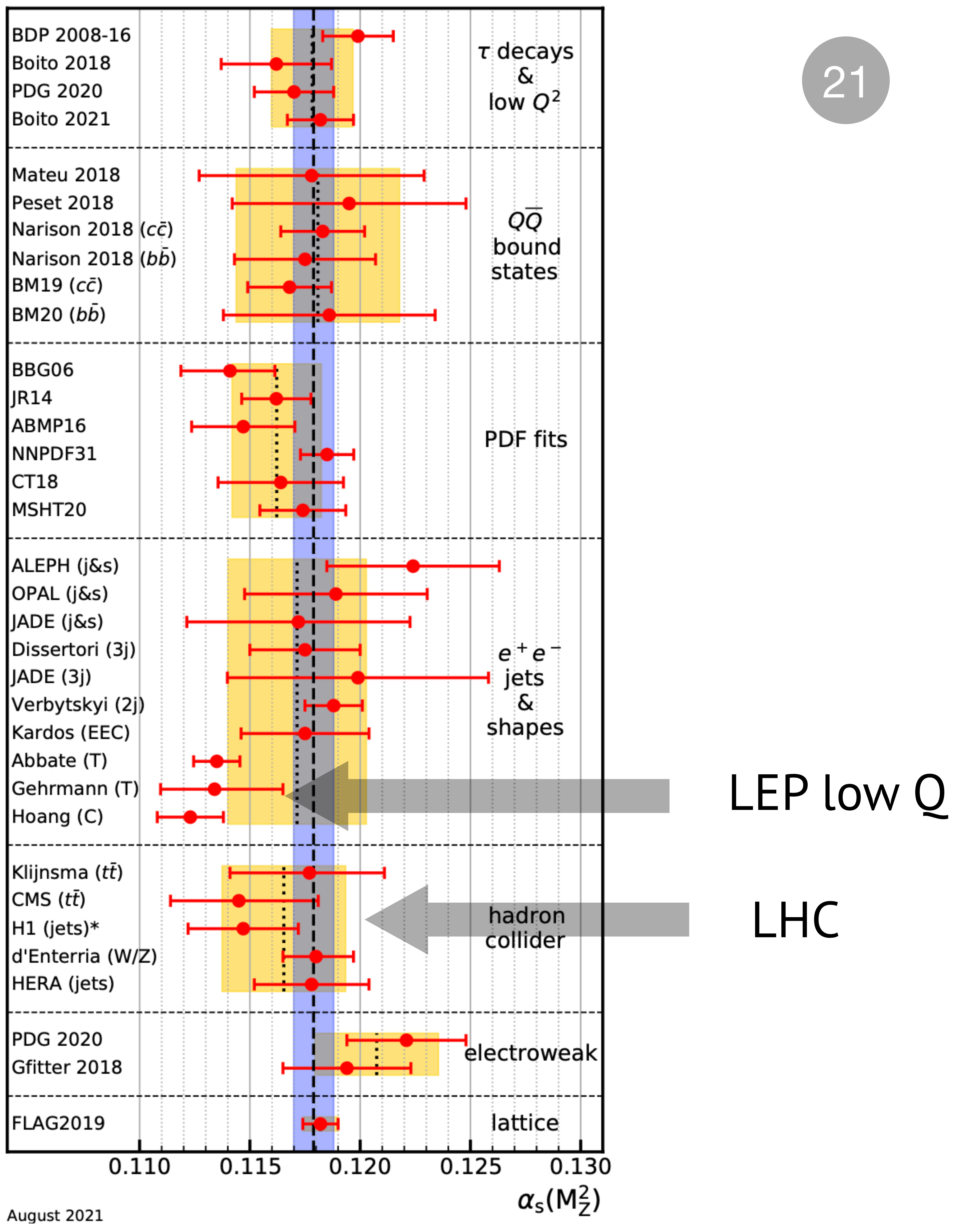
PDG

LEP at collinear region: not consistent with world average

LHC: cross section measurement

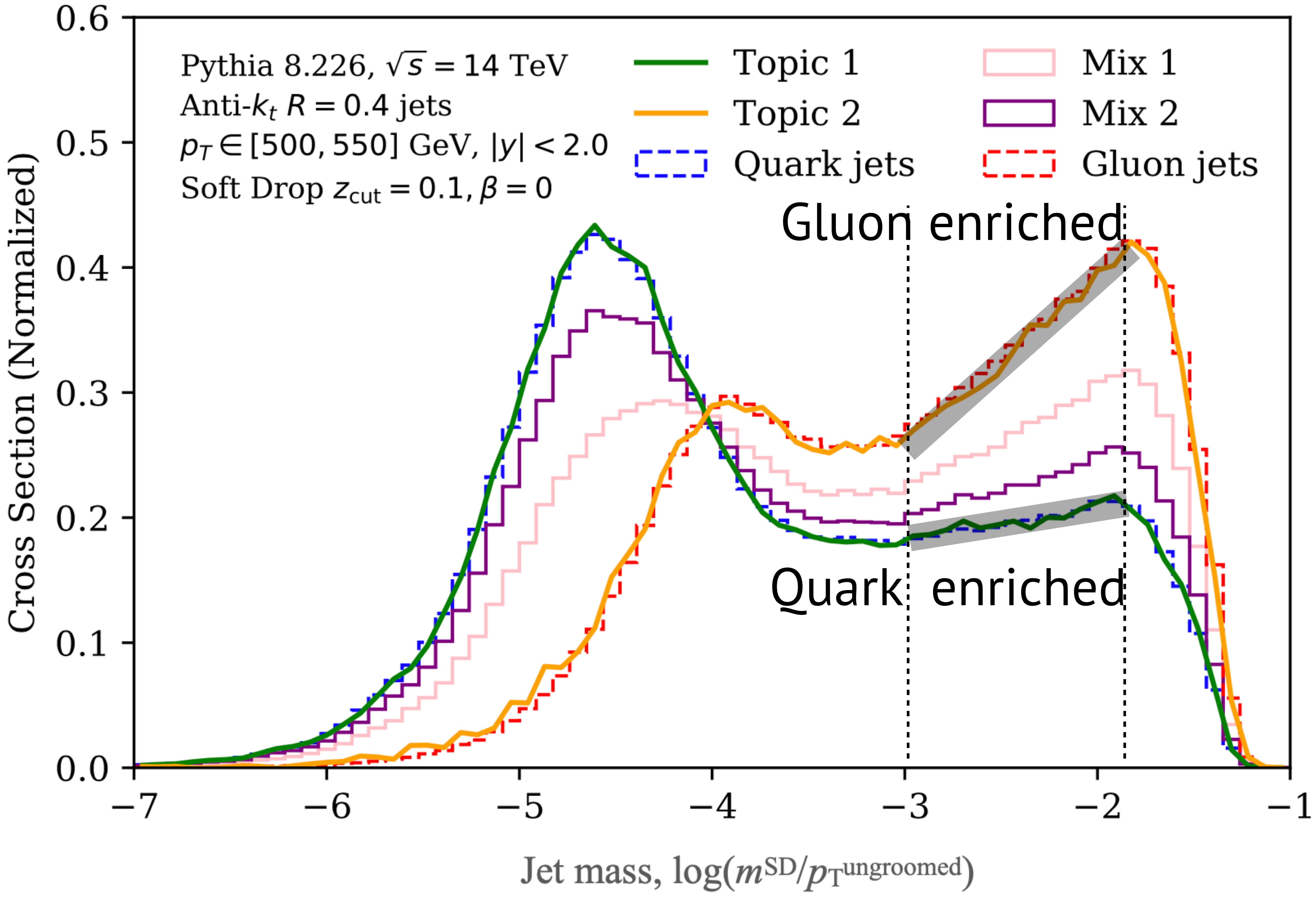
Q: O(100GeV) ~ O(TeV)





Extraction of α_S using jet substructure

A collinear region probe, low Q



Soft drop mass

Common problem

α_S ~ slope

q/g fraction C_F/C_A

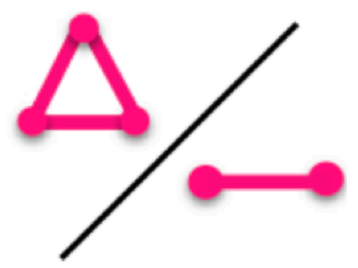
PDF uncertainty dominant

Matt, Benjamin, Christof, *arxiv:2206.10642*

E3C/E2C: a new way to extract α_S

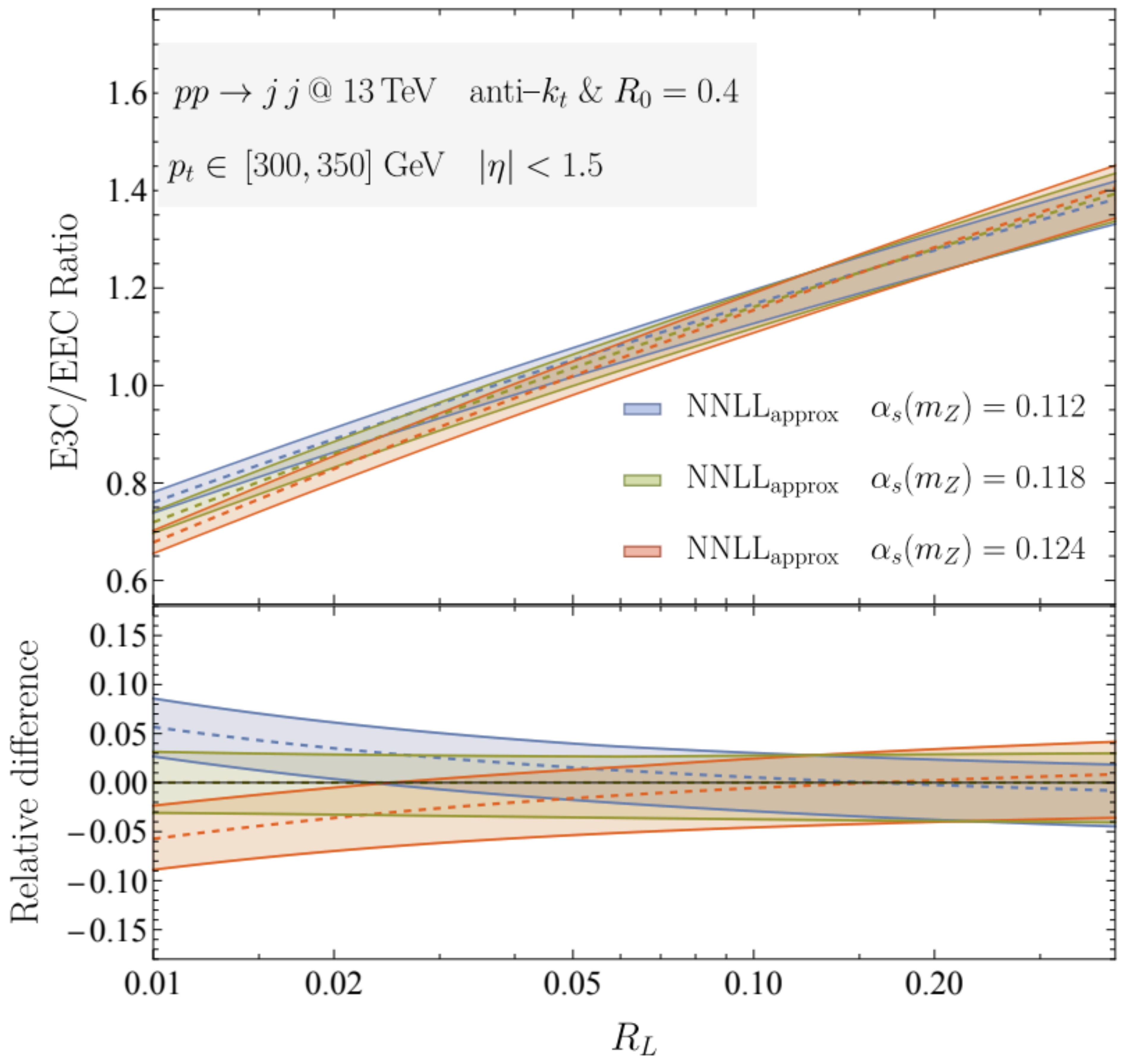
Chen, Gao, Li, Xu, Zhang, Zhu, *arXiv:2307.07510*

At LL, E3C/E2C is a linear function of α_s



$$\propto \alpha_S(Q) \ln x_L + O(\alpha_s^2)$$

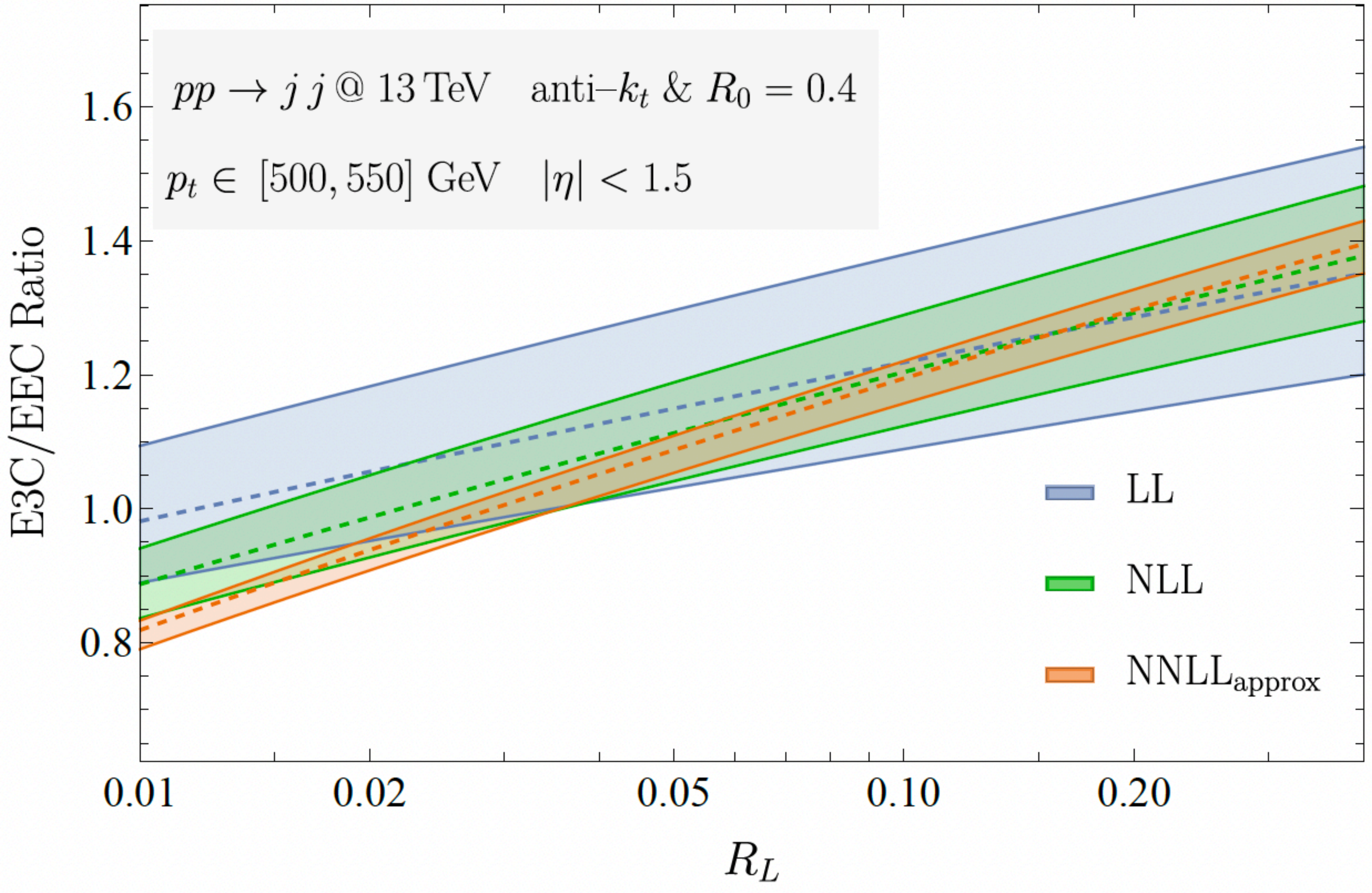
Ci factors enter E3C and E2C and partially cancel



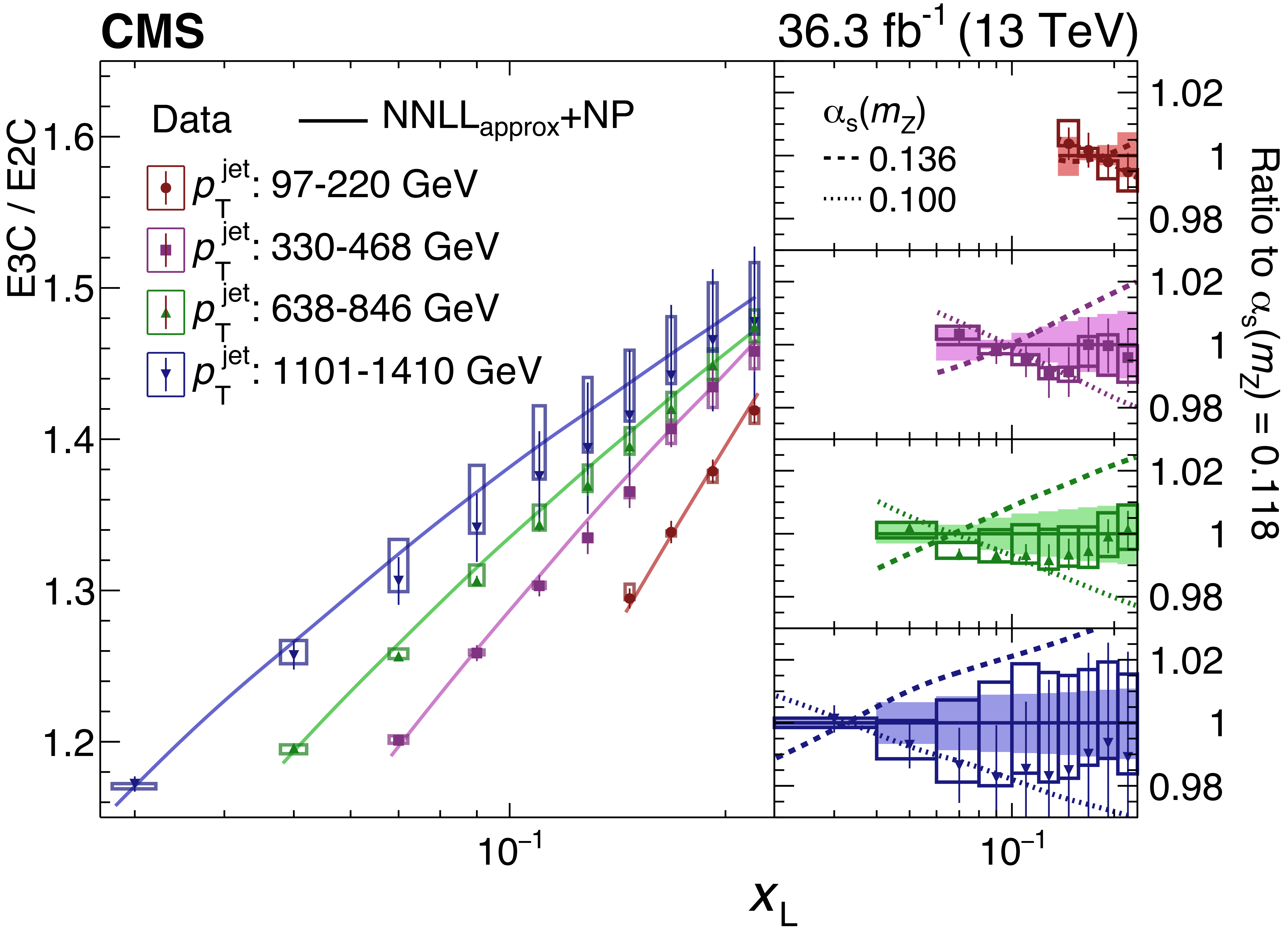
$\alpha_S(M_Z) \uparrow$ Slope $\uparrow$

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

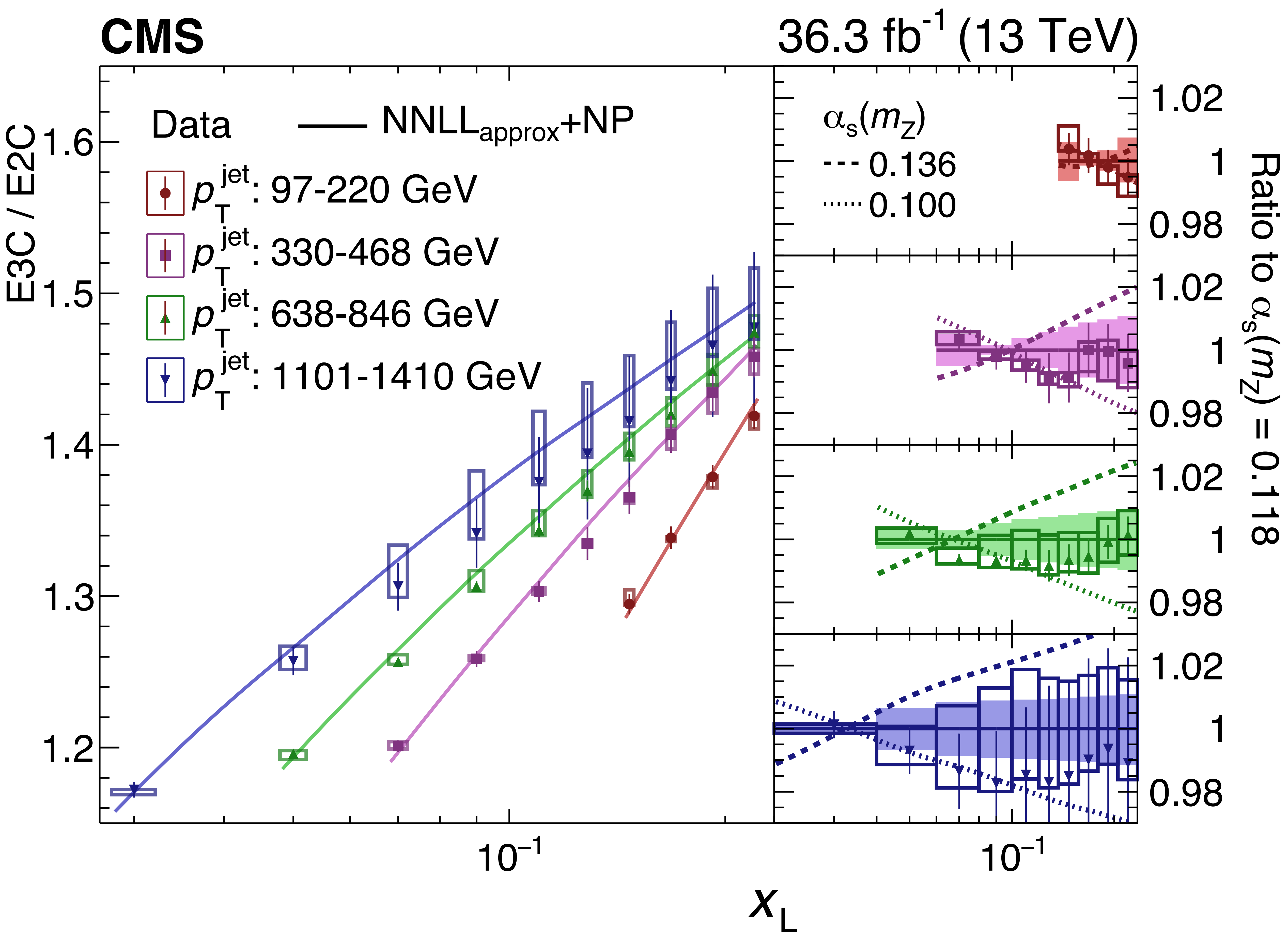
Initial proposal, Chen, Moult, Zhang, and Zhu, arXiv:2004.11381
NLO+NLL, Lee, Meçaj, and Moult, arXiv:2205.03414
NLO+NNLL$_{approx}$, Chen, Gao, Li, Xu, Zhang, and Zhu, arXiv:2307.07510



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

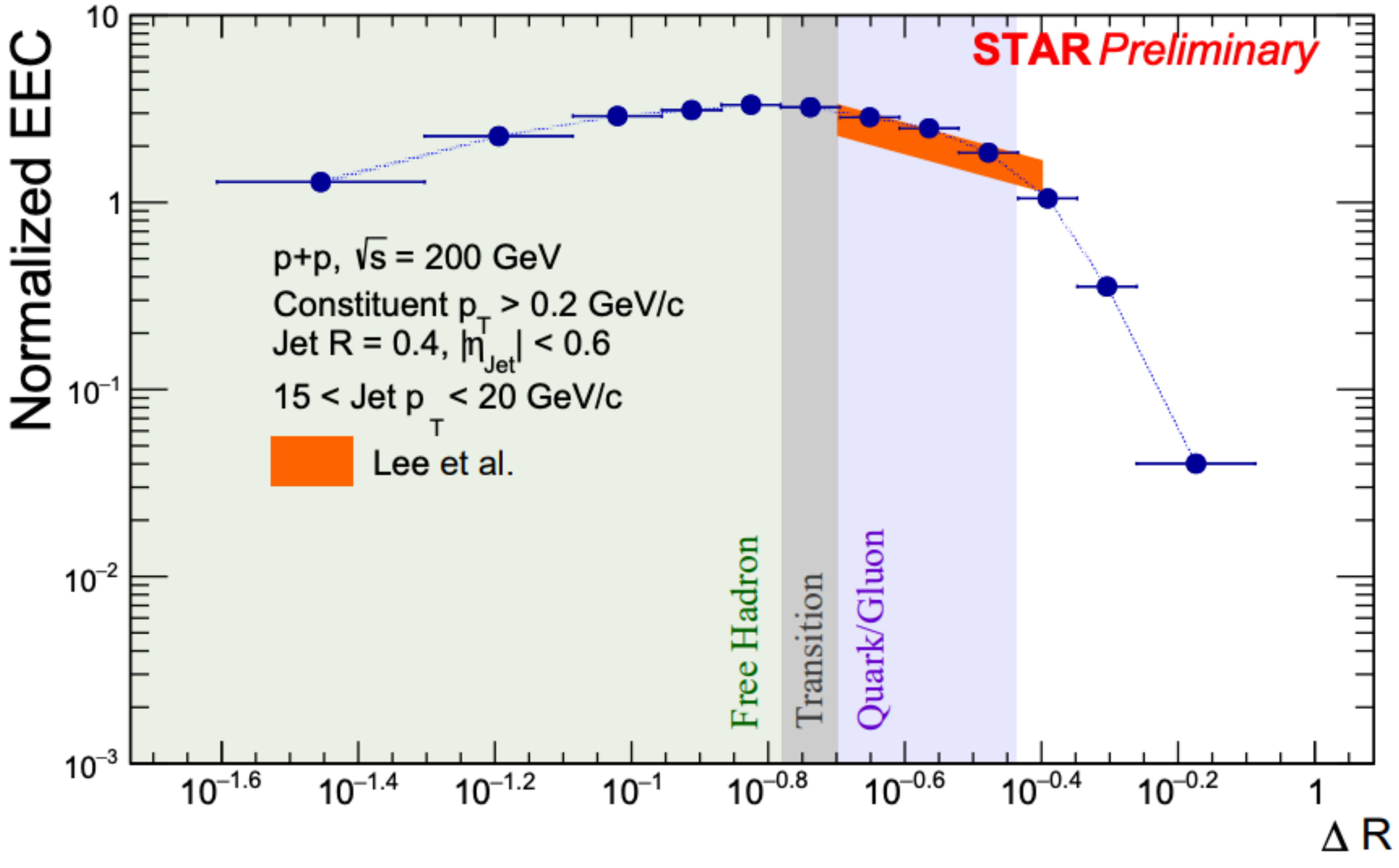
QCD scale of NNLL$_{approx}$

Neutral hadron energy scale

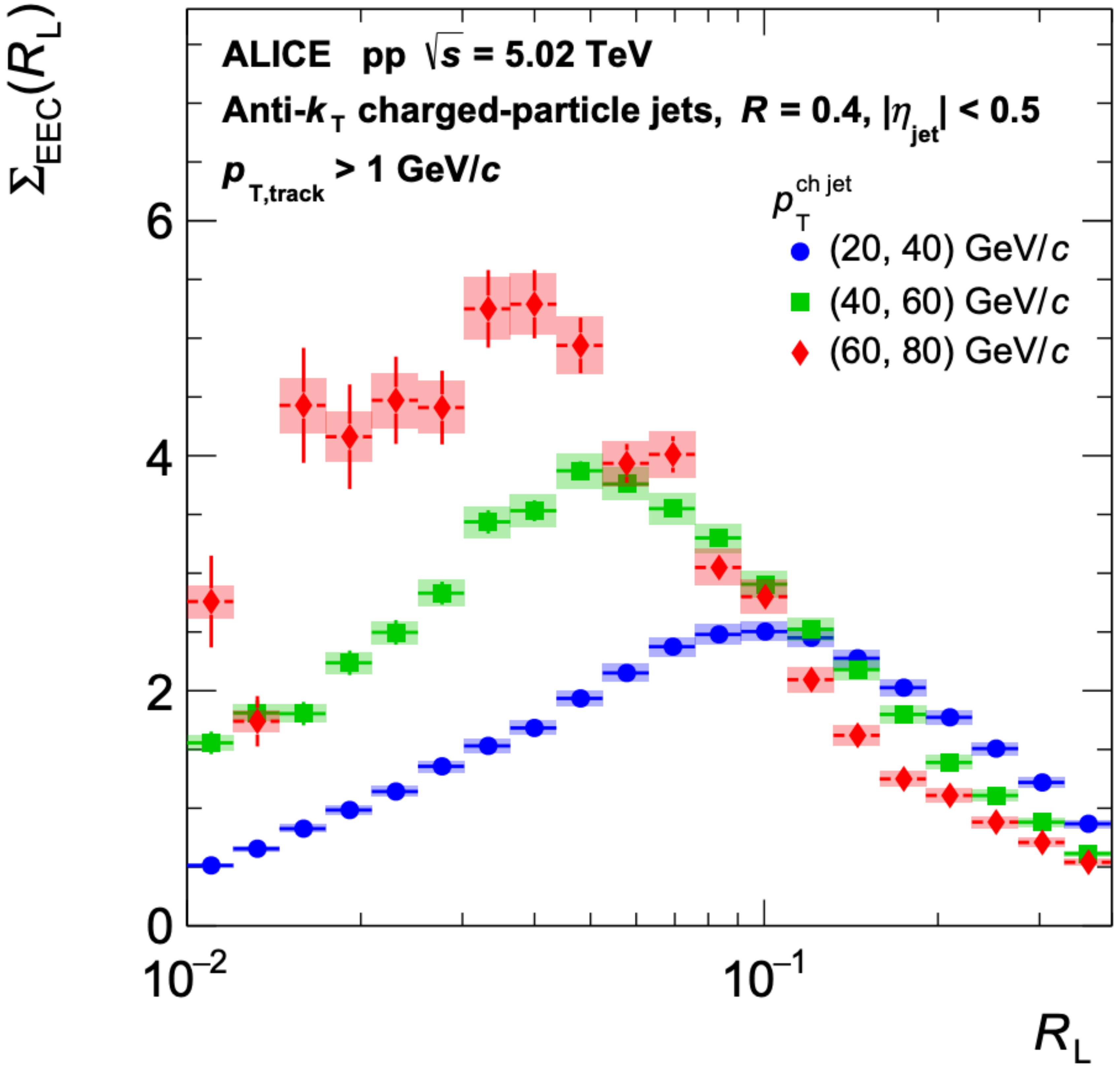
Uncertainty ~ 4%,
Q~ O(10) GeV, collinear regime
Most precise from jet substructure to date

Many EEC measurements ongoing

STAR: PoS HP2023 (2024) 175

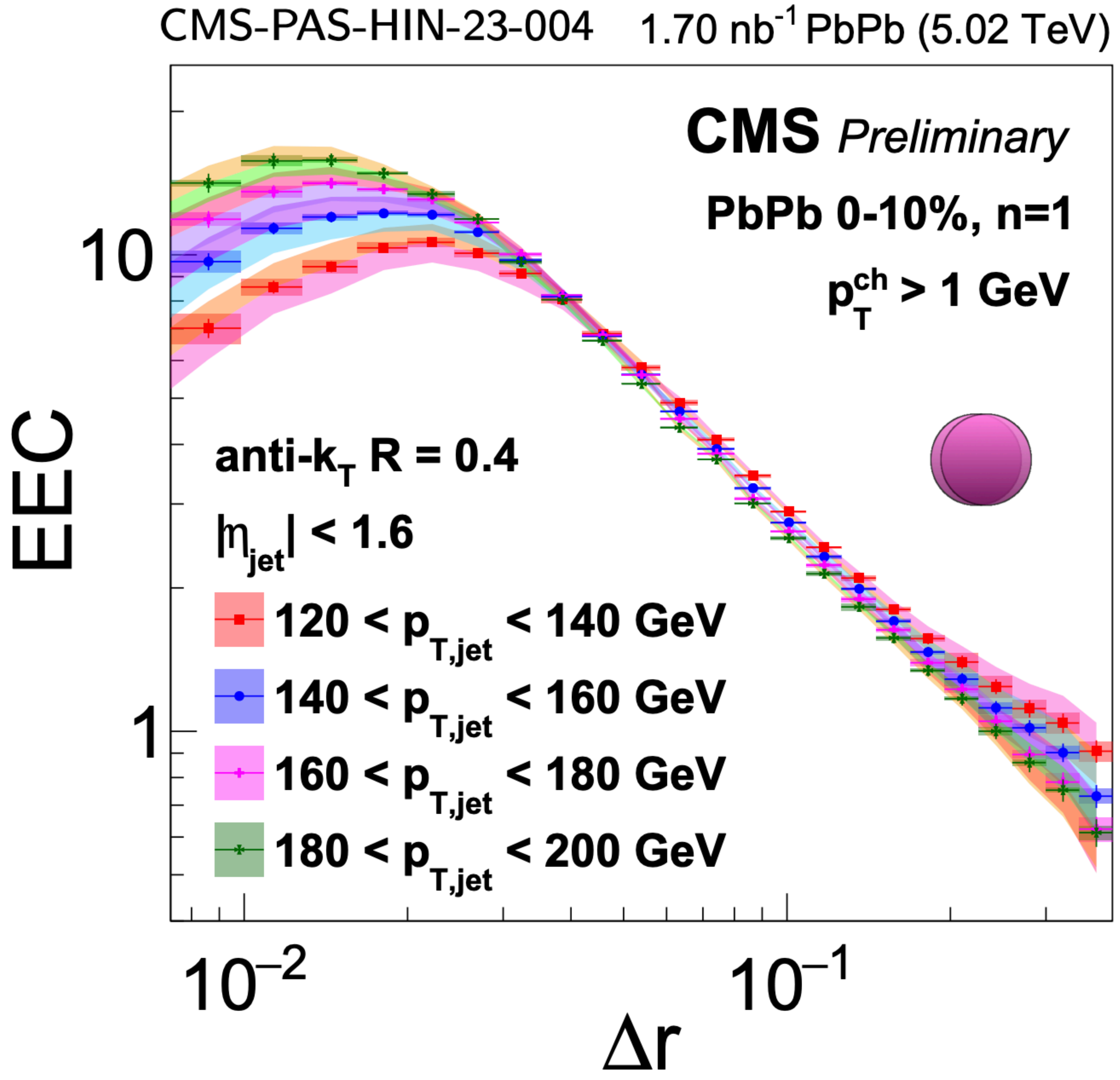


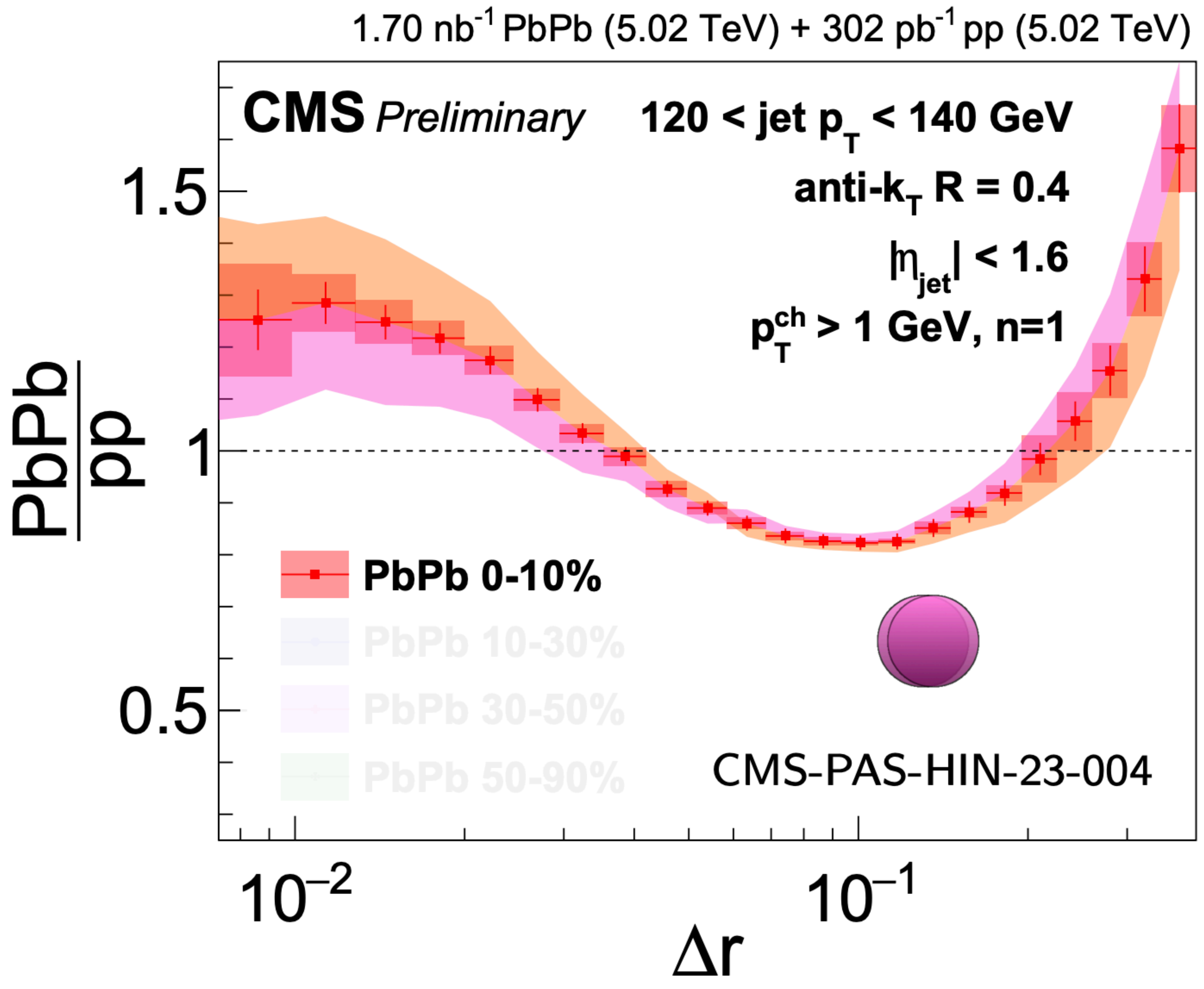
ALICE pp: arXiv:2409.12687



Many EEC measurements ongoing

CMS PbPb, CMS-PAS-HIN-23-004





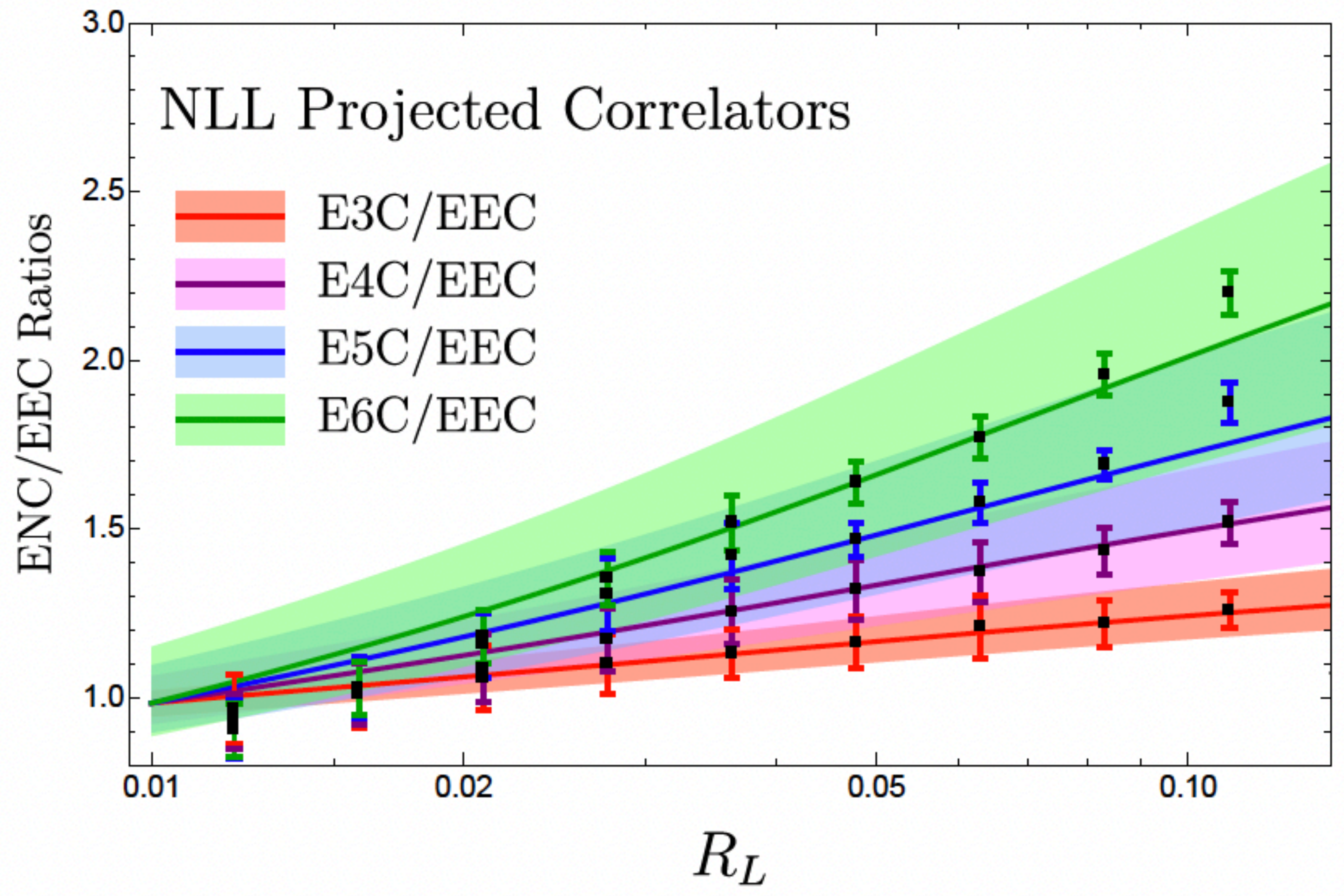
Summary

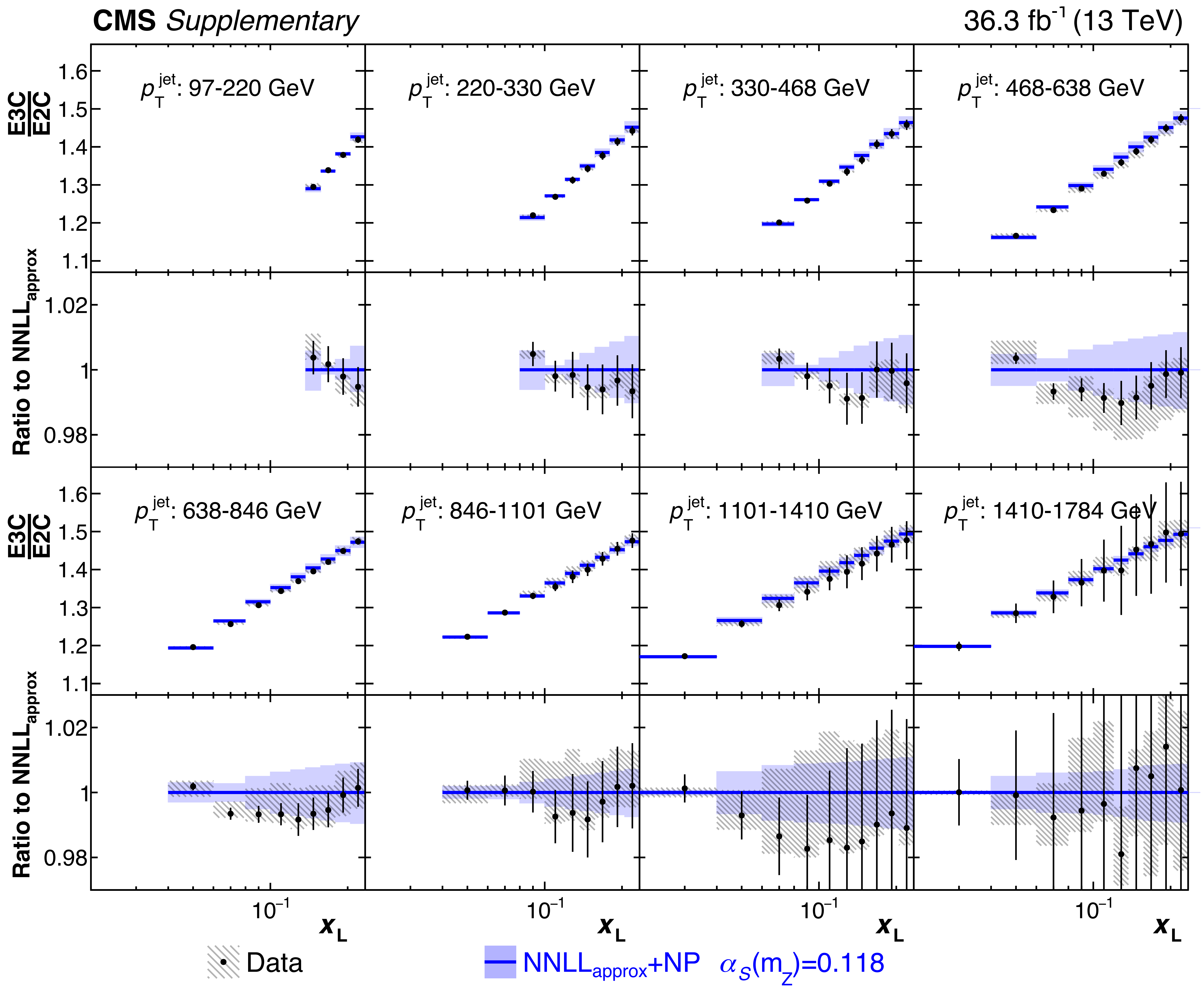
- Energy correlators revive at hadron colliders
- High precision experimental measurements on energy correlators
- Probe many fundamental properties of QCD
- Proven to be a powerful tool for precise α_S determination

From Ian Moult

Improving the α_s measurement

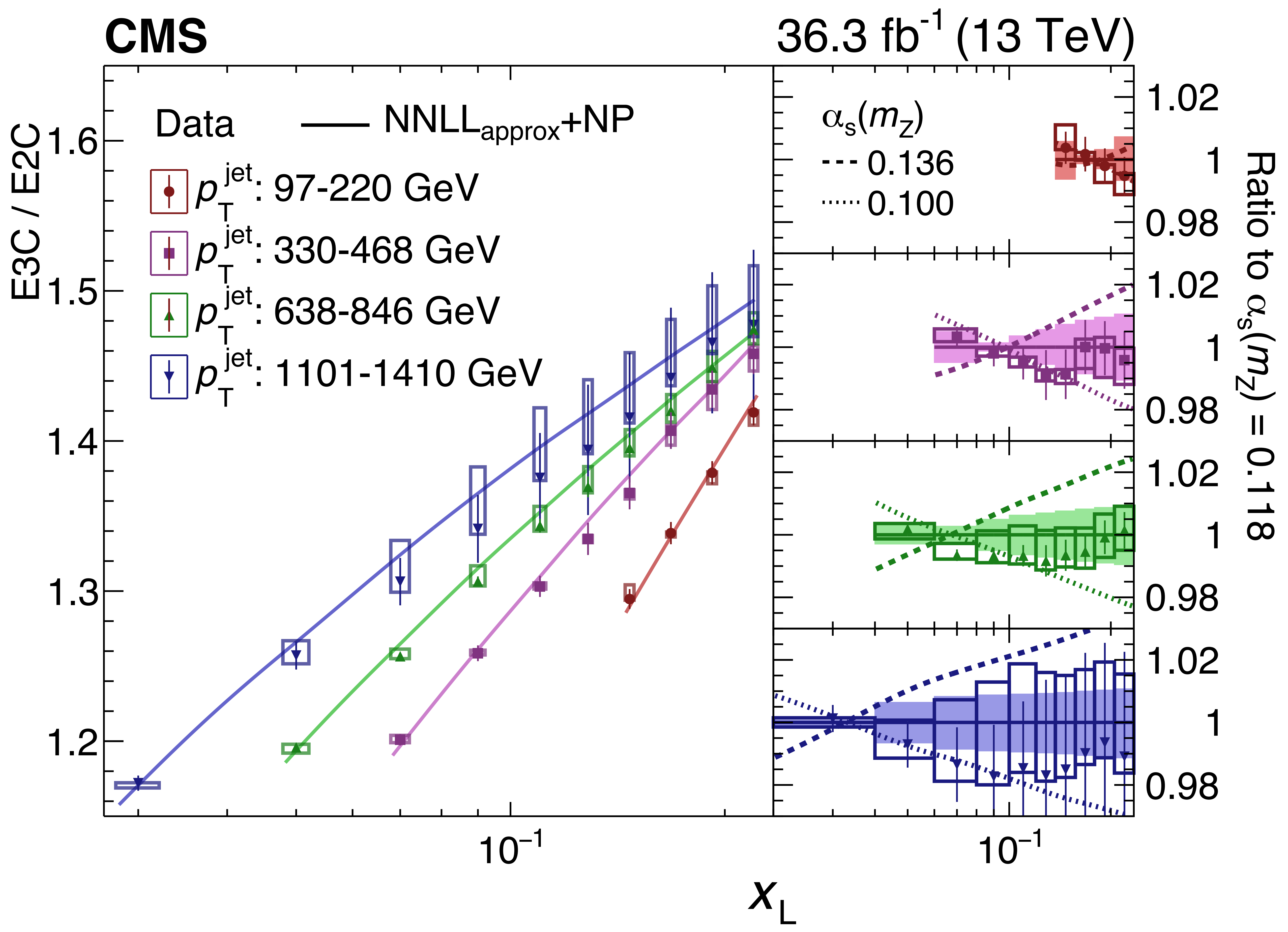
- Measure on tracks.
- Measure the higher point ratios to over constrain α_s from quark gluon fractions.
- Go to highest possible energy.





CMS Supplementary
36.3 fb-1 (13 TeV)
pTjet: 97-220 GeV
pTjet: 220-330 GeV
pTjet: 330-468 GeV
pTjet: 468-638 GeV
pTjet: 638-846 GeV
pTjet: 846-1101 GeV
pTjet: 1101-1410 GeV
pTjet: 1410-1784 GeV
E3C/E2C
Ratio to NNLLapprox
xL
Data
NNLLapprox+NP αS(mZ)=0.118

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