Measurements of energy correlators inside jets and the determination of α_s

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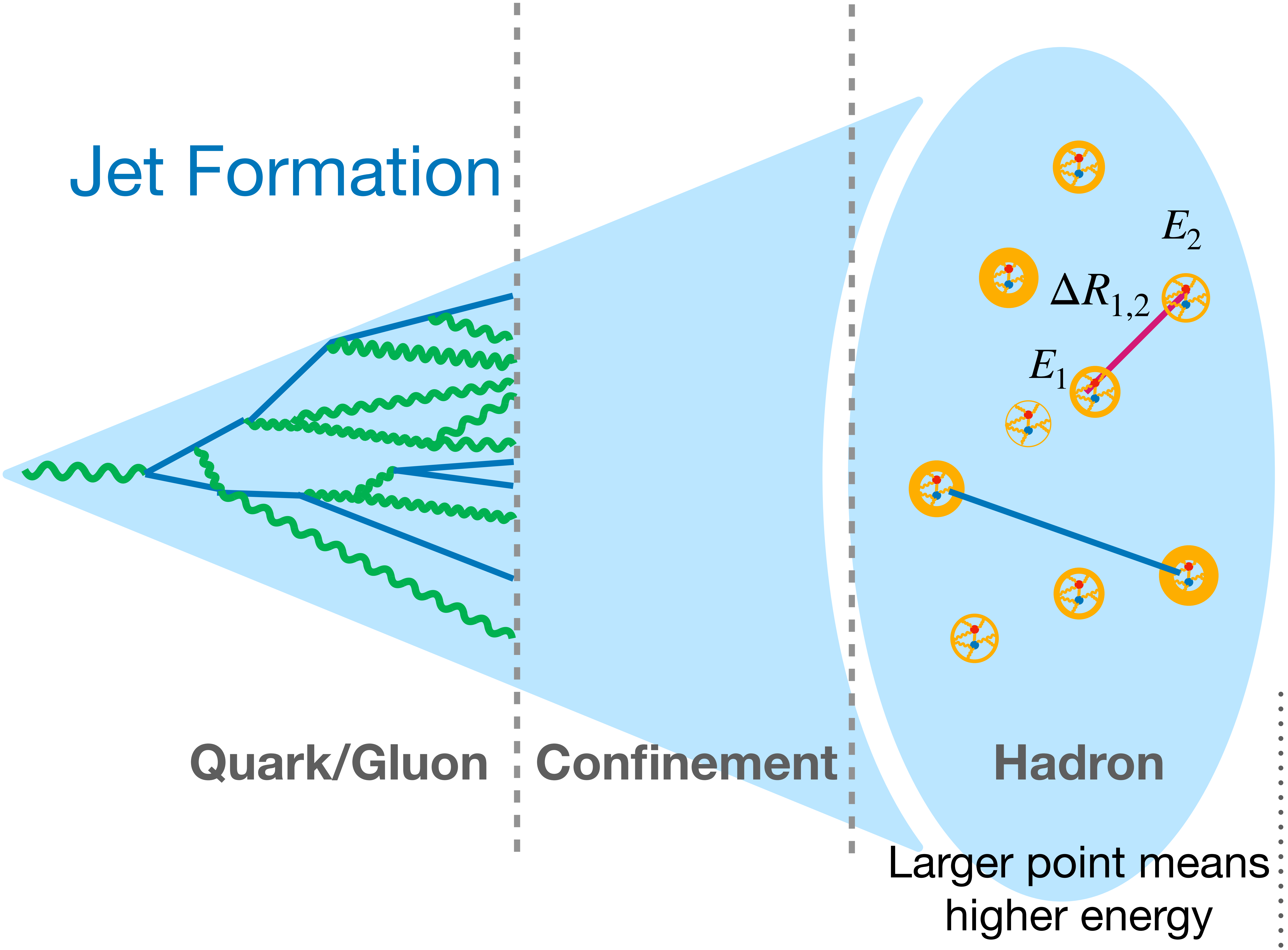
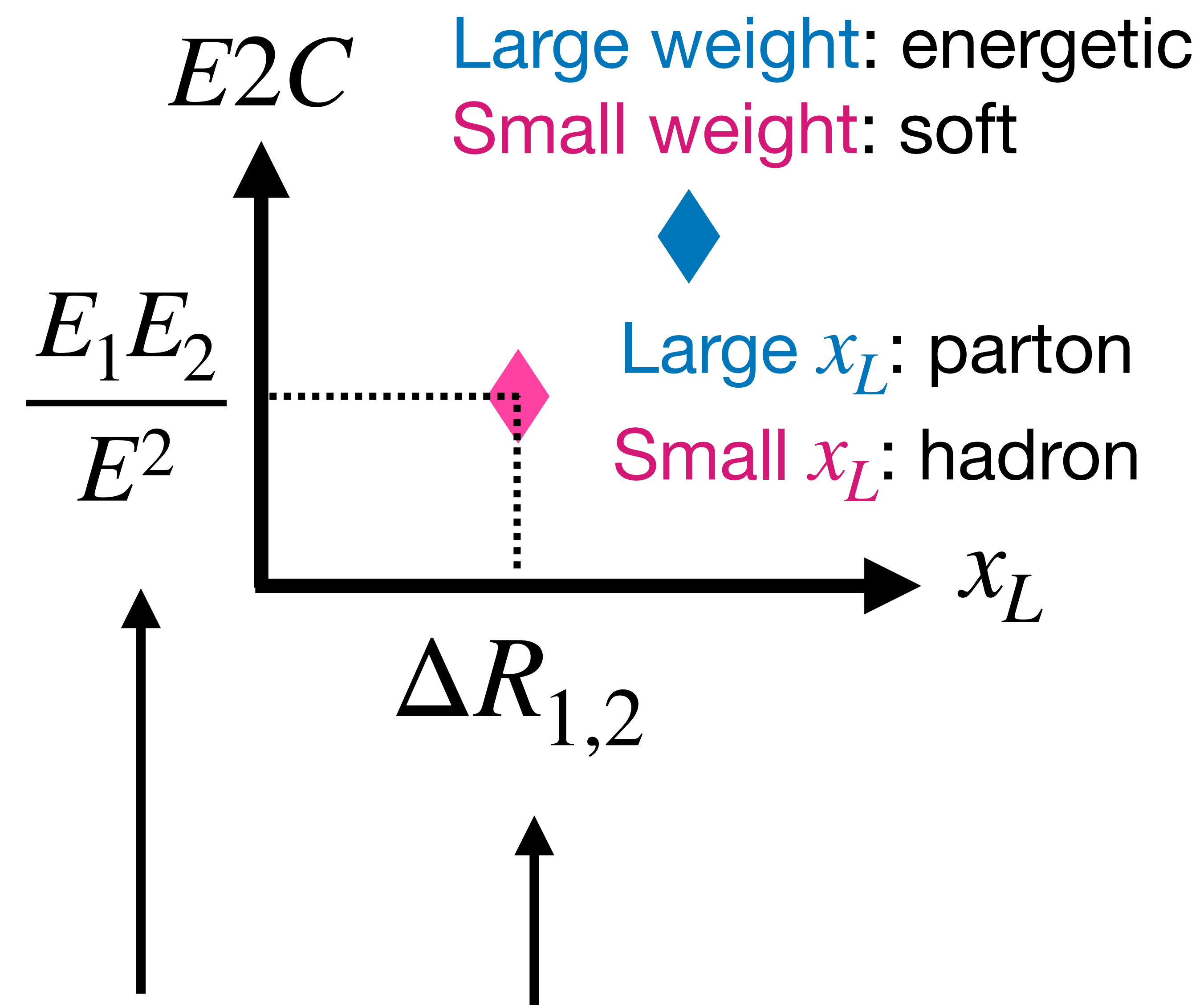
第十四届全国粒子物理学术会议, Aug 14, 2024

Energy correlators in jets: E2C





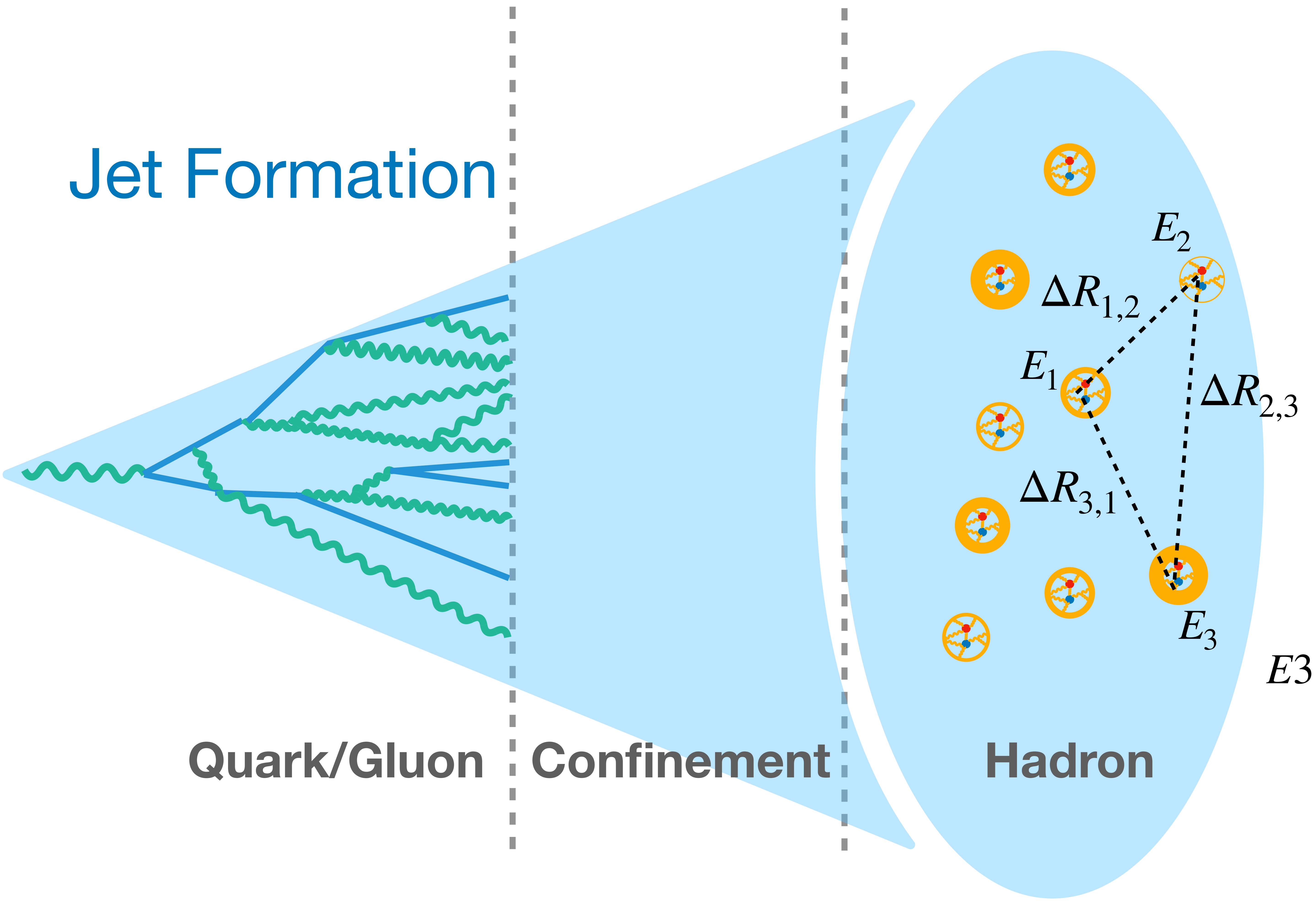
$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_iE_j}{E^2} \delta(x_L - \Delta R_{i,j})$$

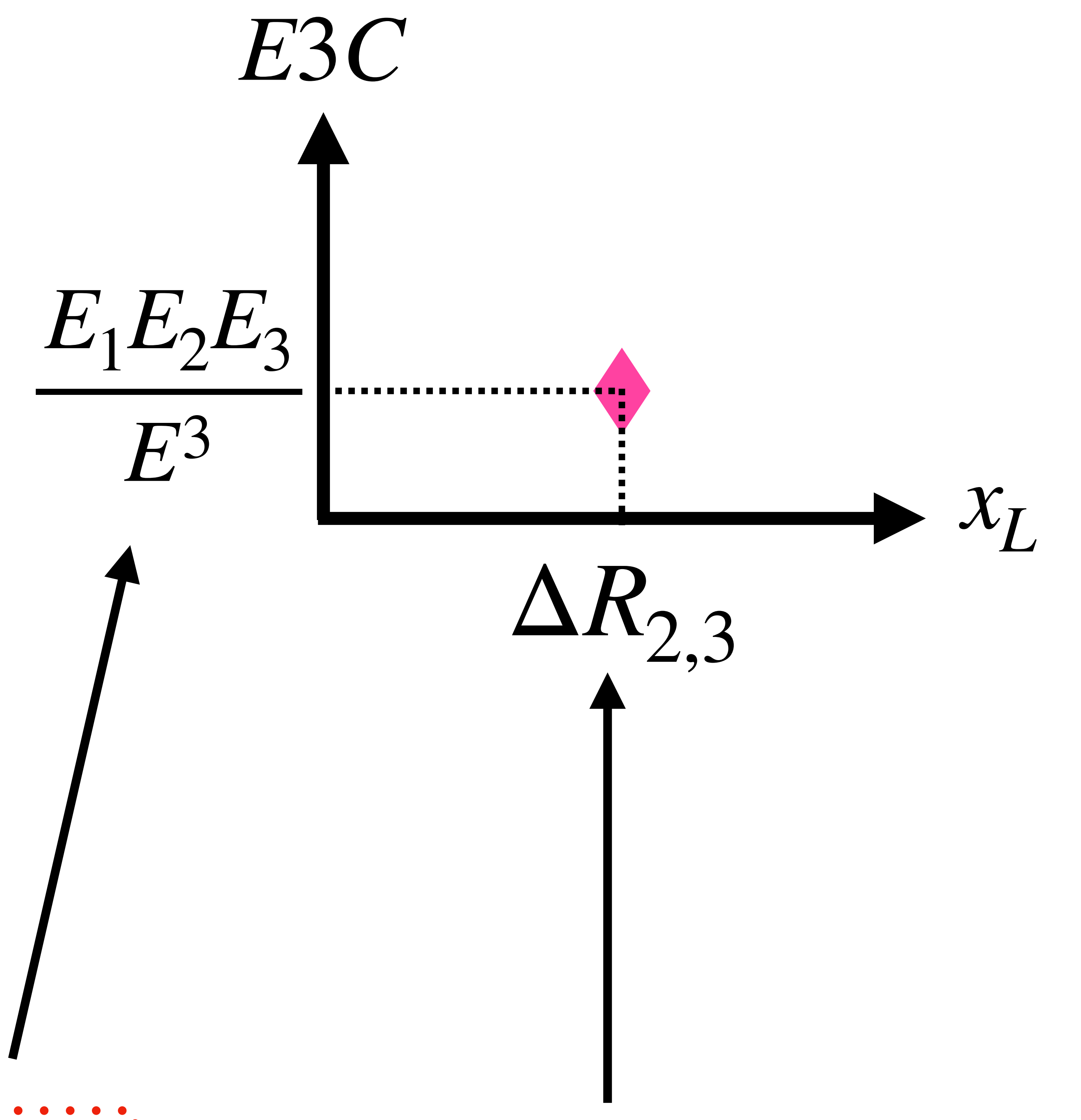
Initial proposal: Chen, Moult, Zhang, and Zhu, *arXiv:2004.11381*

NLO+NLL: Lee, Meçaj, and Moult, *arXiv:2205.03414*

NLO+NNLL$_{\text{approx}}$: Chen, Gao, Li, Xu, Zhang, and Zhu, *arXiv:2307.07510*

Energy correlators in jets: E3C





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

- Loop over all the particles in a jet
- Each jet have an E2C and E3C shape
- EnC in jet not measured before

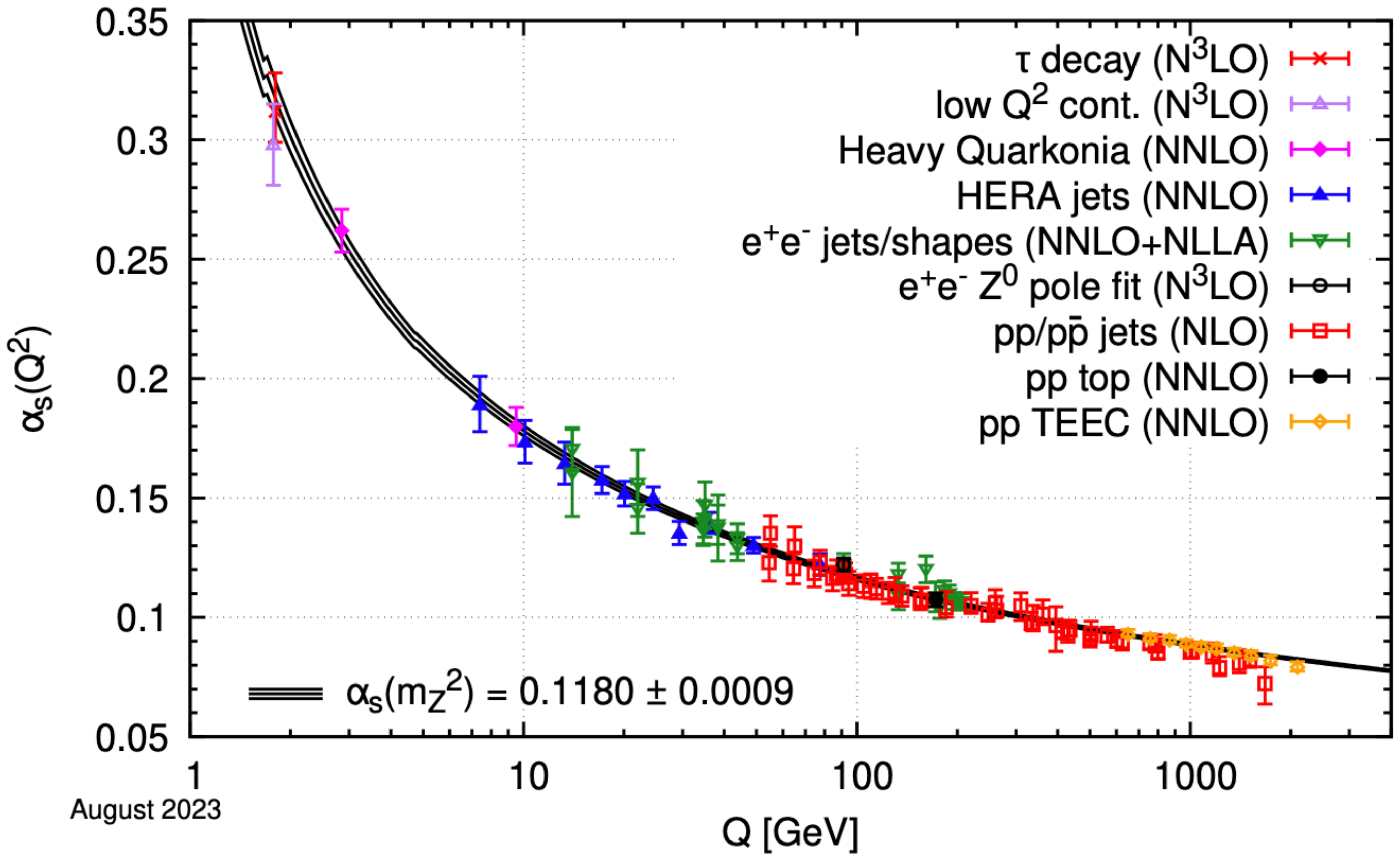
Energy correlator for α_S extraction

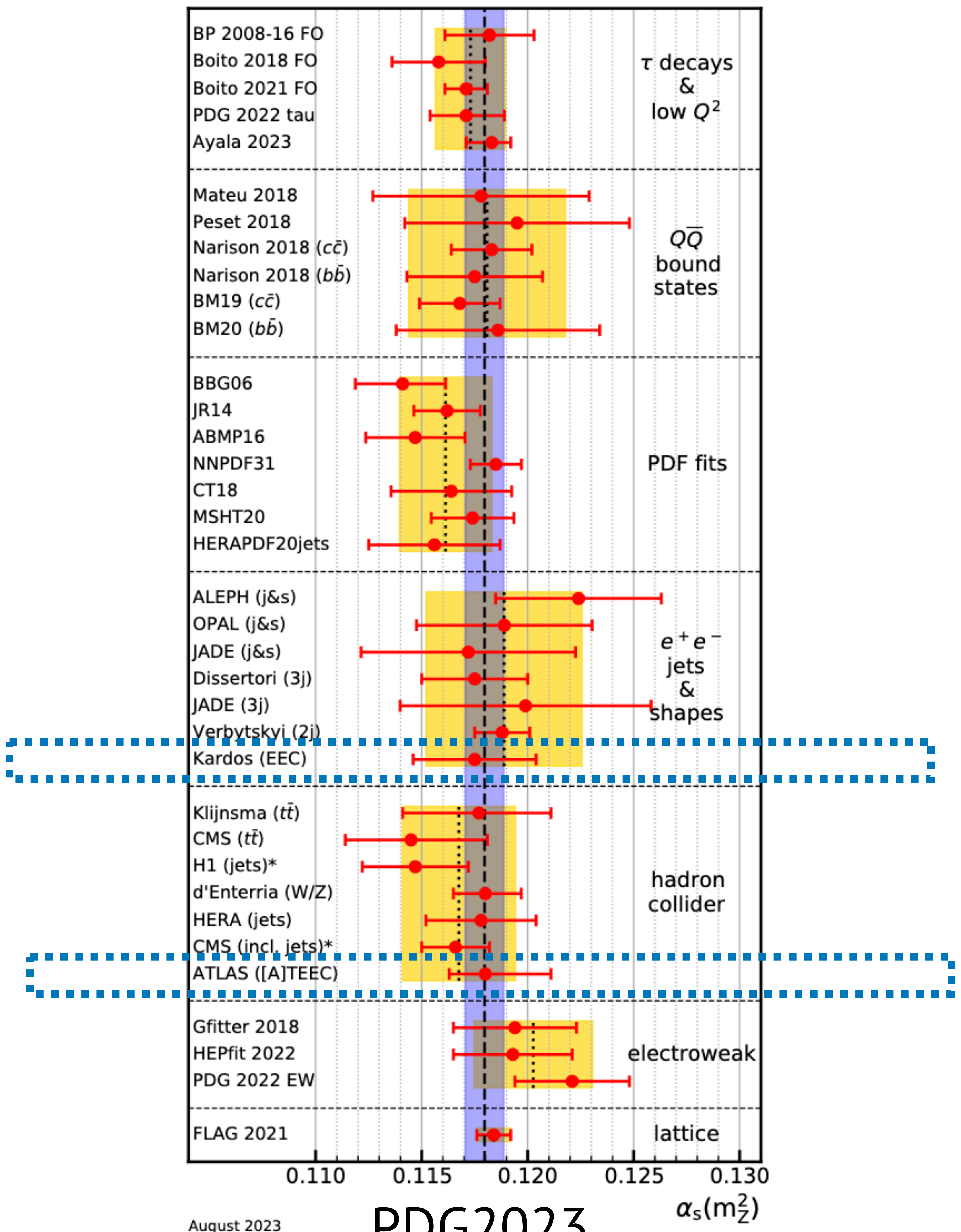
World average: $\alpha_S(m_Z) = 0.1180 \pm 0.0009$

Previous Extraction of α_s using Energy correlator:

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

Lack of extractions in low Q region





PDG2023

Motivation

- Study Jet Formation
  - Parton shower => Confinement => Final Hadrons
- Extract α_s
  - Complementary phase space, in collinear region
    - Typical energy scale: ~ $p_{\mathrm{T}}^{\mathrm{jet}} * x_L/5$, O(10 GeV)
  - High Precision calculation available: $\mathrm{NLO+NNLL_{approx}}$
- Observe asymptotic freedom
  - α_s running along energy scale

Analysis strategy

Events

QCD process, Central dijet region, only take the two leading jets

8 jet pT regions in 97 ~ 1784 GeV: probe the energy scale dependency

Neutral & charged particles with $p_T > 1$GeV: all particles included

Unfolding

Perform 3d unfolding up to particle level: p_T^{jet}, x_L, and energy weight w_{ij}

Uncertainty

Statistical correlation and systematic uncertainties

Extraction of α_S

Comparing unfolded E3C/E2C distributions to NLO+NNLL$_{\text{approx}}$ predictions

Datasets: Data & MC simulations

DATA (HIPM & no-HIPM)

- /JetHT/Run2016*-17Jul2018*/MINIAOD

SIMULATION (preVFP & postVFP)

To derive migration matrix and systematic uncertainties (PDF, QCD scales…)

- **Pythia8.240 (nominal):** /QCD_Pt_*_TuneCP5_13TeV_pythia8/RunIISummer20UL16MiniAOD*/MINIAODSIM
- **MadGraph5+Pythia8:** /QCD_HT*_TuneCP5_PSWeights_13TeV-madgraphMLM-pythia8/RunIISummer20UL16MiniAOD*/MINIAODSIM
- **Herwig7.1.4:** /QCD_Pt-15to7000_TuneCH3_Flat_13TeV_herwig7/RunIISummer19UL16MiniAOD*-106X*/MINIAODSIM
- **MadGraph5+Herwig7:** /QCD_HT*_TuneCH3_13TeV-madgraphMLM-herwig7/RunIISummer20UL16MiniAOD*/MINIAODSIM

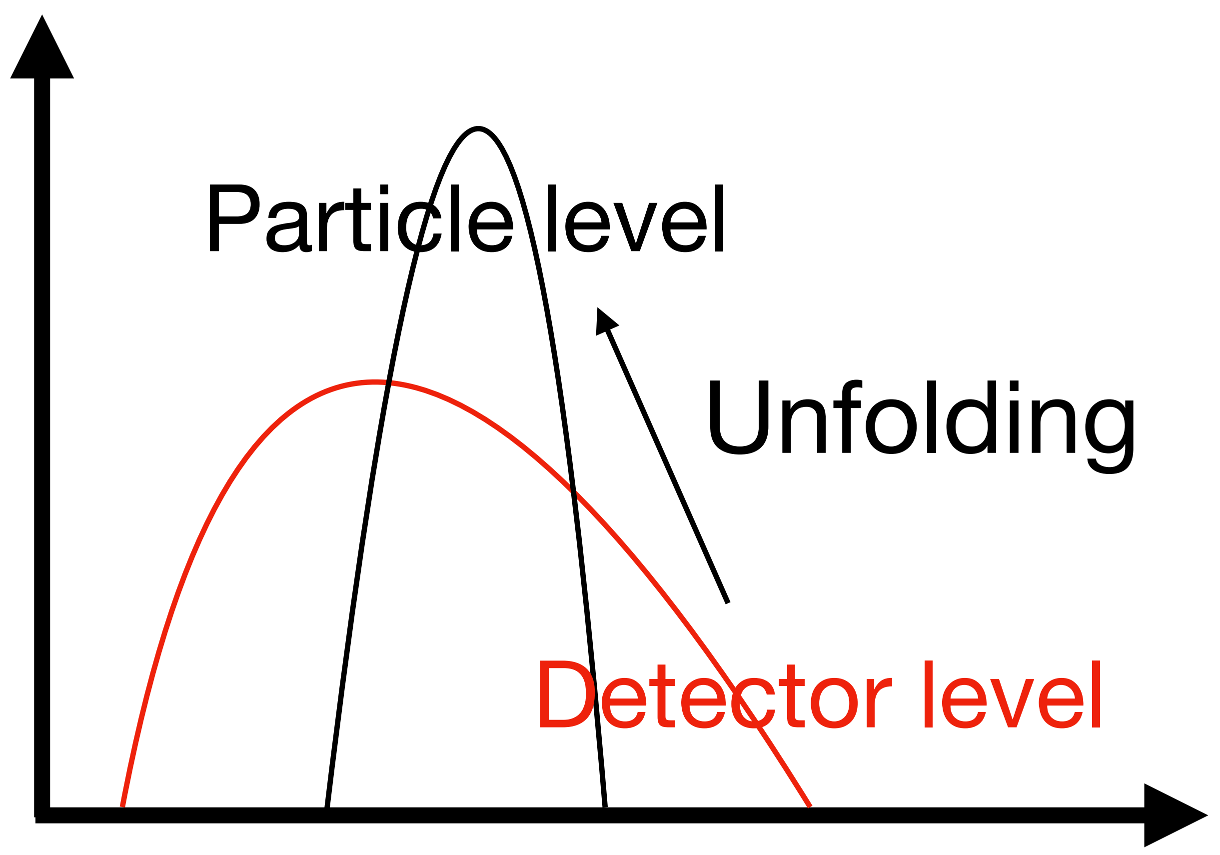
E2C & E3C : constituents unfolding

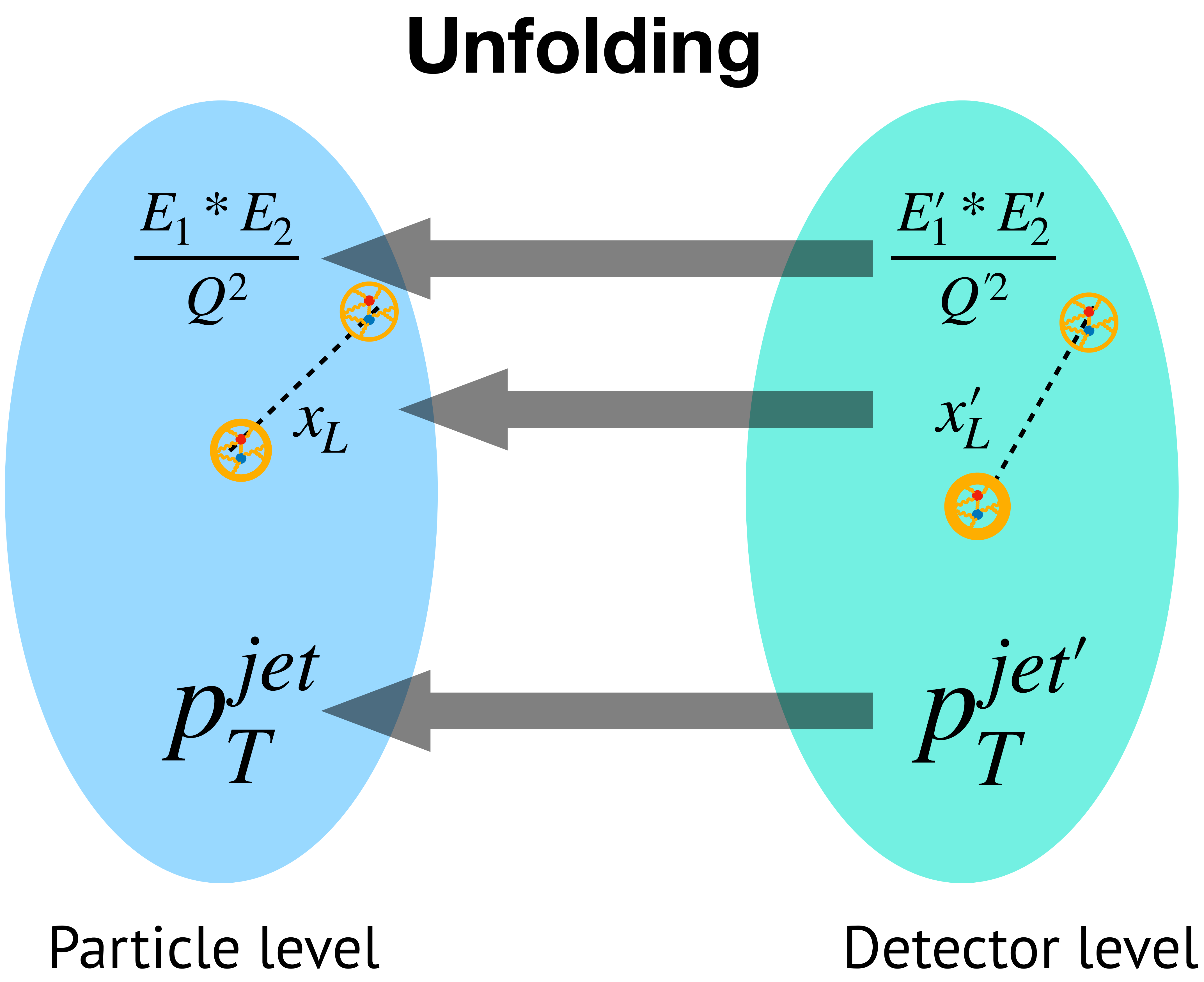
Unfolding: detector level -> particle level

Unfold jet constituents instead of distribution:

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

•D'Agostini: iterative bayesian



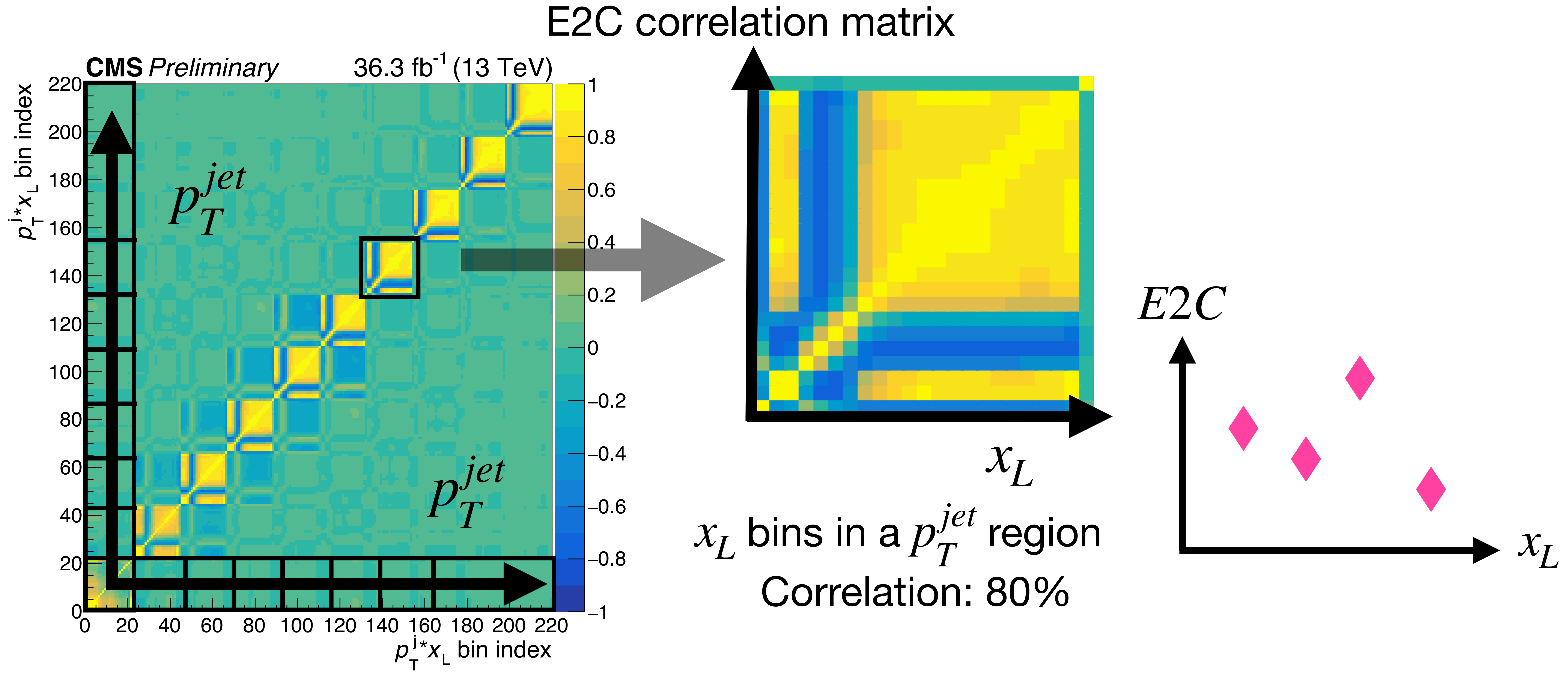


E2C & E3C : statistical correlation

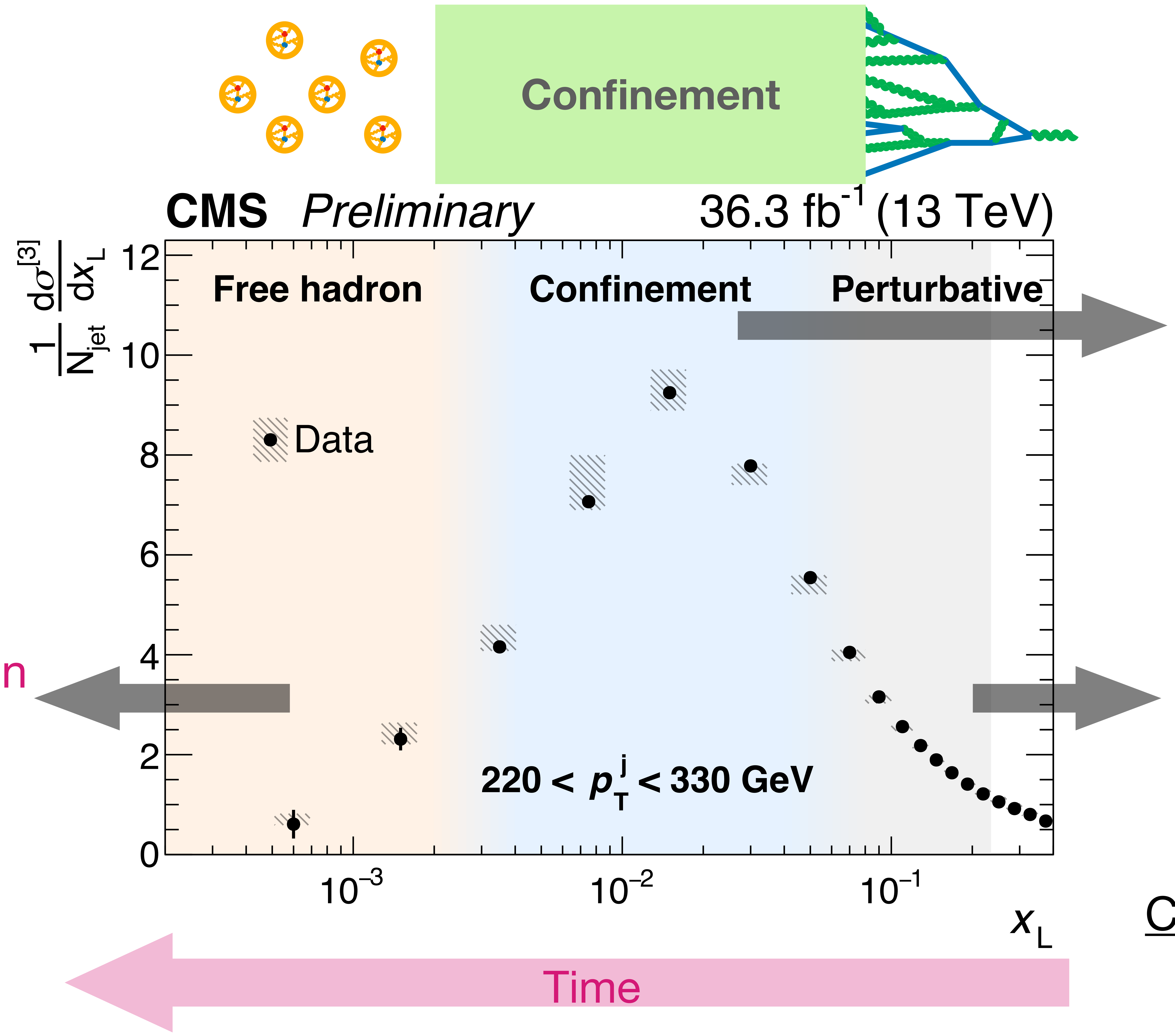
Multi entry distribution for every jet, two jets in an event and normalization requirement

Detector level => Unfolding => Normalization

Use independent statistics for E2C,E3C to avoid further correlation



E3C measurement



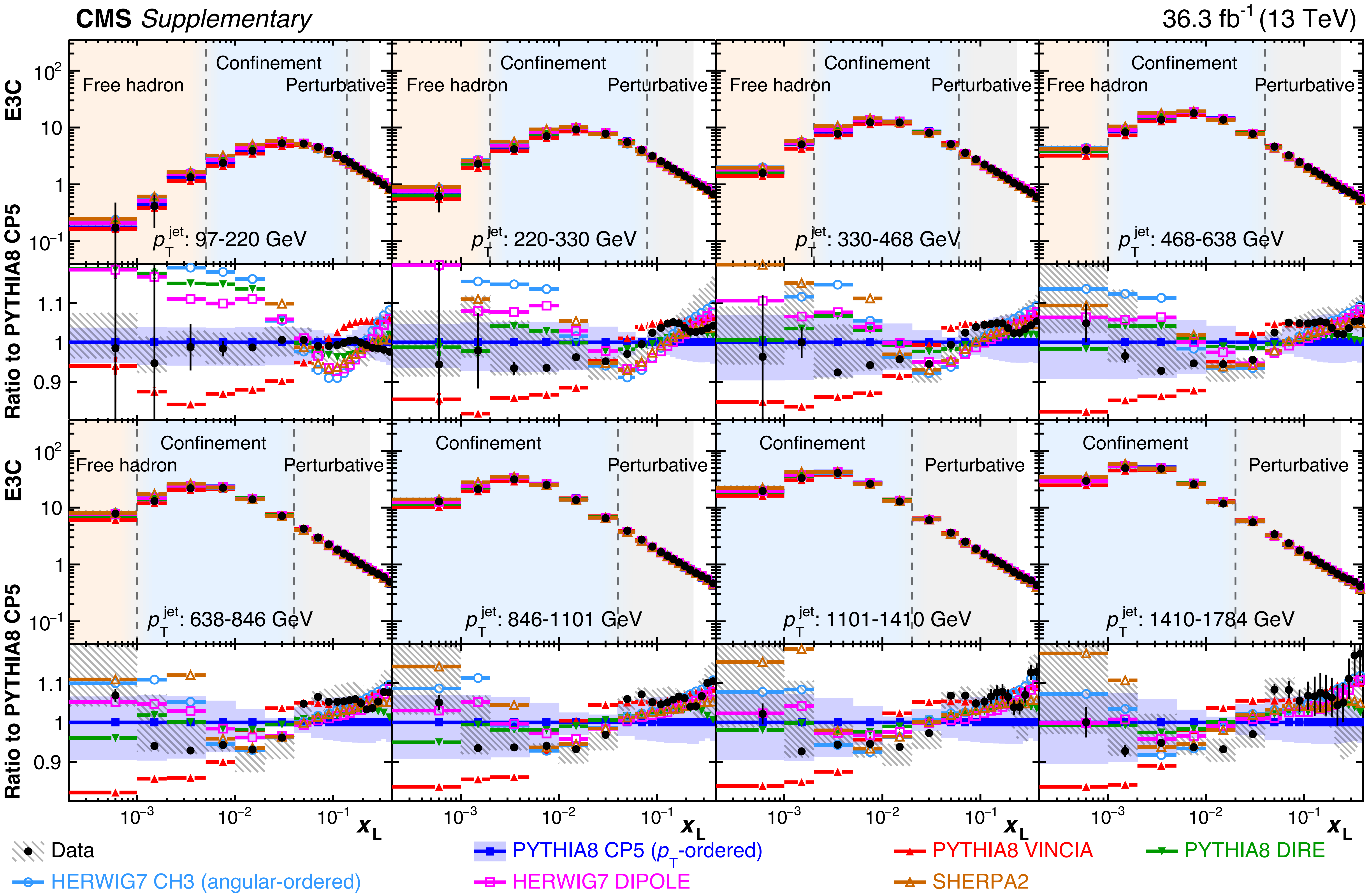
Phase transition
from parton to hadron

Non-interacting hadron
Rising scaling

Interacting partons
Falling scaling

arXiv:2402.13864
CMS-PAS-SMP-22-015

Unfolded E3C vs MC

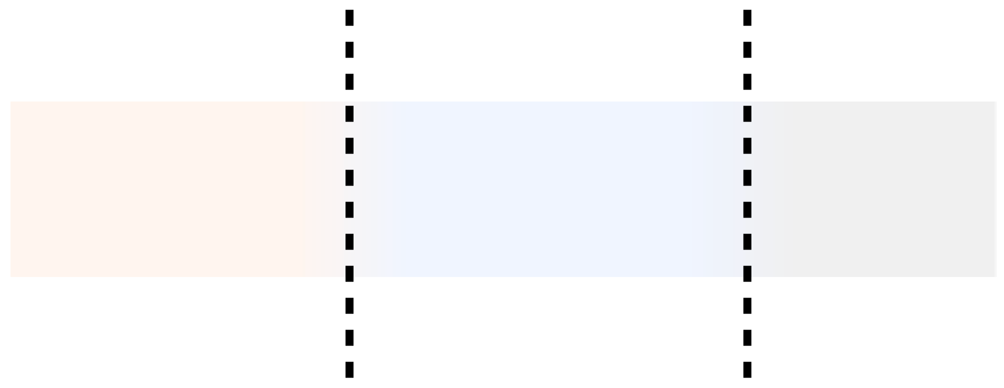


Boundaries shift with jet pT

$$Q \propto x_L{}^* p_T^{jet}$$

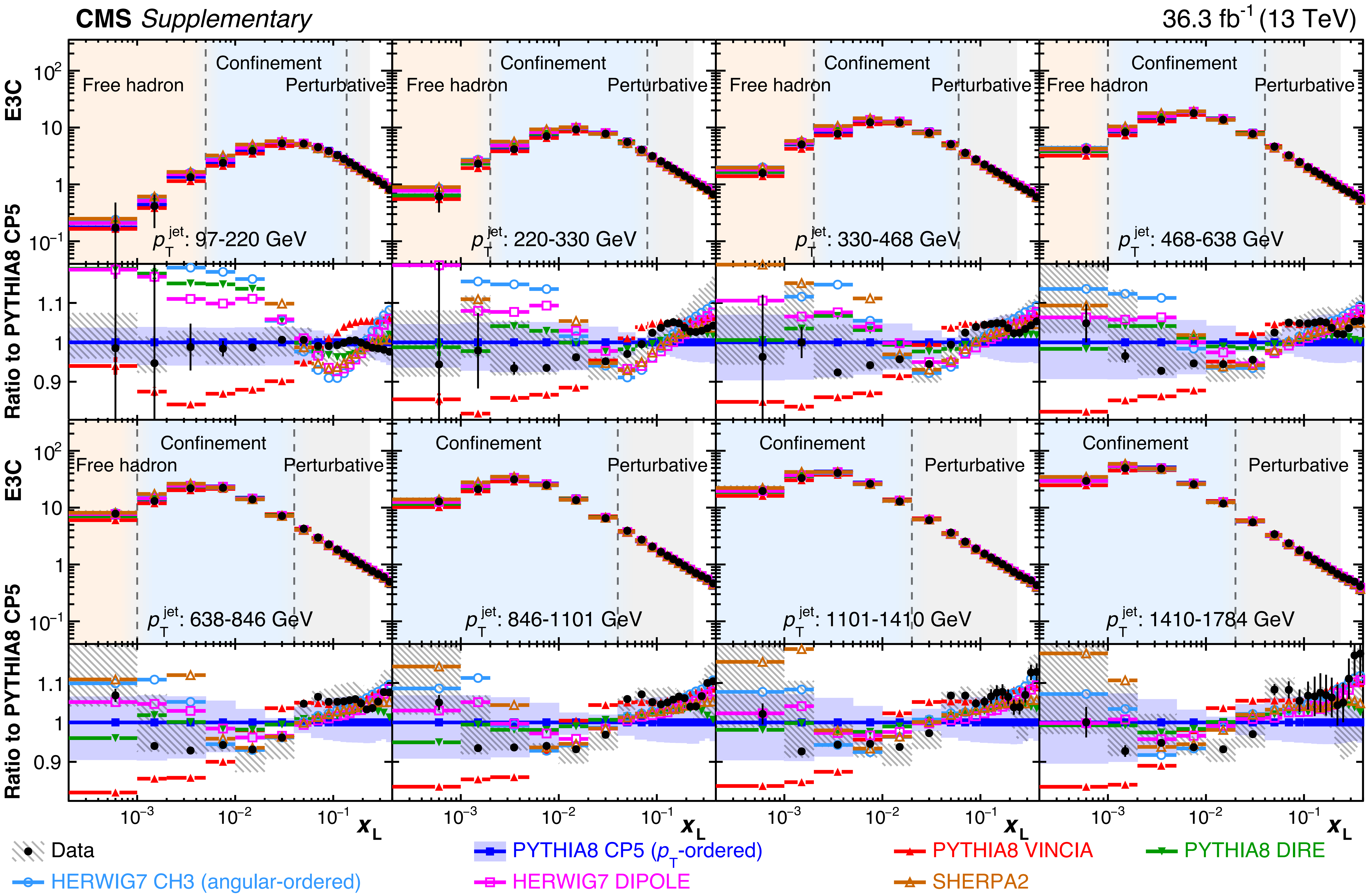
$$p_T^{jet} \uparrow, \; x_L \downarrow$$

Boundary



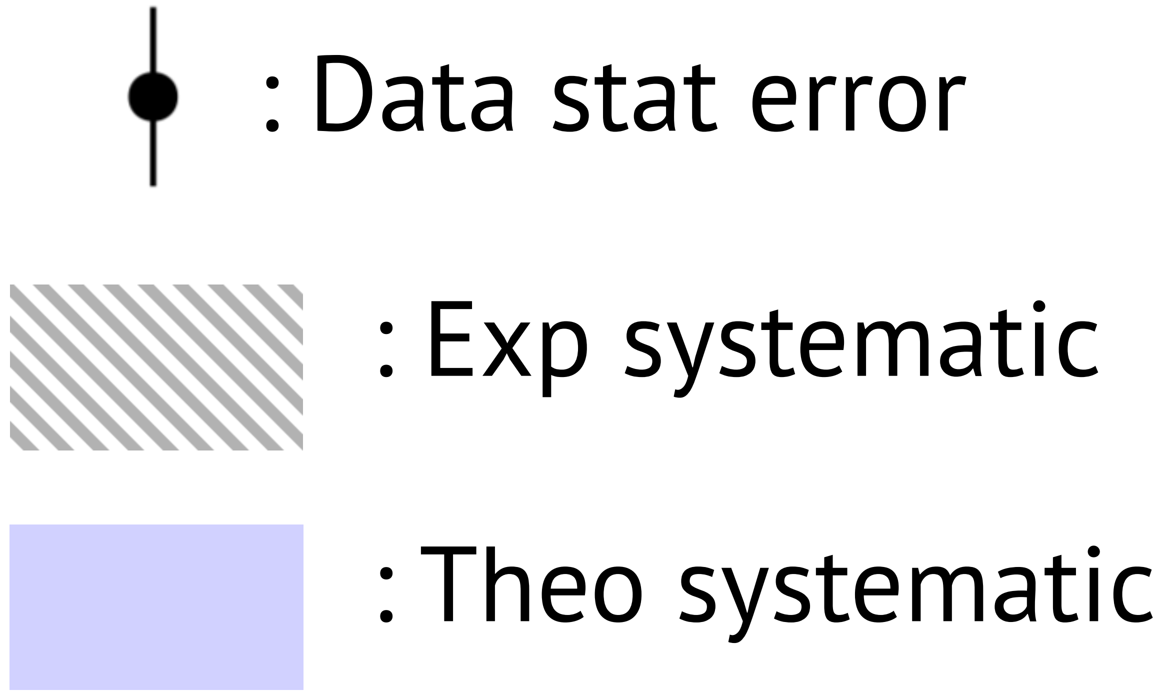
$$x_L \approx \frac{0.8}{p_T^{jet}} \qquad x_L \approx \frac{20}{p_T^{jet}}$$

Unfolded E3C vs MC

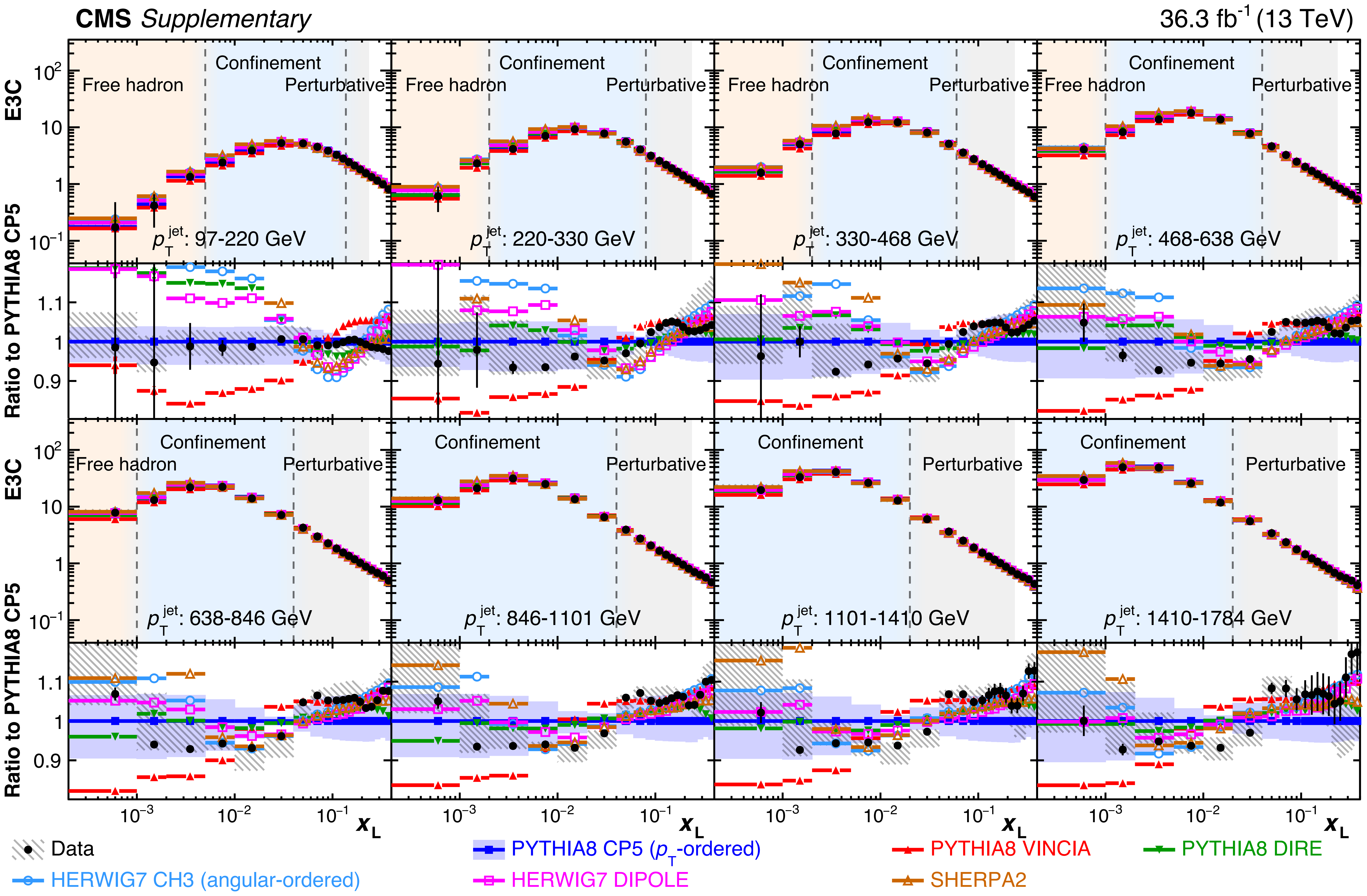


Data vs various parton shower model, difference ~ 10%

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



Unfolded E3C vs MC



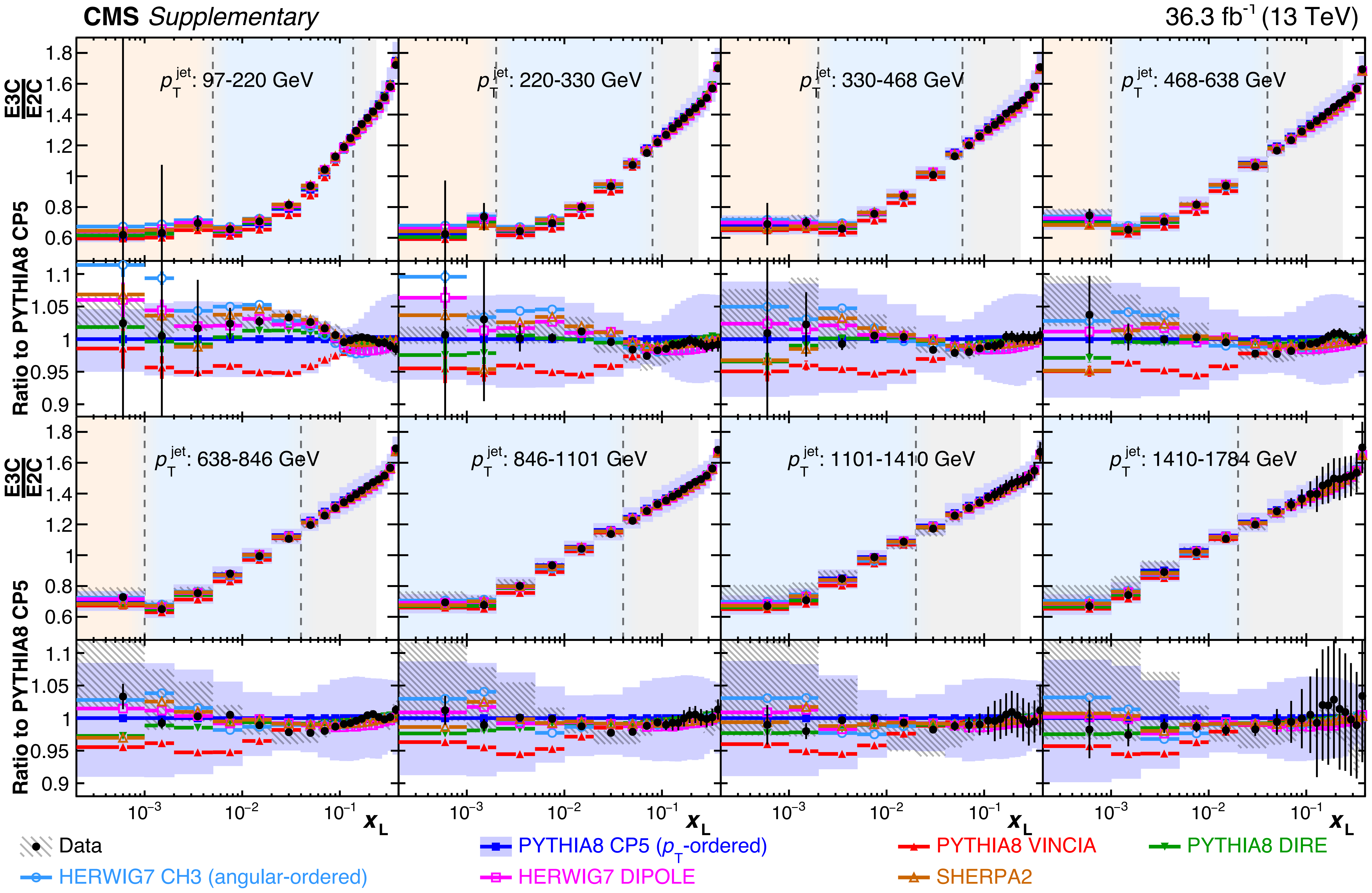
Exp sys:

- Unfolding model: Pythia, Herwig, MG+Pythia, MG+Herwig
- Neutral, photon, charged particle energy scale
- Jet energy scale, jet energy resolution
- Pileup, tracking efficiency, trigger inefficiency (prefiring)

Theo sys:

- QCD scale in parton shower
- QCD scale in hard scattering
- Underlying event + parton shower tune
- PDF

Unfolded E3C/E2C vs MC



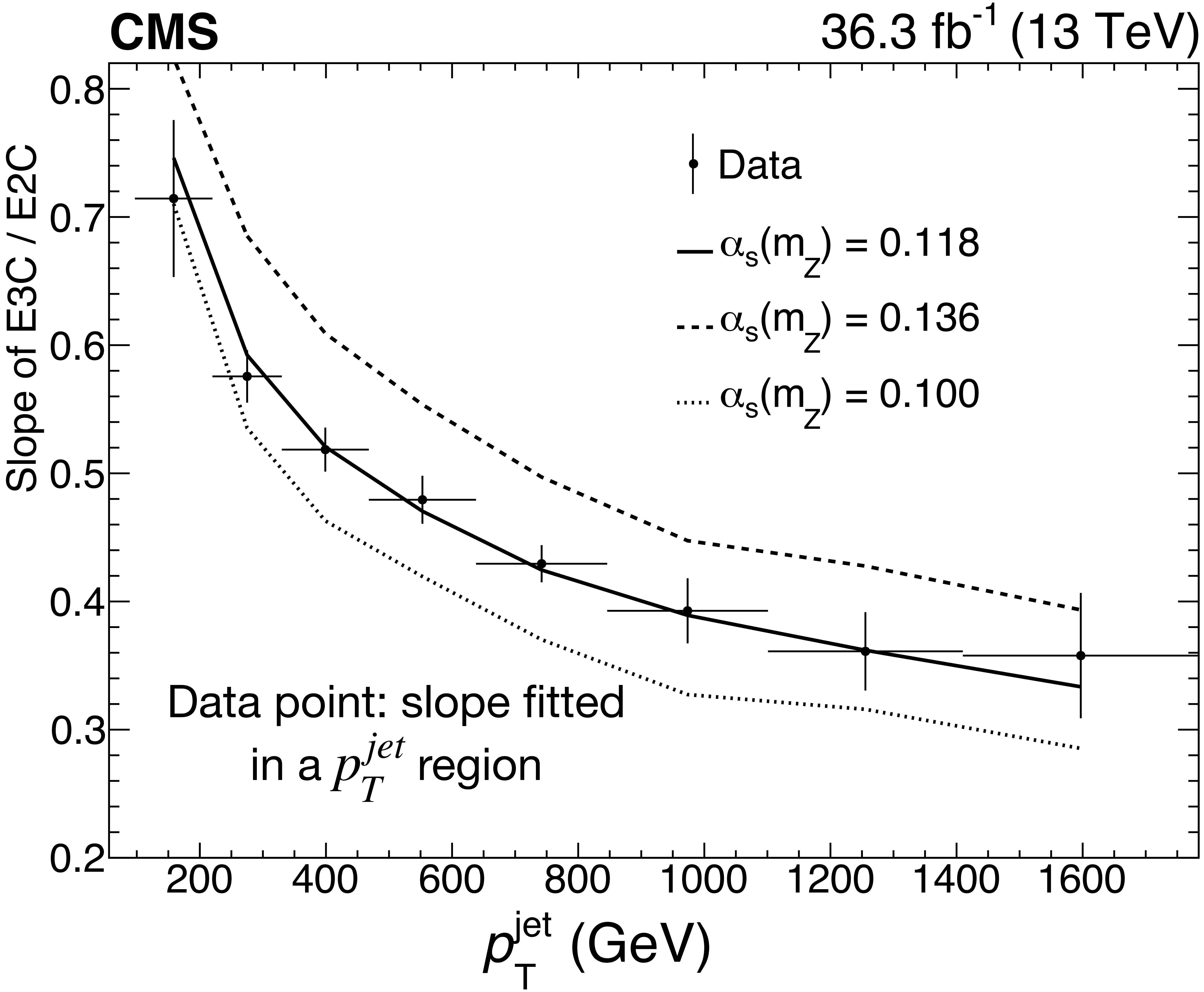
Benefit of taking ratio

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

All models agree well

$p_T^{jet}\uparrow$, Slope $\downarrow$

Direct observation of asymptotic freedom



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

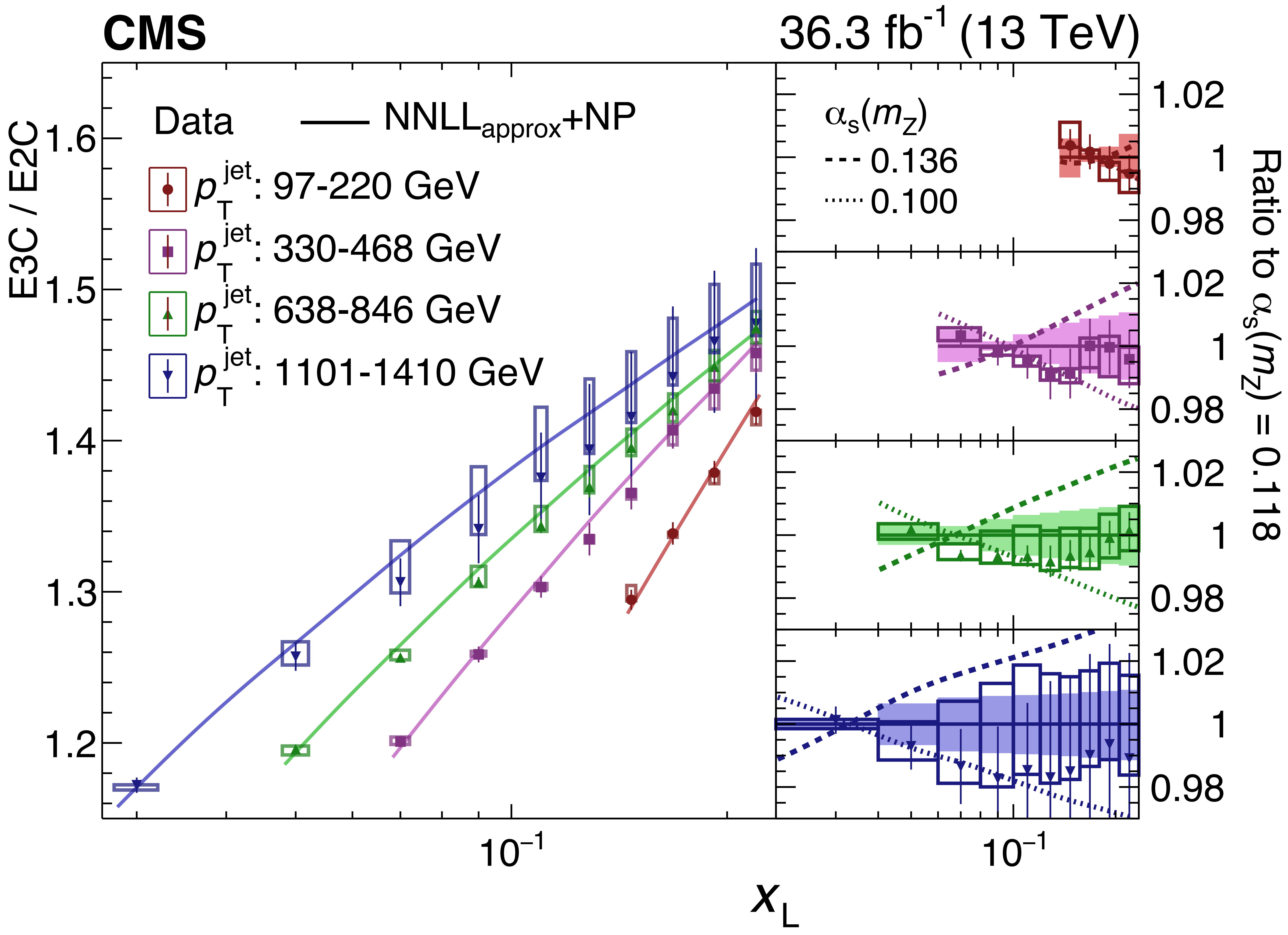
Slope $\downarrow \; \alpha_s(Q) \downarrow$

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

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

Chen, Gao, Li, Xu, Zhang, and Zhu,

arXiv:2307.07510



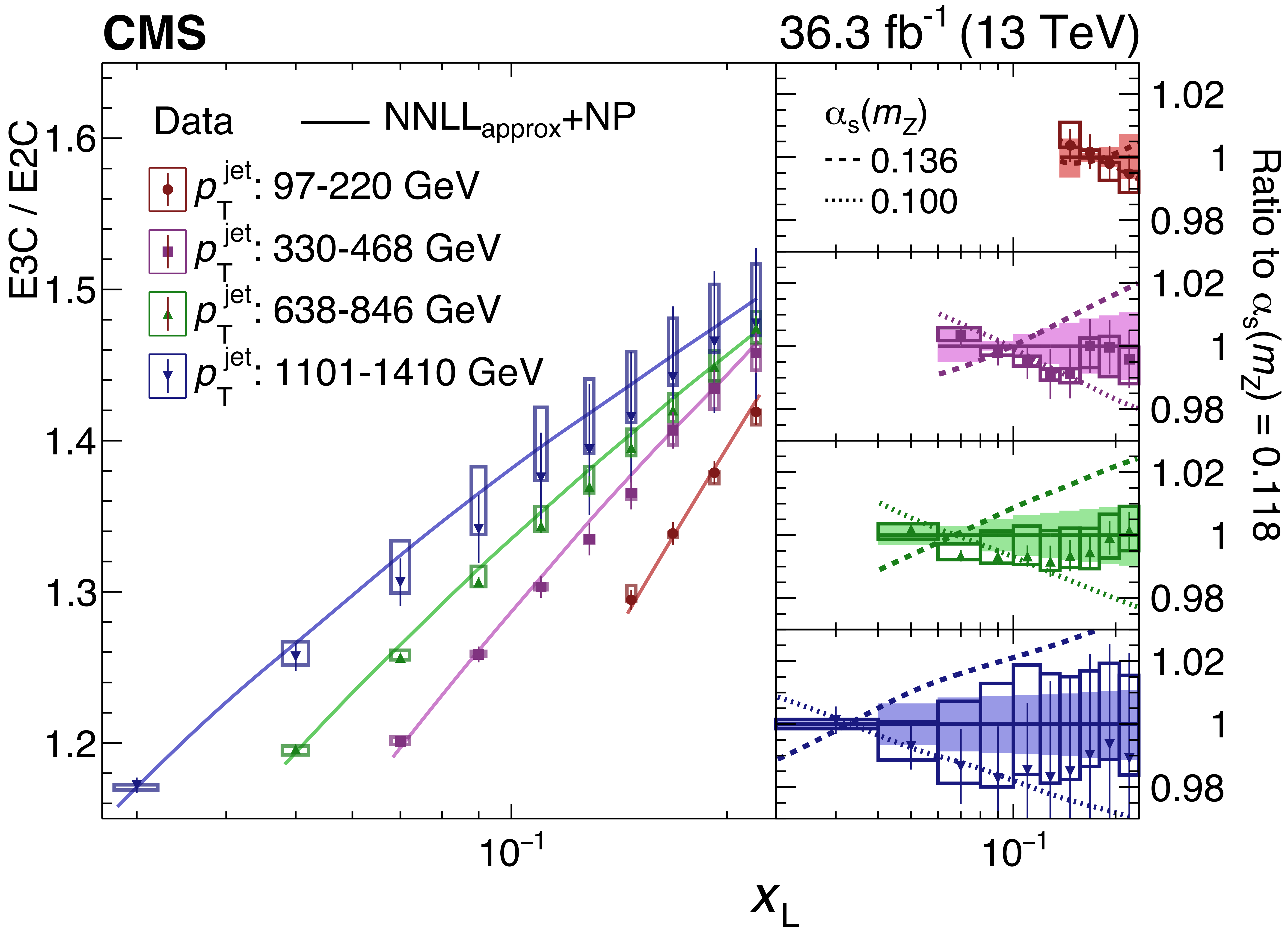
Analytical predictions

- NNLL$_{approx}$: Parton level E3C/E2C
  - 2nd order hard function approximation
- Same phase space as the analysis

Hadronization factors

- Bin by bin factor
  - average of Pythia&Herwig
- E2C, E3C: 5 - 35%
- E3C/E2C: 2%

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



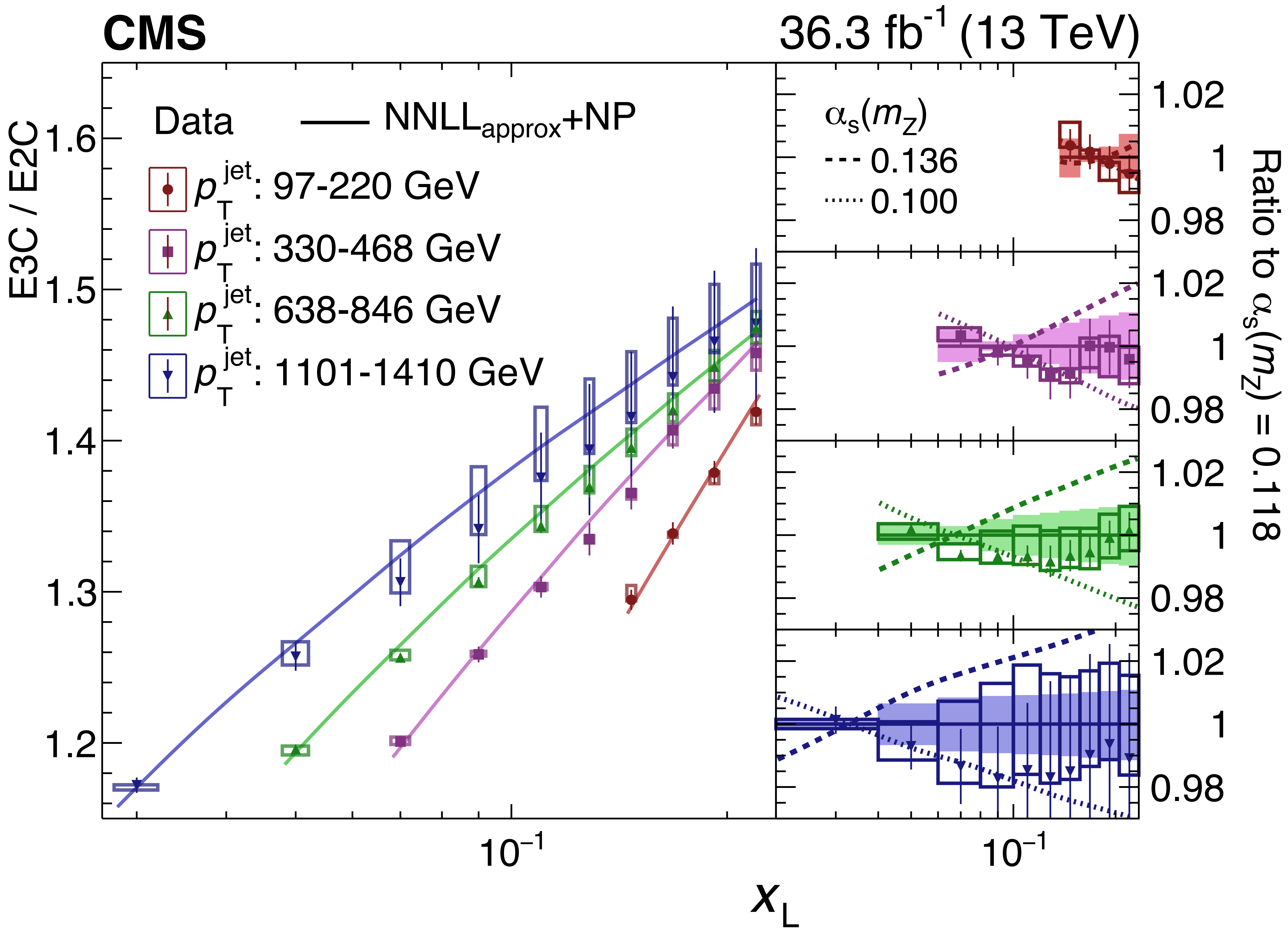
Shape of data agrees with NNLL$_{approx}$ prediction within uncertainty

Theo sys:

(shape only， no normalization effect)

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

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

Covariance matrix

QCD scale of NNLL$_{approx}$

Neutral hadron energy scale

Uncertainty ~ 4%,
most precise from jet-substructure to date

Summary

- Energy Correlators provide new ways to understand the jet formation
  - Color confinement
  - Asymptotic freedom
- 4% precision of α_S, the most precise using jet substructure to date