Determination of α_S from energy correlators in jets at CMS

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on behalf of CMS Collaboration
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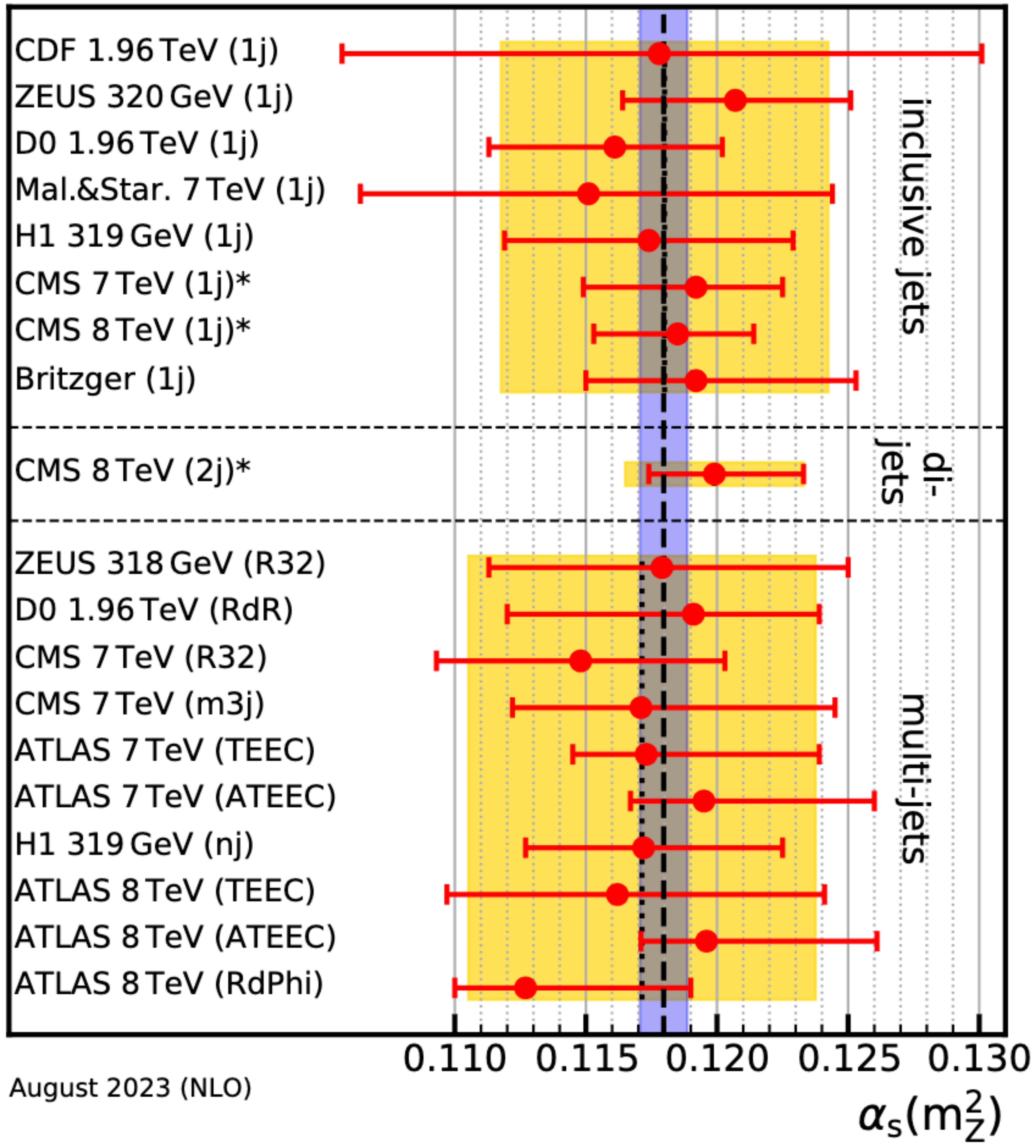
Introduction

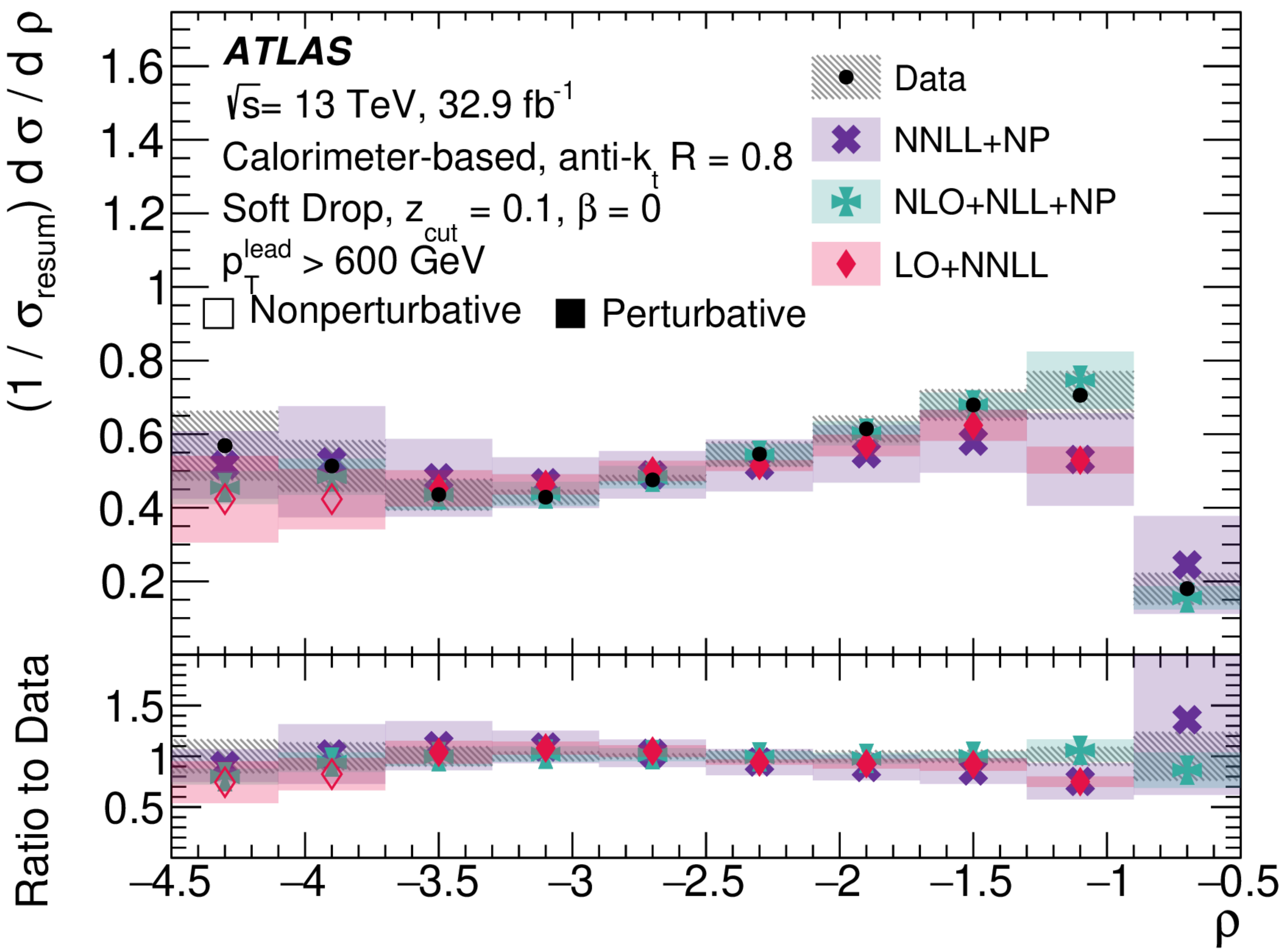


PDG 2023, Summary of α_S extraction using jets

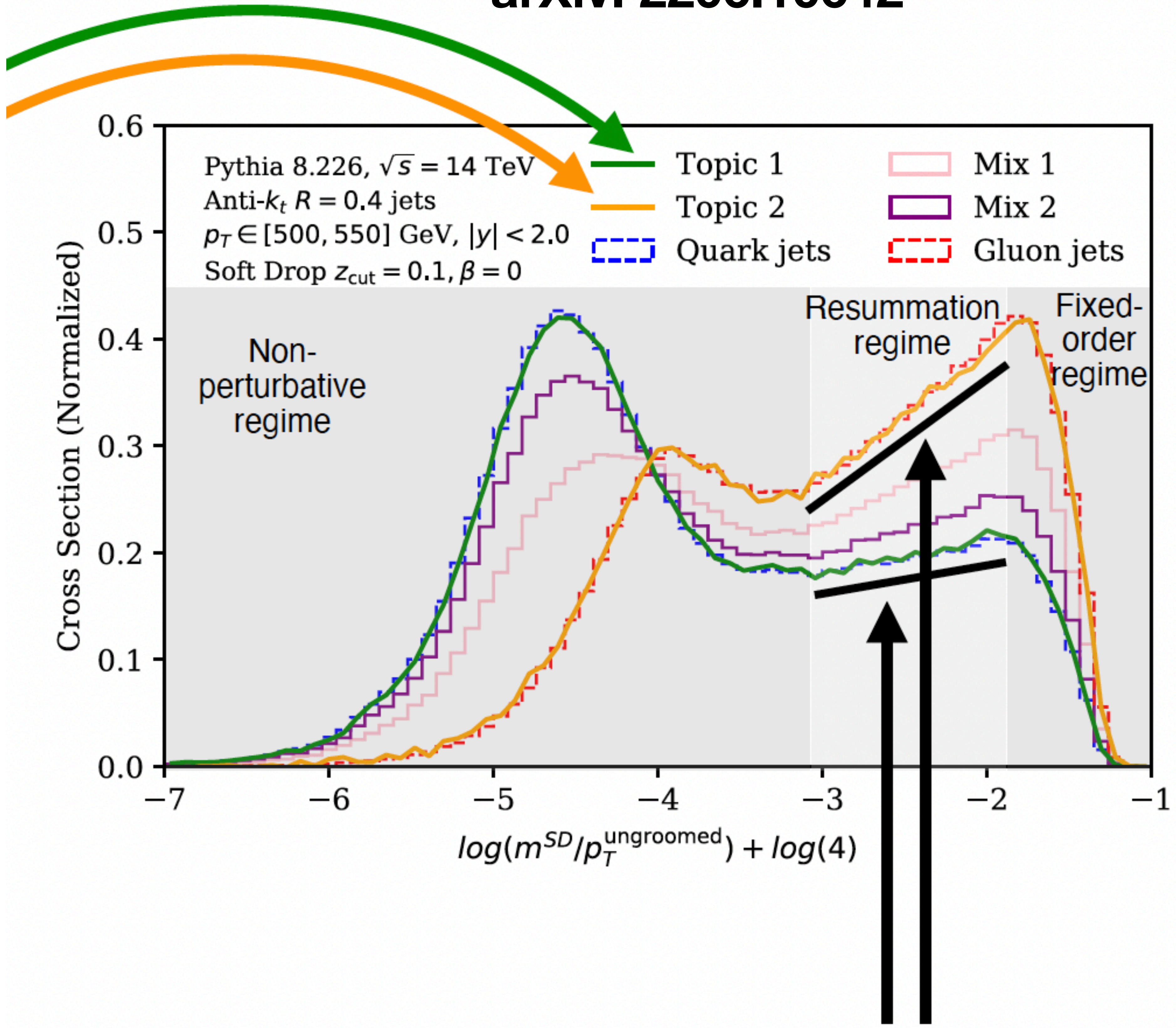
- Jet as a single object is widely used to extract α_S
- Jet substructure (JSS): extensively studied at the LHC
- High precision calculation possible these year
    - Soft-drop mass (LO+NNLL), energy correlators (NLO+NNLL$_{\text{approx}}$)
- Discussion on determining α_S from JSS
    - Les Houches 2017, arXiv: 1803.07977
    - Complementary phase space, in collinear region

Example of α_S extraction from JSS: soft drop mass

PhysRevD.101.052007



arXiv: 2206.10642

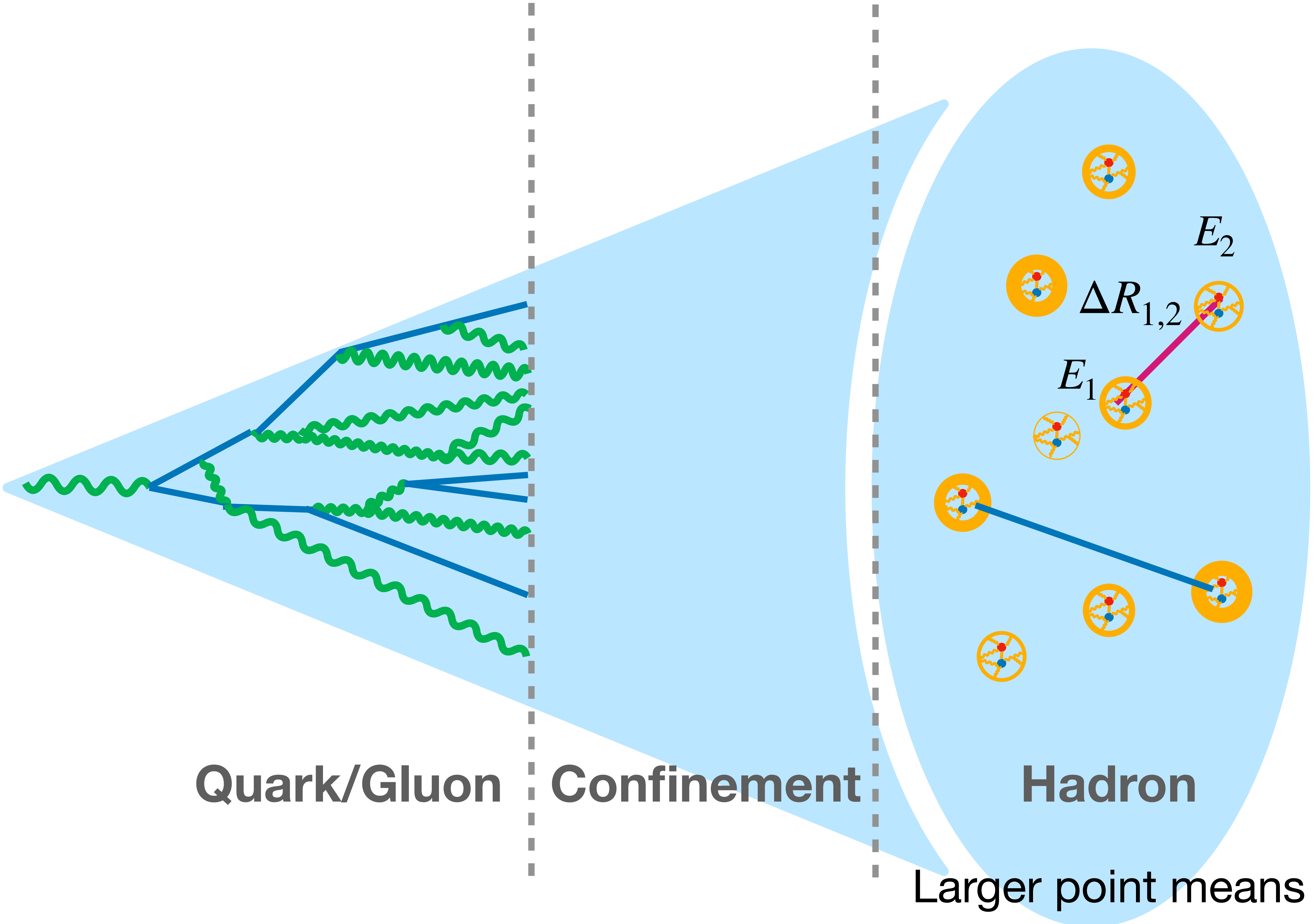


Step 2: Fit for α_S in another observable

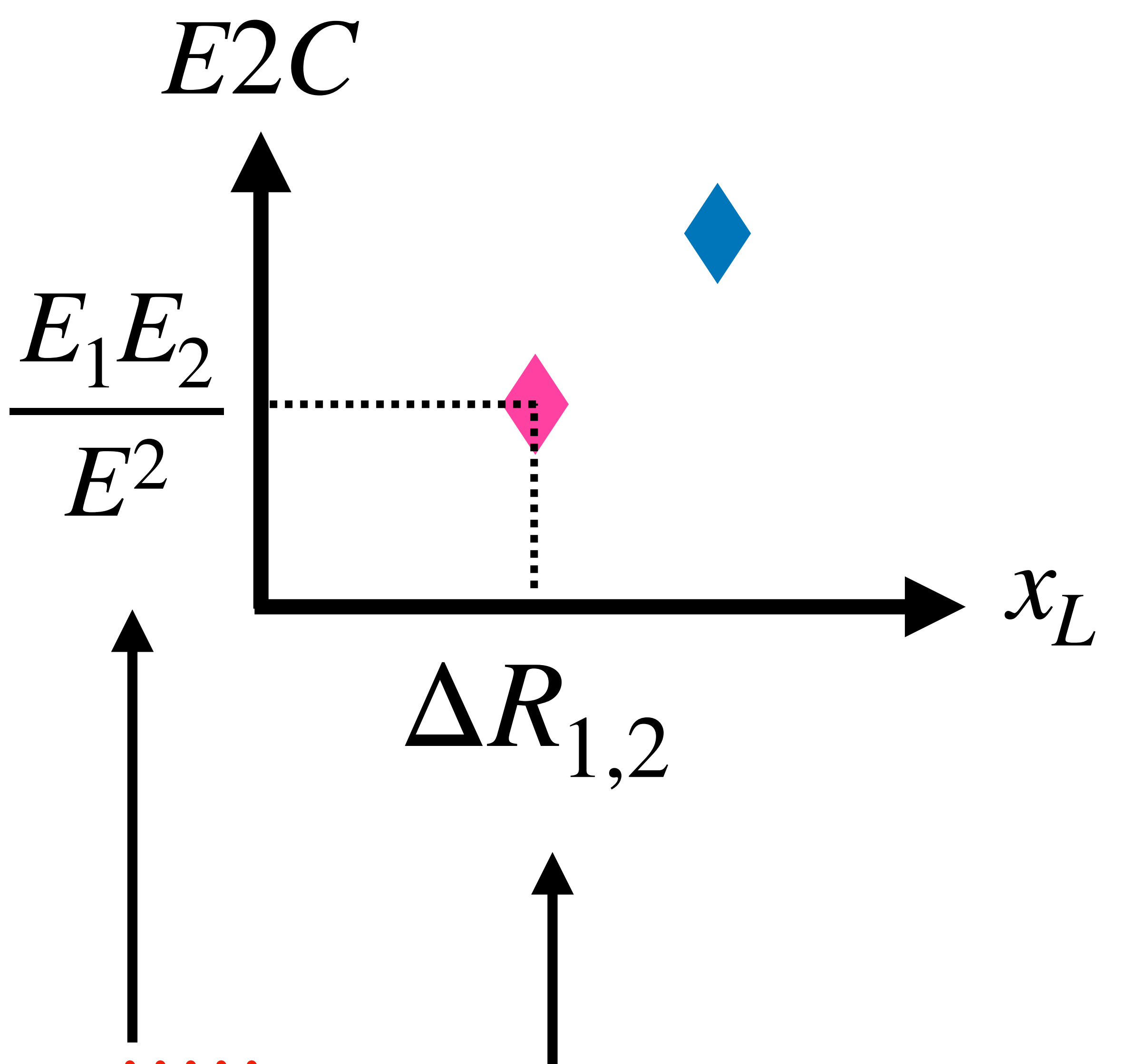
Slope ~ $\alpha_S C_i$ @ LL
q/g fraction needed

Estimated α_S precision from soft-drop mass: ~10%
Limiting factors: precise quark gluon composition (PDFs) and JES
Solutions were proposed: fit the q-g composition from data

Energy correlators: E2C



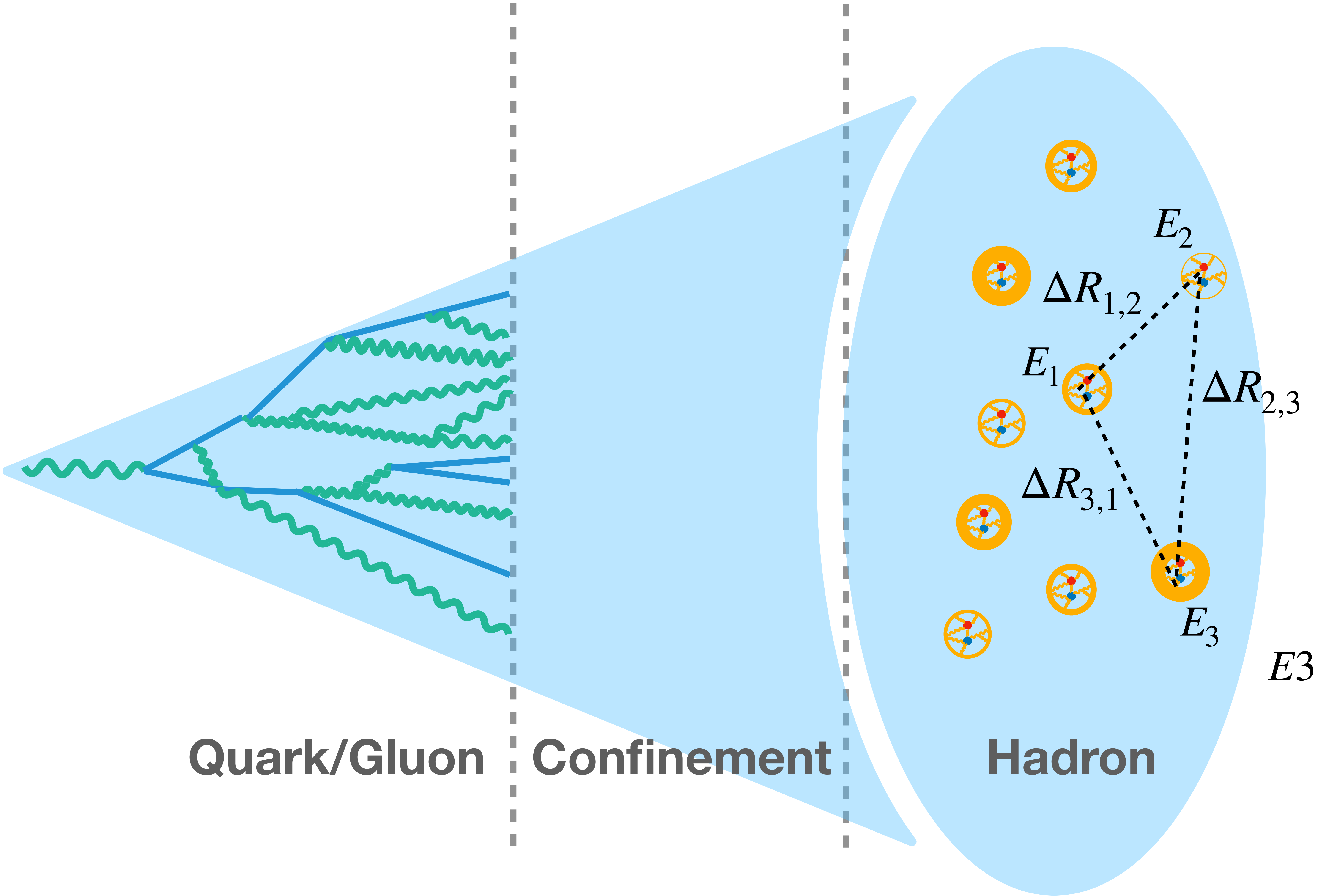
Larger point means higher energy

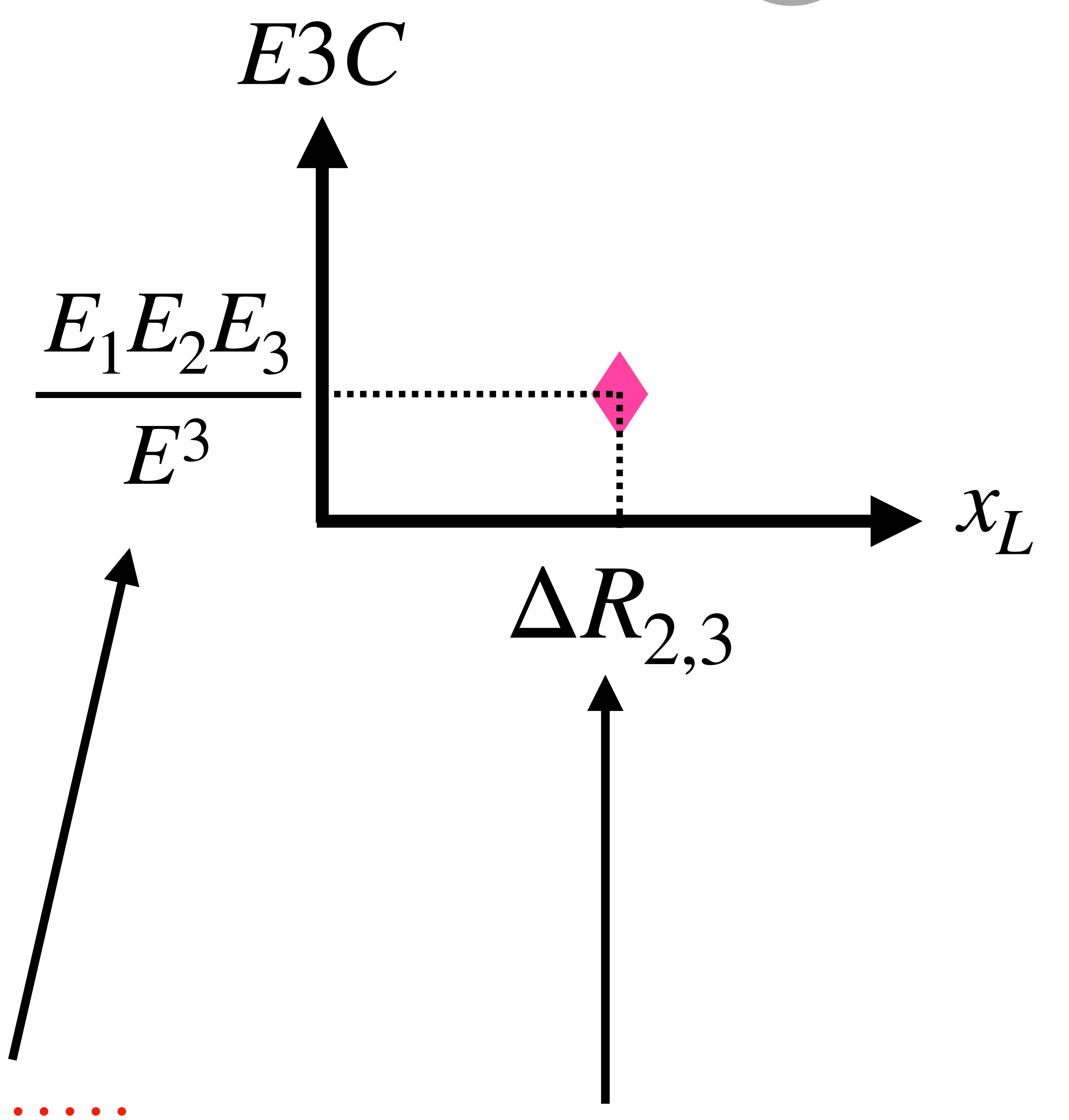


$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \boxed{\frac{E_iE_j}{E^2}} \delta(x_L - \Delta R_{i,j})$$

Collinear and infrared safe => calculable

Energy correlators: E3C





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

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*

E3C/E2C: a new way to extract α_S

@LL, both E3C and E2C depend on

$$c_0 + c_1\alpha_S \ln x_L + O(c_2\alpha_S^2 \ln^2 x_L) + \ldots$$

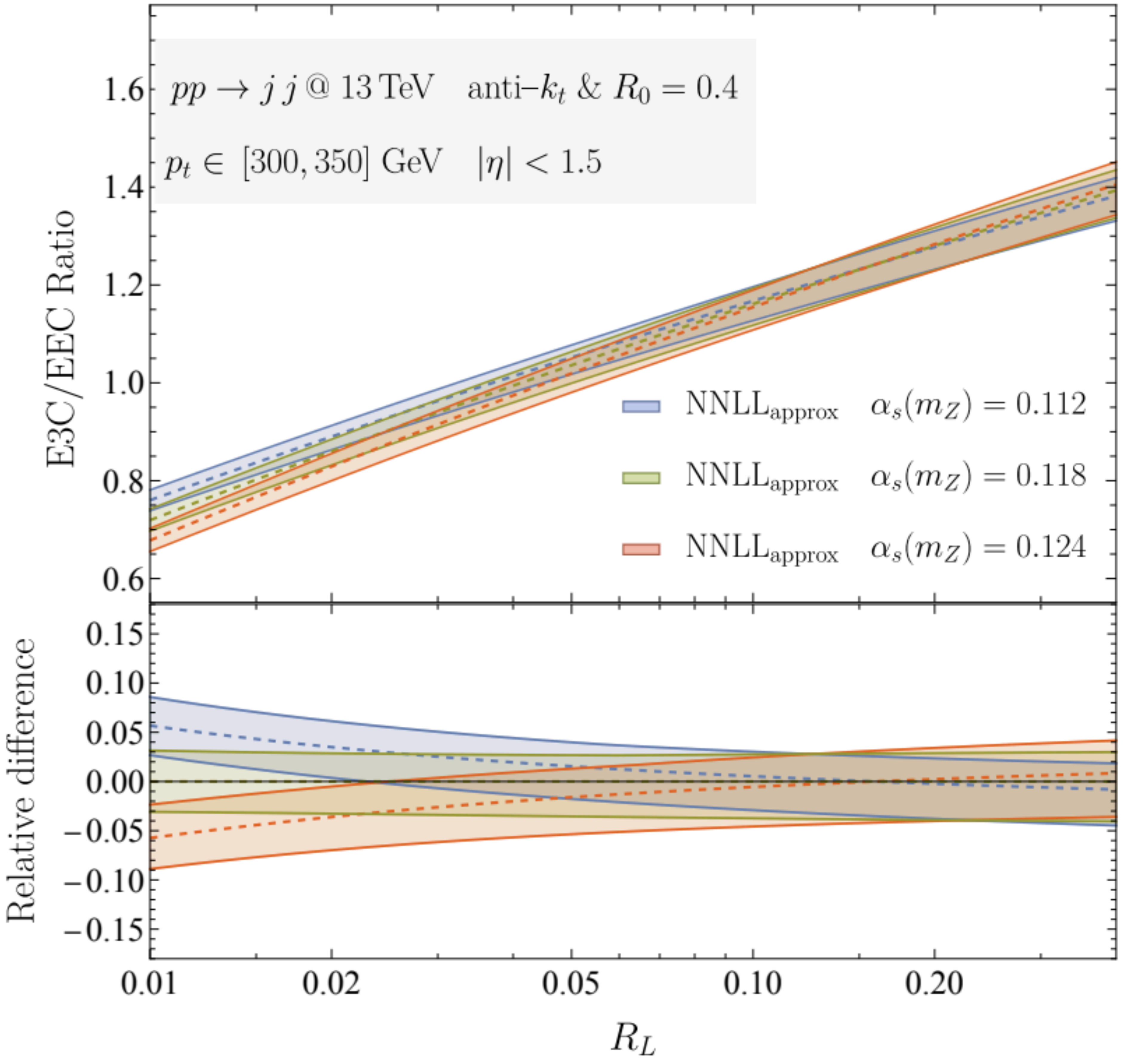
Constant c:

- a function of C_i and depend on q/g fraction
- different for E2C and E3C

Taking the ratio E3C/E2C:

- PDF uncertainty largely cancel out in the ratio
- approx linear of $\alpha_S \ln x_L$

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



$\alpha_S(m_Z)$ ↑ Slope ↑

Experimental measurements

To extract α_S: measure E3C/E2C ratio in multiple jet pT regions and compare to $\mathrm{NNLL}_{\mathrm{approx}}$ prediction

Event selection

- Dijet events, $|\eta| < 2.1$, R = 0.4, CHS (PU charged hadron subtraction)
- 8 p_T^{jet} region in 97 ~ 1784 GeV: probe energy scale dependency
- Neutral & charged particles with p_T > 1 GeV: all particles included
- Unfolding data distributions

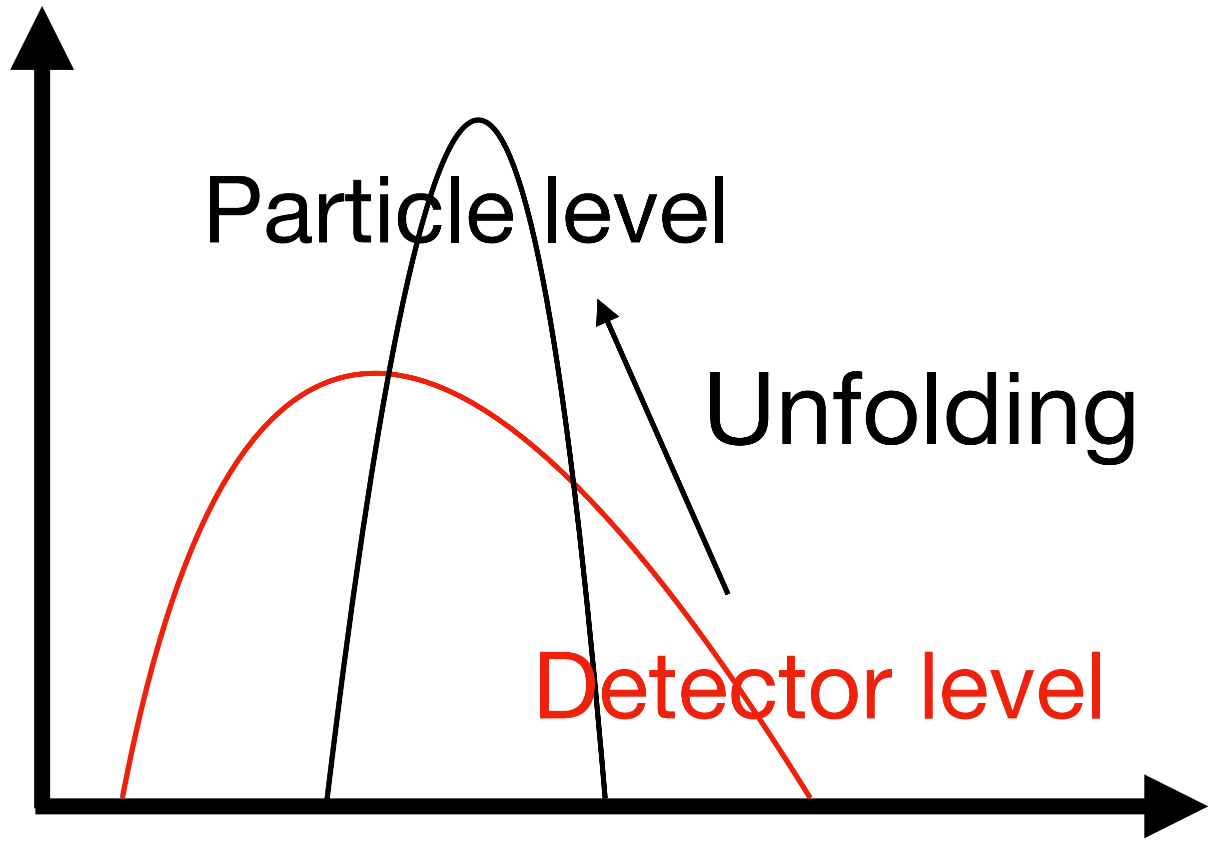
E2C & E3C: constituent unfolding

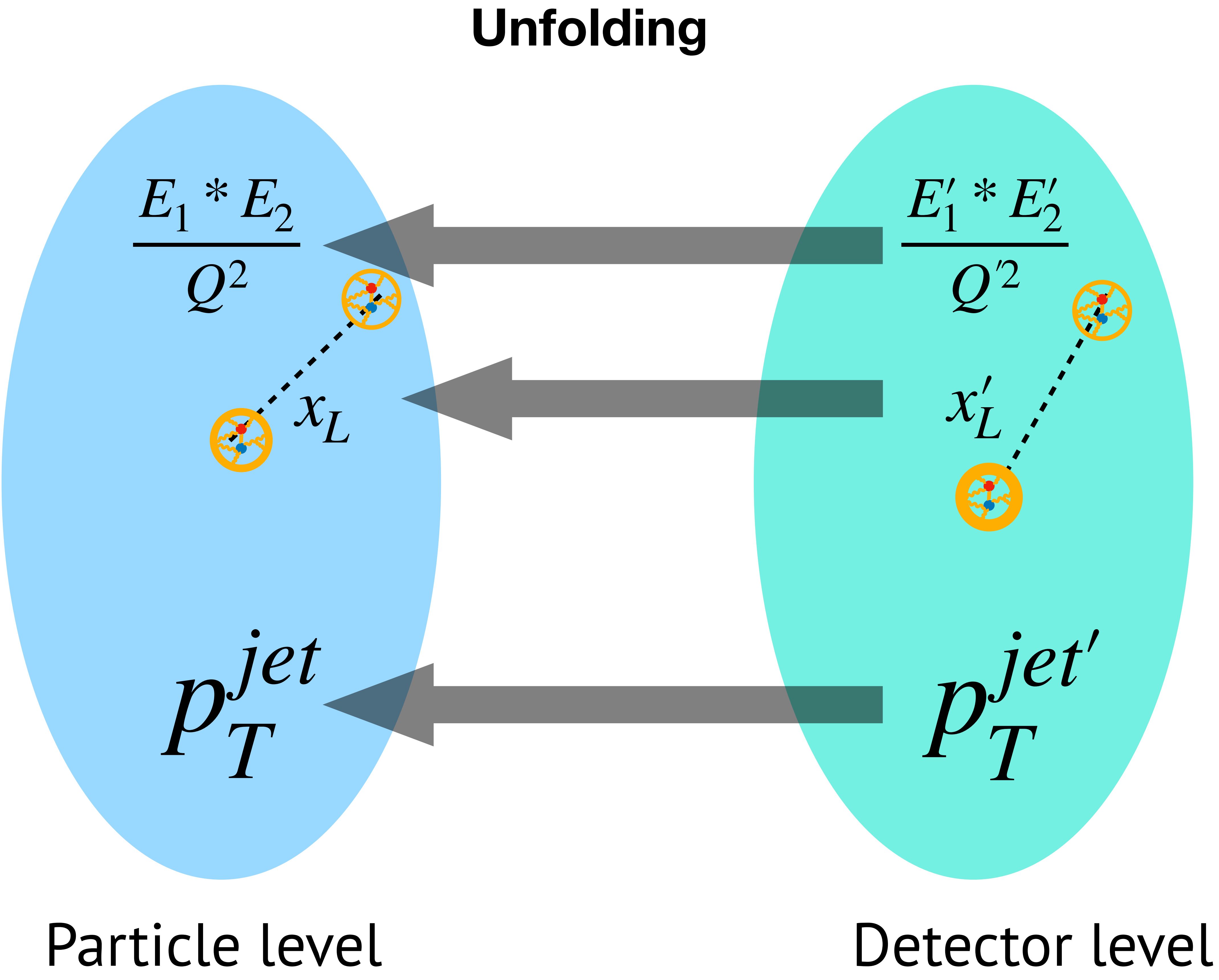
Unfolding: detector level -> particle level

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





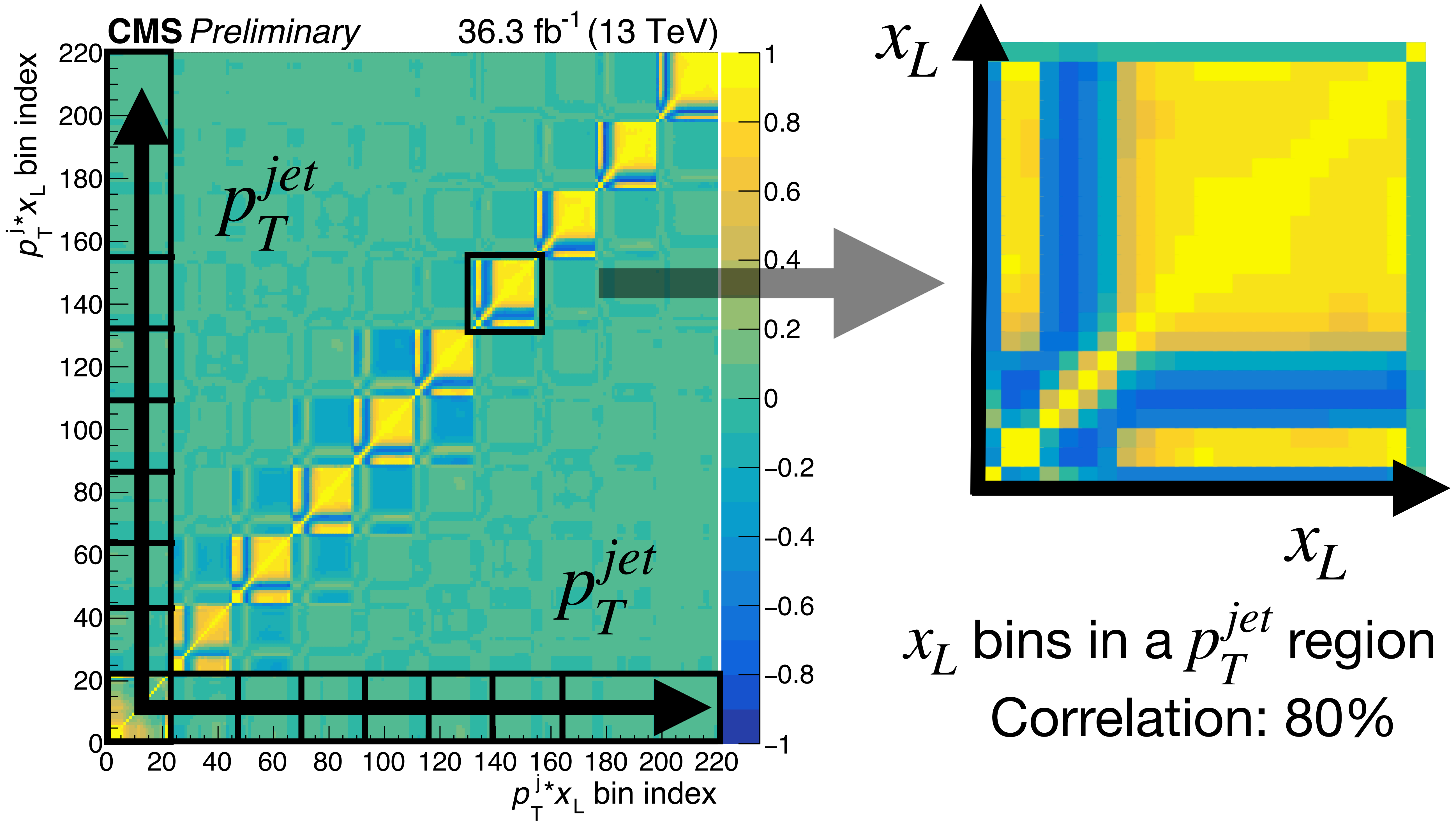
E2C & E3C: statistical correlations

Multi entry distribution for every jet, two jets in an event, statistical correlation important

Detector level => Unfolding => Normalization

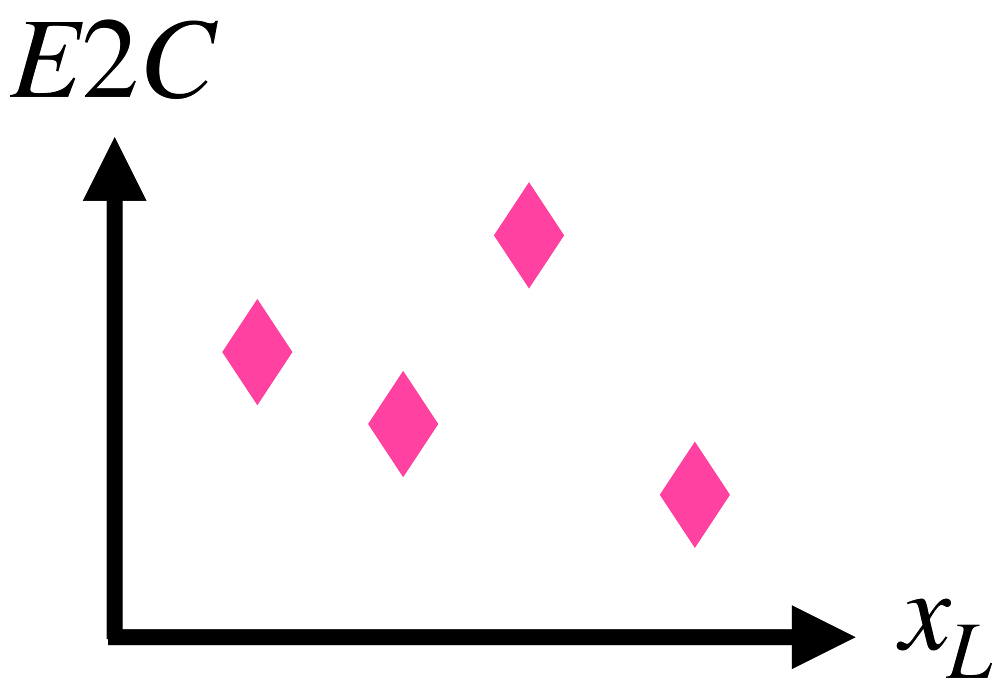
Use independent statistics for E2C, E3C to avoid further correlation

E2C correlation matrix



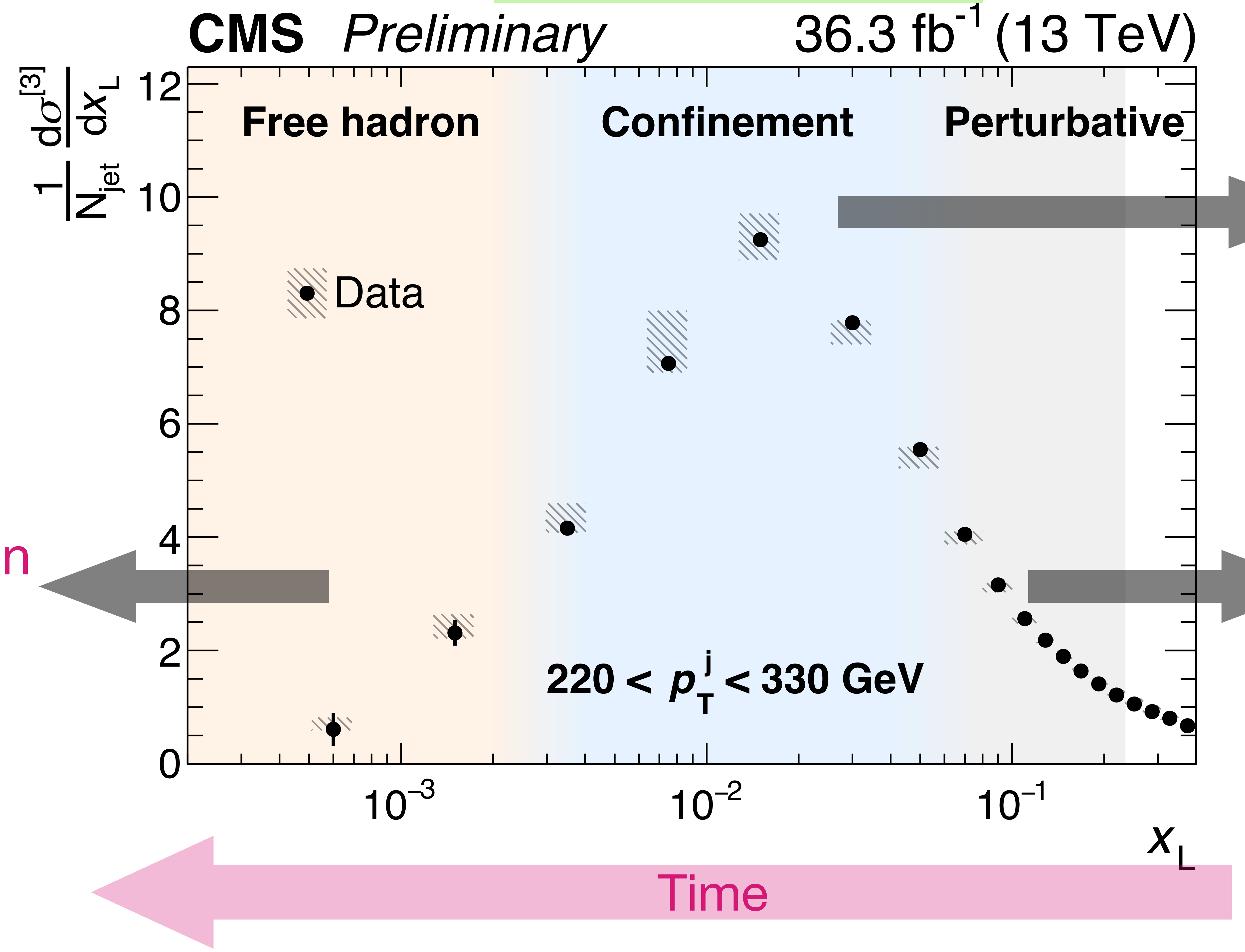
x_L bins in a p_T^{jet} region

Correlation: 80%



E3C measurement

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



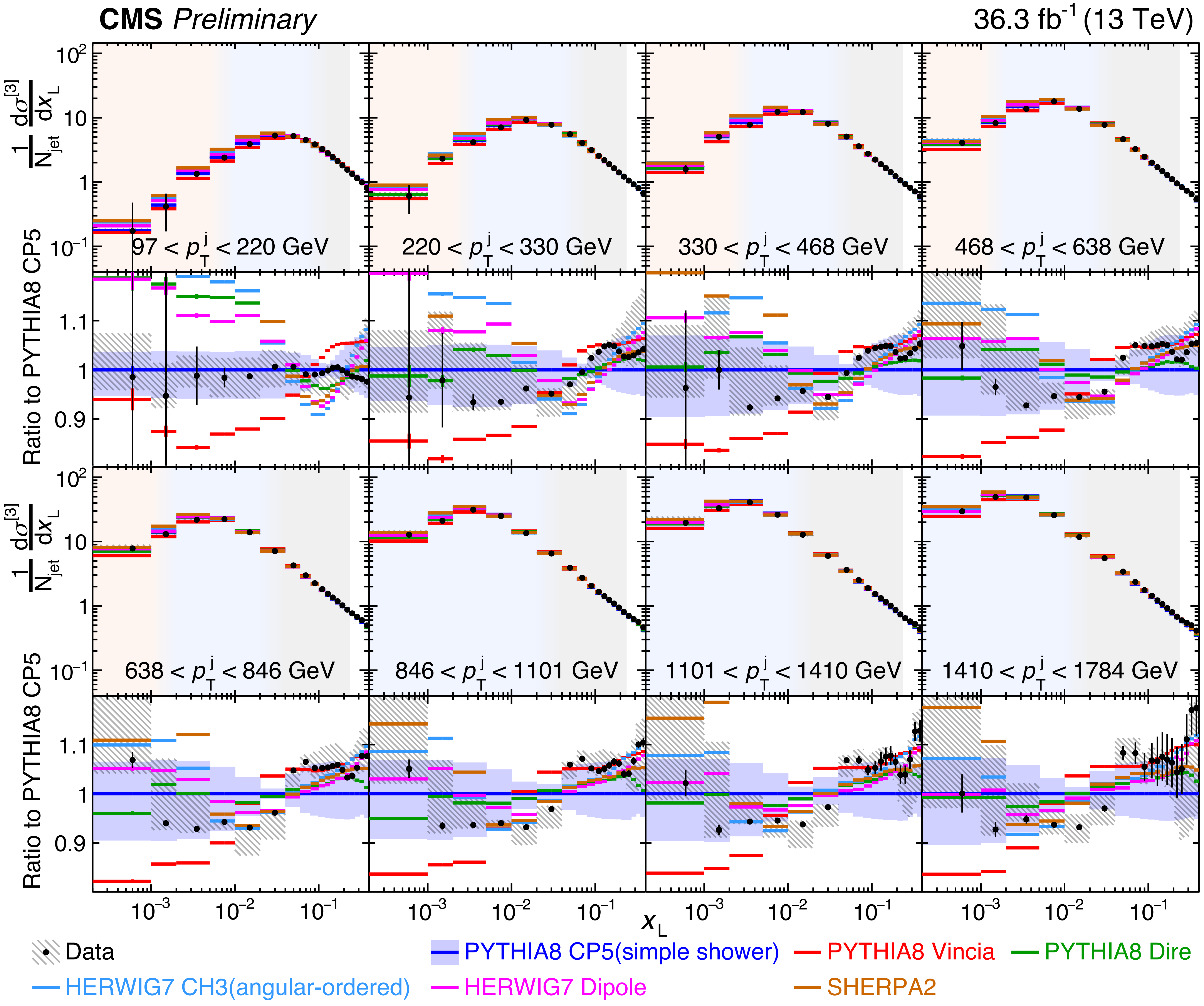
Phase transition
from parton to hadron

Non-interacting hadron
Rising scaling

Interacting partons
Falling scaling

CMS-PAS-SMP-22-015

Unfolded E3C vs MC



Data vs various parton shower model, difference ~ 10%

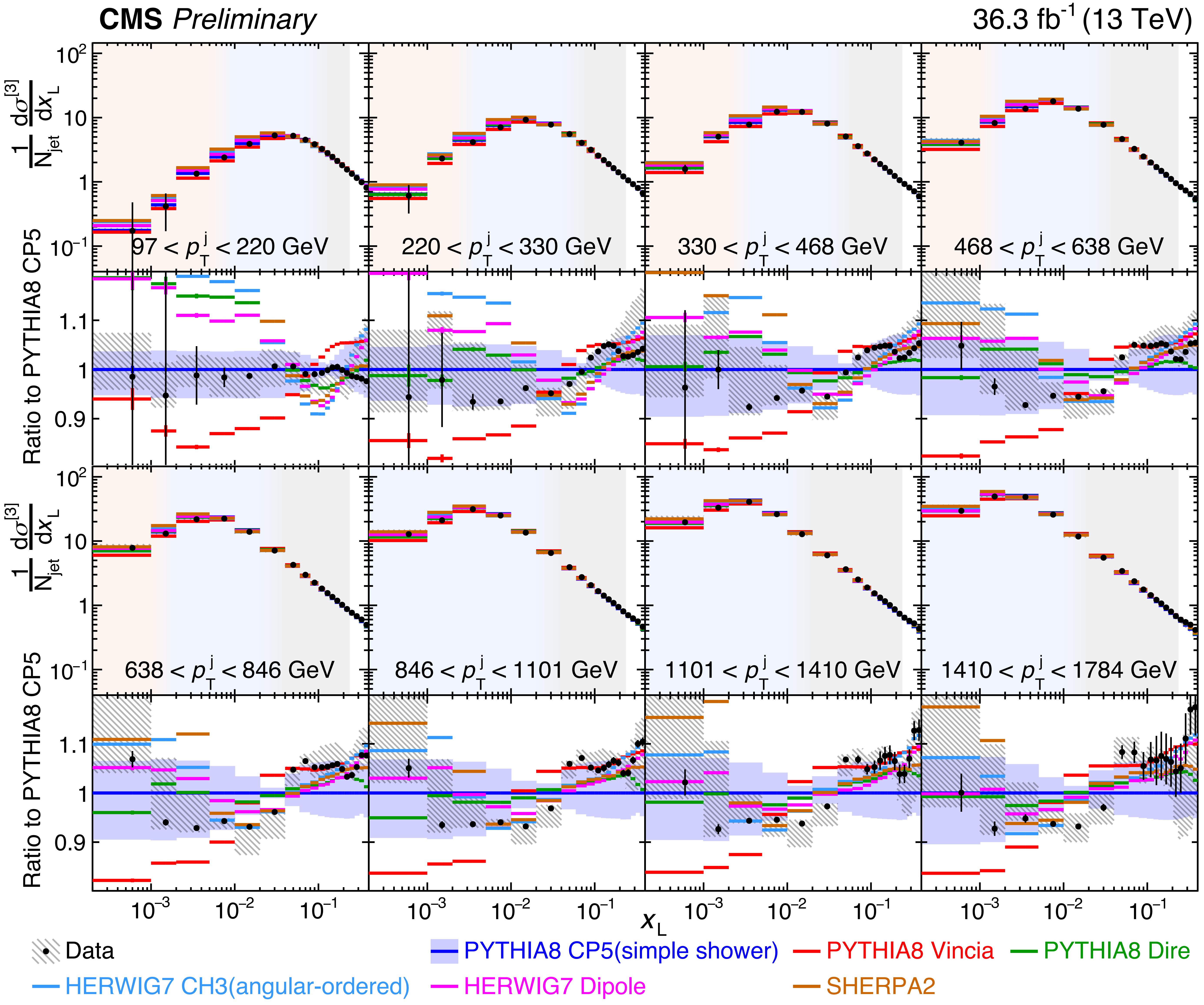
No model match data well in all p_t^{jet} region

● : Data stat error

▨ : Exp systematic

■ : Theo systematic

Unfolded E3C vs MC



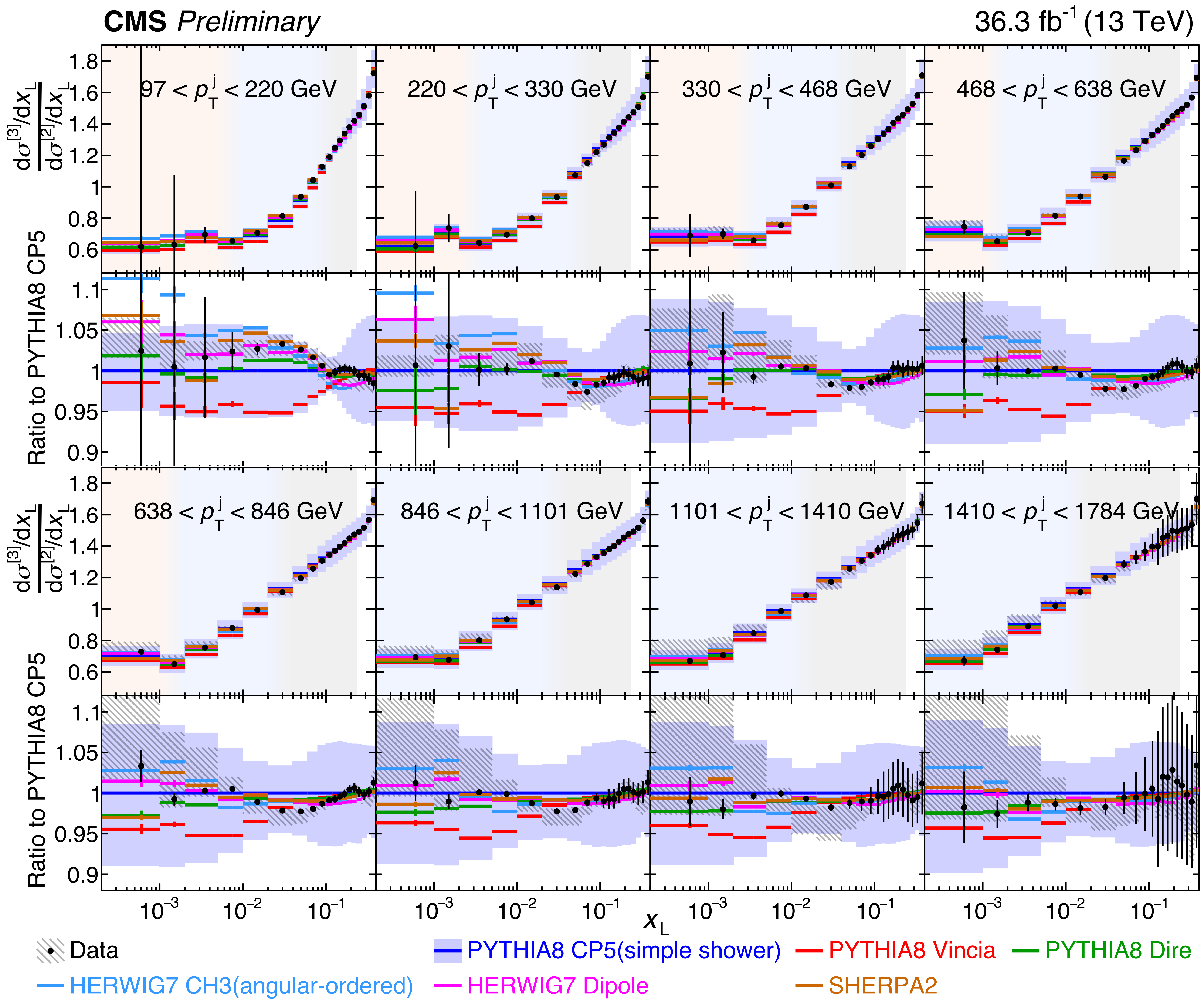
Exp sys: ▨

- 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

E3C/E2C



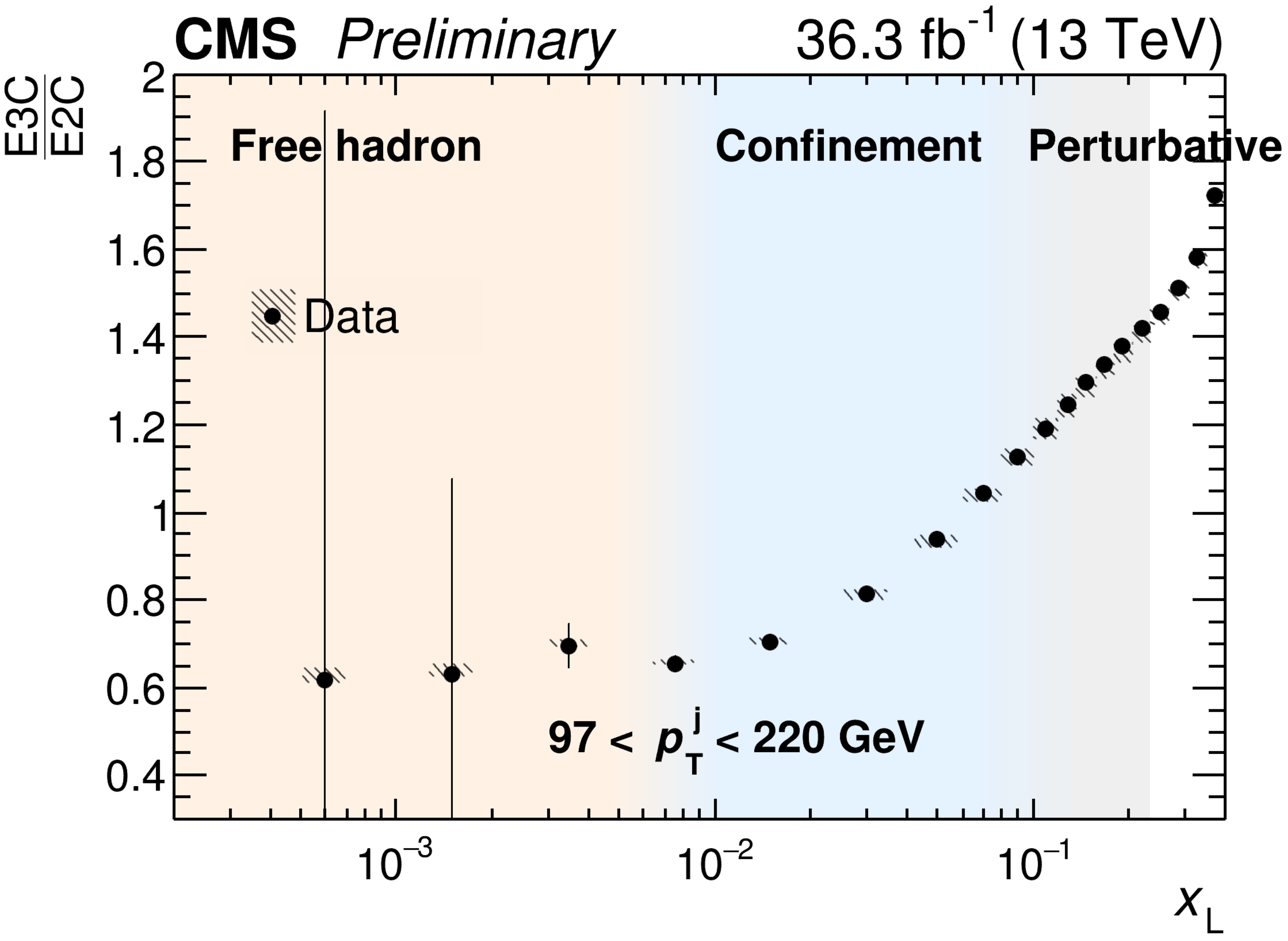
Benefit of taking ratio

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

All models agree well

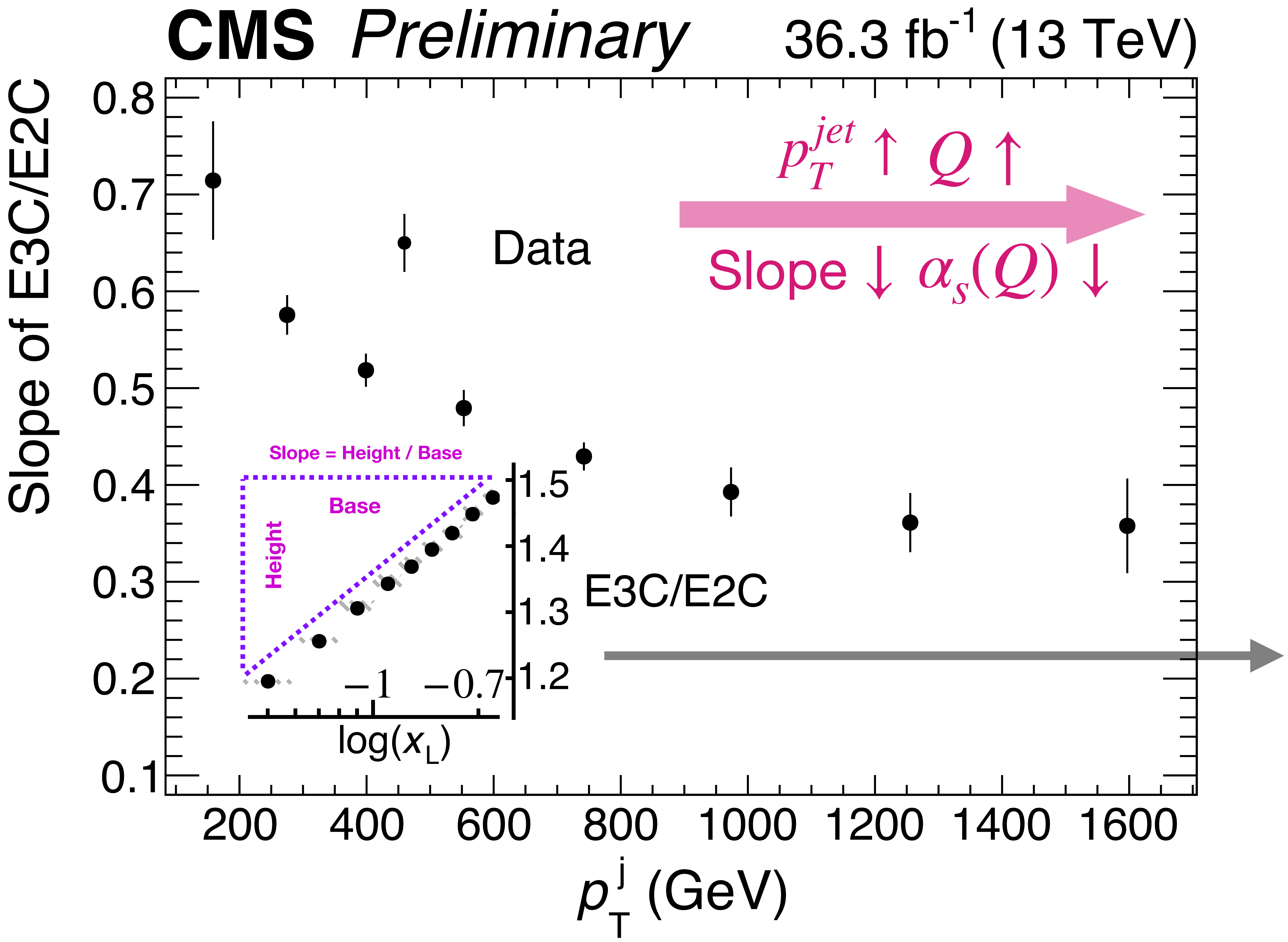
p_T^{jet} ↑ , Slope ↓

E3C/E2C



Animated E3C/E2C in multiple pT regions

Direct observation of asymptotic freedom

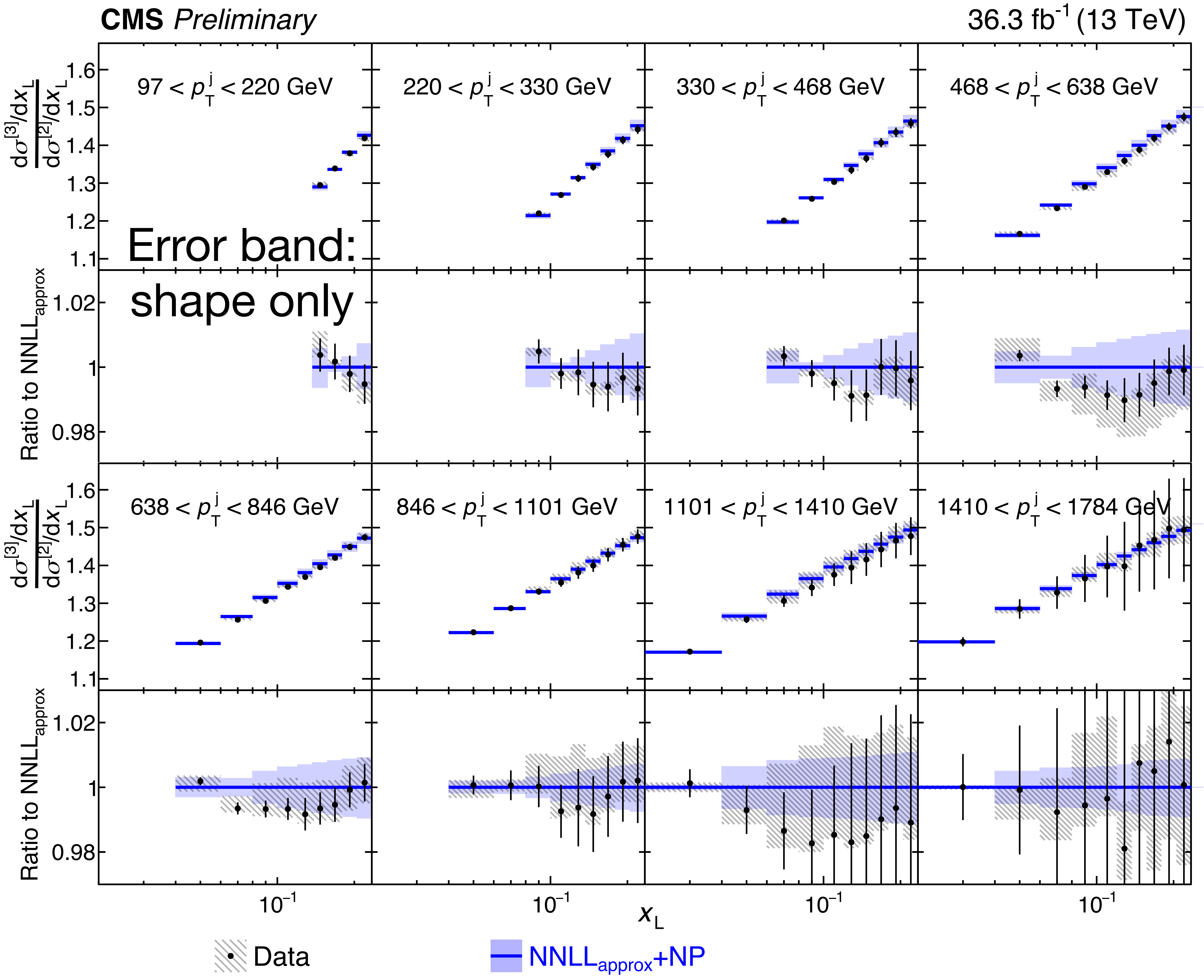


p_T^{jet} ↑ Q ↑

Slope ↓ $\alpha_s(Q)$ ↓

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

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



Error band: shape only

Analytical predictions

- $\text{NNLL}_{\text{approx}}$: Parton level E3C/E2C
    - NLO+NNLLapprox

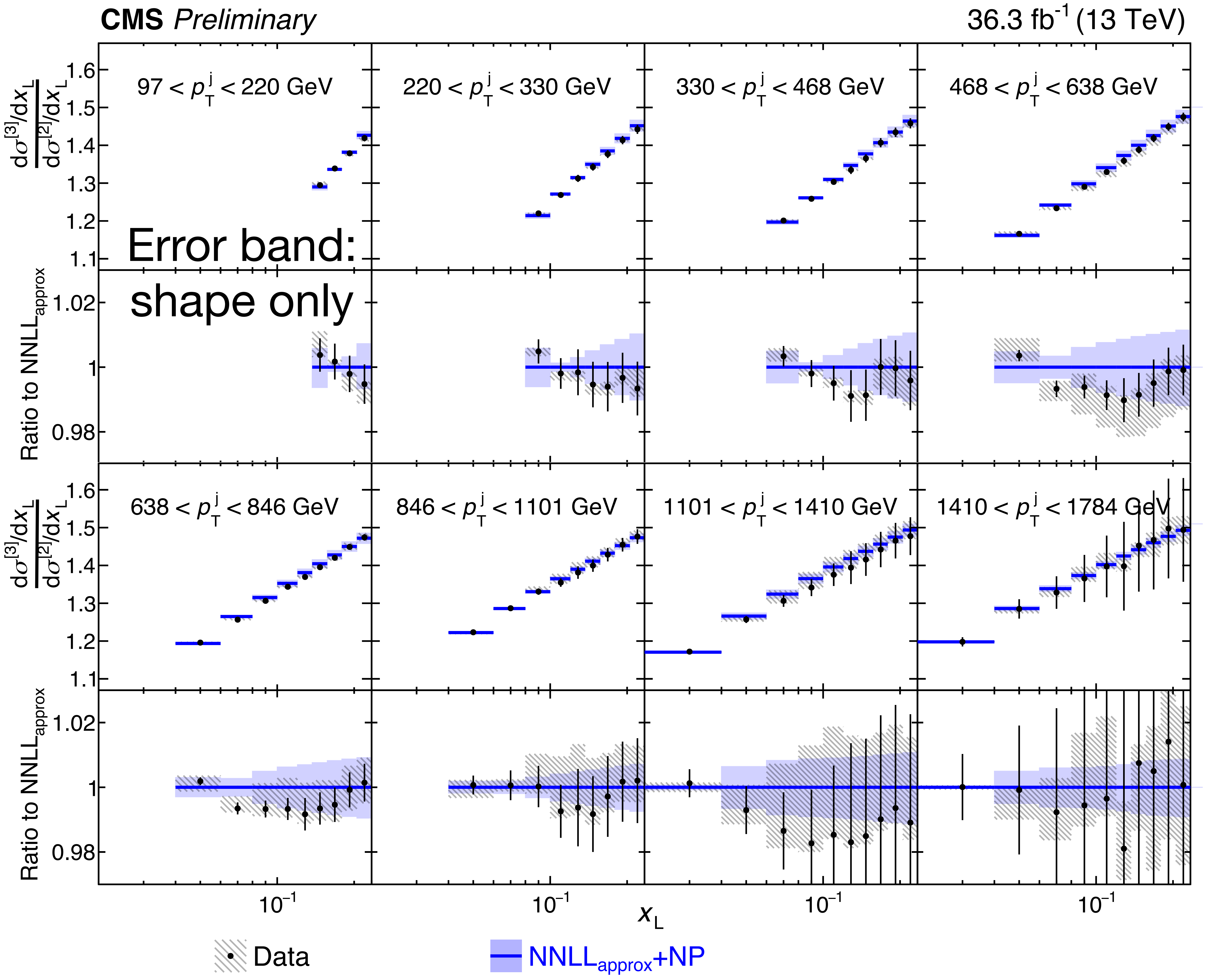
Chen, Gao, Li, Xu, Zhang, and Zhu, *arXiv:2307.07510*

- Same phase space as the analysis

Hadronization factors

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

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



Error band: shape only

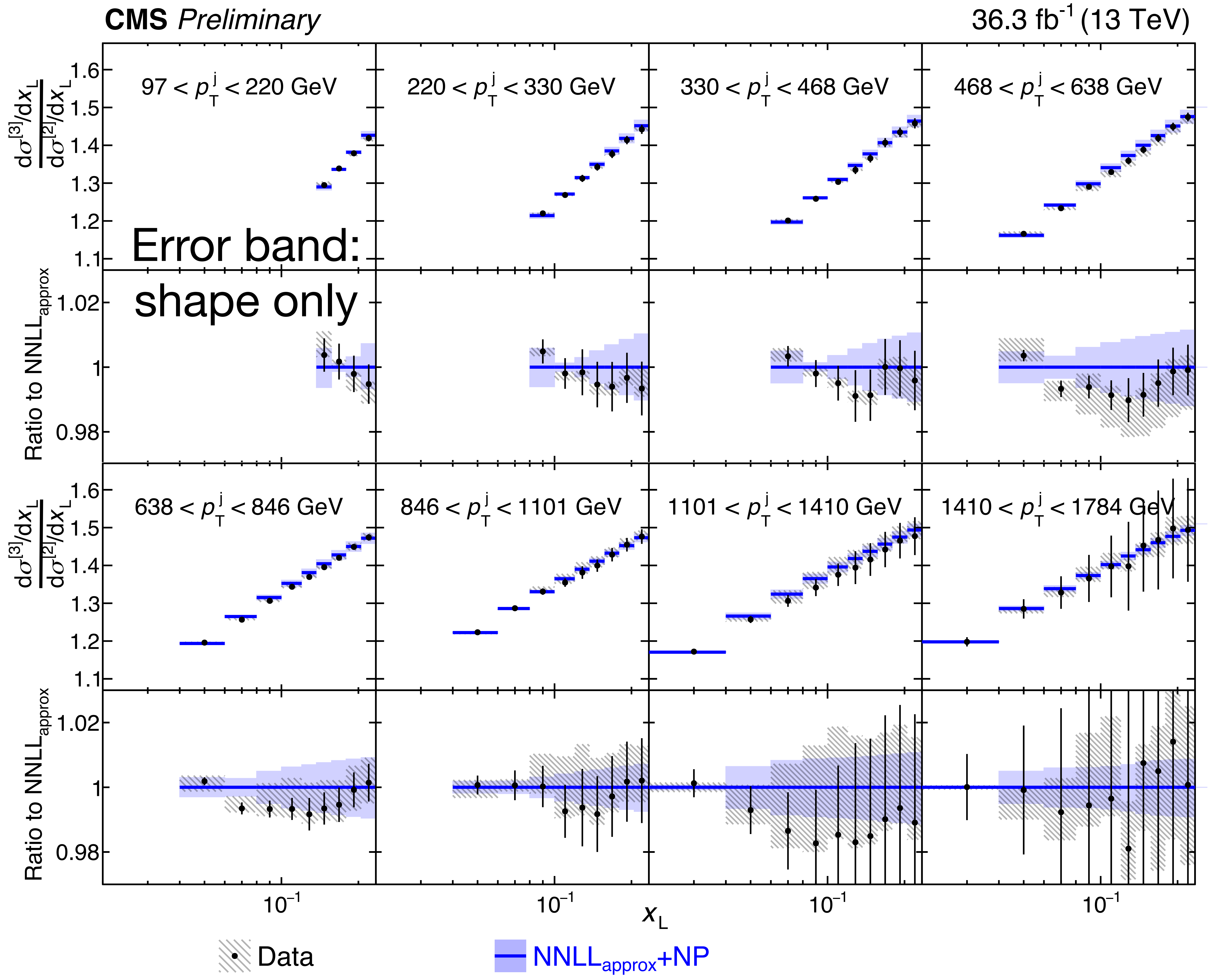
Shape of data agrees with NNLL$_{approx}$ within uncertainty

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$_{approx}$



Error band:
shape only

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

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

major source

Covariance matrix

QCD scale of NNLL$_{approx}$

Neutral hadron energy scale

Uncertainty ~ 4%,
Most precise from jet substructure to date

Summary

- Jet substructure has become a powerful tool to understand QCD with high precision
- 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