Energy correlator measurements at the CMS

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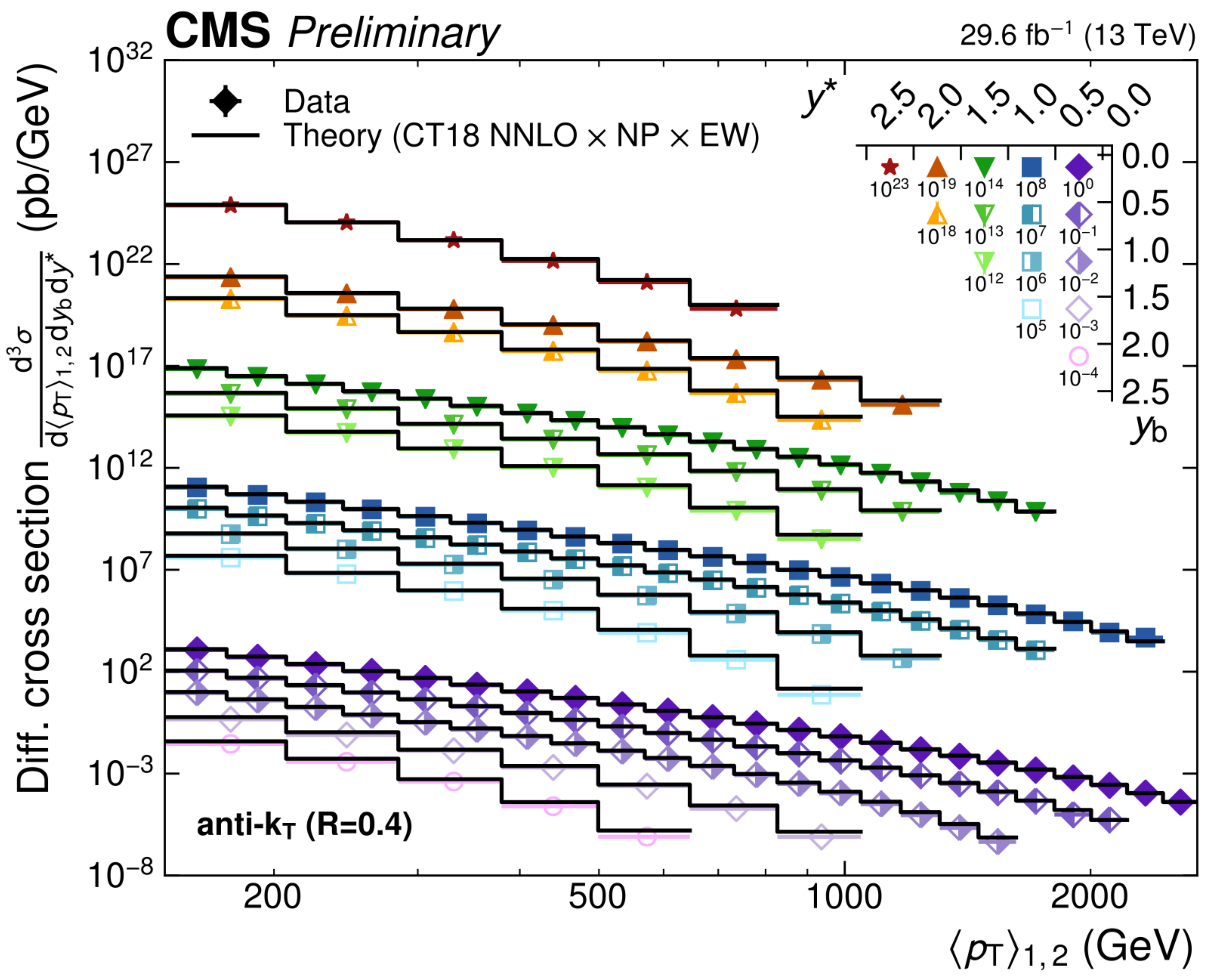
2023 International workshop on CEPC, Nanjing, 2023.10.24

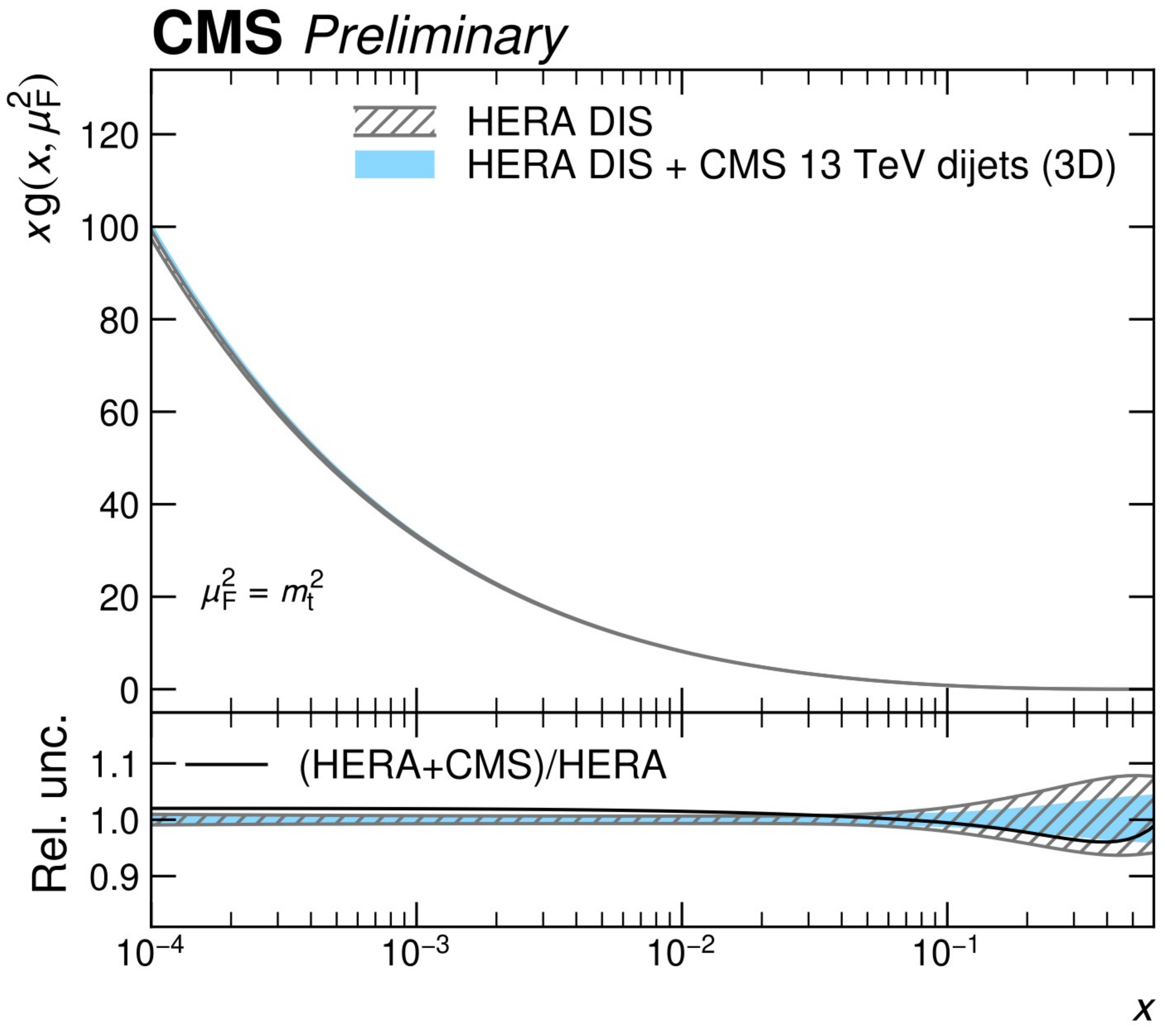
Jets: proxies to study QCD

Di-jet multi-differential cross section Compared to NNLO predictions, 10^{-4} - 10^{23}

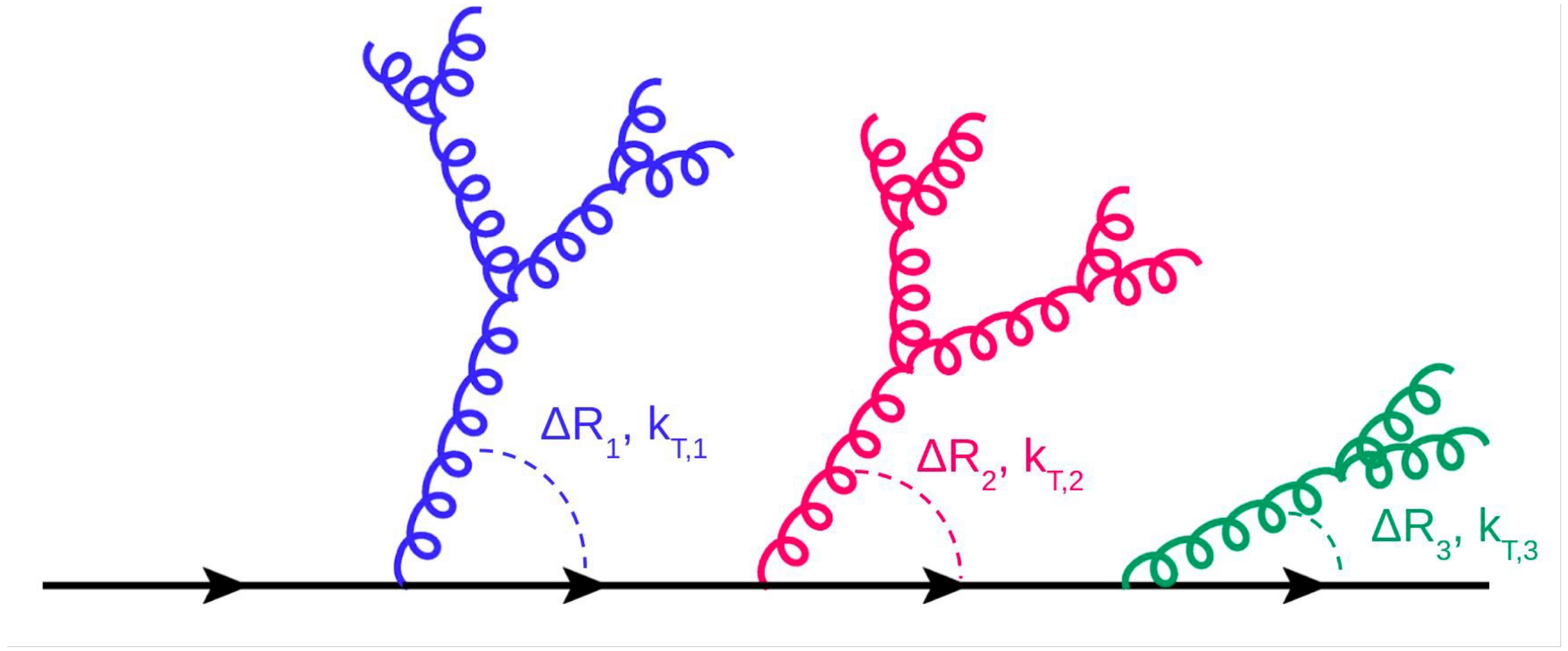


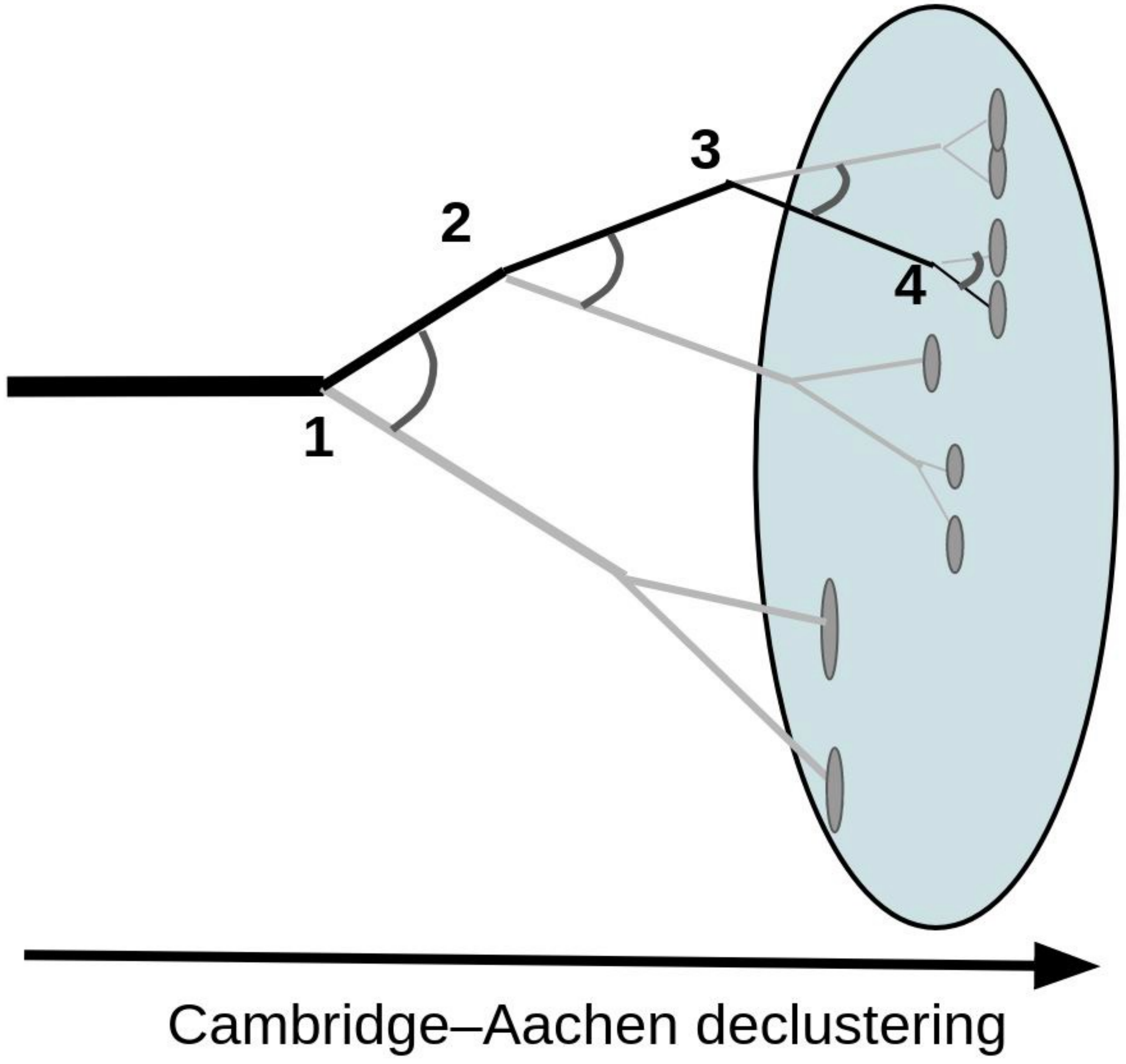
CMS-PAS-SMP-21-008

Constraints on gluon PDF



Jet formation and jet substructure

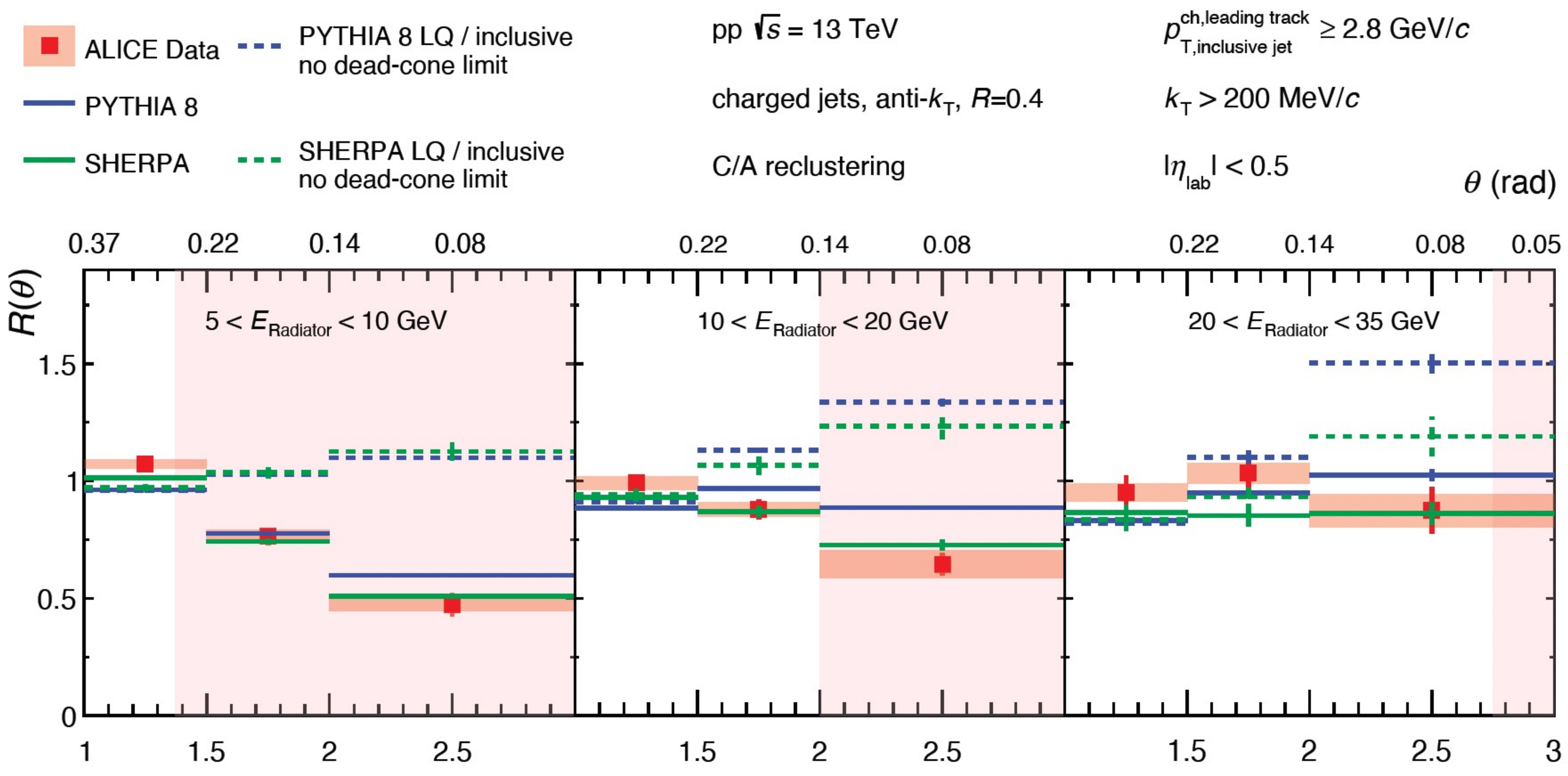




Angular-ordered

Jet substructure studies

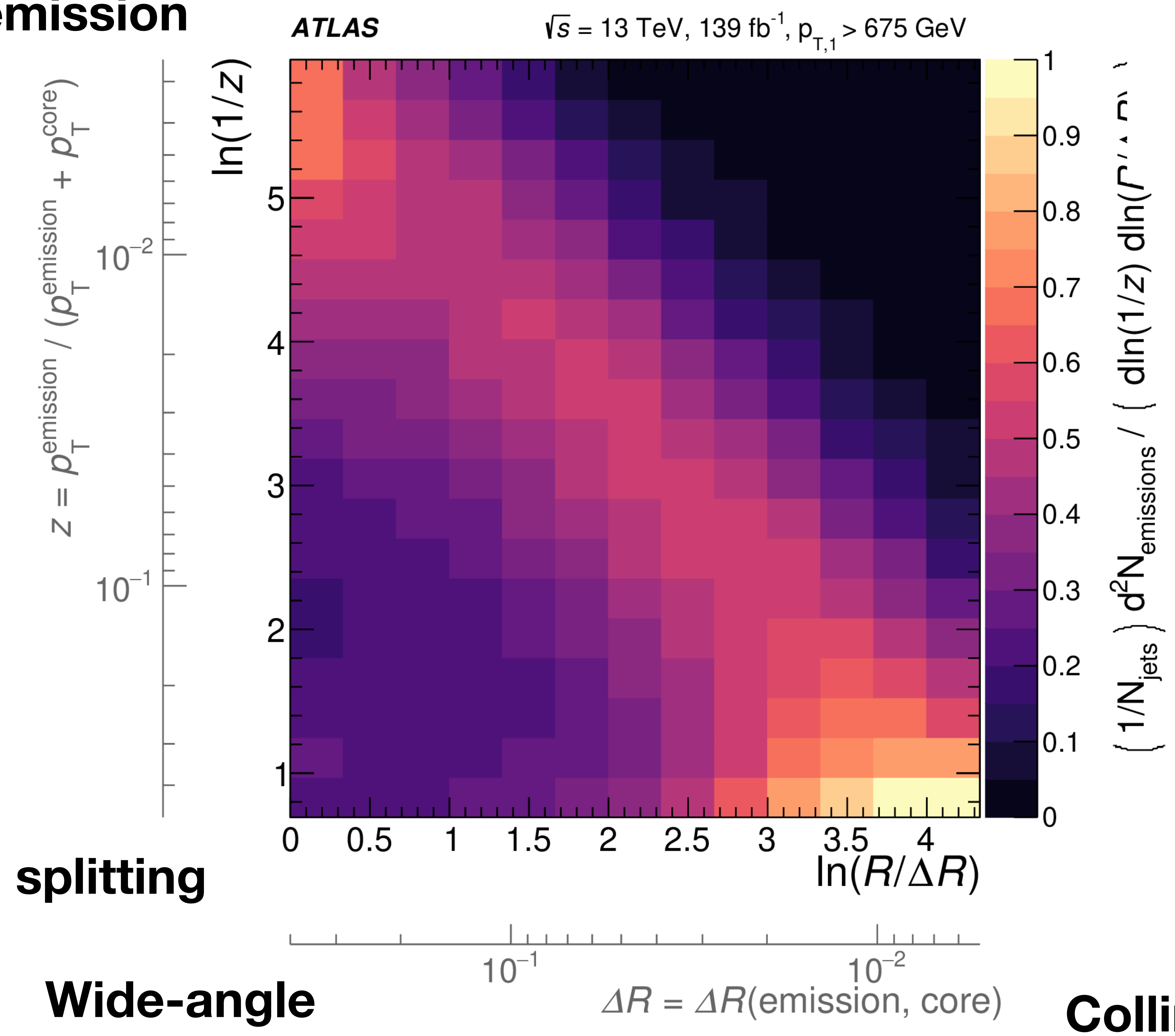
Dead cone



Nature 605, 7910 (2022): 440-446

Lund Plane

Soft-emission



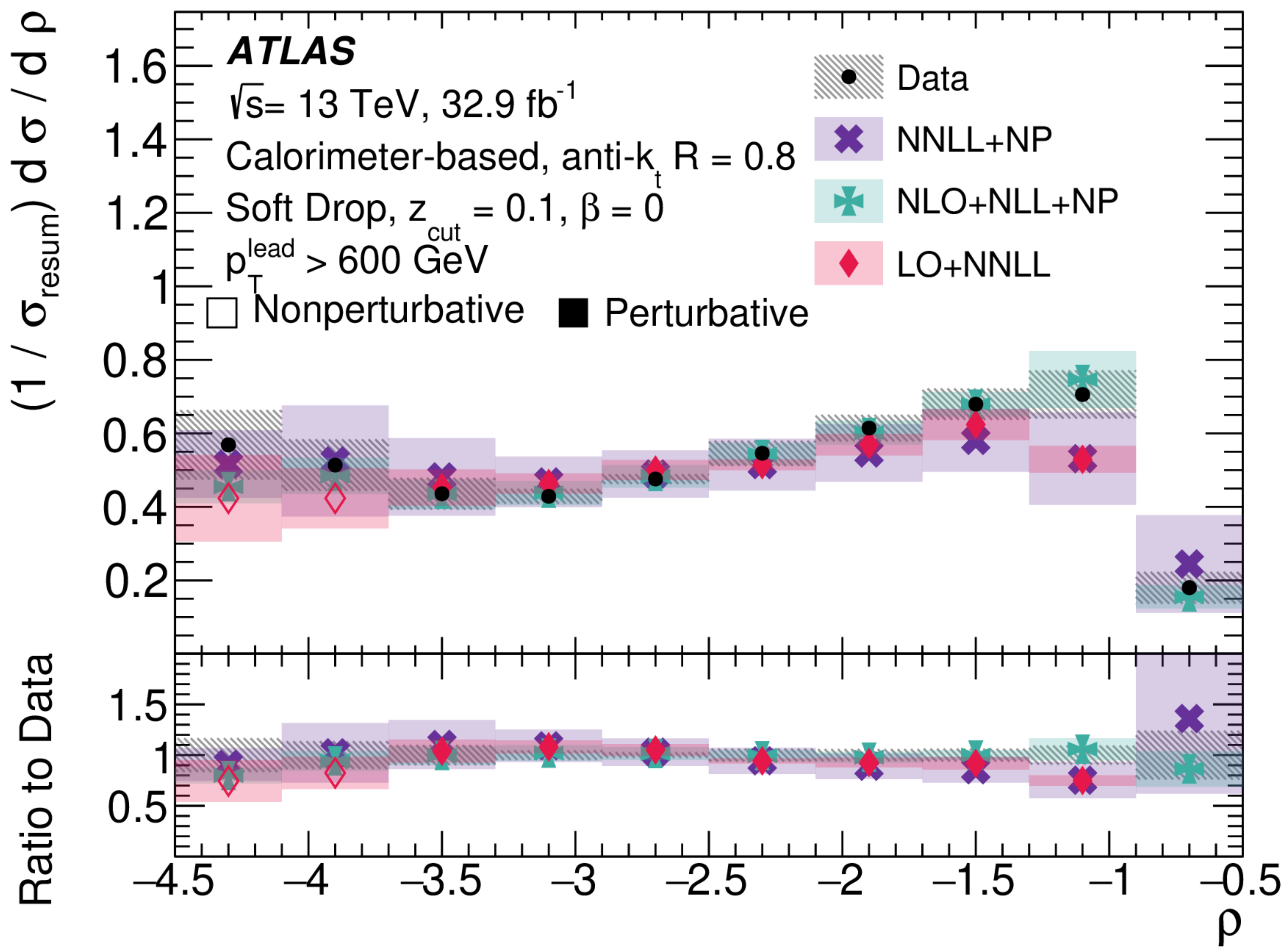
Even splitting

Wide-angle

Collinear

PRL 124 (2020) 222002

Soft drop jet mass



Jet substructure and alphaS

Strong coupling from JSS (Prospects)

LEP Extractions	LHC Extractions	LHC Extractions from JSS
e^+e^-	Underlying event, colour reconnection	soft-drop grooming → mitigate soft/wide-angled contributions
Thrust extraction sensitive in resummation-dominated region	Jet rates, cross-section ratios usually compared to fixed-order calculations	Soft-drop mass prediction → precise resummation

MLB : Tuesday Morning

Hofie : Thursday Morning!

Prediction: we will see the first α_S extractions from JSS during Run 3!

Matt LeBlanc (CERN) — Overview (Experimental) — BOOST 2022 — Slide 41

Leshouches2017, axXiv: 1803.07977, estimated precision on αS: 10%

Current αs measurements

$\alpha_s(M_z) = 0.1179 \pm 0.0009$ (±0.8%)

Hadronic tau decay (4 values):

$\alpha_s(M_z) = 0.1178 \pm 0.0019$ (±1.6%)

Quarkonia properties (4 values):

$\alpha_s(M_z) = 0.1181 \pm 0.037$ (±3.3%)

DIS & PDFs fits (6 values):

$\alpha_s(M_z) = 0.1162 \pm 0.0020$ (±1.7%)

$e^+e^- \rightarrow$ hadrons final states (10 values):

$\alpha_s(M_z) = 0.1171 \pm 0.0031$ (±2.6%)

Hadron collider measurements (5 values):

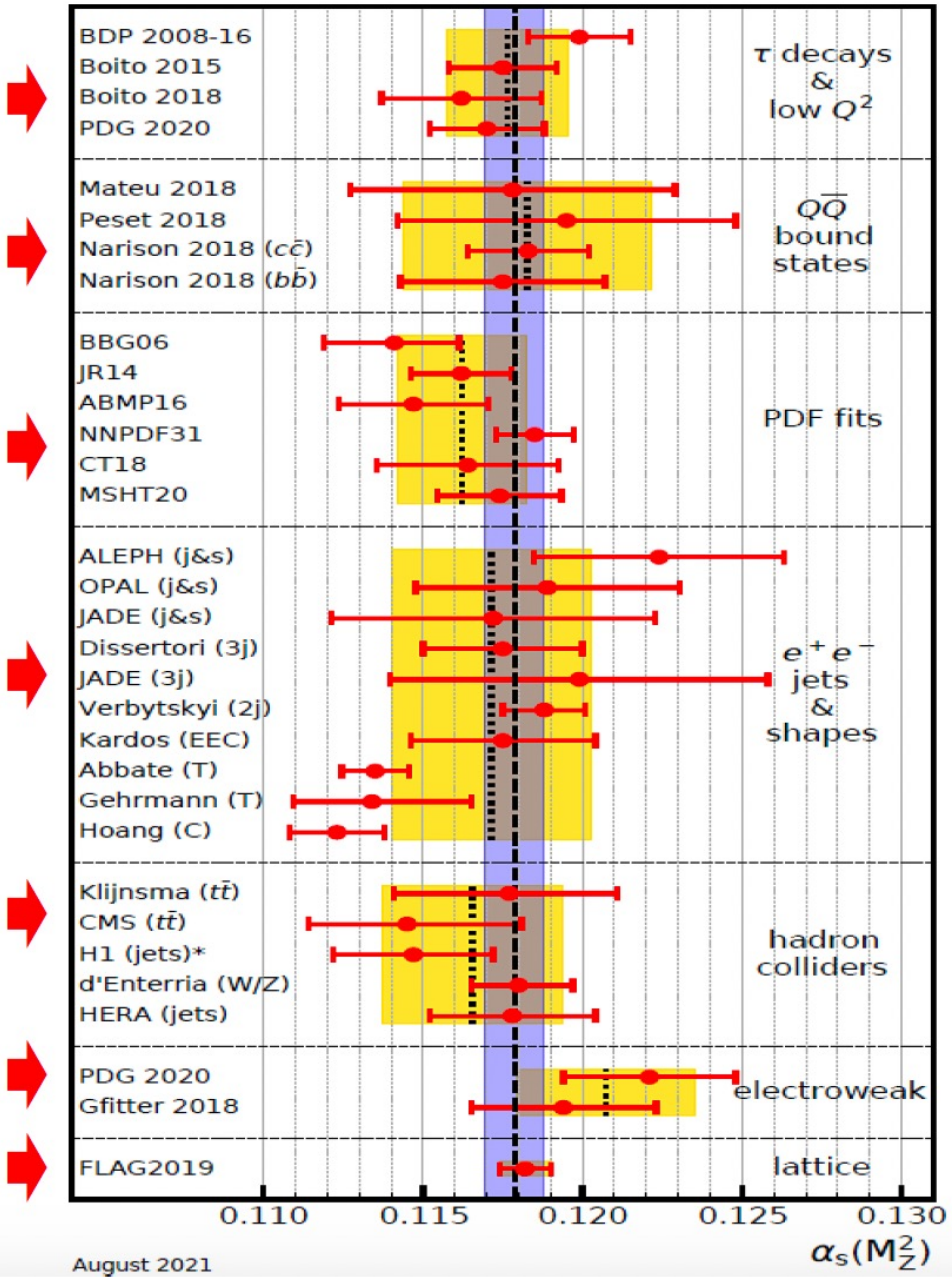
$\alpha_s(M_z) = 0.1165 \pm 0.0028$ (±2.4%)

Electroweak precision fits (2 values):

$\alpha_s(M_z) = 0.1208 \pm 0.0028$ (±2.3%)

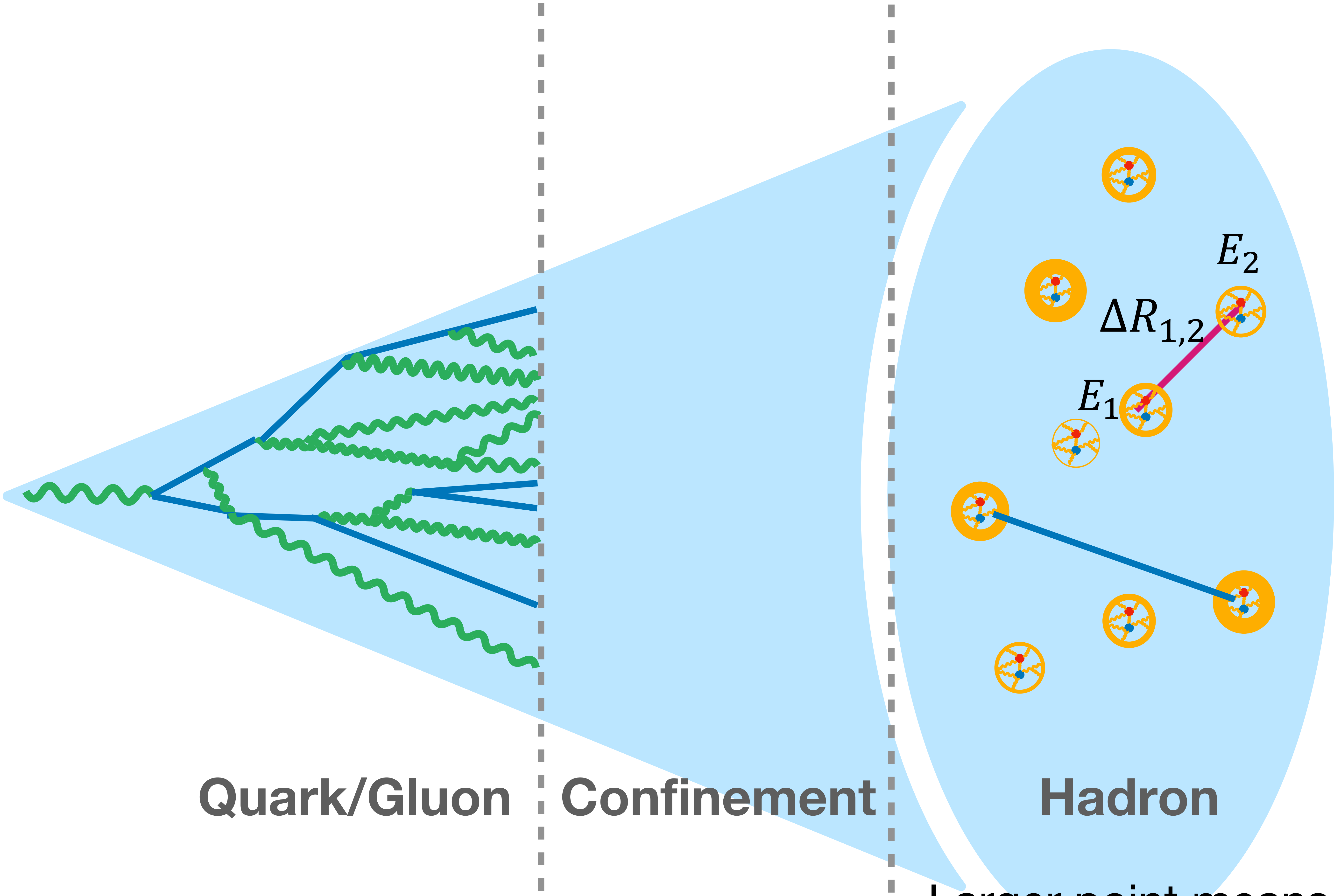
Lattice QCD (1 FLAG value):

$\alpha_s(M_z) = 0.1182 \pm 0.0008$ (±0.7%)

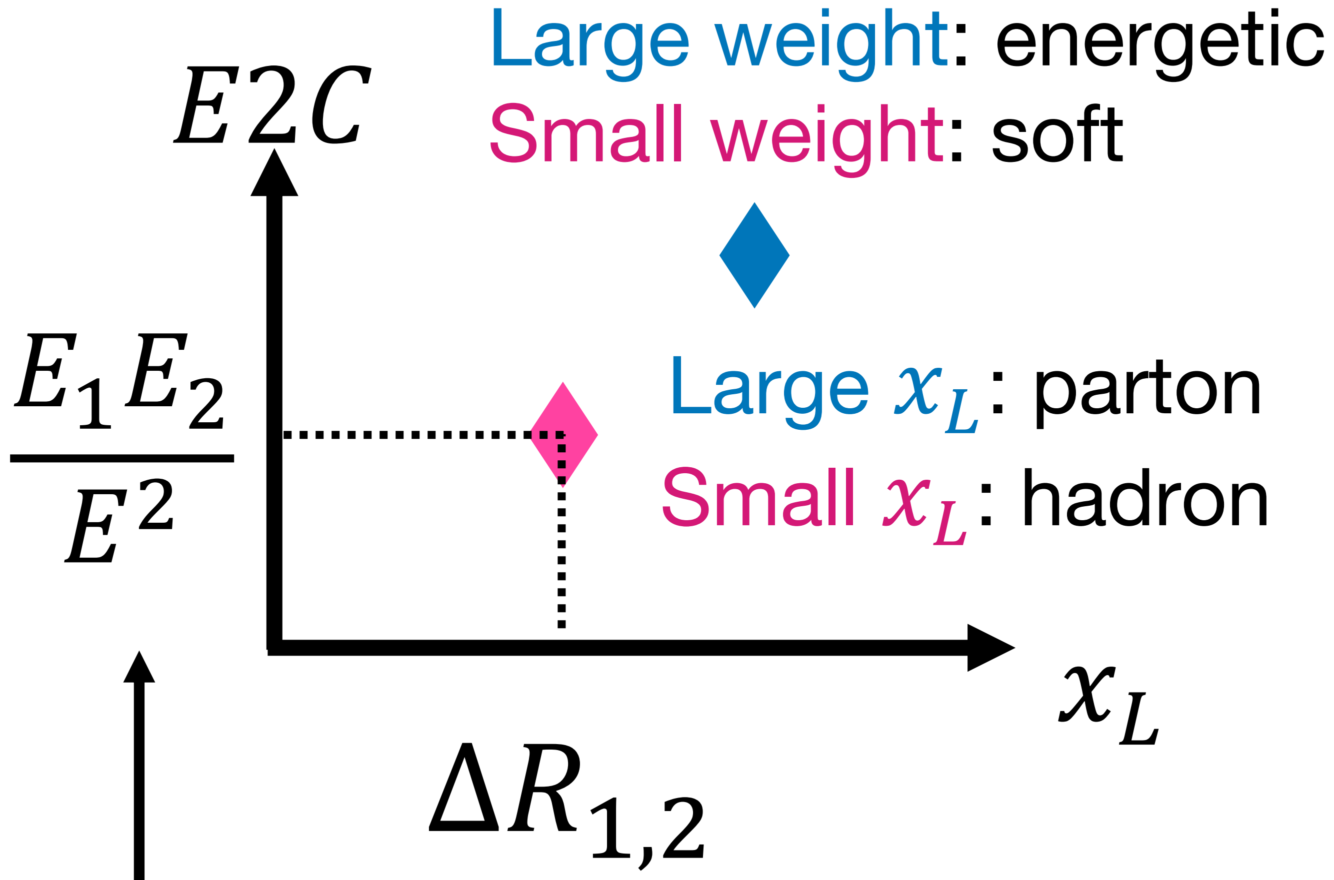


From David d'Enterria

Energy correlators: EnC



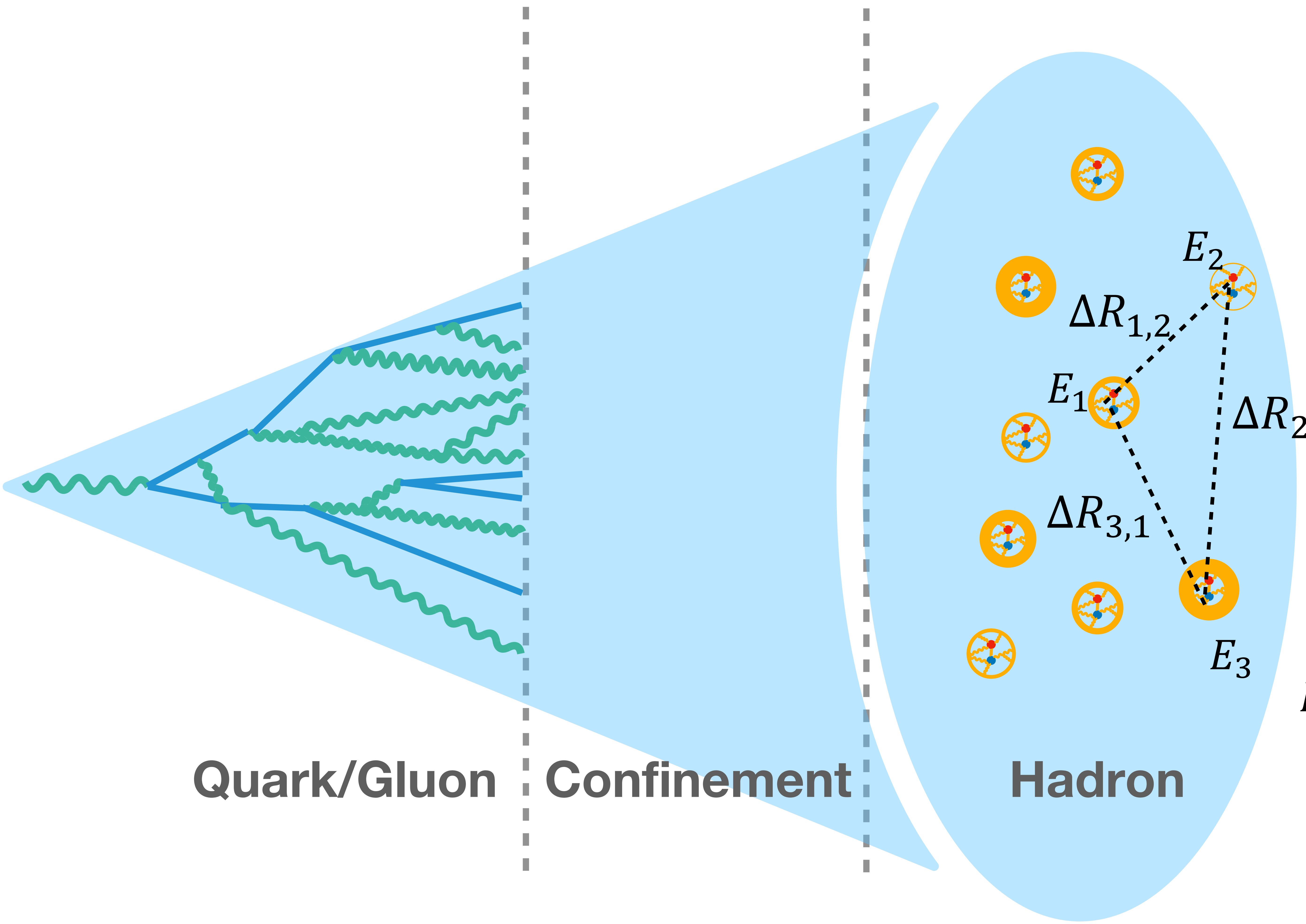
Larger point means higher energy

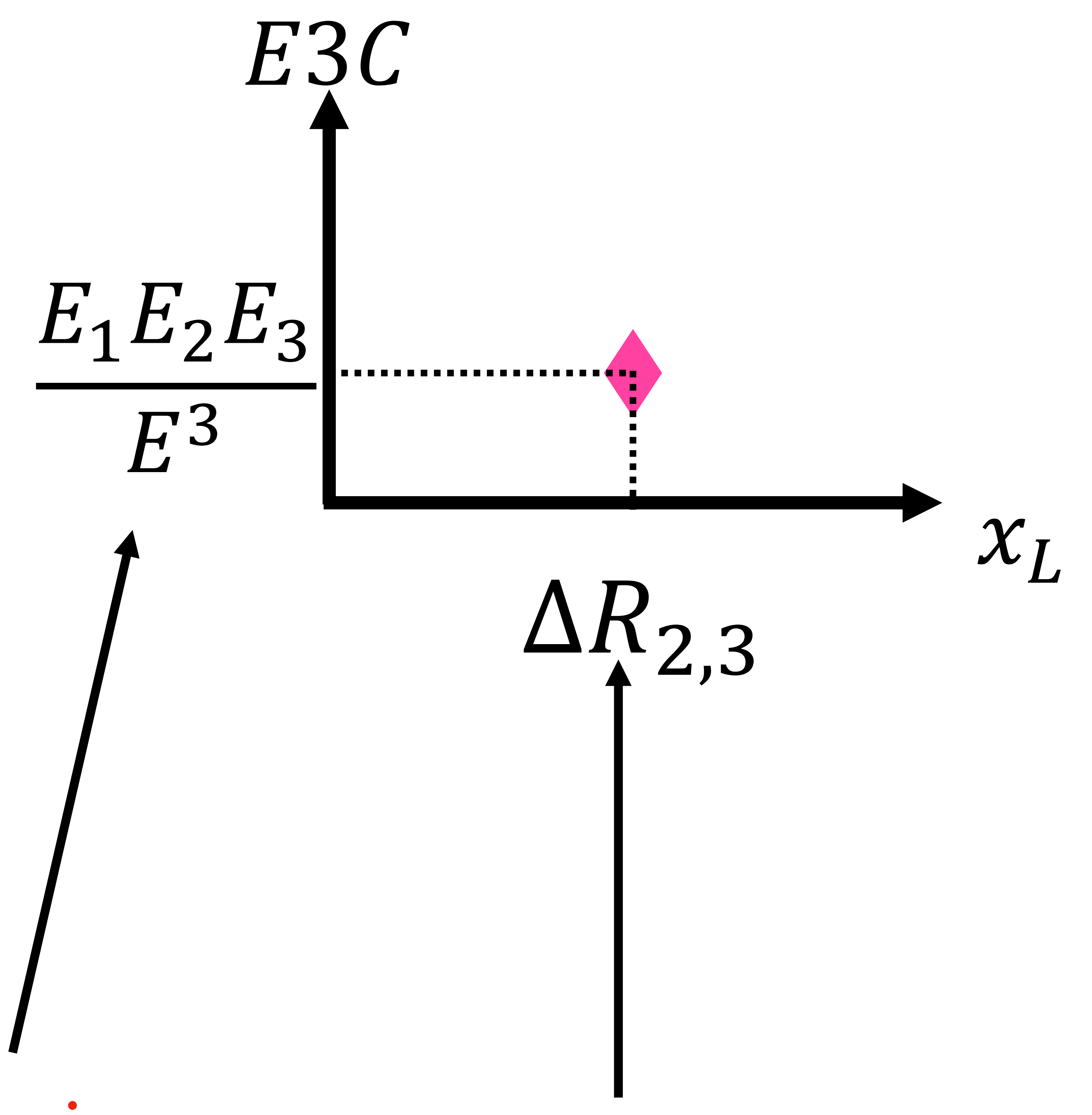


$$E2C = \frac{d\sigma^{[2]}}{dx_L} = \sum_{i,j}^{n} \int d\sigma \frac{E_i E_j}{E^2} \delta(x_L - \Delta R_{i,j})$$

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 correlators: EnC





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

Insensitive to soft radiation

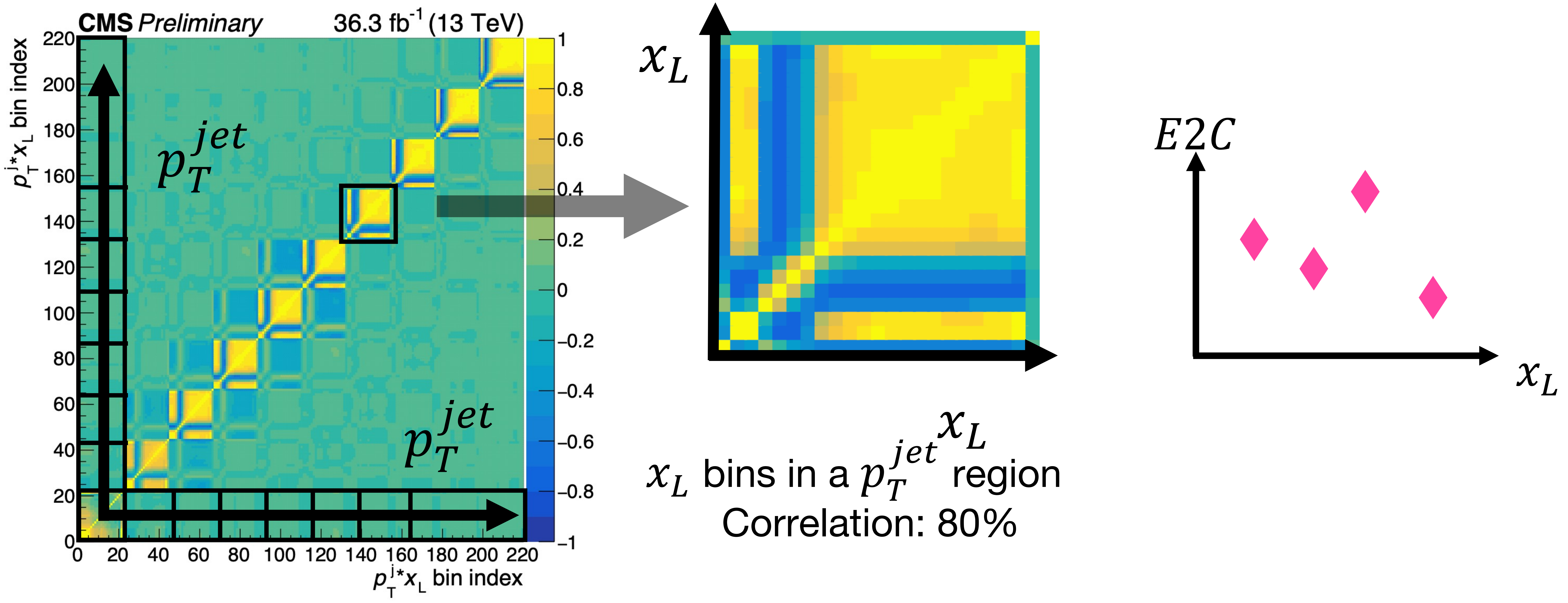
EnC: statistical correlations

Multi entry distribution for every jet, statistical correlation important

Detector level => Unfolding => Normalization

Independent statistics for E2C, E3C

E2C correlation matrix

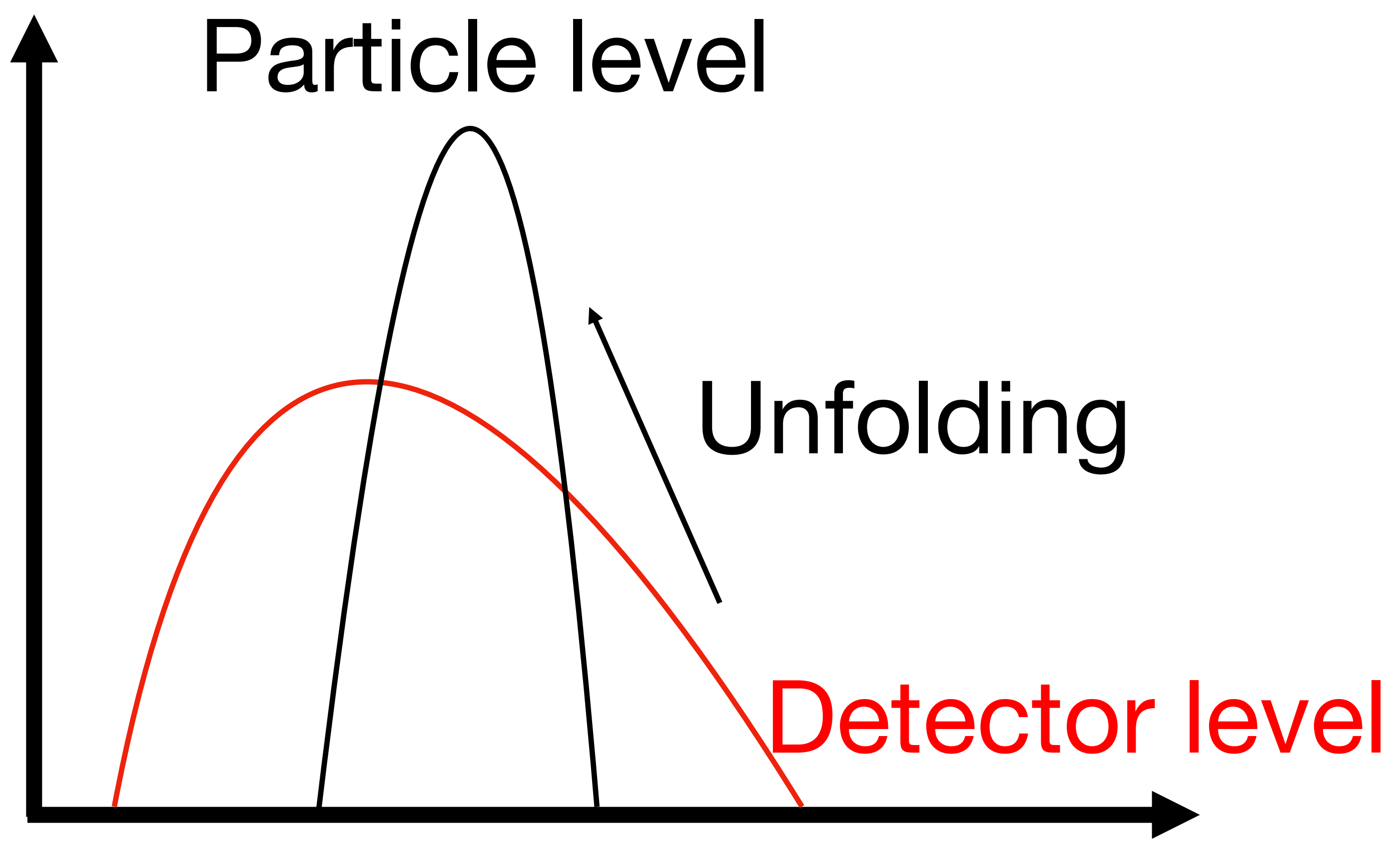


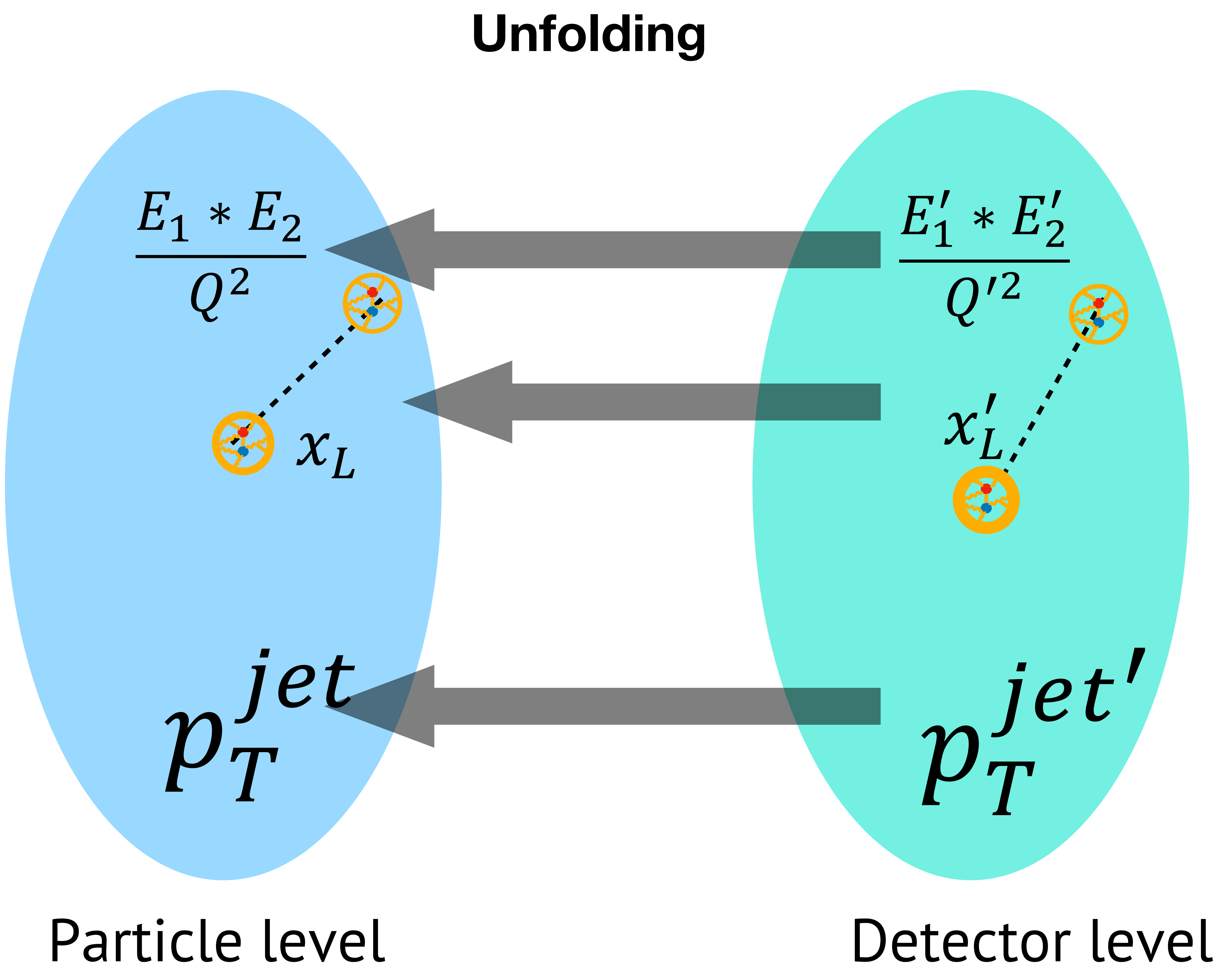
EnC: constituent unfolding

Unfolding: detector level -> particle level

Unfold jet constituents instead of distribution:

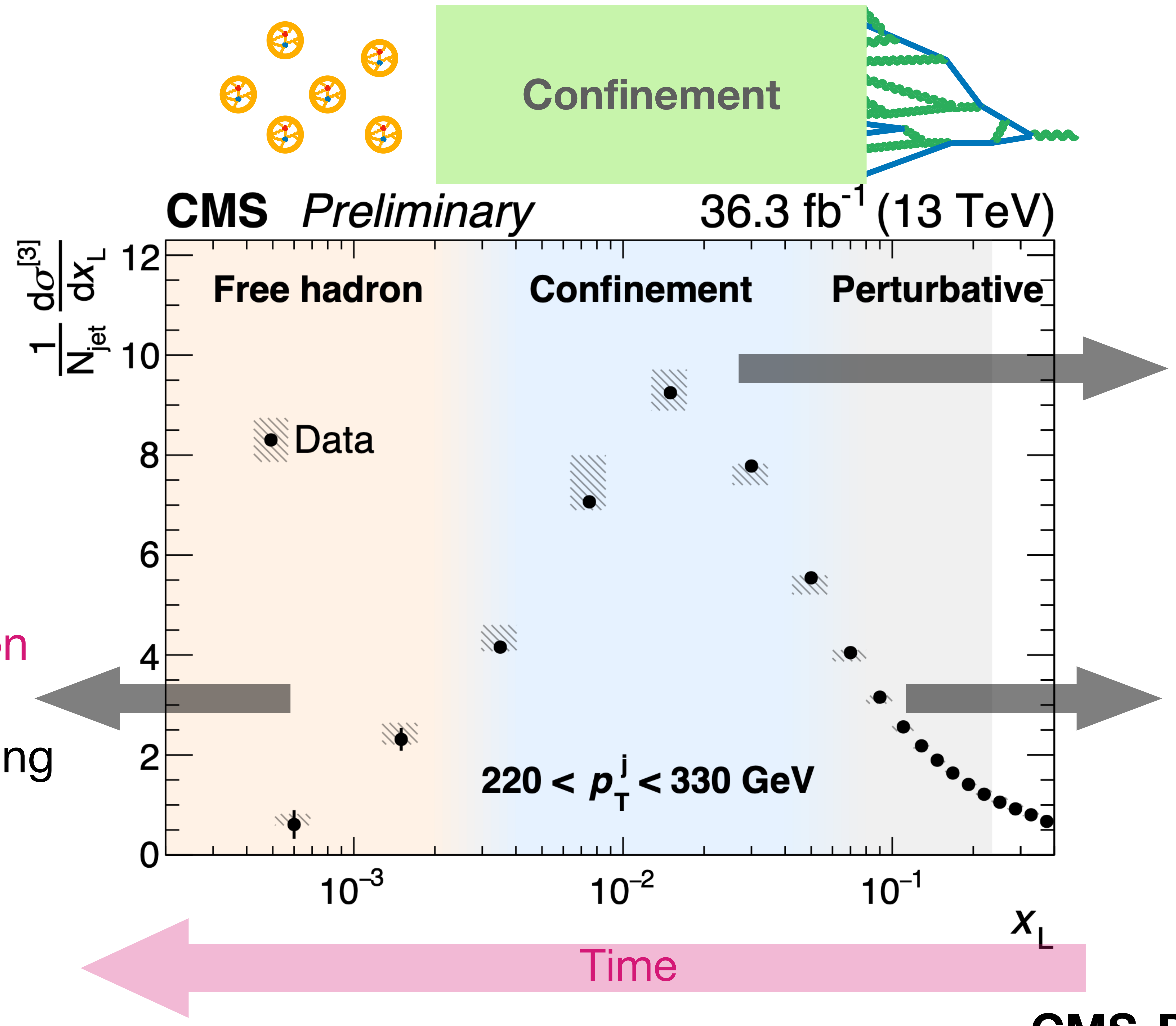
- p_T^{jet}, x_L and energy weight, 3D unfolding
- $10 * 22 * 20 = 4400$ bins





E3C measurement

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



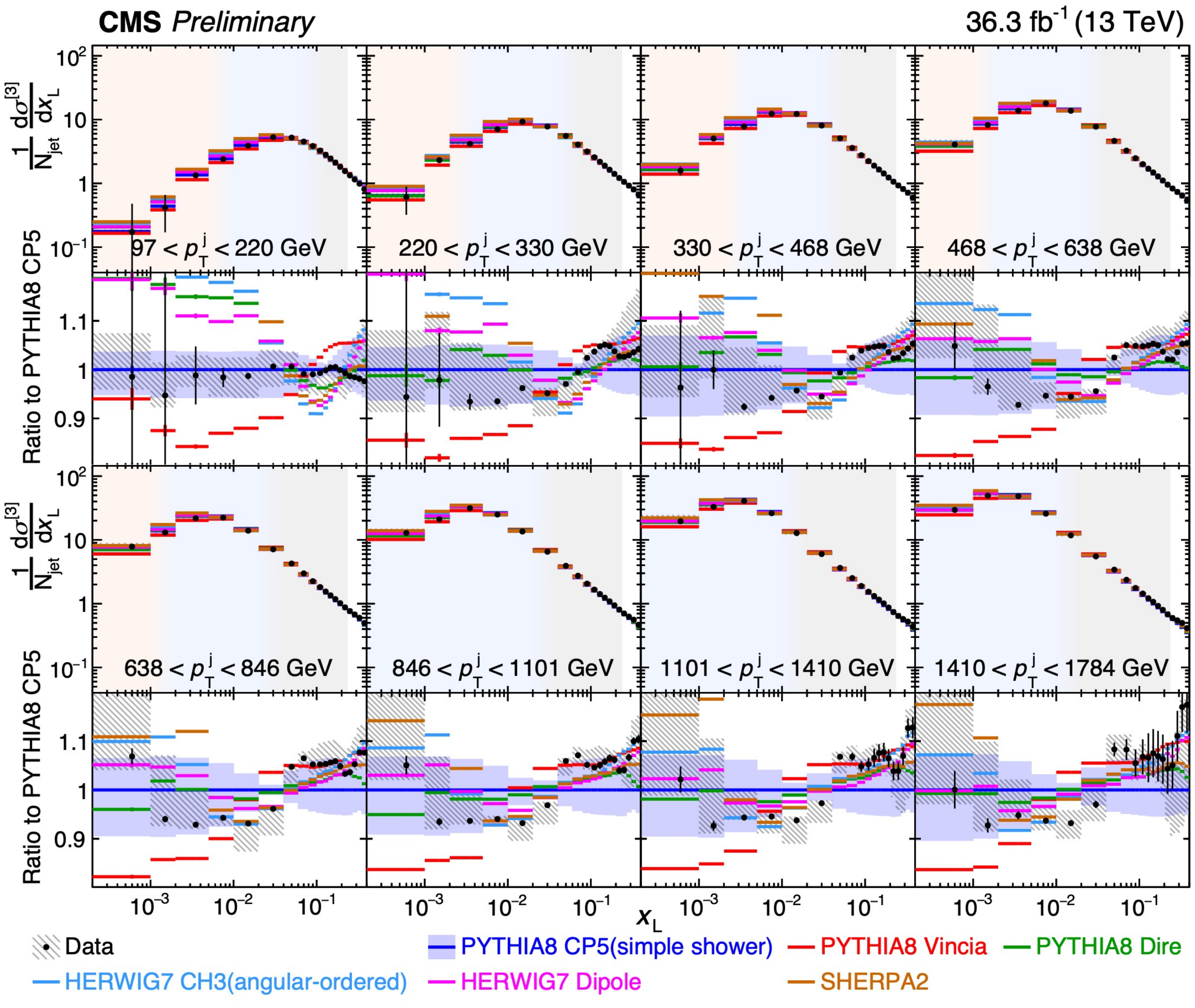
Phase transition
from parton to hadron

Non-interacting hadron
random distribution
integer power-law scaling

Interacting partons
non-integer scaling

CMS-PAS-SMP-22-015
https://cds.cern.ch/record/2866560

E3C in all pT regions

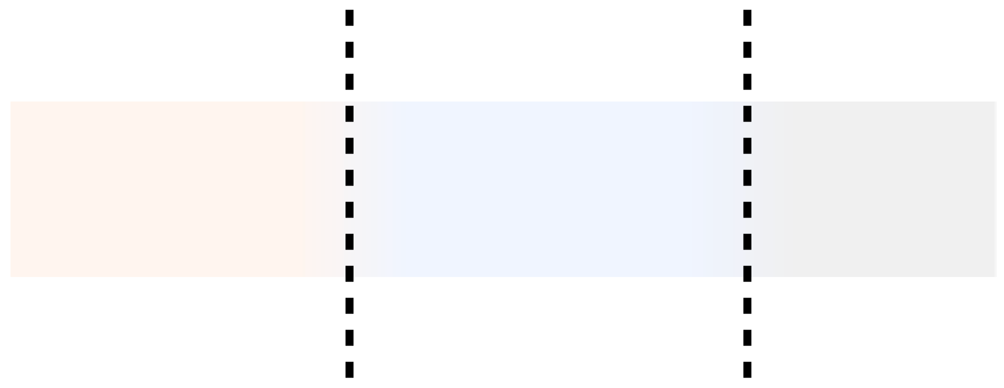


Boundary shift with jet pT

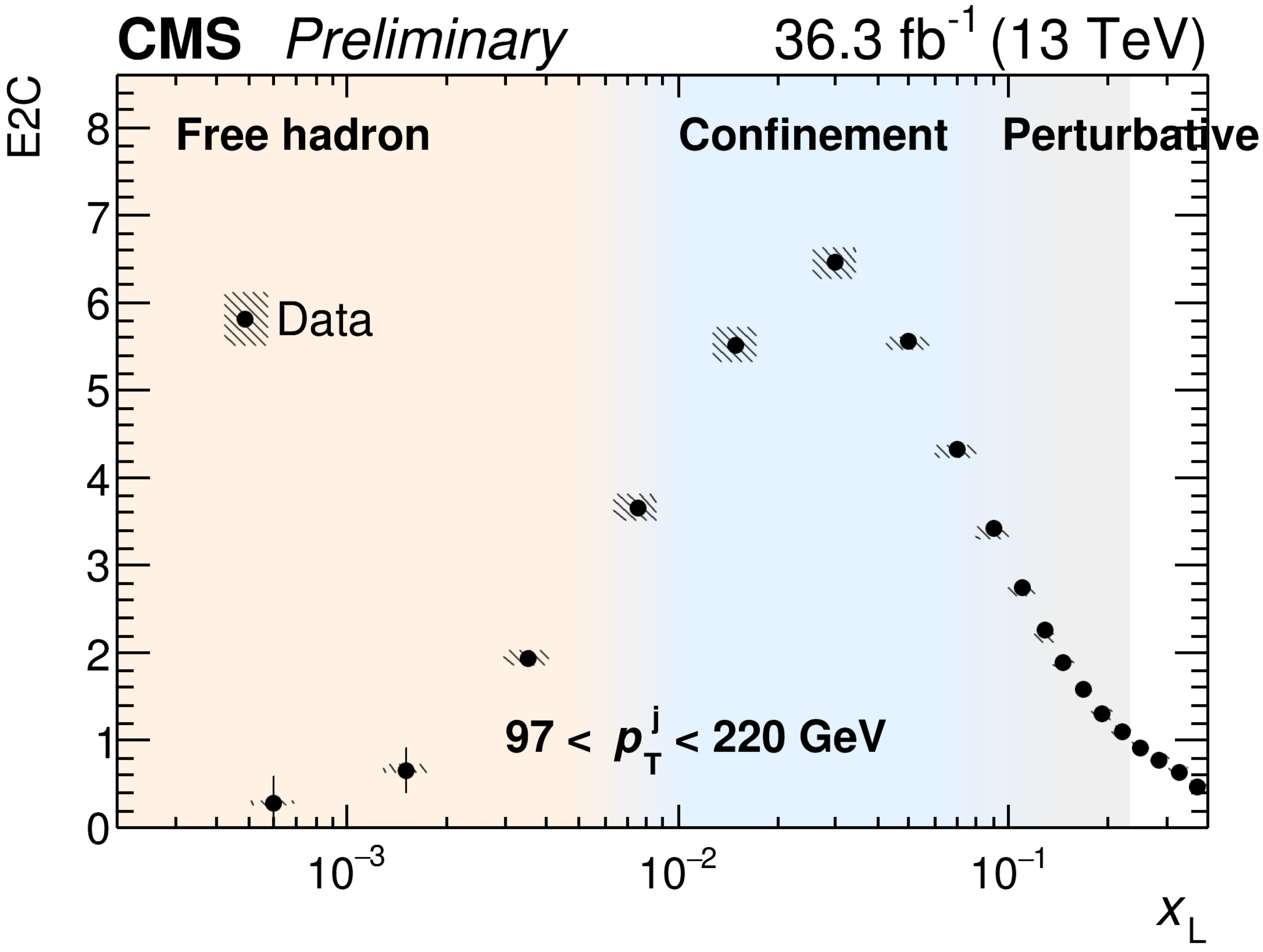
$$Q \propto x_L * p_T^{jet}$$

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

Boundary



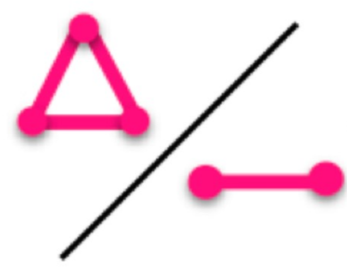
$$x_L \approx \frac{0.8}{p_T^{jet}} \quad x_L \approx \frac{20}{p_T^{jet}}$$


CMS Preliminary
36.3 fb^{-1} (13 TeV)
E2C
Free hadron
Confinement
Perturbative
Data
97 < p_T^j < 220 GeV
0
1
2
3
4
5
6
7
8
10^{-3}
10^{-2}
10^{-1}
x_L

E3C/E2C: a new way to extract α_S

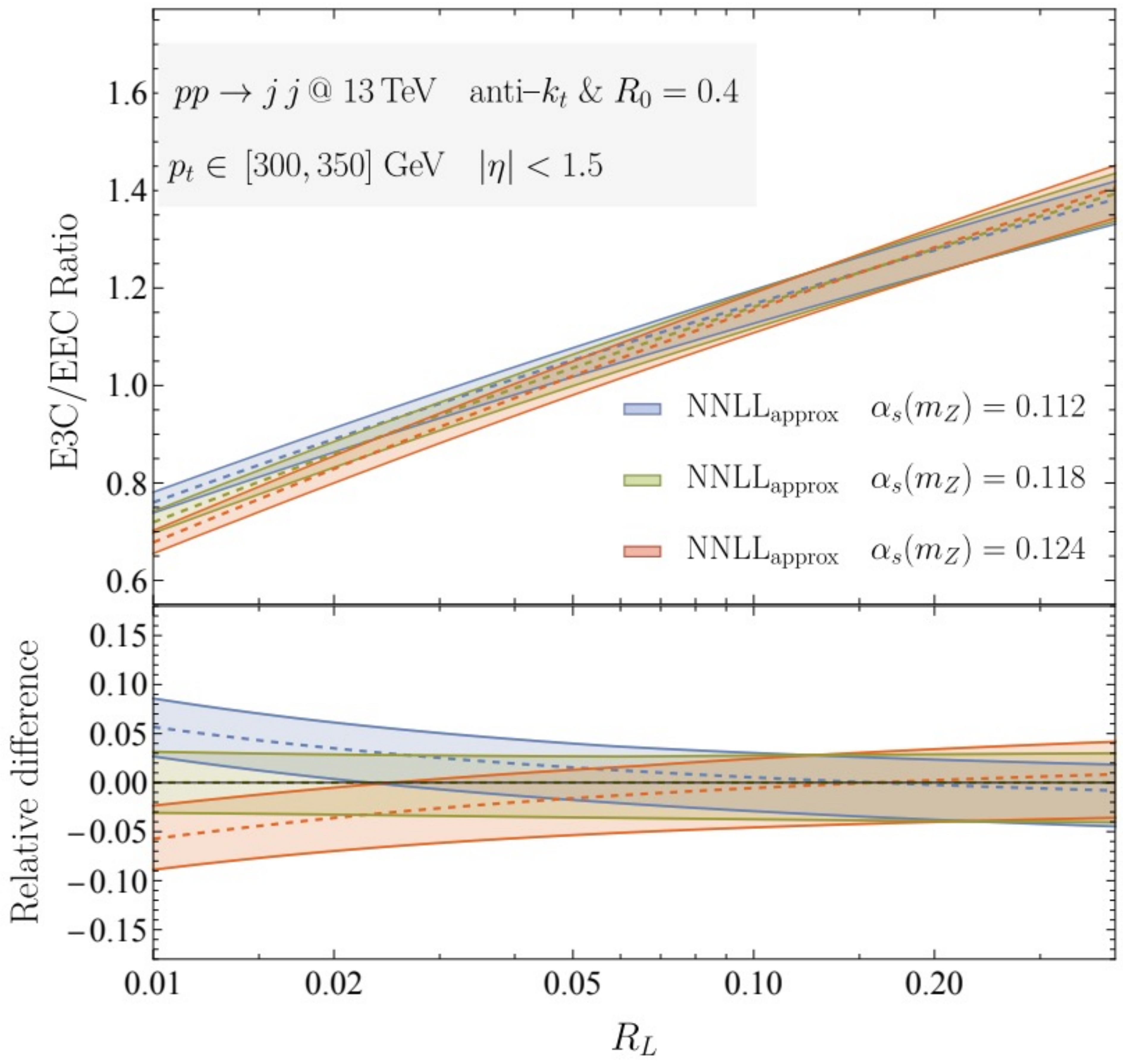
Chen, Gao, Li, Xu, Zhang, Zhu, [arXiv:2307.07510](https://arxiv.org/abs/2307.07510)

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



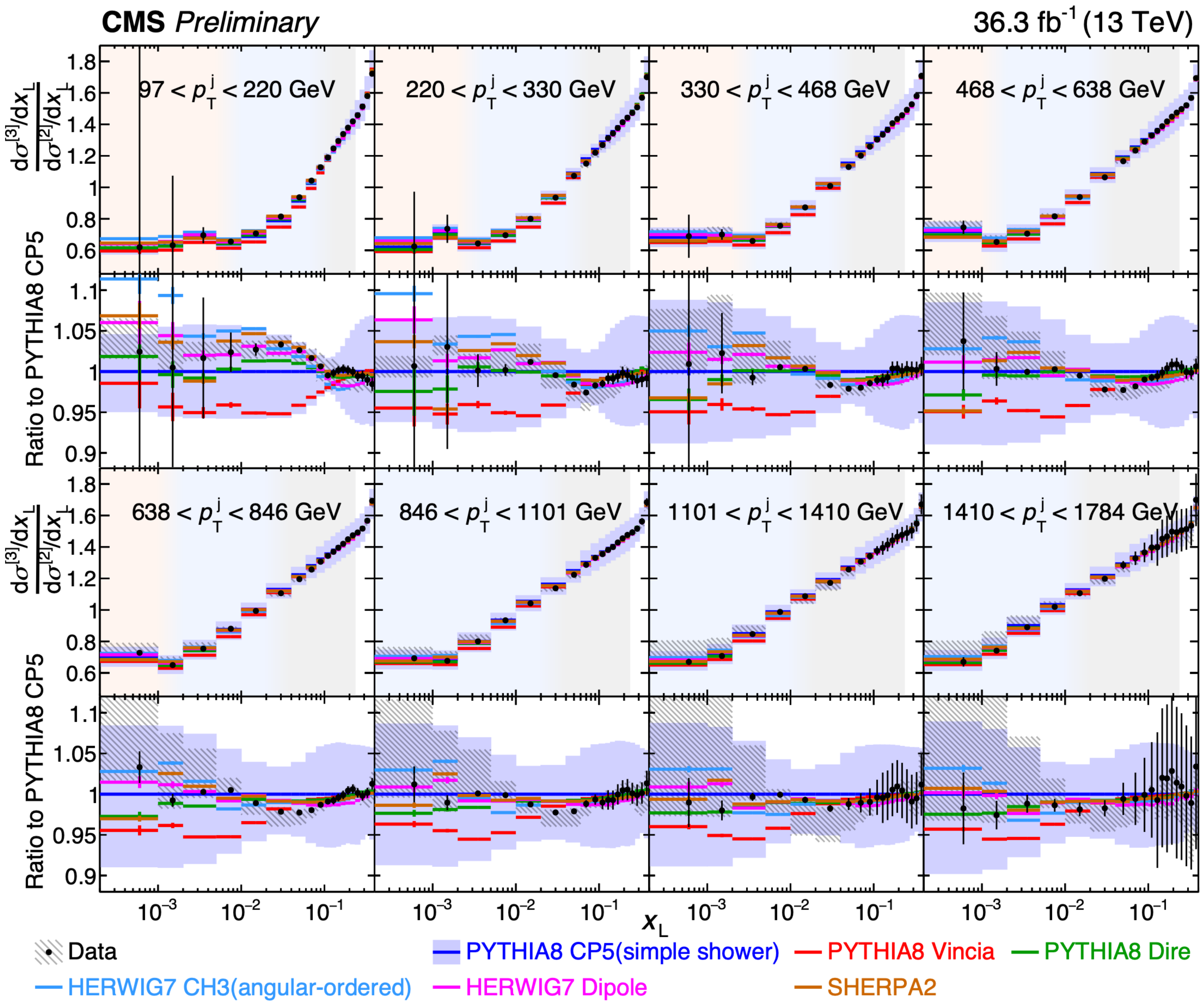
$$\propto \alpha_S(Q) \ln x_L + O(\alpha_S^2)$$

- Ci factors enter E3C and E2C and partially cancel

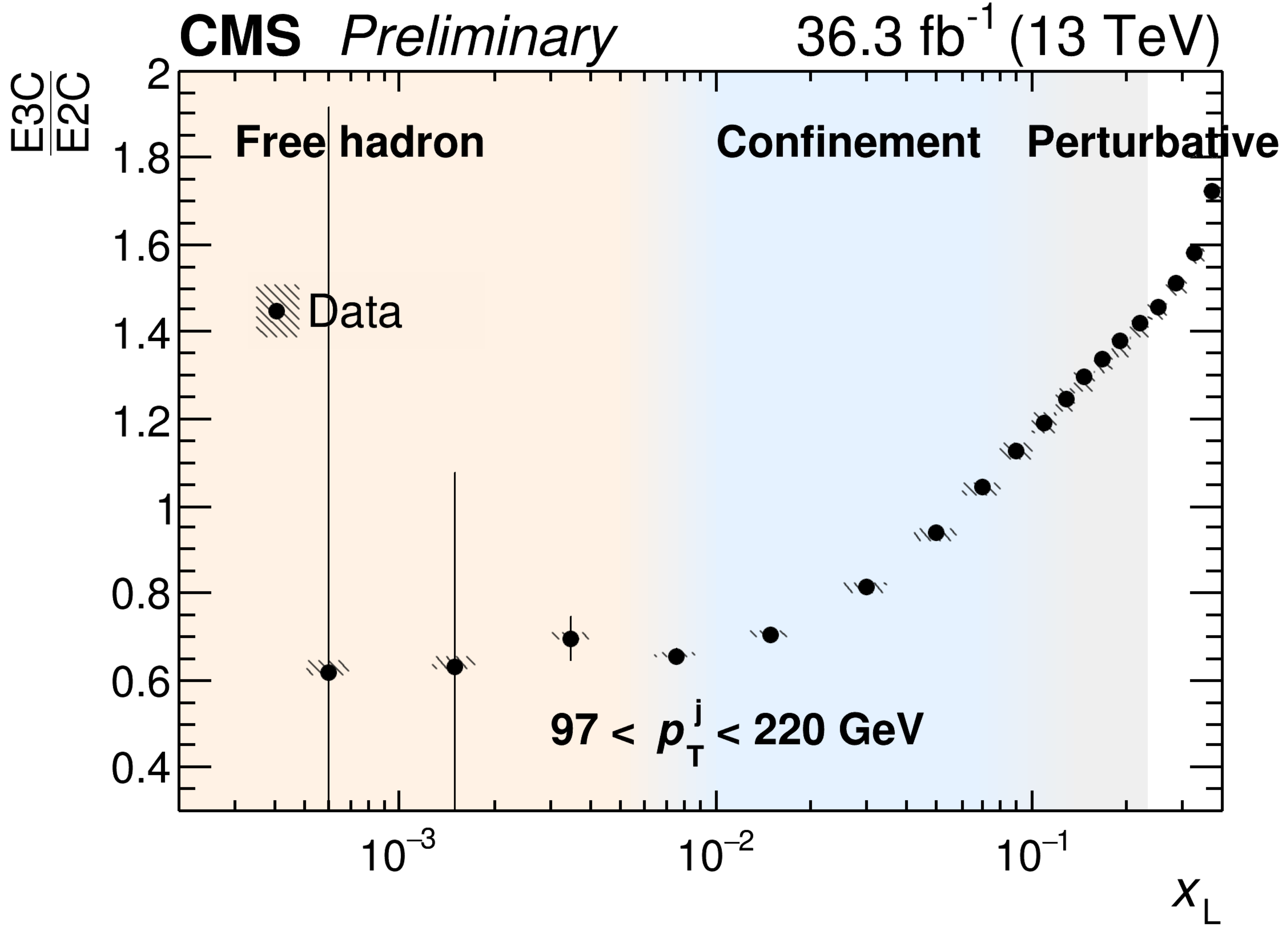


$\alpha_S(M_Z) \uparrow$ Slope $\uparrow$

E3C/E2C



p_T^{jet} ↑, Slope ↓


CMS Preliminary
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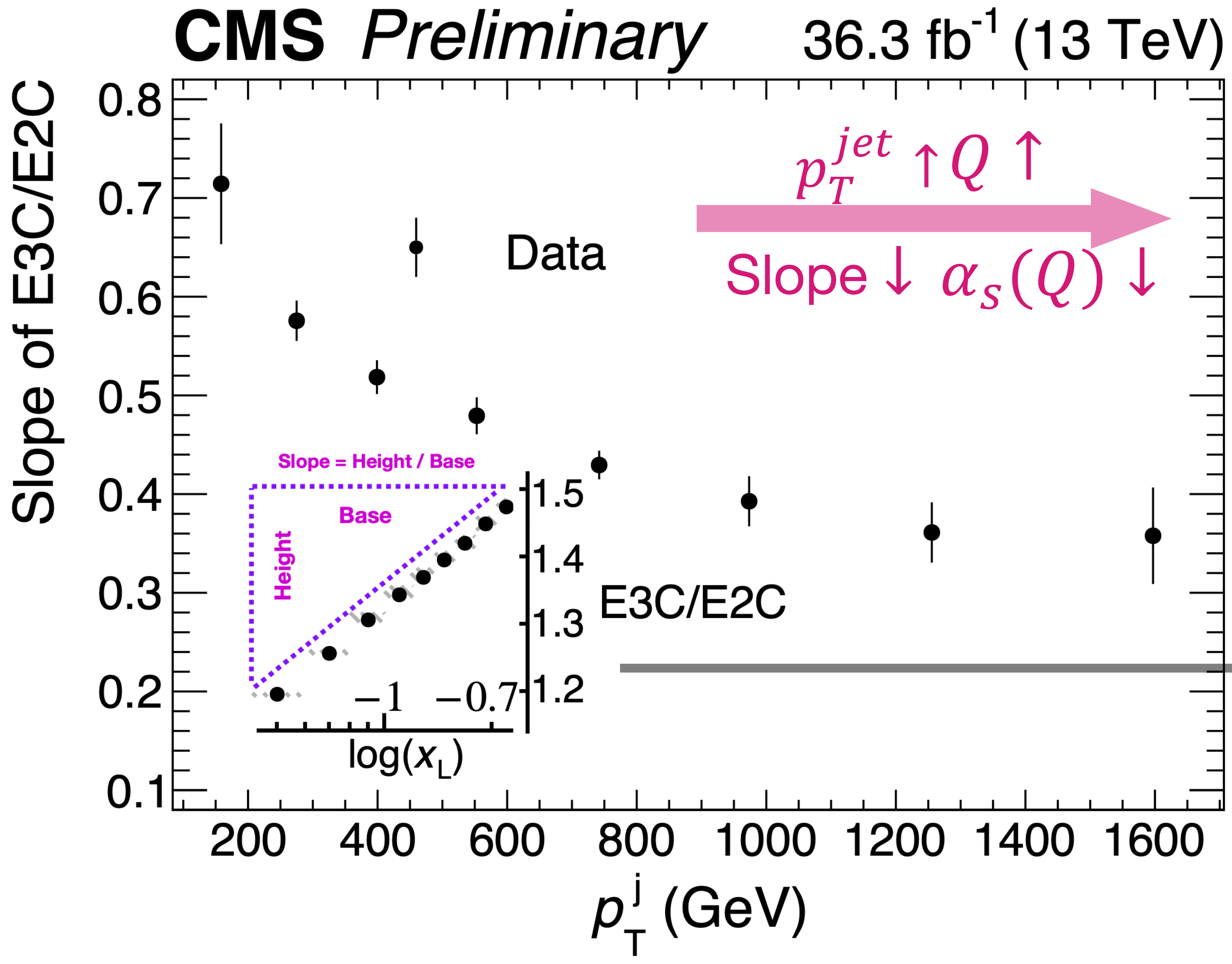
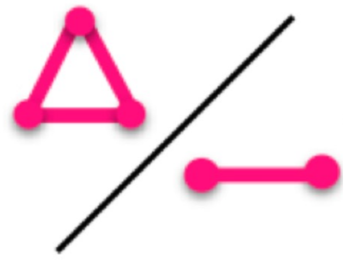
E3C / E2C
Free hadron
Confinement
Perturbative
Data
97 < p_T^j < 220 GeV
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
10−3
10−2
10−1
x_L

p_T^{jet} ↑, Slope ↓

Direct observation of asymptotic freedom

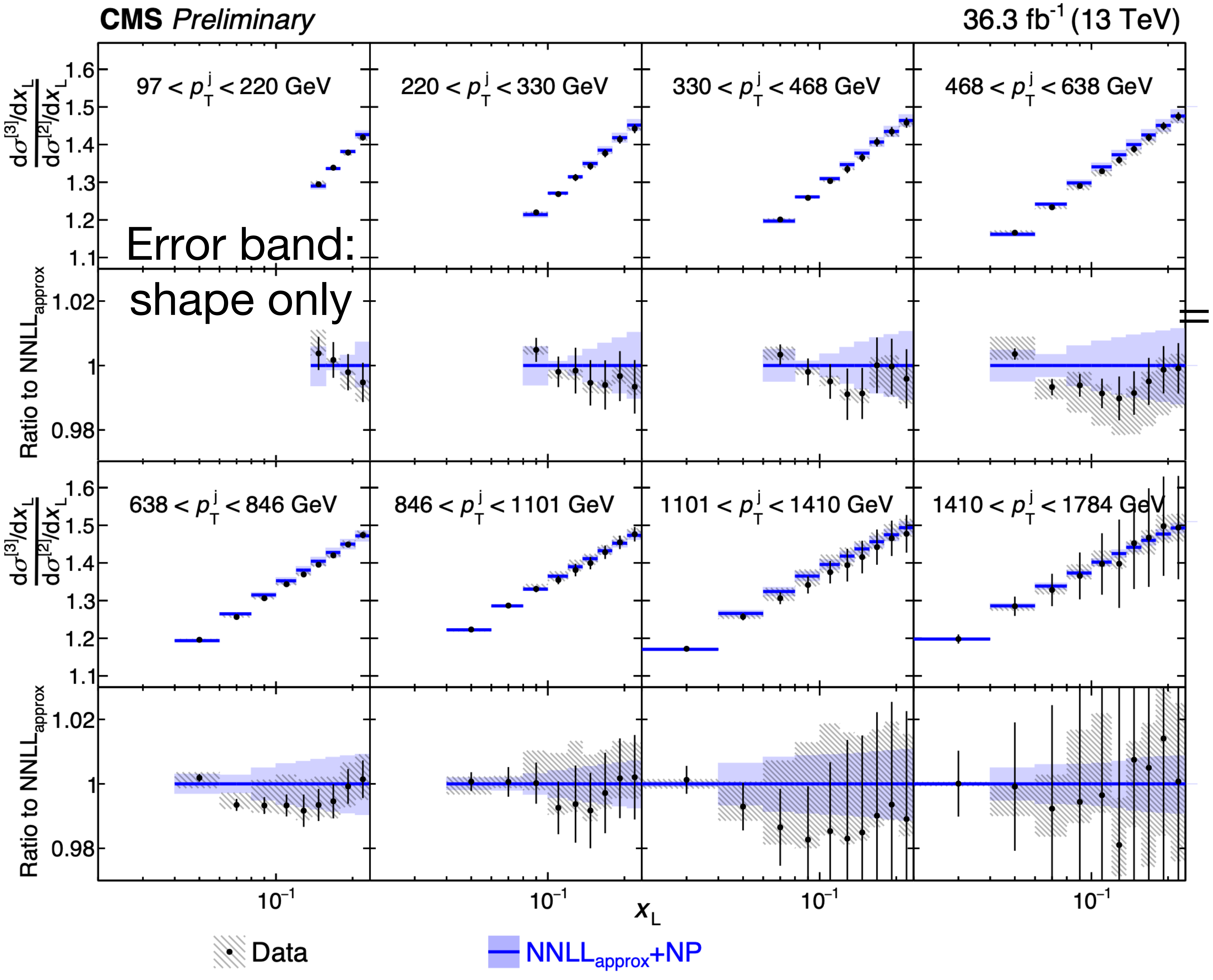




$\propto \alpha_s(Q) \ln x_L + O(\alpha_s^2)$

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

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

- 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