



Measurements of energy correlators in jets and α_S extraction at CMS

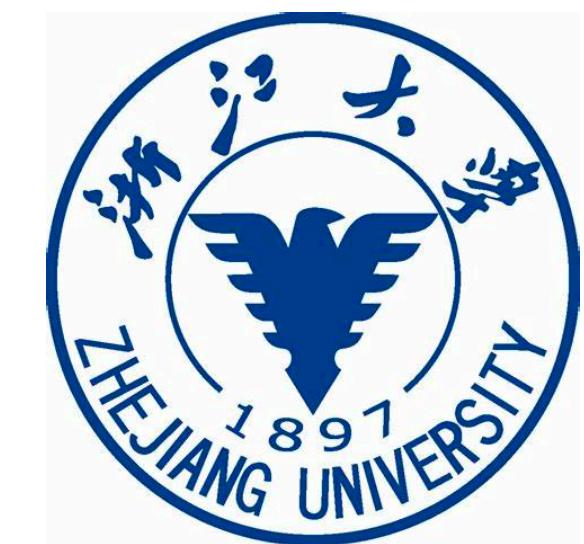
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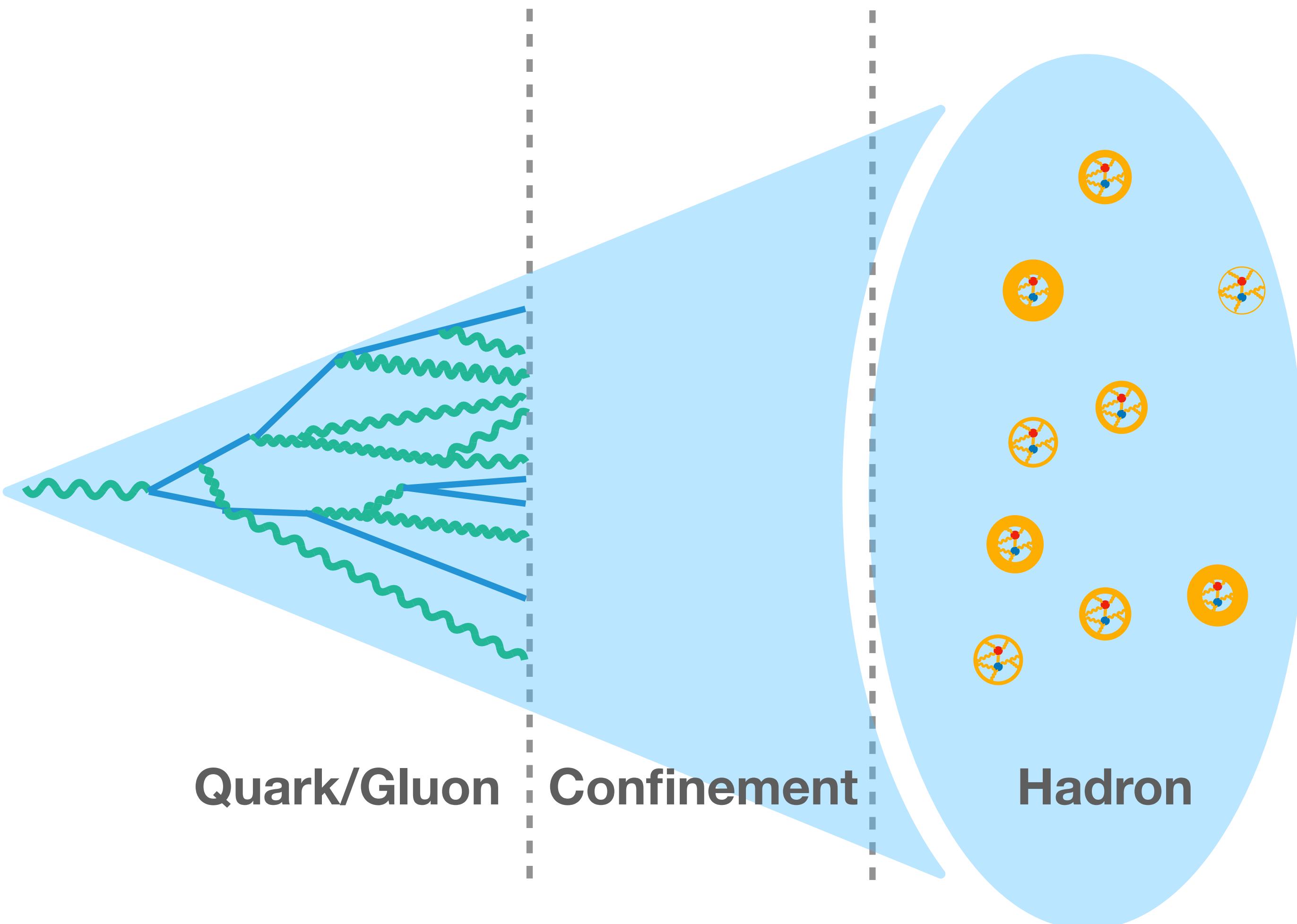
Chenfeng Lu

On behalf of CMS Collaboration, Zhejiang University

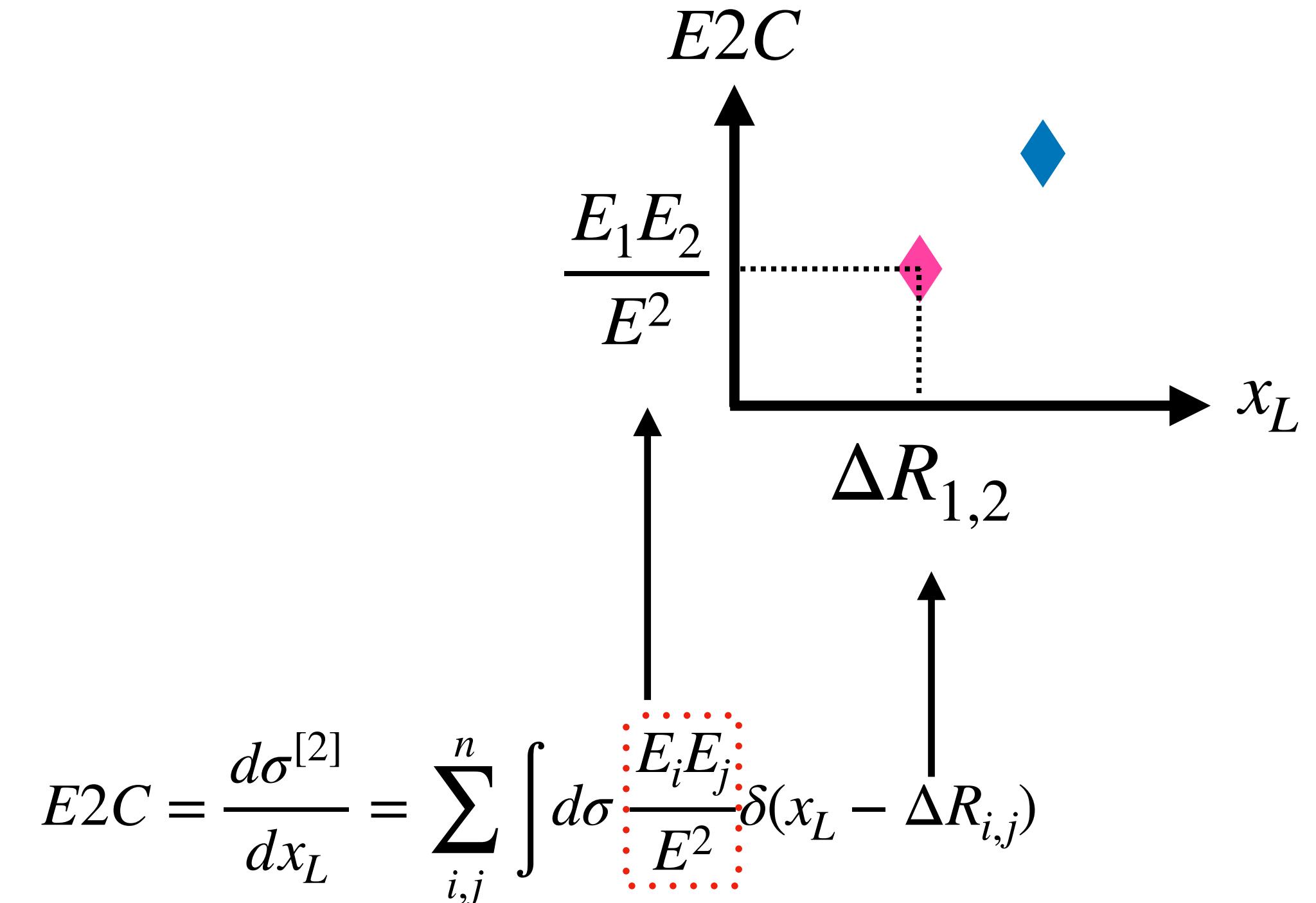
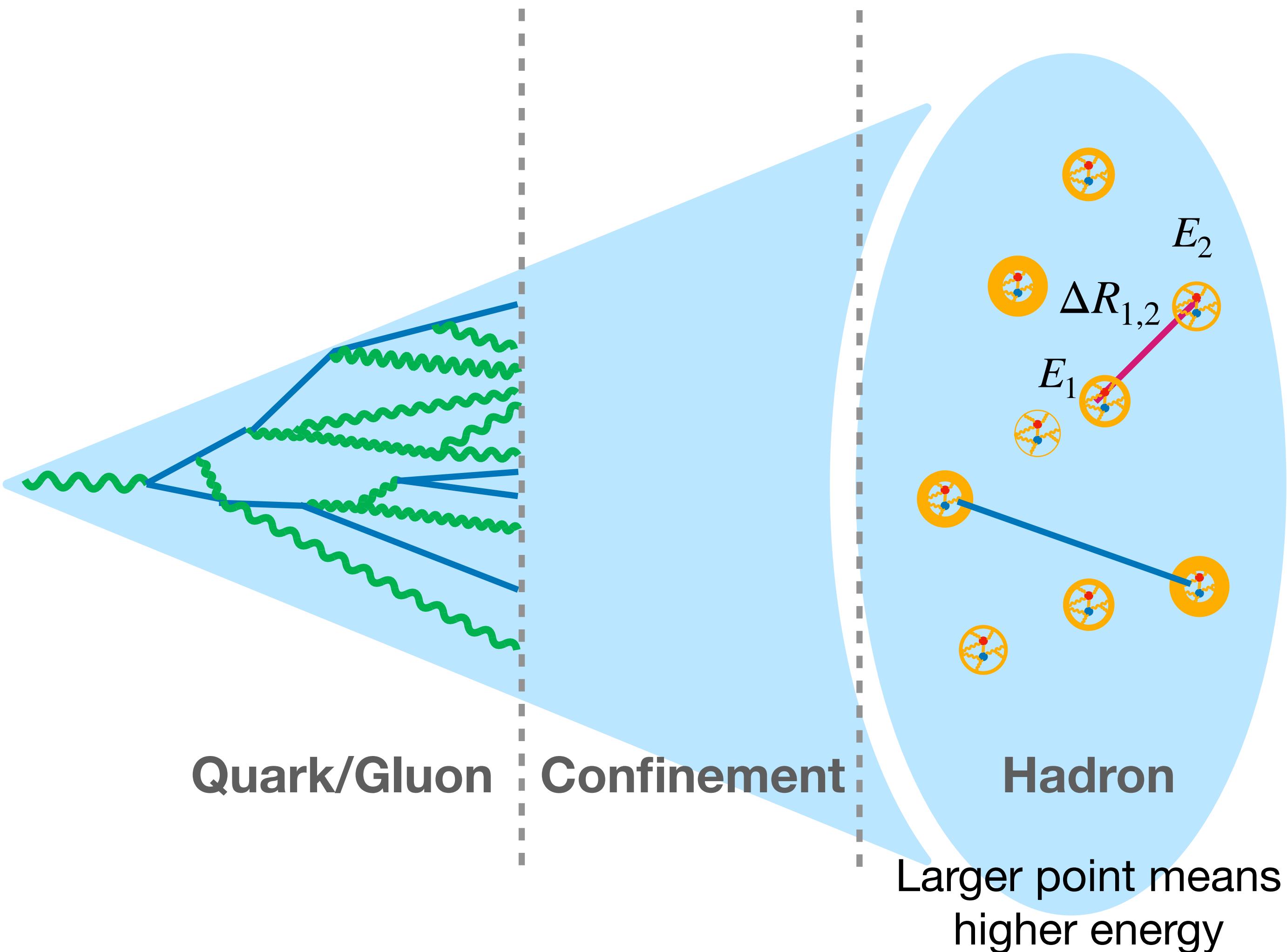
BOOST 2023, July 31, 2023



Jet formation

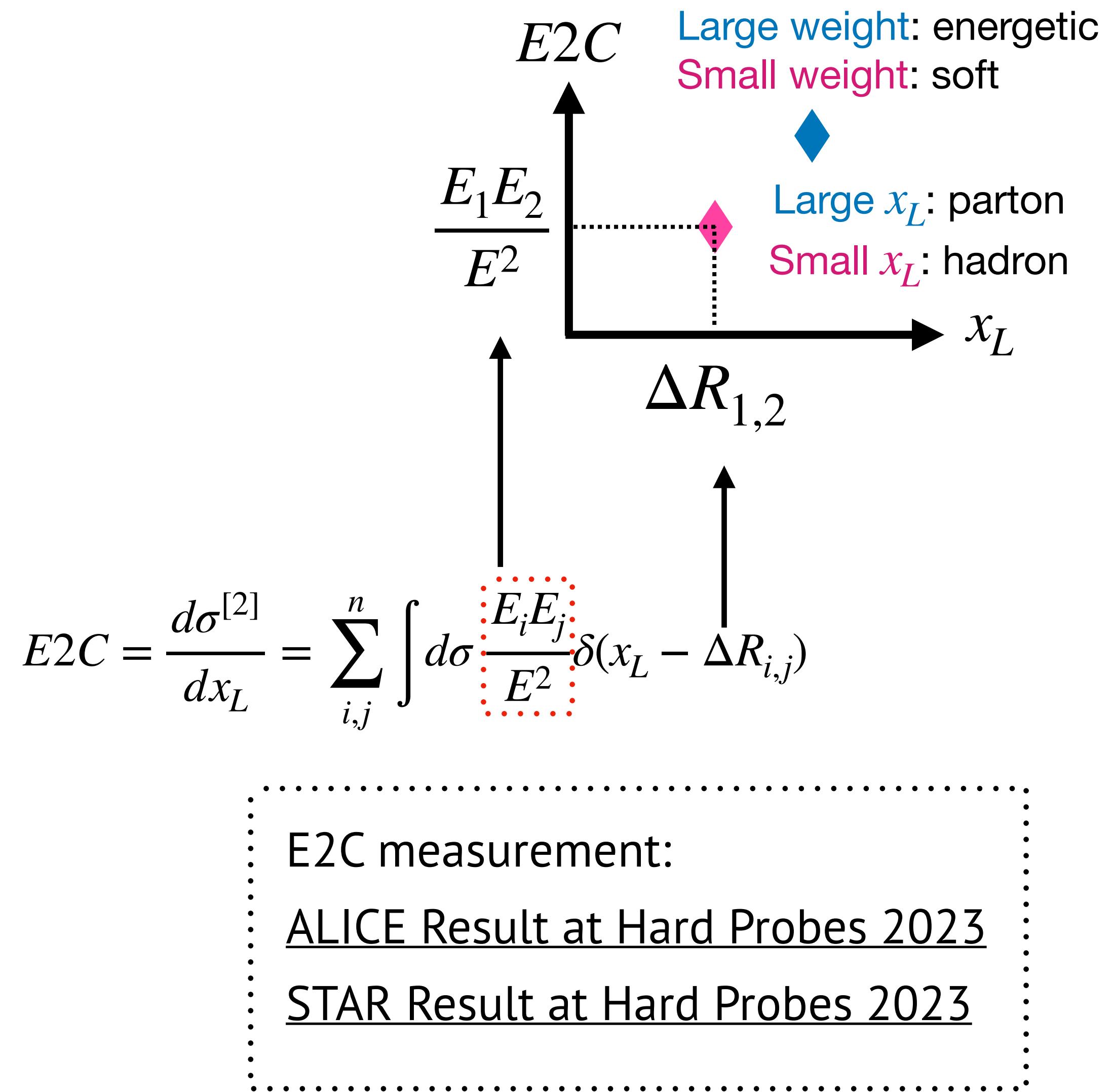
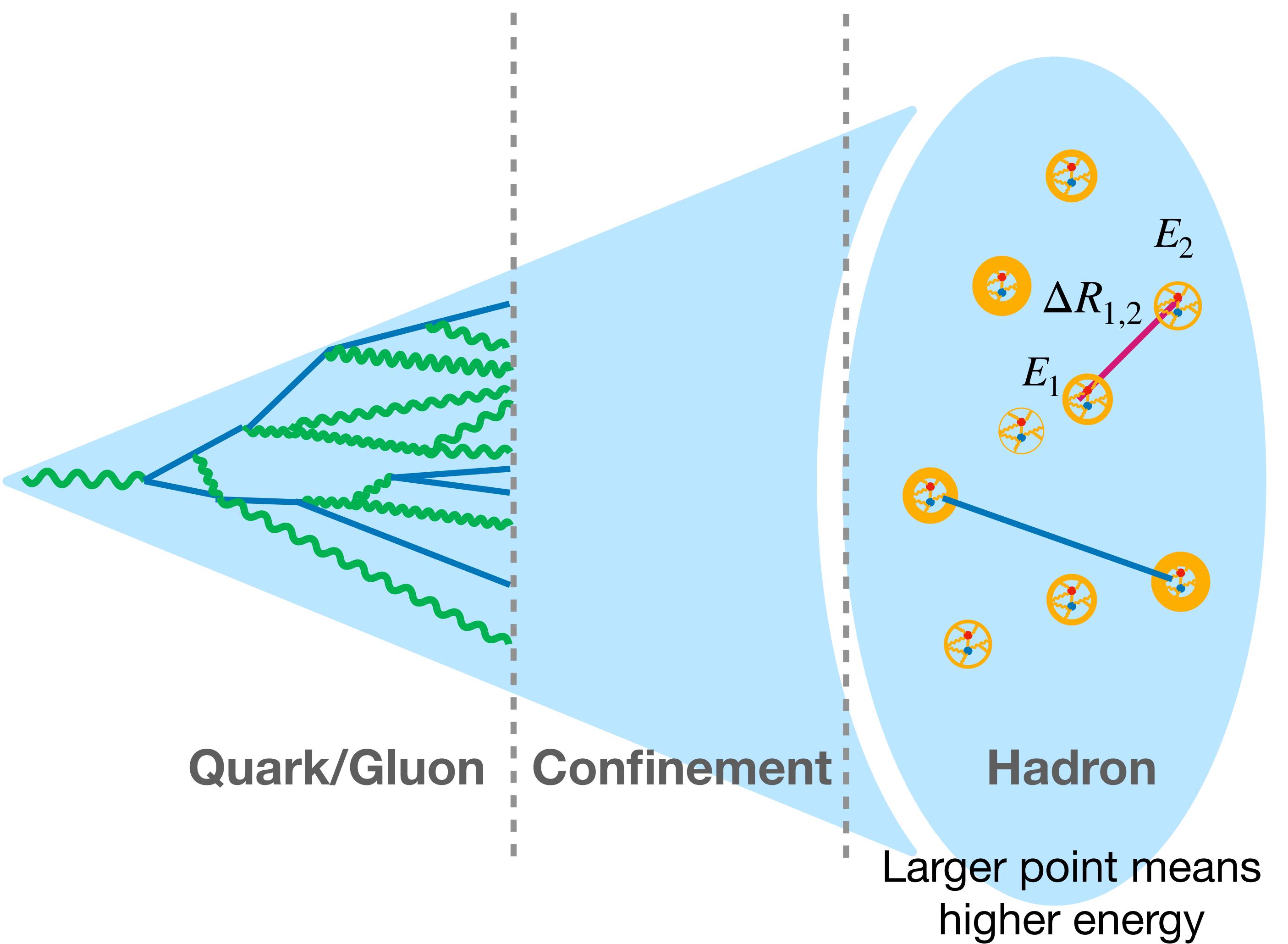


Energy correlators

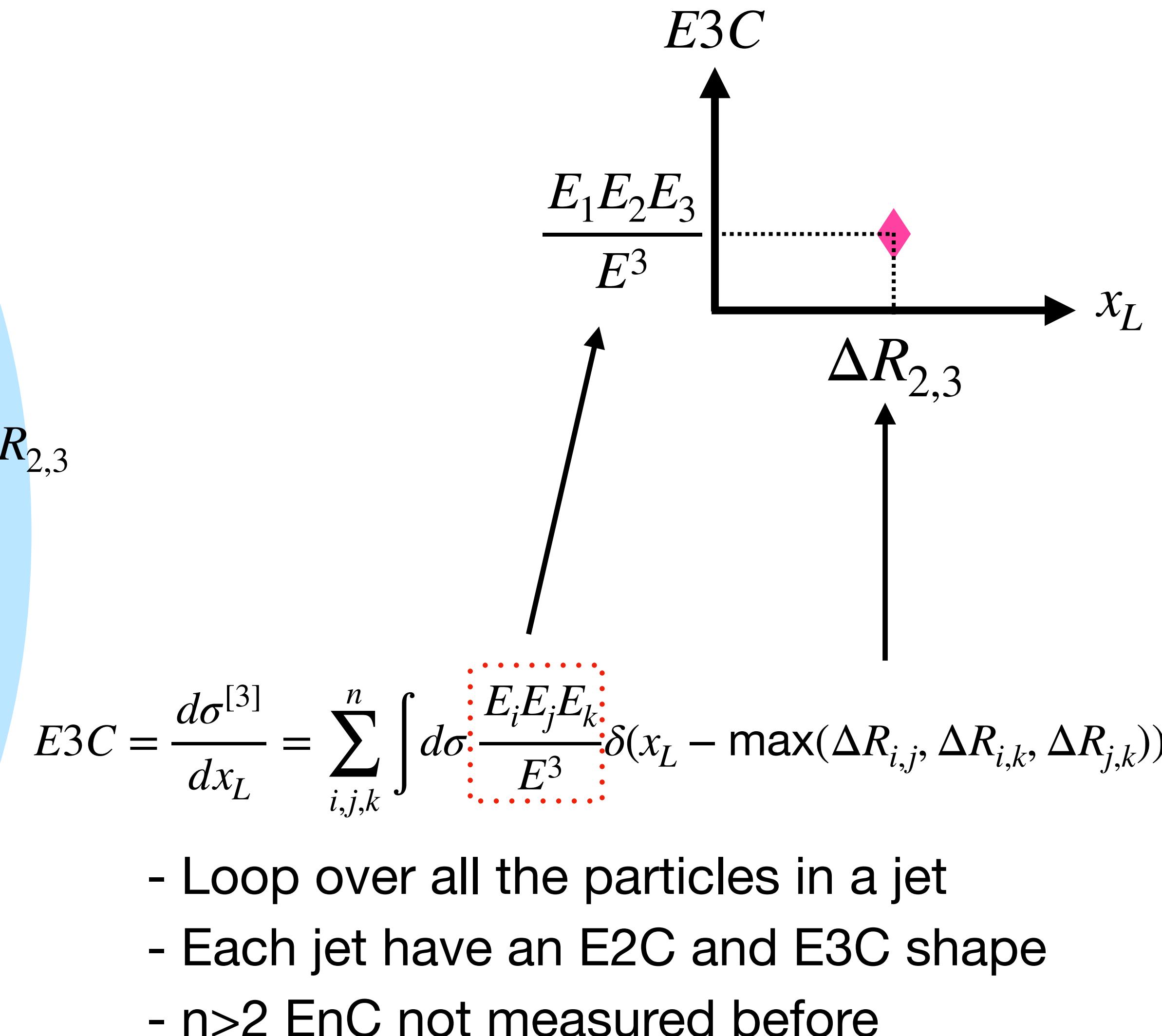
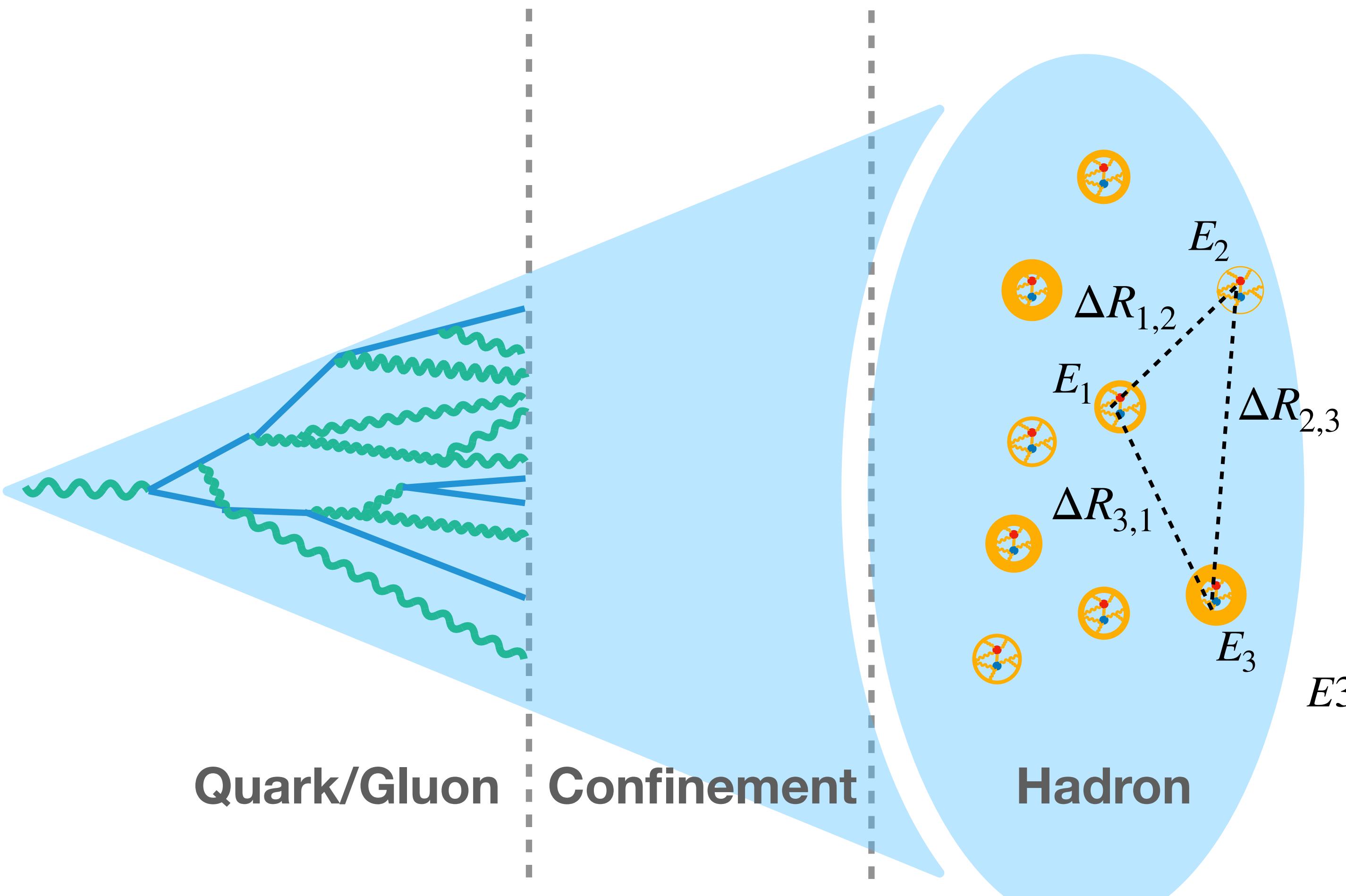


- Chen, Moult, Zhang, and Zhu, [arXiv:2004.11381](https://arxiv.org/abs/2004.11381)
- Lee, Meçaj, and Moult, [arXiv:2205.03414](https://arxiv.org/abs/2205.03414)
- Chen, Gao, Li, Xu, Zhang, and Zhu, [arXiv:2307.07510](https://arxiv.org/abs/2307.07510)

Energy correlators

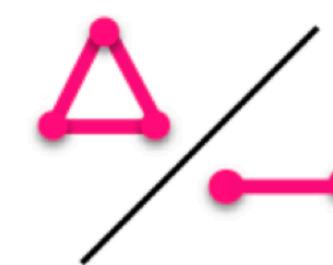


Energy correlators



E3C/E2C: a novel way to extract α_s

In QFT at LL, E3C/E2C is a linear function of α_s



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

Difficulties in extracting α_s from jet substructure:

Degeneracy between q/g fraction and α_s

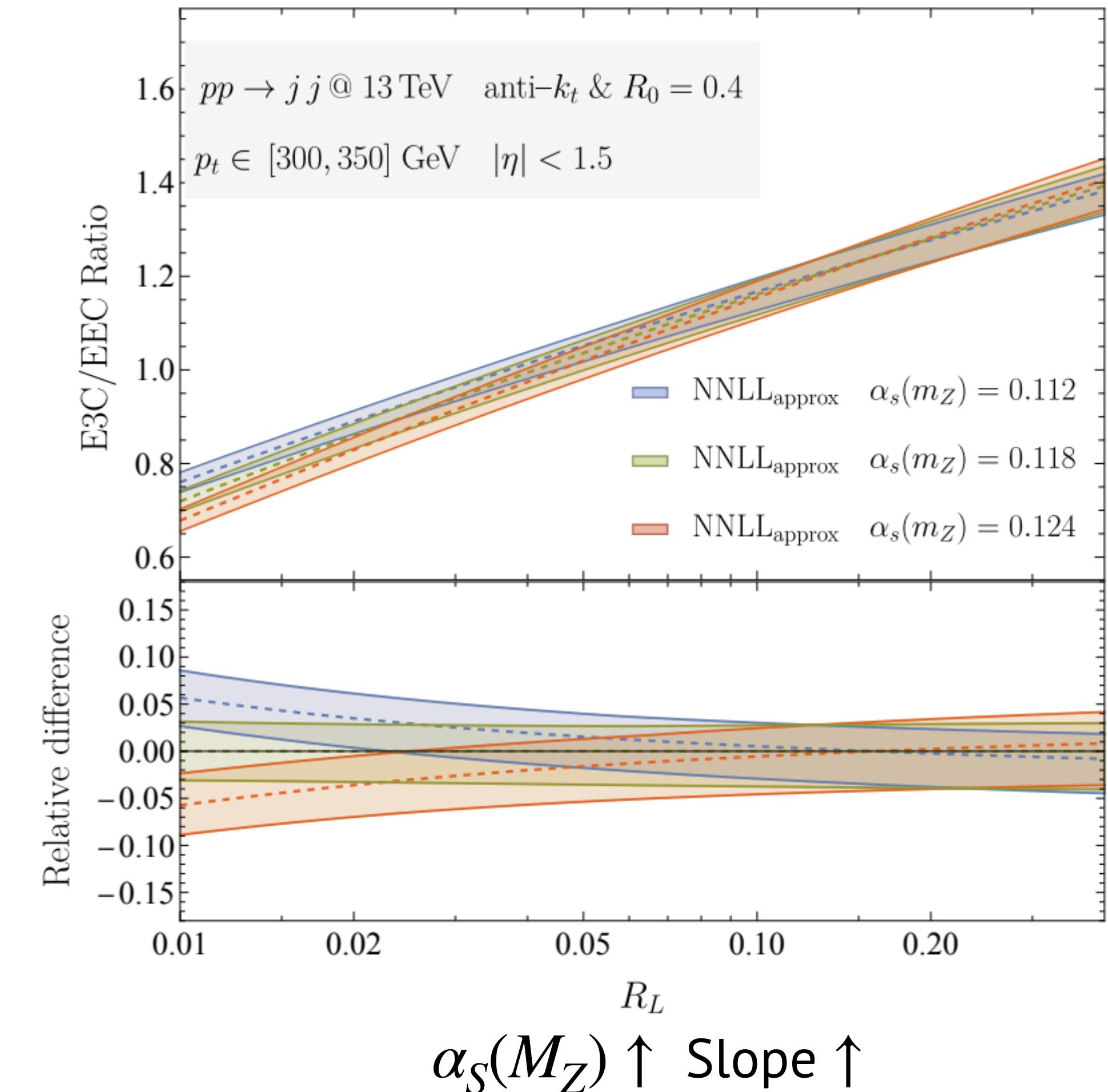
$$\alpha_s * C_i$$

Solution: E3C/E2C ratio mitigates the degeneracy

Former jet substructure α_s extraction: ~ 10%,

[arXiv:1808.07340](https://arxiv.org/abs/1808.07340)

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



Analysis introduction

Dijet events, $|\eta| < 2.1$

Measure E2C, E3C

- Compare to MC

- Large cross section

PF jet, anti-kT with $R = 0.4$,
CHS(PU charged hadron subtraction)

Measure E3C/E2C

- Compare to theoretical calculation
- α_S extraction

$8 p_T^{jet}$ region in $97 \sim 1784$ GeV

- Probe energy scale dependency

Neutral & charged particles with $p_T > 1$ GeV

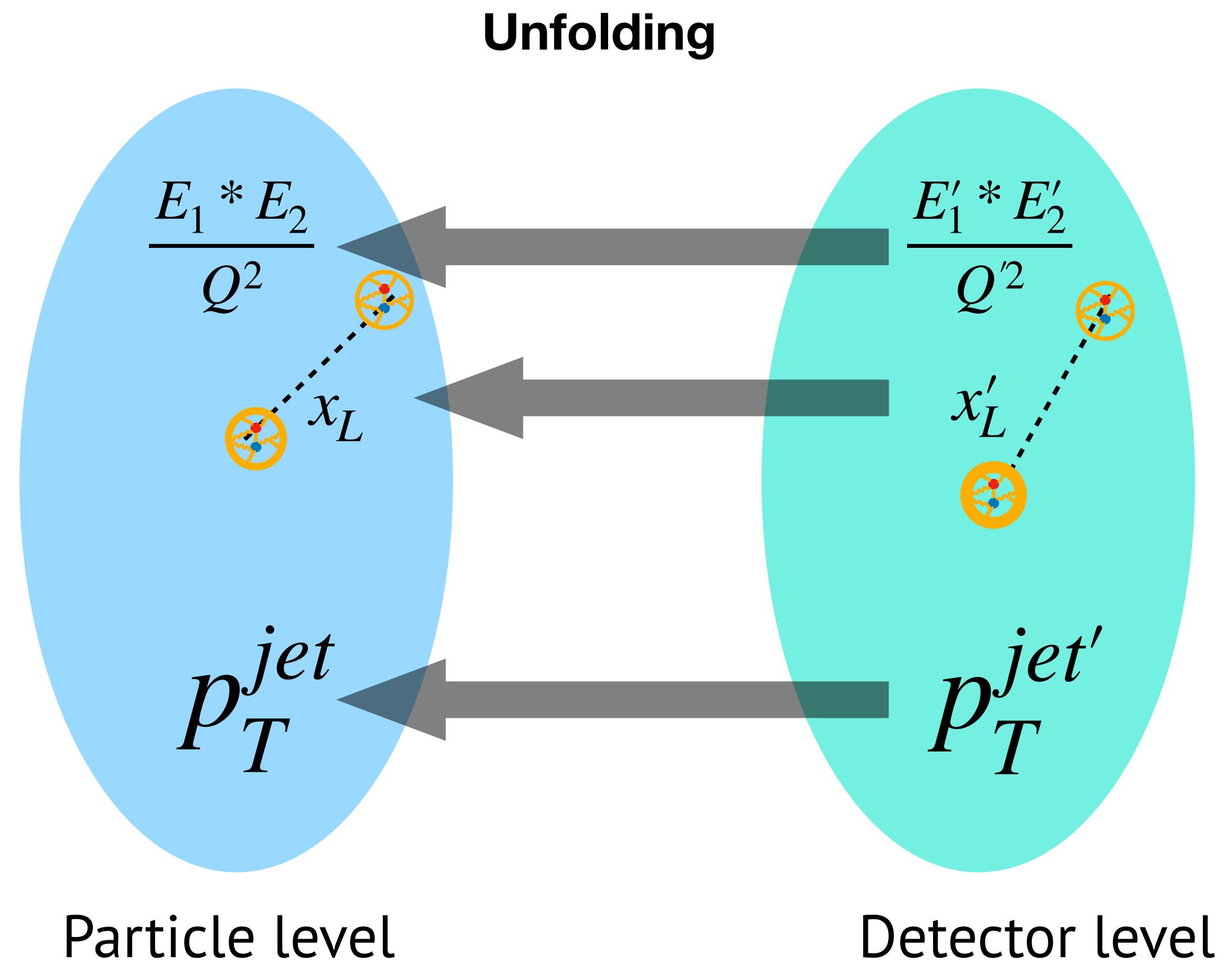
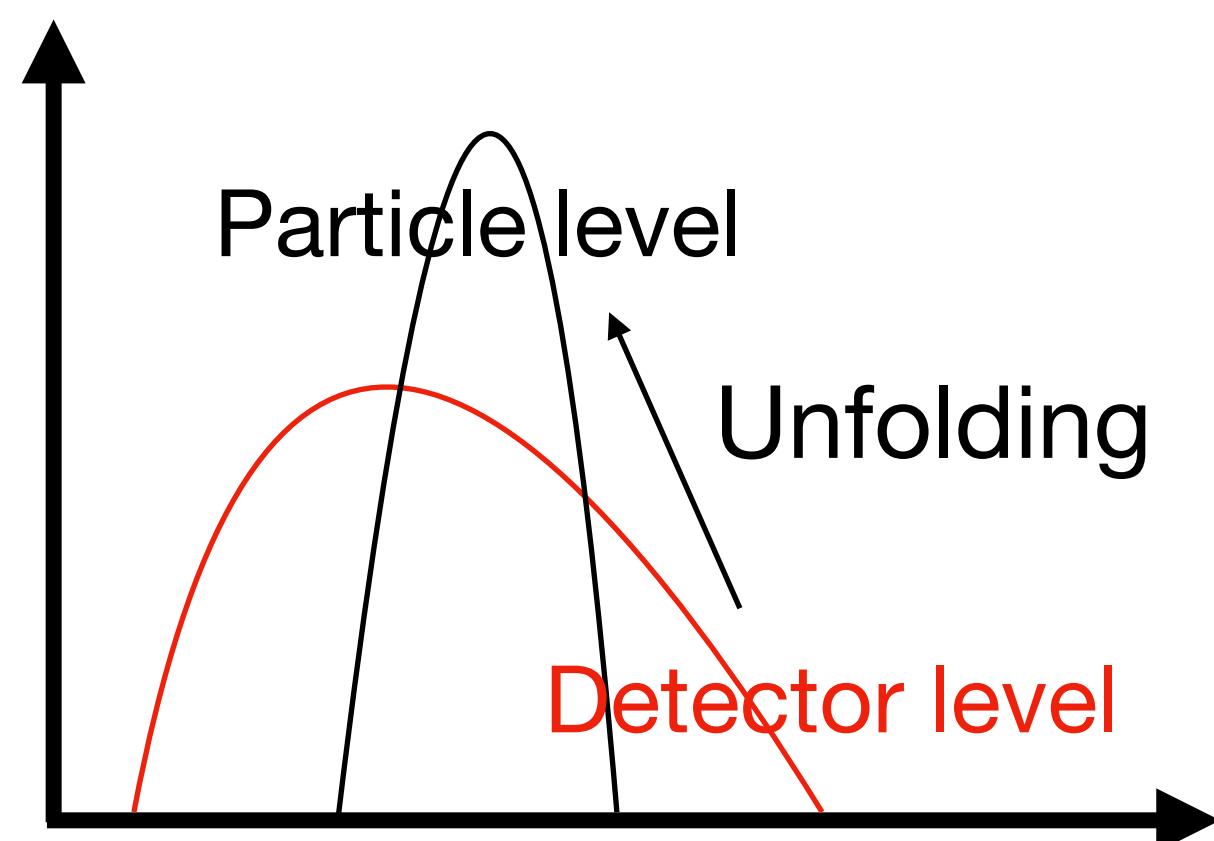
- All particles included, direct comparison with theoretical calculation

Key feature of this analysis: constituents unfolding

Unfolding: detector level \rightarrow particle level

Unfold jet constituents instead of distribution:

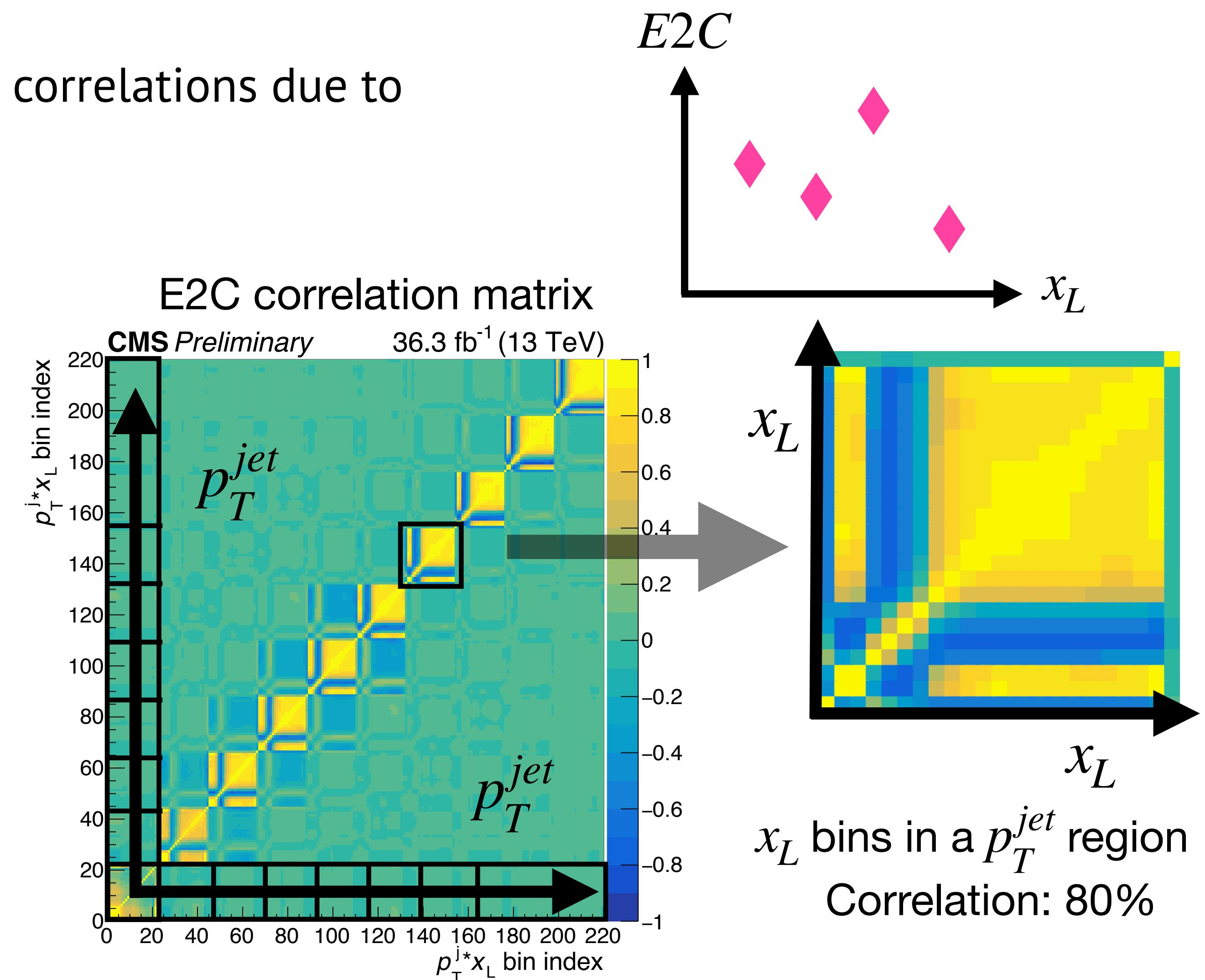
- p_T^{jet}, x_L and energy weight, 3D unfolding
- $10 * 22 * 20 = 4400$ bins
- D'Agostini: iterative bayesian



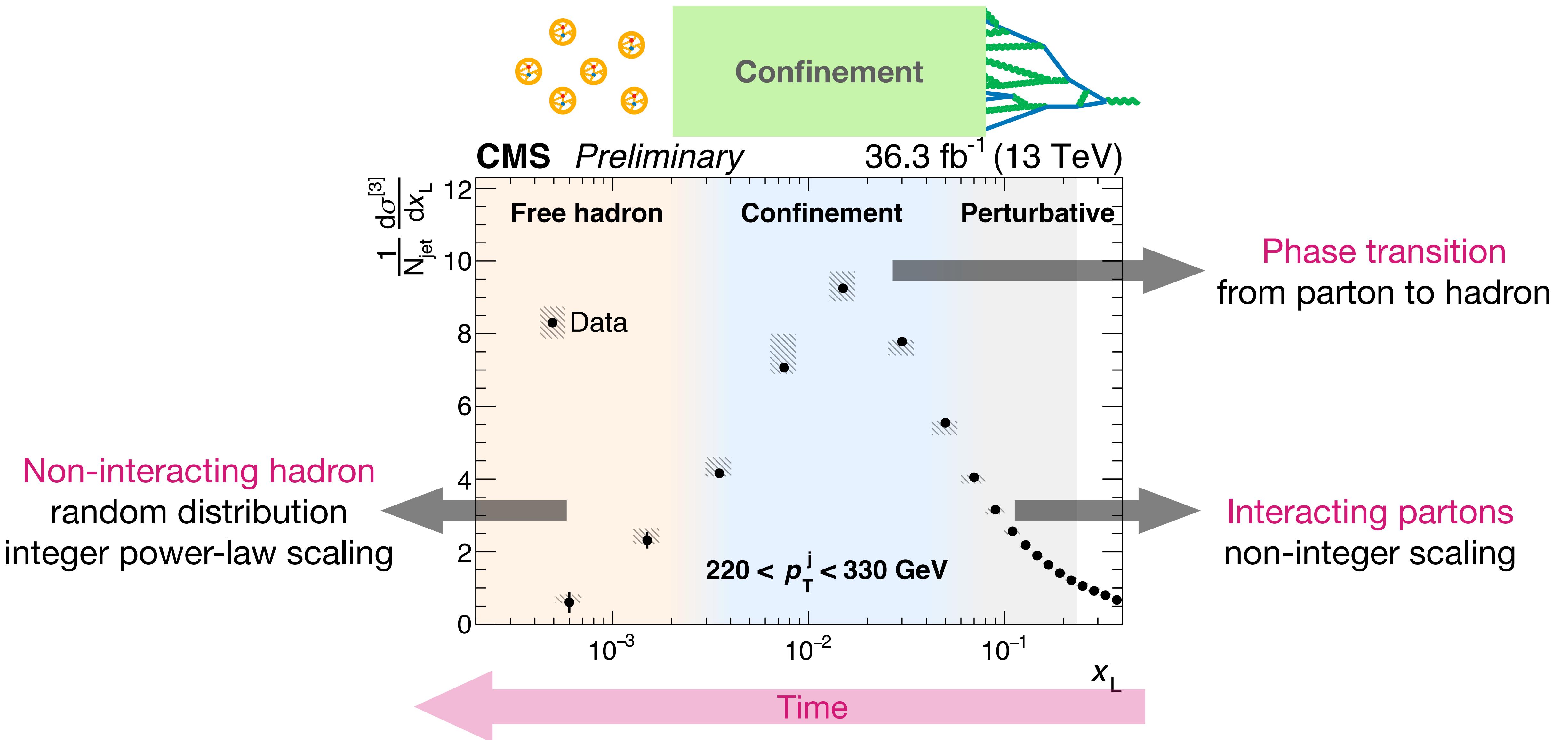
Key feature of this analysis: statistical correlations

EnC is a multi entry distribution for every jet, correlations due to

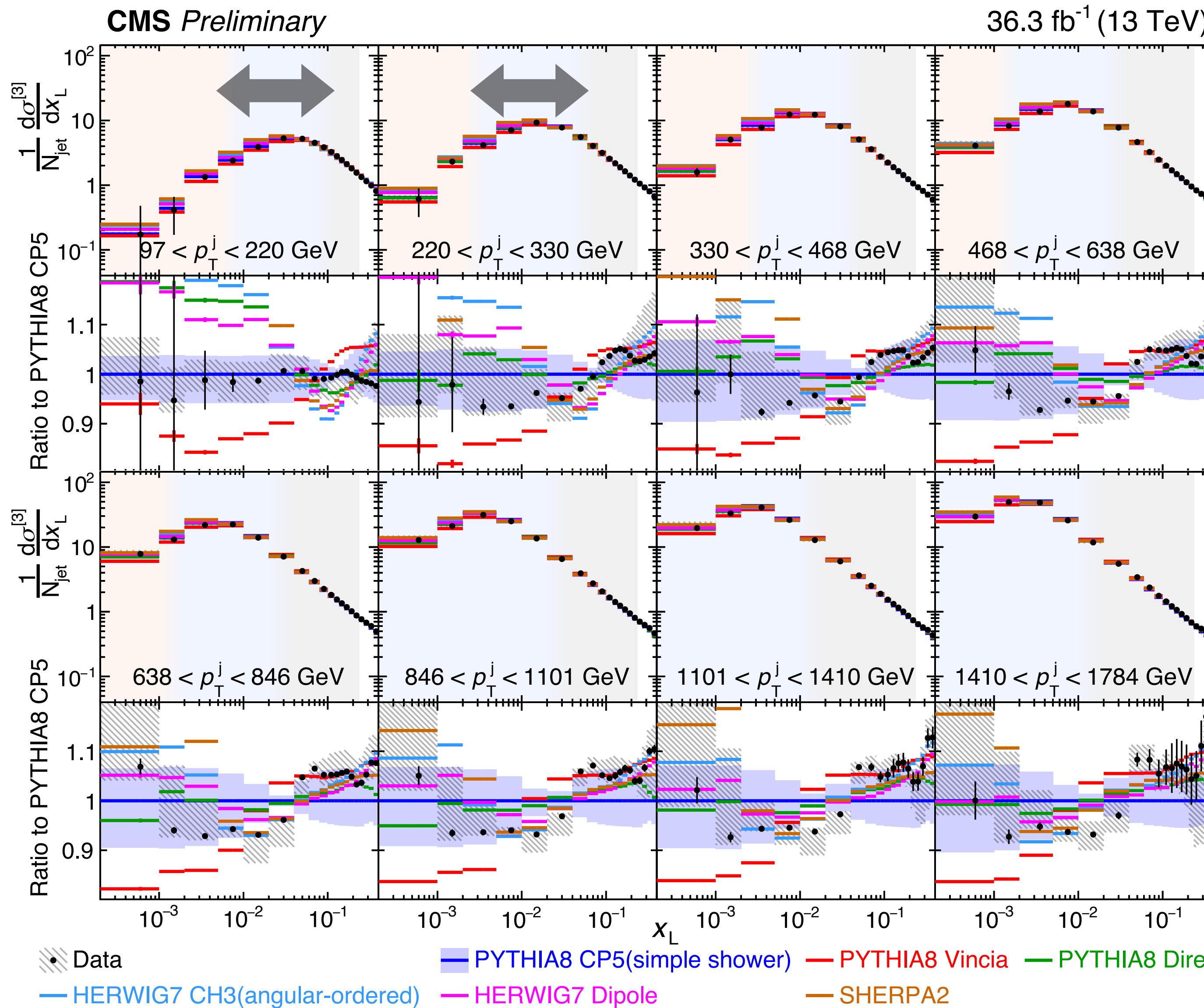
- Multiple particle pairs in a single jet
- Two jets in a single event
- Record covariance matrix at detector level
- Covariance propagation through unfolding
- Additional correlation in normalization
- Independent statistics for E2C, E3C



Unfolded E3C distribution: confinement



Unfolded E3C vs MC



Boundary shift with jet pT

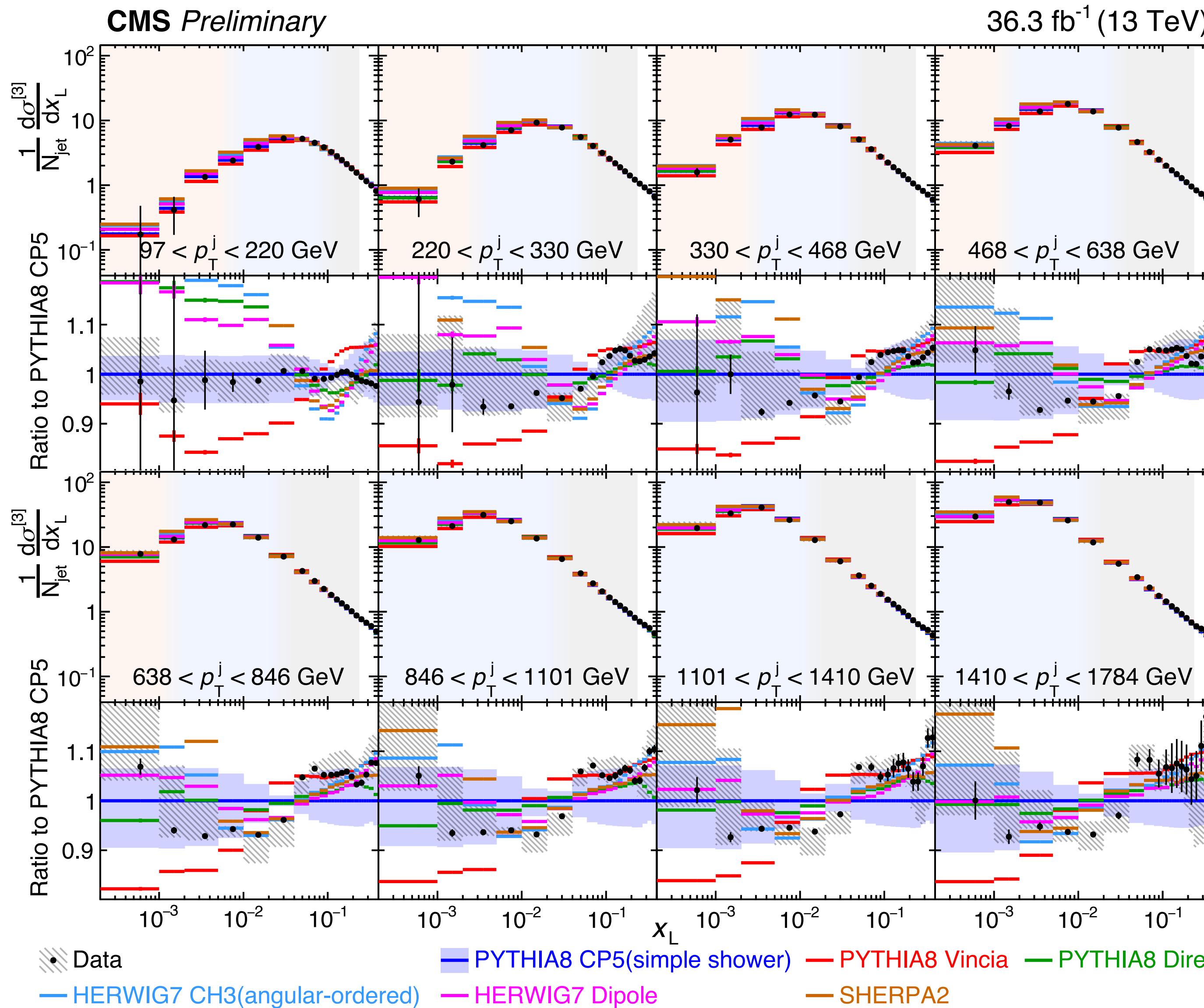
$$Q \propto x_L^* p_T^{jet}$$

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

Boundary

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

Unfolded E3C vs MC



Data vs various parton shower model, difference $\sim 10\%$

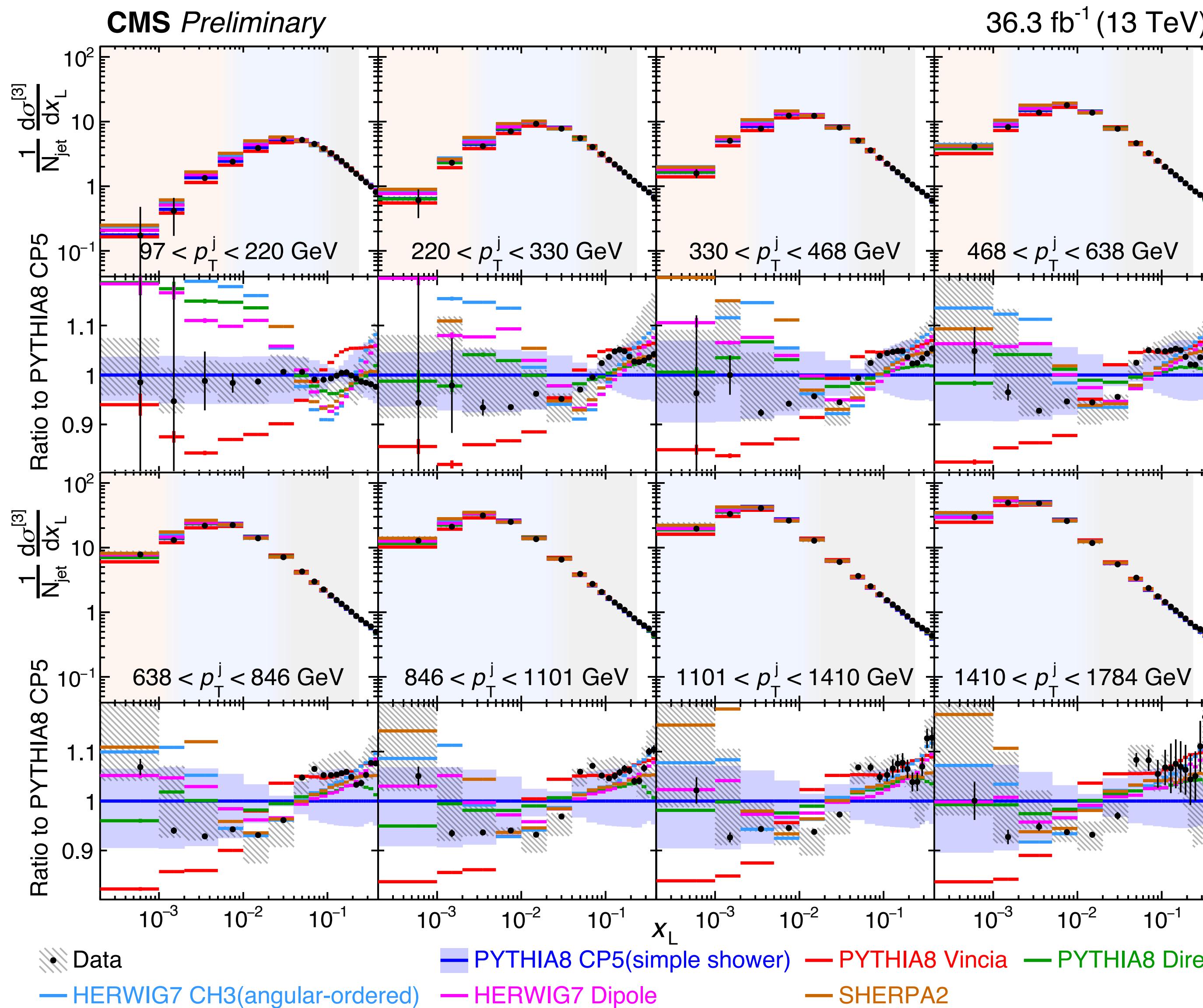
No model match data well in all p_t^{jet} region

● : Data stat error

: Exp systematic

: Theo systematic

Unfolded E3C vs MC



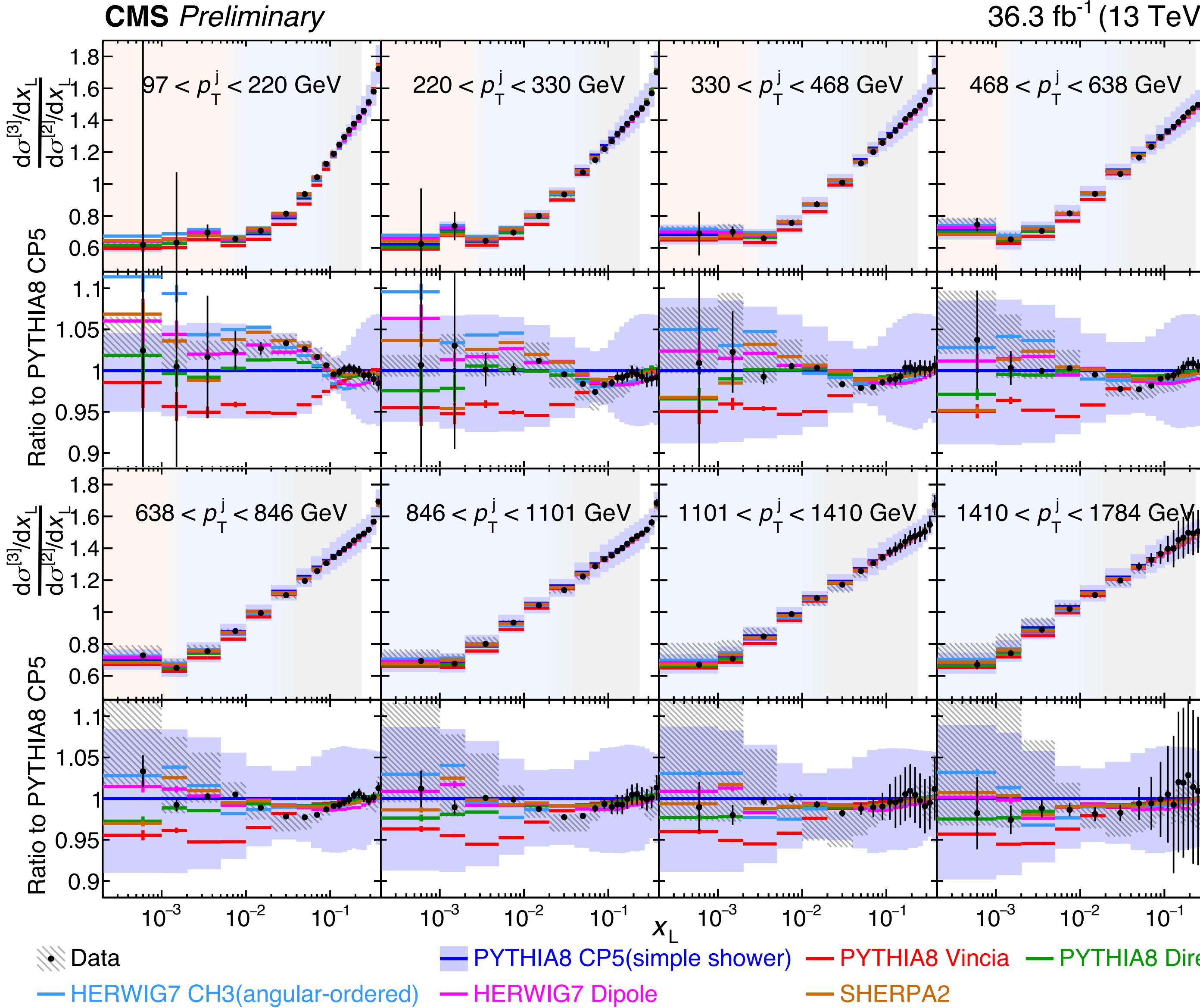
Exp sys:

- **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

Unfolded E3C/E2C vs MC



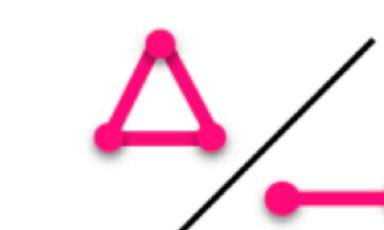
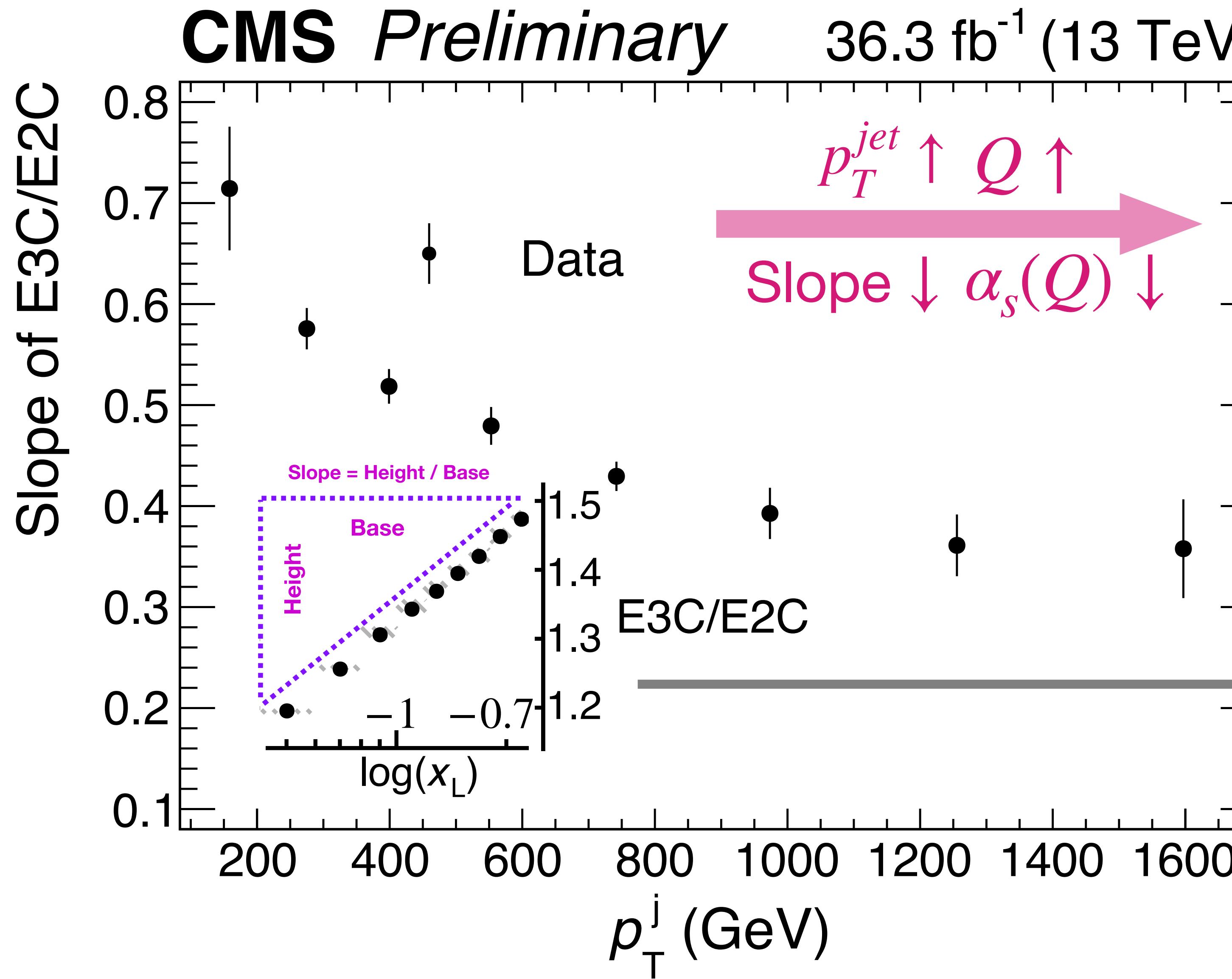
Benefit of taking ratio

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

All models agree well

$p_T^{jet} \uparrow$, Slope ↓

Direct observation of asymptotic freedom



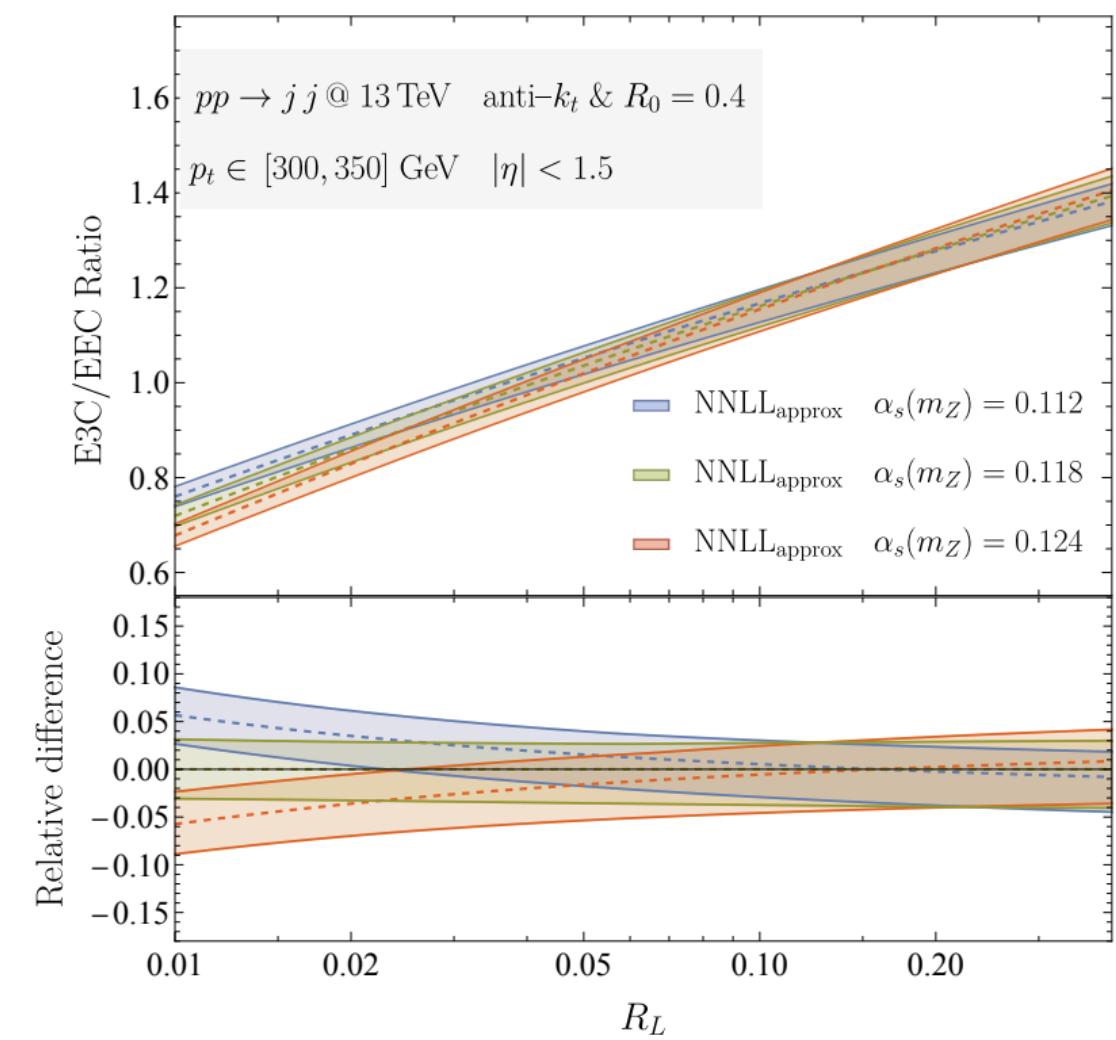
$$\propto \alpha_S(Q) \ln x_L + O(\alpha_s^2)$$

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

α_s extraction from E3C/E2C

Analytical predictions

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

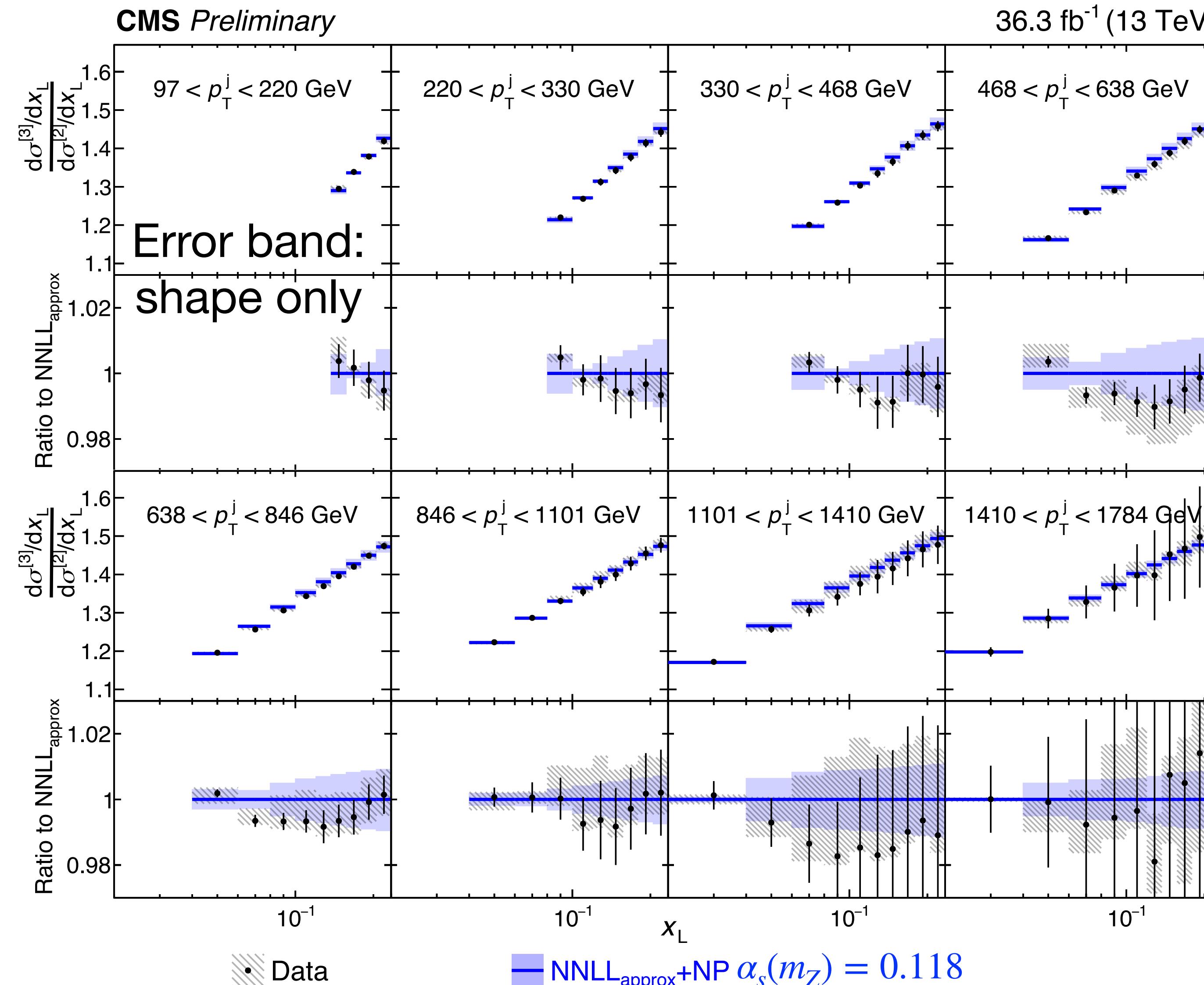


Chen, Gao, Li, Xu, Zhang, and Zhu, [arXiv:2307.07510](https://arxiv.org/abs/2307.07510)

Hadronization factors

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

Unfolded E3C/E2C vs NNLL-approx



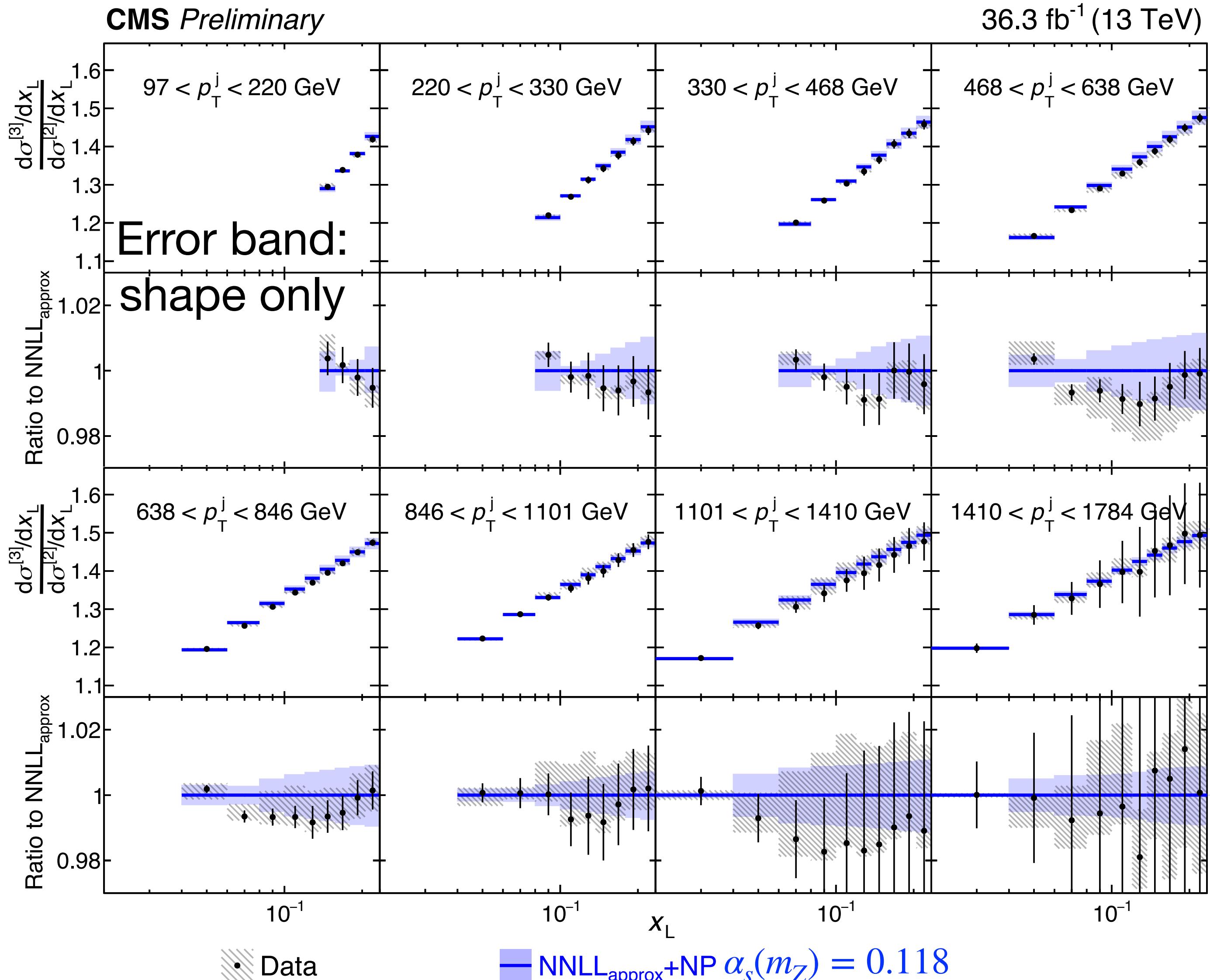
Shape of data agrees with NNLL_{approx} within uncertainty

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

Result



$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$
 $= 0.1229^{+0.0014(\text{stat.})+0.0030(\text{theo.})+0.0023(\text{exp.})}_{-0.0012(\text{stat.})-0.0033(\text{theo.})-0.0036(\text{exp.})}$

major source
 Covariance matrix
 QCD scale of NNLL_{approx}
 Neutral hadron energy scale

Uncertainty $\sim 4\%$, most precise from jet-substructure measurement to date

Benefit from:

Ratio: most uncertainties cancel out

High precision calculation

Summary

- Wide p_T^{jet} range measurement of E2C, E3C, the first measurement on E3C
- Multi-dimensional unfolding: taking into account correlation between variables
- Statistical correlation: significant for E2C and E3C
- Unique features of QCD observed: color confinement, asymptotic freedom
- A novel way to extract α_S , the most precise extraction (4%) of α_S from jet substructure observables.

Backup

Unfolded E2C vs MC

