Probing jet substructure with 2 and projected 3-point energy correlators in pp collisions at ALICE at $\sqrt{s} = 13\text{TeV}$

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for the ALICE Collaboration

2nd workshop on advancing the understanding of non-perturbative QCD using energy flow

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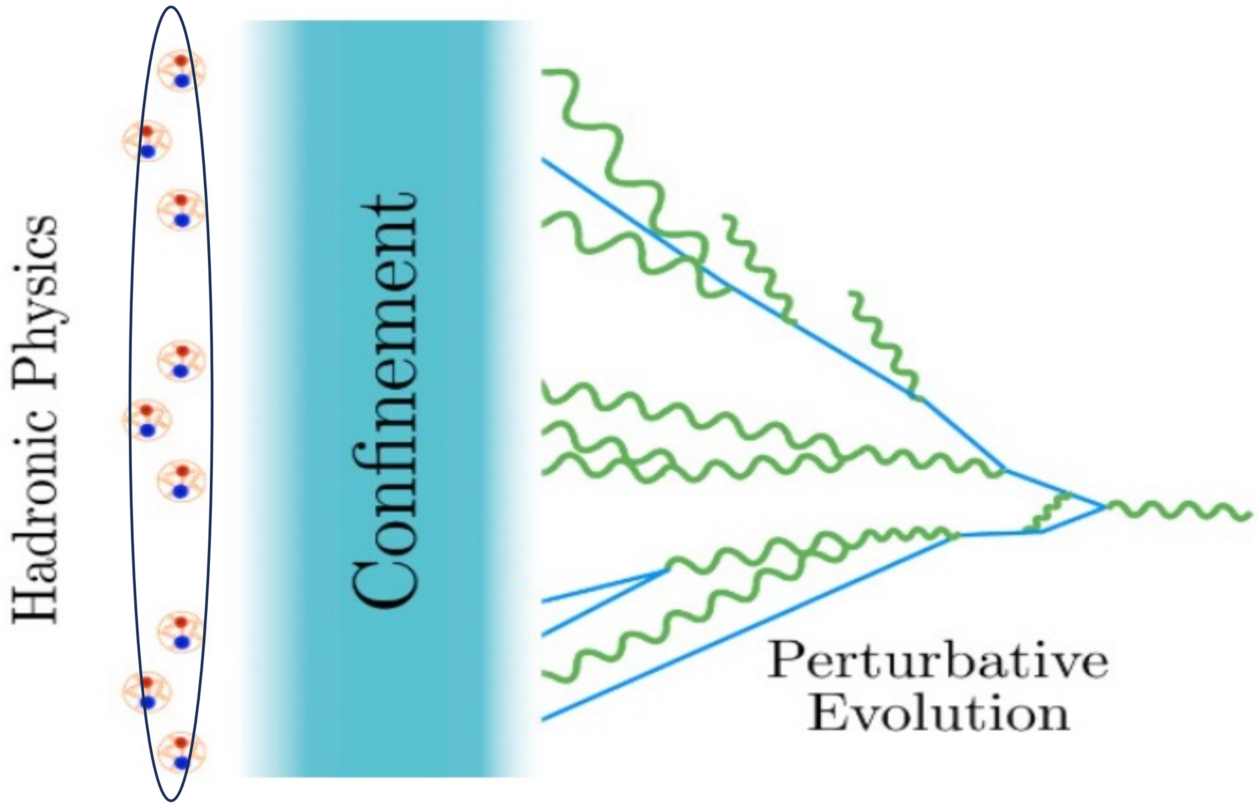
Looking inside jets with N-point Energy Correlators

- Jets are an important tool to probe QCD experimentally.
- IRC safe jet-finding algorithms offer access to partons from initial hard scatterings – useful probe of pQCD.
- Multi-scale objects: feature highlighted by energy correlators.

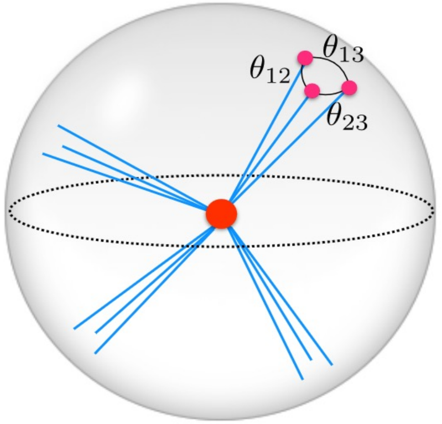


Introduction: N-point Energy Correlators

- **Theoretical definition:**

$$\mathcal{E}(\vec{n}) = \int_0^\infty dt \lim_{r\to\infty} r^2 n^i T_{0i}(t, r\vec{n})$$

$$\mathrm{ENC}(R_L) = \left(\prod_{k=1}^{N} \int d\Omega_{\vec{n}_k}\right) \delta(R_L - \Delta\hat{R}_L) \frac{1}{(E_{\mathrm{jet}})^N} \langle \mathcal{E}(\vec{n}_1)\mathcal{E}(\vec{n}_2)\ldots\mathcal{E}(\vec{n}_N)\rangle$$

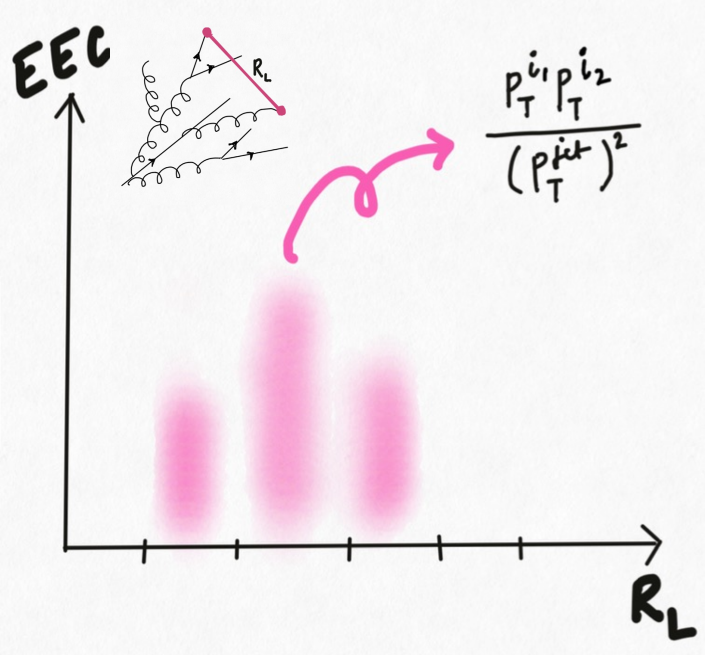


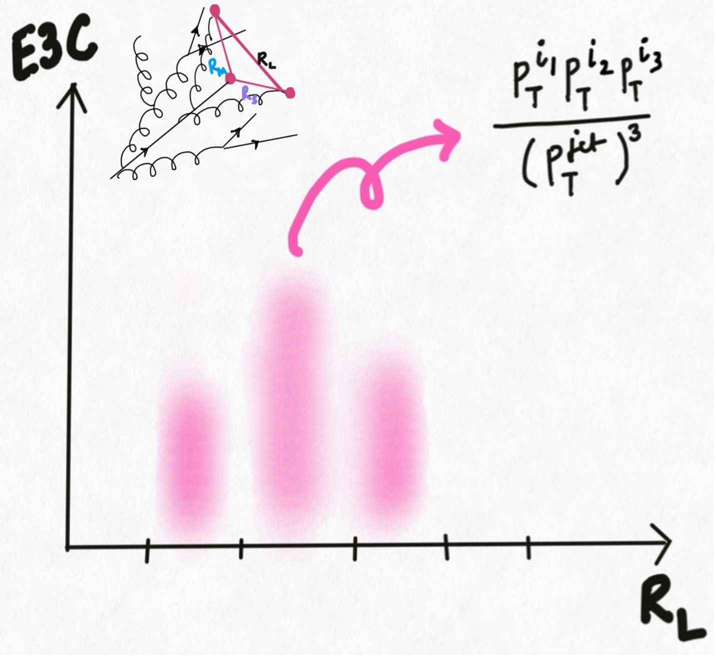
- **Experimental definition:**

Create a weighted histogram as a function of R_L (largest distance between N particles) with weights

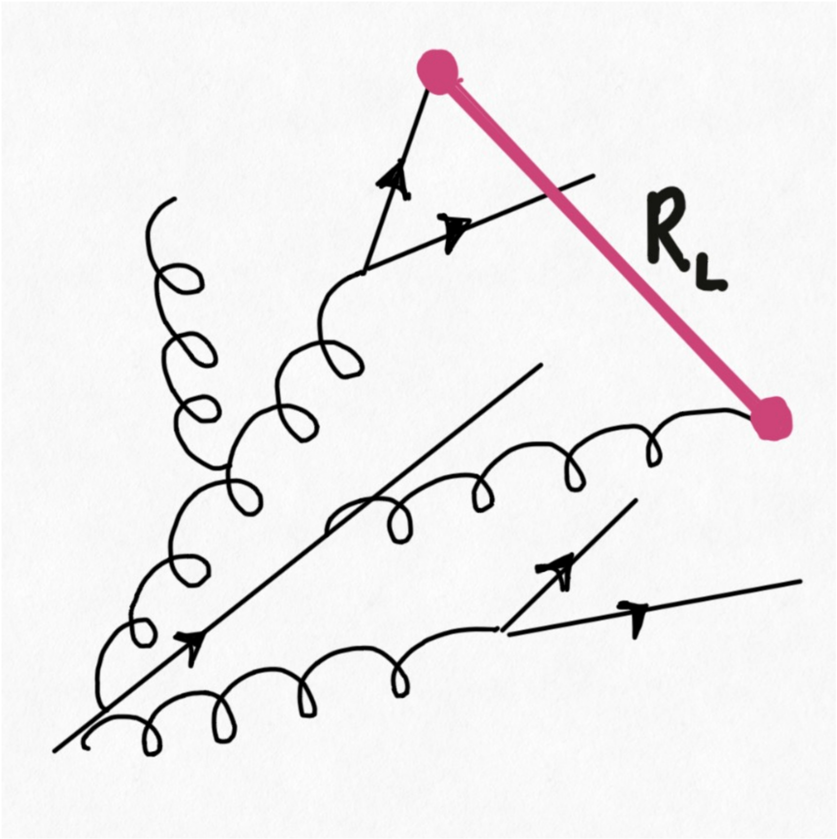
$$ENC(R_L) = \sum_{i_1, i_2, .. i_k}^{i_N} \int dR_L \frac{p_T^{i_1} p_T^{i_2} .. p_T^{i_N}}{p_{T,jet}^N} \delta(R_L - \Delta\hat{R}_L)$$

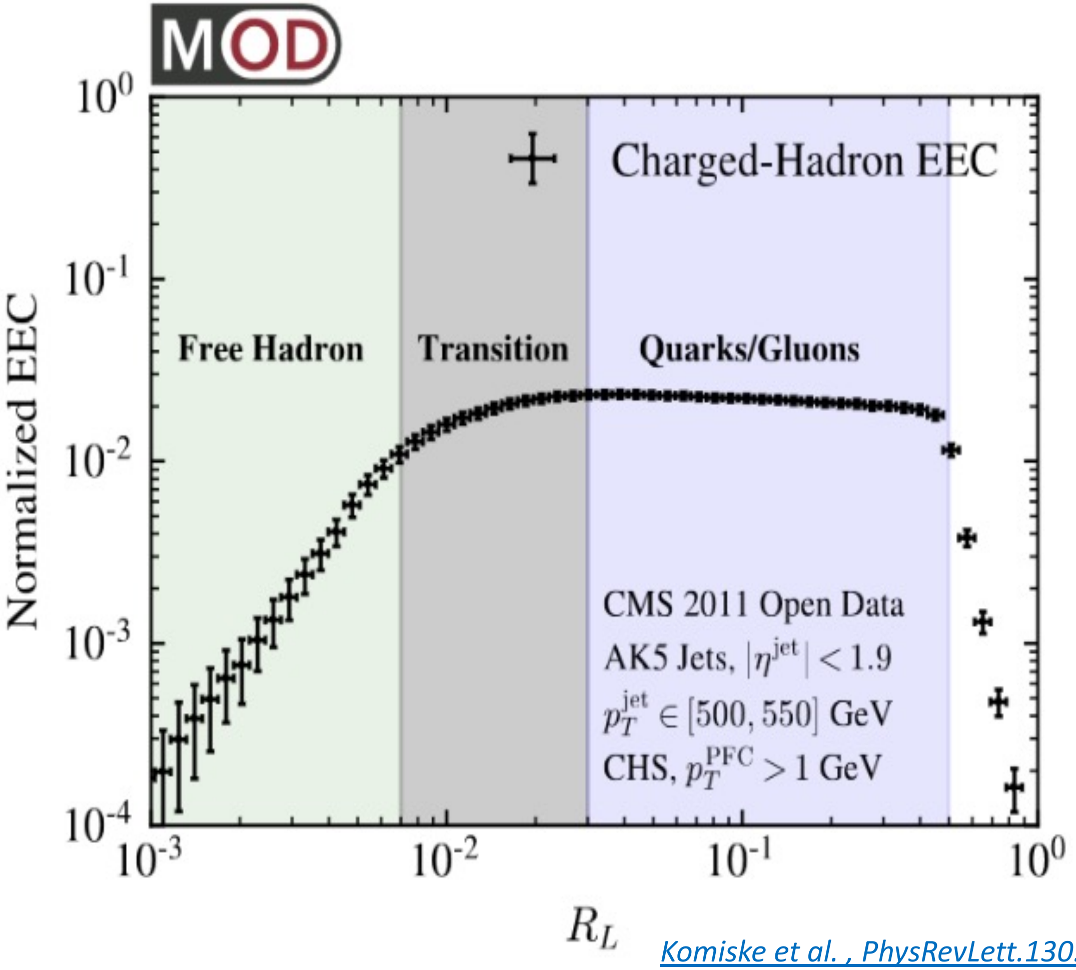
(ensemble averaged over jets)





2-point Energy Correlator (EEC)



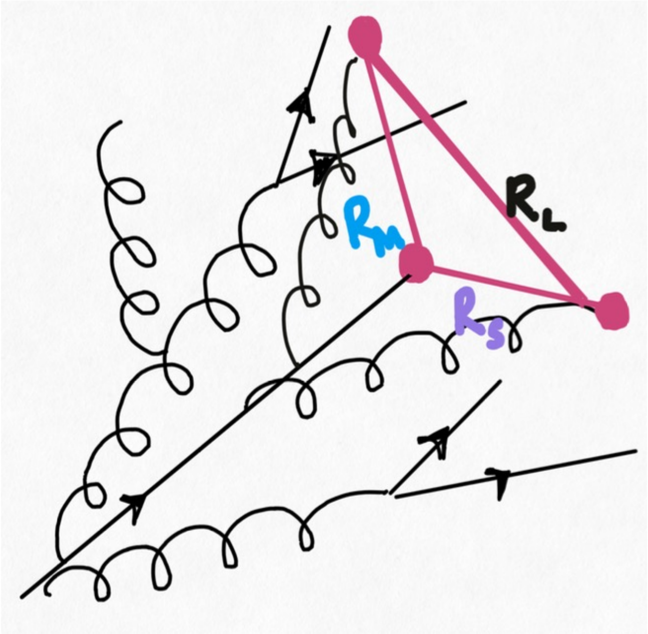


Probes scale dependence of energy flow
Jet evolution imprinted on slopes of the EEC

Komiske et al. , PhysRevLett.130.051901

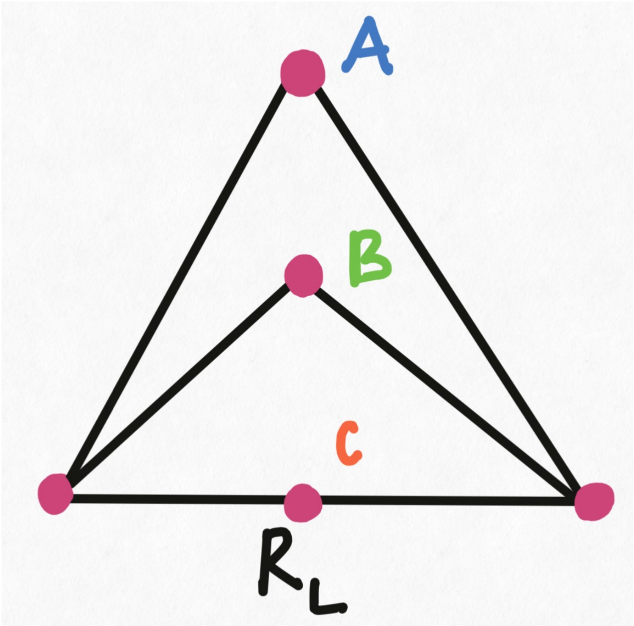
Projected 3-point Energy Correlator (E3C)

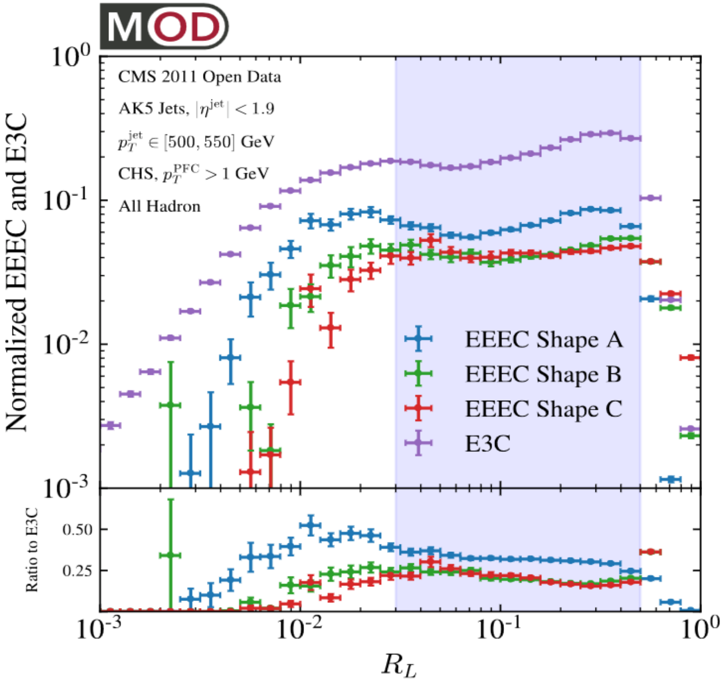
EEEC



Integrate over different configurations of R_M and R_S

E3C





Probes shape dependence of energy flow
+ 1 → 3 splittings

Preserves the scale of the correlation
+ slopes encode the scaling behavior of EEEC (theory)

Komiske et al. , PhysRevLett.130.051901

Motivation: ENC

Theoretical

- Calculable in pQCD using techniques from Conformal Field Theory

Dixon et. al, PhysRevD.100.014009
Kologlu et. al, JHEP01(2021)128

Experimental

- Grooming and reclustering not necessary

- Allows for a clear separation of pQCD and npQCD effects
- Allows for a clear separation of pQCD and npQCD effects

Motivation: E3C/EEC ratios

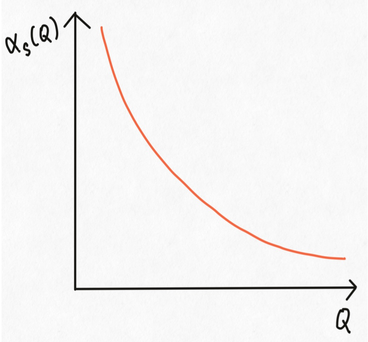
Theoretical

- Access to anomalous dimensions

QFT operators have a scaling/mass dimension $\Delta_{\mathbb{O}}$.
For e.g., in 3+1D, scalar field $[\phi] = 1$, fermion field $[\psi] = 3/2$.
Quantum mechanical effects ⟶ $\Delta_{\mathbb{O}}$ gets shifted by "anomalous dimensions", $\gamma_{\mathbb{O}}$:

$$\Delta_{\mathbb{O}} = \Delta_{\mathbb{O},\, classical} + \gamma_{\mathbb{O}}$$

- Access to the strong coupling constant*



**Chen et al. PhysRevD.102.054012*
Recently measured by CMS (BOOST – 2023)

Experimental

- Minimal detector effects

- Isolation of pQCD & npQCD effects

Analysis Method/Overview

- Compute ENCs on charged anti-k_T jets, R = 0.4
- Bin-by-bin correction: ALICE has great angular resolution (≈ 1mrad for p_T^{track} ≈ 1GeV)

$$f_{corr}\left(R_L^{det}, p_{\mathrm{T,jet}}^{det}\right) = ENC_{det}/ENC_{true}$$
$$ENC_{true}\left(p_{\mathrm{T,jet}}^{true}\right) = (1/f_{corr})ENC_{det}(p_{\mathrm{T,jet}}^{det})$$

- Dominant systematic: p_T migration effects (unfolding checks – ongoing)

Systematics
p_T migration
Single particle tracking efficiency
Pair efficiency
Generator dependence

EEC at 5.02 TeV and 13 TeV at ALICE

Shift in peak with jet p_T

↓

Higher p_T jets move to the left

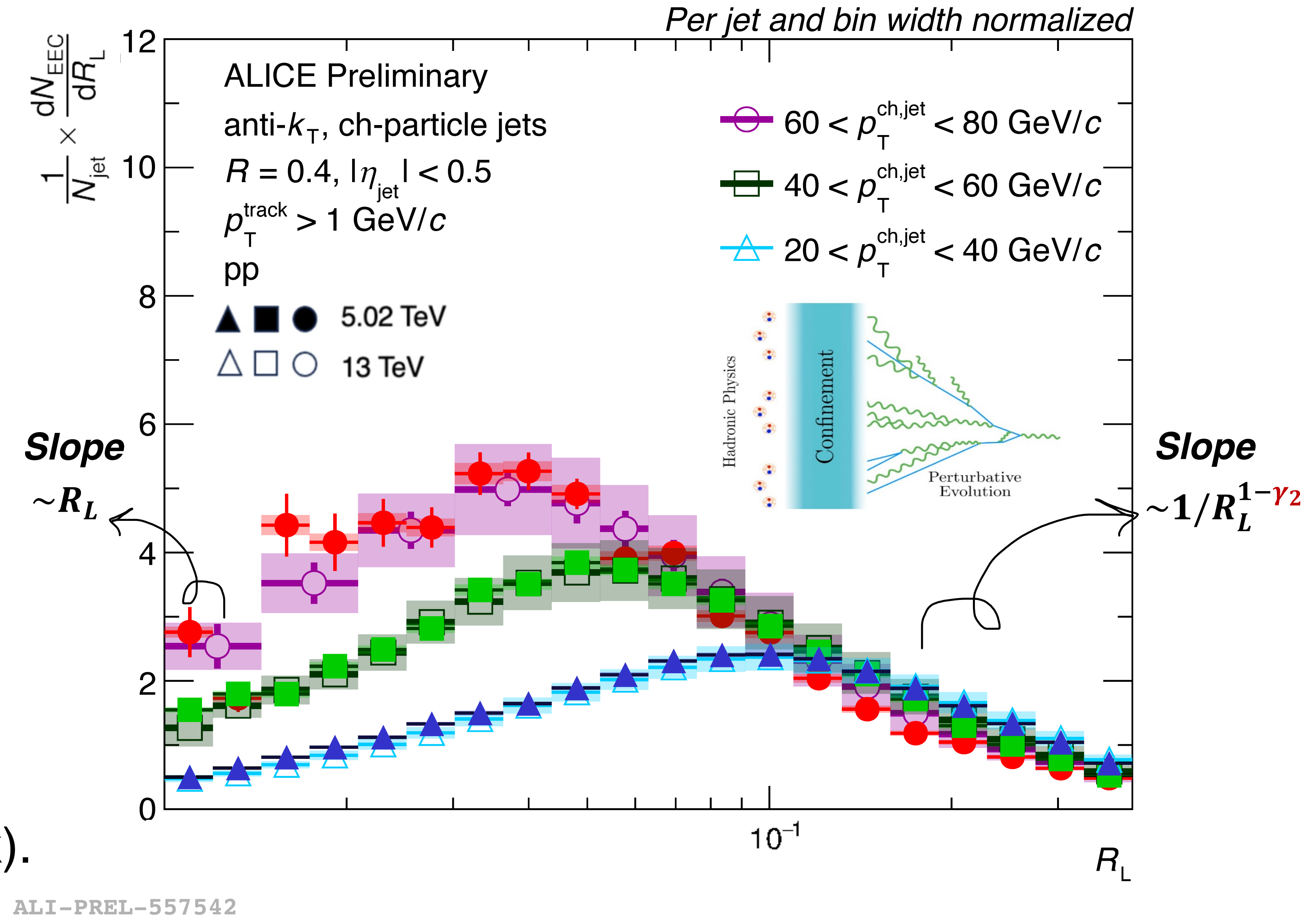
↓

Depicts jet evolution through different stages: angular ordering of QCD.

Small dependence on $\sqrt{s}$!

↓

q/g fractions will modify the slope (see Andrew's talk).



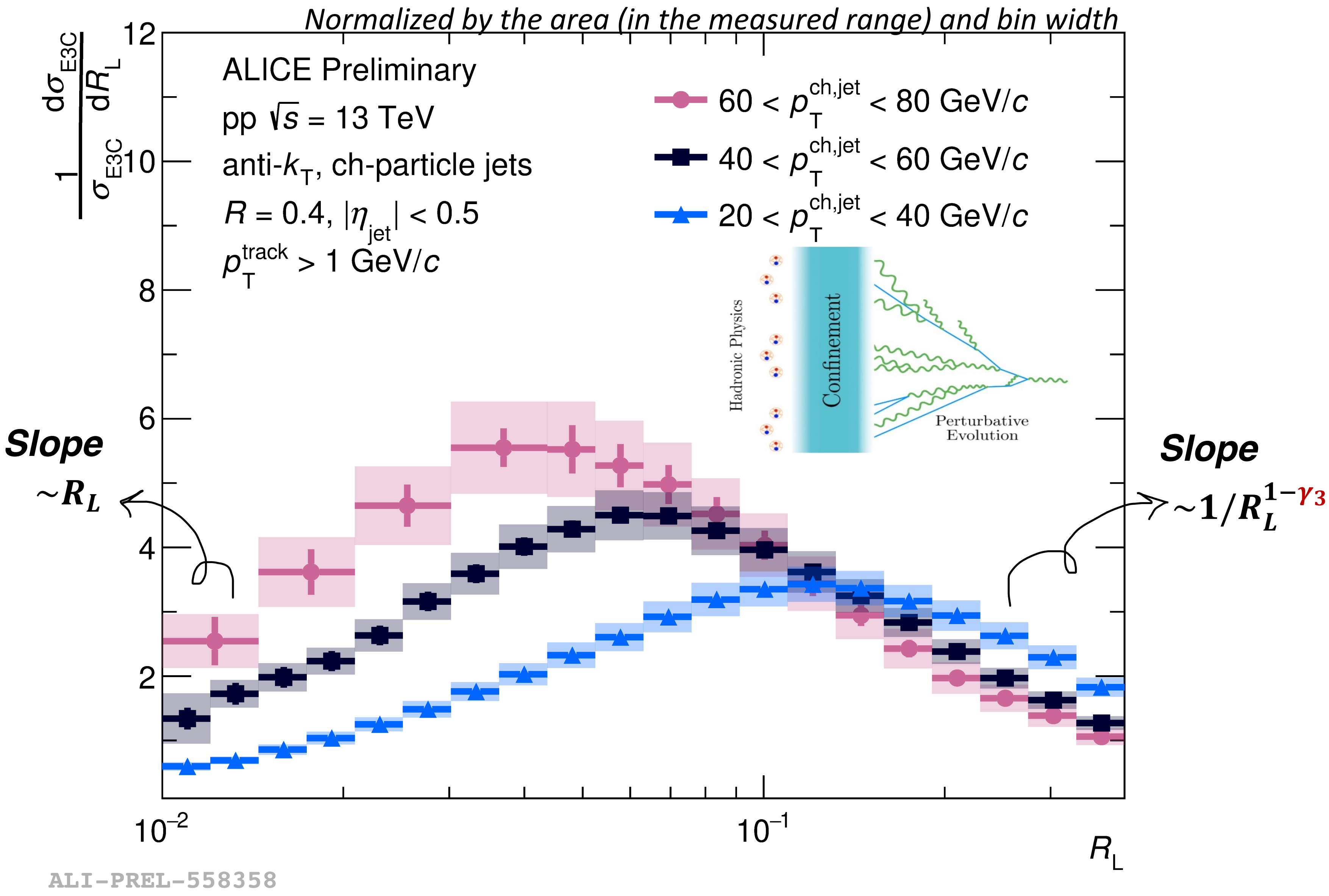
E3C at 13 TeV at ALICE

Same features as the EEC.

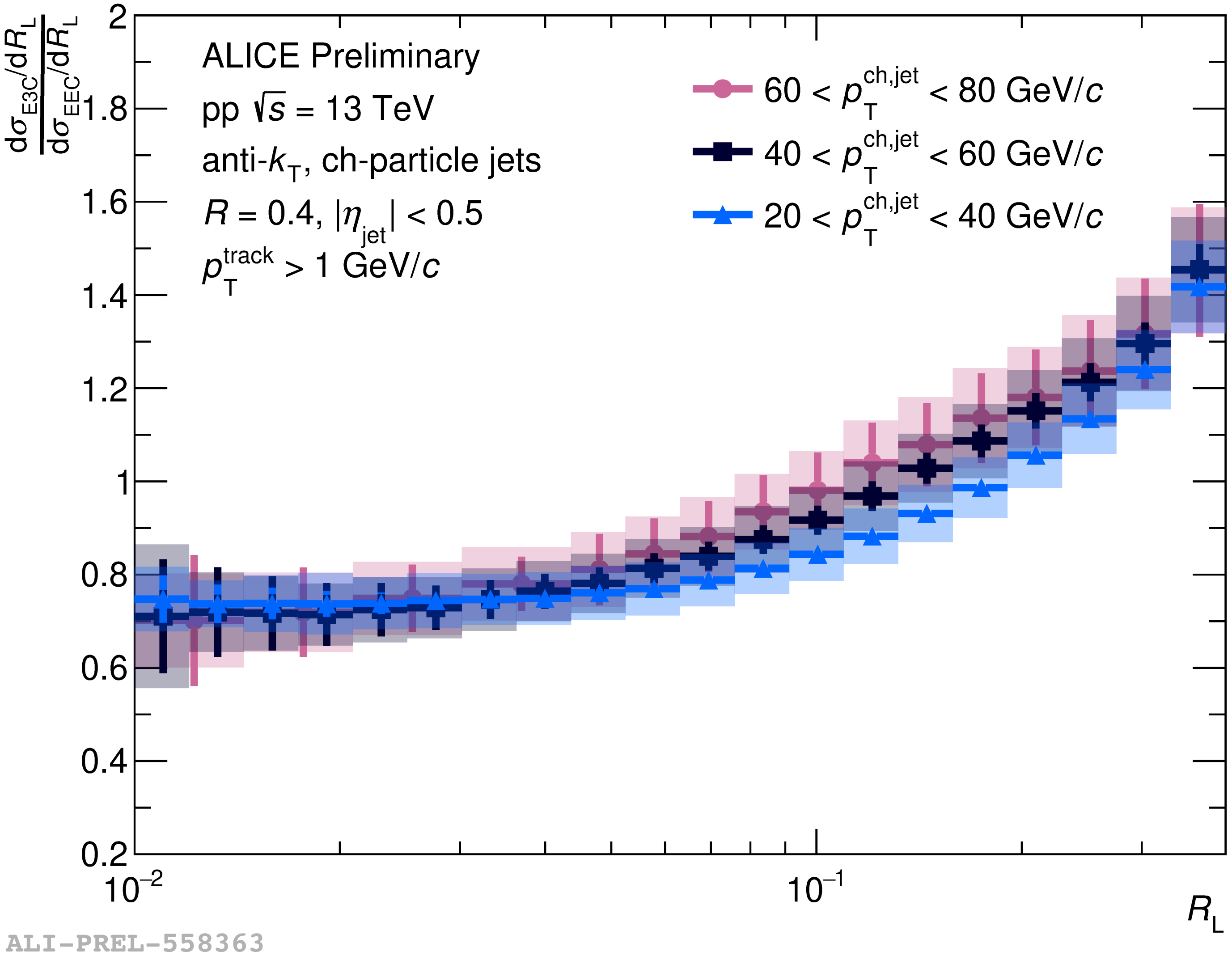
Slopes in the partonic regime different from EEC.

↓

Anomalous dimension of E3C (γ_3) different from EEC (γ_2).



E3C/EEC at 13 TeV at ALICE



Both E3C & EEC are normalized by the area (in the measured range) and bin width

The change in slope with jet p_T indicates running of the coupling, α_S!

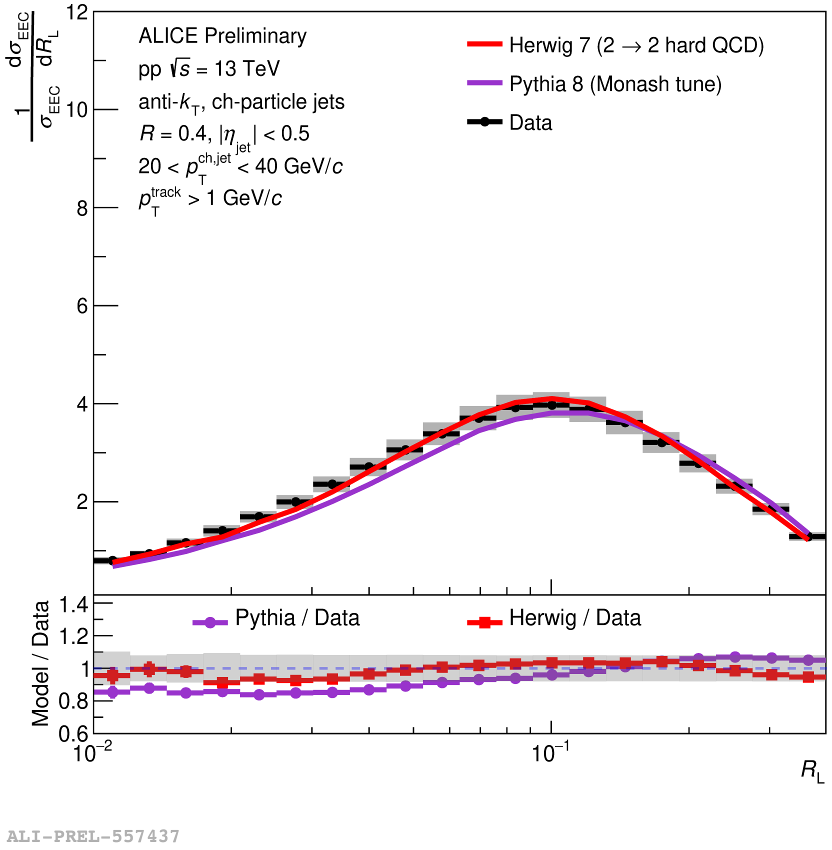
Slope ($\sim R_L^{\gamma_3 - \gamma_2}$) verifies quantum mechanical corrections!

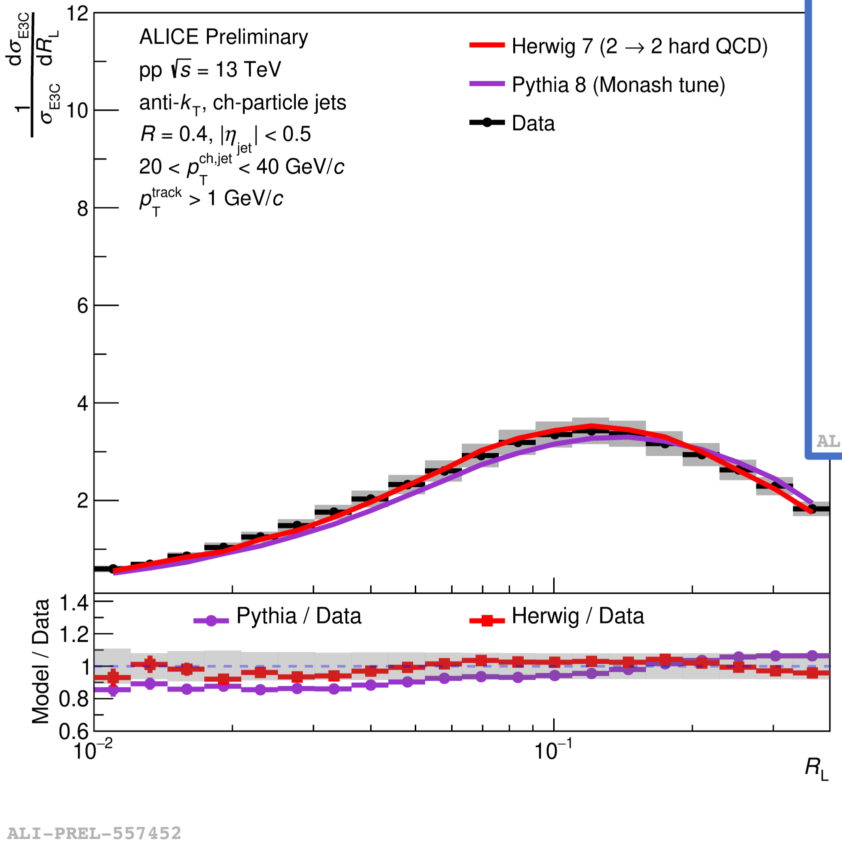
Perturbative regime:
$\gamma_3 > \gamma_2$ (theory) reproduced in data (slope > 1).

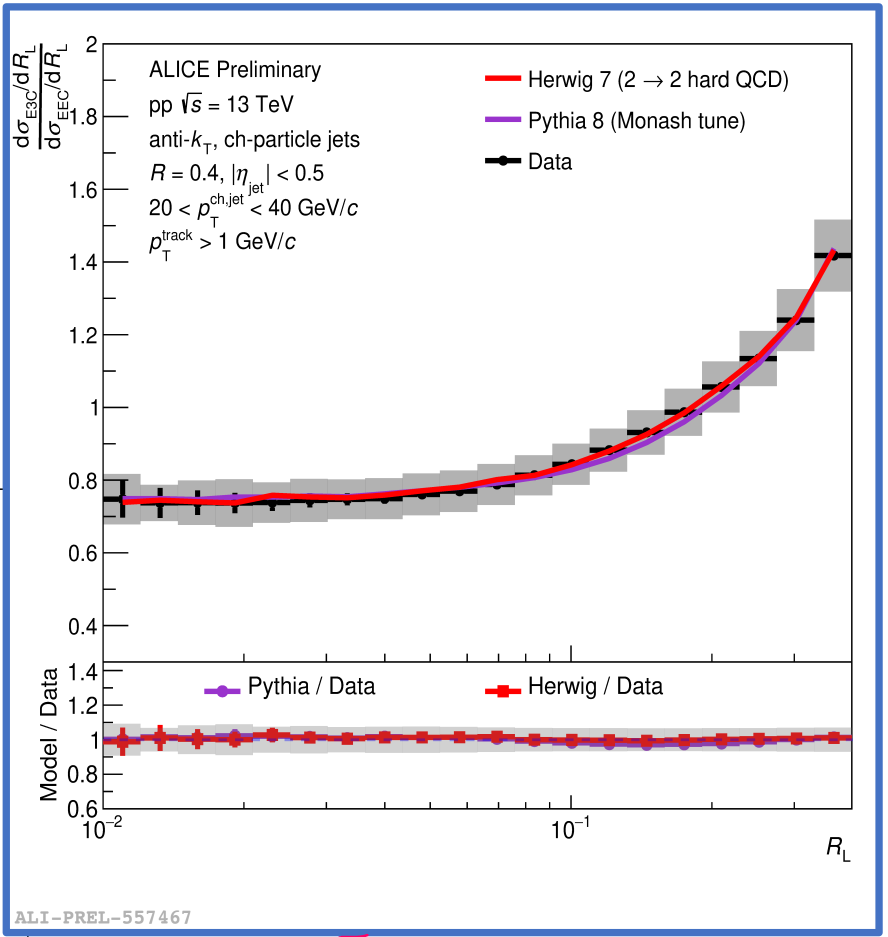
Non-Perturbative regime:
Flat region indicates npQCD effects – Hadronization & trivial correlation between hadrons.

Model Comparison

EEC & E3C
Herwig shows better agreement
Differences more pronounced in the hadronic region –
Possible due to different hadronization mechanisms? Normalization choice?



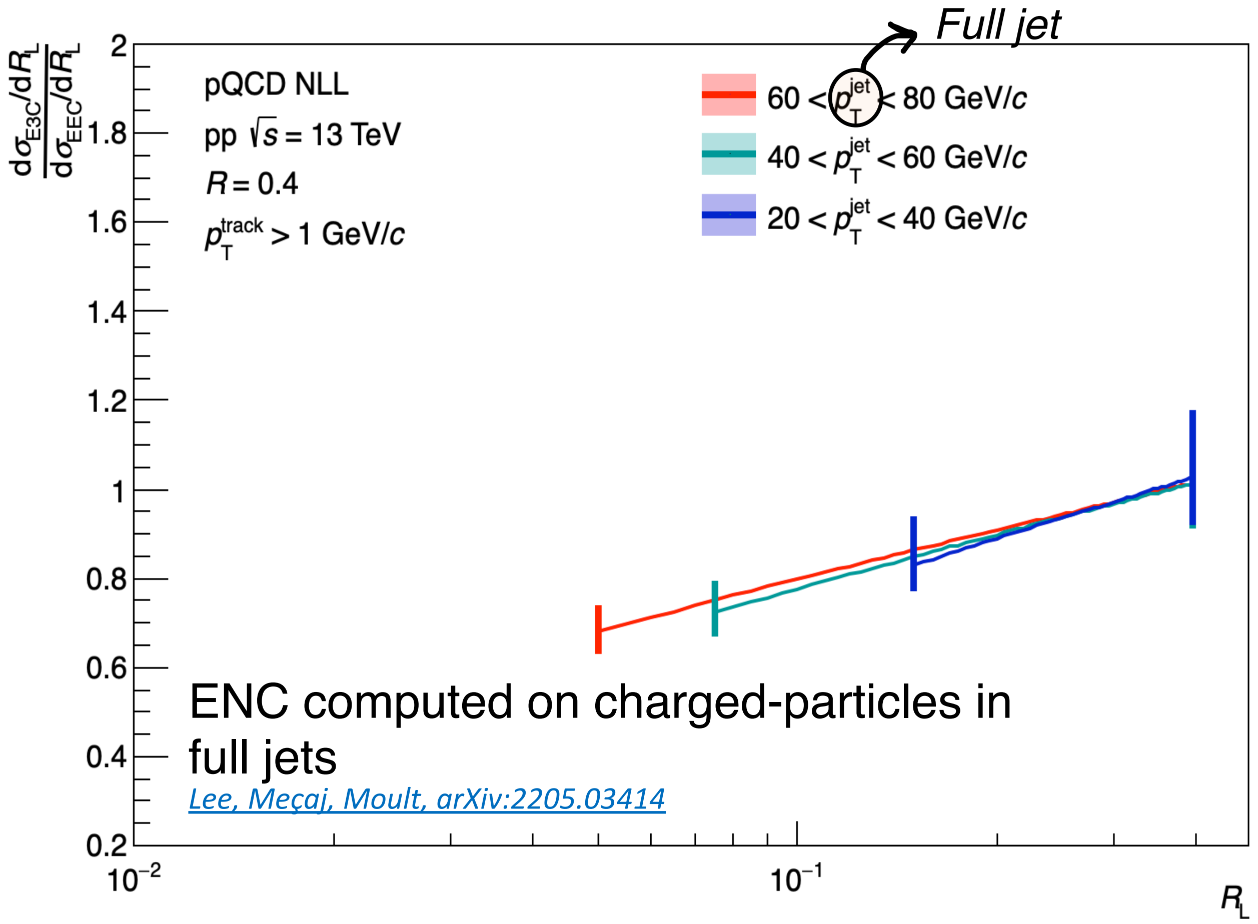


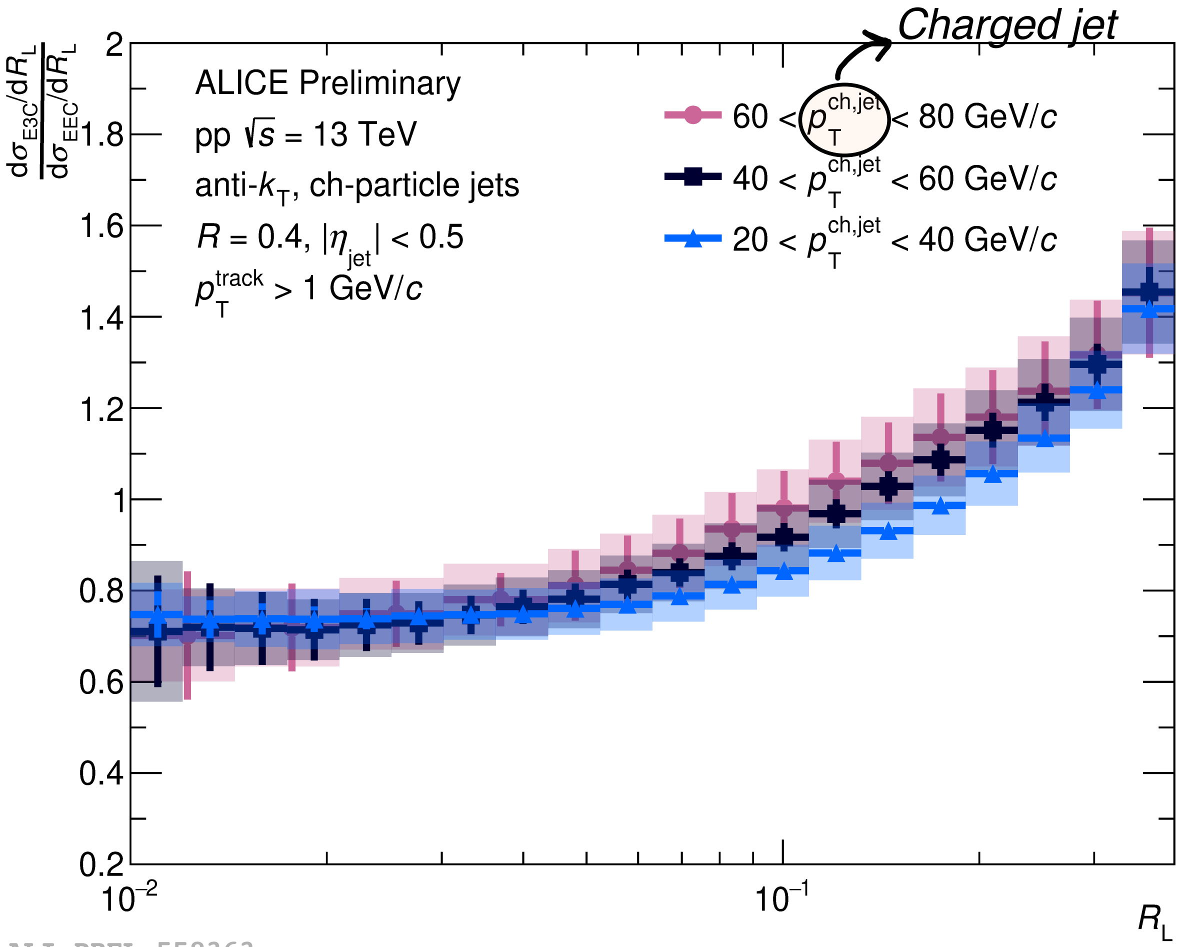


E3C/EEC
Pythia and Herwig both have ratio ≈ 1

Models capture perturbative dynamics well.
Isolates perturbative physics!

Comparison of E3C/EEC with pQCD





ALI-PREL-558363

At LL collinear in pQCD

$$ENC(R_L) = -\frac{d}{dR_L}\left[(1,1)\exp\left(\frac{-\gamma^{(0)}(N+1)}{\beta_0}\ln\frac{\alpha_S(R_L\mu)}{\alpha_S(\mu)}\right)(x_q, x_g)\right] H_J(\mu)$$

Jet p_T scale — q/g fraction — QCD beta function (1 loop) — Jet production crossx

Komiske et al. , PhysRevLett.130.051901

Change in slope with jet p_T → Trends between theory and data agree.

Work is ongoing to make this comparison robust.

Outlook

- ENCs allow us to probe both soft and hard physics!
- Full 3-point correlator (EEEC):
  study full shape dependence of energy flow in pp collisions.
  Komiske et al. , PhysRevLett.130.051901
- Move to more complex systems:

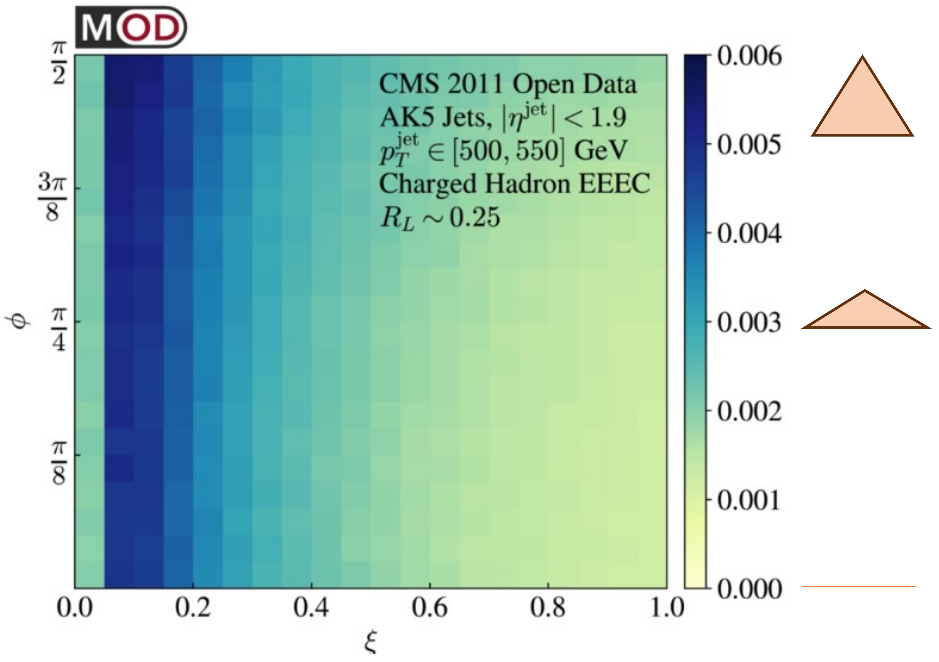
A scale sensitive probe is great for studying more complex systems with inherent scales

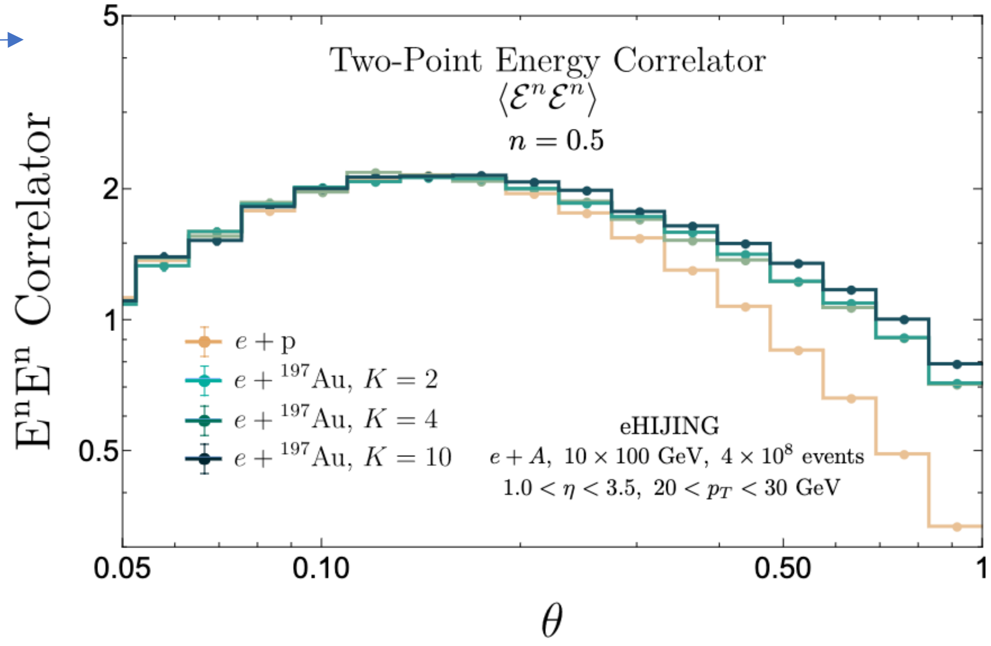
EIC physics – modification due to cold nuclear matter
Deveraux et al., arXiv:2303.08143

QGP physics – isolate effects of the medium, access to soft physics
color coherence effects Andres et al., arXiv:2209.11236
transverse momentum broadening Yang et al., arxiv:2310.01500

Energy Correlators

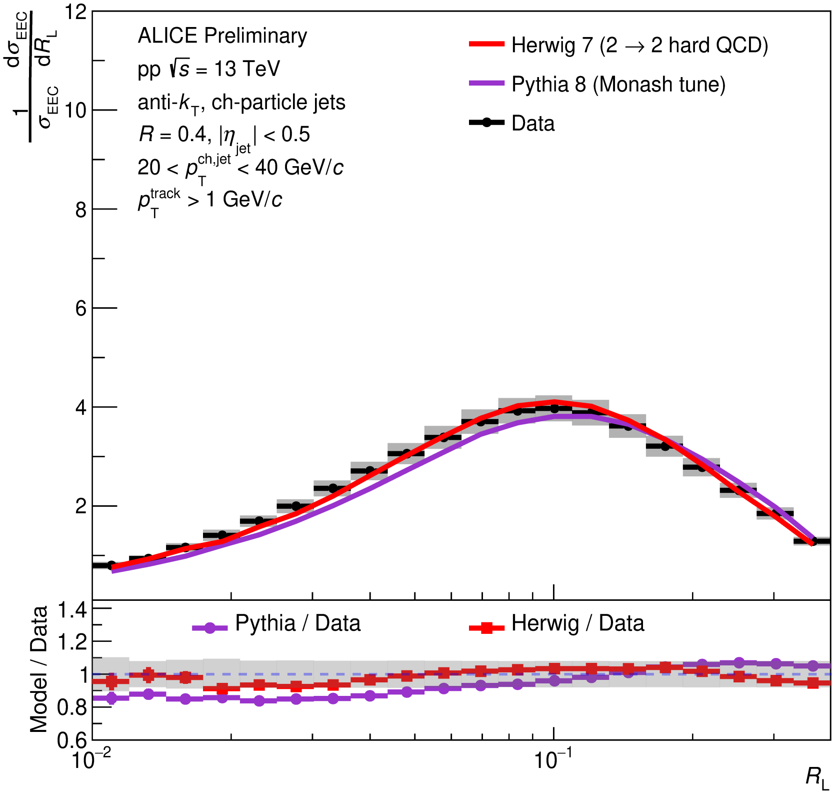
Other substructure observables



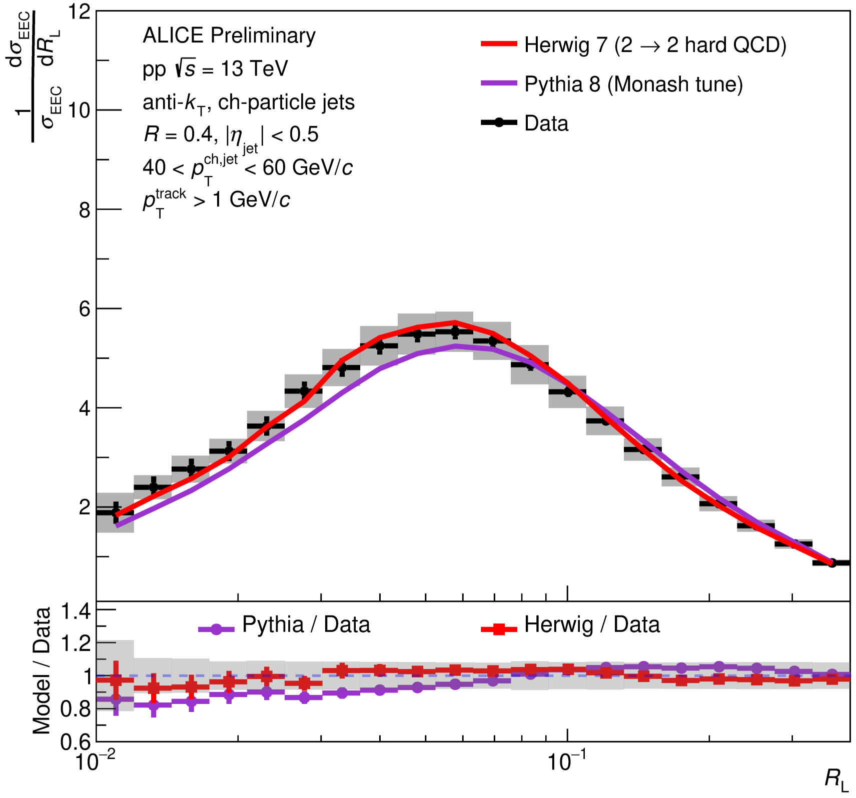


BACKUP

Model Comparison EEC



ALI-PREL-557437



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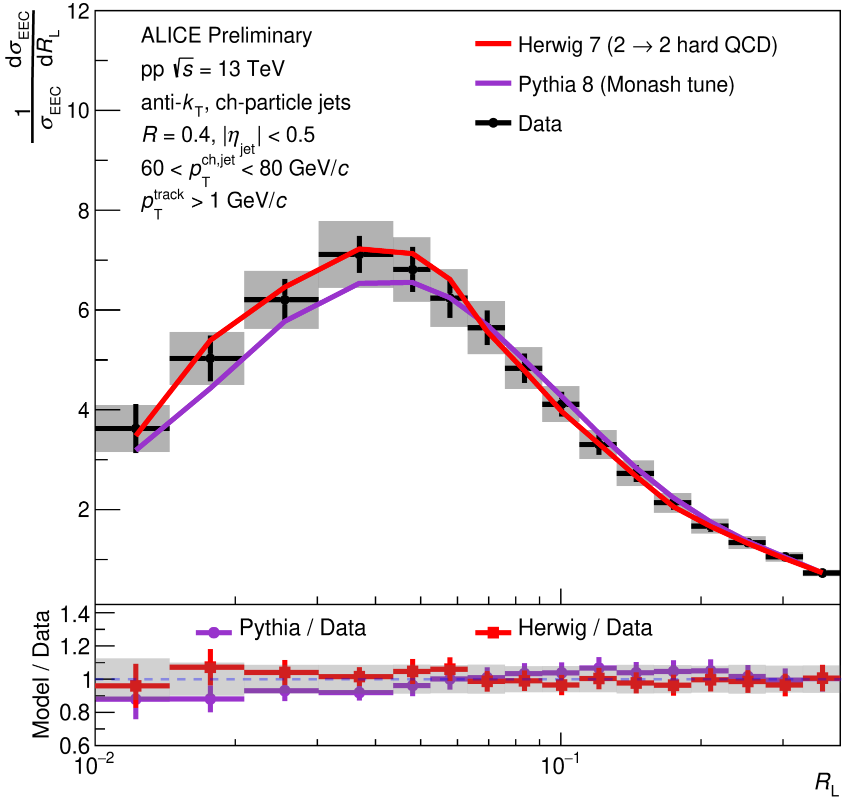
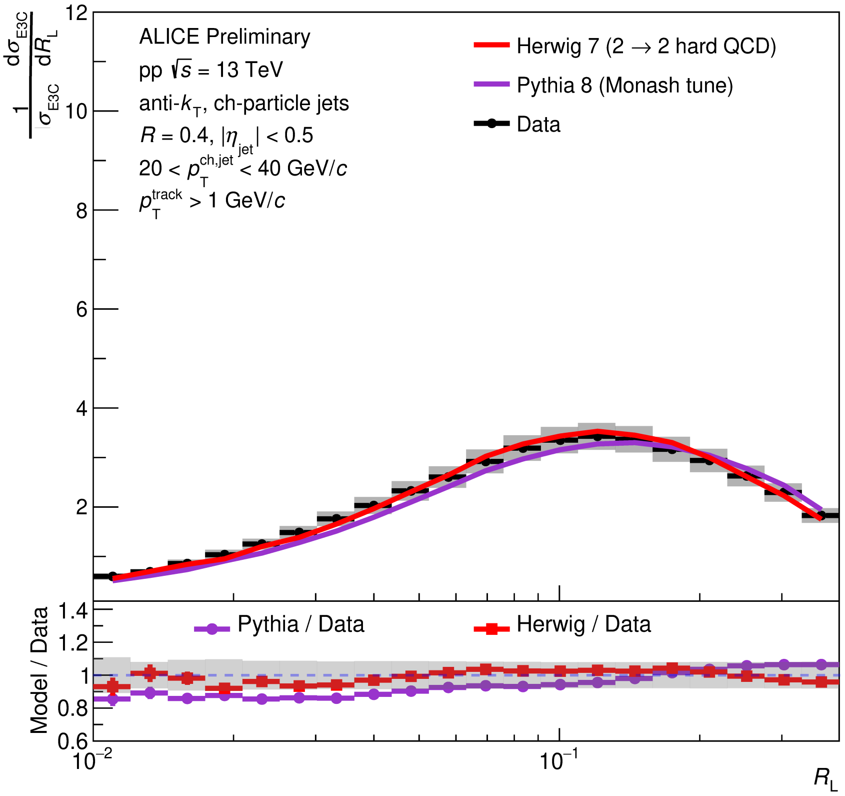


ALI-PREL-557447

Herwig shows better agreement
Differences more pronounced in the hadronic region
Possible due to different hadronization mechanisms?

Model Comparison E3C



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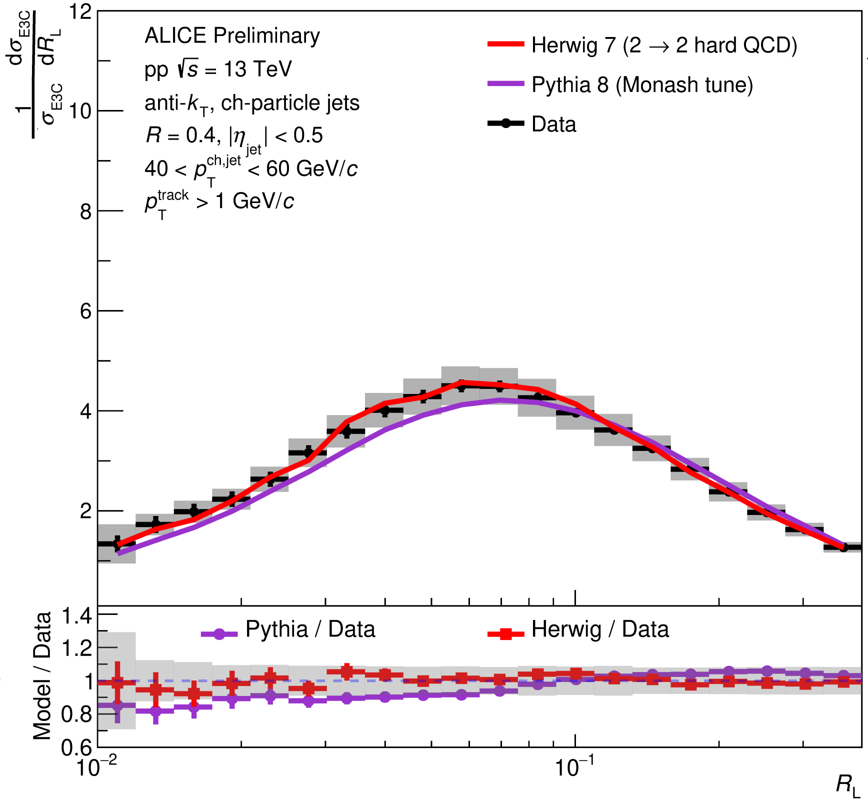

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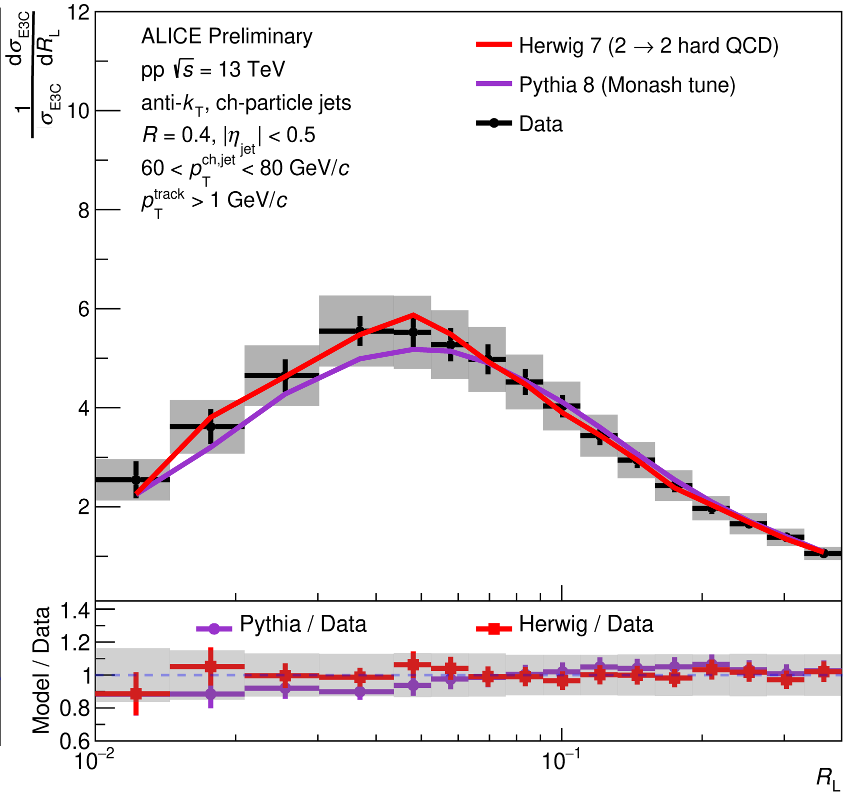
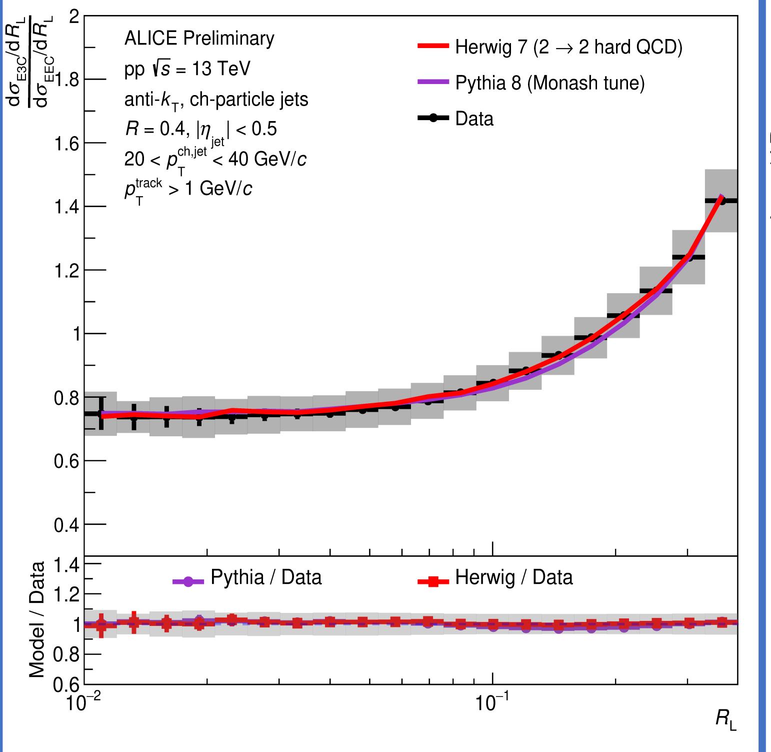
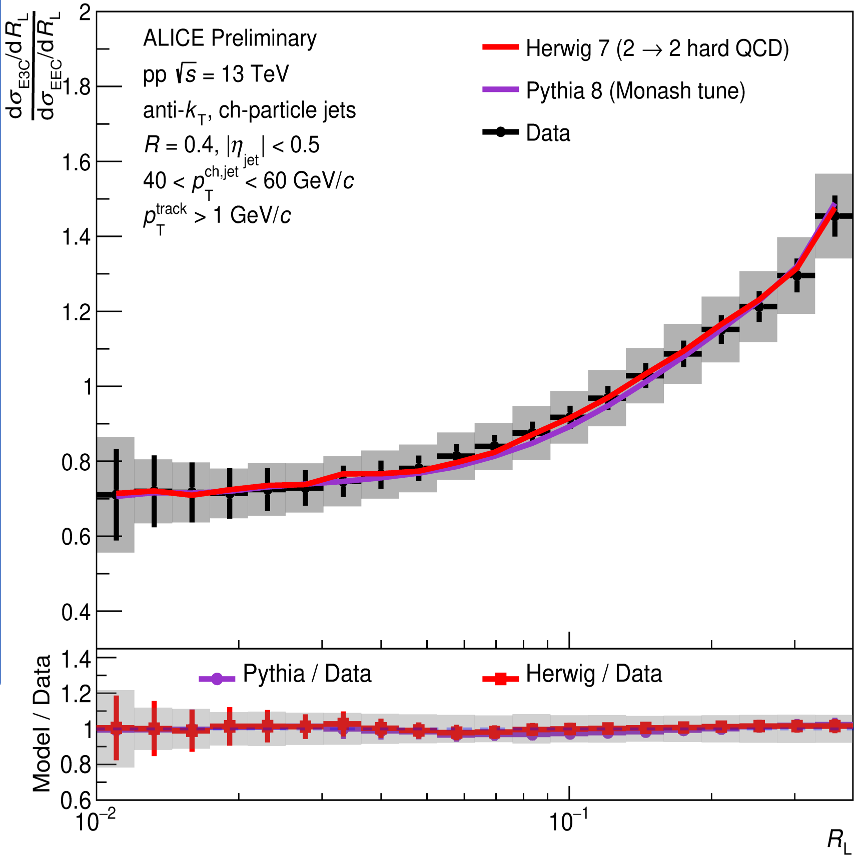


ALI-PREL-557462

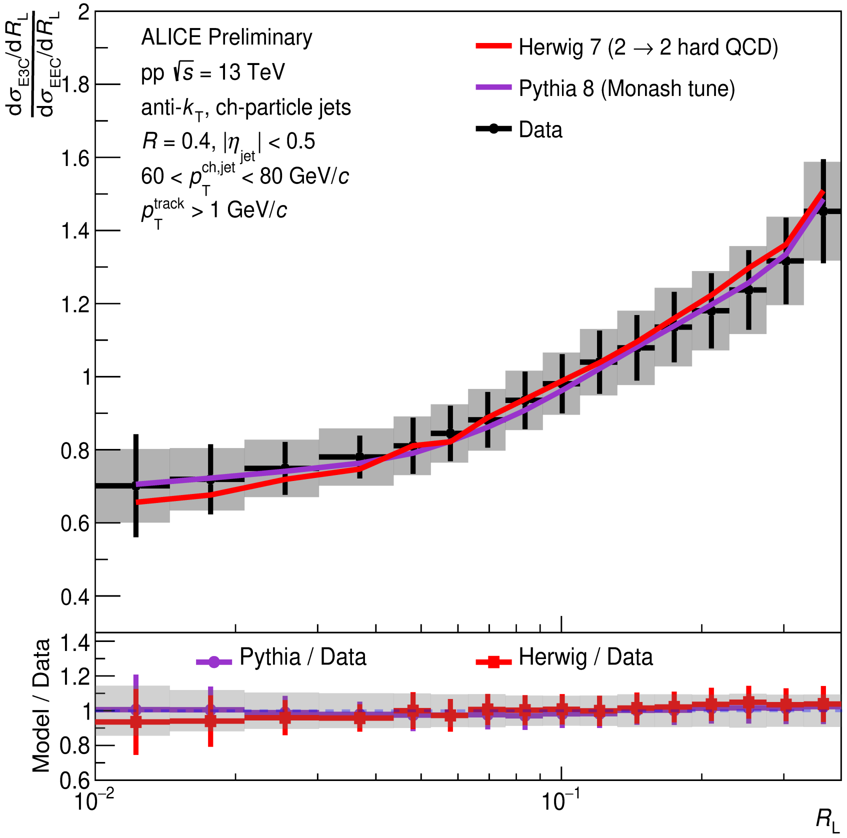
Trends remain similar to EEC. Herwig still agrees better



ALI-PREL-557467



ALI-PREL-557472



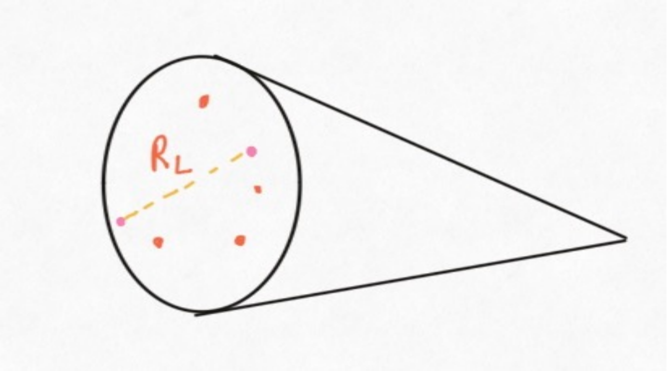
ALI-PREL-557477

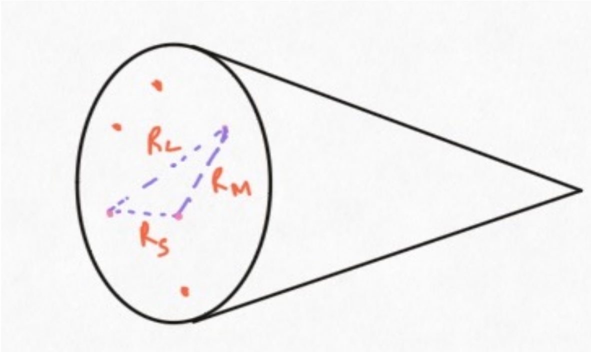
At LL collinear in pQCD

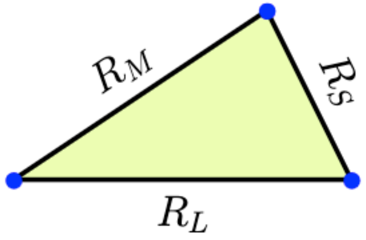
$$\frac{E3C}{EEC} \approx \frac{\gamma_3}{\gamma_2} \exp\left(\frac{\gamma_2 - \gamma_3}{\beta_0} \ln \frac{\alpha_S(R_L\mu)}{\alpha_S(\mu)}\right)$$

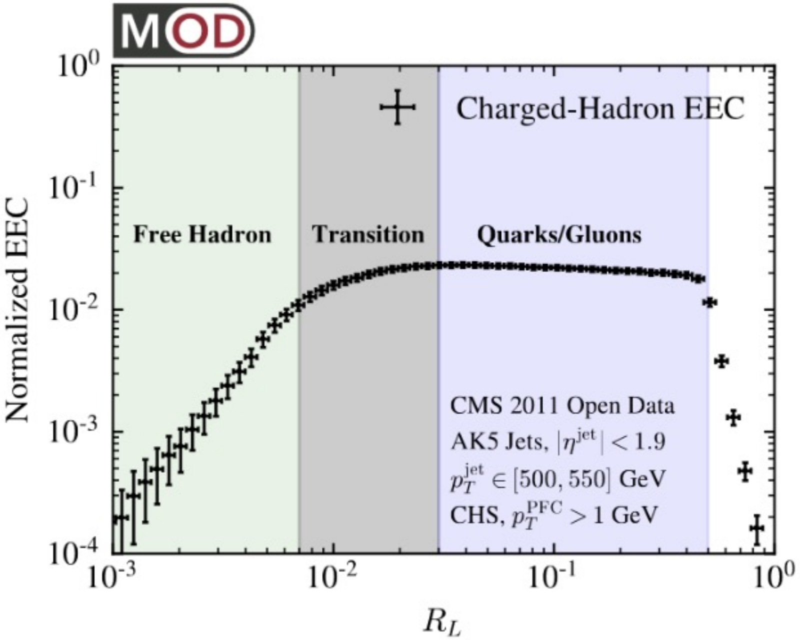
Projected energy-correlators

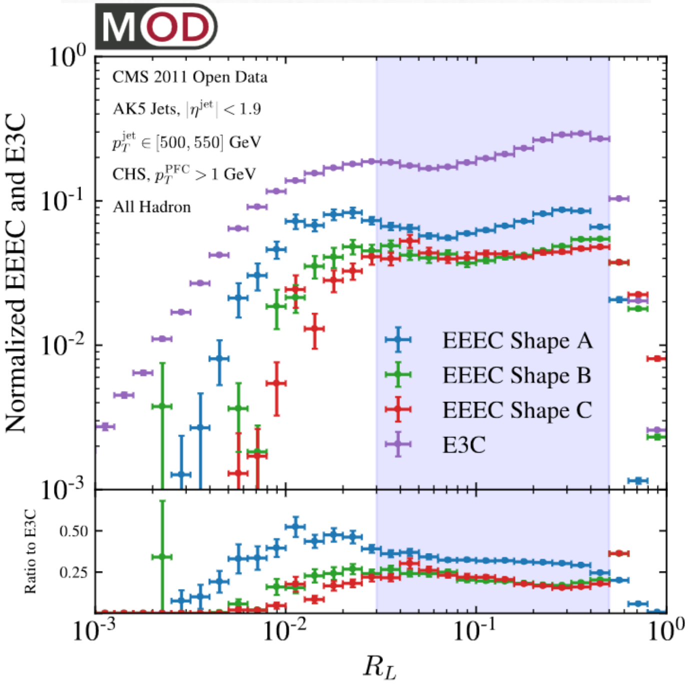
$$ENC(R_L) = -\frac{d}{dR_L}\left[(1,1)\exp\left(\frac{-\gamma^{(0)}(N+1)}{\beta_0}\ln\frac{\alpha_S(R_L\mu)}{\alpha_S(\mu)}\right)(x_q,x_g)\right]H_J(\mu)$$

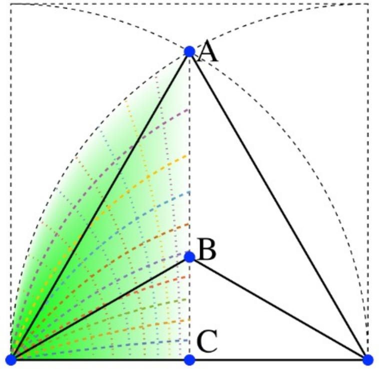








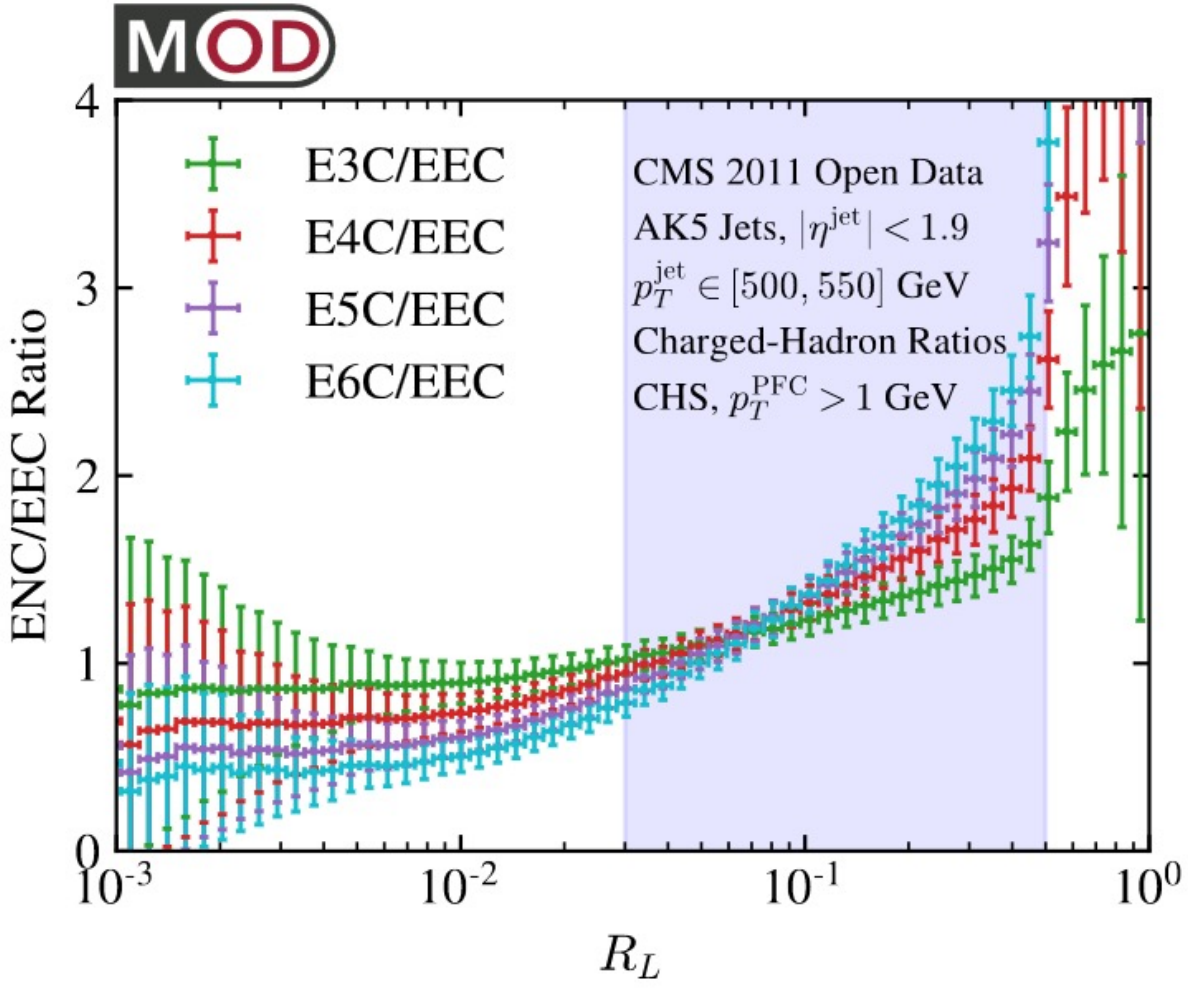




Generators don't capture the scaling behavior of EEEC

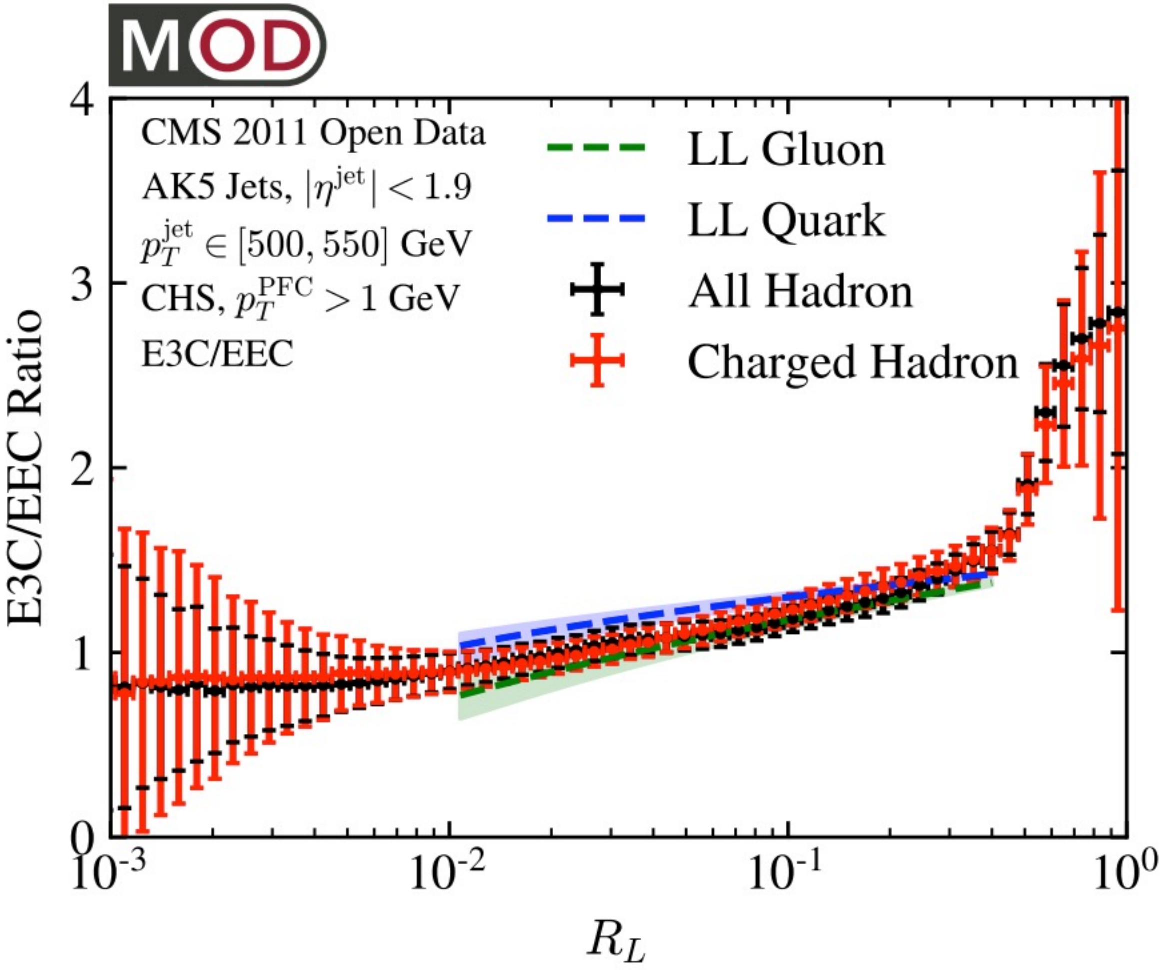
ENC/EEC ratios

- Get rid of non-perturbative and detector effects.
- Probe quantum mechanical corrections.



[Komiske et al. , PhysRevLett.130.051901](#)

E3C/EEC ratios: quarks and gluons



Komiske et al. , PhysRevLett.130.051901