Study of N-point energy correlators in jets with ALICE

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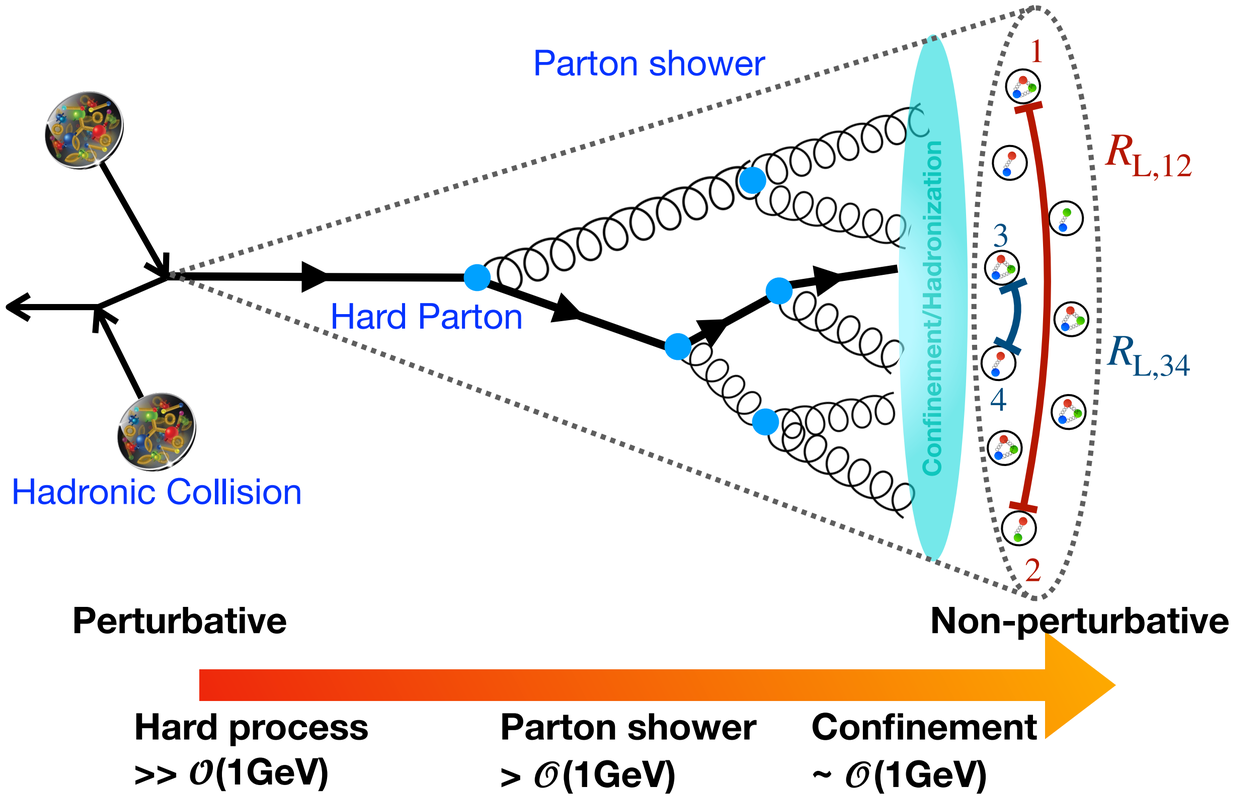
2-point energy correlators in jets



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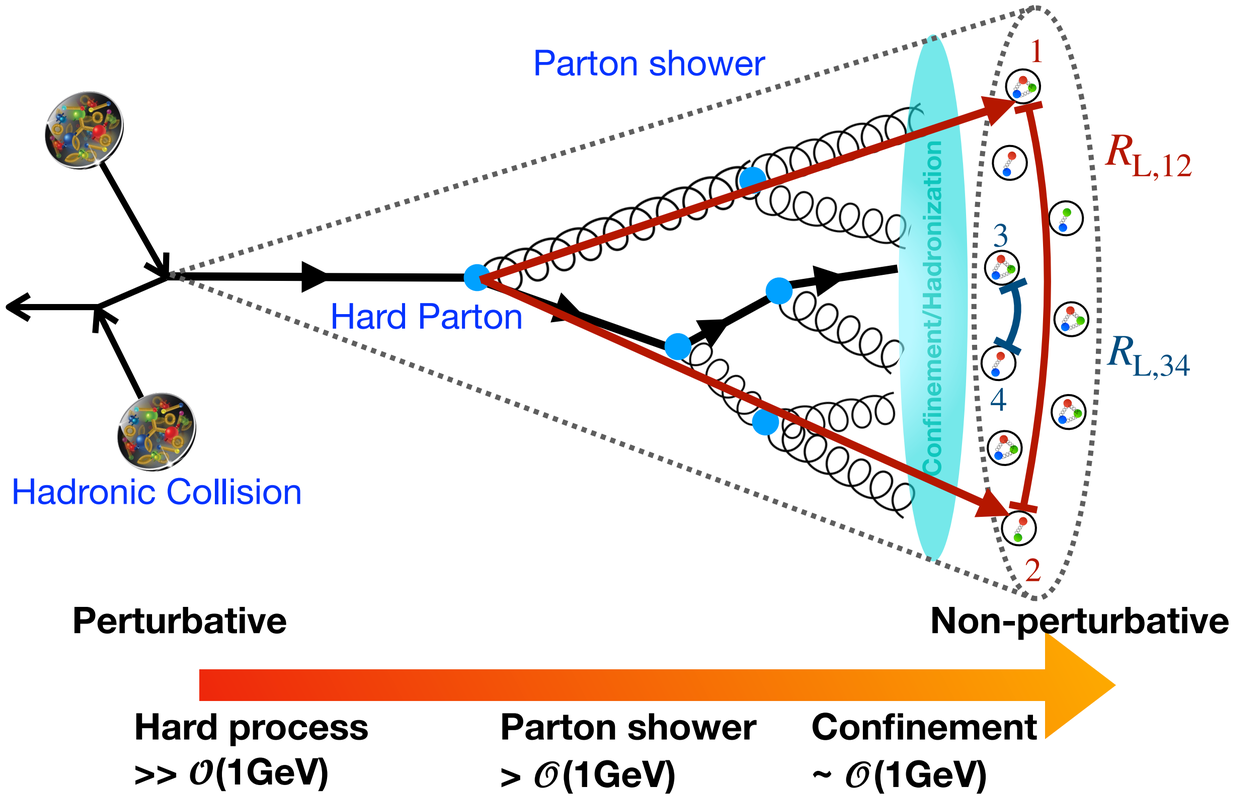
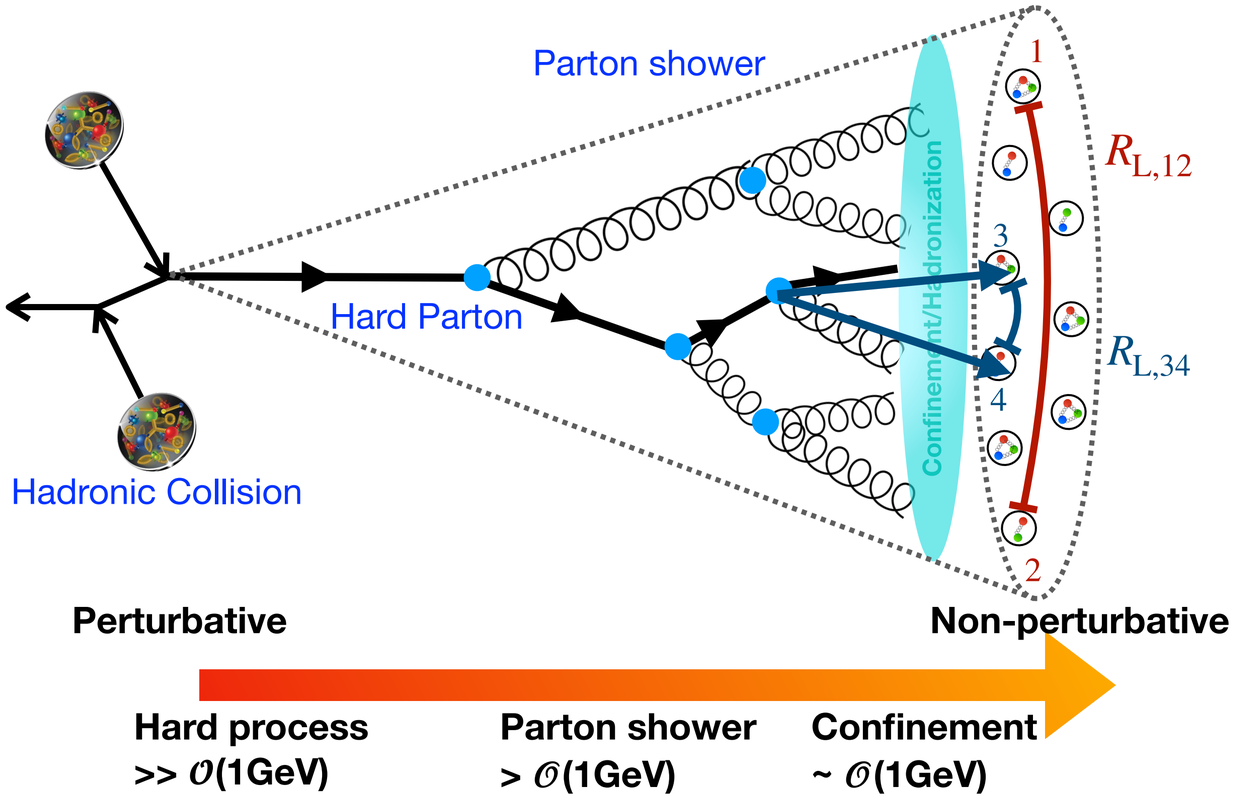


QCD emissions in parton showers are angular ordered

➡ Early splittings (perturbative) wider R_L

2-point energy correlators in jets

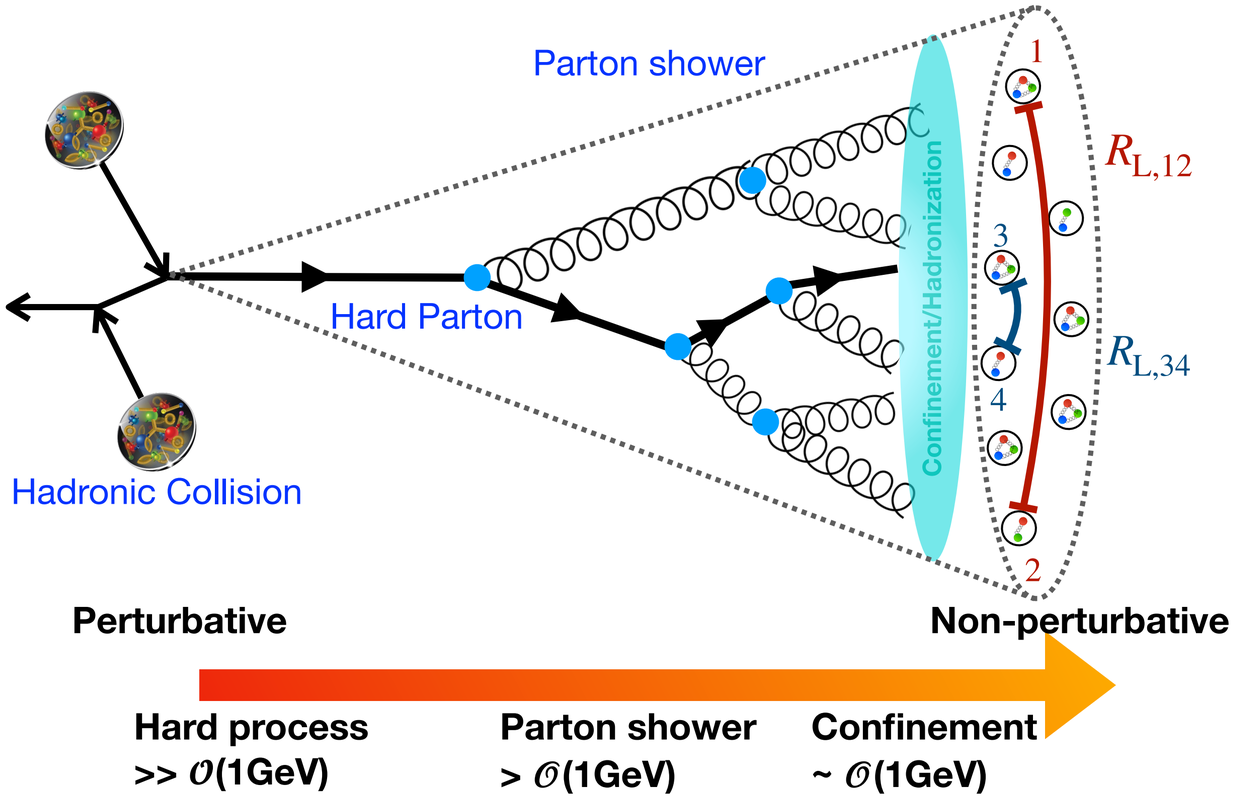


QCD emissions in parton showers are angular ordered

➡ Early splittings (perturbative) wider R_L

➡ Late splittings (non-perturbative) narrower R_L

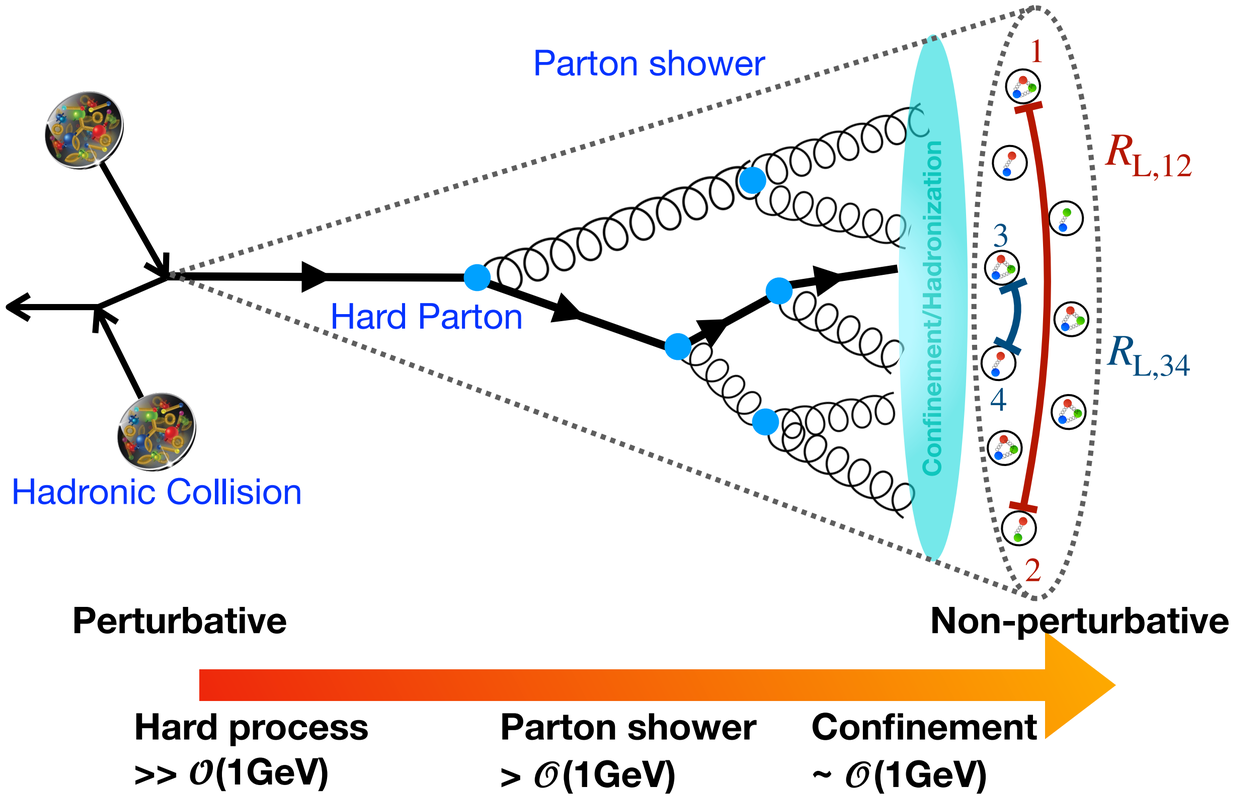
2-point energy correlators in jets



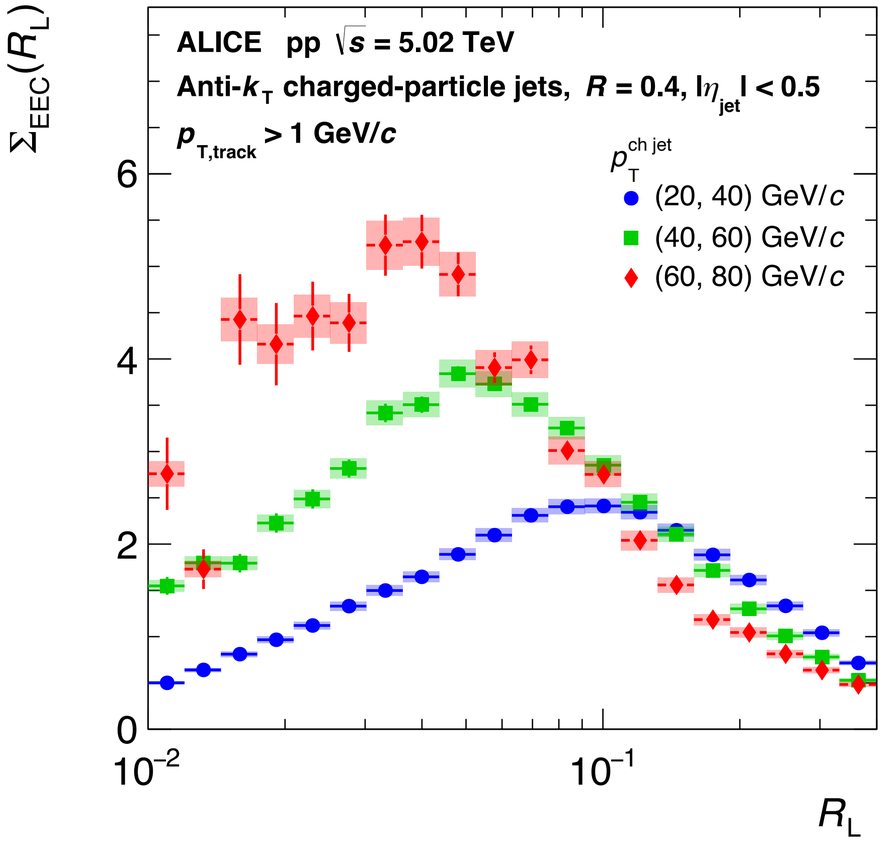
$$\mathrm{EEC}(R_\mathrm{L}) = \frac{1}{N_\mathrm{jet}} \sum_{i,j} \int \mathrm{d}R'_\mathrm{L} \delta(R_\mathrm{L} - R'_\mathrm{L}) \frac{p_{\mathrm{T},i} p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}}$$

Derived from QFT and precise theoretical calculations

Parton–hadron transition



ALICE arXiv:2409.12687



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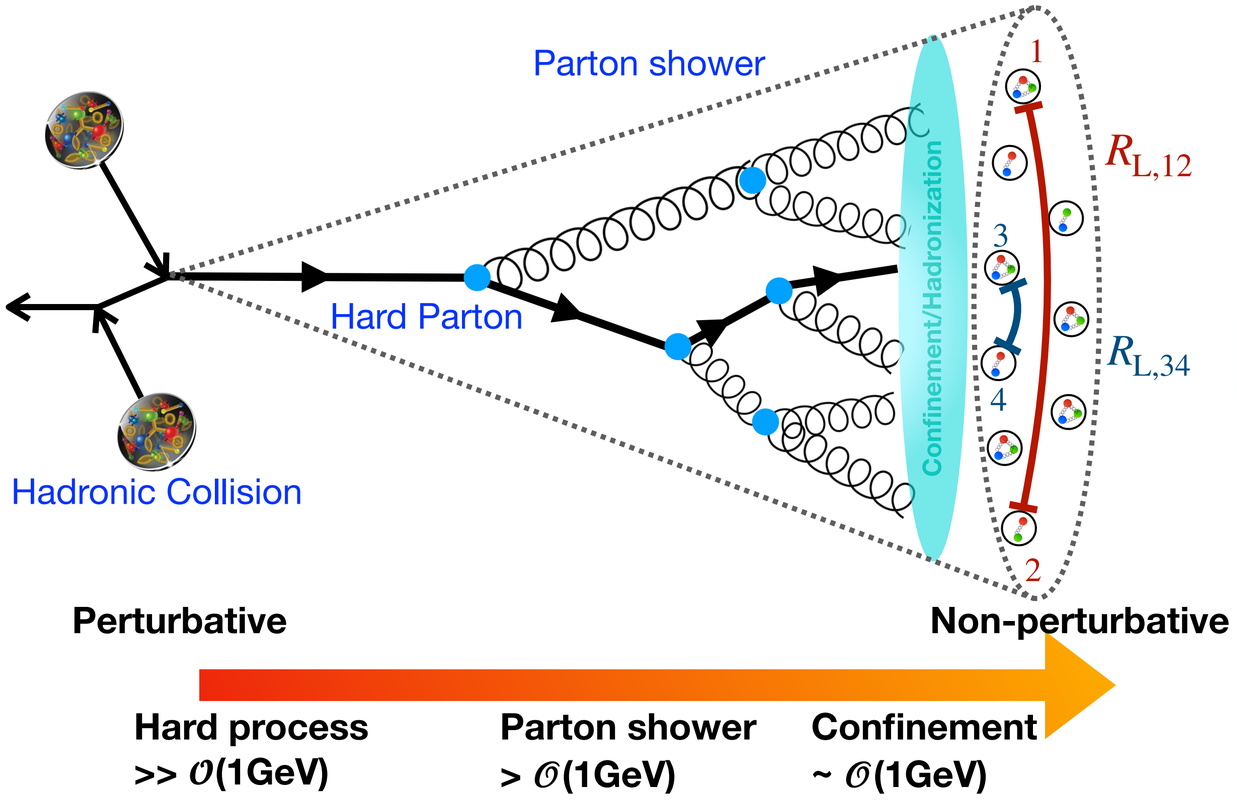

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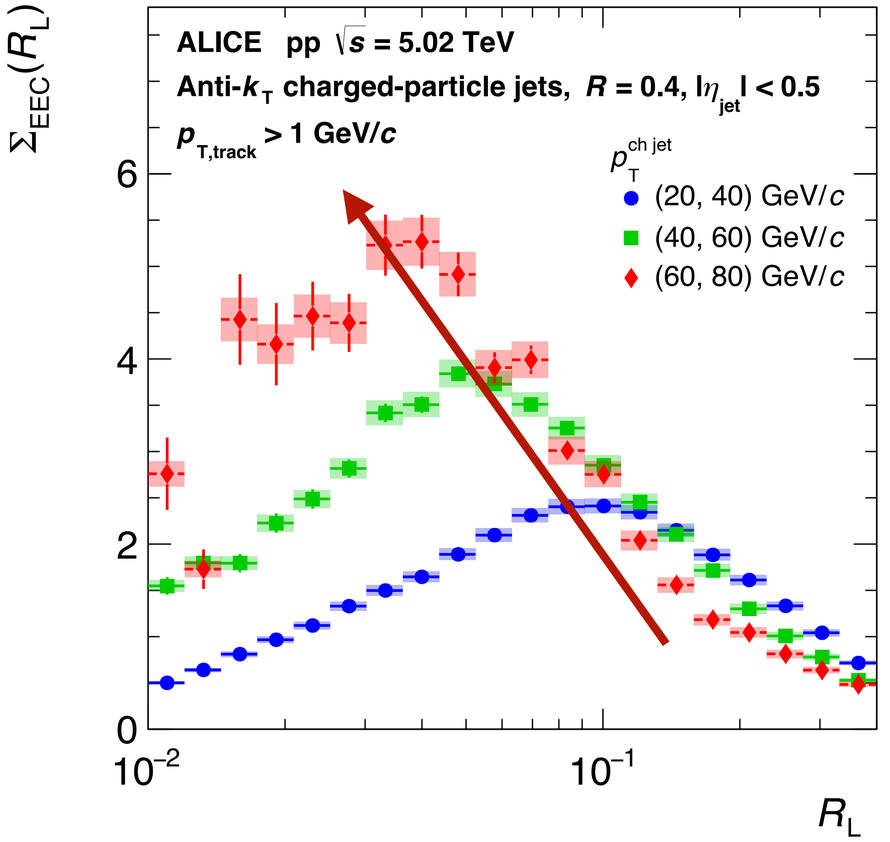

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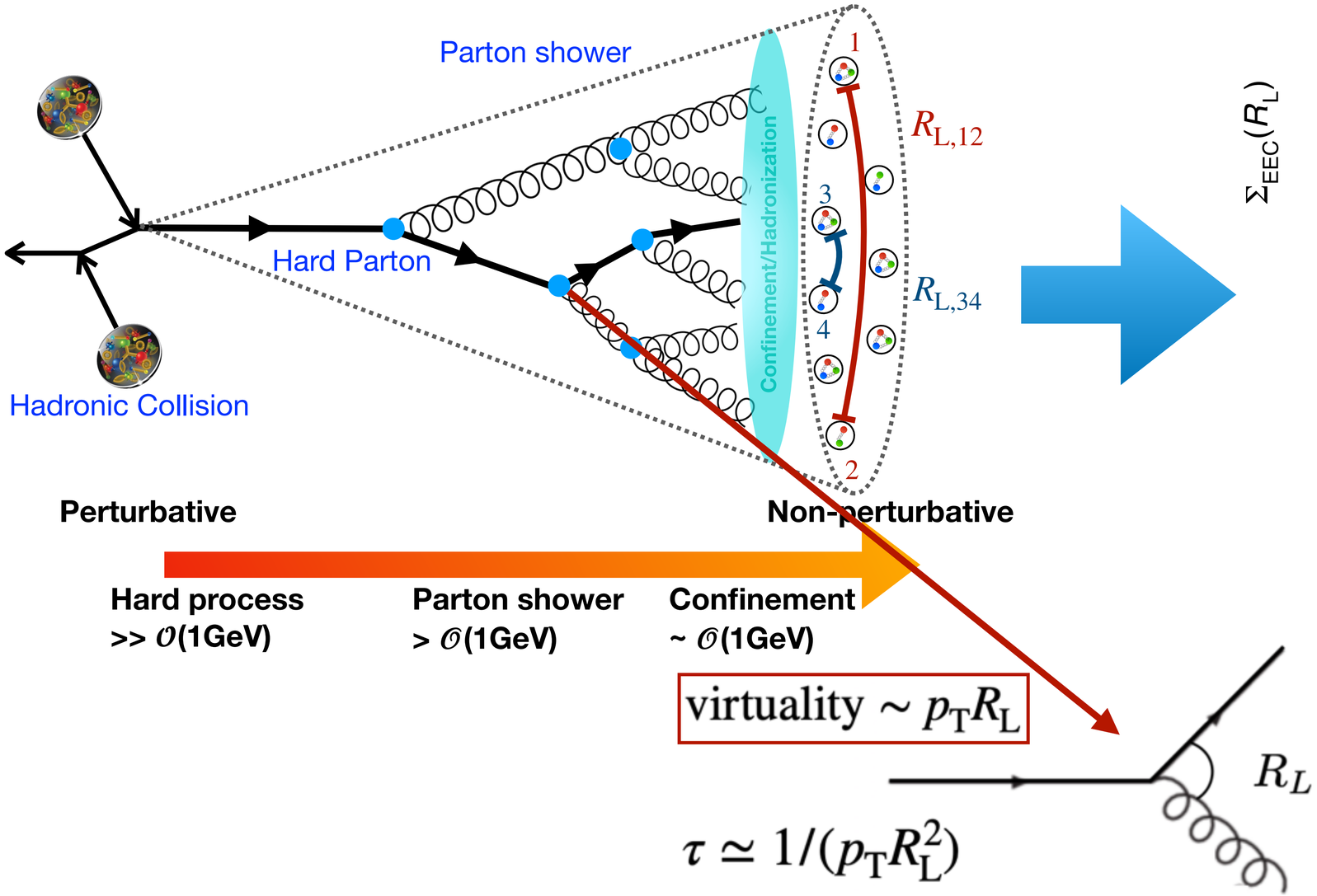

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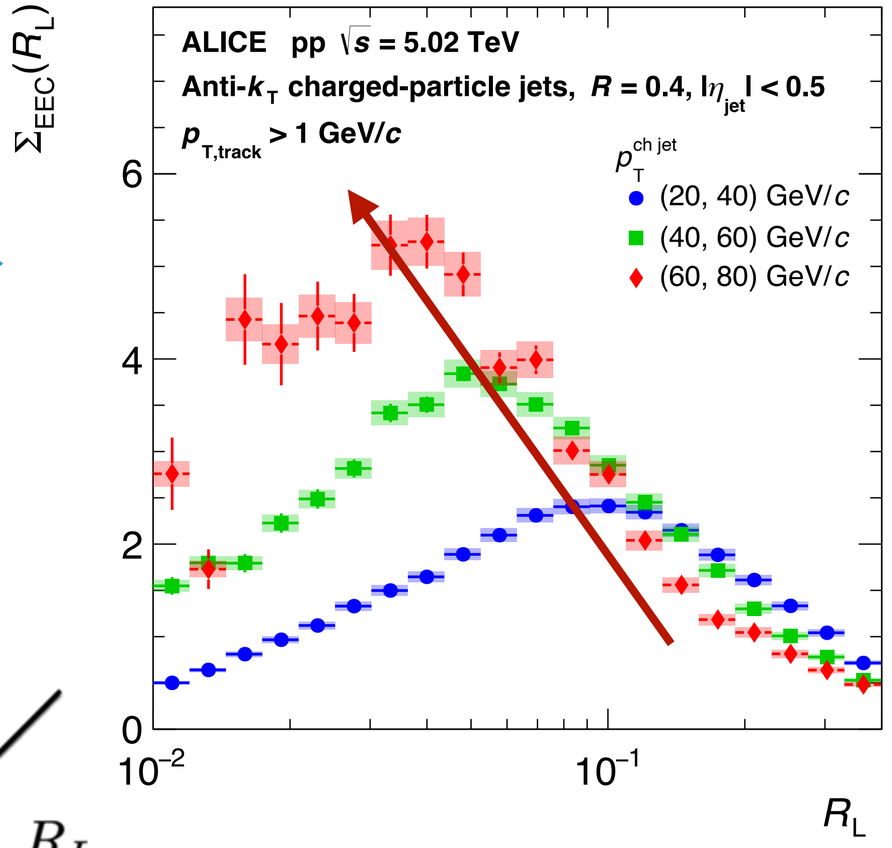

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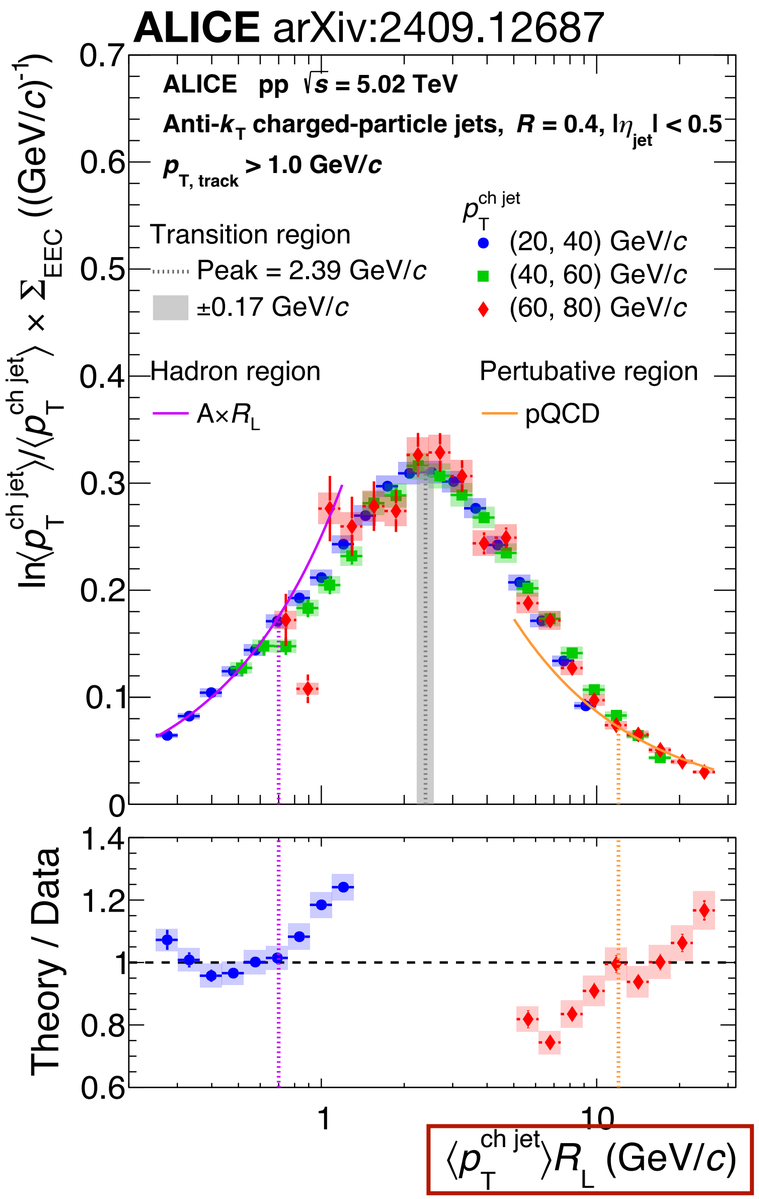
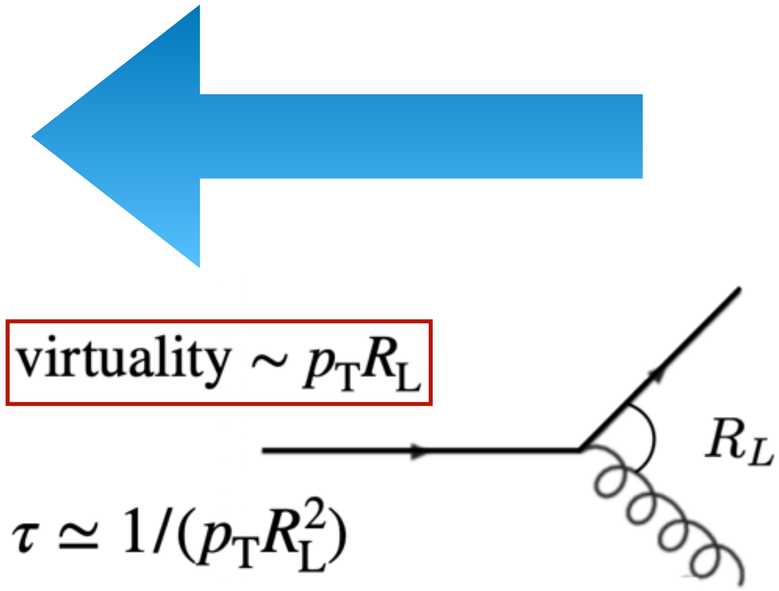
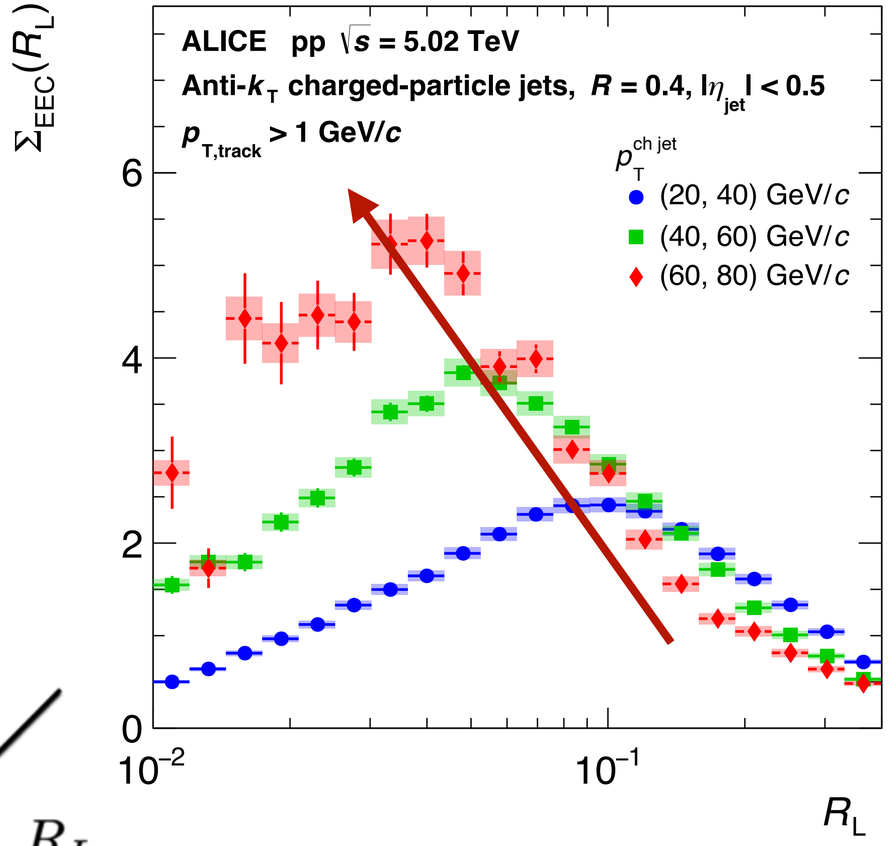


- Scaling Σ_{EEC} with $p_{T,jet}R_L$ ⇒ Proportional to virtuality





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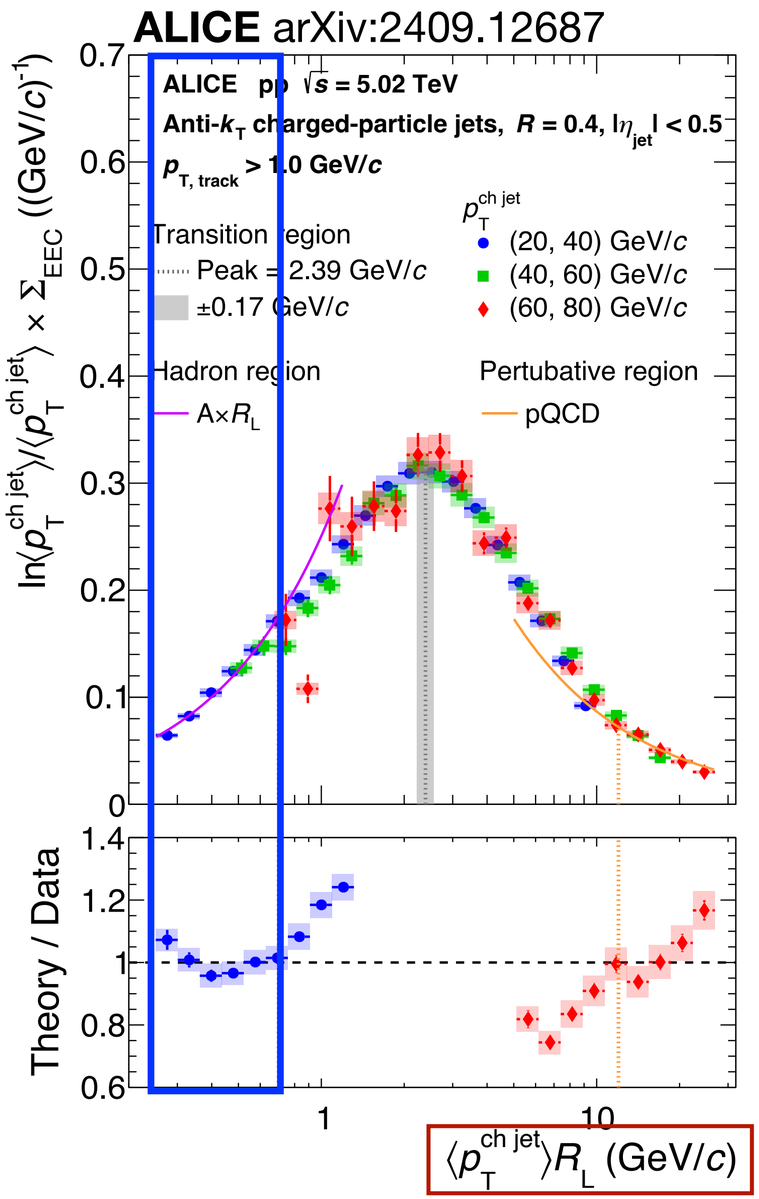

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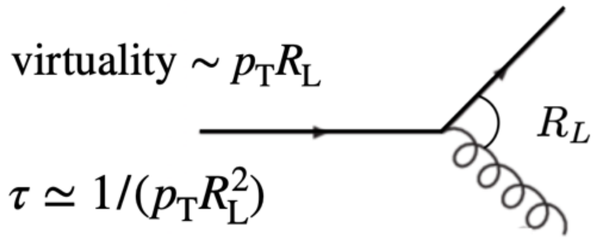
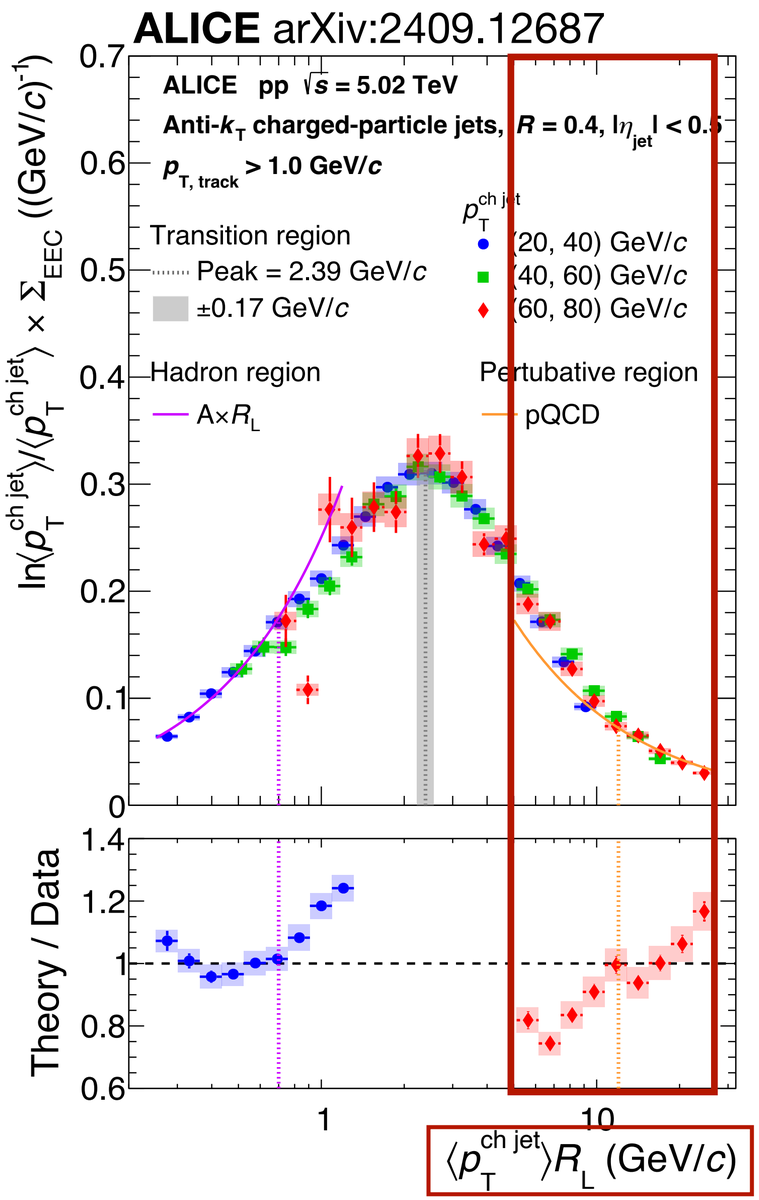


- Small R_L: Clear linear scaling ⇒ “free” hadron regime

$$\mathrm{EEC}(R_\mathrm{L}) = \frac{1}{N_\mathrm{jet}} \sum_{i,j} \int \mathrm{d}R'_\mathrm{L} \delta(R_\mathrm{L} - R'_\mathrm{L}) \frac{p_{\mathrm{T},i} p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}}$$

Parton–hadron transition



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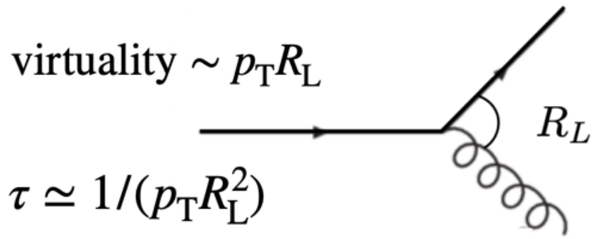
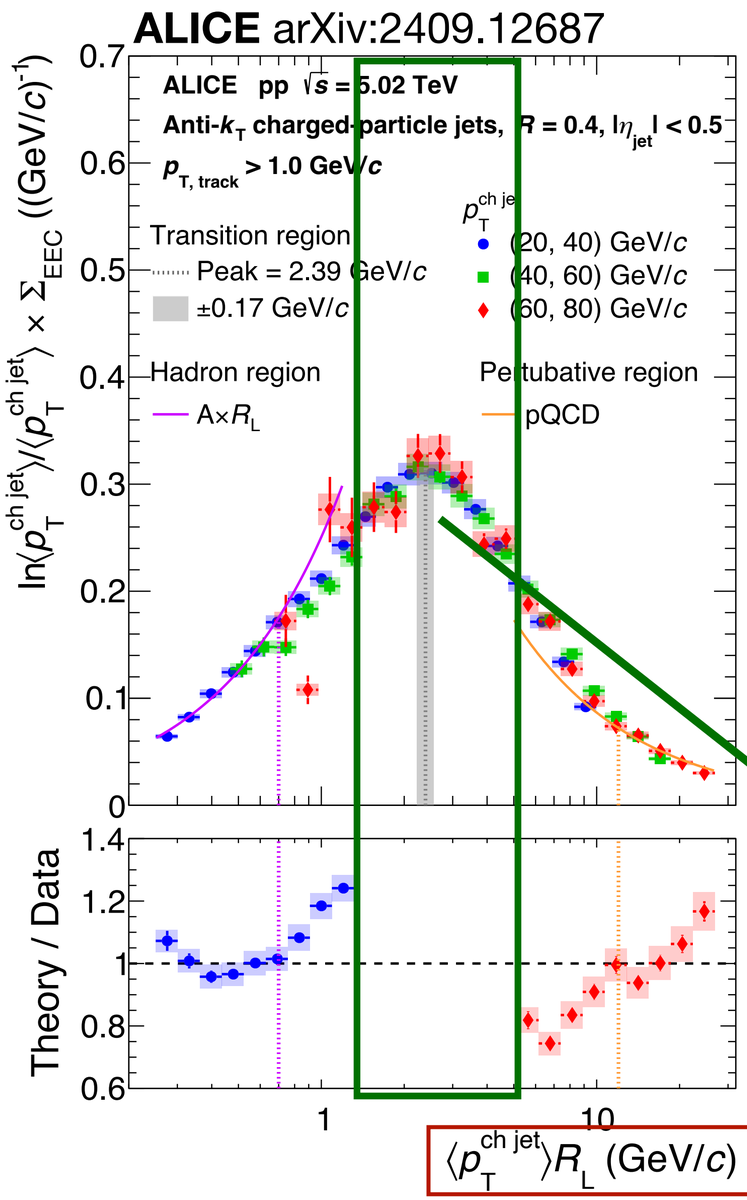


- Small R_L: Clear linear scaling ⇒ “free” hadron regime
- Large R_L: Well described by pQCD ⇒ max. dev. ~20%

Phys. Rev. **D111** (2025) L011502

Parton–hadron transition



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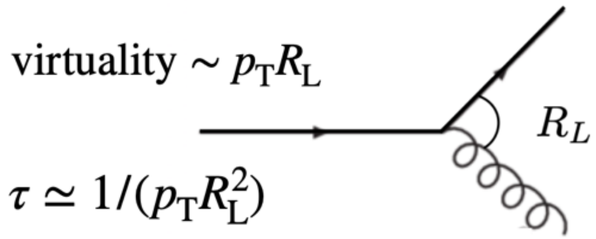


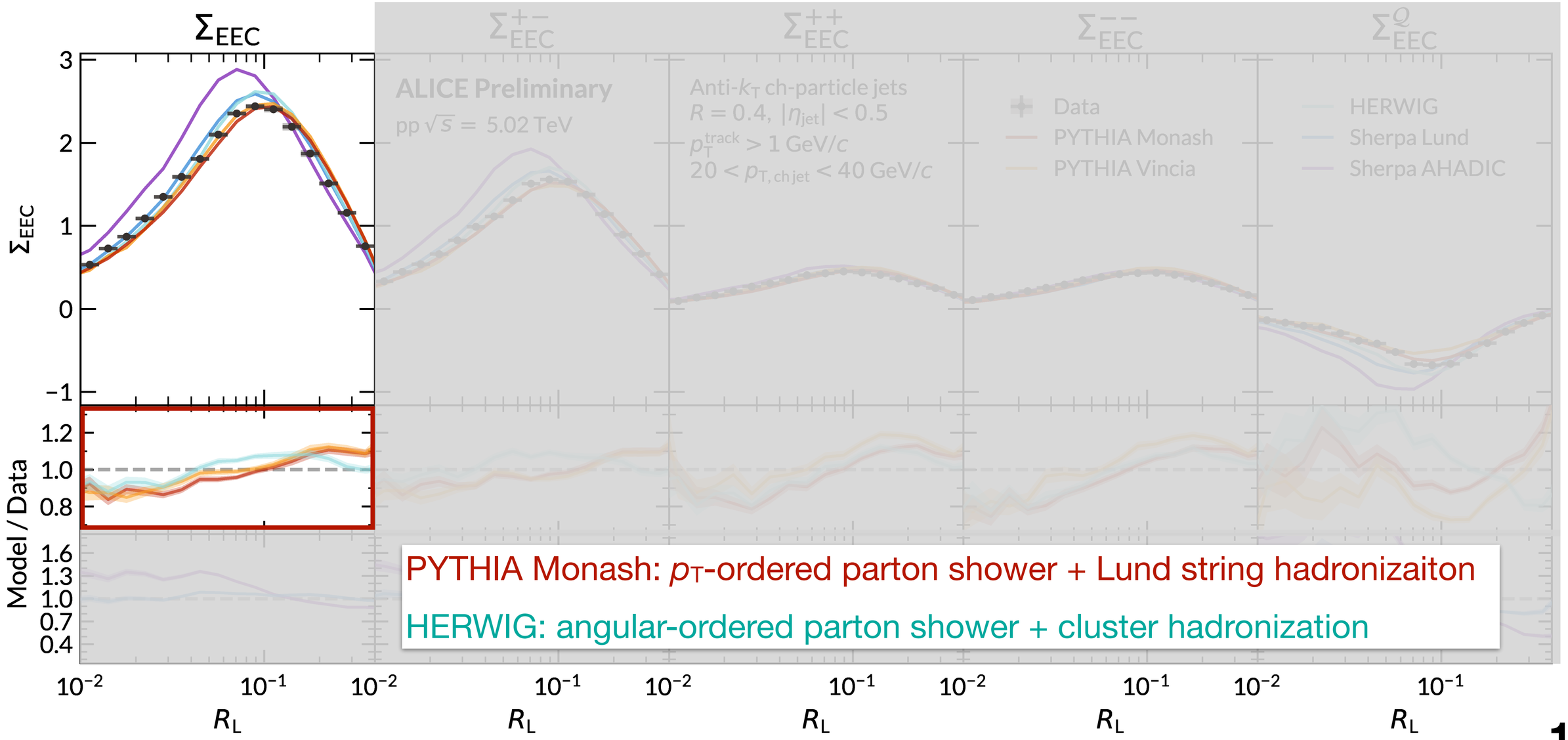
- Small R_L: Clear linear scaling ⇒ “free” hadron regime
- Large R_L: Well described by pQCD ⇒ max. dev. ~20%

Phys. Rev. **D111** (2025) L011502

- Peaks are aligned at $p_{T,jet}R_L \approx 2.4$ GeV/c

➡ Implies a common energy scale for parton–hadron transition

Testing model sensitivity



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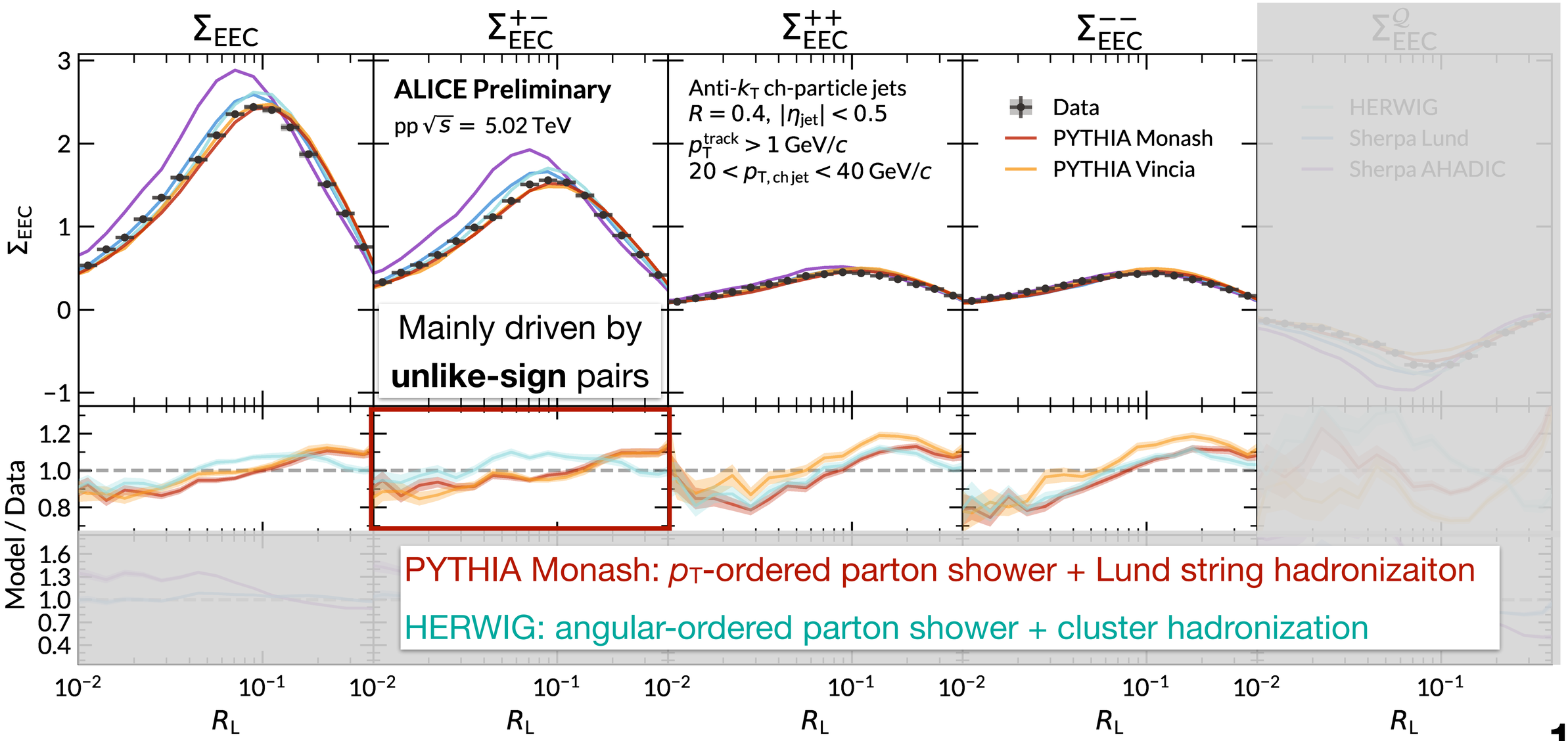

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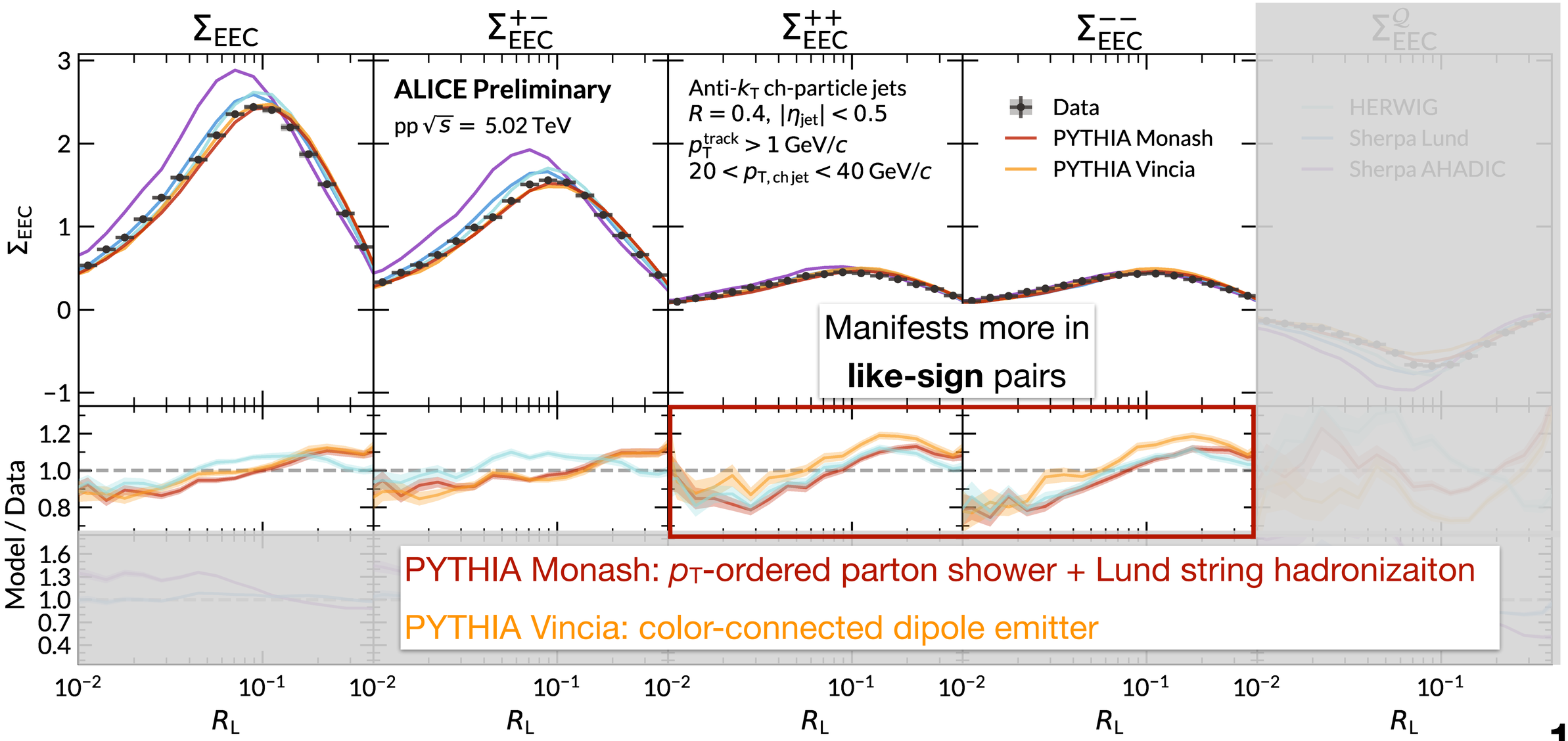

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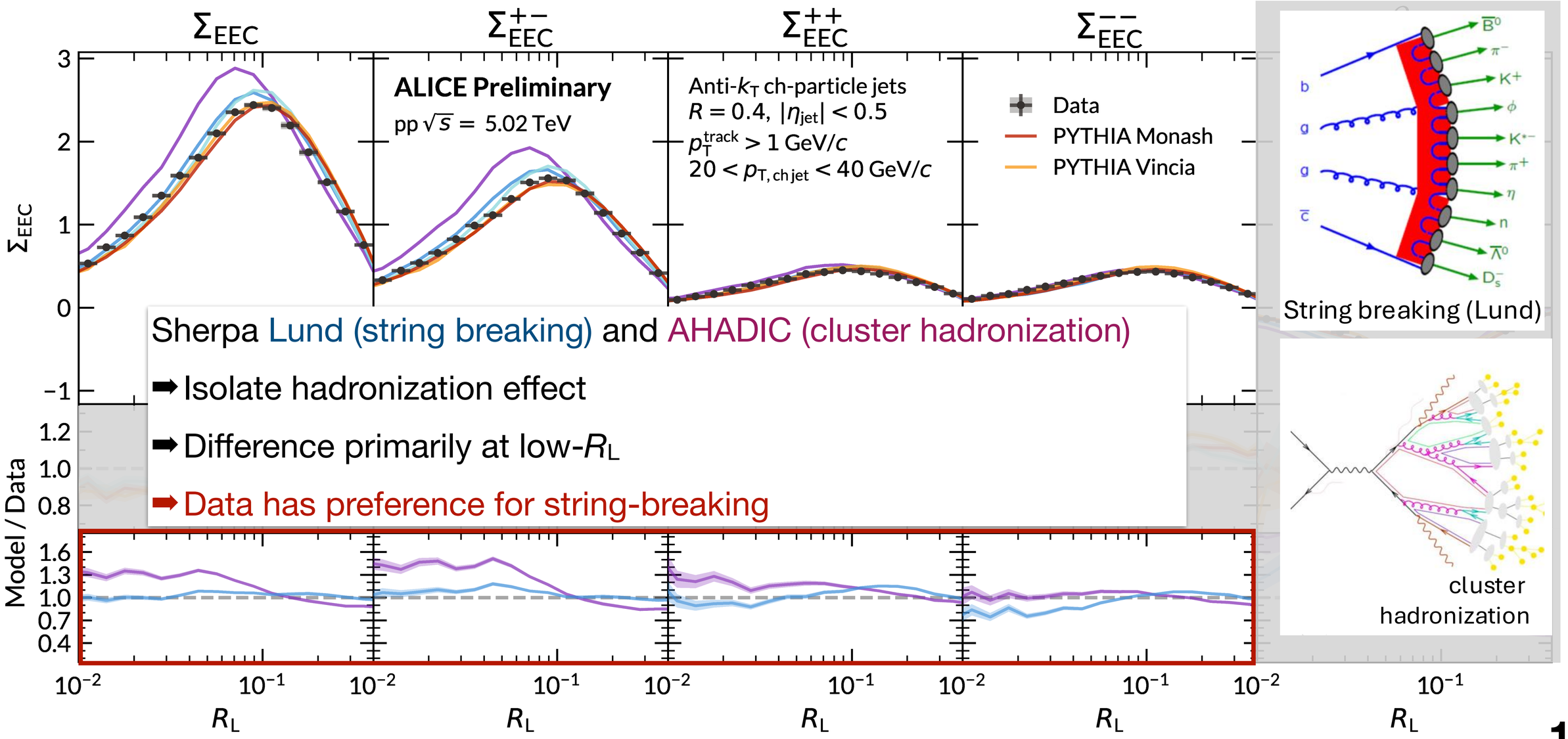


Sherpa Lund (string breaking) and AHADIC (cluster hadronization)

➡ Isolate hadronization effect

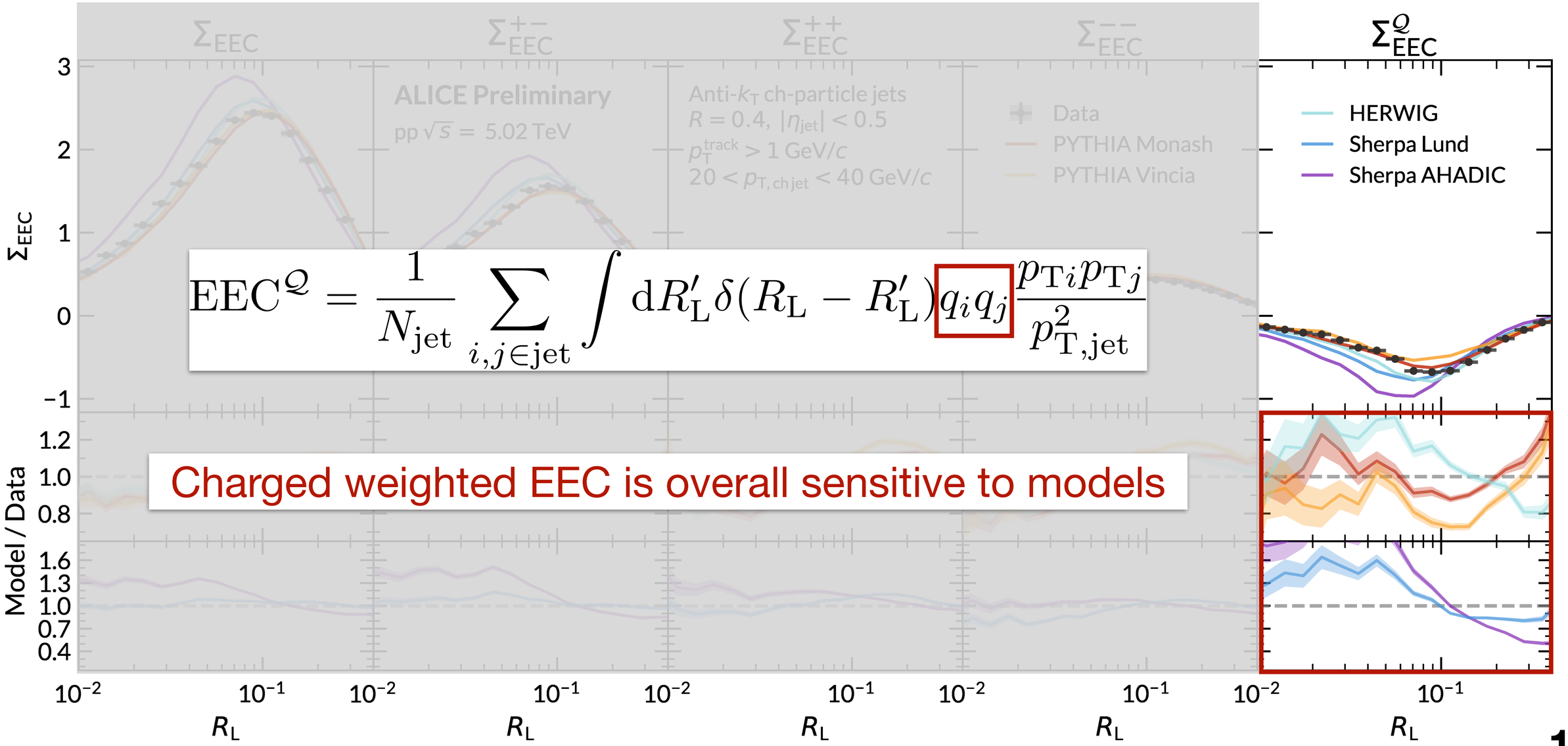
➡ Difference primarily at low-R_L

➡ Data has preference for string-breaking

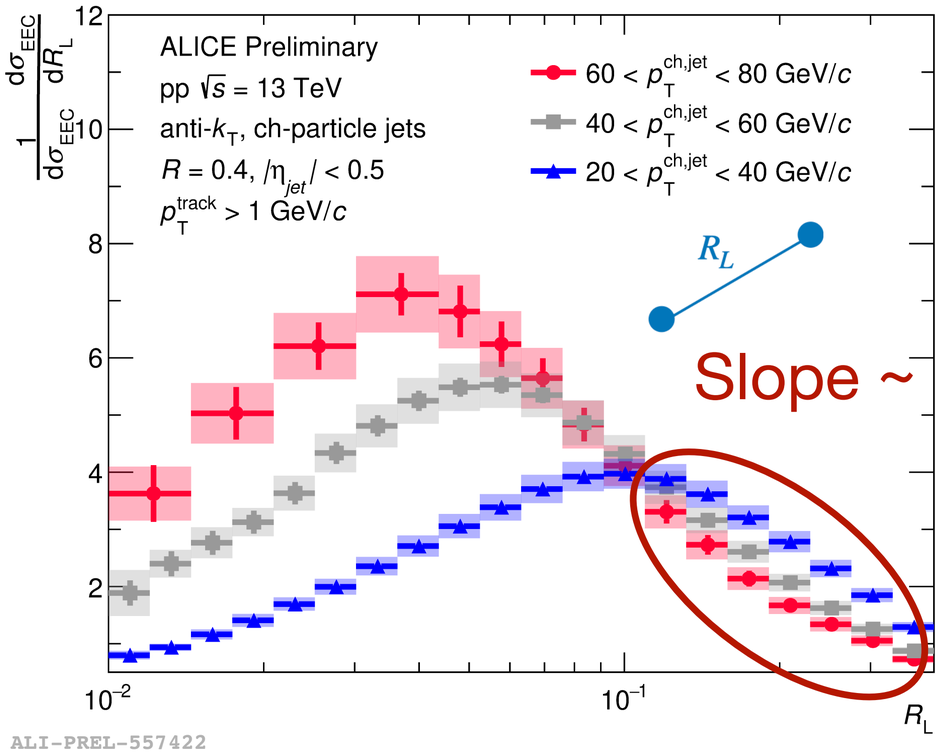
String breaking (Lund)

cluster hadronization

Testing model sensitivity



QFT anomalous demesions



Slope ~ $1/R_L^{1-\gamma_2}$

ALI-PREL-557422

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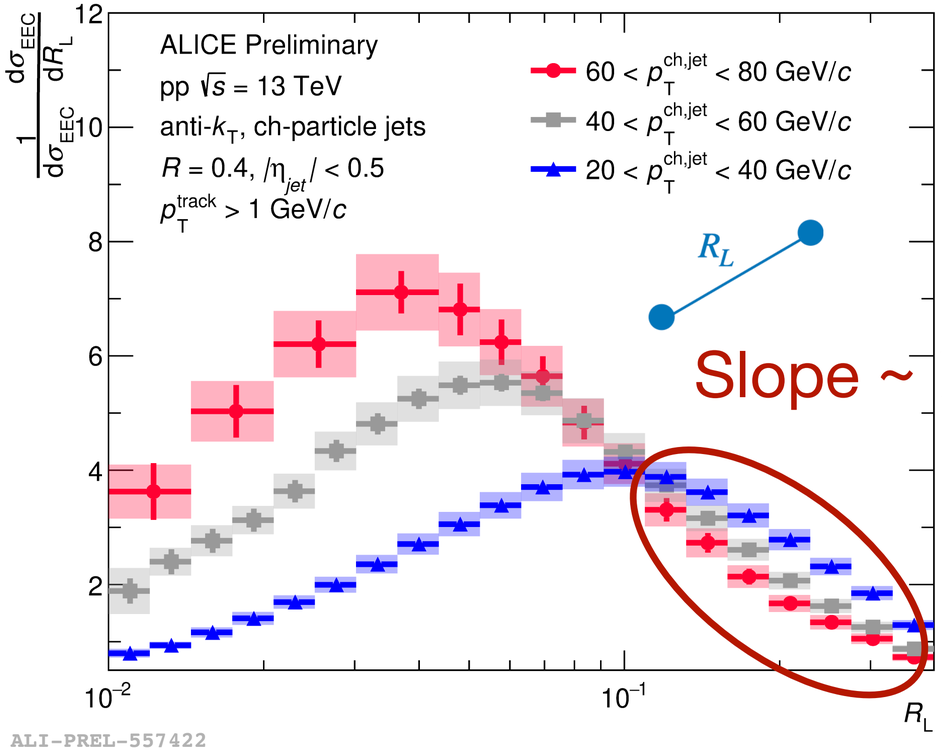

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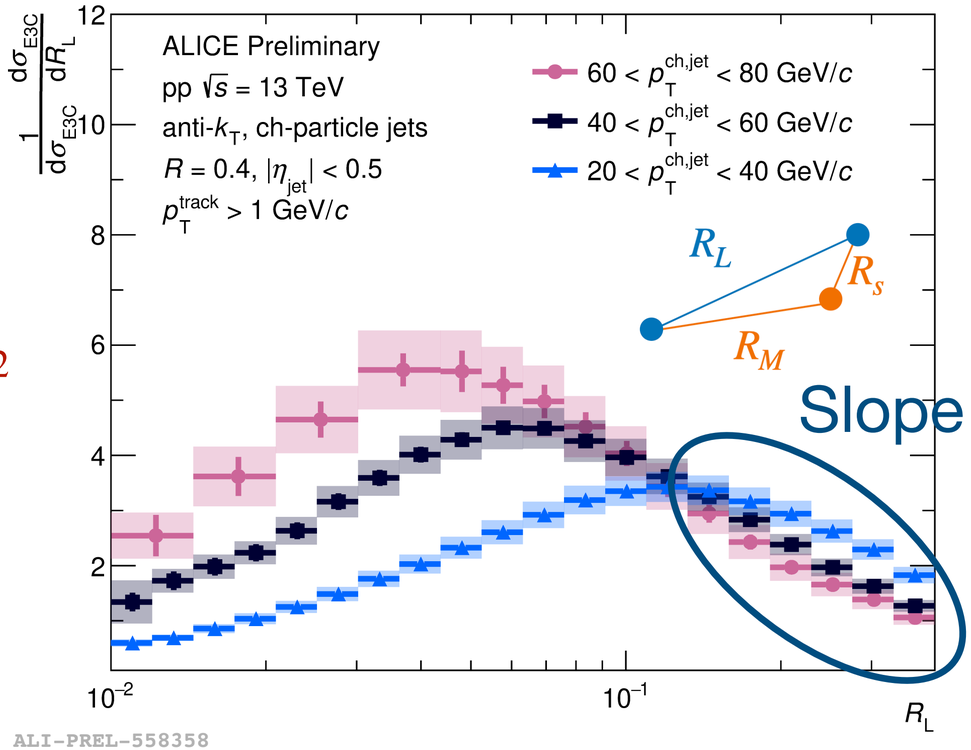
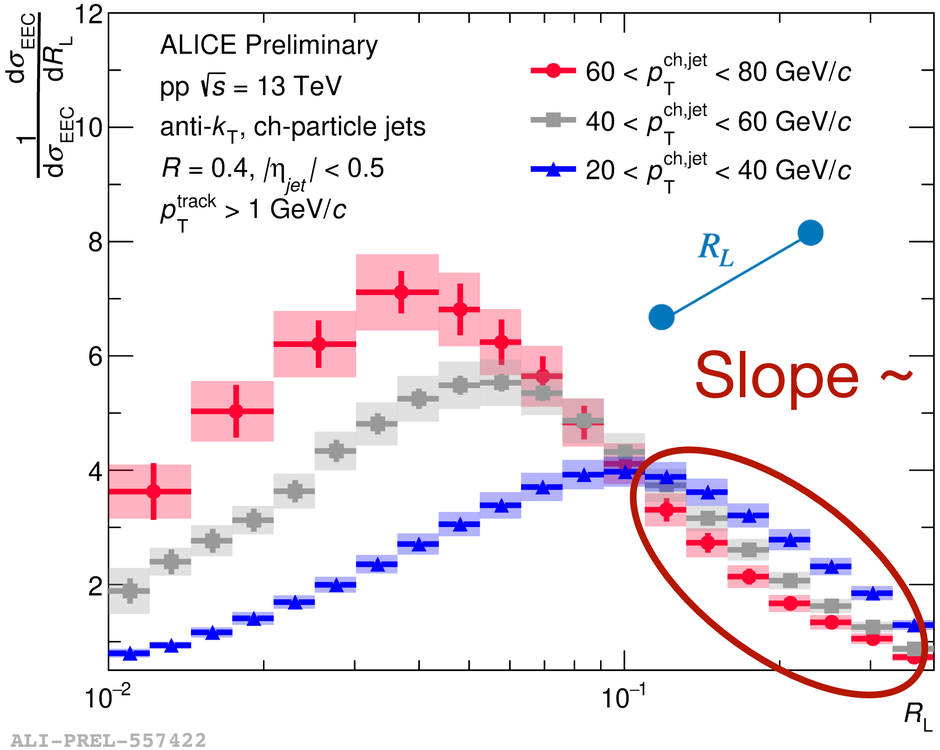


Slope ~ $1/R_L^{1-\gamma_3}$

ALI-PREL-558358

$$\mathrm{E3C}(R_\mathrm{L}) = \frac{1}{N_\mathrm{jet}} \sum_{i,j,k} \int \mathrm{d}R'_\mathrm{L} \delta(R_\mathrm{L} - R'_\mathrm{L}) \frac{p_{\mathrm{T},i} p_{\mathrm{T},j} p_{\mathrm{T},k}}{p^3_{\mathrm{T,jet}}}$$

QFT anomalous demesions



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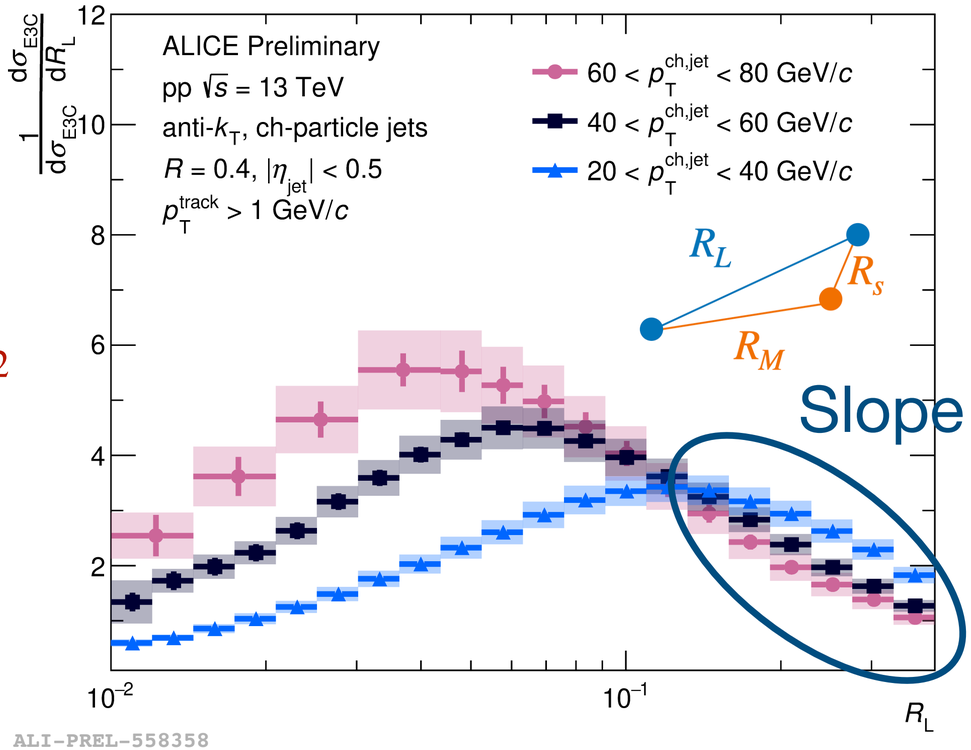
ALI-PREL-557422



Slope ~ $1/R_L^{1-\gamma_3}$

ALI-PREL-558358

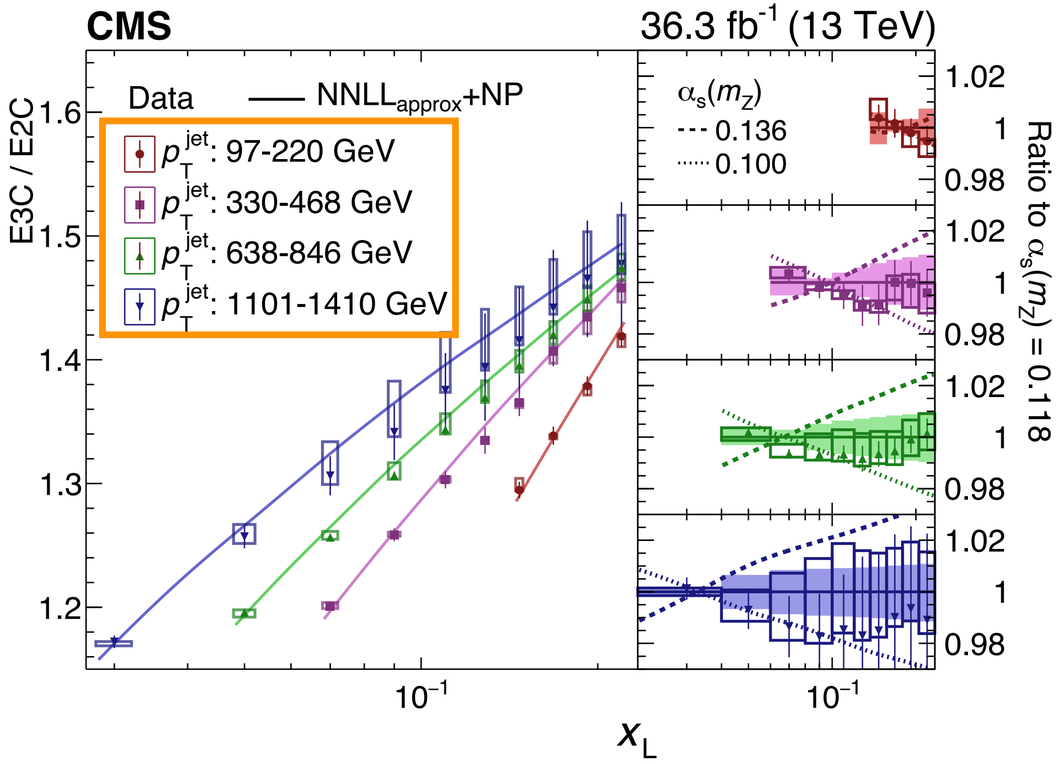
Large-R_L slope: probe the quantum corrections

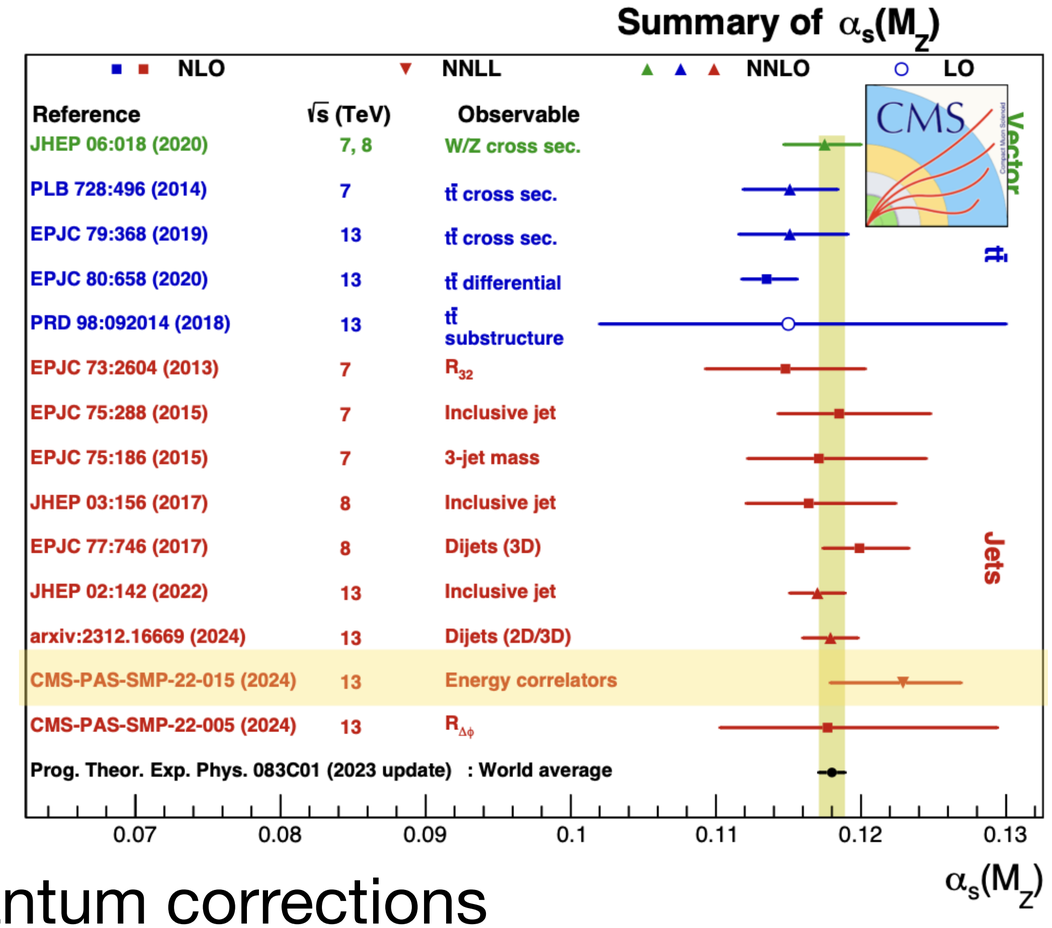
➡ Anomalous dimensions of EEC ($\gamma 2$) and E3C ($\gamma 3$) operators

➡ EEC/E3C $\propto R_L^{\gamma_3-\gamma_2} \propto \alpha_s \ln R_T$ *Phys. Rev.* **D102** (2020) 054012

Determination of α_s

CMS *Phys. Rev. Lett.* **133** (2024) 071903





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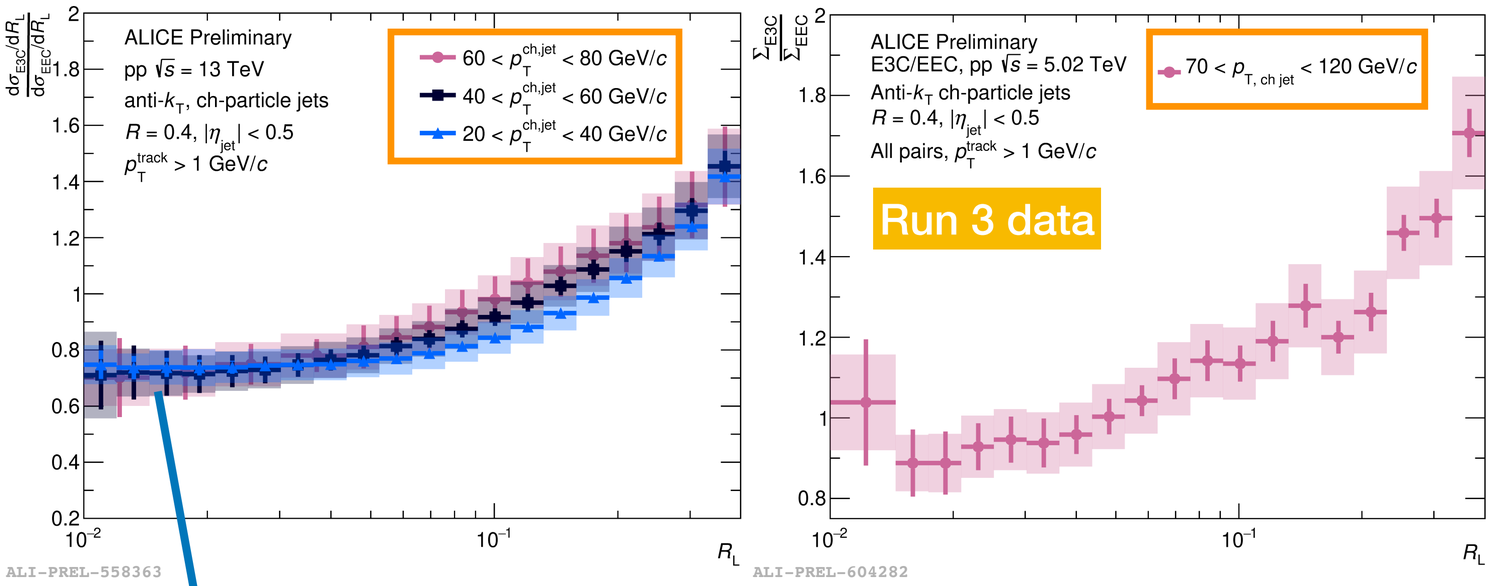
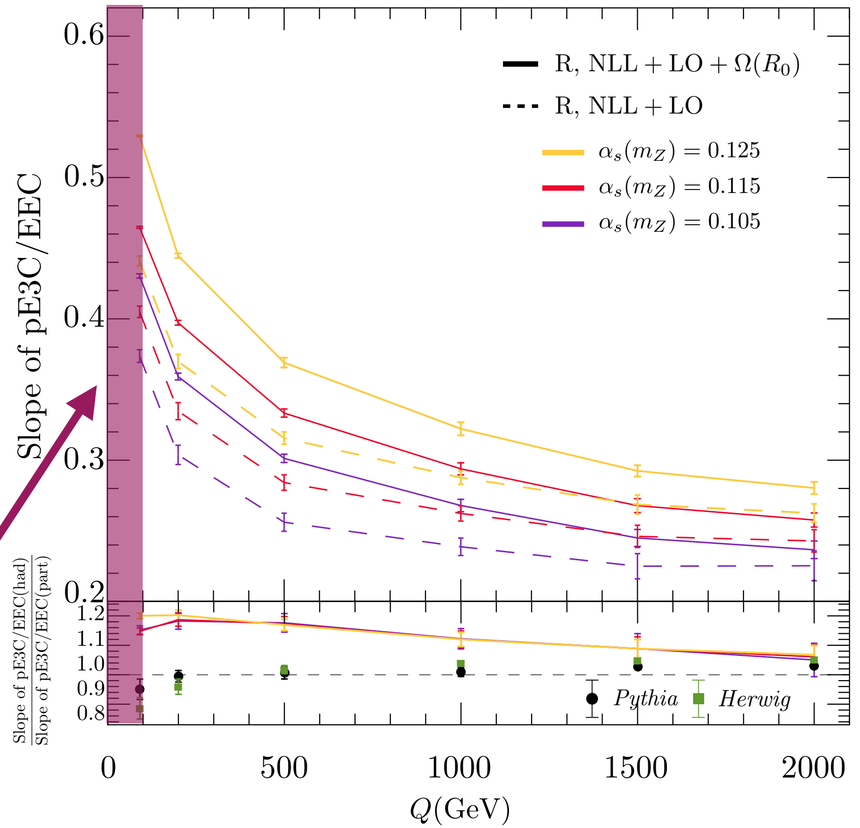
ALICE: Towards lower jet p_T

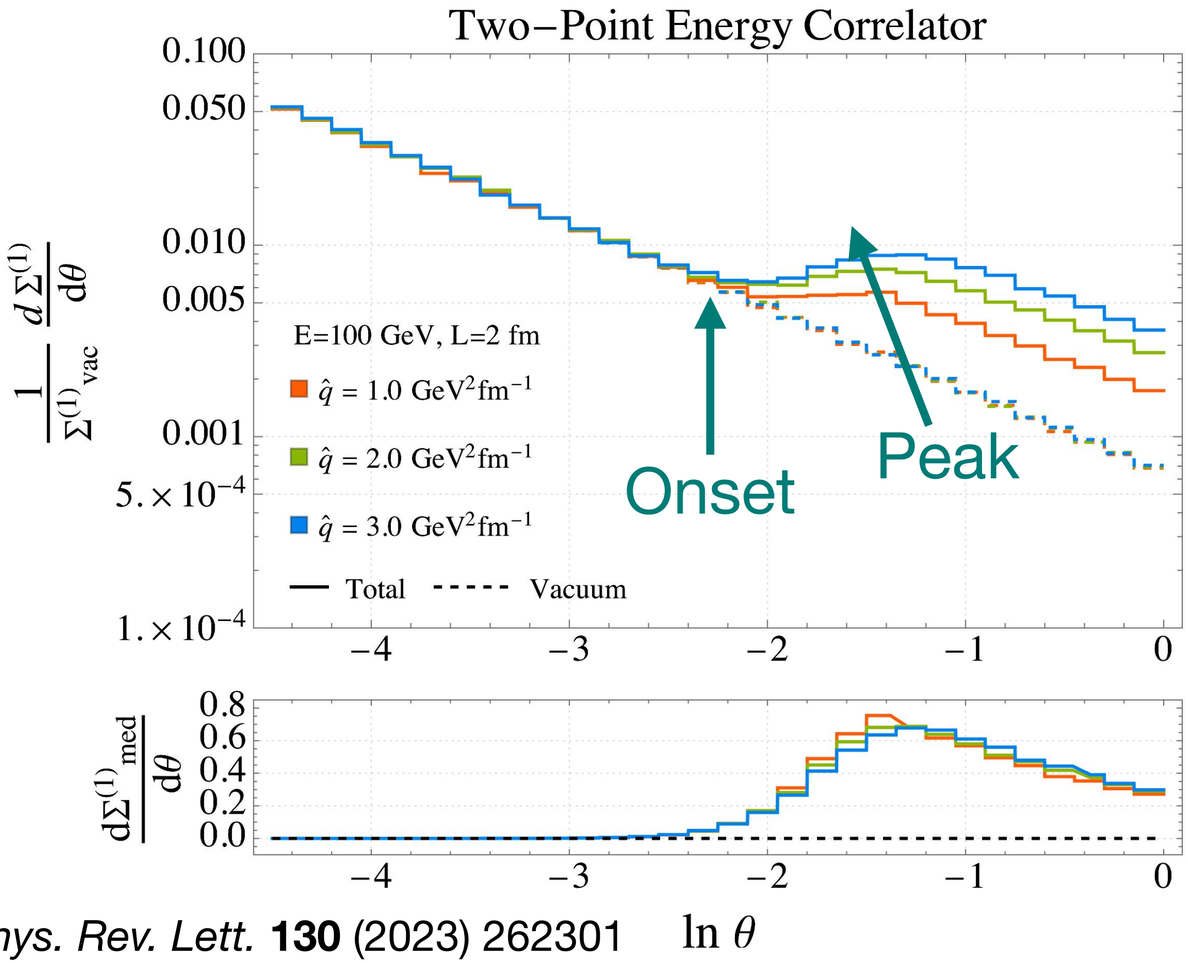


- Charged particle jets down to $p_{T,jet}$ = 20 GeV/c
  - ➡ Small R_L: identical slope for all $p_{T,jet}$ intervals
  - ➡ Map to α_s: access non-perturbative correlations
- Ongoing: map charged to full jets to set energy scale
  - ➡ Track functions, model dependent mapping…



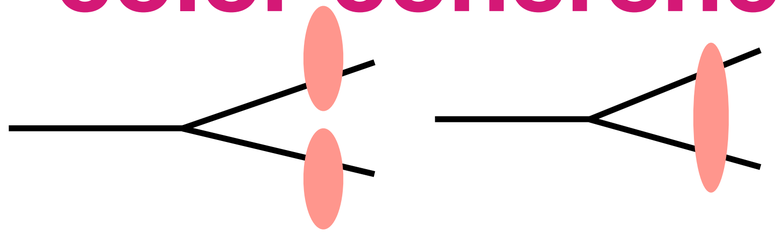
Phys. Rev. Lett. **133** (2024) 231902

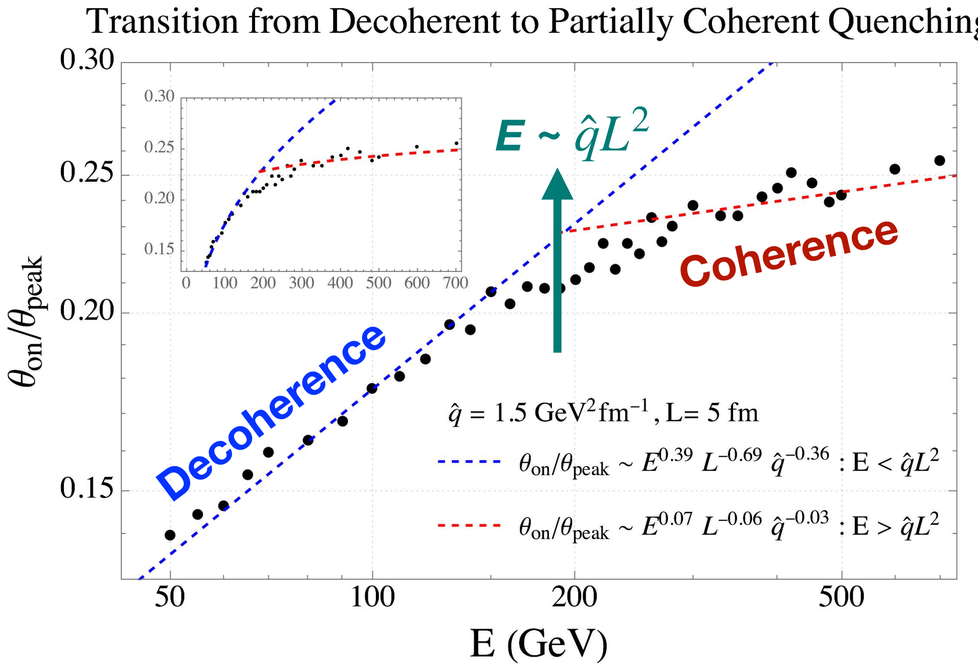
EEC in heavy-ion collisions



Phys. Rev. Lett. **130** (2023) 262301

color coherence

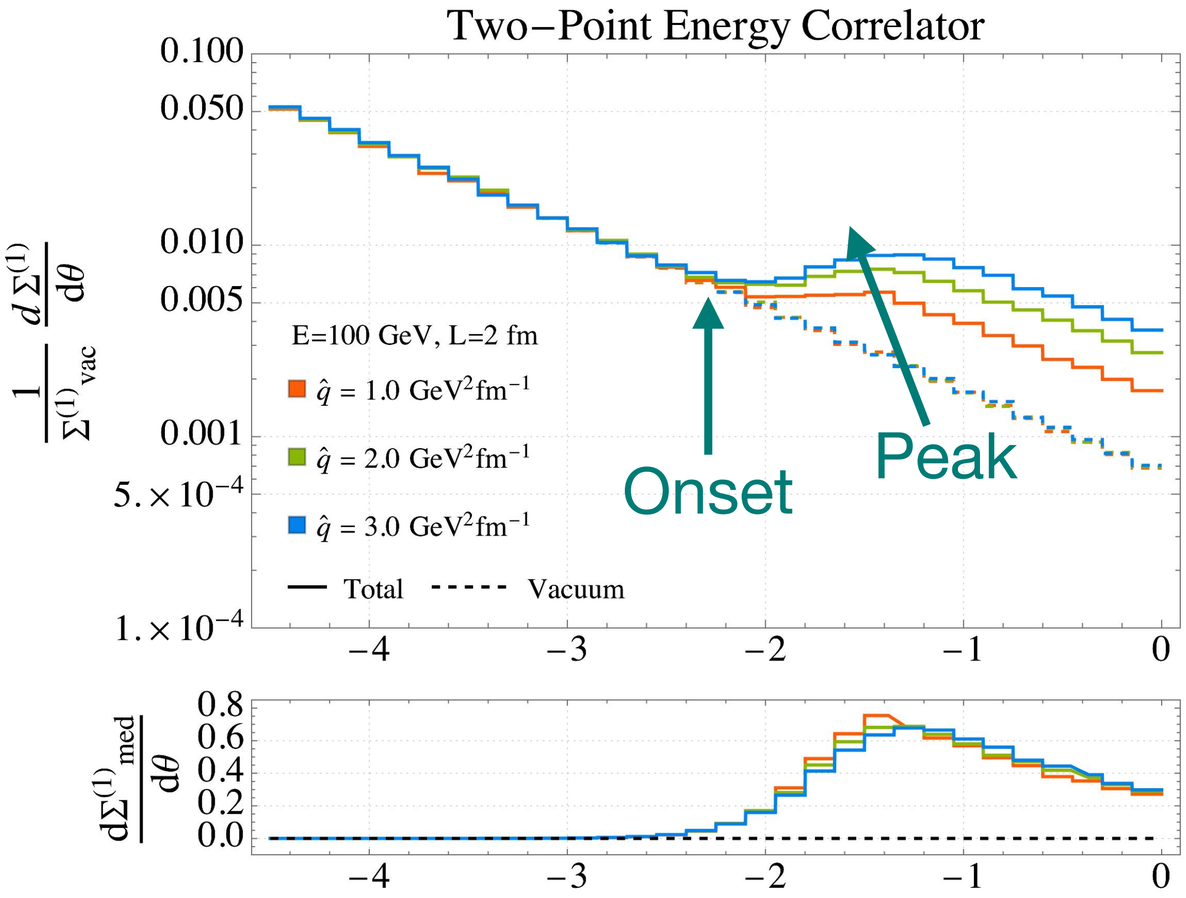




Sensitive to the onset of color coherence

A non-exhaustive list of theoretical activities…

EEC in heavy-ion collisions



Phys. Rev. Lett. **130** (2023) 262301

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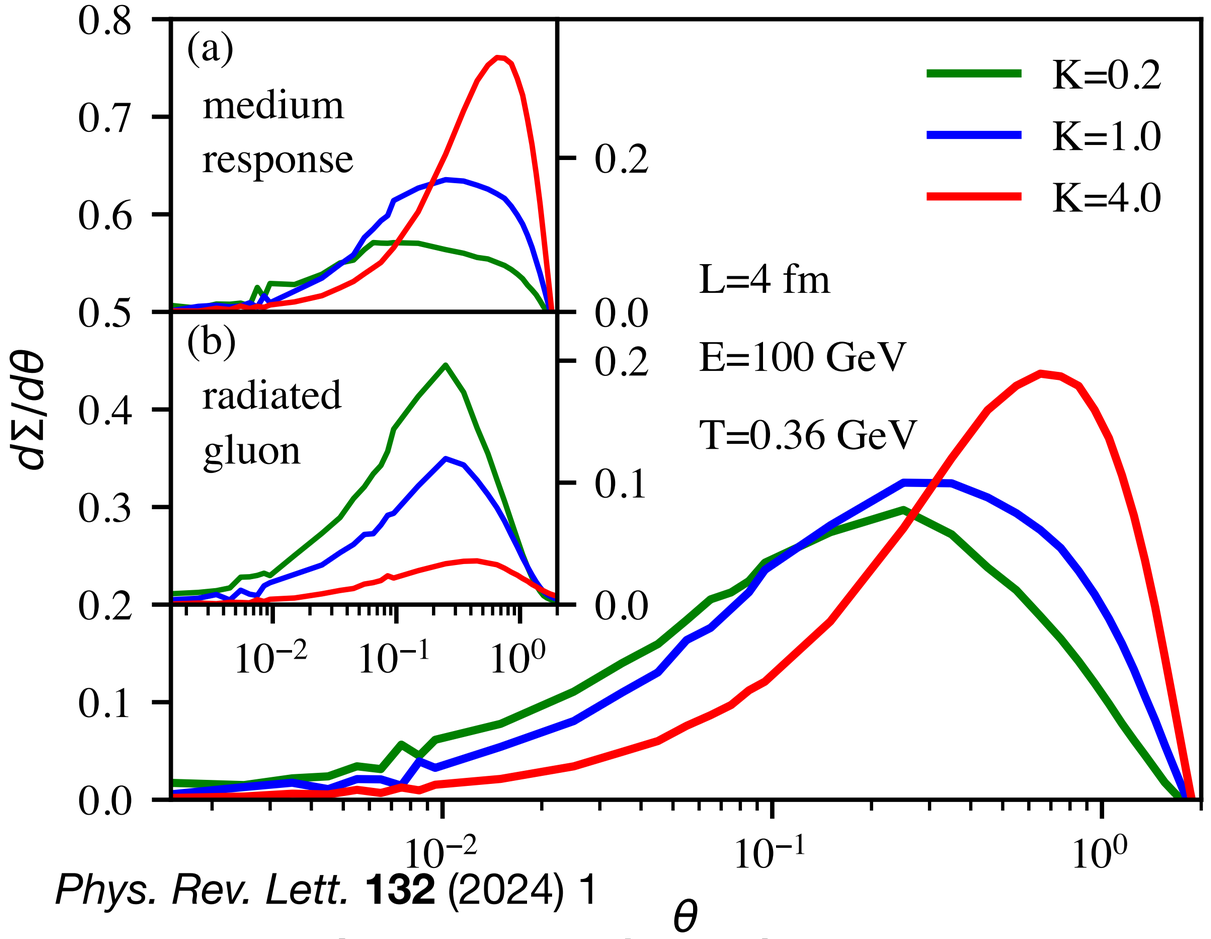
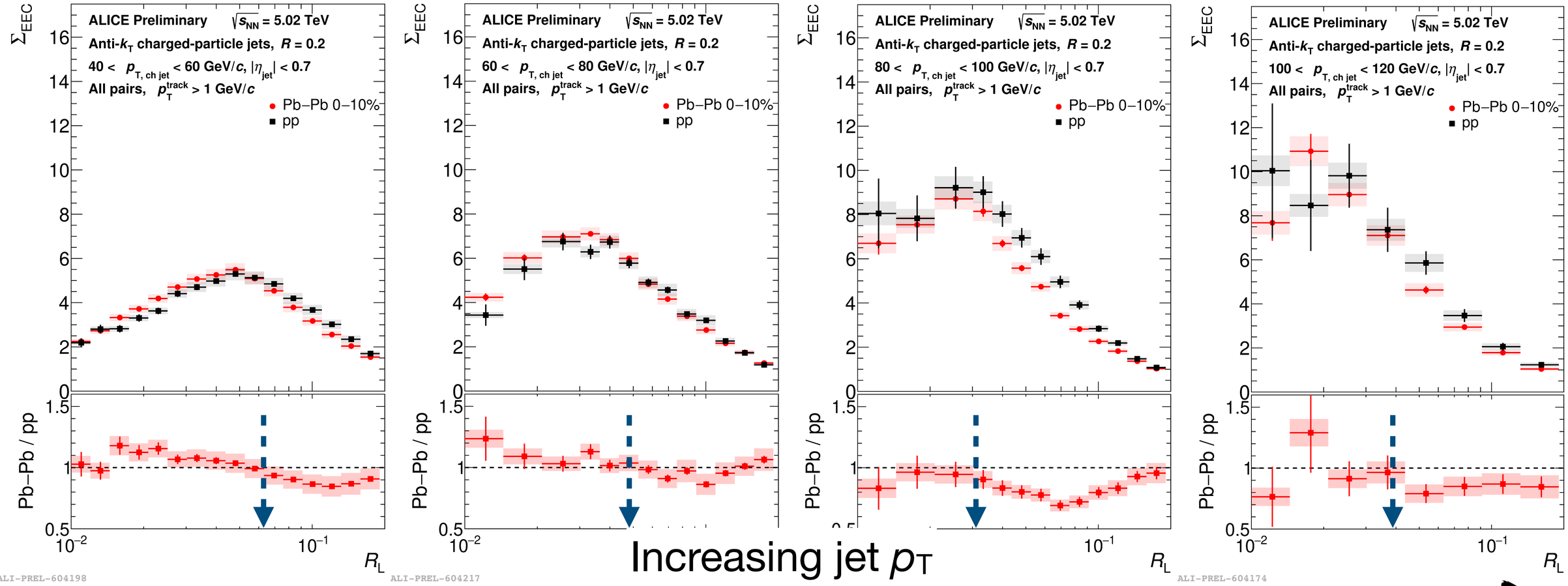


Phys. Rev. Lett. **132** (2024) 1

Large angle enhancement due to medium response

A non-exhaustive list of theoretical activities…

EEC in Pb–Pb collisions

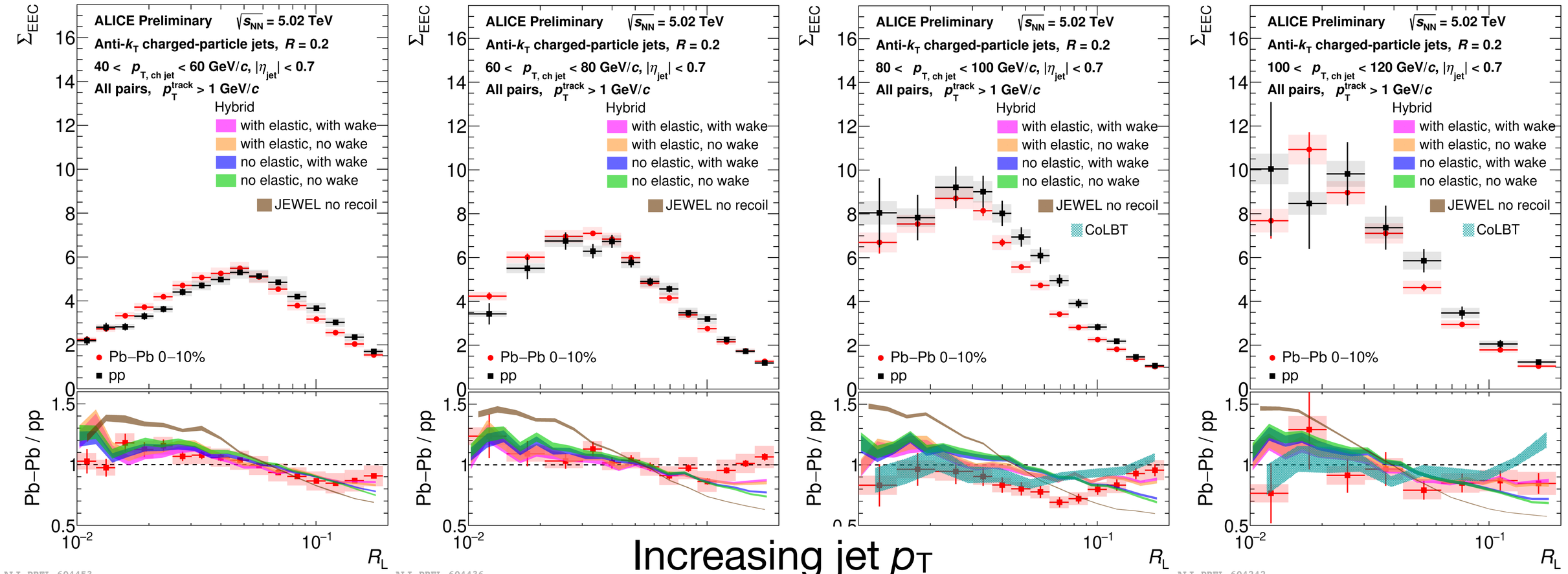


Increasing jet p_T

Onset of suppression seems to shift to smaller angles at higher jet p_T (?)

See also **CMS** arXiv:2503.19993

EEC in Pb–Pb collisions

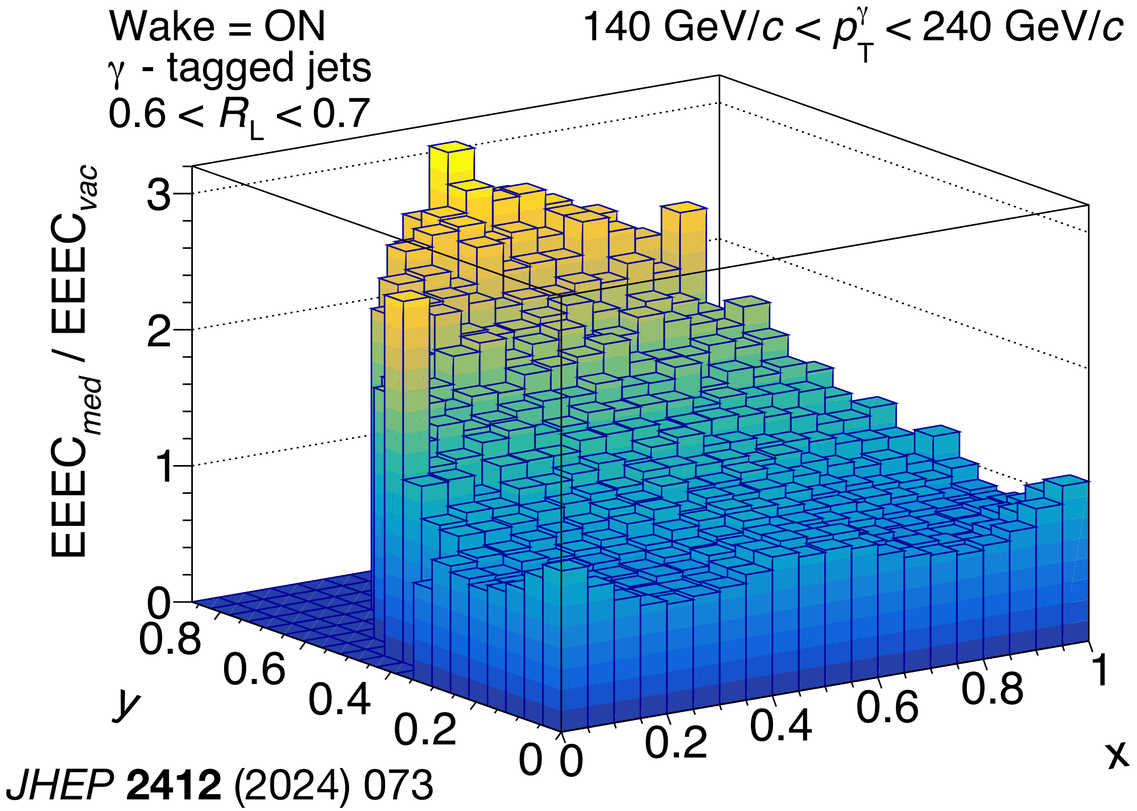


ALI-PREL-604453 ALI-PREL-604436 ALI-PREL-604242

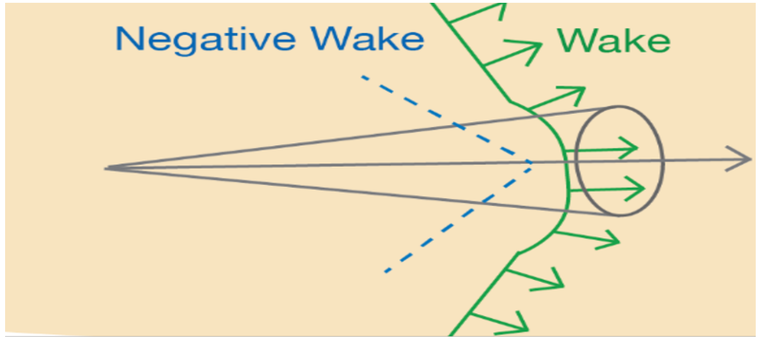
Increasing jet p_T

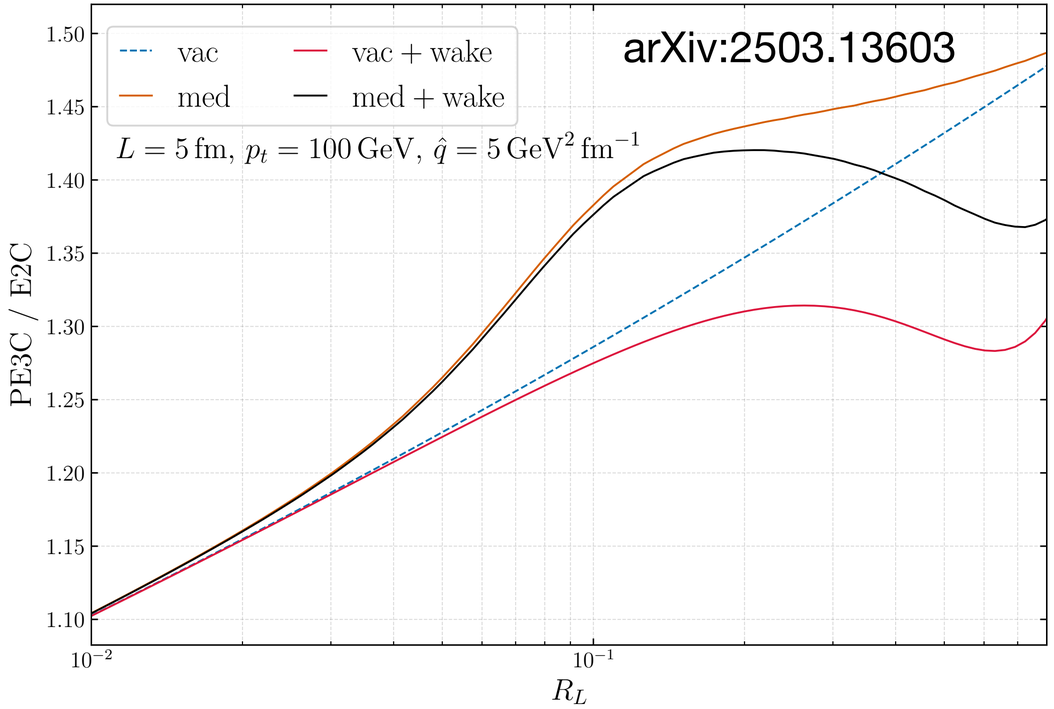
- No significant difference between w and w/o wake, slightly favor elastic scattering?
- JEWEL consistently overestimates the low-R_L enhancement
- CoLBT does well at low-R_L but doesn't capture large-R_L suppression

Next: higher order correlators



JHEP **2412** (2024) 073



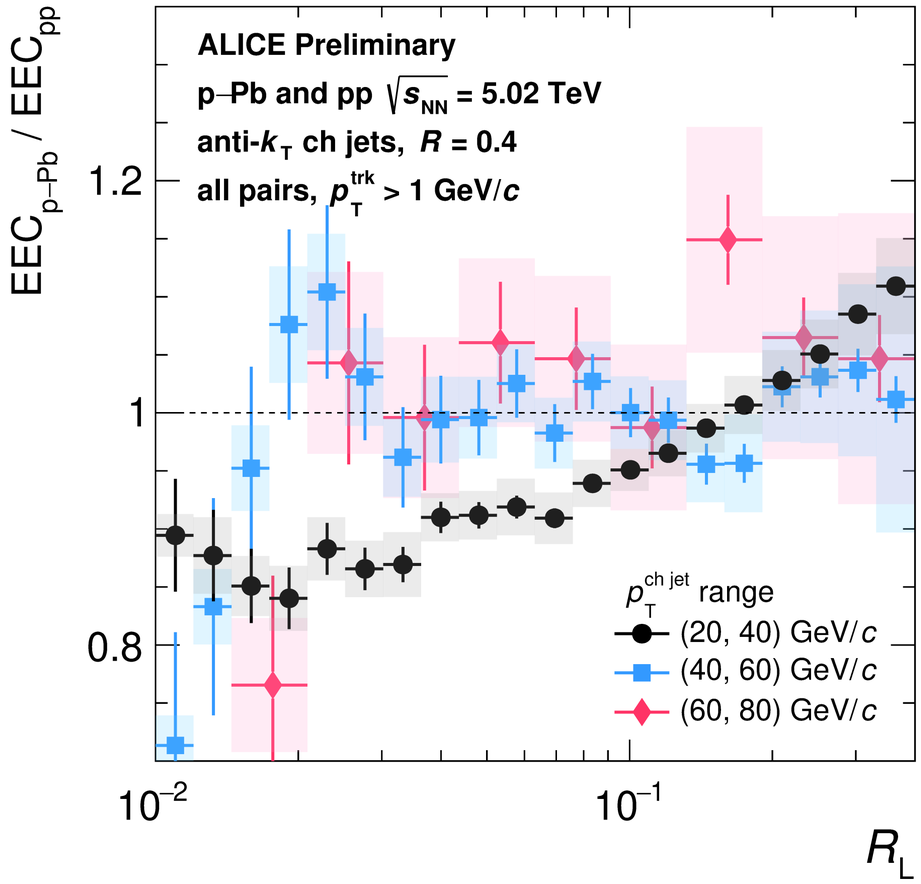


Higher order correlators

- Imaging the wakes of jets with E3C
- Uniquely sensitive to energy flow

A non-exhaustive list of theoretical activities…

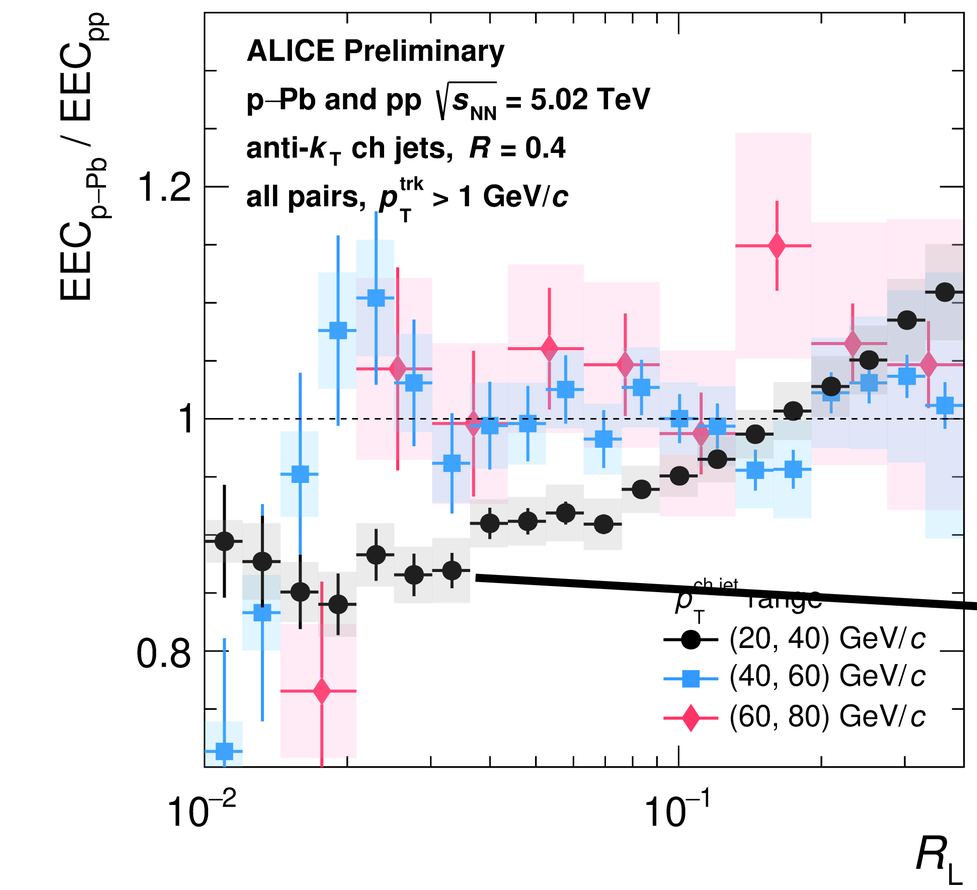
EEC in p–Pb collisions

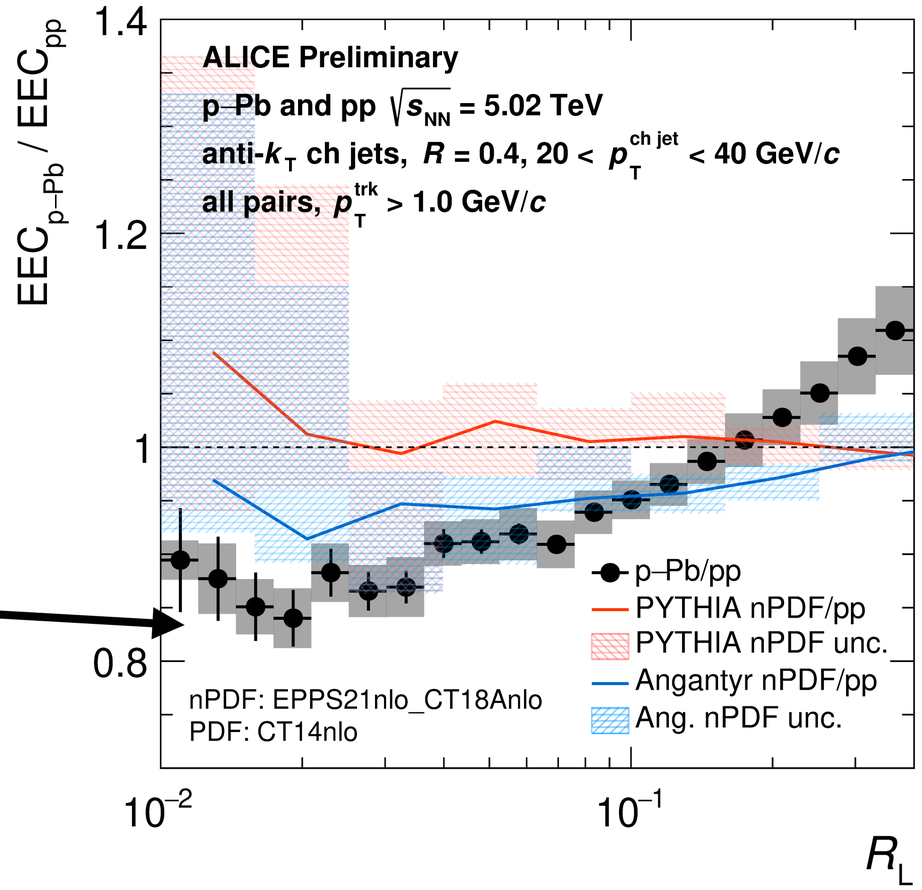


ALI-PREL-581947

- Significant difference between EEC in p–Pb w. r. t. pp at the lowest jet p_T

EEC in p–Pb collisions

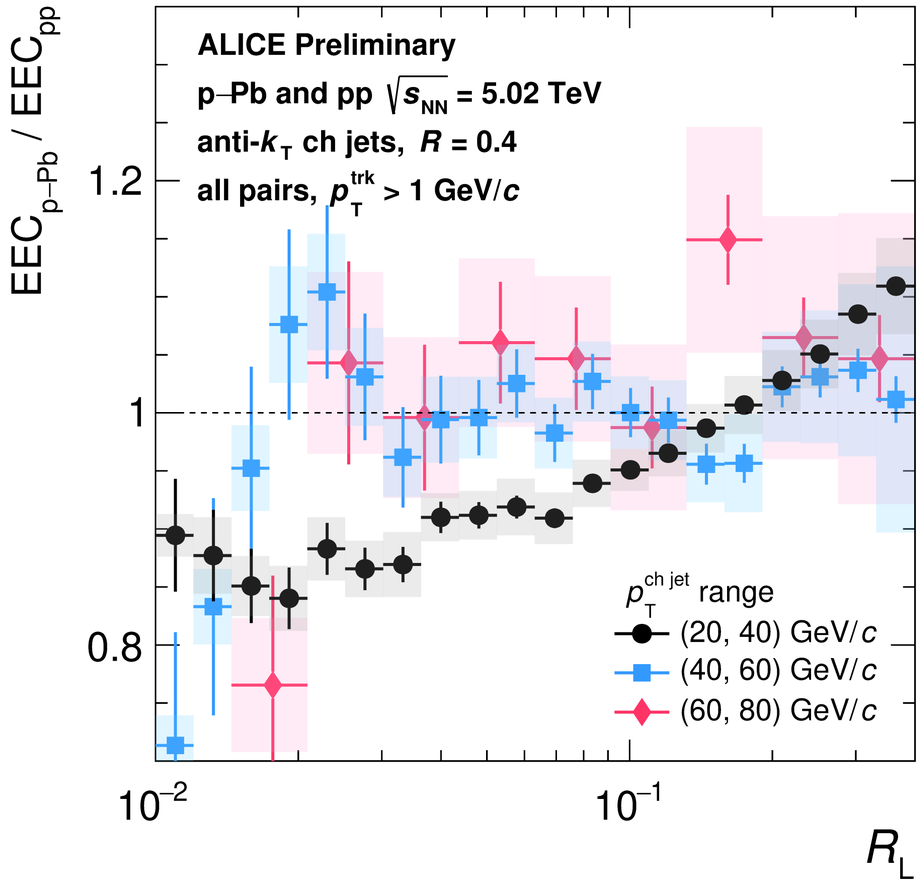


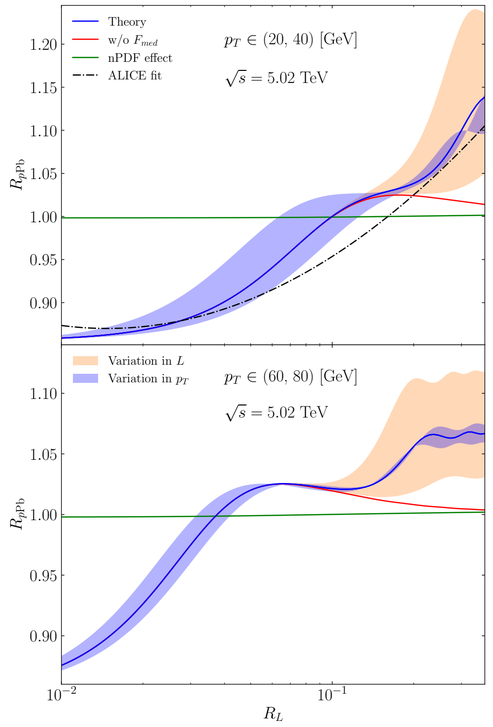


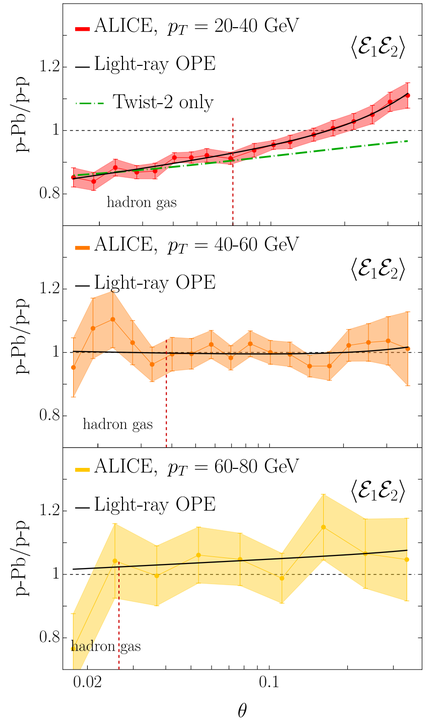
- Significant difference between EEC in p–Pb w. r. t. pp at the lowest jet p_T
- Comparing to PYTHIA with an nPDF turned on, and PYTHIA Angantyr

  ➡ Neither captures behavior at large R_L

EEC in p–Pb collisions







J. Barata *et al.*, *Phys.Rev. Lett.* **134** (2025) 25

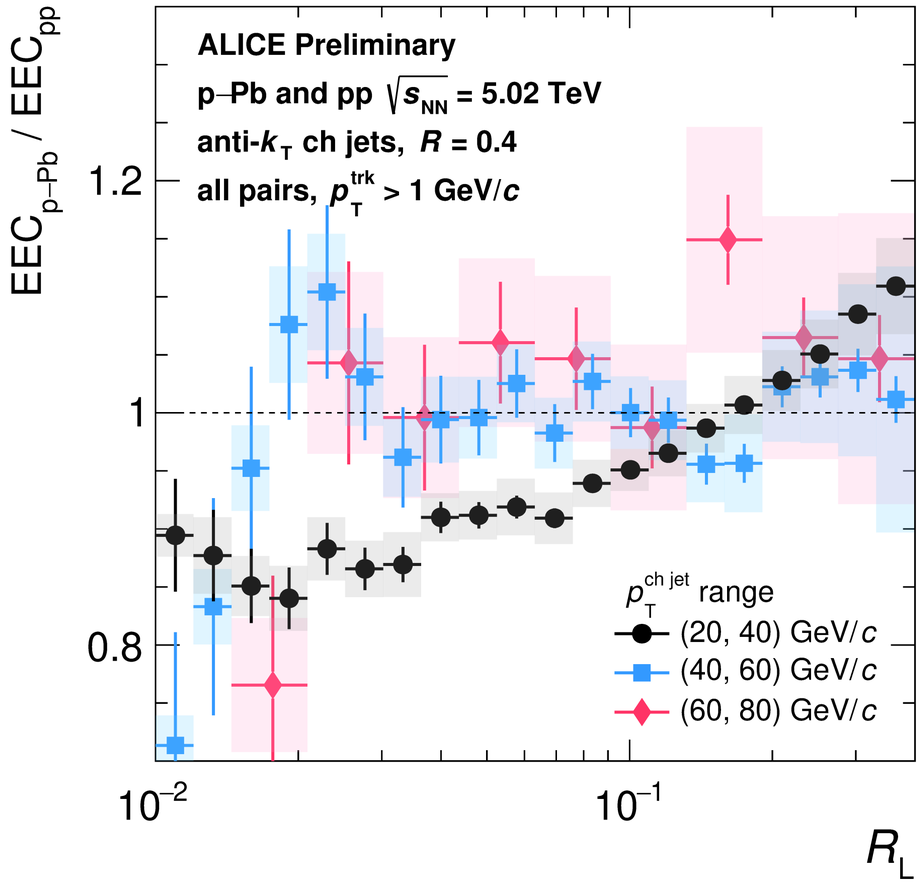
C. Andres *et al.*, arXiv:2411.15298

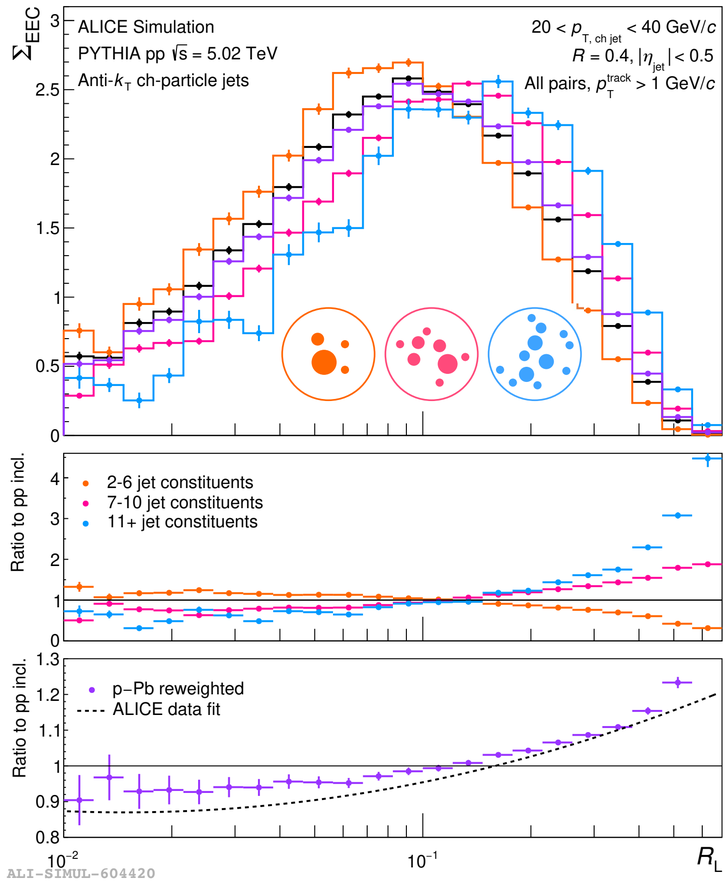
ALI-PREL-581947

- Significant difference between EEC in p–Pb w. r. t. pp at the lowest jet p_T
- Varies mechanisms reproduce data

➡ Multi-scatterings in CNM, k_T-broadening, twist-4 OPE correlations

EEC in p–Pb collisions

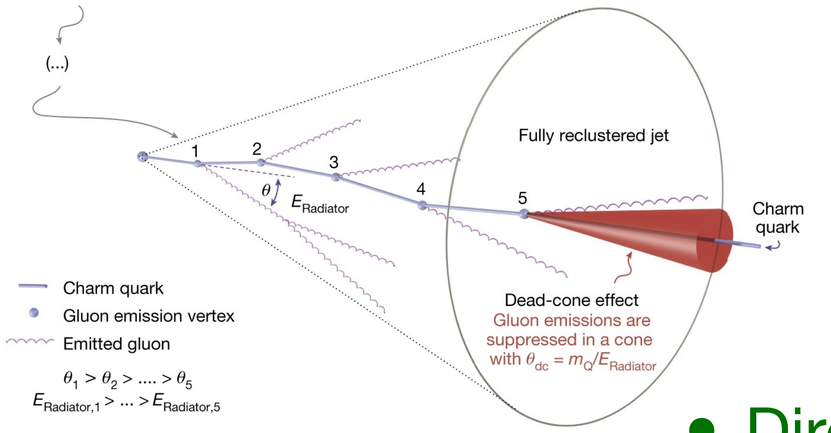




- Significant difference between EEC in p–Pb w. r. t. pp at the lowest jet p_T
- A dramatic shift in the EECs due to jet constituent multiplicity

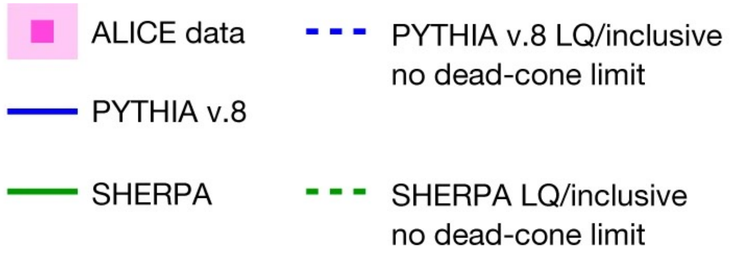
  ➡ Largely reproduce data by shifting 12% of jets to higher multiplicities

Dead-cone of charm radiations

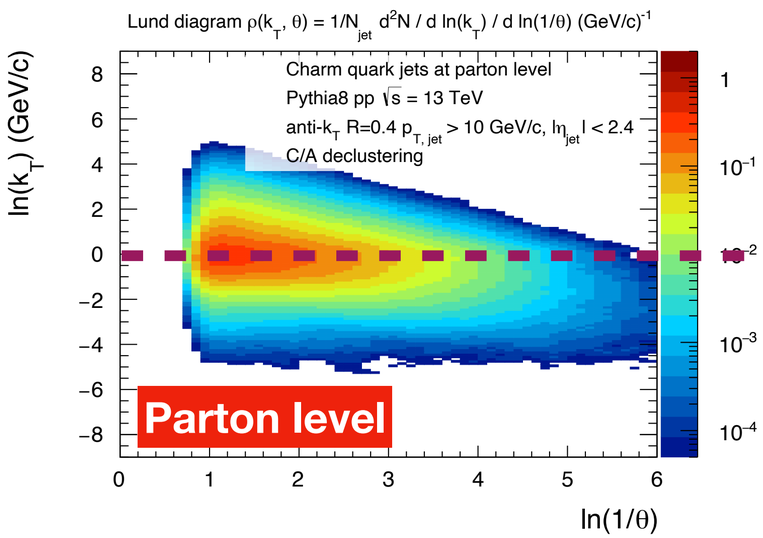


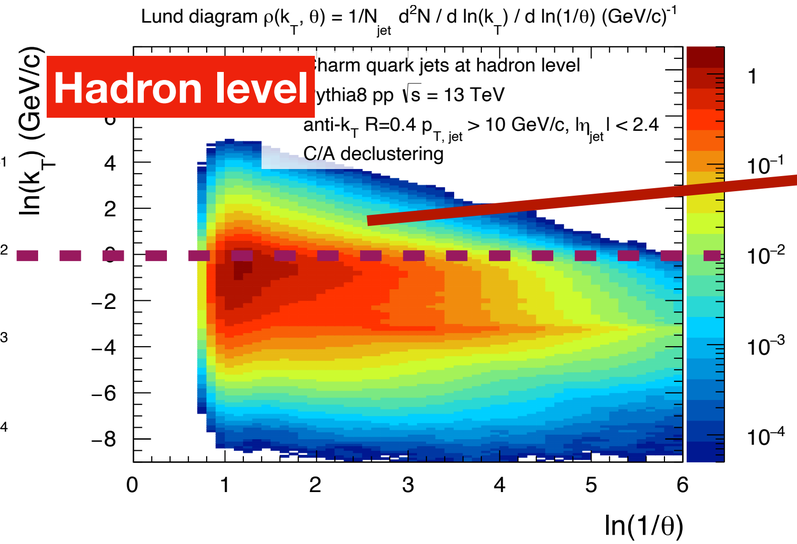
One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect

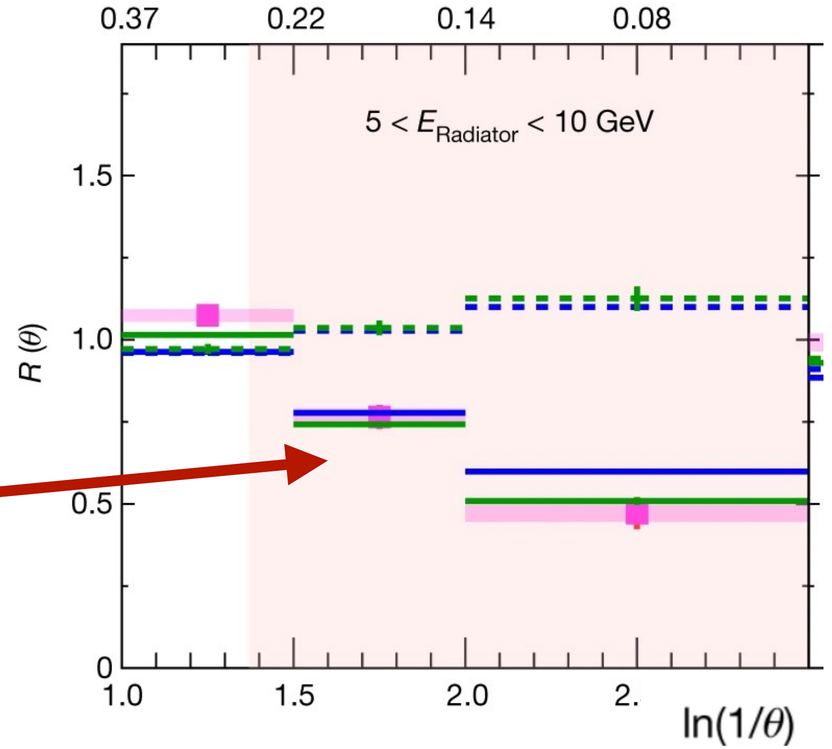
- Direct observation for charm quarks in pp — QCD vacuum



Phys. Rev. **D99** (2019) 074027

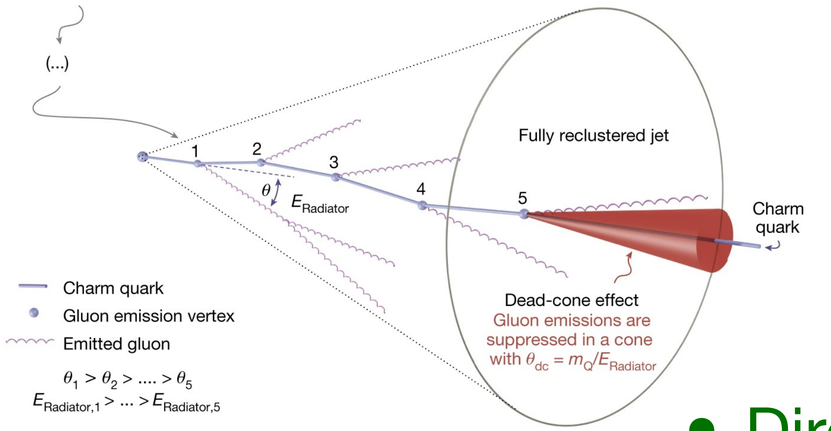






ALICE *Nature* **605** (2022) 440

Dead-cone in QCD medium



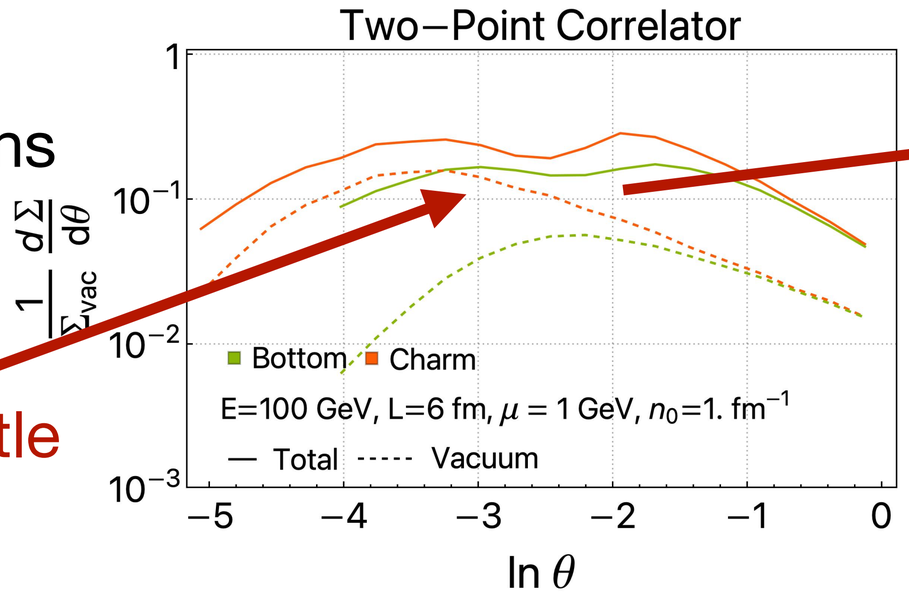
One of fundamental properties of QCD: suppression of gluon emissions within cone $\theta < m_Q / E$ — dead-cone effect

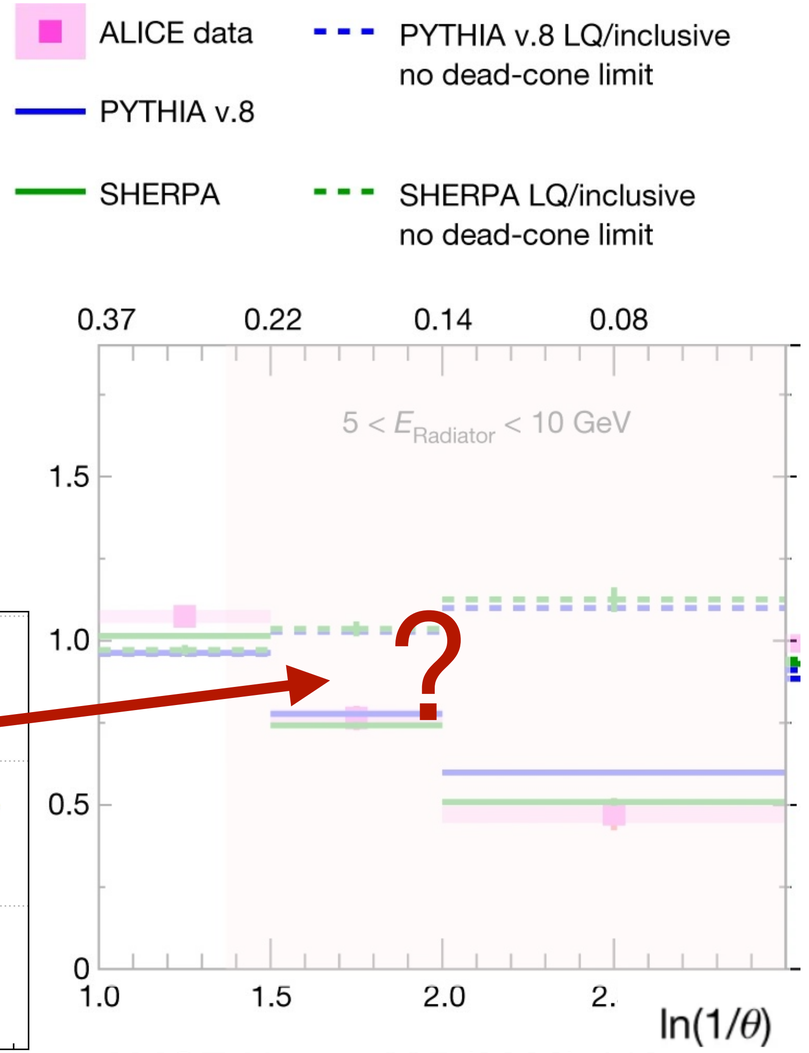
- Direct observation for charm quarks in pp — QCD vacuum

Phys. Rev. **D110** (2024) L031503

- In the QCD medium: the medium-induced radiations fill the dead-cone

➡ Dead-cone resulted depletion becomes gentle





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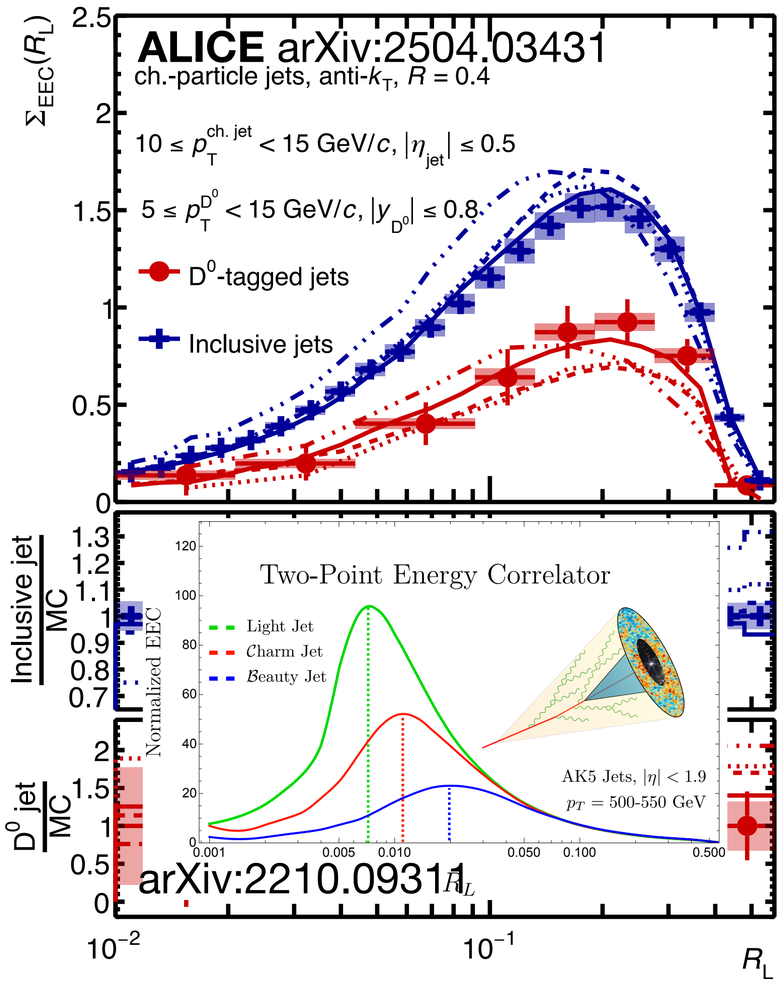
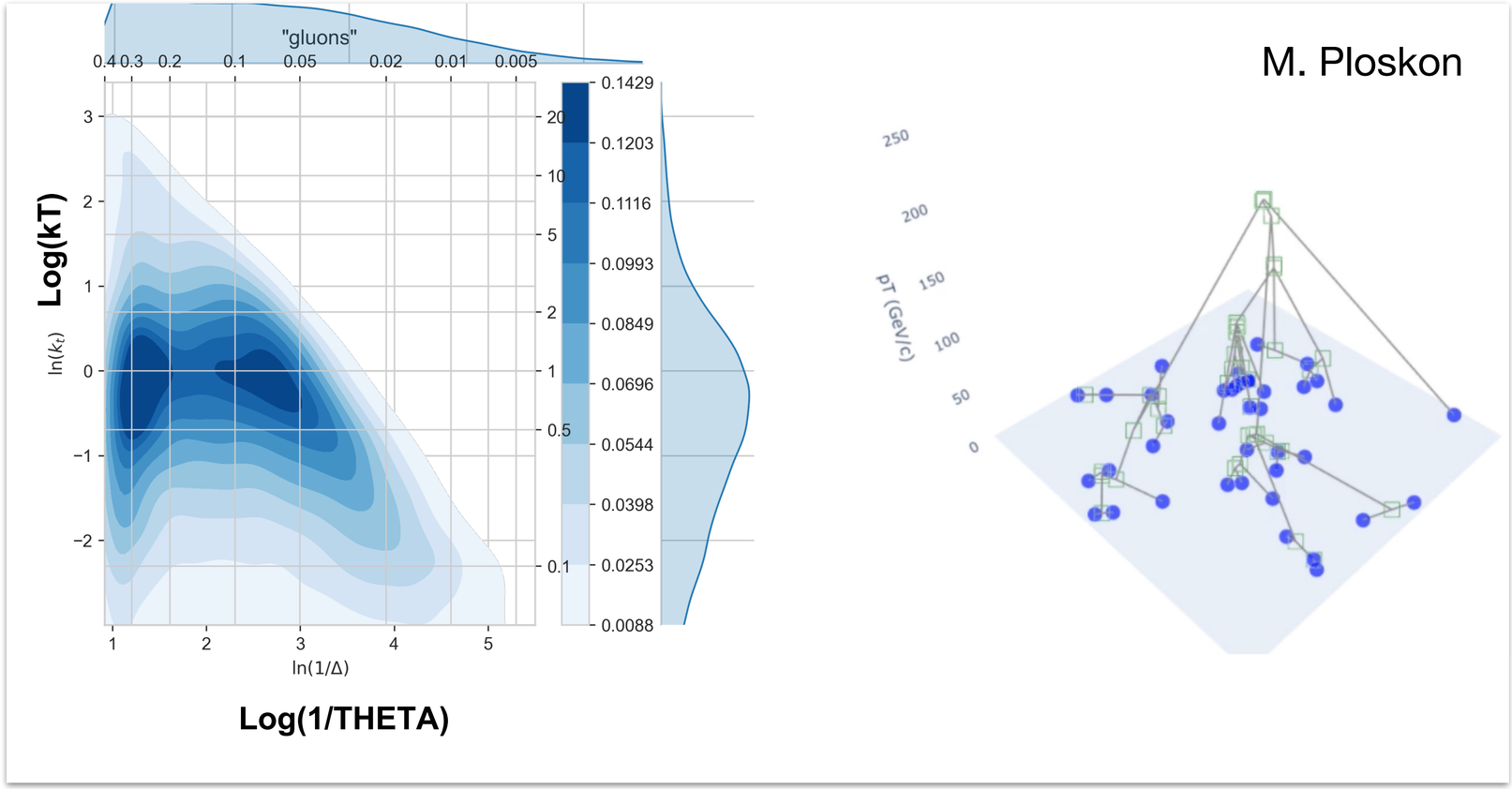
One more thing…



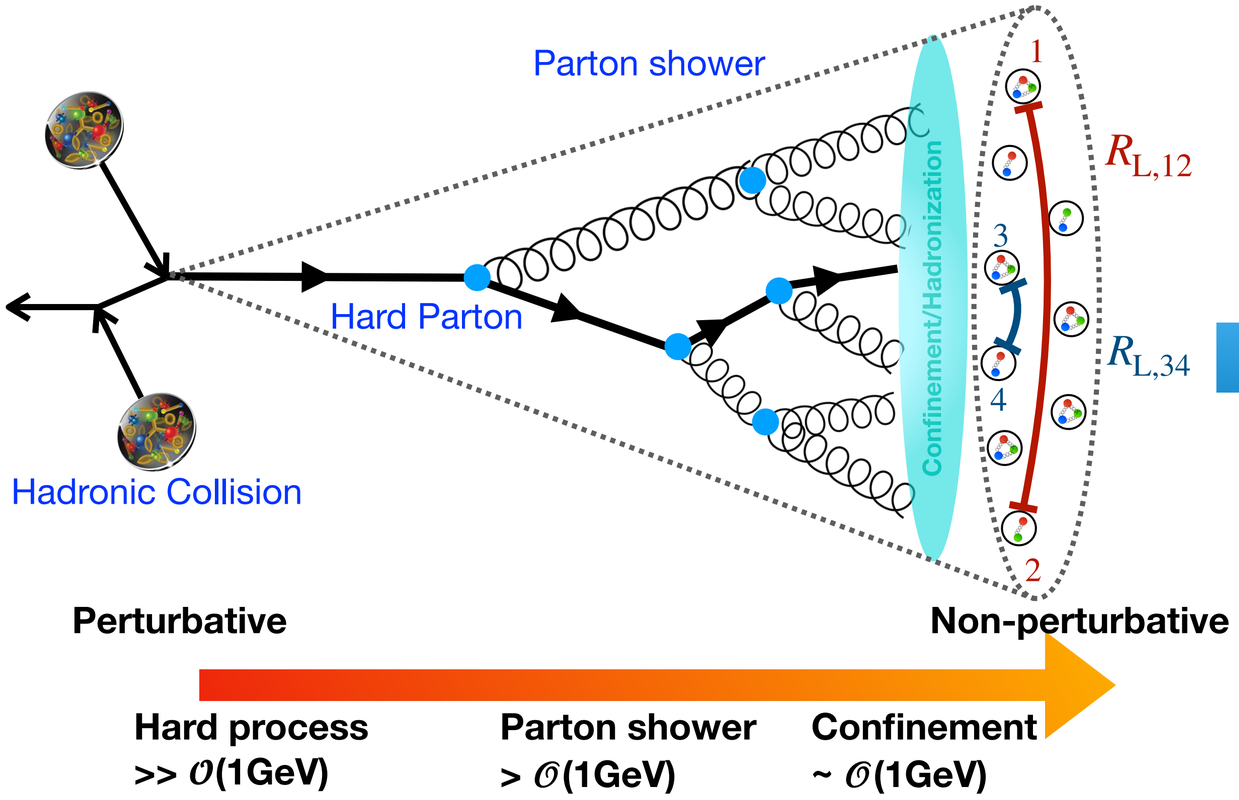


Can ENC + Lund plan image the dead-cone in QCD medium?

➡ First observation in vacuum: **ALICE** *Nature* **605** (2022) 440

Backup

N-point energy correlators in jets



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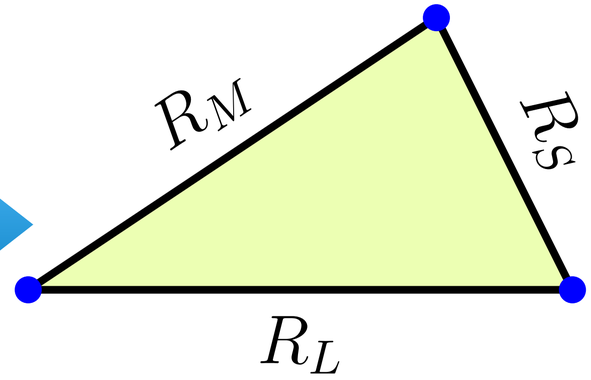
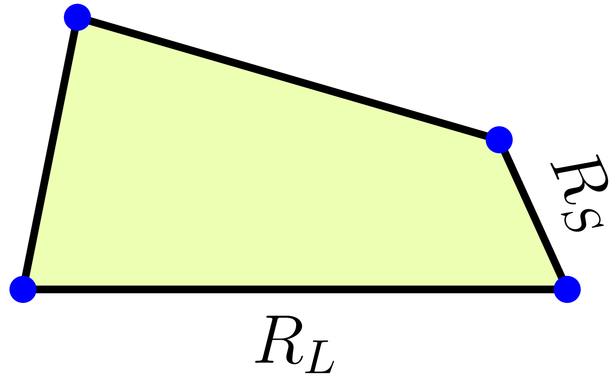


E3C

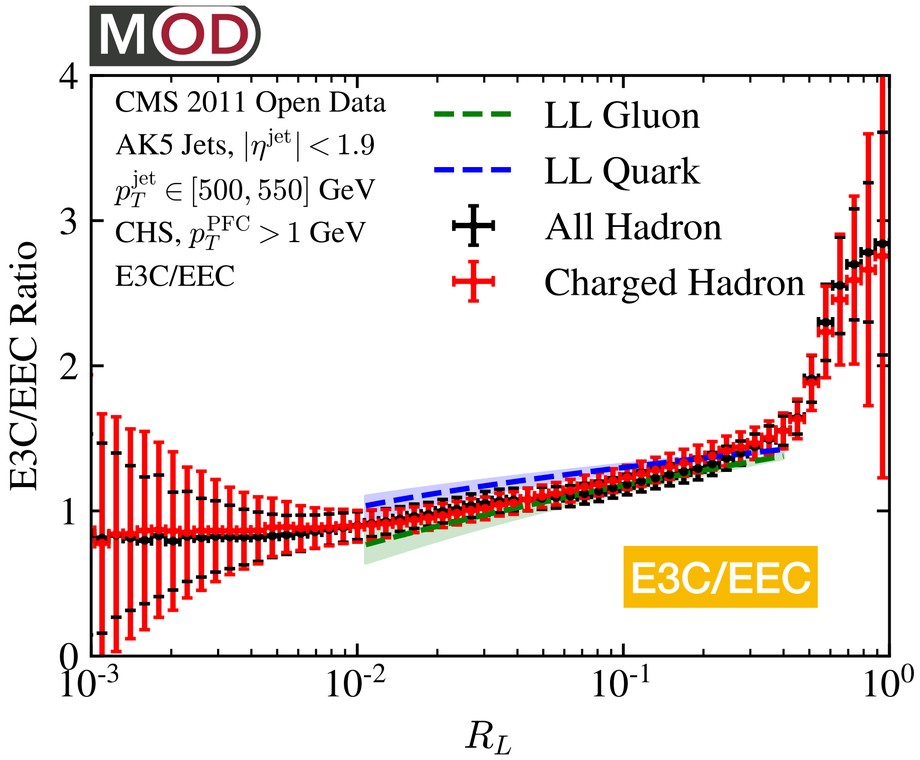


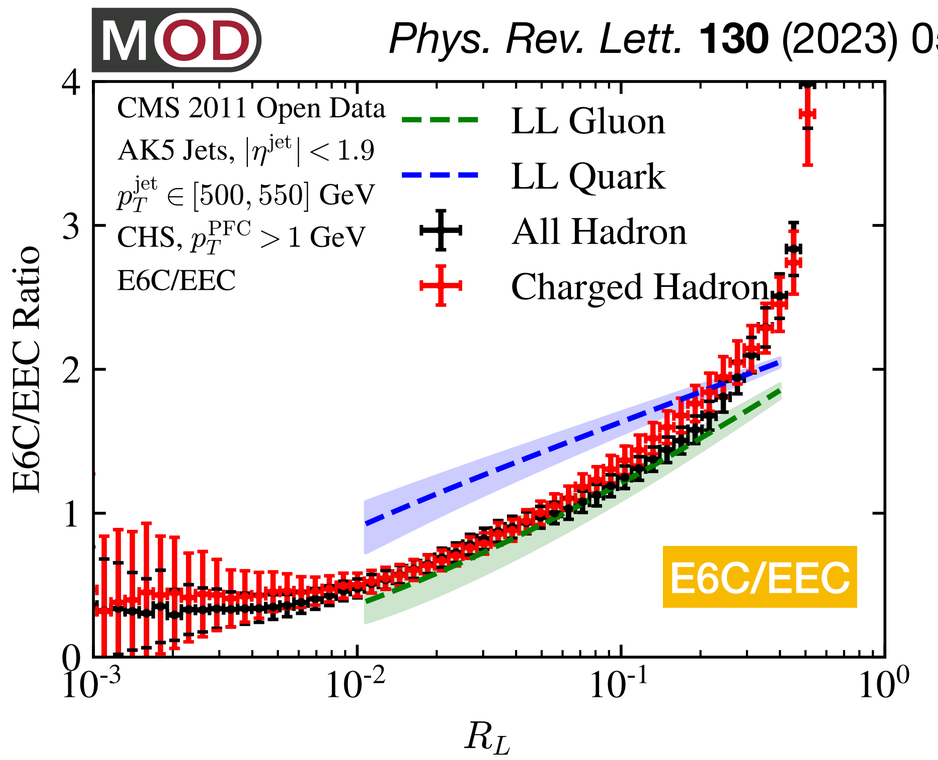
E4C

$$\mathrm{ENC}(R_\mathrm{L}) = \frac{1}{N_\mathrm{jet}} \sum_{k_1,k_2\cdots k_N} \int \mathrm{d}R'_\mathrm{L}\,\delta(R_\mathrm{L} - R'_\mathrm{L}) \frac{\prod_{i=1}^{N} p_{\mathrm{T},k_i}}{p_{\mathrm{T,jet}}^{N}}$$

Derived from QFT and precise theoretical calculations

Higher order correlators



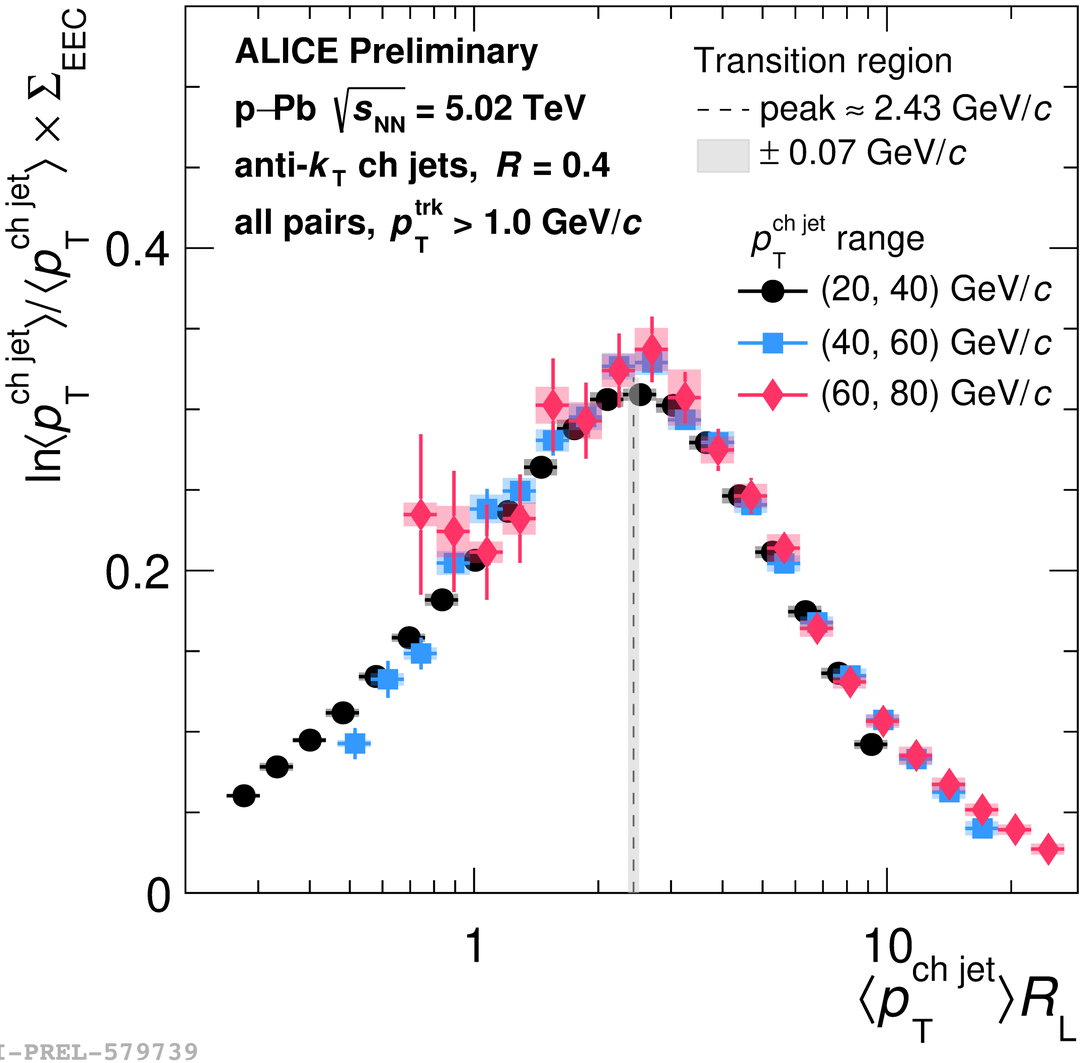


Phys. Rev. Lett. **130** (2023) 051901

ENC/EEC ratio

- Cancel the leading non-perturbative contribution and isolate a clean perturbative scaling
- Higher oder — larger quark–gluon discrimination power

Universal scaling



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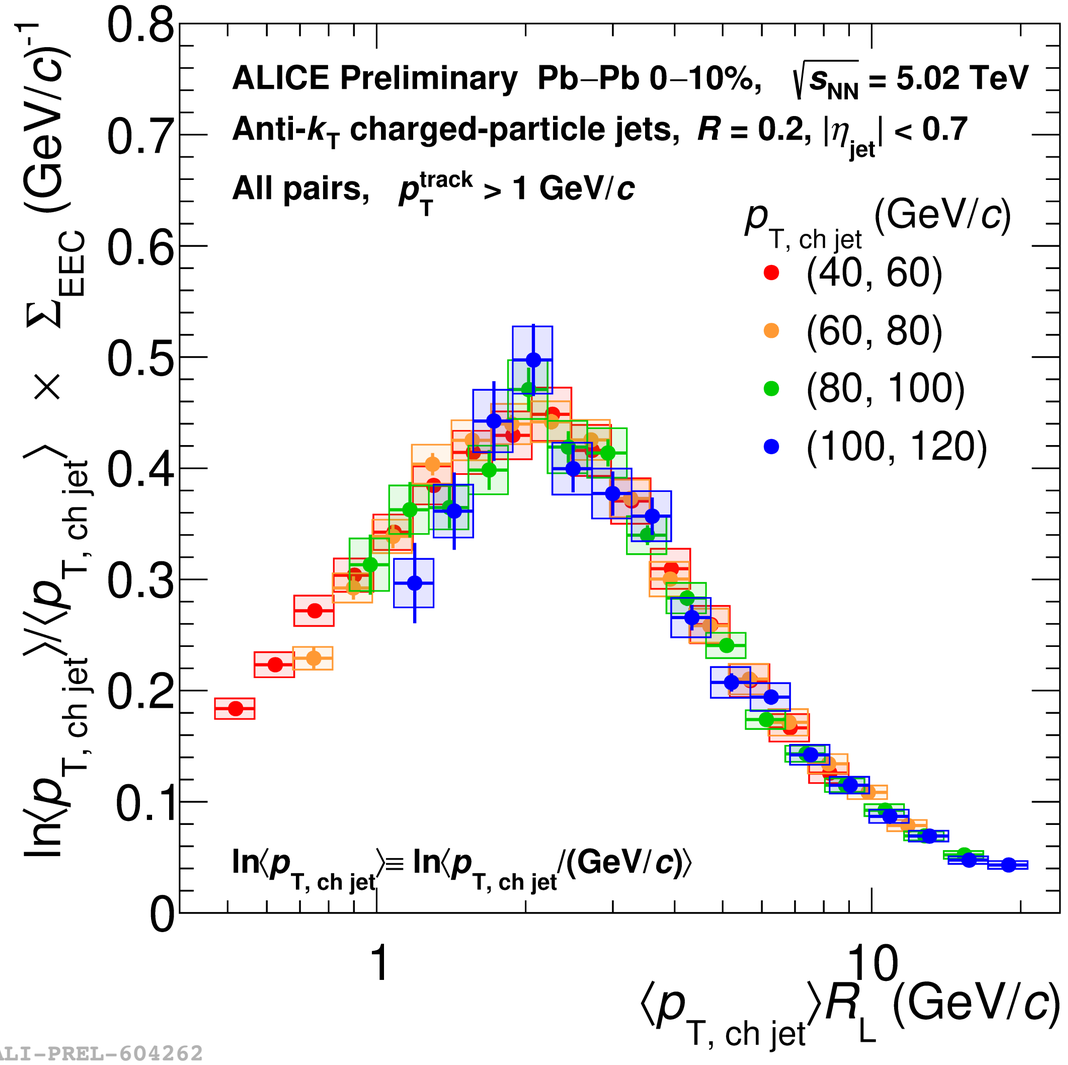

ALI-PREL-604262