EECs in Jets

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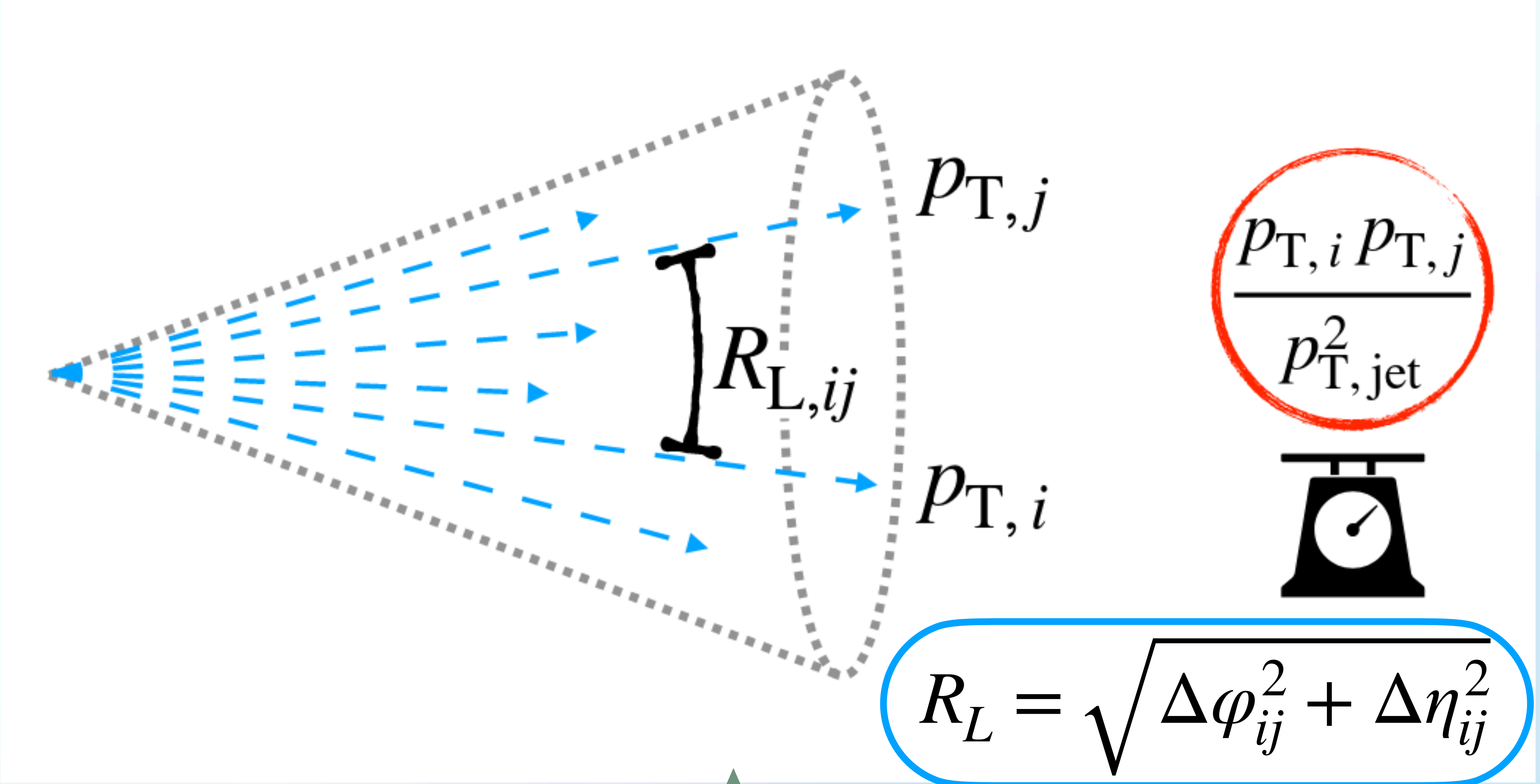
2-point energy energy correlator (EEC)

- EEC = energy-weighted cross-section of particle pairs
- A way to study the angular structure of energy flow in jets
- Clear separation of perturbative, transition and non-perturbative regions
- Allows us to probe parton-level jet formation and how partons are confined into hadrons

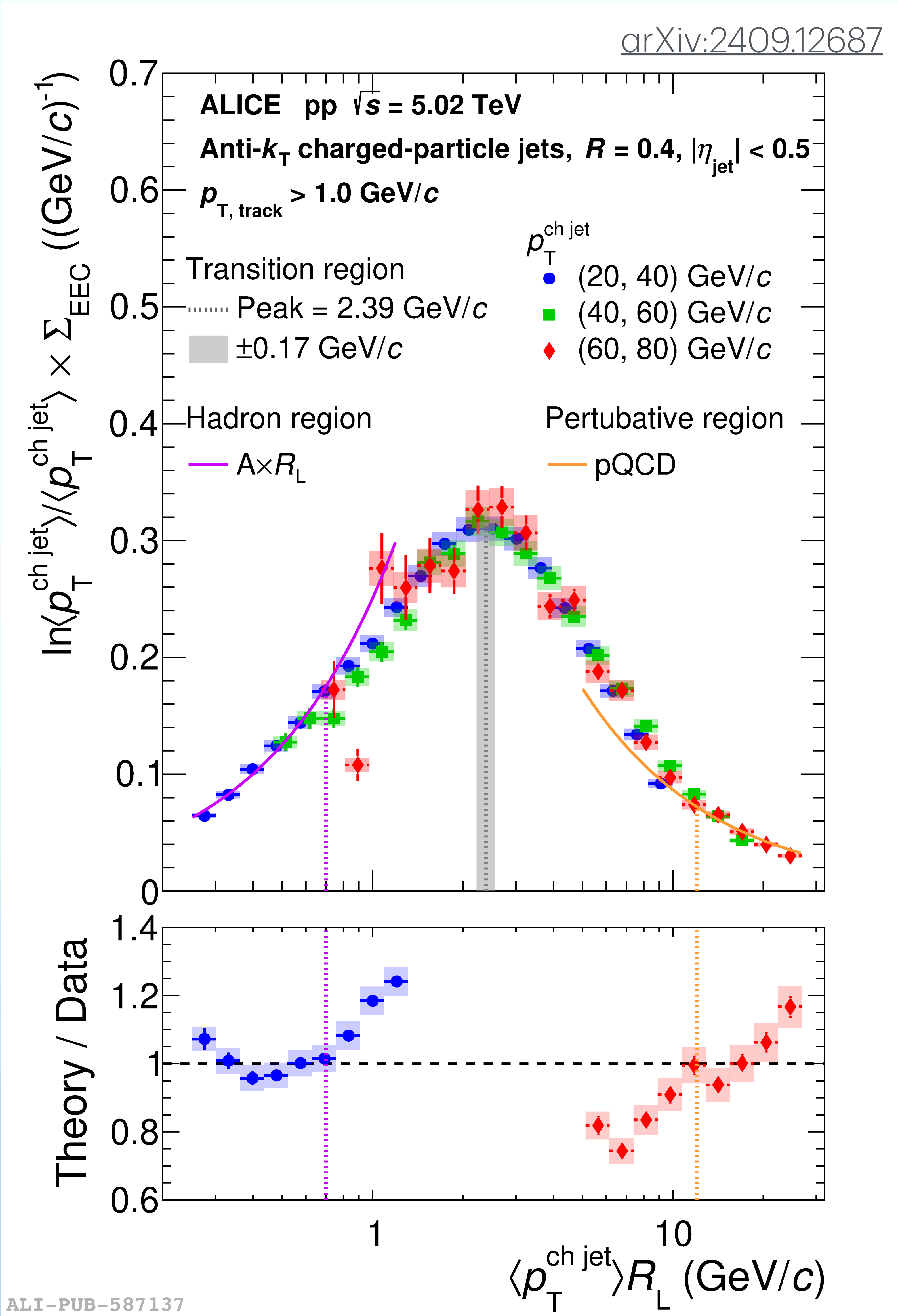
$$\Sigma_{\mathrm{EEC}}(R_{\mathrm{L}}) = \frac{1}{N_{\mathrm{jet}}\Delta}\sum_{N_{\mathrm{jet}}}\int\sum_{i,j}\frac{p_{\mathrm{T},i}p_{\mathrm{T},j}}{p_{\mathrm{T,jet}}^2}\delta(R'_{\mathrm{L}} - R_{\mathrm{L},ij})\mathrm{d}R'_{\mathrm{L}}$$



$$R_L = \sqrt{\Delta\varphi_{ij}^2 + \Delta\eta_{ij}^2}$$

IRC safe!

What can we learn from EECs in pp?



- Small R_L ~ later times, large R_L ~ earlier times
- Peak positions align across different jet p_T
- Shape of large-angle region is partially predicted by pQCD calculation
  - Anchored to 60 < $p_{T,jet}$ < 80 GeV/c data points
- Small-angle region matches expectation for free-hadron scaling

EECs as a function of $\langle p_T\rangle R_L$ reveal a p_T-independent universality in jet dynamics and hadronization.

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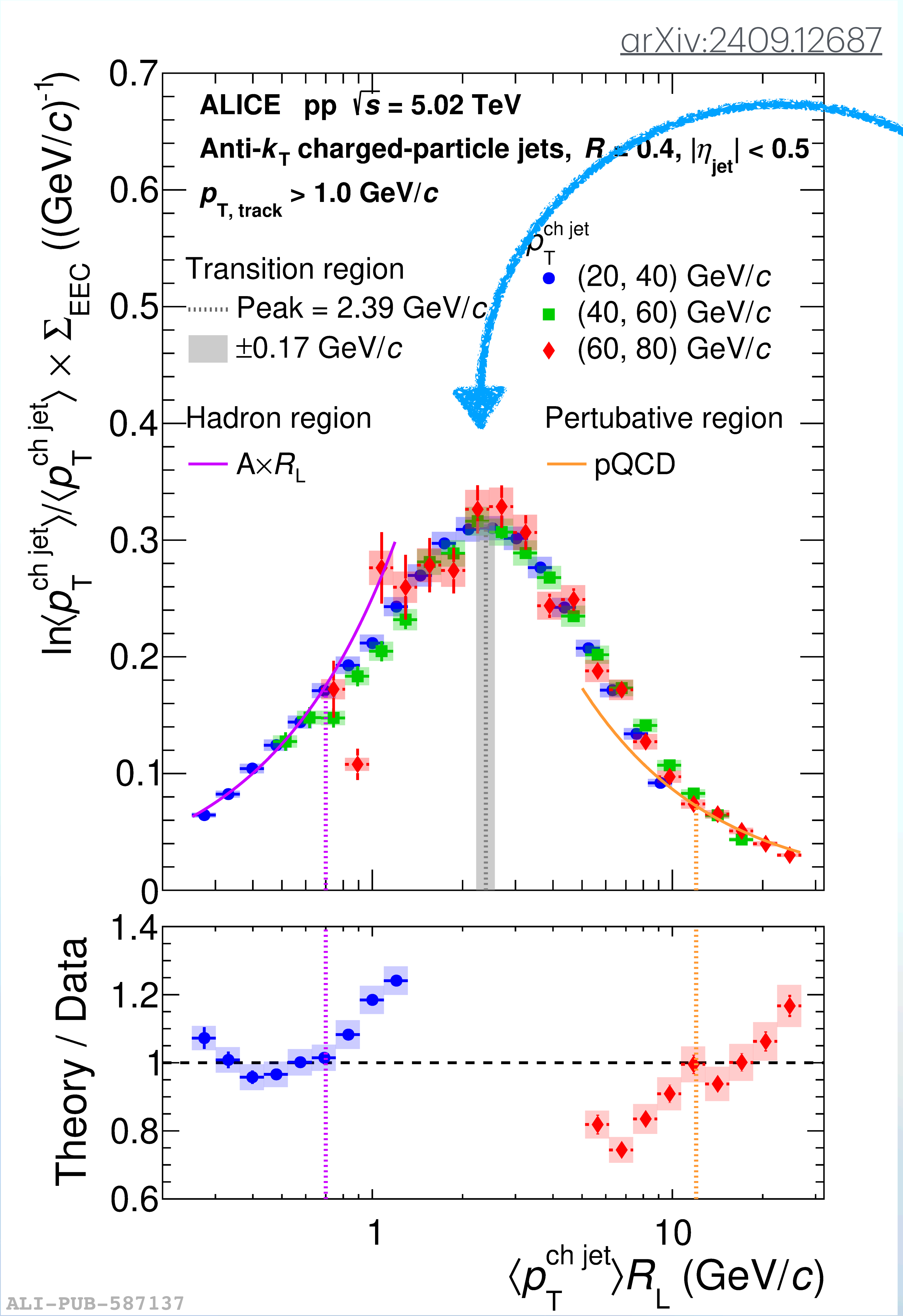

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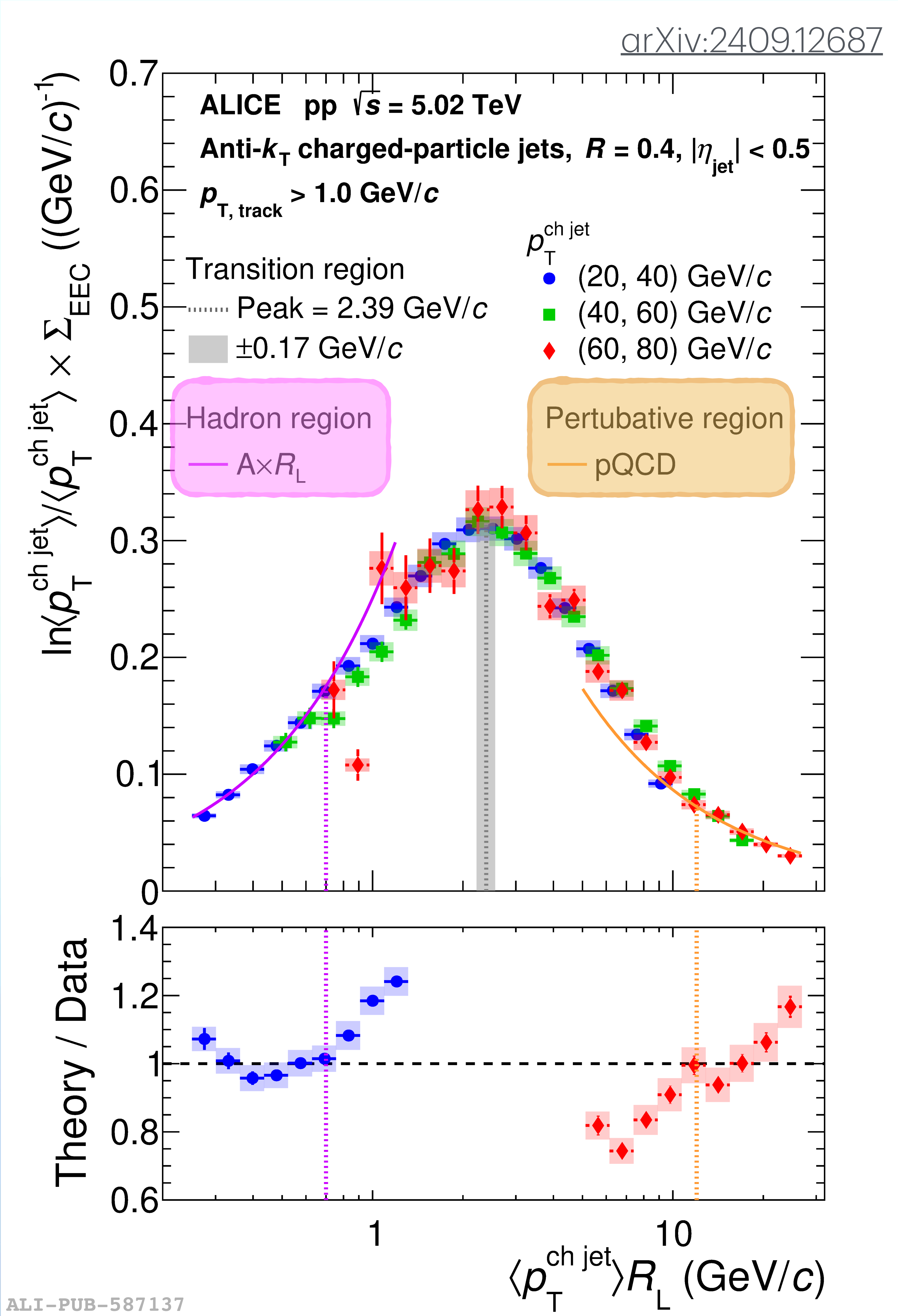

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EECs as a function of $\langle p_T \rangle R_L$ reveal a p_T-independent universality in jet dynamics and hadronization.

What are the LHC/RHIC EEC jet measurements that have been/are being done so far?

Type of EEC	Type of jet	Collision system	Collision $\sqrt{s}$	Experiment	Progress	Resources
EEC	inclusive	pp	5.02 TeV	ALICE	published	arxiv
EEC	D^0-tagged	pp	13 TeV	ALICE	published	arxiv
E3C (and E3C/EEC)	inclusive	pp	13 TeV	ALICE	in progress	slides, slides
EEC	inclusive	p-Pb	5.02 TeV	ALICE	in progress	slides
EEC	inclusive	Pb-Pb	5.02 TeV	ALICE	in progress	slides
charged EEC	inclusive	pp	5.02 TeV	ALICE	in progress	w/ ↓
charged EEC	inclusive	p-Pb	5.02 TeV	ALICE	in progress	poster, slides
EEC	ɣ-tagged	pp	13.6 TeV	ALICE	just started	-
EEC	inclusive	pp	5.02 TeV	CMS	published	w/ ↓
EEC	inclusive	Pb-Pb	5.02 TeV	CMS	published	link, arxiv
E3C (and E3C/EEC)	inclusive	pp	13 TeV	CMS	published	inspirehep, arxiv
charged EEC	inclusive	pp	200 GeV	STAR	published	arxiv
charged E3C	inclusive	pp	200 GeV	STAR	in progress	slides

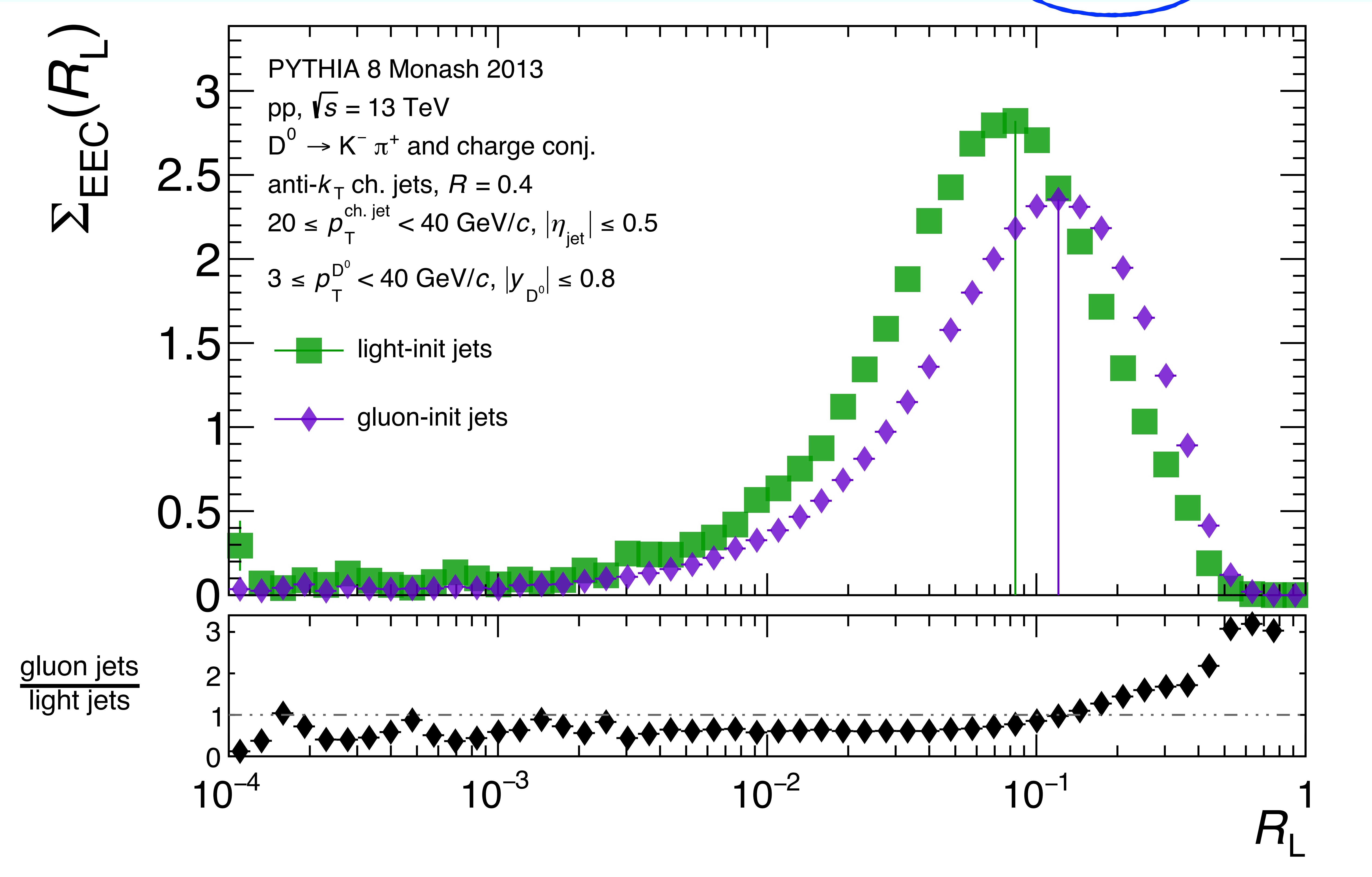
Parton Flavors in pp Collisions

Quarks and gluons

- Inclusive jet composition (PYTHIA)
  - Light-quark initiated jets
  - Gluon-initiated jets
- Gluons have a larger color factor → typically emit at wider angles compared to quarks
- Gluons shed their virtuality earlier than quark

(see another example of this at higher energies in arXiv:2502.11406)

PYTHIA



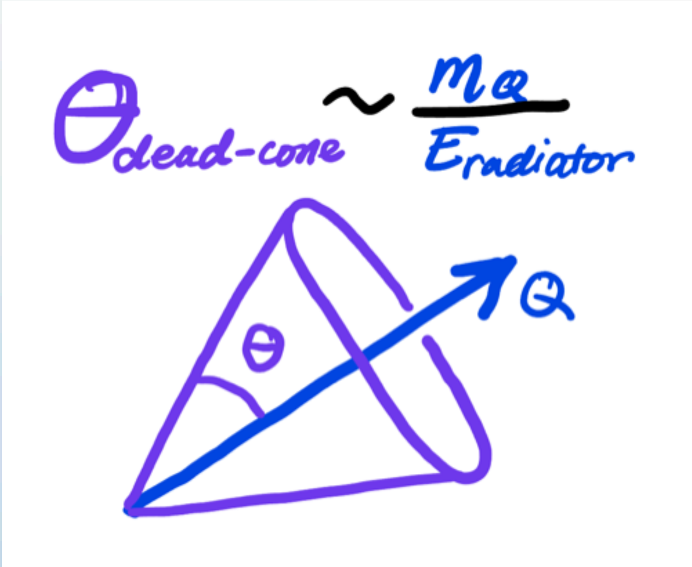
EECs are sensitive to flavor dependence in QCD showers.

What about heavier quarks?

- Heavy-flavor quarks are created in the initial scattering process of high-energy collisions

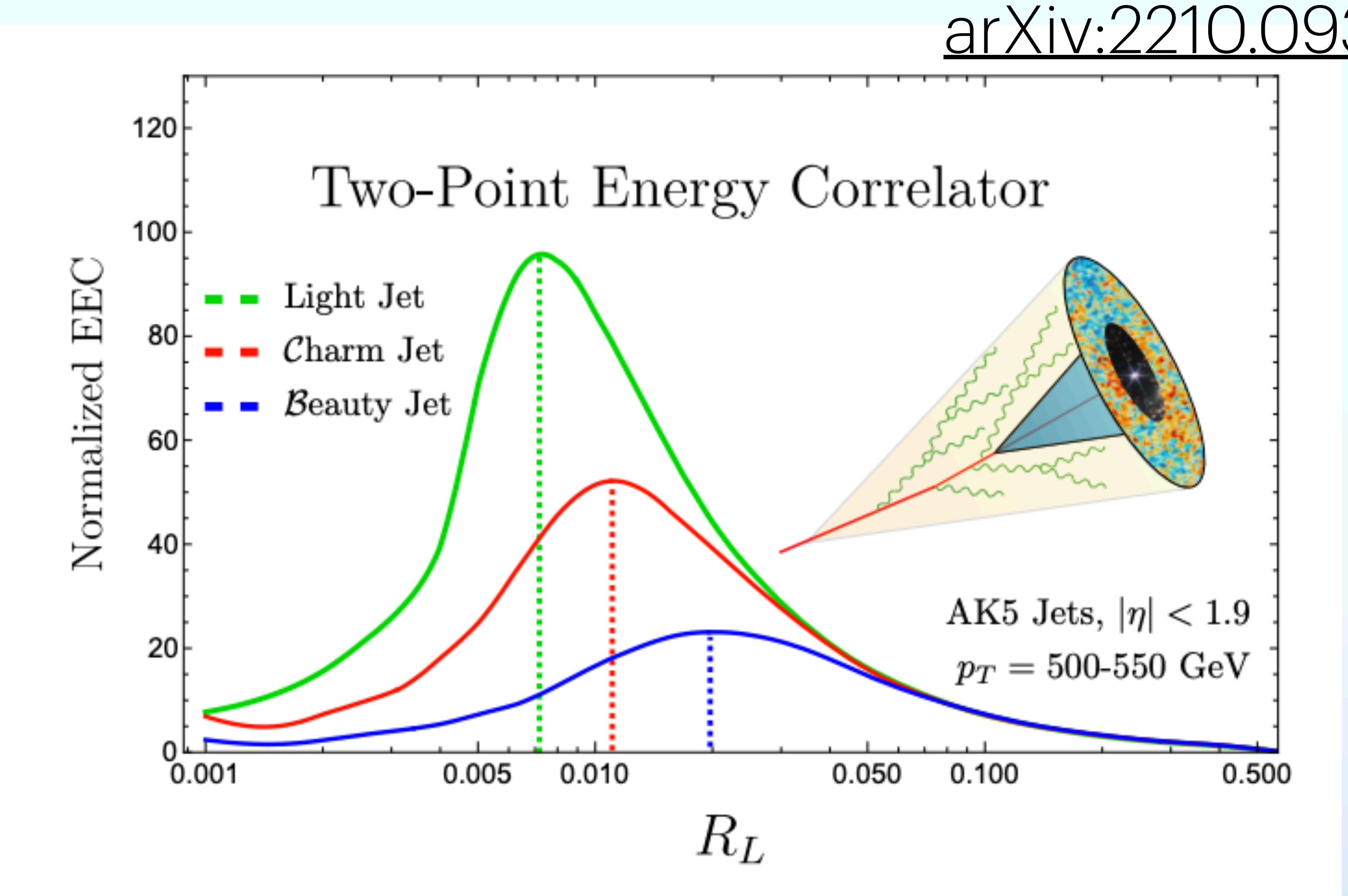
- The heavy-quark mass » the confinement scale of QCD (Λ_{QCD} ~ 200 MeV/c^2)
  - Production is governed by pQCD

- Dead-cone effect = suppression of gluon radiation in $\theta < m/E_{\text{rad}}$



drawing thanks to Emma Yeats

arXiv:2210.09311



- D^0 are composed of $c\bar{u}$

- Use D^0 as a proxy for the charm quark

- $D^0 \rightarrow K^{\pm}\pi^{\mp}$ with a BR of ~3.947 ± 0.03%

D^0-jet EEC

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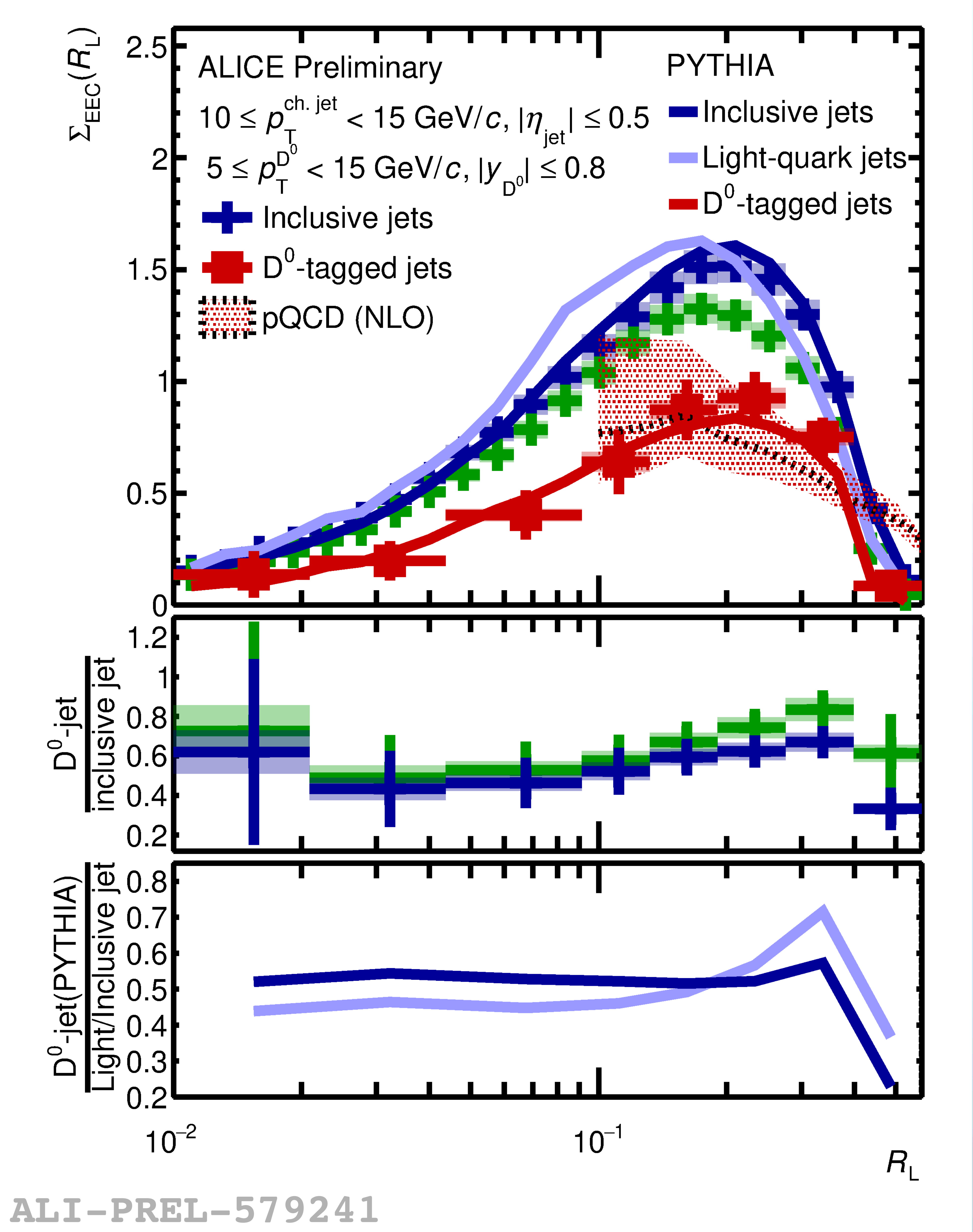
- Charm jet EEC has a lower amplitude than inclusive jet EEC → dead-cone effect!
- Peak positions: D^0 ~ inclusive
  - Charm peak position impacted by its heavier mass
  - Gluon peak position impacted by its larger color factor
- pQCD calculation in high R_L region[1]

[1]calculation done by Kyle Lee



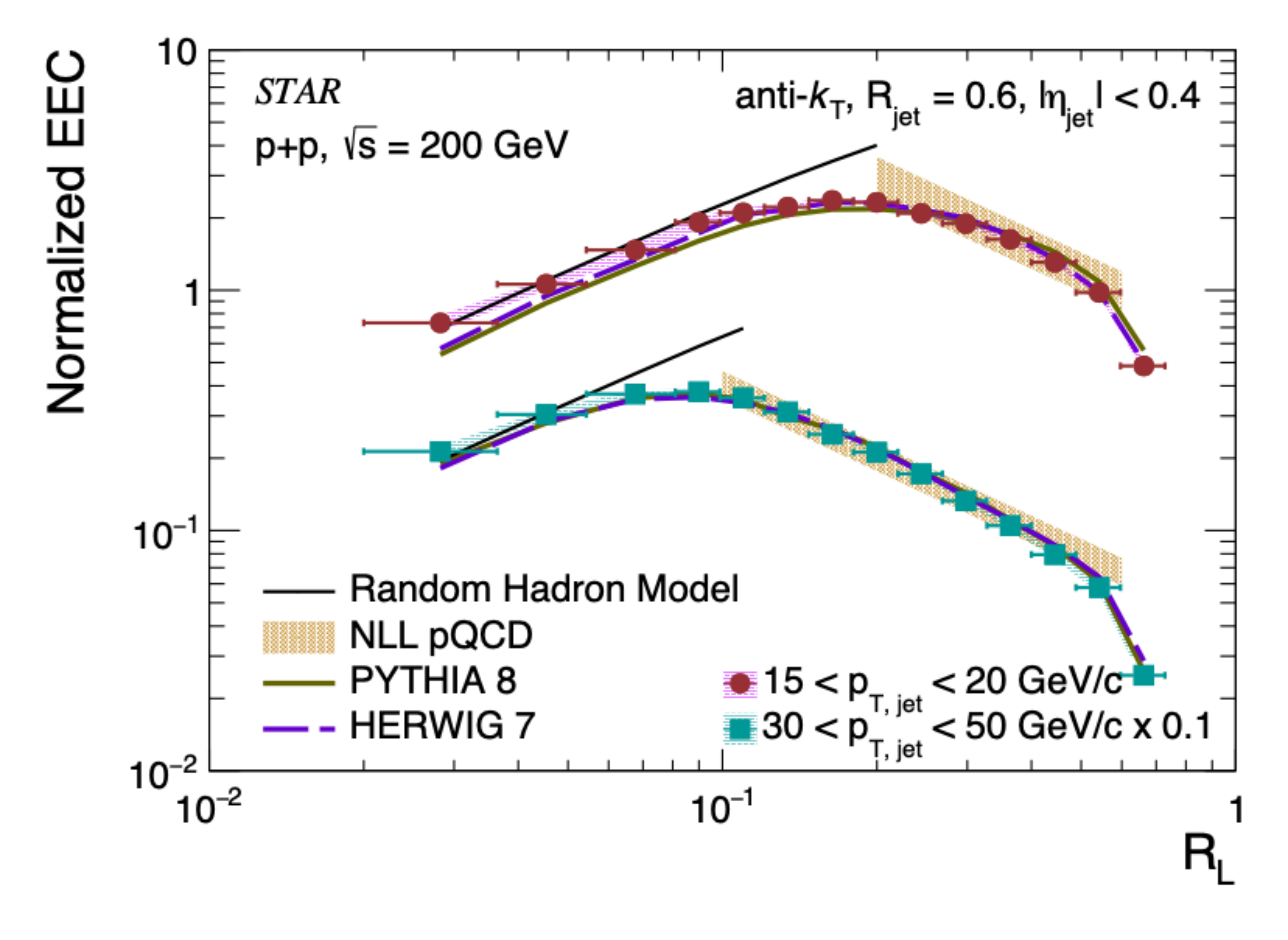
arXiv:2504.03431

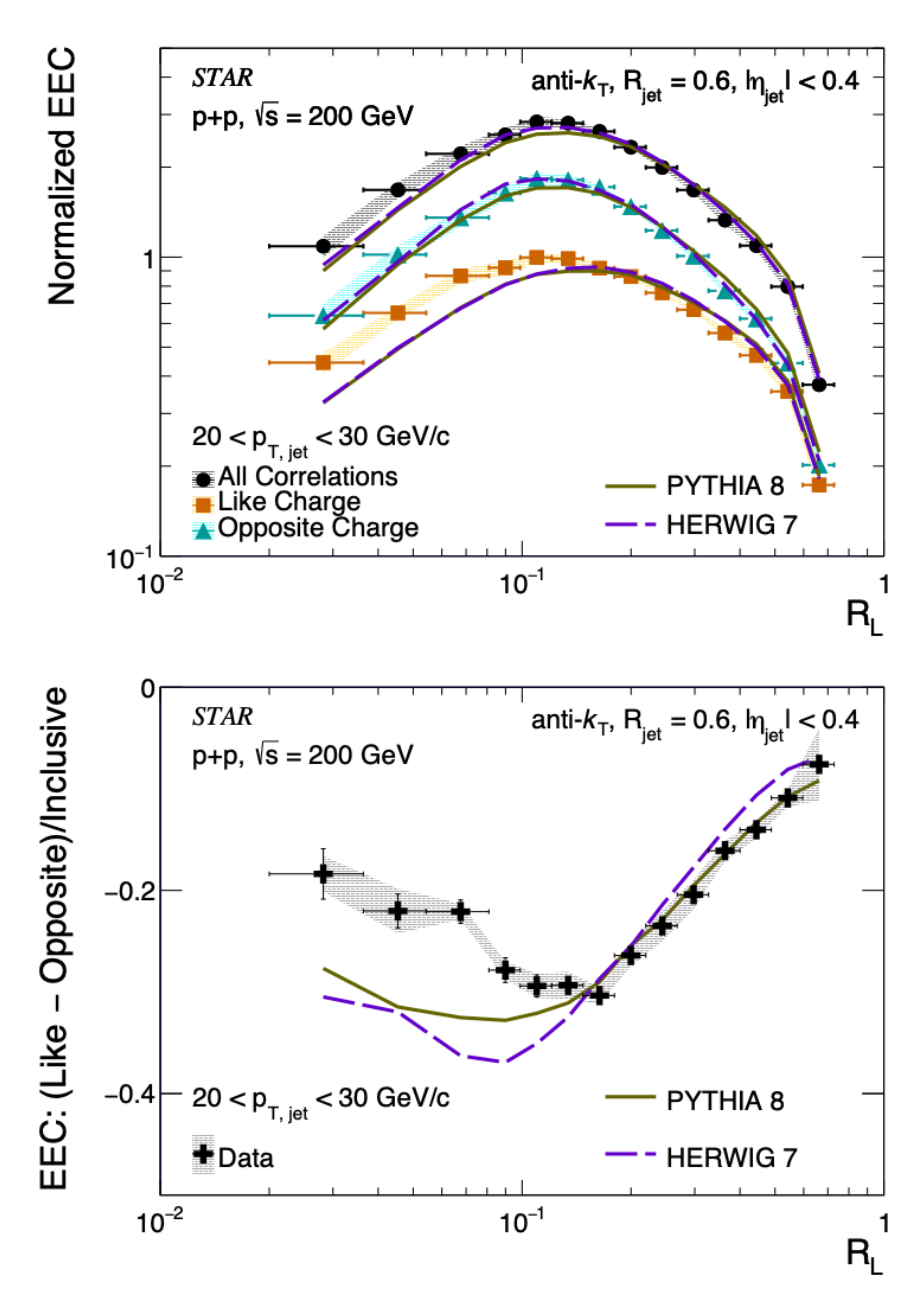
Charged EEC

STAR

arXiv:2502.15925

- String breaking expected to enhance correlations of opposite-sign pairs at small angles
- Similar observations in shape:
  - Small angle region replicated by random hadron scaling
  - Large angle region replicated by pQCD calculation





Charged EEC

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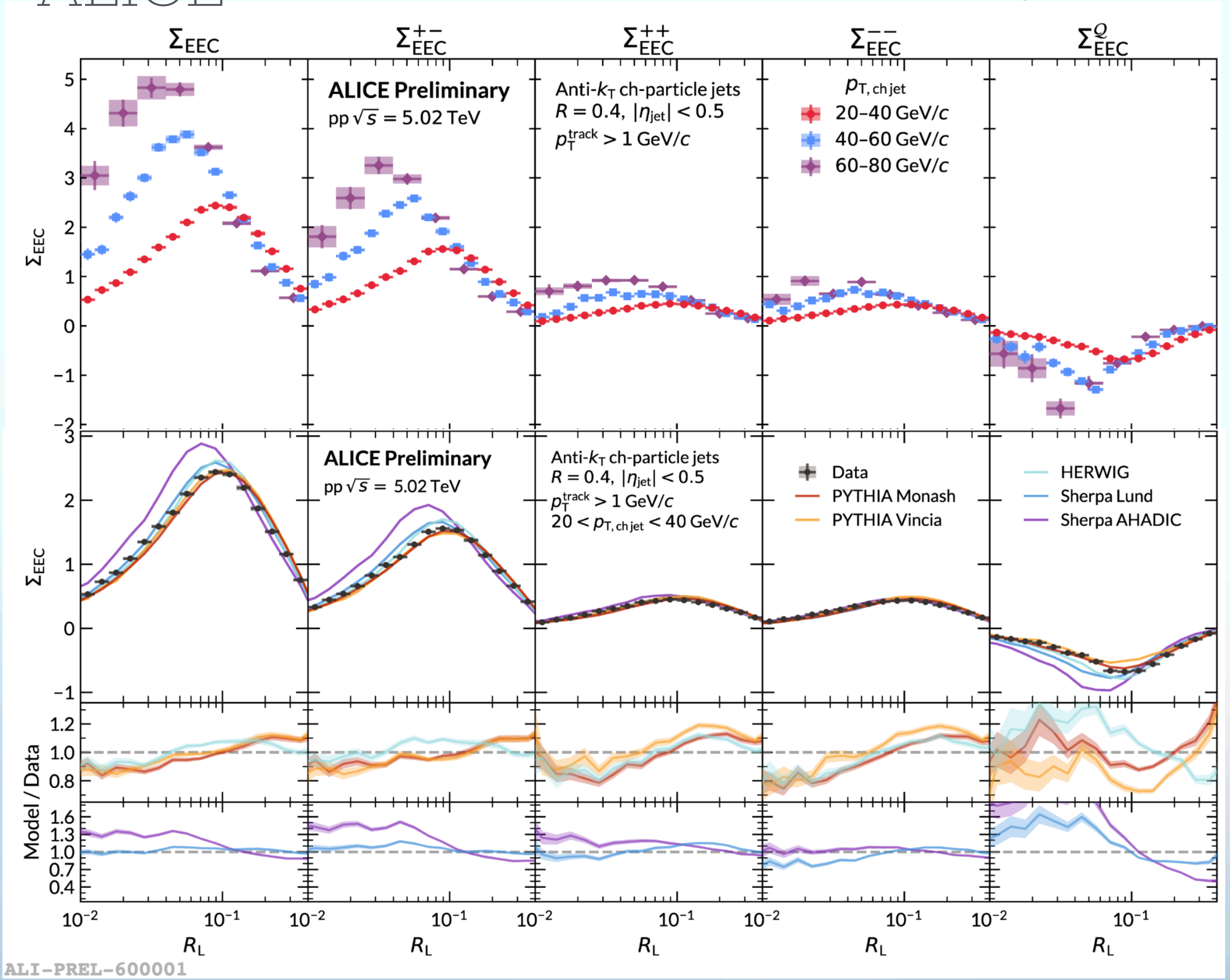
T. Hwang QM 2025

$$\Sigma^{Q}_{\mathrm{EEC}}(R_{\mathrm{L}}) = \frac{1}{N_{\mathrm{jet}}}\int \mathrm{d}R \sum_{i,j\in jet} q_i q_j \frac{p_{\mathrm{T,i}}}{p_{\mathrm{T}}^{\mathrm{jet}}}\frac{p_{\mathrm{T,j}}}{p_{\mathrm{T}}^{\mathrm{jet}}}\delta(R - R_{\mathrm{L}})$$



- Correlations of unlike-and like-sign pairs show familiar features.
- Charge-weighted EEC is overall negative: more unlike-sign pairs.
- **Data favor string-breaking models?**

Charged EEC

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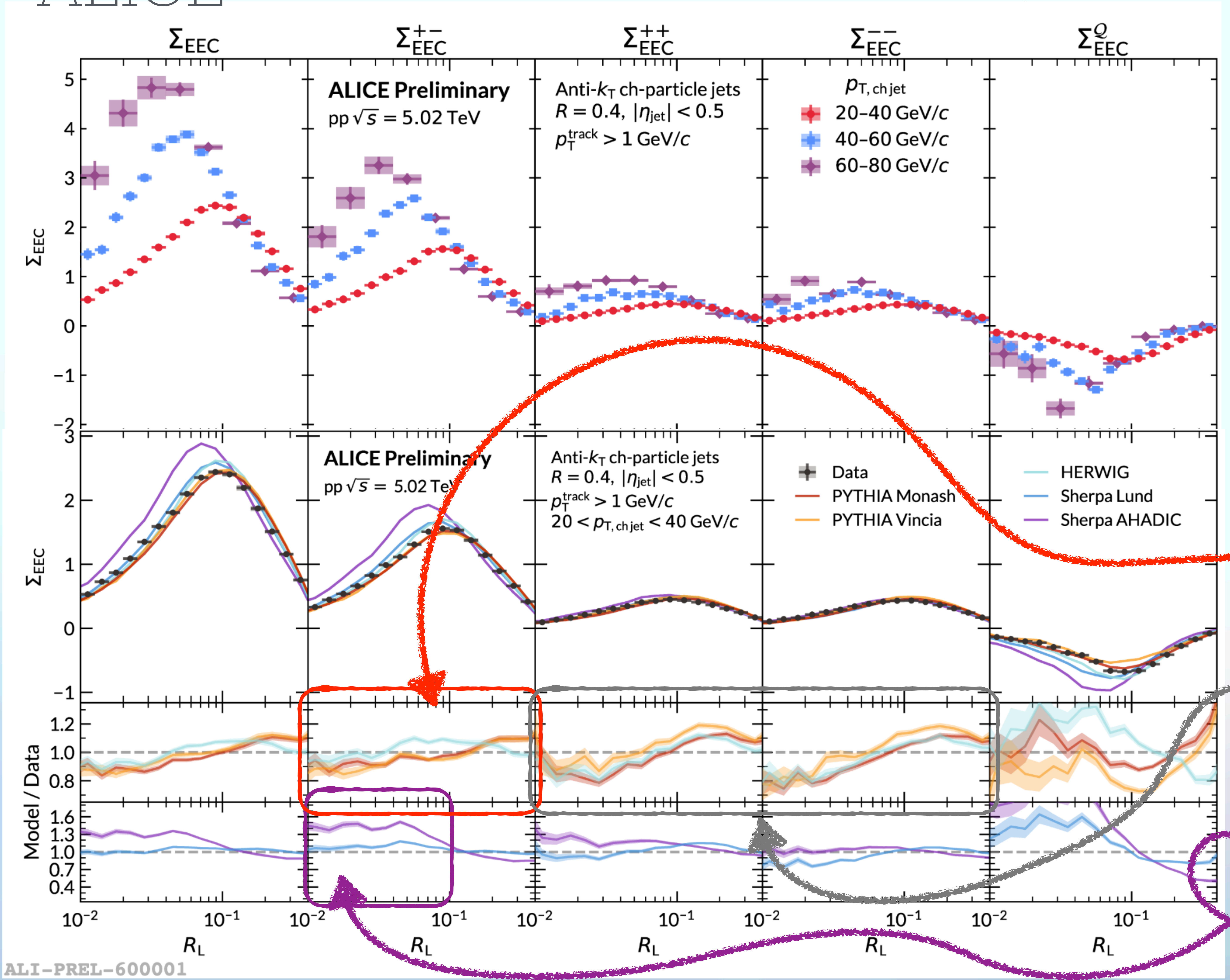

- Correlations of unlike-and like-sign pairs show familiar features.
- Charge-weighted EEC is overall negative: more unlike-sign pairs.
- **Data favor string-breaking models?**
- Model differences tell us:
  - PYTHIA and HERWIG differ most in unlike-sign EEC
  - Parton shower: Monash and Vincia differ most in like-sign EEC
  - Hadronization: Lund and AHADIC differ most in low-R_{L} unlike-sign

Collision Systems

What does the EEC look like in p-Pb?

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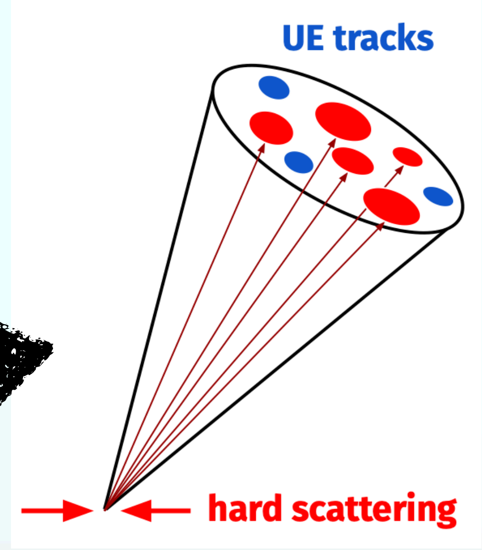
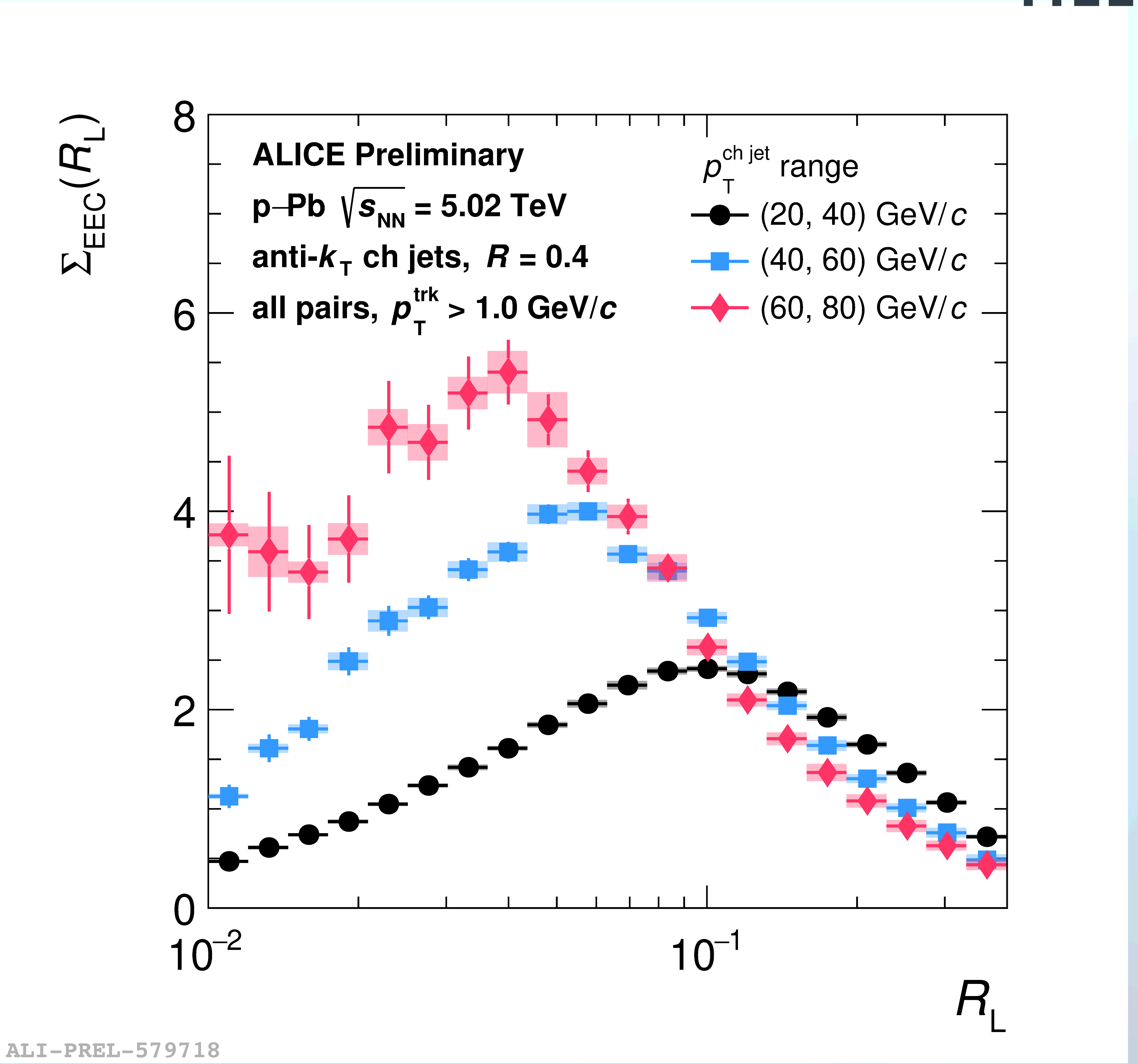
- UE is subtracted
  - Correct jet p_T for UE
  - Correct contribution from UE track pairs in the EEC with a perpendicular-cone method
- Similar features to pp EEC





A. Nambrath QM 2025

pPb / pp ratio

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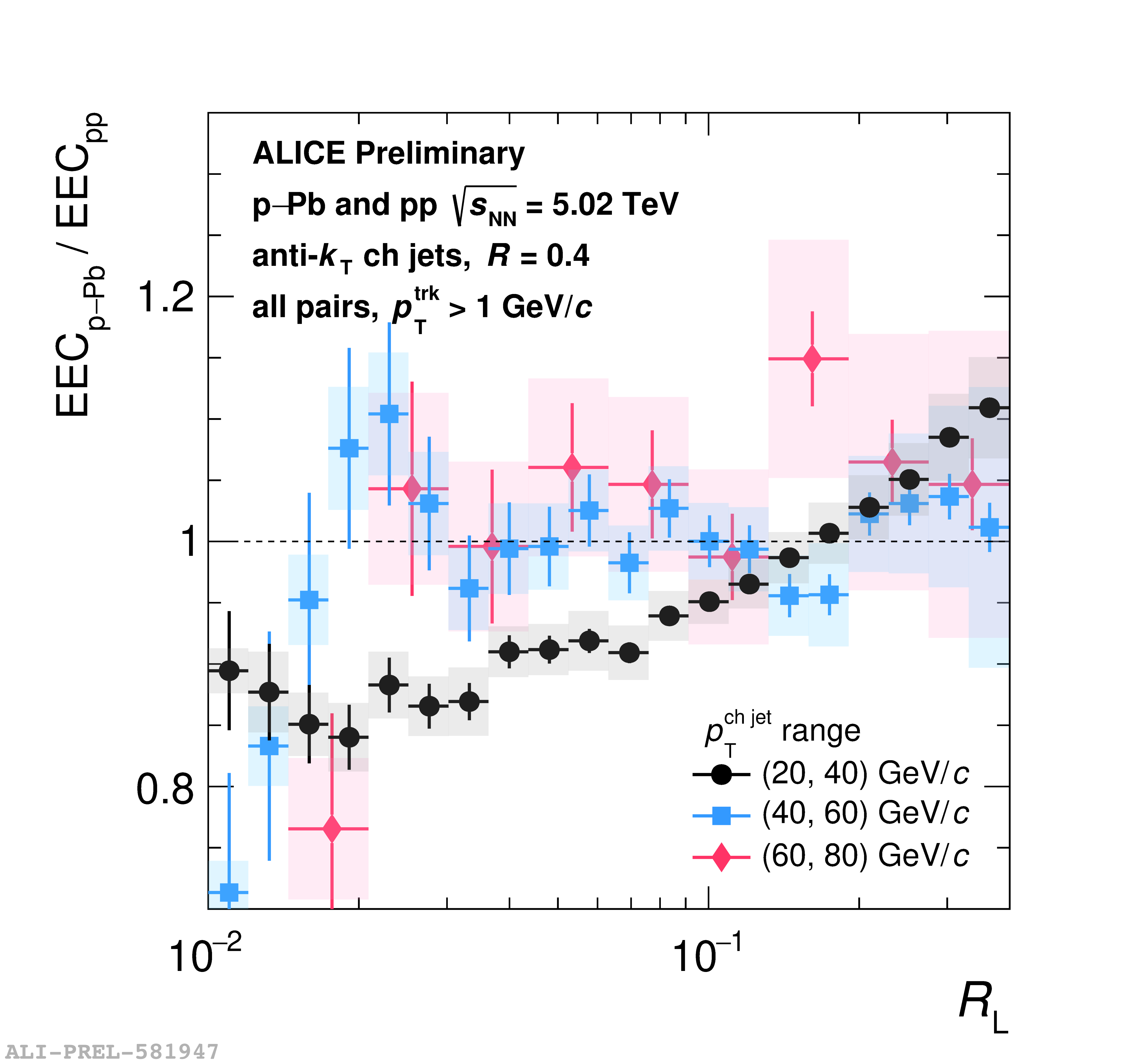

- pp baseline also background subtracted
- Higher jet p_T does not show modification
- 20 < $p_{T,\,jet}$ < 40 GeV/c ratio shows:
  - Small-angle region: ~10% suppression
  - Large-angle region: ~10% enhancement

What is responsible for this modification??

pPb / pp ratio

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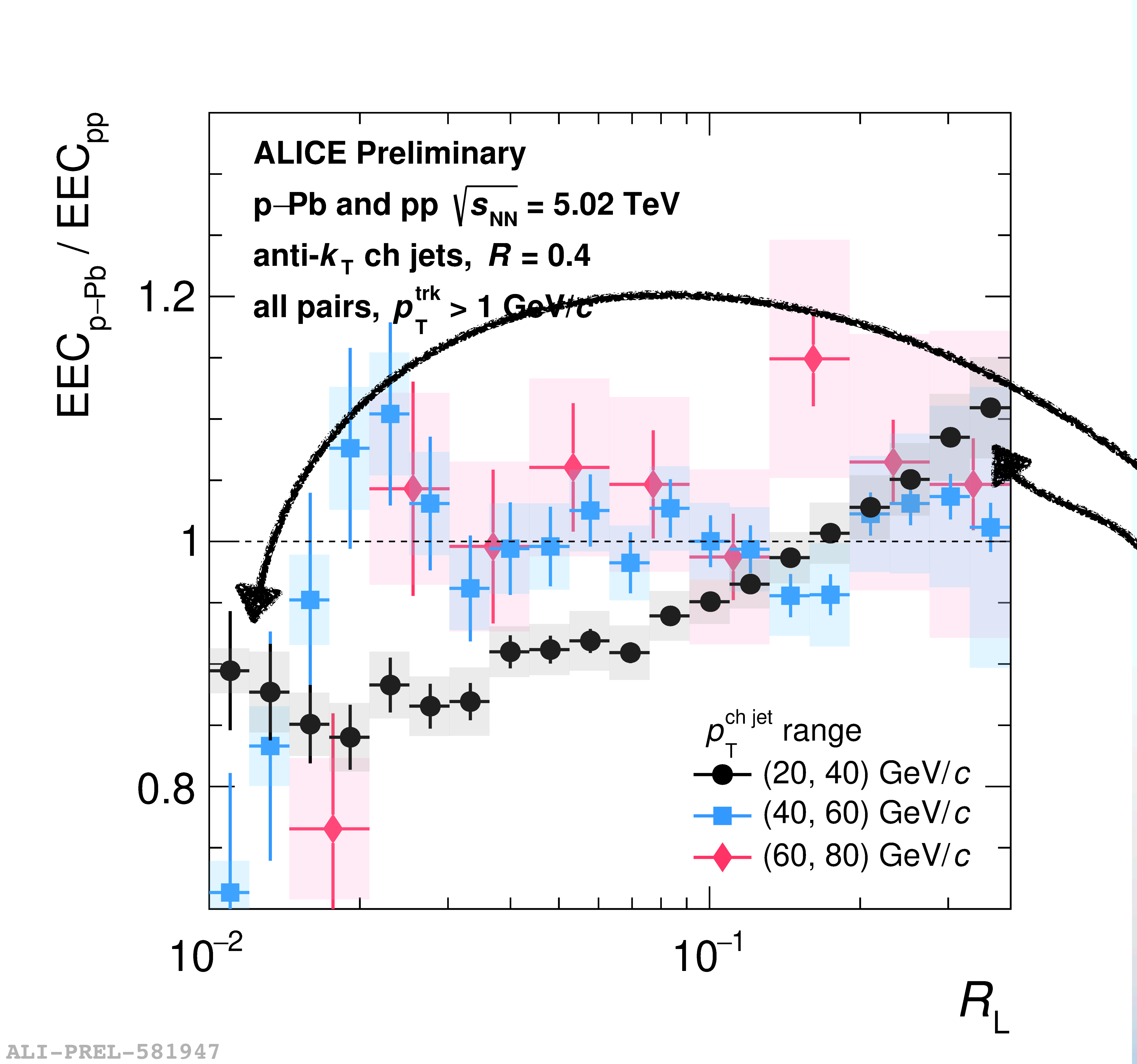

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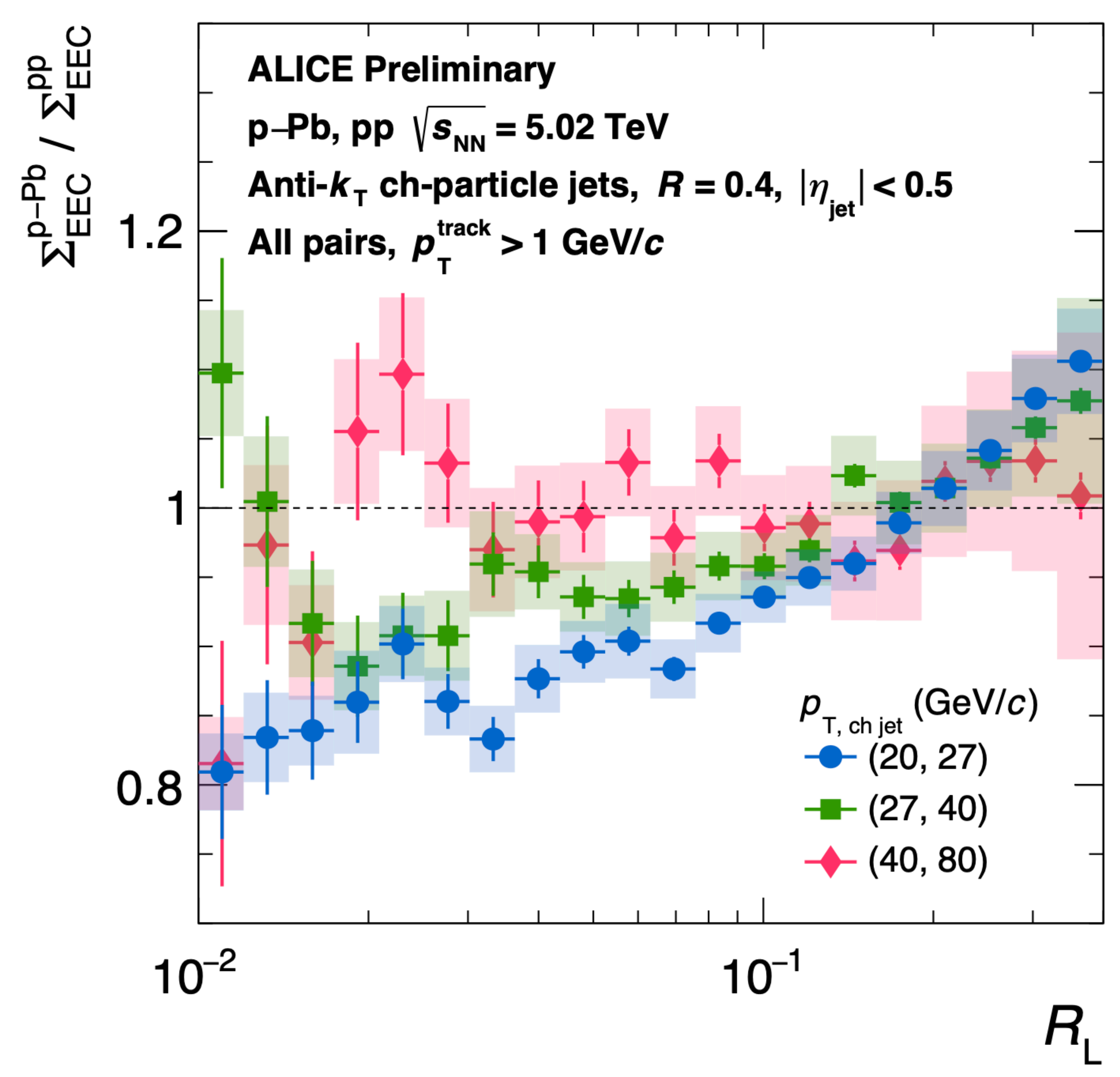
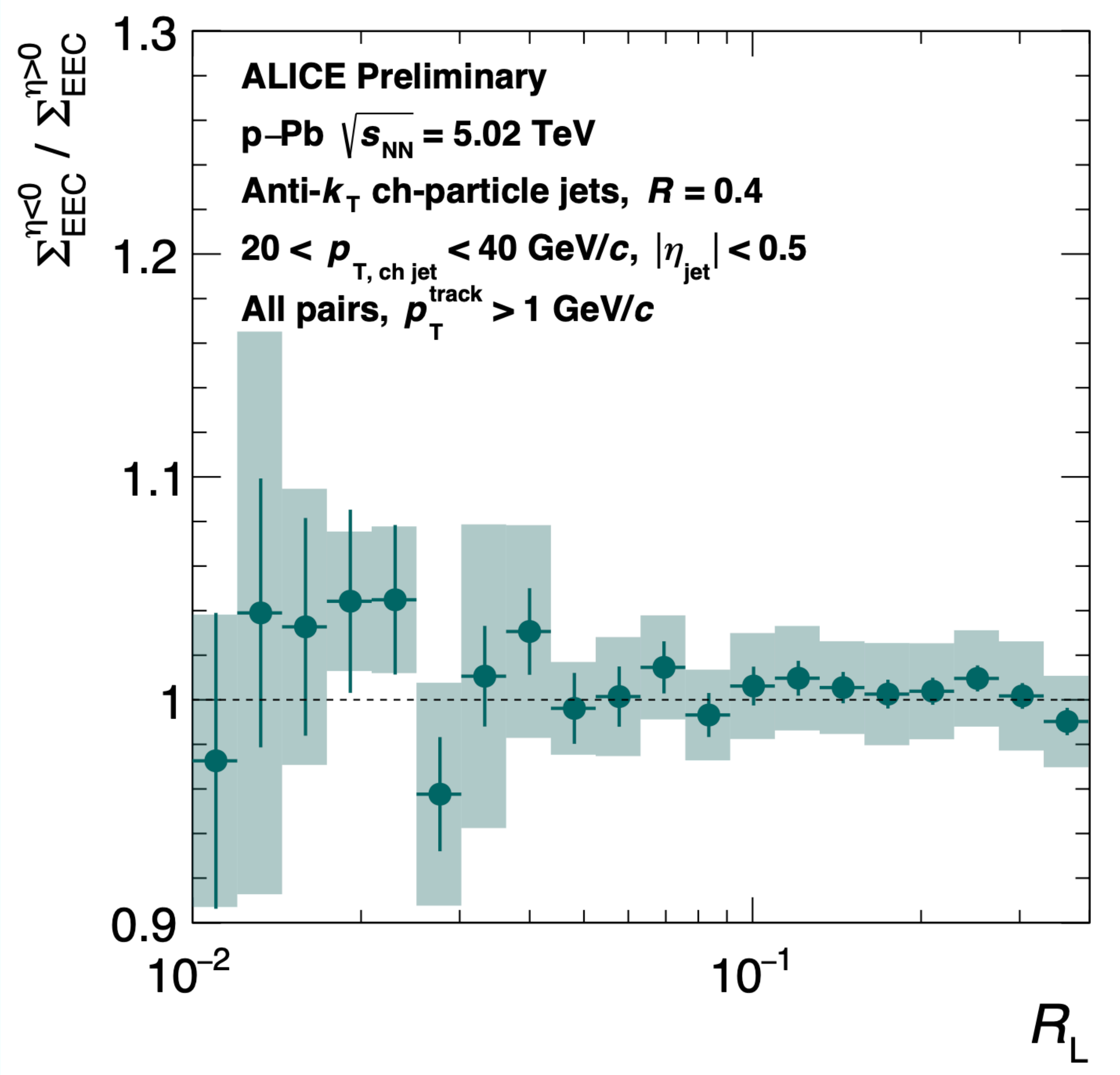
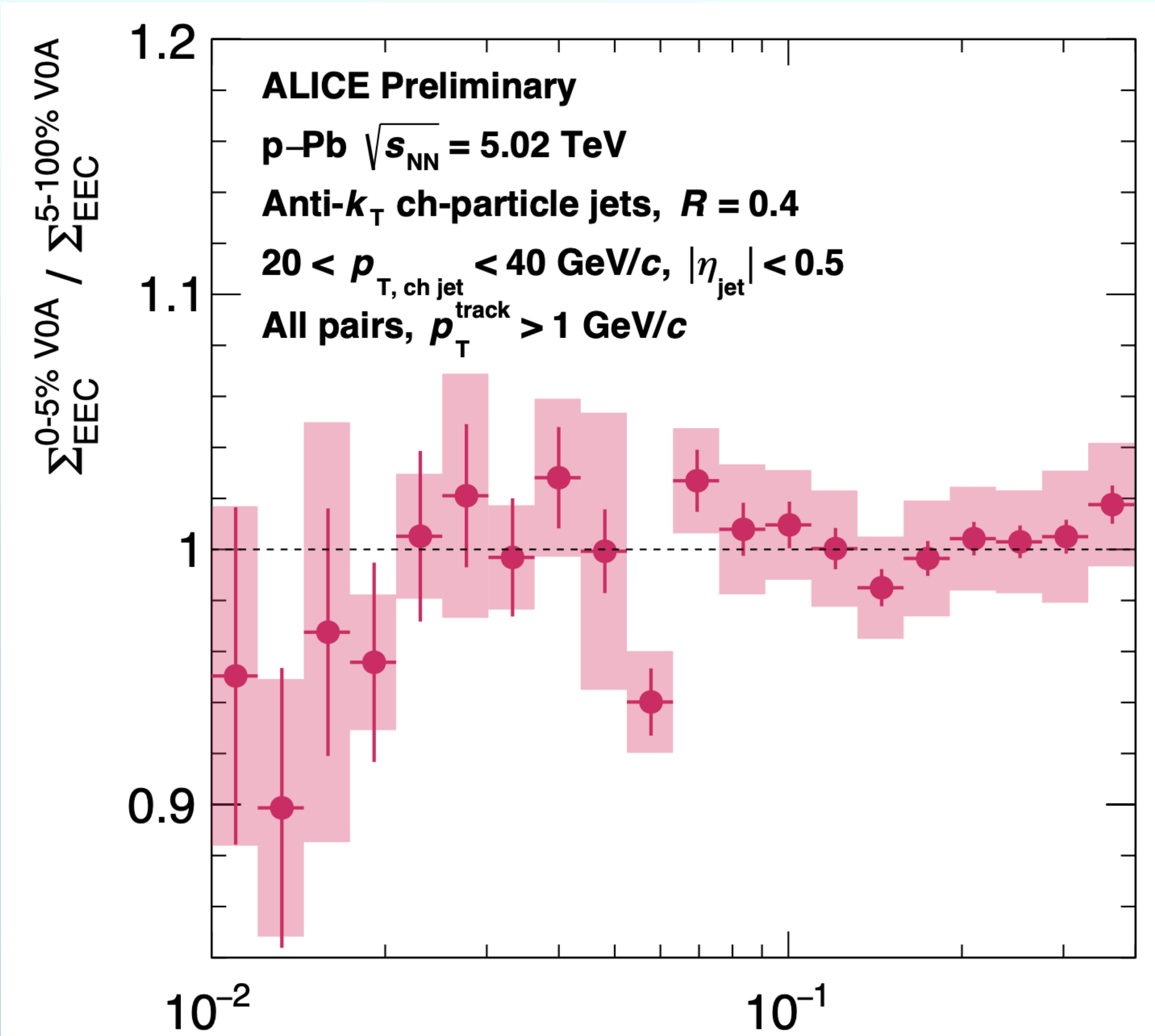
What could the ratio depend on?







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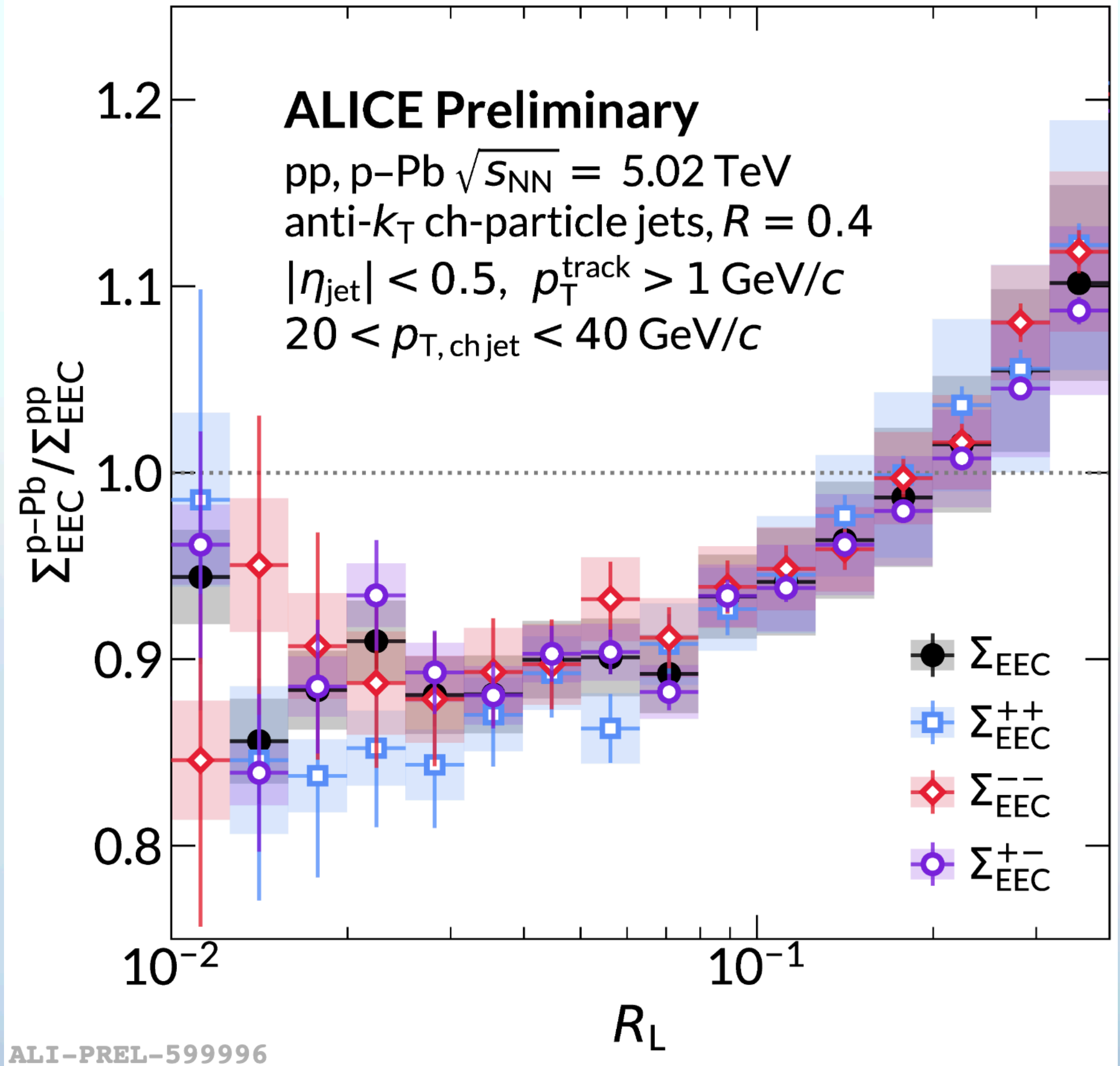
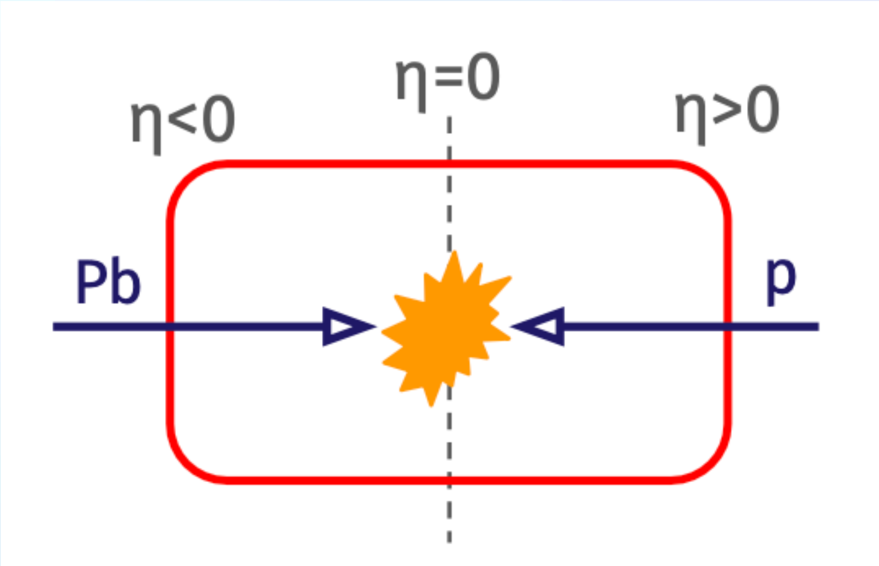


- Some jet p_T dependence is visible
- No dependence on:
  - rapidity
  - event activity
  - particle charge

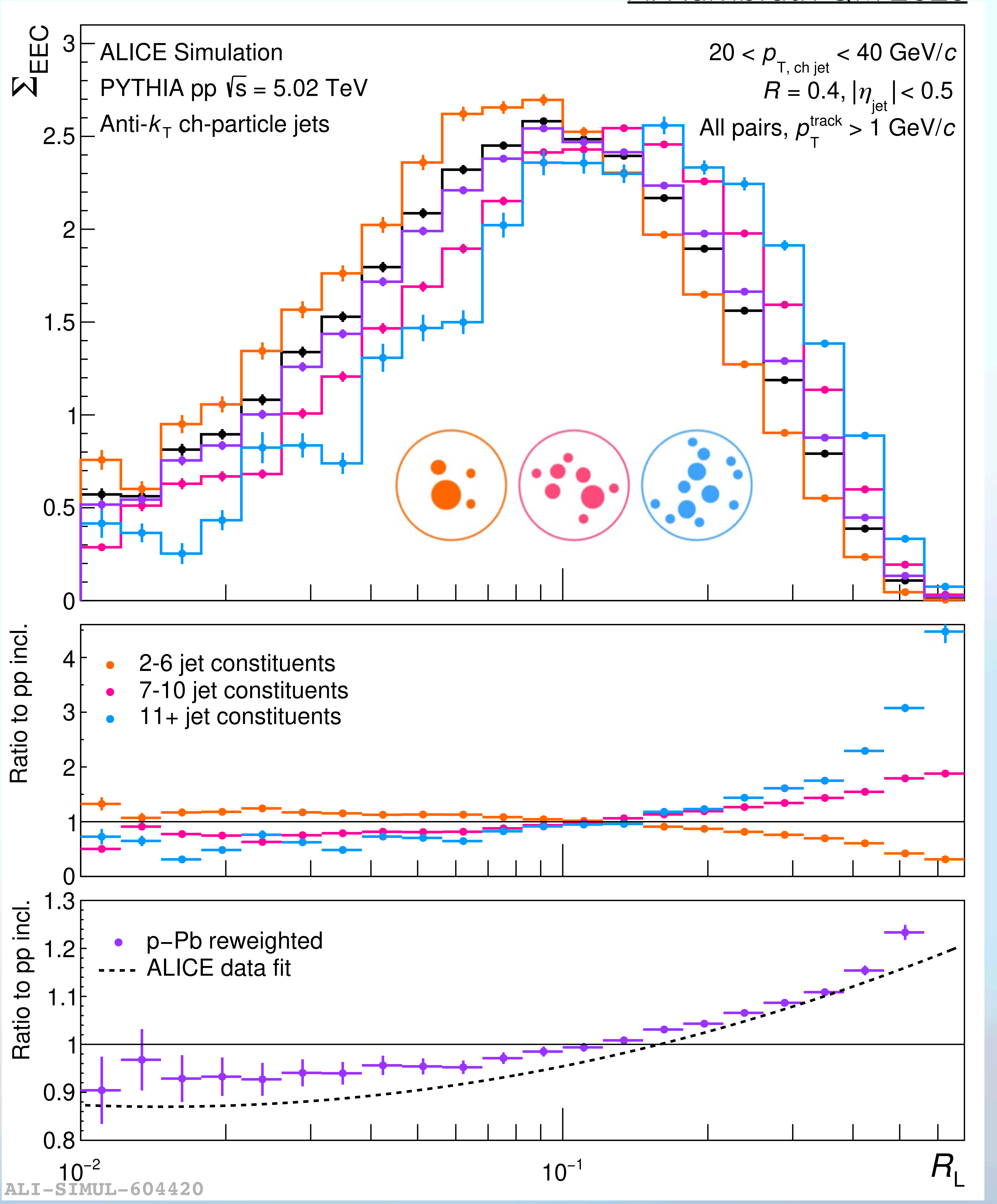


- What about jet constituent multiplicity…?

Jet multiplicity

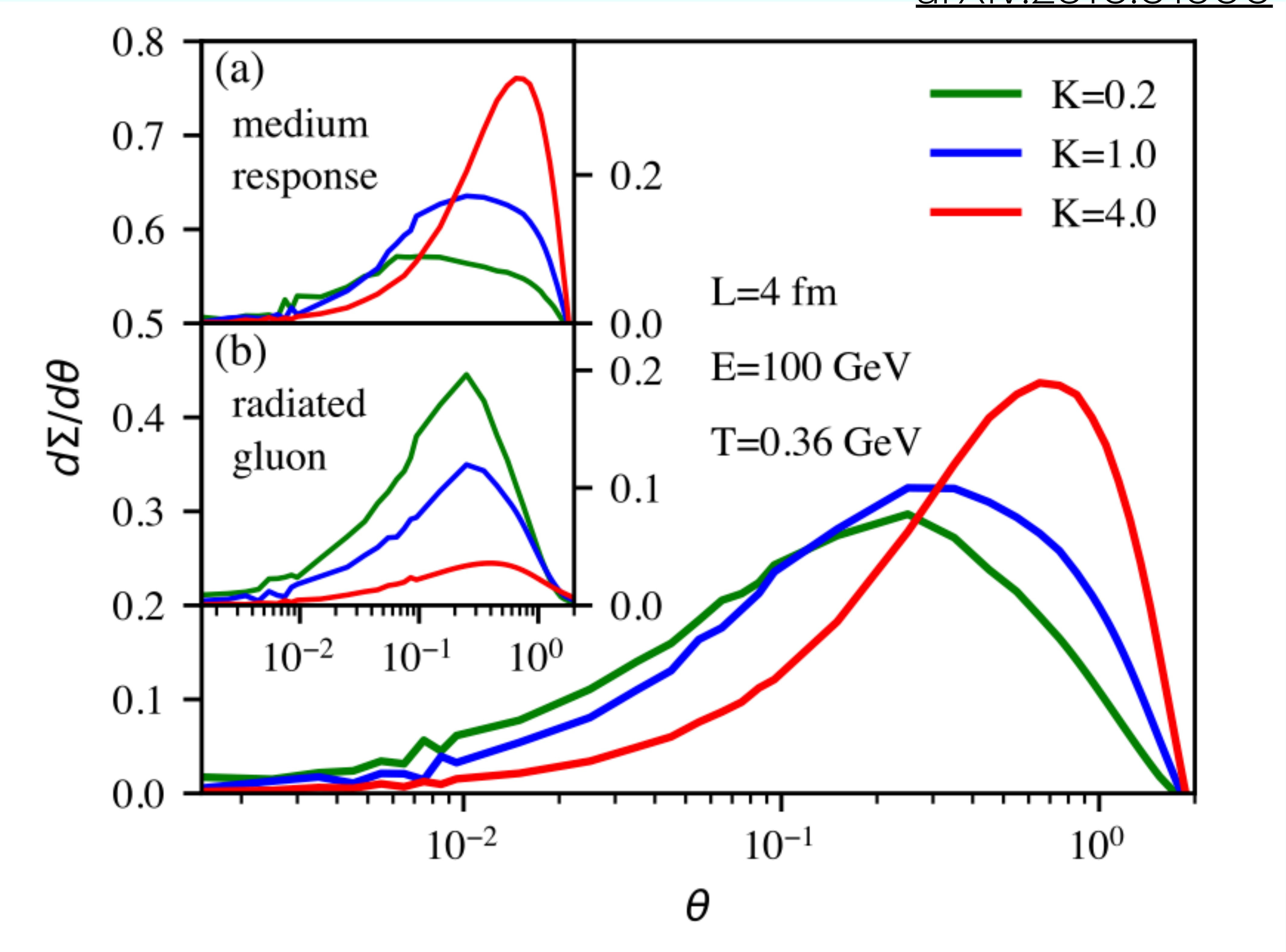
A. Nambrath QM 2025

- Separate EECs based on the # of charged jet constituents
  - inclusive EEC from PYTHIA
  - EEC from jets with 2-6 tracks
  - EEC from jets with 7-10 tracks
  - EEC from jets with 11+ tracks
- Dramatic shift in the EECs due to jet constituent multiplicity
- If 12% of jets are redistributed to higher multiplicities, measured p-Pb EEC modification is largely reproduced

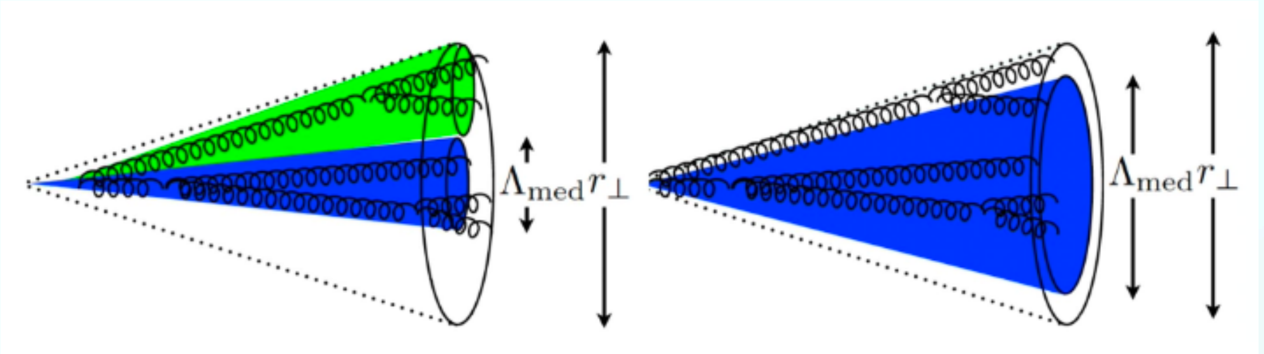


What are some effects when we add a QGP?

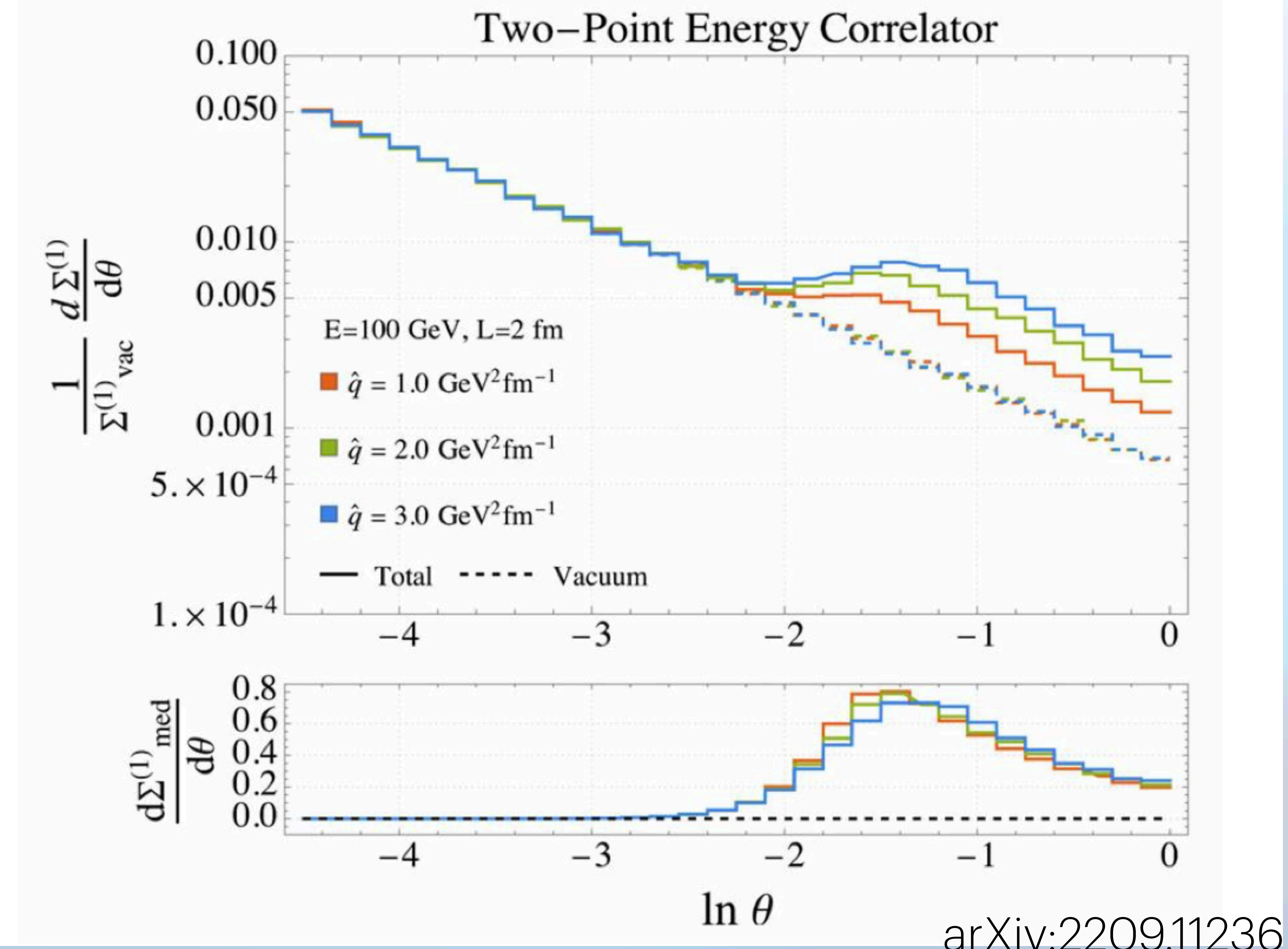
arXiv:2310.01500



- Color coherence



  - Angle of emission determines how the medium resolves a splitting



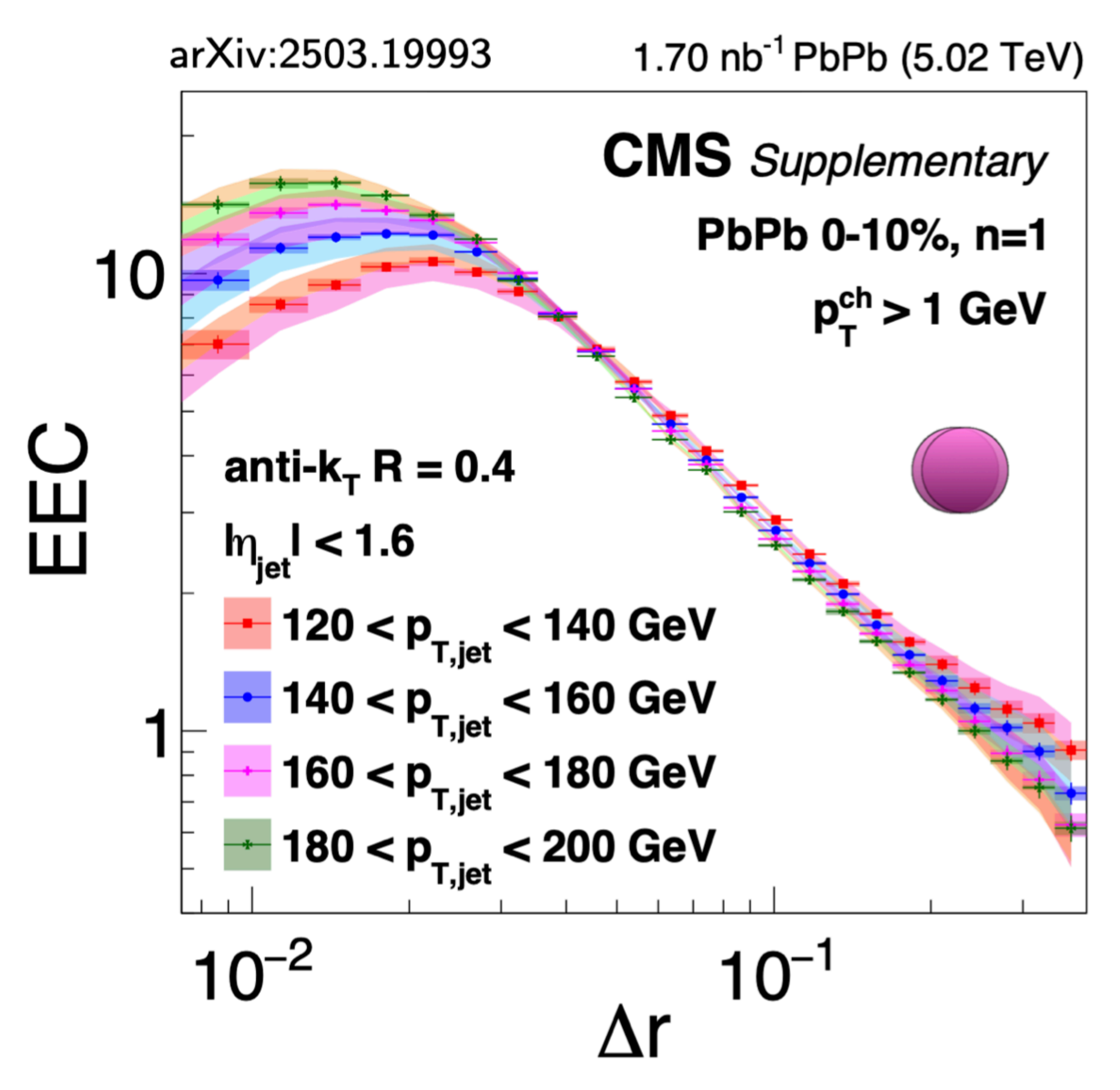
arXiv:2209.11236

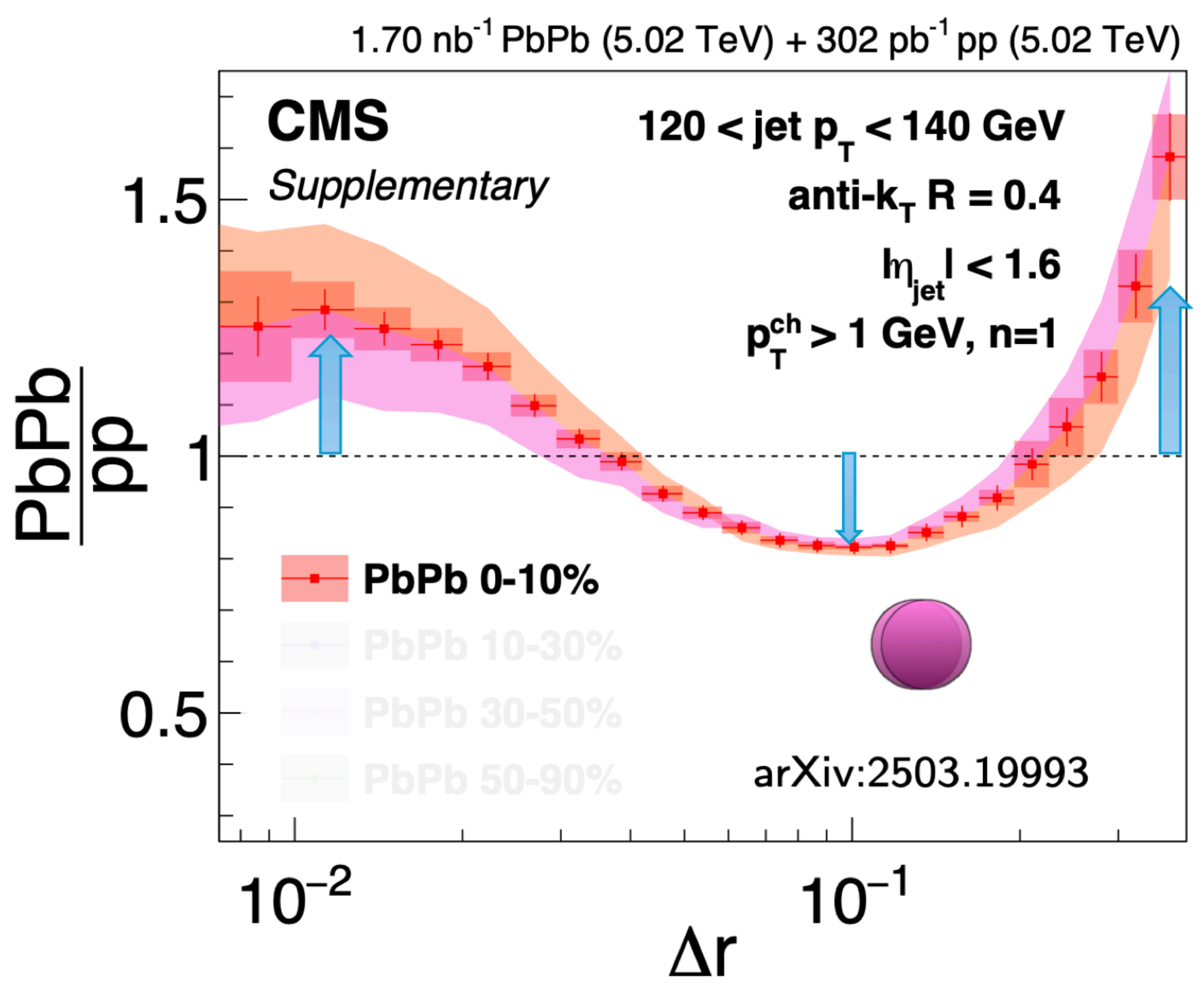
- Medium response
  - Recoil partons + back-reaction
  - Depletion caused by energetic partons pulling the medium - jet wake?

Pb-Pb results

CMS

arXiv:2503.19993





- Energy loss moves the peak to smaller angles
- Interesting modification seen at larger angles

- Similar features to the EEC in PbPb as in pp
- EEC peak moves to smaller angles as jet p_T increases and collisions get more central

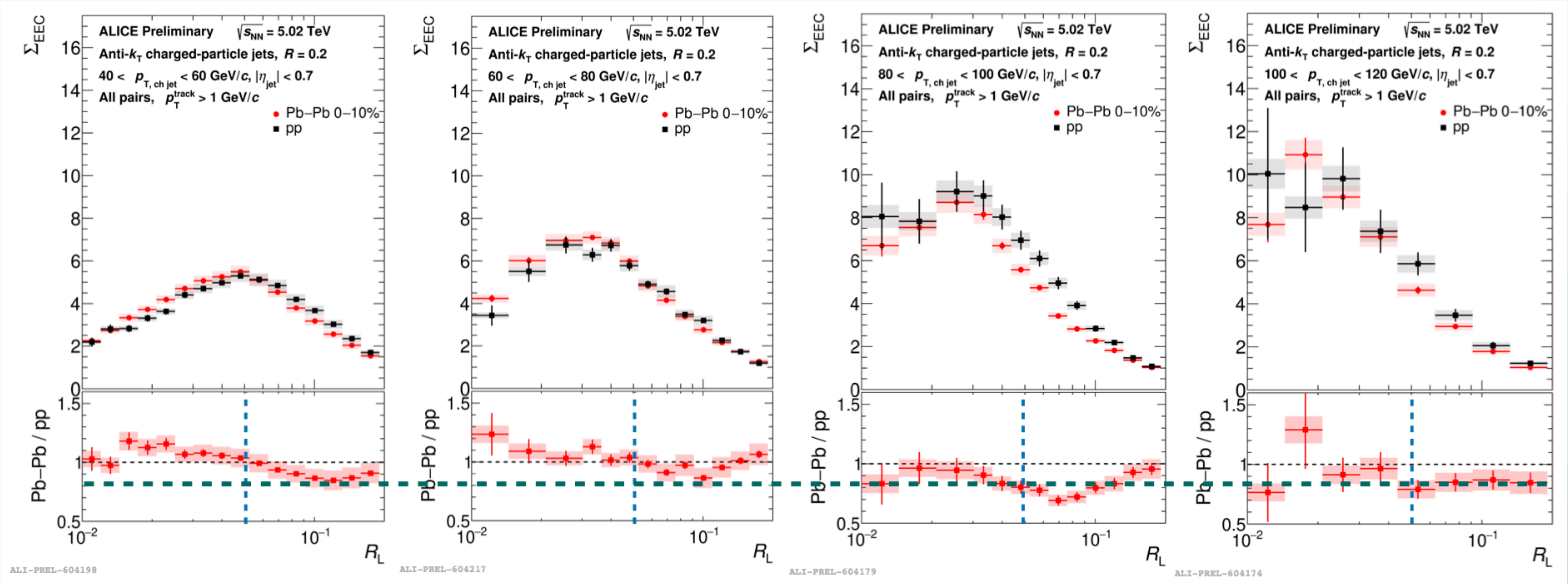
Pb-Pb results

ALICE

increasing jet p_T

A. Rai QM 2025

ALICE results extend to lower jet p_T ranges

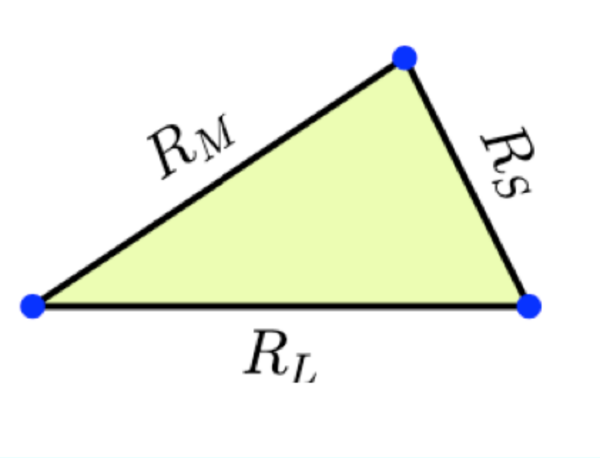


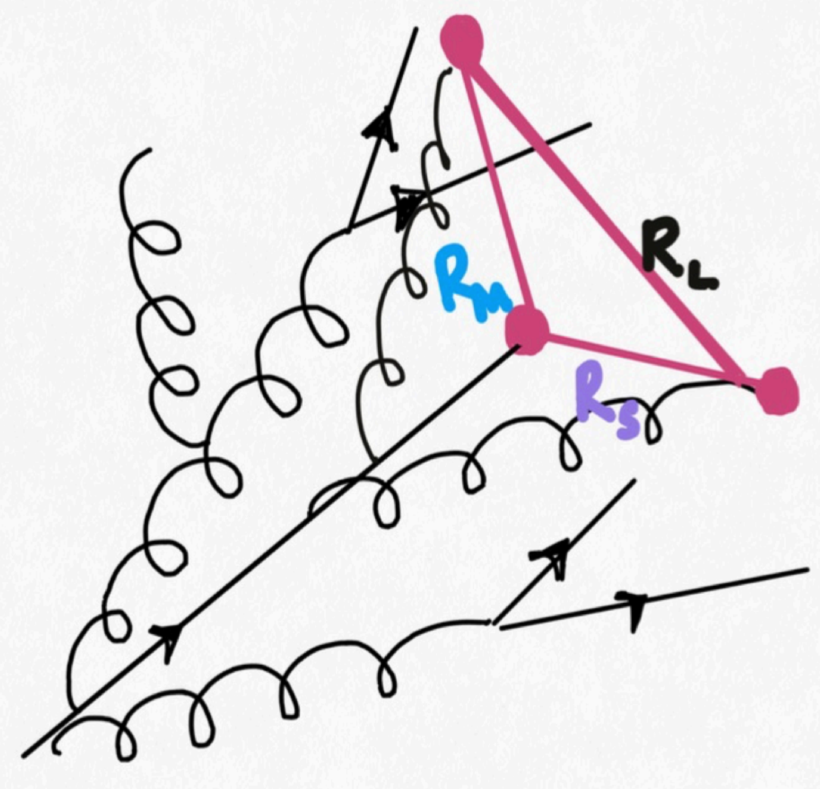
- Hint of enhancement at low R_L
- Hint of suppression at high R_L
- Onset of suppression shifts to the left
- Low jet p_T dependence in modification

3-point Energy Correlator

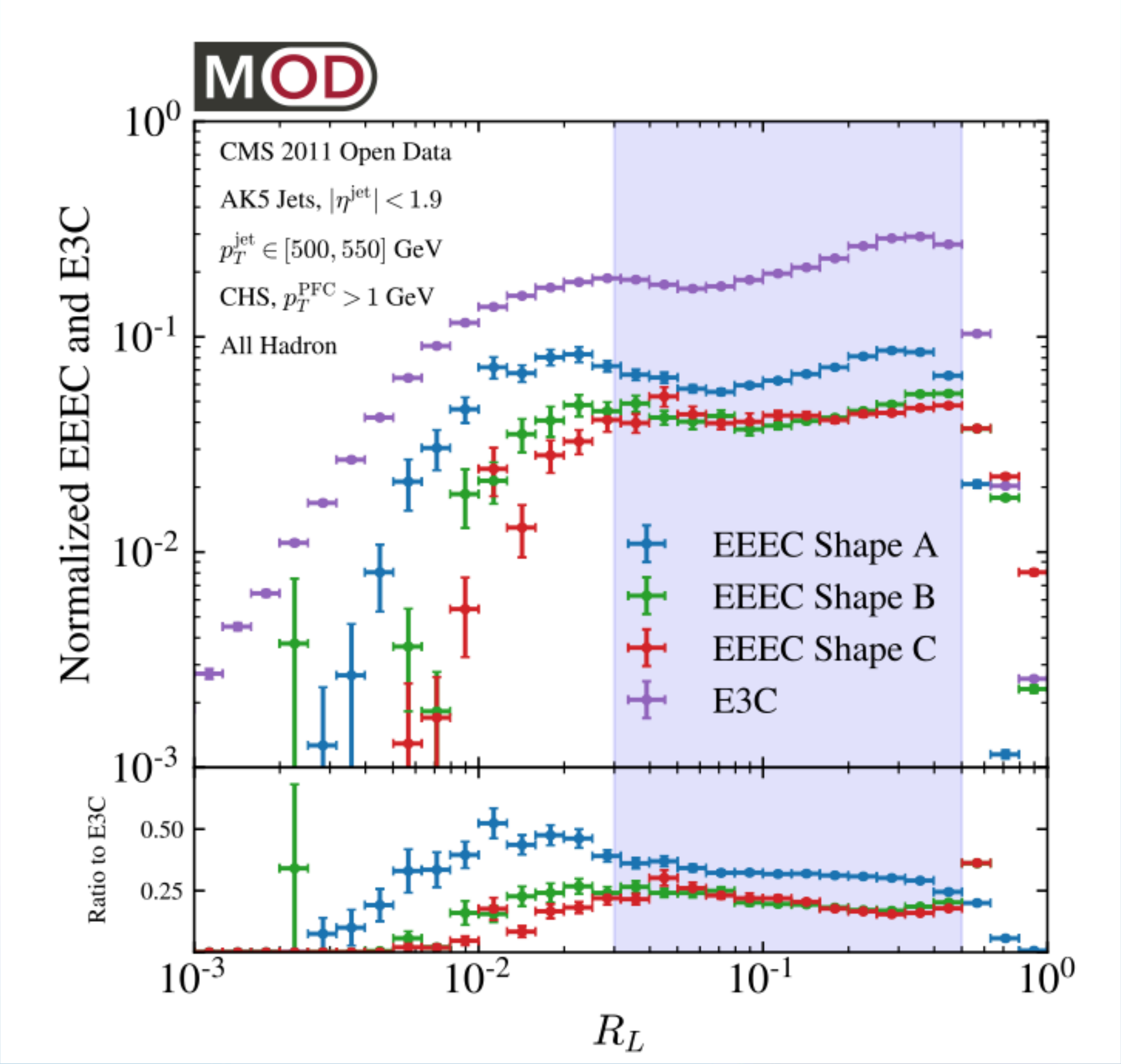
What is the 3-point correlator?

$$\text{E3C}(R_L) = \Sigma_{i,j,k} \int dR_L \frac{p_{\text{T},i} p_{\text{T},j} p_{\text{T},k}}{p_{\text{T,jet}}^3} \delta(R_L - \Delta \hat{R}_L)$$





- Probes shape dependence of energy flow
- E3C: projected 3-point correlator
  - Use the largest distance between N=3 points
- Access to the strong coupling constant
  - Most precise way of calculating α_s using jet substructure



arXiv:2201.07800

EEC vs E3C

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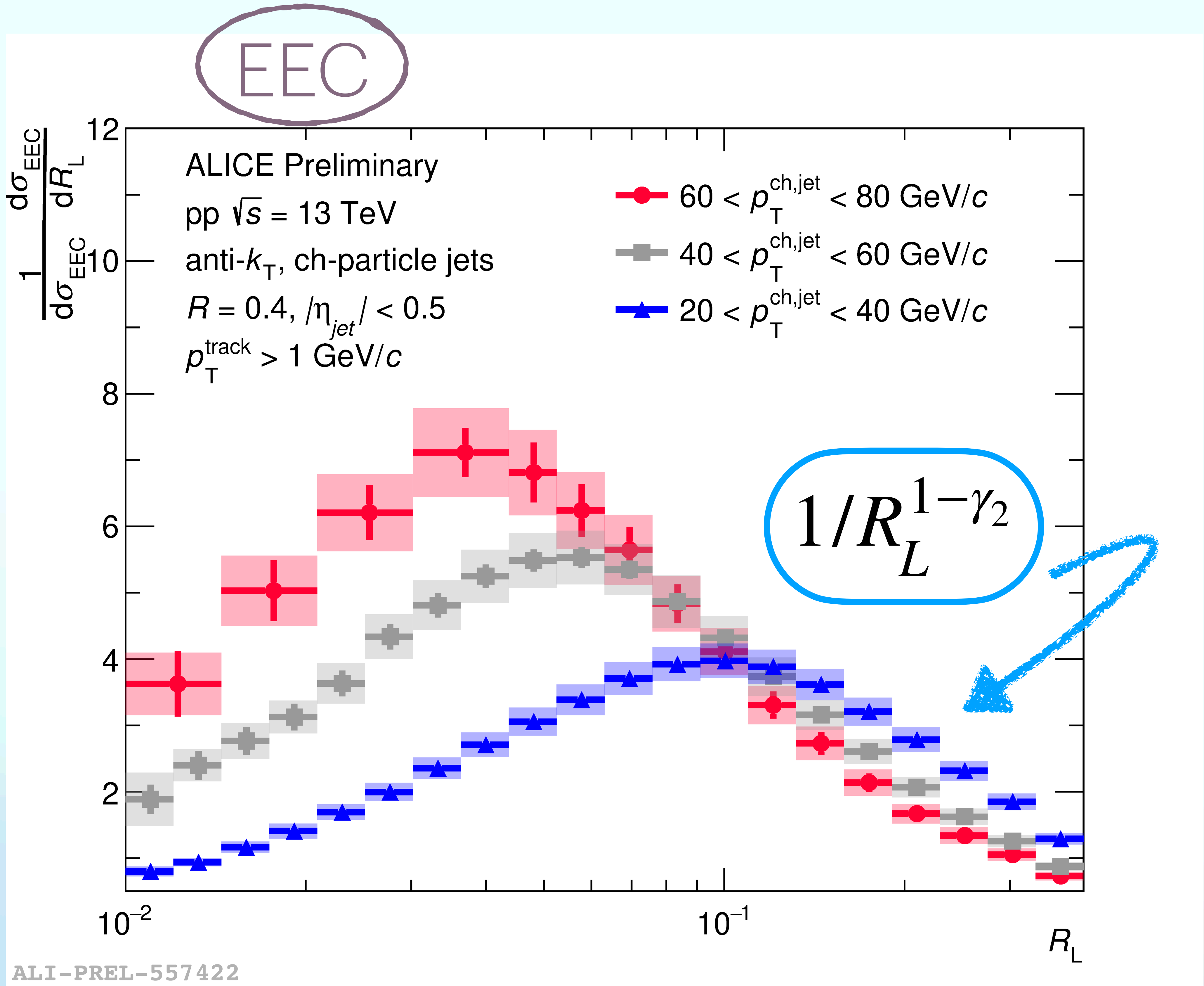

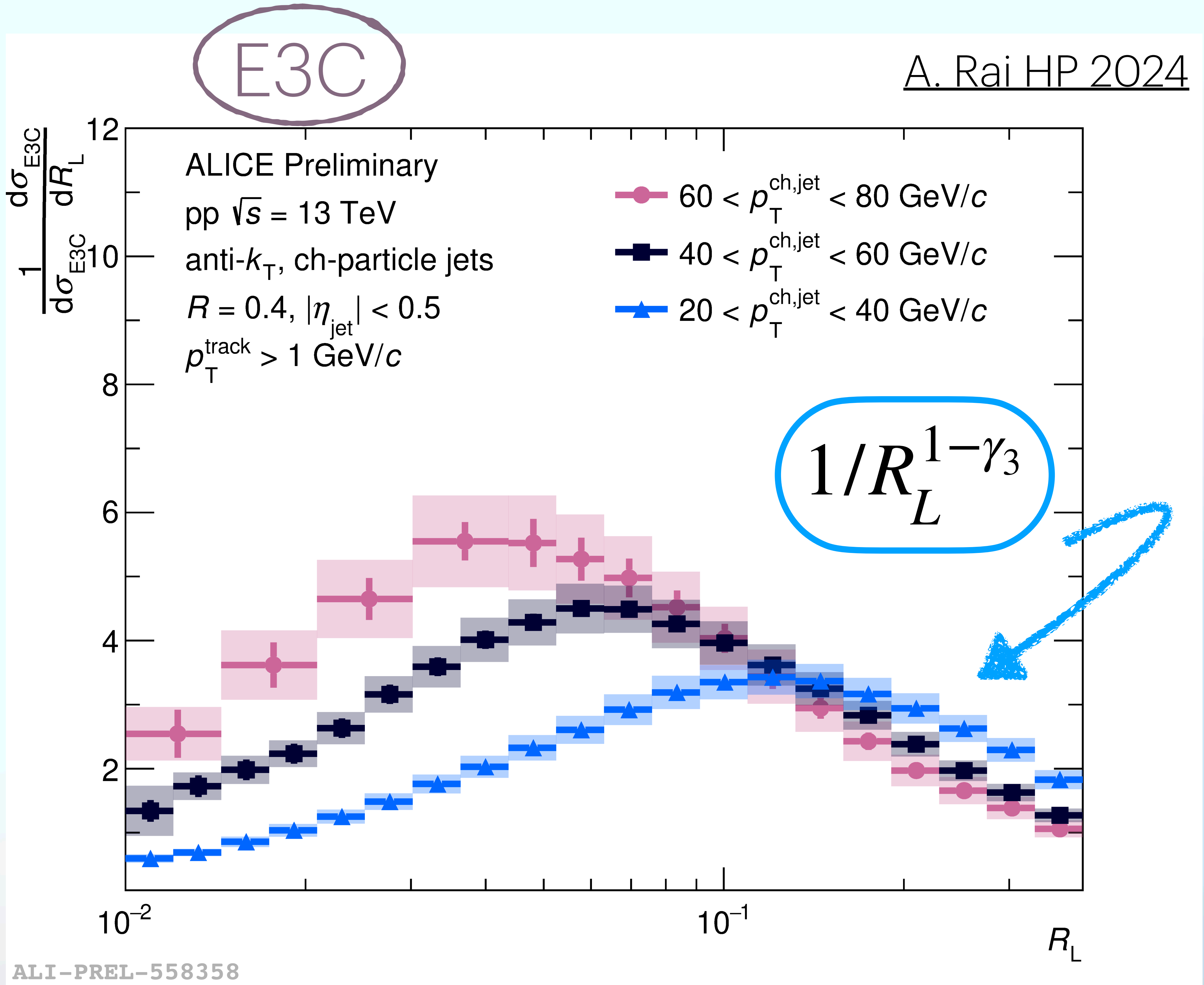

- EEC and E3C have the same qualitative features
- Partonic region slopes are different — EEC (γ_2) vs E3C (γ_3) quantum corrections

E3C / EEC ratio

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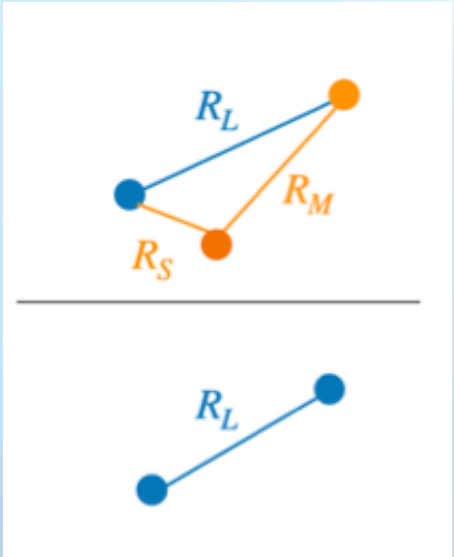
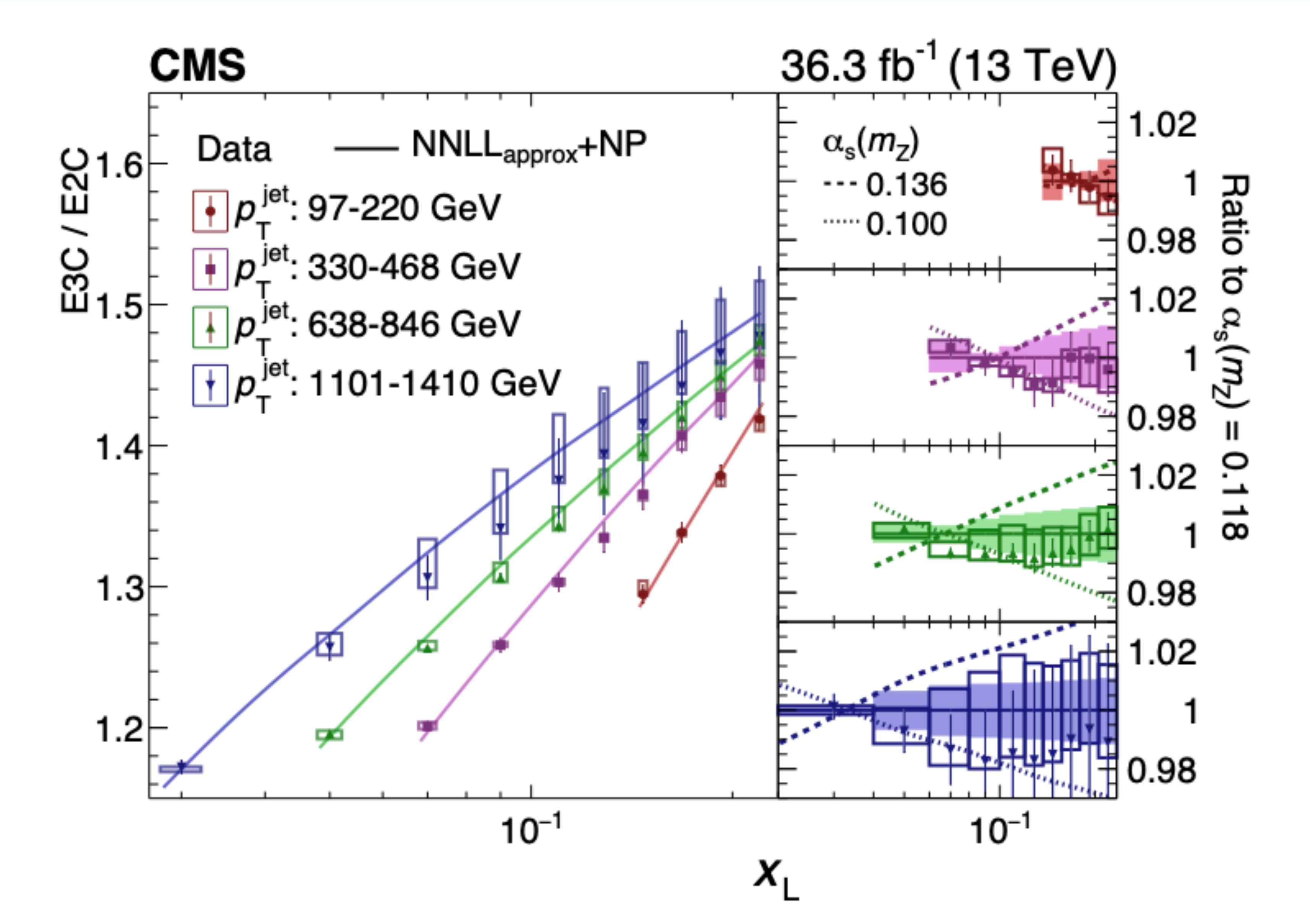
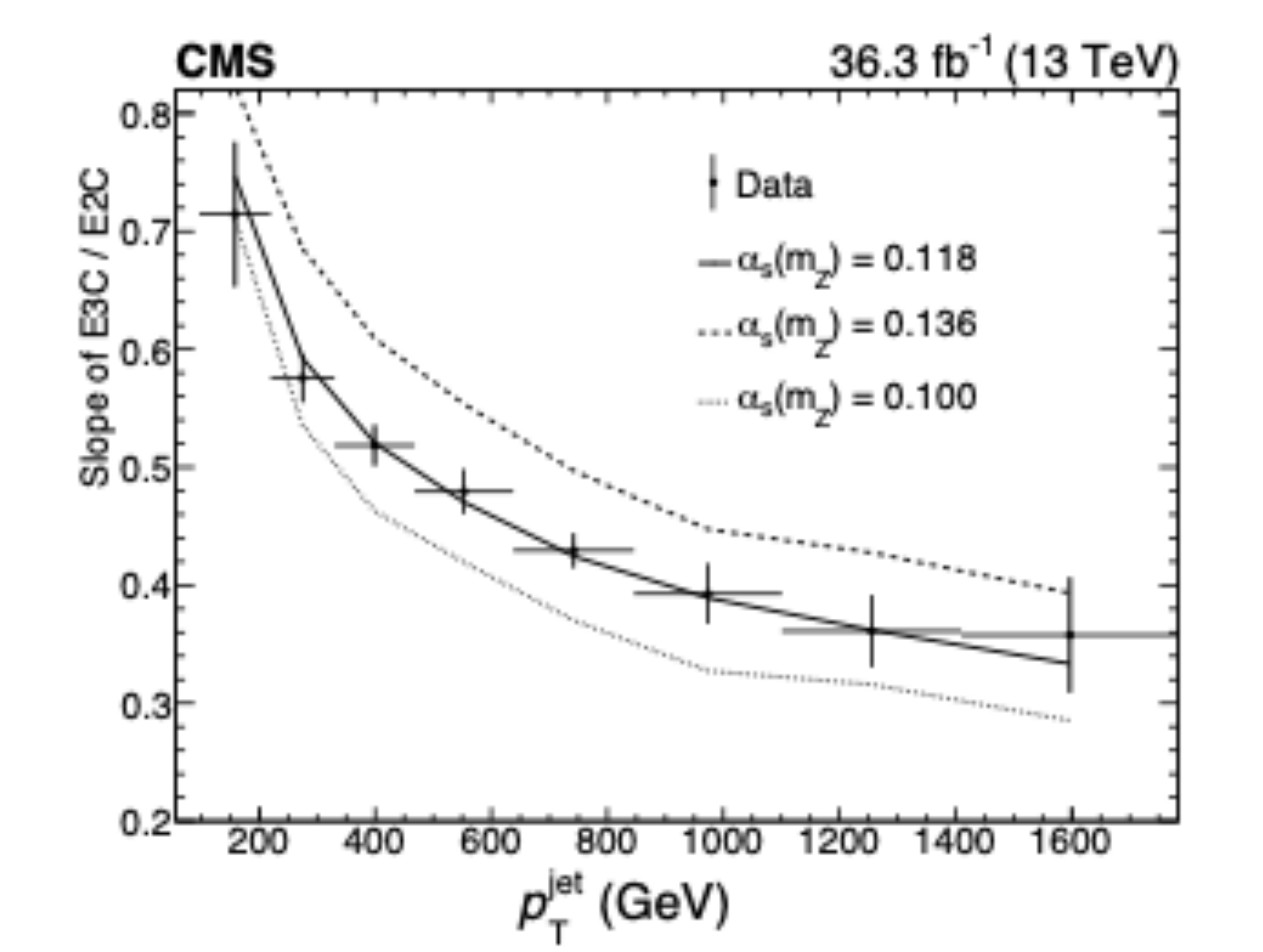
- Perturbative regime:
  - Change in slope of E3C / EEC with jet p_T is sensitive to the running of the strong coupling constant!
    - Slope ~ $R_L^{\gamma_3-\gamma_2} \propto \alpha_s \ln(R_L)$



$\propto \alpha_S \ln(R_L)$

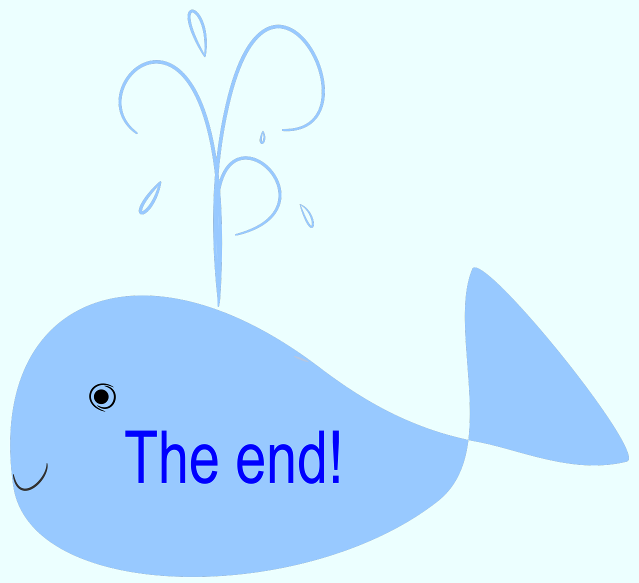




arXiv:2402.13864

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

Summary

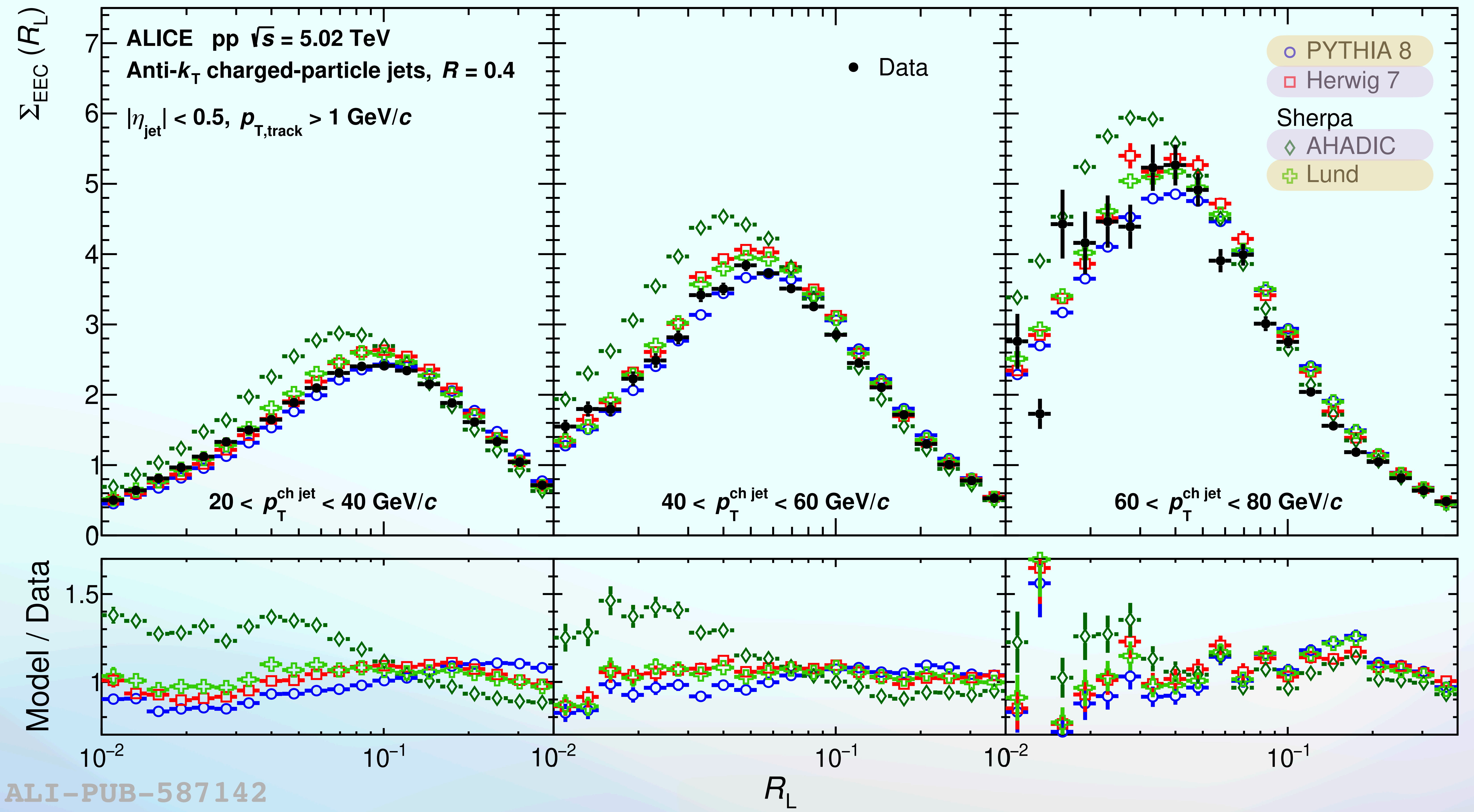


- EECs are a powerful tool to study parton correlations and hadron formation
  - Universality across jet energy and collision system of the overall EEC shape and turnover region
  - Many experiments are working to calculate EECs in every configuration
  - E3C gives the most precise extraction of α_S using jet substructure
- Flavor effects visible via EECs
  - Mass effects and Casimir effects alter the position of the peak
  - Still many mysteries about hadronization
- EECs are sensitive to changes in collision system
  - Questions remain about the modification seen in these systems
  - More measurements need to be done to draw more robust conclusions — stay tuned!

Thank you!

Backup

And what about across event generators?



- Lund-string hadronization
  - PYTHIA
  - Sherpa Lund
- Cluster hadronization
  - Herwig
  - Sherpa AHADIC

Models appear to show that clustering-hadronization model causes a later hadronization compared to Lund-string breaking.

Z-tagged EEC

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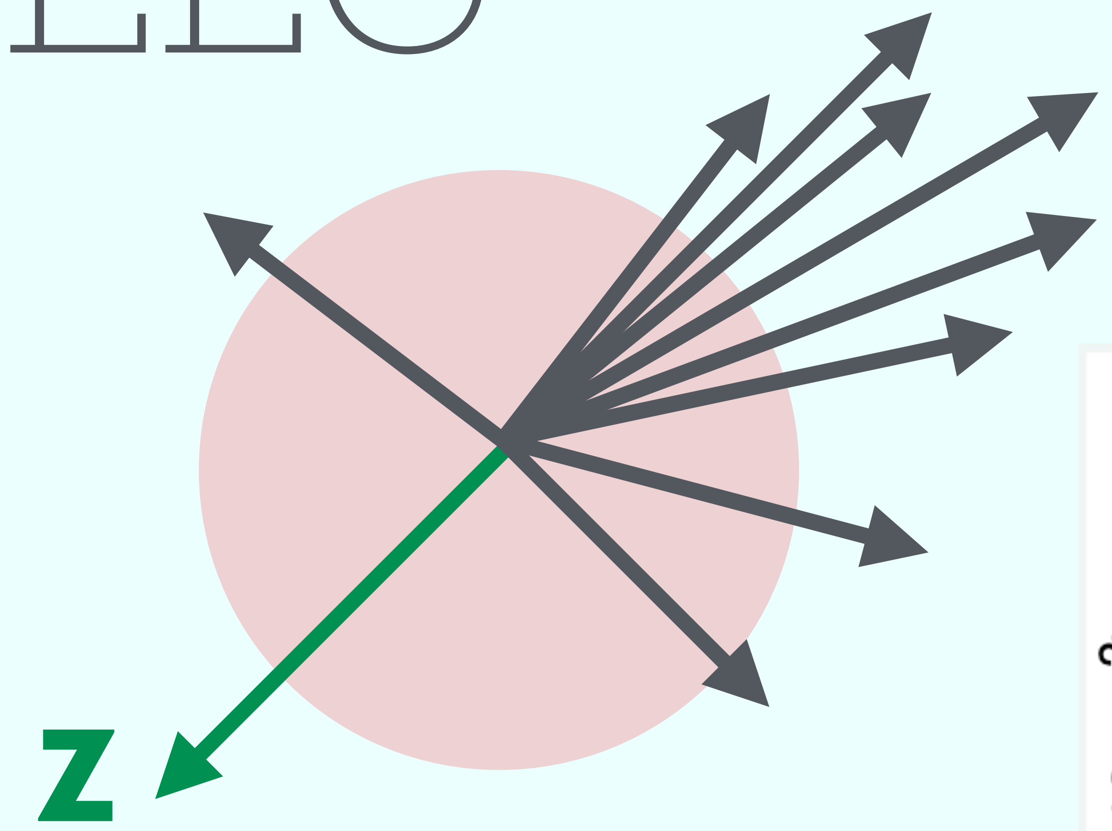
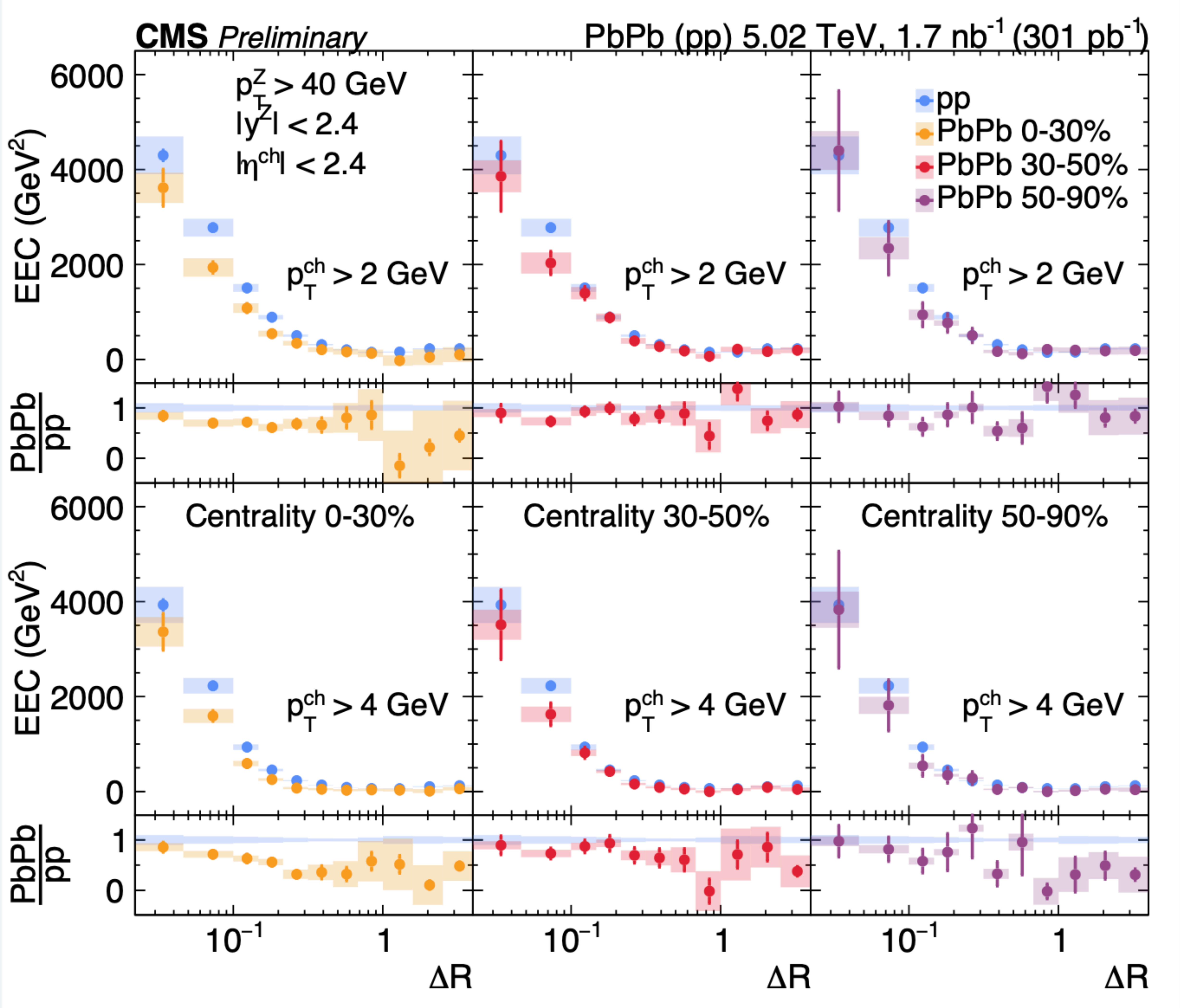


- Use $Z \rightarrow \mu^+\mu^-$
- Event mixing removes contributions from UE
- Full event EEC (as opposed to a jet EEC)
    - Looking beyond jet angles



Z-tagged EEC

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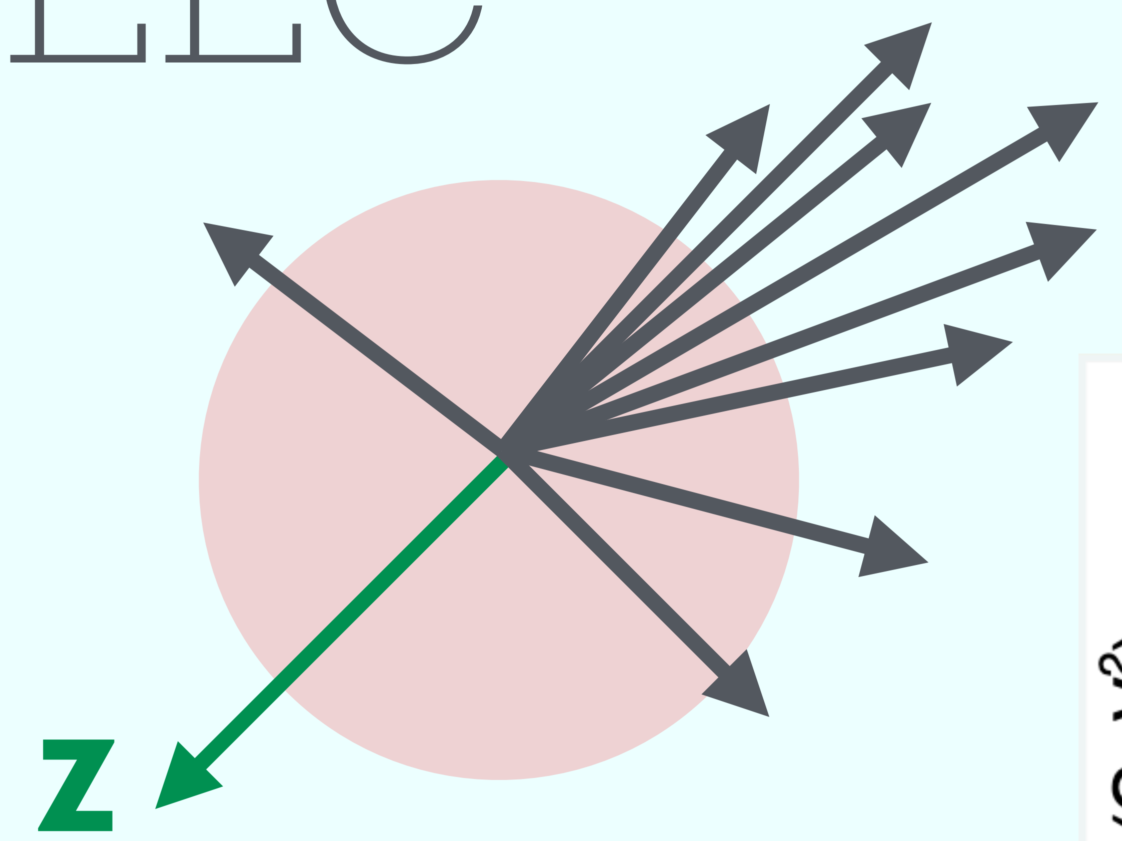

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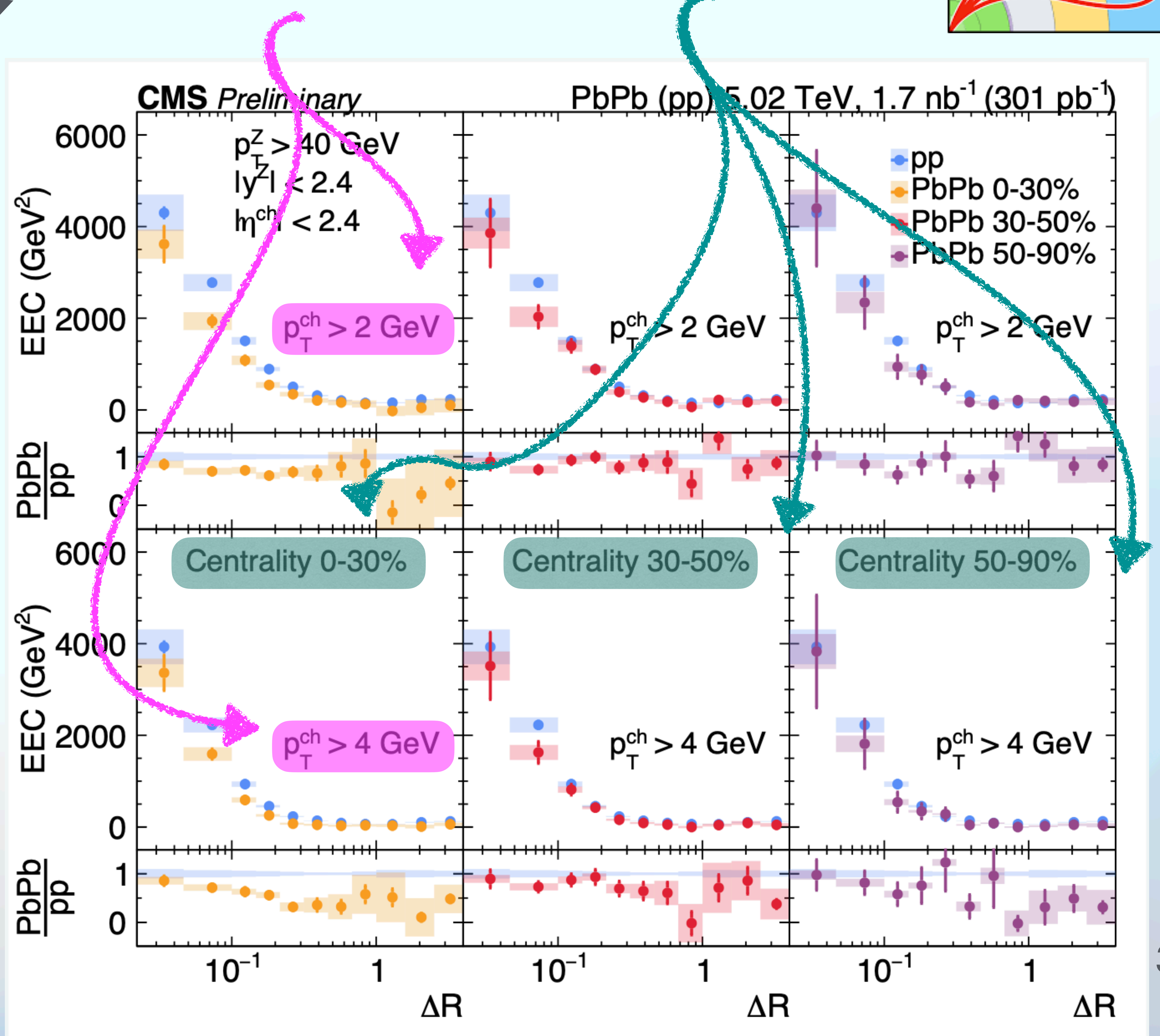
p_T threshold **centrality**

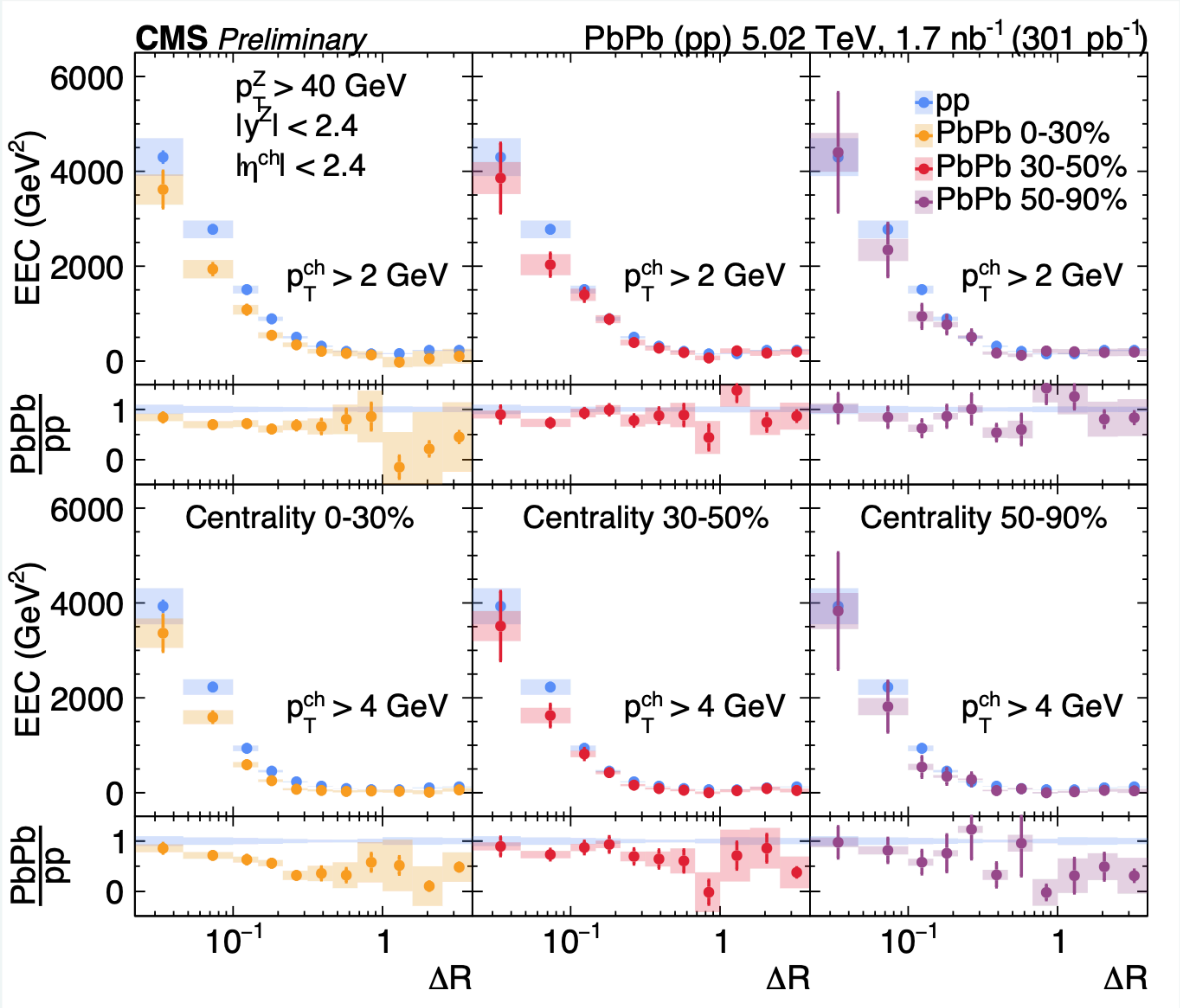


Z-tagged EEC

CMS

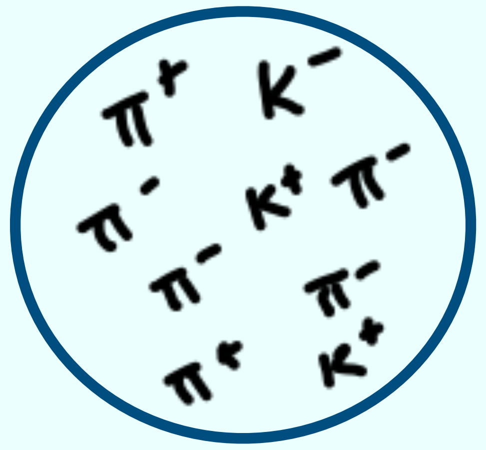
Yi Chen QM2025 slides

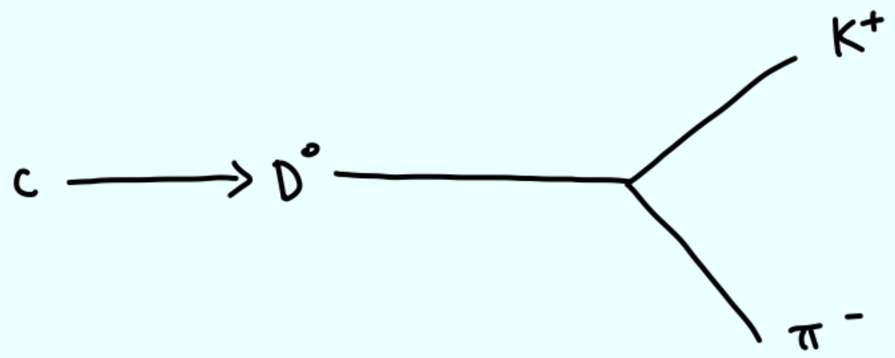
- For higher p_T, more central collisions show stronger suppression → jet quenching
- For central collisions, higher p_T shows stronger suppression → medium effect stronger at low pT
- Downward trend at small angles is dominated by “in-jet” pairs
- Selecting high p_T isolates hard core of the showers



How to find the D⁰ EEC

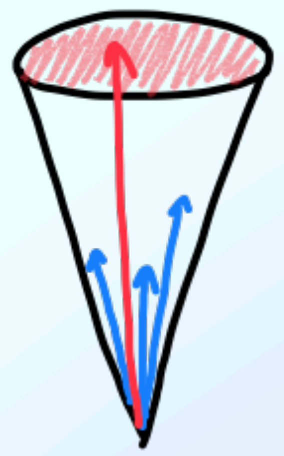
Start with the charged final-state particles from each event.

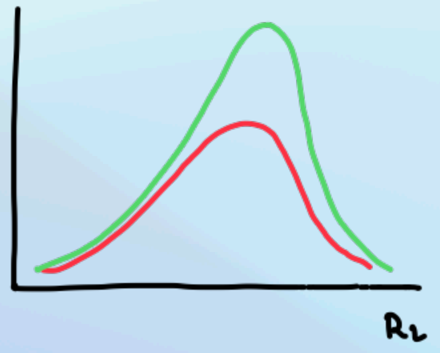




Replace $K^{\pm}\pi^{\mp}$ pairs with D^0 track to reconstruct the D^0.

Use Fastjet anti-k_{T} algorithm to make an $R = 0.4$ jet.





Find every combination of pairs within the jet, calculate EEC, and assign weights based on p_{T}.

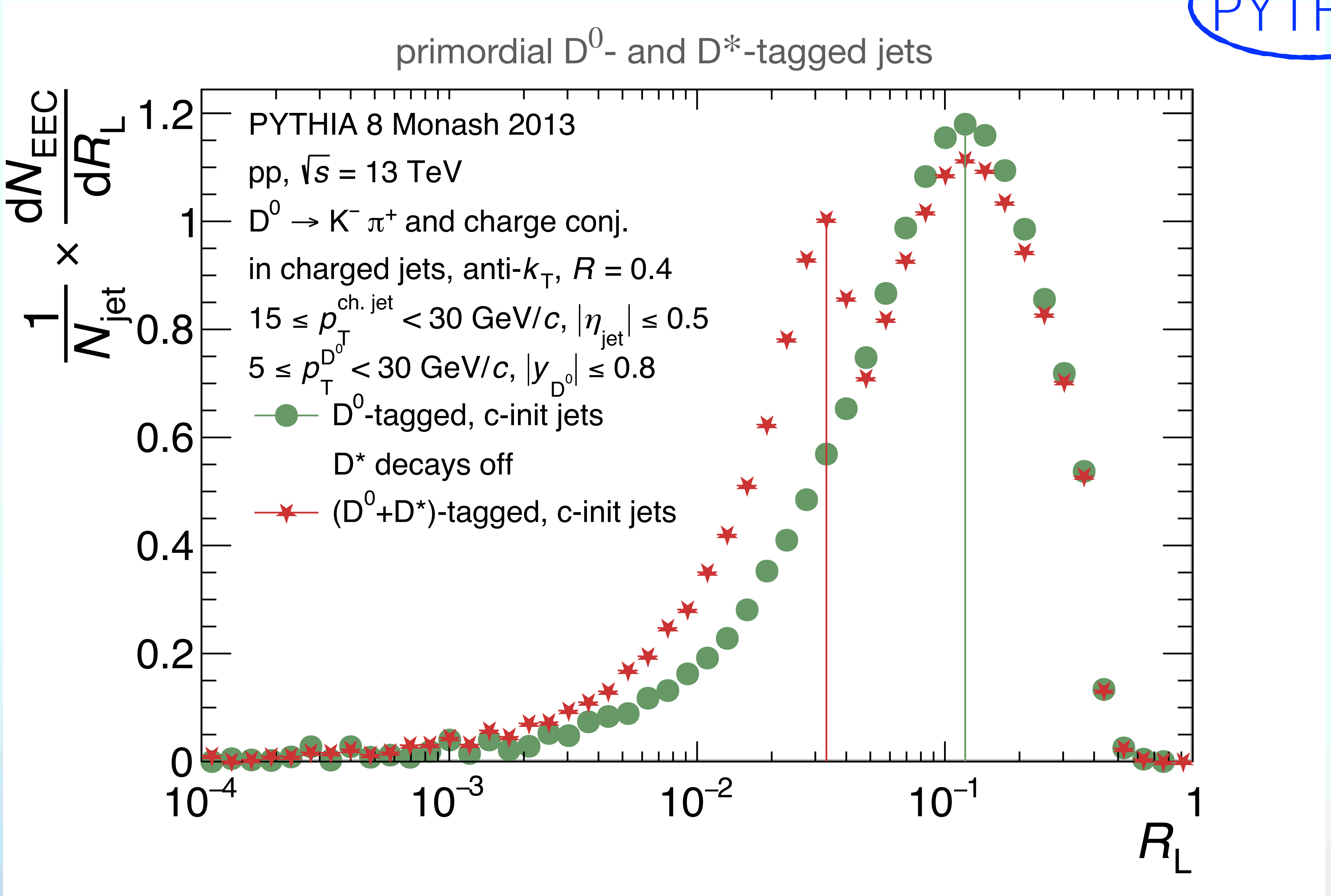
Correct for detector effects, feeddown, and D*.

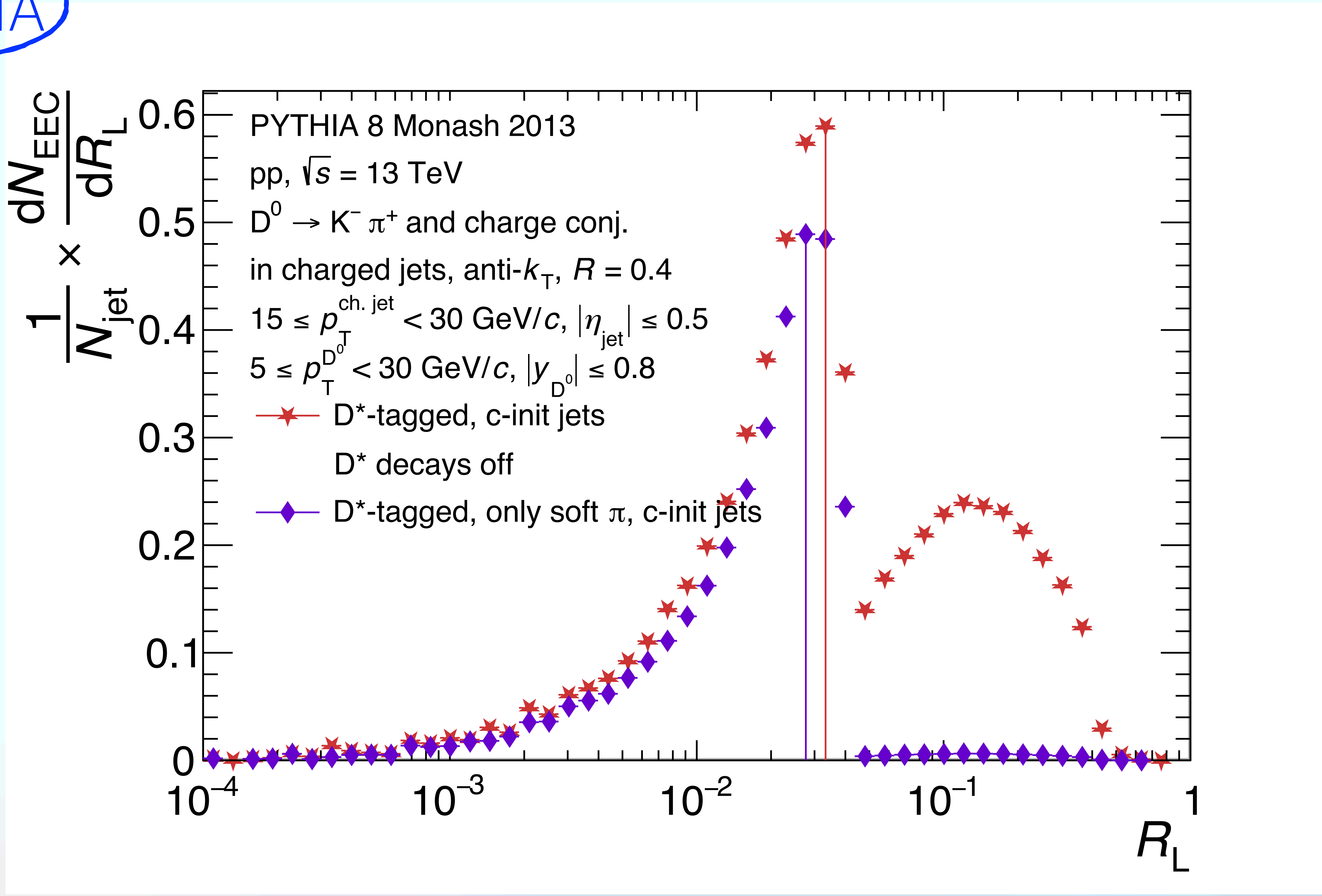
How do resonance decays contribute?

$$c \to D^0 \to K^\mp \pi^\pm$$

$$c \to D^{*\pm} \to D^0 \pi^\pm \to K^\mp \pi^\pm \pi^\pm$$

PYTHIA

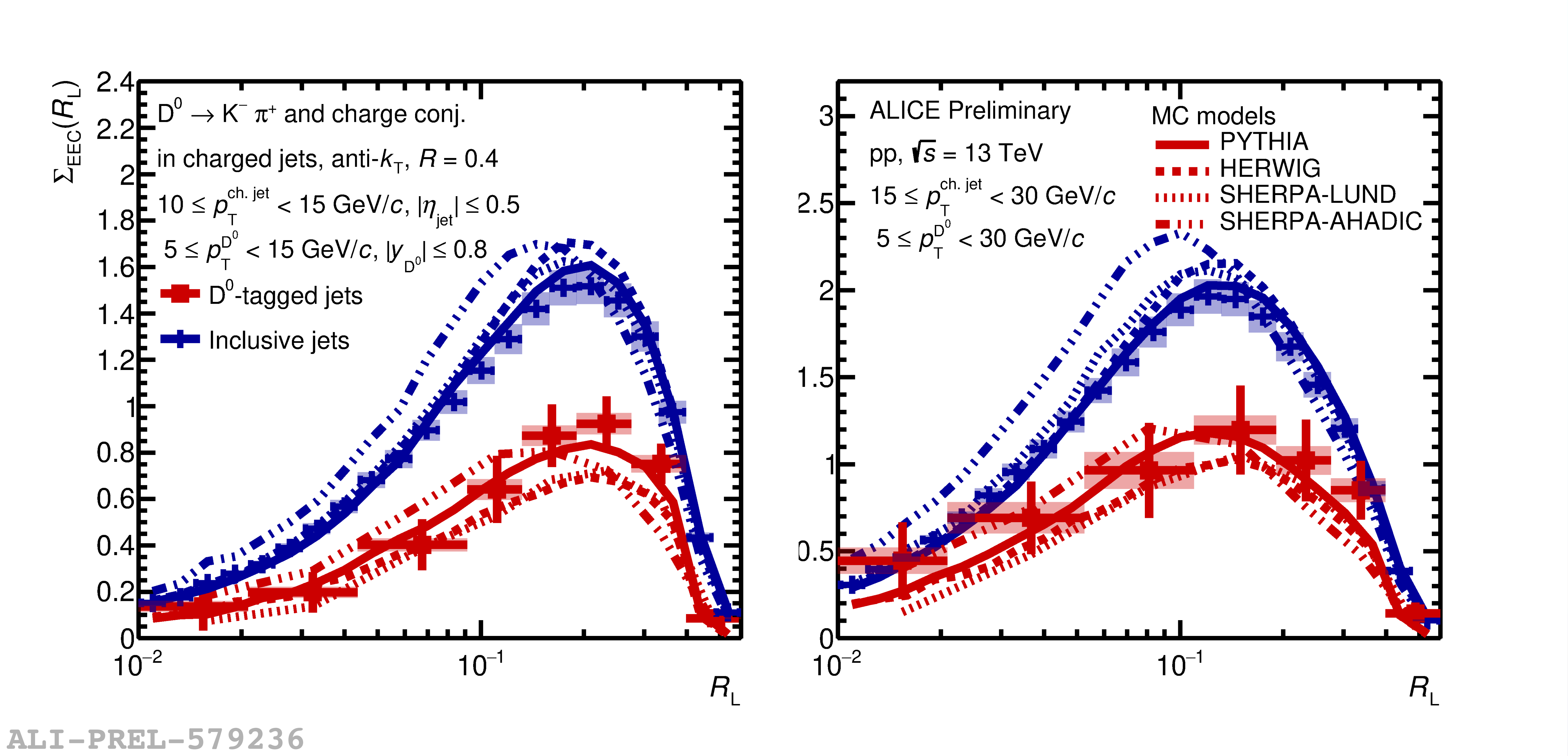




The D0 EEC shows the resonance of the D* to the left of the normal peak — MC correction employed!

D⁰-jet EEC comparison to MC

Reminder!
Lund string models: PYTHIA, Sherpa Lund
Cluster hadronization models: Herwig, Sherpa Ahadic



- In general, Lund string models do better than the cluster hadronization models?
- Herwig over-predicts peak of inclusive jets, under-predicts peak of D⁰ jets
  - Sensitivity to hadronization vs parton shower implementation
- Models appear to show that clustering hadronization model causes a later hadronization compared to Lund string breaking.

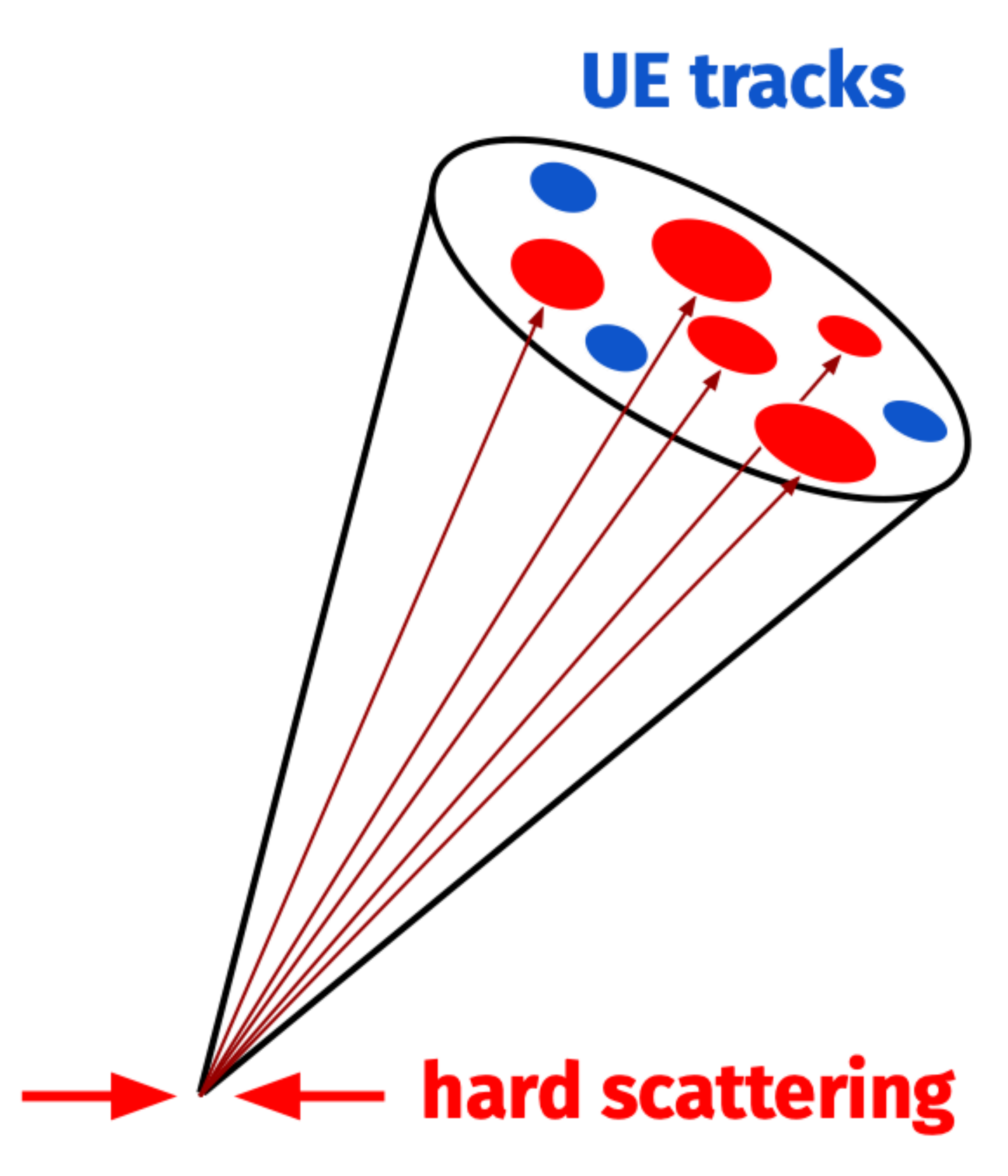
Background subtraction in p-Pb

1. Subtract UE energy density from the jet p_T:

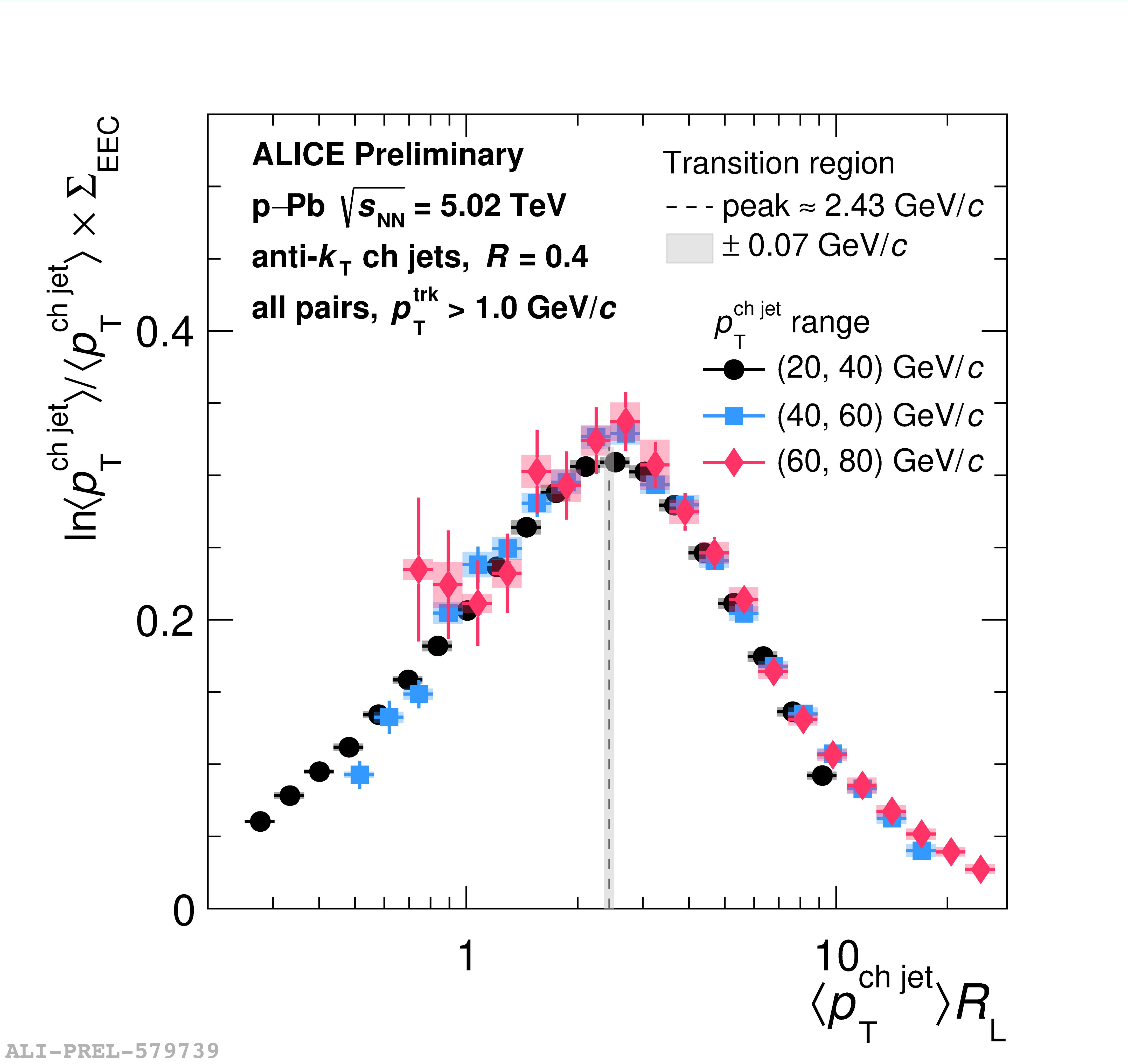
$$\rho = \text{median}\left\{\frac{p_{\mathrm{T,jet}}^{k_T}}{A_{\mathrm{jet}}^{k_T}}\right\}\cdot C \qquad\qquad C = \frac{\sum_j A_j}{A_{\mathrm{acc}}}$$

2. Correct the EEC distribution for combinatorial background:
   1. signal-signal
   2. signal-background
   3. background-background

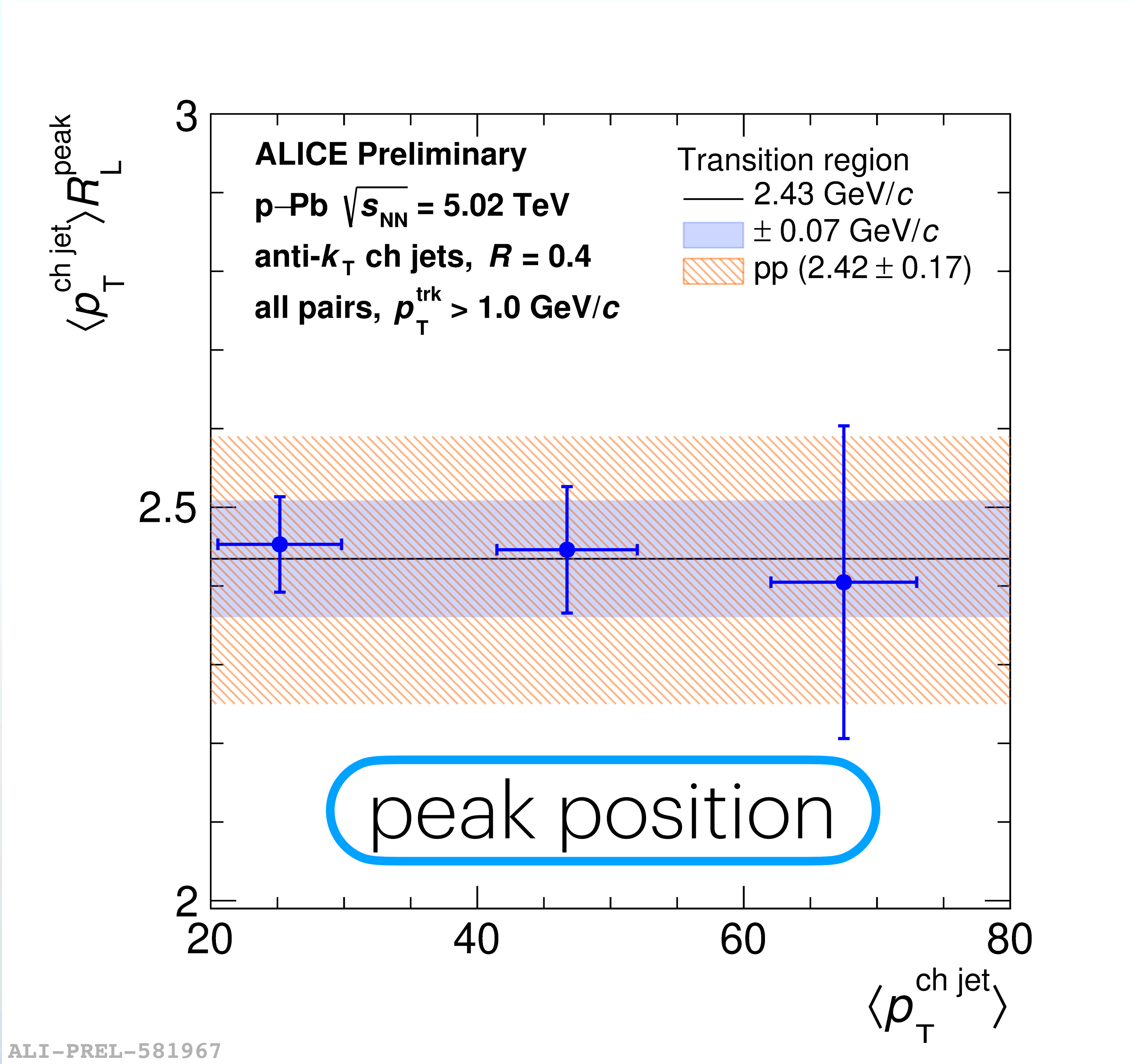
We use the perpendicular cone to estimate the latter two contributions.

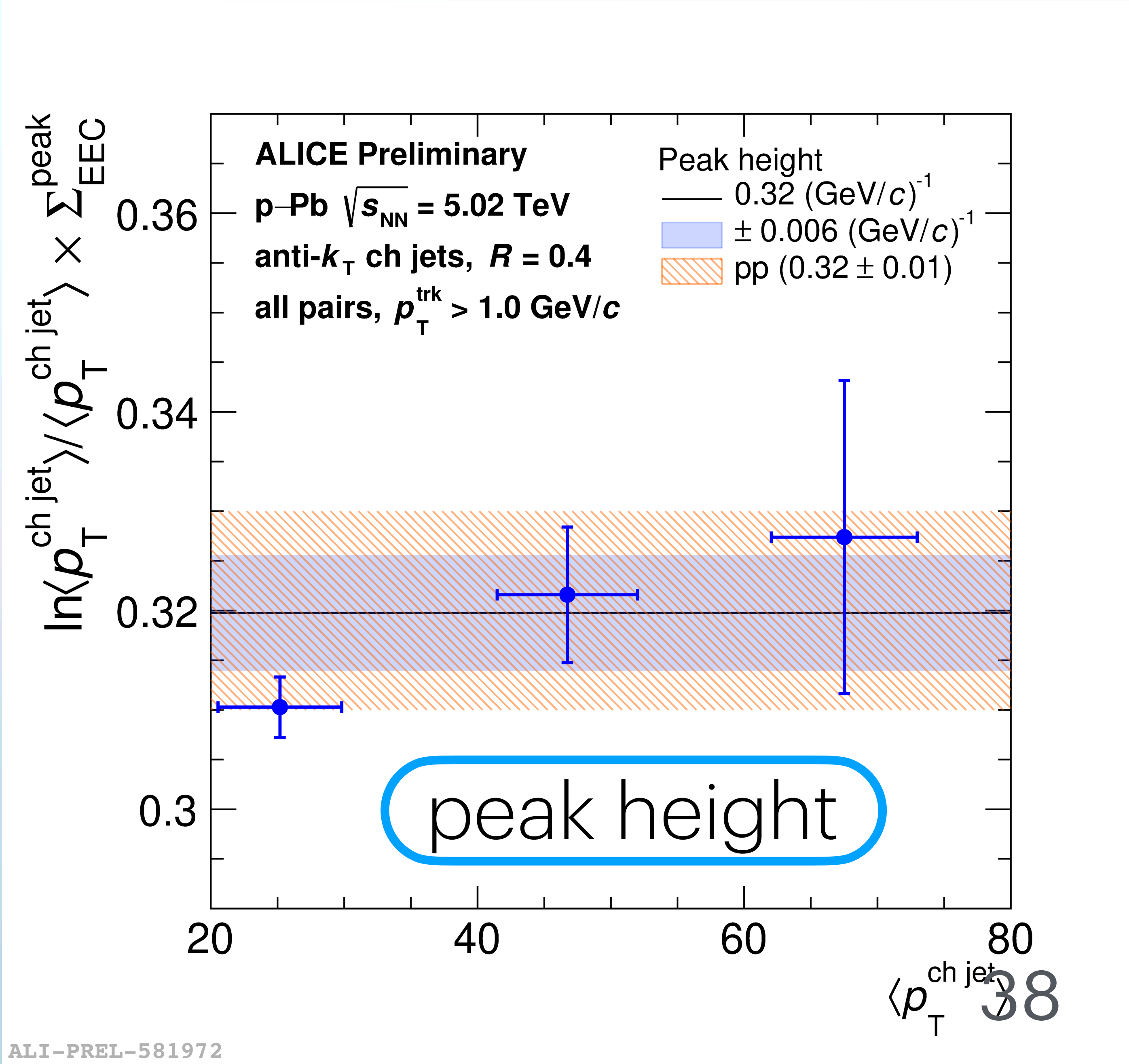


EEC transition region



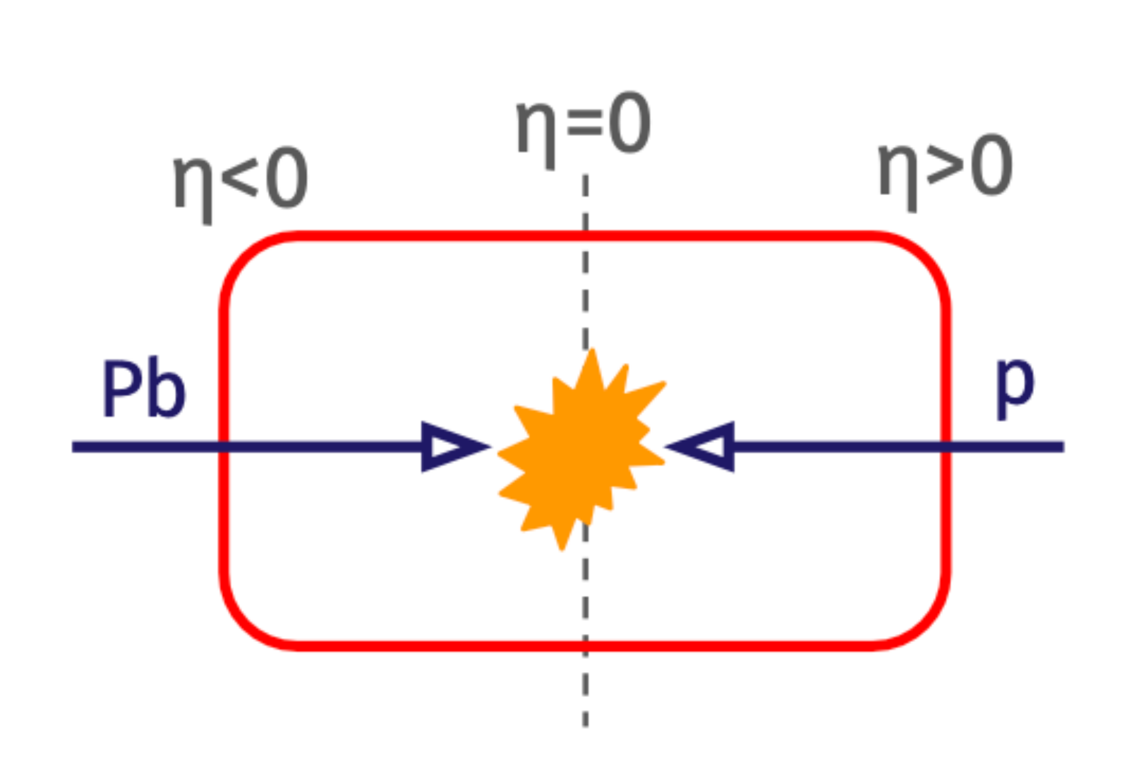
- Universality of the peak position is retained across collision systems
- Peak determined by log-normal fit
- Peak for 20 < $p_{T,\,jet}$ < 40 jets lower than higher p_T regions

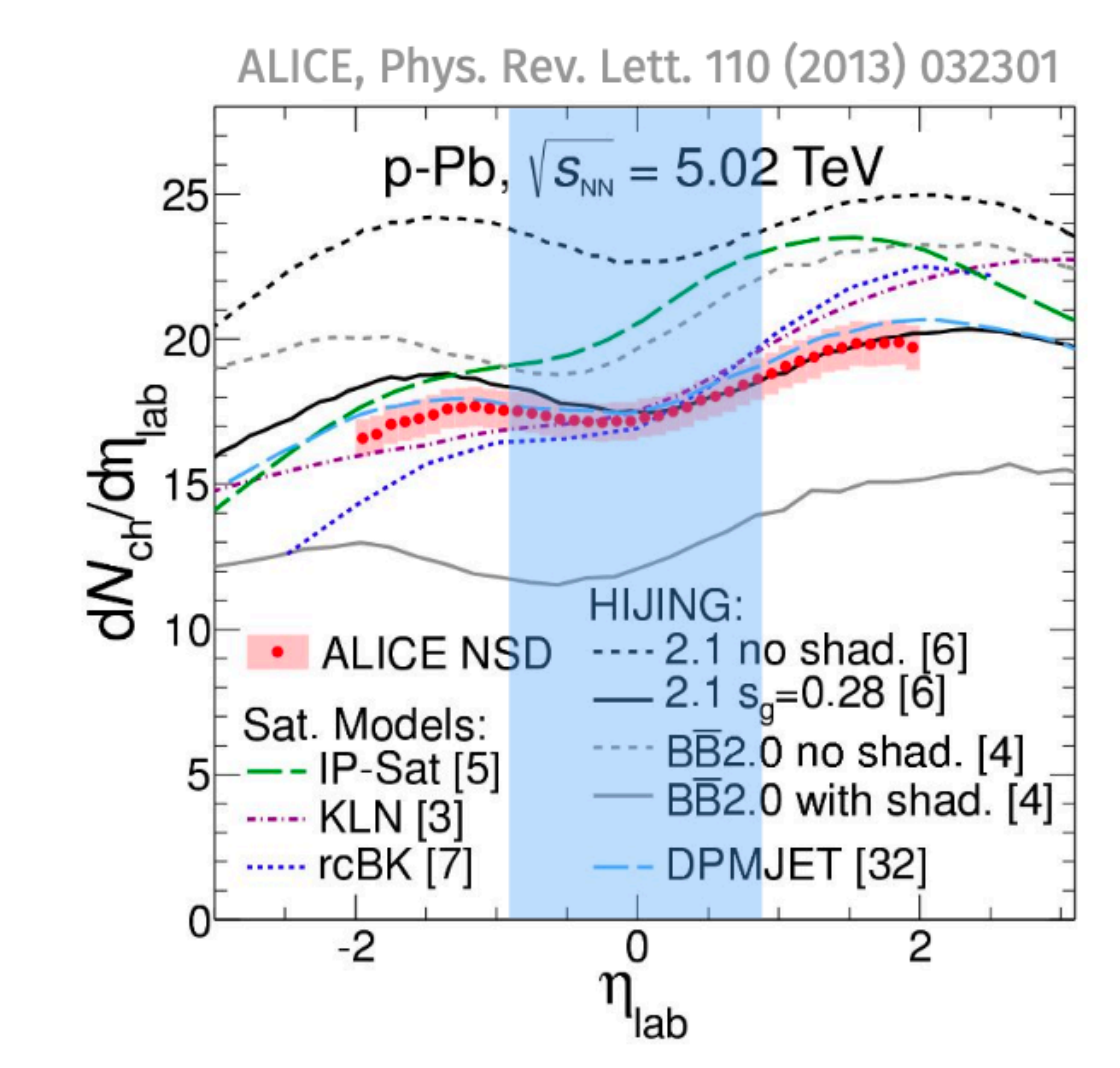




Rapidity dependence for p-Pb

- EECs for jets with η>0 (forward) and η<0 (backward)
- Backward (p-going) and forward (Pb-going) EECs agree within 5%

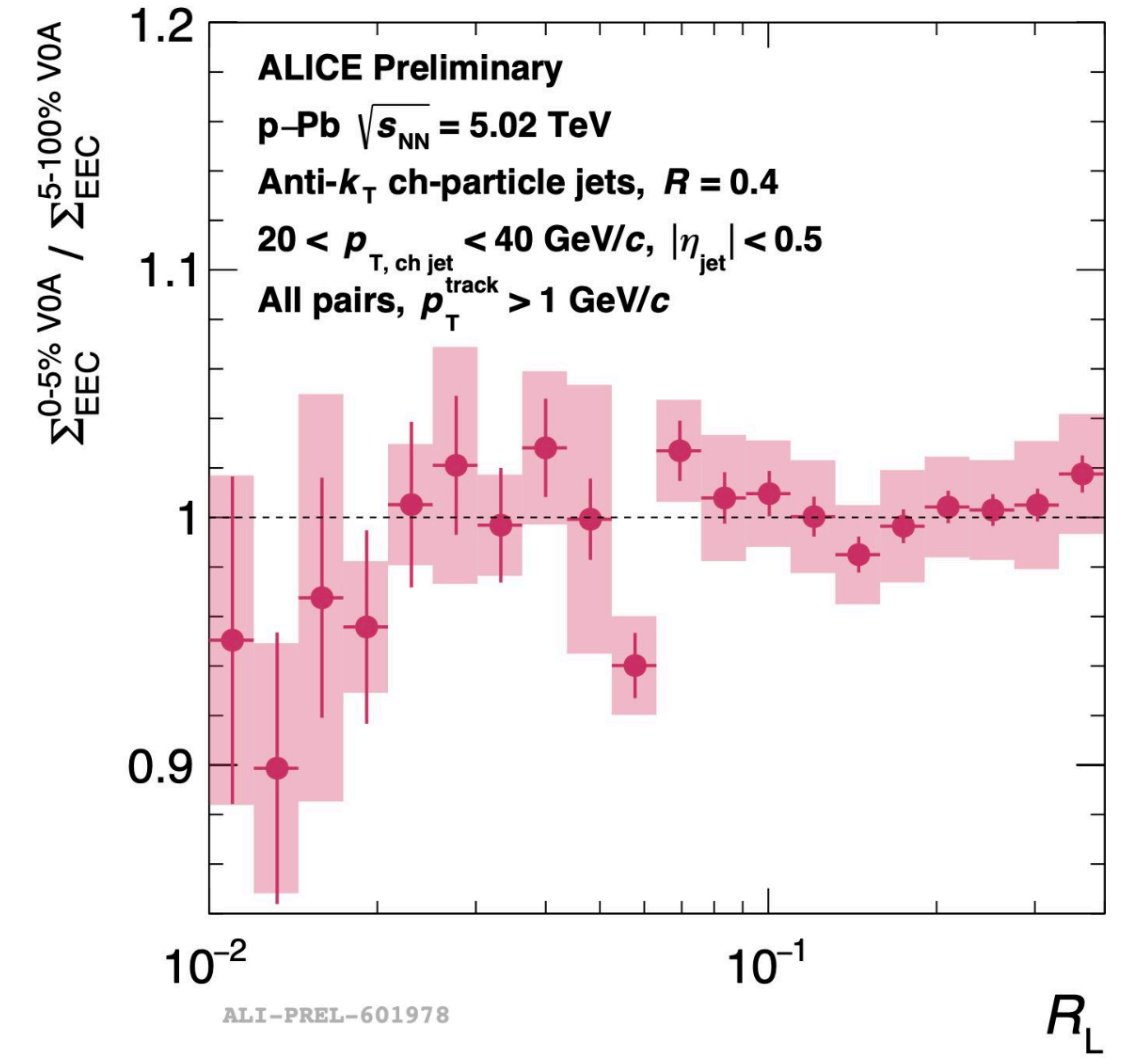




Asymmetry in dN/dη doesn't affect EEC!

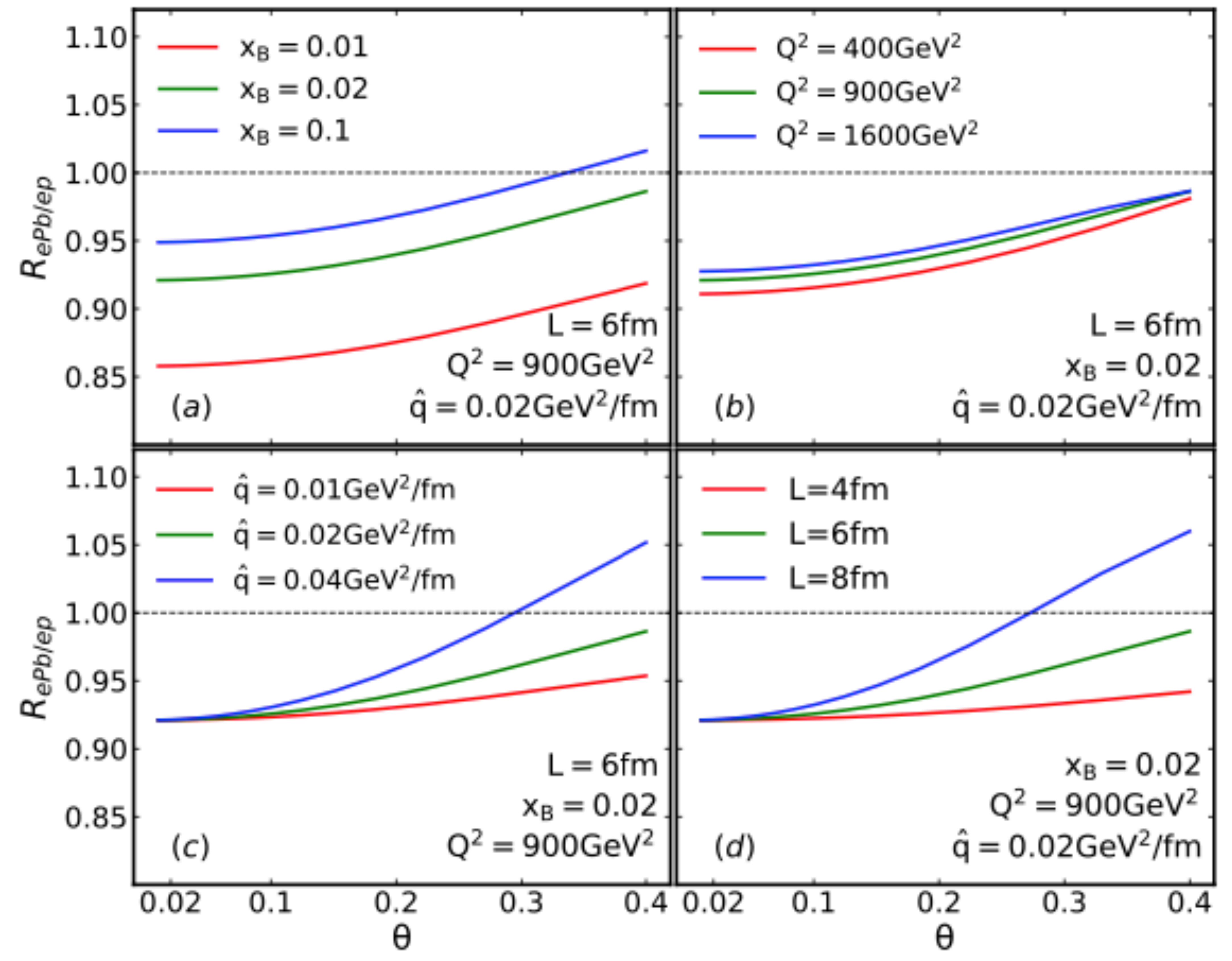
Forward multiplicity dependence for p-Pb

- Categorize jets based on V0A multiplicity in corresponding event
  - V0A detector sits in Pb-going direction, covering 2.8<η< 5.1
- Label events by V0A percentile
  - High-multiplicity: top 5%
  - Low-multiplicity: bottom 95%
- HM/LM EEC ratio is consistent with 1

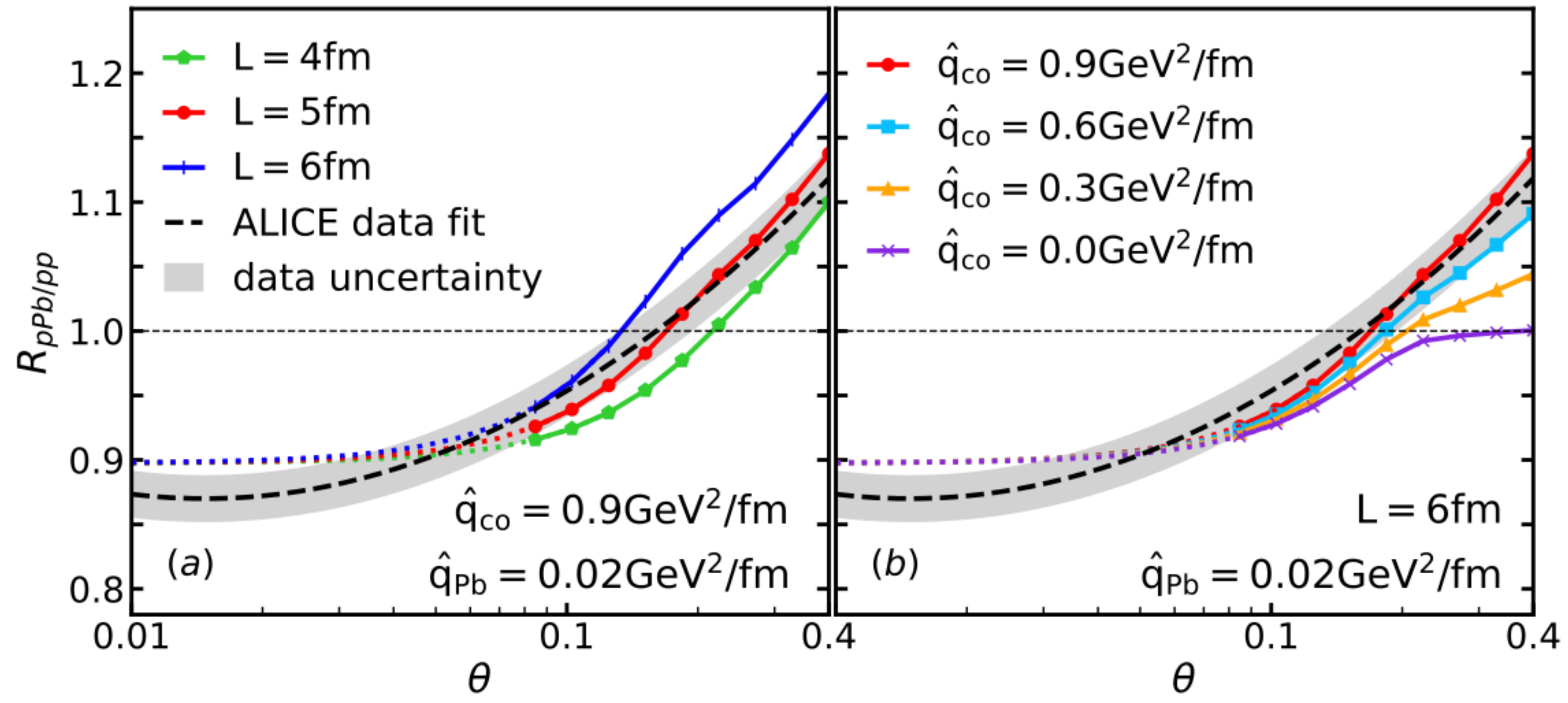


What does the theory tell us?

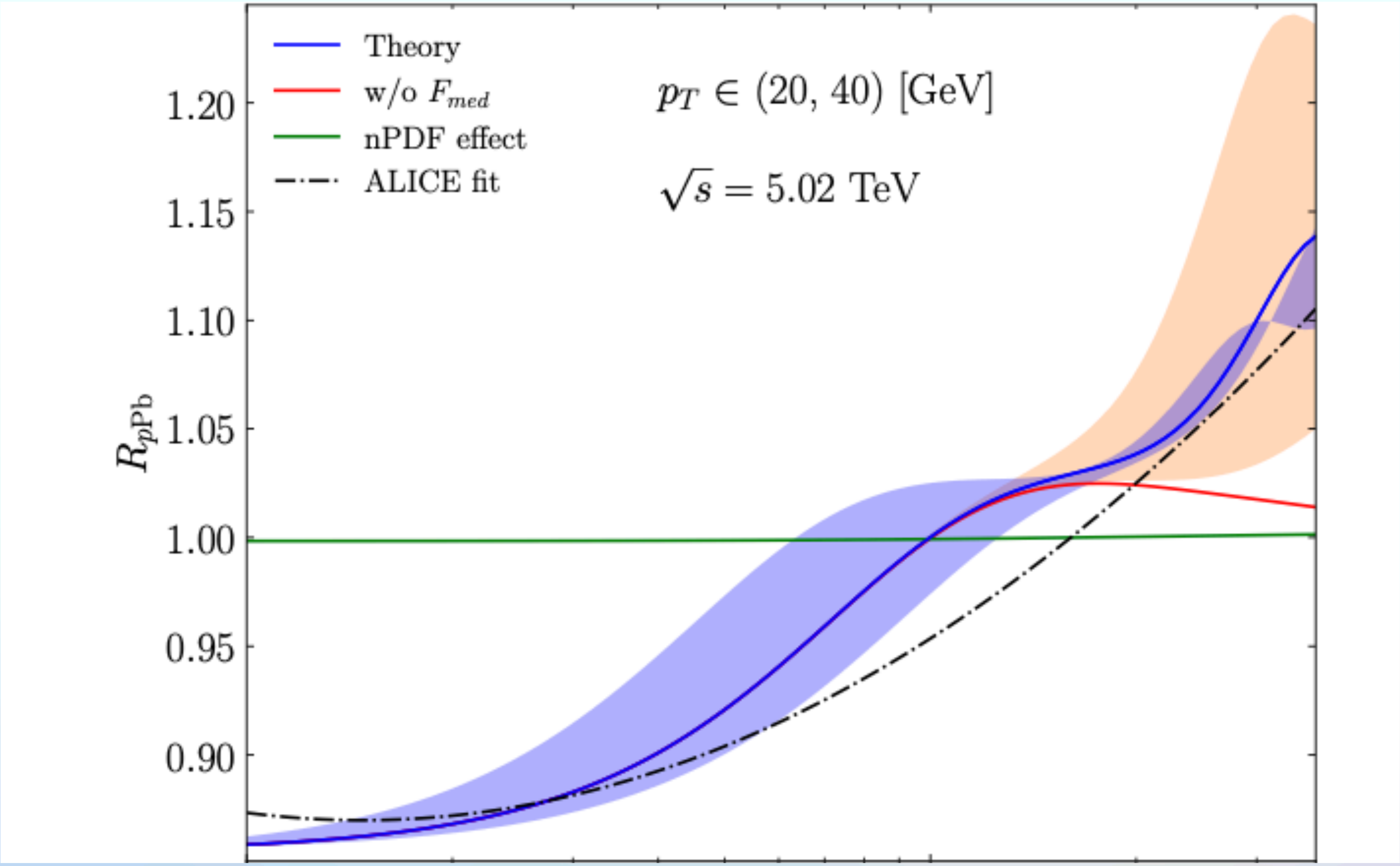
1. Fu et al.
    - Higher twist formalism
        - Describes hard processes in strong interactions that are suppressed by a power of the hard scale
    - Initial state effects cause global modification
    - Final state effects create angle-dependent modification → comovers capture enhancement



arXiv:2411.04866



What does the theory tell us? cont.



arXiv:2411.11782

2. Barata et al.

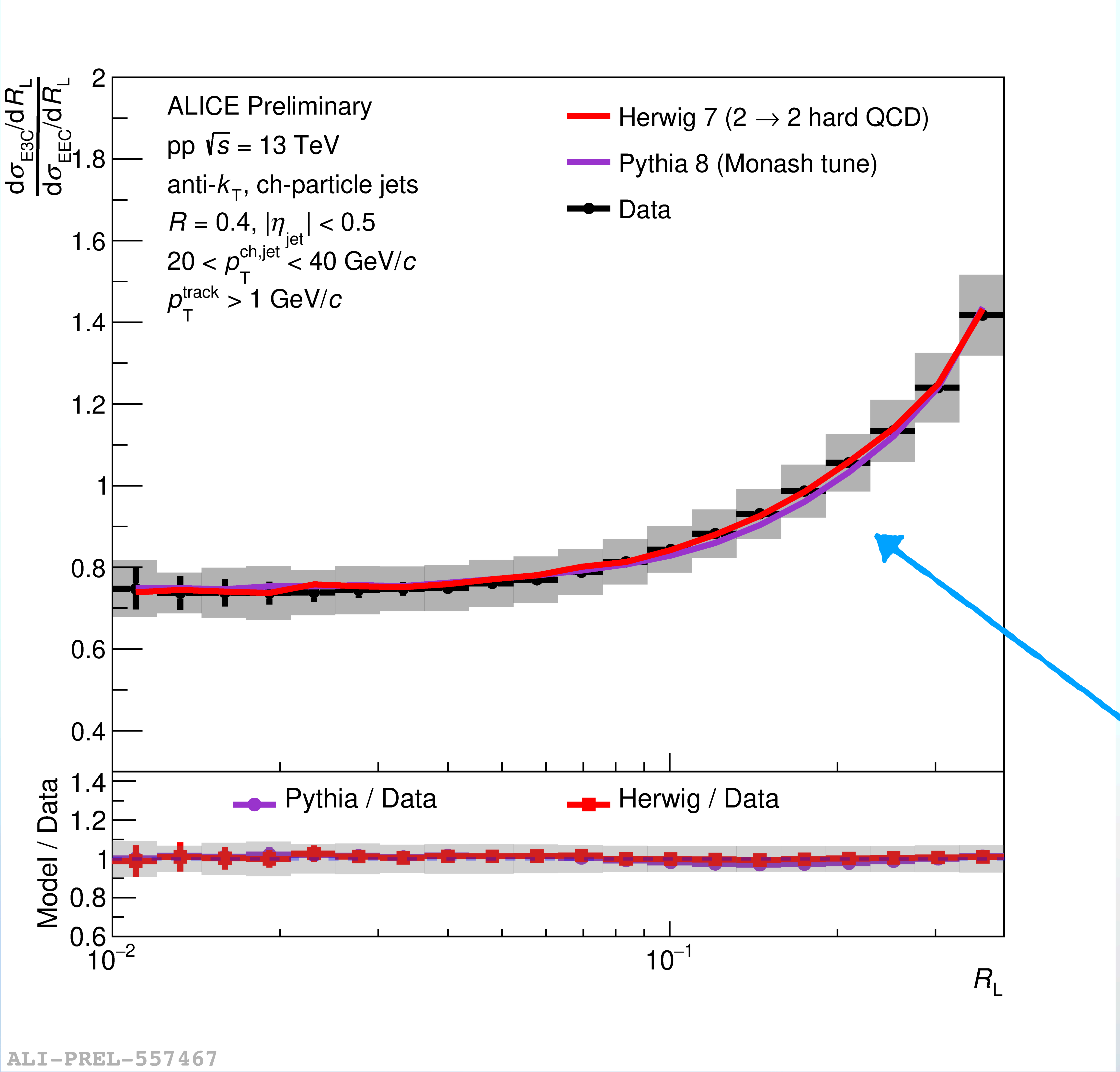
- NP TMD with transverse momentum broadening
- Multiple scatterings with CNM
- Small angle: medium induced broadenings
- Large angle: medium induced power corrections

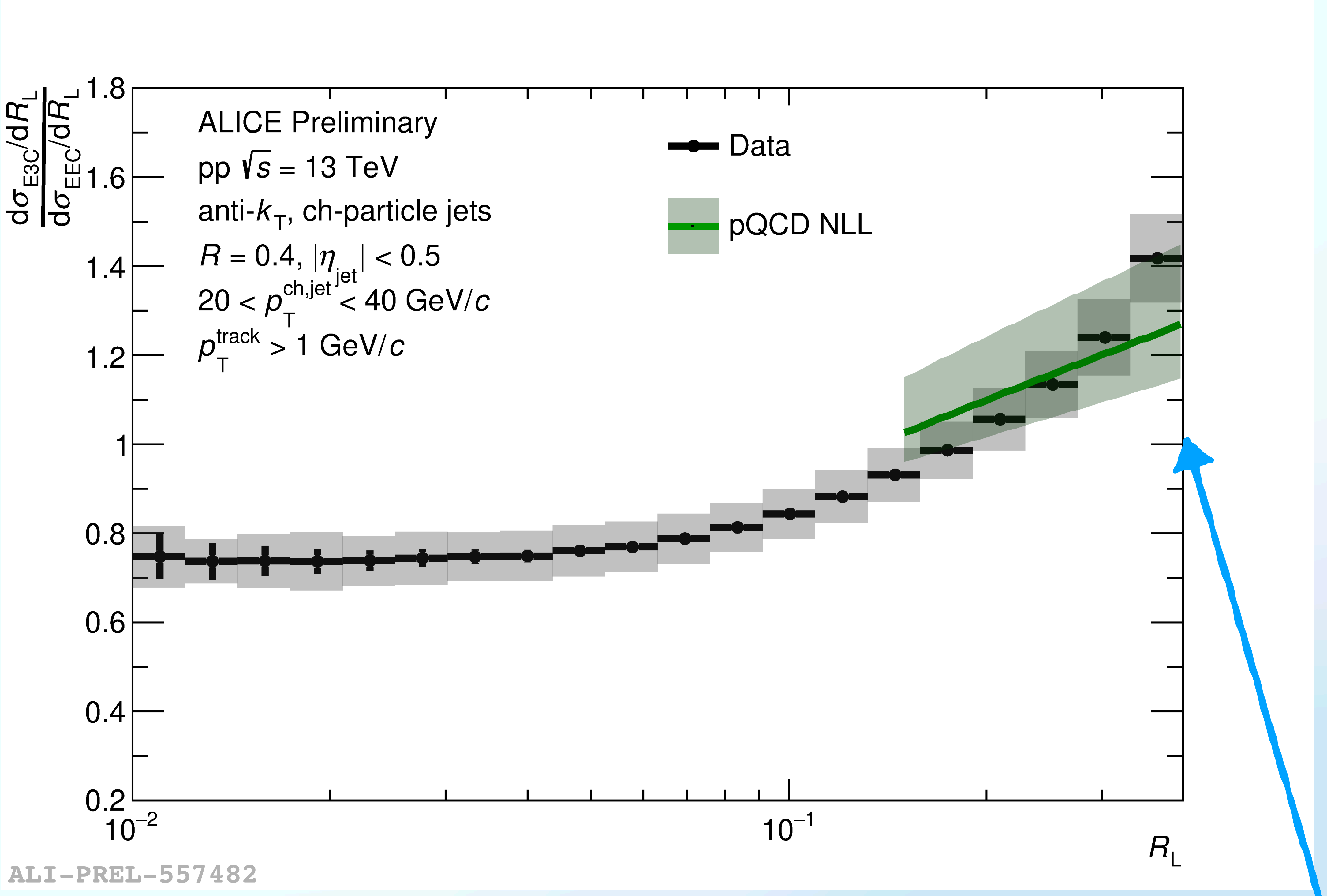
What are the anomalous dimensions?

- Probes quantum mechanical corrections of physical quantities
  - Great way to probe QCD dynamics
- If Δ is the full scaling dimension, $\Delta = \Delta_{classical} + \gamma$

For energy correlators, extracting anomalous dimensions probes strong coupling constant, α_s

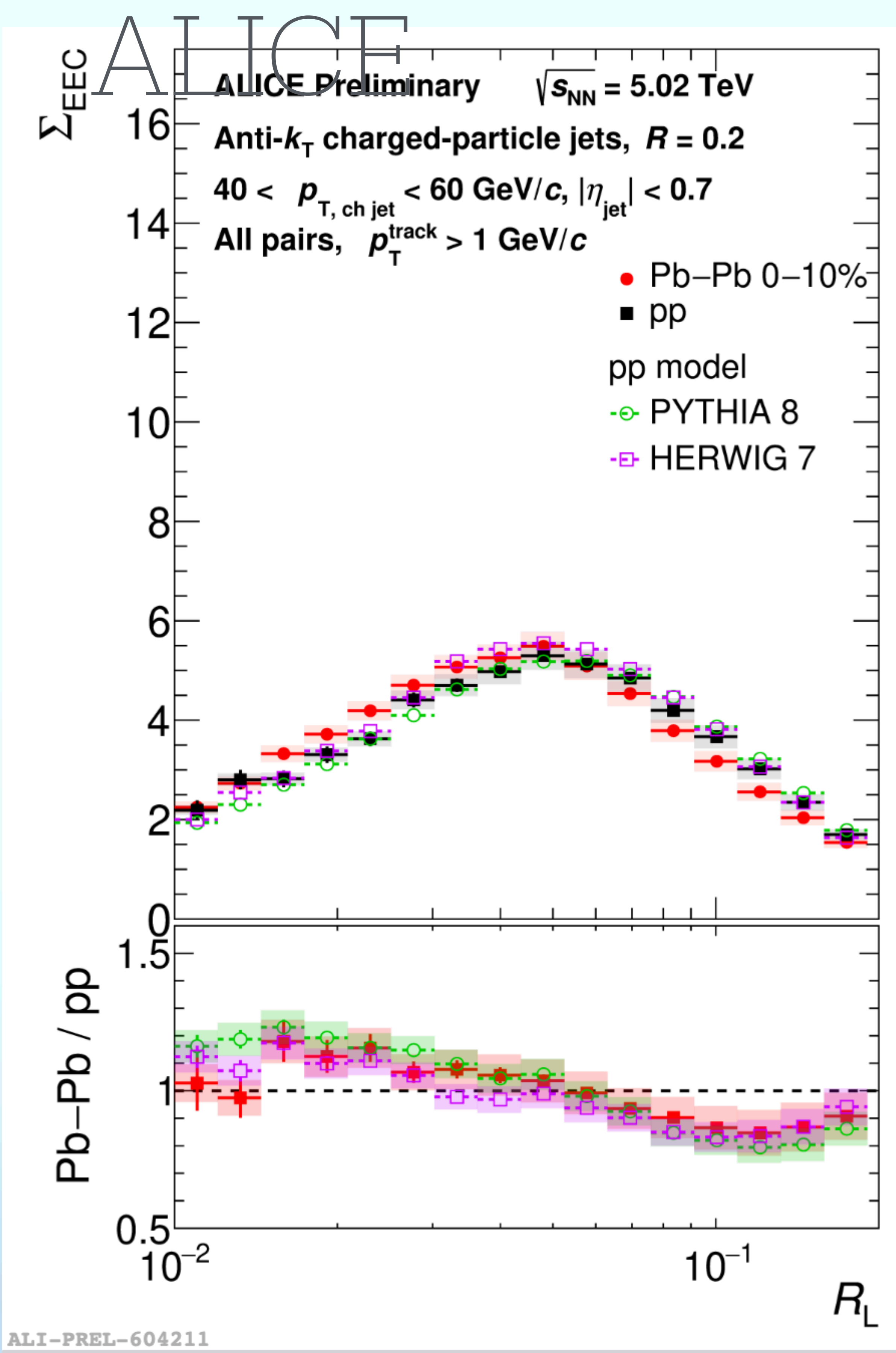
E3C / EEC comparison with models

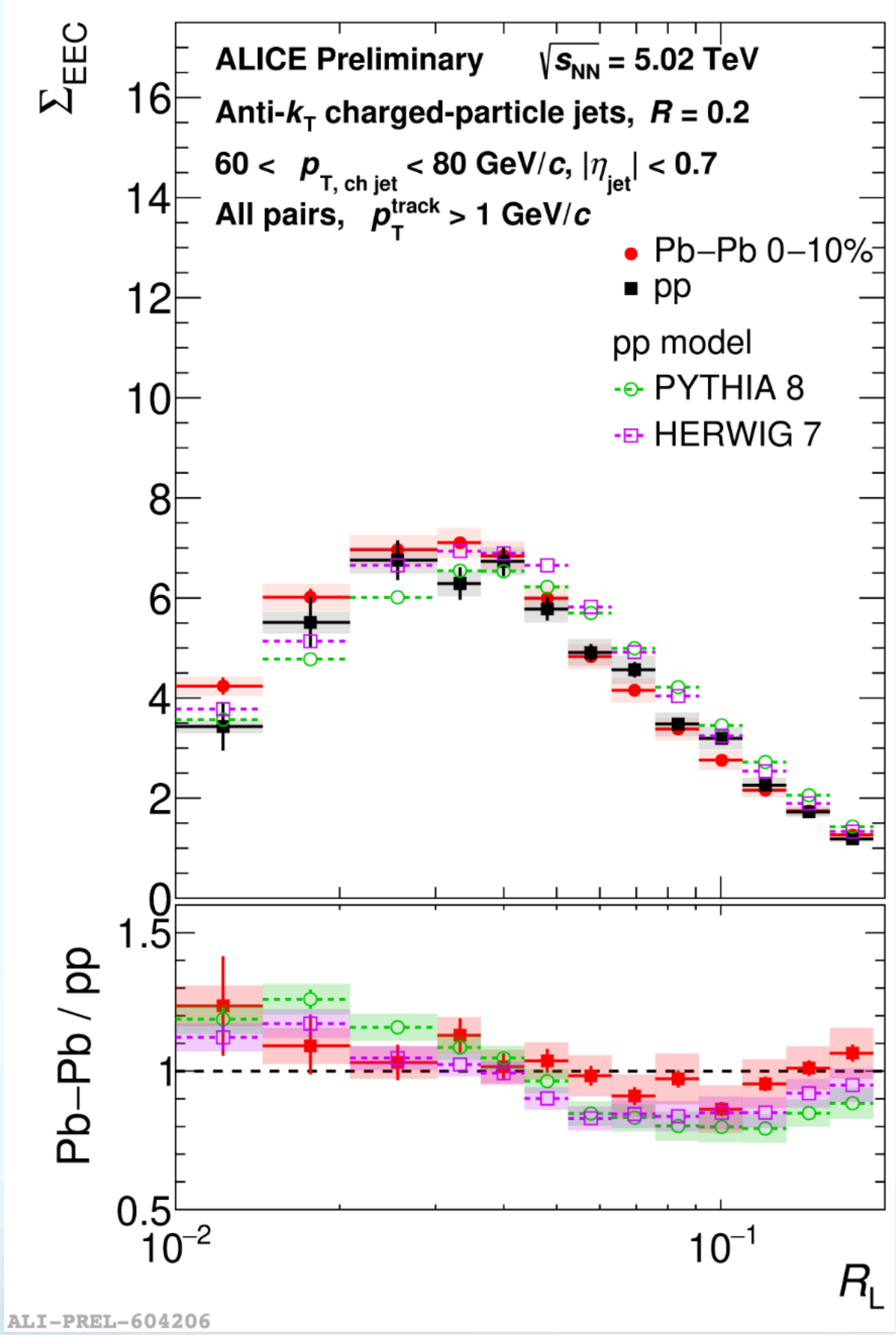


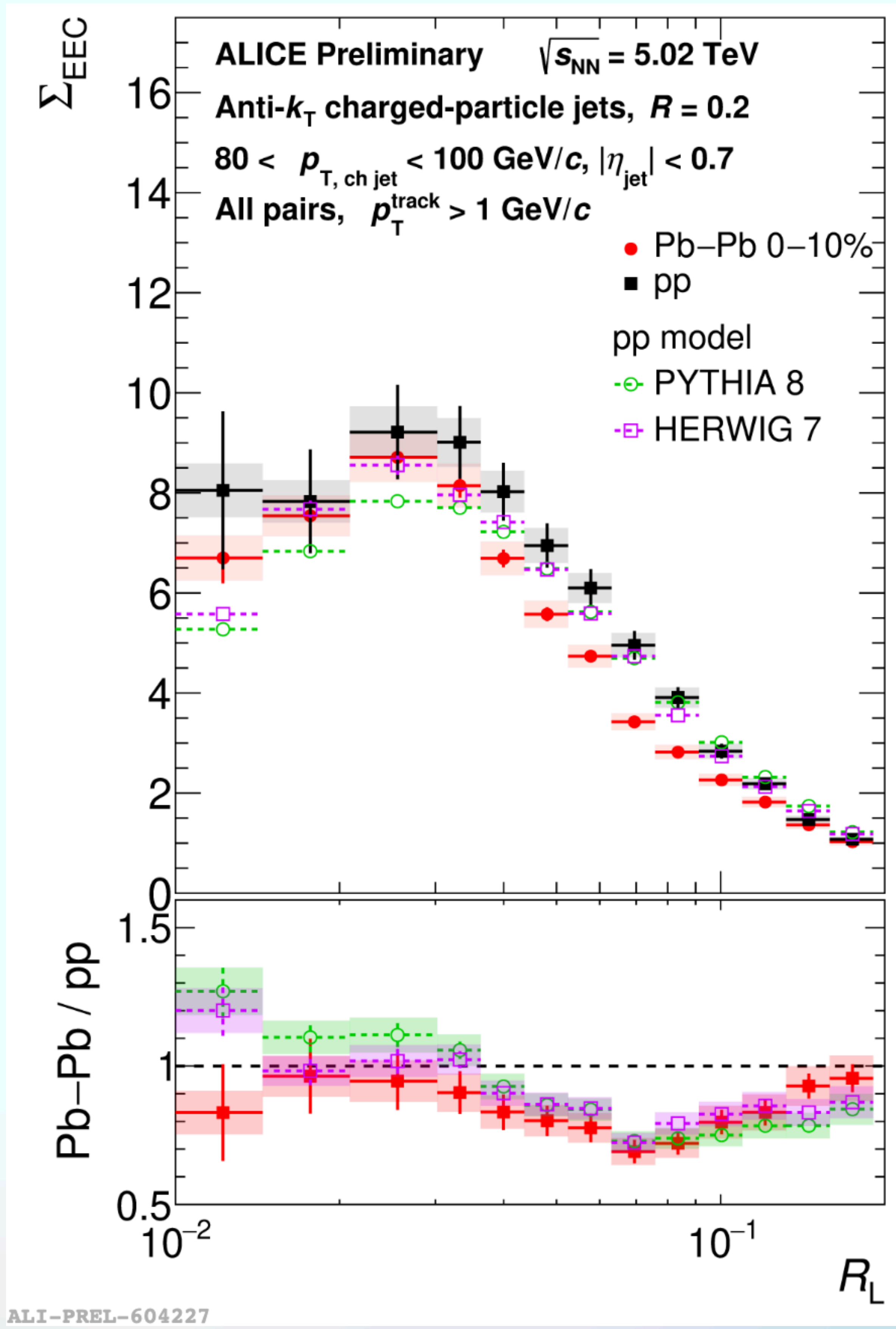


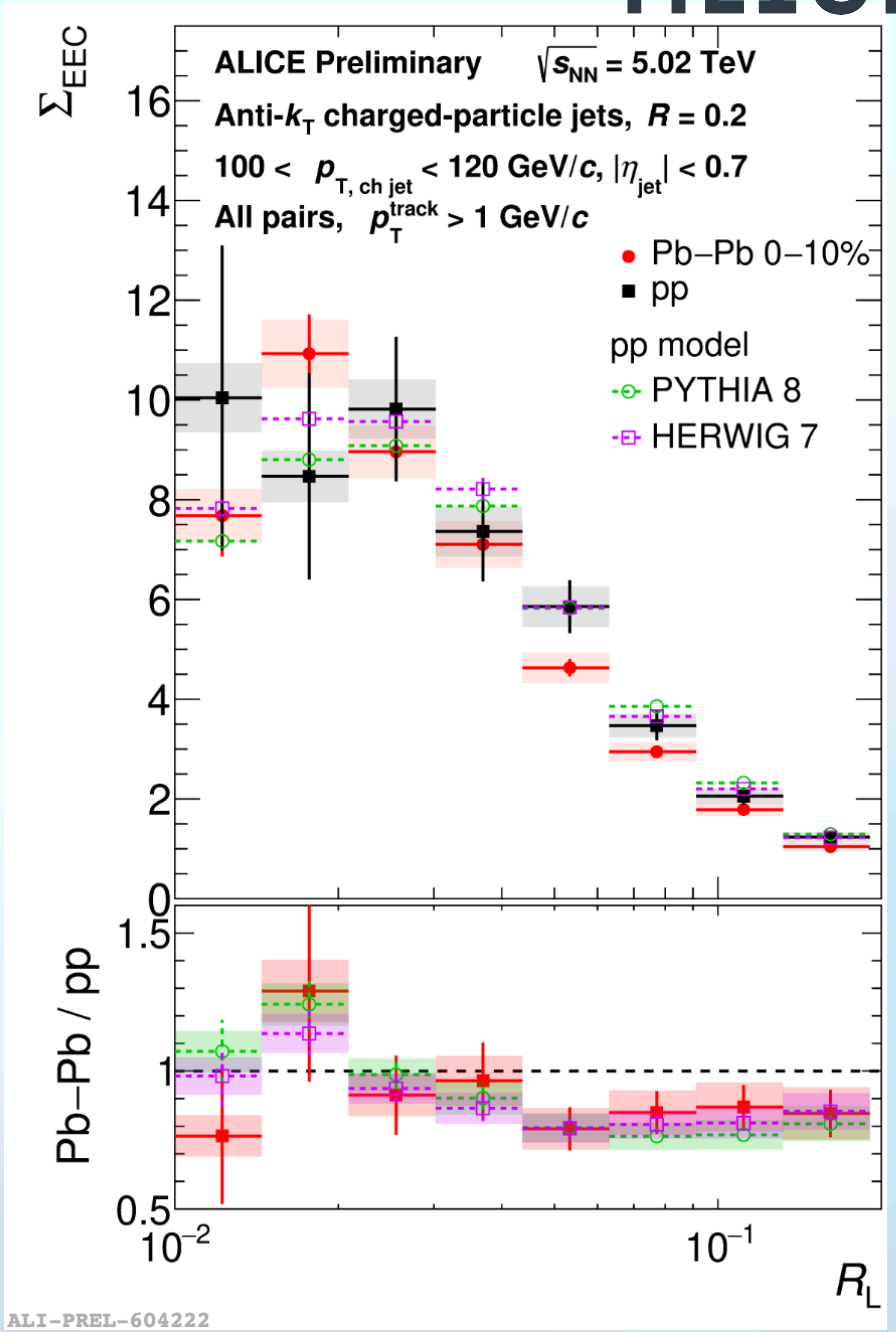
- Models replicate ratio very well — perturbative dynamics captured
- pQCD calculation shows some tension with the ratio
- α_s calculation in progress

Pb-Pb results - comparing to MC









- ALICE results extends to lower jet p_T ranges
- Onset of suppression shifts to the left
- Agreement seen between ALICE & CMS results

What are the LHC/RHIC EEC measurements that have been/are being done so far?

Type of EEC	Type of jet	Collision system	Collision $\sqrt{s}$	Experiment	Progress	Resources
EEC	inclusive	pp	5.02 TeV	ALICE	published	arxiv
EEC	D^0-tagged	pp	13 TeV	ALICE	published	arxiv
E3C (and E3C/EEC)	inclusive	pp	13 TeV	ALICE	in progress	slides, slides
EEC	inclusive	p-Pb	5.02 TeV	ALICE	in progress	slides
EEC	inclusive	Pb-Pb	5.02 TeV	ALICE	in progress	slides
charged EEC	inclusive	pp	5.02 TeV	ALICE	in progress	w/ ↓
charged EEC	inclusive	p-Pb	5.02 TeV	ALICE	in progress	poster, slides
EEC	ɣ-tagged	pp	13.6 TeV	ALICE	just started	-
EEC	inclusive	pp	5.02 TeV	CMS	published	w/ ↓
EEC	inclusive	Pb-Pb	5.02 TeV	CMS	published	link, arxiv
E3C (and E3C/EEC)	inclusive	pp	13 TeV	CMS	published	inspirehep, arxiv
EEC	Z-tagged	Pb-Pb	5.02 TeV	CMS	in progress	slides
EEC	Z-tagged	pp	5.02 TeV	CMS	in progress	slides
charged EEC	inclusive	pp	200 GeV	STAR	published	arxiv
charged E3C	inclusive	pp	200 GeV	STAR	in progress	slides

Outline

1. (2-point) EEC in pp collisions

2. EEC in different flavors

3. EEC in different collision systems

4. 3-point E3C in pp collisions