Energy-energy correlators in jets across collision systems

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New Opportunities in Particle and Nuclear Physics with EECs
May 6–17, Wuhan

In this talk: differential measurements of EECs

1. EECs in pp
   probing perturbative and non-perturbative phenomena

2. EECs in D^0-tagged jets
   probing flavor effects

3. EECs in p-Pb
   probing jets in higher-multiplicity environments

4. EECs in Pb-Pb
   probing jets in the presence of the QGP

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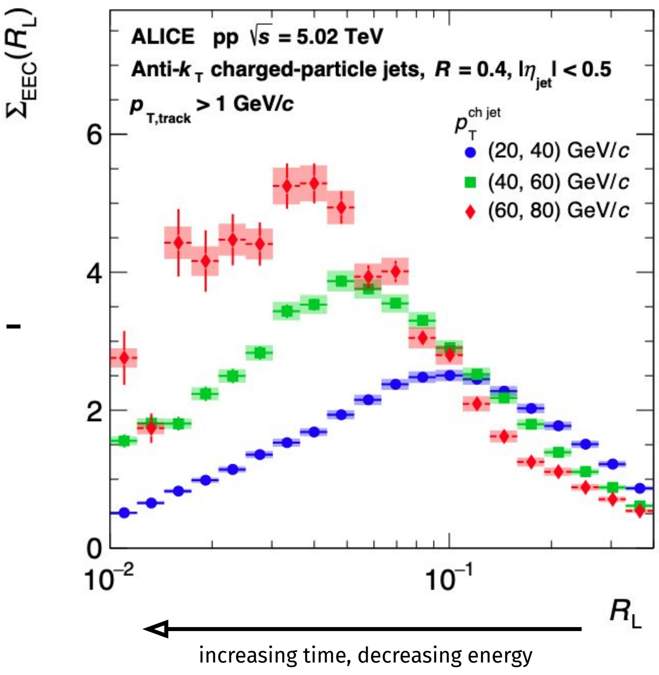
EECs in pp

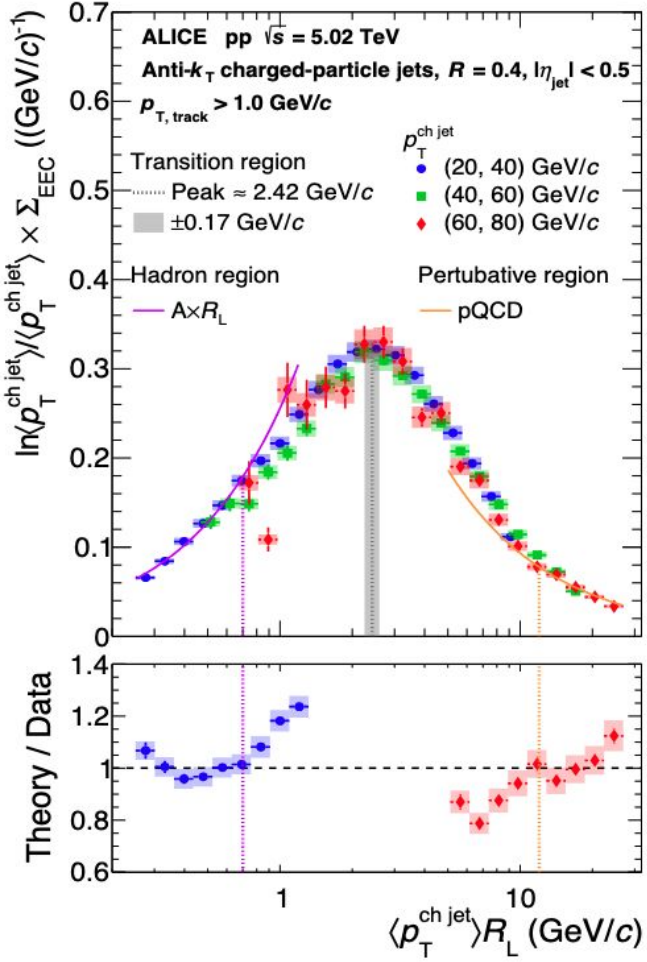
Clear separation of perturbative and non-perturbative regions.

EEC peak is visibly dependent on jet p_T.

Universal transition region
after rescaling the x-axis to $\langle p_T^{\text{ch jet}} \rangle R_L$ (common peak position and height).

arXiv:2409.12687





pQCD calculation from K. Lee: arXiv:2205.03414

We can probe hadronization with pp EECs...

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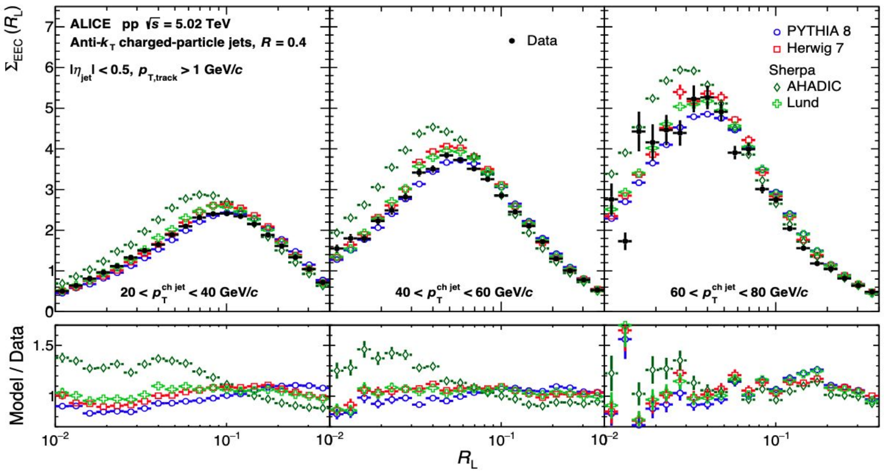
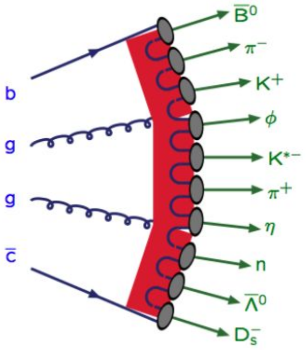
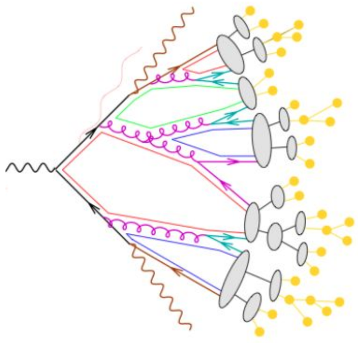


- PYTHIA & Herwig perform well, *Herwig captures peak position*
- Sherpa Lund does well, AHADIC does not
- *both cluster models peak at smaller R_L*

Lund string models: PYTHIA 8, Sherpa Lund
Cluster models: Herwig 7, Sherpa AHADIC



string models



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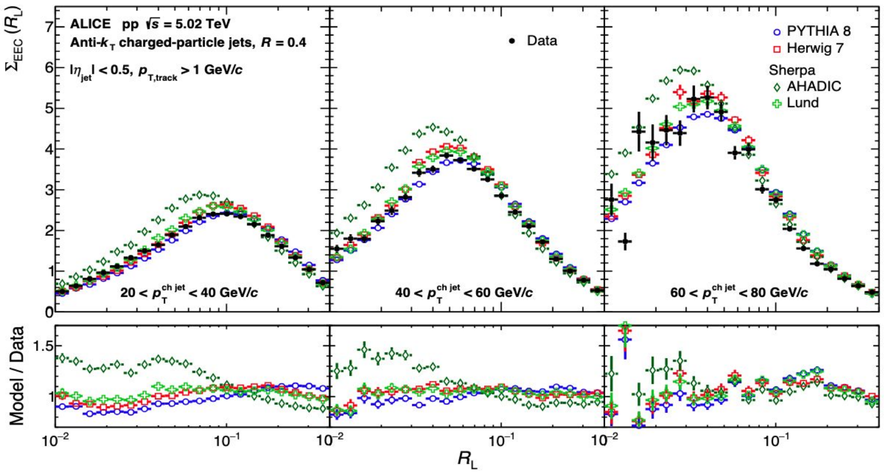

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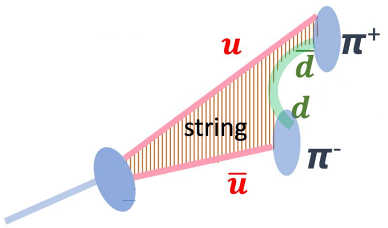
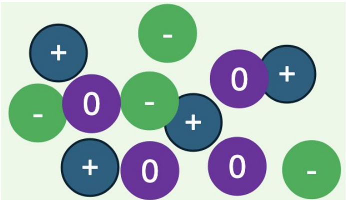
... or with charged energy correlators!

Lund string models: expect correlations between leading di-hadrons in jets



Infinite neutral bath: expect no charge correlations among pairs

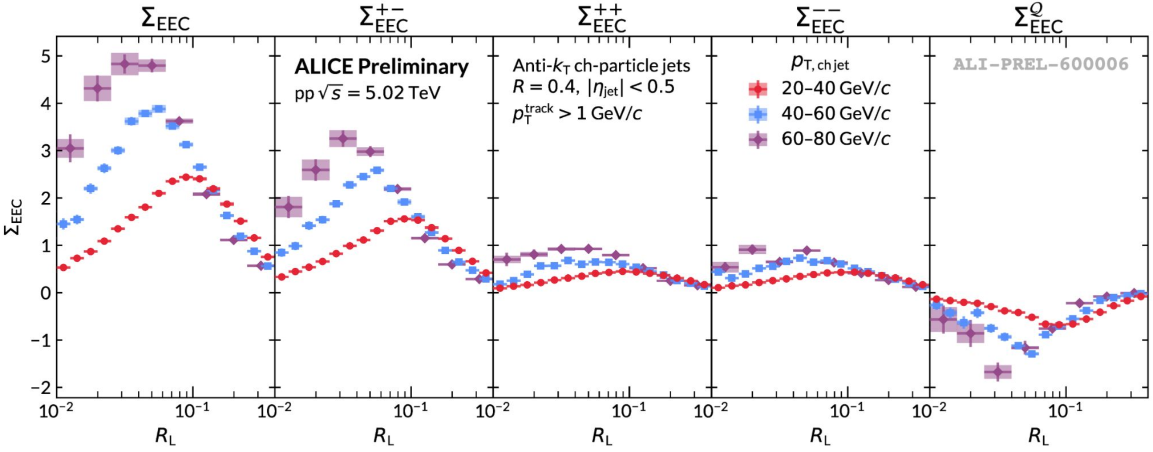


- Are there more unlike-sign or like-sign correlations? $\langle \mathcal{E}_+\mathcal{E}_- \rangle$ or $\langle \mathcal{E}_+\mathcal{E}_+ \rangle + \langle \mathcal{E}_-\mathcal{E}_- \rangle$
- Exploring correlations in angle and charge *increases sensitivity to different hadronization mechanisms.*

arXiv:2308.00746 [hep-ph] (Lee, Moult) / images from Youqi Song

ALICE measured charged correlators.

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



Correlations of unlike-and like-sign pairs show familiar features.

Charge-weighted EEC is overall negative: more unlike-sign pairs.

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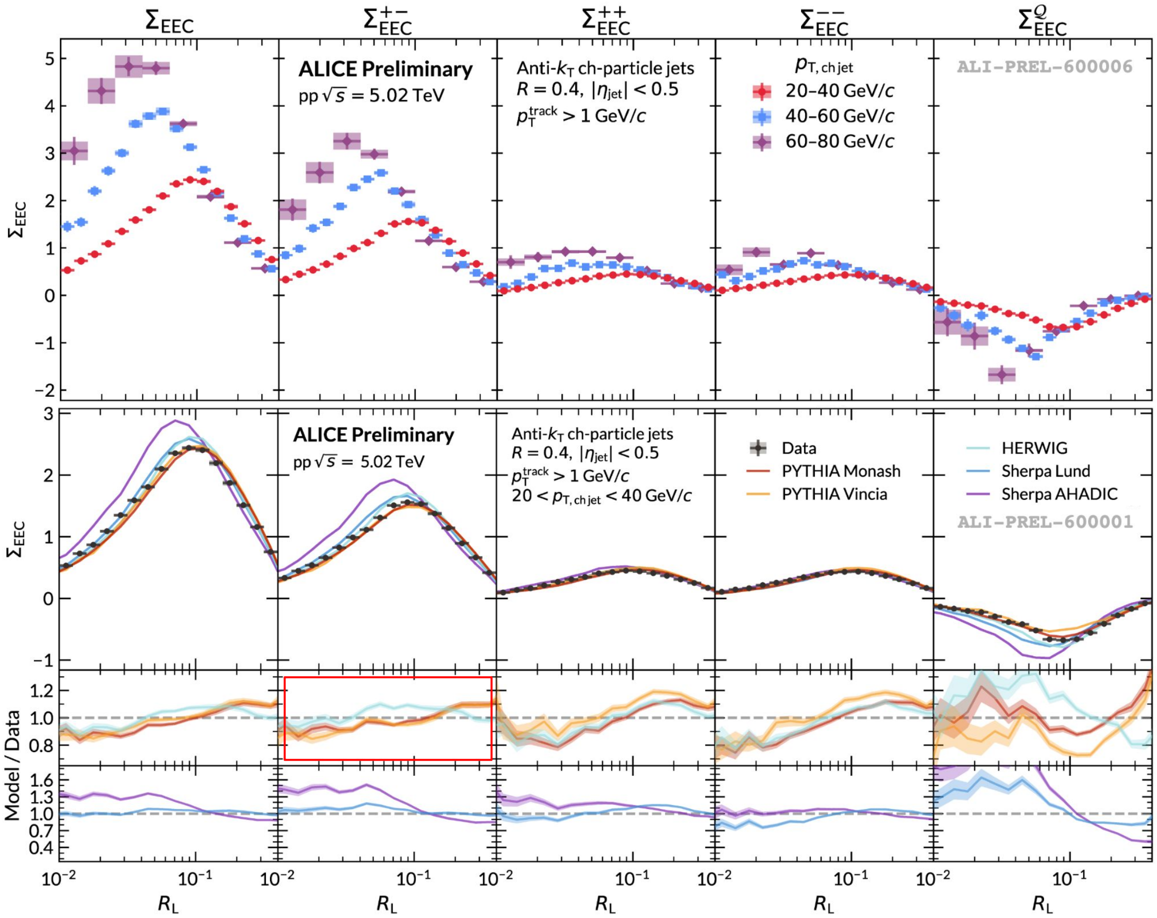

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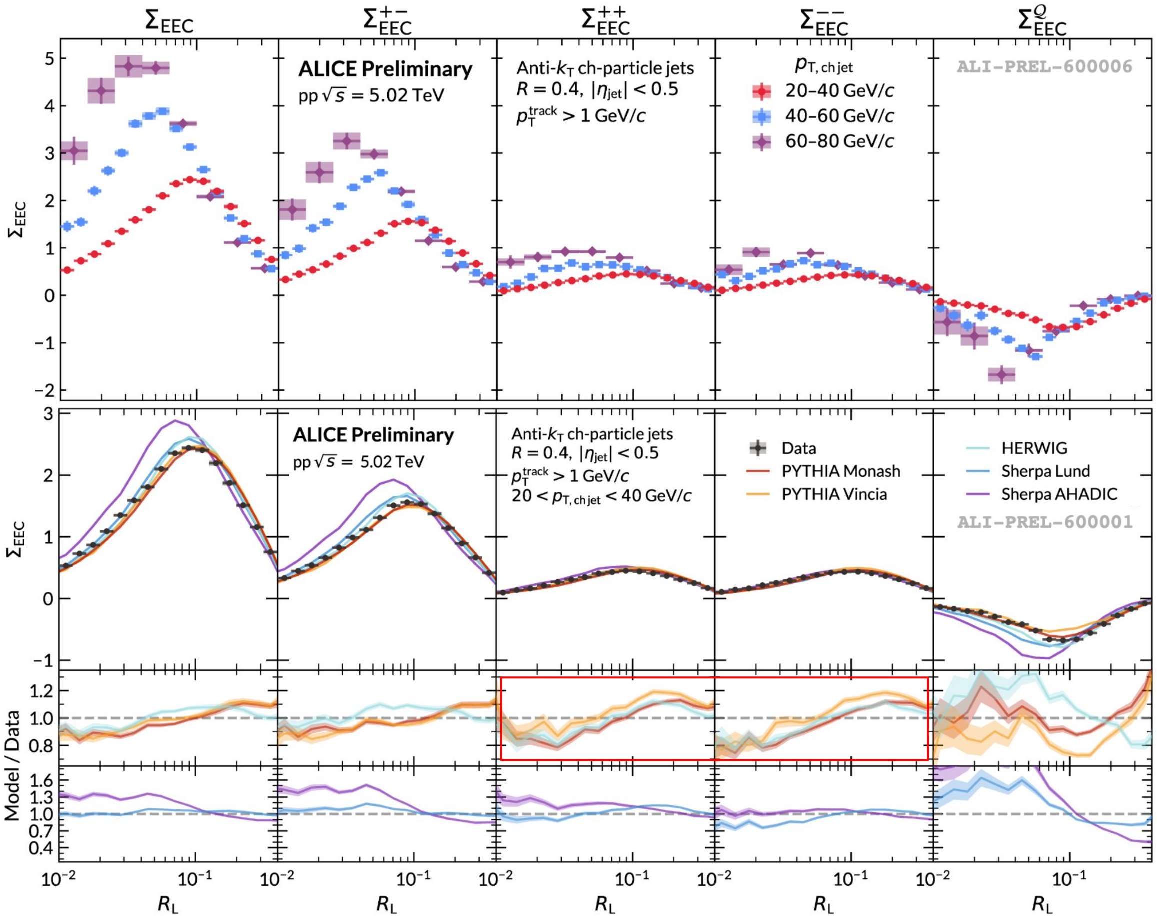
Data favor string-breaking models? Best captures small R_L de-correlation.

We can parse model differences:

- PYTHIA and HERWIG differ most in unlike-sign EEC

Charged EECs are sensitive to model differences.



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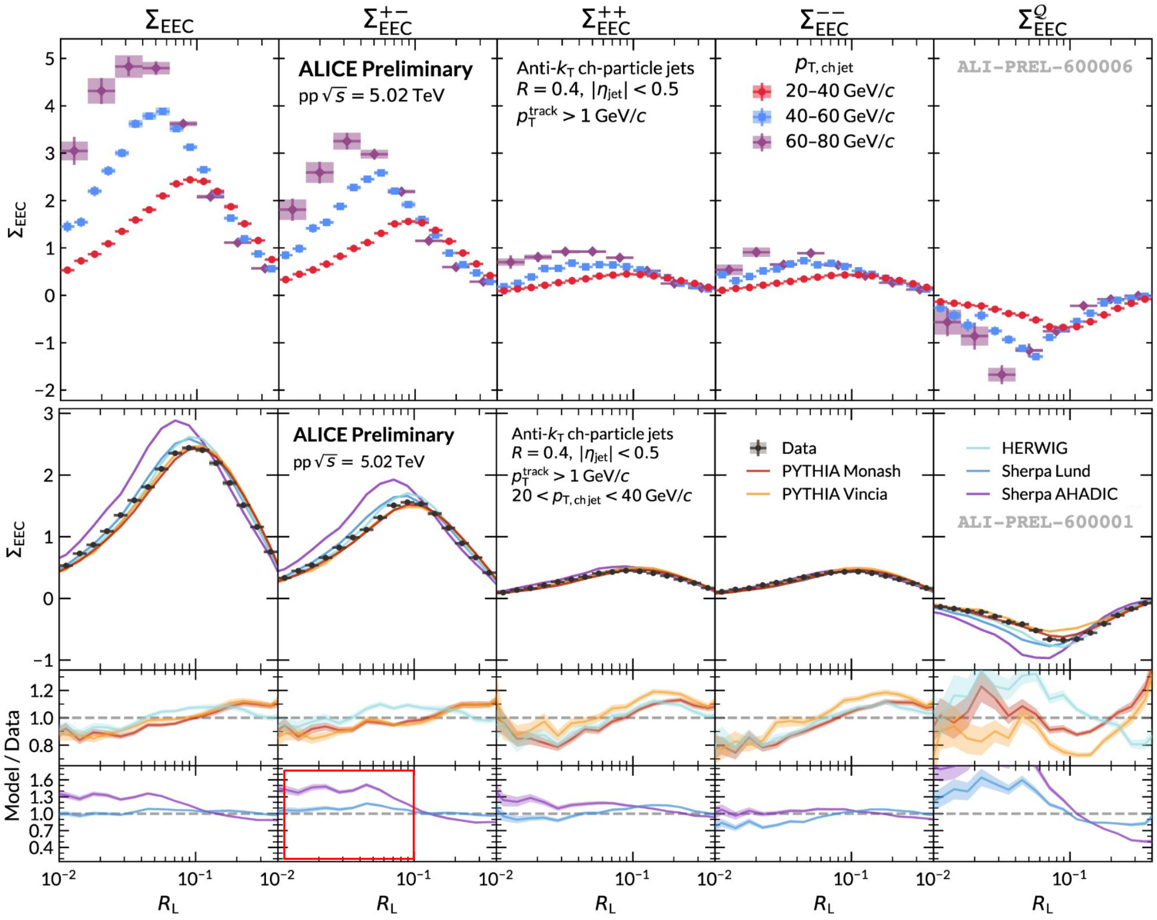

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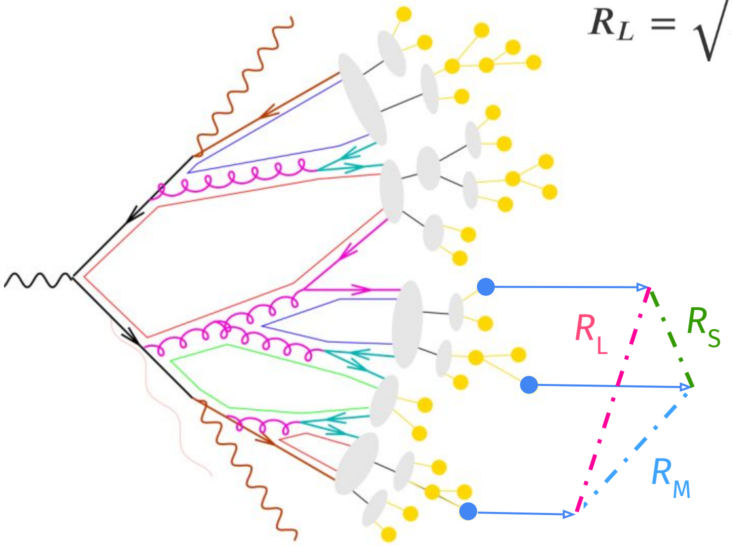
- Monash and Vincia differ most in like-sign EEC (parton shower)
- Lund and AHADIC differ most in low-R_L unlike-sign (hadronization)

Another perspective on EECs: three-point correlators.

ENC definition:

$$ENC(R_L) = \sum_{i,j,k..n}^{N} \int dR_L \boxed{\frac{p_T^i p_T^j..p_T^n}{p_{T,jet}^n}} \delta(R_L - \Delta\hat{R}_L)$$

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

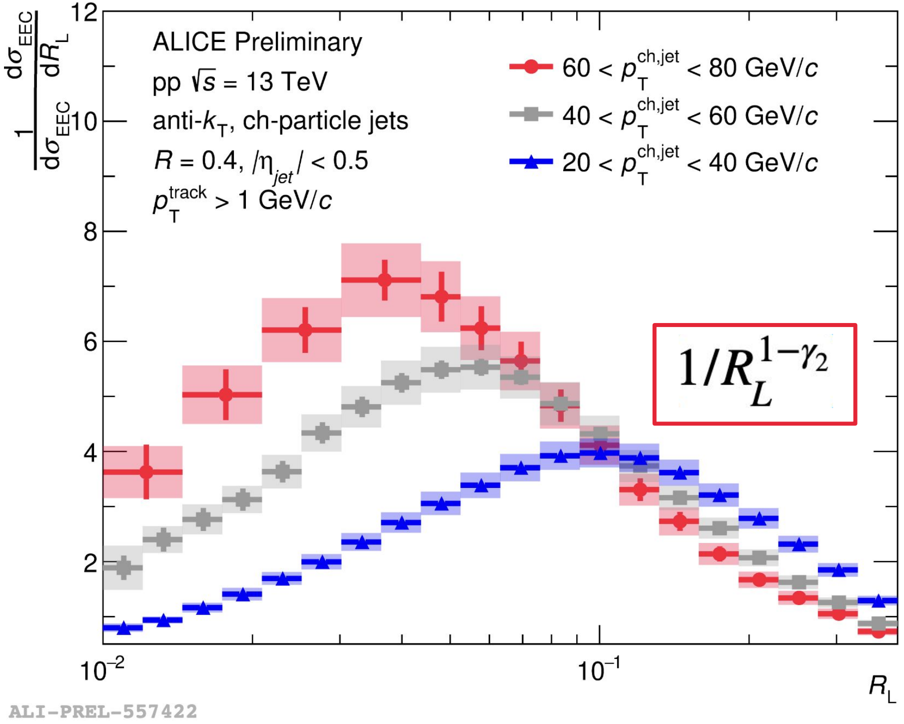


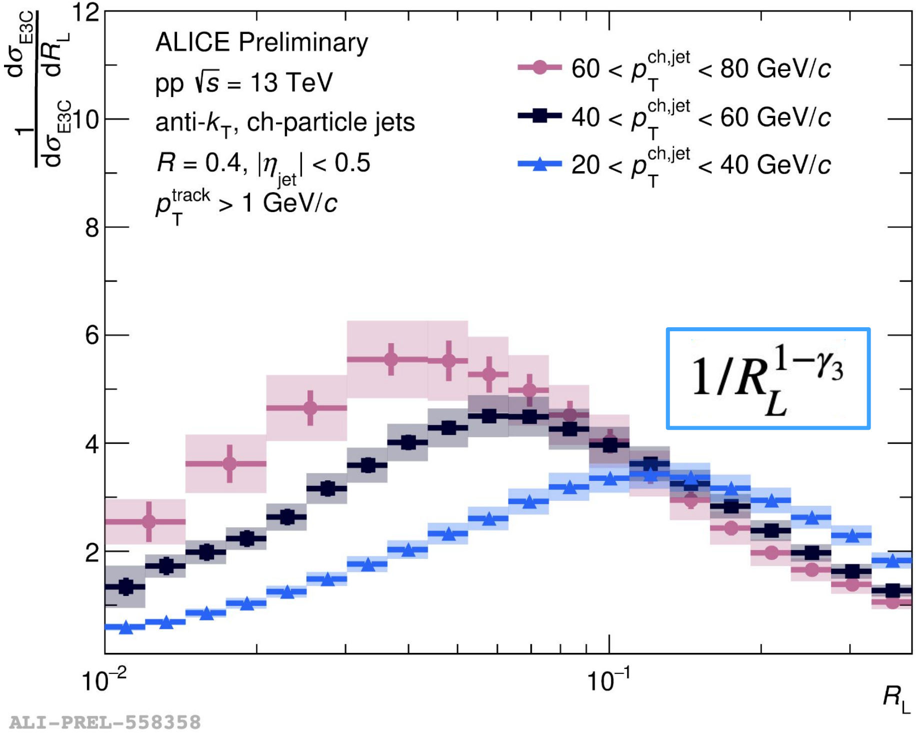
1. For each triplet of tracks inside the jet, calculate the energy weight.
2. Fill energy-weighted histogram of triplets as a function of R_L.

Allows us to probe shape dependence of energy flow.

Gives precise access to α_s using jet substructure!

The large-R_L scaling of EECs and E3Cs is different.





Large-R_L slope is set by quantum corrections: anomalous dimensions of EEC (γ_2) and E3C (γ_3) operators.

We can probe these corrections with the E3C/EEC ratio.

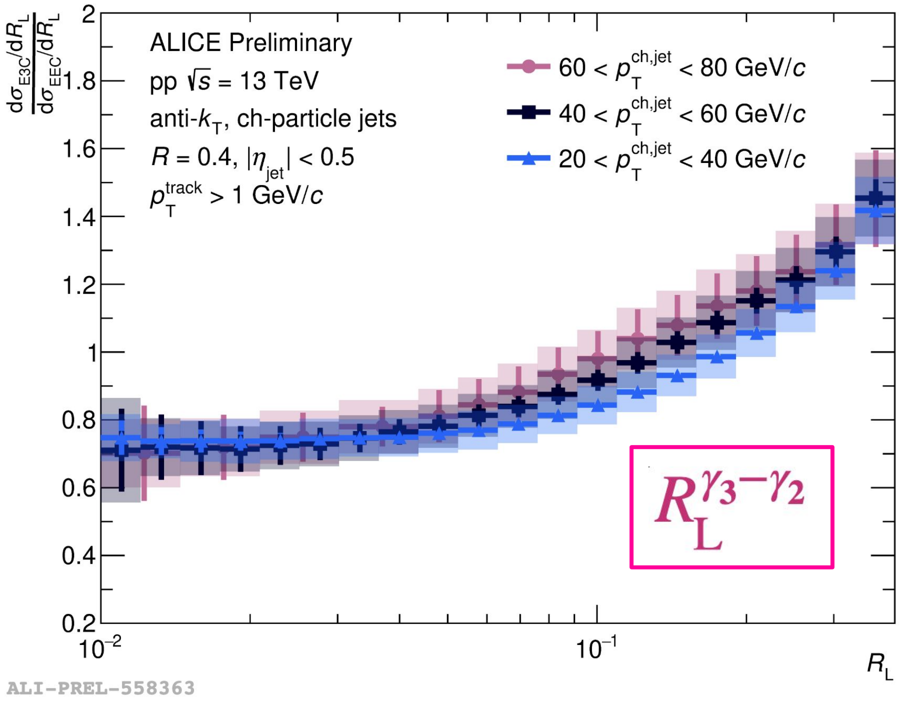
E3C/EEC $\propto R_L^{\gamma_3-\gamma_2} \propto \alpha_s \ln(R_L)$

In the perturbative regime:

- the change in slope with jet p_T is sensitive to the running of the coupling constant

In the non-perturbative regime:

- flat slope indicates consistent hadronic scaling



Extraction of α_s is underway at ALICE – complicated because of charged jets.

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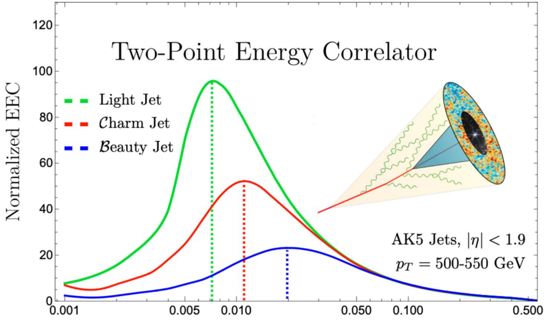
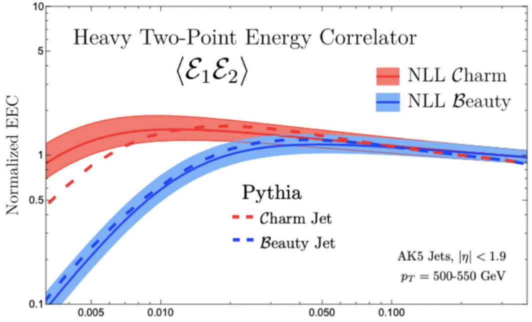
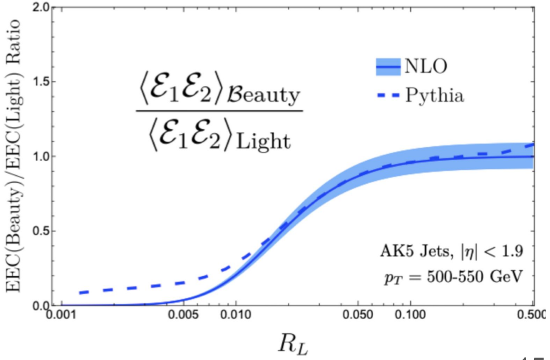
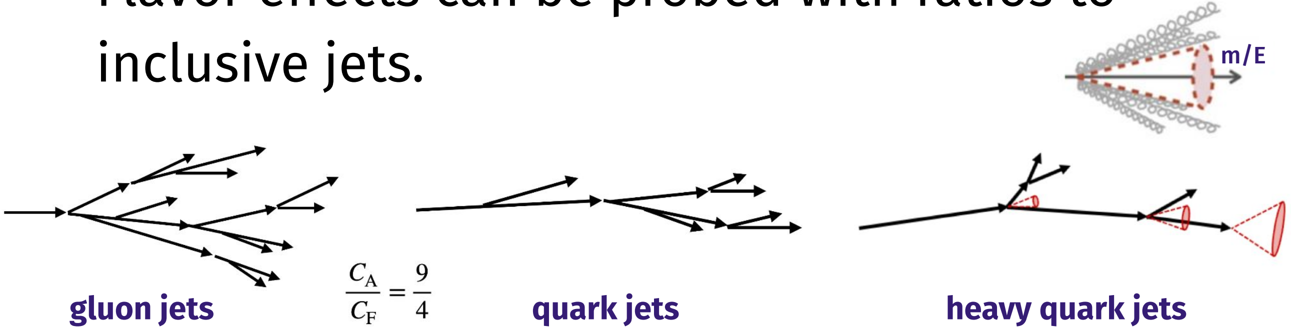
How does the shower depend on flavor?

- At the largest R_L, the scaling behavior in heavy-flavor jets is identical to light quark jets.
- *Turnover exhibits a mass dependence!*
- Change of shape at small angles is a consequence of the dead cone.
- Flavor effects can be probed with ratios to inclusive jets.









arXiv: 2210.09311 (Craft, Lee, Meçaj, Moult)

D^0-tagged jet EECs show mass-effect modifications.

Upper panel:

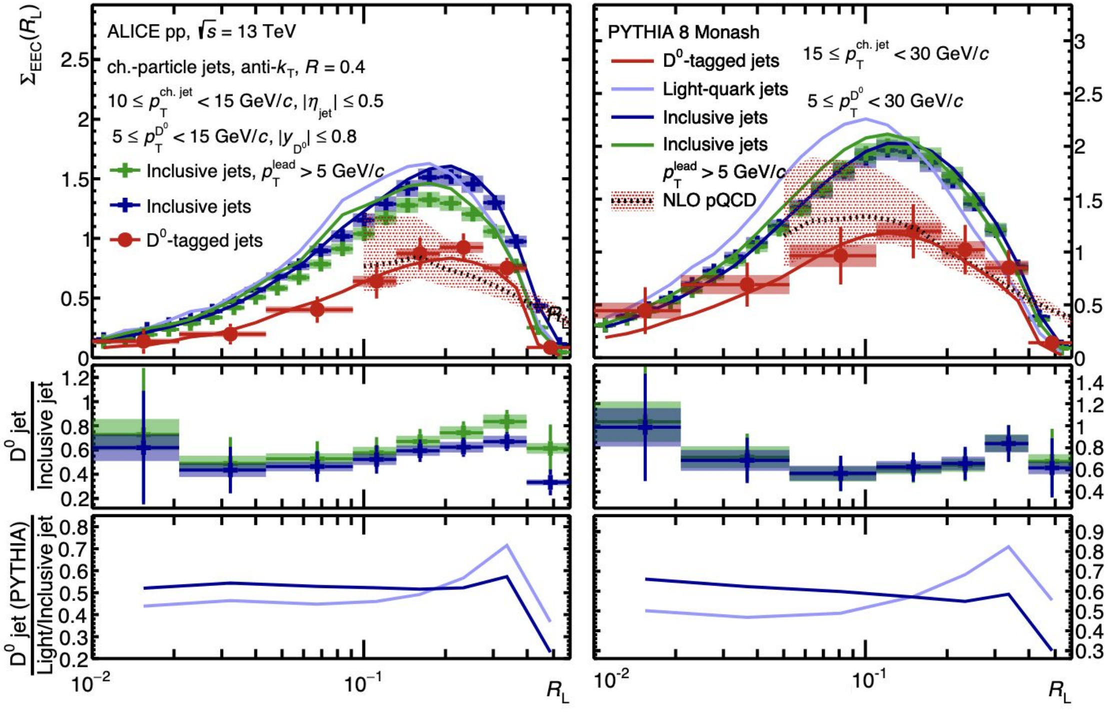
- p_T cut on leading track in incl. jets to study fragmentation bias
- significant suppression at all R_L, slopes at large R_L seem different
- peak positions are similar due to gluon contribution to inclusive

From the ratios:

- D^0/inclusive → mass + Casimir
- D^0/LF → isolated mass effects

Clear mass effect in D^0 jets!

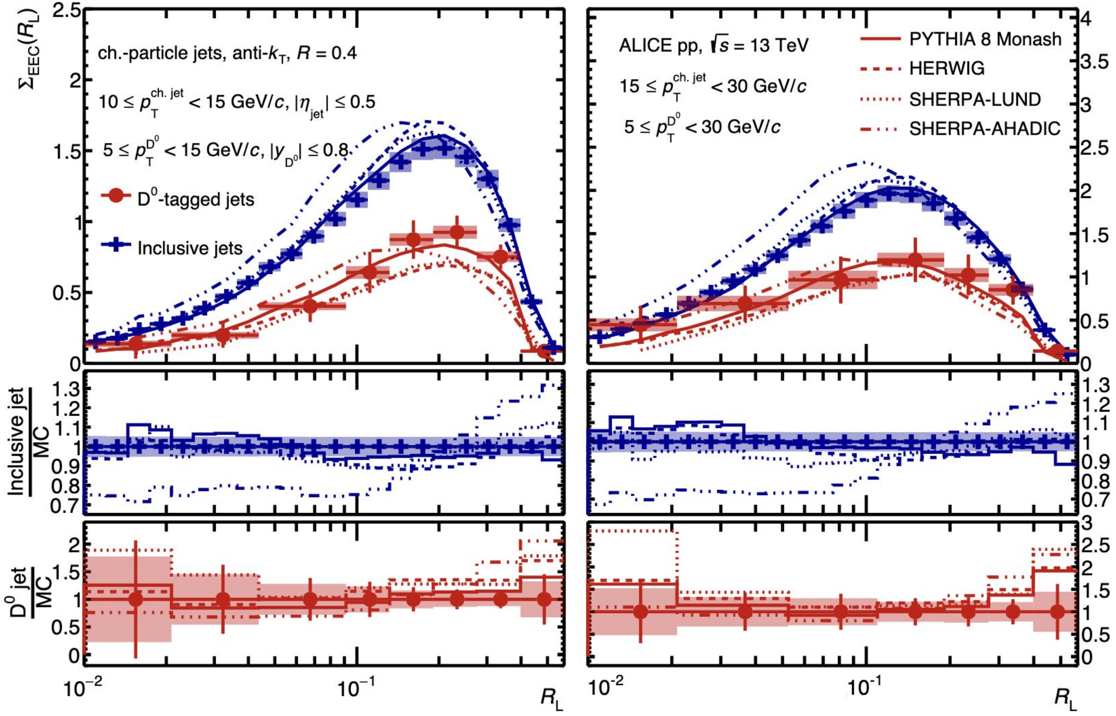
ALICE, arXiv:2504.03431 [hep-ex]



pQCD calculation from K. Lee

Probing hadronization with D⁰-tagged jet EECs

ALICE, arXiv:2504.03431 [hep-ex]



Data appear to favor PYTHIA.

- Herwig overpredicts inclusive jet EECs; underpredicts in HF
- Sherpa Lund consistently underpredicts the data
- AHADIC consistently predicts a too-small peak position

Lund string models: PYTHIA 8, Sherpa Lund
Cluster models: Herwig 7, Sherpa AHADIC

Can we say: PYTHIA does well in pp inclusive EECs, and better in charged and HF EECs?

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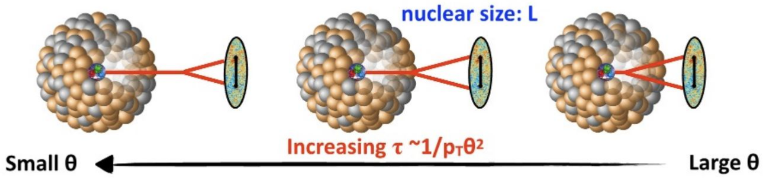
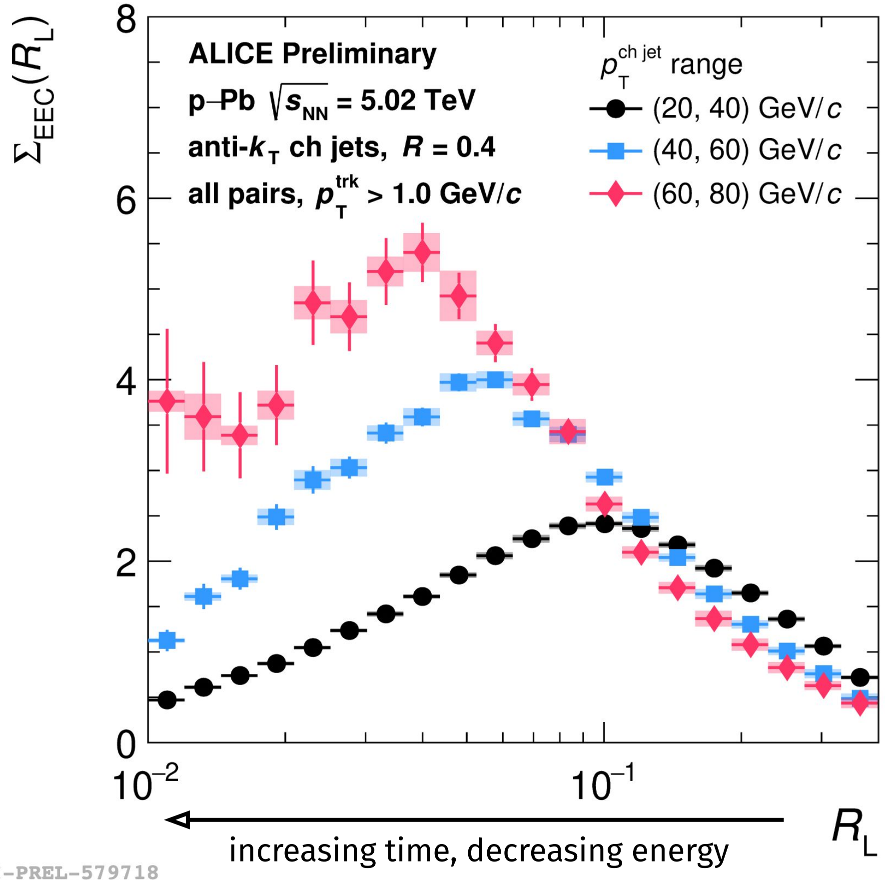
Are EECs modified in p-Pb?

Differences from pp:

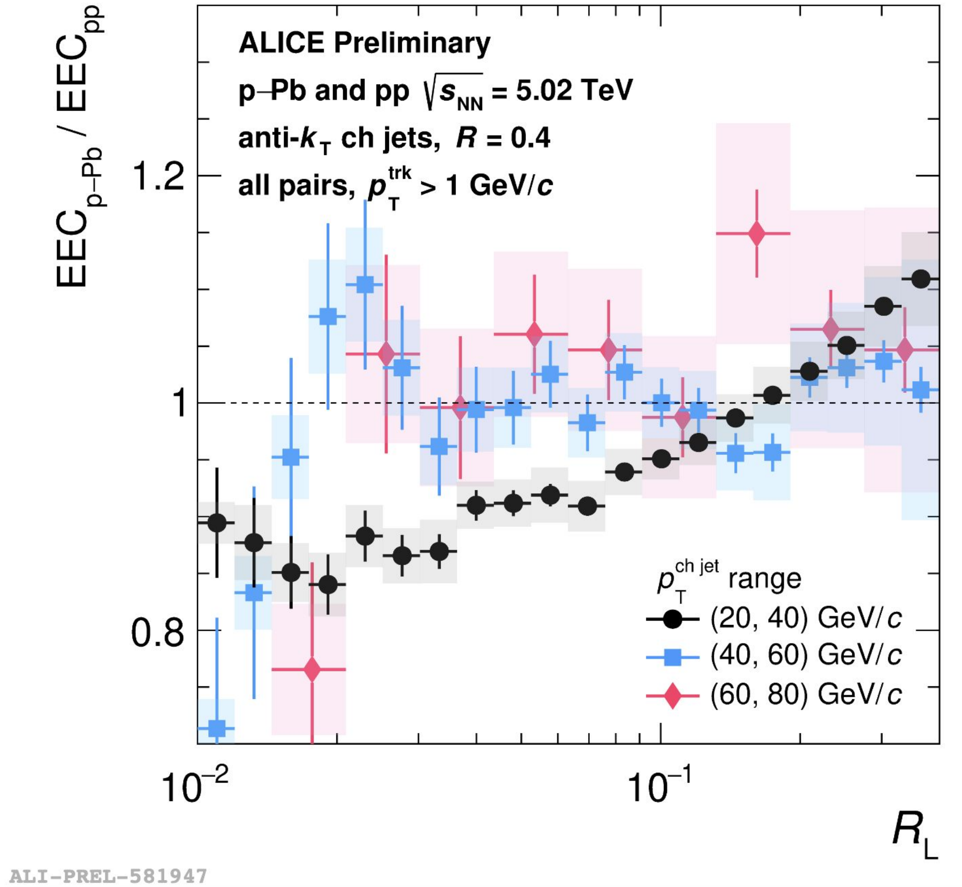
- initial state (nPDF, isospin)
- final-state interactions?
- comovers? collectivity??



EECs in p-Pb are a window into interactions in small systems.



EECs are modified in p-Pb in the lowest jet p_T bin.



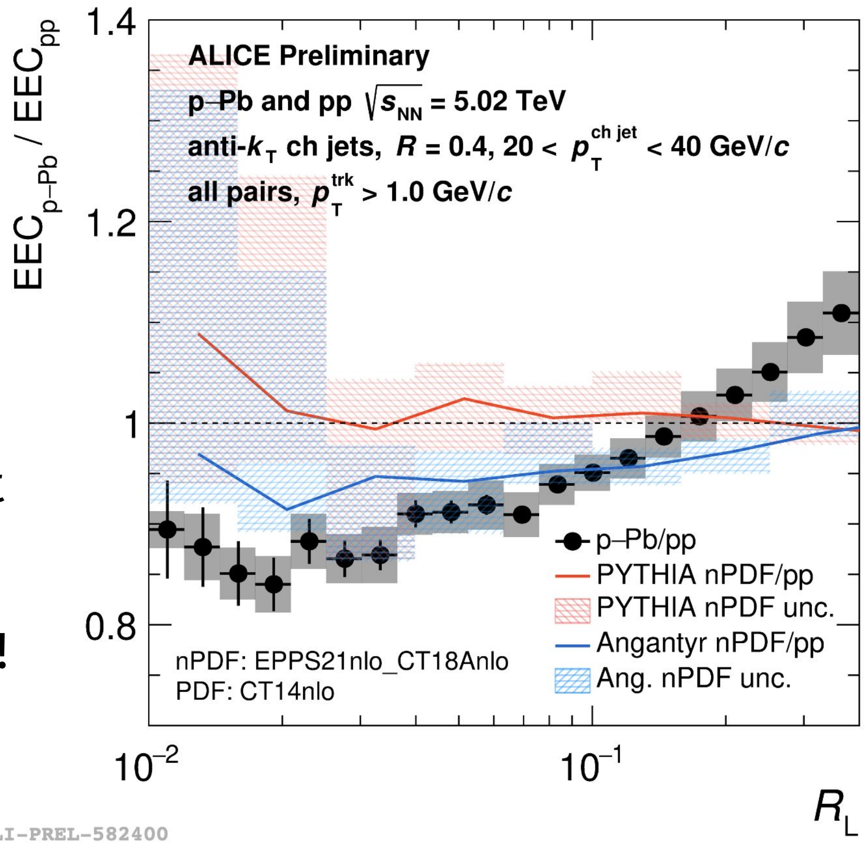
- *Significant difference between EECs in p-Pb compared to pp!*
- Jet structure appears to be altered only in the lowest jet p_T range
- Initial state or final state effect?

- Modification is comparable to ALICE measurement* of HM/MB z_{ch} in pp

* ALICE, arXiv:2311.13322

nPDF models do not fully capture the data.

- Comparing to PYTHIA with an nPDF turned on, and PYTHIA Angantyr
- PYTHIA results use:
  - nPDF: EPPS21nlo_CT18Anlo
  - PDF: CT14nlo
- nPDFs are within ~1σ at small R_L – but these have very large uncertainties
- Neither captures behavior at large R_L!



Some theory models can reproduce the enhancement.

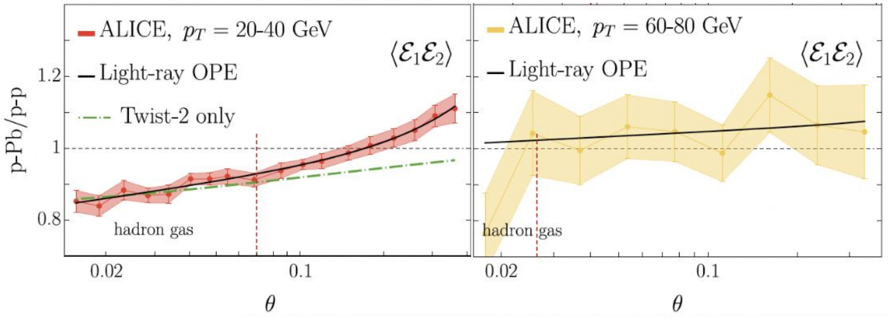
Theory colleagues have suggested a variety of mechanisms:

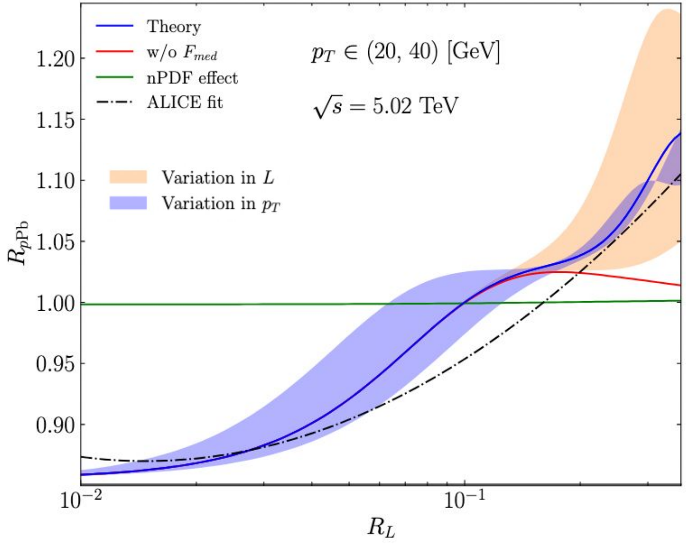
- multiple scatterings with CNM
- transverse momentum broadening
- twist-4 OPE corrections

We can look at a few things in the data:

- jet p_T dependence
- jet rapidity
- forward multiplicity
- track charge
- track p_T cut

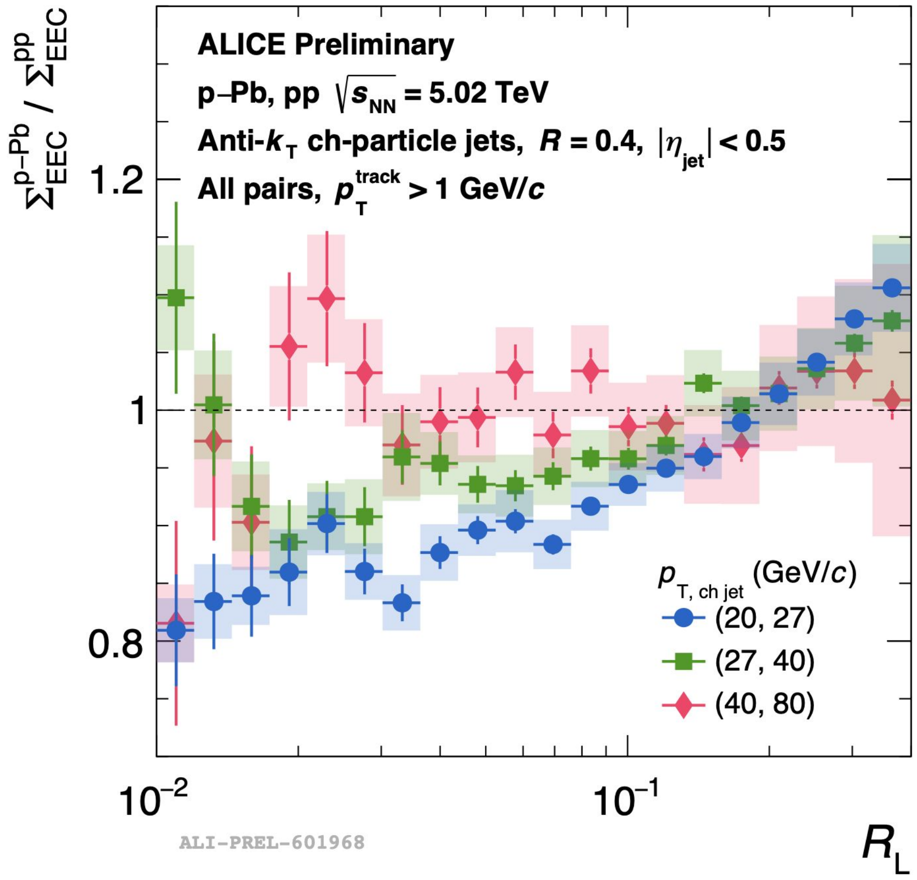
arXiv:2411.15298 [hep-ph] (Andres, Dominguez, Holguin, Marquet, Moult)





arXiv:2411.11782 [hep-ph] (Barata, Kang, Mayo López, Penttala)

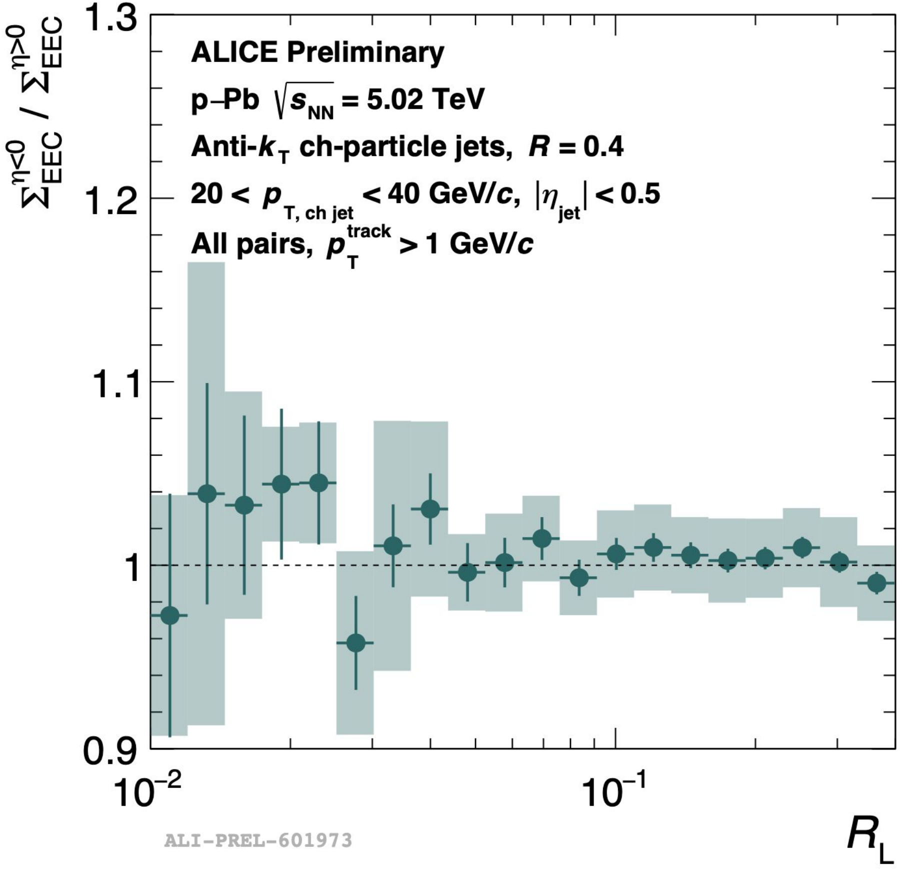
Some jet p_T dependence is visible in the EEC ratio.



- Split the 20-40 GeV/c jet p_T bin into 20-27 GeV/c and 27-40 GeV/c
- Jet p_T dependence in p-Pb/pp ratio: still see modification in 27-40 GeV/c jets
- 40-80 GeV/c combined bin is essentially flat

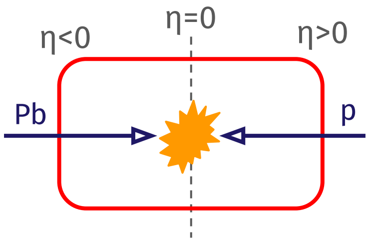
The modification is strongest at low jet p_T and fades at higher energy.

The EEC does not depend on rapidity.

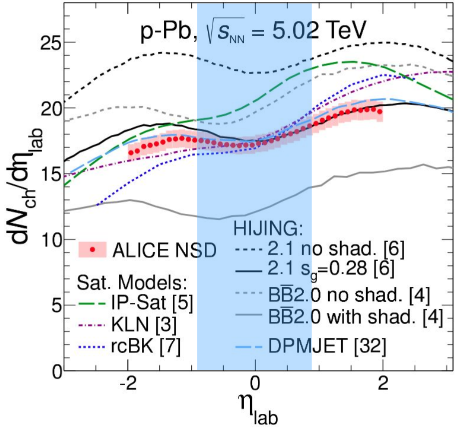


- EECs for jets with η > 0 (forward) and η < 0 (backward)
- Backward (p-going) and forward (Pb-going) EECs agree within 5%

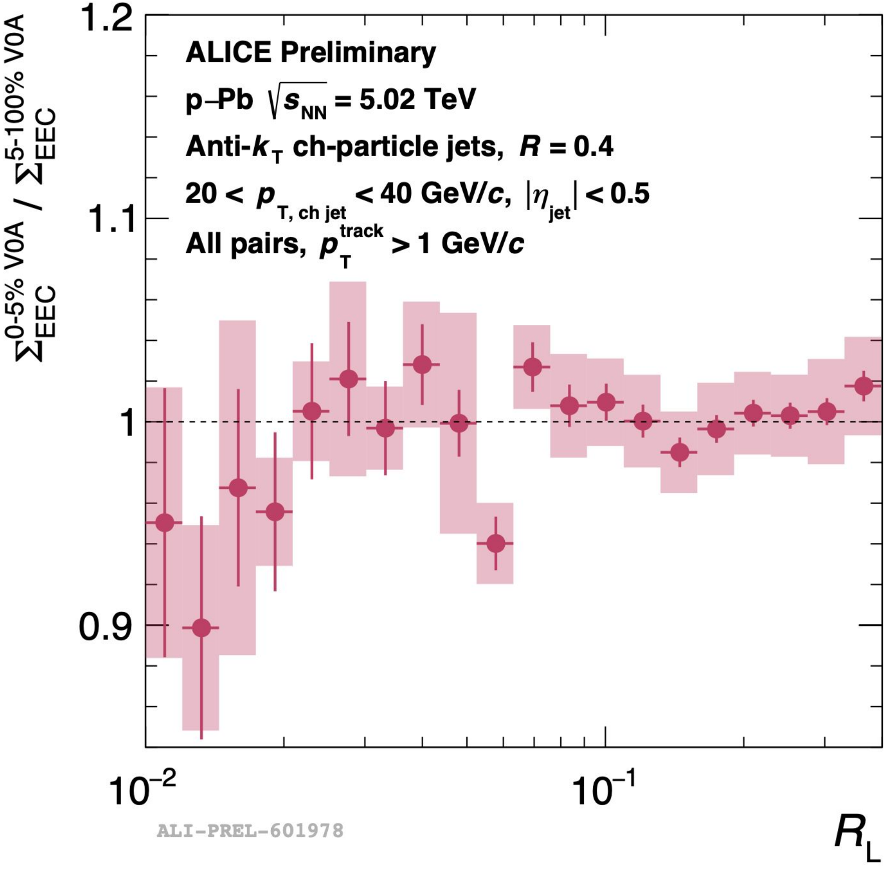
Asymmetry in dN/dη doesn't affect EEC!



ALICE, Phys. Rev. Lett. 110 (2013) 032301



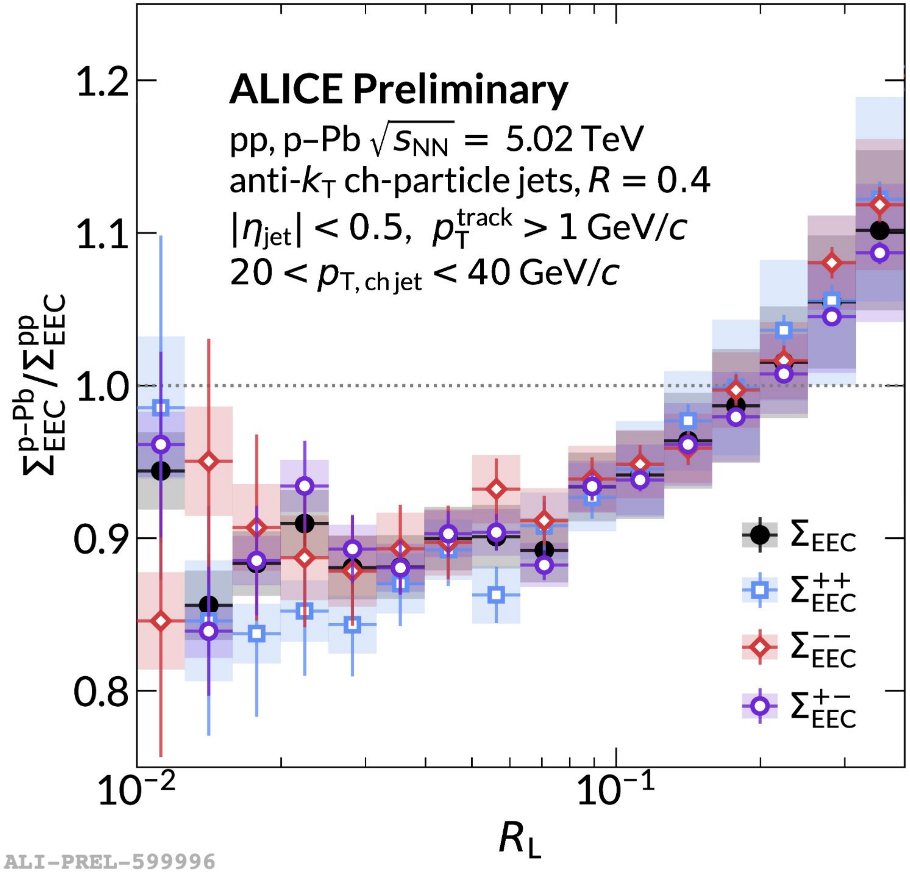
The EEC does not depend on forward multiplicity.



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

We see no dependence on event activity.

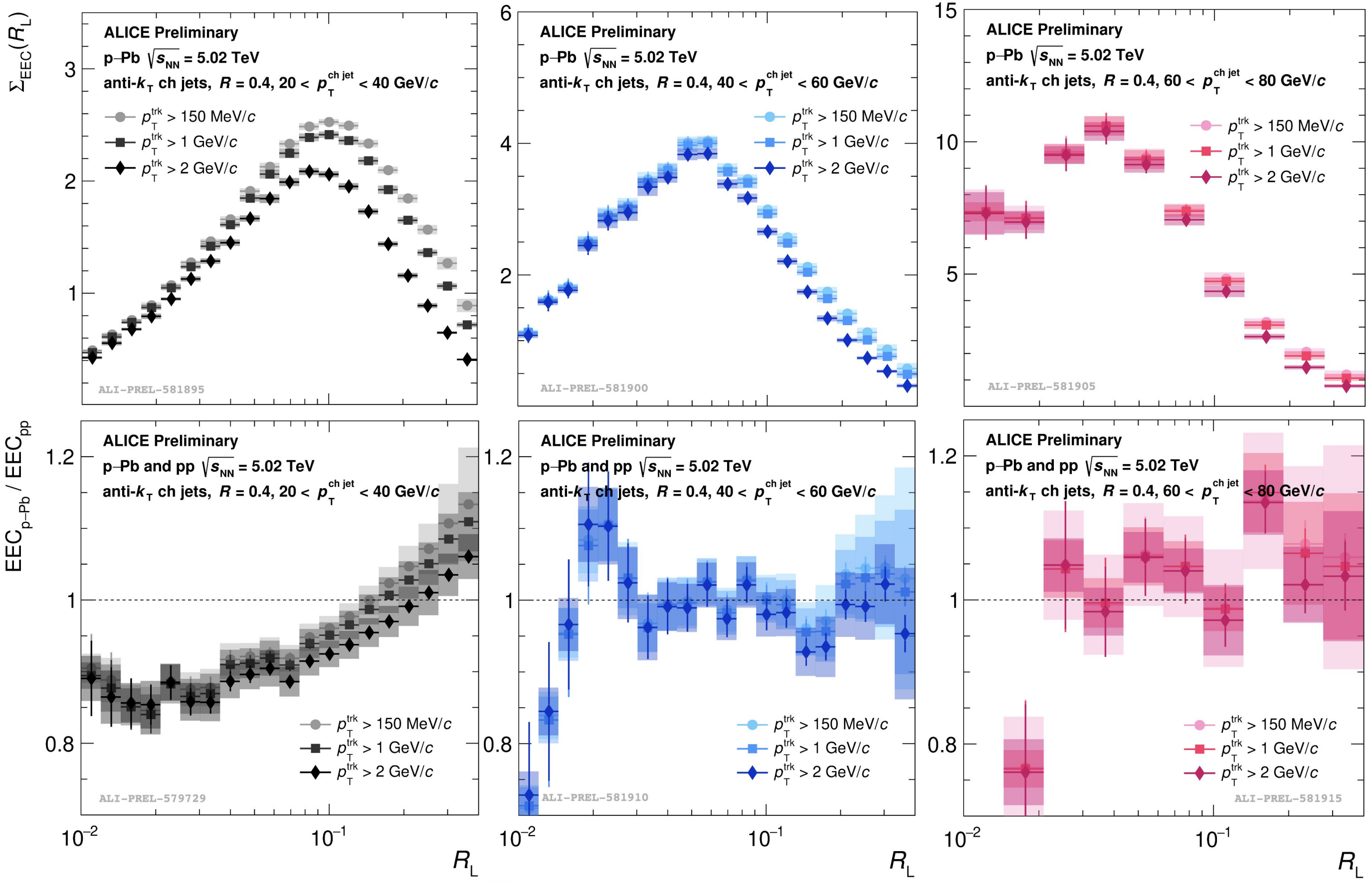
The EEC does not depend on particle charge.



- Build the EEC separately from like-sign and unlike-sign pairs
  - like-sign: EEC^{++} and EEC^{--}
  - unlike-sign: EEC^{+-}
- Charged energy correlators are sensitive to the parton shower and hadronization mechanisms

Charged EECs show the same p-Pb/pp ratio — no charge dependence.

Varying the track cut changes the EEC behavior at large R_L.



Strong sensitivity to track p_T cut in low p_T jets!

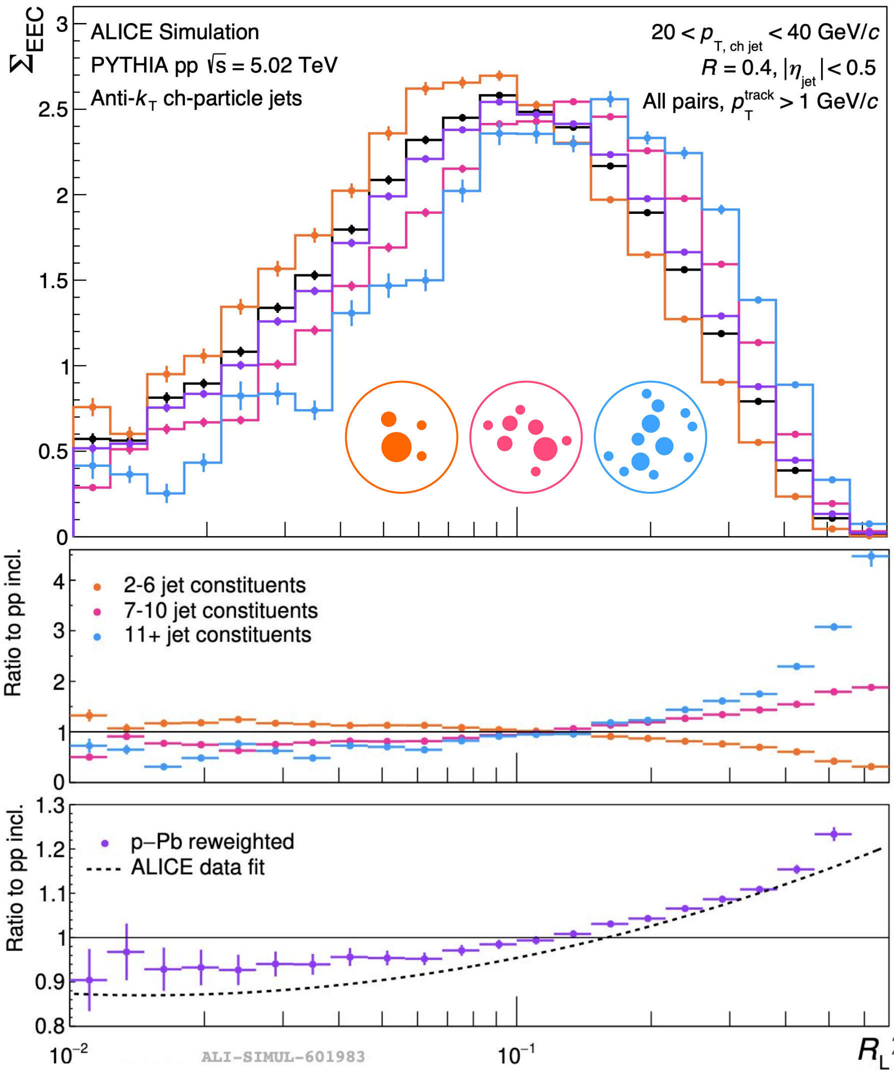
- non-perturbative effects increase for lower jet p_T

Track cut modifies the large-R_L enhancement in ratio

Even if we only use tracks with p_T > 2 GeV, we still see the 20-40 GeV/c modification.

The EEC depends on jet constituent multiplicity.

- Separate EECs based on the # of jet constituents (charged hadrons)
  - inclusive EEC from PYTHIA
  - EEC from jets with 2-6 tracks
  - EEC from jets with 7-10 tracks
  - EEC from jets with 11+ tracks
- We see a dramatic shift in the EECs due to jet constituent multiplicity
- If we redistribute 12% of jets to higher multiplicities, we can largely reproduce the measured p-Pb EEC modification



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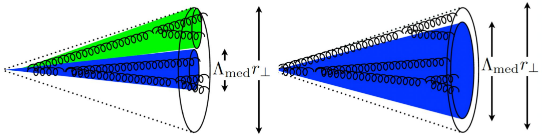
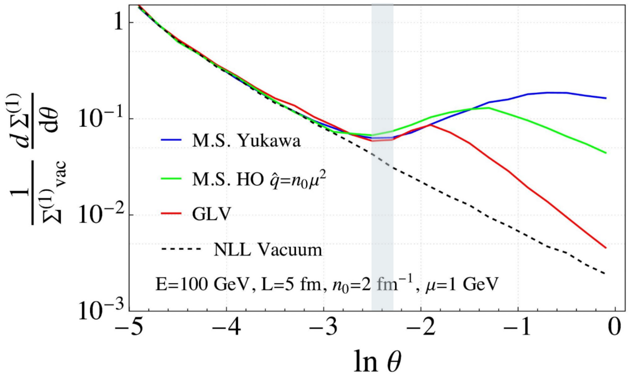
EECs in Pb-Pb can probe various medium effects.

JHEP 09 (2023) 088
(Andres, Dominguez, Holguin, Marquet, Moult)

Color coherence



- *large angle emission*: medium resolves emitted gluon as a separate object
- *small angle emission*: gluon and emitter resolved as single object
- *critical angle*: minimum separation to resolve separately



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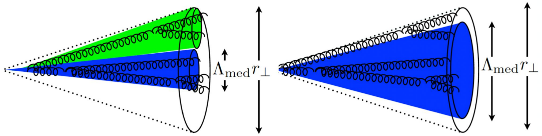

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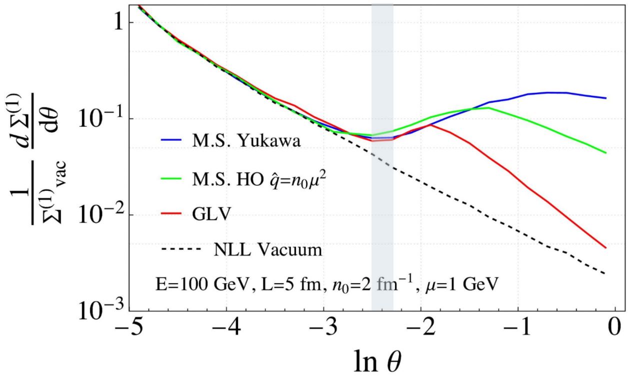

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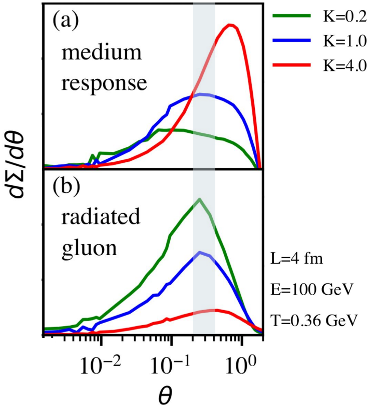
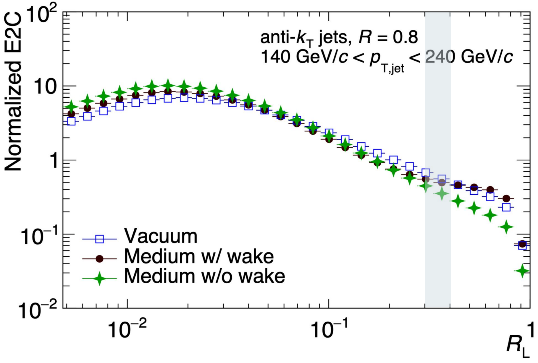
Medium response

- Jets can induce a *medium response* (recoil partons and back-reaction).
- Energetic partons can pull the medium, leaving a depletion called the *"jet wake"*.

PRL 132 (2024) 1, 011901
(Yang, He, Moult, Wang)



arXiv:2407.13818 [hep-ph]
(Bossi, Kudinoor, Moult, Pablos, Rai, Rajagopal)



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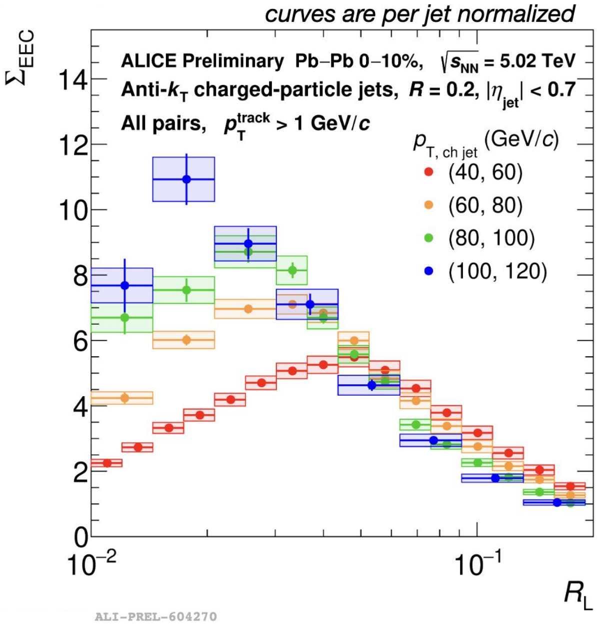
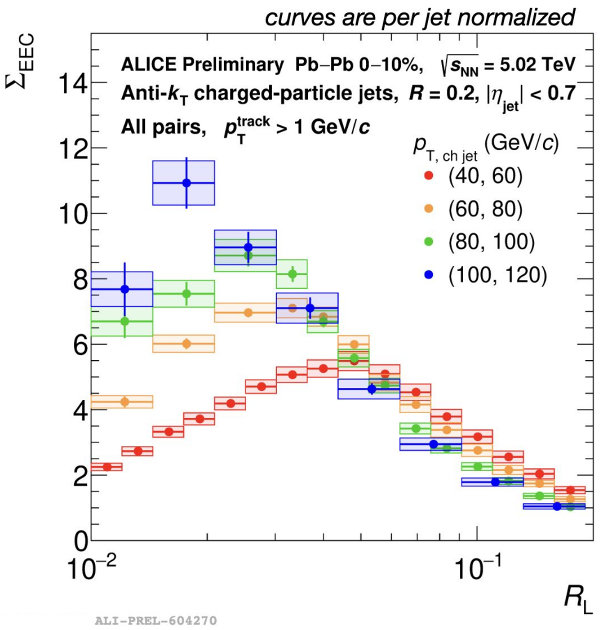


Pb-Pb loosely has the same features as observed in pp.

ALICE measured EECs in Pb-Pb.



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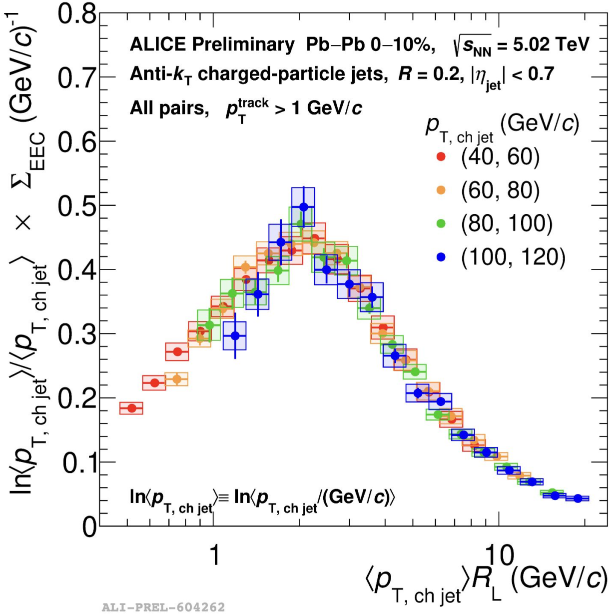
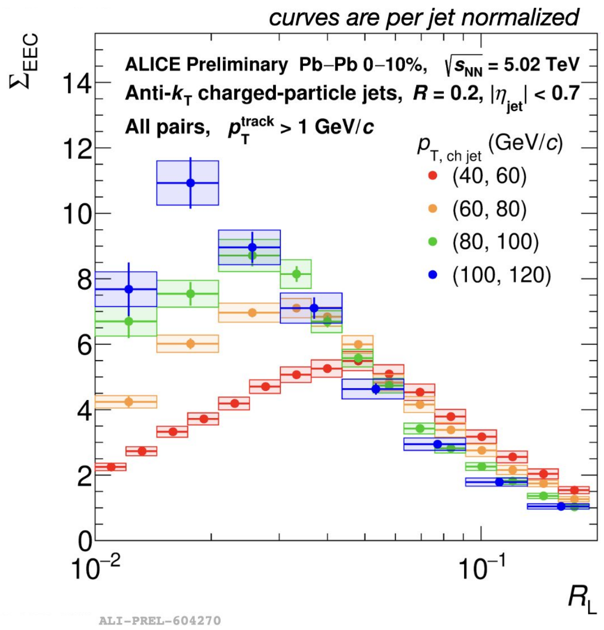


Pb-Pb exhibits a peak universality similar to pp.

ALICE sees EECs are modified in Pb-Pb!



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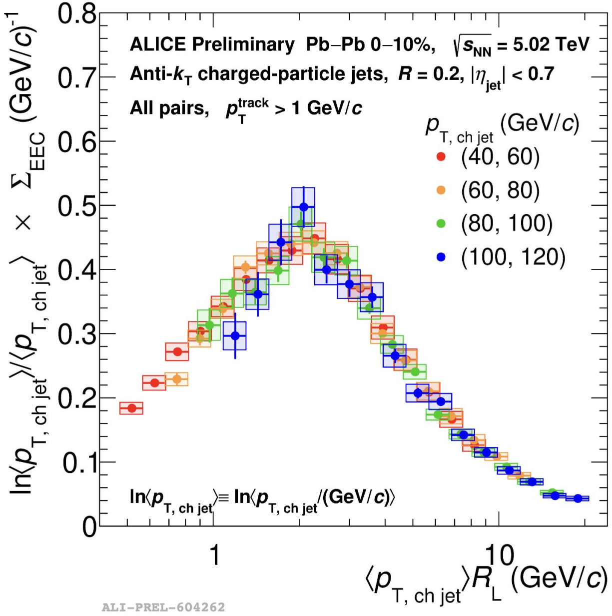

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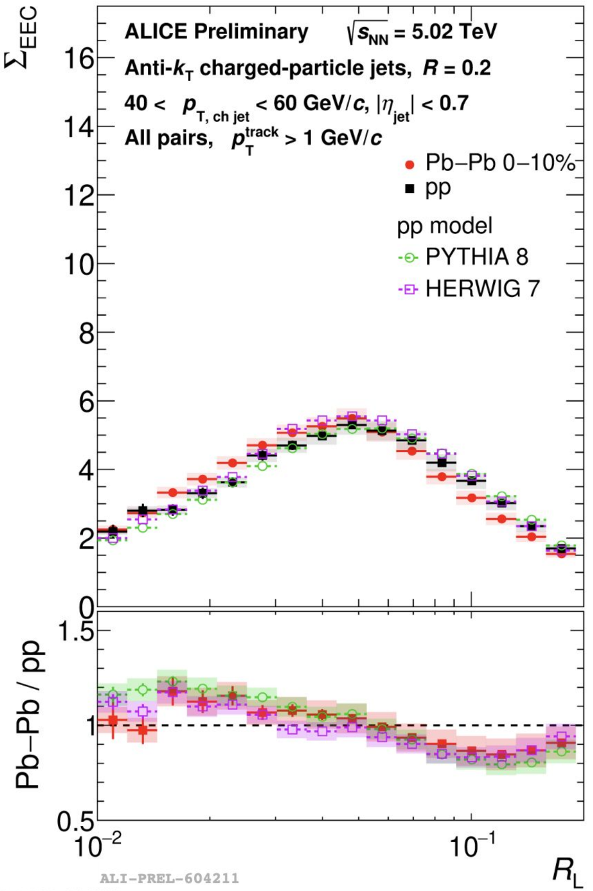
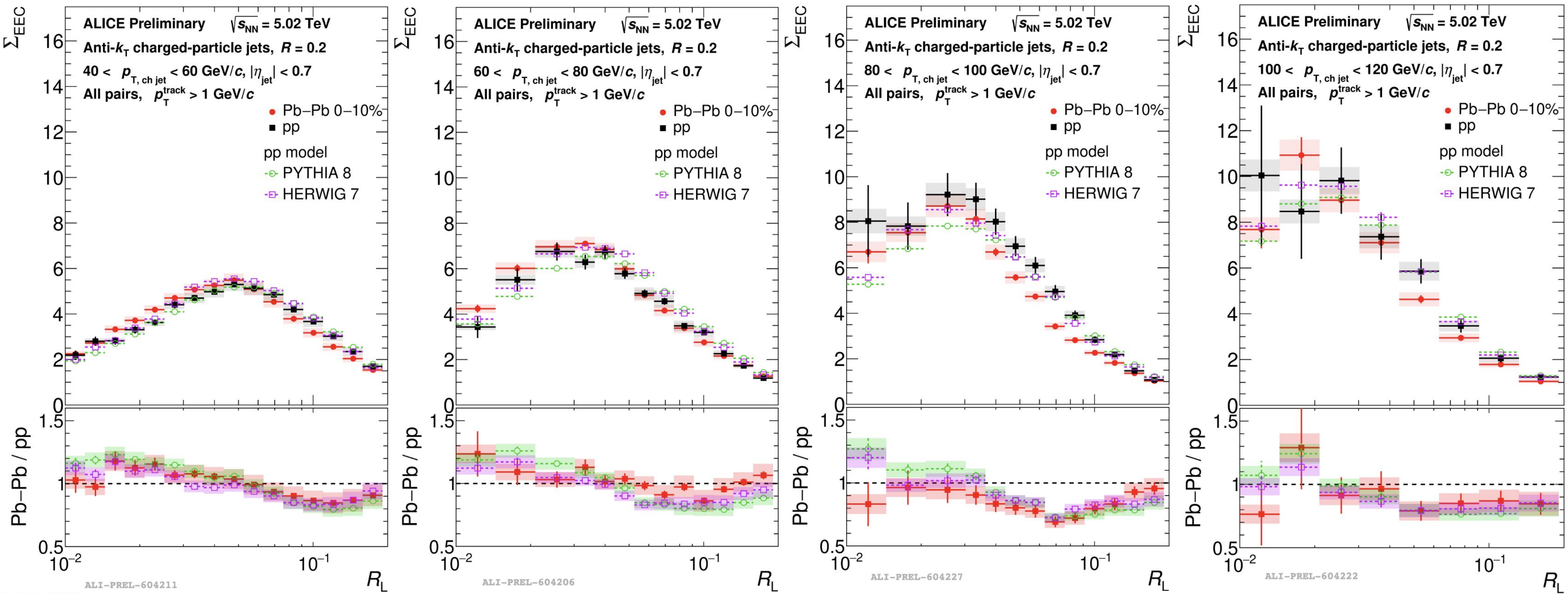


Pb-Pb EECs show a ~20% modification relative to pp!

We don't see a strong jet p_T-dependent modification.



Pb-Pb/pp ratio shows an enhancement at small R_L (energy loss) and suppression at large R_L.

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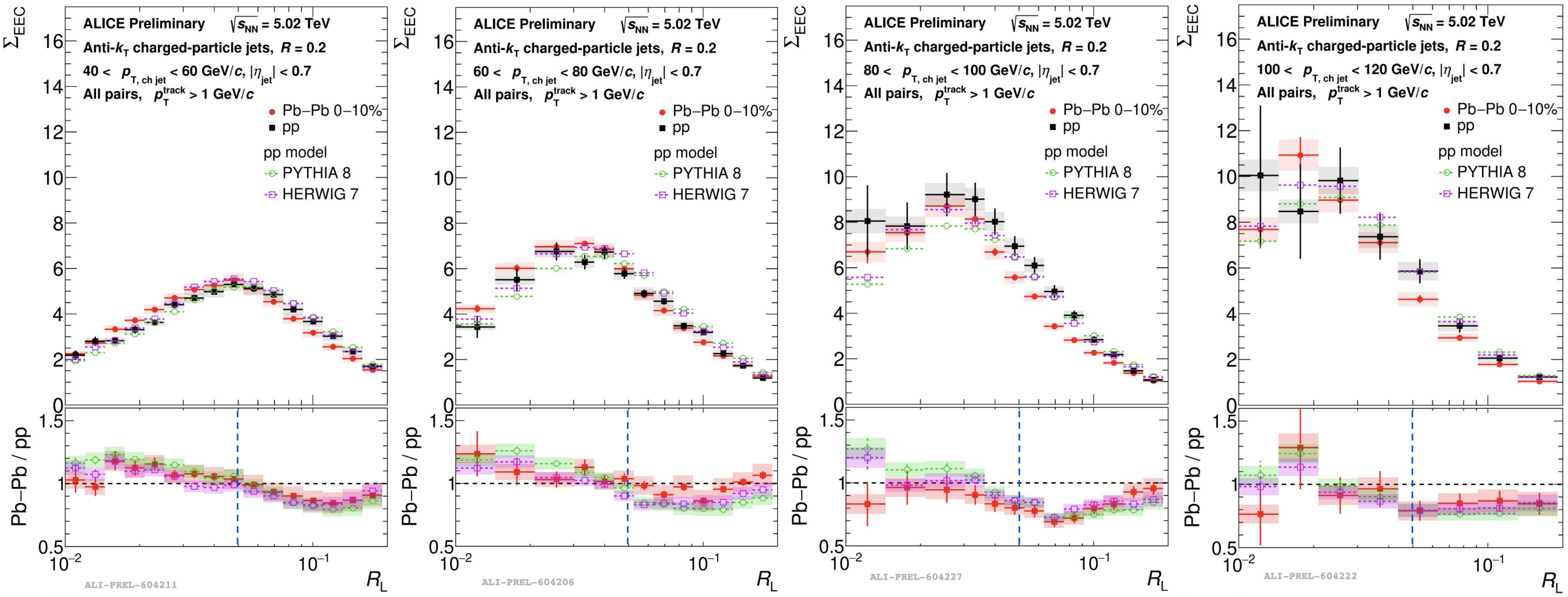

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Onset of suppression seems to shift to smaller angles at higher jet p_T.

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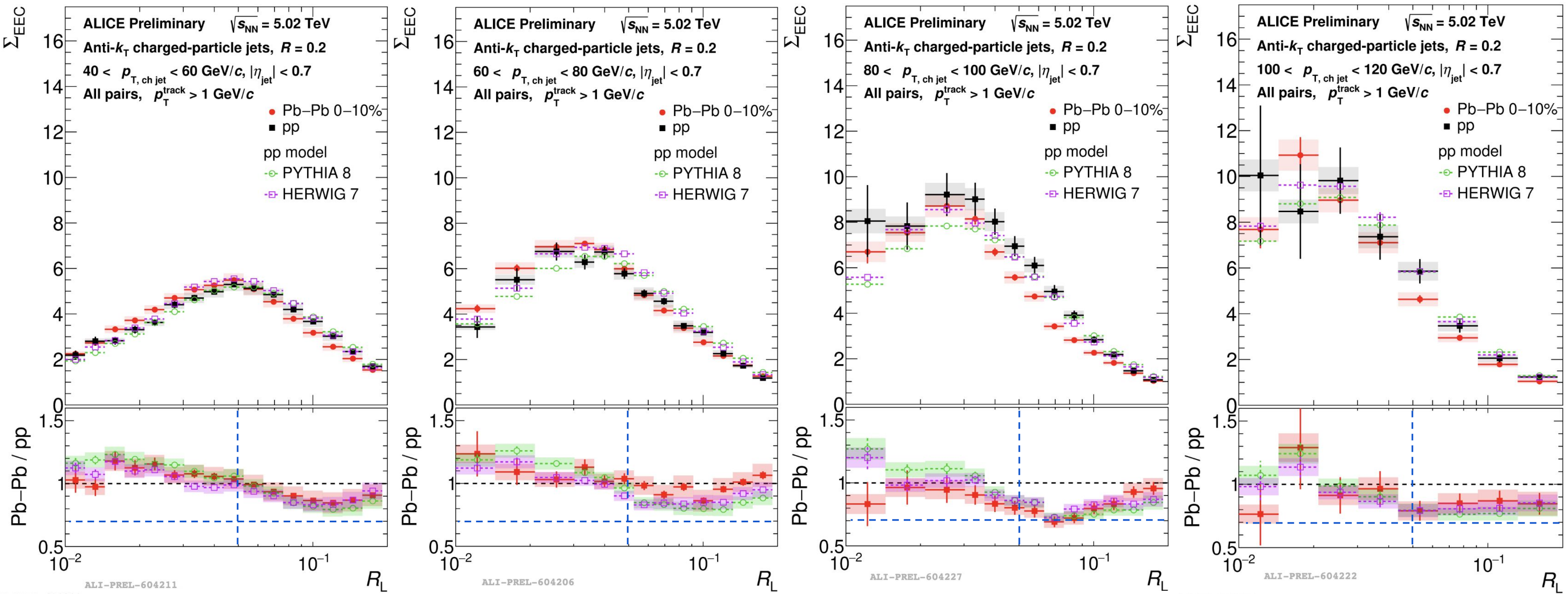
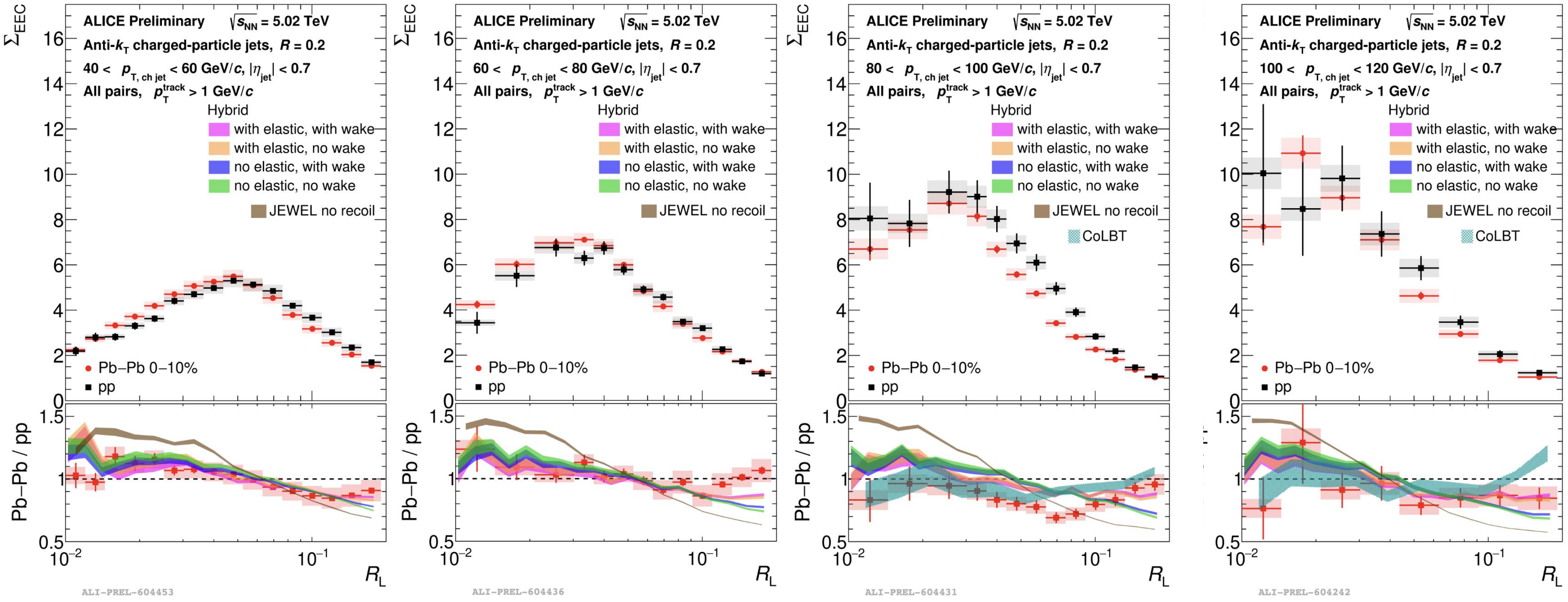


Pb-Pb/pp ratio shows an enhancement at small R_L (energy loss) and suppression at large R_L.

Onset of suppression seems to shift to smaller angles at higher jet p_T.

Level of modification does not show strong jet p_T dependence!

How do models compare to this data?



Can't really differentiate between Hybrid with/without wake. Slightly favor elastic scattering?

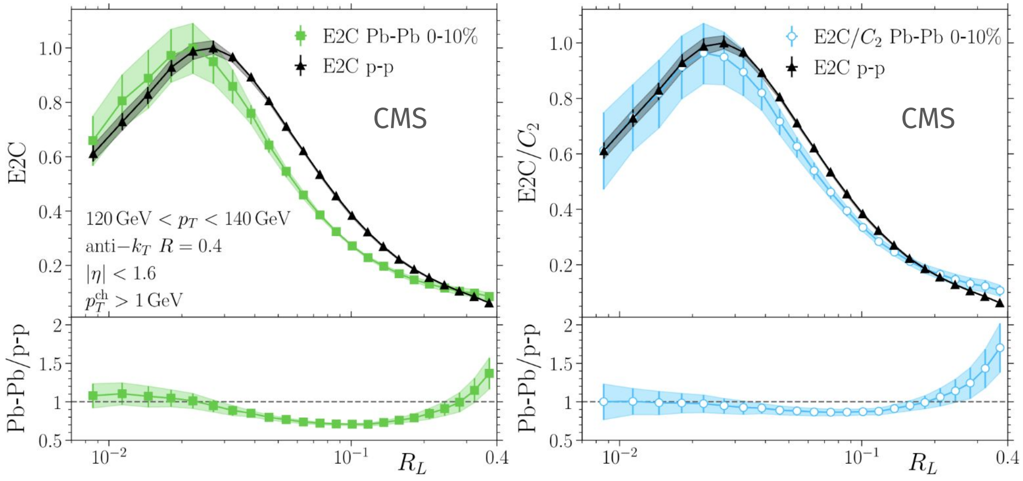
JEWEL consistently overestimates the low-R_L enhancement.

CoLBT does well at low R_L but doesn't capture large-R_L suppression.

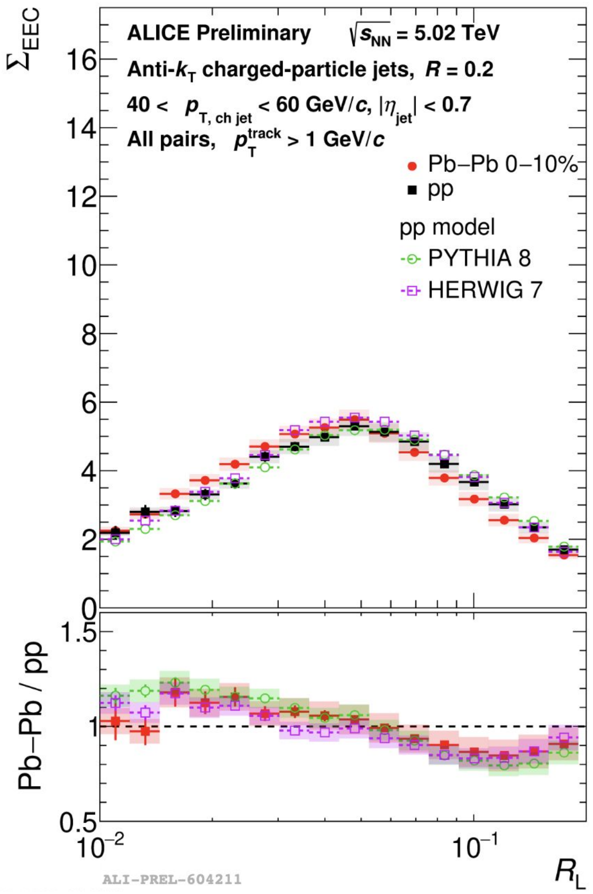
Getting more out of this measurement

- Lower the p_T track cut slightly? Extend R_L range? Look at jets with larger R? Study E3Cs?

- Apply C_2 correction to control for energy loss / selection bias and isolate other physics at play:



arXiv:2409.07526 [hep-ph] (Andres, Holguin)



Summary and outlook

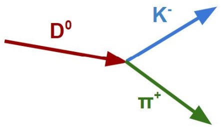
- Universality of EEC shape and turnover in pp
  no very obvious conclusions about hadronization
- EECs are altered in HF jets
  dramatic reduction in amplitude – clear mass/flavor effect
- EECs are modified in p-Pb
  strong sensitivity to jet constituent multiplicity
- Energy loss is visible in Pb-Pb EECs
  along with some interesting features at large R_L (medium response?)

We have a rich EEC program at ALICE – more to come!

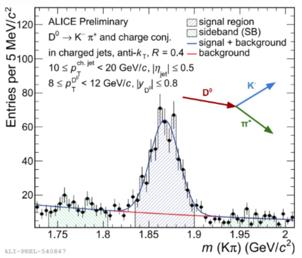
Backup

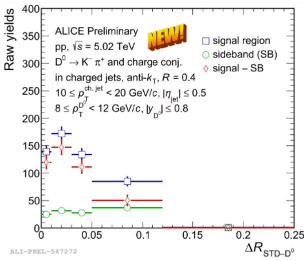
D^0 reconstruction steps

D^0 candidates were reconstructed from daughter tracks using topological and particle identification selections ($D^0 \rightarrow K^- + \pi^+$, and charge conjugates).

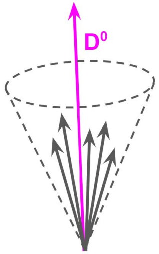


Invariant mass analysis was performed to remove combinatorial $K^-\pi^+$ pairs surviving the D^0 selections.

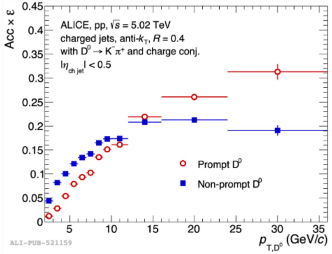




D^0-tagged charged jets were created using the anti-k_T algorithm (R=0.4) for each candidate.

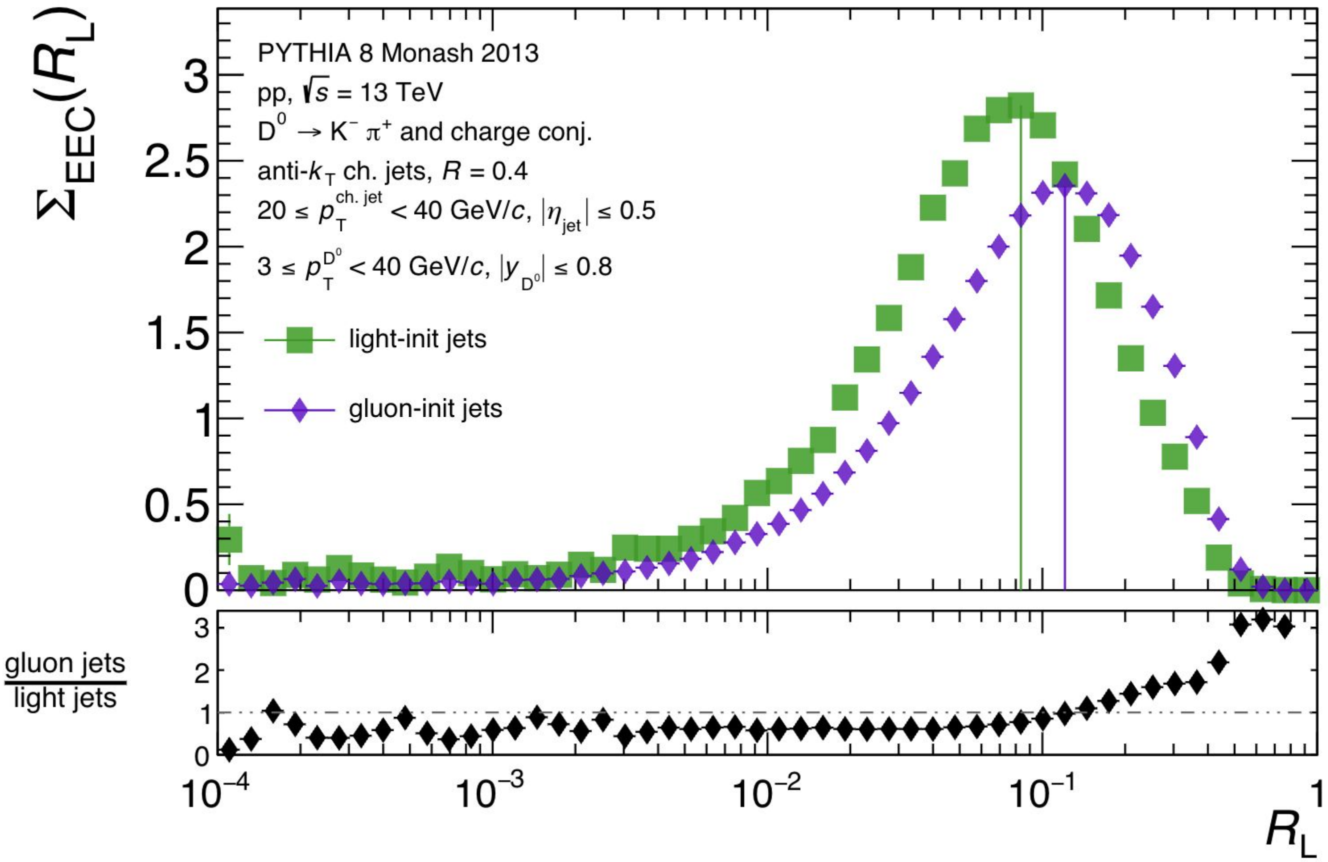


Corrected the EECs for the efficiency of D^0-tagged jet reconstruction and removed the contribution from beauty decays.



Corrected the EECs for detector effects with a bin-by-bin correction method.

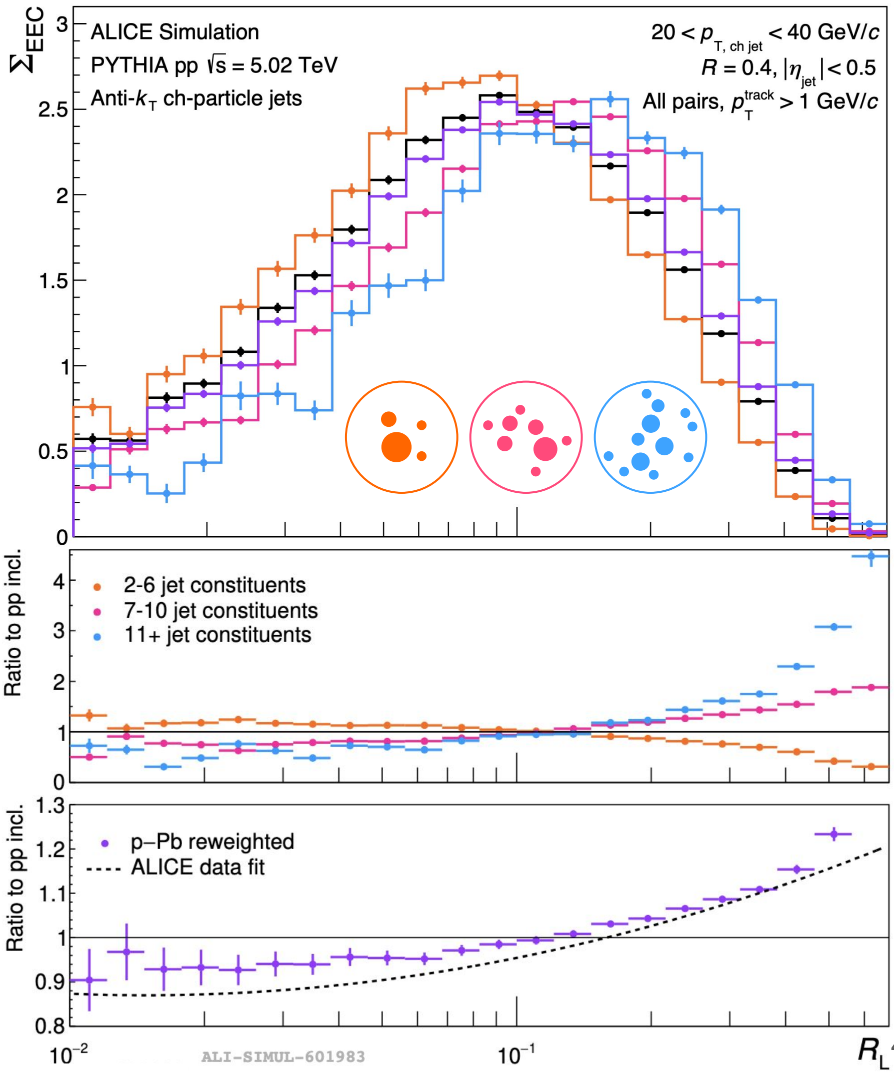
Quark-jet and gluon-jet EECs



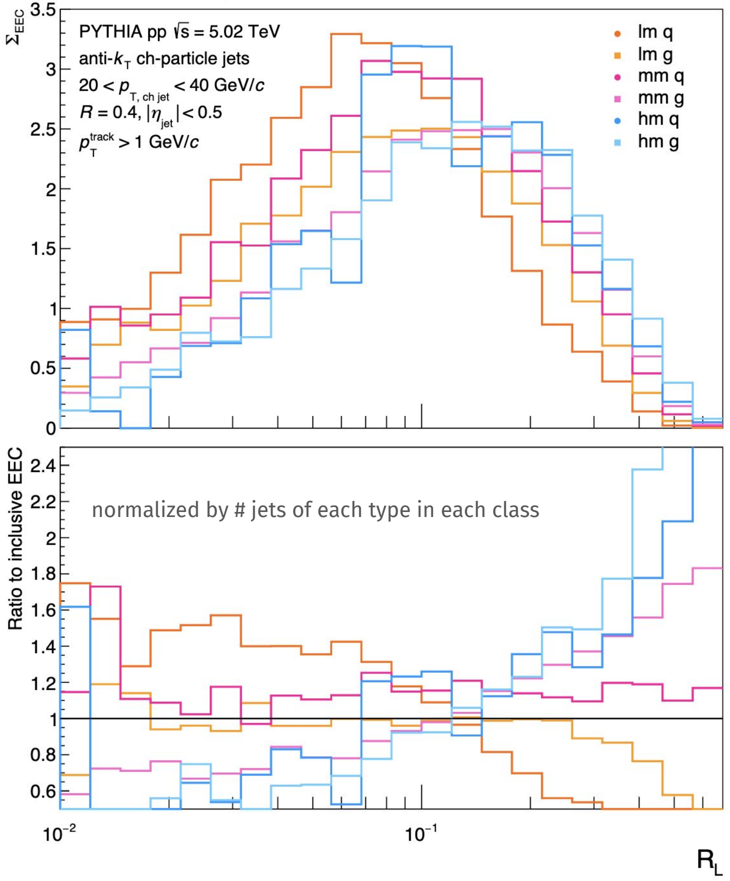
The EEC depends on jet constituent multiplicity.

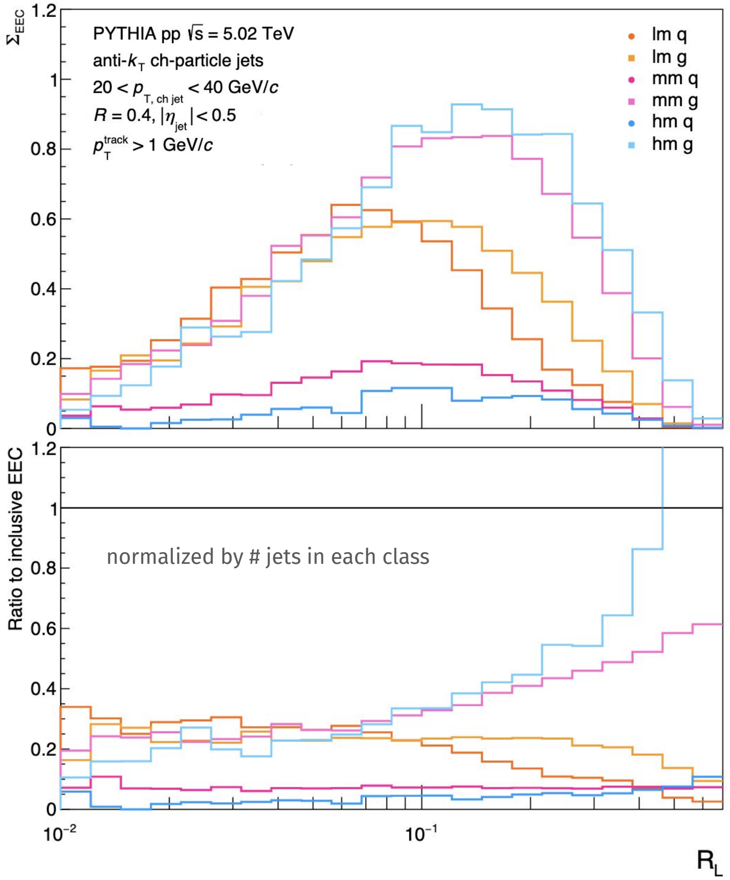
- inclusive EEC (100%)
- EEC from jets with 2-6 tracks (59%)
- EEC from jets with 7-10 tracks (38%)
- EEC from jets with 11+ tracks (3%)

- If we redistribute 12% of jets, we can largely reproduce the measured p-Pb modification
    - 47%, 47%, 6%



Quark- and gluon-jet EECs by jet constituent multiplicity



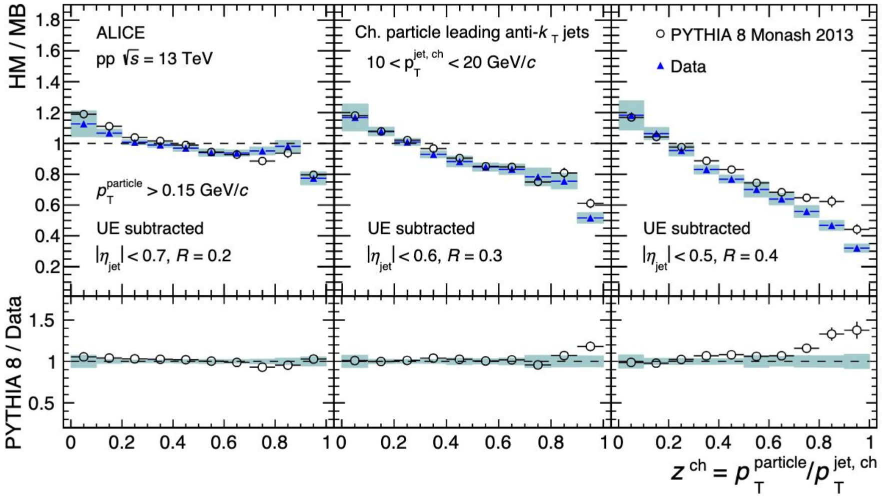


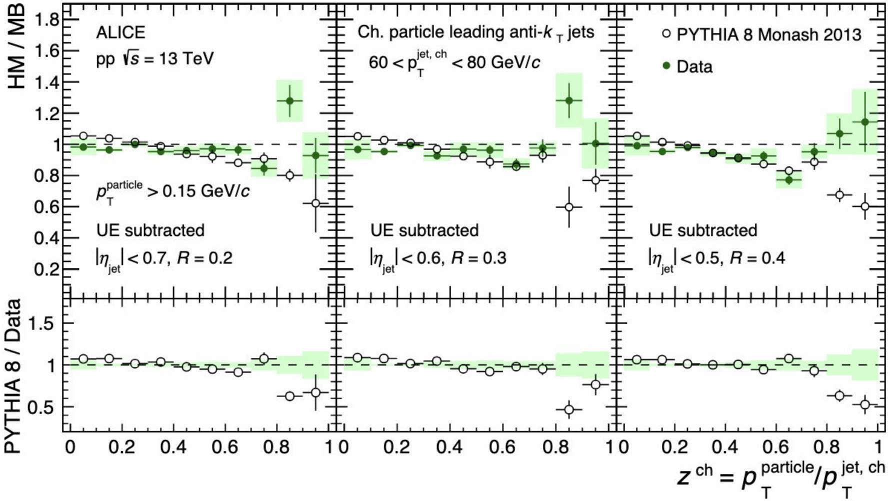
HM/MB z_{ch} in pp

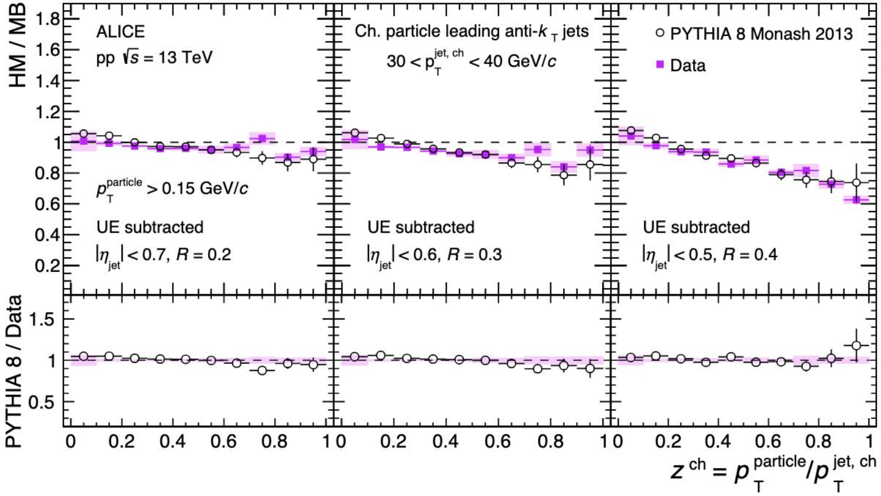
arXiv:2311.13322
ALICE

Fragmentation probability of particles at low z_{ch} is enhanced in HM compared to MB

- more pronounced with increasing jet *R*
- less pronounced at higher jet p_T
- qualitatively described by PYTHIA





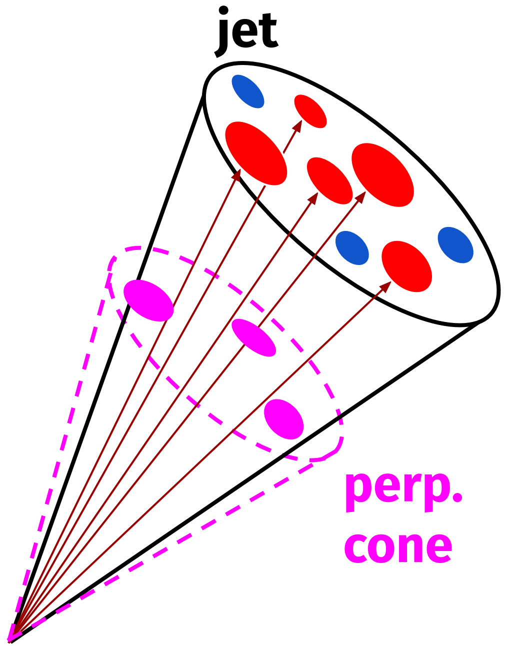


Perp. cone for combinatorial EEC background

- Particles from jet: sig + bkg
- Particles from perp cone: bkg'
- Pairs in the combined cone:

(sig + bkg + bkg')(sig + bkg + bkg') = sig*sig + 2sig*bkg

+ bkg*bkg + $\underbrace{\boxed{\text{2sig*bkg' + 2bkg*bkg'}}}_{\text{jet-perp}}$ + $\underbrace{\boxed{\text{bkg'*bkg'}}}_{\text{perp-perp}}$



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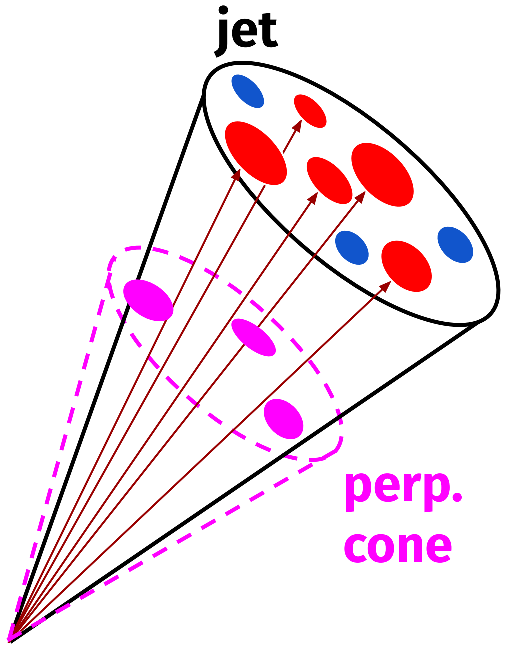
- Pairs in the combined cone:

(sig + bkg + bkg')(sig + bkg + bkg') = sig*sig + 2sig*bkg

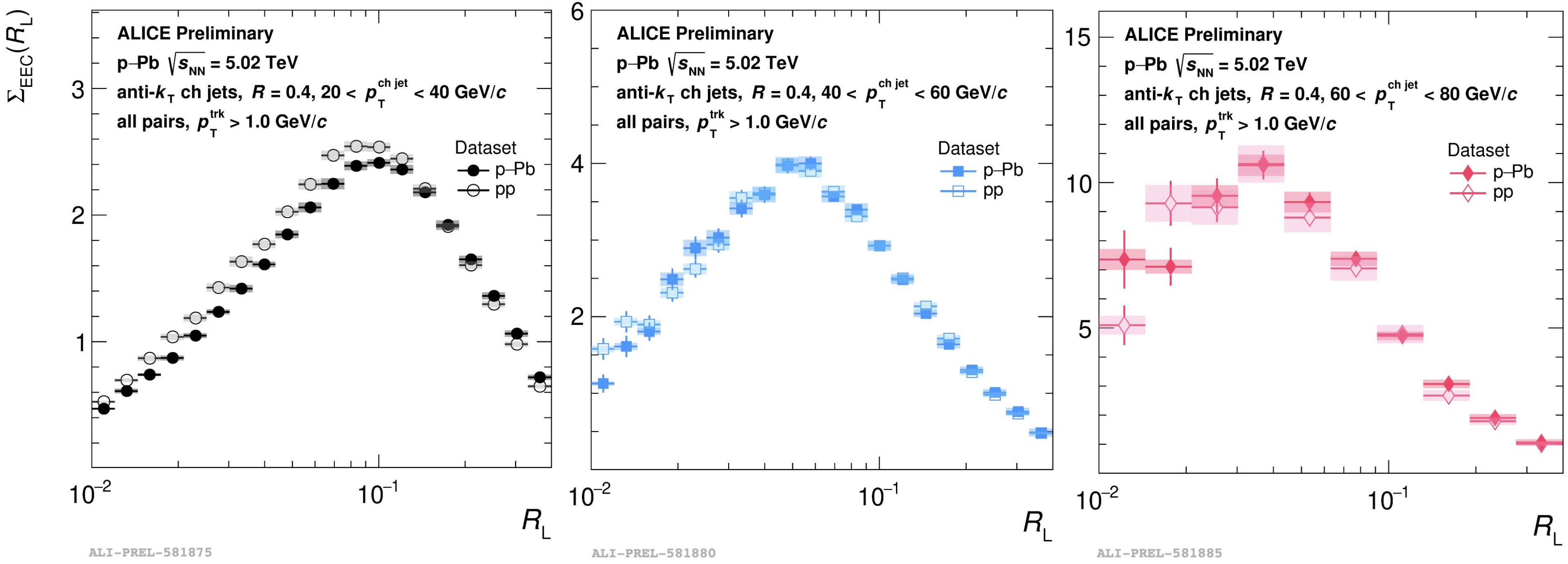
+ bkg*bkg + [2sig*bkg' + 2bkg*bkg'] + [bkg'*bkg']

jet-perp perp-perp

- Sig-bkg pairs: jet-perp — 2 perp-perp
- Bkg-bkg pairs: perp-perp
- **Total background: jet-perp — perp-perp**

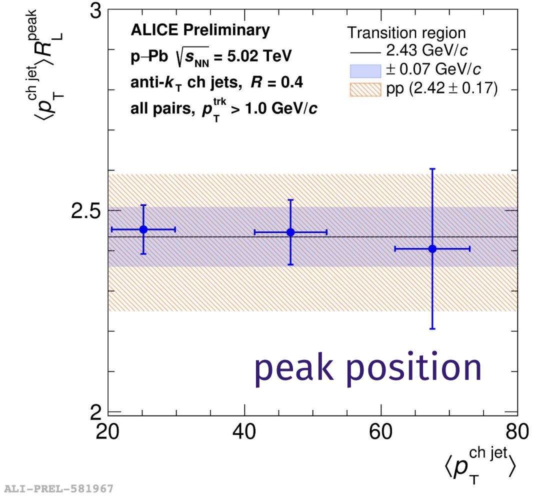


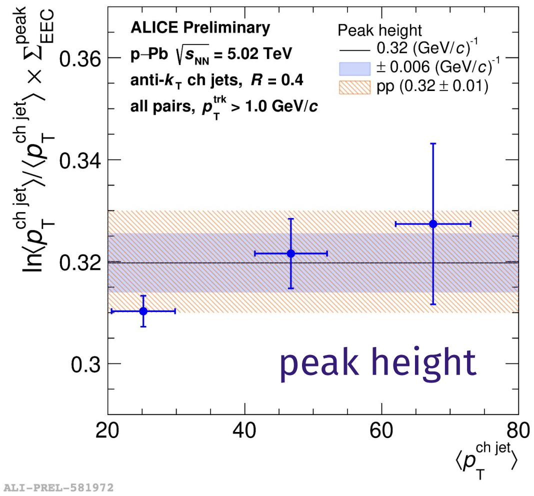
p-Pb and pp comparison

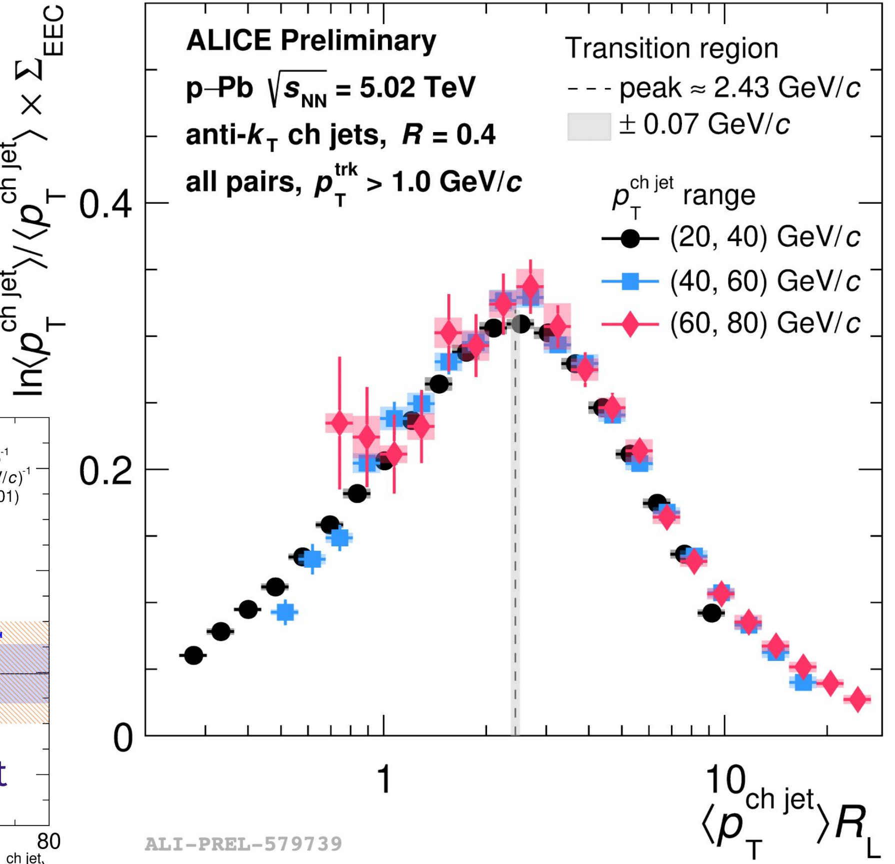


The transition region in p-Pb resembles pp.

- Universality of the EEC peak position across jet p_T and collision system.
- EEC peak height for 20-40 GeV/c jets is slightly lower than for other jets.







p-Pb conclusions

- We know R_{pA} is ~1 for the jet cross-section
- The EEC at low $p_{T,\ ch\ jet}$ shows a modification
- We see that the EEC does not depend on jet rapidity, forward multiplicity, or charge
- p-Pb modification could come from a relative increase in high constituent multiplicity jets

To answer: why does the average jet constituent multiplicity shift to larger values in p-Pb collisions?

ALICE, JHEP 05 (2024) 041