Energy-energy correlators in jets across collision systems with ALICE

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In this talk: differential measurements of EECs

1. EECs in pp: final results
   universal shape independent of jet p_T

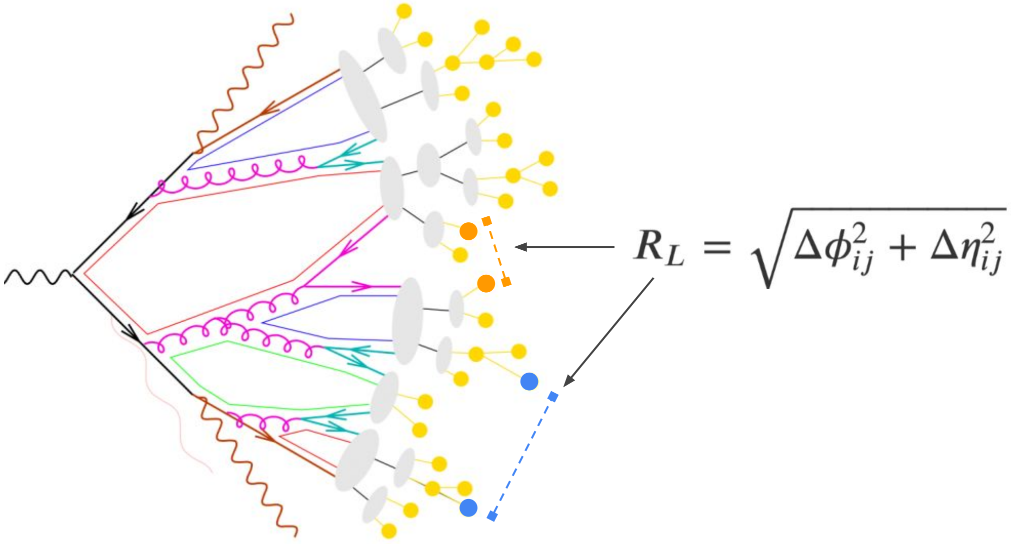
2. First measurement of EECs in D^0-tagged jets
   probing flavor effects

3. First measurement of EECs in p-Pb
   probing EECs in high-multiplicity environments

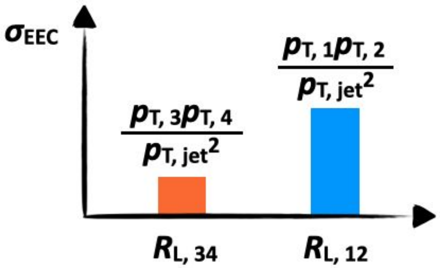
The two-point EEC is calculated from pairs of tracks.

EEC definition:

$$\frac{d\sigma_{EEC}}{dR_L} = \sum_{i,j} \int d\sigma(R'_L) \boxed{\frac{p_{T,i}\, p_{T,j}}{p_{T,jet}^2}} \delta(R'_L - R_{L,ij})$$

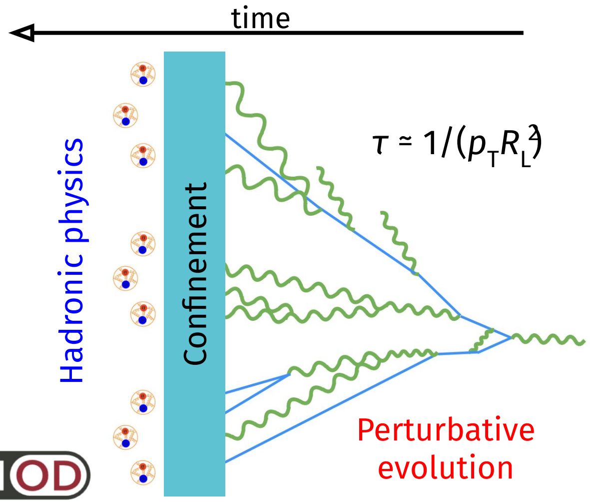


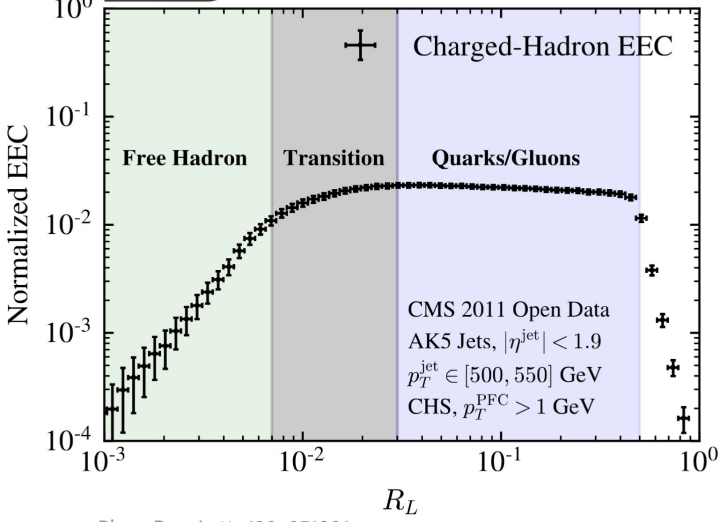
1. For each pair of tracks inside the jet, calculate the energy weight.
2. Count the number of weighted track pairs as a function of R_L.



EECs show a clear transition region.

- Transition between perturbative (large R_L, partonic) and non-perturbative regimes (hadronic, small R_L)
- Time evolution of jet formation is imprinted onto the EEC angular scaling
- EECs let us probe jet formation and confinement!



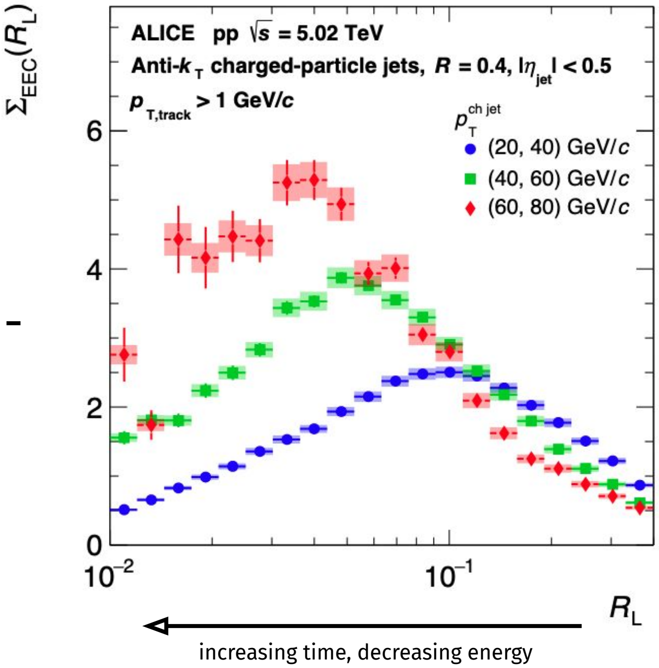


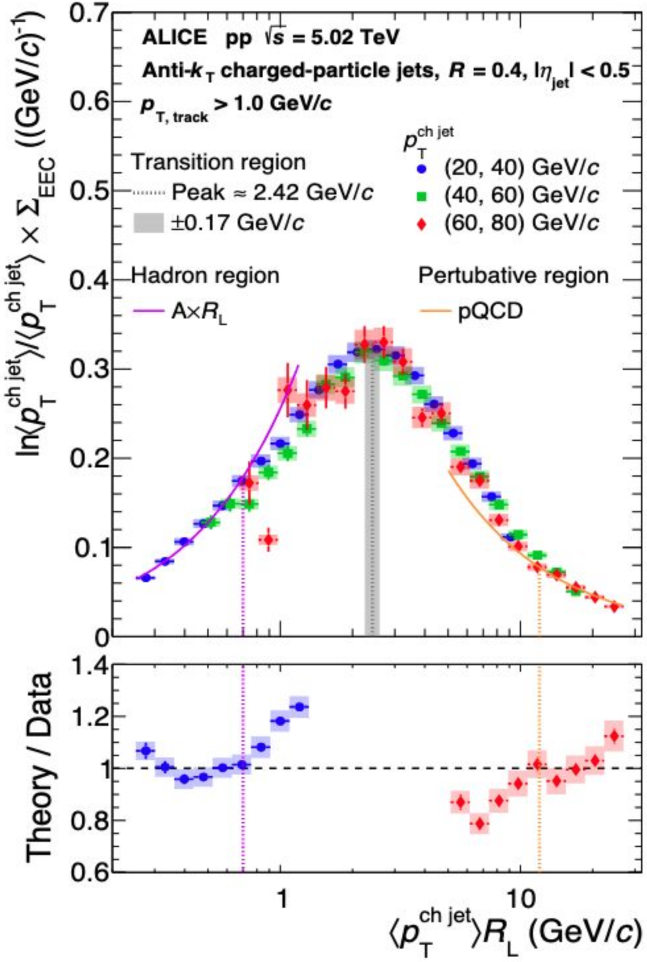
Phys. Rev. Lett. 130, 051901

EECs in pp

Clear separation of perturbative and non-perturbative regions.

EEC peak is visibly dependent on jet p_T.





Universal transition region

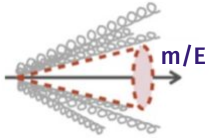
after rescaling the x-axis to $\langle p_T^{\text{ch jet}} \rangle R_L$ (common peak position and height).

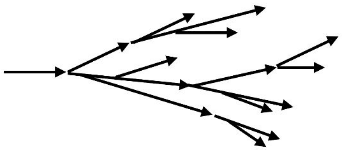
on arXiv! arXiv:2409.12687 [hep-ex]

pQCD: arXiv:2205.03414

How does the shower depend on flavor?

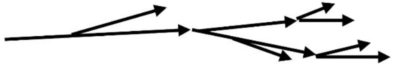
- At the largest R_L, the scaling behavior in heavy-flavor jets is identical to light quark jets.
- **Turnover exhibits a mass dependence!**
    - Flavor effects can be probed with ratios to inclusive jets.
- Change of shape at small angles is a consequence of the dead cone.



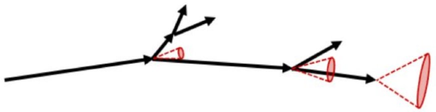


gluon jets

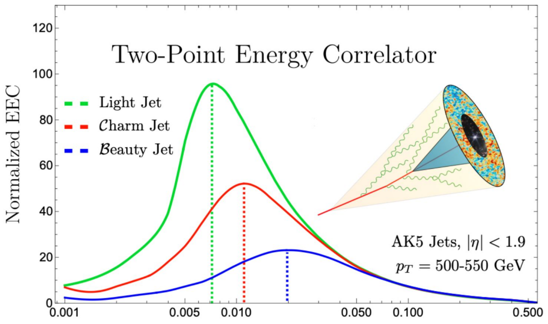
$$\frac{C_A}{C_F} = \frac{9}{4}$$

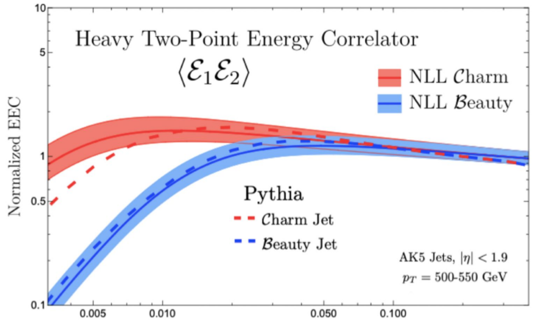


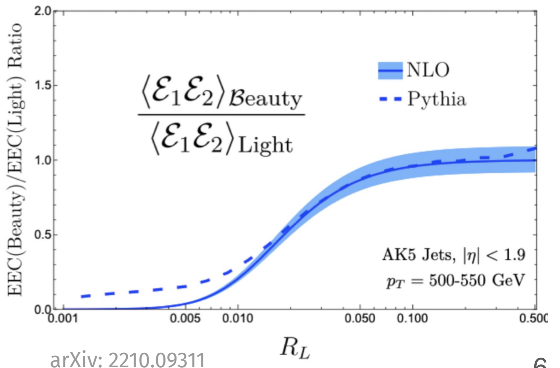
quark jets



heavy quark jets







arXiv: 2210.09311

Comparing D^0-tagged jet to inclusive jet EECs

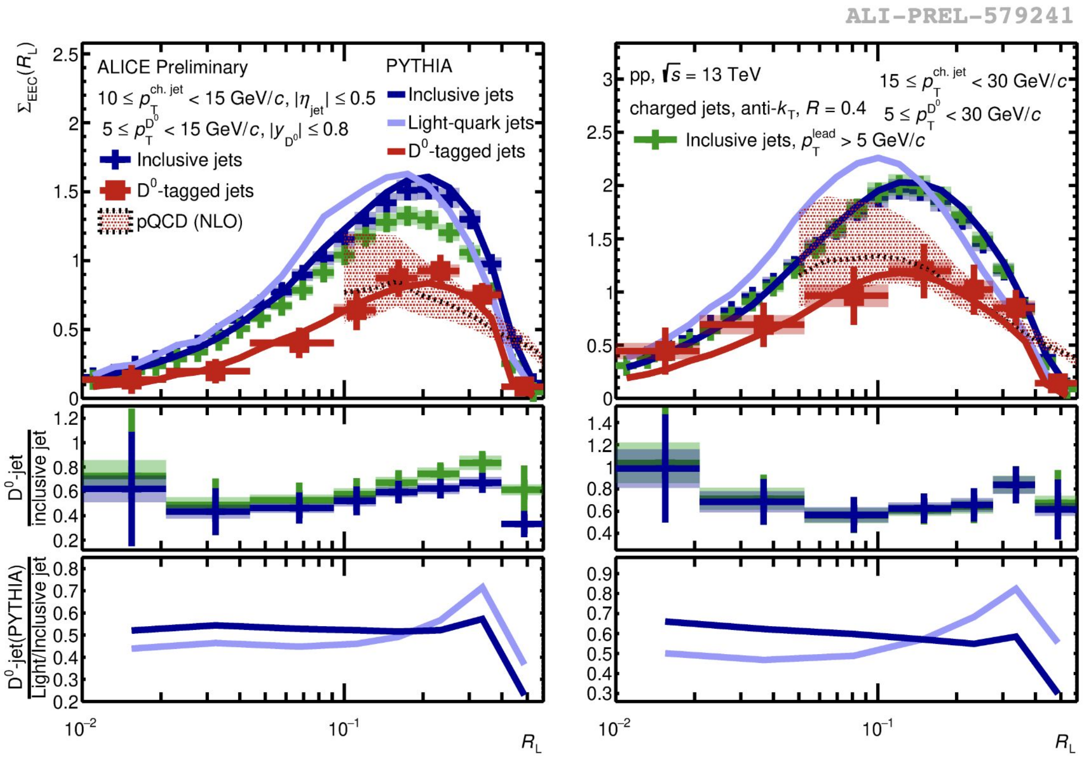
Upper panel:

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

From the ratios:

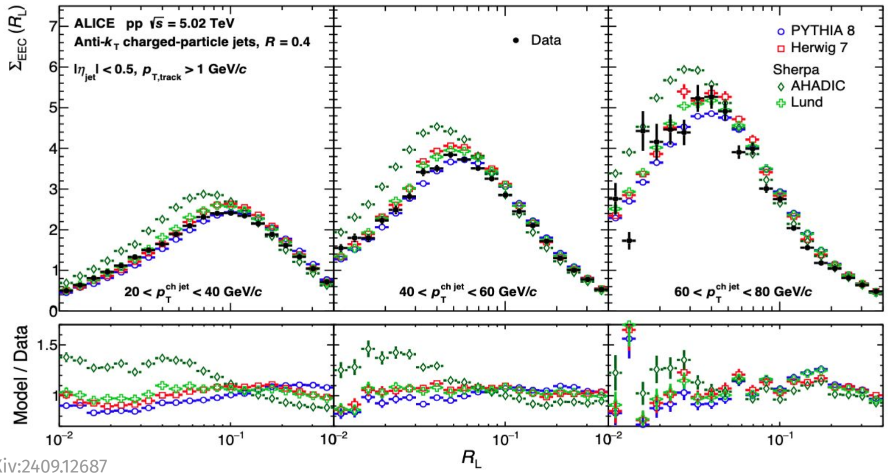
- D^0/inclusive → mass + Casimir
- D^0/LF → isolated mass effects

Clear mass effect in D^0 jets!

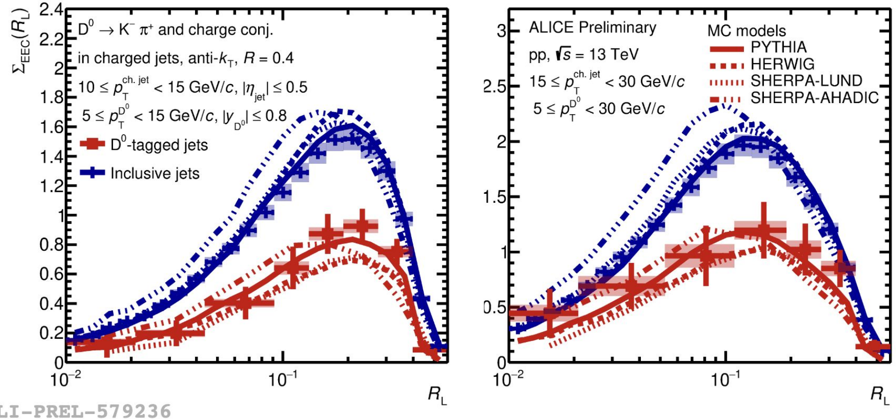


Probing hadronization with pp EECs

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



arXiv:2409.12687



ALI-PREL-579236

Inclusive jets:

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

Heavy flavor jets:

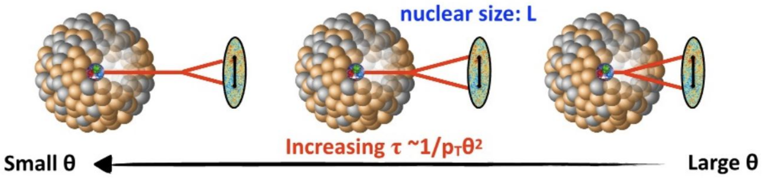
- *data favors PYTHIA's implementation*
- Herwig overpredicts inclusive jet EECs; underpredicts in HF
- Sherpa Lund underpredicts the data
- AHADIC fails to describe the peak

Cluster hadronization for higher p_T jets, string-breaking models for D^0 jets?

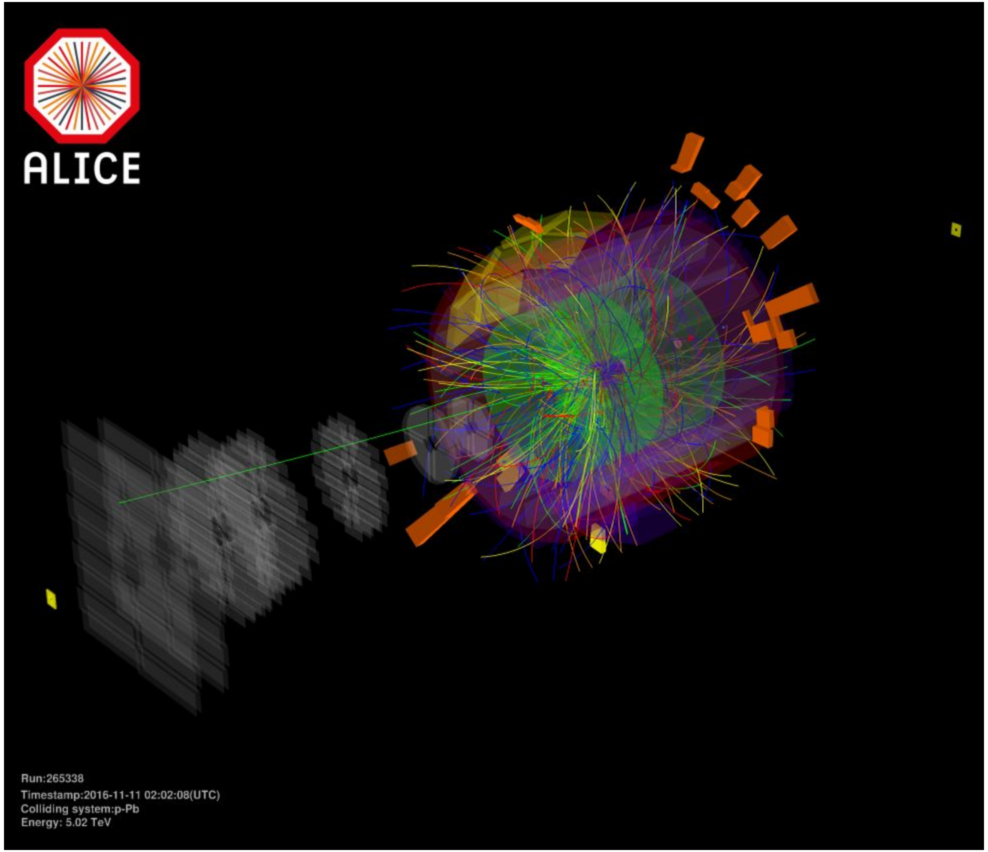
Are EECs modified in p-Pb?

Differences from pp:

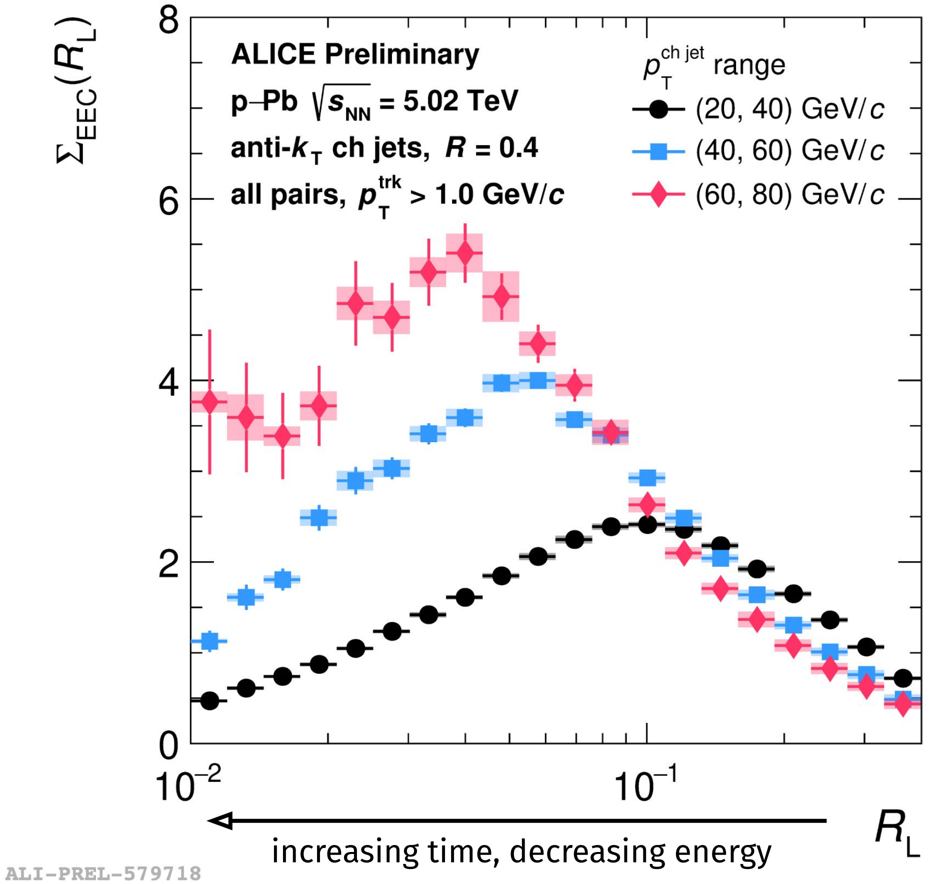
- initial state (nPDF, isospin)
- final-state interactions?
- comovers? collectivity??



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



EECs in p-Pb have the same overall shape as pp.



About the data:

- R = 0.4 charged-particle jets
- $p_T^{ch\ jet}$ in [20, 80] GeV/c
- threshold cut: p_T^{trk} > 1 GeV/c

These are subtracted for UE and corrected for detector effects:

- background subtraction for jet p_T and EEC distribution
- bin-by-bin correction for detector effects

EEC measurements in more complex systems require background subtraction techniques.

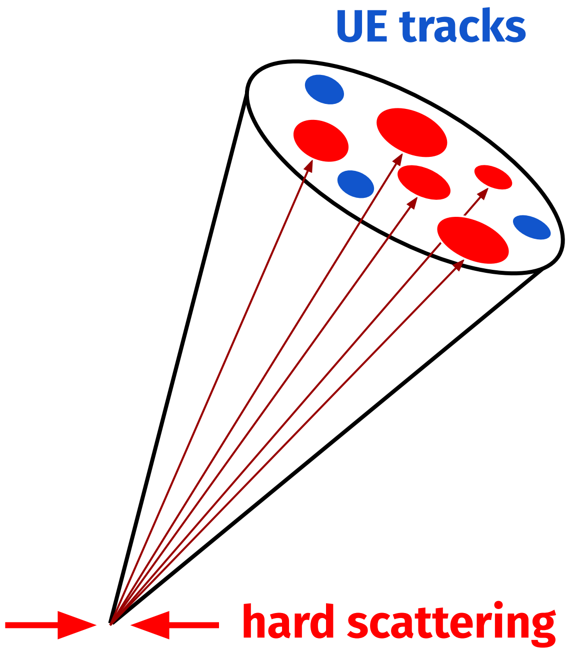
1. Subtract UE energy density from the jet p_T:

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

2. Correct the EEC distribution for combinatorial background:

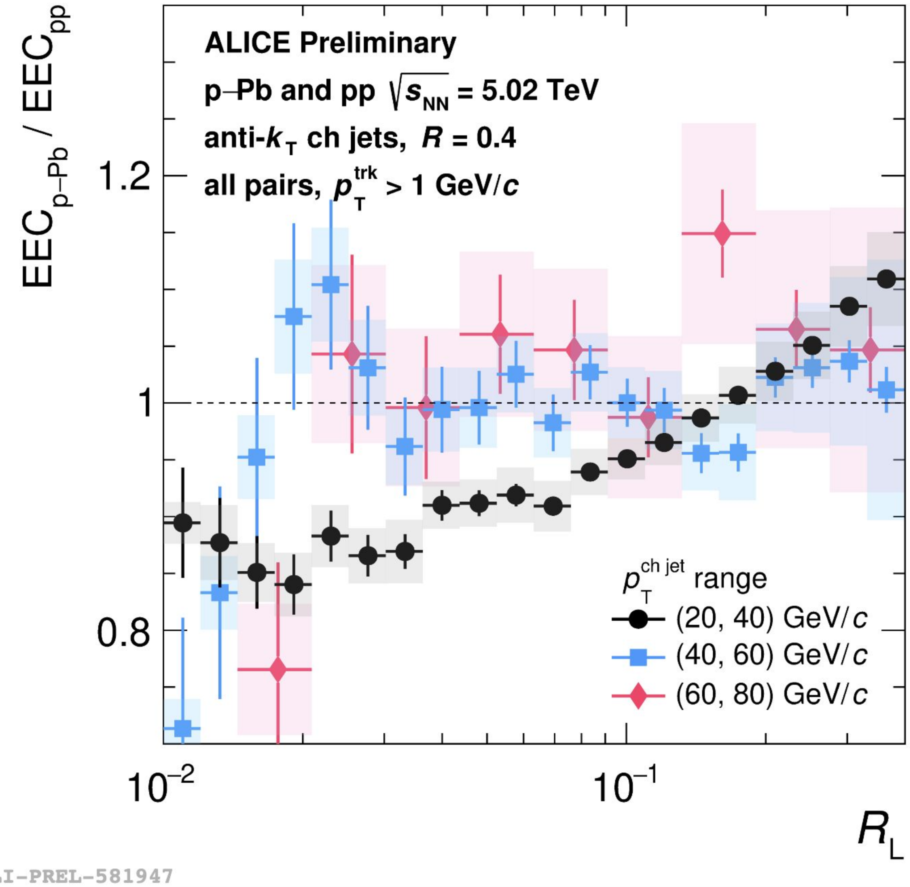
   - signal-signal (what we want!)
   - signal-background
   - background-background

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



These subtraction steps are also performed for the pp baseline.

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

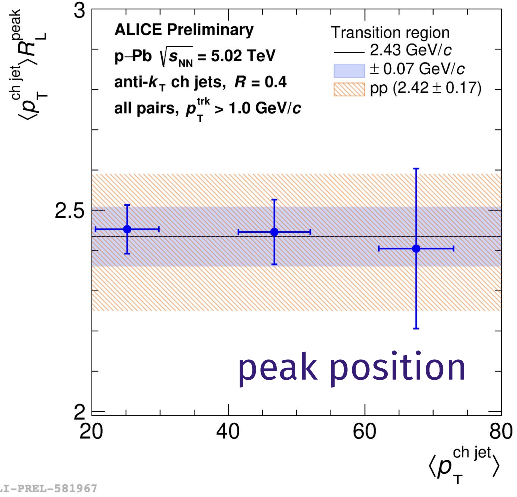


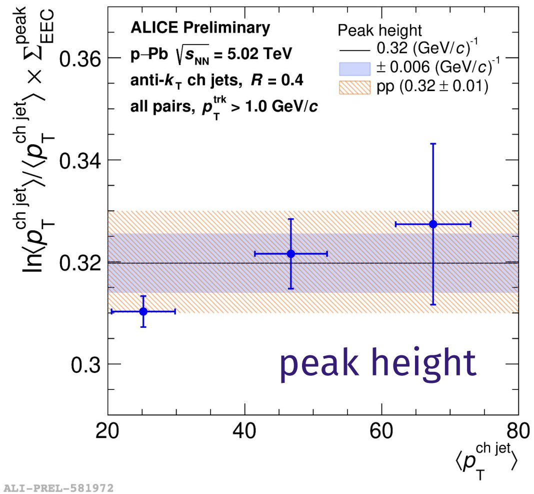
- **Significant difference between EECs in p-Pb compared to pp!**
  - jet structure appears to be altered only in the lowest jet p_T range
- Initial state effect?
  - some models lead to a qualitatively similar effect
- Final state effect?
  - modification is qualitatively consistent with ALICE measurement* of HM/MB z_{ch} in pp

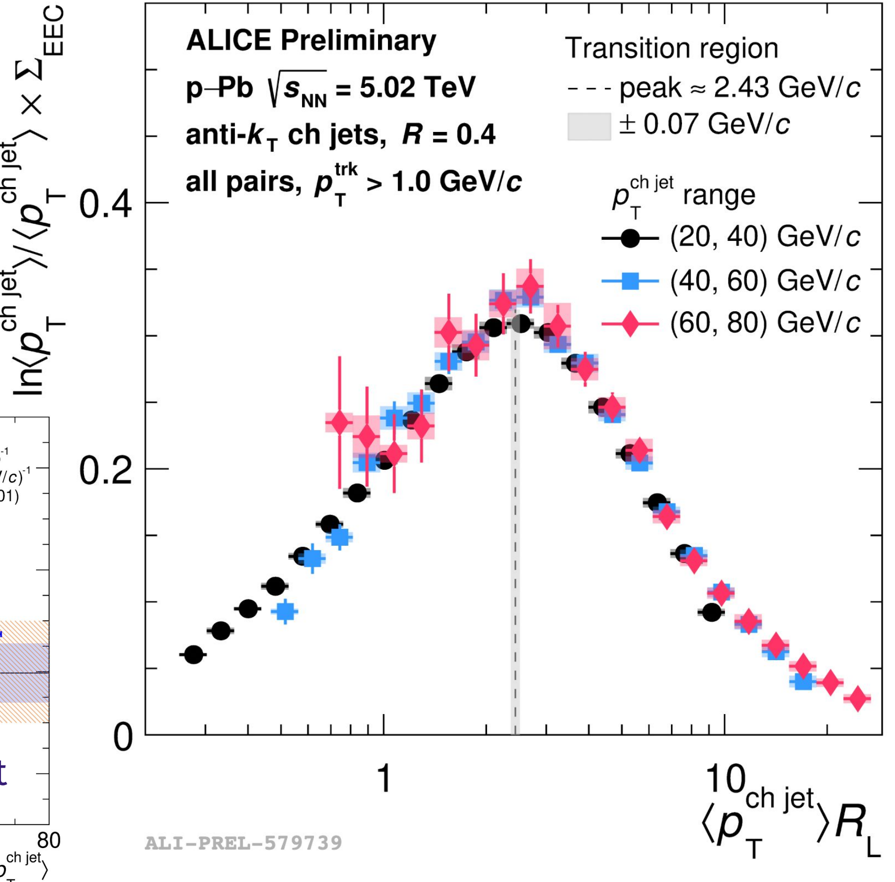
* arXiv:2311.13322

The transition region in p-Pb resembles pp.

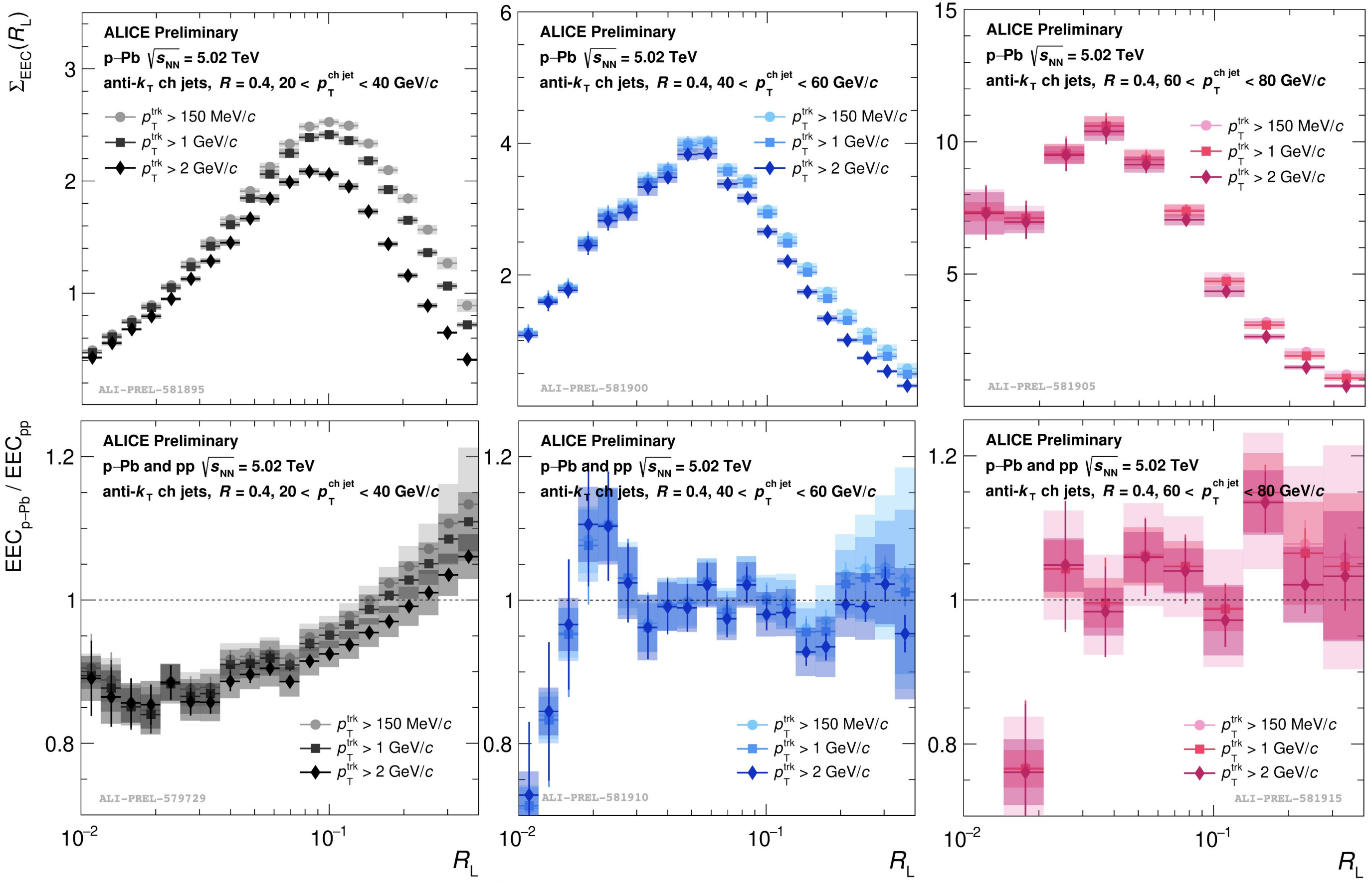
- Universality of the EEC peak position across jet p_T and collision system.
- EEC peak height for 20-40 GeV/c jets is slightly lower than for other jets.







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

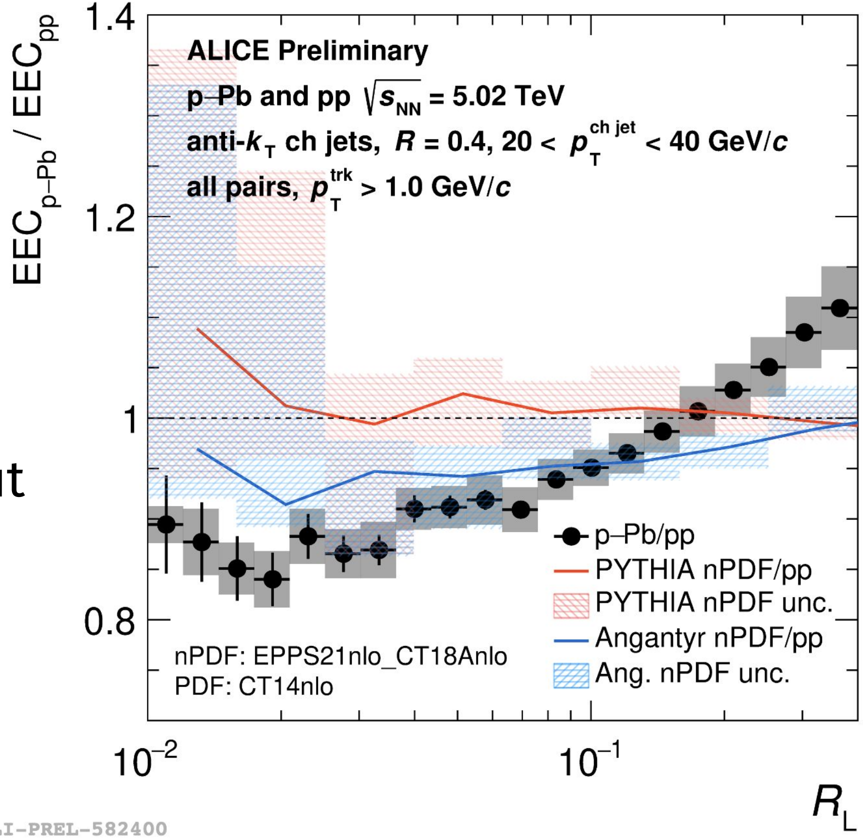
Track cut modifies the enhancement in ratio

- but not the small-R_L suppression

Suggests that the origin of the effect lies in softer interactions at small x!

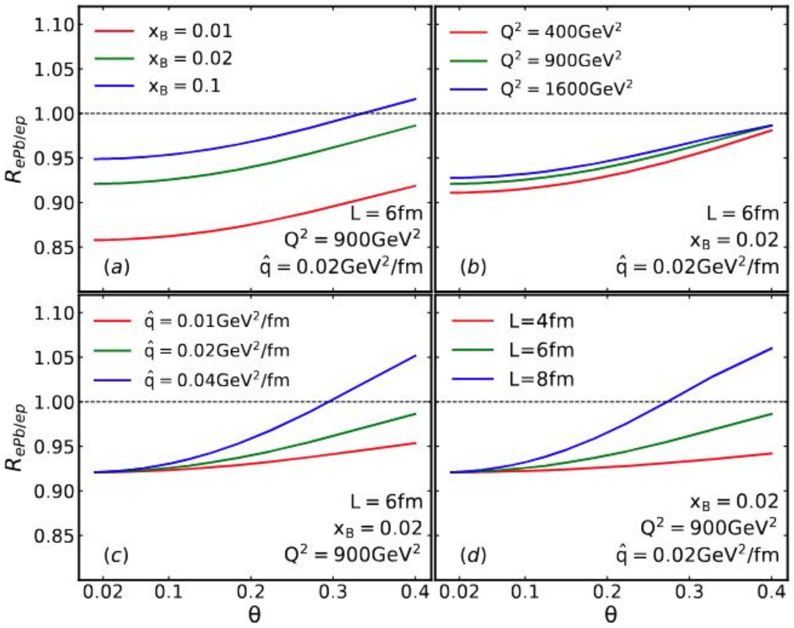
nPDF models do not fully capture the enhancement and suppression seen in data.

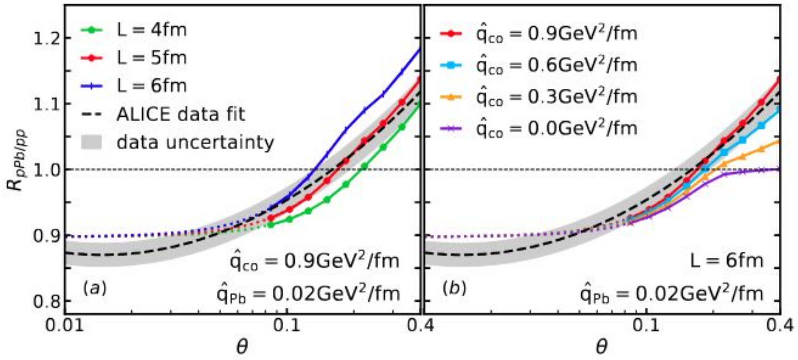
- Comparing to PYTHIA with an nPDF turned on, and PYTHIA Angantyr
- PYTHIA results use:
    - nPDF: EPPS21nlo_CT18Anlo
    - PDF: CT14nlo
- nPDFs are within ~1σ at small R_L – but these are very large uncertainties
- Neither captures the behavior at large R_L



Higher-twist formalism calculations come closer to reproducing the data.

- HT calculations of final-state interactions from Fu et al.*
  - $p_T^{\text{ch jet}}$ of 30 GeV/c
  - R_{pPb} is chosen to be 0.85 (for x=0.01)
  - $\hat{q}_{\text{CNM}}$ is 0.02 GeV^2/fm (BDMPS 1997)
  - $\hat{q}_{\text{co}}$ and L are varied
- Incorporating interactions from comovers reproduces the observed modification.

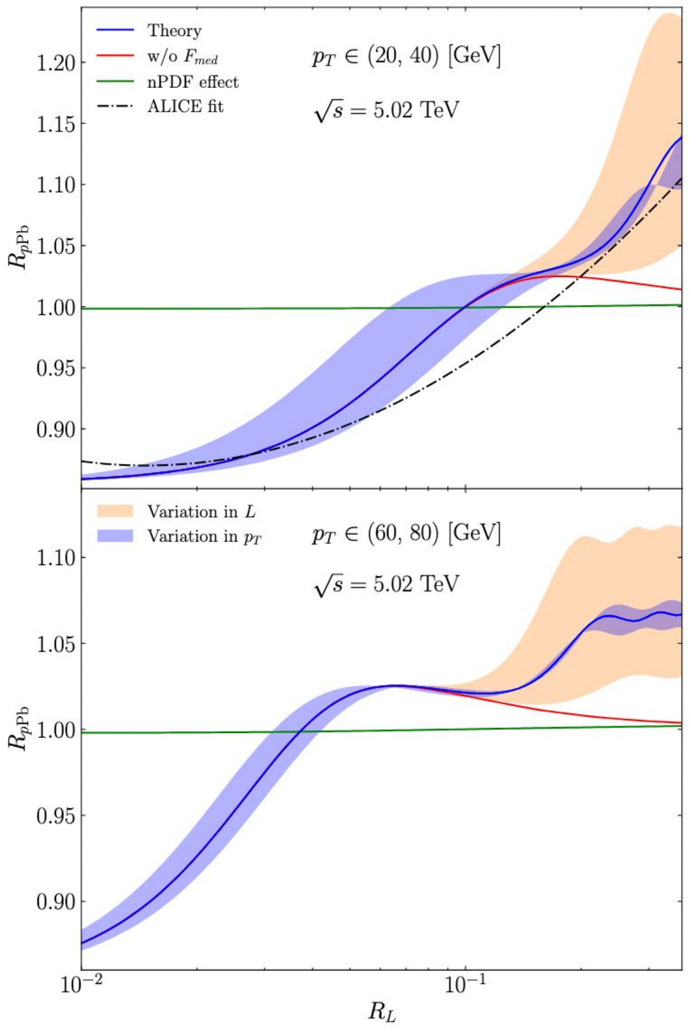




* arXiv:2411.04866 [nucl-th]

Multiple scattering and TMD fragmentation can also reproduce the data.

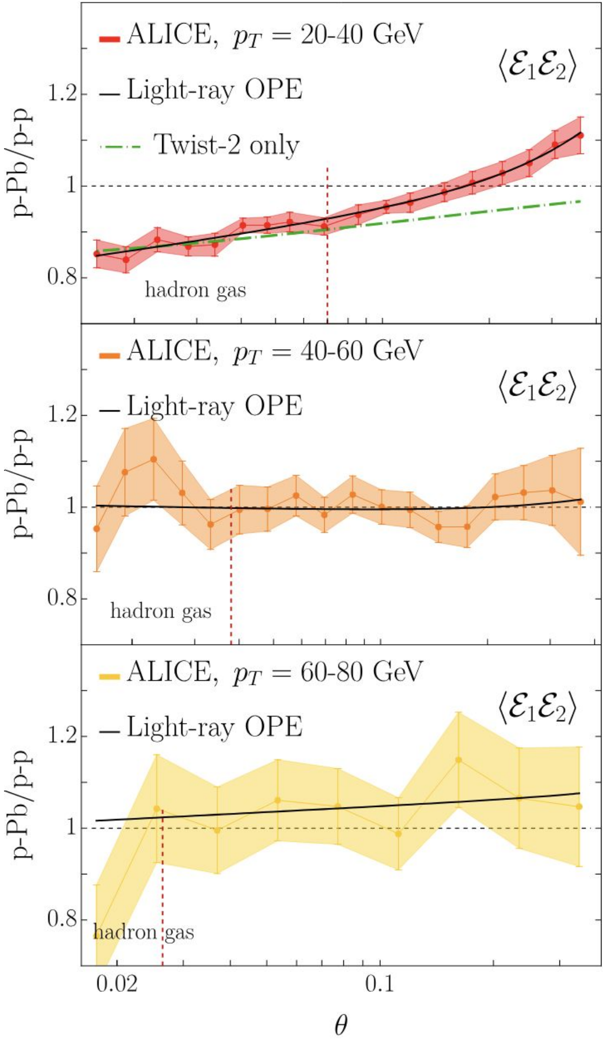
- Non-perturbative model from Barata et al.*
  - HT/power correction to the jet's perturbative evolution ($\hat{q}$ and L)
  - multiple scattering of jet partons (transverse momentum broadening)
  - $\hat{q}_{CNM}$ = 0.02 GeV^2/fm, L = 3 fm
- Momentum broadening is crucial for EEC suppression in this model.



* arXiv:2411.11782 [hep-ph]

A twist-4 correction to the light-ray operators could also play a role.

- Light-ray OPE approach from Andres et al.*
  - twist-4 corrections to EEC operator
  - logarithmic modifications to q-g fractions (fit indicates 30-70, consistent with nPDFs)
  - predicts the p_T-dependent diminishing of the EEC modification in p-Pb
- Unfortunately I am a little out of my depth here!



* arXiv:2411.15298 [hep-ph]

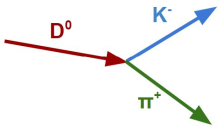
Summary and outlook

- Universality of EEC shape and turnover in pp
- EECs are altered in HF jets
  - dramatic reduction in amplitude – clear flavor effect
- EECs are modified in p-Pb
  - modification is not explained by purely initial-state models!
  - recent theoretical calculations provide plausible explanations

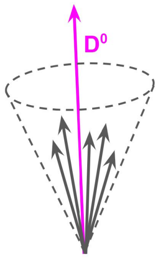
Backup

D^0 reconstruction steps

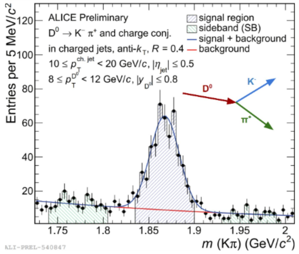
D^0 candidates were reconstructed from daughter tracks using topological and particle identification selections ($D^0 \rightarrow K^- + \pi^+$, and charge conjugates).

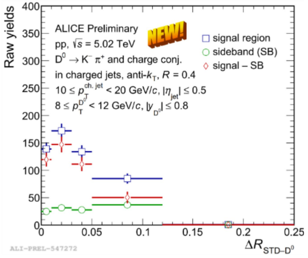


D^0-tagged charged jets were created using the anti-k_T algorithm (R=0.4) for each candidate.

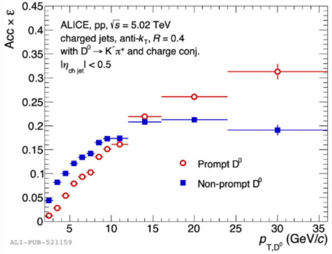


Invariant mass analysis was performed to remove combinatorial $K^-\pi^+$ pairs surviving the D^0 selections.





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.

Perp. cone for combinatorial EEC background

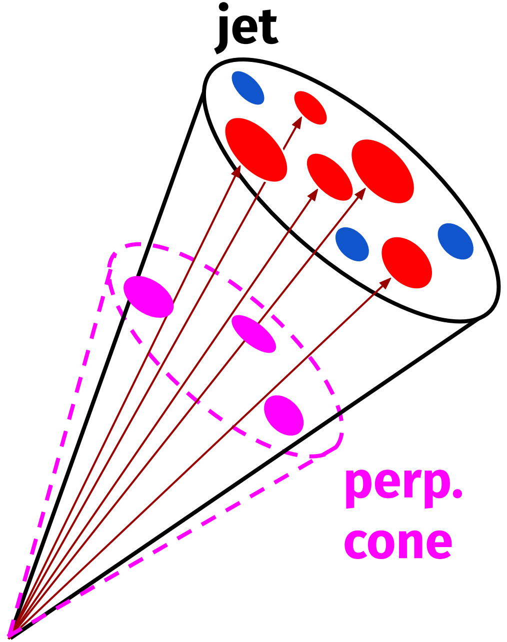
- Particles from jet: sig + bkg
- Particles from perp cone: bkg'
- Pairs in the combined cone:

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

+ bkg*bkg + 2sig*bkg' + 2bkg*bkg' + bkg'*bkg'

jet-perp (2sig*bkg' + 2bkg*bkg')

perp-perp (bkg'*bkg')



Perp. cone for combinatorial EEC background

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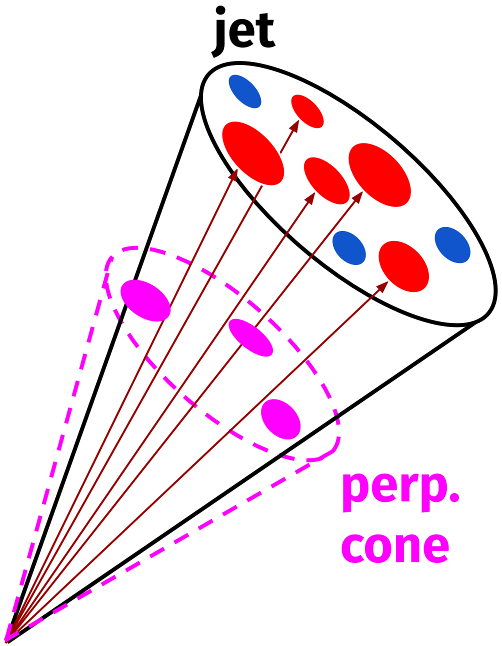
- Pairs in the combined cone:

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

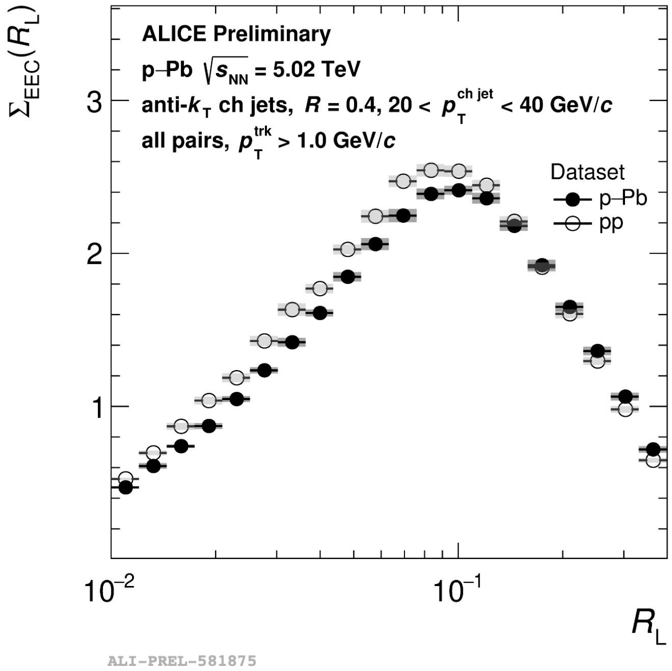
+ bkg*bkg + 2sig*bkg’ + 2bkg*bkg’ + bkg’*bkg’

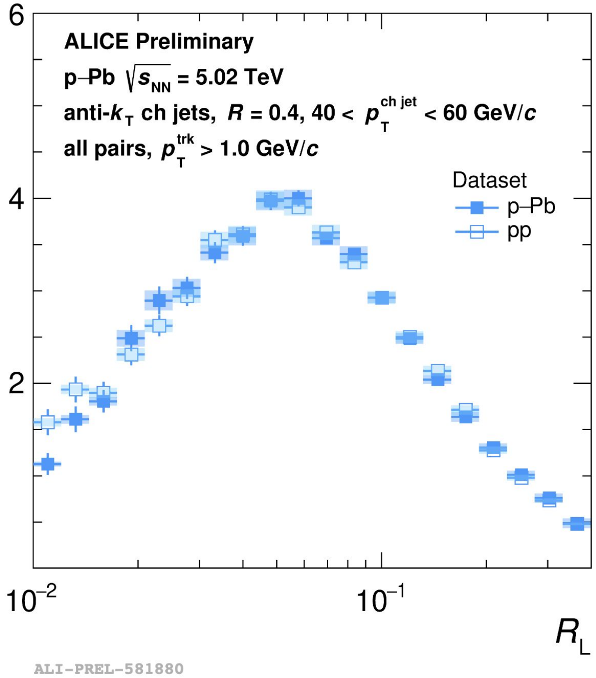
jet-perp (2sig*bkg’ + 2bkg*bkg’) perp-perp (bkg’*bkg’)

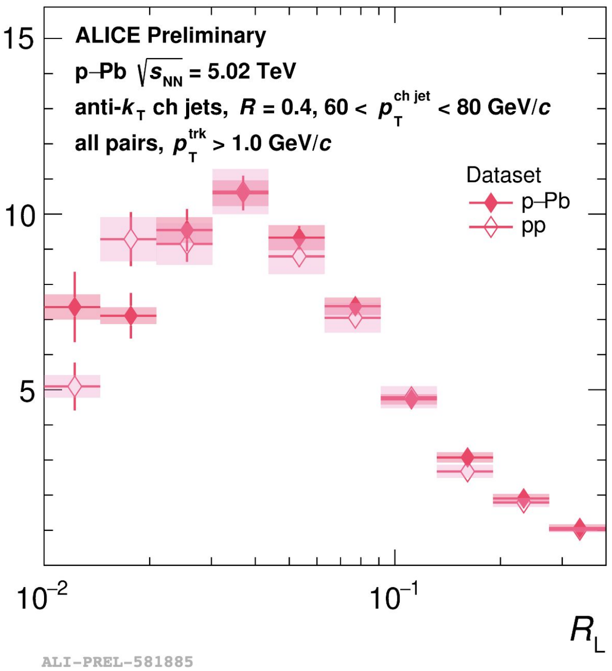
- Sig-bkg pairs: jet-perp — 2 perp-perp
- Bkg-bkg pairs: perp-perp
- **Total background: jet-perp — perp-perp**



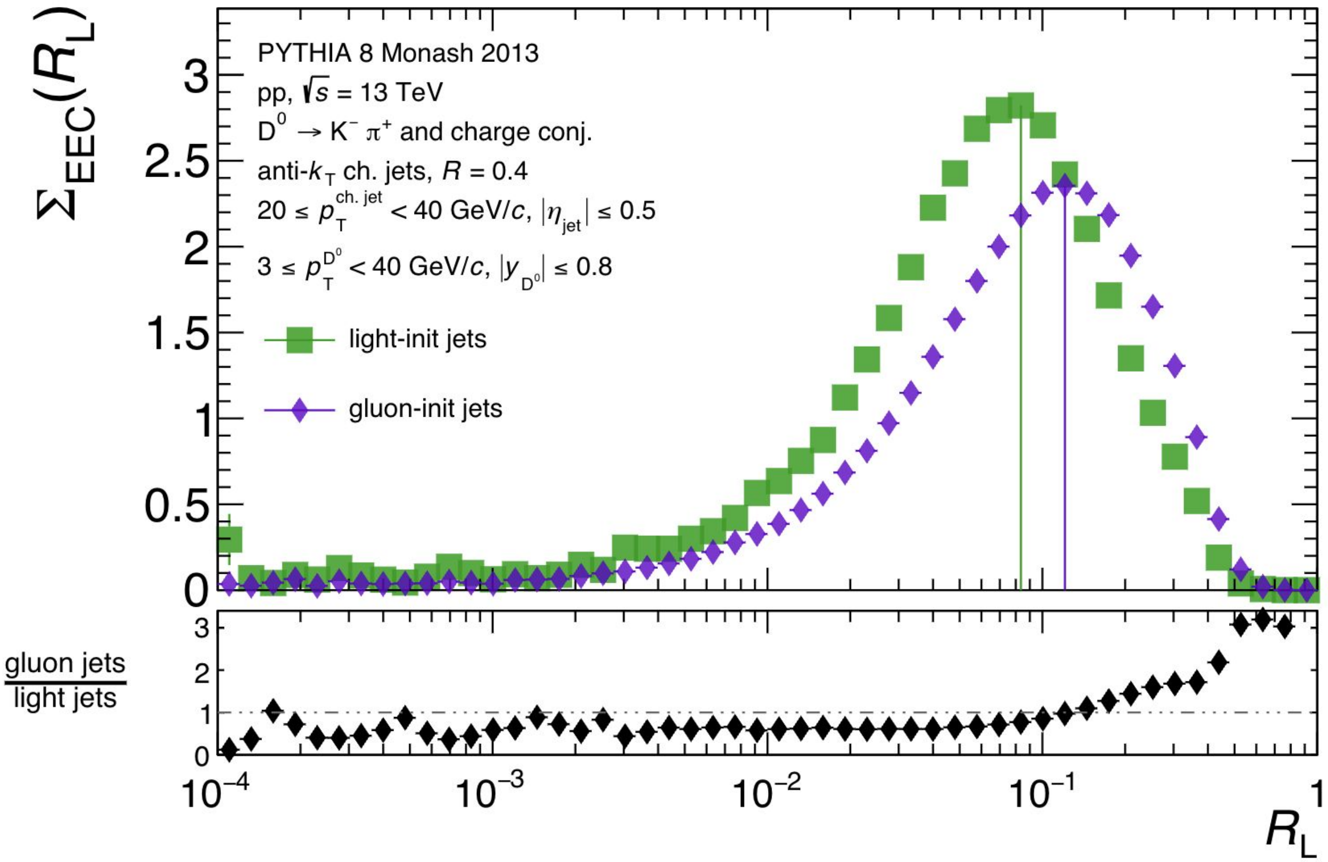
p-Pb and pp comparison







Quark-jet and gluon-jet EECs



Quark-jet and gluon-jet and D^0-tagged jet EECs