Energy-energy correlators in jets across collision systems

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Jet substructure observables describe the dynamics of high-energy partons and their confinement into hadrons.

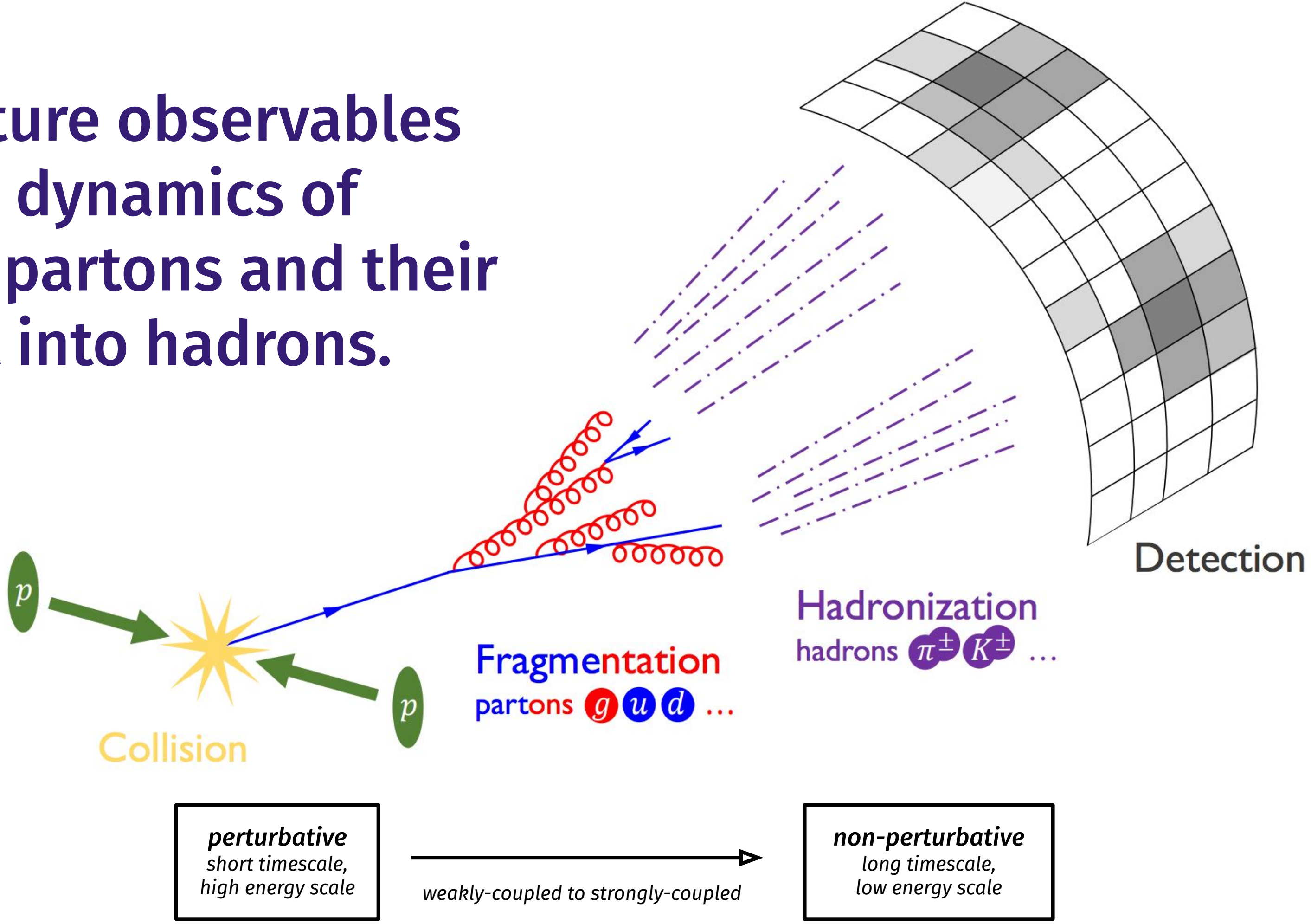


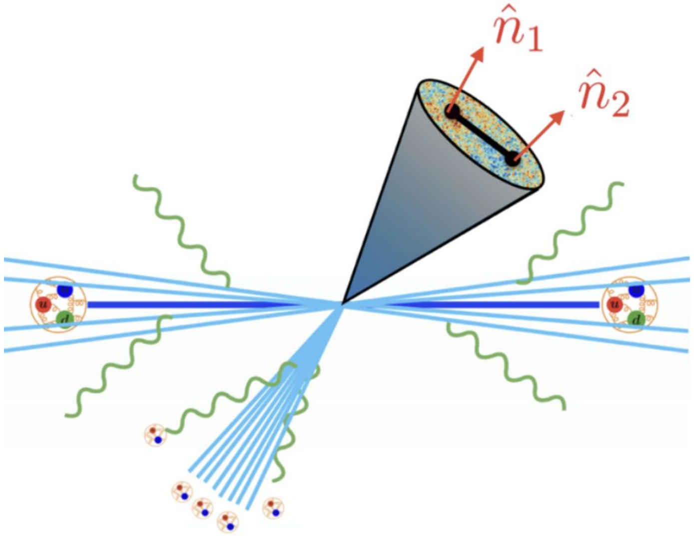
image from Erik Metodiev

Energy correlators are a novel jet substructure observable.

Energy-energy correlators measure statistical correlations of energy flow within jets.

- correlations of energy flow operators
- IRC-safe and well-defined in QFT!
- no need for declustering or grooming

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



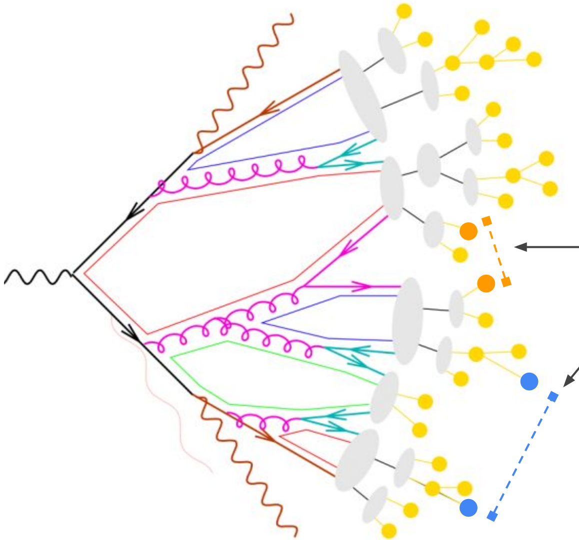
EECs are fundamental theoretical objects *and* experimentally measurable!

Phys. Rev. D 111, L011502 (Lee, Meçaj, Moult)

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

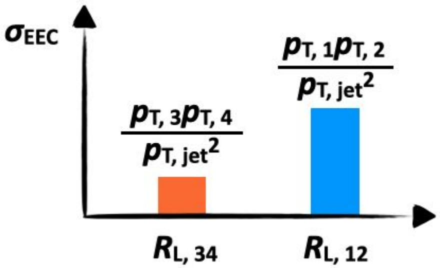
EEC definition:

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



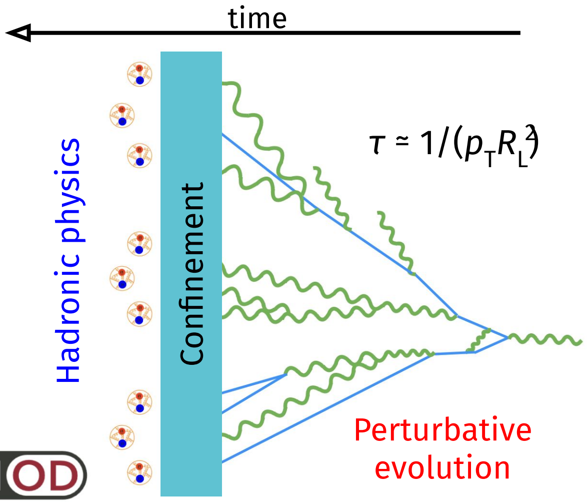
$$R_L = \sqrt{\Delta\phi^2_{ij} + \Delta\eta^2_{ij}}$$

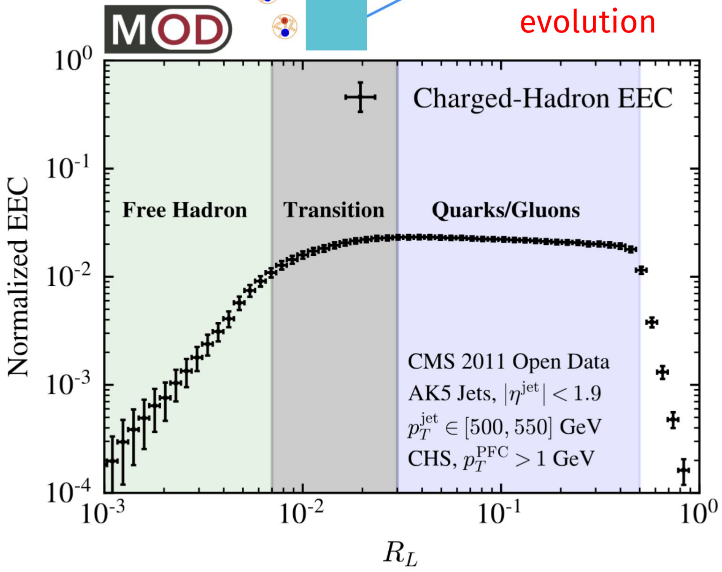
1. For each pair of tracks inside the jet, calculate the energy weight.
2. Count the number of weighted track pairs as a function of R_L.



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 (Komiske, Moult, Thaler, Zhu)

In this talk: differential measurements of EECs

1. EECs in pp
   probing hadronization

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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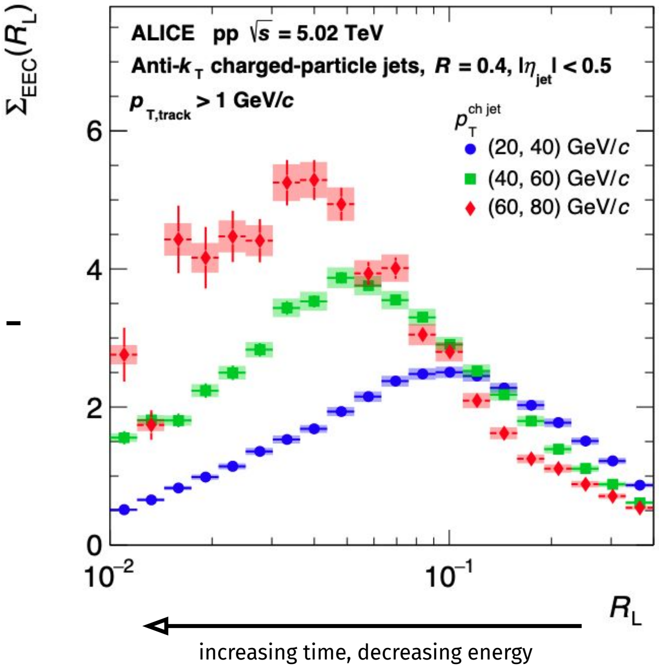
EECs in pp

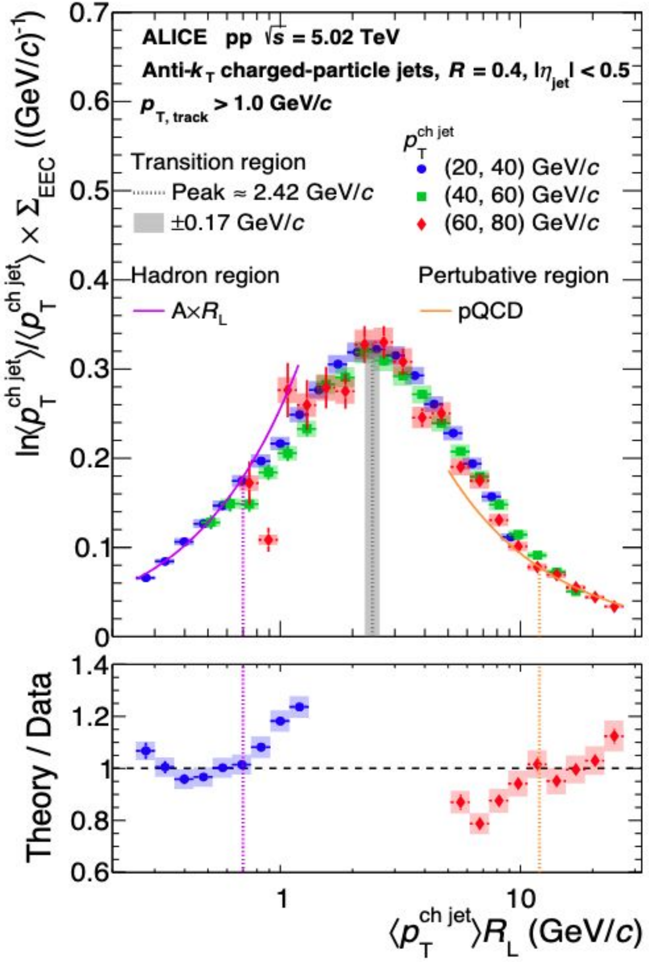
Clear separation of perturbative and non-perturbative regions.

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).

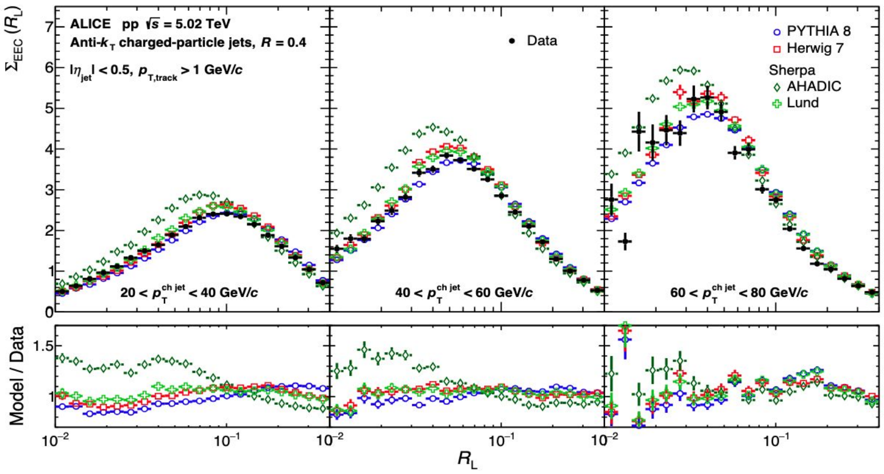
arXiv:2409.12687





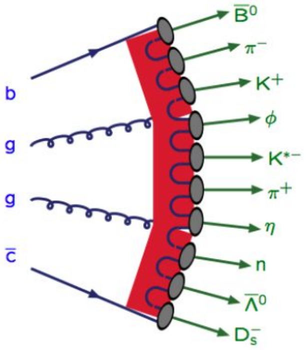
pQCD calculation from K. Lee: arXiv:2205.03414

We can probe hadronization with pp EECs…

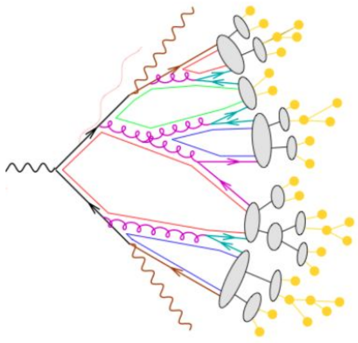


- PYTHIA & Herwig perform well, *Herwig captures peak position*
- Sherpa Lund does well, AHADIC does not
- *both cluster models peak at smaller R_L*

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



string models



cluster models

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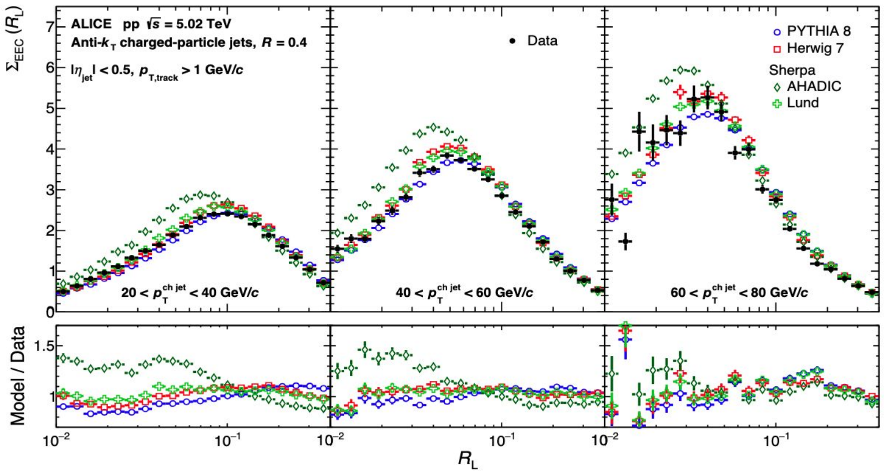

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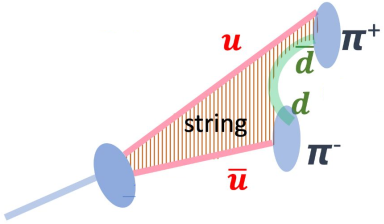
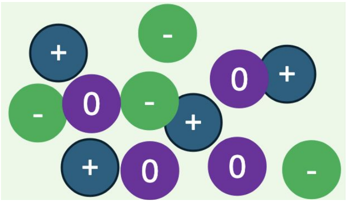
Lund string models: PYTHIA 8, Sherpa Lund
Cluster models: Herwig 7, Sherpa AHADIC

... 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



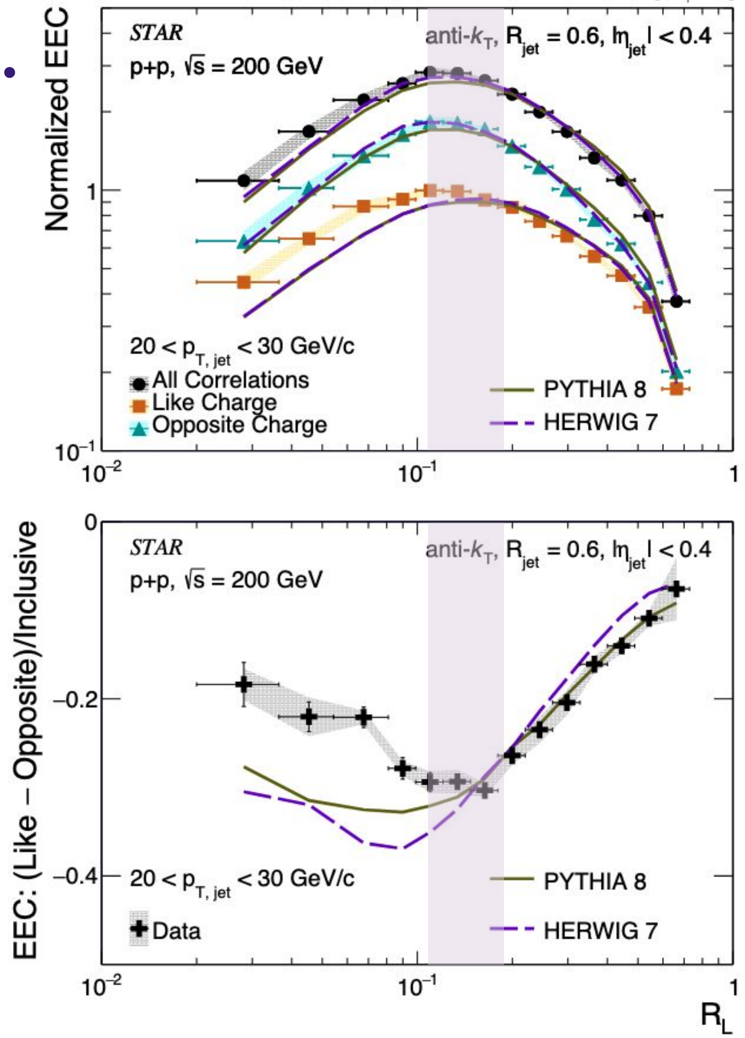
- Are there more unlike-sign or like-sign correlations? $\langle \mathcal{E}_+\mathcal{E}_- \rangle$ or $\langle \mathcal{E}_+\mathcal{E}_+ \rangle + \langle \mathcal{E}_-\mathcal{E}_- \rangle$
- Exploring correlations in angle and charge *increases sensitivity to different hadronization mechanisms.*

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

STAR measured charged correlators.

- The charged EECs align in the perturbative region with MC predictions.
- MCs underpredict like-sign EEC at small R_L!
- Cannot resolve the predicted shift in EEC peak

- Herwig (cluster) and PYTHIA (string) predict similar behavior in the charge-weighted ratio
- *PYTHIA captures large R_L behavior, but neither model describes small R_L de-correlation!*
    - resembles STAR r_c measurement
      [slides from Youqi Song here]



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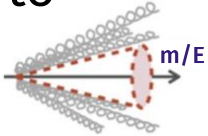
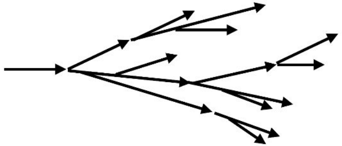
How does the shower depend on flavor?

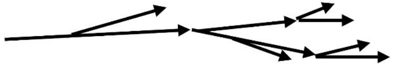
- At the largest R_L, the scaling behavior in heavy-flavor jets is identical to light quark jets.
- *Turnover exhibits a mass dependence!*
- Change of shape at small angles is a consequence of the dead cone.
- Flavor effects can be probed with ratios to inclusive jets.



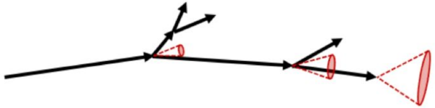


gluon jets

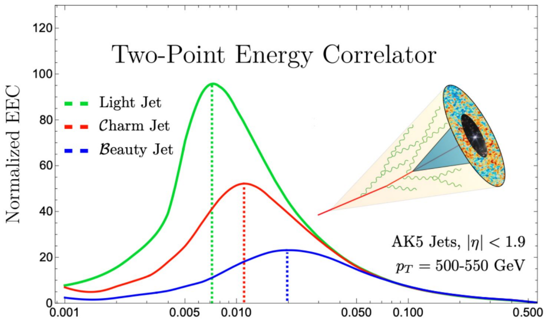
$$\frac{C_A}{C_F} = \frac{9}{4}$$

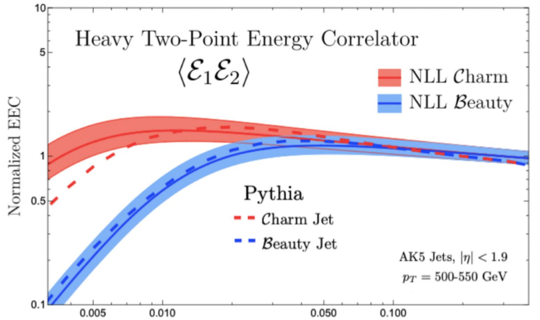


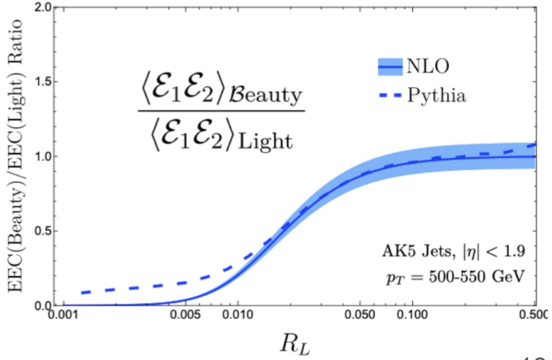
quark jets



heavy quark jets







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

Comparing D^0-tagged jet to inclusive jet EECs

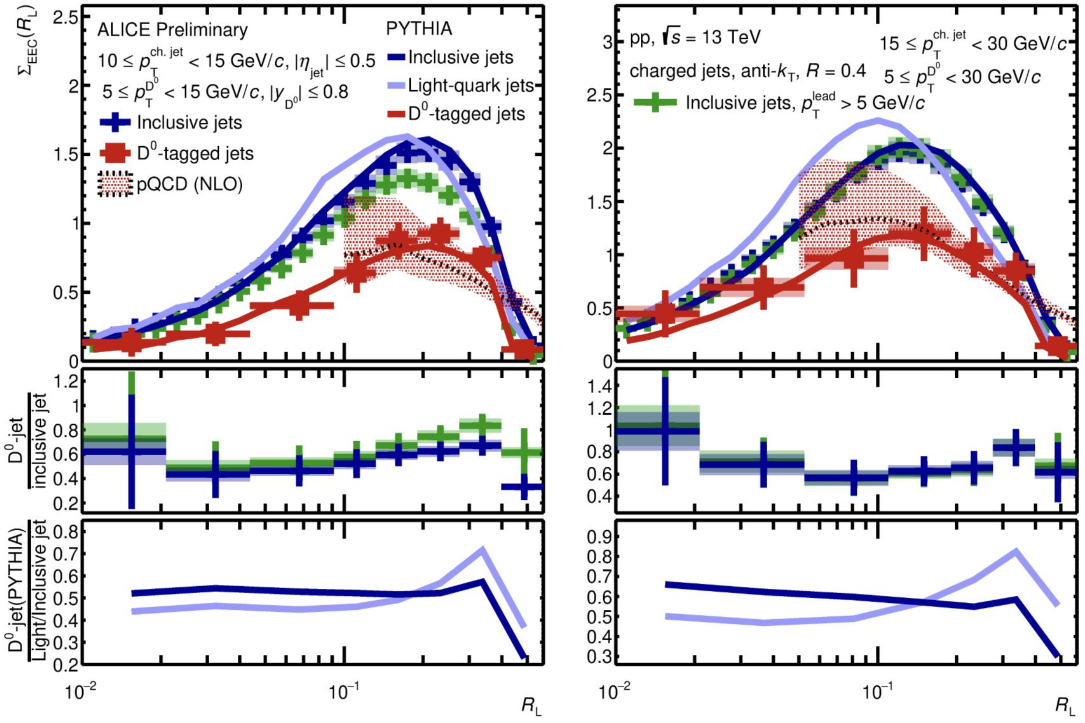
Upper panel:

- 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!



pQCD calculation from K. Lee

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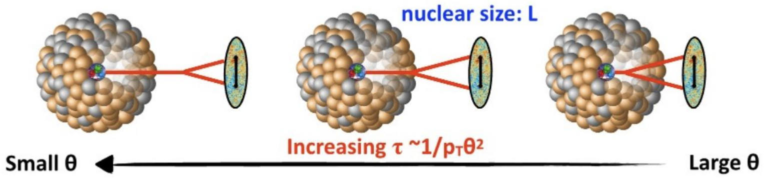
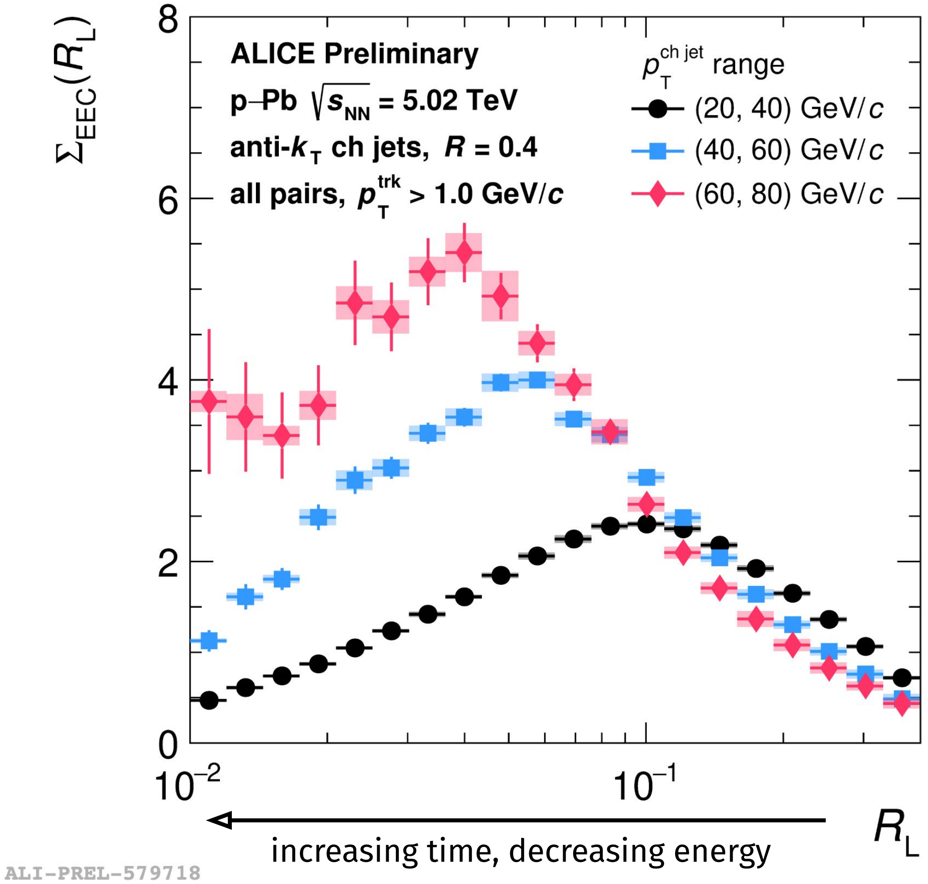
Are EECs modified in p-Pb?

Differences from pp:

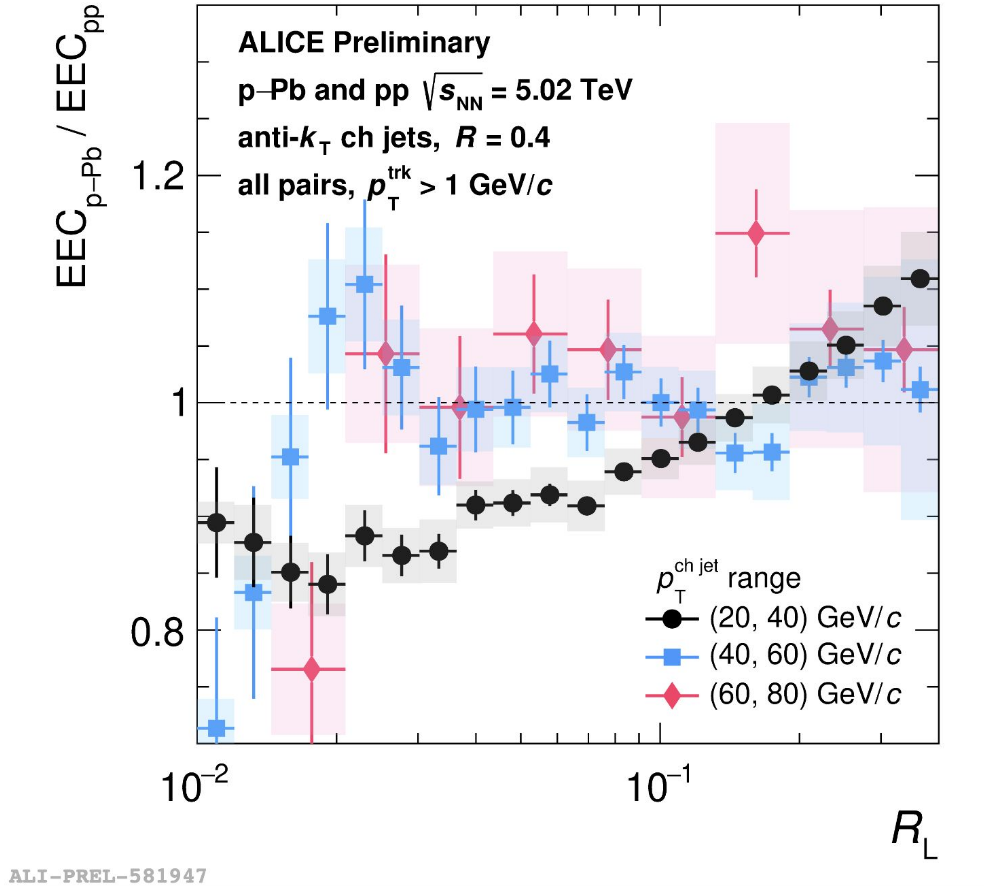
- initial state (nPDF, isospin)
- final-state interactions?
- comovers? collectivity??



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



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

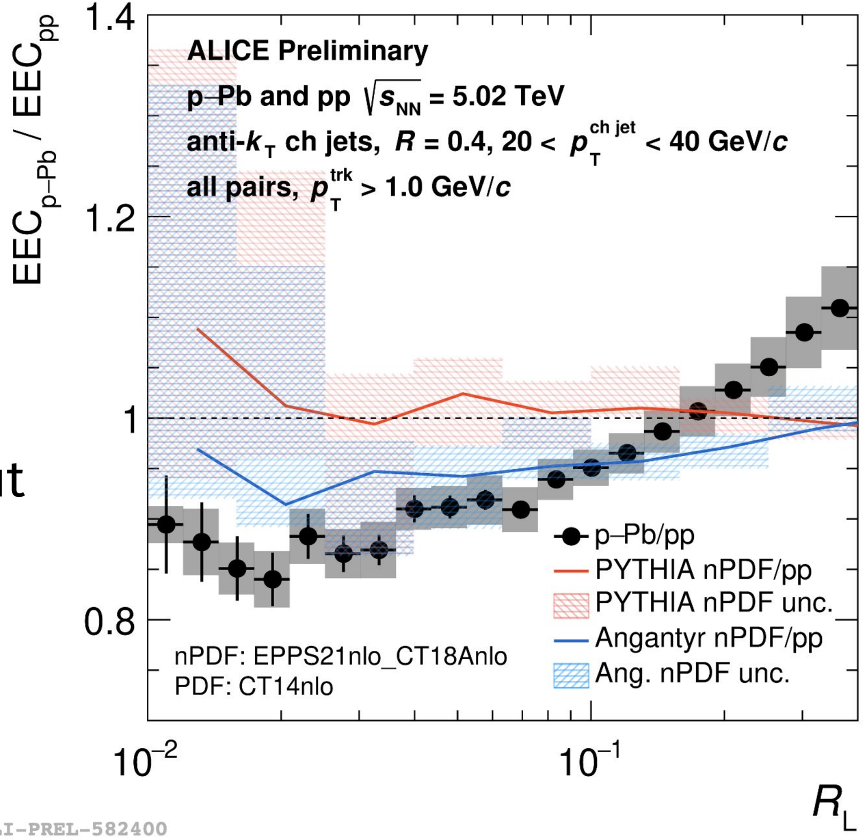


- *Significant difference between EECs in p-Pb compared to pp!*
    - jet structure appears to be altered only in the lowest jet p_T range
- Initial state effect?
    - some models lead to a similar effect
- Final state effect?
    - some calculations reproduce this
- Modification is qualitatively consistent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

* arXiv:2311.13322

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

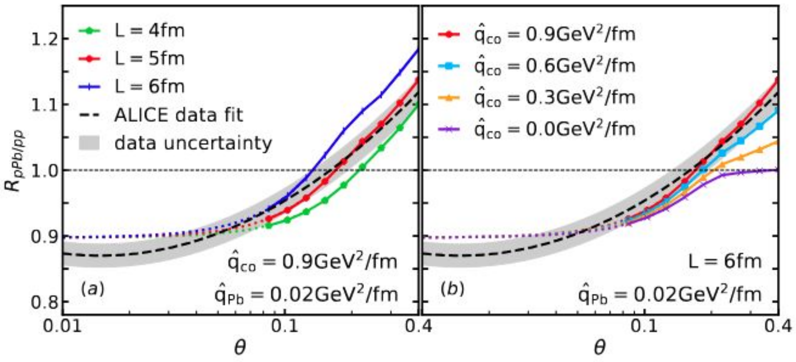
- Comparing to PYTHIA with an nPDF turned on, and PYTHIA Angantyr
- PYTHIA results use:
  - nPDF: EPPS21nlo_CT18Anlo
  - PDF: CT14nlo
- nPDFs are within ~1σ at small R_L – but these are very large uncertainties
- Neither captures the behavior at large R_L.

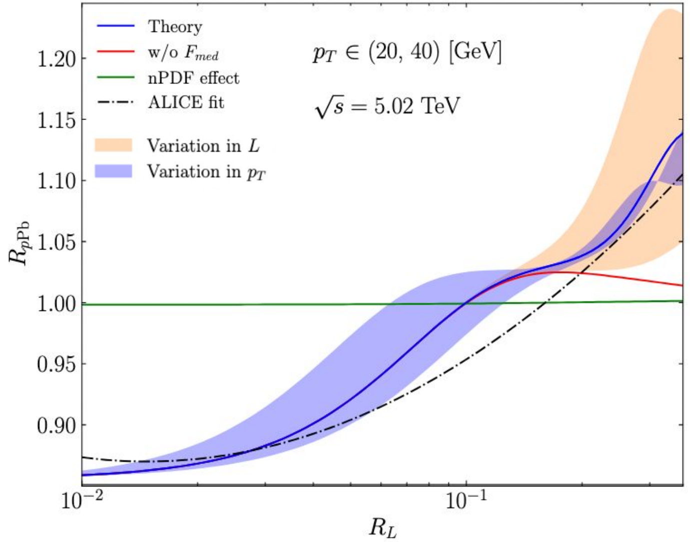


Some theory models can reproduce the enhancement.

- Fu et al. use a higher-twist model and require comovers to capture the enhancement
  - p_T^{jet} of 30 GeV/c, R_{pPb} chosen to be 0.85
- Barata et al. capture the NP region as well with multiple scatterings and transverse momentum broadening
  - HT correction to jet's perturbative evolution
  - p_T broadening in TMD fragmentation function

arXiv:2411.04866 [nucl-th] (Fu, Müller, Sirimanna)





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

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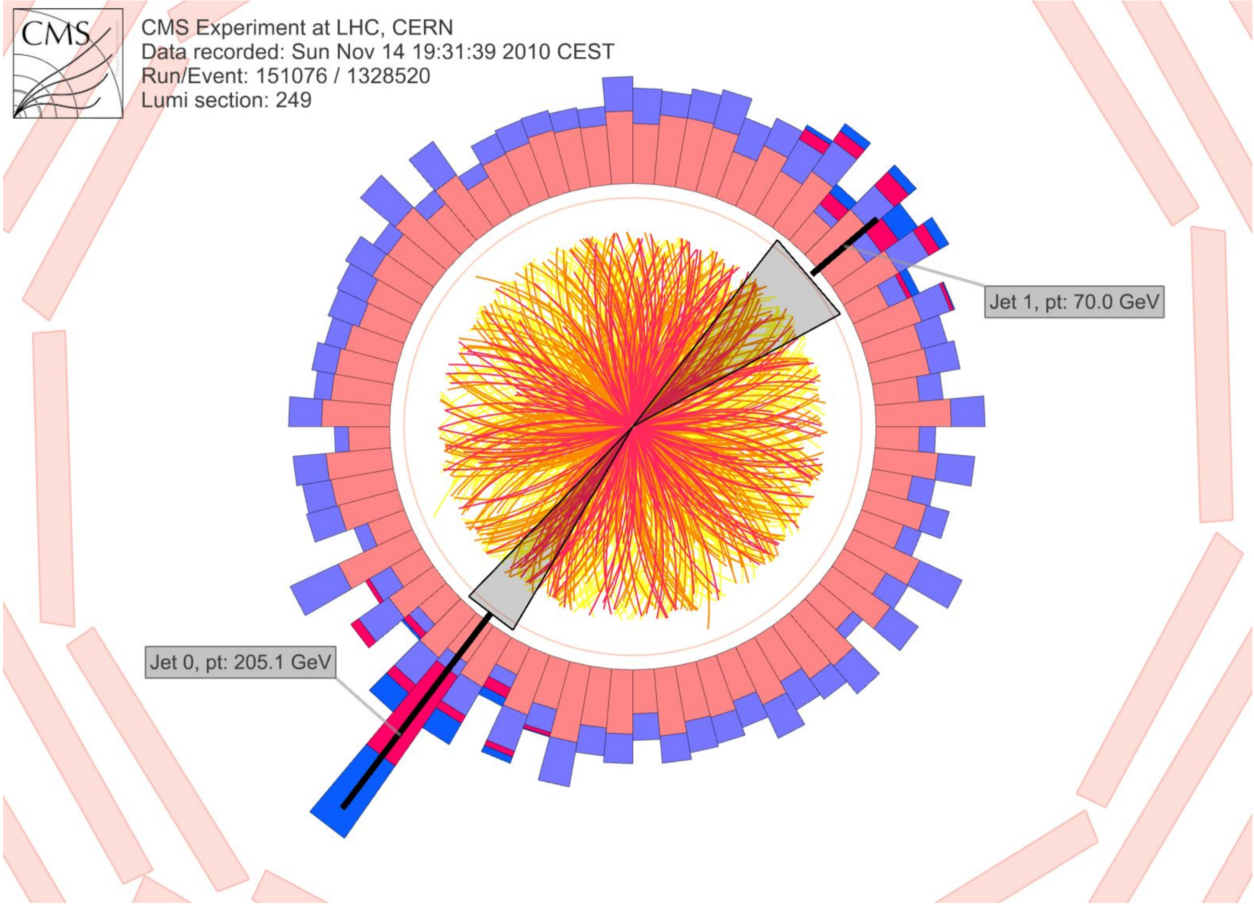
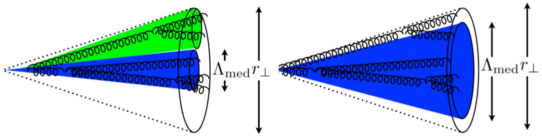
Jets lose energy as they traverse the quark-gluon plasma.



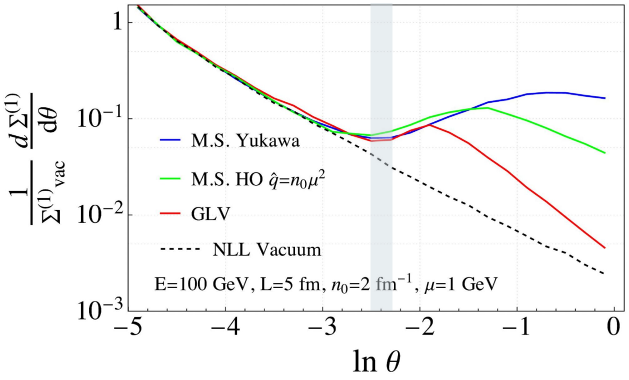
EECs in Pb-Pb can probe various medium effects.

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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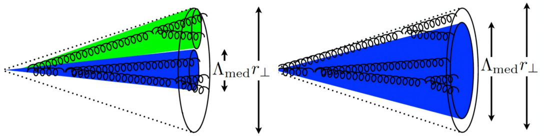

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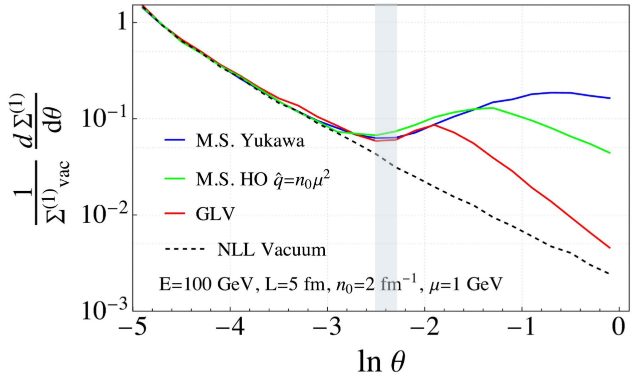
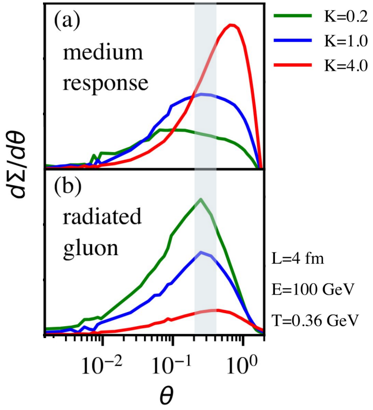


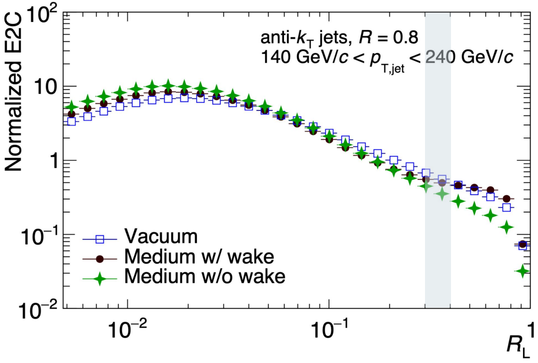
Medium response

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

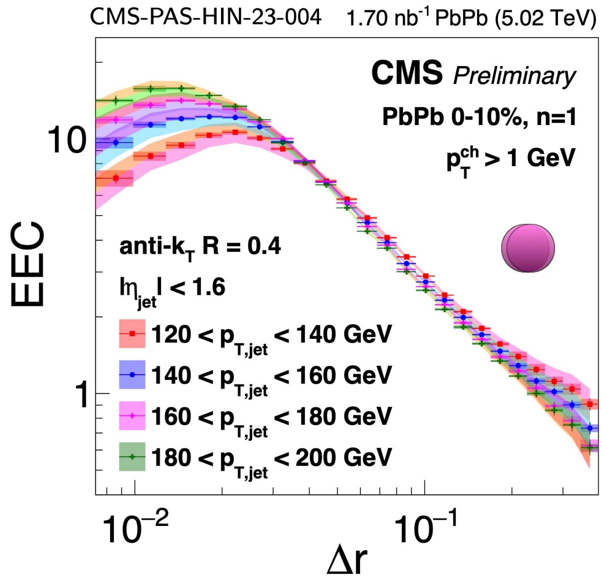
PRL 132 (2024) 1, 011901
(Yang, He, Moult, Wang)



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

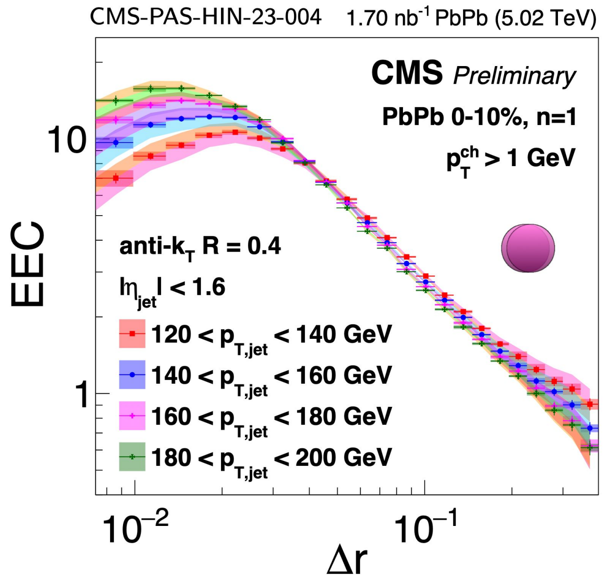


CMS measured EECs in Pb-Pb...



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

CMS measured EECs in Pb-Pb... and found differences.



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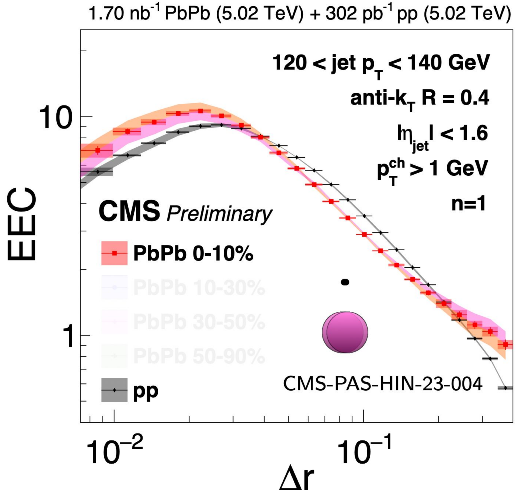
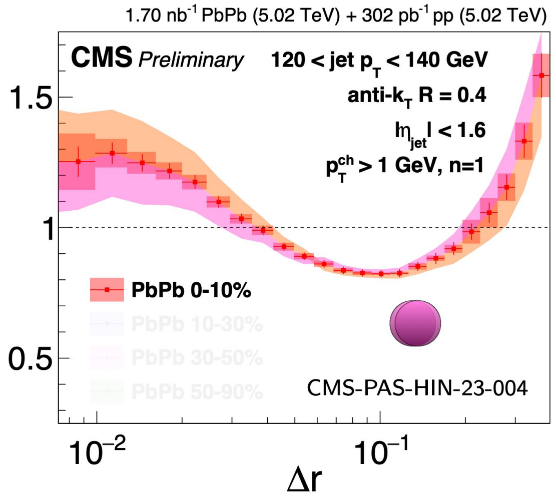




- *Pb-Pb peaks at smaller R_L than pp*
  - energy loss: Pb-Pb jets have higher initial virtuality
  - flat trend at lowest R_L (free hadron scaling)
- *Pb-Pb EEC has a different shape at large R_L*
  - at R_L~ 0.1, we see another enhancement

How do calculations stack up against this data?

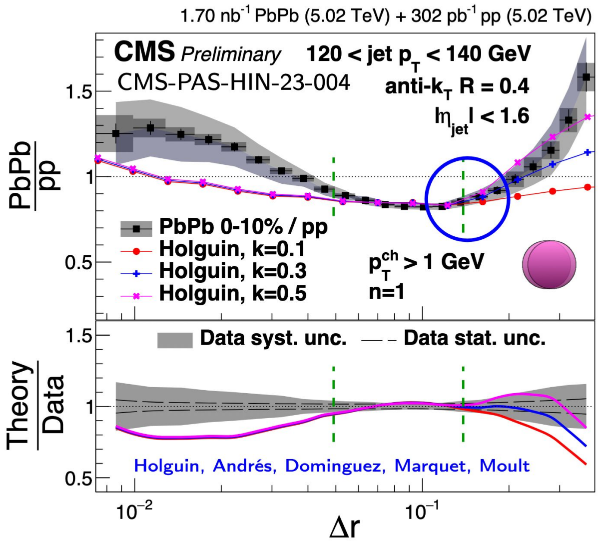
Color coherence

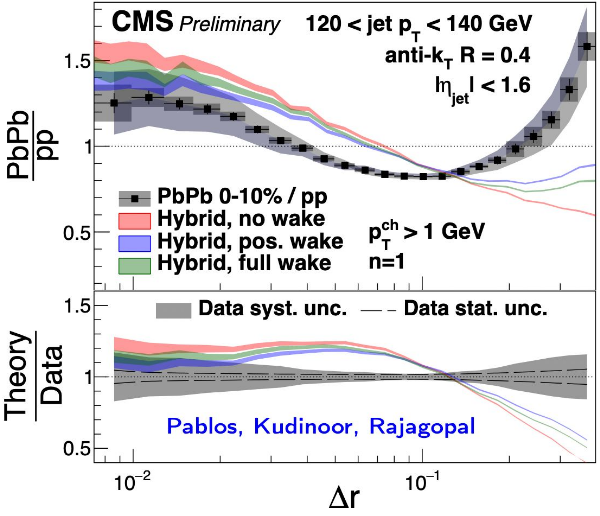
- Holguin et al. calculation* has two free parameters: *k* and normalization
- Calculation is normalized to data in $0.042 < R_L < 0.126$
- Turn-on angle is similar in data and calculation!

* arXiv:2407.07936 [hep-ph] (Andres, Dominguez, Holguin, Marquet, Moult)

Medium response

- Modeling medium response using jet wake in Hybrid
- Hybrid only predicts the large-R_L enhancement with the wake included
    - does not capture the magnitude or onset of the effect
- JEWEL (not shown) requires recoils for enhancement





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
  models with final-state interactions capture large R_L trends
- Energy loss is visible in Pb-Pb EECs
  along with some interesting large R_L effects (medium response?)

Not shown here: *N*-point energy correlators, recent theory developments, and more!

Many more results are coming at QM25 – it's an exciting time in the world of EECs.

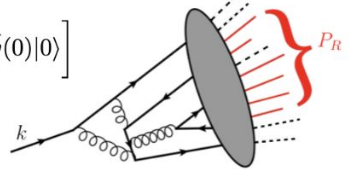
Backup

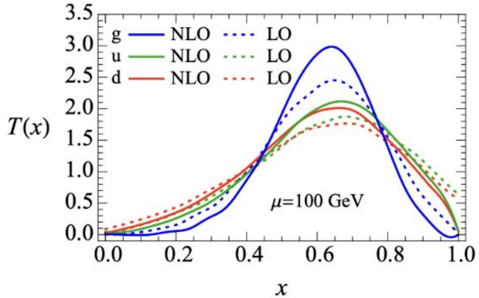
TRACK FUNCTIONS

Chang, Procura, Thaler, Waalewijn `13
Li, Moult, Waalewijn, Zhu et al `21, 22

- **Track functions are non-perturbative functions describing the momentum fraction of initial parton converted to hadrons with a particular property R.**

$$T_q(x) = \int dy^+ d^2 y_\perp e^{ik^- y^+/2} \frac{1}{2N_c} \sum_X \delta\left(x - \frac{P_R}{k_-}\right) \mathrm{tr}\left[\frac{\gamma^-}{2} \langle 0 | \psi(y^+, 0, y_\perp) | X \rangle \langle X | \bar{\psi}(0) | 0 \rangle\right]$$

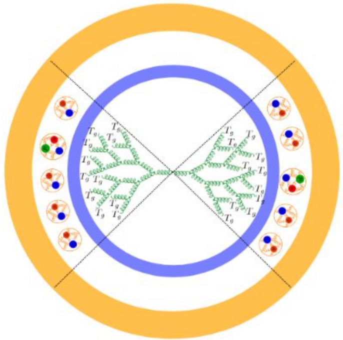




- **Track functions are technically what is needed for calculating the usual jet shape observables on track (jet mass, jet angularities, jet charge, etc...), but is technically challenging**

$$\delta(e - \hat{e}(\{p_i^\mu \in X_J\})) \to \delta(e - \hat{e}(\{x_i p_i^\mu \in X_J\}))$$

requires simultaneous knowledge of all the tracks in jet.



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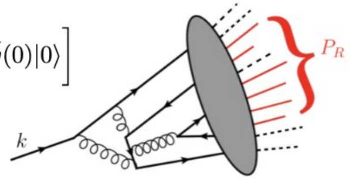
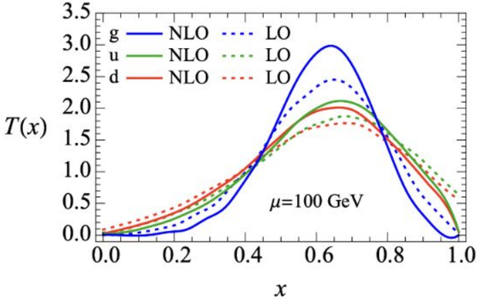
Li, Moult, Waalewijn, Zhu et al `21, 22

- **Track functions are non-perturbative functions describing the momentum fraction of initial parton converted to hadrons with a particular property R.**

$$T_q(x) = \int dy^+ d^2 y_\perp e^{ik^- y^+/2} \frac{1}{2N_c} \sum_X \delta\left(x - \frac{P_R}{k_-}\right) \mathrm{tr}\left[\frac{\gamma^-}{2} \langle 0 | \psi(y^+, 0, y_\perp) | X \rangle \langle X | \bar{\psi}(0) | 0 \rangle\right]$$





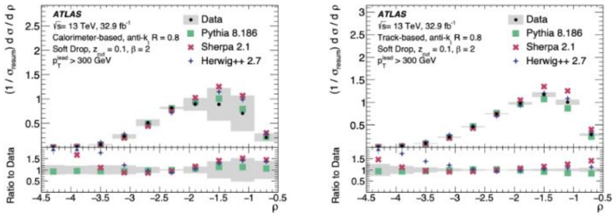
- **Ten years after track function formalism is developed, the computation still remains elusive.**

bservables. For all of these observables, the uncertainties for the track-based observables are significantly maller than those for the calorimeter-based observables, particularly for higher values of β, where more oft radiation is included within the jet. However, since no track-based calculations exist at the present me, calorimeter-based measurements are still useful for precision QCD studies.

[ATLAS Collaboration, 1912.09837]

selection of charged particle jets. Note that track-based observables are IRC-unsafe. In general, perturbative track functions can be used to directly compare track-based measurements to analytical ulations [67–69]; however, such an approach has not yet been developed for jet angularities. Two

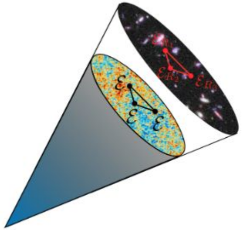
[ALICE Collaboration, 2107.11303]

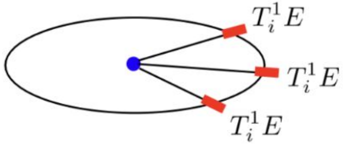


[ATLAS (2019)]

ENERGY CORRELATORS ON TRACK

- **From this "detector" as a fundamental operator perspective, track function formalism provides the essential matching between partonic and hadronic detectors.**

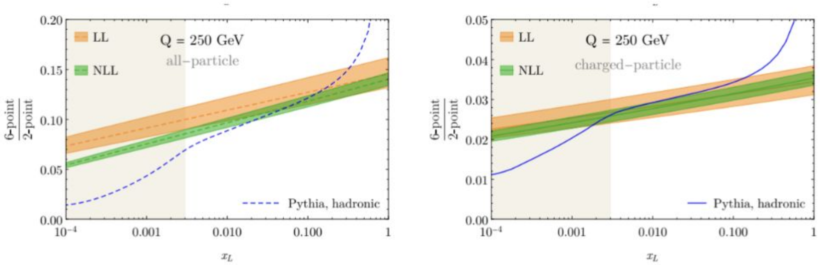




$$\langle \mathcal{E}_R(\vec{n}_1)\,\mathcal{E}_R(\vec{n}_2)\cdots\mathcal{E}_R(\vec{n}_k)\rangle = \sum_{i_1,i_2,\cdots i_k} T_{i_1}(1)\cdots T_{i_k}(1)\,\langle \mathcal{E}_{i_1}(\vec{n}_1)\,\mathcal{E}_{i_2}(\vec{n}_2)\cdots\mathcal{E}_{i_k}(\vec{n}_k)\rangle$$

+ contact terms. Requires up to k-th moment

- **Aside from the fact that this is technically much simpler, it only involves NP *numbers*, not functions.**



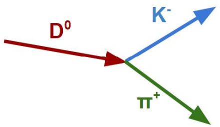
Up to 6 point EEC computed on tracks at NLL!

Jaarsma, Li, Moult, Waalewijn, Zhu `23

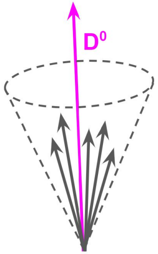
$$\langle \mathcal{E}(n_1)\,\mathcal{E}(n_2)\cdots\mathcal{E}(n_k)\rangle \to \langle \mathcal{E}_R(n_1)\,\mathcal{E}_R(n_2)\cdots\mathcal{E}_R(n_k)\rangle \to \langle \mathcal{E}_{R_1}(n_1)\,\mathcal{E}_{R_2}(n_2)\cdots\mathcal{E}_{R_k}(n_k)\rangle$$

D^0 reconstruction steps

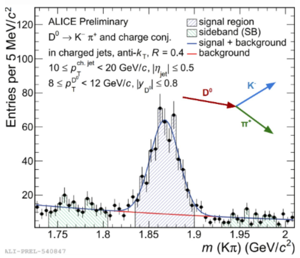
D^0 candidates were reconstructed from daughter tracks using topological and particle identification selections ($D^0 \rightarrow K^- + \pi^+$, and charge conjugates).

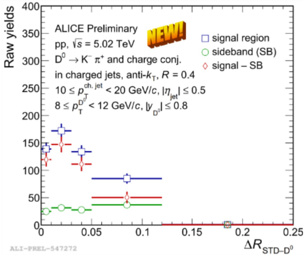


D^0-tagged charged jets were created using the anti-k_T algorithm (R=0.4) for each candidate.

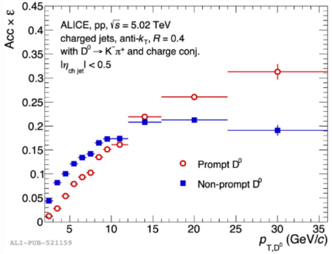


Invariant mass analysis was performed to remove combinatorial $K^-\pi^+$ pairs surviving the D^0 selections.





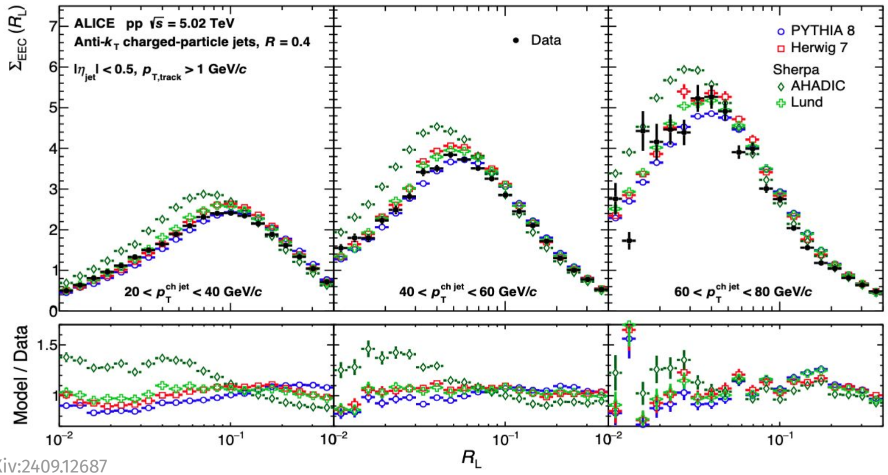
Corrected the EECs for the efficiency of D^0-tagged jet reconstruction and removed the contribution from beauty decays.



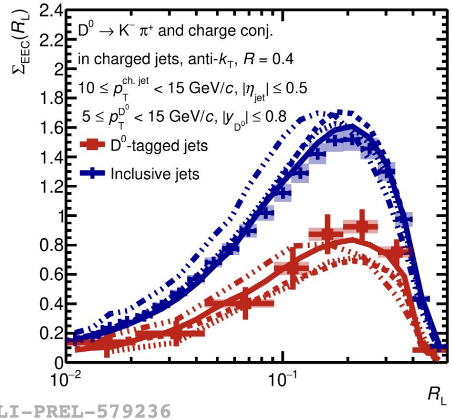
Corrected the EECs for detector effects with a bin-by-bin correction method.

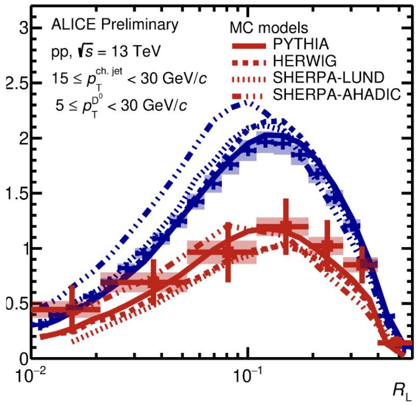
Probing hadronization with pp EECs

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



arXiv:2409.12687





ALI-PREL-579236

Inclusive jets:

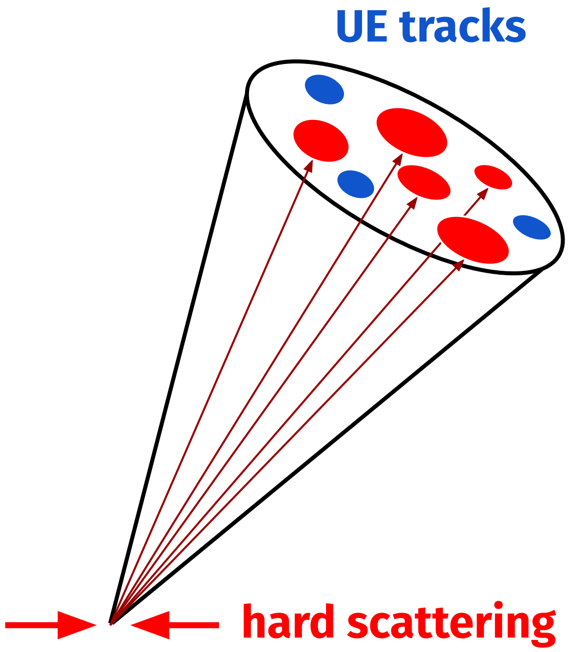
- PYTHIA & Herwig perform well, *Herwig captures peak position*
- Sherpa Lund does well, AHADIC does not
- *both cluster models peak at smaller R_L*

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?

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.

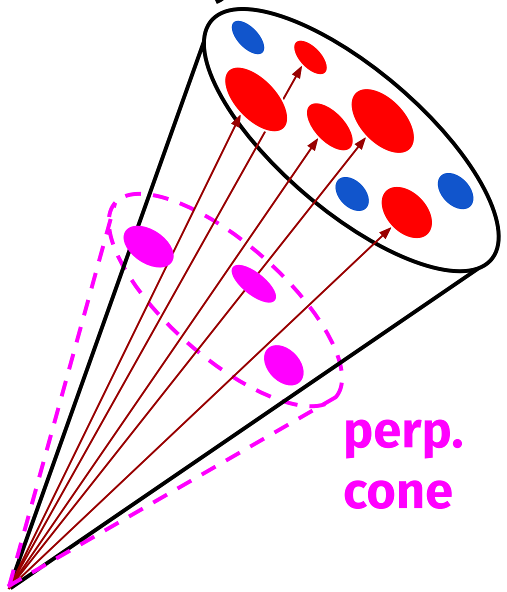
Perp. cone for combinatorial EEC background

- 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 + $\boxed{\text{2sig*bkg’ + 2bkg*bkg’}}$ + $\boxed{\text{bkg’*bkg’}}$

jet-perp perp-perp



Perp. cone for combinatorial EEC background

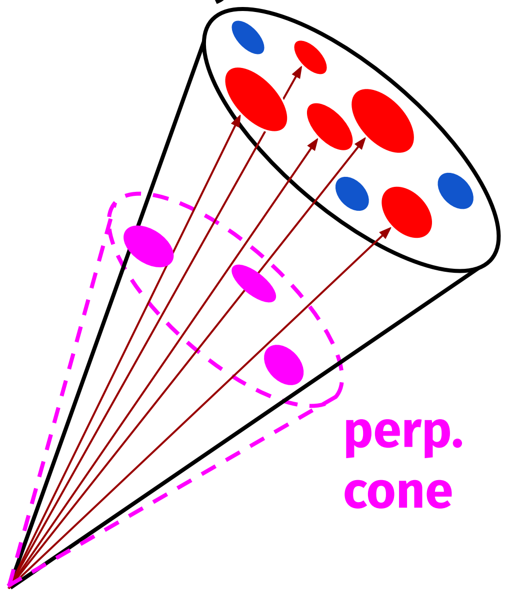
- Particles from jet: sig + bkg
- Particles from perp cone: bkg'
- Pairs in the combined cone:

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

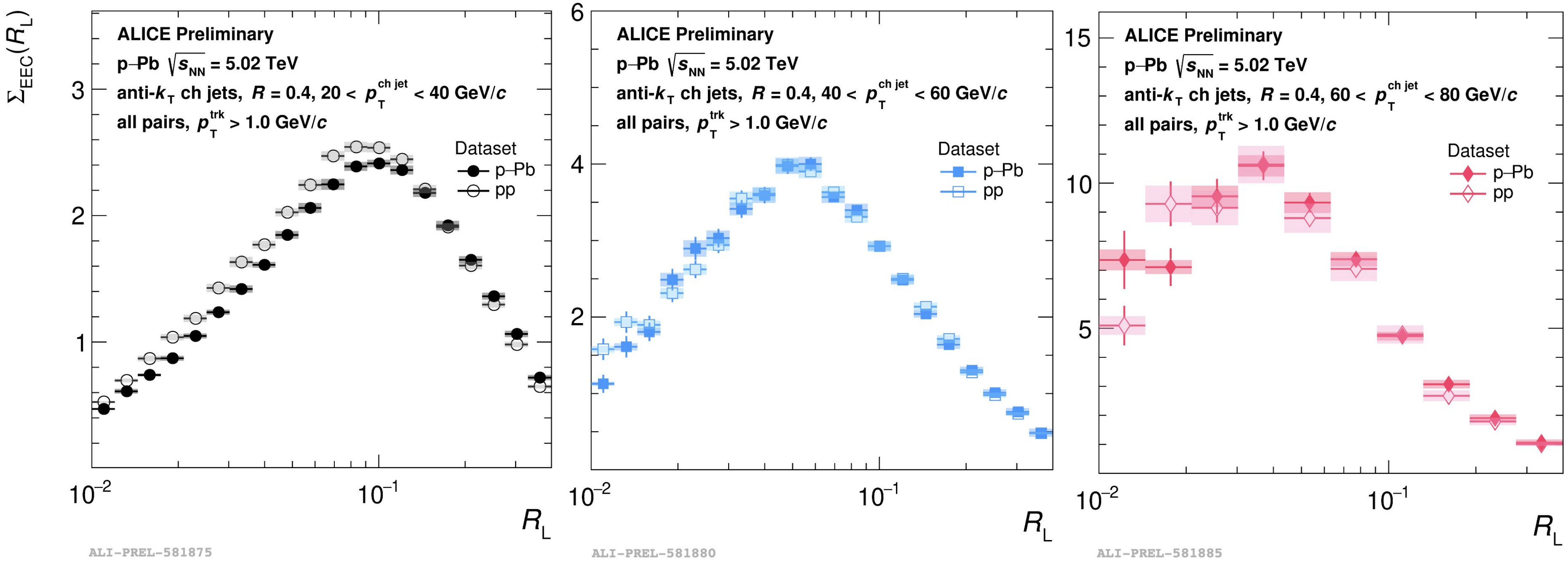
+ bkg*bkg + $\boxed{\text{2sig*bkg' + 2bkg*bkg'}}$ + $\boxed{\text{bkg'*bkg'}}$

jet-perp perp-perp

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

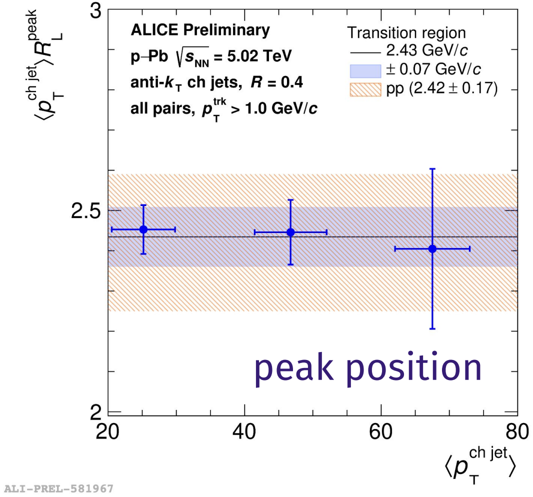


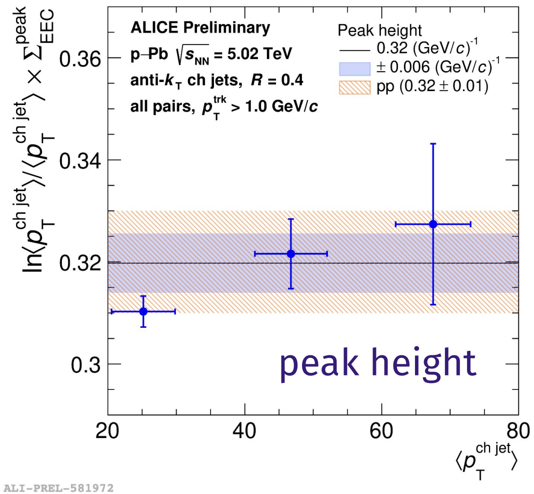
p-Pb and pp comparison

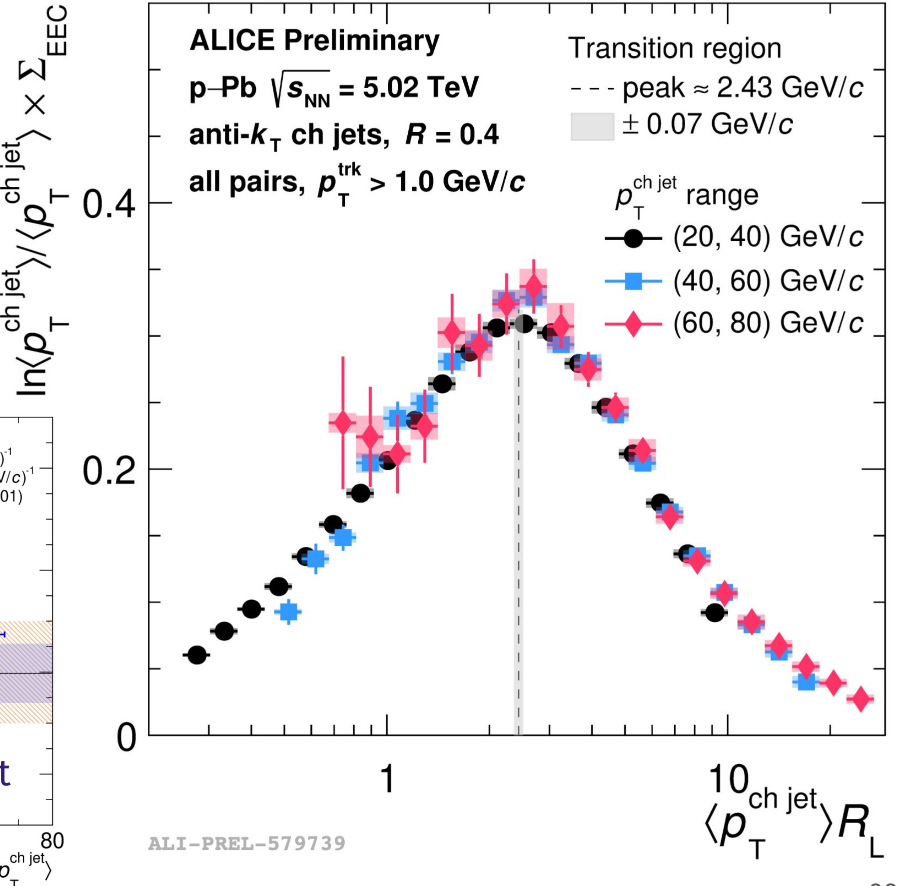


The transition region in p-Pb resembles pp.

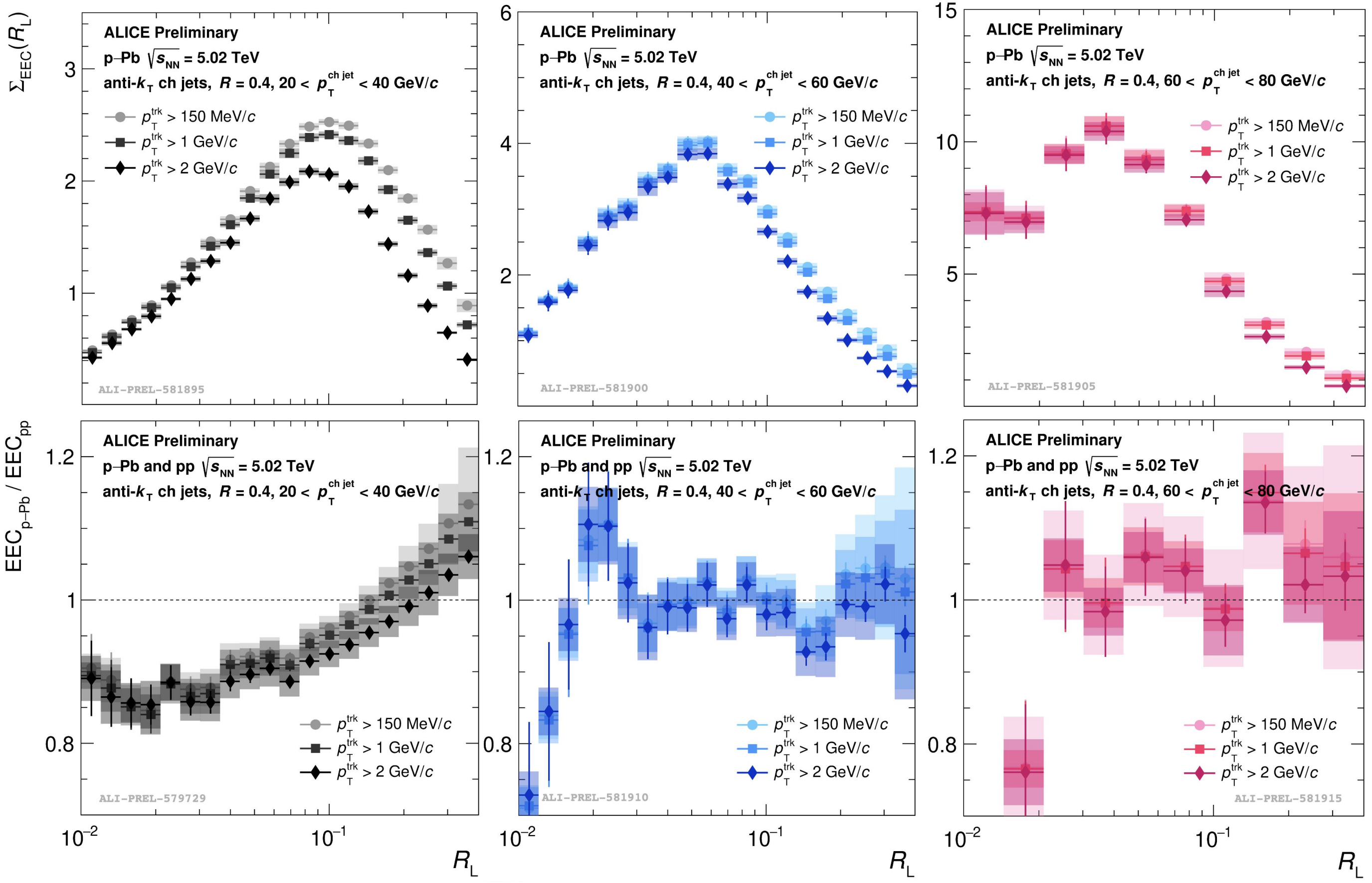
- Universality of the EEC peak position across jet p_T and collision system.
- EEC peak height for 20-40 GeV/c jets is slightly lower than for other jets.







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

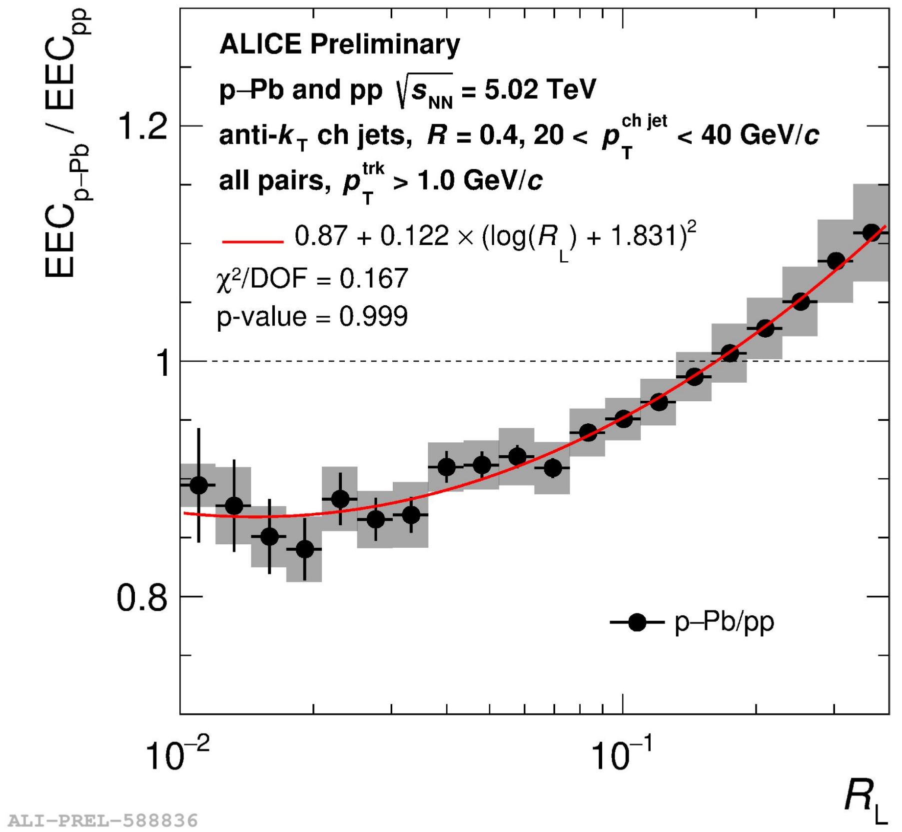
Track cut modifies the enhancement in ratio

- but not the small-R_L suppression

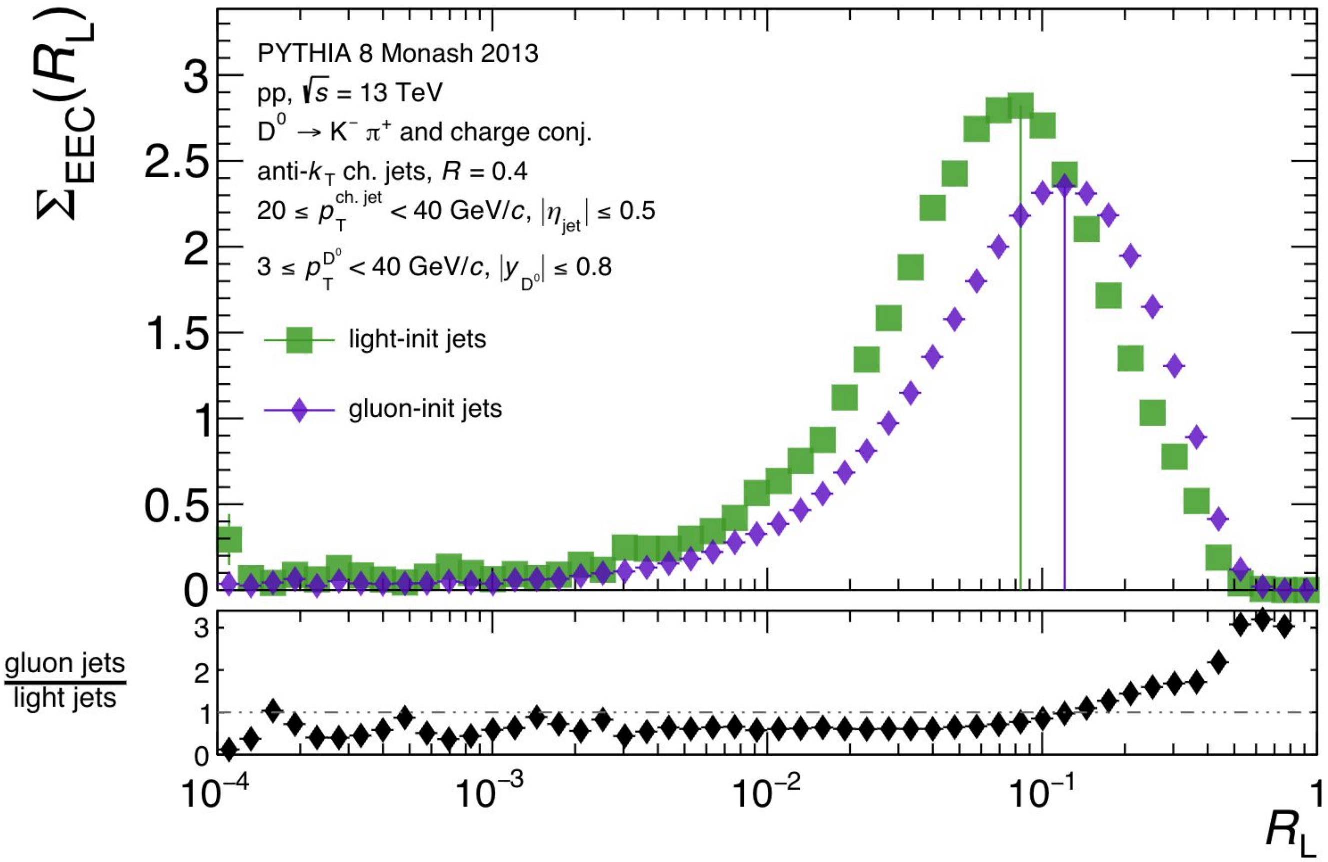
Suggests that the origin of the effect lies in softer interactions at small x!

$\log(R_L)^2$ shape of the p-Pb/pp ratio — why?

- The ratio appears to follow a $\log(R_L)^2$ scaling. Why: change in q/g ratio?



Quark-jet and gluon-jet EECs



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