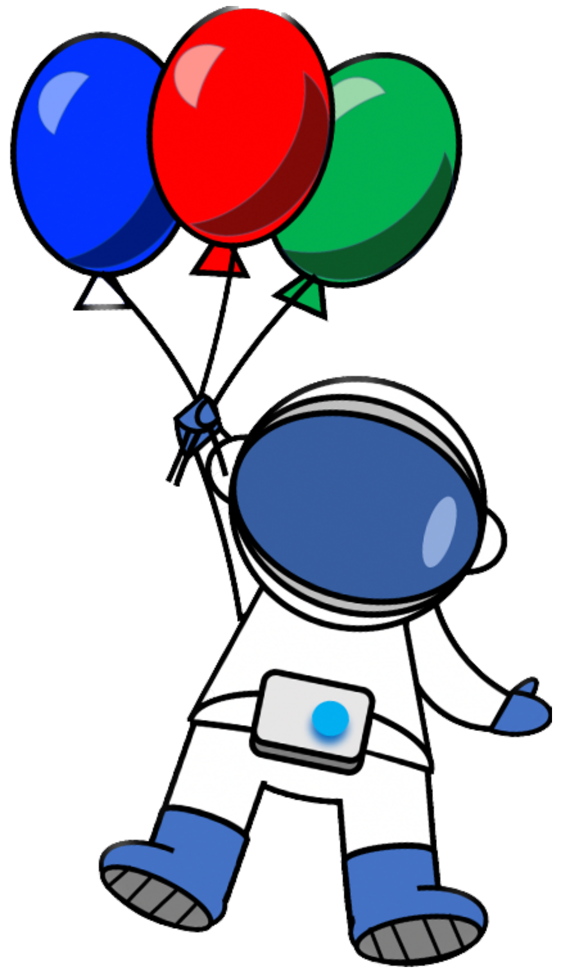
First energy-energy correlators measurements for inclusive and heavy-flavour tagged jets with ALICE

Wenqing Fan for ALICE Collaboration

Quark Matter 2023

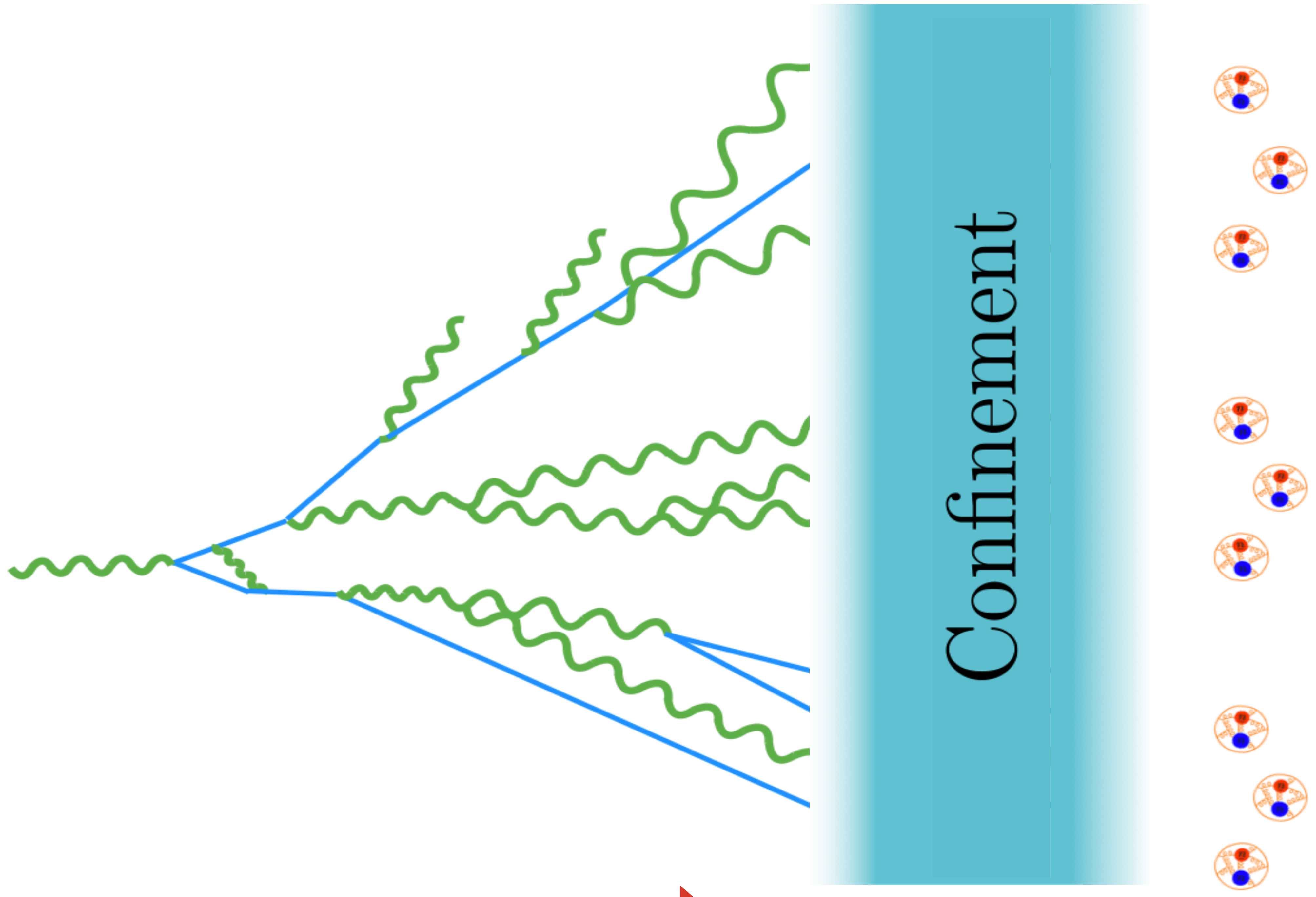


BERKELEY LAB

ALICE

Unravel different QCD scales with jet substructure

- Jet formation encodes rich QCD dynamics
  - Original splitting
  - Confinement/hadronization



Perturbative

Short time scale
High energy scale

from weak to strong coupled limit

Nonperturbative (NP)

Long time scale
Low energy scale

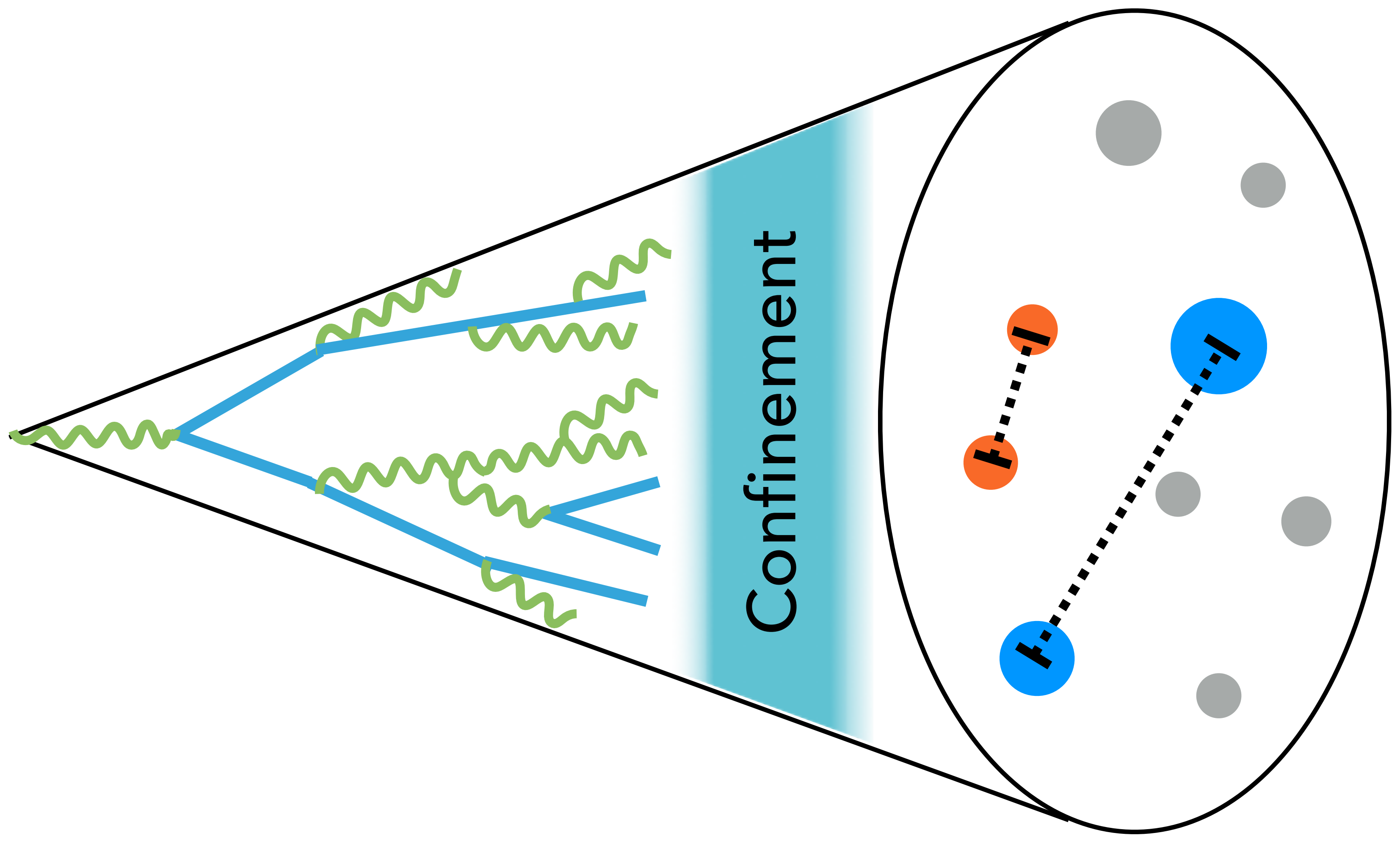
What can we learn about perturbative interactions between q/g?

What can we learn about hadronization?

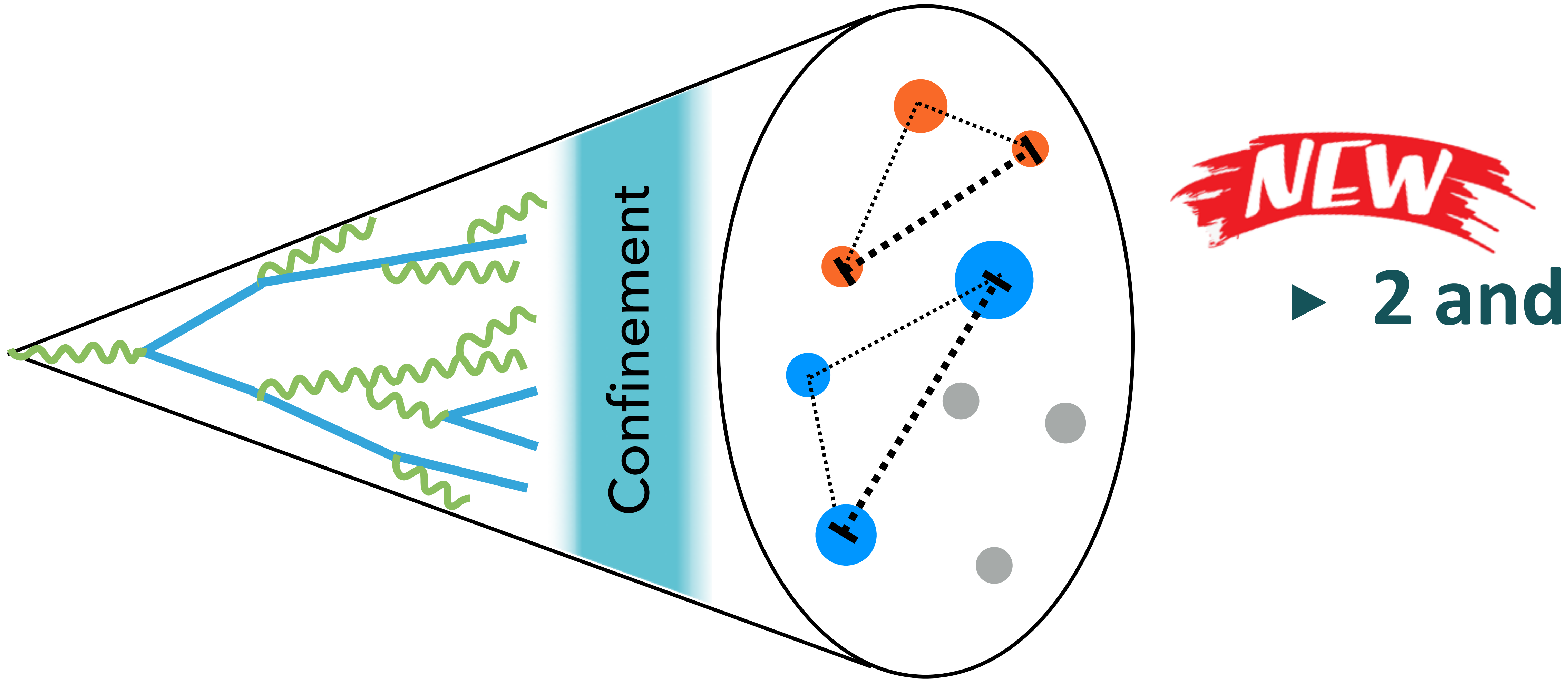
What is the role of color charge and mass?

How does the medium modifies the jet evolution?

Outline



- 2 point energy correlator results in pp at 5 TeV

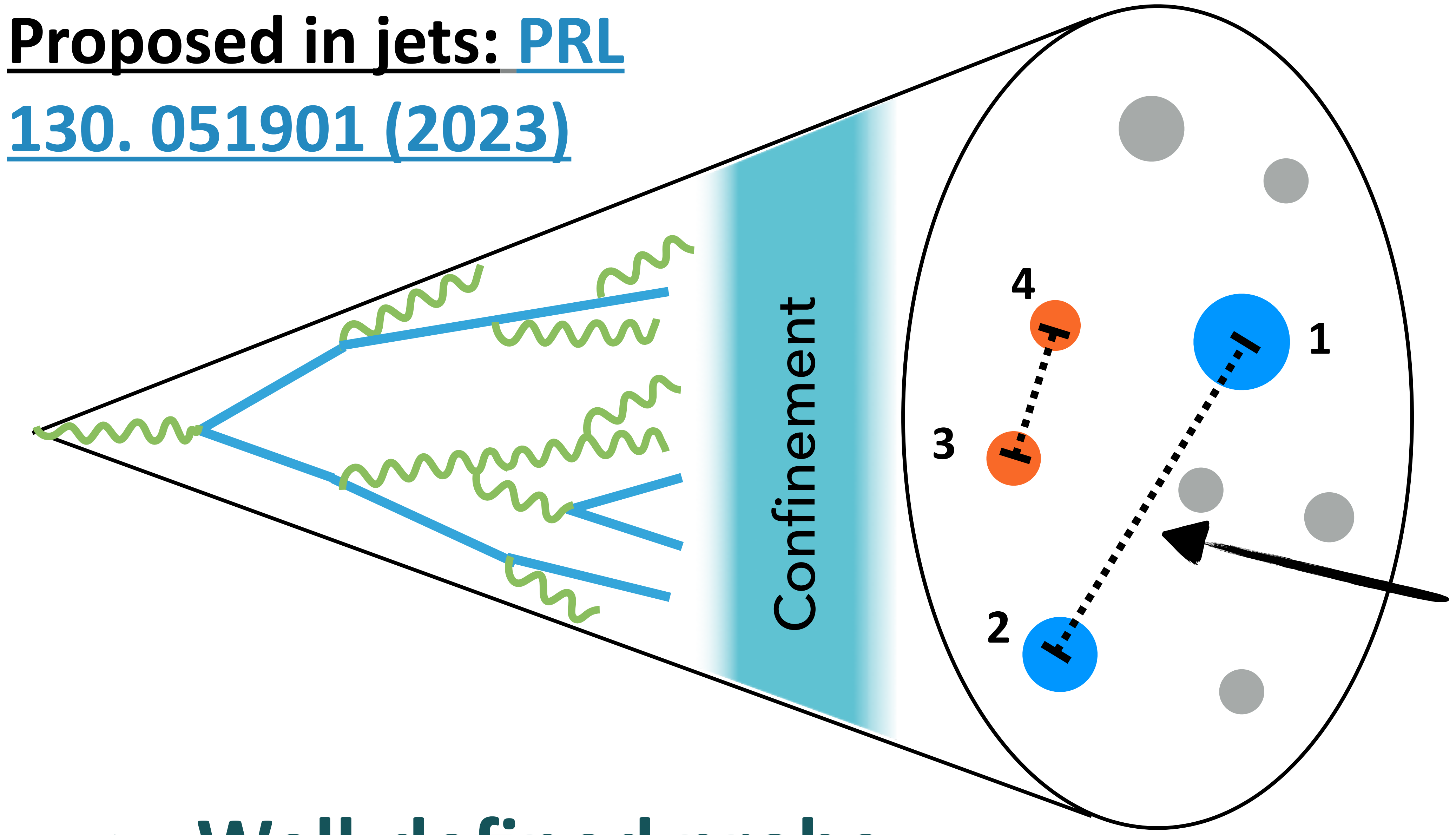


- 2 and 3 point energy correlator results in pp at 13 TeV

- Outlook of the ongoing heavy-flavor studies

A new jet substructure observable: 2 point energy correlators

Proposed in jets: PRL 130. 051901 (2023)

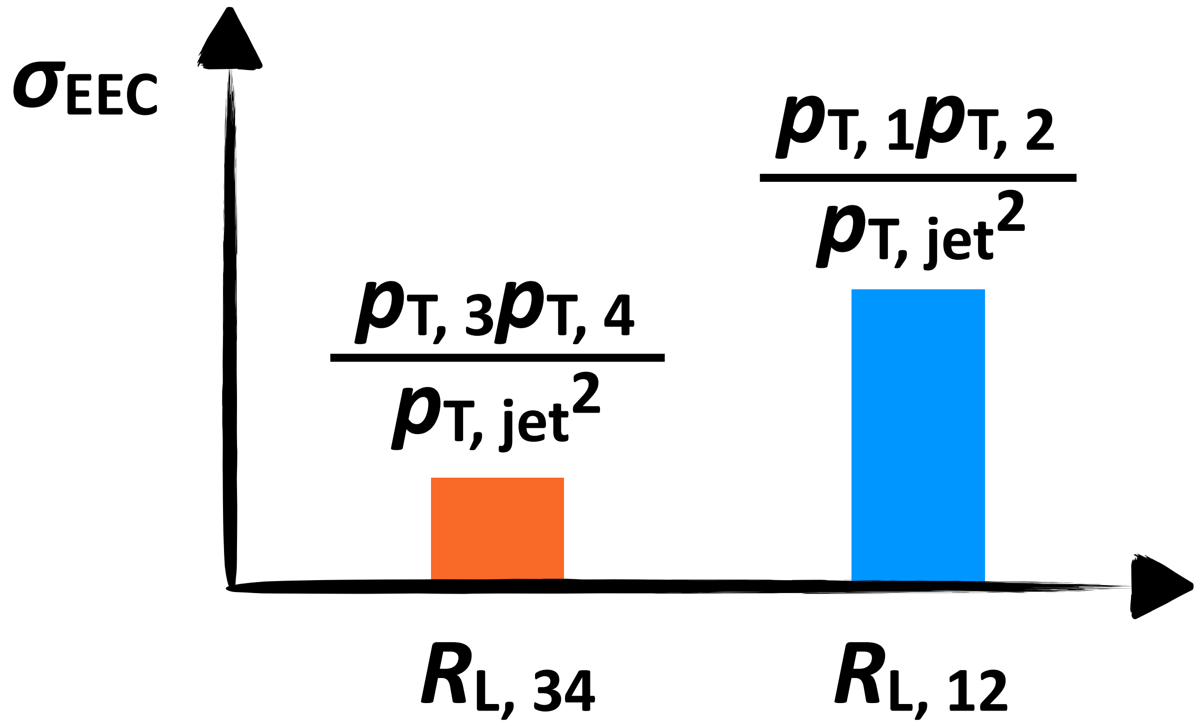


Count number of weighted pairs as function of R_L

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

Energy weight

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



- Well-defined probe
  - IRC safe + pQCD calculation available: K. Lee, B. Mecaj, I. Moult (arXiv:2205.03414)
  - Soft contribution (MPI, UE) power suppressed by energy weight: no need for grooming when comparing to pQCD calculation

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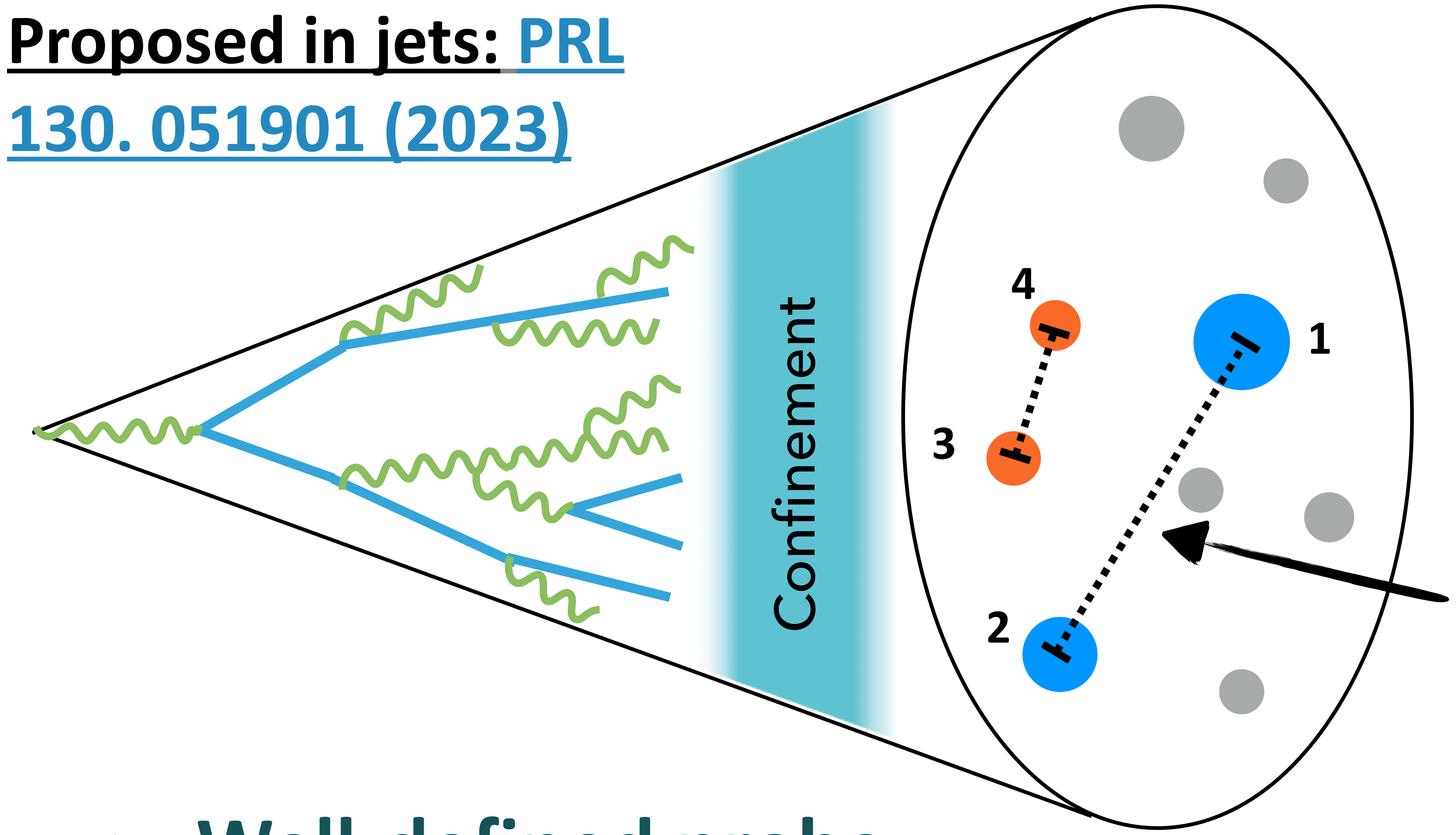

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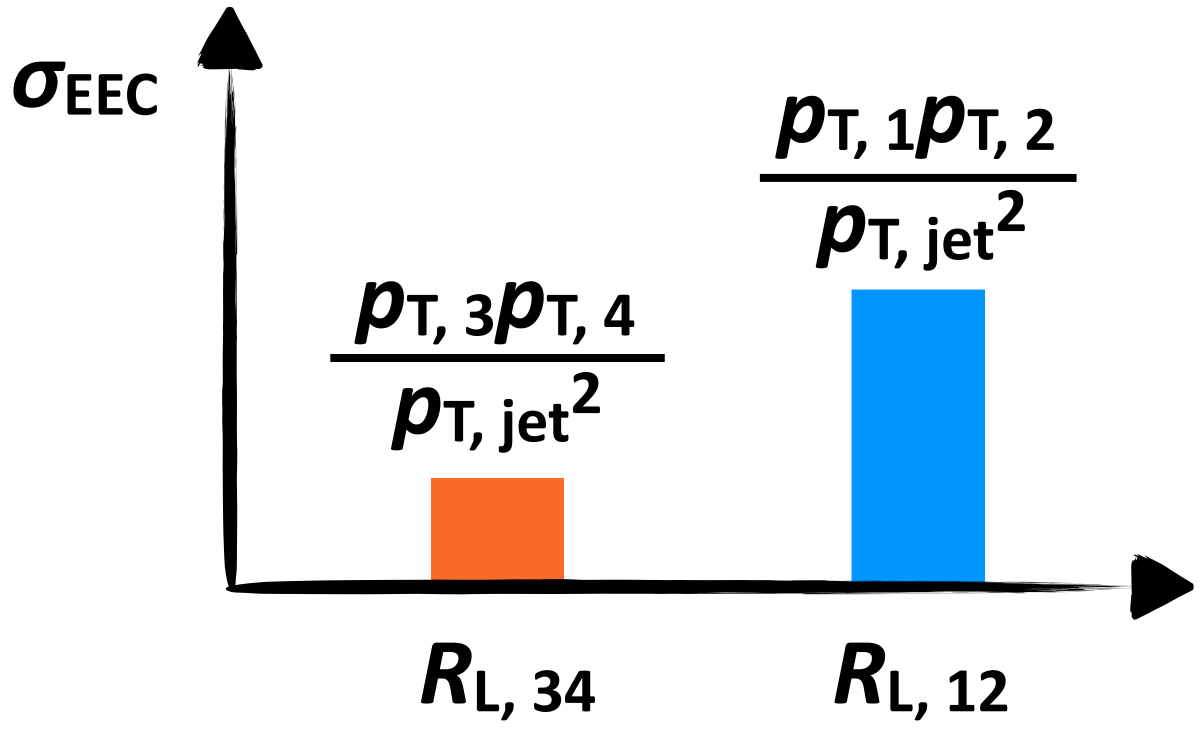

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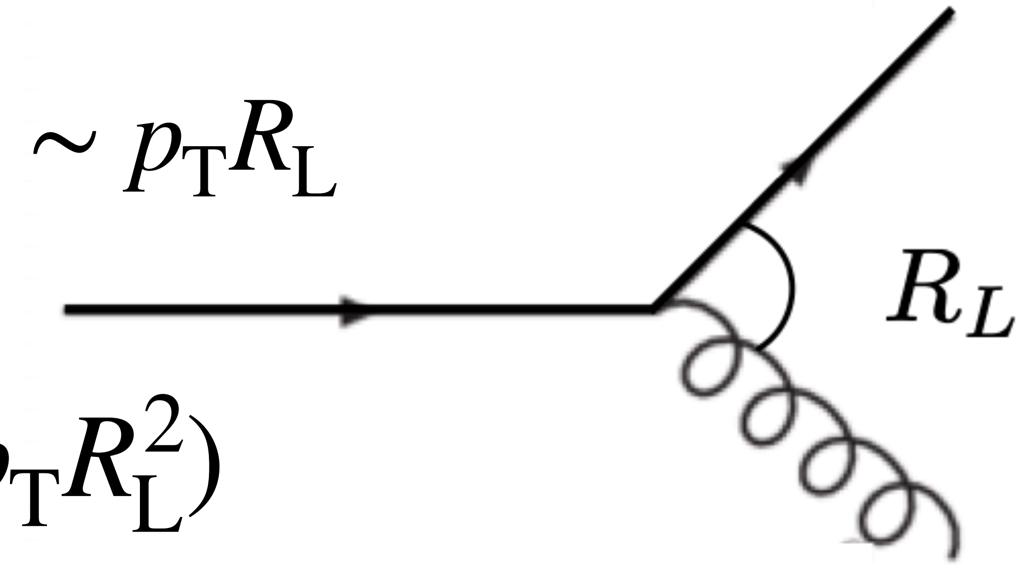
- **Probing fixed scale with fixed R_L**
  - Large ➜ small angle: perturbative ➜ NP scales
  - When the virtuality approaches $\mathcal{O}(\Lambda_{QCD})$, EEC undergo transition into confinement region

virtuality $\sim p_T R_L$

$\tau \simeq 1/(p_T R_L^2)$



Transition $R_L \sim \mathcal{O}(\Lambda_{QCD})/p_{T,jet}$

Analysis results

- Measurement carried out for R = 0.4 charged-particle jets with p_T in [20, 80) GeV/c
- Detector effects corrected bin-by-bin
  - Data well described by MC simulation
  - Small migration along R_L axis
  - Correction factor is small
  - Total systematics < 4%

Different scaling behavior observed in the perturbative (large R_L) and NP region (small R_L)

Transition position shifts to lower R_L for higher jet p_T range

Also measured by STAR and CMS

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

Energy weight

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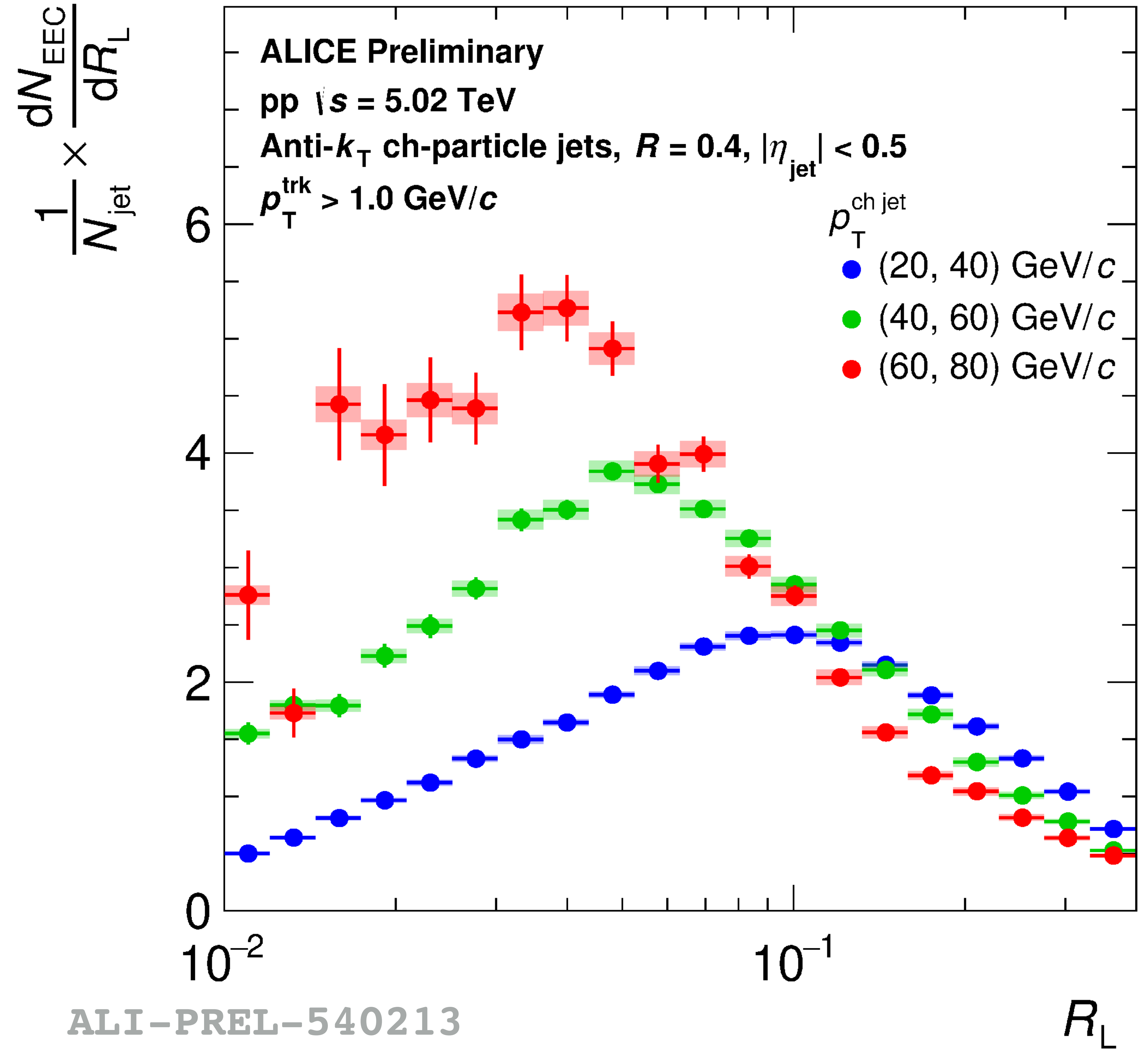


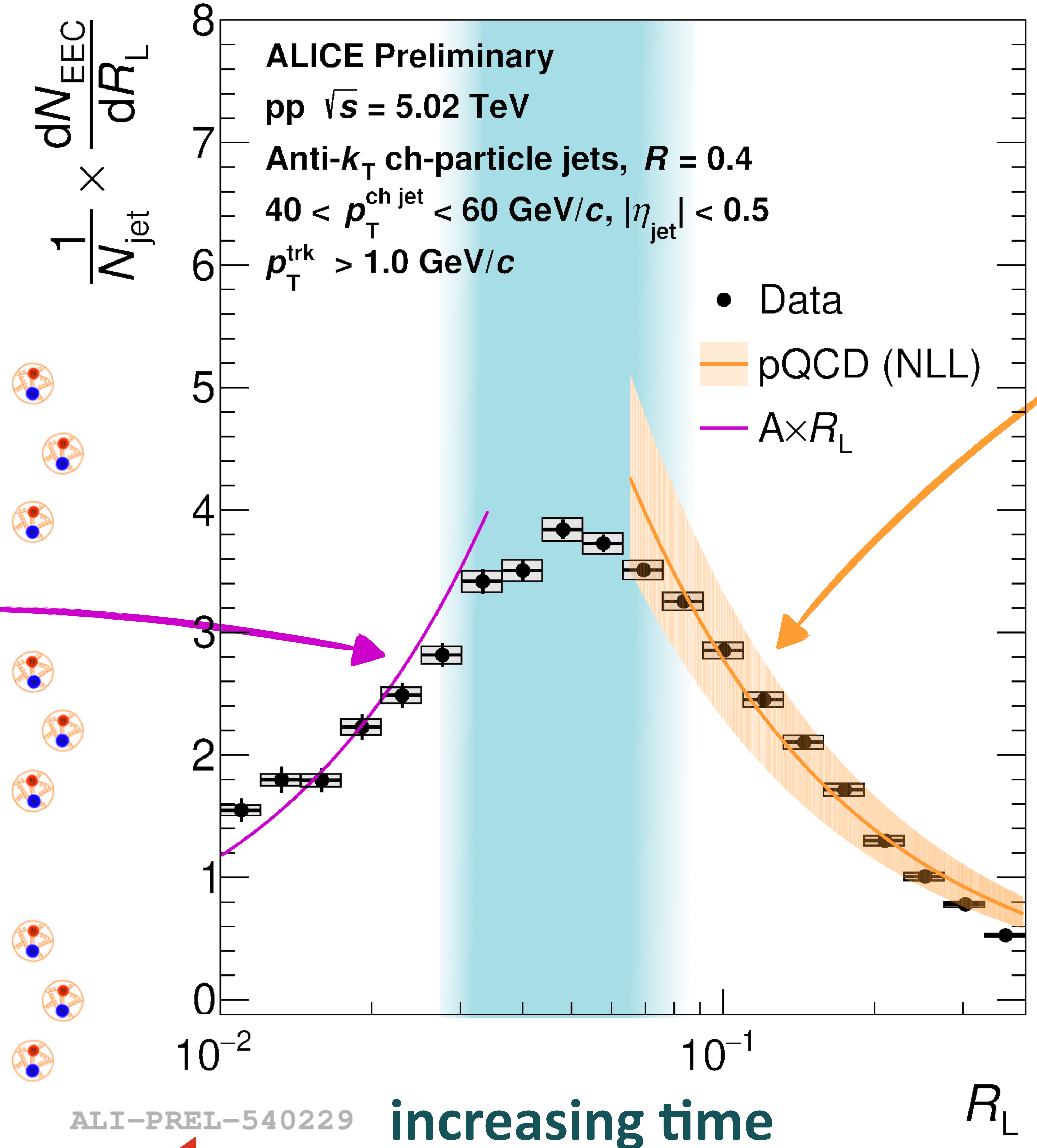
Comparison with pQCD

Confinement

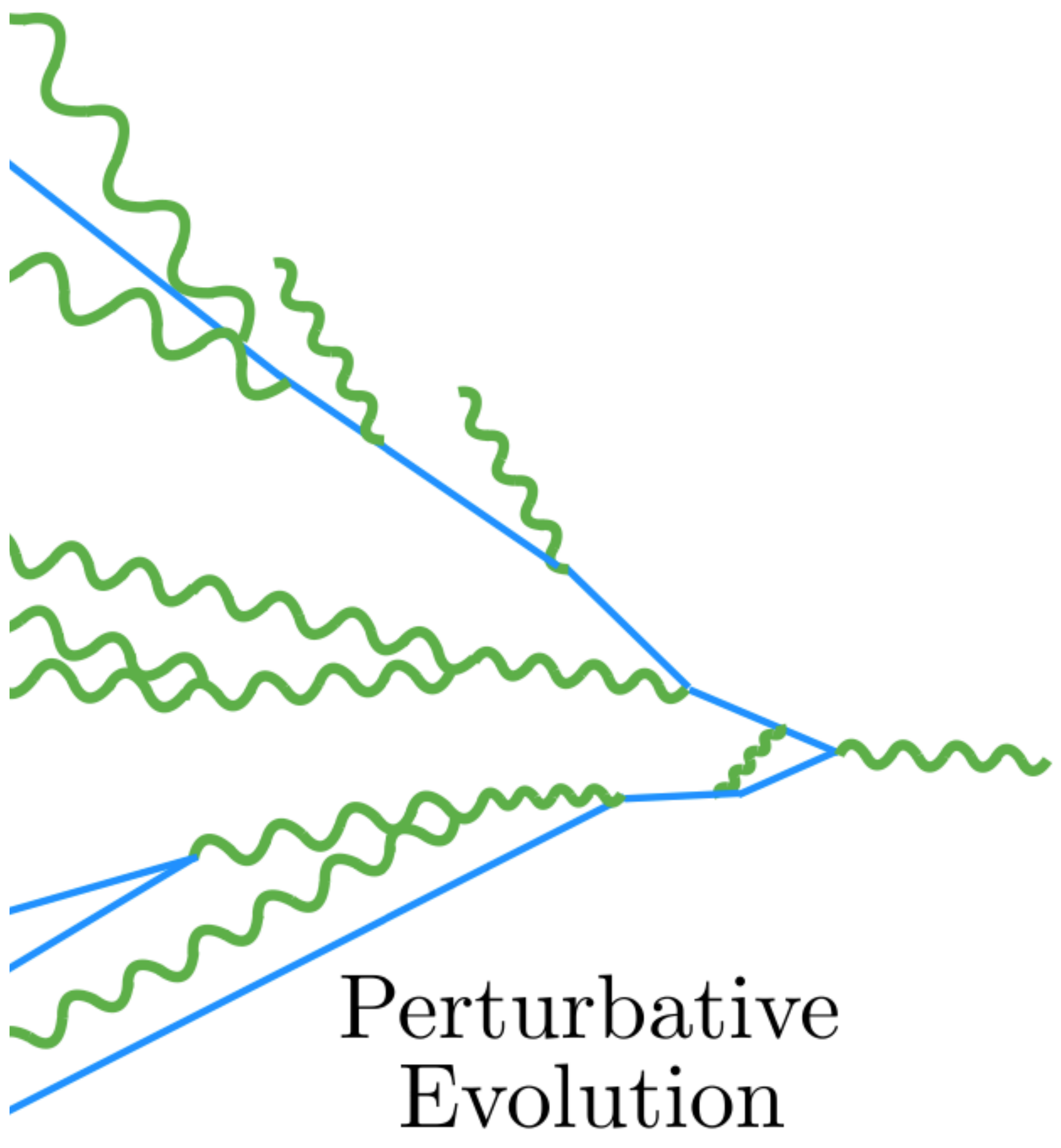
$$\frac{d\sigma}{dR_L^2} = \text{constant}$$

$$\rightarrow \frac{d\sigma}{dR_L} \propto R_L$$

Free hadron scaling (hadronic degree of freedom)



pQCD scaling (partonic degree of freedom)



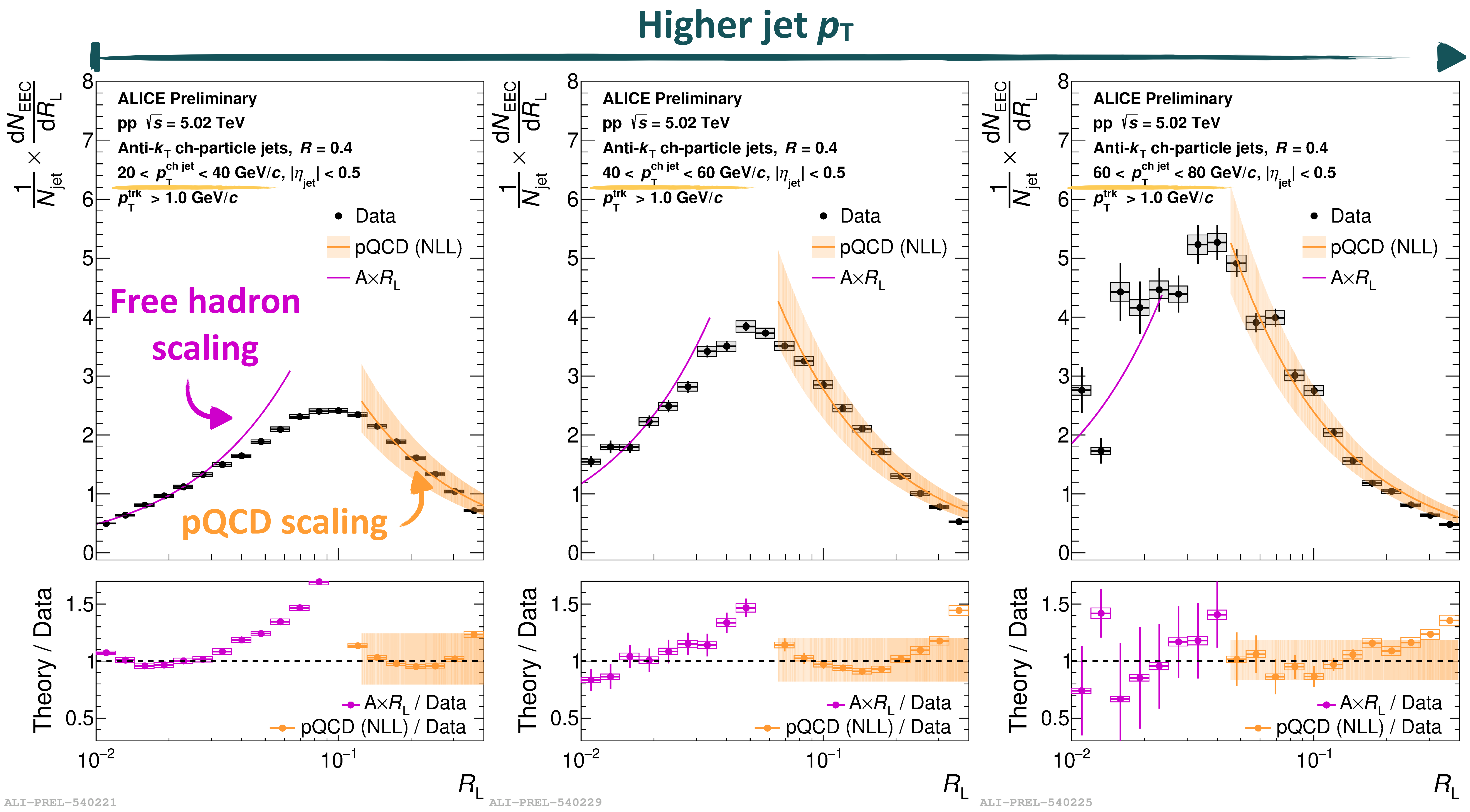
increasing time

Small angle

Large angle

decreasing energy scale

Comparison with pQCD



From large to small angle

Large angle: pQCD scaling

Deviation from pQCD near transition region: increasing NP effects

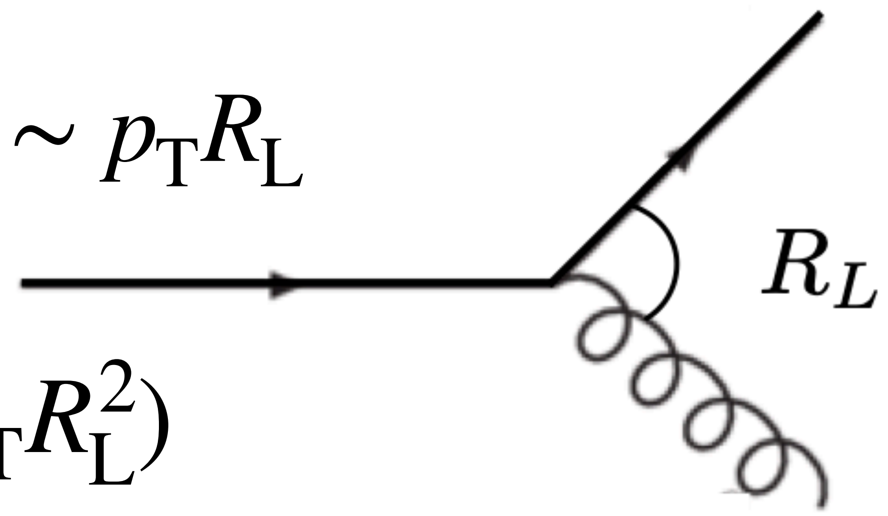
Small angle: free hadron scaling

NLL calculations correspond to full (charged+neutral) jets and are normalized to data in perturbative region (arXiv:2205.03414)

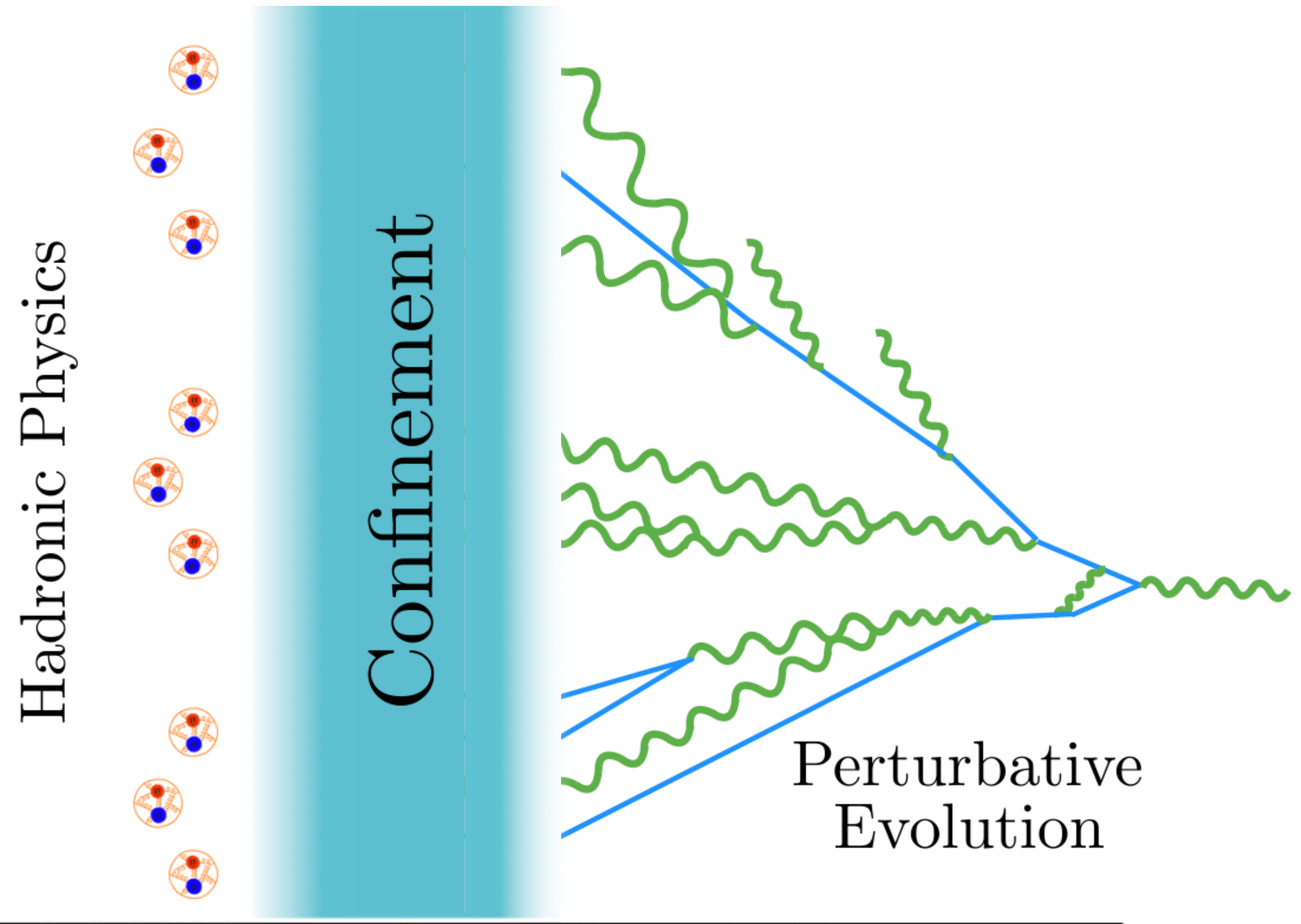
Universal transition behavior

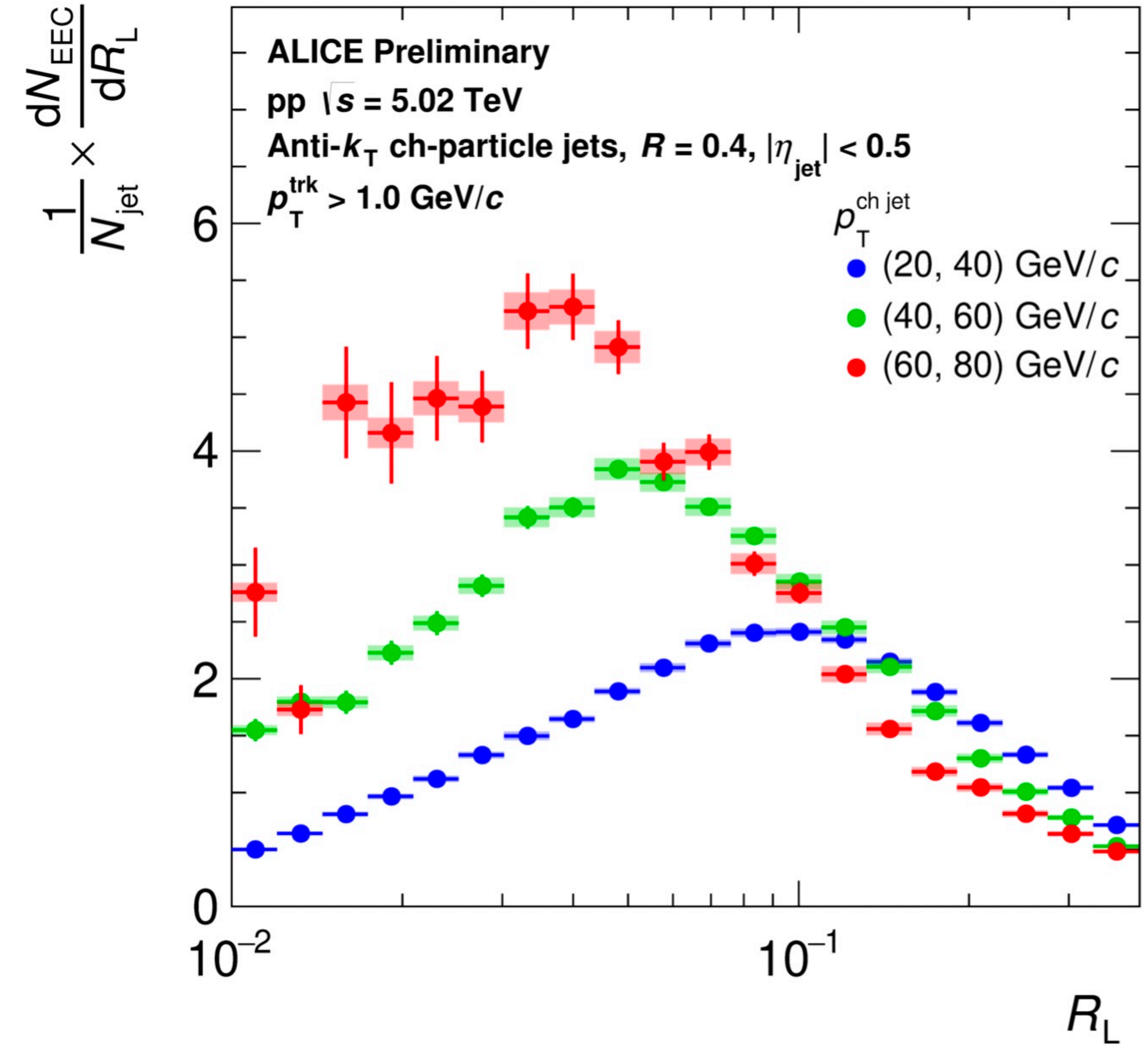
virtuality $\sim p_T R_L$

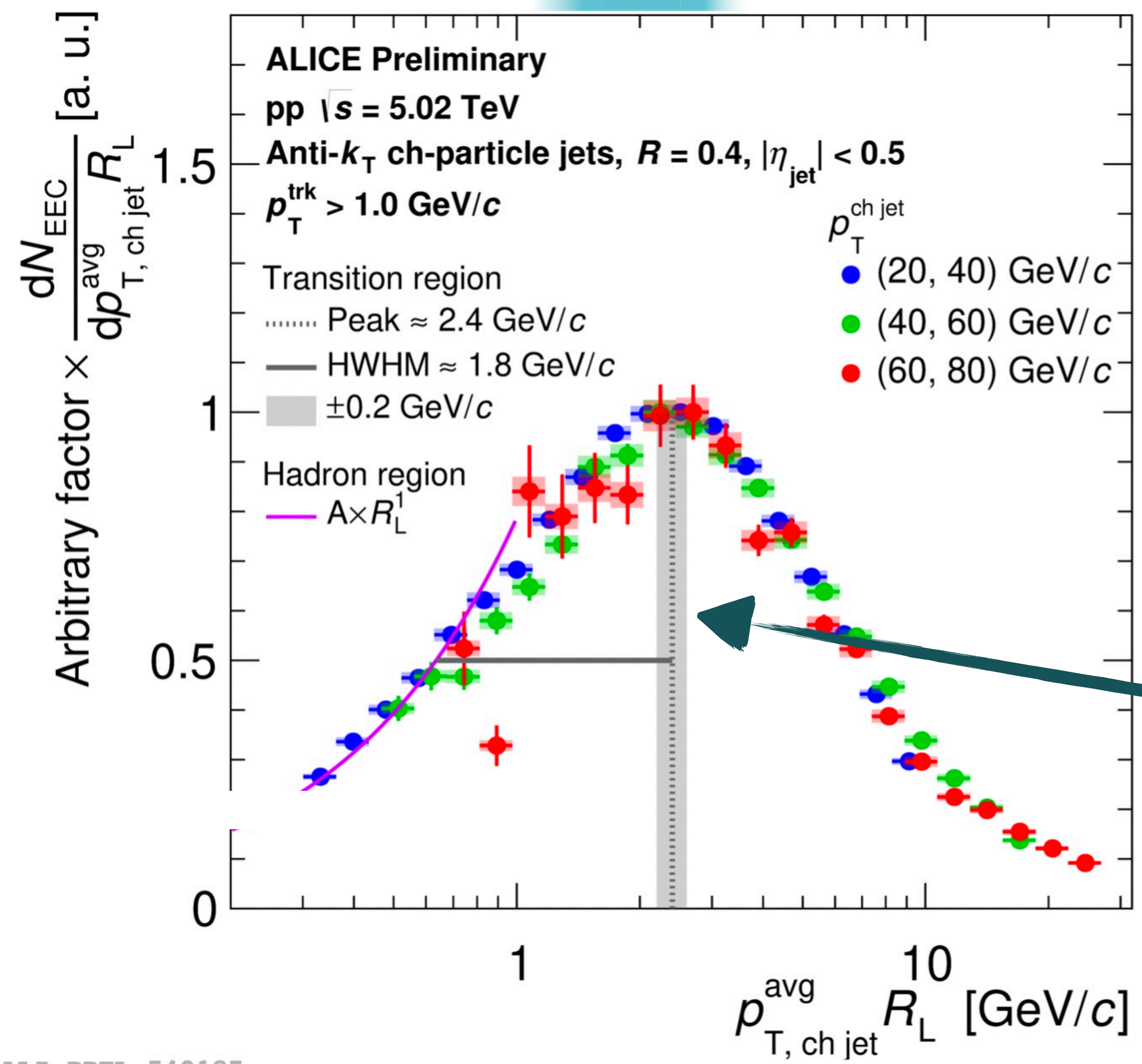
$\tau \simeq 1/(p_T R_L^2)$



Scaling angle R_L by jet p_T and normalize y scale





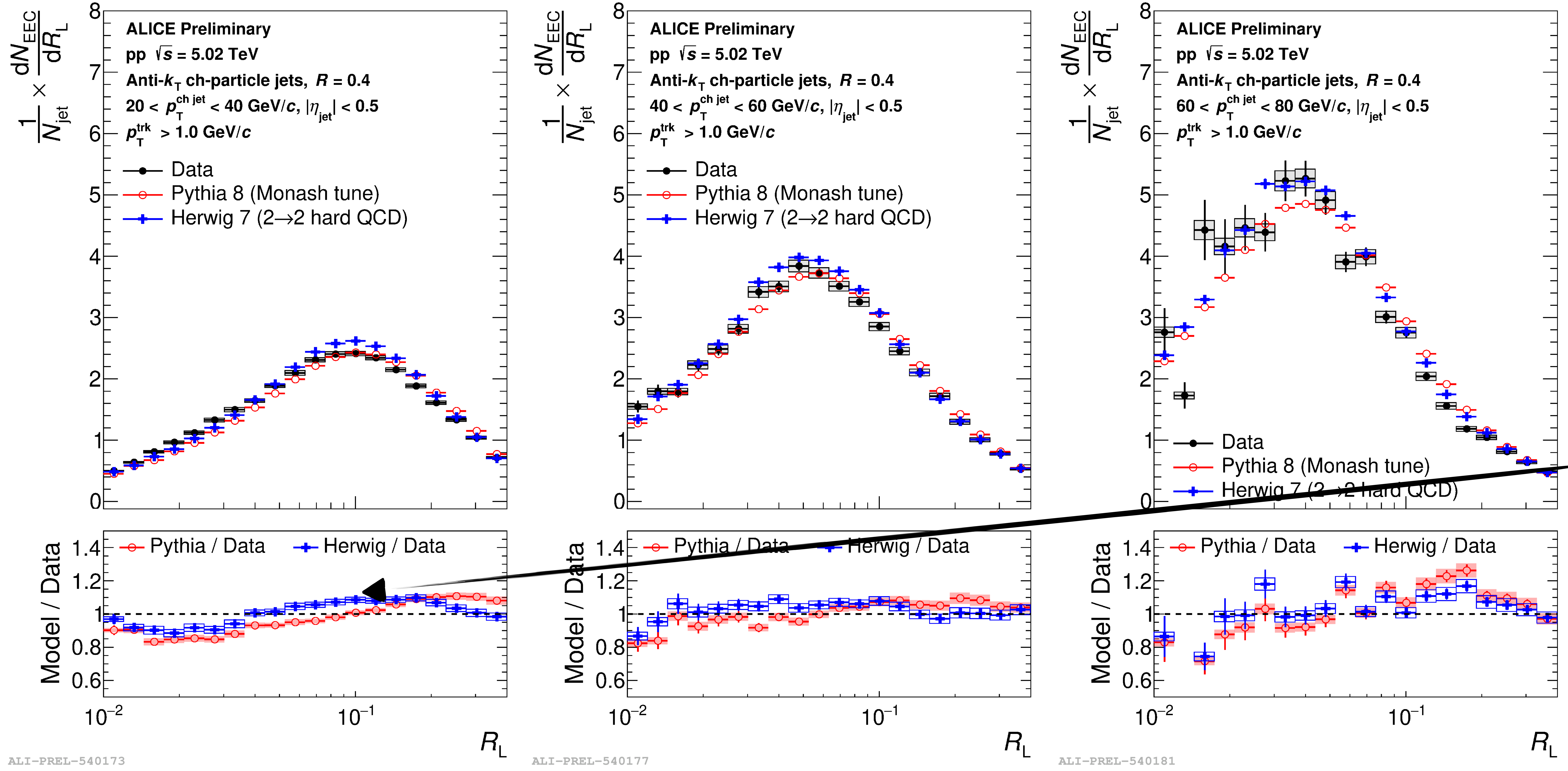


EEC distributions in different jet p_T bin have similar shape

Transition peak position ~2.4 GeV

Comparison with MC models

- Different hadronization mechanism in Pythia (string-breaking) and Herwig (clustering)
  - Transition peak in Herwig at smaller angle w.r.t. Pythia ⇔ later hadronization with clustering

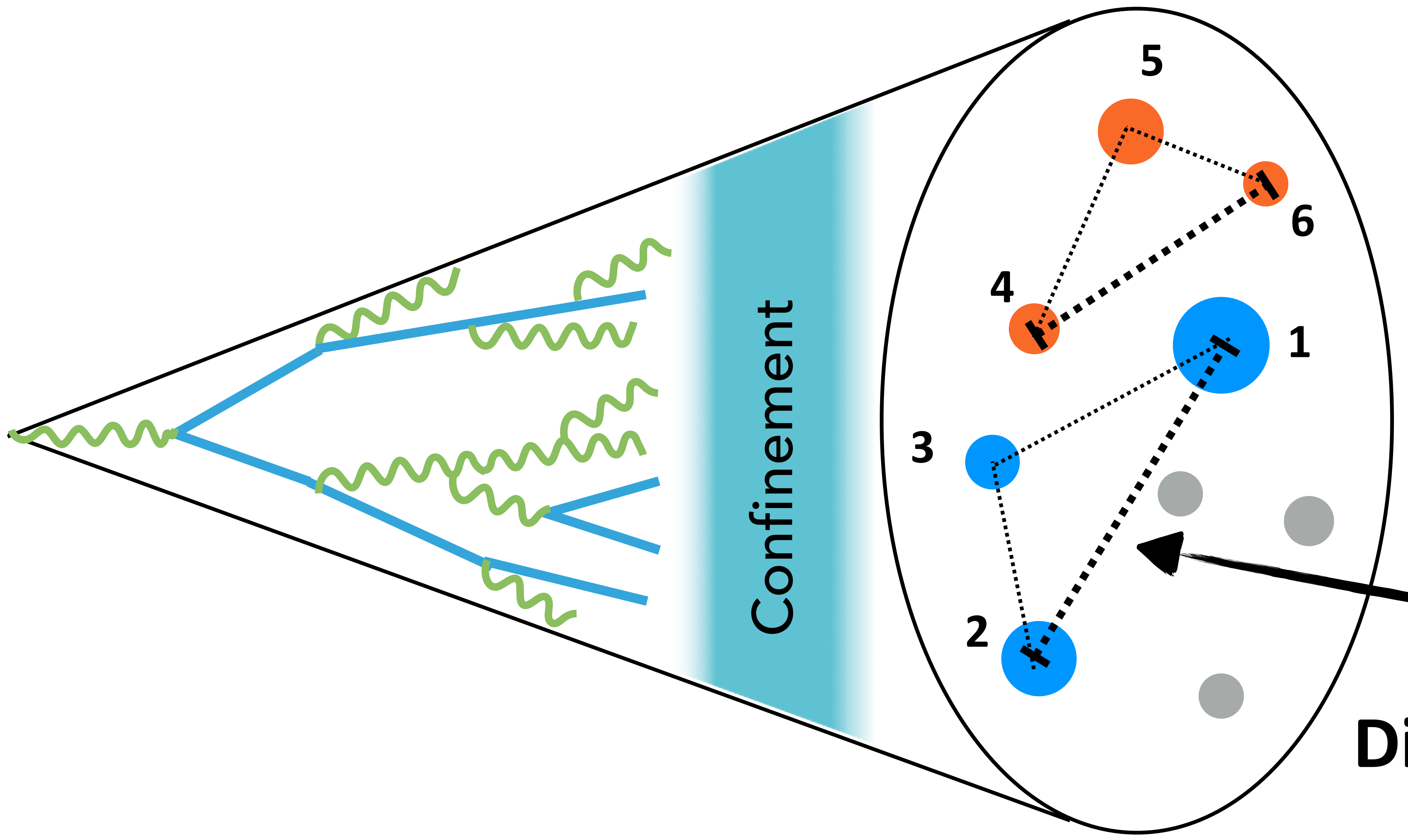


Herwig describes data slightly better than PYTHIA in peak position

Data has broader width than Herwig

Also looking into comparison with Sherpa and JETSCAPE

Going beyond 2 point energy correlators: EEC to E3C



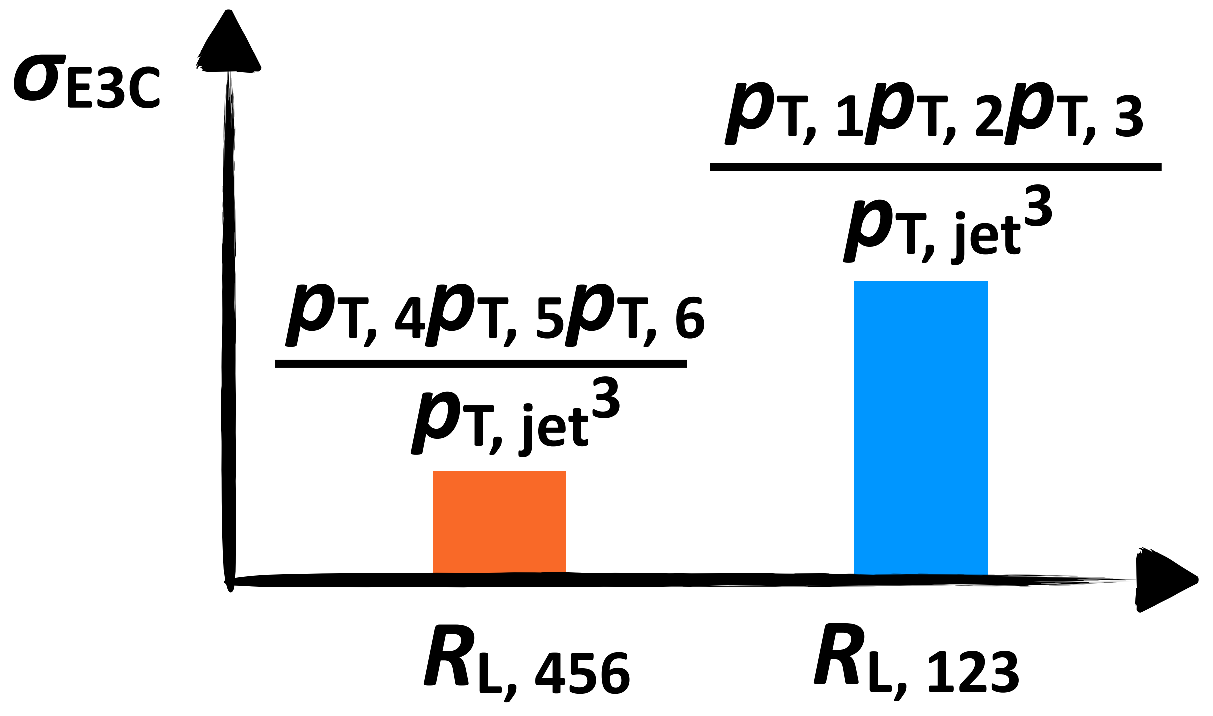
Count number of weighted triplets as function of R_L

$$\frac{d\sigma_{E3C}}{dR_L} = \sum_{i,j,k} \int d\sigma(R'_L) \frac{p_{T,i}\, p_{T,j}\, p_{T,k}}{p^3_{T,jet}} \delta(R'_L - R_{L,ijk})$$

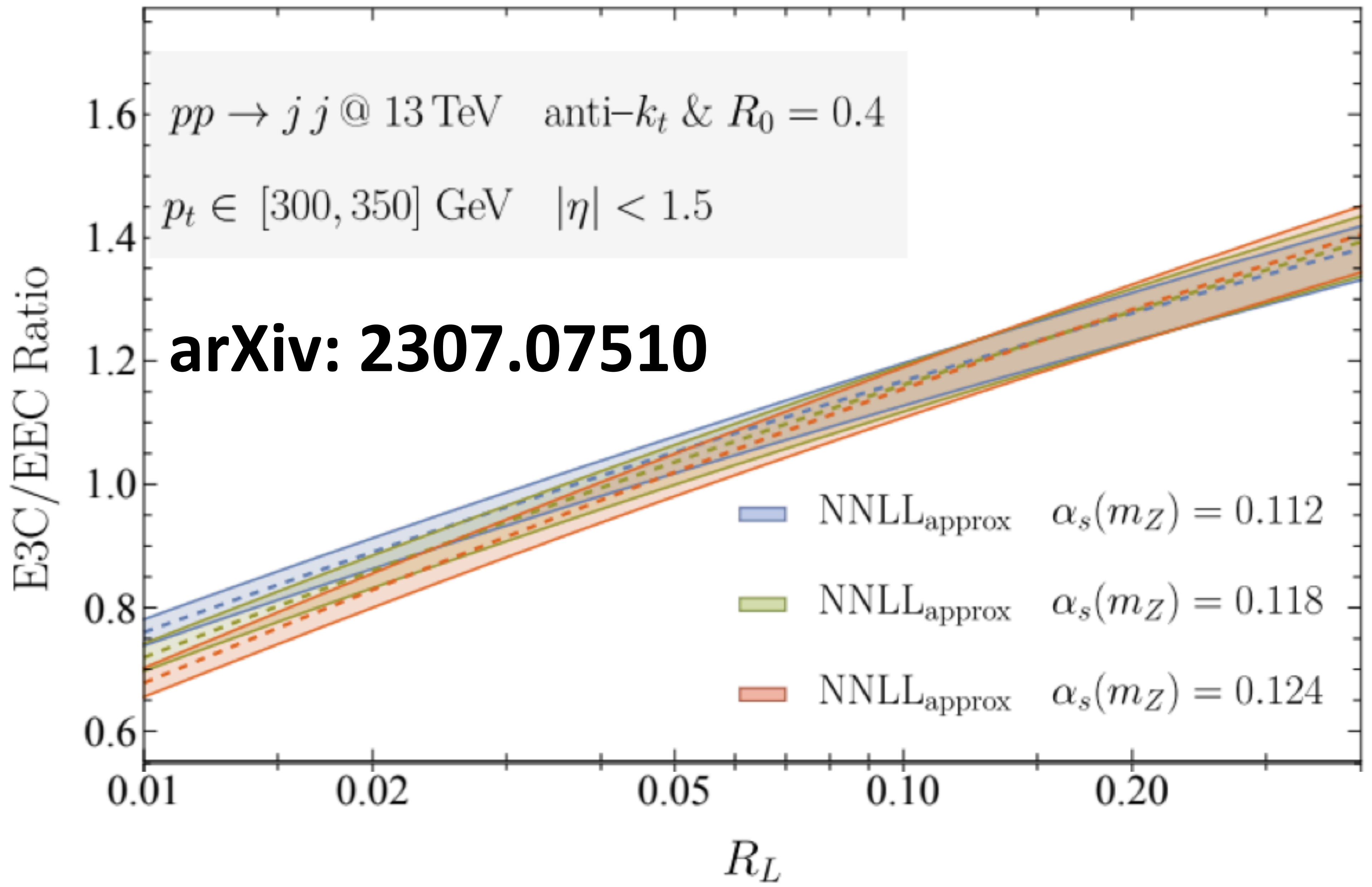
Energy weight

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

Distance along the longest side

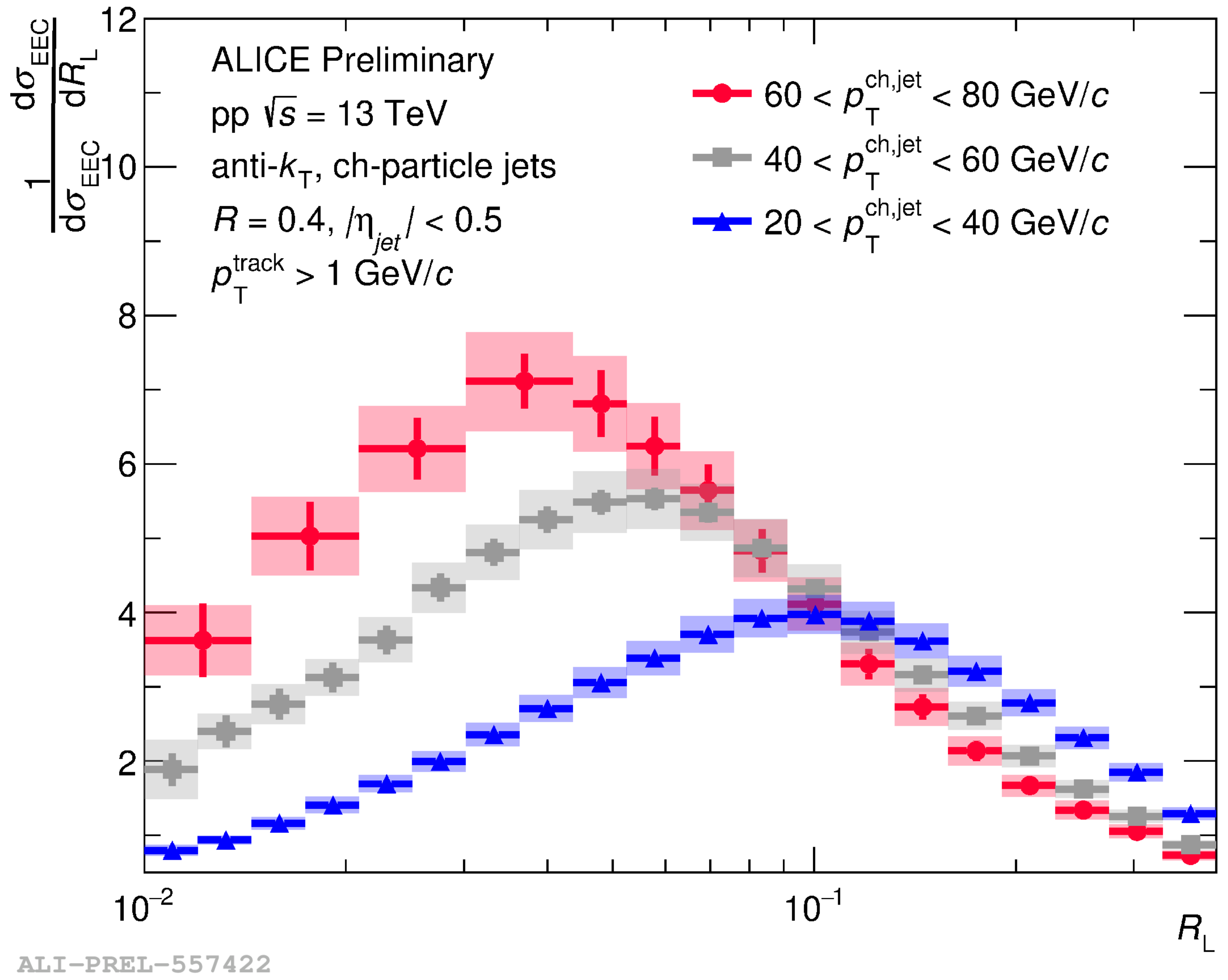


- Accessing higher order QCD dynamics: 1 ➜ 3 splitting
- More precision on the perturbative QCD studies
  - Cancellation of NP effects via E3C/EEC ratio



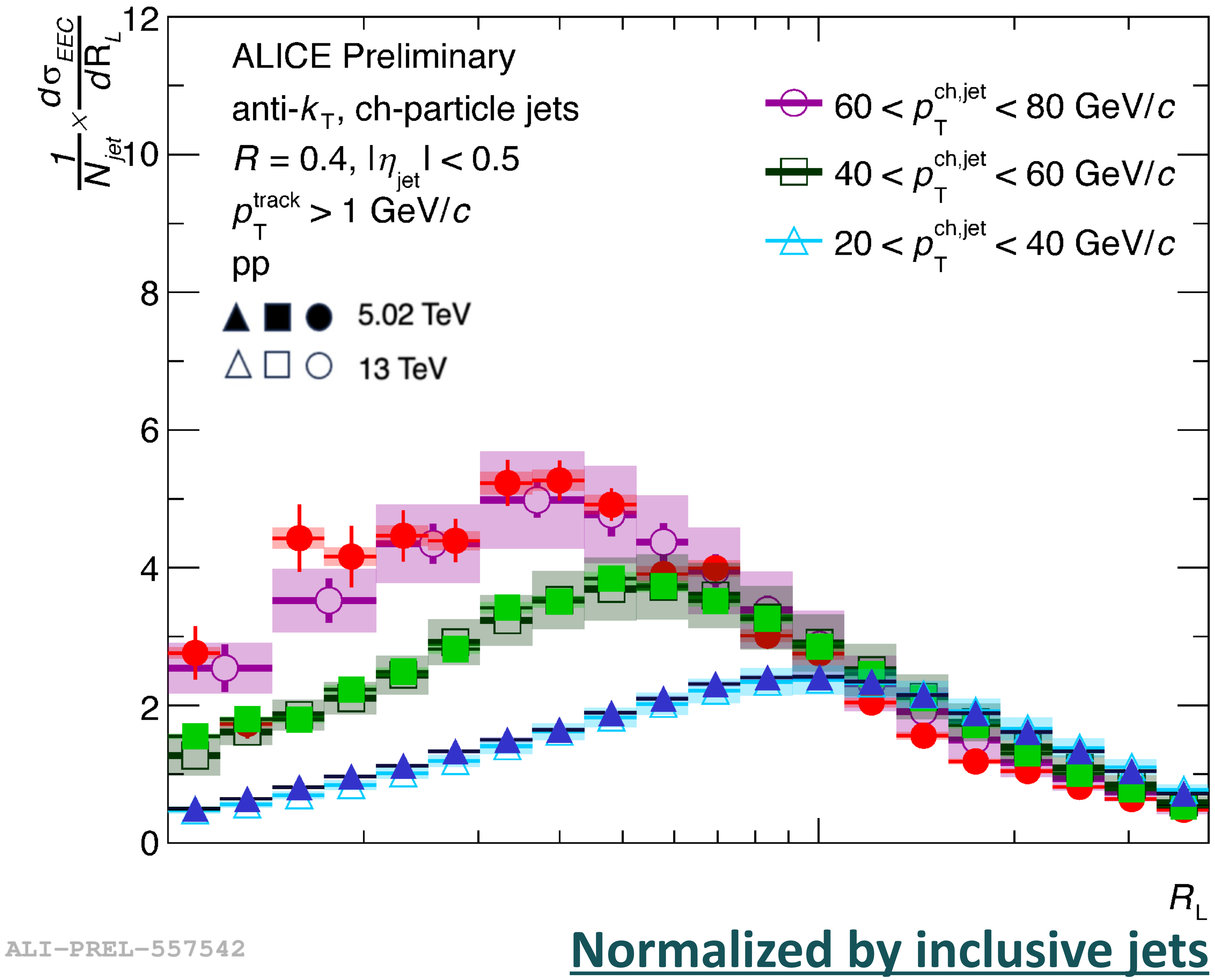
EEC in 5 TeV and 13 TeV

EEC



Area normalized in the measured range

EEC

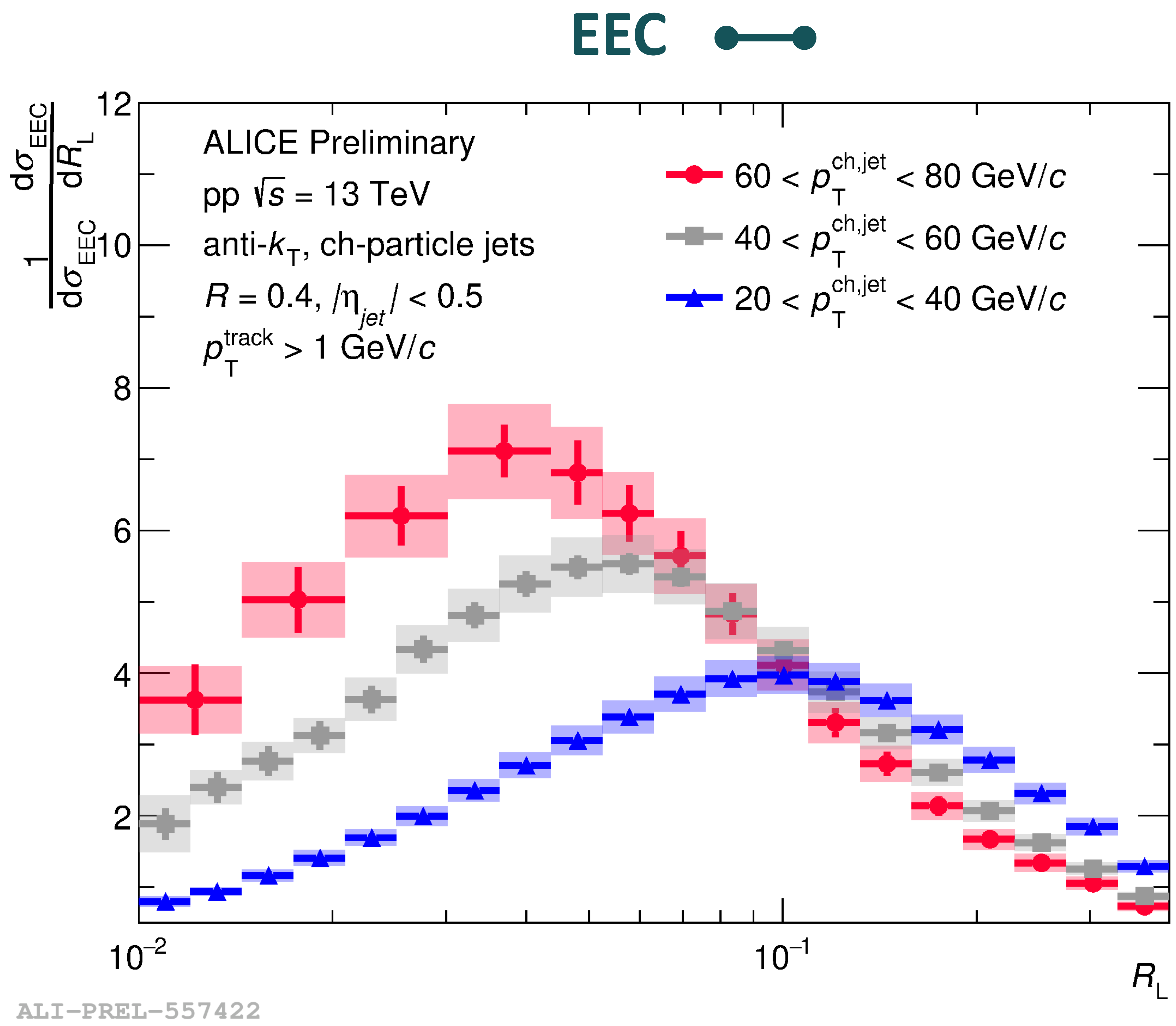


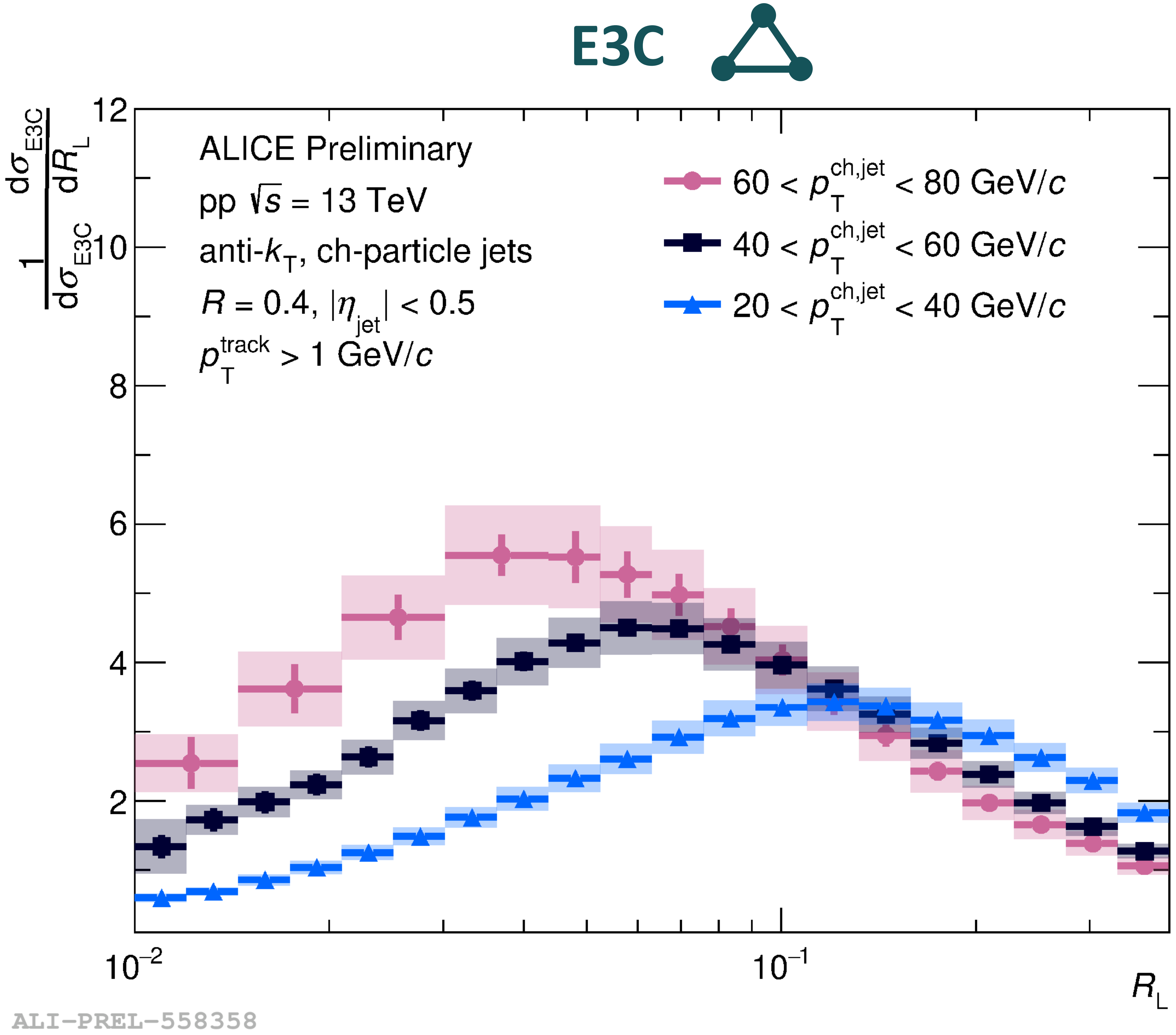
Normalized by inclusive jets

Similar EEC distributions at 5 and 13 TeV

No significant beam energy dependence for the transition peak

EEC and E3C results at 13 TeV





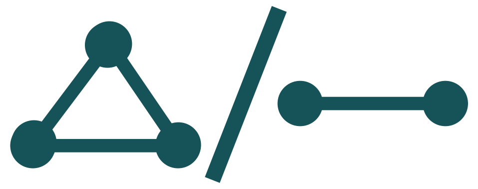
Area normalized in the measured range

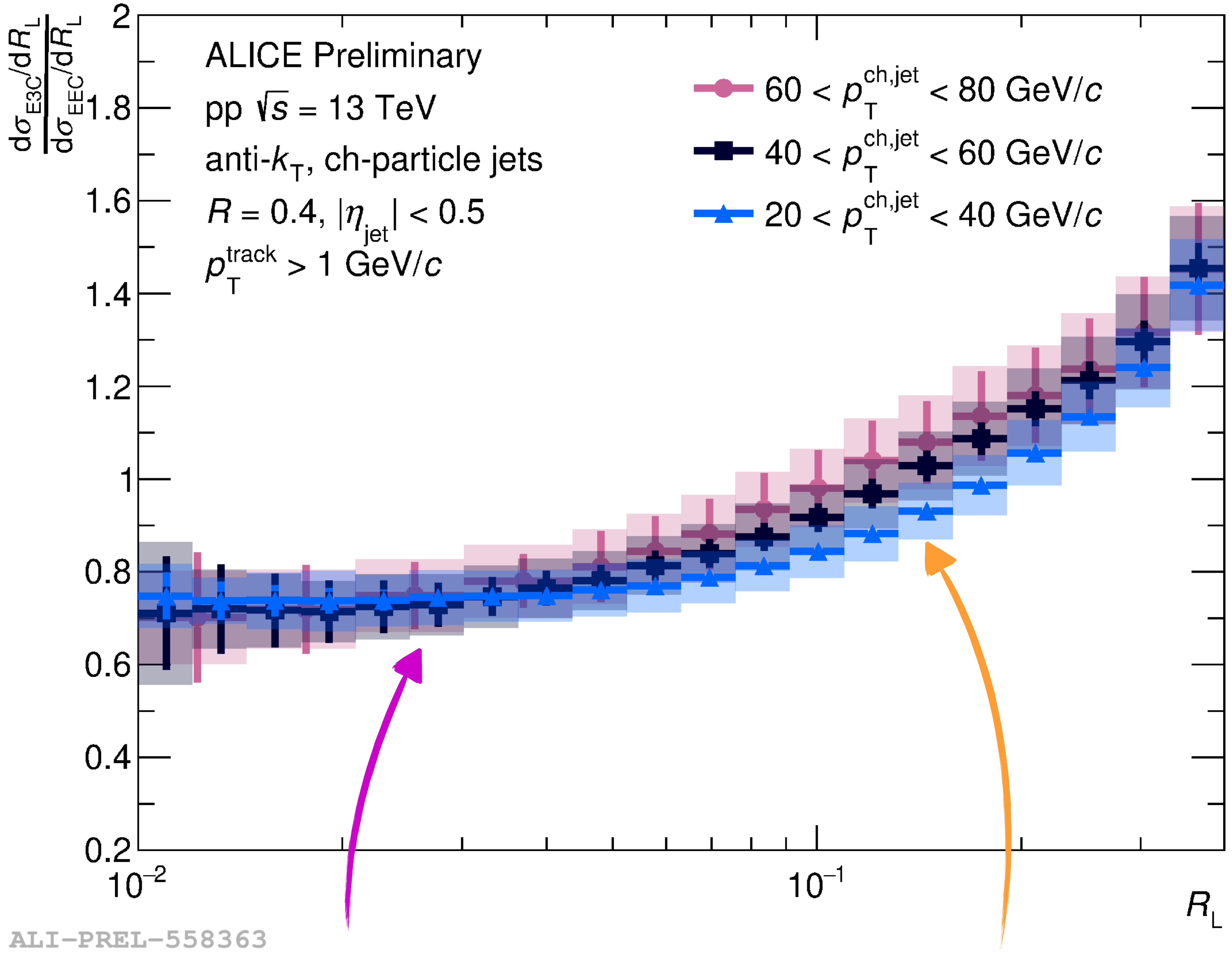
Similar EEC distributions at 5 and 13 TeV

Separation of NP and perturbative scaling behavior also in E3C

Different pQCD scaling behavior in E3C

E3C/EEC ratio: isolate perturbative scaling behavior

E3C/EEC 



Free hadron scaling region

Perturbative scaling region

- Cancellation of NP effects and systematic uncertainties
  - Small R_L: flat shape for free hadron region
  - Large R_L: slope sensitive to α_s

E3C/EEC ratio $\propto \alpha_s(Q) In R_L + \mathcal{O}(\alpha_s^2)$

High precision constraint on α_s from jet substructure

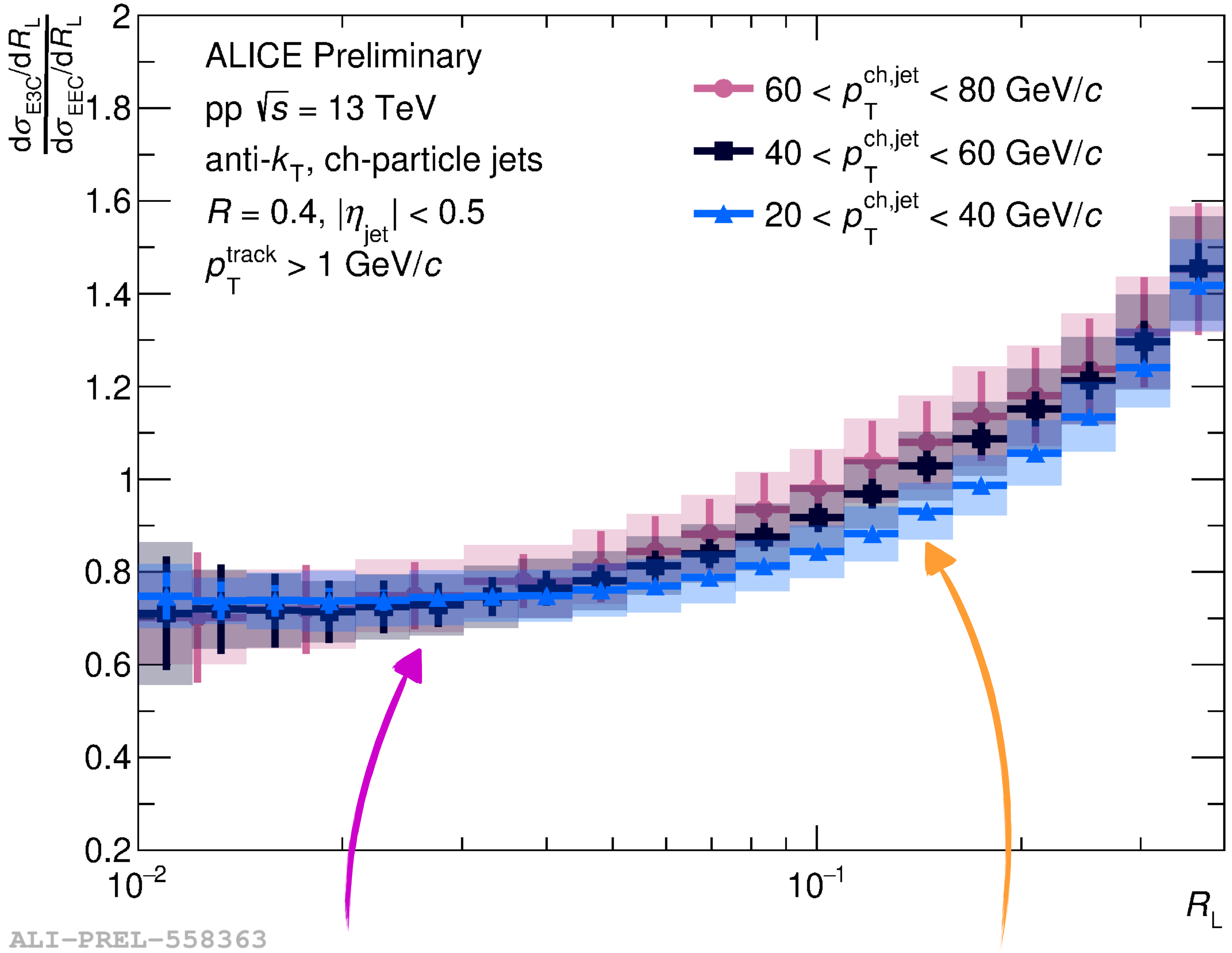
- Slope decrease towards higher jet p_T
  - Higher jet p_T ➜ higher Q ➜ smaller α_s ➜ smaller slope

Consistent with running of the coupling!

Also reported by CMS in BOOST 2023

E3C/EEC ratio: comparison with pQCD

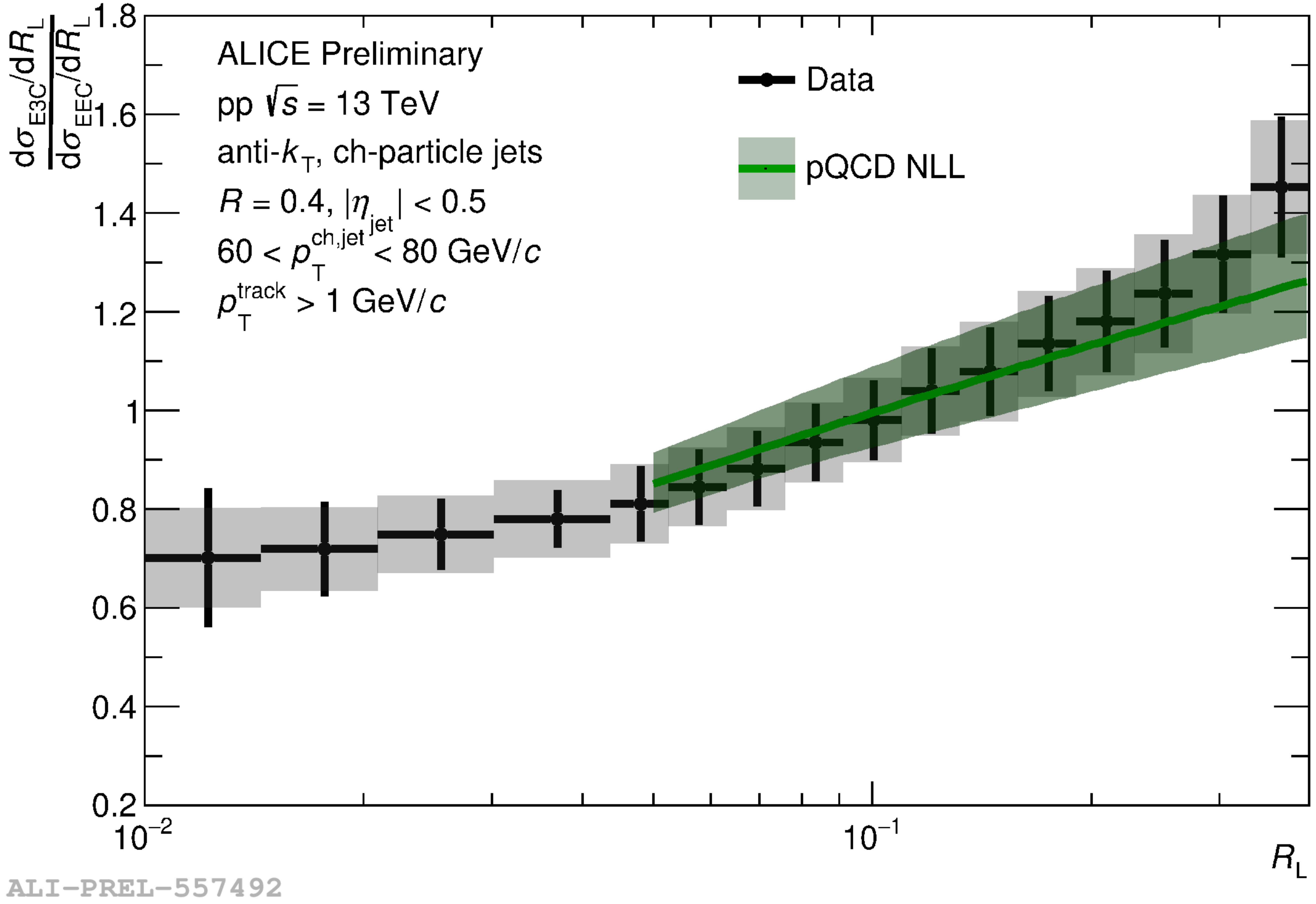
E3C/EEC



Free hadron scaling region

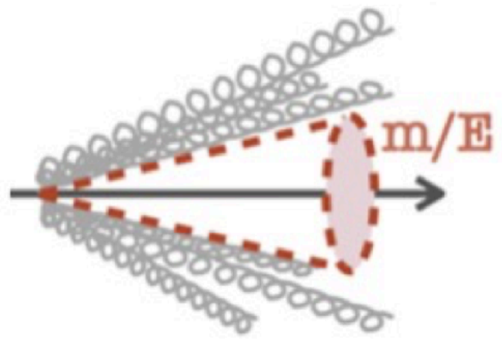
Perturbative scaling region

E3C/EEC

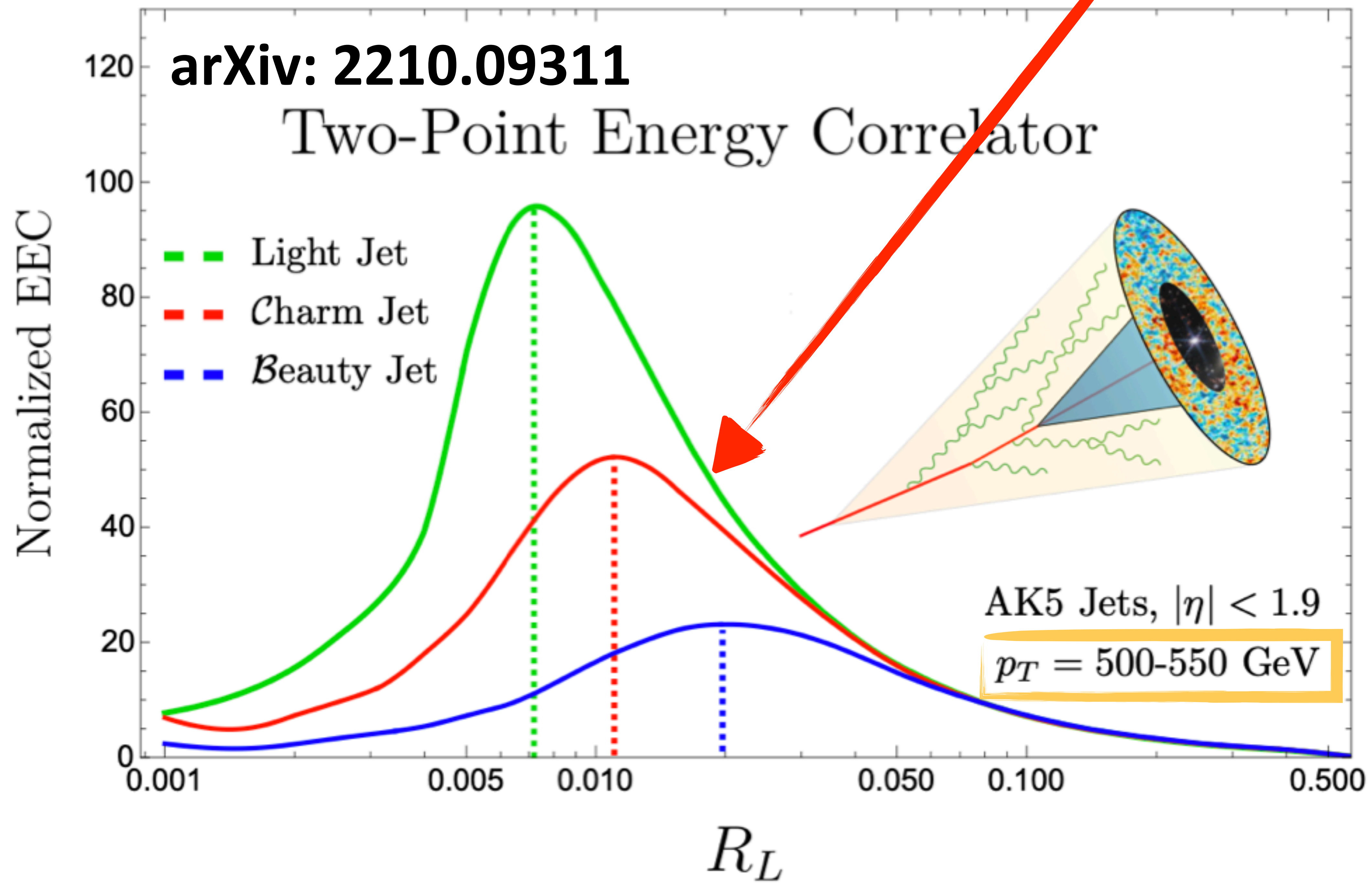


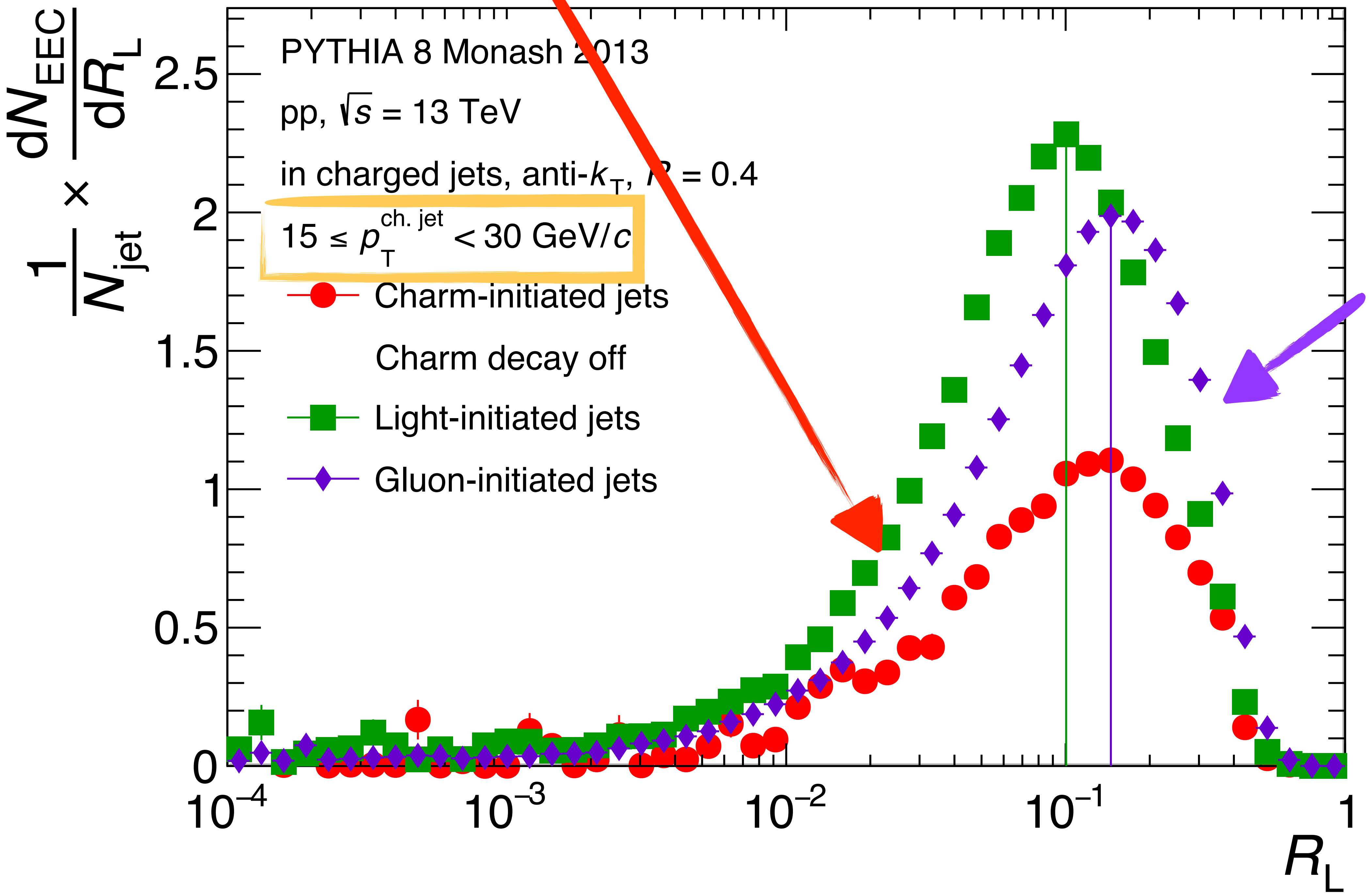
Agreement with pQCD prediction

Probing color charge and mass dependence



Suppression of small angle radiation due to dead-cone



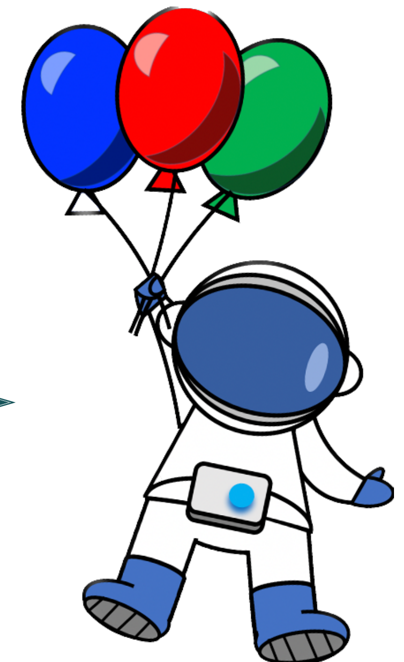


Wider fragmentation for gluon jets due to color factor

Summary and outlook

- 2 point energy correlator results in pp at 5 TeV
  - A clear separation between perturbative region (pQCD scaling) and NP region (free hadron scaling)
  - Hadronization transition at $p_{\mathrm{T}}R_{\mathrm{L}}$ ~ 2.4 GeV
- 2 point and 3 energy correlator results in pp at 13 TeV
  - Precision study of pQCD via E3C/EEC ratio, stringent constraint on α_s
- Outlook of the ongoing heavy flavor: probing mass effect and color charge dependence of jet dynamics
- Baseline to study modifications in p-Pb and Pb-Pb: study the medium modified parton shower and hadronization in cold and hot nuclear medium

Stay tuned for more results from ALICE!



EEC in D^0 tag jets

Poster by Beatrice Liang-Gilman

EEC in pp and p-Pb

Poster by Anjali Nambrath

EEC and E3C

Poster by Ananya Rai

Heavy flavor jet substructure

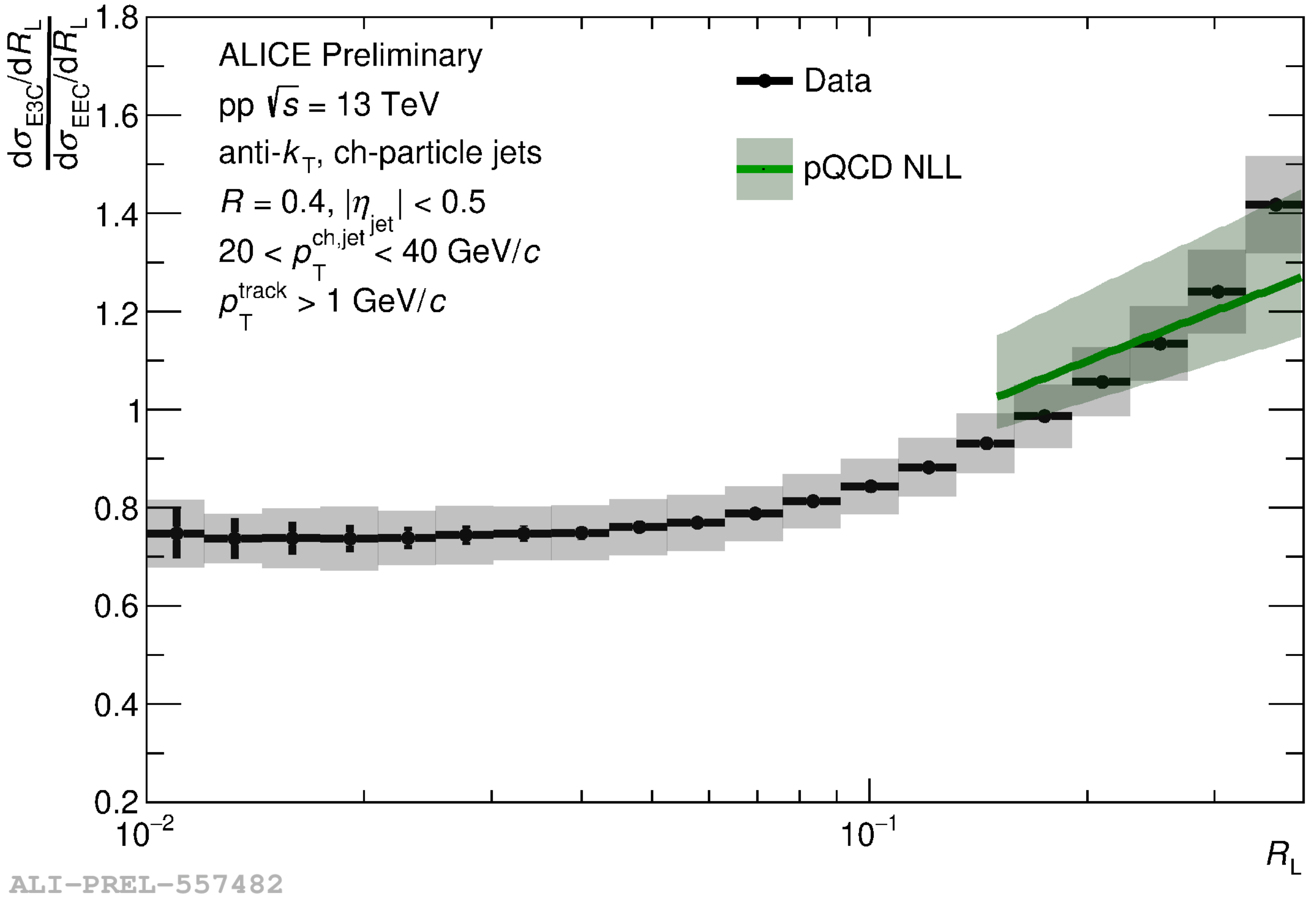
Talk by Nima Zardoshti (Wed 16:50)

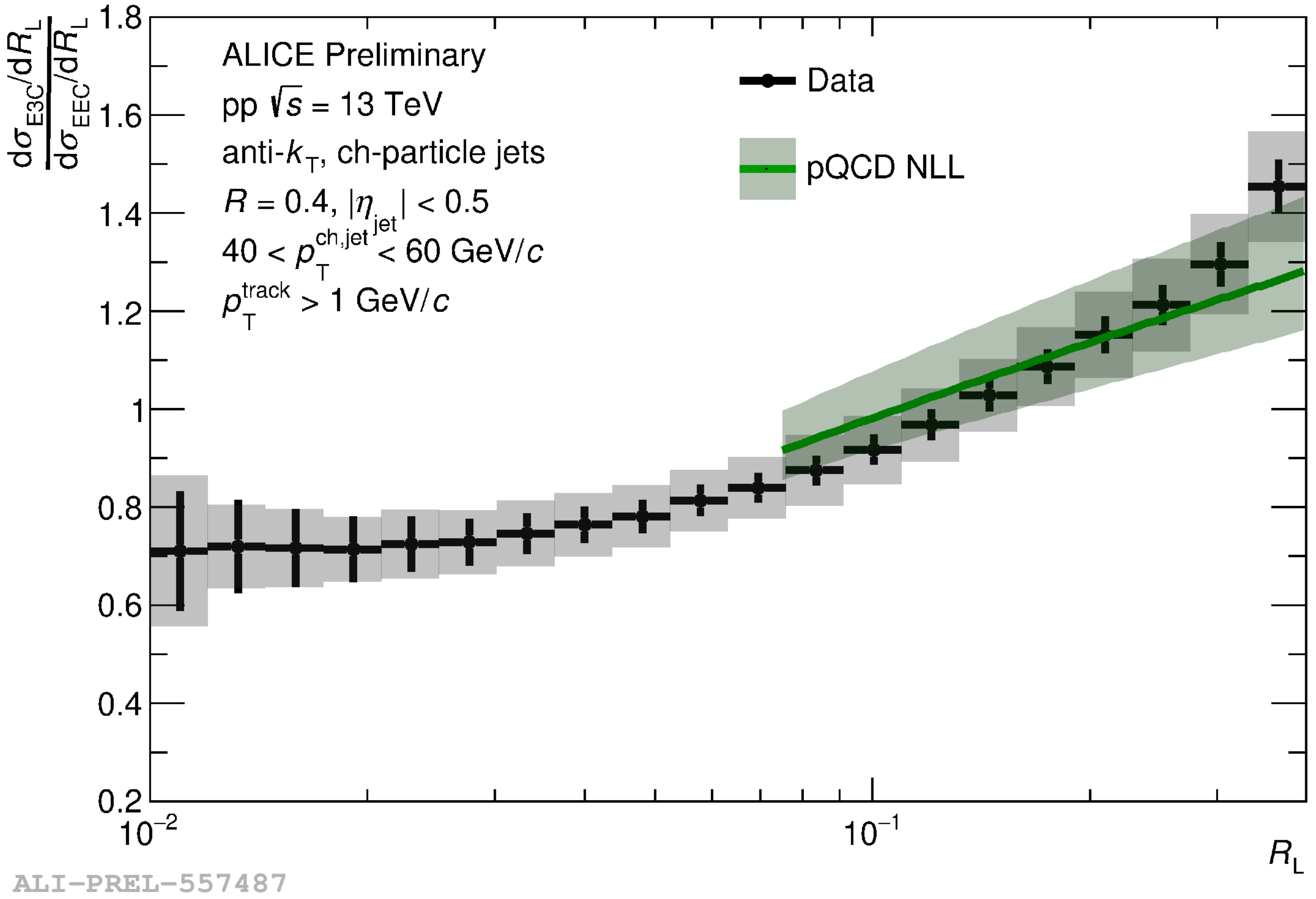
Jet substructure in Pb-Pb

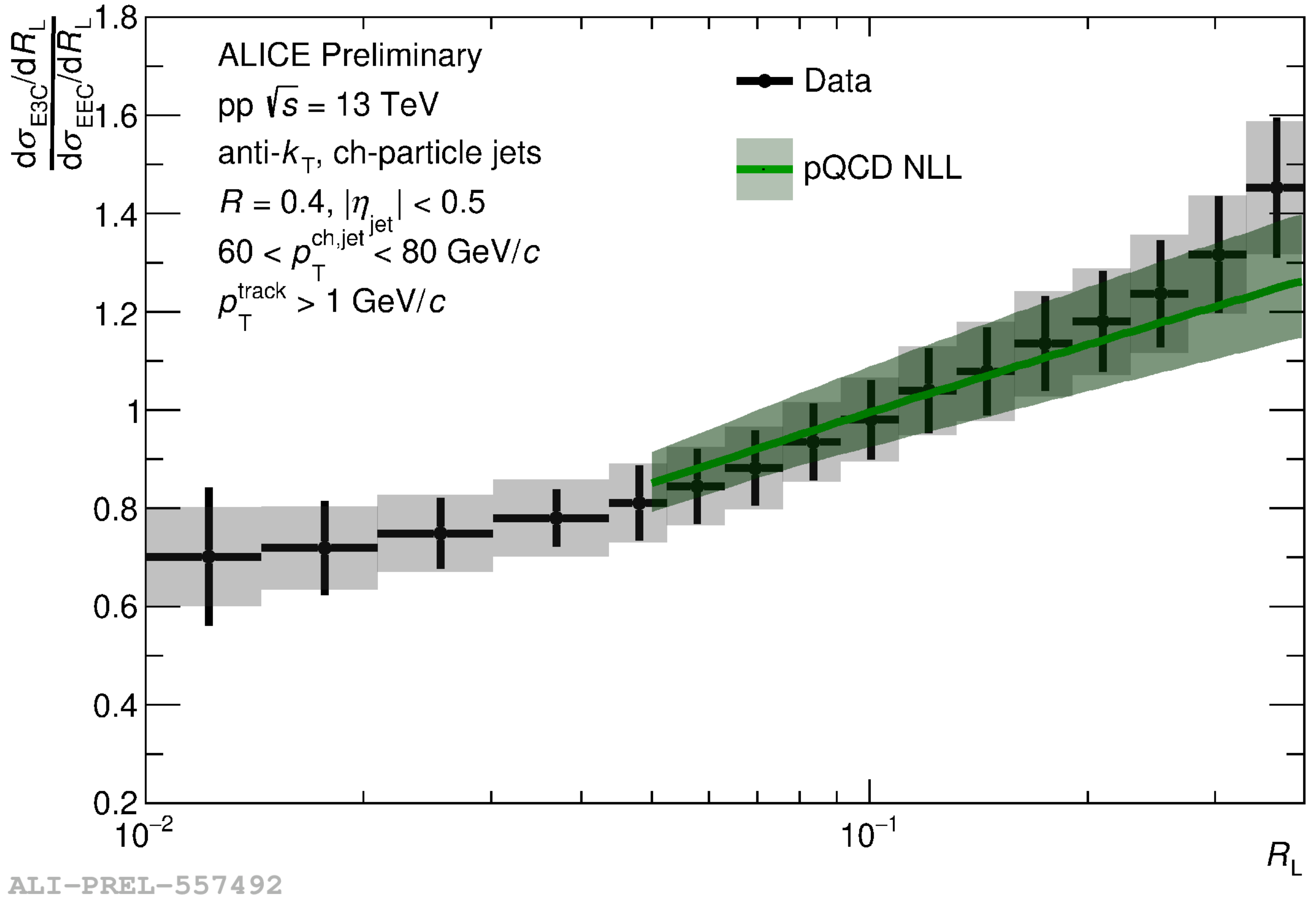
Talk by Hannah Bossi (Tues 11:20)

THANKS!

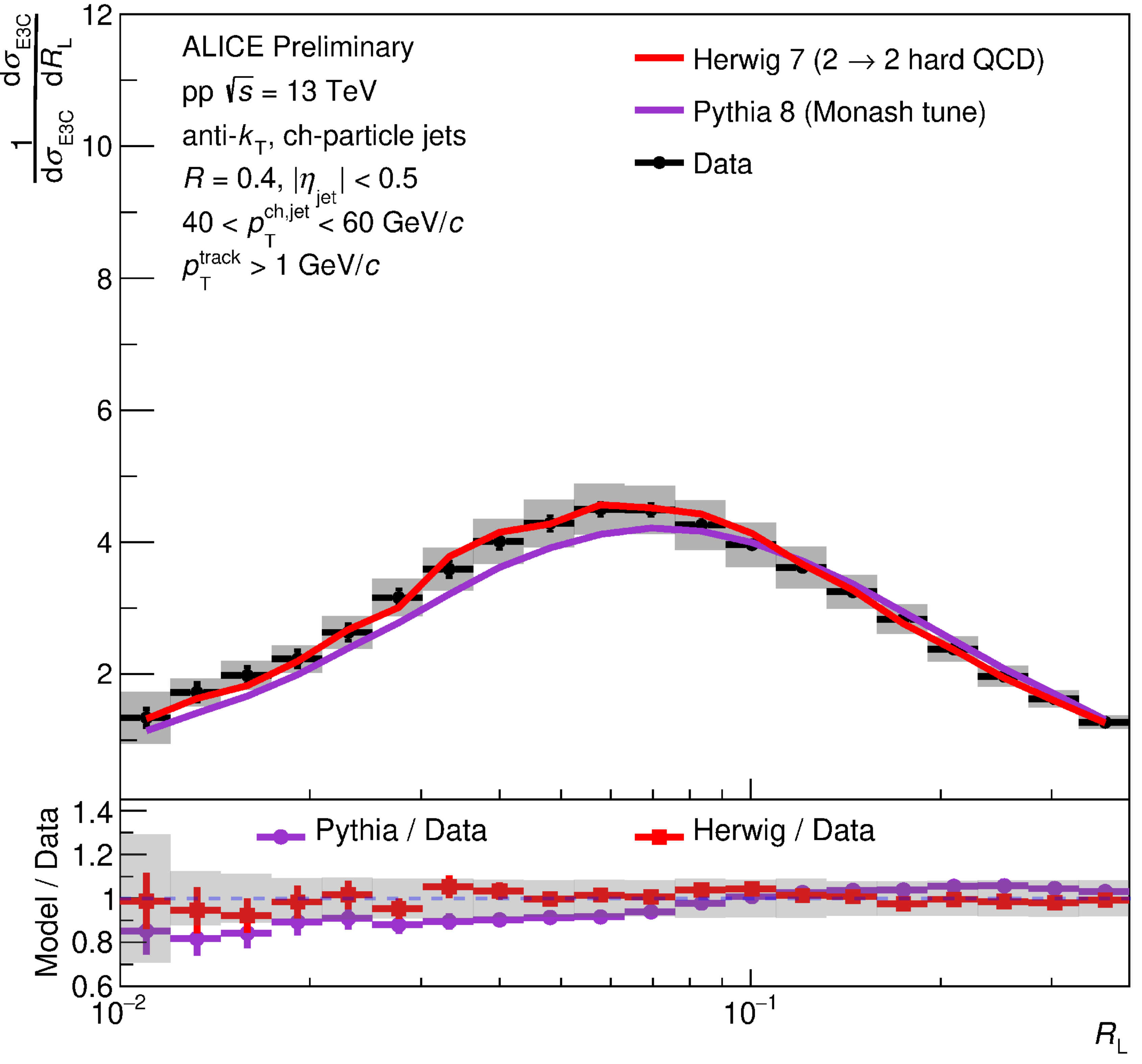
Theory comparison for E3C/EEC ratio



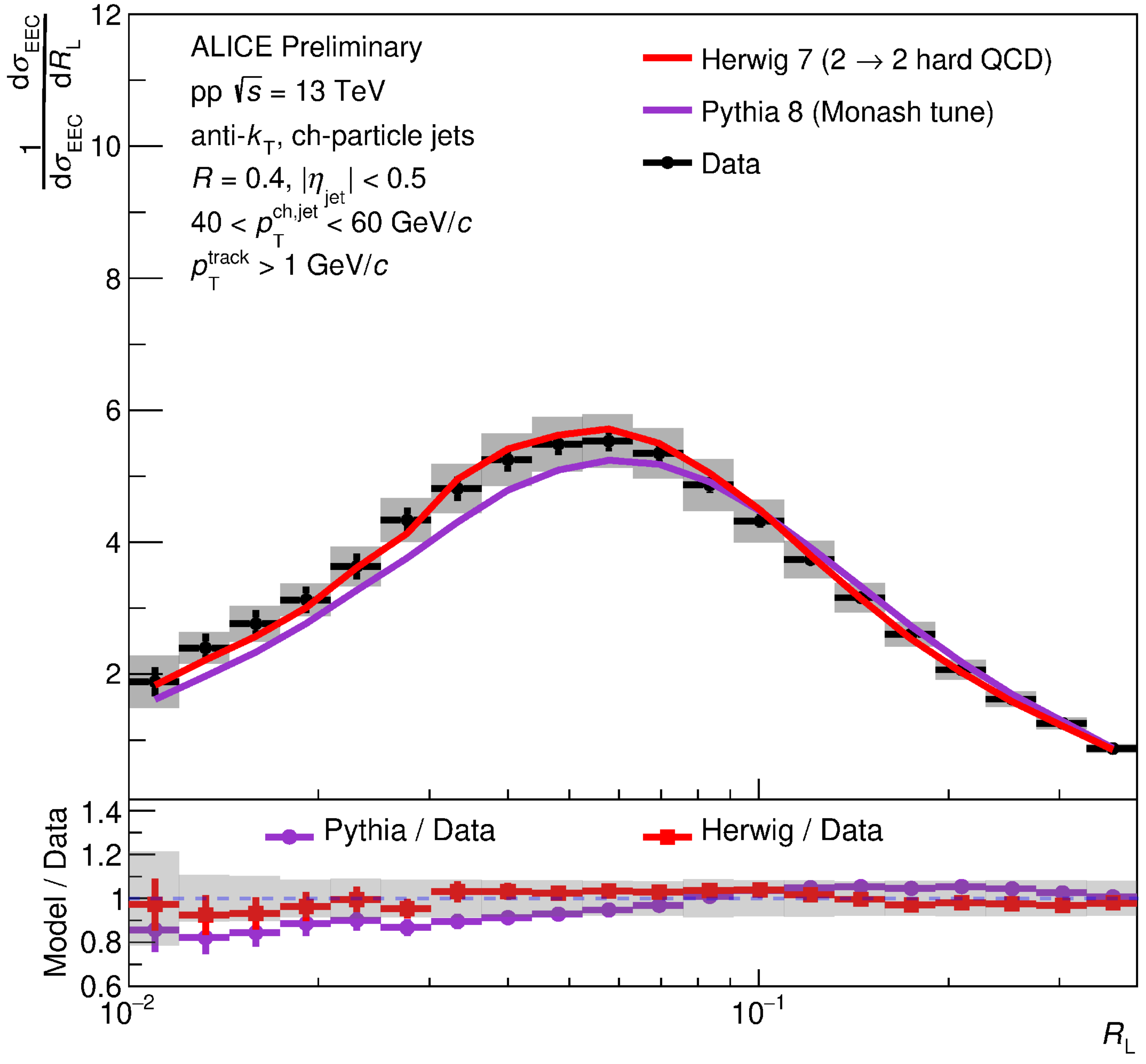




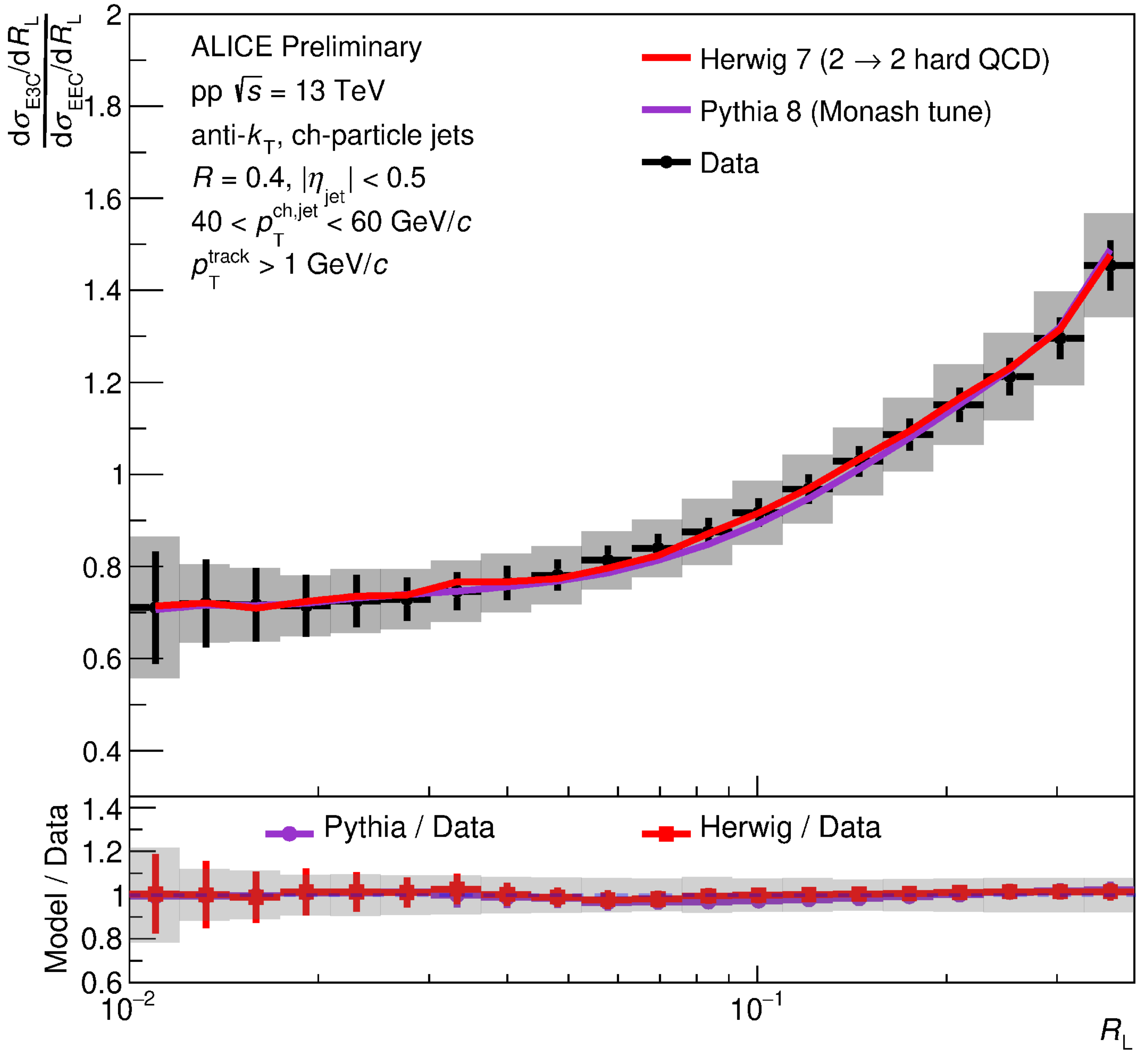
Model comparison for pp results at 13 TeV



ALI-PREL-557457



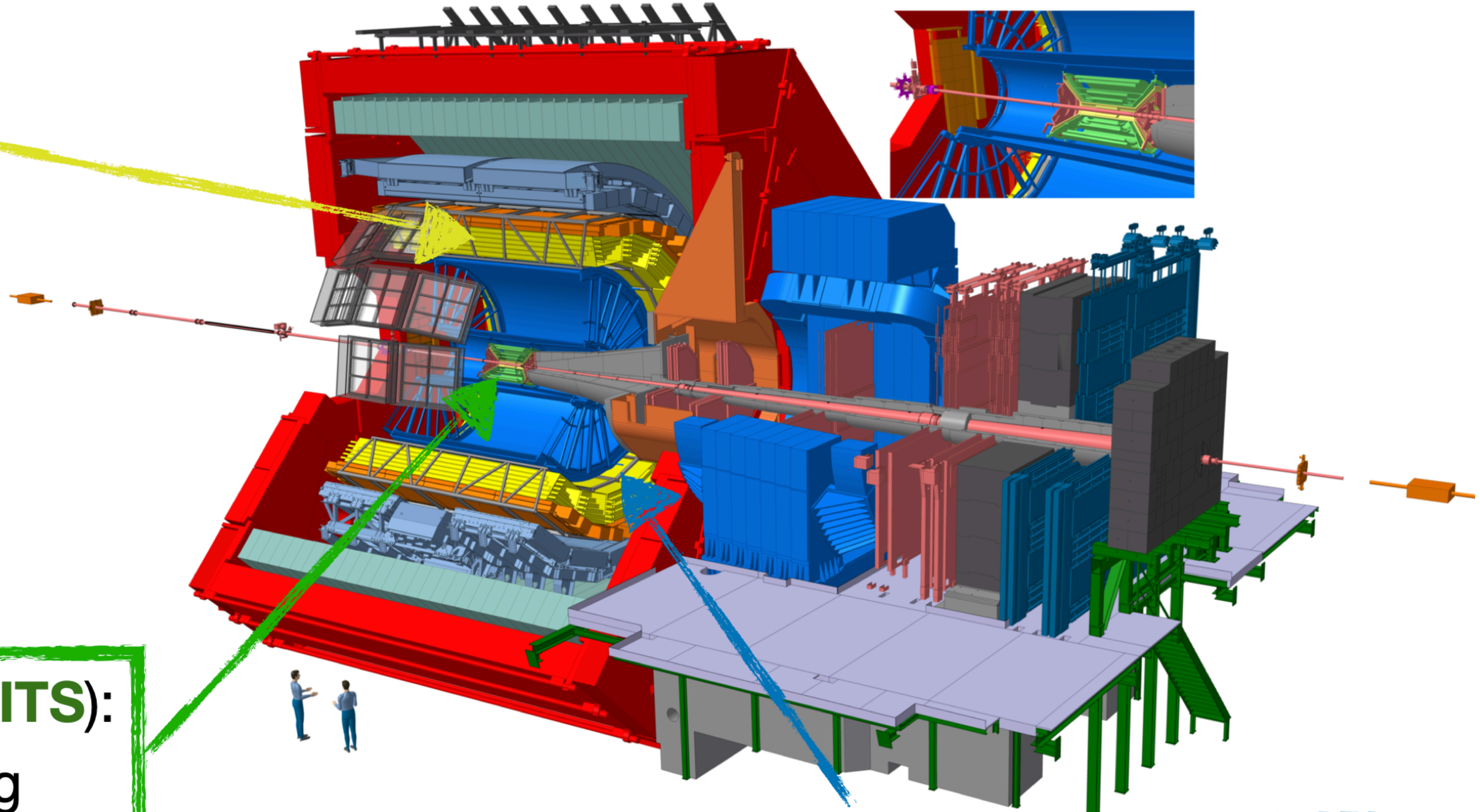
ALI-PREL-557442



ALI-PREL-557472

ALICE detector

Time-Of-Flight (TOF):
PID via time of flight



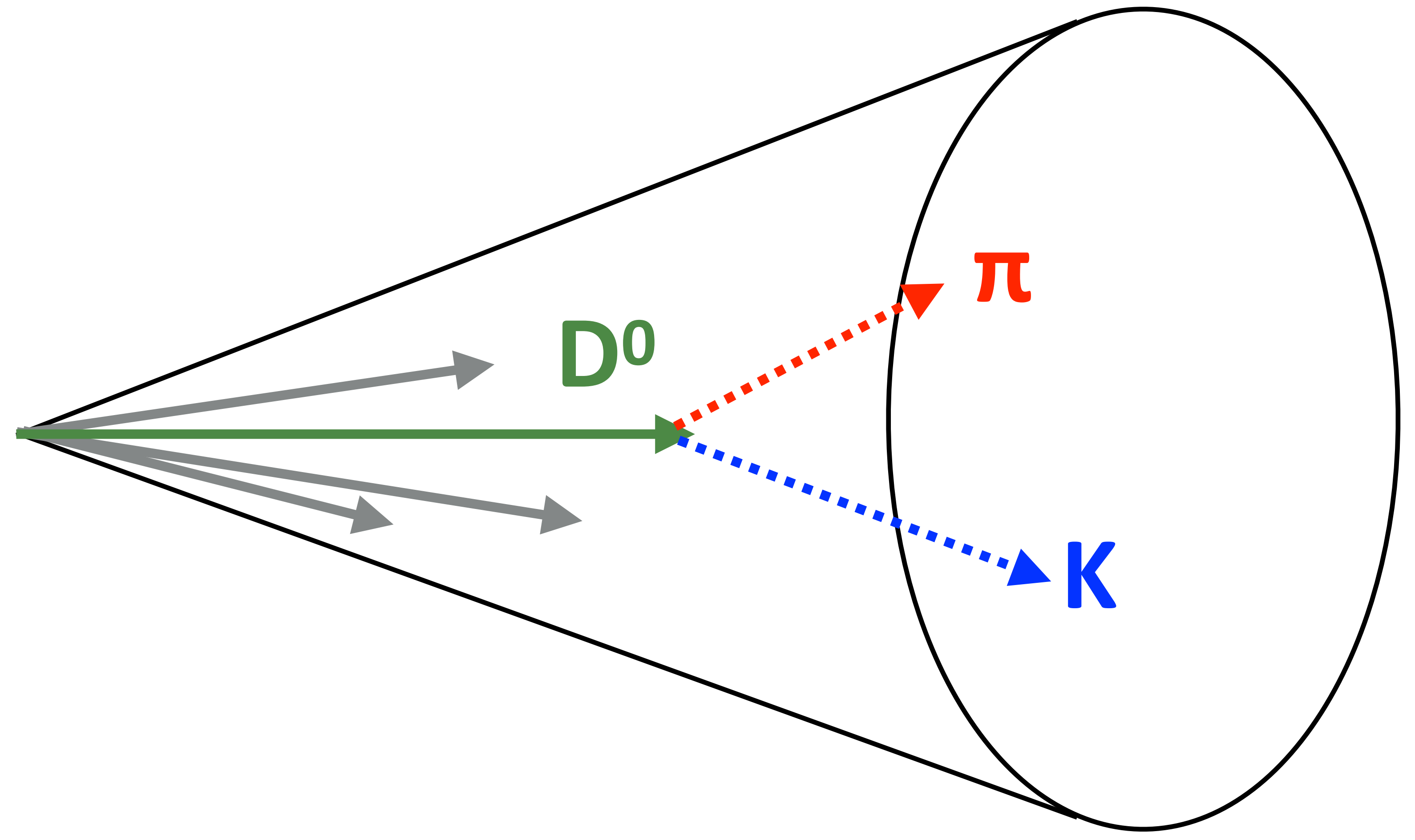
Inner Tracking System (ITS):
tracking and vertexing

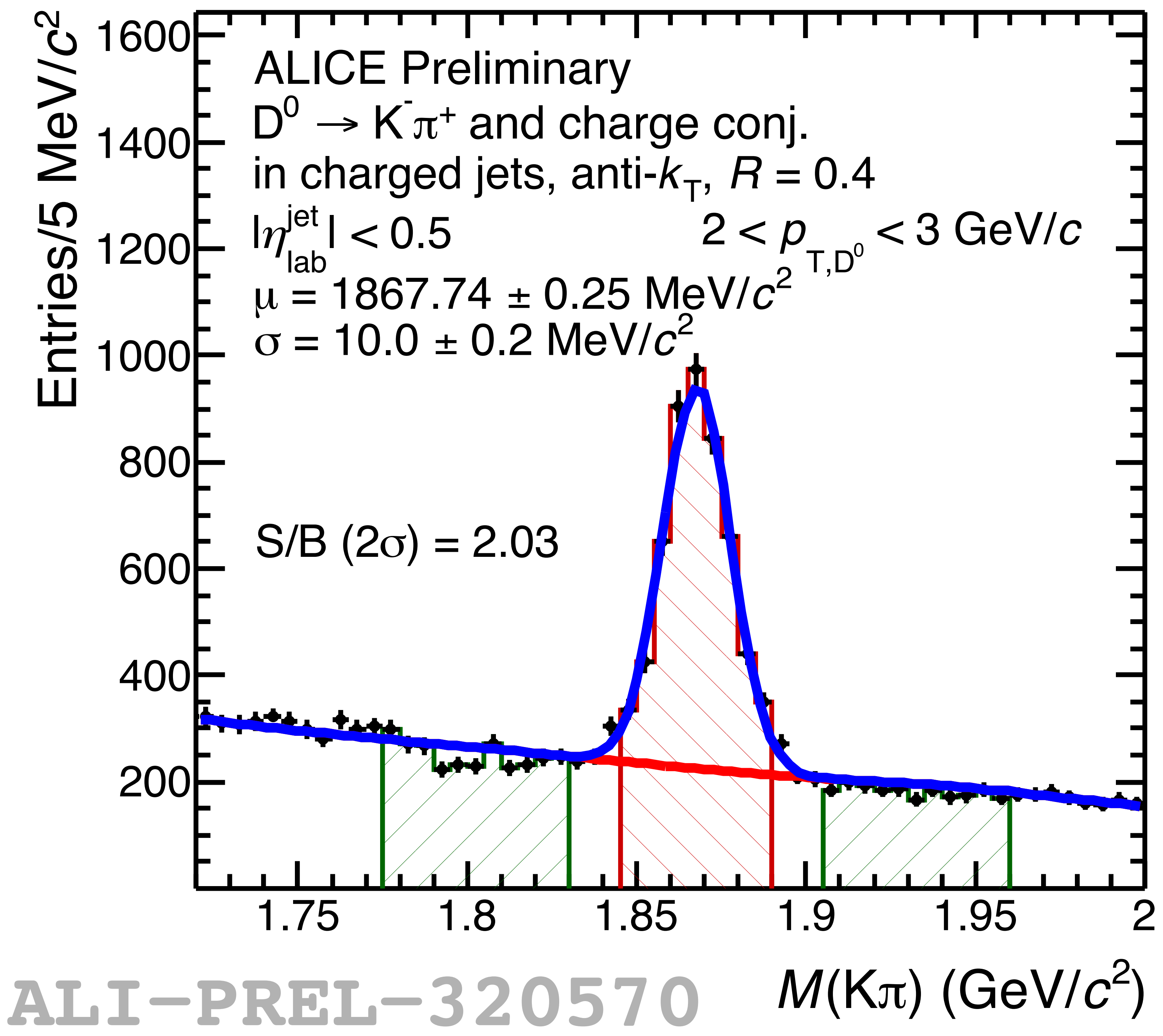
Time Projection Chamber (TPC):
tracking and PID via d*E*/d*x*

EEC in D^0 tagged jets in pp at 13 TeV

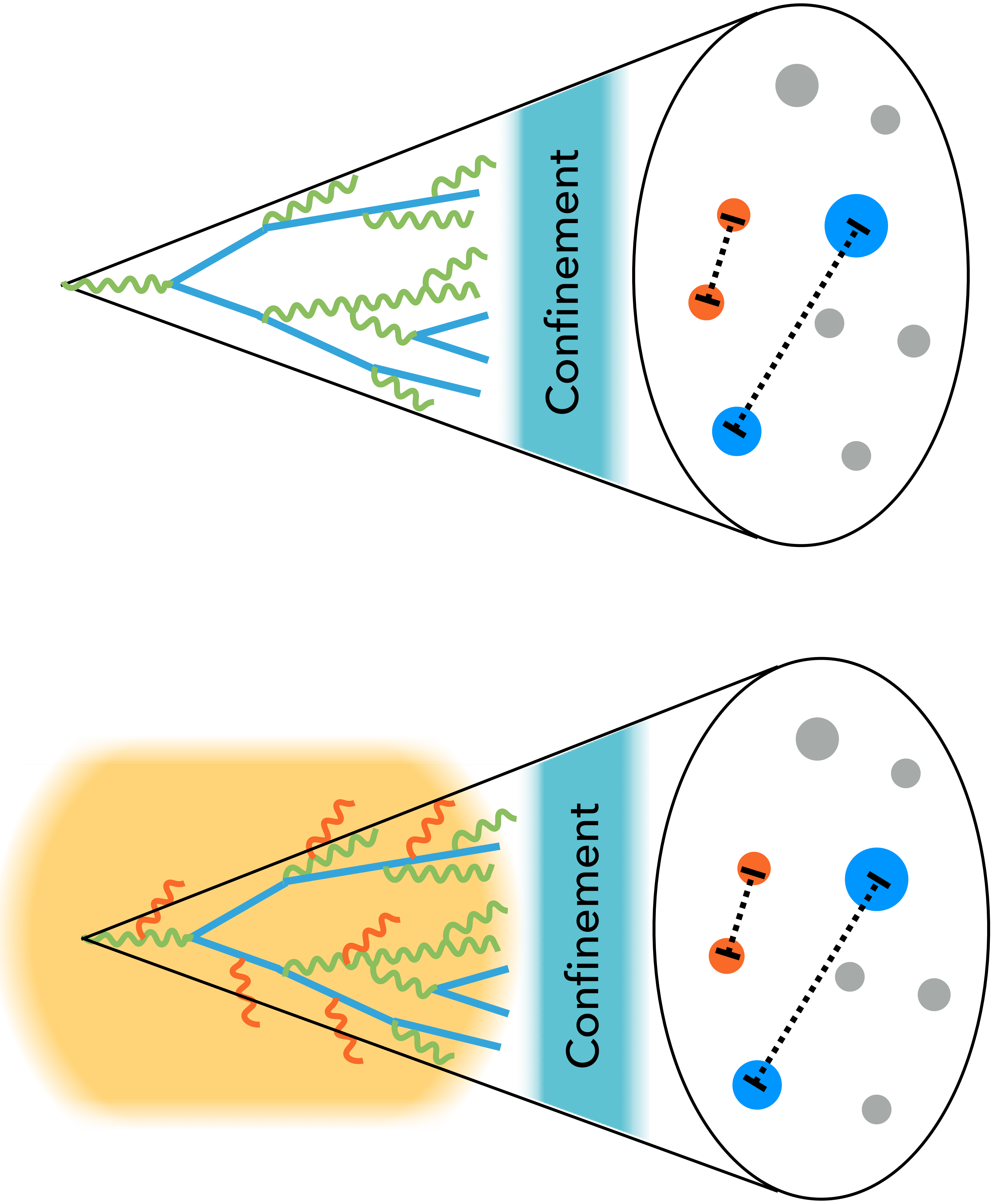
- D^0 reconstruction: $D^0 \rightarrow \pi^+K^-$ (anti $D^0 \rightarrow \pi^-K^+$)
  - Particle ID on decay daughters: identified π/K
  - Decay topology cuts
  - πK candidate in pair p_T 2 to 36GeV
- Replace πK candidate by D^0 and perform jet finding
  - Require D^0 candidate in anti-k_T R = 0.4 charged jet
  - Construct EEC in D^0 tagged jets
- D^0 signal extraction via side band subtraction method
- Efficiency and feed-down correction for D^0
  - Non-prompt contribution estimated through POWHEG + PYTHIA8 simulations
- Detector effect correction for EEC

Talk by Nima Zardoshti
(Wed 16:50)

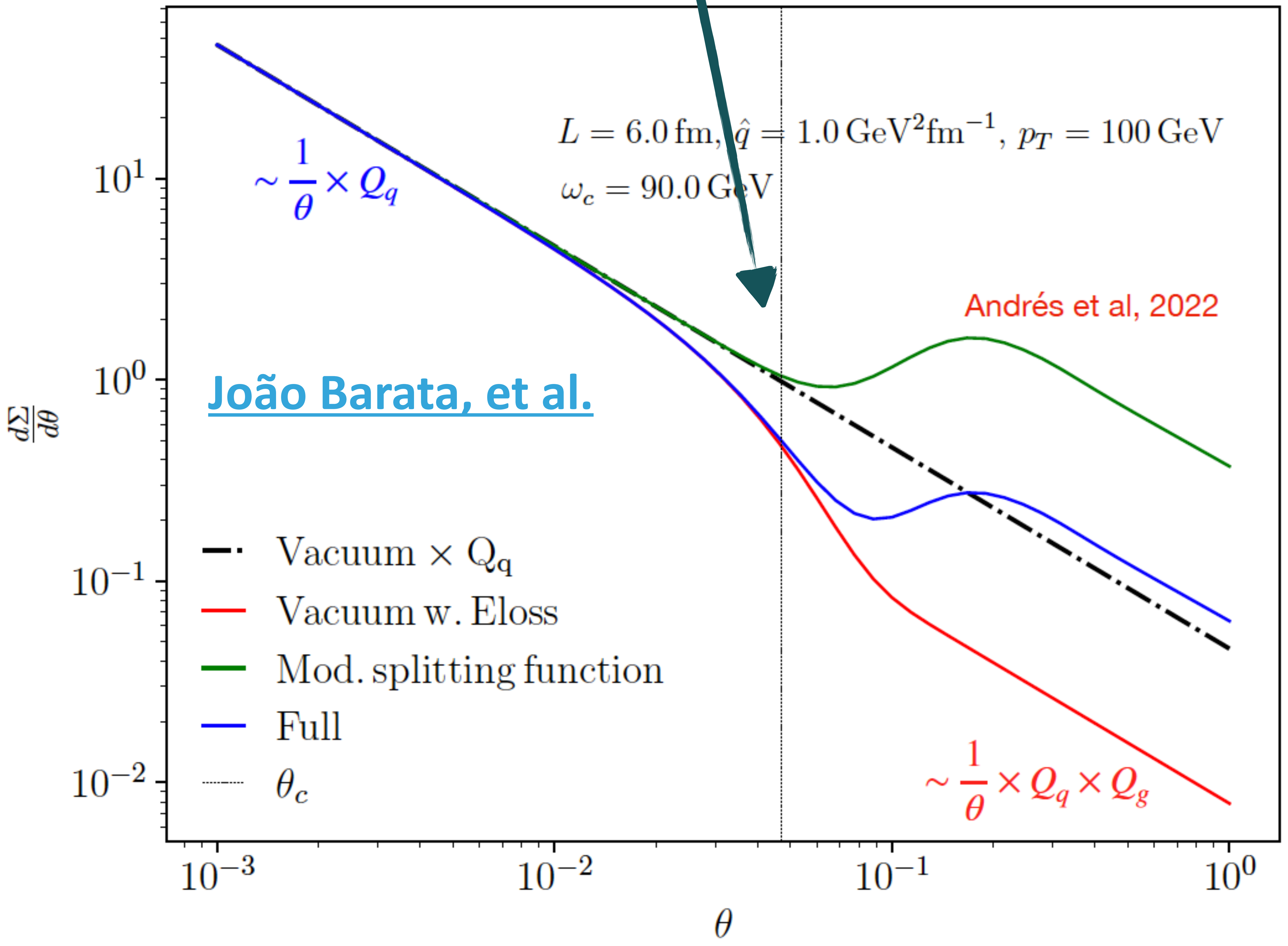




Probing QGP with energy correlators



Onset of modification sensitive to medium size



Different hadronization in pp from JETSCAPE

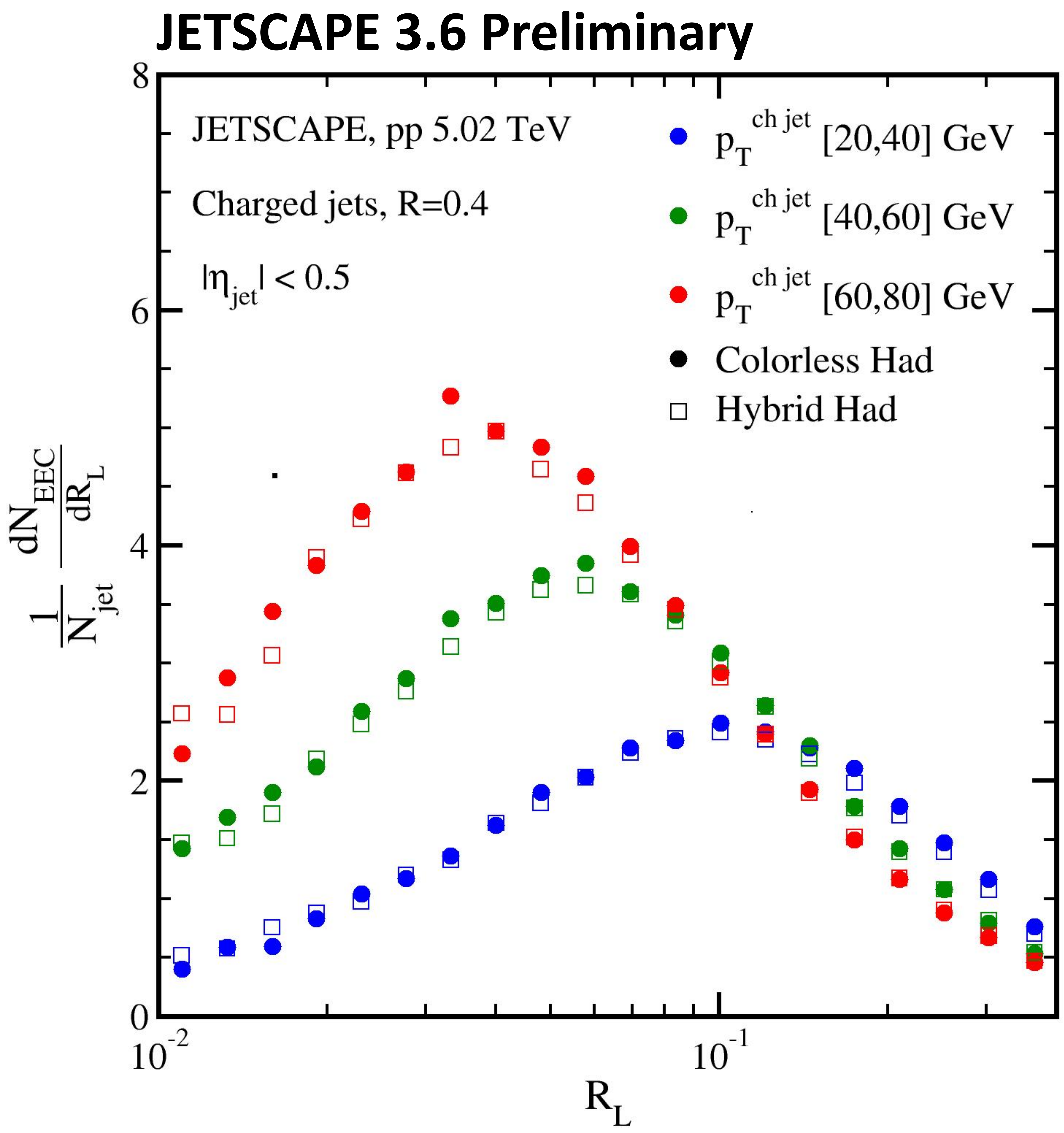


Figure from Chathuranga Kumara Sirimanna

Analysis details

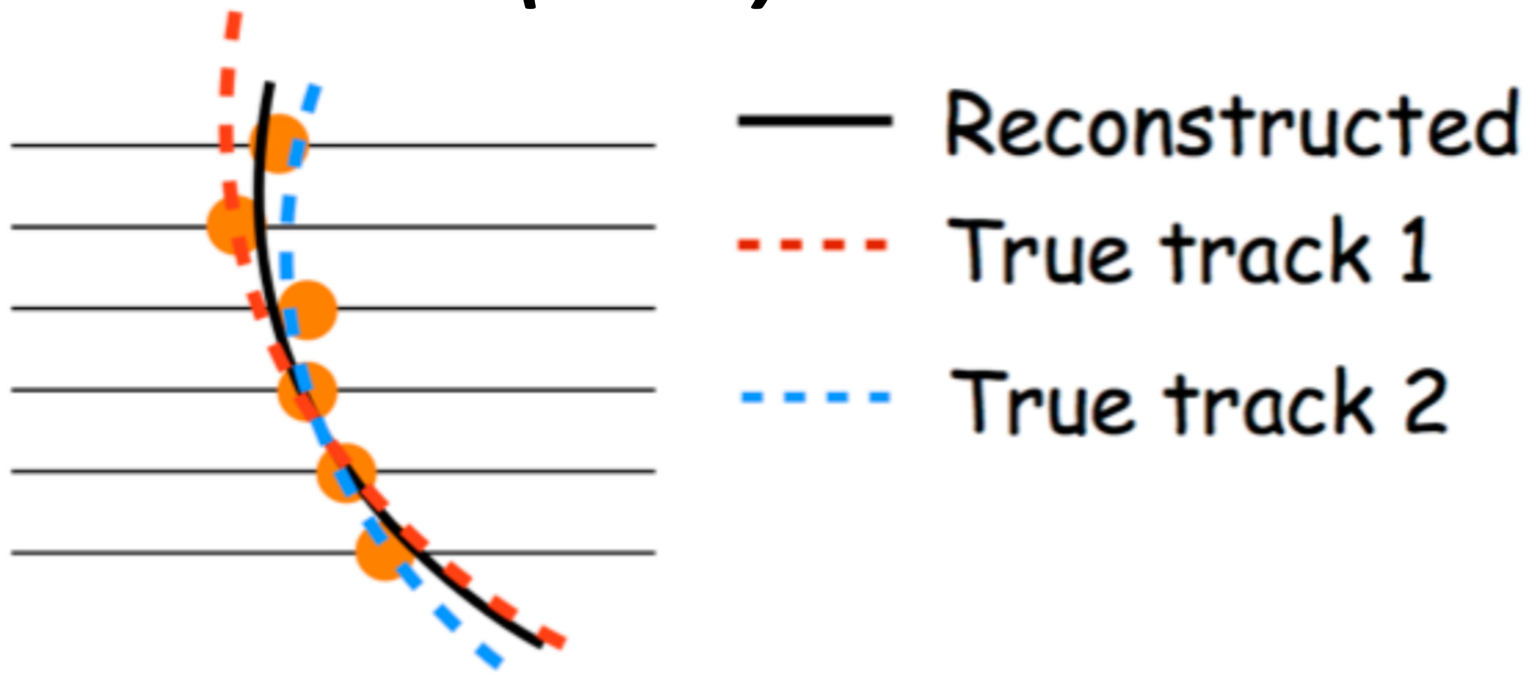
- **Detector acceptance/efficiency/resolution mainly affect $\sigma_{EEC}(R_L)$ rather than R_L**
  - Precise angular resolution leads to minimal migration along R_L axis
  - Dominant effects: jet p_T resolution and pair inefficiency at small R_L due to track merging
- **Corrected with bin-by-bin correction method**
  - Correction factor extracted from GEANT simulation and applied bin-by-bin on the measured raw distributions for data
- **Why bin by bin correction?**
  - Small migration along R_L axis
  - Potential bias with bin-by-bin correction addressed by the generator dependence and p_T variation studies, which are included in systematic uncertainties

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

Energy weight

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

Phys. Lett. B 785 (2018) 320



$$f_{corr}(dR_L^{det}, p_{T,jet}^{det}) = \frac{dN_{pair}^{det} / dR_L^{det}(p_{T,jet}^{det})}{dN_{pair}^{truth} / dR_L^{truth}(p_{T,jet}^{truth})}$$

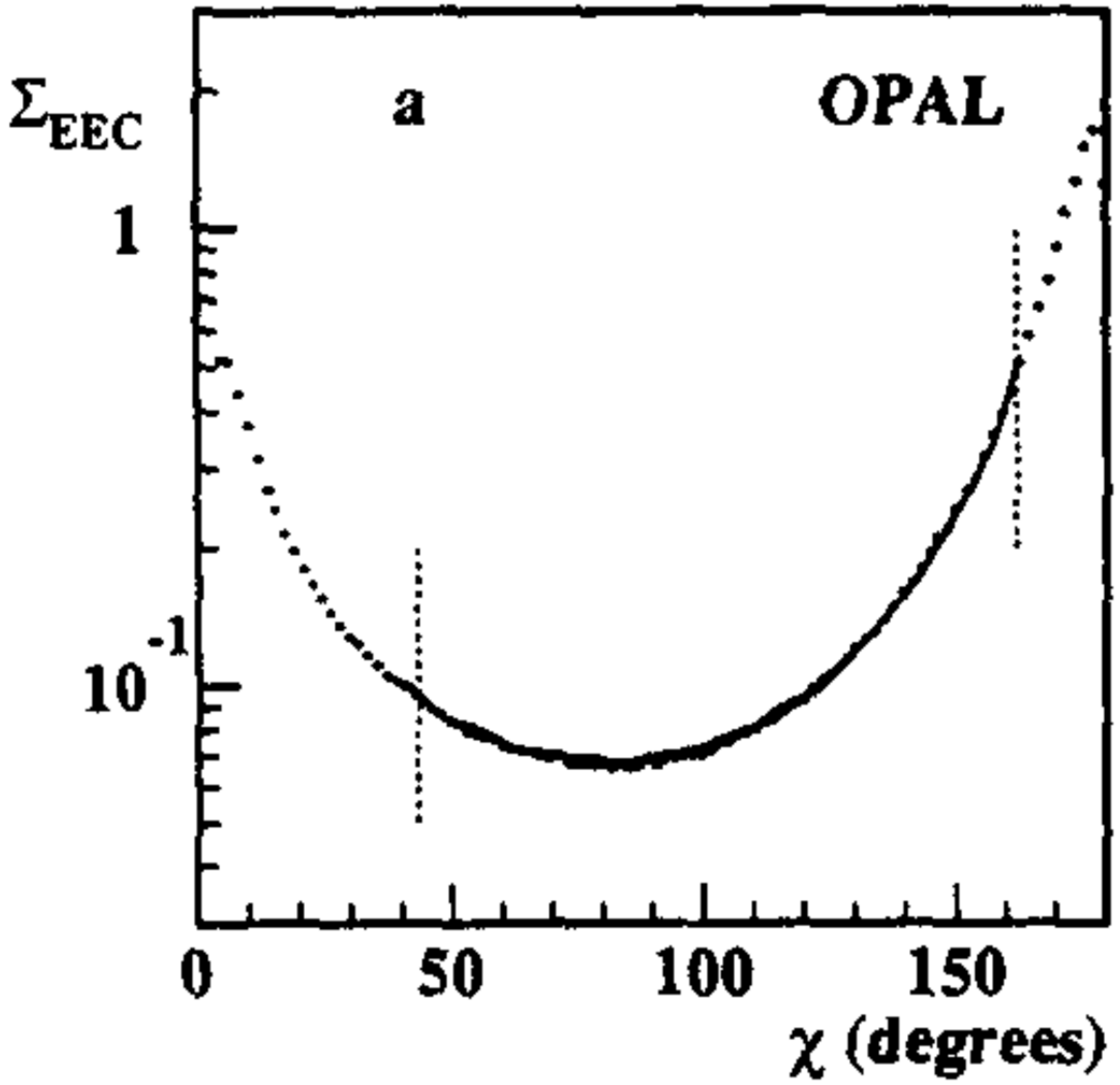
$$dN/dR_L(p_{T,jet}^{truth}) = \frac{1}{f_{corr}} \cdot dN/dR_L(p_{T,jet}^{det})$$

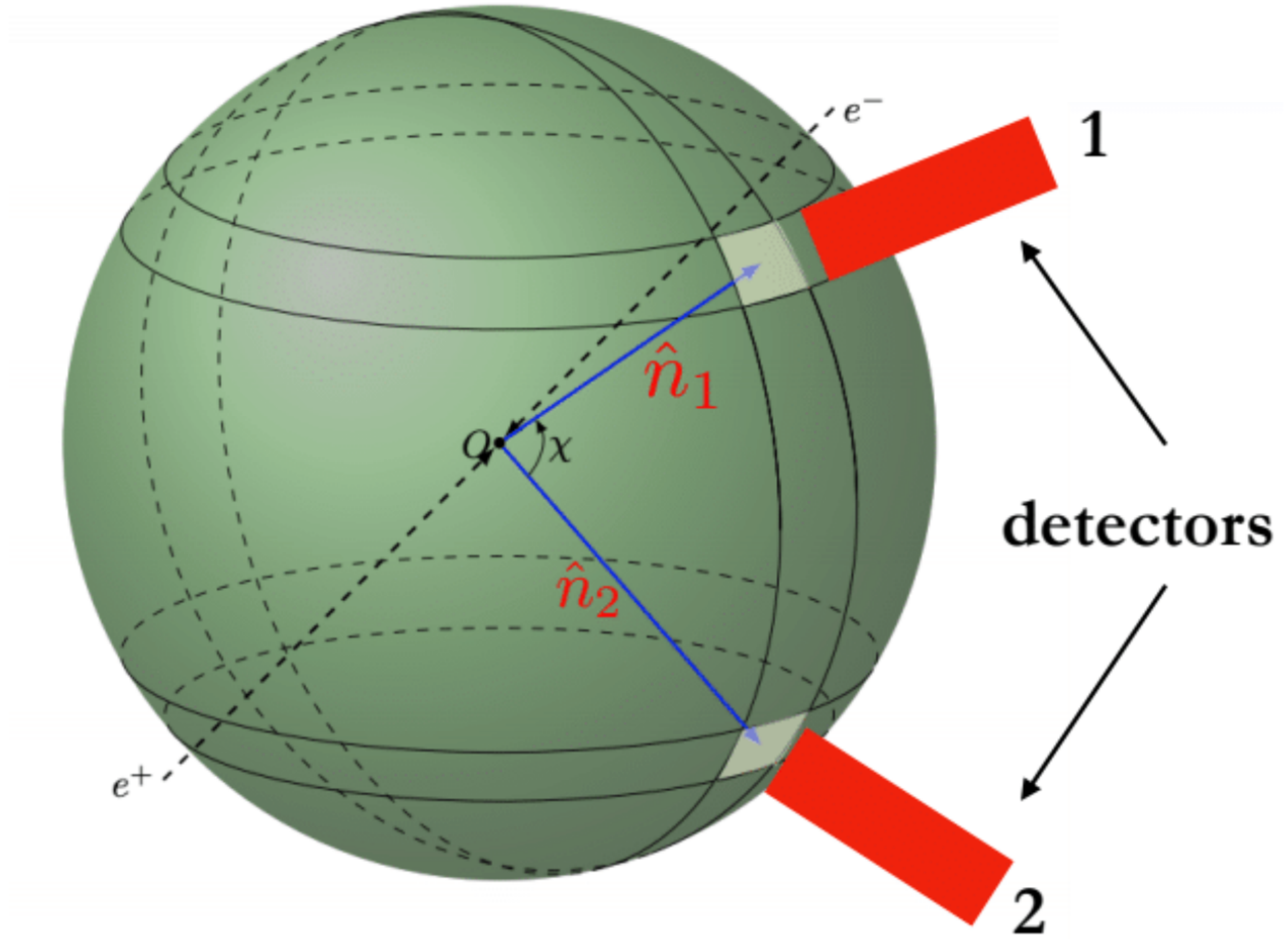
Energy-energy correlator at e^+e^- collider

Proposed in 1978: [Phys. Rev. Lett. 41, 1585]

- IRC safe, energy weighted cross section
  - Has been predicted and measured in e^+e^- collider
  - Used to constrain α_s

[Phys. Lett. B 276, 547–564]





$$\Sigma_{\mathrm{EEC}}(\chi)=\frac{1}{\Delta\chi\cdot N}\sum_{N}\int_{\chi-\frac{1}{2}\Delta\chi}^{\chi+\frac{1}{2}\Delta\chi}\sum_{i,j}\frac{E_i E_j}{E_{\mathrm{vis}}^2}\cdot\delta(\chi'-\chi_{ij})\,\mathrm{d}\chi', \qquad (4)$$

where E_i and E_j are the energies of particles i and j, E_{vis} is the sum over the energies of all particles in the event, $\Delta\chi$ is the angular bin width and N is the total number of events. The normalization ensures that the integral of $\Sigma_{\mathrm{EEC}}(\chi)$ from $\chi=0°$ to $180°$ is unity.

Model comparison

Better agreement between data and Herwig

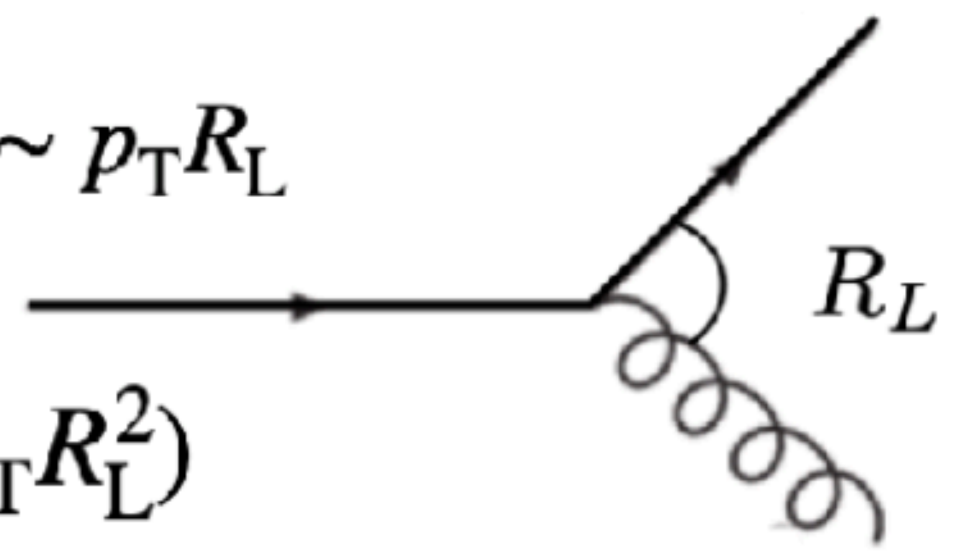
Pythia seems to show a slightly higher transition peak

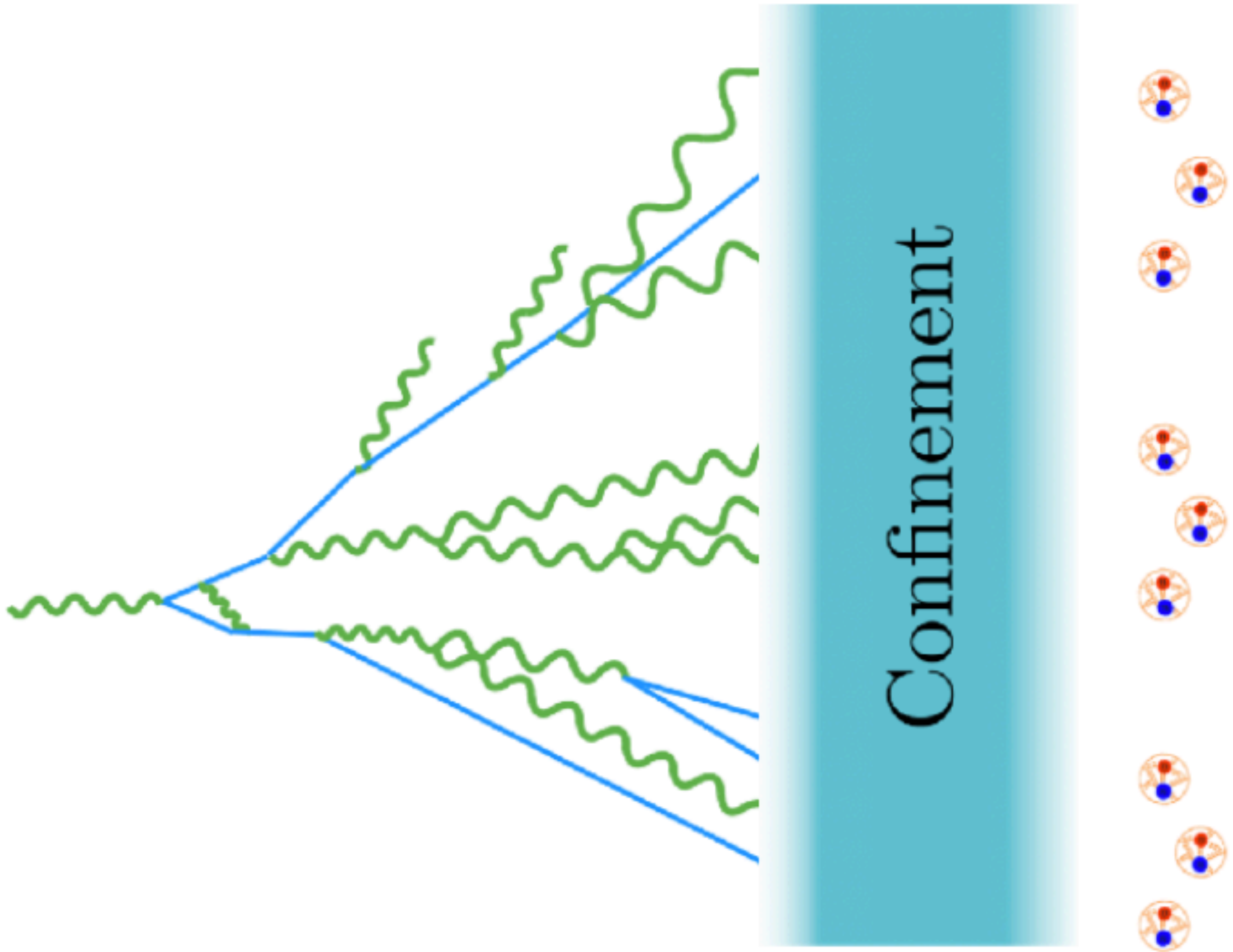
Slide from Berndt Mueller

Perturbative evolution of EEC is due to gluon radiation

virtuality $\sim p_{\mathrm{T}} R_{\mathrm{L}}$

$\tau \simeq 1/(p_{\mathrm{T}} R_{\mathrm{L}}^2)$





Radiation must stop at a virtuality scale, below which there are no gluon states in the vacuum: **Glueball mass**

Glueball masses in MeV

J^{PC}	0^{++}	2^{++}	1^{+-}	0^{-+}
YM	1710	2390	2980	3640
QCD_3	1795	2620	3270	4490

Glueball mass in $\sqrt{\sigma}$

G	SU(2)	SU(3)
$m_{0^{++}}$	3.78	3.55
$m_{2^{++}}/m_{0^{++}}$	1.44	1.35

A. Dymarsky, D. Melnikov, JHEP 11 (2022) 164 [2208.14826 hep-lat]

Compares well virtuality scale of the EEC peak (2.4 GeV)