QNP 2024

Elucidating QCD using energy-energy correlator at RHIC and LHC

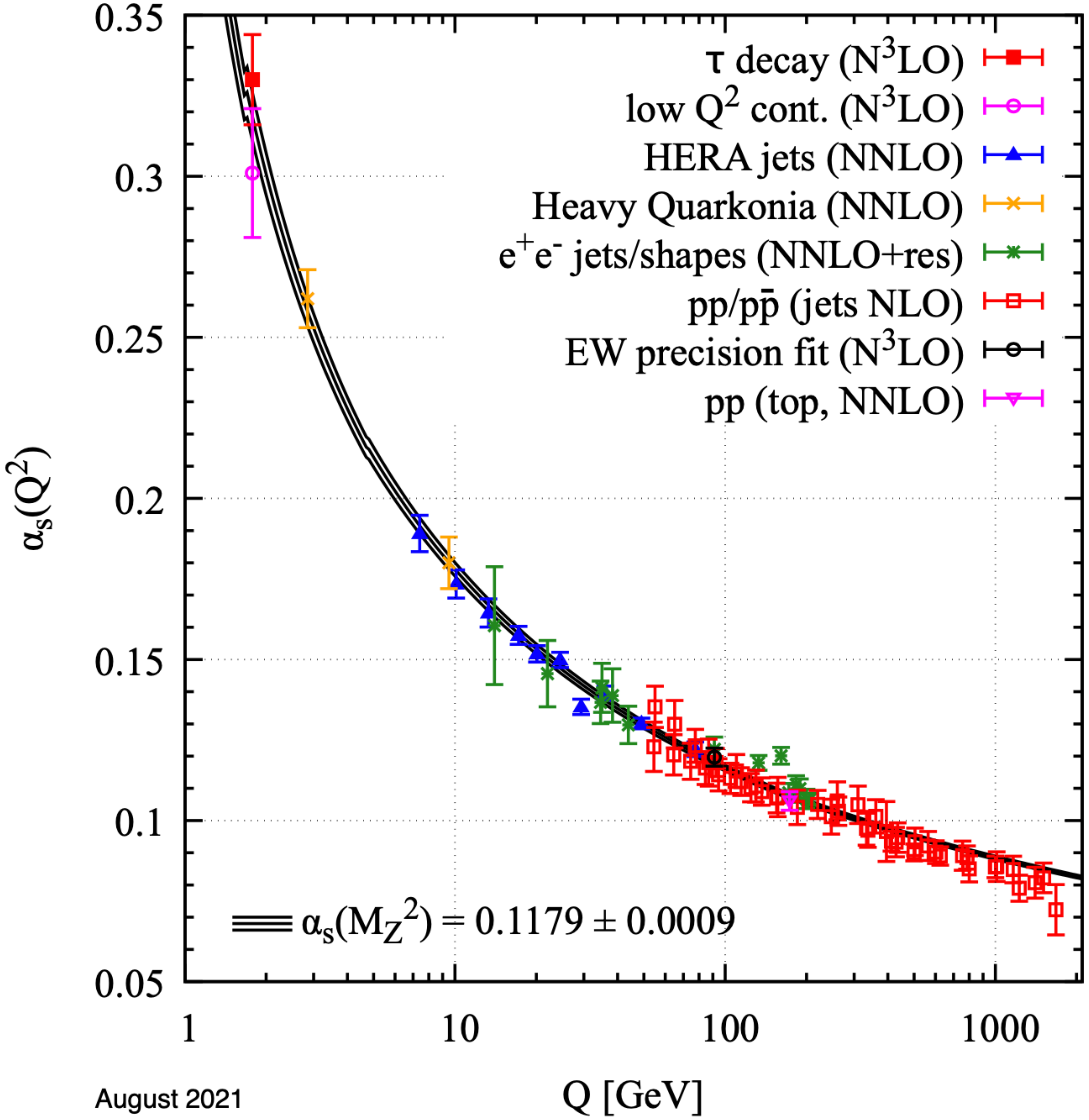
Preeti Dhankher

University of California, Berkeley/Lawrence Berkeley National Lab

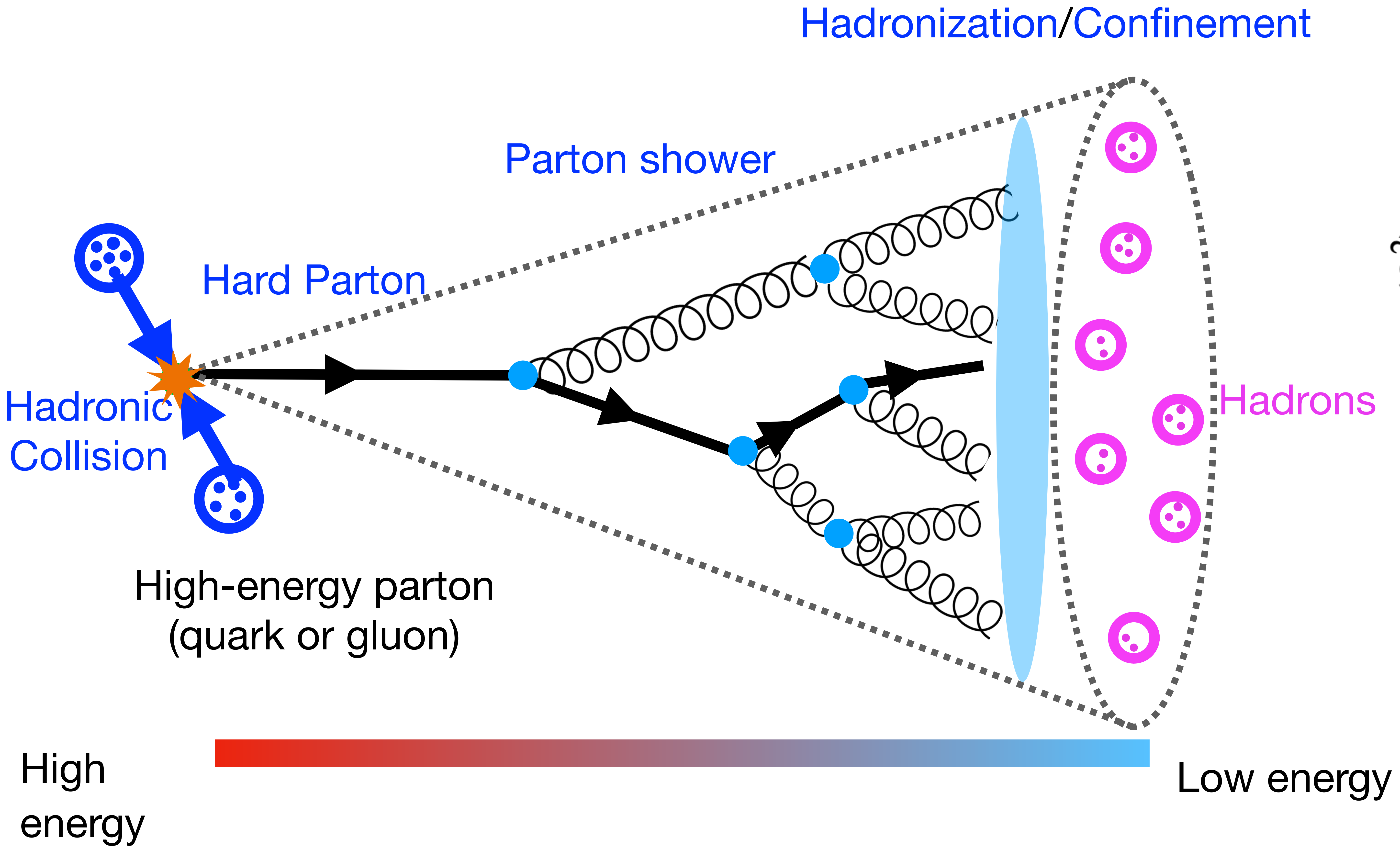
International Conference on Quarks and Nuclear Physics

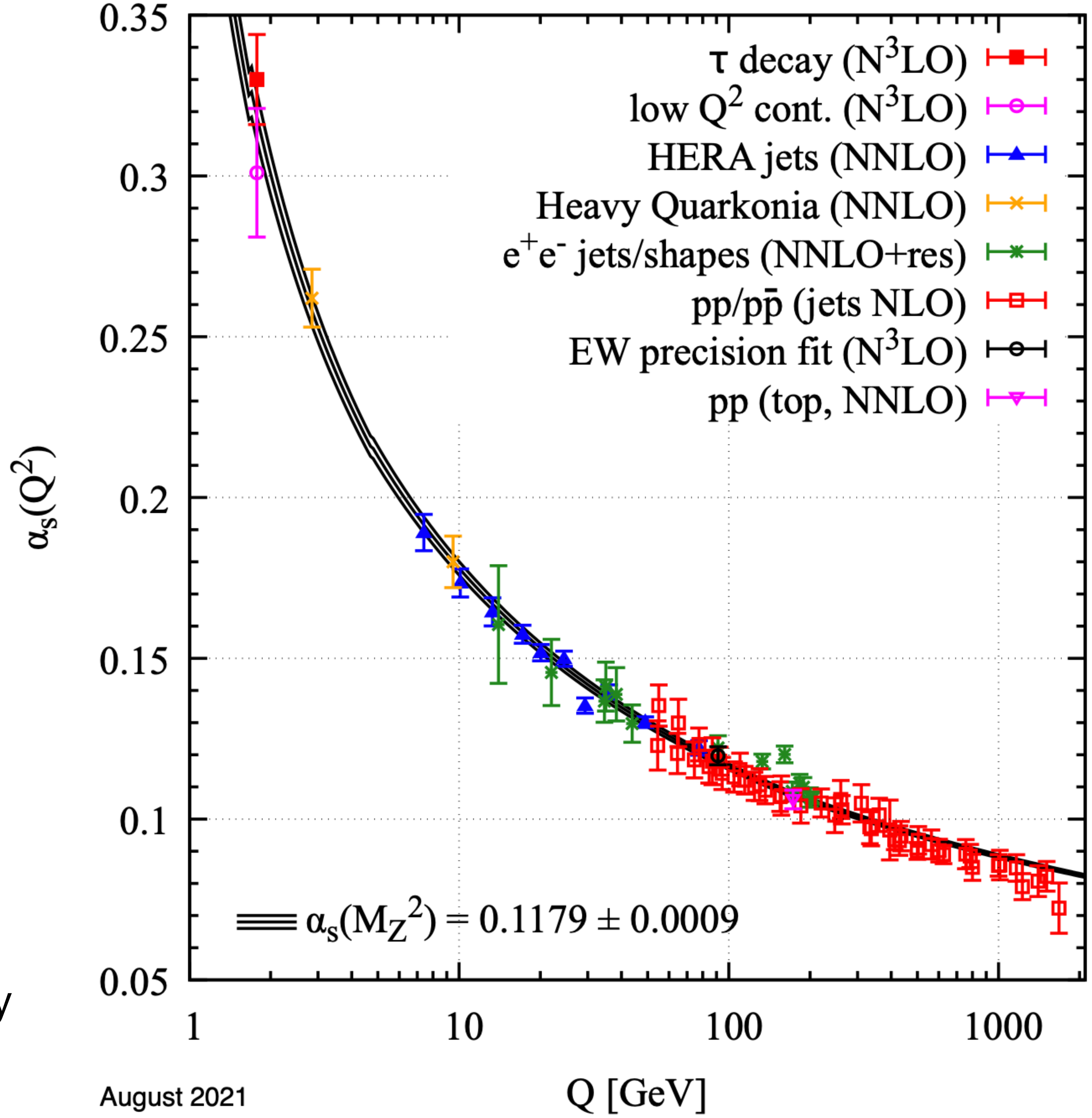
07/11/2024

Jets probe a wide range of Q^2

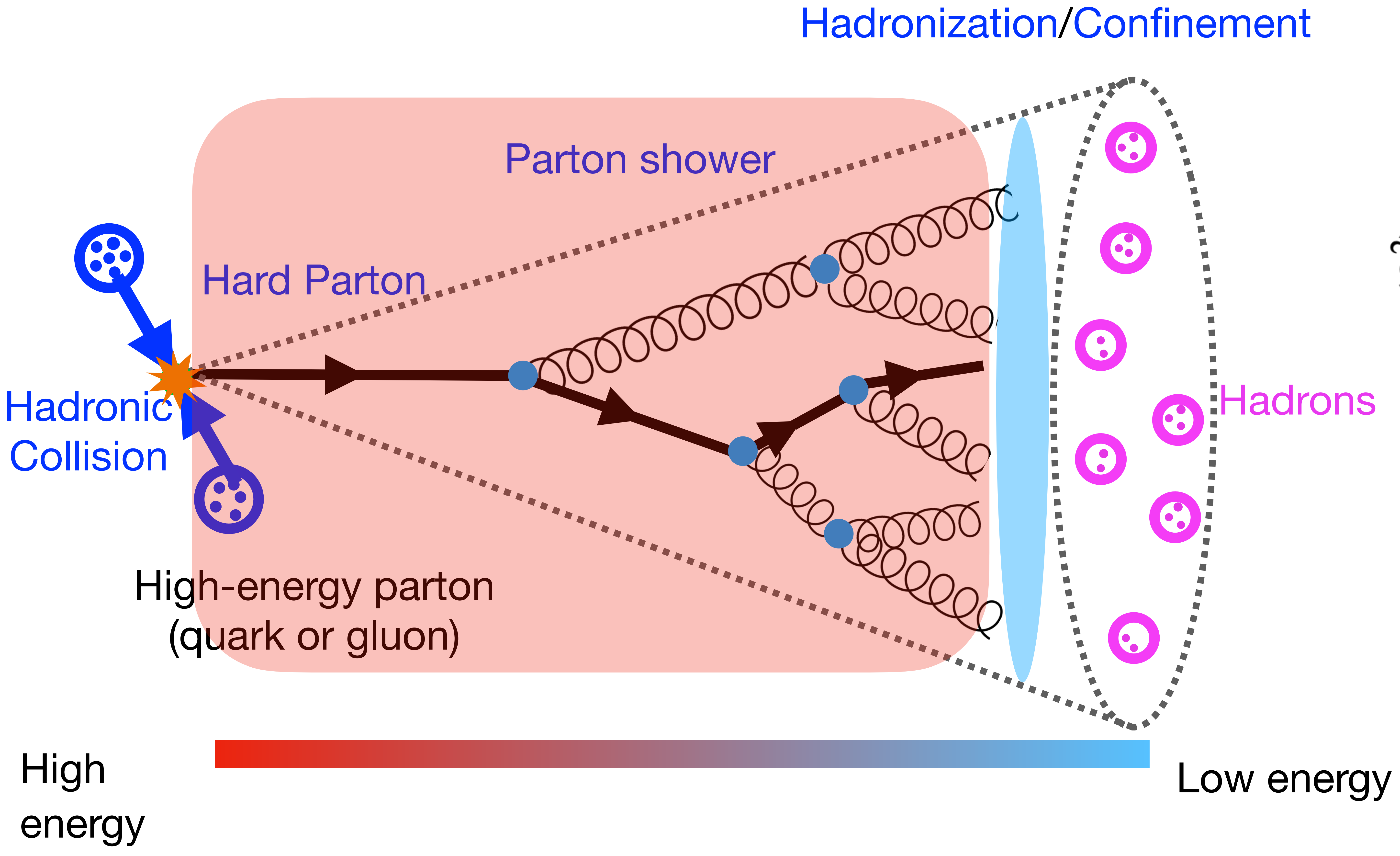


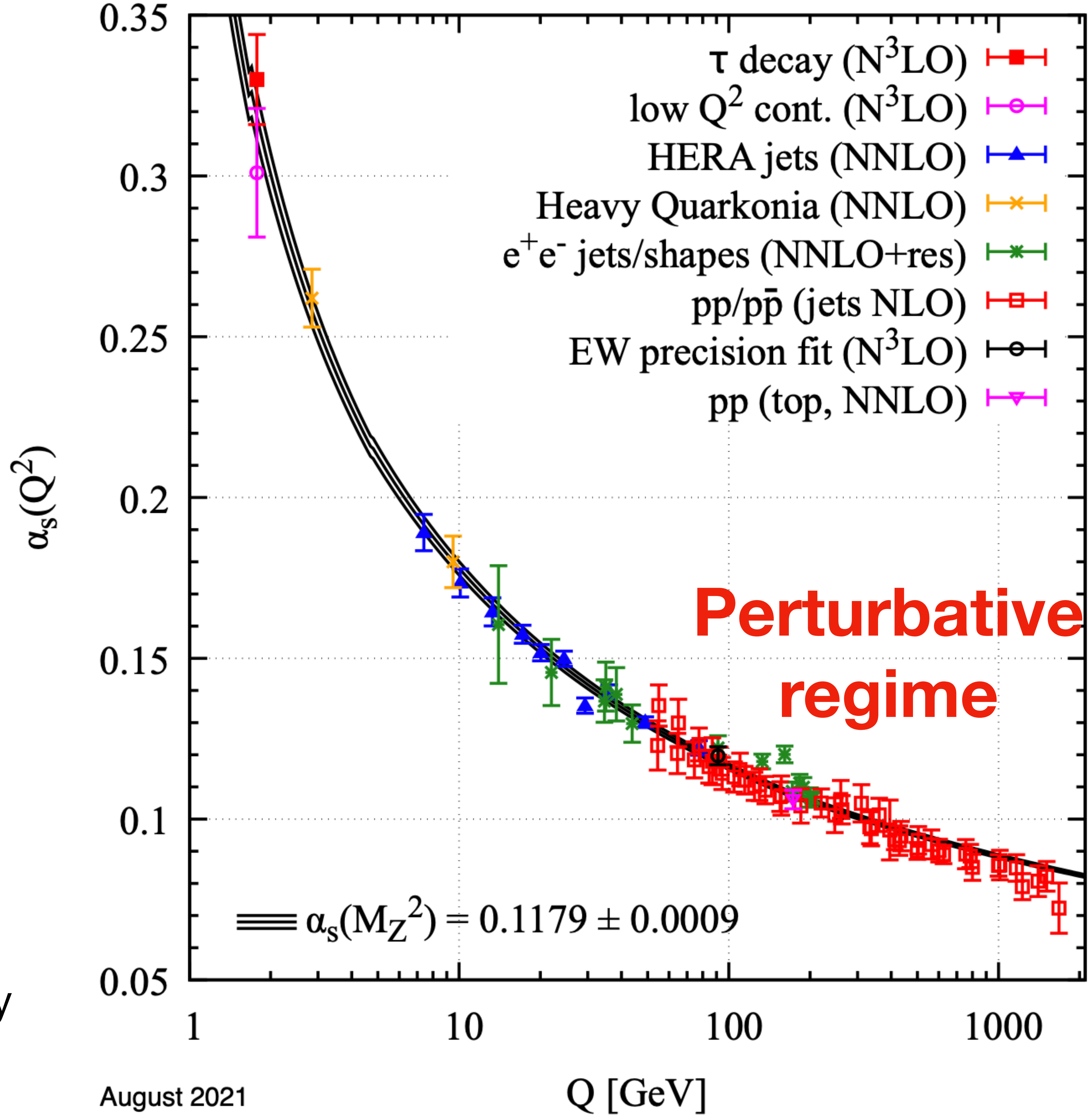
Jets probe a wide range of Q^2





Jets probe a wide range of Q^2



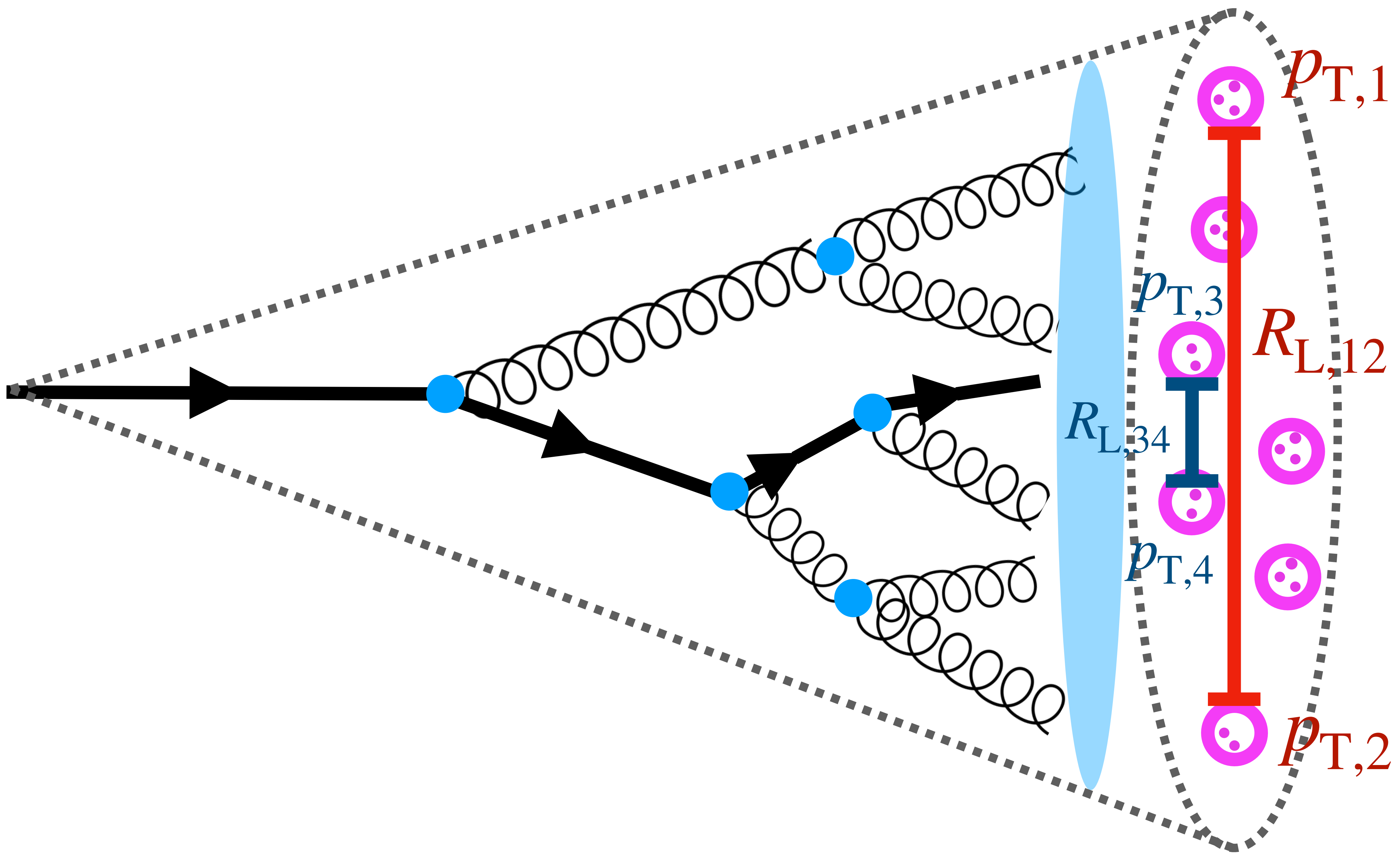


Energy-energy correlators (EECs)

- **What are EECs?**
- **Why do we study EECs?**
- **What do we learn from EECs?**
  →Six lessons from EECs

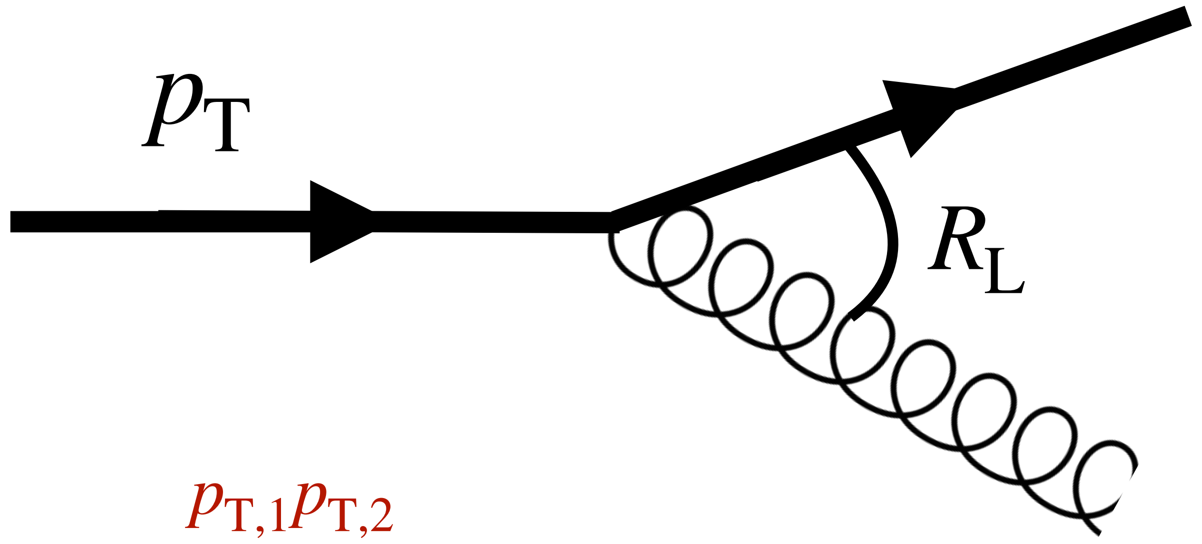
Energy-energy correlators

First proposed as event shape observable in 1978!
PRL 41.1585 (1978)



1. Energy weighted two particle correlation inside jet
2. pQCD calculation available in perturbative region → well defined probe Lee, Mecaj, Moult (arXiv:2205.03414)
3. EEC shows different scaling as a function of R_{L}
   Large R_{L} →early splitting →perturbative regime
   Small R_{L} →late splitting →non-perturbative regime

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



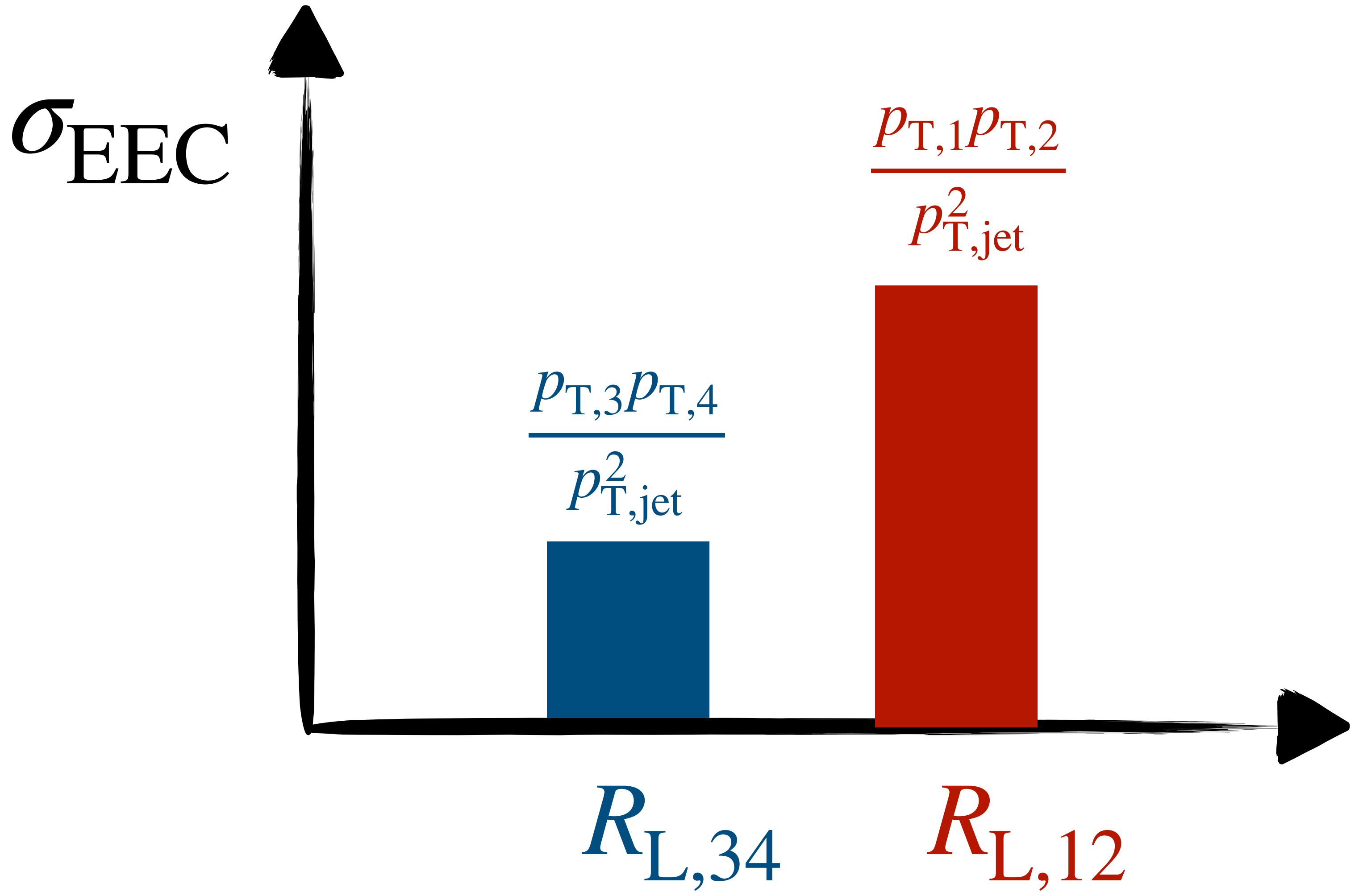
$\tau \simeq 1/(p_{\mathrm{T}} R_{\mathrm{L}}^2)$

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

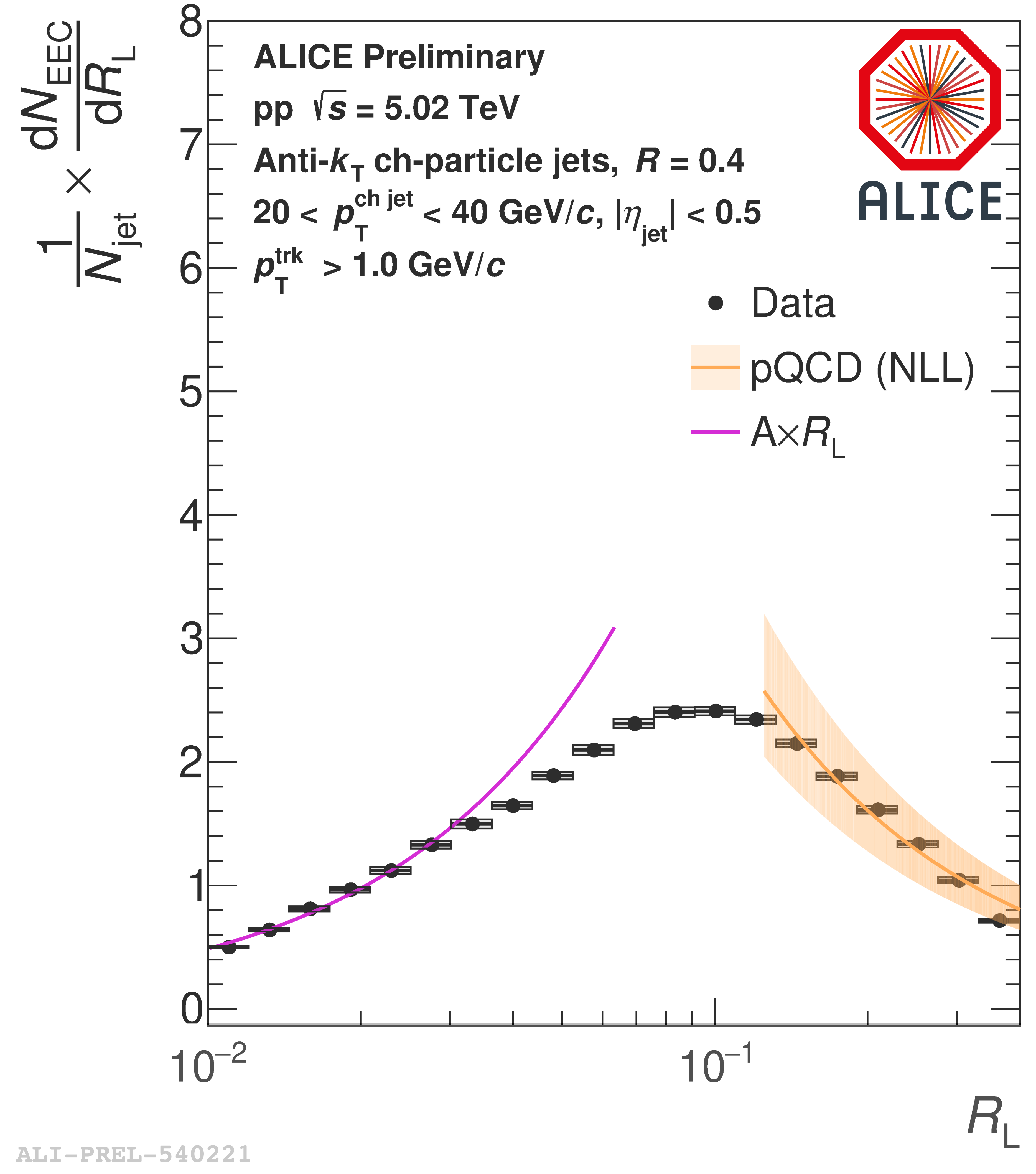
Energy weight

Soft contribution (MPI, UE) power suppressed by energy weight

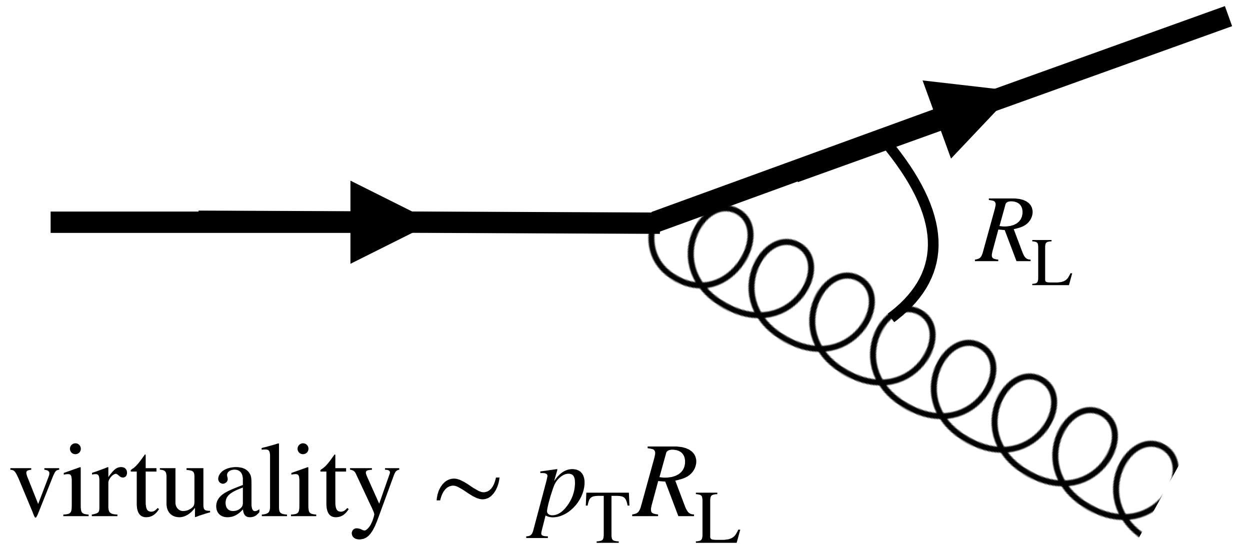
$$\Delta R_{\mathrm{L,ij}} = \sqrt{\Delta\phi_{\mathrm{ij}}^2 + \Delta\eta_{\mathrm{ij}}^2}$$



Why do we study energy-energy correlator?

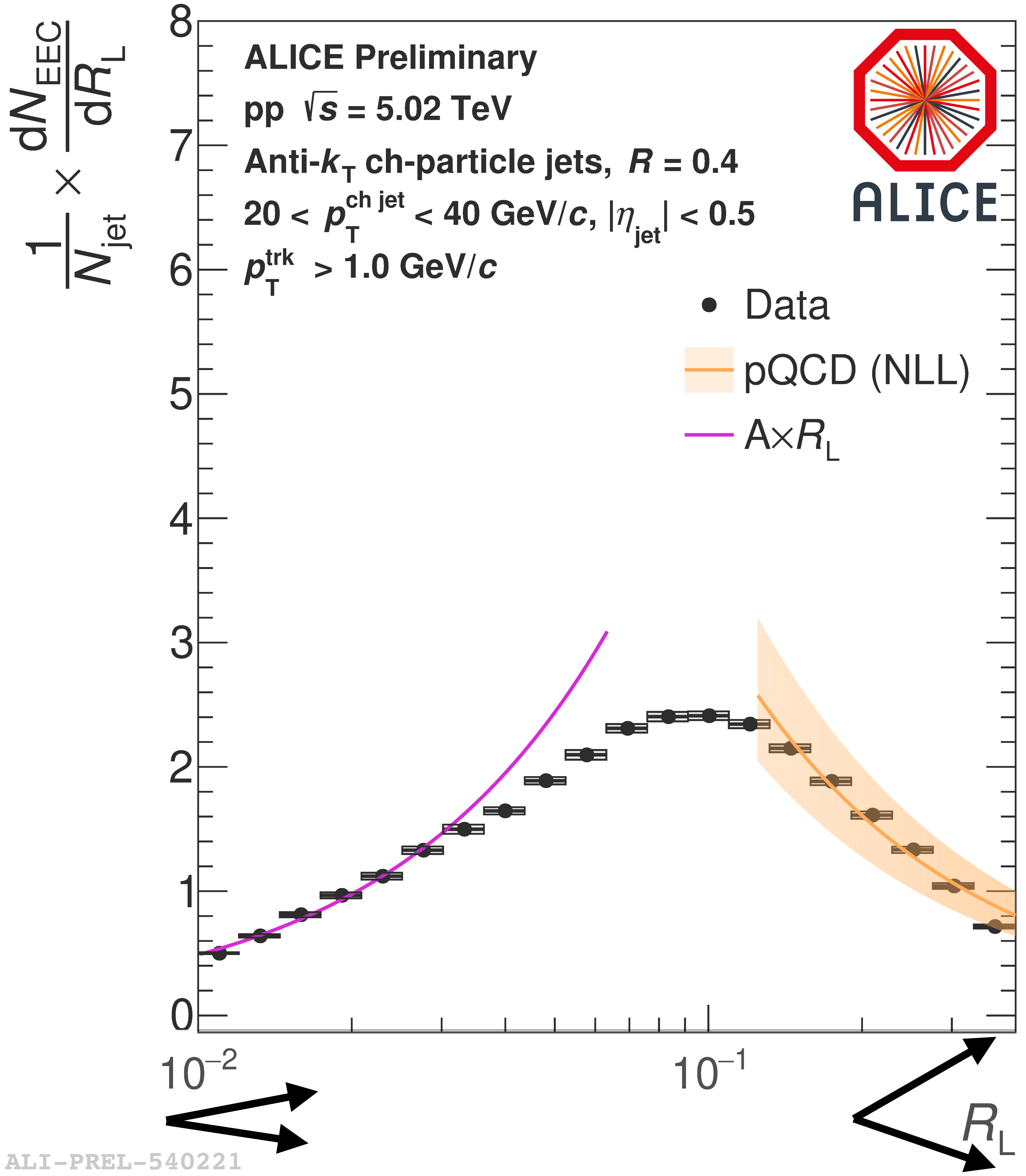


Why do we study energy-energy correlator?

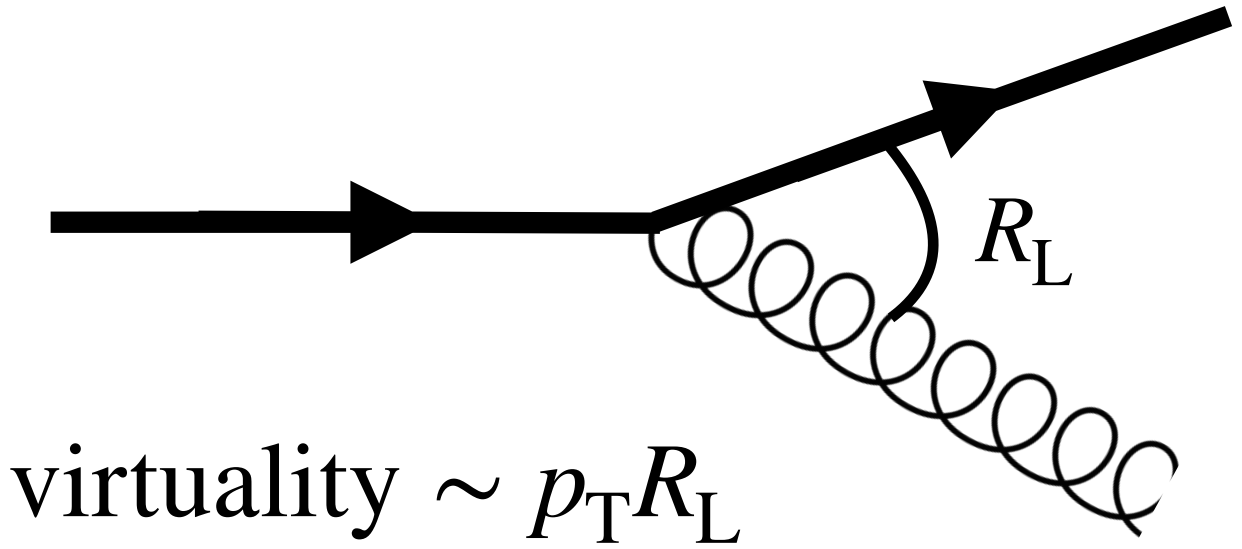


virtuality $\sim p_T R_L$

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

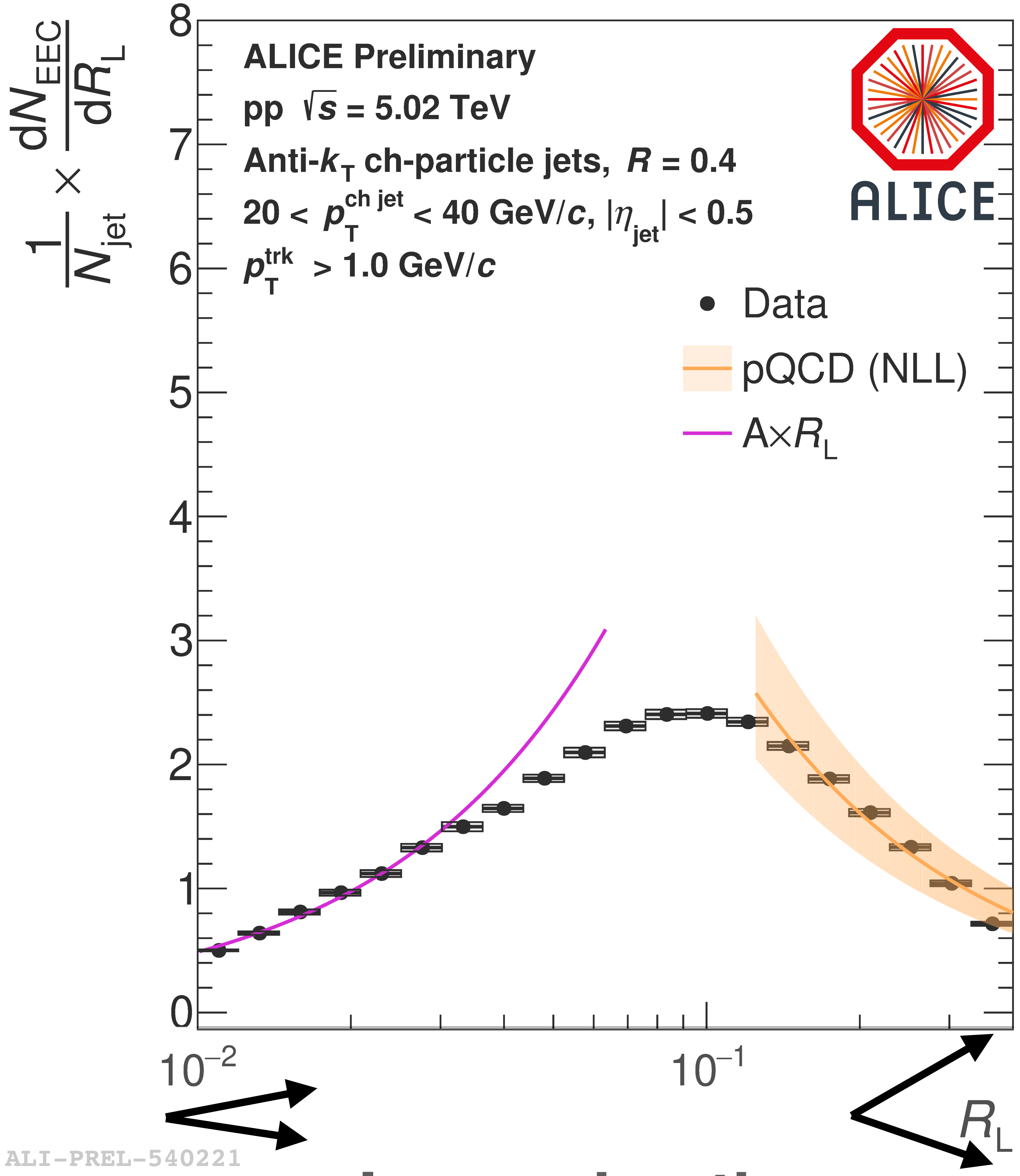


Why do we study energy-energy correlator?



virtuality $\sim p_T R_L$

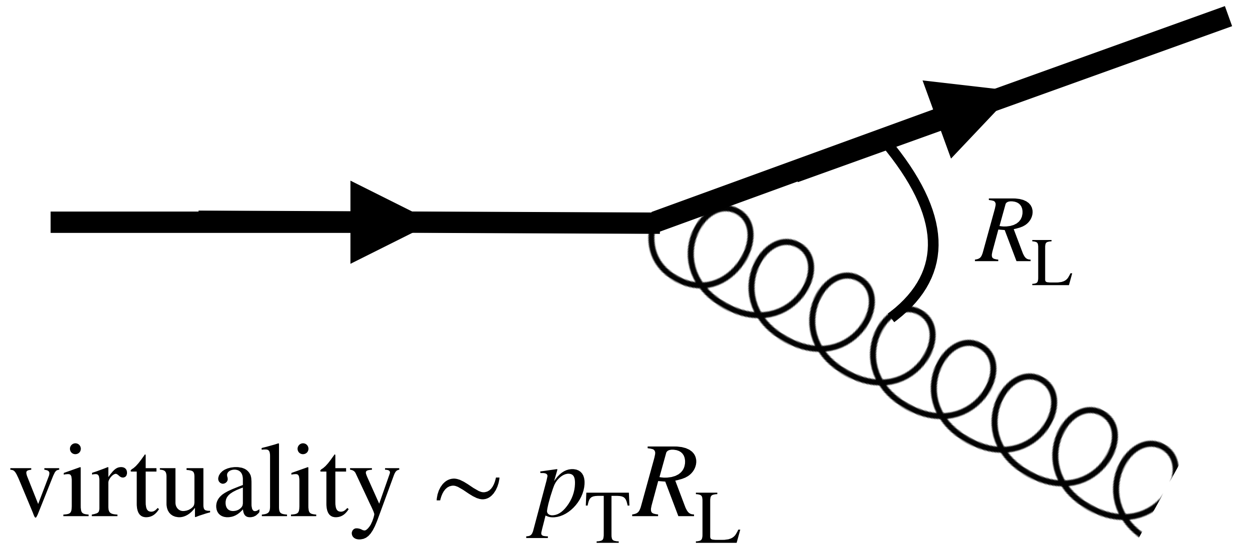
$\tau \simeq 1/(p_T R_L^2)$



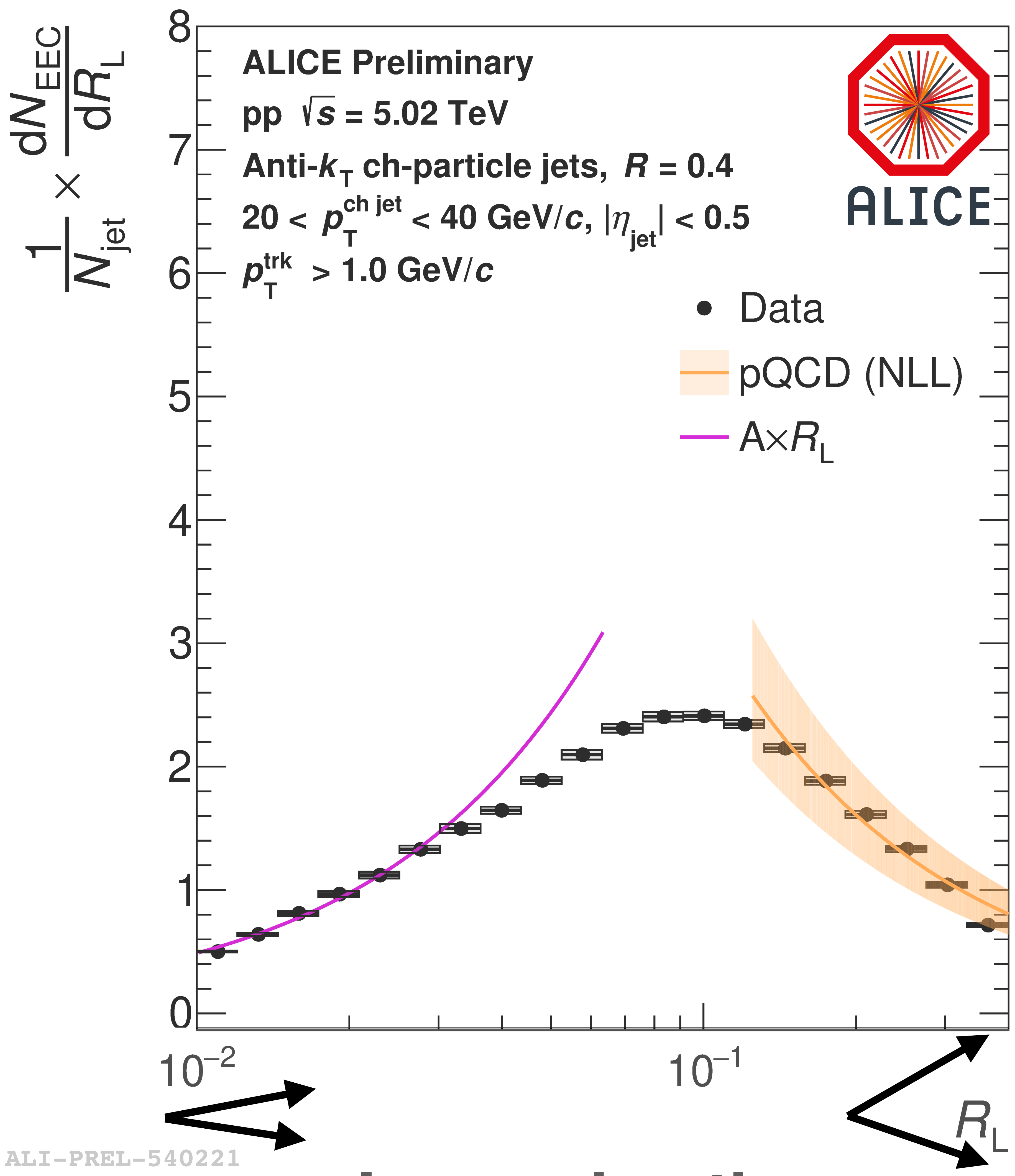
Increasing time

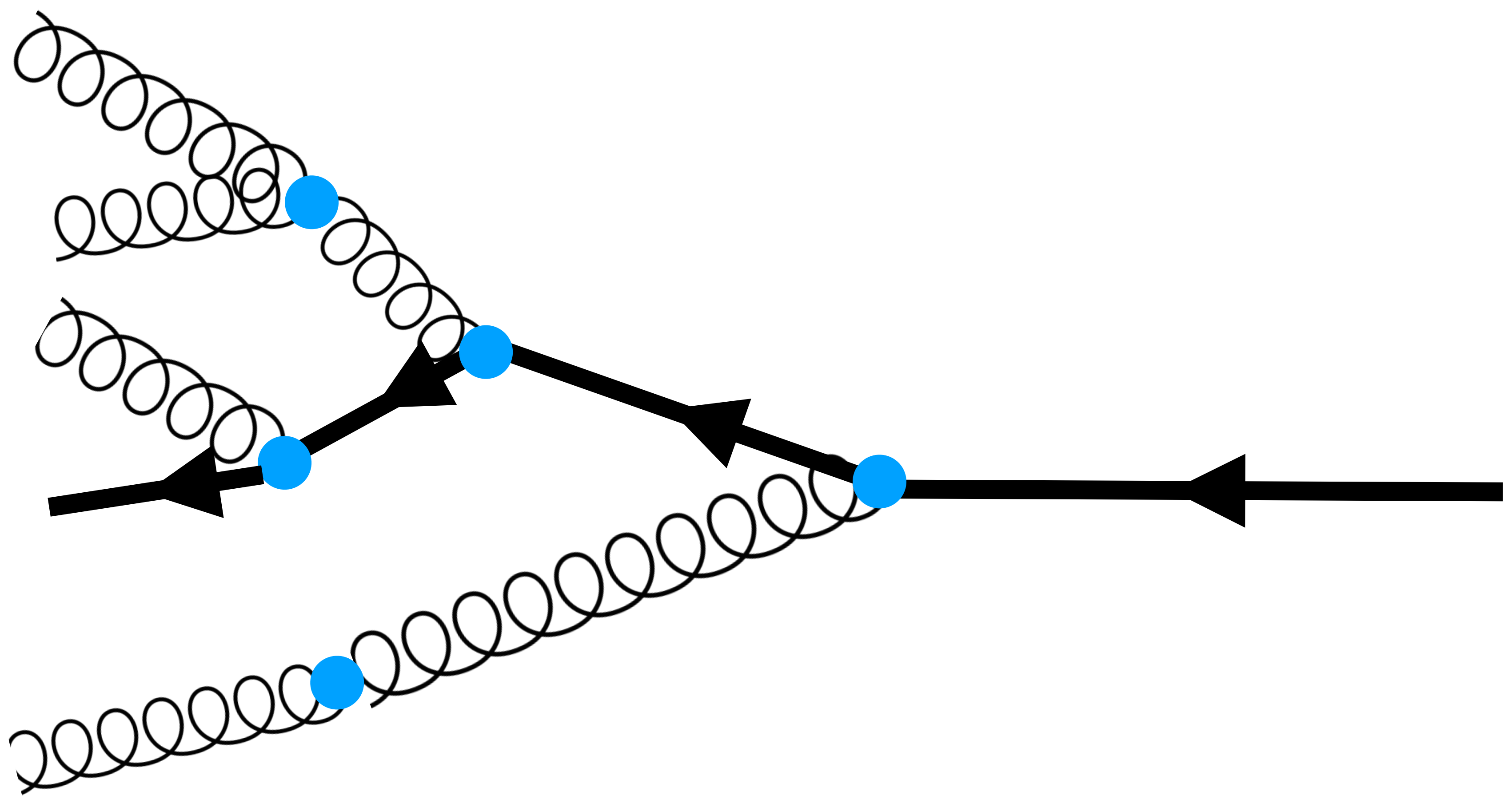
Decreasing energy scale

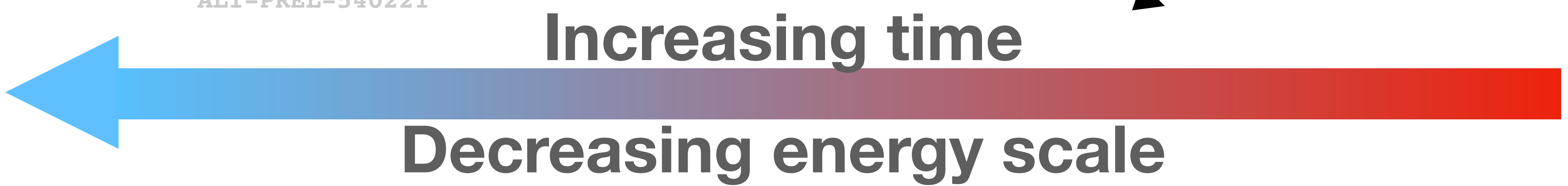
Why do we study energy-energy correlator?



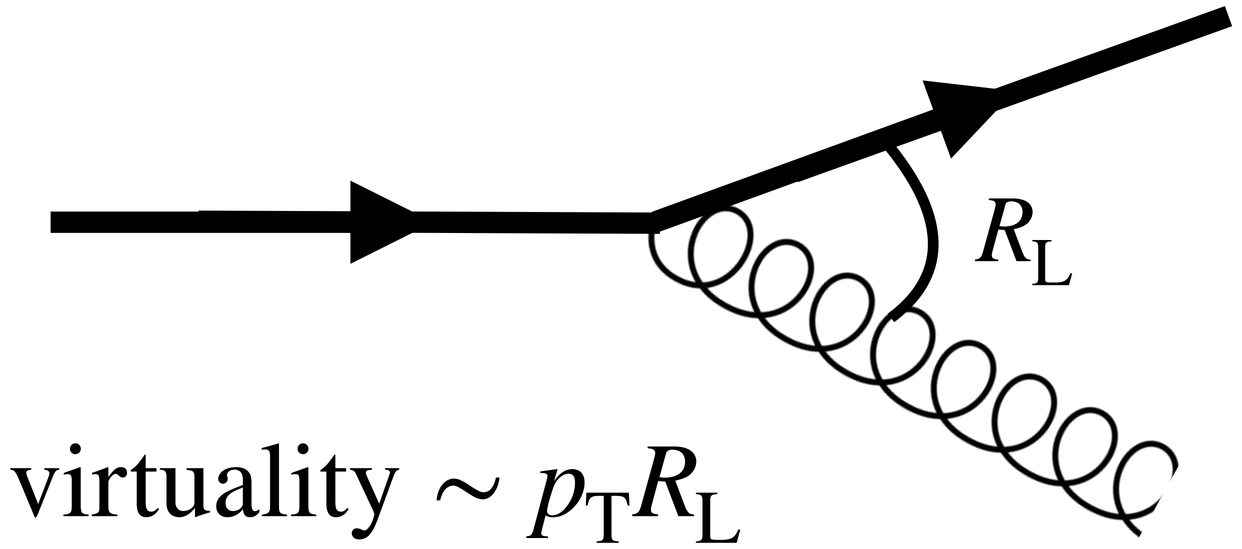
virtuality $\sim p_T R_L$
$\tau \simeq 1/(p_T R_L^2)$





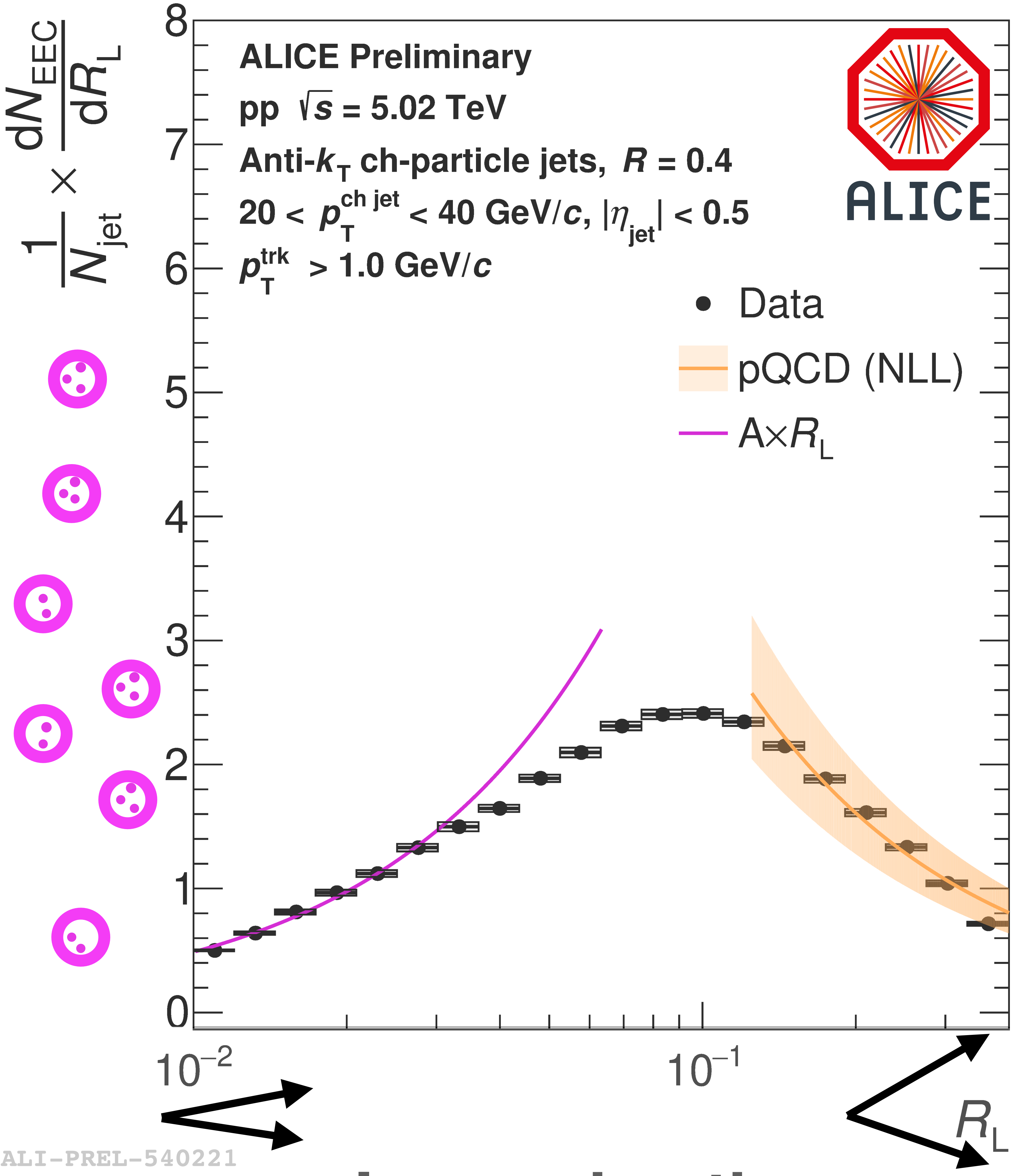


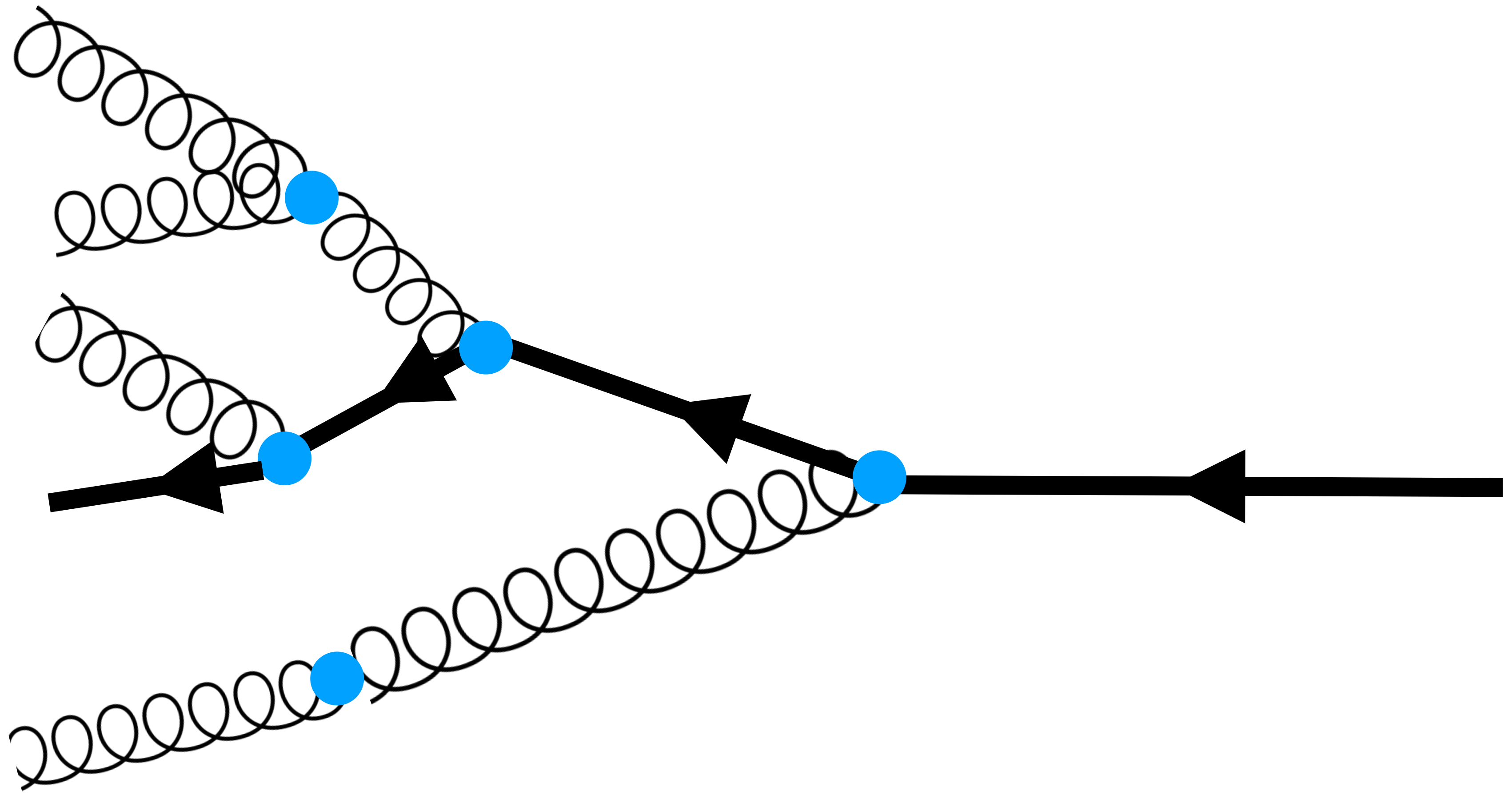
Why do we study energy-energy correlator?



virtuality $\sim p_T R_L$

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

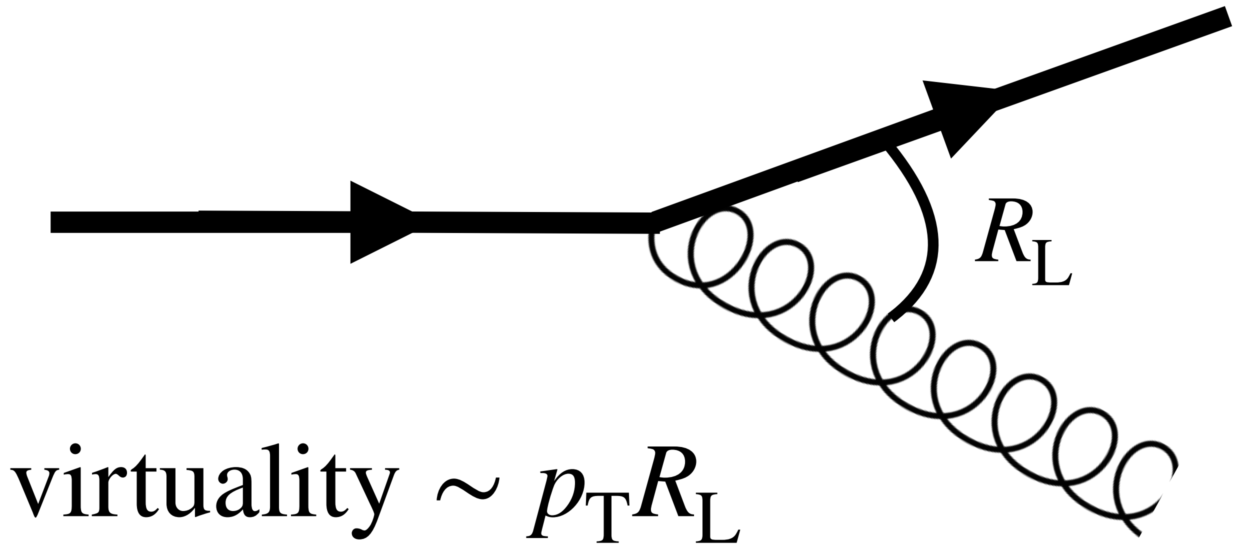




Increasing time

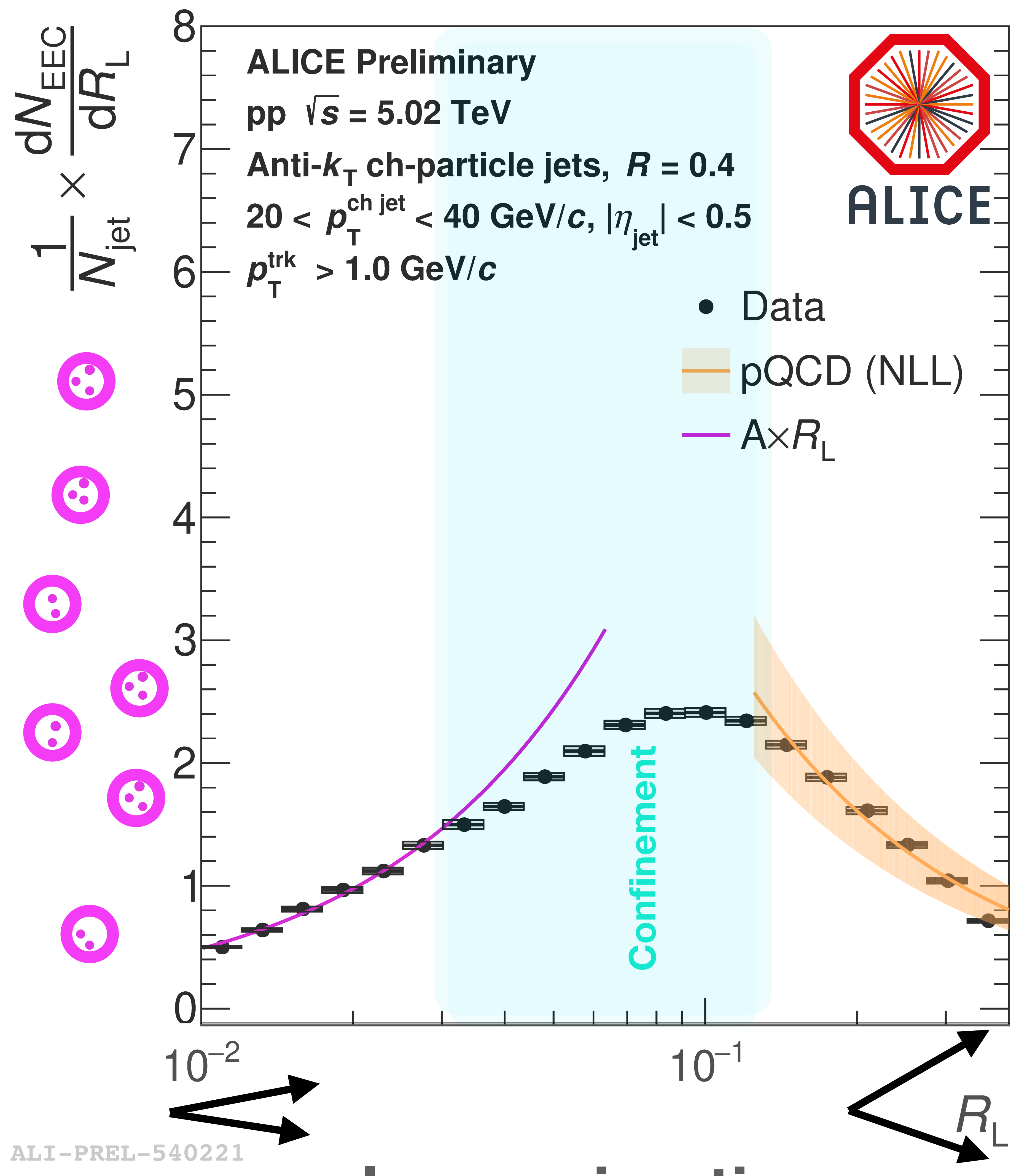
Decreasing energy scale

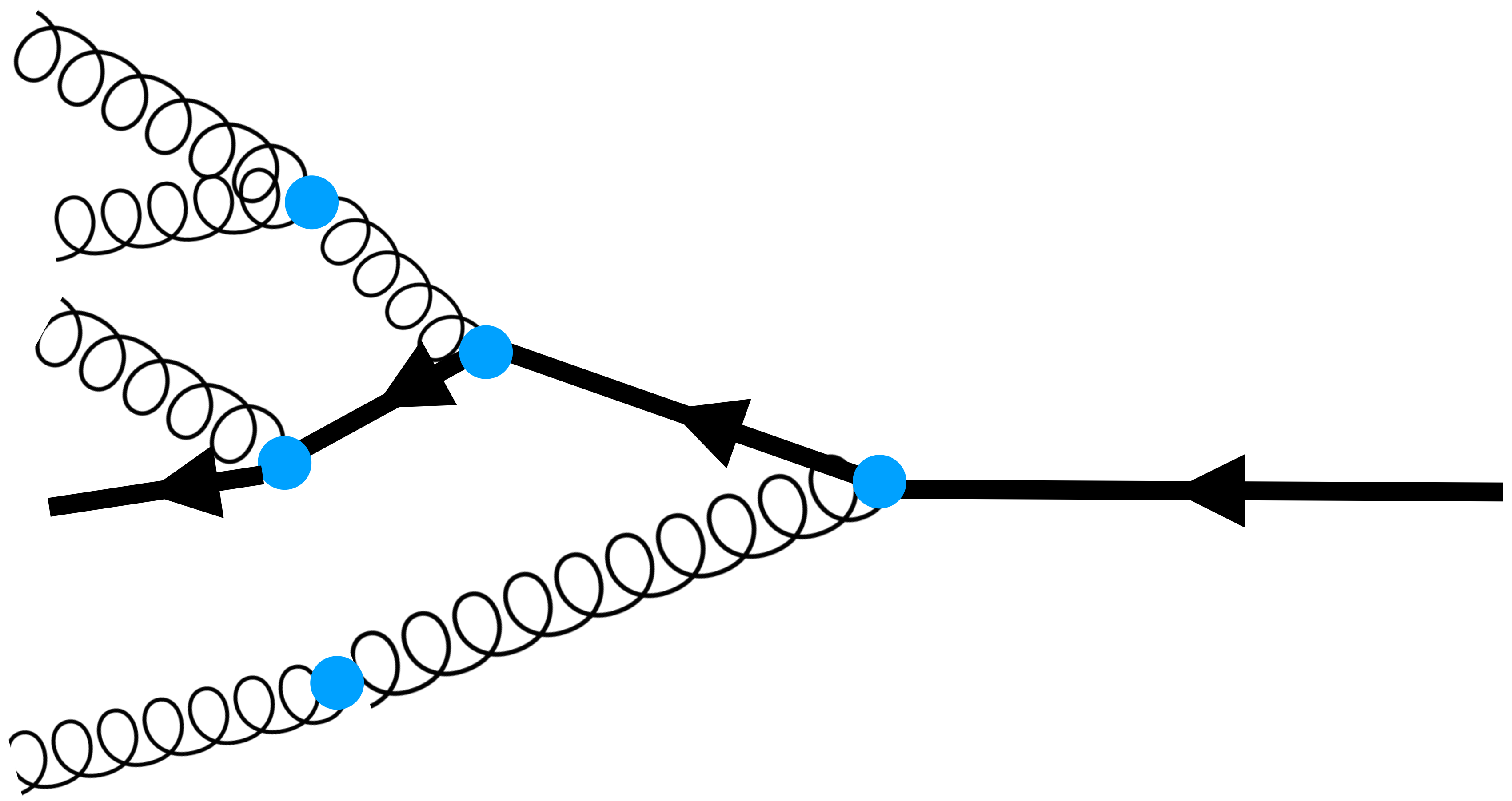
Why do we study energy-energy correlator?



virtuality $\sim p_T R_L$

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

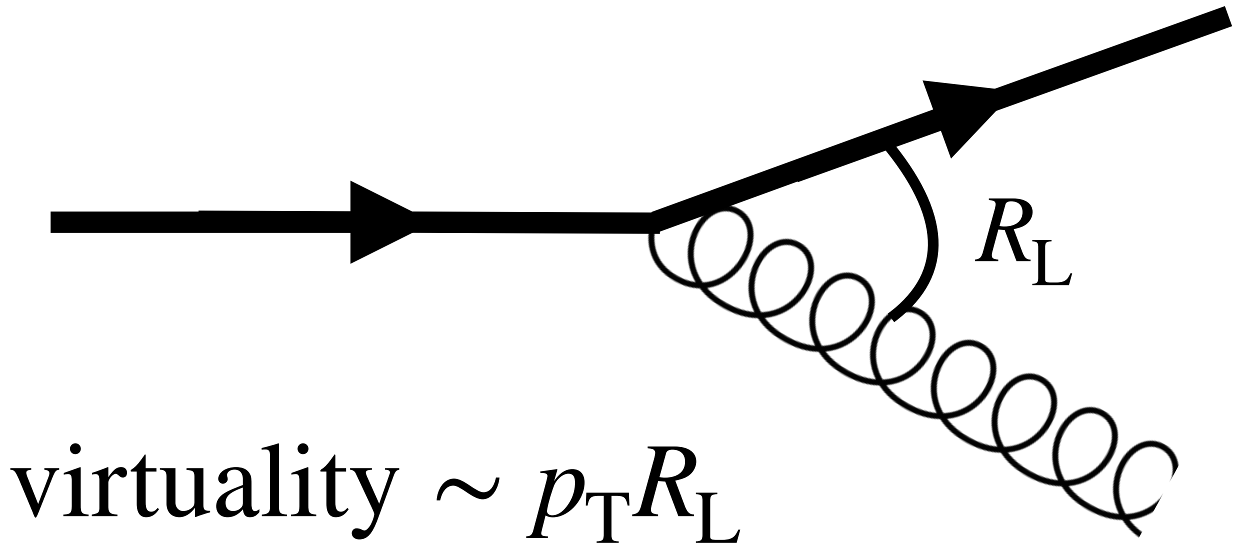




Increasing time

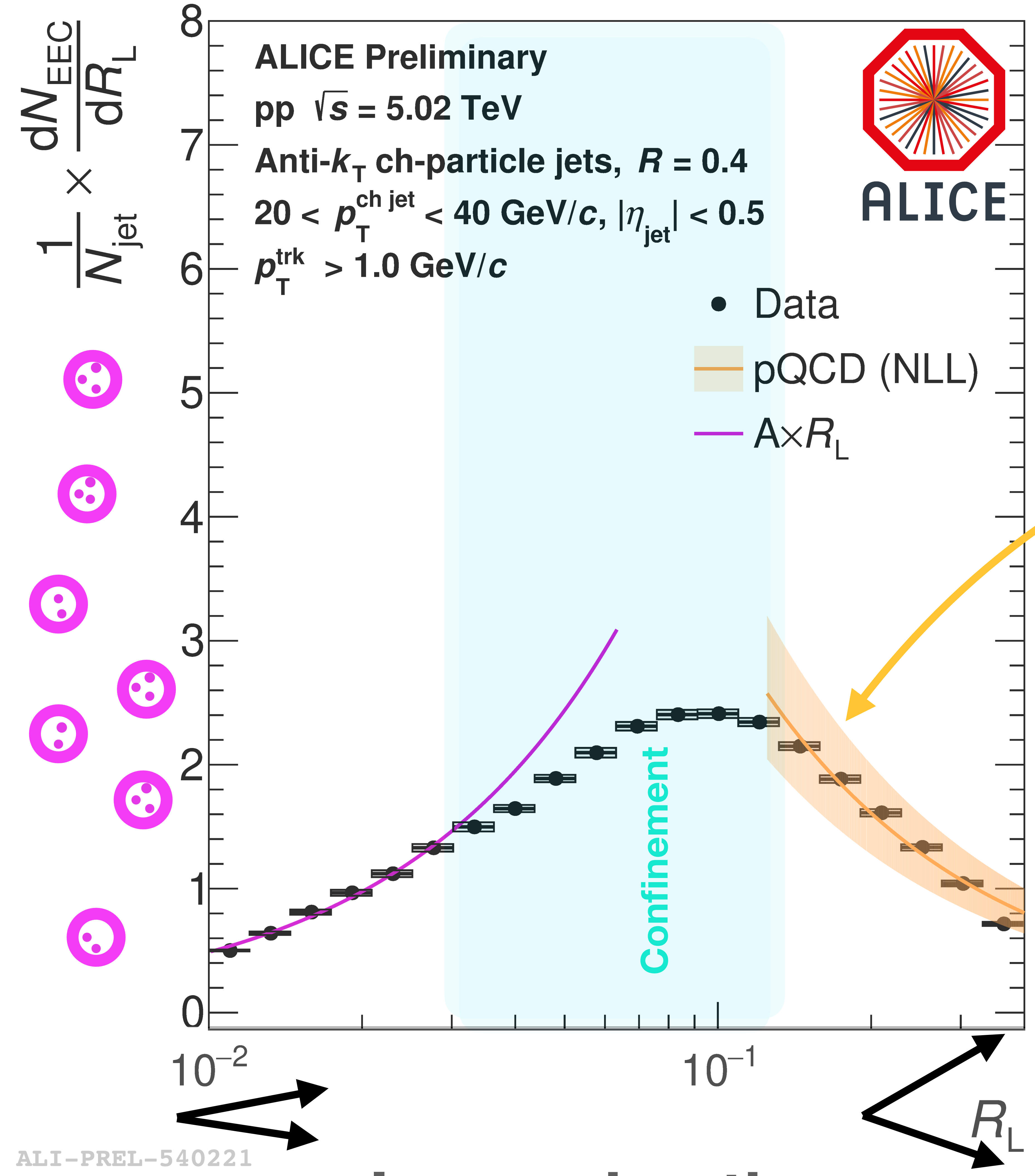
Decreasing energy scale

Why do we study energy-energy correlator?

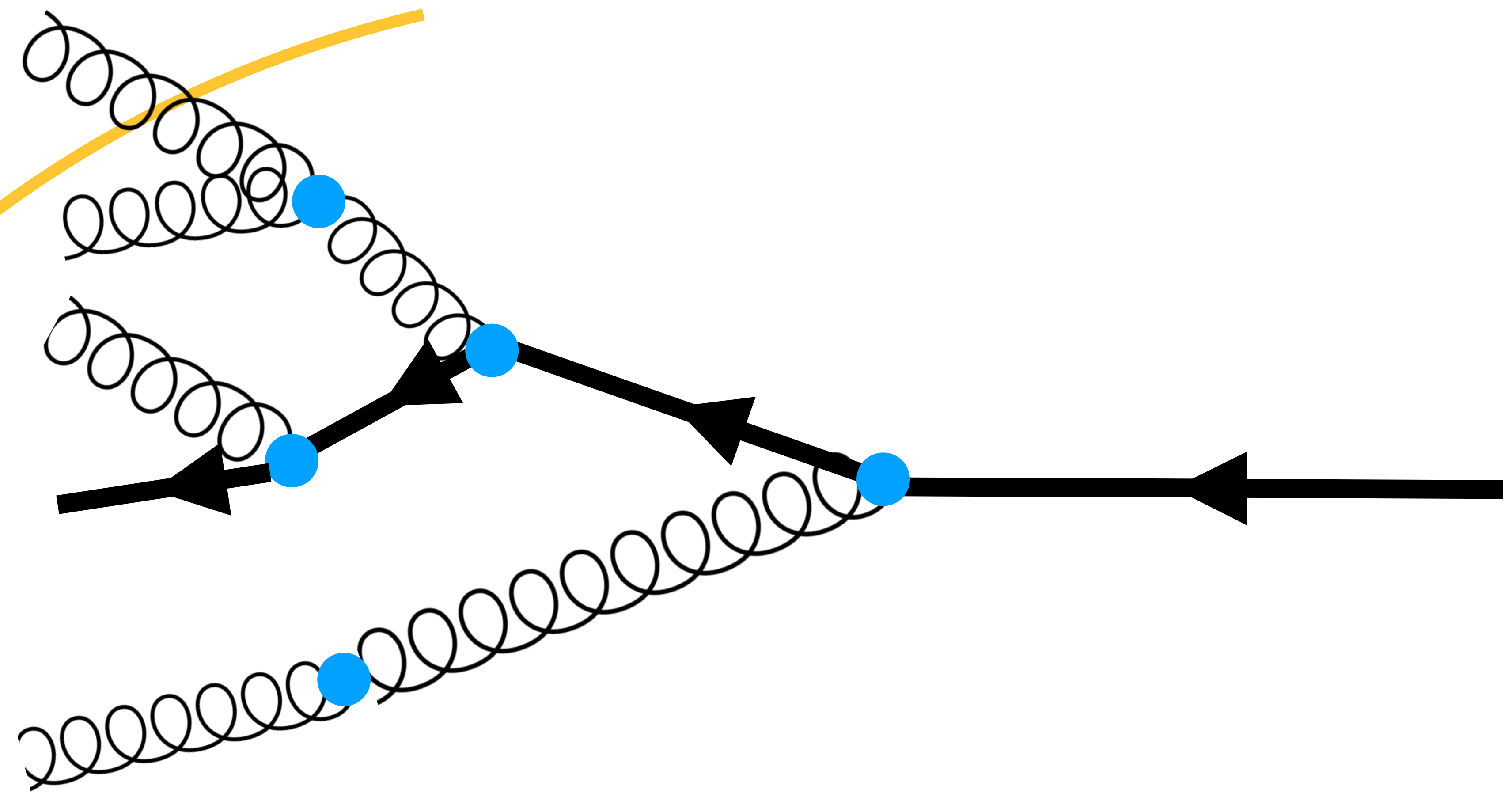


virtuality $\sim p_T R_L$

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



Perturbative regime

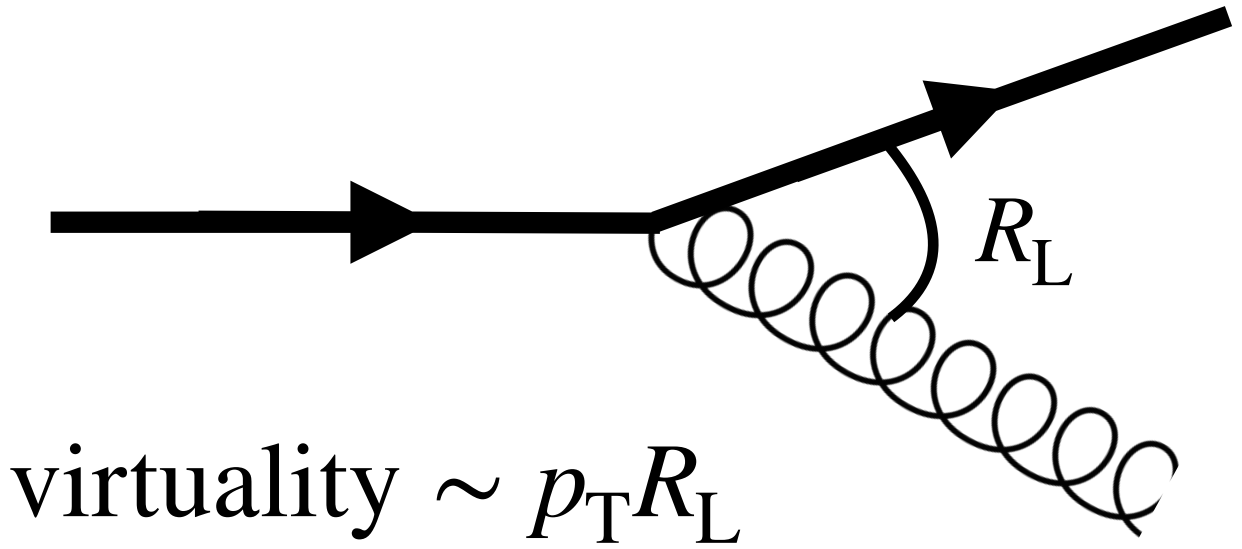


Data in good agreement with pQCD calculation

Increasing time

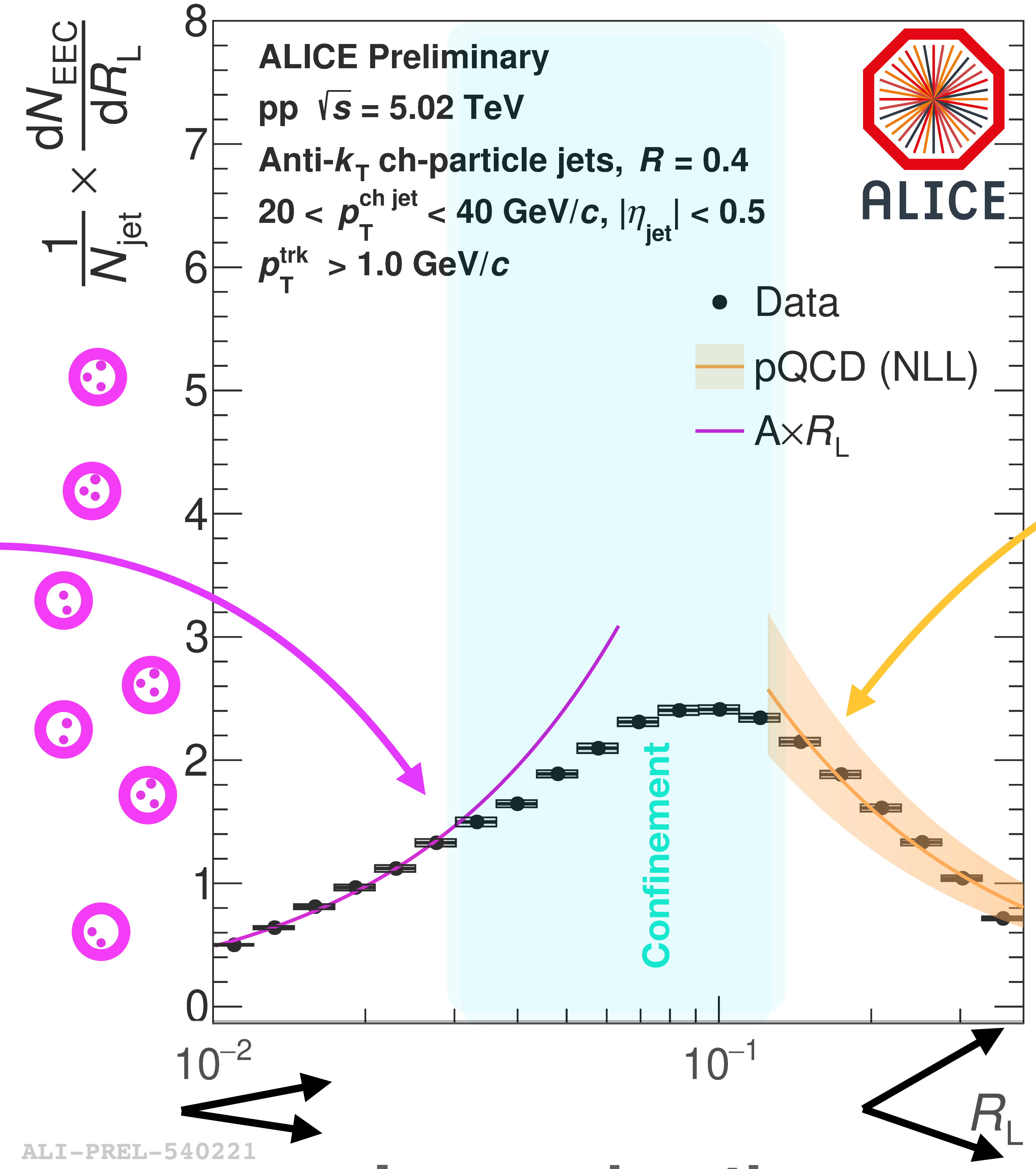
Decreasing energy scale

Why do we study energy-energy correlator?



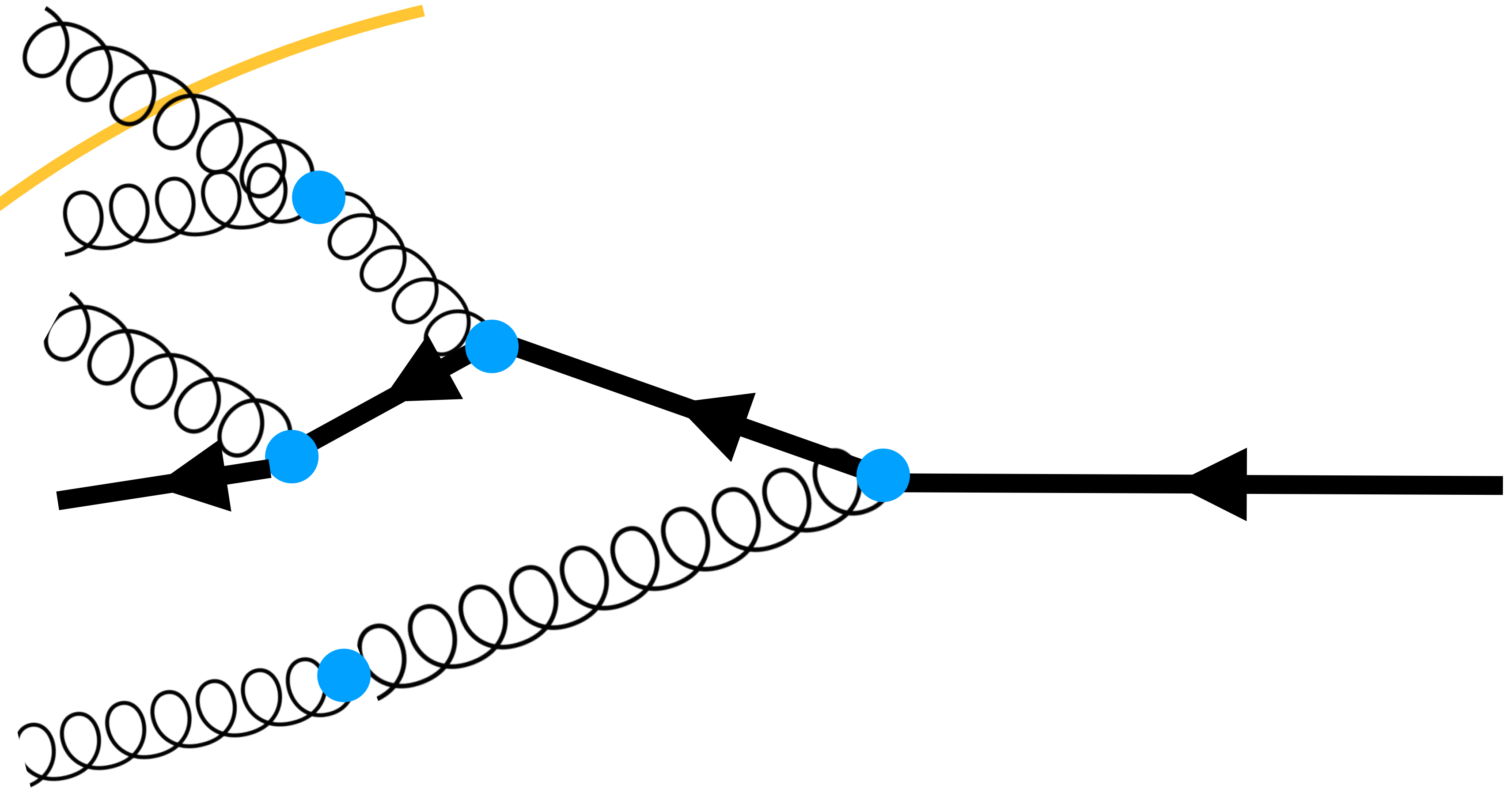
virtuality $\sim p_T R_L$

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



Non-perturbative regime

Perturbative regime



Data agrees free hadron scaling

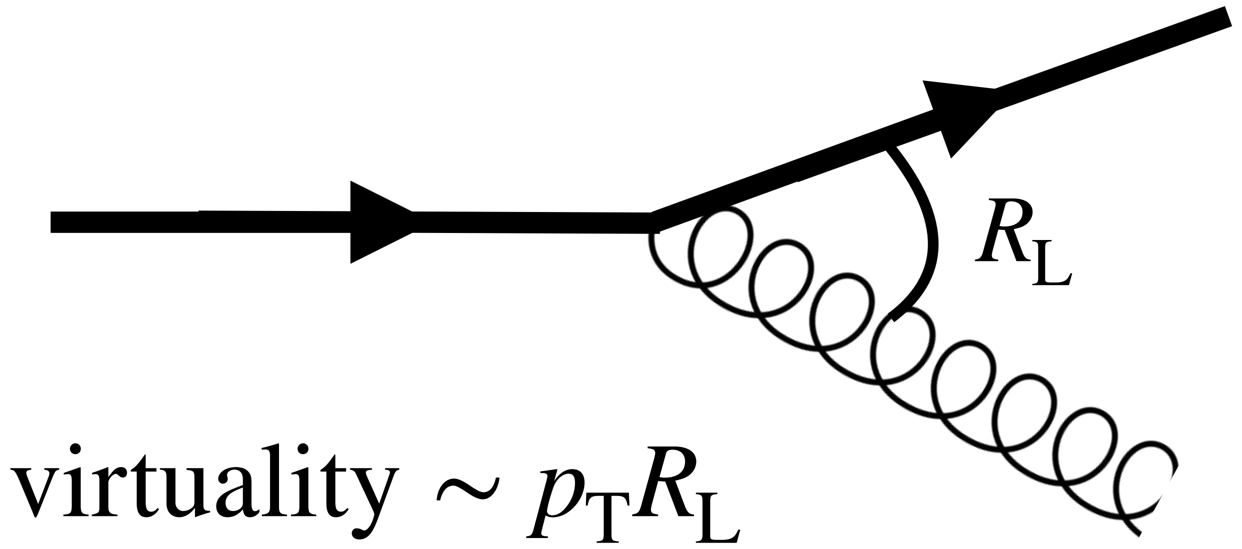
Data in good agreement with pQCD calculation

Increasing time

Decreasing energy scale

Why do we study energy-energy correlator?

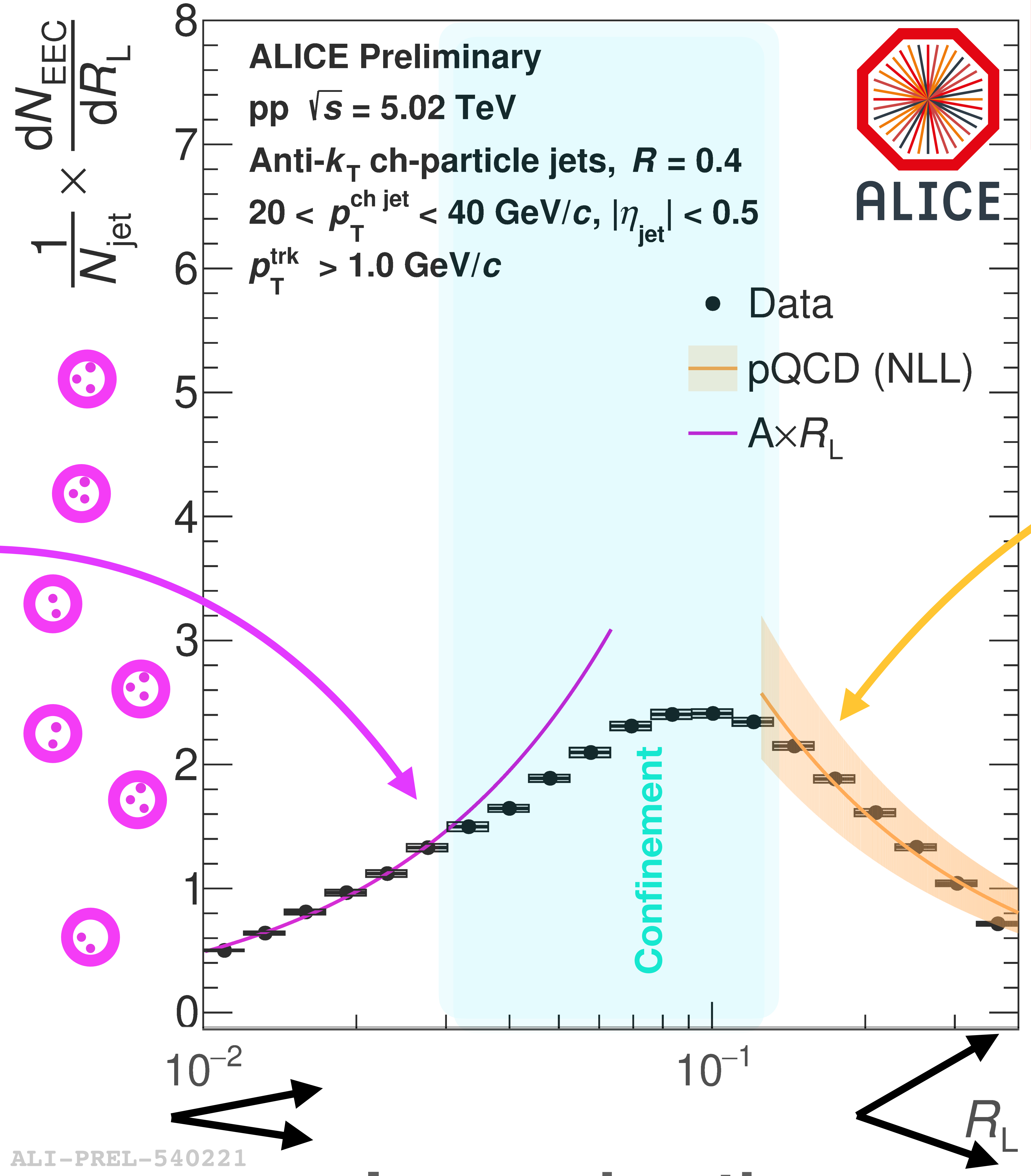
1

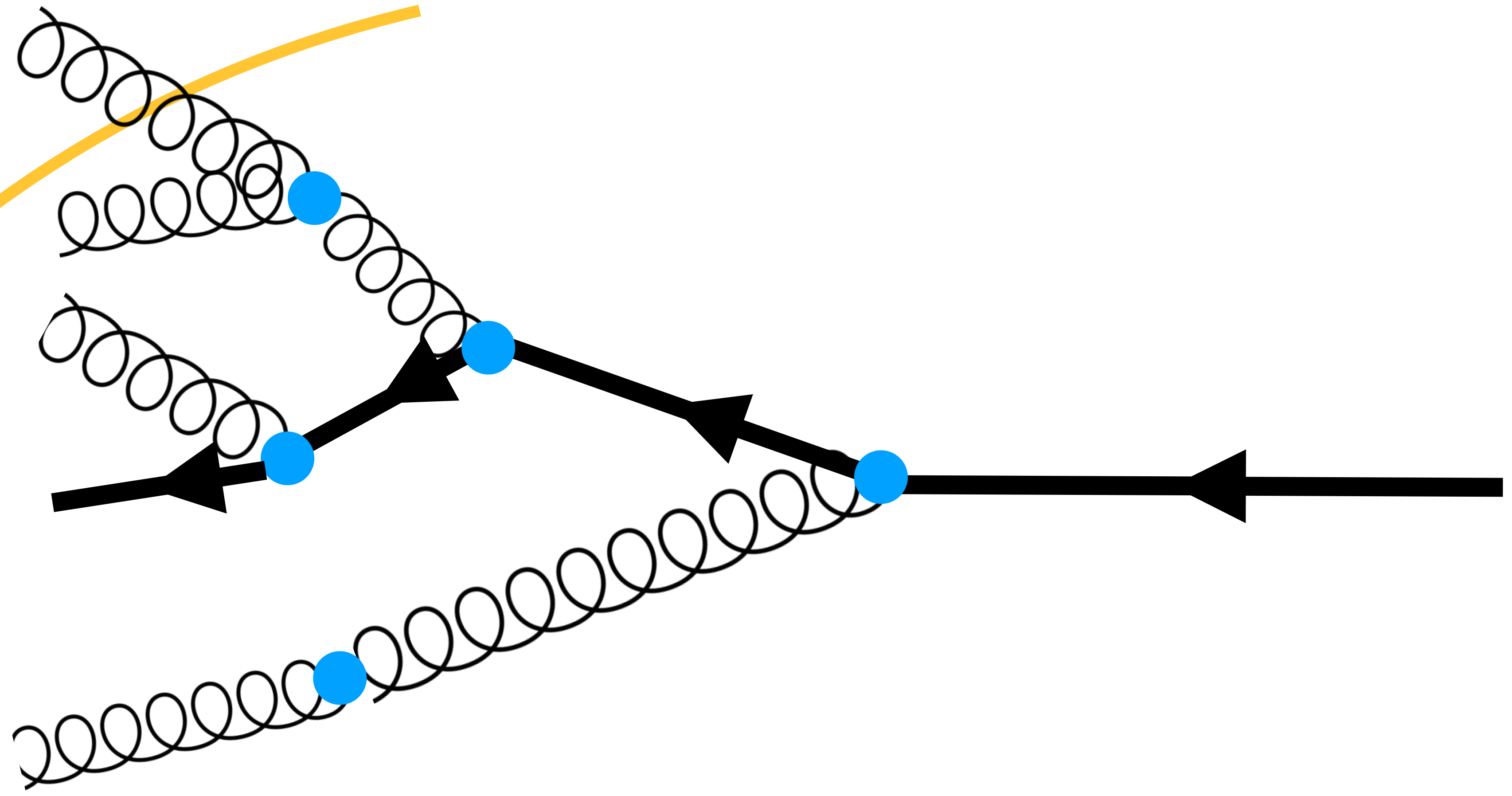


virtuality $\sim p_T R_L$

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

Clear separation of perturbative and non-perbative regime!





Perturbative regime

Non-perturbative regime

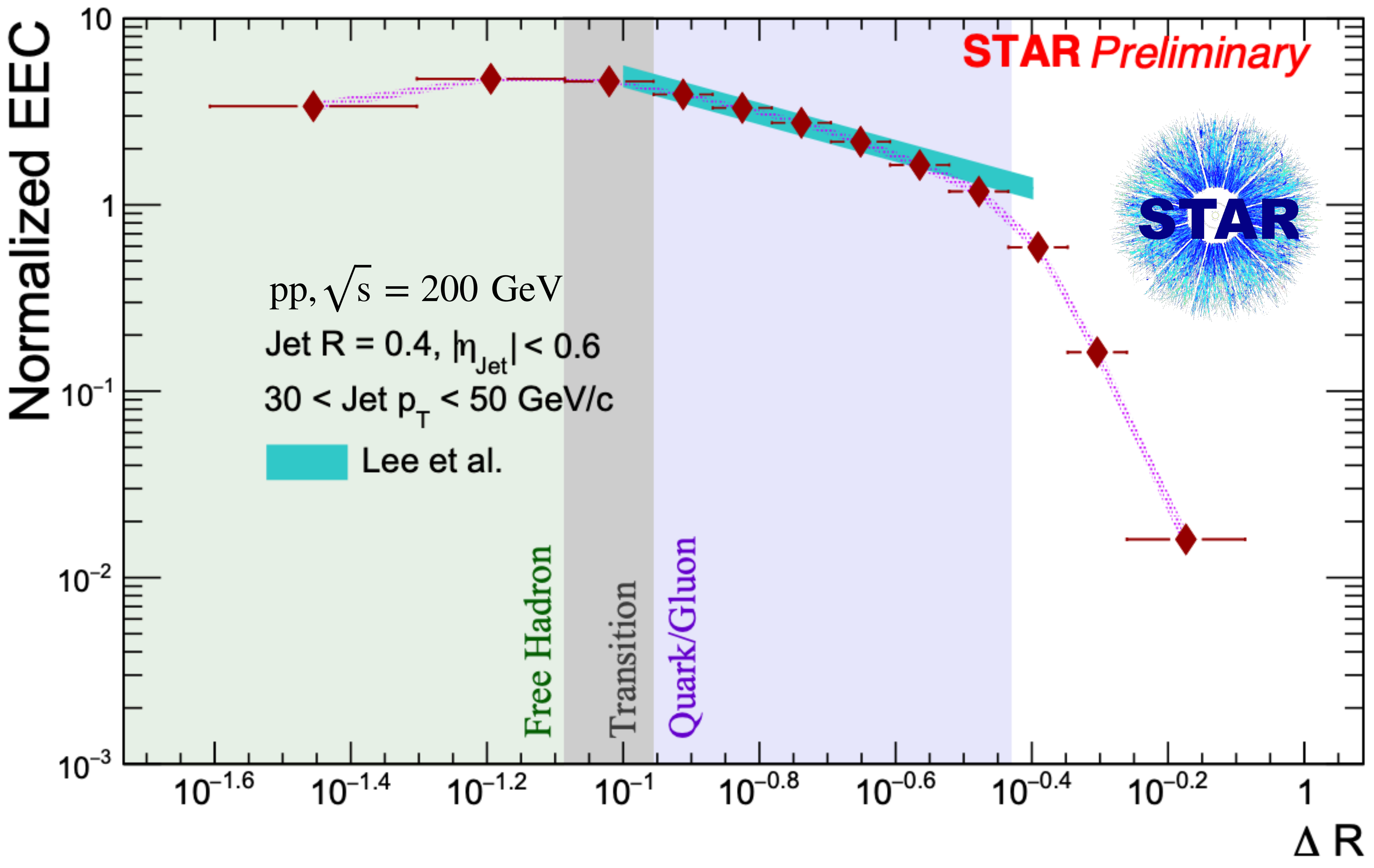
Data agrees free hadron scaling

Data in good agreement with pQCD calculation

Increasing time

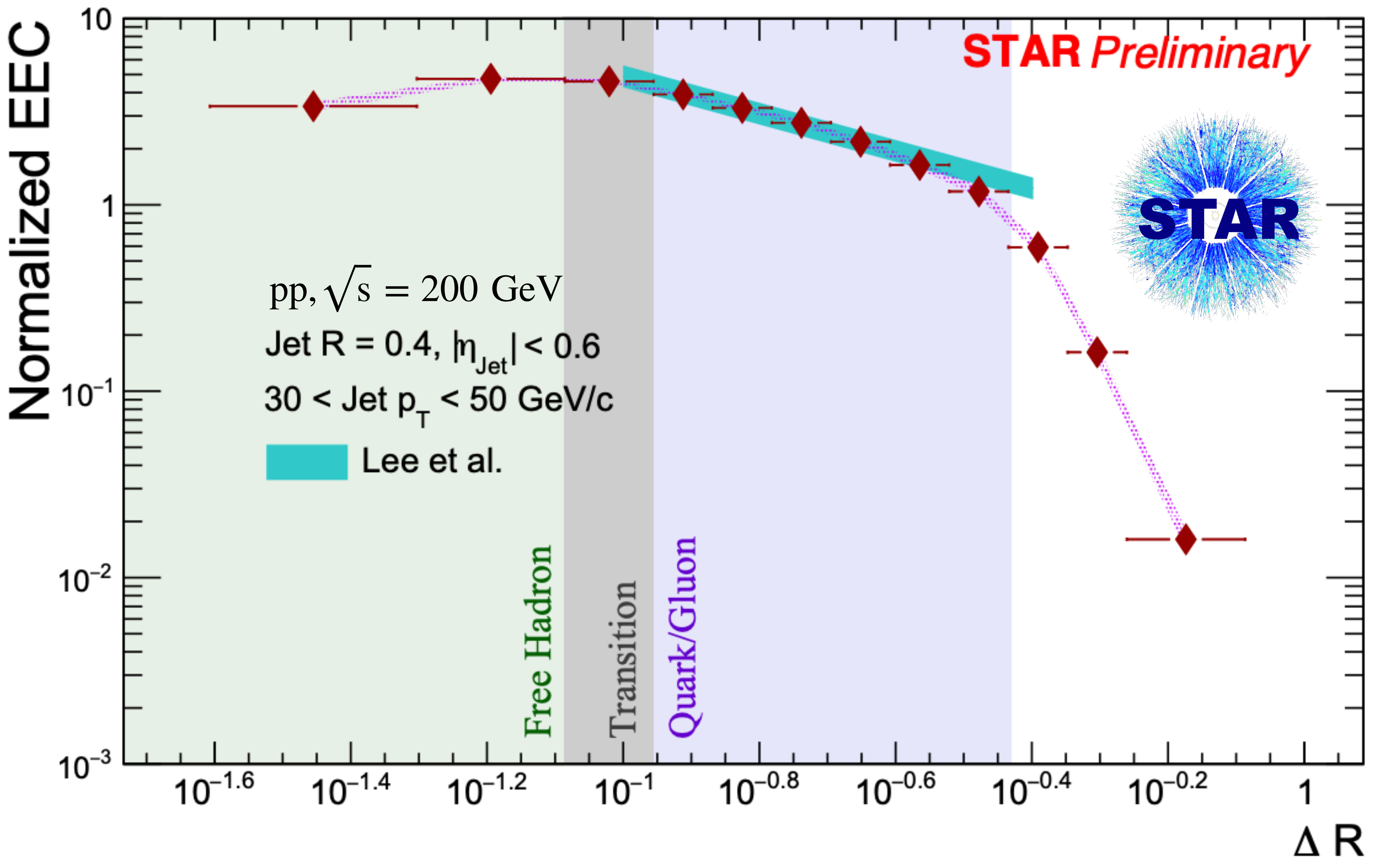
Decreasing energy scale

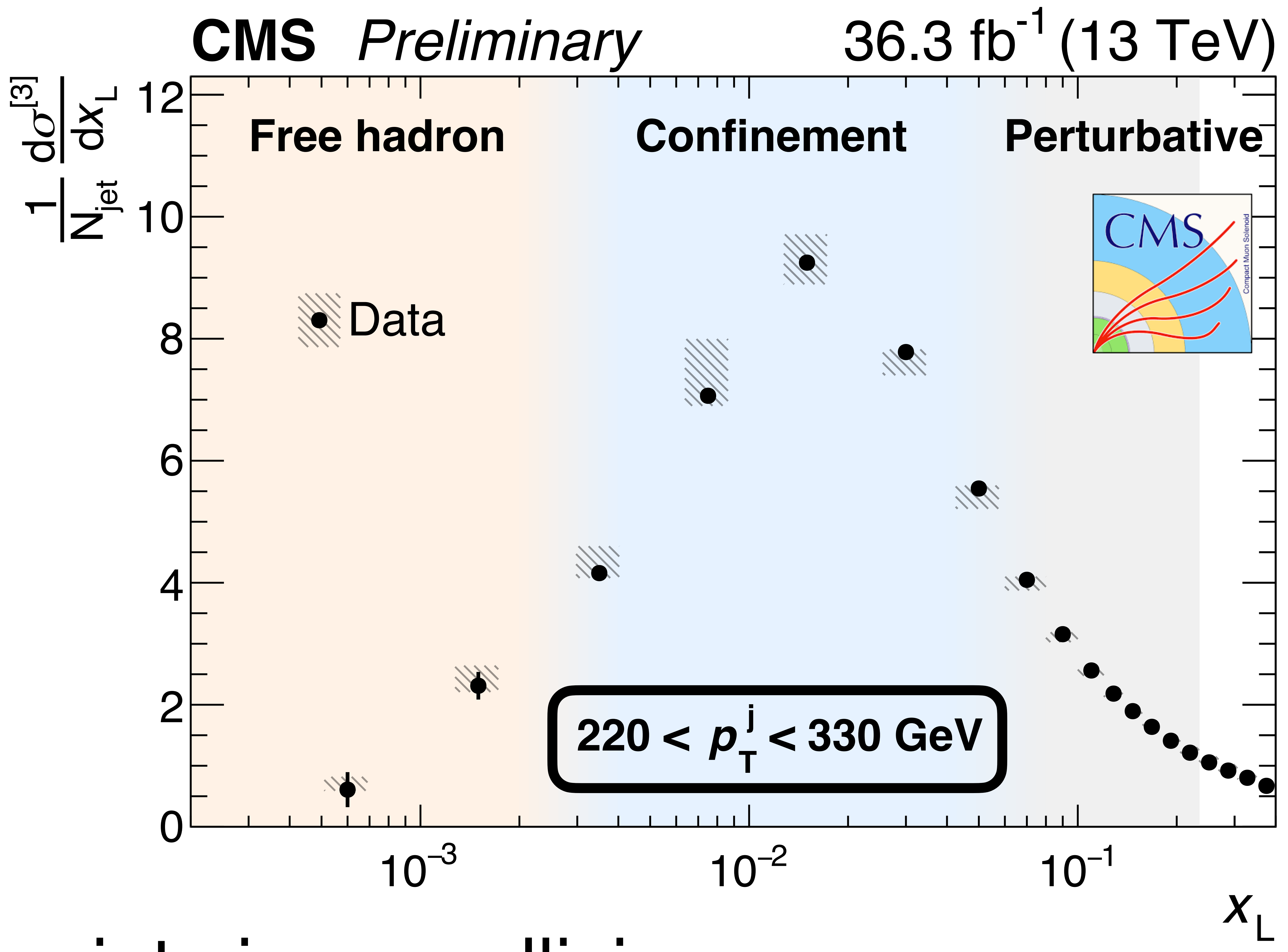
Energy-energy correlators (E2C) at LHC and RHIC



- **STAR** at **RHIC** also measured EEC for jets in pp collisions.
  - Similar trend: Separation of perturbative & non-perturbative regimes.
  - Data at large R_L well-described by pQCD calculations.

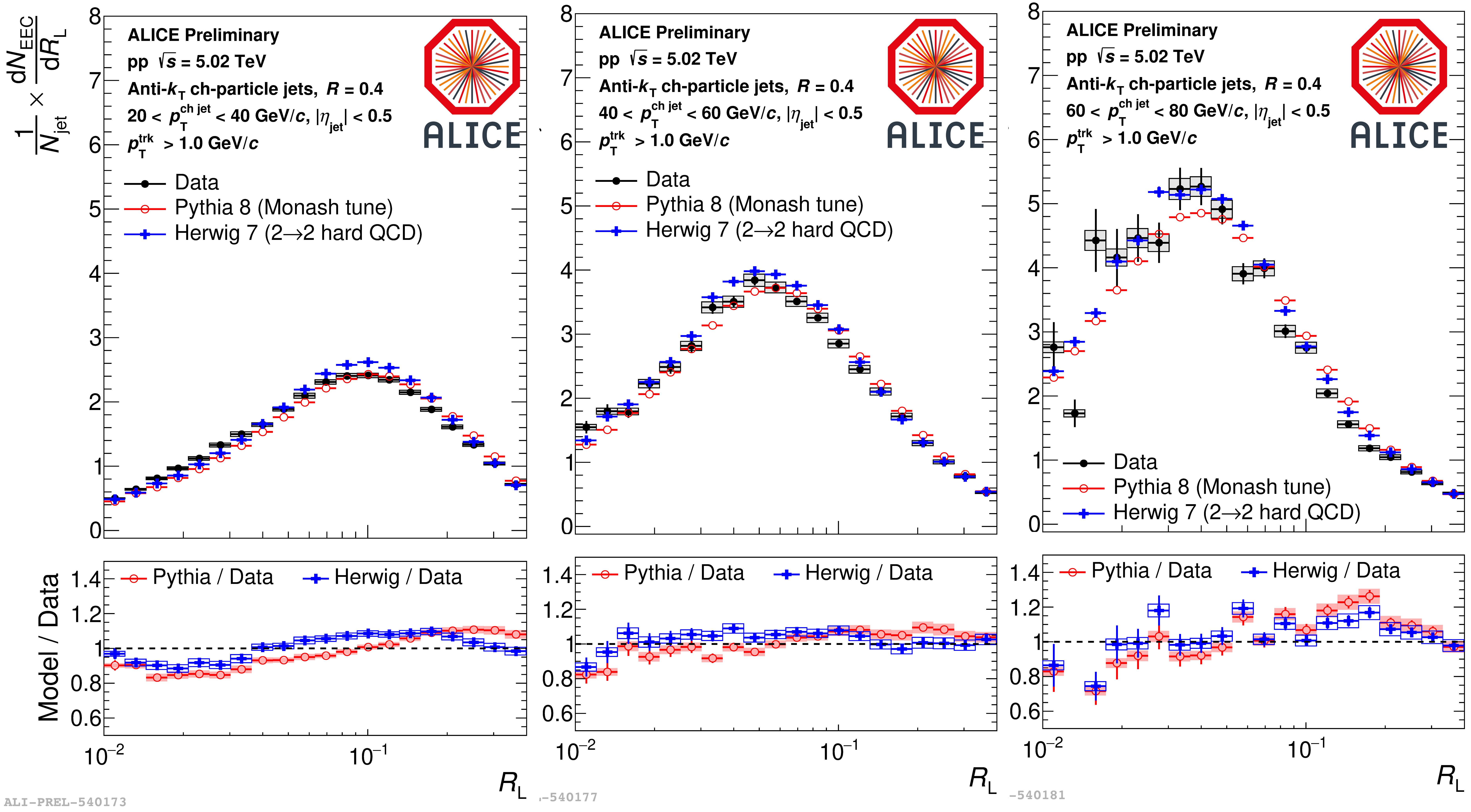
Energy-energy correlators (E2C) at LHC and RHIC





- **STAR** at **RHIC** also measured EEC for jets in pp collisions.
  - Similar trend: Separation of perturbative & non-perturbative regimes.
  - Data at large R_L well-described by pQCD calculations.
- **CMS** at the **LHC** measured EECs at higher jet p_T and higher $\sqrt{s}$.

What do we learn about hadronization?

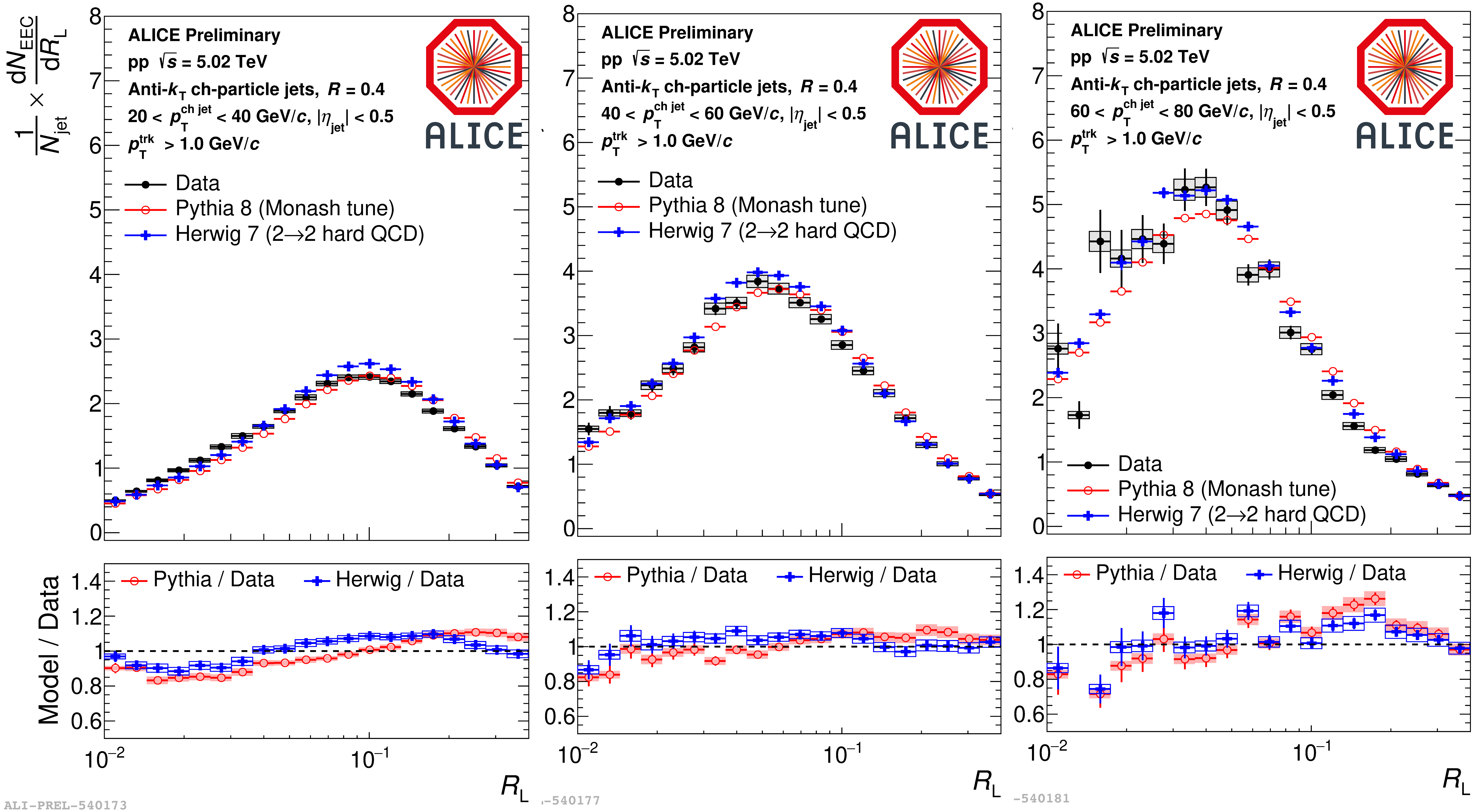


Data compared to **PYTHIA 8** and **HERWIG 7** MC generators

PYTHIA 8 uses **Lund string model** for hadronization

HERWIG 7 uses **cluster model** for hadronization

What do we learn about hadronization?



Data compared to **PYTHIA 8** and **HERWIG 7** MC generators

PYTHIA 8 uses **Lund string model** for hadronization

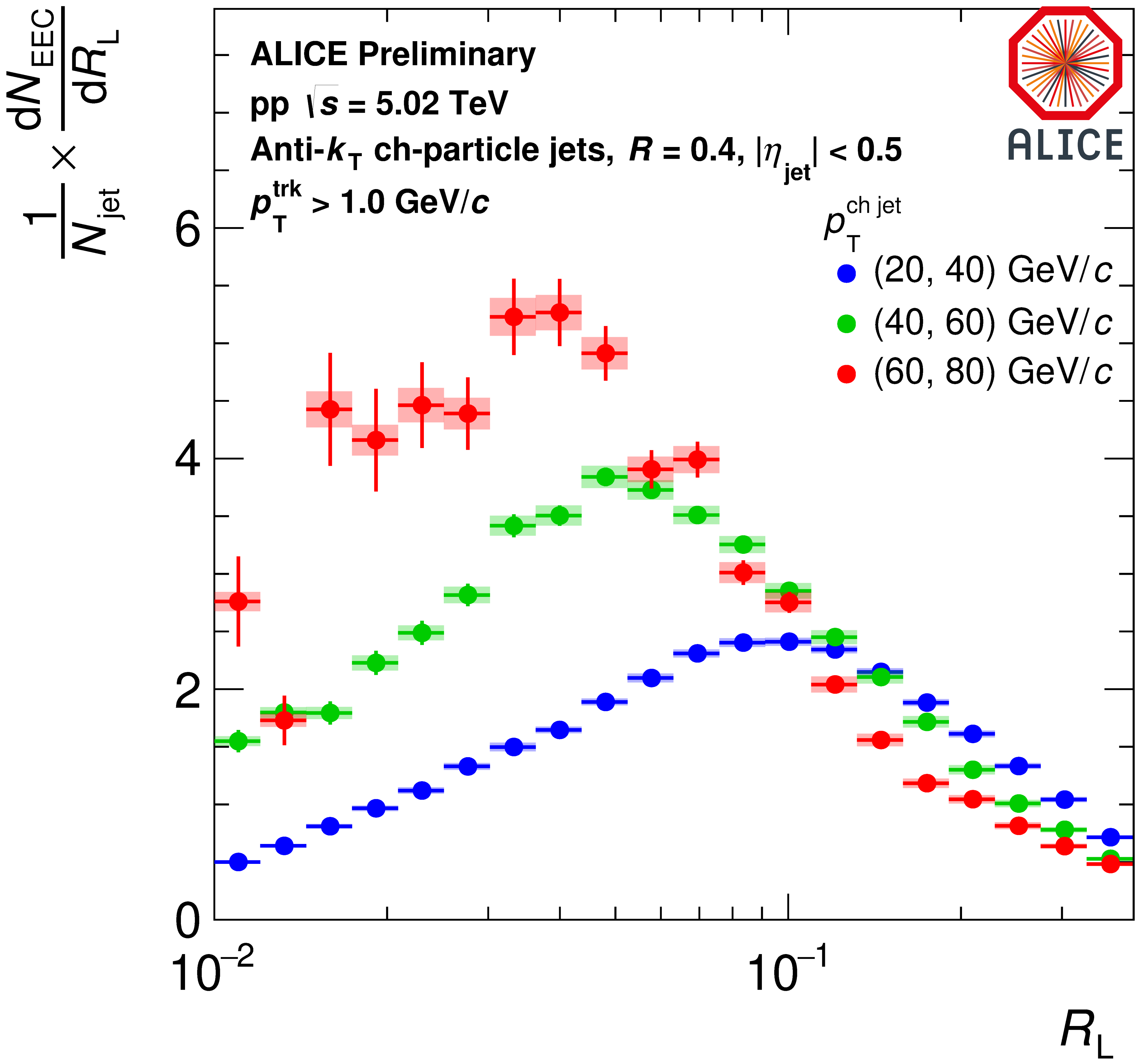
HERWIG 7 uses **cluster model** for hadronization

Both PYTHIA and HERWIG describe the data within 20%

HERWIG better predicts the peak R_L position over PYTHIA

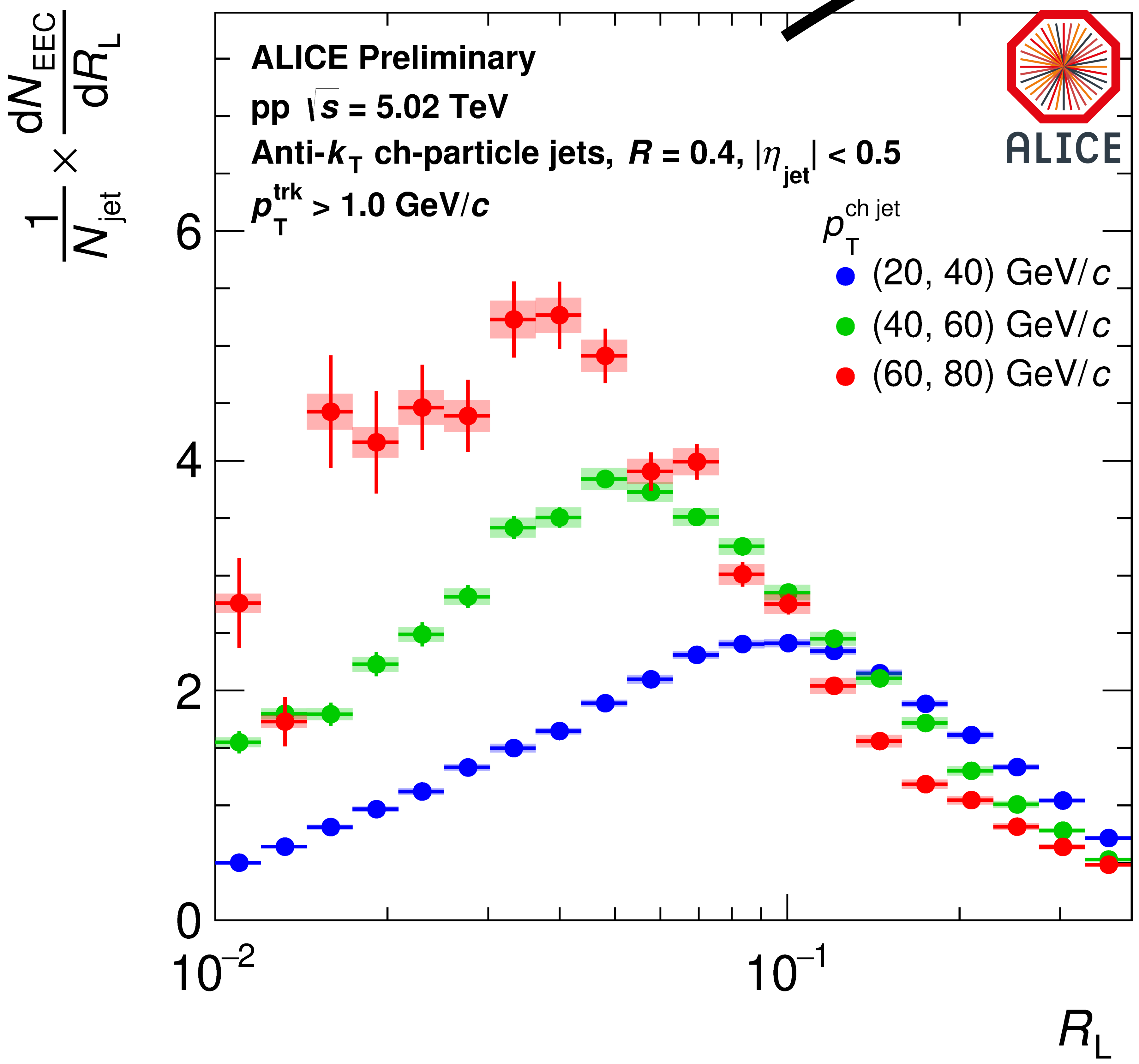
2

Universal transition behavior



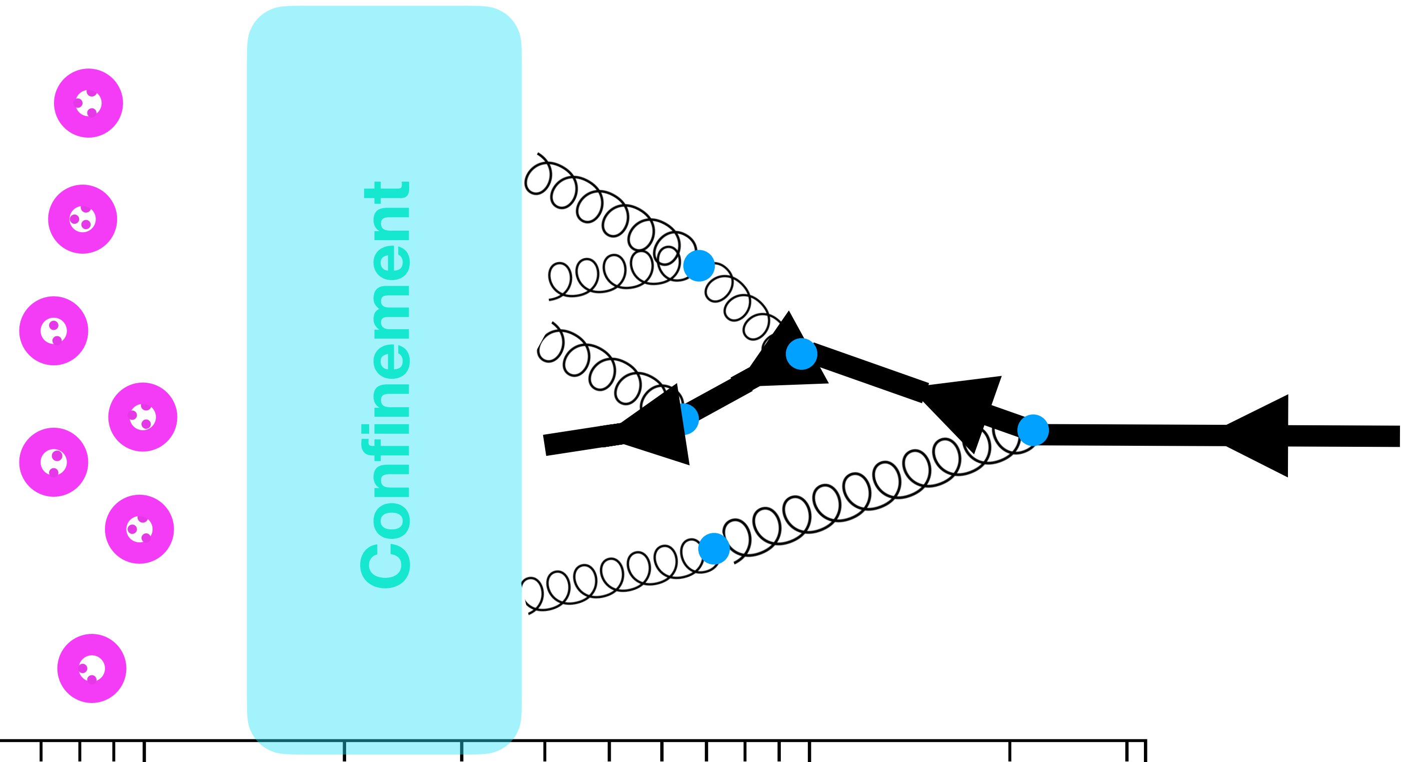
Universal transition behavior

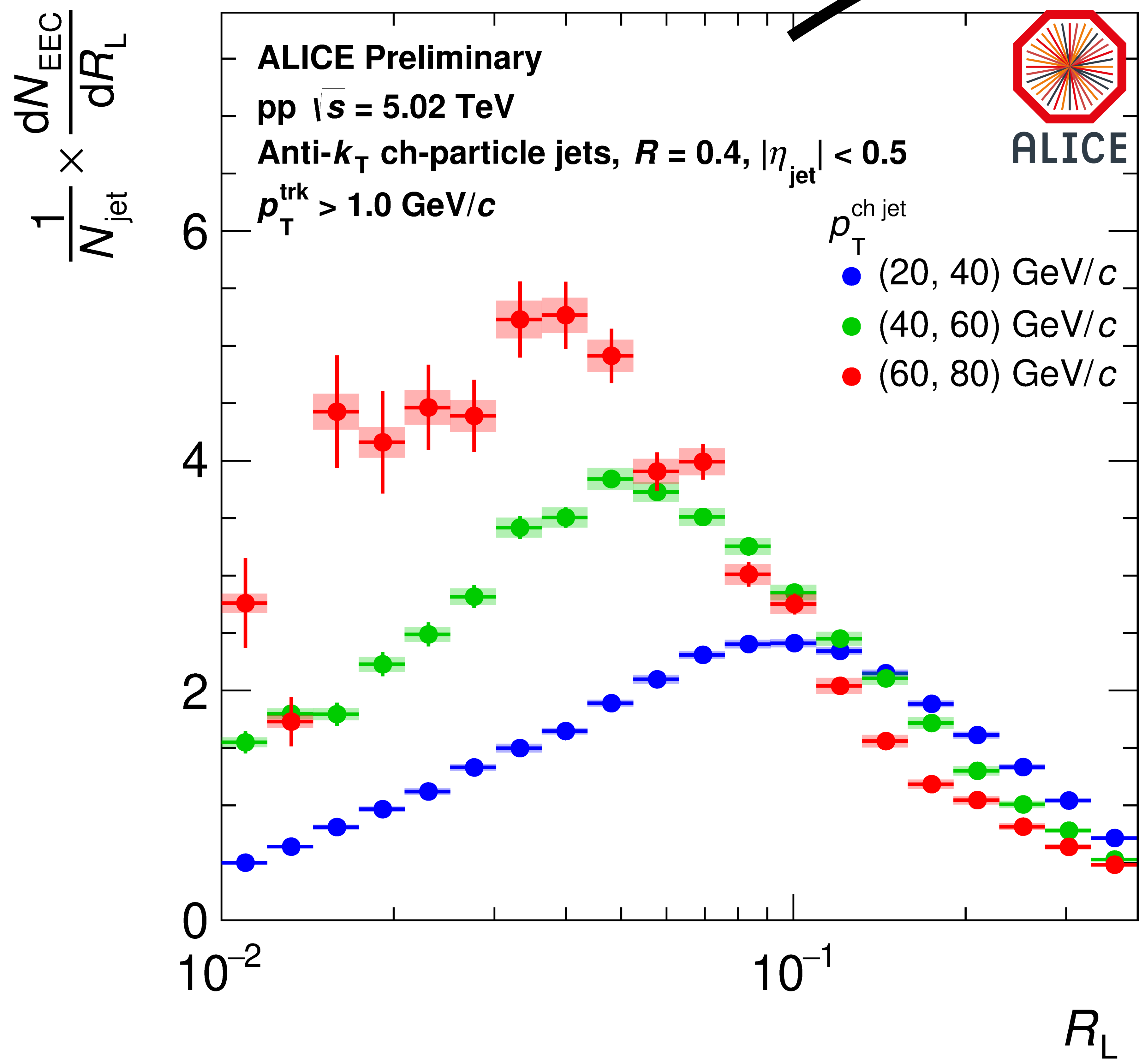
Scaling angle R_L by jet p_T and normalizing the y-scale.

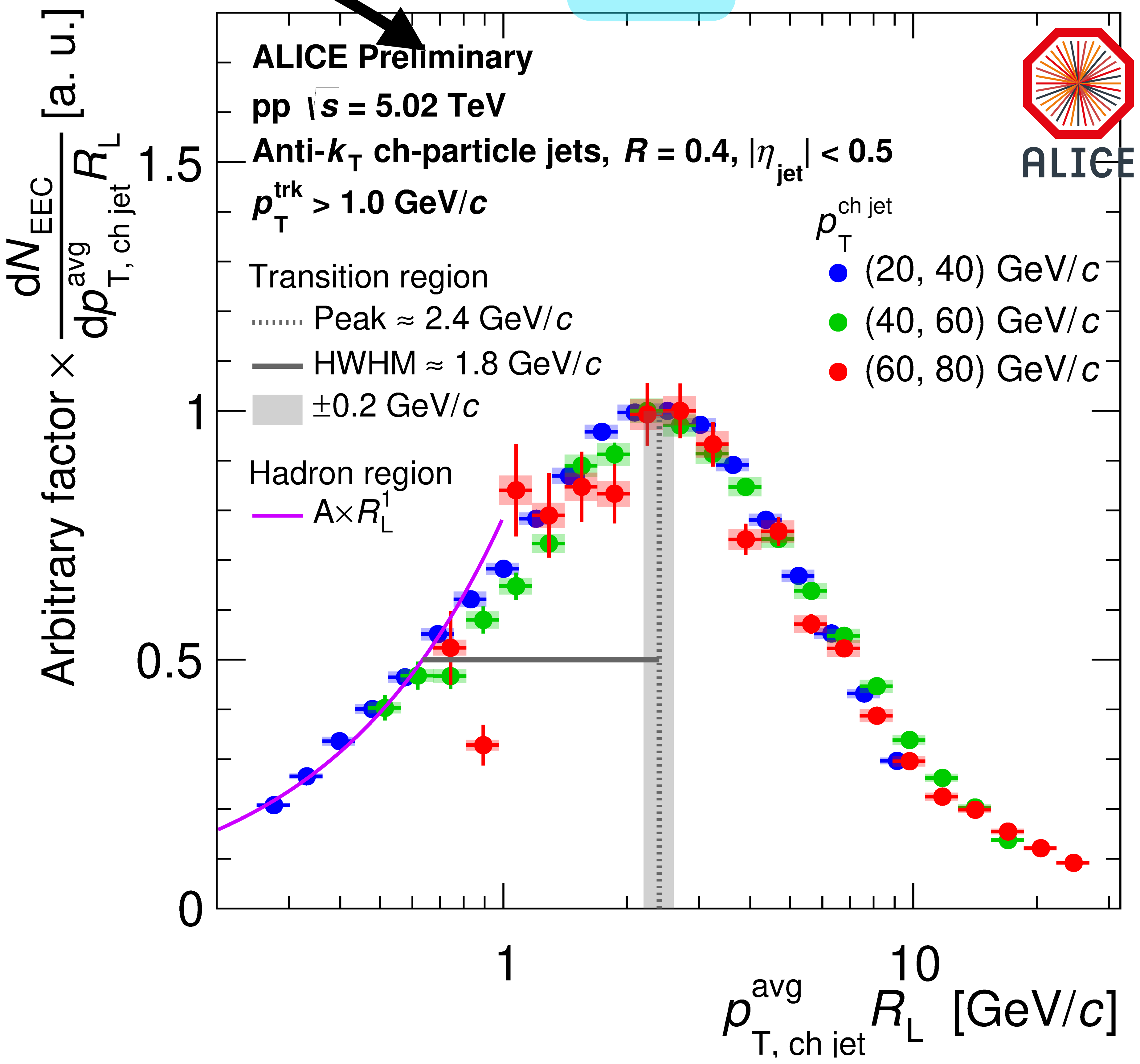


Universal transition behavior

Scaling angle R_L by jet p_T and normalizing the y-scale.

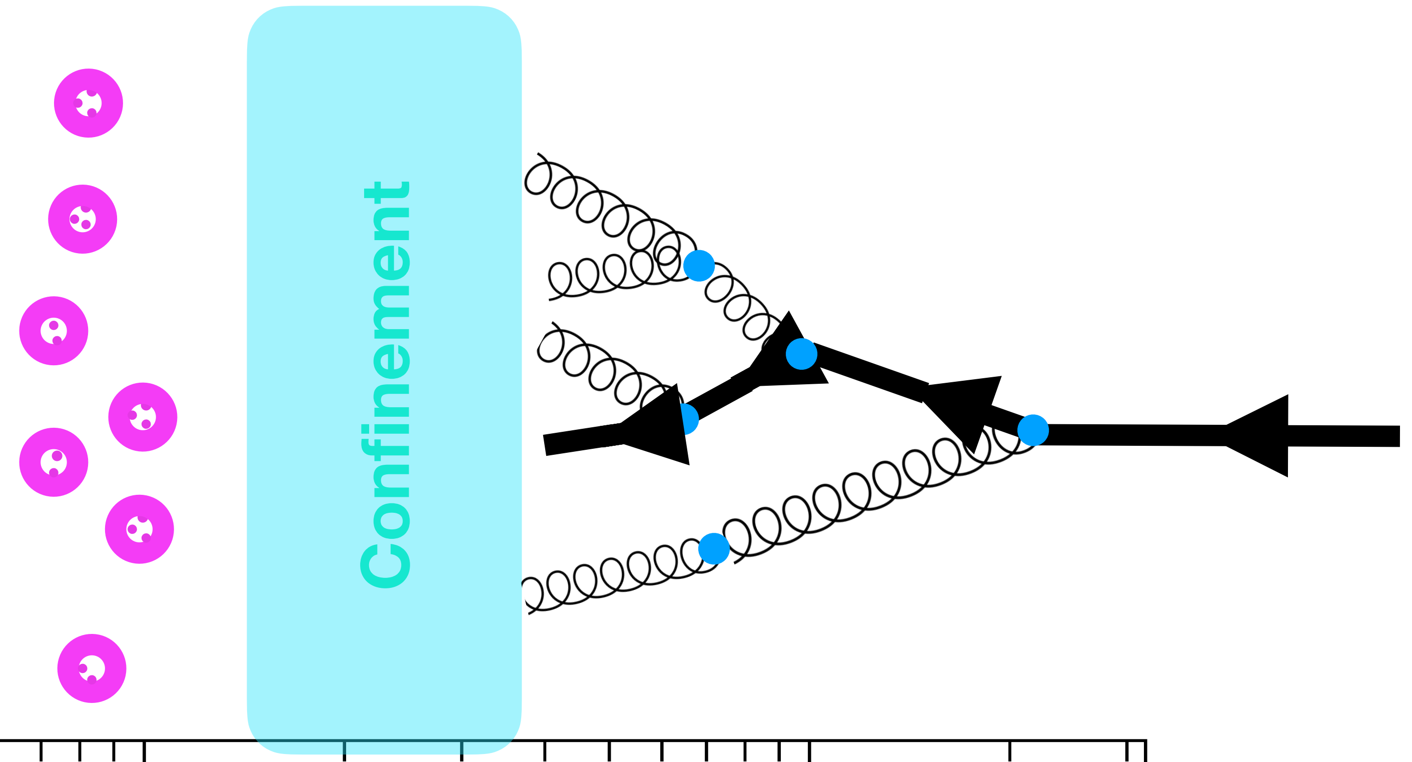




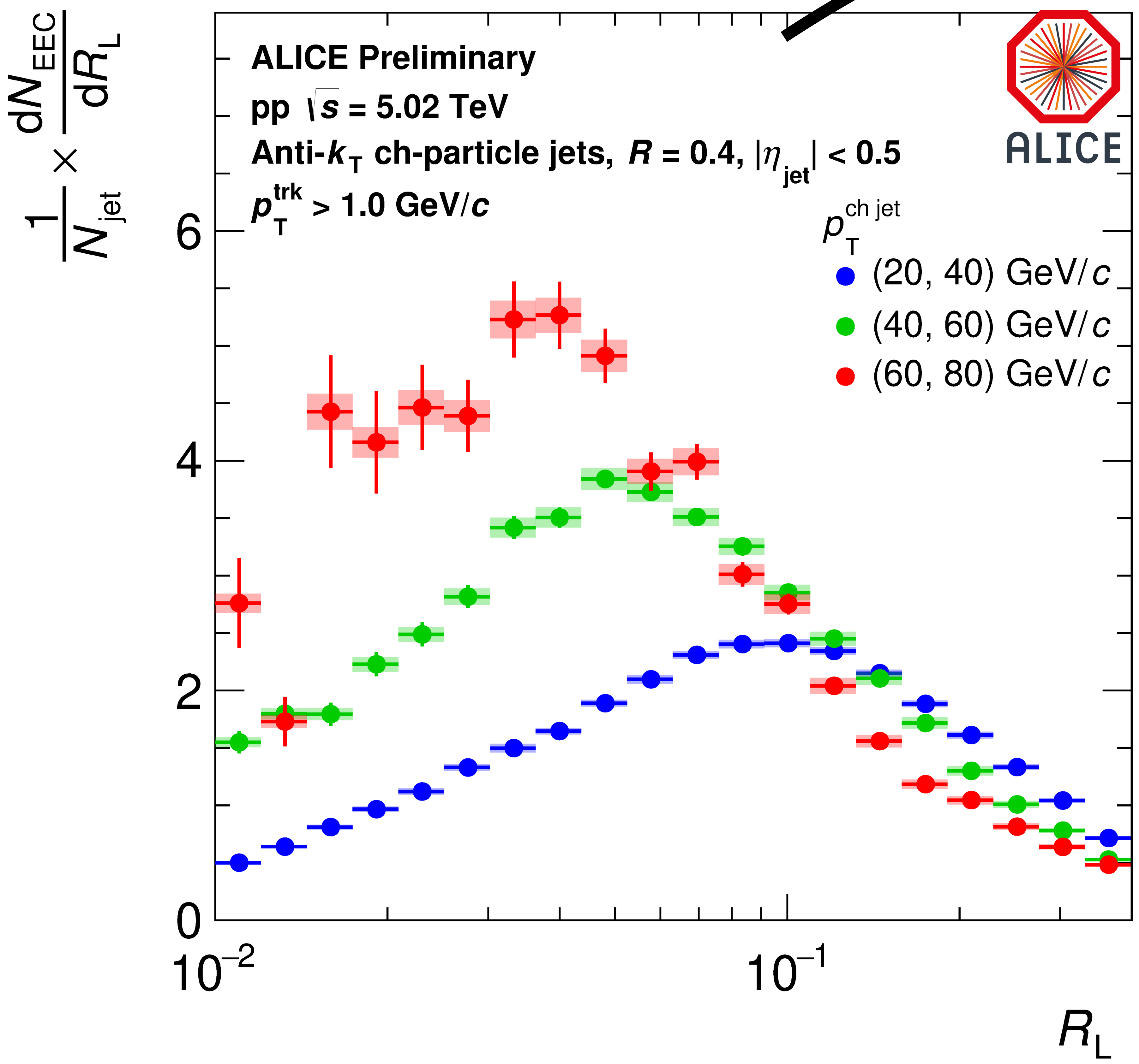


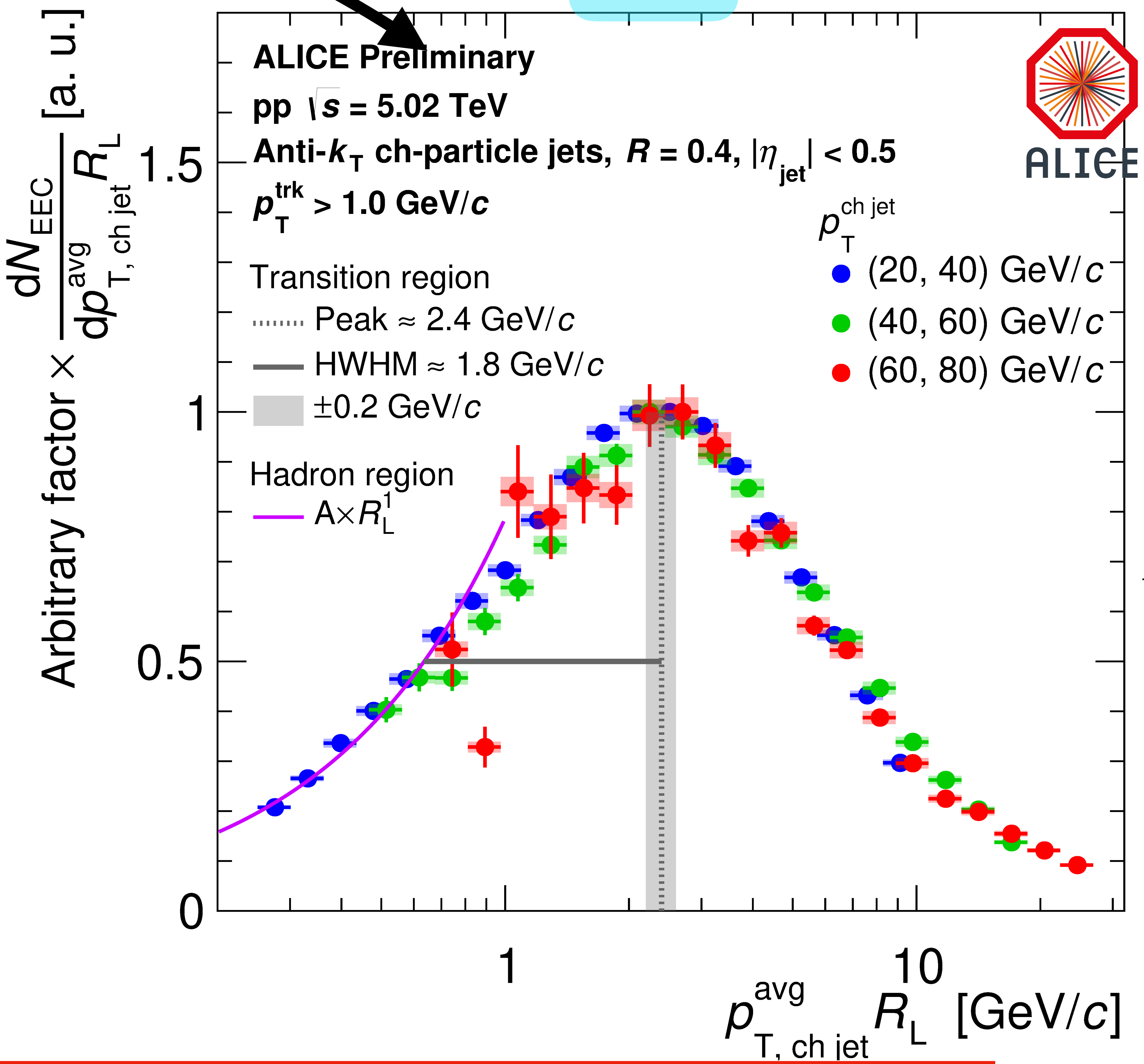
Universal transition behavior

3



Scaling angle R_L by jet p_T
and normalizing the y-scale.



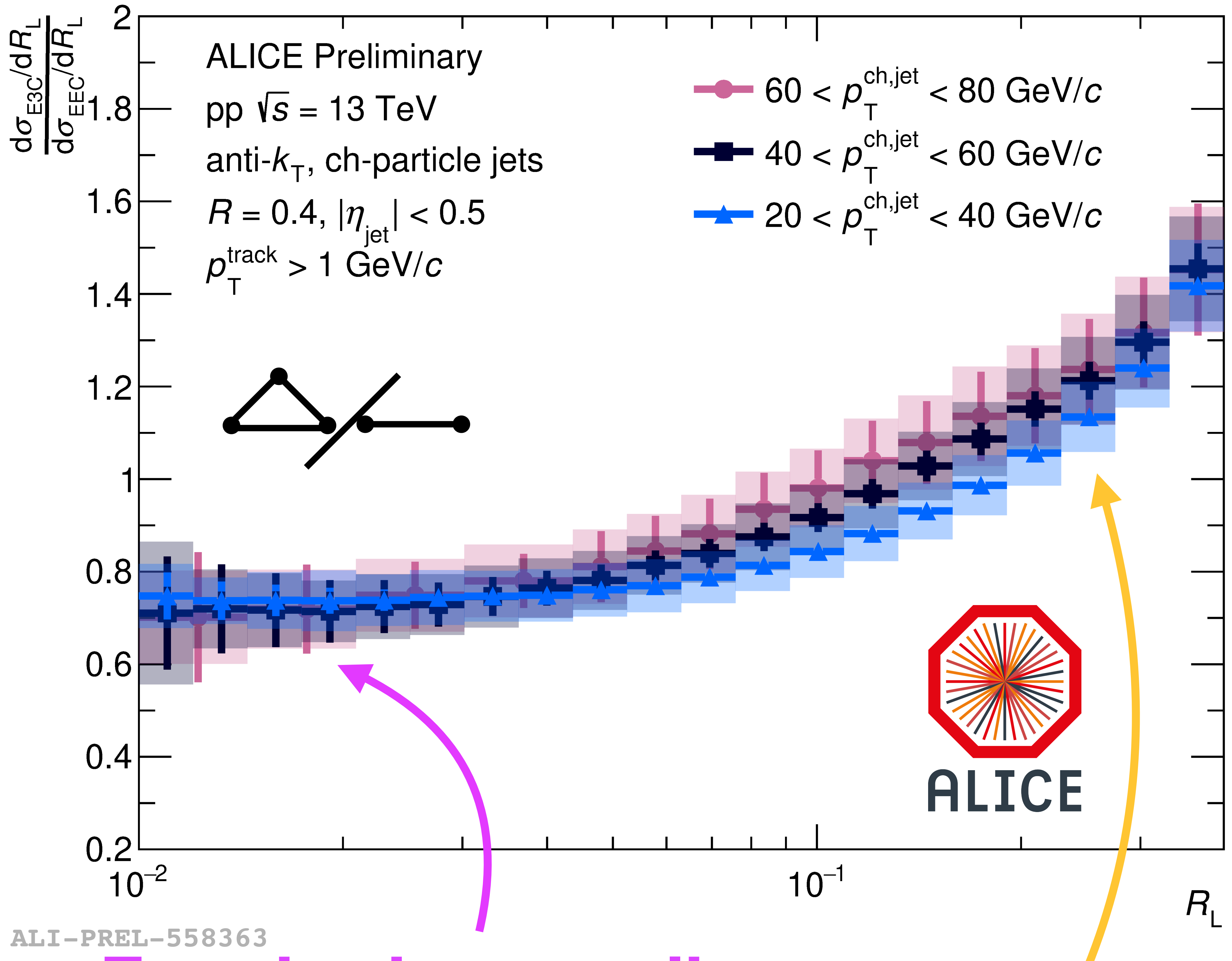


$$\Lambda_{QCD} \sim p_{T,jet} R_L$$

EECs distribution in different jet p_T aligns around 2.4 GeV/c
→ Universal scaling behavior !

Higher point energy correlator: EEEC (E3C)/EEC (E2C)

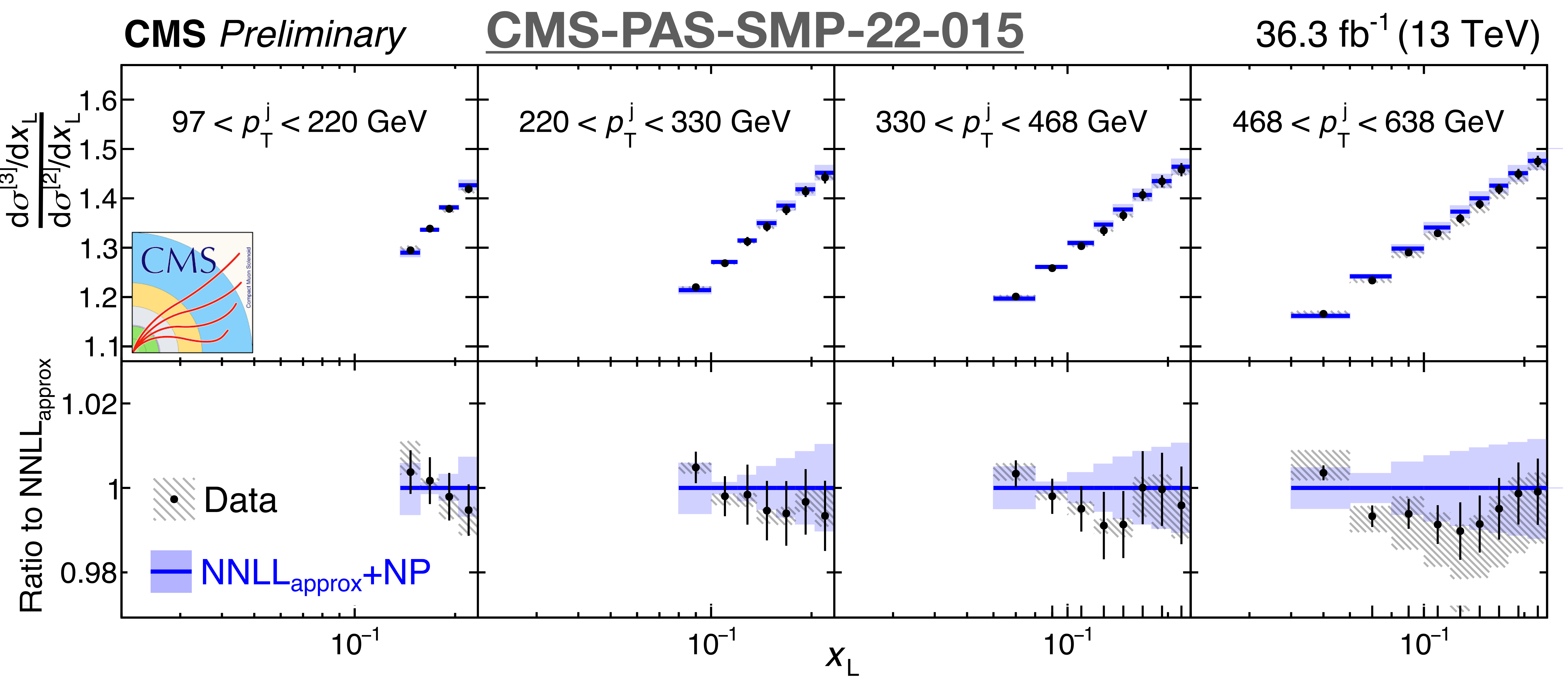
Higher point energy correlator: EEEC (E3C)/EEC (E2C)



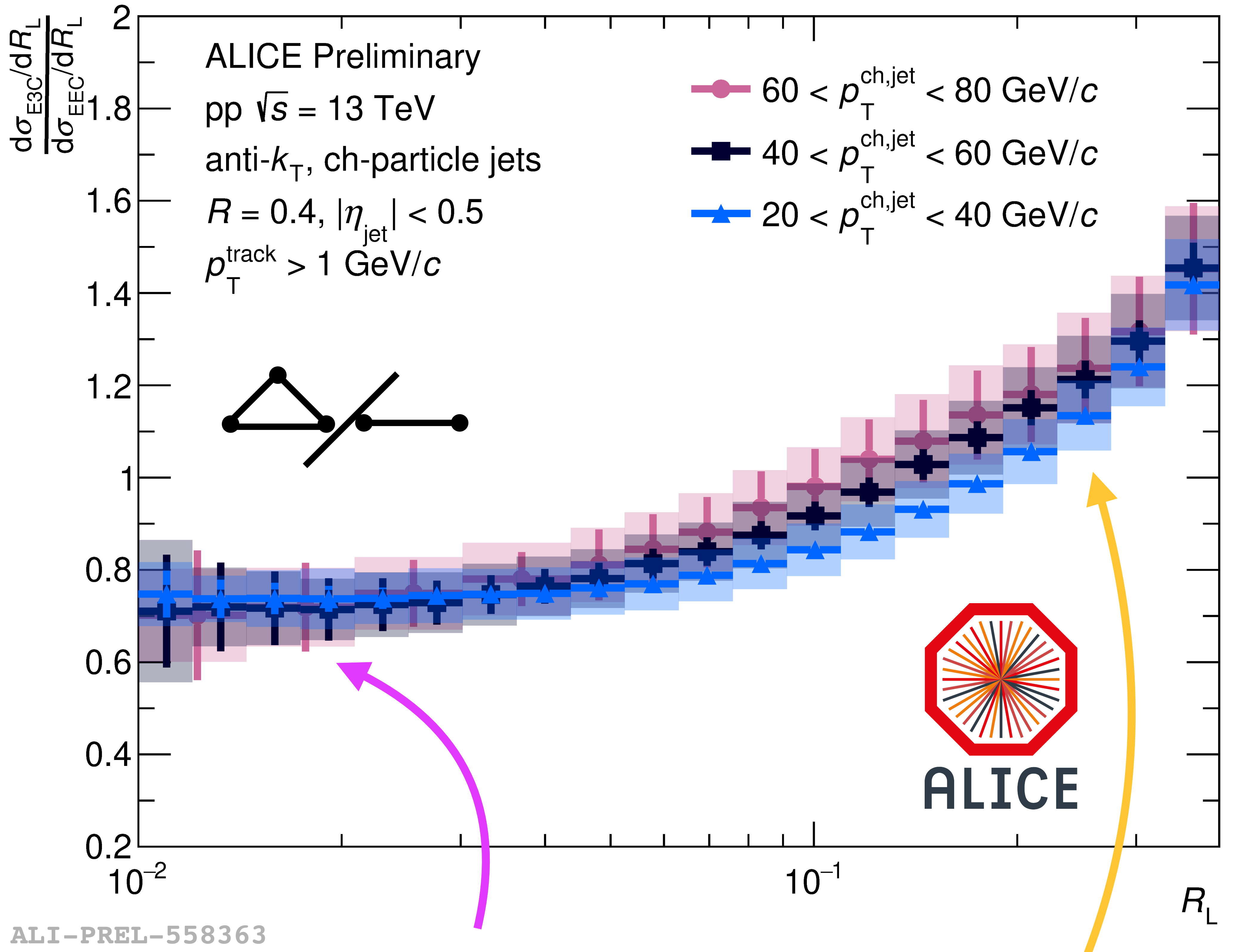
Free hadron scaling region: Flat

Perturbative region: slope sensitive to α_S

Higher point energy correlator: EEEC (E3C)/EEC (E2C)



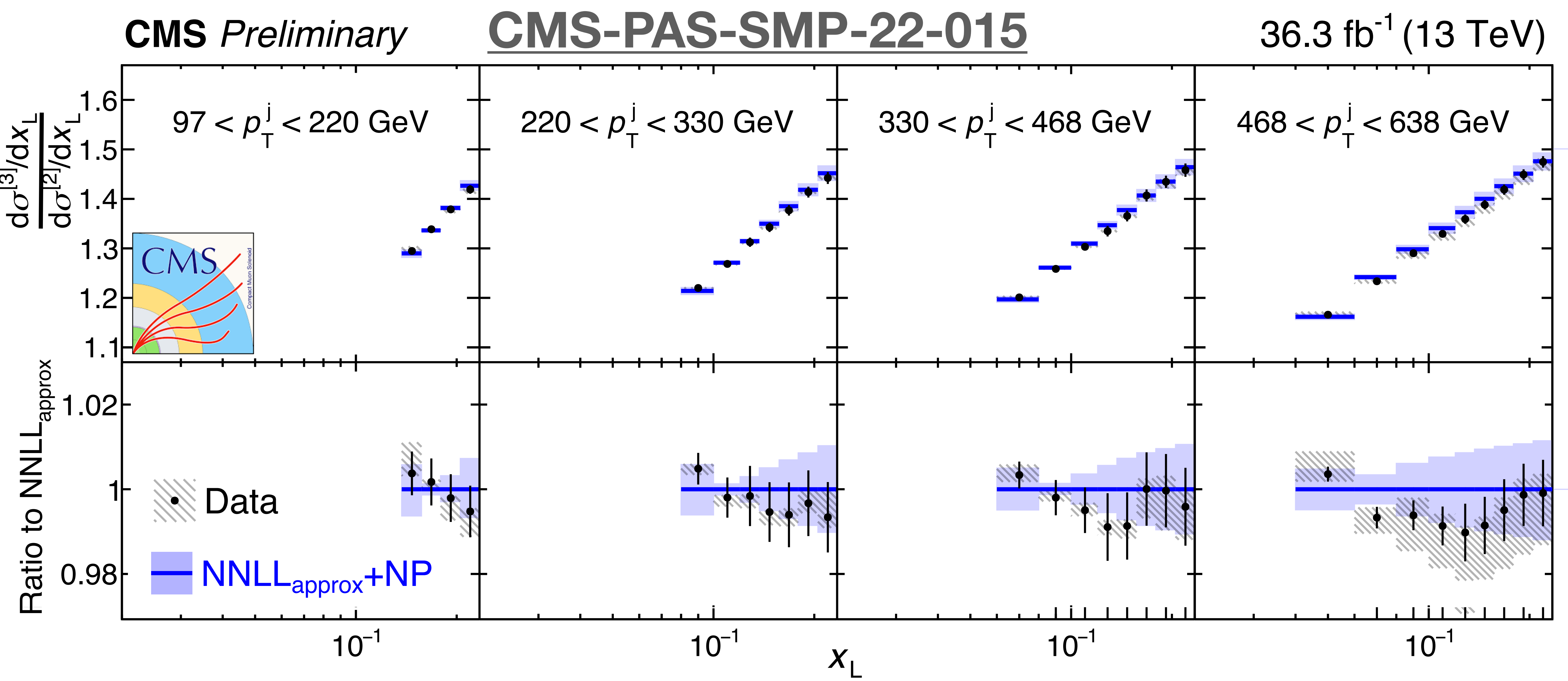
arXiv: 2307.07510

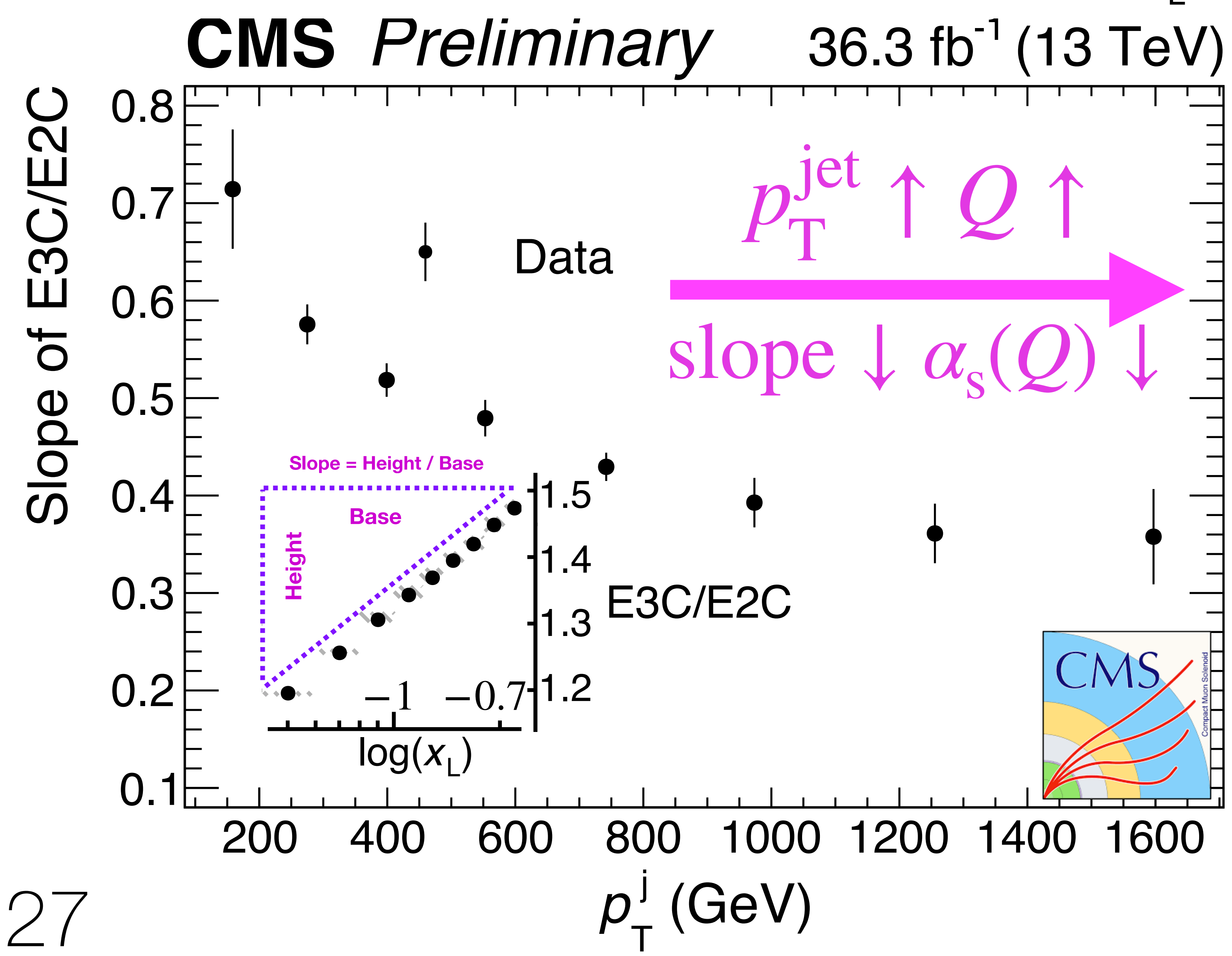


Free hadron scaling region: Flat

Perturbative region: slope sensitive to α_S

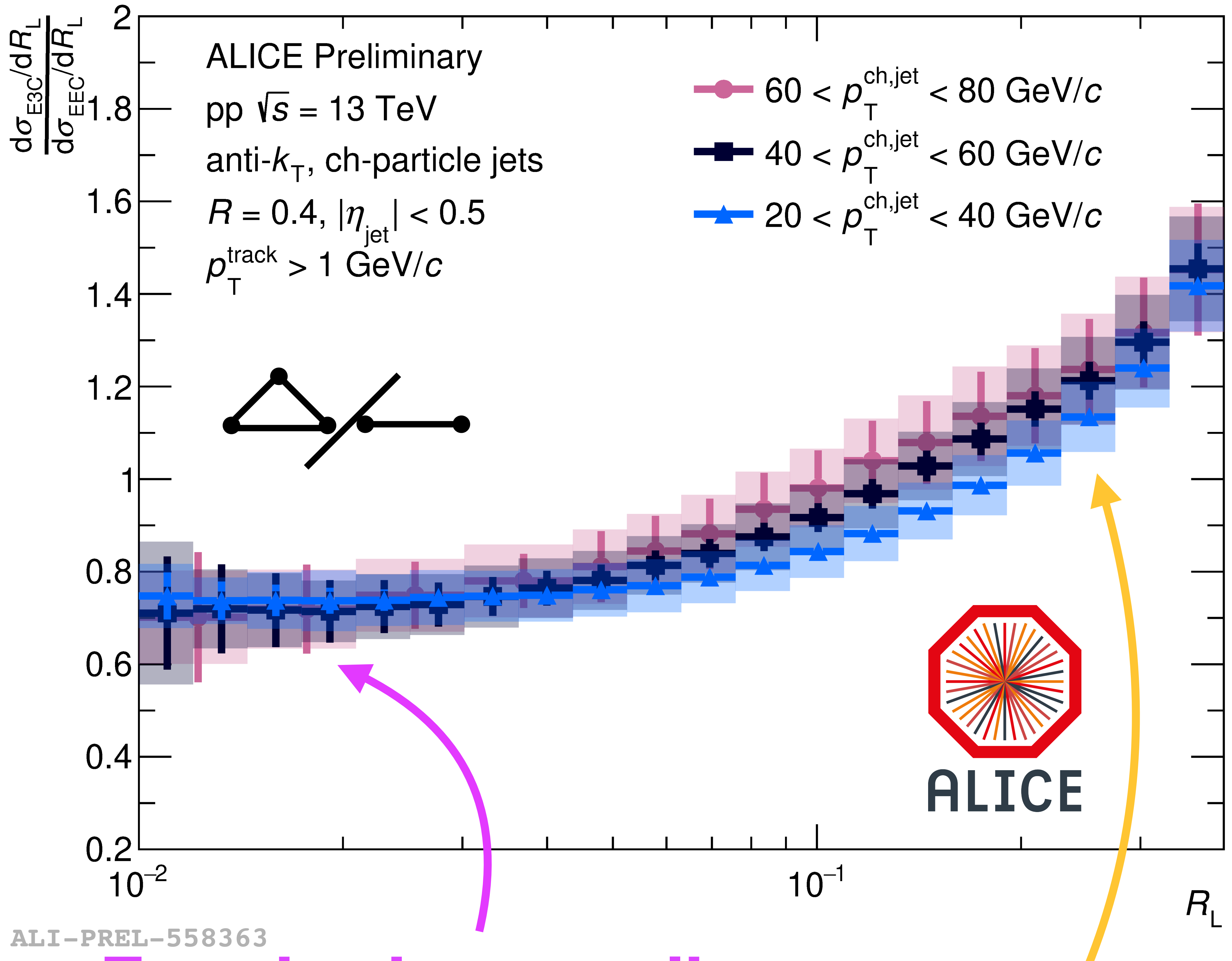
Higher point energy correlator: EEEC (E3C)/EEC (E2C)





arXiv: 2307.07510

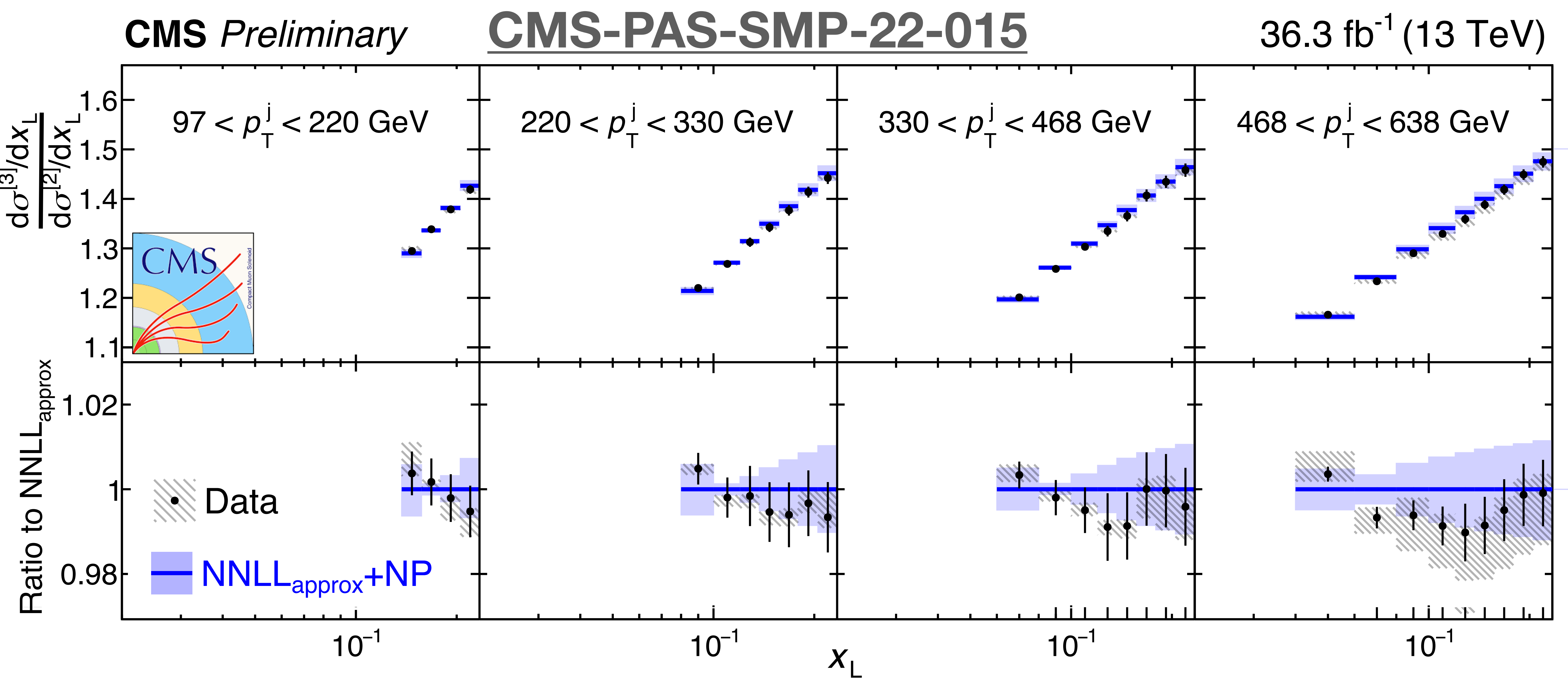
$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

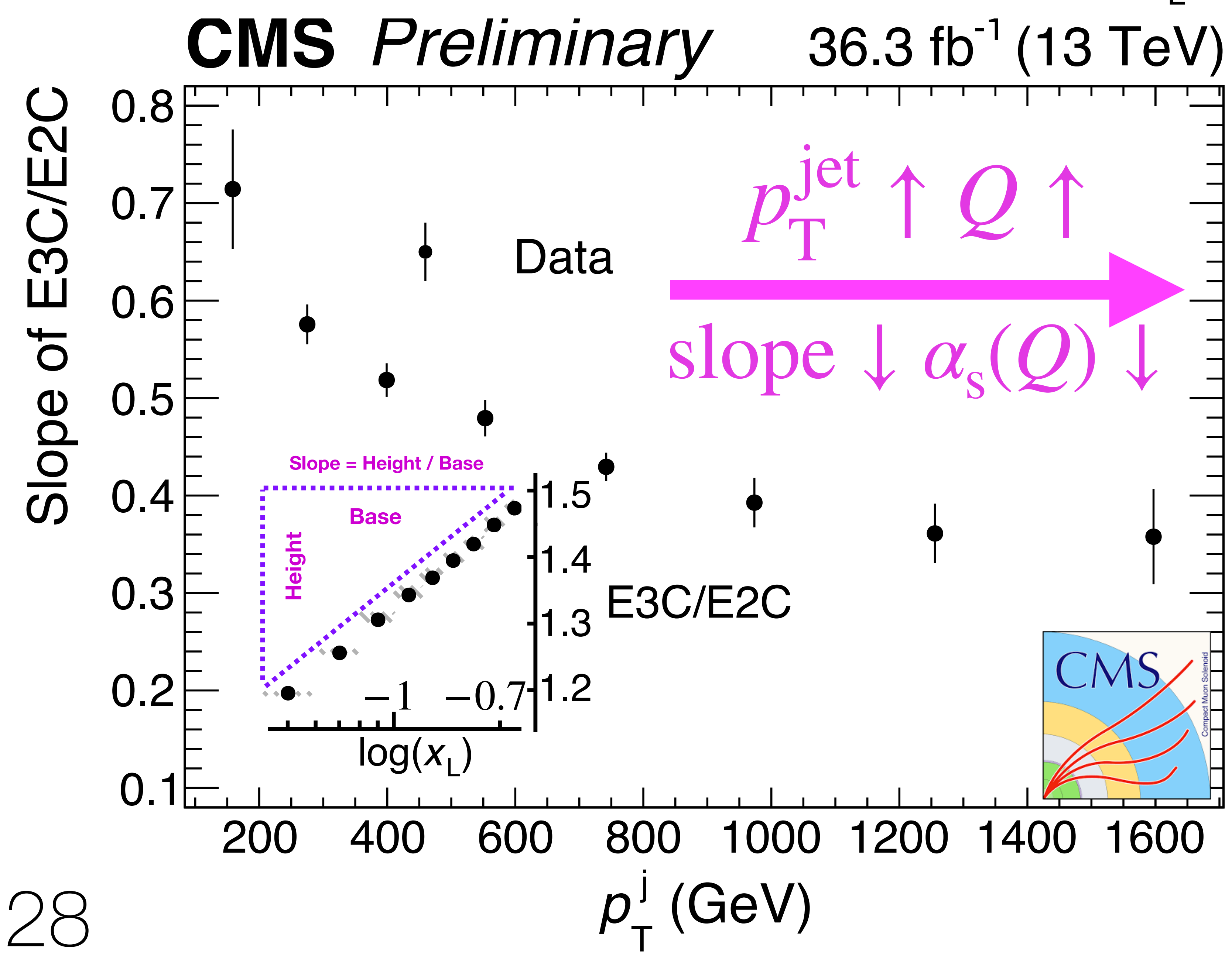


Free hadron scaling region: Flat

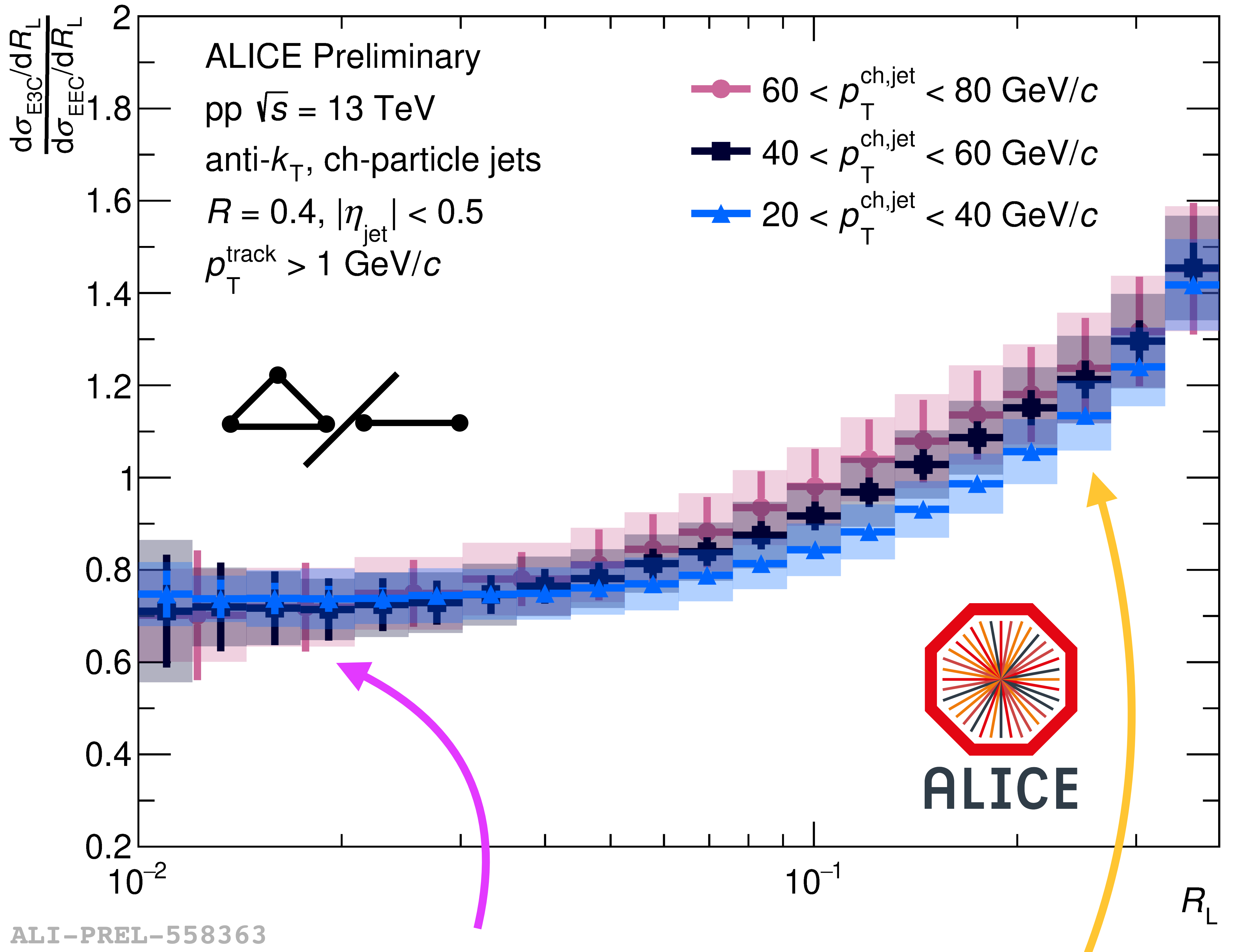
Perturbative region: slope sensitive to α_S

Higher point energy correlator: EEEC (E3C)/EEC (E2C)





arXiv: 2307.07510



Free hadron scaling region: Flat

$$\alpha_s(m_Z) = 0.1229^{+0.0040}_{-0.0050}$$

Highest precision constraint on α_s using jet substructure!

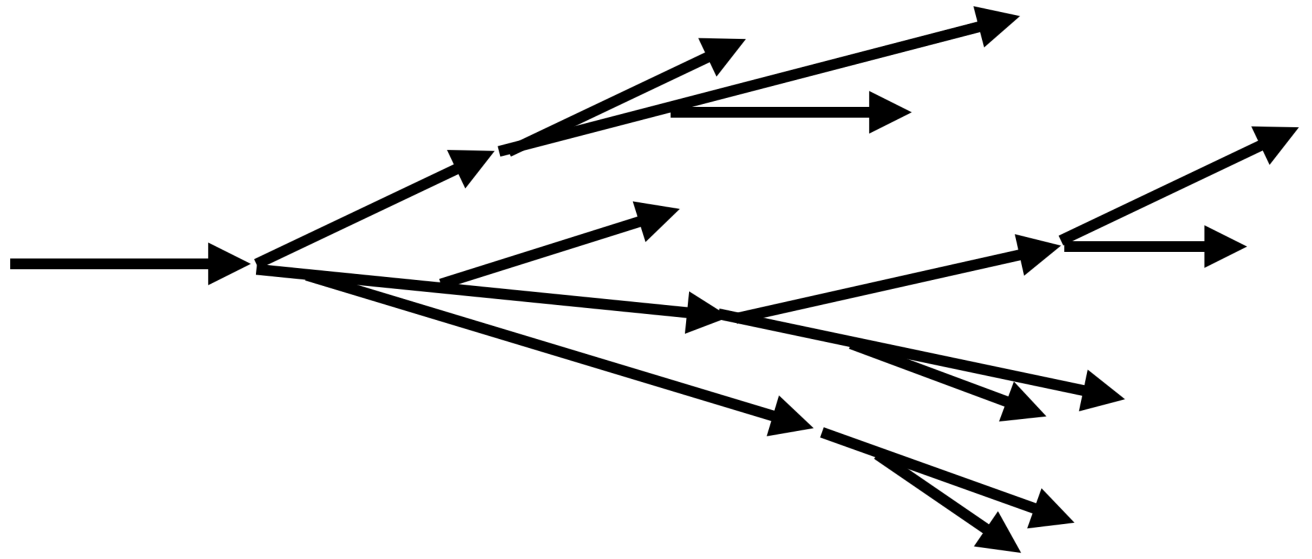
4

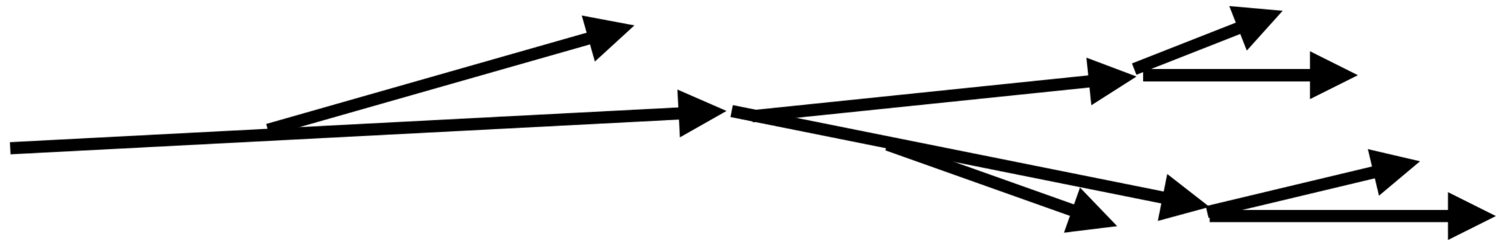
Perturbative region: slope sensitive to α_s

Flavor dependence in the QCD shower

Gluon-initiated shower

Quark-initiated shower





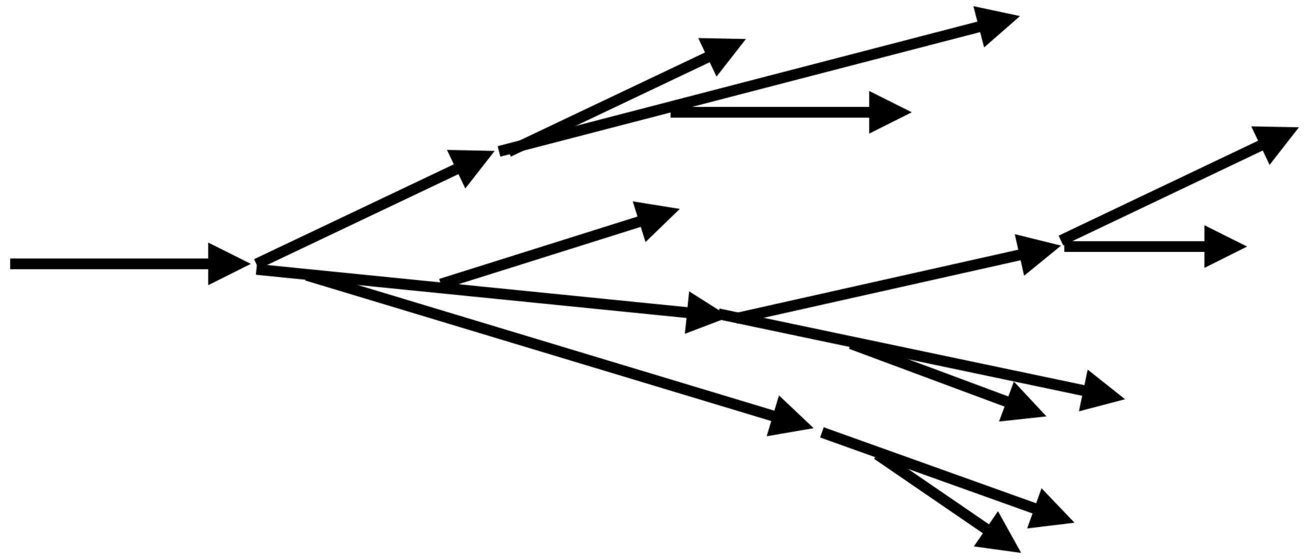
$$\frac{C_A}{C_F} = \frac{9}{4}$$

Casimir color factors

Gluon-initiated showers are expected to have a broader and softer fragmentation profile than quark-initiated showers

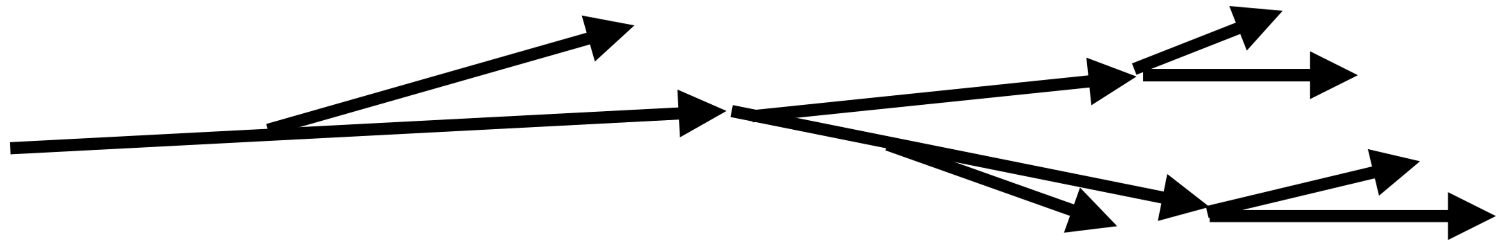
Flavor dependence in the QCD shower

Gluon-initiated shower

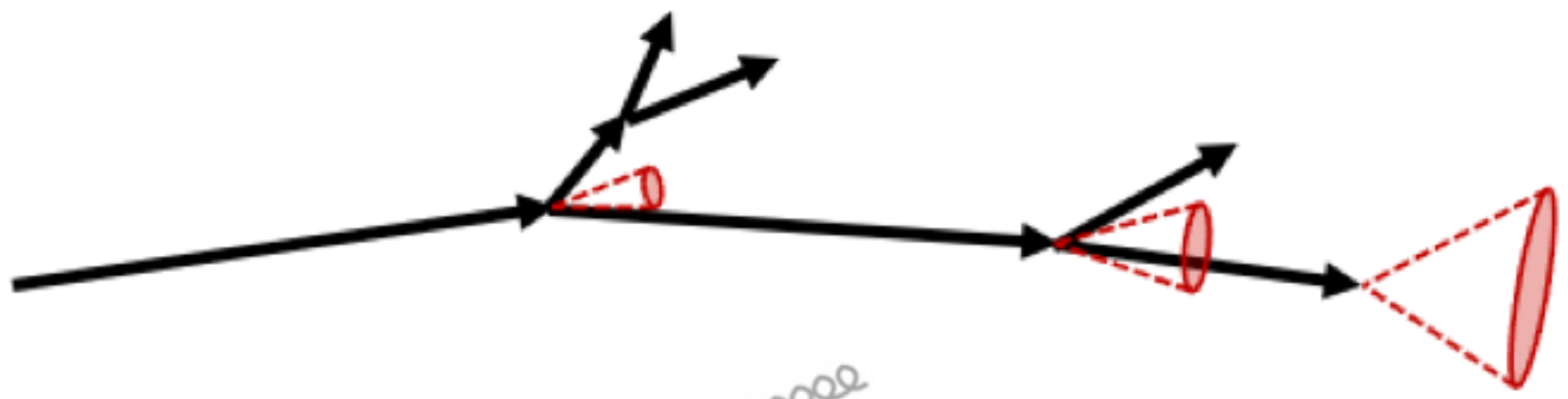


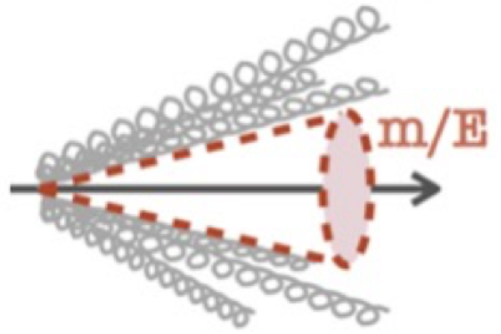
$$\frac{C_A}{C_F} = \frac{9}{4}$$

Quark-initiated shower



Heavy-quark-initiated shower





Casimir color factors

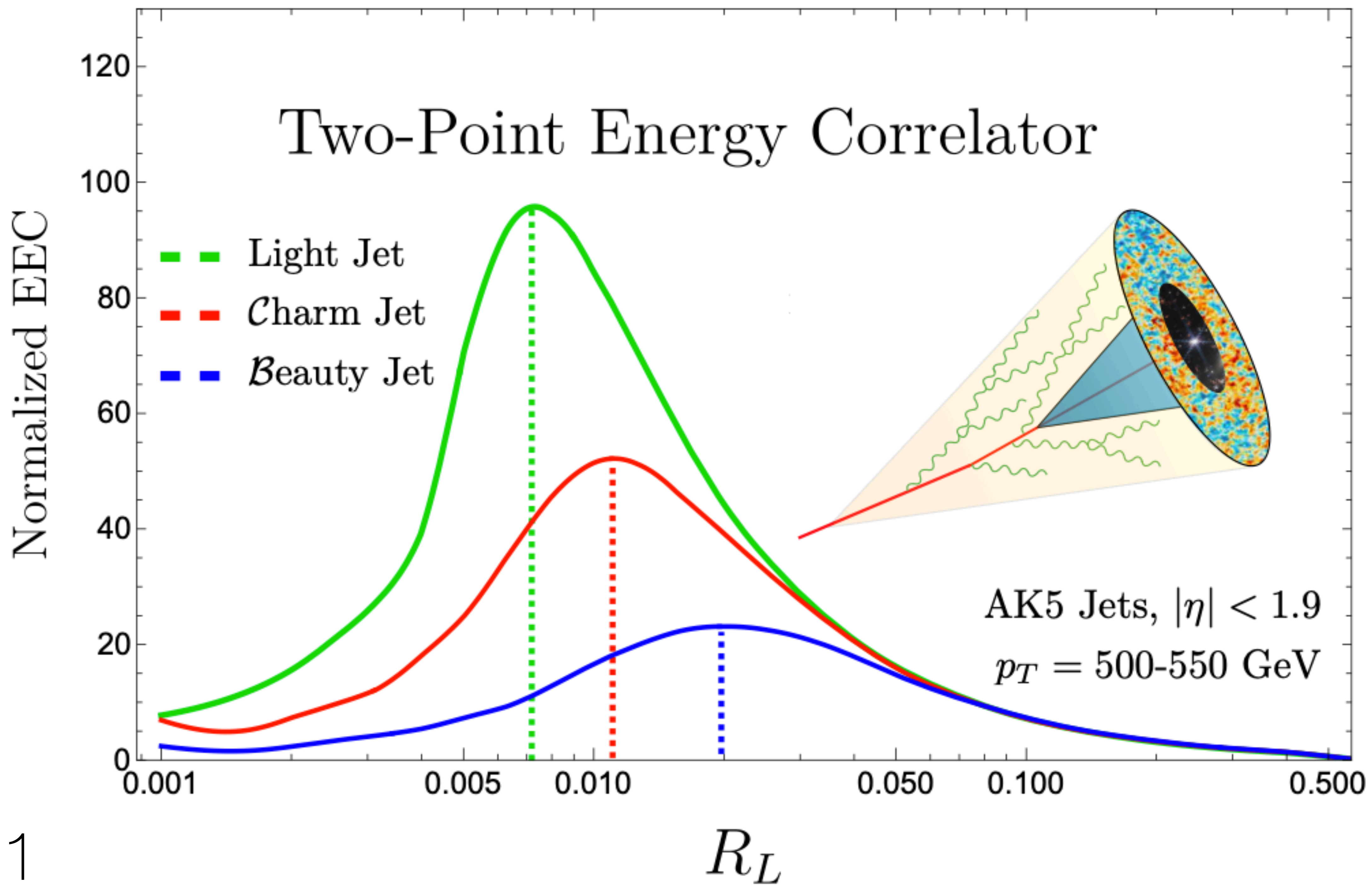
Gluon-initiated showers are expected to have a broader and softer fragmentation profile than quark-initiated showers

Mass effects

A harder fragmentation is expected in low energy heavy-quark initiated showers due to the presence of a dead cone

Heavy-flavor jet EECs

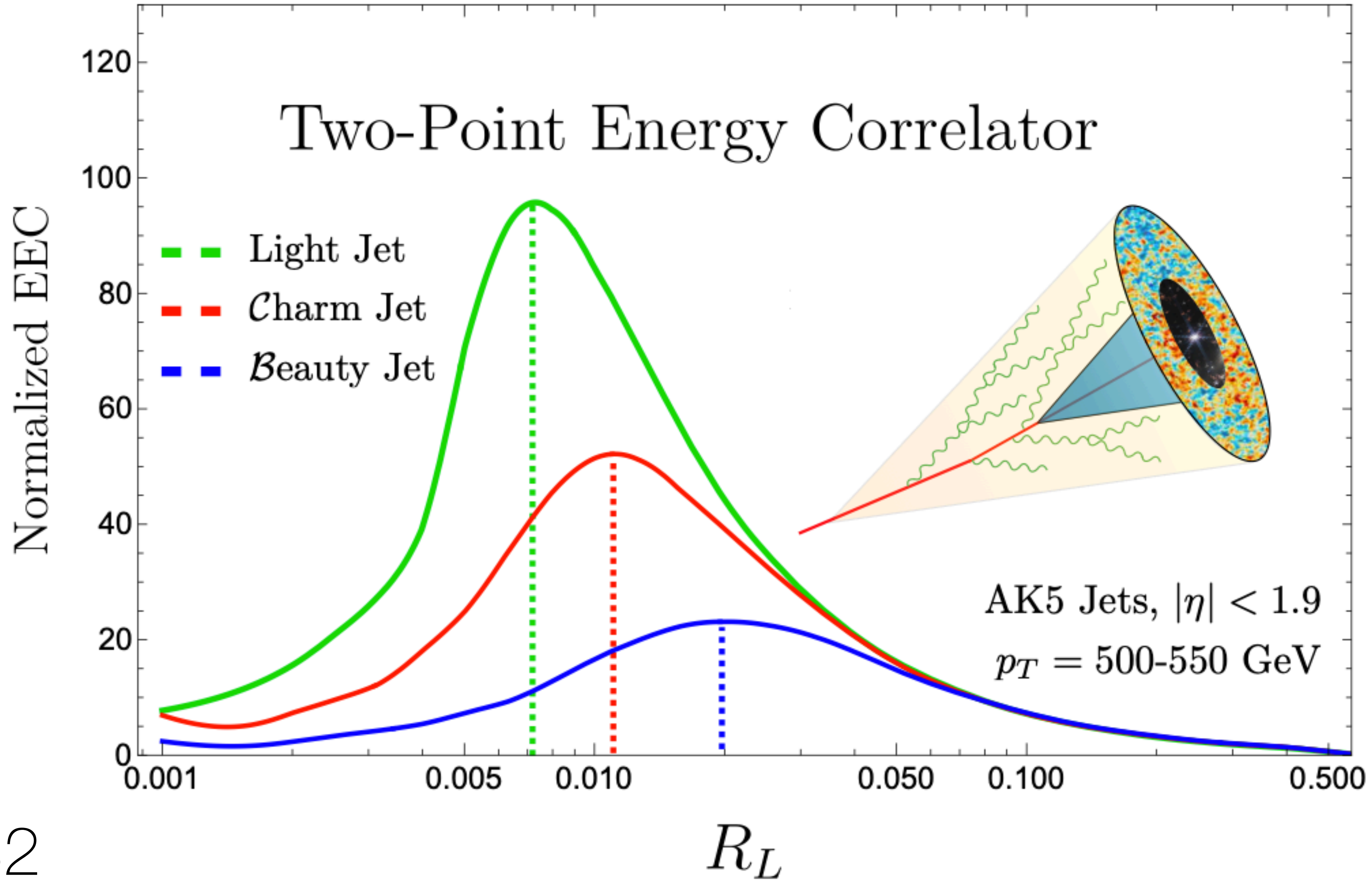
arXiv: 2210.09311



Heavy-flavor jet EECs

- Small angle correlation suppressed for heavy-quark initiated jet (beauty < charm < light)
- Transition region shifted to larger R_L due to mass

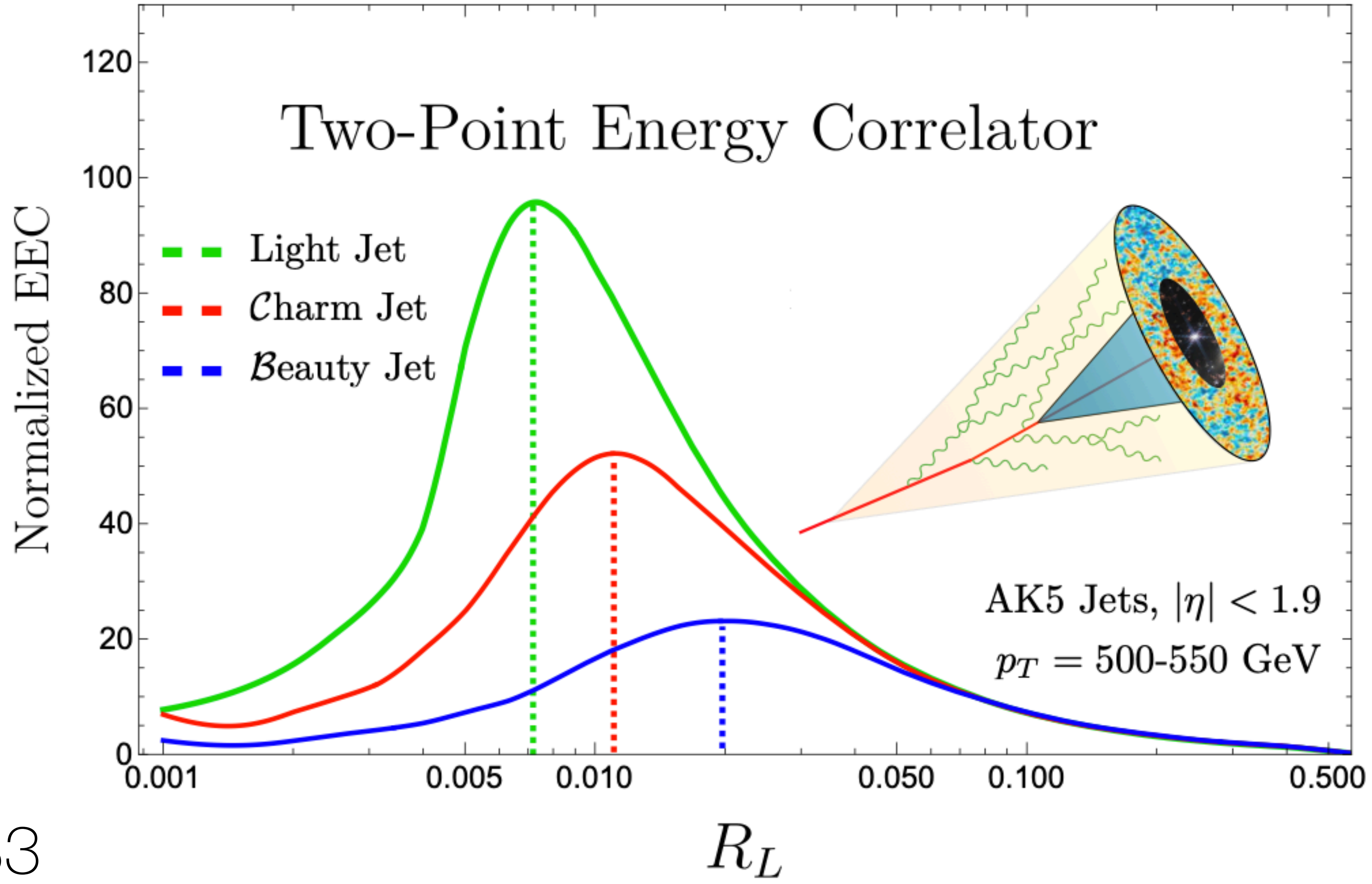
arXiv: 2210.09311



Heavy-flavor jet EECs

- Small angle correlation suppressed for heavy-quark initiated jet (beauty < charm < light)
- Transition region shifted to larger R_L due to mass

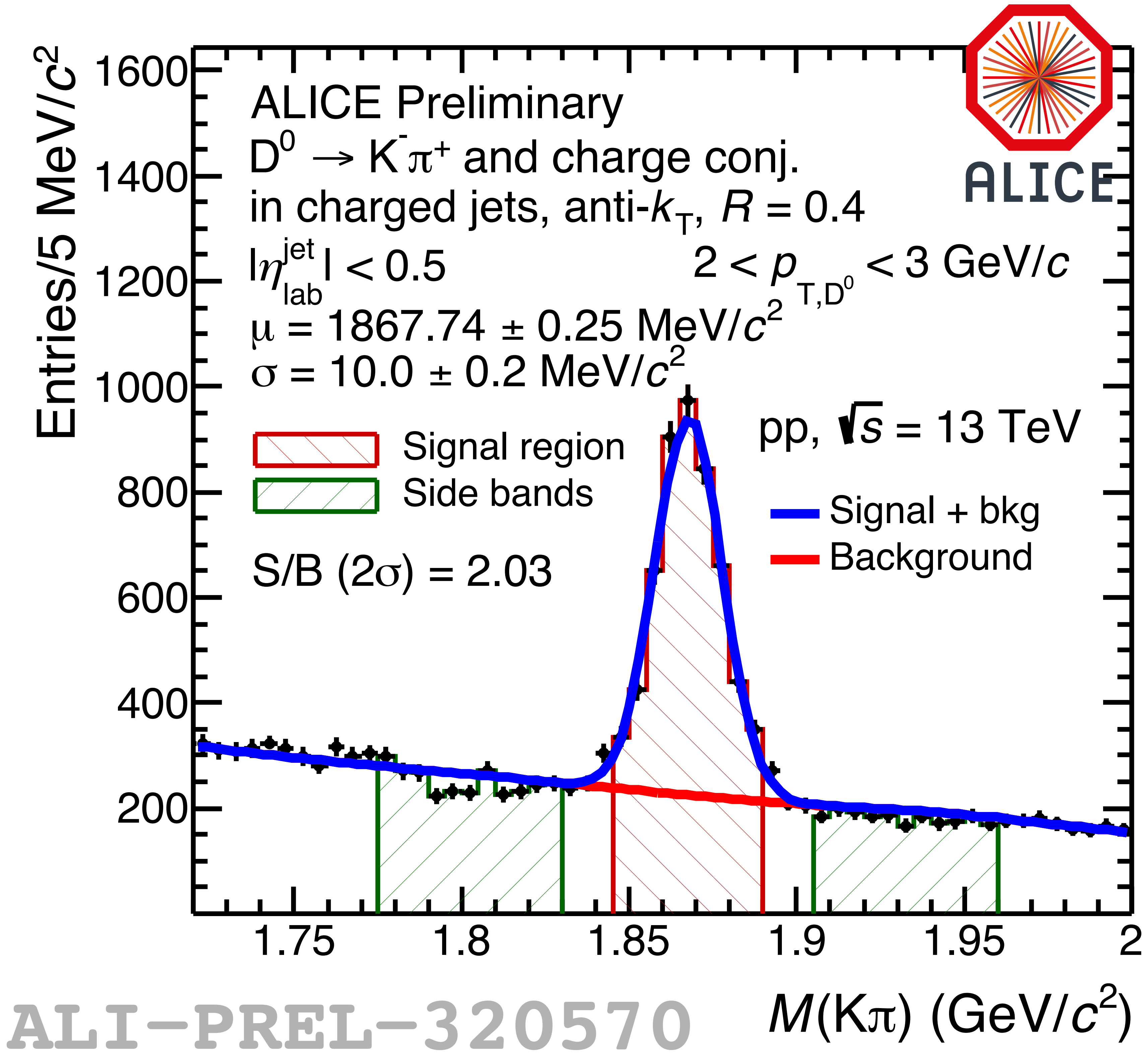
arXiv: 2210.09311

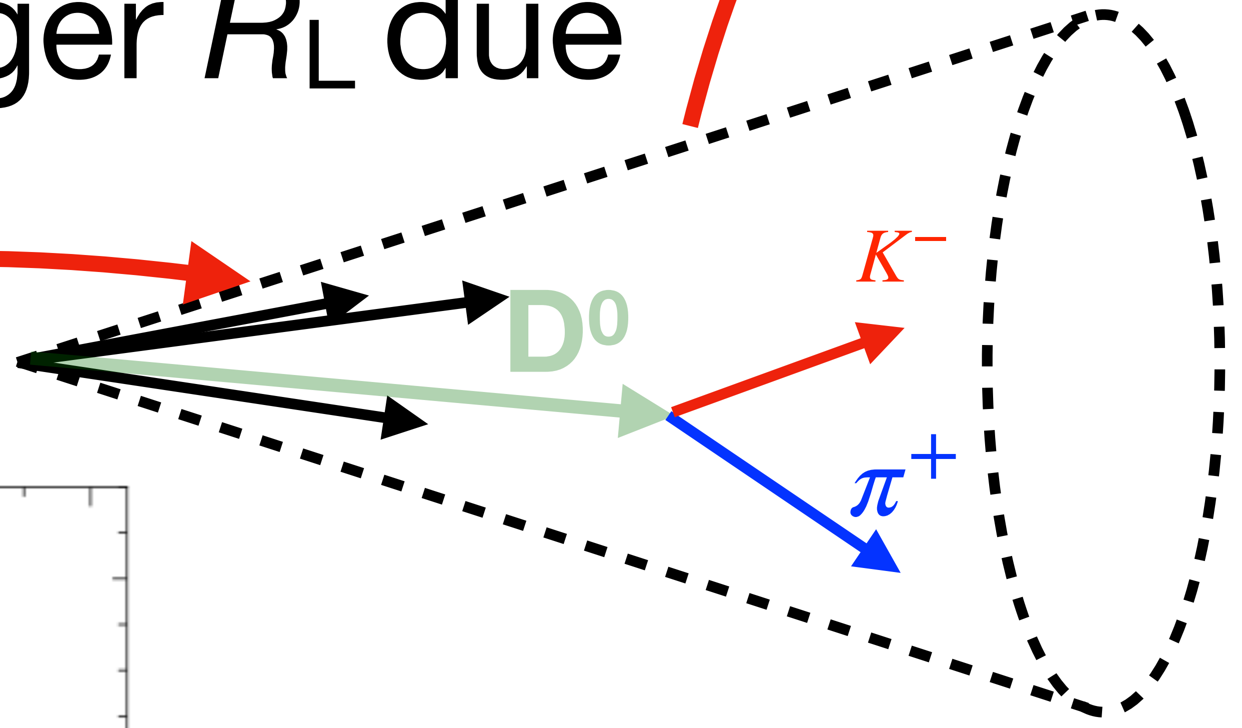


Unique opportunities with ALICE due to the excellent PID + vertexing

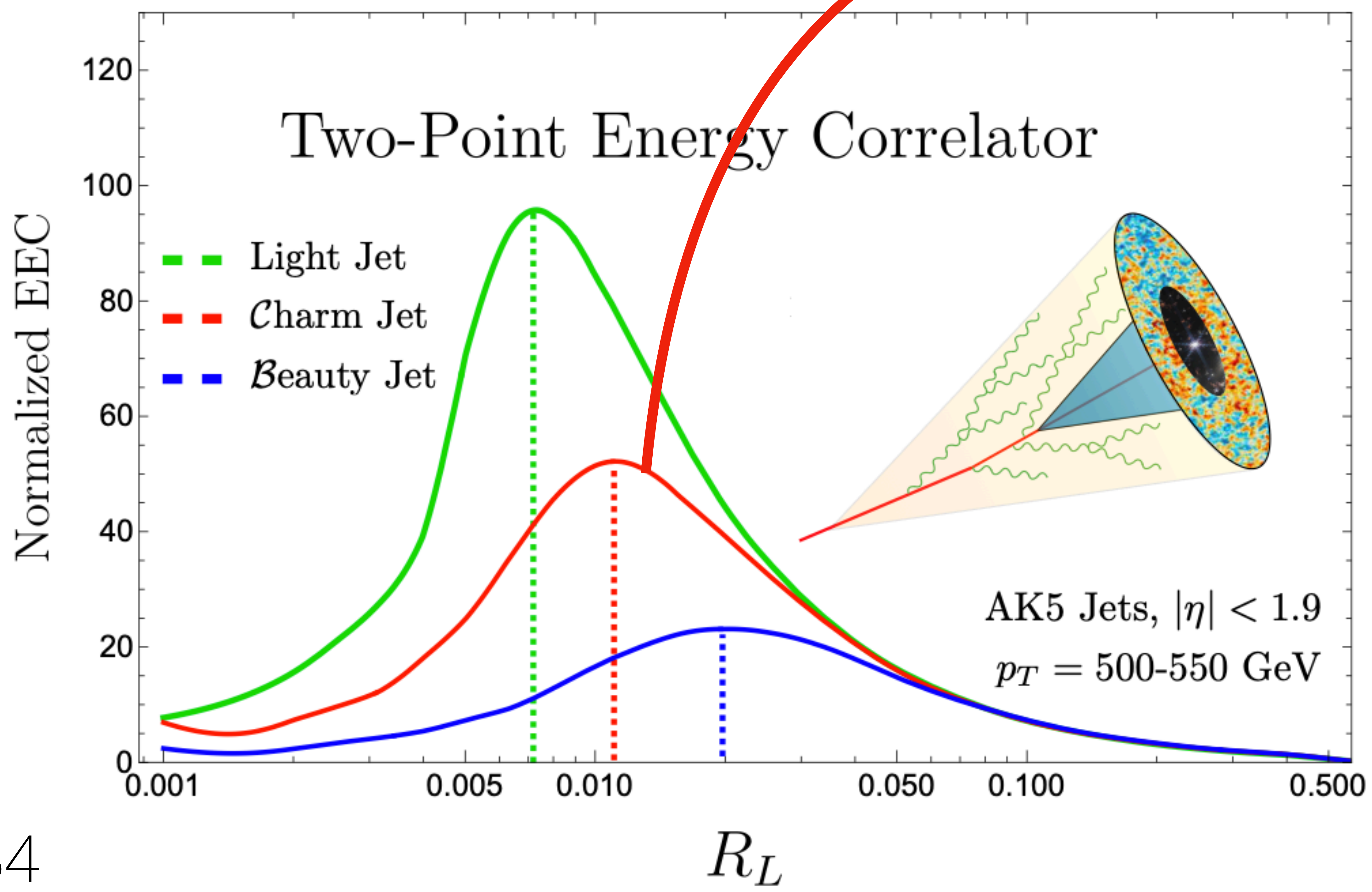
Heavy-flavor jet EECs

- Small angle correlation suppressed for heavy-quark initiated jet (beauty < charm < light)
- Transition region shifted to larger R_L due to mass





arXiv: 2210.09311



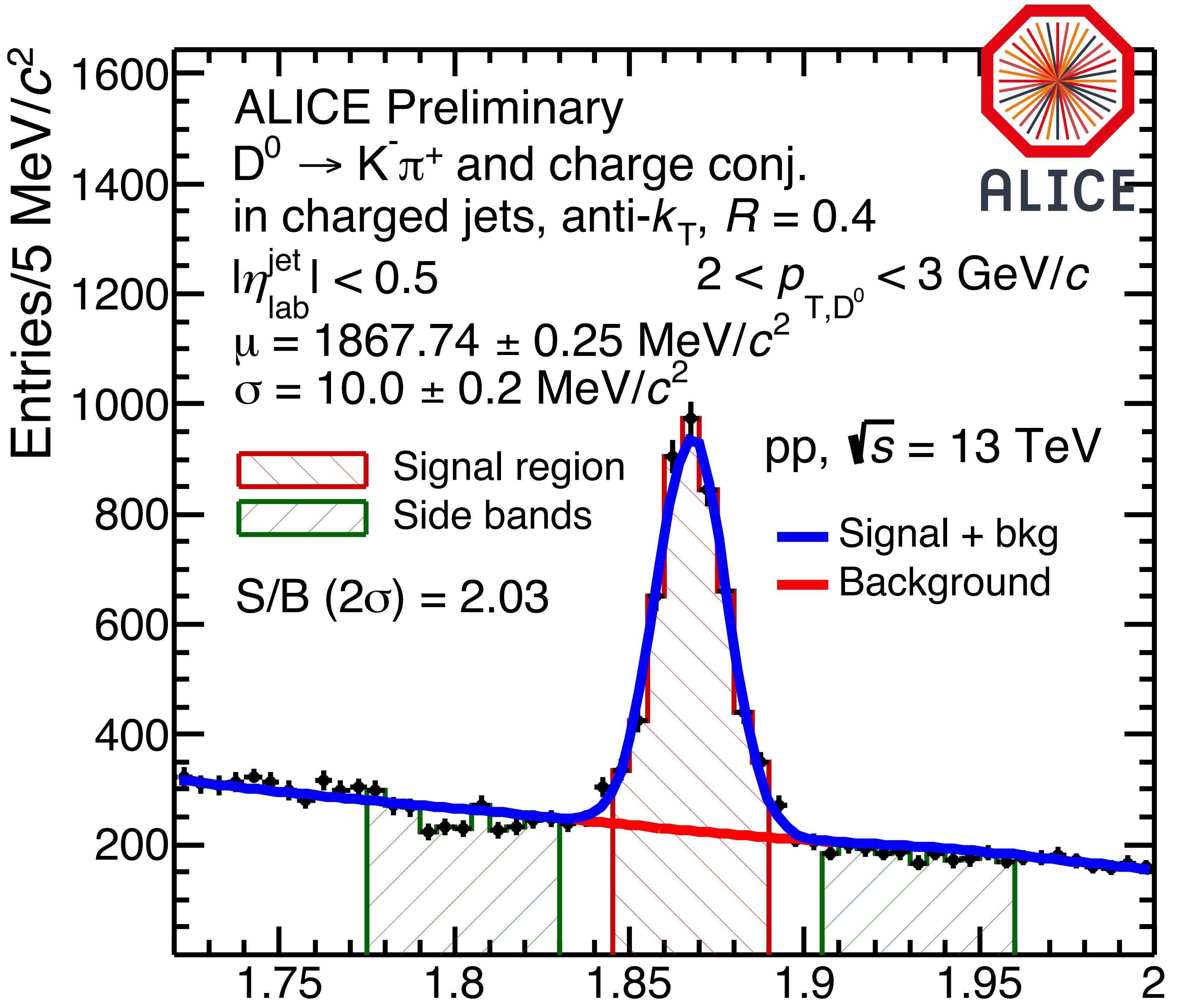
Unique opportunities with ALICE due to the excellent PID + vertexing

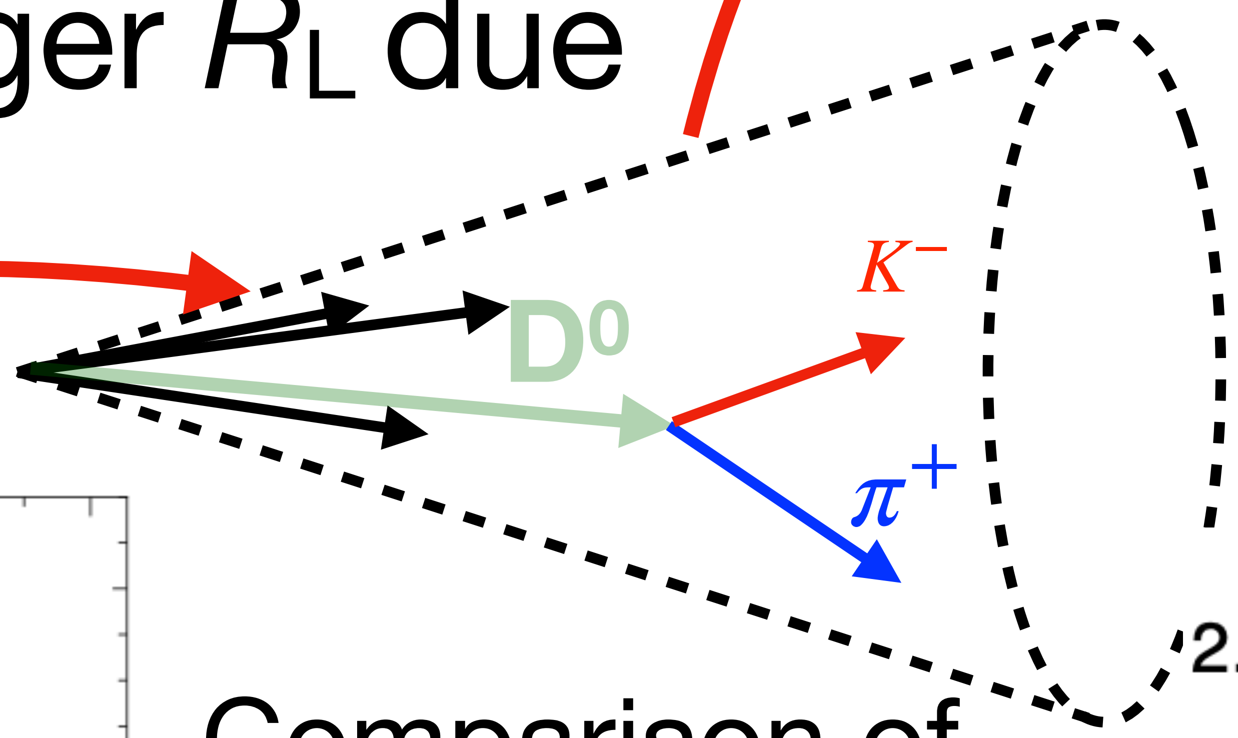
charm jet: tag heavy flavor jet with fully reconstructed charm heavy flavor hadron

Heavy-flavor jet EECs

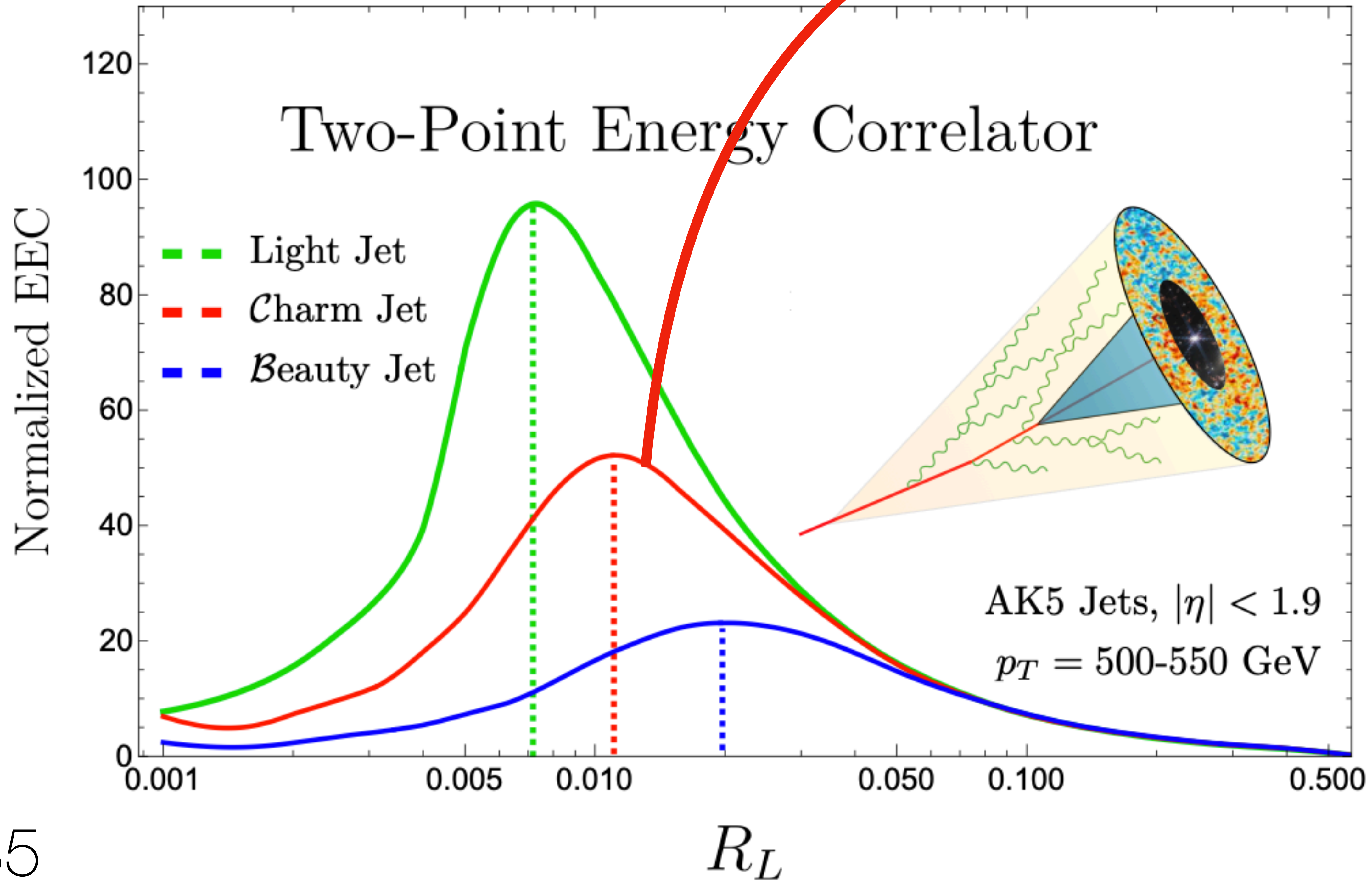
5

- Small angle correlation suppressed for heavy-quark initiated jet (beauty < charm < light)
- Transition region shifted to larger R_L due to mass



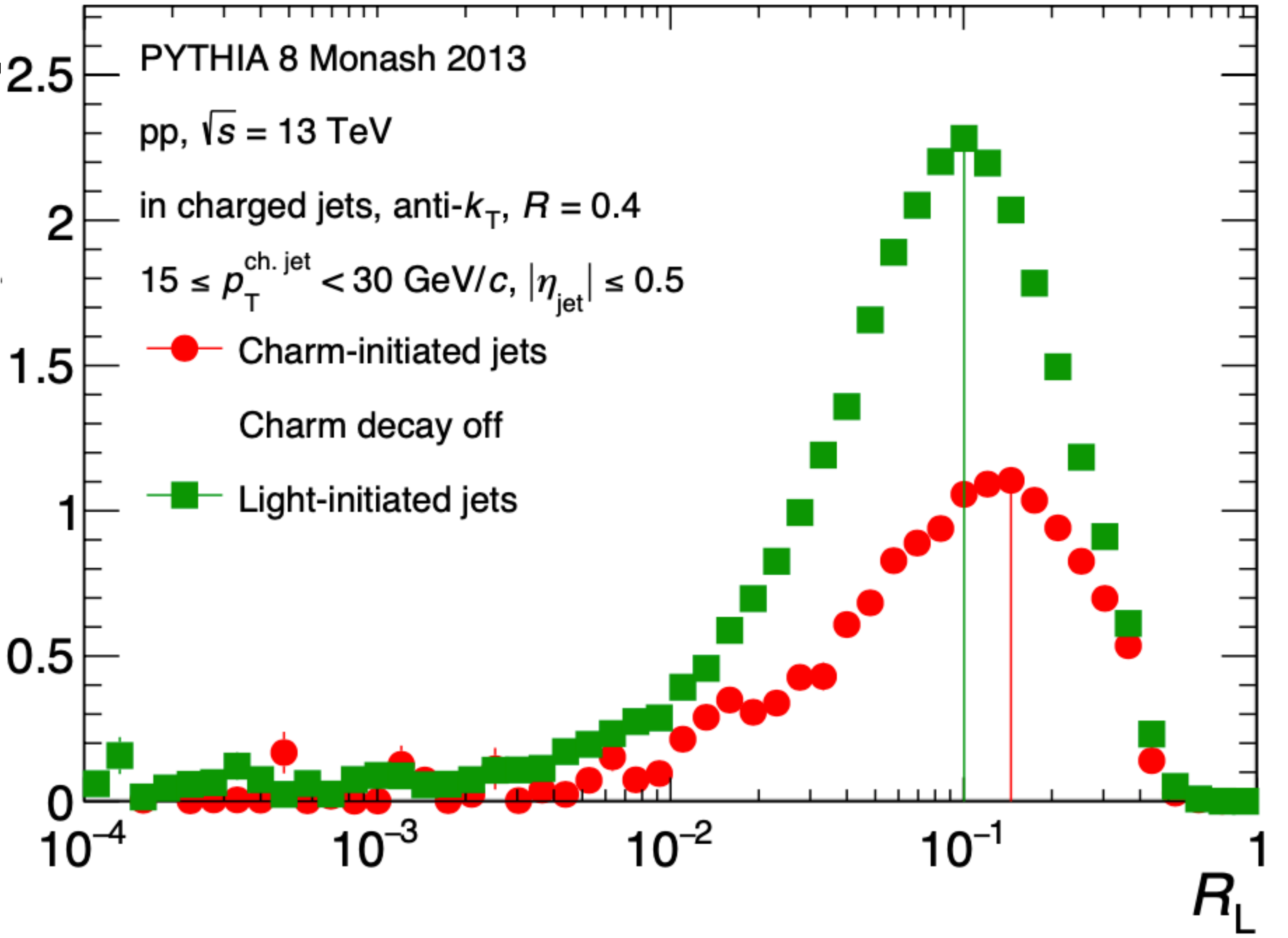


arXiv: 2210.09311

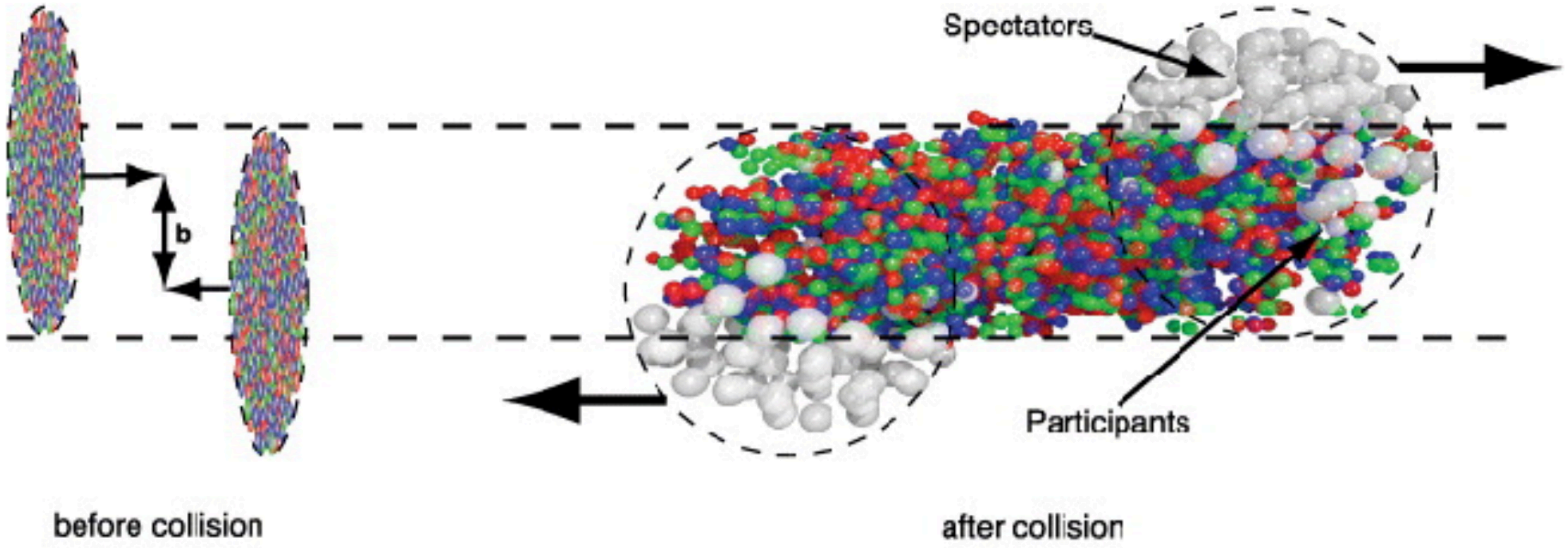


Comparison of Inclusive jet (gluon dominated) and HF jet at very low jet p_T.

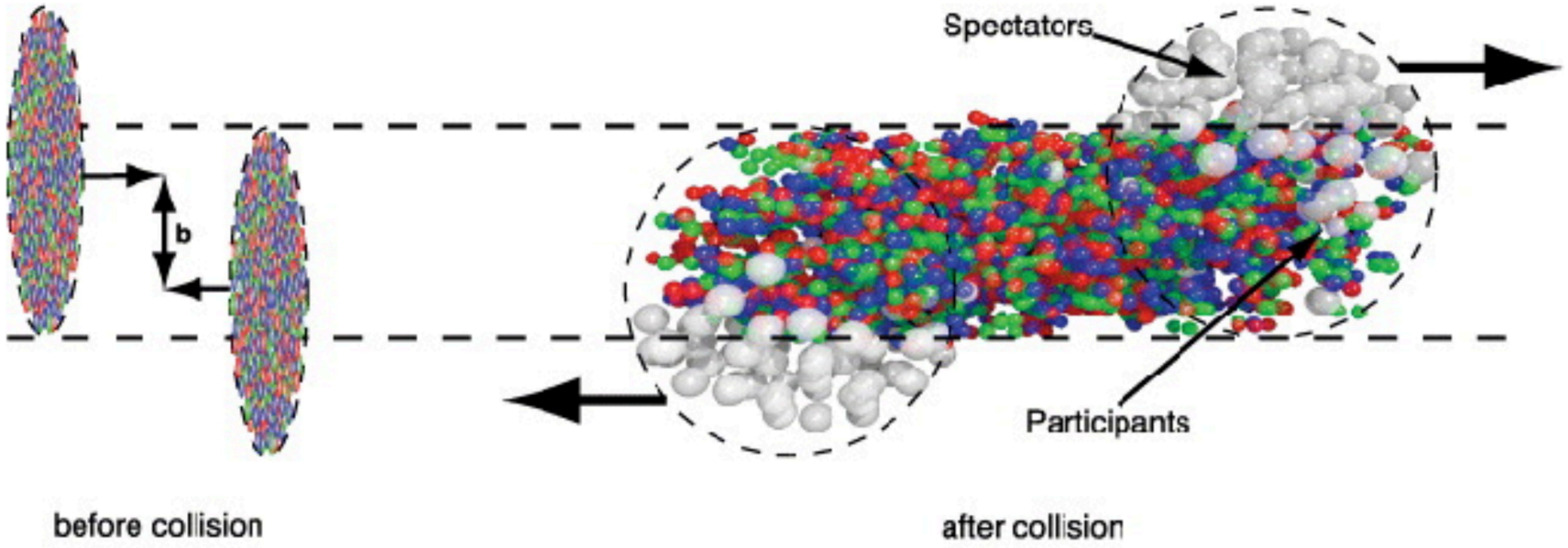
aiming for Hard Probes 2024!

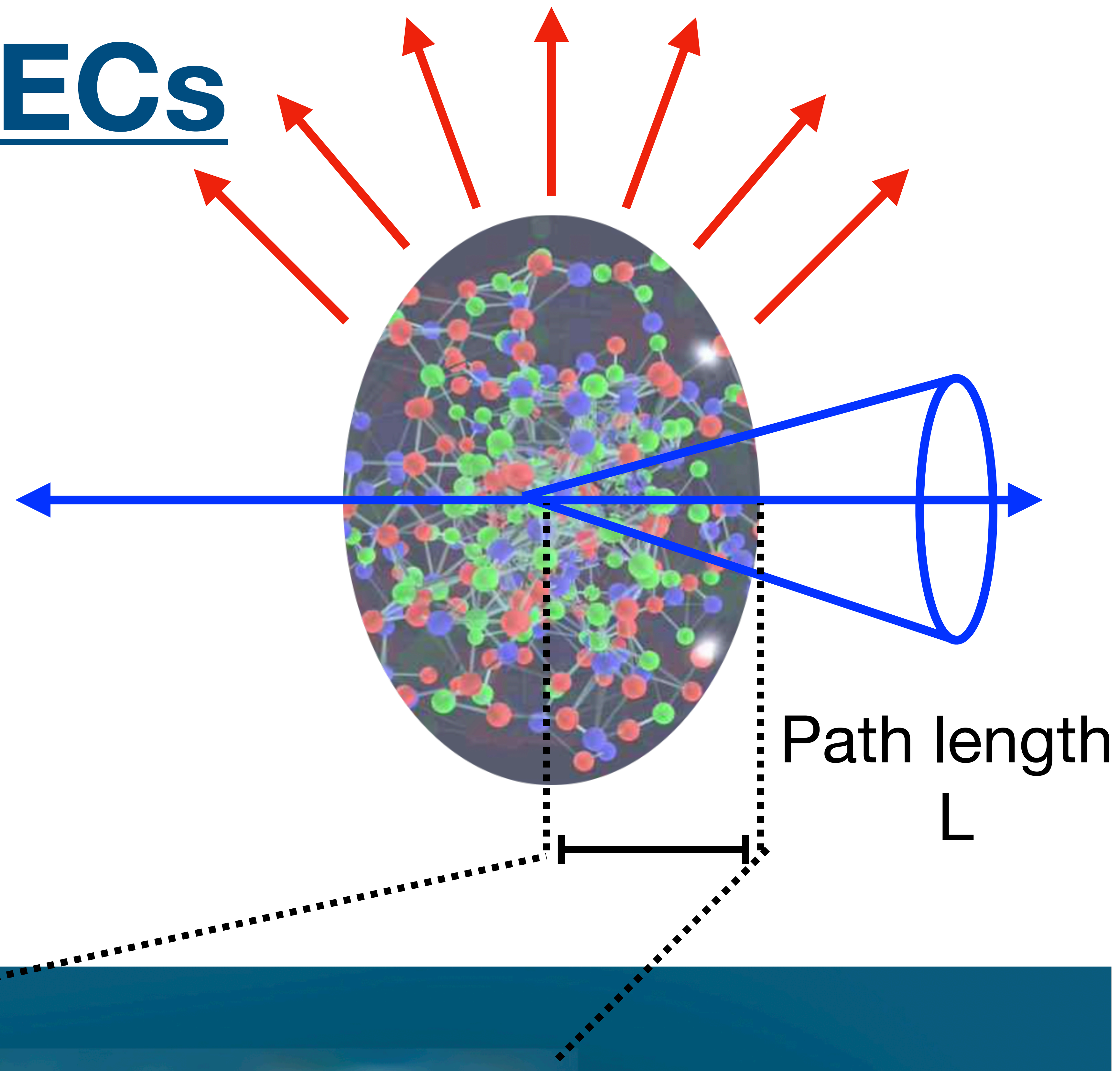


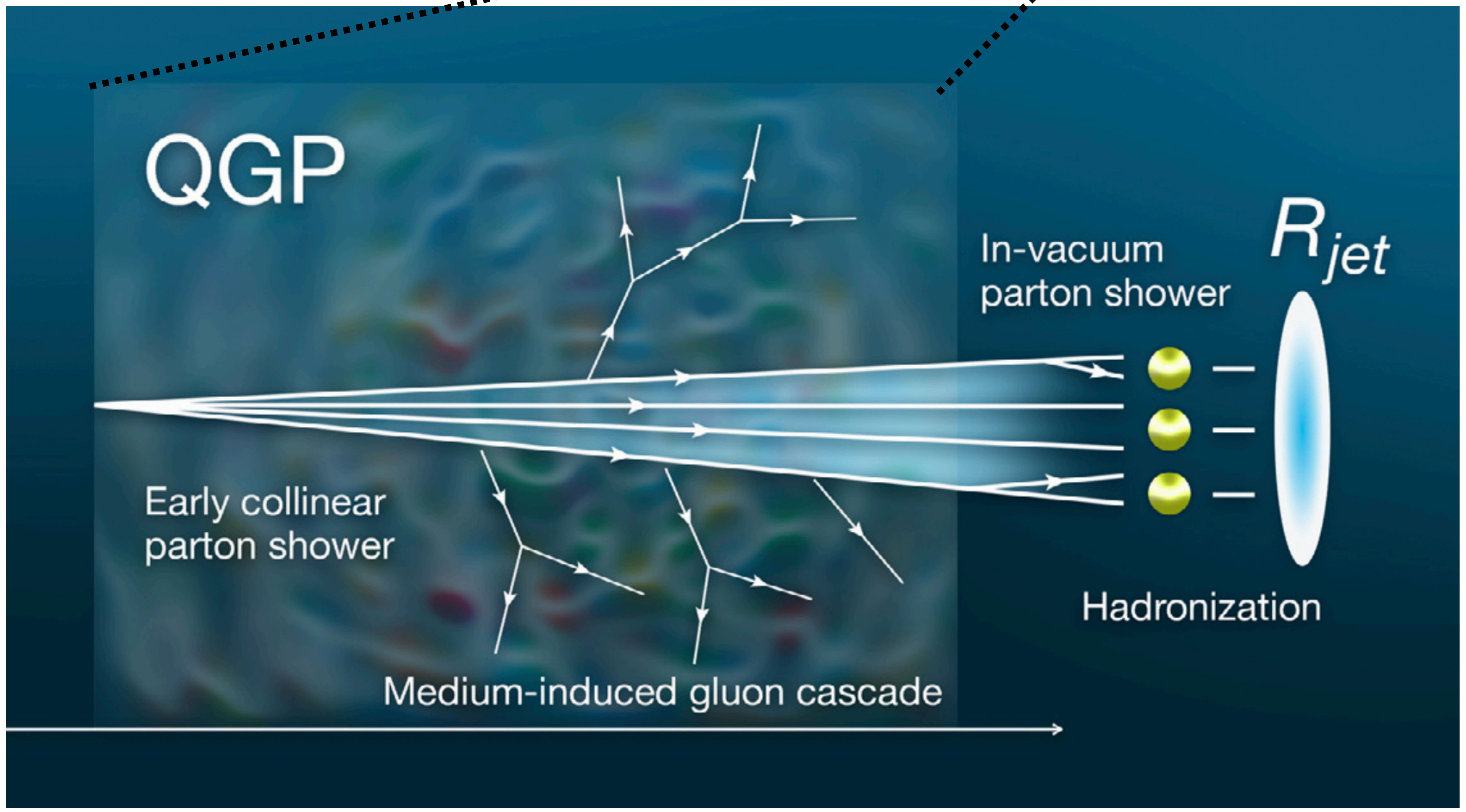
Exploring quark-gluon plasma with EECs



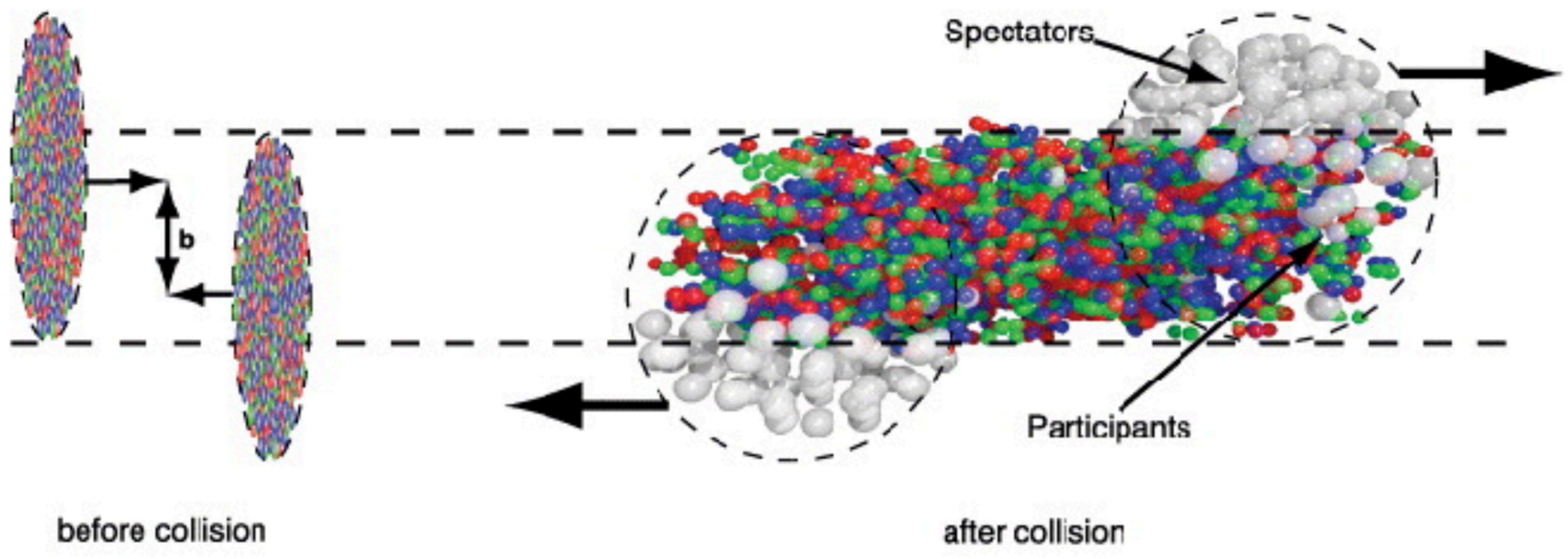
Exploring quark-gluon plasma with EECs

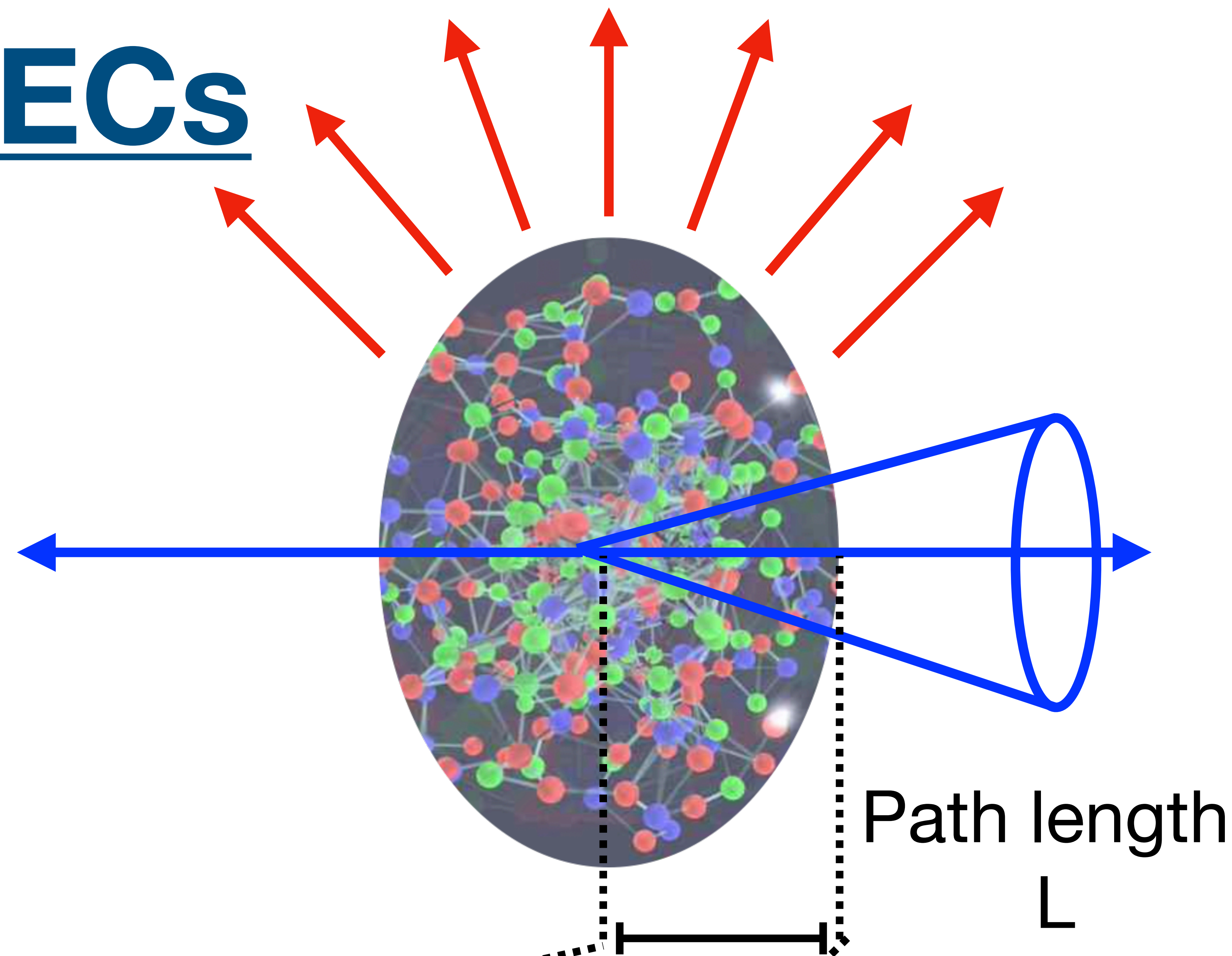






Exploring quark-gluon plasma with EECs

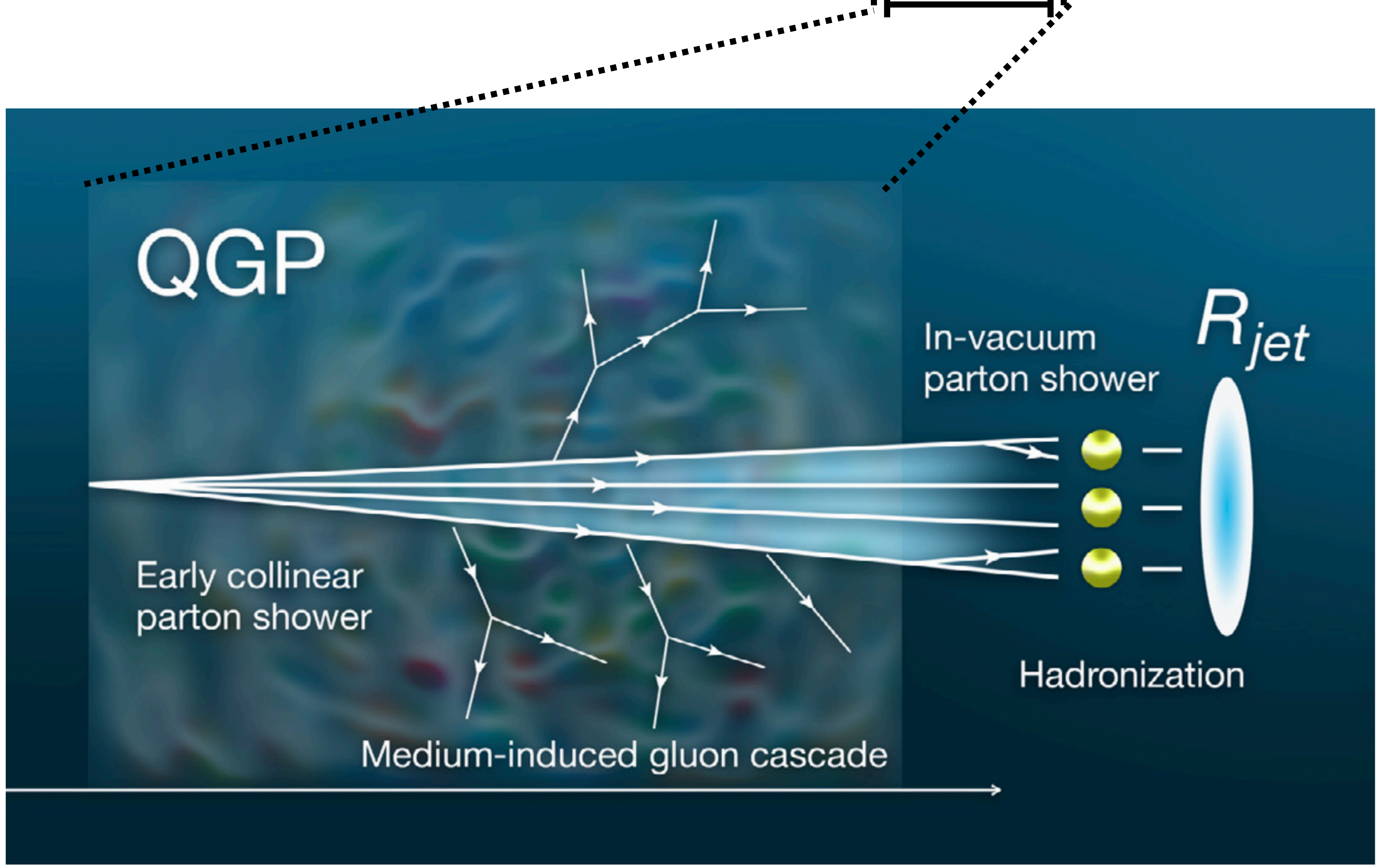




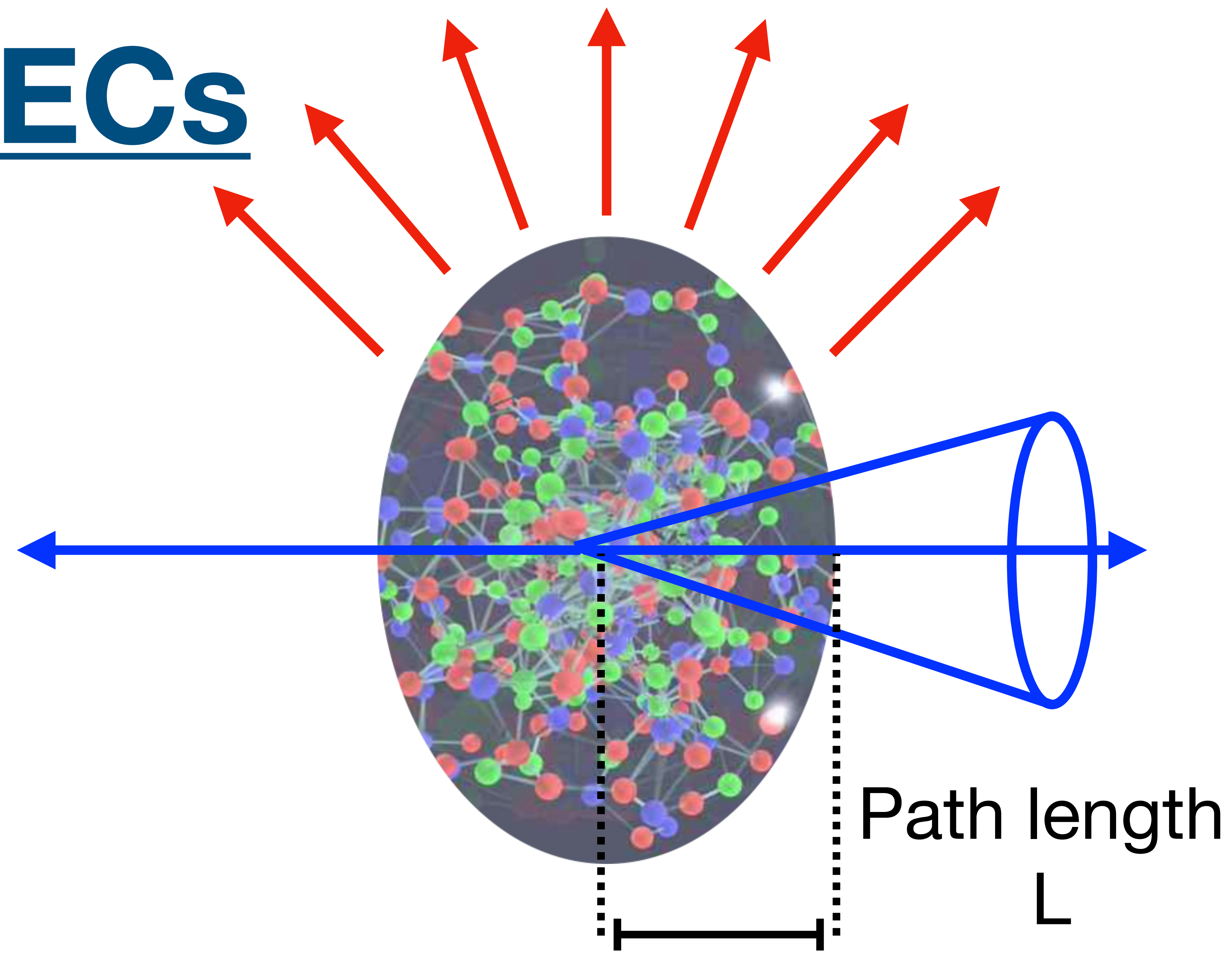
Partons traversing through QGP:

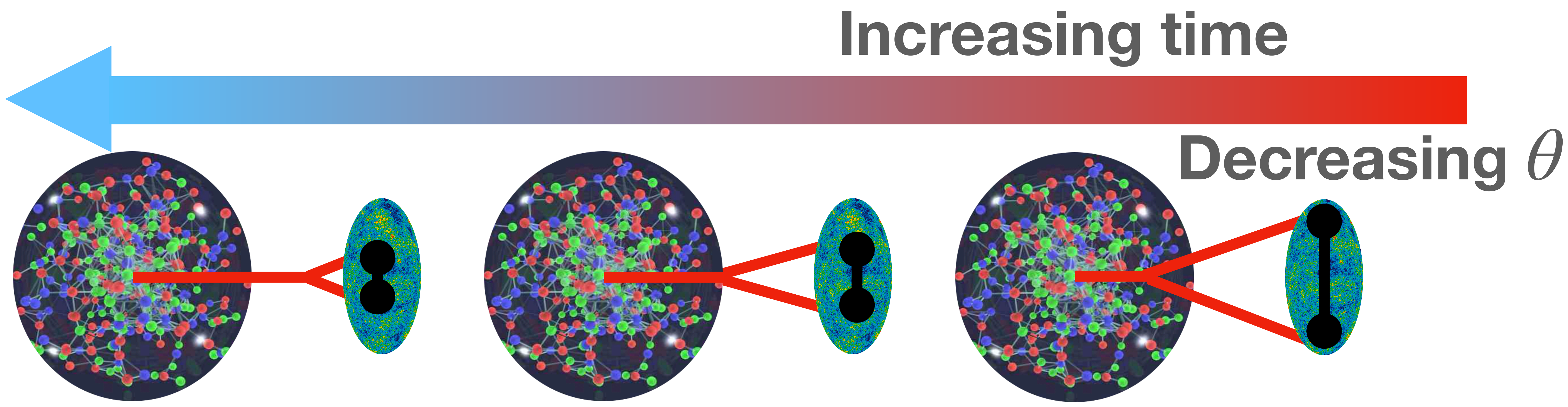
- How does parton loses energy?
- How does energy redistribution happen?
- Role of parton color charge and mass?
- What's the path-length dependence?
- …

Then find out about QGP: medium properties, transport coefficient …

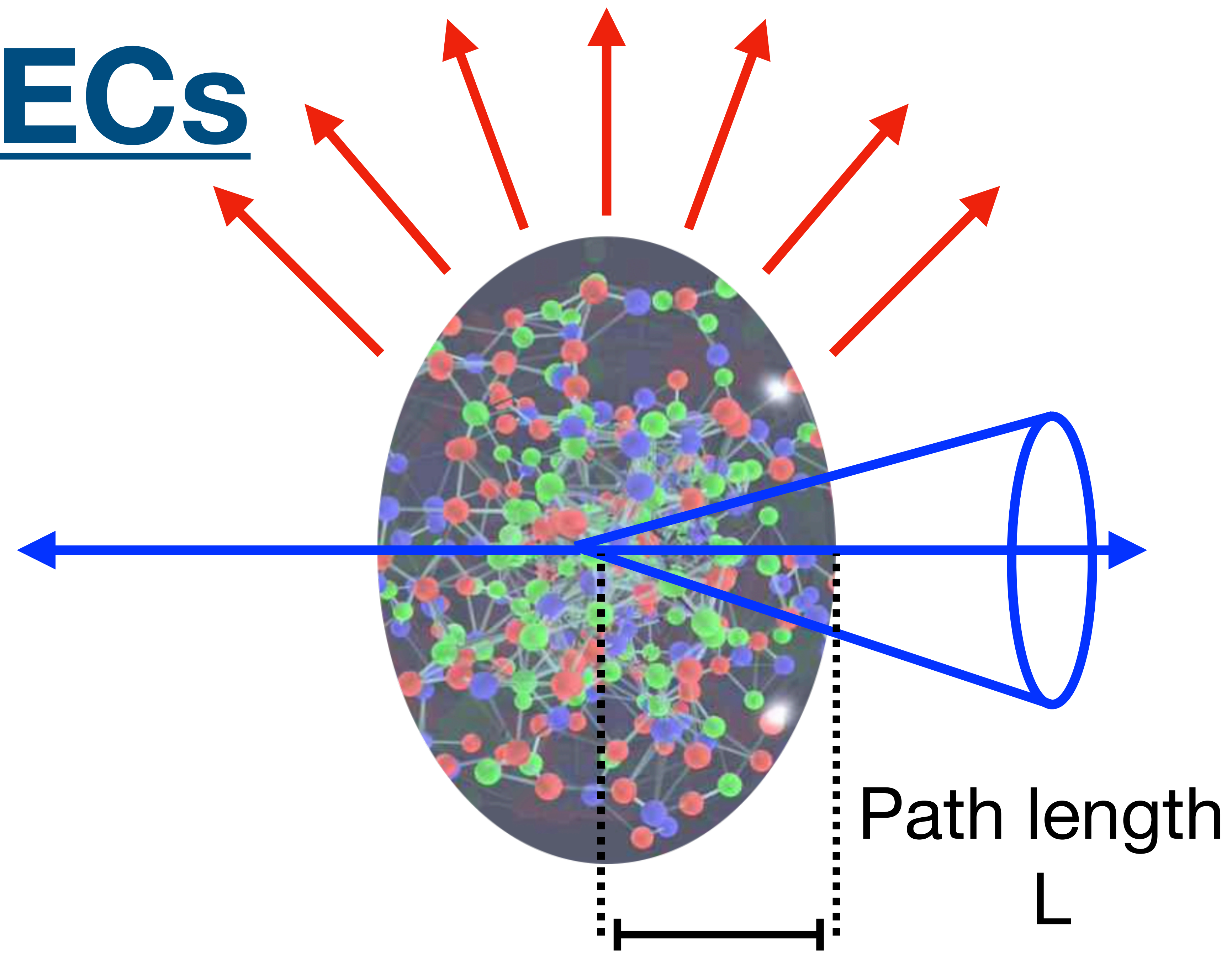


Exploring quark-gluon plasma with EECs





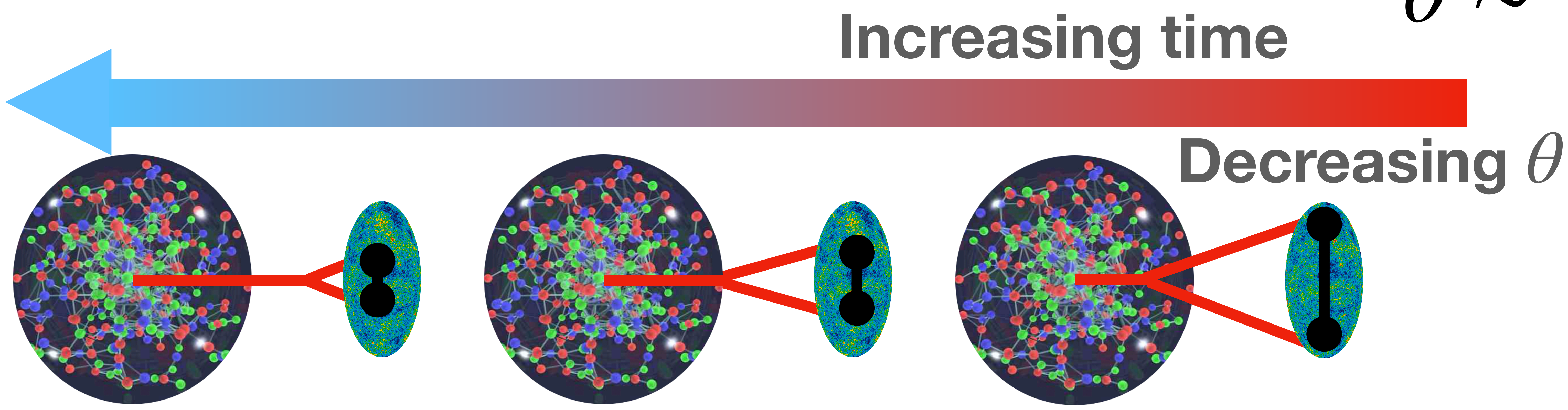
Exploring quark-gluon plasma with EECs



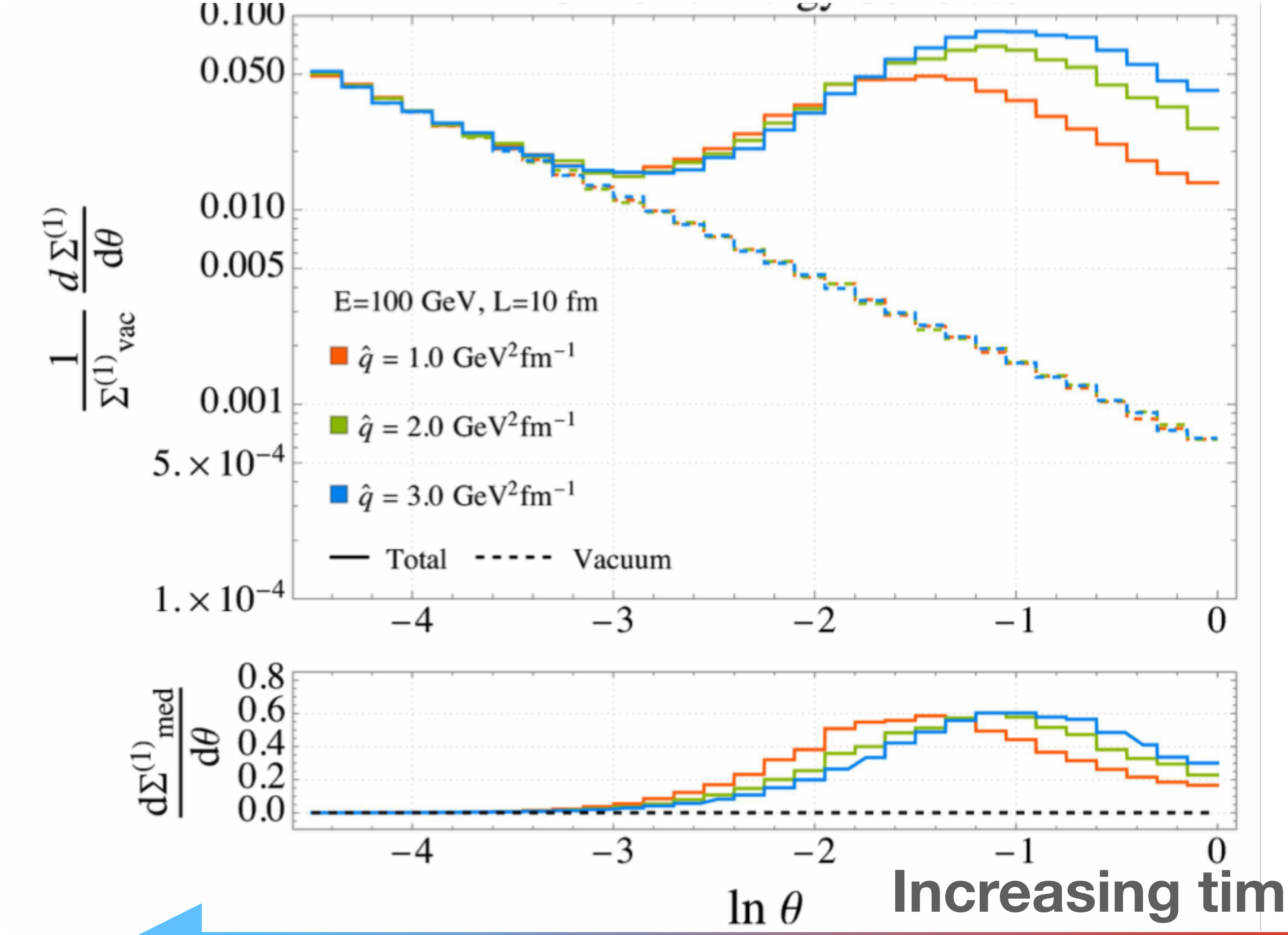
QGP introduces new scale: θ_{L}

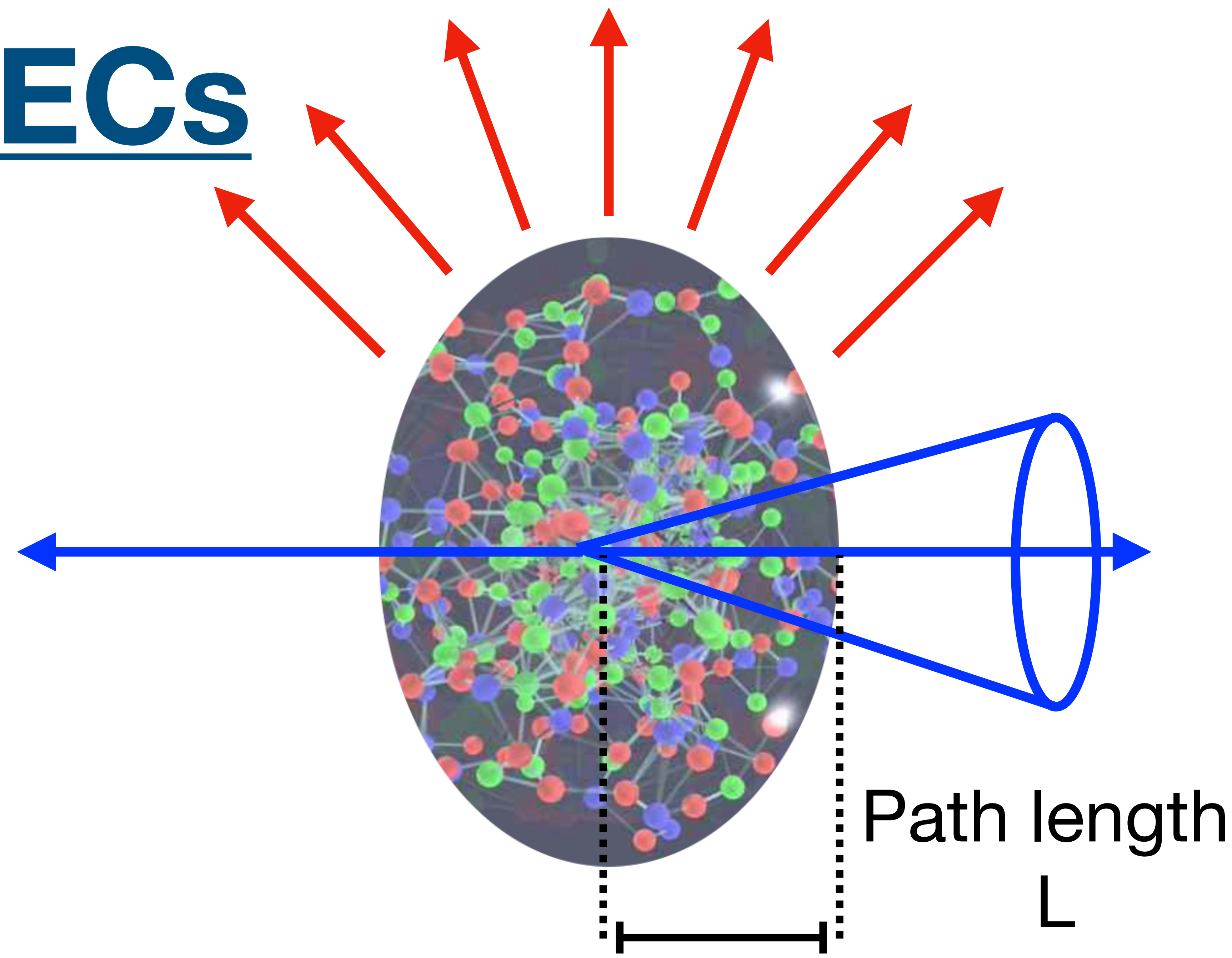
Splitting time: $\tau \sim 1/p_{\mathrm{T}}\theta^2$

$\theta \sim 1/\sqrt{\mathrm{L}}$



Exploring quark-gluon plasma with EECs

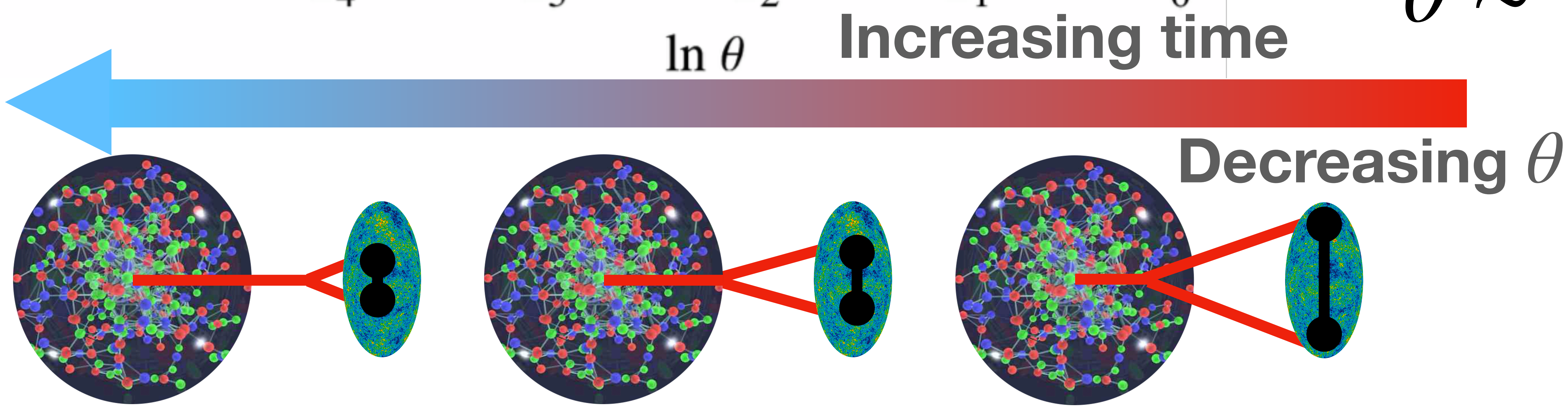




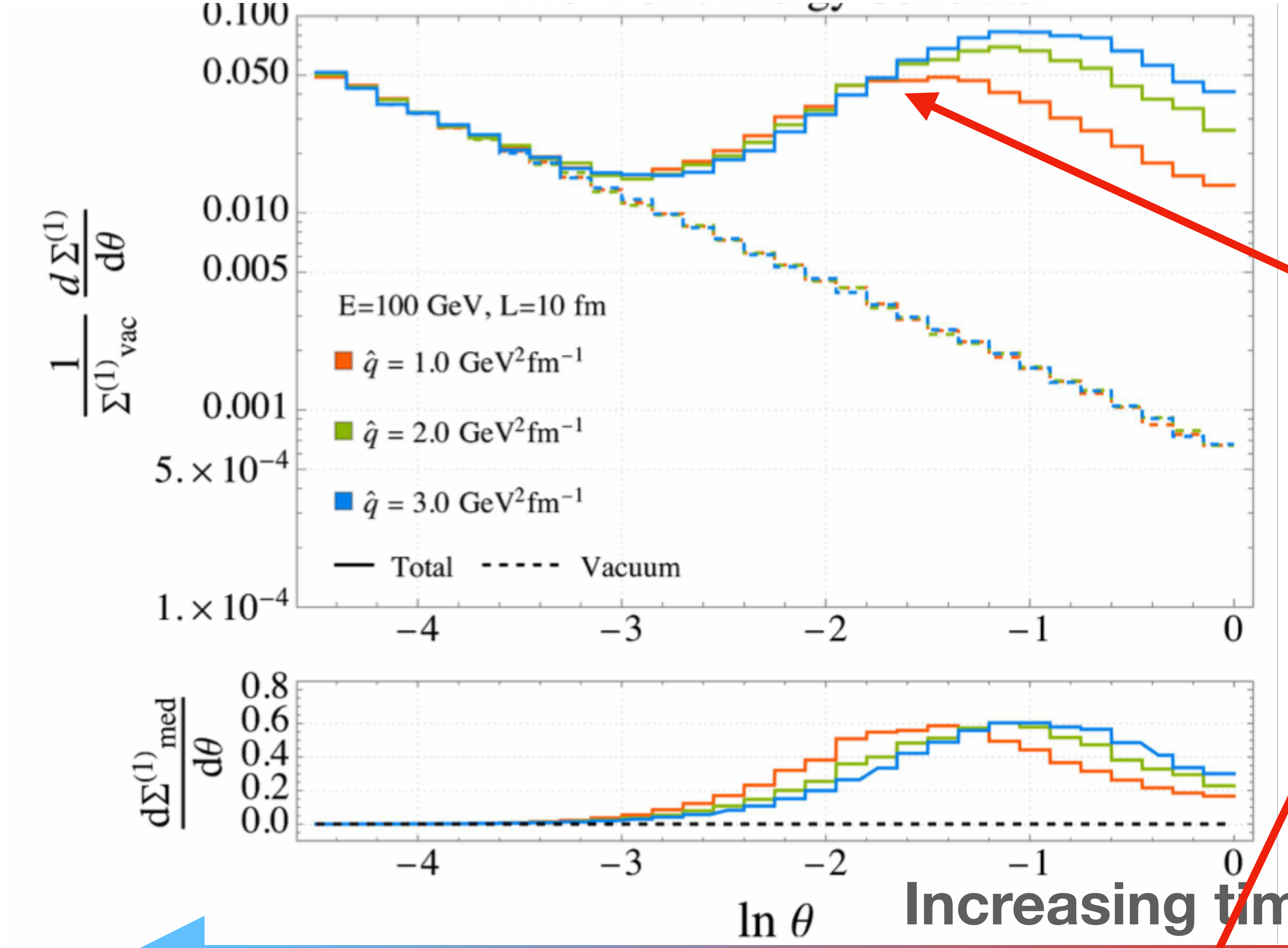
QGP introduces new scale: θ_{L}

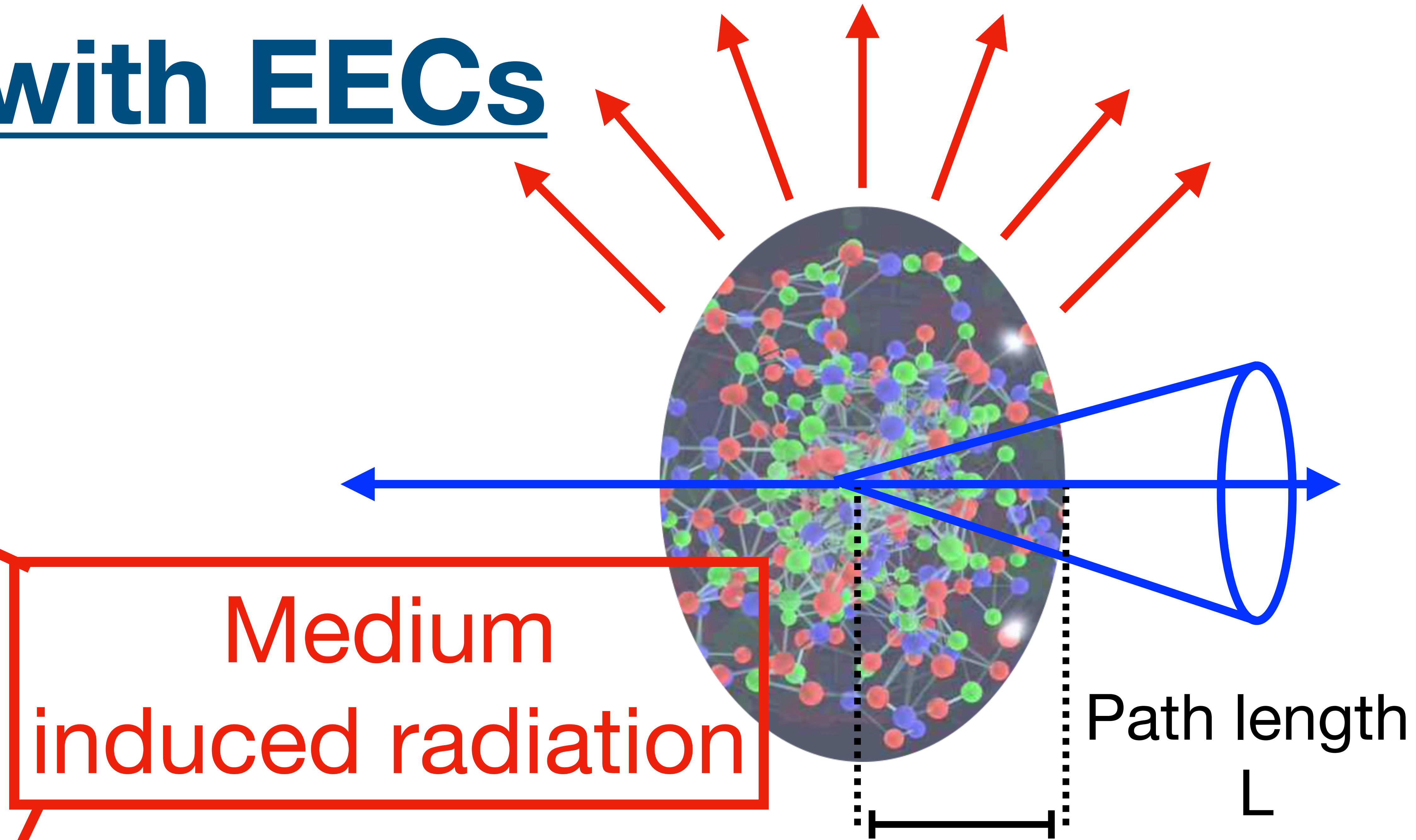
Splitting time: $\tau \sim 1/p_{\mathrm{T}}\theta^2$

$\theta \sim 1/\sqrt{\mathrm{L}}$



Exploring quark-gluon plasma with EECs

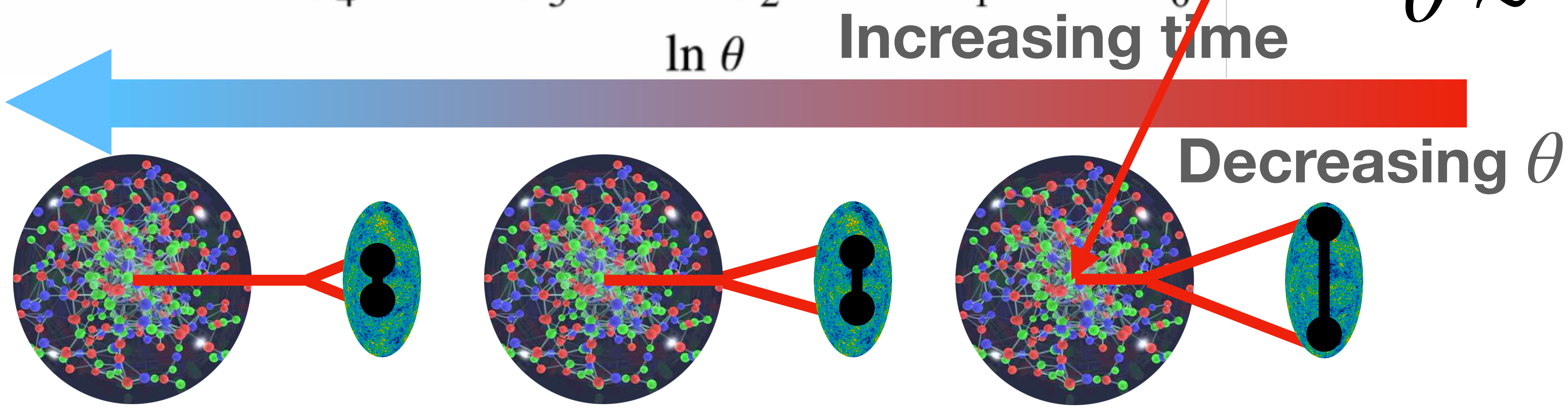




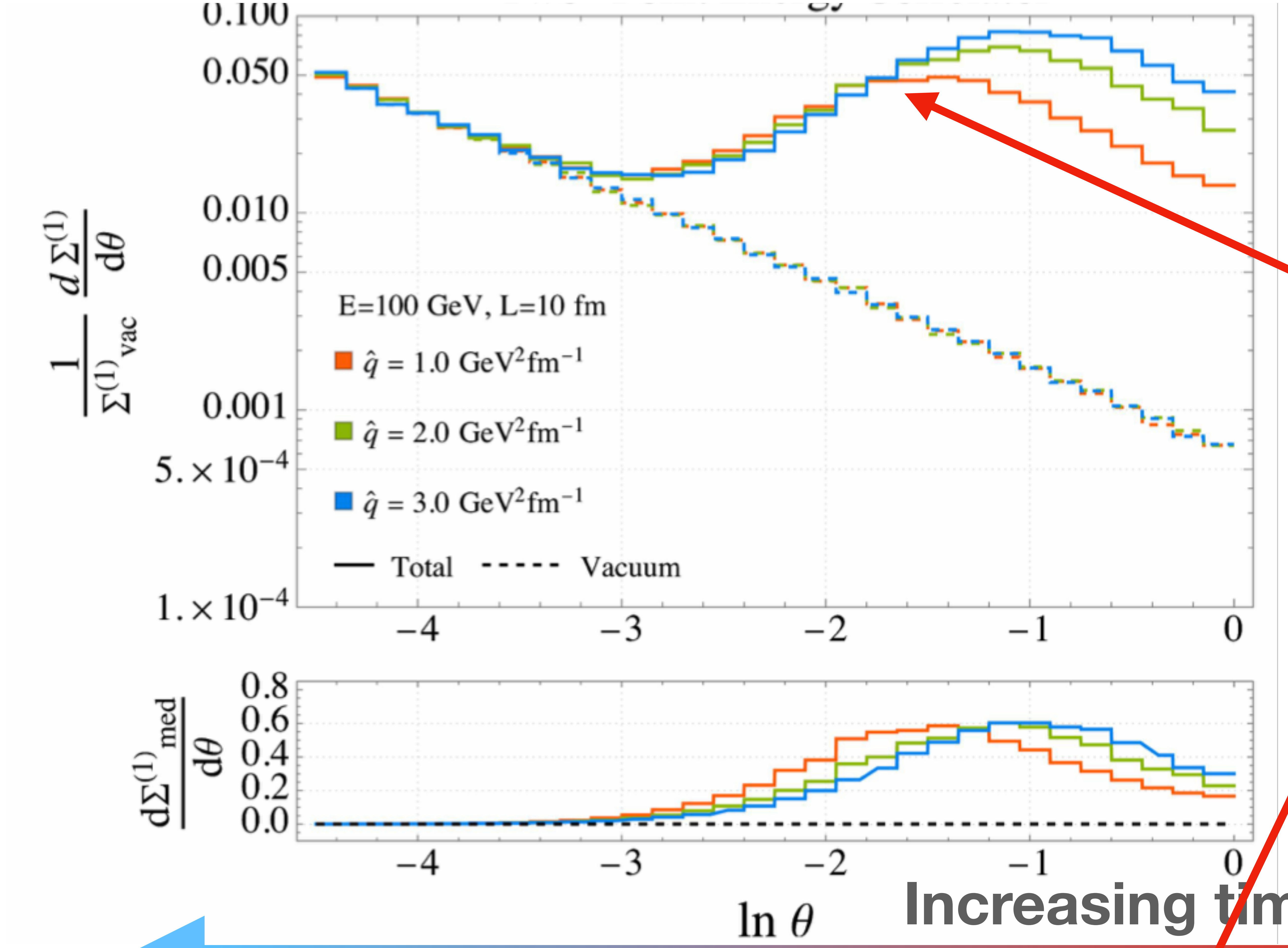
QGP introduces new scale: θ_{L}

Splitting time: $\tau \sim 1/p_{\text{T}}\theta^2$

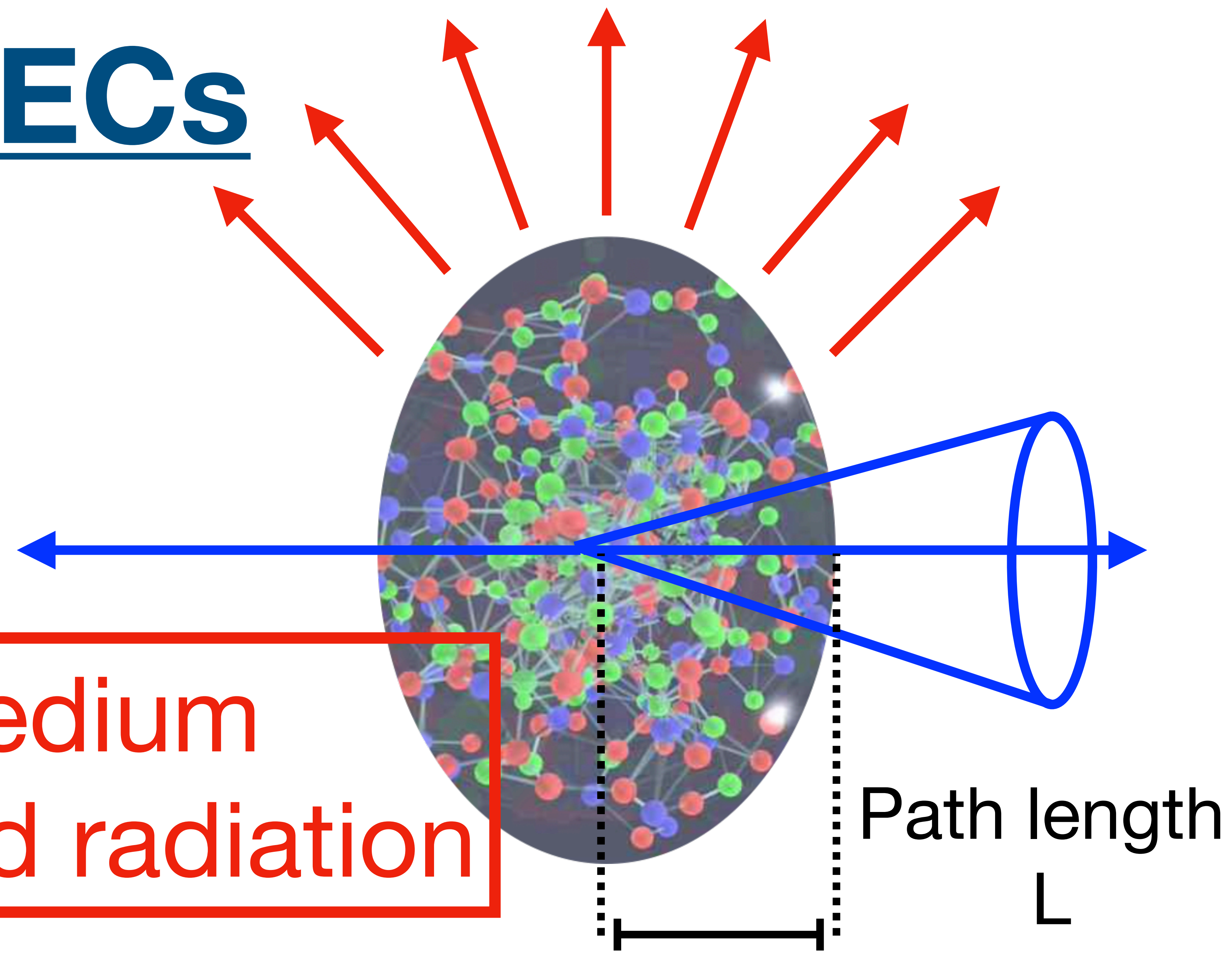
$\theta \sim 1/\sqrt{\text{L}}$



Exploring quark-gluon plasma with EECs



Medium induced radiation

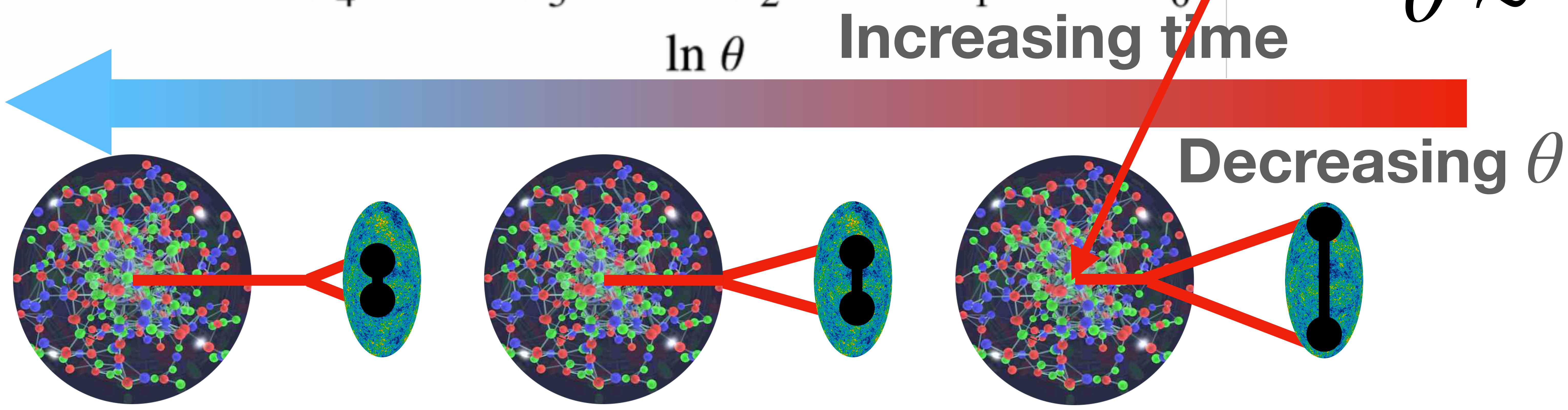


QGP introduces new scale: $\theta_{\rm L}$

Splitting time: $\tau \sim 1/p_{\rm T}\theta^2$

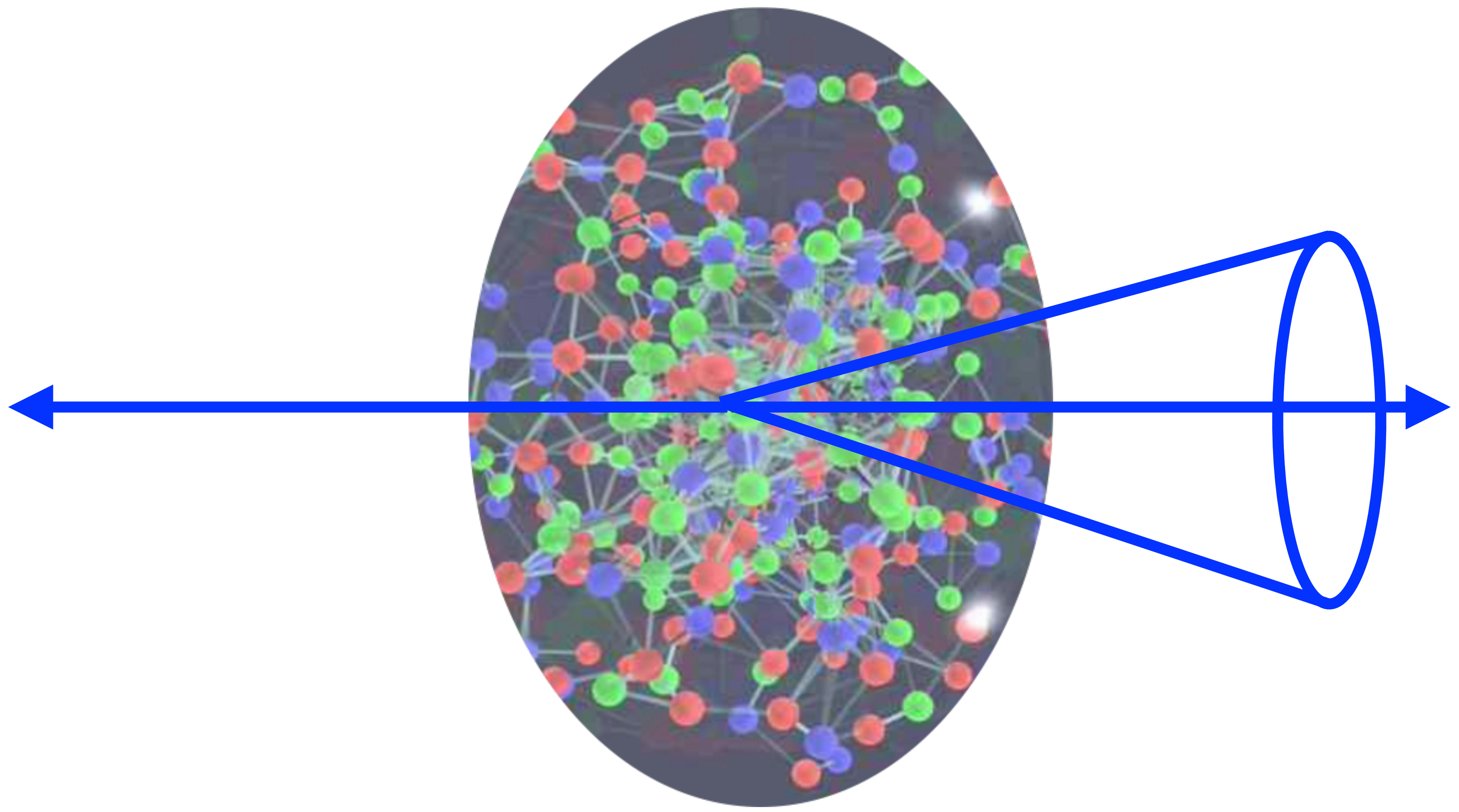
$\theta \sim 1/\sqrt{\rm L}$

6

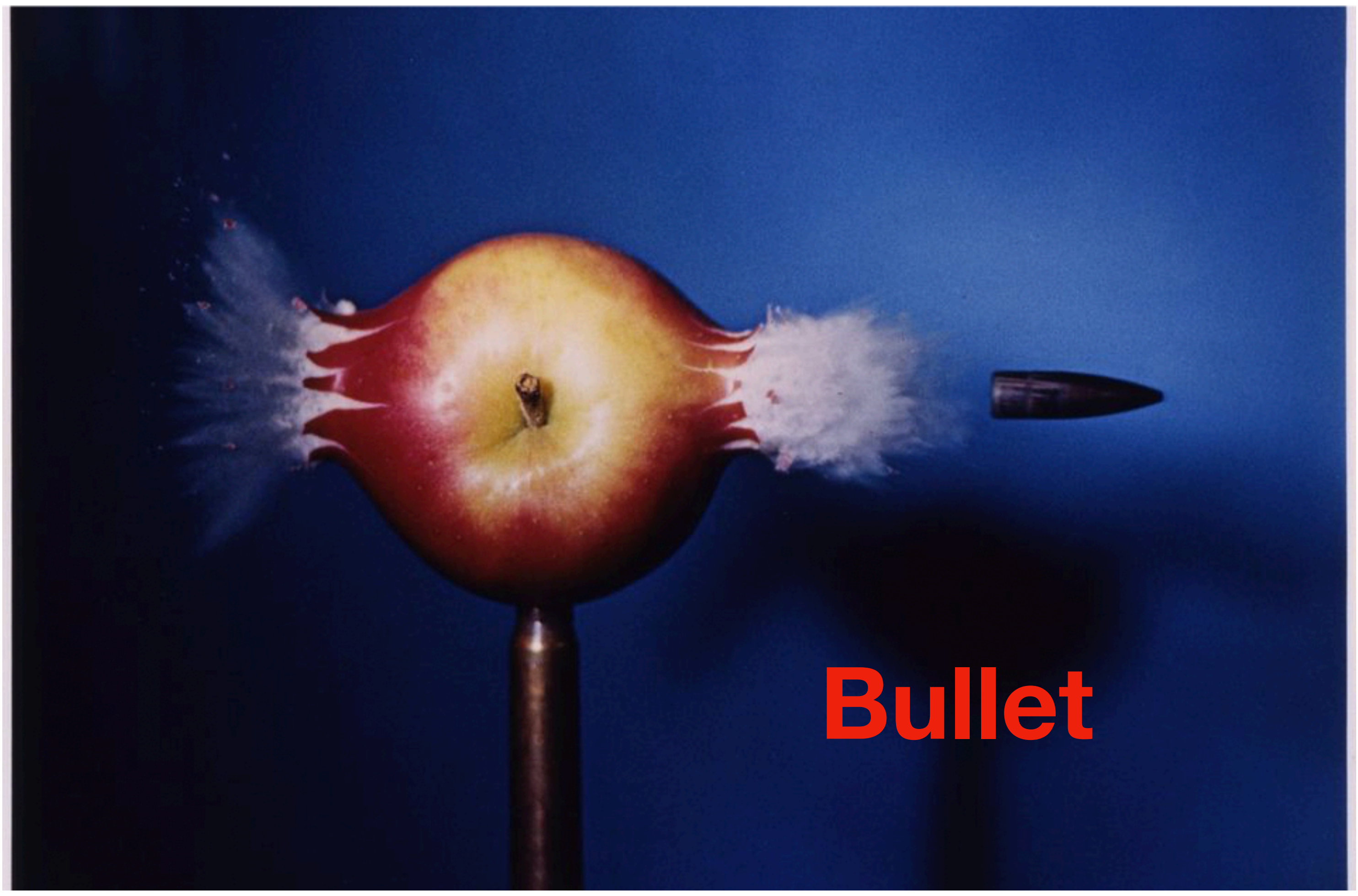


QGP signal cleanly imprinted in EECs!

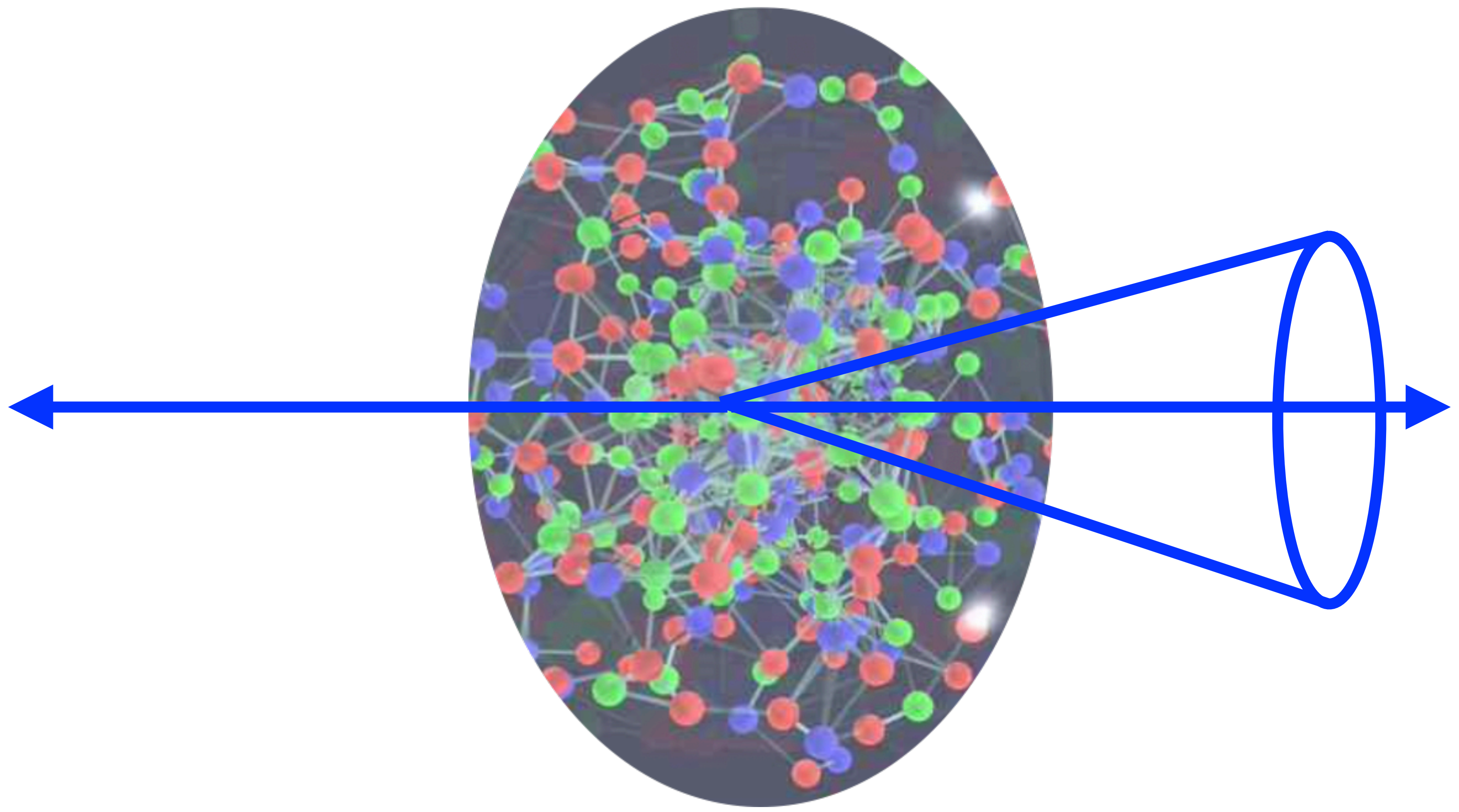
Exploring quark-gluon plasma with EECs



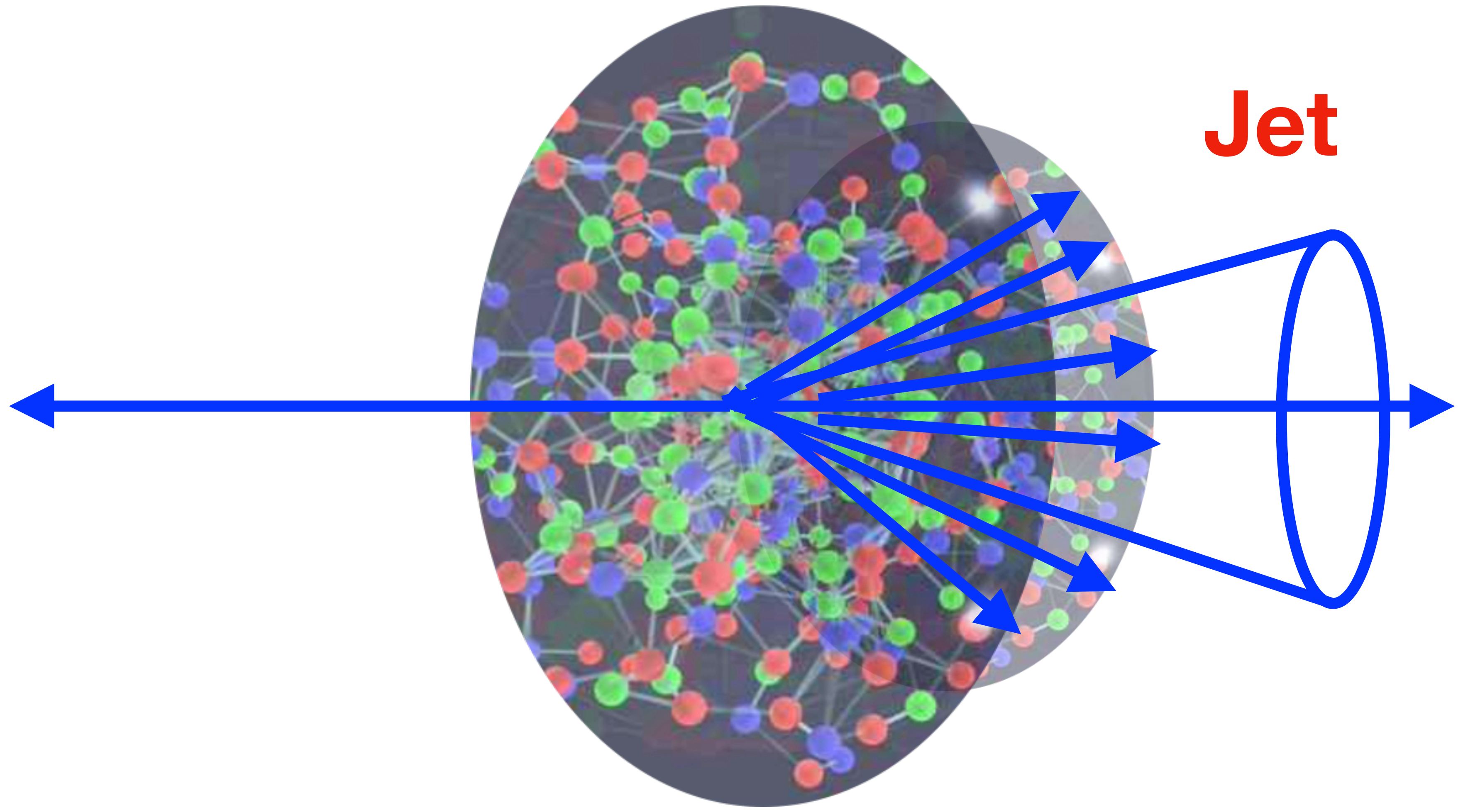
Impact of medium on jet:
Jet modified by the medium



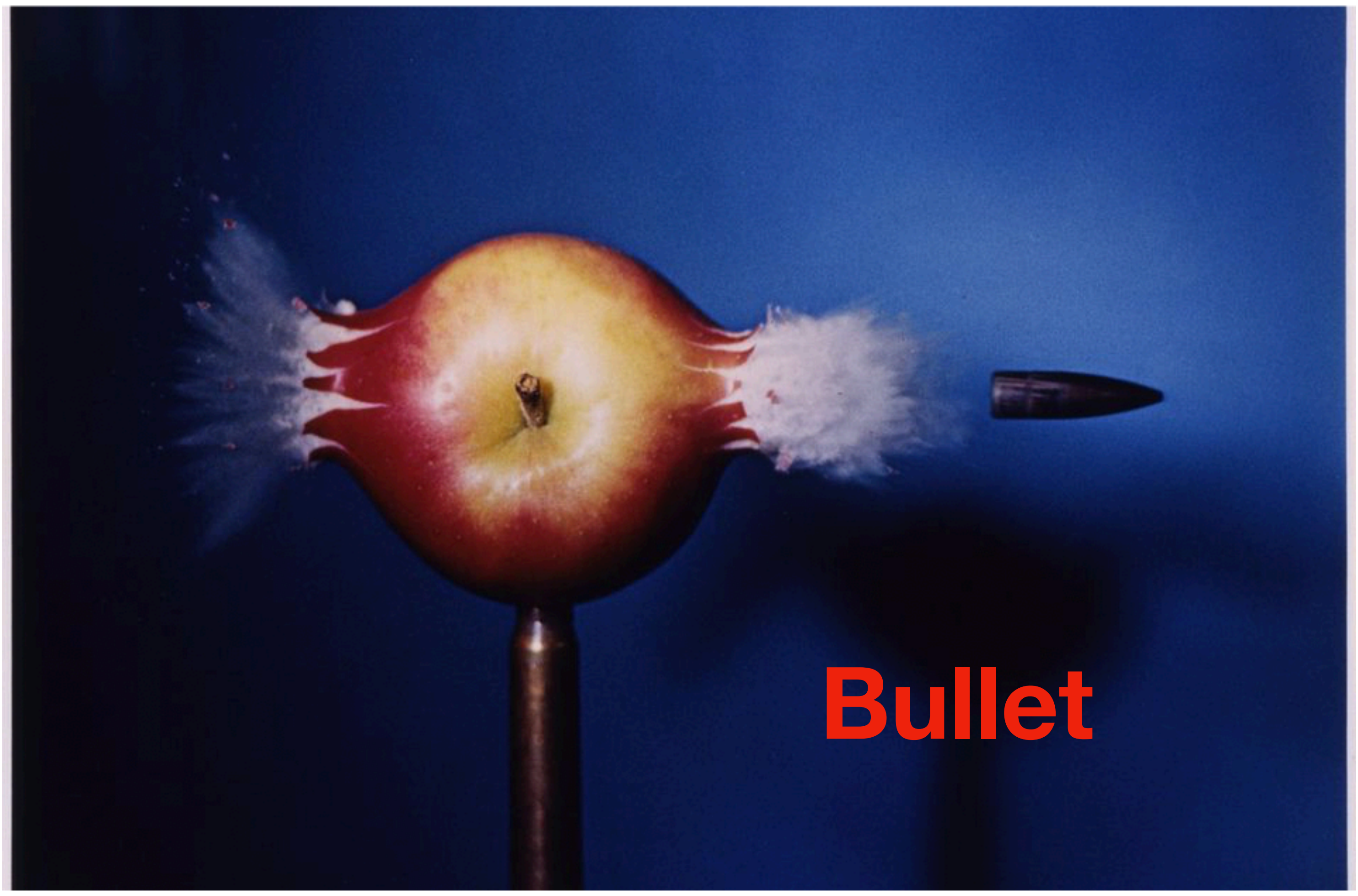
Exploring quark-gluon plasma with EECs



Impact of medium on jet:
Jet modified by the medium

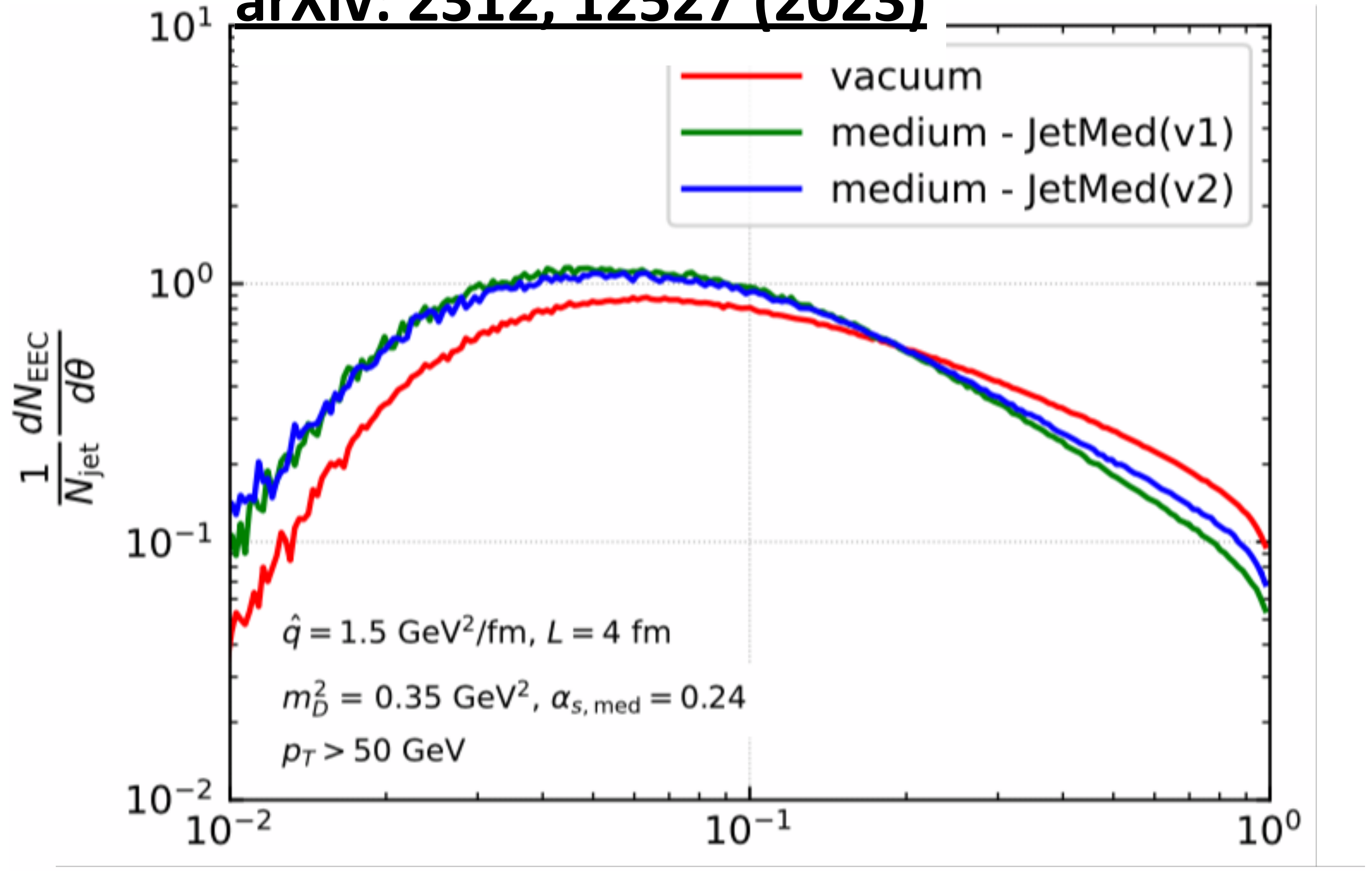


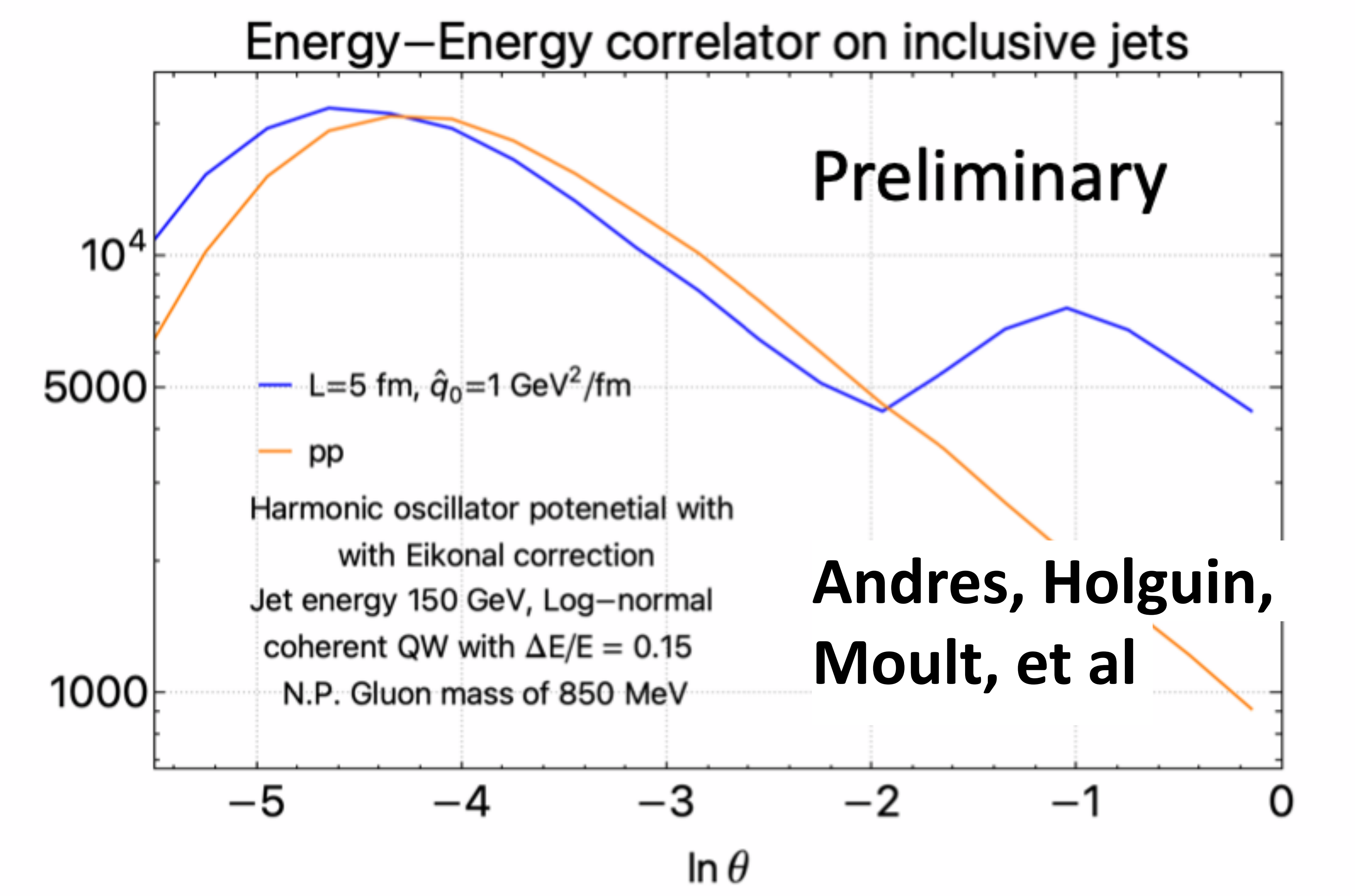
Impact of jet on medium:
Hydrodynamic wake



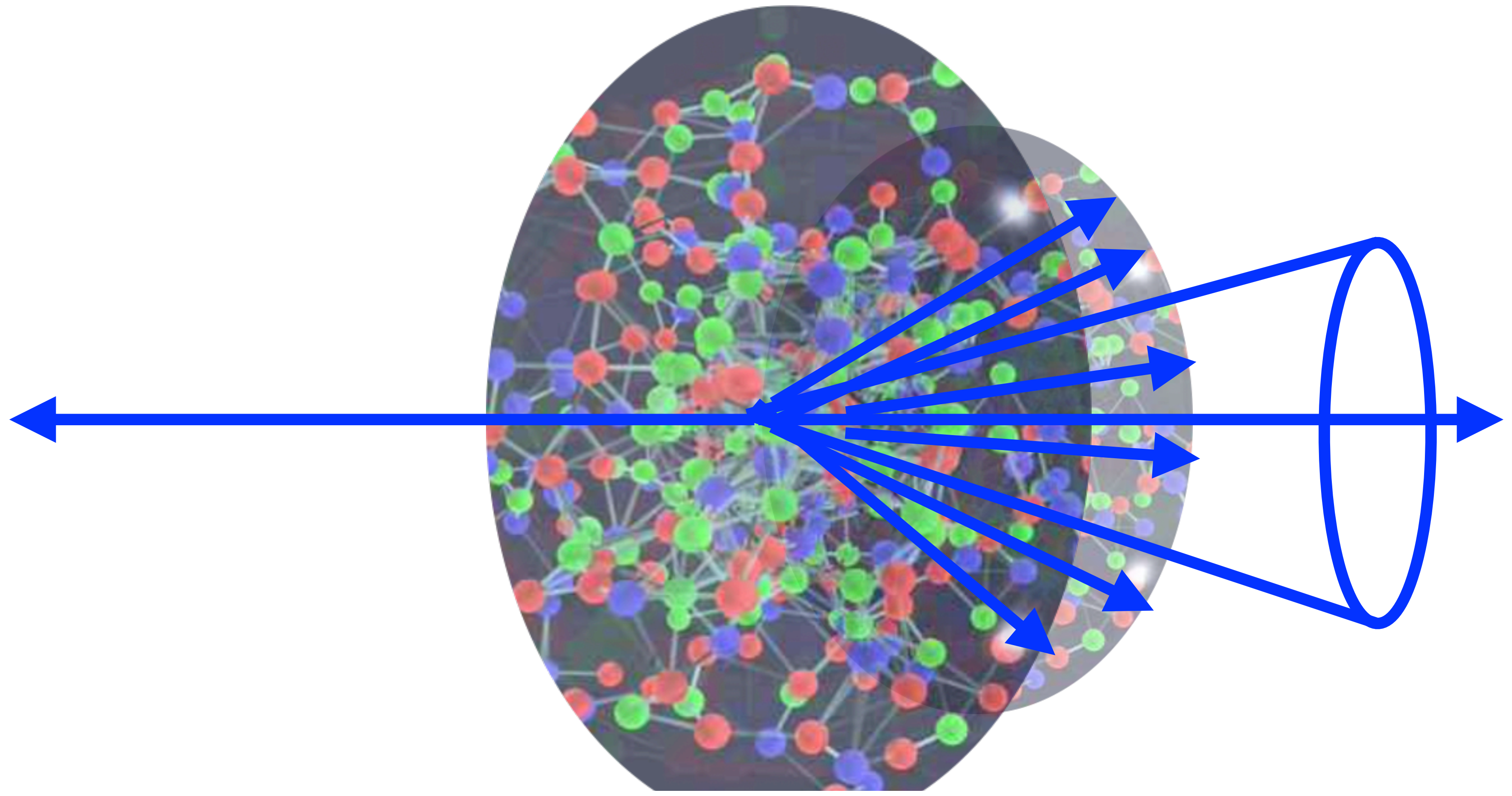
Different predictions for EECs in heavy-ion

arXiv: 2312, 12527 (2023)

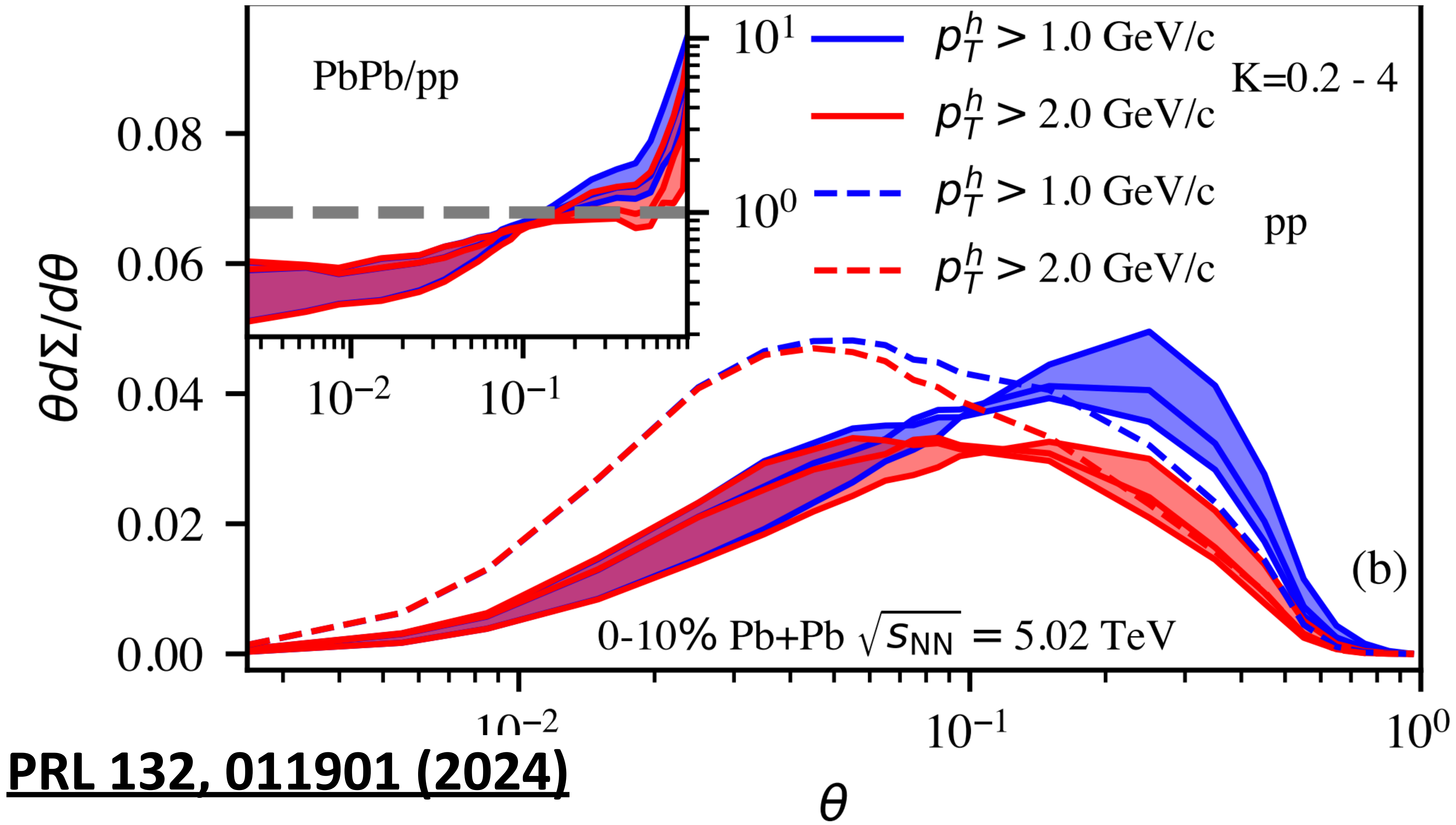




Andres, Holguin, Moult, et al



CoLBT: Transport model with effect of medium “wake”



PRL 132, 011901 (2024)

Different predictions for EECs in heavy-ion

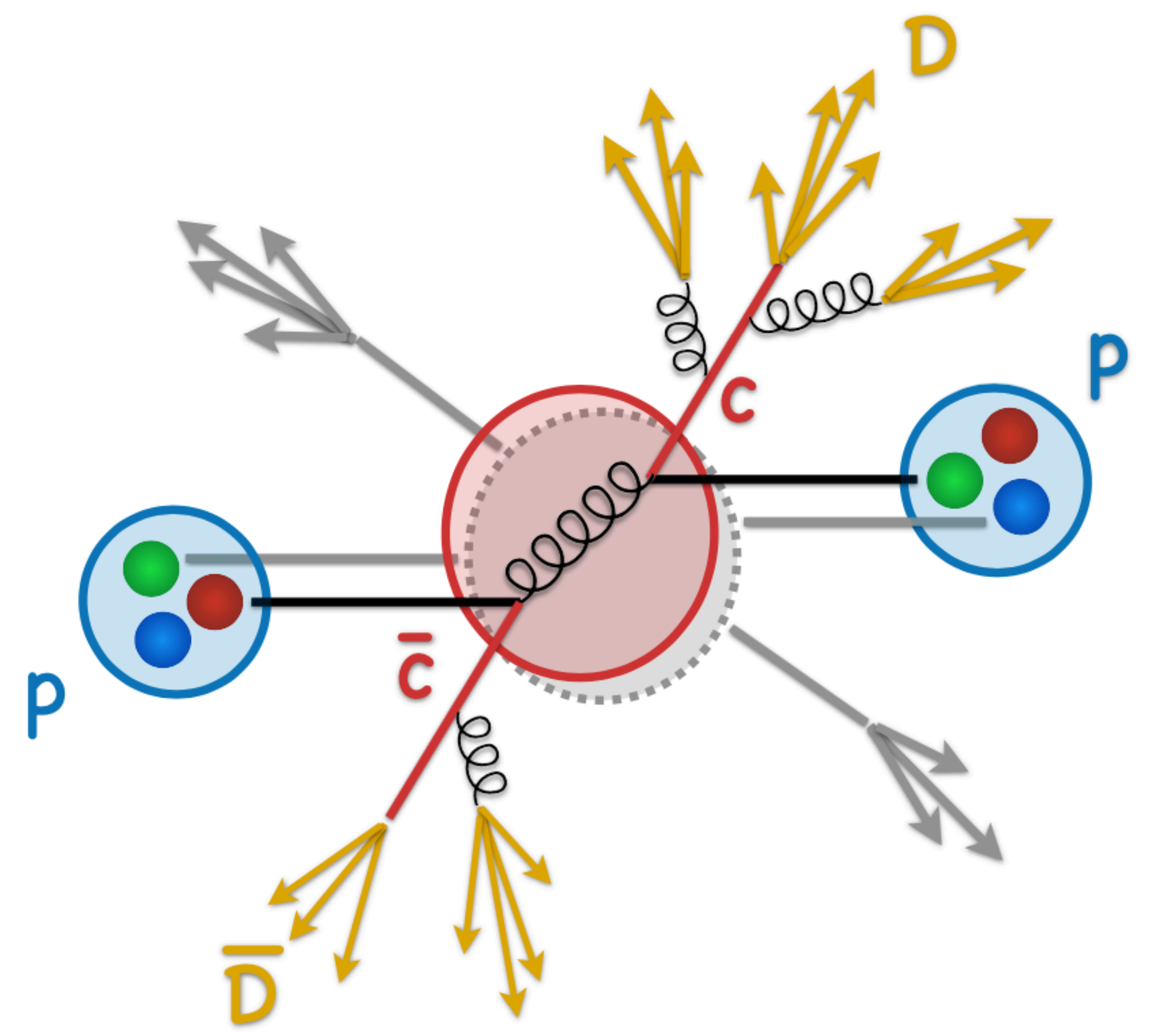
Different predictions for EECs in heavy-ion

Summary

- We have entered an exciting era in studying QCD with energy-energy correlators.
  1. **Showed clear separation of perturbative and non-perturbative regime**.
  2. Data showed reasonable agreement with MC. HERWIG better predicts the peak R_L of the distribution over PYTHIA.
  3. **Universal transition behavior:** EEC distribution in different jet p_T intervals aligns around 2.4 GeV/c when angle R_L scaled by jet p_T
  4. Highest **precision constraint on α_S** using jet substructure.
  5. EEC amplitude and peak position **depend on the flavor of the parton** initiating the shower.
  6. In heavy-ion collisions, EECs help to understand the QGP and put **constraints on jet quenching predictions.**

Backup slides

Heavy quark production in pp collisions



$$\sigma_{\mathrm{hh}\to\mathrm{Hh}} = \mathrm{PDF}(x_a, Q^2)\ \mathrm{PDF}(x_b, Q^2) \otimes \sigma_{\mathrm{ab}\to\mathrm{q}\bar{\mathrm{q}}} \otimes D_{\mathrm{q}\to\mathrm{h}}(z_q, Q^2)$$

Parton distribution functions (non perturbative)

Partonic cross section (perturbative)

Fragmentation functions (non perturbative)