Perspectives on recent LHC jet measurements

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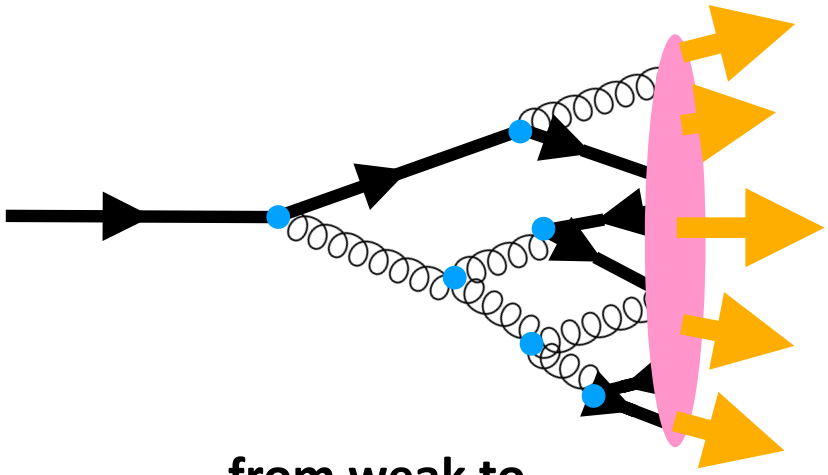
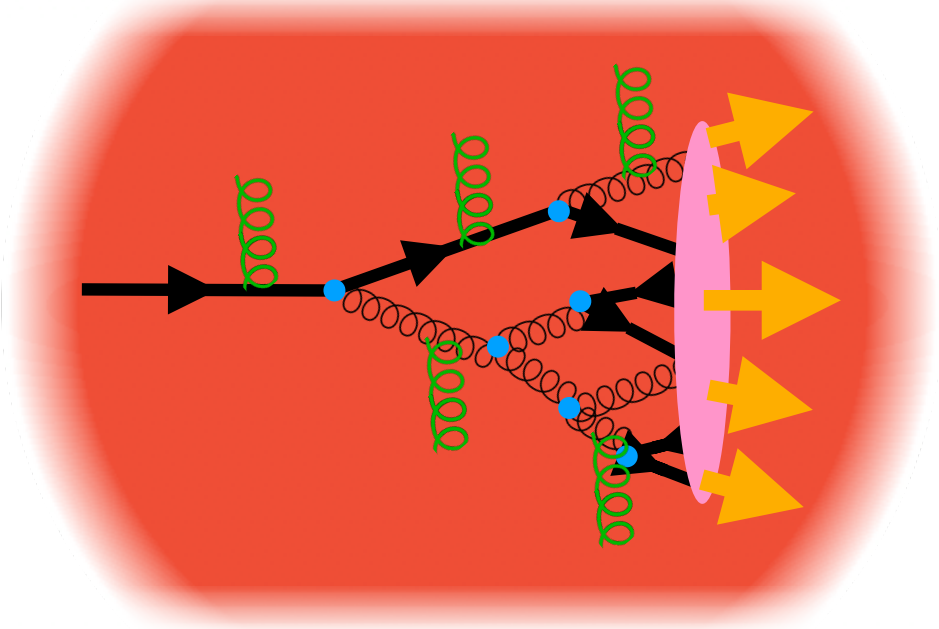
Jet as object and probe

- p+p: precision study of the perturbative and non-perturbative (NP) aspects of QCD in vacuum
- A+A: probe the properties of QGP





from weak to strong coupled limit

Perturbative → **NP**

Short time scale
High energy scale

Long time scale
Low energy scale

Jet as object and probe

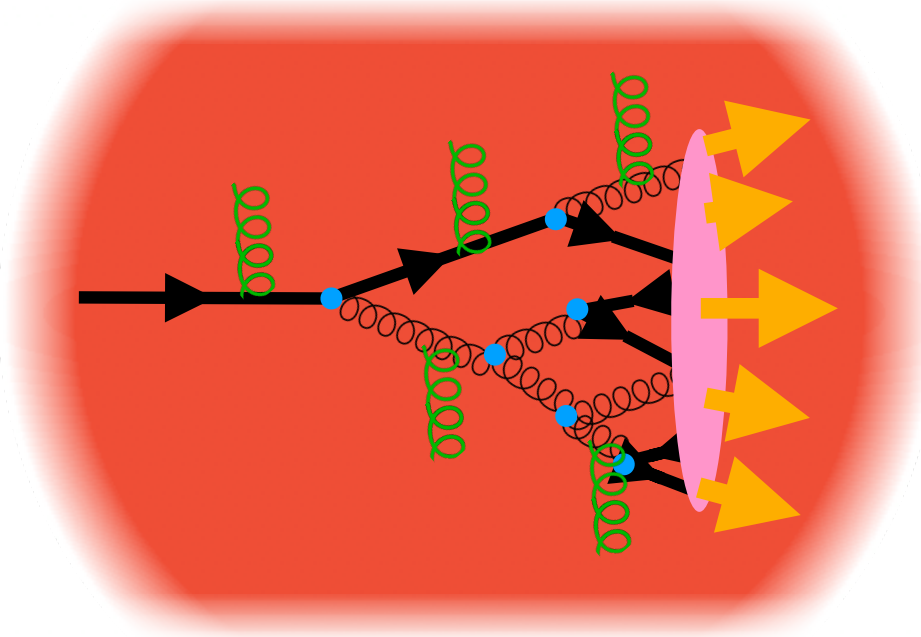
This talk will mostly focus on the results from the heavy ion side

How does energy redistribution happen?

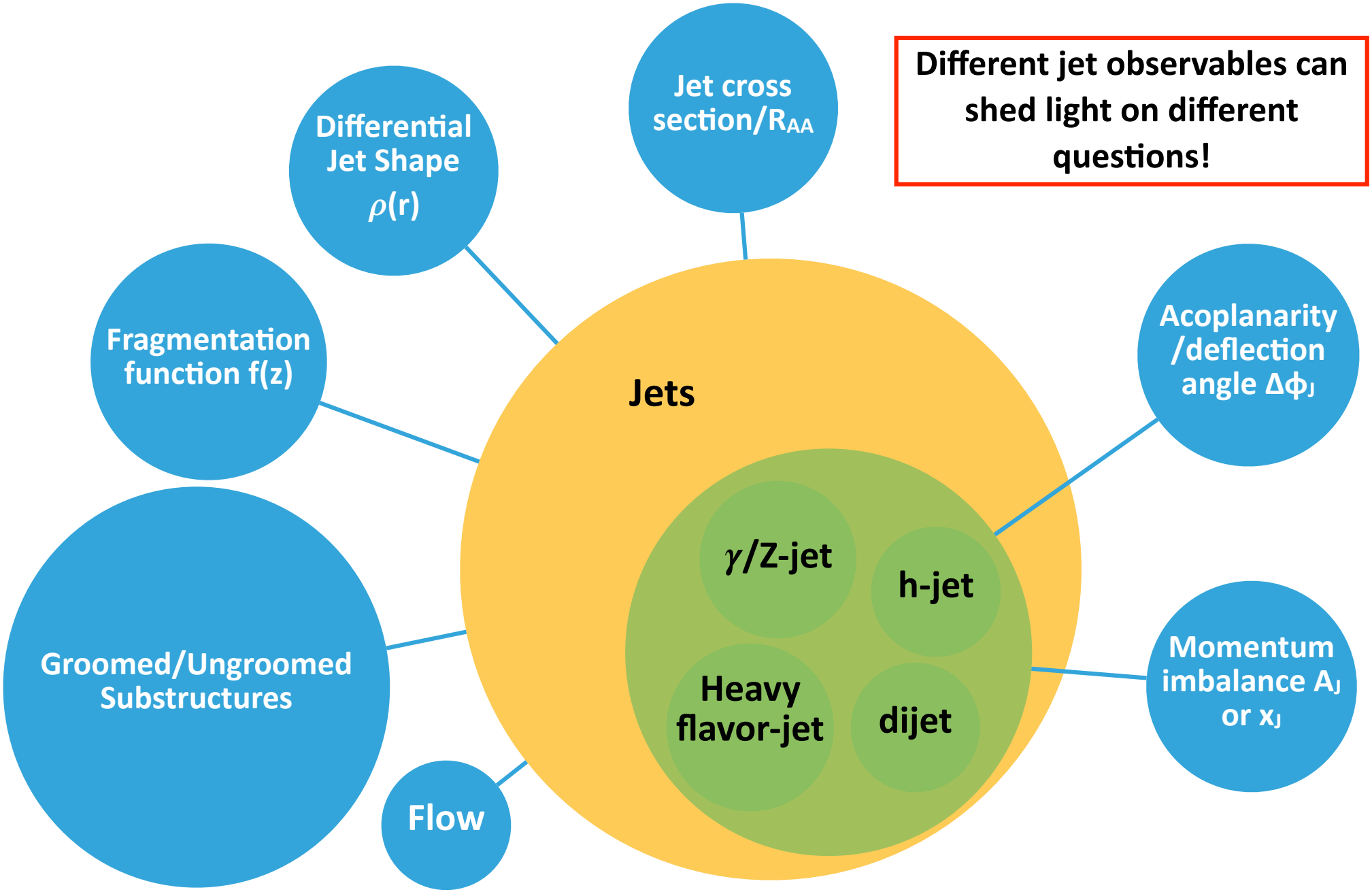
What is the path-length dependence? What is the role of parton color charge and mass?

Properties of QGP: medium size, transport coefficient, coherence length, quasi-particles?

- **A+A: probe the properties of QGP**

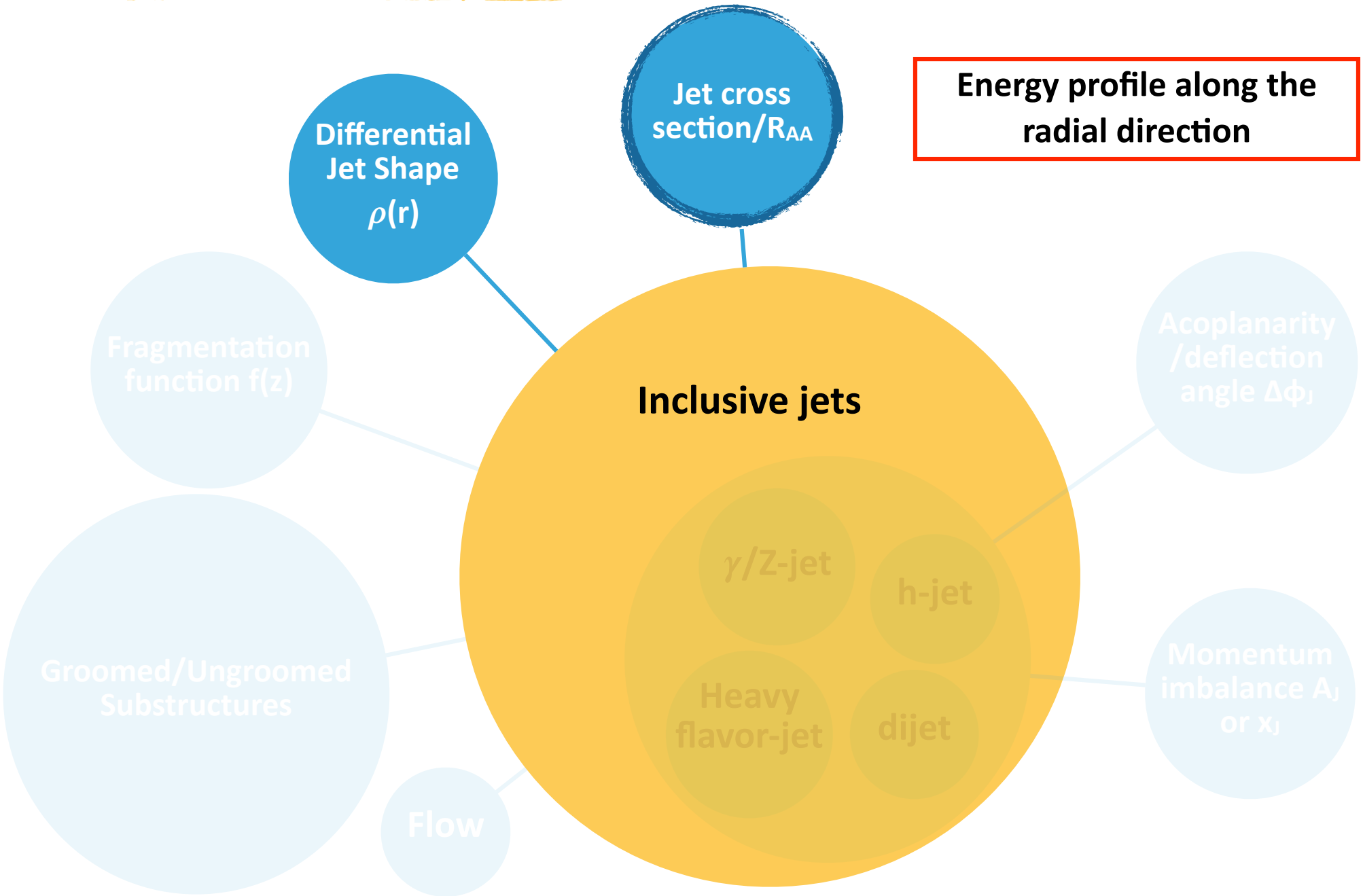


A (incomplete) roadmap of jet measurements



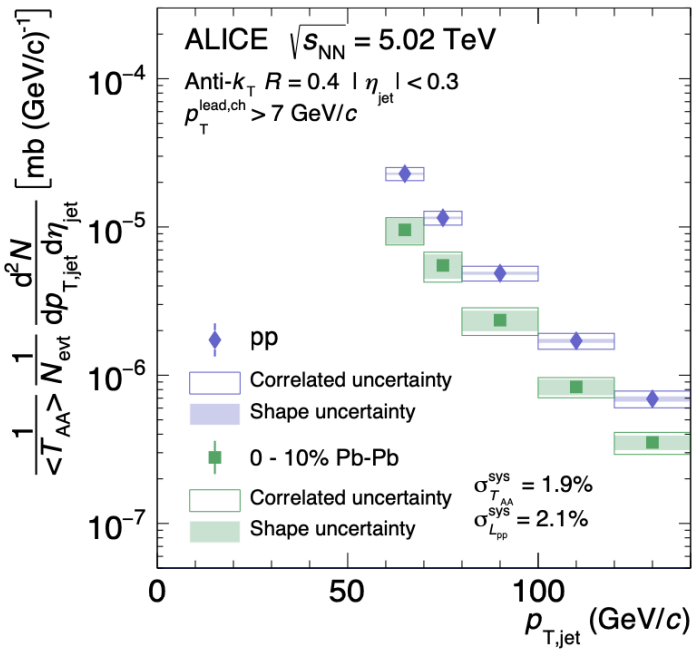
Different jet observables can shed light on different questions!

“Energy loss”: how/where did the lost energy go?

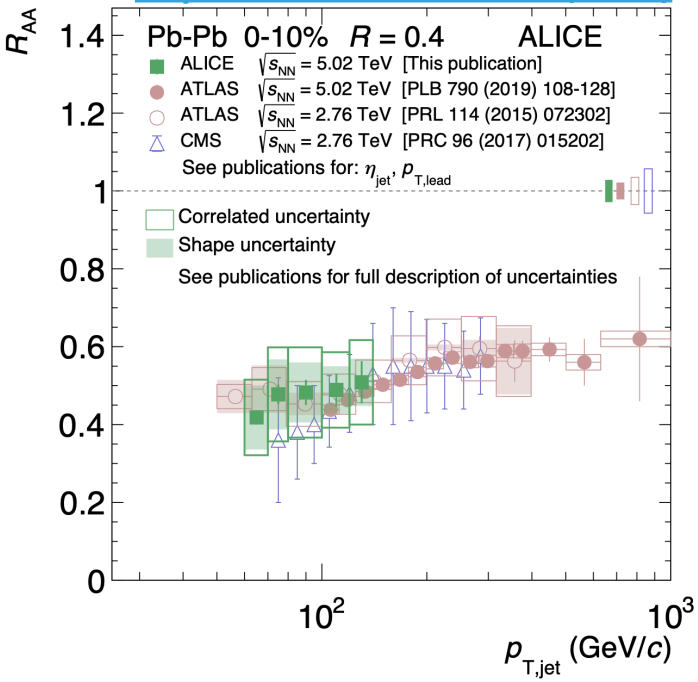


Energy "loss" towards larger jet R?

- There is no energy "loss" but just redistribution
  - Modified jet splittings
  - Medium response

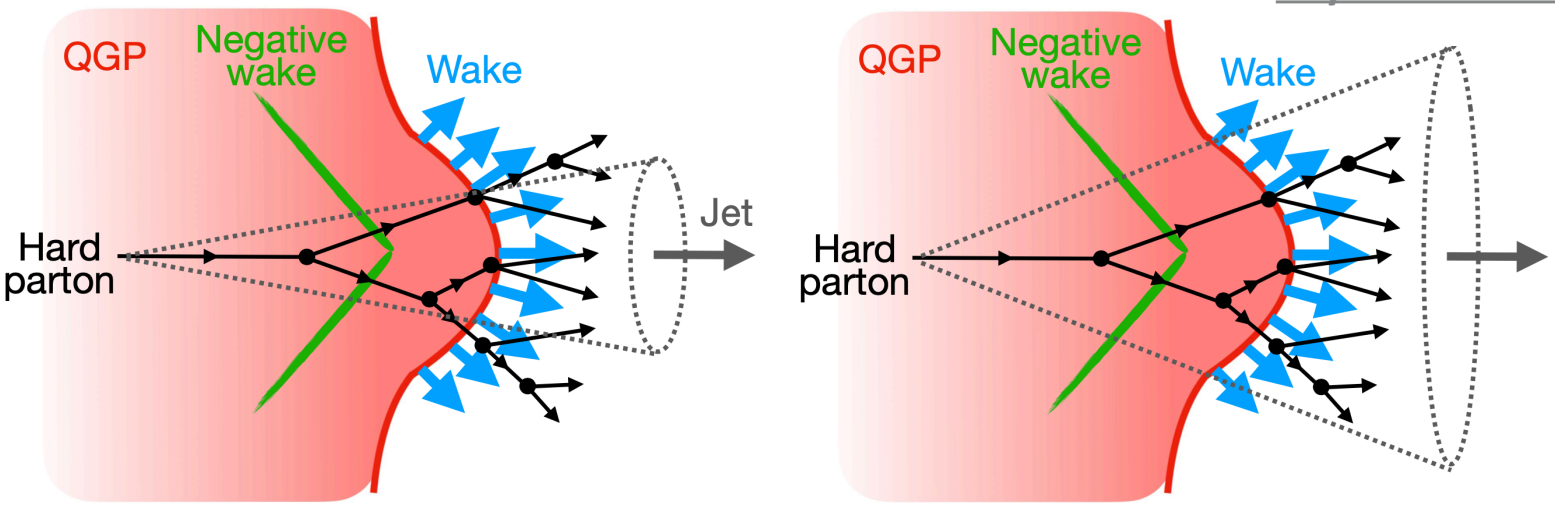


Phys. Rev. C 101, 034911 (2020)



Small to large jet radius

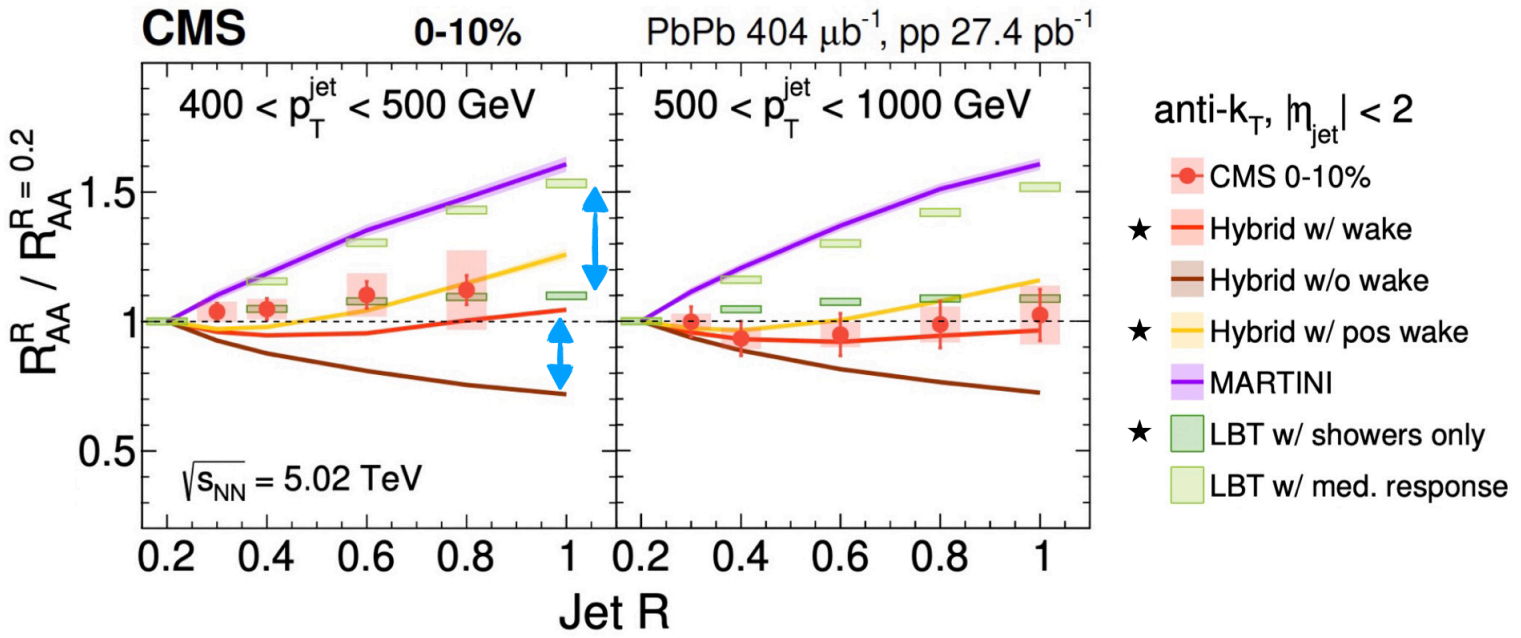
Figure credit: Rey Cruz Torres



Energy recovery towards larger jet radius?

R_{AA} of different jet R at high p_T

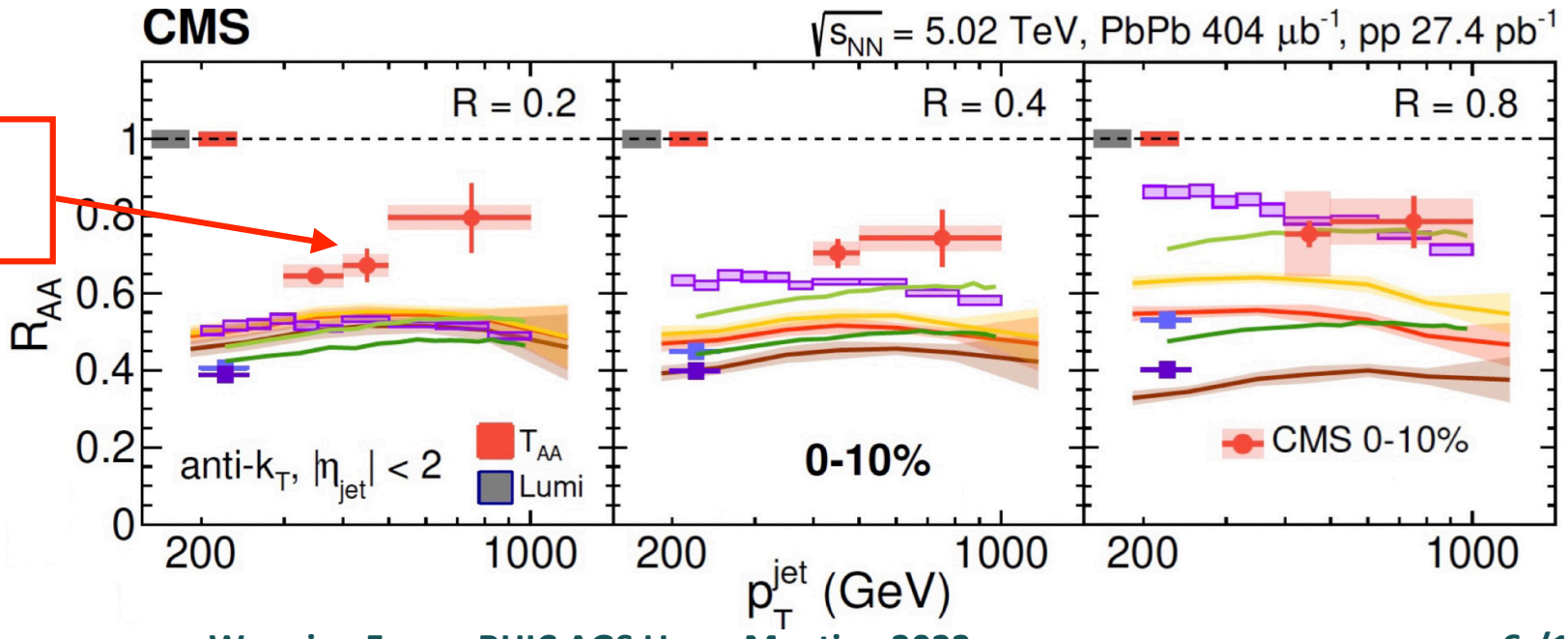
JHEP 05, 284 (2021)



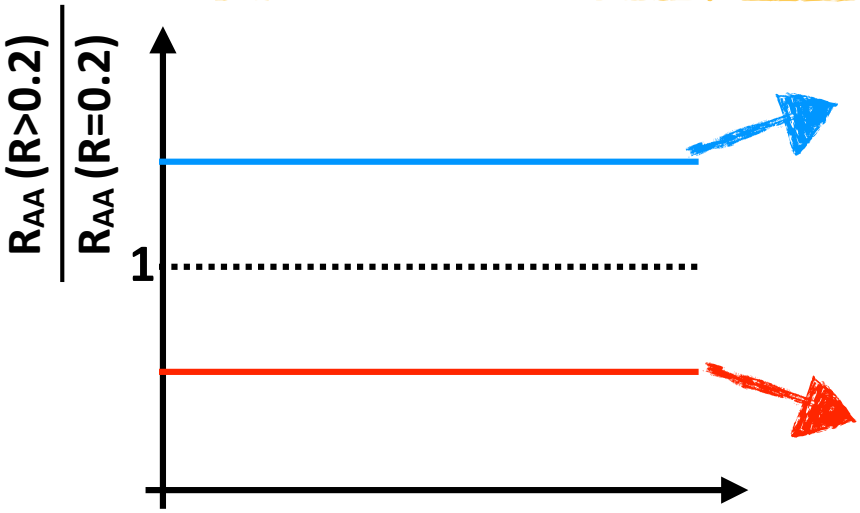
No strong R dependence for high energy jets

Discriminating power on models

Larger effect at lower p_T

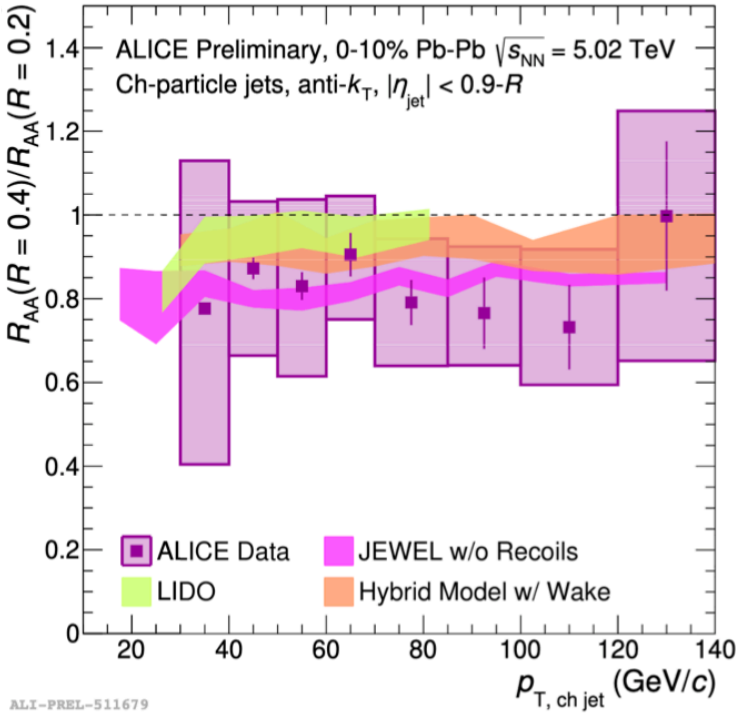


R_{AA} of different jet R at low p_T

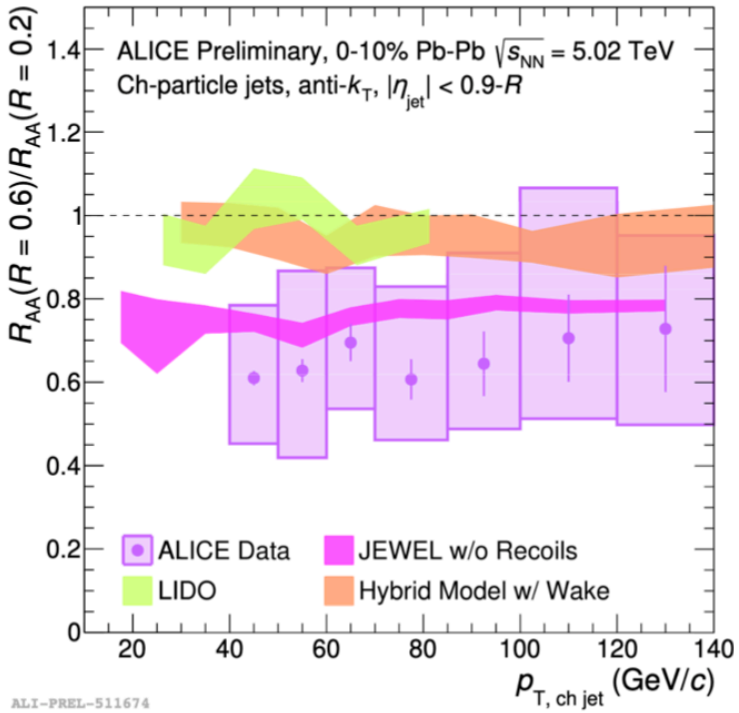


- Recovery of wide angle radiation
- Medium response adds energy to the jet cone
- Large R jets have more effective energy loss sources hence more quenched
- Large R jets with larger gluon/quark fraction, gluon lose more energy

R = 0.4 / R = 0.2

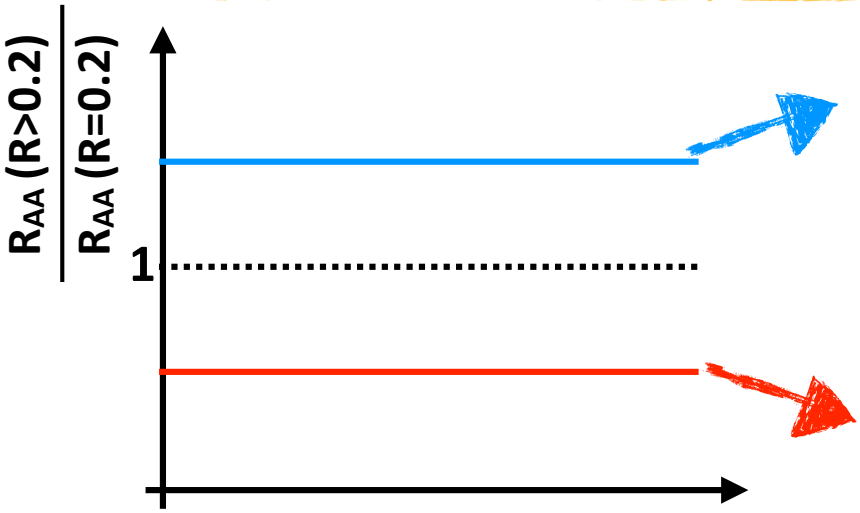


R = 0.6 / R = 0.2



Larger/wider jets are more suppressed (up to R=0.6)

R_{AA} of different jet R at low p_T



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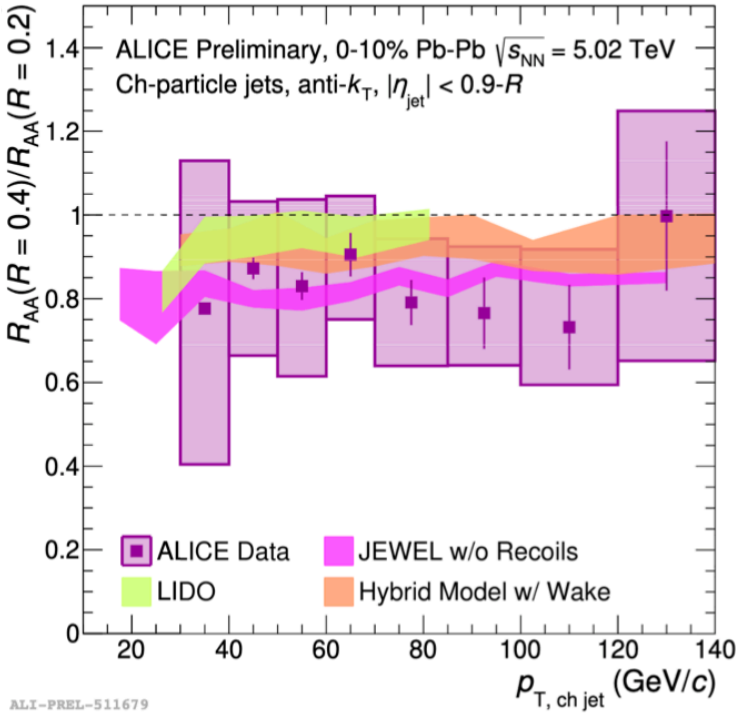

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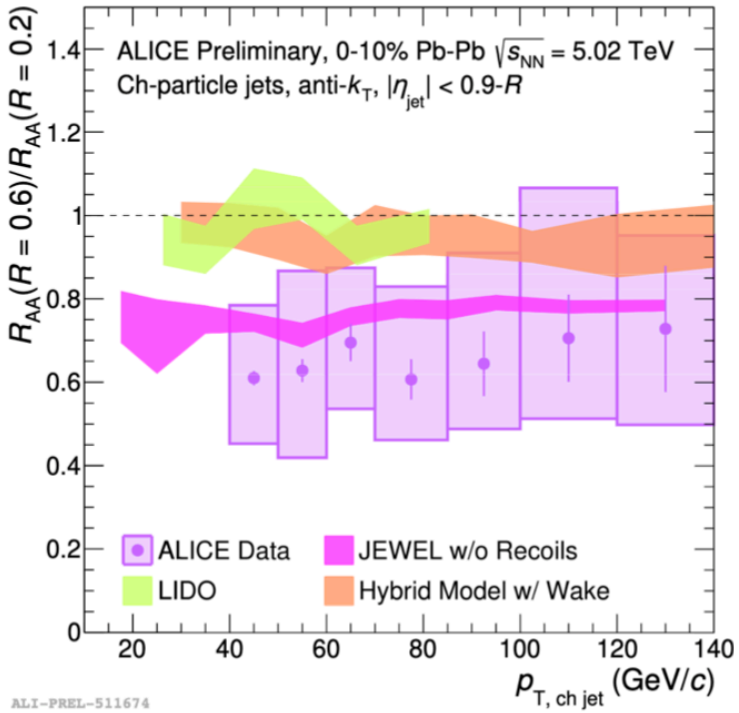
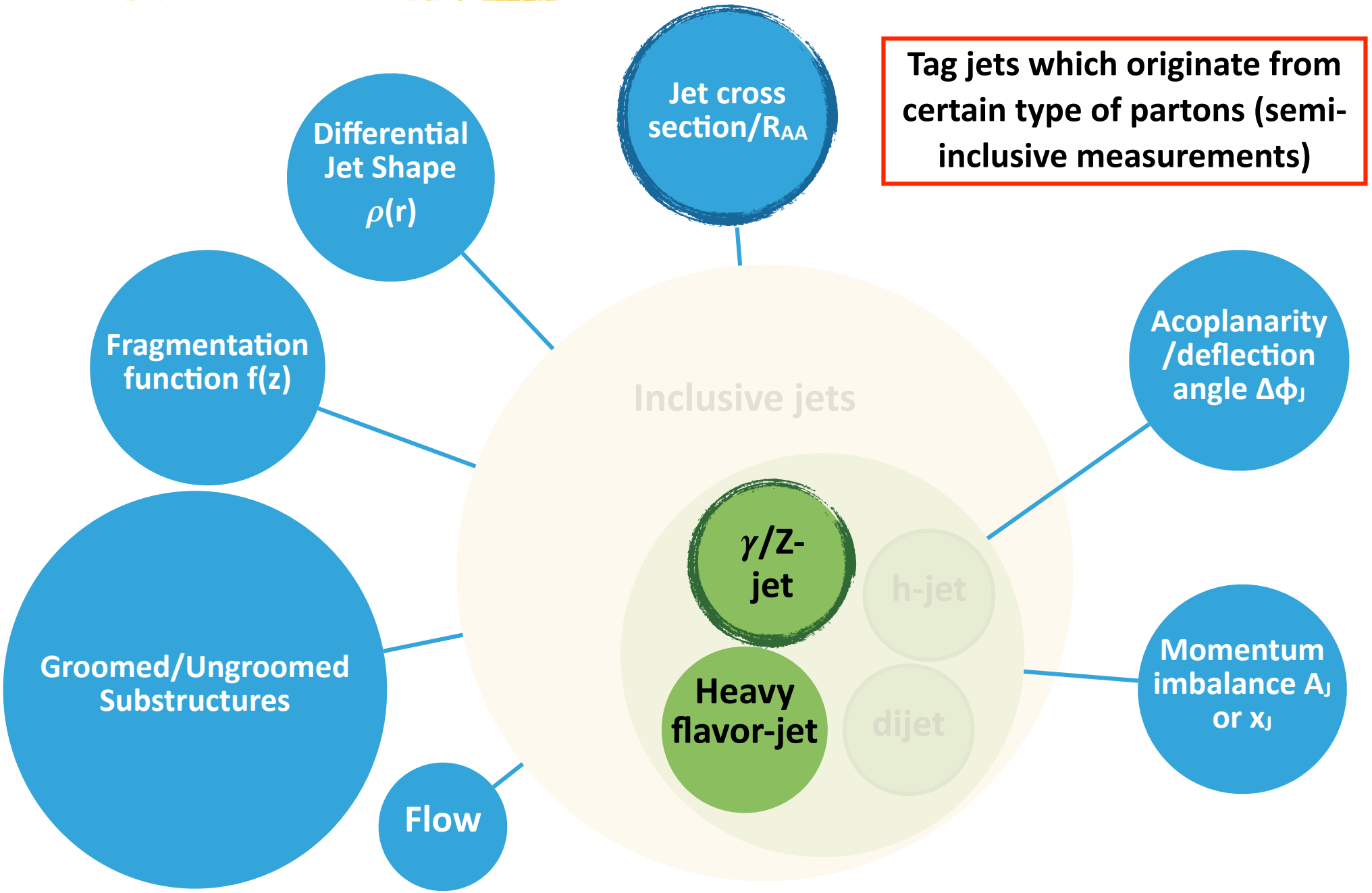


Tag quark jet with γ/Z-jet!

Larger/wider jets are more suppressed (up to R=0.6)

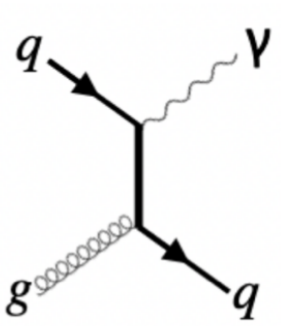
What is the role of parton color charge and mass?

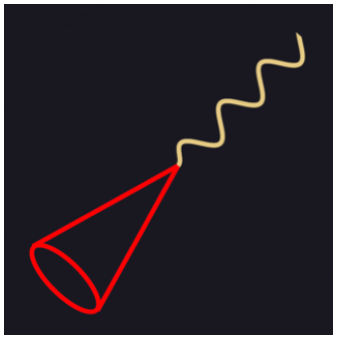


Tag jets which originate from certain type of partons (semi-inclusive measurements)

Quark jets v.s. gluon jets

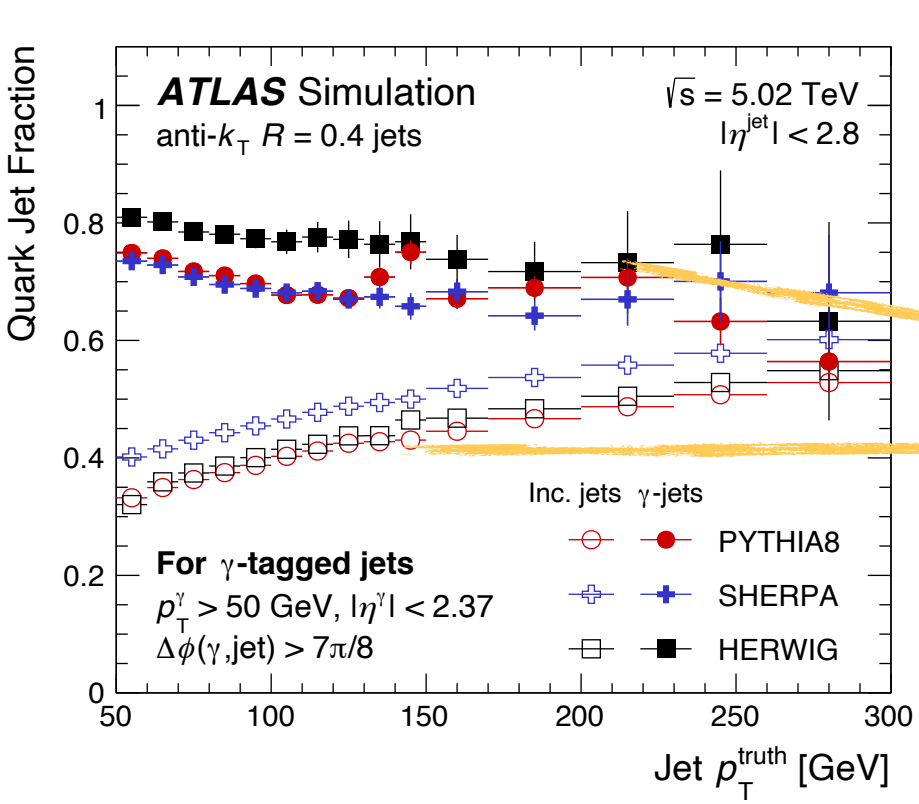
- γ/Z-tagged jets
  - Enrich the fraction of jets originate from quarks

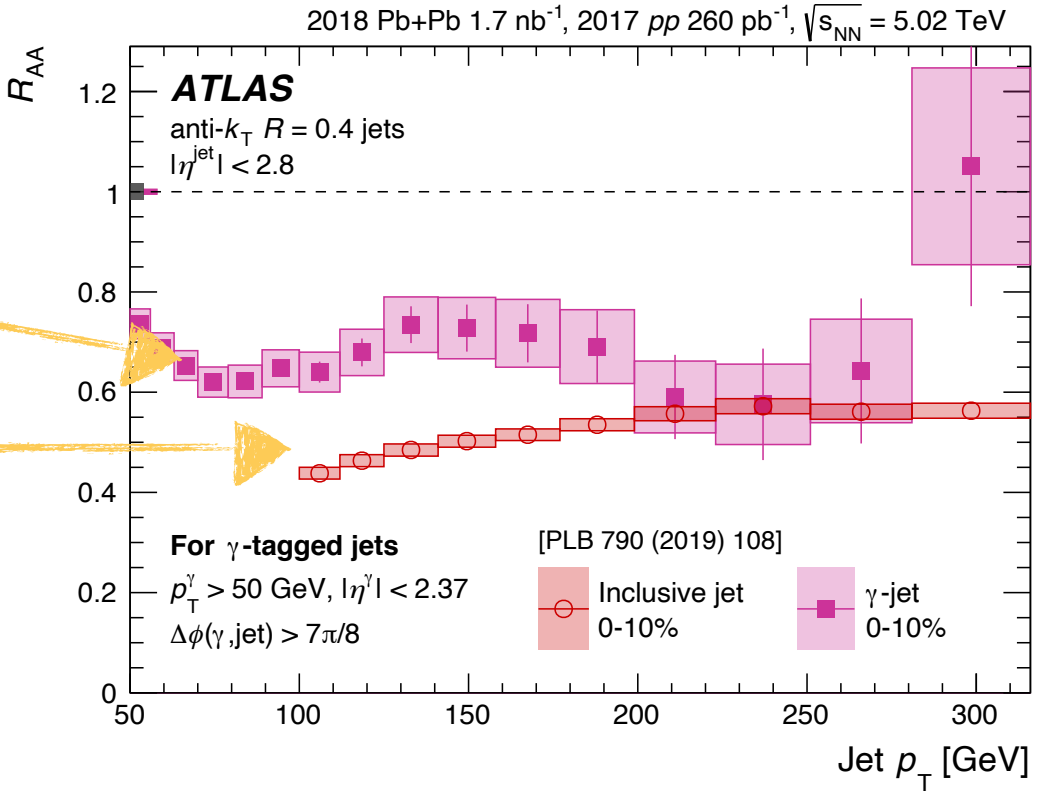




Smaller modification for quark jets compared to gluon jet

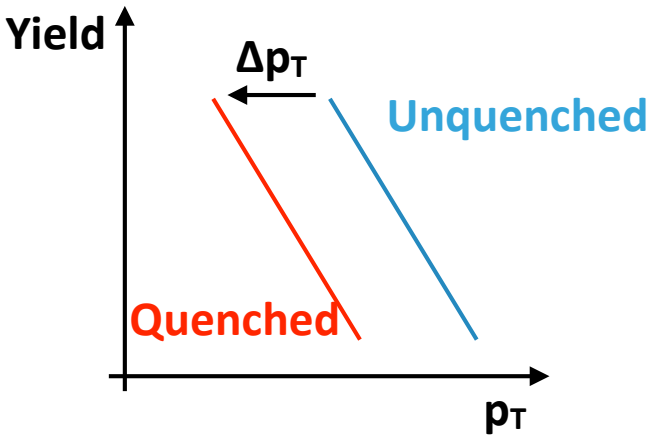
arXiv:2303.10090

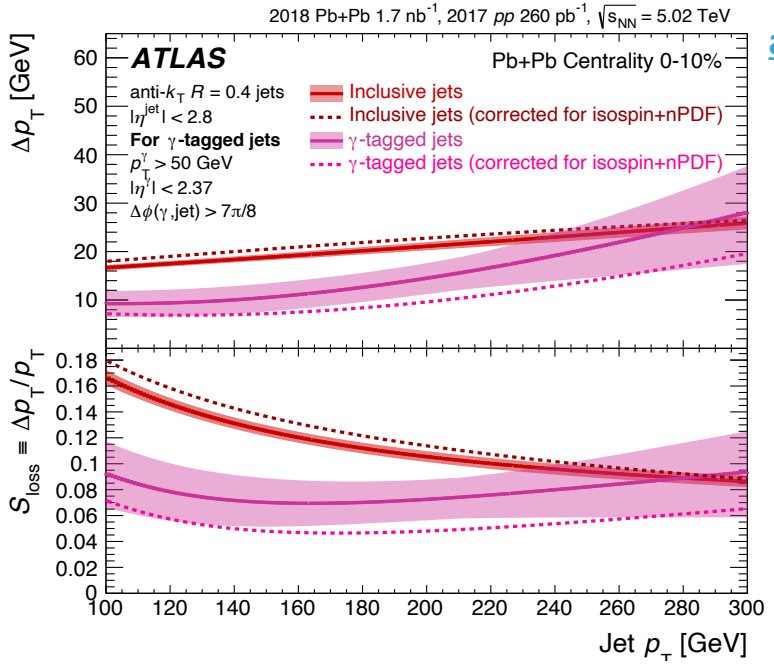




More energy loss with gluon jets

Quantify the per jet energy loss from spectra + R_{AA}





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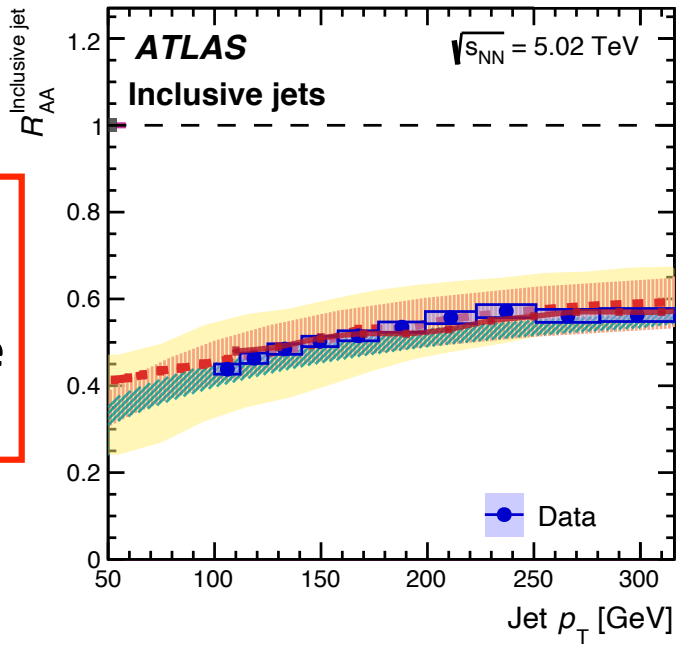
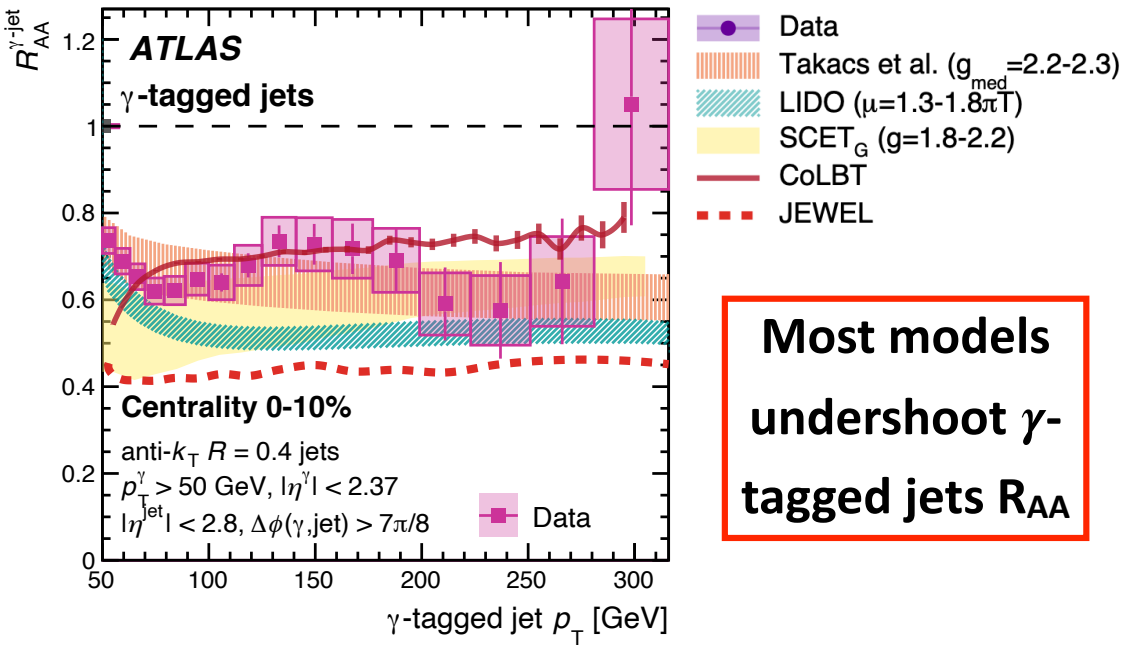
Smaller energy loss for quark jets compared to gluon jet

Good agreement for inclusive jets

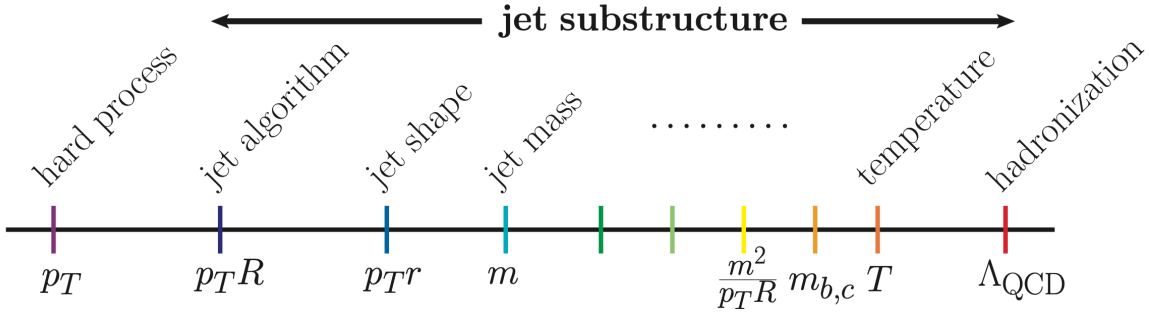




Most models undershoot γ-tagged jets R_{AA}

Can we study the medium modification at a certain scale?

YangTing Chien QM18



Access different QCD scales with jet substructures

Inclusive jets

Groomed/ Ungroomed Substructures

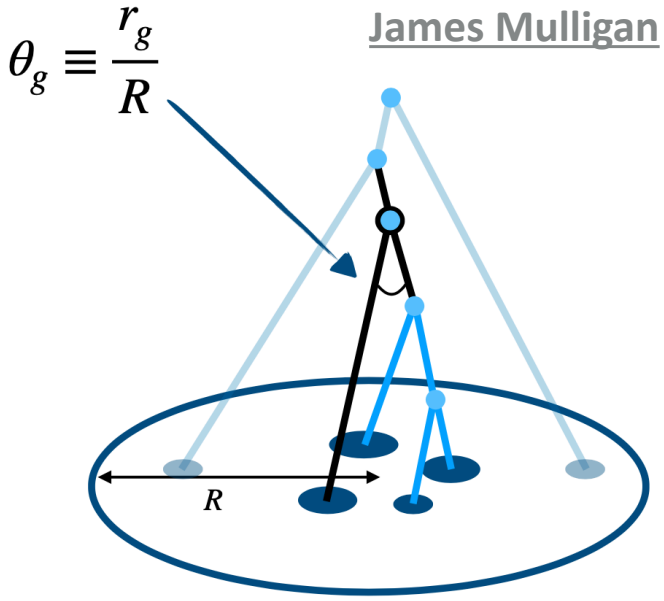
- r_g or θ_g
- z_g
- $k_{T,g}$
- Jet charge
- Lund plane
- Energy correlators
- Angle between jet axes
- Angularity

- Fragmentation function $D(z)$
- Acoplanarity /deflection angle $\Delta\phi_J$
- γ/Z-jet
- h-jet
- Heavy flavor-jet
- dijet
- Momentum imbalance A_J or x_J

Groomed jet radius

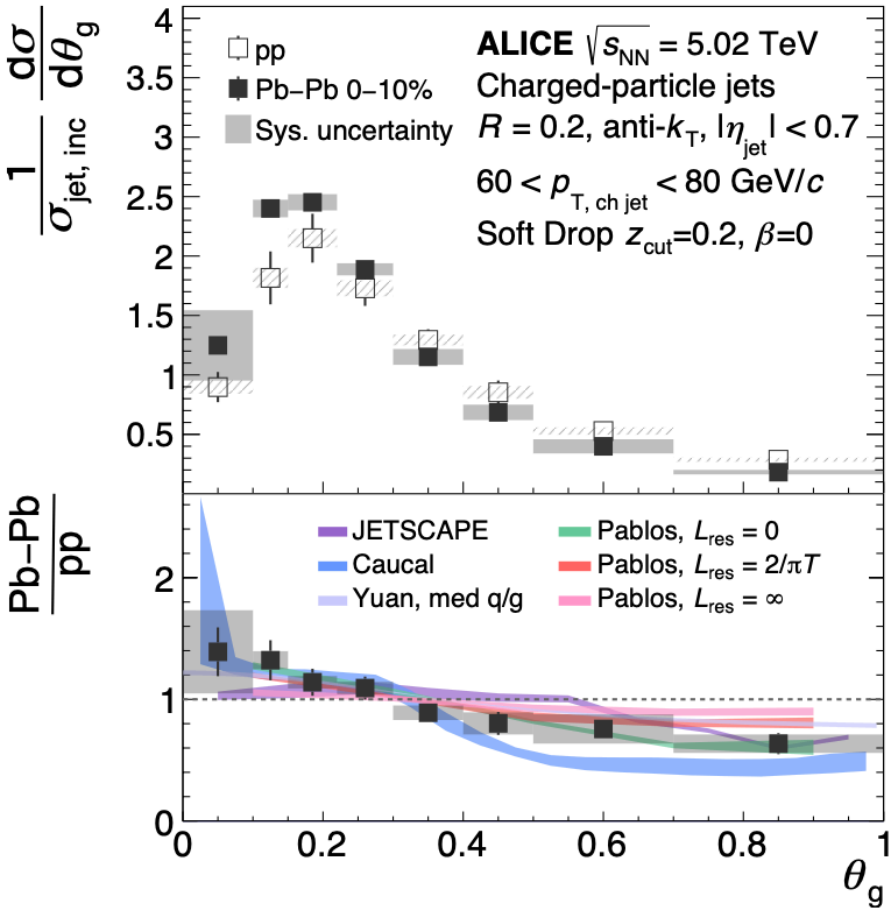
- How the hard splitting core of jet is modified? Does the jet quenching magnitude depends on that?
- Grooming: access to the hard parton structure of a jet
  - Remove the large angle soft radiation (suppress UE)

Figure credit:
James Mulligan



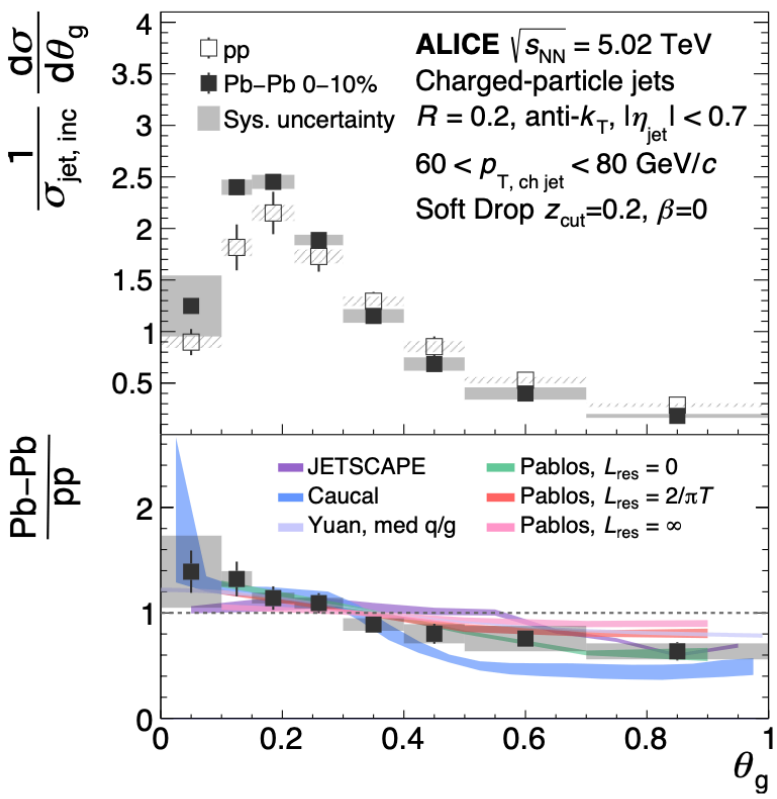
The cores of jets are narrower in PbPb compared to pp

PRL 128, 102001 (2022)



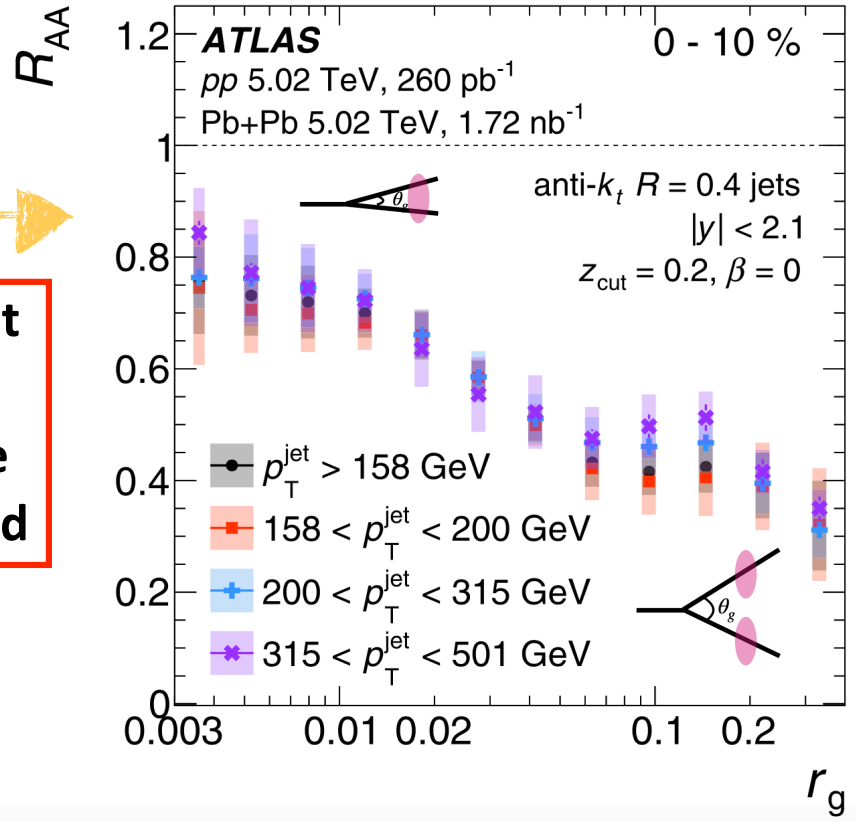
Jets with wider cores wider are more suppressed?

PRL 128, 102001 (2022)



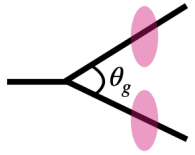
Narrowing of jet core: jets with wider cores are more suppressed

Phys. Rev. C 107, 054909 (2023)



- **Two possible explanations:**
  - **Wider jets are more resolved by medium: sensitive to QGP resolution scale (θ_c)**
  - **Wider gluon jets are more suppressed as compared to narrower quark jets: color charge difference**

$\theta_g > \theta_c$



$\theta_g < \theta_c$

Interesting to measure in γ/Z-jets

Energy-energy correlators (EEC): energy correlation inside jets

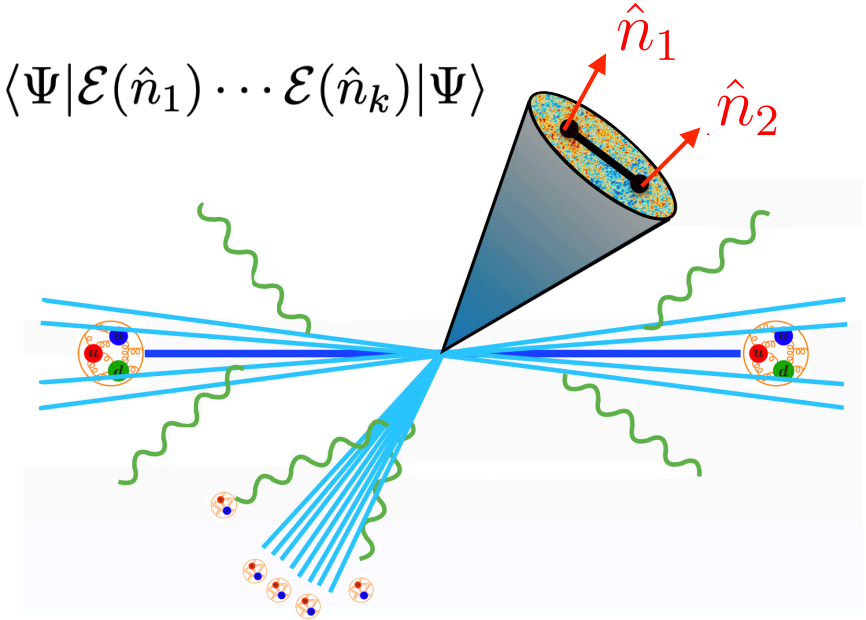
$$\frac{\mathrm{d}\sigma_{\mathrm{EEC}}}{\mathrm{d}R_{\mathrm{L}}} = \sum_{i,j} \int d\sigma(R'_{\mathrm{L}}) \frac{p_{\mathrm{T},i}\, p_{\mathrm{T},j}}{p^2_{\mathrm{T,jet}}} \delta(R'_{\mathrm{L}} - R_{\mathrm{L},ij})$$

Energy weight

Angular distance

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

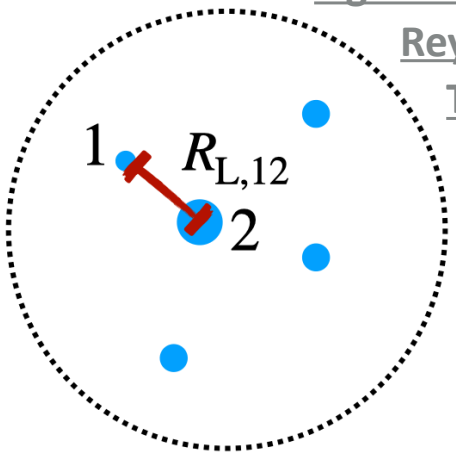
Step 1. Jet clustering



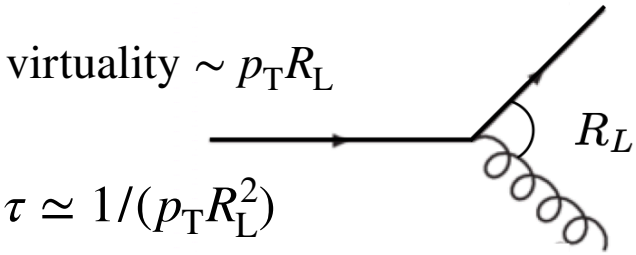
Step 2. Count number of weighted track pairs as function of R_L

Figure credit: Rey Cruz Torres

$$\frac{p_{\mathrm{T},1}\, p_{\mathrm{T},2}}{p^2_{\mathrm{T,jet}}}$$



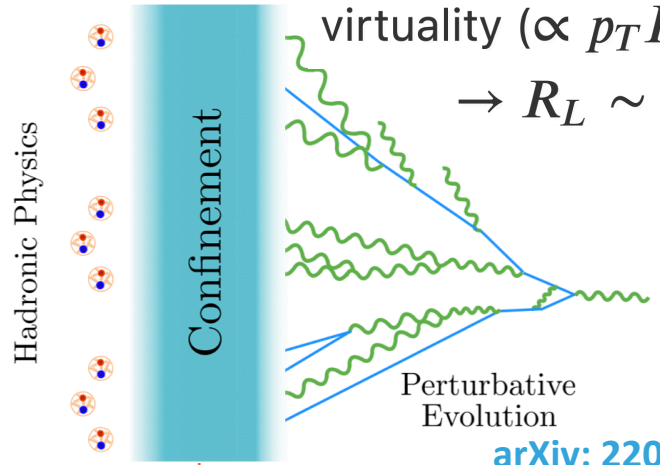
- **IRC safe and well-defined in QFT: correlation functions of the energy flux**
  - **pQCD calculation available for p+p**
  - **Soft background suppressed by energy weight**
  - **Probing fixed scale with fixed R_L**



Small R_L ← **Increasing τ / decreasing μ** → **Large R_L**

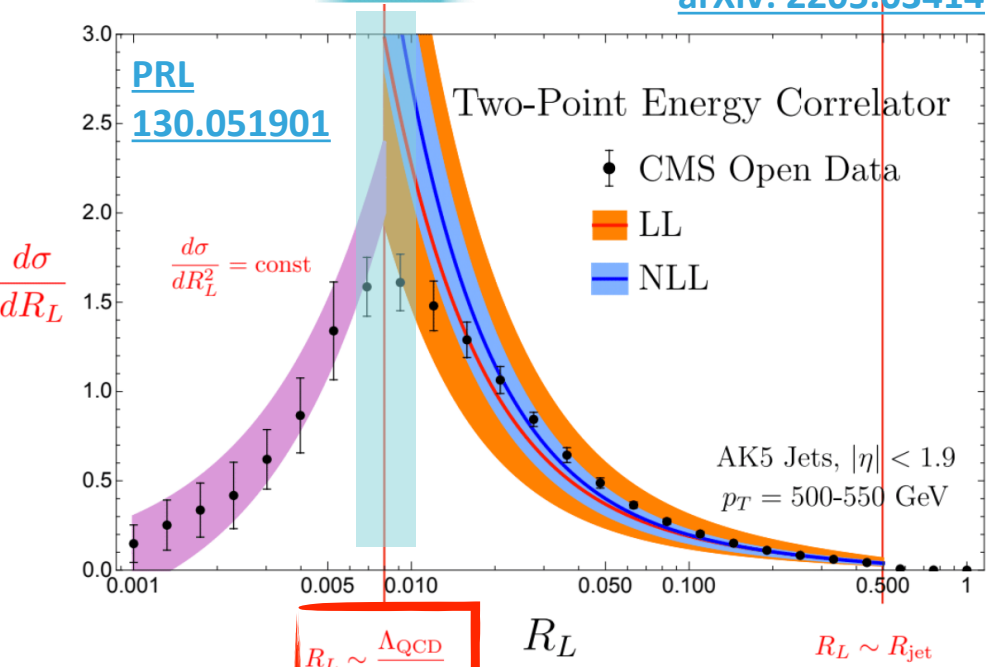
Clear separation of parton region and hadron region

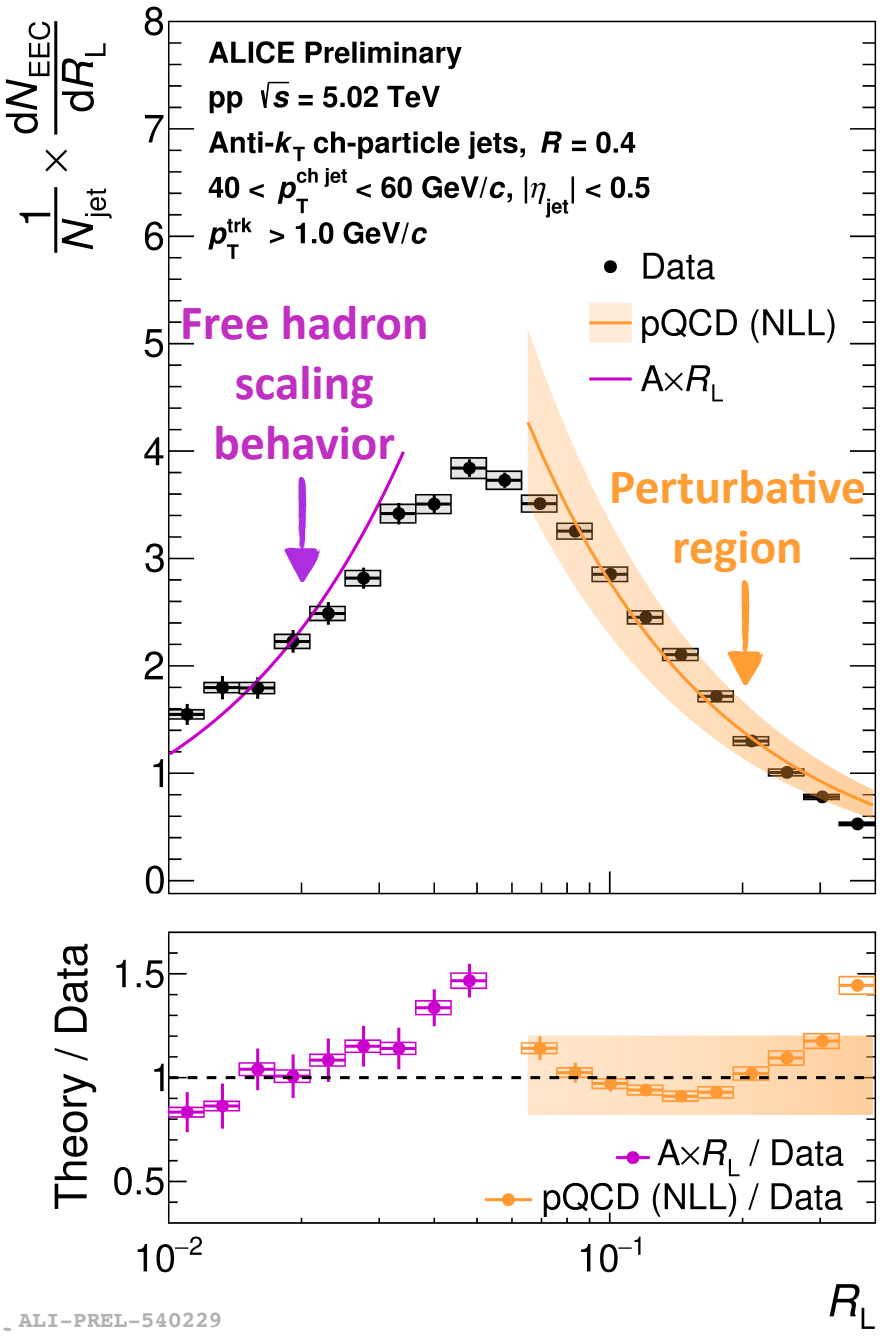
When the virtuality approaches $\mathcal{O}(\Lambda_{QCD})$, EEC undergo transition into confinement region



$$\text{virtuality } (\propto p_T R_L) \sim \Lambda_{QCD}$$
$$\rightarrow R_L \sim \Lambda_{QCD}/p_{T,\,jet}$$

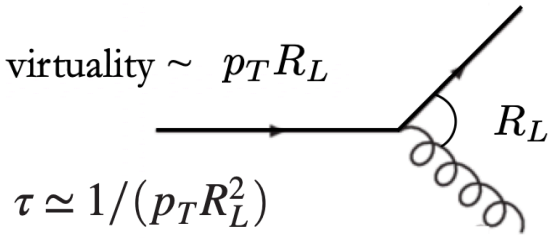
arXiv: 2205.03414



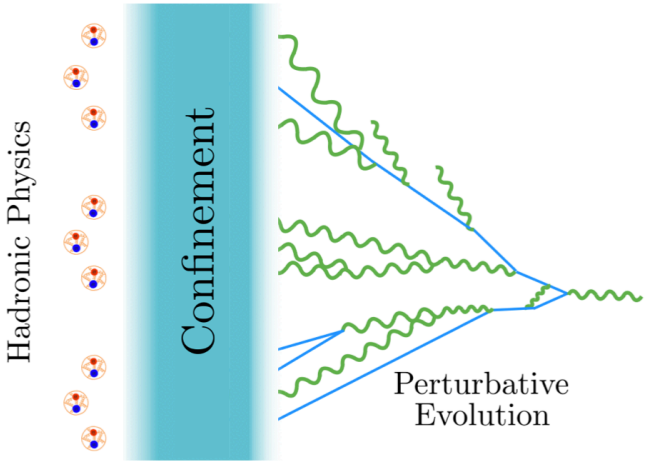


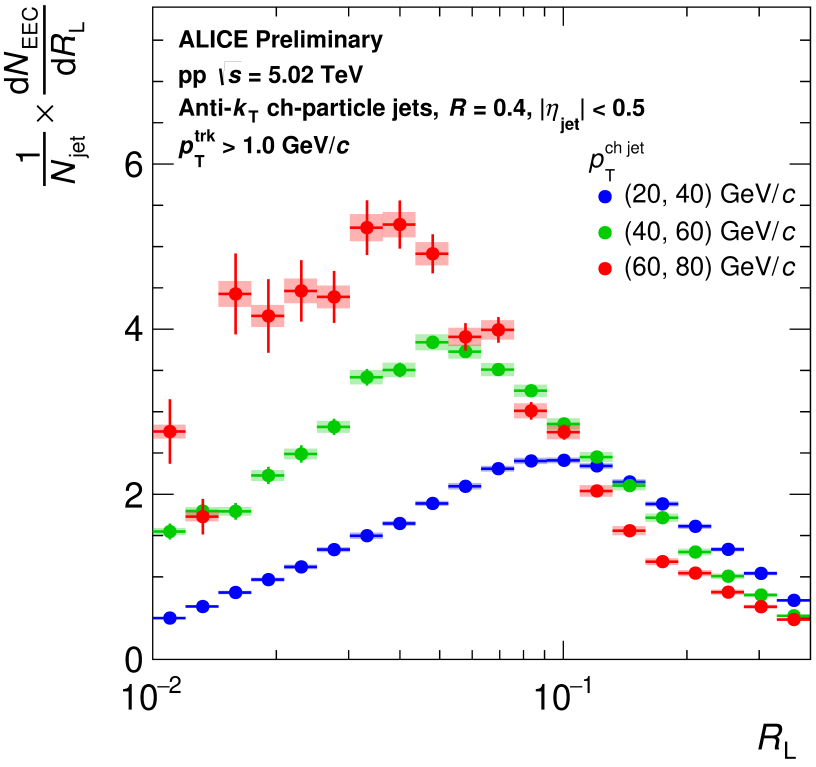
ALI-PREL-540229

Universal behavior of the transition region



Scaling angle R_L by jet p_T and normalize y scale





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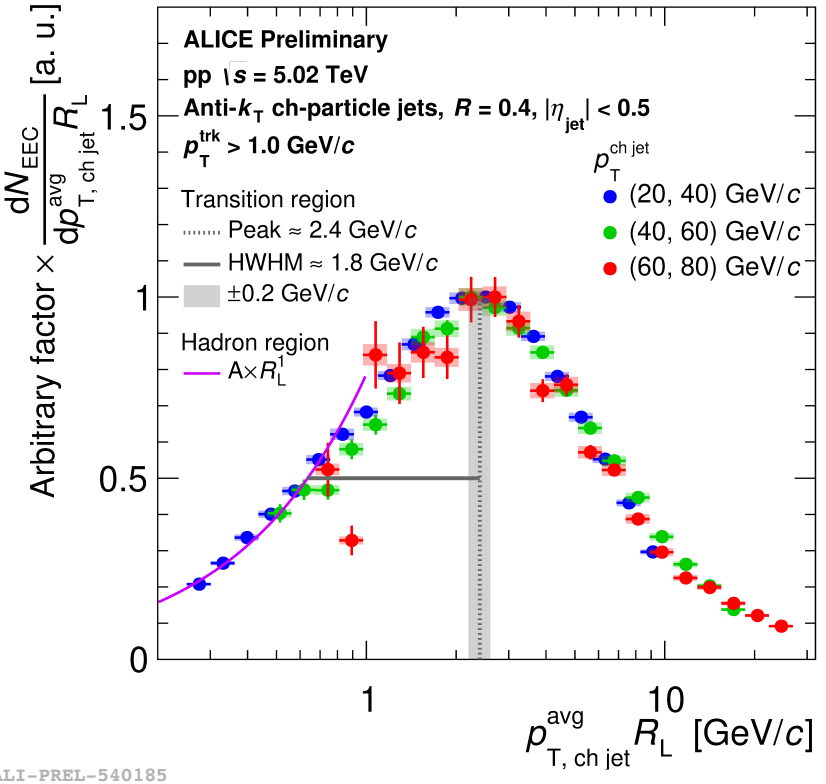
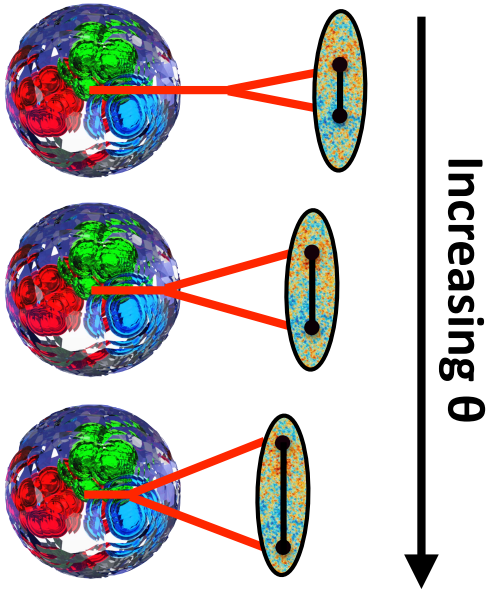


ALI-PREL-540185

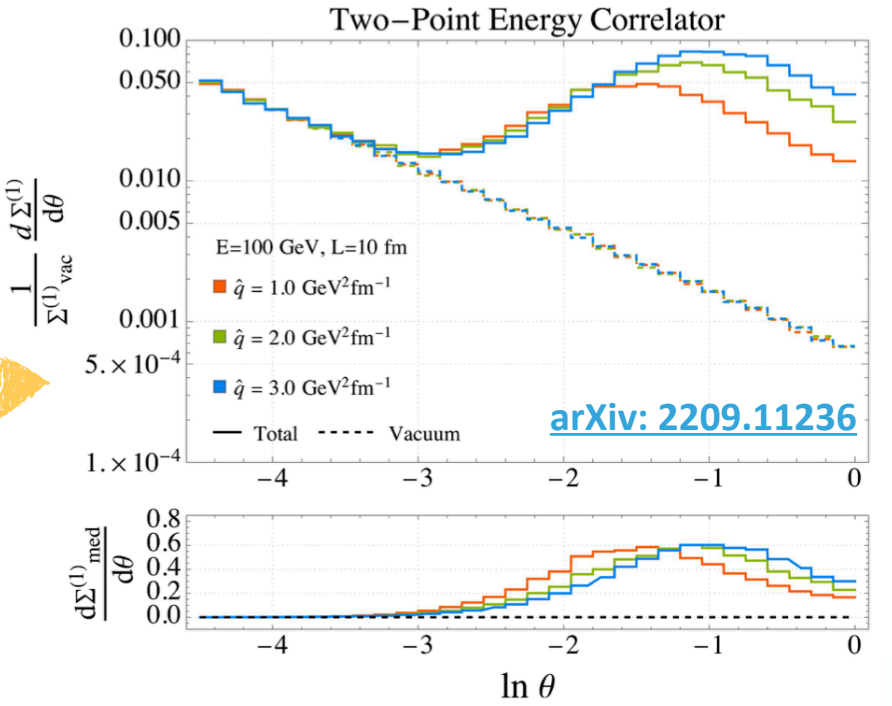
EEC distributions in different jet p_T bin have similar shape

Transition peak position ~2.4 GeV

Probing different scales in QGP with energy correlators

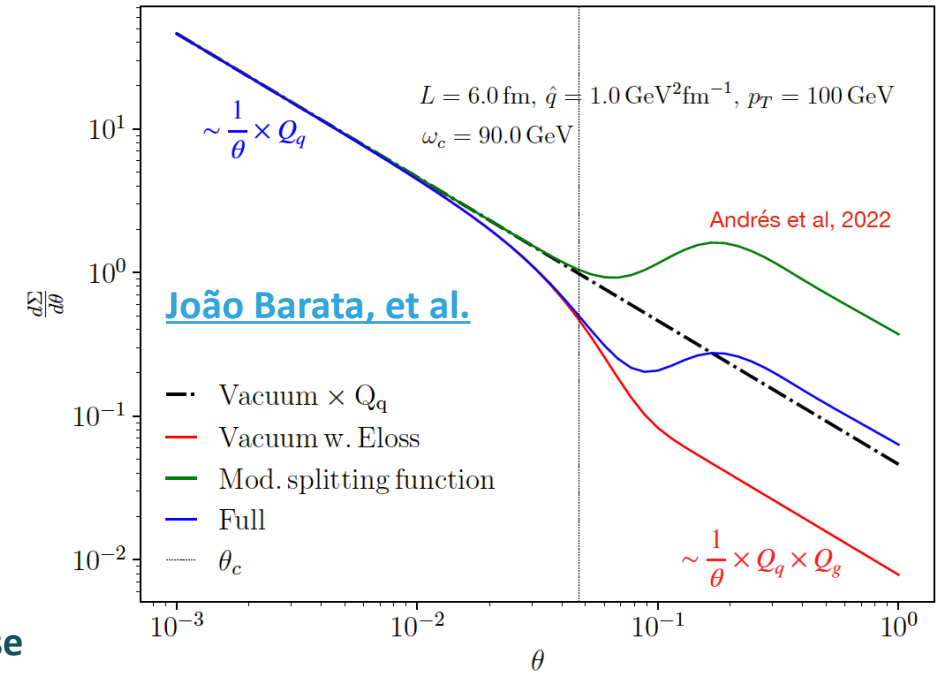


Onset of modification sensitive to medium size



- In the perturbative region:
  - Induced splitting when parton shower in the medium ➜ enhancement at large angle
  - Energy loss of the hard splitting ➜ suppression at large angle
- In the NP region: modified hadronization?

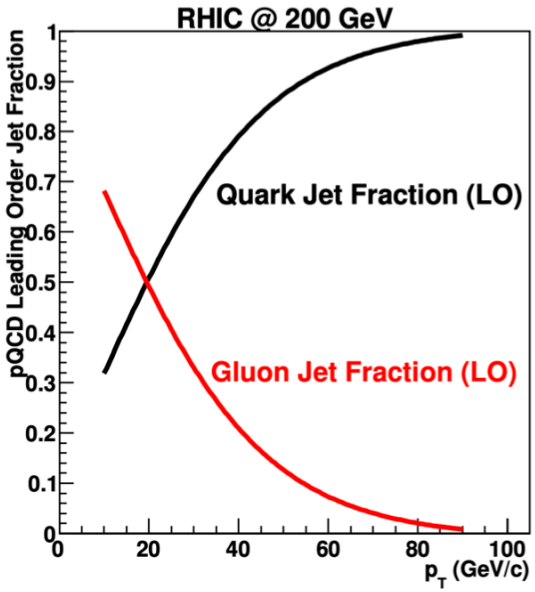
PbPb data analysis ongoing!



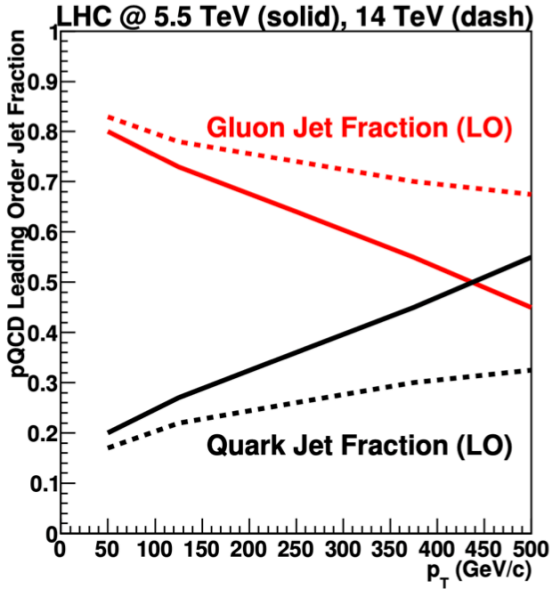
RHIC + LHC: a coherent global picture

- Overlapping and non-overlapping kinematic ranges
  - Consistency in the overlapping region
  - Unique kinematic coverage from RHIC to LHC (medium temperature, q/g fraction)

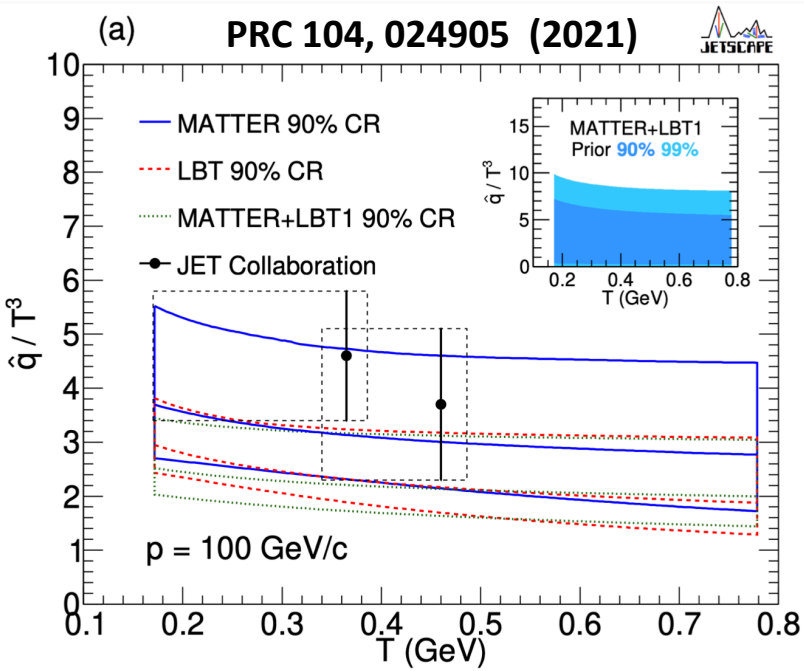
RHIC



LHC



- p + p: universality of factorization in pQCD, constraining non-perturbative effects for lower energy regime
- A + A: a coherent global picture of interaction between colored object and de-confined QGP and **quantitatively** understanding of the medium property



Summary and outlook

- What have we learnt from result shown
  - New kinematic regimes explored (low p_T, large R) in order to fully capture the dynamics of jet quenching
  - Correlation between the magnitude of energy loss and inner structure of jet
  - New and more precise information on color and mass dependence of energy loss with γ/Z-jet and heavy flavor jet

- General trend moving forward
  - More precise (high luminosity, upgraded detectors) + new tools (ML for calibration/ tagging/background subtraction/unfolding)
  - More differential: z_g vs R_g, gluon/light quark/heavy quark, event shape engineer etc.
  - Develop new observable sensitive to particular underlying physics process