Latest Jet Measurements at the LHC

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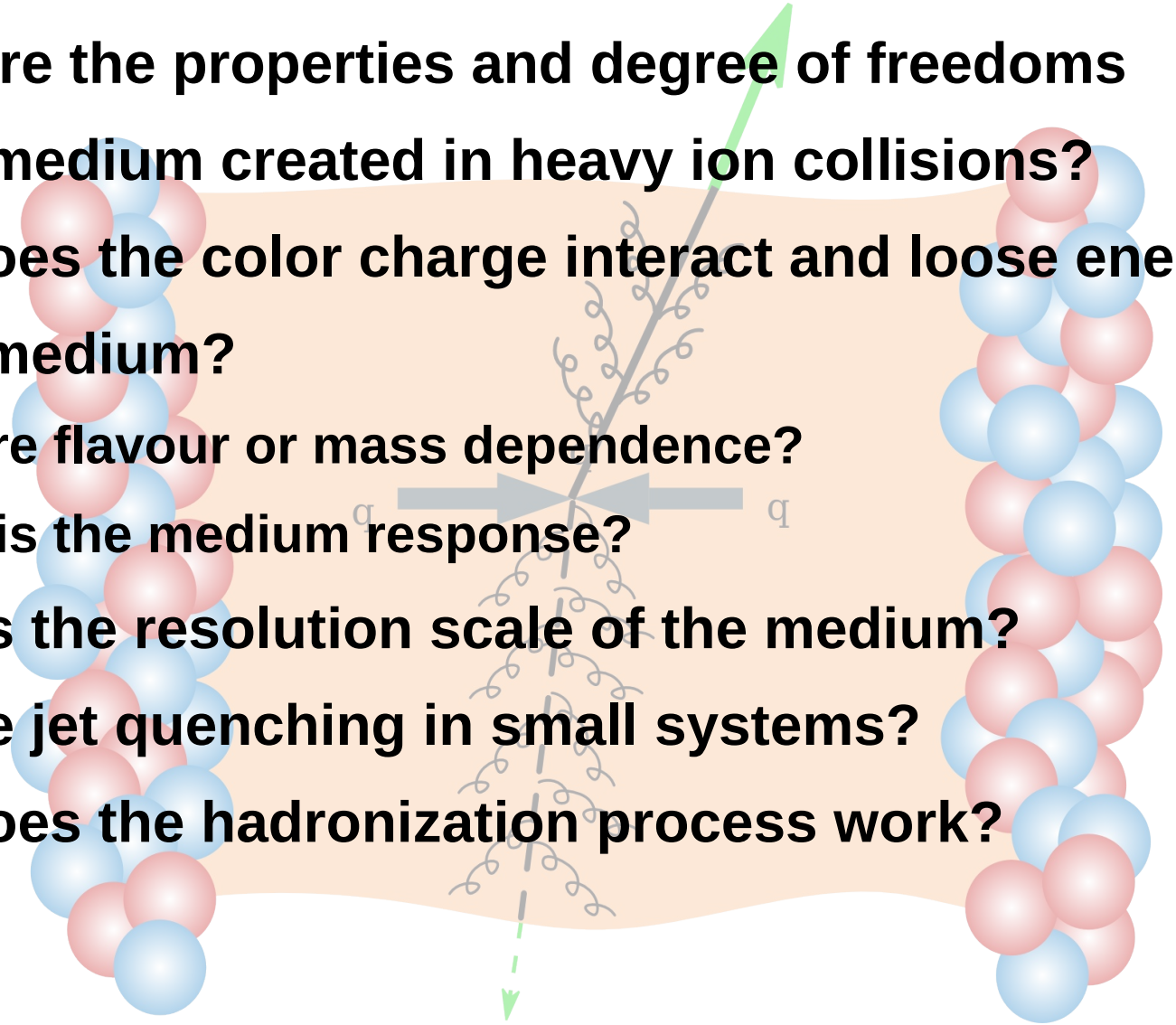
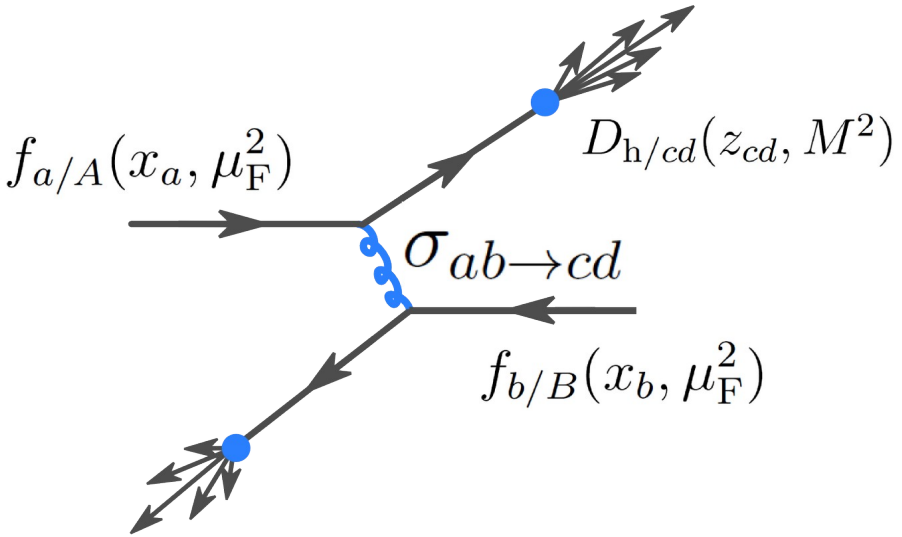
What do we want to know...

- What are the properties and degree of freedoms of the medium created in heavy ion collisions?
- How does the color charge interact and loose energy in the medium?
  - Is there flavour or mass dependence?
  - What is the medium response?
- What is the resolution scale of the medium?
- Is there jet quenching in small systems?
- How does the hadronization process work?



Jets as probes of QGP

We can use jets to answer these questions!



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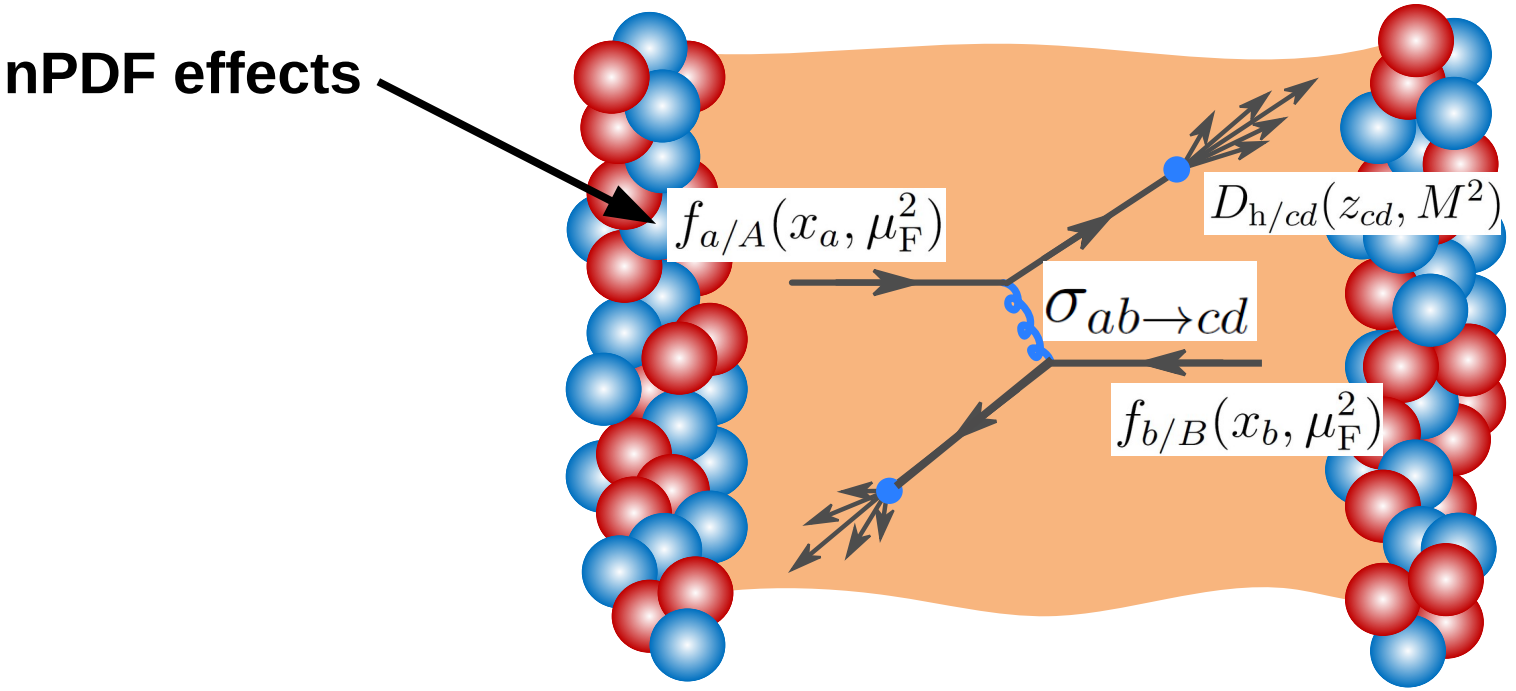

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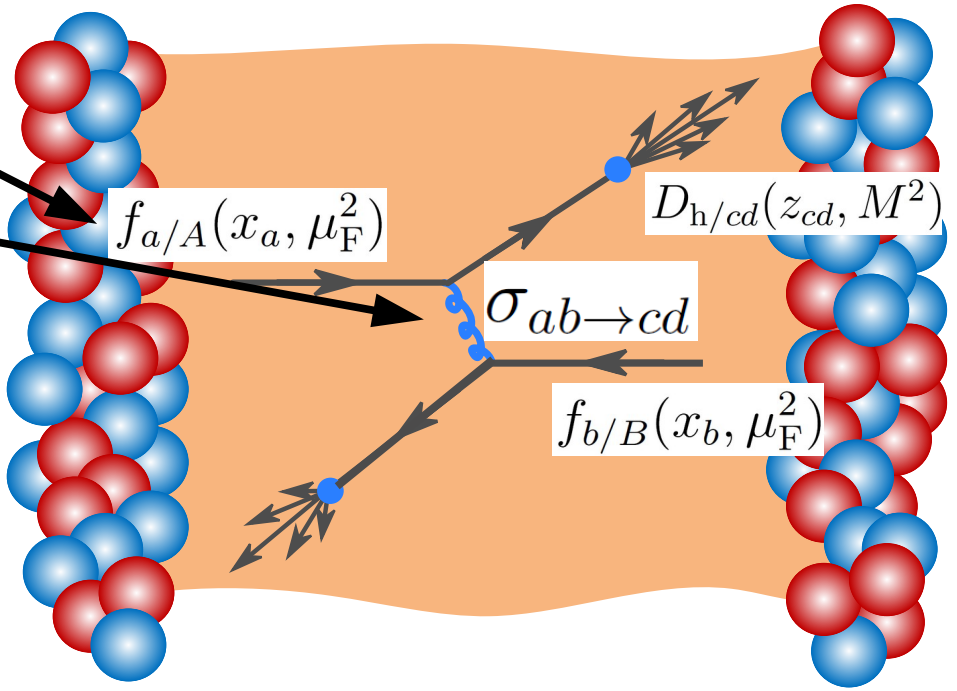
nPDF effects

Hard scattering: high energy, short distance



Jets as probes of QGP

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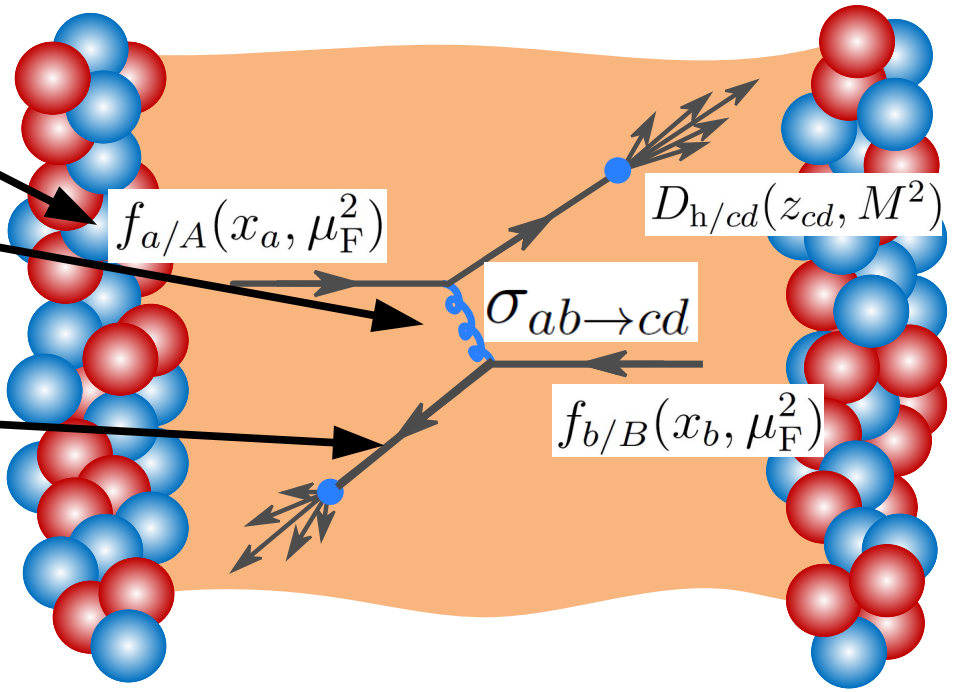
nPDF effects

Hard scattering: high energy, short distance

Emissions of collinear and soft partons



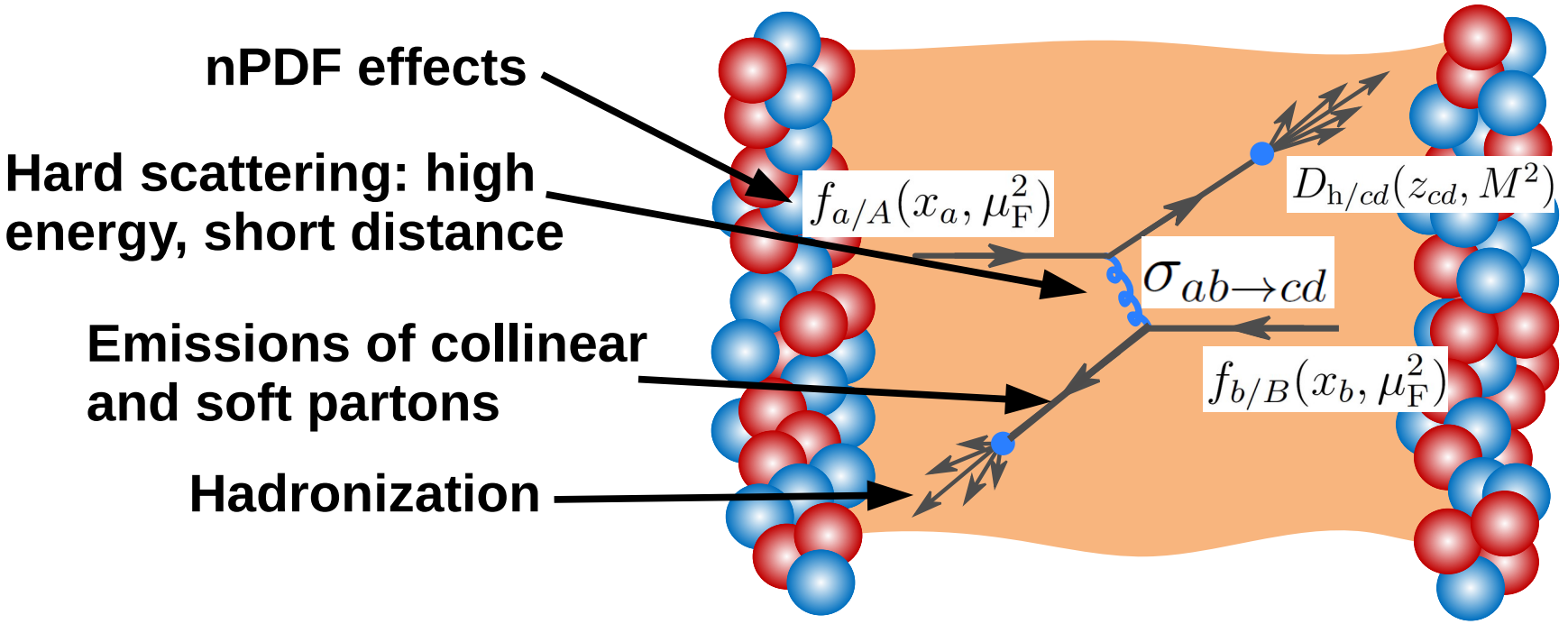
- Elastic scattering, medium induced radiation or “drag force” in strong coupling picture.

➡ fast partons lose energy ➡ jet quenching

- Jets are multi-scale probes of QGP.

Jets as probes of QGP

We can use jets to answer these questions!



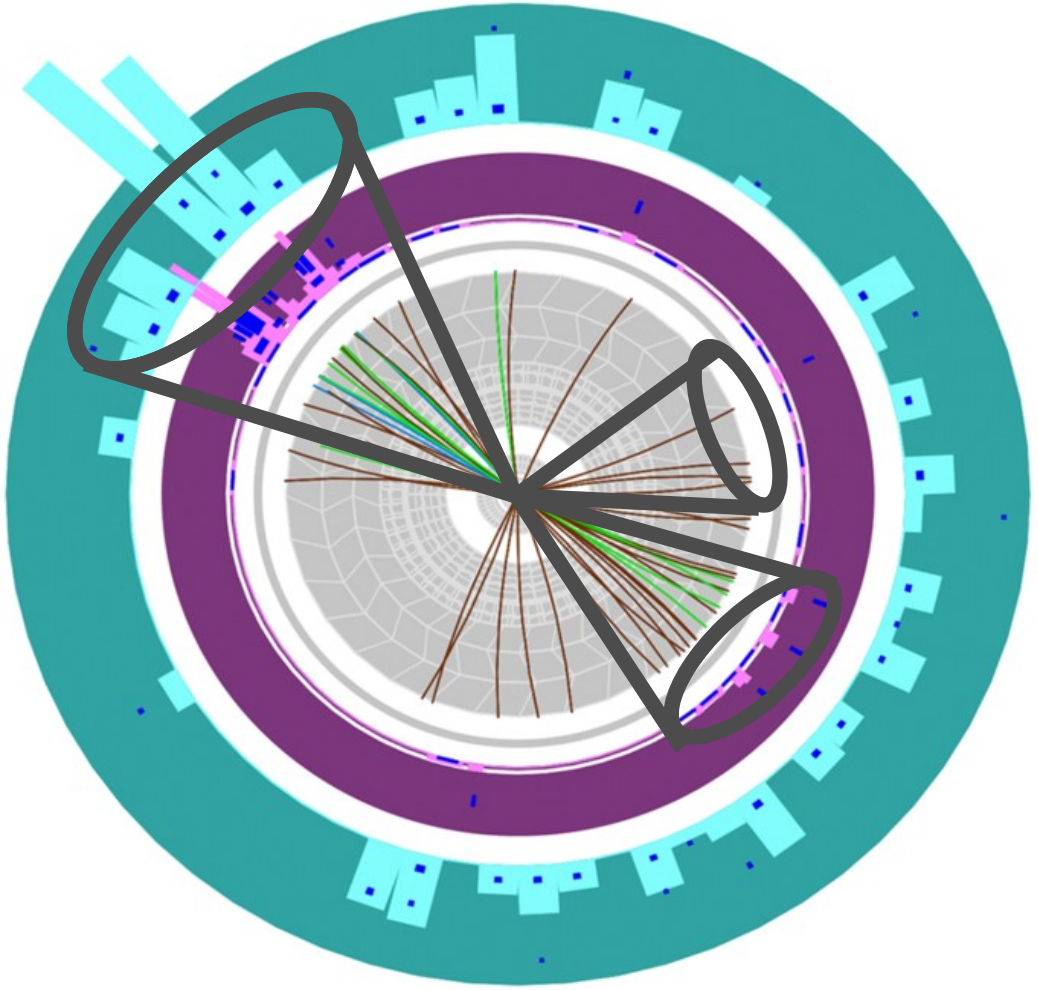
- Elastic scattering, medium induced radiation or “drag force” in strong coupling picture.

➡ fast partons lose energy ➡ jet quenching

- Jets are multi-scale probes of QGP.

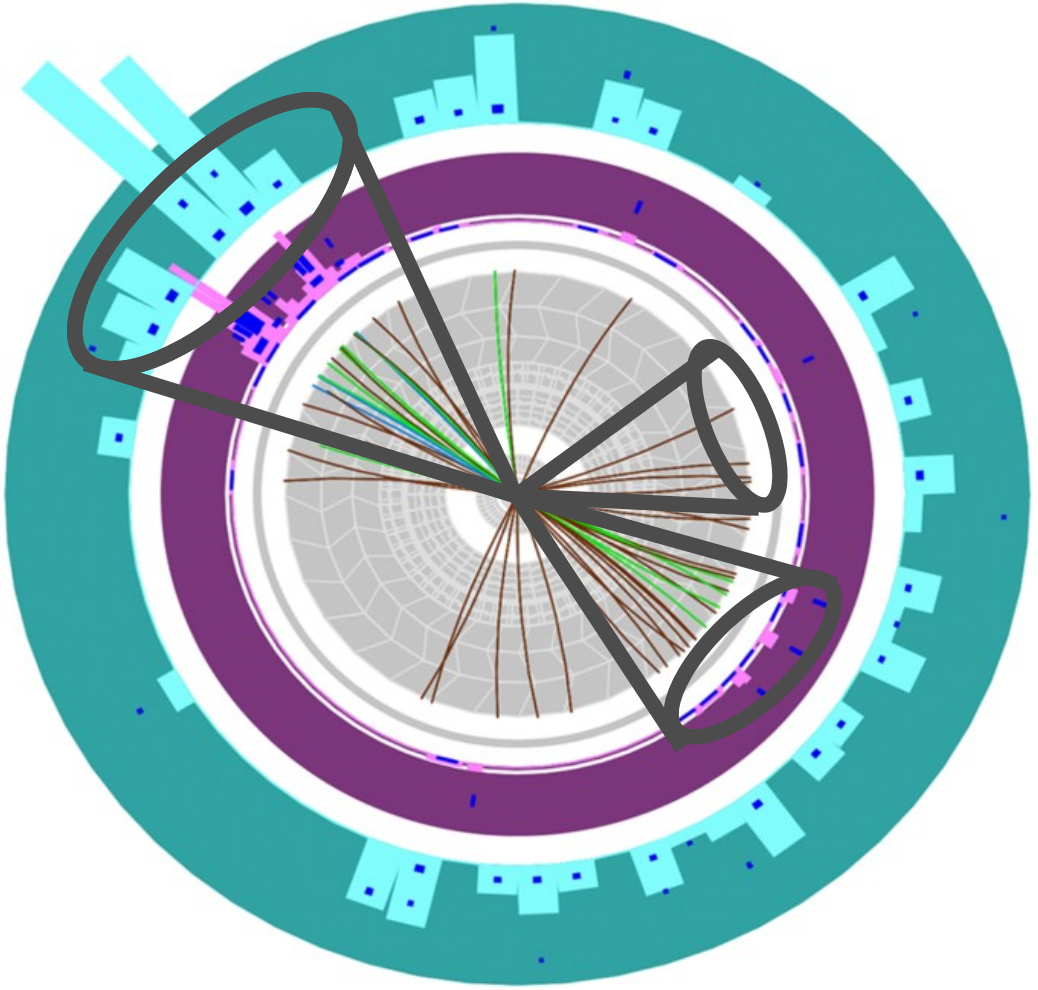
Jet quenching measurement

Many observables: inclusive jets, balance, jet structure...



…each observable is sensitive to different aspects of energy loss.

Let’s start with jet counting….



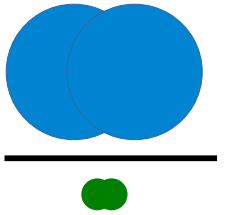
Measure of modifications: Nuclear modification factor

- Observable: nuclear modification factor.

QCD in medium

Yields in A+A

$$R_{AA} = \frac{1}{N_{\mathrm{coll}}} \frac{\mathrm{d}N_{AA}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}N_{pp}/\mathrm{d}p_{\mathrm{T}}} = \frac{1}{T_{AA}} \frac{\mathrm{d}N_{AA}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}}}$$



QCD in vacuum

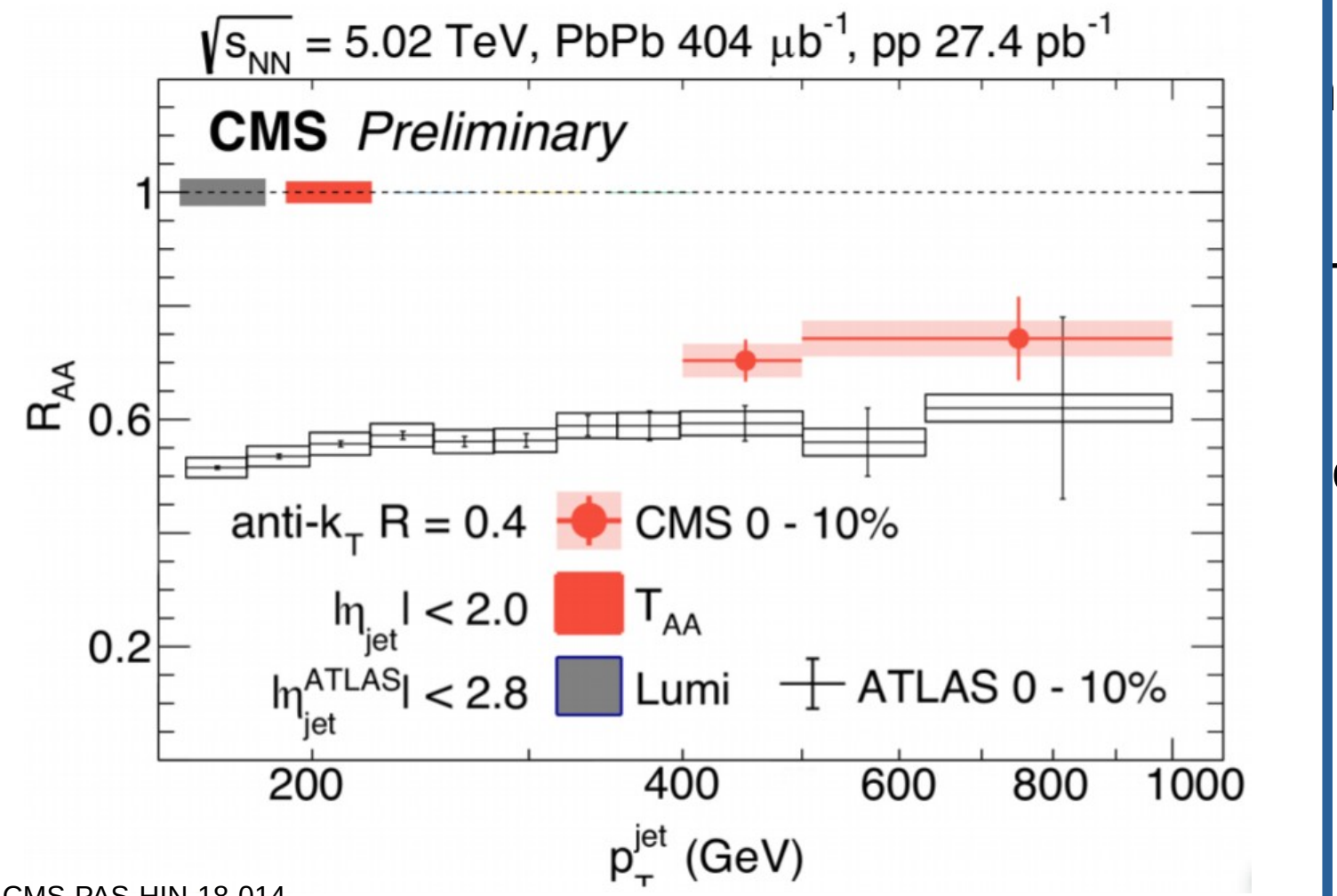
pp reference

Caveats on R_{AA}:
Sensitive to shapes of p_{T} spectra

Measure of modifications: Nuclear modification factor

- Ob

R_A



CMS-PAS-HIN-18-014

A+A

$$\frac{\mathrm{d}N_{AA}/\mathrm{d}p_{\mathrm{T}}}{\mathrm{d}\sigma_{pp}/\mathrm{d}p_{\mathrm{T}}}$$

ence

Measure of modifications: Nuclear modification factor

- Ob

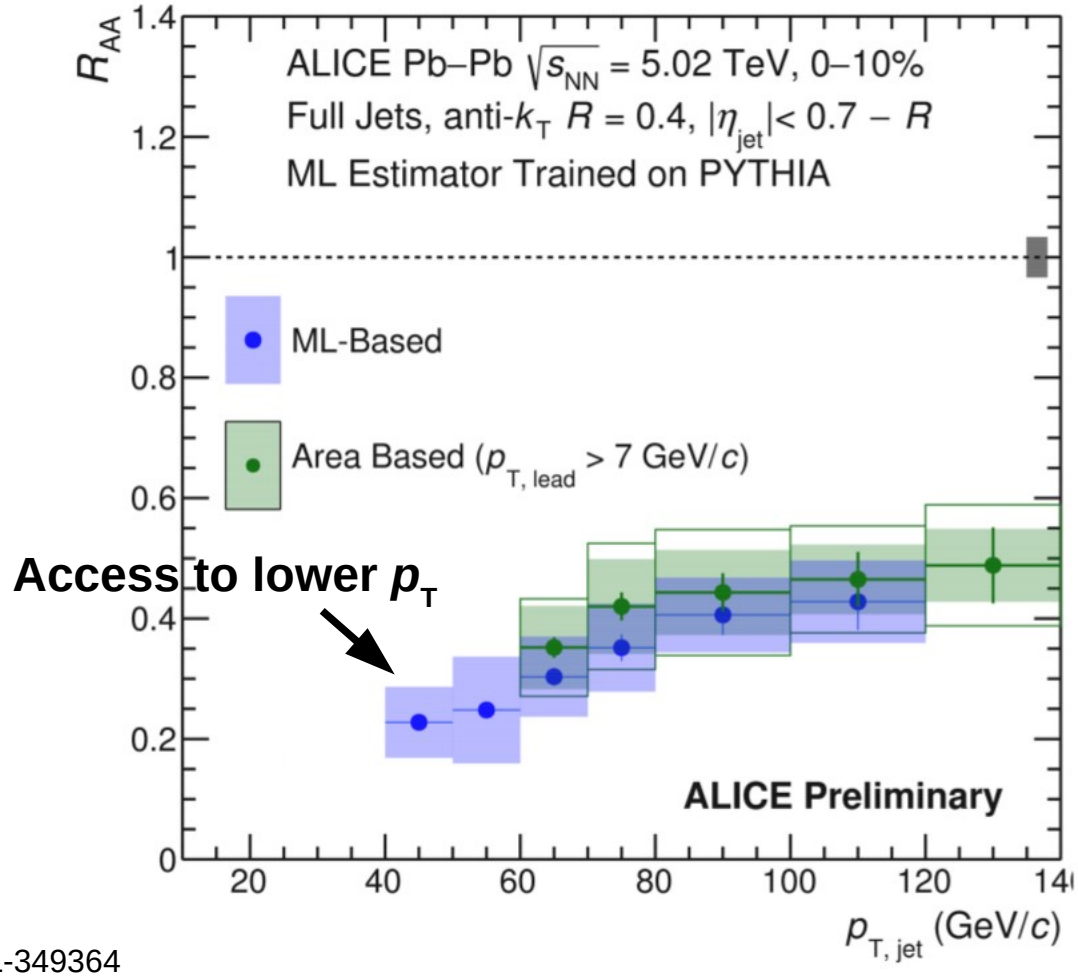
R_A

A+A

$$\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}} \Big/ \frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}p_{\mathrm{T}}}$$

ence

Using novel techniques to improve performance



ALI-PREL-349364

Measure of modifications: Nuclear modification factor

- Ob

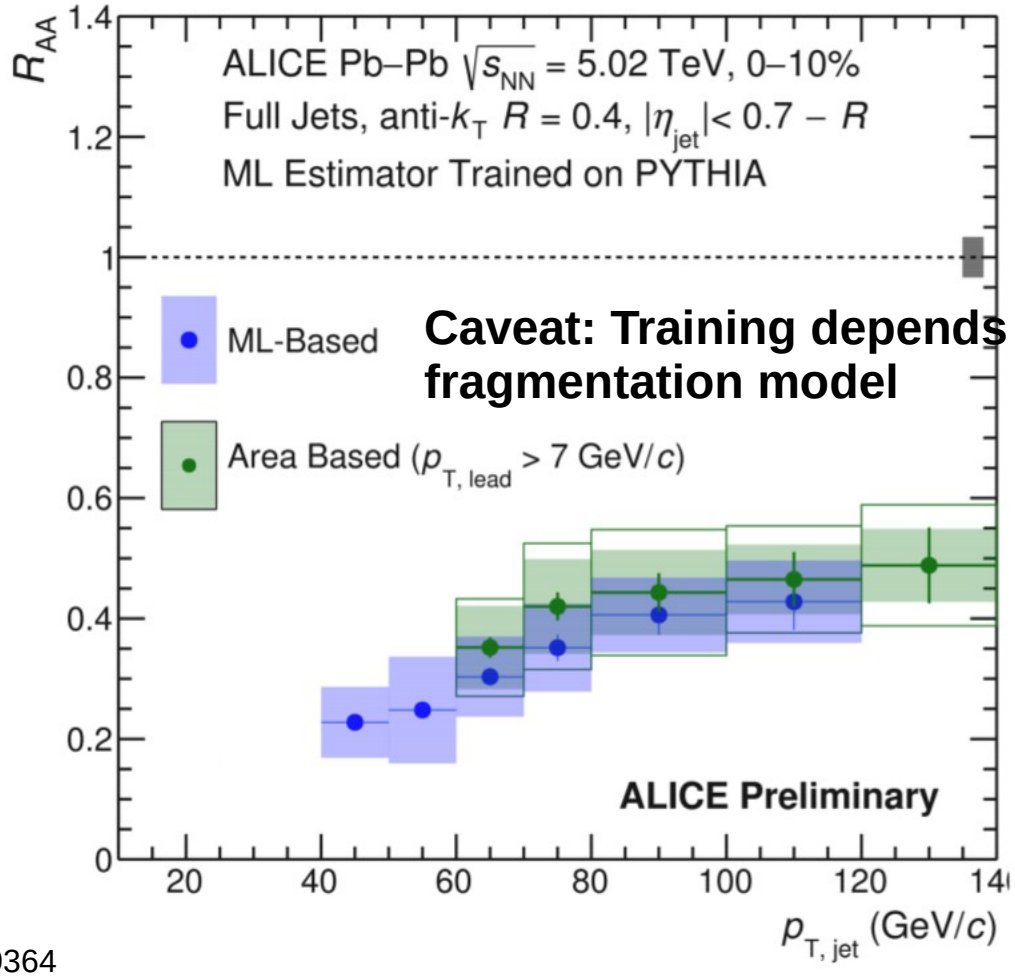
R_A

A+A

$$\frac{\mathrm{d}N_{AA}}{\mathrm{d}p_{\mathrm{T}}} \Big/ \frac{\mathrm{d}\sigma_{pp}}{\mathrm{d}p_{\mathrm{T}}}$$

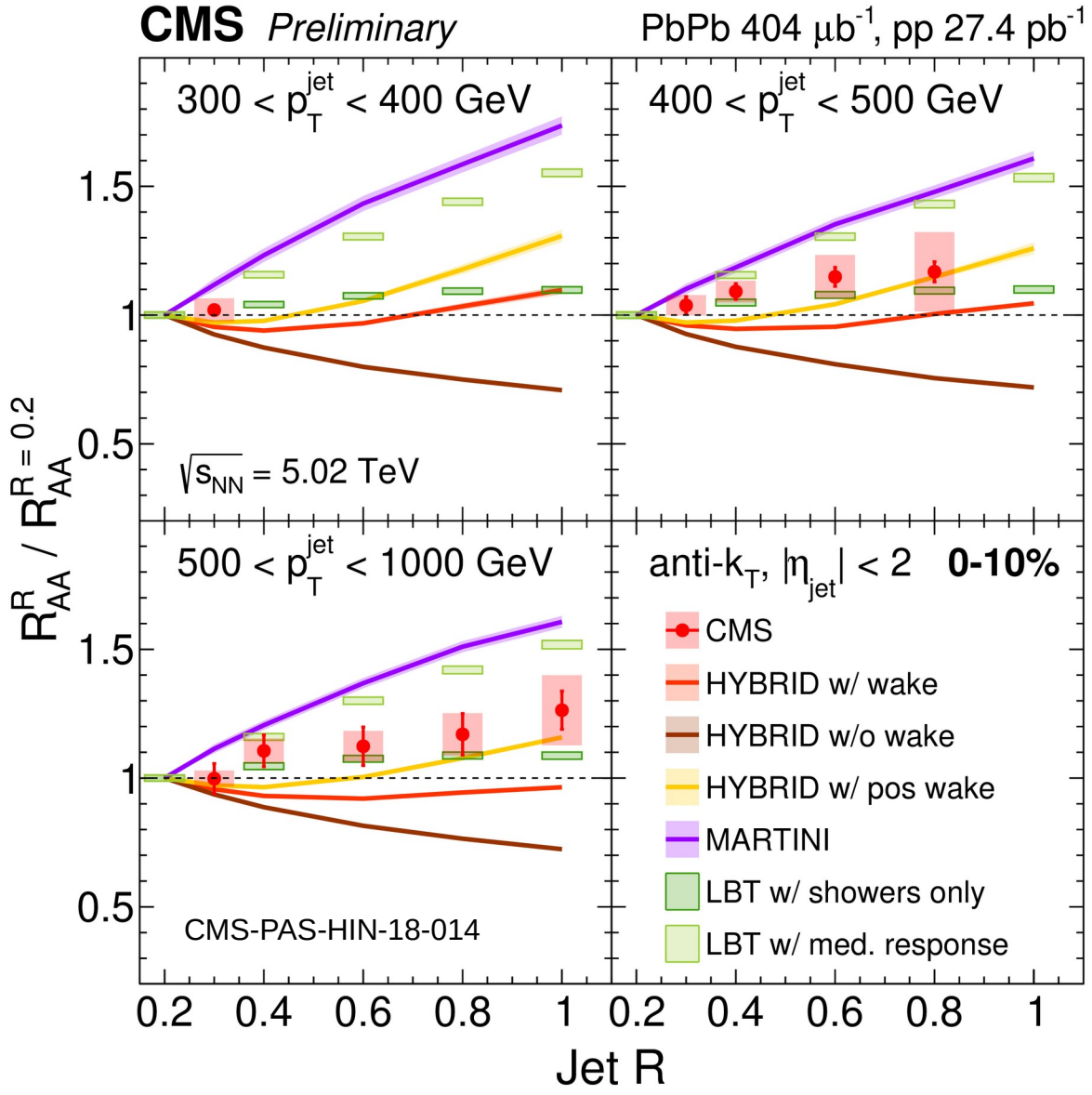
ence

Using novel techniques to improve performance



ALI-PREL-349364

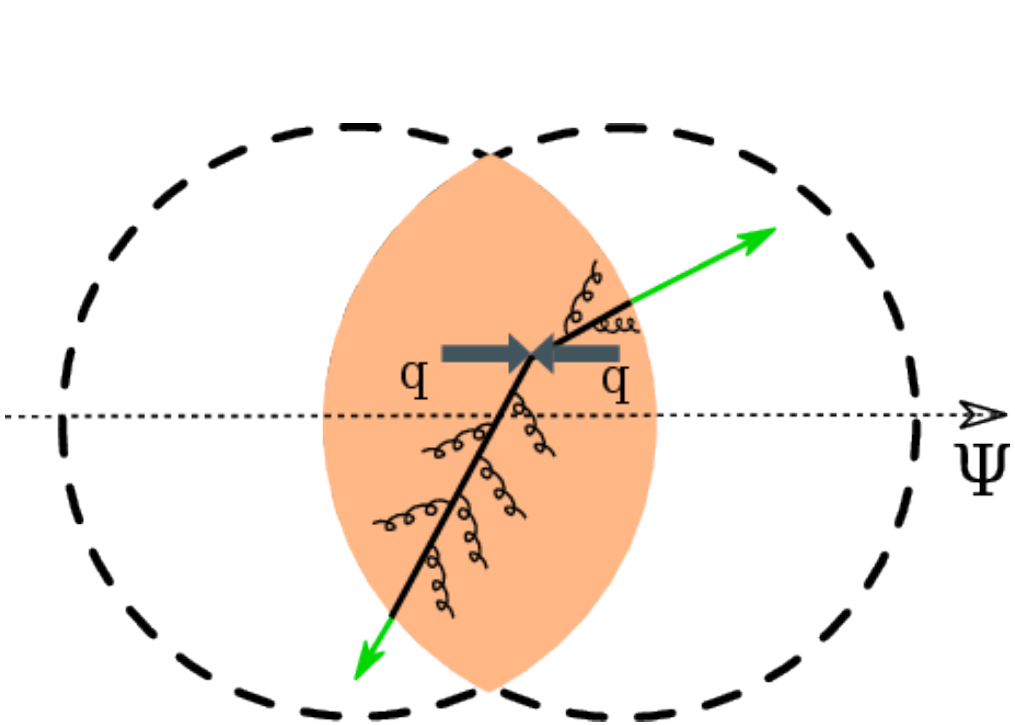
Radial scan for missing energy

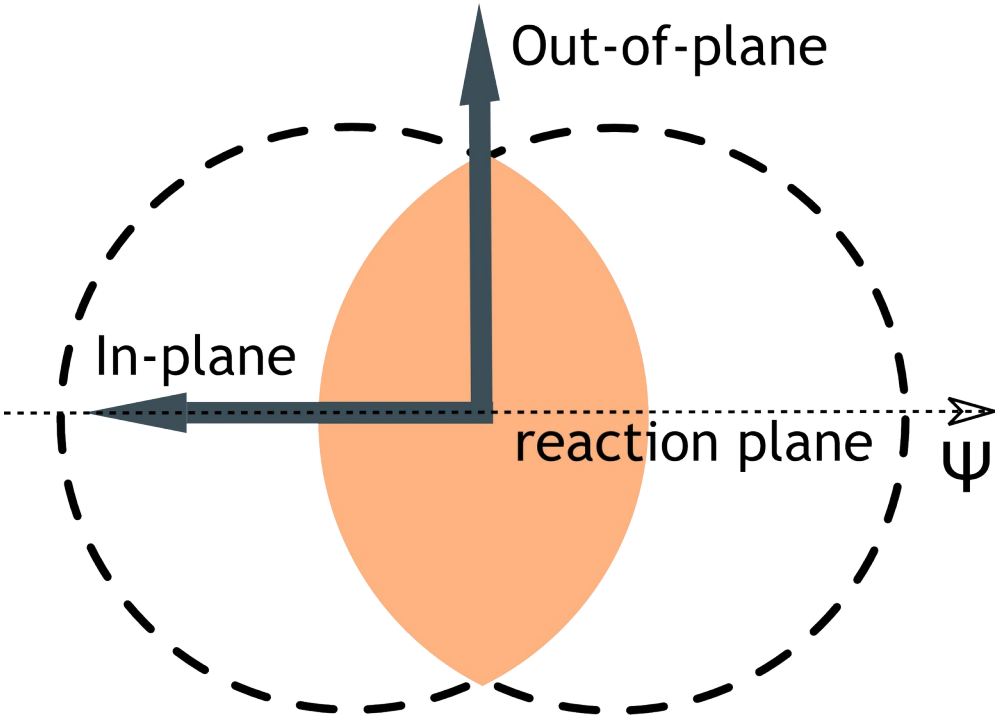


- Large underlying event restrict the phase space of the measurement.
- Measurement sensitive to the role of jet substructure in the quenching.
- Suppression is modestly recovered with larger *R*.
- Excellent discrimination power among models and their parameters.

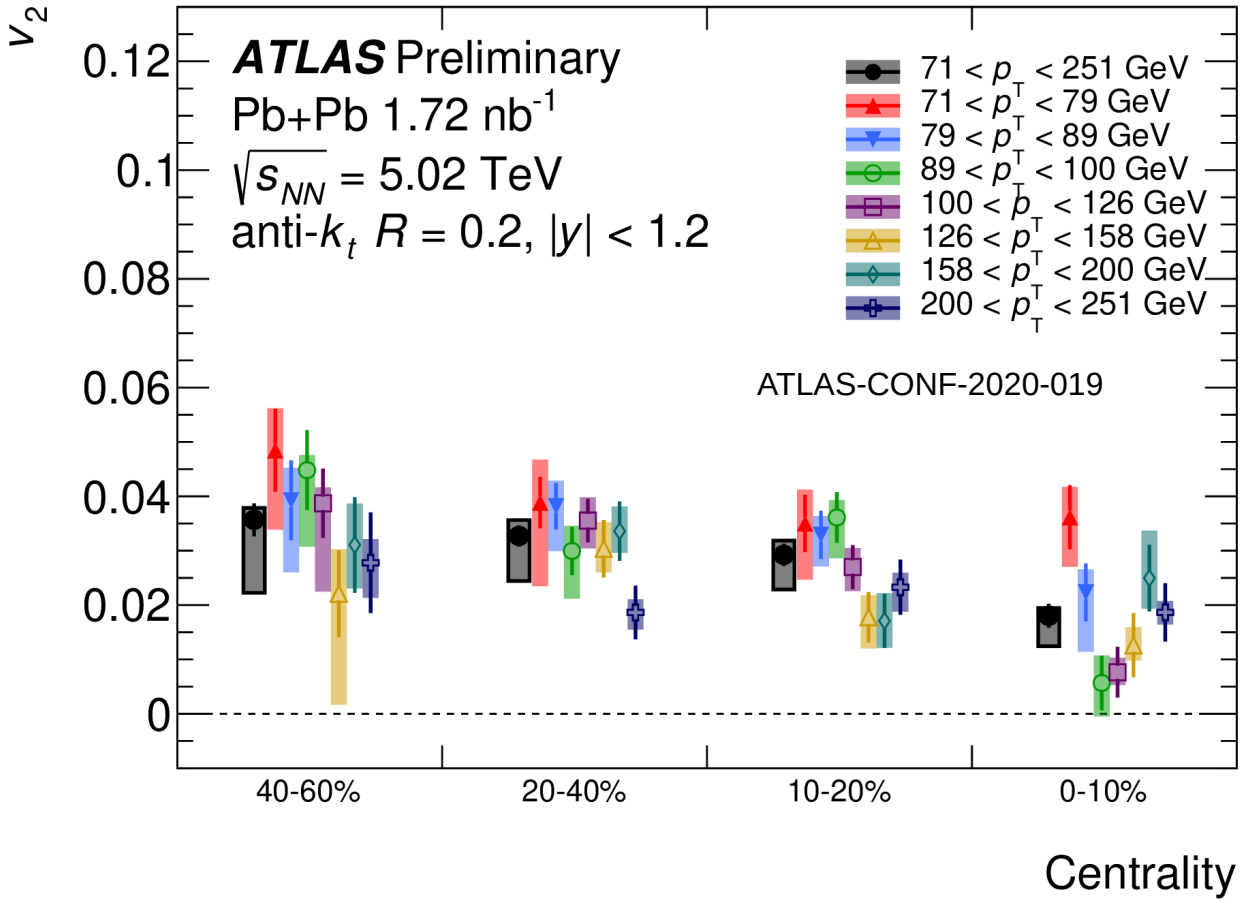
Jet anisotropies

- Measuring jet yields deferentially w.r.t. reaction plane.





Path-length dependence: jet v_2

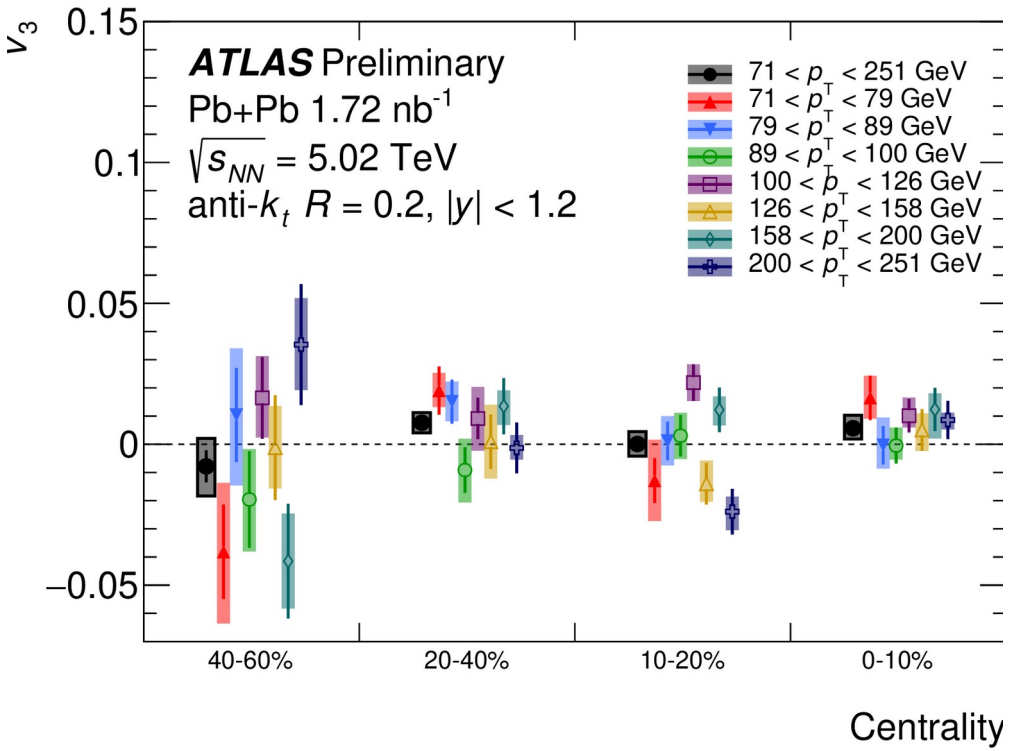


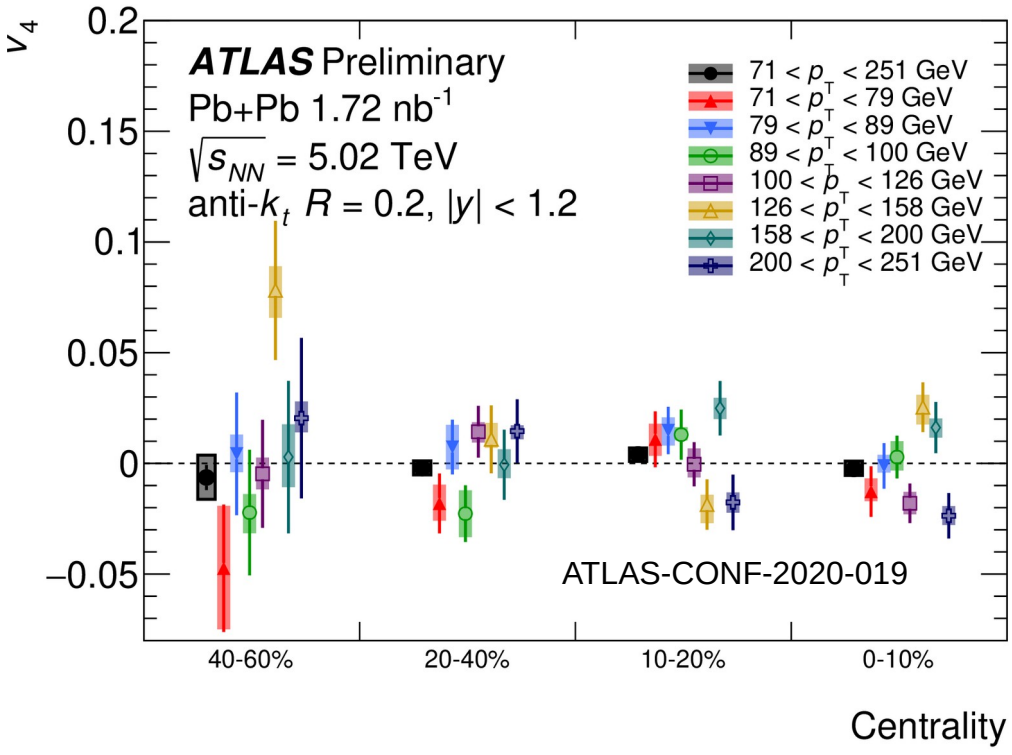
In-plane: shorter path length in the medium ➡ less suppression

Out-of-plane: shorter path length in the medium ➡ more suppression ➡ **positive v_2.**

Fluctuations: Jet $v_{n;n>2}$

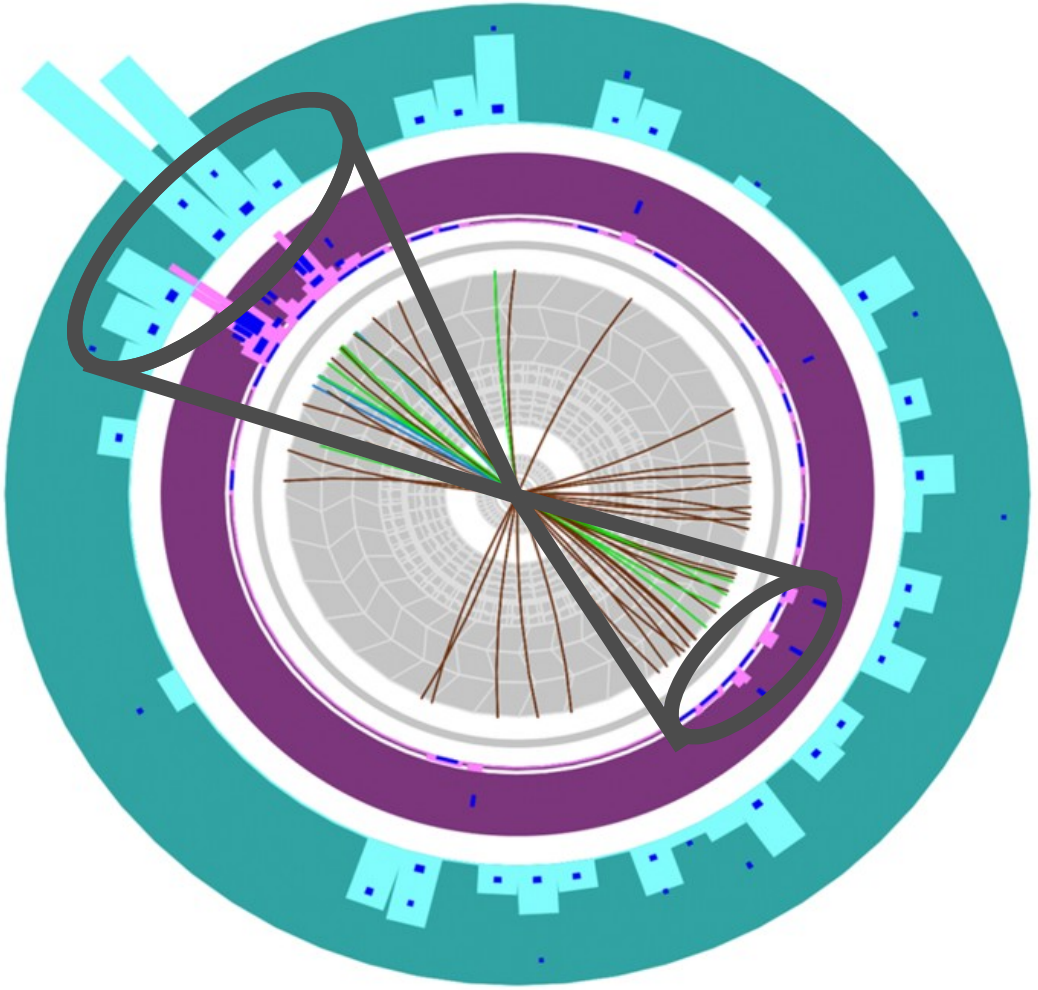
Can give insight into the role of fluctuations in the initial state.





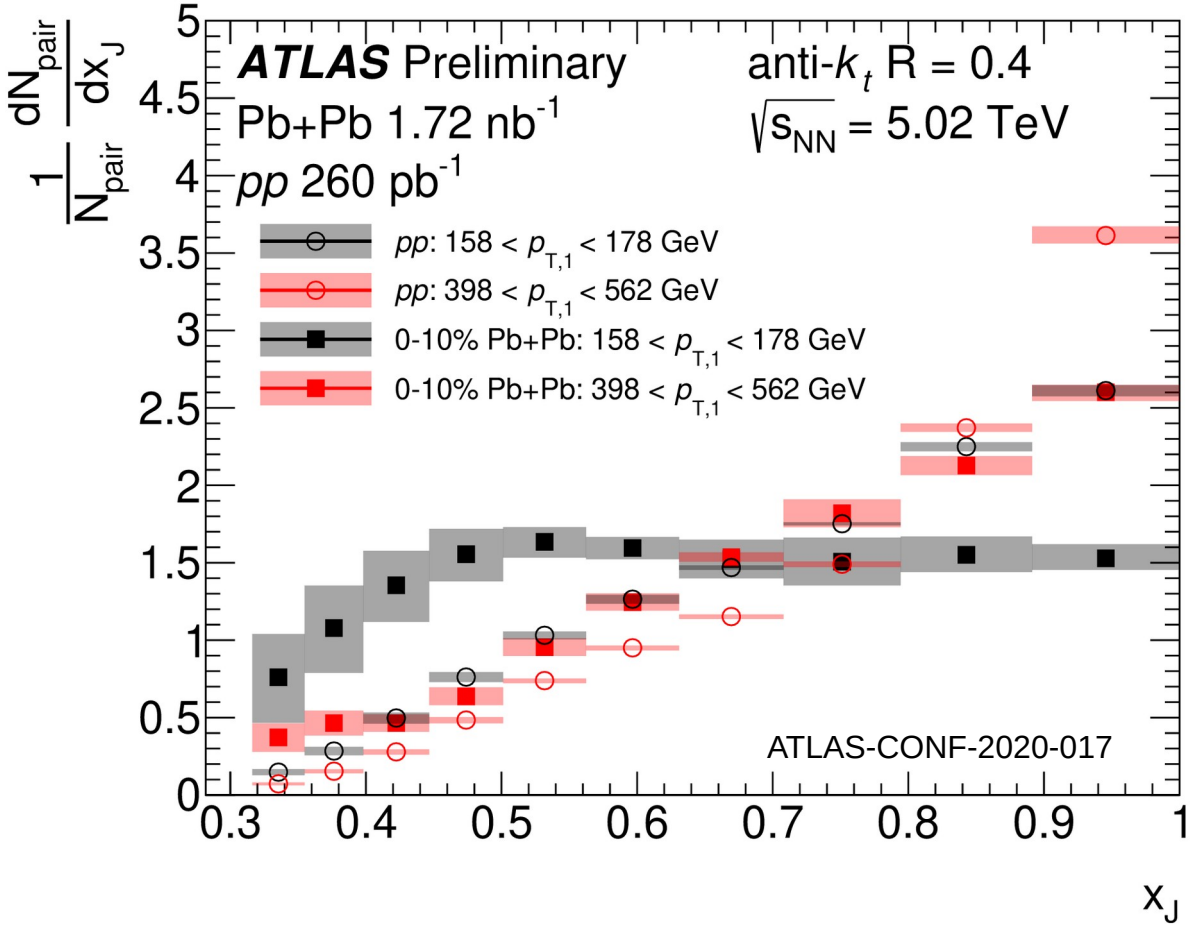
- Jet v_3 and v_4 compatible with 0 with current precision.

Balance & angular correlation measurements



Di-jet balance

Probes path-length dependence and per-jet fluctuations of the jet quenching.

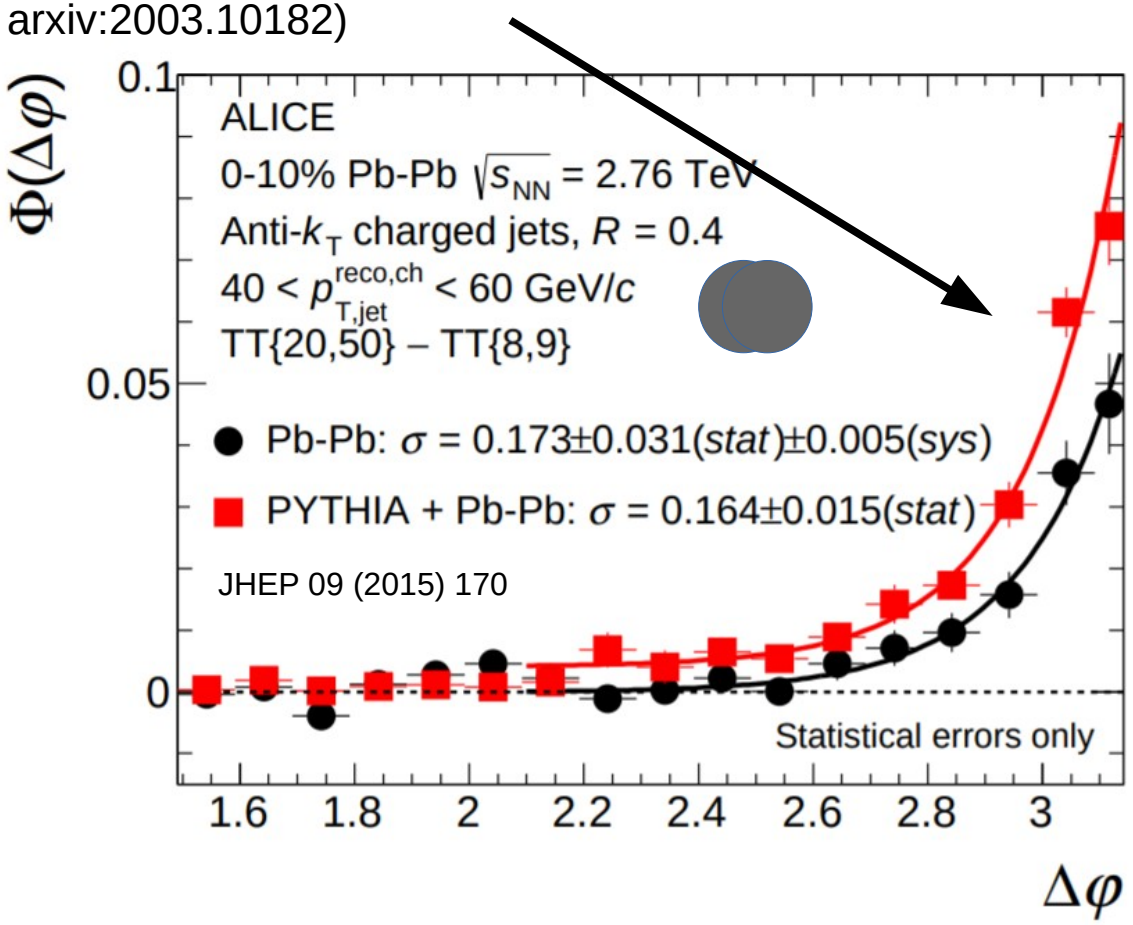


$$x_{\mathrm{J}} \equiv p_{\mathrm{T}_2}/p_{\mathrm{T}_1}$$

- Flattening of the x_{J} distributions in central Pb+Pb at lower p_{T}.
- Still some, but smaller, modification between Pb+Pb and *pp* for jets > 400 GeV.

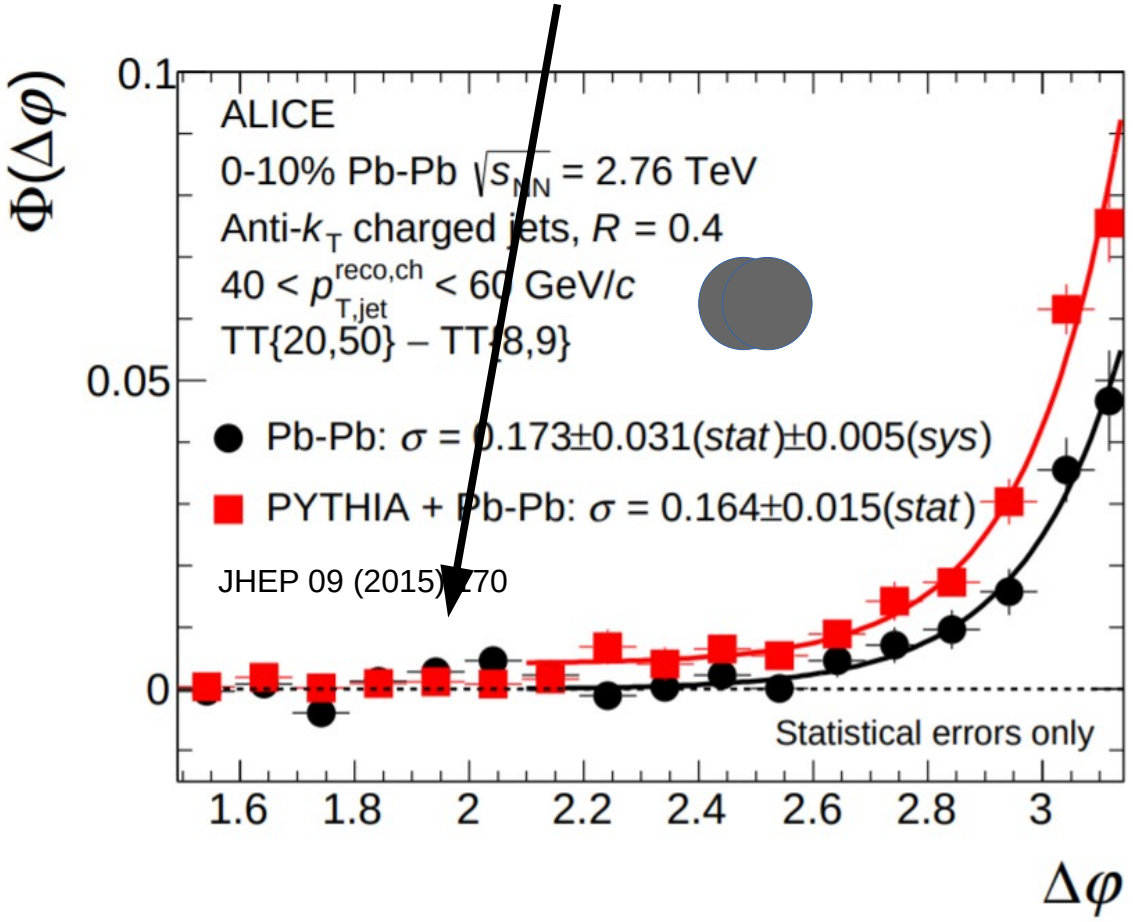
Jet acoplanarity in Pb+Pb

- Back-to-back topology sensitive to Sudakov radiation and multiple soft scatterings (broadening) and radiative corrections (narrowing) (Chen et al, PLB 773 (2017) 672 Gyulassy et al., arxiv:1808.03238 Zakharov, arxiv:2003.10182)



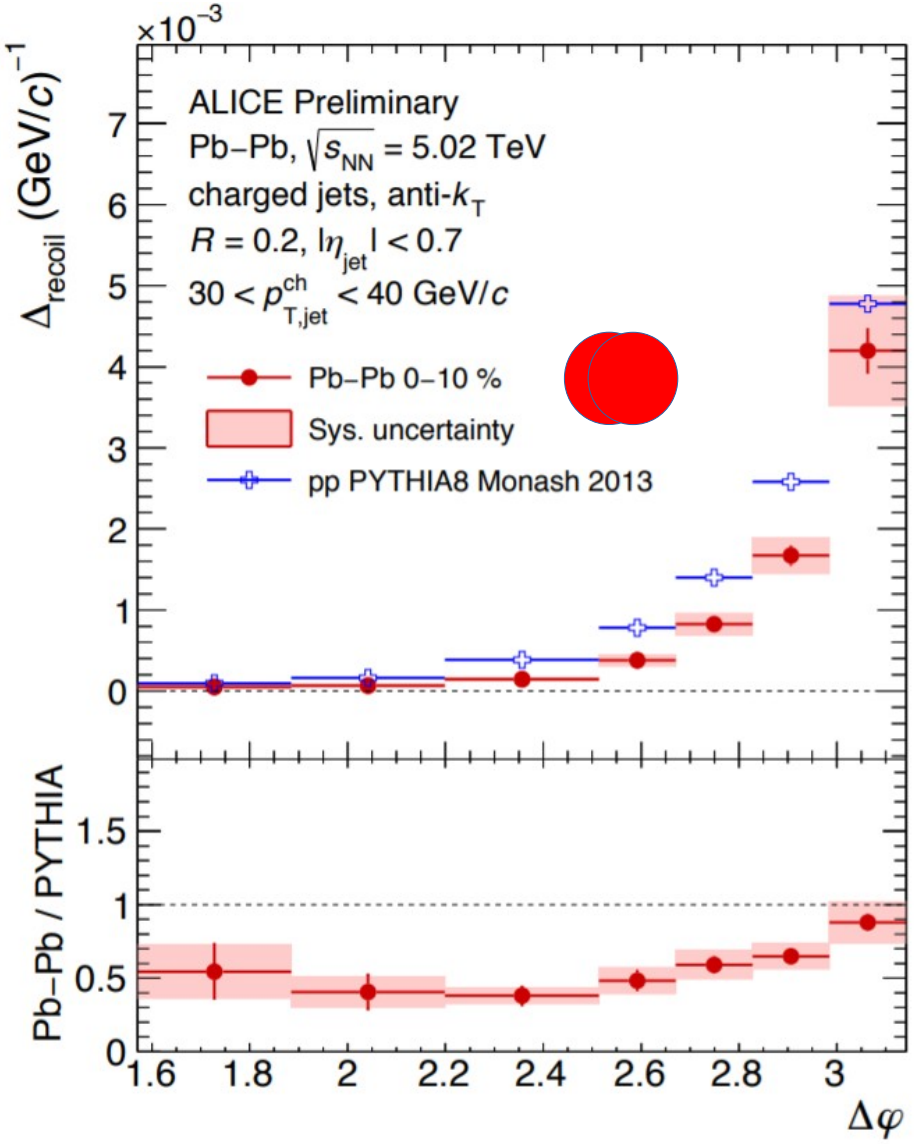
Jet acoplanarity in Pb+Pb

- Region at large angles sensitive to deflection of hard partons, i.e. probes short distance partonic structure (D'Eramo, Rajagopal, Yin, JHEP 01 (2019) 172).



Jet acoplanarity in Pb+Pb

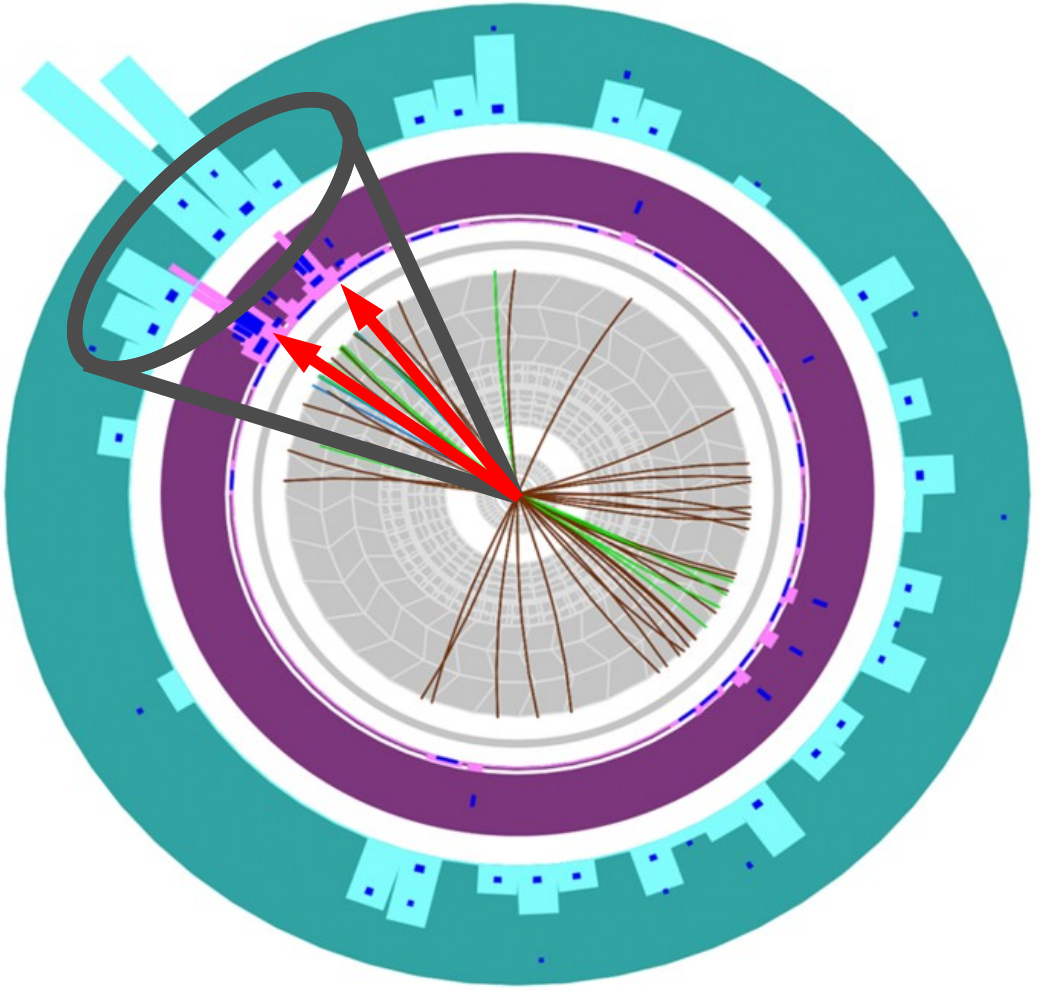
Trigger-normalized yield of jets recoiling from a trigger hadron



$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{\text{AA}}} \frac{\mathrm{d}^3 N_{\text{jet}}^{\text{AA}}}{\mathrm{d}p_{\text{T,jet}}^{\text{ch}} \mathrm{d}\Delta\varphi \mathrm{d}\eta_{\text{jet}}} \Bigg|_{p_{\text{T,trig}} \in \text{TT}}$$

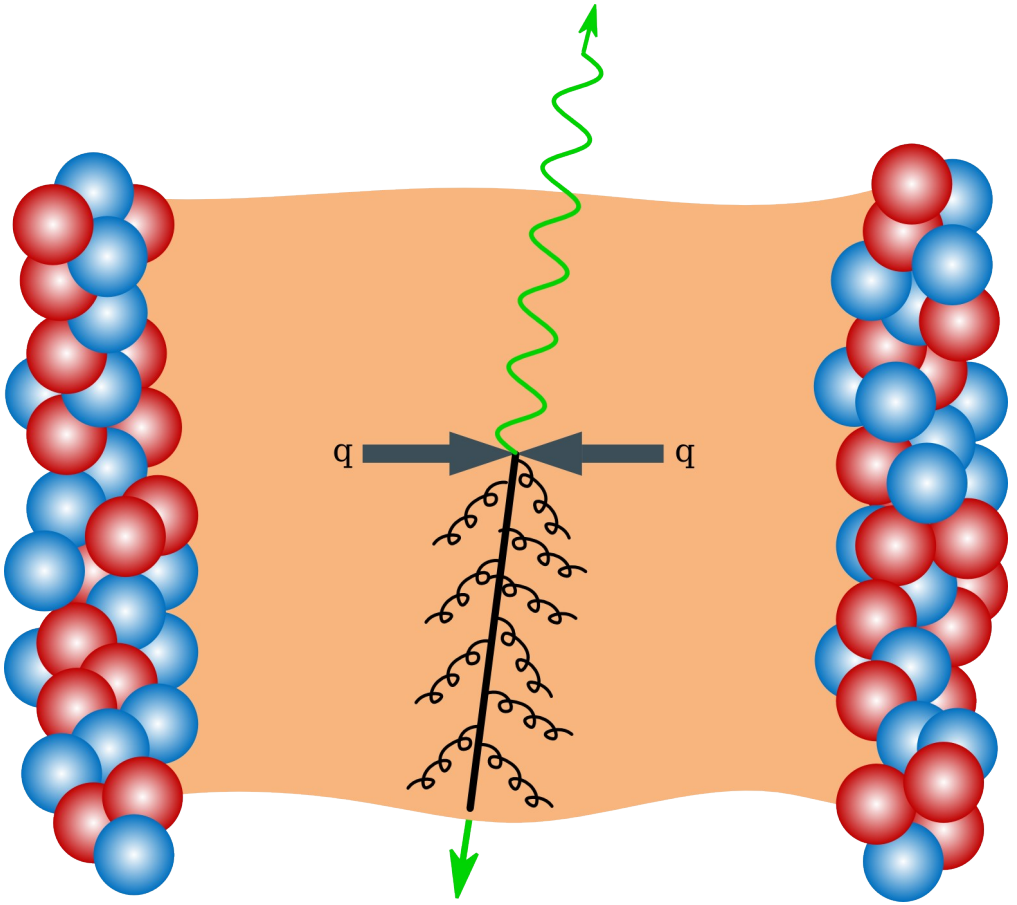
- Yields suppressed with respect to PYTHIA reference.
- Indication of narrowing.
- Effects of flavour, radiative corrections?

Jet structure and substructure



Moving forward with measurements of hadrons in jets

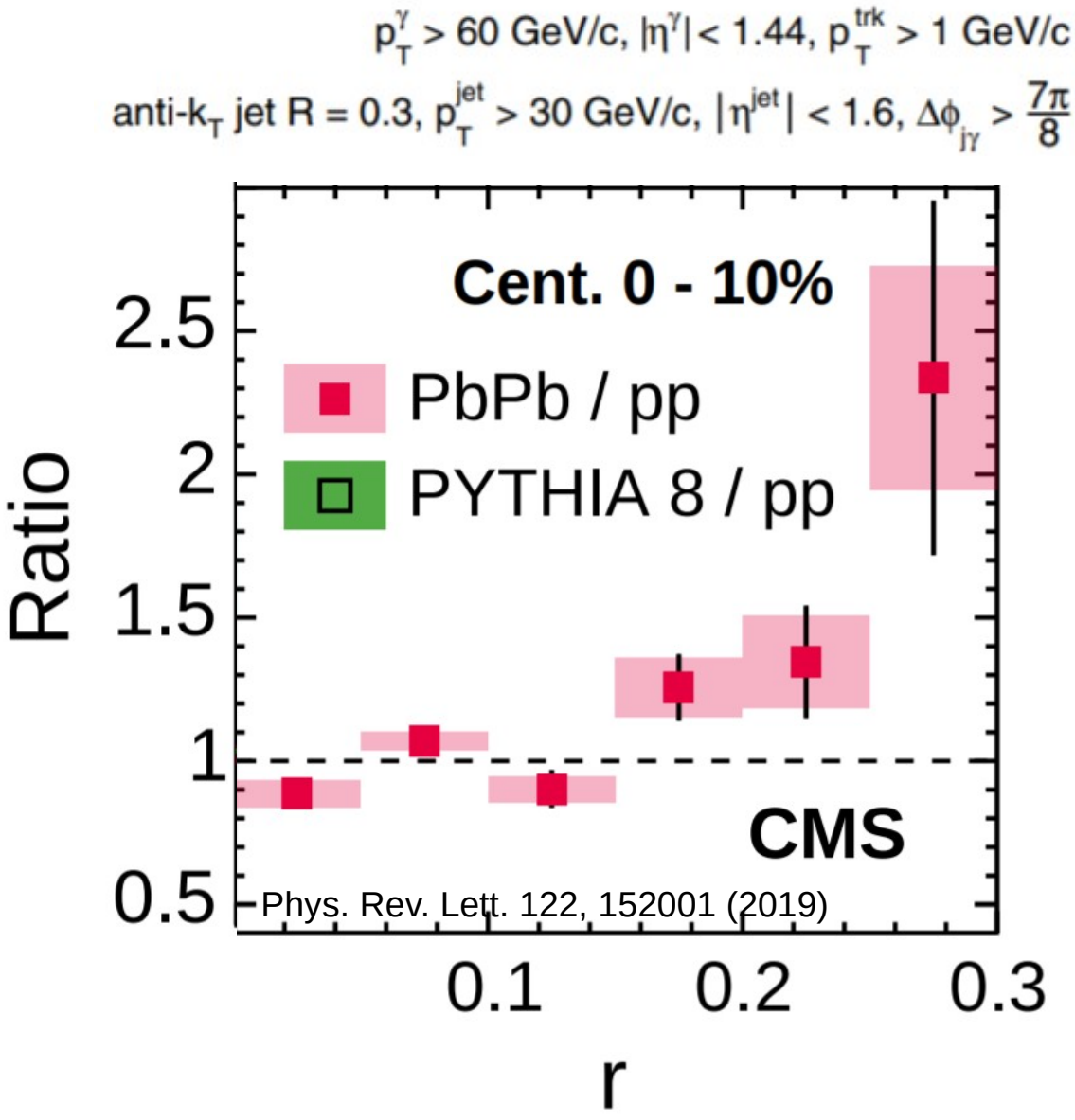
- Expanding existing measurements of inclusive jet fragmentation measurements and jet shapes (including large angles) measurements:
- **Tagged jets and identified hadrons...**



γ-tagged measurements

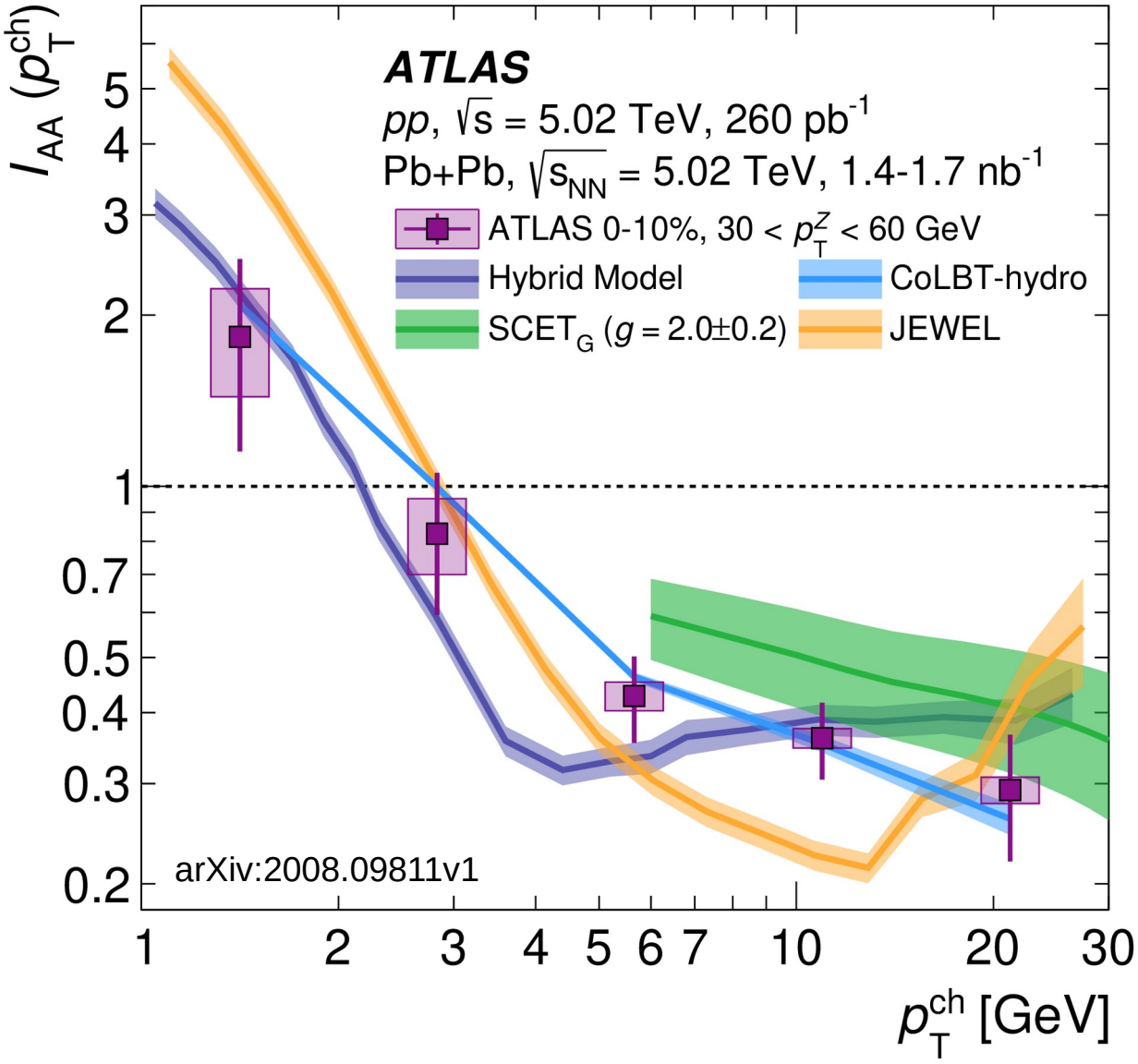
$$\rho(r) = \frac{1}{\delta r} \frac{\sum_{\text{jets}} \sum_{r_a < r < r_b} (p_T^{\text{trk}} / p_T^{\text{jet}})}{\sum_{\text{jets}} \sum_{0 < r < r_f} (p_T^{\text{trk}} / p_T^{\text{jet}})}$$

- Jet shapes of quark dominated jet sample.
- Qualitatively similar behavior as for inclusive sample.
- Also measurement of b-jet shapes by CMS (arXiv:2005.14219)



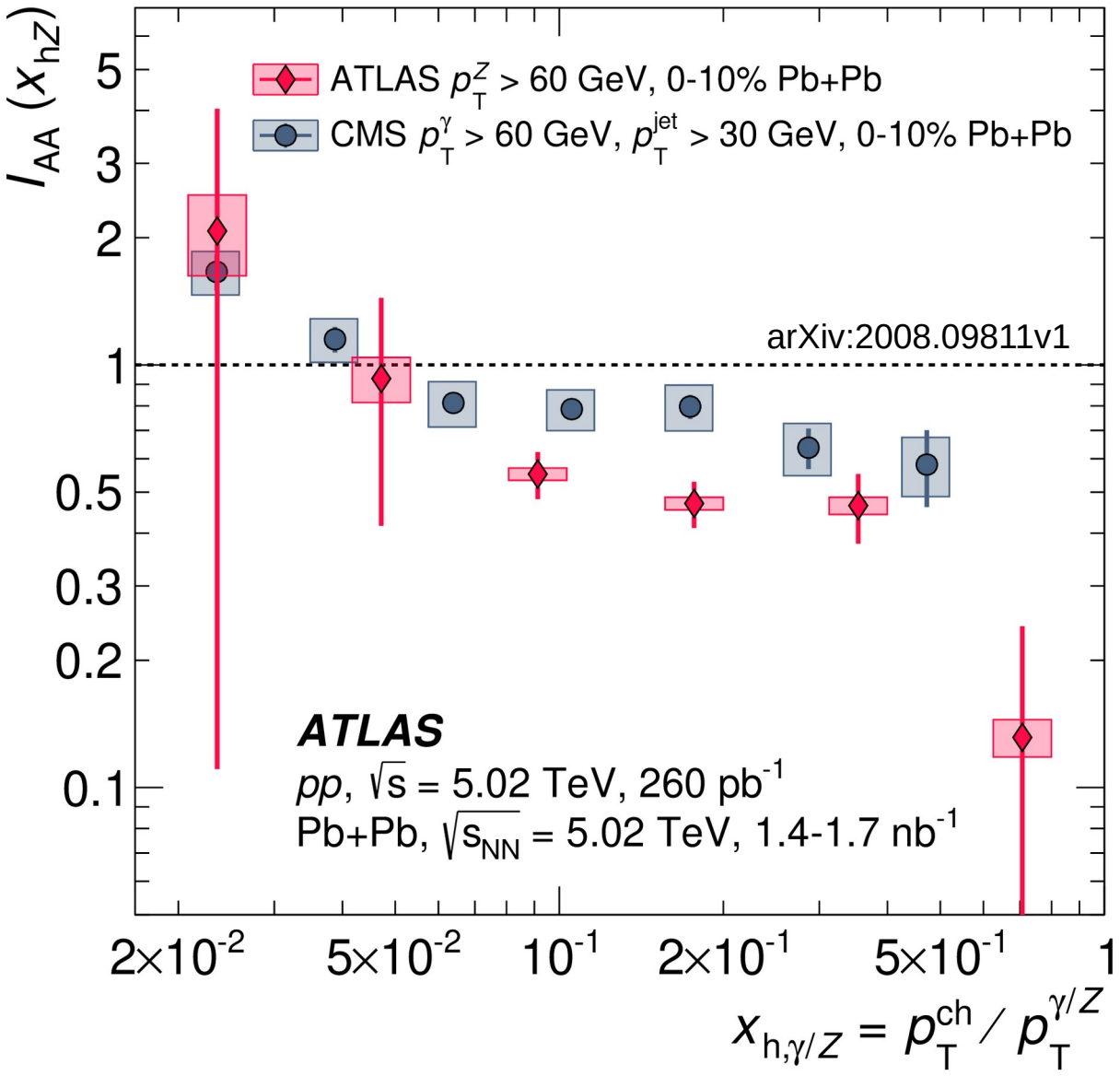
Z-tagged measurements

- Quark dominated jet sample.
- Access to low p_T region.
- Comparable features as in other measurements of jet fragmentation.
- Similar measurement also by CMS.



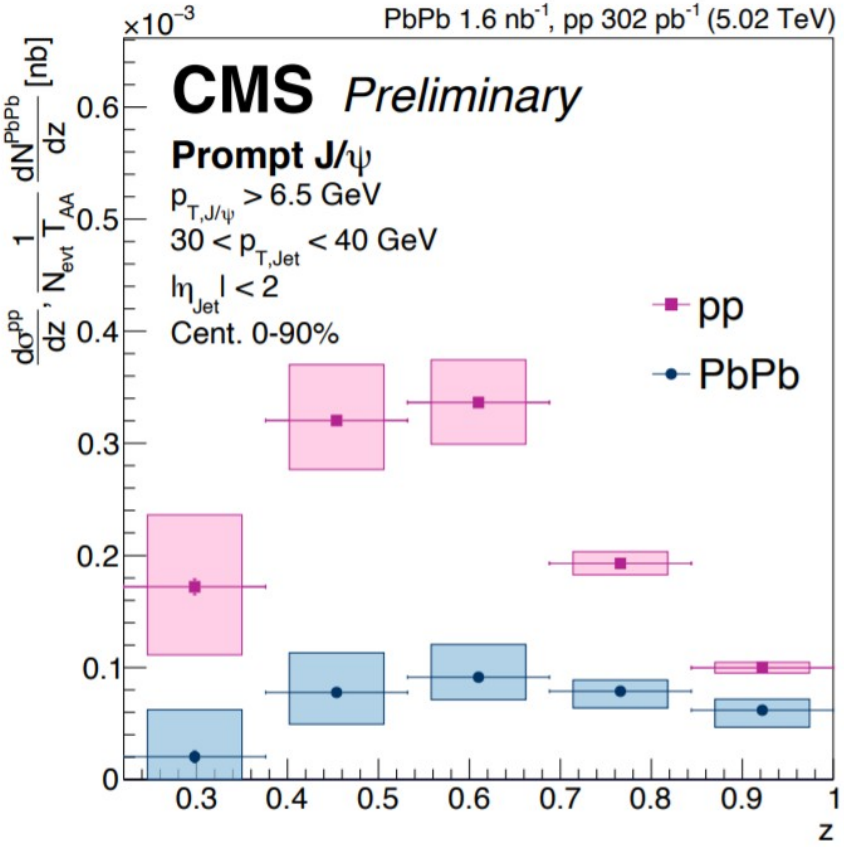
Z-tagged measurements

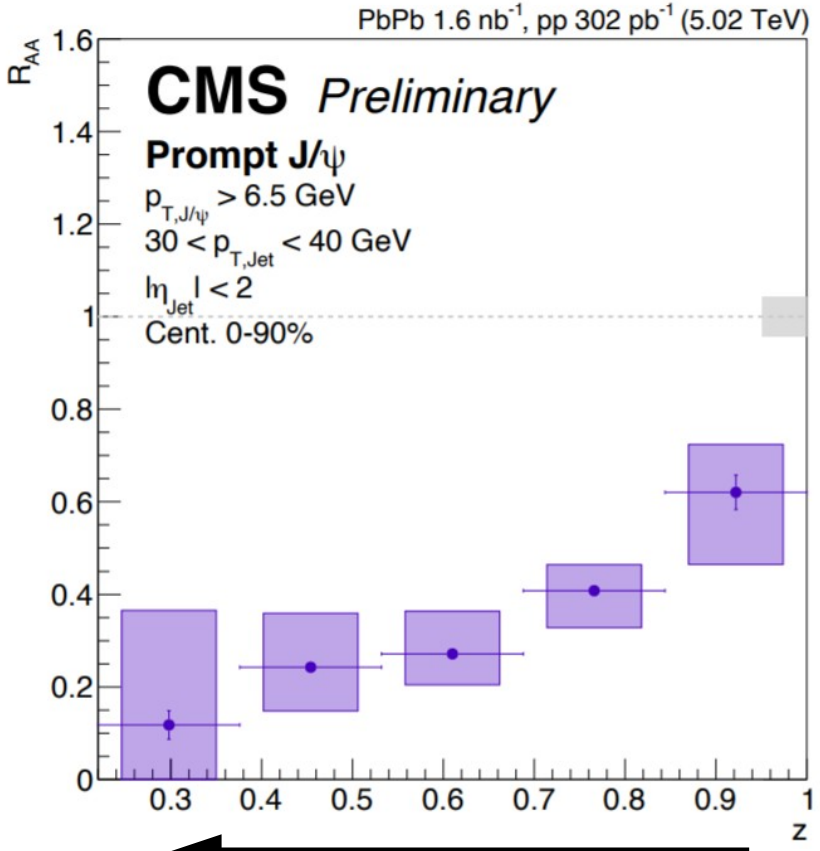
- Quark dominated jet sample.
- Testing role of parton virtuality when comparing Z- and γ-tagged measurements.
- Access to low p_T region.
- Results: similar as in γ-tagged measurements.



Identified hadrons in jets: Fragmentation of J/ψ in jets

- Problem: J/ψ production not well understood even in *pp* (polarization vs cross-section).
- Does jet quenching play a role in J/ψ suppression in HI?

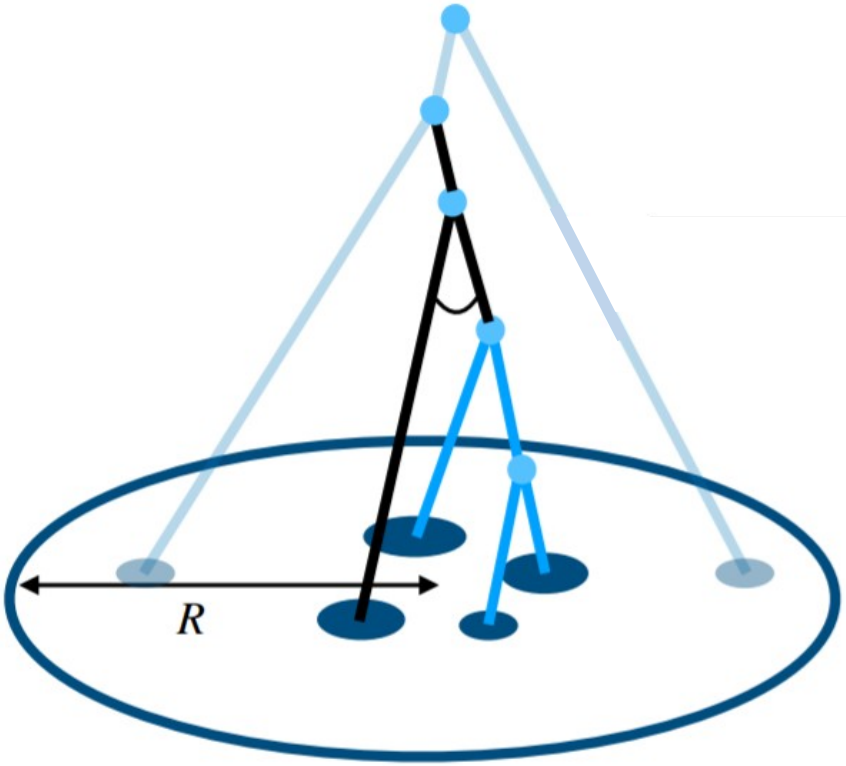


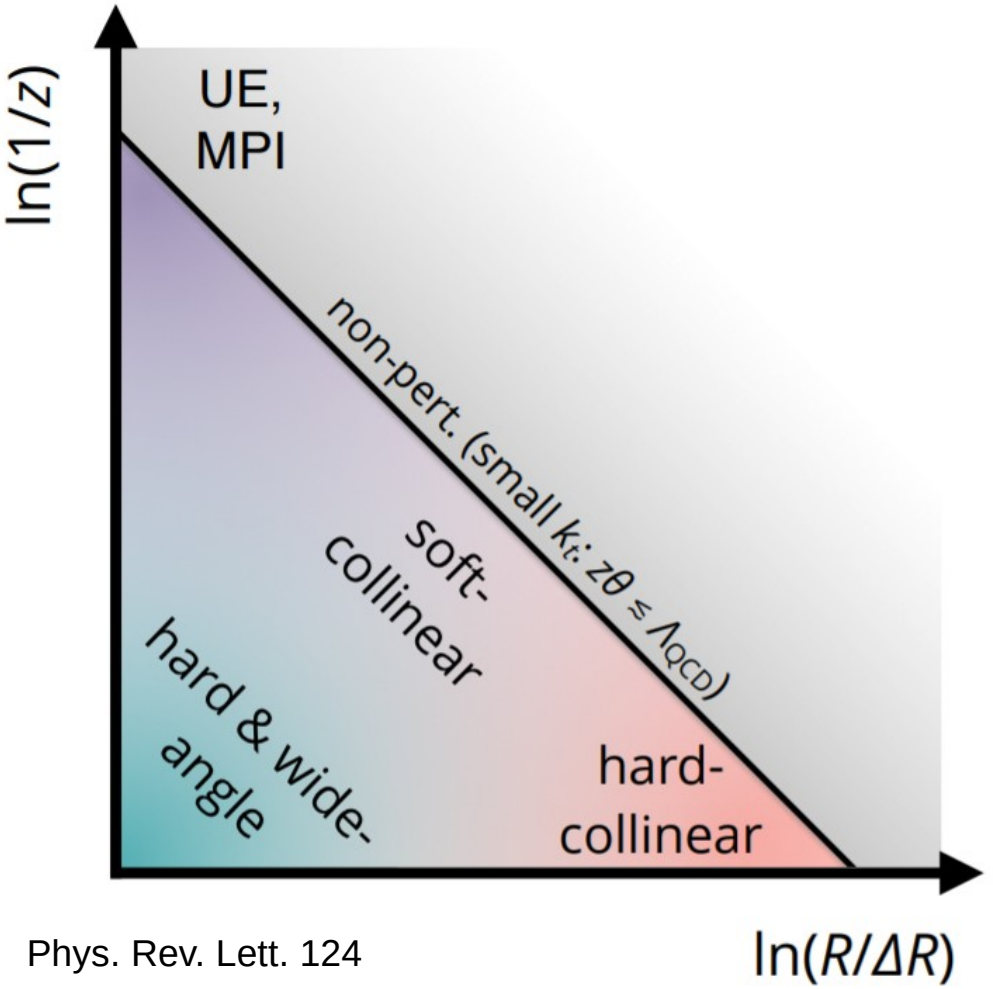


Produced latter in shower

Jet substructure

Classifying parton splittings using opening angle and momentum fraction *z*.

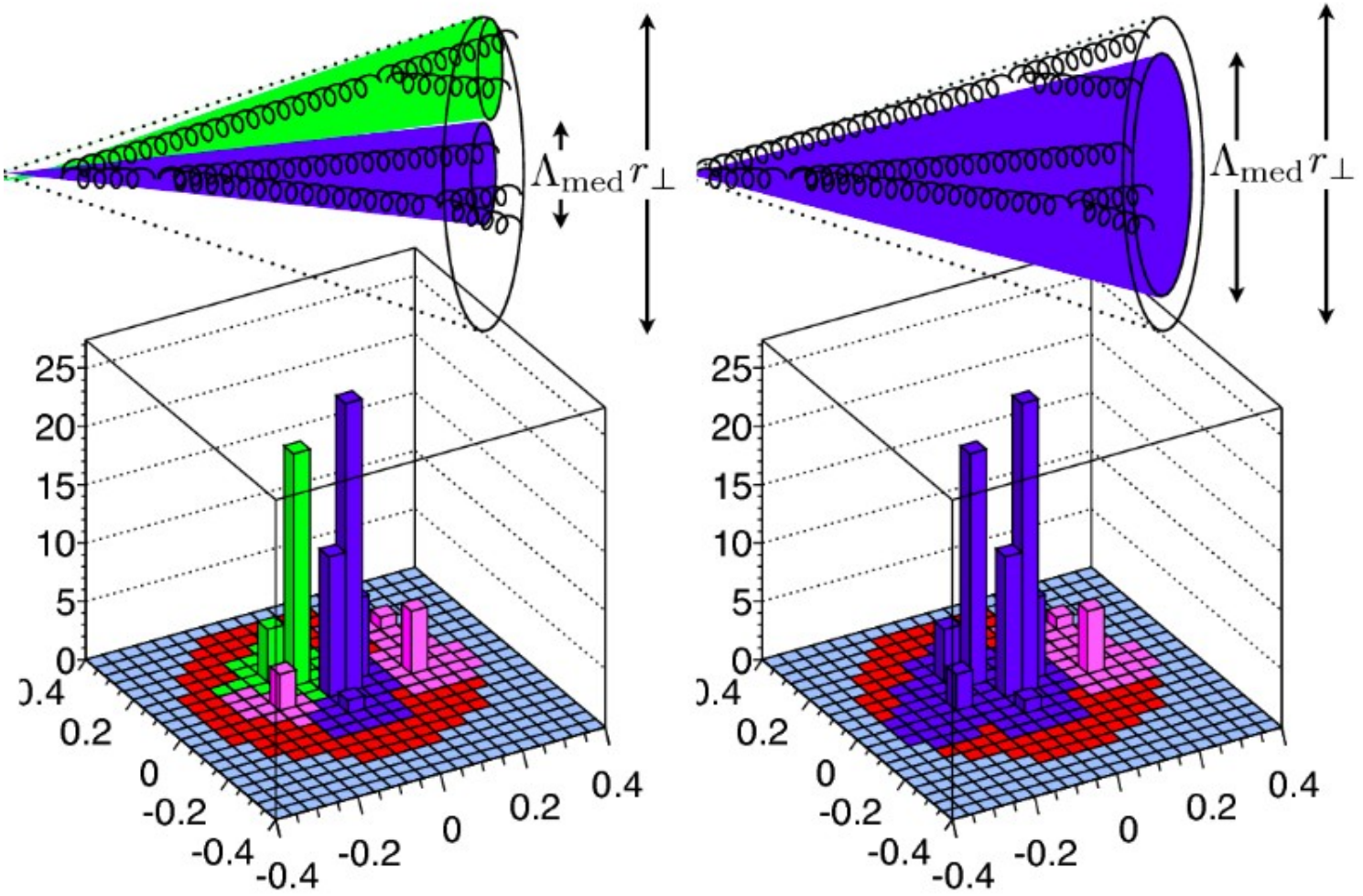




Phys. Rev. Lett. 124

Jet substructure

Does the jet suppression depend on jet structure?



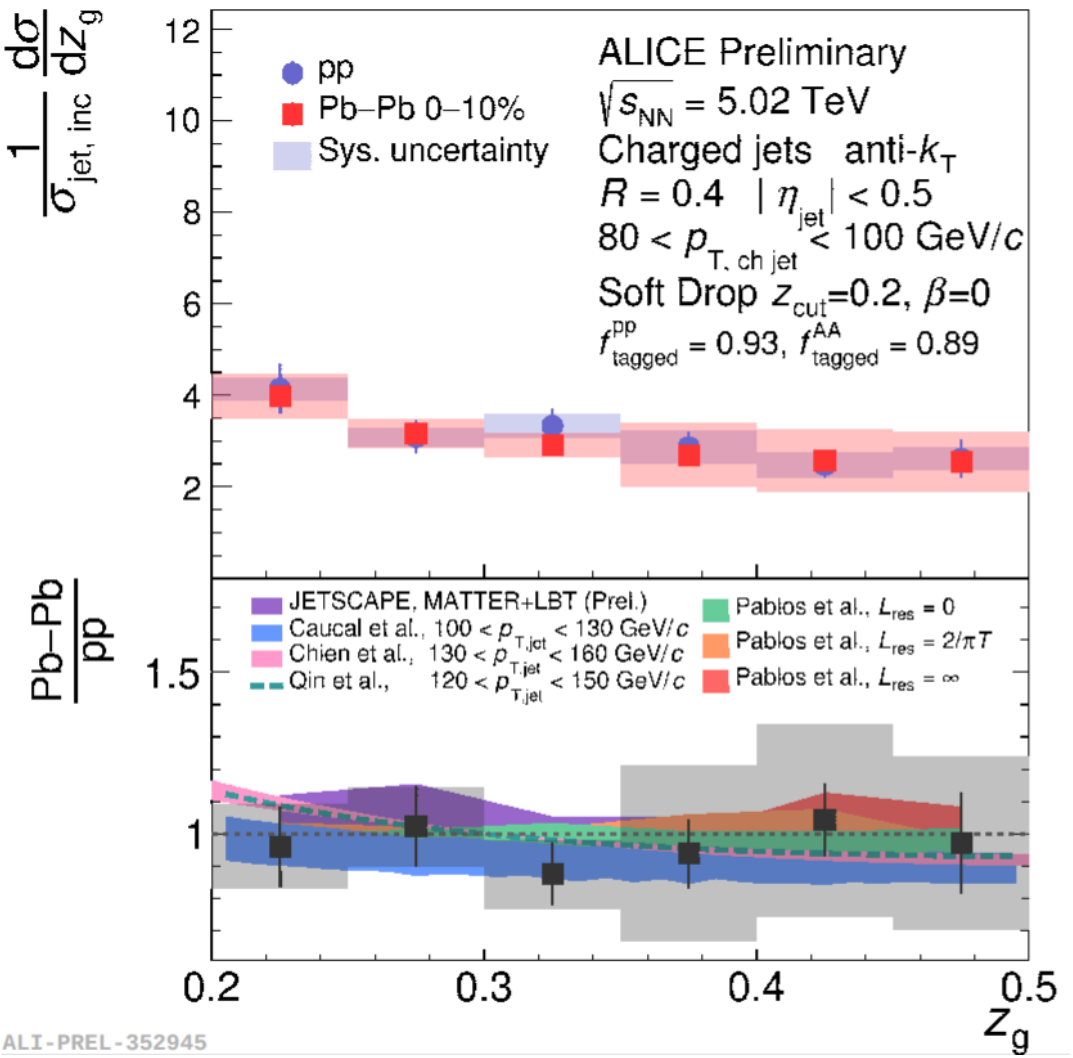
J. Casalderrey-Solana, Y. Mehtar-Tani, C. A. Salgado, K. Tywoniuk, Phys. Lett. B725 (2013) 357

Splittings in the medium

- Improved UE subtraction, optimized&more aggressive grooming → ability to unfold.
- Soft drop:

$$z_g = \frac{min(p_1, p_2)}{p_1 + p_2} > z_{cut}\theta^{\beta}$$

No modification of QCD splitting within uncertainties.



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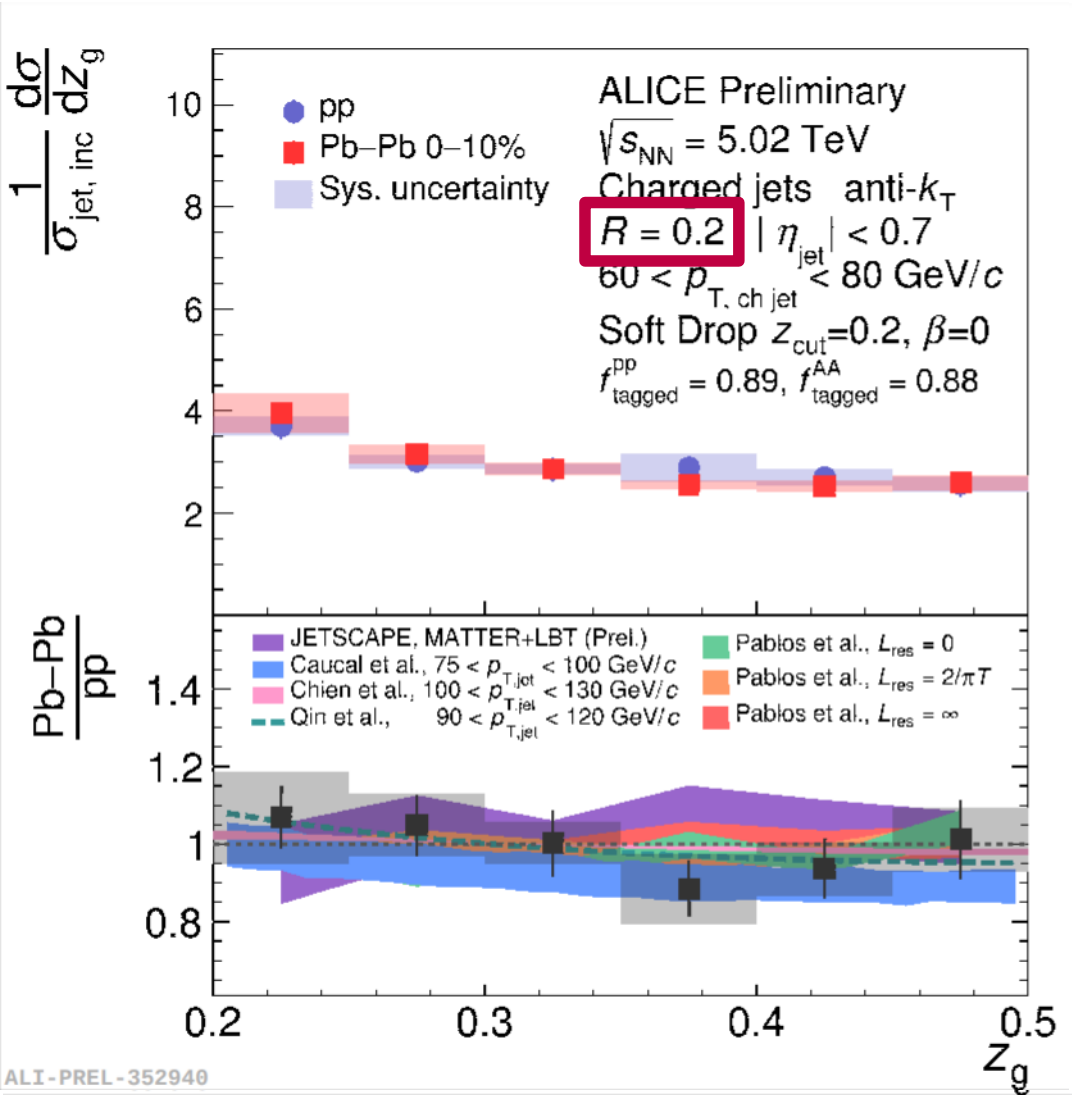
- Soft drop:

$$z_g = \frac{min(p_1, p_2)}{p_1 + p_2} > z_{cut}\theta^{\beta}$$

Similar result for R=0.2 jets with smaller uncertainties.



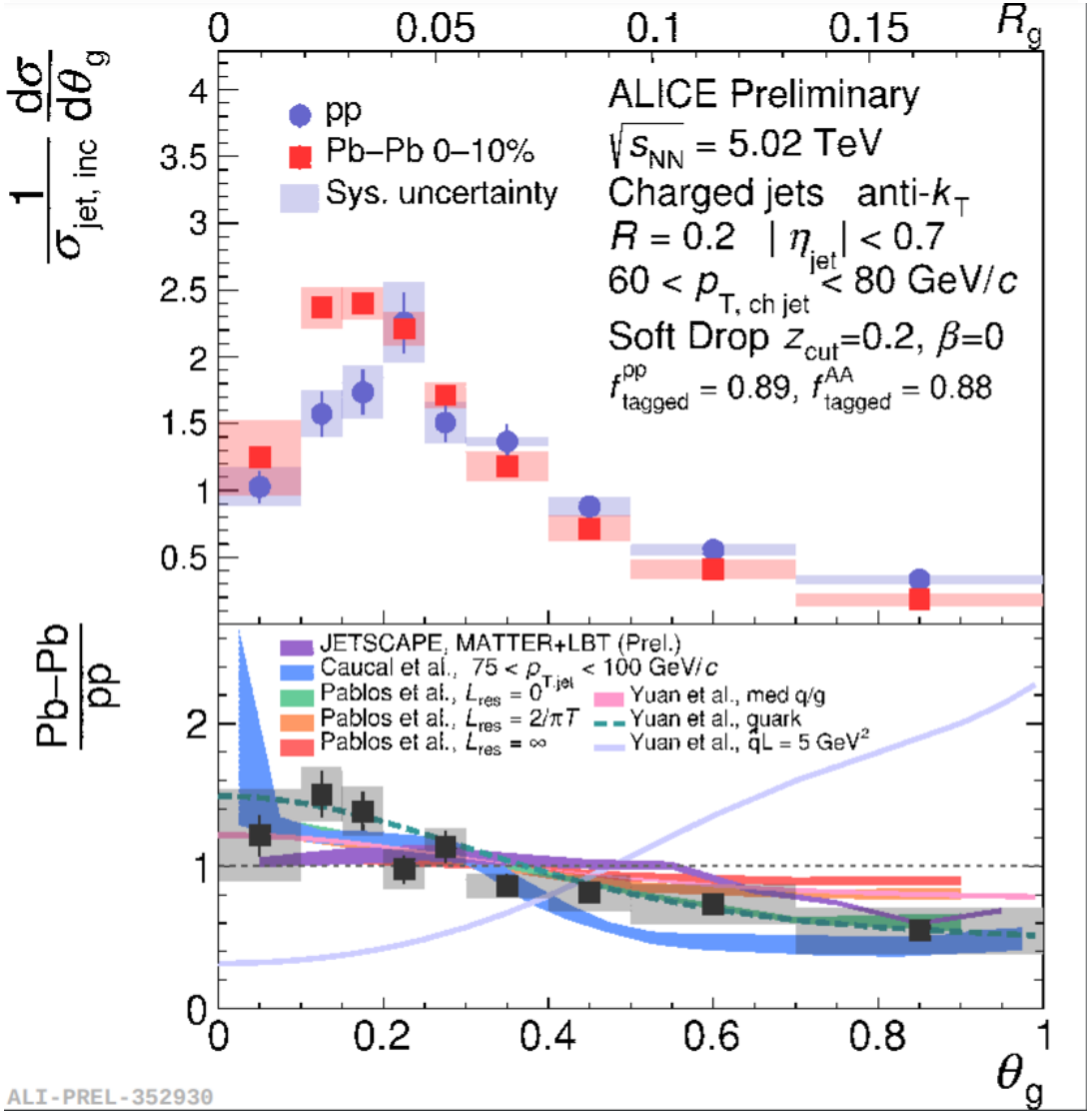
Splittings in the medium

- Improved UE subtraction, optimized&more aggressive grooming → ability to unfold.
- Splitting angle:

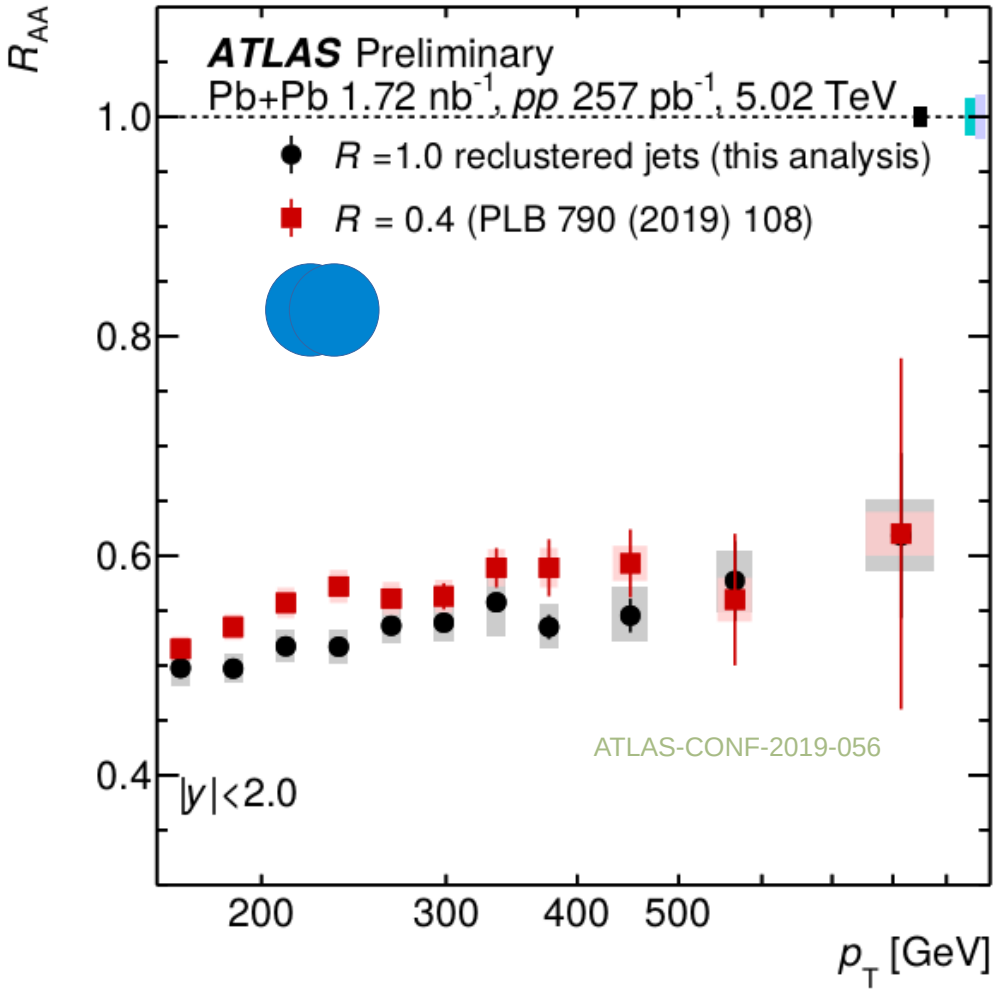
$$\theta_g = \frac{\Delta R_{1,2}}{R}$$

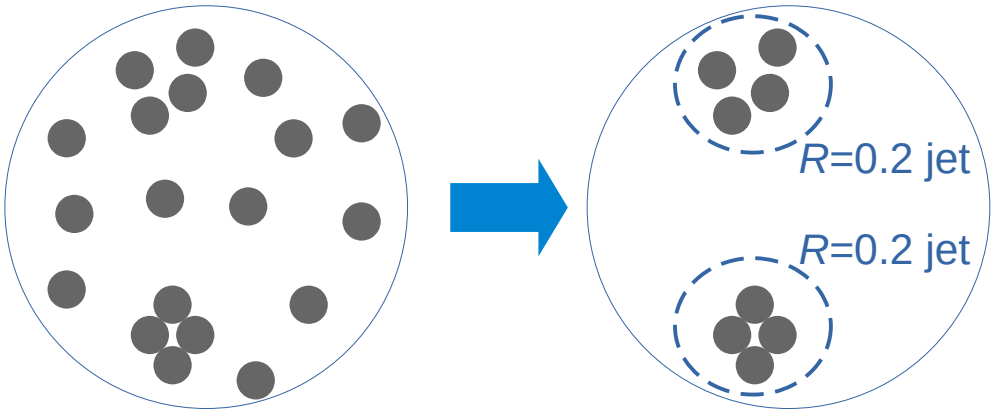
Jet narrowing (similarly for 0.2 jets)

Modification enhanced when more symmetric splittings are selected.



Dependence of jet suppression on substructure



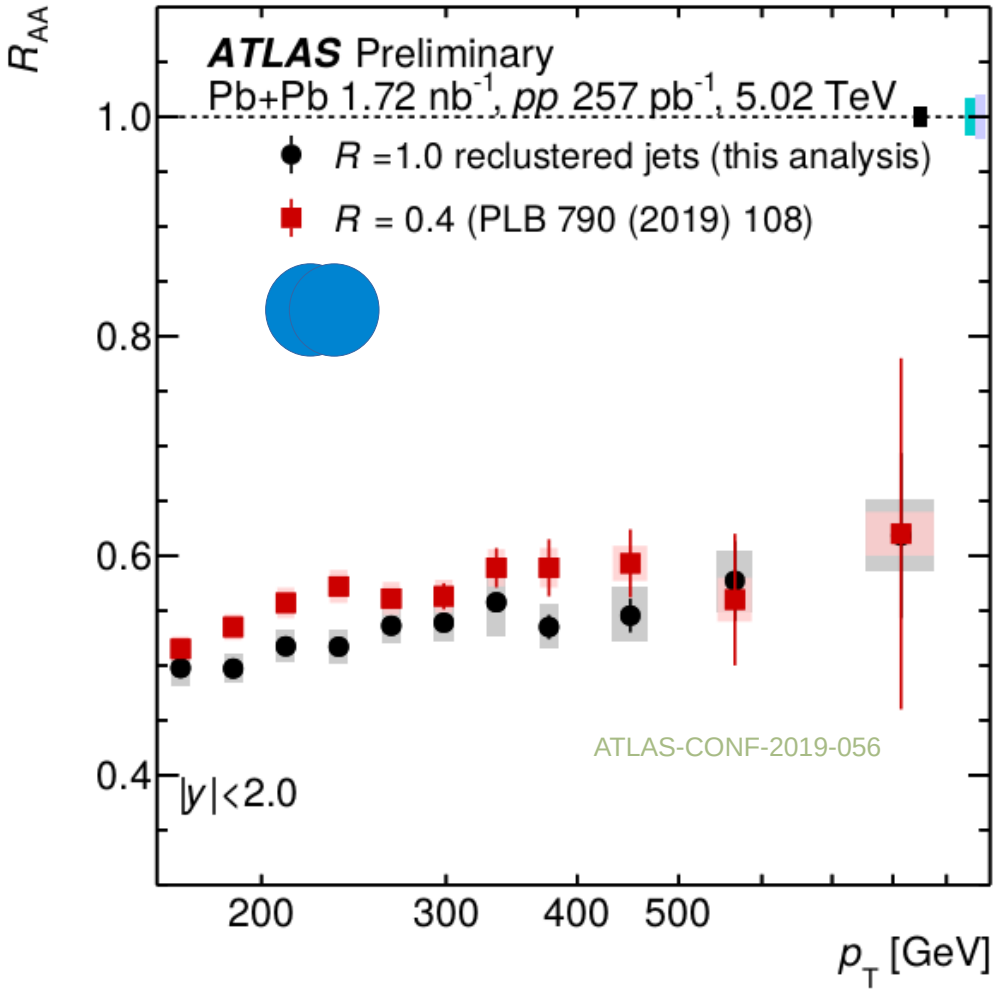


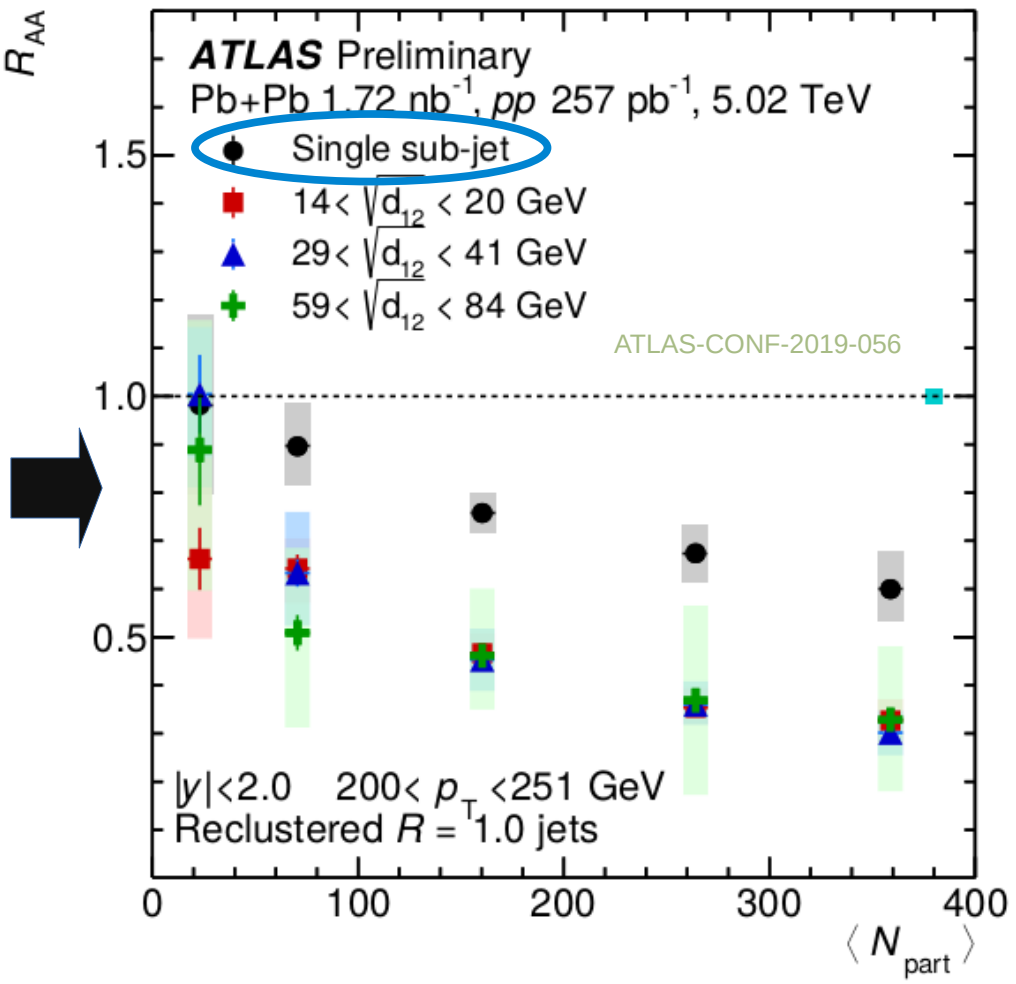
"Conventional" large-*R* jet

Re-clustered large-*R* jet with 0.2 jets as constituents

- Soft contribution is removed from *R*=1.0 re-clustered jets.
  - → Larger suppression compared to ordinary small-*R* jets.
  - → Focus on hard splittings.

Dependence of jet suppression on substructure





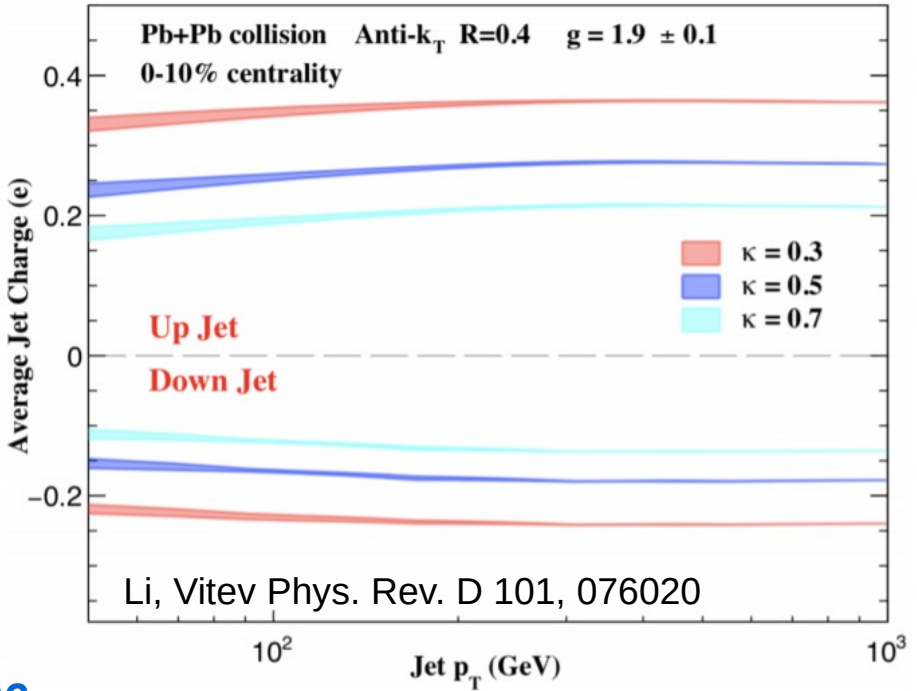
- A continuous increase of the suppression with increasing centrality.
- The jets with single sub-jet are less suppressed with respect to those with higher sub-jet multiplicity → color decoherence.

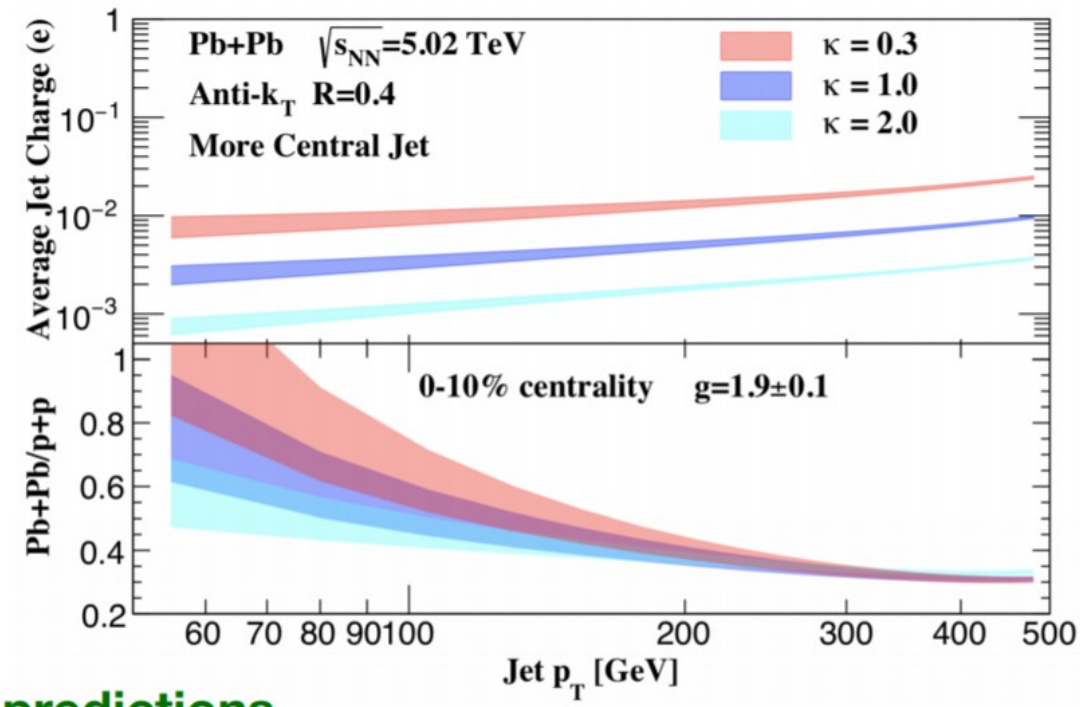
Quark vs Gluon energy loss

- Medium-induced radiation larger for gluons than quarks initiated jets.
- Jet charge is sensitive to the electric charge of the initiating parton.

$$Q^{\kappa} = \frac{1}{(p_{\mathrm{T}}^{\mathrm{jet}})^{\kappa}} \sum_{i \in \mathrm{jet}} q_i p_{\mathrm{T},i}{}^{\kappa}$$

sensitivity of jet charge to low and high particles

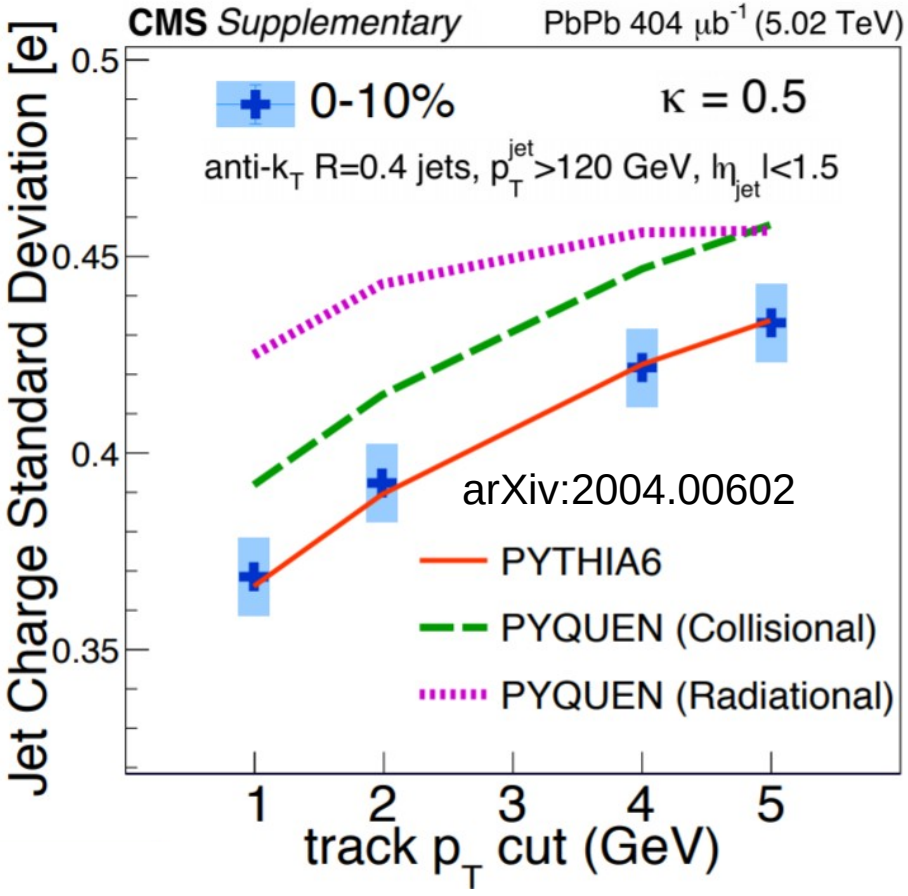




SCET$_G$ predictions

Quark vs Gluon energy loss

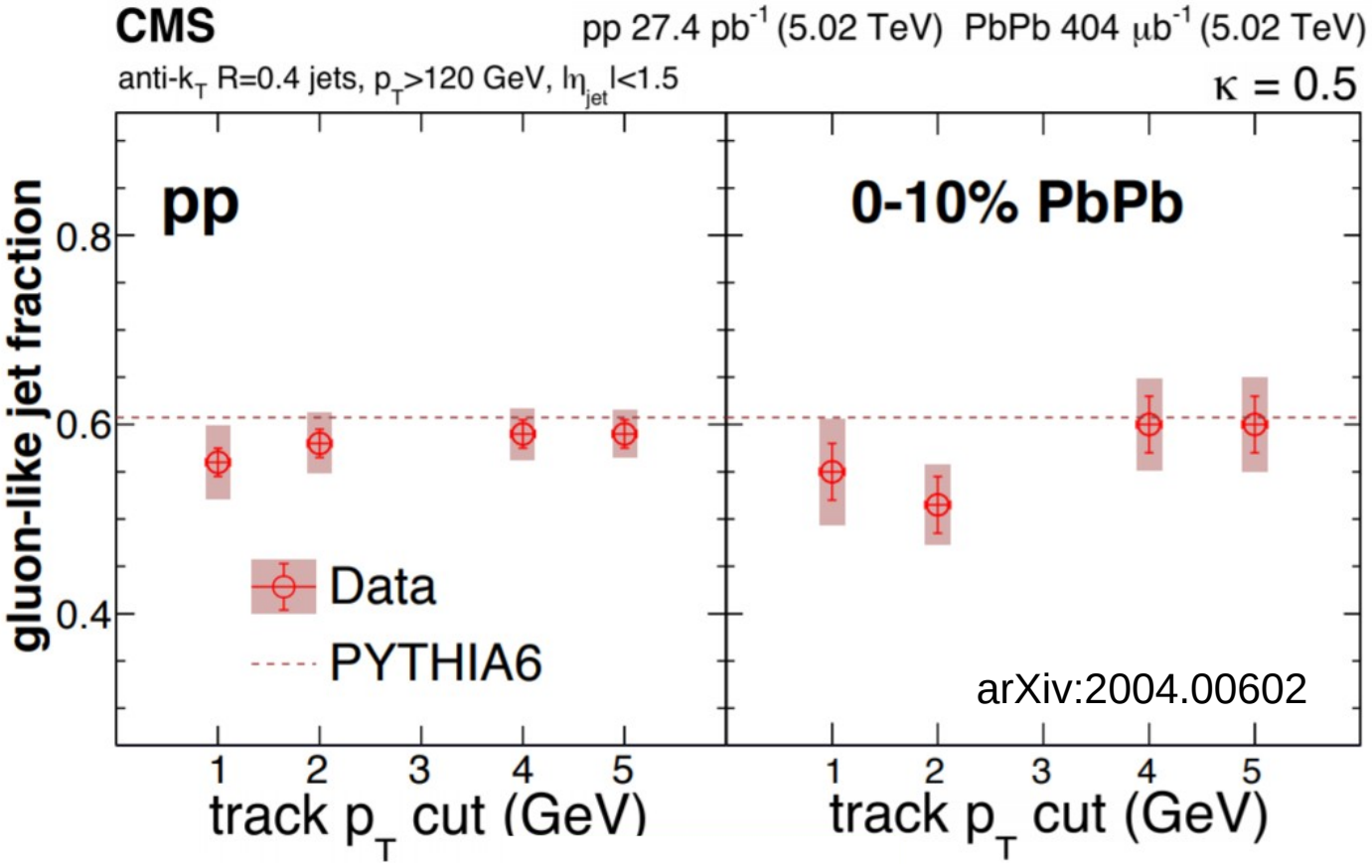
- Quark and gluon fraction extracted using Pythia templates and fully corrected.



- No significant modification observed in the jet charge with centrality.
- Pyquen not compatible with data.

Quark vs Gluon energy loss

- Quark and gluon fraction extracted using Pythia template fits and fully corrected..



- Comparable fractions in *pp* and Pb+Pb.

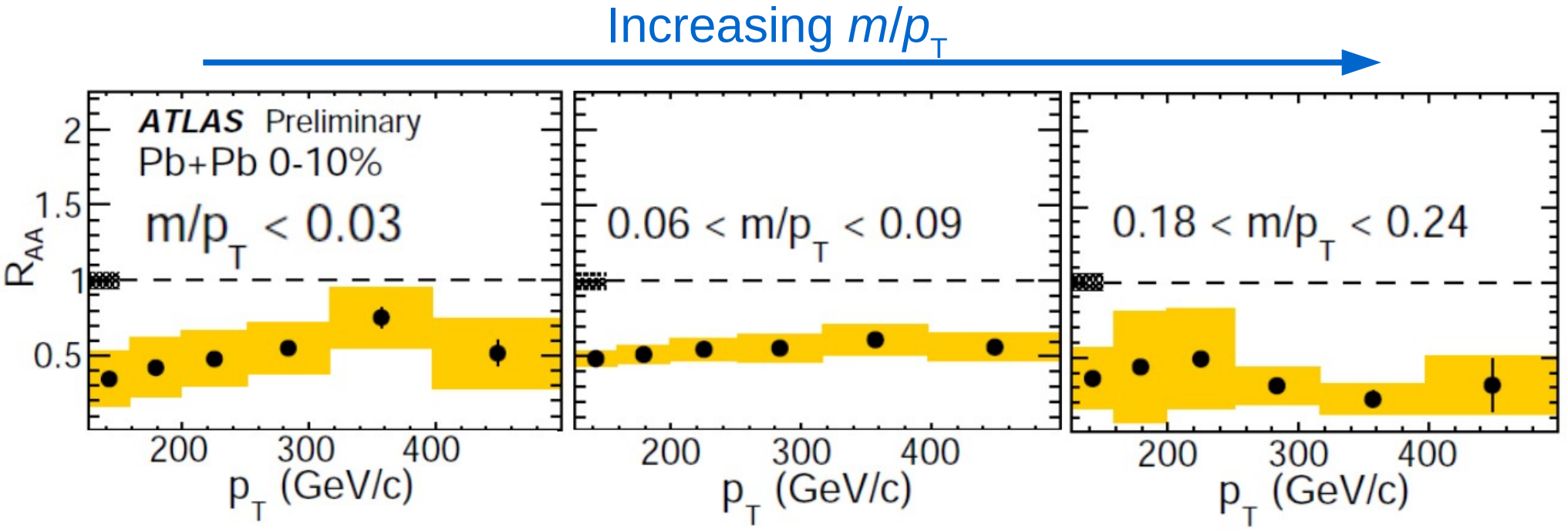
Summary

- Jets provide access into various QCD phenomena.
- Jet substructure is a fast developing field and still growing.
  → Distributions like jet shape and fragmentation function well established.
  → New jet substructure and differential measurements come along with new techniques and performance improvement.
- Using high statistics LHC data and new techniques bring us to era of precise measurements HI collisions.
  → Strong constraints on theoretical models.
  → Models are able to describe various features in the result.
  → Improvement of the MC simulations.
- But there are opened questions…
  → Resolution scale of the QGP, role of medium response, quenching in small systems...

Backup

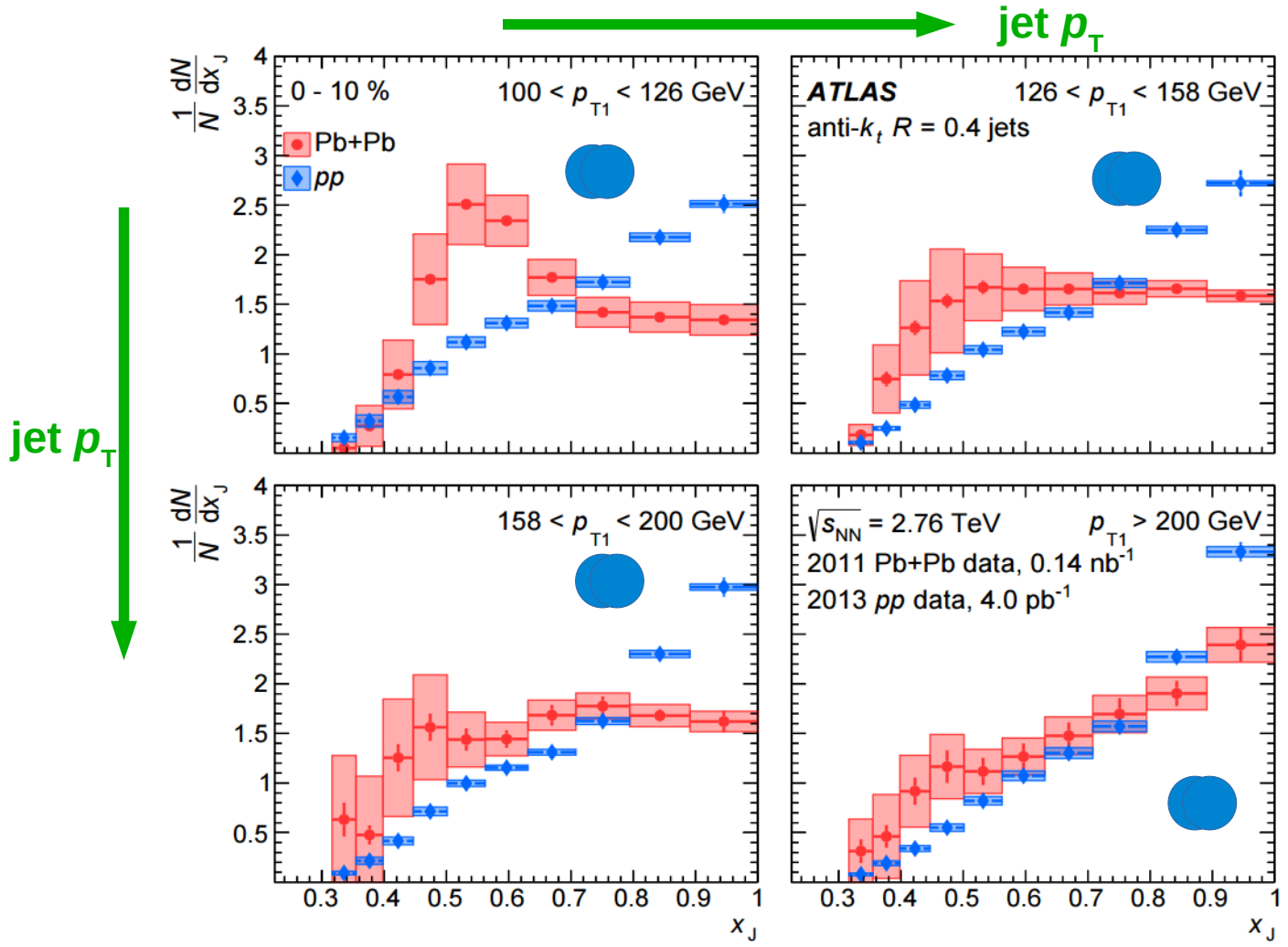
Jet substructure in HI collisions

- Does the jet suppression depend on jet structure?
- Jet mass carries information about transverse structure of jet.
  - connection to virtuality of initial parton.



- No significant change of R_{AA} with mass
  → consistent with inclusive jet R_{AA}.

Di-jet asymmetry

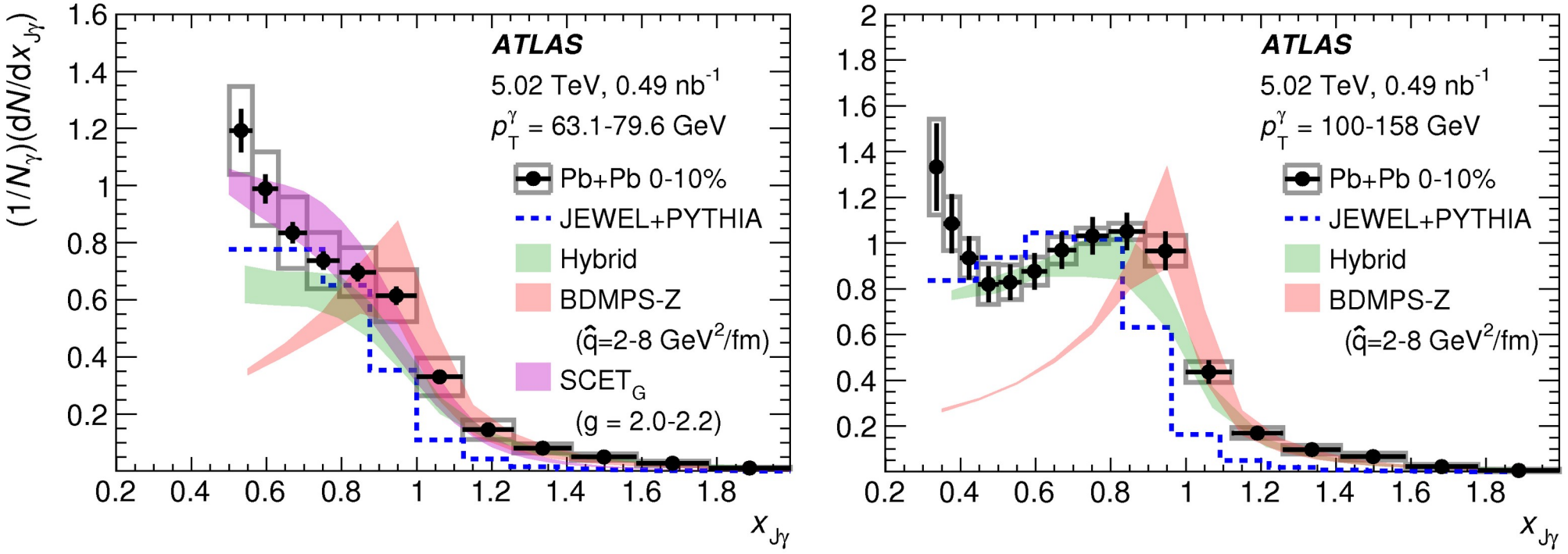


- Much less modification at high p_T.

arXiv:1706.09363

Gamma-jet balance

Increasing photon p_T



- Some models able to describe basis features.
- Difficult to describe detail behavior of the distribution.