Status and Prospects for Heavy-Ions Jet Physics A look at the LHC

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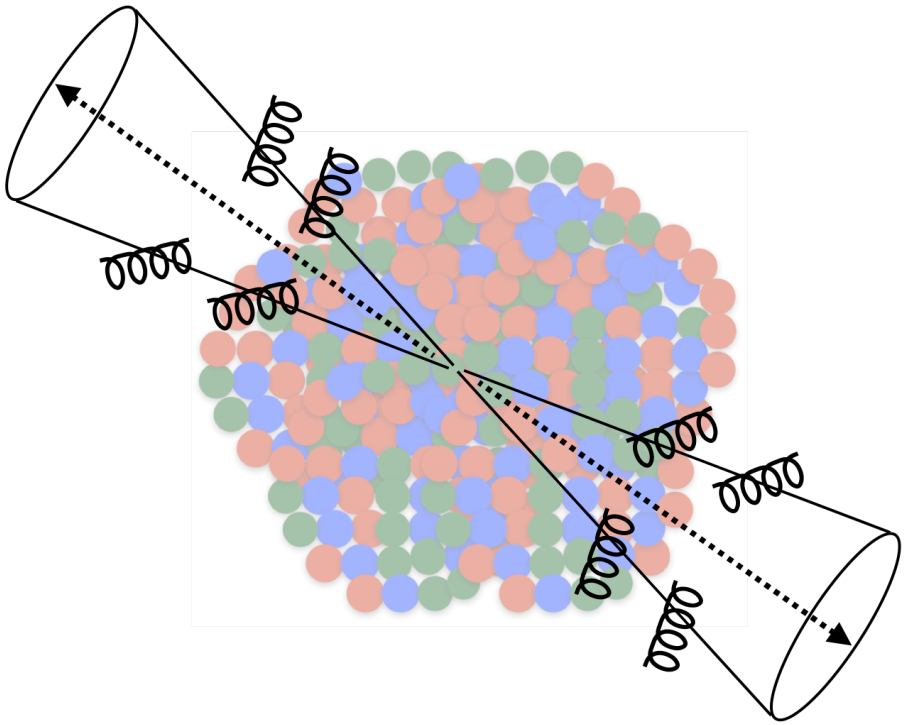
What are we trying to learn?

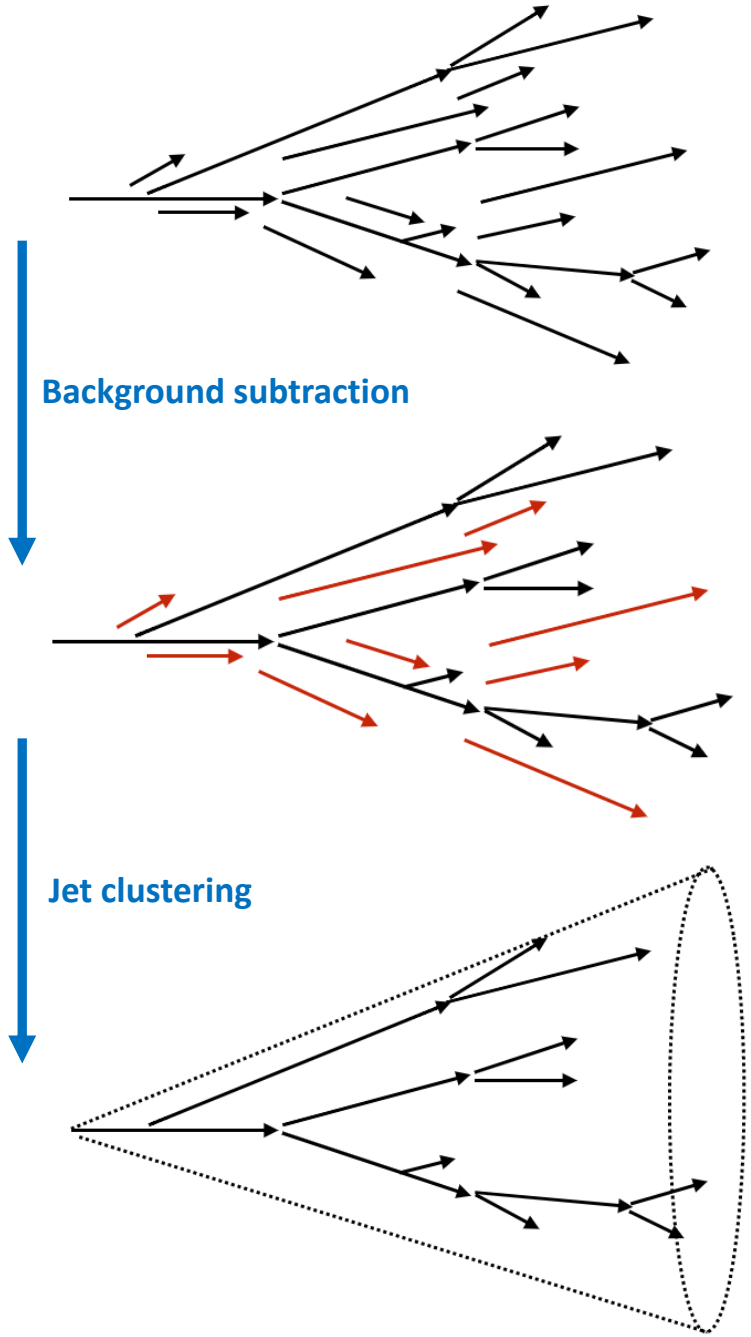
- Emergence of a strongly coupled system from a weakly coupled theory
  - ❖ need to probe with a wide range of resolutions
- Jets are well described probes with perturbative production
  - ❖ ideal tool to investigate the evolution of the system
- Jets interact with the medium constituents via collisional and radiative processes
  - ❖ modification of jets compared to the vacuum



What can we learn about the medium through jet interactions?

What tools have we developed?

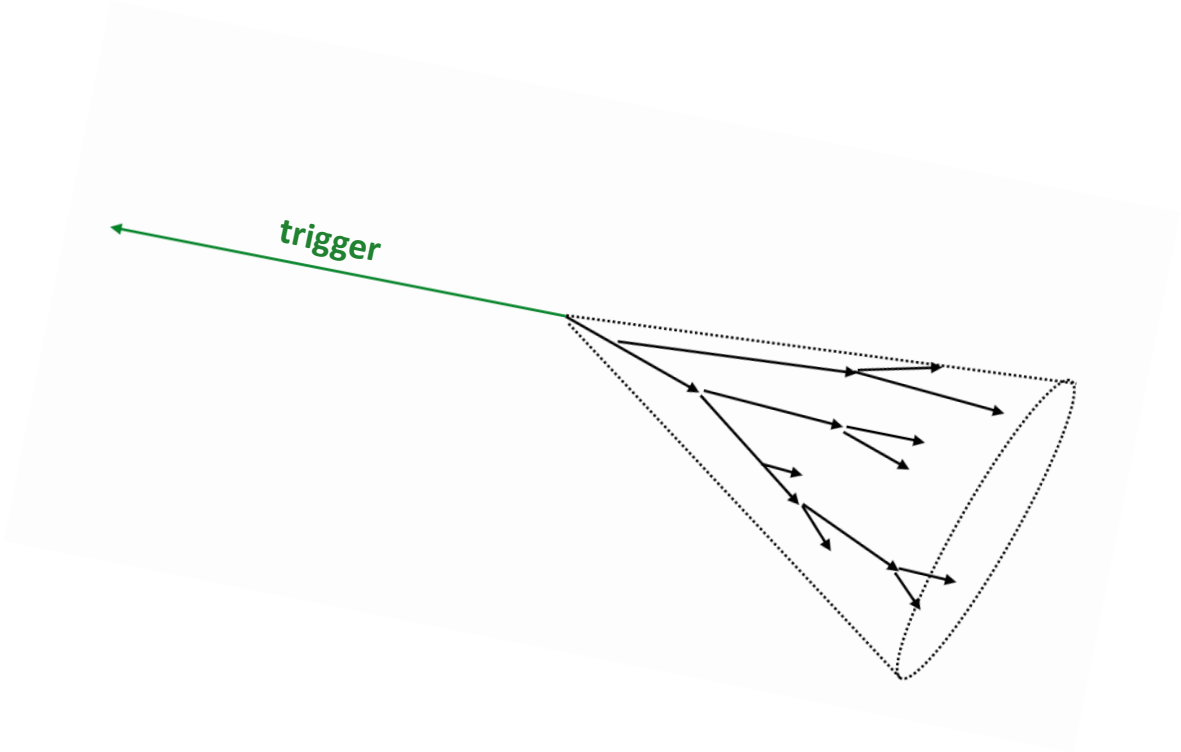
- Identifying jets in the medium



What tools have we developed?

- Identifying jets in the medium

- Unquenched reference to recoil from



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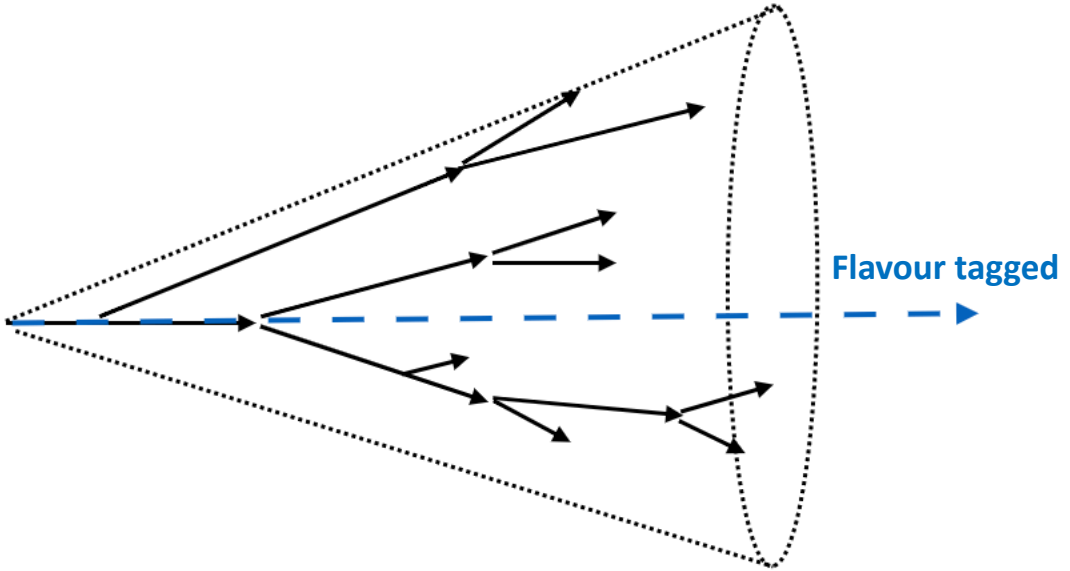
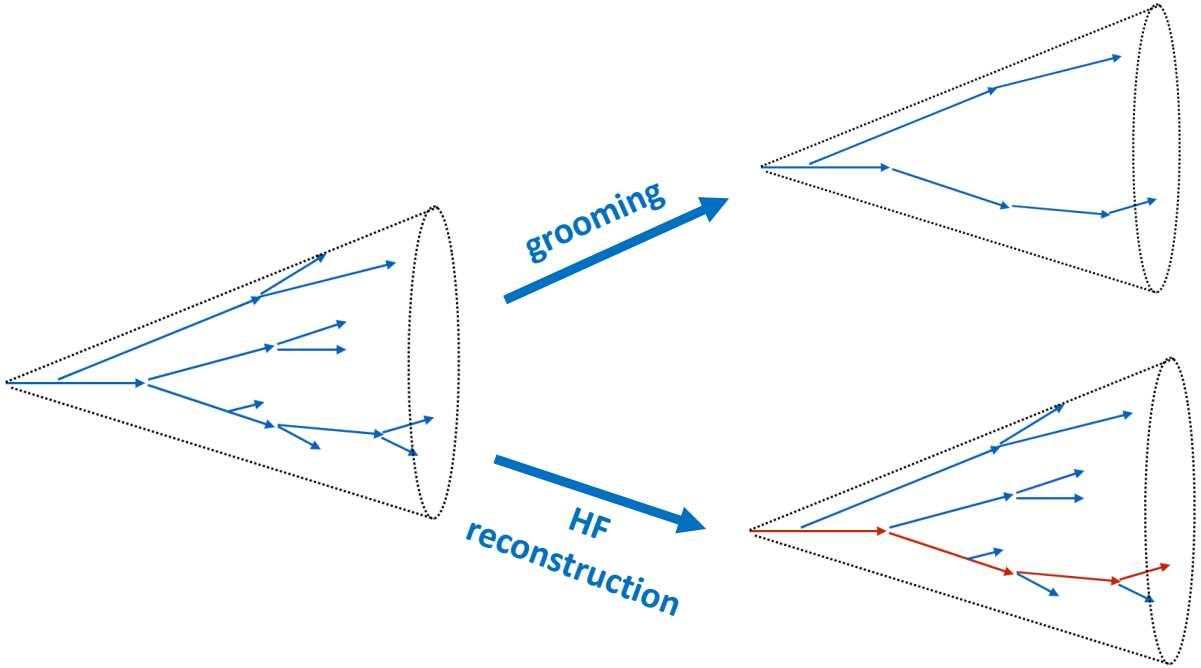
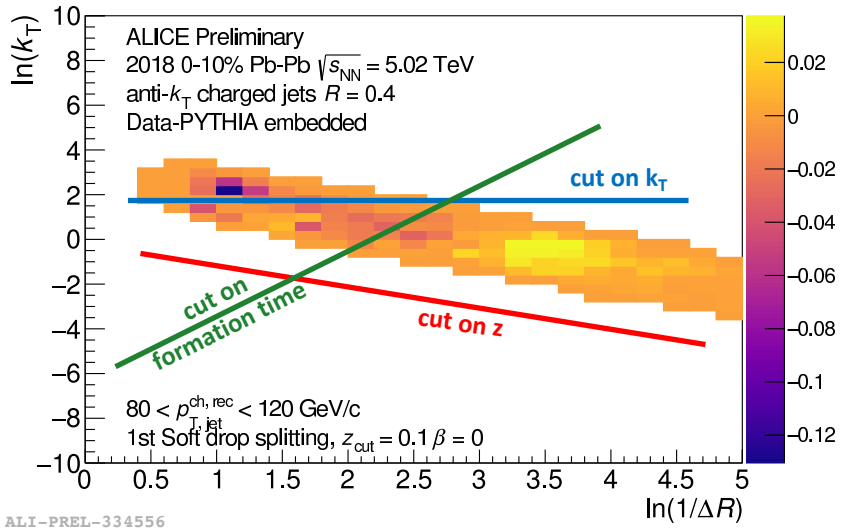
- Tag initiating parton flavour



What tools have we developed?

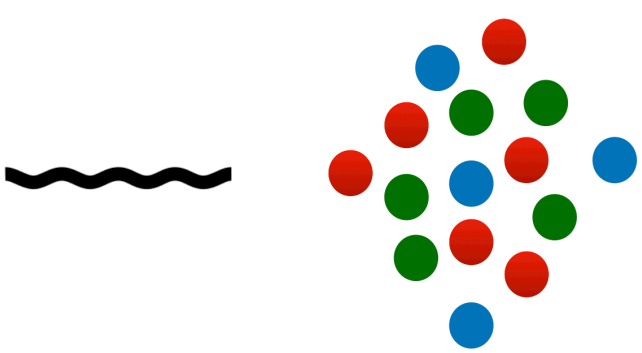
- Identifying jets in the medium
- Unquenched reference to recoil from
- Tag initiating parton flavour
- Jet substructure



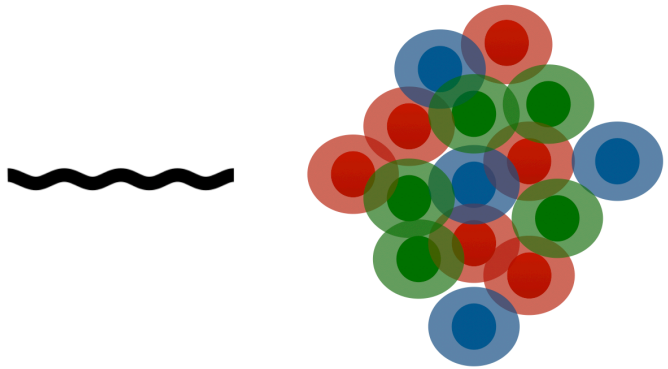


What are the degrees of freedom of the medium under different resolutions?

Can we identify point like scattering centres in the medium?



Weakly coupled



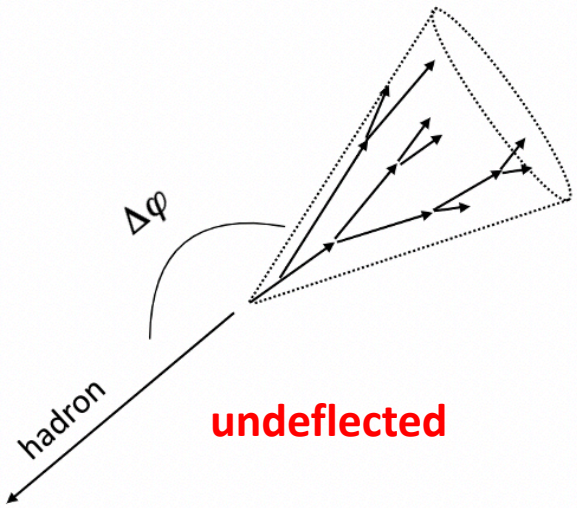
Strongly coupled

Point like scattering in the medium - dijets

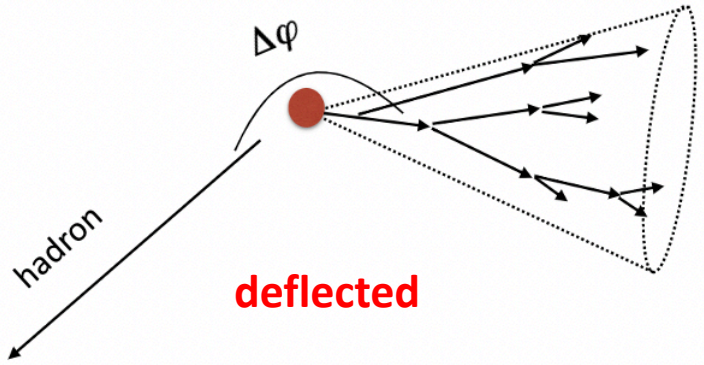
$$\Delta_{\text{recoil}} = \frac{1}{N_{\text{trig}}^{AA}} \frac{d^2 N_{\text{jet}}^{AA}}{d p_{T,\text{jet}}^{\text{ch}} d\eta_{\text{jet}}}\Big|_{p_{T,\text{trig}} \in TT_{\text{Sig}}} - c_{\text{Ref}} \cdot \frac{1}{N_{\text{trig}}^{AA}} \frac{d^2 N_{\text{jet}}^{AA}}{d p_{T,\text{jet}}^{\text{ch}} d\eta_{\text{jet}}}\Big|_{p_{T,\text{trig}} \in TT_{\text{Ref}}}$$

A jet recoiling from a trigger hadron

Can we observe large angle deflections of the jet axis off of medium constituents (moliere scattering)?

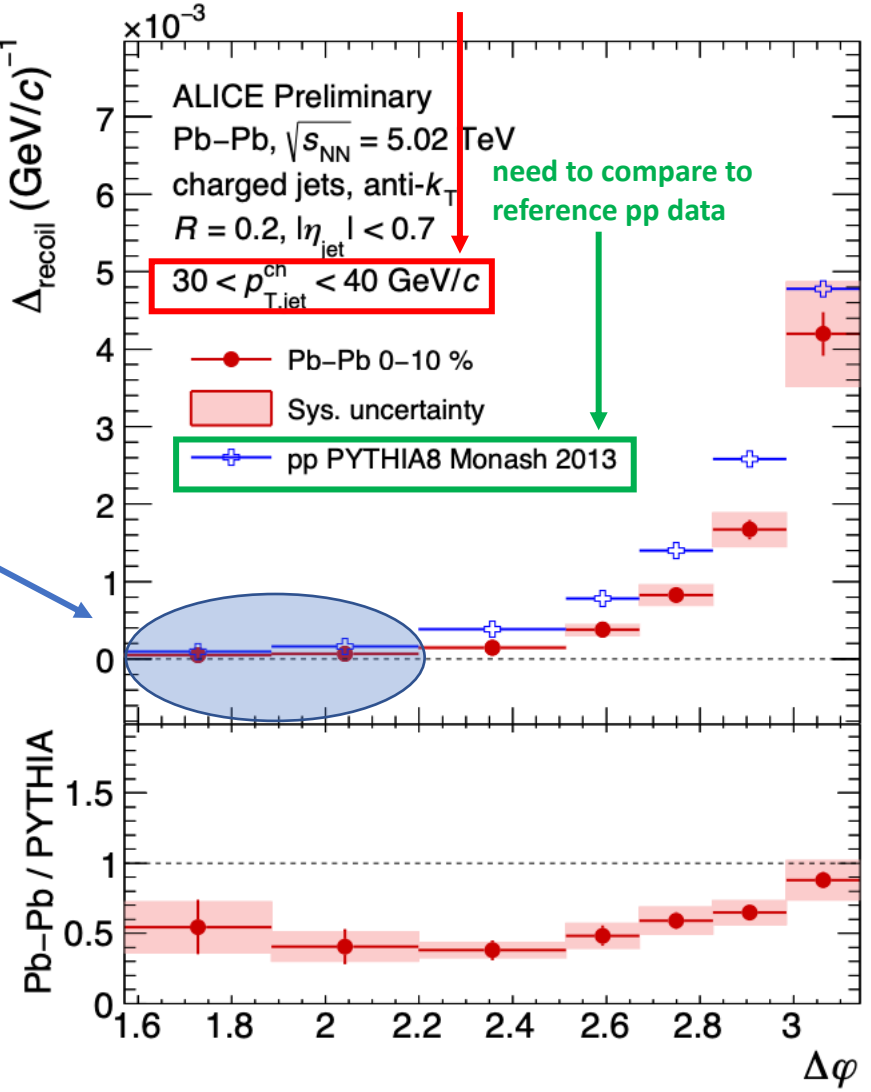


undeflected



deflected

Effects enhanced at lower p_T ? Need to be careful about hadronisation effects



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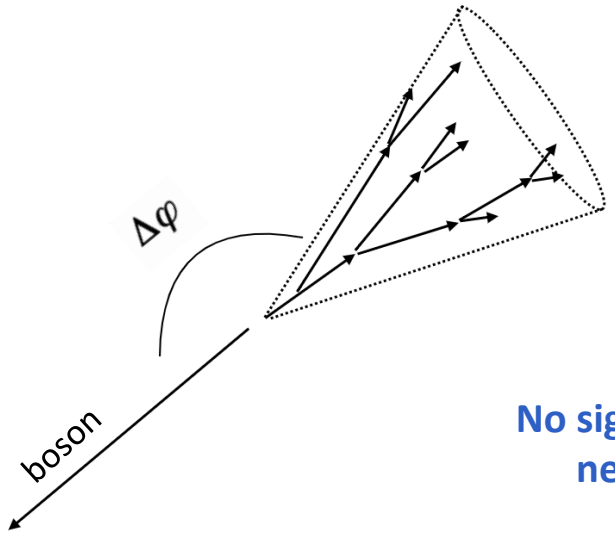
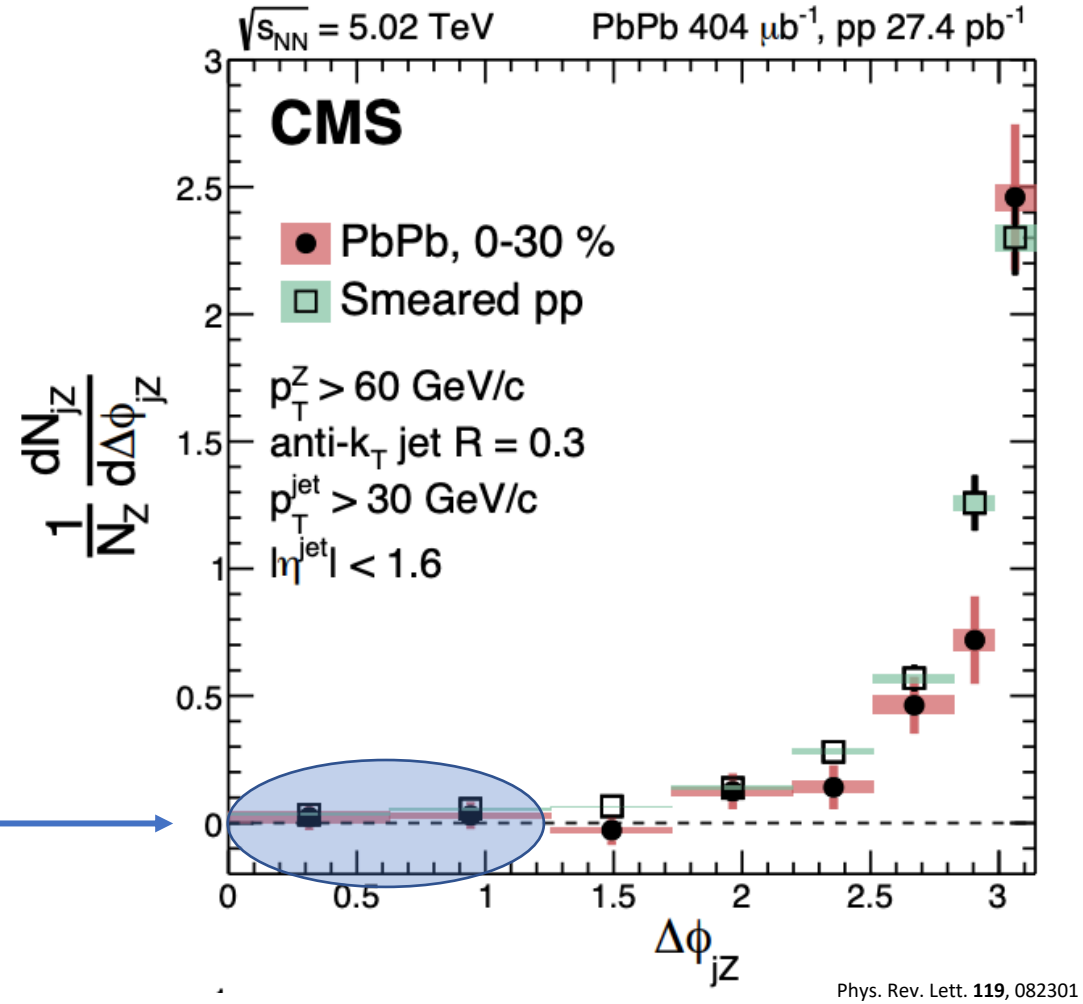
Point like scattering in the medium – boson + jet

Can we find a cleaner proxy for the initial jet direction?
Jets recoiling from non-coloured objects



No significant modification need more statistics

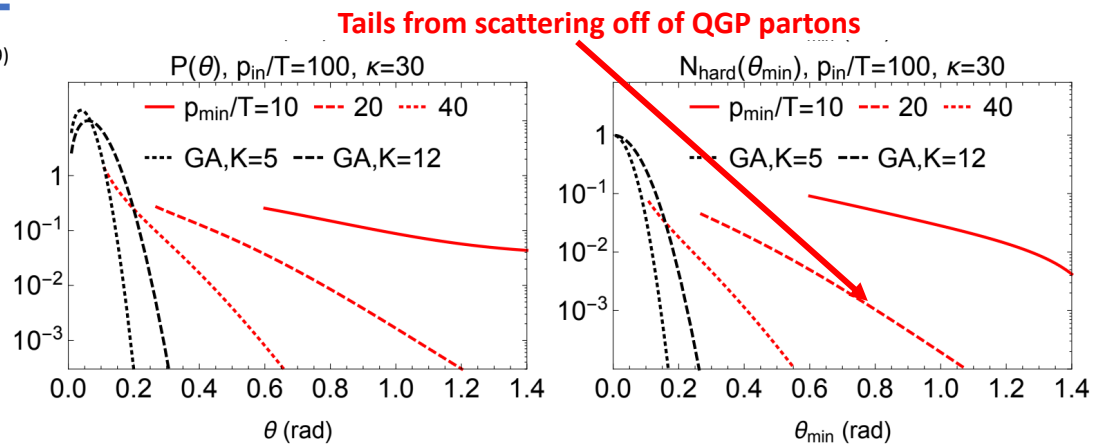


Phys. Rev. Lett. **119**, 082301

Point like scattering in the medium - substructure

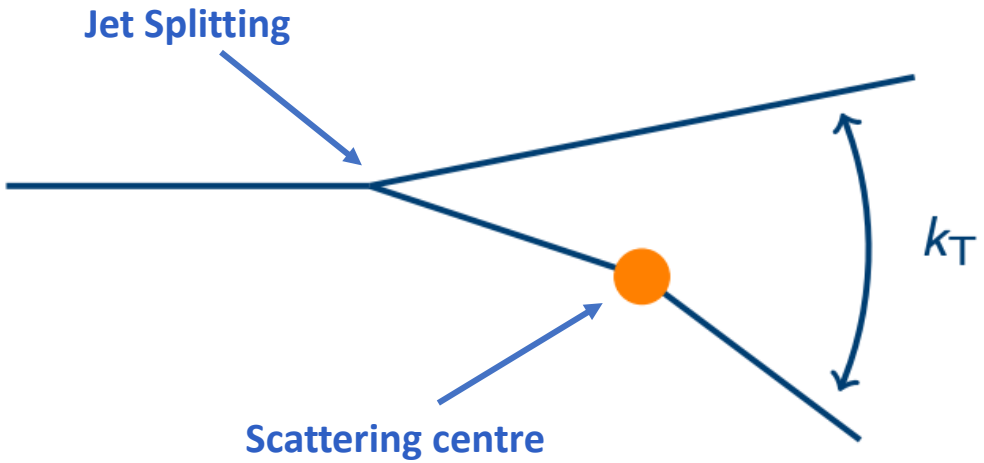
J. High Energ. Phys. **2019,** 172 (2019)

Parton incident upon a weakly coupled brick of QGP



Can we look into substructure?

Large k_T kicks in the splitting tree from point like scattering



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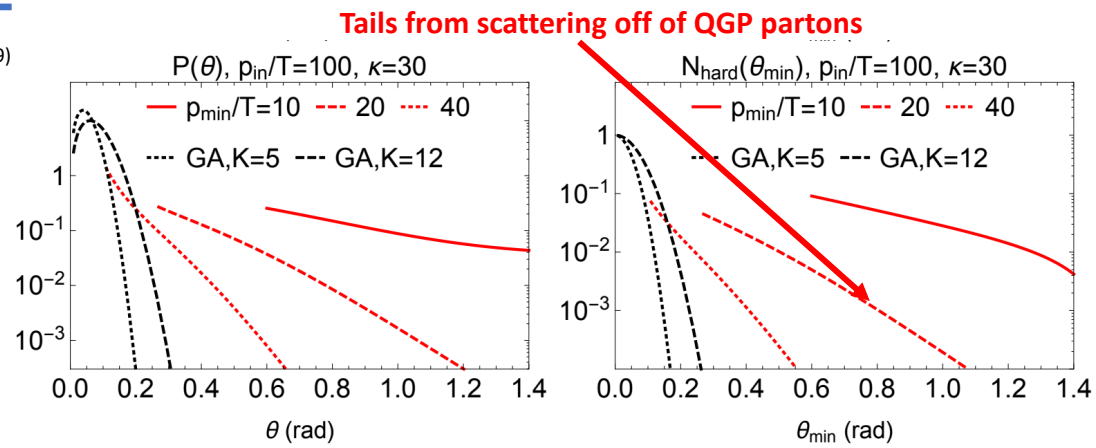

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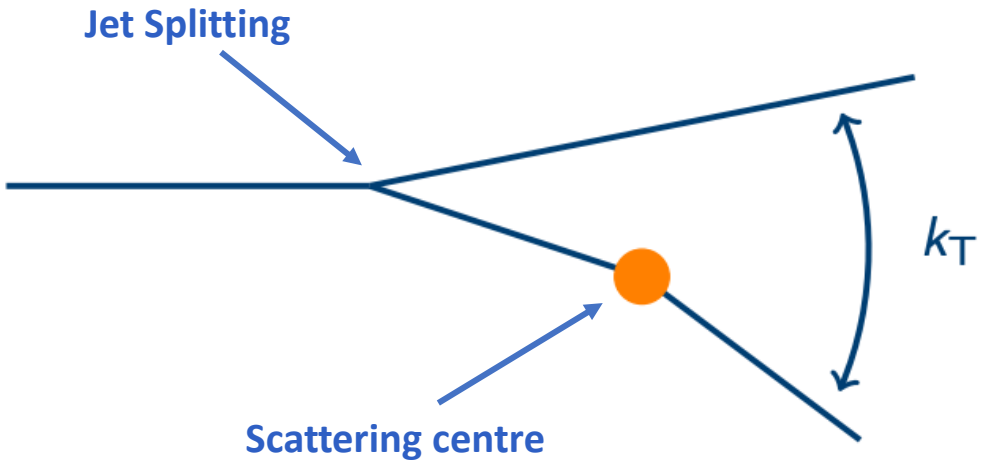
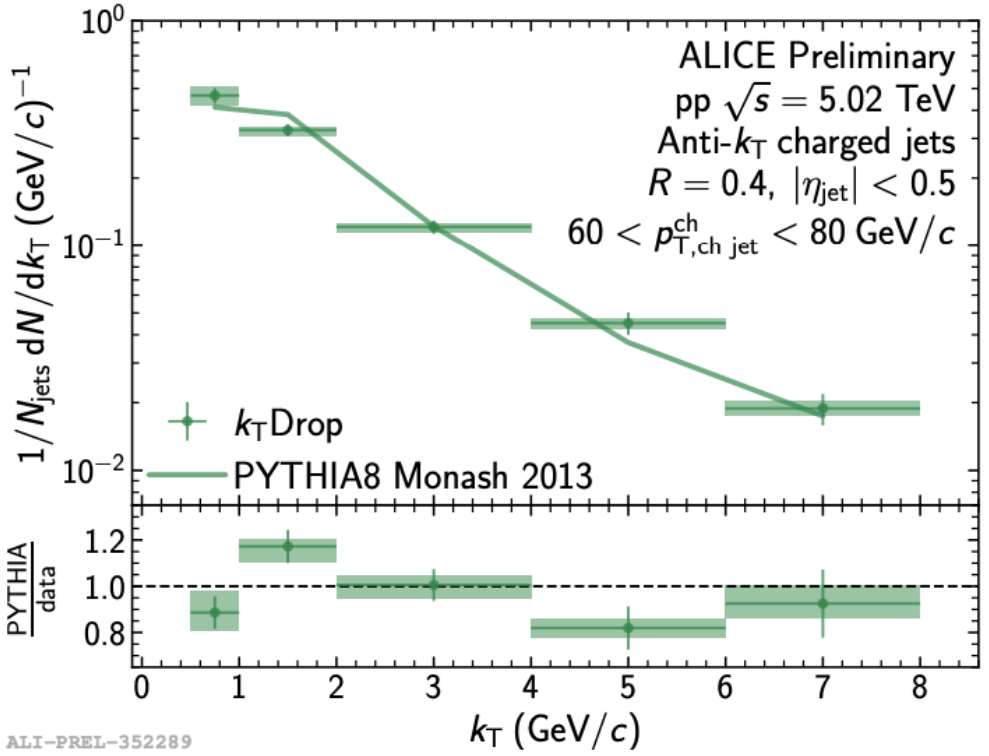
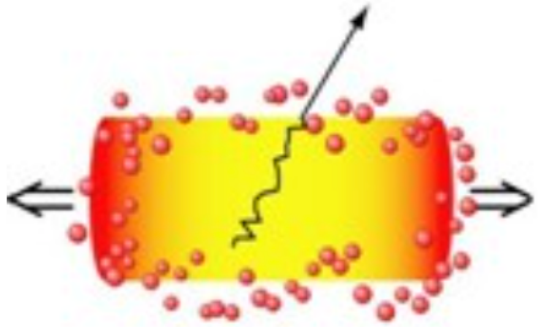


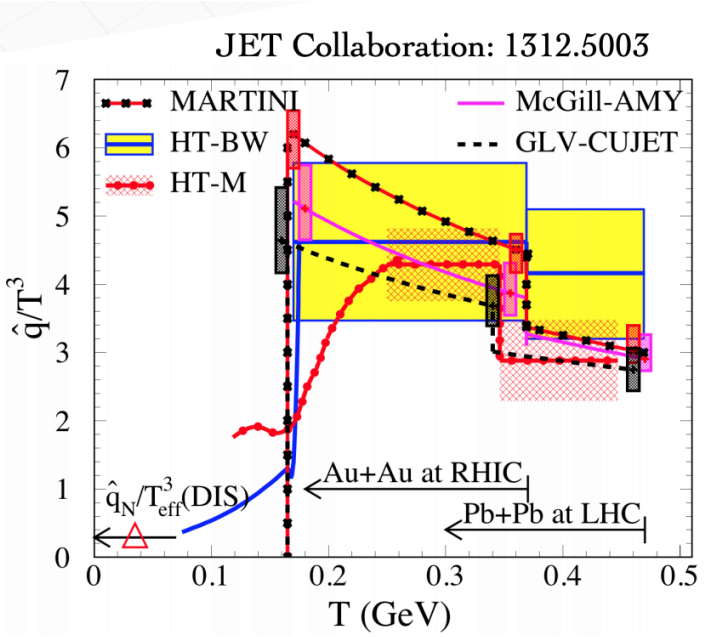
Measurement to be made in PbPb



Can we learn about the transport properties of the medium?

Characterise the energy loss of jets traversing the medium

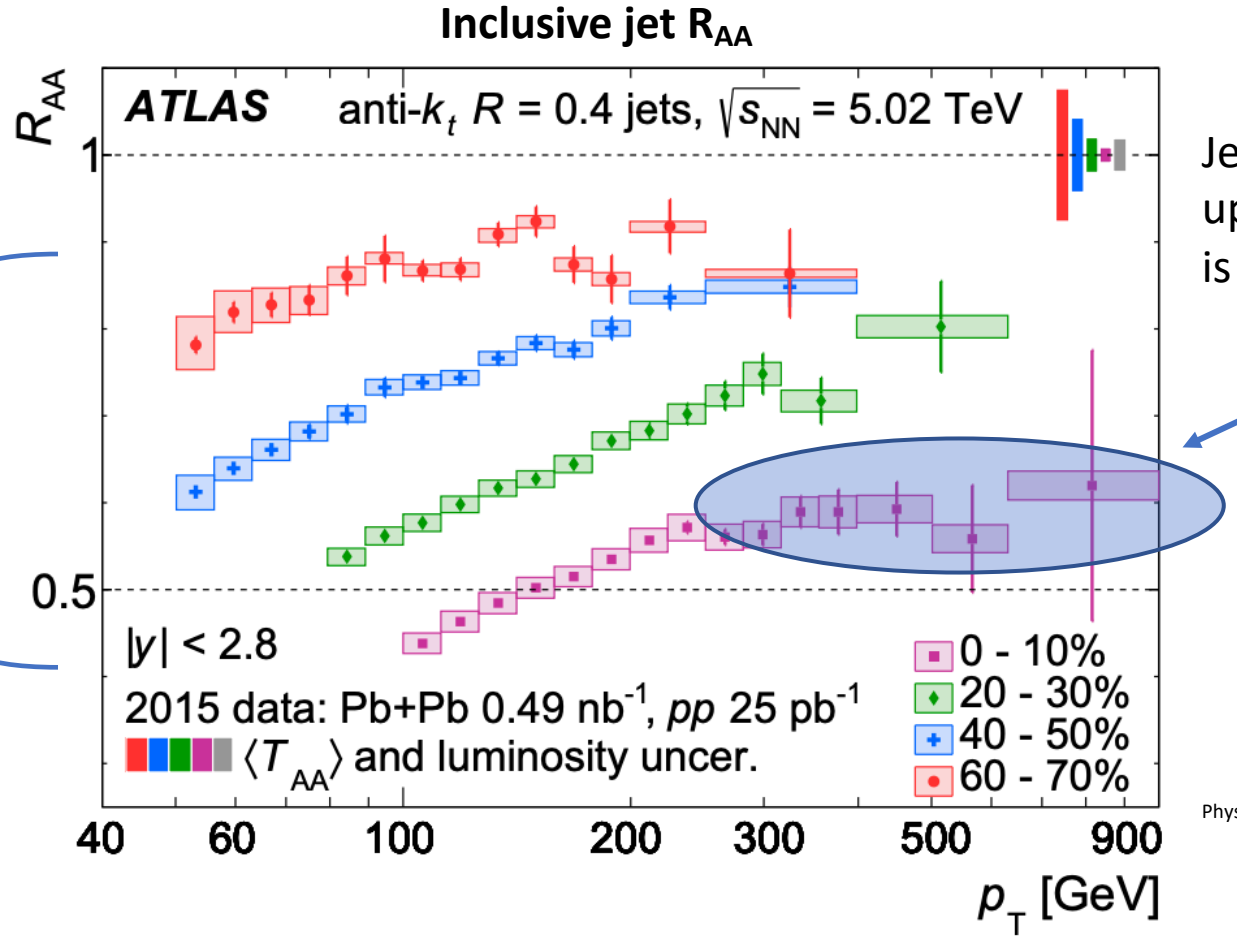




Phys. Rev. C 90, 014909 (2014)

Using jets to quantify energy loss

Strong centrality dependence observed



Jets lose significant energy up to TeV scales – medium is opaque to the jet

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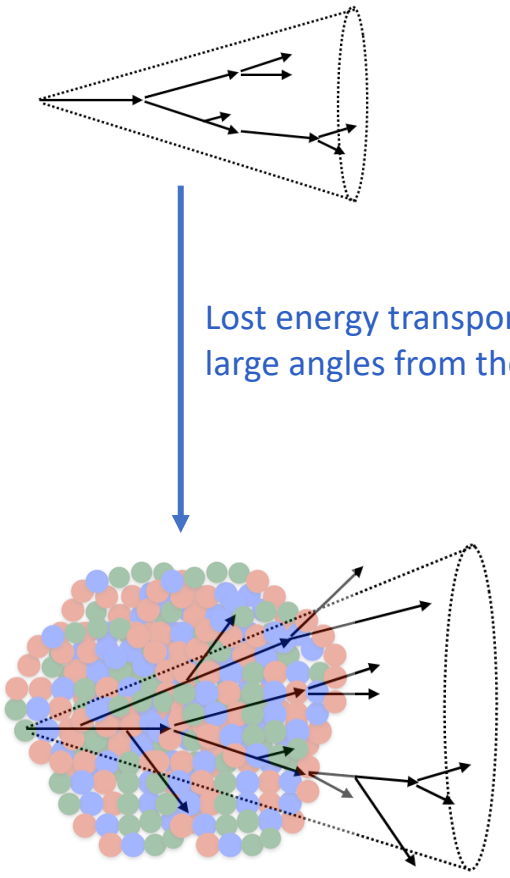
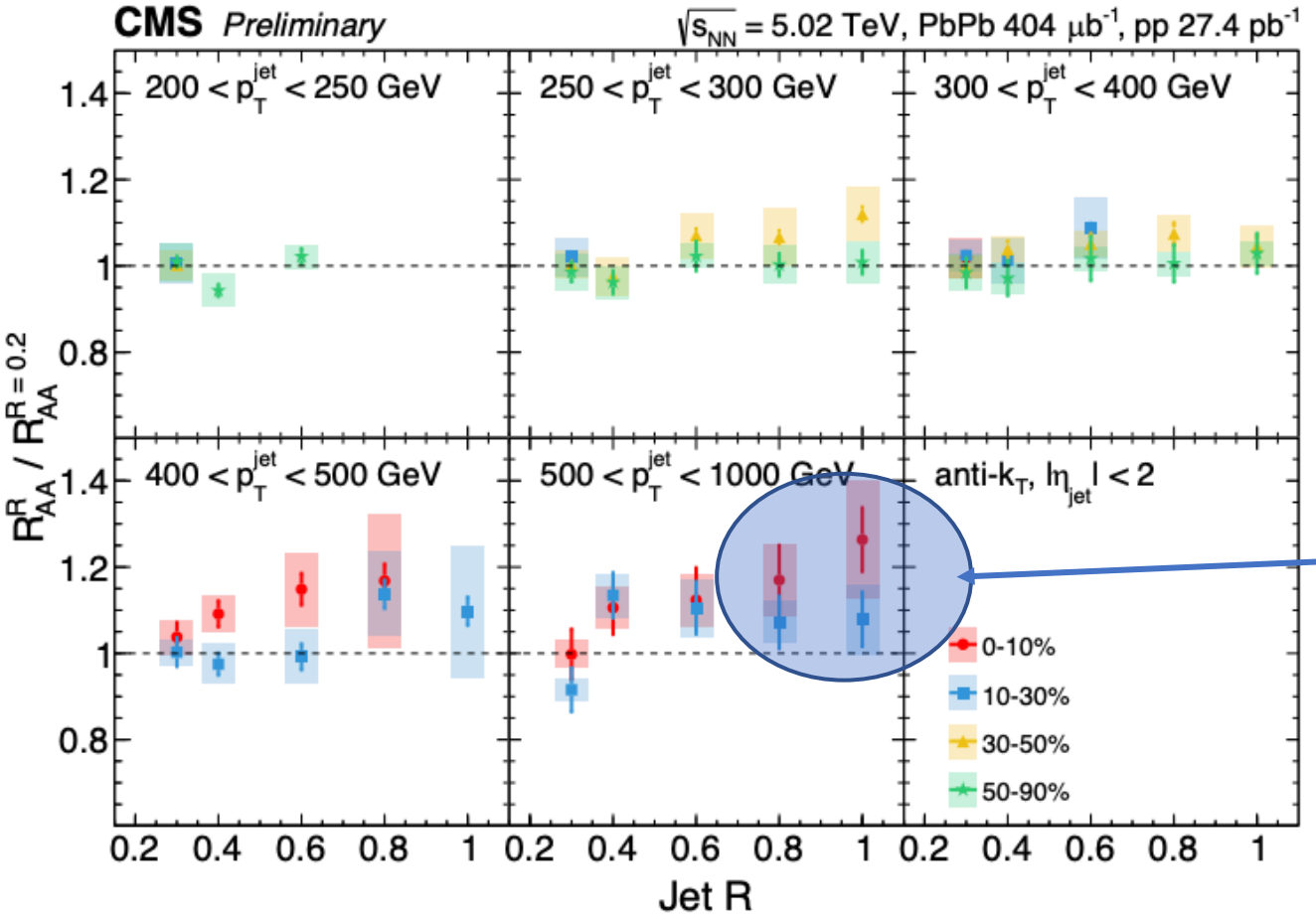
Can we recover the lost energy?

Extend the phase space of jet measurements



Lost energy transported to large angles from the jet axis

Inclusive jet $R_{AA\ (R=x)}$ / Inclusive jet $R_{AA\ (R=0.2)}$



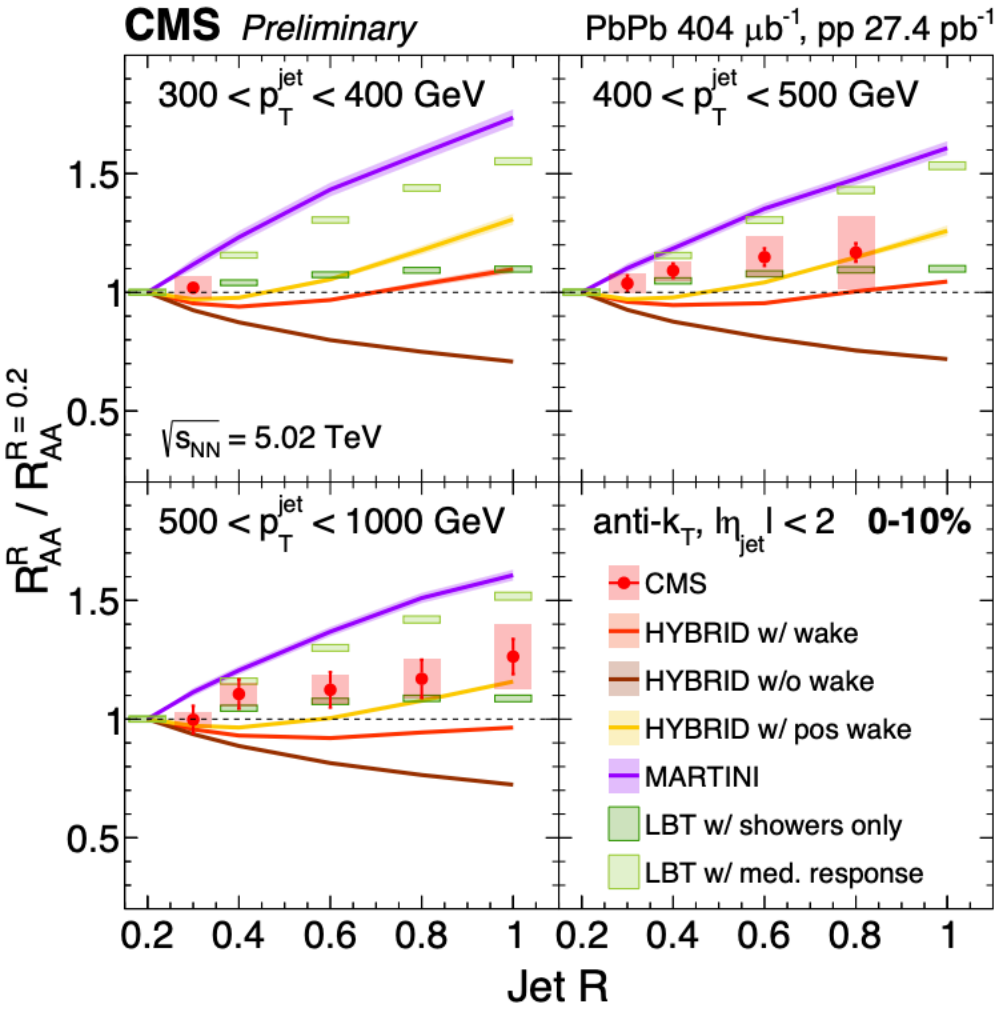
Hints of energy recovery at large angles
need more stats

Can we recover the lost energy?

Extend the phase space of jet measurements

Differentiate between models with different energy loss mechanisms and implementations of medium response

Inclusive jet $R_{AA\ (R=x)}$ / Inclusive jet $R_{AA\ (R=0.2)}$



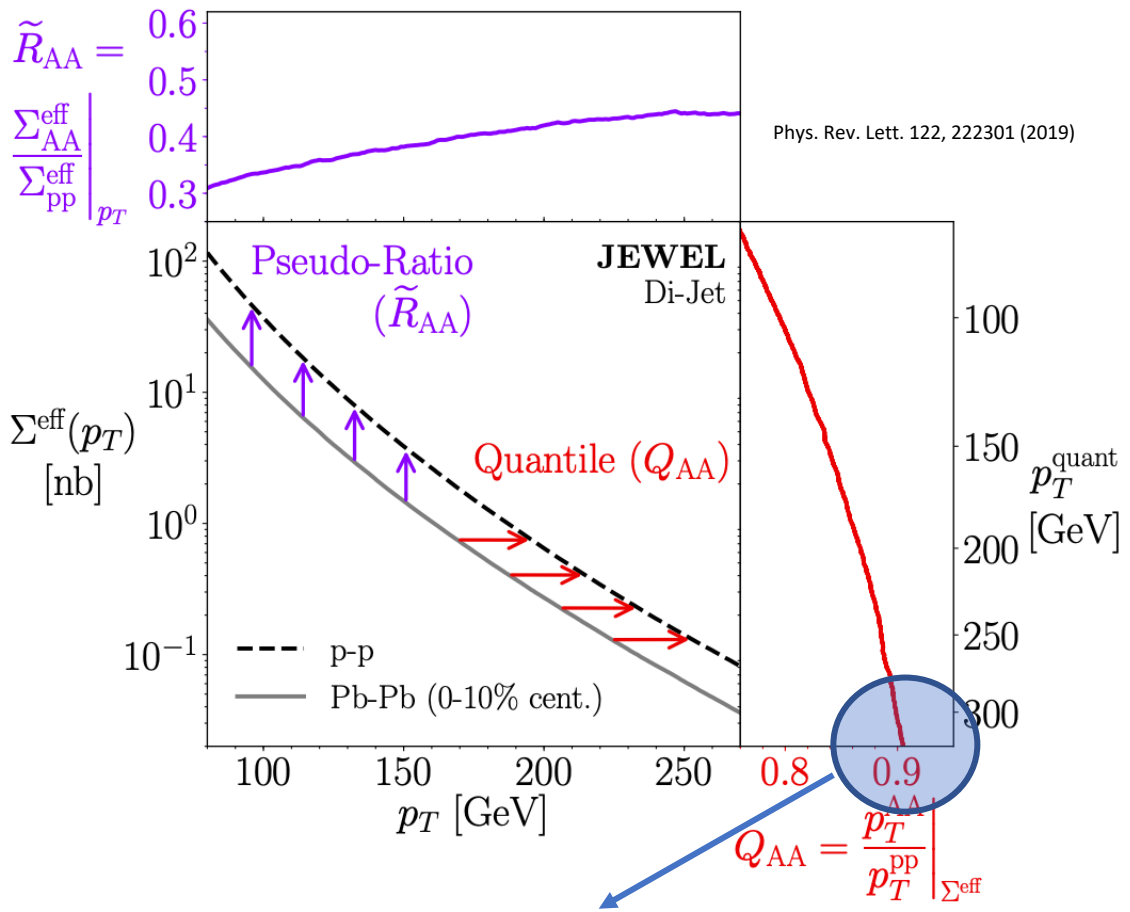
Are we comparing the correct jets in the medium and vacuum?

Steeply falling jet spectrum biases p_T bins with unmodified jets

Quantile matching : statistically match jets between HI and reference collision systems

$$R_{\mathrm{AA}} = \left.\frac{\sigma^{\mathrm{eff}}_{\mathrm{AA}}}{\sigma^{\mathrm{eff}}_{\mathrm{pp}}}\right|_{p_T} \longrightarrow Q_{\mathrm{AA}} = \left.\frac{p_T^{\mathrm{AA}}}{p_T^{\mathrm{pp}}}\right|_{\Sigma^{\mathrm{eff}}}$$

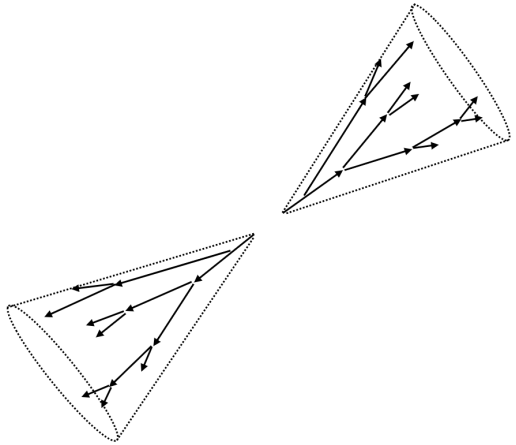
Compare quenched jets with original population



Highest p_T jets lose a small fraction of their energy

Can we measure energy loss on an event by event basis?

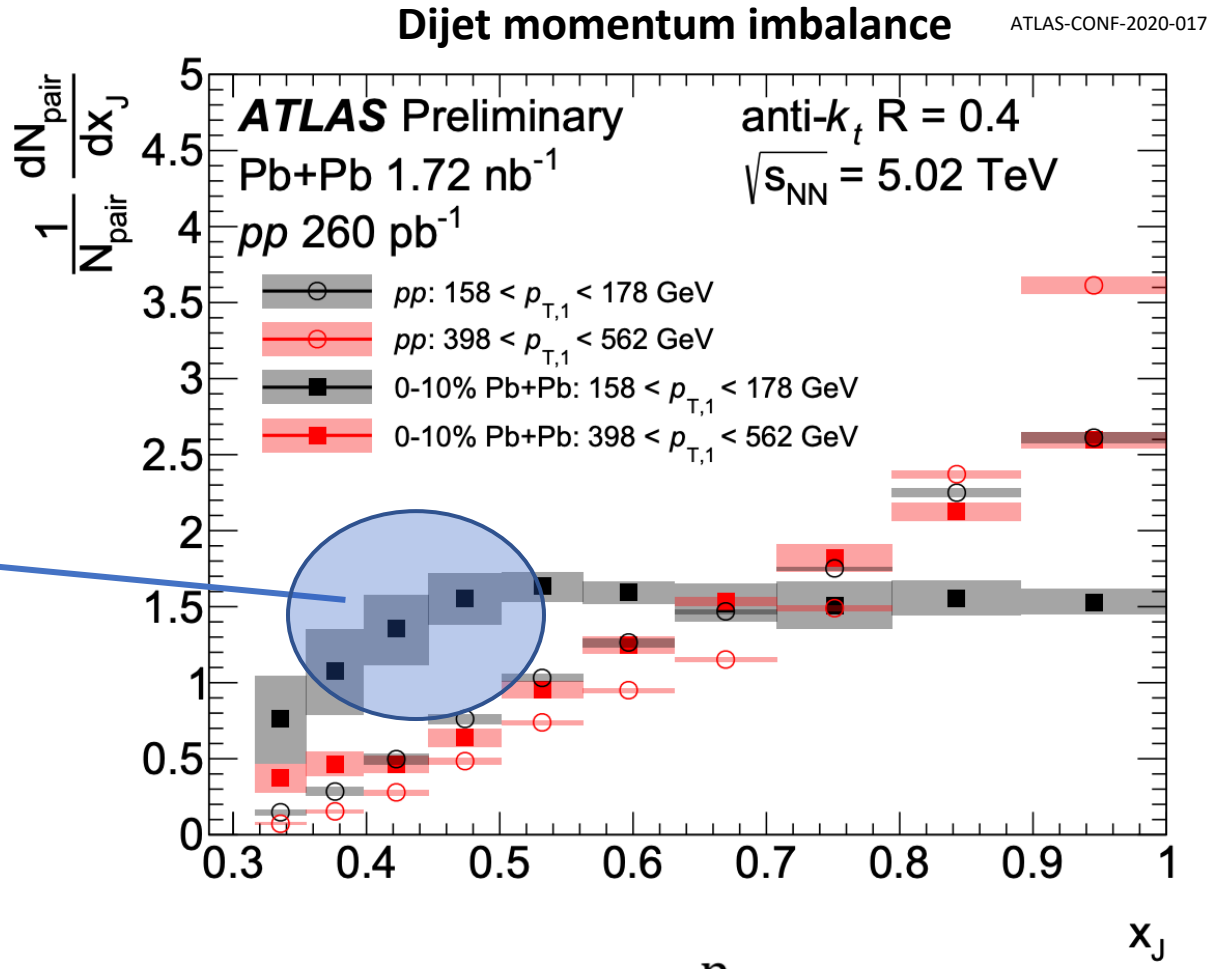
Find a proxy for the original jet energy – dijet system



Significant asymmetry in dijet populations in central HI collisions

Recoiling jet loses more energy

Imbalance reduced with increasing p_T

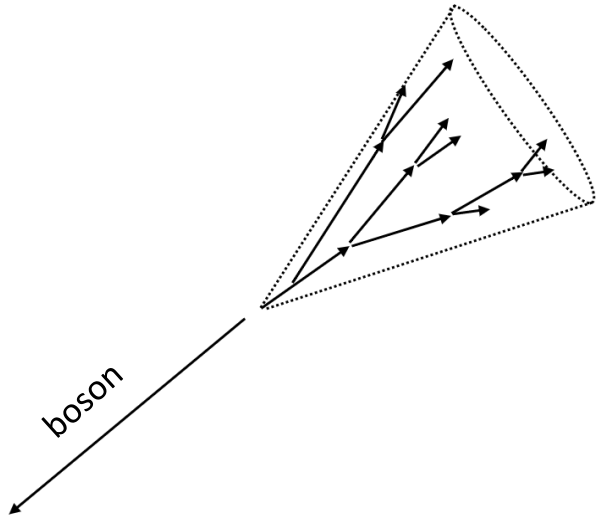


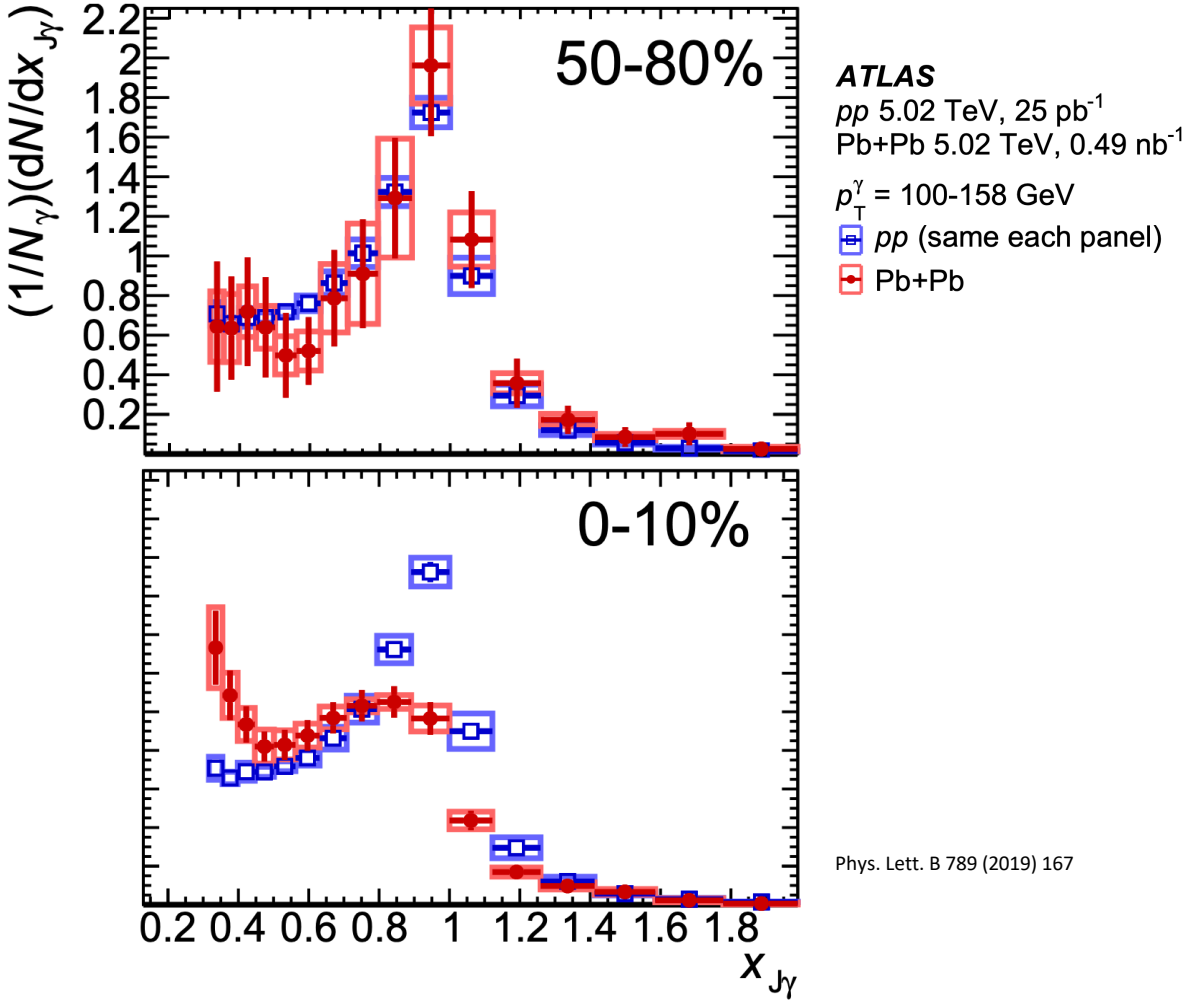
$$x_J = \frac{p_{T,subleading}}{p_{T,leading}}$$

Can we increase the sensitivity?

Accessing the initial energy of the jet - unquenched Boson + jet

Strong centrality dependent asymmetry observed
path length dependance of energy loss?





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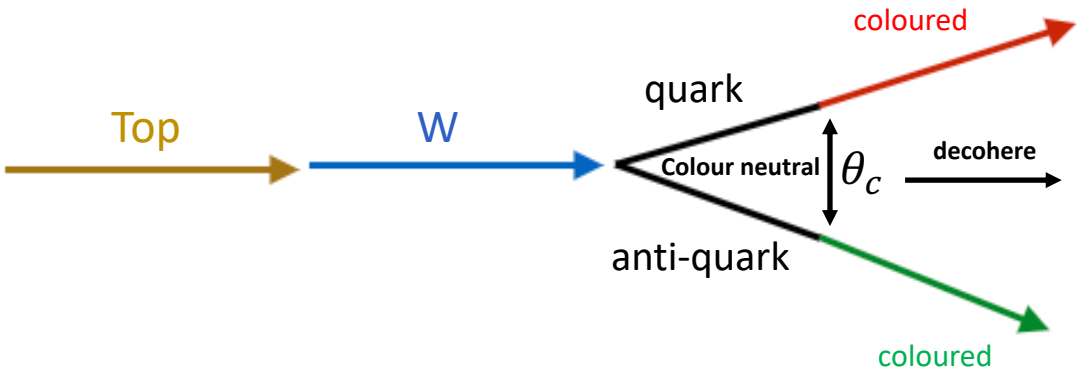
Can we control the path length?

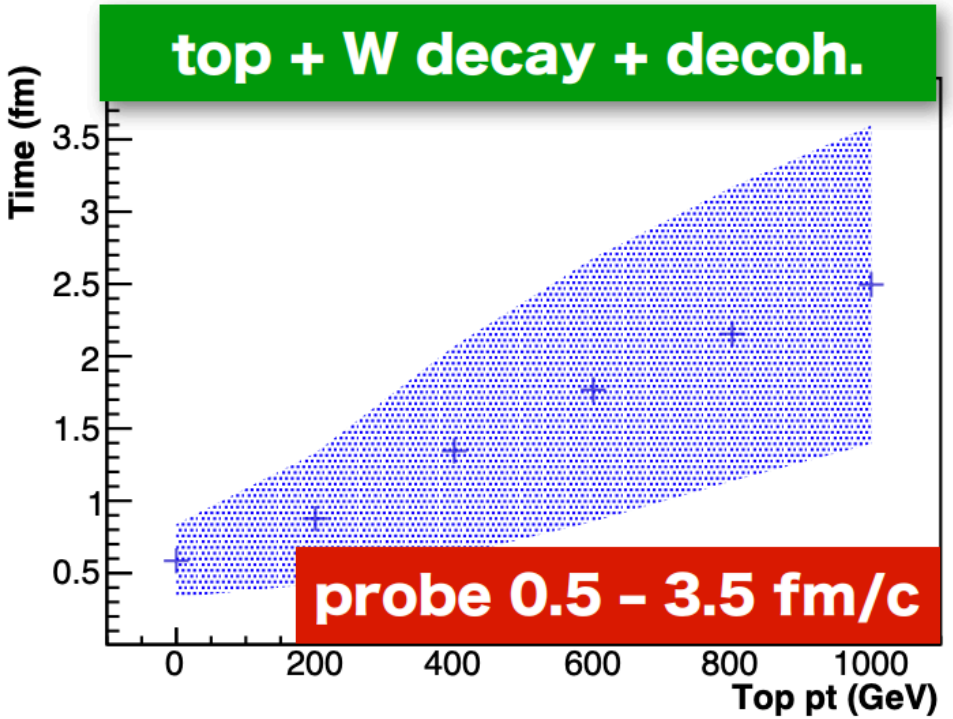
Selecting substructure configurations that allow to tune the onset of quenching



Quenching starts once quarks decohere $\tau_d = \left(\frac{12}{\hat{q}\theta_{q\bar{q}}^2}\right)^{1/3}$

Decoherence time in the medium

Phys. Rev. Lett. 120, 232301 (2018)

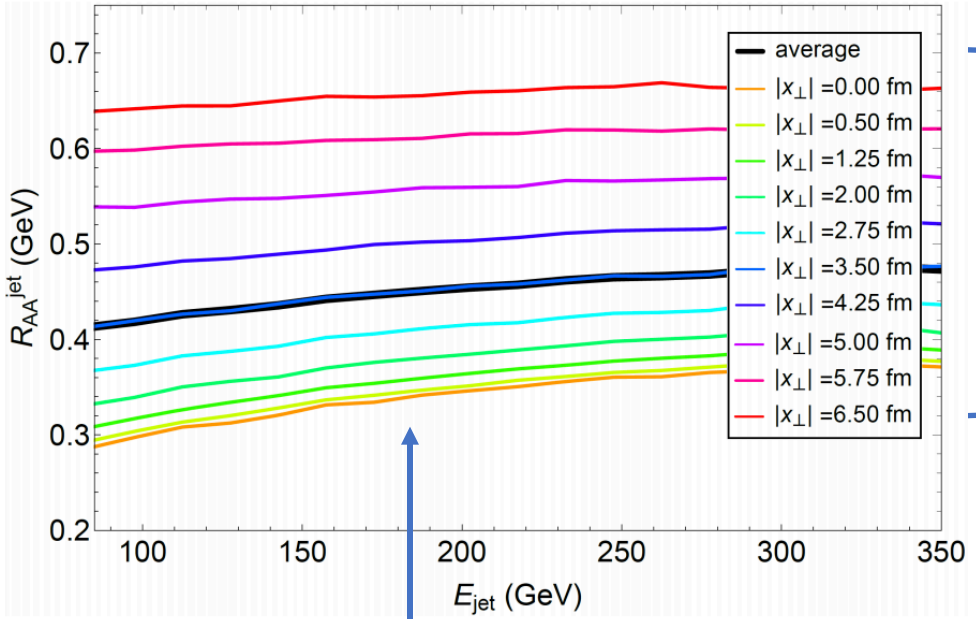


Top quark boost sets quenching time

Is quenching sensitive to in medium path length?

jet R_{AA}

arXiv:1809.10695



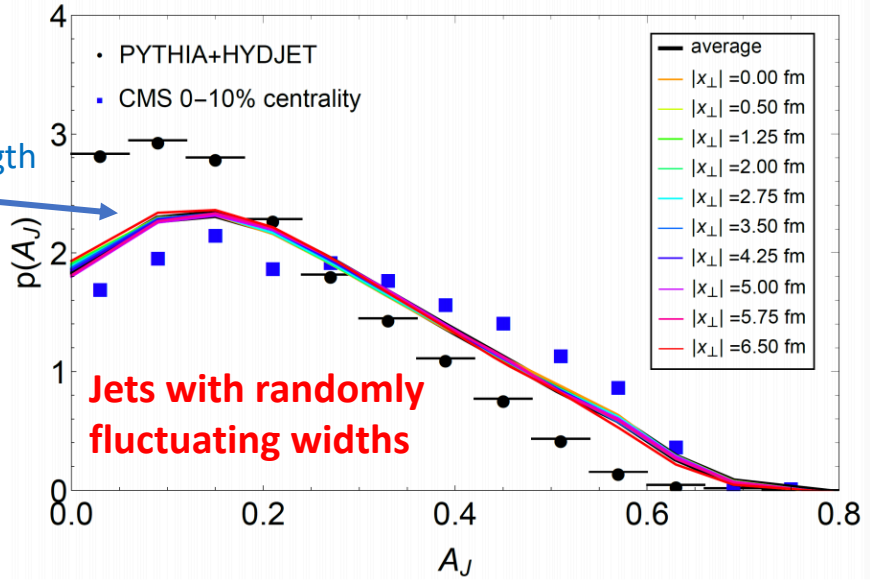
In medium path lengths

R_{AA} shows sensitivity to in medium path length

Do these observations point to coherence effects?

$p_{T,1,2}$ > (120, 30) GeV **Dijet momentum imbalance**

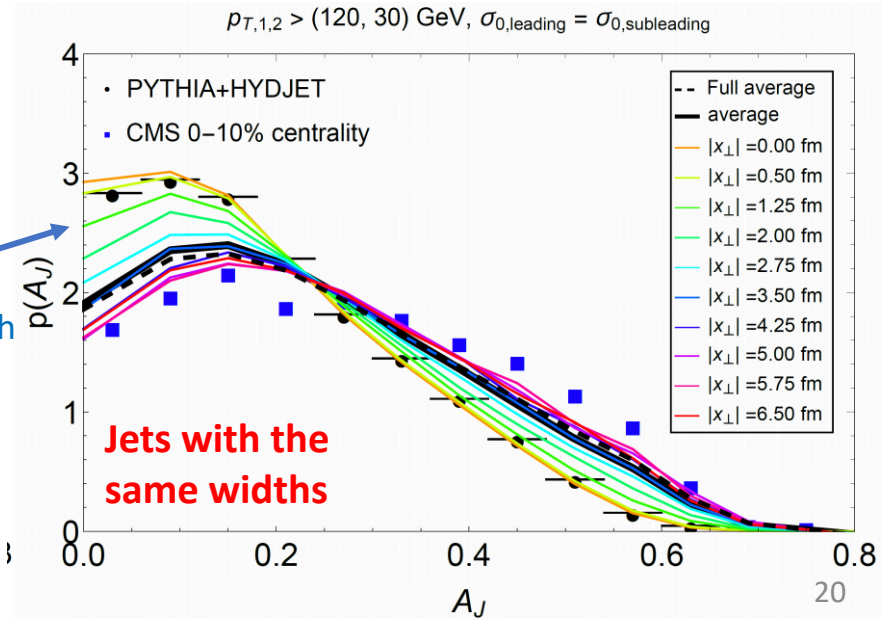
Insensitive to path length



In medium path length sensitivity overshadowed by jet width fluctuations

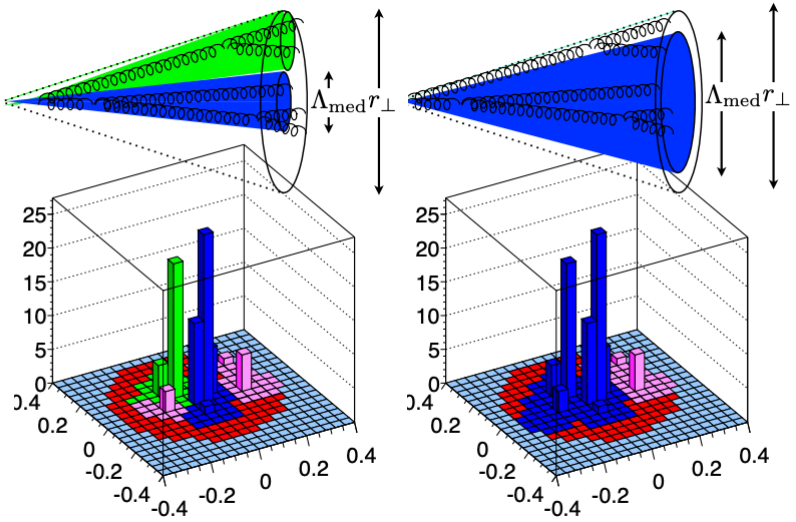
$p_{T,1,2}$ > (120, 30) GeV, $\sigma_{0,leading} = \sigma_{0,subleading}$

Sensitive to path length



What is the resolving power of the medium?

Phys. Lett. B 725 (2013) 357



resolved **unresolved**

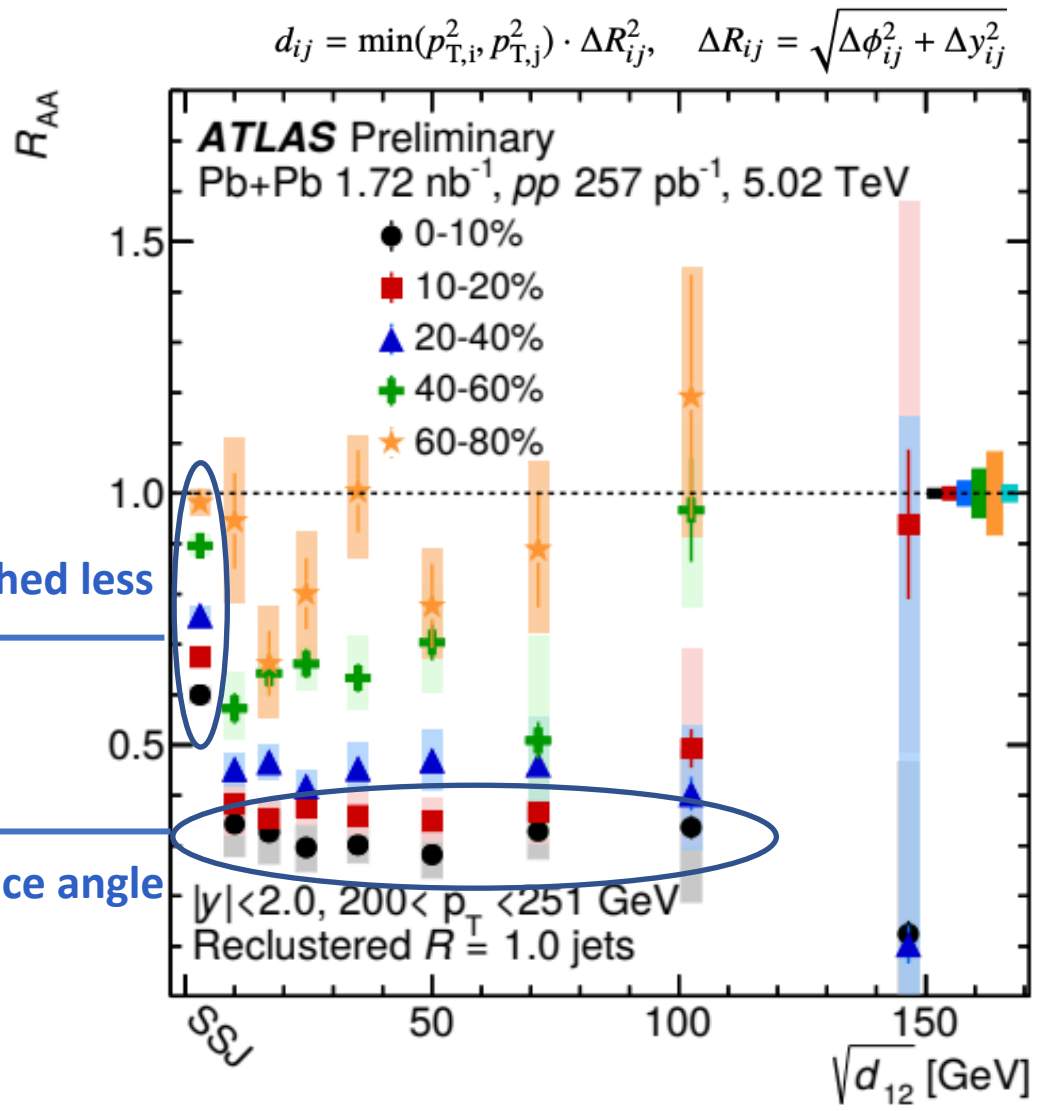
$$\Delta_{\rm med} \simeq 1 - {\rm e}^{-\frac{1}{12}\hat{q}Lr_\perp^2} \equiv 1 - {\rm e}^{-(\Theta/\theta_c)^2}$$

Can jet substructure probe colour resolution?

Evaluate quenching as a function of angular separation of jet substructures

Can we extract the coherence angle?

R_{AA} of hard core jets



Single cored jets quenched less

Limited sensitivity to coherence angle

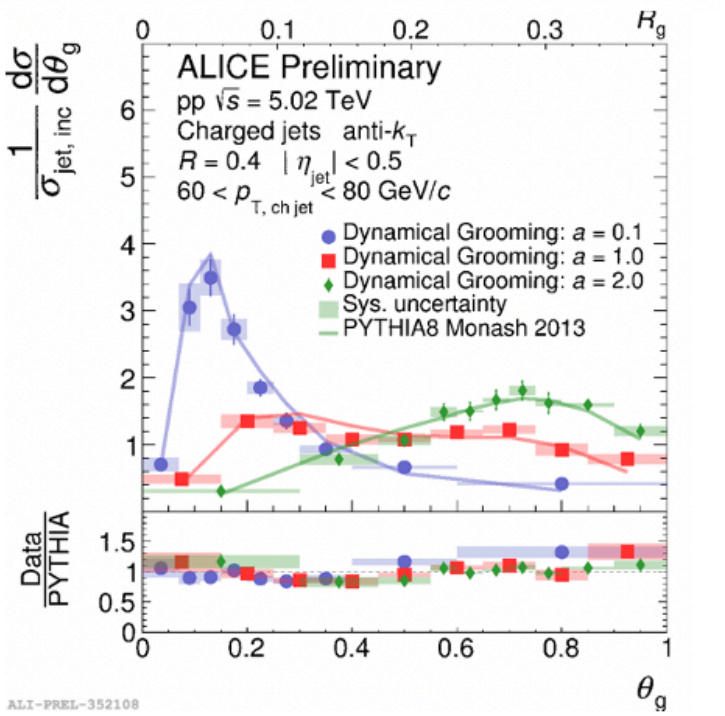
Correlated with larger angle between subjets

Can we directly measure the coherence angle?

Find perturbative splittings using grooming methods

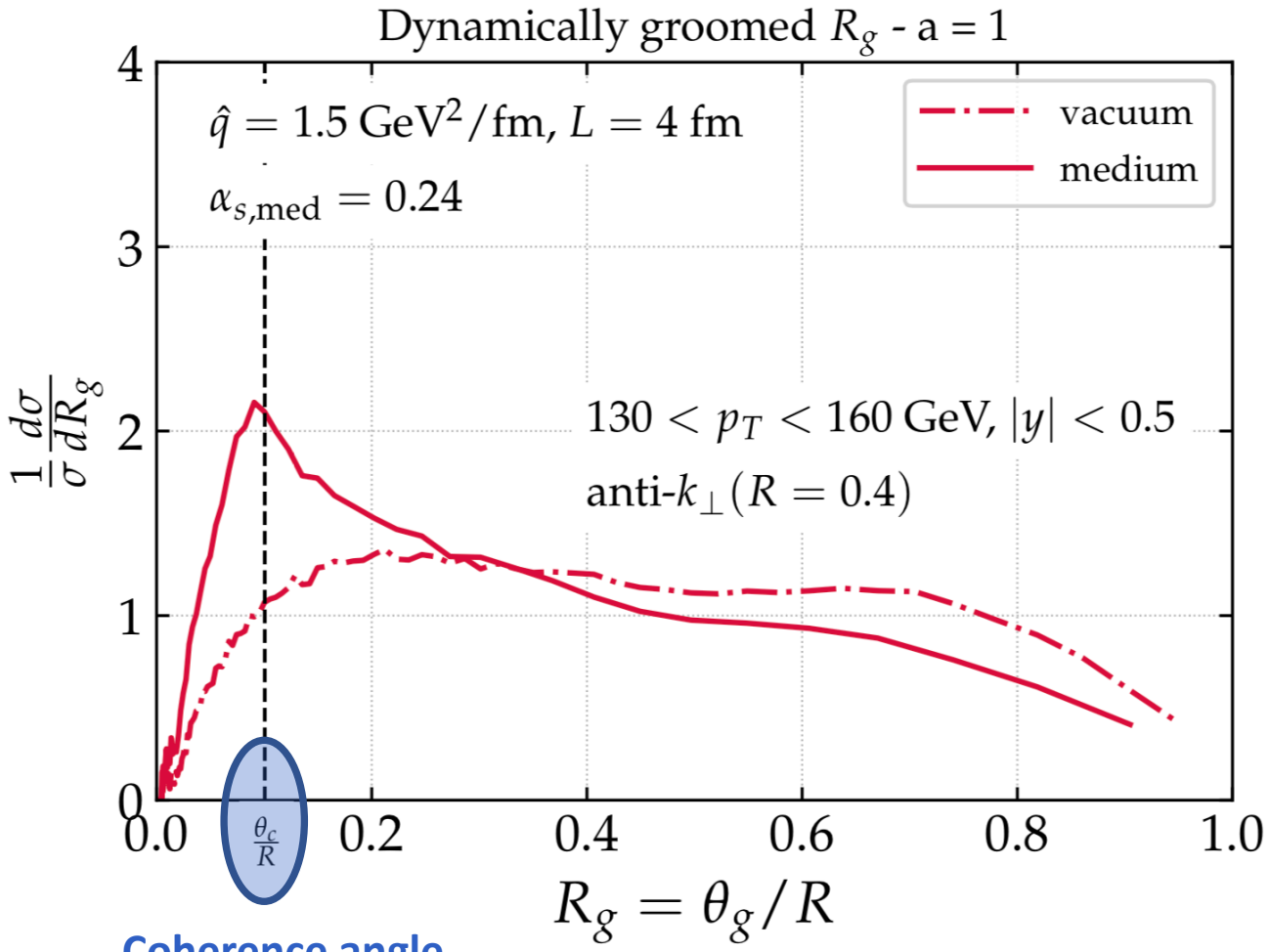
Isolate particular regions of the phase space

pp measurement



Phys. Rev. D 101, 034004 (2020)

Dynamical grooming

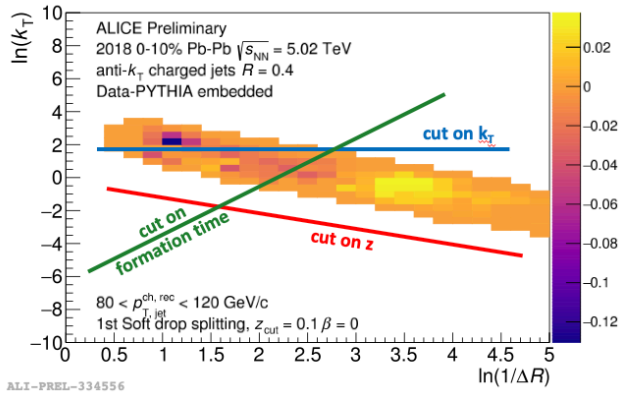


Coherence angle

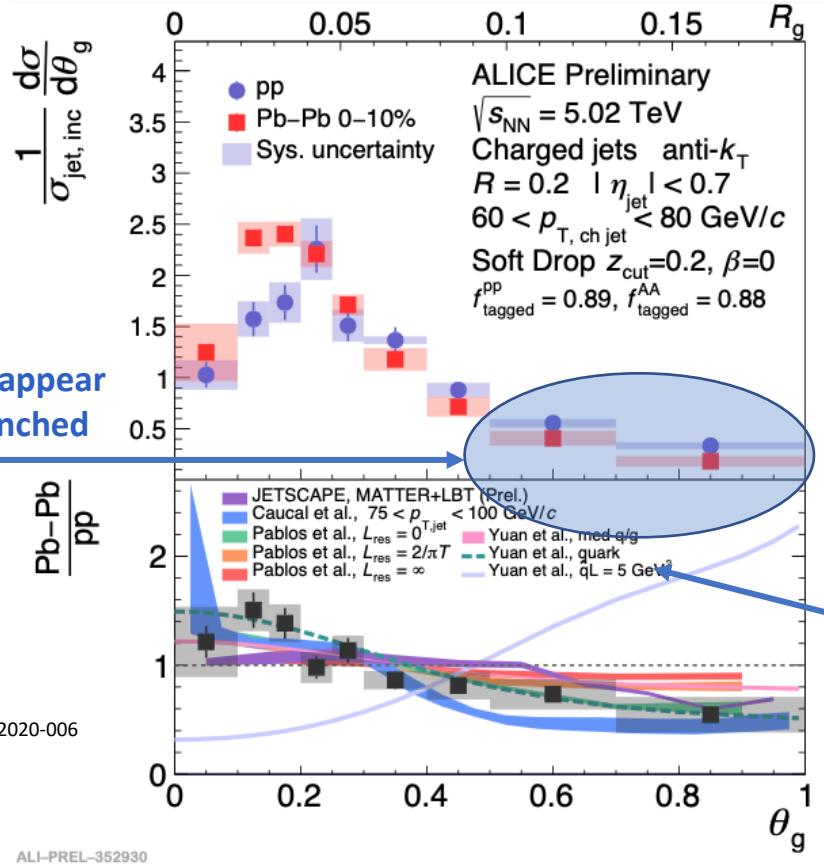
Can we directly measure the coherence angle?

Find perturbative splittings using grooming methods

Isolate particular regions of the phase space



Soft Drop



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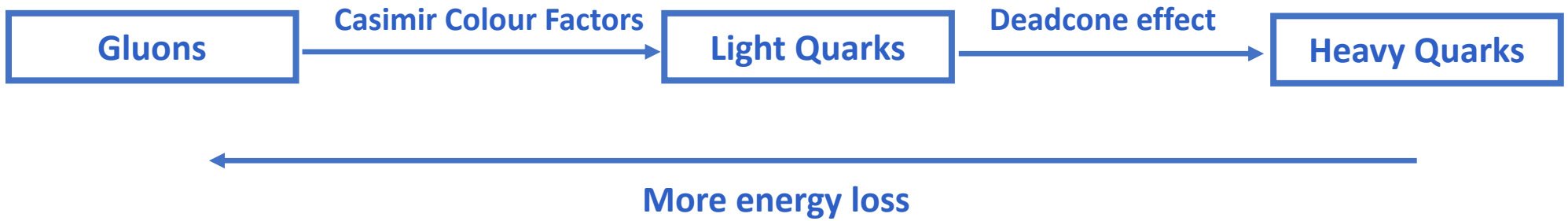
Wider jets appear more quenched

narrow jets **wide jets**

Can we make substructure based selections on dijet populations? Differential measurements of momentum asymmetry

Coherence effects or changes in q/g ratio?

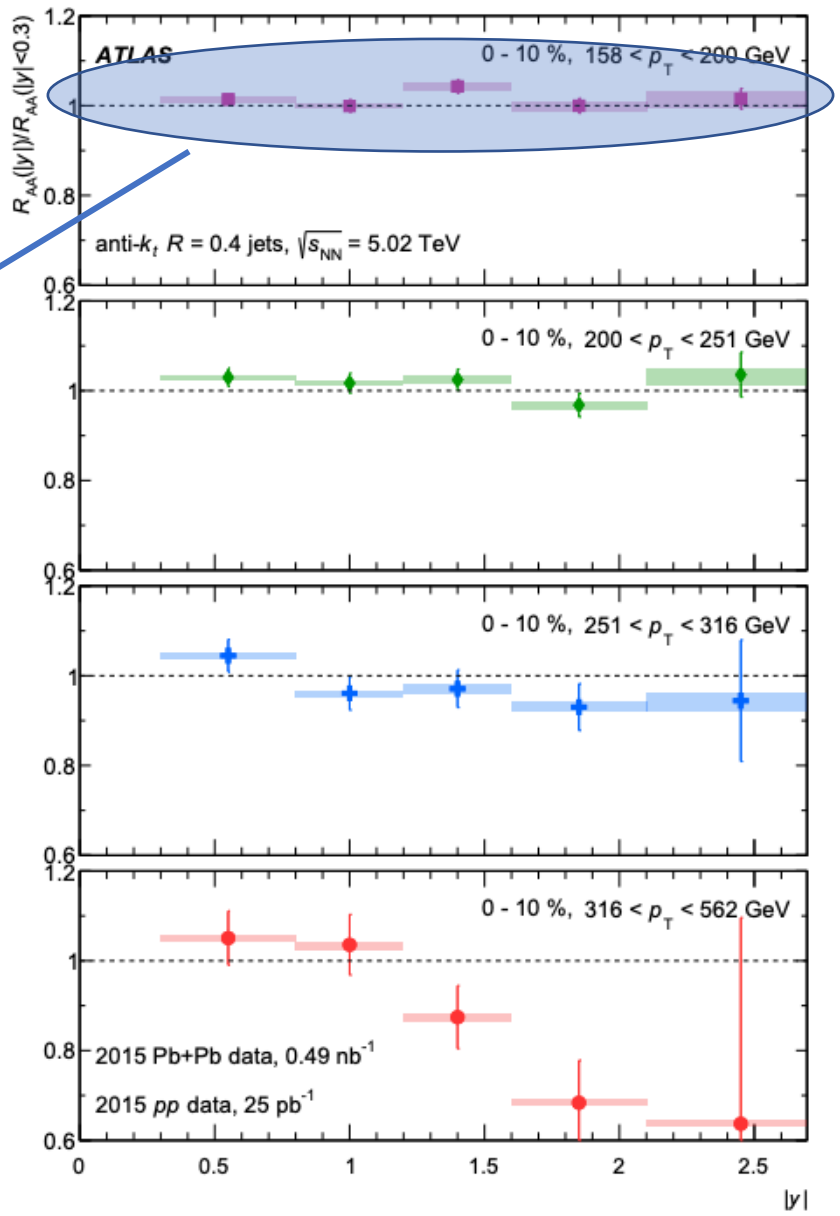
Is there a flavour dependence of energy loss?



Can we vary the q vs g ratio?

Quark vs Gluon quenching can be studied by varying their measured fractions

R_{AA} Increasing quark fraction



No discernable difference between q vs g quenching

Masked by the steeply falling spectrum?

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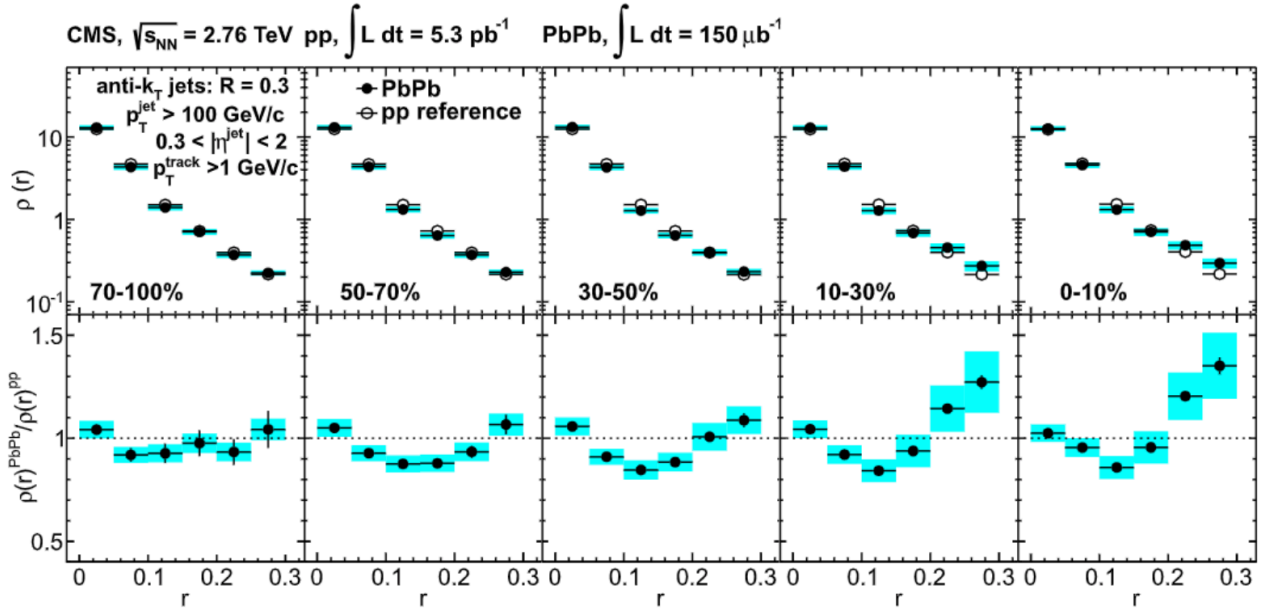
Can we vary the q vs g ratio?

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

Quark vs Gluon quenching can be studied by varying their measured fractions

Inclusive jets show larger modification to radial profile



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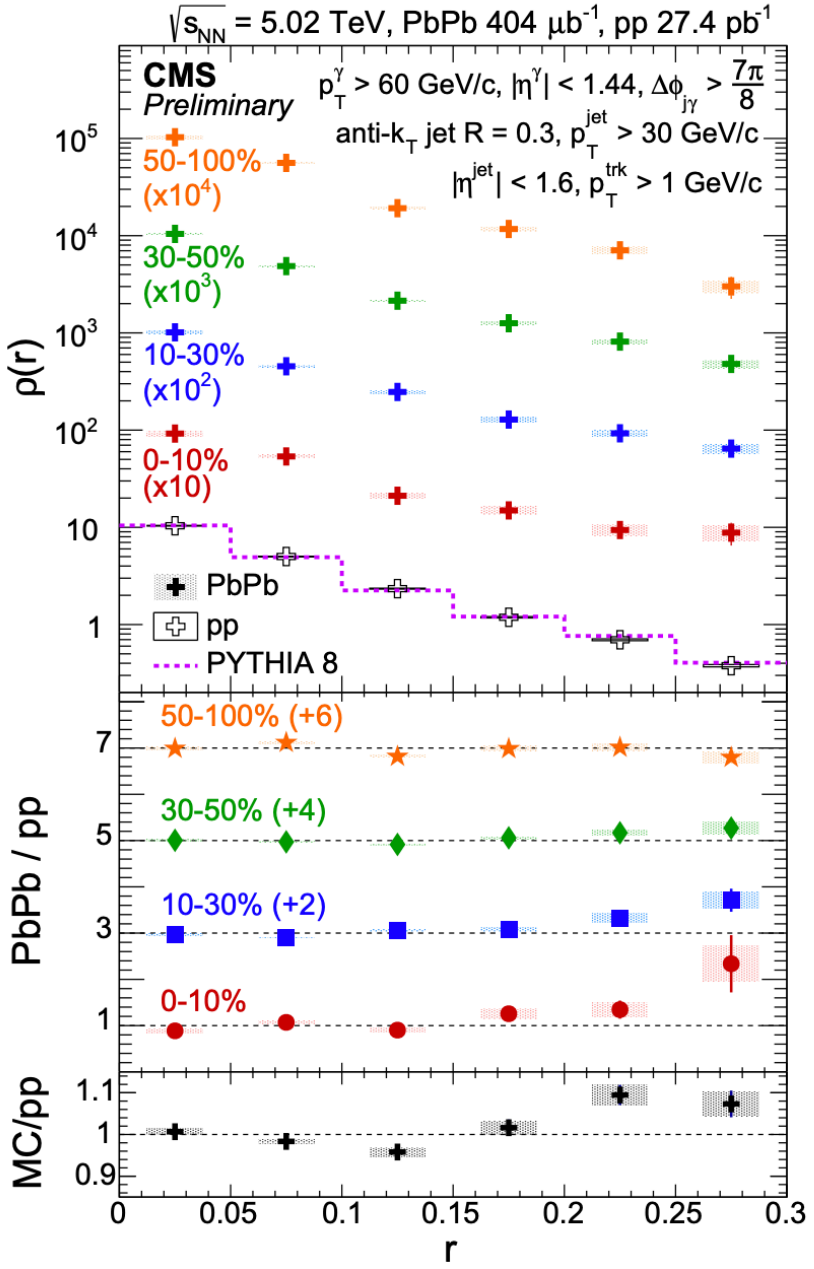
Inclusive jets

Photon-tagged recoil jets



Increased quark fraction

CMS PAS HIN-18-006

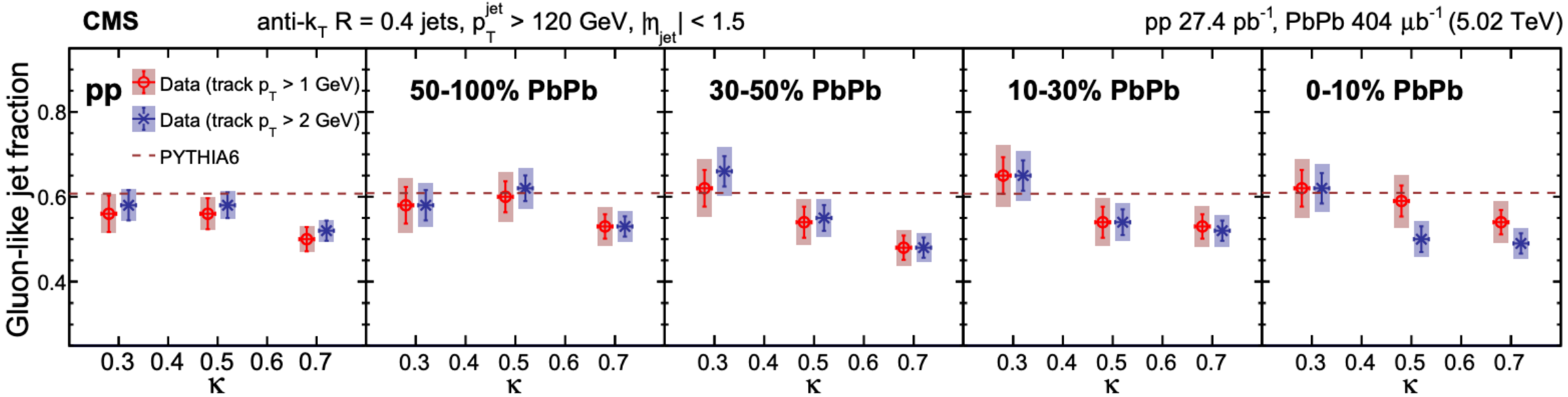
Can we directly measure the q vs g ratio?

Use jet substructure to tag quark and gluon jets – jet charge

Measure fraction surviving after quenching

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

Jet charge measurements show no variation in the gluon fraction from pp to Heavy-Ions



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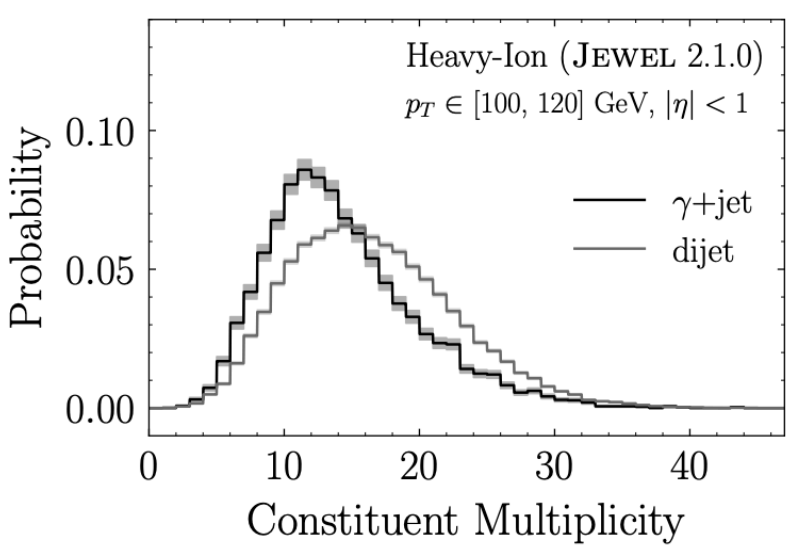
Can we directly measure the q vs g ratio?

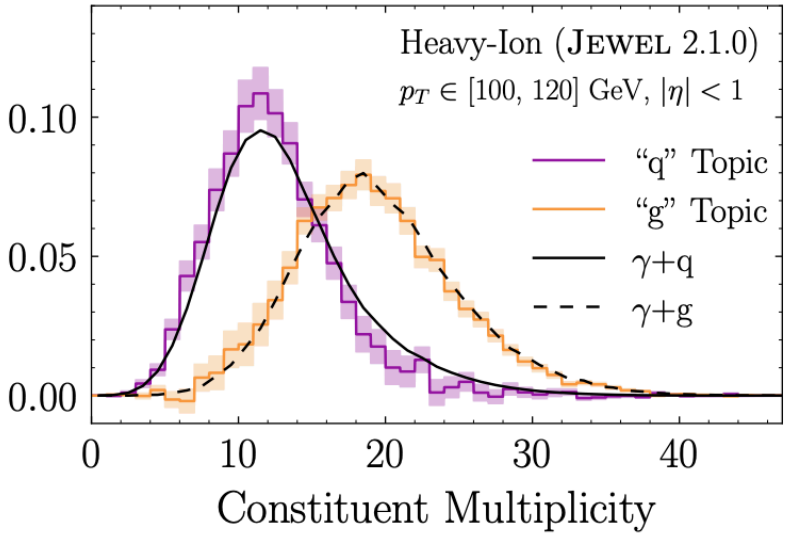
Use jet substructure to tag quark and gluon jets

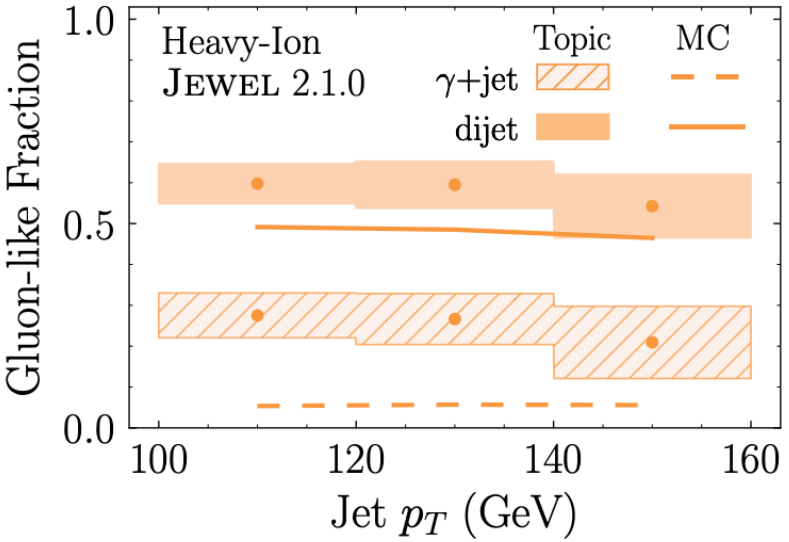
Measure fraction surviving after quenching

Model independent?

Newly proposed statistical method to extract quark or gluon fraction from two mutually irreducible distributions







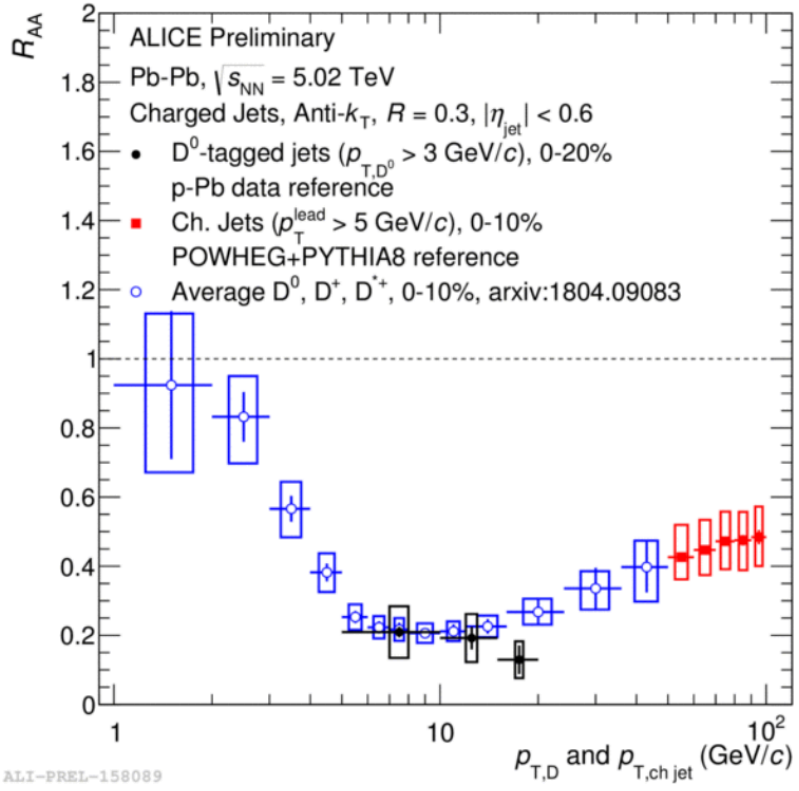
arXiv:2008.08596

Looking to heavy-flavour jets

enriched quark sample + deadcone

Do heavy-flavour jets lose less energy?

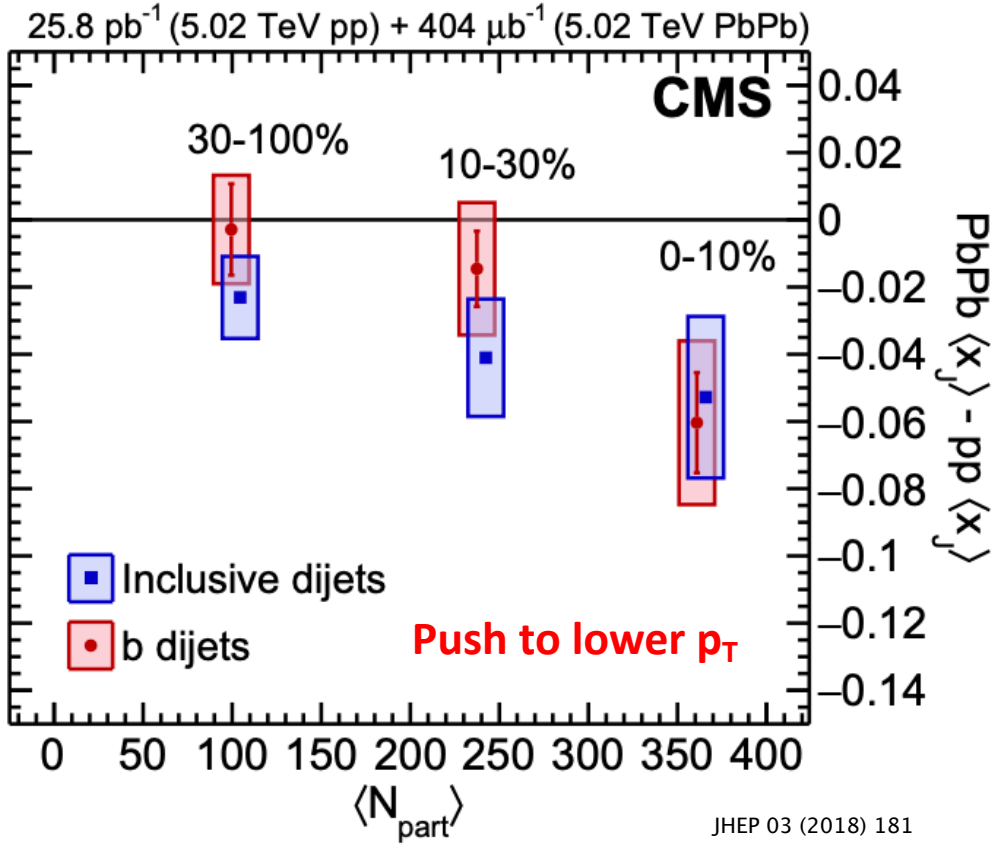
D^0-tagged jet R_{AA}



Need more statistics

No significant differences in momentum imbalance between inclusive and beauty dijets

Mean momentum imbalance



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Need to extend measurements to overlapping regions

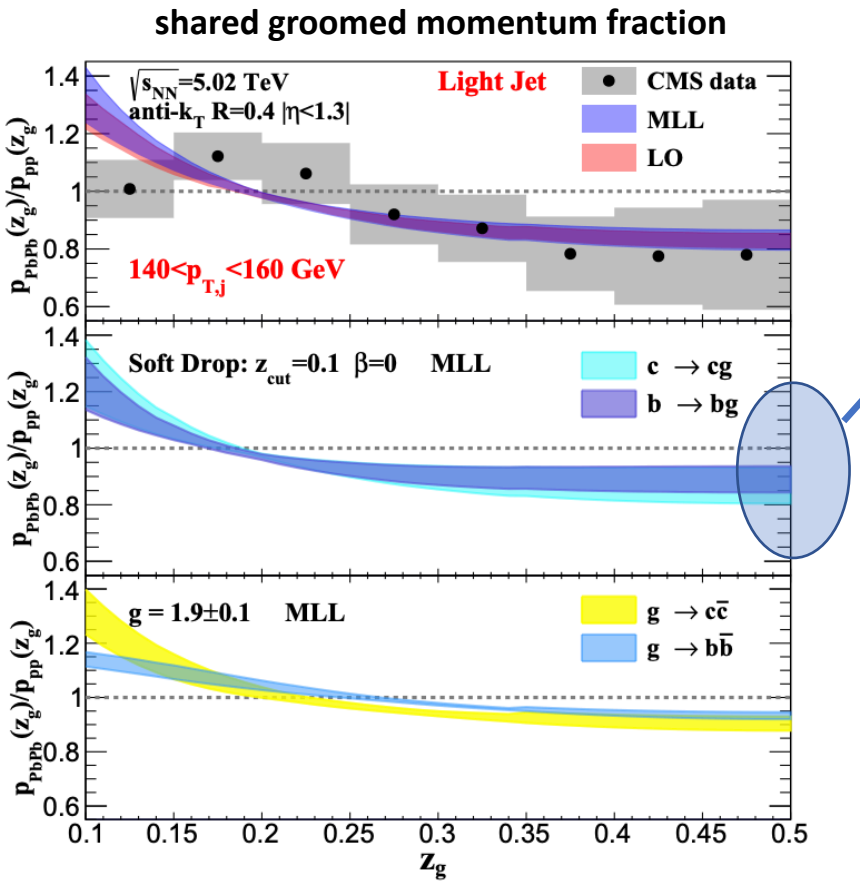
Heavy flavour substructure

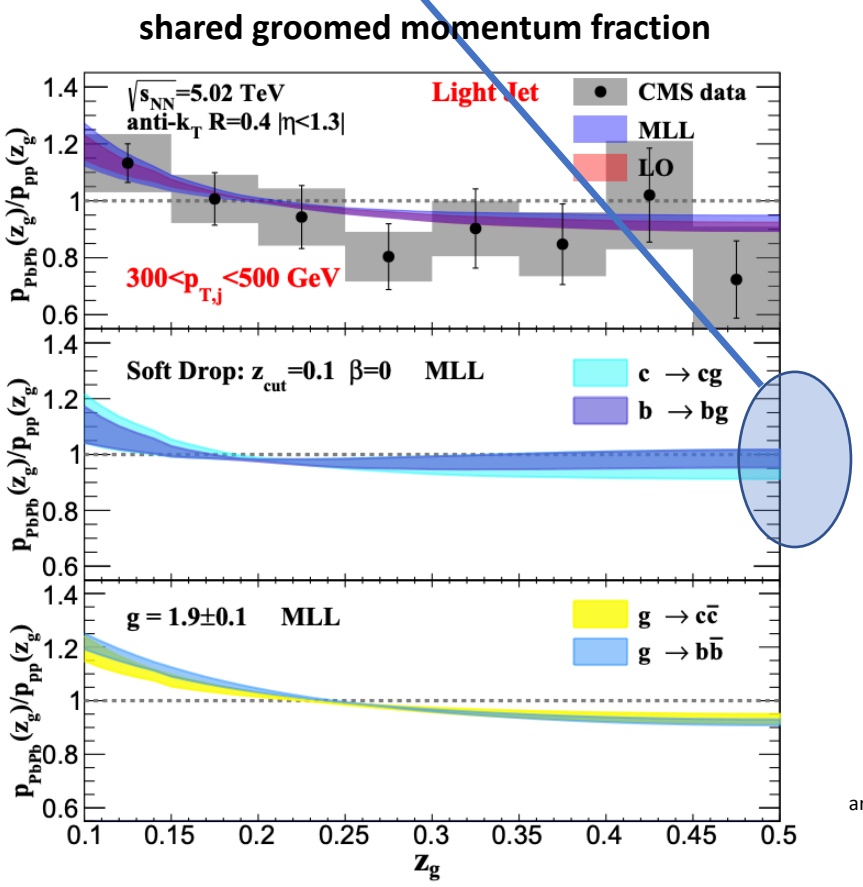
Heavy flavour substructure sensitive to flavour differences of energy loss

Measurements can give better control on mass corrections of the in medium parton shower

Mass effects predicted to vanish at high p_T

Low p_T regime is an interesting phase space for heavy-flavour jets





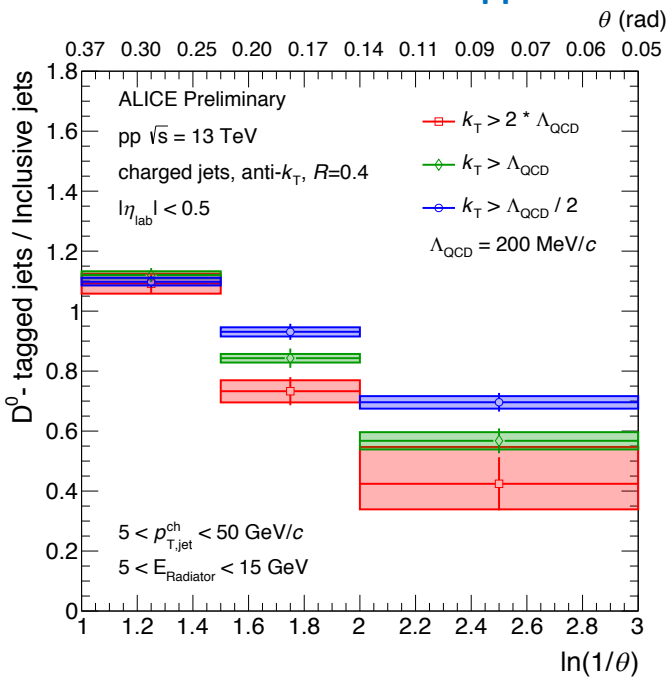
arXiv:1812.03348

Can we use the deadcone?

Vacuum emissions are suppressed in the deadcone region of heavy quarks

Medium induced gluon radiation is expected to fill the deadcone – can it be isolated?

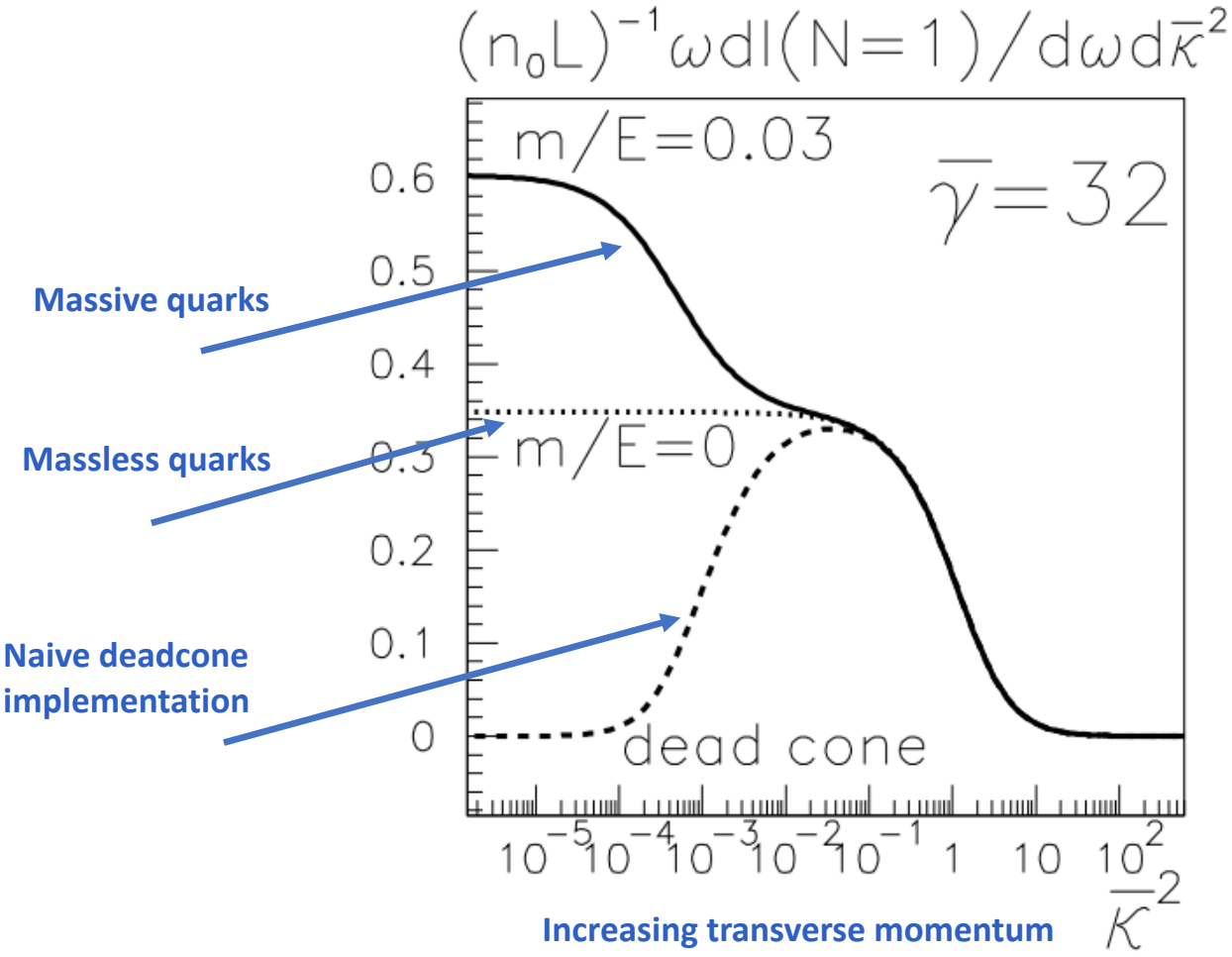
Charm deadcone in pp



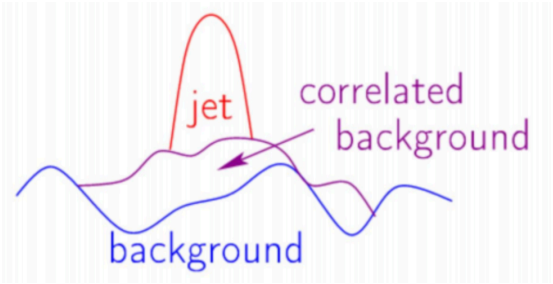
Extend measurement to PbPb

Phys.Rev.D69:114003,2004

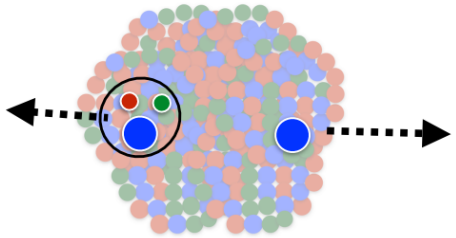
Calculations of medium induced gluon transverse momentum distributions



What is the medium back reaction?



How is hadronisation modified in the presence of the medium?



What are the new detector capabilities to look forward to at the LHC?

What upgrades will the next two LHC runs bring?

Heavy flavour will be the name of the game
Larger statistics will allow for more differential boson + jet

ALICE – Run 3

- New inner tracker to improve pointing resolution
- GEM readouts for TPC allowing 50kHz data taking
- Muon forward tracker
- Increased heavy flavour capabilities down to low p_T

ATLAS – Run 4

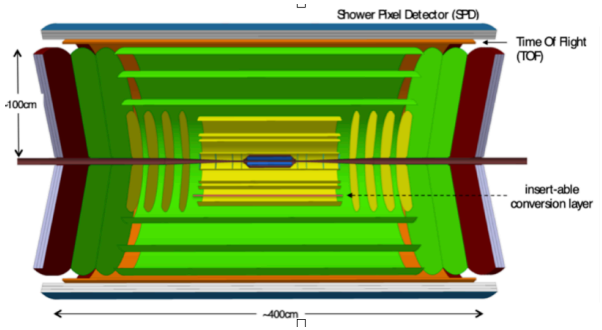
- New all silicon tracker up to $|\eta| < 4$
- High granularity timing detector
- Increased charged jet and heavy flavour capabilities

CMS – Run 4

- Upgraded inner tracker up to $|\eta| < 4$
- New MIP timing detector allows for particle ID down to low p_T
- Increased heavy flavour and high multiplicity capabilities

LHCb – Run 3

- Upgrades to all trackers
- Vertex locator moved to within 5mm of the nominal beam spot
- Improved PbPb performance



New ALICE and LHCb detectors in run5?

Lighter ions?