Jet quenching

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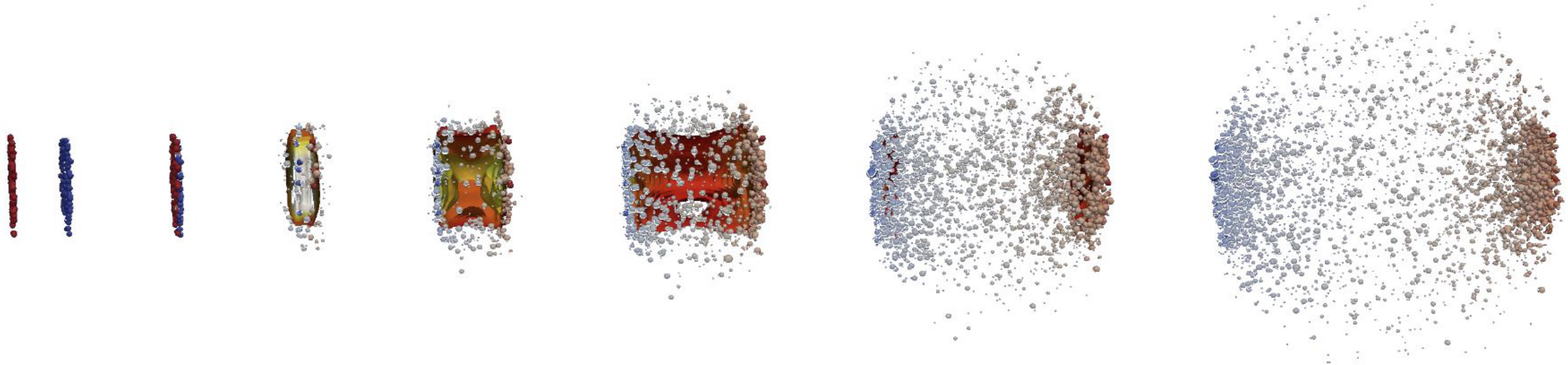
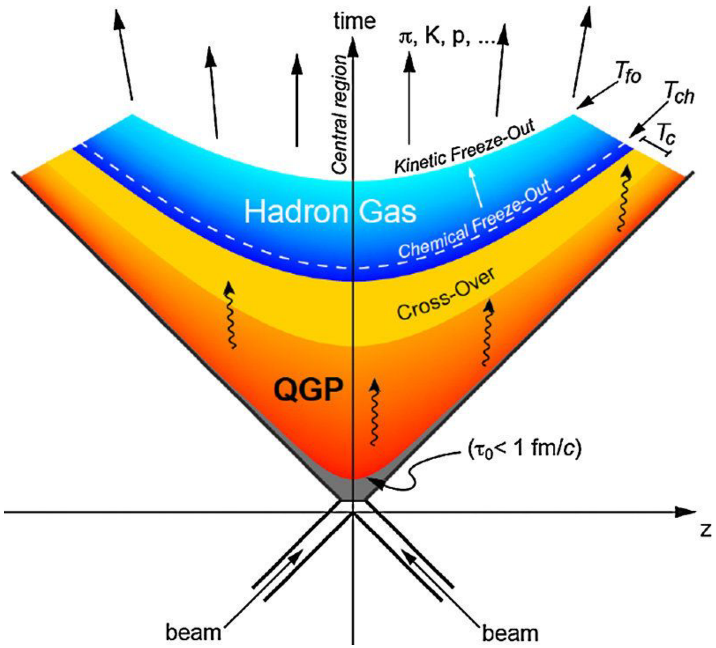
Physics 290E

Heavy-ion collisions produce a hot and dense medium.



- Nuclei approach each other and collide
- QGP medium forms and expands while particles are emitted
- QGP dissipates as the hadron gas expands

Hard scatterings (and jet production) occurs early.

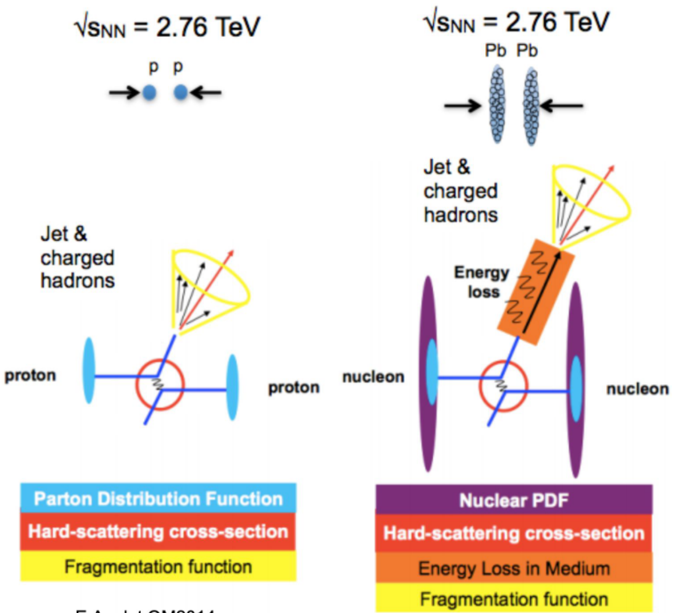


- Hard processes are modified due to interactions with the medium.

$$\sigma^{hh\to J/\Psi} = f_i(x_1,Q^2)\otimes f_j(x_2,Q^2)\otimes\sigma^{ij\to[c\bar{c}]}(x_1,x_2,Q^2)\langle\underline{\mathcal{O}([c\bar{c}]\to J/\Psi)}\rangle$$

- **This term** in the J/ψ cross-section describes a cc̄ pair hadronizing into a final-state J/ψ.
- Modified by screening in the medium!

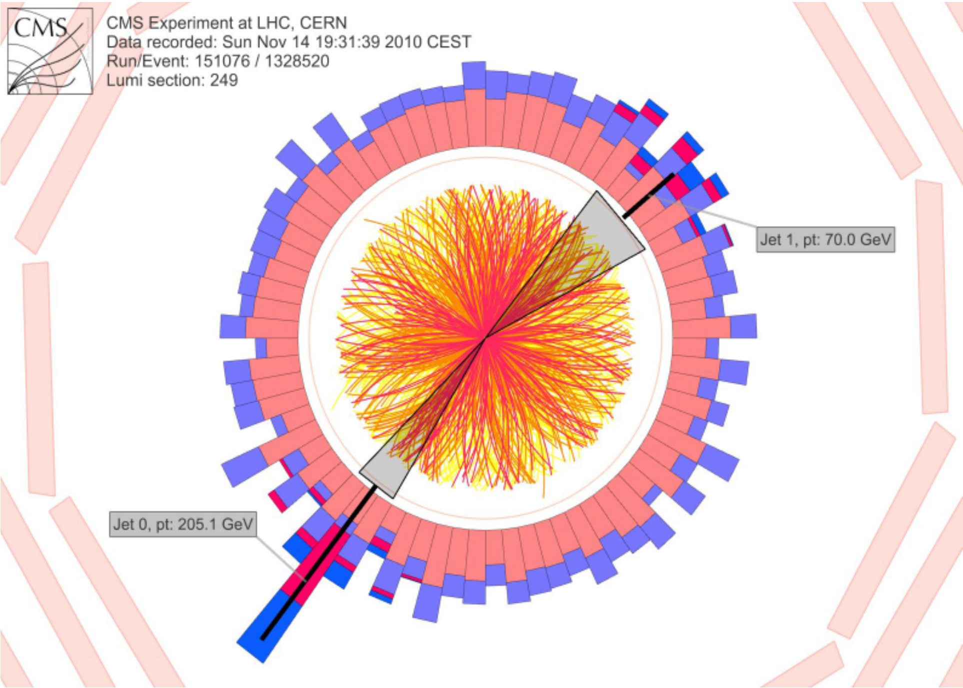
Jet quenching describes the modification and energy loss of high-p_T particles through a dense medium.



Parton Distribution Function
Hard-scattering cross-section
Fragmentation function

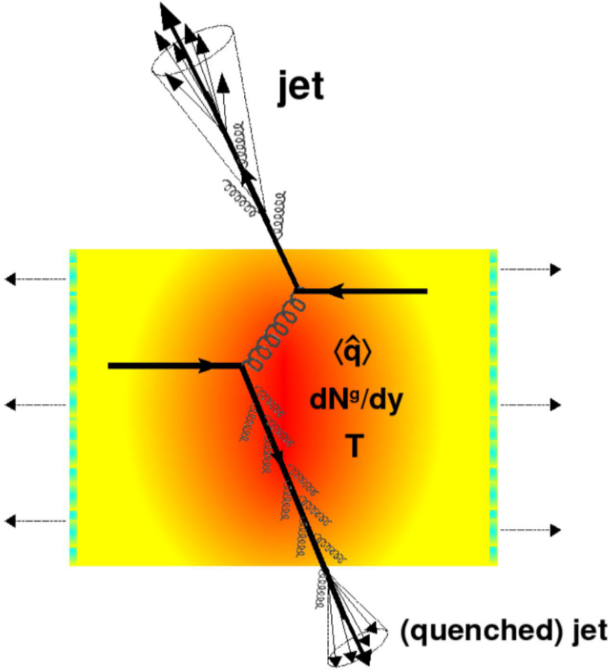
Nuclear PDF
Hard-scattering cross-section
Energy Loss in Medium
Fragmentation function

E.Applet QM2014



Jet quenching depends on various properties of the quark-gluon plasma.

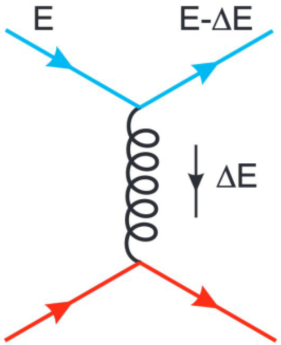
- the **mean free path** $\lambda = 1/(\rho\sigma)$
  ρ is medium density, σ is particle-medium xsec
- the **opacity** $N = L/\lambda$
  scatterings experienced by a particle in a medium of thickness L
- the **Debye mass** $m_D(T)$
  inverse of the screening length of the plasma fields
- the **transport coefficient** $\hat{q} = m_D^2/\lambda$
  the “scattering power” of the medium; momentum transferred to the particle per unit path-length



arXiv:0902.2011 [nucl-ex]

Energy loss mainly occurs through two mechanisms.

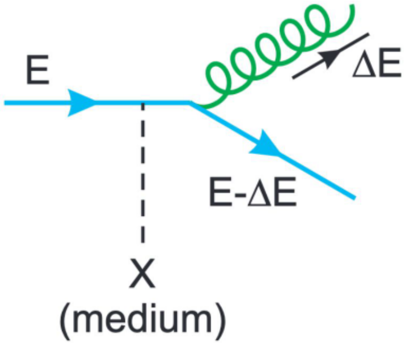
Collisional energy loss



- elastic scatterings with the medium
- dominates at lower momentum
- ΔE is linear in medium thickness

$$-\frac{dE_{coll}}{dl}\Big|_{q,g} = \frac{1}{4} C_R \alpha_s(ET)\, m_D^2 \ln\left(\frac{ET}{m_D^2}\right)$$

Medium-induced gluon radiation (dominant mechanism)



- inelastic scatterings with the medium
- **photon and gluon bremsstrahlung**

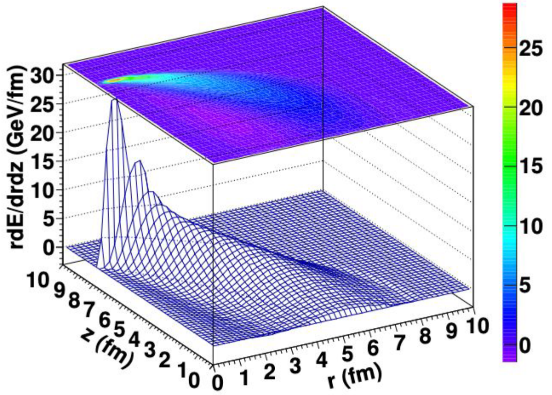
$$\Delta E_{rad}^{BH} \approx \alpha_s\, \hat{q} L^2 \ln(E/(m_D^2 L))$$

$$\Delta E_{rad}^{LPM} \approx \alpha_s \begin{cases} \hat{q}L^2 & (\omega<\omega_c) \\ \hat{q}L^2 \ln(E/(\hat{q}L^2)) & (\omega>\omega_c) \end{cases}$$

Phenomenological and Monte Carlo models of jet quenching also include other effects.

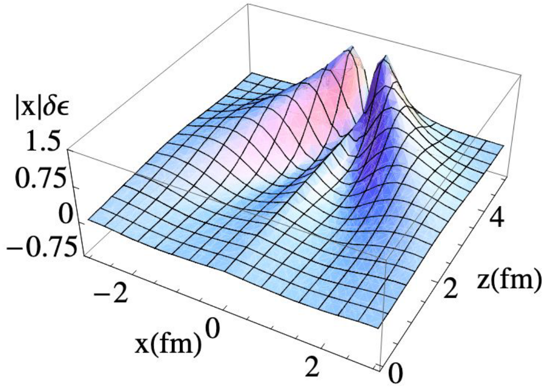
Medium response:

- recoil partons are scattered from the medium by jets, producing back-reaction partons (JEWEL)
- momentum loss thermalizes with the medium and hadronizes, leading to a diffusion wake behind the jet (HYBRID)
- Molière scattering: large-angle deflections of jets due to q/g being weakly coupled over short distance scales



above: energy density distribution of the jet-induced medium response by a gluon

below: hydrodynamical response to energy deposition by a quark-initiated jet

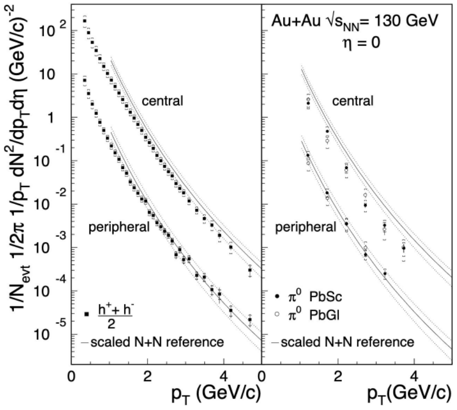


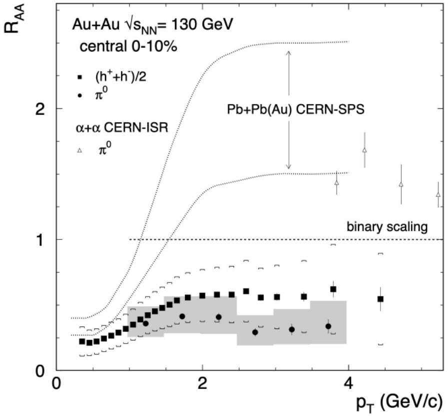
arXiv:2002.04028 [hep-ph], arXiv:1808.03250 [hep-ph]

Early measurements of ~jet quenching happened at RHIC.

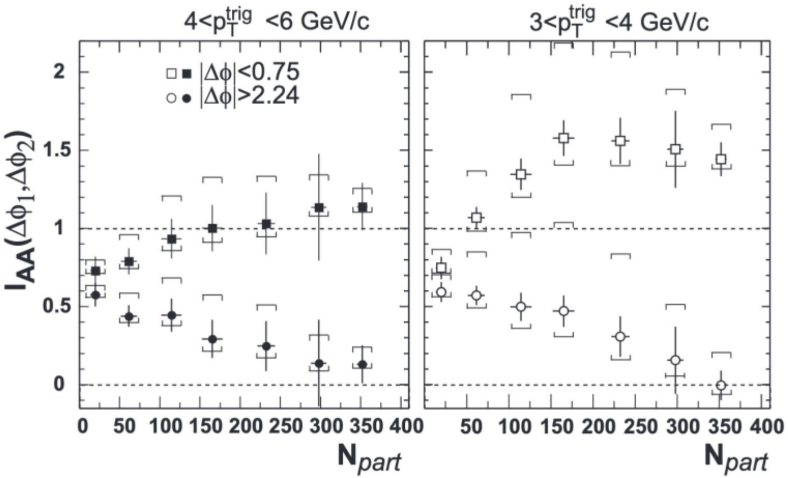
2001: PHENIX measured R_{AA} in Au-Au collisions for charged hadrons and π^0.

$$R_{AA}(p_T) = \frac{dN^{AA}/dp_T}{\langle N_{coll}\rangle dN^{pp}/dp_T}$$





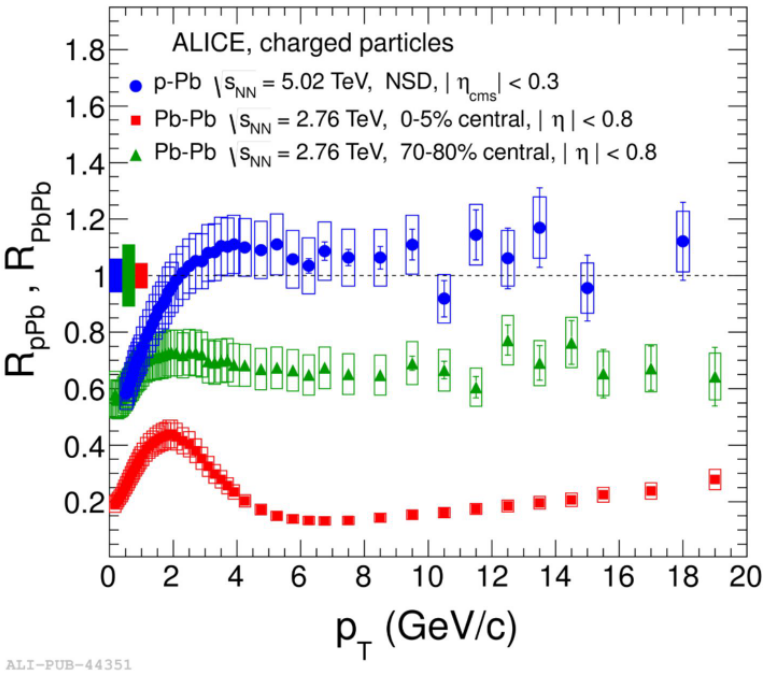
2002: STAR measured back-to-back hadron correlations in central Au-Au.



Ratio of Au-Au/p-p for small-angle and back-to-back azimuthal regions versus number of participating nucleons.

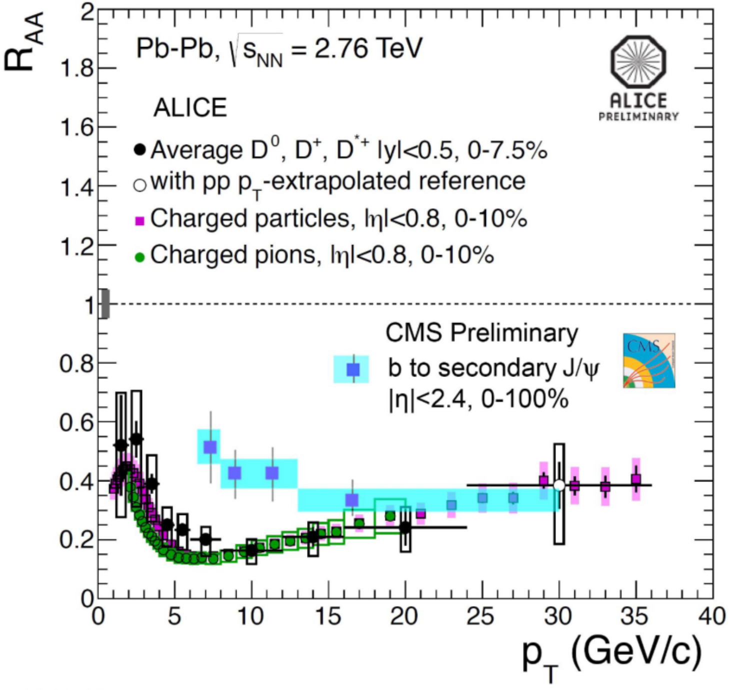
PHENIX: arXiv:nucl-ex/0109003, STAR: arXiv:nucl-ex/0210033

Later hadron R_{AA} studies show ~0.2 for central events.



R_{pPb}, R_{AA} for charged particles, ALICE (2012)

arXiv:1210.4520 [nucl-ex]

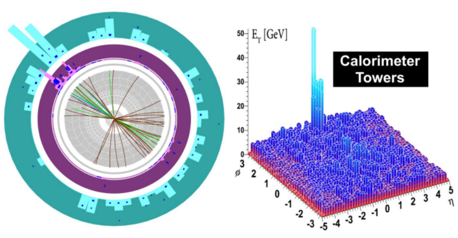


R_{AA} for D-mesons and J/psi (ALICE, CMS)

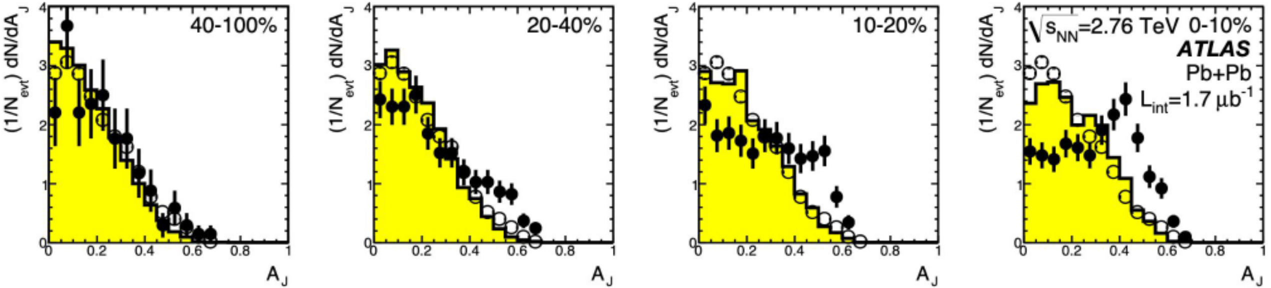
John W Harris 2015 J. Phys: Conf. Ser. 630 012052

10 years later: jet measurements at LHC from ATLAS, CMS.

2010: ATLAS measured dijet asymmetry in Pb-Pb: $A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}, \Delta\phi > \frac{\pi}{2}$

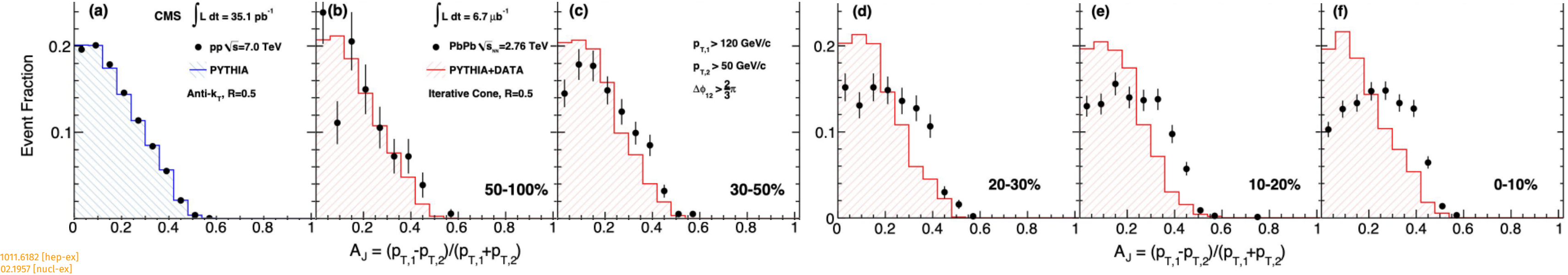


Heavily quenched event display.



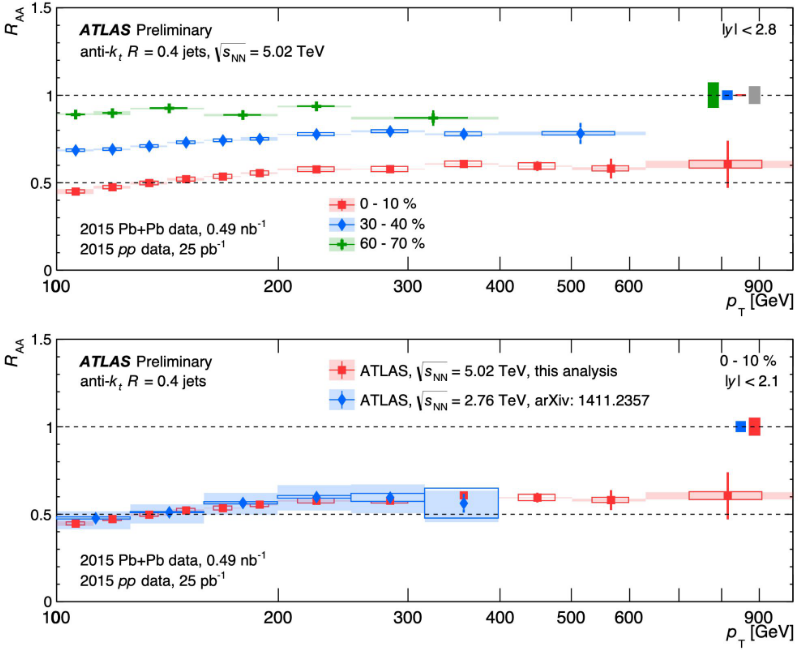
Dijet asymmetry for Pb-Pb (solid), p-p (open), and unquenched HIJING+PYTHIA (yellow), as function of centrality.

2011: CMS published its asymmetry measurement.



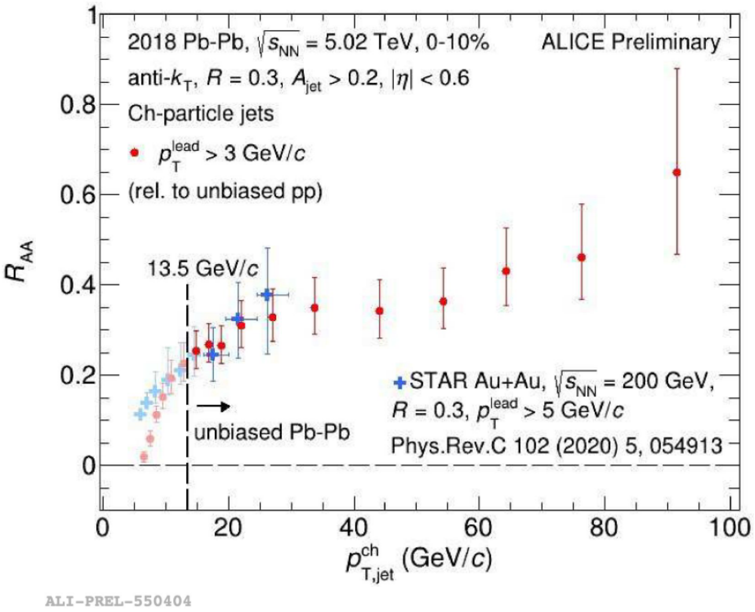
ATLAS: arXiv:1011.6182 [hep-ex]
CMS: arXiv:1102.1957 [nucl-ex]

Jet R_{AA} at LHC: centrality and and center-of-mass energy



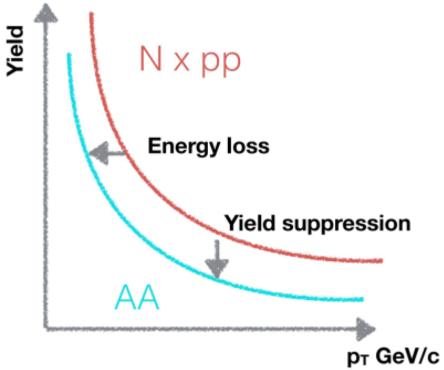
Jet R_{AA} is ~0.6 for jets at 0.2–0.9 TeV in central events, with little s_{NN} dependence.

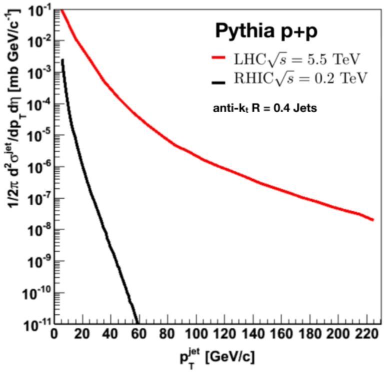
ATLAS-CONF-2017-009



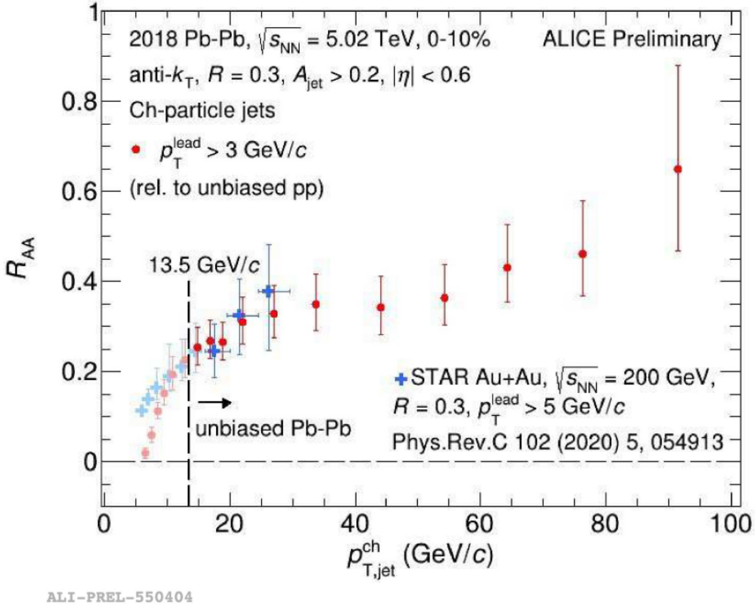
Earlier this year from ALICE: comparison between RHIC and LHC R_{AA} measurements!

However: R_{AA} doesn't tell the whole energy loss story.





Raghav Kunnawalkam Elayavalli QM 2023

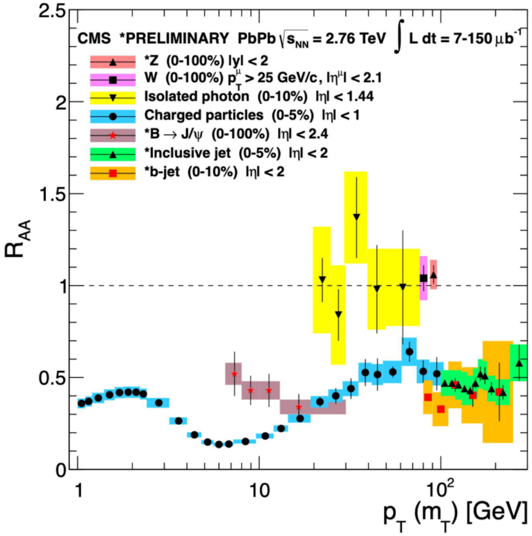


- Whether there's a shift in p_T or a shift in yield, we see $R_{AA} < 1$.
- LHC has a much harder spectrum and is more gluon-dominated than RHIC.
- Seeing similar R_{AA} doesn't mean similar energy loss.

So: this is an interesting result but not entirely straightforward to interpret.

Nadine Grünwald QM 2023

We can study gamma-jet and Z-jet systems.



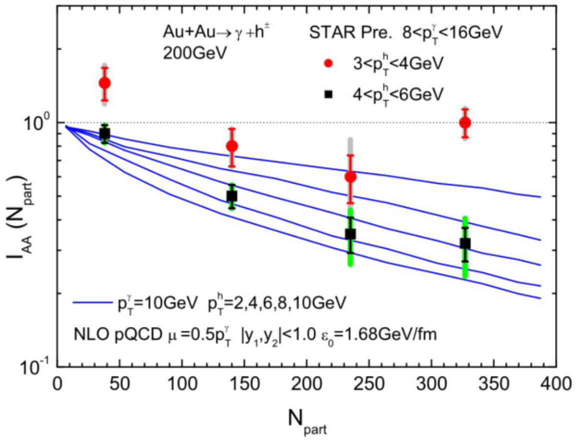
Photons and W and Z bosons are great references for energy loss studies because they pass through the medium unscathed.

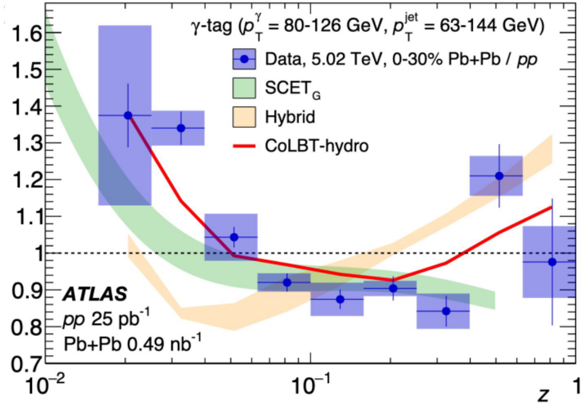
We can measure the momentum imbalance between the triggered photon or Z and the associated jet.

$$I_{\rm AA}(z_{\rm T}) \equiv \frac{\frac{1}{N_{\rm trig}}\frac{dN^{\rm asso}}{dz_{\rm T}}|_{\rm AA}}{\frac{1}{N_{\rm trig}}\frac{dN^{\rm asso}}{dz_{\rm T}}|_{\rm pp}}$$

z_T measures the p_T imbalance between the triggered γ or Z and the paired jet: $z_{\rm T} = p_{\rm T}^{\rm asso}/p_{\rm T}^{\rm trig}$

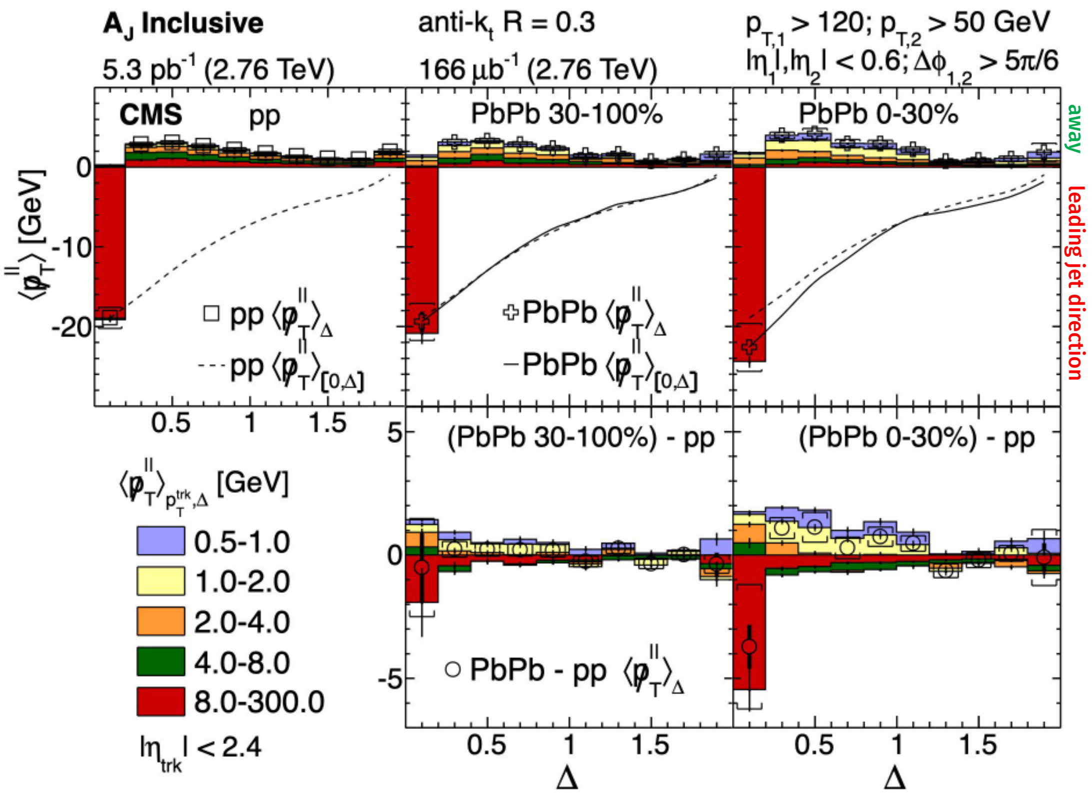
I_{AA} is the AA/pp ratio of tagged fragmentation functions.





arXiv:1902.10007 [nucl-ex]

Where does the lost energy go? Wide and soft.



1. Project tracks onto the event's dijet axis to get the longitudinal momentum.

$$p_T^{\parallel} = -c^{\mathrm{trk}}\, p_T^{\mathrm{trk}} \cos\left(\phi_{\mathrm{trk}} - \phi_{\mathrm{dijet}}\right)$$

2. Add up the p_T of tracks in bins of Δ around the dijet axis (i.e. annular rings).
3. Also bin by track p_T (colors).

Upper row: distributions for pp, peripheral, and central collisions.

- 5 track p_T bins, 10 Δ bins.
- Open markers: all track p_T
- Lines: integrating up to Δ

Lower row: difference between AA and pp distributions.

arXiv:1509.09029 [nucl-ex]

Jet substructure: microscopic insights into modification.

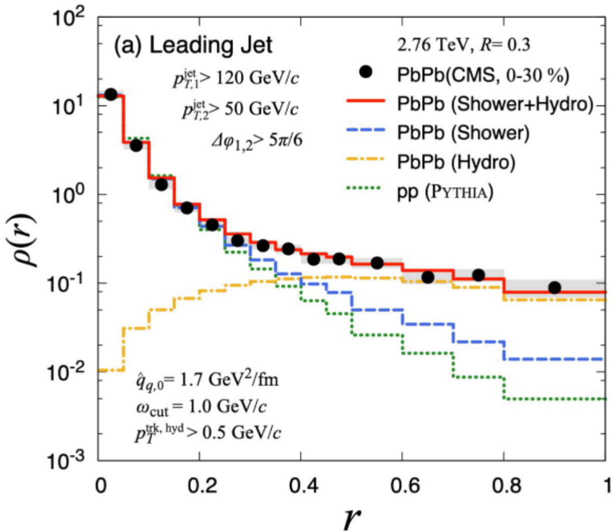
Jet shape: $$\rho(r) \equiv \frac{1}{\Delta r}\frac{1}{N_{\mathrm{jet}}}\sum_{\mathrm{jet}}\frac{p_{\mathrm{T}}^{\mathrm{jet}}(r-\Delta r/2, r+\Delta r/2)}{p_{\mathrm{T}}^{\mathrm{jet}}(0,R)}$$

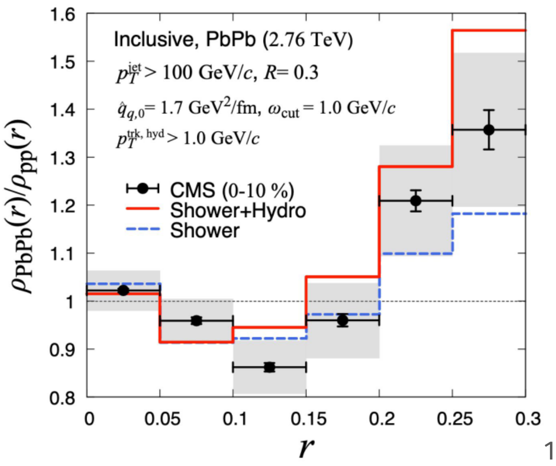
(One of many shape observables – also called jet energy density profile.)

At low *r*: dominated by partons from the jet shower.

At high *r*: soft hadrons from jet-induced hydrodynamic response. Indication of wake!

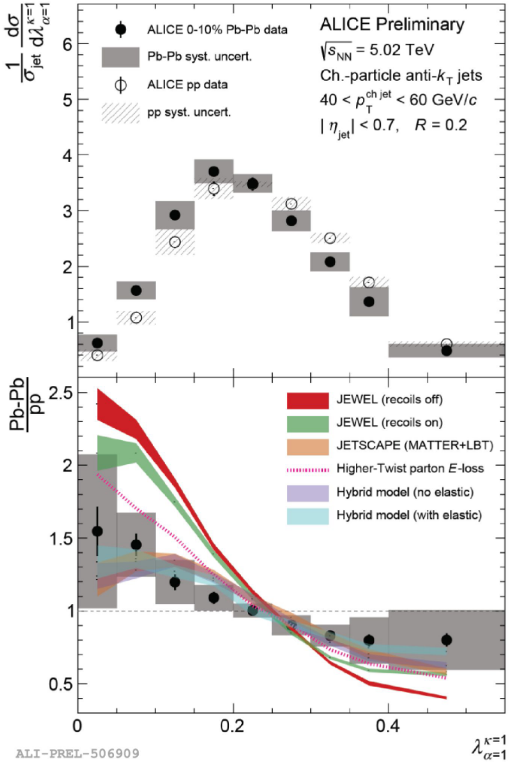
NMF also shows enhancement without response because the jet broadens regardless — didn't precisely constrain.

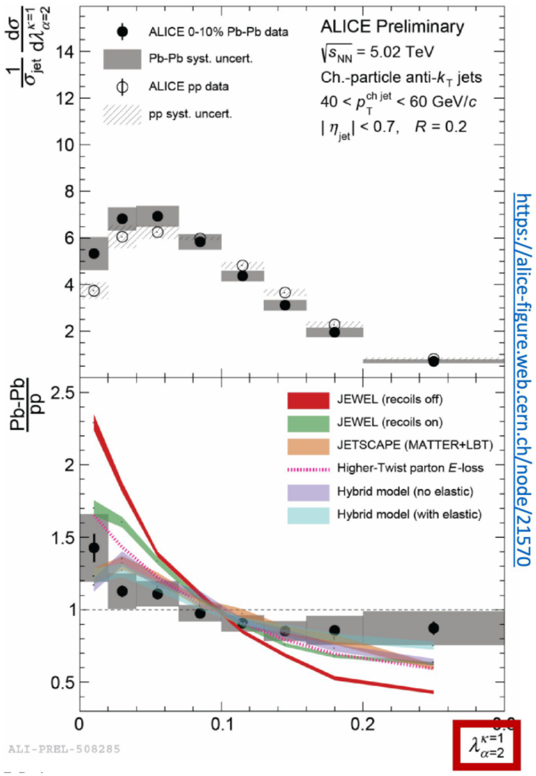




arXiv:1701.07951 [nucl-th]

Jet angularities: jet narrows as it passes through QGP.

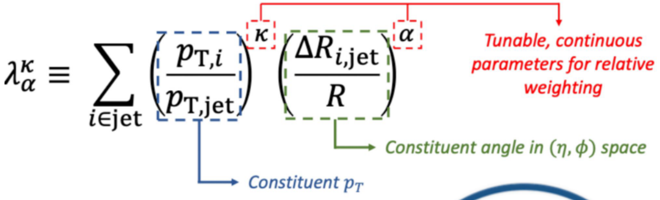




https://alice-figure.web.cern.ch/node/21570

Class of substructure observables dependent on p_T and angular distributions inside the jet.

Jet girth: λ_1^1, **jet thrust**: λ_2^1, etc.



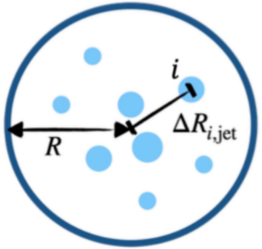
$$\lambda_\alpha^\kappa \equiv \sum_{i\in\text{jet}} \left(\frac{p_{\text{T},i}}{p_{\text{T,jet}}}\right)^{\boxed{\kappa}} \left(\frac{\Delta R_{i,\text{jet}}}{R}\right)^{\boxed{\alpha}}$$

Tunable, continuous parameters for relative weighting

Constituent angle in (η, ϕ) space

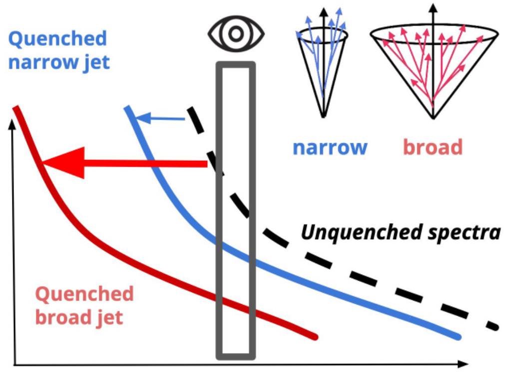
Constituent p_T

Shift toward lower angularities is consistent with jet narrowing in Pb-Pb.



Jet axis, groomed observables, etc…

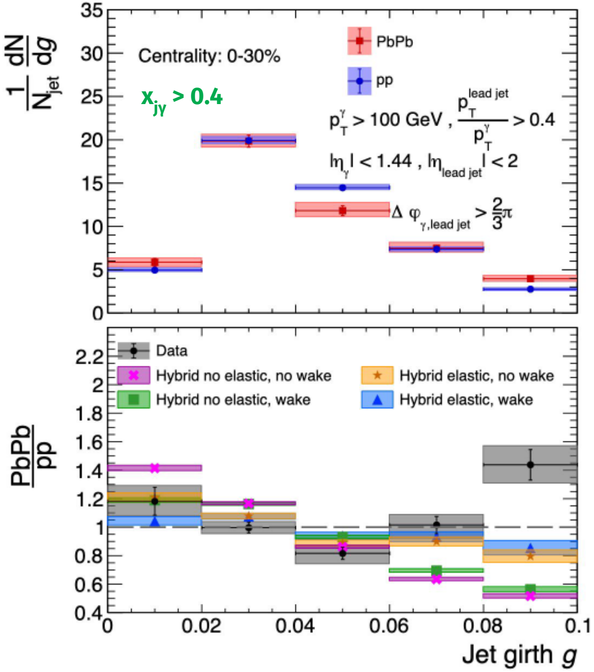
NB: survival bias of quenched jets affects these results.



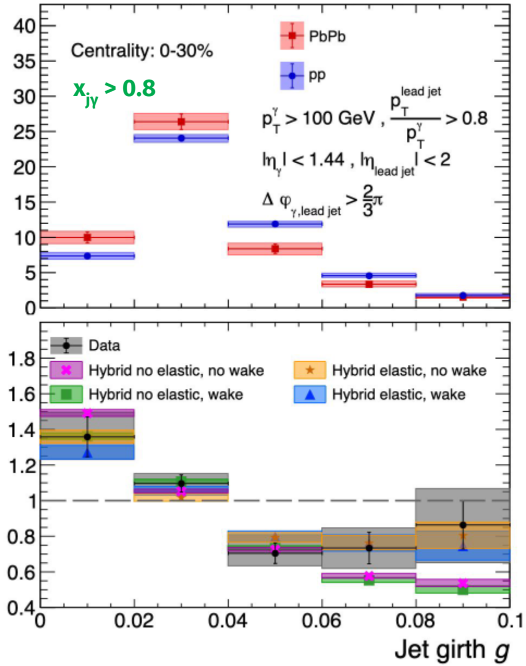
CMS, PAS-HIN-23-001

- quark (gluon) jets tend to be narrow (broad)
- broader jets are quenched more than narrow
- end up with a population of disproportionately narrow jets

Using gamma-tagged jets, select for more/less quenching with cuts on $p_T^{jet}/p_T^{\gamma} = x_{j\gamma}$. Less quenched: $x_{j\gamma} > 0.8$, quenched: $x_{j\gamma} > 0.4$.



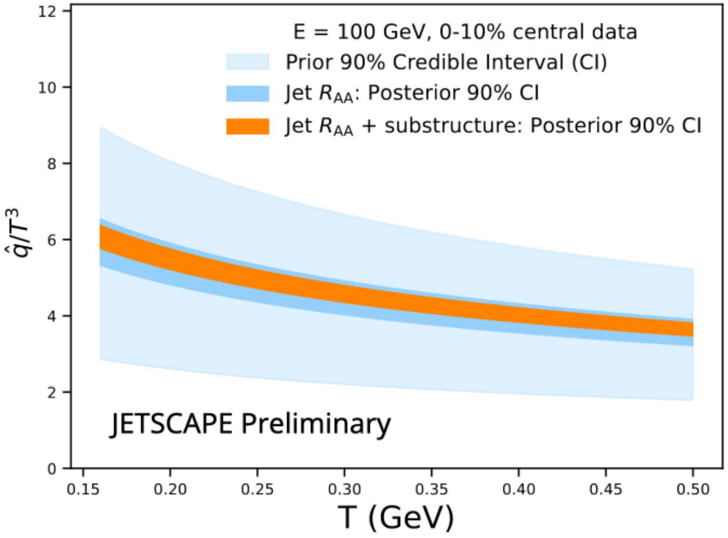
More quenching → no narrowing.

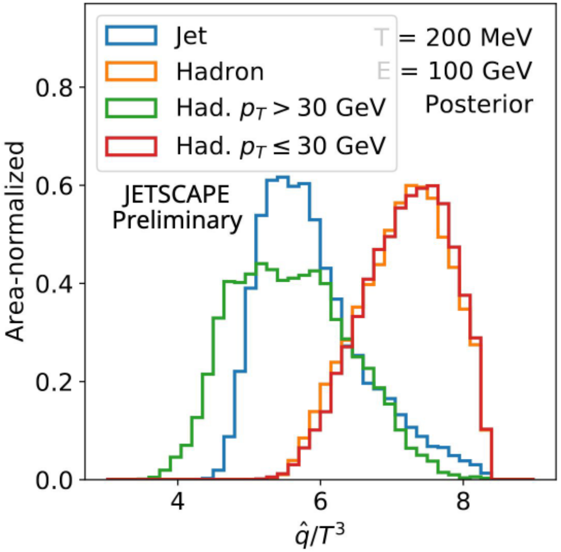


Less quenching → clear narrowing.

JETSCAPE has taken steps to measure medium properties.

- There are lots of measurements of quenching but we draw largely qualitative conclusions.
- We can start to quantify things! Bayesian inference using R_{AA} and substructure measurements.





Low p_T measurements dominate the result because the experimental uncertainty is smallest.

High p_T results are consistent with jet results.

Model improvements might bridge the soft-hard gap?

To summarize:

1. The quark-gluon plasma modifies jets.
2. Jets lose energy and the medium responds. (How?)
3. Measurements of nuclear modification factors, asymmetries, and substructure tell us about energy loss and where the energy goes.
4. We can extract properties of the medium from these observations.

Thanks!