Jet radius dependence of dijet momentum balance and pair nuclear modification factor in Pb+Pb and pp collisions with the ATLAS detector

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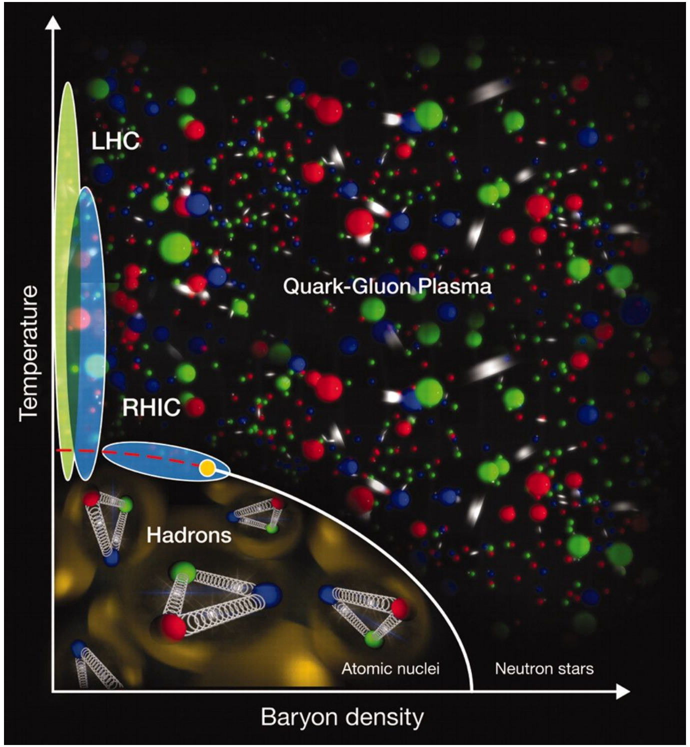
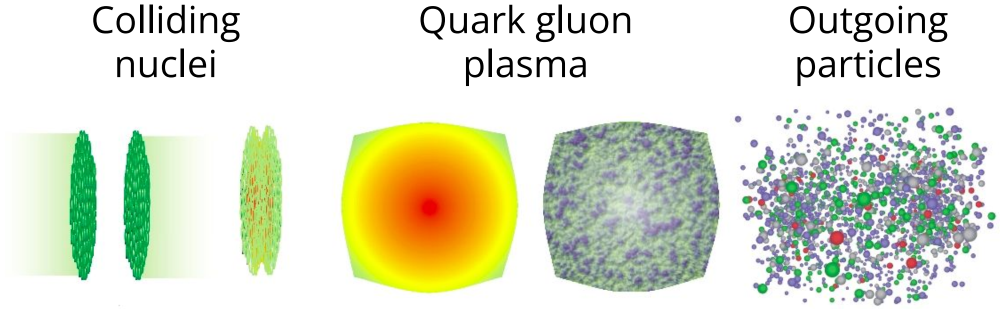
Quark gluon plasma

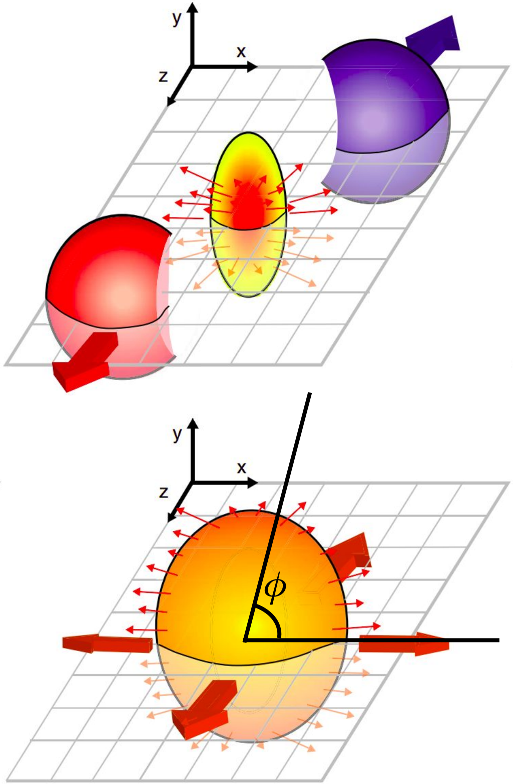


https://doi.org/10.1126/science.1215901

- High energy, high density state of matter made of quarks and gluons.
- Can be created in ultra relativistic heavy ion collisions.



Flow in the quark gluon plasma

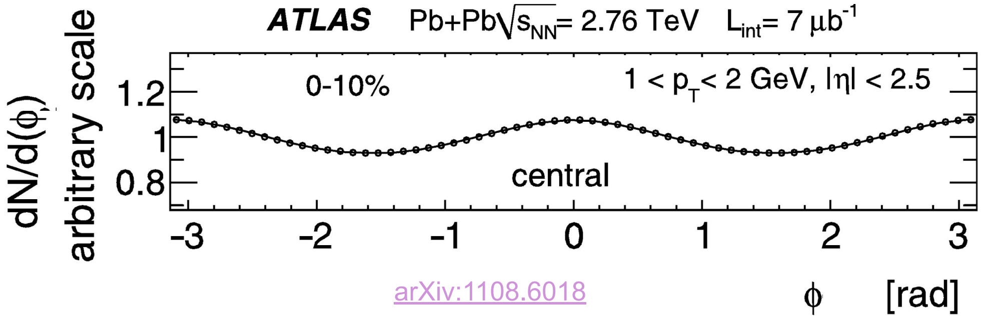


arXiv:1705.01974

- Initial geometry causes pressure gradients inside the QGP.
- Particles are emitted anisotropically.
- Modulation can be described by Fourier series:

$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n cos(n\phi)$$

- Low specific viscosity η/s obtained from flow measurements is close to theoretical limit.



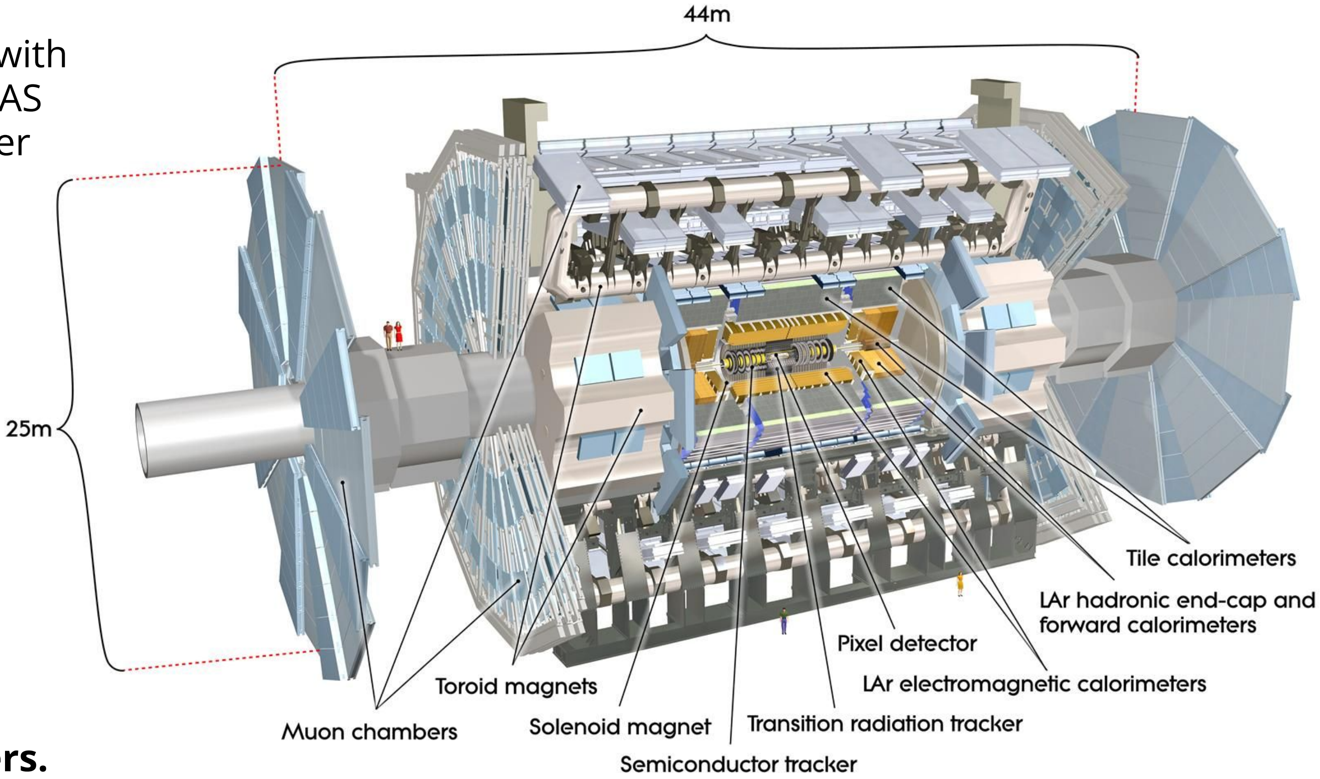
arXiv:1108.6018

The ATLAS detector at the LHC

We can measure the QGP with a particle detector like ATLAS at the Large Hadron Collider (LHC).

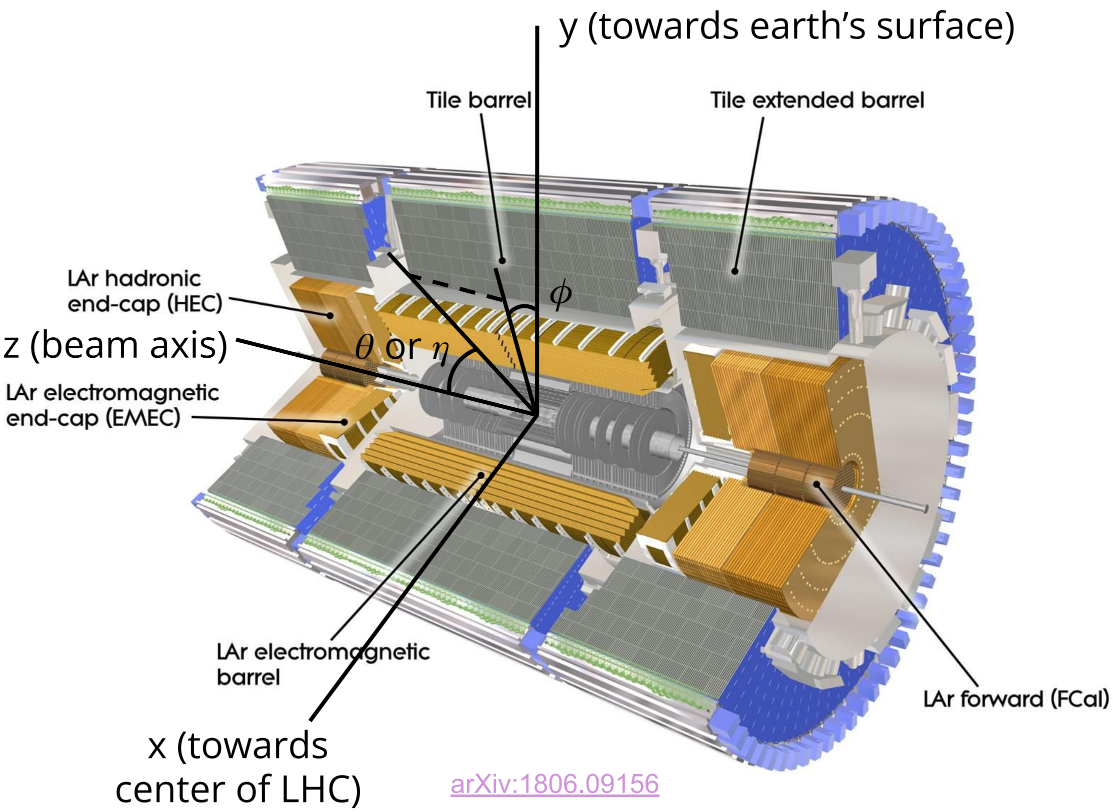
Composed of:

- Tracker.
- Magnets.
- **Hadronic and electromagnetic calorimeters.**
- Muon spectrometer.
- **Forward calorimeters.**



https://doi.org/10.1088/1748-0221/3/08/S08003

Some basic definitions



arXiv:1806.09156

- Spherical coordinates (r,ϕ,θ) defined in terms of (x,y,z).
- Pseudorapidity:

$$\eta = -\ln(\tan(\theta/2))$$

- Angular distance:

$$\Delta R = \sqrt{(\eta_i - \eta_j)^2 + (\phi_i - \phi_j)^2}$$

- Rapidity:

$$y = \frac{1}{2}\ln(\frac{E+p_z}{E-p_z})$$

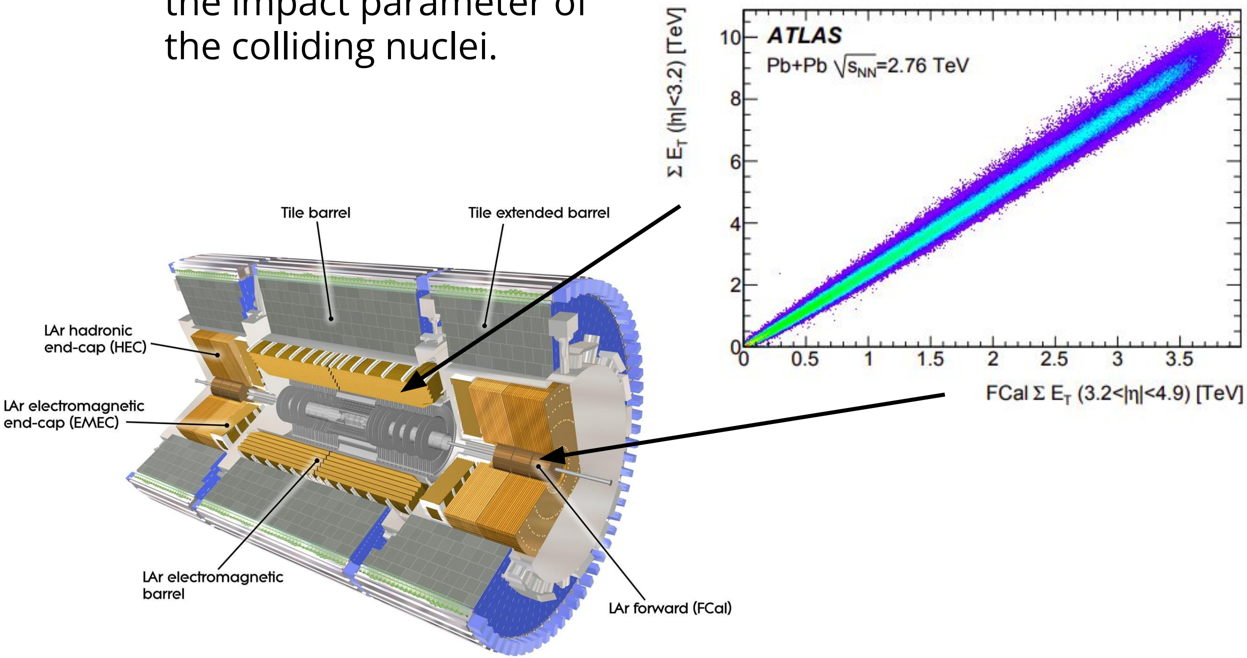
- Transverse energy E_T and transverse momentum p_T defined in x-y plane.

https://doi.org/10.1088/1748-0221/3/08/S08003

What is centrality?

- Centrality correlates with the impact parameter of the colliding nuclei.

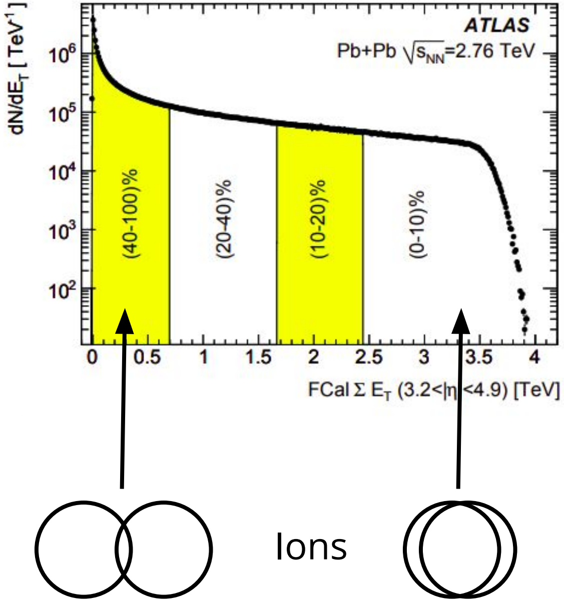
Barrel energy vs. FCal energy



arXiv:1806.09156

arXiv:1011.6182

Number of events per unit energy vs. FCal energy

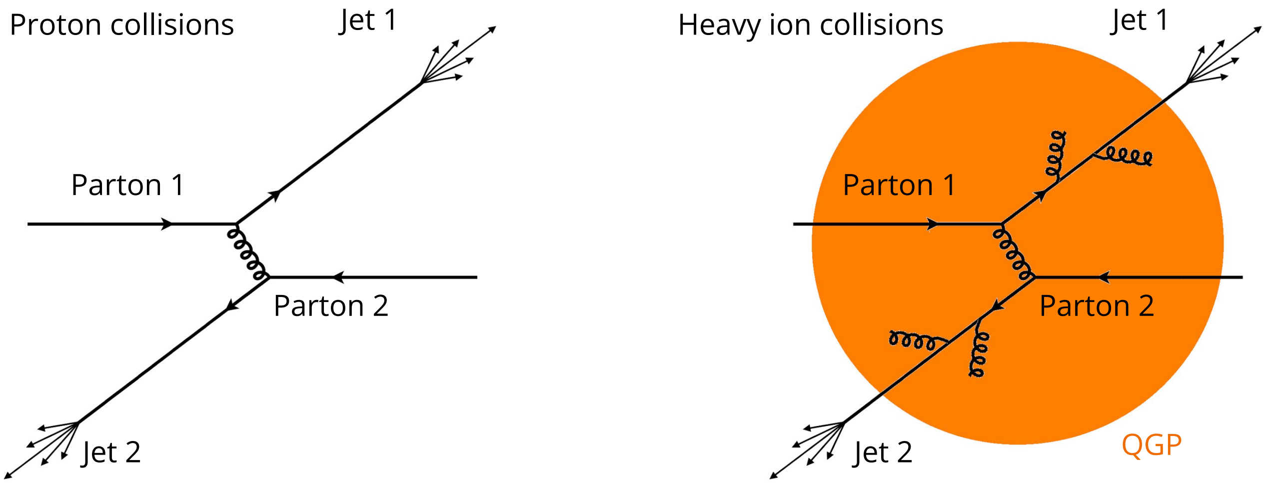


Ions

Peripheral collisions

Head on collisions

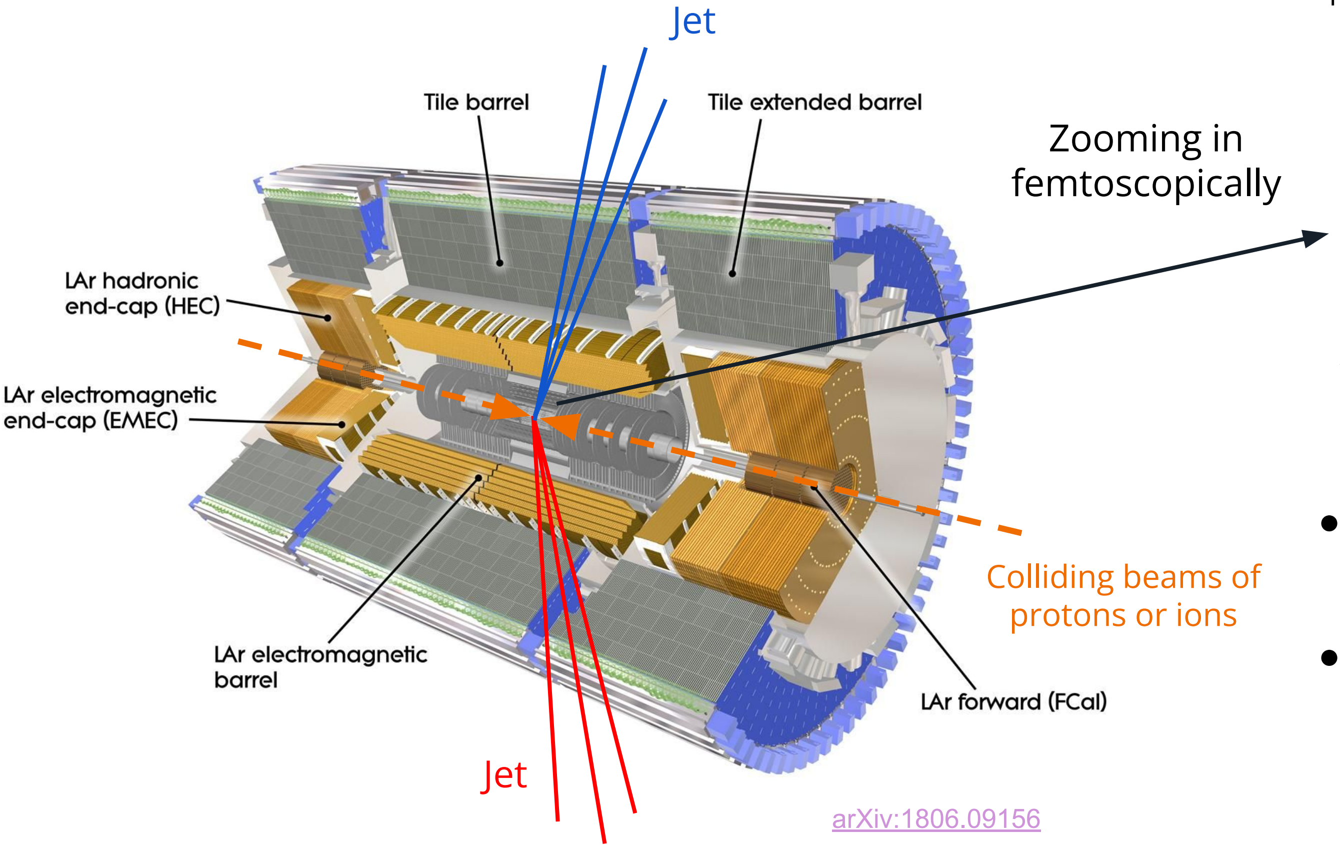
Jets as probes of the QGP



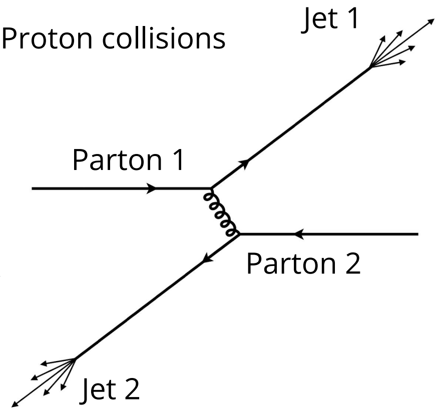
- Additional interactions within the QGP cause the hard scattered partons to lose energy, which leads to **jet quenching**.

- Jets can be used to study the QGP.

Jets in the ATLAS detector



arXiv:1806.09156



- Jets are proxies for partons.
- Jets are defined with the anti-k_T algorithm, where particles are clustered within a radius R.

Nuclear modification factor

$$R_{\mathrm{AA}} = \frac{\boxed{\dfrac{1}{N_{\mathrm{evt}}}\dfrac{\mathrm{d}^2 N_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}\Bigg|_{\mathrm{cent}}}{\boxed{\langle T_{\mathrm{AA}}\rangle}\boxed{\dfrac{\mathrm{d}^2\sigma_{\mathrm{jet}}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}\Bigg|_{pp}}$$

Normalization factor

arXiv:1805.05635

Distribution of jets N_{jet} per unit of jet momentum p_T and rapidity y

-> QGP

Cross section of jets σ_{jet} per unit of jet momentum p_T and rapidity y

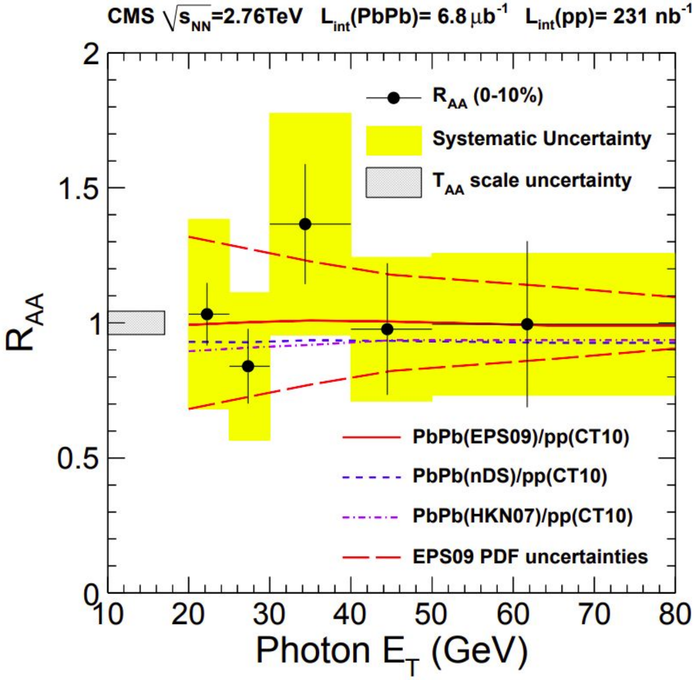
-> vacuum

Nuclear modification factor of uncolored probes

<u>Uncolored</u>

Ratio of photon yields in lead collisions to proton collisions

arXiv:1201.3093



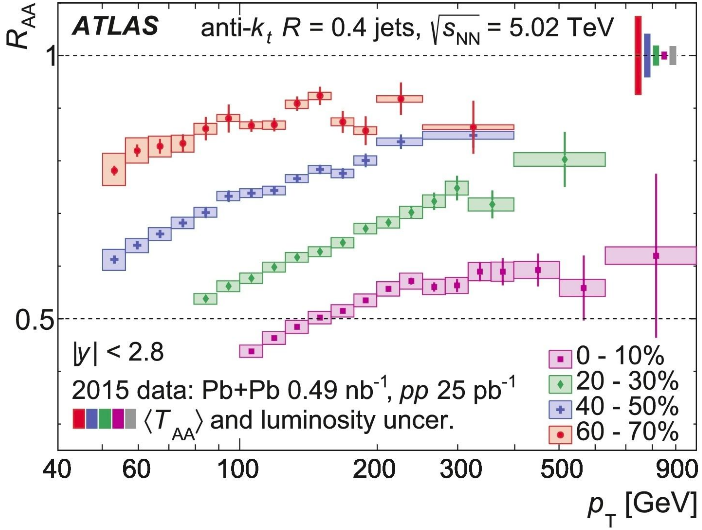
- Measurements of color neutral probes in heavy ion collisions do not show modifications with respect to proton collisions.

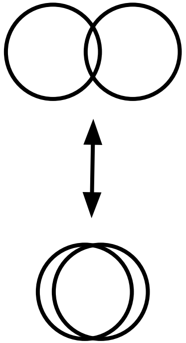
Nuclear modification factor of colored probes

Colored

Ratio of jet yields in lead collisions to proton collisions

arXiv:1805.05635





- Jets are more suppressed in collisions where there is a QGP.
- Jet suppression increases with centrality and decreases with jet momentum.

Jet azimuthal anisotropies

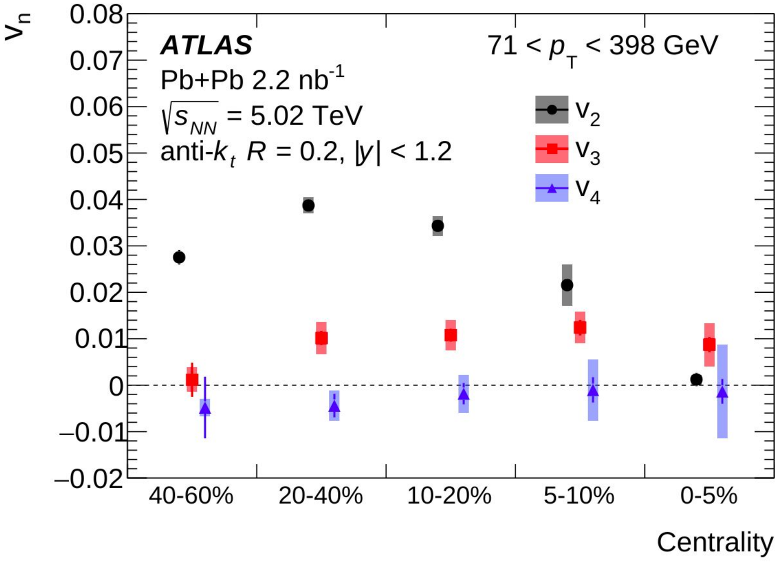
arxiv:2111.06606

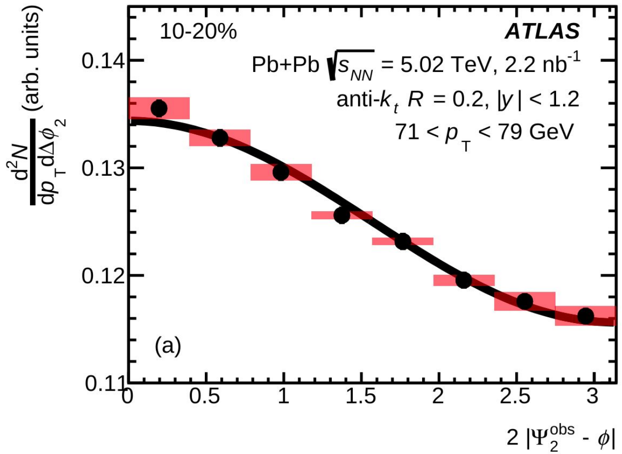
- Initial collision geometry causes jet modulation:

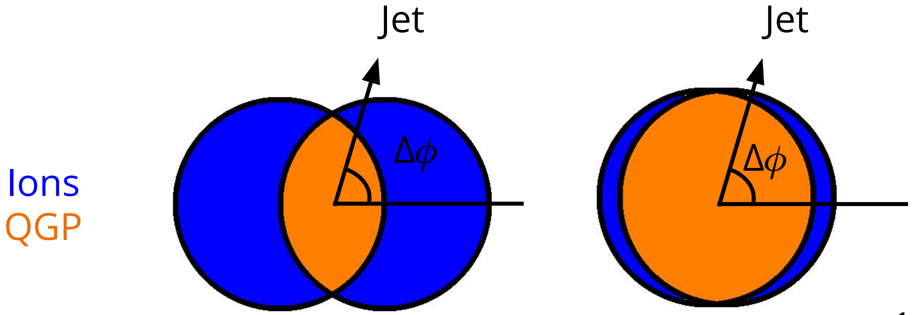
$$\frac{dN_{jet}}{d\Delta\phi} \propto 1 + 2v_n cos(n\Delta\phi)$$

- v_2 correlates with elliptical geometry. v_3 and v_4 are due to fluctuations of the initial geometry.

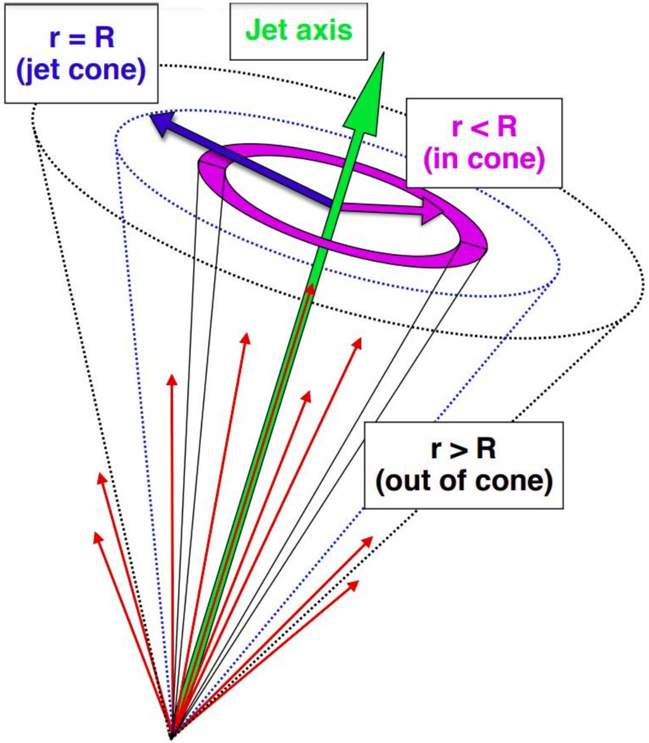
- Jet energy loss is path length dependent.







2D fragmentation function



Number of
charged particles

$$D(p_T, r) = \frac{1}{N_{\text{jet}}} \frac{1}{2\pi r dr} \frac{dn_{\text{ch}}(p_T, r)}{dp_T}$$

Number
of jets

Area of circular shell
around jet axis

Particle
momentum

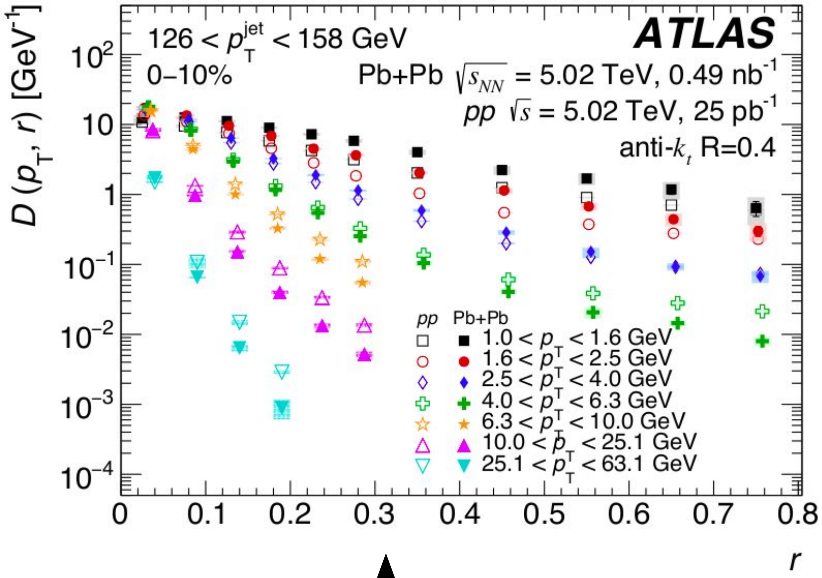
$$R_{D(p_T,r)} = \frac{D(p_T, r)|_{\text{PbPb}}}{D(p_T, r)|_{\text{pp}}}$$

Ratio QGP/vacuum

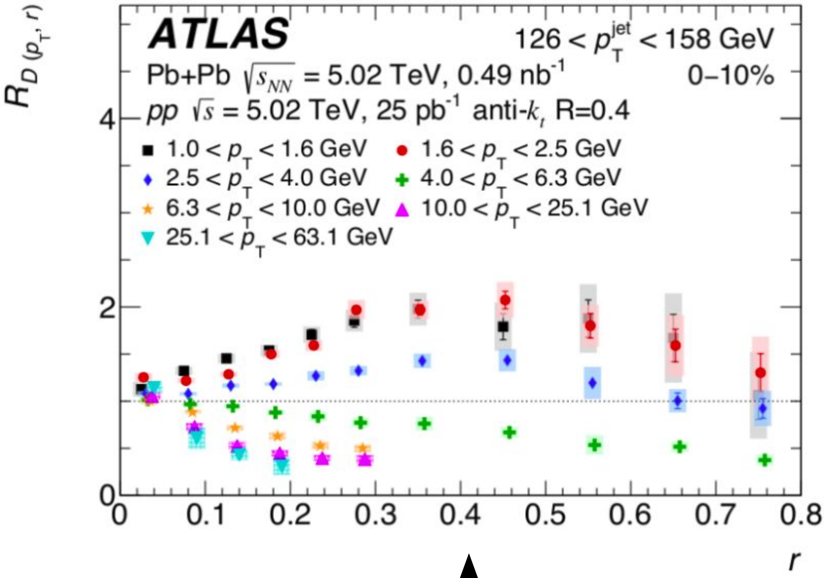
arXiv:1908.05264

2D fragmentation function

arXiv:1908.05264

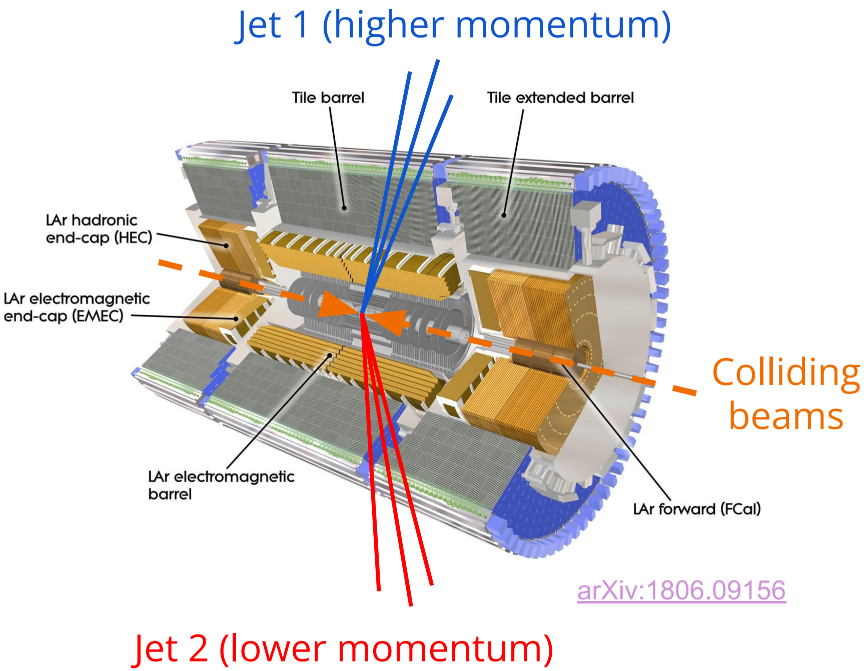


Lower momenta particles are emitted at larger angles with respect to jet axis.



Medium causes jets to lose high energy particles and gain low energy particles.

Dijet momentum balance



arXiv:1806.09156

$$x_J = \frac{p_{T,2}}{p_{T,1}}$$

p_{T1} = momentum of jet 1
(leading jet)

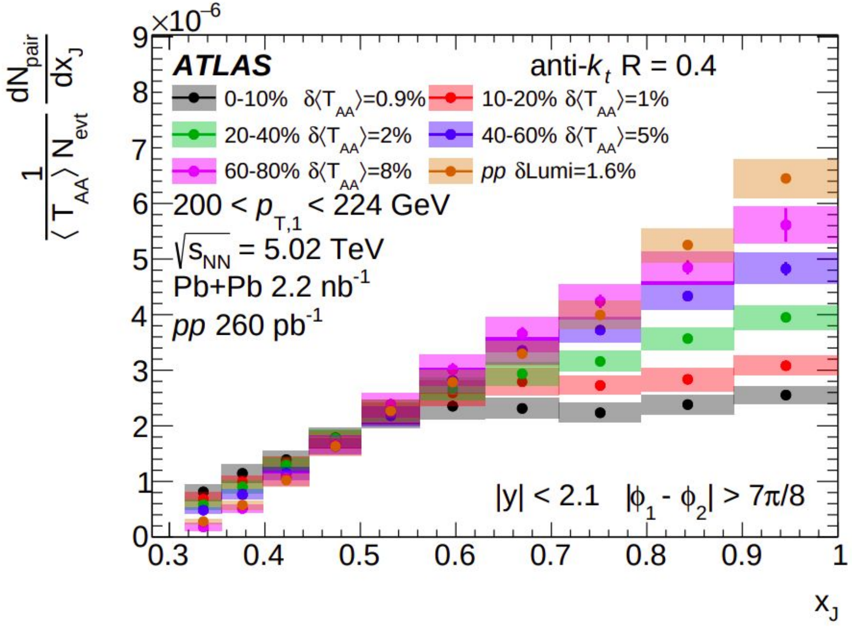
p_{T2} = momentum of jet 2
(subleading jet)

$p_{T1} > p_{T2}$

Dijet momentum balance

- One of the jets in the dijet loses more energy than the other.
- Dijets are more suppressed in more central collisions.

Distribution of dijets as a function of absolutely normalized x_J



arxiv:2205.00682

Jet radius dependent dijet analysis

We know that the QGP causes:

- Jets to lose high momentum particles and gain low momentum particles, with the lower momentum particles being emitted at larger angles.
- Dijets to become more imbalanced and suppressed towards more central collisions.

How are these two effects connected?

⟶A jet radius dependent dijet analysis will be sensitive to both effects.

Jet radius dependent dijet analysis

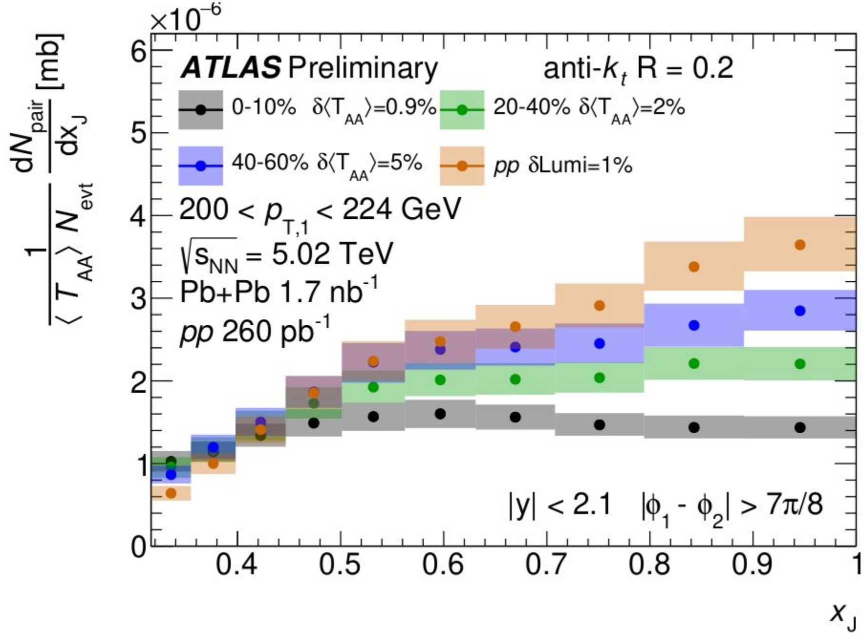
- Measured R=0.2, 0.3, 0.4, 0.5 and 0.6 dijets in Pb+Pb and pp collisions.

- Focused on these observables:
    - Absolutely normalized x_J distribution.
    - J_{AA} distributions: PbPb to pp ratios of absolutely normalized x_J distributions.
    - Leading and subleading R_{AA}^{pair} distributions.

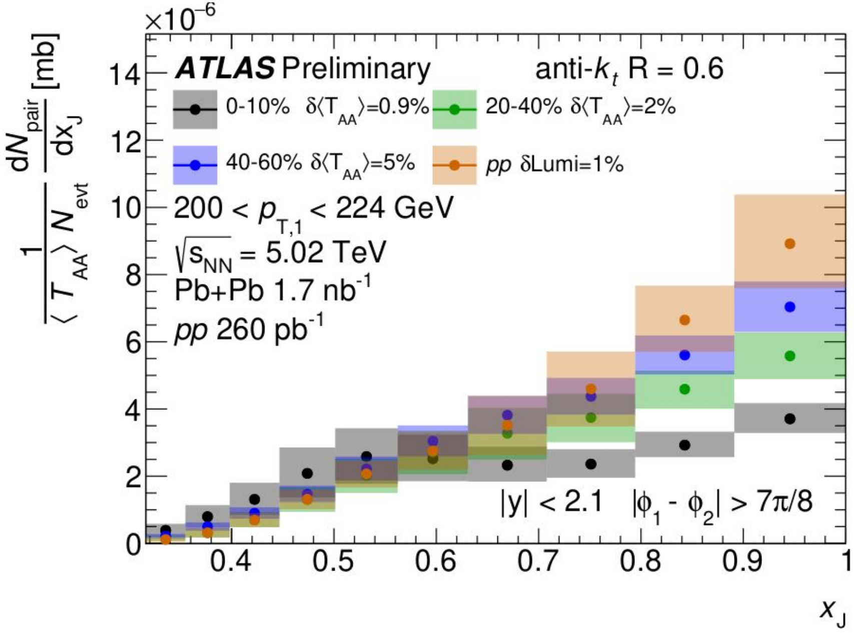
Centrality dependence of x_J

- Both large and small jets are more quenched towards more central collisions.

R=0.2

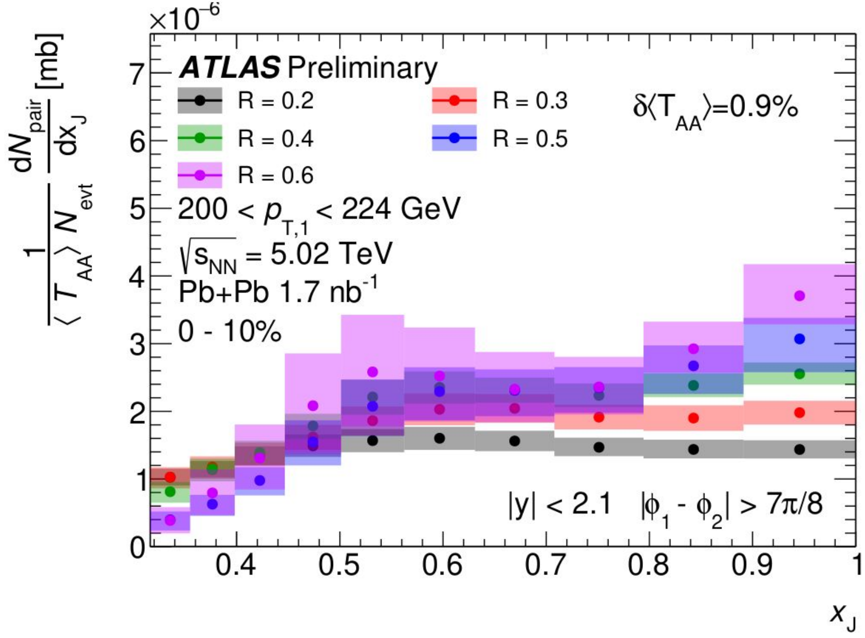


R=0.6

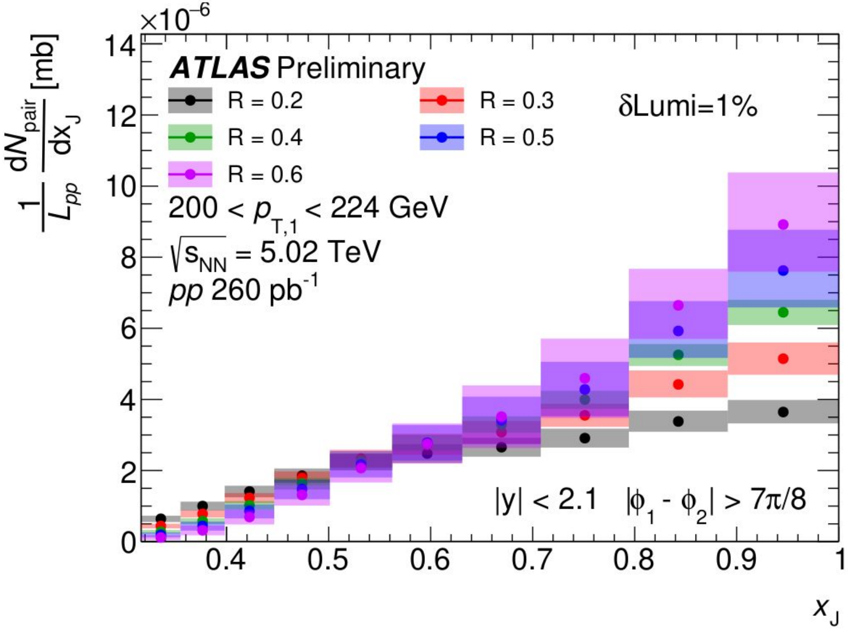


Jet radius dependence of x_J

- Larger jets have more peaked x_J distributions whereas smaller jets have flatter distributions.



Central Pb+Pb

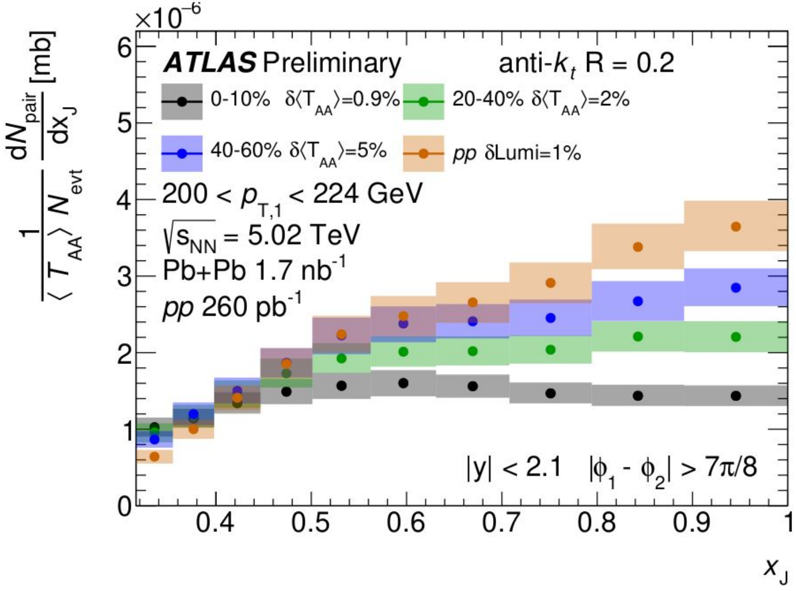


pp

Jet radius dependence of J_{AA}

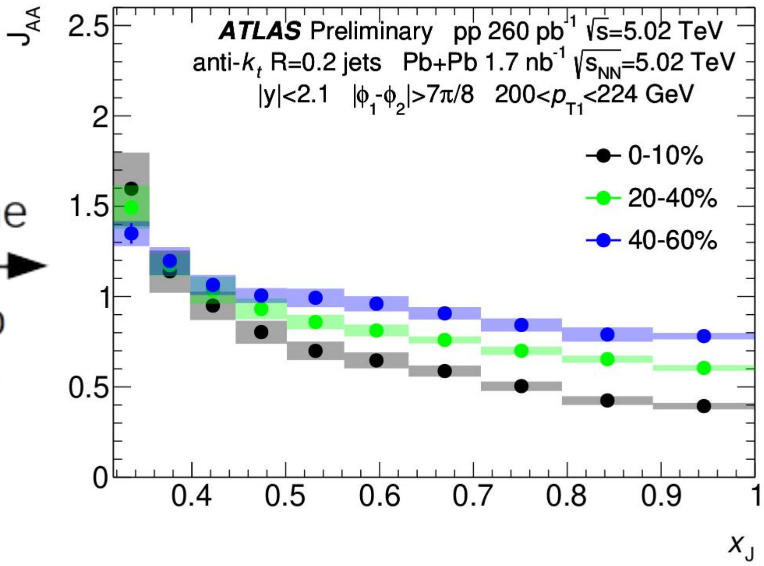
$$J_{AA} = \frac{\frac{1}{\langle T_{AA}\rangle N_{\mathrm{evt}}^{\mathrm{AA}}} \frac{dN_{\mathrm{pair}}^{\mathrm{AA}}}{dx_J}}{\frac{1}{L_{pp}} \frac{dN_{\mathrm{pair}}^{pp}}{dx_J}}$$

- J_{AA} defined as the PbPb to pp ratio of dijet yields.
- Comparing PbPb to pp collisions, dijet yields are suppressed for balanced dijets and enhanced for imbalanced dijets.



Taking the

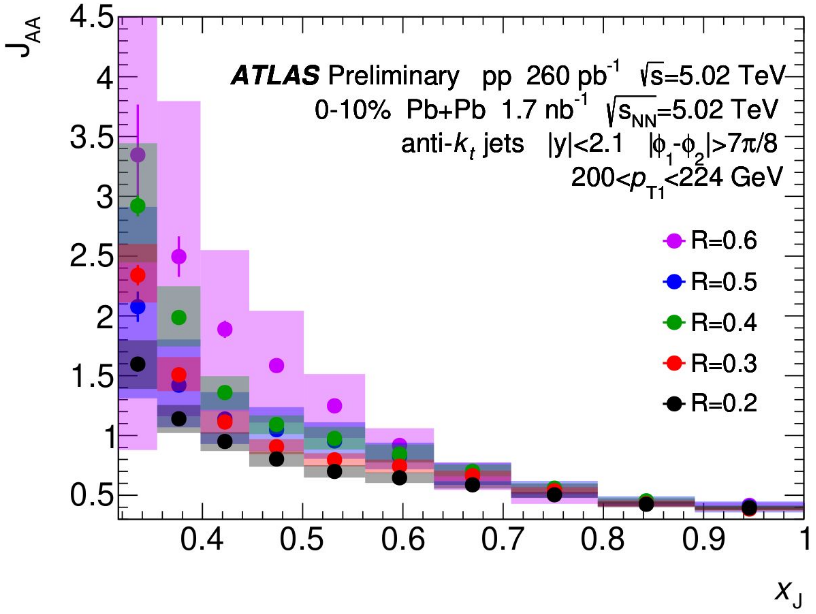
PbPb to pp ratio



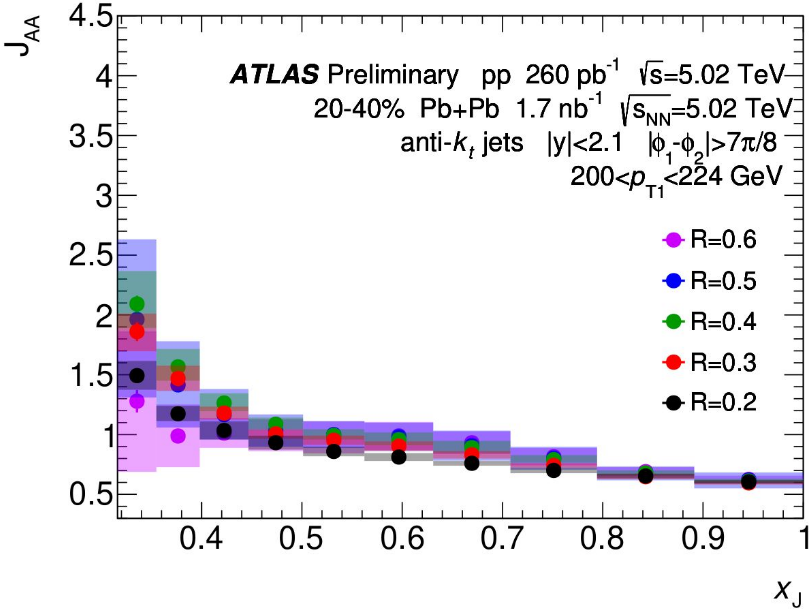
Jet radius dependence of J_{AA}

- PbPb to pp ratios of dijet yields are generally larger for larger jets, more noticeable for more imbalanced dijets.

Central Pb+Pb



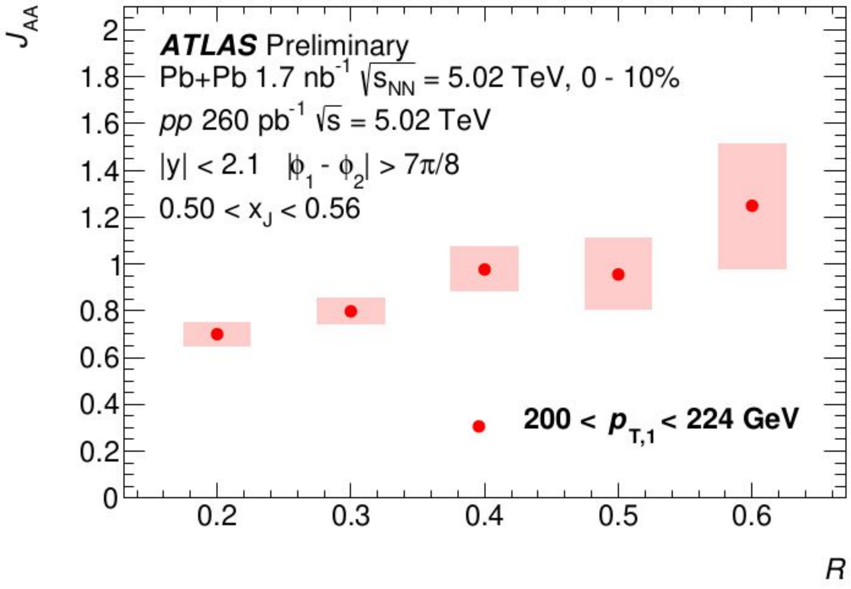
Mid central Pb+Pb



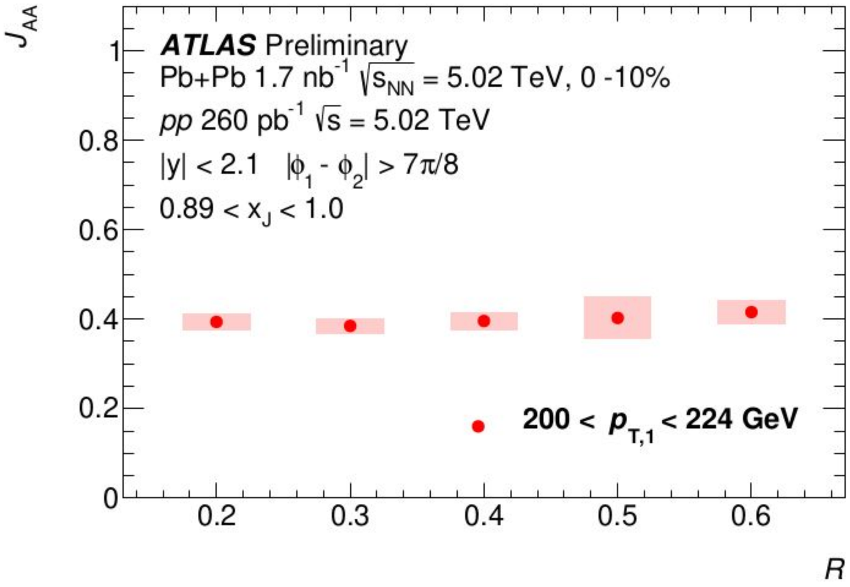
Jet radius dependence of J_{AA}

- PbPb to pp ratios of dijet yields are generally larger for larger jets, more noticeable for more imbalanced dijets.

Imbalanced dijets



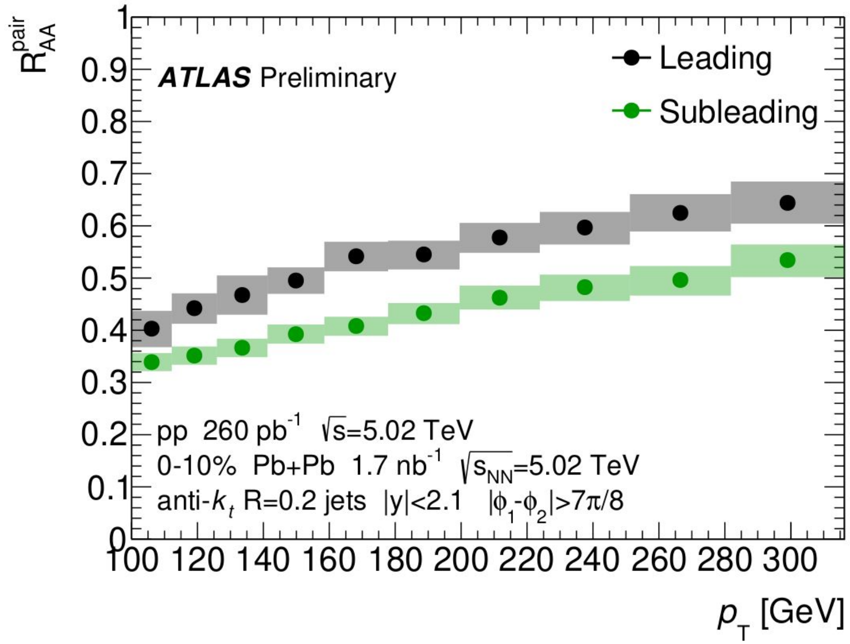
Balanced dijets



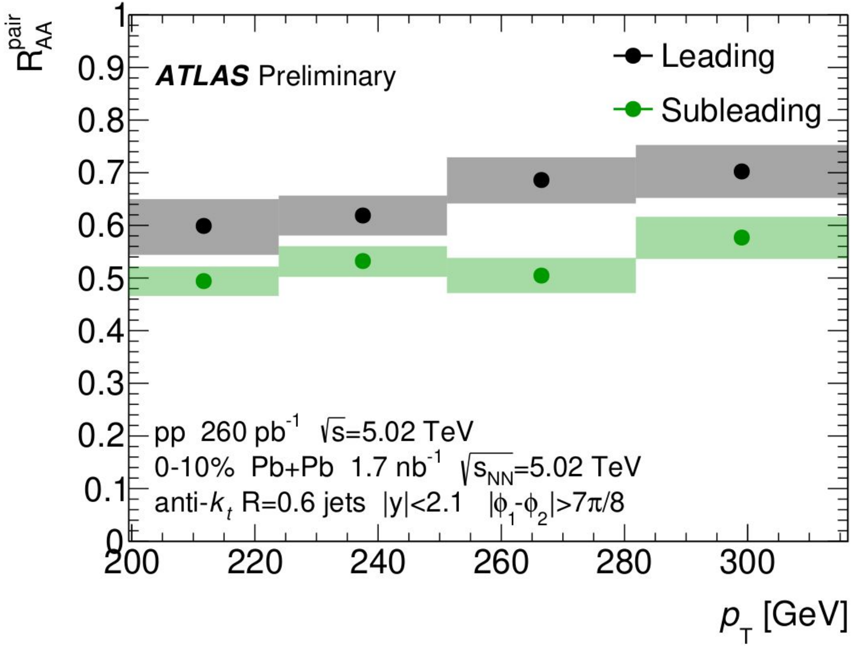
Leading and subleading R_{AA}^{pair}

- Subleading jets are more suppressed than leading jets, for both large and small jets.

R=0.2

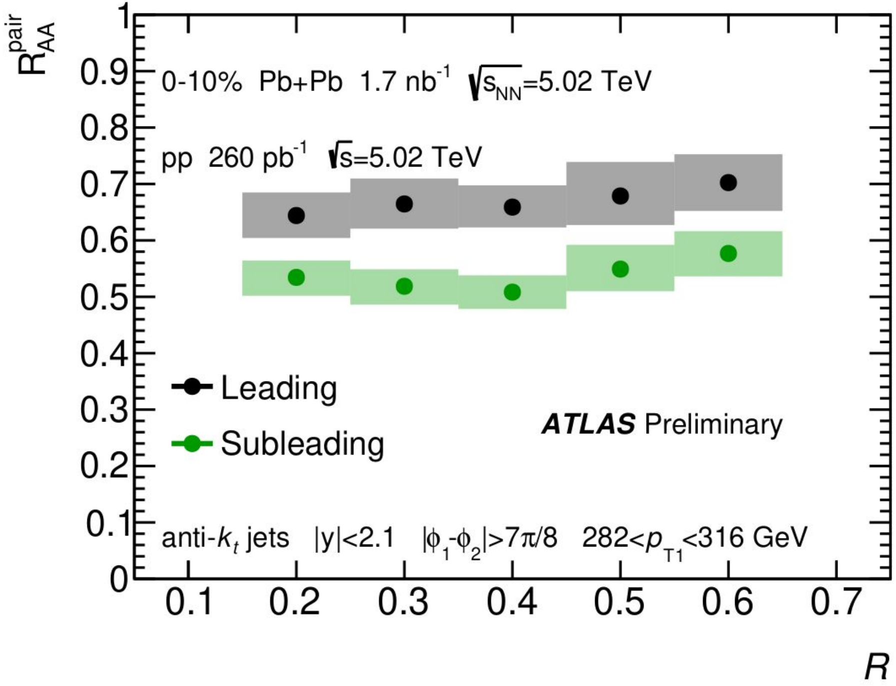


R=0.6



Jet radius dependence of R_{AA}^{pair}

- No significant jet radius dependence observed on the R_{AA}^{pair} at high p_T.
- Expect more jet radius dependence at lower p_T.



Summary

- Jet quenching is the energy loss of jets when traversing the QGP.

- The QGP can be studied through measurements of jet quenching with observables such as:
    - Nuclear modification factor.
    - Jet azimuthal anisotropies.
    - Dijet momentum balance.
    - Fragmentation functions.

- A jet radius dependent analysis is sensitive to both the momentum balance of dijets and the radius dependence of jet fragmentation.
    - Larger dijets are more balanced in p_T.
    - Imbalanced dijets show more dependence on the jet radius than balanced dijets.
    - The R_{AA}^{pair} shows no significant dependence on the jet radius at high p_T.