Measurement of Jet Quenching in ATLAS Heavy Ion Collisions

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Preliminary examination

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Overview

- Background
  - Strong force
  - Quark Gluon Plasma
  - Jets
- Experiment
  - ATLAS at the LHC
  - Heavy ion jet reconstruction
  - Fake jets
- Jet quenching observables
  - Nuclear modification factor
  - Dijet momentum imbalance
  - Jet azimuthal anisotropies
  - Fragmentation functions
- Proposed research

Measurement of dijet momentum imbalance for jets of various radii

Background

Fundamental particles and interactions

Particles:

Quarks, leptons and force carriers

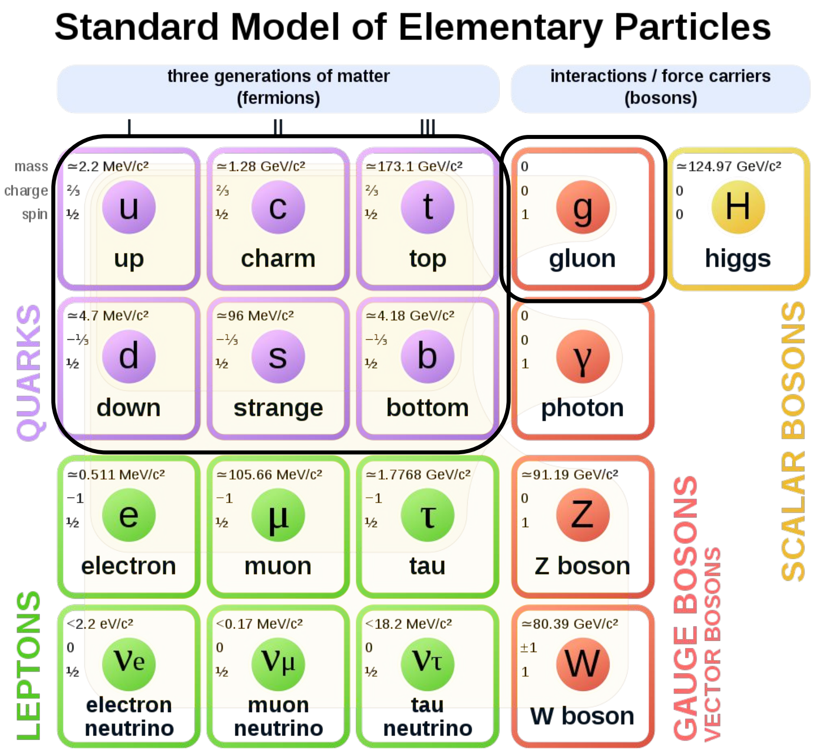
Interactions:

Gravitational force

Electromagnetic force

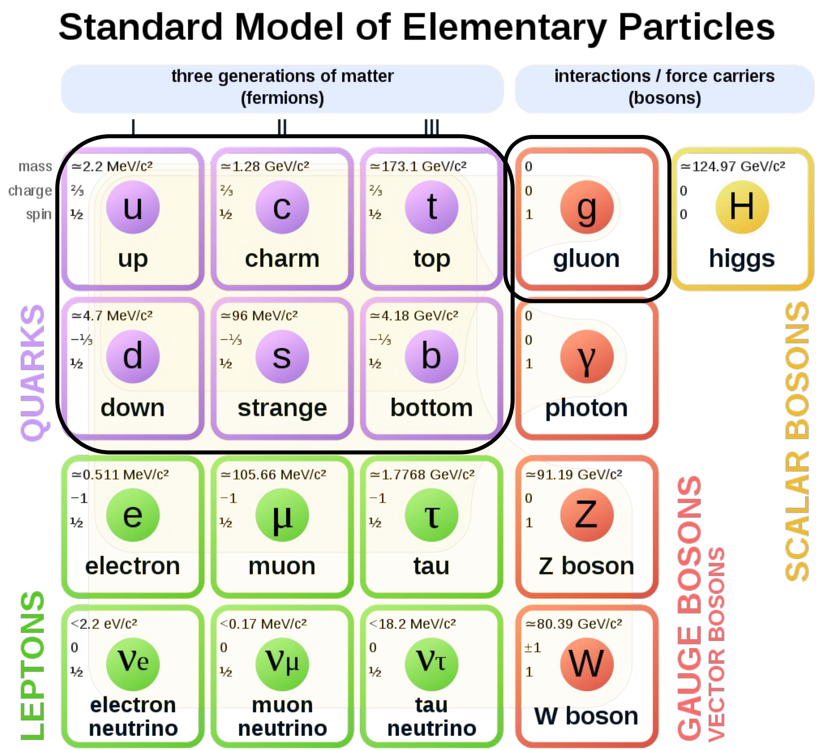
Weak force

Strong force

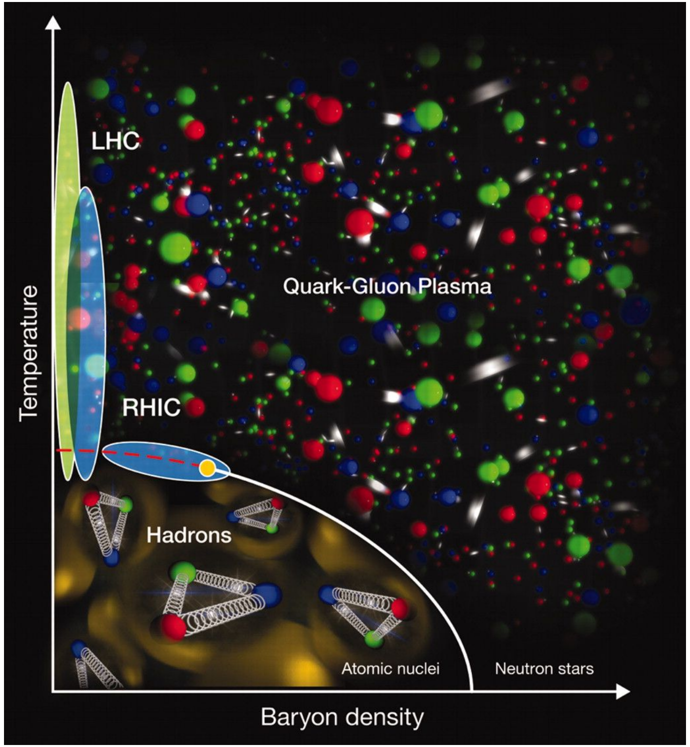


Quarks, gluons and the strong force

- Quarks and gluons are collectively called partons.
- Partons interact through the strong force, described in the theory of quantum chromodynamics (QCD).
- Partons carry color charge that has to be bleached -> confinement.
- Asymptotic freedom.

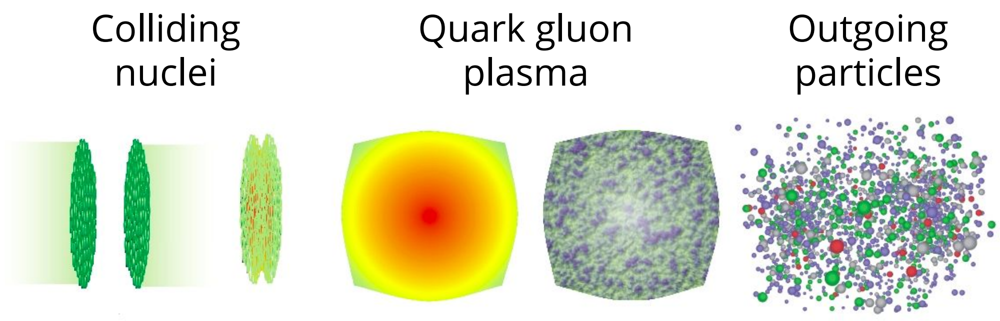


Quark gluon plasma

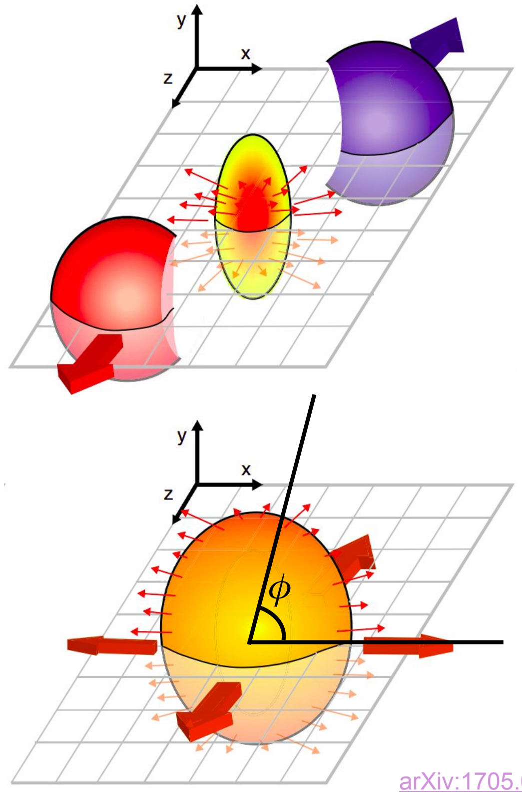


https://doi.org/10.1126/science.1215901

- 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

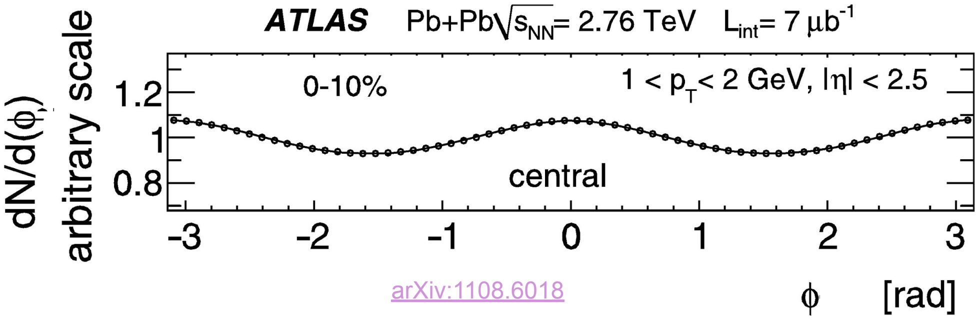


arXiv:1705.01974

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

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

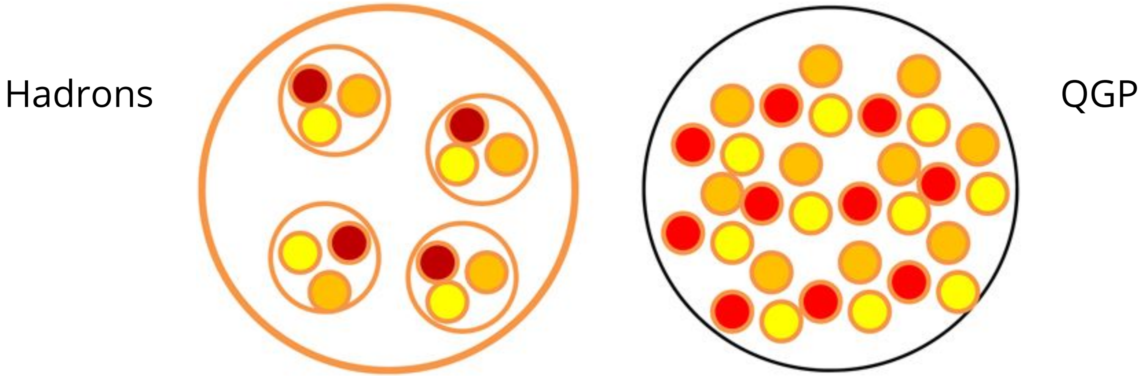
- Low specific viscosity η/s obtained from flow measurements is close to theoretical limit.



arXiv:1108.6018

Why is the quark gluon plasma interesting?

- Reasons related to the QGP as a medium:
    - The QGP is a strongly correlated system and flow emerges from the collective behavior of partons.
    - Studying how hadrons melt and form a state of matter of deconfined partons.



arXiv:1207.7028

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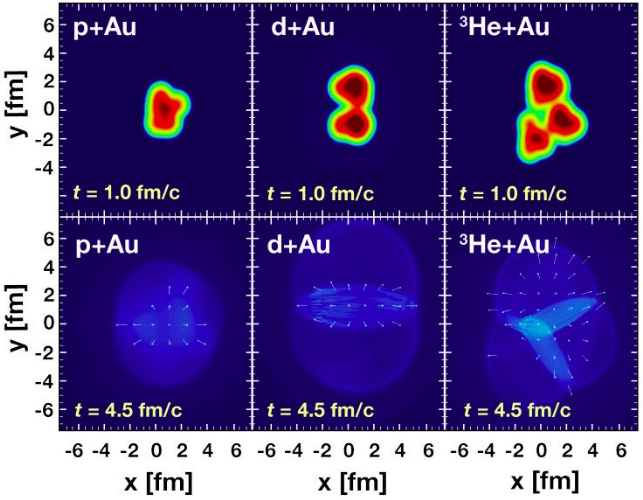
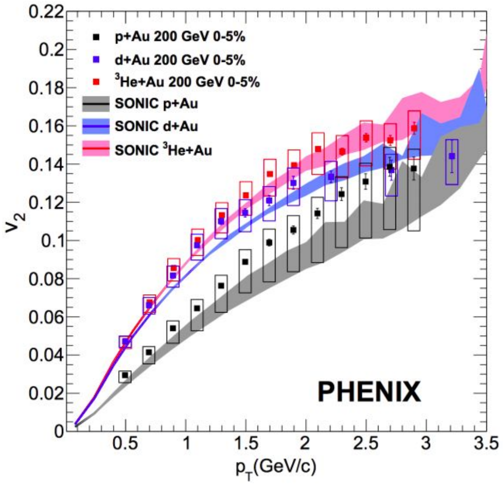
  - Smaller systems also show flow.





arXiv:1801.03477

Why is the quark gluon plasma interesting?

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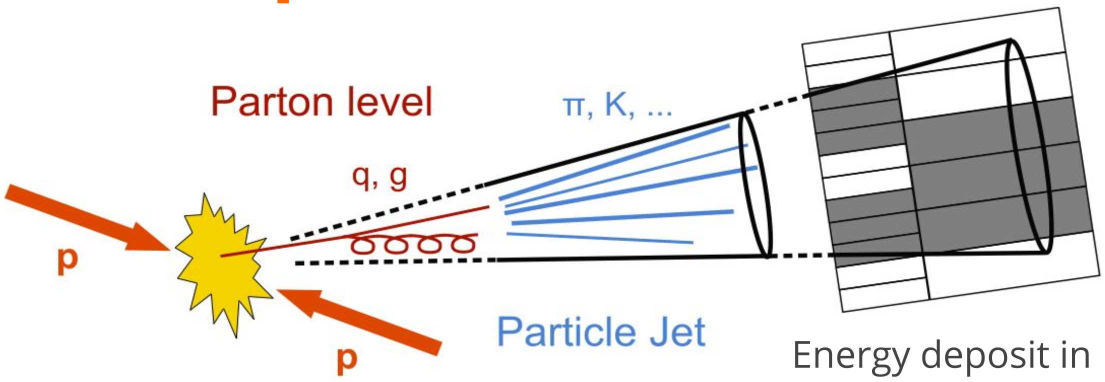
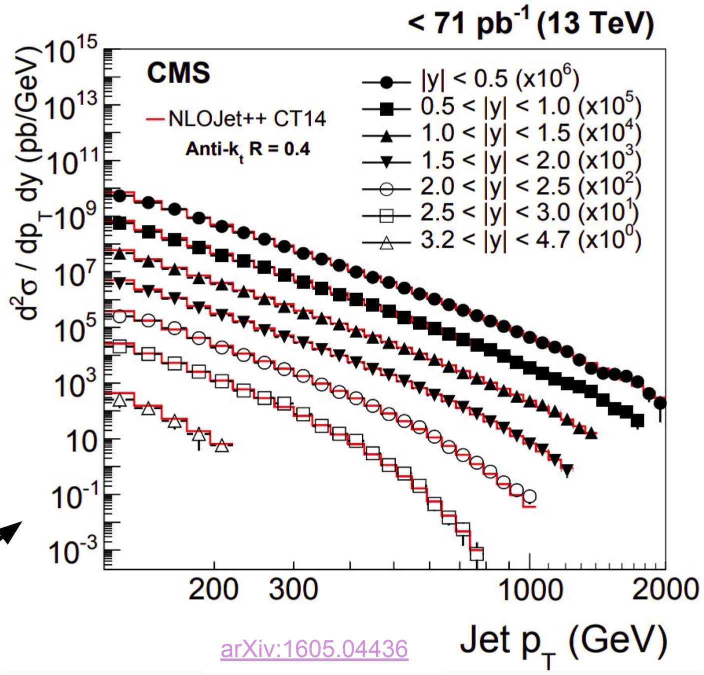
  - The QGP is a strongly correlated system and flow emerges from the collective behavior of partons.
  - Studying how hadrons melt and form a state of matter of deconfined partons.
  - Smaller systems also show flow.
- QCD reasons:
  - The QGP is the only medium in which partons are deconfined.
  - The QGP can be used to study the stopping power dE/dx of partons in a strongly interacting medium.
  - Parton energy loss can be studied through measurements of jet quenching.

Jets in proton collisions



Energy deposit in detectors

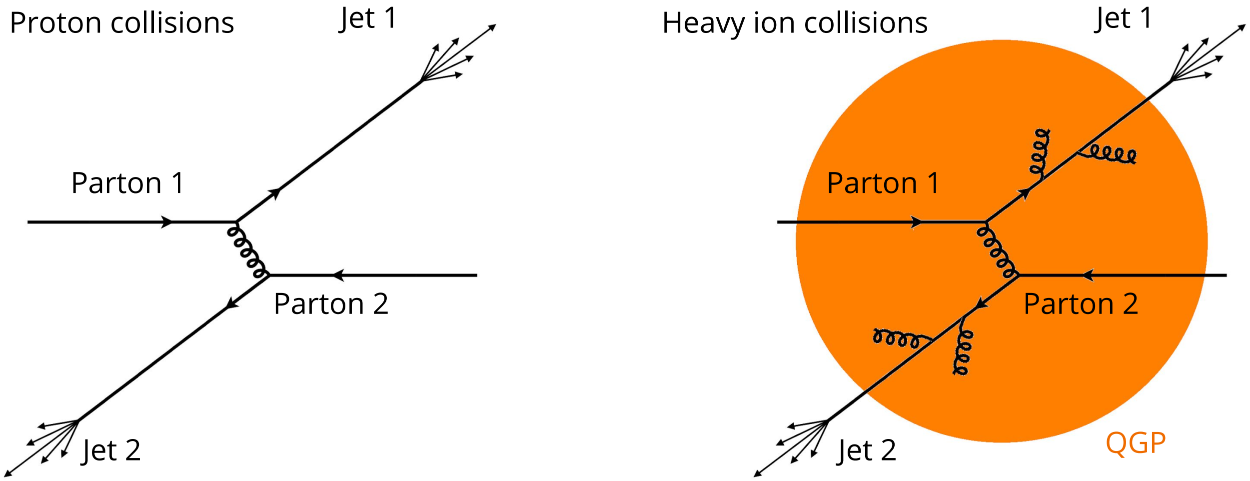
Jet cross section vs. jet momentum in proton collisions



arXiv:1605.04436

- A jet is a spray of particles coming from a hard scattered parton.
- Jets are formally defined using computational algorithms that cluster correlated detector signals to reconstruct the initial parton's kinematics.
- Jets from proton collisions are well modeled within QCD.

Jets as probes of the QGP



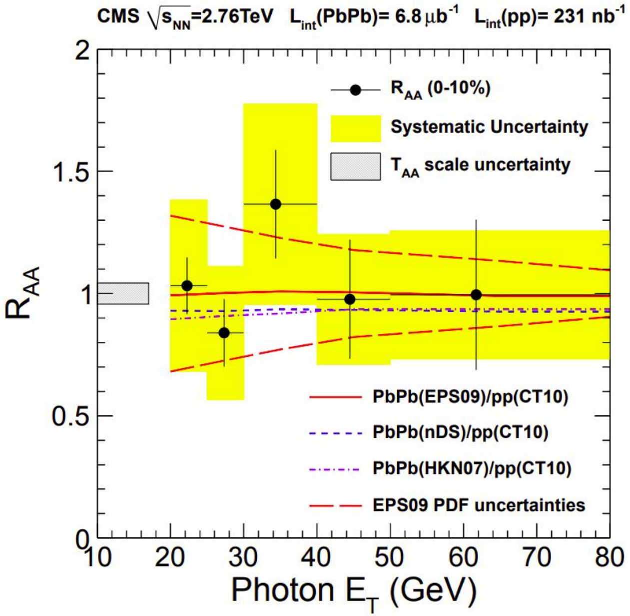
- Additional interactions within the QGP cause the hard scattered partons to lose energy, which leads to **jet quenching**.
- Jets can be used to study the QGP.

Jets as probes of the QGP

Uncolored

Ratio of photon yields in lead collisions to proton collisions

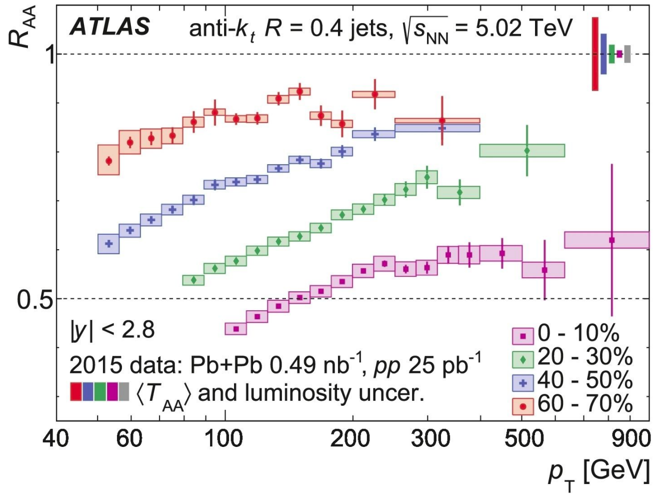
arXiv:1201.3093



Colored

Ratio of jet yields in lead collisions to proton collisions

arXiv:1805.05635



- Measurements of color neutral probes from heavy ion collisions do not show modifications with respect to proton collisions, but colored probes do show modifications.

Experiment

Measuring the QGP with sPHENIX at RHIC

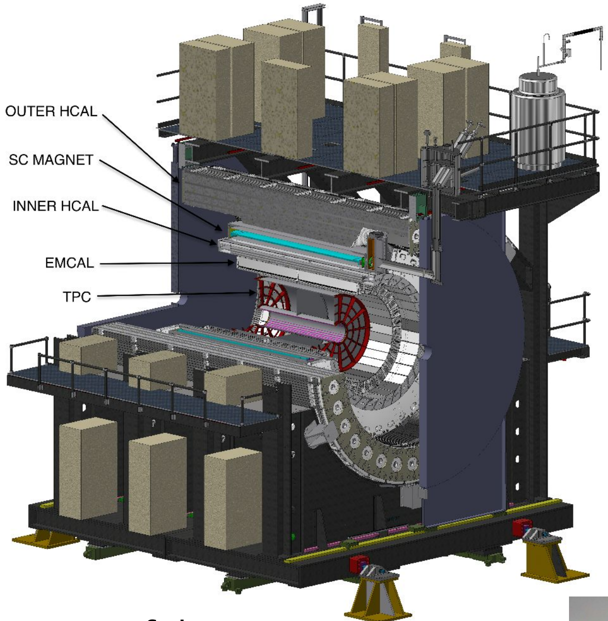
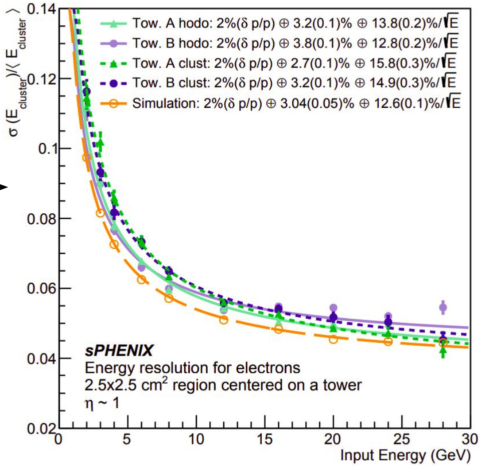


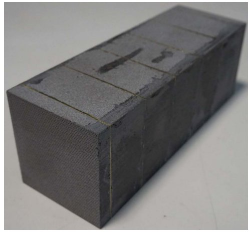
Diagram of the sPHENIX detector

- sPHENIX is an upcoming experiment at the Relativistic Heavy Ion Collider that will measure the QGP.
- The sPHENIX detector is designed with several subdetectors, one being an electromagnetic calorimeter (EMCal).
- The EMCal consists of blocks made of scintillating fibers and tungsten.
- A prototype of the EMCal was constructed and tested.
- I contributed to:
  - Testing of EMCal blocks.
  - Testbeam at Fermilab.
  - EMCal energy resolution analysis.
  - Paper accepted to IEEE TNS.



arXiv:2003.13685

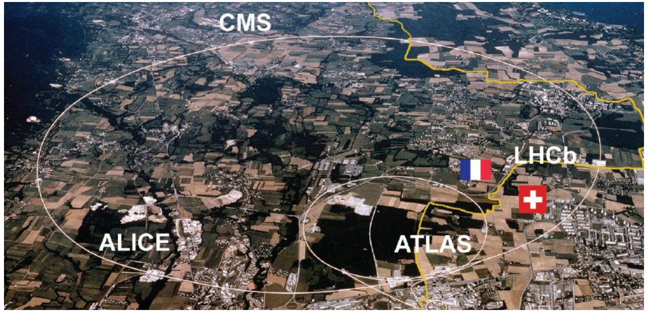
EMCal block



Measuring the QGP with ATLAS at the LHC

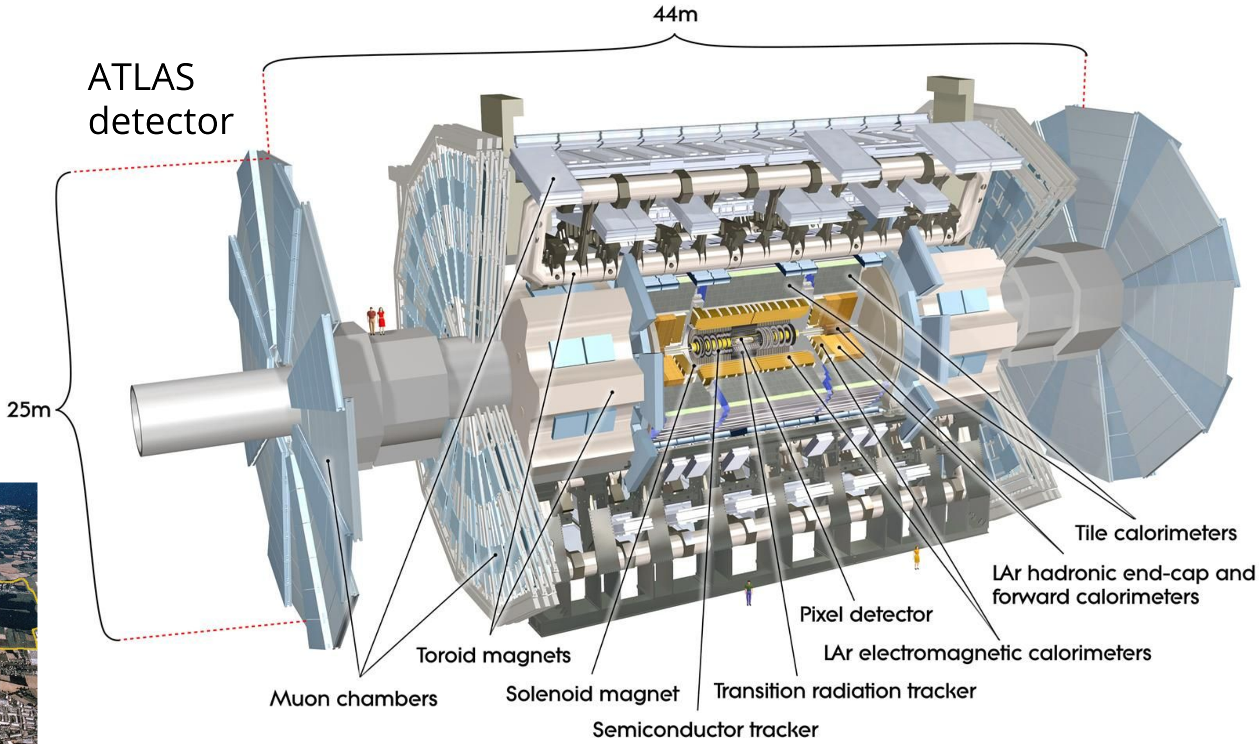
- Tracker -> tracks/particles
- Barrel calorimeters -> jets
- Forward calorimeters (FCal) -> centrality

Large Hadron Collider at CERN



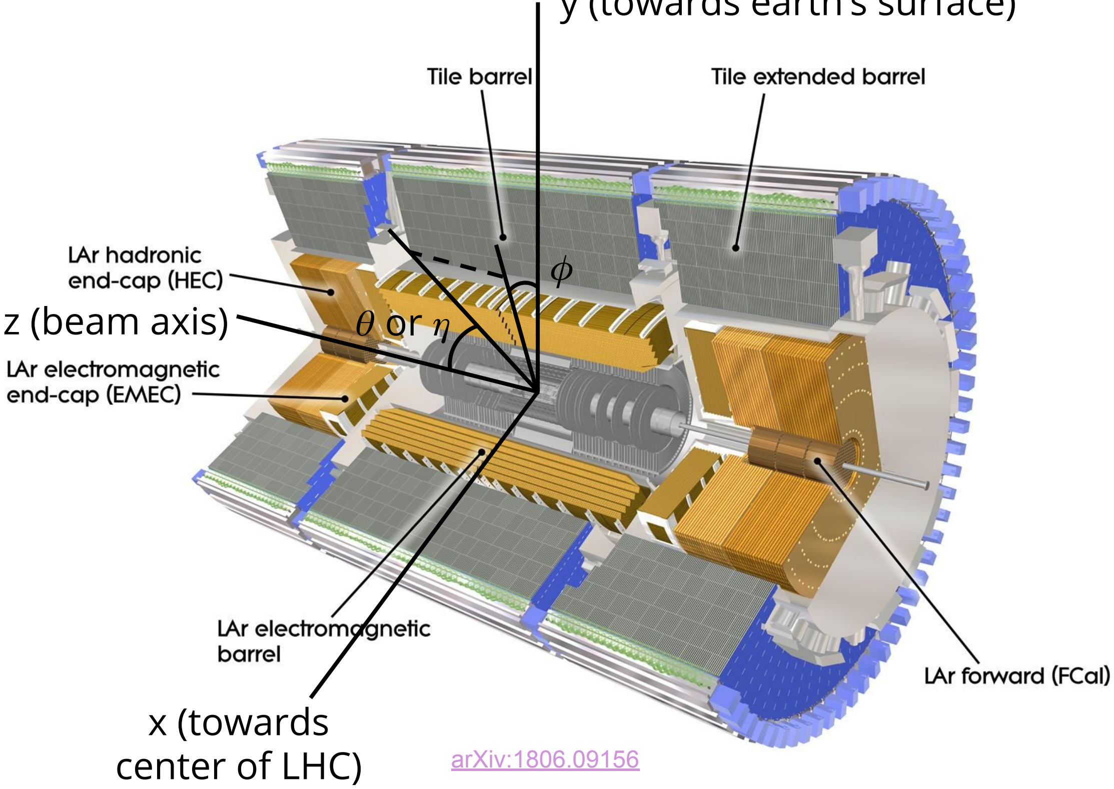
Fields & Carver (2017)

ATLAS detector



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

Some basic definitions



arXiv:1806.09156

- Coordinates: 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:

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

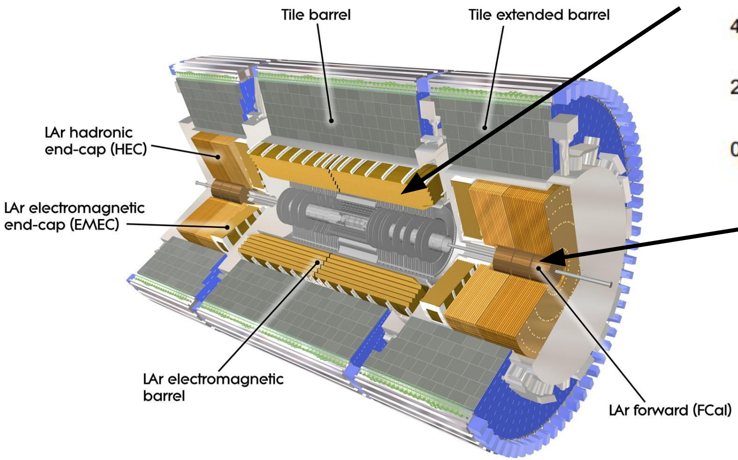
- Transverse energy E_T and transverse momentum p_T defined in x-y plane.

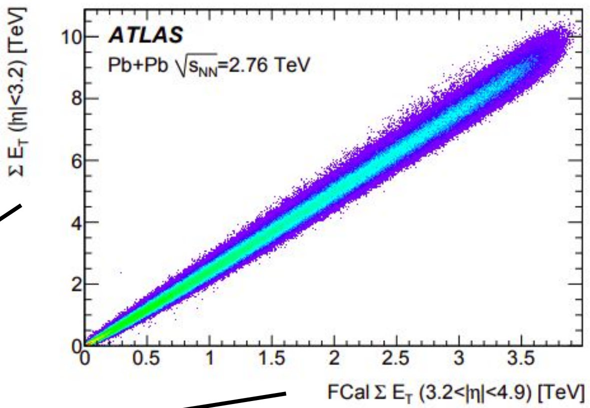
https://doi.org/10.1088/1748-0221/3/08/S08003

What is centrality?

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

Barrel energy vs. FCal energy

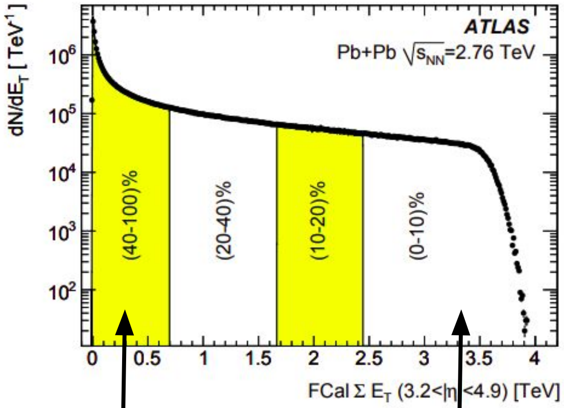




arXiv:1806.09156

arXiv:1011.6182

Number of events vs. FCal energy

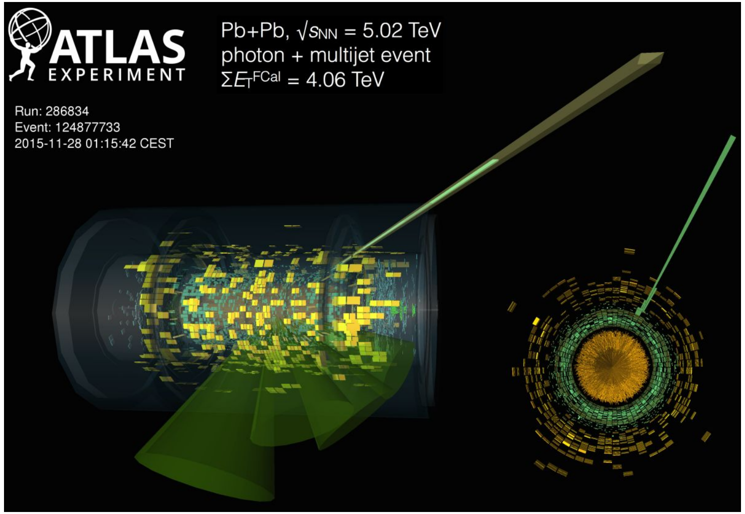


Peripheral collisions

Head on collisions

The anti-k_T jet clustering algorithm

- Jets are clustered within a given radius parameter R.
- The algorithm takes as inputs “objects” (particles, tracks, calorimeter towers of $\Delta\eta\times\Delta\phi$=0.1x0.1, etc.) with momentum p_T and position (η,ϕ).
- Objects are clustered in an iterative procedure that gives preference to objects with higher p_T or spatially close.



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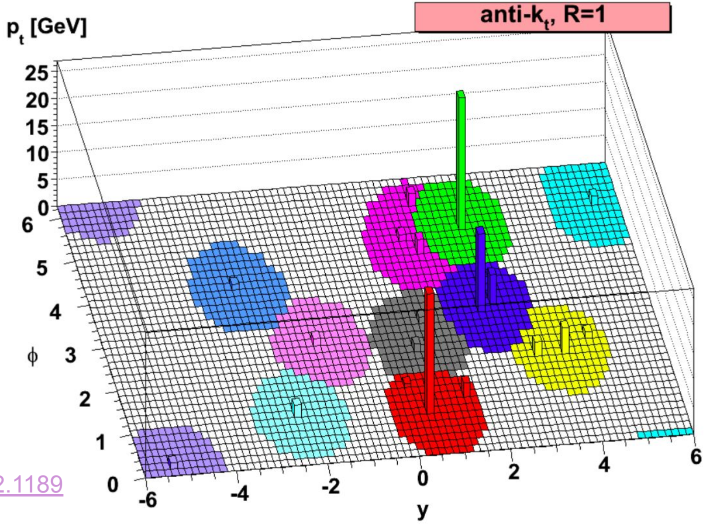
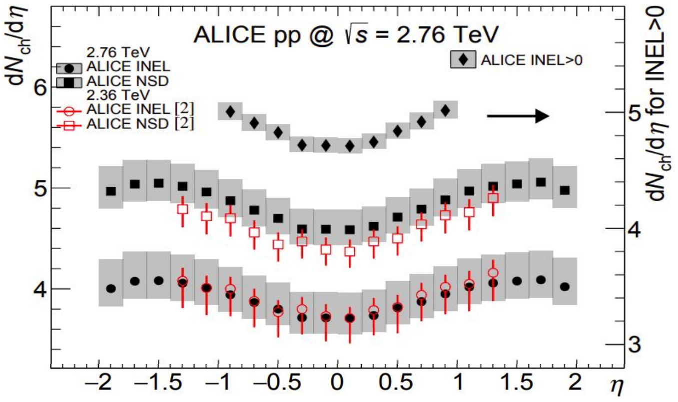


arXiv:0802.1189

ATLAS heavy ion jet reconstruction: UE subtraction

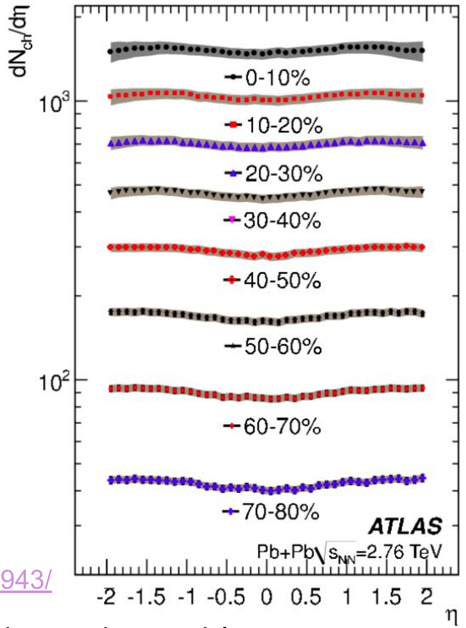
- Background from collisions is called underlying event (UE) and corresponds to everything that does not come from a hard scattering. In heavy ion collisions, the UE is QGP decay products.
- The UE can contribute significantly to jet measurements, so an iterative procedure is used to subtract the UE.

Number of particles in proton collisions



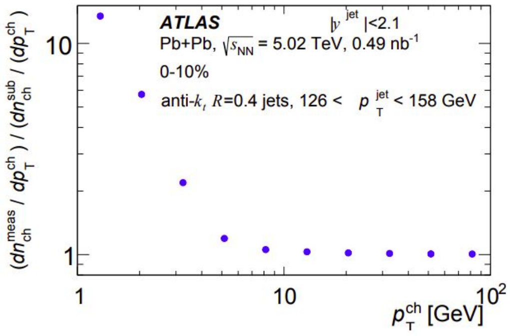
arXiv:1509.07541

Number of particles in heavy ion collisions



cds.cern.ch/record/1541943/

Ratio of number of particles before UE subtraction to after UE subtraction, for central heavy ion collisions



arXiv:1805.05424

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Average transverse energy density

$$\rho(\eta,\phi) \propto \frac{dE_T}{d\eta}(1 + 2v_n cos(n\Delta\phi))$$

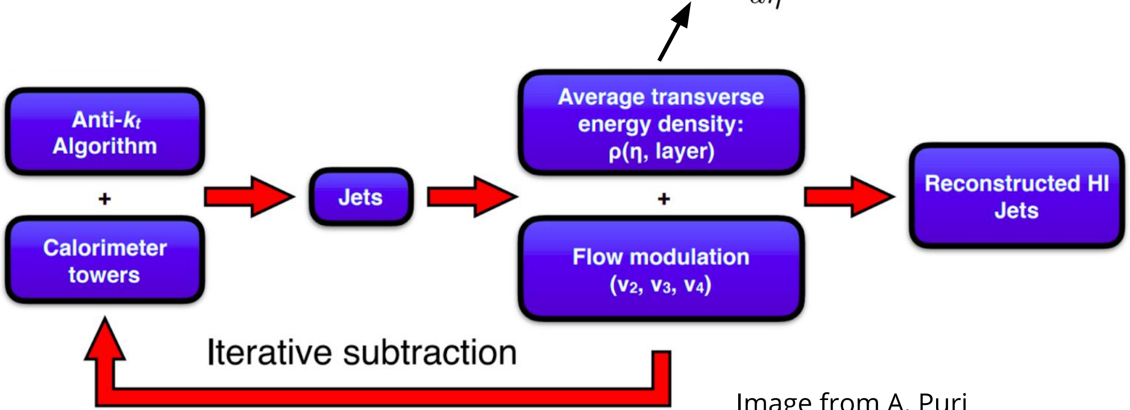
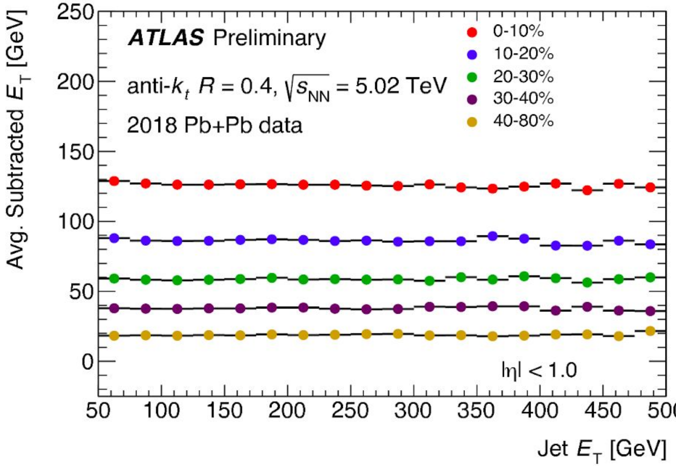


Image from A. Puri

HION-2018-001



ATLAS heavy ion jet reconstruction: jet performance

Jet performance is evaluated in terms of :

- Jet energy scale (JES).
- Jet energy resolution (JER).

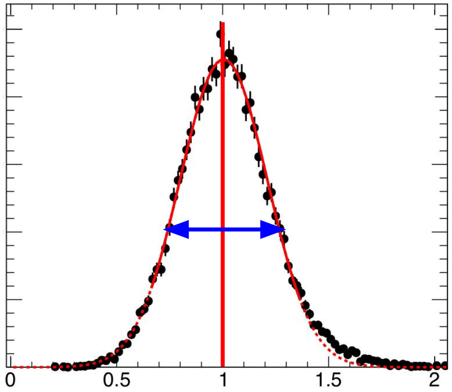
These compare the reconstructed (reco) and true (truth) versions of jets from Monte Carlo (MC) overlay samples.

MC overlay = simulations + data

Jets from proton collisions that are reconstructed taking into account the detector response

UE fluctuations

Distribution of jets as a function of $\frac{p_{\mathrm{T}}^{\mathrm{reco}}}{p_{\mathrm{T}}^{\mathrm{truth}}}$



JES -> accuracy

JER -> precision

Image from V. Bailey

ATLAS heavy ion jet reconstruction: jet performance

Jet performance is evaluated in terms of :

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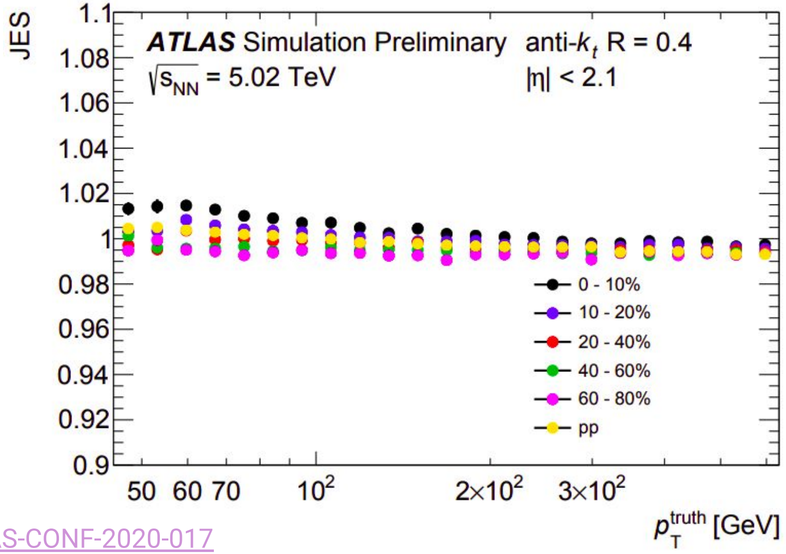
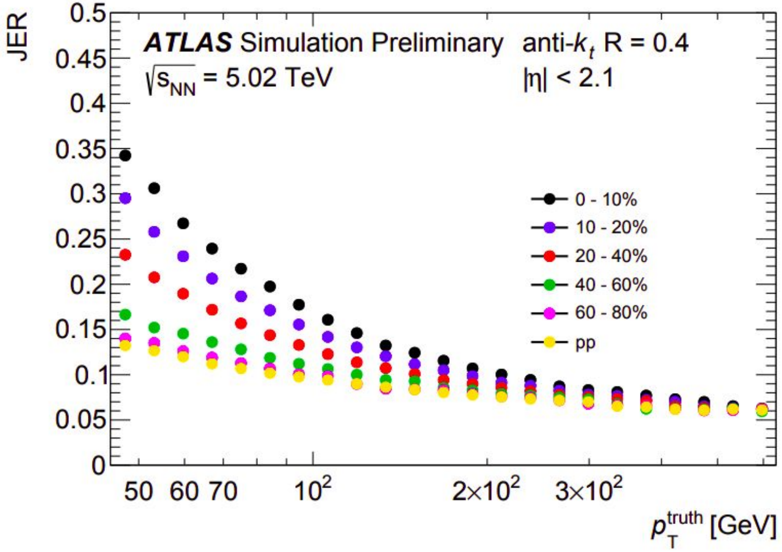
UE fluctuations smear the p_T distribution





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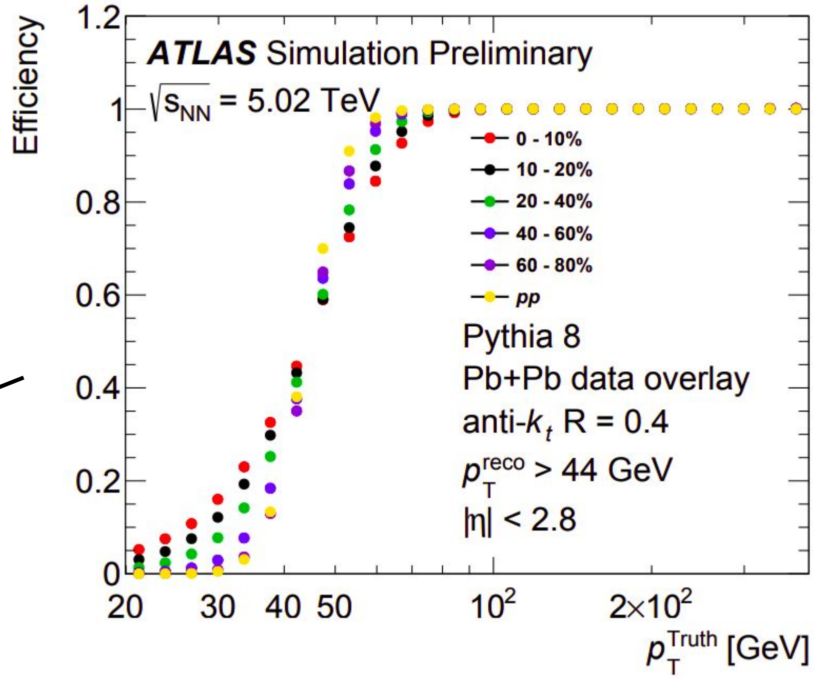
ATLAS heavy ion jet reconstruction: jet performance

Jet performance is evaluated in terms of :

- Jet energy scale (JES).
- Jet energy resolution (JER).
- Jet reconstruction efficiency.

At low p_T jets are not always distinguishable from UE fluctuations, which causes some jets to not be reconstructed.



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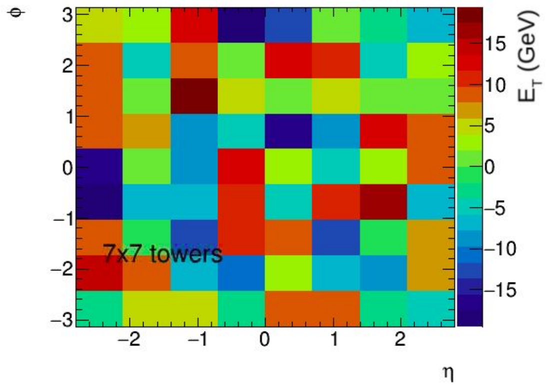
Fake jets

- UE fluctuations can be reconstructed as jets that are called "fake" because they don't come from hard scatterings.
- I studied the UE fluctuations that cause fake jets.

Transverse energy vs. Position for an area equivalent to an R=0.4 jet.

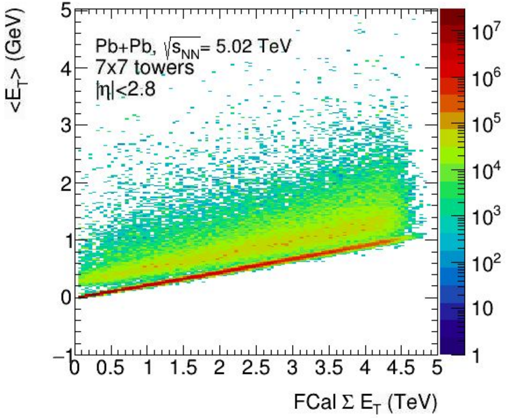


E_T^i = energy of a window of nxn towers

N = total number of windows.

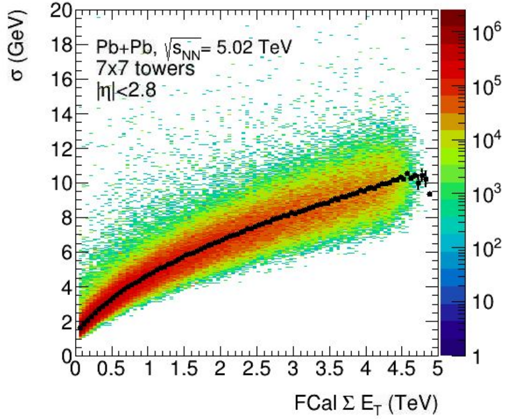
Mean of fluctuations

$$\langle E_T \rangle = \frac{1}{N} \sum_{i=0}^{N} E_T^i$$



Standard deviation of fluctuations

$$\sigma(E_T) = \sqrt{\langle E_T^2 \rangle - \langle E_T \rangle^2}$$



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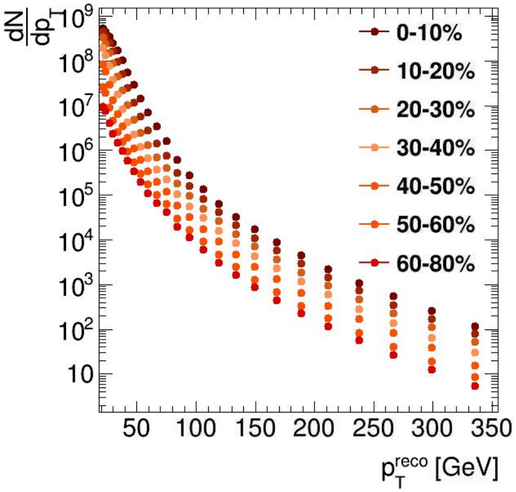
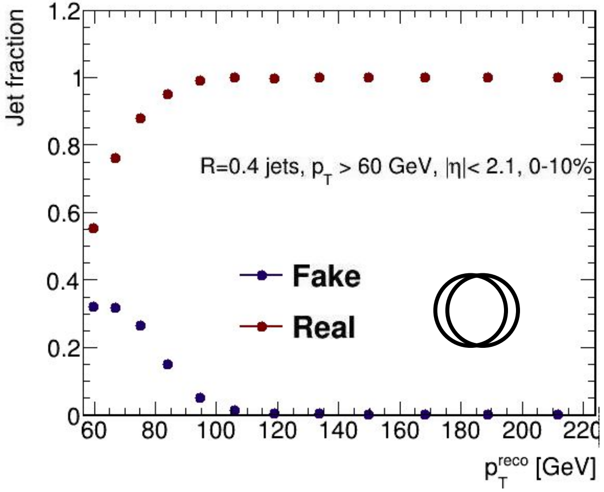
- I studied the rate of fake jets using fake jet rejection criteria.

p_T distribution of R=0.4 jets



Separating into real and fake components by matching to tracks or smaller jets.



Fake rate decreases toward peripheral collisions because UE fluctuations are smaller

Jet Quenching Observables

Nuclear modification factor

$$R_{AA} = \frac{\boxed{\left.\frac{1}{N_{\text{evt}}}\frac{d^2 N_{\text{jet}}}{dp_T dy}\right.}\Big|_{\text{cent}}}{\boxed{\langle T_{AA}\rangle}\boxed{\frac{d^2\sigma_{\text{jet}}}{dp_T dy}}\Big|_{pp}}$$

Normalization factor

Distribution of jets *Njet* per unit of jet momentum *pT* and rapidity *y*

-> QGP

Probability of jets per unit of jet momentum *pT* and rapidity *y*

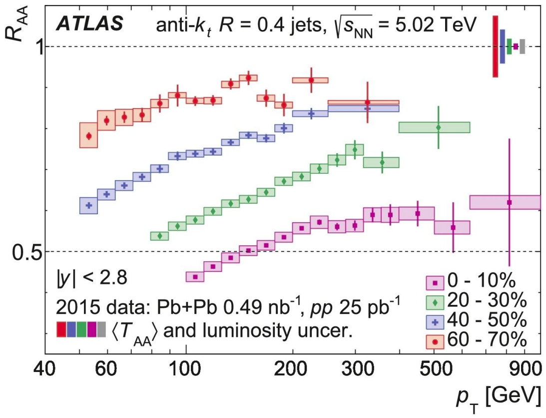
-> vacuum

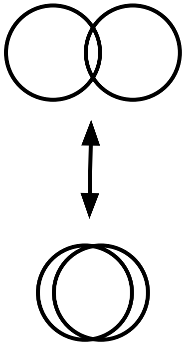
arXiv:1805.05635

Nuclear modification factor

Nuclear modification factor vs. jet momentum

arXiv:1805.05635

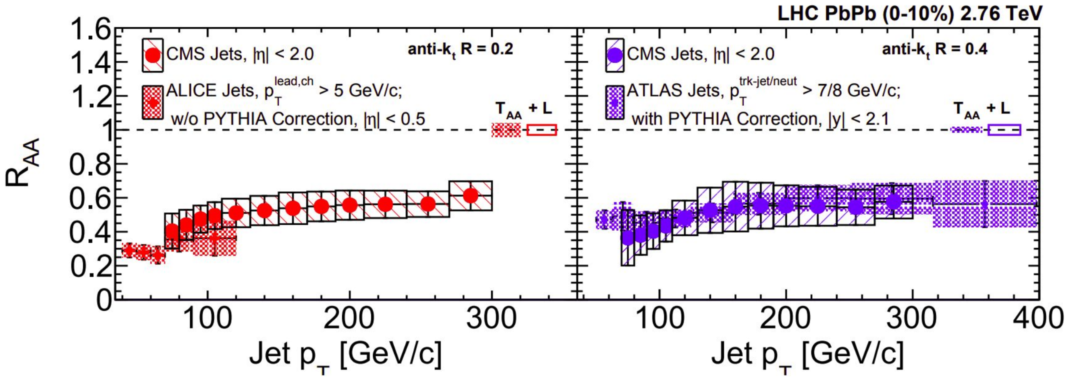


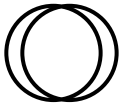


- Jets are suppressed in collisions where there is a QGP.
- Jet suppression increases with centrality and decreases with jet momentum.

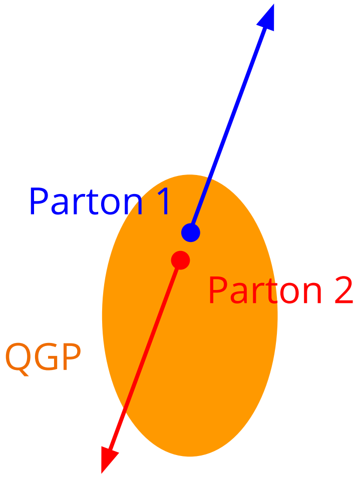
Similar measurements by CMS and ALICE experiments

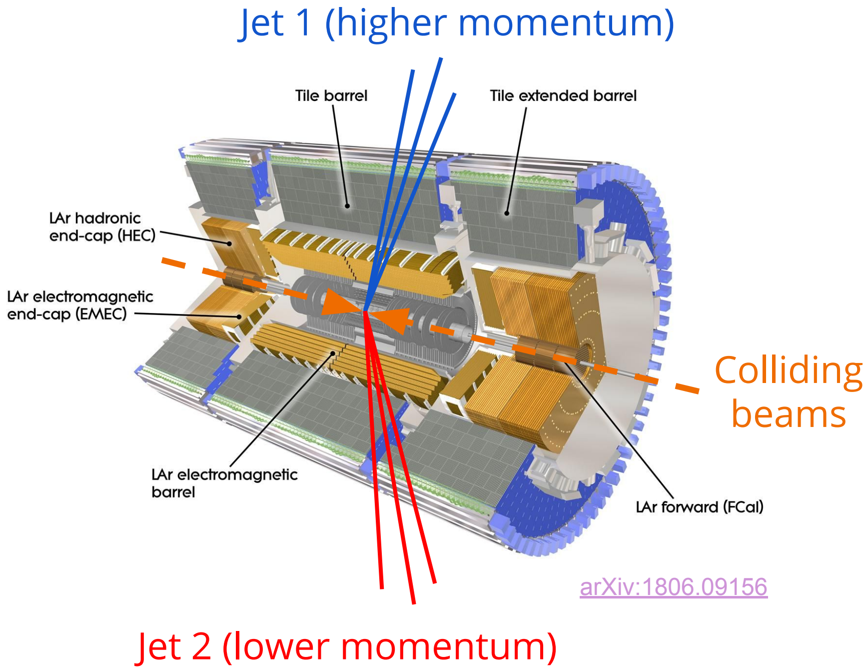
arXiv:1609.05383





Dijet momentum imbalance





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)
$p_{T1} > p_{T2}$

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Dijet momentum imbalance

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

p_{T1} = leading jet momentum
p_{T2} = subleading jet momentum
$p_{T1} > p_{T2}$

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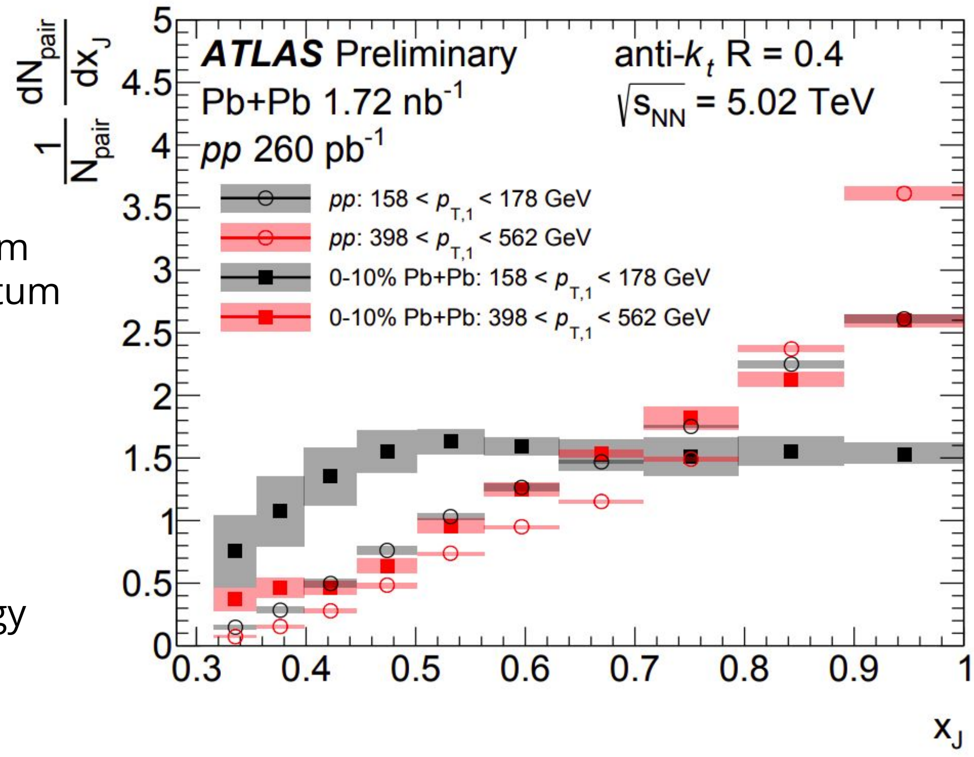
- One of the jets in the dijet loses more energy than the other.

Distribution of dijets as a function of x_J



○ Vacuum
■ QGP

Red: higher jet momentum

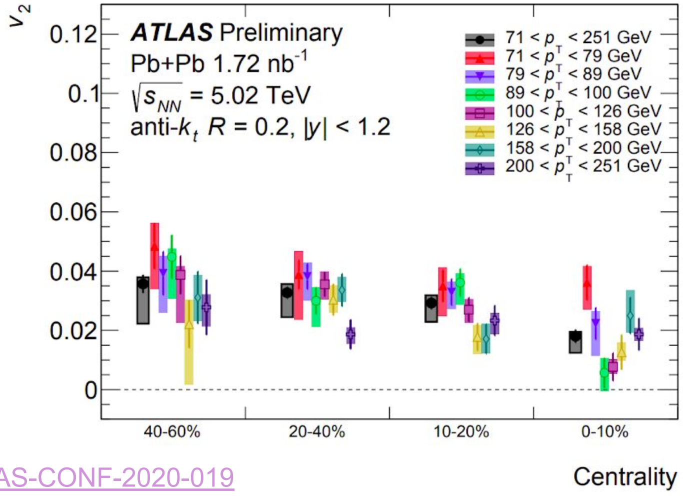
Black: lower jet momentum

Jet azimuthal anisotropies

- Initial collision geometry causes jet modulation:

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

- Jet energy loss is path length dependent.



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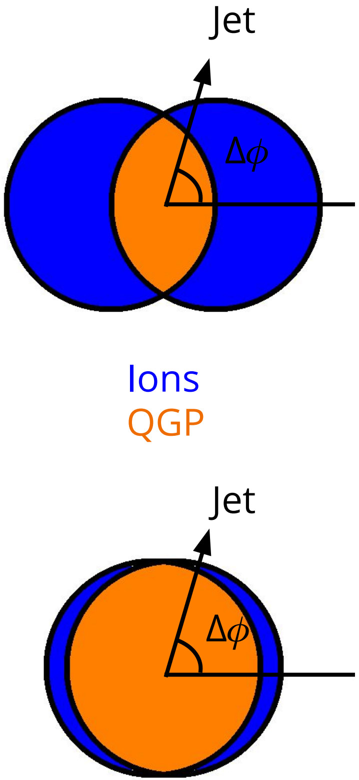
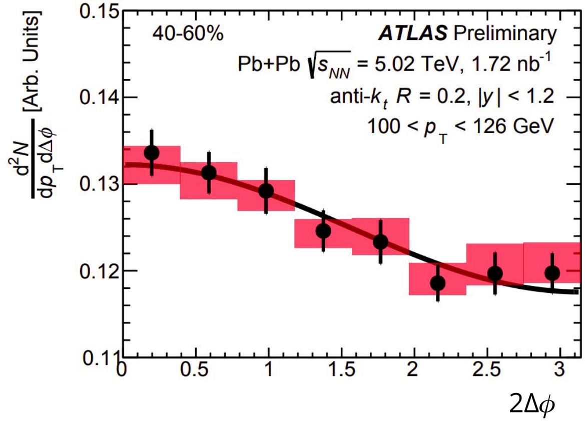
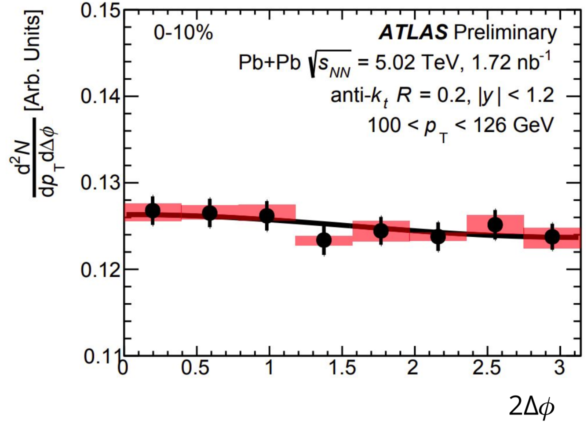






Fragmentation function

Number of charged particles inside the jet

$$D(p_T) = \frac{1}{N_{\text{jet}}} \frac{dn_{\text{ch}}}{dp_T}$$

Number of jets

Particle momentum

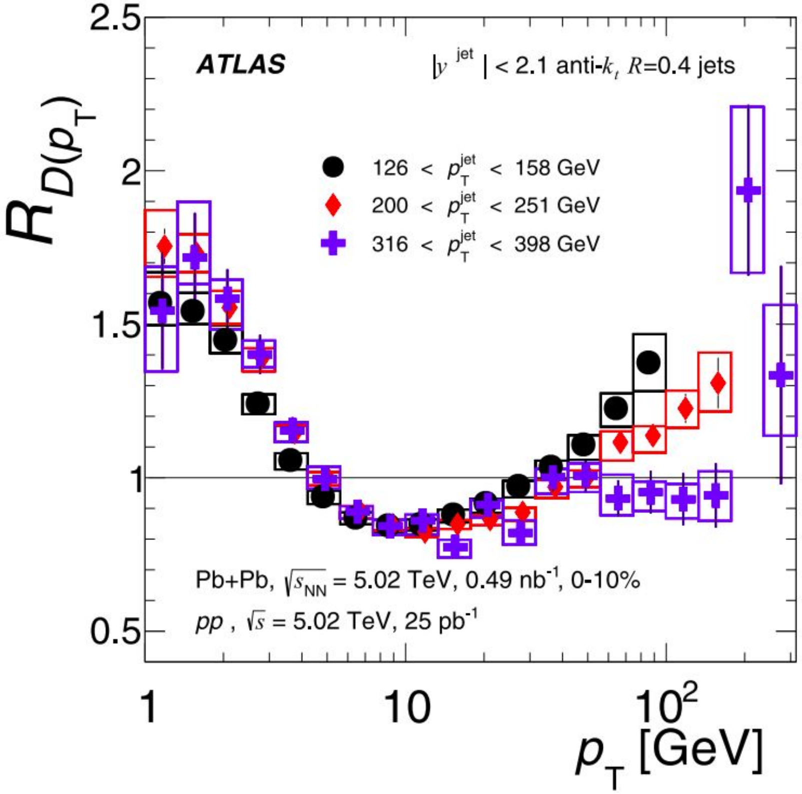
Lead collisions -> QGP

$$R_{D(p_{\mathrm{T}})} \equiv \frac{\boxed{D(p_{\mathrm{T}})_{\mathrm{PbPb}}}}{\boxed{D(p_{\mathrm{T}})_{pp}}}$$

Proton collisions -> vacuum

arXiv:1805.05424

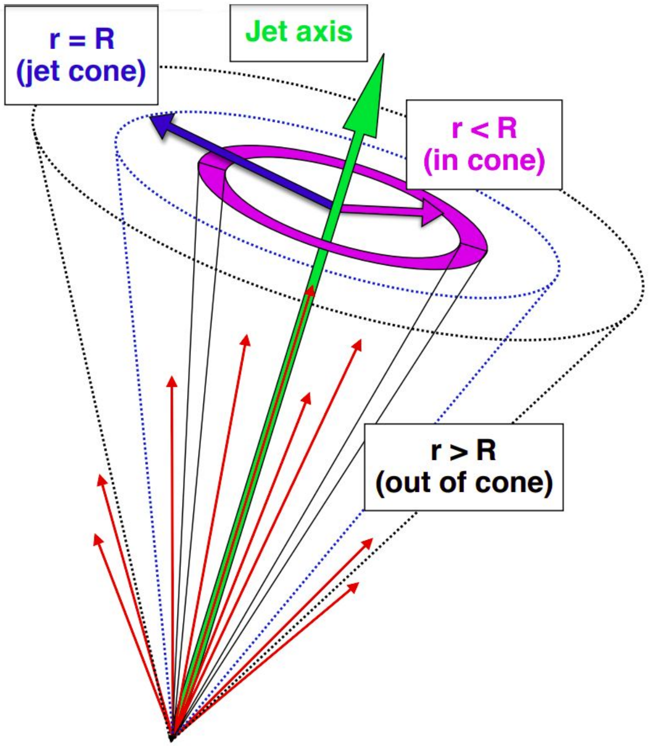
Fragmentation function



arXiv:1805.05424

- QGP causes jets to fragment into lower momenta particles.

2D fragmentation function



Number of charged particles inside the jet

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

Number of jets

Area of circular shell around jet axis

Particle momentum

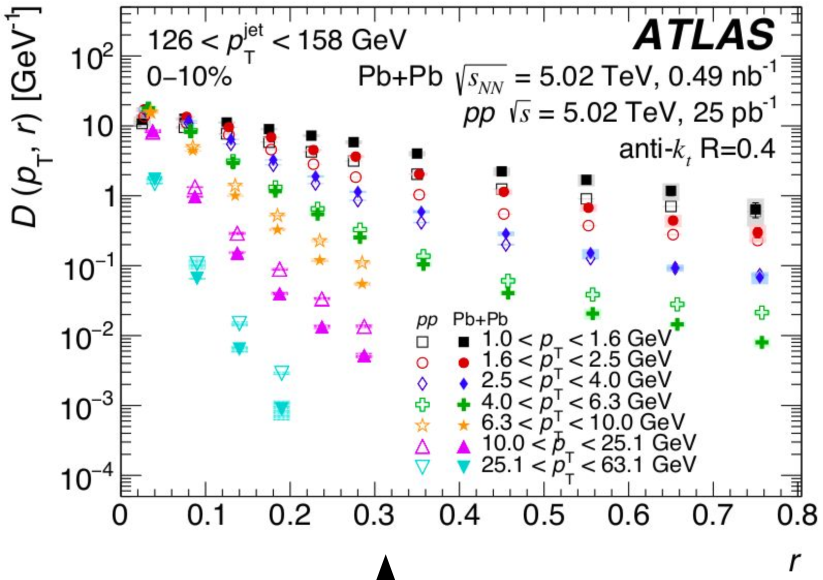
$$R_{D(p_T,r)} = \frac{D(p_T, r)|_{\text{PbPb}}}{D(p_T, r)|_{\text{pp}}}$$

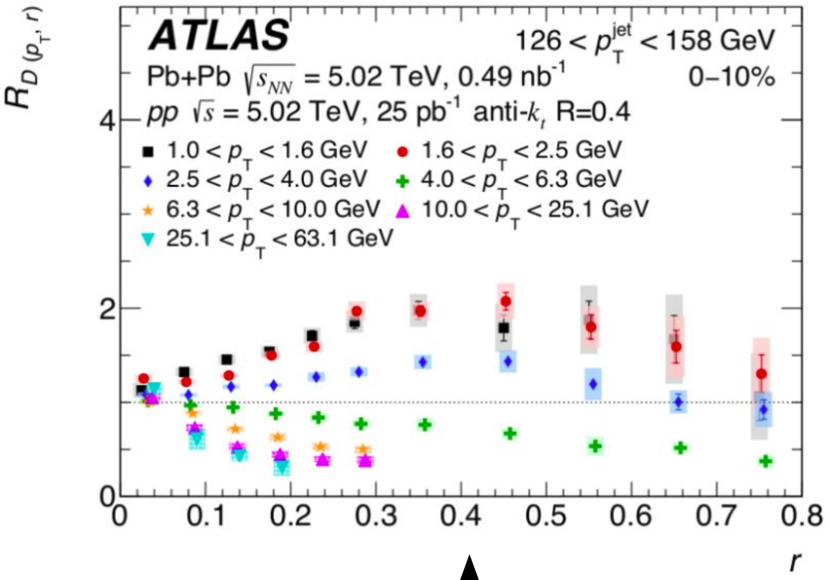
Ratio QGP/vacuum

arXiv:1908.05264

2D fragmentation function

arXiv:1908.05264





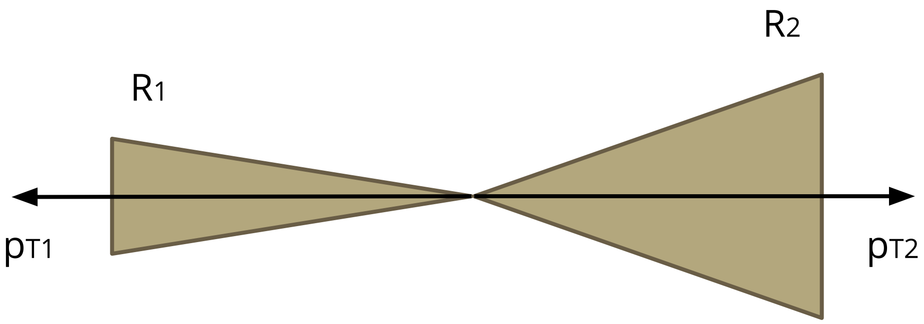
Lower momenta particles are emitted at larger angles with respect to jet axis.

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

Proposed Research

Proposed research

- Open question: where does the energy go after leaving the jet?
- Study momentum imbalance x_J in dijets of various radii R_1 and R_2.
- Measurement of jet quenching and medium response.
- Measurement would be sensitive to how to the energy goes from the jet to the medium.
- Plan to work with ATLAS Pb+Pb data at $\sqrt{s_{NN}}$ = 5.02 TeV.

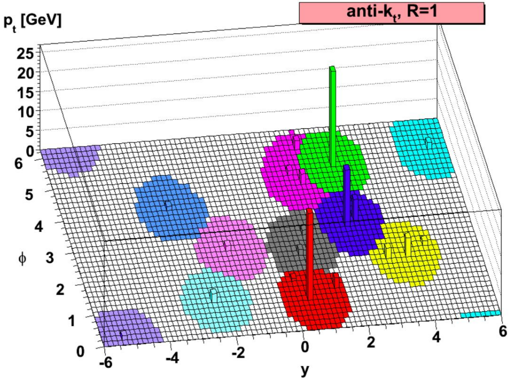


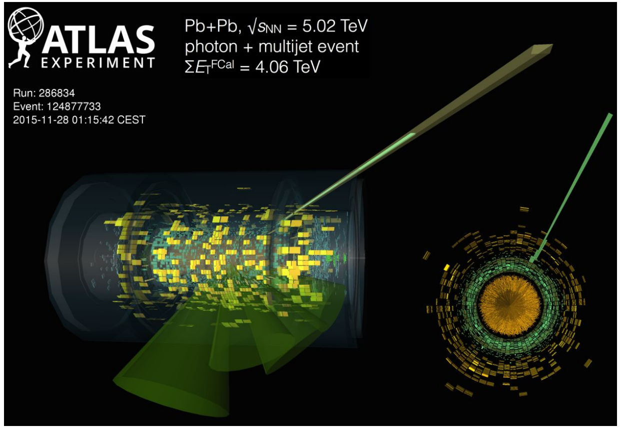
Summary

- The QGP can be studied by measuring jets.
- Jet quenching has been measured through observables such as:
  - Nuclear modification factor.
  - Dijet momentum imbalance.
  - Jet azimuthal anisotropies.
  - Fragmentation functions.
- Proposed new measurement of dijet momentum imbalance for jets of various radii.
  - Measurement is sensitive to:
    - Jet quenching -> study parton energy loss
    - Medium response -> study the QGP.

Backup

The anti-k_T jet clustering algorithm





ATLAS-PHOTO-2018-001

- Consider a list of "objects" (particles, tracks, calorimeter towers of $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, etc.)
- Calculate distances for all the objects in an event:

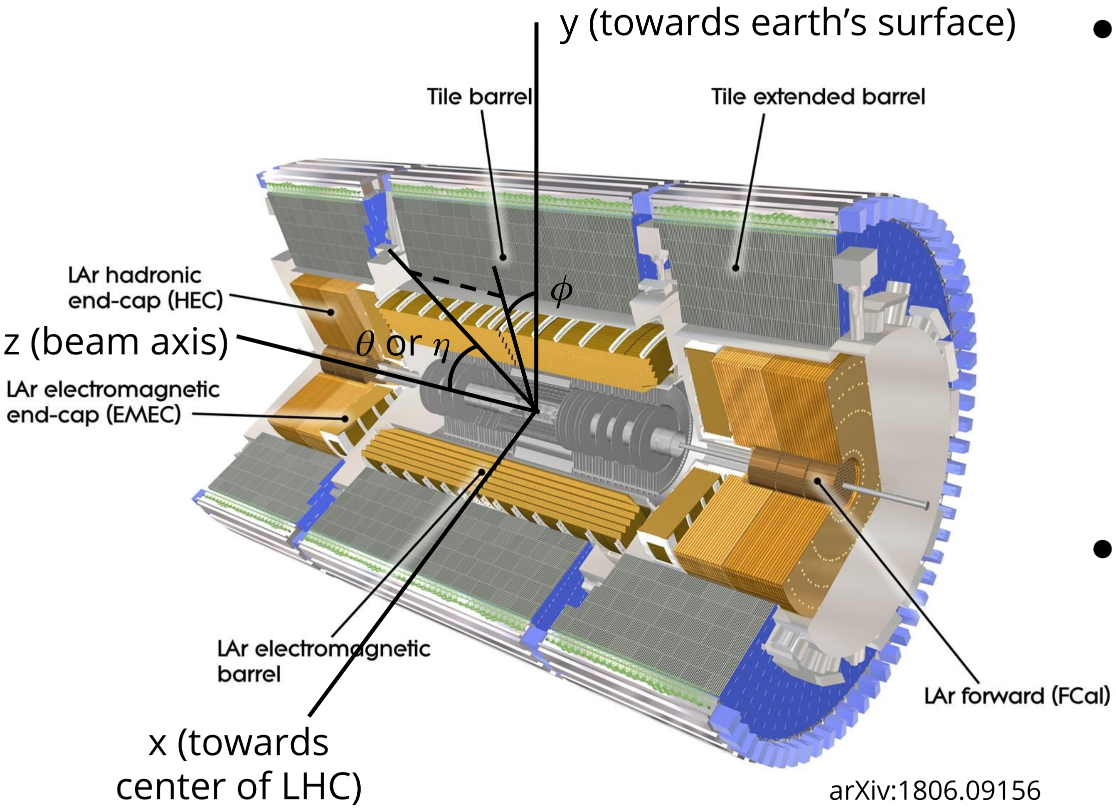
$$d_{ij} = \min(p_{T,i}^{-2}, p_{T,j}^{-2}) \frac{\Delta_{ij}^2}{R^2} \qquad d_{iB} = p_{T,i}^{-2}$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- Iterative process: cluster objects based on minimum distance:
  If $d_{ij} < d_{iB}$, the pair of objects i,j is combined.
  If $d_{iB} < d_{ij}$, the objects are considered a jet and taken out of the list.
- Heavy ion jets are clustered from towers within a radius parameter R.

arXiv:0802.1189

Jet Clustering Algorithms



arXiv:1806.09156

- Consider a list of "objects" (particles, calorimeter towers, jets, etc.)
- Calculate distances for all the objects in an event:

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p}) \frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p}$$

$$\Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2$$

- Iterative process: cluster objects based on minimum distance:
If $d_{ij} < d_{iB}$, the pair of objects i,j is combined.
If $d_{iB} < d_{ij}$, the objects are considered a jet and taken out of the list.

Jet Clustering Algorithms

$$d_{ij} = \min(k_{ti}^{2p}, k_{tj}^{2p})\frac{\Delta_{ij}^2}{R^2}$$

$$d_{iB} = k_{ti}^{2p}$$

- Cambridge/Aachen: p=0

  $d_{ij} \sim \Delta_{ij}^2 / R^2$ and $d_{iB} \sim 1$ — clusters closer objects first

- k_T: p=1

  $d_{ij} \sim k^2 \Delta_{ij}^2 / R^2$ and $d_{iB} \sim k'^2$ — clusters softer and closer objects first

- anti-k_T: p=-1

  $d_{ij} \sim \Delta_{ij}^2 / k^2 R^2$ and $d_{iB} \sim 1/k'^2$ — clusters harder and closer objects first

- SISCone: looks for “stable” cones and then resolves boundaries between overlaping cones.

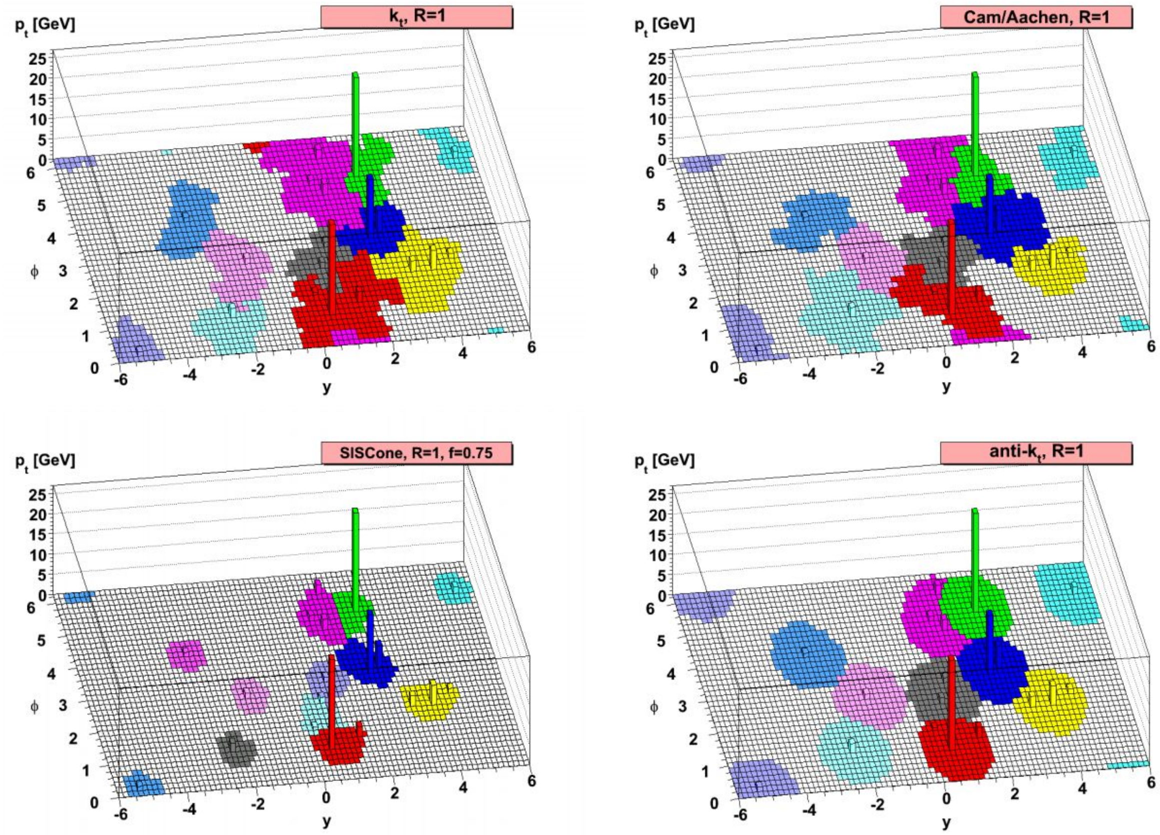
Properties of jet clustering algorithms

- Infrared safe:

  Jets are unchanged by the addition of soft particles.

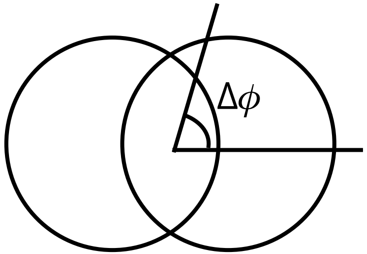
- Collinear safe:

  Splittings that are collinear are reconstructed as a single jet.

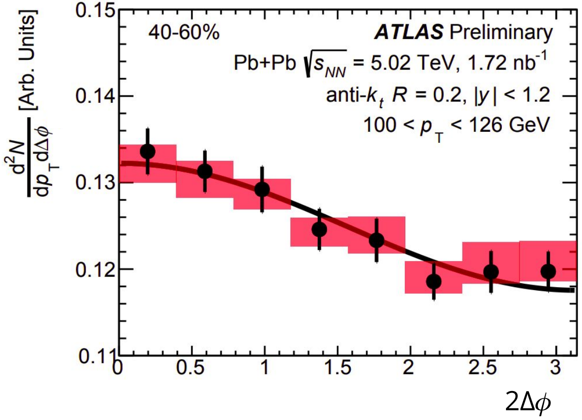


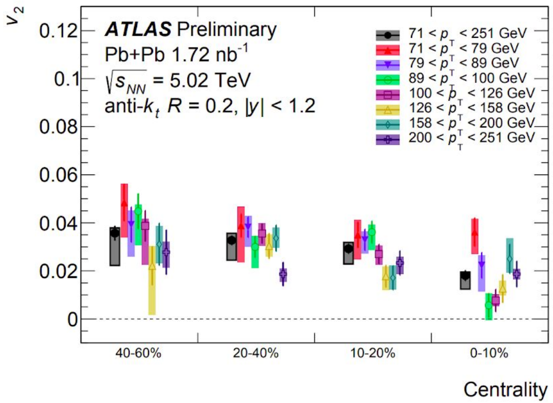
Jet azimuthal anisotropies

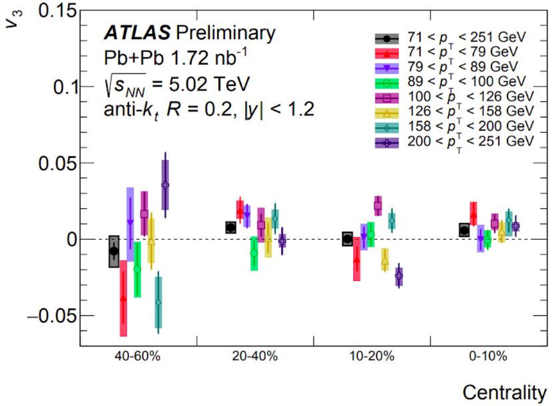
- Initial collision geometry causes jet modulation described by Fourier series: $\frac{dN_{jet}}{d\Delta\phi} \propto 1 + 2v_n cos(n\Delta\phi)$
- Jet energy loss is path length dependent.
- v2 describes the elliptical geometry and v3, v4 describe fluctuations.

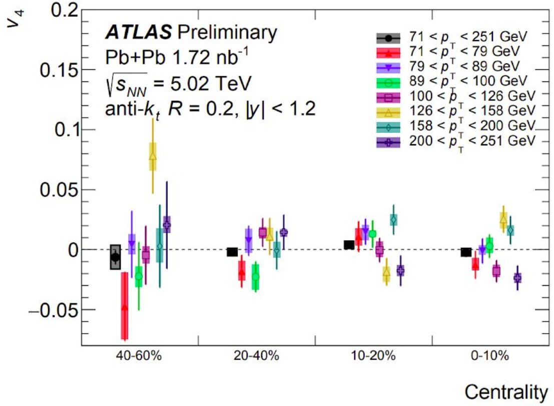


ATLAS-CONF-2020-019









In-cone vs. out-of-cone radiation

- Where does the energy go after leaving the jet?
- CMS looked at in-cone vs. out-of-cone particles as a function of dijet asymmetry.

Missing momentum

$$\not{p}_T^{\parallel} = \sum_i -p_T^i \cos\left(\phi_i - \phi_{\text{leading jet}}\right)$$

Particle momentum

Projection to jet axis in ϕ

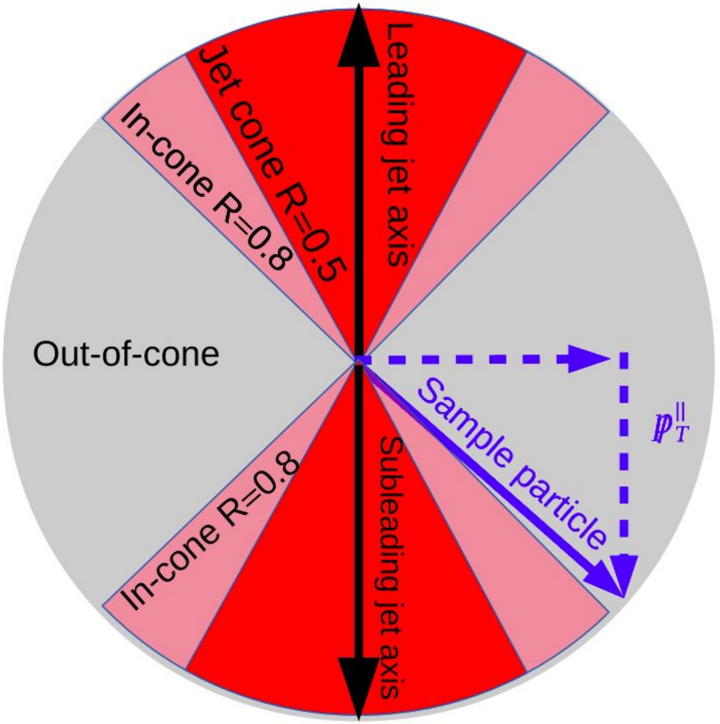
Dijet asymmetry

$$A_J = \frac{p_{\mathrm{T},1} - p_{\mathrm{T},2}}{p_{\mathrm{T},1} + p_{\mathrm{T},2}}$$

Leading jet

Subleading jet

arXiv:1102.1957



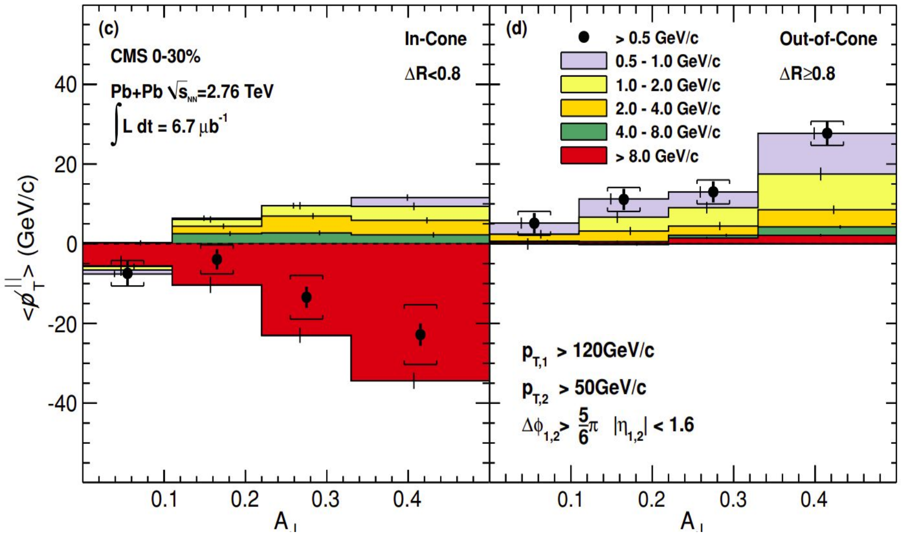
arXiv:1705.01974

In-cone vs. out-of-cone radiation

- High (low) momenta particles are towards (sub)leading jet side.
- Total in-cone momentum correlates with total out-of-cone momentum.
- Total in-cone momentum driven by high momenta particles while total out-of-cone momentum is driven by low momenta particles.

Missing momentum vs dijet asymmetry

In-cone Out-of-cone



- Only R=0.5 dijets were considered.
- R=0.8 is an arbitrary cut for defining in-cone and out-of-cone.
- There is not a clear distinction between the jet and the medium, so the chosen Rs are arbitrary.

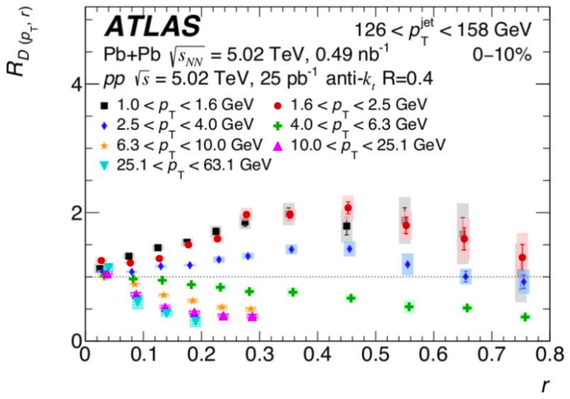
arXiv:1102.1957

CMS and ATLAS radial measurements

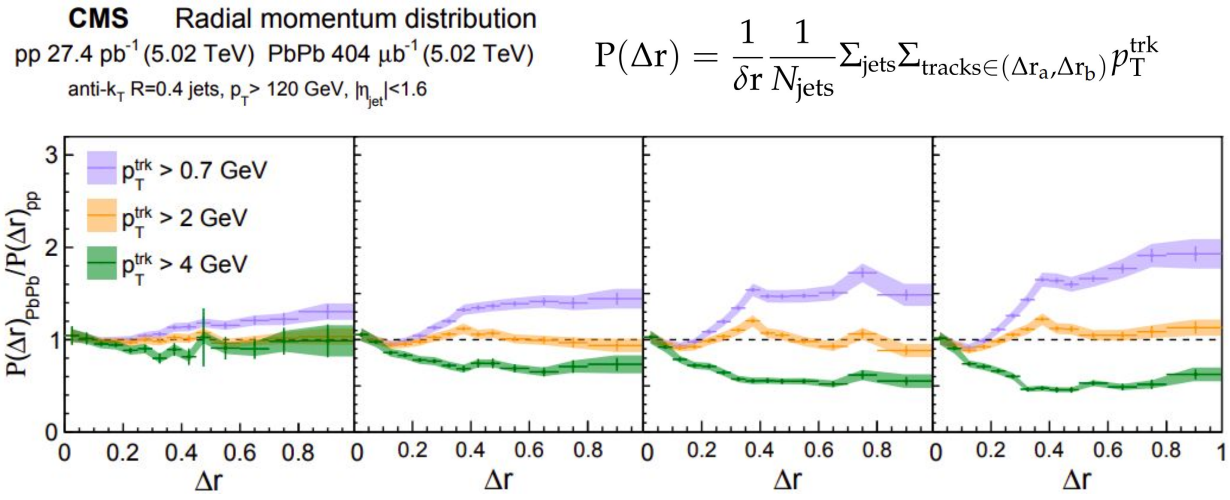
$$D(p_T) = \frac{1}{N_{\text{jet}}}\frac{dn_{\text{ch}}}{dp_T}$$

$$R_{D(p_T)} \equiv \frac{D(p_T)_{\text{PbPb}}}{D(p_T)_{pp}}$$

arXiv:1805.05424



$$\mathrm{P}(\Delta \mathrm{r}) = \frac{1}{\delta \mathrm{r}}\frac{1}{N_{\text{jets}}}\Sigma_{\text{jets}}\Sigma_{\text{tracks}\in(\Delta \mathrm{r_a},\Delta \mathrm{r_b})}\, p_{\mathrm{T}}^{\text{trk}}$$



arXiv:1803.00042

Viscosity from flow

nature/s41567-019-0611-8

- Theory models get implemented in simulations and are compared to data.
- Models make "guesses" about the initial properties of the QGP and are tuned to data.
- The QGP system evolves from some initial state to a final state following some equation of state that include viscous terms:

$$T^{\mu\nu} = eu^{\mu}u^{\nu} - (P+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$$

$$\partial_{\mu}T^{\mu\nu} = 0$$

$T_{\mu\nu}$ = energy-momentum tensor

u_{μ}, u_{ν}= Local fluid velocity

P = fluid pressure in its rest frame

Π, $\pi_{\mu\nu}$ = viscosities

Equations of motion

- Bayesian estimation of the parameters that describe the QGP:

$$P(\mathbf{x}|\mathbf{y}) \propto P(\mathbf{y}|\mathbf{x})\,P(\mathbf{x})$$

Probability of getting a set of final model parameters

Probability that a model with initial parameters **x** describes data **y**

Probability of having some initial parameters **x** of the QGP

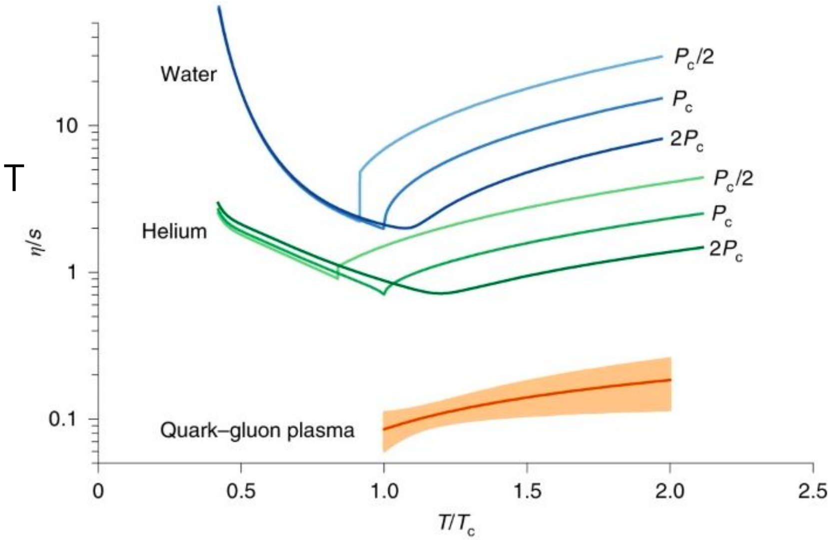
Viscosity from flow

nature/s41567-019-0611-8

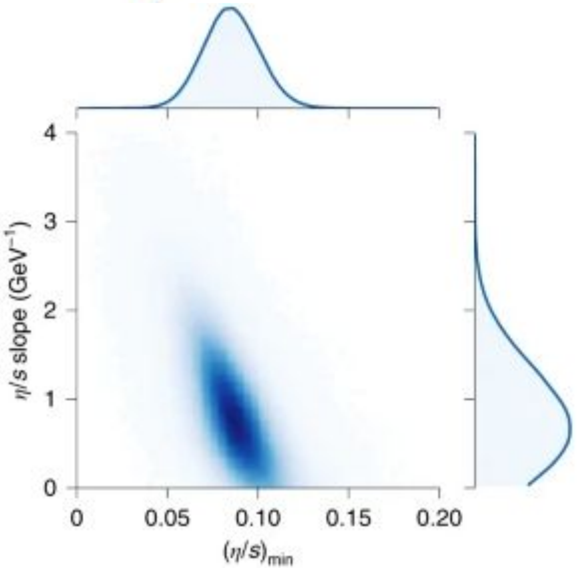
- 14 model parameters **x** are used to estimate specific viscosity η/s as a function of temperature T (T_c is the transition temperature for the formation of the QGP):

$$(\eta/s)(T) = (\eta/s)_{\min} + (\eta/s)_{\text{slope}}(T - T_c)\left(\frac{T}{T_c}\right)^{(\eta/s)_{\text{crv}}}$$

η/s vs. T



Probability distribution of viscosity parameters



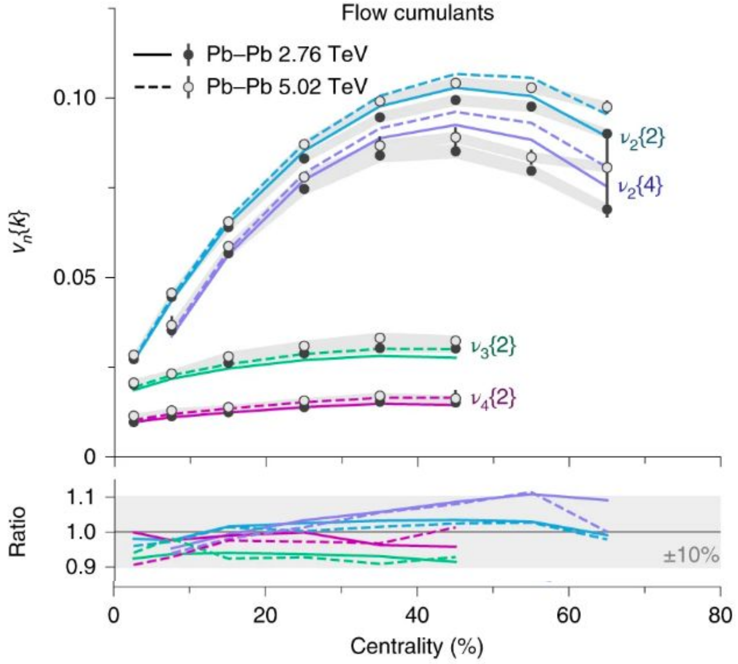
Viscosity from flow

nature/s41567-019-0611-8

- Other model parameters:
  - Initial energy density *e* of the QGP.
  - T_A and T_B are the initial transverse densities of the colliding nuclei.
  - Dimensionless parameter *p*.
  - Effective size of nucleons.

$$e \propto \left(\frac{\tilde{T}_A^p + \tilde{T}_B^p}{2}\right)^{1/p}$$

Flow coefficients v_n as a function of centrality.



Glauber model

arXiv:nucl-ex/0701025

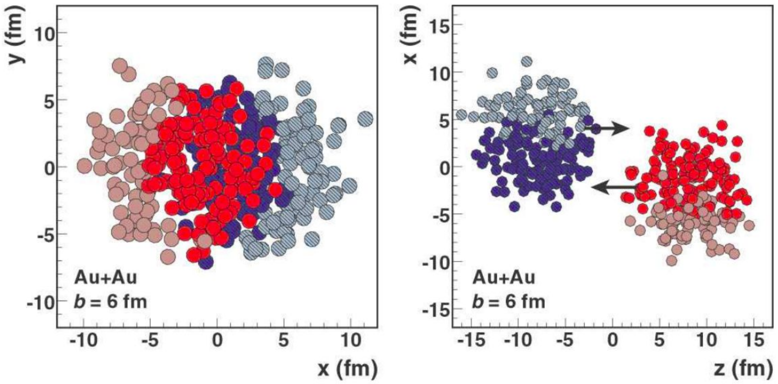
- Monte Carlo simulations varying impact parameter *b*.
- Count number of participants N_{part} (proportional to *b*).
- Assume monotonic relationship between N_{part} and number of emitted particles N_{ch}.
- Define centrality as percentiles of the N_{ch} distribution.

Nucleons are participants if distance *d* between nucleons satisfies:

$$d \leq \sqrt{\sigma_{\text{inel}}^{\text{NN}}/\pi}$$

Inelastic collision cross section measured in experiments

Monte Carlo simulations



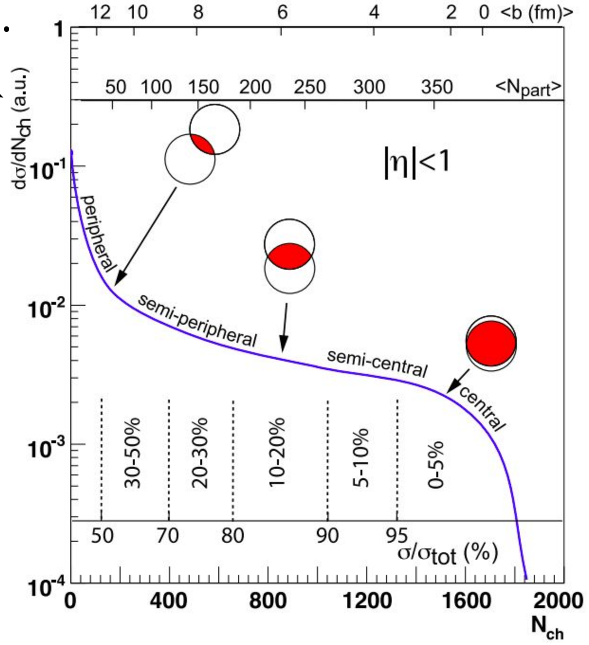
Nucleon density distribution

$$\rho(r) = \rho_0 \cdot \frac{1 + w(r/R)^2}{1 + \exp\left(\frac{r-R}{a}\right)}$$

Nuclear overlap function

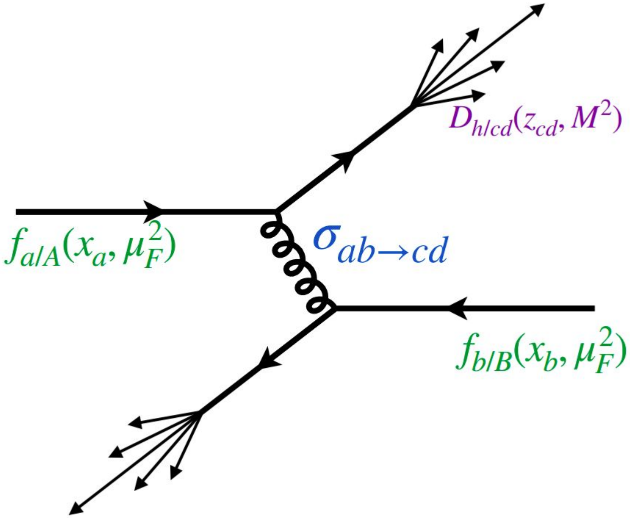
$$\langle T_{\text{AB}} \rangle_{\text{f}} = \langle N_{\text{coll}} \rangle_{\text{f}} / \sigma_{\text{inel}}^{\text{NN}}$$

N_{coll} = Number of nucleon-nucleon collisions



Factorization

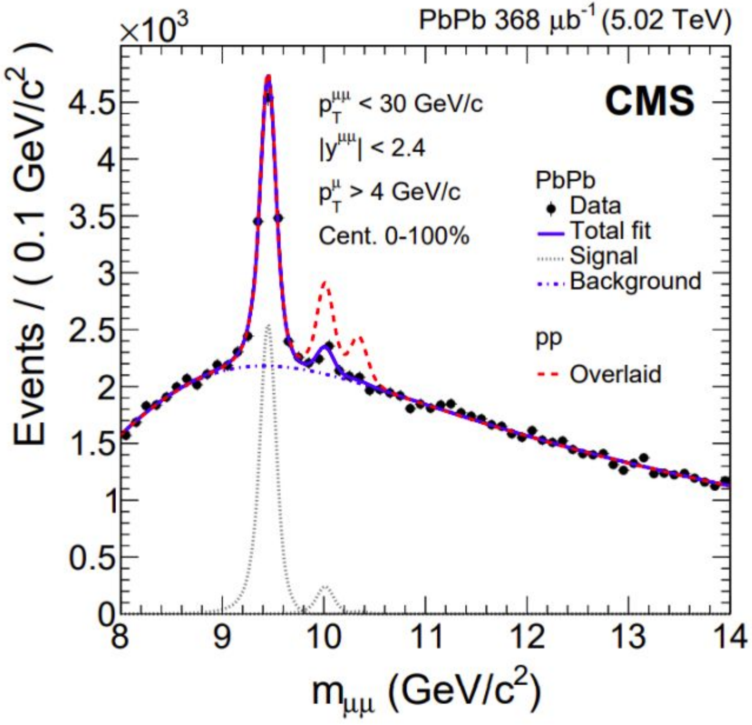
- f are parton distribution functions describing the momentum distribution of partons inside the colliding nucleons.
- σ is the cross section of the scattering.
- D is the fragmentation function describing the outgoing particles.



$$d\sigma_{pp\to hX} \approx \sum_{abjd} \int dx_a \int dx_b \int dz_j\, f_{a/p}(x_a, \mu_f) \otimes f_{b/p}(x_b, \mu_f)$$
$$\otimes\, d\sigma_{ab\to jd}(\mu_f, \mu_F, \mu_R)$$
$$\otimes\, D_{j\to h}(z_j, \mu_f)$$

Evidence of the existence of the QGP

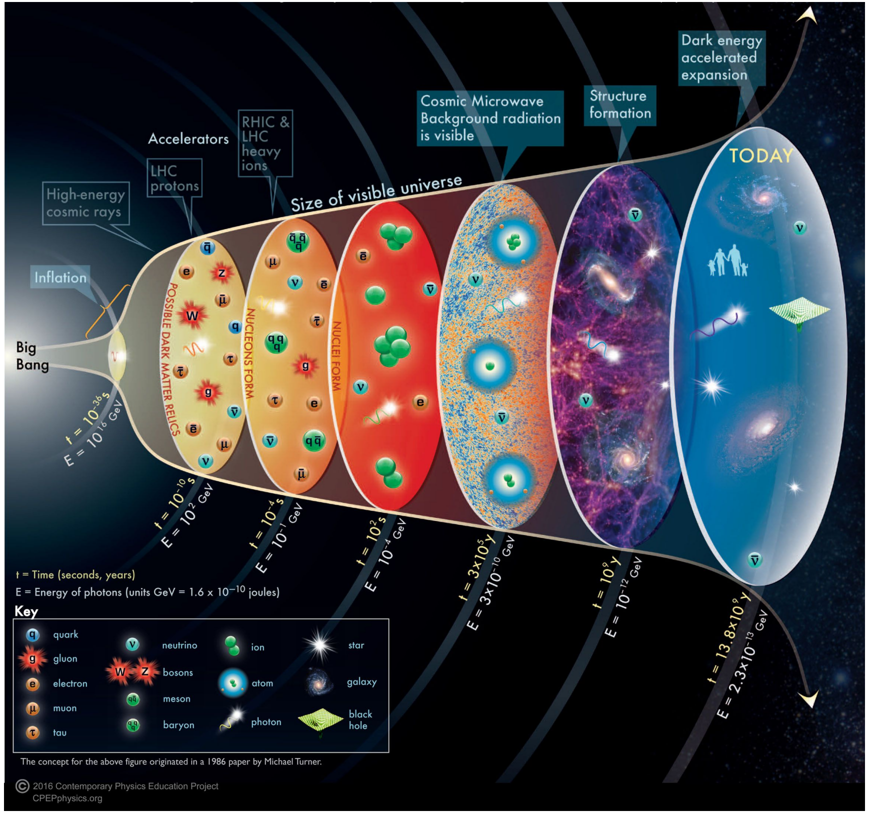
- Flow.
- Jet quenching.
- Charmonium melting.



arXiv:1802.04801

Why is the quark gluon plasma interesting?

- Cosmological reasons:
  - The QGP was present at 10 μs after the Big Bang and it is theorized to be present at the nucleus of neutron stars.
  - Heavy ion collisions provide a way of creating a microscopic Big Bang and studying cosmology without the use of telescopes.



arXiv:1802.04801 cpepphysics.org