Preliminary Exam

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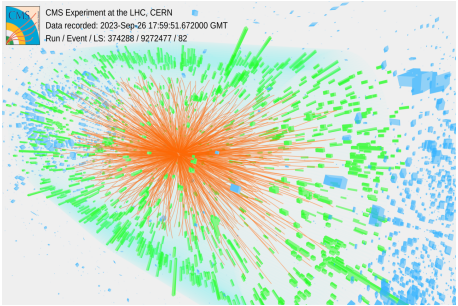
Overview

1. Introduction
2. QCD & Quark-Gluon Plasma
3. Heavy-Ion Collisions
4. Detectors and Accelerators
5. Signatures of Qaurk Gluon Plasma

Introduction : What, Why and How ?

- After the Big Bang, the universe was filled with hot soup of quarks and gluons - the **Quark-Gluon Plasma.**
- What is Quark-Gluon Plasma (QGP) ?
- Why is it important ?
- How do we study QGP ?



Standard Model

- Standard Model
  - **Quantum Electrodynamics** : Electromagentic field mediated by photons
  - **Weak Interaction** : Weak interaction mediated by W and Z bosons
  - **Quantum Chromodynamics** : Strong interactions mediated by gluons.

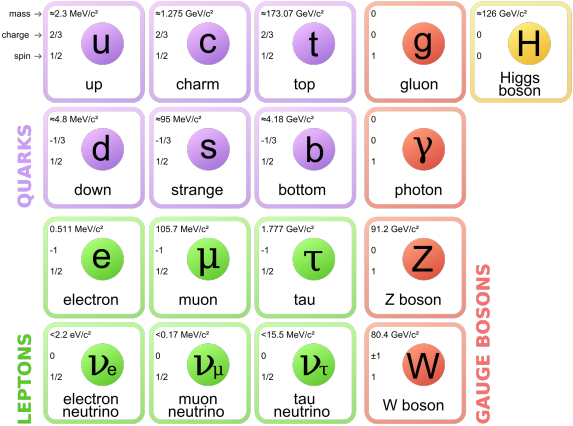


Image Ref

Quantum Chromodynamics (QCD)

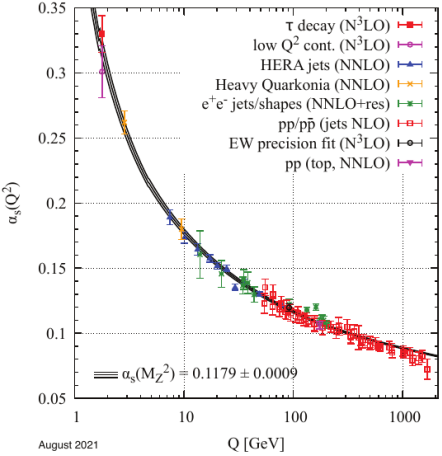
- QCD describes strong interaction (one of the four fundamental forces) between quarks and gluons.
- QCD Lagrangian is

$$\mathcal{L} = i\bar{\psi}\gamma^{\mu}D_{\mu}\psi - \frac{1}{4}G^{a}_{\mu\nu}G^{\mu\nu}_{a}$$

- QCD coupling α_S depends on momentum transfer (Q), also known as running coupling as following

$$\alpha_S(Q^2) \propto \frac{1}{\ln\left[\frac{Q^2}{\Lambda^2_{\mathrm{QCD}}}\right]}$$

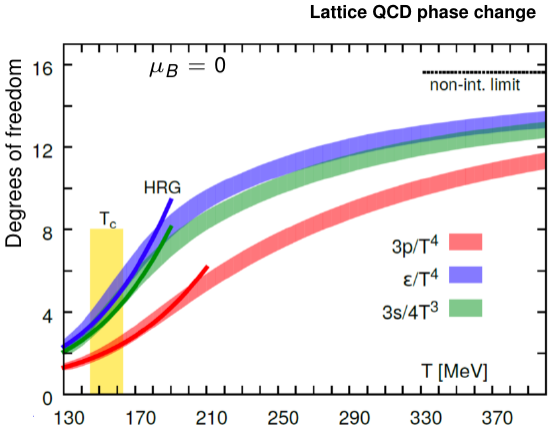
- Running coupling $\rightarrow$ Color confinement and asymptotic freedom



Progress of Theoretical and Experimental Physics, Volume 2022, Issue 8, August 2022, 083C01

What is QGP ?

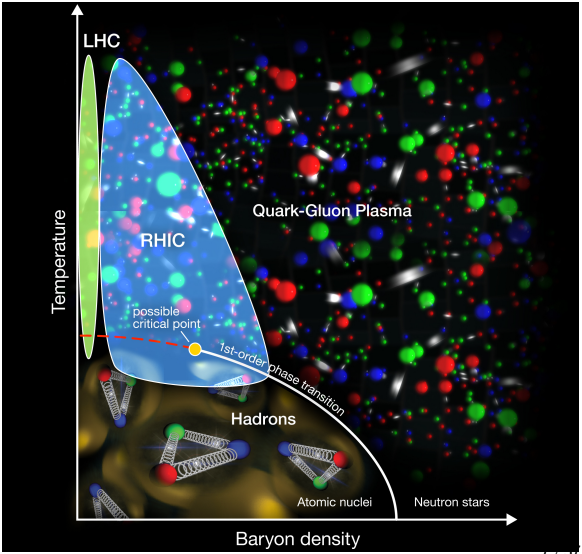
- Bound state of quark → Very low momentum transfer → lattice QCD
- Hadronic matter phase transition at 150-170 MeV
- Quarks and gluons no longer confined in hadron
- New phase of matter → **Quark-Gluon Plasma**



Phys. Rev. D 90, 094503

QCD Phases

- Hadron to QGP phase transition → Smooth crossover
- Increase in baryon chemical potential → First order phase transition
- Increase the temperature → QGP
- High temperature → High momentum transfer → perturbative QCD



Why QGP?

- Insight into early universe $\rightarrow$ Right after the Big Bang
- Study of extreme states of matter like neutron stars
- Test of QCD in perturbative region
- To study exotic phases of matter
- Technological advances

How to produce QGP ?

Heavy-Ion Collision

Recreating the Big Bang

Why Heavy-Ion Collision?

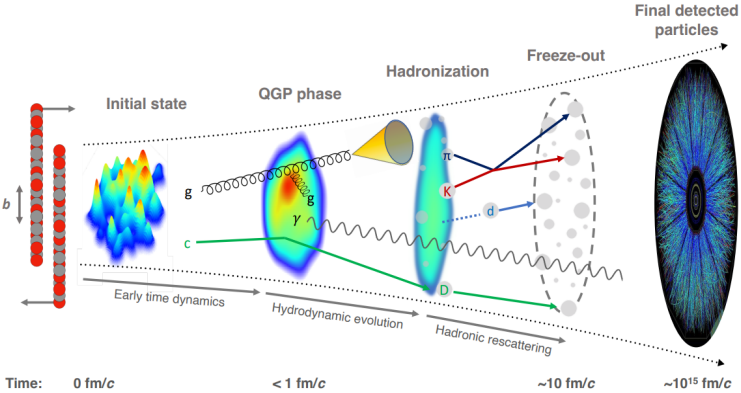
- To form QGP :
  - Temperature > 155 MeV
  - High energy density
  - Large interaction volume
- Early Universe
- Astrophysical Environment
- **High energy hadron collision**

$\longrightarrow$

- Proton-Proton Collisions
  - Small number of interacting nucleons
  - Insufficient energy density
  - Low interaction volume
  - Very short lived
- Heavy-Ion Collisions
  - Large number of interacting nucleons
  - High energy density
  - Measurable different signatures
  - Better candidate for QGP formation

Evolution of Heavy-Ion Collision

- Heavy nuclei collide at relativistic speed $\rightarrow$ QGP
- QGP extremely short lived and goes through different states

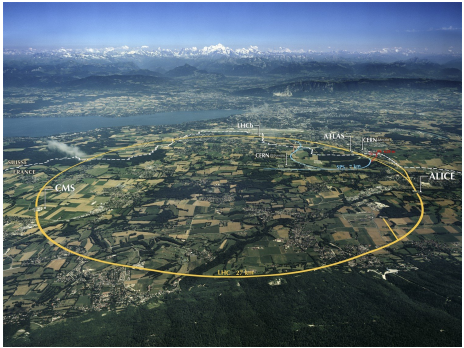


arXiv:2303.17254

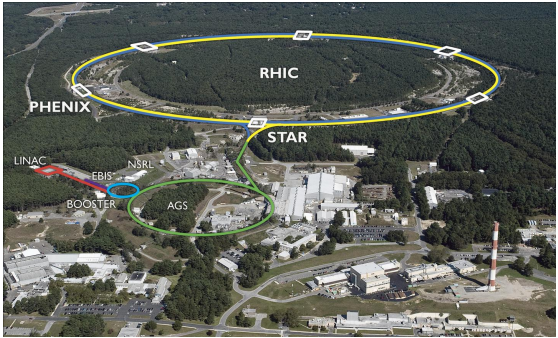
Accelerator Facilities

Epitome of Engineering

Particle Accelerators



(a) Large Hadron Collider

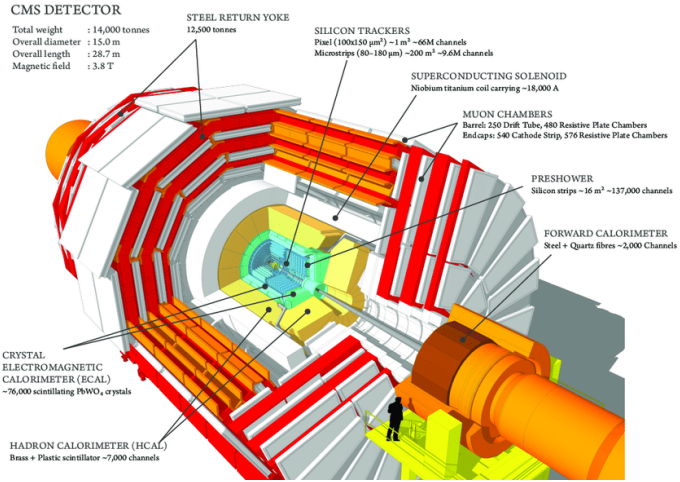


(b) Relativistic HeavyIon Collider

Detectors

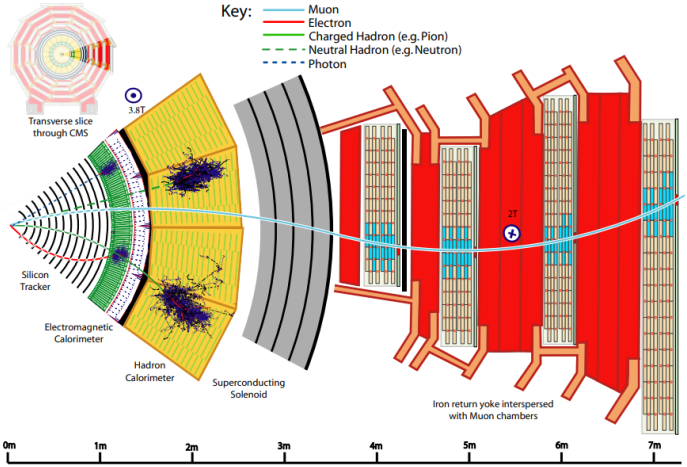
Seeing the Invisible

CMS Detector



arXiv:1706.04965

CMS Detector Cross Section



arXiv:1706.04965

Detector Geometry

- Detector geometry is cylindrical. Use of cylindircal co-ordinates makes life easy.
- In natural units ($\hbar = c = 1$)
  - Transverse Momentum :

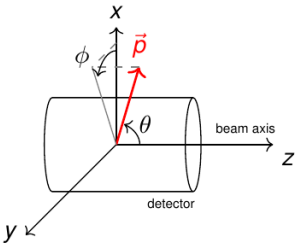
$$p_T = \|\vec{p}\| \sin\theta$$

  - Rapidity :

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

  - Pseudo Rapidity :

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



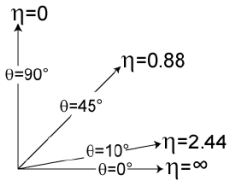


fig. ref.

Signatures of QGP

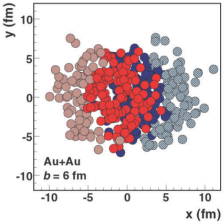
Existence of Exotic Phase

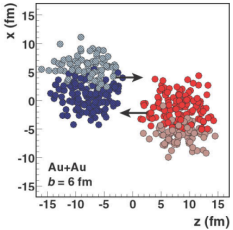
What are we studying?

- Thermalization of QGP $\rightarrow$ Anisotropic Flow
- Deconfinement $\rightarrow$ Strangeness Enhancement
- Color Charge Screening $\rightarrow$ Quarkonia Suppression
- Energy Loss $\rightarrow$ Jets and Jet Suppression

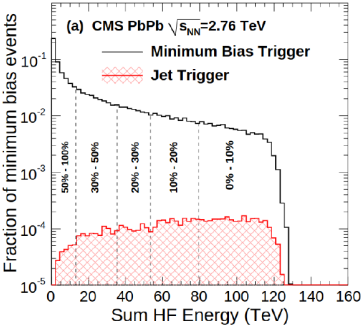
Centrality

- Number of participating nucleons N_{part} $\rightarrow$ Overlap of two nuclei & impact parameter (b)
- Binary collisions N_{coll} $\rightarrow$ Energy deposited in forward calorimeter
- Glauber Model $\rightarrow$ b, N_{part}, N_{coll}
- Centrality class $\rightarrow$ Total energy deposited in forward calorimeter





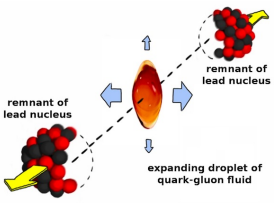
arXiv:nucl-ex/0701025

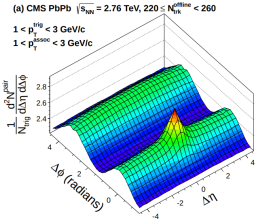


arXiv:1408.2549

Anisotropic Flow

- QGP thermalize → Expansion of medium
- Initial spatial anisotropies → Final state momentum anisotropies
- Pressure gradient → Expansion of medium
- Expansion described by hydrodynamics
- Is QGP ideal fluid ?





Physics Letters B 724.4–5 (July 2013)

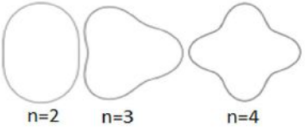
Azimuthal Anisotropic Flow Coefficients

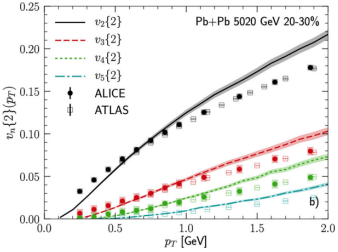
- Flow coefficients calculated by hydrodynamics

$$\frac{dN}{d\phi} = A\left(1 + 2\sum_{n=1}^{\infty} v_n \cos[n(\phi - \bar{\Psi}_n)]\right)$$

  - $v_1 \rightarrow$ Directed flow
  - $v_2 \rightarrow$ Elliptic flow
  - $v_3 \rightarrow$ Triangular Flow

- Measure specific viscosity $\frac{\eta}{s} \approx 0.16 \rightarrow$ Almost ideal fluid

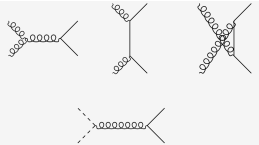


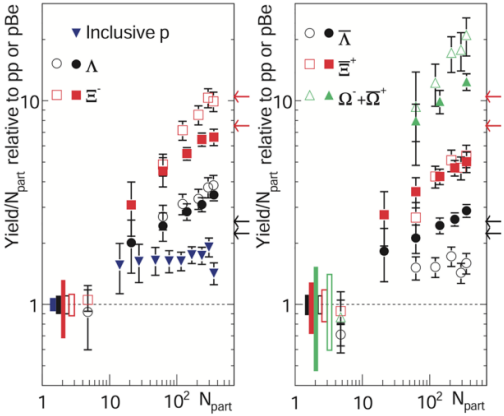


Eur. Phys. J. C 84, 247 (2024)

Strangeness Enhancement

- Formation of QGP → Asymptotically free quarks and gluons
- Deconfined quarks and gluons → Formation of strange quarks
- Abundance of strange quark → Enhanced production of strange hadrons
- Sign of deconfinement





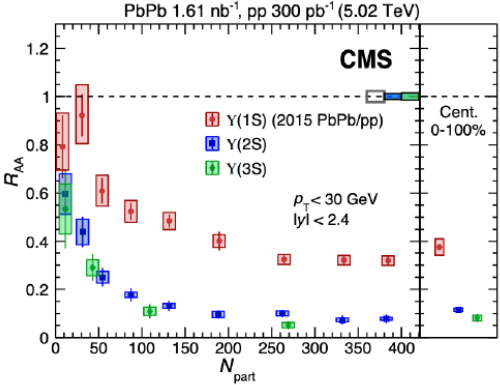
Eur. Phys. J. C 84, 247 (2024)

Quarkonia Suppression

- Quarkonia flavorless meson $\rightarrow$ Charmonium ($c\bar{c}$) or Bottomonium ($b\bar{b}$)
- Color charge screening losens the quarkonia binding strength.
- Quarkonia melts above critical temperature $\rightarrow$ Dissociation temperature (T_{dis})
- Upper bound on (T_{dis}) for different states changes $\rightarrow$ Sequential suppression
- Nuclear modification factor

$$R_{\text{AA}} = \frac{dN_{\text{AA}}/dp_T}{\langle N_{\text{coll}} \rangle \, dN_{\text{pp}}/dp_T}$$

- Quarkonia is good thermometer for QGP.



arXiv:2303.17026

Jets

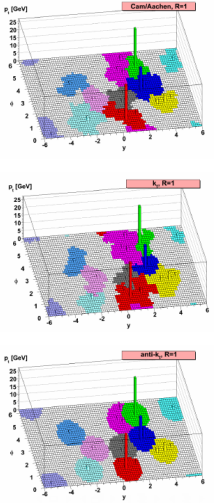
- Jet is collimated spray of hadrons resulting from high-Q^2 parton-parton interaction.
- Jets are often produced back to back.
- Computational process to cluster group of particles
- Different jet algorithms in use

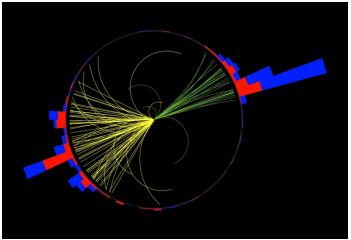
$$d_{ij} = min(p_{T,i}^{2k}, p_{T,j}^{2k}) \frac{\Delta R_{ij}^2}{R^2}$$

$k = 0 \rightarrow$ Cambridge-Aachen algorithm

$k = 1 \rightarrow k_T$ algorithm

$k = -1 \rightarrow$ anti k_T algorithm



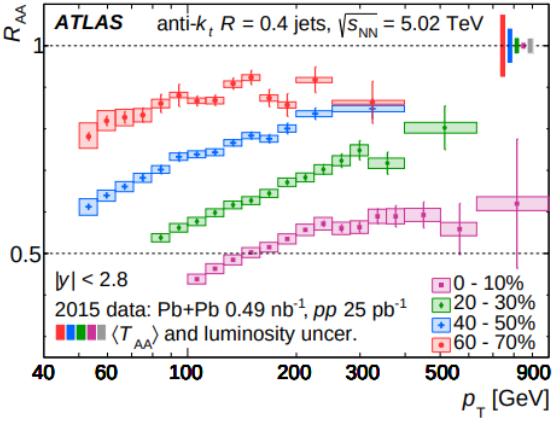


Jet R_{AA}

- Relative jet yields in pp and PbPb to measure medium properties
- Jet R_{AA} : measurement of suppression of jet production

$$R_{AA}^{jet} = \frac{dN_{jet}^{AA}/dp_T}{\langle N_{coll} \rangle \, dN_{jet}^{pp}/dp_T}$$

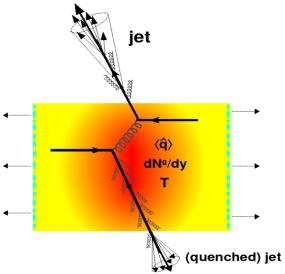
- Ratio with respect to jet production in pp
- Any deviation attributed to QGP

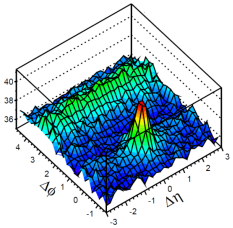


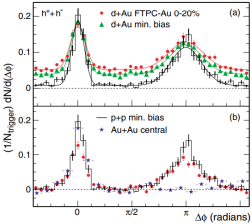
arXiv:1805.05635

Jet Quenching

- Monetum conservation → Back to back jets in azimuthal angle
- Jet travelling through generated medium → Energy loss due to interaction
- Energy imbalance between back to back jets → Jet quenching
- Energy loss is due to different mechanism :
  - Collisional energy loss
  - Radiative energy loss (Bremsstrahlung)







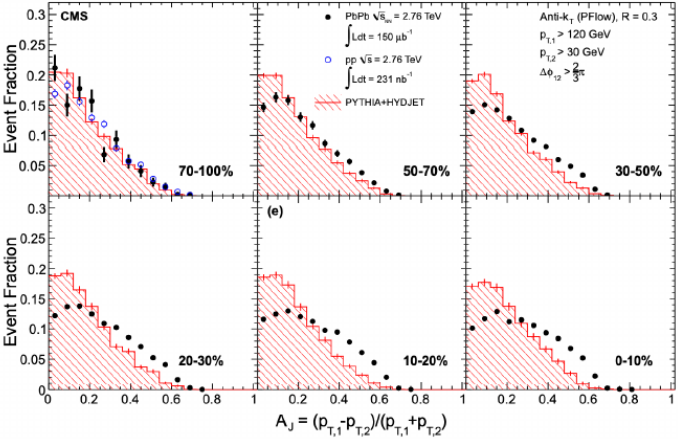
Phys. Rev. Lett. 91, 072304

Jet Asymmetry

- Jet Asymmetry :

$$A_j = \frac{p_{(T,1)} - p_{(T,2)}}{p_{(T,1)} + p_{(T,2)}}$$

- $p_{(T,1)}$: Leading jet transverse momentum > 100 GeV
- $p_{(T,2)}$: Subleading jet transverse momentum > 30 GeV
- Azimuthal sepration $\Delta\phi > 2\pi/3$



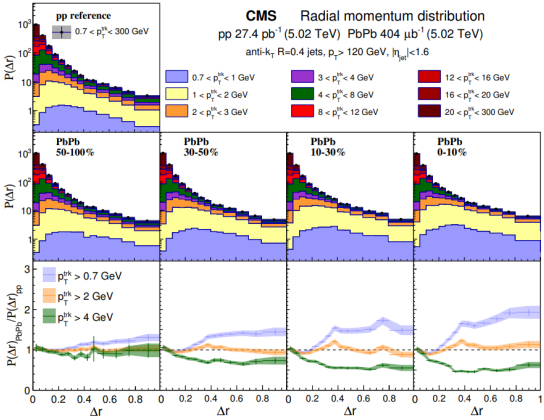
Phys. Rev. C 84 (2 Aug. 2011), p. 024906

Jet Shapes

- Jet Shape : Transverse momentum weighted distribution of particle around the jet axis

$$\rho(\Delta r) = \frac{1}{(\delta r) N_{\text{jets}}} \sum_{\text{jets}} \frac{\sum_{\text{tracks}\in[r_a, r_b)} p_T^{\text{ch}}}{p_T^{\text{jet}}}$$

- QGP formation $\rightarrow$ Soft hadrons at larger angular distance from jet axis $\rightarrow$ Pushing matter out of side of jet cone $\rightarrow$ Broadening of Jets



JHEP 2018.5 (May 2018).

Search for jet quenching using transverse momentum balance in high-multiplicity pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\ \mathrm{TeV}$

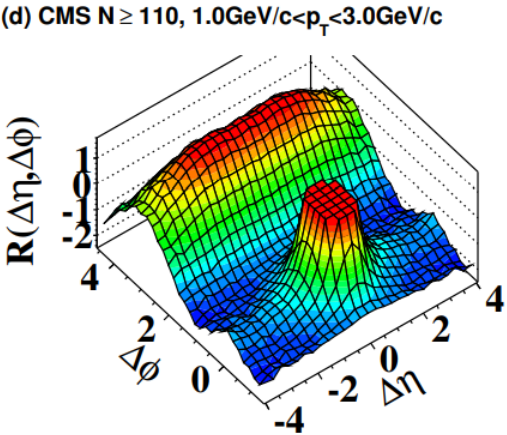
The first measurement of the dijet transverse momentum balance (x_j) in proton-lead (pPb) collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16\ \mathrm{TeV}$ is presented. The analysis uses data collected with the CMS detector in 2016, corresponding to an integrated luminosity of 174.6 nb^{-1}. The x_j distribution and its average are measured as functions of the event charged-particle multiplicity for three different center-of-mass pseudorapidity configurations: forward, backward, and midrapidity, enabling measurements in distinct Bjorken x for both proton- and lead-going directions. High-multiplicity triggers are used to select events with up to 400 charged particles, aimed at probing potential jet-quenching effects. The ratio of x_j in high- versus low-multiplicity events is used to quantify the results. Measurements are consistent with simulations of the hard-scattering process that do not include quark-gluon plasma production. These results provide constraints on jet-quenching signature of 1.26% at 90% confidence-level for the pPb system in high-multiplicity events that exhibit the strongest signals of the collectivity.

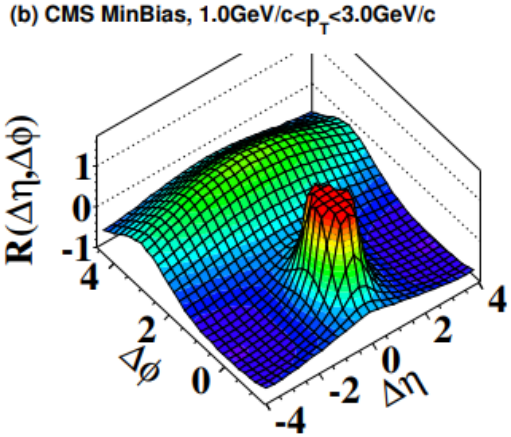
Future Prospectus

Small Systems

- Heavy-ion collision is better for QGP formation compared to pp.
- Small systems $\rightarrow$ Involves one light ion or proton
- Does QGP form in small system ?

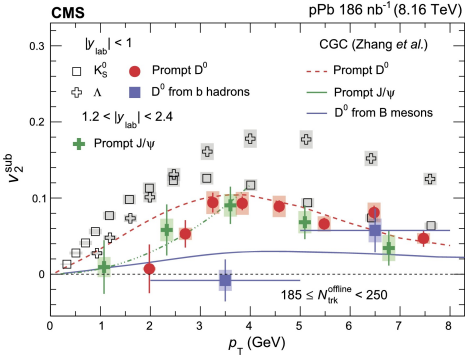
Anisotropic Flow in Small Systems



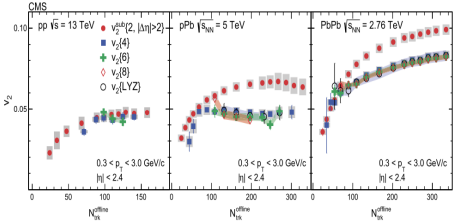


JHEP 1009:091,2010

Anisotropic Flow in Small Systems

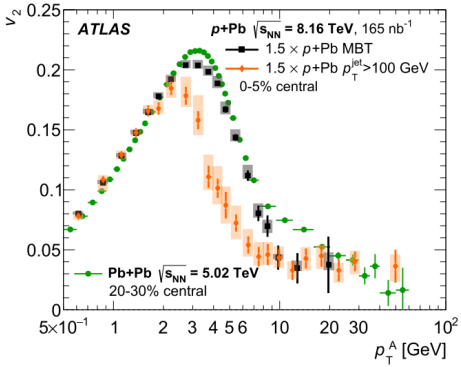


Phys.Lett. B 813 (2021) 136036

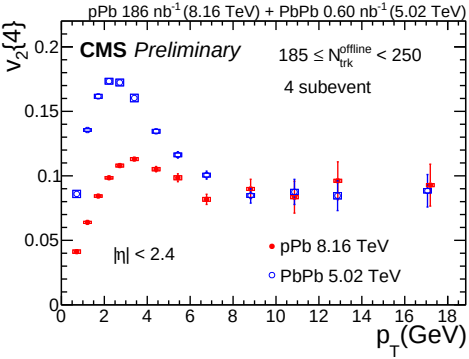


Phys. Lett. B 813 (2021) 136036

High-p_T Anisotropic Flow in pPb ?



Eur. Phys. J. C 80 (2020) 73



CMSPAS-HIN-23-002

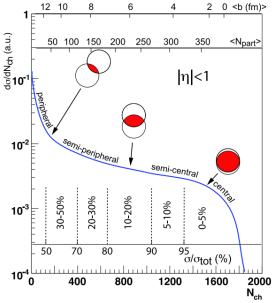
The End

Back Up

Glauber Model Monte Carlo Approach

- Distribute A nucleons of nuclei A and B nucleons of nuclei B as per their nuclear density distribution
- Draw random impact parameter b from $d\sigma/db = 2\pi b$
- Nuclei collides if distance between their center

$$d < \sqrt{\frac{\sigma_{\text{inel}}^{\text{NN}}}{\pi}}$$

- Glauber Model depends on geometry of nuclei
  - $N_{part} \xrightarrow{\text{scales}}$ Volume of interaction region
  - $N_{\text{coll}} \propto N_{\text{part}}^{\frac{4}{3}}$

- For centrality class
  - Measure charge particle multiplicity N_{ch}
  - Bin class by fraction of total integral