Experimental Overview of Heavy Ion Collisions

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on behalf of the LHCb collaboration

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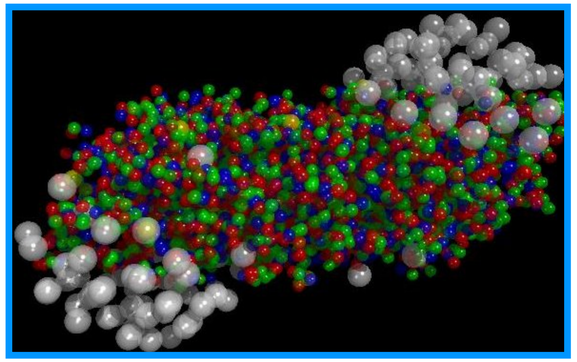
Why study heavy ion collisions?

Study the Quark Gluon Plasma (QGP)

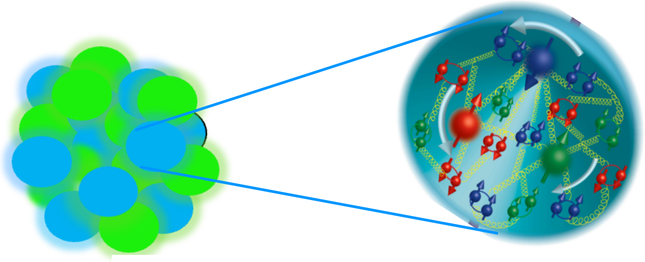
Unique phase of strongly-interacting matter in which quarks and gluons are completely deconfined from nucleons and nuclei

Expected state of early universe and a near perfect fluid



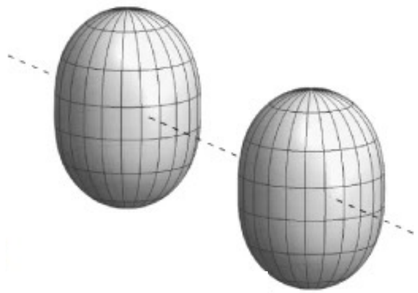
Understand the sub-nucleonic structure of nuclei

How do quark and gluon interactions give rise to nuclei?



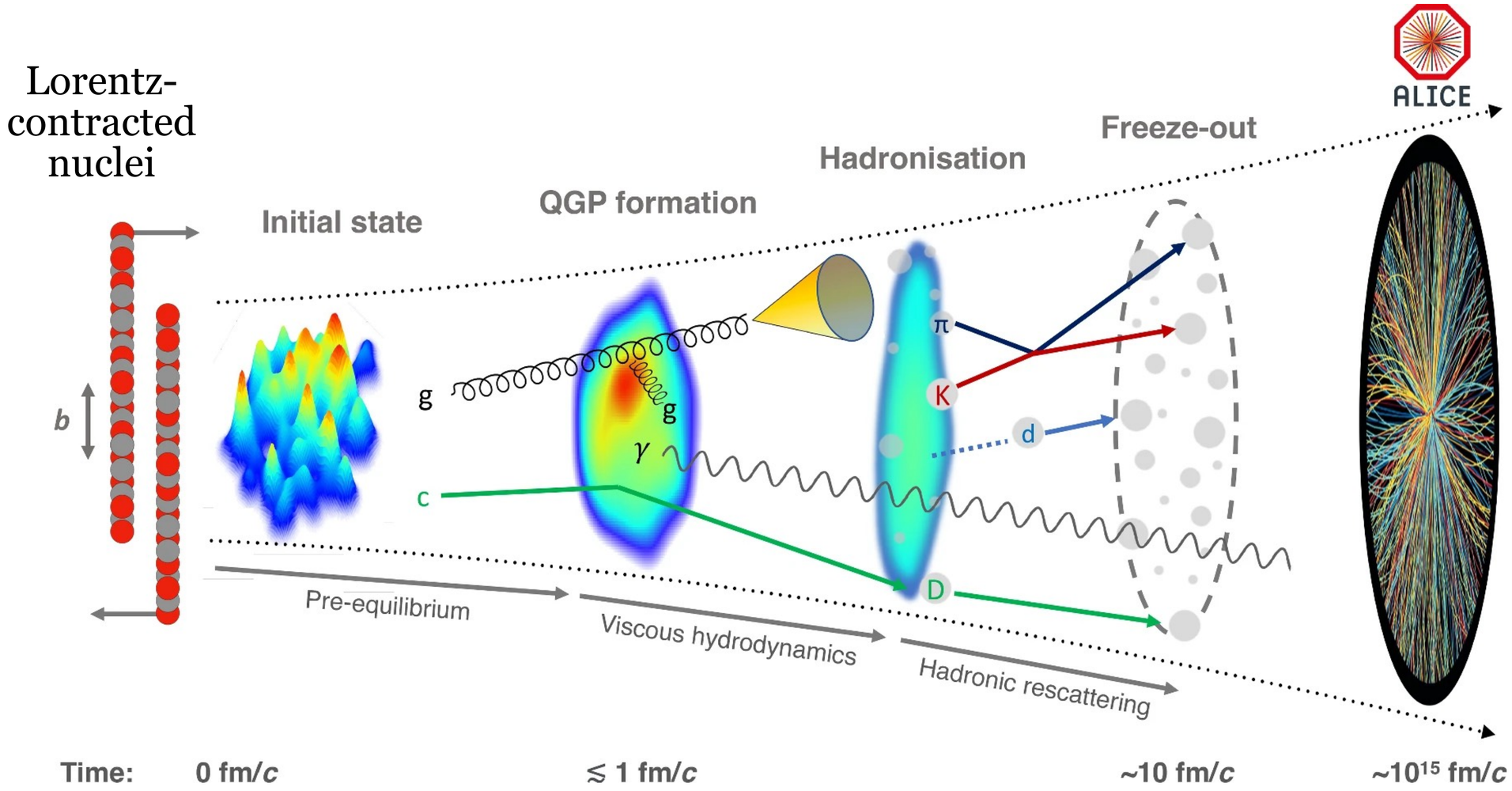
Constrain global nuclear structure properties

A growing subfield in heavy ion physics!



Nature 635, 67-72 (2024)

Quark-gluon plasma formation in a heavy ion collision

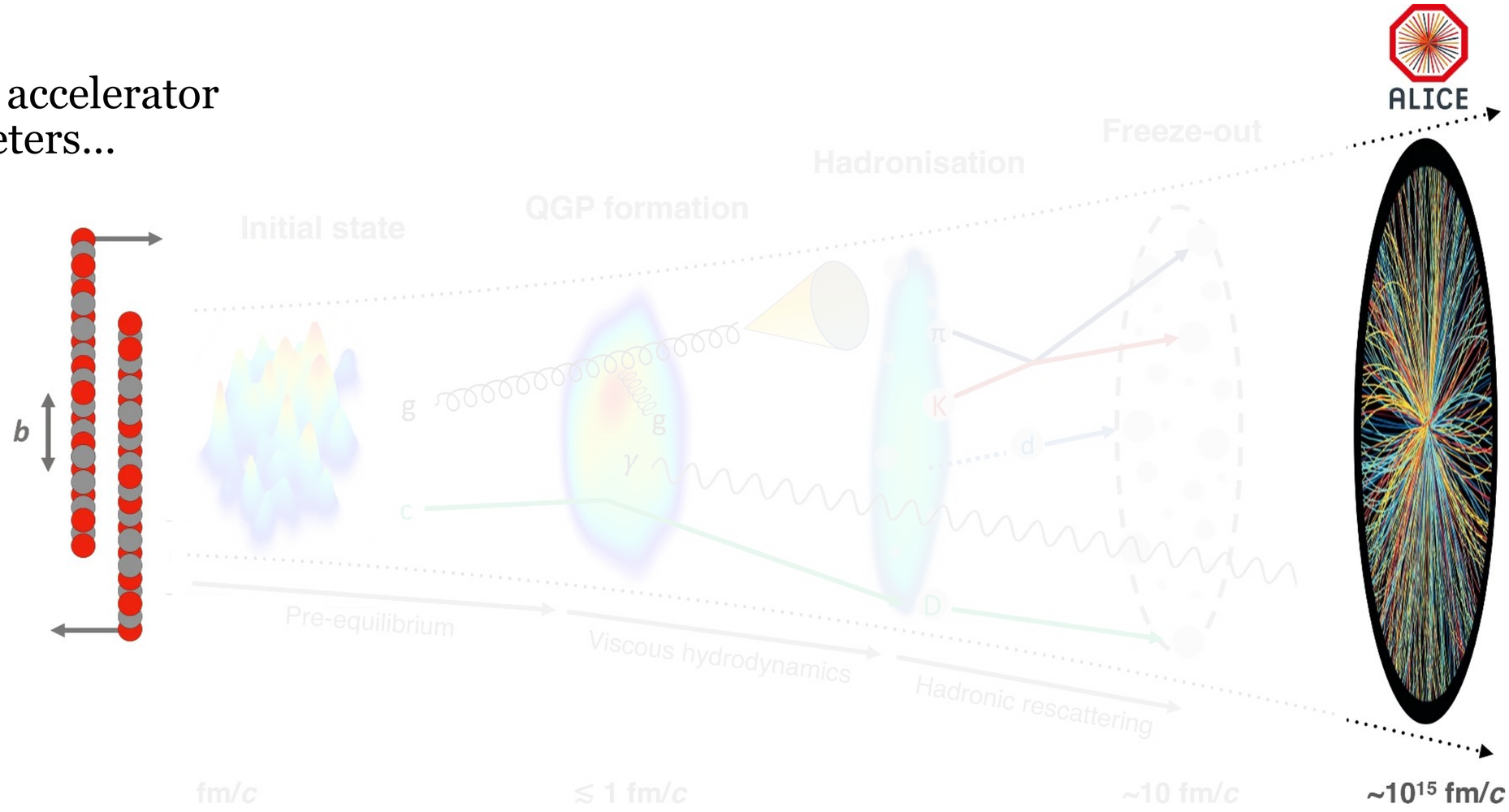


EPJC 84 (2024) 813

Experimental study of quark-gluon plasma

Given initial accelerator parameters…

nuclear species, beam energy, luminosity,..



EPJC 84 (2024) 813

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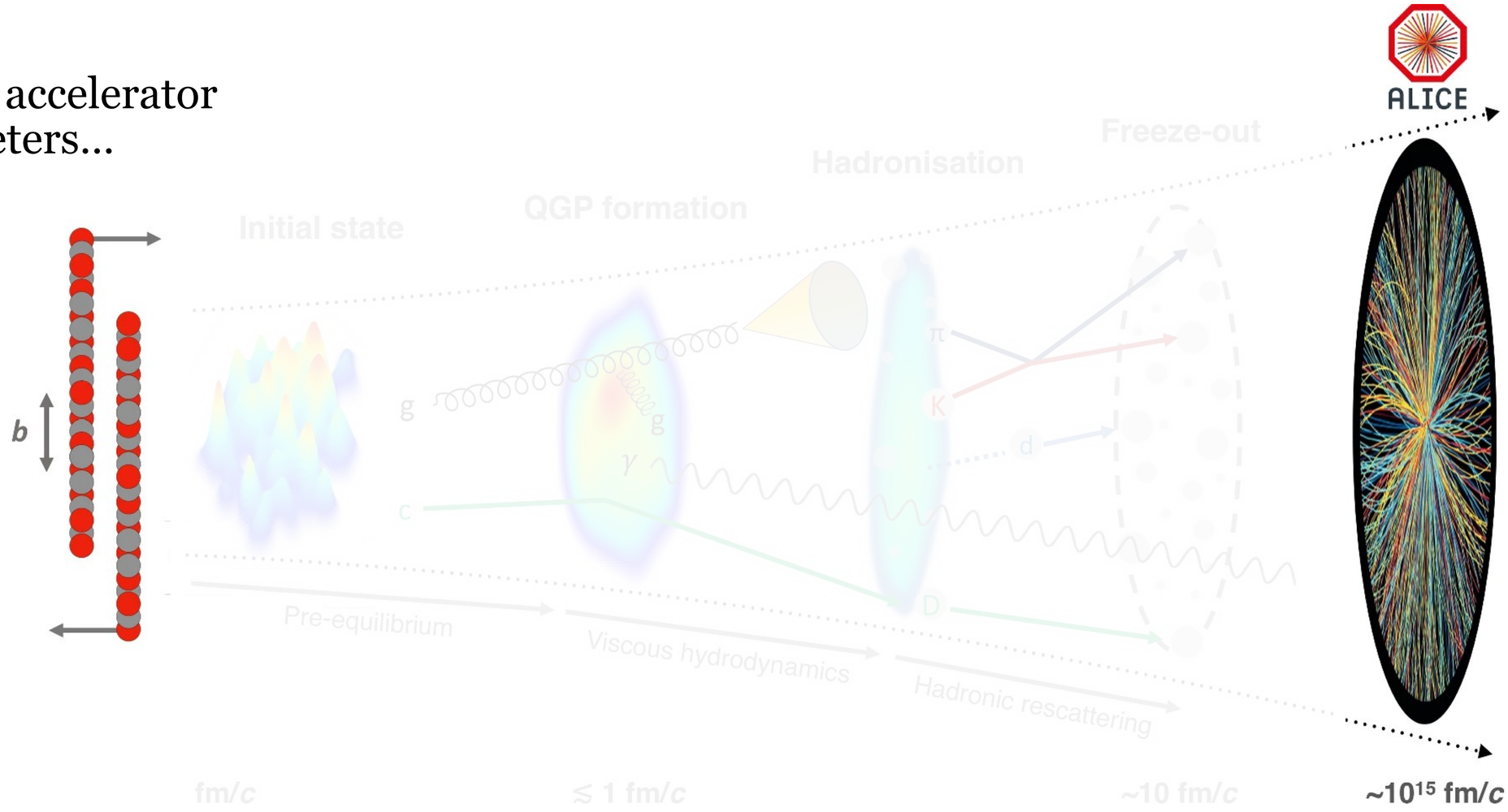


and experimental measurements in the detector:

charged particle trajectories (tracks),

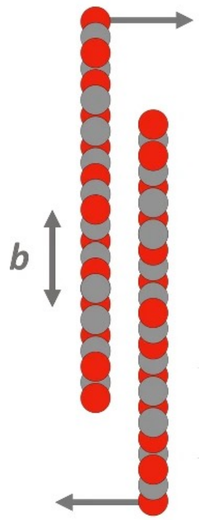
energy deposits of neutral particles in calorimeters,..

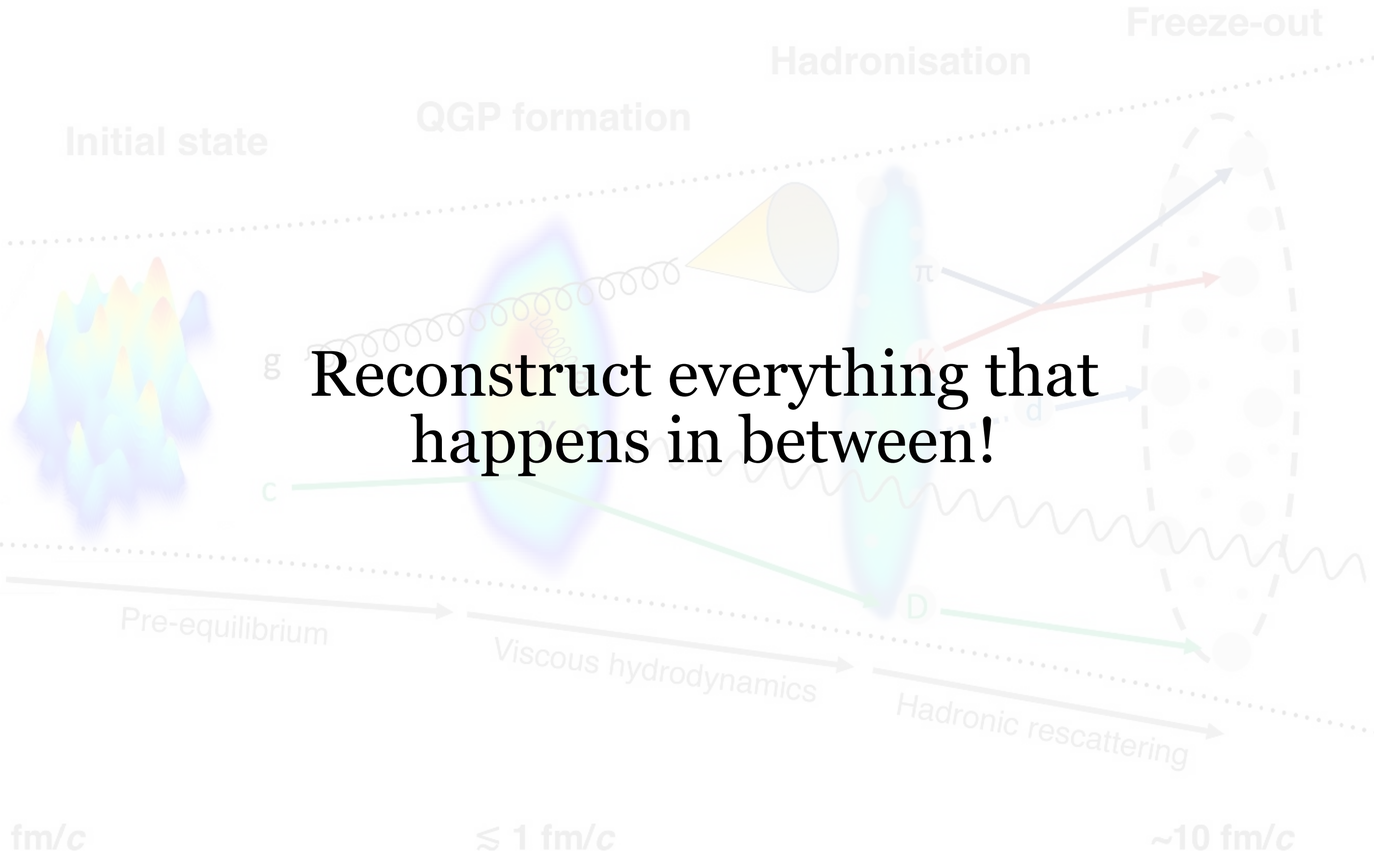
EPJC 84 (2024) 813

Experimental study of quark-gluon plasma

Given initial accelerator parameters…

nuclear species, beam energy, luminosity,..





Reconstruct everything that happens in between!

and experimental measurements in the detector:

charged particle trajectories (tracks),

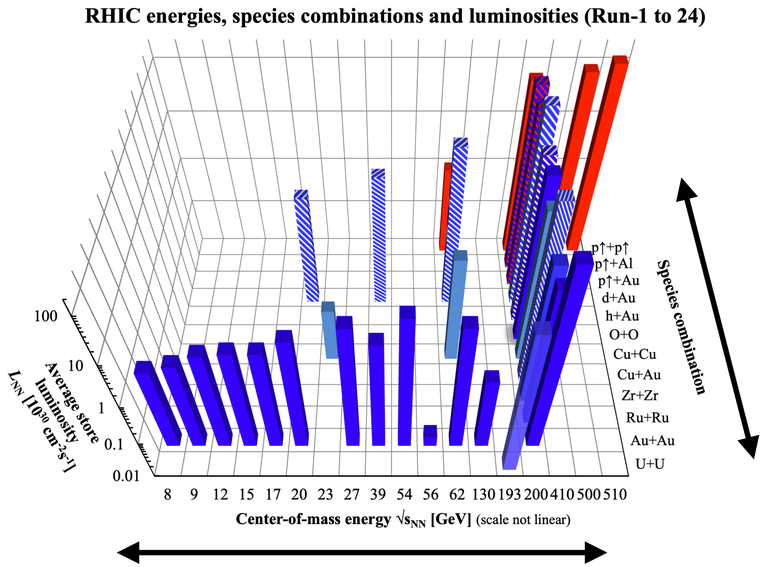
energy deposits of neutral particles in calorimeters,..

EPJC 84 (2024) 813

Experimental facilities

Relativistic Heavy Ion Collider (RHIC)

📍 Brookhaven National Laboratory, USA



Multiple nuclear collision species

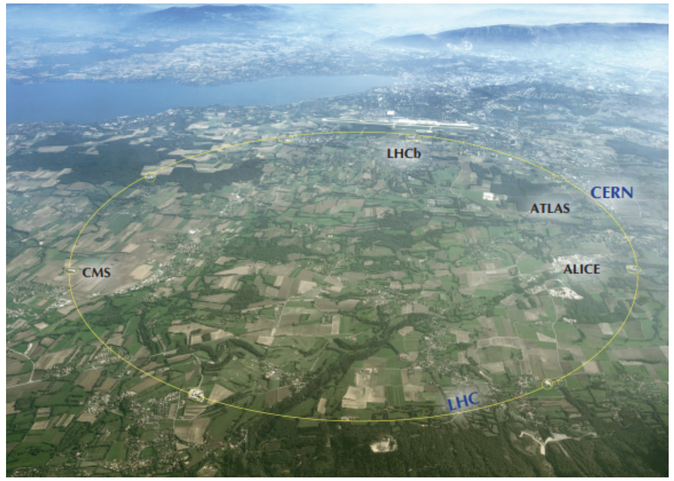
Large range of center of mass energy

$\sqrt{s_{NN}}$ = 8 - 200 GeV

Extremely versatile collider!

Large Hadron Collider (LHC)

📍 CERN, Geneva, Switzerland



Highest energies available for nuclear collisions

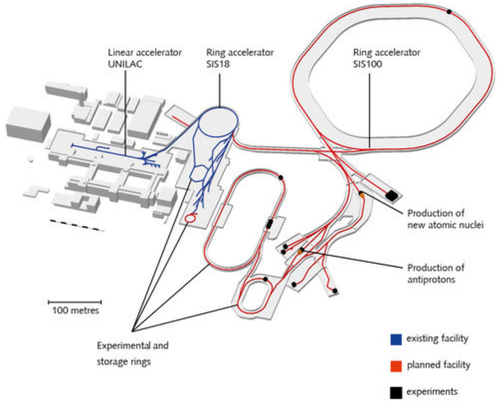
$\sqrt{s_{NN}}$ ~ 5 TeV

- PbPb + special runs such as XeXe
- New in 2025: OO and NeNe!
- Fixed-target experiments at SPS and LHCb

GSI

📍 Darmstadt, Germany

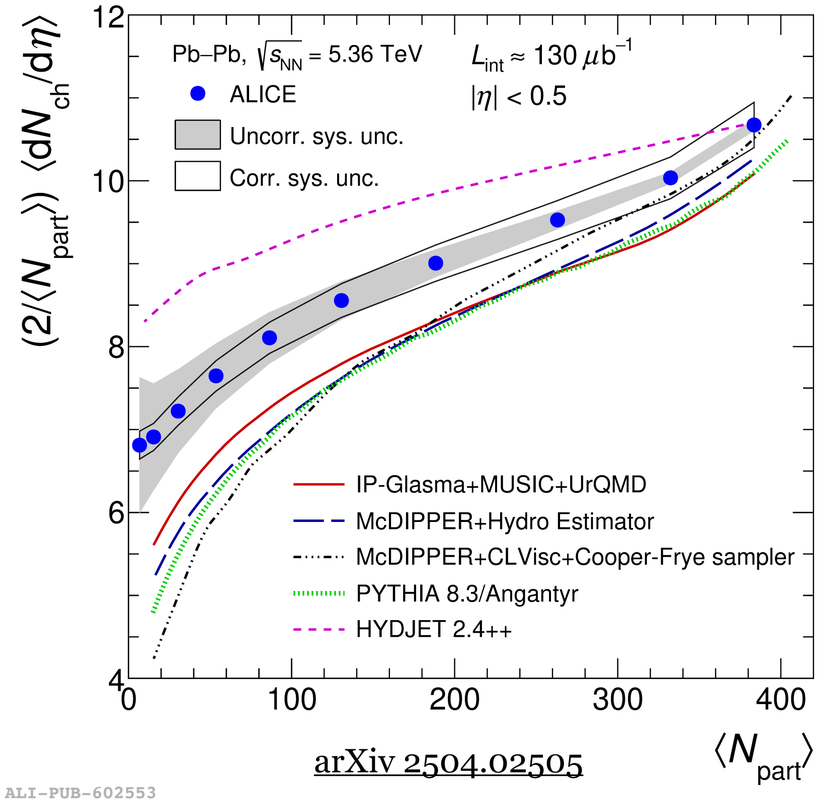
Fixed-target experiments with complementary phase space coverage to collider experiments



Constraining QGP models with charged particle production

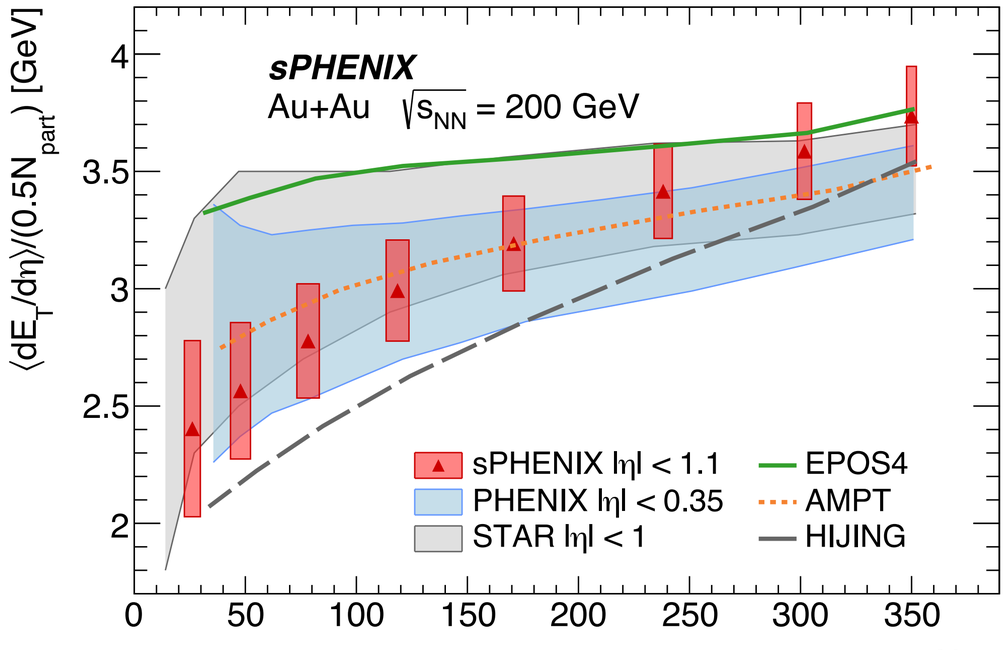
Charged particle measurements constrain models of the initial energy density and system evolution

Charged particle density at the LHC

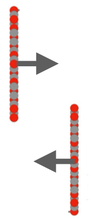


arXiv 2504.02505

Charged particle energy density at RHIC

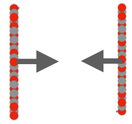


PRC 112 (2025) 024908



Small N_{part}:

less overlap between nuclei, "peripheral" collisions



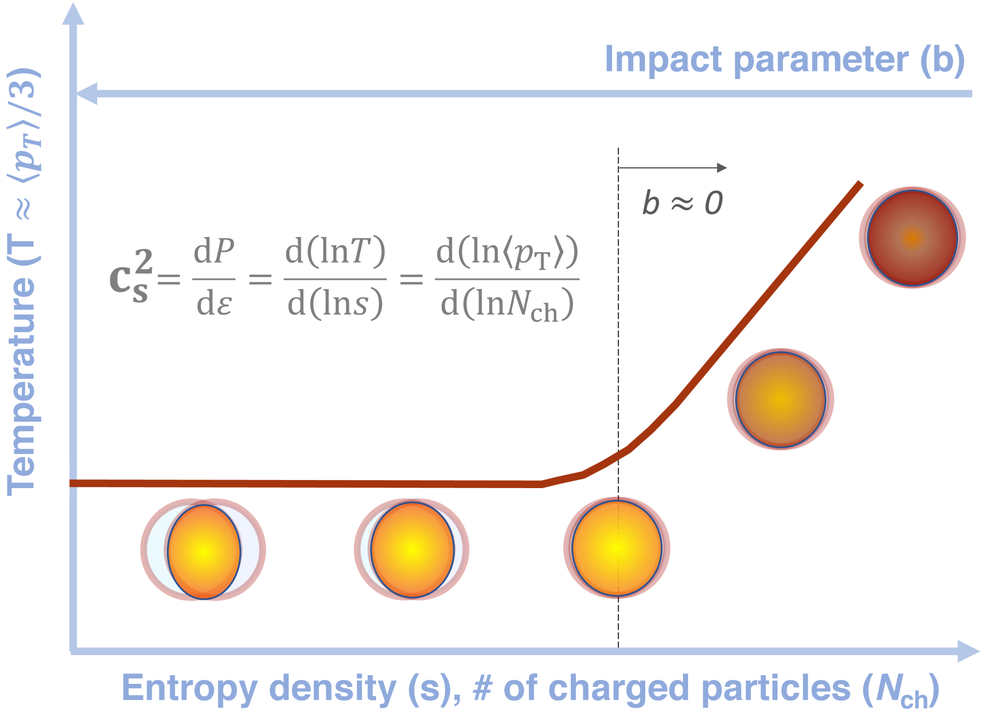
Large N_{part}:

head-on "central" collisions

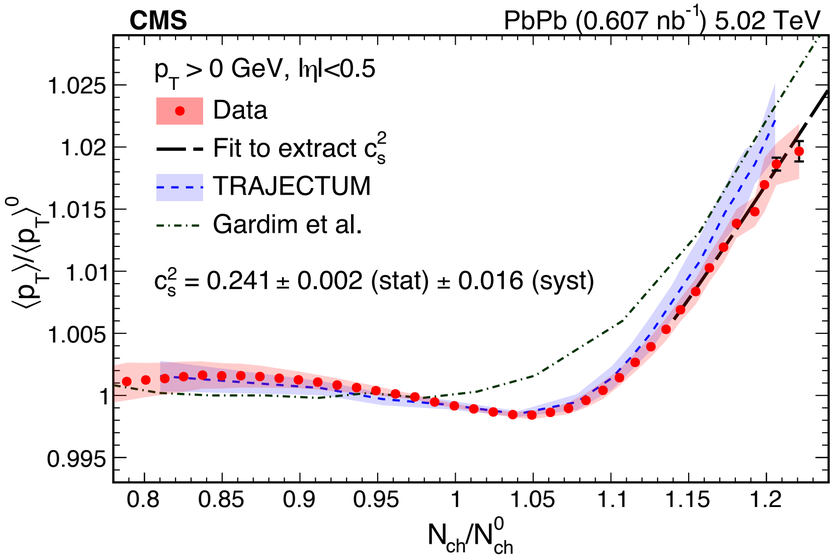
N_{part} : average number of nucleons participating in the collision

Measuring the speed of sound in quark-gluon plasma

The speed of sound is determined from the average transverse momentum of particles measured as a function of the particle multiplicity

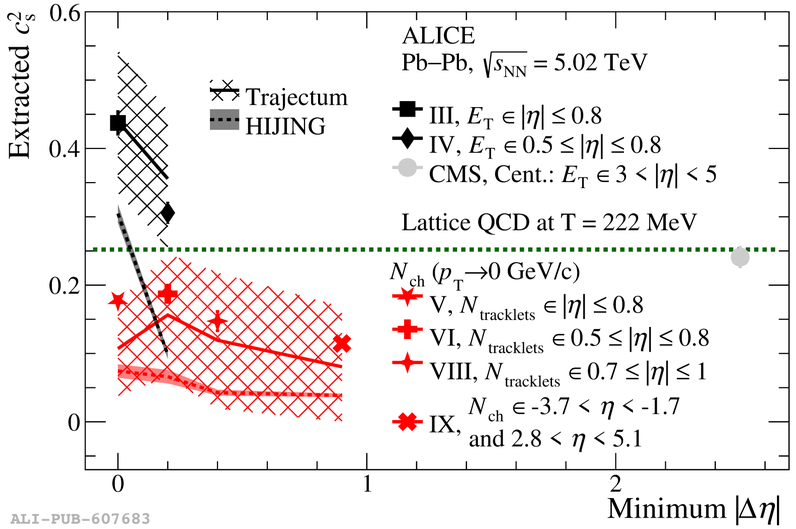


Data in good agreement with models!



Rep. Prog. Phys. 87, 077801 (2024)

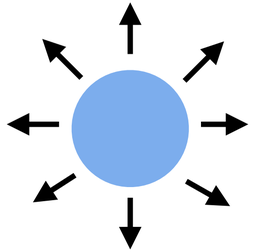
Extracted speed of sound depends on method used to determine centrality



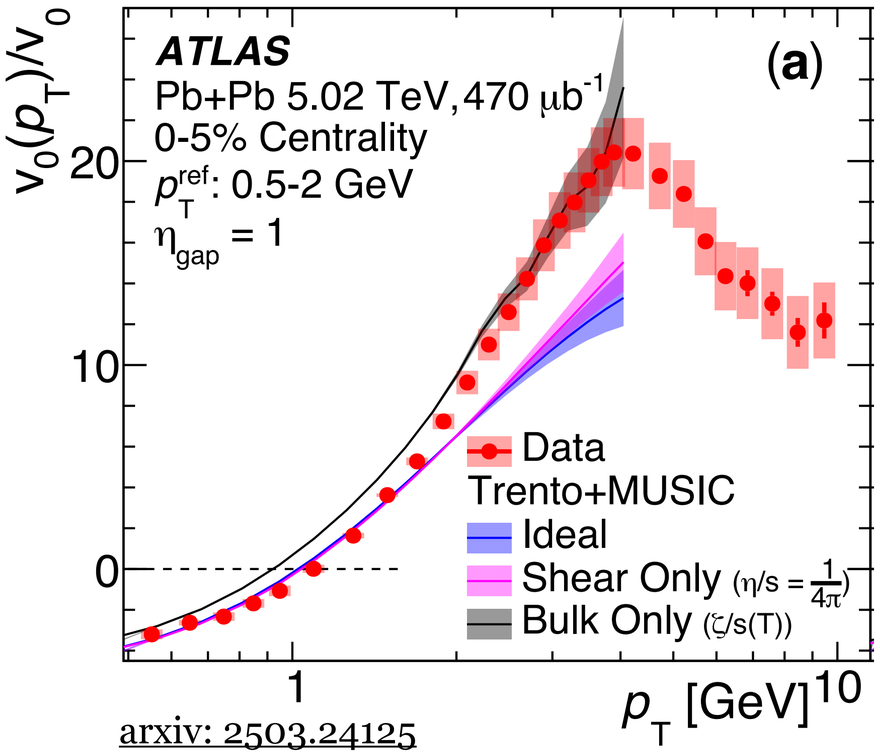
arxiv: 2506.10394

Radial flow probes plasma bulk viscosity

Radial flow measured as a function of particle transverse momentum is sensitive to the bulk viscosity of the quark-gluon plasma

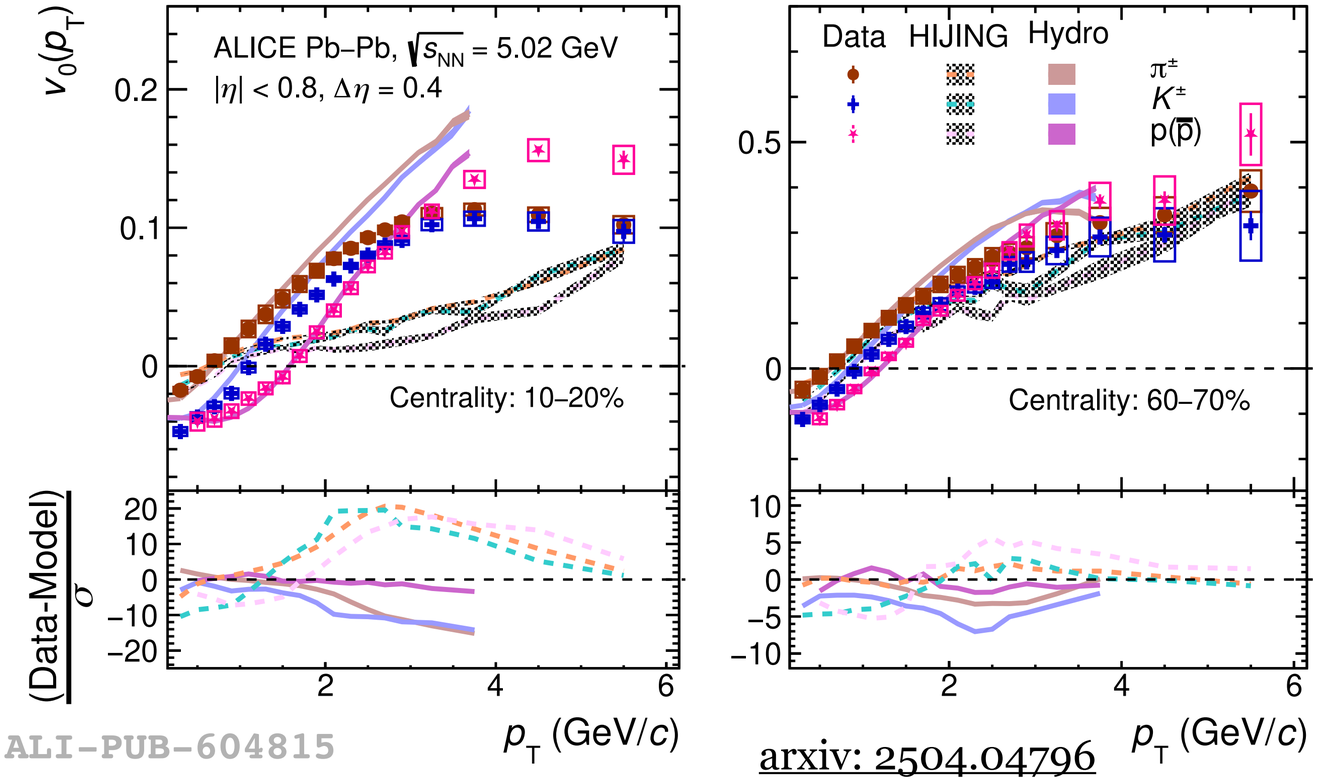


Radial flow of inclusive charged particles



arxiv: 2503.24125

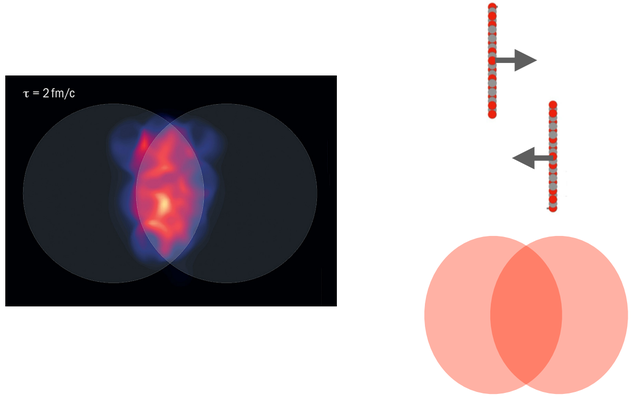
Radial flow of $\pi^{\pm}, K^{\pm}, p/\bar{p}$



arxiv: 2504.04796

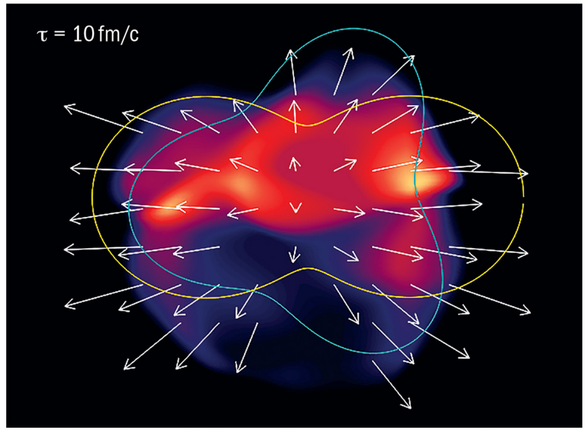
Anisotropic flow of particles in the quark-gluon plasma

Spatial anisotropy of the collision system



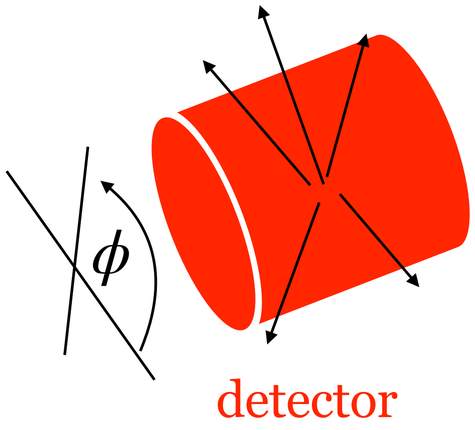
Range of nuclear overlap
(“centrality”)

Pressure gradients in the strongly-interacting plasma



CERN, MUSIC hydrodynamic simulations
PRL 110, 012302 (2013)

Anisotropic particle distribution



Decompose angular distribution of particles into a Fourier series with flow coefficients v_n:

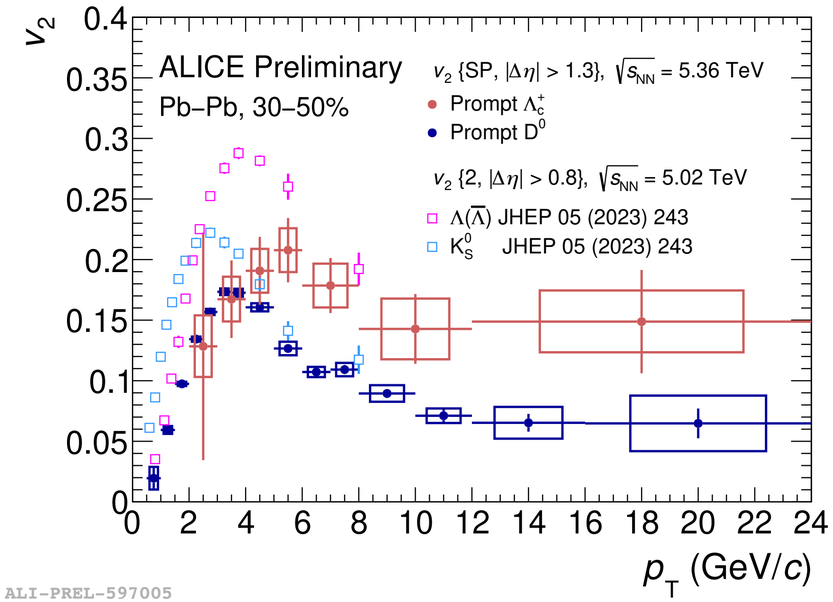
$$\frac{dN}{d\phi} \propto 1 + \sum_{n=1}^{\infty} 2v_n(p_T)\cos(n(\phi - \Psi))$$

Anisotropic flow probes quark dynamics

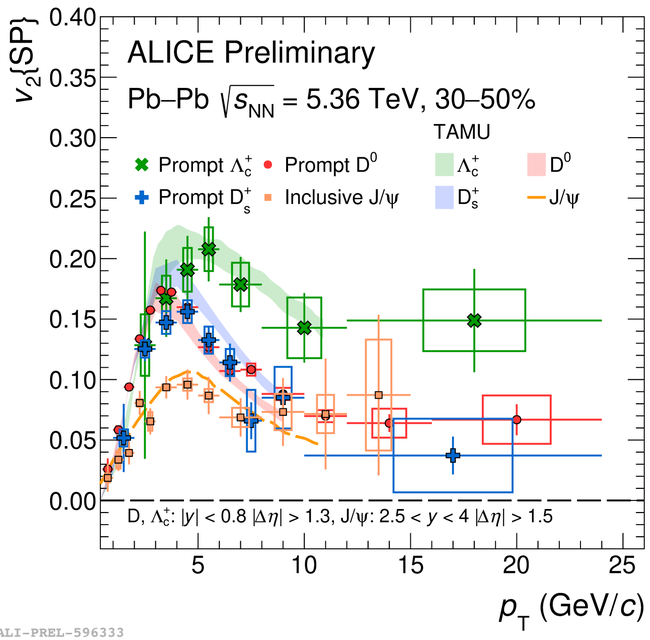
Measuring the anisotropic flow (v_2) of different particles gives insight into how different flavor quarks experience the quark-gluon plasma

Heavy quarks: excellent probes of QGP as due to their heavy mass, they are produced before QGP formation

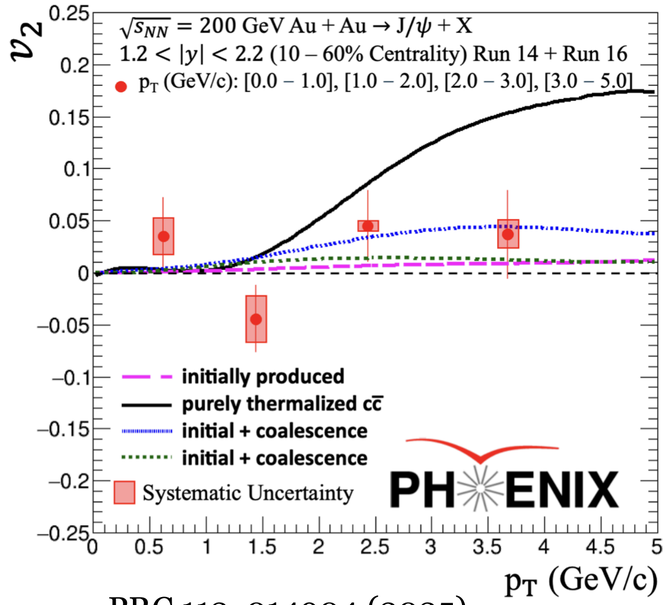
Heavy quarks flow less than light quarks, but baryons still flow more than mesons



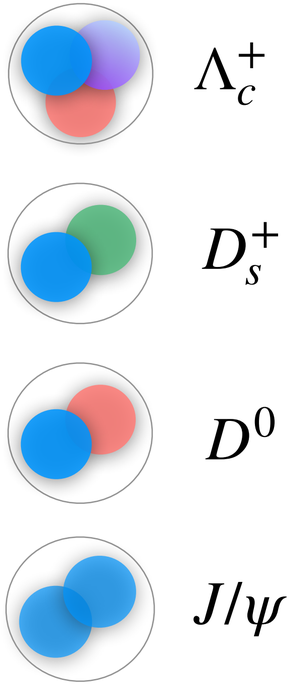
Higher statistics with Run 3 data enables first Λ_c^+ flow measurement



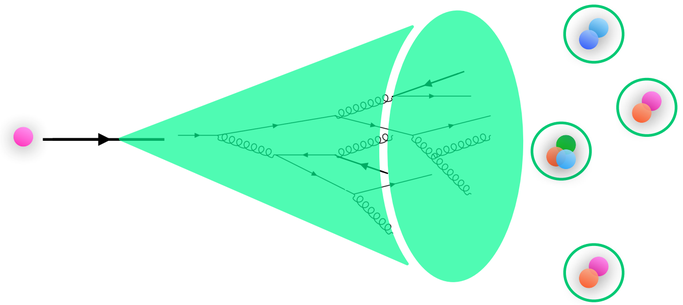
J/ψ flow consistent with zero at RHIC: cooler medium, no $c\bar{c}$ regeneration



PRC 112, 014904 (2025)



Searching for the wake in the quark-gluon plasma



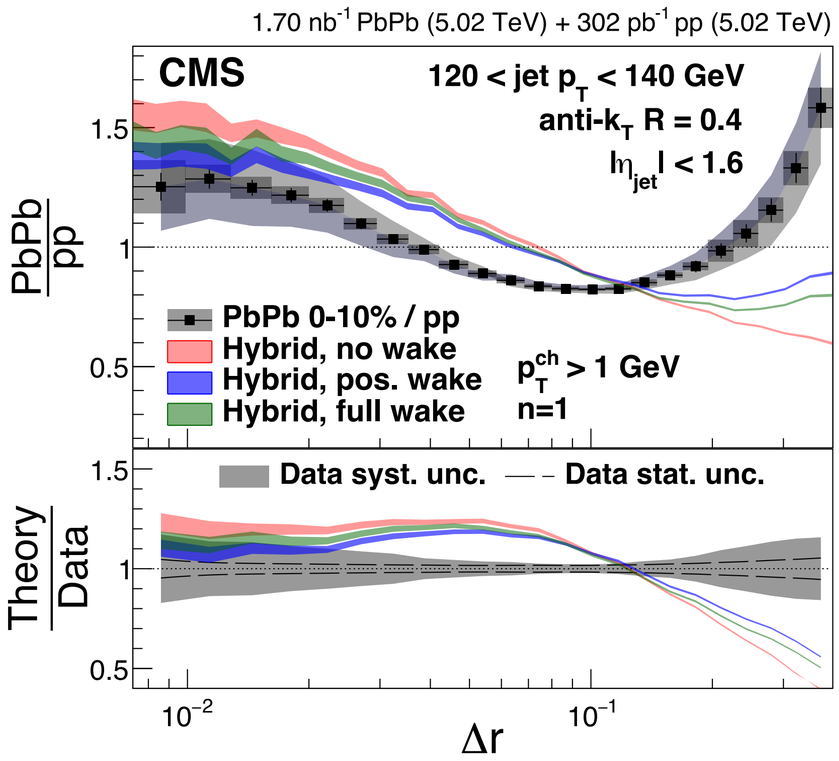
Jets: groups of particles produced from the hadronization of a single quark or gluon

"New" observable: Energy-Energy correlators

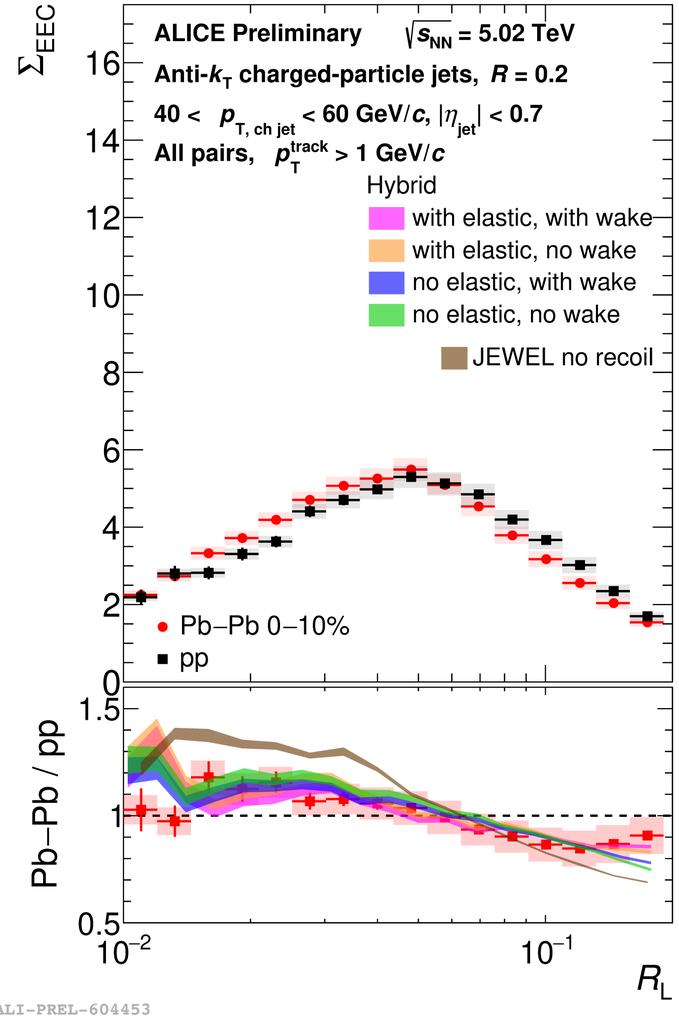
Correlation functions between particles in a jet

Sensitive to models of the jet "wake" in the QGP

Can we see "waves" in the quark gluon plasma after a jet has passed through it?



PLB 866, 139556 (2025)

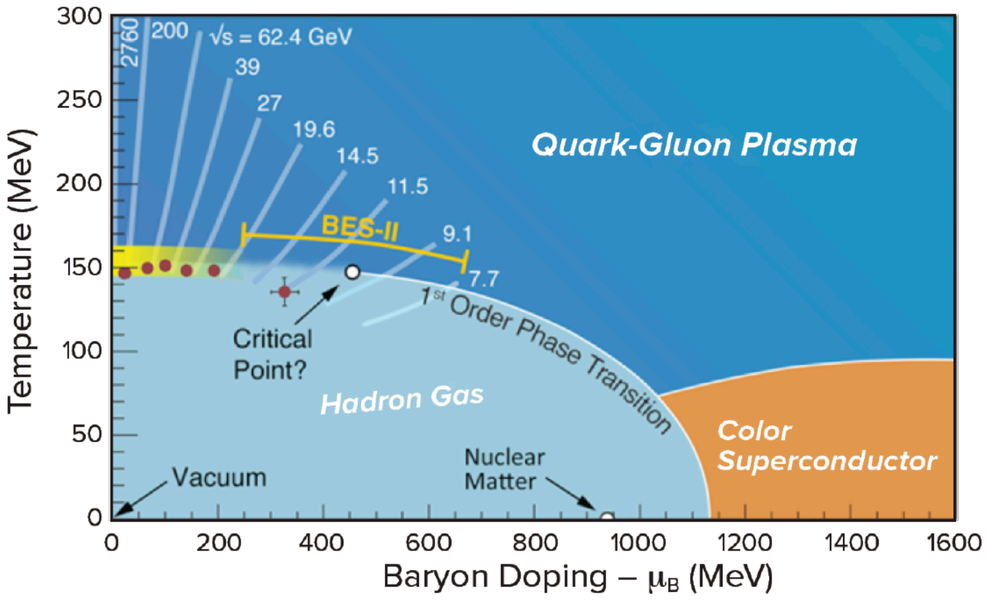


Mapping the phase diagram of heavy ion collisions

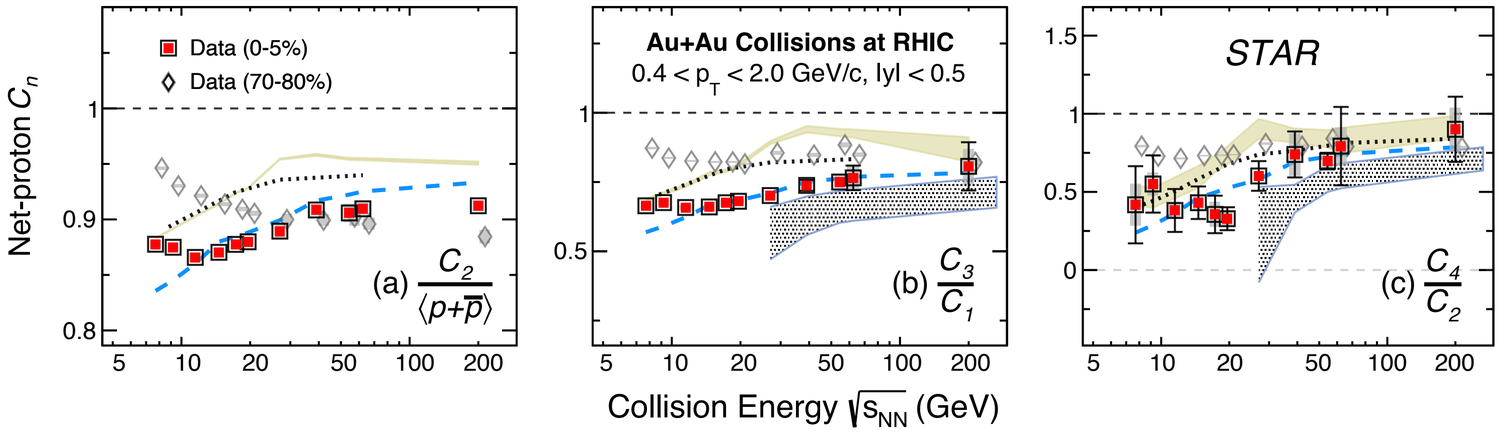
Where does the first-order phase transition between quark-gluon plasma and a hadron gas occur?

Search by varying center of mass energy and measuring event-by-event fluctuations of the net proton number:

- Cumulants: $C_1 = < N >$, $C_2 = < \delta N^2 >$ ... where $\delta N = N - < N >$
- Factorial cumulants κ_n: $\kappa_1 = C_1, \kappa_2 = - C_1 + C_2, ...$
- Related to correlation length of the system



New results from Beam Energy Scan II Program at RHIC



arxiv: 2504.00817

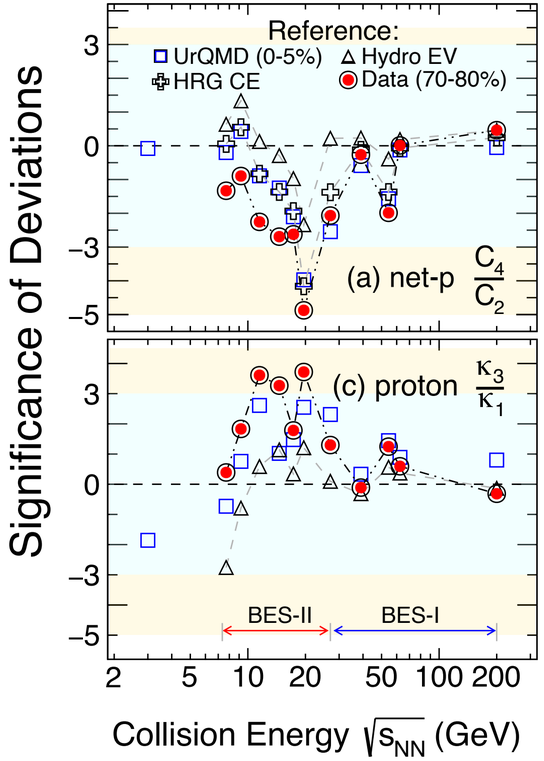
Mapping the phase diagram of heavy ion collisions

Where does the first-order phase transition between quark-gluon plasma and a hadron gas occur?

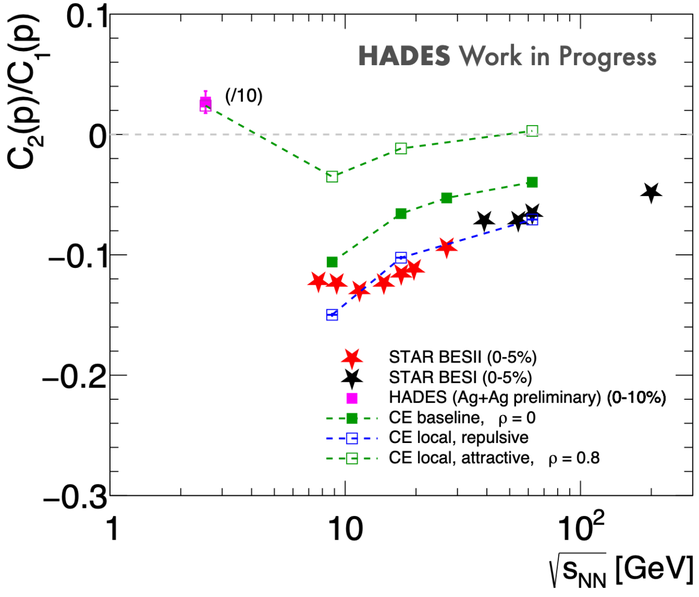
Search by varying center of mass energy and measuring event-by-event fluctuations of the net proton number

5σ deviation from non-critical-point models observed at RHIC

arxiv: 2504.00817

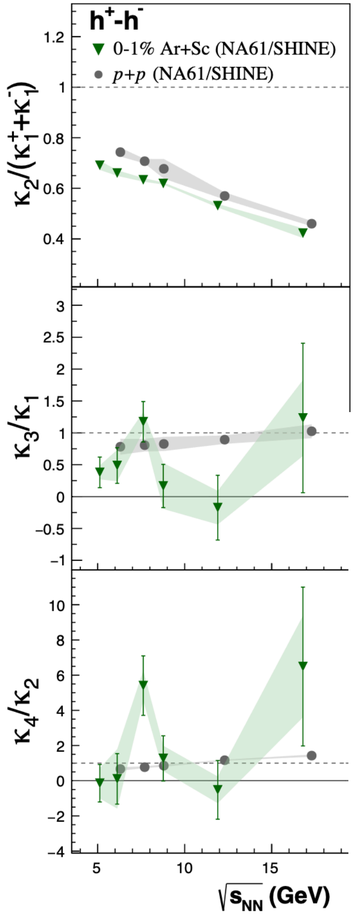


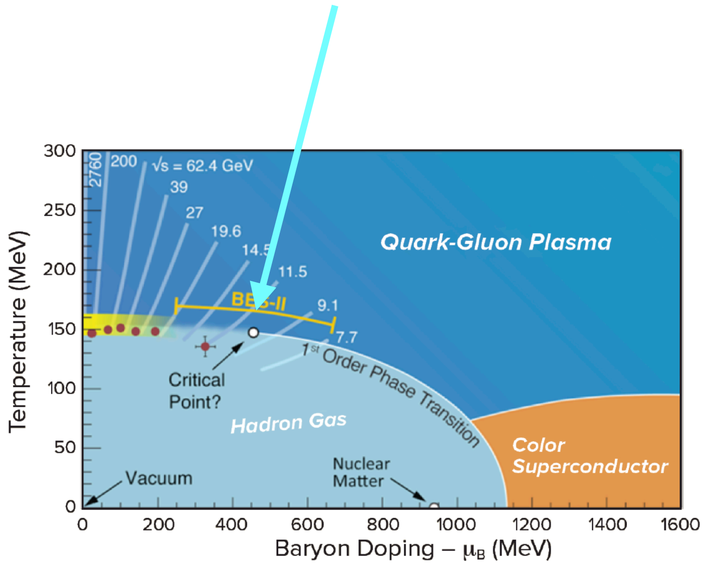
Ongoing parallel searches at NA61/SHINE (CERN) and HADES (GSI)



HADES: Hanna Zbroszczyk, Quark Matter 2025

NA61/SHINE: EPJC 85, 918 (2025)

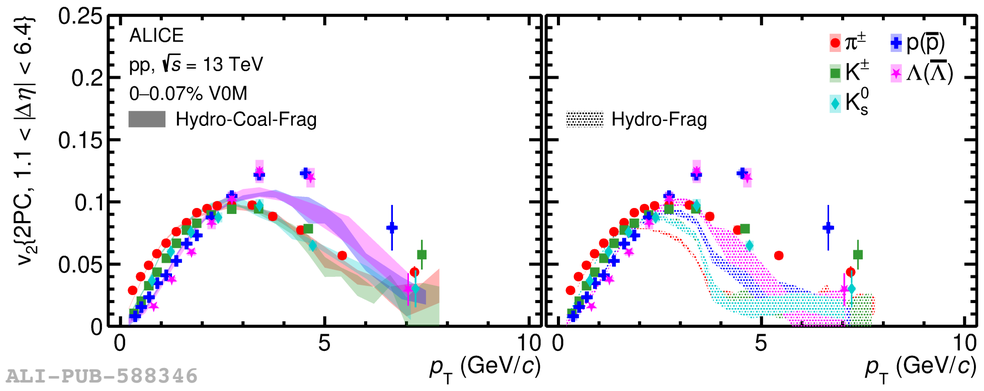




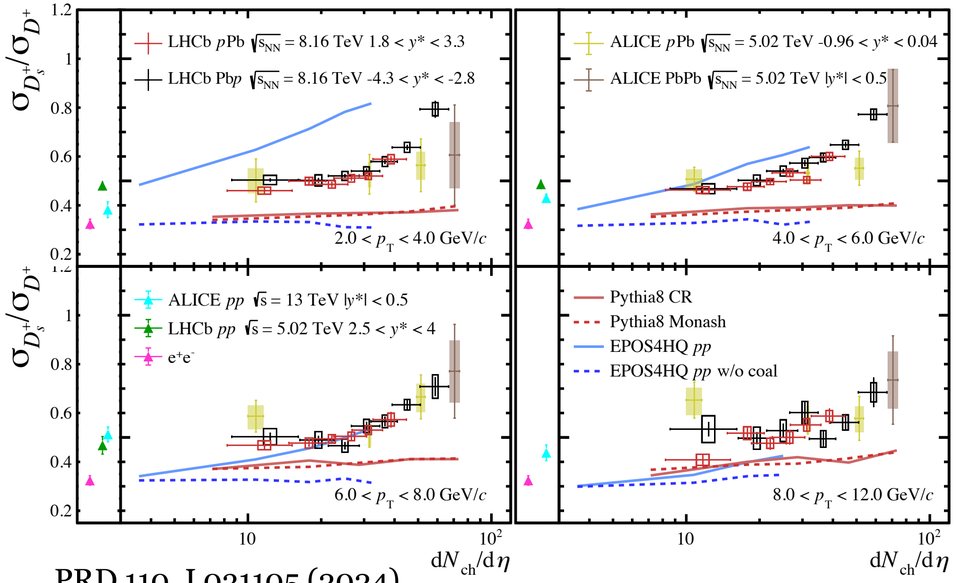
Does QGP form in small collision systems?

Flow described by hydrodynamic models in *pp* collisions!

arxiv: 2411.09323

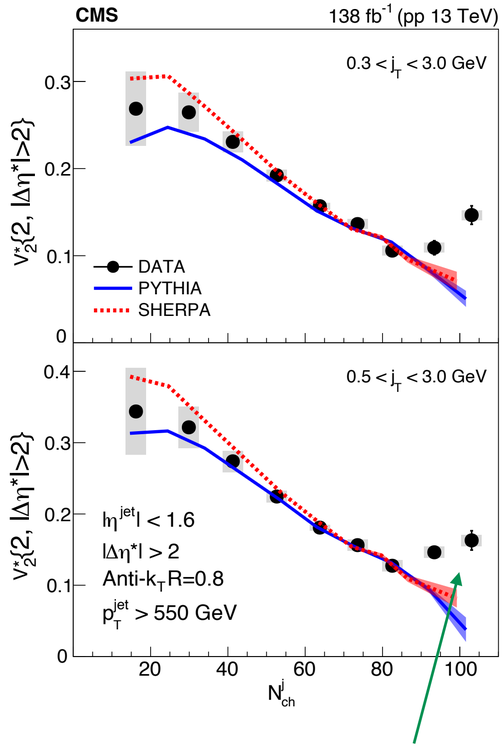


Strangeness enhancement at high multiplicity



PRD 110, L031105 (2024)

Flow in jets!

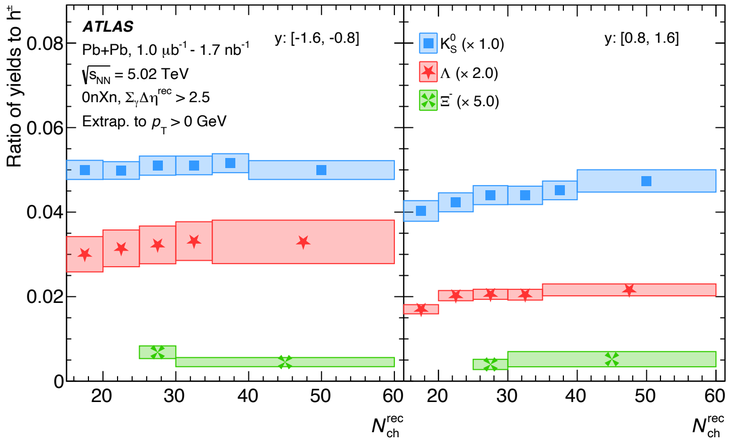


Onset of collective behavior?

PRL 133 (2024) 142301

Strangeness enhancement in ultra-peripheral PbPb collisions

PRC 111, 064908 (2025)



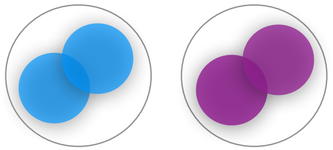
Are these signatures of quark-gluon plasma formation? Or are they due to other collective QCD phenomena?

A very active area of research in the heavy ion community!

Disentangling “hot” vs “cold” nuclear matter effects

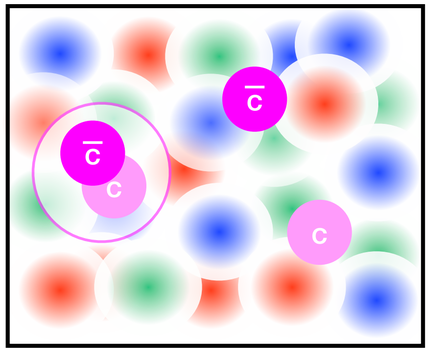
How can we differentiate phenomena caused by the hot plasma phase from non-plasma effects?

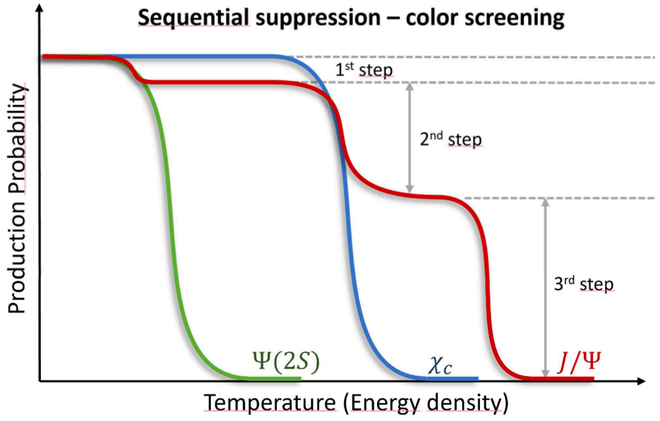
Key observable: quarkonia, bound states of two heavy quarks



Hot nuclear matter effects: study in AA collisions

Quarkonia states are predicted to “melt” in the hot quark-gluon plasma



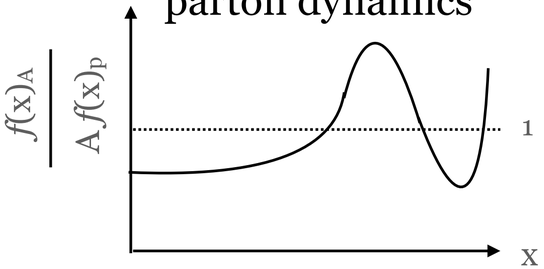


- Excited states dissociate earlier than ground state → potential to use as “thermometers” of the QGP

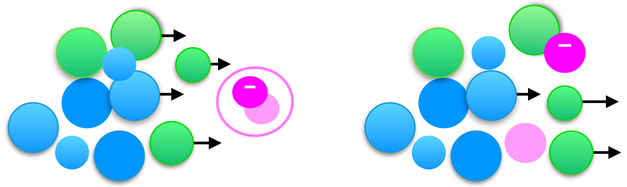
Cold nuclear matter effects: study in pA collisions

Many non-plasma effects can break apart quarkonia:

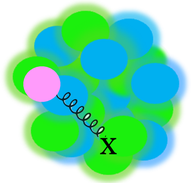
Nuclear structure & internal parton dynamics



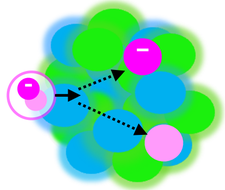
Breakup due to “co-moving” particles



Parton energy loss



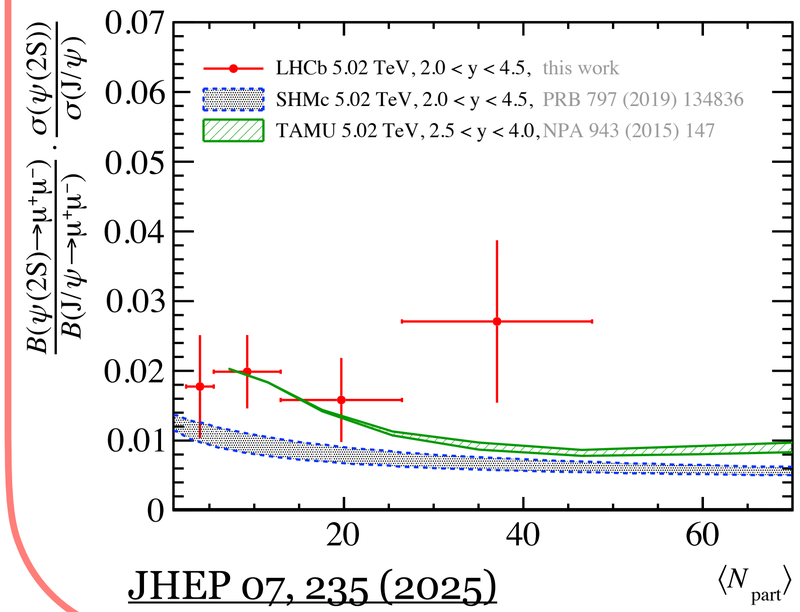
Nuclear “absorption” - breakup by the interaction with the nucleus



Disentangling "hot" vs "cold" nuclear matter effects

J/ψ and $\psi(2S)$ suppression in non-central (60-100% centrality) PbPb collisions

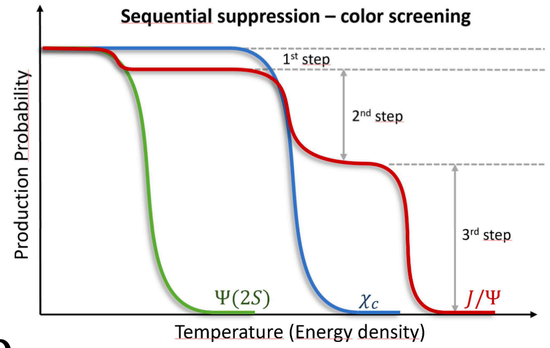
Measurements in the forward rapidity region provide additional constraints on models

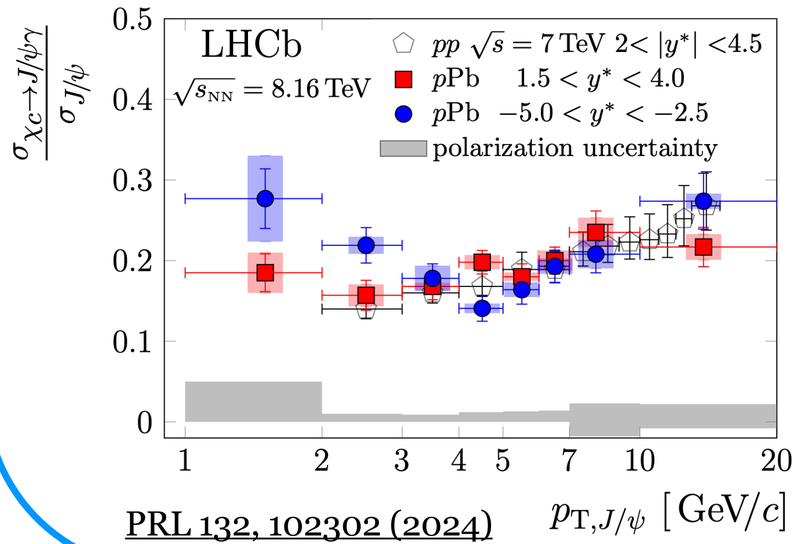


JHEP 07, 235 (2025)

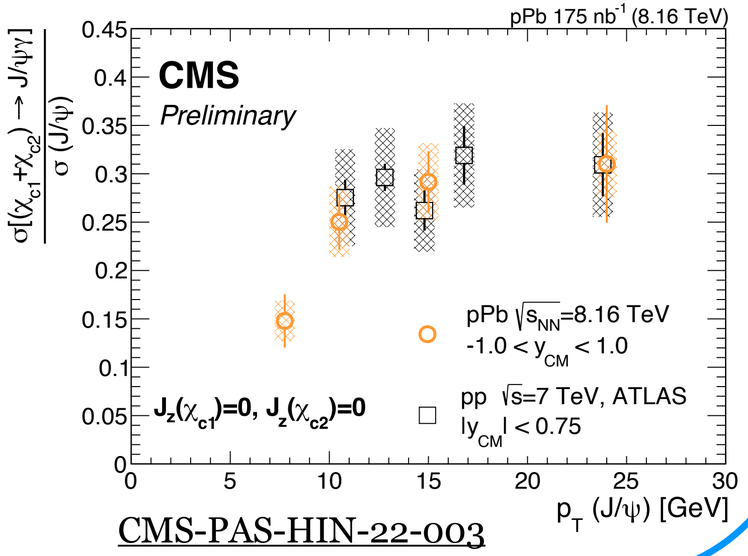
Filling in a missing piece: what happens to χ_c ?

- χ_c in pPb is consistent with previous pp measurements → no dissociation
- Could indicate that temperature in pPb is not hot enough to form QGP





PRL 132, 102302 (2024)



CMS-PAS-HIN-22-003

How does nuclear matter change with nuclear size?

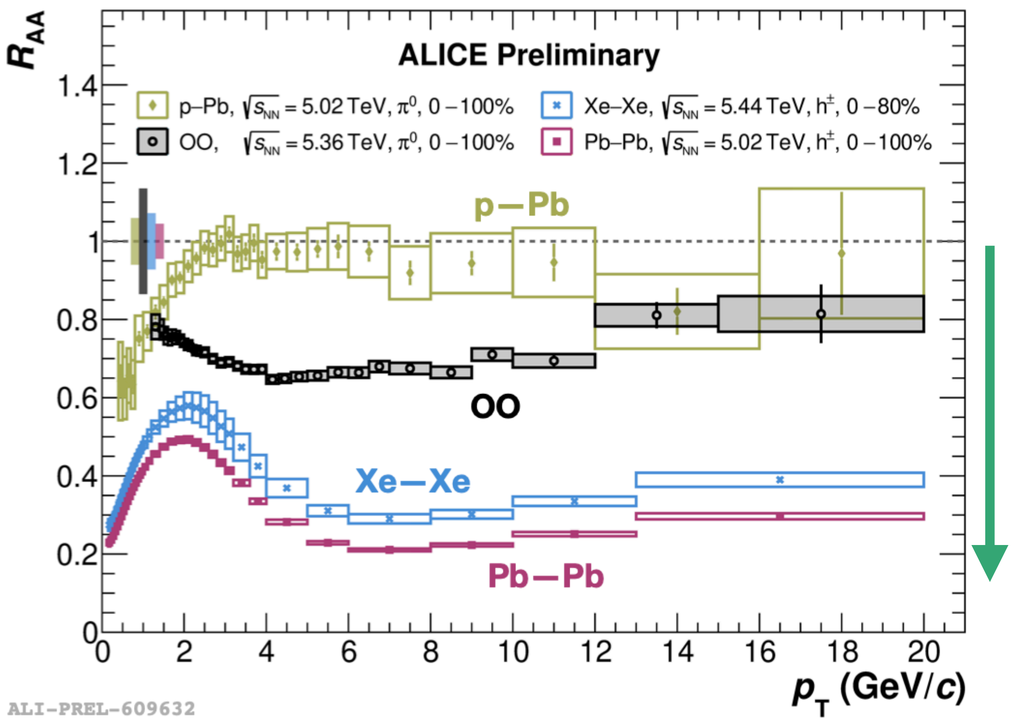
How does partonic nuclear matter change from small to large collision systems?

Quantify difference compared to "vacuum" (*pp* collisions) with nuclear modification factor R_{AA}:

$$R_{AA} = \frac{\sigma_{AA}}{A^2 \sigma_{pp}}$$

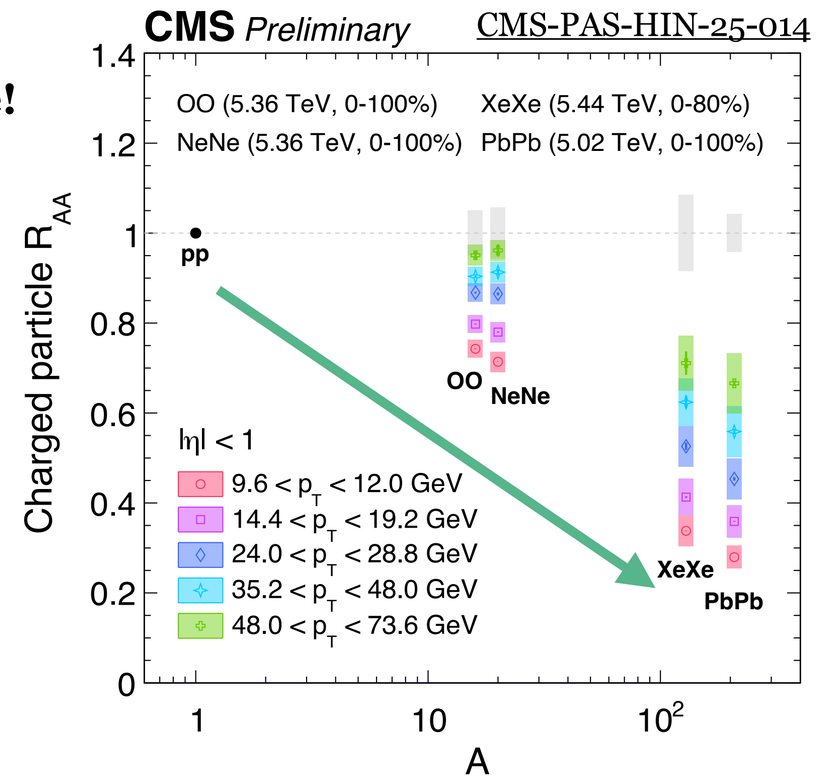
Measured cross section in AA or *p*A

Measured cross section in *pp* scaled by average number of interactions in AA or pA



New OO and NeNe data from the LHC help fill in the picture!

The larger the system size, the larger the suppression ($R_{AA} < 1$)



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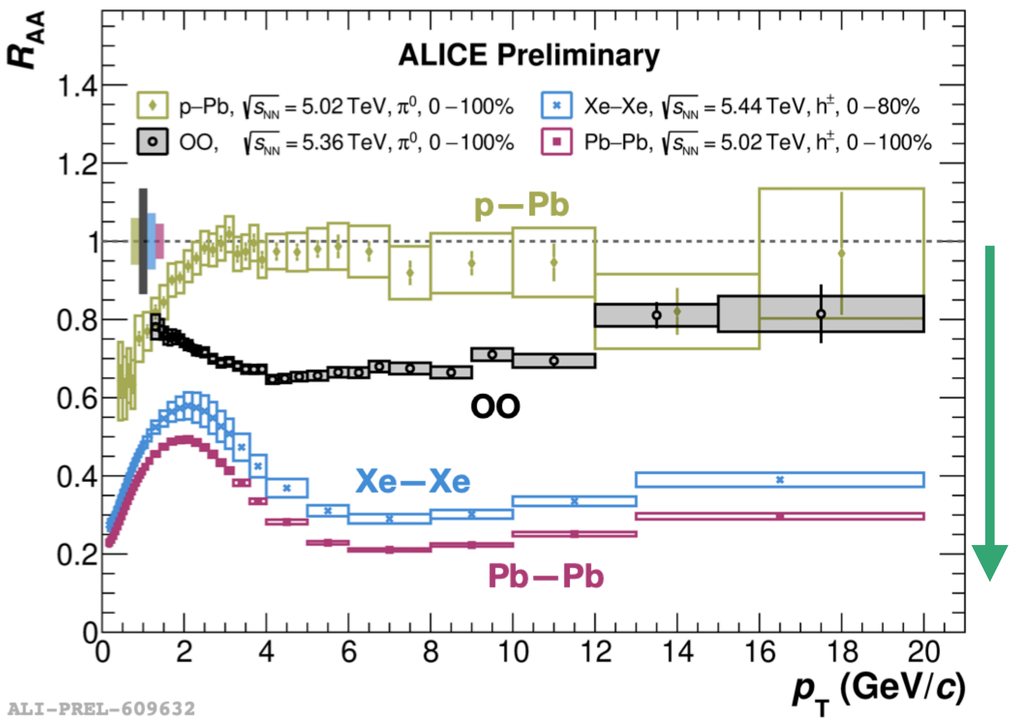

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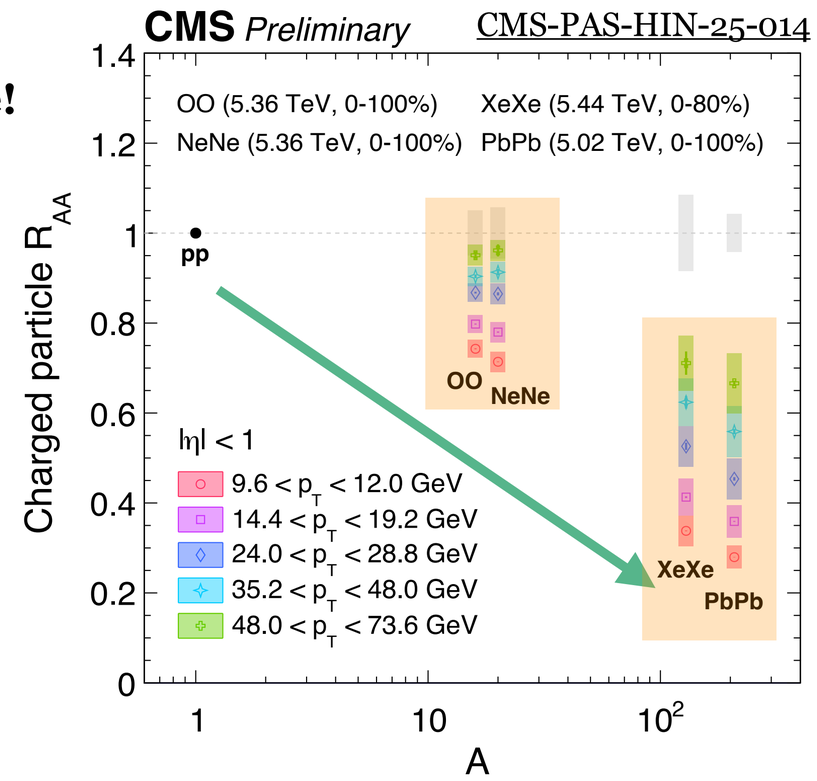
High transverse momentum (≳ 10 GeV/c) particles: suppression follows a clear p_T-ordering



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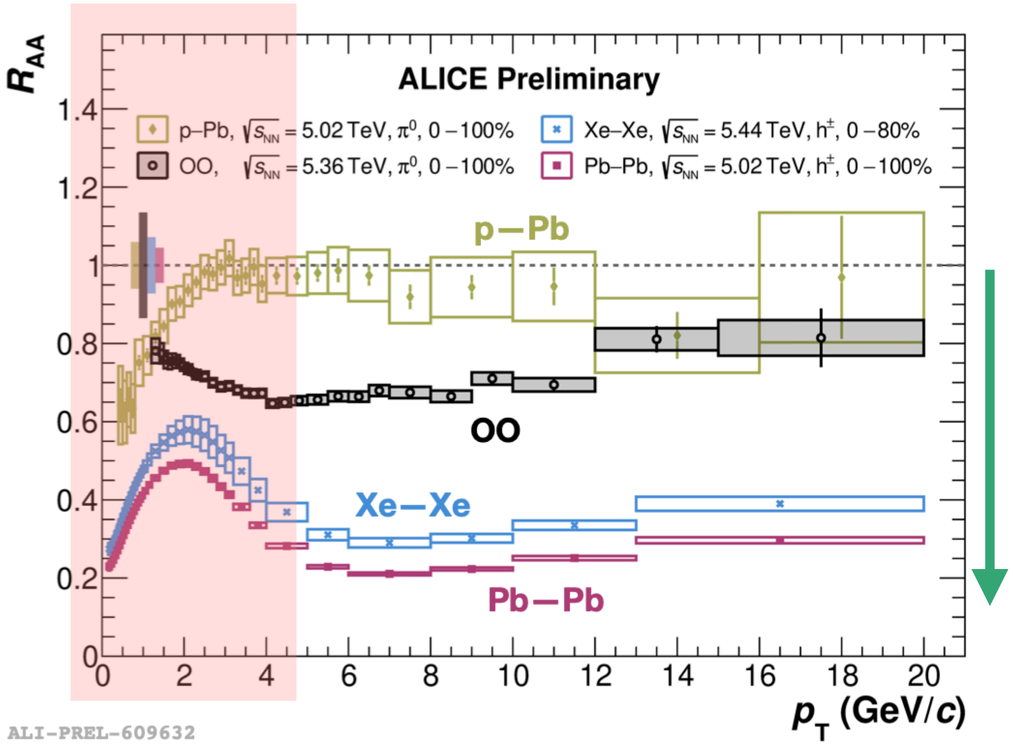

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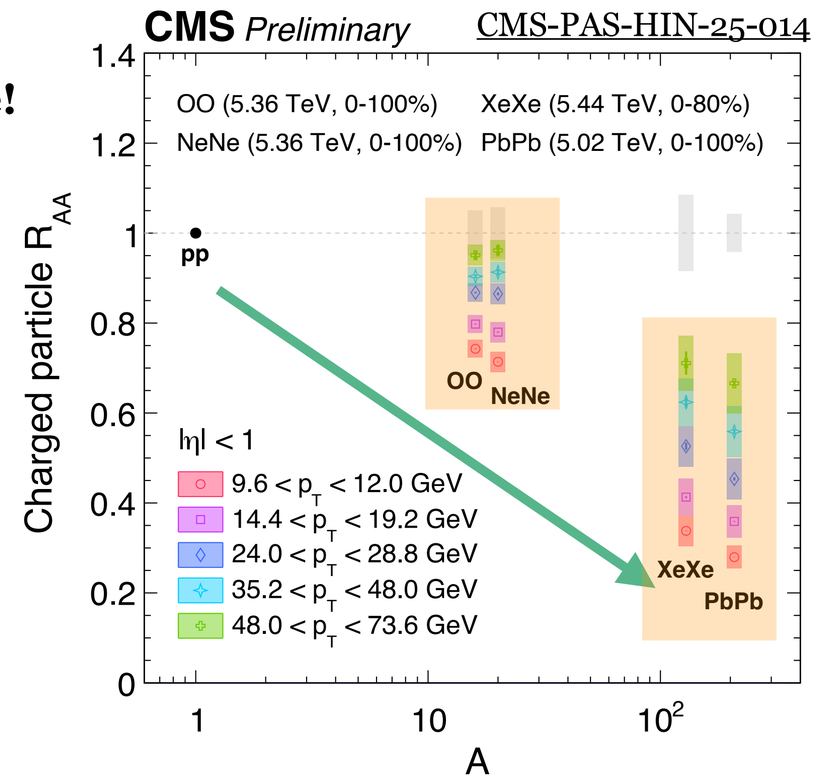
The larger the system size, the larger the suppression ($R_{AA} < 1$)

High transverse momentum (≳ 10 GeV/c) particles: suppression follows a clear p_T-ordering

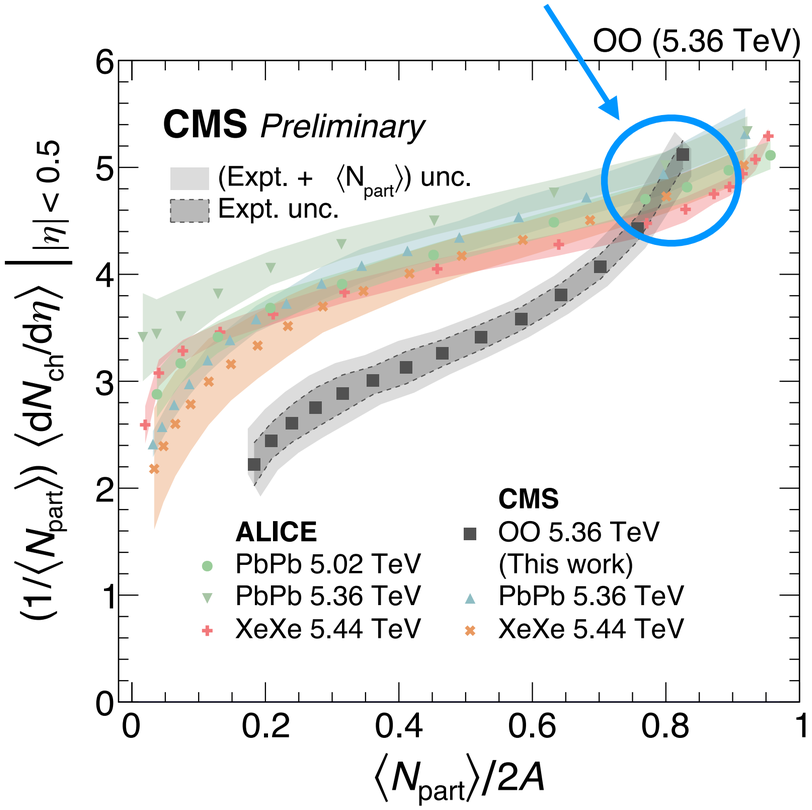
Low transverse momentum particles: dynamics are more complex



A closer look at OO collisions

Charged particle density in OO

Density in most central OO collisions similar to that in PbPb!



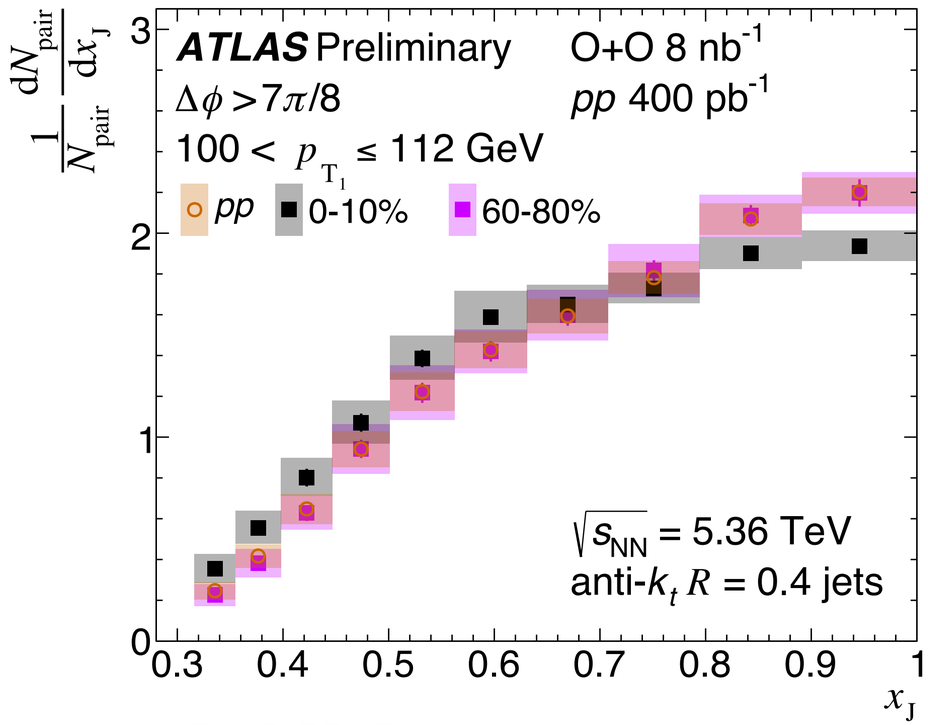
CMS-PAS-HIN-25-010

N_{part}: average number of nucleons participating in the collision

Probing path-dependent energy loss with dijets

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

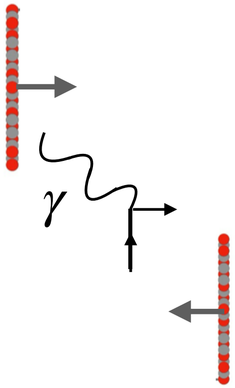
$x_J < 1$ implies different path lengths traveled by each jet



ATLAS-CONF-2025-010

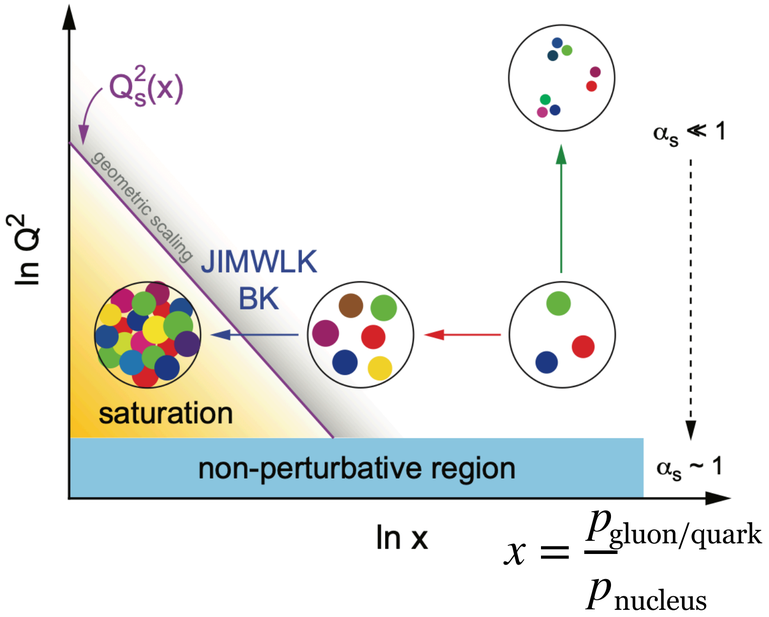
Central OO collisions have fewer balanced dijets

How is nuclear structure described in terms of quarks and gluons ?



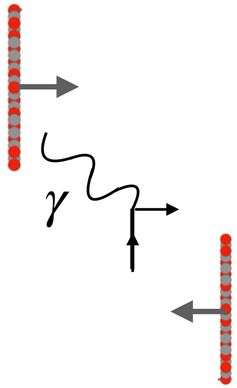
Electromagnetic interactions in Ultra-Peripheral Collisions (UPC) allow to "image" the quarks and gluons in nuclei

- Measurements of coherent vector meson production constrain models of how quark and gluon distributions are modified in nuclei
- Search for onset of saturation regime, where gluon density is maximized



$$x = \frac{p_{\text{gluon/quark}}}{p_{\text{nucleus}}}$$

How is nuclear structure described in terms of quarks and gluons ?



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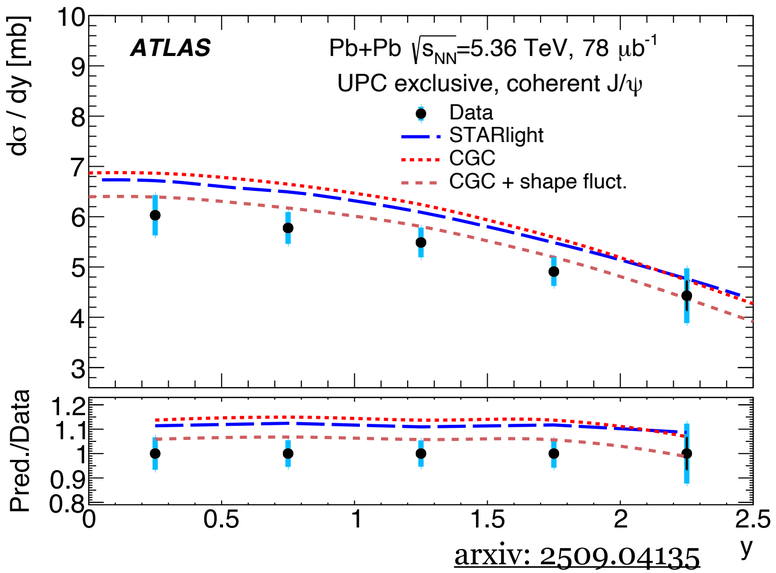
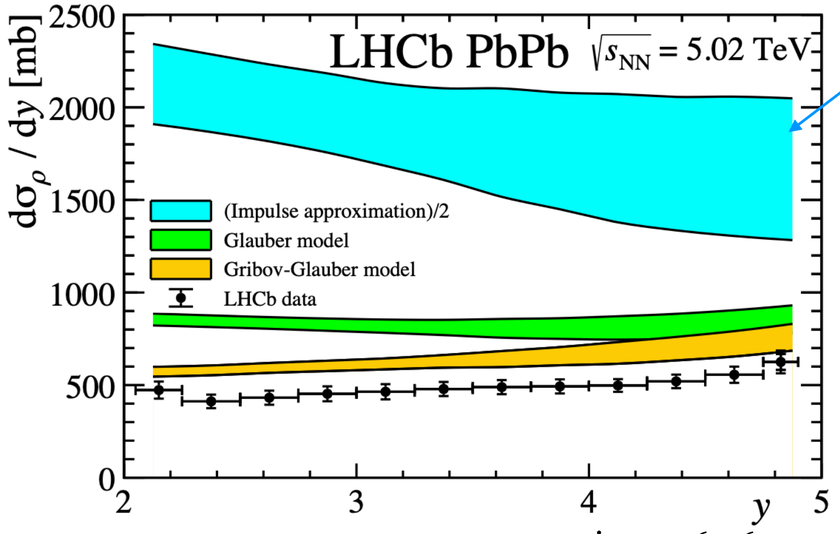
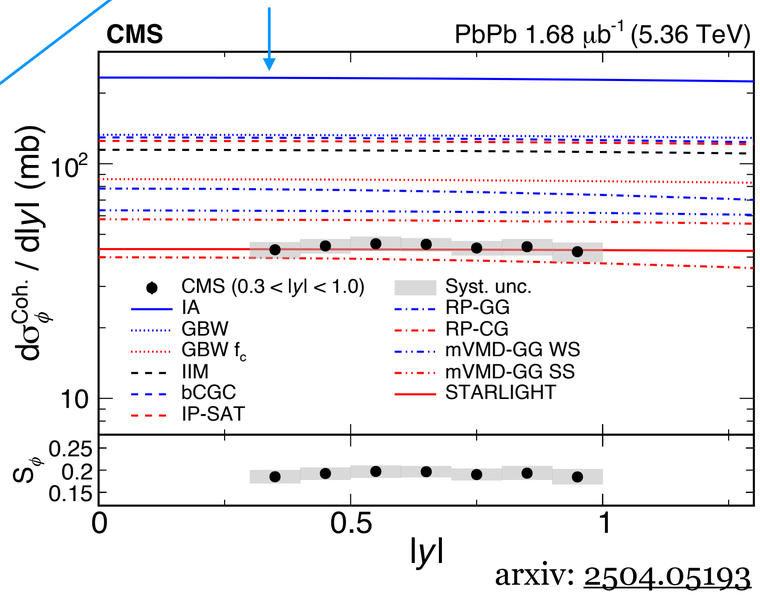
Impulse approximation: free quarks and gluons in nuclei



arxiv: 2509.04135



arxiv: 2506.06250



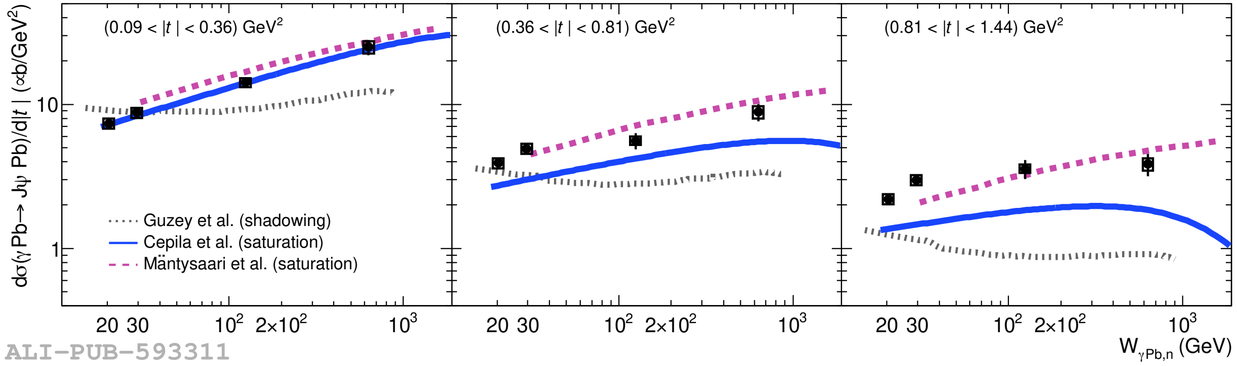
arxiv: 2504.05193

How is nuclear structure described in terms of quarks and gluons ?

Signs of gluon saturation?

- Incoherent J/ψ photoproduction as a function of momentum transfer $|t|$ more sensitive to differentiate saturation and shadowing models
- Data are compatible with gluon saturation models

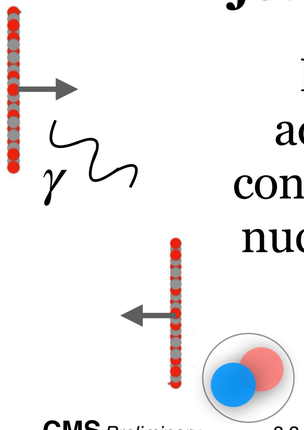
Increasing $|t|$ = momentum transfer in interaction



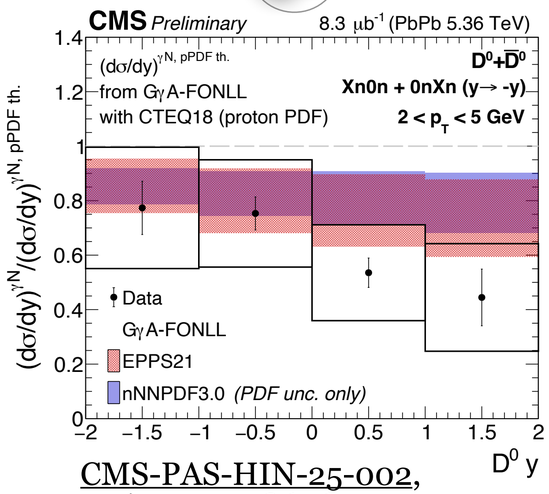
$W_{\gamma Pb,n}$ = center of mass energy per nucleon in γ + Pb collision

arxiv 2503.18708

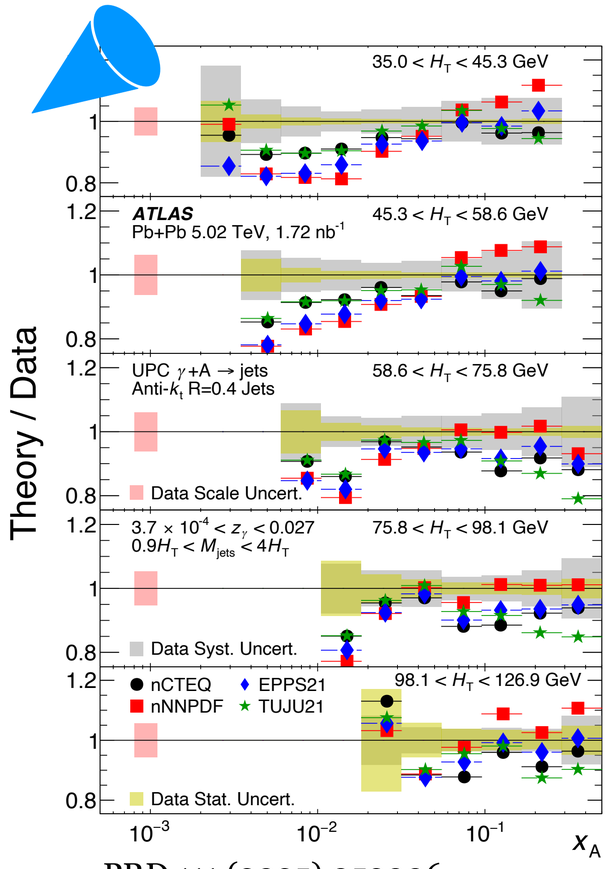
New probes in ultra peripheral collisions : jets and open heavy flavor



Provide additional constraints on nuclear PDFs



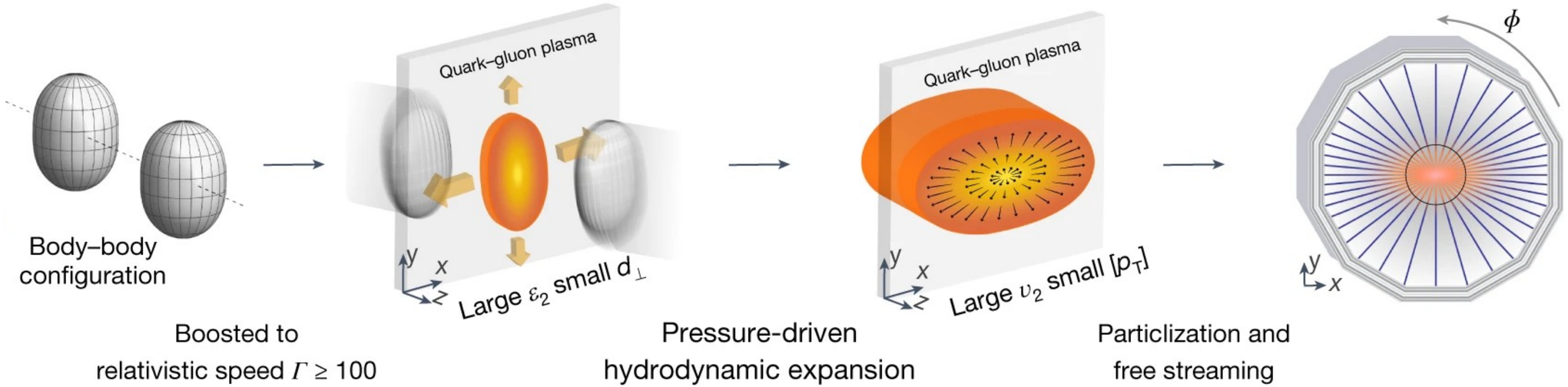
CMS-PAS-HIN-25-002, arxiv 2509.08626

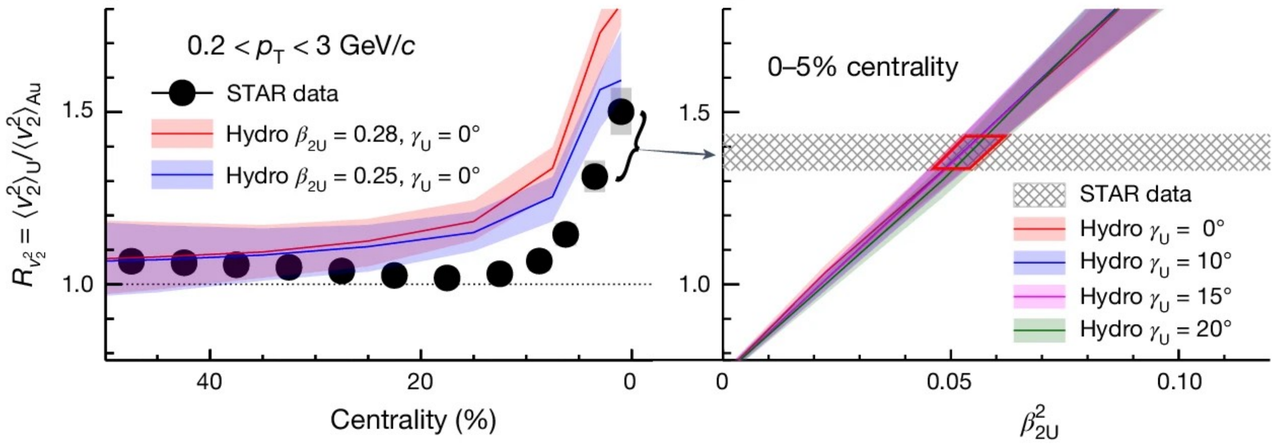


PRD 111 (2025) 052006

Probing nuclear structure with heavy ion collisions

Idea pioneered by the STAR experiment at RHIC: anisotropic flow can be related to global nuclear structure properties



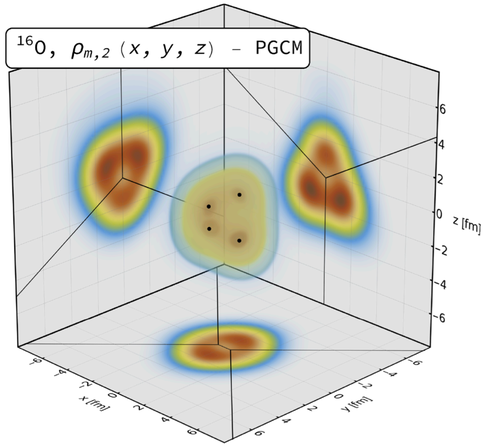


- Measurements of $< v_2^2 >$ in UU and AuAu collisions were compared to hydrodynamic calculations with specific parameters for the quadrupole deformation magnitude β_2 and triaxiality parameter γ
- Extracted values are compatible with low-energy nuclear structure measurements

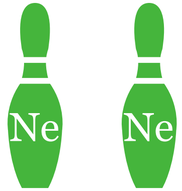
Nature 635, 67-72 (2024)

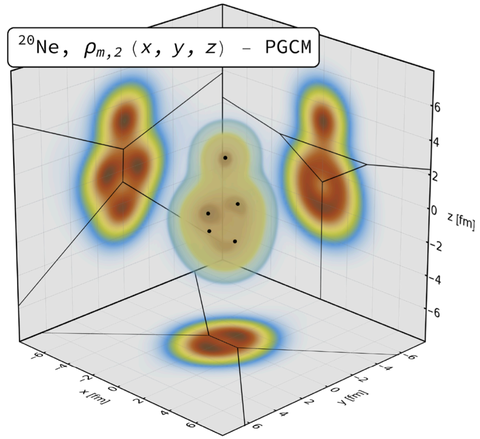
Probing nuclear structure with heavy ion collisions

Can anisotropic flow measurements reflect differences in the nuclear structure of oxygen and neon?



vs.



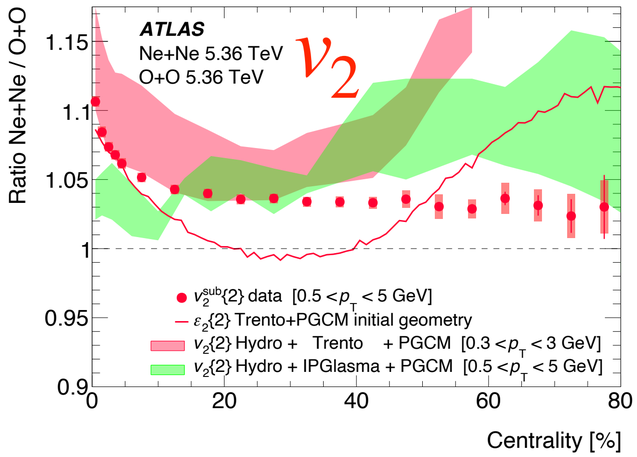


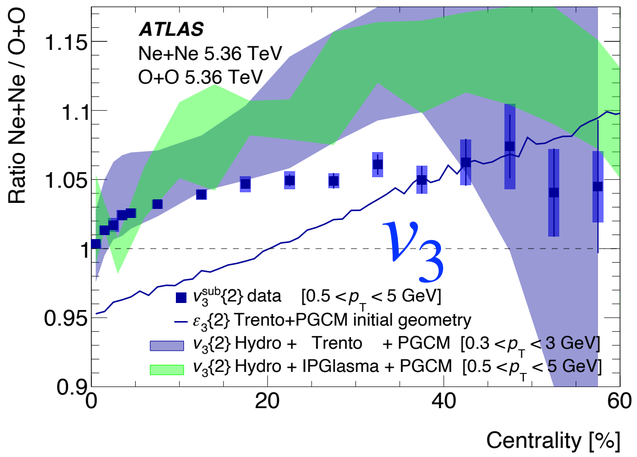
PRL 135, 012302 (2025)

Probing nuclear structure with heavy ion collisions

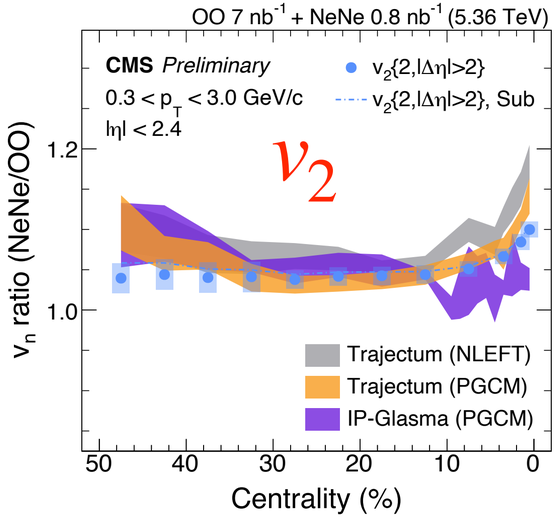
Can anisotropic flow measurements reflect differences in the nuclear structure of oxygen and neon?

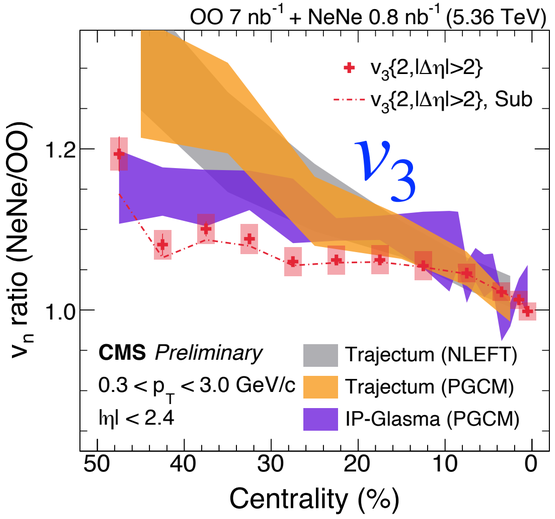
arxiv: 2509.05171



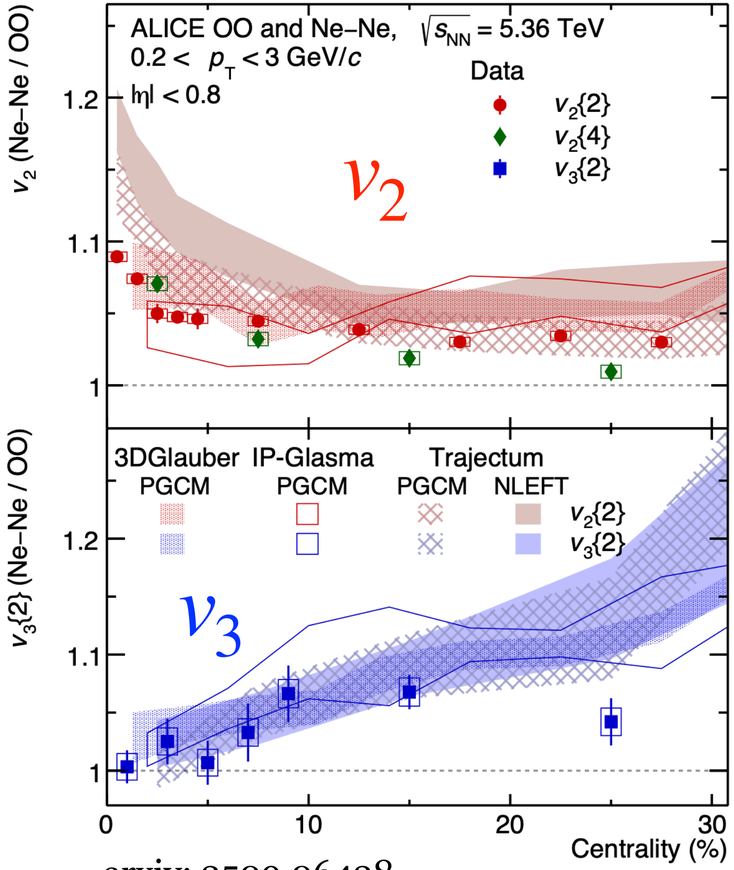


CMS-PAS-HIN-25-009





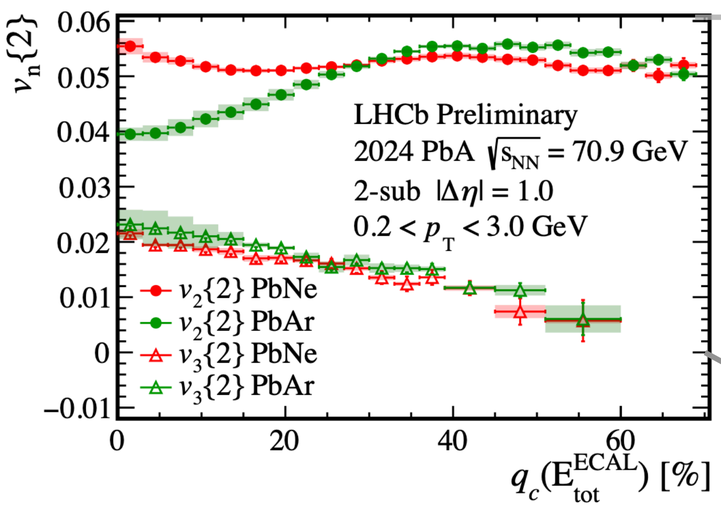
Hydrodynamic models incorporating nuclear structure describe the data reasonably well!



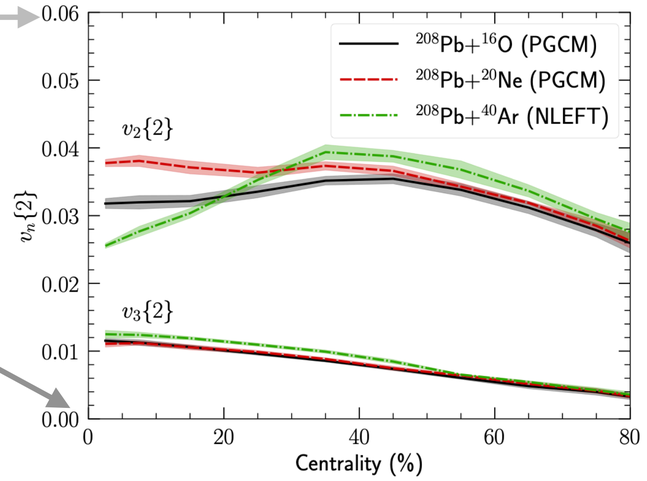
arxiv: 2509.06428

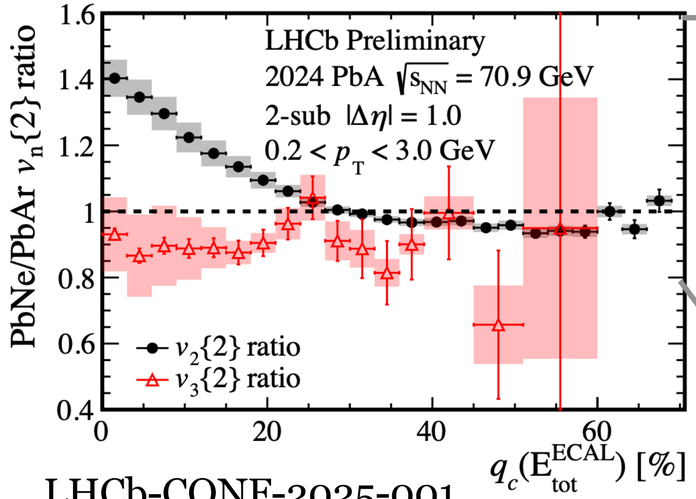
Probing nuclear structure with heavy ion collisions

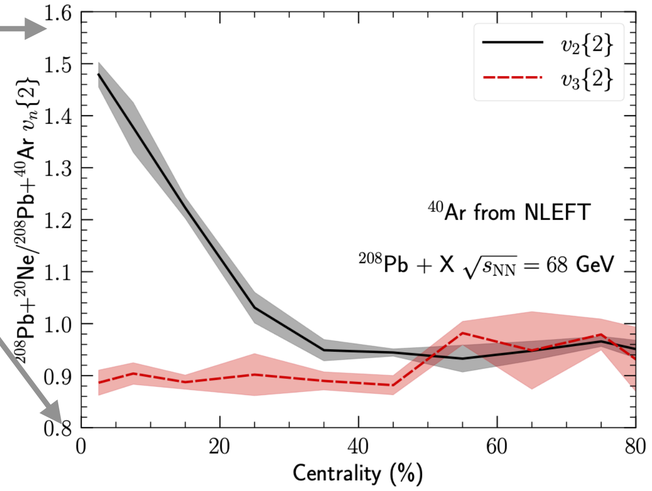
Data



Theoretical predictions



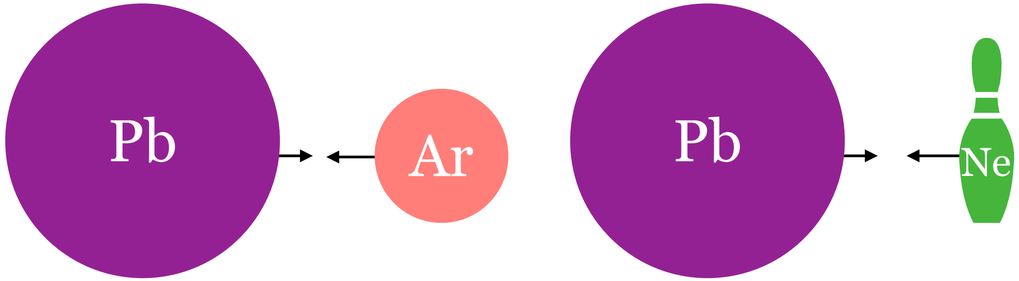




LHCb-CONF-2025-001

LHCb experiment in fixed-target mode (SMOG2) can collect *p*A and PbA collisions for several gas targets

Compare flow coefficients in PbAr vs PbNe collisions:

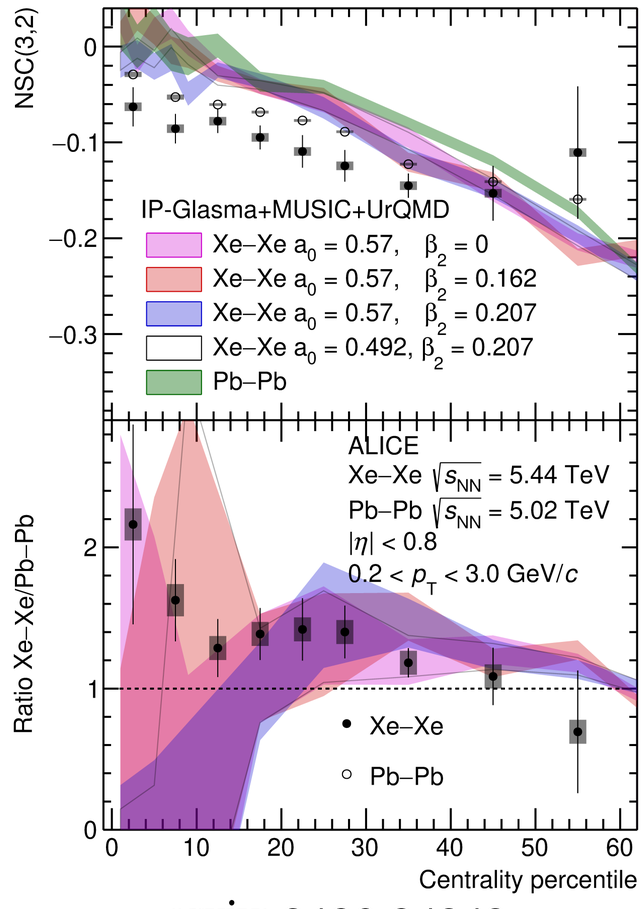


Preliminary measurements closely follow the trends predicted by theory!

Centrality determination in progress, then direct data/theory comparisons will be made

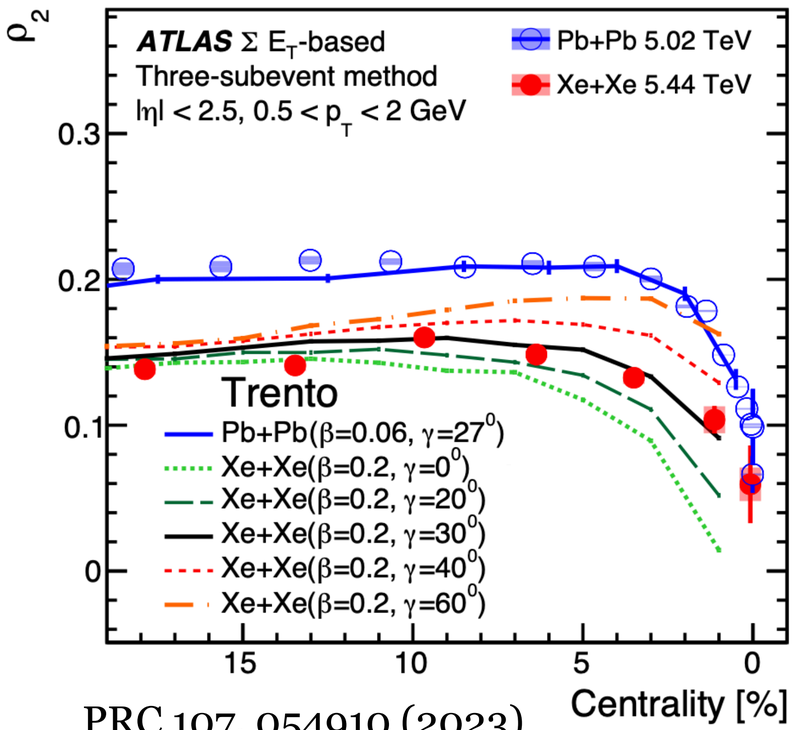
Probing nuclear structure with heavy ion collisions

Multiparticle correlations constrain the quadrupole deformation magnitude β_2 and triaxiality parameter γ in Xe



arxiv: 2409.04343

Evidence for triaxial deformation of ^{129}Xe

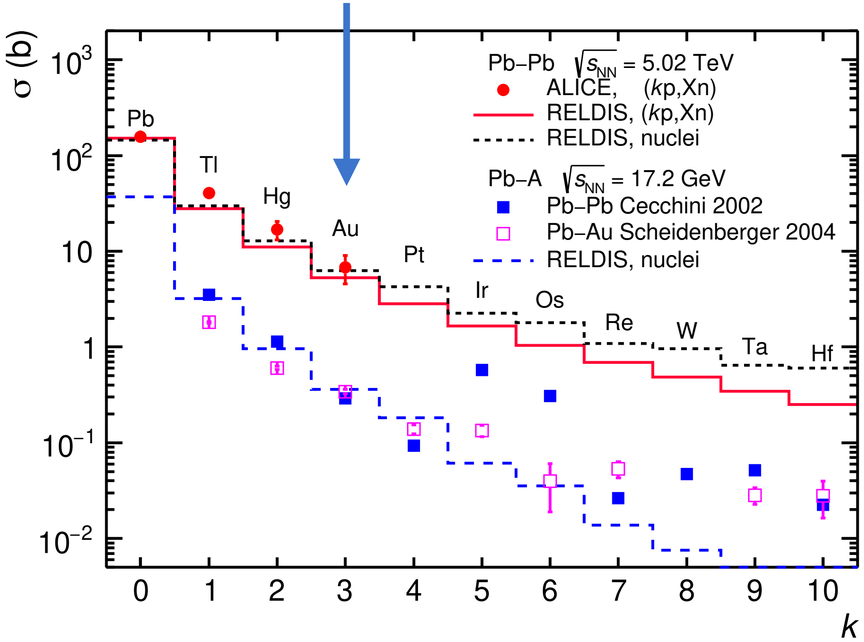


PRC 107, 054910 (2023)

"Alchemy" at the LHC !

Electromagnetic dissociation of Pb nuclei measured via proton and neutron emissions

Turning Pb into Au!



PRC 111, 054906 (2025)

Summary

- Progress is being made on understanding both the global "bulk" properties of the unique quark-gluon plasma, and the fundamental quark and gluon interactions that give rise to them
- A lively ongoing debate exists in the community about whether quark-gluon plasma is formed in small systems, even as small as *pp* or ultra-peripheral collisions
- LHC NeNe and OO special data-taking runs have provided a wealth of new data for intermediate collision species between pp and AuAu/PbPb
- Measurements in ultra-peripheral nucleus-nucleus collisions help us better understand the structure of nuclei in terms of quarks and gluons
- Several measurements now clearly demonstrate how heavy ion collisions can also be used to learn about low-energy nuclear structure

Many more exciting results soon to come !

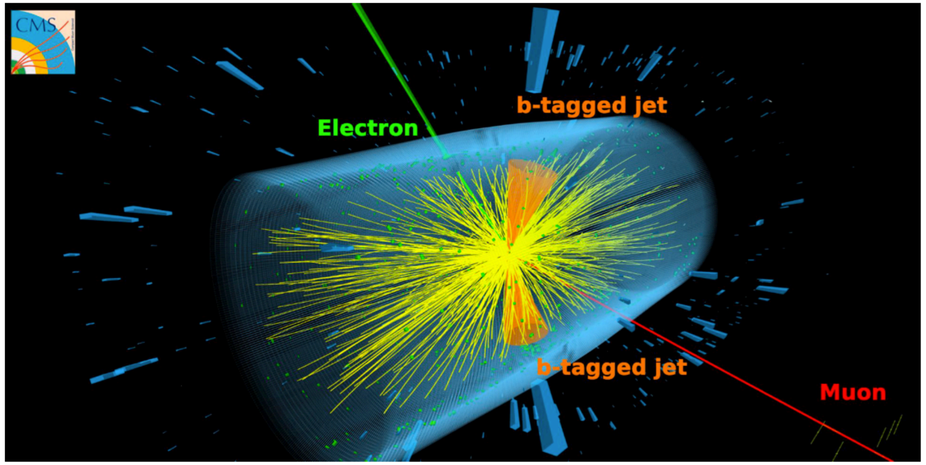
Thank you for your attention

Backup

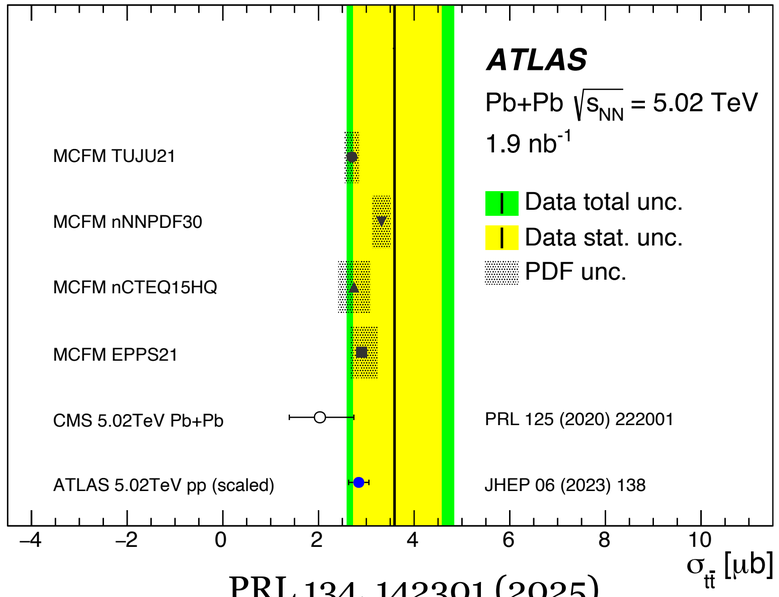
Top quarks in the quark gluon plasma

Observation of the top quark in heavy ion collisions confirmed that all quark flavors are present in the pre-equilibrium stage of the QGP

Very challenging to measure! Requires high-statistics, heavy-flavor-tagged jets, and machine learning techniques

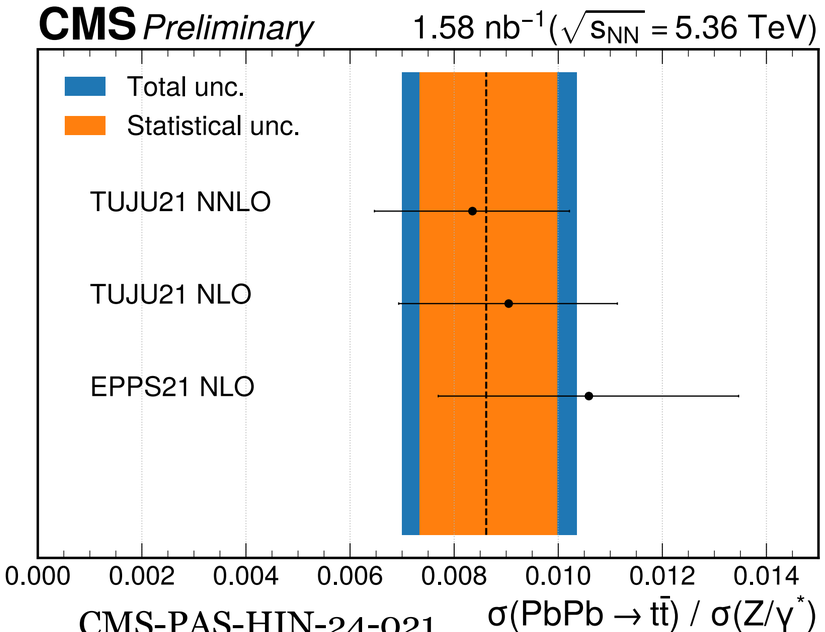


Measurement of top and anti-top quark production cross section with Run 2 data



PRL 134, 142301 (2025)

Improved measurement precision with Run 3 LHC data



CMS-PAS-HIN-24-021