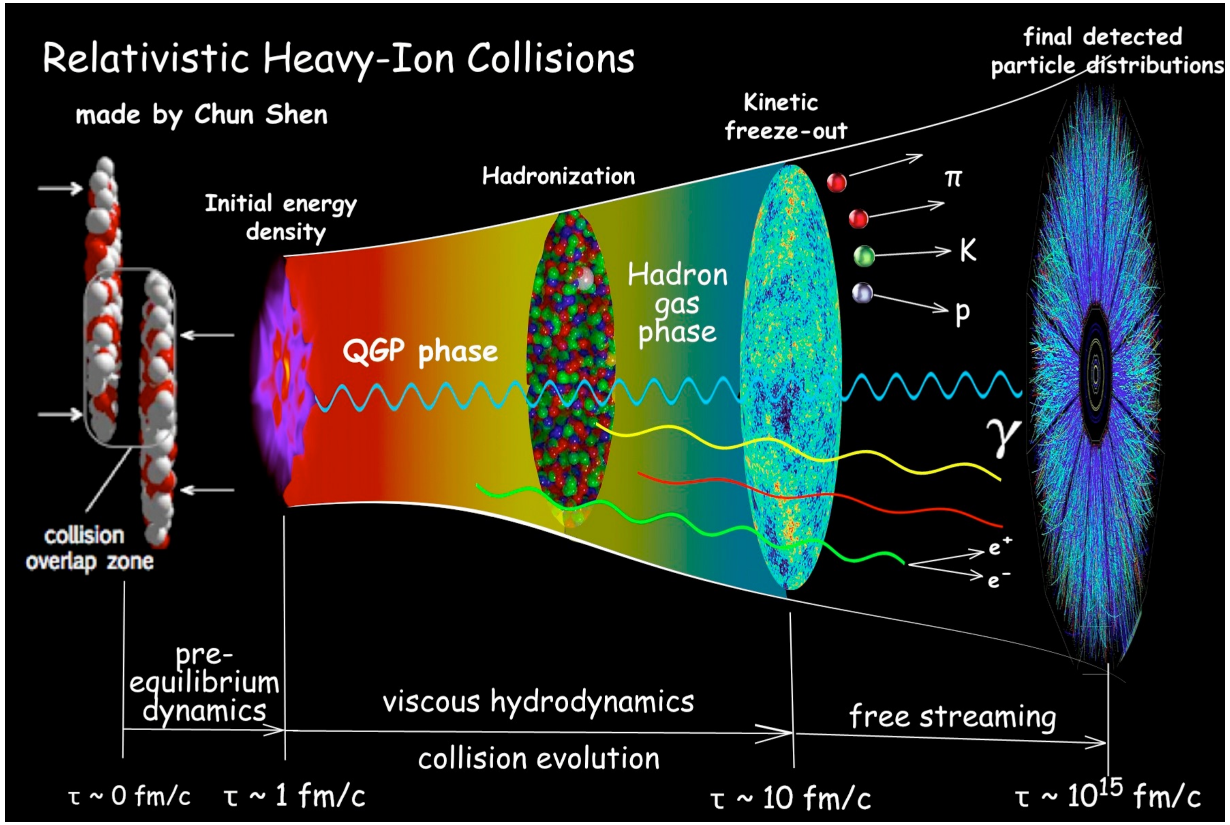
Experimental results on hot and dense matter physics in heavy ion reactions

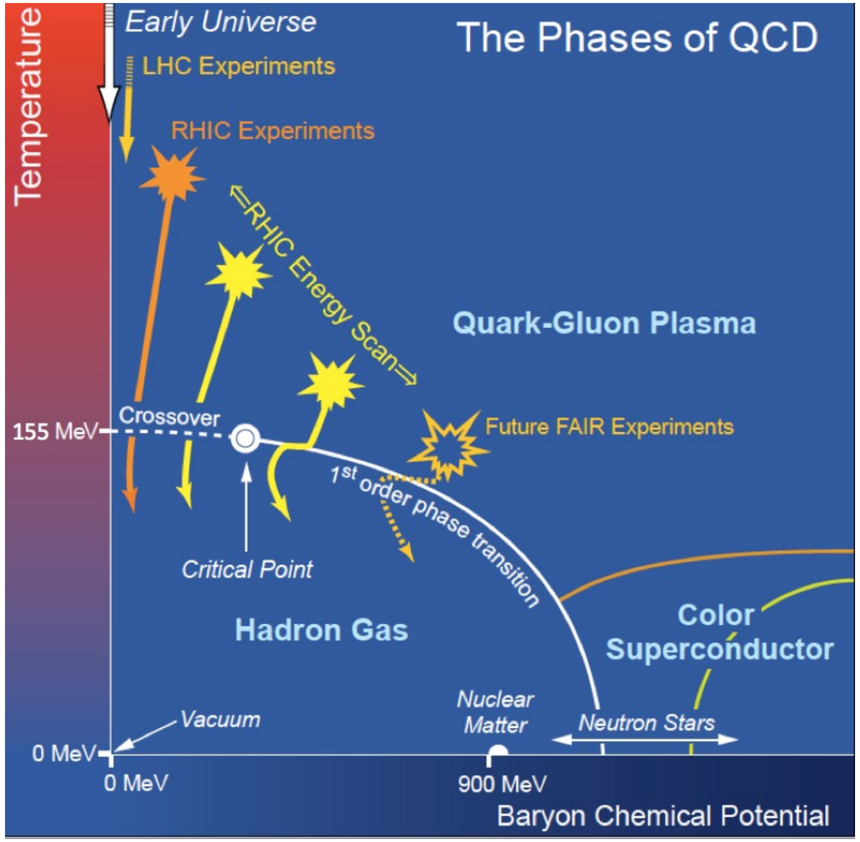
Bedangadas Mohanty
National Institute of Science Education and Research, India

9th September 2021

Relativistic Heavy Ion Collisions

Study the phase structure of QCD phase diagram





Quark gluon phase and properties – what we know so far

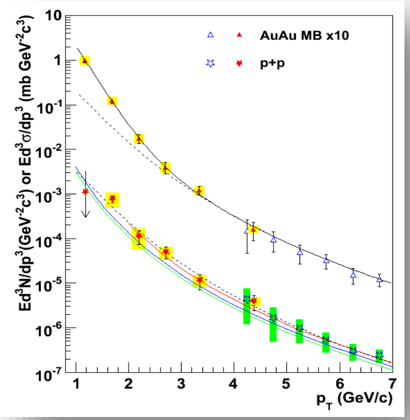
QCD matter produced in relativistic heavy ion collisions have **quark and gluon degrees of freedom.**

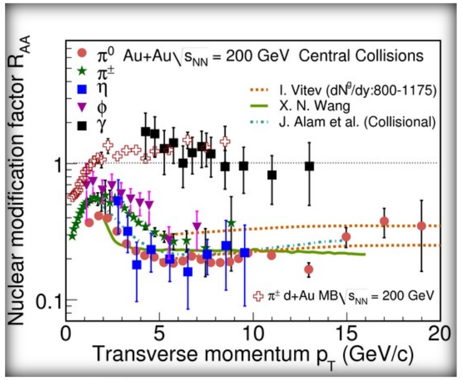
Matter attained ***high temperature,*** has **large energy density** and **opacity,** and exhibits ***partonic collectivity.***

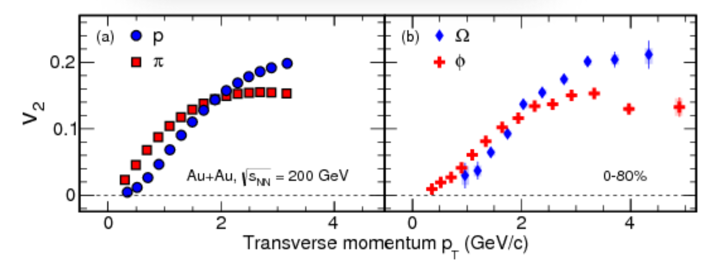
Shows emergent properties like:

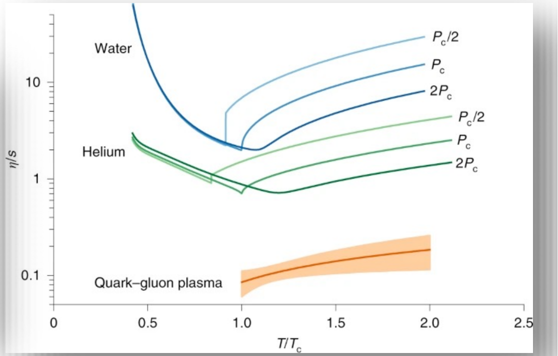
(1) ***Perfect fluid***
(2) Most ***vortical fluid***
(3) ***Heavy-quarks*** exhibiting ***Brownian motion*** in fluid of light quarks.

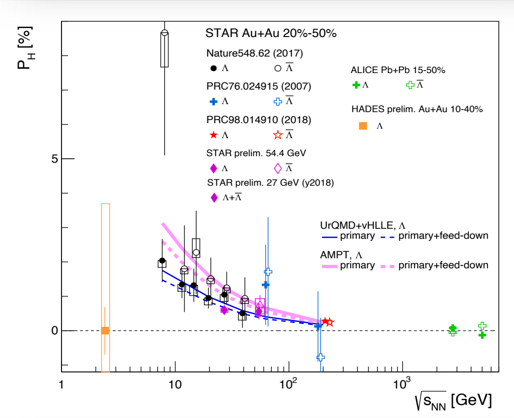
Nature Physics 15, 1113 (2019)
Phys.Rev.Lett. 116 (2016) 6, 062301
Nature 548 (2017) 62-65
Phys.Rev.Lett. 118 (2017) 21, 212301
New J.Phys. 13 (2011) 065031
Phys.Rev.Lett. 104 (2010) 132301

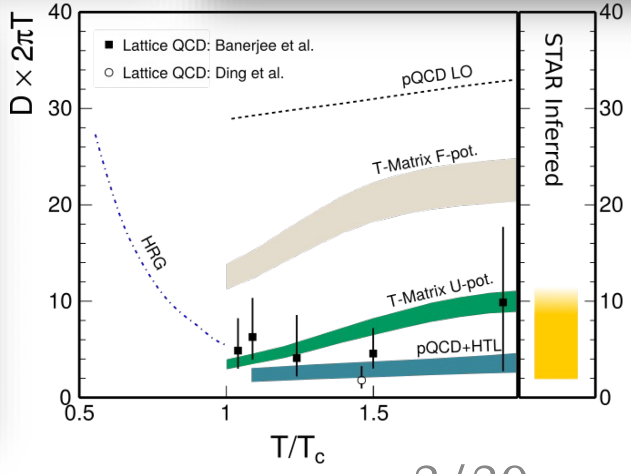






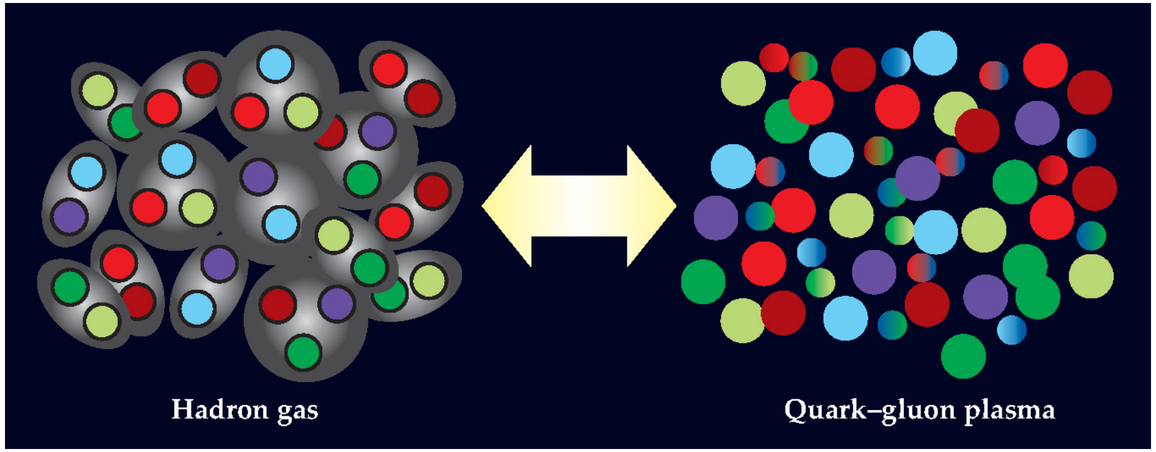






What this talk will cover

Physics Today **63**, 5, 39 (2010)



Phase diagram of QCD

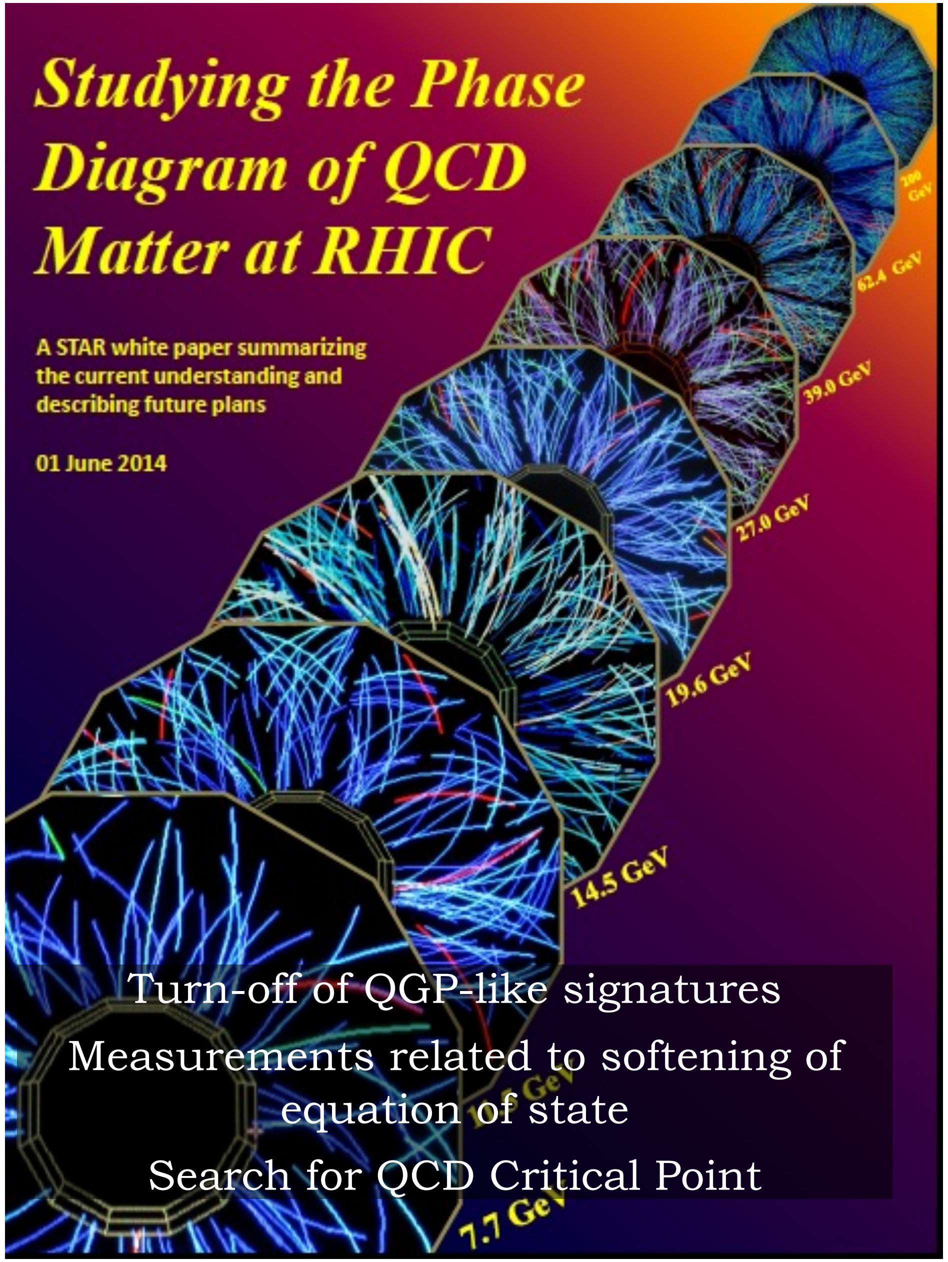
Initial state effects

Surprises in small system collisions

Heavy flavour and jet quenching related measurements

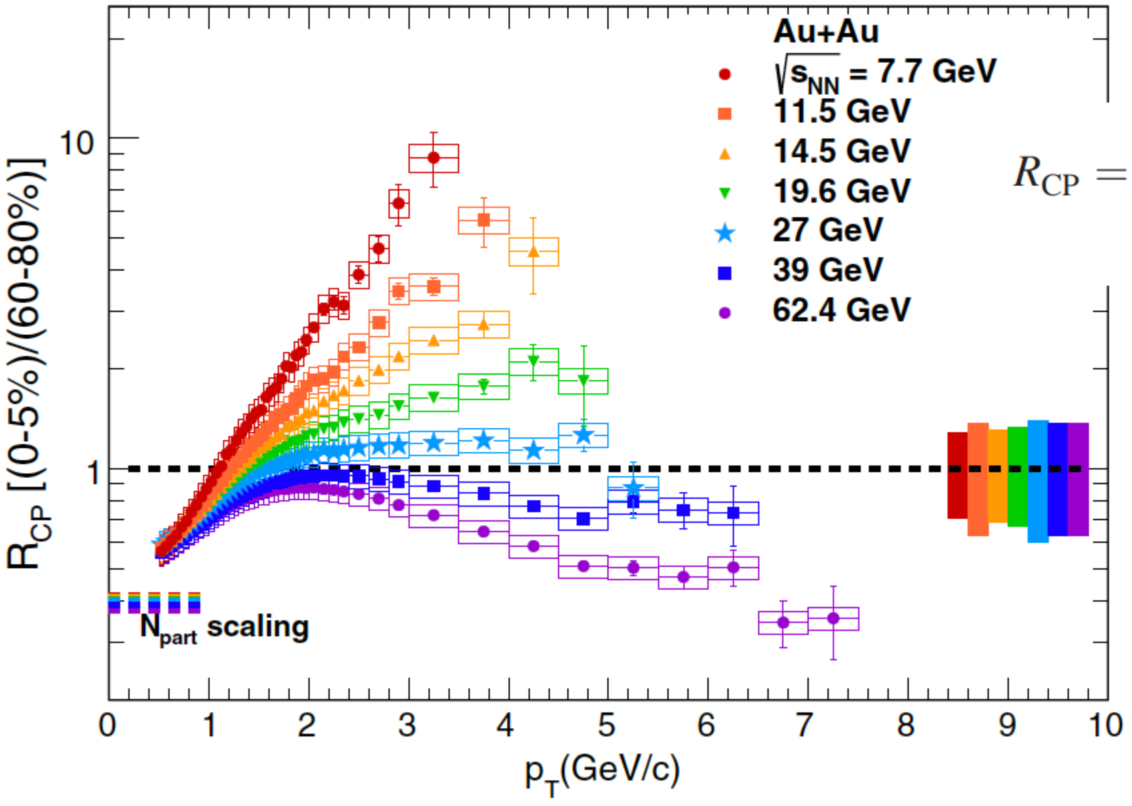
Other interesting measurements

Phase Diagram of QCD & Beam Energy Scan Program

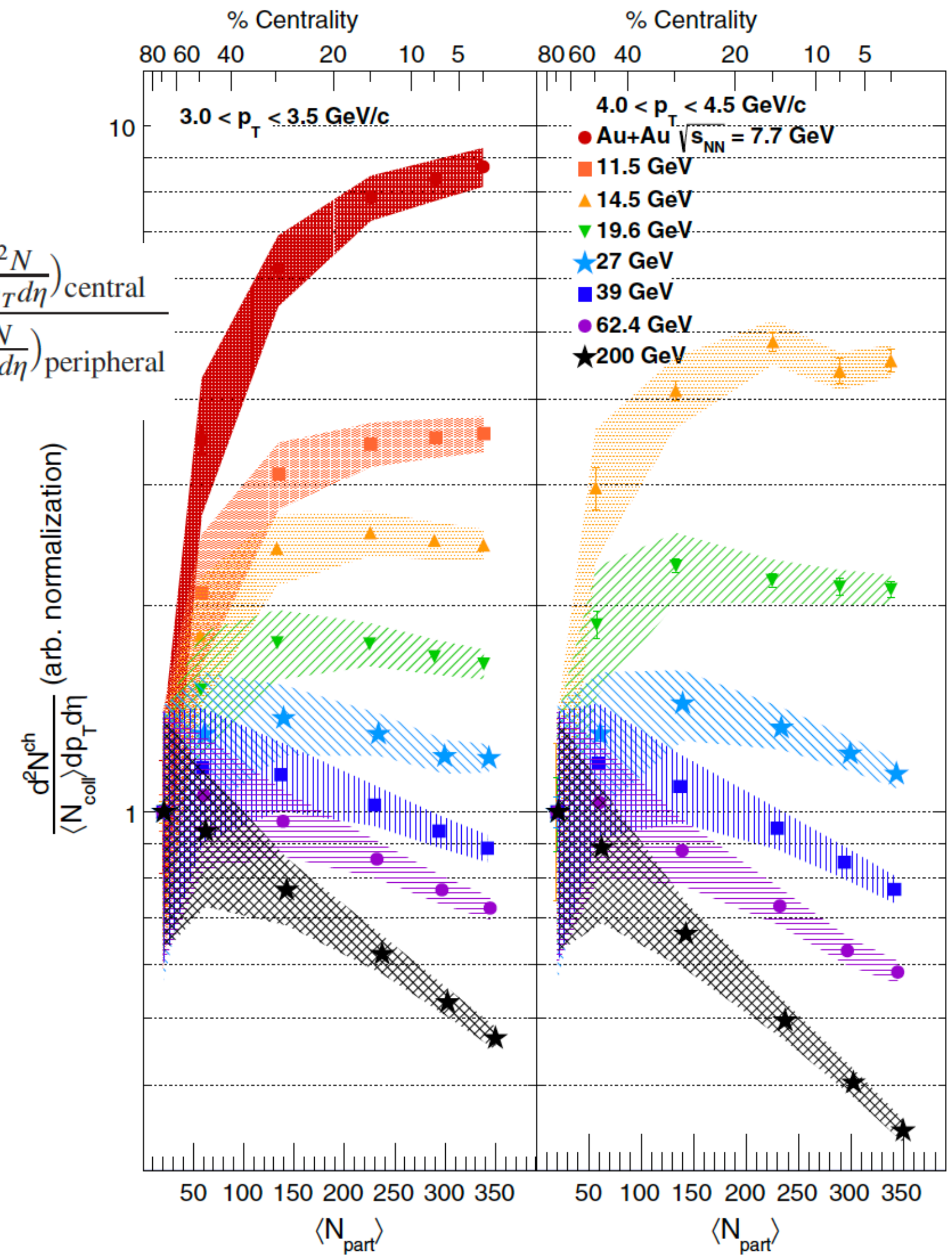


See also talk by - NA61/SHINE
Maja Mackowiak-Pawlowsk

Nuclear modification factor



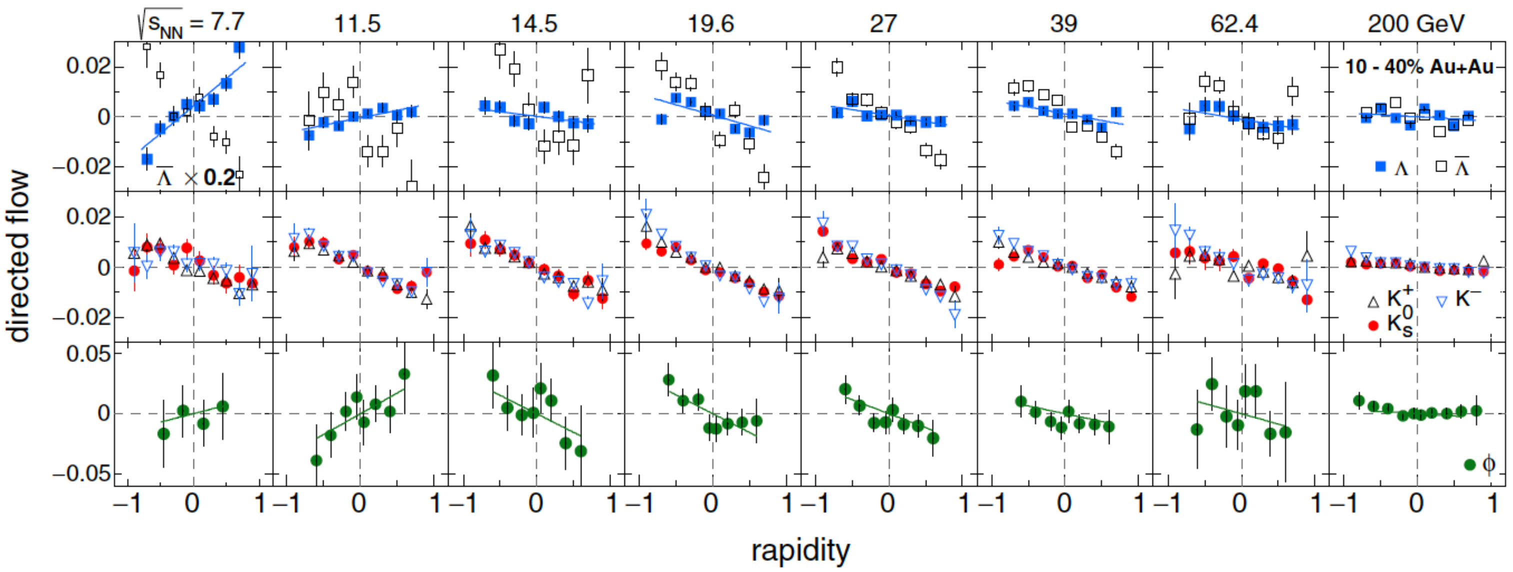
$$R_{CP} = \frac{\langle N_{coll} \rangle_{peripheral}}{\langle N_{coll} \rangle_{central}} \frac{\left(\frac{d^2N}{dp_T d\eta}\right)_{central}}{\left(\frac{d^2N}{dp_T d\eta}\right)_{peripheral}}$$



(1) At the highest transverse momentum measured, nuclear modification factor transits from less than unity to more than unity.
(2) Partonic degrees of freedom to dominance of hadronic degrees of freedom at lower collision energies.

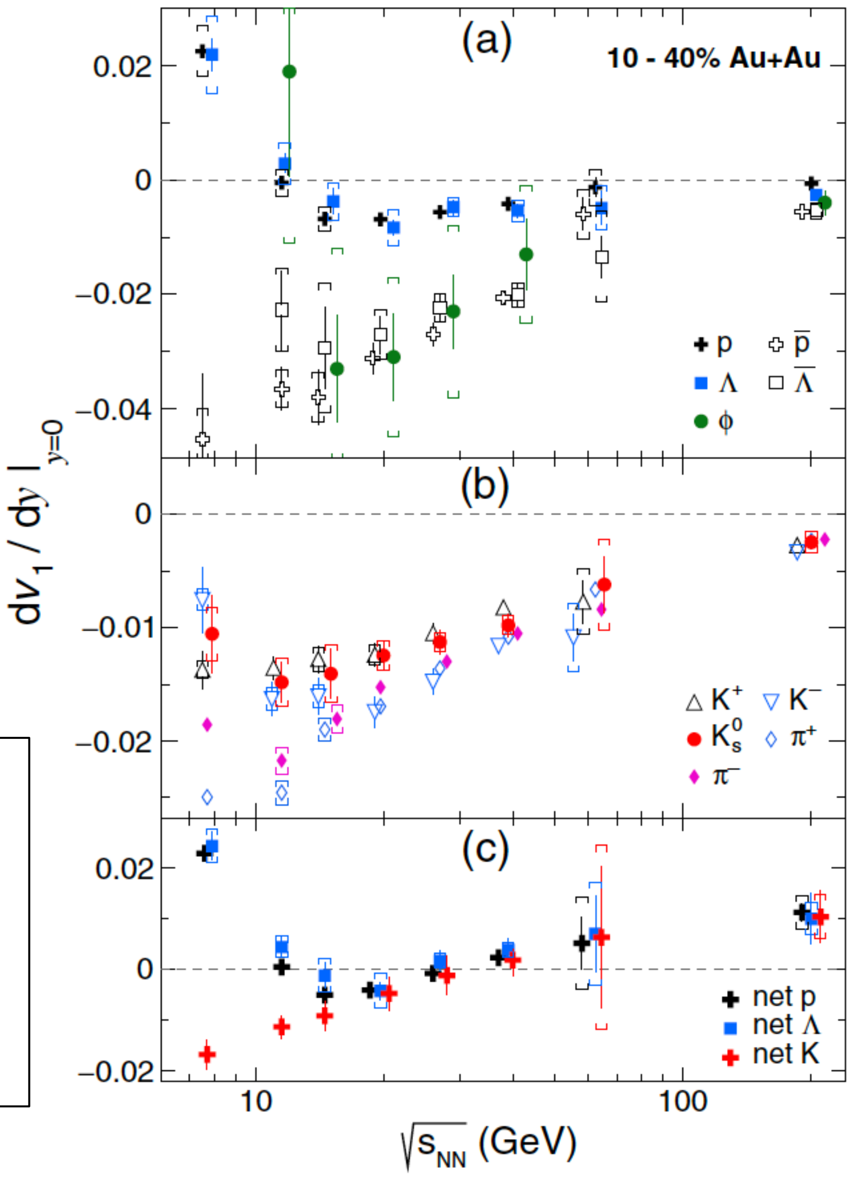
PHYSICAL REVIEW LETTERS 121, 032301 (2018)

Measurements related to softening of equation of state



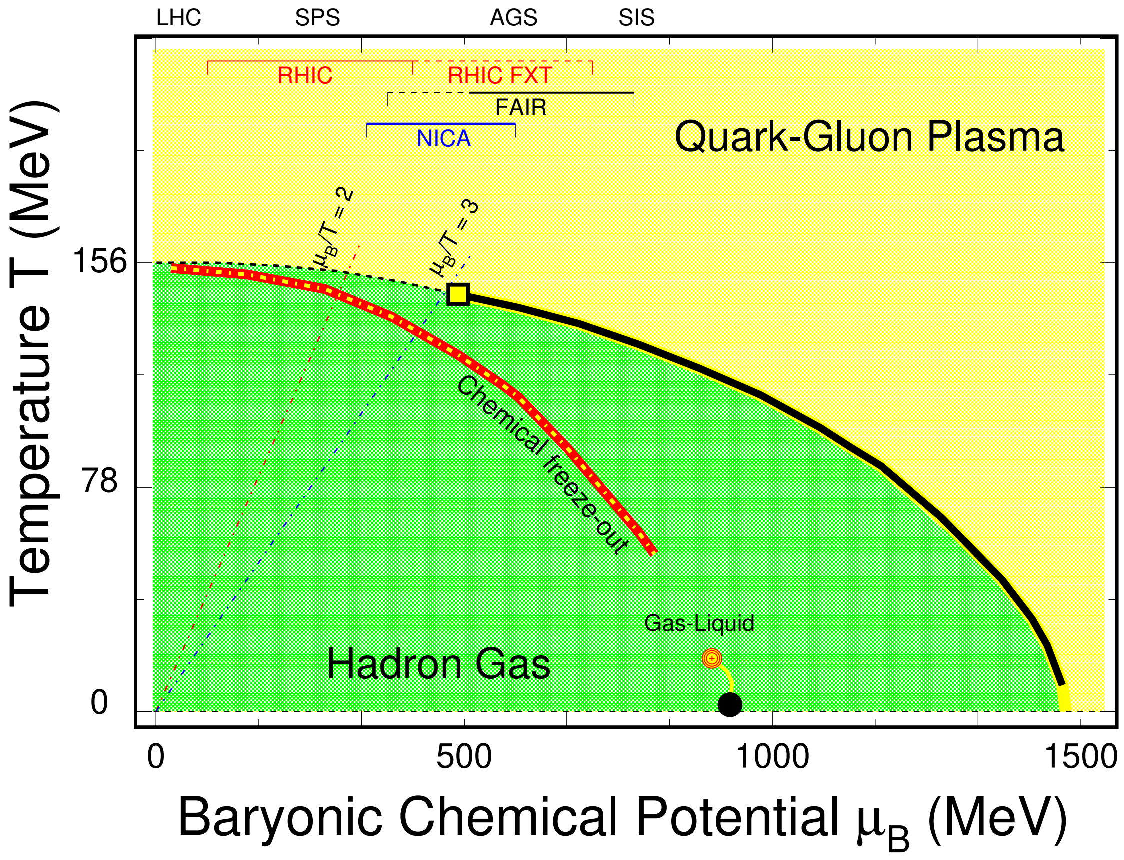
$$v_1 = \langle \cos(\phi - \Psi_{RP}) \rangle,$$

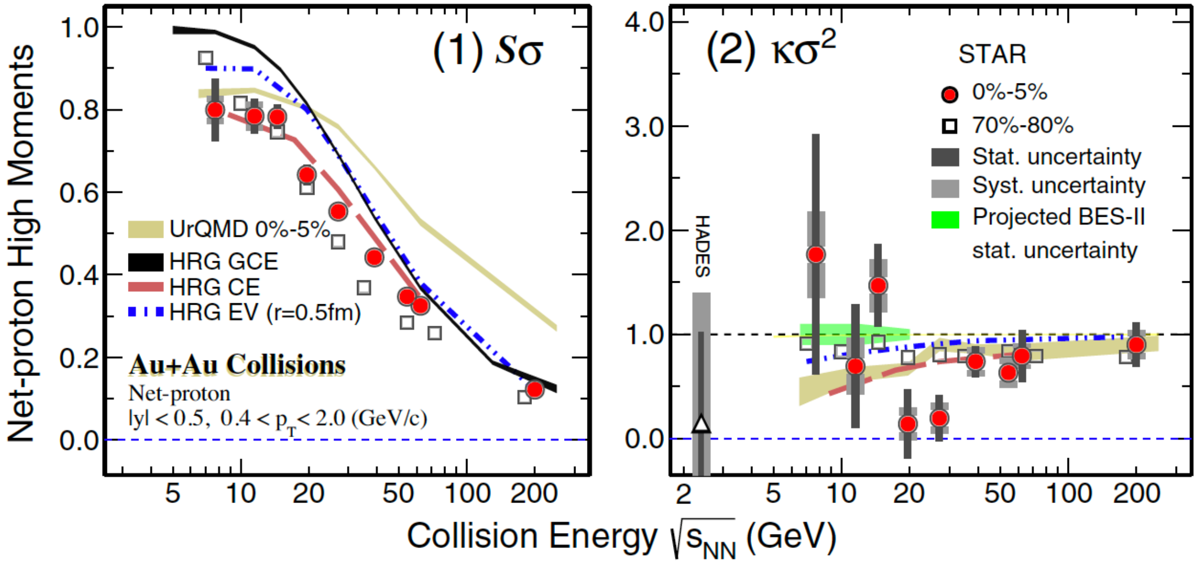
(1) The directed flow slopes for protons and Λ's change sign near 11.5 GeV – nonmonotonic variation.
(2) There is a turn-off below 11.5 GeV for quark coalescence sum rule behaviour.
(3) Transition from partonic degrees of freedom to dominance of hadronic degrees of freedom.

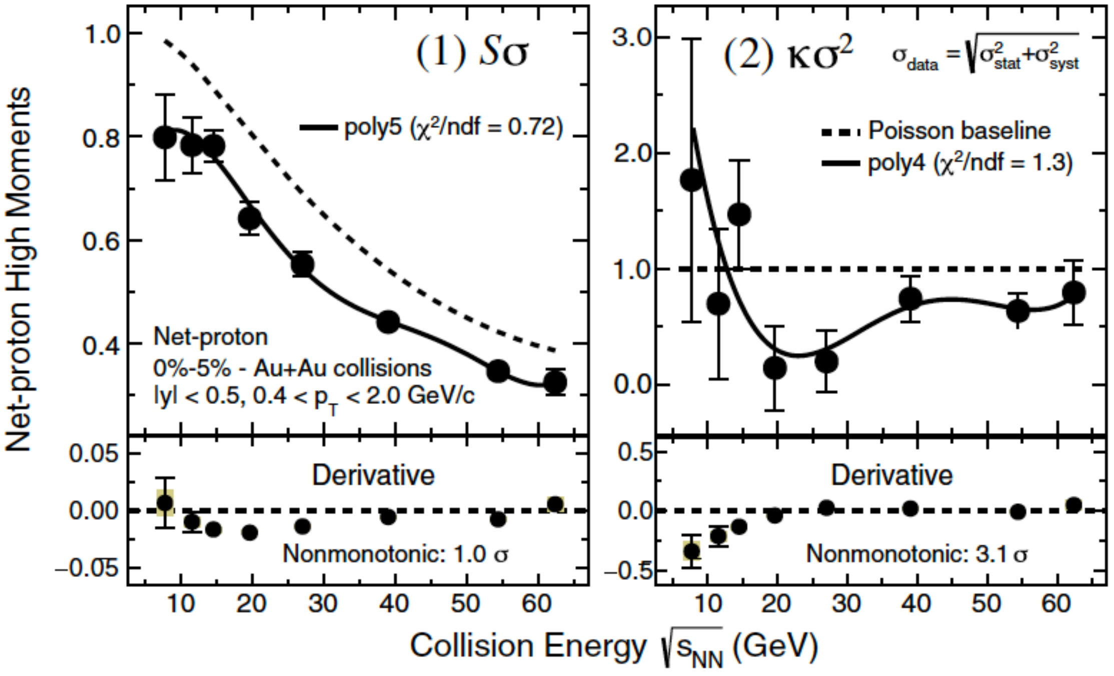


PHYSICAL REVIEW LETTERS 120, 062301 (2018)

QCD critical point search

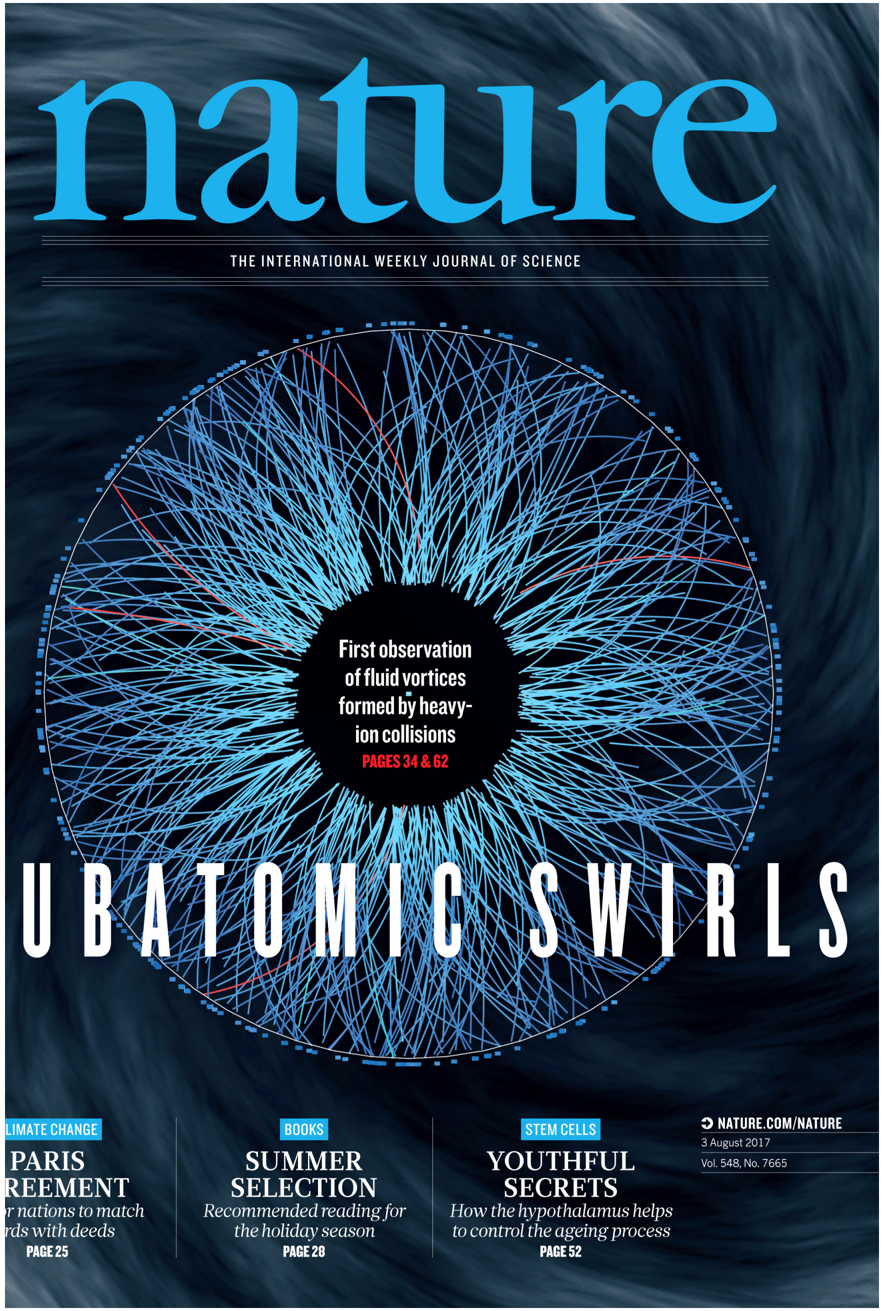




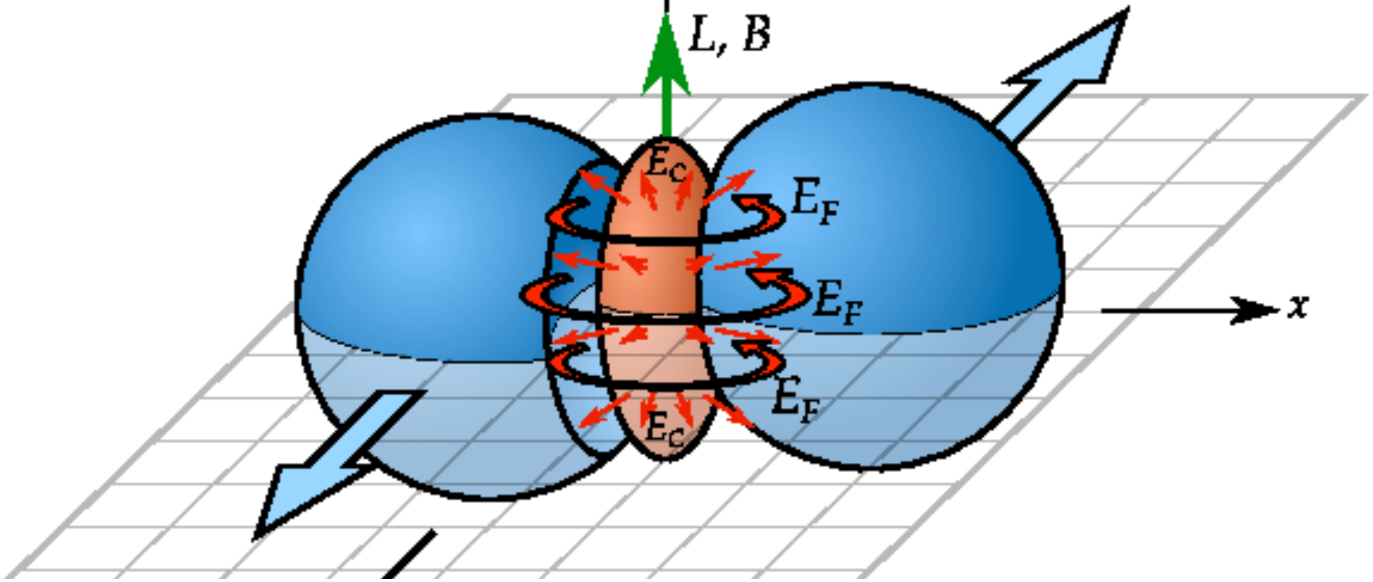


(1) Nonmonotonic variation of observable with collision energy at 3 σ level.
(2) Higher statistics data collected in Beam Energy Scan -Phase-II.

PHYSICAL REVIEW LETTERS 126, 092301 (2021)

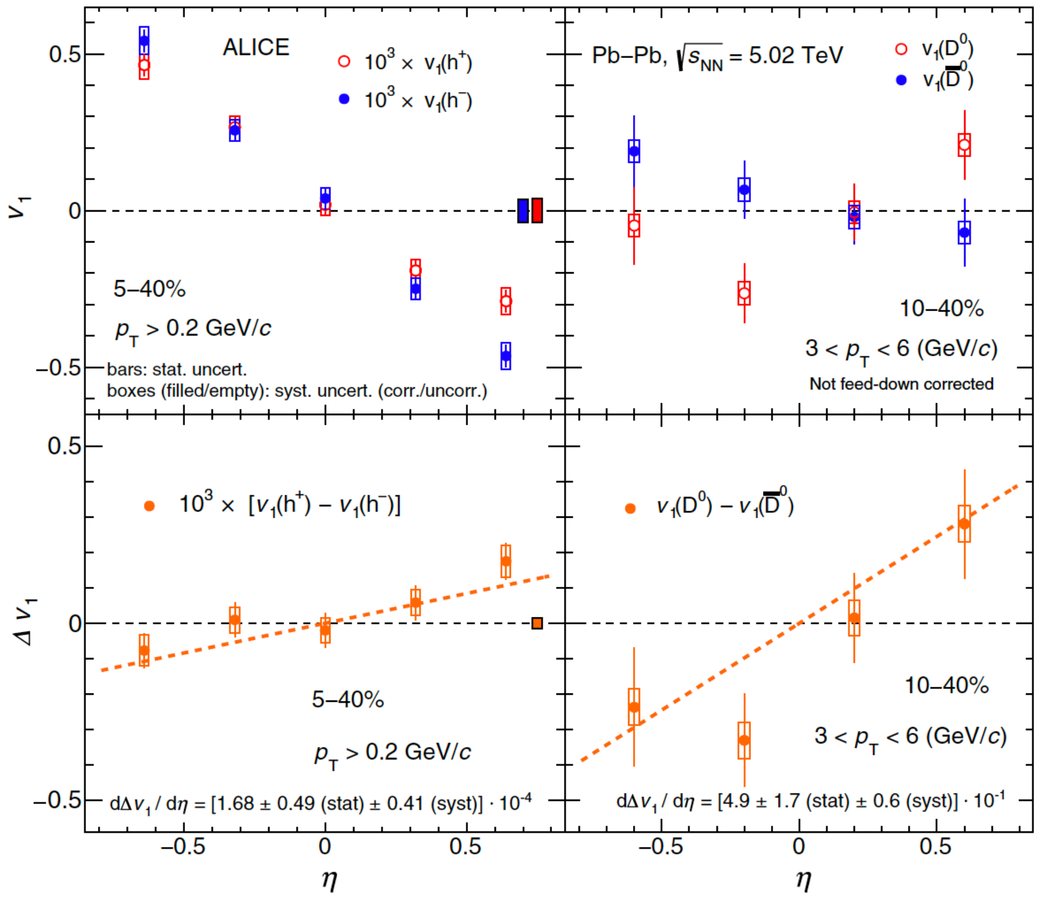


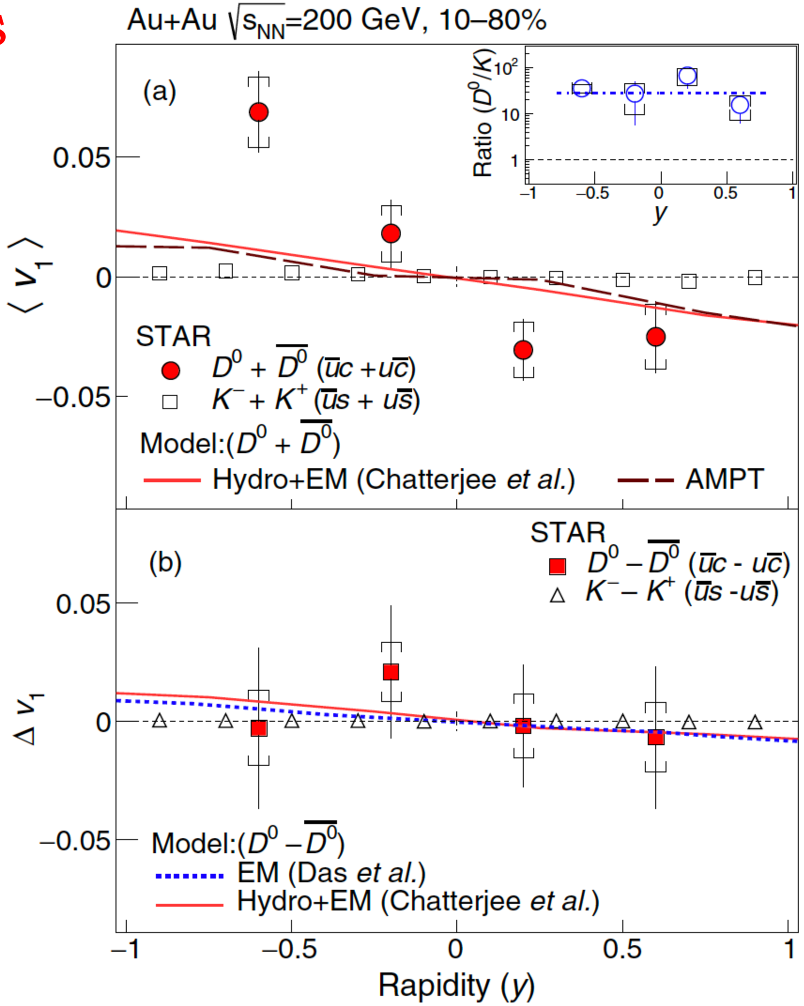
$B \sim 10^{18}$ Gauss $\qquad L \sim 10^5\ \hbar$



Measurements sensitive to initial magnetic field and angular momentum

D-meson directed flow and electromagnetic fields

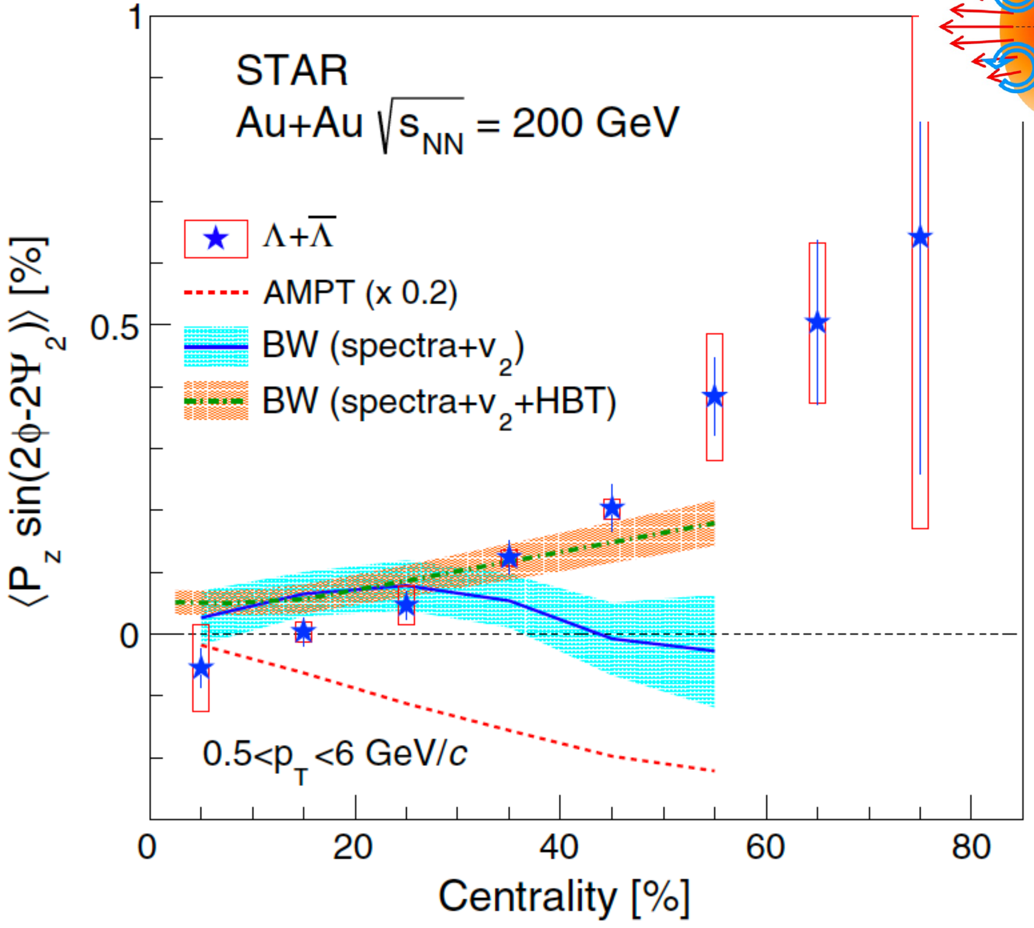


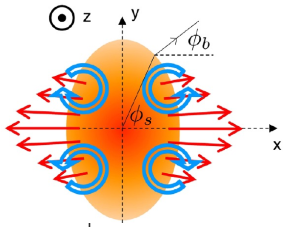


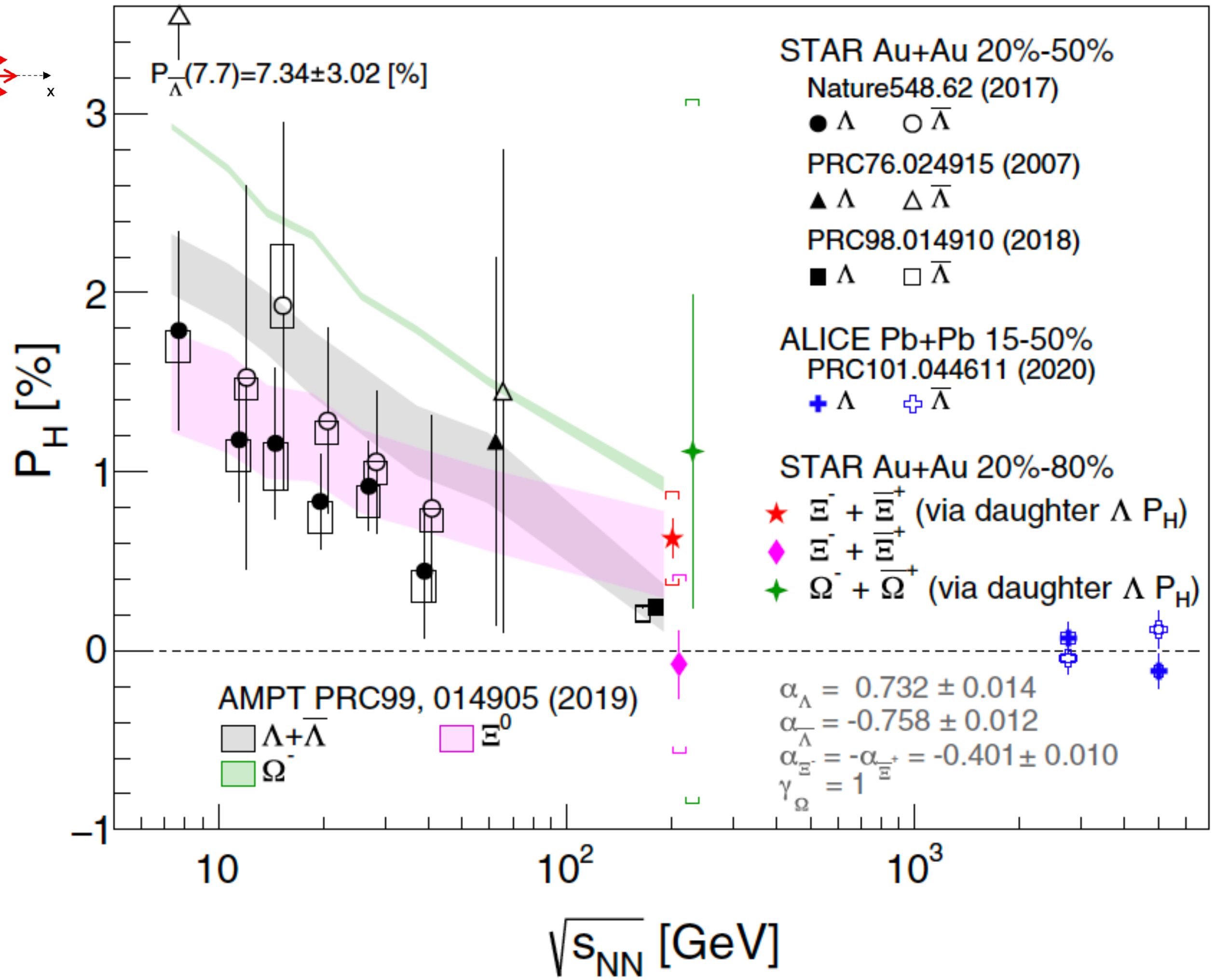
(1) RHIC: D_0 meson dv_1/dy is about 25 times larger than that for charged kaons at 3.4σ.
(2) LHC: D_0 meson dv_1/dy is 1000 times larger than charged hadrons with 2.6σ.
(3) Relative contributions of the Lorentz and Faraday effects.

PHYSICAL REVIEW LETTERS 125, 022301 (2020) PHYSICAL REVIEW LETTERS 123, 162301 (2019)

Polarization of QGP







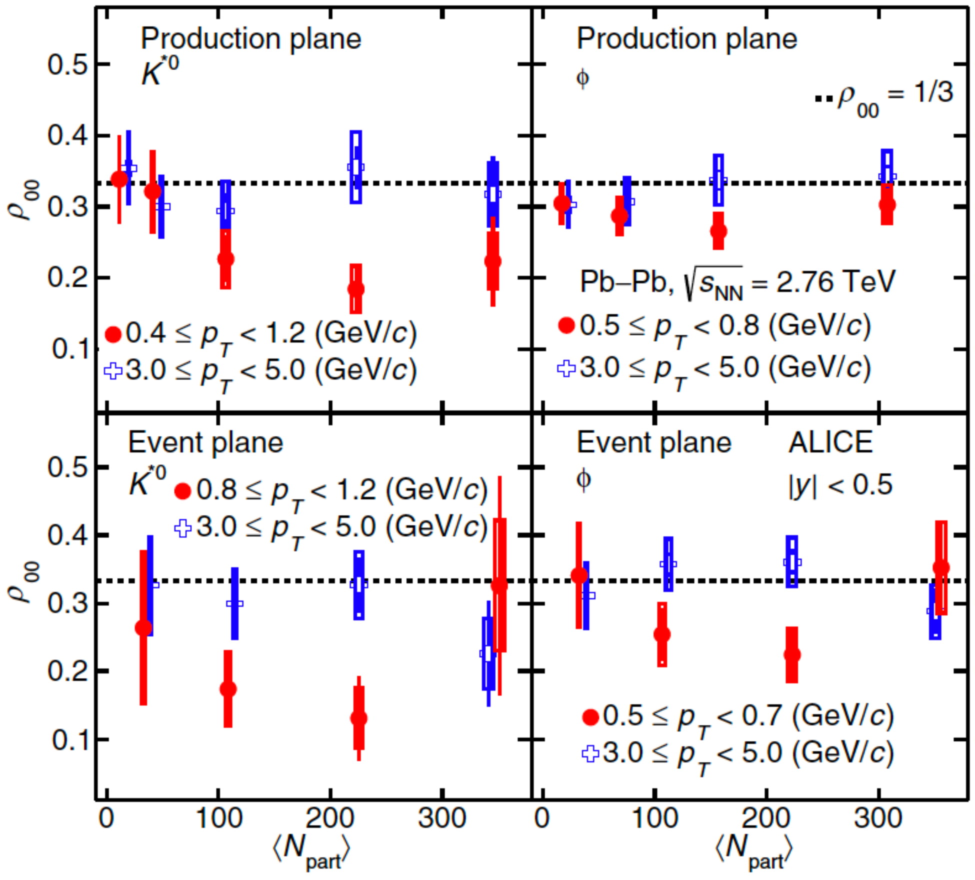
$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_H P_H \cos\theta^*$$

$$\frac{dN}{d\Omega^*} = \frac{1}{4\pi}(1 + \alpha_H \mathbf{P}_H^* \cdot \hat{\boldsymbol{p}}_B^*)$$

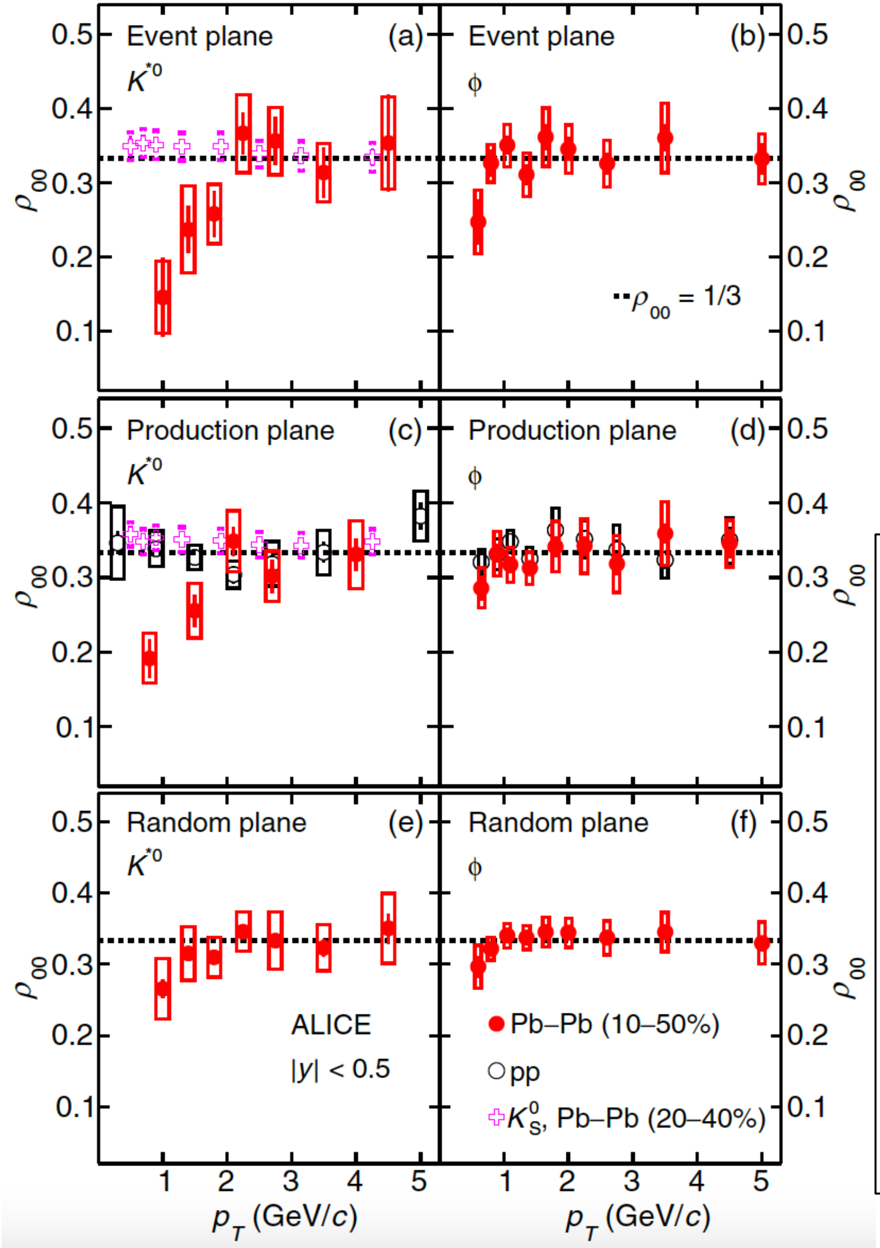
(1) Global polarization picture based on the system fluid vorticity.
(2) Measured polarization exhibit a centrality dependence as expected from the impact parameter dependence of the vorticity.

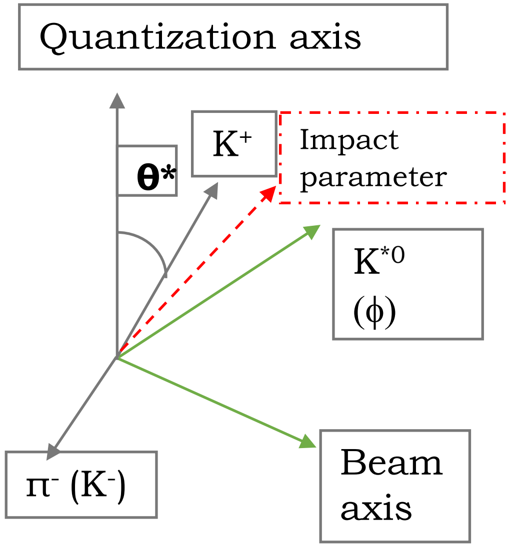
PHYSICAL REVIEW LETTERS 123, 132301 (2019) PHYSICAL REVIEW LETTERS 126, 162301 (2021)

Spin alignment of vector mesons



$$\frac{dN}{d\cos\theta^*} \propto [1 - \rho_{00} + \cos^2\theta^*(3\rho_{00} - 1)]$$





(1) Signals at 3σ level.
(2) Qualitatively consistent with models: polarization of quarks in the presence of angular momentum and a subsequent hadronization by the process of recombination.

PHYSICAL REVIEW LETTERS 125, 012301 (2020)

See also talk by Dukhishyam Mallick (ALICE)

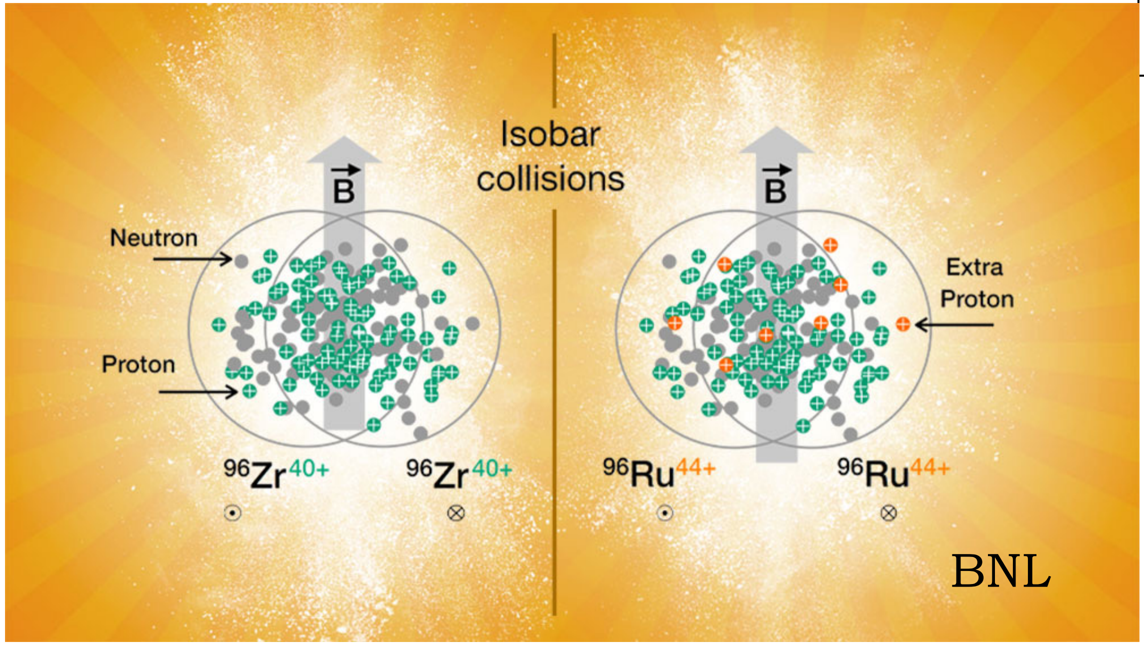
Chiral magnetic effect (CME)

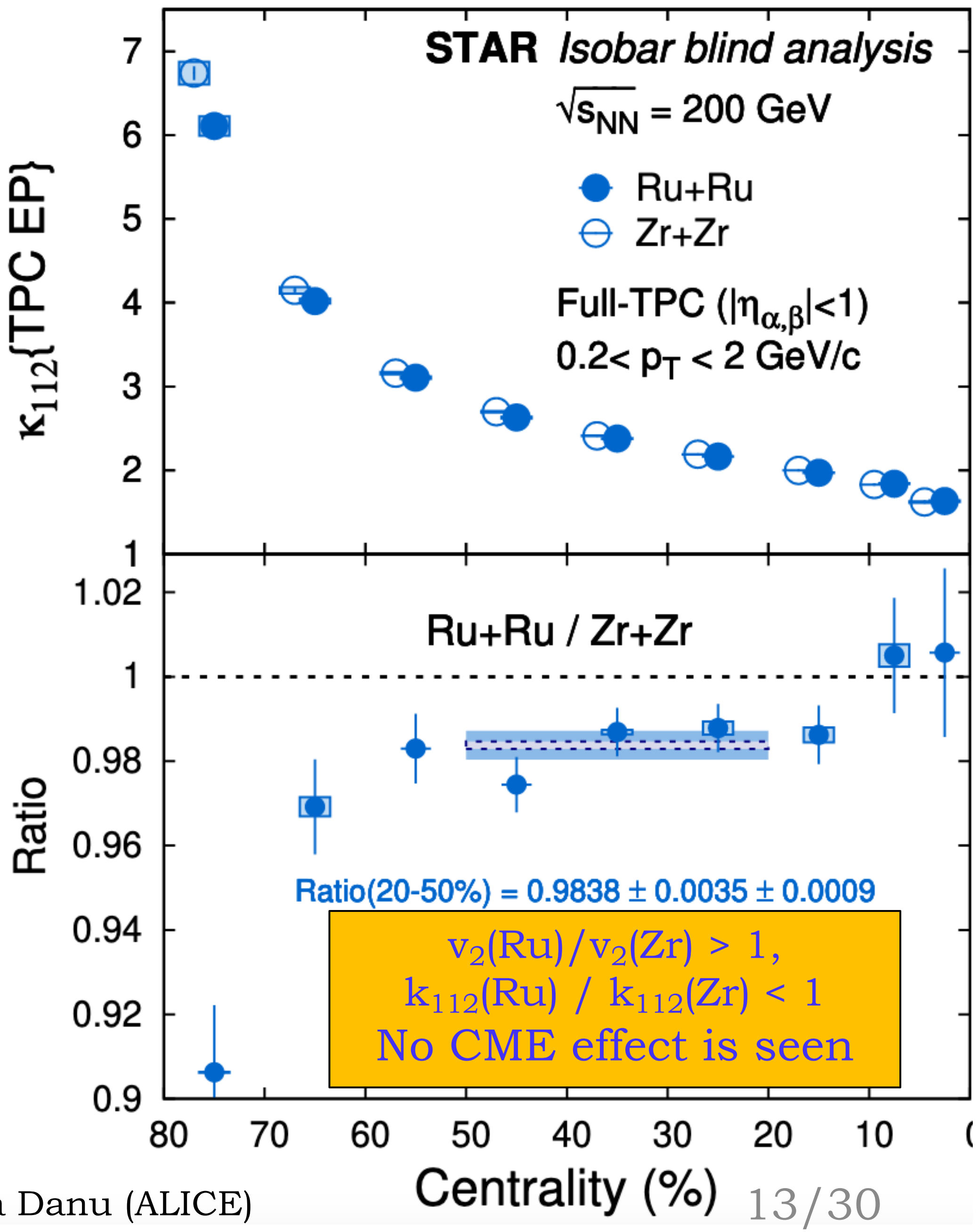
$$\kappa_{112} \equiv \frac{\Delta\gamma_{112}}{v_2 \cdot \Delta\delta}.$$

CME - due a local violation of P and CP symmetries of the strong interaction in presence of strong electro-magnetic field generated in relativistic heavy-ion collisions and QGP.

Experimental signal - separation of positively and negatively charged hadrons along the direction of the magnetic field.

$$\frac{\kappa_{112}^{\mathrm{Ru+Ru}}}{\kappa_{112}^{\mathrm{Zr+Zr}}} > 1.$$





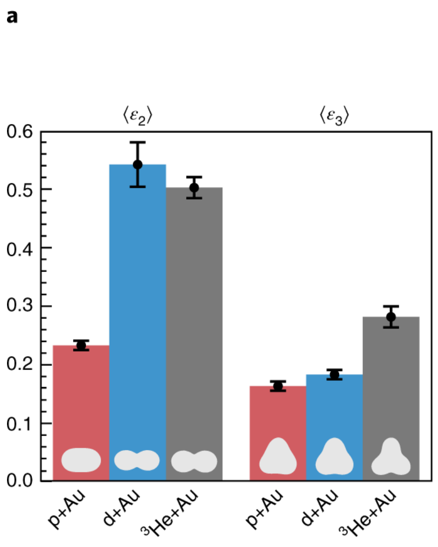
$v_2(\mathrm{Ru})/v_2(\mathrm{Zr}) > 1$,
$k_{112}(\mathrm{Ru}) / k_{112}(\mathrm{Zr}) < 1$
No CME effect is seen

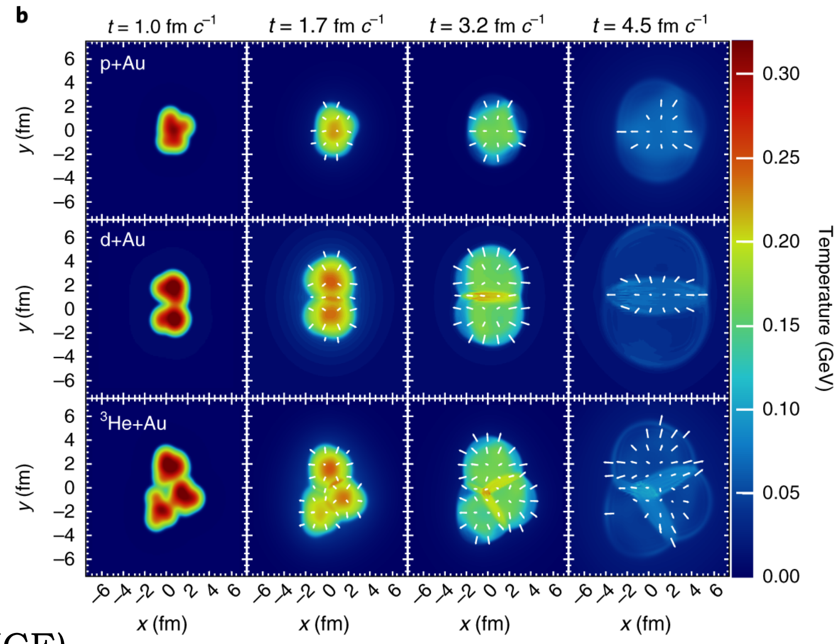
https://arxiv.org/abs/2109.00131

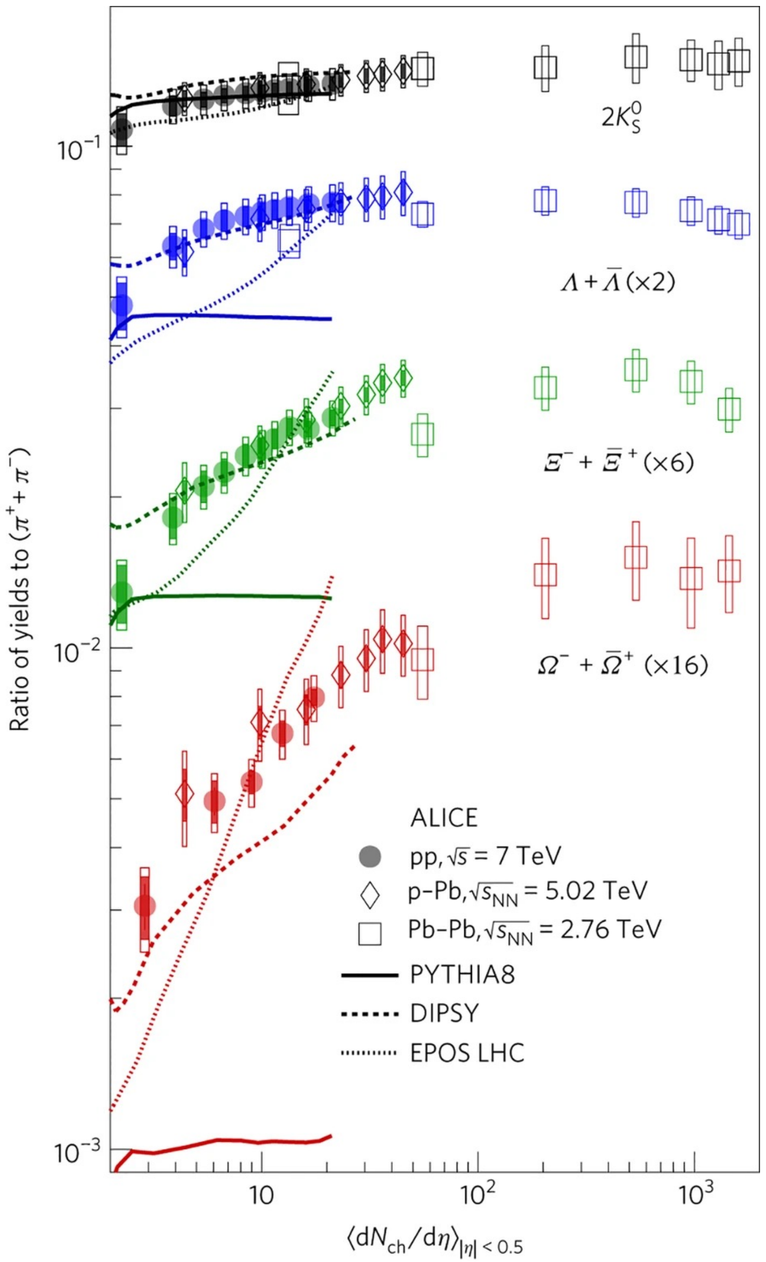
See also talk by Andrea Danu (ALICE)

Small System - Surprises

Nature Physics 13, 535–539 (2017)
Nature Physics 15, 214–220 (2019)

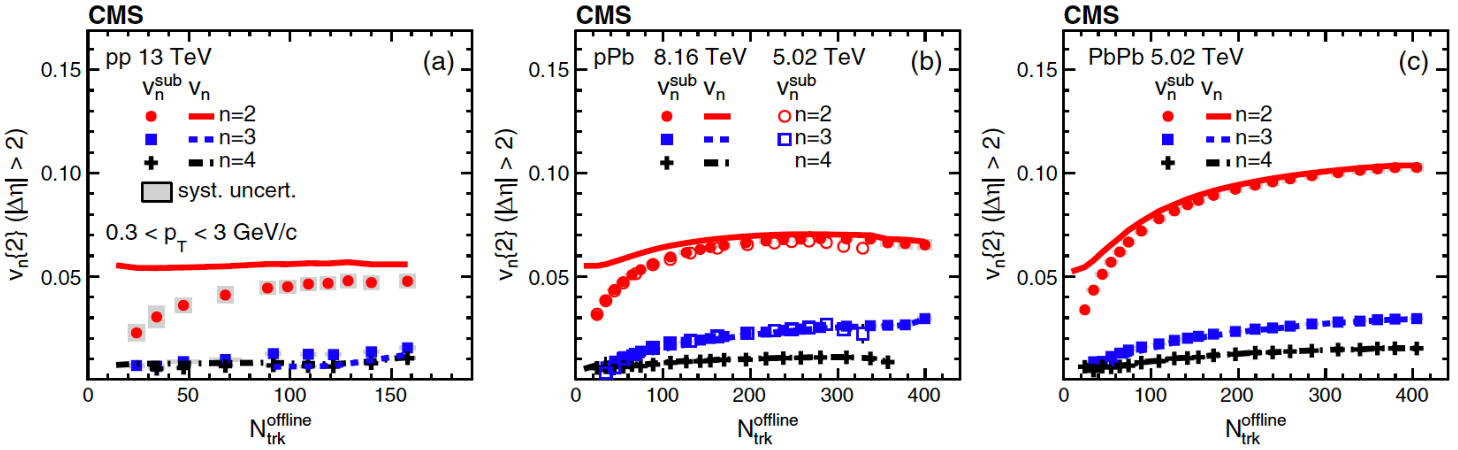


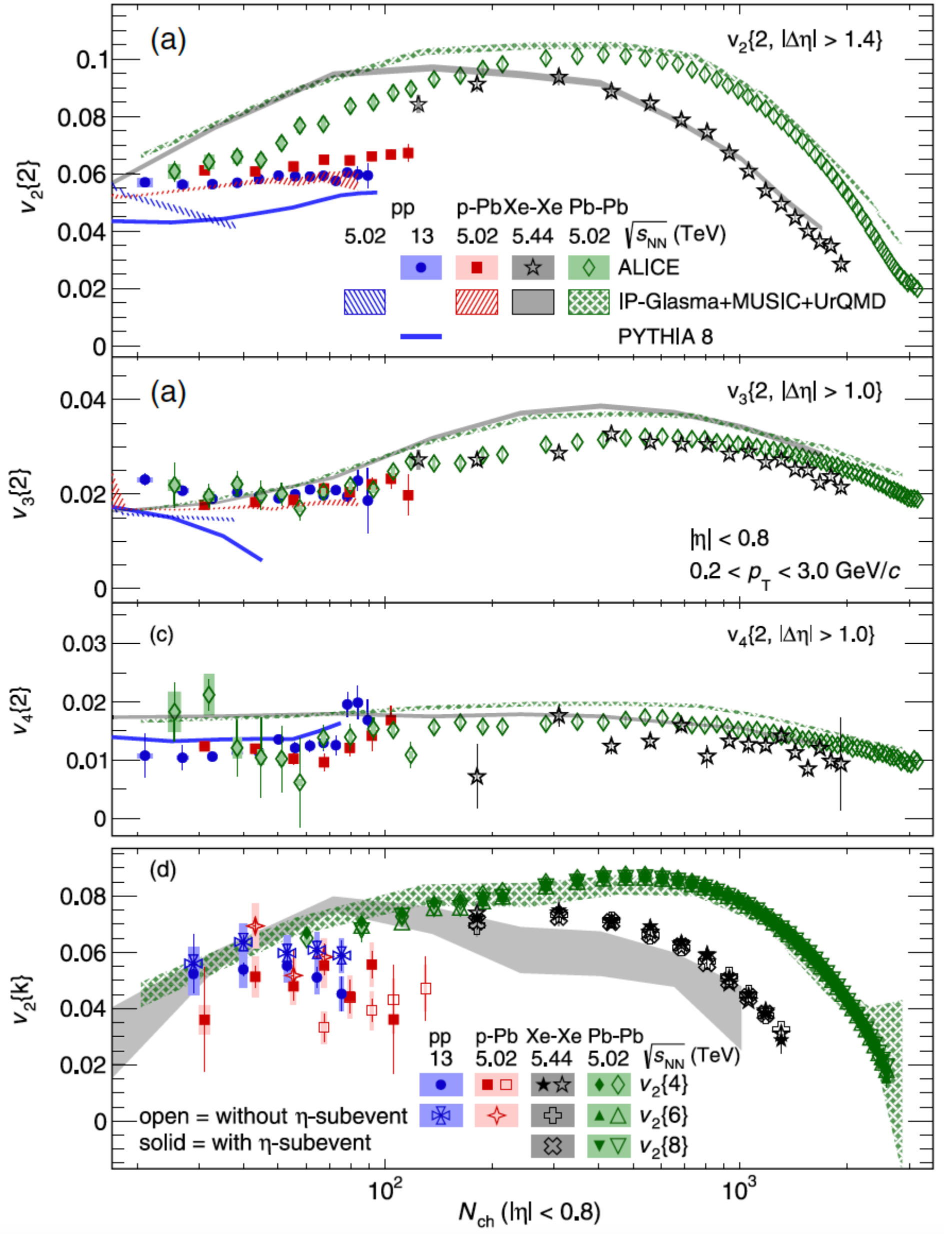




See also talk by Chiara De Martin (ALICE)

Significant collectivity in small systems at LHC





(1) Is there a common origin of the collectivity seen in pPb and Pb-Pb collisions in the measured multiplicity range?

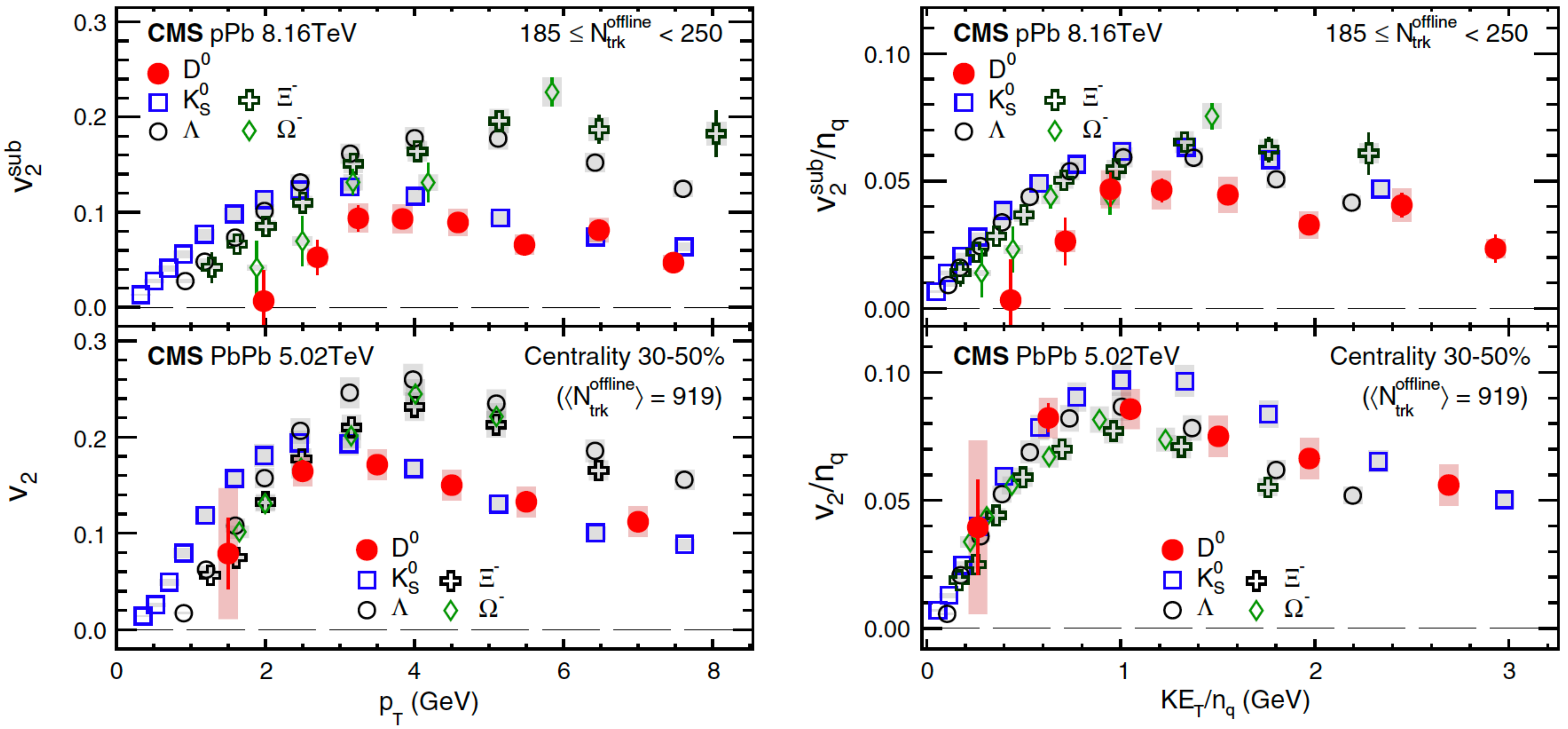
(2) Multiparticle azimuthal correlations in high multiplicity pp and p-Pb collisions can neither be described by PYTHIA 8 nor by impact-parameter-Glasma, MUSIC, and ultra relativistic quantum molecular dynamics model calculations.

(3) Provide new insights into the understanding of collective effects in small collision systems.

PHYSICAL REVIEW LETTERS 120, 092301 (2018) PHYSICAL REVIEW LETTERS 123, 142301 (2019)

See also talk by Dominik Derendarz (ATLAS) and Catalin Ristea (ALICE)

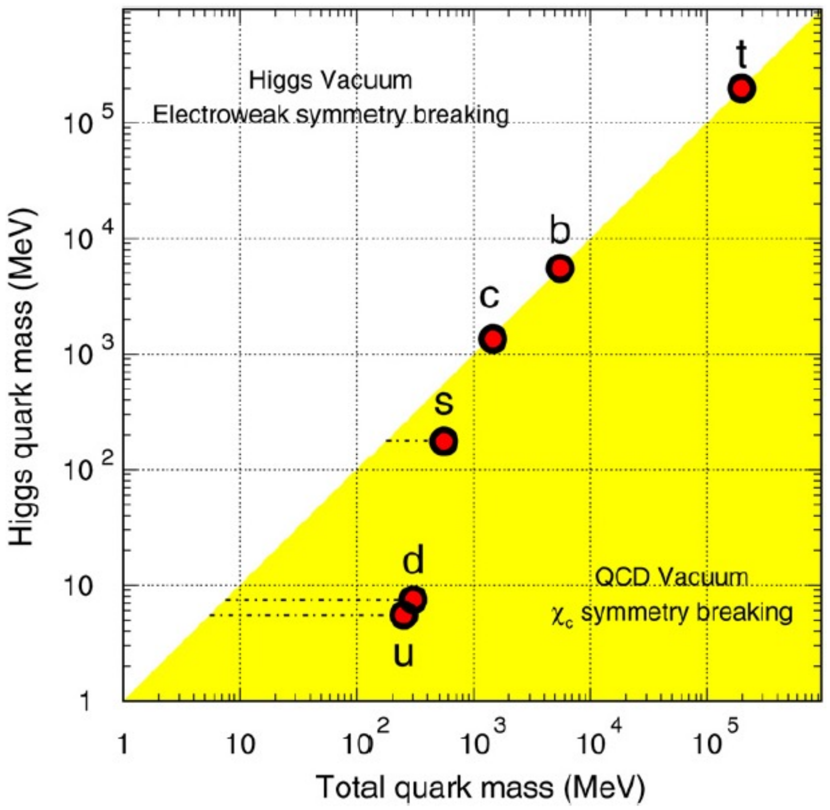
Number of constituent quark scaling in small system

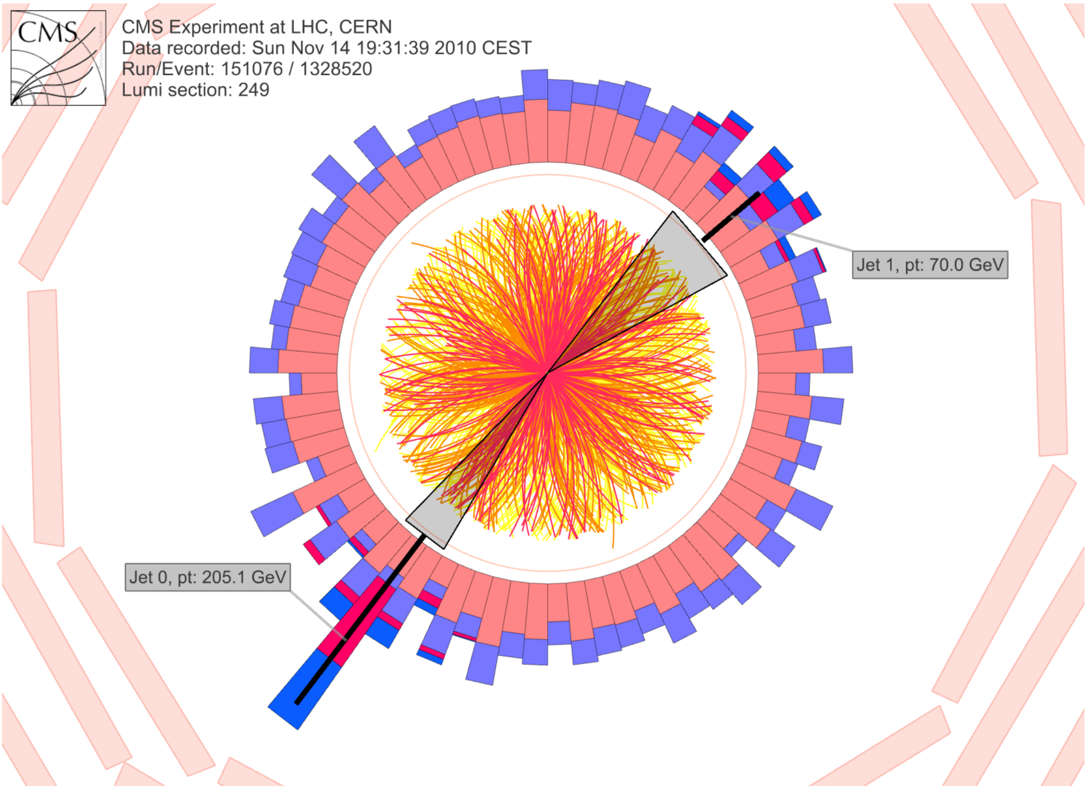


(1) D_0 v_2 values are found to be smaller in pPb than Pb-Pb compared to strange hadrons.
(2) High multiplicity pPb collisions, in contrast to larger nucleus-nucleus collision systems, the collective behaviour of charm quarks is weaker than that of the light-flavor quarks.

PHYSICAL REVIEW LETTERS 121, 082301 (2018)

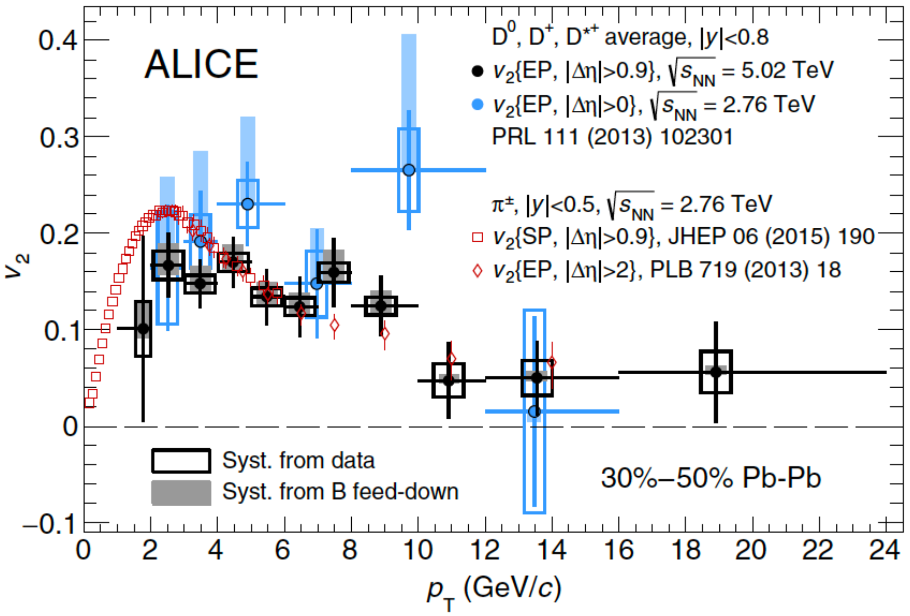
Heavy-Flavour and Jet Measurements

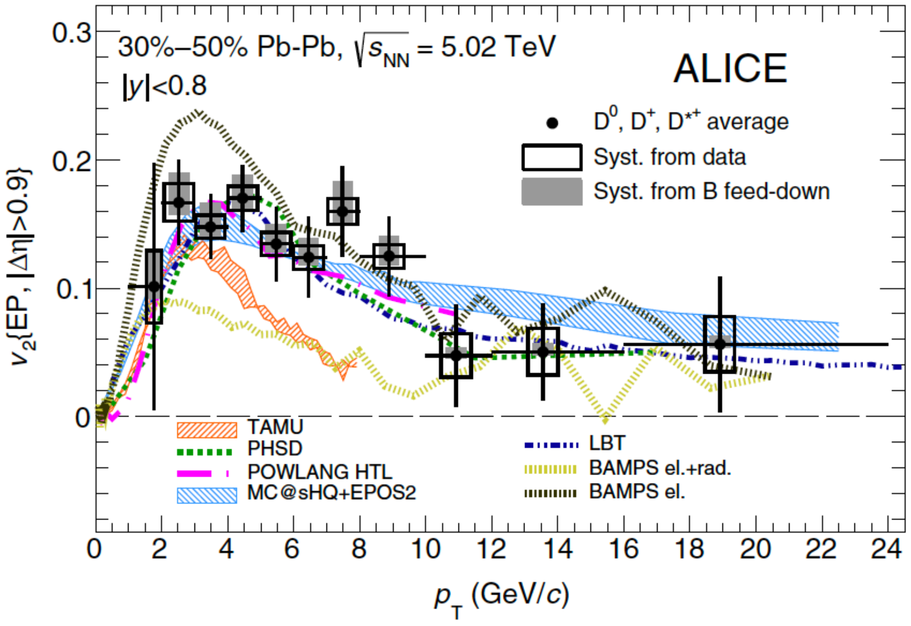


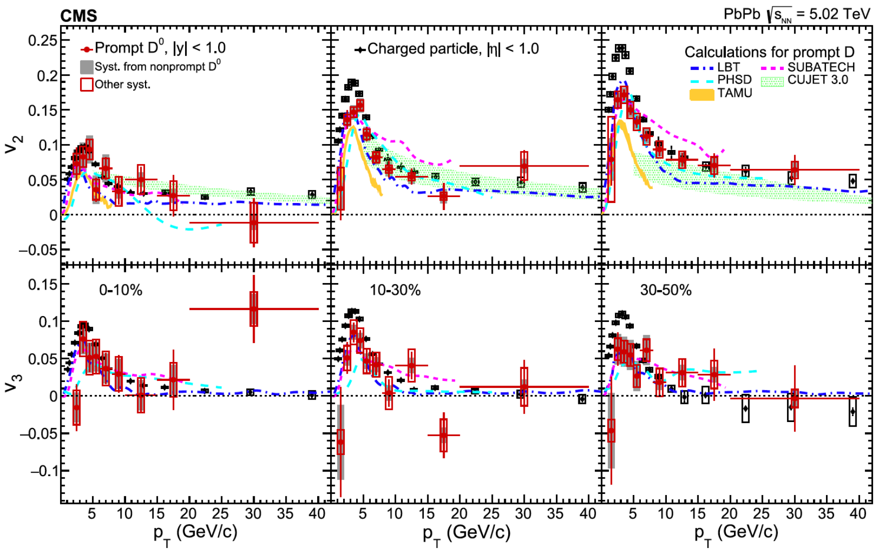


See also talks by: Isakov Artem (ALICE), Christopher McGinn (ATLAS); Mika Shibata (PHENIX); Reynier Cruz Torres (ALICE); Semen Turchikhin (ATLAS), Andrea Rossi (ALICE), Raghunath Pradhan (CMS), Jan Vanek (STAR)

Charm meson collectivity and diffusion co-efficient





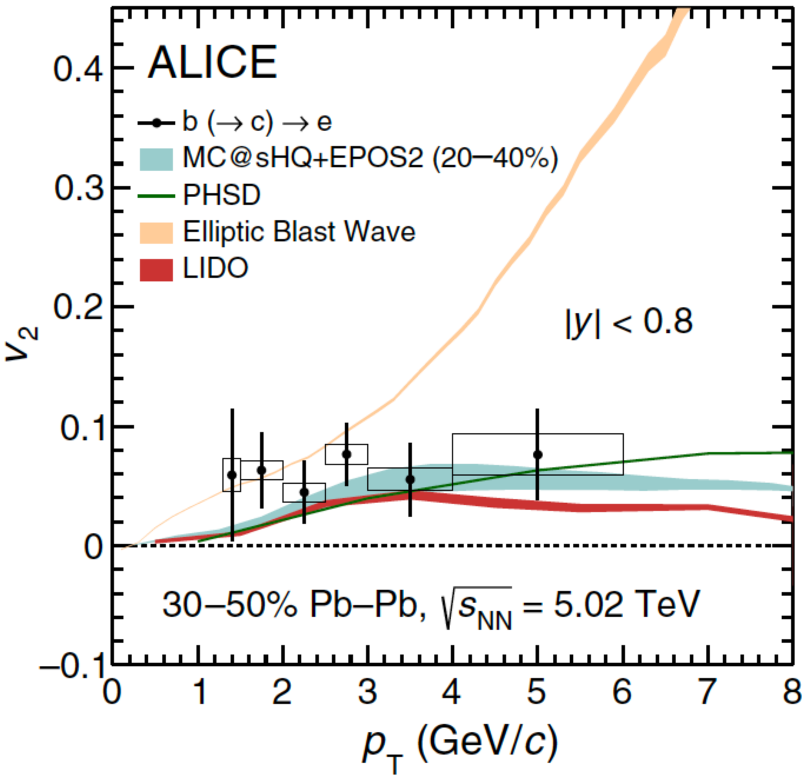


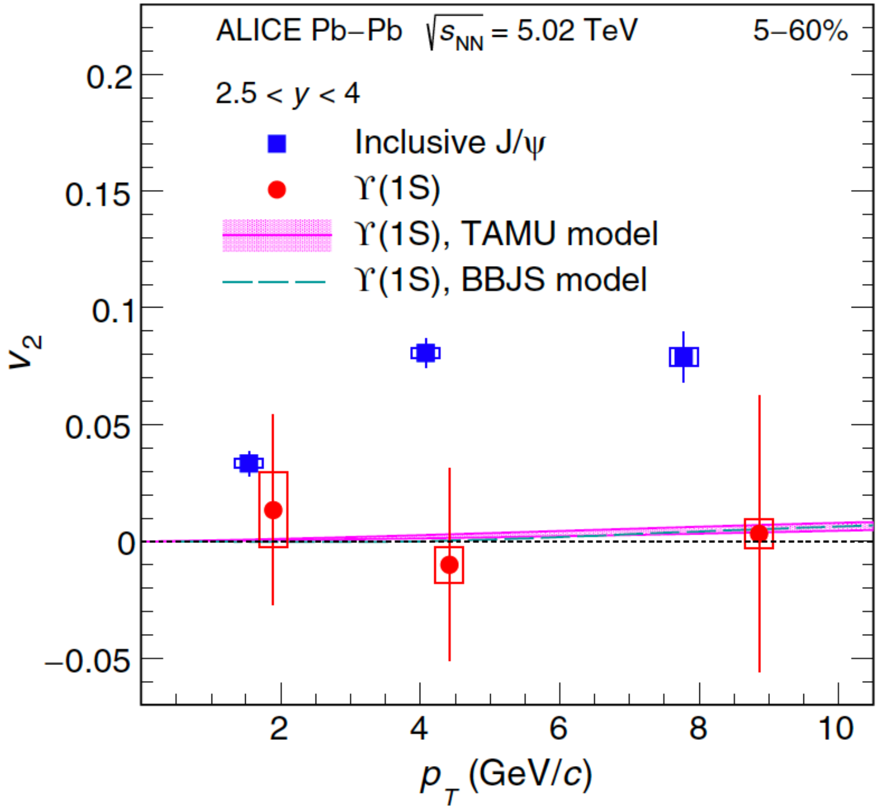
(1) D-meson v_2 compared with that of pions - low-momentum charm quarks take part in the collective motion of the QGP.
(2) Models: collisional interaction processes as well as the recombination of charm and light quarks both contribute to the observed elliptic flow.
(3) Heavy-quark spatial diffusion coefficients in the range of $2\pi T D_s(T) \approx 1.5$–$7$ at the critical temperature Tc.

PHYSICAL REVIEW LETTERS 120, 102301 (2018)

PHYSICAL REVIEW LETTERS 120, 202301 (2018)

Flow of hadrons having bottom quarks



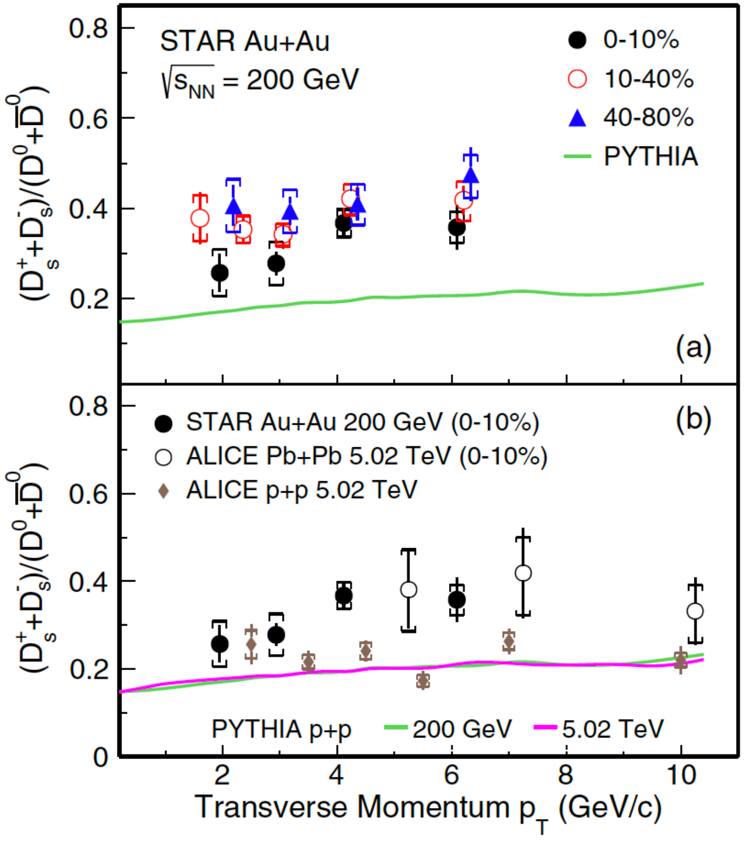


(1) The v_2 of electrons from beauty hadron decays - positive with a significance of 3.75 σ.
(2) Full thermalization of beauty quarks is strongly disfavored at high p_T, but is in agreement with the results at low p_T.

(1) The measured ϒ(1S) v_2 is consistent with 0 and with the small positive values predicted by transport models within uncertainties.
(2) The v_2 coefficient is lower than that of inclusive J/ψ mesons by 2.6 σ.

PHYSICAL REVIEW LETTERS 126, 162001 (2021) PHYSICAL REVIEW LETTERS 123, 192301 (2019)

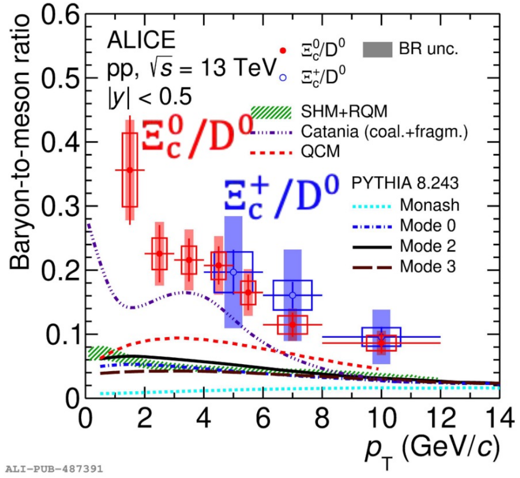
Baryon to meson and strangeness enhancement in charm sector

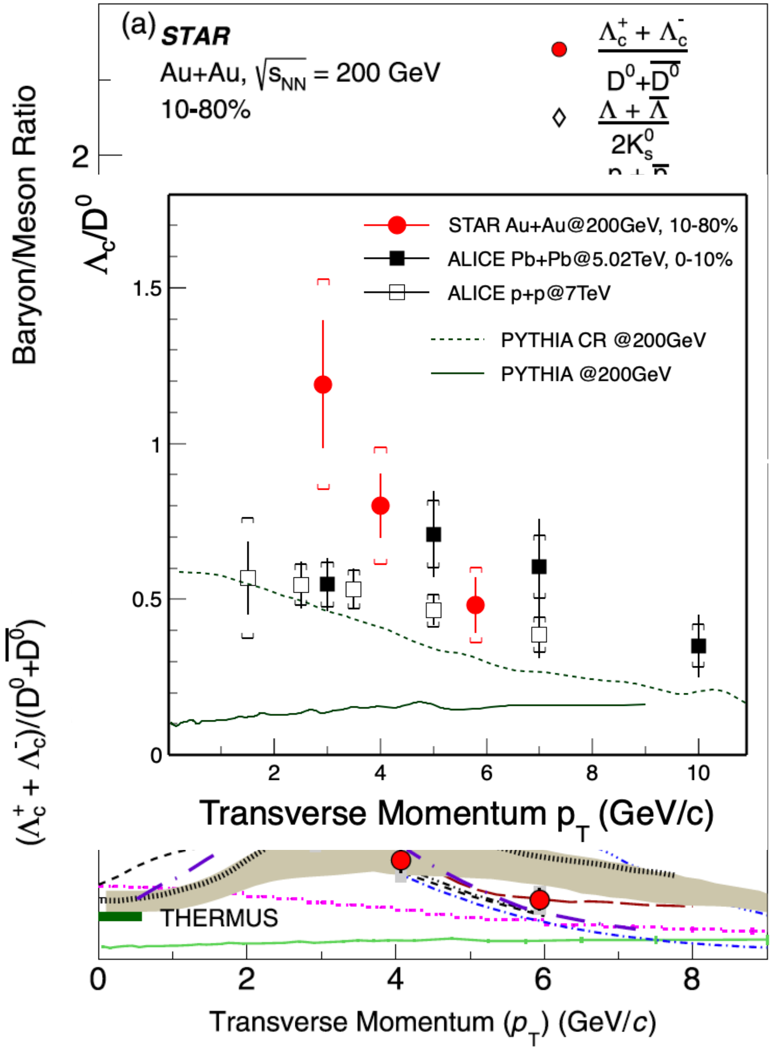


(1) The measured Λ_c/D_0 ratio, is comparable to the baryon-to-meson ratios for light and strange hadrons.
(2) Model: Coalescence hadronization for charmed baryon and meson formation.

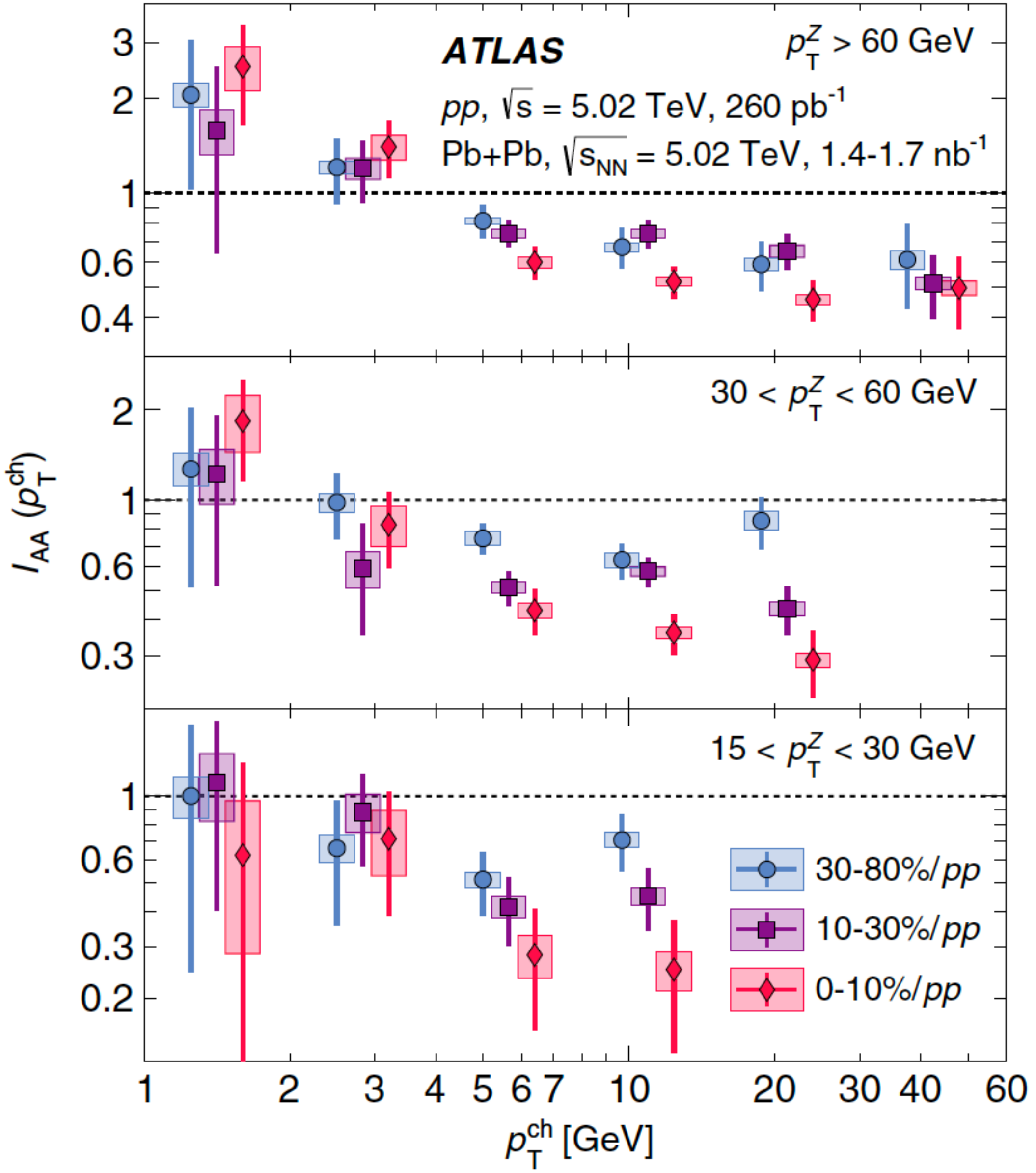
(1) D_s/D_0 yield ratio - enhancement, relative p+p collisions.
(2) Model: abundant strange-quark production in the QGP and coalescence hadronization.

New at the conference from ALICE





Z-boson tagged events and Jet-quenching



Building on earlier γ-jet measurements

(1) Measurement of charged-particle yields produced in the azimuthal direction opposite to a Z boson with $p_T > 15$ GeV.

(2) At fixed p_T, jets balancing Z bosons and photons arise from processes with different Q^2, and can test the sensitivity of the energy loss process to parton virtuality.

(3) The per-Z yields are systematically modified in Pb-Pb collisions compared with pp collisions due to the interactions between the parton shower and the hot and dense QGP medium.

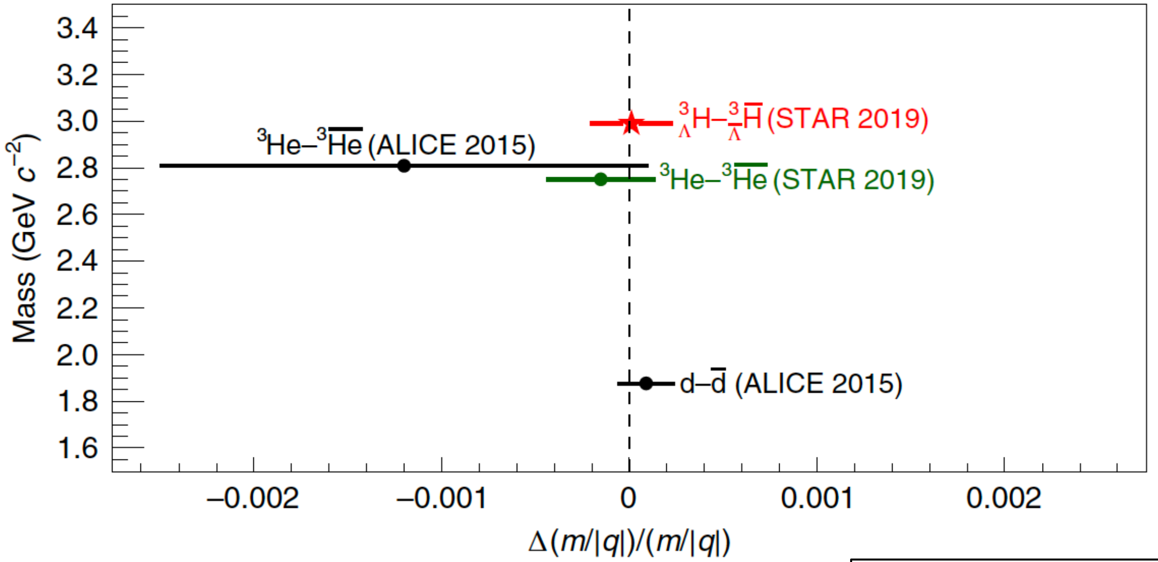
(4) The degree of modification varies with Pb-Pb event centrality, consistent with a larger and hotter QGP being created in more central events.

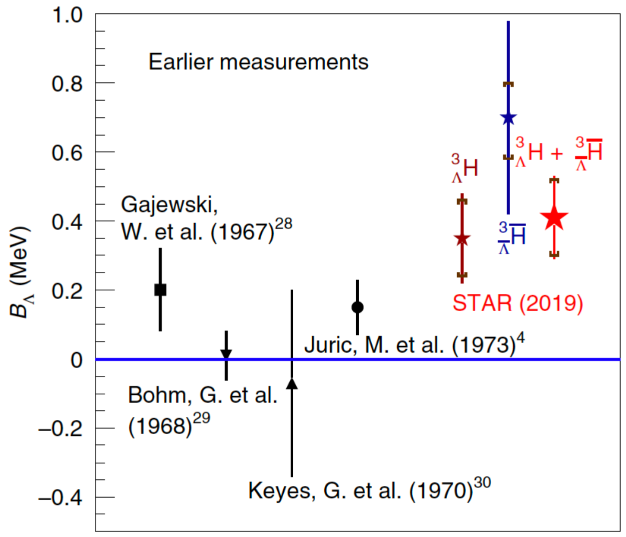
PHYSICAL REVIEW LETTERS 126, 072301 (2021)

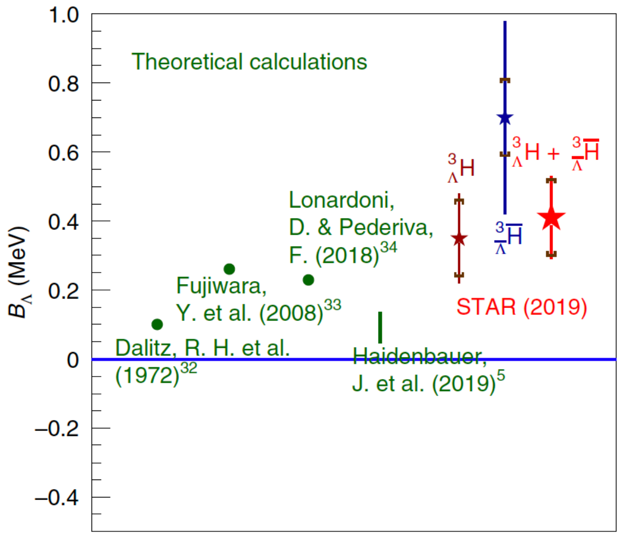
Other interesting topics

- Test CPT symmetry in a nucleus with strangeness
- Strong interactions among hadrons
- Light-by-light scattering and matter - antimatter from photon collisions

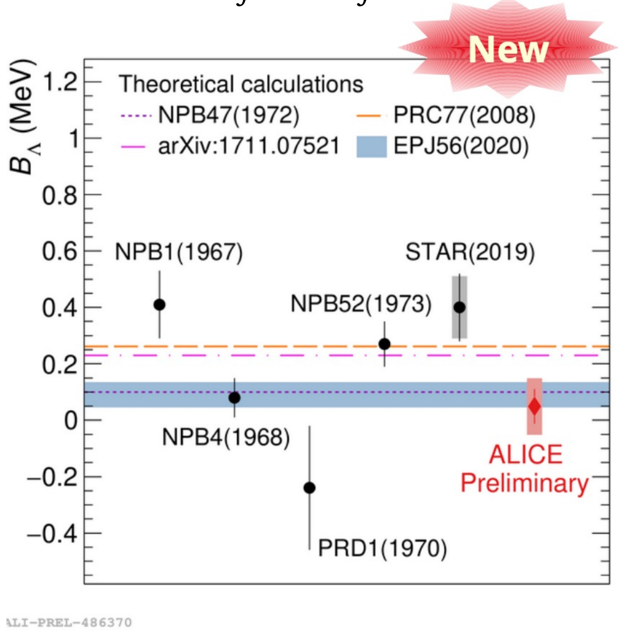
Nuclei production, CPT and YN interactions







At the conference from ALICE



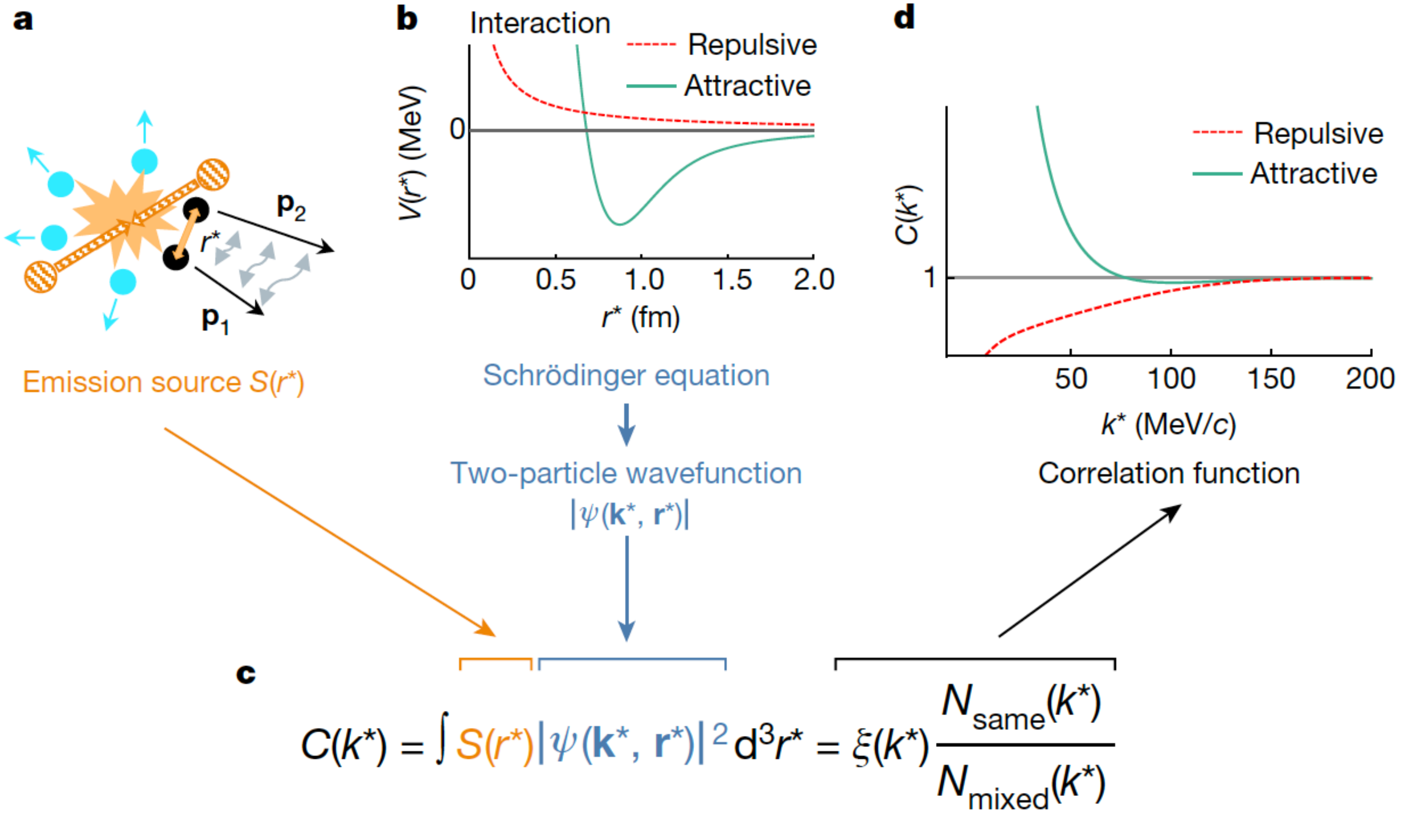
(1) A precise comparison of the masses of the hypertriton and the antihypertriton allows test CPT symmetry in a nucleus with strangeness.
(2) No deviation from the expected exact symmetry observed.

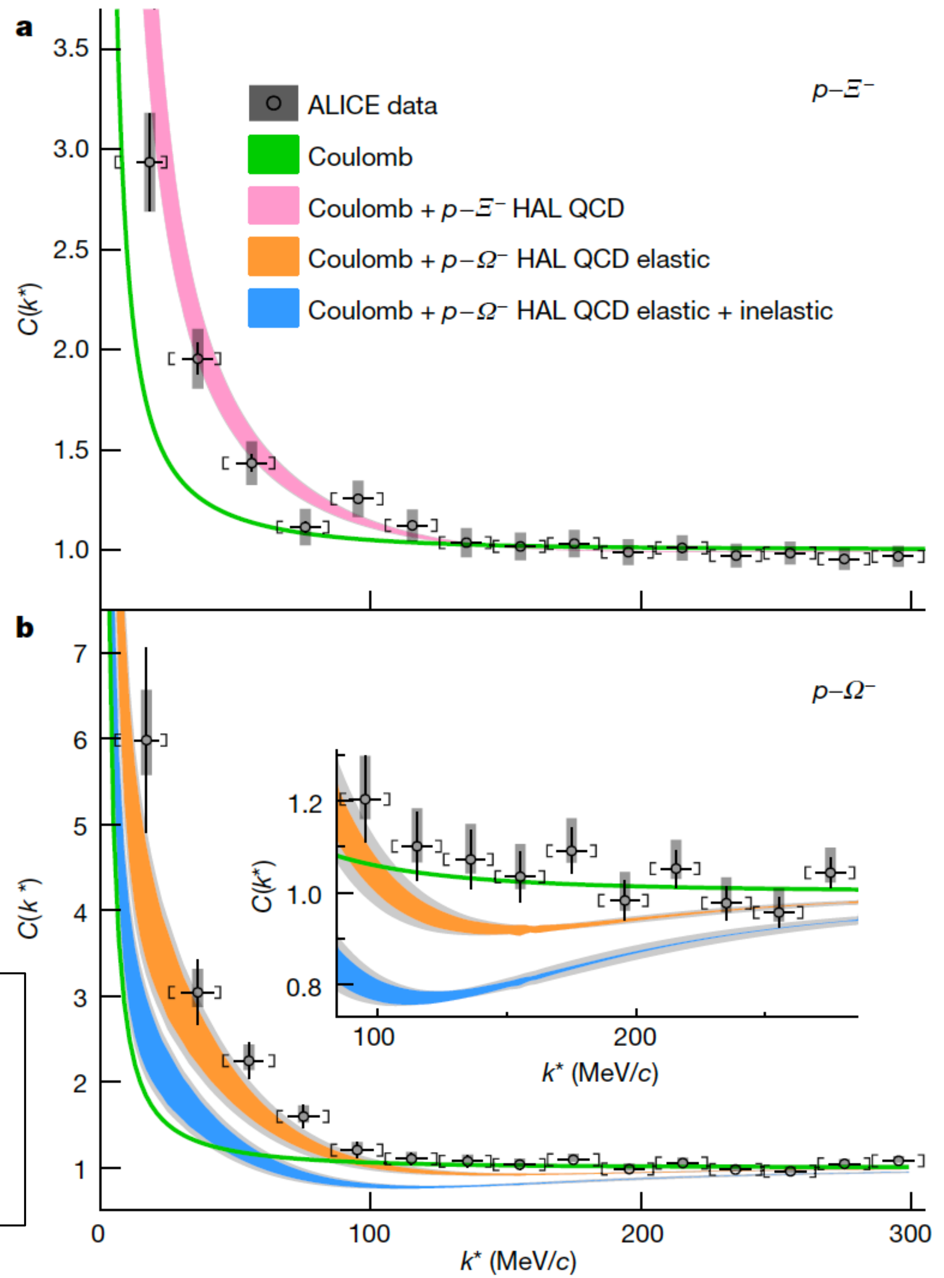
Nature Physics 16 (2020) 409

(1) Latest binding energy result differs from zero with a statistical significance of 3.4σ.
(2) The larger B_Λ and shorter effective scattering length suggest a stronger YN interaction between the Λ and the relatively low-density nuclear core of the 3ΛH.
(3) Implications to physics of neutron stars.

See also talk by Takaya Akaishi (J-PARC); Michael Hartung (AL:ICE)

Understanding strong interaction among hadrons starting from first principles



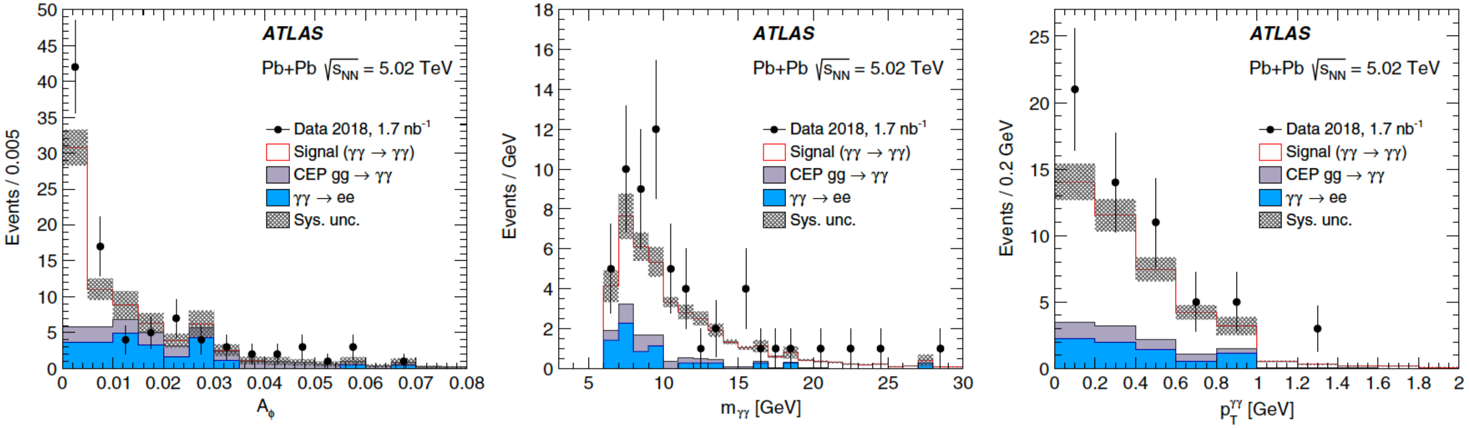


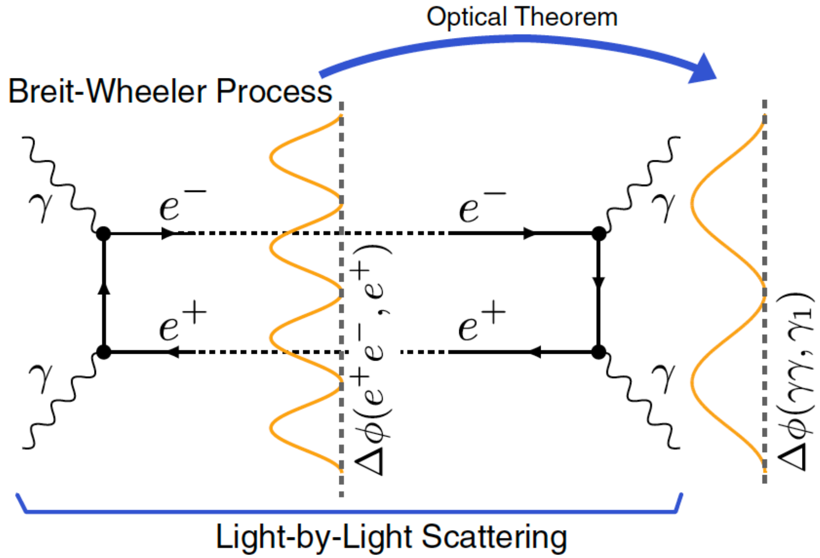
(1) Correlations are well above unity implies the presence of an attractive interaction for both systems.
(2) Large difference in the strong-attractive interaction for the two systems.

Nature 588 (2020) 232

See also talk by Valentina Mantovani Sarti (ALICE) and Michael Jung (ALICE)

Ultra peripheral collisions

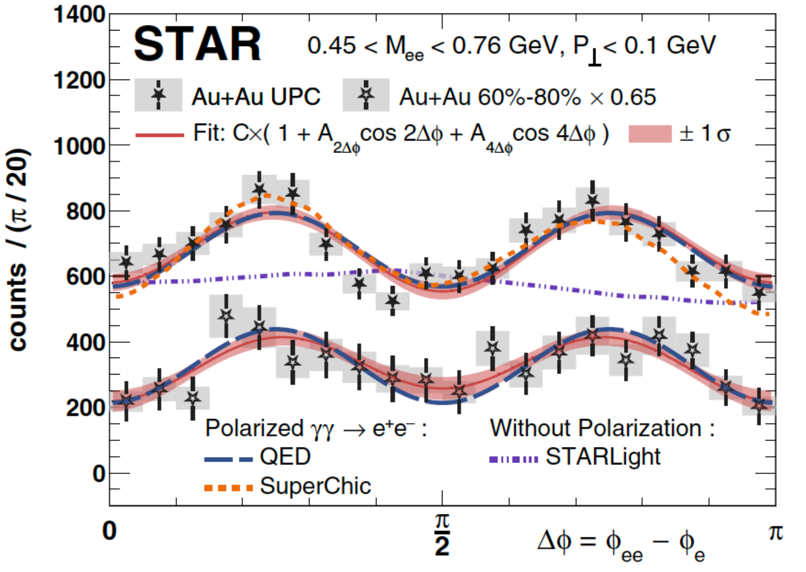




(1) Light-by-light scattering candidates are selected in events with two photons produced exclusively, each with transverse energy E^{γ}_{T} > 3 GeV and $|\eta_\gamma|$ < 2.4, diphoton invariant mass above 6 GeV, and small diphoton transverse momentum and acoplanarity.

(2) 59 events in signal region, 12 +/- 3 background event - 8.2 σ level.

(3) Breit-Wheeler produces matter and antimatter from photon collisions is experimentally investigated through the observation of 6085 exclusive electron-positron pairs in ultraperipheral Au+Au collisions at 200 GeV.



PHYSICAL REVIEW LETTERS 123, 052001 (2019) PHYSICAL REVIEW LETTERS 127, 052302 (2021)

Summary

1. Clear evidences - high energy collisions dominated by partonic degrees of freedom and lower energy dominated by hadronic degrees of freedom.

2. QCD critical point search at a crucial stage – tantalizing hints to be confirmed in high statistics BES-II.

3. The previously discovered perfect fluid of QGP seems to be polarized (in presence of large initial angular momentum and magnetic field).

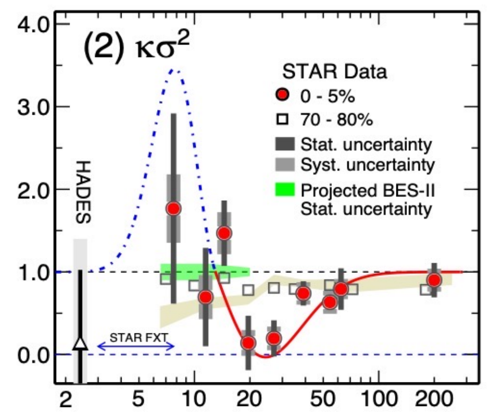
4. No signatures of chiral magnetic effect observed in isobaric collisions – dedicated program at RHIC.

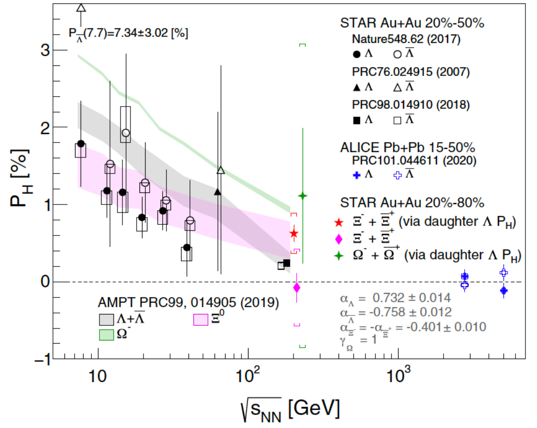
5. Observation of QGP-like collectivity in high multiplicity small systems.

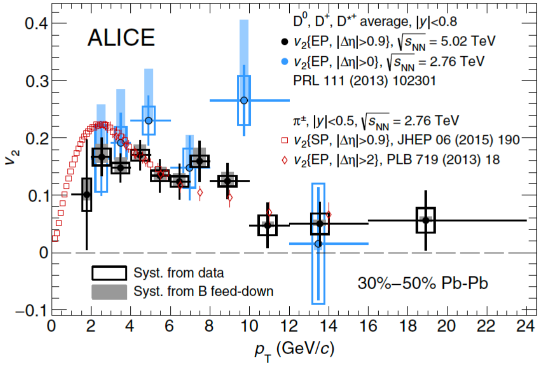
6. Charm quarks thermalization at LHC energies, bottom quarks are not fully thermalized.

7. High statistics measurements like gamma-tagged or Z-tagged now possible – will significantly improve our understanding of jet quenching effect.

8. Results beyond standard studies - strong interactions between hadrons, Light-by-Light scattering and matter antimatter from photon collisions.







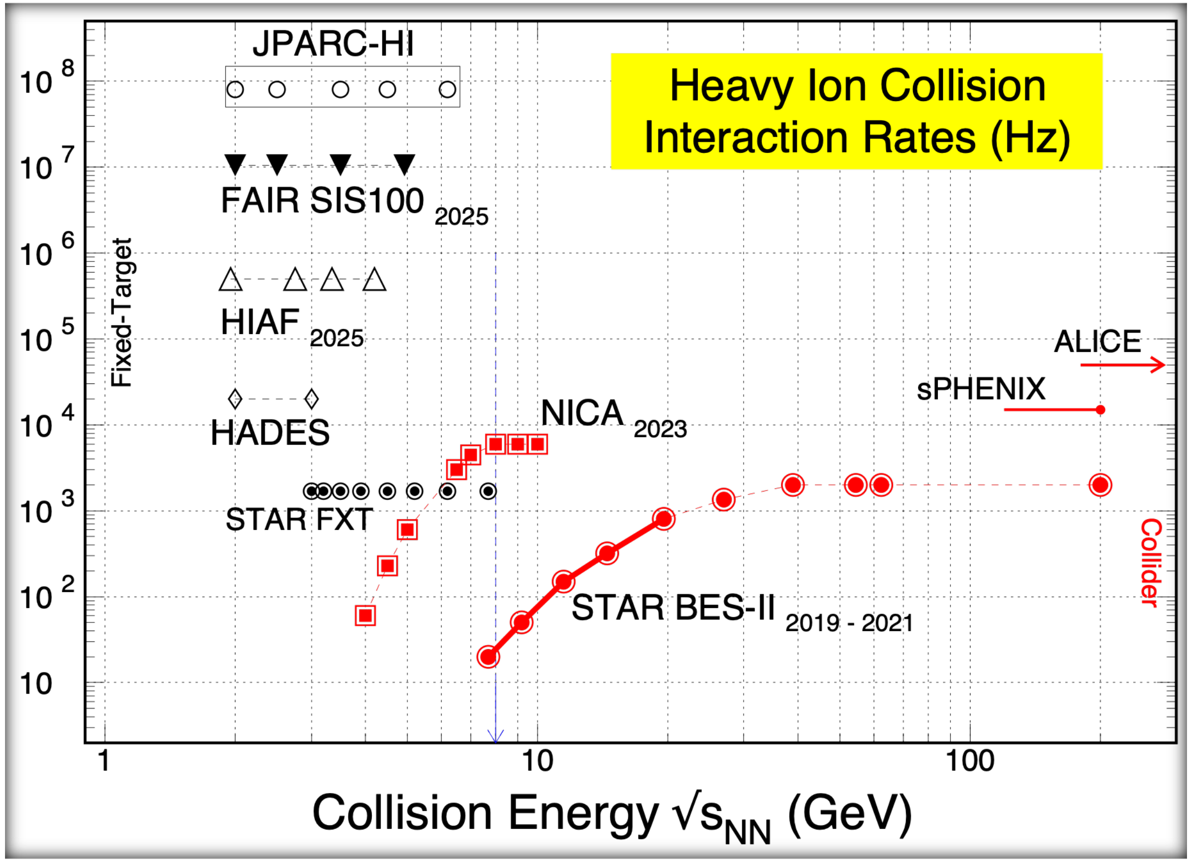
Outlook

(1) High baryon density @RHIC/FAIR/NICA/SPS

Phase structure of phase diagram

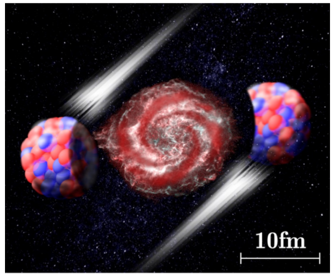
(2) High Luminosity @ LHC and top energy program @RHIC

Properties of QGP



AAPPS Bull. 31 (2021) 1

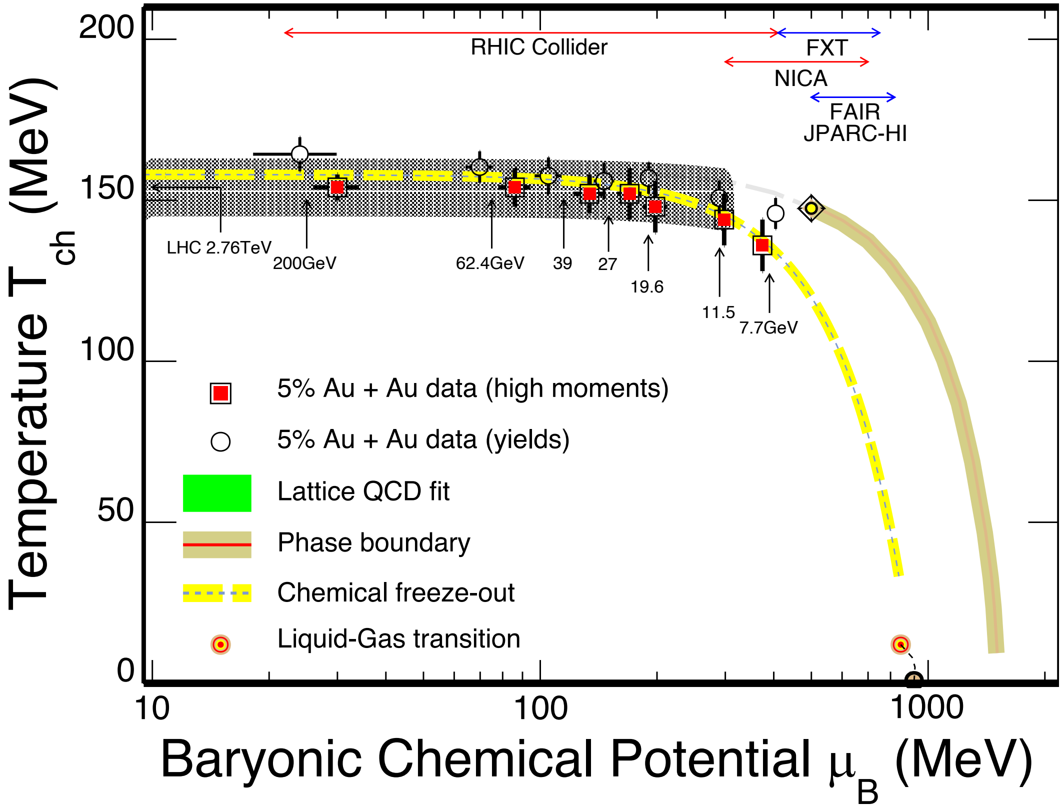
Outlook: High baryon density



1. Systematic study of the phase structure of QCD Phase diagram.

2. Opportunity for a dedicated study of high baryon density matter
   a) Finding direct signals of true phase transition and critical point.
   b) Understanding the properties of high baryon density, rotating QCD matter under magnetic field.
   c) Understanding light-nuclei, hyper-nuclei and exotic nuclei formation and properties.

3. Complementary to research programs at RHIC-BES-II, CERN, FAIR, NICA, J-PARC-HI & CEE-HIAF



AAPPS Bull. 31 (2021) 1

Little-Bang and Femto-Nova in Nucleus-Nucleus Collisions
e-Print: 2009.03006 [hep-ph]

Outlook: High luminosity LHC / RHIC

1. Precision measurement of properties of QCD matter

2. **Jets**: characterization of the energy-loss mechanism and medium density
(a) Differential studies of b-jets, di-jets, g/Z-jets – ATLAS/CMS/ALICE
(b) Flavour dependent in-medium fragmentation functions – ALICE

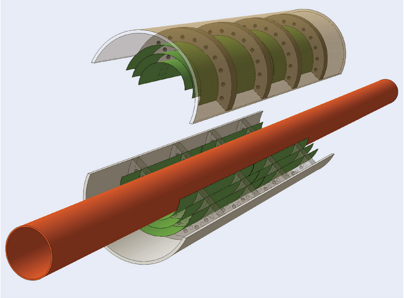
3. **Heavy flavours**: Mass dependence of energy loss, thermalization, hadronization, transport properties
(a) Elliptic flow – ALICE
(b) b-hadrons and b-jets - ATLAS/CMS

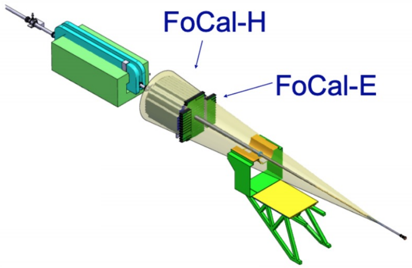
4. **Quarkonia**: Dissociation patterns, deconfinement and medium temperature.
(a) Low p_T – ALICE
(b) Multi-differential studies of Υ states – CMS/ATLAS

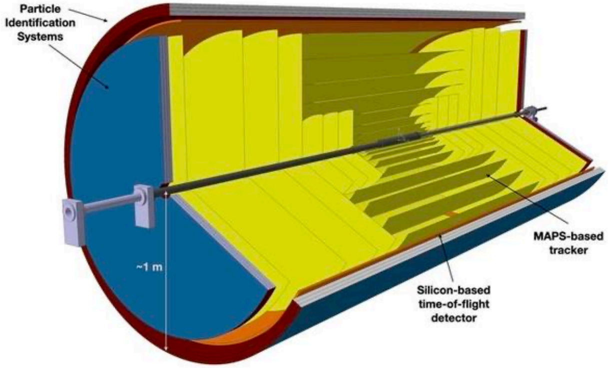
5. **Di-leptons**: Thermal radiation, spectra functions, continuum - ALICE

At least:
×100 larger min. bias sample for ALICE w.r.t. Run 2
×10 larger rare trigger sample for ATLAS/CMS w.r.t. Run 2

Upgrades (ALICE)







Thanks

Organizers