
Welcome to ATHIC 2025
Welcome to Gopalpur, Odisha
Sunrise on 13th January, 2025

Recent experimental results from relativistic heavy-ion collisions

Bedanga Mohanty

NISER, India

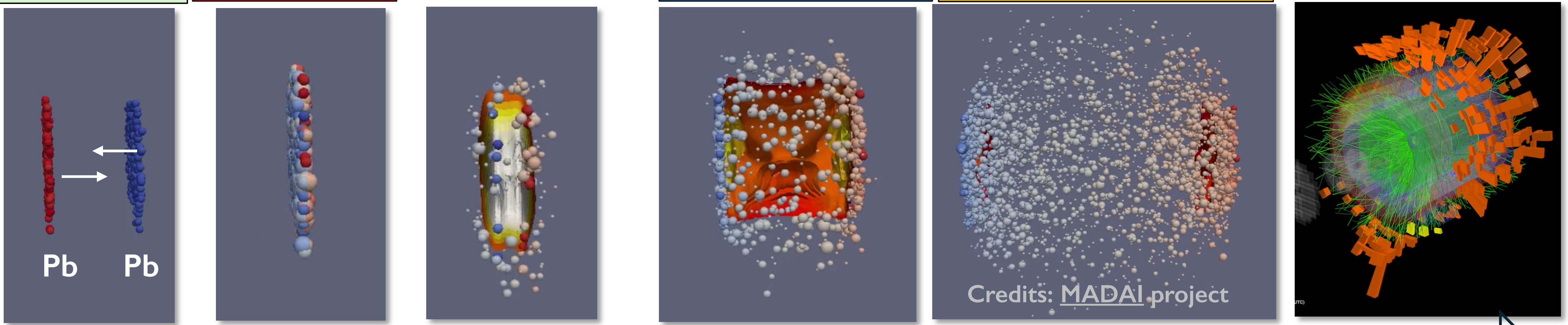
Recently, progress has been made on:

- Obtaining the properties of Quark Gluon Plasma
- Studying the phase structure of QCD
- Understanding the initial conditions
- Studying QCD system using QED interactions (UPC)
- Understanding nuclei and exotic hadron production
- Setting up new experiments for low-x and high baryon density physics

Relativistic heavy ion collisions

Standard picture of evolution

Initial state	Hard scatterings	Quark Gluon Plasma	Hydrodynamic expansion	Hadronization and freeze-out	Detectors



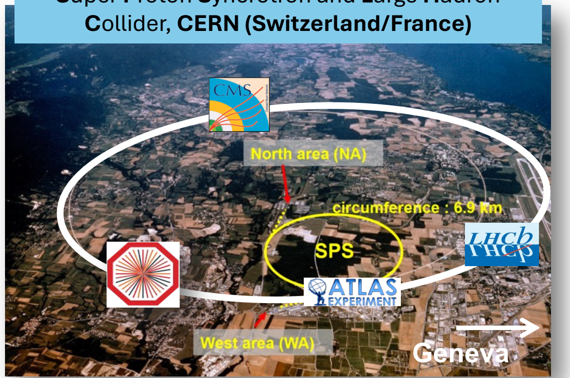
0 — ~ 1 fm/c — ~ 10 fm/c — TIME

TEMPERATURE — ~ 800 – 200 MeV — 156 MeV — ~ 155 – 100 MeV

Running collider facilities

Relativistic Heavy Ion Collider, Brookhaven (USA)

Super Proton Syncrotron and Large Hadron Collider, CERN (Switzerland/France)



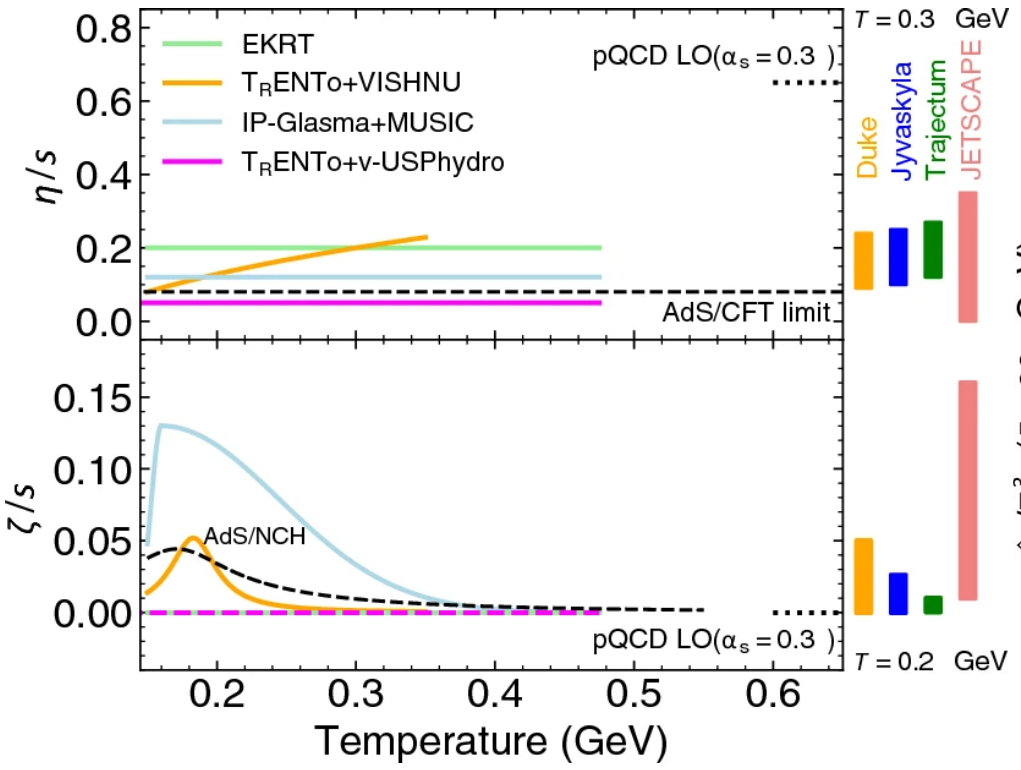
Properties of QGP

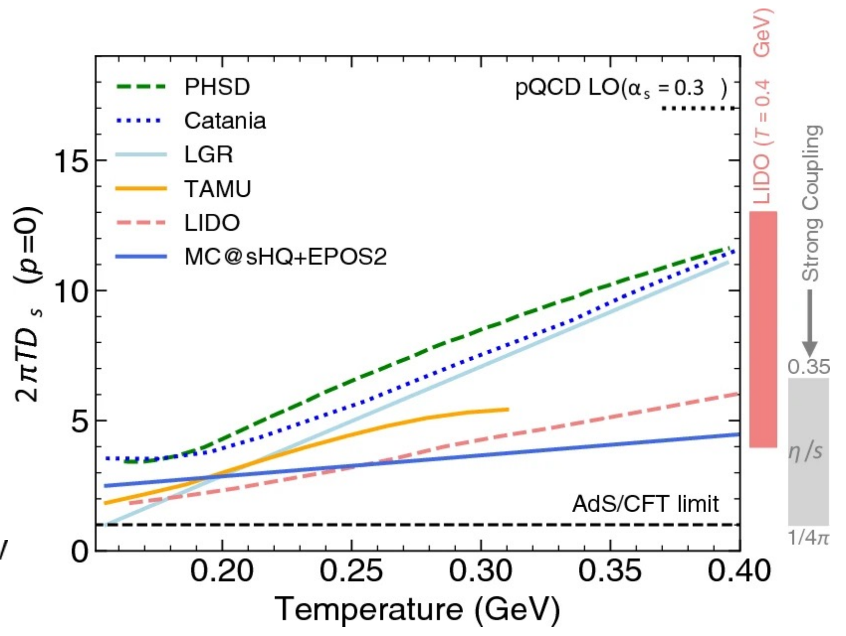
Shear and bulk viscosity
Drag /diffusion coefficient
Opacity or energy loss
Conductivity

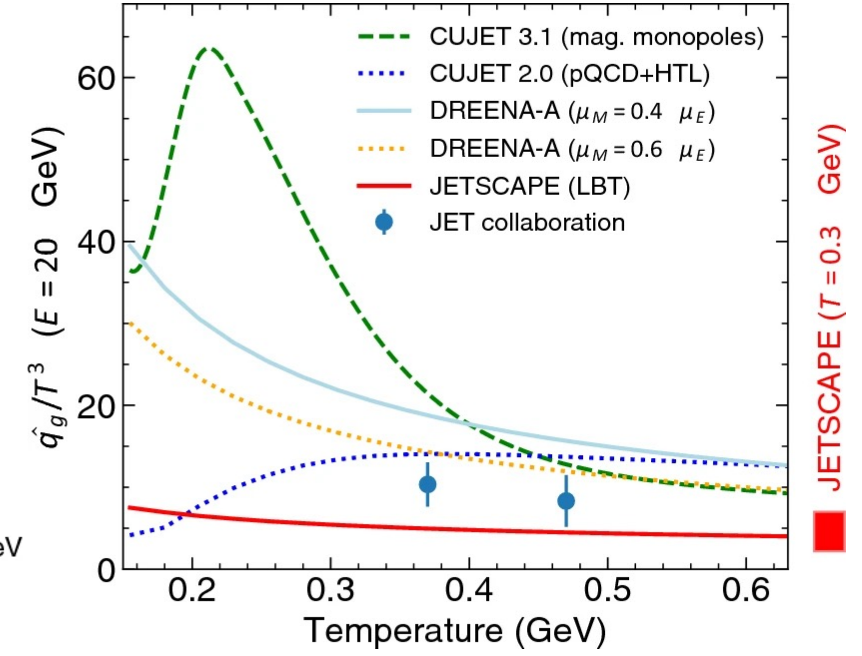
We have progressed beyond discovering a QCD matter with quark and gluon degrees of freedom

Experimental measurements+theory have put constraints on the temperature dependence of these properties.

ALICE: Eur.Phys.J.C 84 (2024) 8, 813

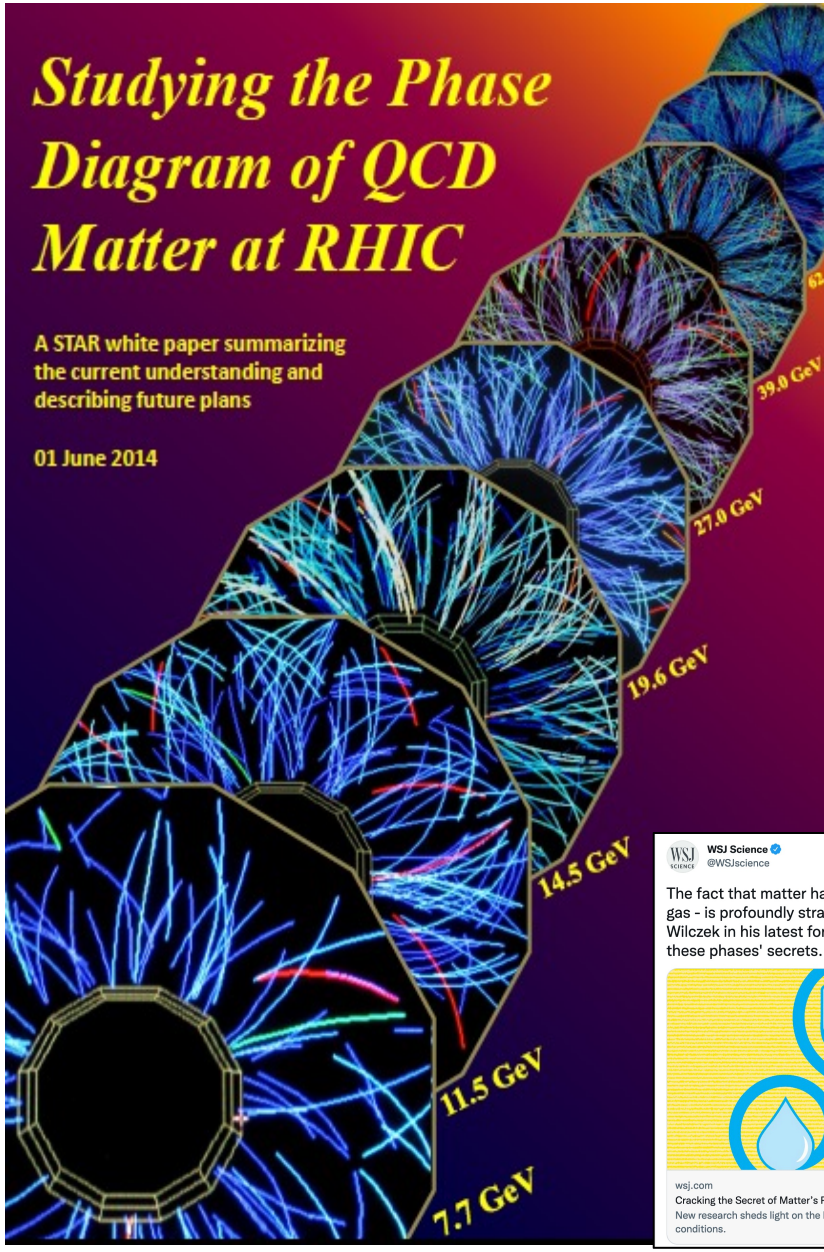




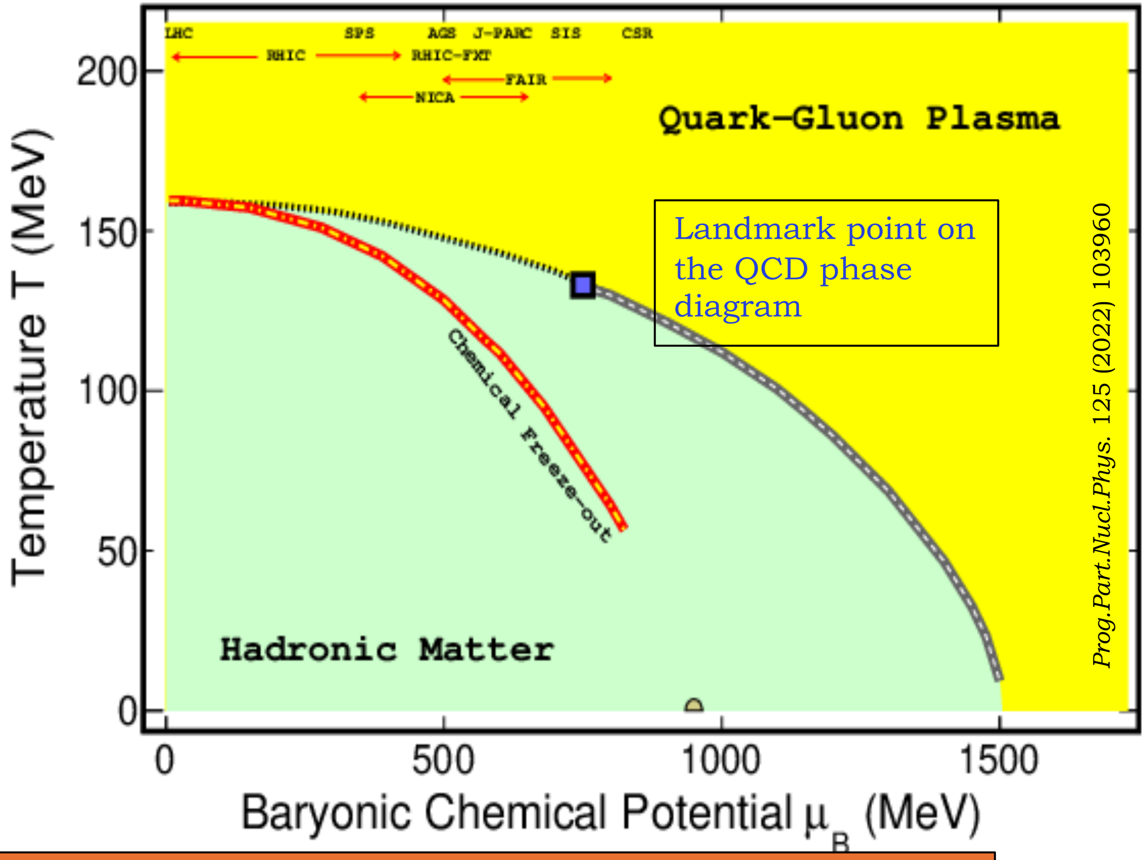


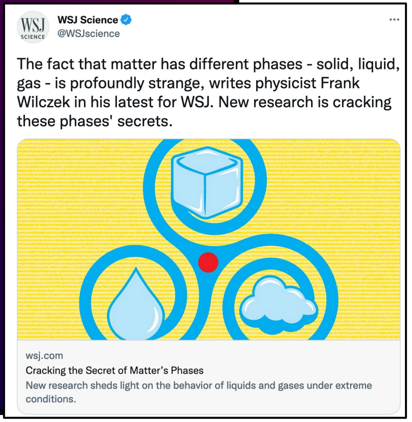
See talks by: Roli Esha, Dibyendu Bala, Minjung Kweon, Mayank Singh, Zebo Tang, Maya Shimomura, Nihar Sahoo, Varun Vaidya, Saehanseul Oh

Phase structure of QCD



Strong participation from groups in ATHIC countries in this area.




WSJ Science @WSJscience

The fact that matter has different phases - solid, liquid, gas - is profoundly strange, writes physicist Frank Wilczek in his latest for WSJ. New research is cracking these phases' secrets.

wsj.com
Cracking the Secret of Matter's Phases
New research sheds light on the behavior of liquids and gases under extreme conditions.

Themordynamic system
Phases of QCD
Nature of phase transition
Search for the QCD critical point

Phase structure of QCD

December 2009 – Establishing RHIC Beam Energy Scan Program

Referee:

1) There is a significant amount of off-putting essentially political cant that might be appropriate for a proposal, but has no place in the refereed literature, beginning with this sentence in the abstract

"These results also demonstrate the readiness of the STAR detector to undertake the proposed QCD critical point search and the exploration of the QCD phase diagram at RHIC,"

which should be removed.

STAR: We have modified this sentence to emphasize the point that we have successfully operated STAR at a CM energy that is a factor of 20 lower than its original design energy. In the Beam Energy Scan program, we will be operating the detector up to a factor of 40 lower in CM energy. Detector experts raised very serious concerns prior to the analysis of the test run reported in this paper, and argued strongly that such a test was essential before devoting resources on a large scale to a Beam Energy Scan at RHIC. Therefore, our conclusions in this paper include the important scientific finding that the original serious scientific concerns are allayed and that the STAR detector has now demonstrated satisfactory performance at this low beam energy.

But then there is also

P. 7: "demonstrates the success of the test run in achieving its objectives. The measurements shown here are the first step towards a detailed exploration of the QCD phase diagram at RHIC."

STAR: For the reasons outlined above, we prefer to keep this particular sentence in the introduction (p. 7). We in STAR believe that the study reported here marks the start of the scientific program for the QCD critical point search at RHIC. We note the similarity to a statement in the very first paper that reported RHIC results in the year 2000:

"The measurements shown here represent the first step toward the development of a full picture of the dynamical evolution of nucleus-nucleus collisions at RHIC energies."

By PHOBOS Collaboration (B. B. Back et al.), Published in Phys. Rev. Lett. 85, 3100-3104 (2000). e-Print: hep-ex/0007036

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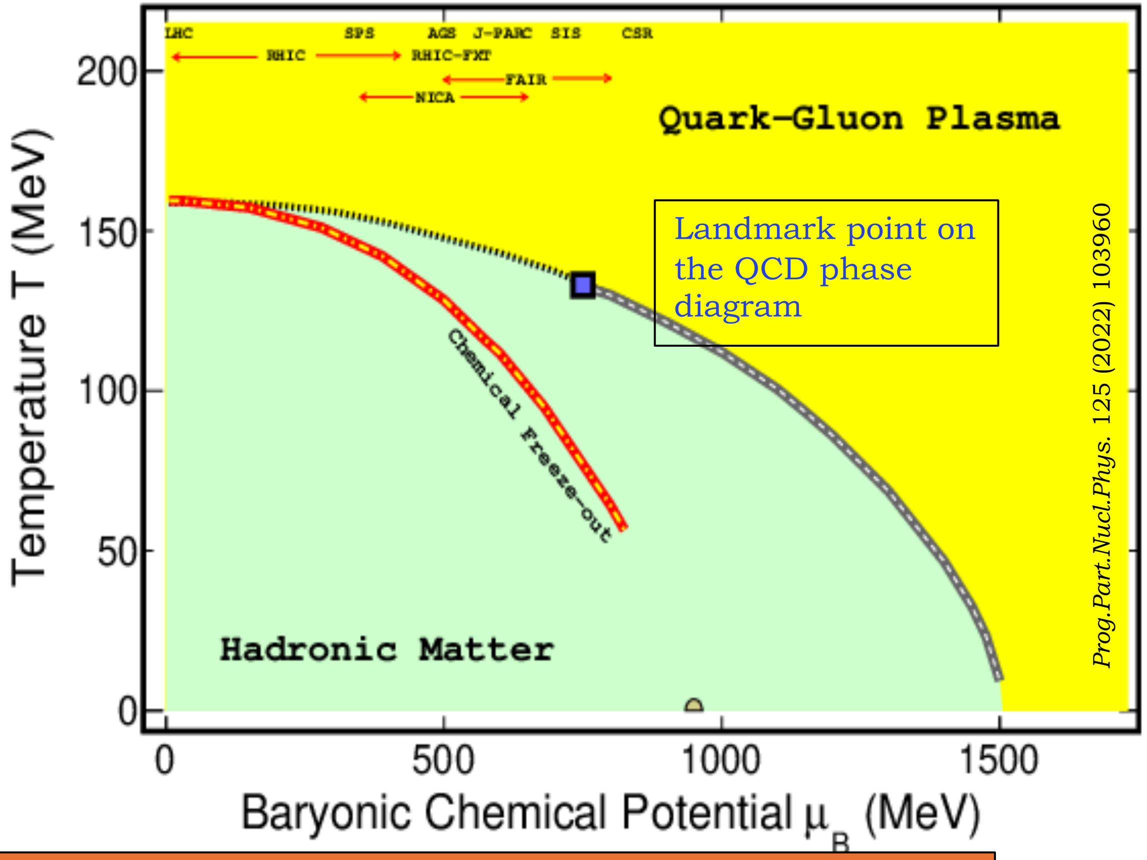

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Establishing thermalization (1) – open issue

Is the system formed in heavy-ion collisions thermal?

If thermal, what is the mechanism behind fast thermalization – experimental proof ?

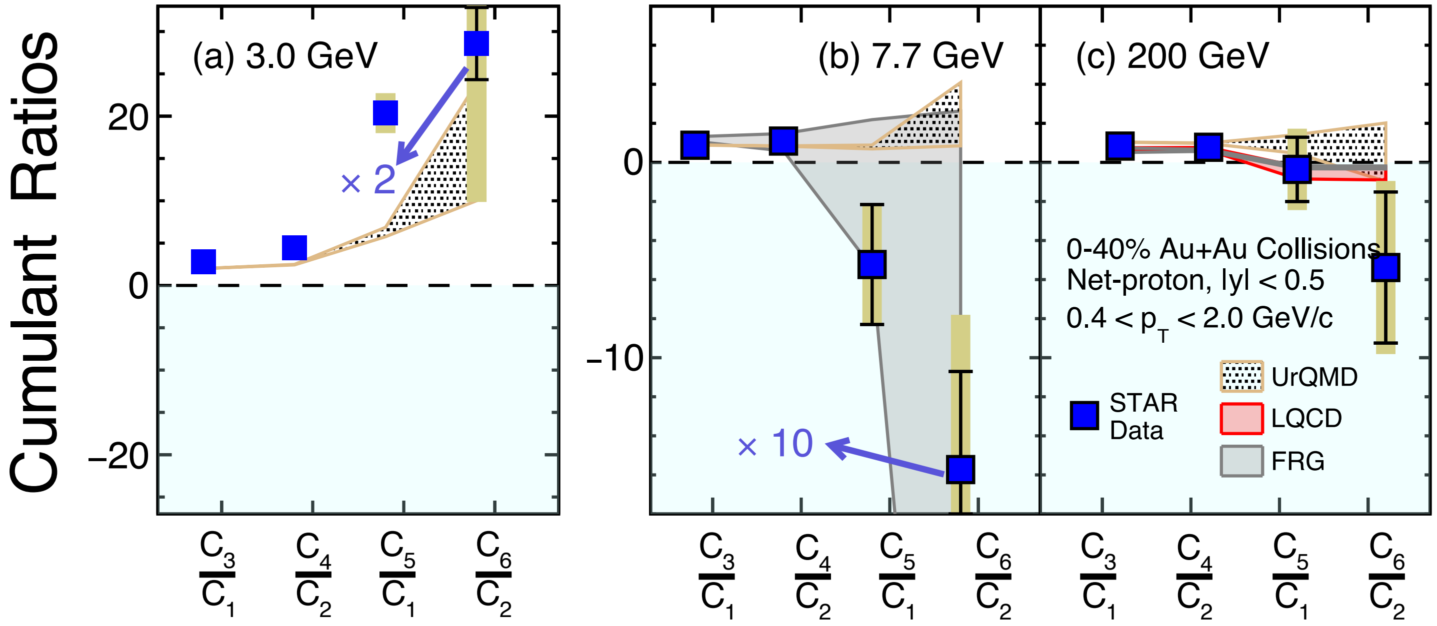
Theory observation

Experimental measurements

LQCD thermodynamics: Ordering of susceptibility ratios (Net-baryon)

$$\frac{\chi_6^B(T,\vec{\mu})}{\chi_2^B(T,\vec{\mu})} < \frac{\chi_5^B(T,\vec{\mu})}{\chi_1^B(T,\vec{\mu})} < \frac{\chi_4^B(T,\vec{\mu})}{\chi_2^B(T,\vec{\mu})} < \frac{\chi_3^B(T,\vec{\mu})}{\chi_1^B(T,\vec{\mu})}$$

PHYS. REV. D 101, 074502 (2020)

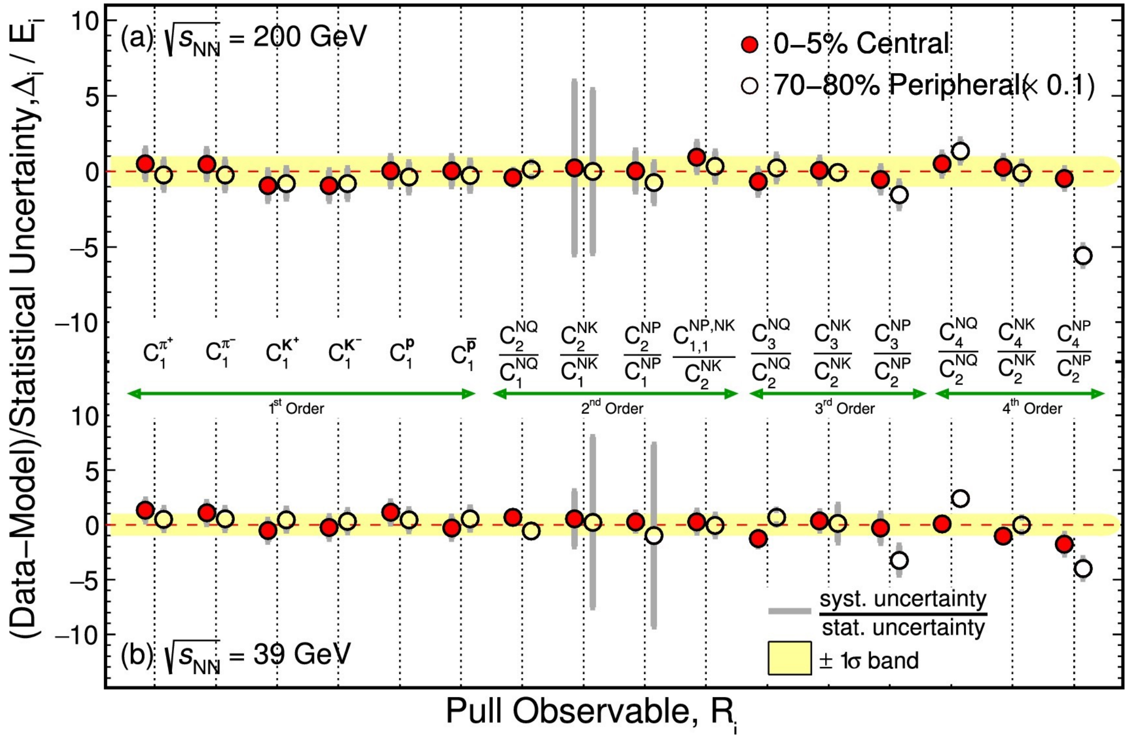


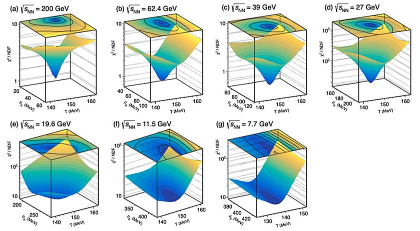
- Ordering of ratios as per LQCD thermodynamics observed for collision energies > 7 GeV
- Reverse ordering observed for collision energy of 3.0 GeV.

STAR: PRL 130 , 82301 (2023)
STAR: PRL 128, 202303 (2022)
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)

Establishing thermalization (2) – open issue

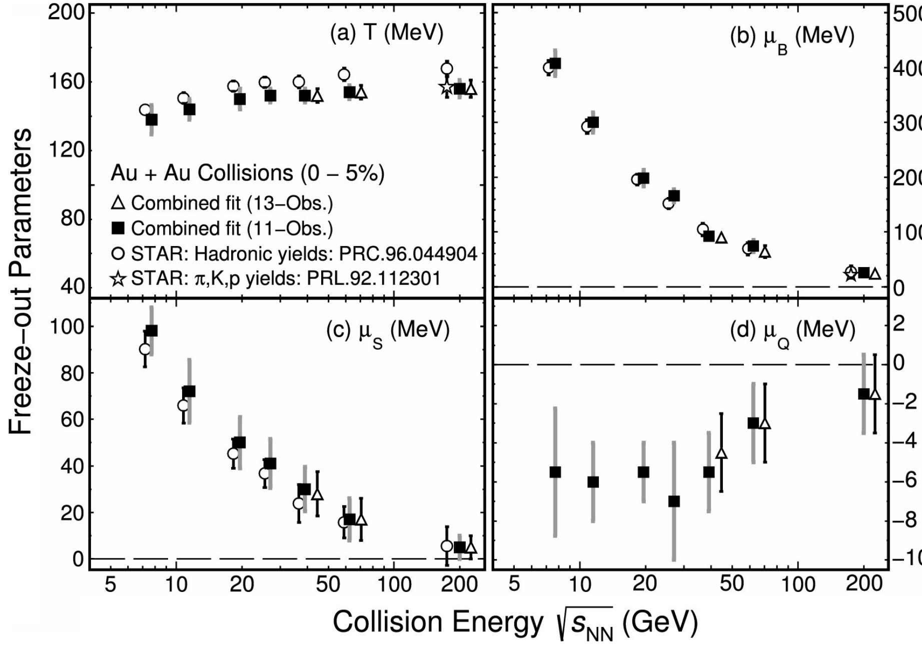
For 30 years, approach is comparing the mean yields of particles to thermal model. However, we need to prove the full distribution is thermal.





$$C_n^X = (V/T)T^n \chi_X^{(n)}$$

$$\chi_X^{(n)} = d^n P/d\mu_X^n$$



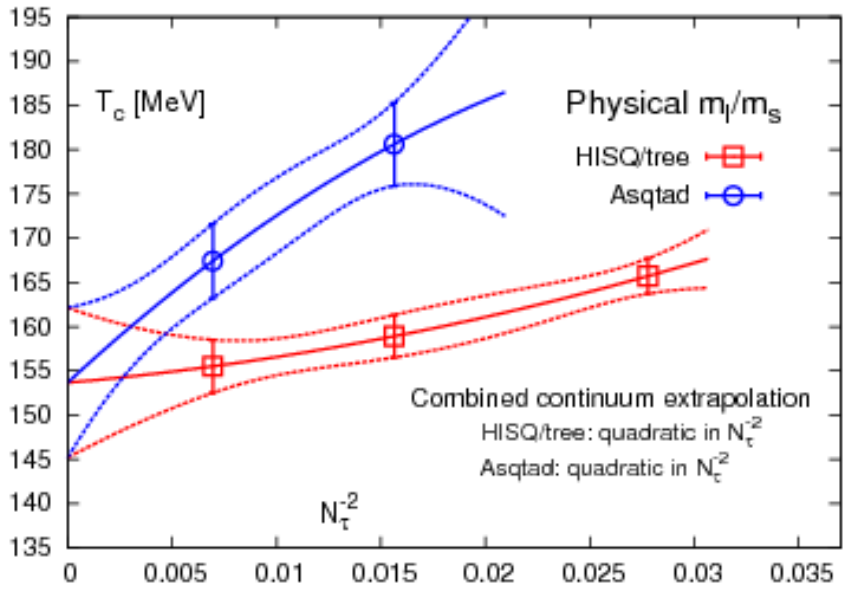
Phys.Lett.B 829 (2022) 137021

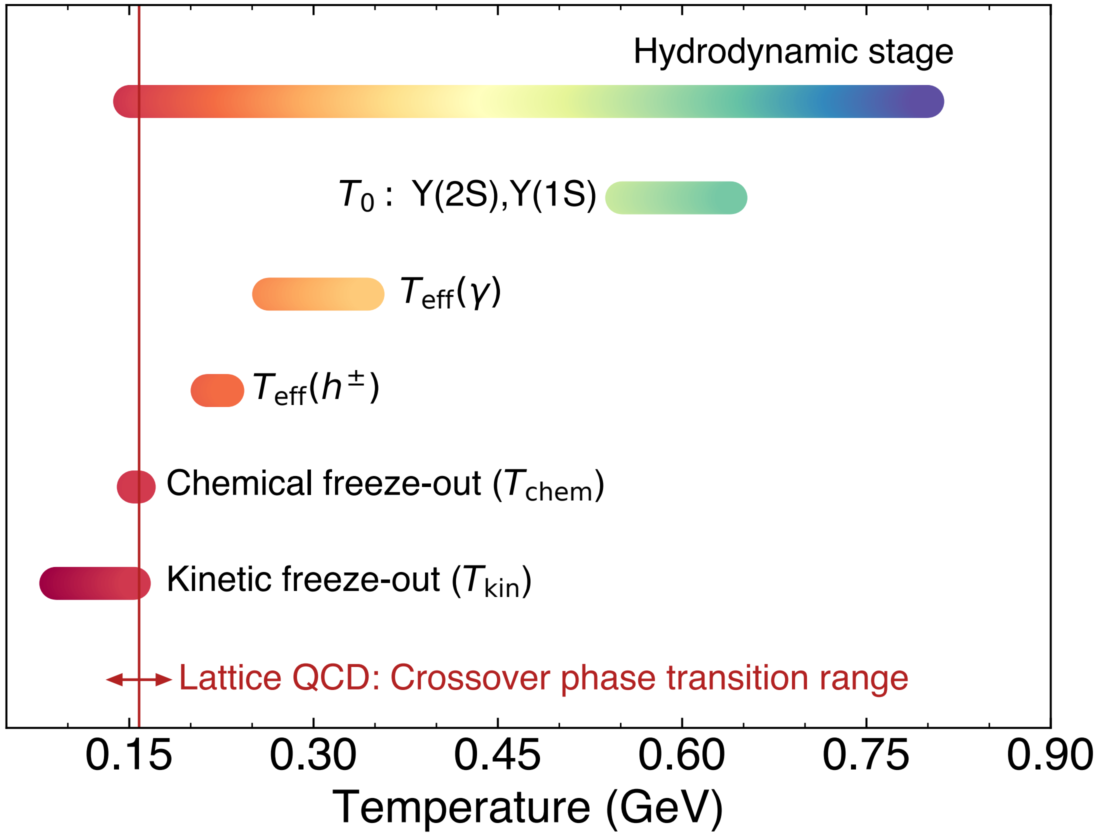
- Thermal nature of multiplicity distributions tested up to 4th order.
- The distributions look thermal for central heavy ion collisions for collision energies above 30 GeV.

Establishing thermalization (3) – Temperatures

1. Initial temperature
2. Deconfinement temperature
3. Chemical Freeze-out temperature
4. Kinetic Freeze-out temperature

Phys.Rev.D 85 (2012) 054503



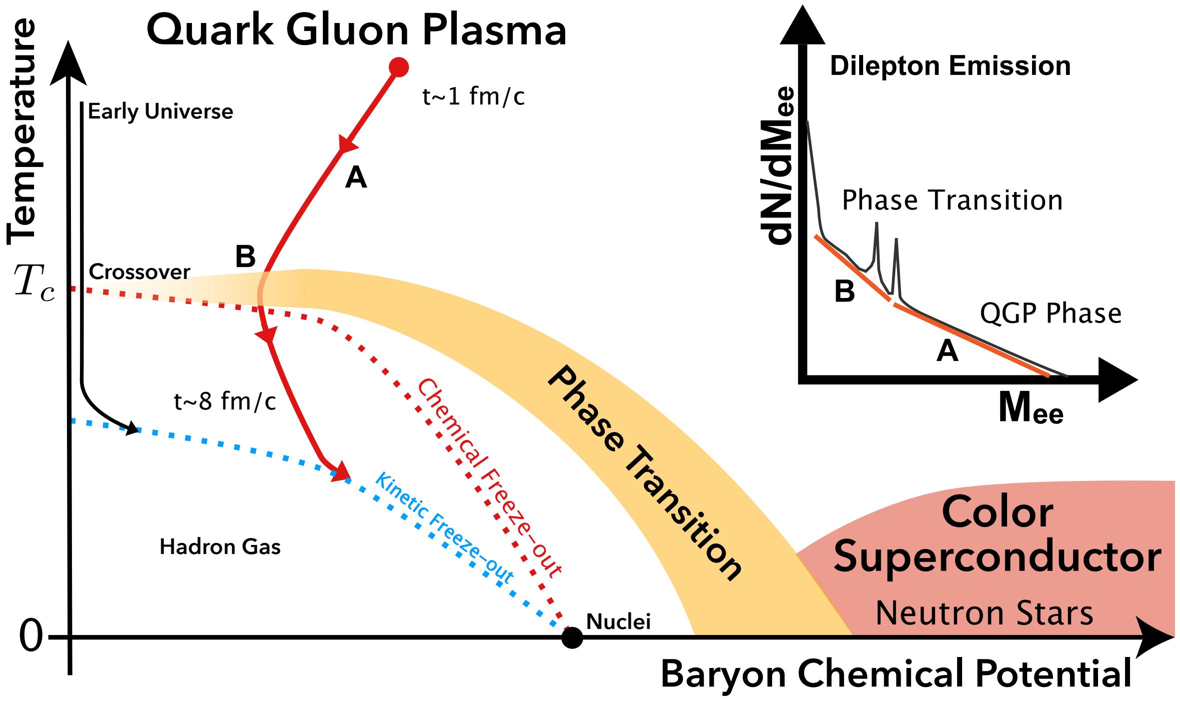


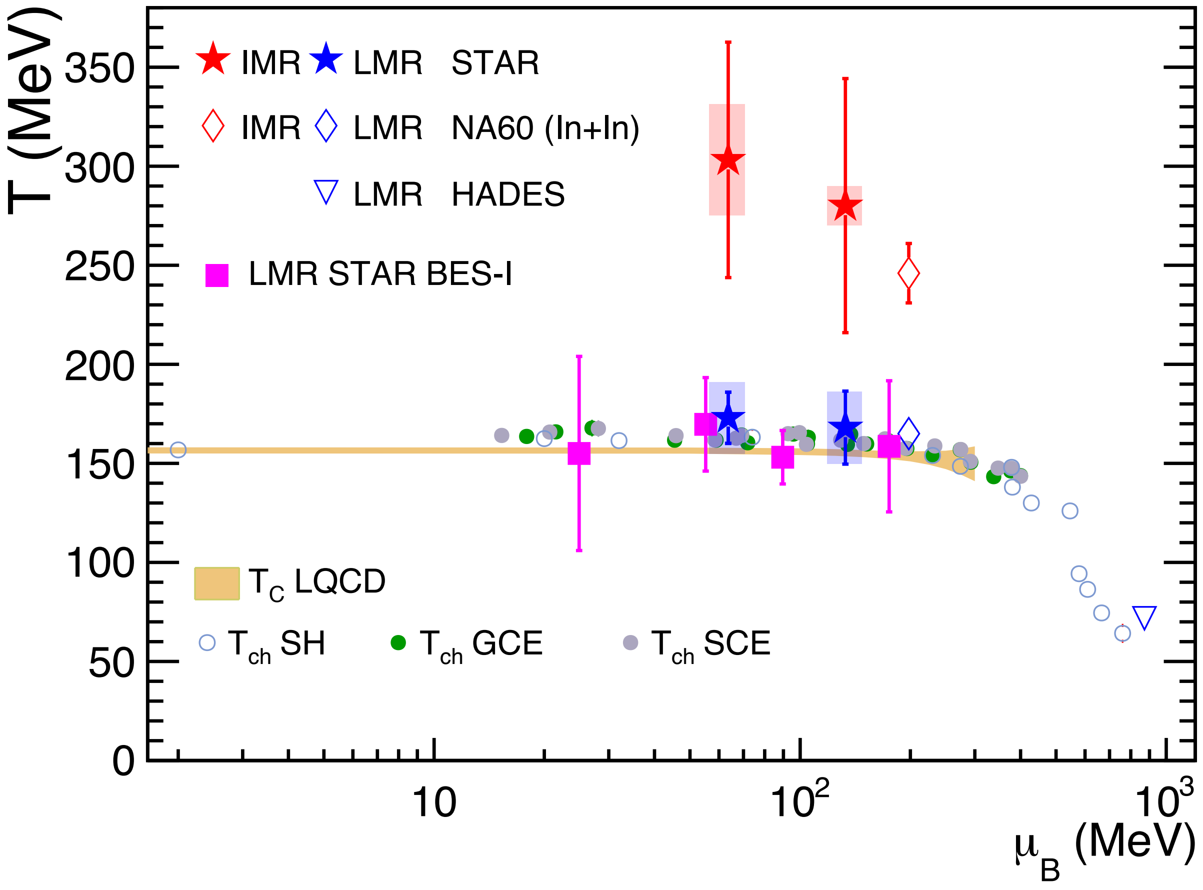
ALICE: Eur.Phys.J.C 84 (2024) 8, 813

Lattice QCD – transition temperature, T_c=156.5 ± 1.5 MeV.
Initial temperatures at LHC can reach 800 MeV (~5 times T_c).
Chemical temperature and transition temperature close to each other.
Kinetic freeze-out temperatures could be lower.

Establishing thermalization (4) – Temperatures

1. Initial temperature
2. Deconfinement temperature
3. Chemical Freeze-out temperature
4. Kinetic Freeze-out temperature



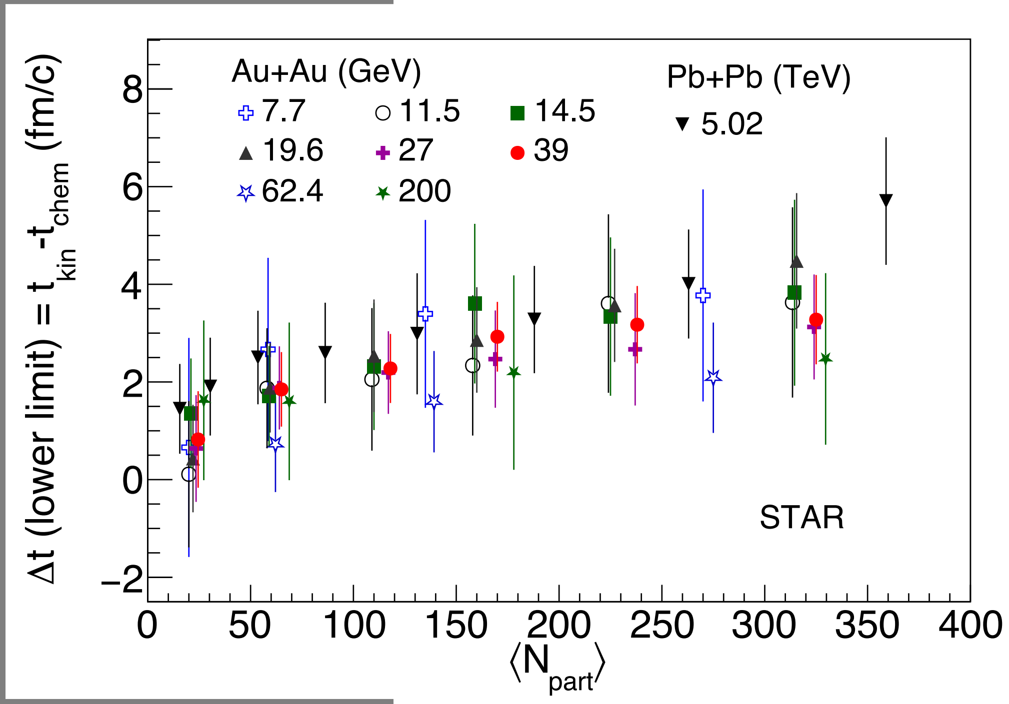


STAR: 2402.01998

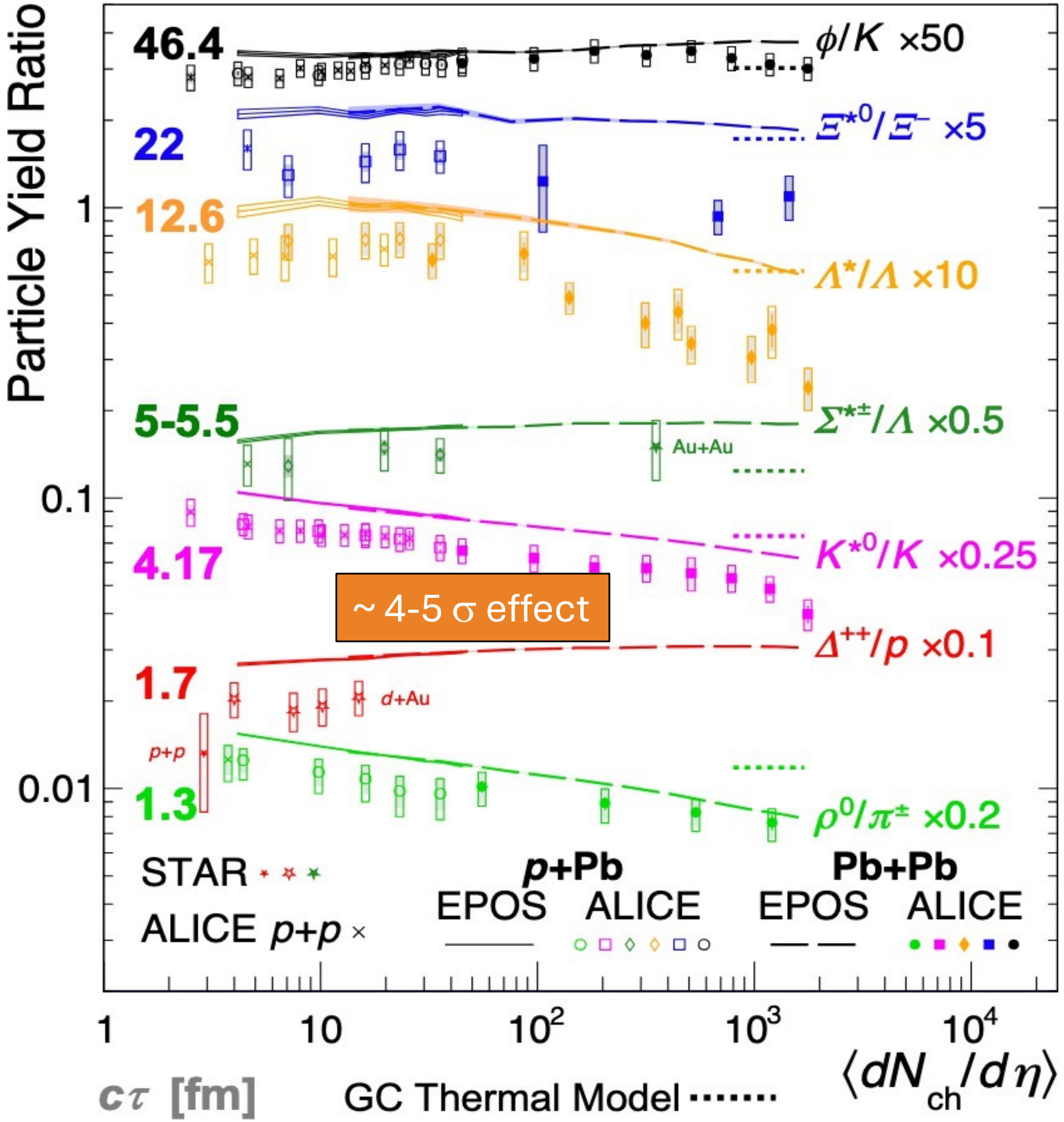
Lattice QCD – transition temperature, T_c=156.5 ± 1.5 MeV
Initial temperatures at RHIC above 300 MeV (~2 times T_c).

Experimental evidence of activity between chemical and kinetic freeze-out

See talks by: Sadhana Dash and Junlee Kim



Lifetime of resonance



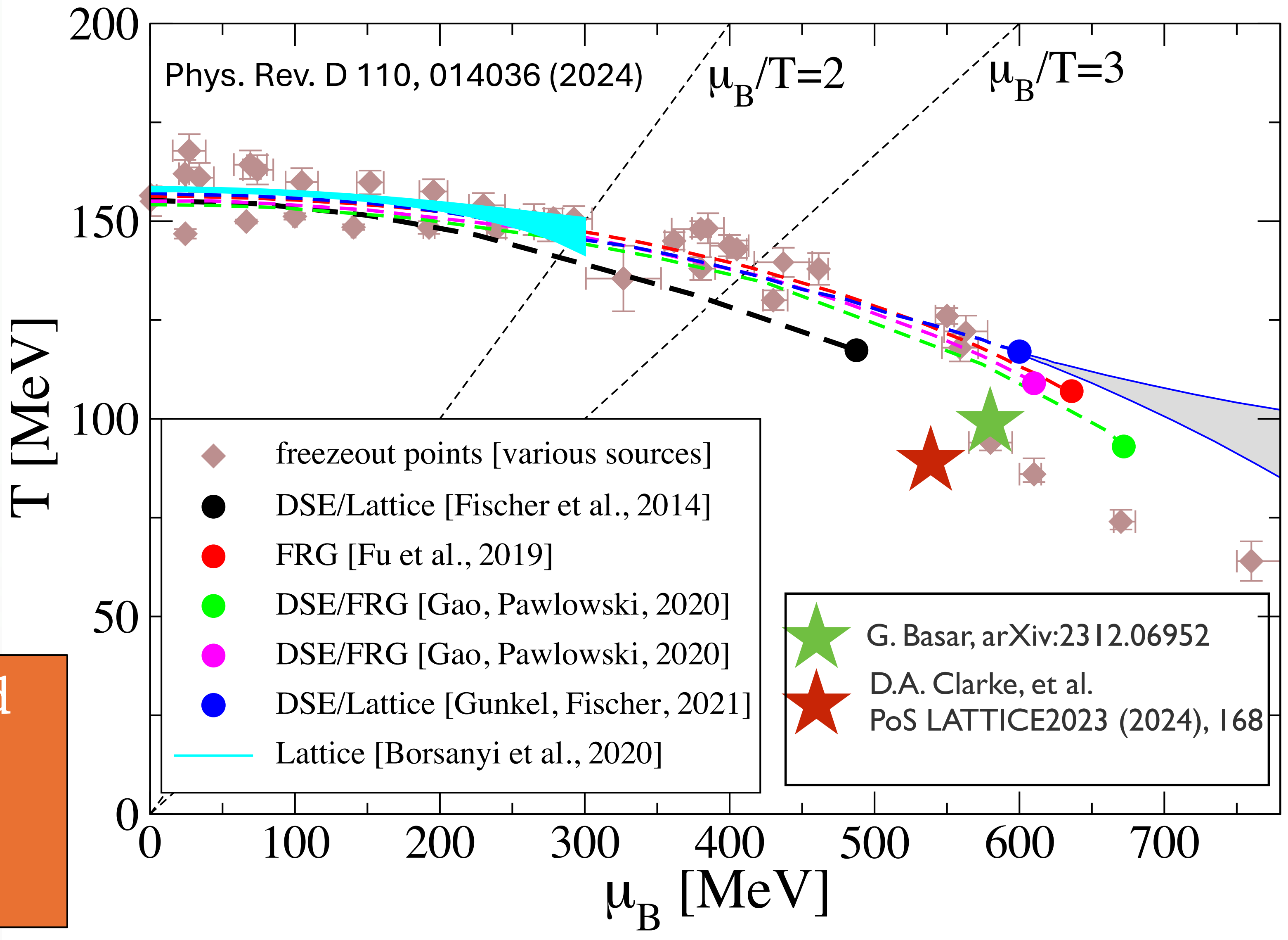
Suppression

STAR: *Phys.Rev.C* 107 (2023) 3, 034907
ALICE: PLB 802 (2020) 135225

Critical point search (1)

Where could the CP be on the QCD phase diagram ?

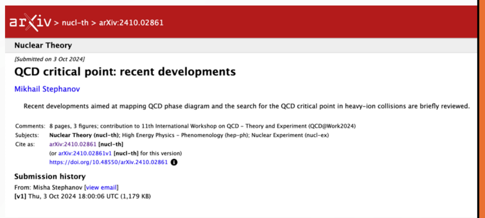
Important to understand the assumptions and limitations for each theoretical model



Critical point search (2)

$\kappa_1 = C_1$
$\kappa_2 = -C_1 + C_2$
$\kappa_3 = 2C_1 - 3C_2 + C_3$
$\kappa_4 = -6C_1 + 11C_2 - 6C_3 + C_4$

CP search – Experimental results from STAR-RHIC BES Phase-II


arXiv > nucl-th > arXiv:2410.02861

Nuclear Theory

QCD critical point: recent developments

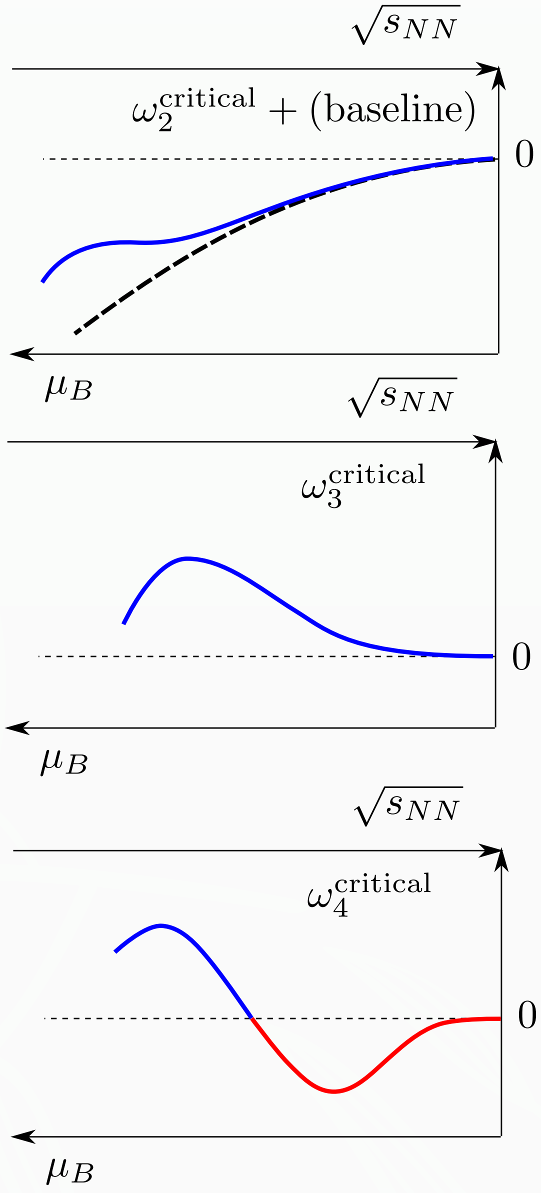
Mikhail Stephanov

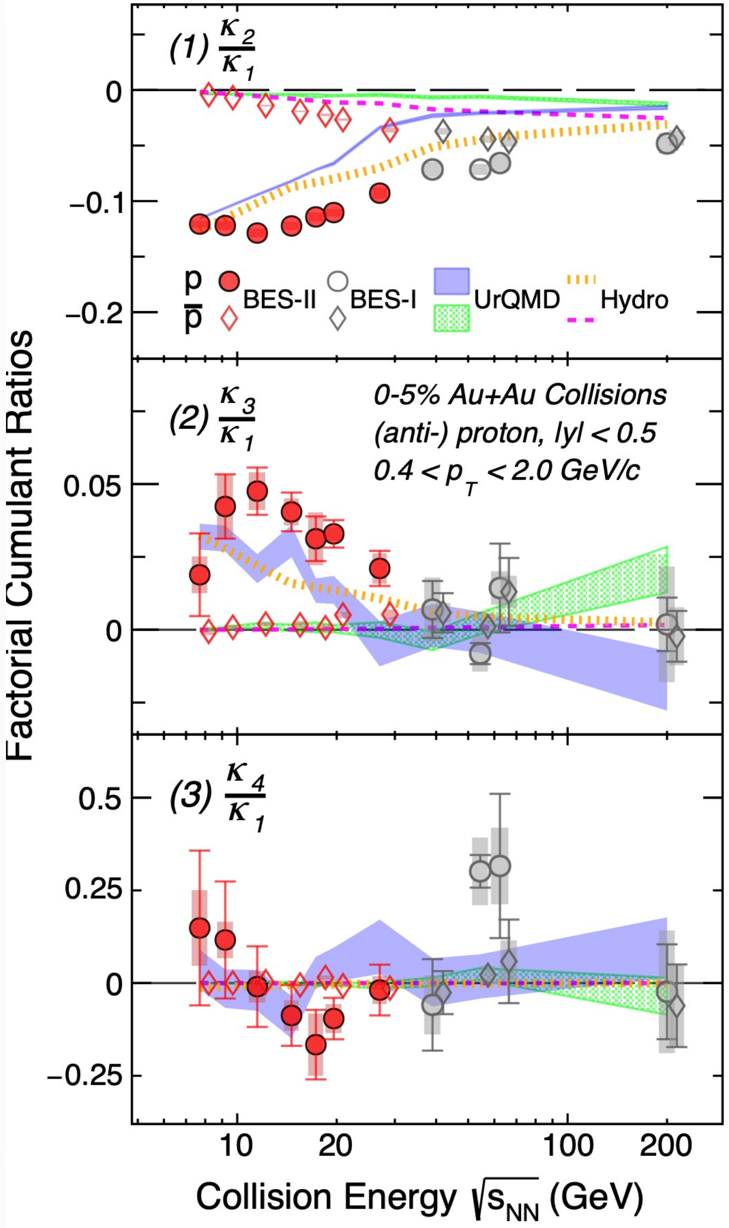
Recent developments aimed at mapping QCD phase diagram and the search for the QCD critical point in heavy-ion collisions are briefly reviewed.

Submission history

CP based model in qualitative agreement with measurements

Caveats
(1) Choice of the baseline
(2) Based on Ising model (singular & regular)
(3) Does not tell the location of CP

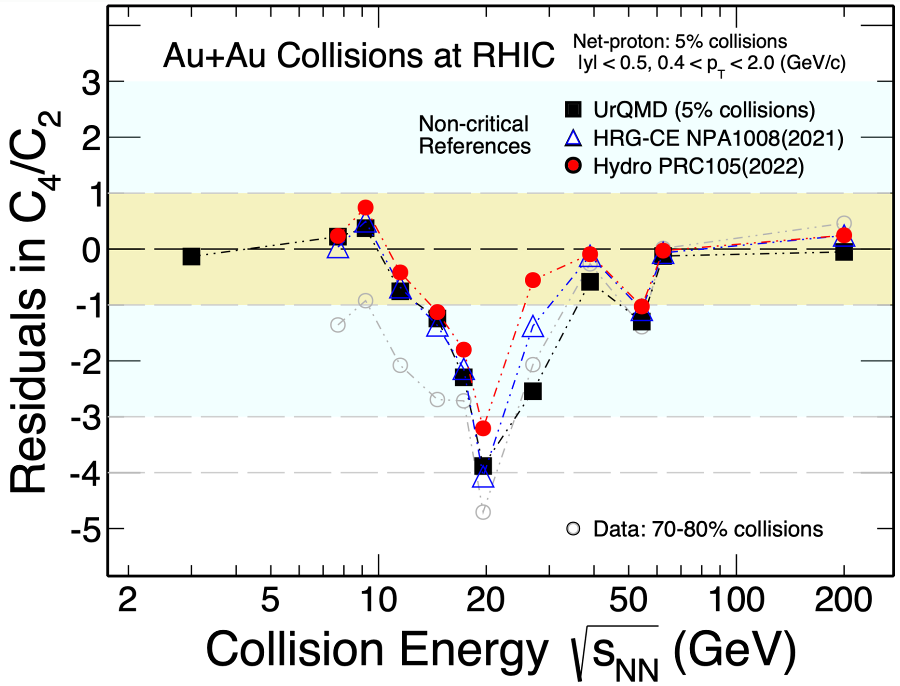




STAR: A. Pandav CPOD2024

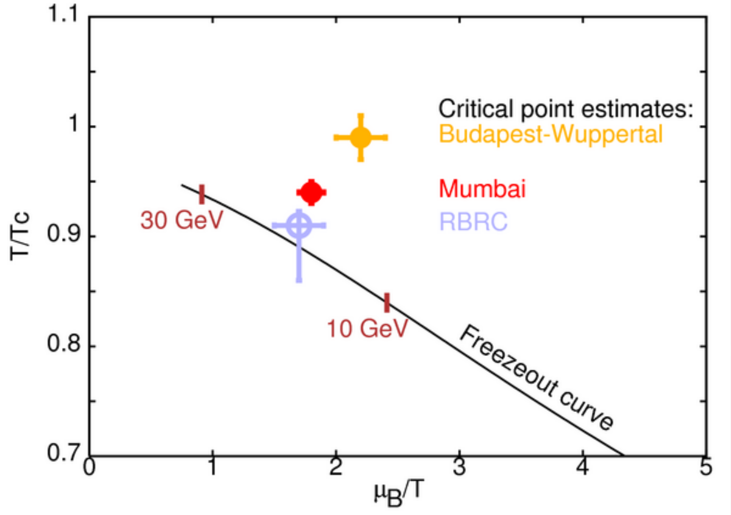
Critical point search (3)

- $C_2 \sim \xi^2 \qquad C_4 \sim \xi^7$
- $\frac{\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}}$



CP search – Experimental results

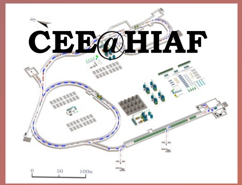
- Intriguing experimental result
- Need theory to confirm/rule out presence of QCD CP



Lattice results at high μ_B needs specific methods. Need to keep in mind system size, continuum extrapolation and scale setting

Next steps – phase diagram of QCD

See talks by: Ashish Pandav, Maneesha Pradeep, Jishnu Goswami, Hirotsugu Fujii and Chandrodoy Chattopadhyay



Effectively use the BES-II data and theory to conclude on

(a) Crossover at small μ_B

(b) Presence / absence of CP at large μ_B

(c) Presence / absence of 1st order phase transition at large μ_B

- Experiments creating high baryon density matter needed
- Theoretical studies – Lattice QCD, QCD based models and hydrodynamics near critical point.
- Need STAR-FXT and CBM + Theory to complete the story

Precision test of thermal models / thermalization

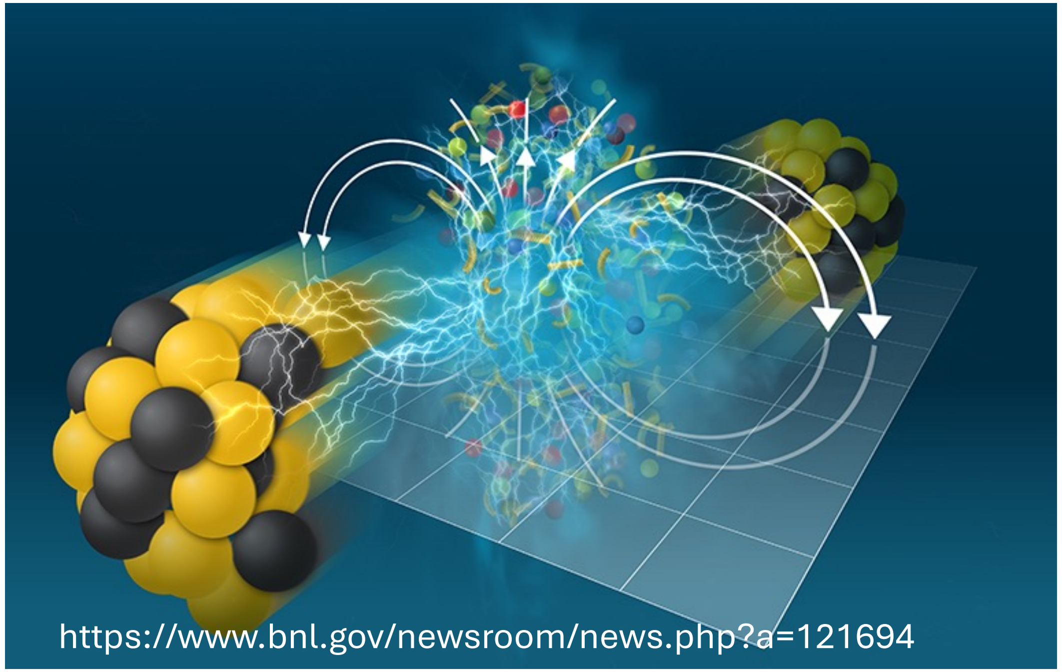
(a) Fluctuations/Correlations

(b) Multi-charm and nuclei

(c) High baryon density regime

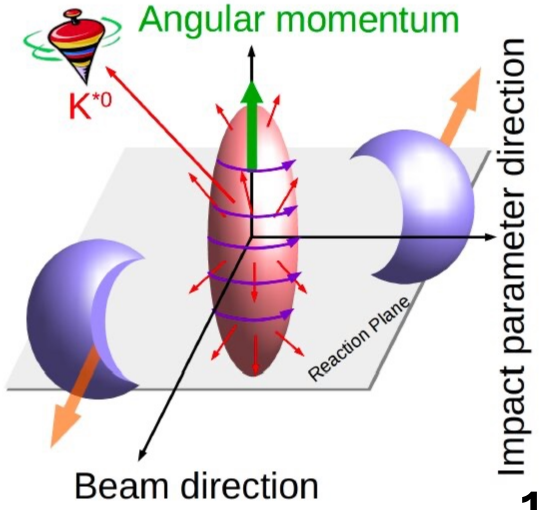
Initial conditions in heavy-ion collisions

Electromagnetic fields
Angular momentum
Parton distribution of the colliding nuclei
Baryon number transport
Nuclear structure

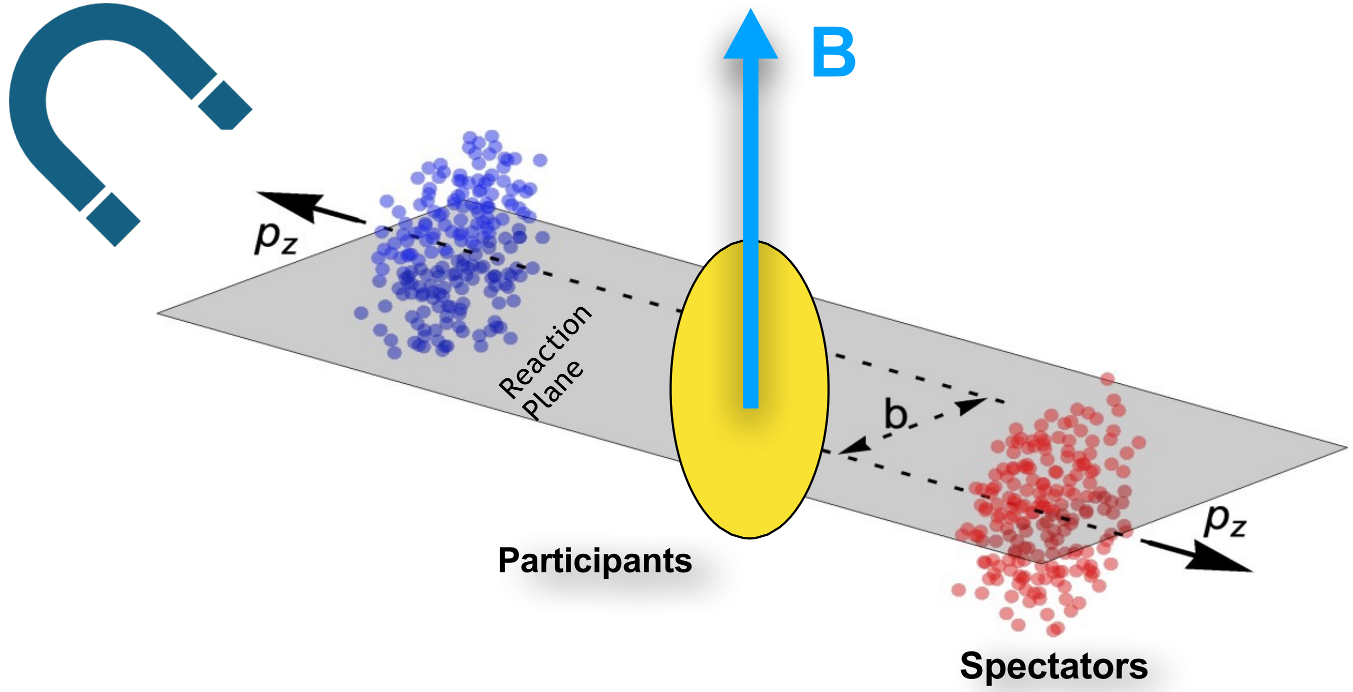


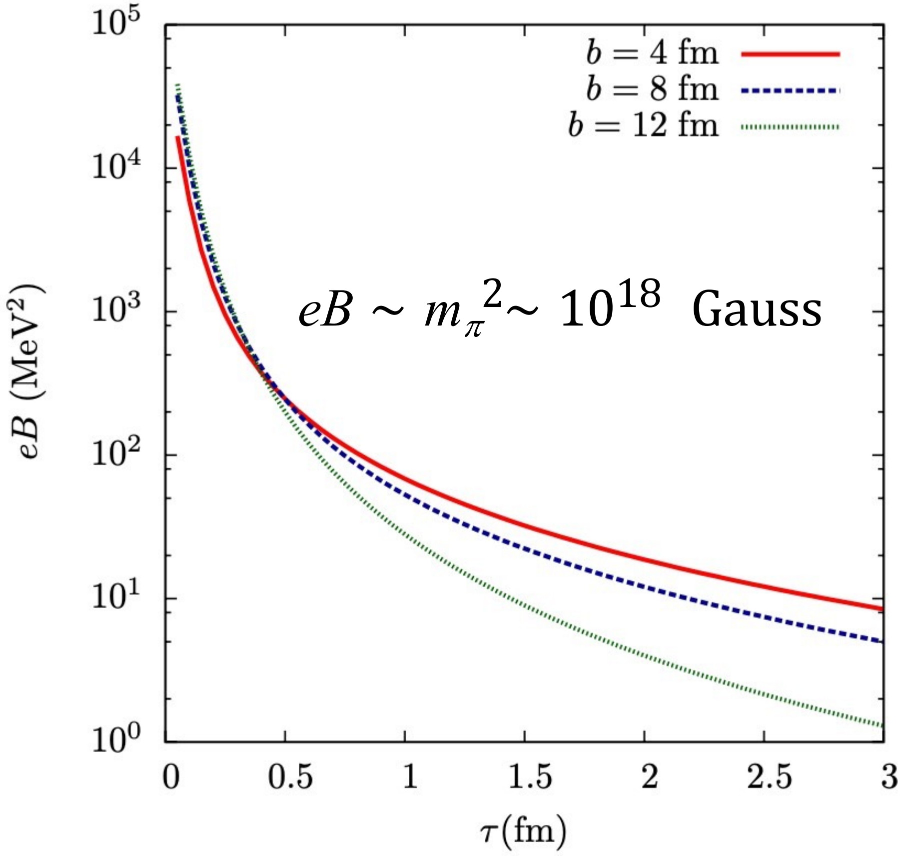
Strong participation from groups in ATHIC countries

Only discuss recent experimental efforts. The difficulty is in constructing an observable, which is not sensitive to the hydrodynamic evolution and the final hadronic rescattering. Instead, is only sensitive to the initial state.



Large initial magnetic field (1)



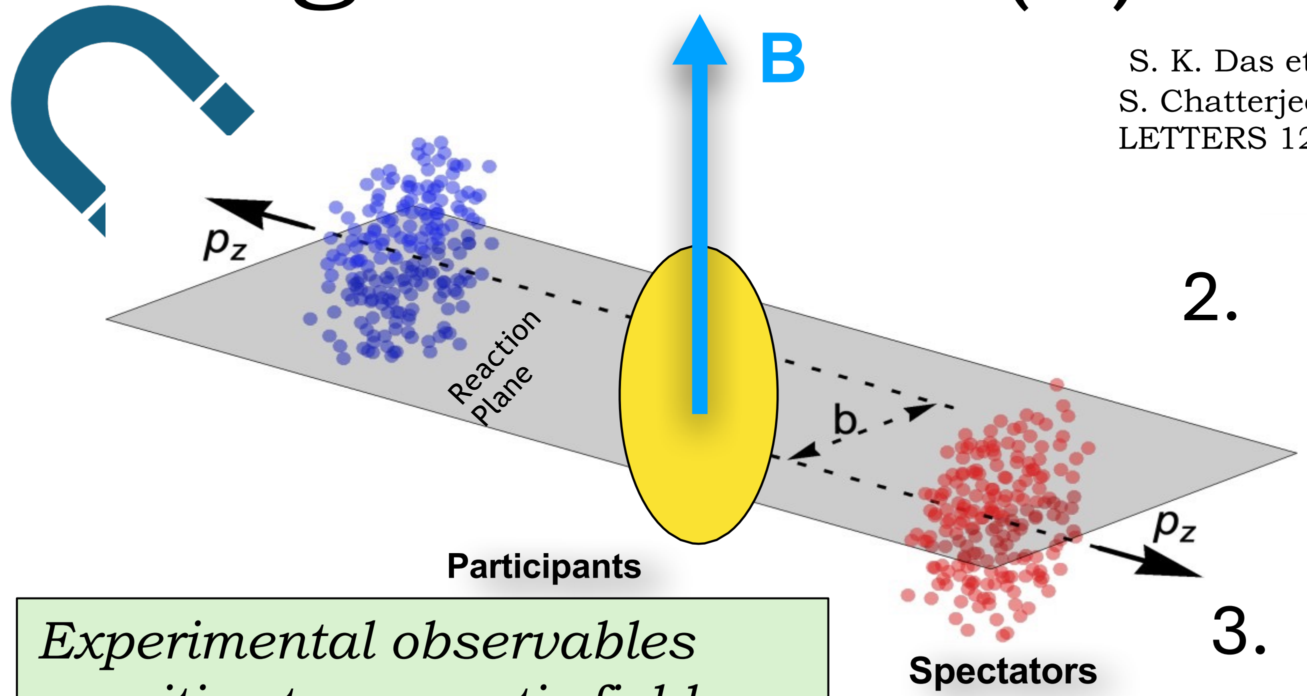


D. E Kharzeev, et al Nucl Phys A803, 227 (2008)

- Initial large magnetic field, but transient, retention depends on conductivity of the medium
- How to experimental detect?

$M^2_\pi \sim 2 \times 10^4$ MeV^2 $\sim 3 \times 10^{14}$ Tesla $\sim 3 \times 10^{18}$ Gauss

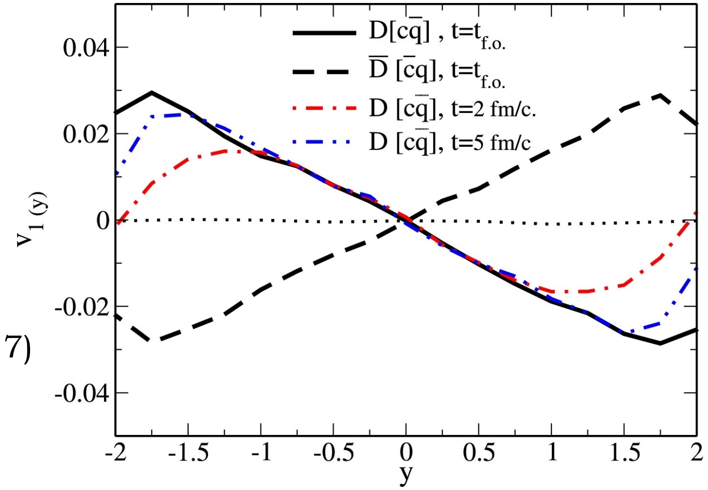
Large initial magnetic field (2)



Experimental observables sensitive to magnetic field

1. Directed flow of charm and anti-charm quark carrying hadrons

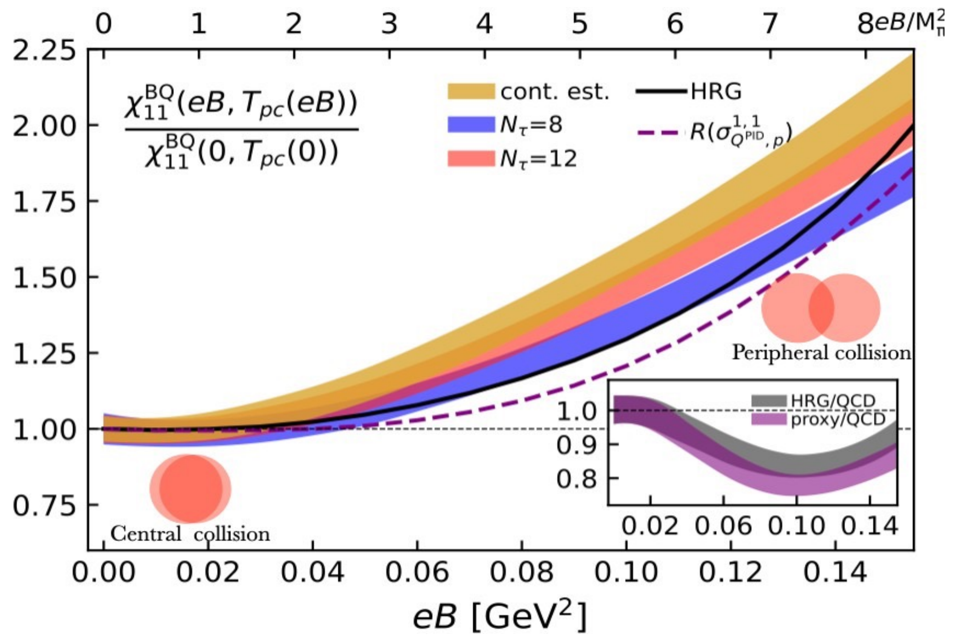
S. K. Das et al, Phys. Lett. B 768, 260 (2017)
S. Chatterjee et al., PHYSICAL REVIEW LETTERS 120, 192301 (2018)



2.

$$(P_\Lambda - P_{\bar{\Lambda}}) \approx \frac{2\mu_\Lambda B}{T}$$

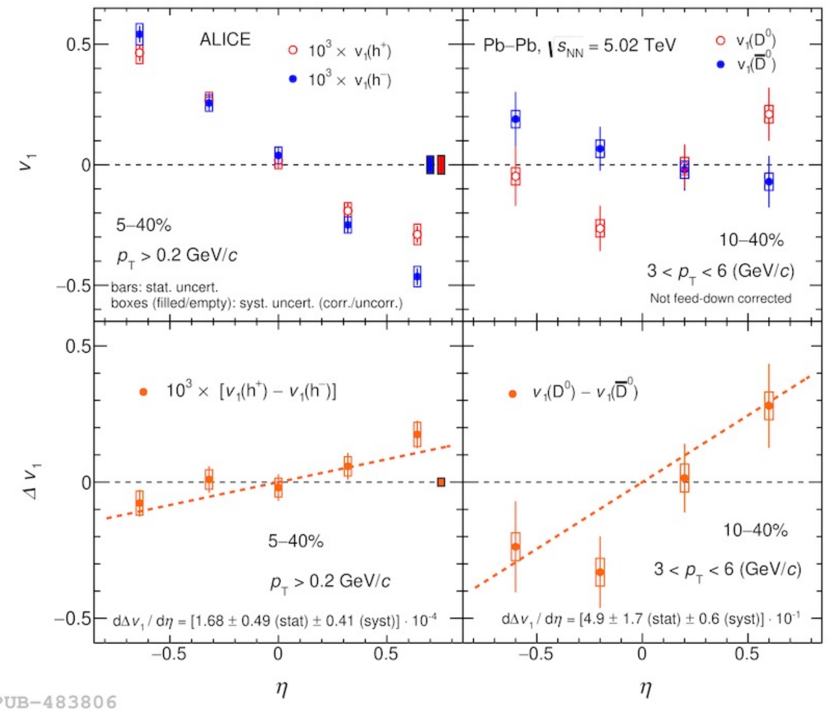
3.



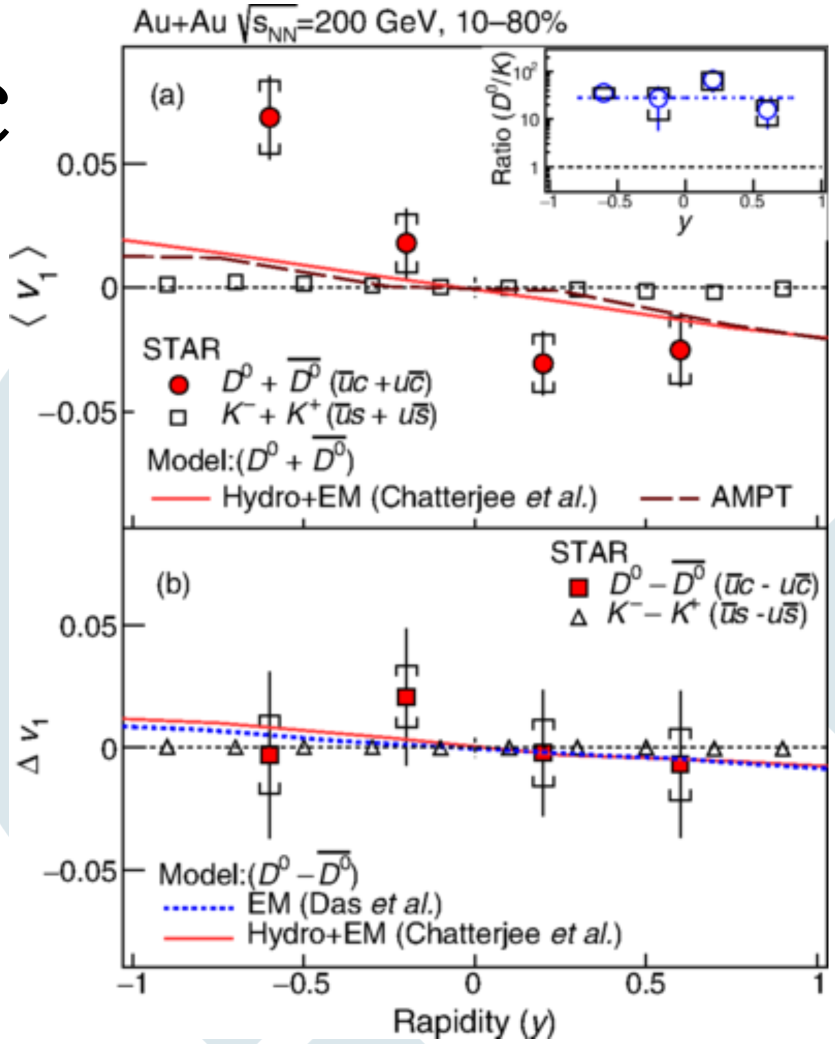
Heng-Tong Ding et al, PRL 132 (2024) 201903

1. Directed flow of charm hadrons
2. Polarization difference between hyperon and anti-hyperons
3. Fluctuations in conserved number

Large initial magnetic field (3)



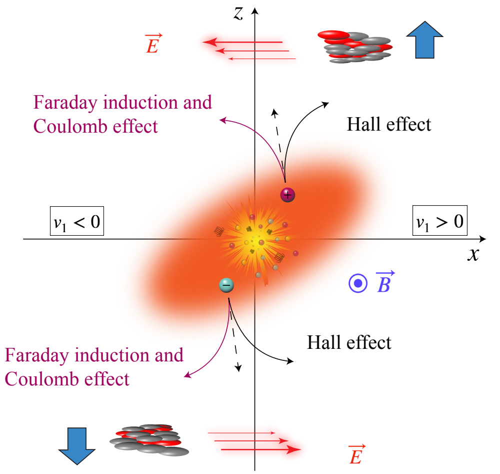
ALICE: Phys. Rev. Lett. 125 (2020) 022301

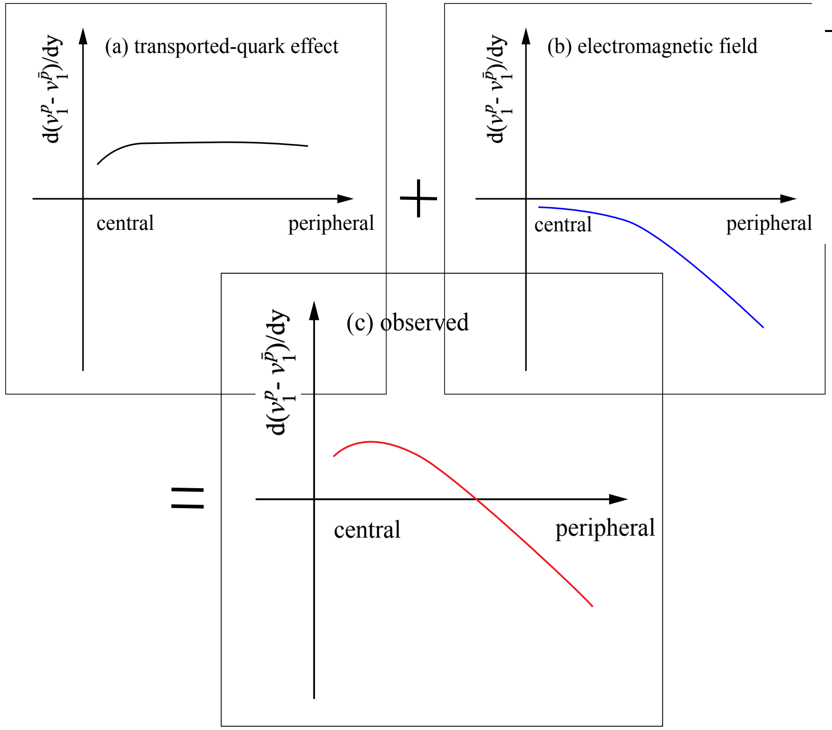


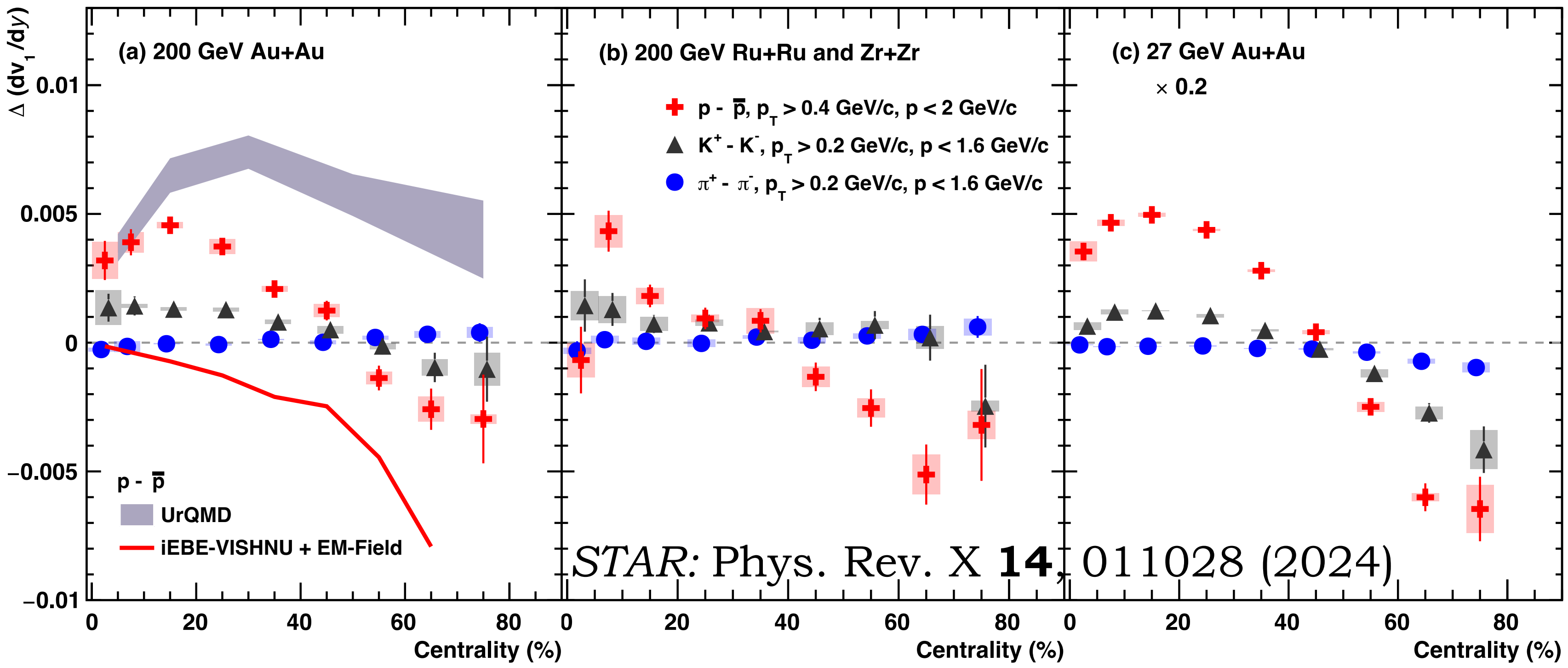
STAR: Phys.Rev.Lett. 123 (2019) 16, 162301

- D0 mesons have larger v_1 compared to charged π/K.
- Difference in D0 and D0bar v_1 larger at LHC energies.

Large initial magnetic field (3)





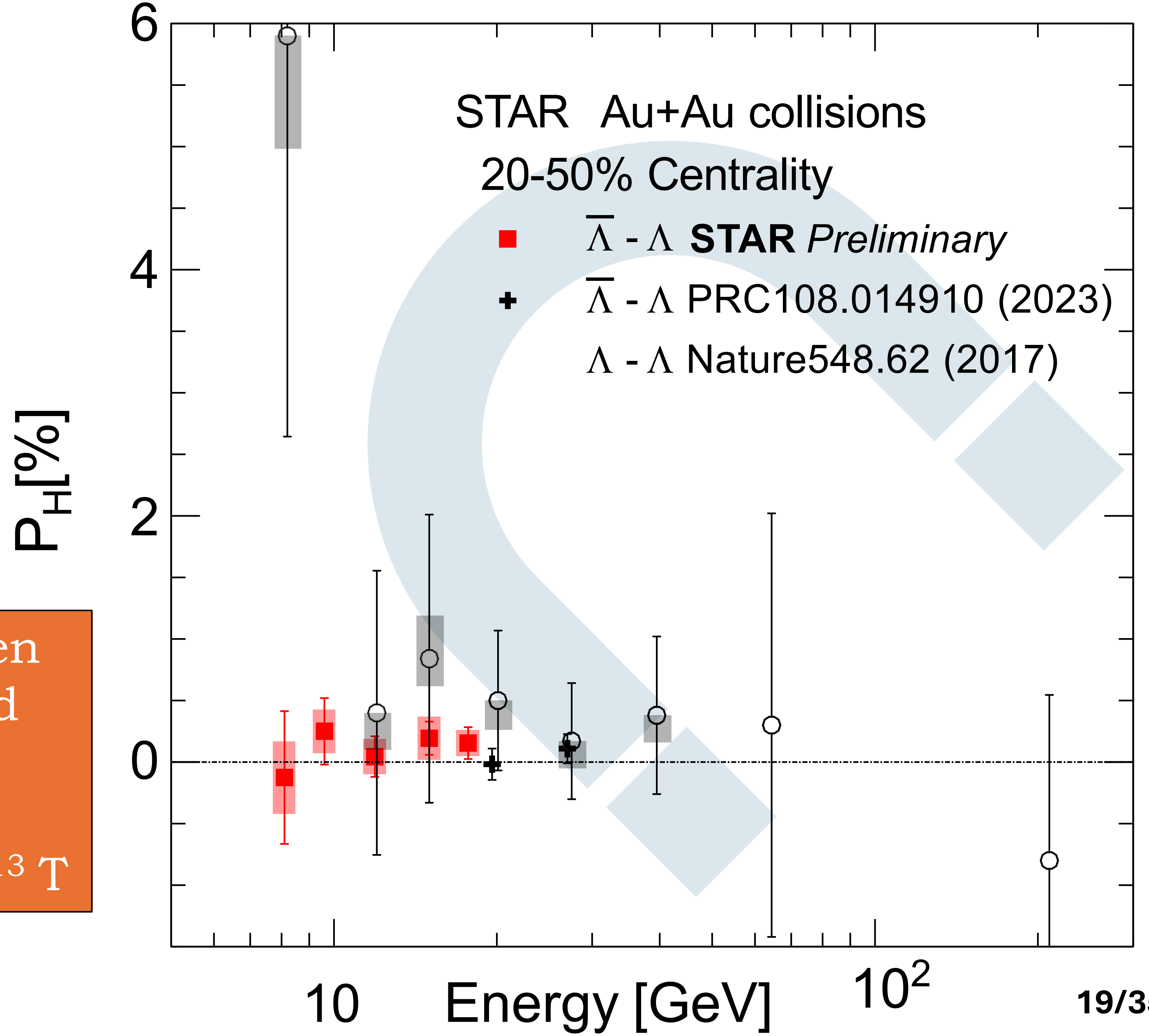


STAR: Phys. Rev. X **14**, 011028 (2024)

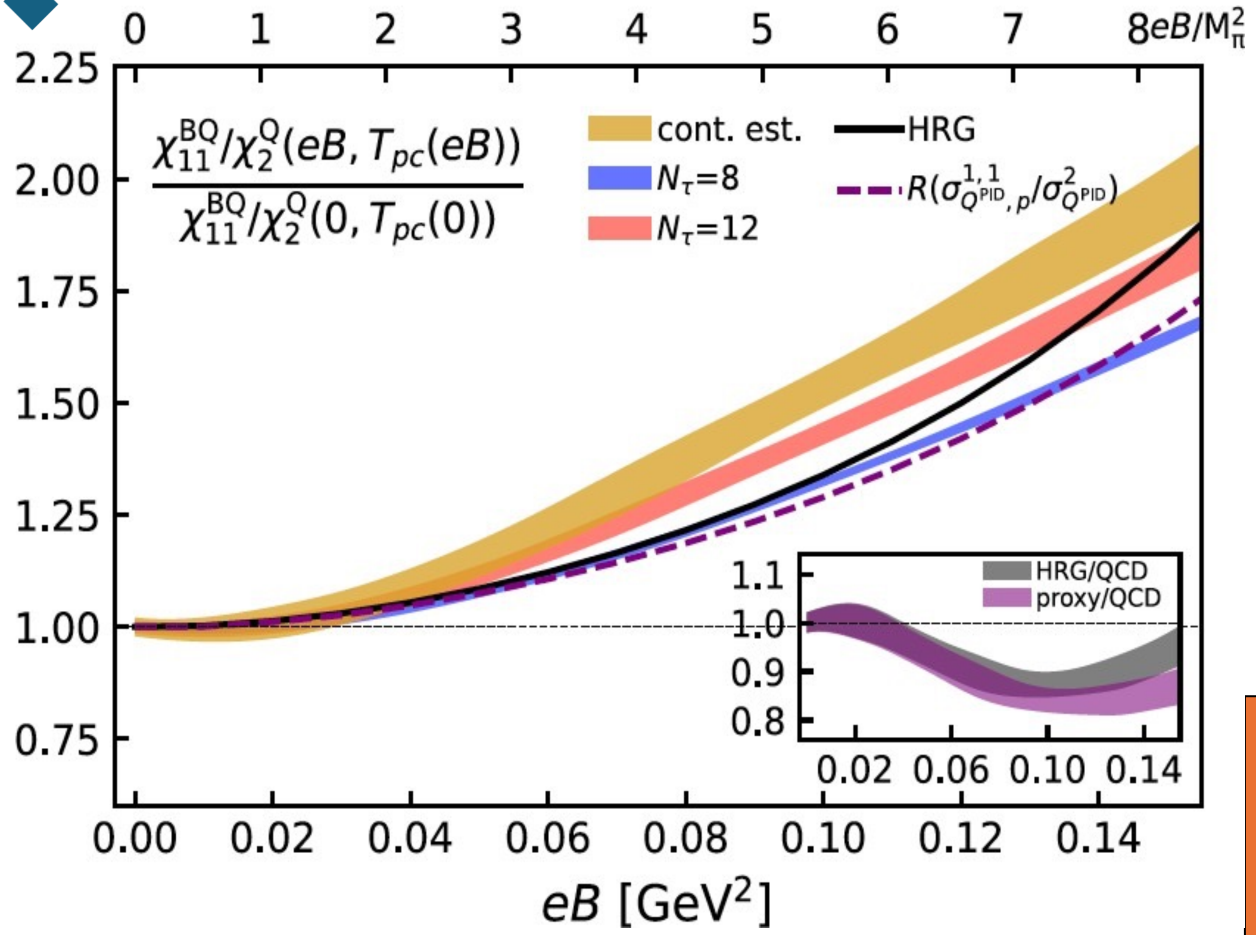
- Quarks and antiquarks carry opposite charges and receive contrary electromagnetic forces that alter their momenta. Splitting in v_1 of particle-anti-particle
- Constraints on the electrical conductivity of the QGP, measurements compatible with LQCD values $\sigma = 0.023\ \mathrm{fm}^{-1}$

Large initial magnetic field (4)

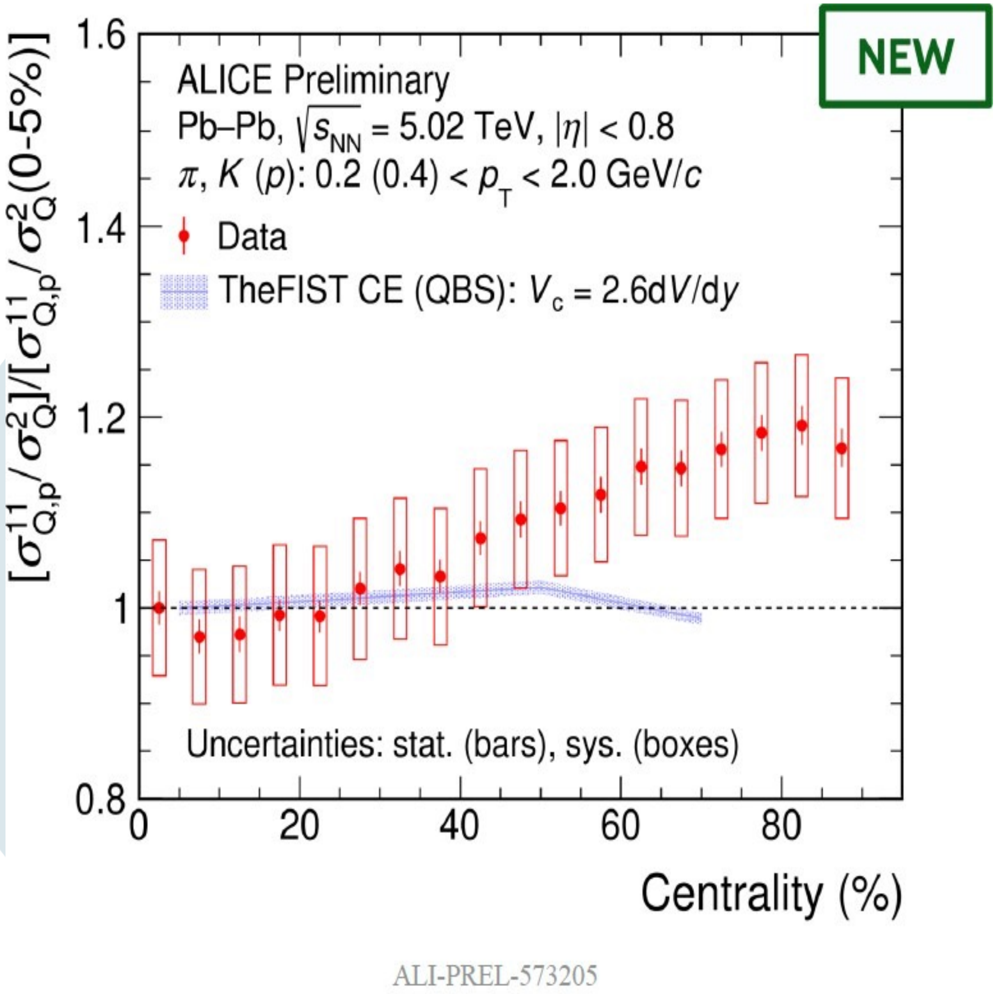
- No difference seen between polarization of lambda and anti-lambda
- Measurements puts a constraint on B field ≤ 10^{13} T



Large initial magnetic field (5)



Heng-Tong Ding, J.-B. Gu, A. Kumar, S.-T. Li, J.-H. Liu, PRL 132 (2024) 201903

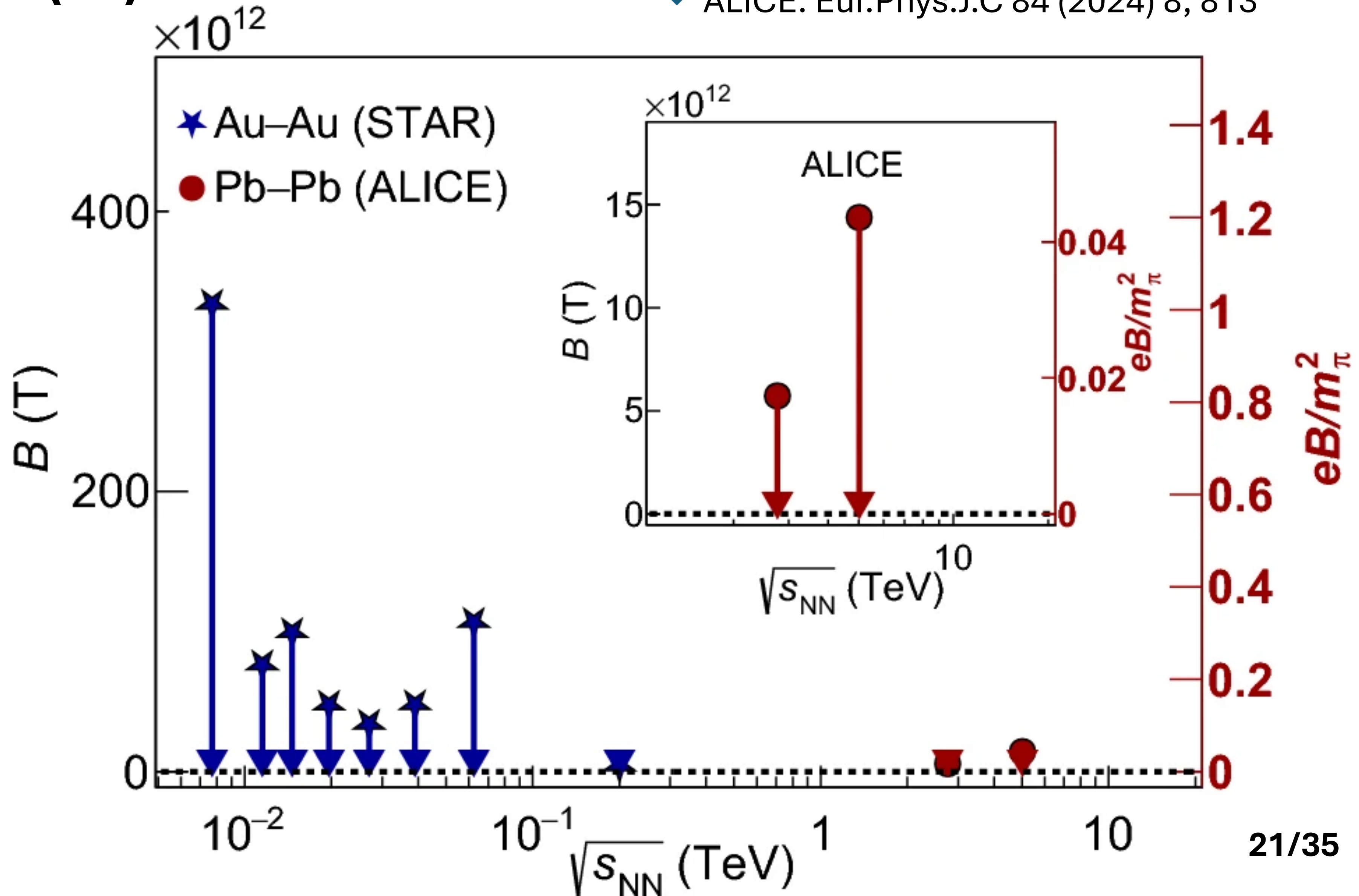


S. Saha for the ALICE collaboration @ SQM 2024

ALICE observes similar trends as seen in fluctuation observables calculated in LQCD in presence of magnetic field

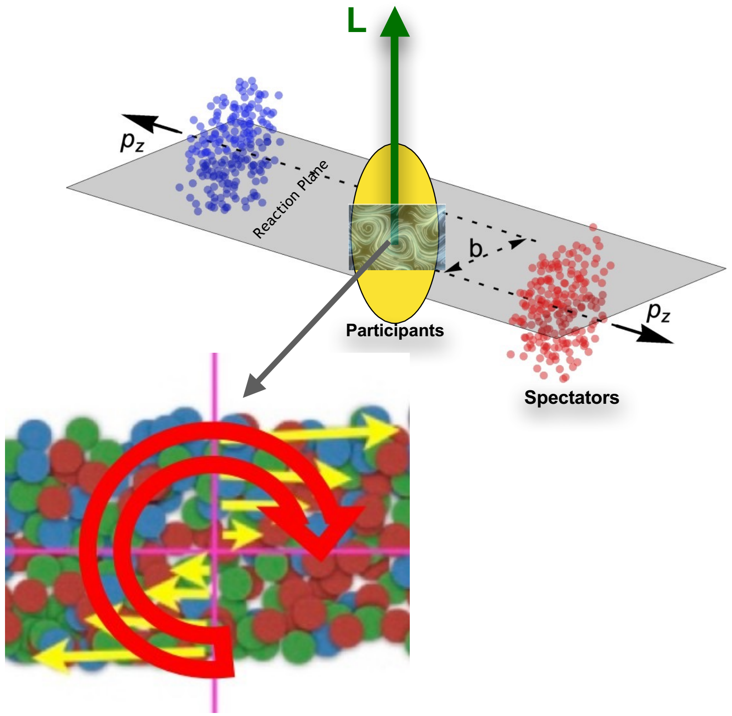
Large initial magnetic field (6)

ALICE: Eur.Phys.J.C 84 (2024) 8, 813



Upper limit on magnetic field

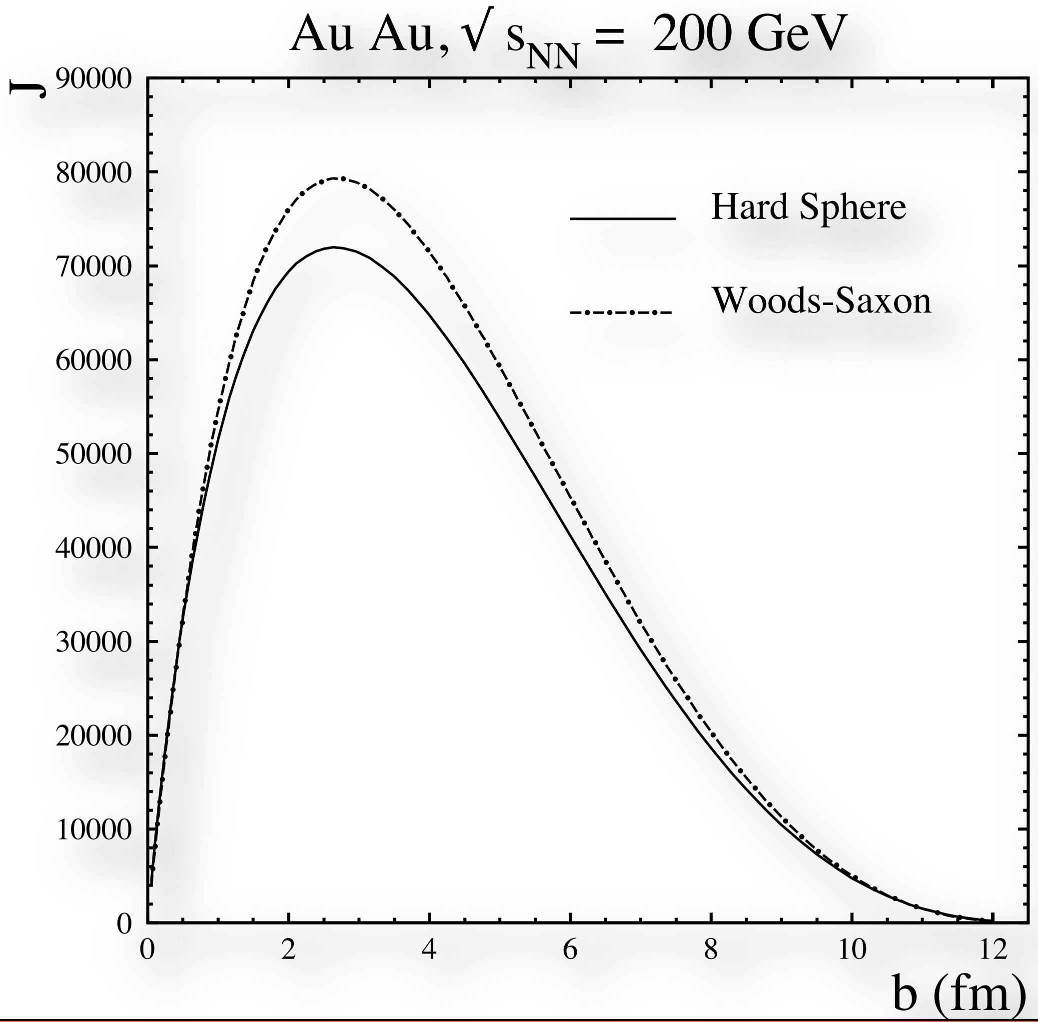
Large angular momentum (1)



Vorticity generation

$$L = r \times p \sim bA\sqrt{s_{NN}} \sim 10^4\,\hbar$$

$$\omega = \frac{1}{2}\nabla \times v \qquad \omega_y = \frac{1}{2}(\nabla \times v)_y \approx \frac{1}{2}\frac{dv_z}{dy}$$



F. Becattini et al., Phys.Rev.C 77 (2008) 024906

- Angular momentum conserved quantity
- Spin-orbital angular momentum interactions – Polarization of hyperons and spin alignment of vector mesons

Large angular momentum (2)

Vector meson spin alignment

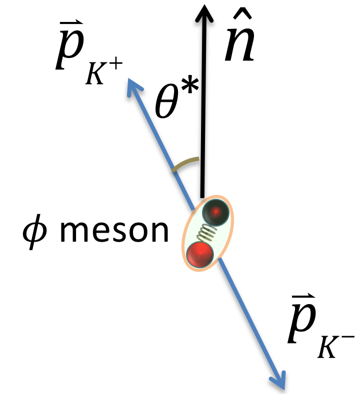
RE: spin alignment highlight

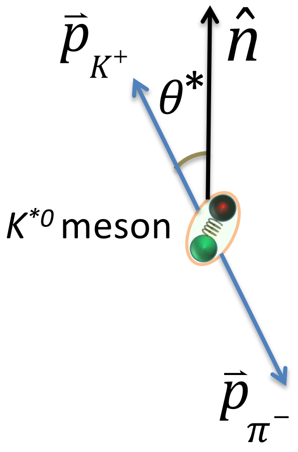
From Huan Z Huang on 2006-10-13 07:02

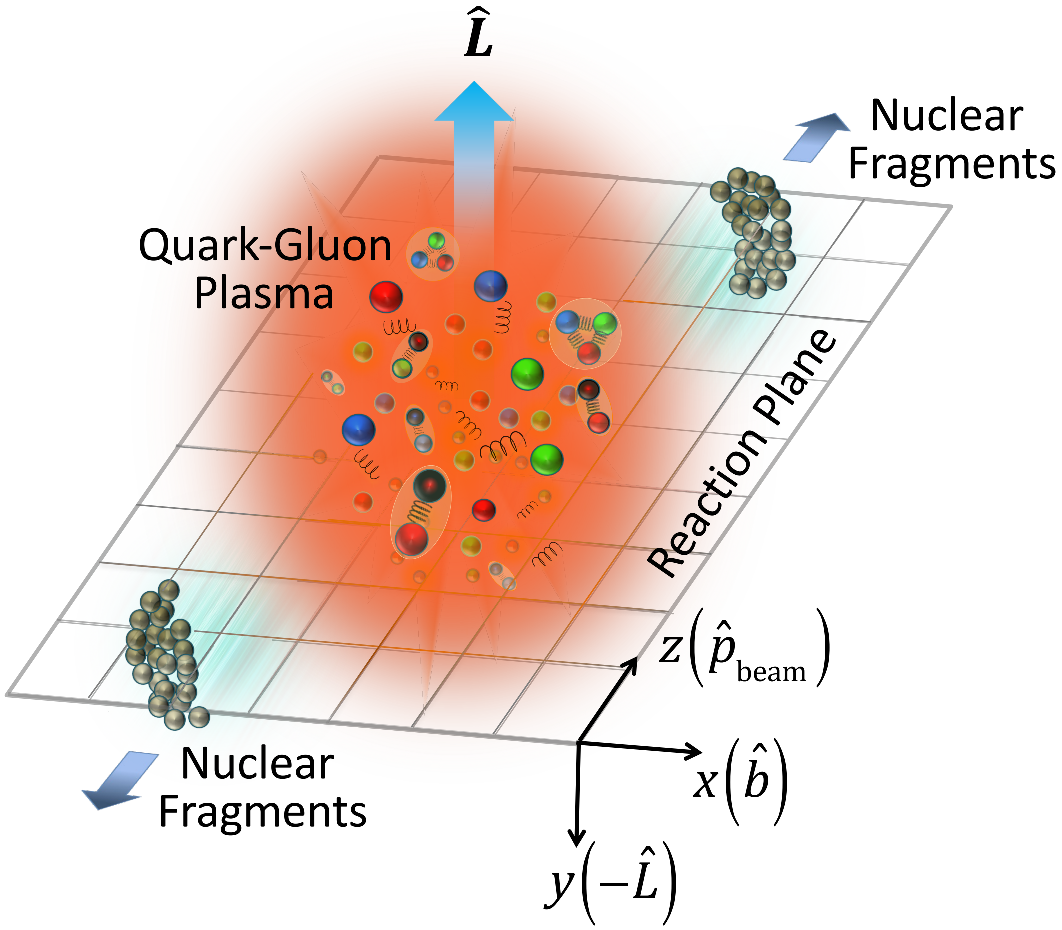
Details

```
Hi Rene,
  Bedanga has nicely summarized the relevant physics with the spin alignment
issues. The references that he pointed out will also be interesting to read.
  I will add that these are relatively new ideas in the past several years
and only recently that STAR can attack the problem systematically through
vector meson alignment and Lambda polarization studies. The STAR TPC as a
general large acceptance detector can really do wonders for new physics
ideas. In this aspect, I would view this work as both a status report on
STAR's effort to pursue new physics ideas and highlight of STAR's potential
as a large acceptance detector.
  Regards,
    Huan
```

$$\frac{dN}{dcos\theta} = N_0\left[1-\rho_{0,0}+cos^2\theta\left(3\rho_{0,0}-1\right)\right]$$

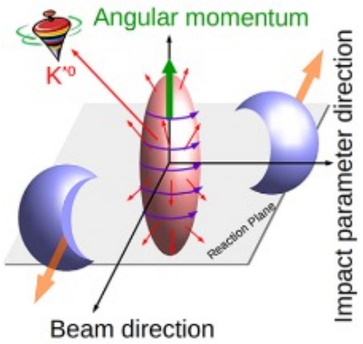






Large angular momentum (3)

ALICE: K* meson spin alignment – 3σ effect



EDITORS' SUGGESTION

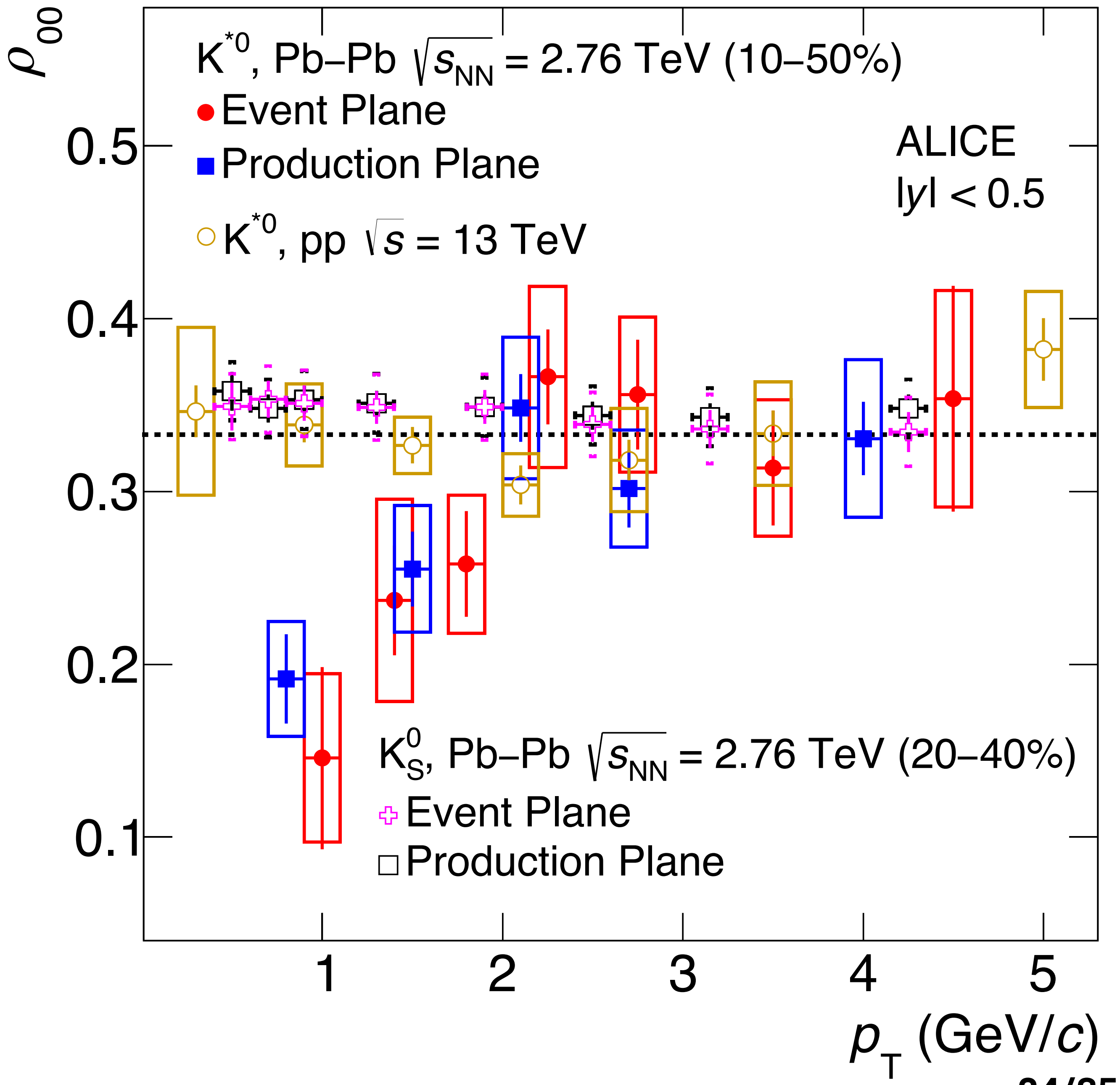
Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

The measured spin alignment of vector mesons in heavy-ion collisions is consistent with that expected from the spin-orbit coupling of quarks with the large angular momentum of the collision.

S. Acharya *et al.* (The ALICE Collaboration)

Phys. Rev. Lett. **125**, 012301 (2020)

$$\frac{dN}{dcos\theta} = N_0\left[1-\rho_{0,0}+cos^2\theta\,(3\rho_{0,0}-1)\right]$$



Large angular momentum (3)

STAR: ϕ meson spin alignment – 8σ effect

nature

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nature > articles > article

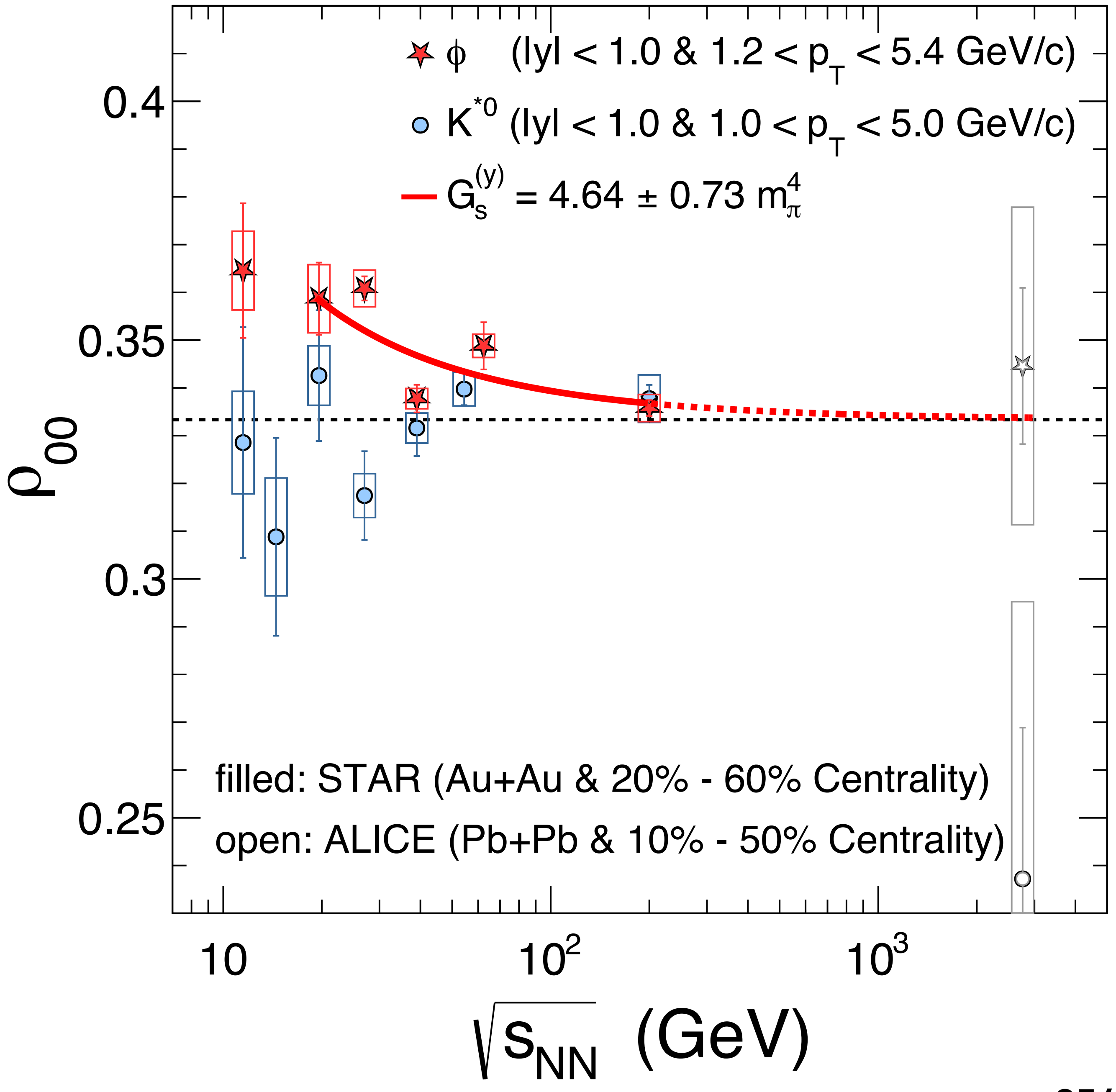
Article | Published: 18 January 2023

Pattern of global spin alignment of φ and K^{*0} mesons in heavy-ion collisions

STAR Collaboration

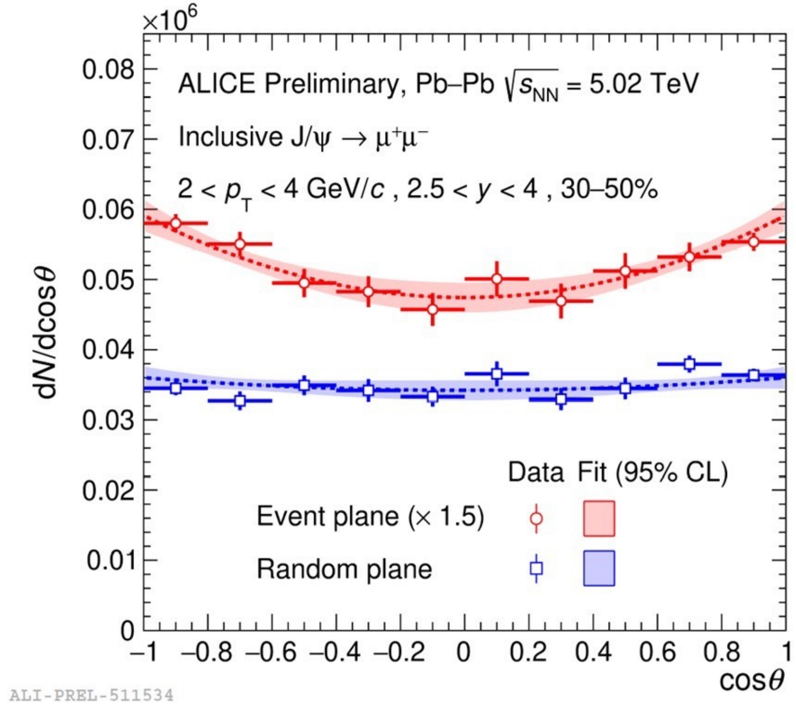
Nature **614**, 244–248 (2023) | Cite this article

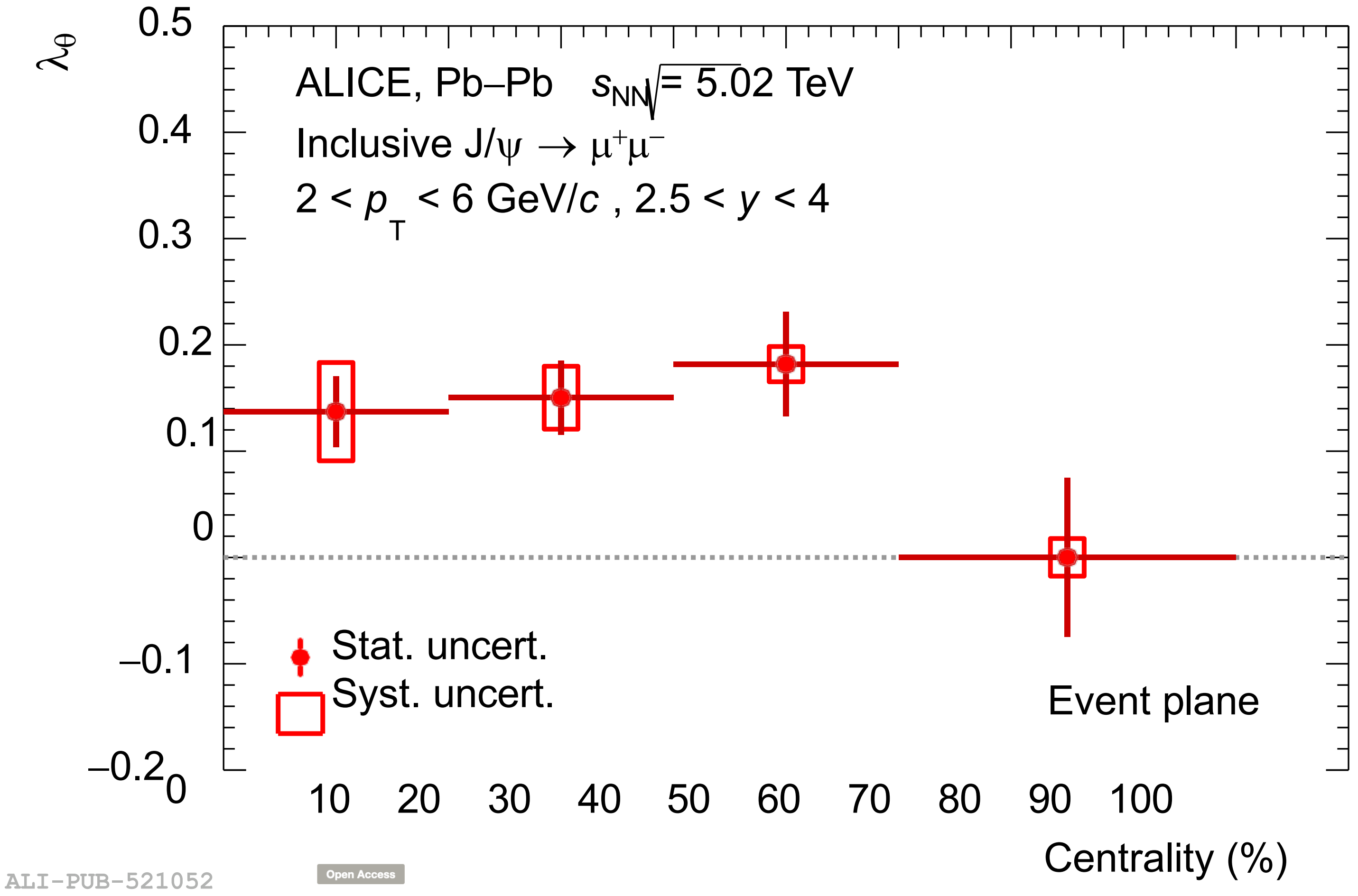
$$\frac{dN}{dcos\theta} = N_0\left[1 - \rho_{0,0} + cos^2\theta\,(3\rho_{0,0} - 1)\right]$$



Large angular momentum (4)

ALICE: J/ψ meson spin alignment – 3.5σ effect (forward rapidity)





- In the dilepton channel:

$$\lambda_\theta = \frac{1 - 3\rho_{00}}{1 + \rho_{00}} \qquad \lambda_\theta > 0 \rightarrow \rho_{00} < 1/3 \qquad \lambda_\theta < 0 \rightarrow \rho_{00} > 1/3$$

Open Access

Measurement of the J/ψ Polarization with Respect to the Event Plane in Pb-Pb Collisions at the LHC

S. Acharya *et al.* (ALICE Collaboration)

Phys. Rev. Lett. **131**, 042303 – Published 25 July 2023

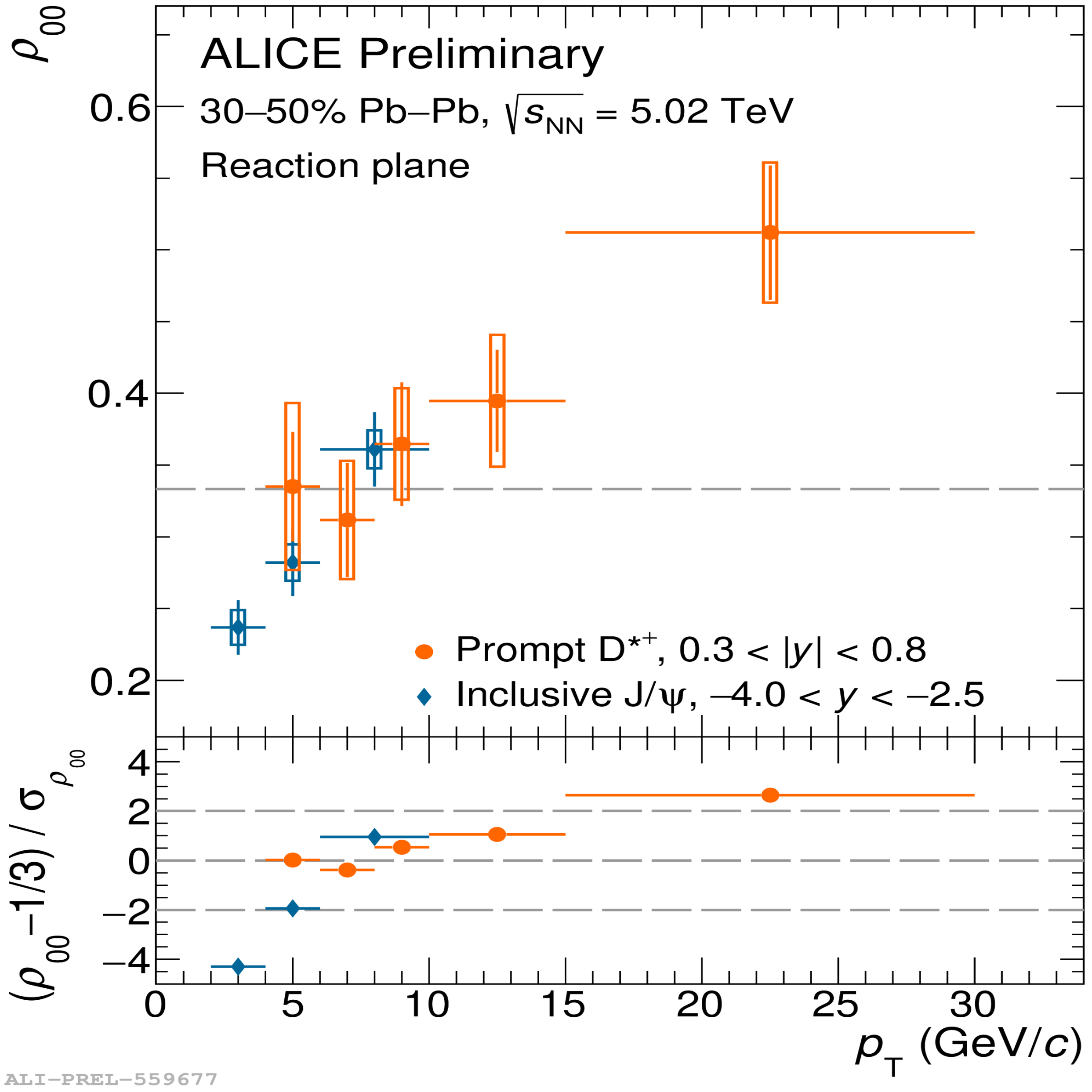
Large angular momentum (5)

ALICE: open charm D^{*+} spin alignment

$\rho_{00} < \frac{1}{3}$ quark recombination at low *momentum*

$\rho_{00} > \frac{1}{3}$ quark fragmentation at high *momentum*

$$\frac{dN}{dcos\theta} = N_0 \left[1 - \rho_{0,0} + cos^2\theta\,(3\rho_{0,0} - 1)\right]$$



Large angular momentum (6)

Interesting experimental program on spin alignment unfolding in pp and AA collisions

	K^*	ϕ	D^{*a}	J/ψ	$\psi(2S)$	χ_c	$\Upsilon(nS)$
pp	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$	$\rho_{00}\sim 1/3$		
Pb-Pb	$\rho_{00} < 1/3$ low p_T	$\rho_{00} < 1/3$ low p_T $\rho_{00} > 1/3$ At RHIC	$\rho_{00} > 1/3$ high p_T	$\rho_{00} < 1/3$ low p_T			

Theoretical efforts to understand the measurements ongoing
Need for a Spin hydrodynamics development which is happening.

Large angular momentum (6)

Interesting experimental measurements on hyperon polarization

For an ensemble of Λs with polarization $\vec{P}$:

$$\frac{dW}{d\Omega^*} = \frac{1}{4\pi}\left(1+\alpha\vec{P}\cdot\hat{p}_p^*\right) = \frac{1}{4\pi}\left(1+\alpha P\cos\theta^*\right)$$

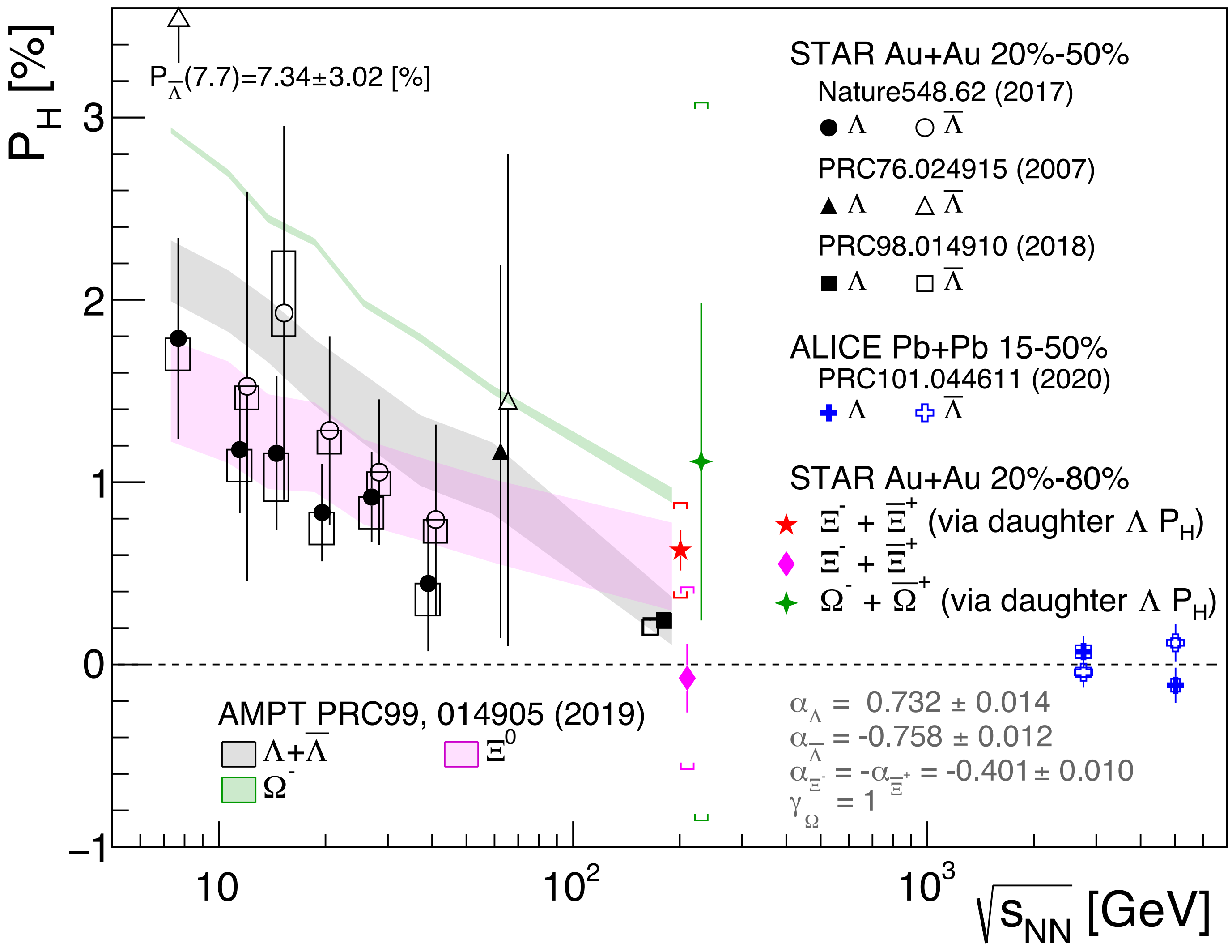
$\alpha = 0.642$ [measured]

$\hat{p}_p^*$ is the daughter proton momentum direction *in* the Λ *frame*

$$0 < |\vec{P}| < 1: \quad \vec{P} = \frac{3}{\alpha}\bar{\hat{p}}_p^*$$

$$P_\Lambda \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T} \qquad P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$

(for small polarizations)



Nature 548, 62 (2017) (STAR Collaboration)
Phys Rev C 98, 14910 (2018) (STAR Collaboration)

Global Polarization of Ξ and Ω Hyperons in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

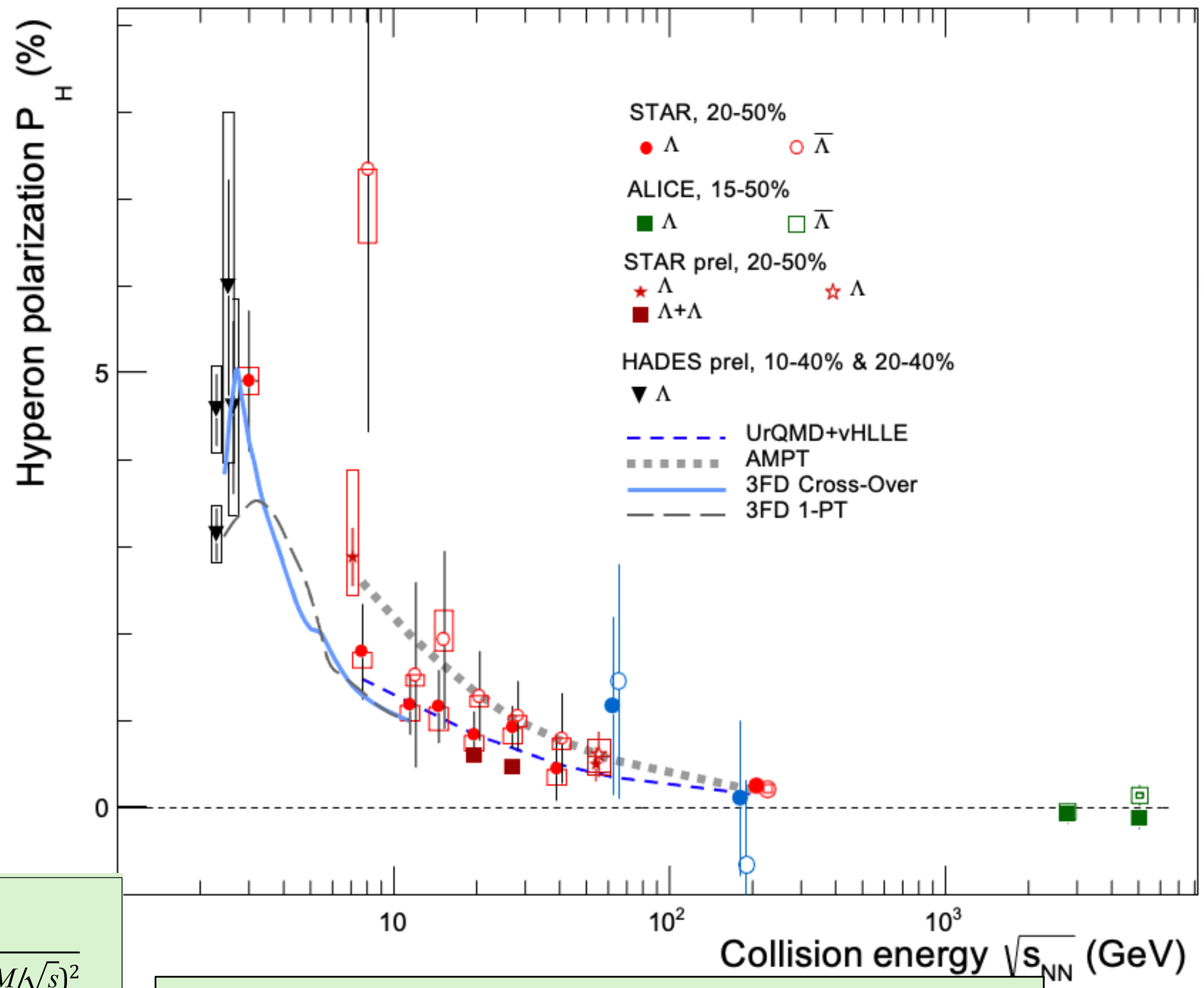
J. Adam *et al.* (STAR Collaboration)
Phys. Rev. Lett. **126**, 162301 – Published 22 April 2021; Erratum Phys. Rev. Lett. **131**, 089901 (2023)

Large angular momentum (Polarization - global)

Energy dependence:
Models reproduce data
Effect an interplay of
(a) Shear flow
(b) Baryon stopping
(c) Rapidity acceptance
(d) Lifetime of the system

Thermal vorticity $\omega = k_B T(P_\Lambda + P_{\bar{\Lambda}})/\hbar$

$\omega \sim (9 \pm 1) \times 10^{21} s^{-1}$



STAR: Phys Rev C 76, 024915 (2007)

Nature 548, 62 (2017)

Becattini, et. al., Phys Rev C 95, 054902 (2017)

Karpenko et. al., Eur Phys J C 77, 213 (2017)

Ivanov et. al., Phys Rev C 100, 014908 (2019)

Ivanov et. al., Phys Rev C 102, 024916 (2020)

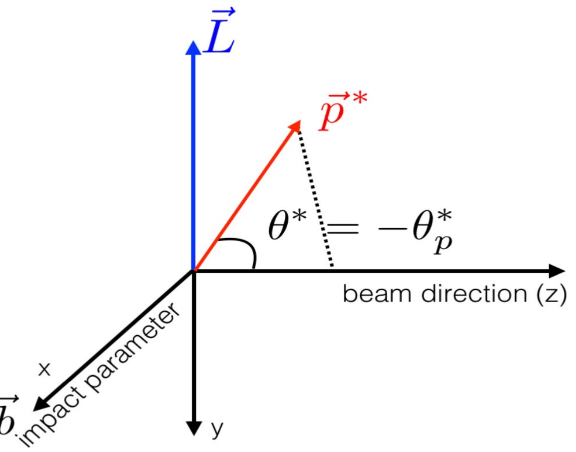
Lower energy - Expectation:

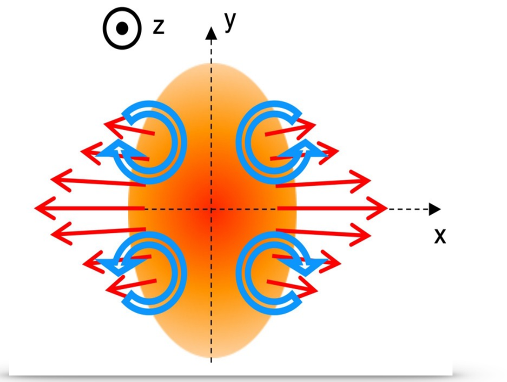
$L \sim \frac{1}{2} Ab\sqrt{s}\sqrt{1-(2M/\sqrt{s})^2}$

$P_\Lambda \sim 0$ at $\sqrt{s_{NN}} \sim 2m_N$

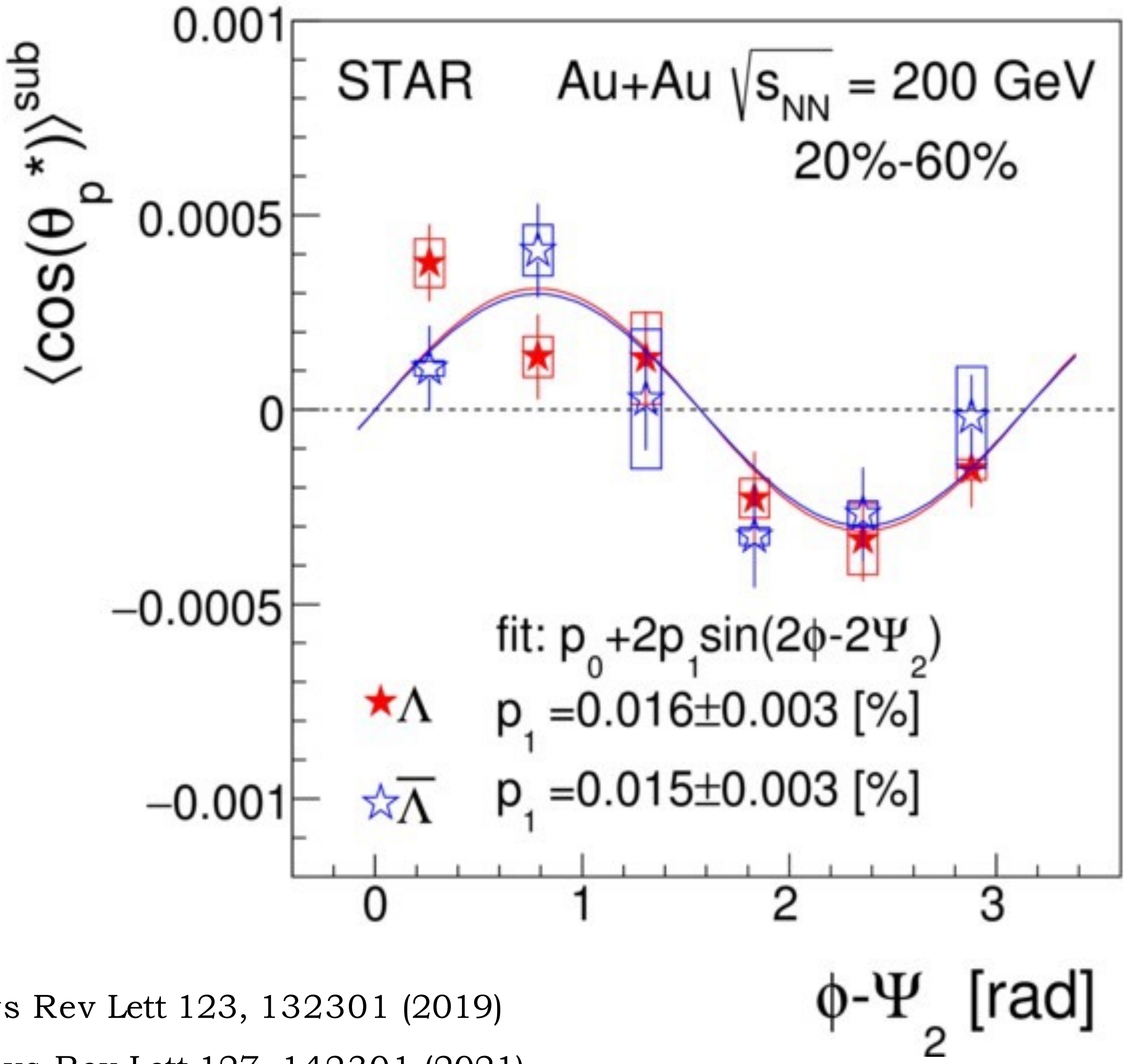
Models do not capture flat rapidity dependence (not discussed)

Large angular momentum (Polarization - local)





Amplitude of sine-modulation sensitive to hydrodynamic gradients. Data explained by model which incorporates shear induced polarization



STAR: Phys Rev Lett 123, 132301 (2019)

Fu et., al, Phys Rev Lett 127, 142301 (2021)

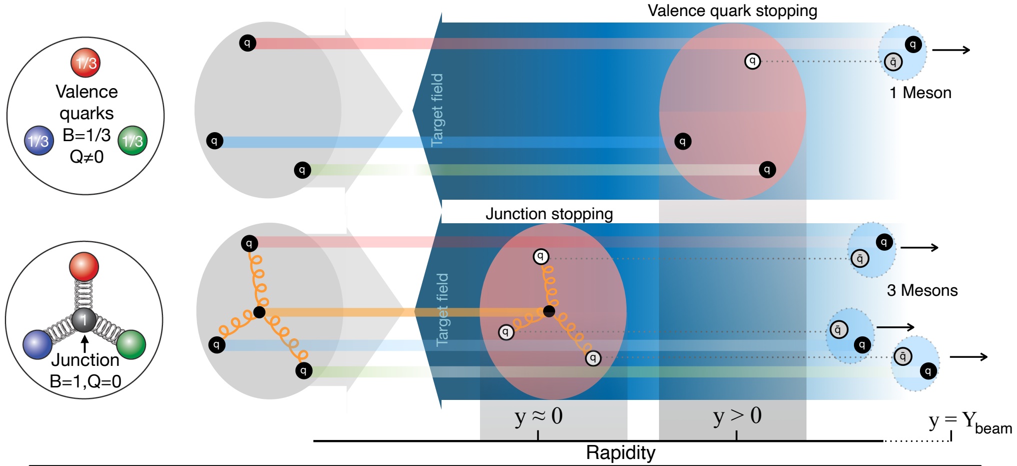
Next steps – EM fields and spin-orbital angular interactions

Experimental program moving fast with new measurements, more differential in nature and better precision.

Theoretical developments need to continue for a relativistic spin-magneto-viscous hydrodynamics to get the complete picture

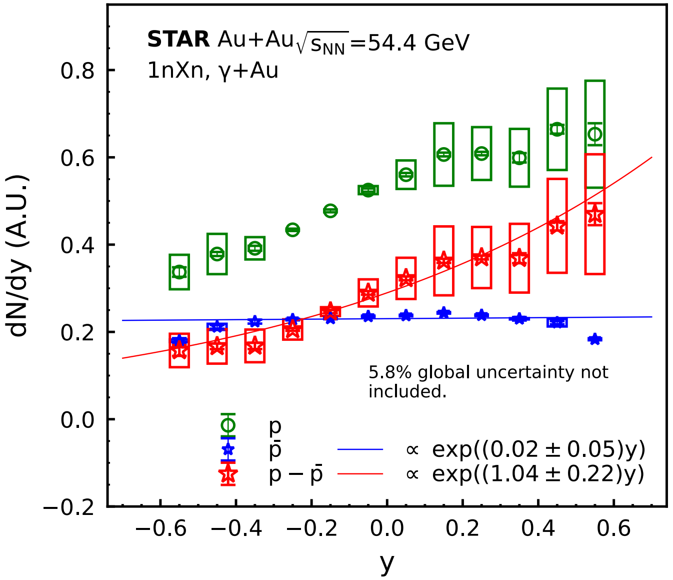
See talks by: Koichi Hattori, Huan Huang, Chiho Nonaka, Ashutosh Dash, Amaresh Jaiswal, Shi Pu and Zhenyu Chen

Two interesting developments on initial conditions



What carries the baryon number – study baryon transport along rapidity

STAR: arXiv:2408.15441



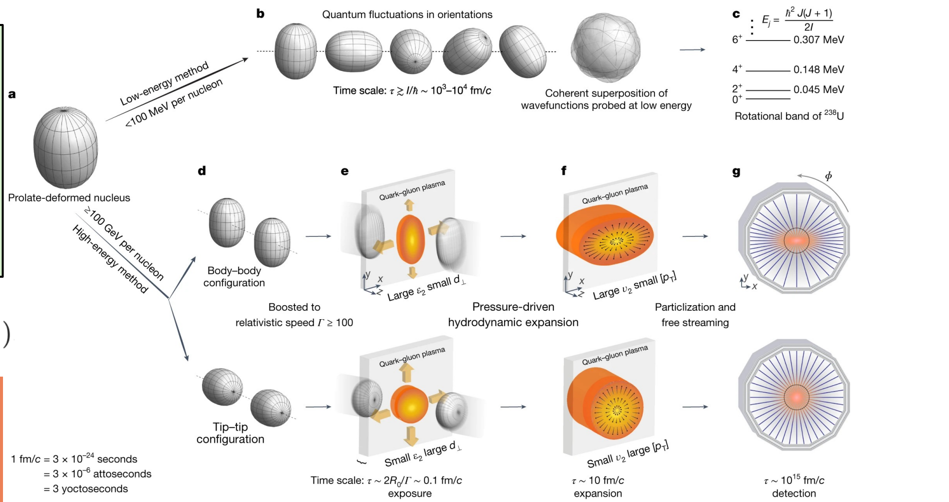
Baryon junction

$$f(y) \propto \exp(-\alpha_B \Delta y)$$

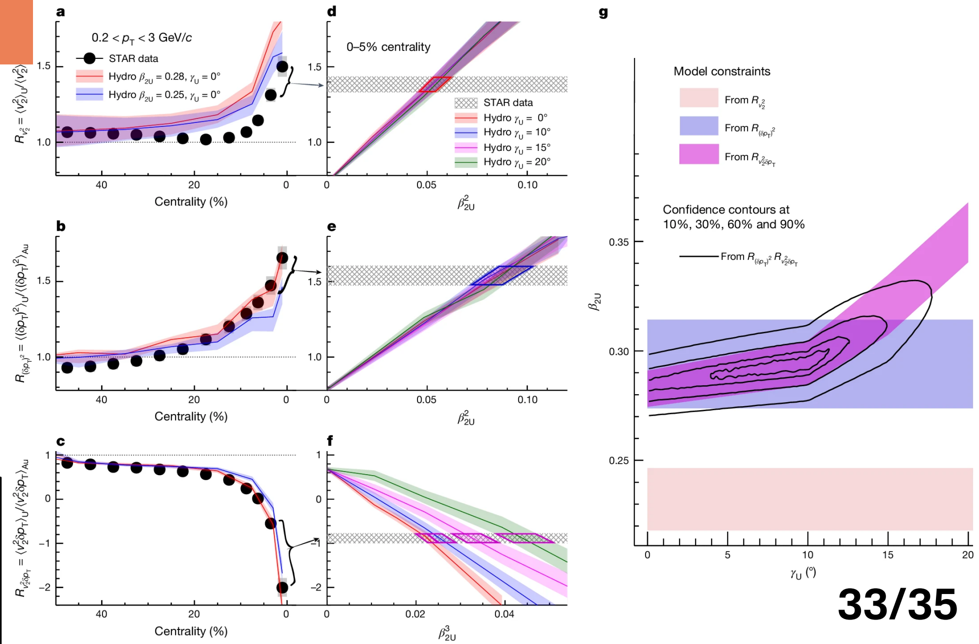
Imaging shapes of atomic nuclei in high-energy nuclear collisions

$$R(\theta,\phi) = R_0(1 + \beta_2[\cos\gamma Y_{2,0} + \sin\gamma Y_{2,2}])$$

Access to quadrupole deformation and triaxiality of nuclei through flow and mean p_T measurements



STAR: *Nature* 635 (2024) 8037, 67-72

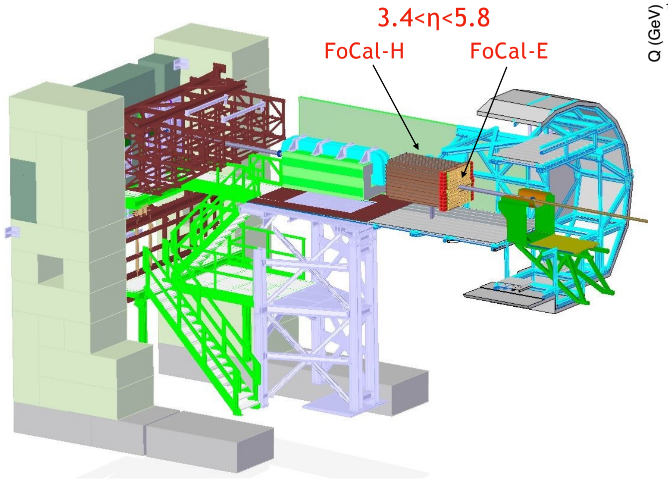


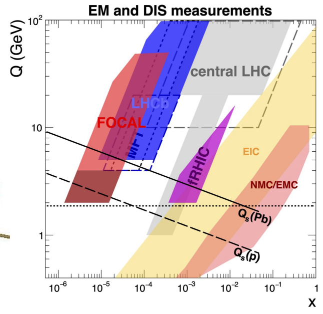
See talks by: Zhangbu Xu, Jiangyong Jia and Somdatta Bhatta

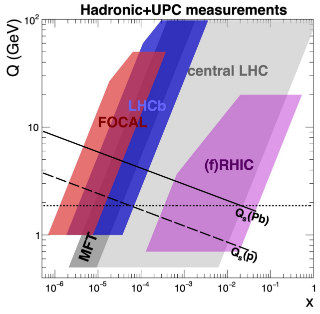
Upcoming experimental programs (selected with ATHIC participation)

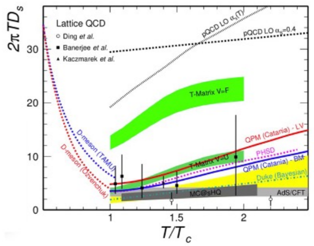
FOCAL@ALICE

LHC

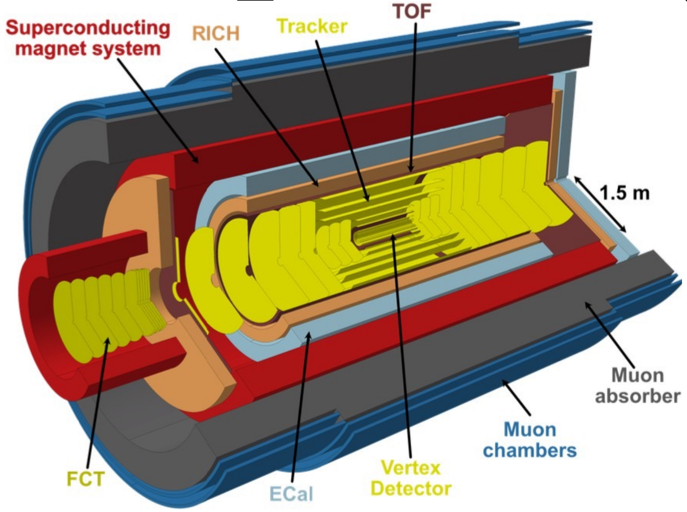




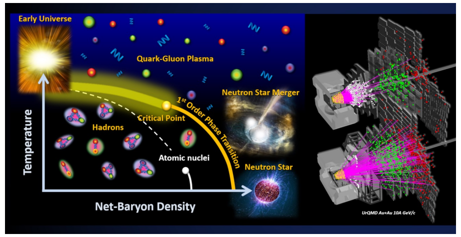


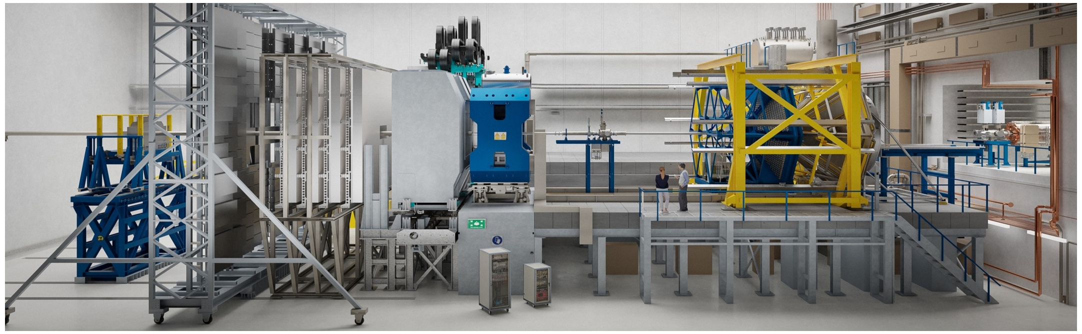


ALICE 3

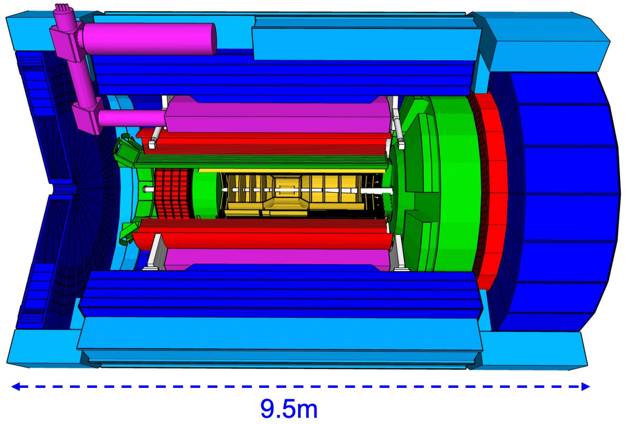


FAIR: CBM





EIC: ePIC

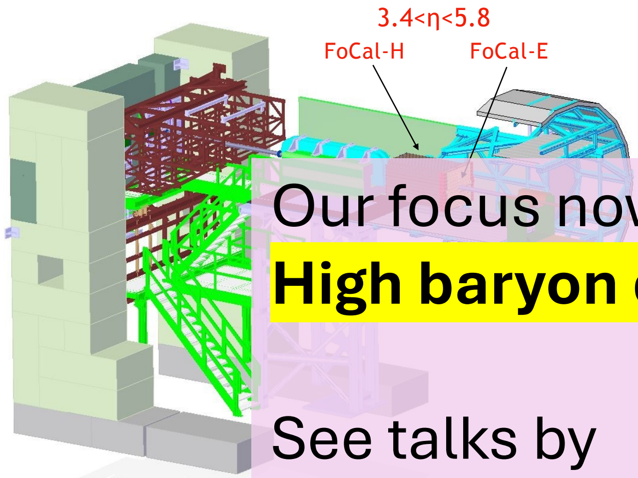


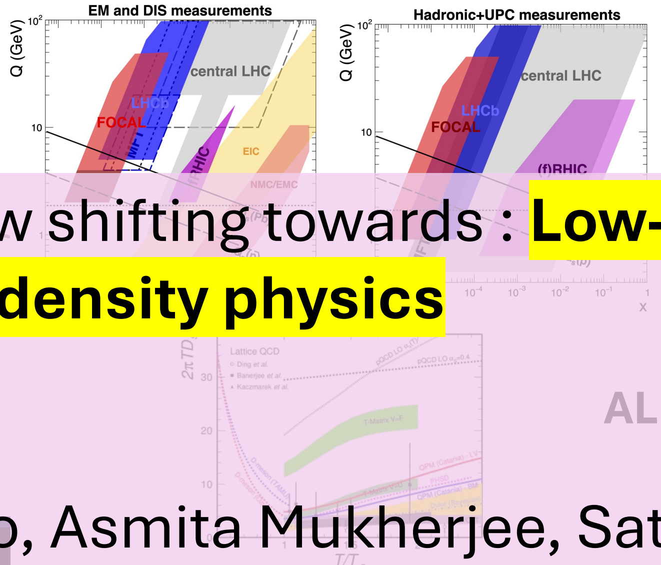
Enormous opportunity for ATHIC members collaboratiing on detectors and physics. Combined effort could lead to greater impact.

Upcoming experimental programs (selected with ATHIC participation)

FOCAL@ALICE

LHC



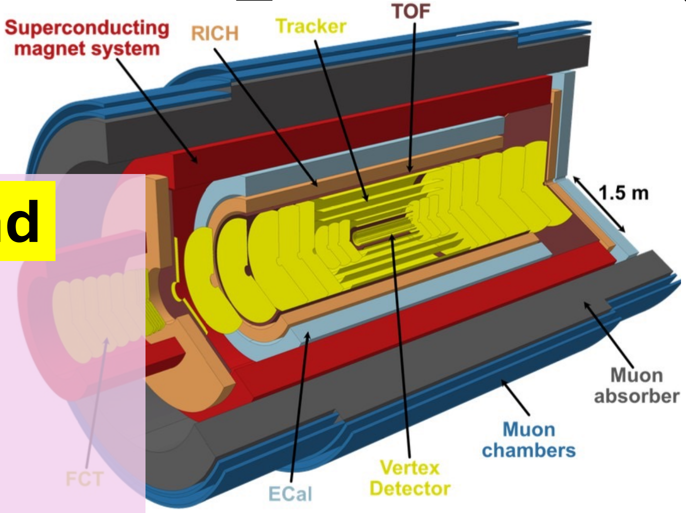


Our focus now shifting towards : **Low-x and High baryon density physics**

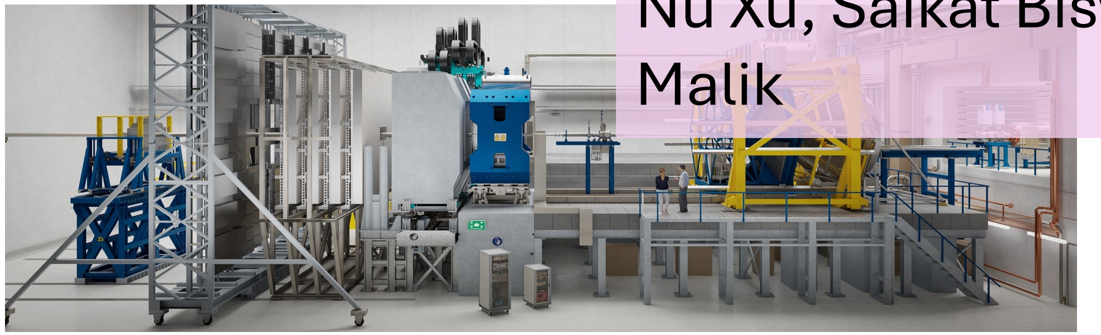
See talks by
Tatsuya Chujo, Asmita Mukherjee, Satoshi Yano, Xingbo Zhao, Lokesh Kumar

Nu Xu, Saikat Biswas, Rana Nandi and Tuhin Malik

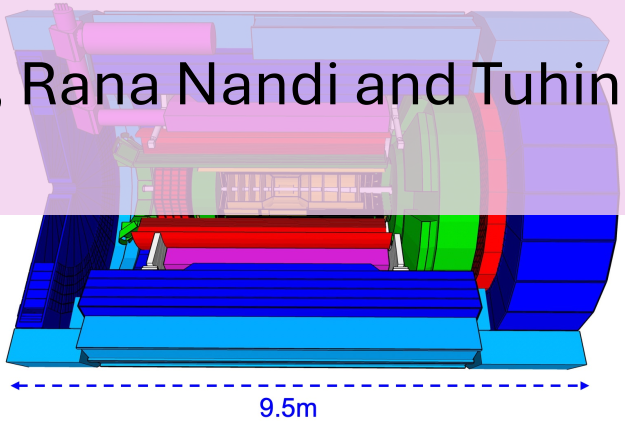
ALICE 3



FAIR: CBM



EIC: ePIC



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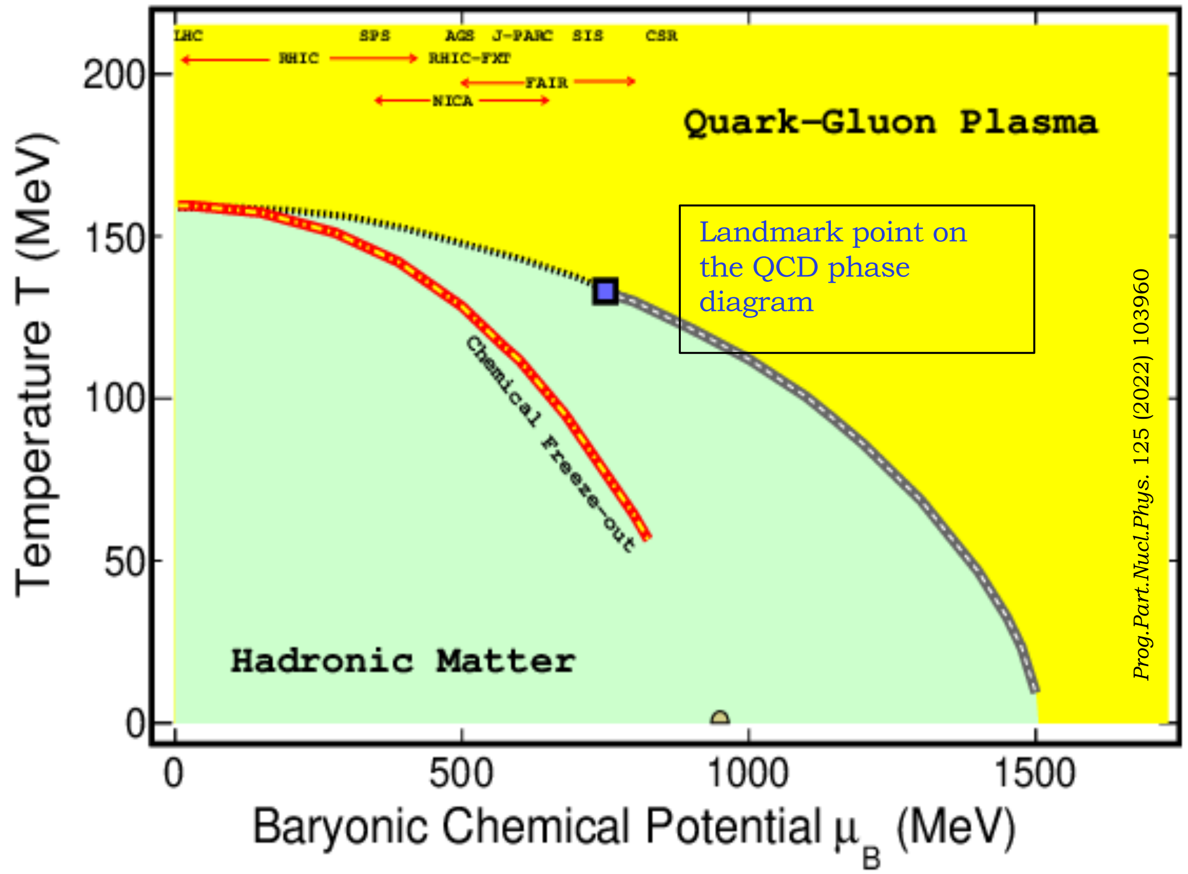

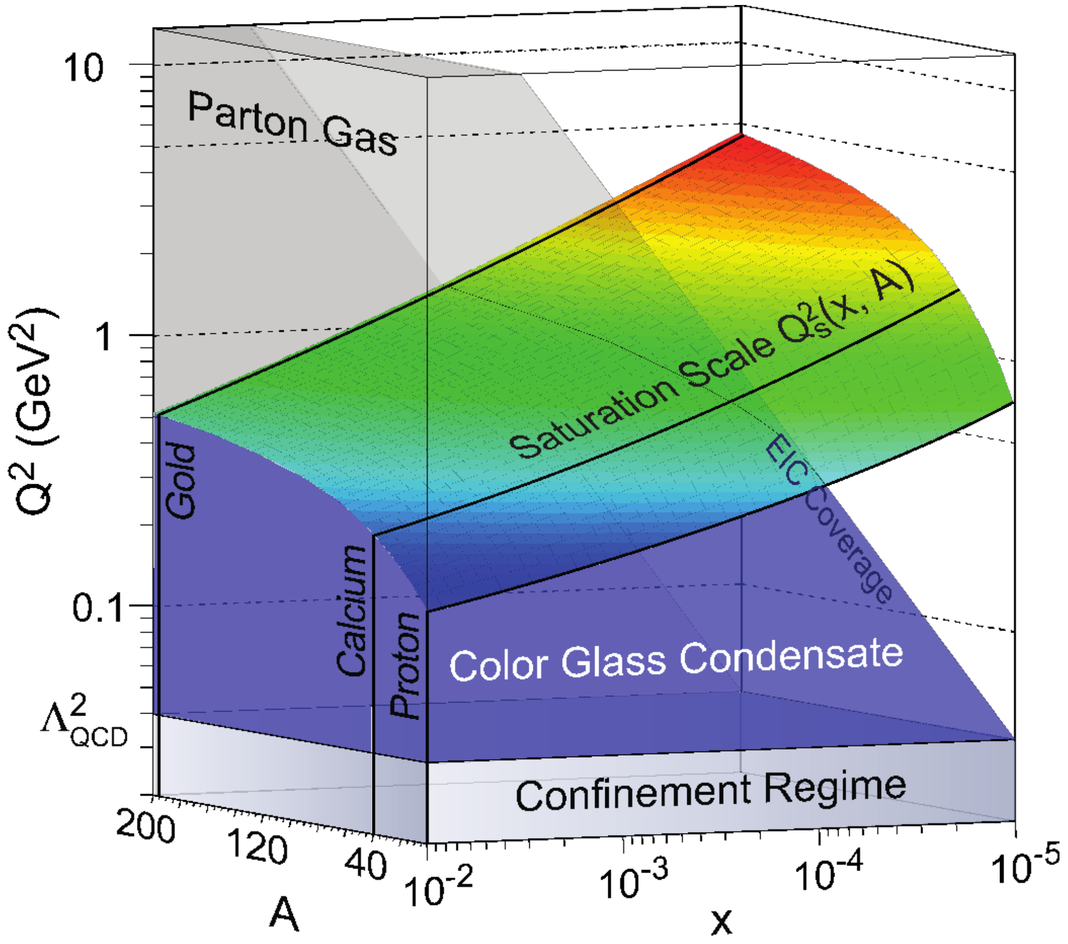

Quest to establish the phase diagrams of cold and hot-dense QCD

Acknowledgements

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STAR

CBM

CERN

Brookhaven National Laboratory

ePIC

Thanks for this opportunity

NISER

Homi Bhabha National Institute

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DAE

Department of Science & Technology, Government of India