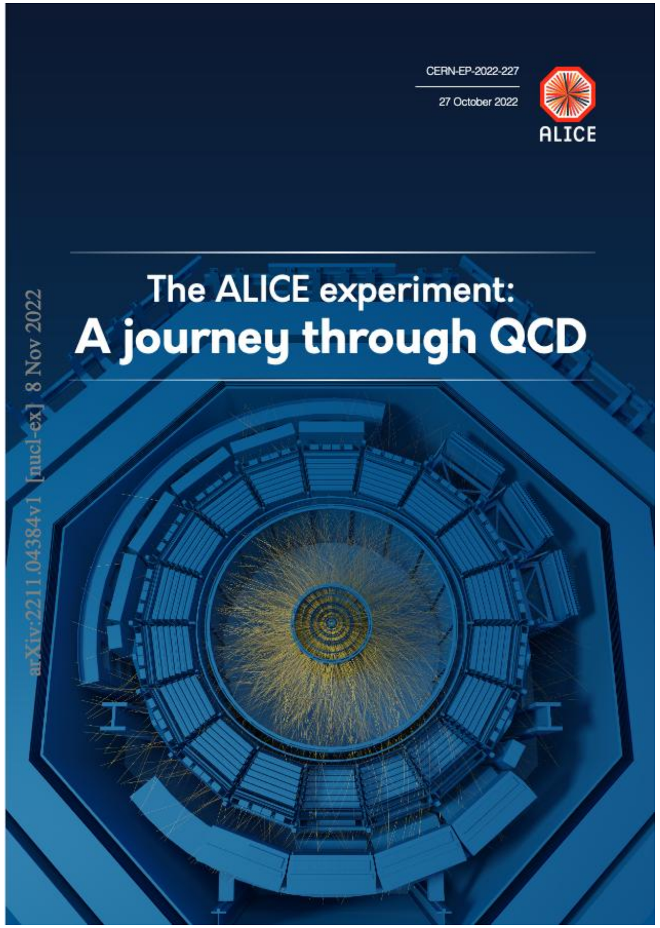
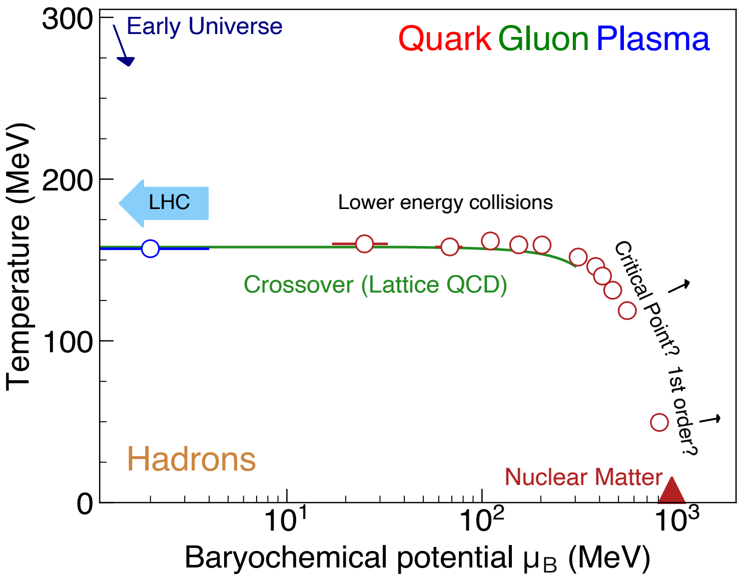
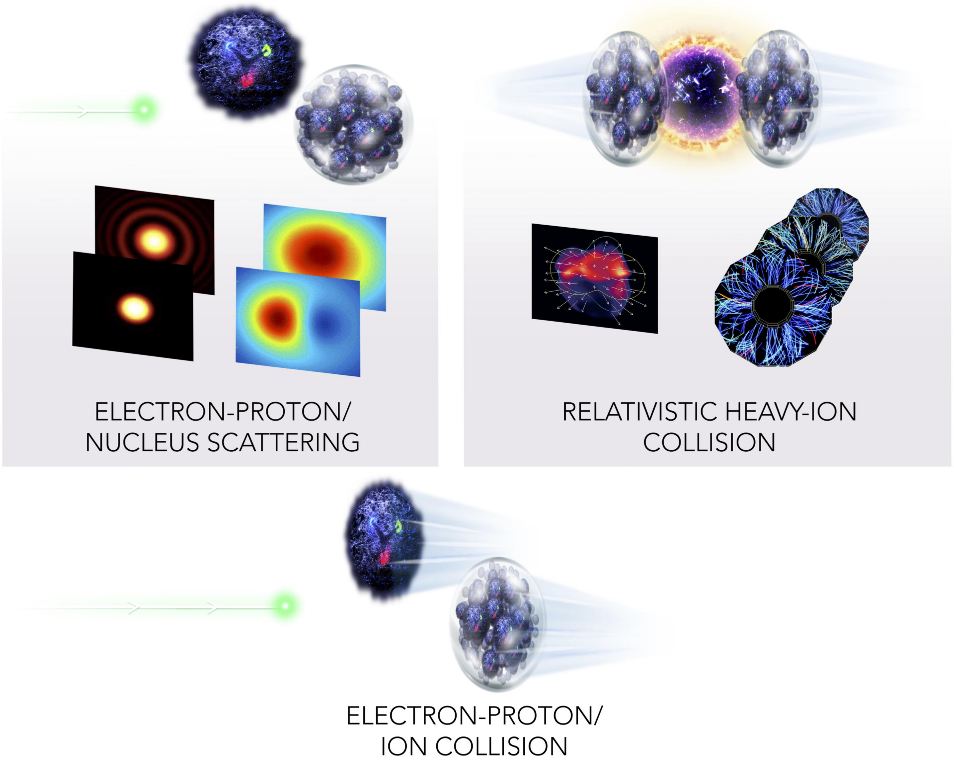






A journey through QCD

ALICE: arXiv:2211.04384

The present and future of QCD
arXiv:2303.02579

Experimental results from the RHIC beam energy scan program and outlook

Bedanga Mohanty
(NISER)

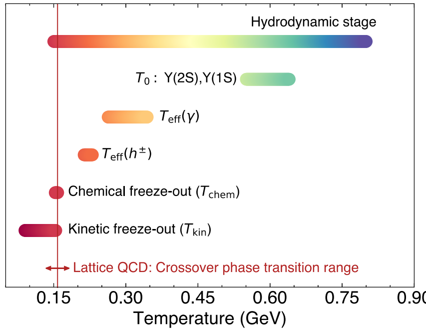
Quark gluon phase and properties — what we know so far

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

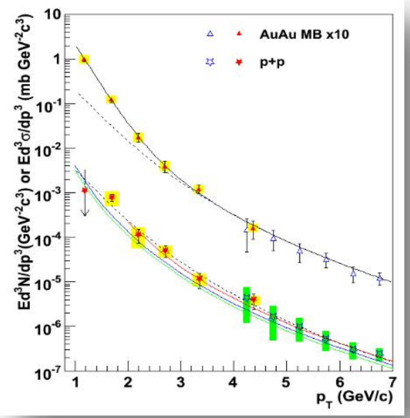
Matter attained ***high temperature,*** has large energy density and exhibits ***partonic collectivity.***

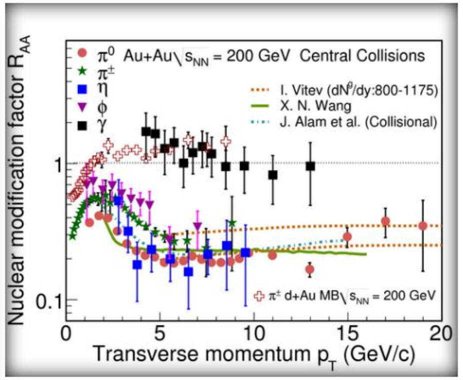
Shows emergent properties like:

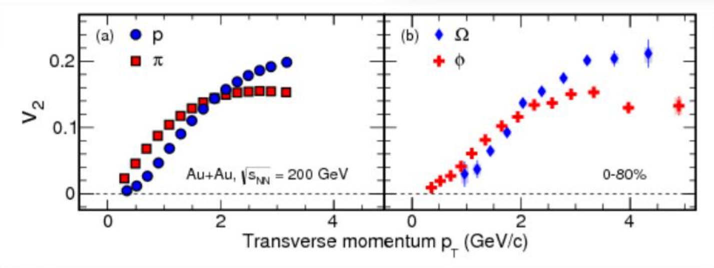
(1) ***Perfect fluid***
(2) ***Vortical fluid***
(3) ***Heavy-quarks*** exhibiting ***Brownian motion*** in fluid of light quarks.

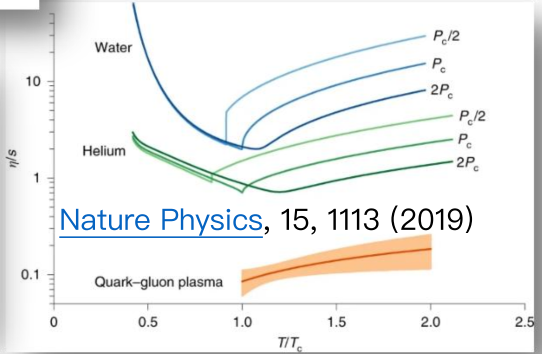


ALICE: arXiv:2211.04384

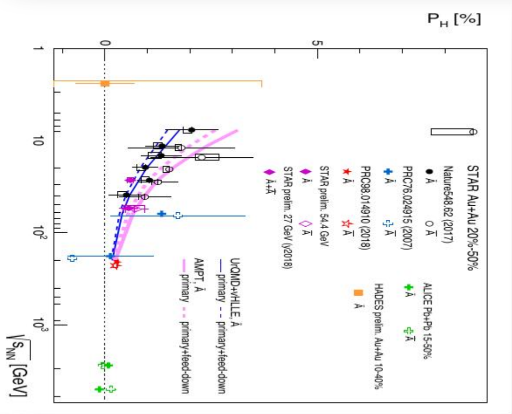


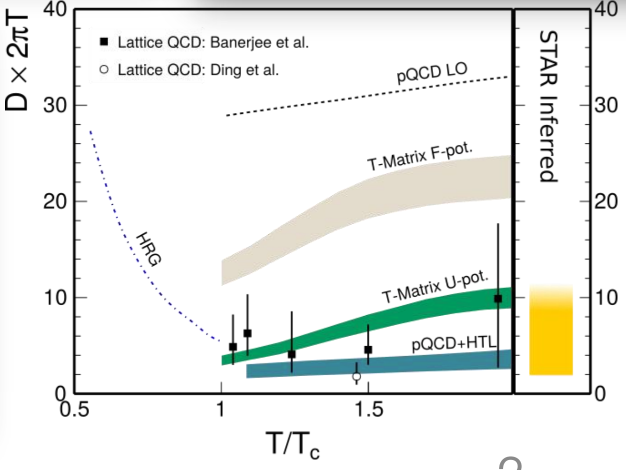






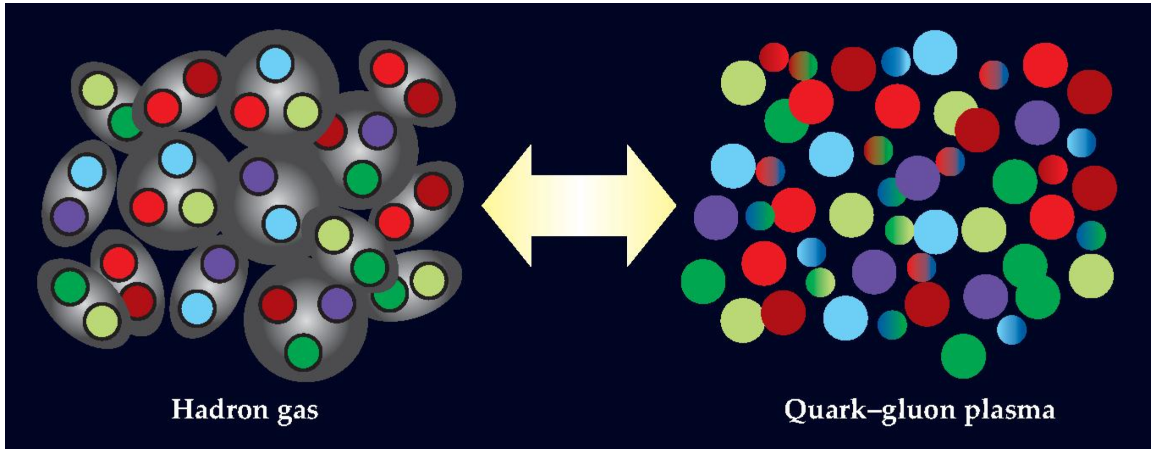
[Nature Physics](), 15, 1113 (2019)





What this talk will cover

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



Phase diagram of QCD

Hyperon polarization

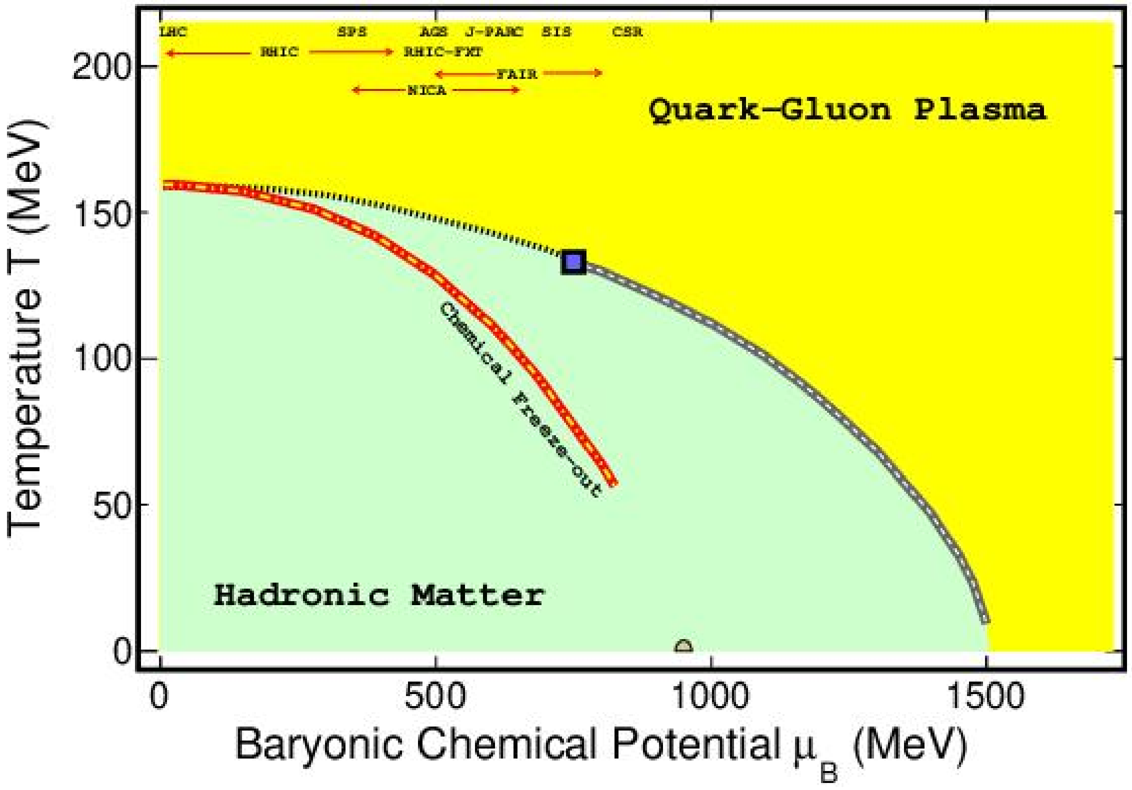
Spin alignment of vector mesons

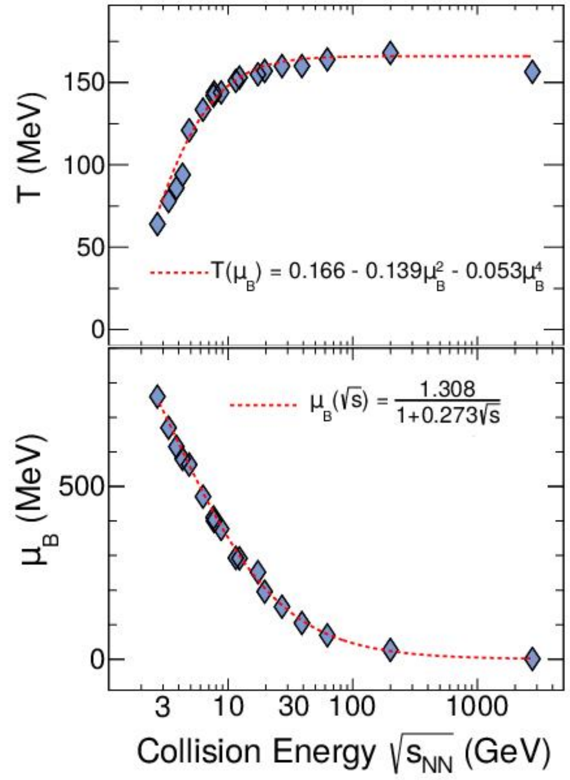
Nuclei production

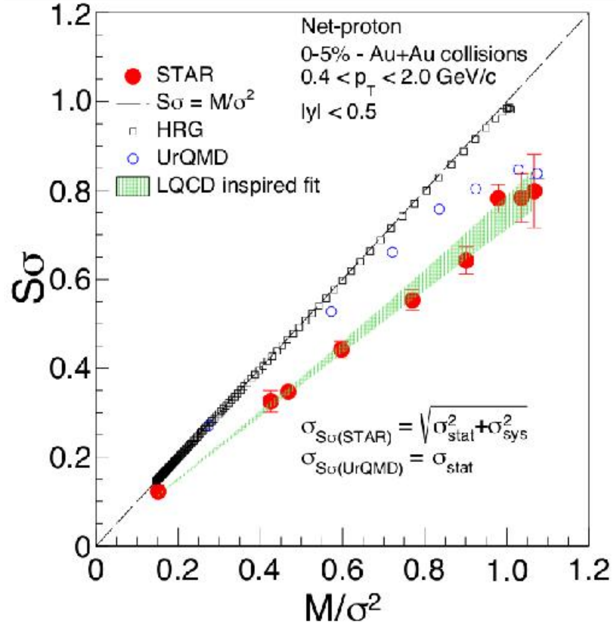
QCD phase diagram

Known (Theory/Experiment)

- Two distinct phases – quark-gluon degrees of freedom/hadronic d.o.f
- Transition temperature at μ_B = 0 MeV
- Small μ_B – crossover







Theory: LQCD, Thermal, transport, hydro etc.

Prog.Part.Nucl.Phys. 125 (2022) 103960

Relativistic heavy-ion collisions allows access to the phase diagram of QCD

Thermalization

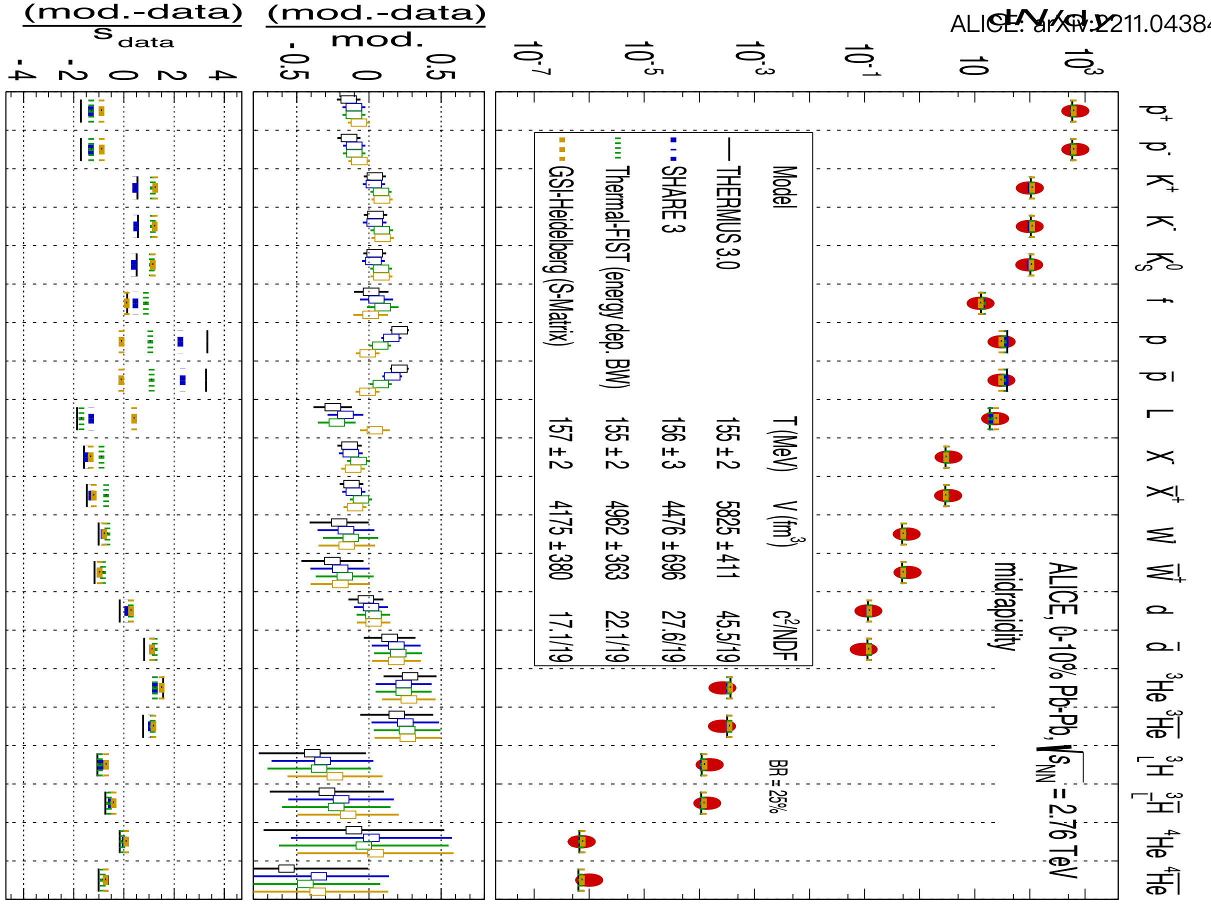
Why address this topic ?

1. To establish quark–gluon plasma
2. To establish the QCD phase diagram
3. To understand several physics conclusions at Relativistic Heavy Ion Collisions

Ways to address the topic

1. Maximum entropy - dS/dt = 0 (Our system short lived) -- *To show experimentally is challenging (impossible?)*
2. Interactions among constituents saturate. (State in thermal equilibrium has no knowledge of past) -- *Can we demonstrate this experimentally ?*
3. Space-momentum distributions reach equilibrium value -- *Can we access this experimentally ?*

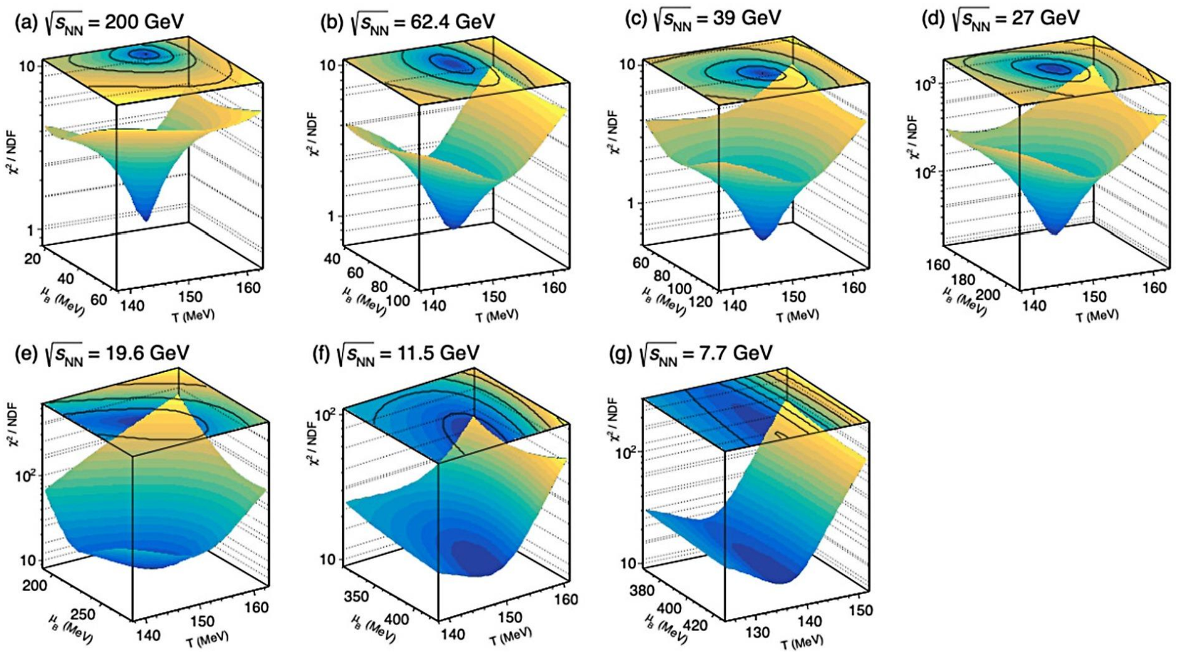
ALICE: arXiv:2211.04384

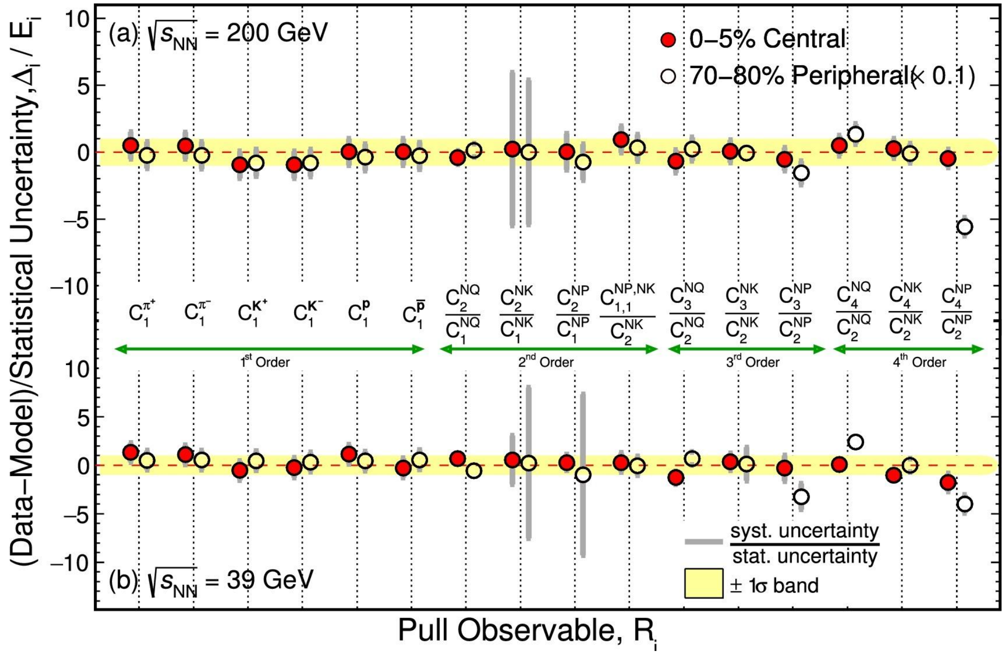


Mean yields have been successfully explained by thermal models. But that is not the full distribution.

Phys.Lett.B 829 (2022) 137021

Higher moments and thermal model

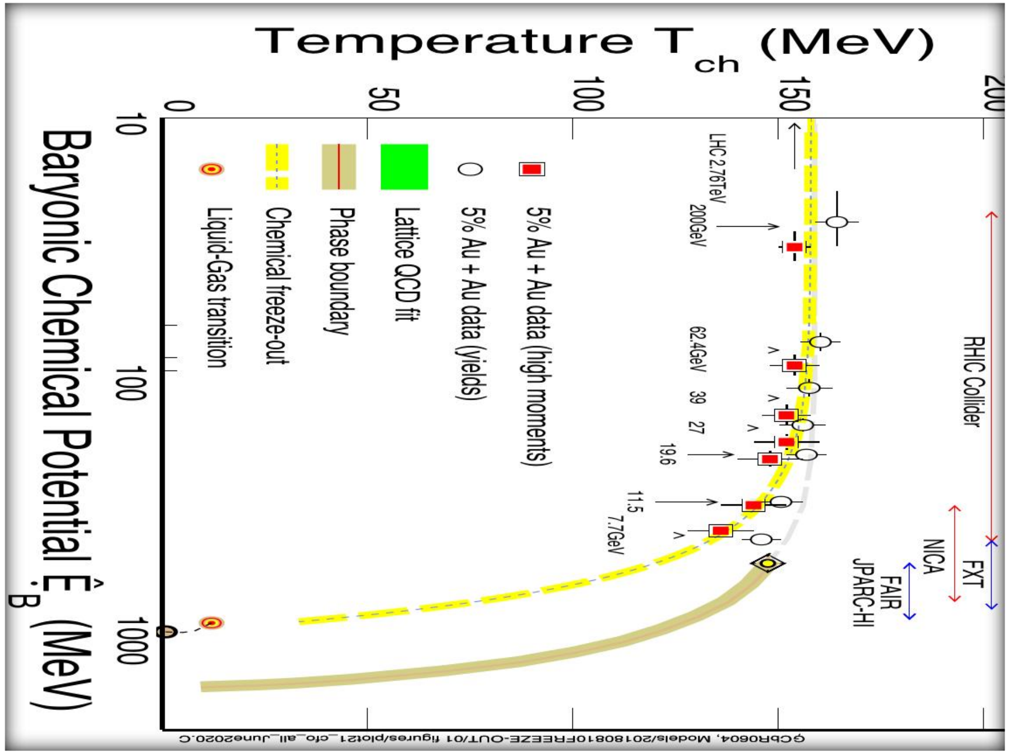




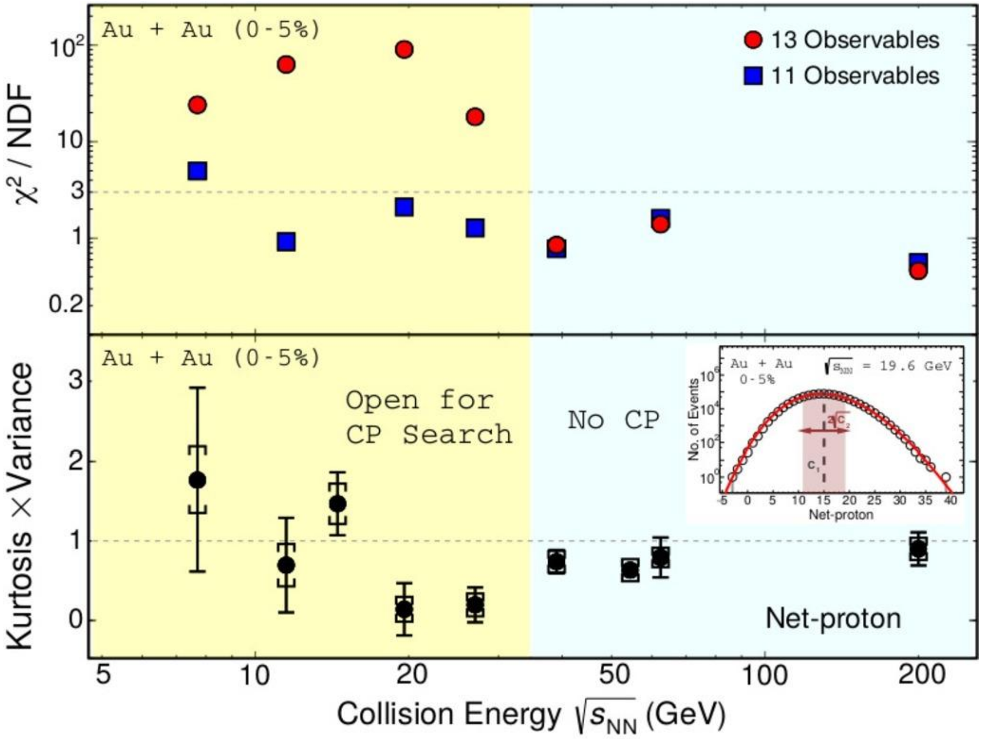
Fits to moments of multiplicity distributions

Measurements in central collisions agrees with thermal model
Peripheral collisions do not.

Higher moments and thermal model



Temperature versus Baryonic chemical potential



Favors a thermal system for collision energies > 30 GeV

Future: (1) Try canonical approach specially at lower collision energies. (2) Fixed target energies and (3) Try the approach in multiplicity dependent proton–proton collisions

QCD thermodynamics

Ordering of ratios (Net–baryon):

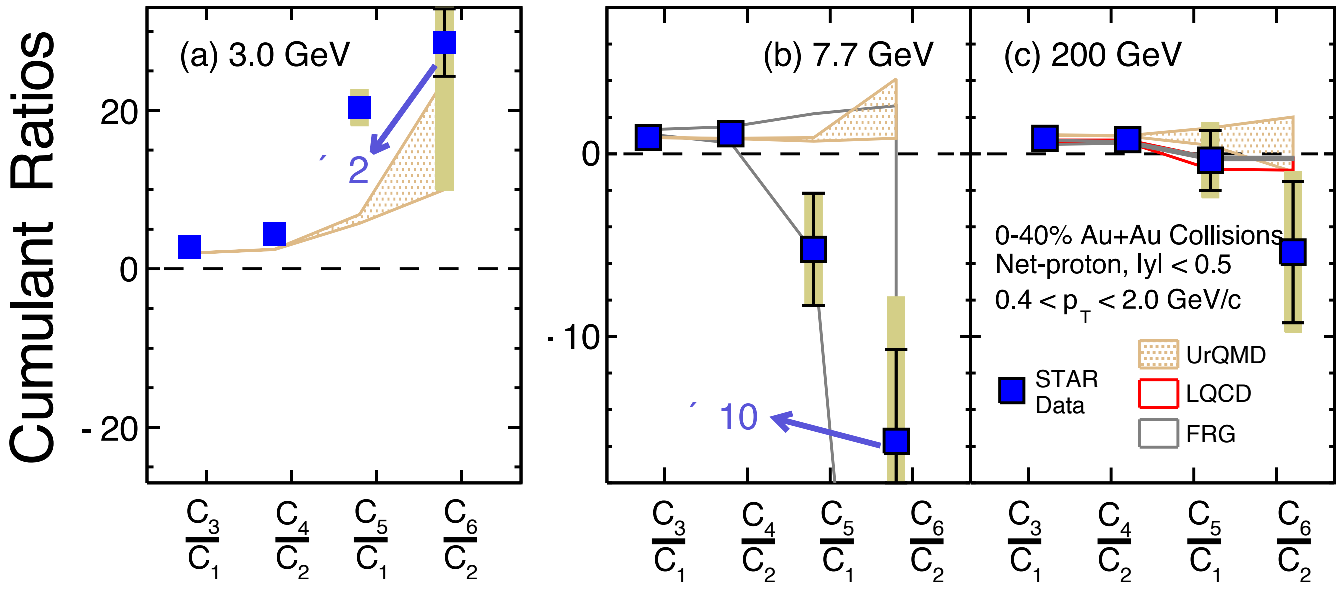
LQCD –

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

$$\frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2}$$

Susceptibility ratio ordering
PHYS. REV. D 101, 074502 (2020)

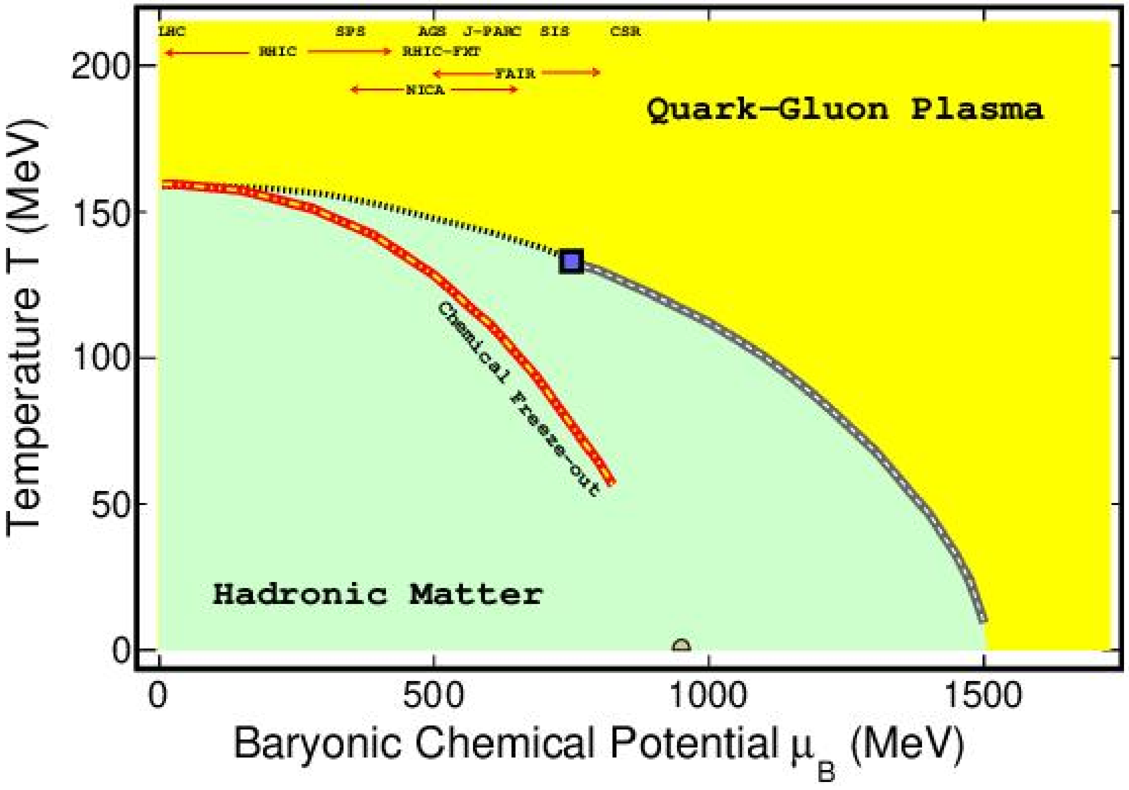
Measurements

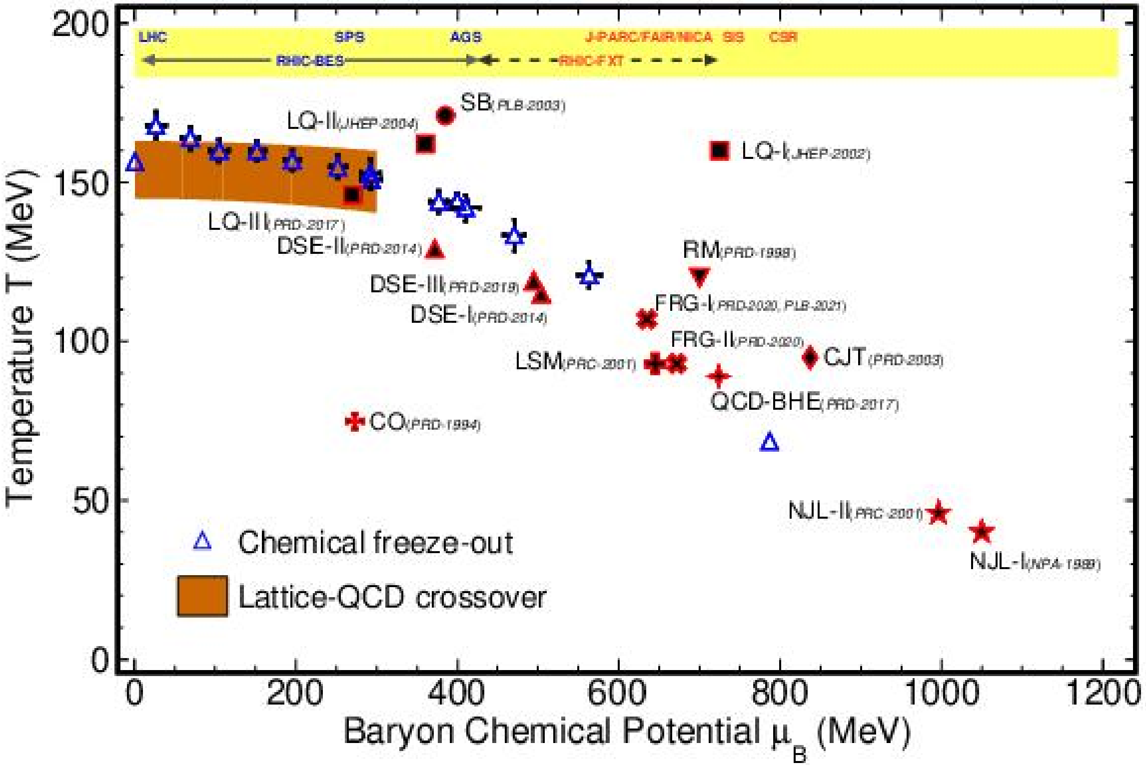


STAR: PRL 130 , 82301 (2023)
STAR: PRL128, 202303 (2022)
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)

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

QCD critical point

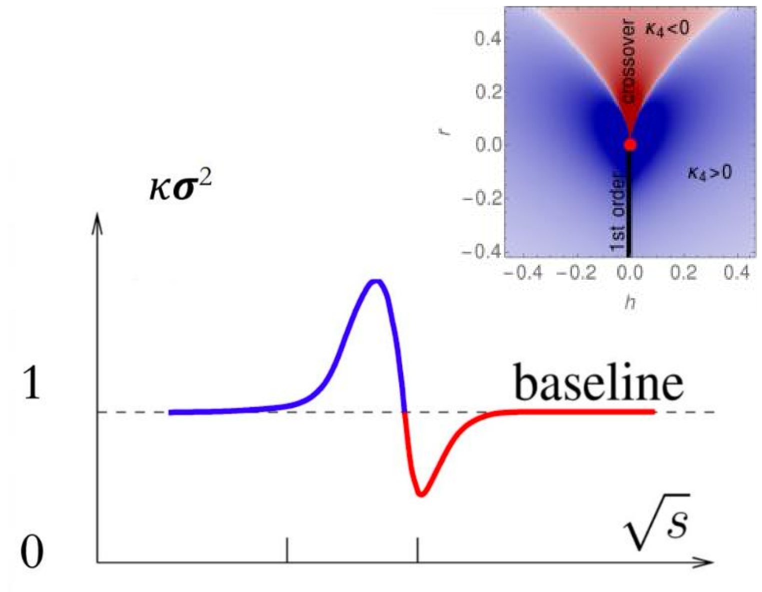




Landmark point on the QCD phase diagram

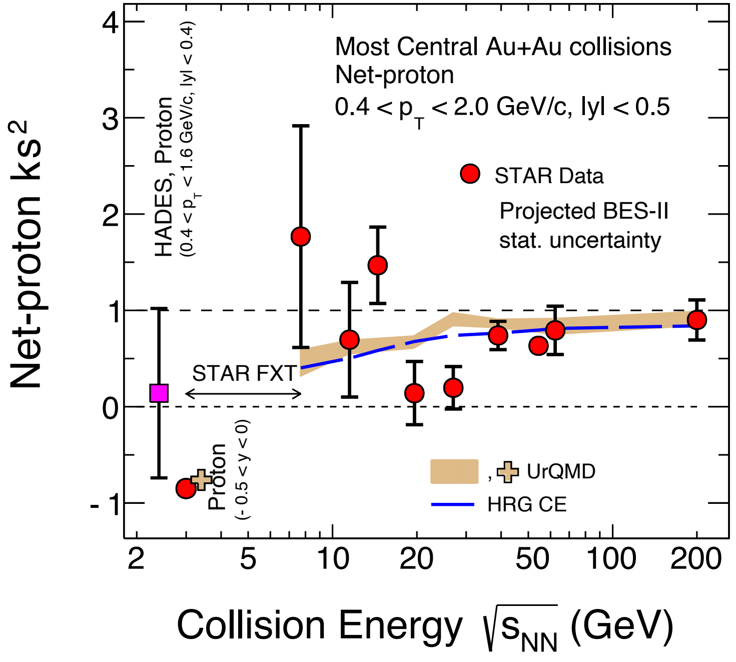
If present beyond μ_B = 200 MeV

Beam energy scan phase – I



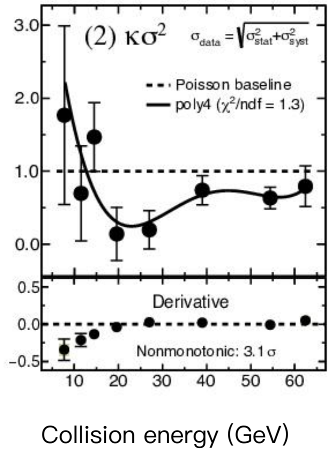
M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301

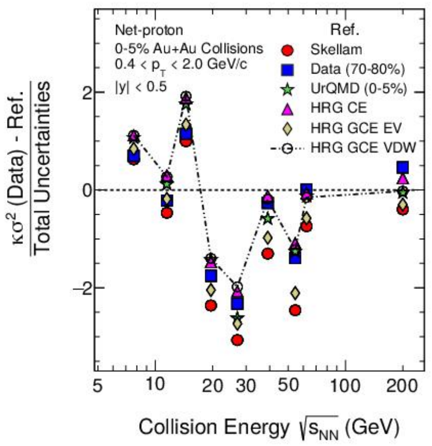
Expected signature



Measurements

HADES: PRC 102,024914(20)





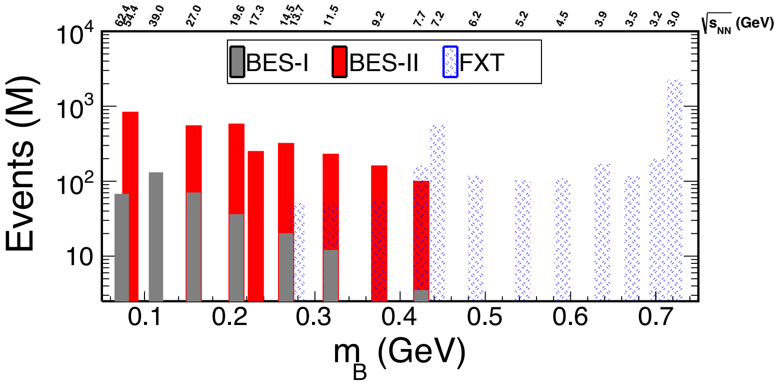
Deviations from baseline

HRG CE: P. B Munzinger et al, NPA1008, 122141(2021)

QCD critical point search

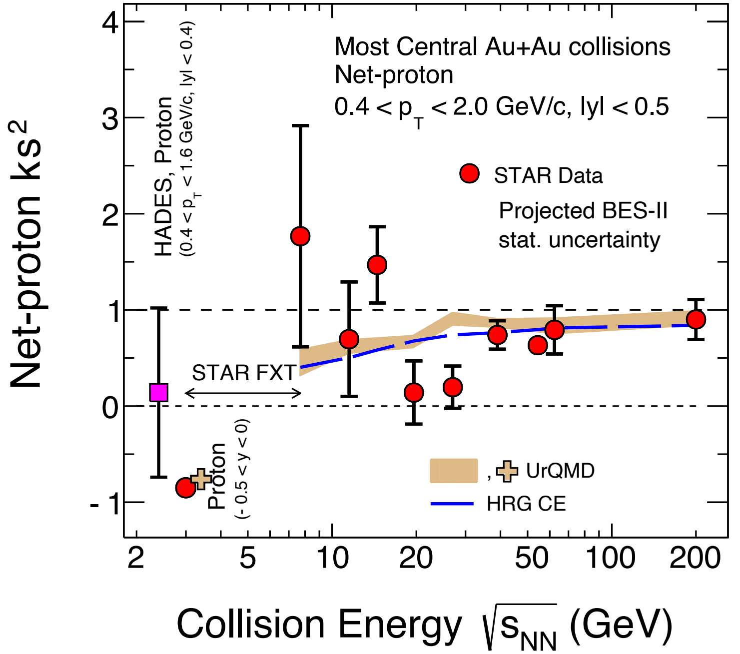
STAR: PRL 130 , 82301 (2023)
STAR: PRL128, 202303 (2022)
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)

Beam energy scan phase – II

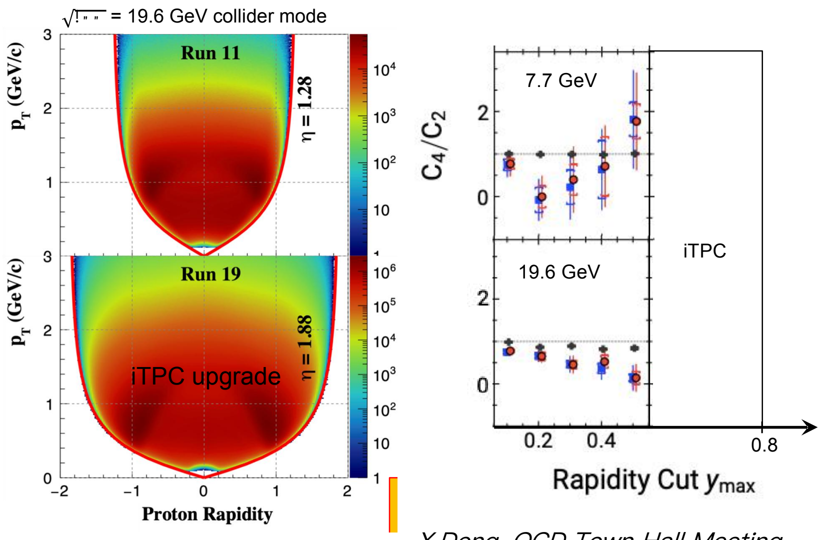


https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Larger statistics



High statistics measurements will come soon



H–S.Ko, SQM22

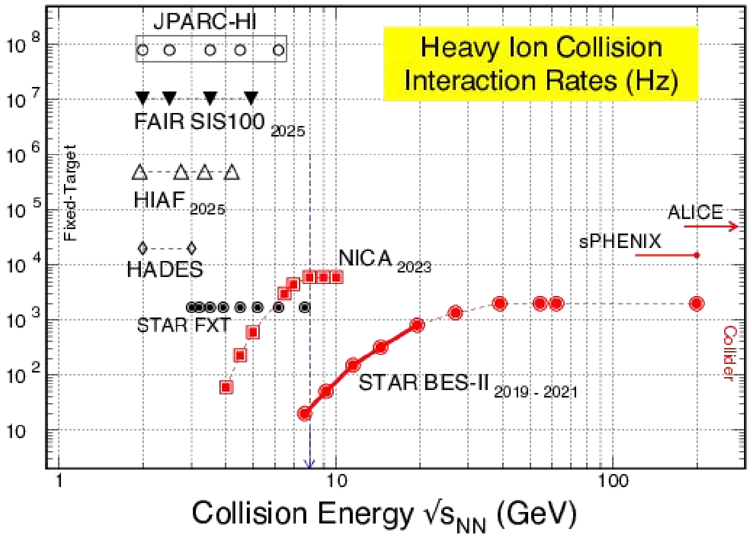
X.Dong, QCD Town Hall Meeting

Larger acceptance and more differential measurements

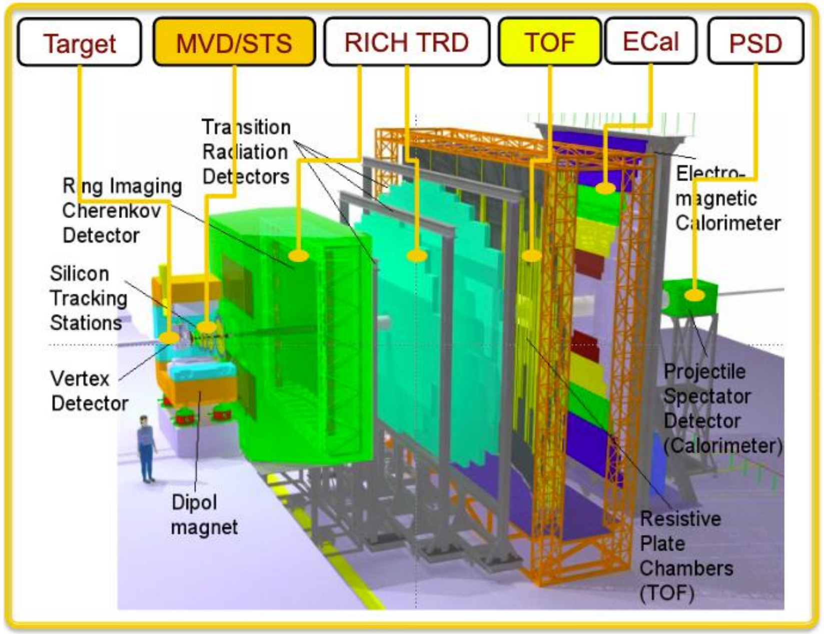
QCD critical point search

Largest search range in T vs. μ_B of the QCD phase diagram in a single experiment

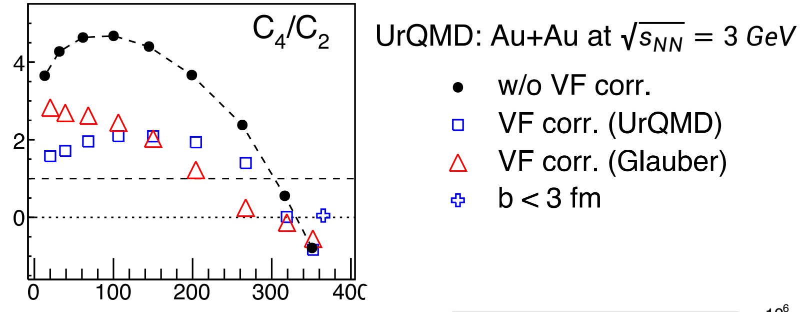
Compressed baryonic matter experiment



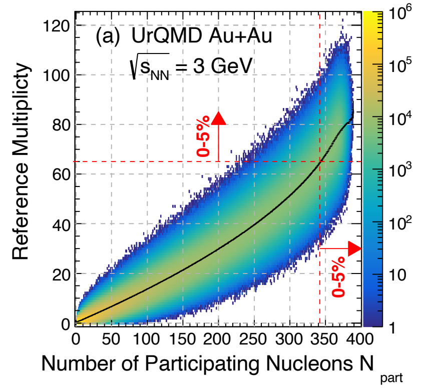
Large statistics
and high baryon density



Experiment



$-0.5 < y < 0$
$p_T: 0.4 - 2\ GeV/c$
proton



New methods needed, e.g *A. Rustamov et al, arXiv:2211.14849*

Challenge: volume fluctuations

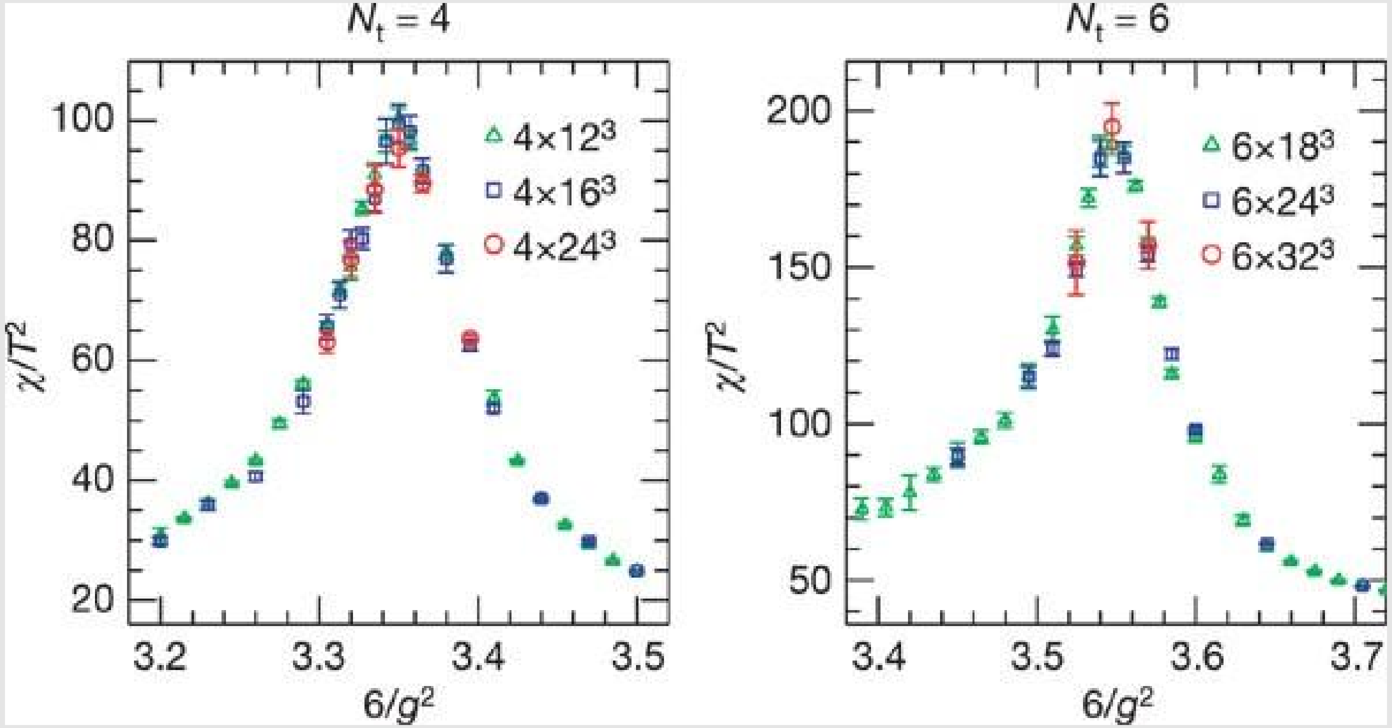
QCD critical point search

e–Print: 2209.05009 [nucl–ex]

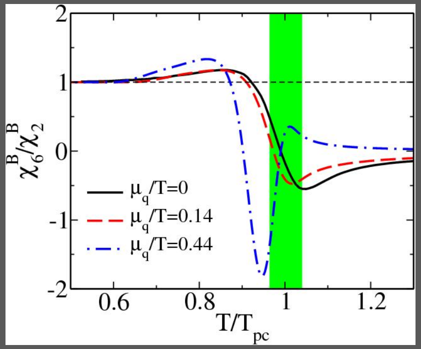
Future experiments like CBM and NICA will probe high baryon density regime

Crossover at μ_B = 0 MeV

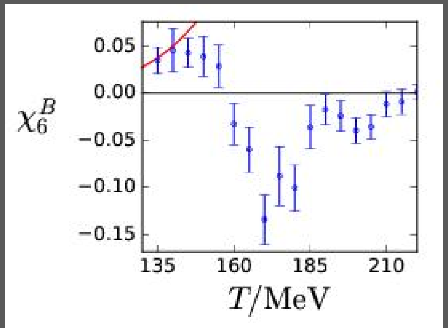
Nature 443 (2006) 675–678



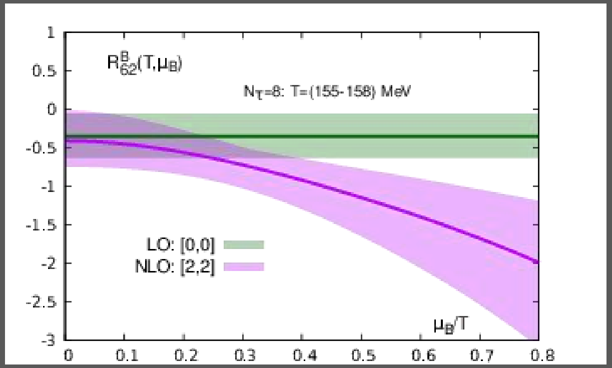
Eur. Phys. J. C 71 1694 (2011)



JHEP 10 (2018) 205

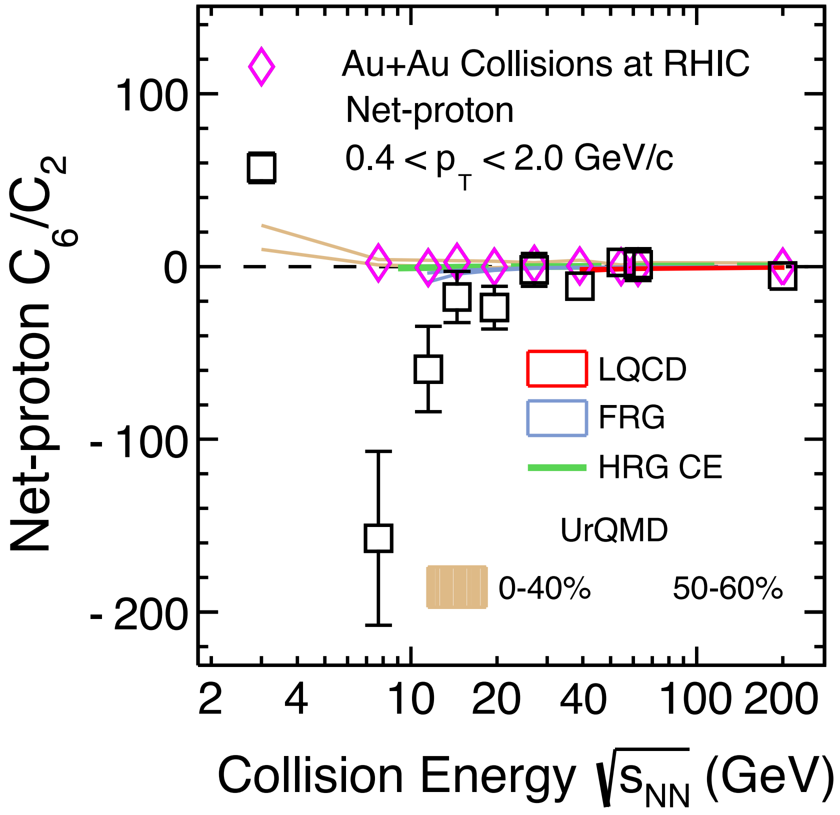


PHYSICAL REVIEW D 101, 074502 (2020)



χ_6/χ_2 or $C_6/C_2 < 0$

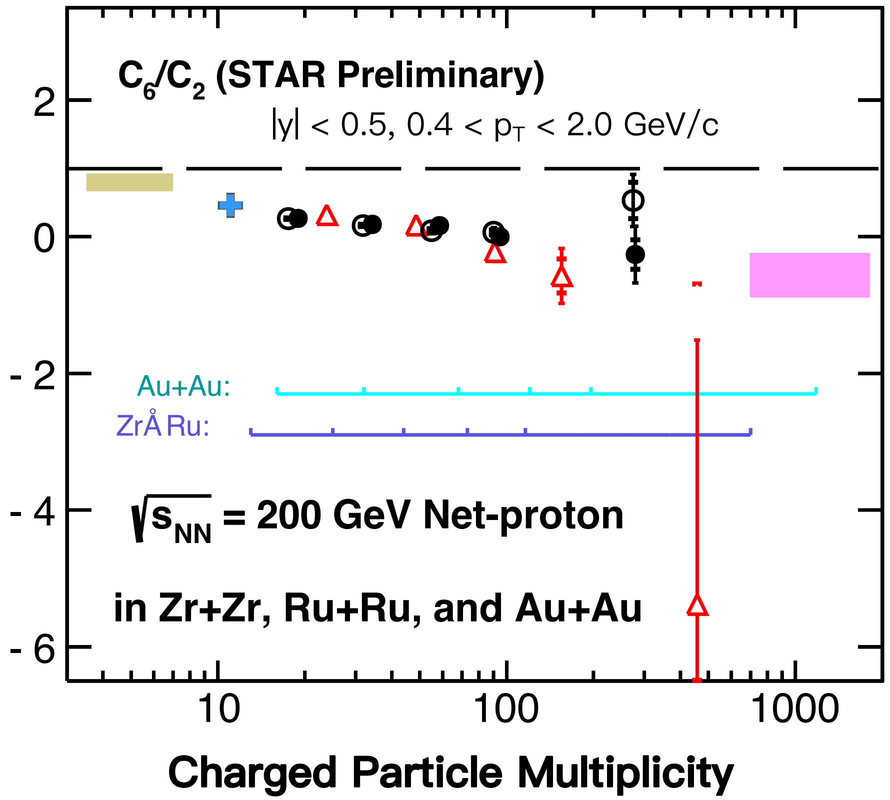
Search for direct experimental evidence of crossover



Sixth order cumulant ratios sign consistent with lattice QCD calculation with a crossover

Except for Au+Au collisions at 3 GeV and proton–proton collisions at 200 GeV

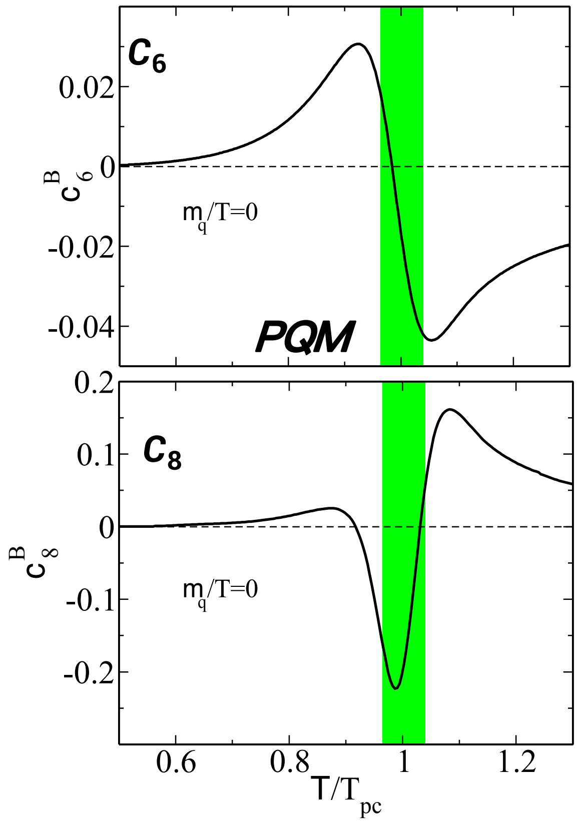
Lower collision energies have large statistical uncertainties



STAR: PRL 130 , 82301 (2023)
STAR: PRL 127, 262301 (2021)
HRG CE: P. B Munzinger et al, NPA1008, 122141(2021)
H.-S. Ko, STAR Collaboration, QM22

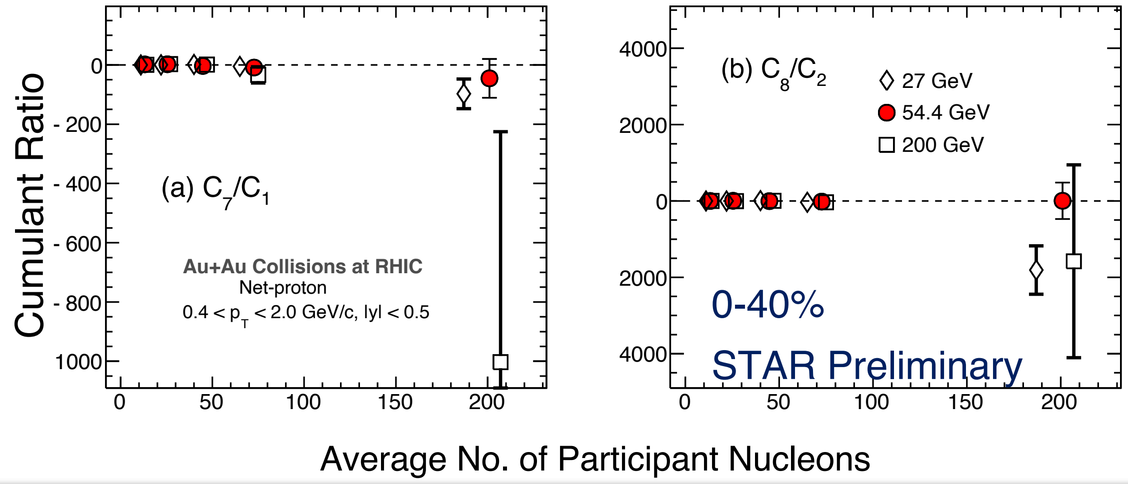
Going to still higher moments

Future: Extending measurements to C_7 and C_8 – more sensitive probes for crossover



HotQCD: PRD101, 074502 (2020), S. Borsanyi et al, JHEP10 (2018) 205, B. Friman et al, EPJC71, 1694(2011)

A. Pandav, STAR Collaboration, SQM22

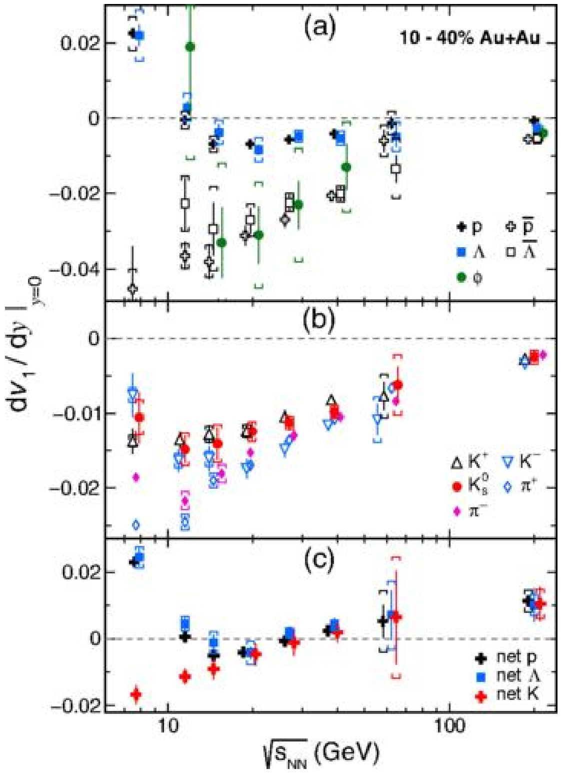


- ❑ STAR: Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: ~ 20 billion event (2023+2025) Au+Au at $\sqrt{s_{NN}}$ = 3 GeV: ~ 2 billion events collected
- ❑ ALICE: Higher order measurements possible with high statistics LHC Run 3 data.

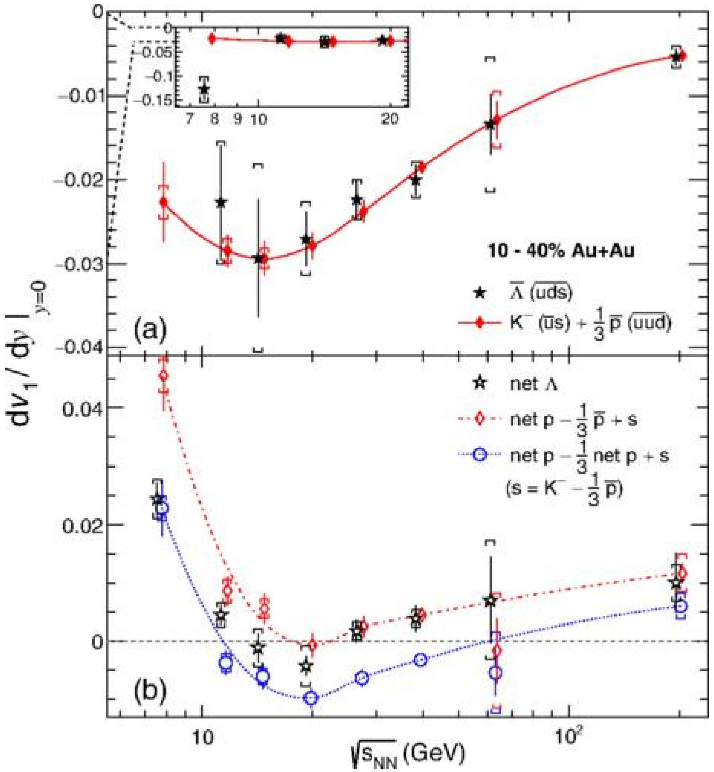
STAR BUR Run22, STAR note 0773, ALICE: arXiv1812.06772

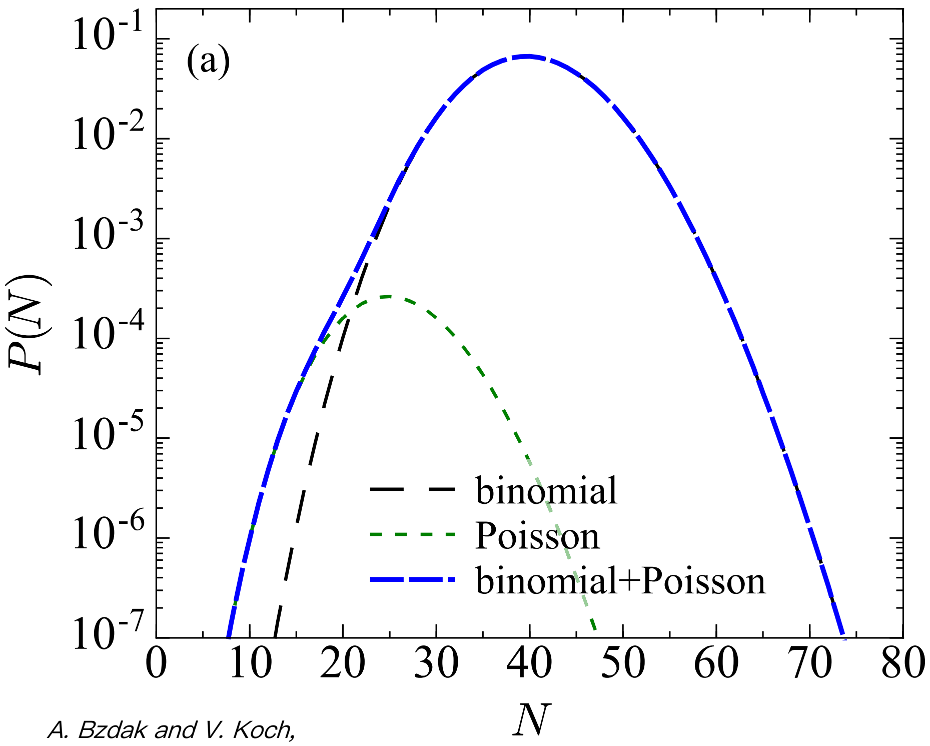
Search for signals of first order phase transition

First order phase transition:
- Multiplicity distribution bi-modal (two phases)
- Proton factorial cumulants κ_n: with increasing order, increase rapidly in magnitude with alternating sign.



Phys.Rev.Lett. 120 (2018) 6, 062301

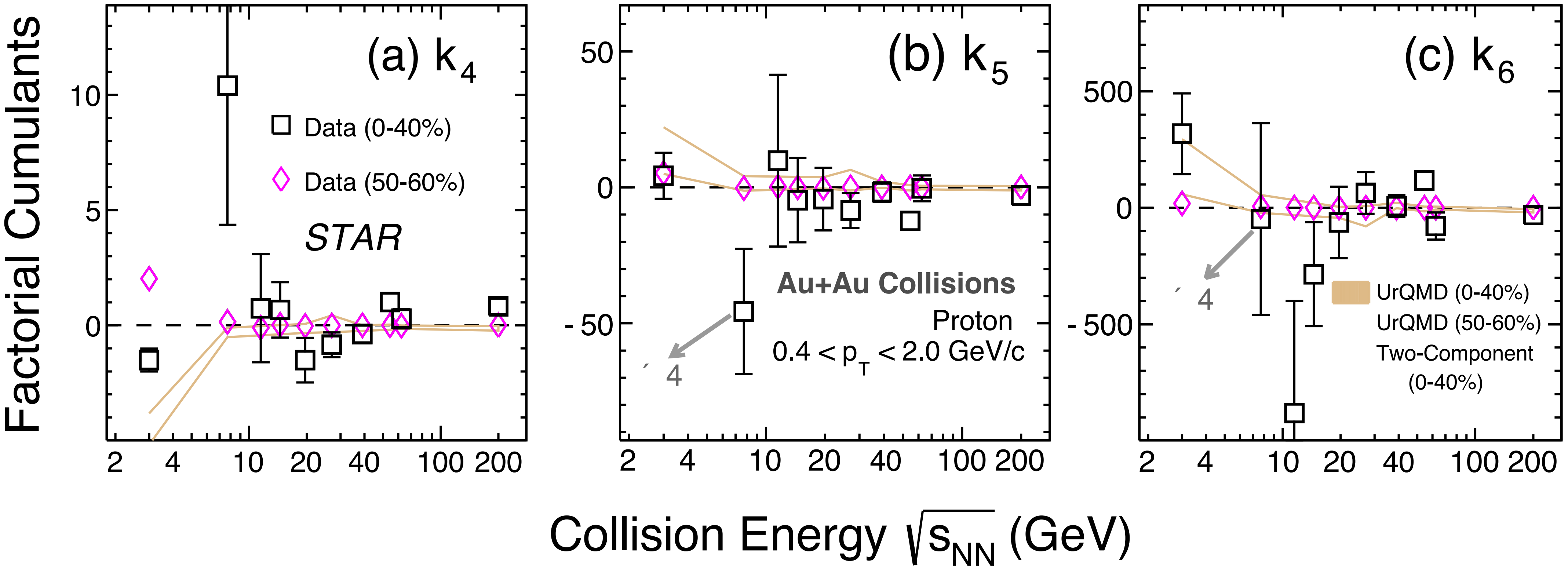




A. Bzdak and V. Koch, PRC100, 051902(R) (2019)

Proper theory calculations with 1st order phase transition needed for interpretation the data

Search for 1st order phase transition signals



- For $\sqrt{s_{NN}} \geq 11.5$ GeV, the proton κ_n within uncertainties does not support the two–component shape of proton distributions. Possibility of sign change at low energy.
- Peripheral data and UrQMD calculations consistent with zero at all energies.

STAR: PRL 130 , 82301 (2023)
STAR: PRL128, 202303 (2022)
STAR: PRL 127, 262301 (2021)
STAR: PRL 126, 092301 (2021)
STAR: PRC 104, 024902 (2021)

Moat regime

e–Print: 2301.11484 [hep–ph]

Theory

PHYSICAL REVIEW LETTERS 127, 152302 (2021)

Signatures of Moat Regimes in Heavy-Ion Collisions

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(Received 23 March 2021; revised 9 June 2021; accepted 8 September 2021; published 5 October 2021; corrected 3 March 2022)

Heavy-ion collisions at small beam energies have the potential to reveal the rich phase structure of QCD at low temperature and nonzero density. In this case spatially modulated regimes with a "moat" spectrum can arise, where the minimum of the energy is over a sphere at nonzero momentum. We show that if the matter created in heavy-ion collisions freezes out in such a regime, particle numbers and their correlations peak at nonzero, instead of zero, momentum. This effect is much more dramatic for multiparticle correlations than for single-particle spectra. Our results can serve as a first guideline for a systematic search of spatially modulated phases in heavy-ion collisions.

DOI: 10.1103/PhysRevLett.127.152302

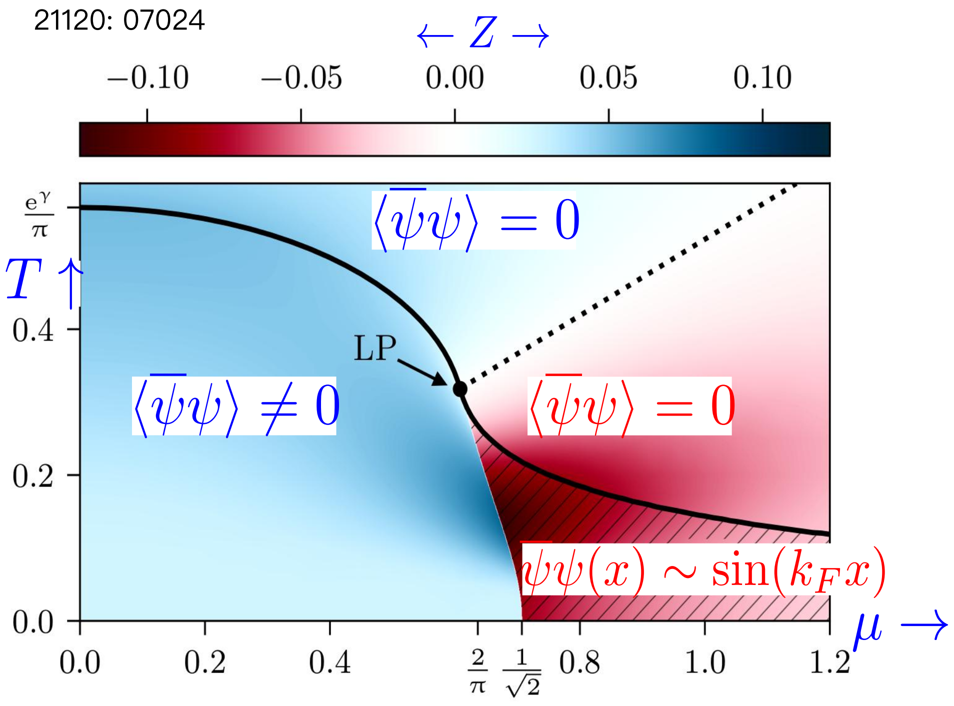
$$\mathcal{L} = \frac{1}{2}(\partial_0\vec{\phi})^2 - \frac{Z}{2}(\partial_i\vec{\phi})^2 - \frac{W}{2}(\partial_i^2\vec{\phi})^2 - \frac{m_{\rm eff}^2}{2}\vec{\phi}^2 + \cdots$$

$$E_\phi(\mathbf{p}^2) = \sqrt{Z\mathbf{p}^2 + W(\mathbf{p}^2)^2 + m_{\rm eff}^2}$$

Z < 1 and W > 0

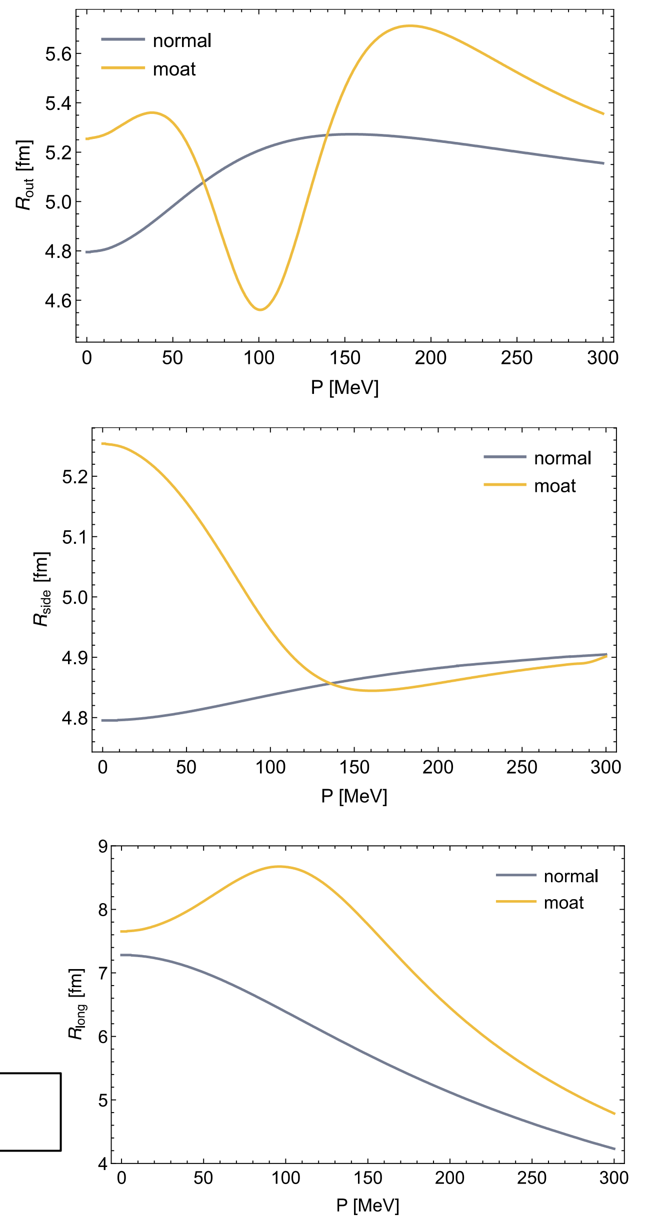
Region in phase diagram

21120: 07024



Low temperature and high baryon density

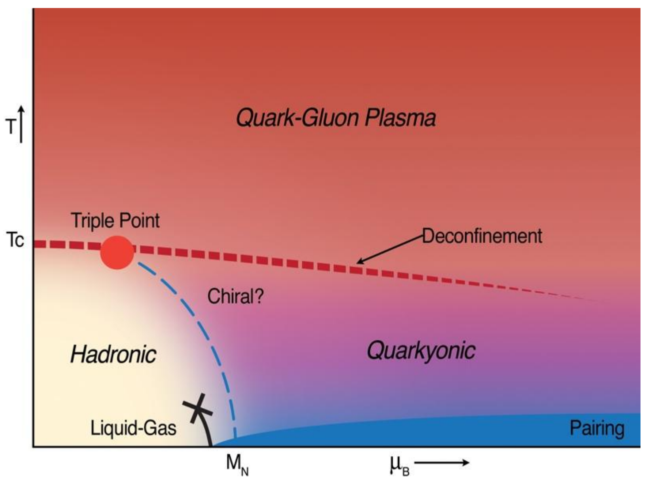
Experimental observable



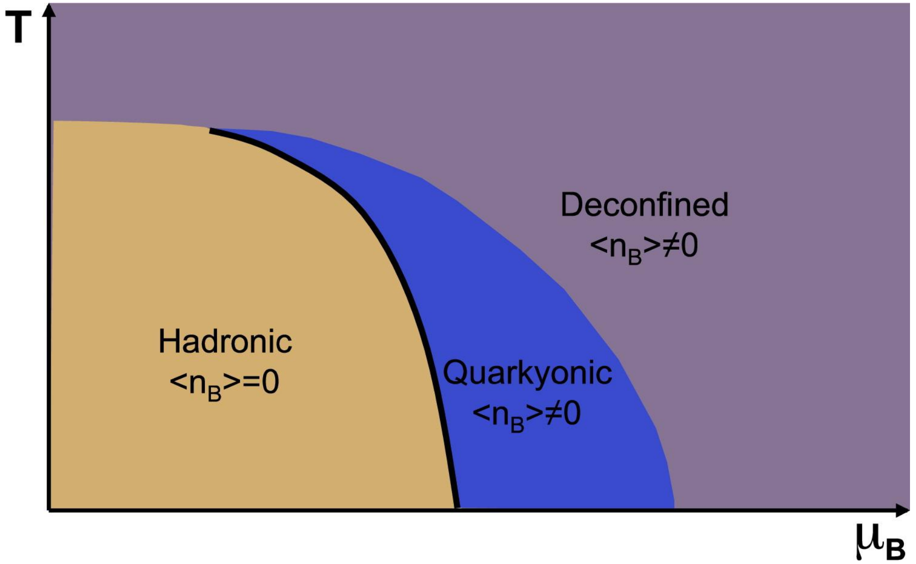
New feature in QCD phase diagram that high baryon density experiments could look for

Quarkyonic matter

QCD–like Theory

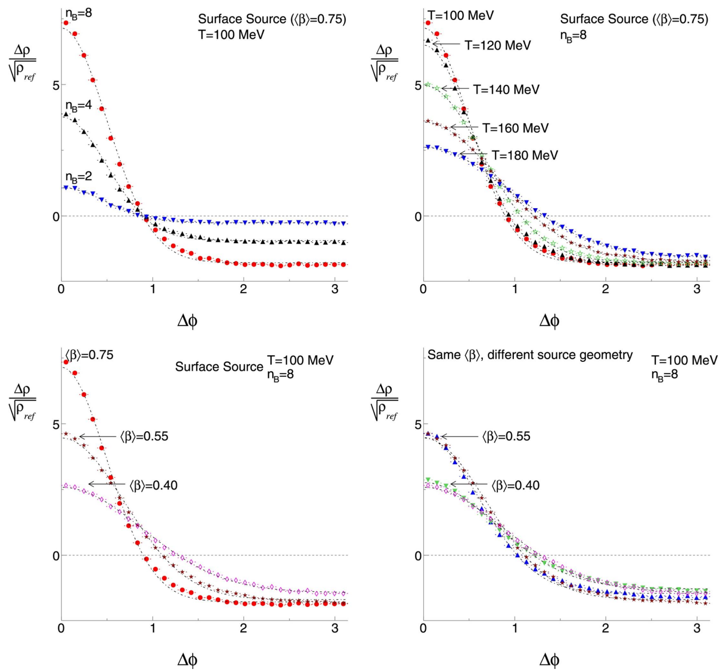


Region in phase diagram



Experimental signature

Phys.Lett.B 690 (2010) 135–140



$$\frac{\Delta\rho}{\sqrt{\rho_{ref}}} = \frac{d^2N/(d\phi_1\, d\phi_2) - (dN/d\phi_1)\cdot(dN/d\phi_2)}{\sqrt{(dN/d\phi_1)\cdot(dN/d\phi_2)}}$$

Phases at large N_c – *dense* nuclear matter but *Confined* phase!
Baryon number is a order parameter for transition.

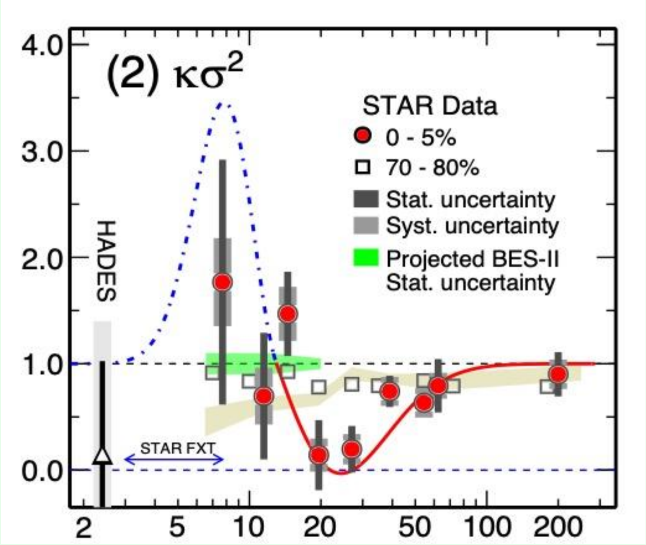
Large *Nc,* baryon mass $M_B \sim N_c \Lambda_{QCD}$. *For T* $\sim\Lambda_{QCD}$, baryon number is $n_B \sim \exp(\mu_B/T - M_B/T) \sim e^{-N_c}$ (negligibly small) and it remains that way as long as $\mu_B < M_B$. For larger μ_B the n_B becomes non– zero. In the deconfined quark—gluon plasma phase there are no baryon masses, so that there is no baryon–number suppression.

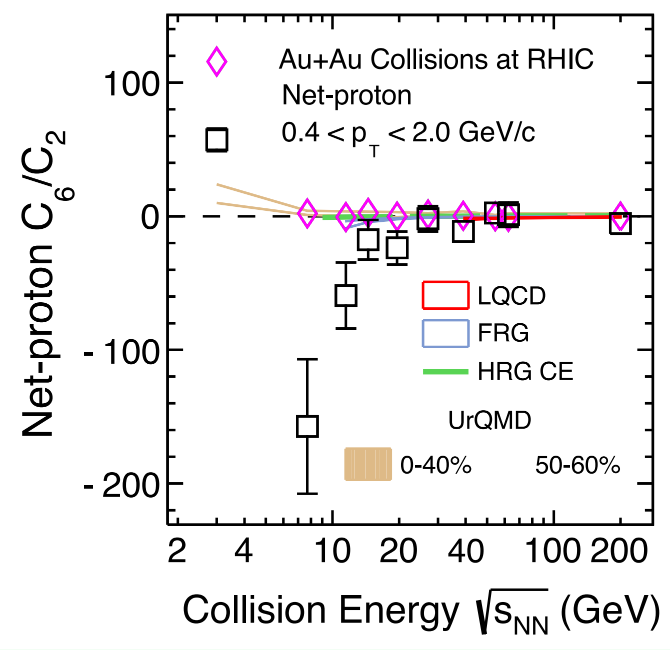
Baryon–Baryon correlations to look for nucleation of baryon rich bubbles surrounded by baryon free regions

L. McLerran, R.D. Pisarski
Nucl. Phys. A, 796 (2007), p. 83
Y. Hidaka, L.D. McLerran, R.D. Pisarski
Nucl. Phys. A, 808 (2008), p. 117

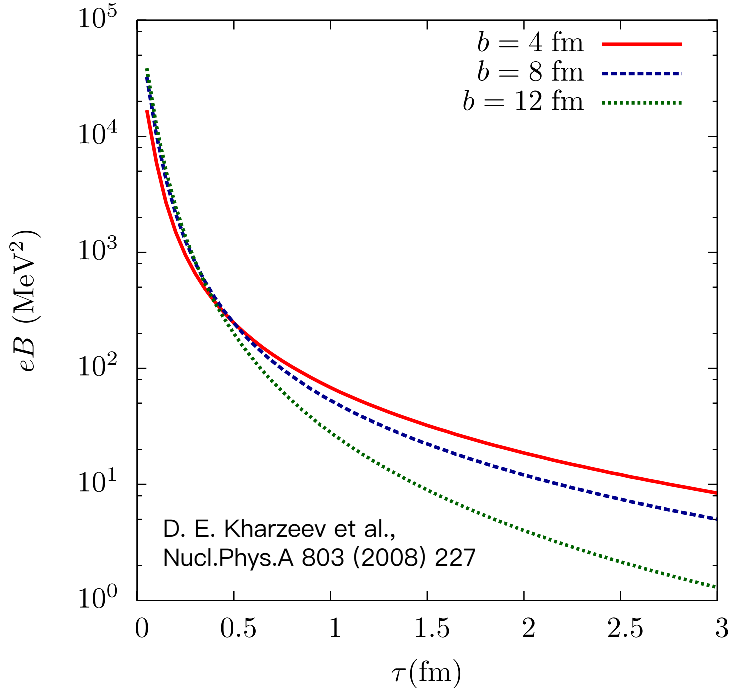
For high baryon density regime experiments to look for

Summary – QCD phase structure

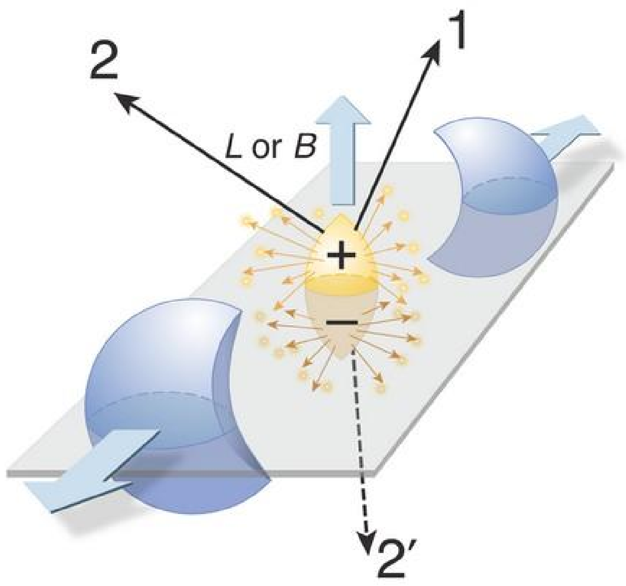


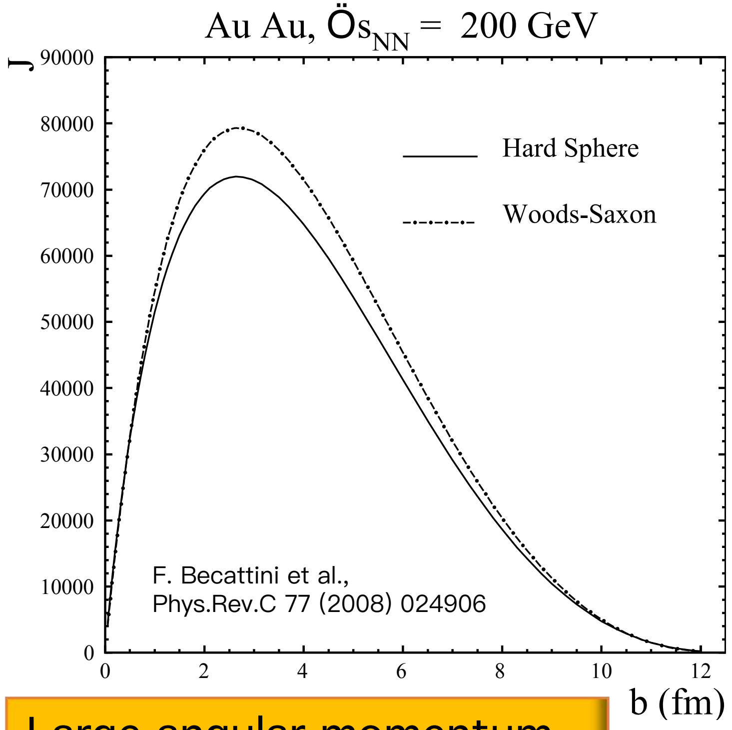


- Programs to carry out systematic study of the phase structure of QCD phase diagram through relativistic heavy ion collisions underway
- Higher moments measurements seem to follow QCD thermodynamics except at 3 GeV
- Experimental evidences of signatures related to critical point observed at a 3 σ level
- Lattice QCD clearly shows cross over at $\mu_B = 0$.
- Experimental indications of cross over at $\mu_B = 20$ MeV observed at < 2 σ level
- Hints of change of equation of state at high μ_B
- Need to continue the dedicated programs in the high baryon density regime to unfold the QCD phase diagram. This includes looking for Moat Quarkyonic matter regimes
- Experiments: STAR@RHIC BES–II, CBM@FAIR, NICA@JNIR, SHINE@CERN–SPS, J–PARC–HI and CEE–HIAF complementary to each other



Large magnetic field

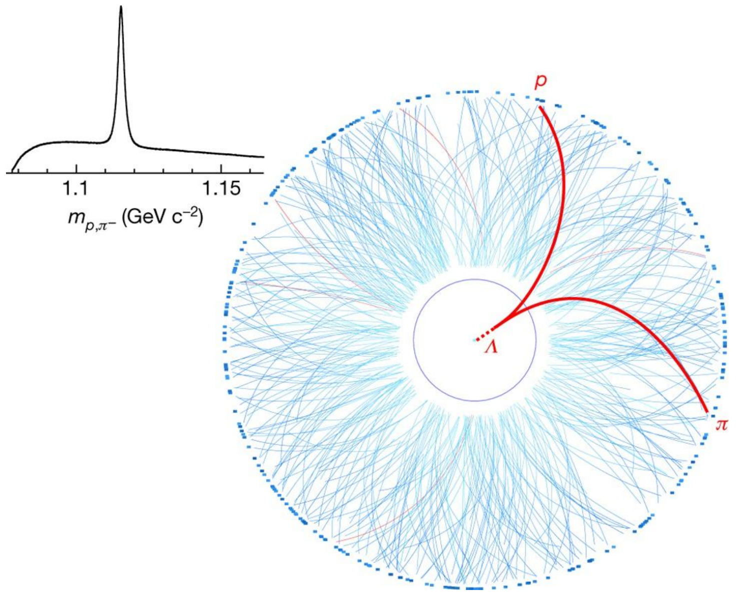


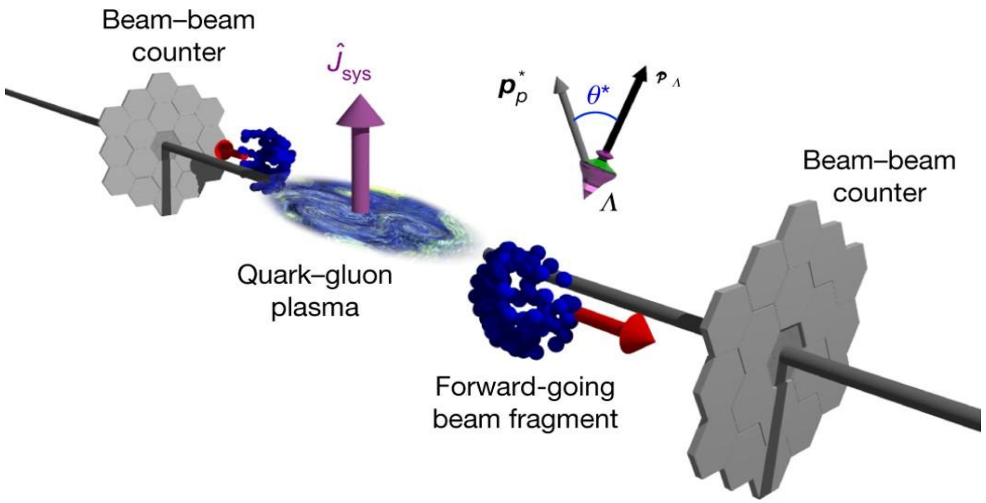


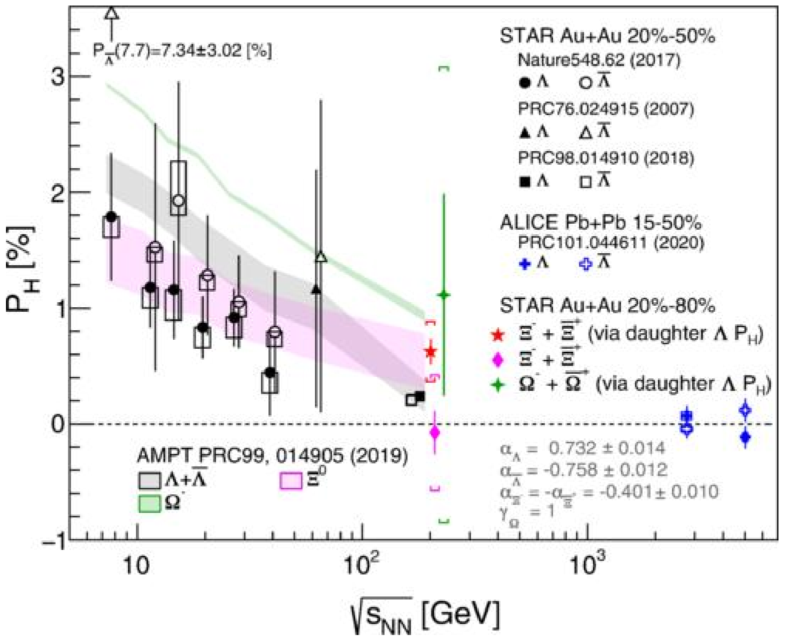
Large angular momentum (Conserved Quantity)

Angular momentum and magnetic field

Polarization of hyperons



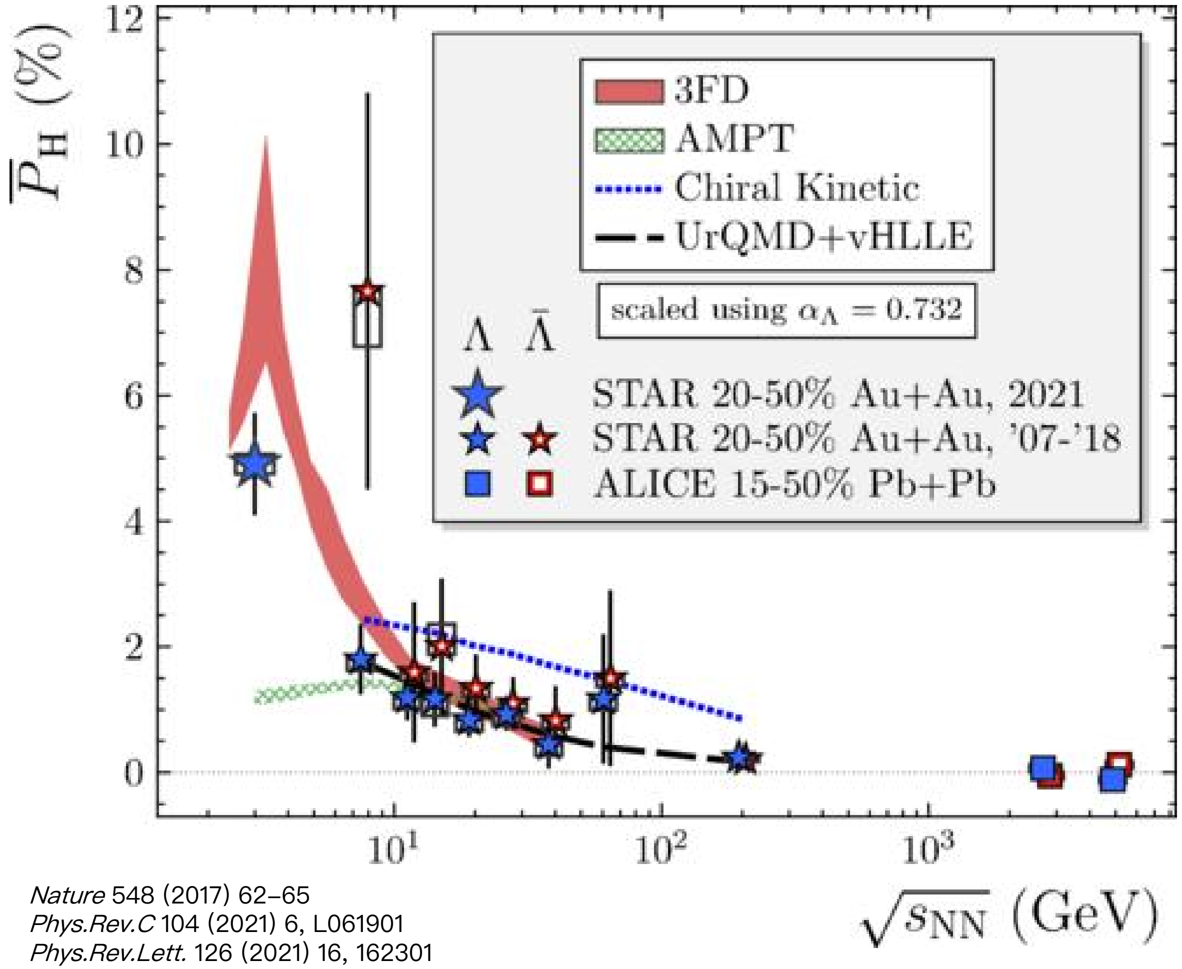




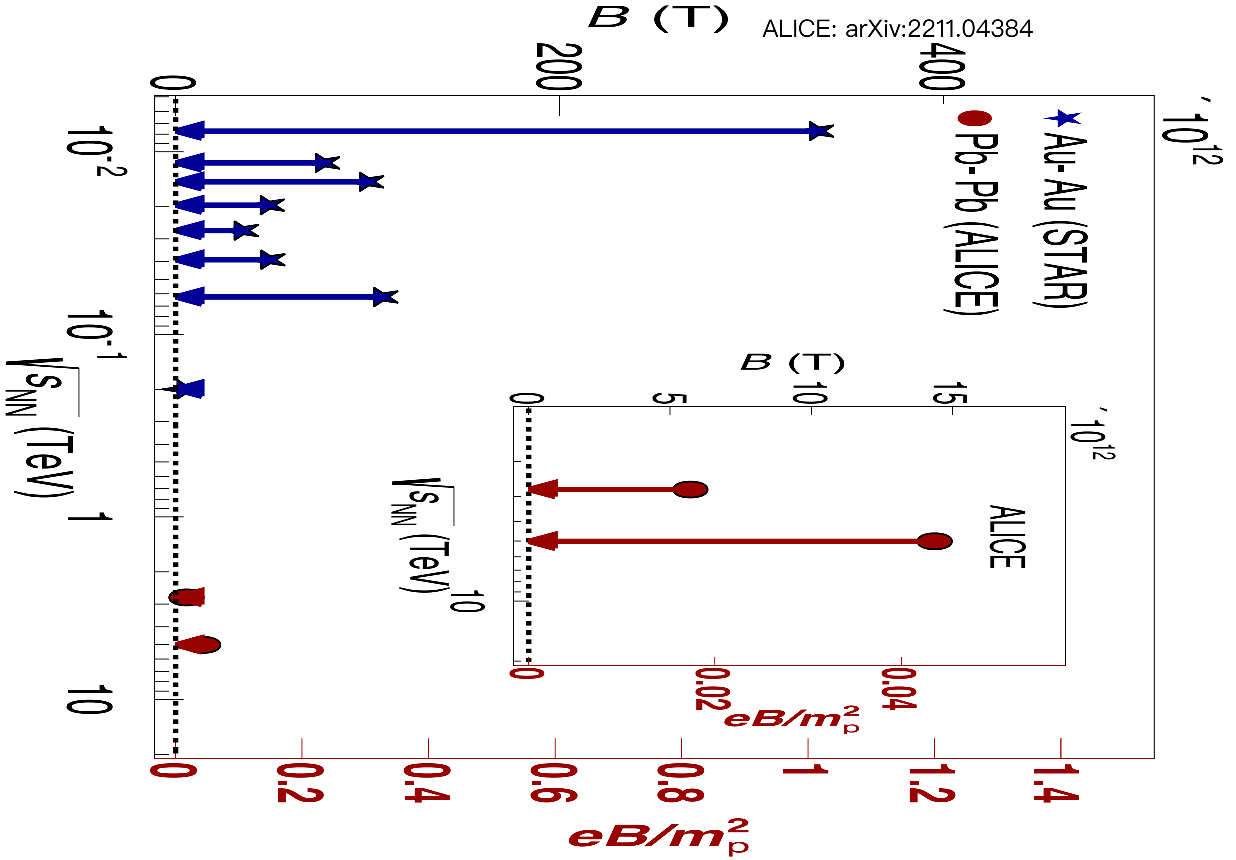
$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta^*} = \frac{1}{2}(1+\alpha_{\mathrm{H}}|\mathcal{P}_{\mathrm{H}}|\cos\theta^*) \quad (1)$$

STAR:
Nature 548 (2017) 62–65
Phys.Rev.C 104 (2021) 6, L061901
Phys.Rev.Lett. 126 (2021) 16, 162301
Phys.Rev.C 98 (2018) 014910

Global hyperon polarization



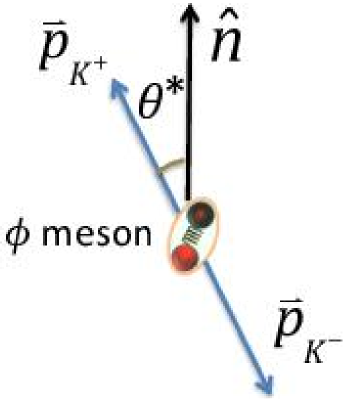
Nature 548 (2017) 62–65
Phys.Rev.C 104 (2021) 6, L061901
Phys.Rev.Lett. 126 (2021) 16, 162301
Phys.Rev.C 98 (2018) 014910

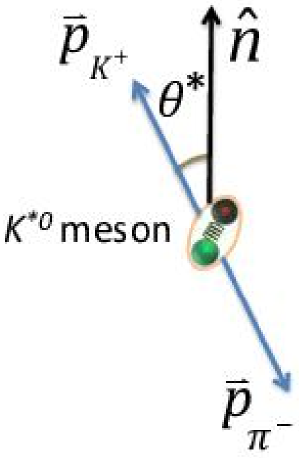


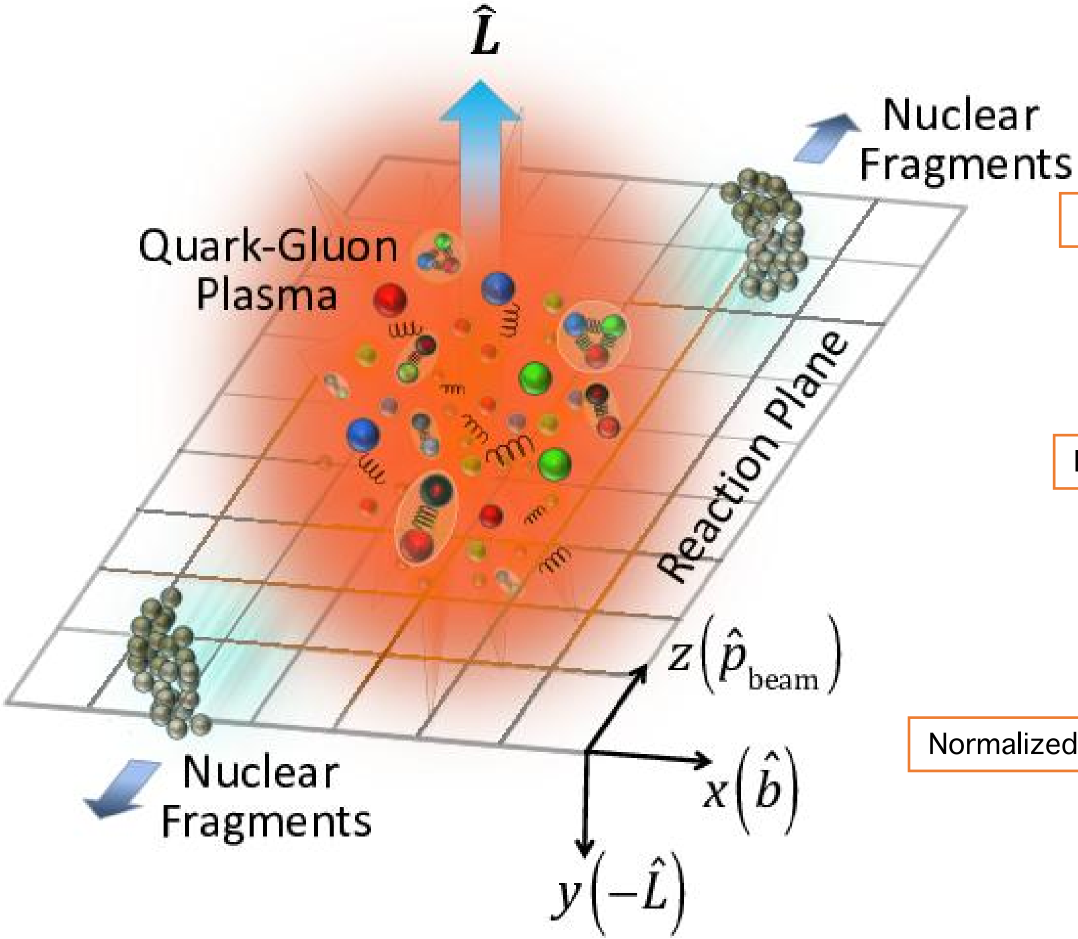
$P_\Lambda \approx 0.5\omega/T + |\mu_\Lambda|B/T$ and $P_{\bar{\Lambda}} \approx 0.5\omega/T - |\mu_\Lambda|B/T$, where ω is the vorticity of the QGP, used to constrain the value of the magnetic field at freeze-out by evaluating ($P_\Lambda - P_{\Lambda bar}$).

BES-II higher statistics will allow for estimate of magnetic field

Spin alignment of vector mesons







K. Schilling et al., Nucl. Phys. B 15 (1970) 397

$$\frac{dN}{dcos\theta d\phi} = \langle\theta,\phi,\lambda_1,\lambda_2|M\rho M^\dagger|\theta,\phi,\lambda_1,\lambda_2\rangle$$
$$= \sum_{\lambda_V}\sum_{\lambda_{V'}}\langle\theta,\phi,\lambda_1,\lambda_2|M|\lambda_V\rangle\langle\lambda_V|\rho|\lambda_{V'}\rangle\langle\lambda_{V'}|M^\dagger|\theta,\phi,\lambda_1,\lambda_2\rangle$$

λ = Helicities
ρ = spin density matrix
M = Decay amplitude

In terms of spherical harmonics

$$\frac{dN}{dcos\theta d\phi} = |C|^2 \times \sum_{m_1,m_2} Y^*_{1,m_1}(\theta,\phi)Y_{1,m_2}(\theta,\phi)\rho_{m_1,m_2}$$

Integrating over azimuthal angle

$$\frac{dN}{dcos\theta} = |C|^2 \times \frac{3}{8\pi}\left[sin^2\theta\rho_{-1,-1} + 2cos^2\theta\rho_{0,0} + sin^2\theta\rho_{1,1}\right] \times 2\pi$$
$$= |C|^2 \times \frac{3}{4}\left[sin^2\theta\left(\rho_{-1,-1} + \rho_{1,1}\right) + 2cos^2\theta\rho_{0,0}\right]$$

Normalized spin density matrix – Trace = 1

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

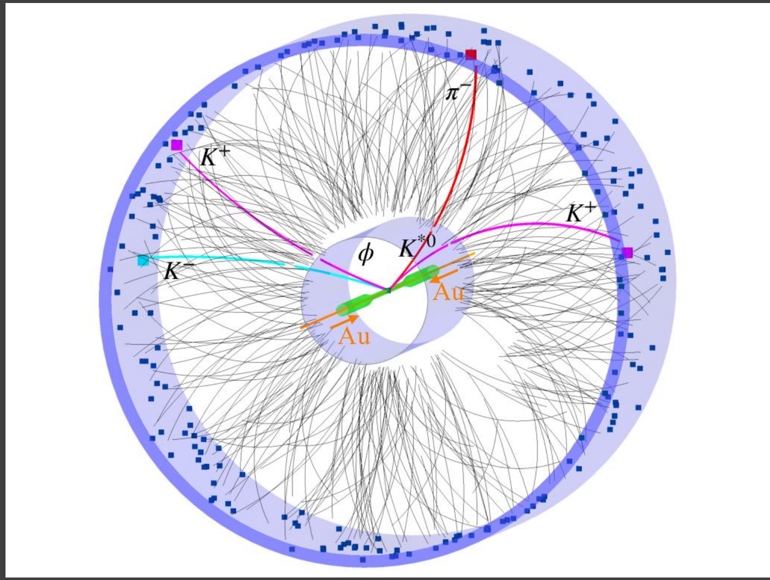
ρ_{00}: Probability vector meson is in spin state = 0
: 1/3 no spin alignment

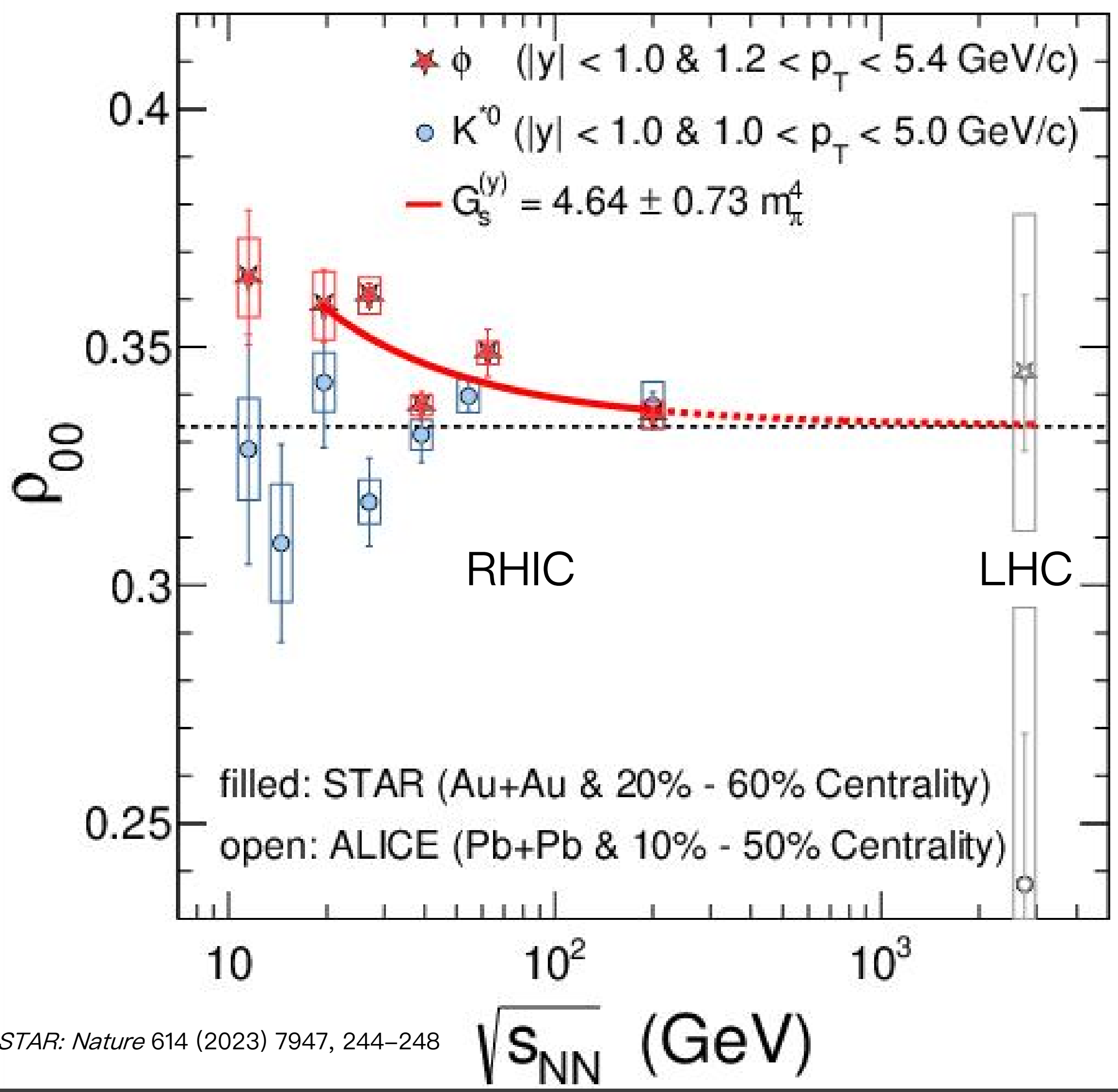
STAR: *Nature* 614 (2023) 7947, 244–248

Physics processes and theory expectations

Physics process	Theory	Remarks	Reference
Vorticity (ω)	$\rho_{00}(\omega) < 1/3$	$\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta\omega)^2$	*F. Becattini et al., Phys. Rev. C 95 (2017) 054902*
Magnetic field (B)	$\rho_{00}(B) > 1/3$ $\sim \frac{1}{3} - \frac{1}{9}\beta \frac{q_1 q_2}{m_1 m_2} B^2$ $\rho_{00}(B) < 1/3$	Electrically neutral vector mesons Electrically charged vector mesons	*Y. Yang et. al., Phys. Rev. C 97 (2018) 034917*
Hadronization	$\rho_{00}(rec) < 1/3$ $\sim \frac{1-P_q P_q}{3+P_q P_q}$ $\rho_{00}(frag) > 1/3$ $\sim \frac{1+\beta P_q P_q}{3-\beta P_q P_q}$	Recombination Fragmentation	*Z. Liang et. al., Phys. Lett. B 629 (2005) 20 (2005)* *Z. Liang and X. N. Wang Phys.Rev.Lett. 94 (2005) 102301*
Effective meson field	$\rho_{00} > 1/3$	ϕ mesons	*X. L. Sheng et. al., arXiv:1910.13684*

Spin alignment of vector mesons

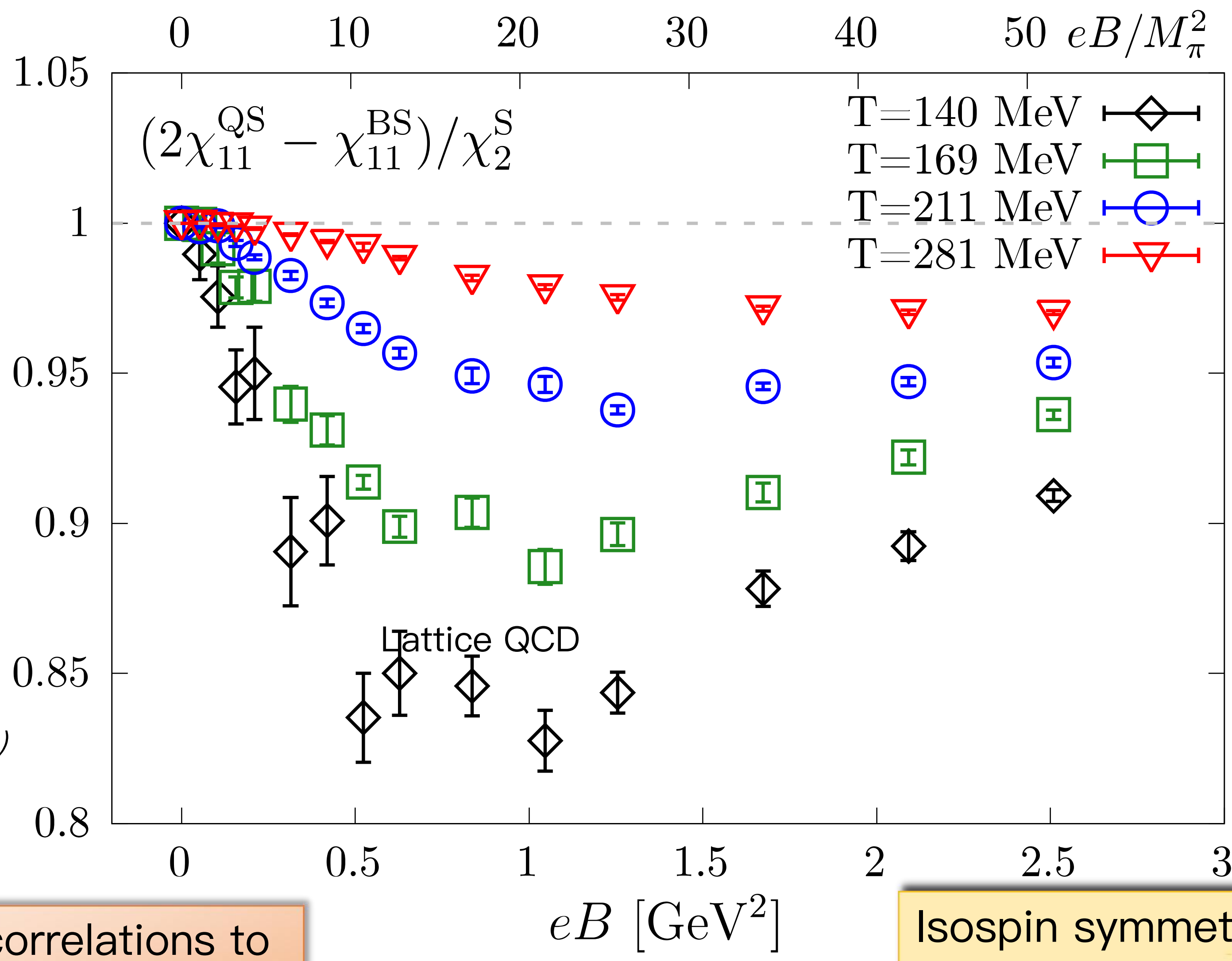




STAR: Nature 614 (2023) 7947, 244–248

BES–II — higher statistics will allow for differential measurements

Probing magnetic field in HIC using correlations

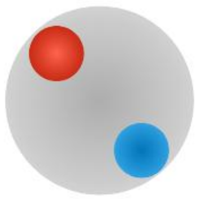


H.T. Ding et al, EPJA 57.202 (2021)

Measuring BS, BQ, QS correlations to probe magnetic field in HIC

Isospin symmetry broken due to magnetic field.

Nuclei production in heavy–ion collisions

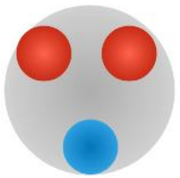


Deuteron

$E_b = 2.22$ MeV

$\sqrt{\langle R_c^2 \rangle} = 2.13$ fm

Rev. Mod. Phys. 88 (2016) 035009



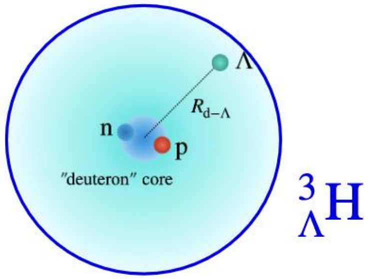
^{3}He

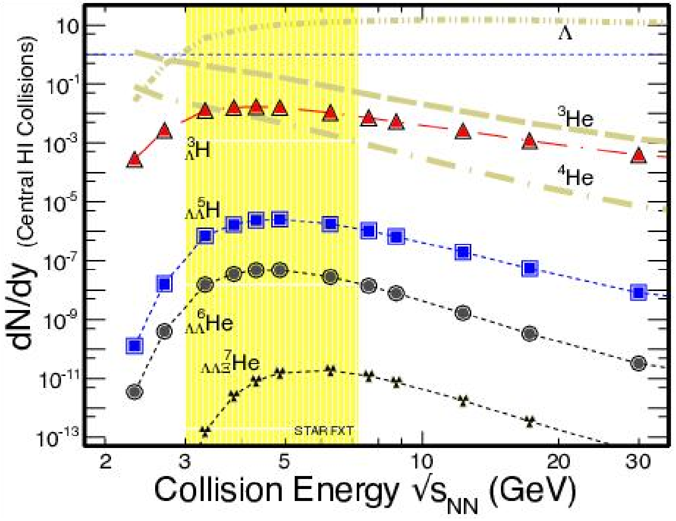
$E_b = 7.72$ MeV

$\sqrt{\langle R_c^2 \rangle} = 1.96$ fm

Nucl. Data Sheets 130, 1 (2015)

How can loosely bound objects like nuclei (binding energy B ~ 1 MeV) be formed and survive in such a hot environment (kinetic freeze-out temperature $T_{fo} \sim 100$ MeV)?

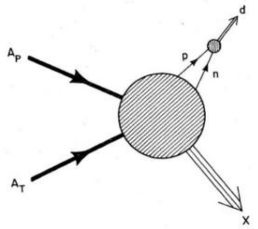




Thermal model

$$dN/dy \propto \exp\left(-\frac{m}{T_{ch}}\right)$$

Coalescence model



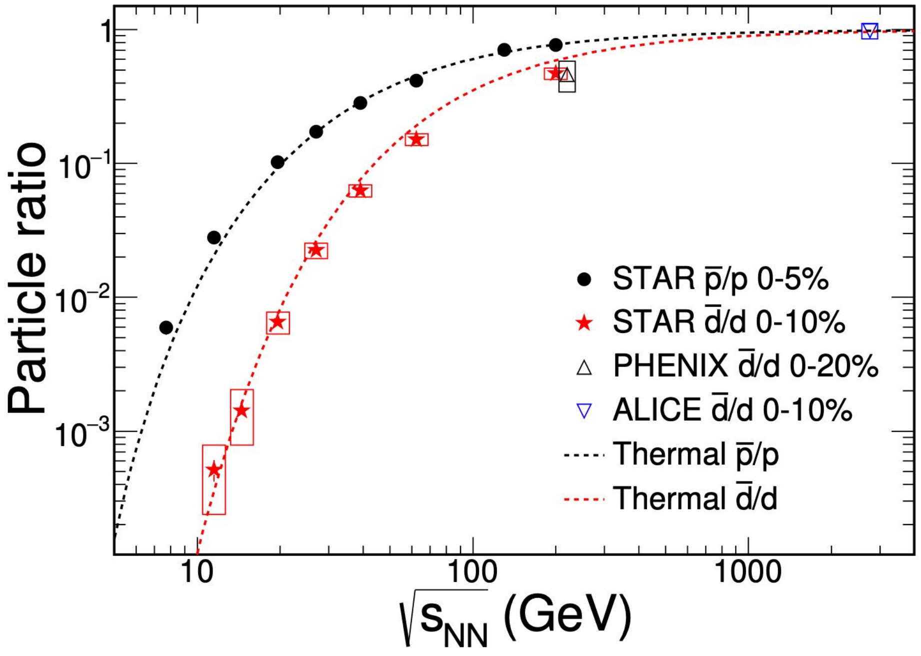
$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

J. Kapusta, Phys. Rev. C 21 (1980) 1301

Measuring the yields of hyper–nuclei and their life–time will provide valuable inputs to understanding the hyperon–nucleon interactions in heavy ion collisions and our understanding inner dynamics of compact stars.

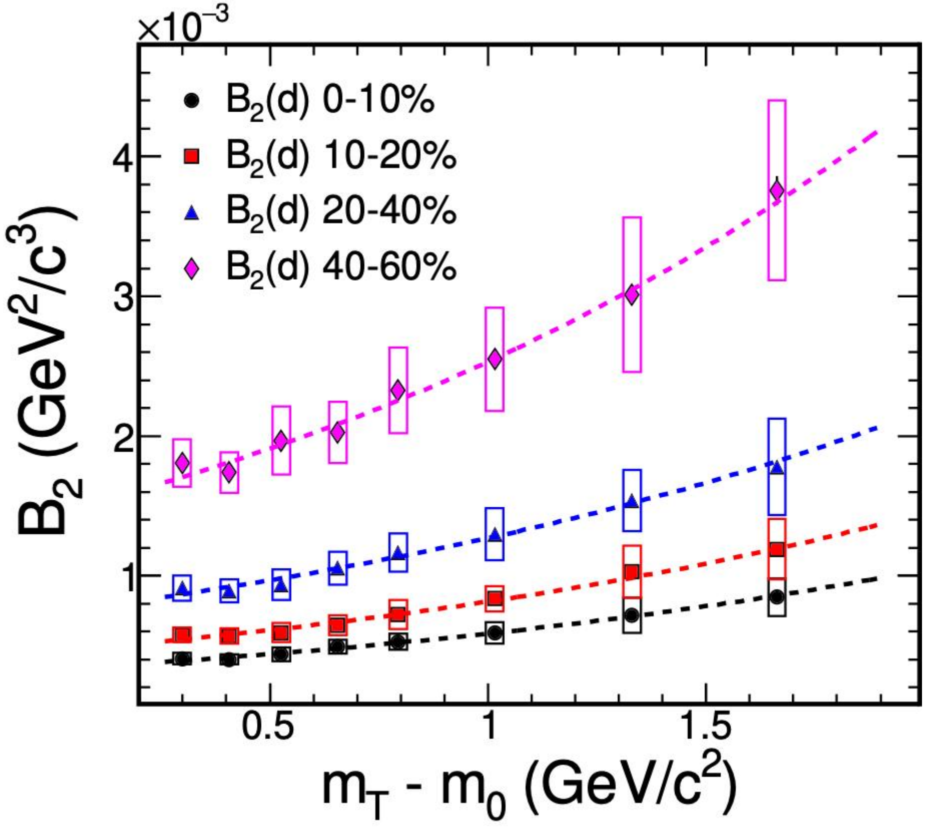
AAPPS Bull. 31 (2021) 1

Nuclei production: thermal vs. coalescence



STAR: Phys. Rev. C 99, 064905 (2019)

Anti–particle to particle ratio explained by thermal model for a wide range of $\sqrt{s_{NN}}$.

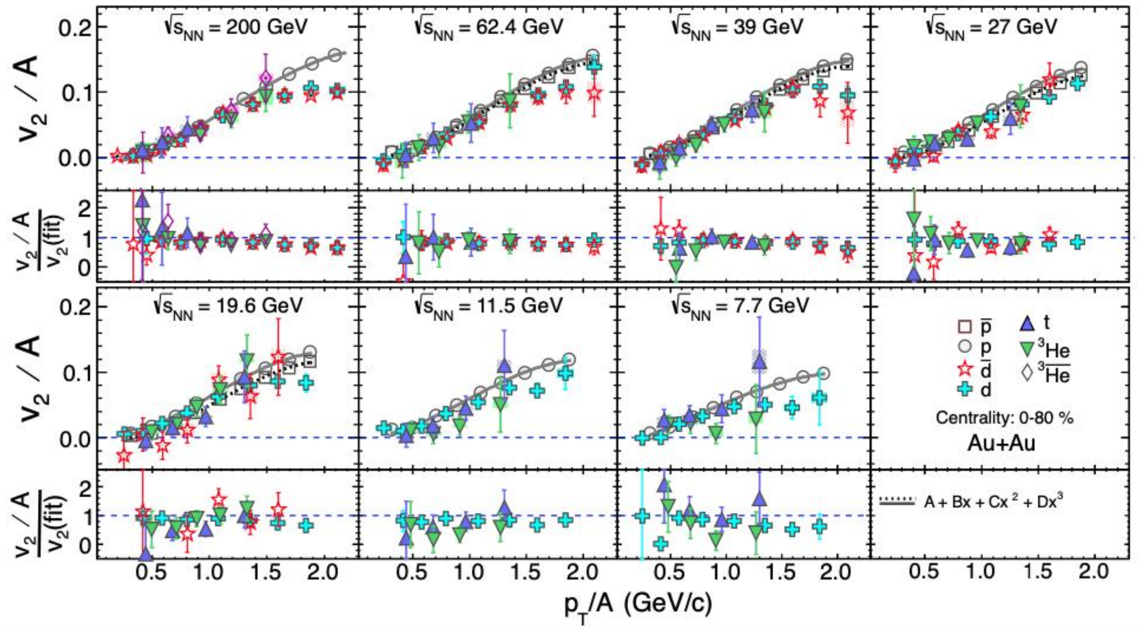


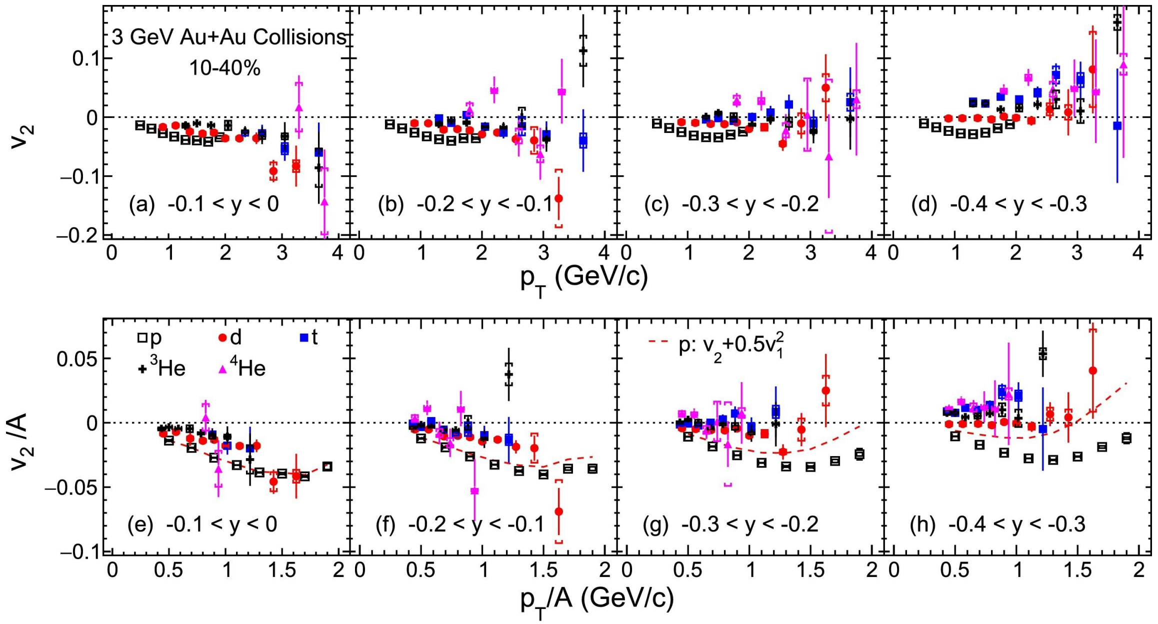
STAR: Phys. Rev. C 99, 064905 (2019)

$B_2 \propto e^{(m_T ð -mð)}$, $Bð_2 \propto (4/3)\pi ð p_0^3$

p_0: Radius in momentum space.

Collectivity in light nuclei

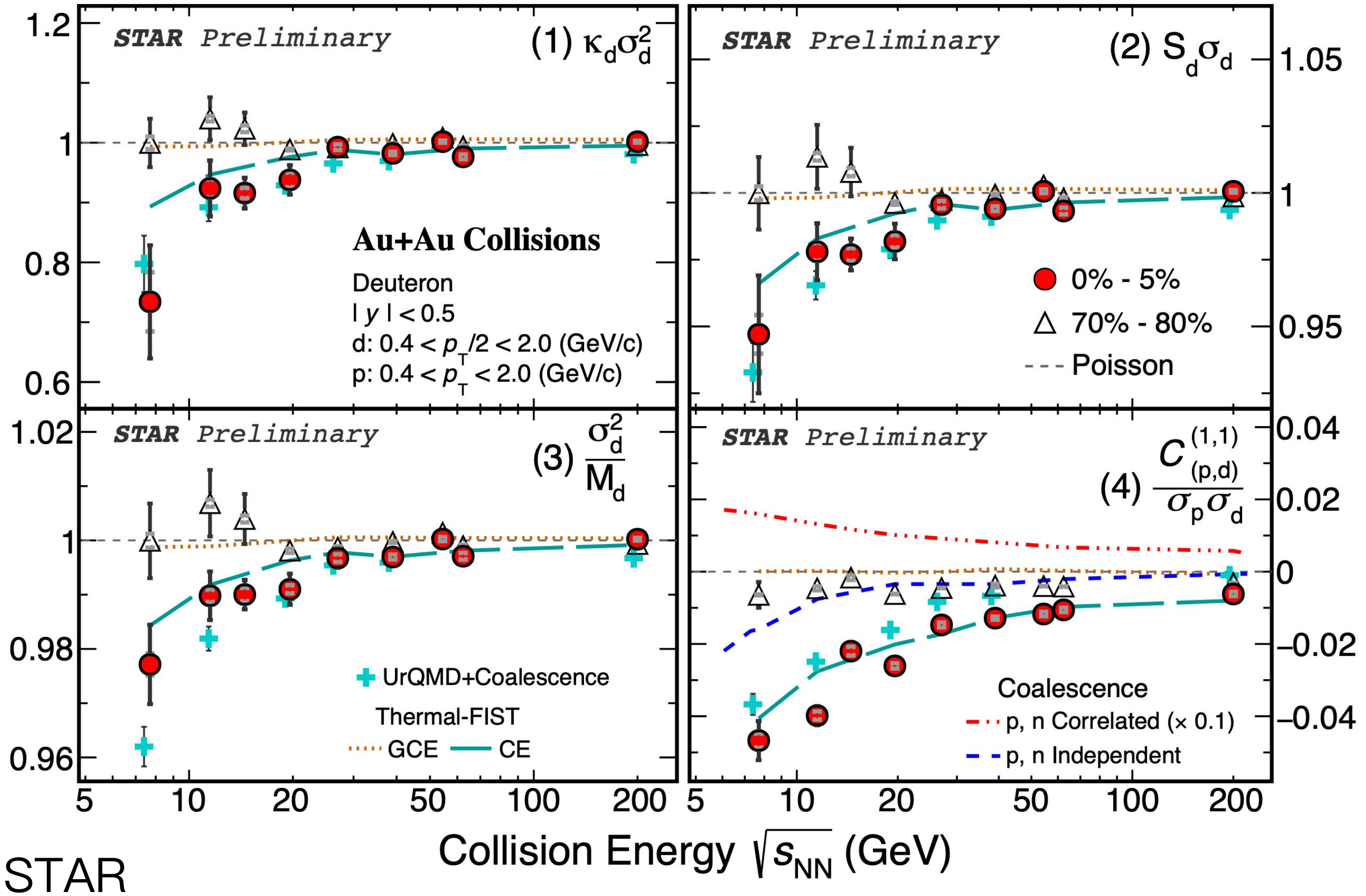




Nucleon coalescence picture works up to $p_T/A \leq 1.5$ GeV/c.

v_2 values at mid-rapidity for all light nuclei are negative and no scaling is observed with the atomic mass number.

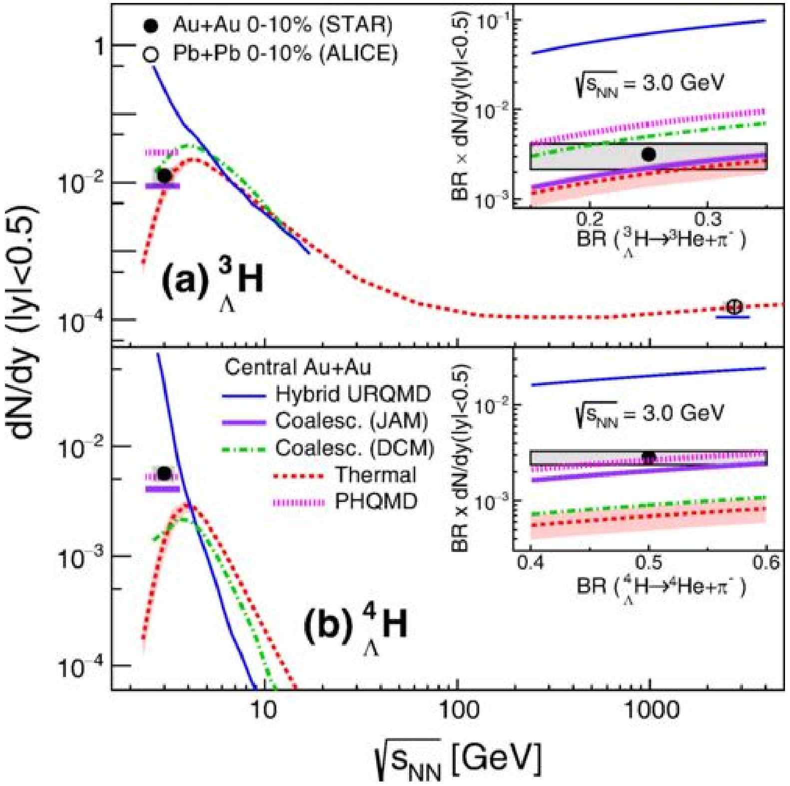
Deuteron number fluctuations and proton–deuteron correlations

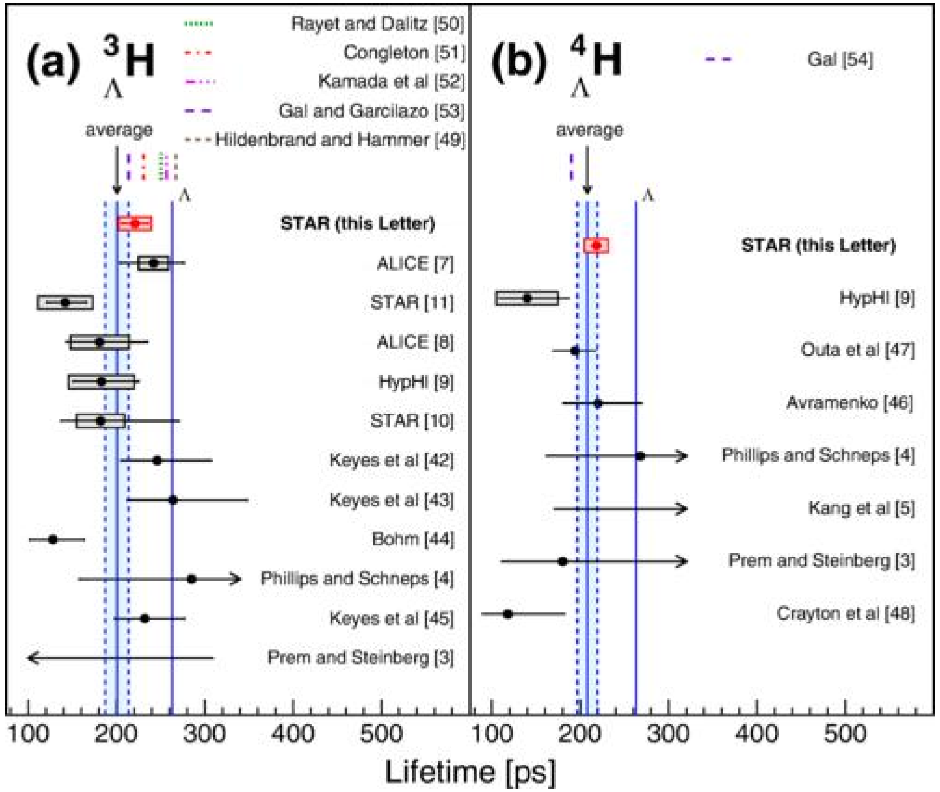


Discriminates some thermal models and some coalescence models depending on collision energy

D. Mallick, QM2022, STAR

Hypernuclei – lifetime





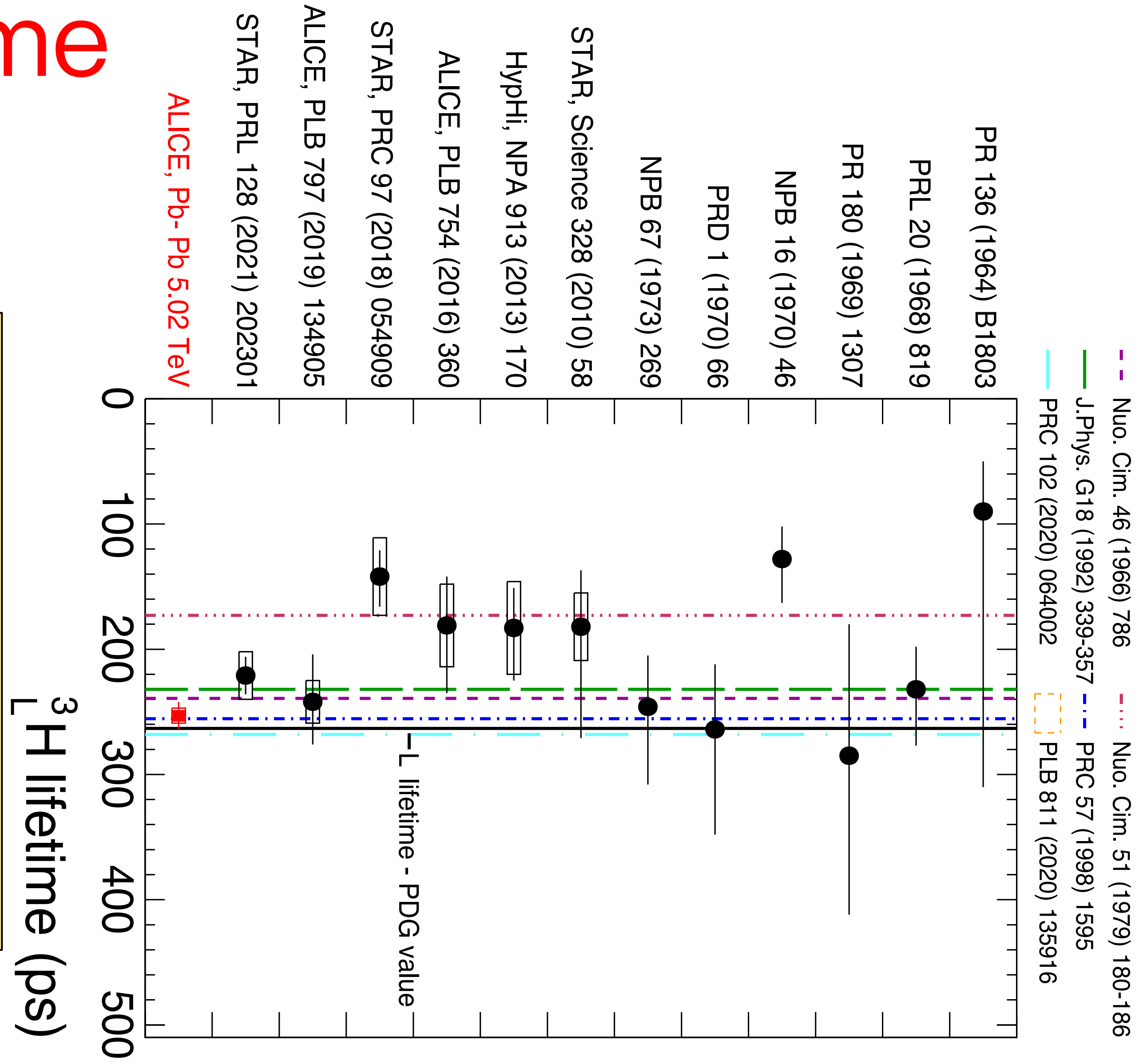
Properties of hypernuclei give access to the study of interactions among hyperons and nucleons.

Hypertriton lifetime

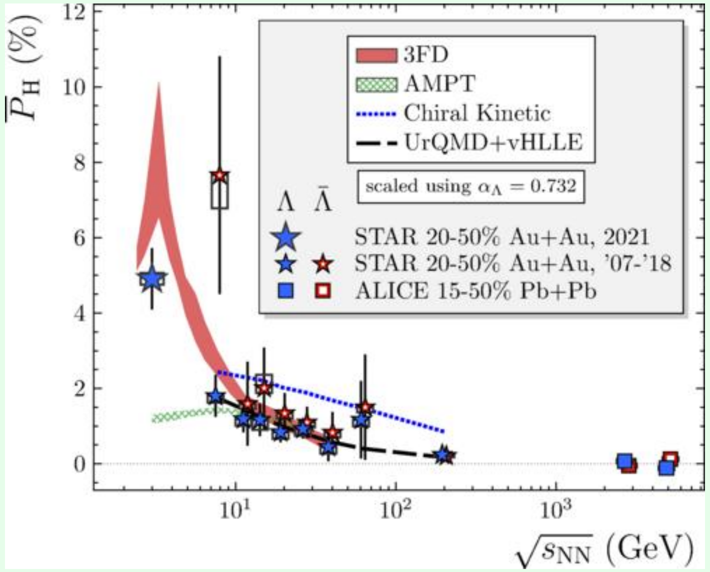
Small separation energy of the Λ to the pn core implies the lifetime of the hypertriton is very close to that of the free Λ hyperon.

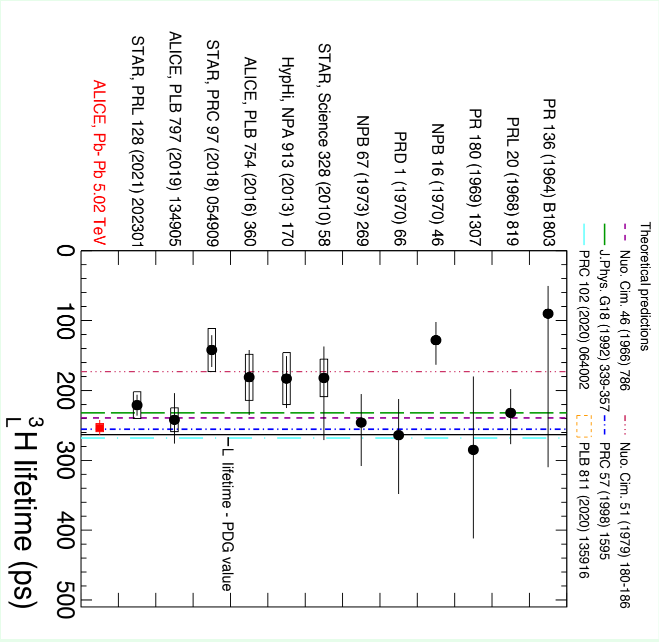
In a quantum–mechanical model, the RMS radius of this hypernucleus is about 10.6 fm, if a deuteron–Λ bound state is assumed.

The Λ is with a very high probability several femtometer away from the other nucleons.



Summary – polarization & nuclei





- Experimental measurements of polarization of hyperons and spin alignment of vector mesons have spurred systematic theoretical study of relativistic spin magneto hydrodynamics
- Finite global polarization of hyperons observed, which increases as we go to lower collision energies.
- Finite spin alignment of vector mesons observed, it has implications of new kinds of mesonic fields
- Nuclei production mechanism still under debate, several kinds of experimental measurements exists and with higher statistics will be available in future.
- Hypernuclei lifetime measurements are interesting inputs to hyperon-nucleon interactions and has implications beyond the field of heavy-ion collisions
- Experiments: STAR@RHIC BES-II, CBM@FAIR, NICA@JNIR, SHINE@CERN-SPS, J-PARC-HI and CEE-HIAF complementary to each other

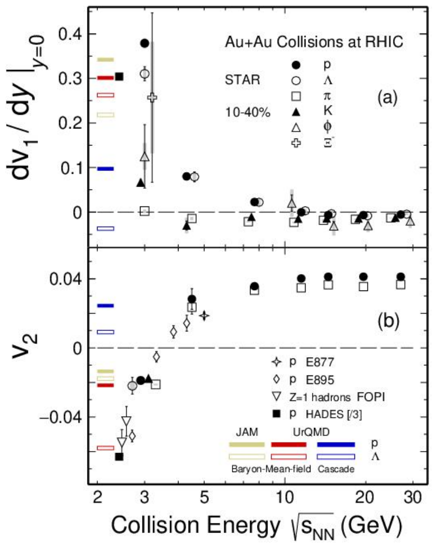
Fixed target vs. collider energies at RHIC

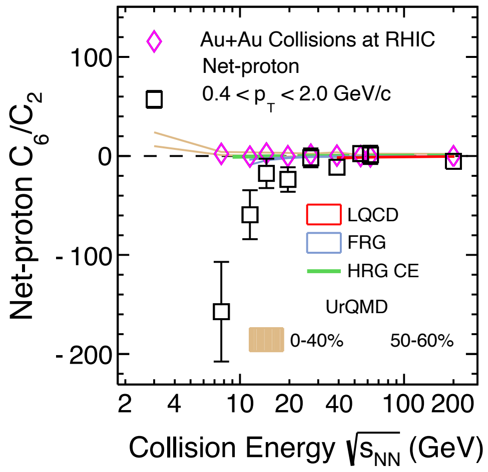
Hadronic degrees of freedom

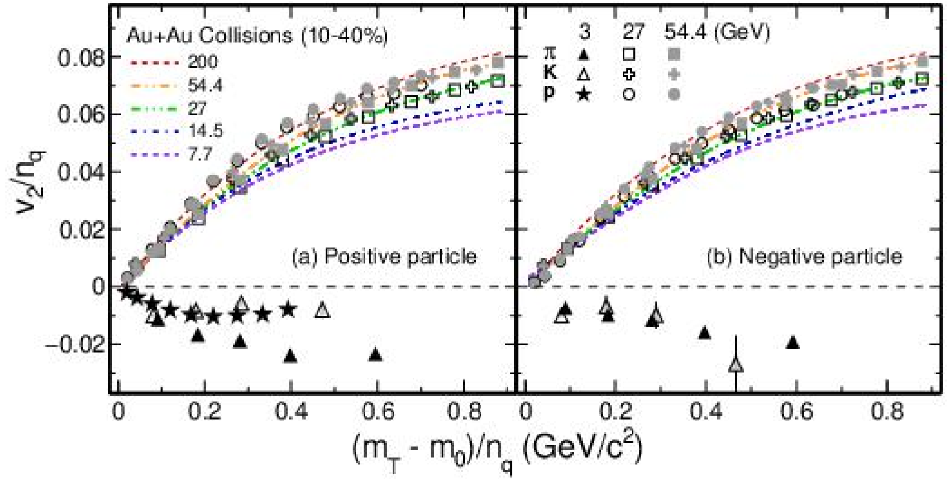
vs.

quark gluon degrees of freedom

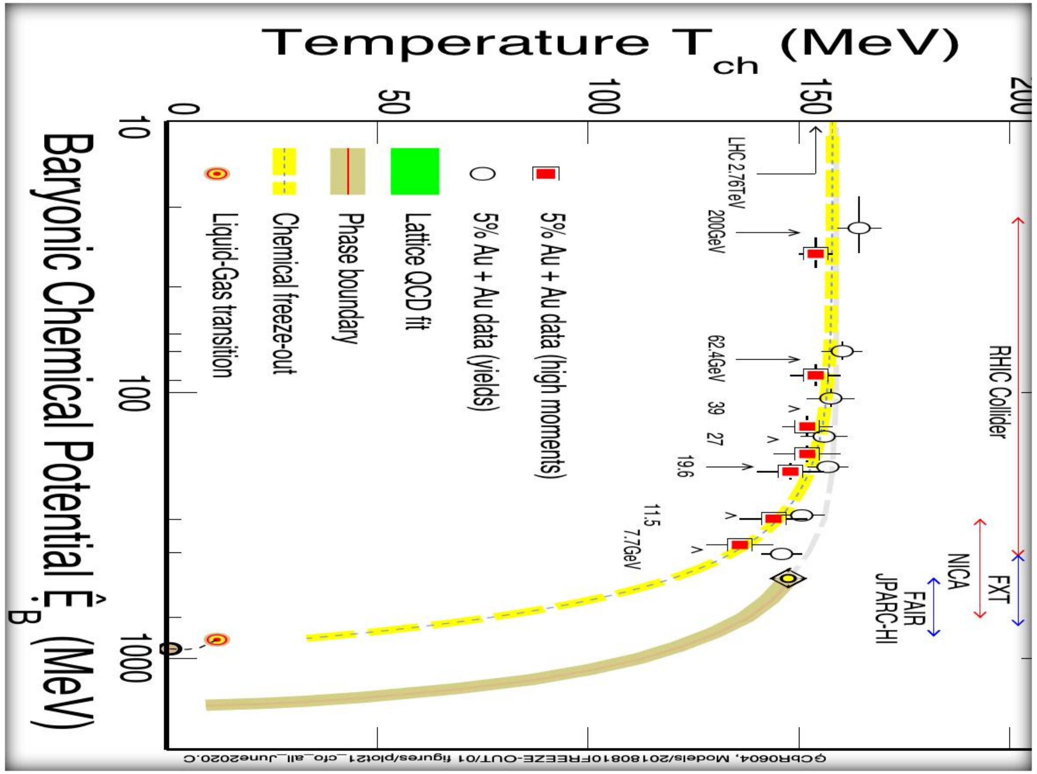
STRA: Phys.Lett.B 827 (2022) 137003
STAR: PRL 130 , 82301 (2023)

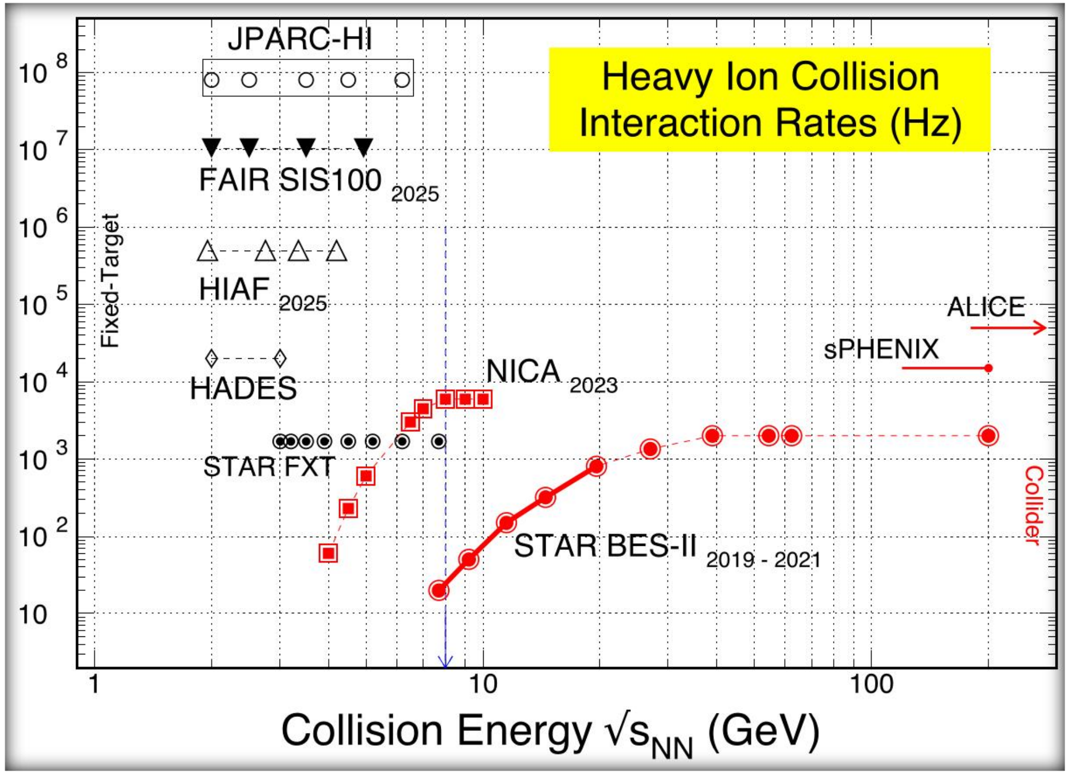




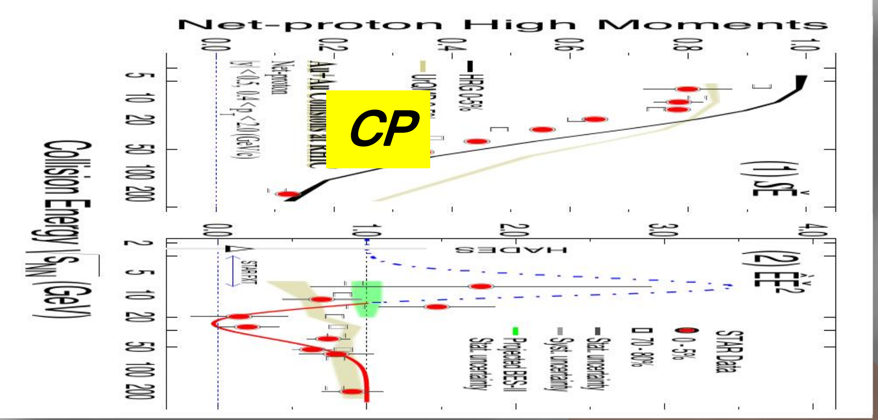


Experimental program for high baryon density matter

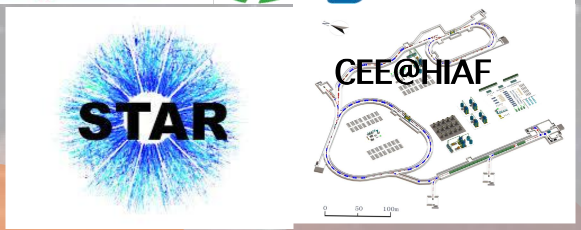


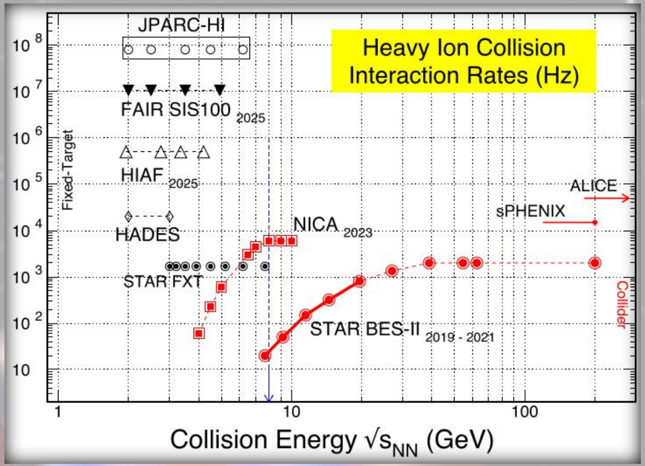


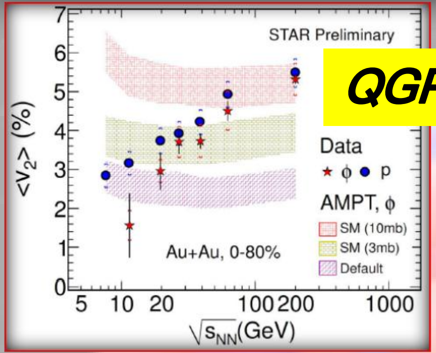
AAPPS Bull. 31 (2021) 1



High baryon density experiments

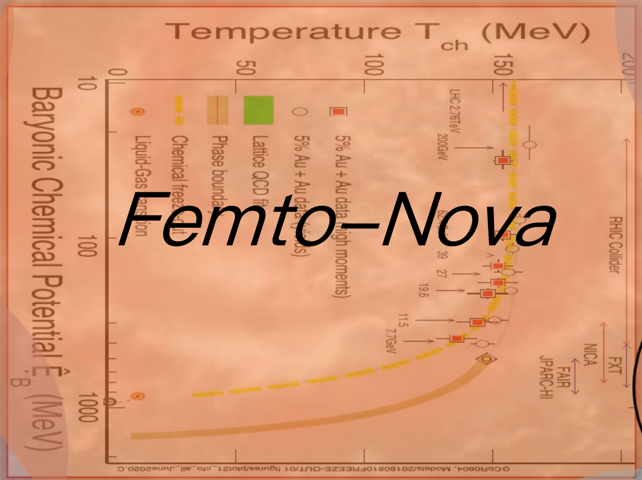


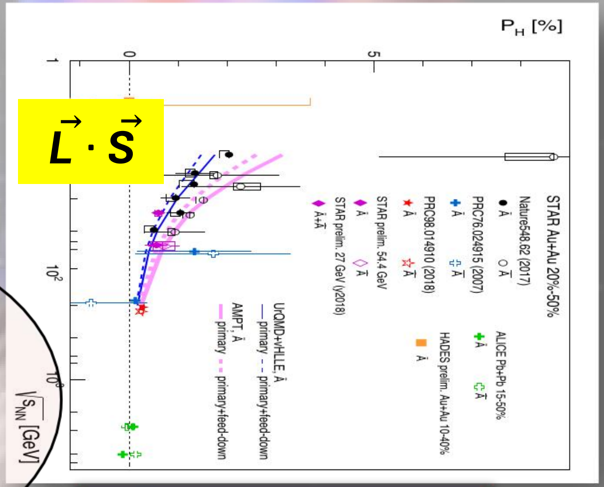




Criticality

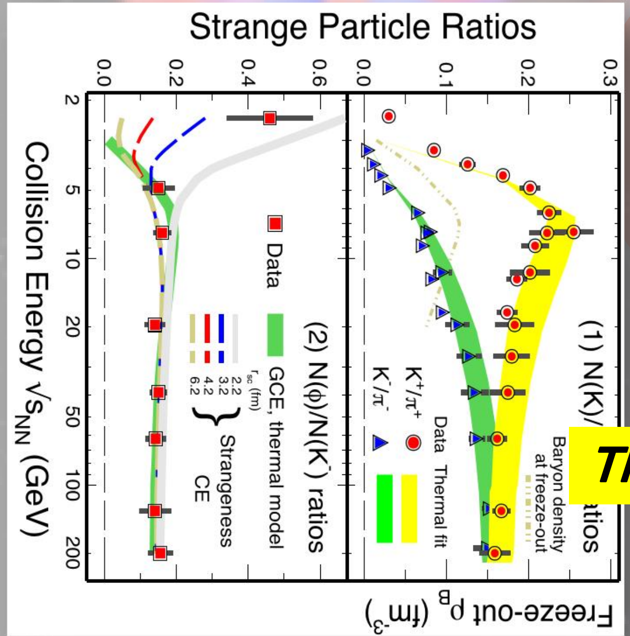
Polarization

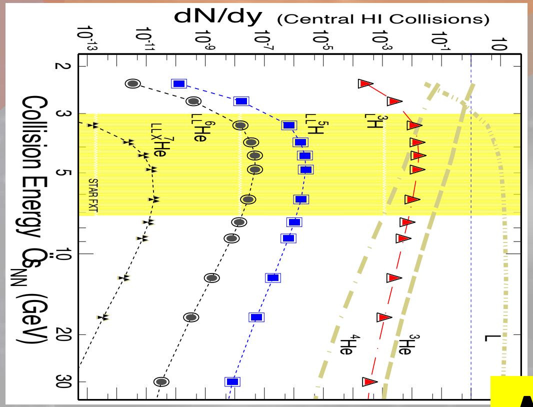




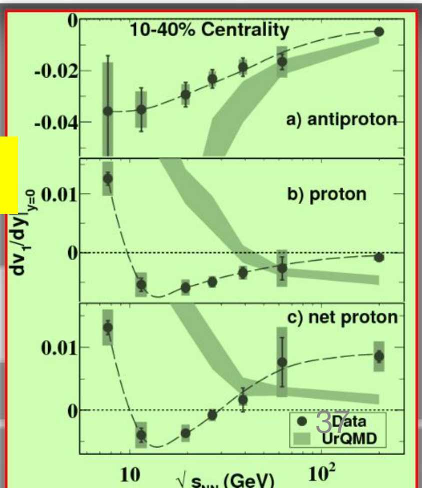
Collectivity

Test of Thermal models





Hyper–Nuclei



Nuclei

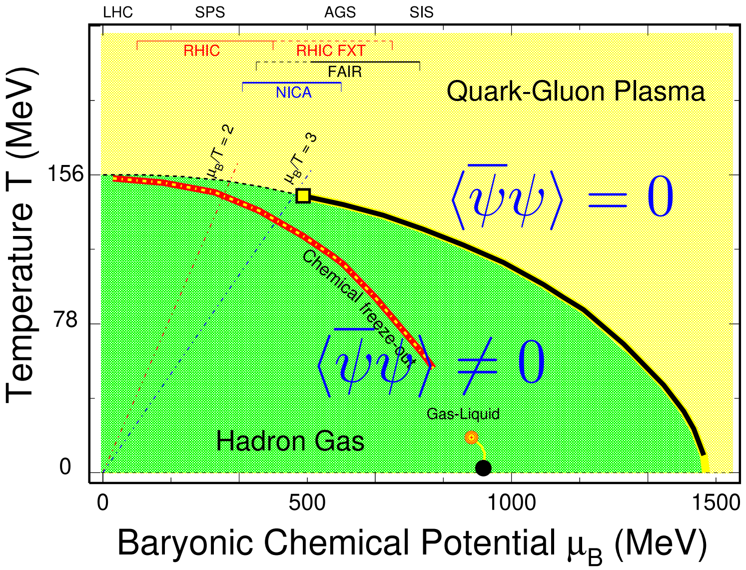
Xu, Fukushima, Mohanty AAPPS Bull. 31 (2021) 1

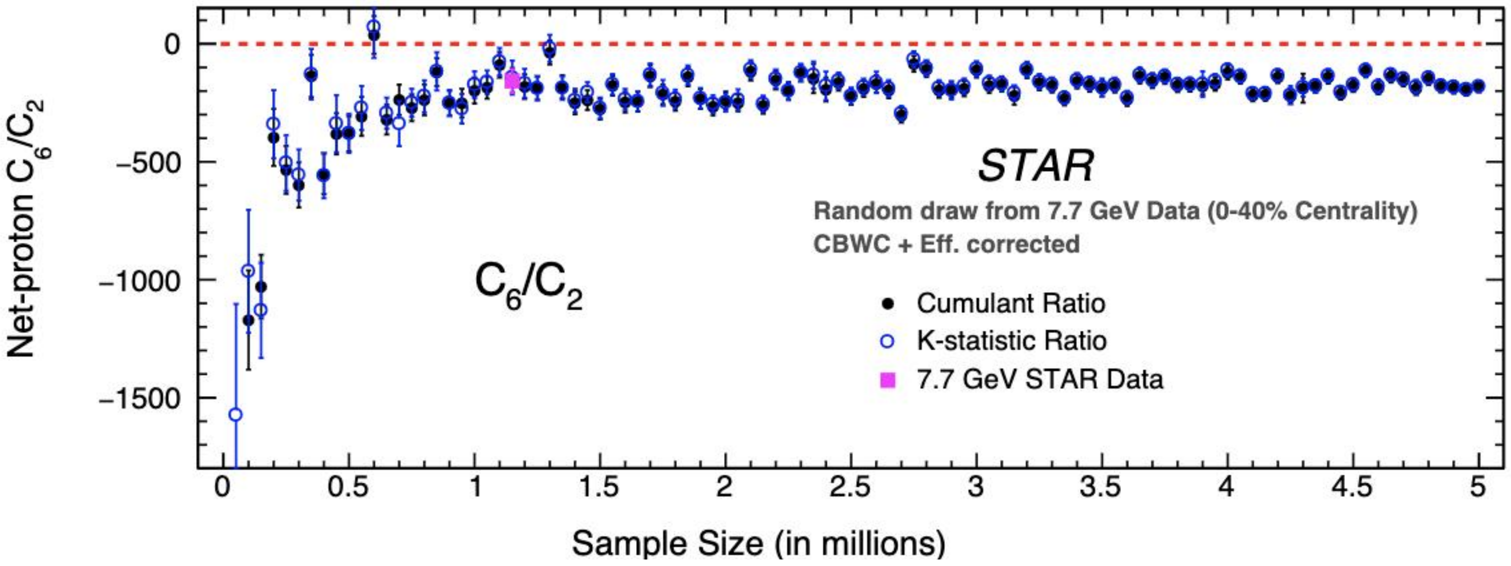
Acknowledgements

All members of the STAR Collaboration, ALICE Collaboration, CBM Collaboration, D. Mishra, R. Pisarski, F. Karsch, S. Gupta & R. Gavai, A Jaiswal, V. Roy, N. Haque, S. Chatterjee.

Thanks to the organizers for the invitation.

Back up





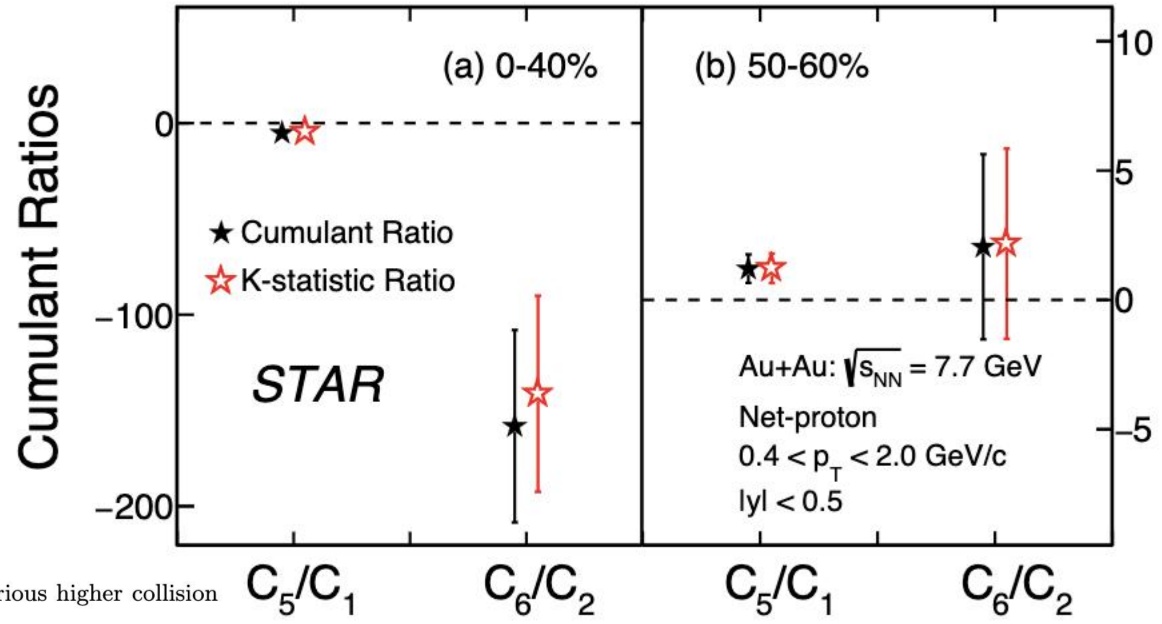
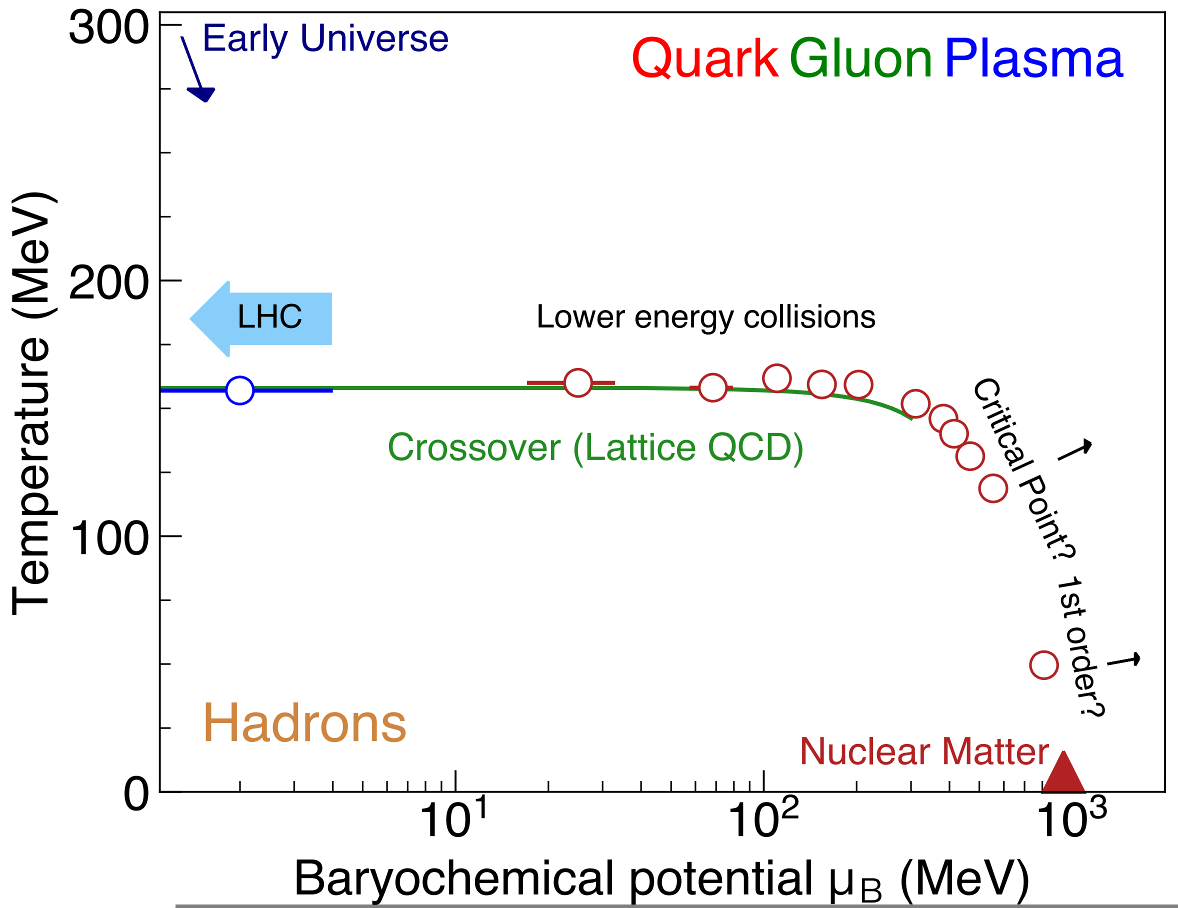


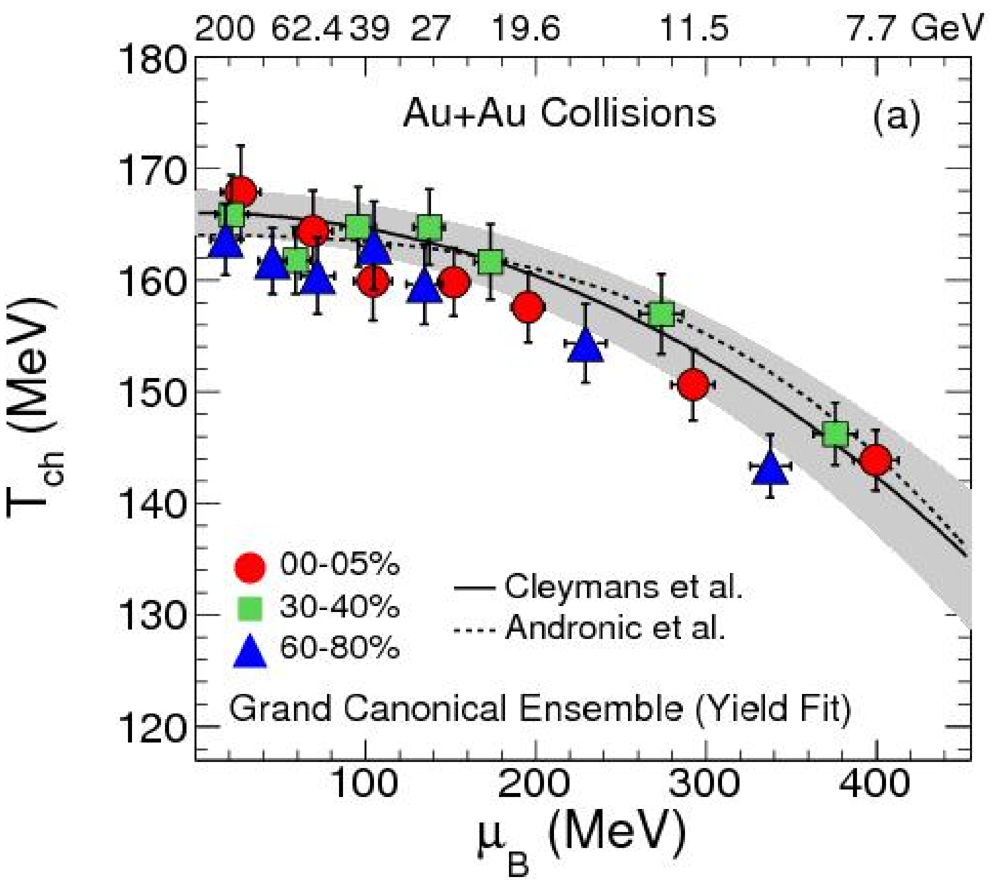
TABLE S2. Probability (in %) of observing a reverse ordering as shown by $\sqrt{s_{NN}} = 3$ GeV data, at various higher collision energies

$\sqrt{s_{NN}}$ (GeV)	7.7	11.5	14.5	19.6	27	39	54.4	62.4	200
Probability (in %)	0.858	2.5991	8.0209	0.1756	0.1424	0.6911	2.192	10.0739	2.0769



Phase diagram of QCD

ALICE: arXiv:2211.04384



Freeze-out conditions at RHIC BES energies

STAR: Phys.Rev.C 96 (2017) 4, 044904

Experimental results from the RHIC beam energy scan program and outlook

Bedanga Mohanty (NISER)