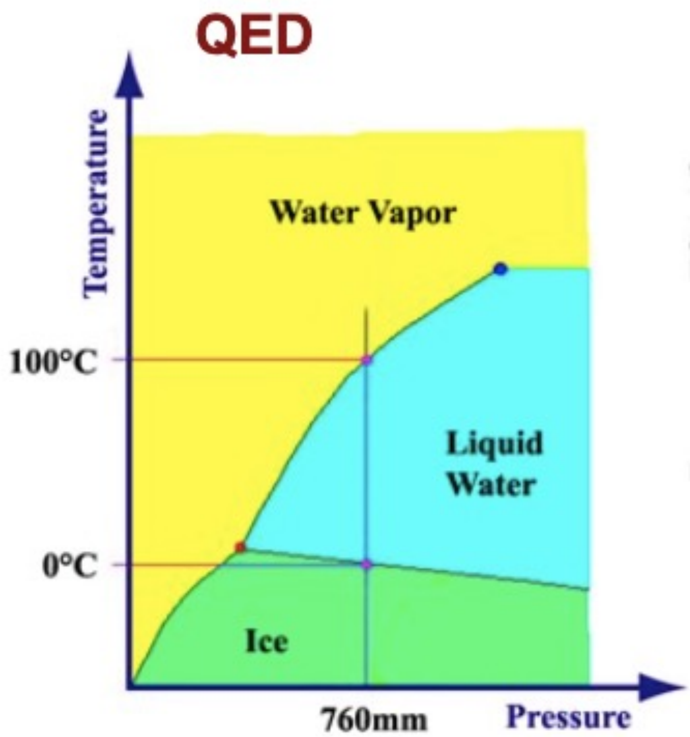
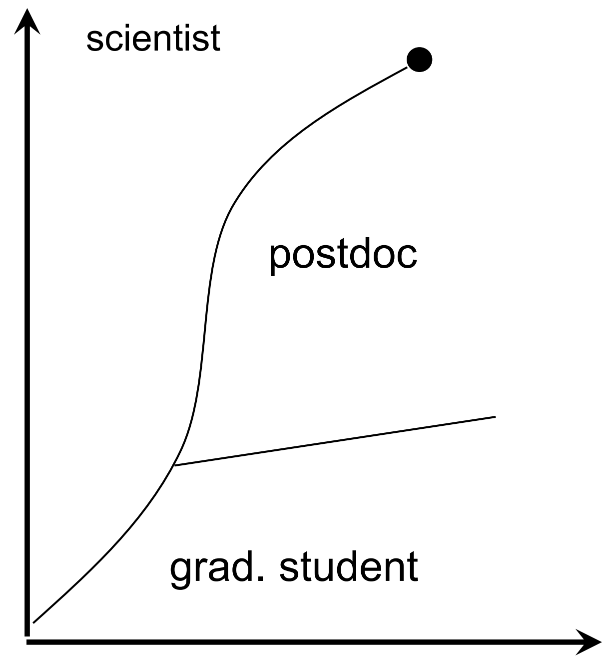
Phase Diagrams





QCD Phase Diagram – Ask ChatGPT

X tell me about QCD phase diagram

The Quantum Chromodynamics (QCD) phase diagram represents the various phases of matter and their transitions as a function of temperature and baryon density in the context of QCD, the theory that describes the strong nuclear force. Understanding the QCD phase diagram is crucial for exploring the behavior of nuclear matter, particularly at extreme conditions. The primary phases and features of the QCD phase diagram include:

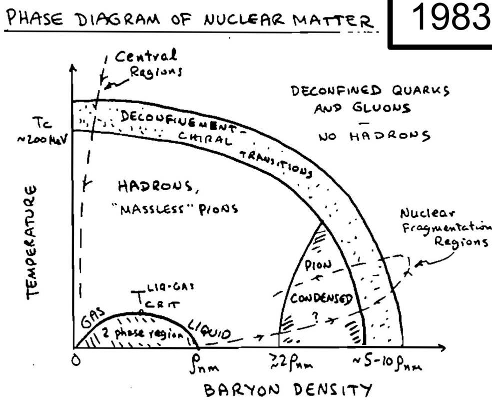
1. **Hadronic Phase:** At low temperatures and low baryon densities, nuclear matter exists in the hadronic phase. In this phase, quarks and gluons are confined within hadrons, which are color-neutral particles like protons, neutrons, and mesons. The strong force is dominant in this phase, binding quarks together.
2. **Quark-Gluon Plasma (QGP) Phase:** At high temperatures and/or high energy densities, it is believed that nuclear matter undergoes a phase transition to the quark-gluon plasma. In this phase, quarks and gluons are no longer confined within hadrons but are free to move independently. The QGP is thought to have existed in the early universe shortly after the Big Bang.
3. **Crossover Region:** Between the hadronic phase and the QGP phase, there is a region where the transition between these phases is not a sharp phase transition but rather a crossover. In this region, there is a gradual change from hadronic matter to quark-gluon plasma. The exact location and nature of this crossover are areas of ongoing research.
4. **Critical Point:** In the QCD phase diagram, it is hypothesized that there may be a critical point, which is a unique set of conditions (specific temperature and baryon density) where certain properties of the system change dramatically. The existence and precise location of the critical point are still subjects of active research and experimentation.

The QCD phase diagram is a topic of great interest in nuclear and particle physics. Researchers seek to better understand the behavior of nuclear matter under extreme conditions, such as those found in high-energy nuclear collisions, to gain insights into the early universe and the fundamental forces that govern it.

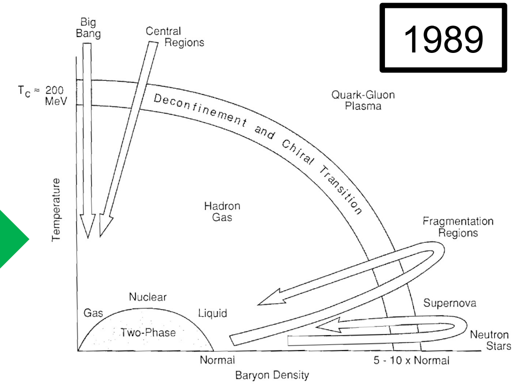
Experiments at particle accelerators like the Large Hadron Collider (LHC) and the Relativistic Heavy Ion Collider (RHIC) are conducted to study the properties of matter at high temperatures and energy densities, effectively exploring the QCD phase diagram. The experimental results help refine our understanding of the phase transitions and critical points in the QCD phase diagram.

QCD Phase Diagram

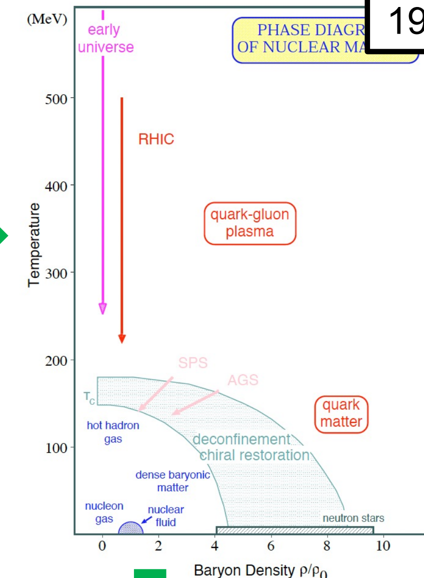
1983



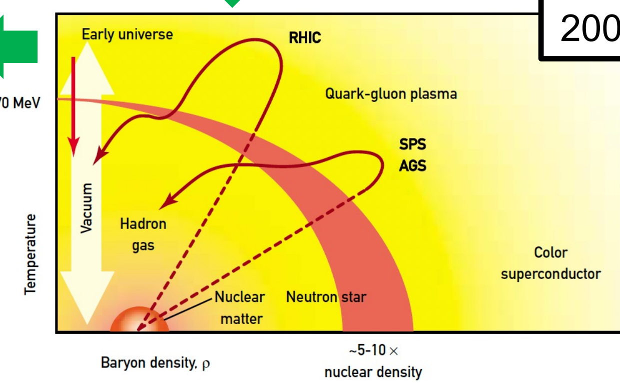
1989



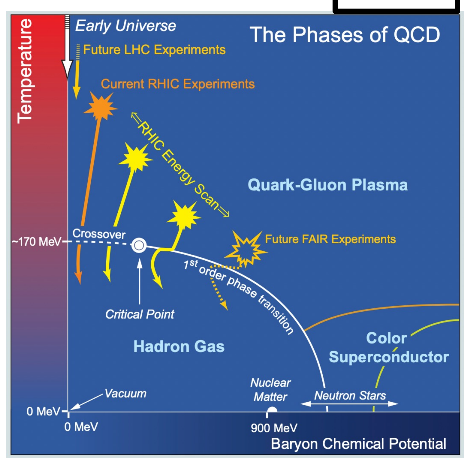
1996



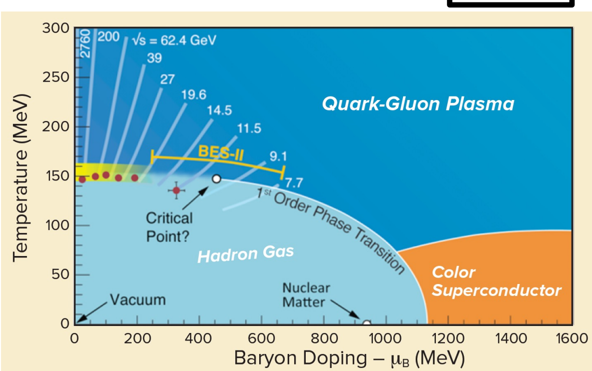
2002



2007

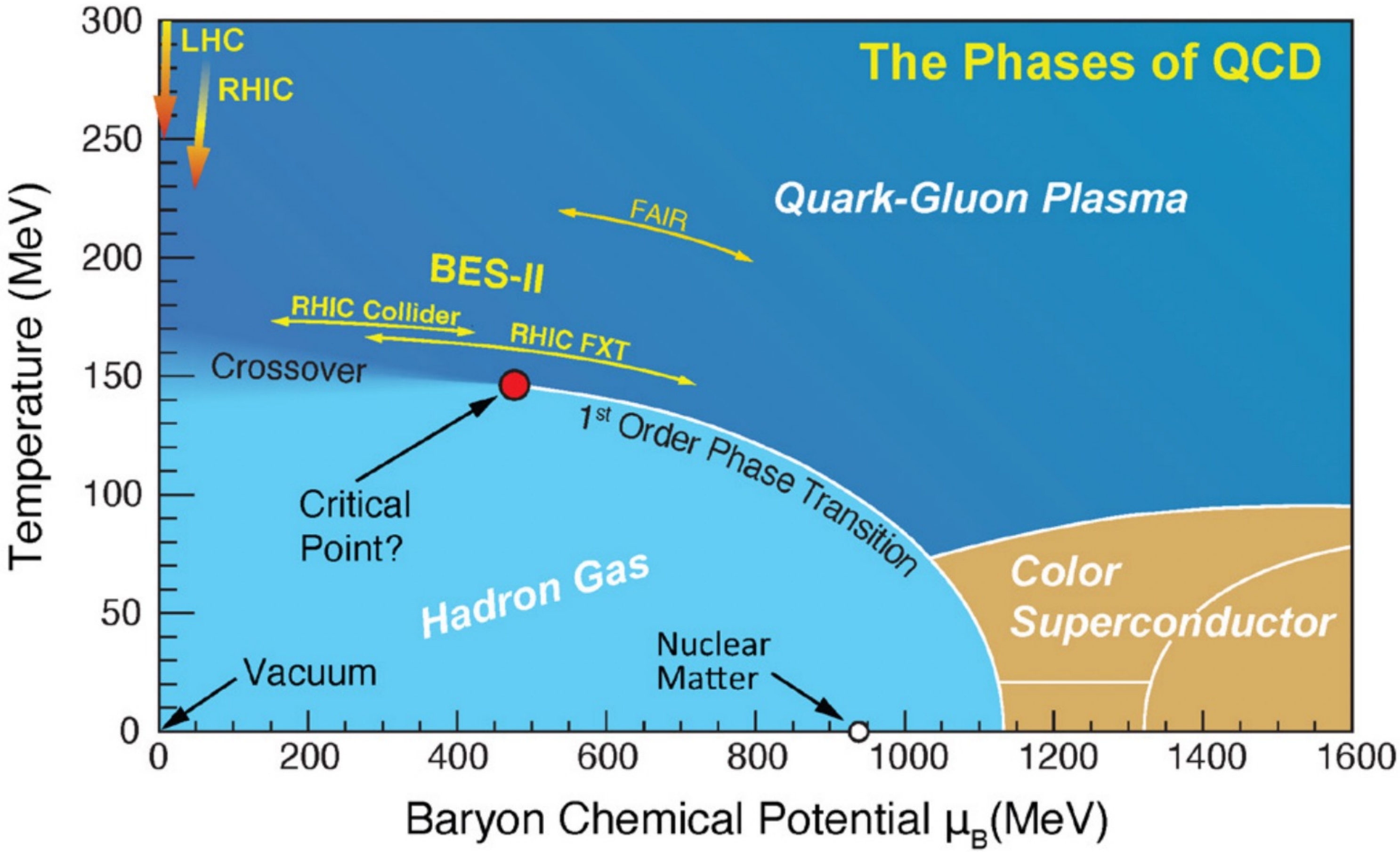


2015



QCD Phase Diagram

2023 LRP



Outline

Monday: QCD Phase Transition and QGP Properties

Tuesday: Beam Energy Scan (BES) Program and Selected Results from BES-I

Thursday: BES-II Status, Prospects and Future

Format:
Mainly Lectures
Questions any time
+ Quizzes (first two lectures)

Monday Outline

QCD and QCD Phase Transition

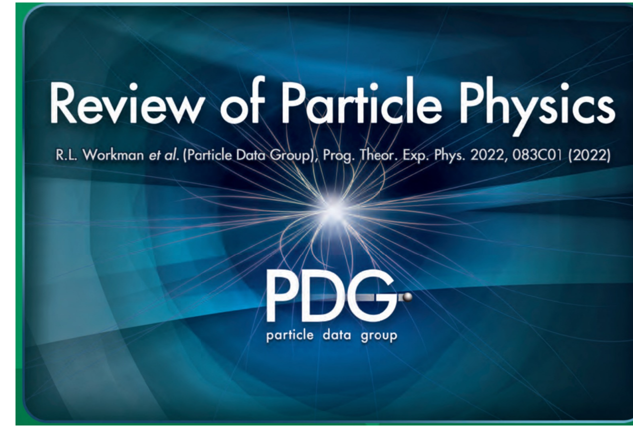
Introduction to Heavy Ion Collisions

QGP Signatures and Experimental Evidences

Recent Developments and Future Directions at $\mu_B = 0$

Quantum Chromodynamics

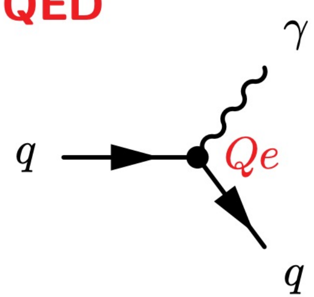
http://pdg.lbl.gov



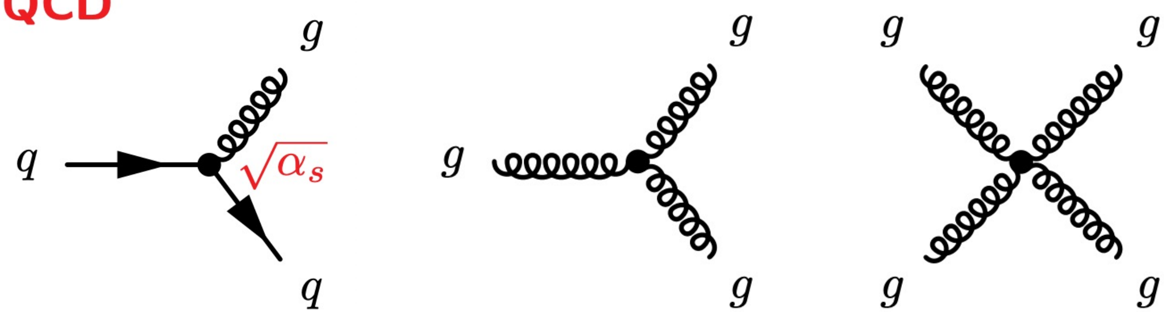
QCD – theory to describe quarks and gluons, and strong interaction between them

$$\mathcal{L}_{\mathrm{QCD}} = \bar{\psi}_i \left(i\gamma^\mu (D_\mu)_{ij} - m\,\delta_{ij}\right)\psi_j - \frac{1}{4} G^a_{\mu\nu} G^{\mu\nu}_a$$

QED



QCD



QCD is not just a stronger version of QED

QCD is a non-abelian field theory! Gluons can self-interact!

Running Coupling and Asymptotic Freedom

2004 Physics

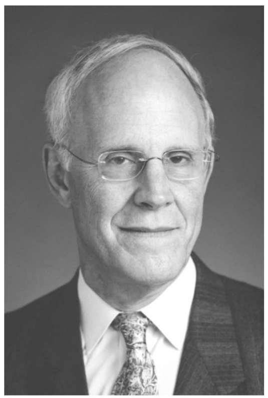


Photo from the Nobel Foundation archive.
David J. Gross
Prize share: 1/3

Photo from the Nobel Foundation archive.
H. David Politzer
Prize share: 1/3

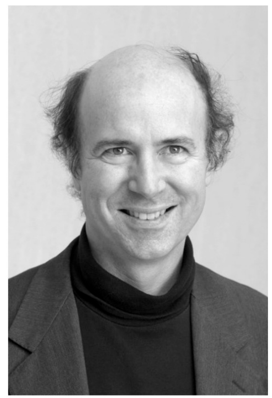
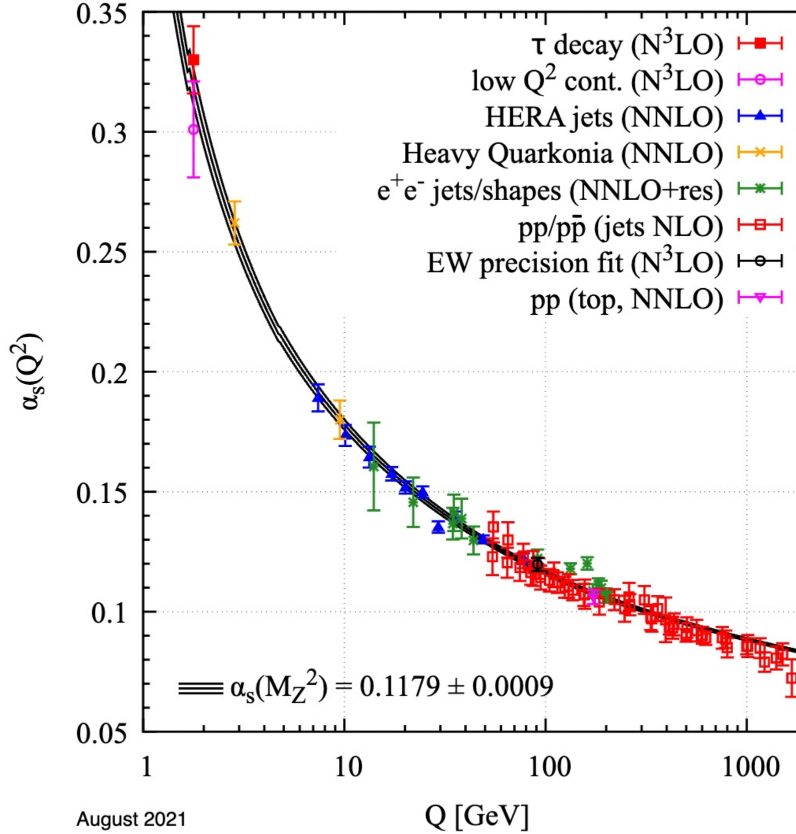


Photo from the Nobel Foundation archive.
Frank Wilczek
Prize share: 1/3

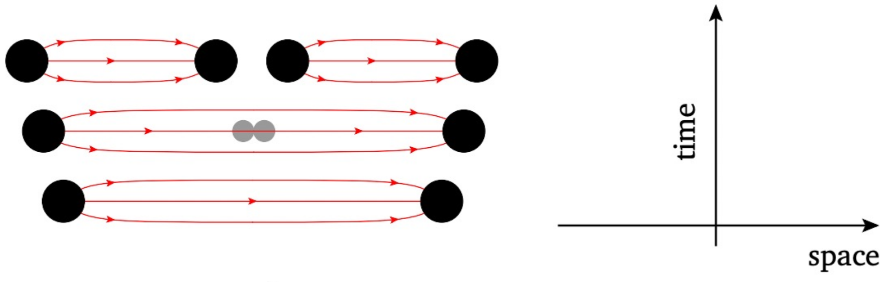
for the discovery of ***asymptotic freedom*** *in the theory of the strong interaction*

PDG 2022



QCD is calculable perturbatively at high energy scale!

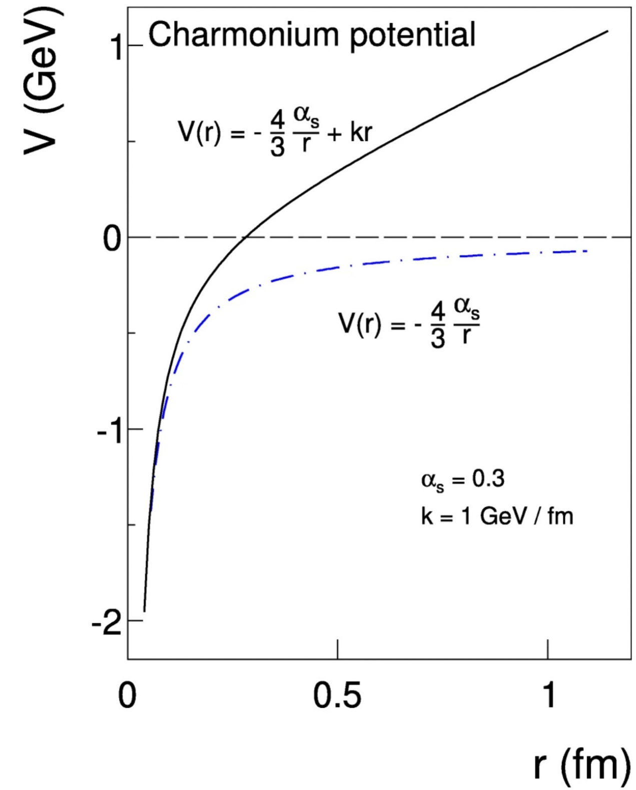
Color Confinement



$$V_{\rm QCD} = -\frac{4}{3}\frac{\alpha_s}{r} + kr$$

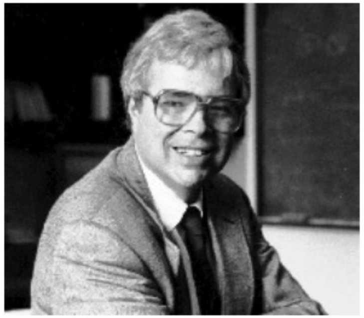
Coulomb-like interaction

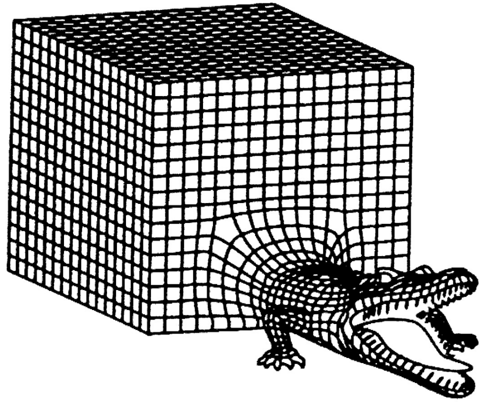
Confinement



Color confinement / hadronization is non-perburbative and remains a challenge in QCD!

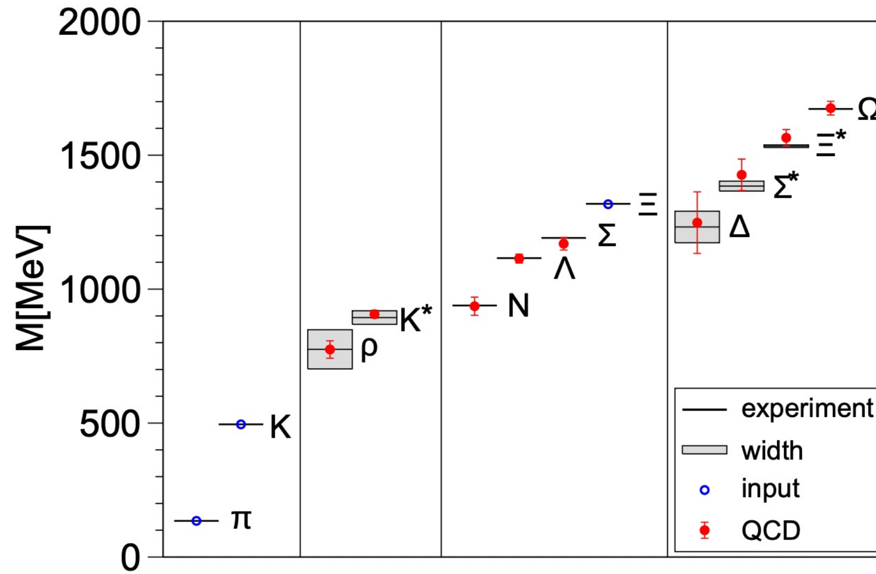
Lattice QCD





Kenneth Wilson suggested 1974 to regularize QCD by introducing a 4-d (Euclidean) space-time lattice.

K. Wilson, PRD10 (1974) 2445



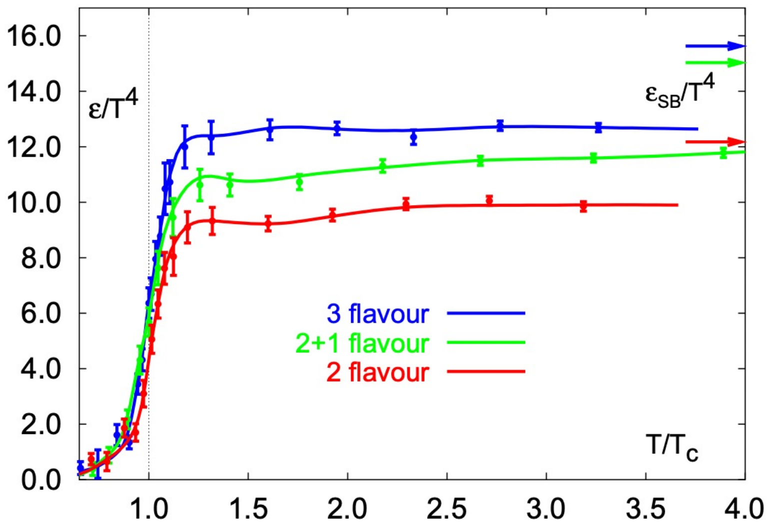
S. Durr et al, Science 322 (2008) 1224

- 4D Euclidean lattice → continuum limit
- Choice of mass scale → physical mass
- QCD gauge fields → q/g and 2+(1)+(1) QCD
- Monte Carlo technique → statistics with super computer

Lattice QCD calculations often considered as the first-principle results!

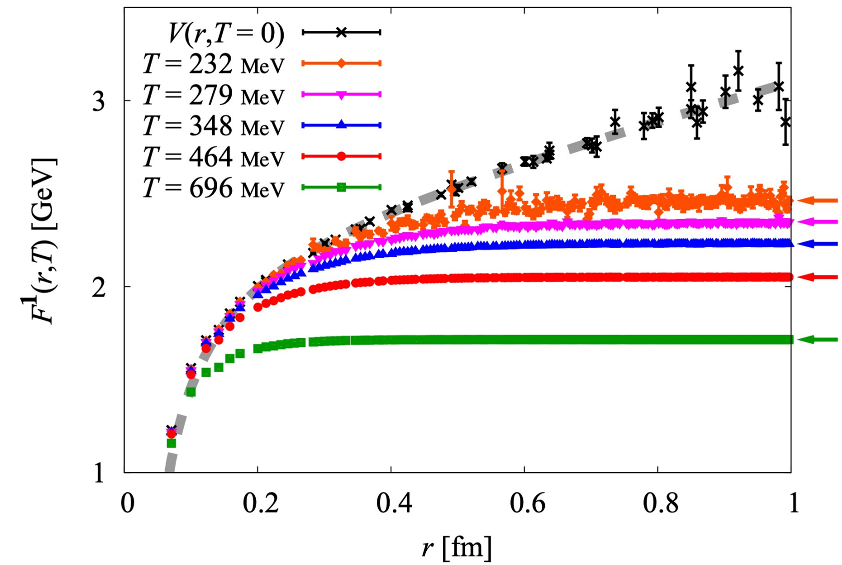
Deconfinement – QCD Phase Transition

Lattice QCD on thermodynamical parameters



F. Karsch et al., PLB 478 (2000) 447

Lattice QCD on QQbar free energy



CP-PACS and JLQCD Coll. PRD 78 (2008) 011502

Lattice QCD calculations predict a phase transition at sufficiently high temperature

QCD Phase Transition Temperature

Ideal gas of quark-gluon system in thermal equilibrium:

Pion Gas | Quark Gluon Plasma

$$P = g_H \frac{\pi^2}{90} T^4 \quad \overset{\text{at phase transition}}{=\!=} \quad P = g_{QGP} \frac{\pi^2}{90} T^4 - B$$

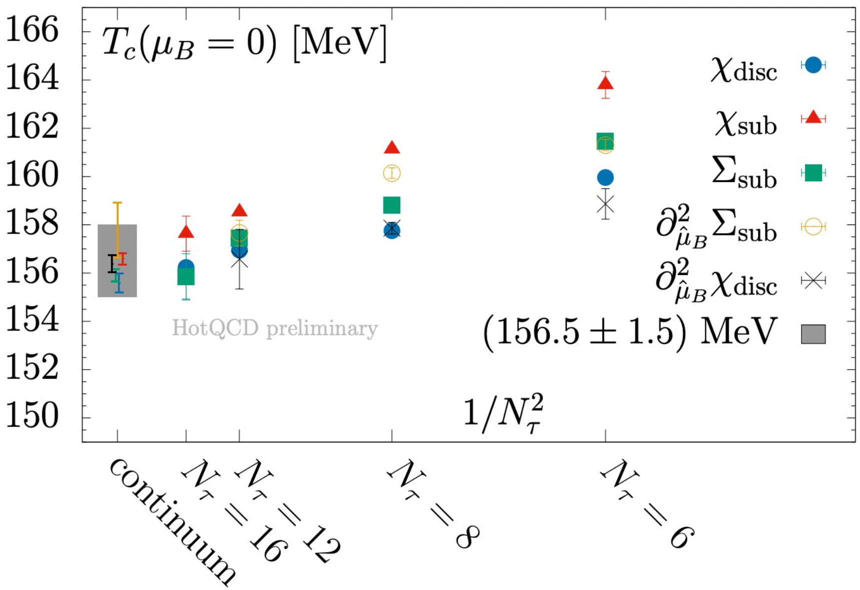
$$g_H = 3, \qquad g_{QGP} = \frac{7}{8}(g_q + g_{\bar{q}}) + g_g = \frac{7}{8} N_c N_s N_f \times 2 + (N_c^2 - 1) N_s = 37$$

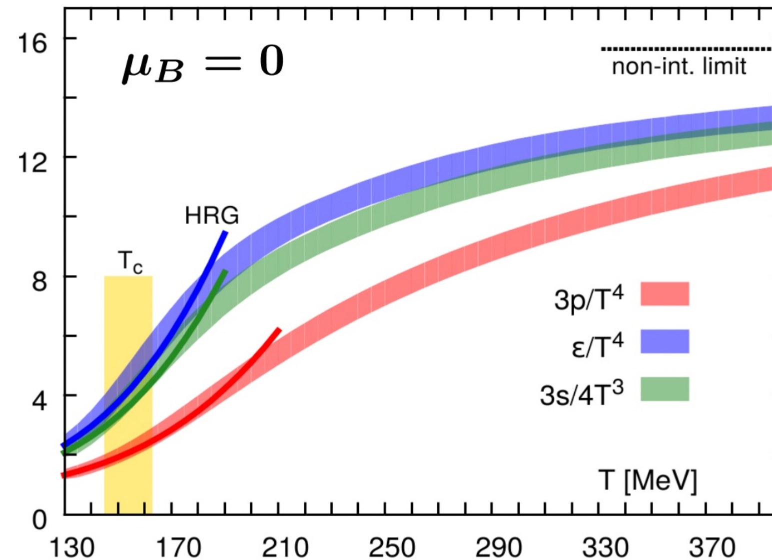
B: "bag" constant. $B^{1/4}$ ~ 200 MeV estimated from 3-quark proton radius

$$T_c = \left(B \frac{90}{\pi^2 \Delta g}\right)^{1/4} \sim 144 \text{ MeV}$$

Quiz: Estimate ideal QGP gas energy density at T = 200 MeV

T_c and Equation-of-State from Lattice QCD





(2+1) flavor
Physical quark mass
Continuum extrapolation

Lattice QCD predicts at μ_B= 0:
$T_c = 156.5 \pm 1.5$ MeV
cross over phase transition

HotQCD, arXiv;1807.05607

Introduction to Heavy Ion Collisions

Heavy Ion Collisions

Nuclear matter energy density

$$\epsilon_N = \frac{Am_u}{4\pi/3R^3} = \frac{m_u}{4\pi/3r_0^3} \approx 0.16 \text{ GeV/fm}^3$$

$$R = r_0 \cdot A^{1/3}$$
$$m_u = 0.9315 \text{ GeV}$$
$$r_0 = 1.12 \text{ fm}$$

Recall: energy density for ideal QGP gas at 200 MeV: 2.5 GeV/fm^3

Initial energy density

$$\epsilon_0 = \frac{< m_\perp > (dN/dy)^{AA}}{V_0} \simeq 0.1 A^{\alpha - 2/3} \ln\left(\frac{\sqrt{s}}{2m_p}\right) \text{ GeV/fm}^3$$

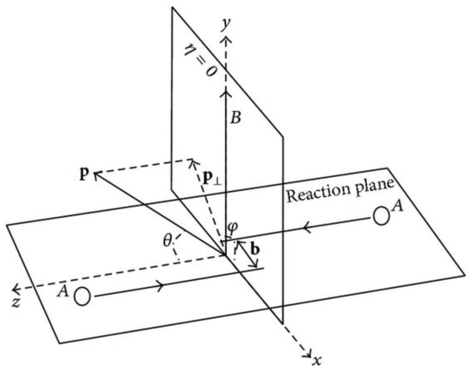
Z. Lin, Ph.D. Thesis, 1996

High energy heavy ion collisions: an effective way to reach high energy density

Initial Bjorken energy density $\epsilon_{Bj} = \frac{1}{A_\perp \tau}\frac{dE_T}{dy}$

RHIC (200 GeV): **~ 5 GeV/fm^3** in central Au+Au collisions

Kinematics



rapidity

$$y \equiv \frac{1}{2} \ln \frac{E + p_z}{E - p_z}$$

pseudo-rapidity

$$\eta \equiv \frac{1}{2} \ln \frac{p + p_z}{p - p_z}$$

Invariant cross-section/yield:

$$E\frac{d^3\sigma}{dp^3} = \frac{d\sigma}{2\pi p_T dp_T dy d\phi} = \frac{d\sigma}{2\pi m_T dm_T dy d\phi}$$

Natural unit: $\hbar = c = kB = 1$ $\hbar c$ = 197.3 MeV · fm

Collision energy:

Center-of-mass (CoM) energy per nucleon-nucleon pair: $\sqrt{s_{\rm NN}}$

Fixed-target: single beam energy (E_b) / kinetic energy ($T=E_b-m_u$)

SPS energy 158 **A GeV** ← kinetic energy

Quiz: SPS 158 A GeV (T) and RHIC 3.85 GeV (E_b) ➜ CoM $\sqrt{s_{\rm NN}}$?

Quiz: Show y is additive in Lorentz transformation, and $Ed^3\sigma/dp^3$ is boost-invariant.

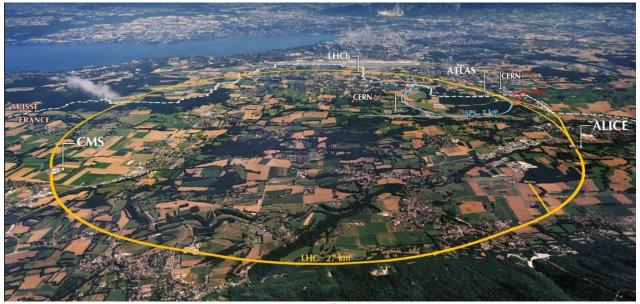
Quiz: QCD T_c @ □$_B$=0 in standard unit (Kelvin).

Major Heavy Ion Collision Facilities

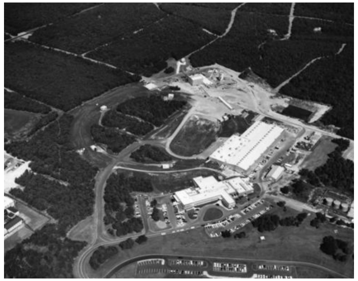
Bevalac (~ 2 GeV)

SPS (~ 17 GeV)

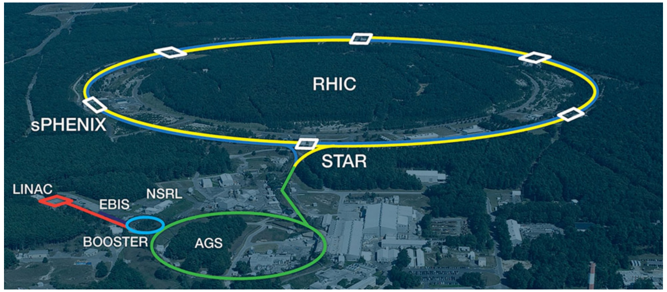
LHC (~ 2760 - 5500 GeV)



1980 1990 2000 2010 2020



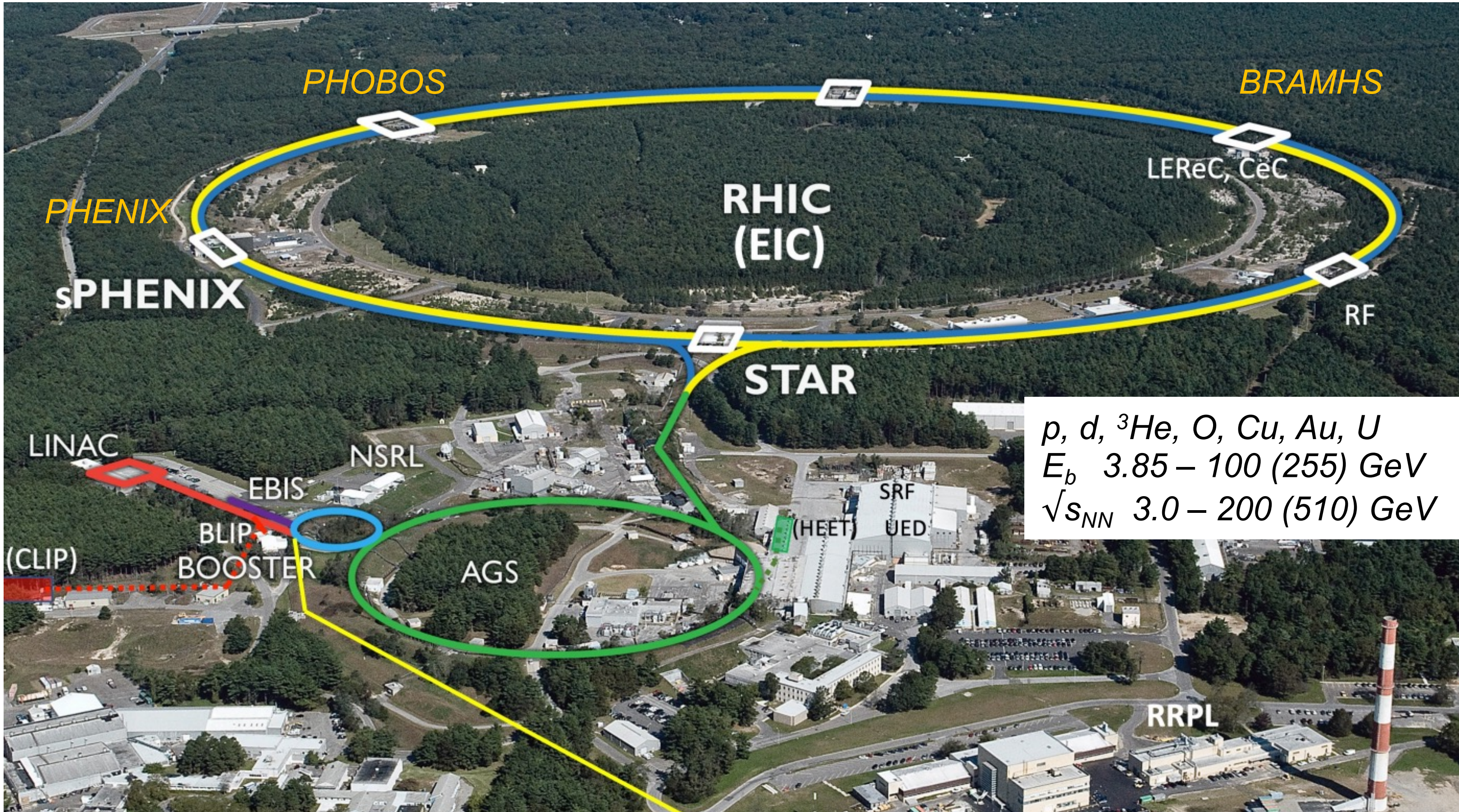
AGS (~ 8 GeV)



RHIC (3 - 200 GeV)

FAIR (2-5 GeV)

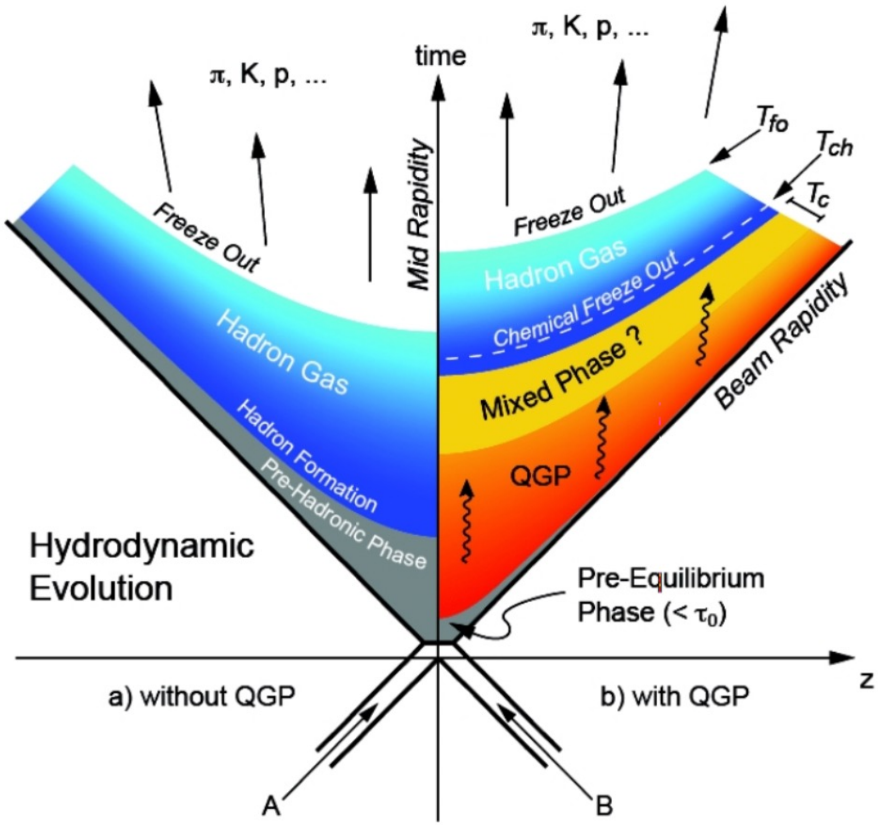
Relativistic Heavy Ion Collider



p, d, ^{3}He, O, Cu, Au, U
E_b 3.85 – 100 (255) GeV
$\sqrt{s_{NN}}$ 3.0 – 200 (510) GeV

Quiz: Estimate how much gold does RHIC smash every RHIC-Run (~6 months).
- 10^9 ions per bunch, ~100 bunches per store (avg. 8 hr), down time ~50%

Heavy Ion Collision Evolution



<u>RHIC 200 GeV collisions:</u>

Two nuclei collide

passage time: $2R/\gamma \sim 0.1$ fm/c

Pre-equilibrium: < 1 fm/c

QGP evolution: ~ 5-10 fm/c

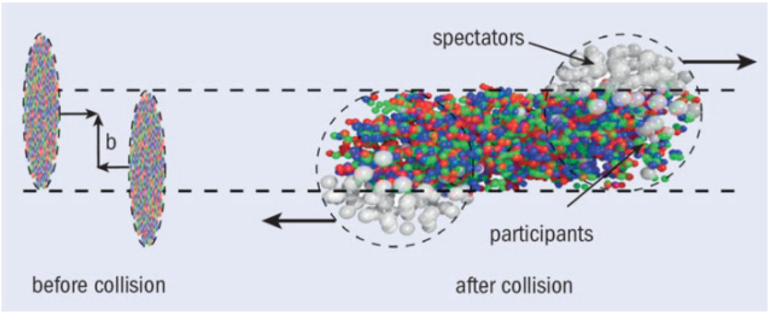
Hadronization:

Hadron gas evolution:

chemical freeze-out

kinetic freeze-out ~ 10-20 fm/c

Heavy Ion Collisions - Geometry



Number of participants: N_{part}

Number of binary collisions: N_{bin} or N_{coll}

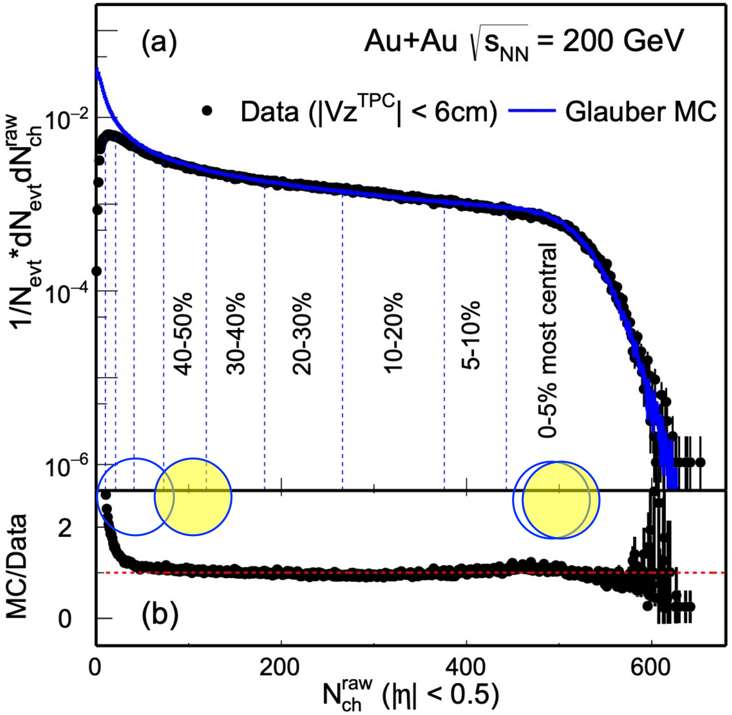
Collision centrality

ideally to trace impact parameter

Experimentally determined through final state multiplicity distributions and a fit to Glauber Model calculations:

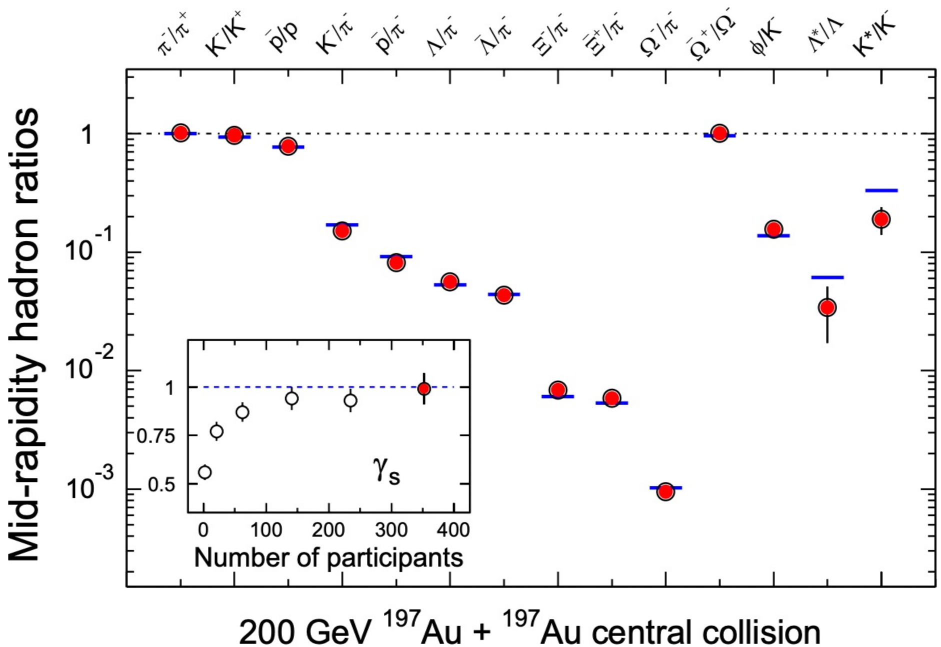
centrality classes / bias

N_{part} and N_{bin} etc.



Chemical Freeze-out

Chemical FO: inelastic collisions cease and particle yields freeze
FO parameters extracted through thermal model fit to particle yield (ratio)



Thermal model description:

Grand Canonical Ensemble:
quantum numbers conversed on average

$$N_i^{GC} = \frac{g_i V}{2\pi^2} \sum_{k=1}^{\infty} (\mp 1)^{k+1} \frac{m_i^2 T}{k} K_2\left(\frac{k m_i}{T}\right) e^{\beta k \mu_i}$$

$$\mu_i = B_i \mu_B + S_i \mu_S + Q_i \mu_Q, \qquad \beta \equiv 1/T$$

Canonical Ensemble:
quantum numbers conversed event-by-event

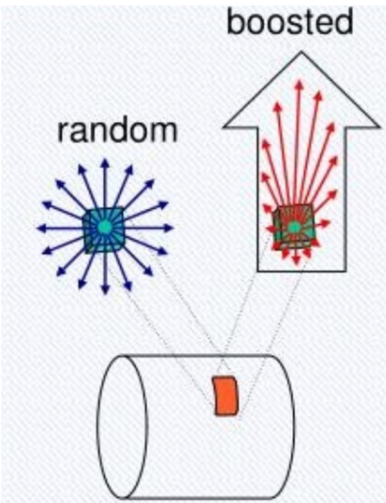
Complications: Ensemble applicability / Feed-down contributions

Quiz: pbar/p ~ 0.8 at 200 GeV, determine □$_B$ (ignore □$_S$, □$_Q$ and T_{ch} = 160 MeV).

Kinetic Freeze-out

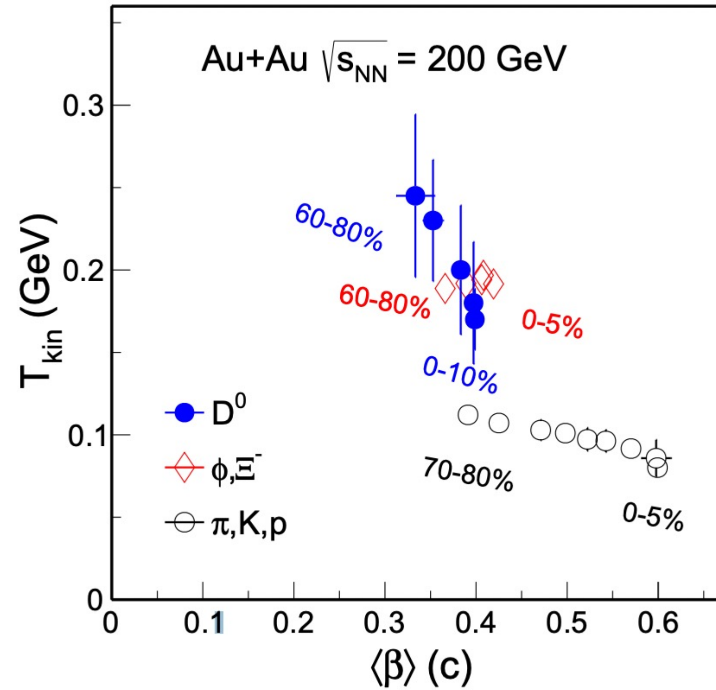
Kinetic FO: elastic collisions cease and particle momenta freeze
FO parameters extracted through Blast Wave model fit to particle p_T spectra

$$\frac{dN}{m_T dm_T} \propto \int_0^R r dr m_T I_0(\frac{p_T \sinh\rho}{T}) K_1(\frac{m_T \cosh\rho}{T})$$



$$\rho = \tanh^{-1}\beta_r$$

$$\beta_r(r) = \beta_s(\frac{r}{R})^n$$

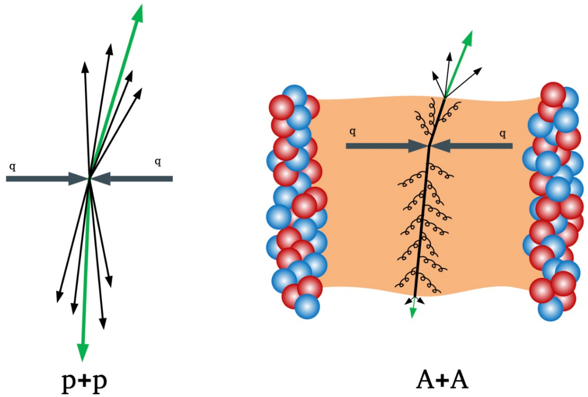


Multi-strange/charm hadrons freeze-out earlier than light hadrons
- FO temperature close to T_c

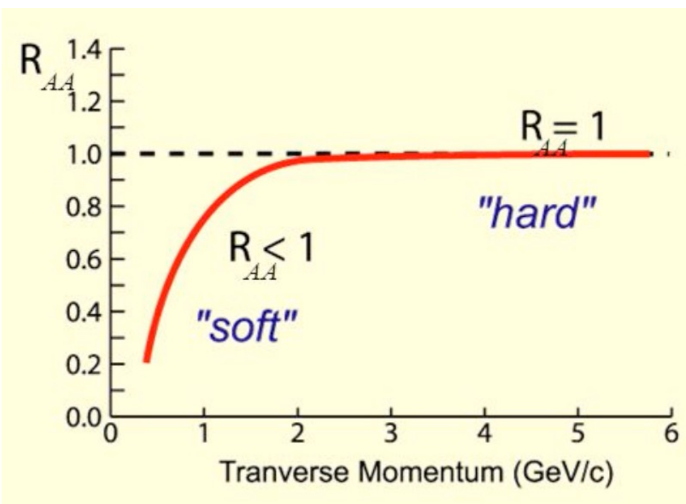
QGP Signatures and

Experimental Evidences

Jet Quenching in QGP Medium



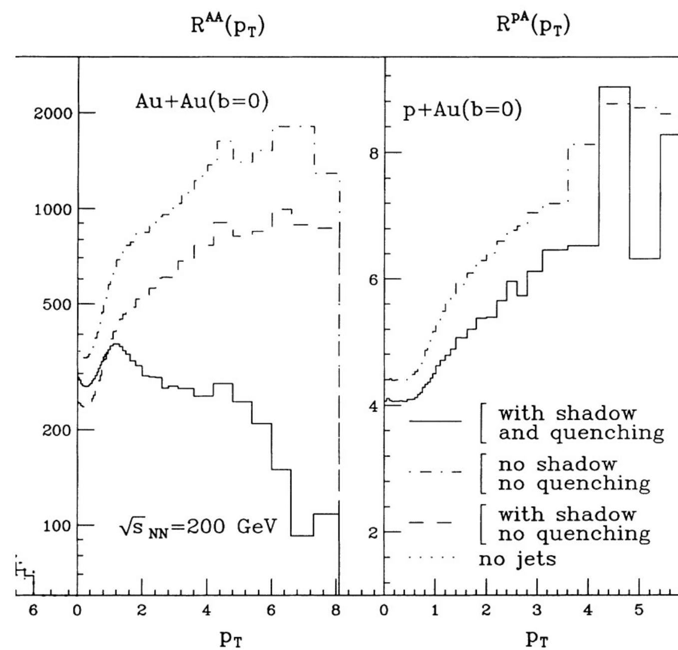
$$R_{AA}(p_T) = \frac{d^2N_{AA}/d\eta dp_T}{\langle N_{coll}\rangle\, d^2N_{pp}/d\eta dp_T}$$



No medium effect

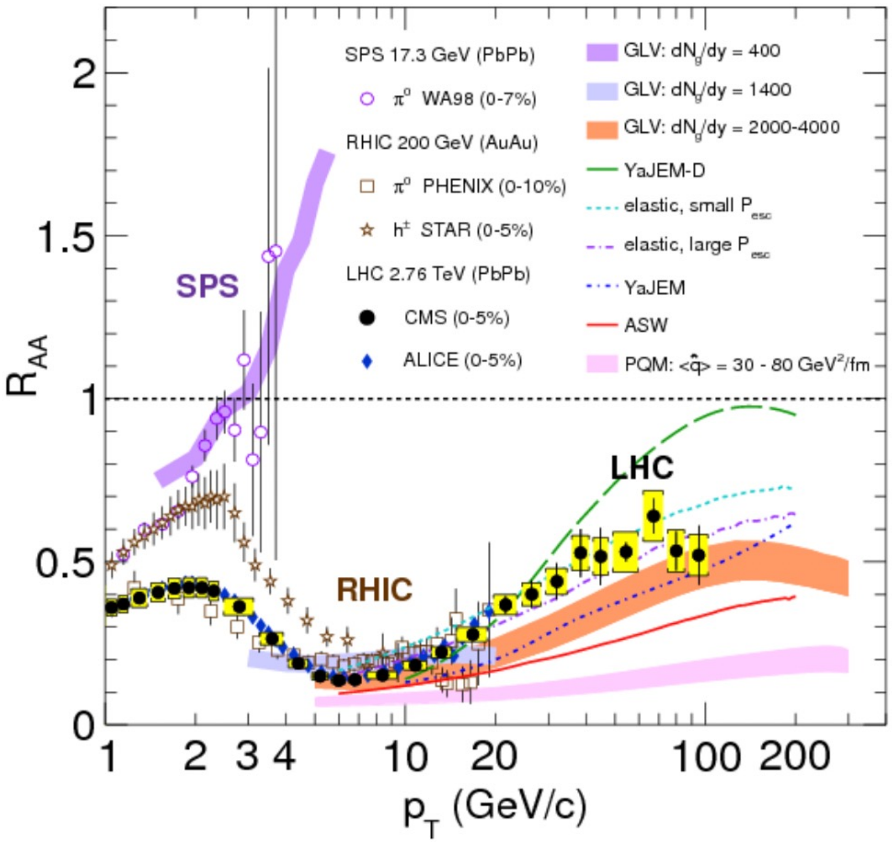
Medium energy loss

X.N. Wang and M. Gyulassy, PRL 68 (1992) 1480



QGP drags/quenches fast moving partons!

QGP Signature – Jet Quenching



SPS: R_{AA} increases with p_T

RHIC/LHC:

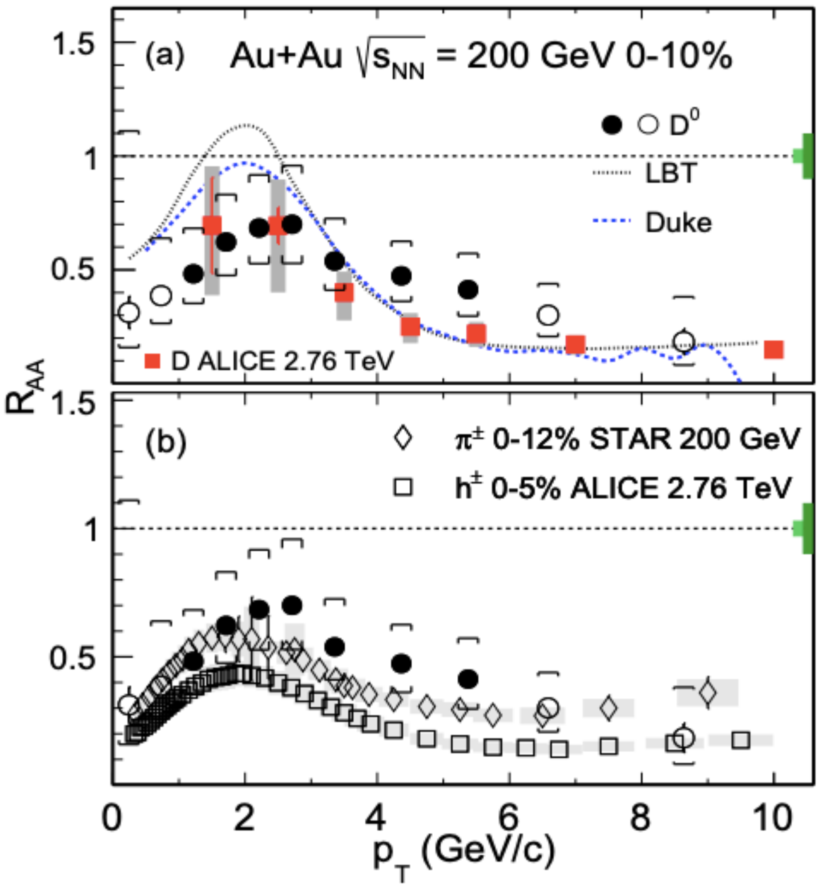
$R_{AA} \sim 0.1 – 0.2$ at $p_T > 6$ GeV/c

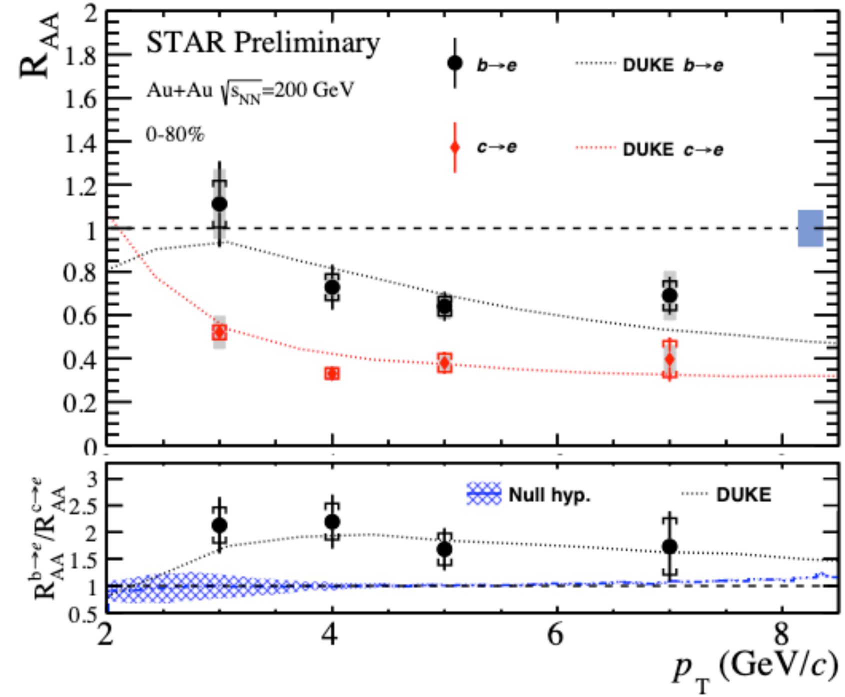
Suppression due to hot and dense medium – QGP signature

pQCD works reasonably well in describing the large suppression of R_{AA}

Quiz: pQCD $\sigma \propto 1/p_T^6$, assuming $R_{AA} = 0.2$ flat, what is the equivalent Δp_T?

Mass/Flavor Dependence of Parton Energy Loss





$$R_{\mathrm{AA}}(D) \sim R_{\mathrm{AA}}(h)$$

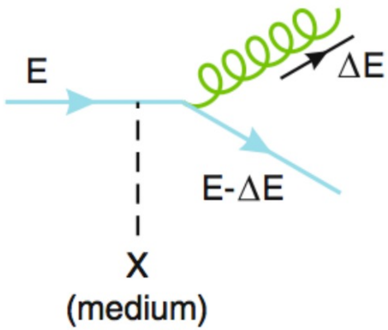
$$R_{\mathrm{AA}}(e_b) > R_{\mathrm{AA}}(e_c)$$

consistent with energy loss hierarchy

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$$

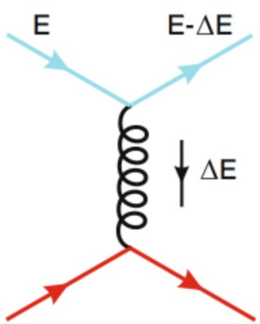
Parton Energy Loss

radiative energy loss



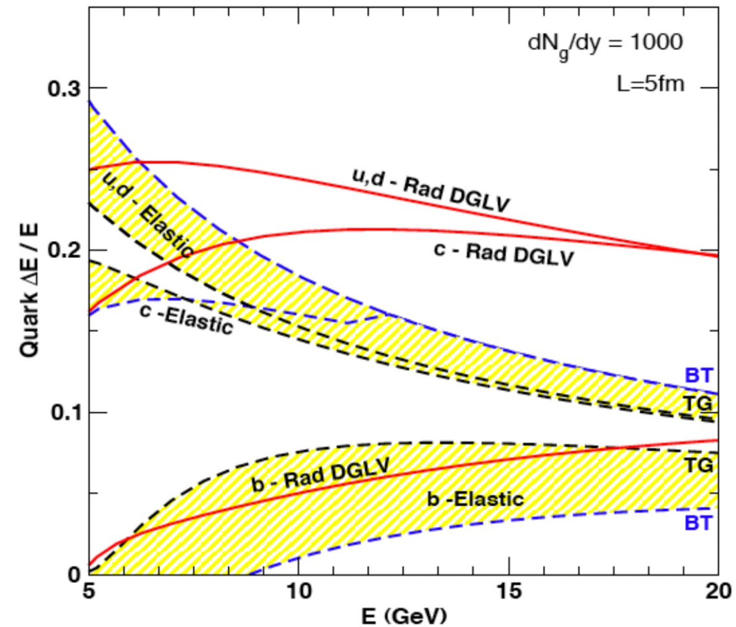
dominate at high p_T
coherence effect
L^2-dependence

collisional (elastic) energy loss



dominate at low p_T

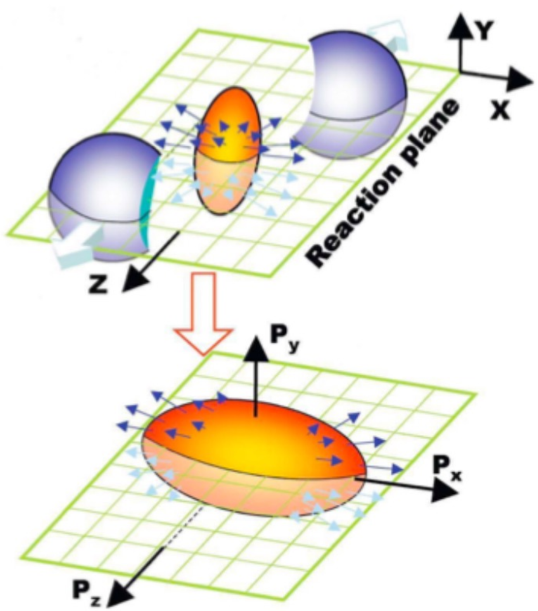
radiative energy loss for heavy quarks suppressed due to “dead-cone” effect



Energy loss hierarchy for both radiative and collisional energy loss

$$\Delta E_g > \Delta E_q > \Delta E_c > \Delta E_b$$

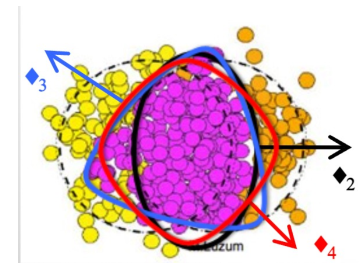
Collective Flows



$$E\frac{d^3N}{dp^3} = \frac{d^2N}{2\pi p_T dp_T dy}(1 + \sum_{n=1}^{\infty} 2v_n cos[n(\phi - \Psi_{rp})])$$

$$v_n = \langle cos[n(\phi - \Psi_{rp})]\rangle$$

v_0: radial flow
v_1: directed flow
v_2: elliptic flow
v_3: triangular flow
$v_{4,5,6}\cdots$



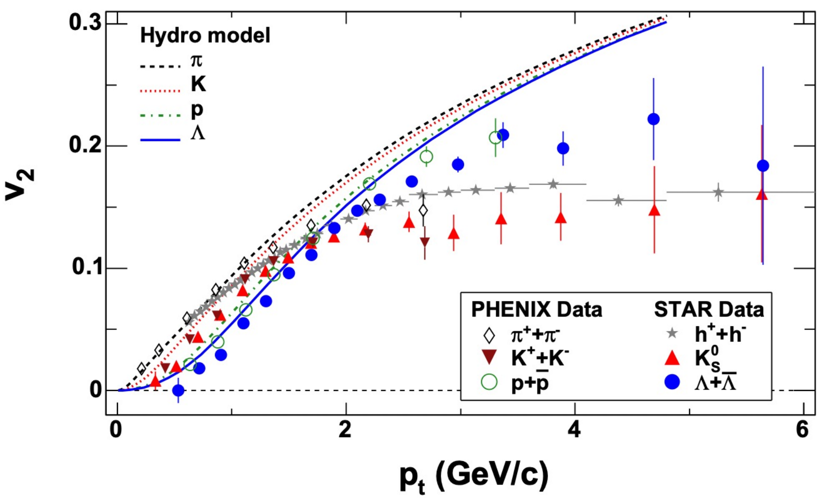
pressure gradient / Equation-of-State

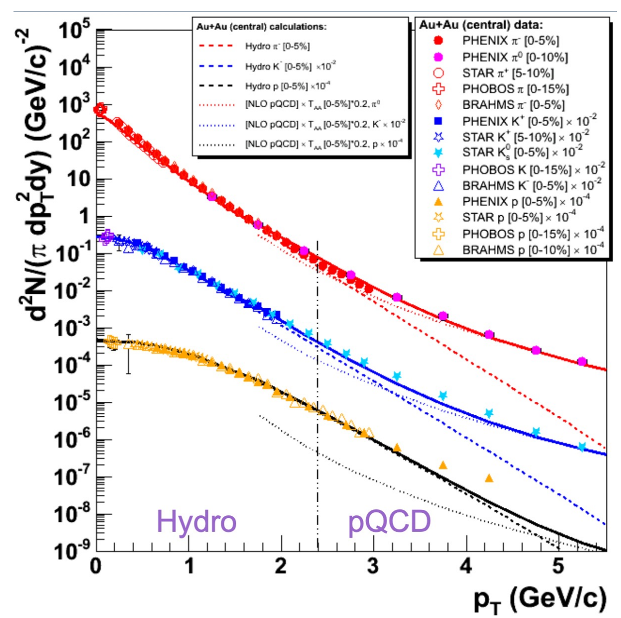
Geometry anisotropy → Momentum anisotropy

QGP pushes partons to flow!

Hydrodynamics

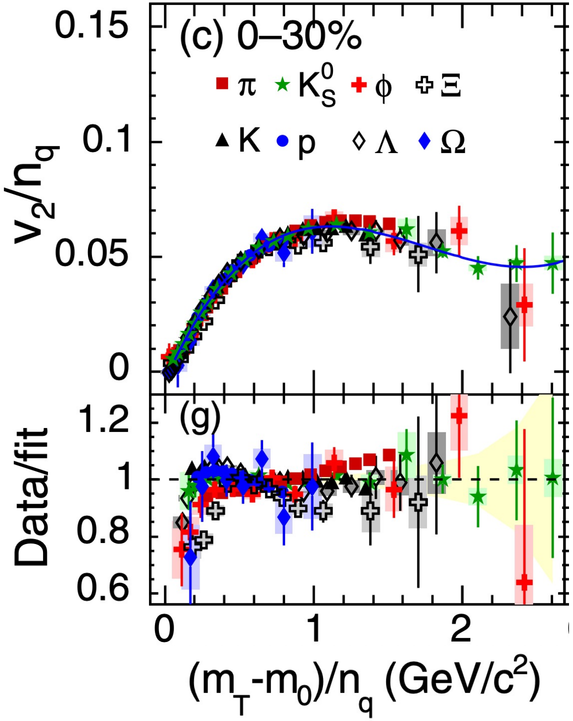
Energy-momentum conservation	$\partial_\mu T^{\mu\nu}(x) = 0$ $T^{\mu\nu} = eu^\mu u^\nu - (p + \Pi)\Delta^{\mu\nu} + \pi^{\mu\nu}$
Equation-of-State	Lattice input for $\square_B = 0$
Initial and freeze-out conditions	Glauber/CGC(in), Cooper-Fryer(out)

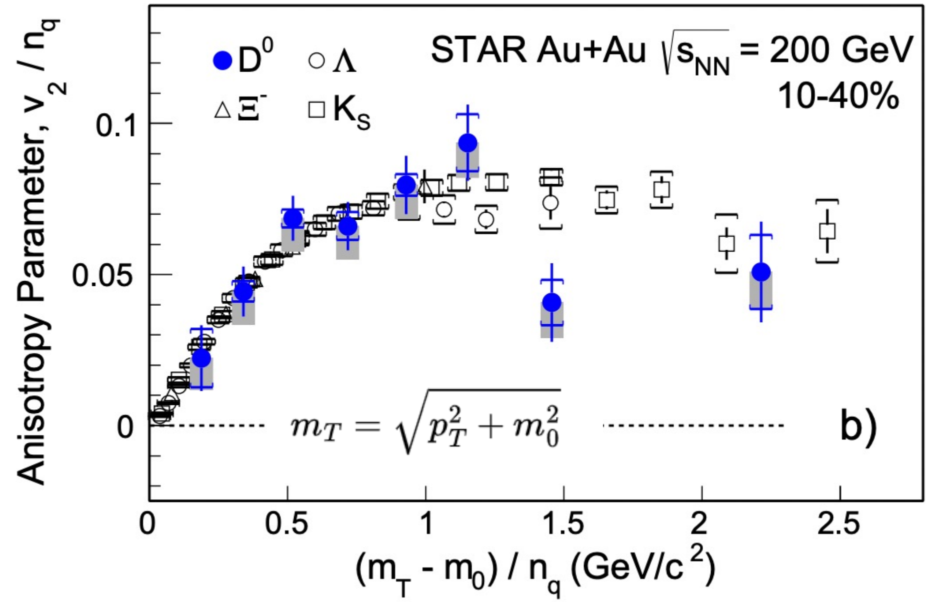




Hydrodynamic model describes low p_T spectra and v_2 well!

QGP Signature - Partonic Collectivity



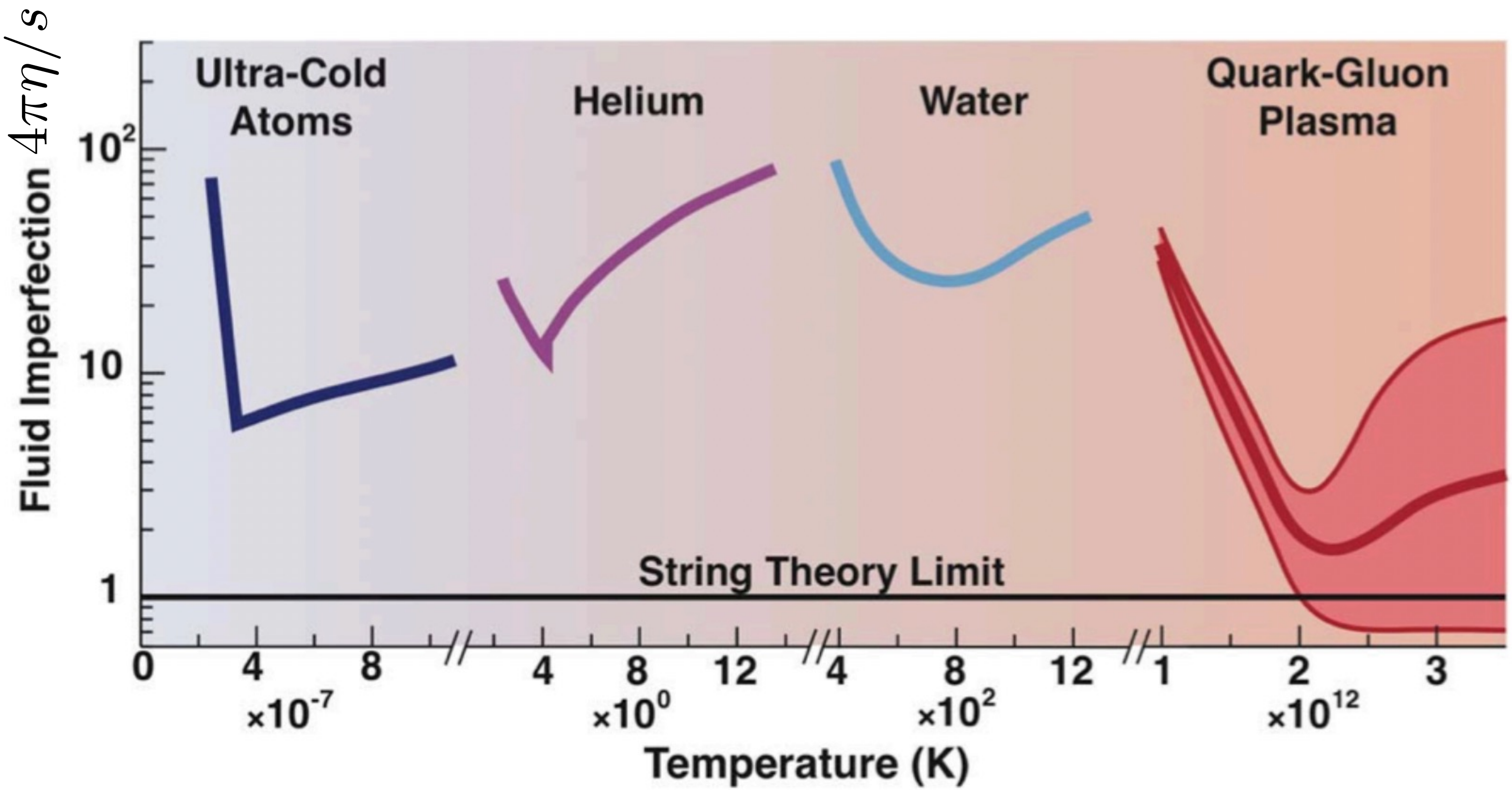


STAR, PRL 116 (2016) 062301, PRL 118 (2017) 112301

v_2 of light, strange and charm hadrons follow the same universal trend
- low p_T: mass ordering → hydrodynamic behavior
- intermediate p_T: Number-of-Constituent-Quark (NCQ, n_q) scaling

Partonic Collectivity

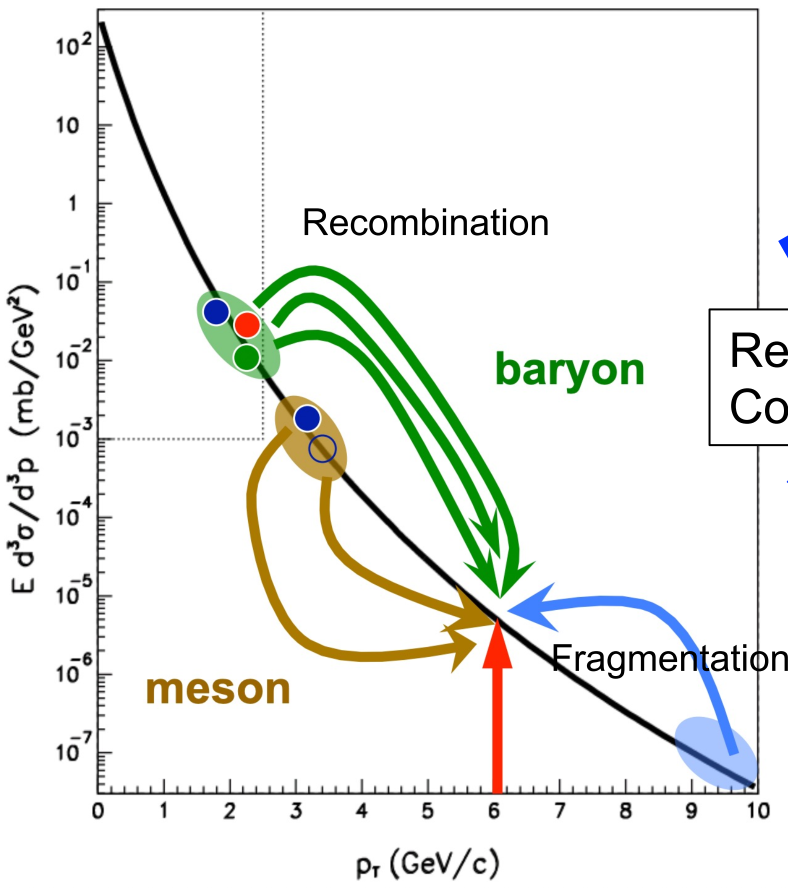
Shear Viscosity-to-entropy Ratio



$$1 < 4\pi\frac{\eta}{s} < 2.5$$

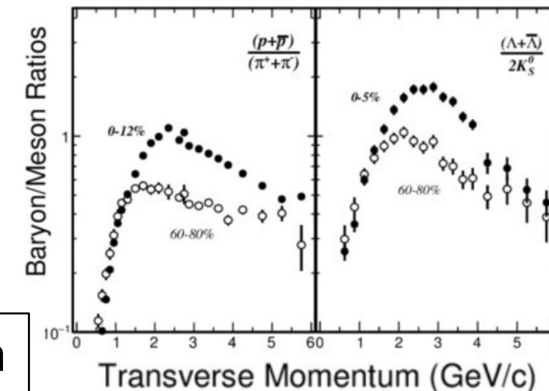
Quantum bound suggested by AdS/CFT

Quark Recombination / Coalescence

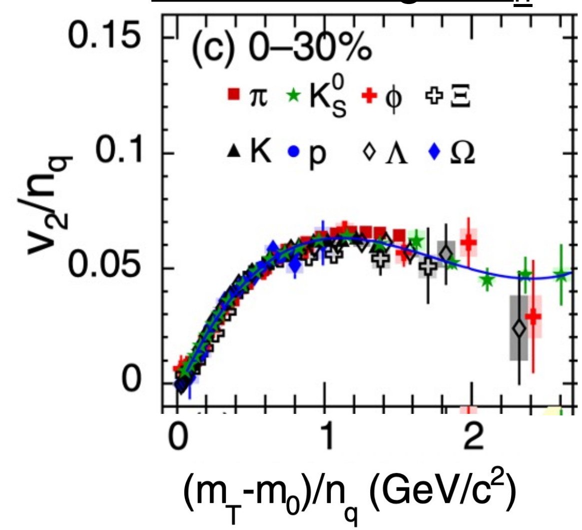


Recombination
Coalescence

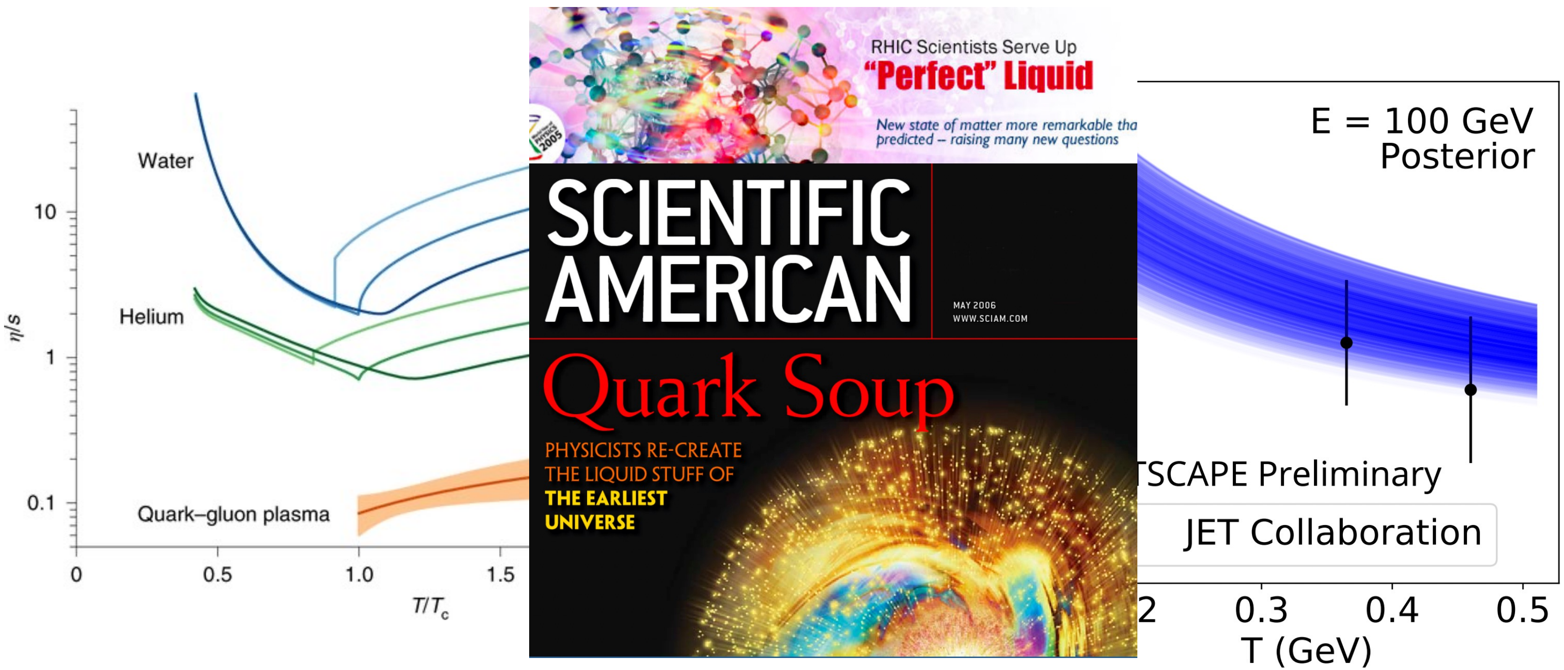
enhancement in baryon/meson ratio



NCQ-scaling of v_n



Perfect Liquid / sQGP



J.E. Bernhard et. al, Nature Physics 15 (2019) 1113

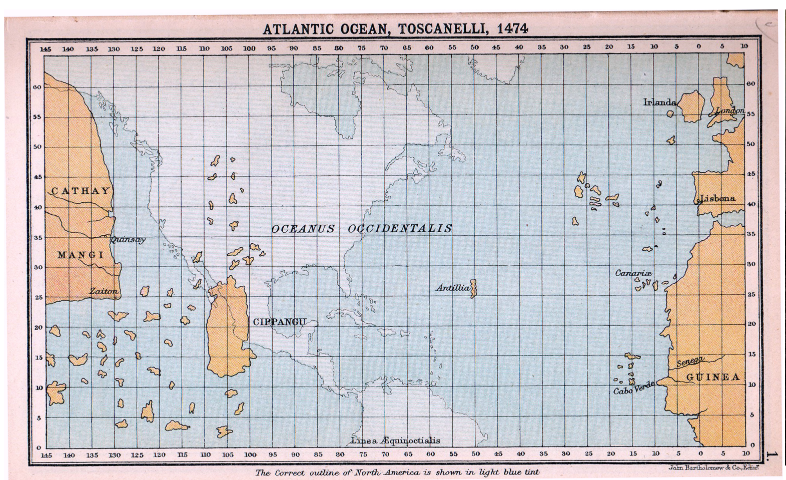
JETSCAPE, QM23

What is discovered is not what you planned

Strongly-interacting liquid - sQGP ⟷ Weakly-interacting gas - wQGP

Columbus's Discovery of America

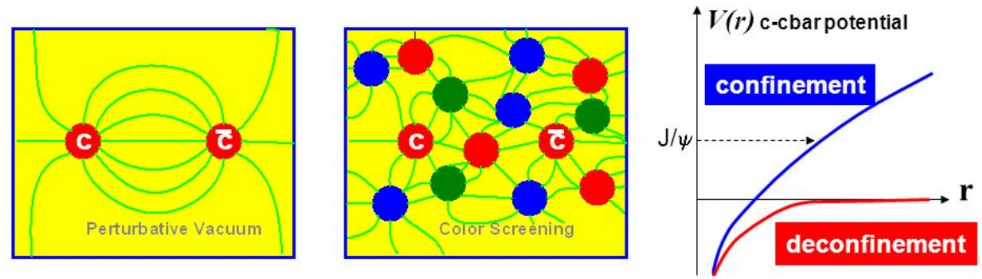
America ⟷ Asia

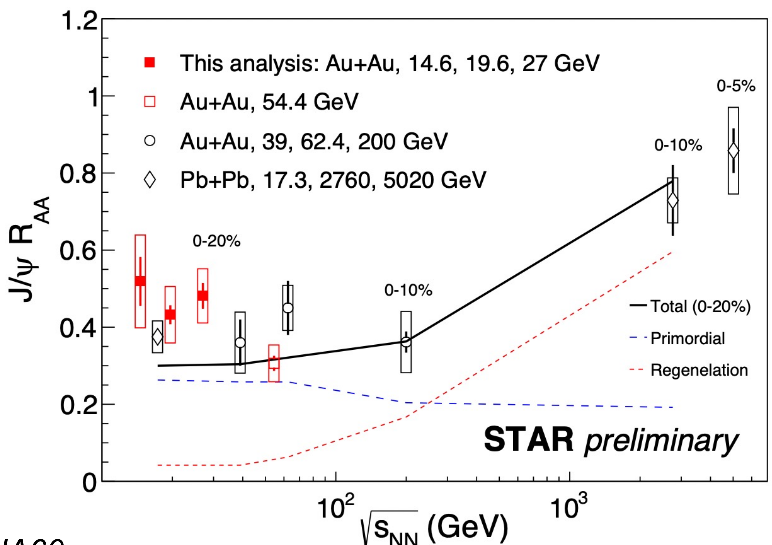


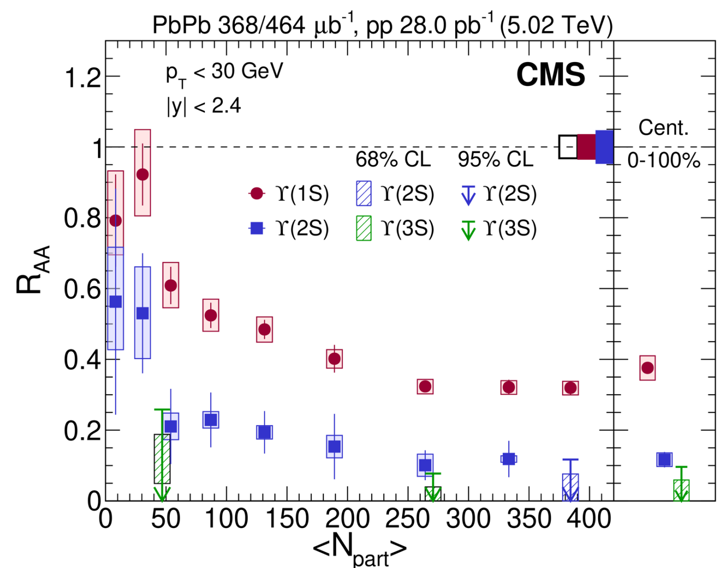
QGP Evidence – Quarkonia Suppression

T. Masui and H. Satz, PLB 178 (1986) 416

Quarkonia suppression in QGP medium due to color screening
- smoking-gun for deconfined medium







NA60
STAR
ALICE

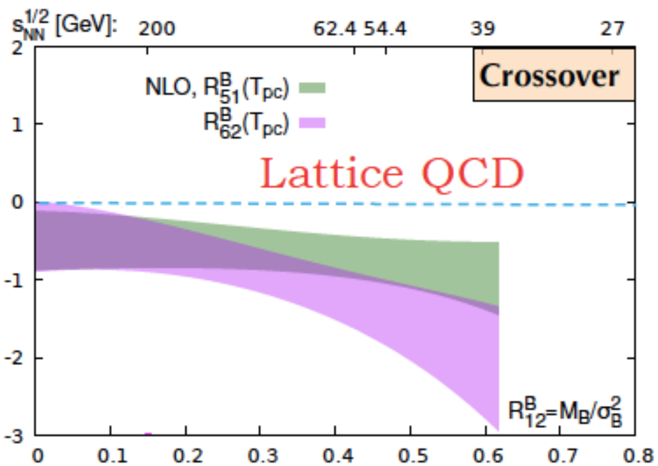
CMS, PLB 790 (2019) 270

Sequential suppression of different quarkonium states – Strong evidence of color screening due to sQGP

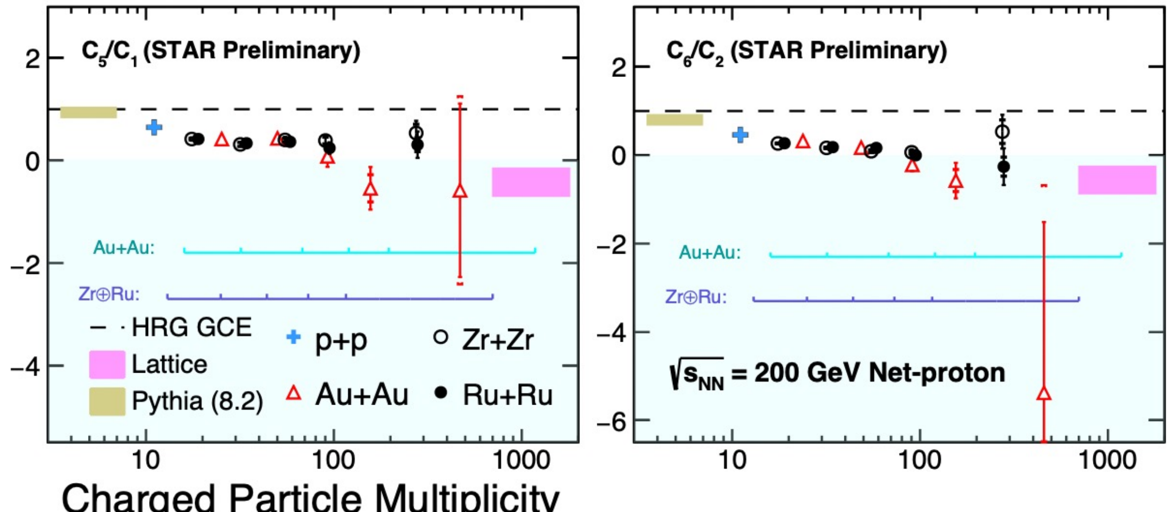
QGP Evidence – Net-Proton Cumulant Ratios

Multiplicity cumulants
→ susceptibilities of conserved quantities
Calculable in Lattice QCD

$$\delta N = N - \langle N \rangle \quad C_1 = \langle N \rangle, C_2 = \left\langle (\delta N)^2 \right\rangle$$
$$C_3 = \left\langle (\delta N)^3 \right\rangle, C_4 = \left\langle (\delta N)^4 \right\rangle - 3\left\langle (\delta N)^2 \right\rangle^2$$
$$C_2 = \sigma^2, \;\; S = C_3/(C_2)^{3/2}, \kappa = C_4/(C_2)^2$$



HotQCD, PRD101 (2020) 074502
Wei-jie Fu et. al, PRD 104 (2021) 094041



STAR, PRL 127 (2021) 262301, SQM 2022

Net-proton cumulant ratios decrease as multiplicity increases
→ consistent with Lattice QCD for thermalization + crossover transition

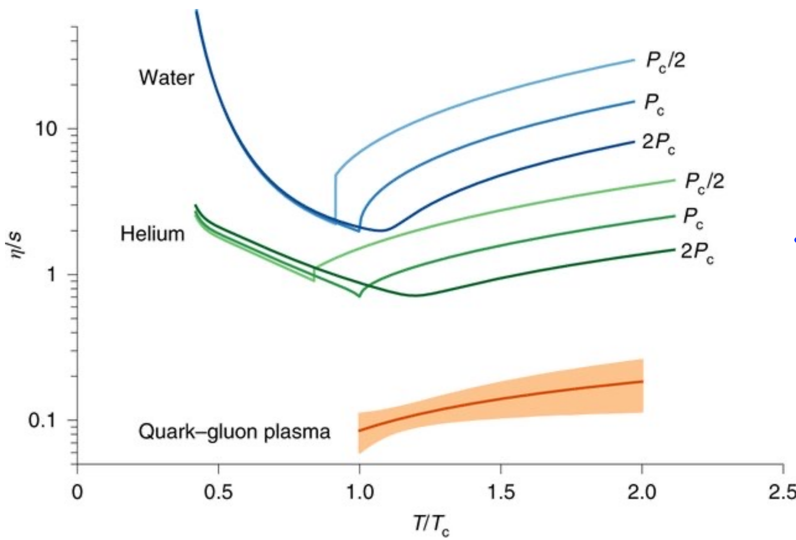
Recent Developments and

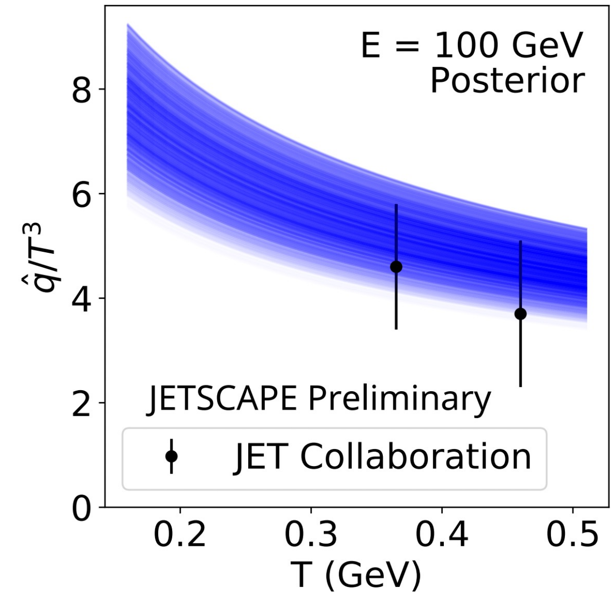
Future Directions at $\square_B = 0$

Properties of sQGP

~2 ~6 p_T (GeV/c)

hydrodynamics coalescence pQCD

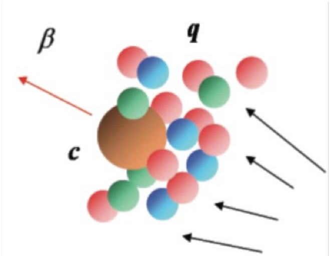




Precision determination of sQGP properties (T, p-dep etc.) and their relations

$$\eta/s, \hat{q}, \hat{e}, \mathcal{D}_s, \sigma_{\mathrm{EM}} \ \ldots$$

Future Direction: Heavy Quark Transport in sQGP



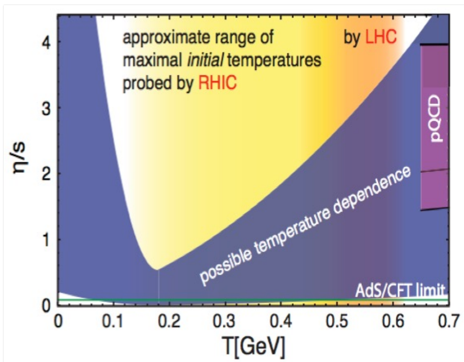
Femtoscopic "Brownian" motion

$$\frac{d\vec{p}}{dt} = -\eta_D(p)\vec{p} + \vec{\xi}$$

Langevin stochastic simulation

$M_Q >> T,\ M_Q >> gT$

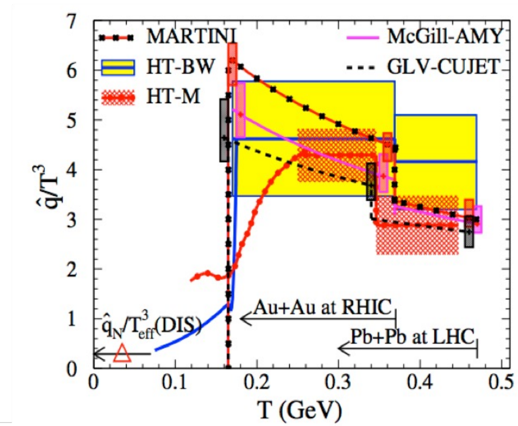
$$D_s \equiv \frac{\langle x^2(t)\rangle - \langle x^2(0)\rangle}{2dt} = \frac{t}{M\eta_D(p=0)}$$



$$D_s(2\pi T) \sim \eta/s$$

ratio depends on the strong/weak coupling nature of QGP

R. Rapp and H. van Hees, 0903.1096



$$\hat{q} = \frac{\Delta p_T^2}{\lambda} = \frac{4D_p E_p}{p}$$

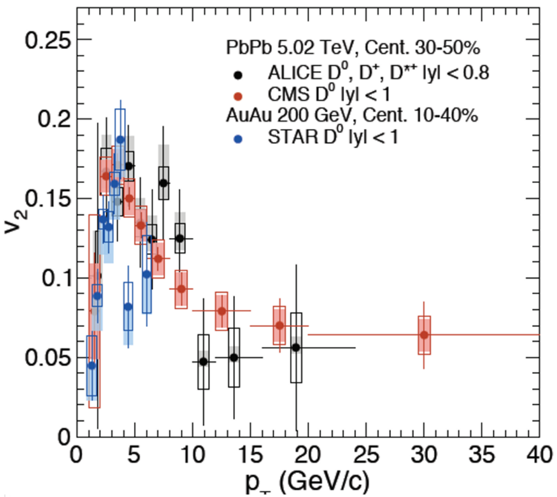
$$2\pi T D_S = \frac{8\pi T^3}{\hat{q}(p \to 0)}$$

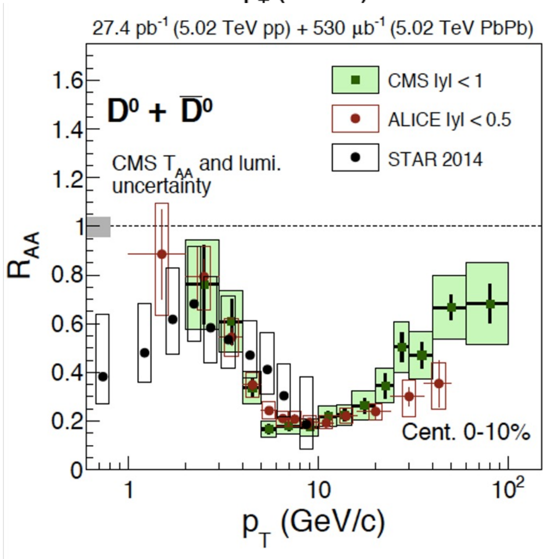
collisional vs. radiative energy loss

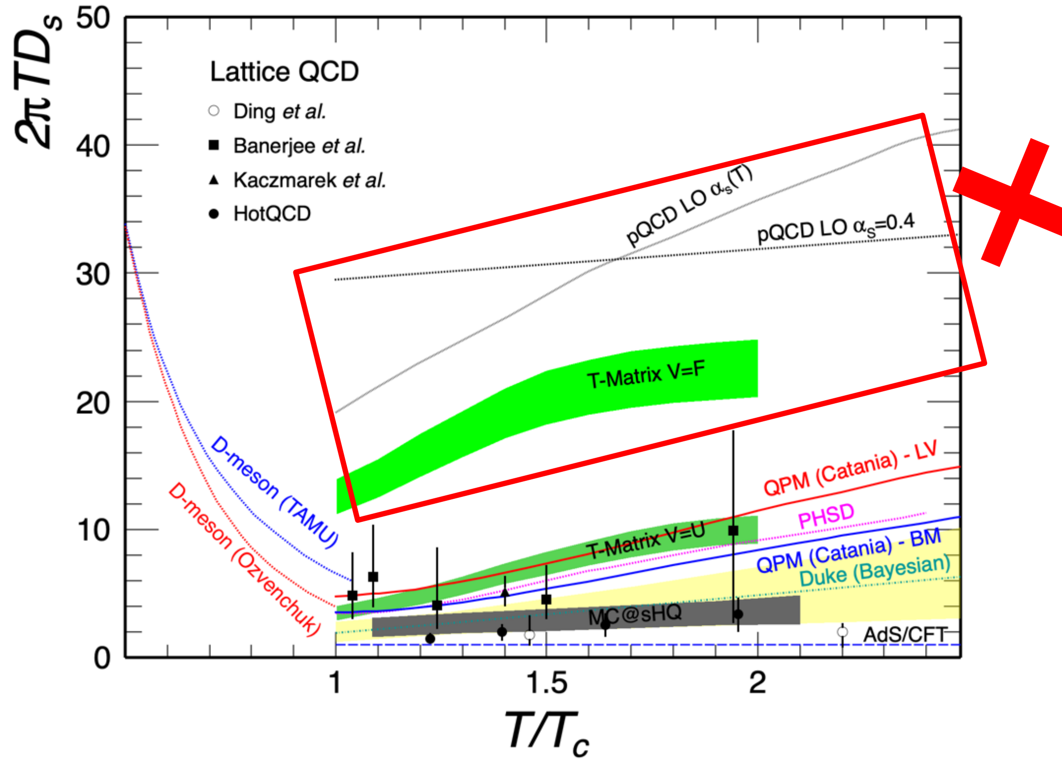
Heavy quark transport – to probe QGP with comprehensive p_T coverage

- unique insights to both perturbative and non-perturbative regimes

Future Direction: Heavy Quark Transport in sQGP





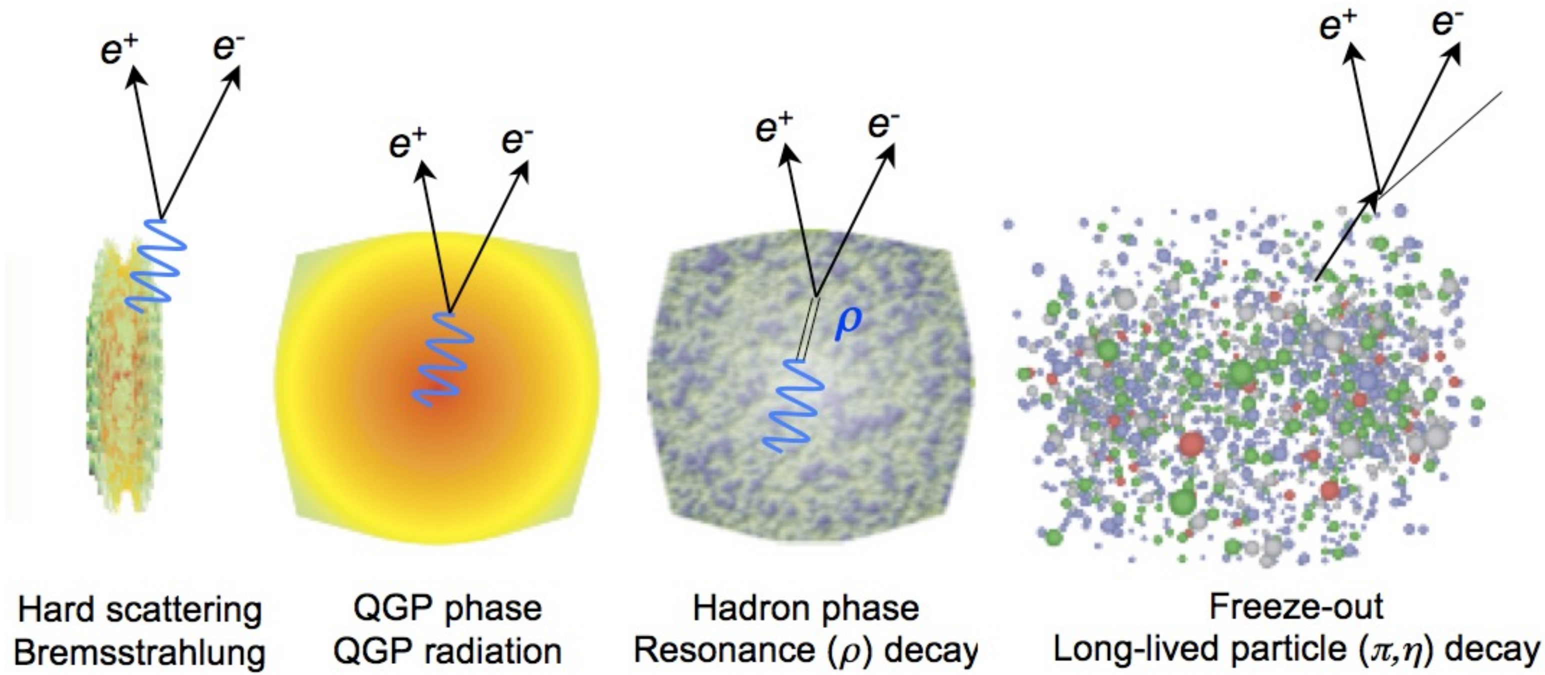


- Weakly coupled scenarios ruled out
- $2\pi D_s \sim 1 - 4$ @ T_c

  LQCD calculation ~1-3

  close to quantum bound from AdS/CFT

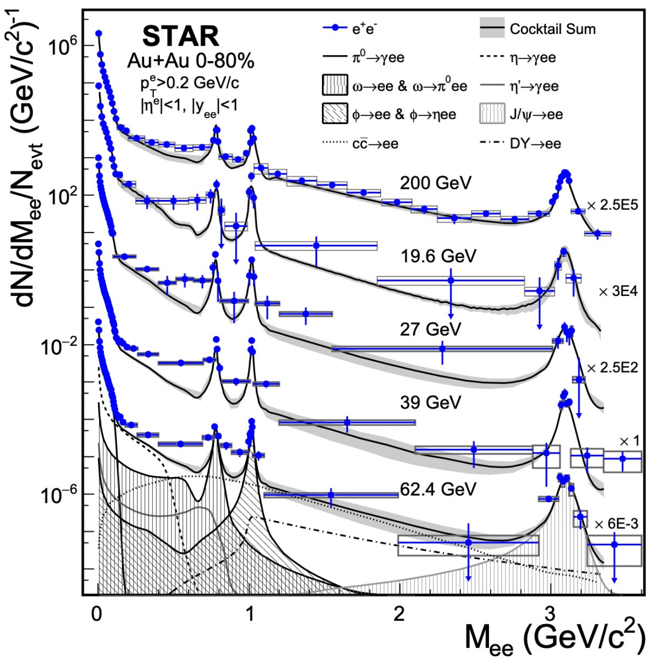
Future Direction: Dileptons



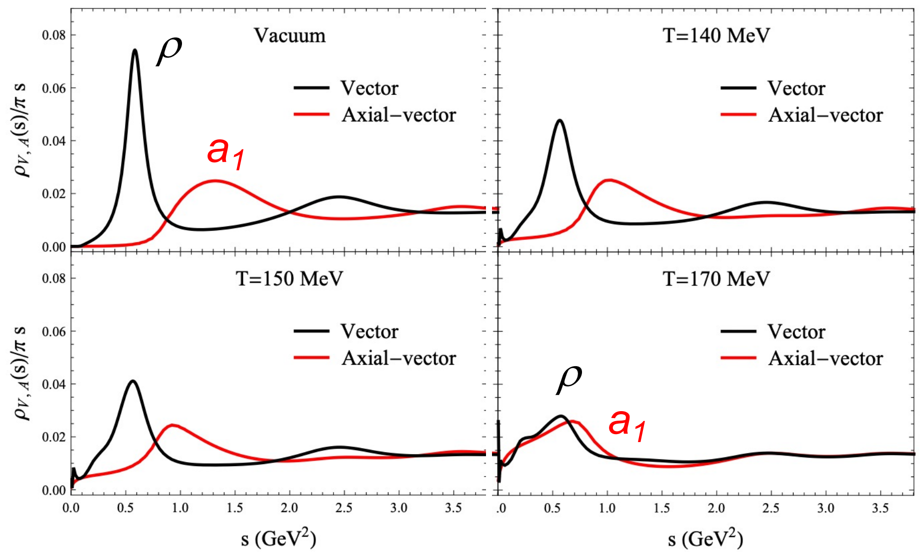
Thermal dileptons: no strong interaction, no blue-shift effect

Golden probe to characterize hot QCD medium at different stages!

Dileptons – Chiral Properties



STAR, PRC 107 (2023) L061901

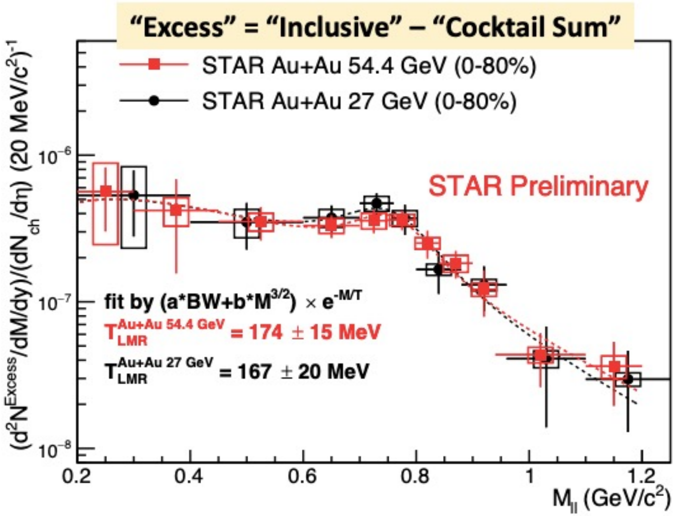


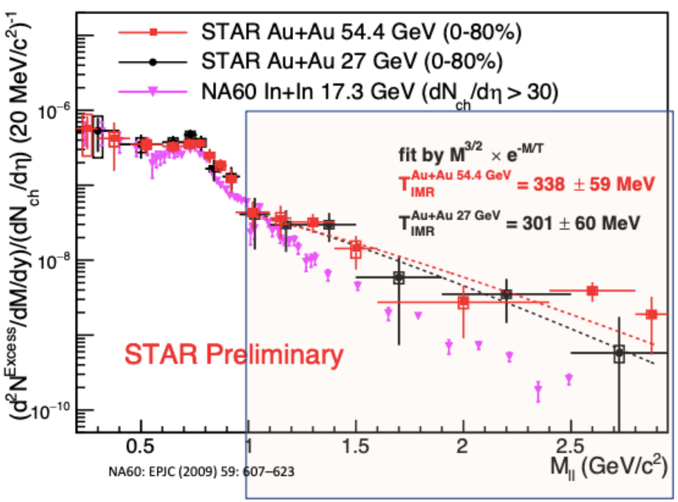
P. Hohler and R. Rapp, PLB 731 (2013) 103

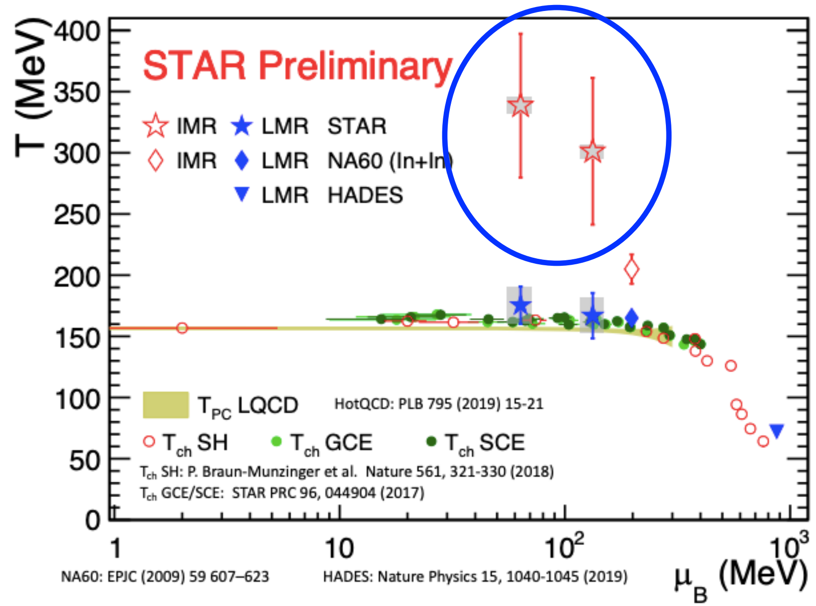
Significant broadening of dilepton low mass spectra from SPS to RHIC

- ρ in-medium interactions with baryons in the hot QCD medium
- consistent with (partial) CSR in the hot QCD medium

Dileptons – Medium Thermometer







STAR, QM2022

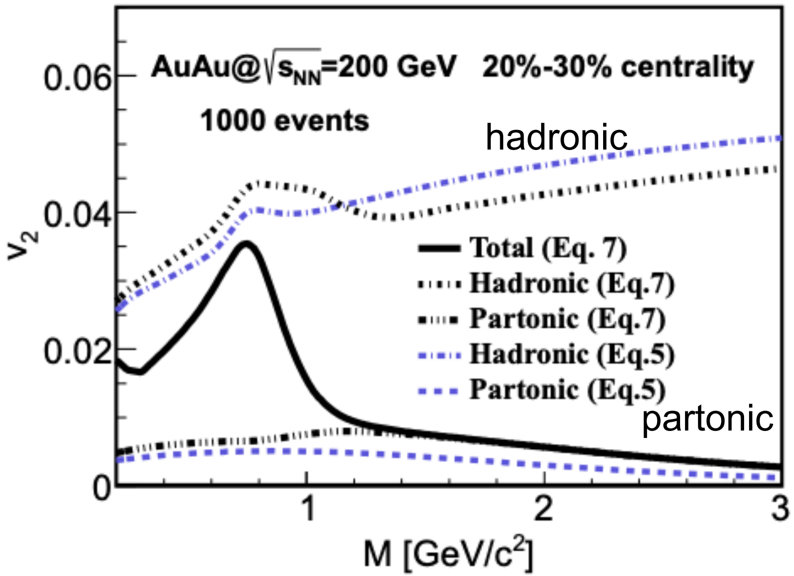
$$\frac{dN}{dM_{ee}} \propto M_{ee}^{3/2} e^{-M_{ee}/T}$$

First "clean" measurement of hadronic medium and sQGP temperatures

Dileptons to Prob QGP Properties at Different Stages

Thermal dileptons at IMR (1.1 < M < 3. GeV/c²)

Partonic or Hadronic thermal source – Elliptic flow



H.J. Xu et al., PRC 89 (2014) 064902

Polarization (angular distribution) to probe the degree of thermalization

$$\frac{d\sigma}{d\Omega^*} \propto 1 + \alpha \cos\theta^*$$

Initial Drell-Yan, fully polarized α=1

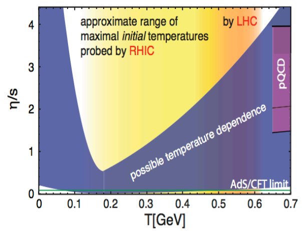
Completely thermalized, isotropic α=0

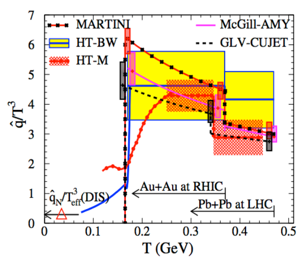
E. Shuryak, 1203.1012

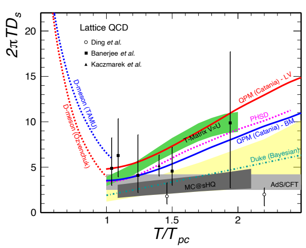
→ Cross section, v_2, α (M, p_T)

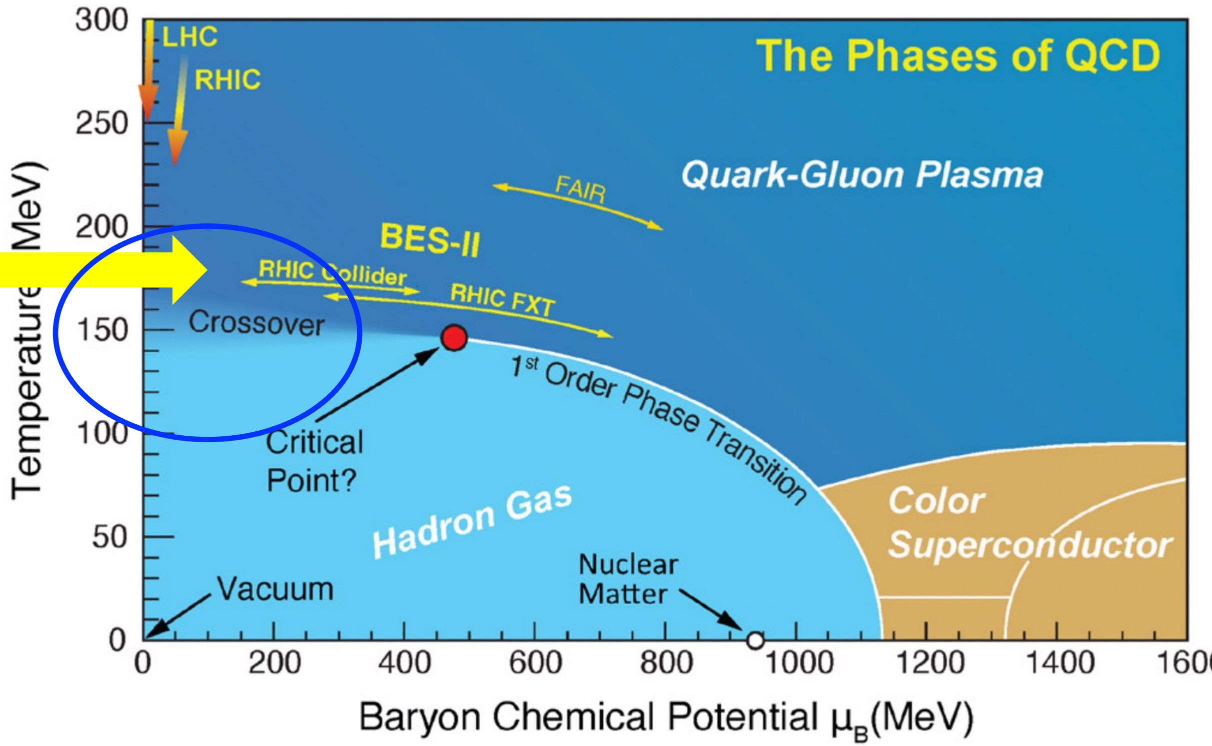
Summary

QGP Properties
@ $\square_B$ ~ 0









At $\square_B$ ~ 0, overwhelming evidences : **sQGP** at RHIC and LHC
Exp. + Lattice QCD: **Crossover phase transition**

Future focus:
Quantitative characterization of emergent QGP properties

Homework

1) Estimate ideal QGP gas energy density at T = 200 MeV.

2) SPS single beam kinetic energy 158 A GeV (T) and RHIC single beam energy 3.85 GeV (E_b). Convert them into CoM energies.

3) Show rapidity (y) is additive in Lorentz transformation, and $Ed^3\sigma/dp^3$ is boost-invariant.

4) QCD T_c @ $\square_B$=0 in standard unit (Kelvin).

5) Estimate how much gold does RHIC smash every RHIC-Run (~6 months).
- 10^9 ions per bunch, ~100 bunches per store (avg. 8 hr), down time ~50%

6) pbar/p ~ 0.8 at 200 GeV, determine $\square_B$ (ignore $\square_S$, $\square_Q$ and T_{ch} = 160 MeV).

7) pQCD $\sigma \propto 1/p_T^6$, assuming R_{AA} = 0.2 flat, what is the equivalent Δp_T?

High Energy Frontiers

Jets	– Yaxian Mao
Heavy Flavor	– Zhenwei Yang, Xiaoming Zhang
Chirality / Vorticity	– Qiye Shou, Qinghua Xu

Answers

1) *Calculate ideal QGP gas energy density at T = 200 MeV*

$$\varepsilon = 3P = g_{QGP}\frac{\pi^2}{30}T^4 \sim 2.5\ \text{GeV/fm}^3\ \ @\ T = 200\ \text{MeV}$$

1) *SPS single beam kinetic energy 158 A GeV (T) and RHIC single beam energy 3.85 GeV (E_b). Convert them into CoM energies*

3) *Show y is additive in Lorentz transformation, and $Ed^3\sigma/dp^3$ is boost-invariant.*

4) *QCD T_c @ $\square_B$=0 in standard unit (Kelvin).*

5) *Estimate how much gold does RHIC smash every RHIC-Run (~6 months).* *- 10^9 ions per bunch, ~100 bunches per store (avg. 8 hr), down time ~50%*

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7) *pQCD $\sigma \propto 1/p_T^6$, assuming R_{AA} = 0.2 flat, what is the equivalent Δp_T?*

Tuesday Presentation

Tuesday Outline

QCD Phase Structure at Finite $\square_B$

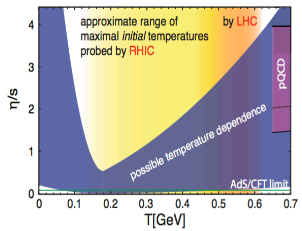
Beam Energy Scan Program at RHIC

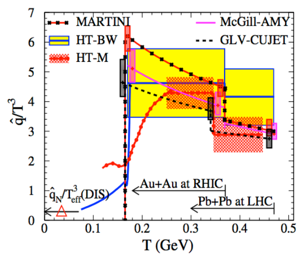
Selected Results from BES-I

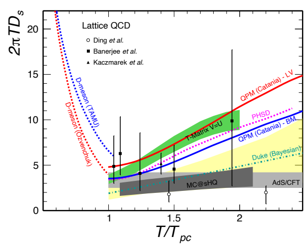
Preparation for BES-II

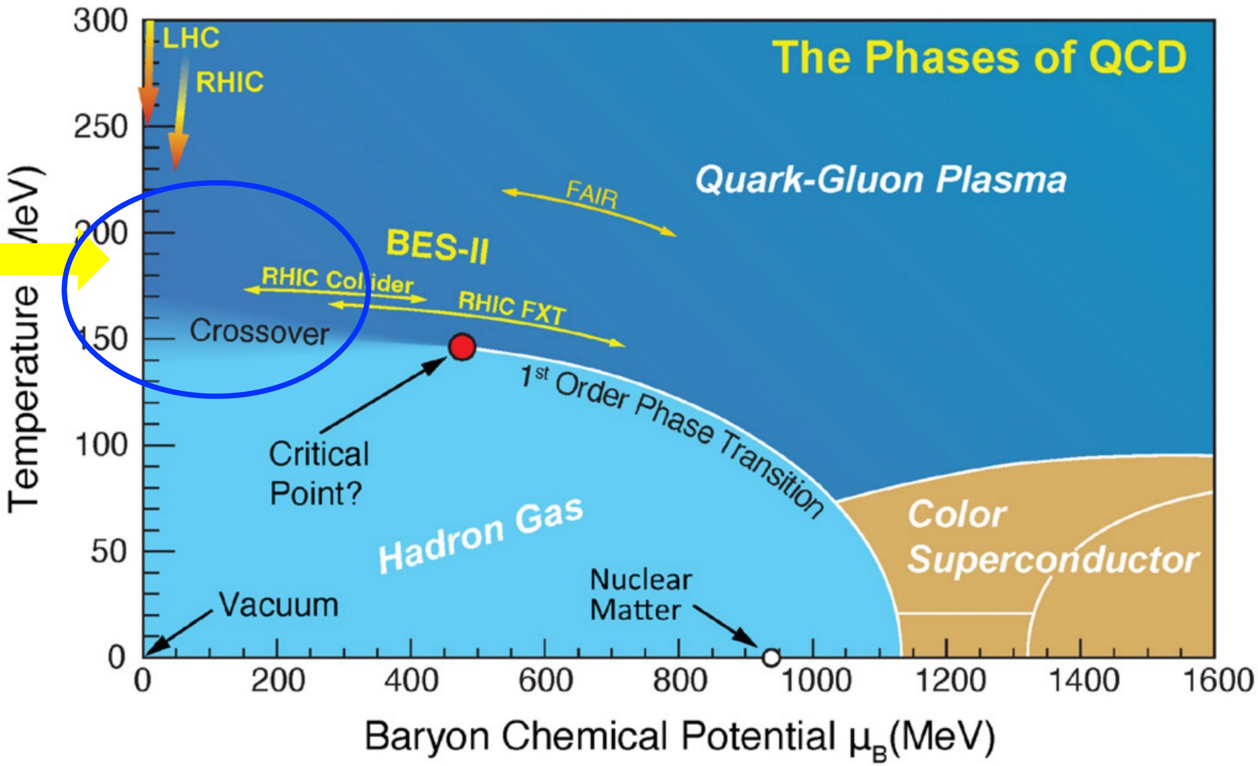
QCD Phase Diagram

QGP Properties
@ μ_B ~ 0



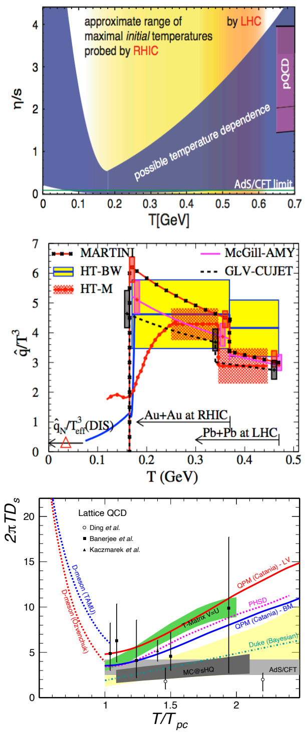




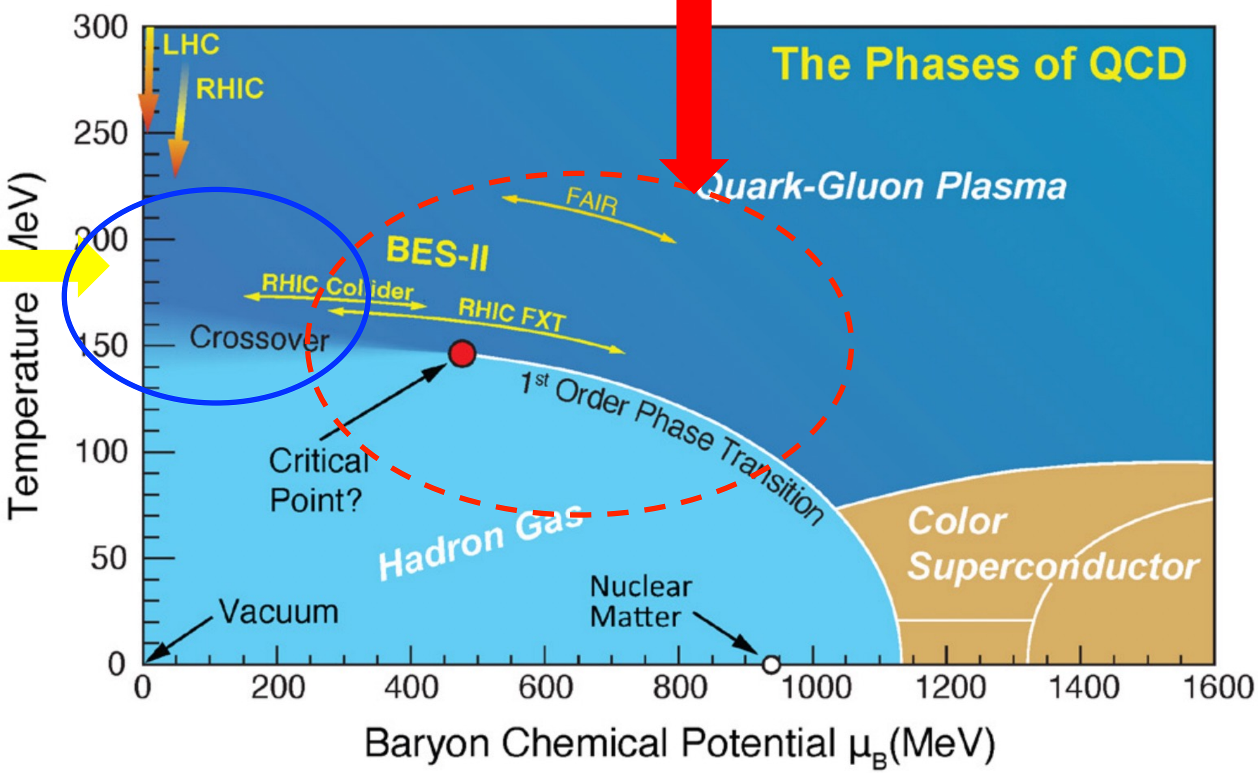


QCD Phase Structure at Finite μ_B

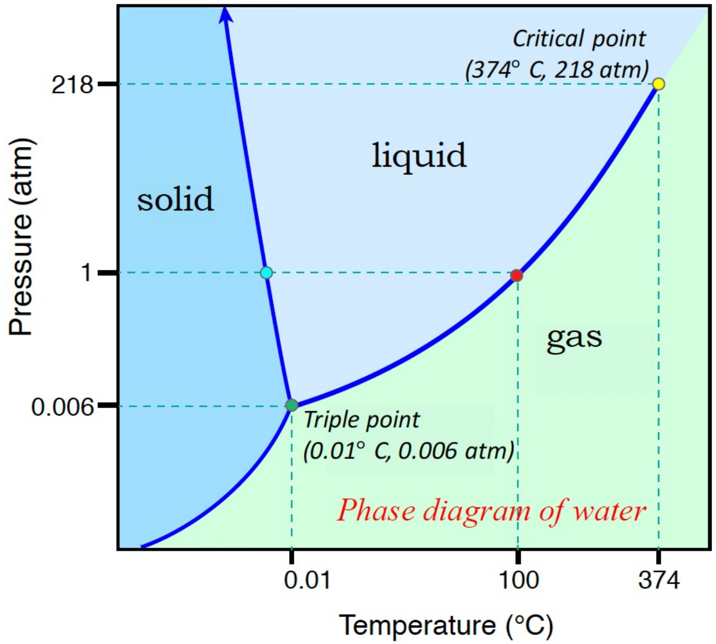
QGP Properties
@ μ_B ~ 0

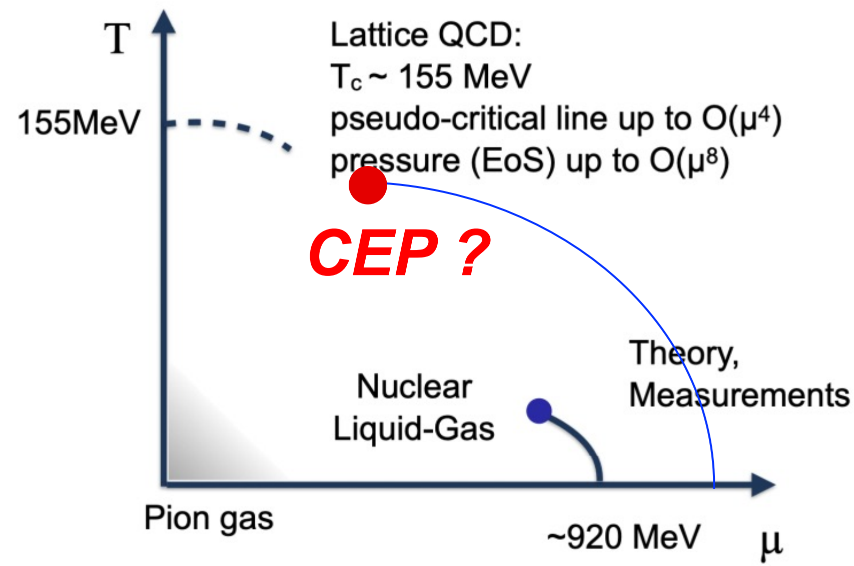


QCD Phase Structure
@ finite μ_B



Is There a Critical End Point (CEP)?

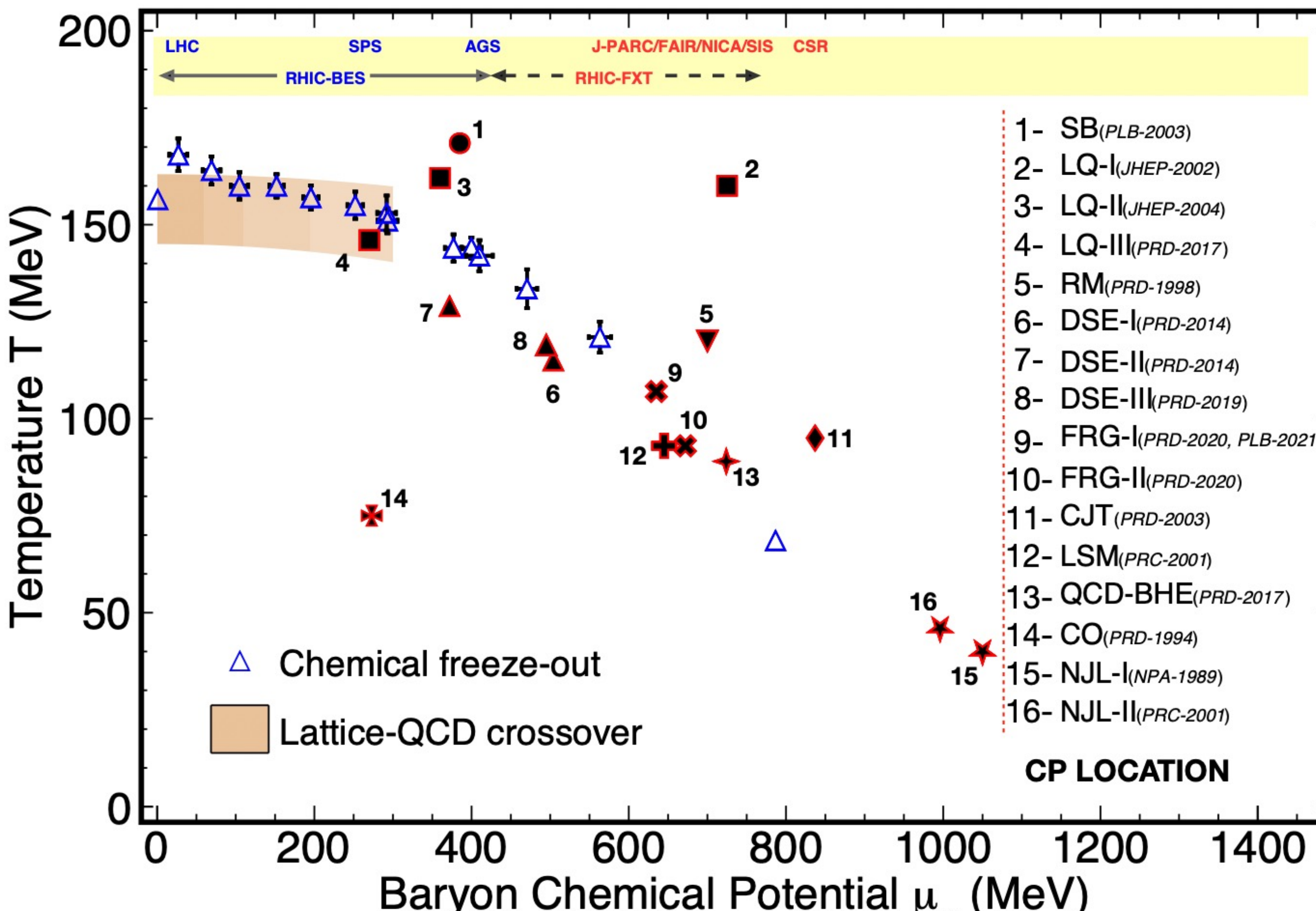




Model calculations suggest a first-order phase transition at sufficiently high μ_B

Is there a critical end point (CEP) of first order phase transition?

Model Predictions on QCD CEP at Finite μ_B

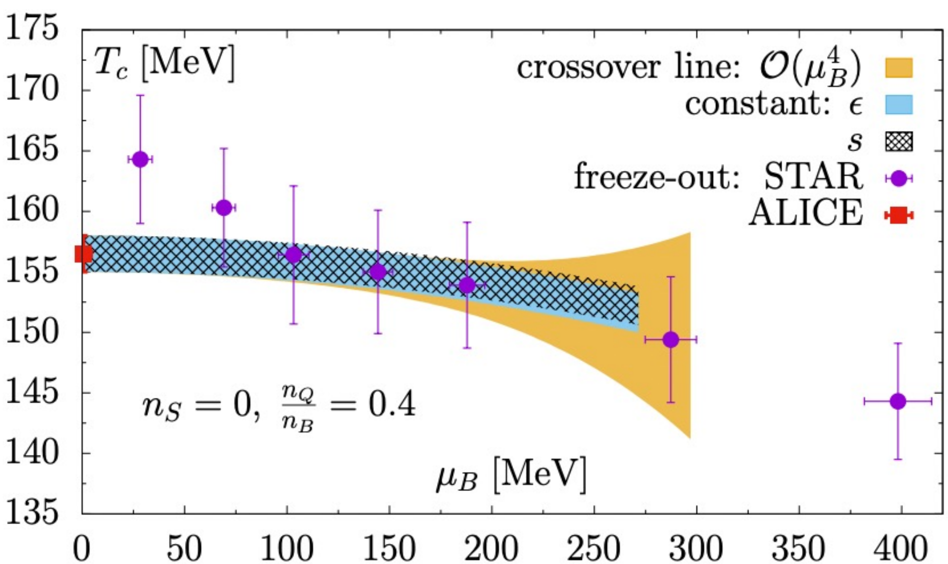


A. Pandav et al, PPNP 125 (2022) 103960

Lattice QCD on CEP

At finite □$_B$: Tyler expansion method – sign problem makes it challenging

$$\frac{p(T,\mu_B)}{T^4} = \frac{p(T,0)}{T^4} + \sum_{n=1}^{\infty} \frac{1}{n!} \frac{\partial^n (p/T^4)}{\partial(\frac{\mu_B}{T})^n}\Bigg|_{\mu_B=0} \left(\frac{\mu_B}{T}\right)^n = \sum_{n=0}^{\infty} c_n(T) \left(\frac{\mu_B}{T}\right)^n$$



A. Bazavov et al., PLB 795 (2019) 15

Calculations for χ_n up to 8th order favor:

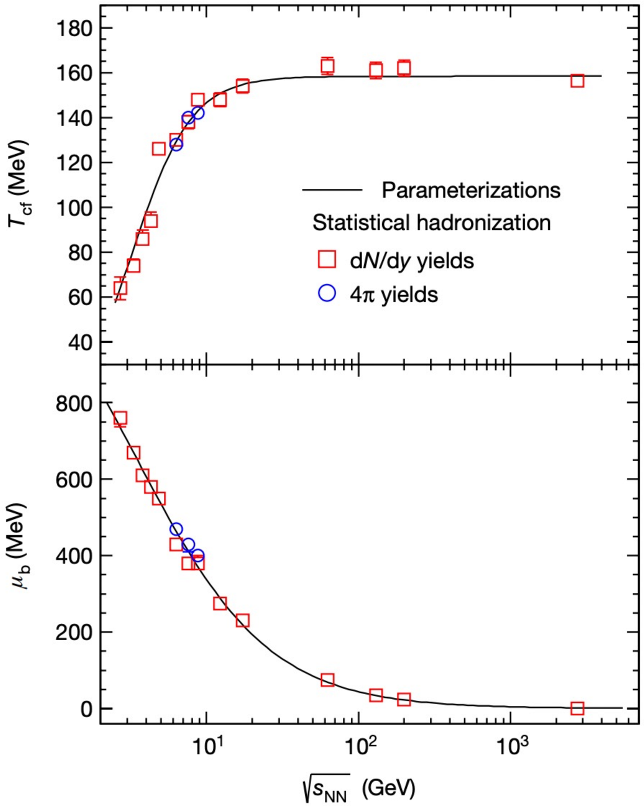
$$T_{CEP} < 140\text{MeV}\ ,\ \mu_B^{CEP} > 400\text{MeV}$$

or CEP likely locates at

$$\frac{\mu_B}{T} > 3$$

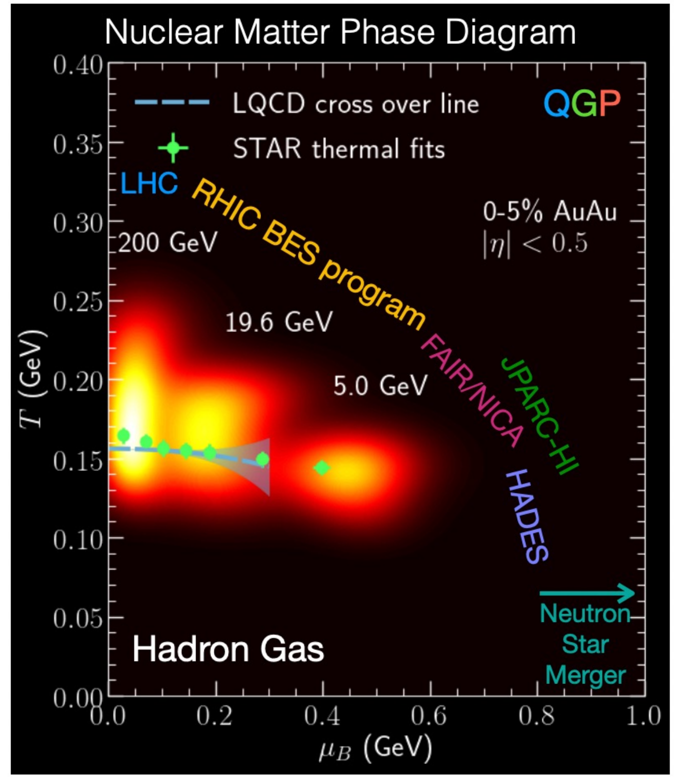
Experimentally Accessing Phase Diagram

Empirical fit to chemical FO parameters



A. Andronic et al, Nature 561 (2018) 321

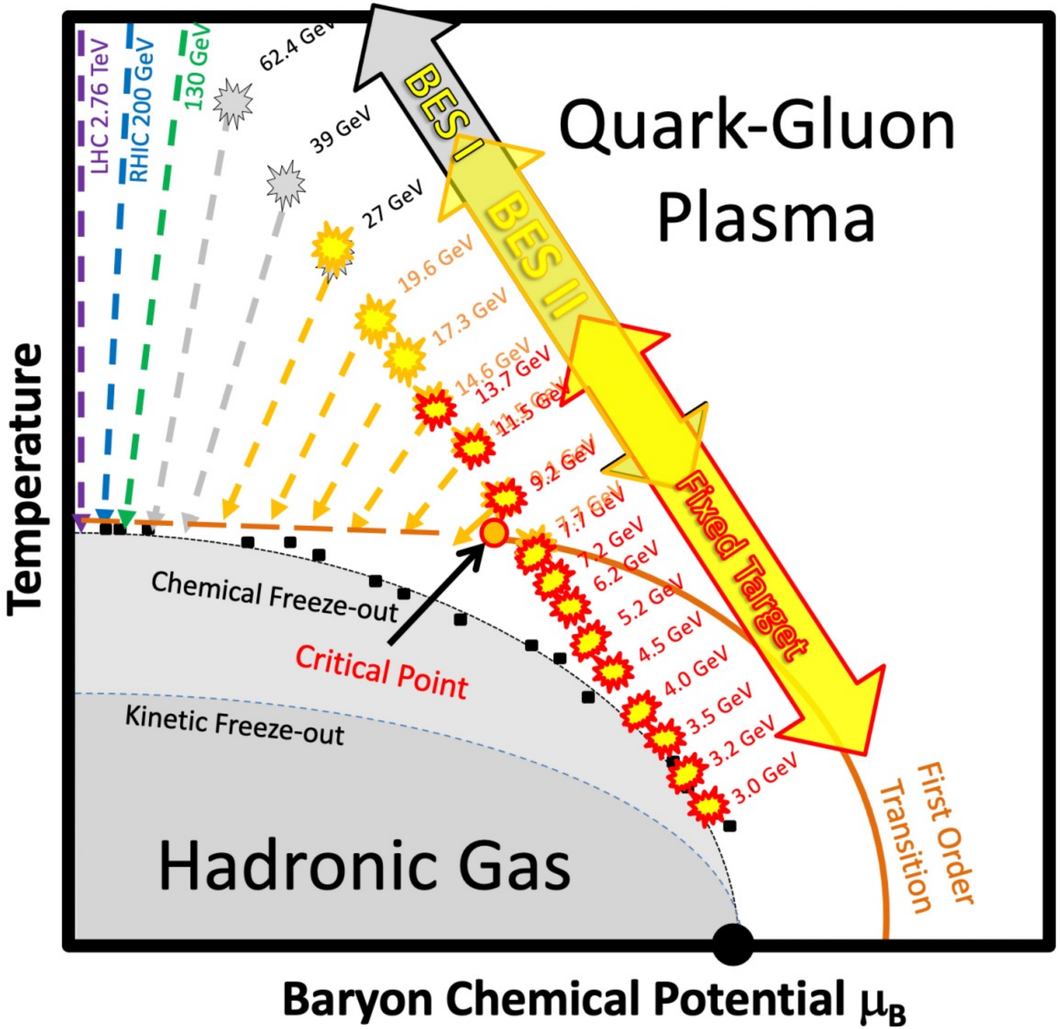
E-by-E simu from hydro calculation



C. Shen et al., arXiv:2010.12377

Beam Energy Scan Program at RHIC

Beam Energy Scan Program at RHIC



BES-I (2010 – 2014):

μ_B: 70 – 400 MeV

62.4, 39, 27, 19.6, 14.6, 11.5, 7.7

BES-II (2018 – 2021):

μ_B: 150 – ~720 MeV

Collider mode

27, 19.6, 17.3, 14.6, 11.5, 9.2, 7.7

Fixed Target mode

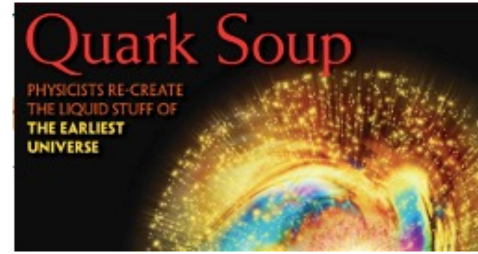
13.7, 11.5, 9.2, 7.7, 7.2, 6.2, 5.2, 4.5, 3.9, 3.5, 3.2, 3.0

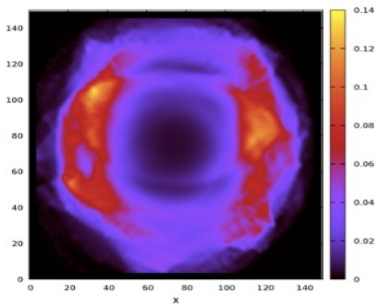
Why Should We Return to AGS/SPS Energies?

Established evidences for sQGP formation at 200 GeV

jet quenching

partonic collectivity





Theoretical advances in understanding heavy-ion collisions

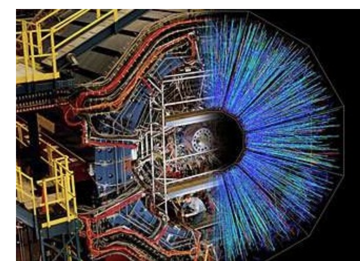
pQCD for energy loss in medium

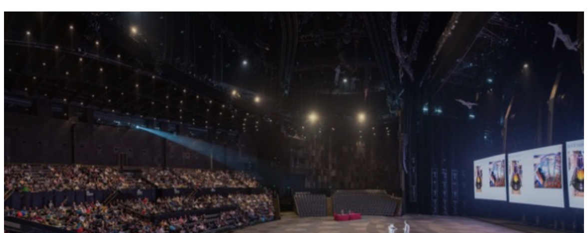
standardized hydro model

Experimental technique advances

machine dev. allowing high stat. collision

much improved detector technologies

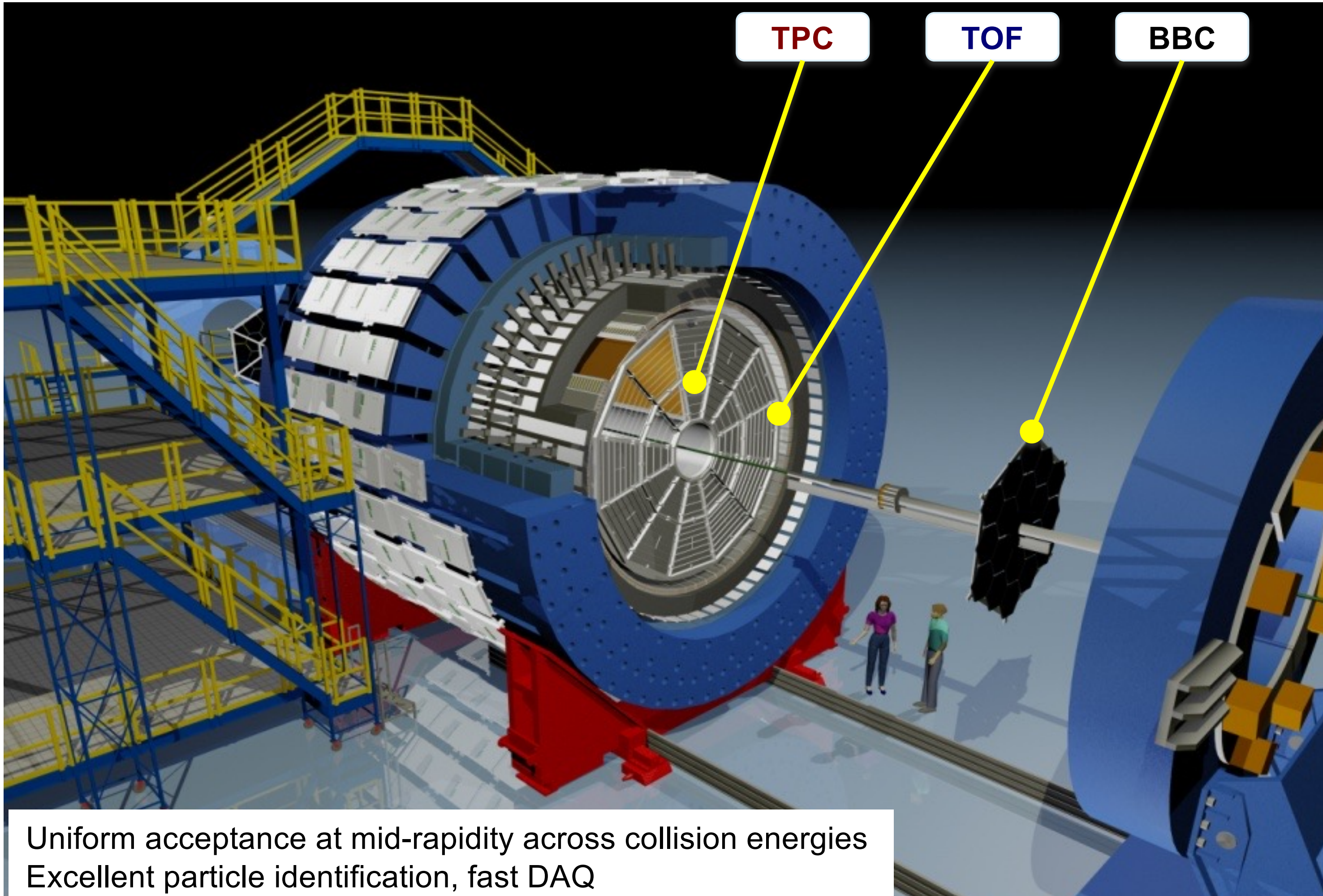




Community expansion

new generation of researchers

STAR Detector (2010-2014)



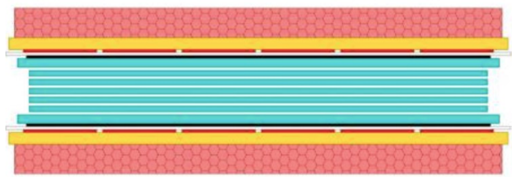
Uniform acceptance at mid-rapidity across collision energies
Excellent particle identification, fast DAQ

STAR Detector Upgrade 2010

Full Barrel Time-of-Flight (BTOF) in physics data taken starting 2010

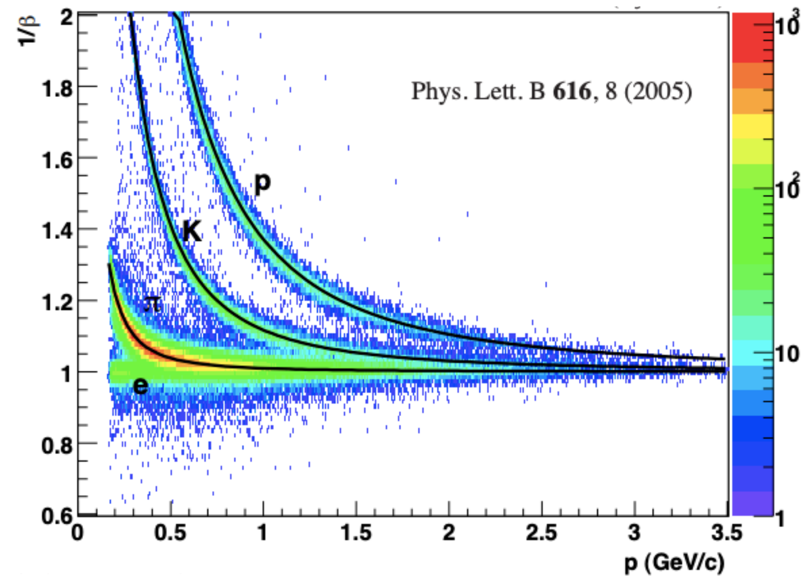
A major US-China collaboration project

Multi-gap Resistive Plate Chamber (MRPC)



Timing resolution < 75ps
proton PID extended to ~ 3 GeV/c

Key contributions from USTC, Tsinghua, CCNU, SINAP etc.



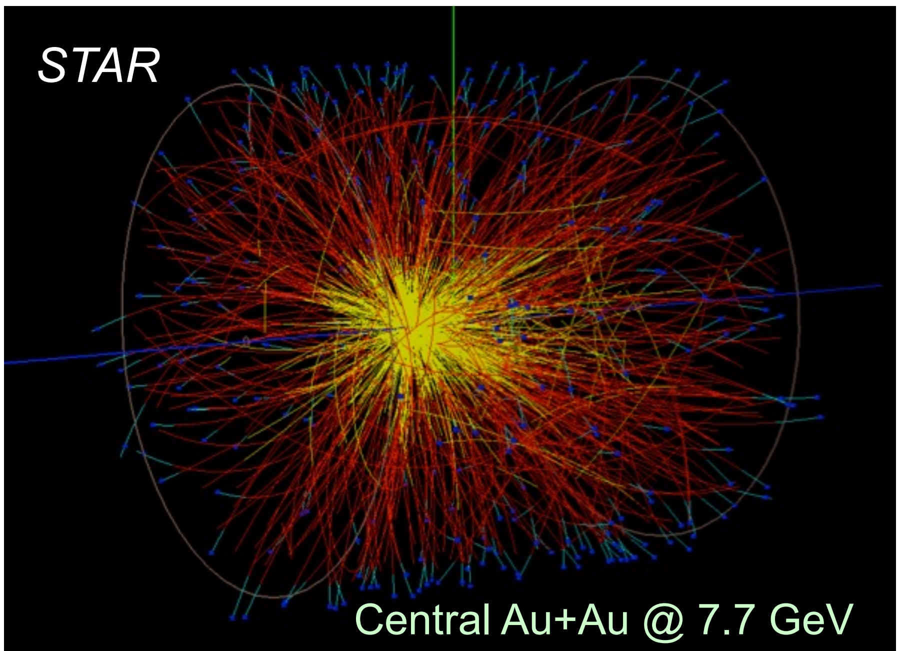
DAQ 1000 TPC read-out upgrade to enable large statistics (both MB and triggered) datasets to take advance of RHIC luminosity upgrade

Quiz: time resolution needed for STAR TOF to allow 3σ separation of protons from π/K? (L~ 2.1m)

BES-I (2010-2014)

Pilot run 2009, Au+Au 9.2 GeV, 3k events. - *one Ph.D. thesis, one publication*

2010 Au+Au 7.7 GeV

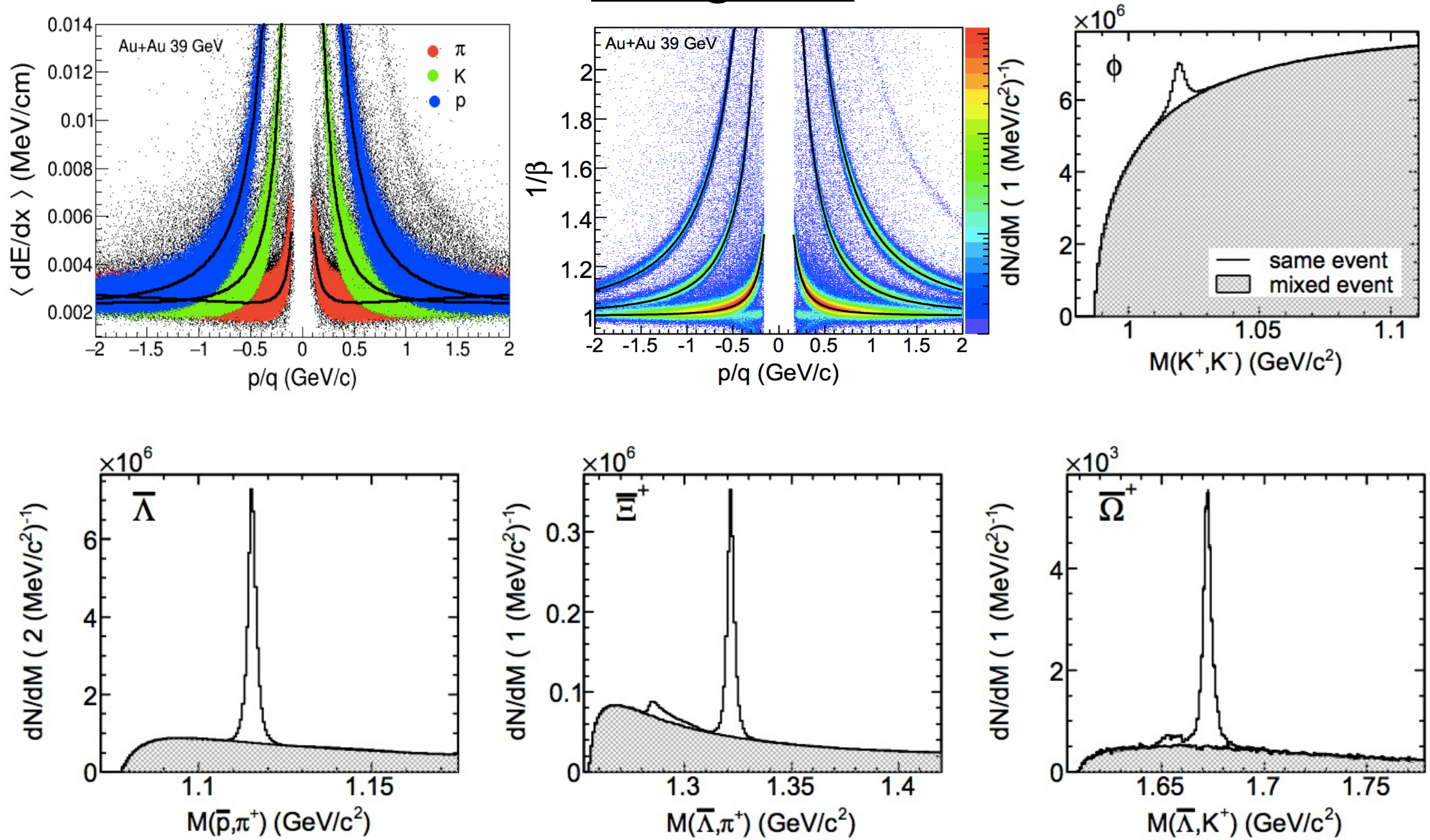


BES Phase-I

Year	$\sqrt{s_{NN}}$ (GeV)	Events by STAR (10^6)
2010	62.4	67
2010	39	130
2011	27	70
2011	19.6	36
2014	14.5	20
2010	11.5	12
2010	7.7	5

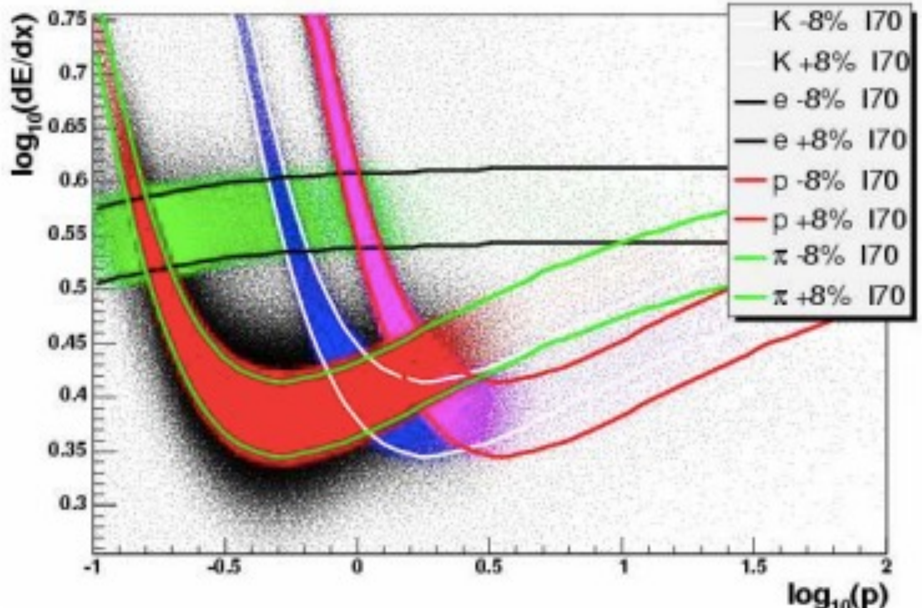
Particle Identification

Au+Au @ 39 GeV

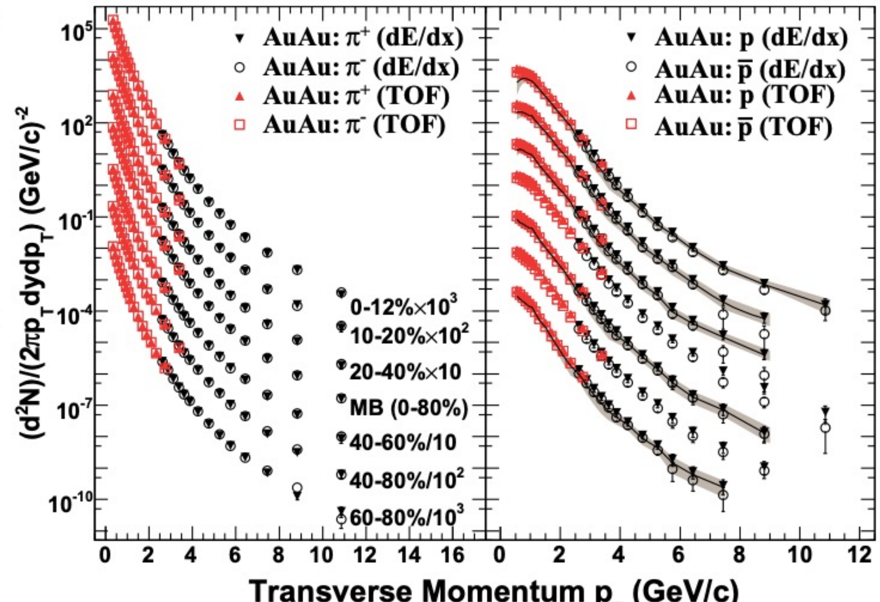


PID in Full Momentum Region

rdE/dx for PID beyond TOF



M. Shao et al, NIMA 558 (2006) 419



STAR, PRL 97 (2006) 152301

8% dE/dx resolution → ~ 2σ separation between pions / K+p

dE/dx + TOF + rdE/dx. →

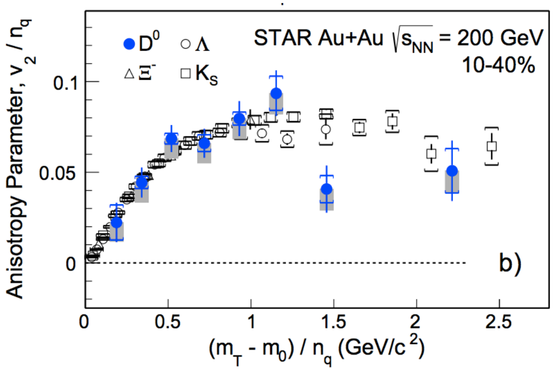
Identification of pions and protons in full momentum region

Quiz: Can this be applied to kaons? Any way to identify K+/- at high p?

Signatures

Onset of sQGP evidences

STAR, PRL 118 (2017) 212301



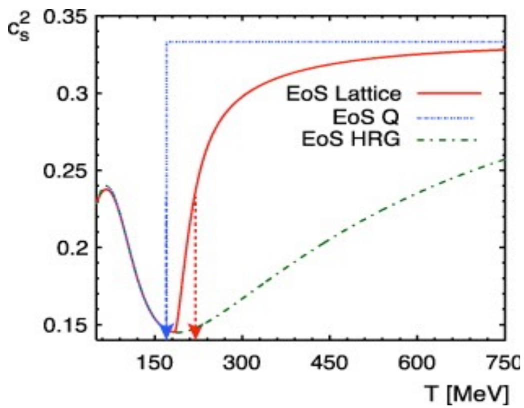
Au+Au @ 200 GeV

- partonic collectivity
- jet quenching

Softest Pressure Point

- 1st order phase transition

P. Huovinen and P. Petreczky, NPA 837 (2010) 26



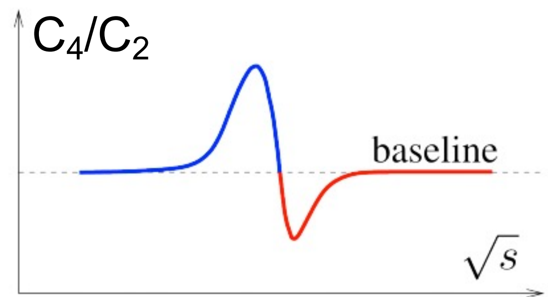
Potential signatures

- minimum in (net-)proton dv_1/dy
- plateau in particle spectra slope parameter
- enhancement in dielectron yield

Enhanced Fluctuations

– critical point

M. Stephanov, PRL 107 (2011) 052301



- Nonmonotonicity in net-B, net-Q, net-S high order cumulants

Selected Results from BES-I

Chemical Freeze-out Properties

Statistical thermal model **THERMUS** used for extract chemical freeze-out parameters

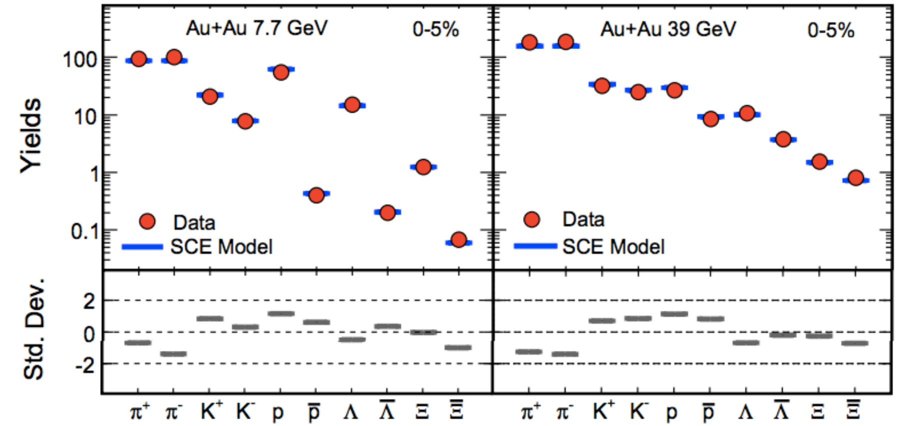
Particle yields/ratios including all measured particles ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, K_S, Λ, $\bar{\Lambda}$, Ξ^-, $\bar{\Xi}^+$) used in the fit

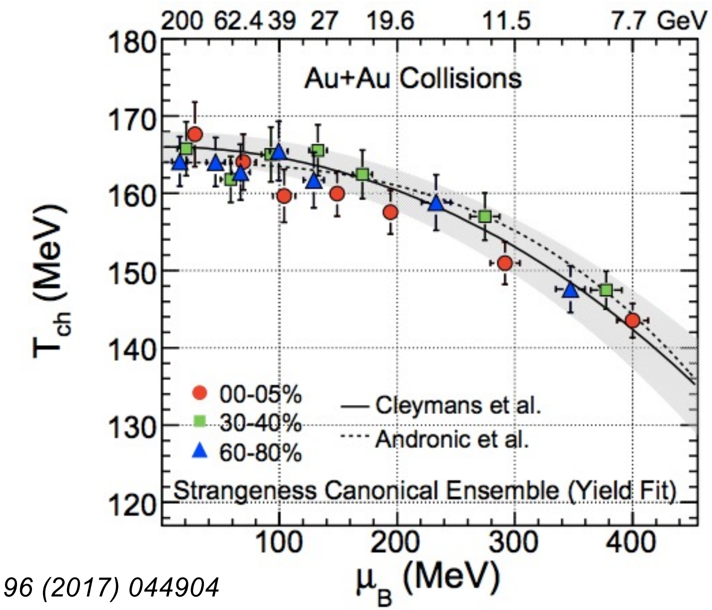
- Grand canonical ensemble (GCE)
- Strangeness canonical ensemble (SCE)

$$N_i^{GC} = \frac{g_i V}{2\pi^2} \sum_{k=1}^{\infty} (\mp 1)^{k+1} \frac{m_i^2 T}{k} K_2\left(\frac{k m_i}{T}\right) e^{\beta k \mu_i}$$

$$N_i^S = \left(\frac{Z_{S-S_i}}{Z_S}\right) N_i^{GC}\Big|_{\mu_S=0}$$

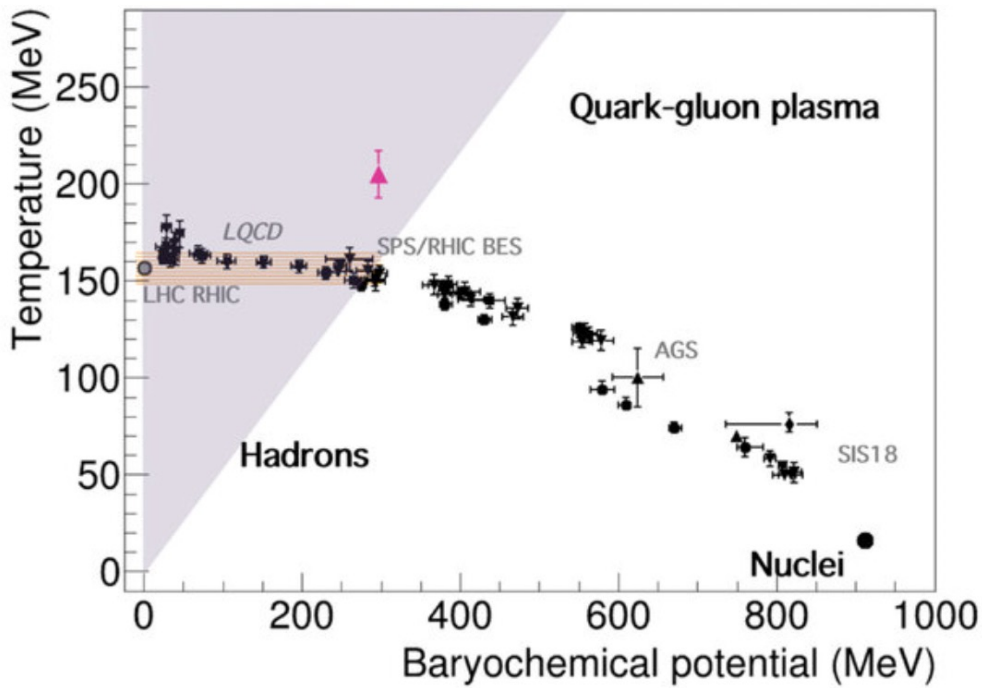
THERMUS: Comput. Phys. Commun. 180 (2009) 84

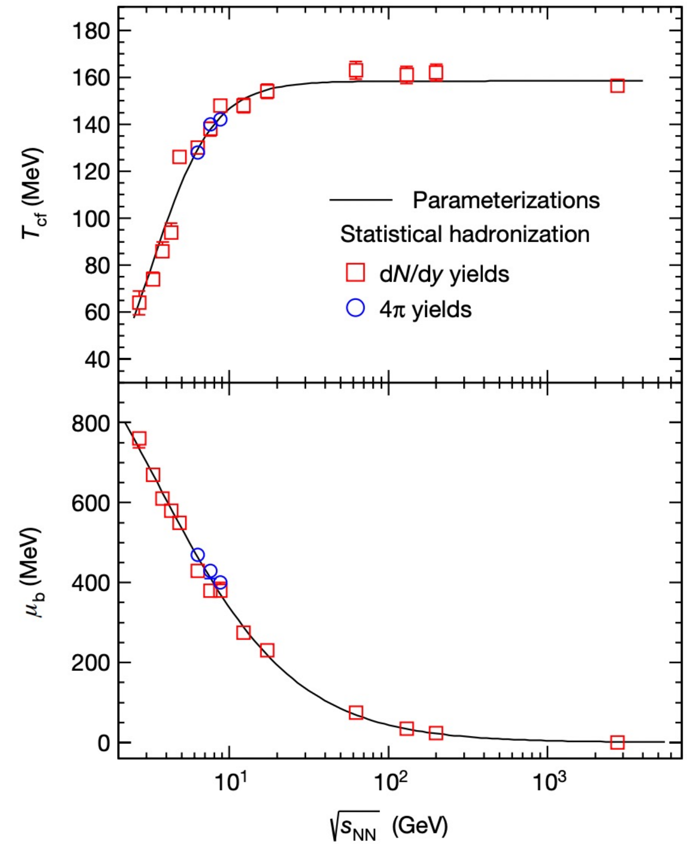




STAR, PRC 96 (2017) 044904

Energy Dependence of Chemical Freeze-out



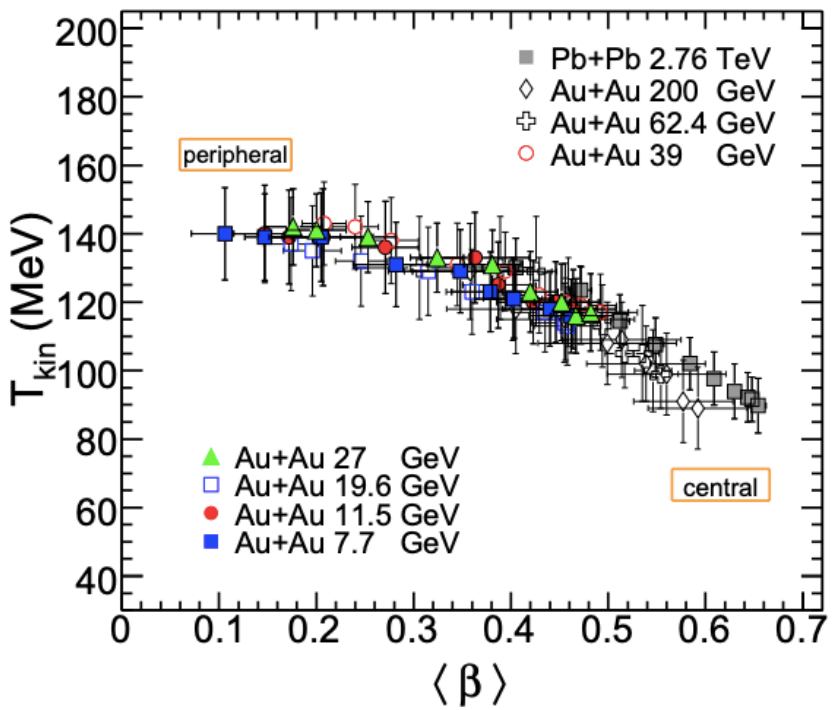


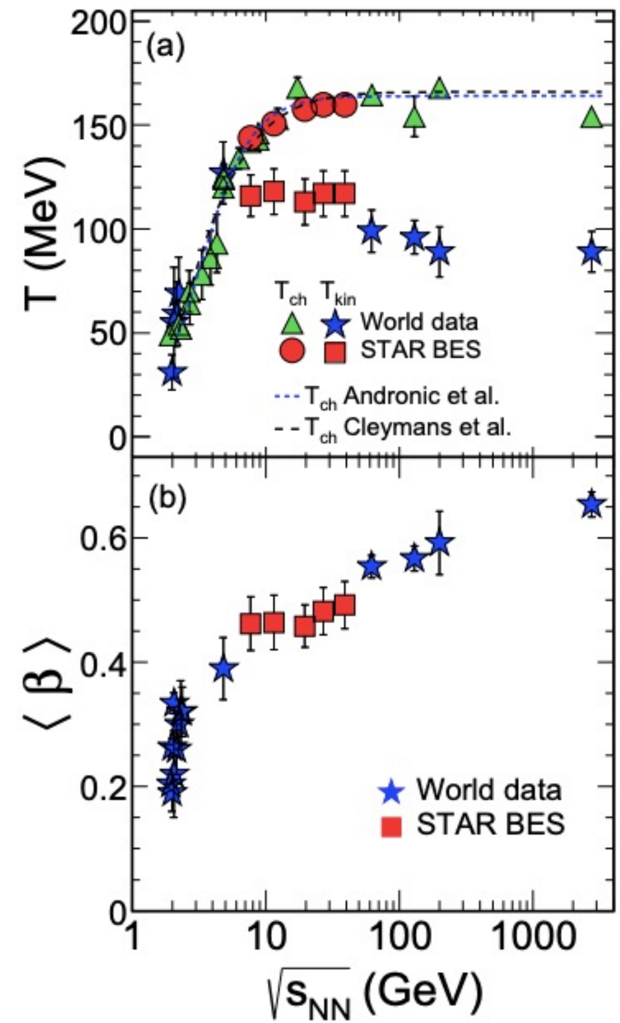
Chemical FO temperature from SPS to LHC (accidentally) consistent with T_c from Lattice

Energy dependence → empirical function fit

A. Andronic et al, Nature 561 (2018) 321

Kinetic Freeze-out Properties





Freezeout parameters fall on universal trend
Energy dependence:
T_{ch}-T_{kin} prolonged hadronic evolution

STAR, PRC 96 (2017) 044904

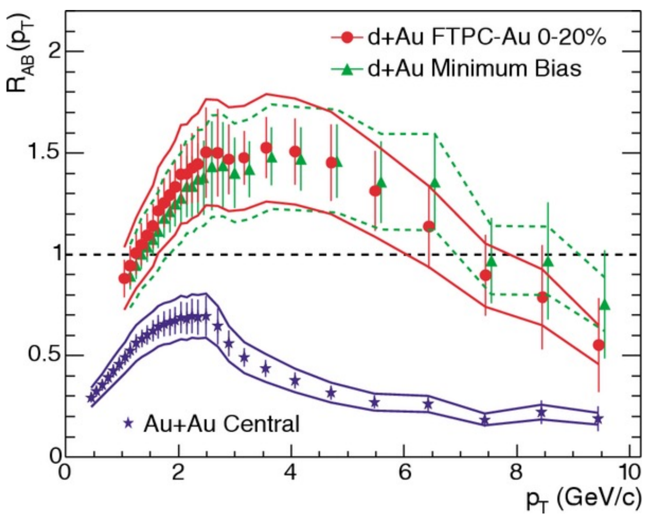
Evidences of the Formation of sQGP at 200 GeV

"Jet Quenching"

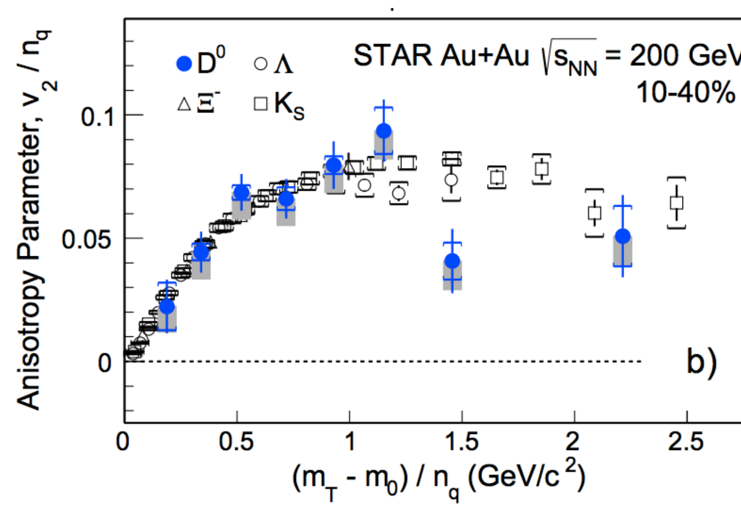
- Significant suppression in particle yield at high p_T in central heavy ion collisions

"Partonic Collectivity"

- Strong collective flow, even for multi-strange hadrons (ϕ, Ω) and charmed hadrons (D^0)
- Flow driven by Number-of-Constituent-Quark (NCQ) in hadrons

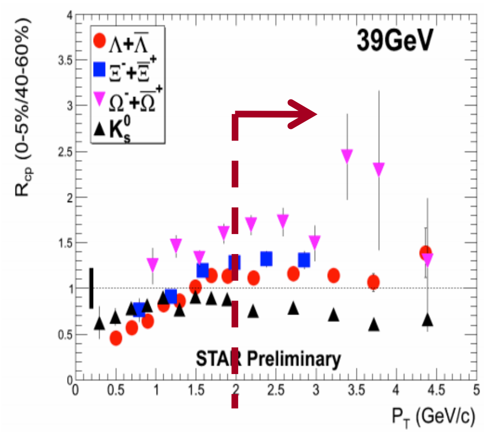


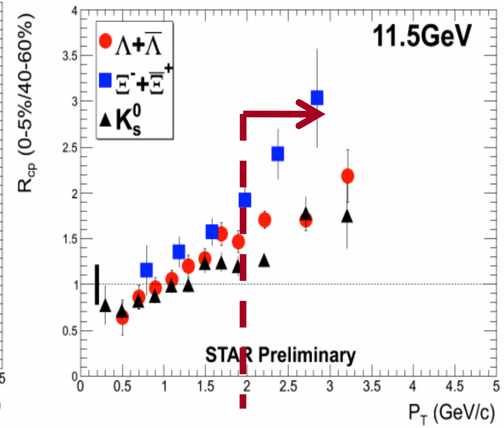
STAR, PRL 91 (2003) 072304

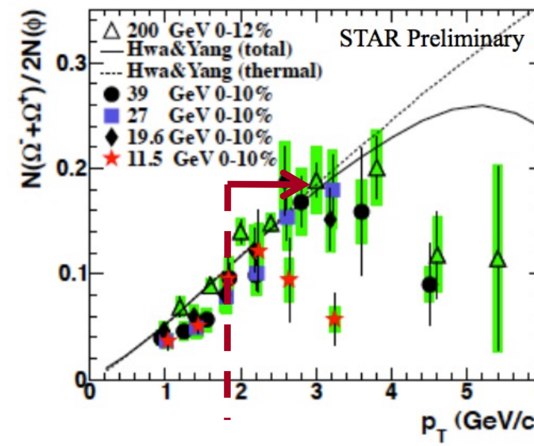


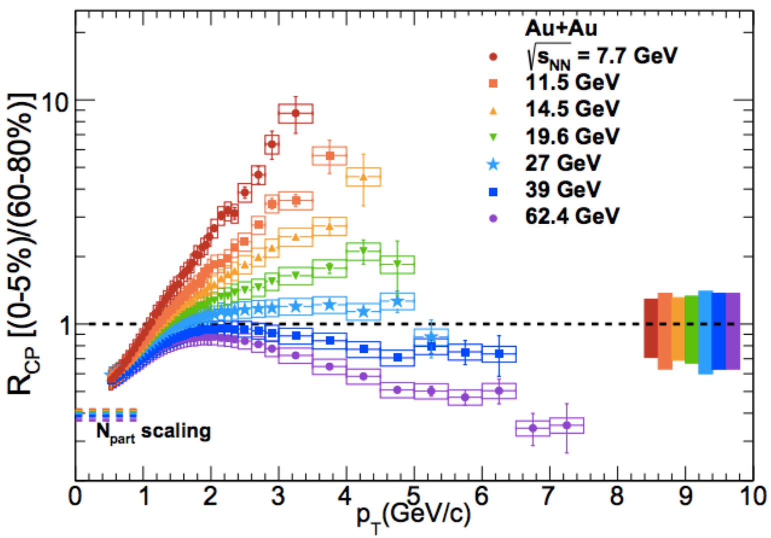
STAR, PRL 118 (2017) 212301

Disappearance of R_{cp} Suppression





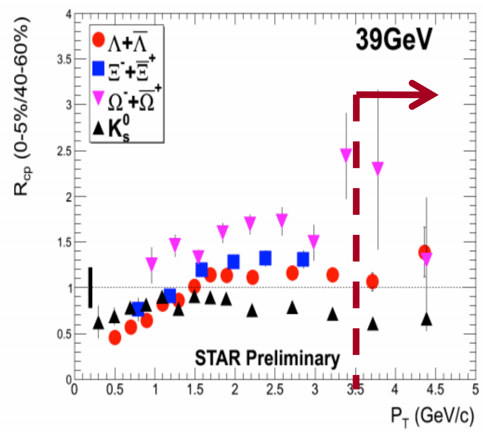


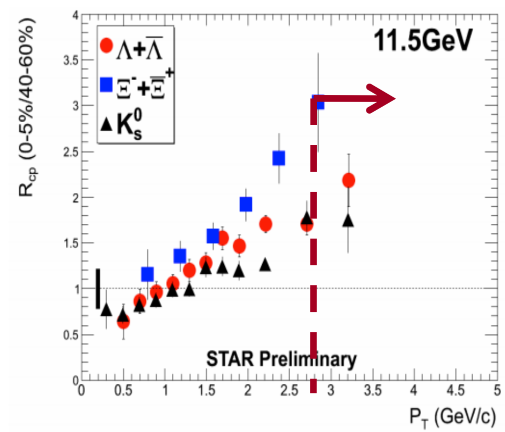


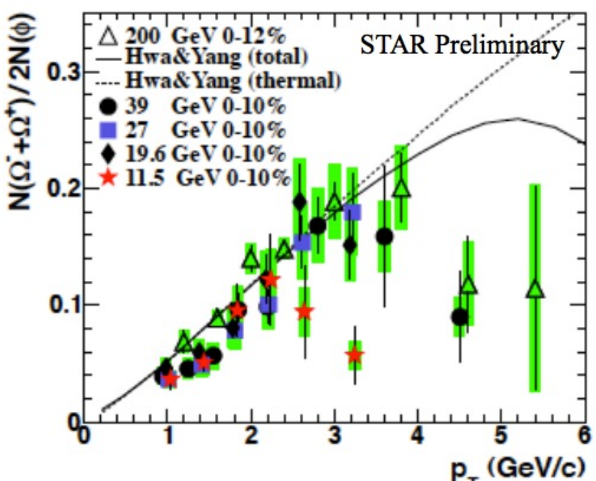
- R_{cp} >~ 1 at 11.5, 7.7 GeV. - Cronin effect?

  R_{cp} suppression NOT seen at lower energies!

STAR, PRL 121 (2018) 032301

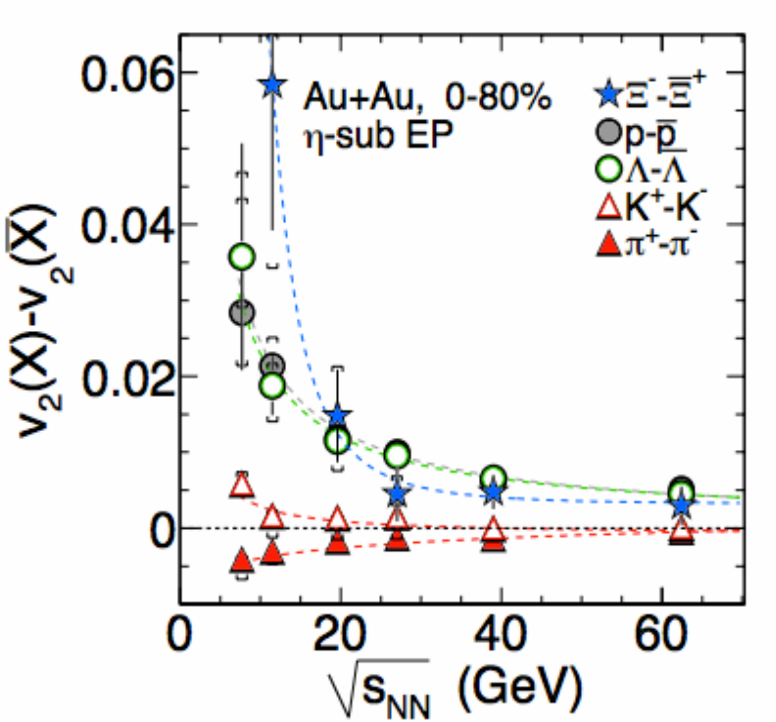


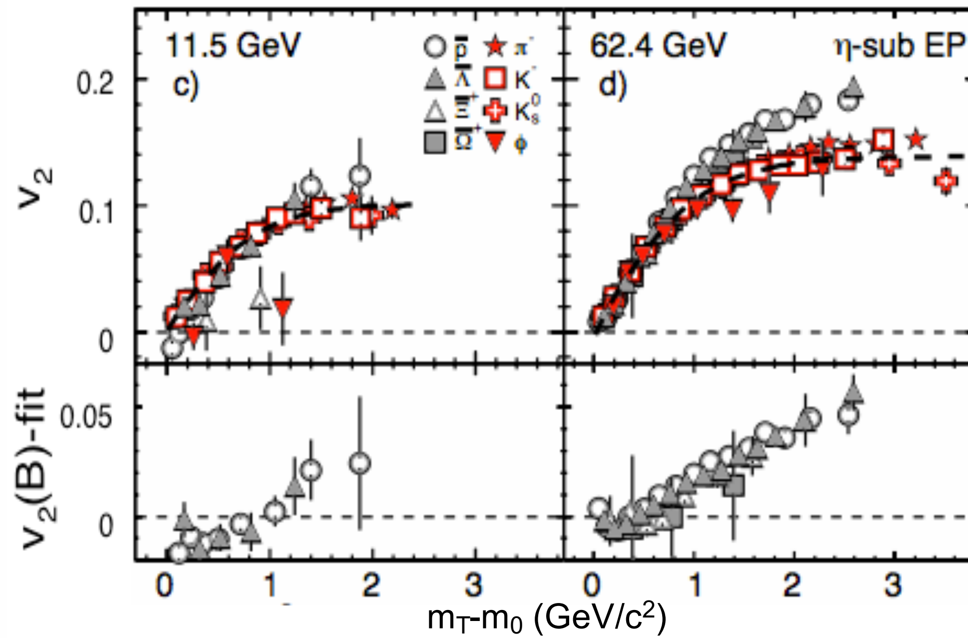




- Baryon-meson splitting reduces and disappears with decreasing energy.
- Ω/ϕ ratio falls off at 11.5 GeV.

Breakdown of Universal NCQ-scaling



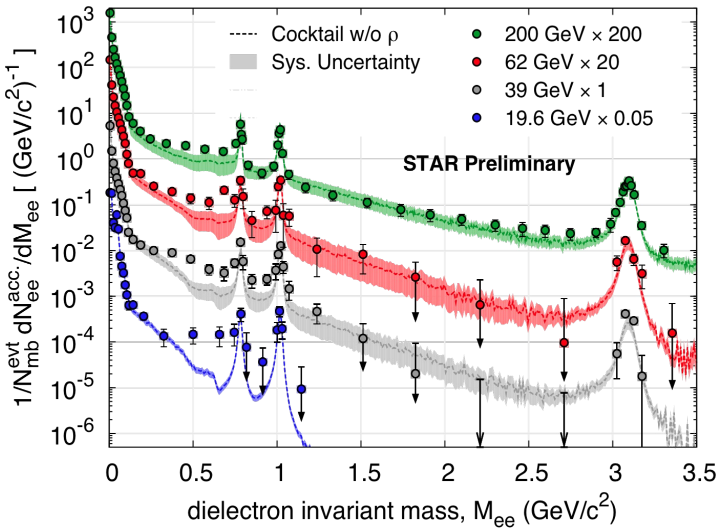


STAR, PRL 110 (2013) 142301, PRC 88 (2013) 014902

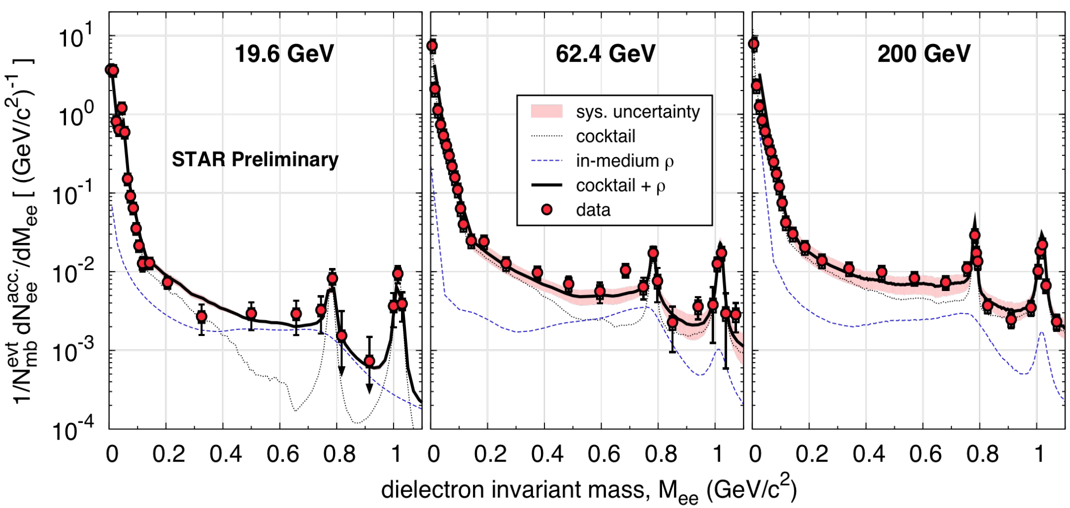
- Significant difference between baryon-antibaryon v_2 at lower energies.
- No clear baryon/meson grouping for anti-particles at <=11.5 GeV.

Universal NCQ scaling is broken at lower energies!

Dielectron Production



- Systematic measurements of dielectron mass spectra over a broad energy range.
- Low mass enhancement persists down to 19.6 GeV.
- Theoretical calculations of in-medium ρ broadening with similar baryon densities from 19.6 - 200 GeV reproduce LMR excesses.

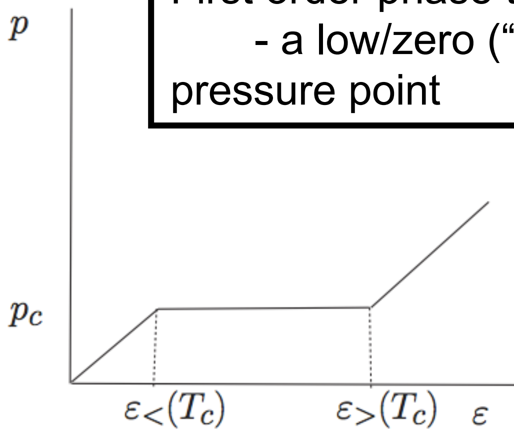


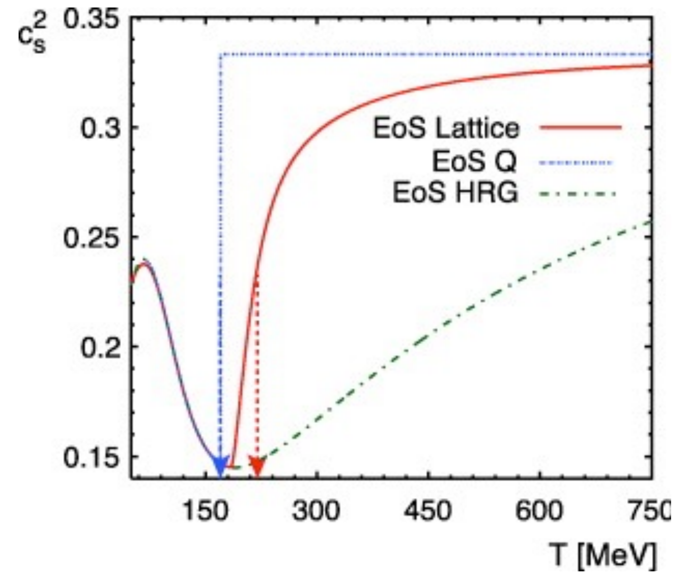
One main goal:
Search for onset of the sQGP thermal radiation

In-medium ρ broadening
R. Rapp: private communications

First Order Phase Transition Search

First order phase transition
- a low/zero ("soft") pressure point





Observables:

- **Transverse momentum spectrum**

  - flattening of $\langle p_T \rangle$ could be an indication of 1st order phase transition

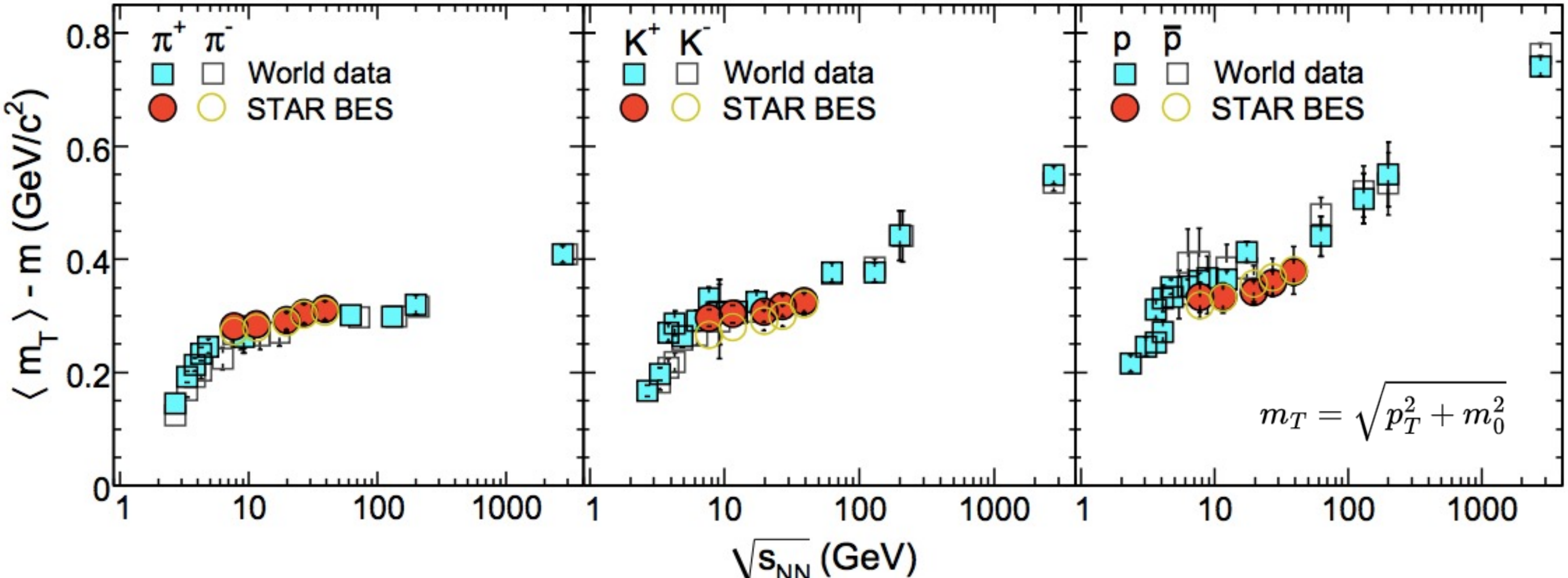
  L. van Hover, PLB 118 (1982) 138

- **Directed flow of protons**

  - A hydro model calculation including 1st order phase transition predicts a double-sign change in the proton directed flow slope parameter.

  H. Stocker, NPA 750 (2005) 121

Flatness in <m_T>



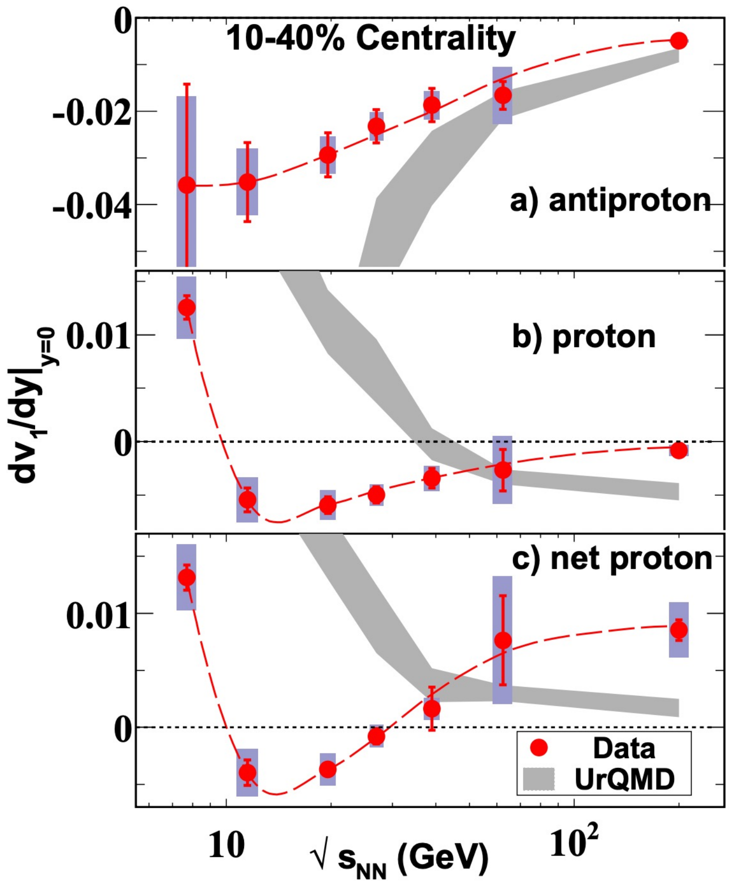
STAR, PRC 96 (2017) 044904

Flatness of <m_T> could be an indicative of mixed-phase

- caution: m_T contains contributions from thermal + collectivity

Quiz: invariant spectrum follows exp(-m_T/T), derive <m_T>

Dip in Directed Flow of (Net-)Protons



- Proton v_1 slope changes sign from + to – between 7.7 and 11.5 GeV and remains small but negative up to 200 GeV.
- v_1 slopes for other particles are negative.
- “net-proton” v_1 slope shows a minimum around 11.5-19.6 GeV.
- UrQMD models cannot explain data.

$$v_1^p = r \cdot v_1^{\bar{p}} + (1-r) \cdot v_1^{\mathrm{net}-p}$$

$$r = \bar{p}/p$$

STAR, *PRL 112 (2014) 162301*

Critical End Point Search

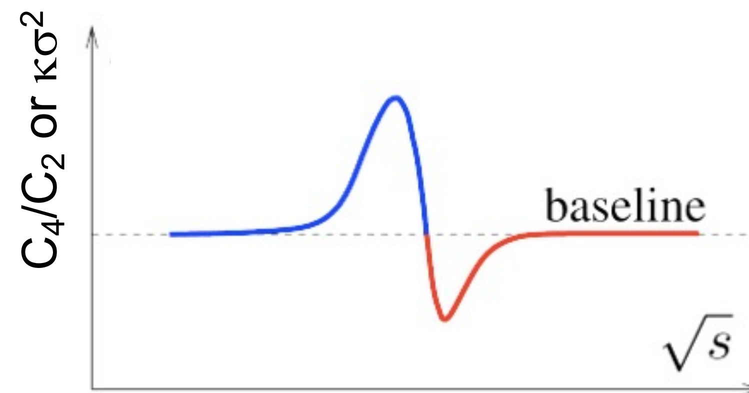
Lattice calculation of QCD critical point at finite $\square_B$ is still challenging.
At critical point with an infinite system
- correlation length should diverge
- susceptibilities should diverge

$$\chi_n^B = -\frac{1}{3^n}\frac{\partial^n f/T^4}{\partial \hat{\mu}_q^n}$$

<u>Proposed Experimental Observables:</u>

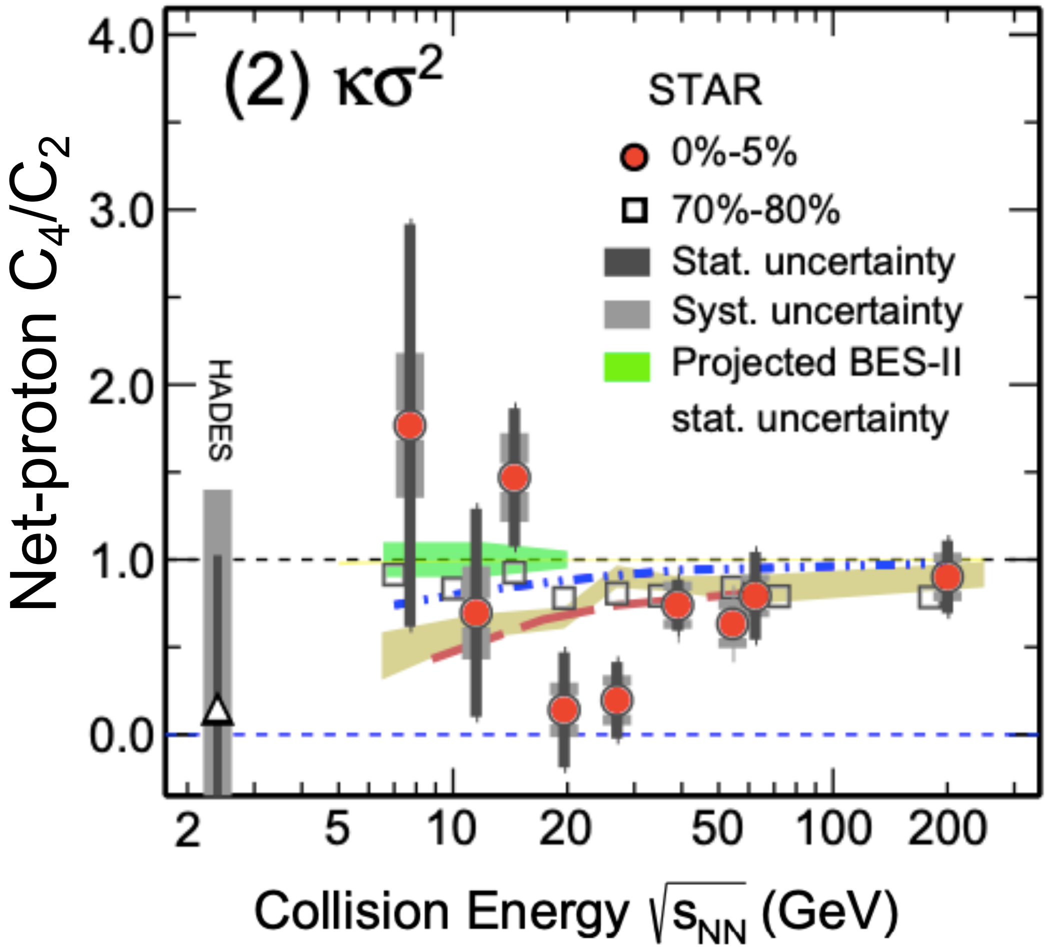
Moments of conserved quantities: net-baryon number, net-strangeness, net-charge etc.
- directly related to the susceptibility ratios (calculable from Lattice QCD)
- sensitive to correlation lengths *(M. A. Stephanov, PRL 102 (2009) 032301)*

$$\begin{aligned}
\text{mean} : \mathrm{M} = \langle N \rangle &= C_1, \\
\text{variance} : \sigma^2 = \langle (\delta N)^2 \rangle &= C_2, \\
\text{skewness} : \mathrm{S} = \langle (\delta N)^3 \rangle / \sigma^3 &= C_3/C_2^{3/2}, \\
\text{kurtosis} : \kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 &= C_4/C_2^2.
\end{aligned}$$



Quiz: what are skewness and kurtosis for a Gaussian distribution (□,σ)?

"Non-monotonic" - Higher Moments of Net-protons



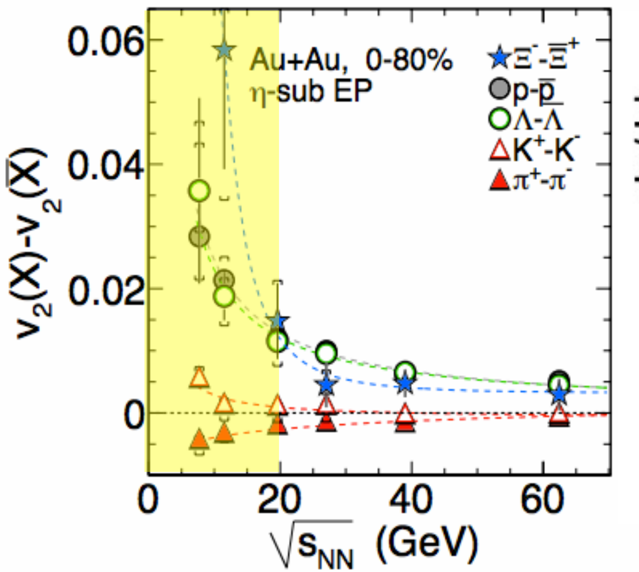
- $\kappa^*\sigma^2$ in peripheral collisions ~ 1

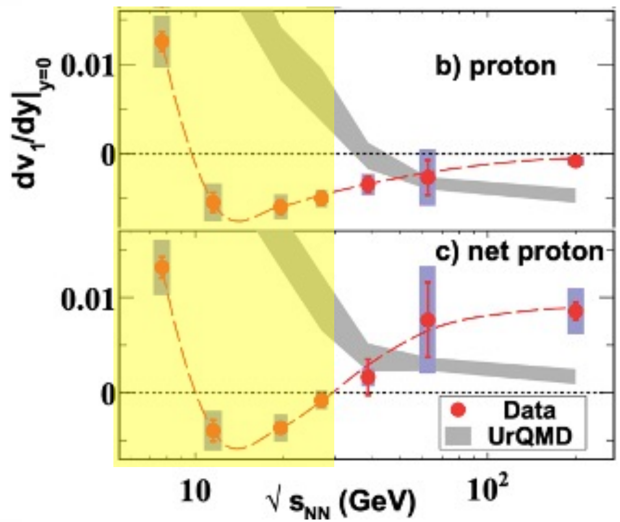
- Non-monotonic distribution vs. collision energy for $\kappa^*\sigma^2$ in central collisions
  - evidence of CEP?

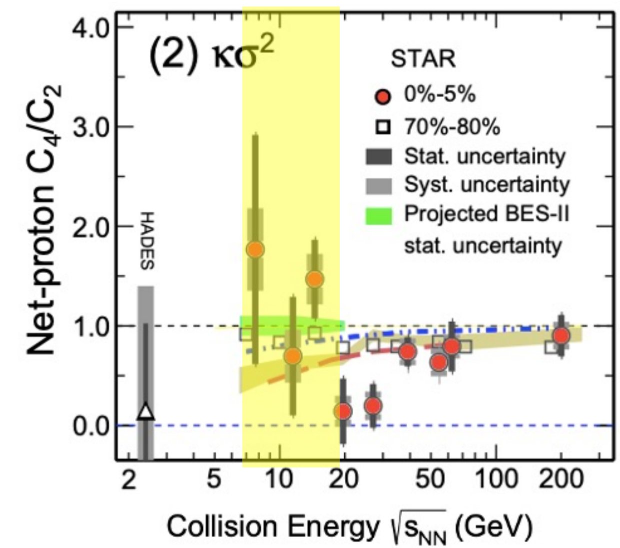
- UrQMD (no QCD CEP) shows a monotonic dependence vs. energy

STAR, PRL 126 (2021) 092301

Summary from BES-I







Many observables show drastic change at energies below 20 GeV
- compared to the results obtained at 200 GeV (formation of sQGP)

→ Beam Energy Scan Phase II with focused energies + increased statistics

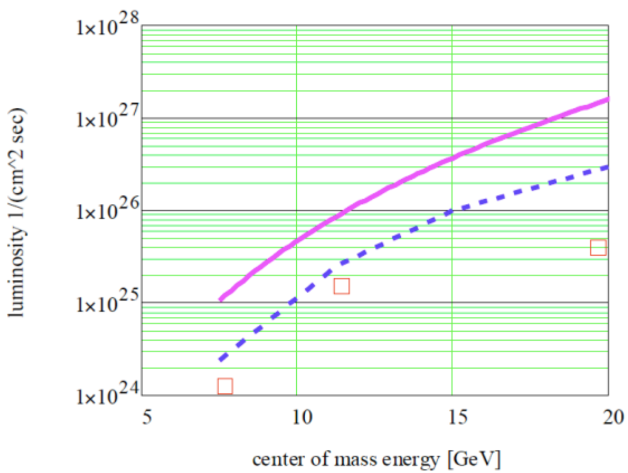
Preparation for BES-II

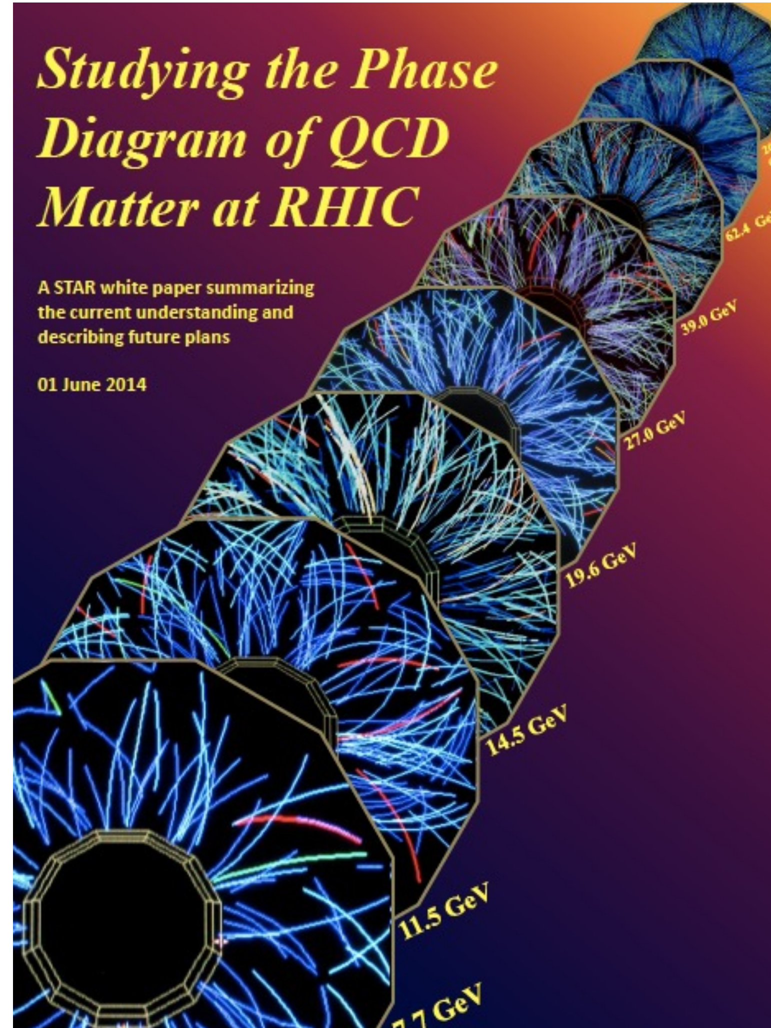
Proposal for BES-II

Observables:

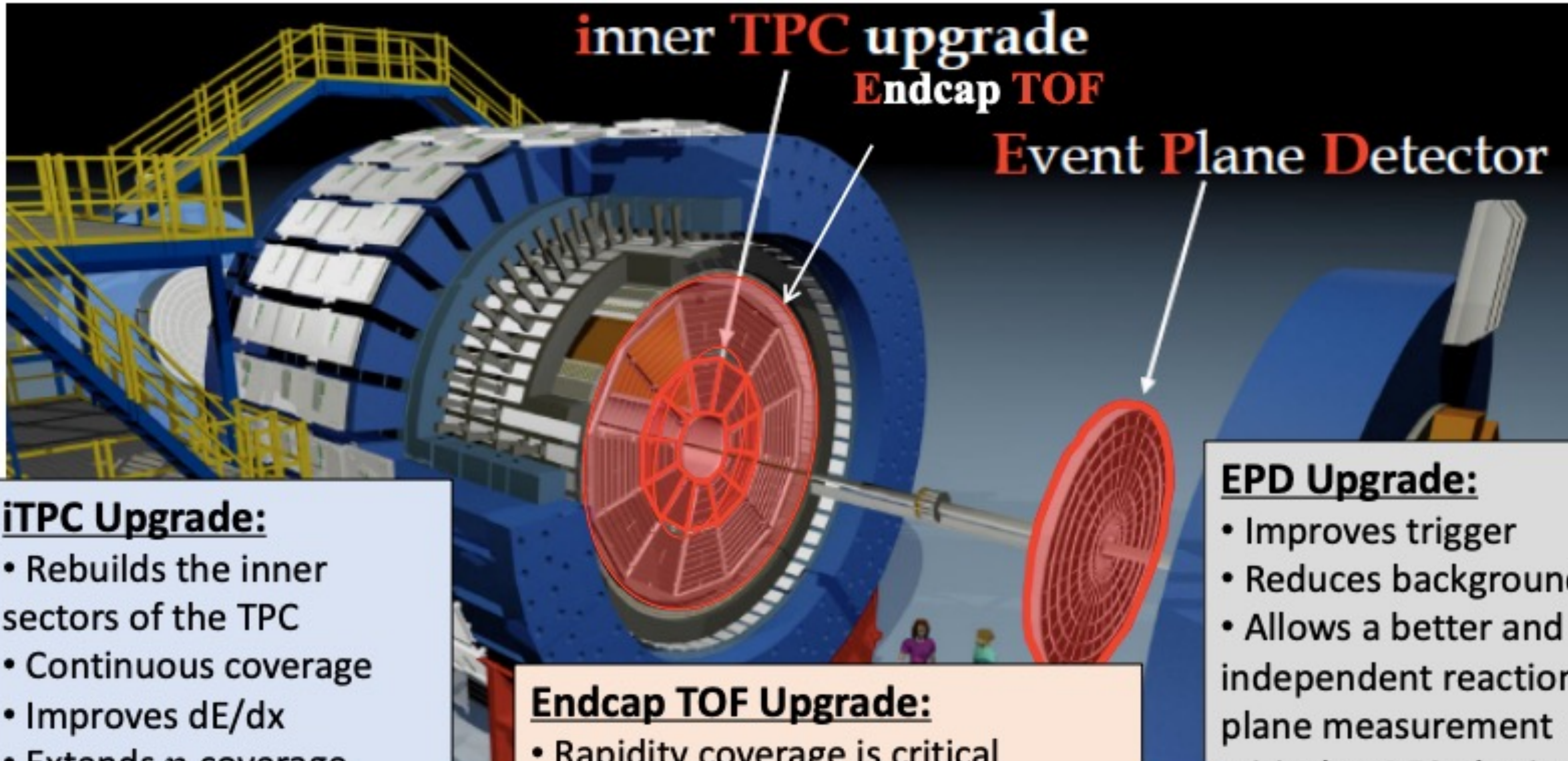
R_{CP} up to p_T = 5 GeV/c
Elliptic Flow (ϕ mesons)
Chiral Magnetic Effect
Directed Flow (protons)
Azimuthal Femtoscopy (protons)
Net-Proton Kurtosis
Dileptons

Require increase of beam luminosities with electron cooling - ***LEReC***





STAR Detector Upgrades for BES-II



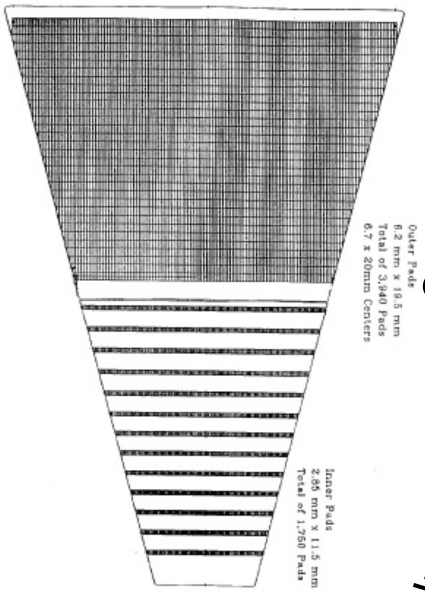
iTPC Upgrade:
- Rebuilds the inner sectors of the TPC
- Continuous coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-off from 125 MeV/c to 60 MeV/c

Endcap TOF Upgrade:
- Rapidity coverage is critical
- PID at η = 1.1 to 1.5
- Improves the fixed target program
- Provided by CBM at FAIR

EPD Upgrade:
- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

inner TPC (iTPC) Upgrade

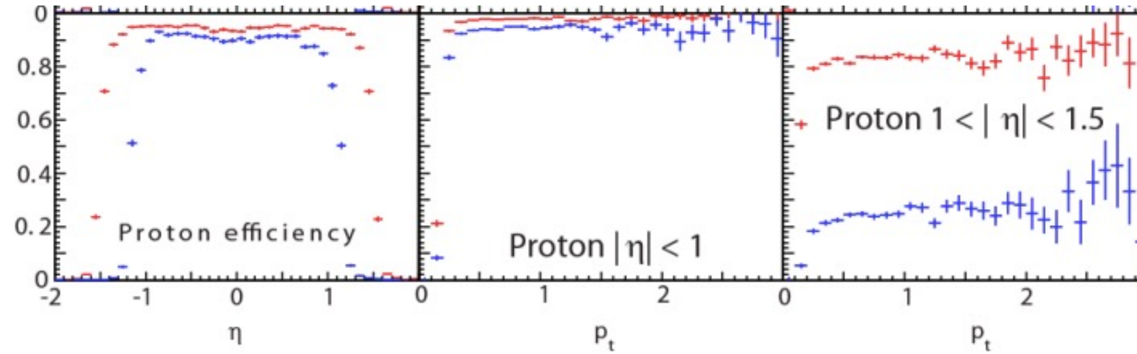
TPC Sector



Outer (32 layers)

Inner (13 layers)
~20% area

full coverage
→ iTPC



Key contributions from SDU, USTC, SINAP etc

Significantly improved tracking efficiency at $1<\eta<1.5$

Improved dE/dx and momentum resolution

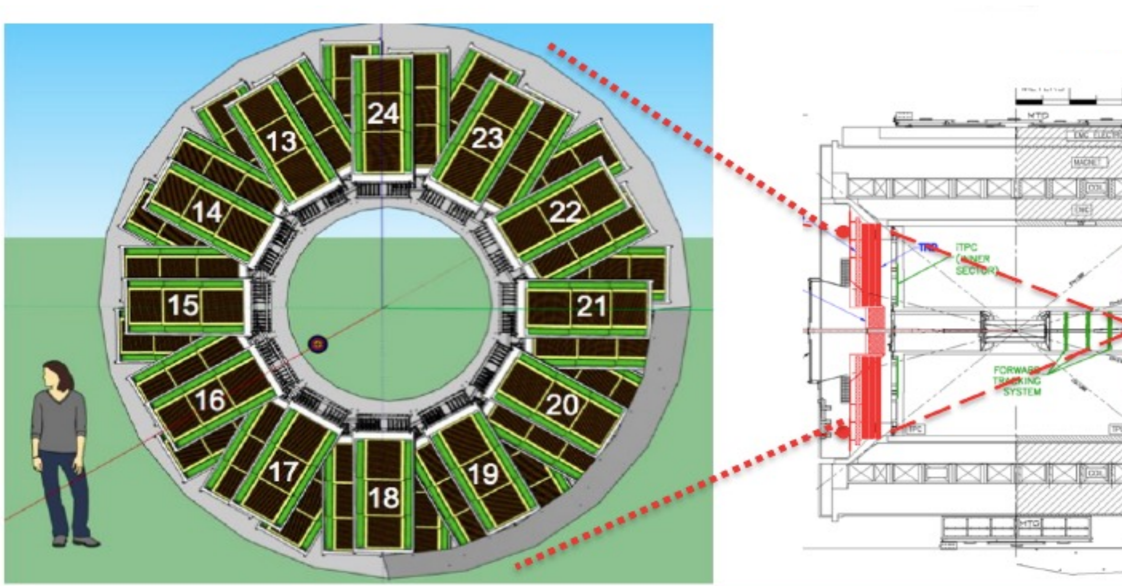
Tracking threshold pushed to 60 MeV/c (125 MeV/c)

engineering run in 2018

fully operation in 2019

Quiz: iTPC 40 layers (r= 56-128cm), tracking need 15 hits minimum (B=0.5 T), derive tracking p_T threshold.

Endcap TOF (eTOF) Upgrade

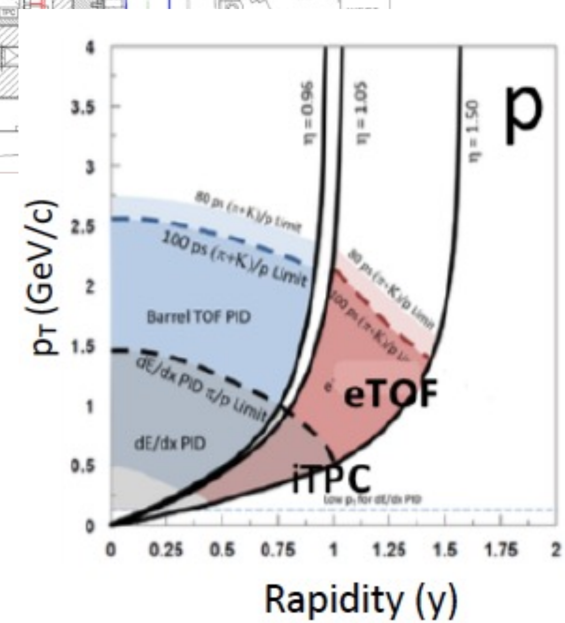


CBM MRPC TOF modules (FAIR Phase-0)

New PID capability

extend rapidity range (1<η<1.6) (Collider)

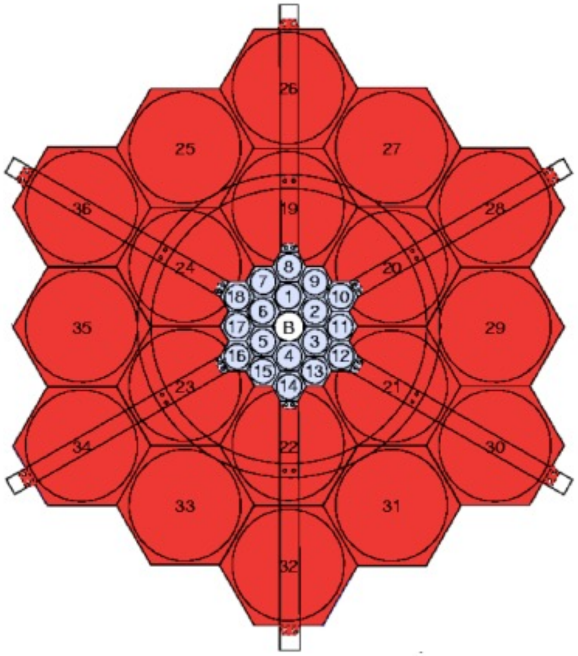
midrapidity in CoM frame in FXT mode



fully operation in 2019

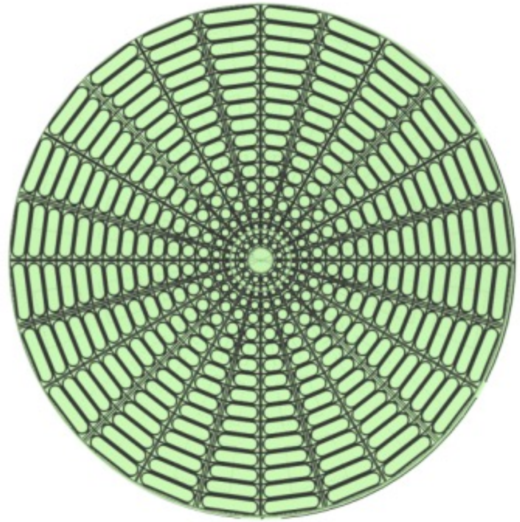
Event Plane Detector (EPD) Upgrade

fully operation in 2018



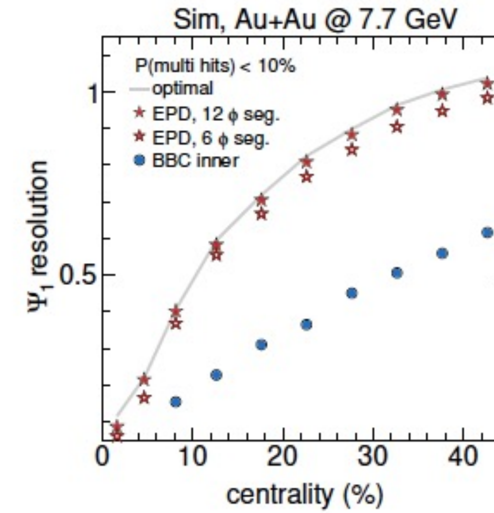
(a) Beam-Beam Counters

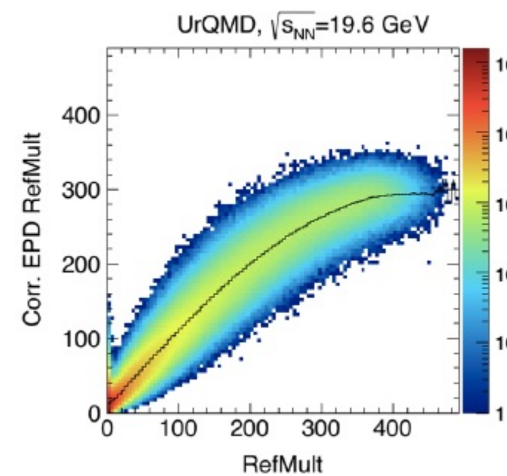
32 channels



(b) Event Plane Detector

768 channels

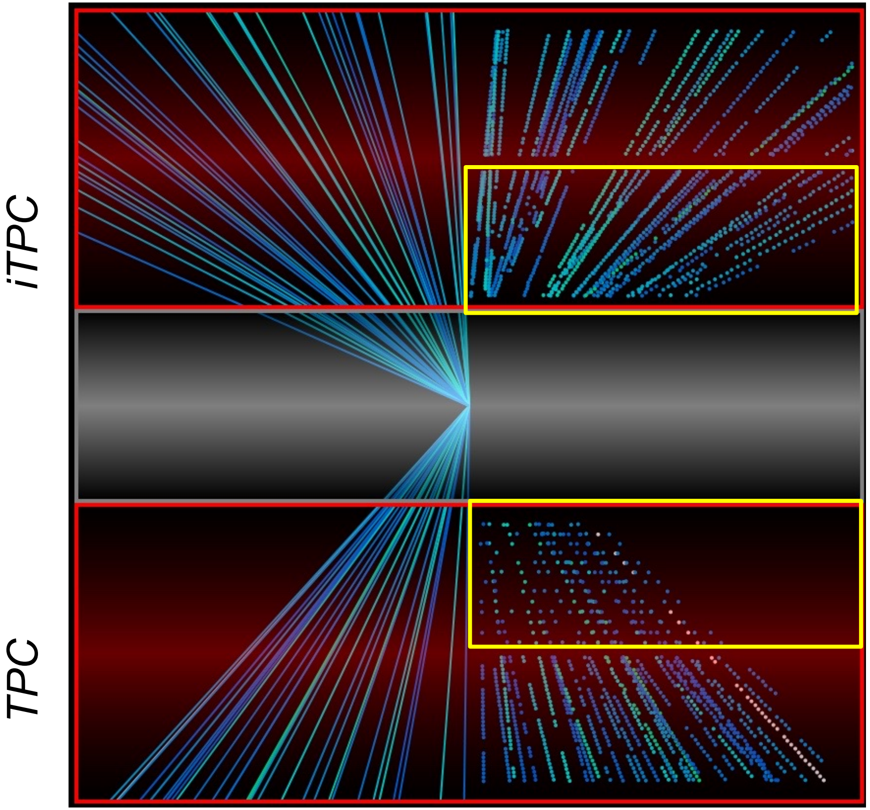




Significantly improved granularity →

- Event plane recon.
- Centrality selection
- Triggering

Summary



With the LEReC and STAR upgrade detectors, RHIC launched Beam Energy Scan Phase-II from 2019 - 2021

- ***high statistics***
- ***extended kinematic coverage***
- ***extended PID capability***

54.4 GeV in 2017 and 27 GeV in 2018 are broadly considered as BES-II as well, though these datasets didn't benefit from the detector upgrades

Hoeworks

1) *Time resolution needed for STAR TOF to allow 3σ separation of protons from π/K? (L~ 2.1m)*

2) *Can the rdEdx method be applied to kaons? Any way to identify K+/- at high p?*

3) *Invariant spectrum follows exp(-m_T/T), derive $\langle m_T \rangle$.*

4) *What are skewness and kurtosis for a Gaussian distribution (□,σ)?*

5) *iTPC 40 layers (r= 56-128cm), tracking need 15 hits minimum (B=0.5 T), derive tracking p_T threshold.*

Thursday Presentation

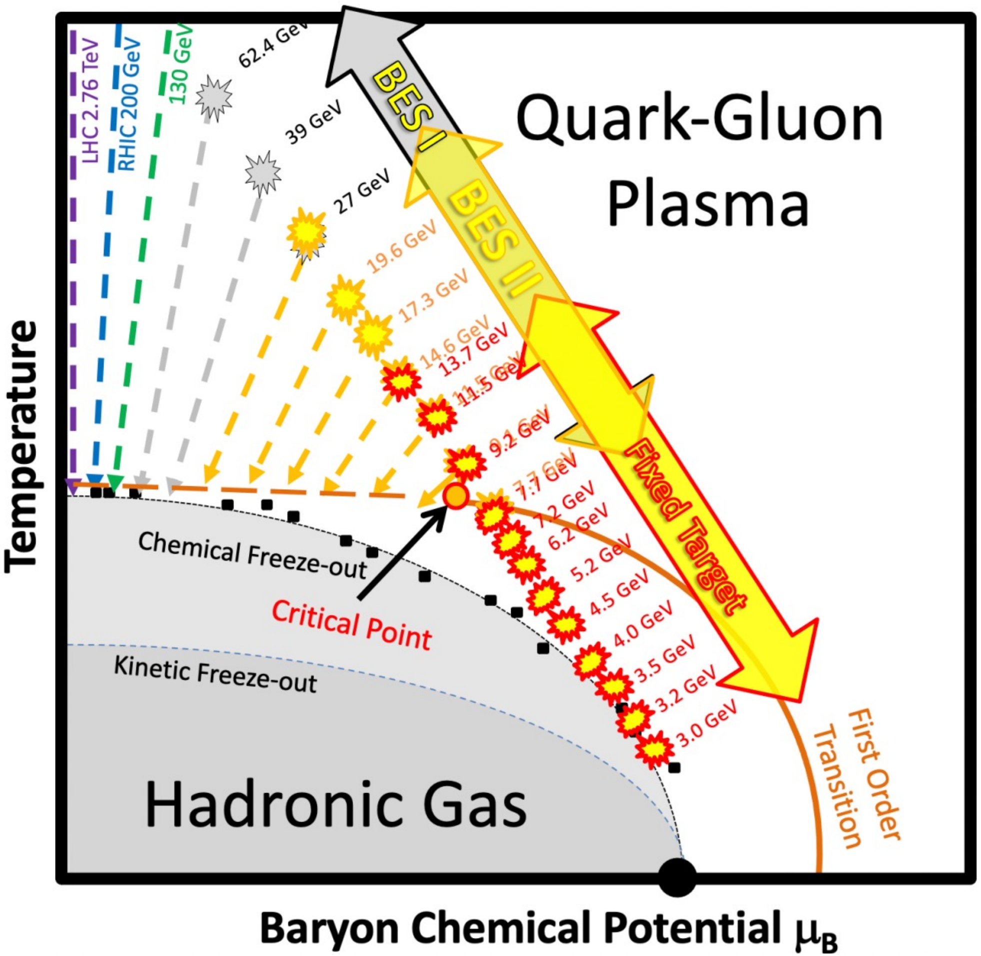
Thursday Outline

Beam Energy Scan Phase-II Data Taken

Recent Results from BES-II

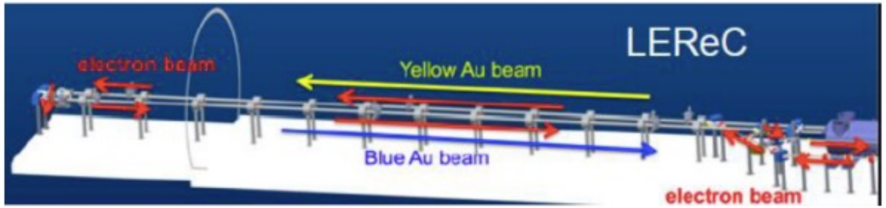
High $\square_B$ Physics: Future Prospects from BES-II and Beyond

RHIC Beam Energy Scan Program



	$\sqrt{s_{NN}}$ (GeV)	Beam E (GeV)	# of Good Events	BES-I
2017	54.4		1350 M	
2018	27		560 M	70 M
	7.2	26.5 (FXT)	155 M	
	3.0	3.85 (FXT)	258 M	
2019	19.6		582 M	36 M
	14.6		324 M	20 M
	7.7	31.2 (FXT)	50.6 M	
	3.9	7.3 (FXT)	52.7 M	
	3.2	4.59 (FXT)	201 M	
2020	11.5		235 M	12 M
	9.2		162 M	
	7.7	31.2 (FXT)	112 M	
	7.2	26.5 (FXT)	317 M	
	6.2	19.5 (FXT)	118 M	
	5.2	13.5 (FXT)	103 M	
	4.8	11.5 (FXT)	235 M	
	4.5	9.8 (FXT)	108 M	
	3.9	7.3 (FXT)	117 M	
	3.5	5.75 (FXT)	116 M	
2021	17.3		250 M	
	7.7		101 M	5 M
	13.5	100 (FXT)	50.7 M	
	11.5	70 (FXT)	51.7 M	
	9.1	44.5 (FXT)	53.9 M	
	3.0	3.85 (FXT)	2.0 B	

Electron Cooling - LEReC

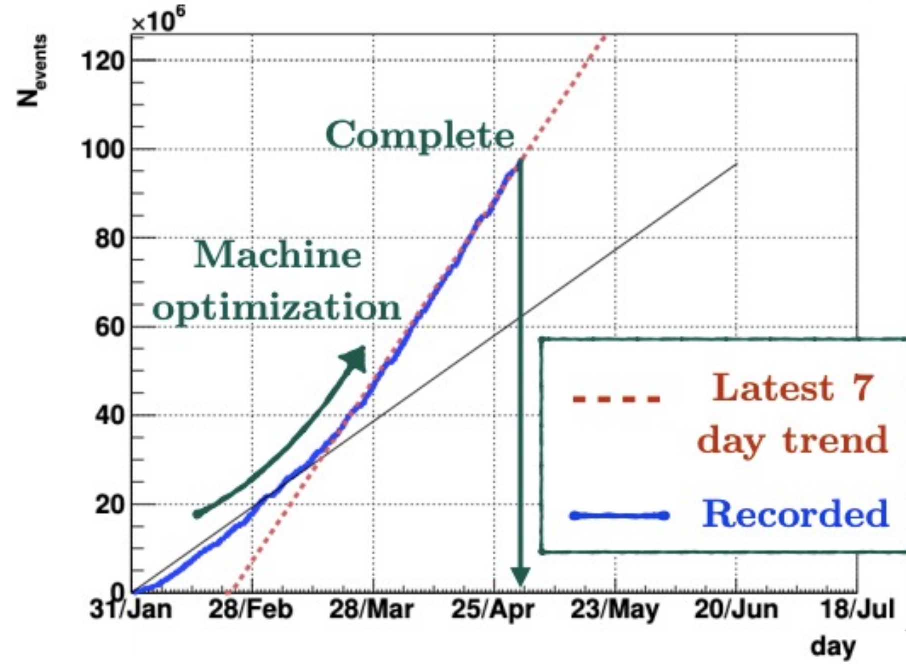


LEReC – Low Energy RHIC electron Cooling

Good Event Rate

$\sqrt{s_{NN}}$ (GeV)	BES-I	BES-II
19.6	80	500
17.3	-	400
14.6	25	190
11.5	20	120
9.2	6	40
7.7	7	30

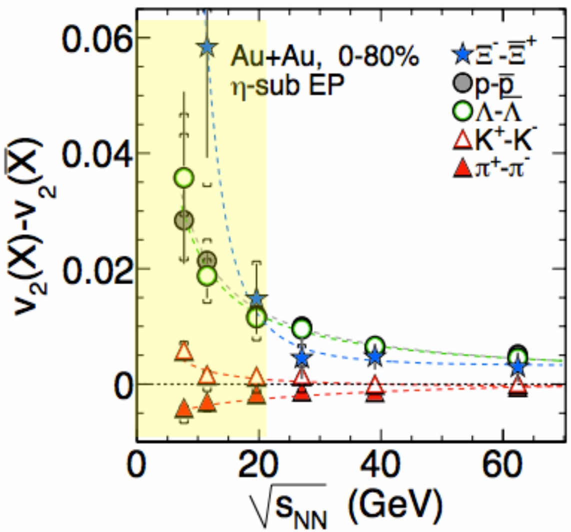
Au+Au 7.7 GeV in 2021



7.7 GeV goal finished within 12.1 weeks!
(estimated 20 weeks)

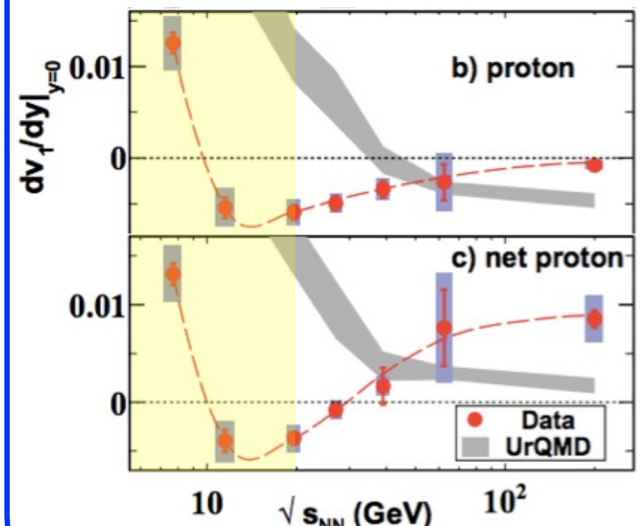
Key Findings from STAR BES-I

Breakdown of NCQ-scaling between P and anti-P



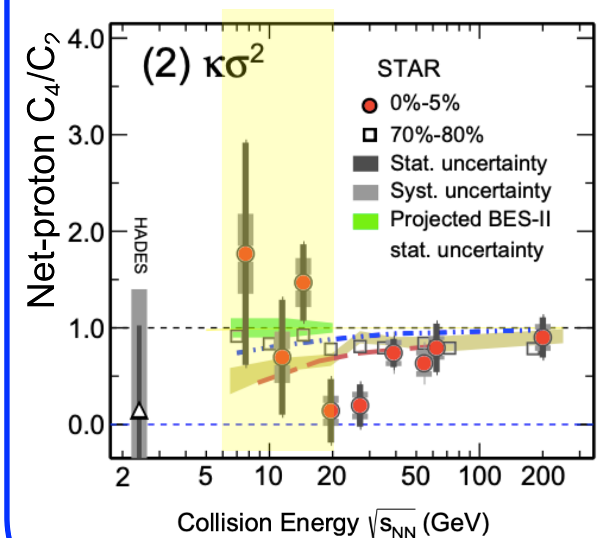
PRL 110 (2013) 142301

Minimum of net-proton v_1



PRL 112 (2014) 162301

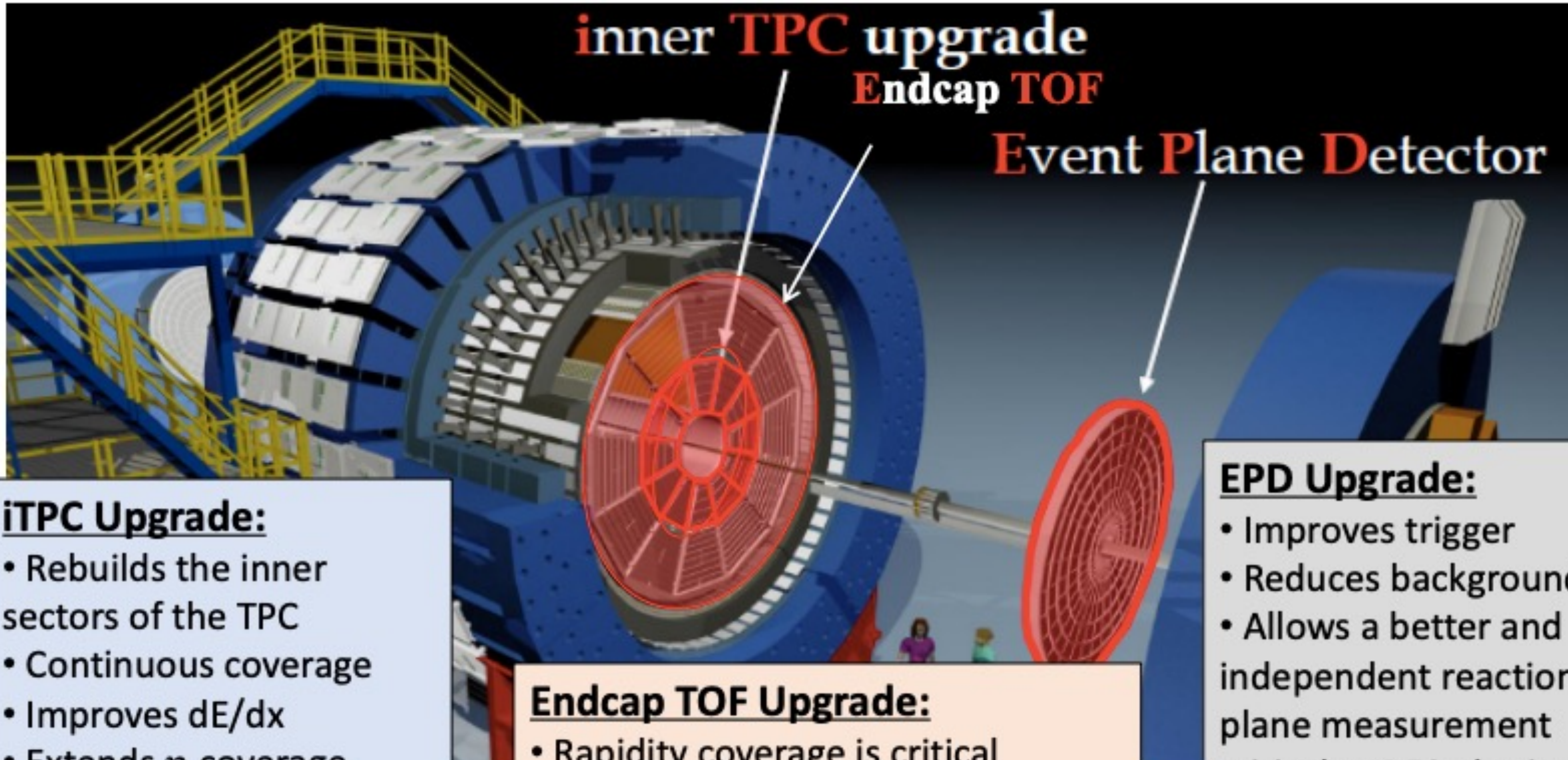
Nonmonotonicity of net-proton C_4/C_2



PRL 126 (2021) 092301

Many different features observed at low energies, while uncertainties at < 20 GeV are limited
→ Beam Energy Scan Phase-II (high statistics + extended kinematic coverage/PID capability)

STAR Detector Upgrades for BES-II



iTPC Upgrade:

- Rebuilds the inner sectors of the TPC
- Continuous coverage
- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-off from 125 MeV/c to 60 MeV/c

Endcap TOF Upgrade:

- Rapidity coverage is critical
- PID at η = 1.1 to 1.5
- Improves the fixed target program
- Provided by CBM at FAIR

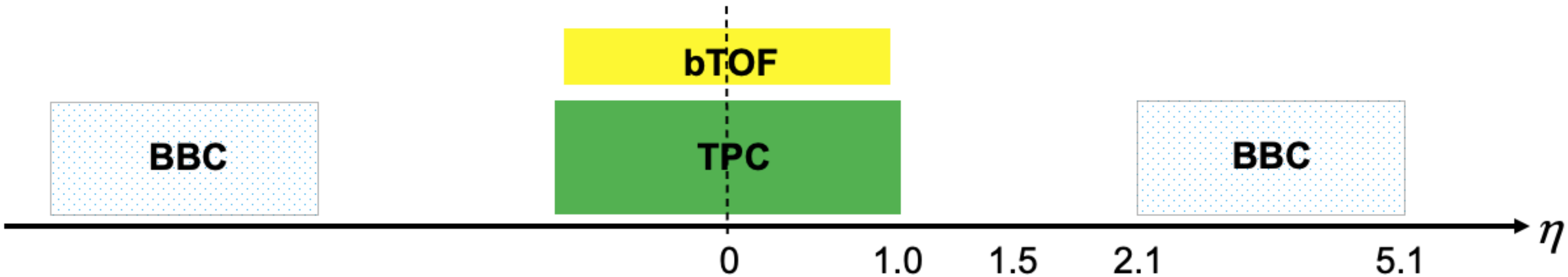
EPD Upgrade:

- Improves trigger
- Reduces background
- Allows a better and independent reaction plane measurement critical to BES physics

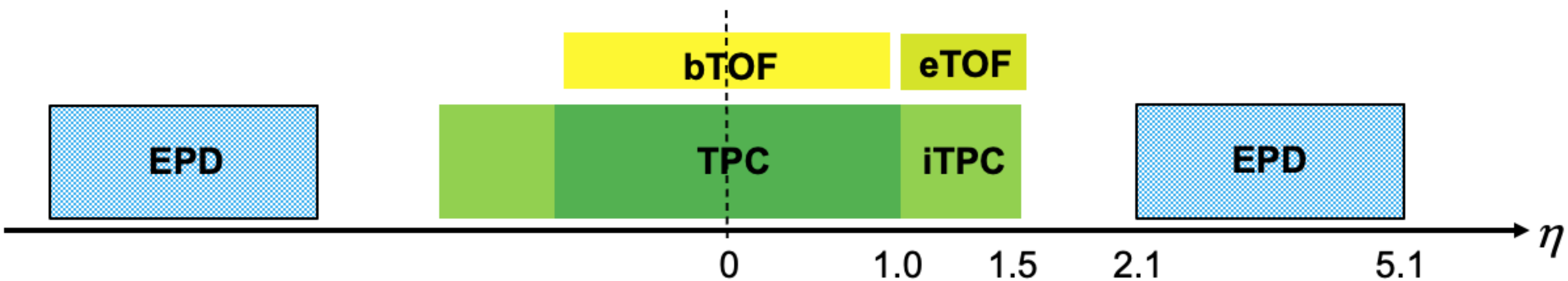
Detector Acceptance Coverage

STAR @ BES-I

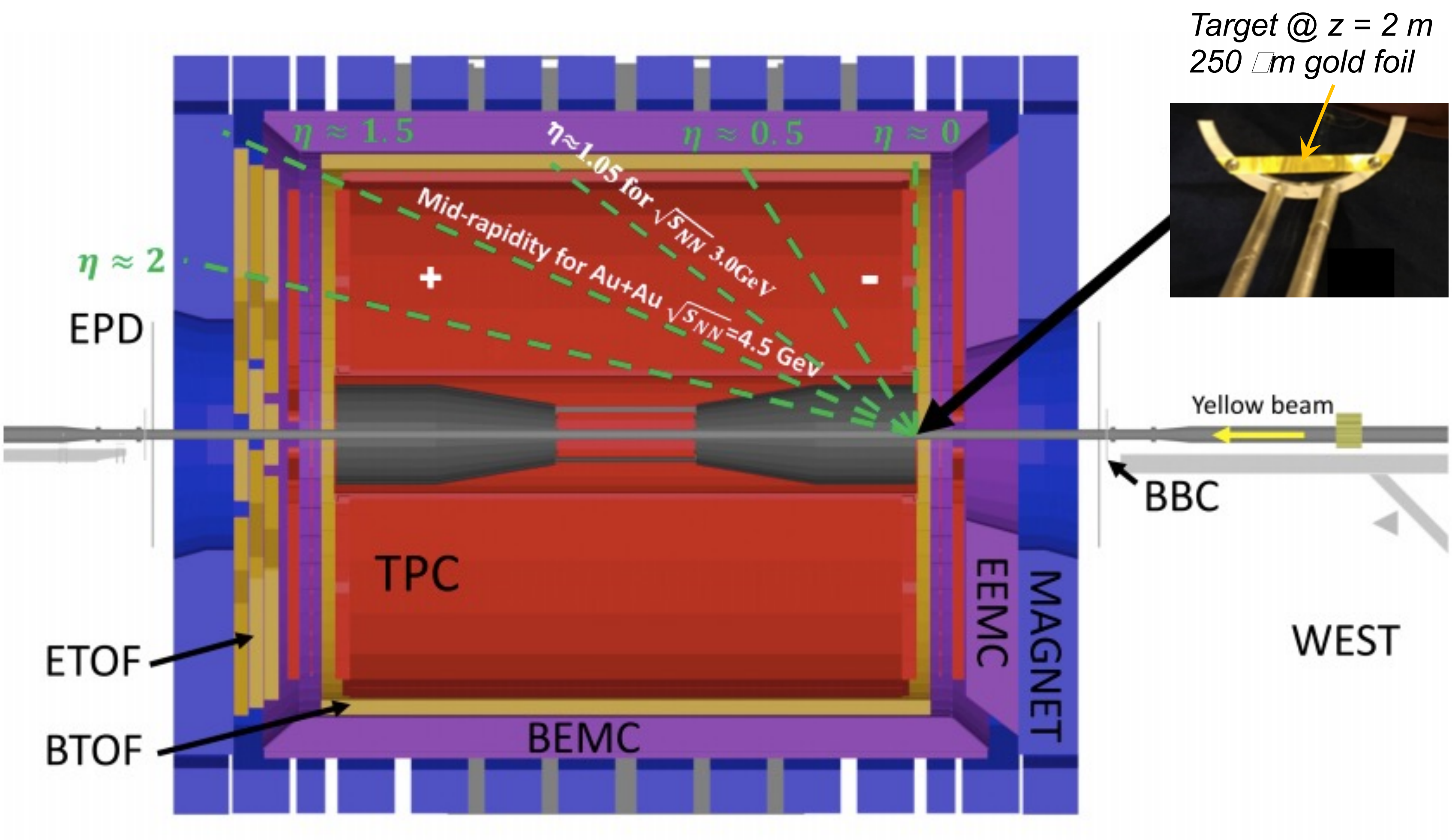
Collider Mode



STAR @ BES-II



STAR Fixed-Target (FXT) Configuration

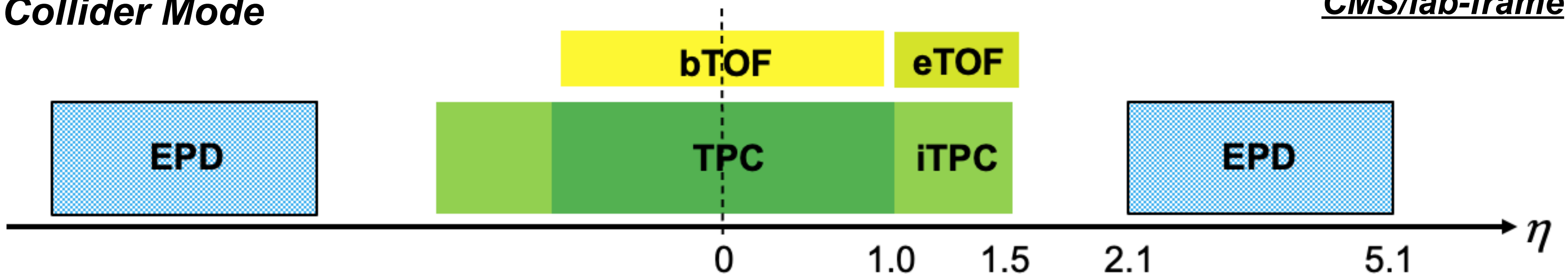


Courtesy of Benjamin Kimelman

STAR Acceptance: Collider vs. Fixed-target

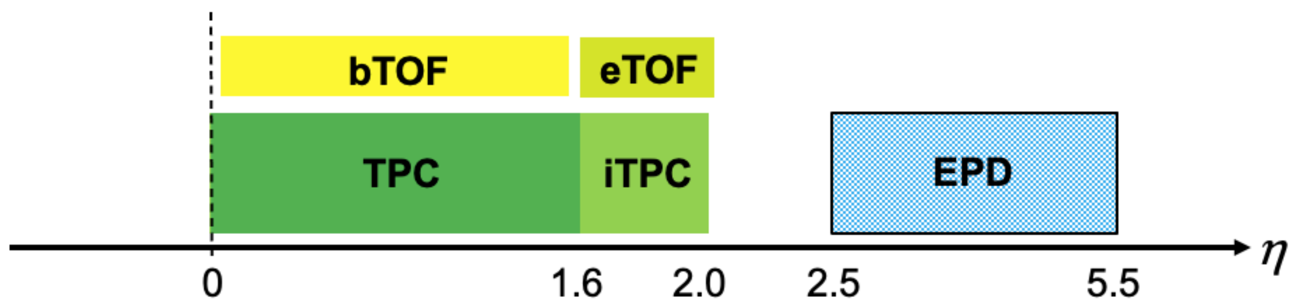
Collider Mode

CMS/lab-frame



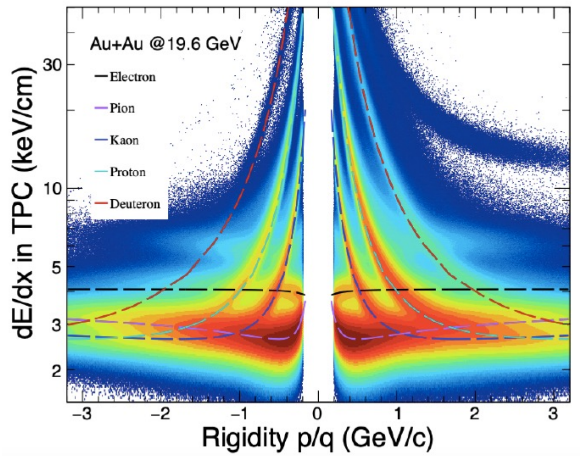
Fixed-target Mode

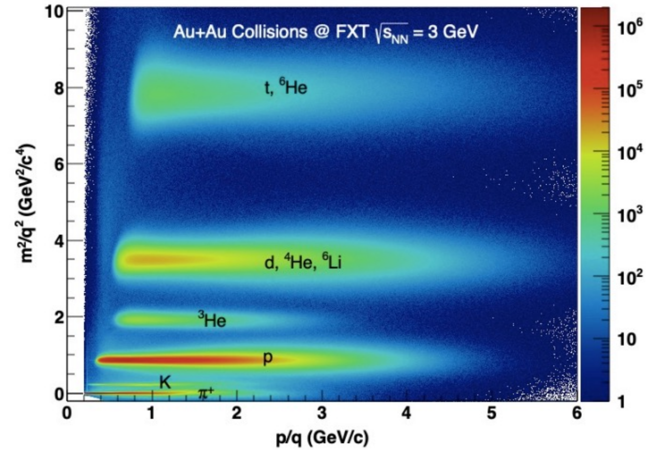
lab-frame

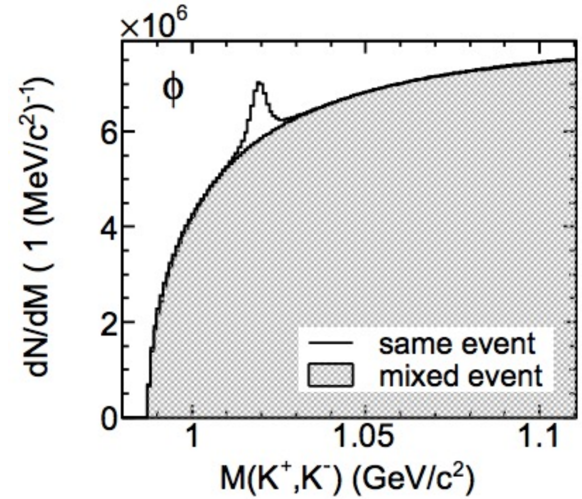


y_{mid}	1.05	1.53	2.1
$\sqrt{s_{NN}}$ (GeV)	3.0	4.5	7.7

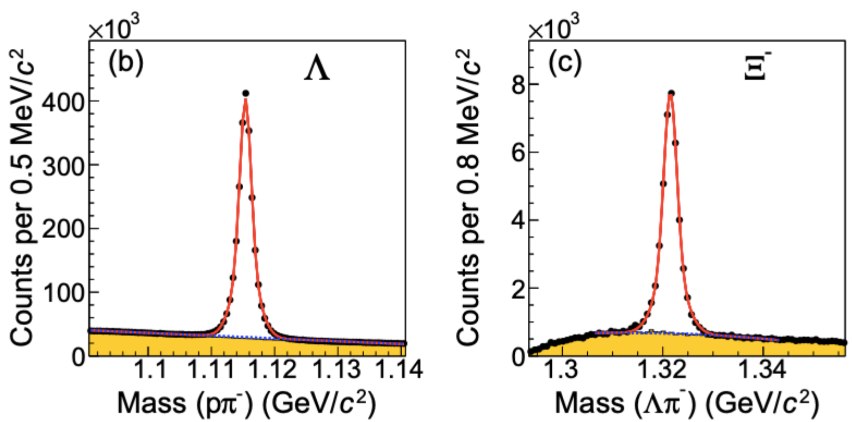
Particle Identification



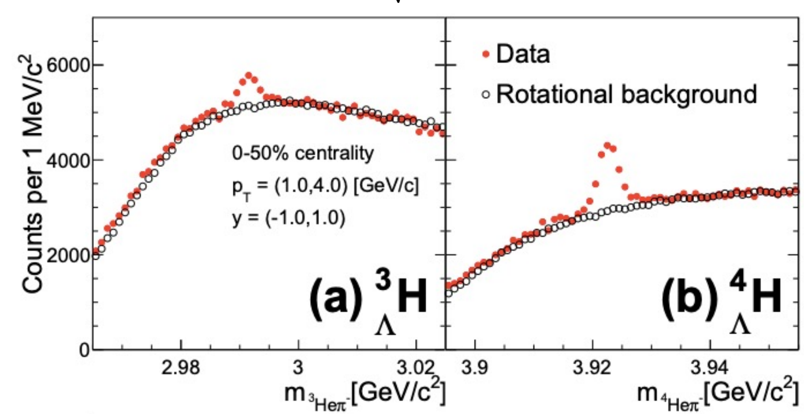




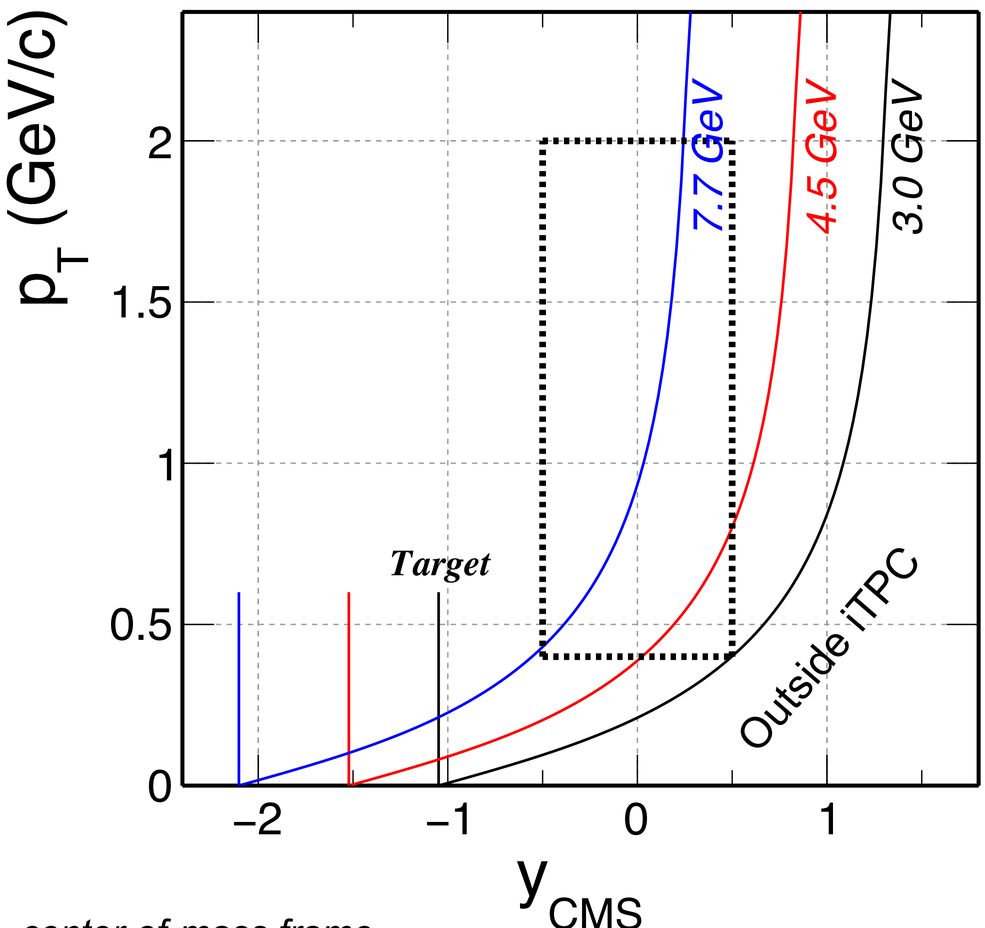
STAR, $\sqrt{s_{NN}}$ = 7.7 GeV Au+Au (0-80%), $|y|$<0.5



Au+Au $\sqrt{s_{NN}}$ = 3.0 GeV



Proton Acceptance in Center-of-Mass Frame in FXT



center-of-mass frame

Dashed box:

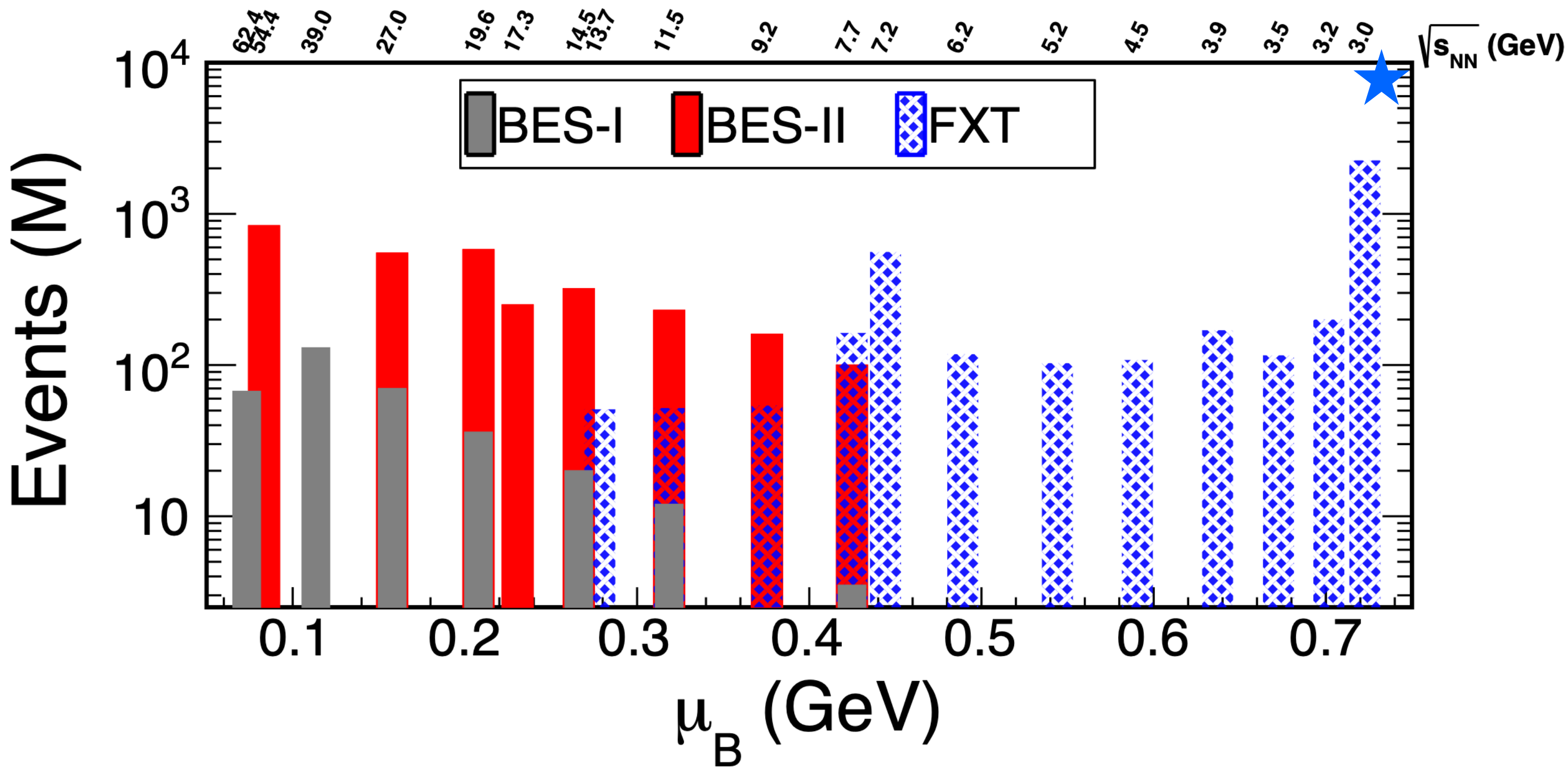
- $0.4<p_T<2.0$ GeV/c
- $|y|<0.5$

- Used in collider net-proton cumulant measurements

At 3.0 GeV, STAR with iTPC+eTOF covers full range of $0.4<p_T<2.0$, $|y|<0.5$ for proton cumulants measurements.

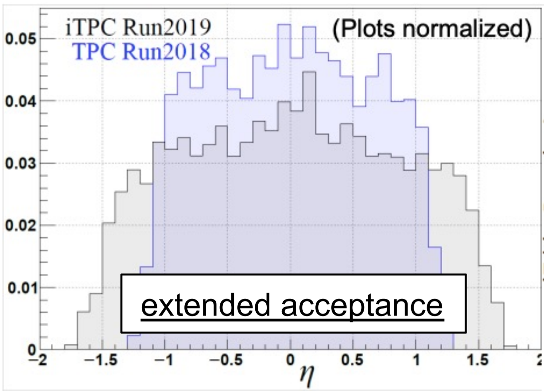
Datasets from Beam Energy Scan Phase-II

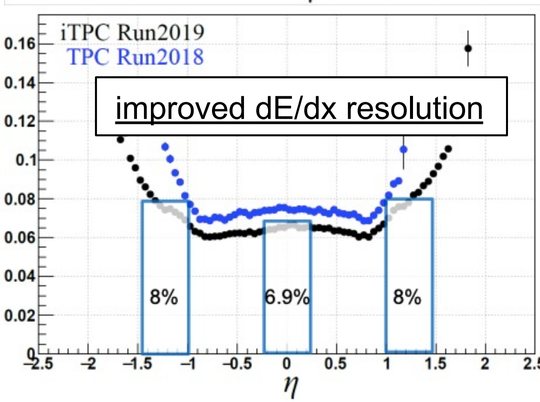
- x10-20 more statistics compared to BES-I at collider energies
- 8 collider energies (7.7 – 54.4 GeV) / 12 fixed-target energies (**3.0** - 13.5 GeV)



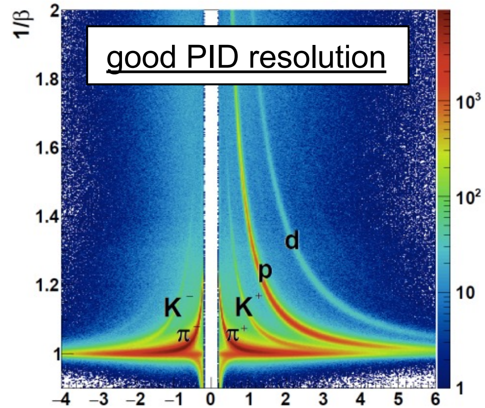
Detector Performance

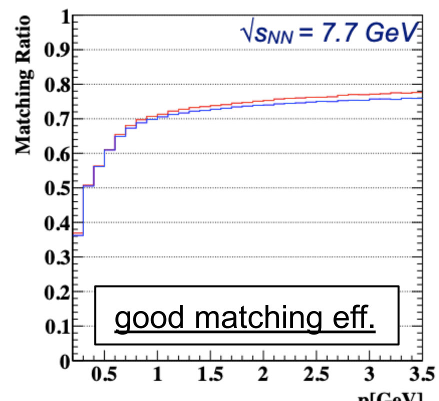
iTPC (2019+)



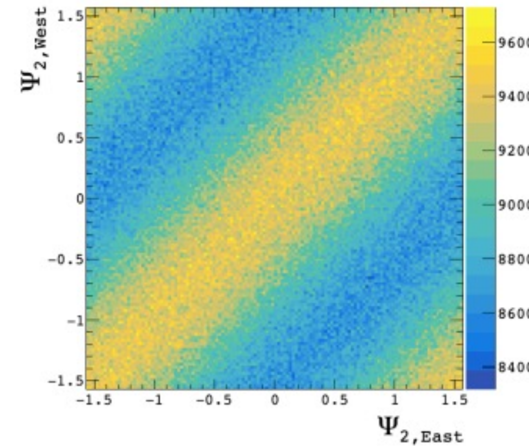


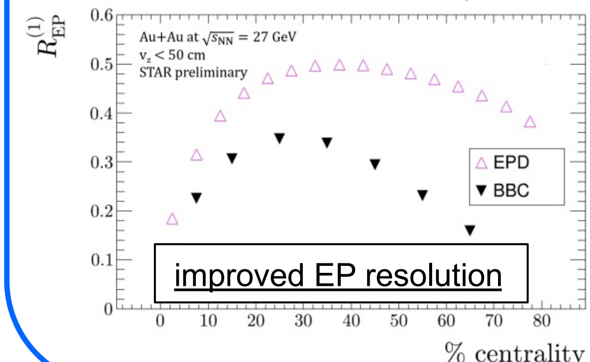
eTOF (2019+)





EPD (2018+)

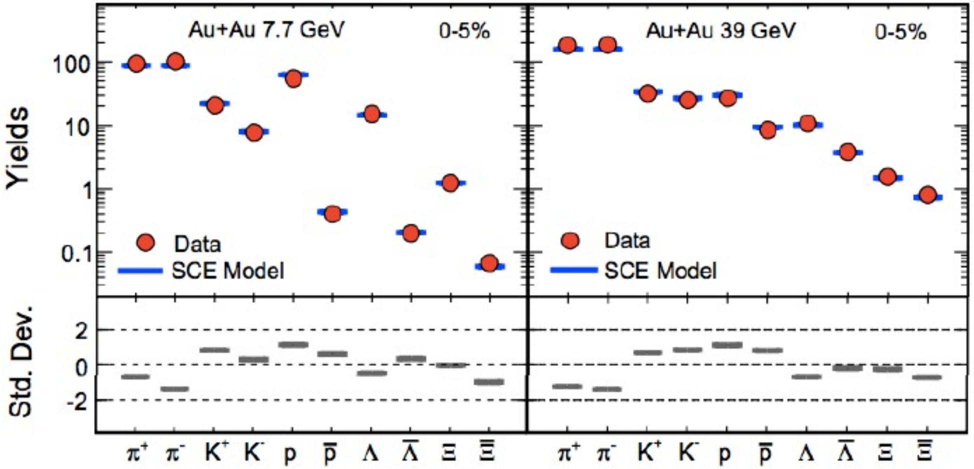


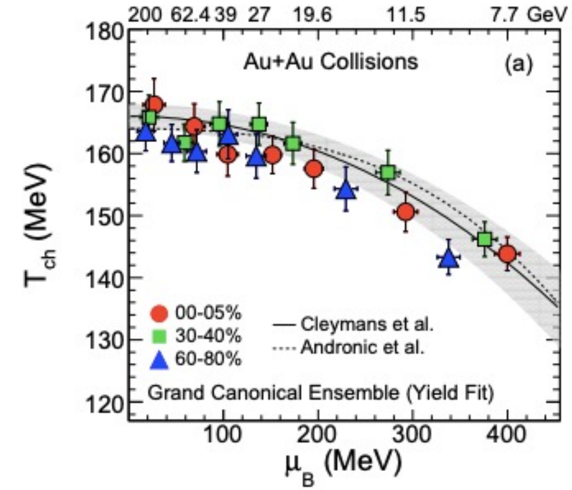


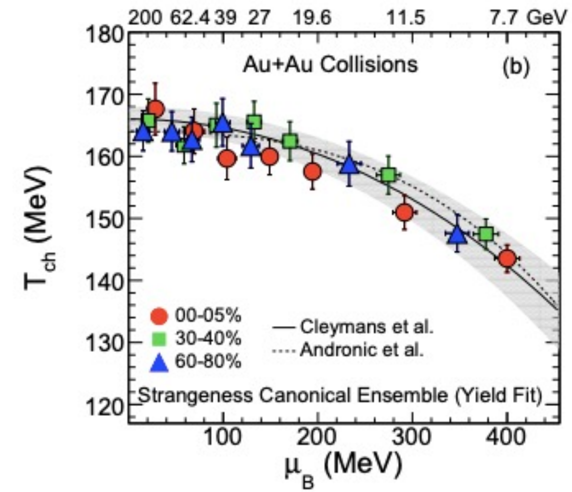
Recent Results from BES-II

Particle Yield and Chemical Freeze-out

PRC 96 (2017) 044904







- Statistical model THERMUS used to extract FO parameters
- Particle yields/ratios ($\pi^{\pm}$, $K^{\pm}$, p, $\bar{p}$, K_S, Λ, $\bar{\Lambda}$, Ξ^-, $\bar{\Xi}^+$)
  - *midrapidity / 4π*

Grand Canonical Ensemble

$$N_i^{GC} = \frac{g_i V}{2\pi^2} \sum_{k=1}^{\infty} (\mp 1)^{k+1} \frac{m_i^2 T}{k} K_2\left(\frac{k m_i}{T}\right) e^{\beta k \mu_i}$$

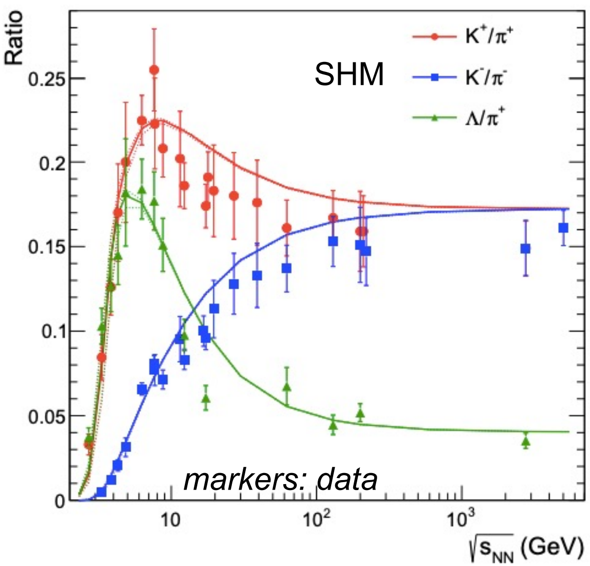
Canonical Ensemble

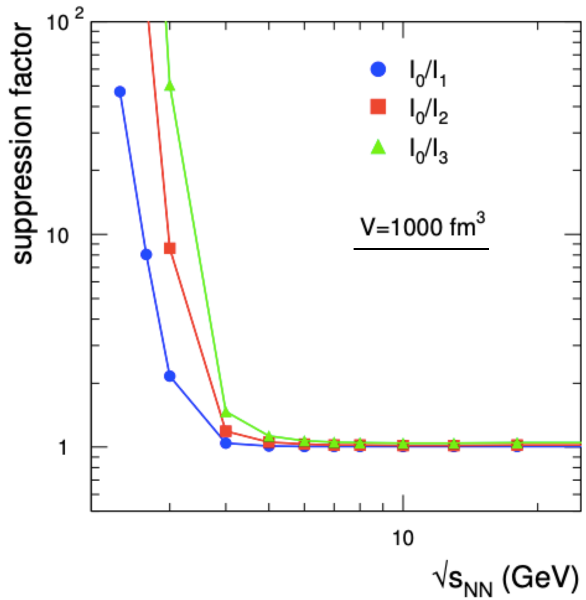
$$N_i^S = \left(\frac{Z_{S-S_i}}{Z_S}\right) N_i^{GC}\Big|_{\mu_S=0}$$

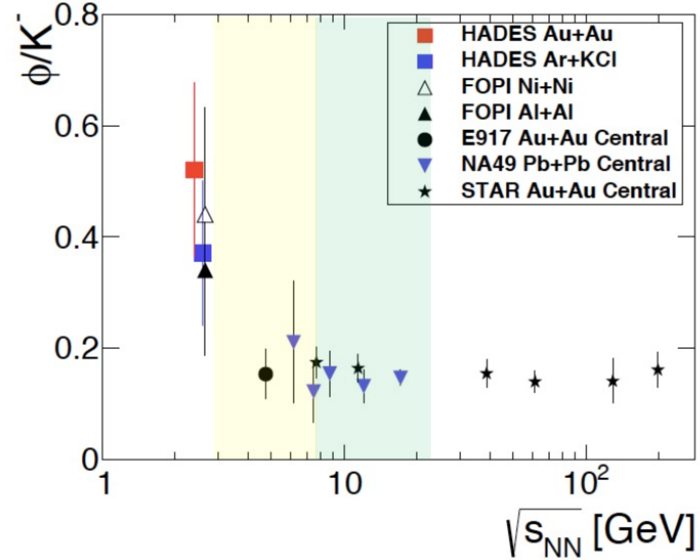
Strange Production and "Canonical Suppression"

SHM: A. Andronic et al, Nature 561 (2018) 321

HADES, PLB 778 (2018) 403







canonical suppression (correction) factor for open strange hadrons

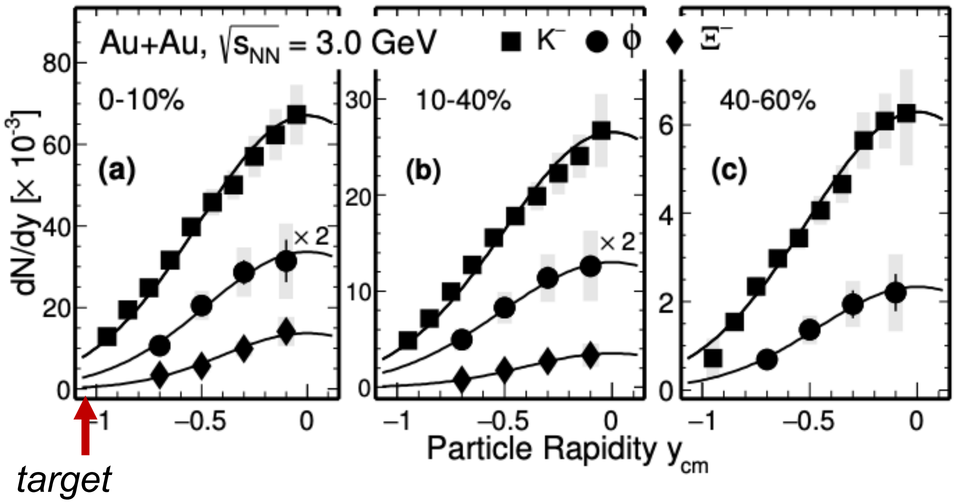
$$n^{C}_{K,\Lambda} = n^{GC}_{K,\Lambda} \cdot \frac{I_1(N_S)}{I_0(N_S)},$$
$$n^{C}_{\phi} = n^{GC}_{\phi}$$

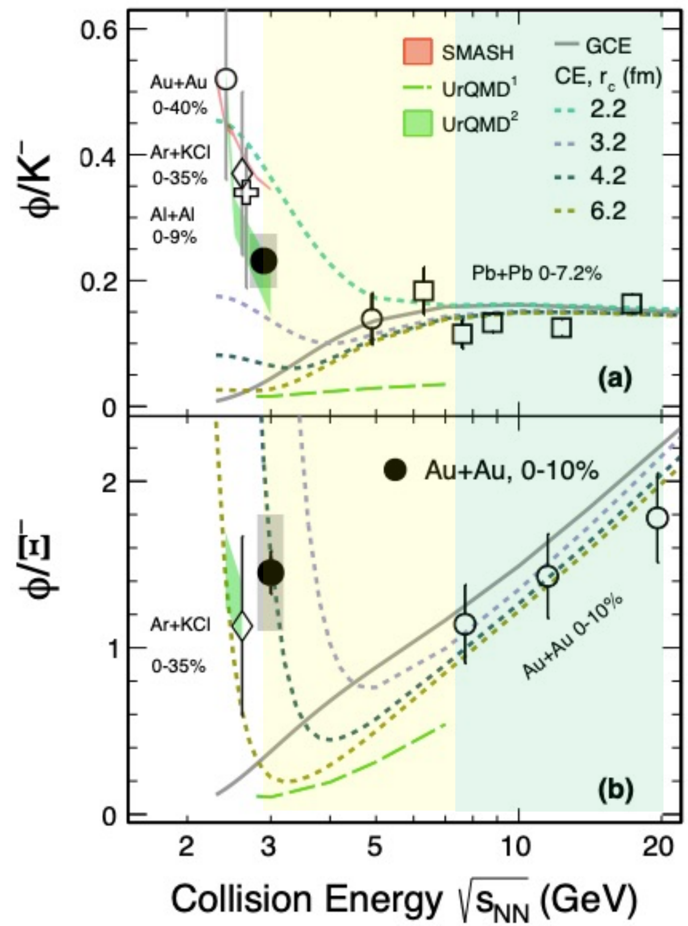
φ/K, φ/Ξ – probe canonical ensemble

- Hint of φ/K enhancement at SIS energies

Multi-strange Hadrons in Au+Au Collisions at 3 GeV

STAR, PLB 831 (2022) 137152





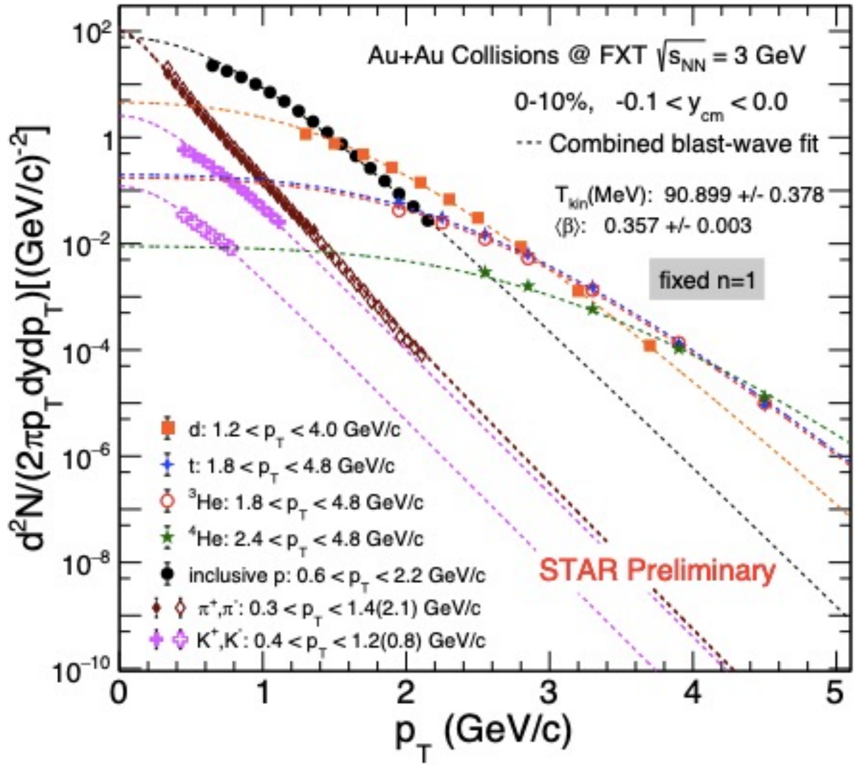
At 3 GeV Au+Au collisions:

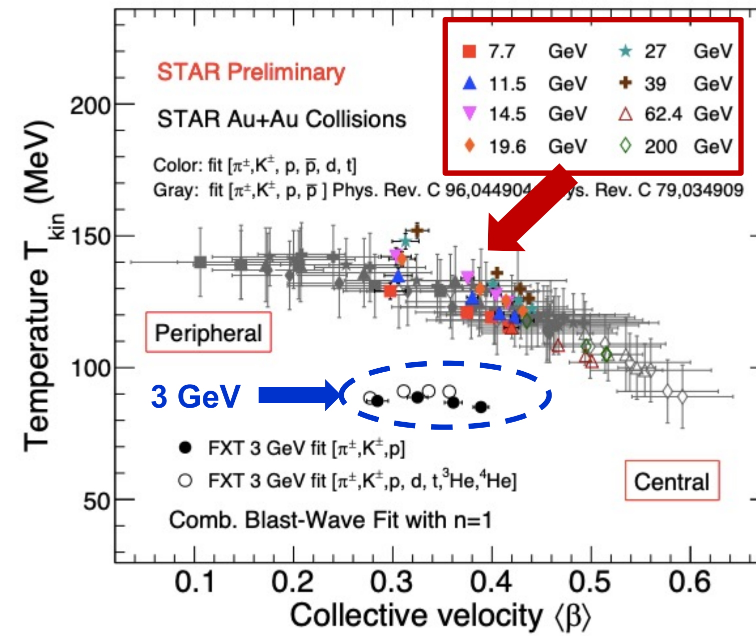
- ϕ/K ratio ~5σ > 0 (~Grand Canonical Ensemble)
- ϕ/K and ϕ/Ξ favors Canonical Ensemble
  - *- event-by-event strangeness conservation*
  - \- However, same r_c parameter cannot describe ϕ/K and ϕ/Ξ simultaneously in central collisions
  - *- threshold: 2.9 GeV (ϕ), 3.2 GeV (Ξ)*

→ Different medium in 3 GeV collisions

Different Kinetic Freeze-out Properties at 3 GeV

Au+Au @ 3 GeV, midrapidity, 0-10%



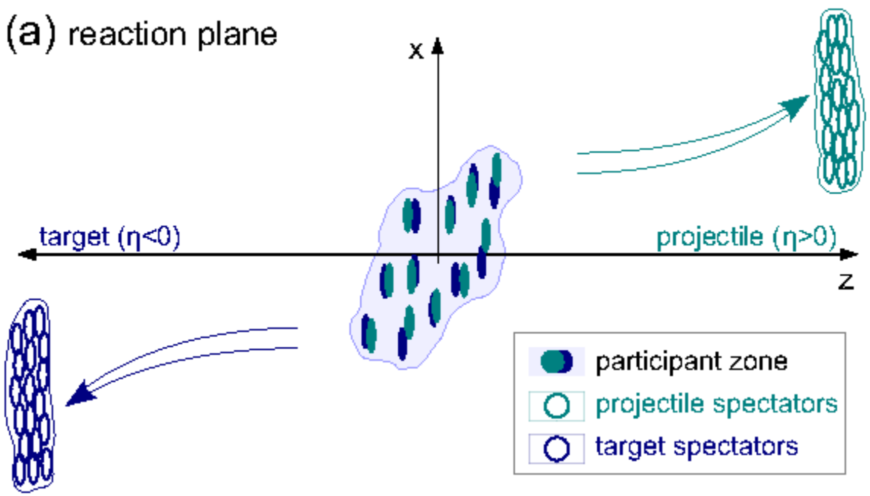


Similar trend of (T_{kin}, β_T) at 7.7 – 200 GeV
Significant different at 3.0 GeV
- lower T_{kin} and/or smaller β_T

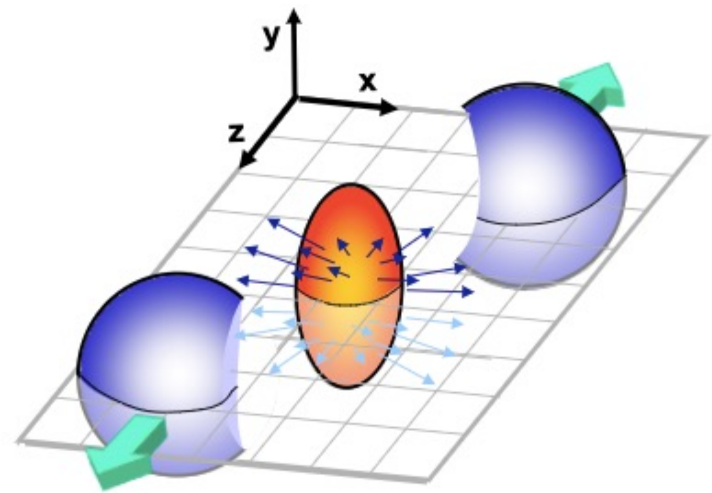
→ Different medium properties in Au+Au collisions @ 3 GeV

Azimuthal Anisotropic Collectivity

Directed Flow (v_1)



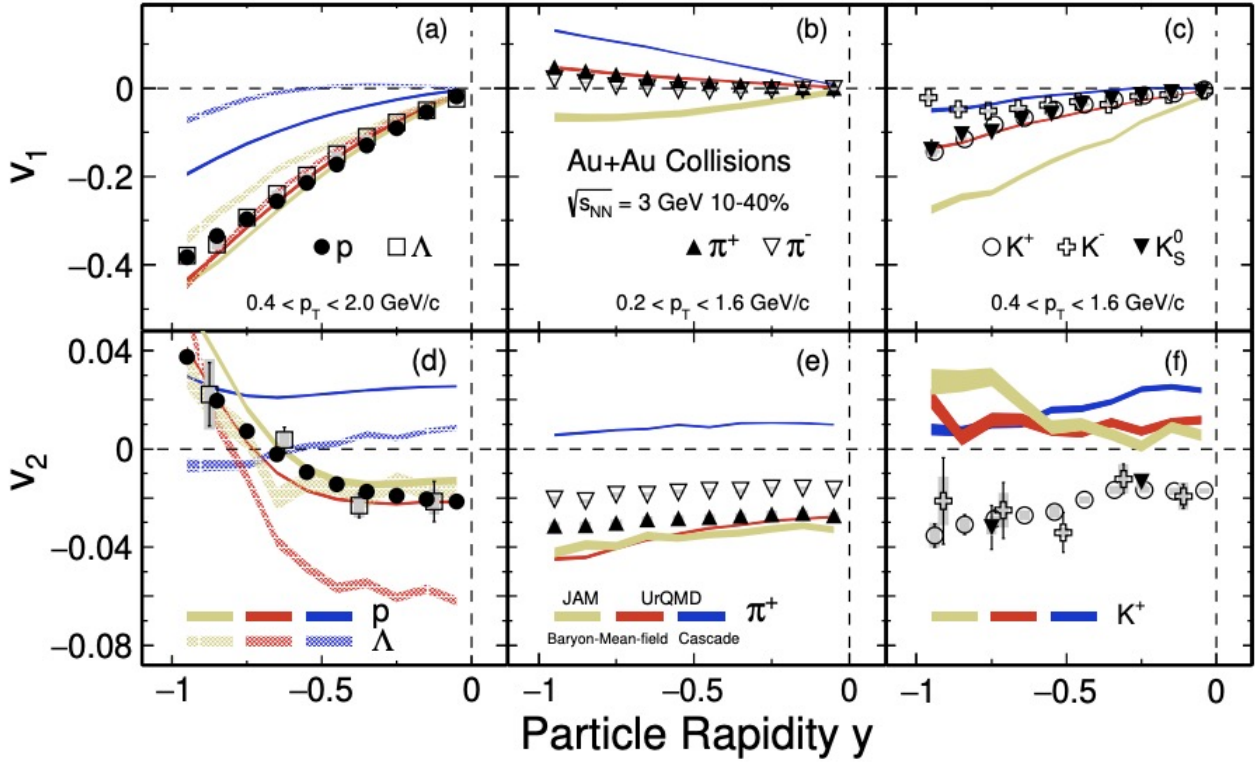
Elliptic Flow (v_2)



momentum space anisotropy ↔ pressure gradient in system evolution

v_1, v_2 … Equation-of-State (EoS)

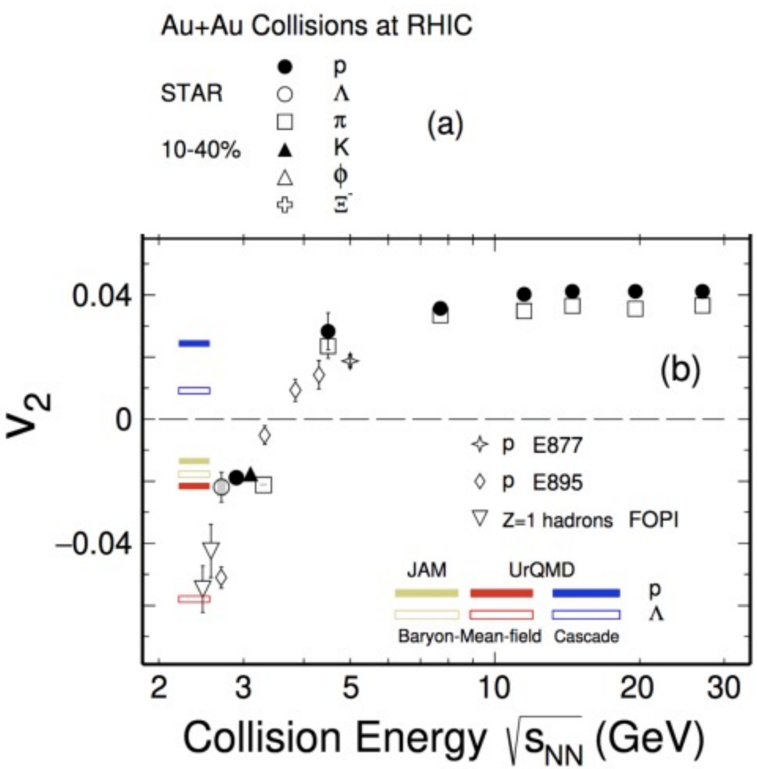
Directed/Elliptic Flows at 3 GeV



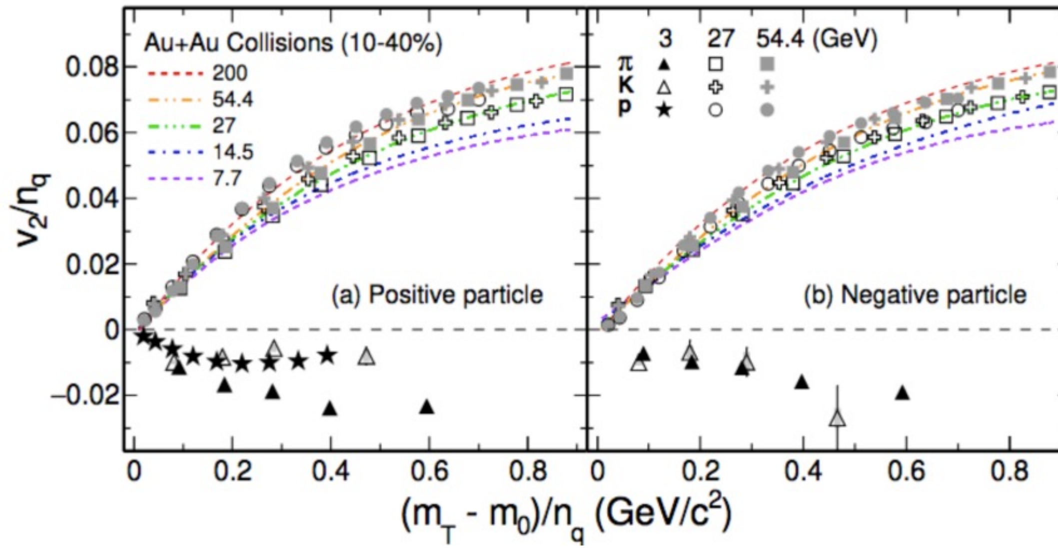
STAR, PLB 827 (2022) 137003

- Midrapidity v_1 slope positive for all particles (negative at high energies)
- Midrapidity v_2 negative for all particles (positive at high energies)
- UrQMD/JAM with baryonic mean field describe proton v_1/v_2 data

Particle Collectivity at Au+Au 3 GeV



STAR, PLB 827 (2022) 137003

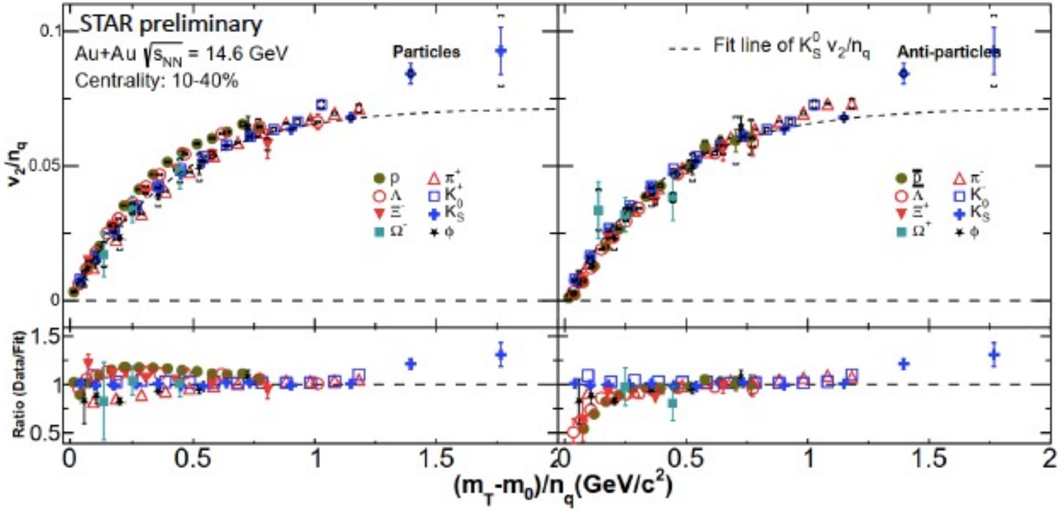


Au+Au collisions at 3 GeV:

- Negative midrapidity v_2 for all particles
- No Number-of-Constituent-Quark (NCQ) scaling
- UrQMD with baryonic mean-field potential qualitatively consistent with data

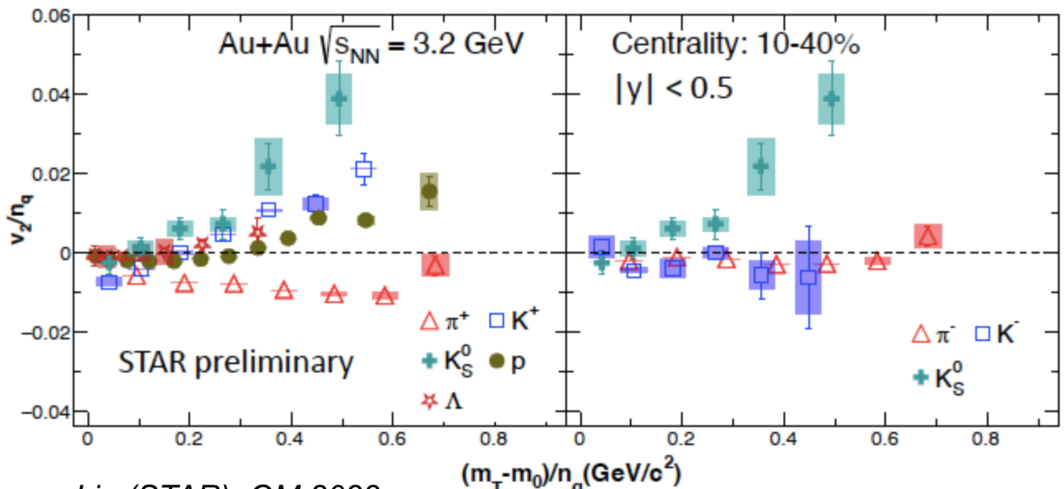
→ Equation-of-State dominated by baryonic interactions in 3 GeV Au+Au collisions.

New Updates at 3.2 and 14.6 GeV from QM



14.6 GeV

NCQ scaling holds within 25%

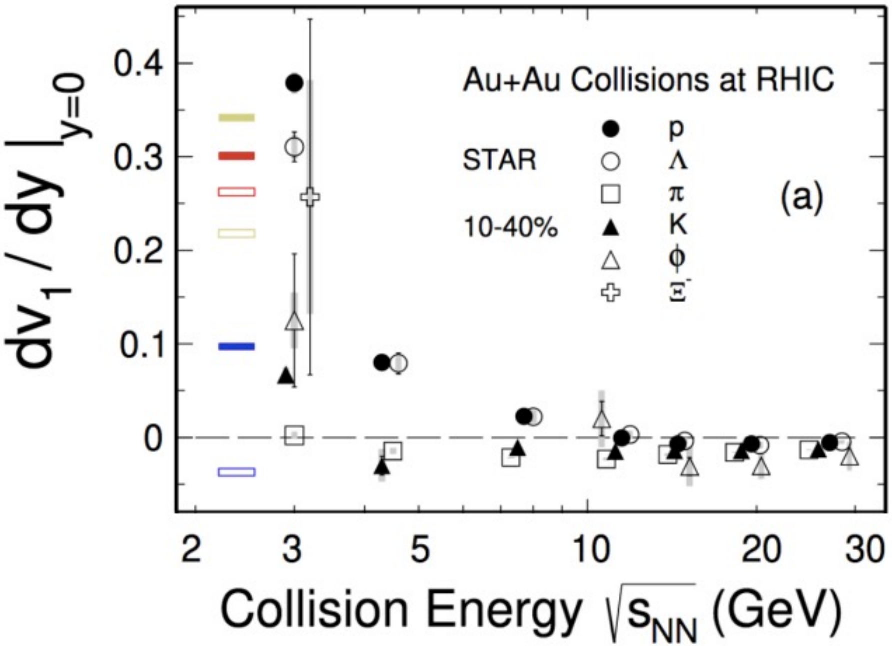


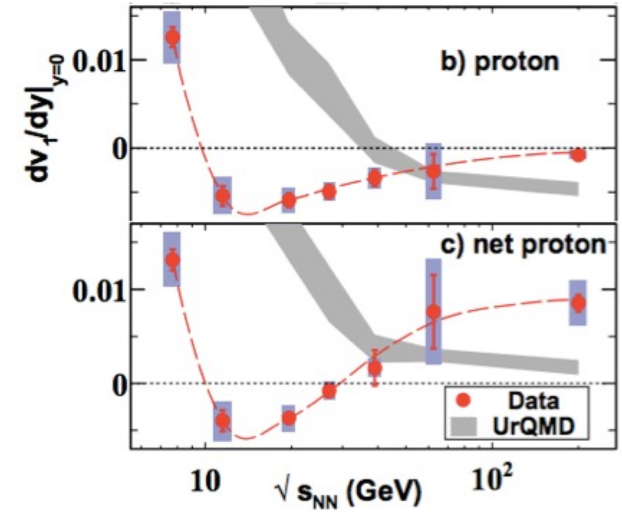
3.2 GeV

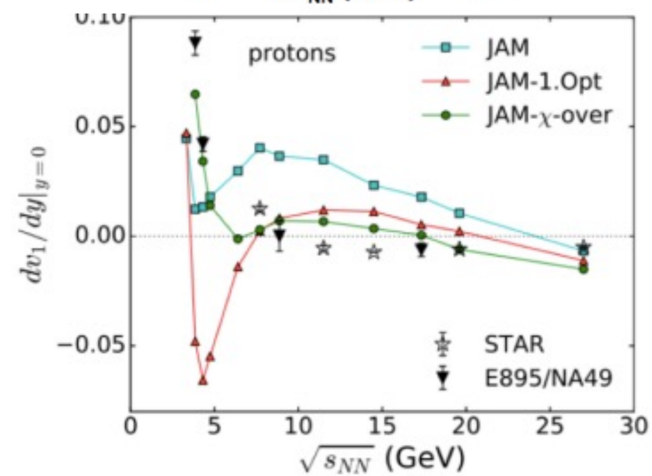
No NCQ scaling

Zuowen Liu (STAR), QM 2023

(Net-)Proton Directed Flow



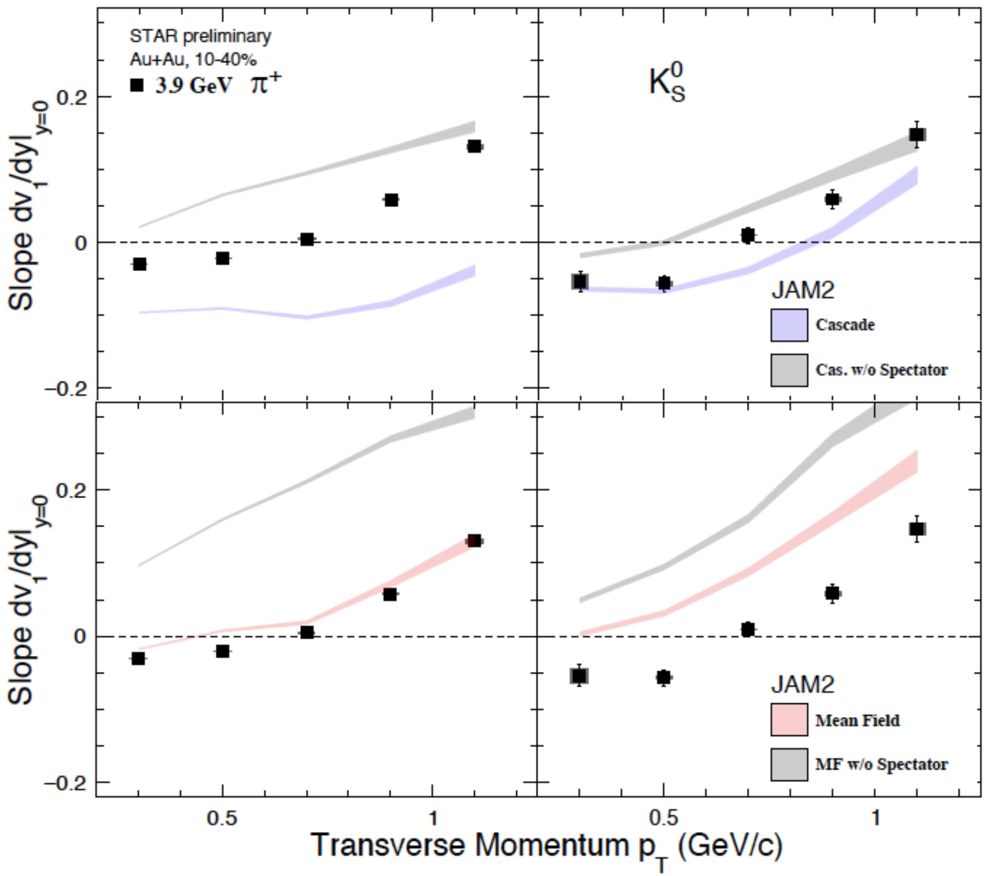




- Nearly all particle v_1 slopes are positive at 3 GeV
- Proton/net-proton v_1 vs. energy show a minimum
  - *Connection to 1st order phase transition?*
  - *model predicts a dip at much lower energy*

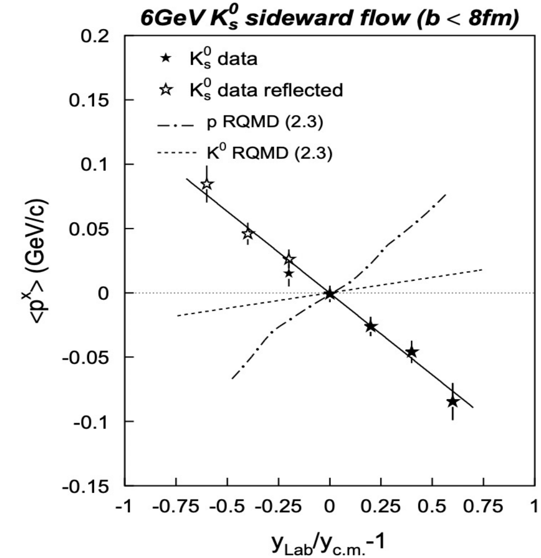
Y. Nara et al, PLB 769 (2017) 543

Kaon Anti-flow from QM23



Zuowen Liu (STAR), QM 2023

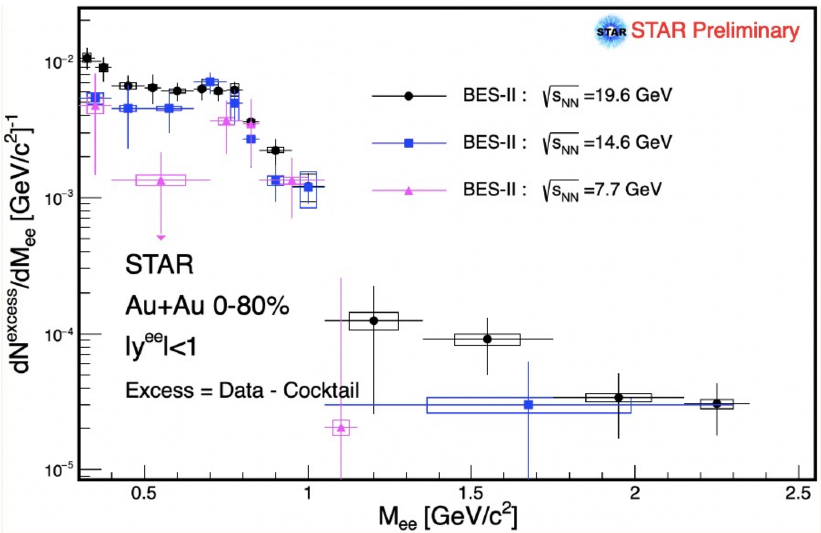
E895, PRL 85 (2000) 940



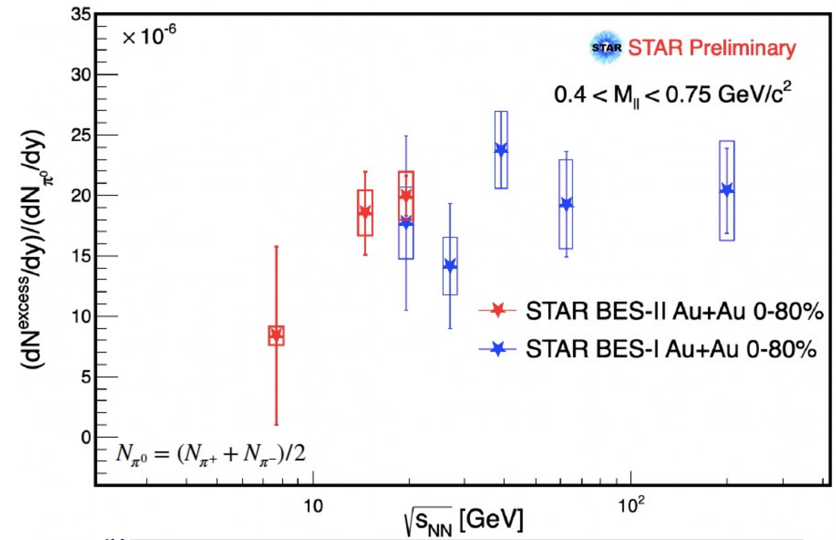
Ks and pi+ anti-flow at low p_T
- Observed in 3 – 3.9 GeV

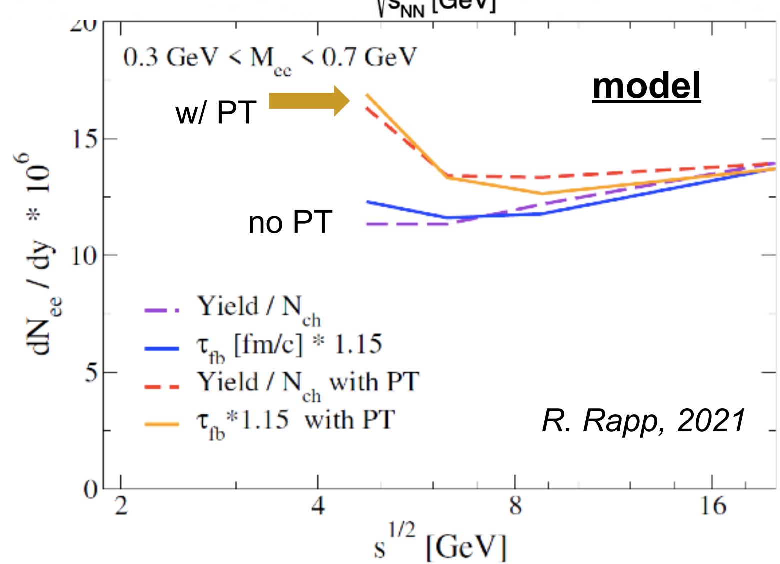
Spectator contributions may explain v_1 reduction at low p_T

Dielectrons Production



Yiding Han (STAR), QM 2023

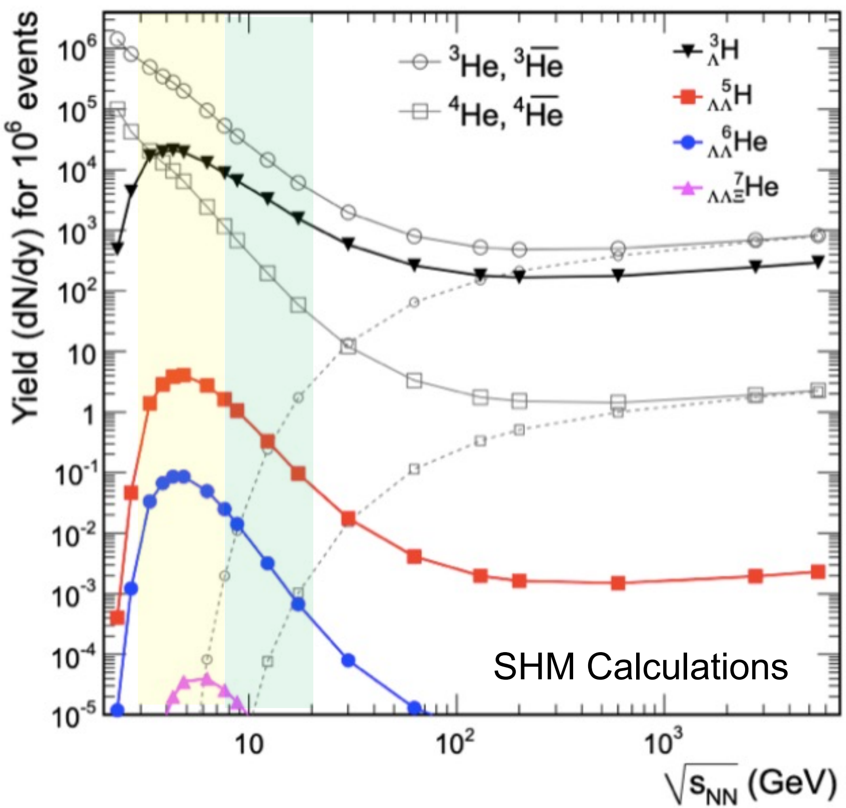




- New dielectron invariant mass measurement at 19.6, 14.6 and 7.7 GeV
- Energy dependence yield: hint of decreasing at low energy?

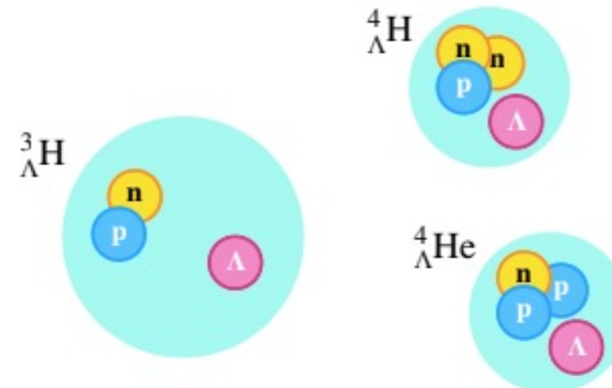
Heavy-Ion Collisions – "Light Hypernuclei Factory"

BES-II



A. Andronic et al., PLB 697 (2011) 203

Courtesy of Yue-Hang Leung



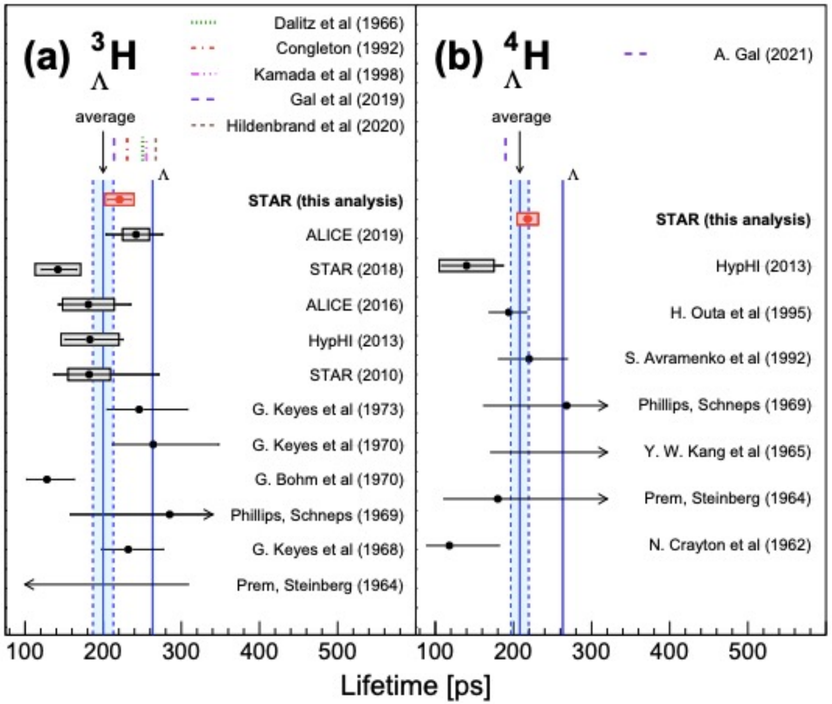
Hypernuclei in heavy-ion collisions

- hyperon-nucleon (Y-N) interaction
- EoS under high baryon density region
  - *connection to compact stars*

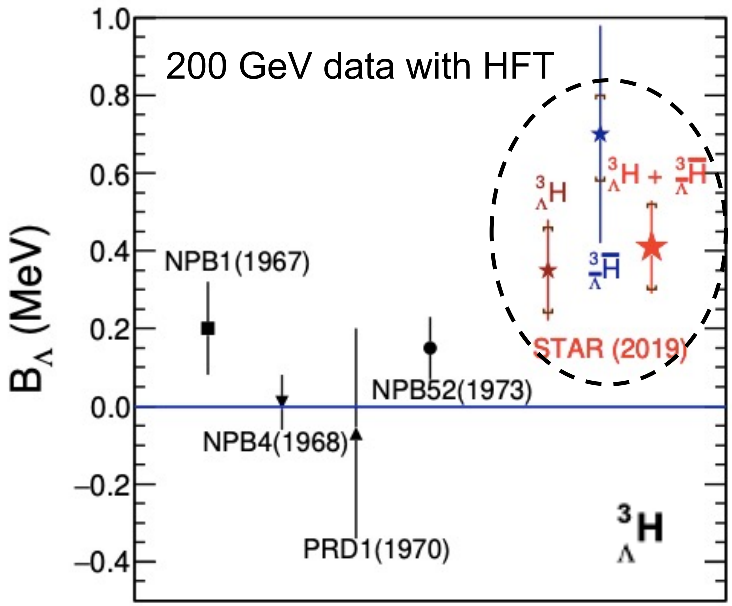
- Lifetime, binding energy
- Production yields, collective flows
- New hypernuclei states

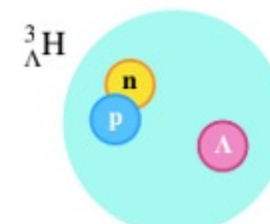
Hypernuclei Structure: Y-N Interaction

arXiv: 2110.09513



Nature Physics 16 (2020) 409



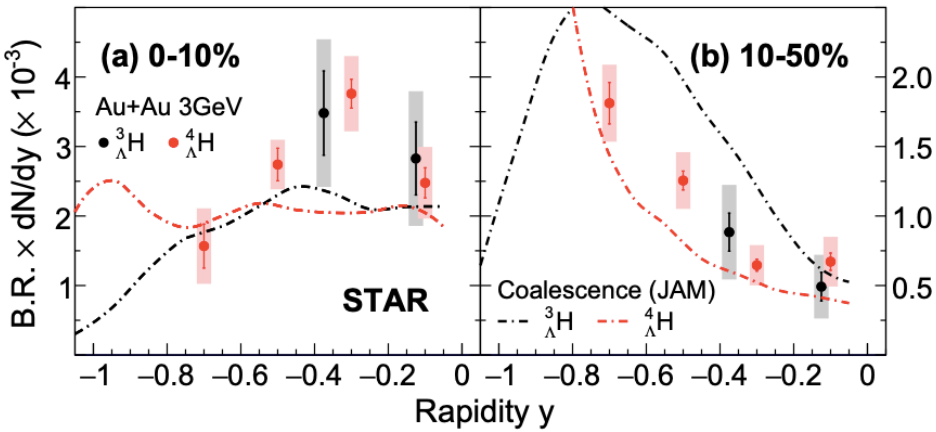


$\tau(^{3}_{\Lambda}H,\ ^{4}_{\Lambda}H) \sim 0.8\ \tau(\Lambda)$

$B_{\Lambda}(^{3}_{\Lambda}H) = 0.4 \pm 0.2$ MeV

Λ loosely bounded inside hypertriton,
lifetime impacted by final state interactions (π-N)

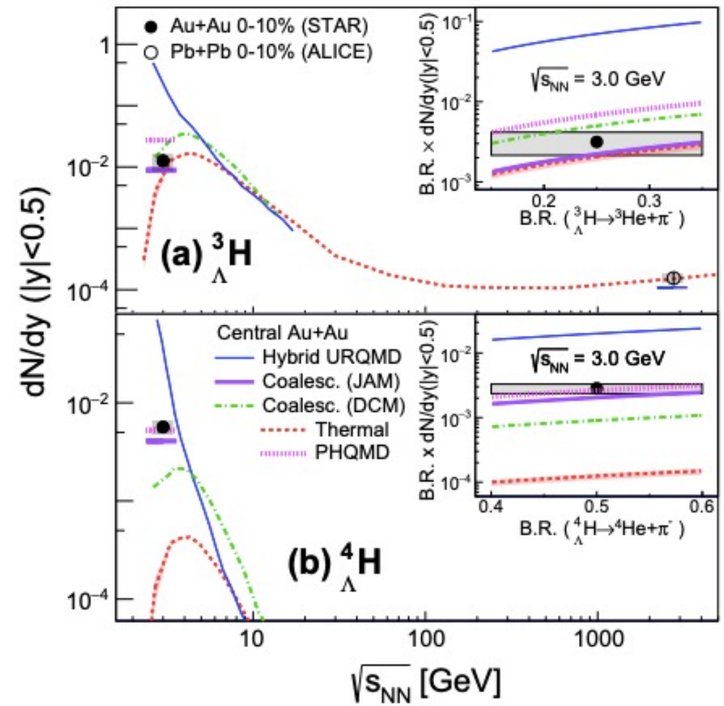
Hypernuclei Production dN/dy in Heavy-Ion Collisions



- JAM + coalescence reasonably consistent with data
- Coalescence parameters ↔ Y-N interaction

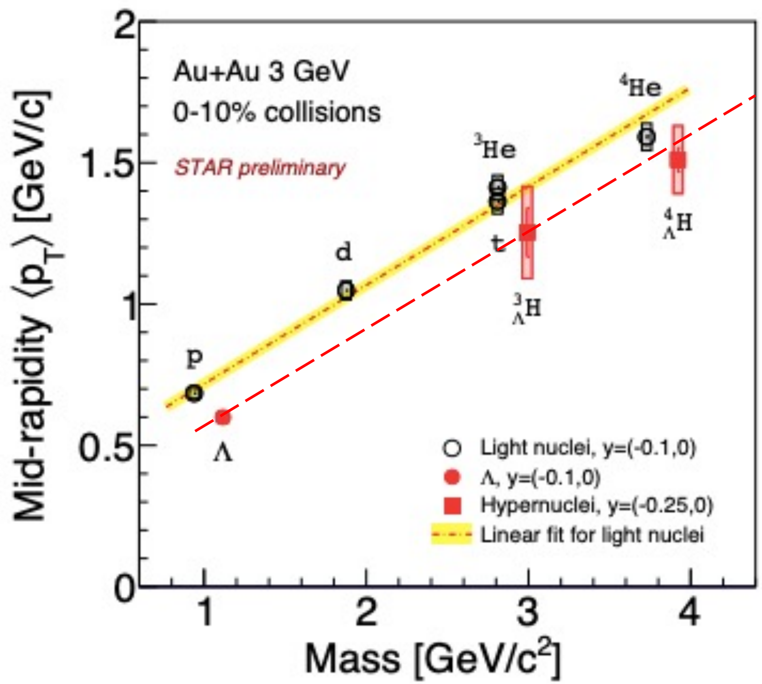
nuclei	(r_C/fm, p_C/GeV)	B/A (B_Λ) (MeV)
d	*(4.5, 0.3)*	*1.1*
t	*(4.0, 0.3)*	*2.8*
${}^3_\Lambda H$	***(4.0, 0.12)***	***~0.3***
${}^4_\Lambda H$	*(4.0, 0.3)*	*~2.6*

STAR, PRL 128 (2022) 202301

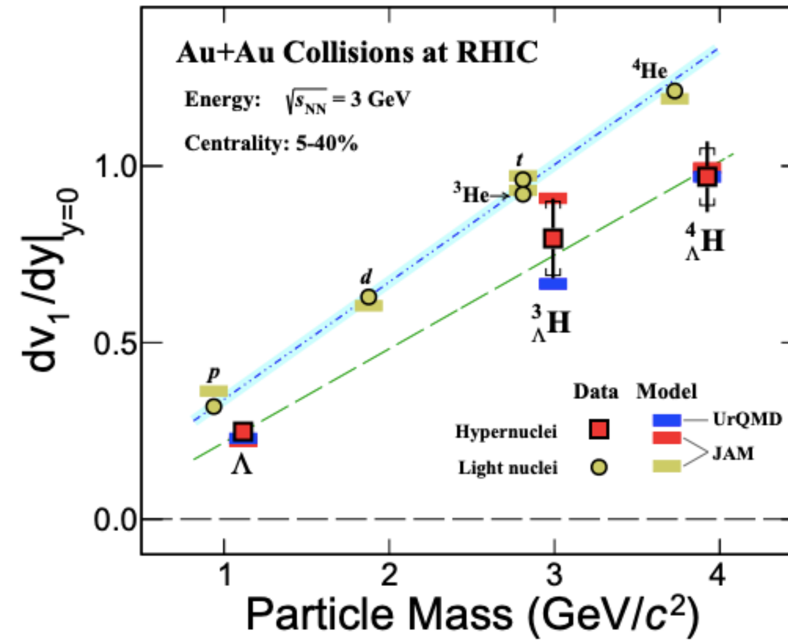


- Thermal model w/ CE consistent with ${}^3_\Lambda H$, but underestimate ${}^4_\Lambda H$
- Transport models (JAM or PHQMD) reasonably consistent with data

Hypertriton Collective Flow



STAR, QM 2022

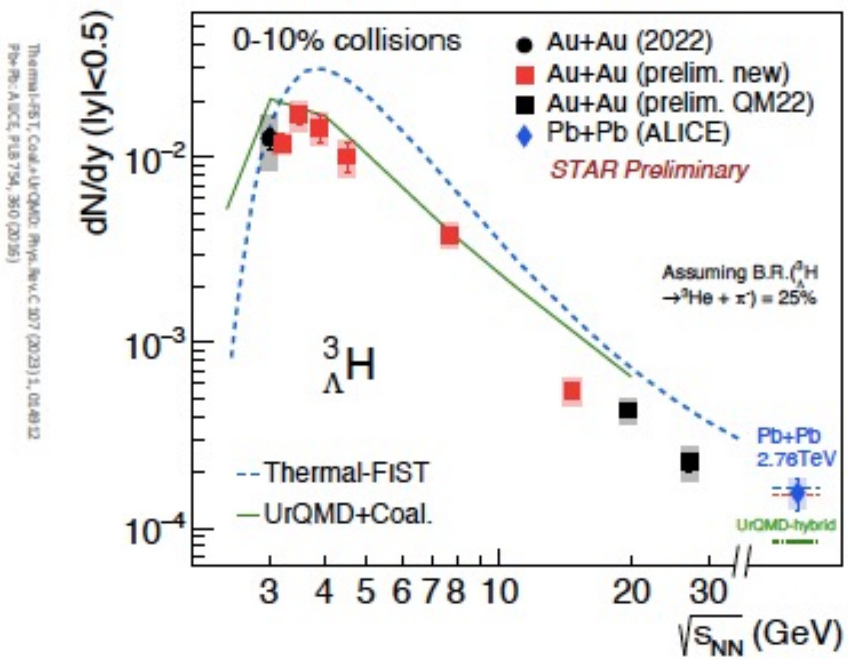


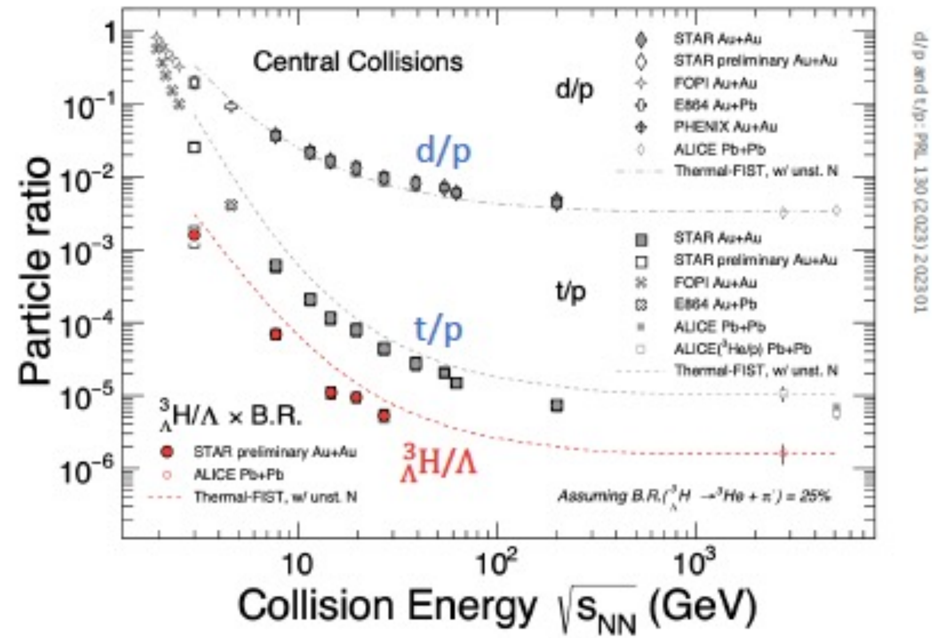
STAR, PRL 130 (2022) 212301

Both midrapidity <p_T> and dv_1/dy follow the mass number scaling

Coalescence production mechanism dominant for hypernuclei at 3 GeV

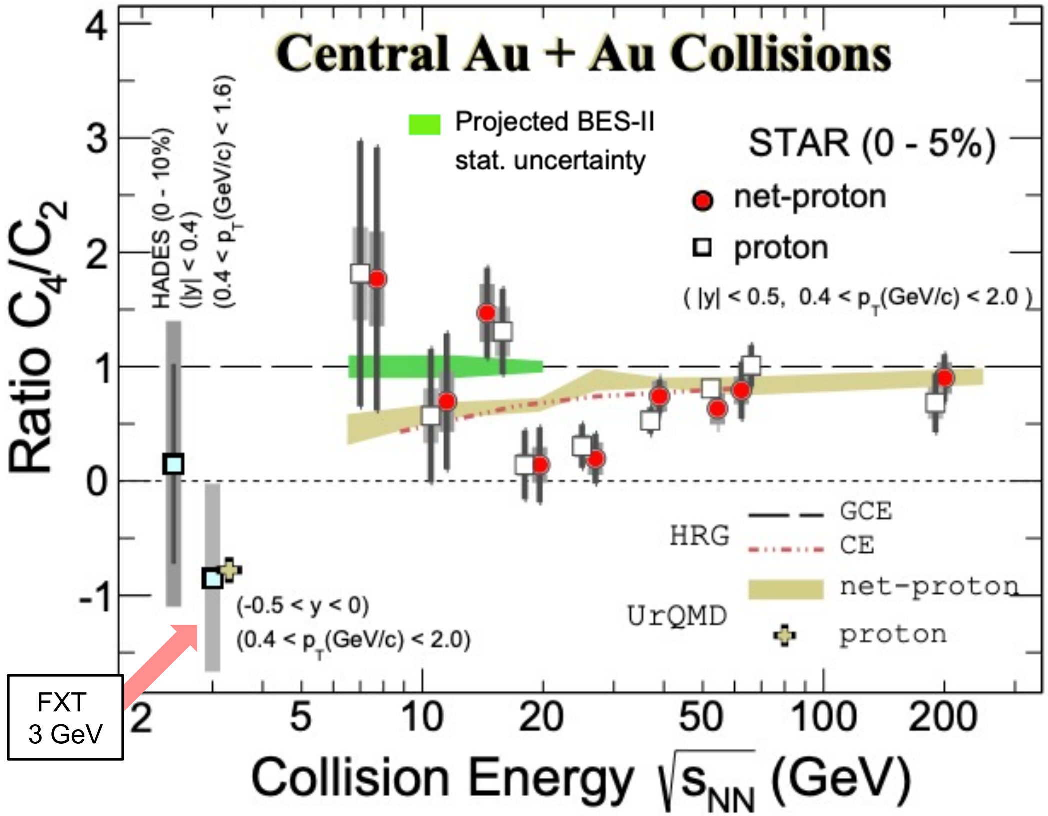
Energy Dependence of Hypertriton Production





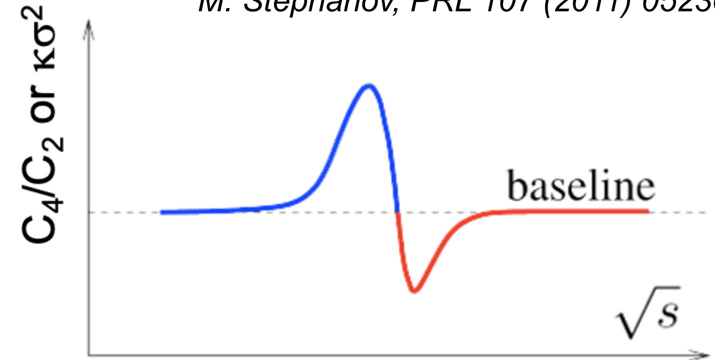
- Hadronic transport + coalescence models qualitatively describe the data
- Thermal model calculation ~2 times higher than data in BES-II energies

Energy Dependence of (Net-) Proton High Moments



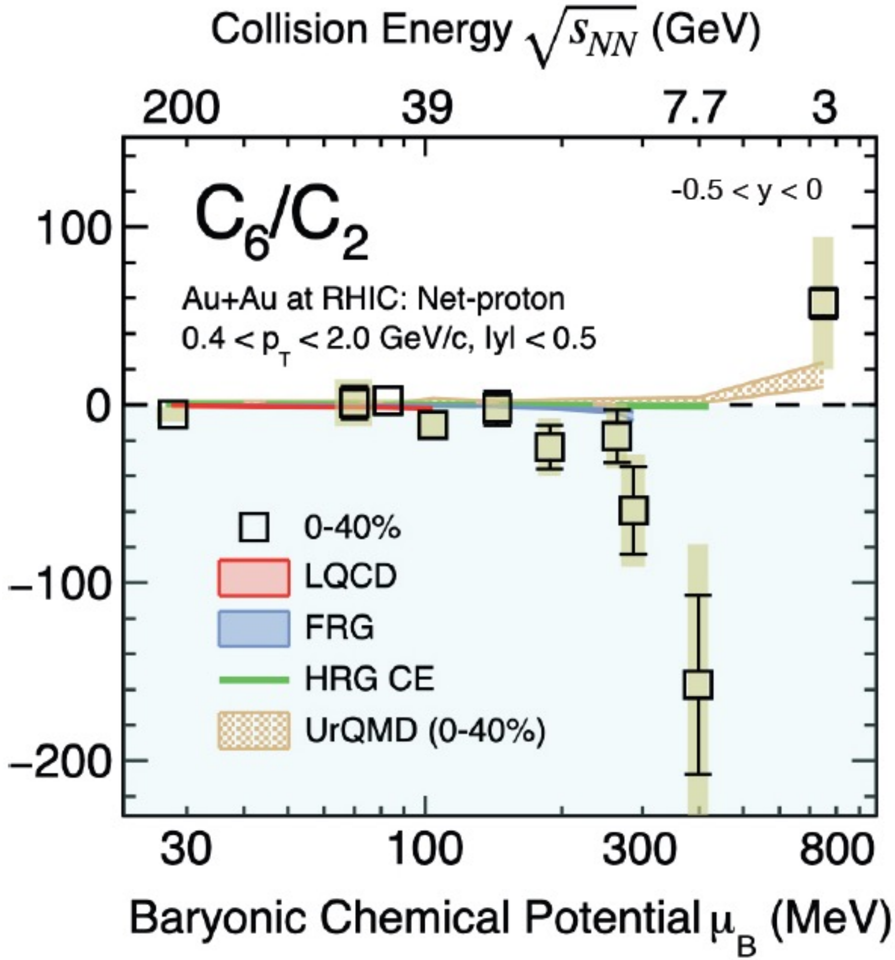
BES-I: PRL 126 (2021) 092301
3 GeV data: PRL 128 (2022) 202303

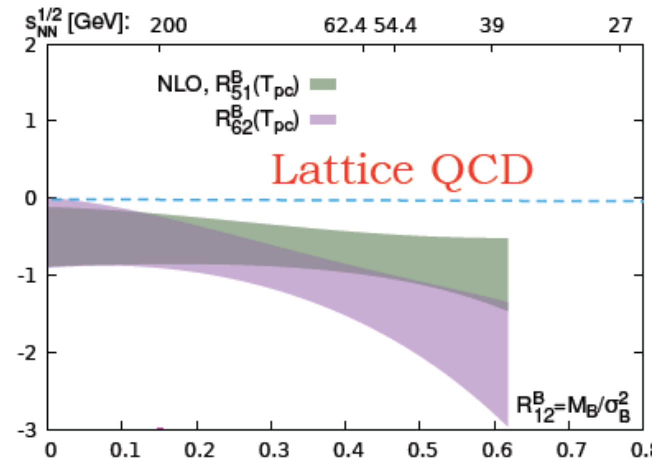
M. Stephanov, PRL 107 (2011) 052301



- Non-monotonic energy dependence in central Au+Au collisions (3.1σ)
- Strong suppression in proton C_4/C_2 at 3 GeV
  - consistent with UrQMD hadronic transport model calculation

C_6/C_2 Cumulant Ratios





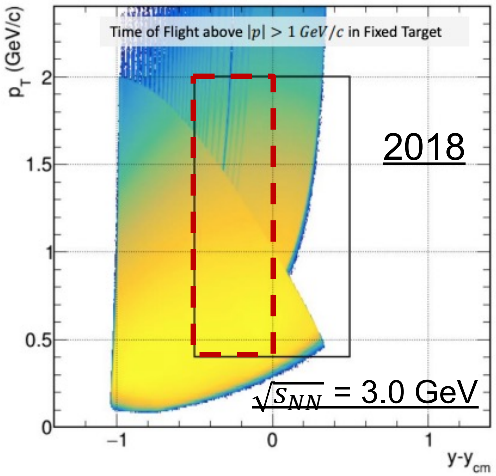
Increasingly negative C_6/C_2 down to 7.7 GeV (1.7σ) – consistent with Lattice expectation

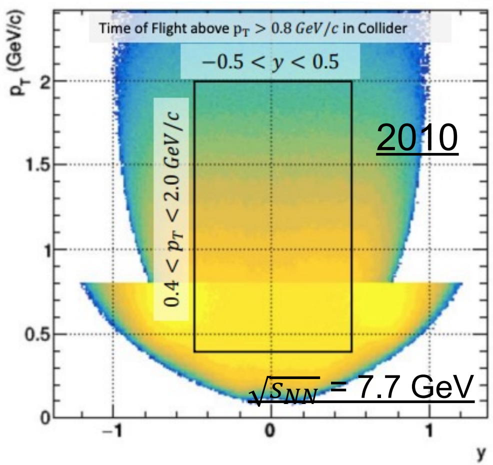
C_6/C_2 > 0 at 3 GeV, consistent with UrQMD calculation

STAR, PRL 127 (2021) 262301 (2021), PRL 130 (2023) 082301

High Moments Measurements in FXT Dataset

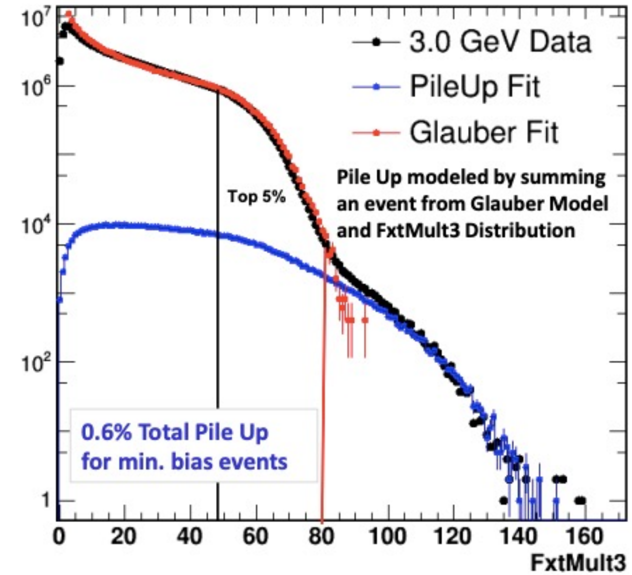
Proton Acceptance





"Pile-up" effect

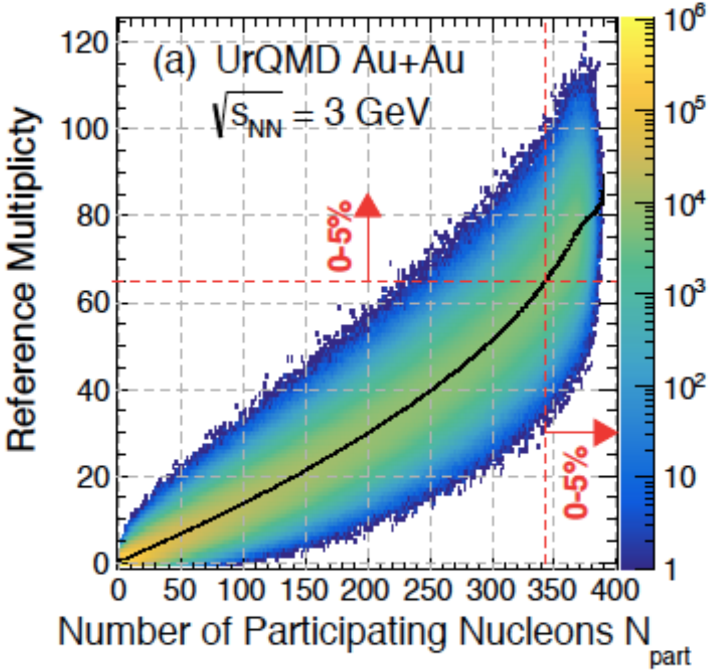
Sam Heppelmann, Yu Zhang

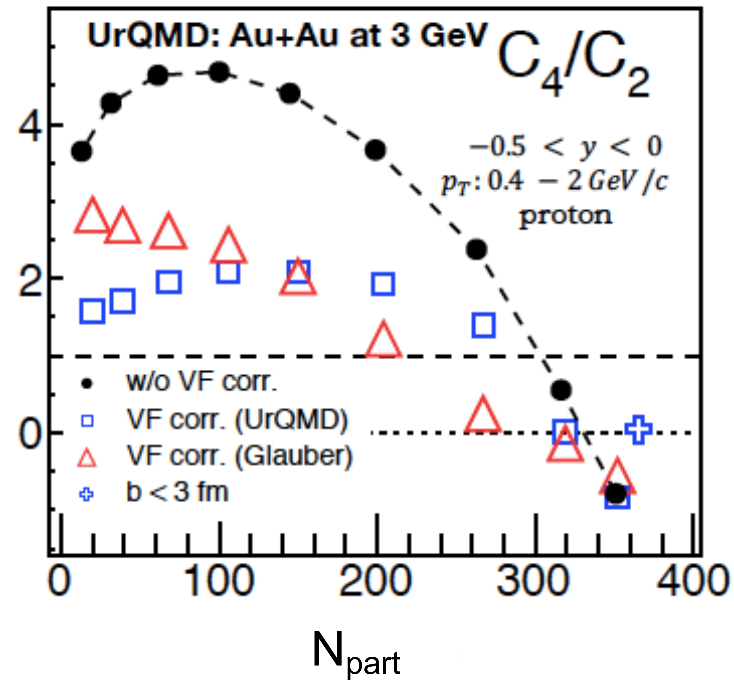


- "Two-component" unfolding technique
  T. Nonaka et al, NIMA 984 (2020) 164632
- Controllable precision on pile-up level $(0.6 \pm 0.1)\%$ with centrality dependence
  - negligible in collider data

Volume Fluctuation Effect at Low Energies

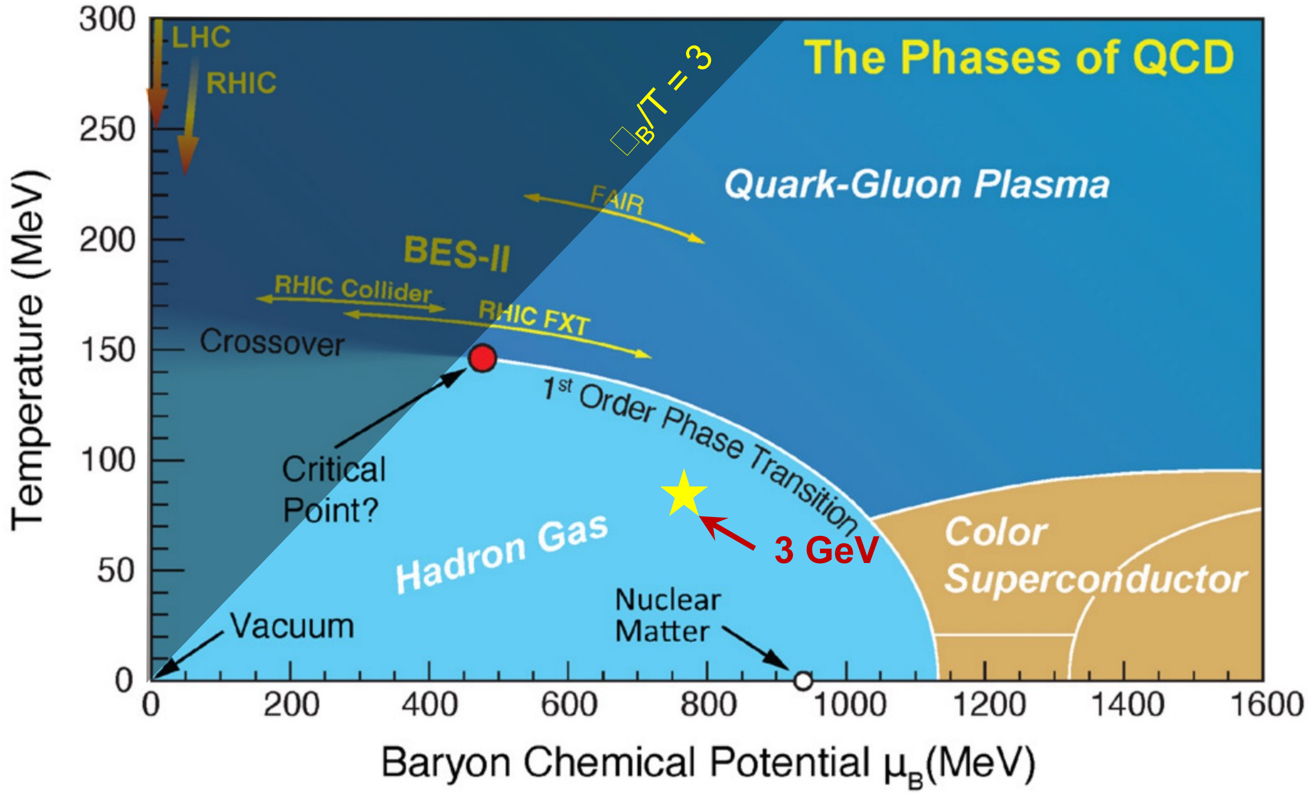
STAR, PRC 107 (2023) 024908





Low collision energies → much reduced multiplicity
→ worsened centrality resolution / large volume fluctuation
Currently corrections rely on models (model-dependence)
→ A data-driven way to assess the IVF?

Summary



Lattice QCD predicts
μ_B(CEP) > 400 MeV

BES-II

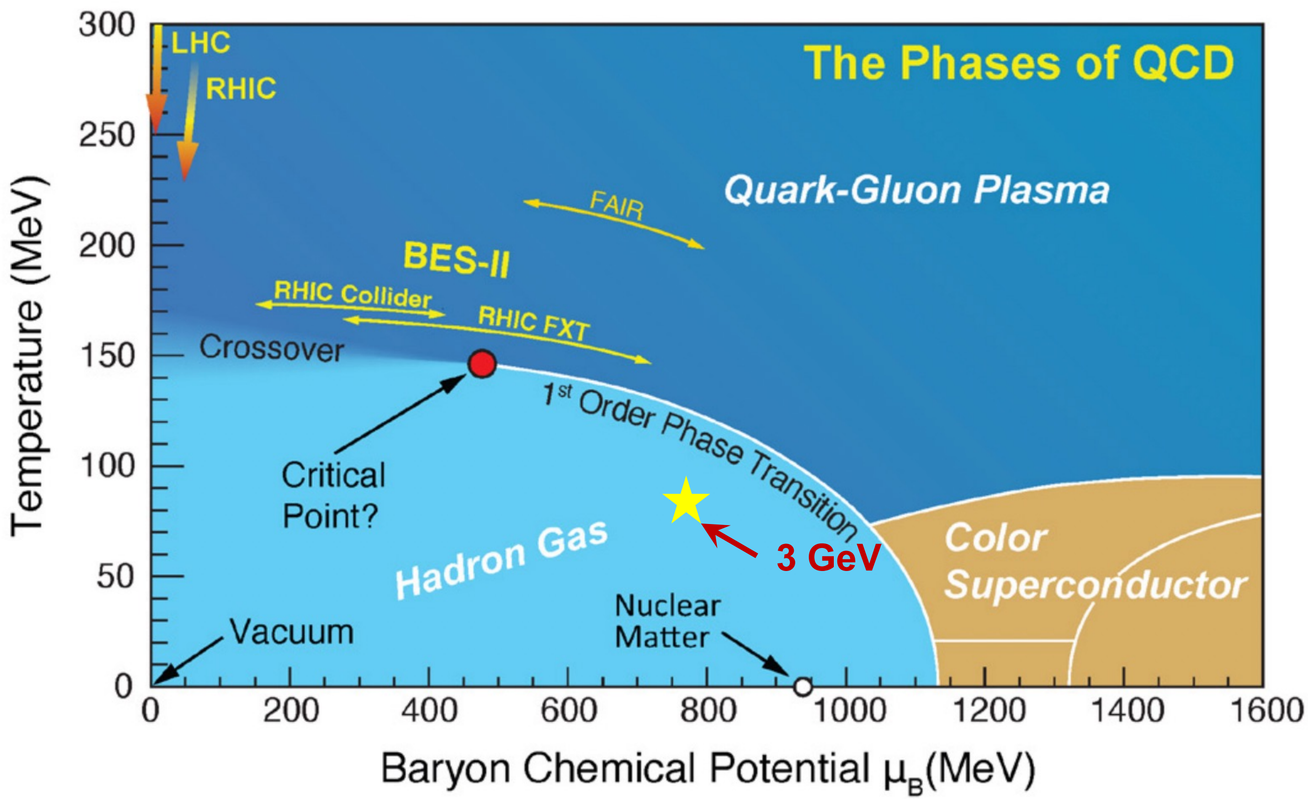
AuAu collisions @ ~**3 GeV – hadronic phase**

- v_1/v_2 dominated by baryonic mean field
- ϕ Ξ production driven by CE
- Proton C_4/C_2, C_6/C_2 consistent with UrQMD

High $\square_B$ Physics:

Future Prospects from BES-II and Beyond

High □B Physics Goals

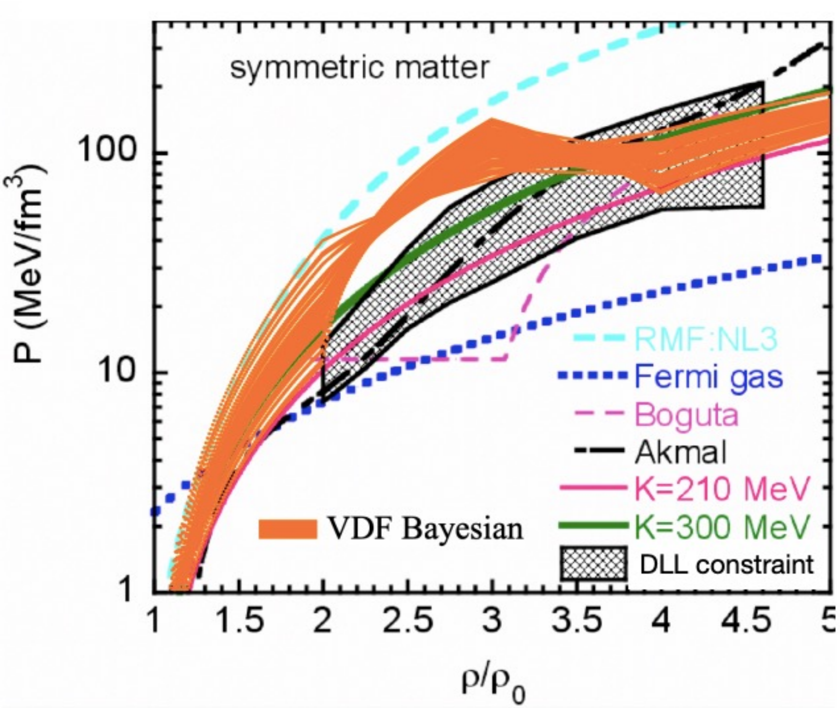


1) Search and locate the QCD CEP or 1st-order phase boundary

2) Constrain the QCD Equation-of-State at high density region

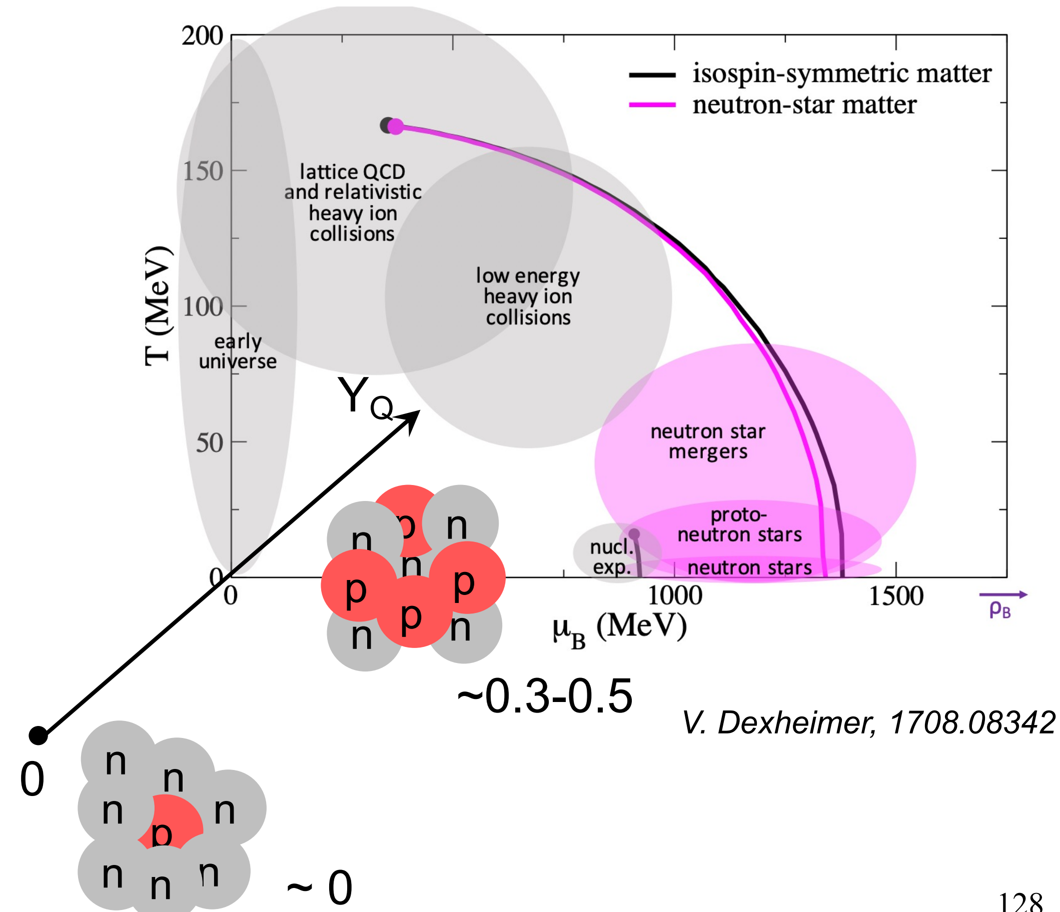
Nuclear Matter Equation-of-State at High Density

Bayesian analysis using HIC v_1, v_2 data



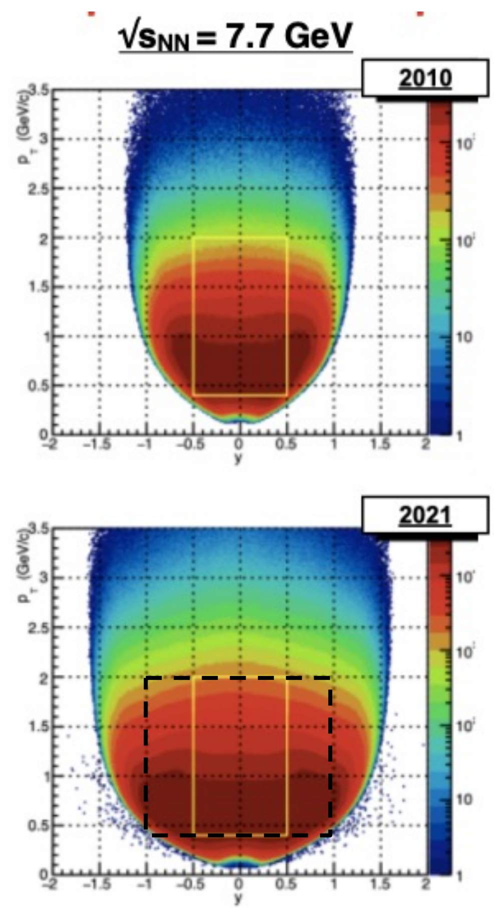
D. Oliinychenko et al, PRC 108 (2023) 034908

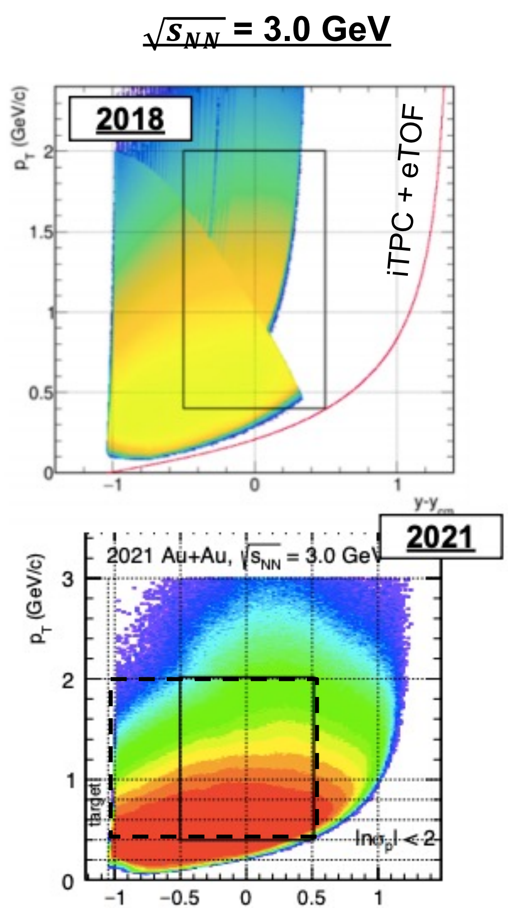
n-p asymmetry $Y_Q \equiv \frac{Z}{A}$



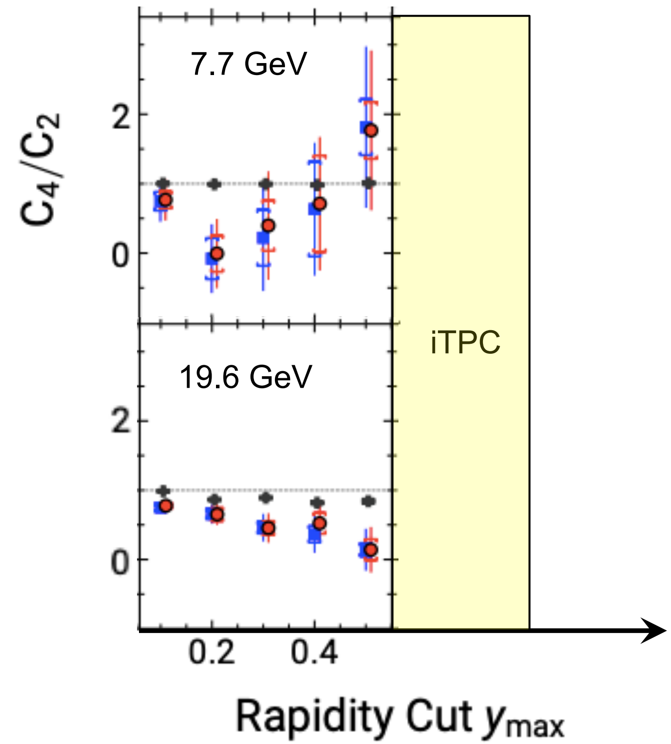
V. Dexheimer, 1708.08342

Prospects from (Net-)Proton Fluctuations at BES-II



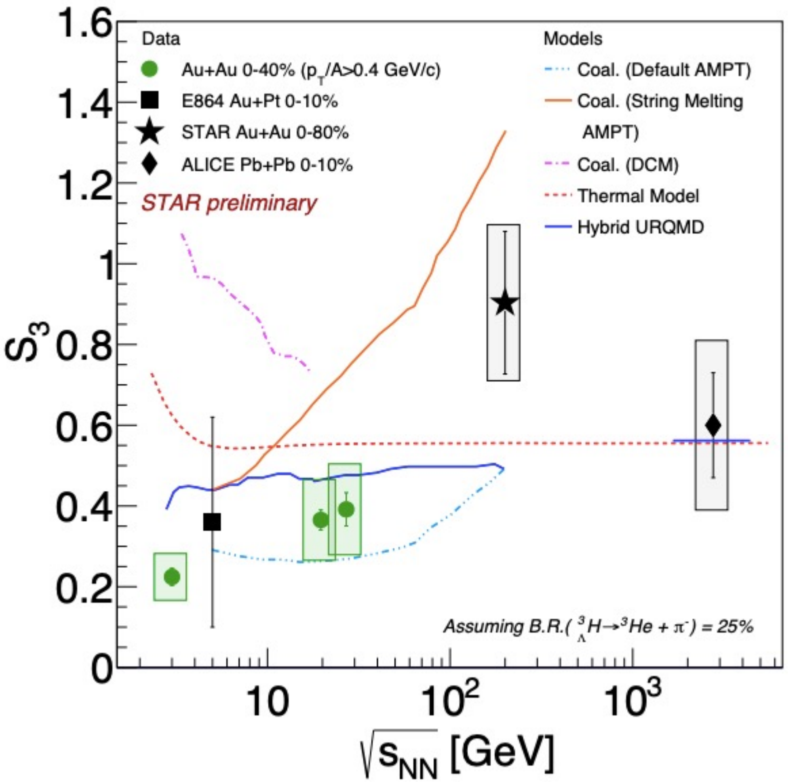


Rapidity windows at BES-II
Collider: extended rapidity window
FXT: -1.0<y<0.5 @ 3 GeV

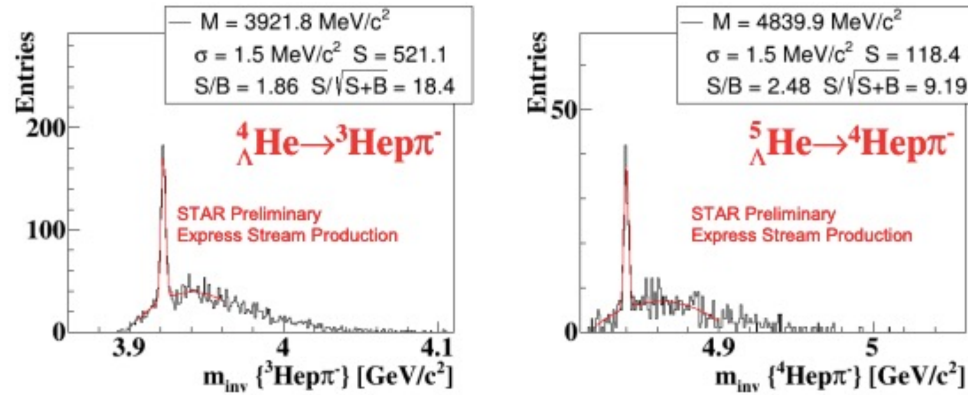


Hypernuclei Measurements

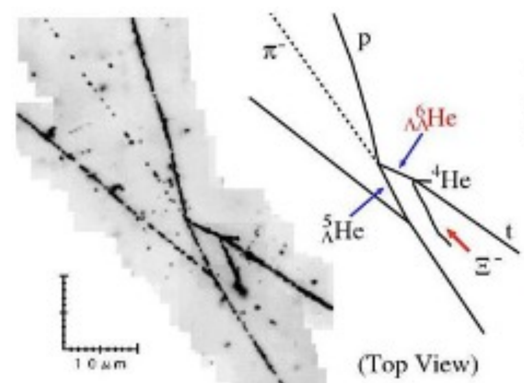
$$S_3 \equiv \frac{{}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}}{\Lambda/p}$$



A=4,5 hypernuclei from X-press prod.



Search for double-Λ hypernuclei
- access Y-Y interaction

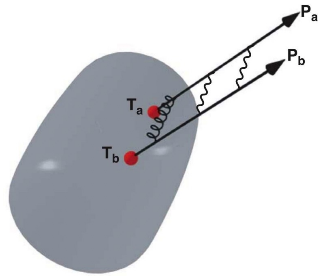


NAGARA event

Two-Particle Correlation (HBT)

Two-particle momentum space correlation function

$$C(\mathbf{p_1}, \mathbf{p_2}) = \frac{P_{1,2}(\mathbf{p_1}, \mathbf{p_2})}{P_1(\mathbf{p_1}) \cdot P_2(\mathbf{p_2})}$$



$$C(\mathbf{k}^*) = \int S(\mathbf{k}^*, \mathbf{r}^*) \, |\Psi(\mathbf{k}^*, \mathbf{r}^*)|^2 d^4\mathbf{r}^* \qquad k^* = \tfrac{1}{2} \cdot |\mathbf{p}_1^* - \mathbf{p}_2^*|$$

emitting source

wave function between two particles

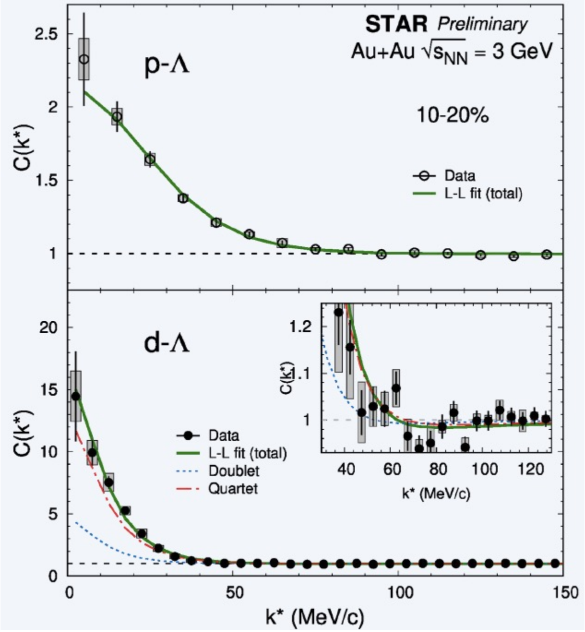
Experimentally, this is measured via

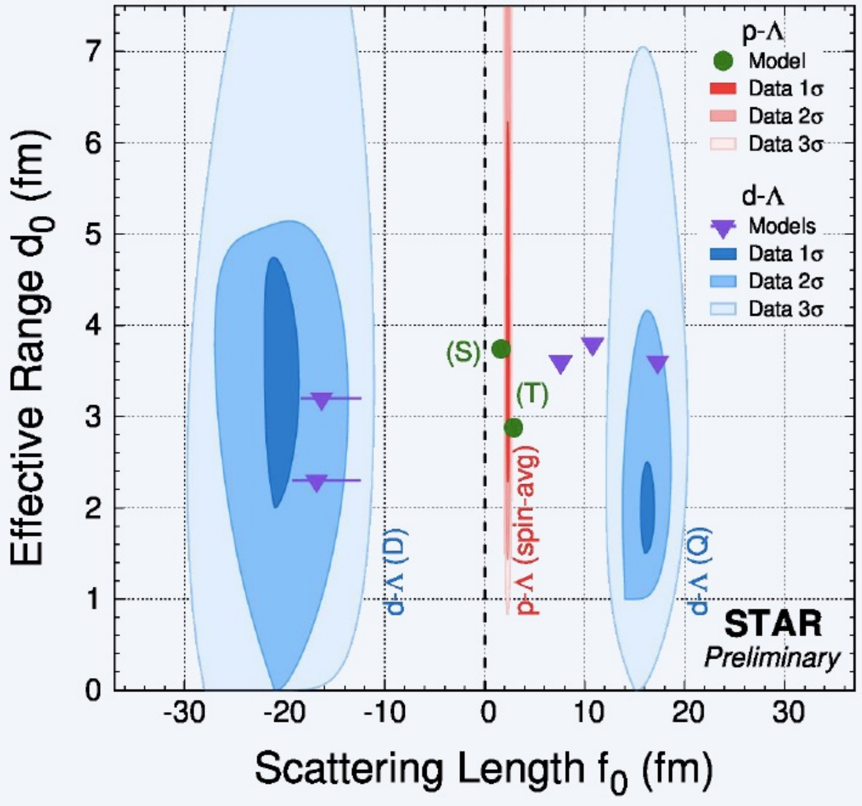
$$C(k^\star) = \mathcal{N} \frac{N_{\mathrm{corr}}(k^\star)}{N_{\mathrm{uncorr}}(k^\star)} = \mathcal{N} \frac{N_{\mathrm{same-evt}}(k^\star)}{N_{\mathrm{mix-evt}}(k^\star)}$$

- Fireball source size
- Strong interactions
- *Coulomb interaction*

Baryon-Baryon/Hyperon Correlations

scattering amplitude $$f(k) = (\frac{1}{f_0} + \frac{1}{2}d_0k^2 - ik)^{-1}$$

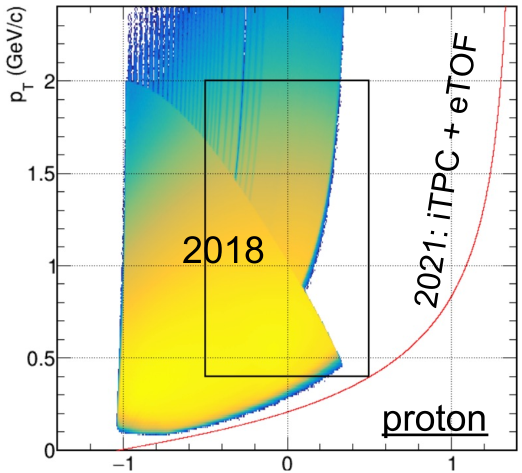


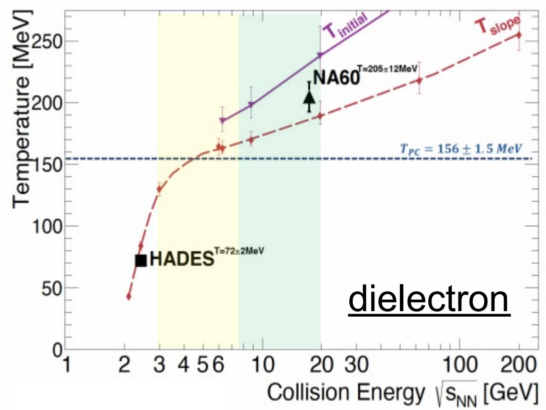


p-Λ/d-Λ strong interaction parameters through Lednicky-Lyuboshitz fit

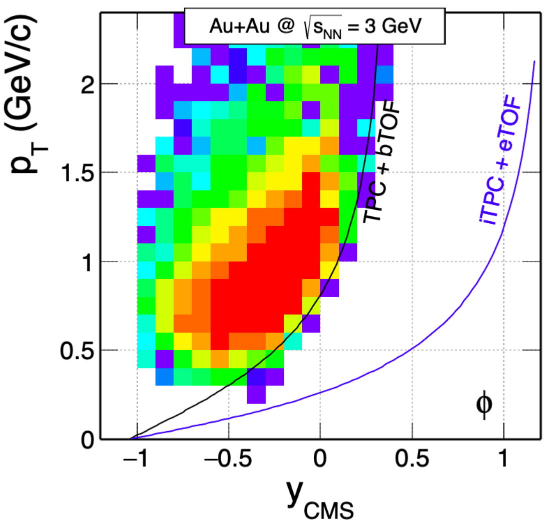
- New insights in Y-N and hypernuclei structure

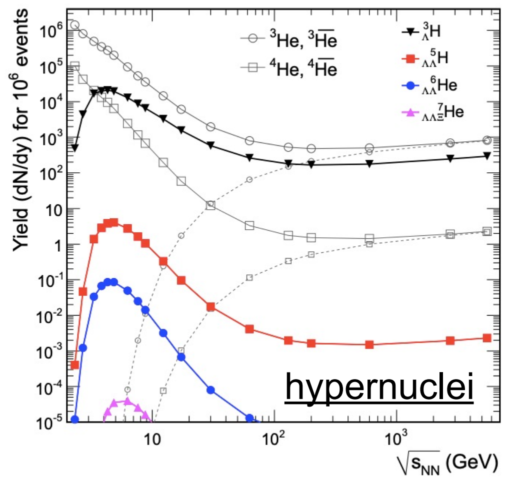
New 2.0B Dataset at 3 GeV in 2021!





Highest $\square_B$ ~ 720-750 MeV RHIC has reached

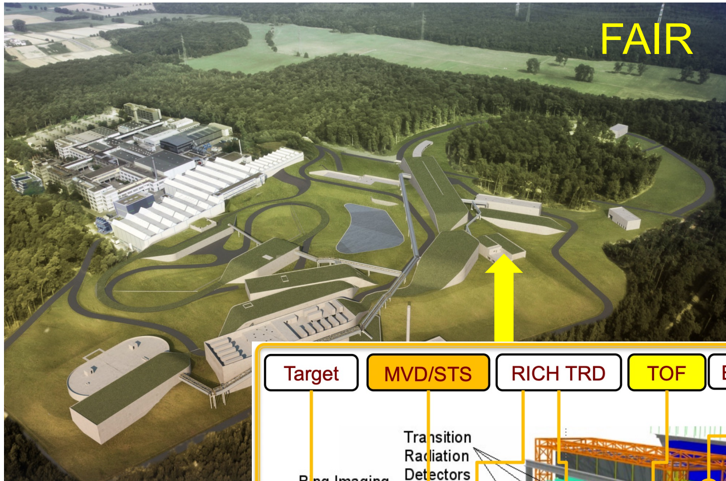


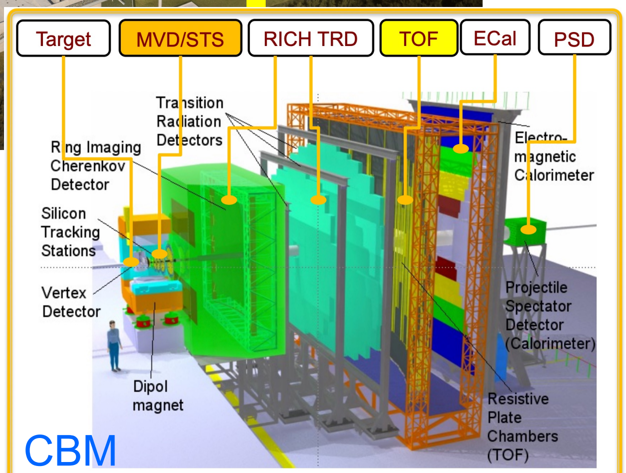


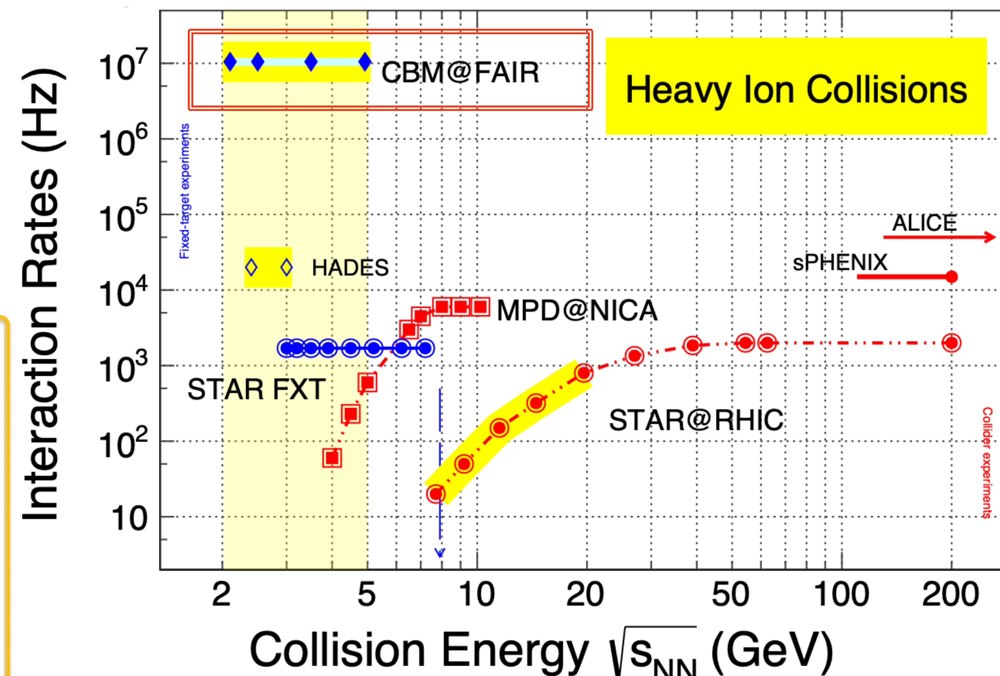
2.0 B high statistics data with iTPC+eTOF recorded in 2021

- Proton cumulants (C_1-C_6) in full rapidity window
- Dielectron yield/T_{slope}
- ϕ/Ξ yield with low p_T reach for better systematics
- Hypernuclei production and search for ΛΛ-hypernuclei
- N-N/Y-N/Y-Y correlations
- …

Next Phase BES Program at CBM@FAIR







Compressed Baryonic Matter (CBM) @ FAIR facility, Germany ($\sqrt{s_{NN}}$ = 2.9 – 4.9 GeV)

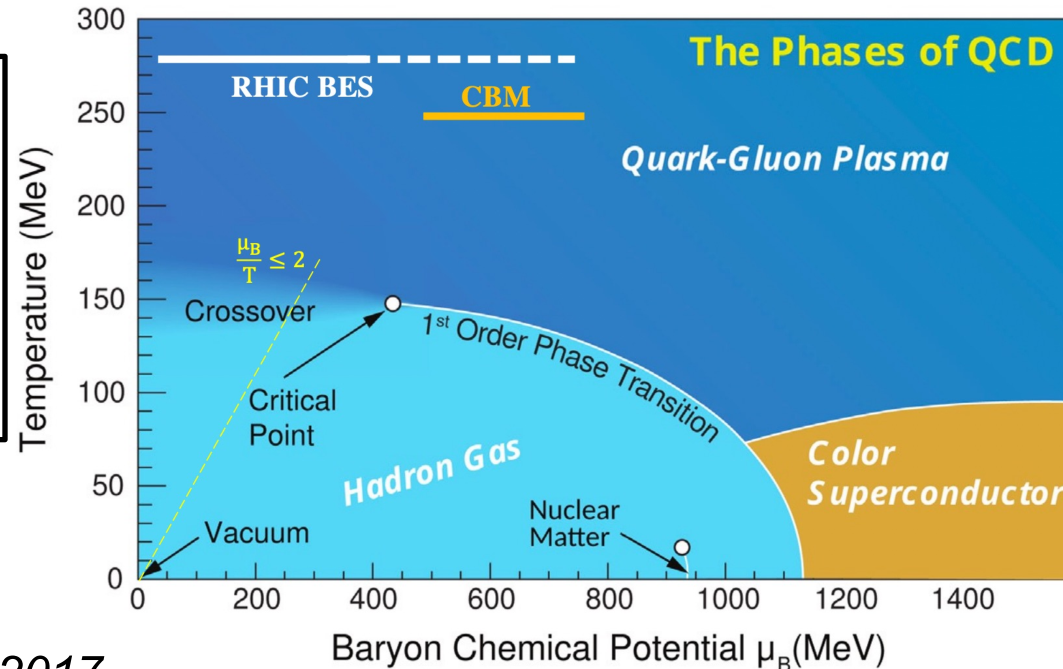
physics anticipated to start in ***~2027+***

Collision rate ~ 10 MHz, dedicated detectors enabling unprecedented statistics

Next Phase BES Program at CBM@FAIR

Proton full midrapidity at BES-II:
$\sqrt{s_{NN}}$ (GeV): 3.0, 7.7 – 19.6
μ_B (MeV): 750, 400 - 200

CBM@FAIR:
$\sqrt{s_{NN}}$ (GeV): **2.9 --- 4.9**
μ_B (MeV): **800 --- 540**



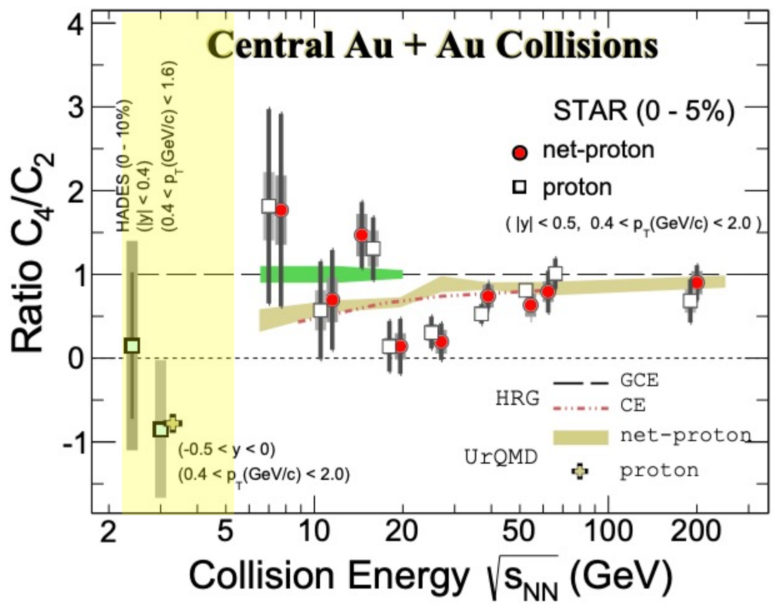
#1 priority in Europe NuPECC LRP 2017

Complete urgently the construction of the ESFRI flagship FAIR and develop and bring into operation the experimental programme of its four scientific pillars APPA, CBM, NUSTAR and PANDA.

NuPECC

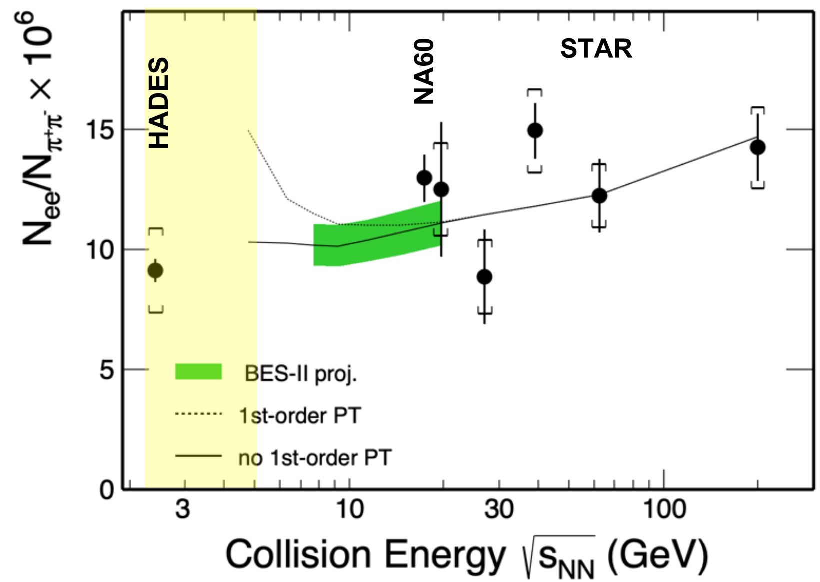
CBM Scientific Goals - I

Baryon Fluctuations/Correlations



- critical point search
- $\sqrt{s_{NN}}$ (μ_B) coverage for full mid-rapidity coverage
- dedicated instrument for controlling initial volume fluctuation

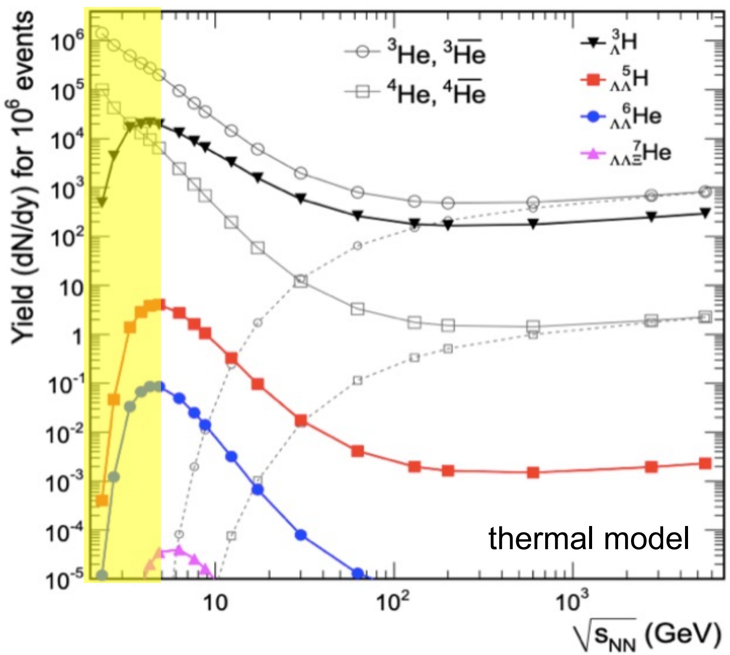
Dileptons



- 1st order phase transition / chiral property
- significantly high statistics
- dedicated instruments for both dielectron / dimuon channels

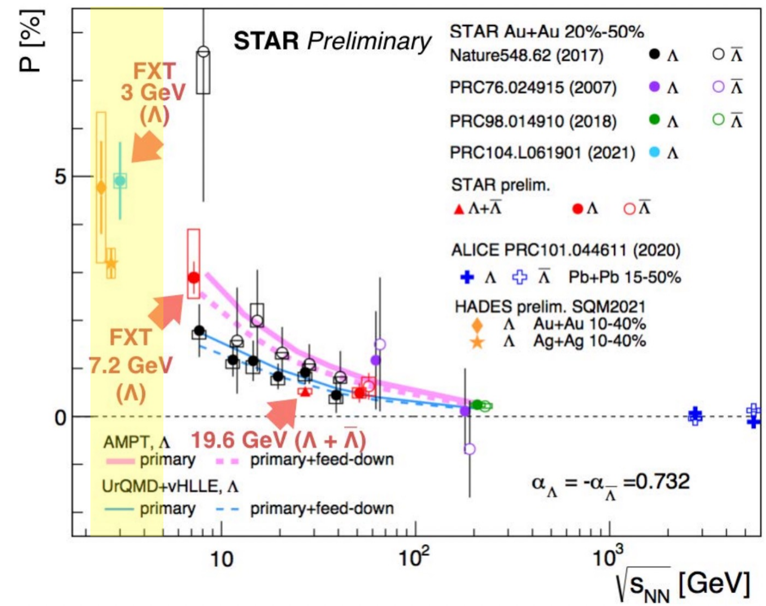
CBM Scientific Goals - II

Hypernuclei



- Y-N/Y-Y interaction / EoS
- high statistics enabling *S*=-2 hypernuclei
- dedicated tracker for reconstruction

Polarization / Spin Alignment



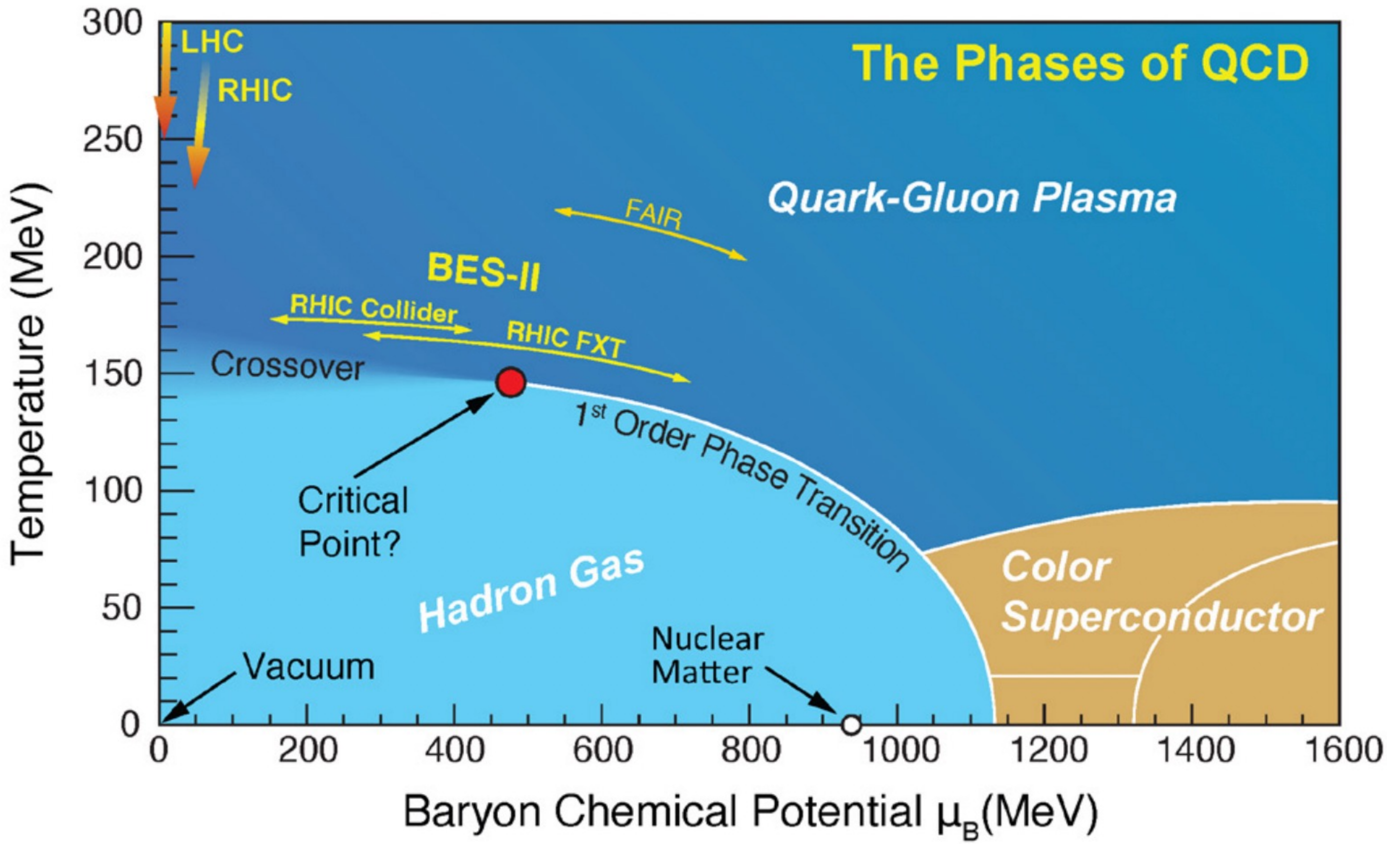
- medium properties / EoS at high μ_B
- high statistics for multi-dimension analysis

2023 LRP draft

US participation in the international collaboration of the Compressed Baryonic Matter experiment at this facility, driven by unprecedented beams from the superconducting heavy-ion synchrotron SIS100, will allow the US nuclear physics program to build on its successful exploration of the QCD phase diagram, use the expertise gained at RHIC to make complementary measurements, and contribute to achieving the scientific goals of the BES program.

A NEW ERA OF DISCOVERY

THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE



- Backup

Available Datasets

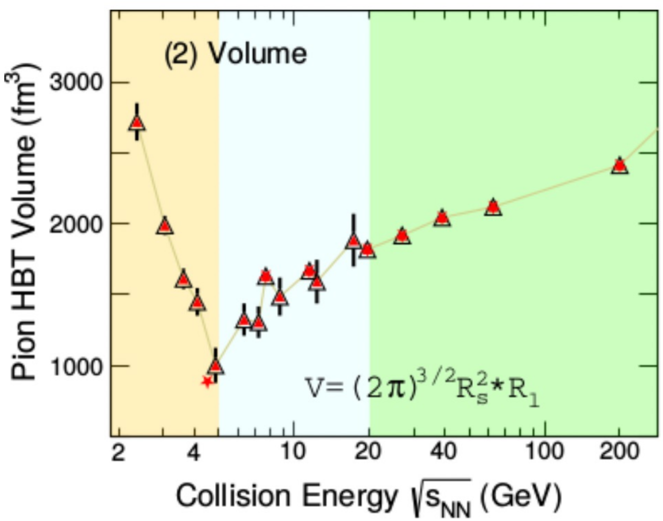
	$\sqrt{s_{NN}}$ (GeV)	Beam E (GeV)	# of Good Events	BES-I
2017	54.4		1350 M	
2018	27		560 M	70 M
	7.2	26.5 (FXT)	155 M	
	3.0	3.85 (FXT)	258 M	
2019	19.6		582 M	36 M
	14.6		324 M	20 M
	7.7	31.2 (FXT)	50.6 M	
	3.9	7.3 (FXT)	52.7 M	
	3.2	4.59 (FXT)	201 M	
2020	11.5		235 M	12 M
	9.2		162 M	
	7.7	31.2 (FXT)	112 M	
	7.2	26.5 (FXT)	317 M	
	6.2	19.5 (FXT)	118 M	
	5.2	13.5 (FXT)	103 M	
	4.8	11.5 (FXT)	235 M	
	4.5	9.8 (FXT)	108 M	
	3.9	7.3 (FXT)	117 M	
	3.5	5.75 (FXT)	116 M	
2021	17.3		250 M	
	7.7		101 M	5 M
	13.5	100 (FXT)	50.7 M	
	11.5	70 (FXT)	51.7 M	
	9.1	44.5 (FXT)	53.9 M	
	3.0	3.85 (FXT)	2.0 B	

Data production all ready
Analyses ongoing

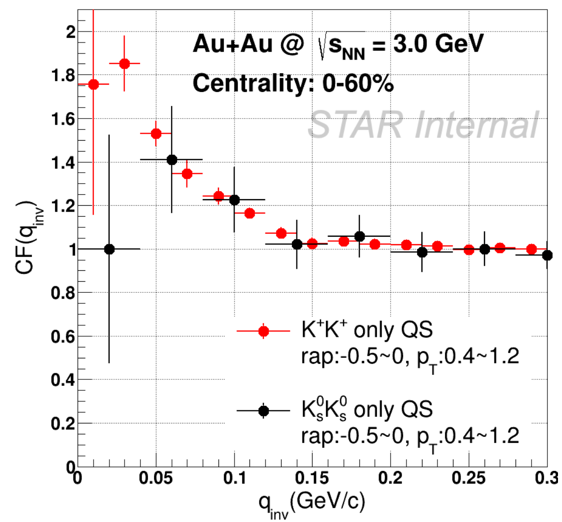
To come soon

Particle Emission Source Size

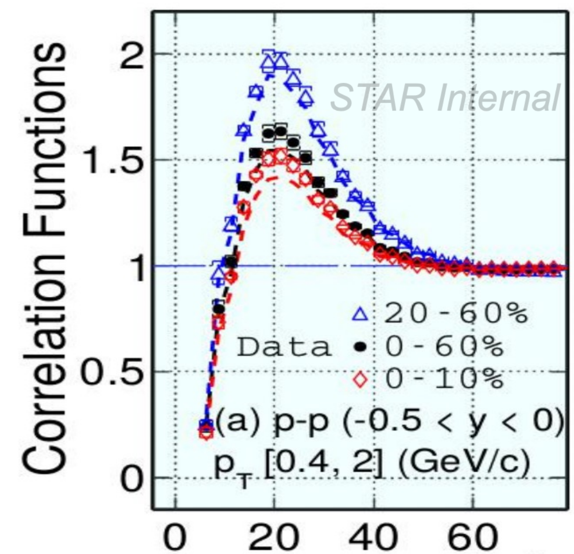
Pion Source Size



Kaon-Kaon



Proton-Proton



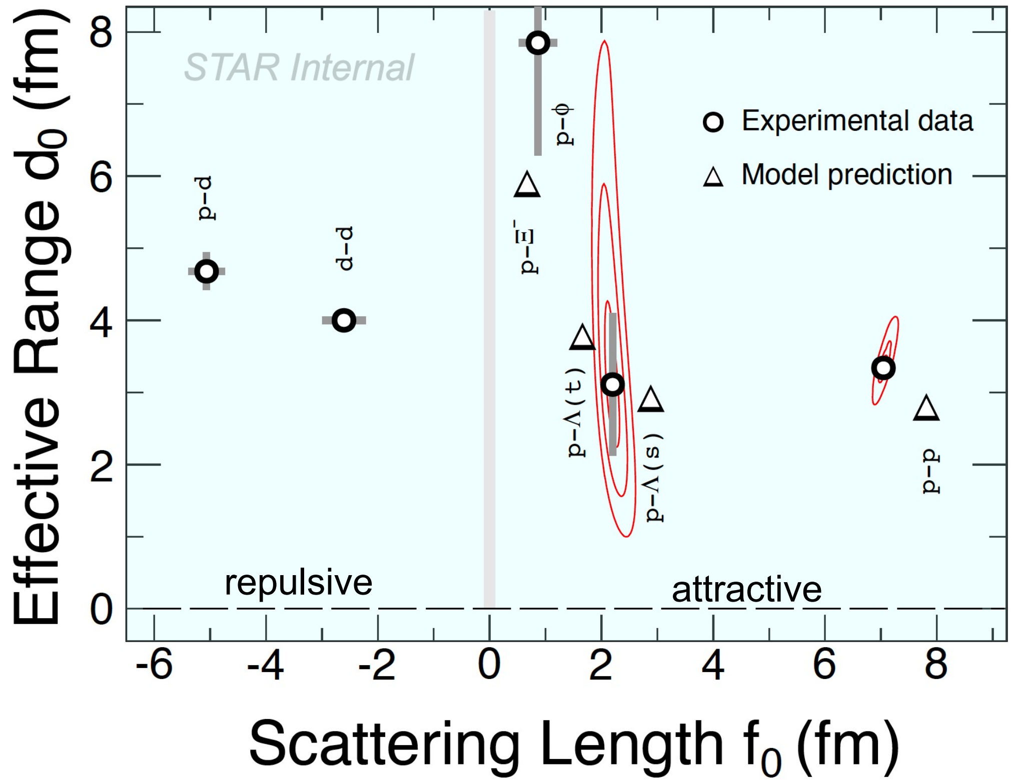
- Non-monotonic energy dependence of pion source size? softest ∂p point?
- BES-II (collider+FXT) data allow us to systematically measure pion, kaon, proton (and others) source sizes and their energy/centrality dependence

Baryon-Baryon/Hyperon Interactions

Lednicky-Lyuboshitz formulism:

Scattering amplitude:

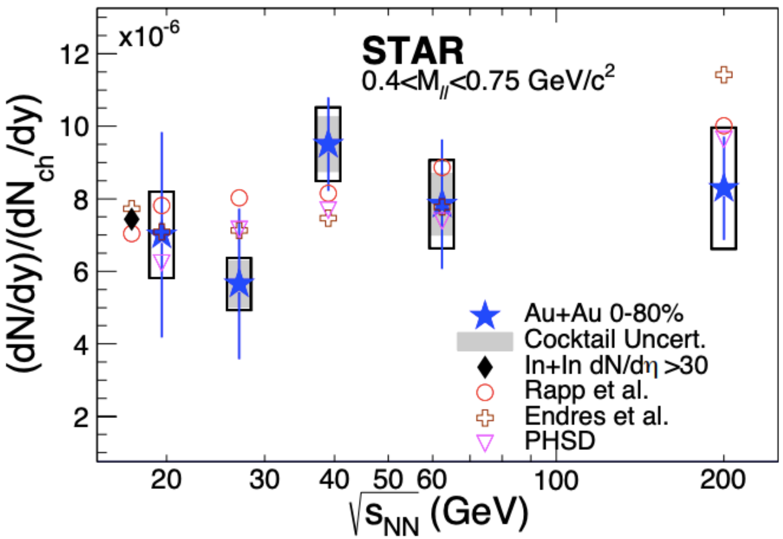
$$f(k) = (\frac{1}{f_0} + \frac{1}{2}d_0k^2 - ik)^{-1}$$



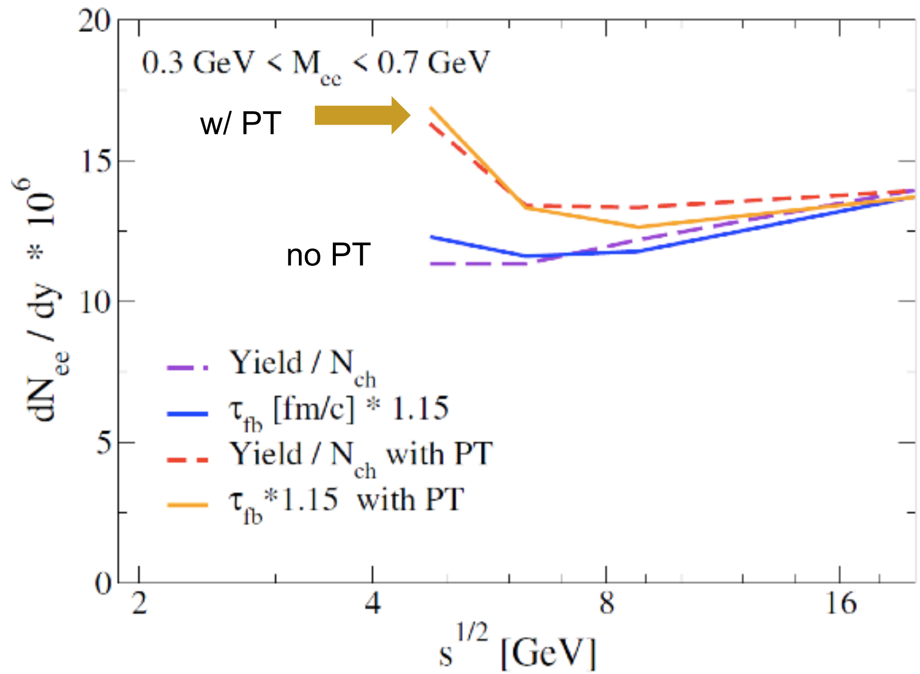
- Important ingredients for nuclear matter Equation-of-State
- Search for exotic states (e.g. H-dibaryon)

Energy Dependence of Dielectron Yield

arXiv: 1810.10159



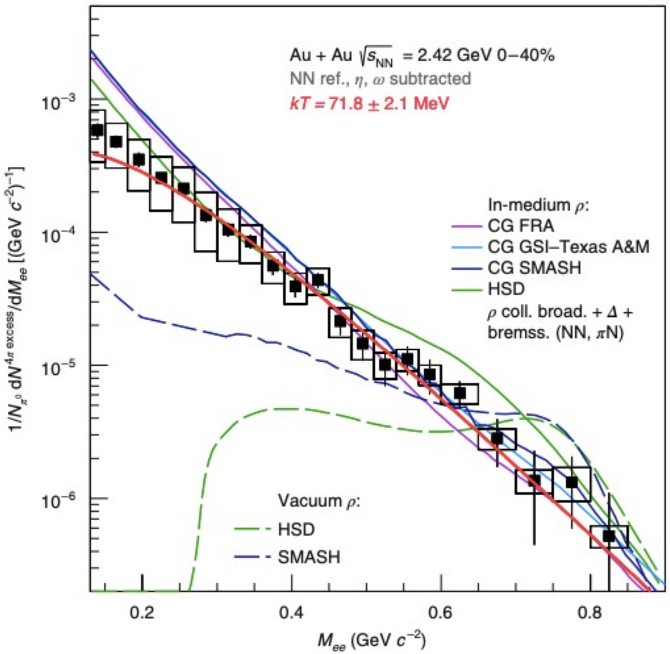
R. Rapp, 2021



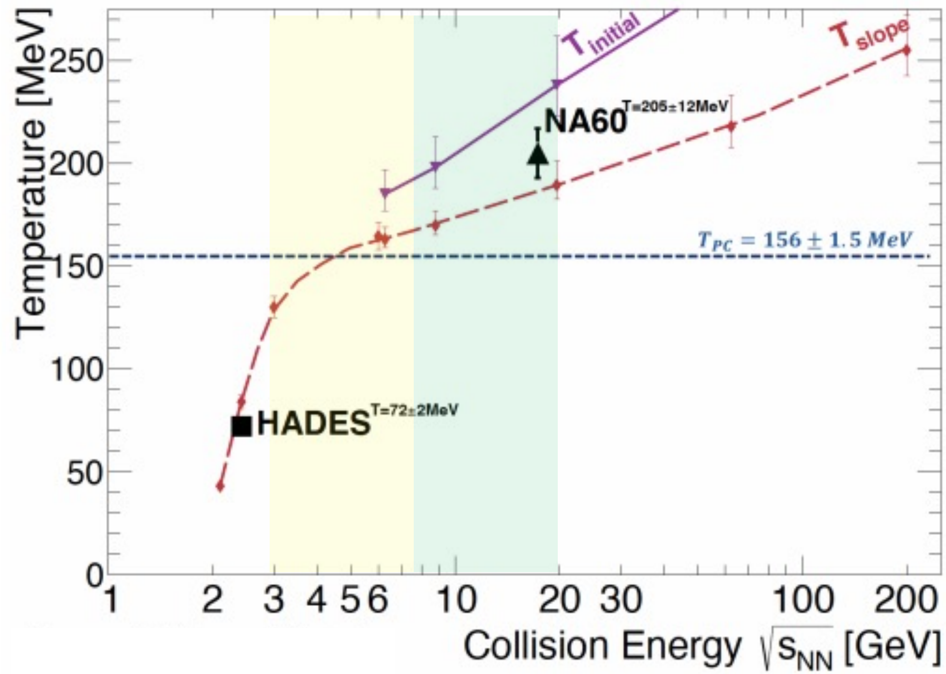
- Mild energy dependence of dielectron yield from SPS to top RHIC energy
- Potential 1st-order phase transition (PT) signature
  → latent heat leads to an increase in lifetime / dielectron yield

Dielectrons – Slope Parameter

HADES, nature physics 15 (2019) 1040



BES-II



$$\frac{dN}{dM_{ee}} \propto M_{ee}^{3/2} e^{-M_{ee}/T}$$

- Boost-invariant measure of the medium temperature
- Sharp transition in T_{slope} at energy of 3-20 GeV
  - no 1st-order PT included

US-CBM White Paper

arXiv: 2209.05009

QCD Phase Structure and Interactions at High Baryon Density: Completion of BES Physics Program with CBM at FAIR

BNL, UC Davis, UCLA, UCR, Duke, UH, UIC, UIUC, IU, KSU, LBNL, MSU, UNC, NCSU, OSU, Pepperdine, Purdue, SBU, Rice, UW, WSU

Executive Summary

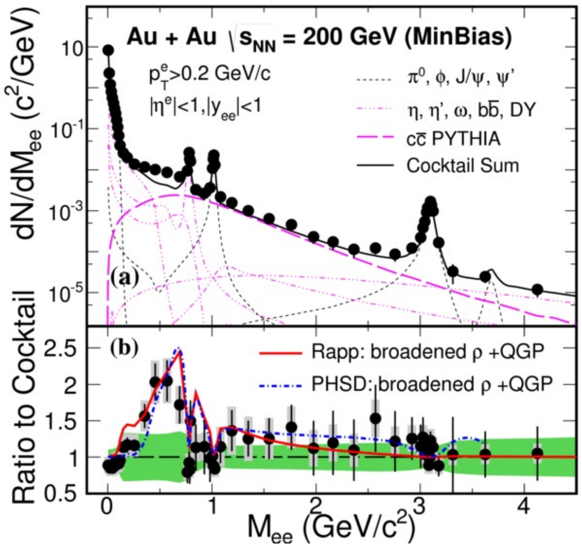
In order to complete the Beam Energy Scan (BES) physics program, including the search for the QCD critical point, the extraction of the hyperon-nucleon interaction, and the determination of constraints on the nuclear matter equation of state at high baryon density, **active US participation in the international collaboration of the Compressed Baryonic Matter (CBM) experiment at FAIR*** is scientifically necessary and cost effective.
…
Without these measurements in the FAIR/CBM energy region, the scientific program pioneered at RHIC with the BES program would risk to be terminated prematurely in the US, and some of the key physics questions may remain unanswered. … *US participation in CBM will not only greatly enhance its physics program, but will also strengthen US leadership in nuclear physics*.

**recommendation as new initiative*

Dielectrons Mass Spectra (17.3 – 200 GeV)

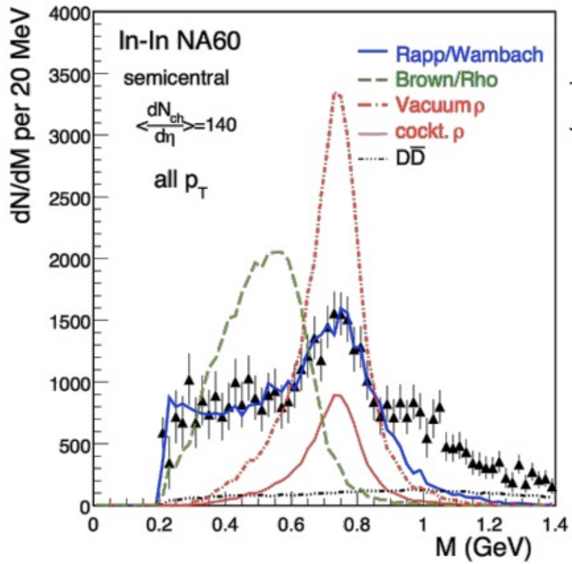
200 GeV - STAR

PRL 113 (2014) 022301



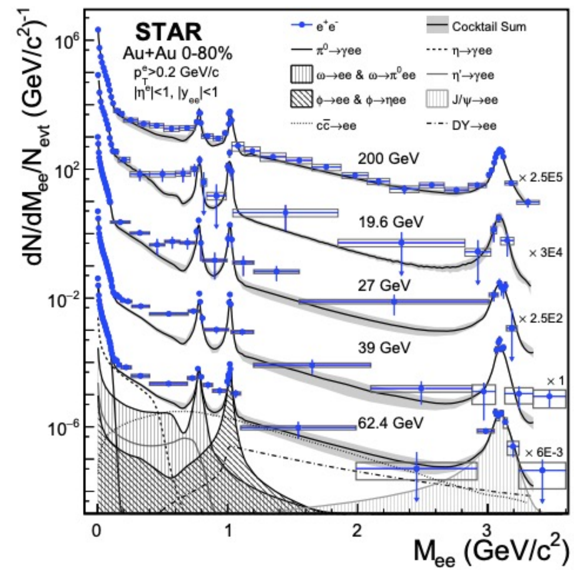
17.3 GeV – NA60

PRL 100 (2008) 022302



19.6 – 200 GeV - STAR

arXiv: 1810.10159



- Enhancement in dilepton invariant mass spectra at 0.3-0.7 GeV/c^2 from 17.3 – 200 GeV
- In-medium ρ-broadening through interactions with baryons describe data consistently from SPS to RHIC

BES-II Datasets and Data Quality

$\sqrt{s_{NN}}$ (GeV)	# of Good Events	BES-I
54.4	1350 M	
27	560 M	70 M
19.6	582 M	36 M
17.3	250 M	
14.6	324 M	20 M
11.5	235 M	12 M
9.2	162 M	
7.7	101 M	5 M
3.0	2000 M	

- *other FXT datasets not listed*

green – datasets calibrated/produced

Critical Point Search

Lattice calculation of QCD critical point (CP) at finite $\square_B$ is still challenging.

- Recent development (Tyler series) predicts CP location:

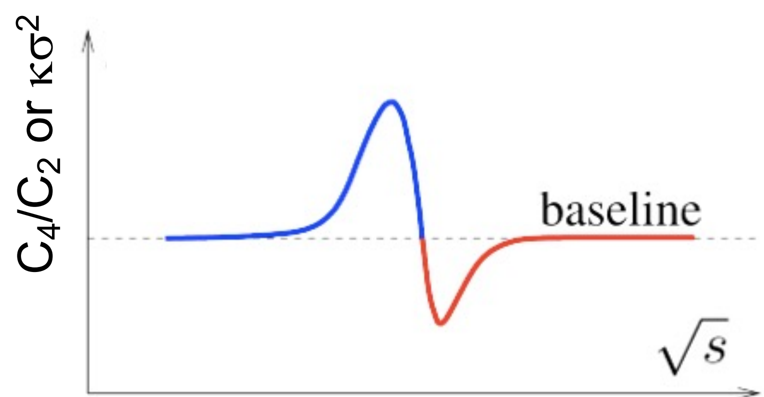
$\square_B$ > 400 MeV or $\square_B/T > 3$ (*F. Karsch, 2021*)

Proposed Experimental Observables:

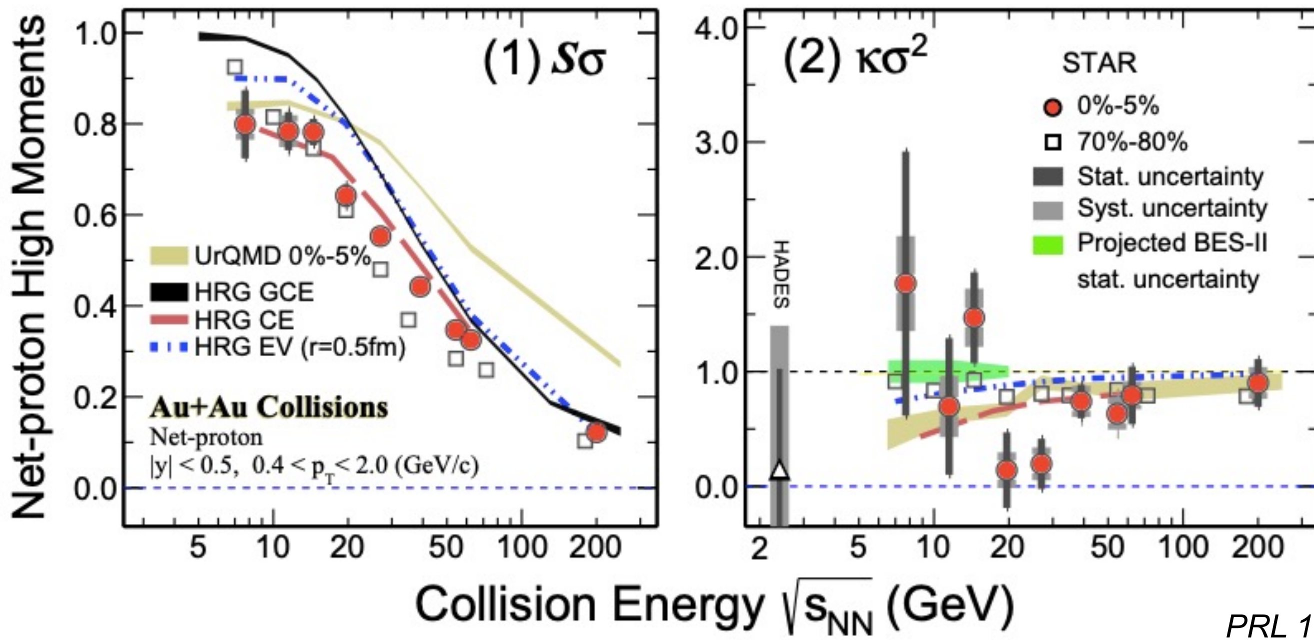
Moments of conserved quantities: net-baryon number, net-strangeness, net-charge etc.

- directly related to the susceptibility ratios (calculable from Lattice QCD)
- sensitive to correlation lengths (*M. A. Stephanov, PRL 102 (2009) 032301*)

$$\begin{aligned}
\text{mean} : \mathrm{M} = \langle N \rangle & = C_1, \\
\text{variance} : \sigma^2 = \langle (\delta N)^2 \rangle & = C_2, \\
\text{skewness} : \mathrm{S} = \langle (\delta N)^3 \rangle / \sigma^3 & = C_3 / C_2^{3/2}, \\
\text{kurtosis} : \kappa = \langle (\delta N)^4 \rangle / \sigma^4 - 3 & = C_4 / C_2^2.
\end{aligned}$$



Net-proton Cumulant Ratios from BES-I

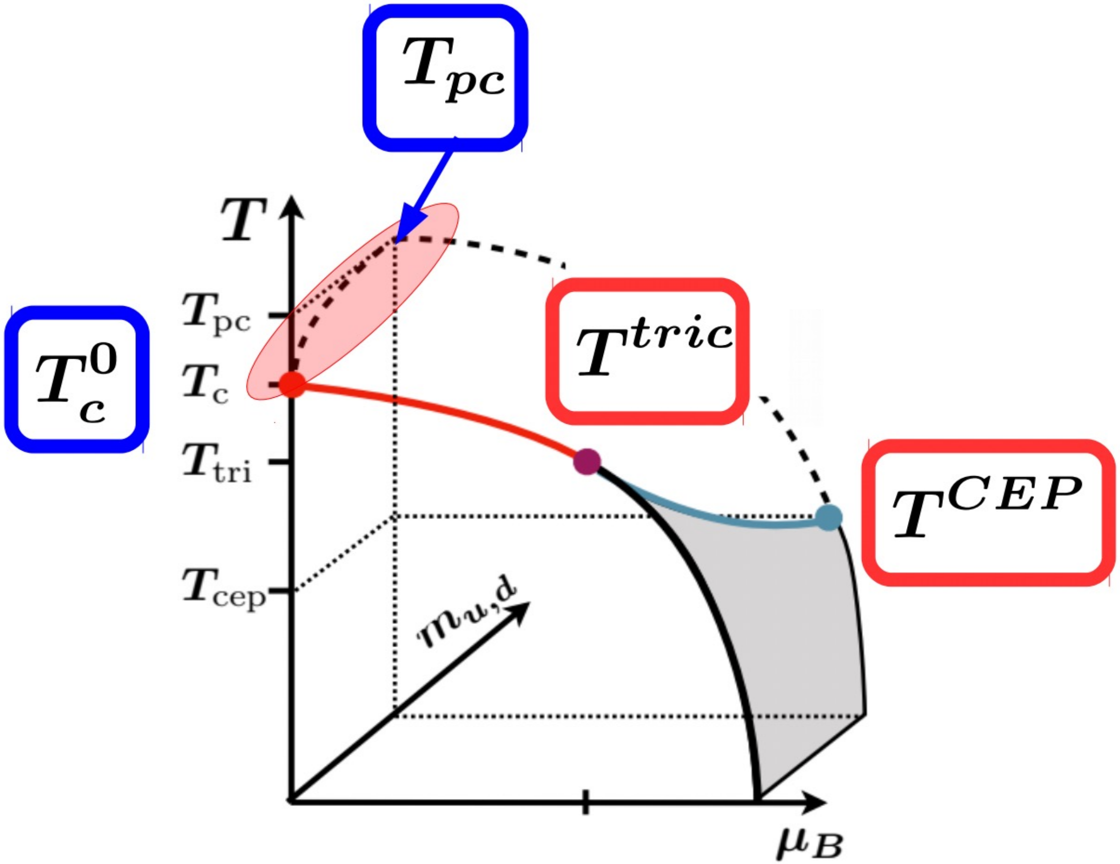


PRL 126 (2021) 092301

<u>*p*-value from χ^2-test</u>

Moments	HRG GCE	HRG EV (r = 0.5 fm)	HRG CE	UrQMD
$S\sigma$	< 0.001	< 0.001	0.0754	< 0.001
$\kappa\sigma^2$	0.00553	0.0145	0.0450	0.0221

Non-monotonic energy dependence of net-proton C_4/C_2 (3.1 σ) from BES-I
- connection to critical point?



physical masses

$$T_{pc}^{phys} = (156.5 \pm 1.5)\ \mathrm{MeV}$$

A. Bazavov et al [HotQCD], arXiv:1812.08235

chiral limit extrapolations

$$T_c^0 = 132^{+3}_{-6}\ \mathrm{MeV}$$

H.-T. Ding et al [HotQCD], arXiv:1903.04801