Review of Recent Heavy-Ion Results from RHIC

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Outline:

- Motivation
- QGP properties
- Beam energy scan: QCD phase diagram
- Summary

Triggering Discoveries in High Energy Physics

September 9-14, 2013, University of Jammu, Jammu

RHIC Heavy-ion Program

Main goals:

1. Study QGP and its properties:
   - Detailed studies for temperature, viscosity, and energy density

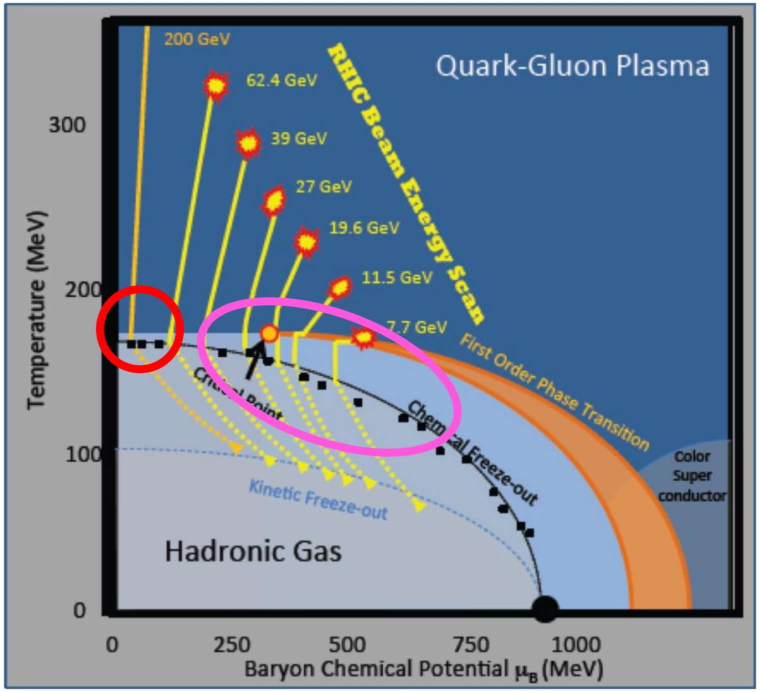
STAR: Nucl. Phys. A 757, 102 (2005)

2. Study QCD phase diagram:

   - Search for the signals of possible phase boundary
   - 1st order phase transition
   - Search for the possible QCD Critical Point

   ⇨ Beam Energy Scan

QCD Phase Diagram:



http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493: arXiv:1007.2613

(A) QGP study and properties

Characterize QGP by measuring it’s properties such as:

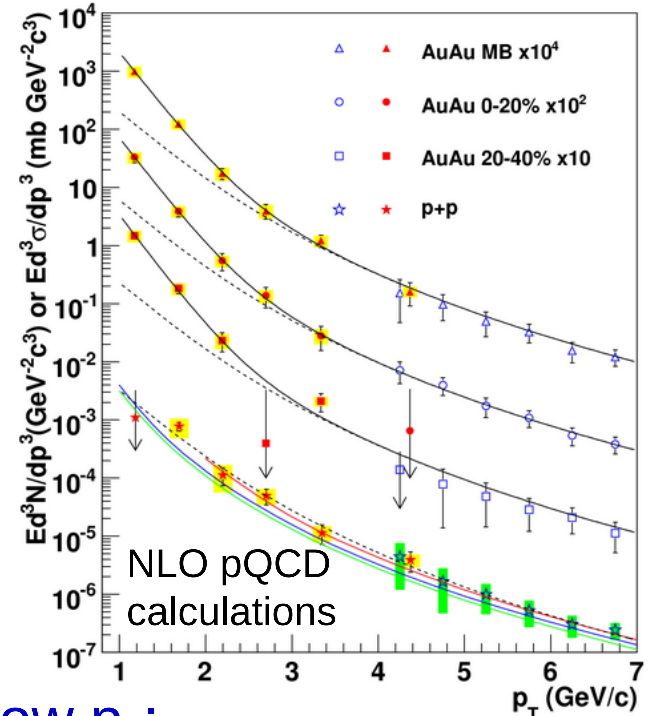
- Temperature
- Energy density
- Viscosity

(I) Initial Temperature

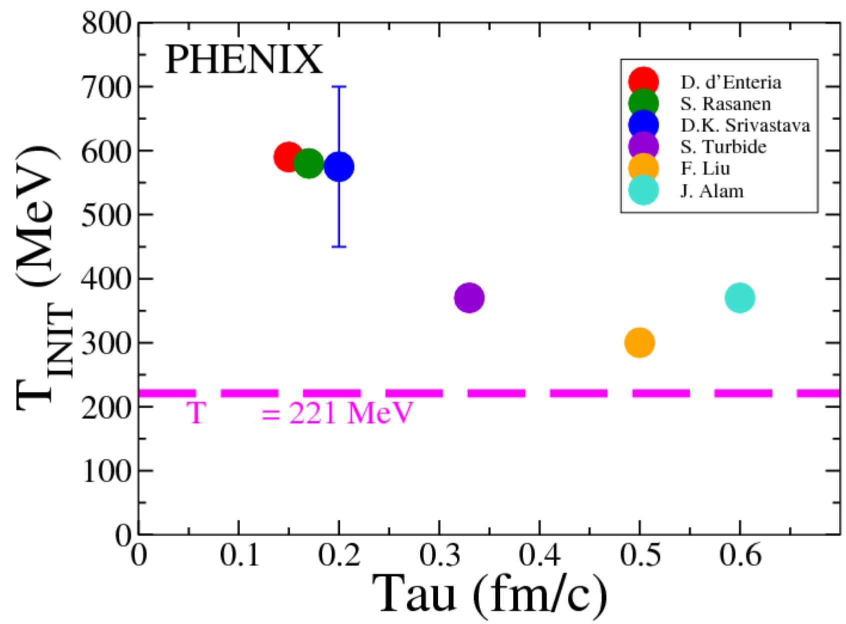
Direct Photons:

i) Initial hard scattering
-- dominant at high p_T
-- information on PDFs, QCD, etc.

ii) Thermal radiation
-- dominant at low p_T
-- information on initial temperature of QGP



PHENIX : PRL,104,132301 (2010)



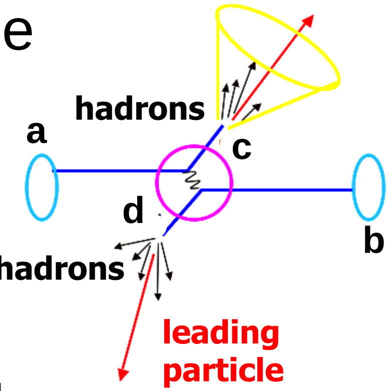
$T_{initial} > T_C$ (Lattice) [~ 170 MeV]

Low p_T:

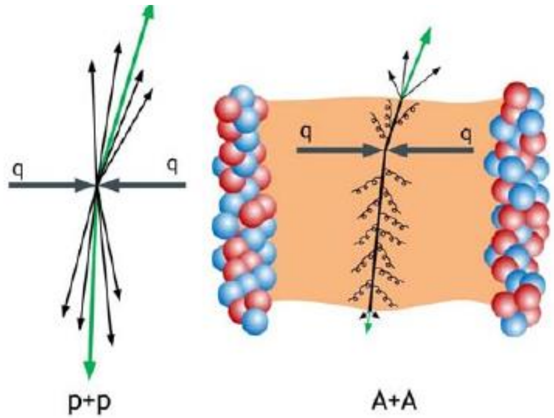
Enhancement of direct photon yields in Au+Au w.r.t. p+p collisions

(II) Suppression of high p_T hadron production

Jet: A localized collection of hadrons which come from a fragmenting parton



Behavior in pp and heavy-ion collisions:



pp collisions: Unaffected
Heavy-ions: Suppressed (if QGP)

Jet Quenching: Suppression in production of high-p_T particles in nucleus-nucleus collisions compared to corresponding data from binary collision scaled p+p collisions

Measure:
Nucelar Modification Factor (R_{AA}/R_{CP})

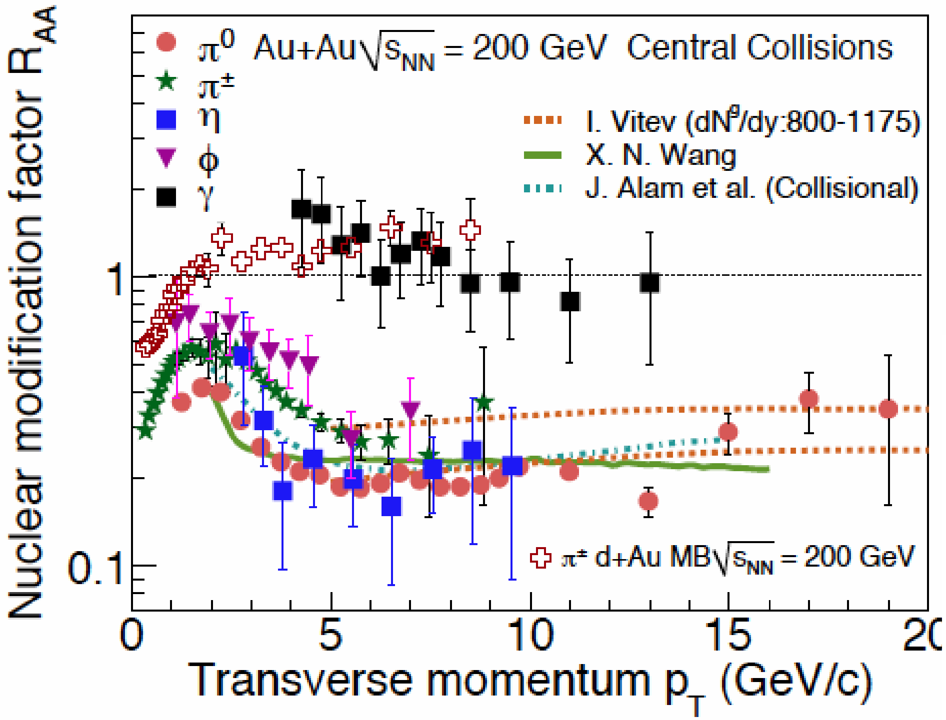
$$R_{AA} = \frac{dN_{AA}/d\eta d^2 p_T}{T_{AB} d\sigma_{NN}/d\eta d^2 p_T}$$

$$T_{AB} = N_{binary}/\sigma^{pp}_{inelastic}$$

N_{binary} No. of binary collisions

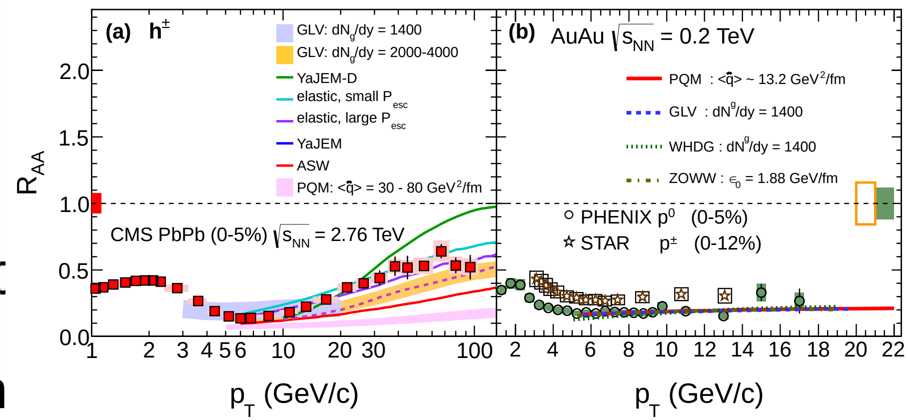
High p_T: $R_{AA}/R_{CP} < 1$ ➔ QGP, $R_{AA}/R_{CP} > 1$ ➔ No QGP

(II) Suppression of high p_T hadron production



B. Mohanty, New J.Phys.13, 065031 (2011)
STAR: PRL 97, 152301 (2006); PLB 655, 104 (2007); PLB 637, 161 (2006).
PHENIX: PRC 83,024909 (2011); PRC 82, 011902 (R) (2010); PRL 101, 232301 (2008); PRL 96, 202301 (2006).

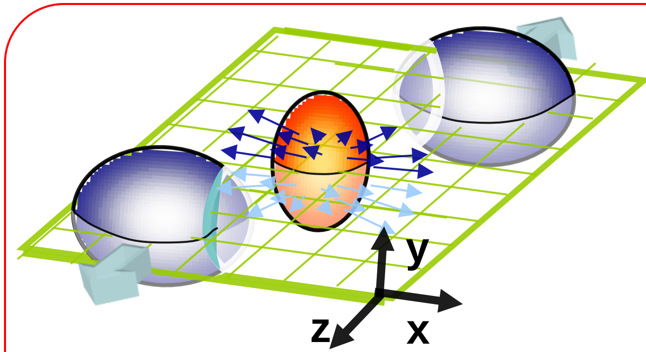
$\varepsilon_{initial} > \varepsilon_c$ (Lattice ~1 GeV/fm^3)

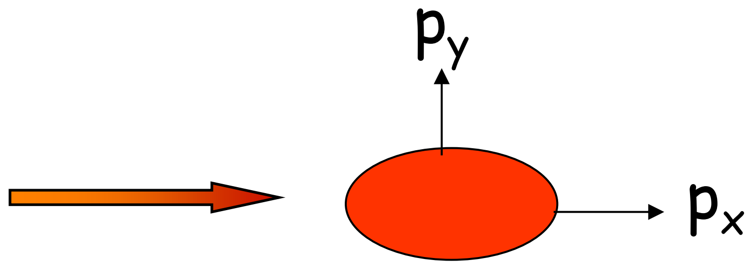


Similar conclusion at LHC

- Large suppression of high p_T meson production in central Au+Au collisions
- No suppression in d+Au experiment
- Similar suppression in π, η and ϕ: *suppression is at partonic level*
- No suppression for direct photons: *final state effect*
- *Models assumption:* $\varepsilon_{initial}$ ~ 5-15 GeV/fm^3

(III) Azimuthal Anisotropy





$$\varepsilon = \frac{\langle y^2 \rangle - \langle x^2 \rangle}{\langle y^2 \rangle + \langle x^2 \rangle}$$

initial spatial anisotropy

$$v_2 = \left\langle \frac{p_x^2 - p_y^2}{p_x^2 + p_y^2} \right\rangle \qquad \phi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

anisotropy in momentum space

$$E\frac{dN^3}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_t dp_t dy}\left(1 + 2v_1\cos(\phi - \Psi_R) + 2v_2\cos(2(\phi - \Psi_R)) + \ldots\right)$$

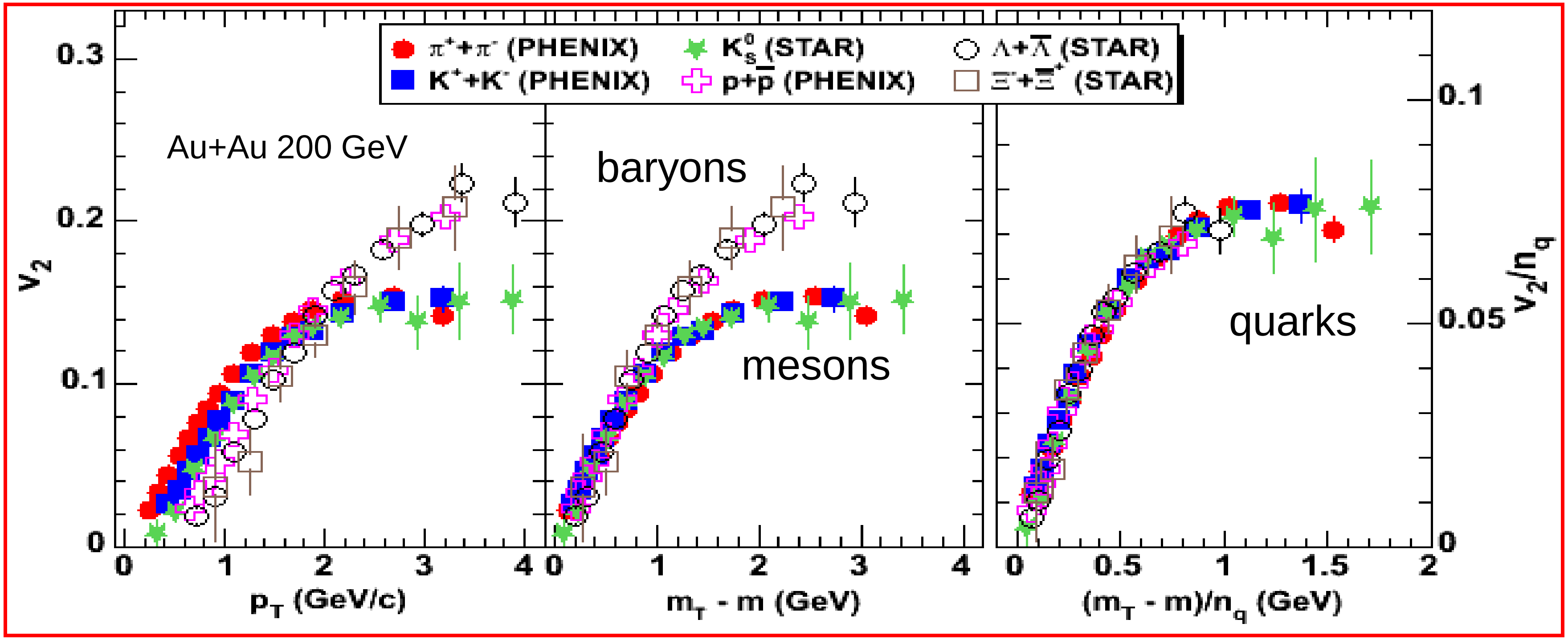
Directed flow (v_1) **Elliptic flow** (v_2)

$$v_n = \langle \cos(n(\phi - \psi_n)) \rangle = \langle e^{in(\phi - \psi_n)} \rangle$$

$$= \text{Correlation to the reaction plane}$$

$$\equiv \text{"anisotropic flow"}$$

(III) Elliptic Flow: $v_n = \langle \cos n(\phi - \psi_n) \rangle, n = 2$



STAR: PRL **95**, 122301 (2005)
PHENIX: PRL **98**, 162301 (2007)

$$m_T = \sqrt{p_T^2 + m^2}$$

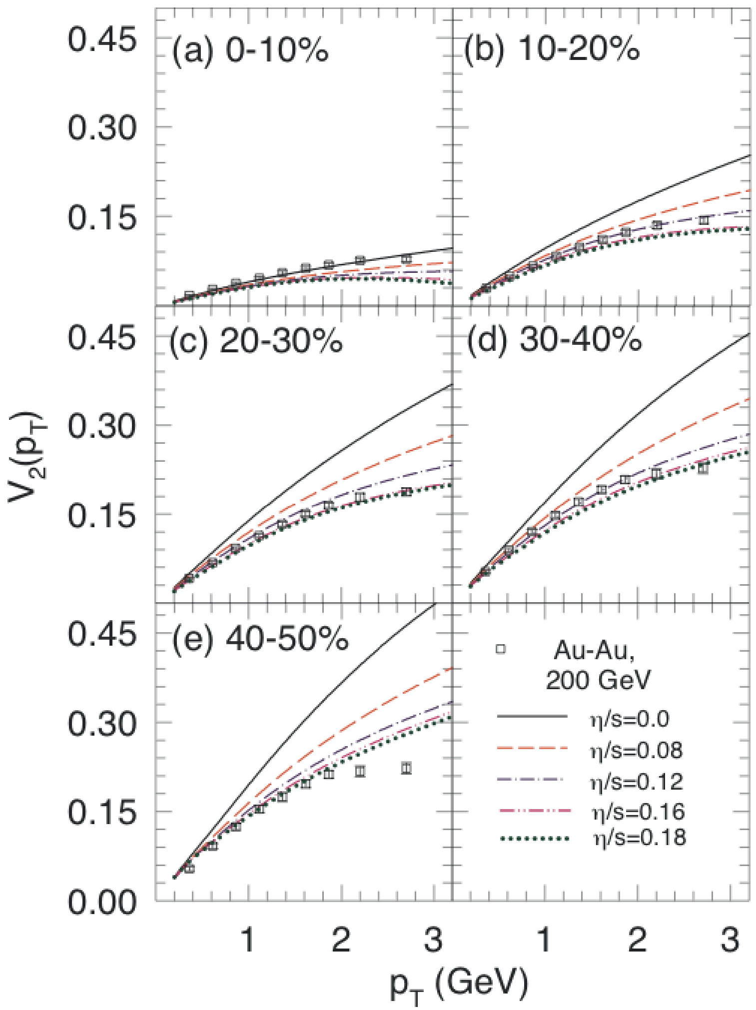
n_q = 2 for mesons, n_q = 3 for baryons

- ✧ Elliptic flow scaled by number of constituent quarks (NCQ) follow a common curve for different particles – NCQ scaling
- ✧ Flow develops at the partonic level (indication of QGP formation)

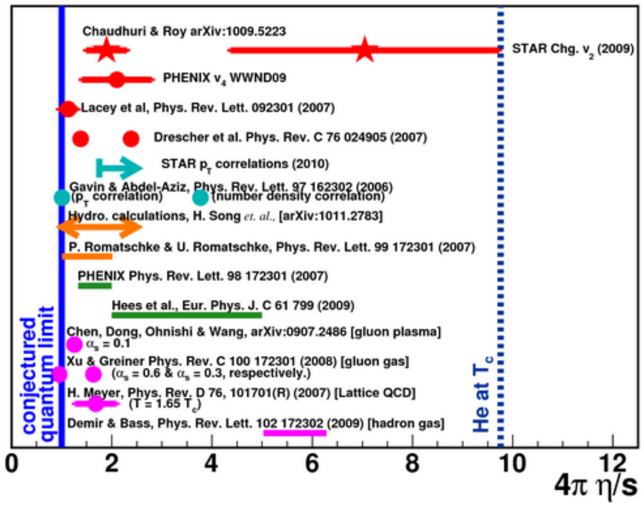
(III) Elliptic Flow: $v_n = \langle \cos n(\phi - \psi_n) \rangle, n = 2$

Shear viscosity to entropy density (η/s):

A. Tang, NPA 830, 673C (2009)



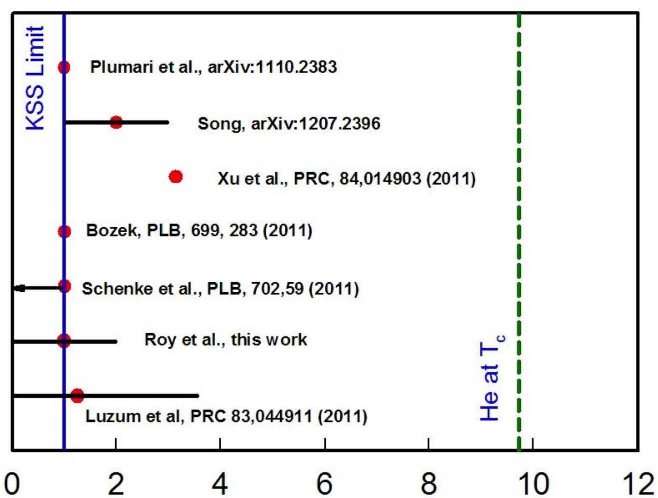
Roy et al., PRC 86, 014902 (2012)



RHIC

1/4π – (10*1/4π)

Similar η/s at RHIC and LHC



Roy et al., JPG: NPP 40, 065103 (2013)

LHC

1/4π – (4*1/4π)

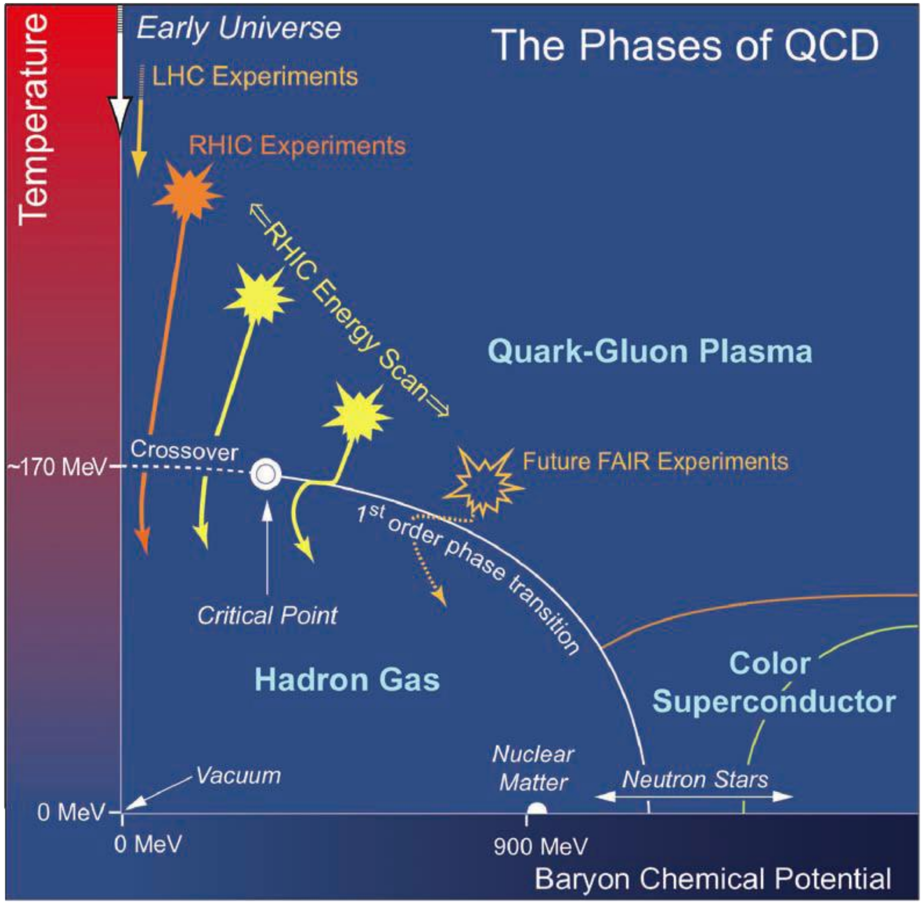
QGP Properties: Conclusions

RHIC has established the formation of QGP: hot and dense

Some of the properties:

Property	Value	Remark
Initial Temperature:	~ (300-600) MeV	QGP phase transition value: ~170 MeV
Initial energy density:	~ (5-15) GeV/fm^3	QGP phase transition value: ~ 1 GeV/fm^3
Shear viscosity to entropy density ratio (η/s):	Close to KSS limit of 1/4π	Similar η/s value observed at LHC

(B) Beam Energy Scan



USA-NSAC 2007, Long-range plan

i) Search for the signals of possible phase boundary

ii) First order phase transition/ softening of equation of state

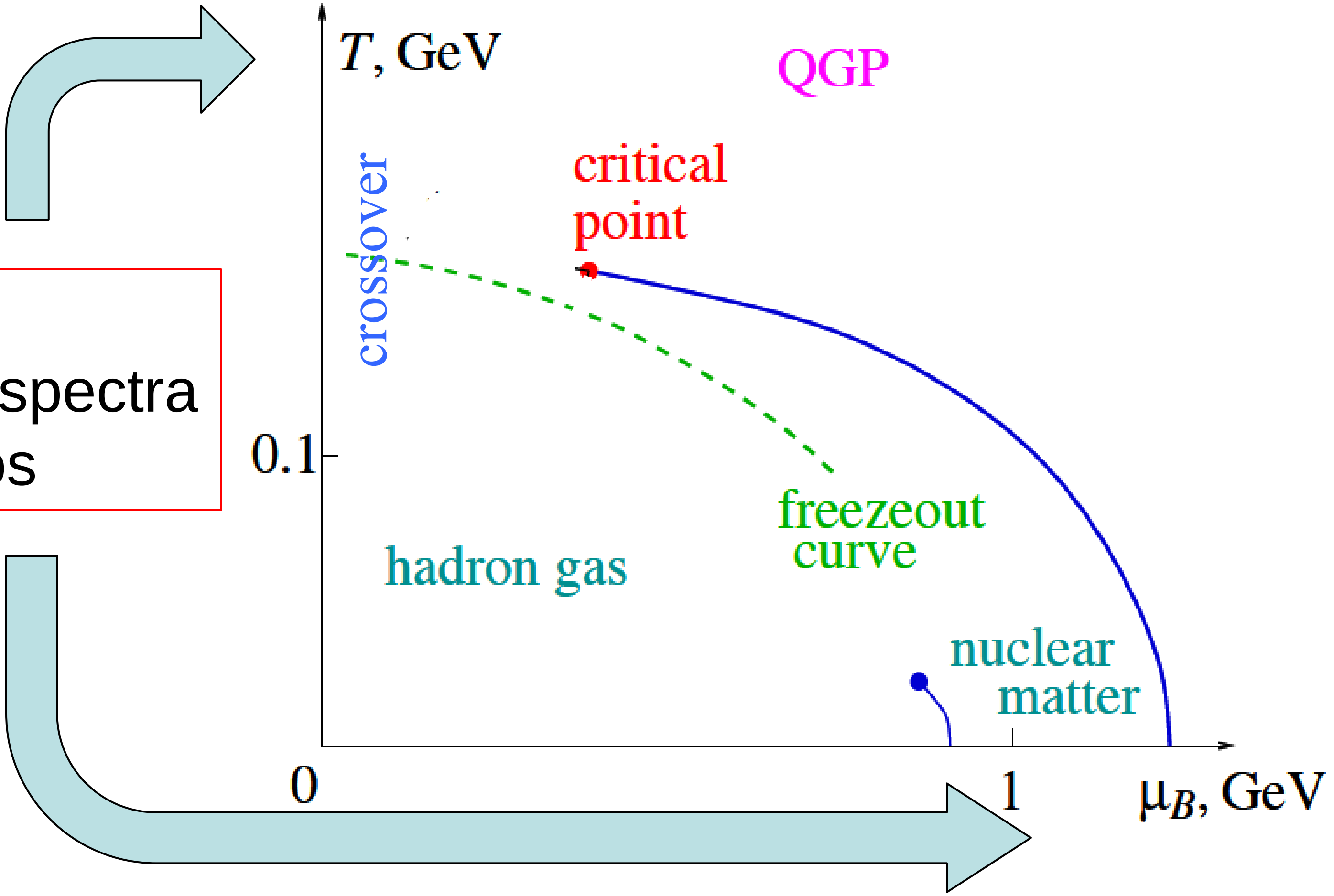
ii) Search for the possible QCD Critical Point

BES-I Data (STAR):

Year	$\sqrt{s_{NN}}$ (GeV)	Events(10^6)
2010	39	130
2011	27	70
2011	19.6	36
2010	11.5	12
2010	7.7	5
2012*	**5**	Test Run

(I) Accessing Phase Diagram

T-μ_B:
From p_T spectra and ratios



Freeze-out Parameters

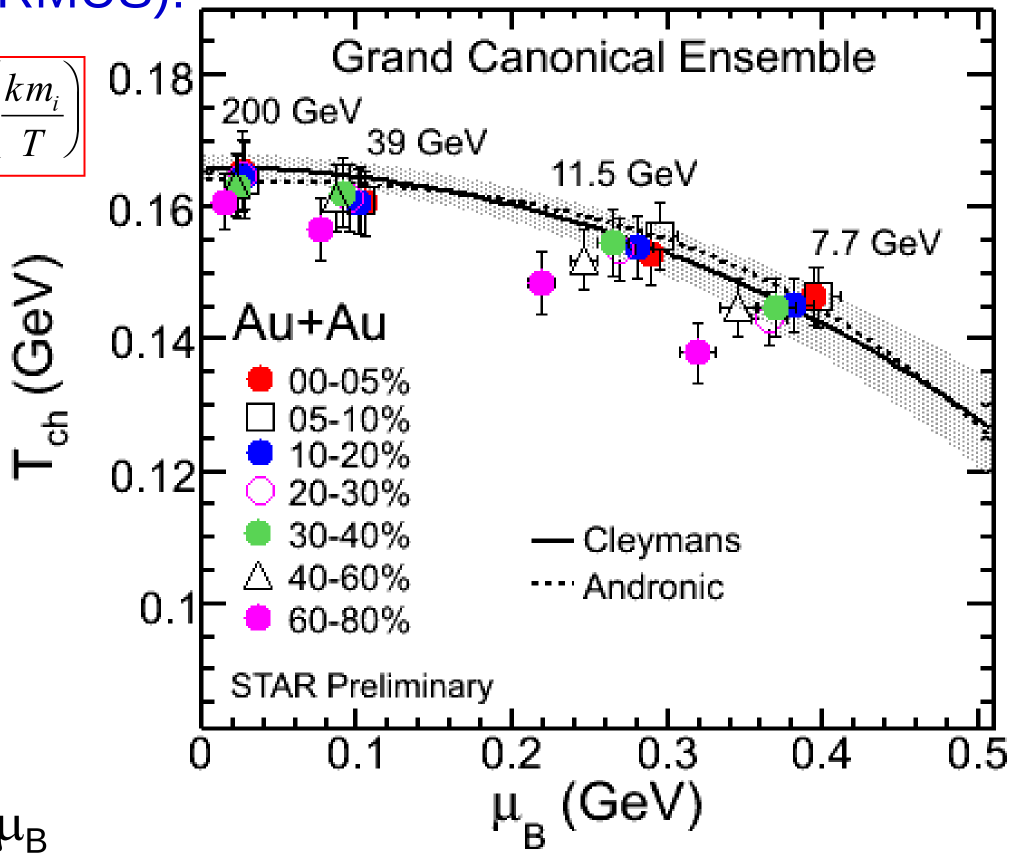
Statistical-Thermal Model (THERMUS):

$$n = \frac{1}{V}\frac{\partial(T\ln Z)}{\partial\mu} = \frac{VTm_i^2 g_i}{2\pi^2}\sum_{k=1}^{\infty}\frac{(\pm1)^{k+1}}{k}\left(e^{\beta k\mu_i}\right)K_2\left(\frac{km_i}{T}\right)$$

β=1/T; -1 (+1) for fermion(boson)
Z=partition function;
m_i = mass of hadron species i;
V = volume; T = Temperature;
K_2= 2^{nd} order Bessel function;
g_i = degeneracy;
μ_i = chemical potential

Particles used:
π, K, p, Λ, K^0_s, Ξ

Two main parameters: T_{ch} and μ_B



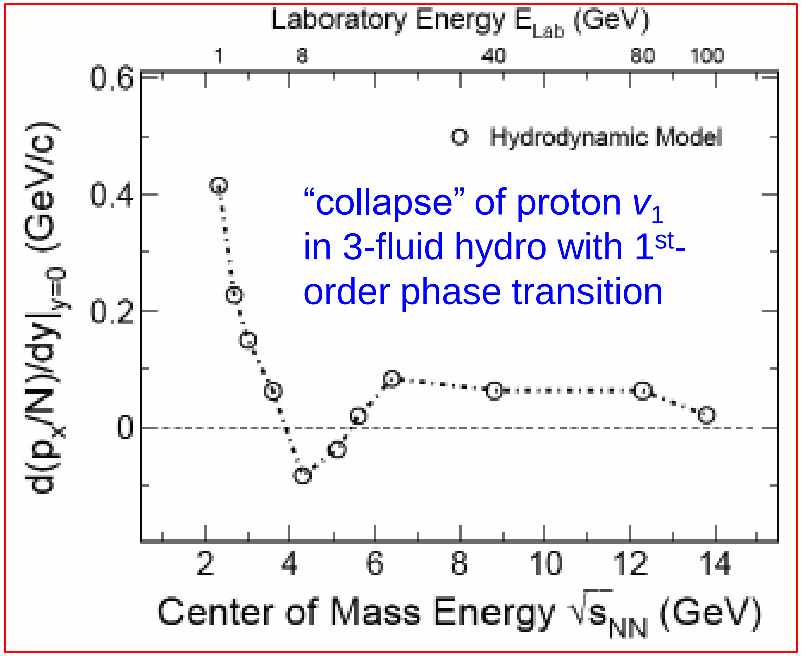
Centrality dependence of freeze-out temperature with baryon chemical potential observed for first time at lower energies

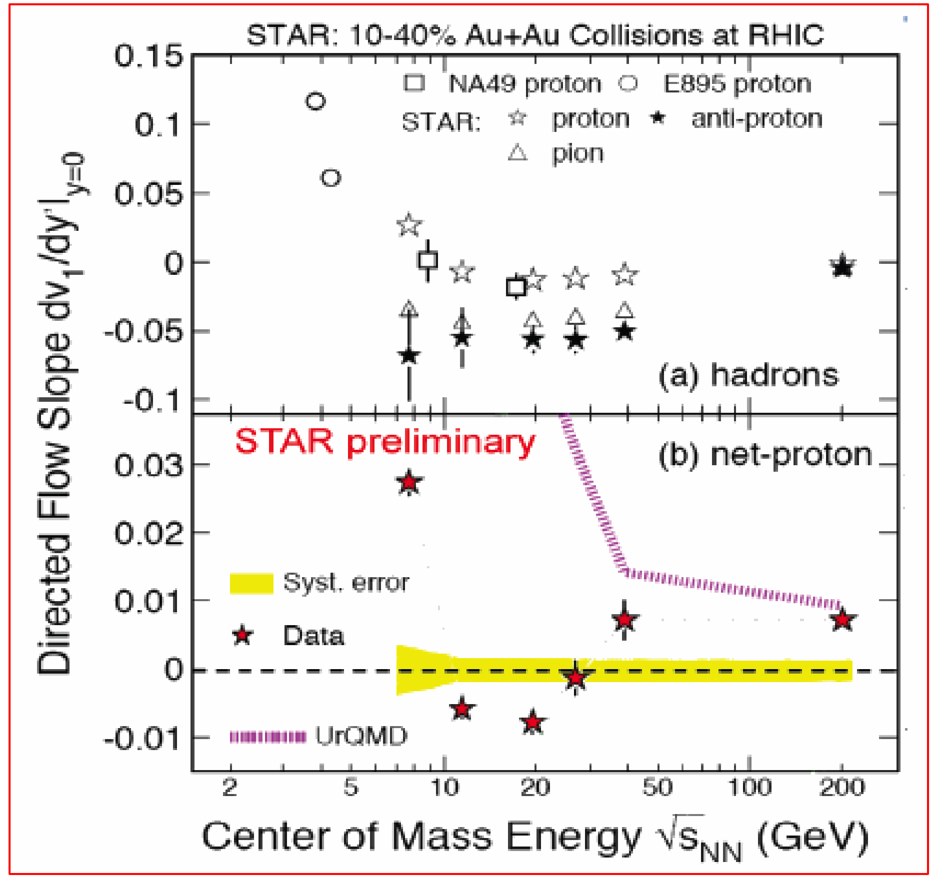
(II) Turn-OFF of QGP Signals/Softening of Equation of State/1st Order Phase Transition

- Net-proton Directed Flow (1st-order phase transition)
- Elliptic Flow (Turn-off of QGP signatures)
- Charge Separation w.r.t. Reaction Plane (Turn-off of QGP)
- Nuclear Modification Factor (Turn-off of QGP signatures)

Directed Flow: $v_n = \langle \cos n(\phi - \psi_n) \rangle, n = 1$

H. Stoecker, NP A**750**, 121 (2005).

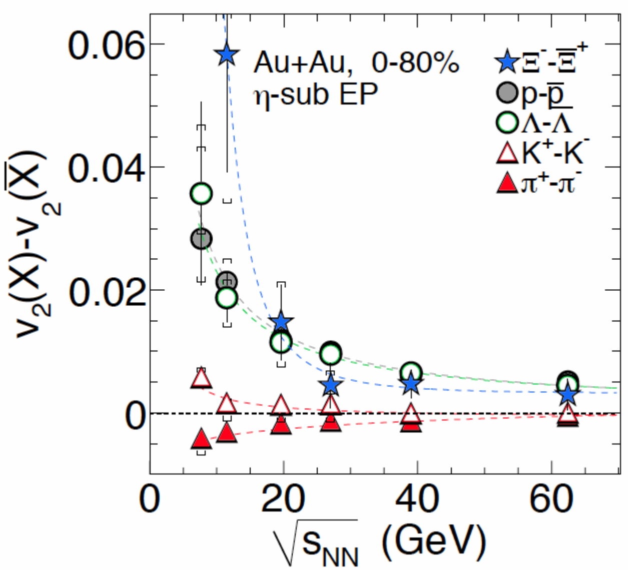




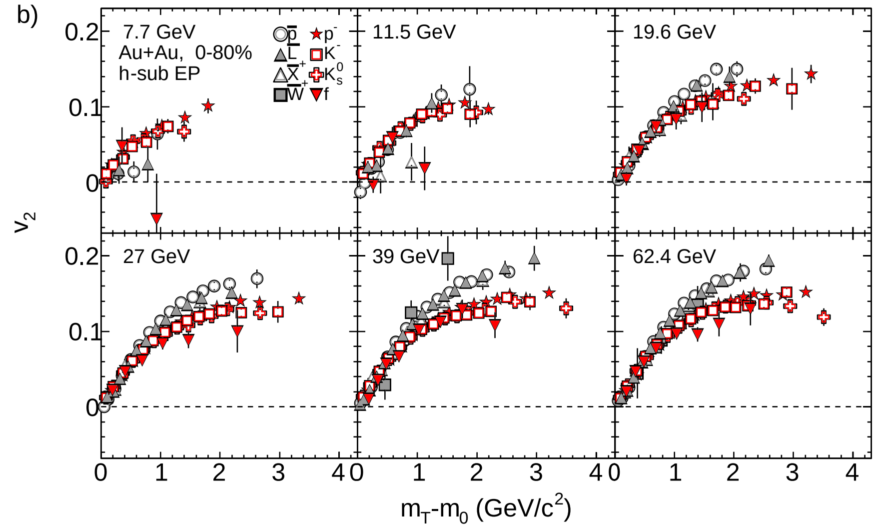
$F_p = r F_{anti\text{-}p} + (1 - r) F_{net\text{-}p}$, r is the observed ratio of antiprotons to protons.

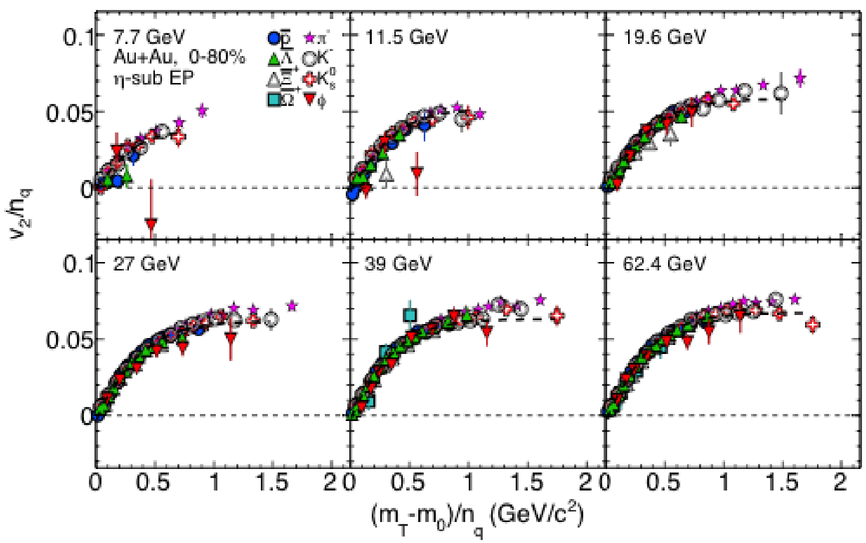
Pion v_1 slope: Always negative (7.7-39 GeV)
(Net)-proton v_1 slope: changes sign between 7.7 and 11.5 GeV (shows a minimum at ~ 19.6 GeV)

Elliptic Flow: $v_n = \left\langle \cos n(\phi - \psi_n) \right\rangle, n = 2$



STAR: PRL 110, 0142301 (2013)



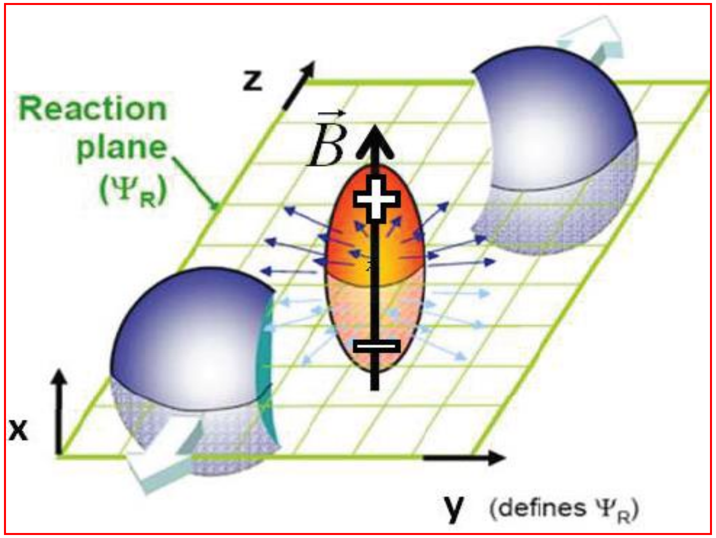


- ✧ Difference in baryon-antibaryon v_2 increases with decreasing $\sqrt{s_{NN}}$:
  baryon transport / hadronic interactions
  -- J. Dunlop et al., PRC 84, 044914 (2011)
  -- J. Xu et al., PRC 85, 041901 (2012)
- ✧ For anti-particles: Baryons and mesons show no splitting at 11.5 GeV
- ✧ ϕ-meson v_2 deviates (~2σ) from others for $\sqrt{s_{NN}} \leq 11.5$ GeV: less collectivity contribution from partonic interactions

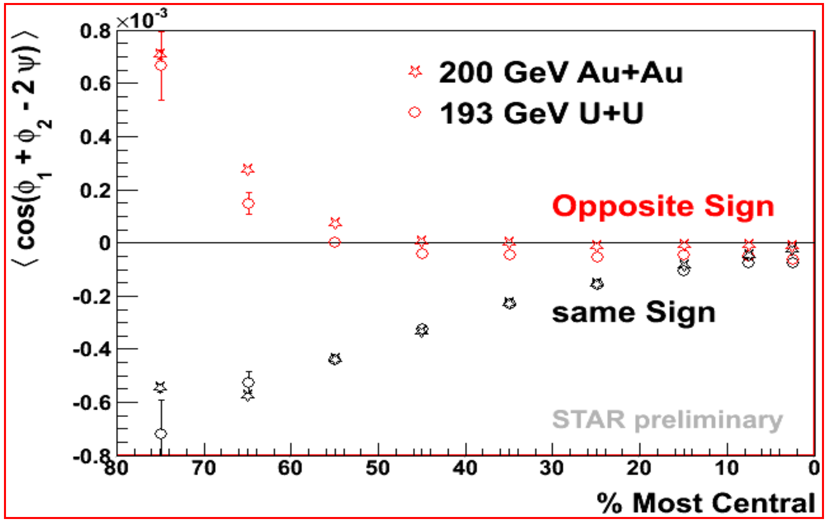
Dynamical Charge Correlations

$$\frac{dN_{\pm}}{d\phi} \propto 1 + 2a_{\pm} \cdot \sin\left(\phi^{\pm} - \Psi_{RP}\right)$$

$$\langle \cos(\phi_{\alpha} + \phi_{\beta} - 2\Psi_{RP}) \rangle \approx (v_{1,\alpha} v_{1,\beta} - a_{\alpha} a_{\beta})$$

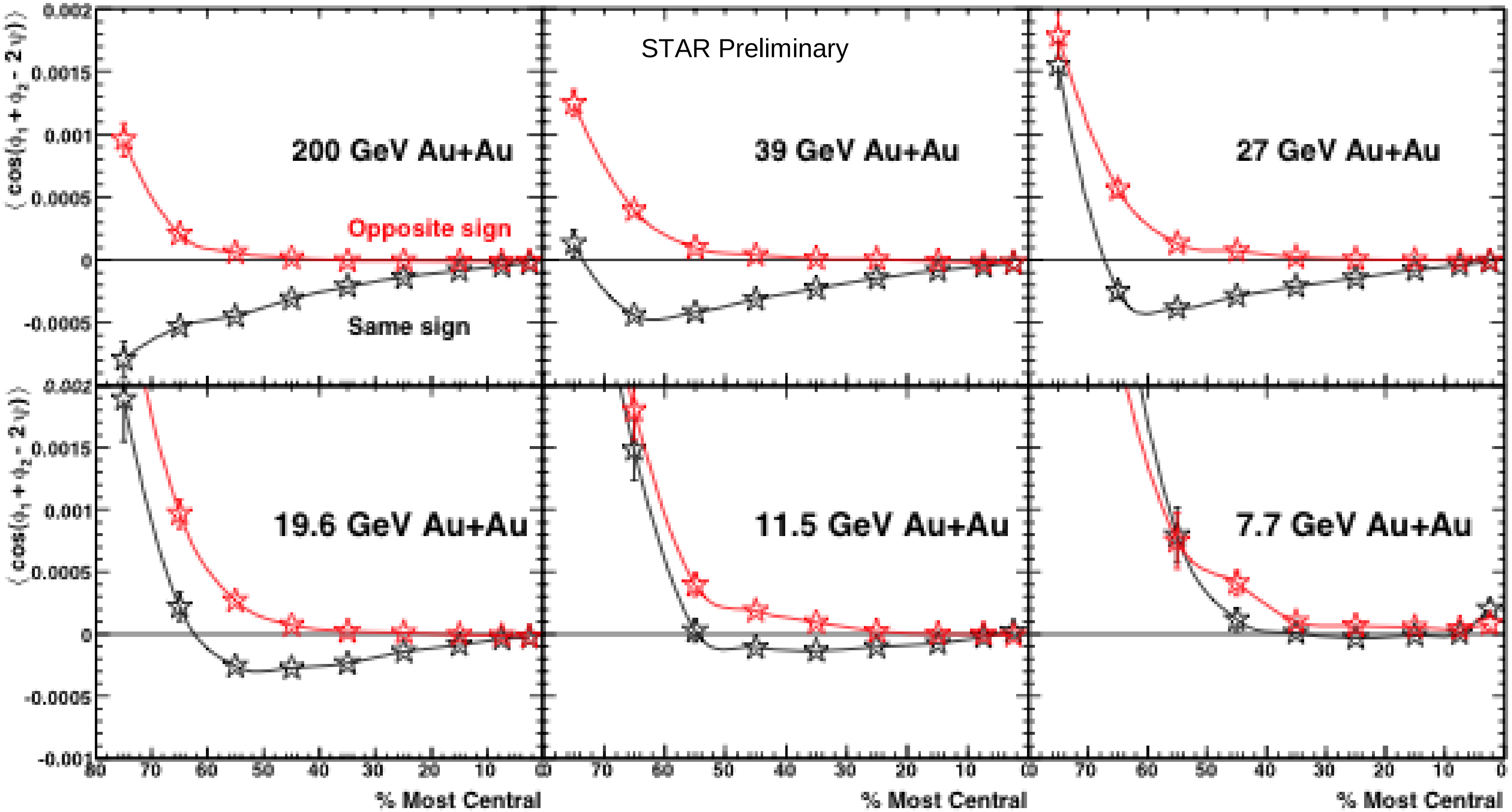


- ✧ De-confined state (QGP): parity may be locally-violated
- ✧ Strong magnetic field, may lead to separation of charges along the angular momentum vector
  → Chiral Magnetic Effect (CME)



Charge separation w.r.t reaction plane

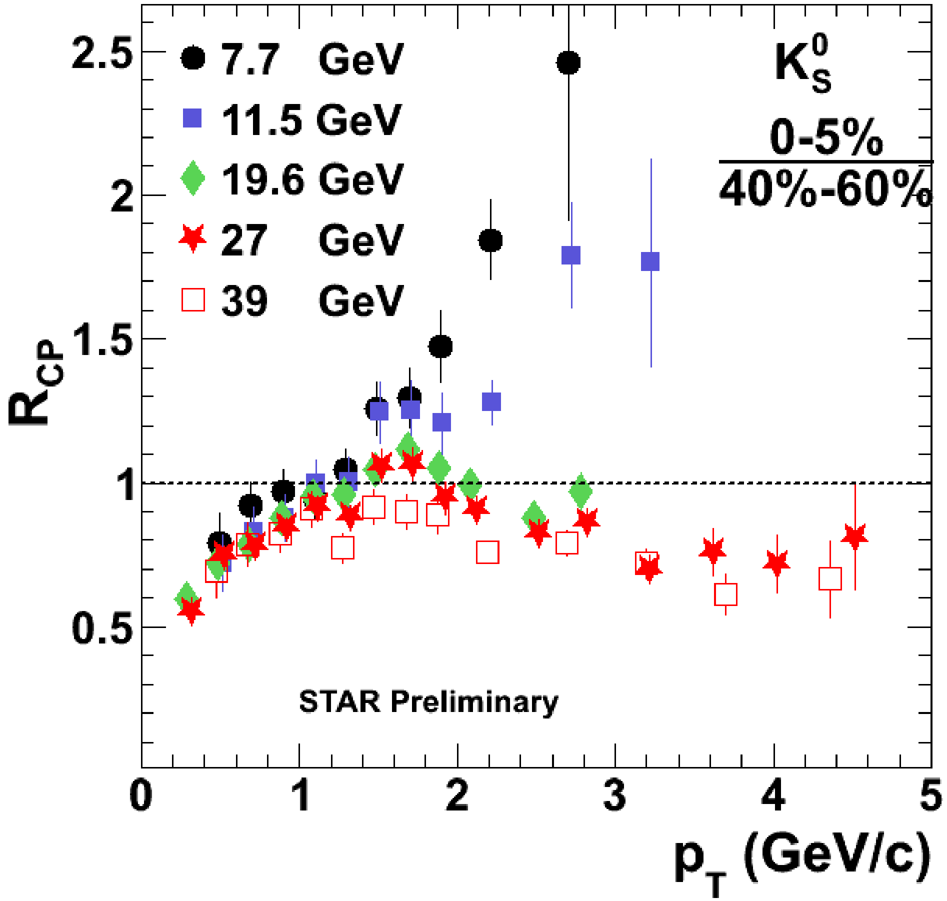
Dynamical Charge Correlations



Splitting between same and opposite-sign charges:

Decreases with decreasing $\sqrt{s_{NN}}$ and disappears below $\sqrt{s_{NN}}$=11.5 GeV

R_{cp} Measurements



For $p_T > 2$ GeV/c:

✧ R_{CP} ($K^0{}_s$) ≤ 1 at $\sqrt{s_{NN}} \geq 19.6$ GeV
✧ $R_{CP} > 1$ for $\sqrt{s_{NN}} \leq 11.5$ GeV

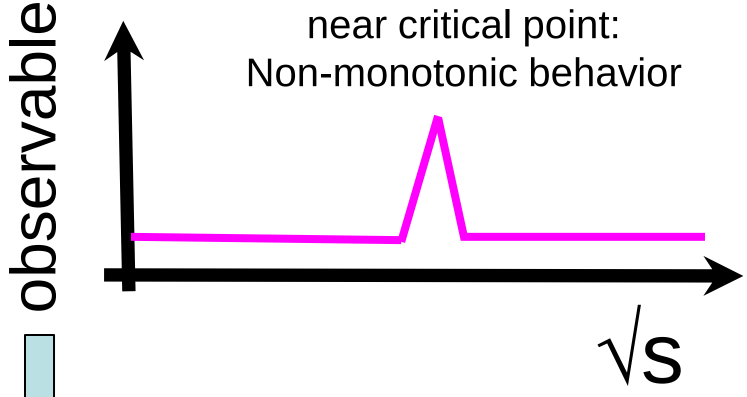
What we learnt?

Observable	Feature	Remarks
Directed flow slope (protons, net-protons)	- Change sign from positive to negative (b/w: 11.5 – 7.7 GeV) - hint of minimum around 19.6 GeV	Could be related to 1st order phase transition signal; need more studies
Elliptic Flow	- No baryon-meson splitting for $\sqrt{s_{NN}} \leq 11.5$ GeV for anti particles at intermediate p_T – ϕ-meson deviates from trend of other particles for $\sqrt{s_{NN}} \leq 11.5$ GeV	Turn-off of QGP Higher statistics for ϕ-meson needed
Dynamical charge correlations	- Difference between same-sign and opposite sign charges disappear for $\sqrt{s_{NN}} \leq 11.5$ GeV	QGP observable at top RHIC energy if could be related to LPV
R_{CP} measurements	- $R_{CP} > 1$ for $\sqrt{s_{NN}} \leq 11.5$ GeV	Turn-off of QGP

Hadronic interactions dominate at $\sqrt{s_{NN}} \leq 11.5$ GeV

(III) Search QCD Critical Point

Enhanced fluctuations
near critical point:
Non-monotonic behavior



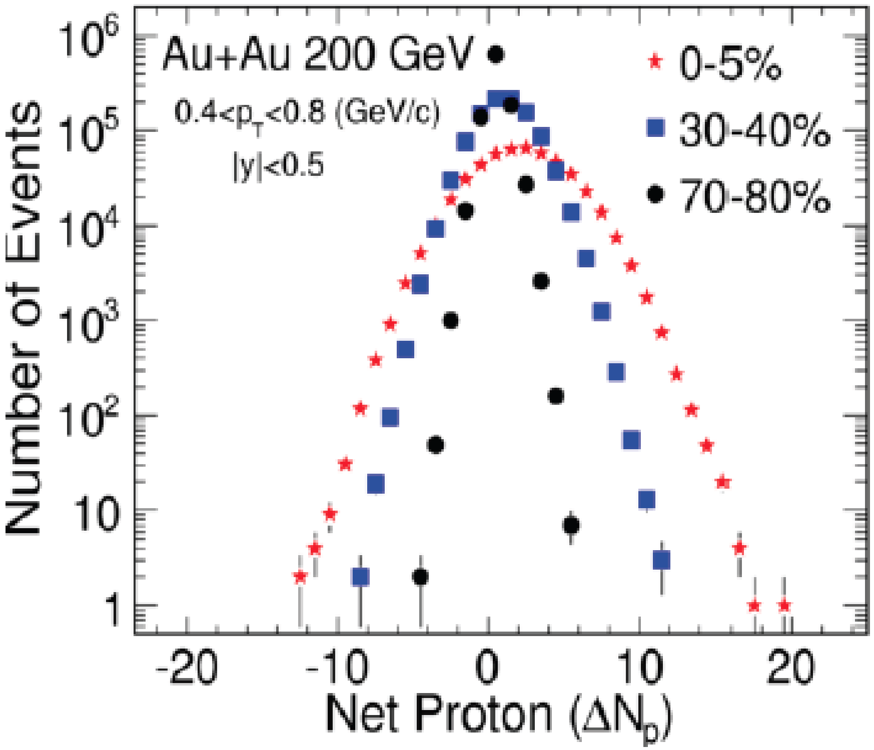
CO_2 near
liquid-gas
transition

T. Andrews. Phil. Trans. Royal Soc., 159:575, 1869

Conserved number fluctuations
- Higher moments of net-protons, net-charge,..

Higher Moments: Net-protons

Typical net-proton distribution:



STAR: PRL105, 022302 (2010)

Various moments: Correlation length:

Sigma: $\sigma = \sqrt{<(N-<N>)^2>}$ $\sim \xi^2$

Skewness: $s = \frac{<(N-<N>)^3>}{\sigma^3}$ $\sim \xi^{4.5}$

Kurtosis: $\kappa = \frac{<(N-<N>)^4>}{\sigma^4} - 3$ $\sim \xi^7$

M. Stephanov, PRL 107, 052301 (2011)
M. Stephanov, PRL 102, 032301 (2009)

Products of moments related to baryon number susceptibility:

$S\sigma \sim \chi_B^{(3)}/\chi_B^{(2)}$ R. Gavai et al. PLB 696, 459 (2011)

$\kappa\sigma^2 \sim \chi_B^{(4)}/\chi_B^{(2)}$ R. Cheng et al. PRD 79, 074505 (2009)

(Volume effect is cancelled)

Experimental measurements can be related to lattice QCD observables for critical point search

Higher Moments: Net-protons

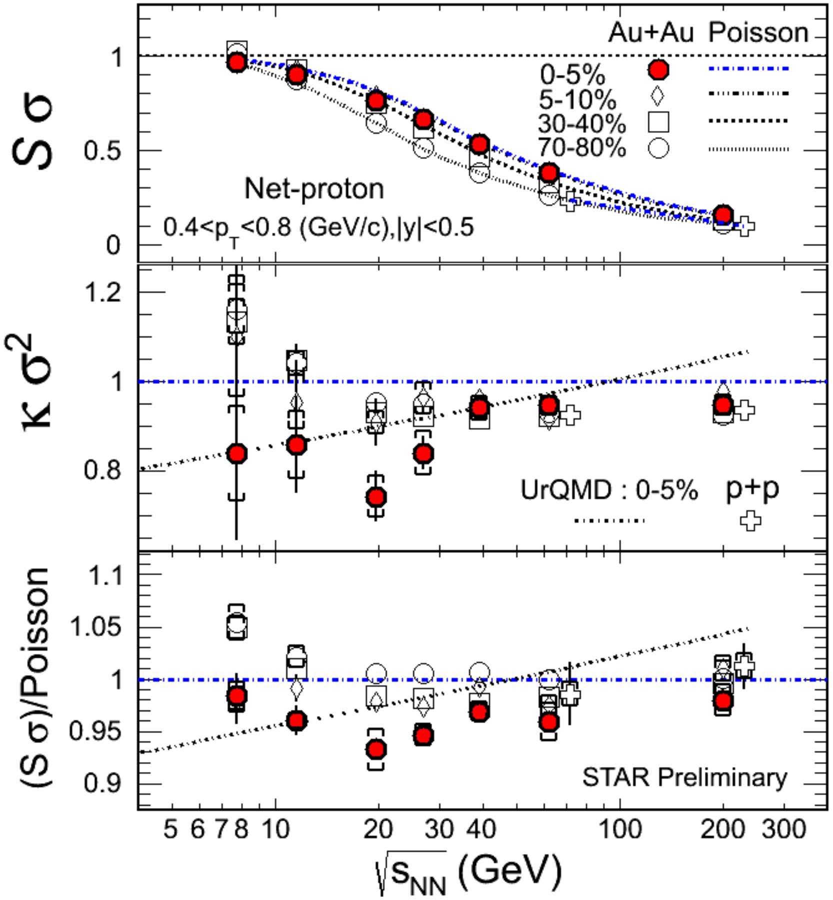
$\sigma = \sqrt{<(N-<N>)^2>}$

$s = \frac{<(N-<N>)^3>}{\sigma^3}$

$\kappa = \frac{<(N-<N>)^4>}{\sigma^4} - 3$

$S\sigma \sim \chi_B^{(3)}/\chi_B^{(2)}$

$\kappa\sigma^2 \sim \chi_B^{(4)}/\chi_B^{(2)}$



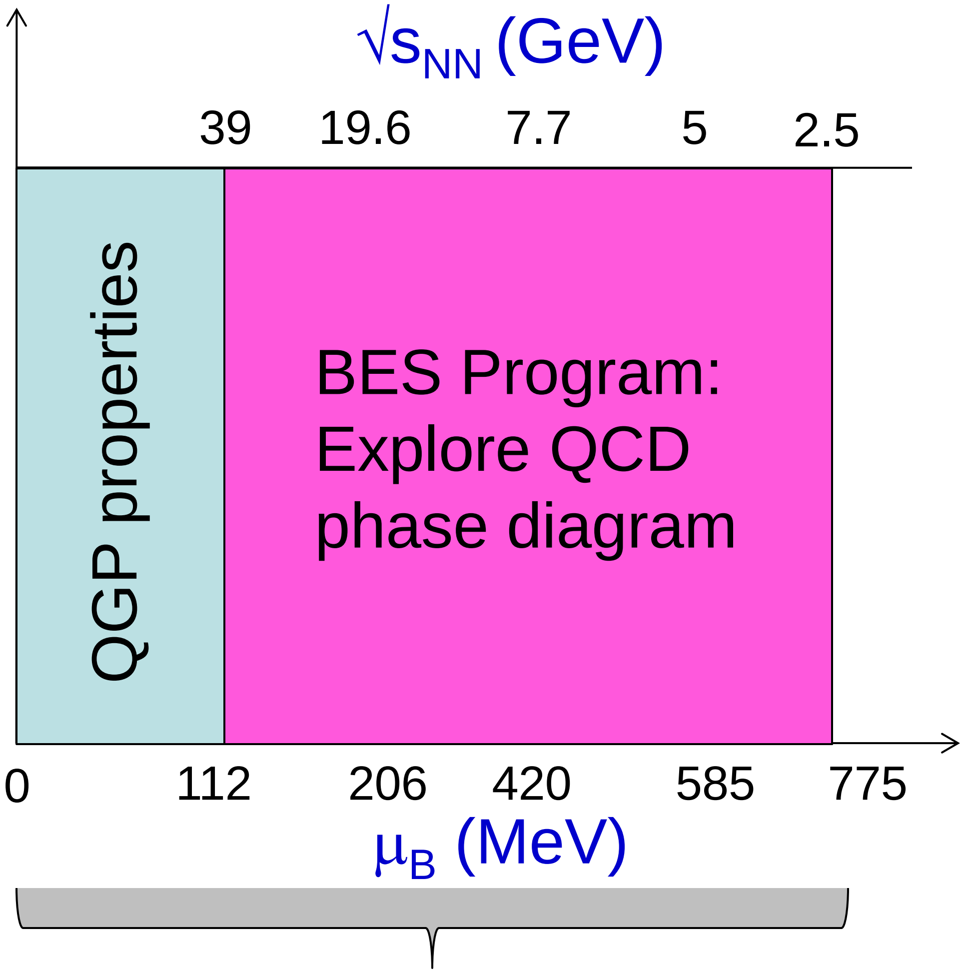
Data: efficiency uncorrected

✧ Poisson may act as a baseline
=> No critical point
✧ Deviation from Poisson
=> Possible critical point
Other baselines: (N)BD, random sampling between p and pbar

✧ Hints of deviation from Poisson
✧ Need higher statistics at low energies

Similar conclusions for net-charge results

Summary : RHIC Heavy-ion Program



Large range of μ_B in phase diagram !!!

QGP properties:

Property	Value
T_{init}	~ (300-600) MeV
ε_{in}	~ 5-15 GeV/fm^3
η/s	~ KSS limit of $1/4\pi$

BES program:

- Hadronic interactions dominate at $\sqrt{s_{NN}} \leq 11.5$ GeV
- BES-II: Higher statistics at $\sqrt{s_{NN}} < 20$ GeV
- Fixed Target: Higher μ_B

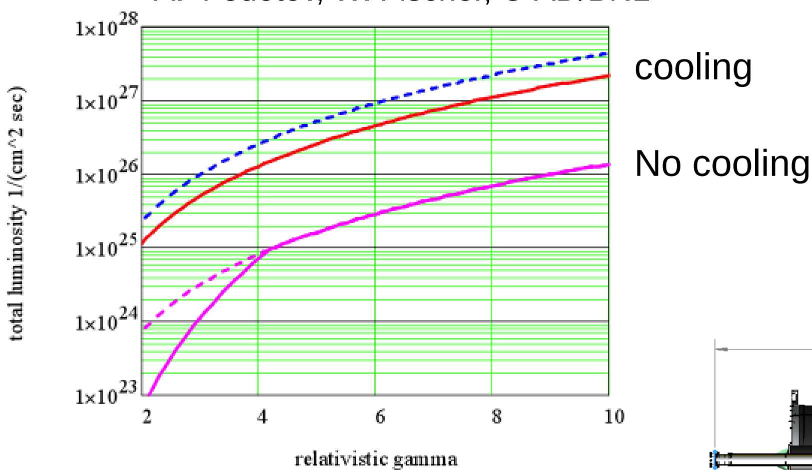
Thank You

Back up

BES Phase-II proposal

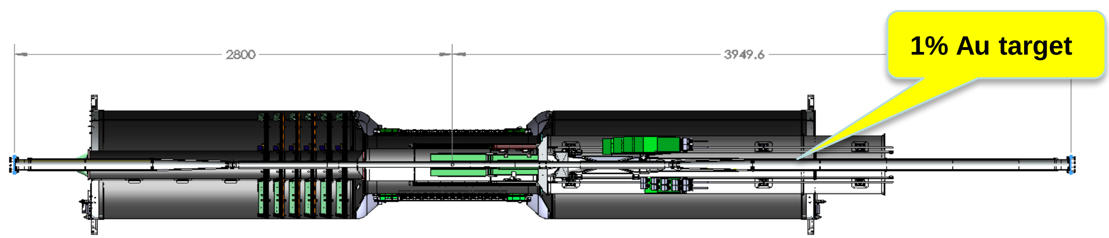
✧ Electron cooling will provide increased luminosity ~ 10 times

A. Fedotov, W. Fischer, C-AD/BNL



Proposal BES-II (Year ~ ≥ 2017):

$\sqrt{s_{NN}}$ (GeV)	μ_B (MeV)	Requested Events(10^6)
Au+Au 19.6	206	150
Au+Au 15	256	150
Au+Au 11.5	316	50
Au+Au 7.7	420	70
U+U: ~20	~200	100



Fixed Target Proposal:

- Gold (Au) target inside the STAR beam pipe (~2m away from center)
- Data taking will be done concurrently with collider mode

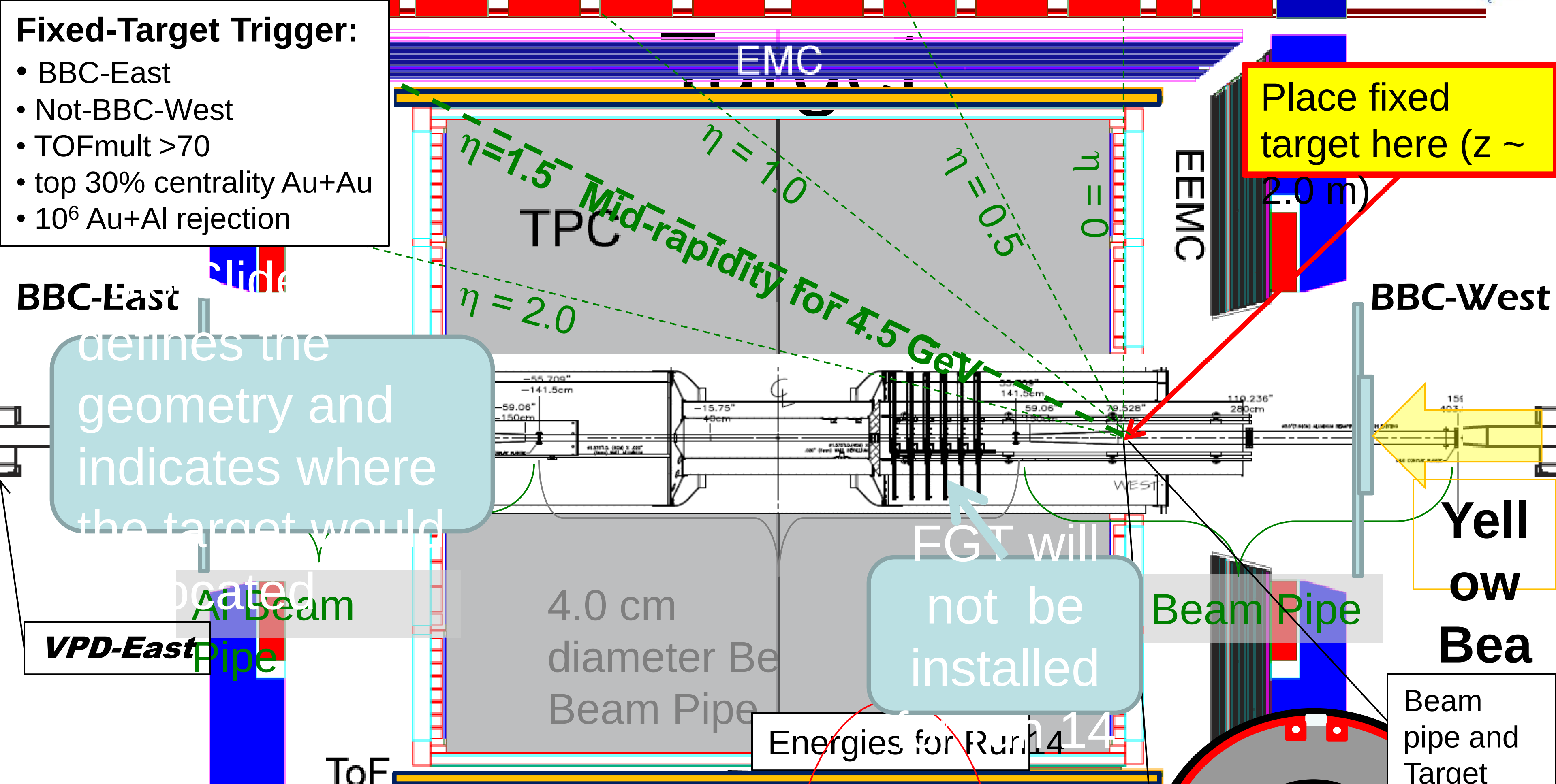
: No disturbance to normal RHIC running

iTPC Upgrade:

- Improved acceptance: higher η (|η|< 1.7) and low p_T (~ 100 MeV/c) reach
- Improved dE/dx and efficiency

STAR Fixed-Target Run14 Set-up

Fixed-Target Trigger:
- BBC-East
- Not-BBC-West
- TOFmult >70
- top 30% centrality Au+Au
- 10^6 Au+Al rejection



Collider mode Energies (GeV)	5	7.7	11.5	15	19.6
Fixed Target $\sqrt{s_{NN}}$ (GeV)	2.5	3.0	3.5	4.0	4.5
Fixed Target μ_B (MeV)	775	720	670	625	585
Fixed Target y_{CM}	0.82	1.05	1.25	1.39	1.52

Fixed Target Set-up

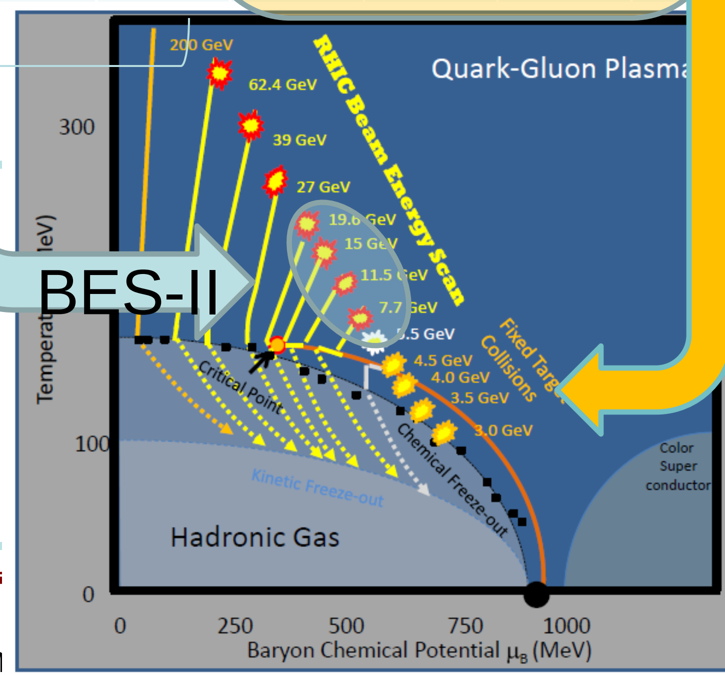
$\sqrt{S_{NN}}$ (GeV)	62.4	39	27	19.6	15	11.5	7.7	5.0	4.5	3.5	3.0
μ_B (MeV)*	70	115	155	205	250	315	420	585	620	670	720
BES I (MEvts)	67	130	70	36	---	11.7	4.3				
Rate(MEvts/day)	20	20	9	3.6	1.6	1.1	0.5				
BES II (MEvts)	---	---	---	400	100	120	80	5	5	5	5
eCooling	---	---	---	8	6	4.5	3				
Beam (weeks)	---	---	---	2	1.5	3.5	7.5				

Fixed Target Collisions

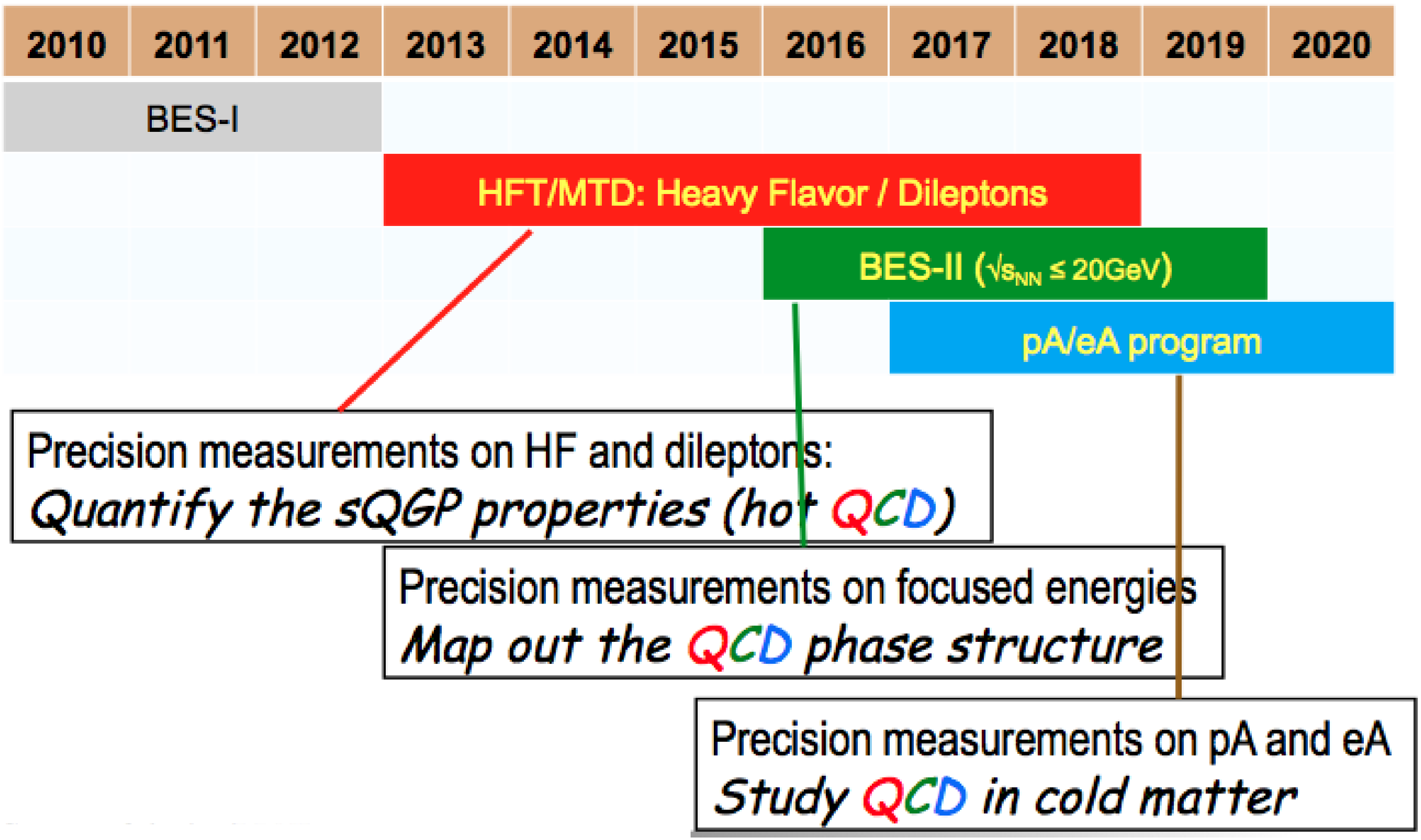
* J. Cleymans, H. Oeschler, K. Redlich, S. Wheaton, PR C73, 034905 (2006).

- We have now put forward BES-II proposal to focus on the most interesting region
- Electron cooling is key to the feasibility of this proposal
- eCooling will take a few years
- Expect BES-II in 2017-2019

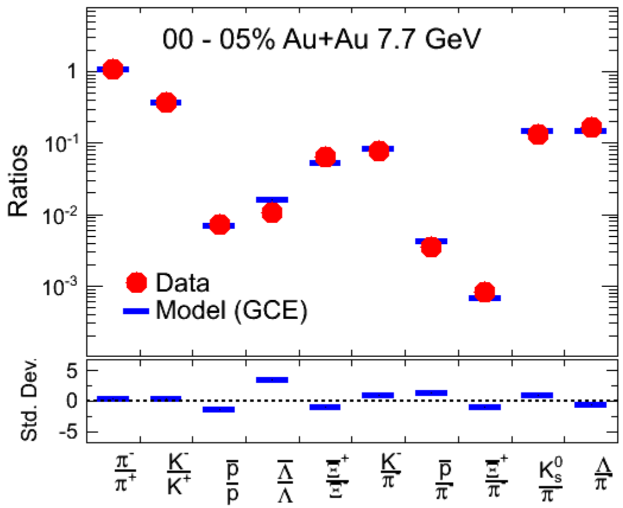
BES-II

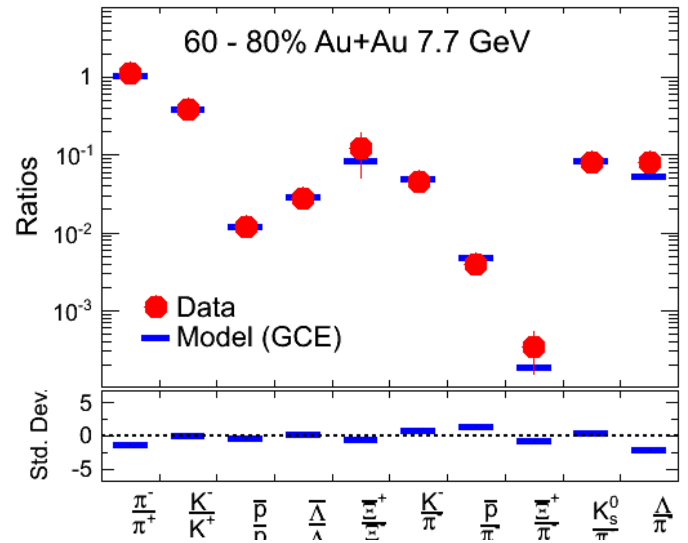


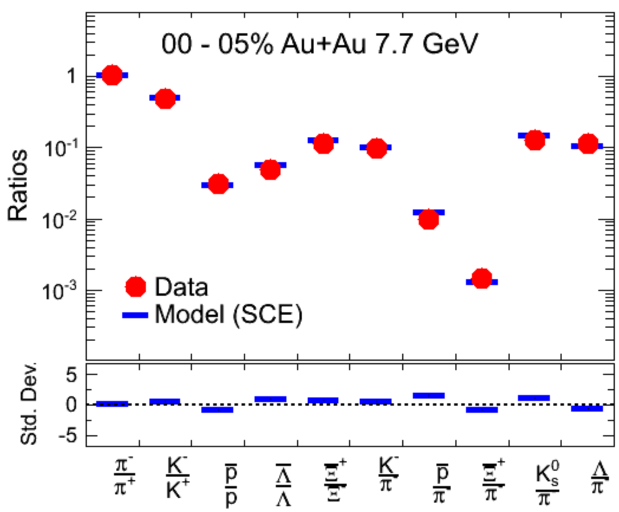
Timeline: STAR

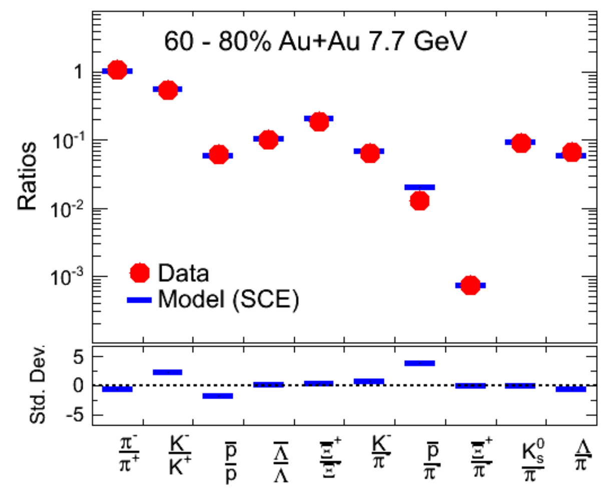


Chemical Freeze-out

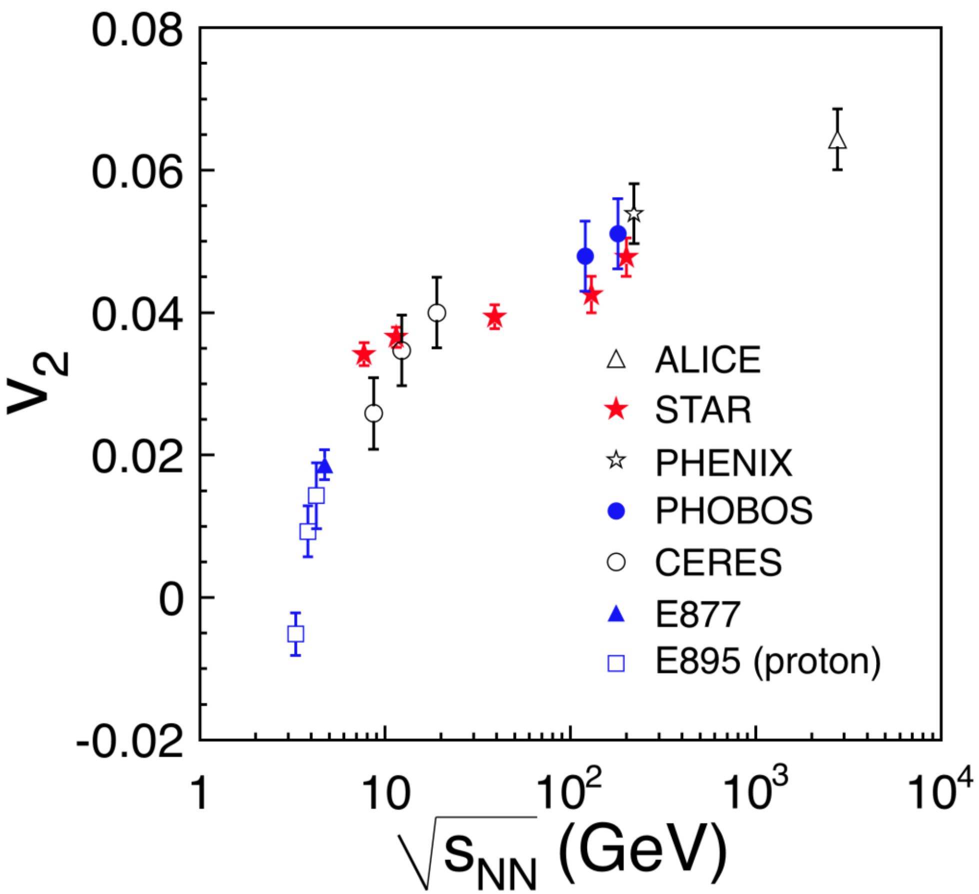








Elliptic Flow



Rate of increase of v_2 is slow from 7.7-39 GeV

Baryon-Meson Ratio