RHIC Beam Energy Scan @ STAR

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Outline

- Beam Energy Scan (BES) program at RHIC
  - Main goals at STAR
  - STAR detectors
- Results
  Step 0: Where are we in the phase diagram?
  Step 1: Turn-off QGP signals
  Step 2: 1st order phase transition & critical point search
- STAR upgrade plans related to BES Phase-II
  - iTPC, event plane detector (HALO)
- Conclusions
RHIC Beam Energy Scan (BES)

- 3 main goals
  - Turn-off signals of QGP
  - Search for phase boundary
  - Search for QCD critical point

<table>
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<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>events ($10^6$)</th>
<th>year</th>
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QCD phase diagram from BNL web site
http://www.bnl.gov/bnlweb/pubaf/pr/photos/2012/07/RHIC_Graphics_Fig1-HR.jpg
STAR - Solenoidal Tracker At RHIC

- Large acceptance: $|\eta| < 1$, full azimuth
- Particle identification: TPC($dE/dx$) + TOF(mass square)
Acceptance

- Acceptance is collision energy independent (thanks to RHIC)
Particle identification

- TPC+TOF: π, K, p and φ
- Topological reconstruction of weak decays
Transverse momentum spectra

Au+Au at 27 GeV
We are at 100-400 MeV in $\mu_B$

- Map ($T_{ch}$, $\mu_B$)
- Fit particle ratio by statistical model
  - Test GCE and SCE ensembles
- BES covers up to ~ 400 MeV in $\mu_B$
- Is QGP gone such high $\mu_B$?
Next step - Turn-off QGP signals

- QGP signals at $\sqrt{s_{NN}} = 200$ GeV
  - Number of Constituent Quark scaling - deconfinement
  - Charge separation - chiral magnetic effect?
  - High $p_T$ suppression - parton energy loss
- What happens on these observables if we decrease beam energies?
Particle vs anti-particle, mesons

- No difference between charged pions in high energies
- $v_2(\pi^+) < v_2(\pi^-)$ for all $p_T$ in low energies
Particle vs anti-particle, baryons

- $v_2(p) > v_2(\bar{p})$ at 62.4 GeV, difference increases in low energies
- Significant difference of $v_2$ (~50%) at 7.7 GeV
Break down of NCQ scaling

FIG. 2 (color online). The difference in single NCQ scaling can be observed for particles and antiparticles, (c) and (d), in 0%-80% central $^{197}$Au+$^{197}$Au collisions at 11.5 GeV and 62.4 GeV. The energy dependence of hadronic interactions in the system evolution with decreasing beam energy. The energy dependence of transported quarks (quarks coming from the antiparticles at this energy in the measured ($^{197}$Au+$^{197}$Au, 0%-80%) and their corresponding antiparticles ($^{197}$Au+$^{197}$Au, 0%-80% $-\text{sub EP}$). While in most of the published theoretical calculations can reproduce the basic pattern but fail to quantitatively reproduce the difference between particles and antiparticles could also be accounted for by considering an increase in nuclear stopping power with decreasing mass, $(\text{mesons})$. The Coulomb repulsion of antiparticles is larger than the particles. At 5 GeV to the one of the particles and to $\text{nuclear meson}$, $(\text{protons})$, the observed difference in NCQ scaling could indicate increased contributions from $\mid\text{C}22\mid$ and possible NCQ scaling was also investigated for particles and antiparticles separately. In Ref. $[21]$, most of the published theoretical calculations can reproduce the basic pattern but fail to quantitatively reproduce the difference 

$\text{v}_{2}^{+} = \text{v}_{2}^{-}$

$\text{v}_{2}^{+} < \text{v}_{2}^{-}$

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$\text{v}_{2}^{+} > \text{v}_{2}^{-}$
Single NCQ scaling can be observed for particles and antiparticles. The error bars depict the combined statistical and systematic errors. The incident nucleons (only at low energies) is larger than the hadronic interactions in the system evolution with decreasing particle energies. This demonstrates that this common NCQ scaling of particle transport in a nucleus can be broken. Such a breaking of the NCQ scaling could indicate increased contributions from particles and antiparticles splits. The difference of the baryon difference becomes negative for the antiparticles at this energy in the measured range up to 2 GeV. While the effect is present for particles at all measured centralities, it is significant at all centralities. The lower panels of Fig. 142301-5 show a smaller difference of transported quarks (quarks coming from the Fock states in the middle) and their corresponding antiparticles (only at low energies). Theoretical calculations show a smaller difference compared to the particles. At 1 GeV, if different production rates for protons and antiprotons as a function of centrality could cause the observed difference. If the Coulomb repulsion of the antiparticles at this energy in the measured (GeV/c^2) range up to 1 GeV is larger than the difference, it could also be accounted for by considering an increase in nuclear stopping power with decreasing range.
Break down of NCQ scaling

The upper panels depict the elliptic flow \( v_2 \) for particles and antiparticles, (a) and (b), and antiparticles, (c) and (d), in 0%–80% central collisions. The difference in the elliptic flow for 0%–80% central Au+Au, \( \eta \)-sub EP collisions at 11.5 GeV, (a) and (b), and Au+Au, 0%-80% collisions at 62.4 GeV. Simultaneous fits to the mesons except the pions are shown as the dashed lines. The difference of the baryon minus the mesons ~ baryons minus mesons is larger than the \( p / C_0 \). The energy dependence of the incident nucleons is larger than the energy dependence of the nucleons. The energy dependence of the incident nucleons is larger than the energy dependence of the nucleons. The energy dependence of the incident nucleons is larger than the energy dependence of the nucleons.

The theoretical calculations \( p / C_2 \) could also be accounted for by considering an increase in nuclear stopping power with decreasing energy. The energy dependence of the incident nucleons is larger than the energy dependence of the nucleons. The energy dependence of the incident nucleons is larger than the energy dependence of the nucleons. The energy dependence of the incident nucleons is larger than the energy dependence of the nucleons. The energy dependence of the incident nucleons is larger than the energy dependence of the nucleons. The energy dependence of the incident nucleons is larger than the energy dependence of the nucleons.

While in reality, the difference between particles and antiparticles could be accounted for by mean field potentials where the difference of the baryon minus the mesons ~ baryons minus mesons is larger than the \( p / C_0 \).
Break down of NCQ scaling

FIG. 2 (color online). The difference in $v_2$ as a function of reduced transverse mass ($m_T - m_0$) for particles and antiparticles at 11.5 and 62.4 GeV Au+Au collisions at 0%-80% centrality. The differences are shown in Figs. 2(a) and 2(b) for charged hadrons and Figs. 2(c) and 2(d) for neutral hadrons. The antiparticles are shown as filled symbols and the particles as open symbols.

The lower panels depict the $v_2$ values normalized by $n_q$, the number of quarks, for baryons and antiparticles. The $v_2/n_q$ values are shown in Figs. 2(a) and 2(b) for charged hadrons and Figs. 2(c) and 2(d) for neutral hadrons. The antiparticles are shown as filled symbols and the particles as open symbols. The difference in $v_2/n_q$ between baryons and antiparticles is shown in the middle panel.

FIG. 4 (color online). The number-of-constituent-quark scaled elliptic flow for selected particles and antiparticles at 11.5 and 62.4 GeV Au+Au collisions at midrapidity. The data are compared to the fits for (a) protons, (b) pions, (c) kaons, and (d) antiprotons. The differences between data and corresponding fits are shown in the lower panel. The antiparticles are shown as filled symbols and the particles as open symbols. The $v_2$ values are shown as a function of reduced transverse mass ($m_T - m_0$) for baryons and antiparticles. The $v_2$ values are shown in Figs. 4(a) and 4(b) for charged hadrons and Figs. 4(c) and 4(d) for neutral hadrons. The antiparticles are shown as filled symbols and the particles as open symbols.
Break down of NCQ scaling

● NCQ scaling of $v_2$ breaks down between particles and anti-particles

- Interpretations; baryon stopping, mean-field potentials in AMPT, hydro+UrQMD, NJL model + coalescence, ....
- Qualitative agreements. No quantitative explanations yet
Disappear charge separation?

- Chiral magnetic effect induces charge separation orthogonal to the reaction plane
  - requires deconfinement + chiral symmetry restoration
- Charge separation \( (\gamma_{os} - \gamma_{ss}) \) decreases with decreasing beam energies, seems to disappear at \( \sqrt{s_{NN}} = 7.7-11.5 \) GeV

\[ \gamma = \langle \cos(\phi_1 + \phi_2 - 2\Psi) \rangle \]

ALICE, arXiv:1207.0900
Below 39 GeV

- Observe change in behavior of $v_2$, charge separation and high $p_T$ suppression pattern below 11.5-39 GeV
  - 1st order phase transition?
Equation of state $\rightarrow$ flow systematics

- 1\textsuperscript{st} order phase transition affects the build up of spatial & momentum anisotropy

$\Rightarrow$ Look at flow systematics


Spatial anisotropy (eccentricity)

- No sudden change on spatial anisotropy
  - except for the CERES data point
- Data agree with pure hadronic cascade UrQMD

Excitation function for freeze-out eccentricity, $e_F$

$K_1 = 0.15-0.6 \text{ GeV/c}$

*Model centralities correspond to data

- E895 - PLB 496, 2004 (7.4-29.7%)
- CERES - PRC 78, 2008 (10-25%)
- STAR (-0.5<y<0.5, 10-30%)
- STAR (1<y<1.5, 10-30%)
- STAR (0.5<y<1, 10-30%)

- UrQMD
- Hybrid[BM]+UrQMD
- Hybrid[HQ]+UrQMD
- 2D hydro EoS-Q
- 2D hydro EoS-H
- 2D hydro EoS-I

STAR preliminary
Momentum anisotropy - elliptic flow

- No sudden change on $v_2\{4\}$, smooth increase as a function of energy
**Directed flow**

**STAR:** PRL **108,** 202301 (2012)

- **Less focus on high energies**
  - Signal is small, large non-flow (momentum conservation)
  - Need 3D models - challenge to transport (and hydro) models

- **Directed flow is also sensitive to 1st order phase transition**
  - Especially slope of $v_1$
  - Very non-trivial energy dependence (prediction)

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**H. Stocker, NPA **750,** 121 (2005)**

Ideal hydrodynamical model with 1st order phase transition

- $\sqrt{s_{NN}}$ (GeV)
  - 1.9
  - 4.5
  - 13.8

**Graphs:**

- Au+Au 200GeV 10%-70% charge pions (stars) and protons (circles).
- Model calculations (RQMD, QGSM*, AMPT, UrQMD, hydro*) for pions, none of them can describe the data.
- The RQMD and AMPT model calculations predict the wrong magnitude of pion data. The UrQMD, QGSM with parton recombination model calculations like UrQMD can describe protons, antiprotons simultaneously.
- In general, the magnitude of the directed flow as currently implemented does not predict the antiflow.

**Equations:**

- $\frac{d(p_x/N)}{dy}|_{y=0}$ [GeV/c]
- $E_{Lab}$ [AGeV]
- $v_1(y)$
- $s_{NN}$

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H. Masui, HIM, Nov/2/2013
Directed flow at BES

- $v_1$ slope is all negative for protons and pions
  - except for protons at 7.7 and 11.5 GeV
- Slope is generally steeper in lower energies in peripheral collisions
- No sudden change on $v_1$ slope would be expected from this results

![Graph showing directed flow at BES](image-url)
Net-proton $v_1$ slope

- Smooth energy dependence for hadrons
  - consistent with trends from NA49 and E895
- However, net-proton $v_1$ slope shows non-monotonic behaviour
  - Minimum around 10-20 GeV, double sign change around 10 and 30 GeV
- Transport calculations UrQMD & AMPT cannot reproduce the results
- Interesting to see other net-hadron $v_1$ slope (not studied yet)
Fluctuations diverge at CP

- At critical point (with infinite system)
  - susceptibilities and correlation length diverge
    - both quantities cannot be directly measured
- Experimental observables
  - Moment (or cumulant) of conserved quantities: net-baryons, net-charge, net-strangeness, ...
  - Moment product (cumulant ratio) ↔ ratio of susceptibility

\[
\kappa_2 = \langle (\delta N)^2 \rangle \sim \xi^2, \quad \kappa_3 = \langle (\delta N)^3 \rangle \sim \xi^{4.5}, \quad \kappa_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \sim \xi^7
\]

\[
S\sigma = \frac{\kappa_3}{\kappa_2} \sim \frac{\chi_3}{\chi_2}, \quad K\sigma^2 = \frac{\kappa_4}{\kappa_2} \sim \frac{\chi_4}{\chi_2}
\]

- directly related to the susceptibility ratios (Lattice QCD)
- higher moments (cumulants) have higher sensitivity to correlation length

- Signal = Non-monotonic behavior of moment products (cumulant ratios) vs beam energy

M. A. Stephanov, PRL102, 032301 (2009)
Non-gaussian fluctuations

- 3rd moment = Skewness $S$
  - Asymmetry
- 4th moment = Kurtosis $K$
  - Peakedness
- Both moments = 0 for gaussian distribution
- Critical point induces non-gaussian fluctuations
Net-proton distributions

- Distributions look like gaussian or poisson by eyeball
- Information of higher moments are mostly encoded in the tail
- We are dealing with tiny signals
These include...
Net-protons & Net-charge

- No significant excess observed for both net-protons & net-charge
  - Something happened below 30-40 GeV?
Current issues

- Net-proton is not net-baryon
  - Net-charge might be better
- Efficiency correction is important
  - Under investigation
- Is Poisson baseline reliable? How about (Negative-) Binomial distribution?
  - Under investigation
- 100 MeV gap in $\mu_B$ between 11.5 and 19.6 GeV
  - 15 GeV is planned in 2014
- Need more statistics at 7.7 and 11.5 GeV
  - BES phase-II in 2018-2019
**Other fluctuation observables**

**Particle ratio fluctuations**

![Graphs showing particle ratio fluctuations](image)

**p_T correlation**

![Graph showing p_T correlation](image)

- None of fluctuation observables show significant excess
  - No sensitivity to CP? Signal is weak? No CP?
Summary of BES phase-I

• Several turn-off signals observed in 10-30 GeV
  ‣ Break down of NCQ scaling of $v_2$ between particles and anti-particles
  ‣ Disappearance of charge separation
  ‣ Disappearance of high $p_T$ suppression

• No conclusive observations for 1st order phase transition and critical point search yet
  ‣ Spatial and momentum anisotropy with respect to second harmonic event plane show monotonic energy dependence
  ‣ Net-proton $v_1$ slope shows non-monotonic behavior
  ‣ Fluctuation observables essentially show monotonic energy dependence
    - we need precision measurements below 20 GeV, especially for higher moments
Future perspective

• Near term: 2014-2015
  ‣ Complete HFT installation (2014)
    - Open charm, di-leptons at 200 GeV - sQGP properties
  ‣ 15 GeV for critical point search

• Middle term: -2019
  ‣ Electron cooling at RHIC (luminosity)
  ‣ Inner TPC upgrade - acceptance, efficiency, pid
  ‣ Forward tracking upgrade - better event plane determination

• Middle and long term: 2016-
  ‣ Forward upgrade towards eRHIC, eSTAR
inner TPC (iTPC) upgrade

- Current pad plane layout with 13 rows and gaps
  - only 13 maximum possible points
  - only reads ~20% of possible gas path length
    - Inner sectors essentially not used in dE/dx
- Essentially limits effective acceptance to |\( \eta \)|<1

Rebuild inner sectors of the TPC
- pseudorapidity coverage extend from 1 to 1.7
- Improve dE/dx - better PID
- Better efficiency, transverse momentum resolution
The minimum tracking requirement for \( \Lambda \) reconstruction is displaced vertex measurement for \( \Lambda \to p + \pi^- \) channel.

The simplest possibility is to combine the proposed event plane detector (HALO) with the calorimeter preshower to do two point tracking.

- Provide better event plane resolution
- Important as trigger detector (~95% events are background at 7.7 GeV in our current trigger)
- Provide independent centrality determination
- Evaluation is on-going for detector implementation
Conclusions

- RHIC BES-I
  - Turned off several key signals at 200 GeV
  - No conclusive evidence for 1st order phase transition and critical point search
  - Therefore, we proposed BES phase-II with 10-20 times better statistics

- RHIC BES-II (2018-2019)
  - Focus on $\sqrt{s_{NN}} < 20$ GeV
  - Electron cooling + longer bunch lengths will increase luminosity
  - iTPC upgrade will extend pseudorapidity coverage, better pid, efficiency, $p_T$ resolution
  - Event plane detector is being evaluated to improve flow measurements (and forward tracking in p+p)
  - (Fixed target mode is also considered at STAR in order to reach lower energies down to ~ 3 GeV)
Back up
The behavior as the particles, and at all lower energies the meson shows the mass, comparable to the most central bin (0%–10%). It is concluded that the driving factors. Only the number of constituent quarks separates the results into the two branches. This observation shows the trend at 7.7 and 11.5 GeV , with the maximum measured values just reaching the lower edge of the expected NCQ scaling range. The values deviate from those for the trend at 7.7 and 11.5 GeV, with the maximum measured values just reaching the lower edge of the expected NCQ scaling range. The values deviate from those for all particles except the pions.

The NCQ scaling should only hold in the transverse momentum range of 1 \( \sigma_T \). The corresponding scaled transverse mass and transverse momentum range 1 \( \sigma_T \) do not change.

The trend observed is a decrease in the baryon-meson splitting as the energy is increased. In the QGP phase of the collision. After hadronization, the flow of the quarks is carried by the measured particles. In a coalescence picture, this will result in the \( \eta \)-sub EP, shows a clear splitting between baryons and mesons. The point-by-point systematic uncertainties are shown by the shaded areas attached to the data points, while the global combined statistical and systematic fit error. With a horizontal line. The red shaded area around each fit shows the
energies. Their correspond to Eq. (17). At the higher energies of 27, 39, and 62.4 GeV, the charged pion values were significantly smaller than the values for their antiparticles, as depicted in more detail in the next sections. The lower the energy, the smaller is the difference between particles with the same mass and number of quarks. At lower energies, an increasing difference between partner particles. The possible physics implications owing to decreasing. However, no narrowing of the spread of differences in particle and antiparticle... Only statistical error bars are shown. Systematic errors are much smaller than the statistical errors. The fit functions to guide the eye were used for the top and bottom panels. The red shaded area around each fit depicts the by-point systematic uncertainties are displayed as the shaded area attached to the data points; otherwise they are smaller than the symbol size. The systematic uncertainties are shown by the shaded areas around each fit. Shown are the global systematic uncertainties are very small and shown as shaded... Only the particle and antiparticle comparison of between a particle and corresponding antiparticle... Fig. 10. (Color online) The elliptic flow, $v_2$, for various particle species are directly compared. For this...