Recent heavy ion results from the STAR experiment

1) Heavy flavor and Quarkonia
2) RHIC Beam energy scan

Róbert Vértesi

vertesi.robert@wigner.mta.hu
Relativistic Heavy-Ion Collider

- The LHC era: bigger, better, higher energy, preciseness; so why still RHIC?
Relativistic Heavy-Ion Collider

- The LHC era: bigger, better, higher energy, preciseness; so why still RHIC?
- Heavy-Ion Physics: not an energy frontier science!
  - Higher energy \(\Leftrightarrow\) higher cross-sections
    but we are often readout-bound
  - “Full-featured” deconfined matter at \(\sqrt{s_{NN}}=200\ \text{GeV}\)
- RHIC: extremely versatile
  - **Collides anything** from protons to Uranium, symmetric or asymmetric
    (even polarized protons for spin studies up to 510 GeV)
  - From 7.7 (3) GeV to 200 GeV with the same apparatus
- Continuous, ongoing machine and detector development
- **Dedicated** to High Energy Heavy Ion physics
The LHC era: bigger, better, higher energy, preciseness; so **why still RHIC?**

Heavy-Ion Physics: **not an energy frontier science!**
- Higher energy \( \iff \) higher cross-sections
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Continuous, ongoing machine and detector development
**Dedicated** to High Energy Heavy Ion physics

**RHIC: the most colorful physics program in HE HI**
Heavy Ion Physics at STAR

- **sQGP at top energy:**
  Thermal, dynamical properties
  - "Soft" (low-$p_T$)
    bulk behavior
    (collective dynamics)
  - "Hard" (high-$p_T$)
    "tomography"
    pQCD+medium
Heavy Ion Physics at STAR

- **sQGP at top energy:**
  - **Soft** (low-$p_T$)
  - bulk behavior
    (collective dynamics)
  - **Hard** (high-$p_T$)
  - “tomography”
  - pQCD+medium

- **Beam Energy Scan:**
  - **Onset** of the sQGP
  - 1$^{\text{st}}$ order **phase transition**
  - Search for the **critical point**
STAR Long-Term Plan

- HFT: Charm
  - Di-lepton
  - sQGP properties
- QCD phase structure
  - Critical Point

AA: HFT+: B, Λ_c
  Jet, γ-jet
pA: CNM, p-spin

Phase structure with dense gluon


HF-I, (e,μ)
HFT/MTD

BESII
e-Cooling, iTPC

HF-II, p↑A
HFT’, Tracking, EM/HCAL (West side)

eSTAR
EMCAL (East side)

physics
upgrade

STAR at RHIC

- EEMC
- Magnet
- MTD
- BEMC
- TPC
- TOF
- BBC
- HFT
Main tracking device: Time Projection Chamber
Coverage: $0 < \phi < 2\pi$, $|\eta| < 1.0$
Uniform acceptance: All energies and particles
Particle ID: $\pi$, $K$, $p$ through TPC $dE/dx$
aided by TOF $1/\beta$
$K^0_s$, $\Lambda$, $\Xi$, $\Omega$, $\phi$ through invariant mass
Barrel Electromagnetic Calorimeter
Coverage: $0 < \phi < 2\pi$, $|\eta| < 1.0$
Particle ID: e vs. hadrons via $E/p$, cluster shape
New 2014: heavy flavor and muons

Muon Telescope Detector (outermost)
Coverage: 45% in azimuth, $|\eta| < 0.5$
Particle ID: muons
Goal: Precise quarkonium measurements
30% of 2014 Au+Au data processed

Heavy Flavor Tracker (innermost)
Secondary vertex reco
Goal: Precise open HF measurements
70% of 2014 Au+Au data processed
Quarkonia

- Debye screening of heavy quark potential → Quarkonia are expected to dissociate
  

- Sequential melting: Different states dissociate at different temperatures
  

Charmonia (cc): J/ψ, Ψ', χ_c

Bottomonia (bb): γ(1S), γ(2S), γ(3S), χ_b

1/⟨r⟩ [fm⁻¹]

T/Tc

γ(1S)
J/ψ(1S)
x_b(2P)
χ_c(1P)
γ″(3S)
ψ′(2S)
Quarkonia

- Debye screening of heavy quark potential → Quarkonia are expected to dissociate
  

- Sequential melting: Different states dissociate at different temperatures
  

Quarkonia may serve as sQGP thermometer

Charmonia (c̅c): J/ψ, Ψ’, χc

Bottomonia (b̅b): γ(1S), γ(2S), γ(3S), χB

$1 \langle r \rangle \text{ [fm}^{-1}\text{]}$

- γ(1S)
- J/ψ(1S)
- χb'(2P)
- χc(1P)
- γ*(3S)
- Ψ'(2S)
"The J/ψ mystery"

PHENIX: PRC 84 (2011) 054912
ALICE: PRL 109,072301 (2012)
“The J/ψ mystery”

- Cold nuclear matter effects
  - Nuclear shadowing (PDF modification in the nucleus)
  - Initial state energy loss
  - Co-mover absorption
- Hot/dense medium effects
  - Coalescence of uncorrelated charm and bottom pairs
- Feed-down
  - $\chi_c$, $\psi'$, B-meson decay to J/ψ
  - $\chi_b$, $\Upsilon(2S)$, $\Upsilon(2S)$ to $\Upsilon(1S)$ …

Contribution of different effects is not well understood
J/ψ suppression vs. beam energy

Suppression

- Similar to light hadrons
- Similar in central collisions from 39 thru 62.4 up to 200 GeV
  Note: 39 and 62.4 GeV CEM references have large uncertainties
- Similar in U+U and Au+Au
- Model with prompt production and regeneration consistent with data
J/ψ suppression and flow in Au+Au

**Suppression**
- Similar to light hadrons
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**Anisotropy (v<sub>2</sub>)**
- J/ψ v<sub>2</sub> consistent with non-flow (p<sub>T</sub>&gt;2 GeV/c; unique among hadrons)
- Model with thermalized charm quark coalescence disfavored

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[32] Zhao, Rapp, PLB 655 (2007) 126
[33] Liu,Xu,Zhuang, NPA834 (2010) 317c
[34] Heinz, Chen (2012)
High-\(p_T\) J/\(\psi\) in Au+Au

- CNM effects are small
- Less regeneration
- Suppression of high-\(p_T\) J/\(\psi\) in central collisions

\[ A+A \rightarrow J/\psi + X \]

\(\sqrt{s_{\text{NN}}} = 200 \text{ GeV} \)

- STAR Au+Au
- STAR \((p_T > 5 \text{ GeV/c})\)
- PHENIX Au+Au \((|y|<0.35)\)
- Zhao, Rapp
- Zhao, Rapp \((p_T > 5 \text{ GeV/c})\)
- Liu et al.
- Liu et al. \((p_T > 5 \text{ GeV/c})\)

\(R_{\text{AA}}\) vs. \(N_{\text{part}}\)

STAR low-\(p_T\): arXiv:1310.3563
STAR high-\(p_T\): PLB722, 55 (2013)
Liu et al., PLB 678, 72 (2009)
Zhao and Rapp, PRC 82, 064905(2010), PLB 664, 253 (2008)
High-$p_T$ $J/\psi$ in $Au+Au$

- CNM effects are small
- Less regeneration
- Suppression of high-$p_T$ $J/\psi$ in central collisions

High-$p_T$ $J/\psi$ suppression is clearly an sQGP effect
$R_{AA}$ of $\Upsilon$ states in Au+Au

- Peripheral $\Upsilon$ consistent with no suppression
- Central $\Upsilon$ shows significant suppression
- Central $\Upsilon(1S)$: indication of a suppression
- Excited states $\Upsilon(2S)$ and $\Upsilon(3S)$ consistent with complete melting

$\Upsilon$ suppression pattern supports sequential melting

**STAR:**
$R_{AA}$ of $\Upsilon$ states: Au+Au vs. U+U

- Peripheral $\Upsilon$ consistent with no suppression
- Central $\Upsilon$ shows significant suppression
- Excited states $\Upsilon(2S)$ and $\Upsilon(3S)$ consistent with complete melting
- Hint of their presence in $U+U$ collisions

New U+U data extends Au+Au trend – is U+U different?
$R_{AA}$ of $\gamma$ states: data vs. models

- No CNM effects, $428 < T < 443$ MeV
- Potential model ‘B’ based on heavy quark internal energy
- Potential model ‘A’ based on heavy quark free energy (disfavored)

- Potential model, no CNM effects
- $T=340$ MeV, only excited states dissociate

- CNM effects included
- Strong binding scenario

Suppression indicates $\gamma$ melting in a deconfined medium

However: CNM effects to be understood $\rightarrow$ RHIC 2015 p+Au run
Open heavy flavor

- **Heavy quarks c, b**
  - Produced in initial hard processes
  - Probe the strongly interacting Quark–Gluon Plasma
  - Modified spectrum: access parton energy loss
  - Flow: sensitive to dynamics, thermalization
Open heavy flavor

- Heavy quarks c, b
  - Produced in initial hard processes
  - Probe the strongly interacting Quark–Gluon Plasma
  - Modified spectrum: access parton energy loss
  - Flow: sensitive to dynamics, thermalization

- Semi-leptonic decays
  - Higher branching ratio, easy to trigger on
  - Indirect access to kinematics
  - Mixture of c and b contributions

- Hadronic reconstruction
  - Direct access to kinematics
  - Large combinatorial bg., difficult to trigger

===> HFT: highly enhanced S/B
**D^0 measurements: R_{AA} and v_2**

- **Significant suppression** in central Au+Au collisions at high p_T
- “Hump” at p_T<2 GeV/c is from the charm-medium coalescence
- **Note: overall charm is conserved**

- **Sizeable flow** (significant v2 above non-flow component at p_T>2 GeV/c)

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*STAR Preliminary*

STAR, PRL 113 (2014) 142301

M. Mustafa, QM15
**D⁰ measurements: \( R_{AA} \) and \( v_2 \)**

- **Significant suppression** in central Au+Au collisions at high \( p_T \)
- Agrees with light meson suppression

- **Sizeable flow** (significant \( v_2 \) above non-flow component at \( p_T > 2 \) GeV/c)
- Less than that observed for light hadrons

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STAR Preliminary

STAR, PRL 113 (2014) 142301

STAR, PLB 655 (2007) 104

M. Mustafa, QM15
**D^0 measurements: theory comparison**

- Data favors models with charm diffusion
  - → charm exhibits collectivity with the medium

- CNM effects may also be important

<table>
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<th>HQ e.loss</th>
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</table>

Beam Energy Scan

- Experimental exploration of the **QCD phase diagram**
- Theory: Critical point may be around $10 < \sqrt{s_{NN}} < 30$ GeV
- Vary $T$, $\mu_B$ by setting different **collision energy**, species

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![Diagram showing QCD phase transitions and critical point estimates.](image)

**Critical point estimates:**
- Budapest-Wuppertal $N_t=4$
- ILGTD $N_t=8$
- ILGTD $N_t=6$
- ILGTD $N_t=4$

References:
Beam Energy Scan

- Experimental exploration of the **QCD phase diagram**
- Theory: Critical point may be around \(10 < \sqrt{s_{NN}} < 30 \text{ GeV}\)
- Vary \(T, \mu_B\) by setting different **collision energy**, species
- **RHIC**: access to a wide range with the same apparatus

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**Critical point estimates:**
- Budapest-Wuppertal \(N_t=4\)
- ILGTI \(N_t=8\)
- ILGTI \(N_t=6\)
- ILGTI \(N_t=4\)

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**References:**
## STAR BES-I

<table>
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<tr>
<th>$\sqrt{s_{NN}}$ (GeV)</th>
<th>$\mu_B$ (MeV)</th>
<th>#Events</th>
<th>#Weeks</th>
<th>Year</th>
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<td>70</td>
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<td>2010</td>
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</table>

![Graph](http://www.bnl.gov/npp/pac.asp)

- **Au+Au (GCE: Ratios)**
  - 200 GeV
  - 14.5 GeV
  - 7.7 GeV

- **STAR Preliminary**
  - 0-5%
  - 20-30%
  - 40-60%
  - 60-80%

- **Cleymans**
- **Andronic**
Find...

1) Turn-off of sQGP signatures

2) 1st order phase transition signs

3) The QCD critical point

High-$p_T$ hadron suppression

- Suppression from 39 GeV up to 2.76 TeV (LHC)
- Enhancement at lower energies
  Understanding: Cronin effect;
  more dominant at lower energies
- Smooth transition
High-$p_T$ hadron suppression

- Suppression from 39 GeV up to 2.76 TeV (LHC)
- Enhancement at lower energies
  Understanding: Cronin effect; more dominant at lower energies
- Smooth transition
- Enhancement balances suppression at $\sim\sqrt{s_{NN}} = 14.5$ GeV.
Azimuthal anisotropy ("flow")

\[ \frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Phi_2) \]

"elliptic flow" (v2)

\[ \frac{dN}{d\phi} \propto 1 + 2 \sum_n v_n \cos n(\phi - \Phi_n) \]

Directed flow (v1), Triangular flow (v3) ...
Substantial particle-antiparticle split at lower $\sqrt{s_{NN}}$

Linear dependence on the baryon chemical potential
"Triangular flow" $v_3$

- Triangular flow is sensitive to the initial state fluctuations
  
  $\Rightarrow$ Related to the duration of low-viscosity phase

  J. Aunvine, H. Petersen PRC 88, 064908

- Sizable $v_3$ at lower energies in central to mid-central centralities

- Peripheral collisions: $v_3$ consistent with zero for $\sqrt{s_{NN}} < 14.5$ GeV
**Triangular flow** is sensitive to the initial state fluctuations

** ==> Related to the duration of low-viscosity phase**

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**Scaling out energy density**

$n_{ch,PP} = dN_{ch}/d\eta/(N_{part}/2)$ is the multiplicity per participant pair ~ system energy density

**Flat trend** $\sqrt{s_{NN}} = 7.7 – 20$ GeV : softening of the EOS?
Exploring the QCD phase diagram

Find...

1) Turn-off of sQGP signatures

2) 1\textsuperscript{st} order phase transition signs

3) The QCD critical point

Directed flow ($v_1$)

- Opposite charge pions follow the same trend
- Protons-antiprotons are different
  → baryon number transport is important
- Proton $v_1$ slope changes sign

Net proton $v_1$ slope

- Net protons: double sign change
  - Simple hydro predicts structure
  - More sophisticated UrQMD fails

- Softening of EOS?
  - Expected in mixed phase


Caloric curve

- 1\textsuperscript{st} order phase transition
  → $T(E)$ plateau
Caloric curve

- 1\textsuperscript{st} order phase transition
  \[ \rightarrow T(E) \text{ plateau} \]

- Similar feature in RHIC data!
  - \(<m_T>\) is related to temperature
  - \(E_T\) is related to energy density

\[ E^*/A \text{ (MeV)} \]

\[ \text{T (MeV)} \]

\[ \begin{array}{c}
\text{24Mg} \\
\text{27Al} \\
\text{40Ca}
\end{array} \]

\[ H. \text{ Feldmeier \& J. Schnack, Rev. Mod. Phys. 72, 655 (2000)}. \]
Femtoscopy: HBT radii

- **Femtoscopy:** Study the particle emitting source via quantum-correlations

\[
R_{\text{side}}^2 = \frac{R_{\text{geo}}^2}{1 + \frac{m_T}{T} \beta_T^2}
\]

\[
R_{\text{out}}^2 = \frac{R_{\text{geo}}^2}{1 + \frac{m_T}{T} \beta_T^2} + \beta_T^2 (\Delta \tau)^2
\]

\[
R_{\text{long}}^2 \approx \frac{T}{m_T} \tau^2
\]

Egy egyszerű modellben:
Makhlin, Sinyukov, ZPC.39.69 (1988)
Femtoscopy and phase transition

- If 1\textsuperscript{st} order phase transition: longer emission duration expected
- Non-monotonicity of $R_{\text{out}}^2$–$R_{\text{side}}^2$ may indicate change in dynamics

In a simple model:
Makhlkin, Sinyukov,
ZPC.39.69 (1988)

$$R_{\text{out}}^2 = \frac{R_{\text{geo}}^2}{1 + \frac{m_T}{T} \beta_T^2} + \beta_T^2 (\Delta \tau)^2$$

$$R_{\text{side}}^2 \approx \frac{T}{m_T} \tau^2$$

**STAR 0-5%**
- $m_T=0.26$ GeV
- $m_T=0.33$ GeV
- $m_T=0.42$ GeV
- $m_T=0.52$ GeV

**ALICE 0-5%**
- $m_T=0.29$ GeV/c
- $m_T=0.38$ GeV/c
- $m_T=0.46$ GeV/c
- $m_T=0.56$ GeV/c

Femtoscopy and critical point?

Finite size scaling?

- Infinite size: susceptibilities diverge at CP
- Finite size: susceptibility peaks close to CP

\[
\frac{1}{\bar{R}} = \sqrt{\left( \frac{1}{\sigma_x^2} + \frac{1}{\sigma_y^2} \right)}
\]

\[
(R_{out}^2 - R_{side}^2)_{\text{max}} \propto \bar{R}^{\gamma/\nu}
\]

\[
\sqrt{S_{NN}}(V) = \sqrt{S_{NN}}(\infty) - k \times \bar{R}^{-(1/\nu)}
\]

height: \( \chi_T^{\text{max}}(V) \sim L^{\gamma/\nu} \)

width: \( \delta T(V) \sim L^{-1/\nu} \)

position: \( \tau_T(V) \sim T^{\text{CEP}}(V) - T^{\text{CEP}}(\times) \sim L^{-1/\nu} \)

Data: STAR (& PHENIX, ALICE)

R. Lacey, PRL114,142301(2015)

R. Vértesi: Recent results from STAR

M. Lisa, QM15

Fitting the scaling for CP:

\( \mu_B \sim 95 \text{ MeV}, T \sim 165 \text{ MeV} \)
Exploring the QCD phase diagram

Find...

1) Turn-off of sQGP signatures
2) 1st order phase transition signs
3) The QCD critical point

Net multiplicities

Uncorrected raw event-by-event net-particle multiplicity distribution:
New data from √s_{NN} = 14.5 GeV Au+Au collisions

- Susceptibilities of conserved quantities (Q, B, S)
- Related to multiplicity distribution moments
- Volume effect → ratios

\[ \chi_B^{(n)} = \left. \frac{\partial^n (P / T^4)}{\partial (\mu_B / T)^n} \right|_T \]

\[ \chi_B^{4} / \chi_B^{2} = (k\sigma)^2 \]

\[ \chi_B^{3} / \chi_B^{2} = (S\sigma) \]

- Non-monotonic behavior expected around critical point
Net charge multiplicity moments (Q)

- No non-monotonous behavior seen
  - $\sigma^2/M$ increases with increasing collision energy
  - For most central collisions (0-5%), $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with Poisson expectation
- UrQMD (no Critical Point), shows no energy dependence

Net kaon multiplicity moments (S)

- No significant non-monotonous behavior seen
  
  - $\sigma^2/M$ increases with increasing collision energy
  
  - For most central collisions (0-5%), $\kappa\sigma^2$ and $S\sigma$/Skellam are consistent with Poisson expectation
  
- UrQMD (no Critical Point), shows no energy dependence

Net proton multiplicity moments

- Non-monotonous behavior (B) in central data
  - $\sigma^2/M$ increases with energy, consistent with poissonian
  - $S_\sigma$/Skellam increases with energy
  - $\kappa\sigma^2$ different from unity, break in trend

- No effect in peripheral data

- UrQMD (no Critical Point) suppression at lower energies is due to baryon number conservation

Open points: *Phys. Rev. Lett.* 113 (2014) 92301
STAR upgrades for BES II

- New forward trigger + Event Plane Detector
- Very important for flow and fluctuation analyses
  → independent from main detector
  → reduces systematics (non-flow, centrality)!
- iTPC upgrade
  → increases TPC acceptance to ~1.5 in $\eta$
  → improves dE/dx resolution

-Jim Thomas
Fixed target program at STAR

- Target inserted into beam pipe
- Only a small percentage
- Does not interfere with collider mode data taking
Fixed target program at STAR

- Extend range towards higher $\mu_B$

- Started in 2014

Collider mode 14.5 GeV

Fixed target 3.9 GeV

<table>
<thead>
<tr>
<th>Collider mode $\sqrt{s_{NN}}$ (GeV)</th>
<th>Fixed target $\sqrt{s_{NN}}$ (GeV)</th>
<th>$\mu_B$ (MeV)</th>
<th>$y_{CM}$</th>
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<td>19.6</td>
<td>4.5</td>
<td>585</td>
<td>1.52</td>
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Summary

1. Heavy Flavor

Quarkonia
- High-$p_T$ J/$\psi$ and $\Upsilon$ suppression: proof for sQGP
- Upsilon in Au+Au and U+U: sequential melting

Open heavy flavor
- $D^0$ mesons suggest charm-medium coalescence

2. Beam Energy Scan

BES-I covers the right (wide) $\mu_B$ range
- sQGP-turnoff signatures: $R_{CP}$, $\Delta v_2$, chiral magnetic effect
- Phase transition: non-monotonic $v_1$, HBT radii, caloric curve
- Critical point: Net-proton moments are the most convincing

BES-II: decisive measurements, finer scan between 7-20 GeV
Summary

1. Heavy Flavor

Quarkonia
- High-$p_T$ J/$\psi$ and $\Upsilon$ suppression: proof for sQGP
- Upilsons in Au+Au and U+U: sequential melting

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BES-II: decisive measurements, finer scan between 7-20 GeV

Toward understanding the QCD properties
Extra slides
Elliptic flow ($v_2$) – particles

- Approximate NCQ scaling holds… DOF=quarks?

Exception: $\phi$ at 7.7 and 11.5 GeV
deviation $\sim 2\sigma$ – more statistics needed
Elliptic flow ($v_2$) – antiparticles

- Approximate NCQ scaling holds… DOF=quarks?
- …but particles and antiparticles are different

**Figure:**
- Plots of $v_2/n_q$ versus $(m_T-m_0)/n_q$ for different energies: 7.7 GeV, 11.5 GeV, 19.6 GeV, 27 GeV, 39 GeV, 62.4 GeV.
- Legend includes various particle types such as $\pi^-$, $\Lambda$, $K^-$, $\Xi^+$, $K_s^0$, $\Omega$, $\phi$.

**Source:**
Higher kinetic temperature corresponds to lower value of average flow velocity and vice-versa.
Spatial eccentricity at the kinetic freeze-out, $\varepsilon_F$

Sensitive to EOS

Smooth, monotonous behavior observed over the BES range
Chiral magnetic effect

- Chiral-magnetic effect: Local parity violation in sQGP
  \[ \frac{dN_\alpha}{d\phi} \propto 1 + 2v_1 \cos(\Delta \phi) + 2a_\alpha \sin(\Delta \phi) + 2v_2 \cos(2\Delta \phi) + \ldots \]

- Measure: 3-point correlator, charge separation

\[ \gamma \equiv \langle \cos(\phi_1 + \phi_2 - 2\Psi_{RP}) \rangle \quad H^\kappa = (\kappa v_2 \delta - \gamma)/(1 + \kappa v_2). \]
Chiral magnetic effect

- QCD allows for local parity violation in sQGP
- Possible signatures:

  1) Three-point correlator

  2) Charge separation

- Drop of charge separation below 11.5 GeV consistent with expectations in a dominant hadronic phase

Quantify the Spectral Function

Temperature dependence of rho spectral function
1. Beam energy range where final state is similar
2. Initial state and temperature evolution different
3. Density dependence by Azimuthal dependence ($v_2$)
4. Use centrality dependence as another knob
5. Direct photon results should match with extrapolation

Baryon dependence of rho spectral function
1. LMR excess expected to be consistent with total baryon density increase
Dilepton Measurements at BES II

Beam Energy

Centrality

STAR Preliminary

BES II enables measurements at energy <20GeV
Non-photonic electrons: 200 GeV

**Suppression**
- Significant suppression of NPE in central collisions ($p_T > 4$ GeV/c)
- Similar to that of light hadrons and $D^0$ mesons

**Anisotropy ($v_2$)**
- Substantial elliptic flow of NPE is seen in 200 GeV Au+Au collisions

Note: It’s challenging for models to describe suppression and flow at the same time.
Non-photonic electrons: 39, 62.4 GeV

Suppression

- No sign of suppression of NPE in 62.4 GeV Au+Au collisions

Note: pQCD-scaled p+p reference

Anisotropy ($v_2$)

- NPE in 39 and 62.4 GeV Au+Au collisions consistent with no flow ($p_T<1$ GeV/c)
Motivation for high-\(p_T\) J/\(\psi\)

- \(d+Au\) \(\rightarrow\) study of cold nuclear matter effects
- \(R_{dAu} \approx 1\) for high \(p_T\)

\(\rightarrow\) CNM effects are small at high-\(p_T\)

- Much less regeneration

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Model:
X. Zhao, R. Rapp, PRC82, 064905 (2010)

Data:
$\gamma R_{dAu} - $ CNM effects

- Models include
  - Gluon nPDF (Anti)shadowing
  - Initial parton energy loss
  - Indication of suppression at mid-rapidity beyond models

- STAR data consistent with E772


$R_{dAu} = 0.48 \pm 0.14\text{(stat)} \pm 0.07\text{(syst)} \pm 0.02 \text{(pp stat)} \pm 0.06 \text{(pp syst)}$

$|y| < 0.5$
Quarkonia in Au+Au with MTD

STAR preliminary

Au+Au @ 200 GeV

- J/ψ → e⁻e⁺, |y| < 1
- J/ψ → μ⁻μ⁺, |y| < 0.5


Projections for Run14+16

CMS, PRL 109 (2012) 222301
STAR (ee), PLB 735 (2014) 127

Y projection, full MTD data

STAR Muon Telescope Detector

60 pb⁻¹ p+p, 20 nb⁻¹ Au+Au

- Y (1S) → e⁺e⁻, |y|<0.5
- Y (2S) → e⁺e⁻, |y|<0.5
- Y (3S) → e⁺e⁻, |y|<0.5

D⁰, model ingredients

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Zhenyu Ye, QM2014