STAR Highlight on Heavy Ion Physics

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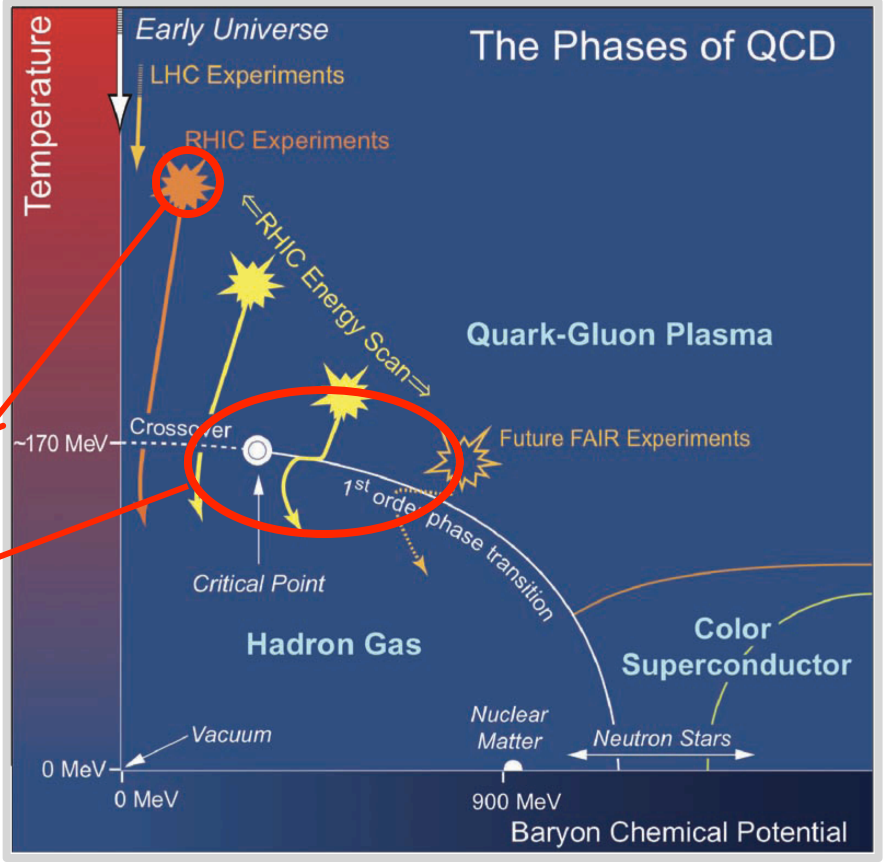
The 3rd International Conference on New Frontiers in Physics 2014

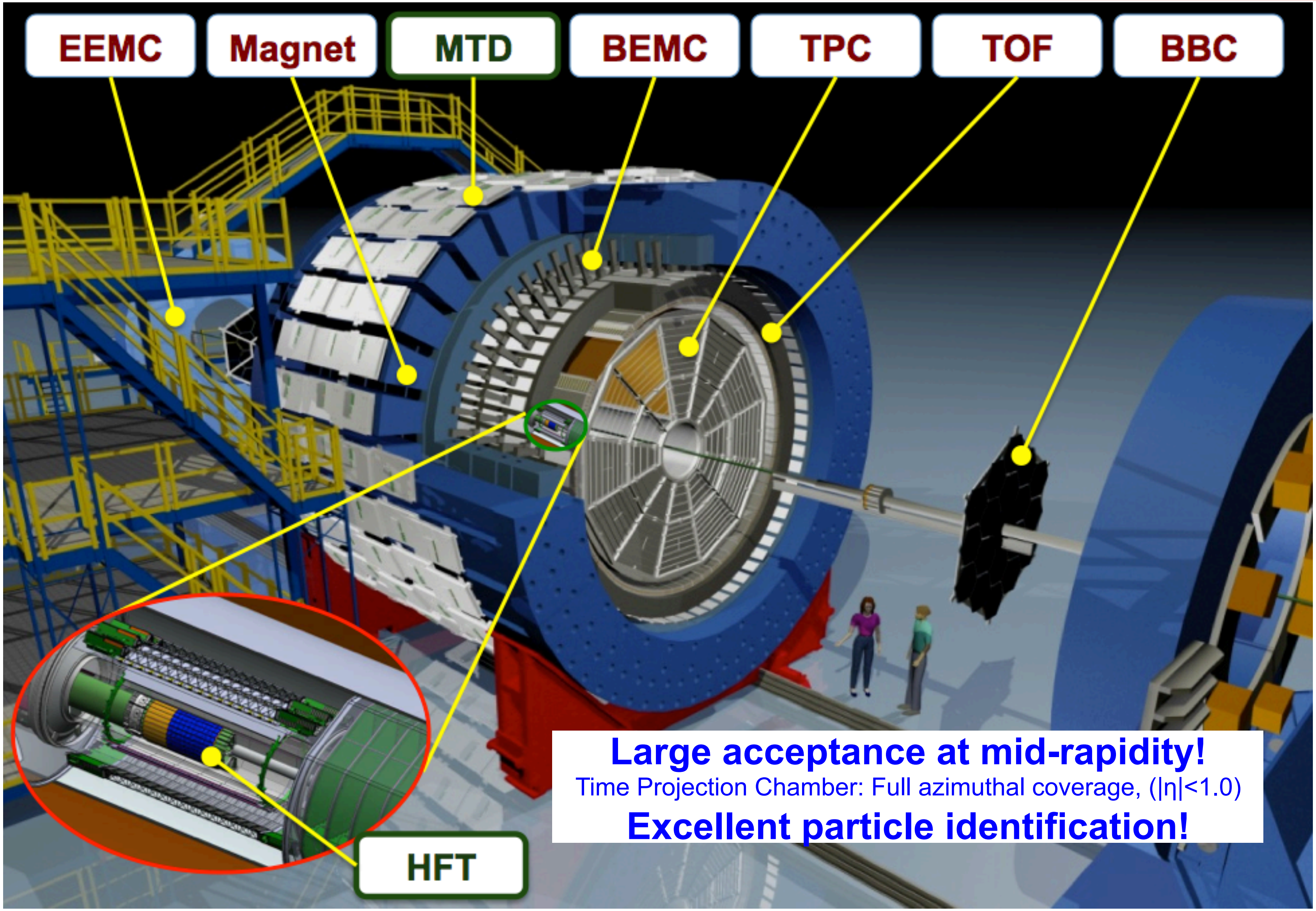
28 July – 6 August 2014, Kolymbari, Crete, Greece

Outline

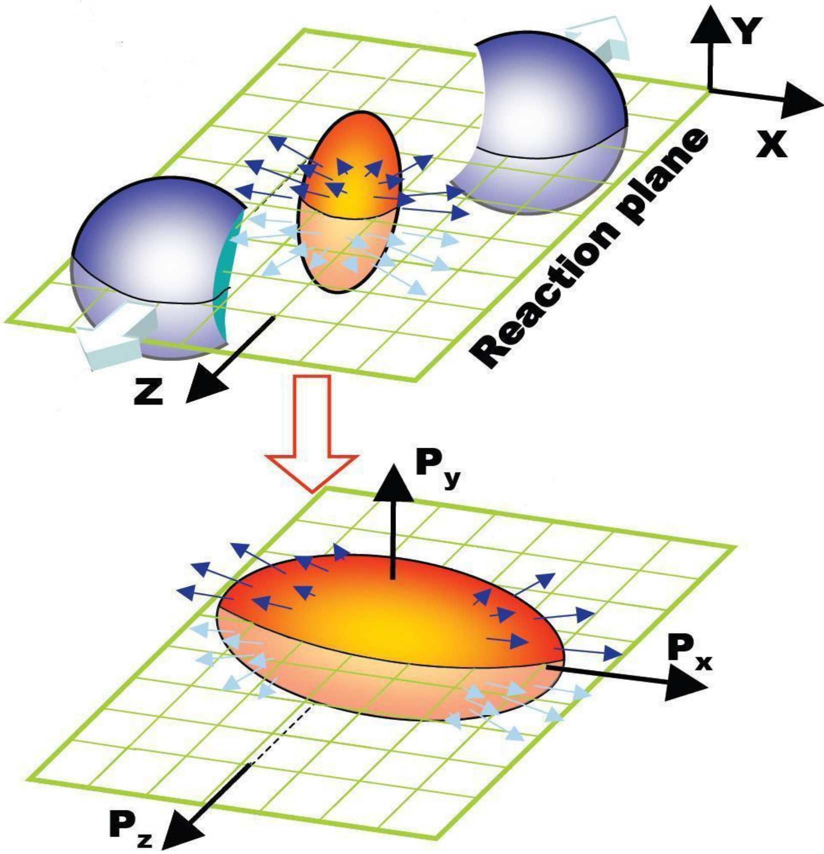
- **Introduction**
- **STAR Detectors**
- **Recent Results**
  - Top energy collisions at RHIC
    - Study the medium properties
  - Beam Energy Scan at RHIC
    - QCD phase boundary and critical point
- **Summary/Outlook**

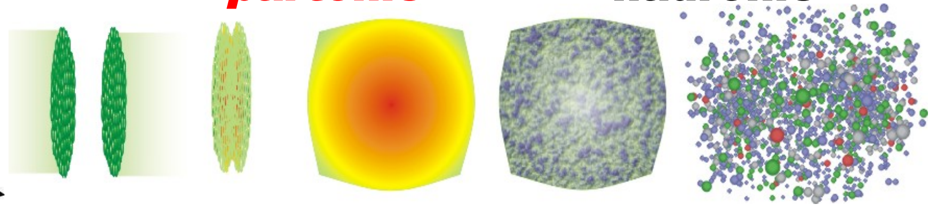


STAR Detectors



Elliptic Flow (v_2)





$$\varepsilon = \frac{\langle y^2 - x^2 \rangle}{\langle y^2 + x^2 \rangle} \Rightarrow v_2 = \langle \cos 2\varphi \rangle, \qquad \varphi = \tan^{-1}\left(\frac{p_y}{p_x}\right)$$

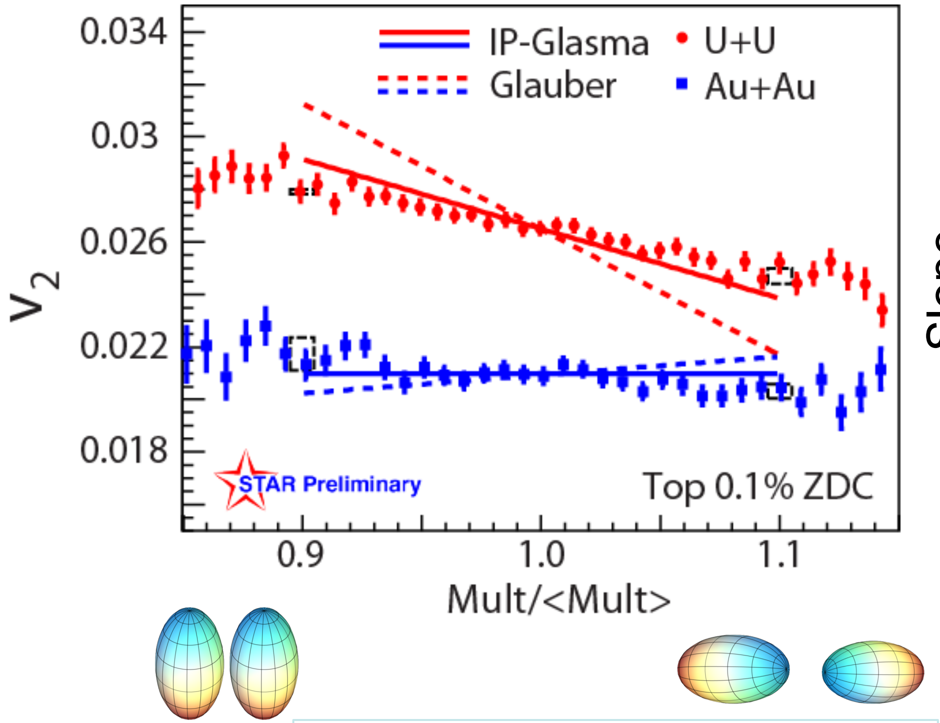
Elliptic flow =>

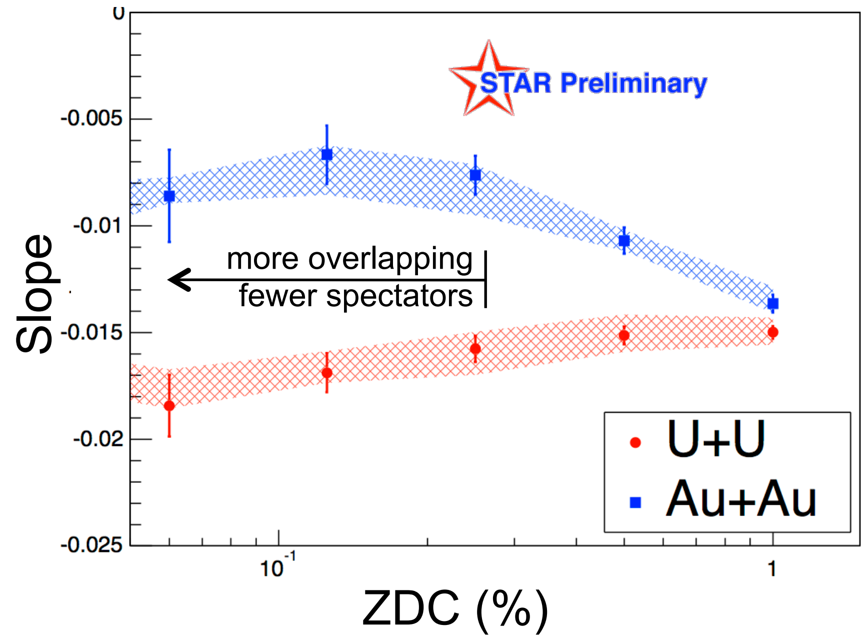
- Initial spatial anisotropy (eccentricity ε)
  ->
  final momentum anisotropy v_2
  by interactions among constituents

- Self-quenching with time
  - Sensitive to the early stages of the system evolution

Good probe of the early stage of the collision.

v_2 in U+U Collisions



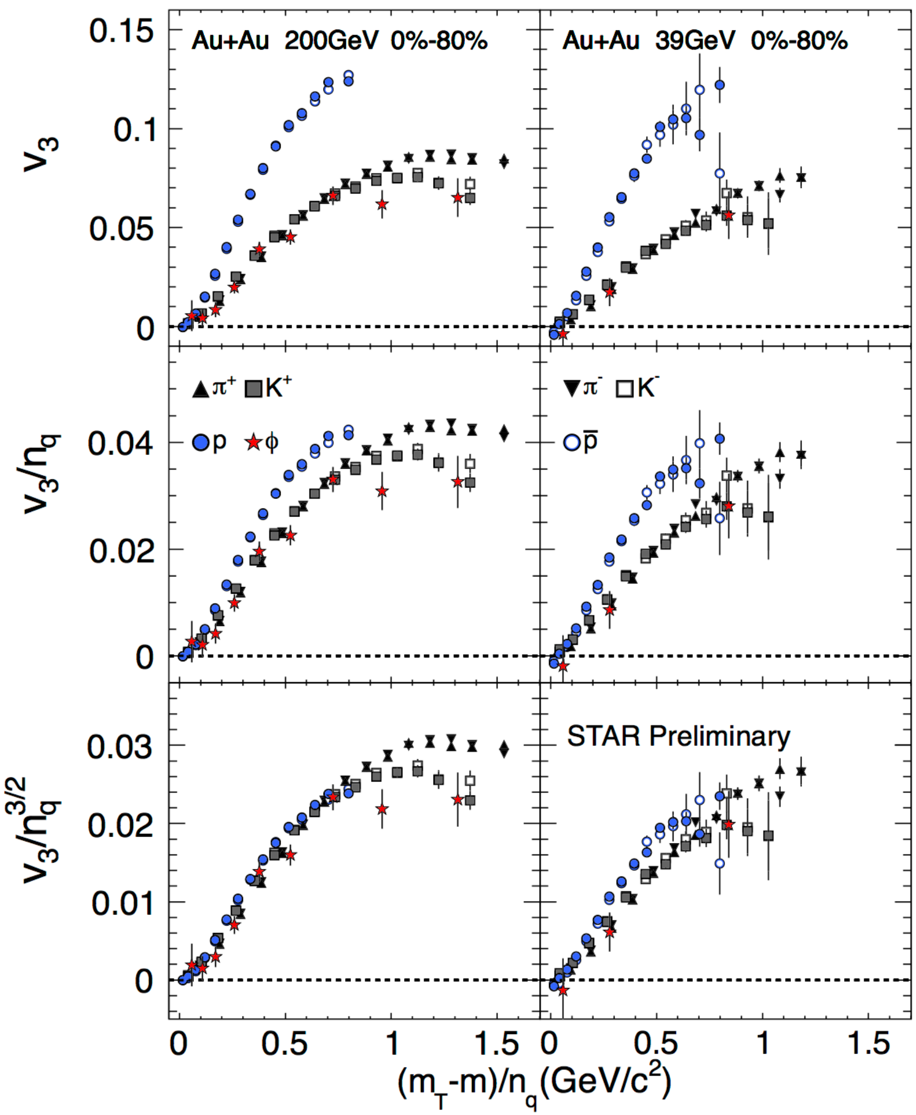


Dashed boxes are systematic errors

- RHIC delivered the U+U collisions in order to study geometry effects
- Tip-tip and body-body enhanced samples selected via ZDC-mult cut
- IP-Glasma model matches the data better

Bjoern Schenke, et al. arXiv:1403.2232
Maciej Rybczyński, et. al. PRC87,044908(2013)

Triangular Flow v_3

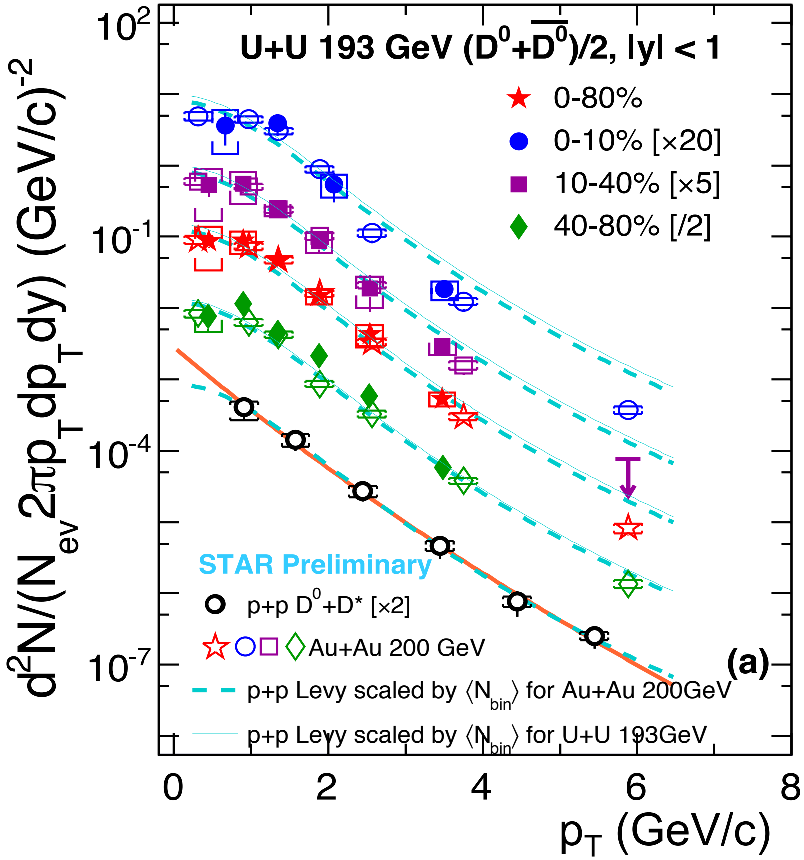


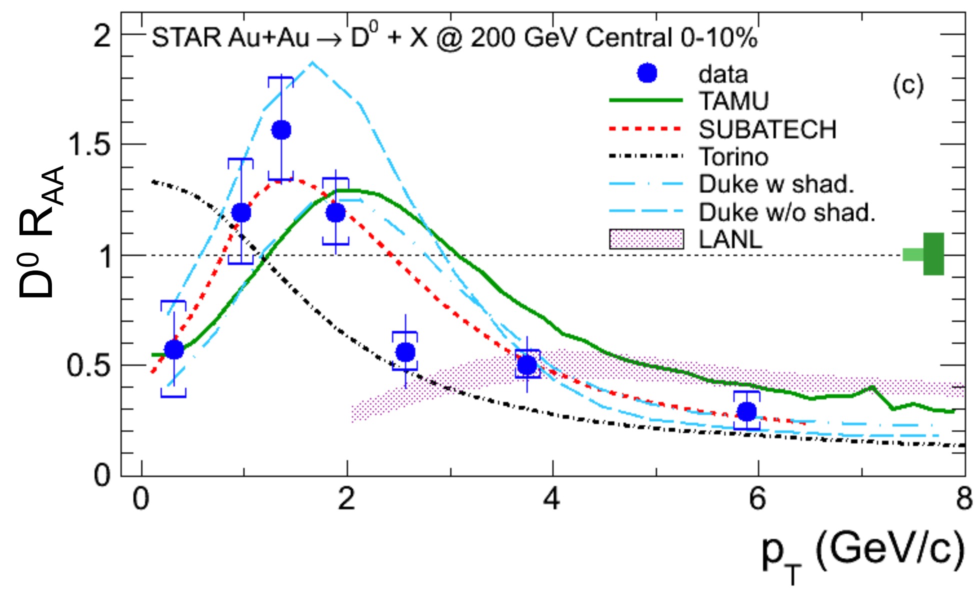
- Event-by-Event fluctuations ε_3 -> v_3
- The number of constituent quark scaling does not work for v_3
- Hydro inspired $(n_q)^{i/2}$, i=3, seems to work for 200 GeV collisions up to $(m_T\text{-}m)/n_q \sim 1$ GeV/c^2

P. Huovinen, Phys. Lett. **B503**, 58 (2001)
R. Lacey, J. Phys. **G38**, 124048(2011)

Open Heavy Flavor

Au+Au@200 GeV: submitted to PRL, arXiv:1404.6185





Average number of binary collisions in A+A

$$R_{AA}(y,p_T) = \frac{1}{<N_{coll}>} \frac{\frac{d^2N_{AA}}{dp_T dy}}{\frac{d^2N_{pp}}{dp_T dy}}$$

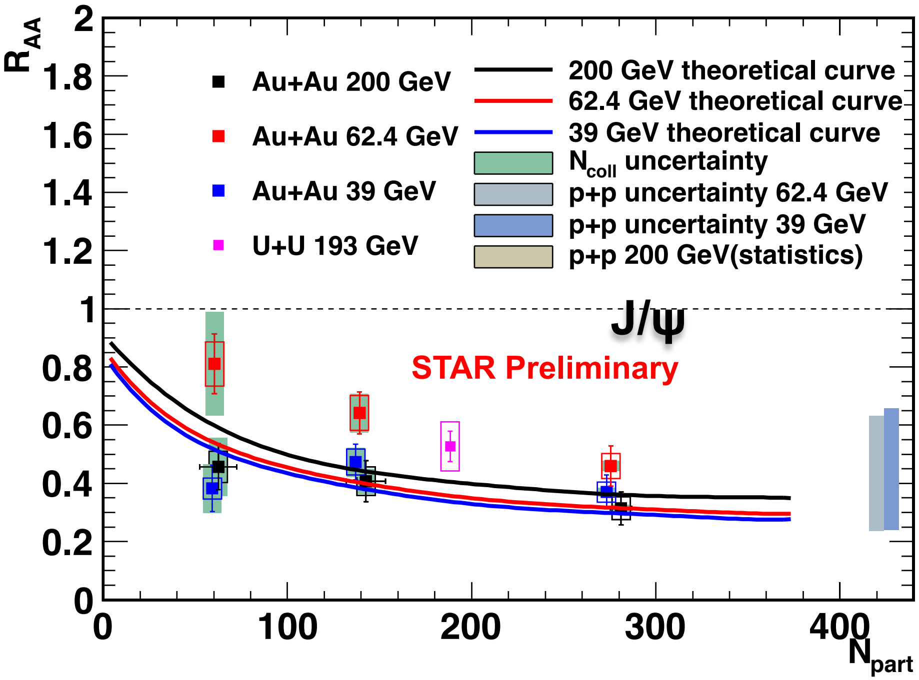
Particle production in A+A

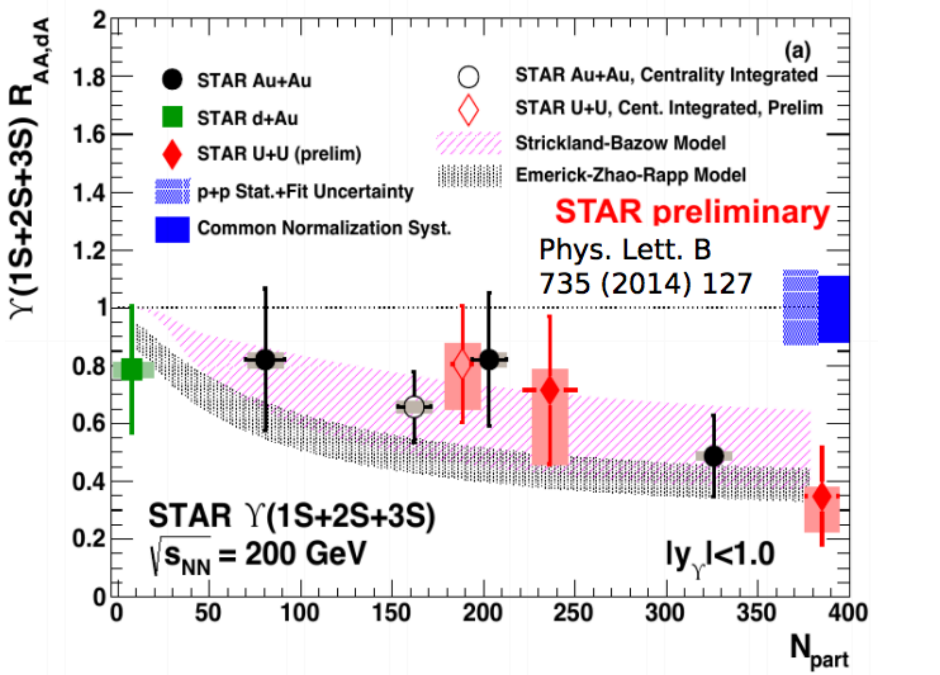
Particle production in p+p

David Tlusty: August 6 [parallel 2]

- Large suppression at high p_T indicates strong charm-medium interactions
- Enhancement at p_T ~ 0.7-2 GeV/c: described by models with charm quark coalescence with light quarks

Quarkonia



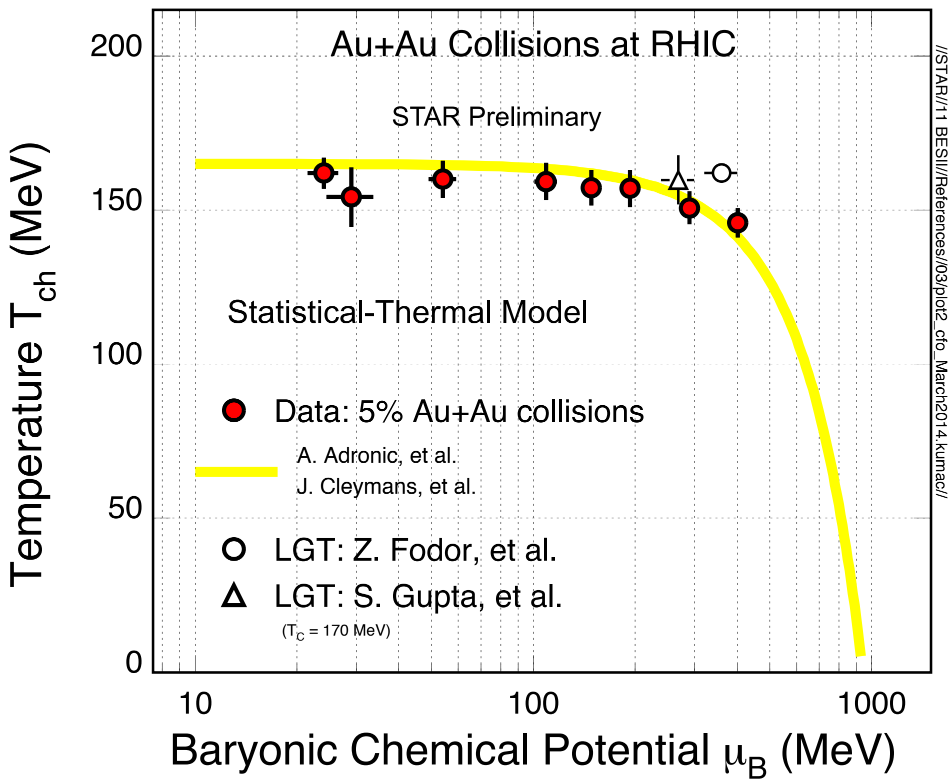


Barbara Trzeciak: August 2 [parallel 4]

- Suppression increases with collision centrality
- Similar suppression in U+U and Au+Au collisions
- Weak beam energy dependence of J/ψ R_{AA}

X.B. Zhao et al., PRC82, 064905(2010)
L. Yan et al., PRL97, 232301(2006)

Beam Energy Scan at RHIC



BES-I

Year 2014

$\sqrt{s_{NN}}$ (GeV)	7.7	11.5	14.5	19.6	27	39
μ_B (MeV)	420	315	260	205	155	115

Observables:

Phase boundary

Charge separation;
v_2 - NCQ scaling

1st order phase transition

Directed flow v_1

Critical point

Fluctuations

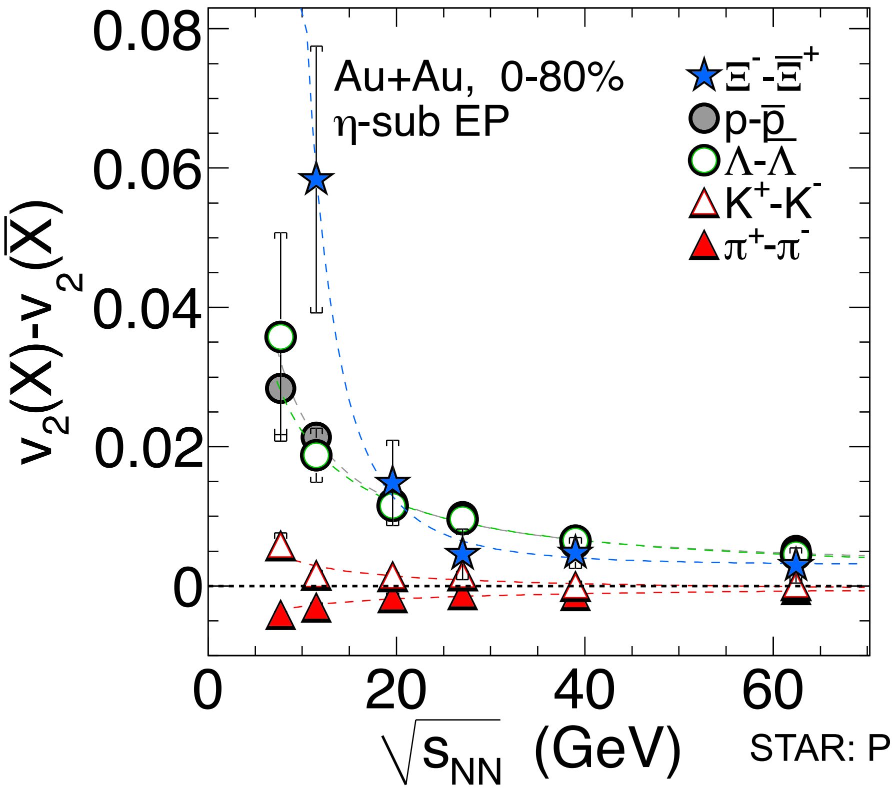
Chiral symmetry restoration

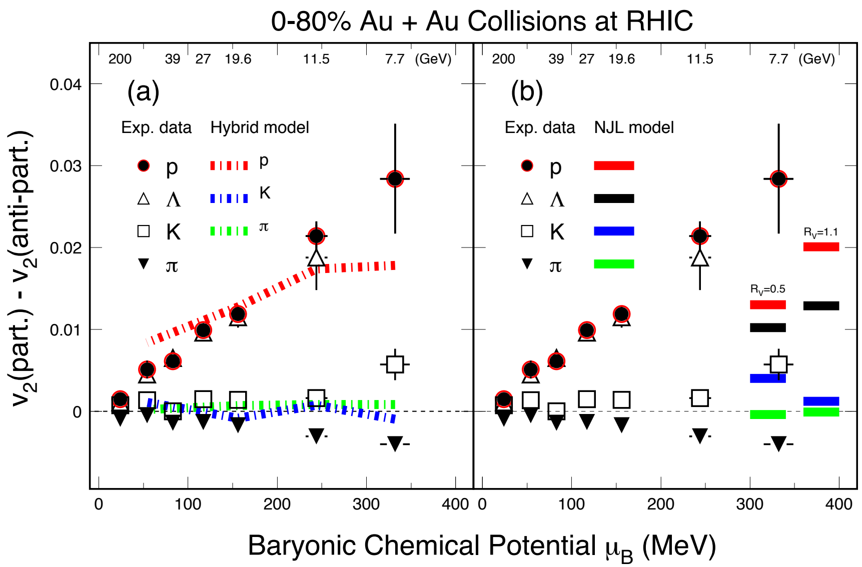
Di-lepton production

Study QCD Phase Structure!

Daniel McDonald: July 29 [FAIR workshop]

Particle vs. Anti-particle v_2



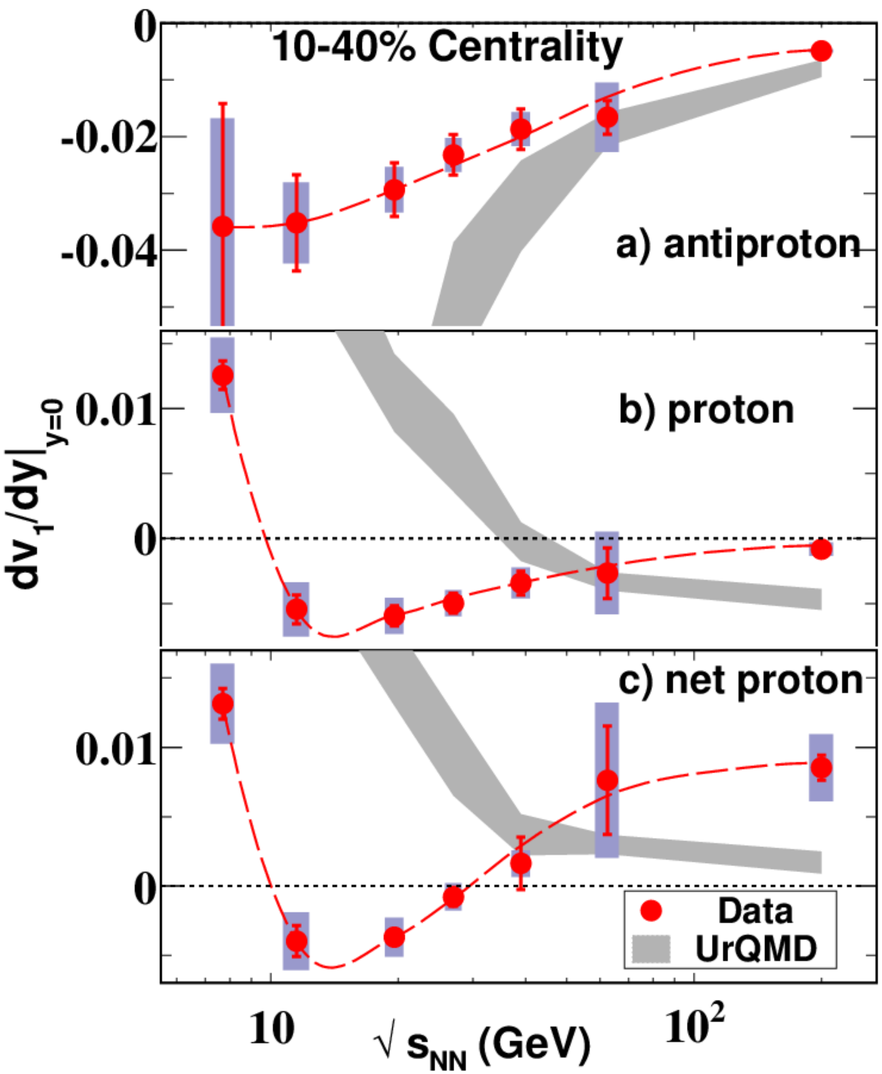


STAR: Phys. Rev. Lett. **110** (2013) 142301

- The difference between particles and anti-particles increases with decreasing beam energy – NCQ scaling breaks
- Model comparison
  - Hydro + Transport (UrQMD): consistent with baryon data
  - Nambu-Jona-Lasino (NJL) model (partonic + hadronic potential): hadron splitting consistent

J. Steinheimer, V. Koch, and M. Bleicher PRC86, 44902(2013); J. Xu, et al., PRL112, 012301(2014)

Directed Flow v_1: Softest Point



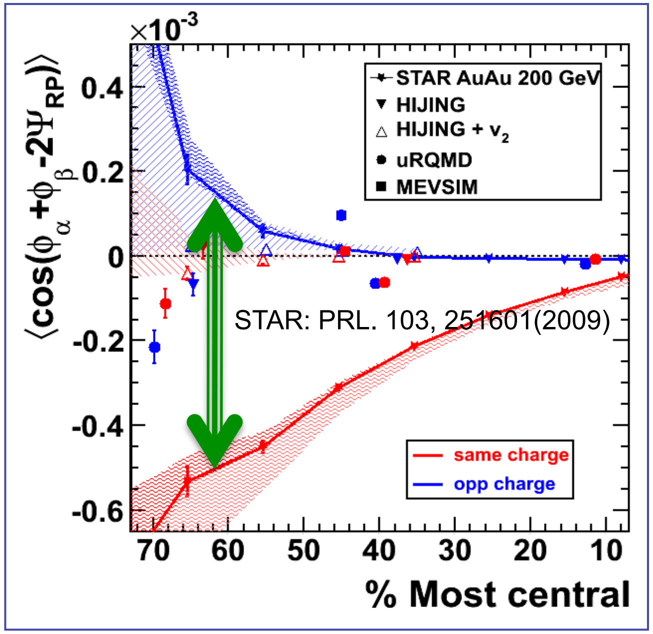
dv_1/dy: the slope of directed flow versus rapidity near mid-rapidity

- Hydro calculation with 1st order phase transition motivates the study
- Net-proton slope changes sign twice
  EOS softest point?
- UrQMD fails to reproduce the data
- BESII improvement:

Improved reaction plane determination
Systematic centrality-dependent analysis

STAR: PRL**112**, 162301(2014)
H. Stoecker, NPA750, 121(2005)

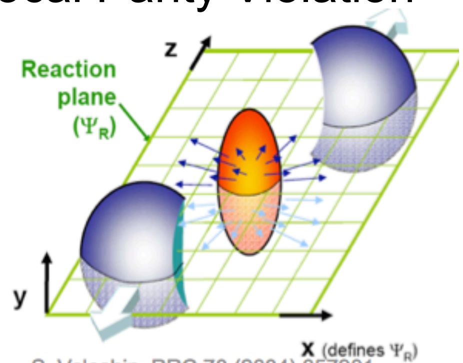
Charge Separation wrt Event Plane



Chiral Magnet Effect + Local Parity Violation

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

A direct measurement of the *P*-odd quantity *"a"* should yield *zero*.



S. Voloshin, PRC 70 (2004) 057901

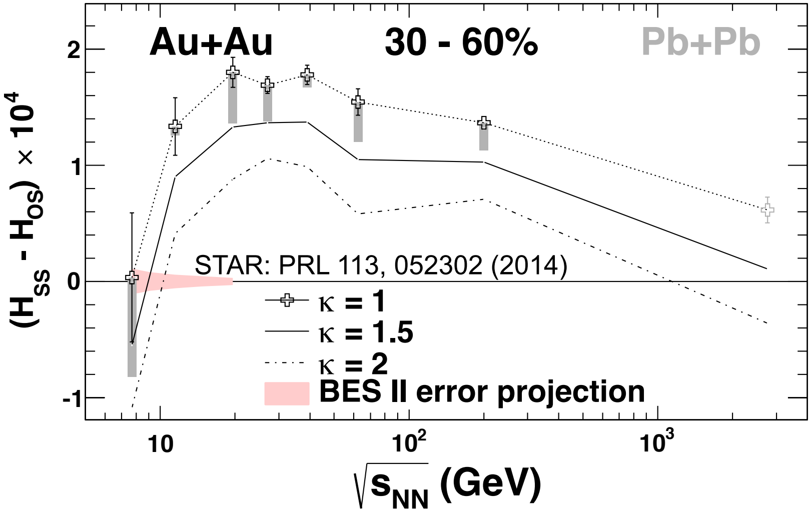
$$\gamma = \left\langle \cos(\phi_\alpha + \phi_\beta - \psi_{RP}) \right\rangle$$

$$= \left[\left\langle v_{1,\alpha} v_{1,\beta} \right\rangle + B_{in}\right] - \left[\left\langle a_\alpha a_\beta \right\rangle + B_{out}\right]$$

Directed flow: expected to be the same for SS and OS

Non-flow/non-parity effects: largely cancel out

P-even quantity: still sensitive to charge separation



- ***H*: CME contributions**

  A. Bzdak et al., Lect. Notes Phys. 871, 501 (2013)

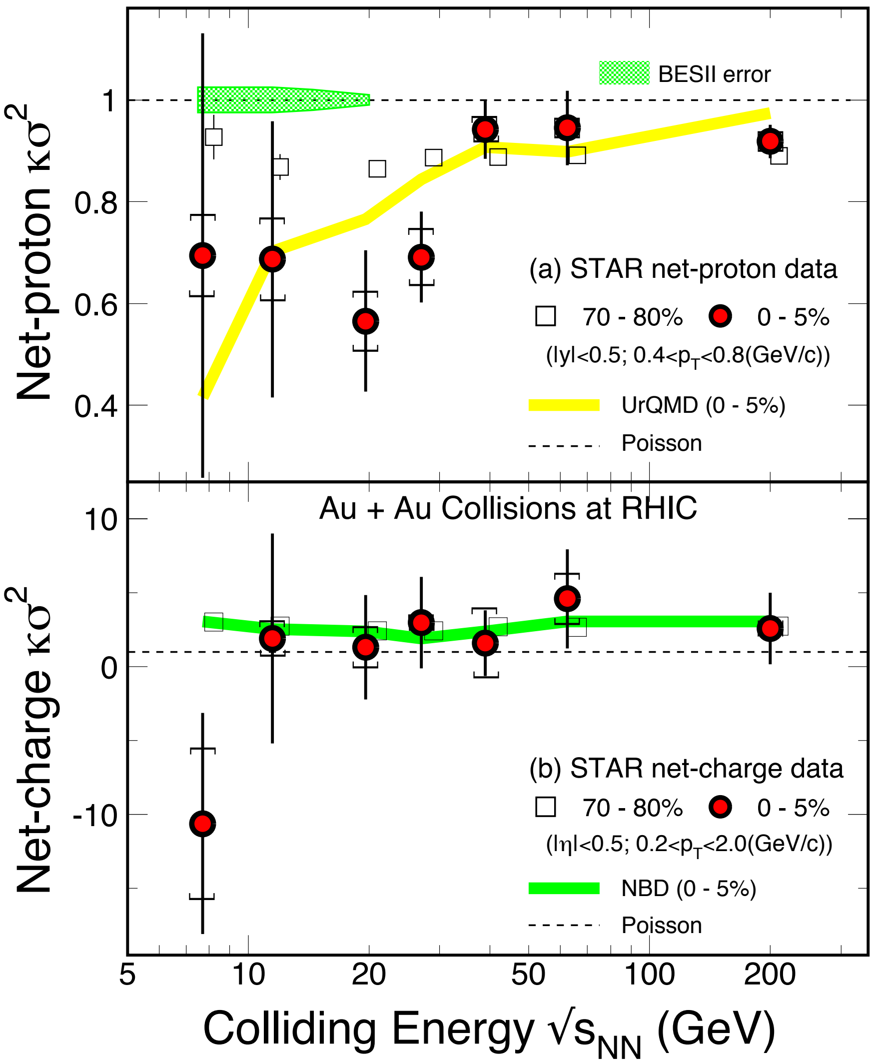
➔Disappears at low energy

hadronic interactions become dominant at $\sqrt{s_{NN}} \leq 11.5$ GeV

D. Kharzeev. PLB633, 260 (2006)

D. Kharzeev, et al. NPA803, 227(2008)

Higher Moments



Sensitive to critical point (ξ correlation length):

$$\left\langle (\delta N)^2 \right\rangle \approx \xi^2, \left\langle (\delta N)^3 \right\rangle \approx \xi^{4.5}, \left\langle (\delta N)^4 \right\rangle \approx \xi^7$$

$$S\sigma \approx \frac{\chi_B^3}{\chi_B^2}, \kappa\sigma^2 \approx \frac{\chi_B^4}{\chi_B^2}$$

Non-monotonic behavior would be indicative of existence of CP

Net-proton results:

- Deviations below Poisson for $\kappa\sigma^2$ at all energies. Relatively larger deviation at $\sqrt{s_{NN}}$~20GeV

STAR: **PRL112**, 32302(2014)

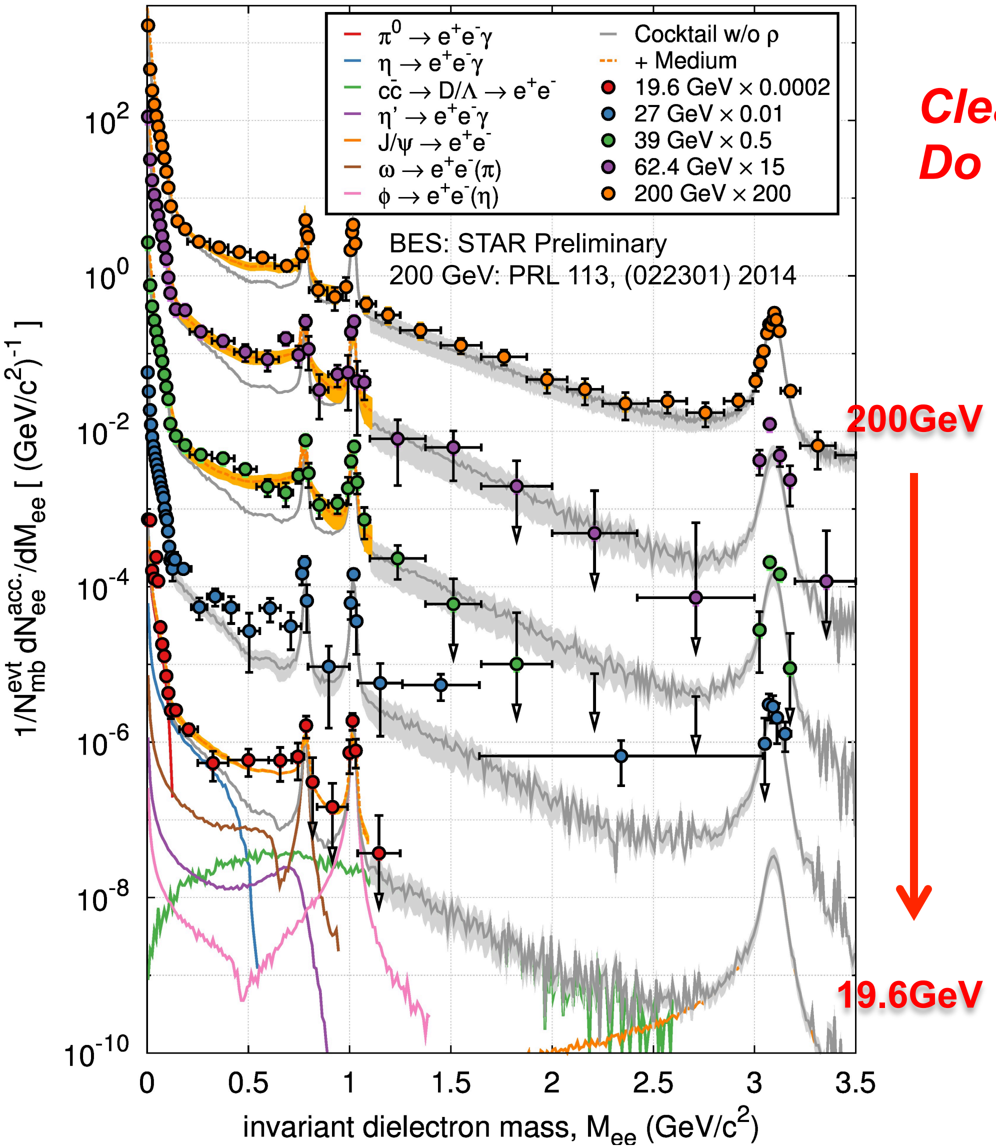
Net-charge results:

- No non-monotonic behavior
- More affected by resonance decays

STAR: arXiv: 1402.1558

Higher statistics needed for collisions at $\sqrt{s_{NN}}$ < 20 GeV

Di-electrons



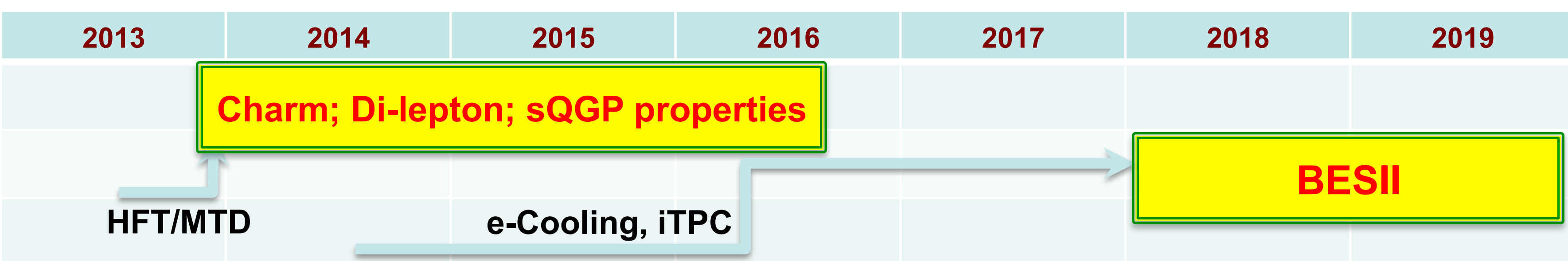
Clean and penetrating probe!
Do not suffer from strong interactions

- **M_{ee} < 1.1 GeV/c²:** Model results with in-medium broadened ρ are consistent with data.
- **1.1 < M_{ee} < 3.0 GeV/c²:** QGP thermal radiation
- **BES-II: high statistics**

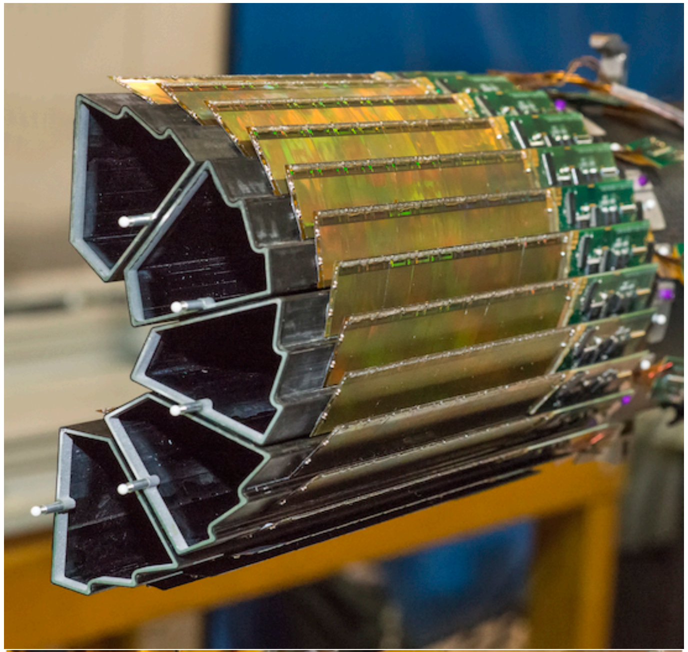
R. Rapp: PoS CPOD13, 008(2013)

Summary/Outlook

- **Top Energy Heavy Ion Collisions**
  - **Initial Condition:**
    U+U collisions: IP-Glasma results match data better
  - **Hot and dense sQGP:**
    Heavy flavor hadron R_{AA}: large suppression for D mesons at high p_T
- **RHIC Beam Energy Scan Program**
  $\sqrt{s_{NN}} \geq 39$ GeV: partonic interactions dominant
  $\sqrt{s_{NN}} \leq 11.5$ GeV: hadronic interactions dominant
- **Outlook**
  - **Heavy flavor program with new upgrade**
    Heavy Flavor Tracker and Muon Telescope Detector
  - **RHIC BES-II**:
    Focus on $\sqrt{s_{NN}} \leq 20$ GeV region



HFT and MTD



Both Fully installed in Run14!

Heavy Flavor Tracker (HFT)

Physics goal: **Precision measurement of heavy quark hadron production in heavy ion collisions**

Collected 1.2 B Au+Au at 200 GeV events in year 2014

Spyridon Margetus: August 5 [parallel 5]

Muon Telescope Detector (MTD):

Physics goal: **Heavy Quarkonia – Upsilon states**

Took 12 nb^{-1} Au+Au collisions at 200 GeV in year 2014 for quarkonium physics

BES II

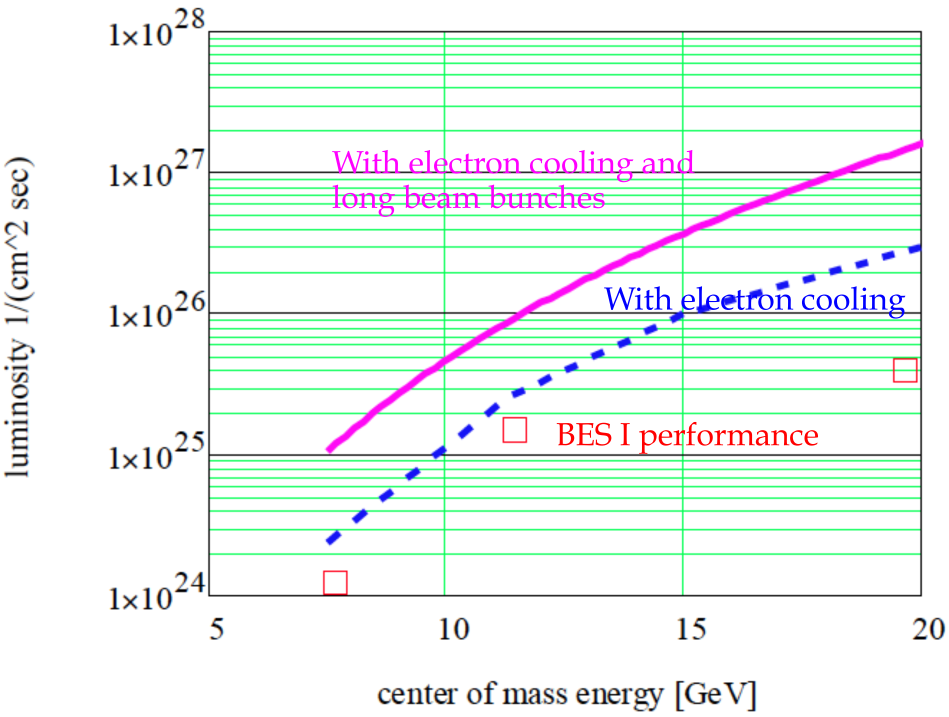
Electron cooling + longer beam bunches for BES II
factor 4-15 improvement in luminosity compared with BES I

Detector upgrade

Grazyna Odyniec: August 4 [Plenary 5]

- **Event Plane Detector**
  important for flow and fluctuation analyses

- **iTPC upgrade**
  increases TPC acceptance to ~1.7 in η; improves dE/dx resolution



Fixed target program

extends STAR's physics reach to region of compressed baryonic matter