PHENIX Perspectives for the RHIC Energy Scan

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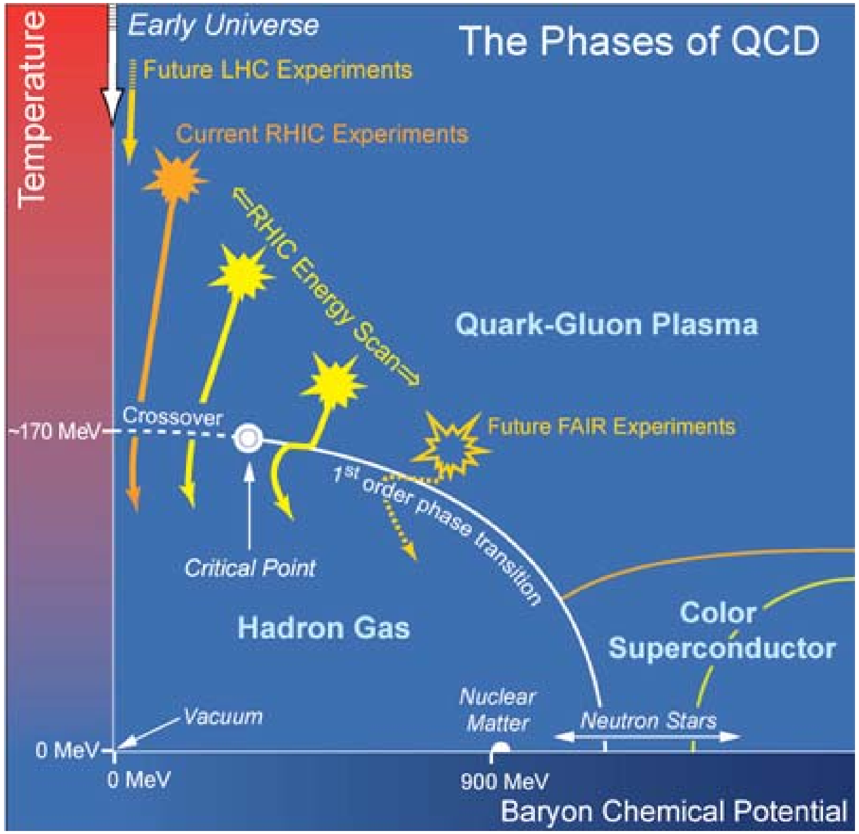
- Introduction
- Search for the QCD Critical Point
- Search for the Onset of sQGP Production
- Summary and Outlook

QCD phase diagram

- goal of high energy heavy-ion physics
  - identify phases of matter and their properties
  - locate transitions and their properties

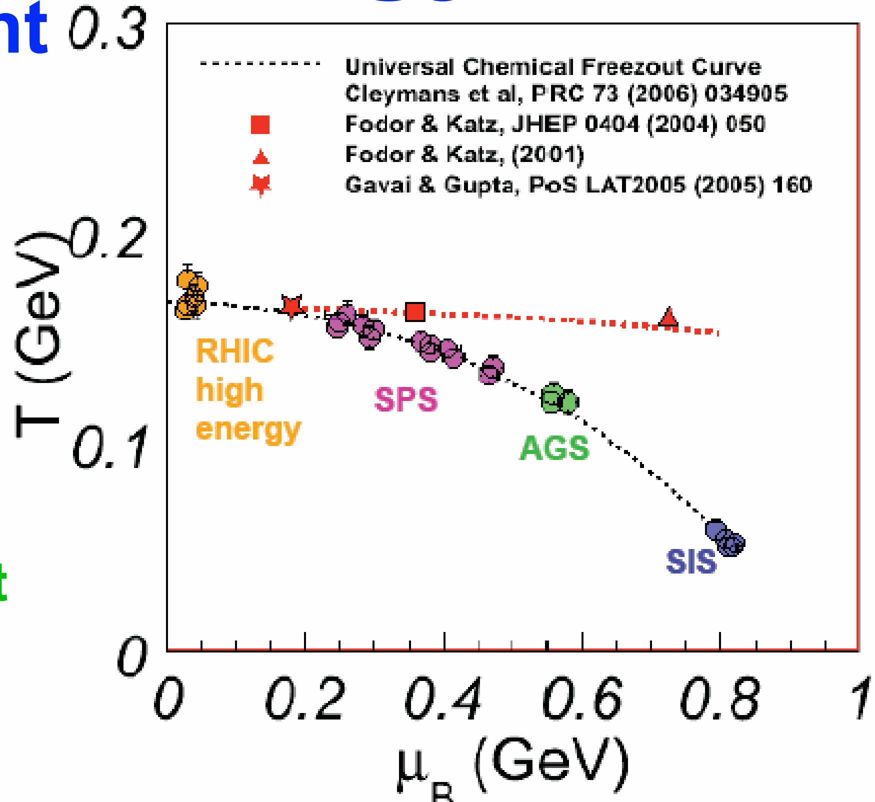


- vanishing μ_B
  - sQGP at top RHIC energy
  - evolution to hadron gas through a continuous rapid crossover transition
- larger μ_B
  - possibility of a 1st order phase transition
    - → critical point?
    - → phase coexistence line?

→ energy scan at RHIC

Questions for an energy scan

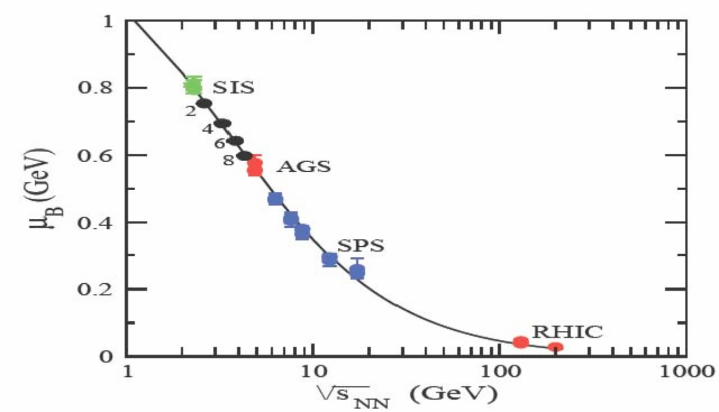
- search for the critical point
  - where should we look?
    - → guidance from lattice QCD
      - – critical point in reach at
        - » FAIR
        - » SPS
        - » RHIC
  - what (T, μ_B) for given $\sqrt{s}$?
    - → constraints from experiment
  - what to measure?

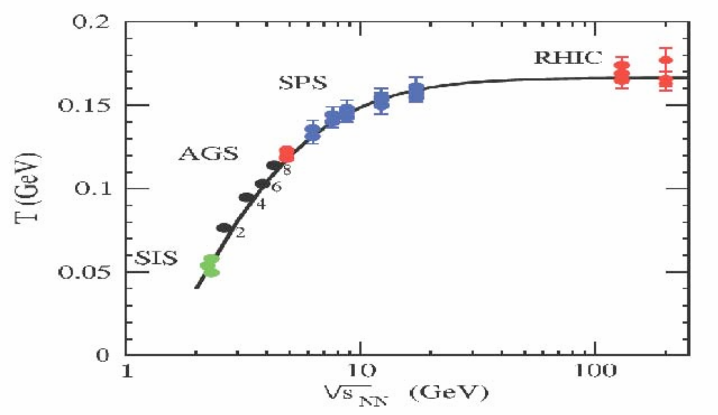


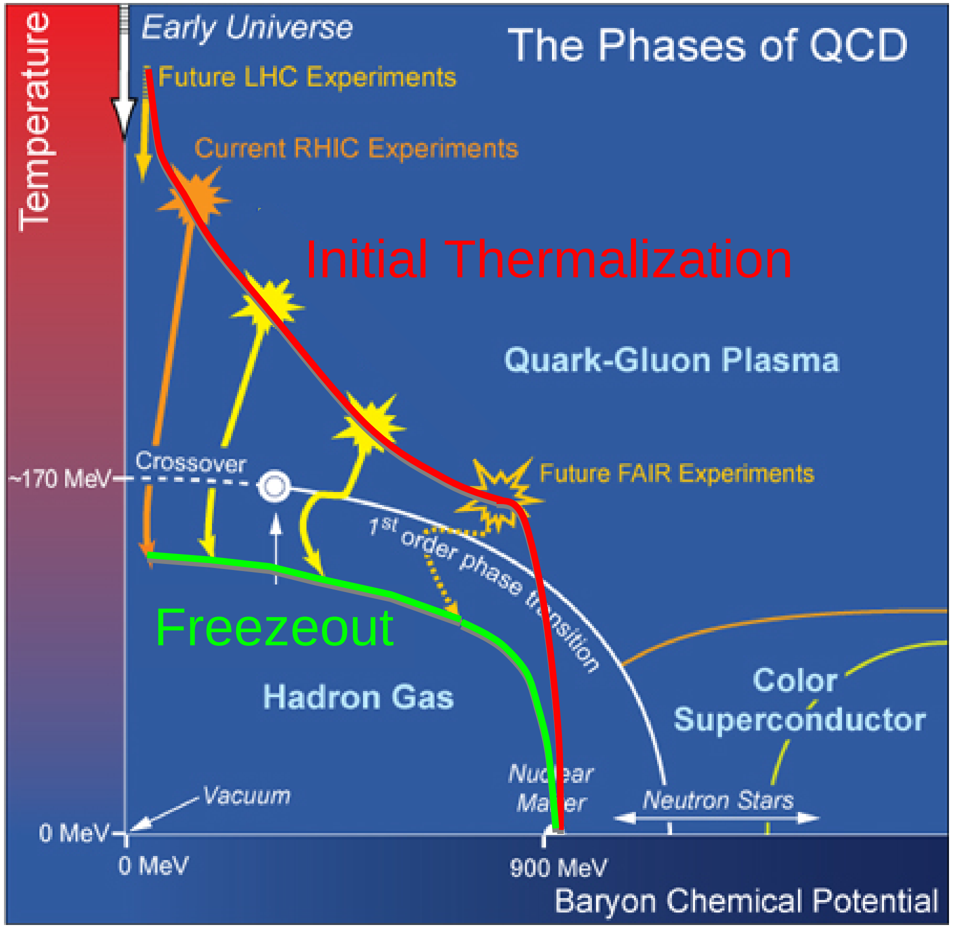
- evolution of the sQGP
  - how do the medium properties evolve with $\sqrt{s}$?
  - where do individual sQGP signatures "turn off"?
- experimental boundary conditions
  - performance of RHIC at lower $\sqrt{s}$?
  - what are the constraints in PHENIX?

Where are we in (T, μ_B)?

- important prerequisite
  - initial thermalization in partonic world
    - some idea of $T_{initial}$?



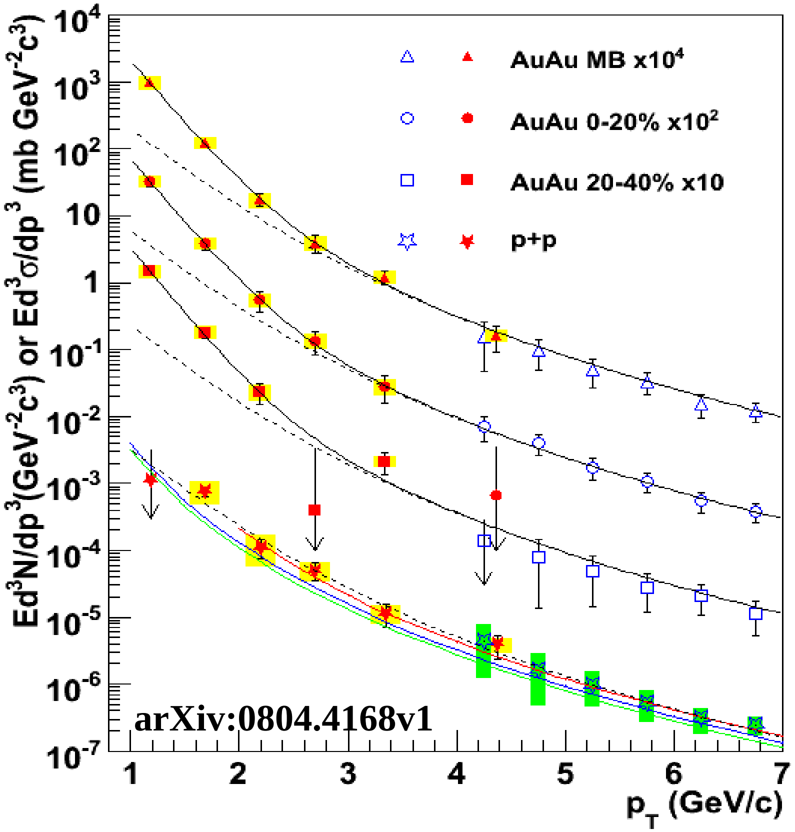


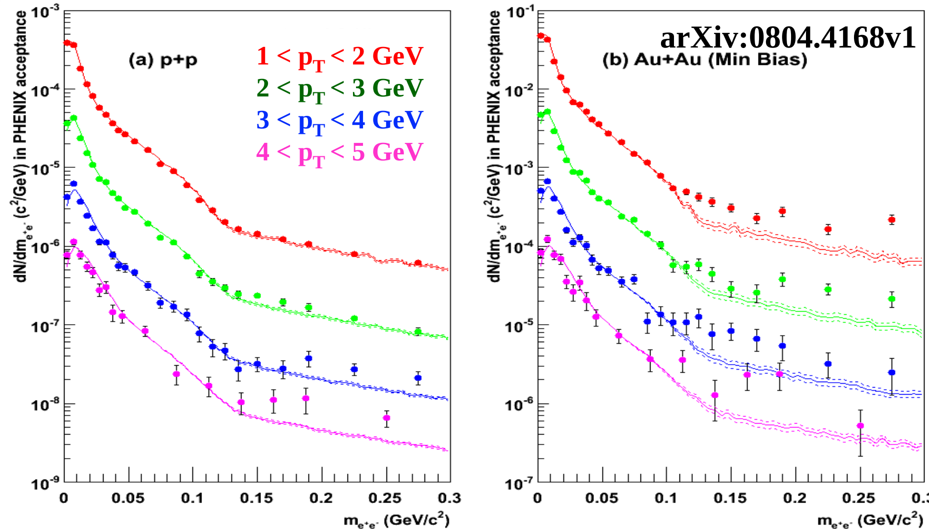


- evolution into hadronic world
  - determine (T, μ_B) at freezeout from particle species ratios

Initial T from thermal photons

- enhanced emission of "soft" low-mass virtual photons in Au+Au compared to pp



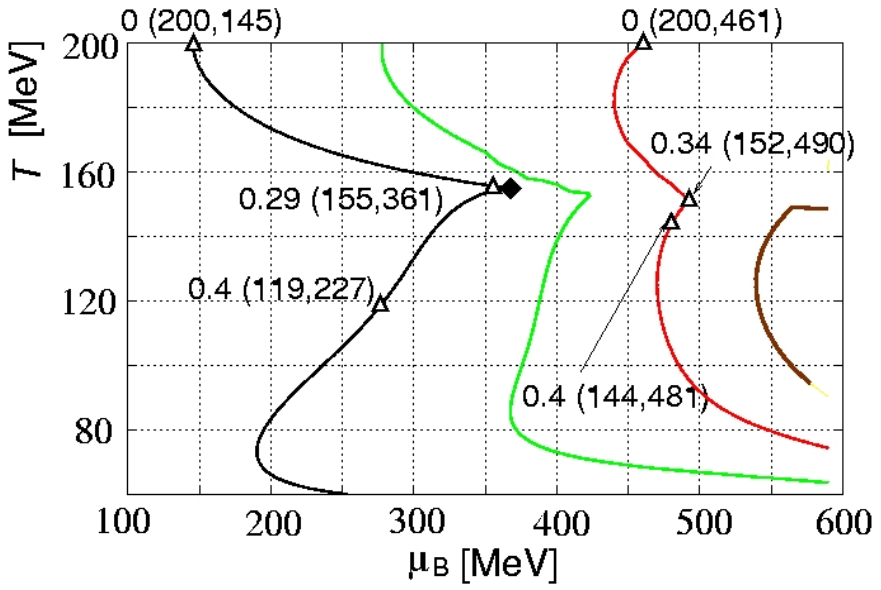


- consistent with hydrodynamic model calculation assuming 300 MeV < $T_{initial}$ < 600 MeV
- difficulties at low √s
  - signal/background
  - interaction rate at RHIC
- feasible at higher end of RHIC energy scan

Finding the critical point

Nonaka & Asakawa, PRC 71(2005)044904

- hydro prediction
  - critical point "attracts" isentropic trajectories in the (T, μ_B) plane
  - focusing causes a broadening of the signal region in (T, μ_B)



→ not necessary to exactly "hit" the critical point in an energy scan!

Stationary state variables

- properties
  - divergence of stationary state variables at critical point
    - compressibility

$$k_T \propto \left(\frac{T - T_C}{T_C} \right)^{-\gamma}$$

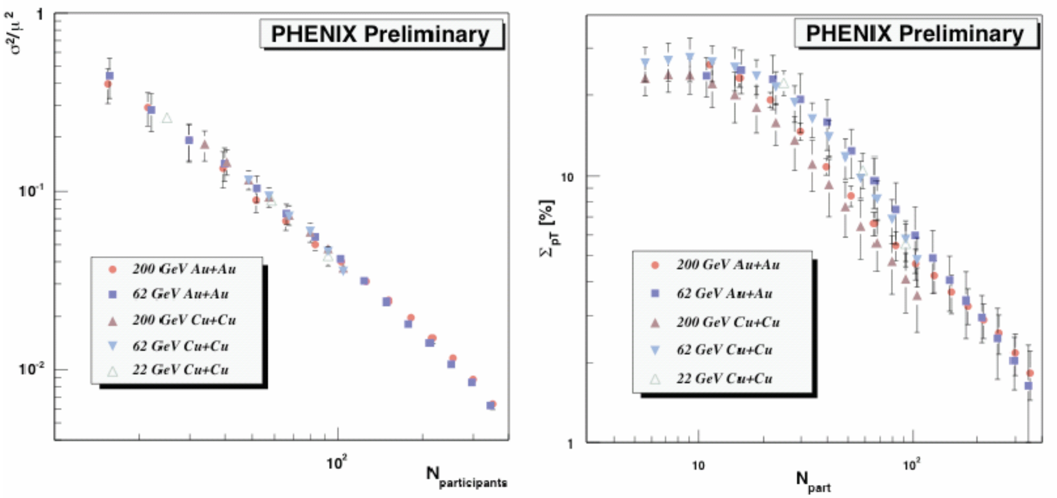
    - heat capacity

$$C_V \propto \left(\frac{T - T_C}{T_C} \right)^{-\alpha}$$

  - related to event-by-event fluctuations of observables
    - multiplicity fluctuations $\frac{\sigma^2}{\mu^2} = k_B (T/V) k_T$
    - $\langle p_T \rangle$ fluctuations $4\sum_{pT} = \frac{1}{C_V}$
- strategy
  - study fluctuations as function of μ_B ($\sqrt{s}$)
  - search for anomalies, i.e. large critical fluctuations

Fluctuations

- PHENIX measures fluctuations



- no compelling evidence for critical fluctuations yet

critical point search needs further observables

- limits and caveats
  - fluctuations σ and correlation length ξ (Stephanov, Rajagopal, Shuryak: PRD 60(1999)114028)

$$\sigma \propto \xi^2$$

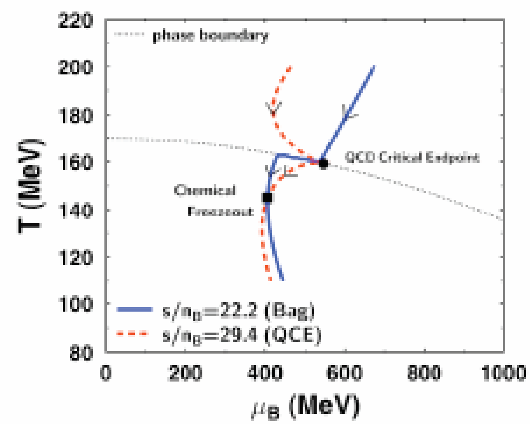
  - – finite system size
  - – finite evolution time
  - → divergence of ξ (and σ) limited
  - system slows down near critical point → fluctuations damped (Berdnikov and Rajagopal: PRD 61(2000)105017)
  - do critical fluctuations survive hadronization?

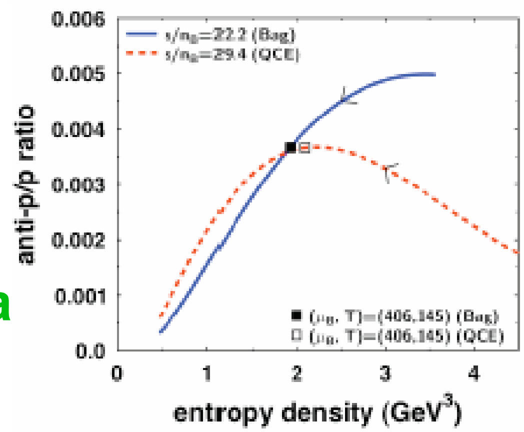
Antiproton-to-proton ratio

- back to hydro
  - critical point deforms ("attracts") isentropic trajectories in the (T, μ_B) plane
  - antiproton-to-proton ratio

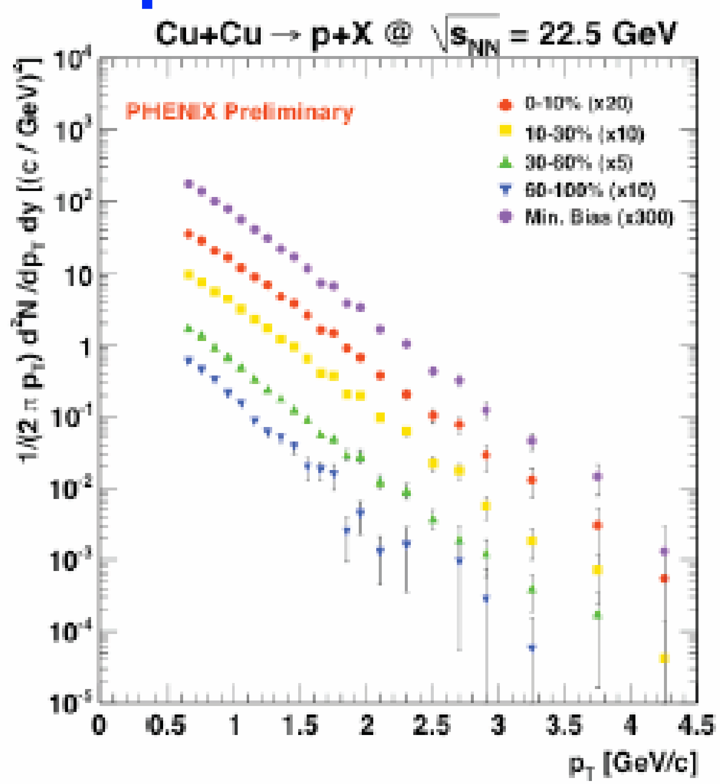
$$\frac{\bar{p}}{p} \sim \exp(-2\mu_B / T)$$

  - prediction (Asakawa et al., arXiv:0803.2449)
    - antiproton spectra are steeper than proton spectra at high p_T
    - more robust than fluctuation observables





- PHENIX measures identified hadron spectra



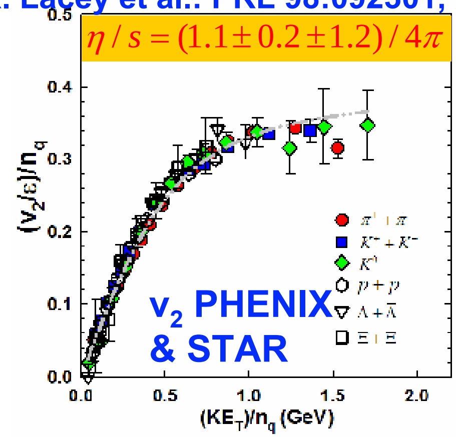
Dynamic variables

- again: correlation length ξ is important
- relation between diffusion constant D and ξ (Son & Stephanov) $D \sim \xi^{-1}$
  - large ξ near critical point → small diffusion constant D
  - → small shear viscosity to entropy density ratio η/s
- bulk viscosity is different $\bar{\eta} \sim \xi^{0.05-0.06}$
- again
  - limited system size
  - no extreme effects
- expectation close to the critical point
  - minimum in shear viscosity to entropy ratio η/s
  - bulk viscosity only somewhat sensitive

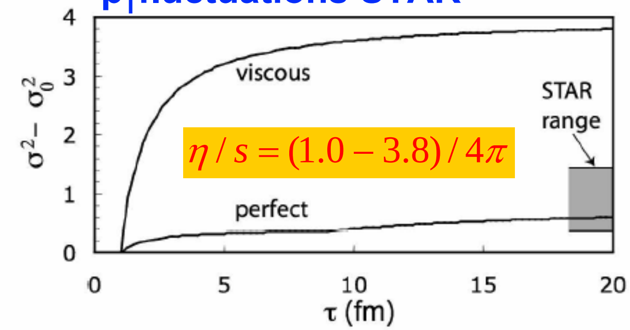
η/s measurements

- need observables that are sensitive to shear stress
- damping ~ η/s
- flow
- fluctuations
- heavy quark motion

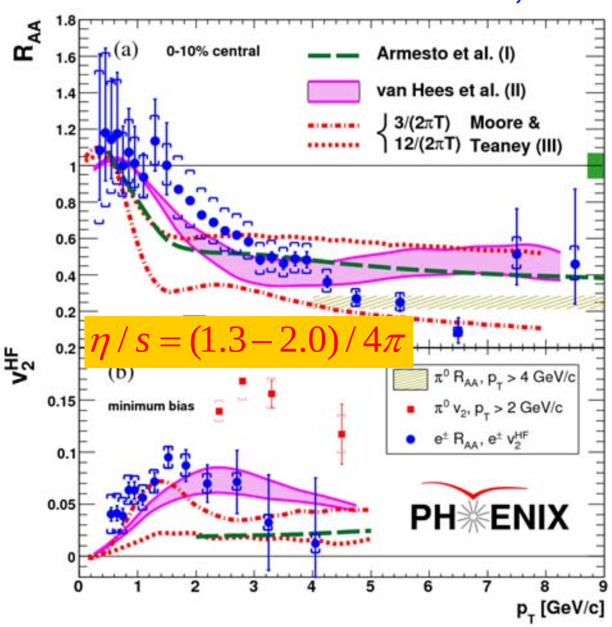
R. Lacey et al.: PRL 98:092301, 2007



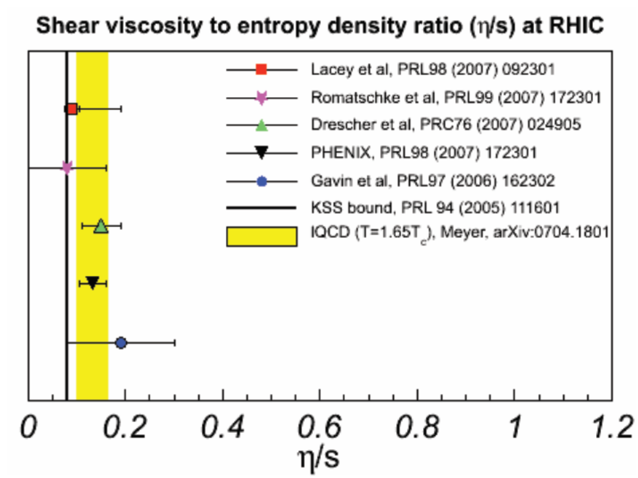
S. Gavin and M. Abdel-Aziz: PRL 97:162302, 2006
p_T fluctuations STAR



A. Adare et al.: PRL 98:092301, 2007



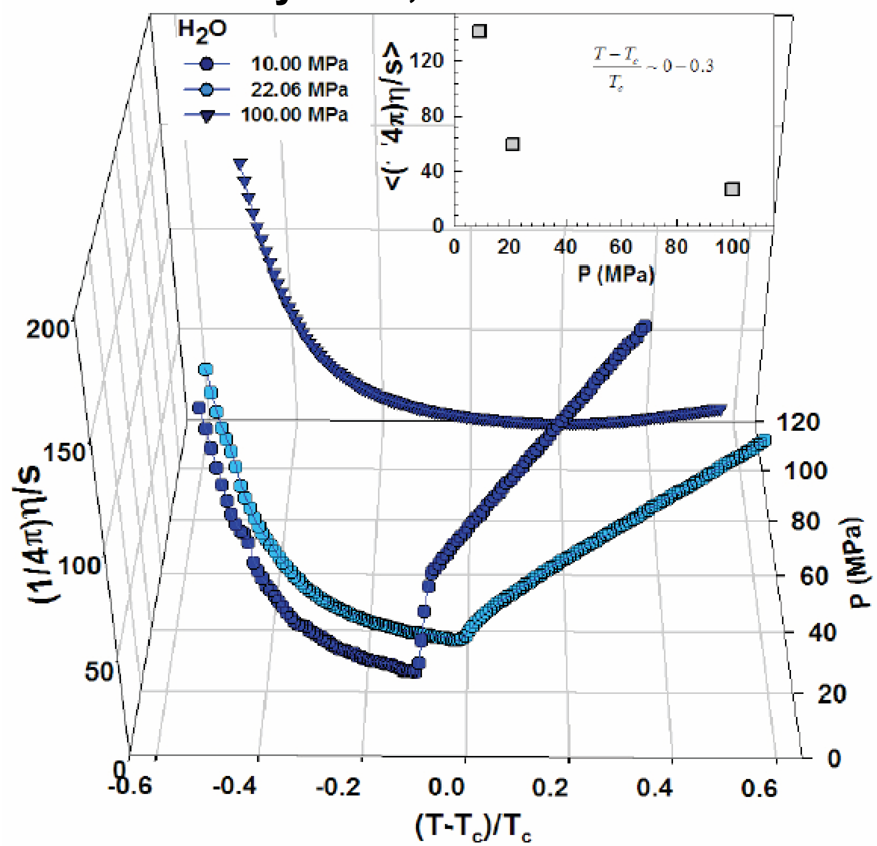
- top RHIC energy
  - η/s close to conjectured minimum 1/4π

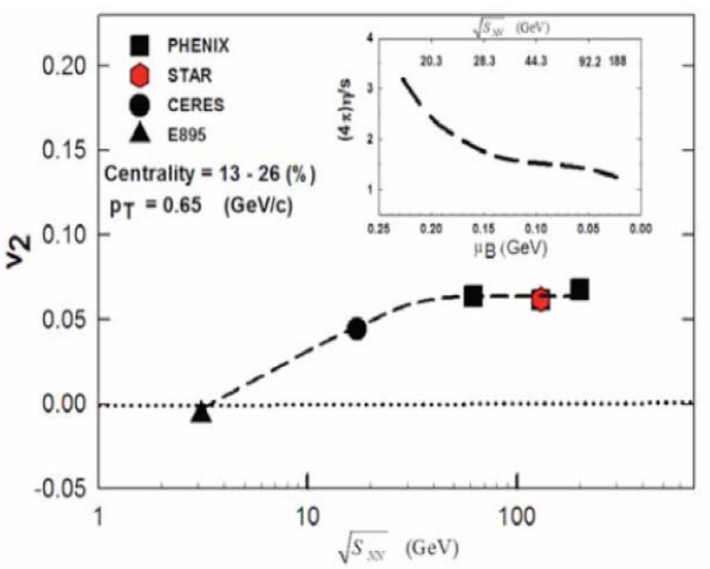


η/s near the critical point

- η/s goes through a minimum near the critical point
  - estimate from Lacey et al. (based on v_2 systematics)
    - T ~ 165-170 MeV
    - μ_B ~ 120-150 MeV

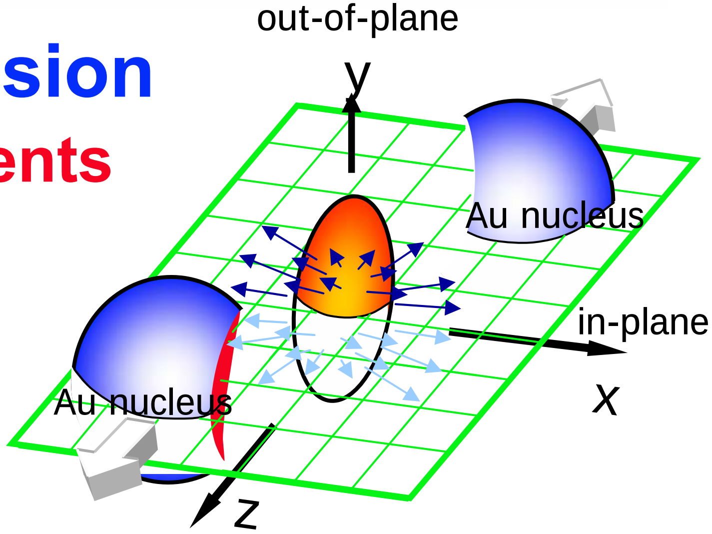
Lacey et al., arXiv:0708.3512





critical point search in the region 20 GeV ≤ √s ≤ 62 GeV

Flow systematics



- **initial state of non-central collision**
  - **large asymmetric pressure gradients**

    → hydrodynamic flow of partons
  - **control parameters: ε_0, η, c_s**
- **translates into**
  - **final state momentum anisotropy**

$$E\frac{d^3N}{d^3p} = \frac{d^3N}{p_T d\varphi dp_T dy}\sum_{n=0}^{\infty} 2v_n \cos\left(n\left(\varphi - \Psi_R\right)\right)$$

$$v_{2n} = \left\langle \cos\left(2n\left[\varphi - \Psi_R\right]\right)\right\rangle$$

- **hydrodynamic flow exhibits scaling properties which can be validated (or invalidated), e.g.:**

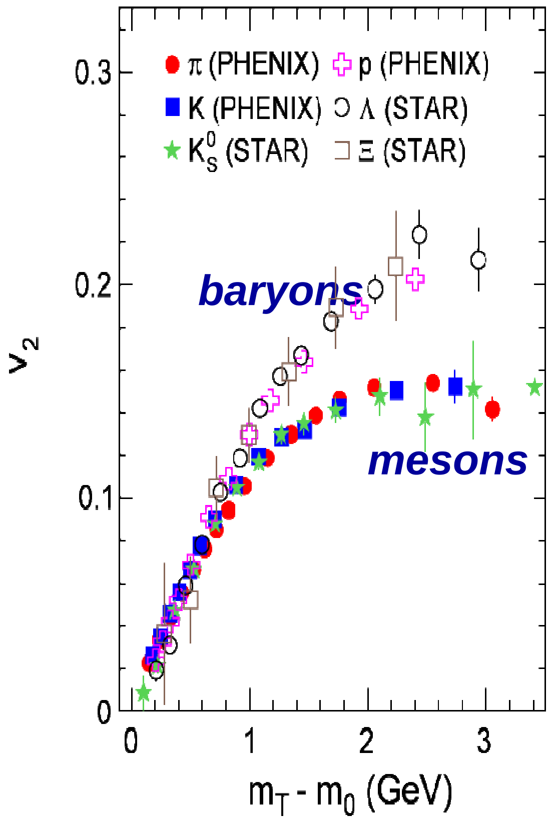
$$\frac{v_{4,M}(2p_T)}{v_{2,M}^2(2p_T)} \approx a\left(\frac{1}{4} + \frac{1}{2}\times\frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)}\right) \qquad \frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)} \approx \frac{1}{2}$$

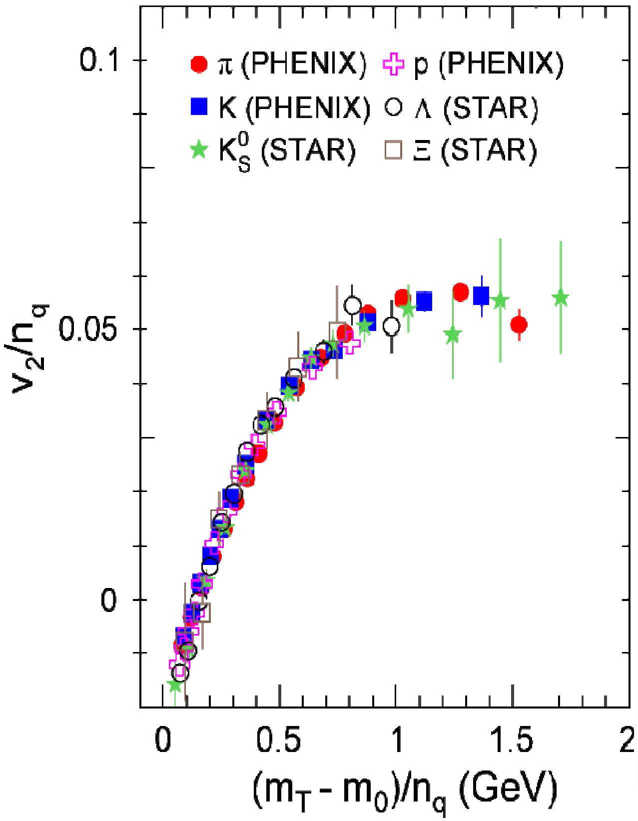
$$\frac{v_{4,B}(3p_T)}{v_{2,B}^2(3p_T)} \approx a\left(\frac{1}{3} + \frac{1}{3}\times\frac{v_{4,q}(p_T)}{v_{2,q}^2(p_T)}\right) \qquad a \approx 1.8$$

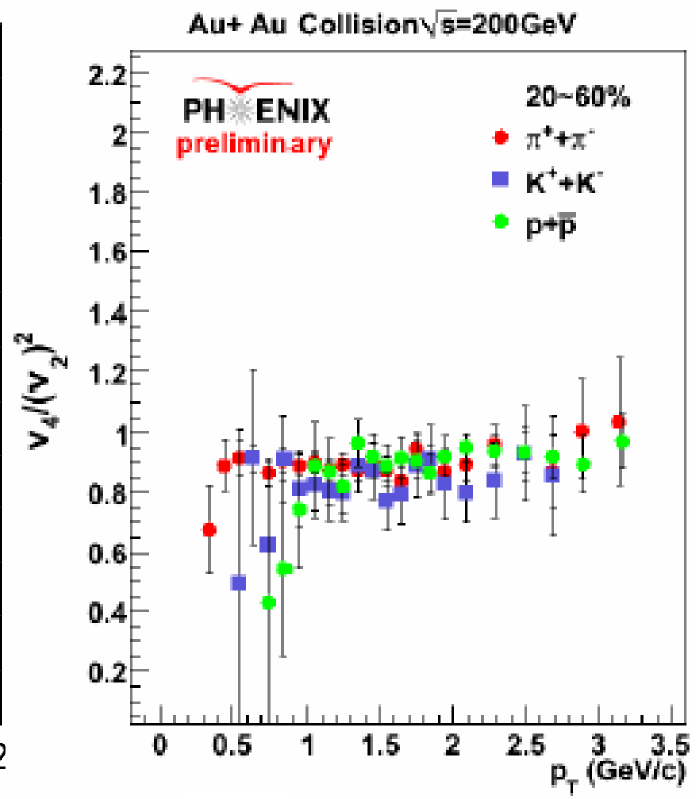
→ $v_4/v_2^2 \approx 0.9$

Flow at RHIC

- flow shows KE_T and quark number scaling at top RHIC energy → flow is dominantly pre-hadronic



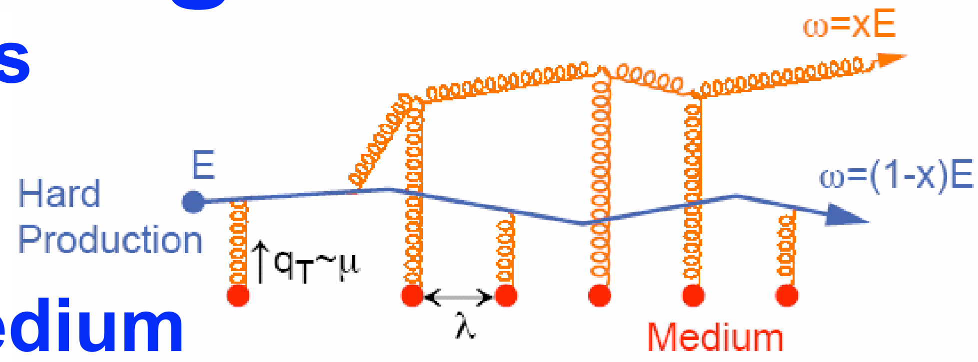




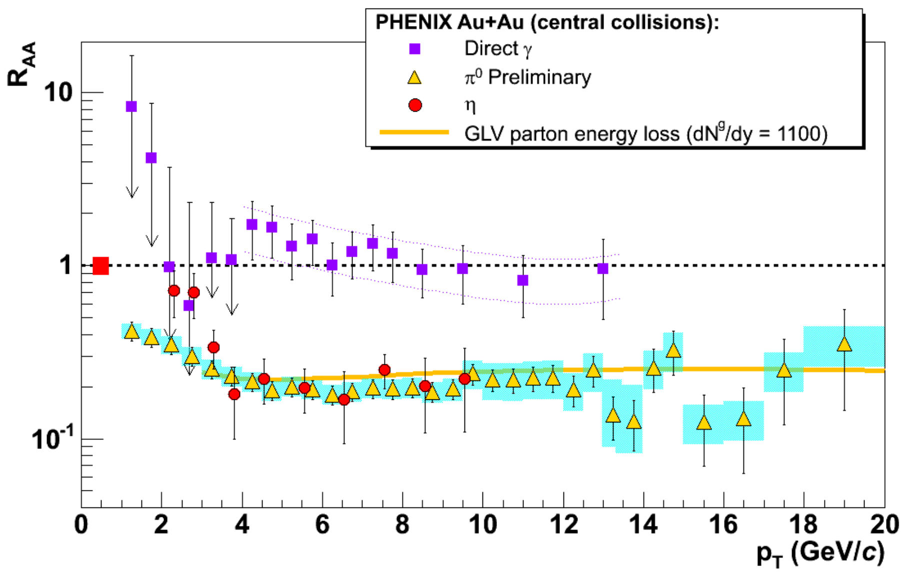
- at what collision energy does scaling set in?

Jet quenching at RHIC

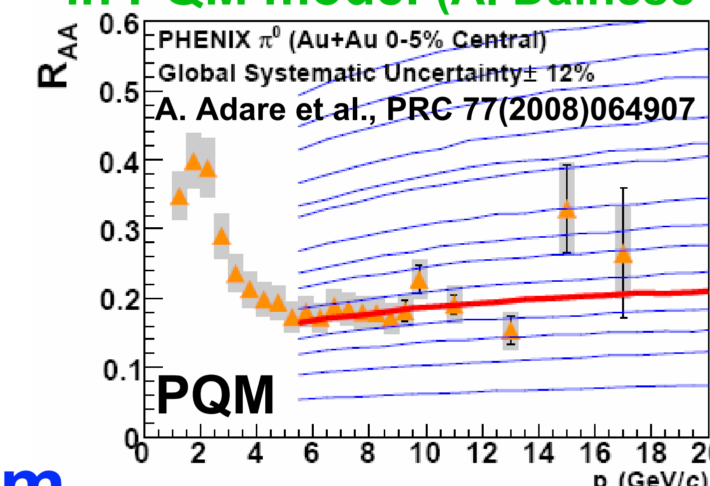
- energy loss of partons from hard scattering through re-scattering in the hot & dense medium



  - nuclear modification factor $R_{AA} << 1$ at high p_T



- access medium properties through statistical analysis
  - example: transport coefficient in PQM model (A. Dainese et al.)



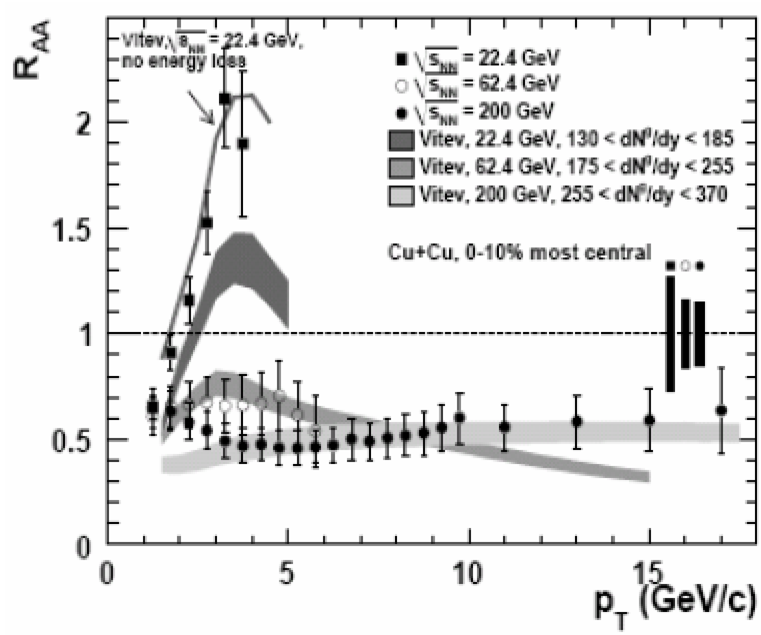
$\rightarrow \langle \hat{q} \rangle = 13.2^{+2.1}_{-3.2}\ \mathrm{GeV}^2/\mathrm{fm}$

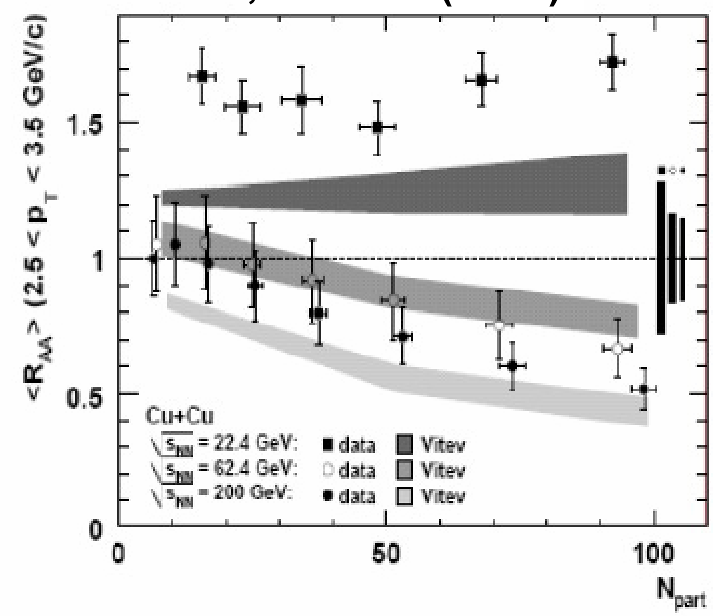
- huge opacity of the medium

Light quark opacity

- at what collision energy does the onset of light quark opacity occur?

A. Adare et al., PRL 101(2008)162301



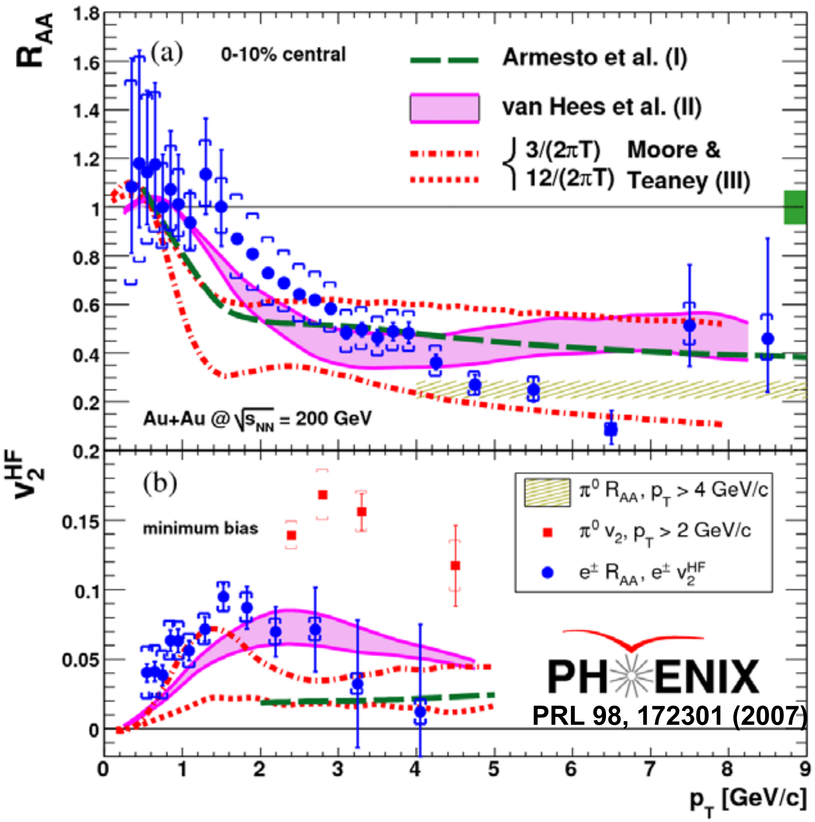


- PHENIX R_{AA} measurements in Cu+Cu collisions
  - onset for 22.4 GeV ≤ $\sqrt{s_{NN}}$ ≤ 62.4 GeV
- needs p+p and d+A samples in addition to A+A
- feasible only for SPS energies or higher

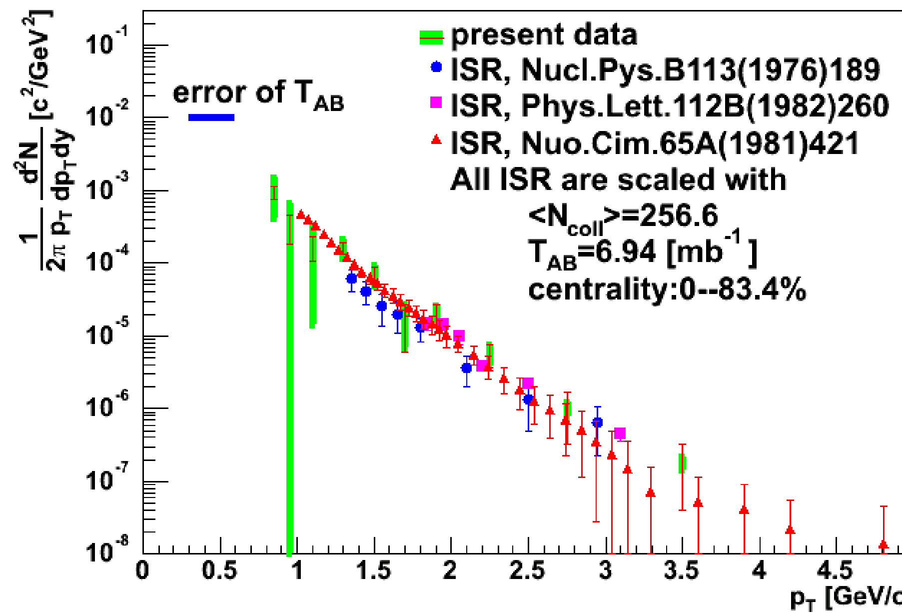
Heavy quark opacity

- where is the onset of heavy quark opacity?

R_{AA} for Au+Au @ $\sqrt{s_{NN}}$ = 200 GeV



R_{AA} for Au+Au @ $\sqrt{s_{NN}}$ = 62.4 GeV

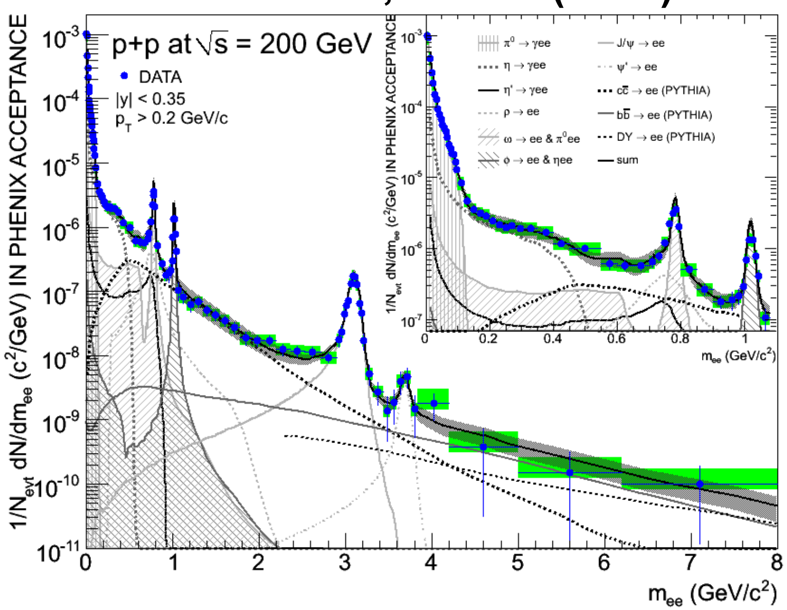


- R_{AA} consistent with unity
  - poor statistics
  - p+p reference missing
- interesting energies for heavy quark observables are above SPS energies, not below

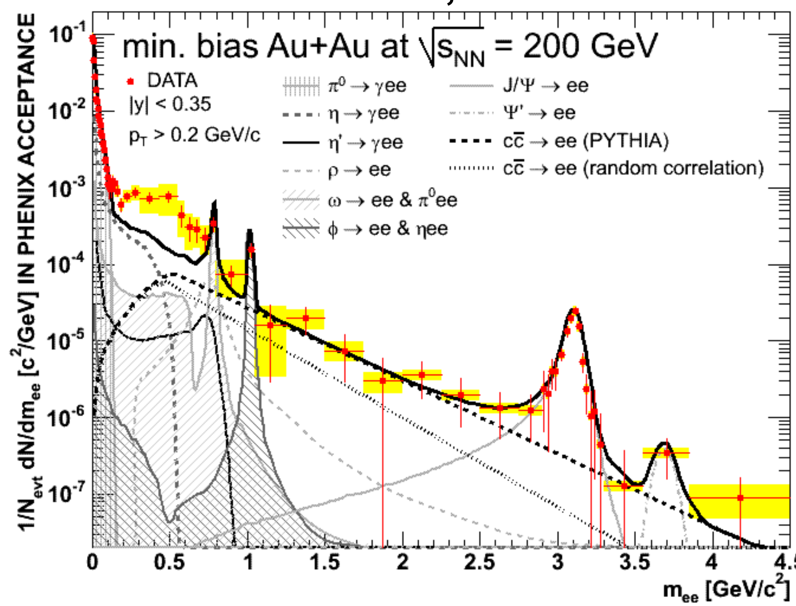
Low-mass dileptons at RHIC

- dielectrons from PHENIX in p+p and Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV

A. Adare et al., PLB 76(2009)313



S. Afanasiev et al., arXiv:0706.3034

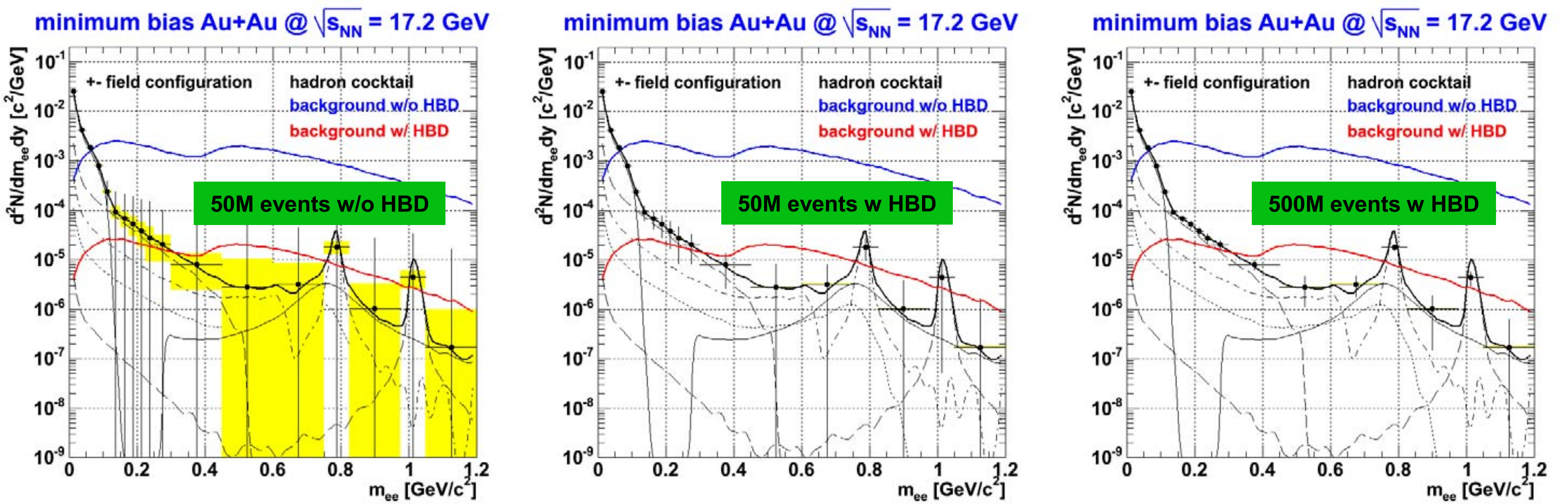


- agreement with expected e^+e^- sources in p+p
- enhancement observed in Au+Au collisions

→ can PHENIX measure e^+e^- in an energy scan?

e^+e^- at low RHIC energies

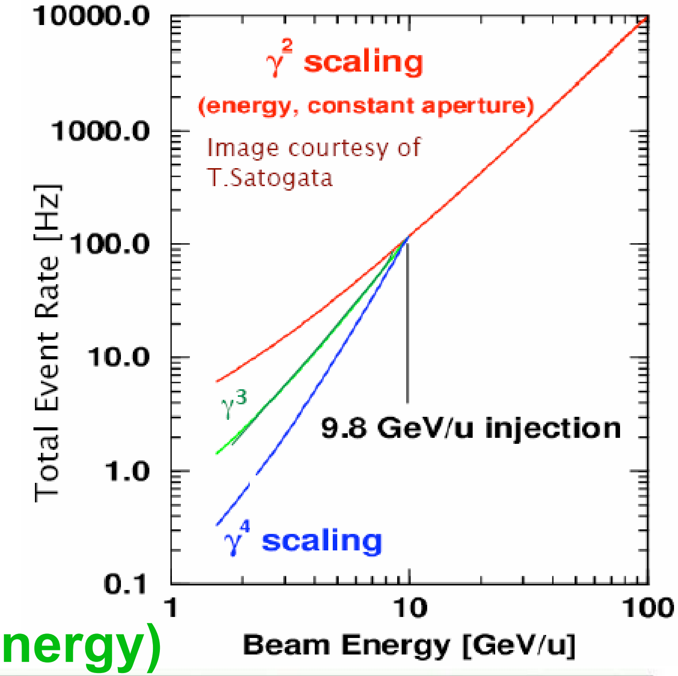
- dielectron cocktail calculation for Au+Au at $\sqrt{s}$ = 17.2 GeV
  - assumptions
    - meson yields and phase space distributions as measured at SPS
    - no low-mass enhancement or any other medium effects
  - key ingredients
    - electron ID beyond PHENIX baseline is a must
      - → Hadron Blind Detector (HBD)
    - increased luminosity (electron cooling) could have a huge impact

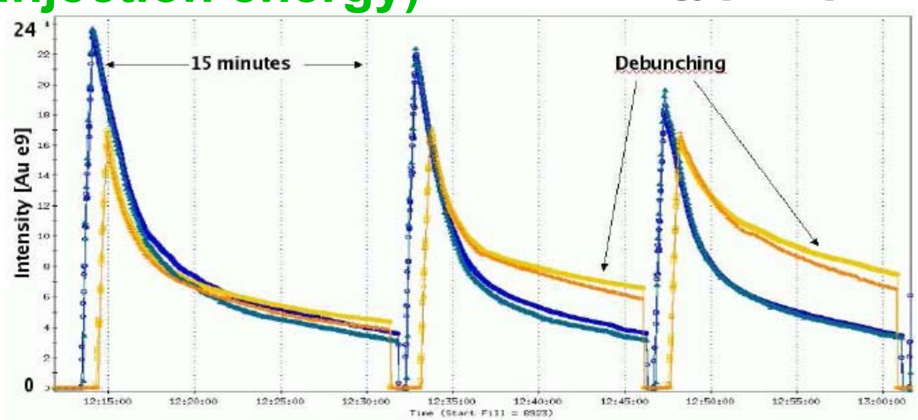


- e^+e^- measurements are possible with "CERES quality" (or better) at low RHIC energies!

RHIC boundary conditions

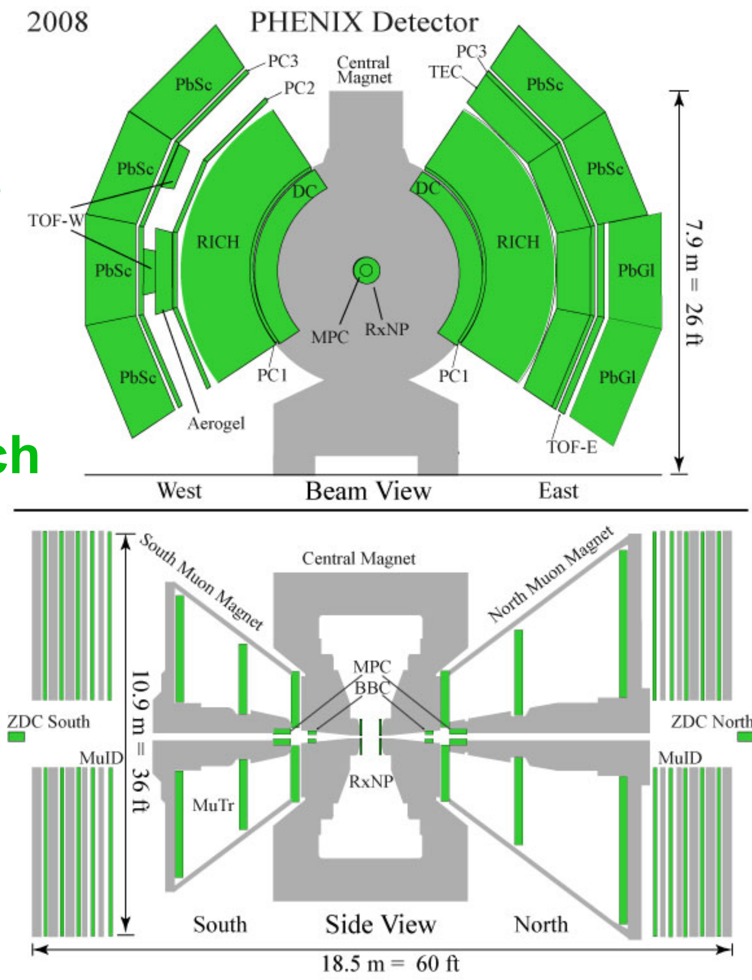
- life becomes difficult towards low energies
- key issues
  - luminosity
    - limited by intra-beam scattering
    - below injection: γ^3 scaling
    - decent event rates above injection
    - difficult below injection energy
    - → improvement: electron cooling
  - lifetime
    - only few minutes (below injection energy)
    - "continuous" injection?
    - → improvement: electron cooling
  - large "diamond" length
    - spread of collision vertices along beam axis
    - → improvement: electron cooling





PHENIX boundary conditions

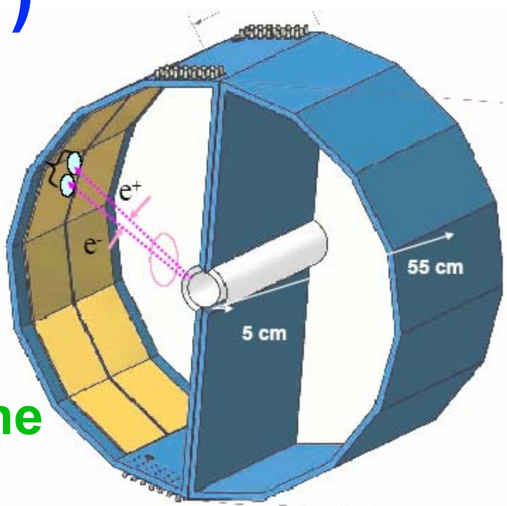
- limitation and strength
  - geometrical acceptance ↔ rare probe capabilities
- perspectives for energy scan
  - above injection energy
    - very strong program to determine
      - onset of sQGP signatures
      - quantitative sQGP properties
  - below injection energy
    - contribution to critical point search
- crucial issues for energy scan
  - event rate
  - collision trigger
  - reaction plane measurement
  - electron identification

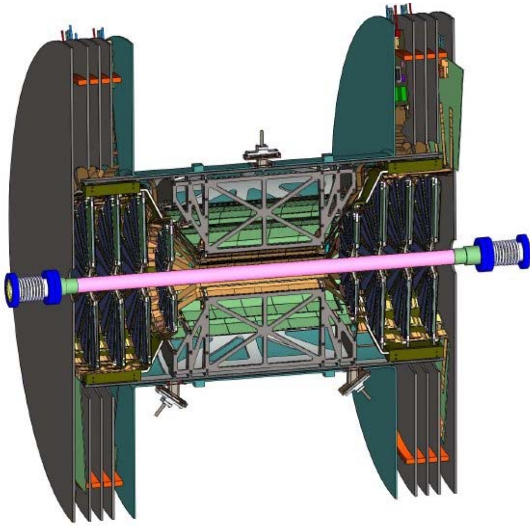


Relevant PHENIX upgrades

- trigger and reaction plane measurement
  - reaction plane detector
    - already implemented
    - compatible with future upgrades

- electron identification
  - Hadron Blind Detector (HBD)
    - commissioning in 2009 p+p run
    - Au+Au run at top energy: 2010
- the future (2010/2011)
  - replace HBD with a barrel silicon vertex spectrometer (later: additional endcaps)
    - secondary vertices
    - trigger & reaction plane
    - limited electron ID





Summary & outlook

- PHENIX topics in a RHIC energy scan
  - above injection energy
    - strong program to
      - investigate onset of sQGP signatures
        - » hydrodynamic flow and scaling properties of flow parameters
        - » light/heavy quark opacity
        - » low-mass dielectron enhancement
        - » initial temperature
        - » (HBT & three/multi-particle correlations)
      - search for the QCD critical point
  - below injection energy
    - contribution to a search for the QCD critical point
    - no rare probe physics program unless
      - drastic improvement in RHIC performance
        - » luminosity
        - » lifetime
        - » length of collision diamond

  → electron cooling could make a huge difference!