Limits on the Viscosity to Entropy Ratio from PHENIX Data on Single Electron Production

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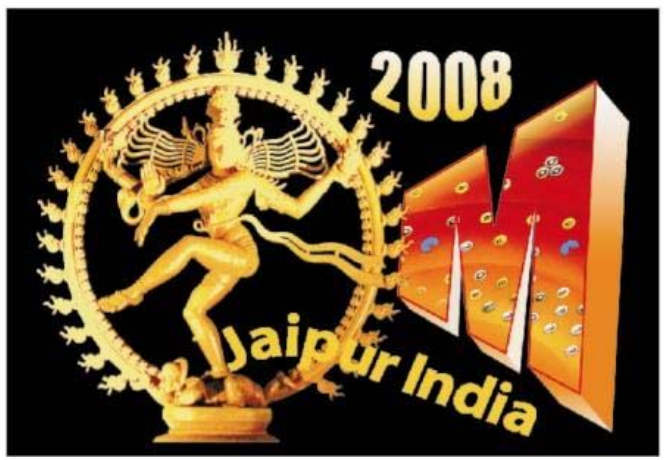
for the PHENIX Collaboration

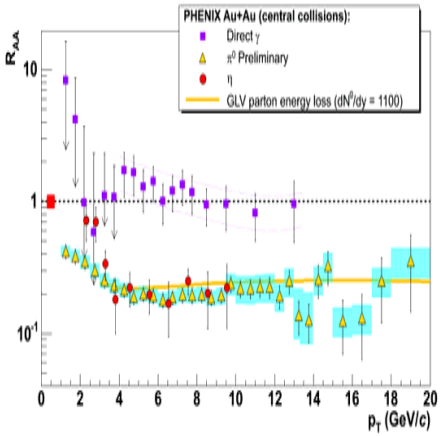
Quark Matter 2008

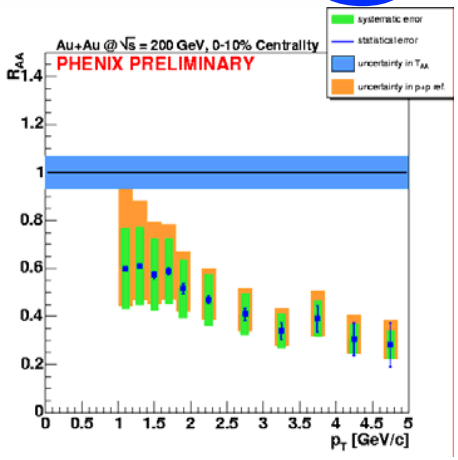


Jaipur, India, February 3-10, 2008

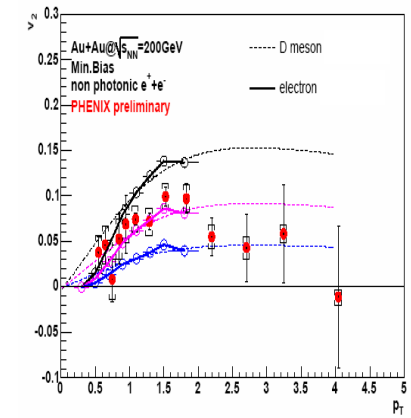
Introduction: sQGP @ RHIC

- **QM 2005**
  - **strongly inter-acting Quark-Gluon Plasma (sQGP) in HI collisions at RHIC**

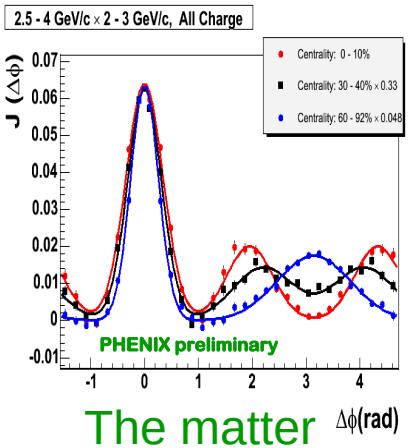




The matter is dense

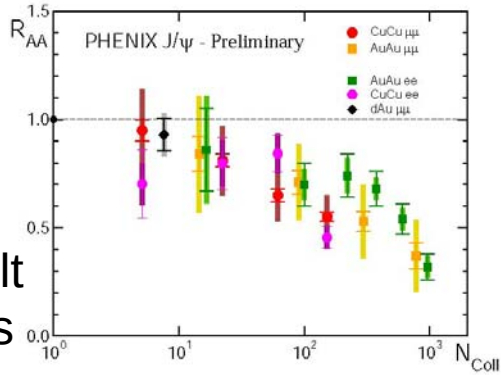


The matter is strongly coupled

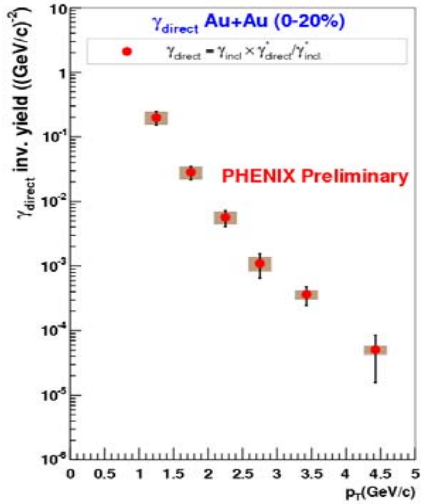


The matter modifies jets

- **recent hot topic: quantify sQGP properties**
- **next steps viscosity/entropy η/s**



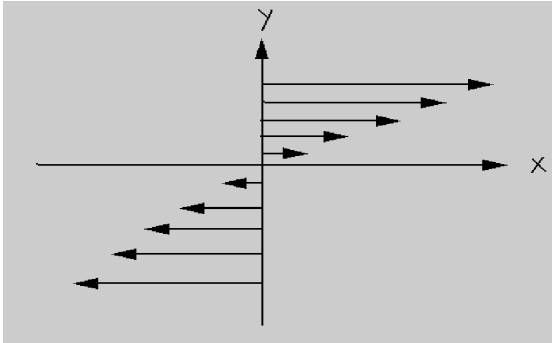
The matter may melt but regenerate J/ψ's



The matter is hot

Viscosity Primer

- viscous fluid
  - supports a shear stress
  - viscosity η defined as $\frac{F_x}{A} = -\eta \frac{\partial v_x}{\partial y}$
  - dimensional estimate



$$\eta \approx (momentum \quad density) \times (mean \quad free \quad path)$$

$$\approx n\ \overline{p}\ mfp = n\ \overline{p} \frac{1}{n\sigma} = \frac{\overline{p}}{\sigma}$$

large cross sections ↔ small viscosity

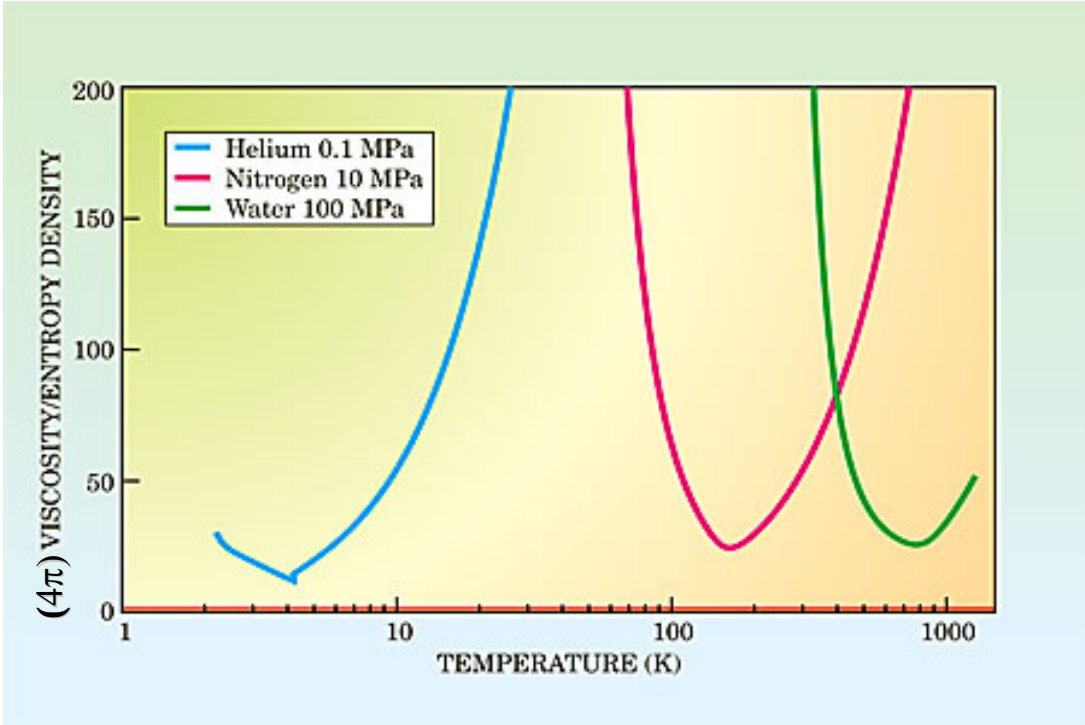
- but how small is "small"?

Viscosity of a "Near Perfect" Fluid

- early hydrodynamic calculations of the medium at RHIC have assumed zero viscosity: $\eta = 0$, i.e. a "perfect fluid"
- conjectured lower quantum limit
  - derived first in (P. Kovtun, D.T. Son, A.O. Starinets, Phys.Rev.Lett.94:111601, 2005)
  - motivated by AdS/CFT (Anti de Sitter space / Conformal Field Theory) correspondence (J. Maldacena: Adv. Theor. Math. Phys. 2, 231, 1998)

$$\frac{\eta}{s} \geq \frac{\hbar}{4\pi}$$

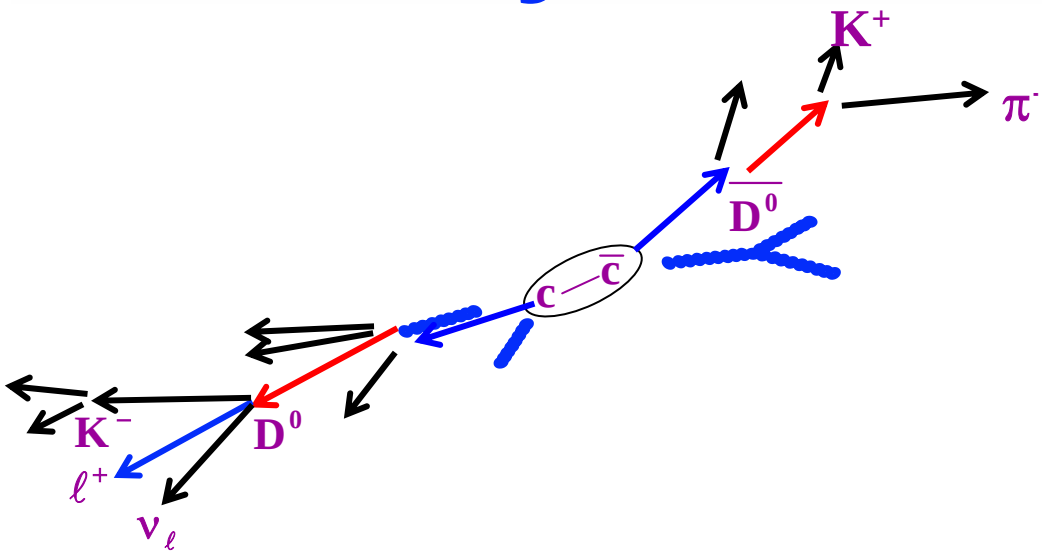
- "ordinary" fluids
  - water (at normal conditions)
    - $\eta/s \sim 380\ \hbar/4\pi$
  - helium (at λ point)
    - $\eta/s \sim 9\ \hbar/4\pi$
- "RHIC fluid"?



Measuring η/s

- need observables that are sensitive to shear stress
- damping (flow, fluctuations, heavy quark motion) ~ η/s
- flow
  - R. Lacey et al.: Phys. Rev. Lett. 98:092301, 2007
    - "Has the QCD critical point been signaled by observations at RHIC?"
  - H.-J. Drescher et al.: Phys. Rev. C76:024905, 2007
    - "The Centrality Dependence of Elliptic Flow, the Hydrodynamic Limit, and the Viscosity of Hot QCD"
- fluctuations
  - S. Gavin and M. Abdel-Aziz: Phys. Rev. Lett. 97:162302, 2006
    - "Measuring Shear Viscosity Using Transverse Momentum Correlations in Relativistic Nuclear Collisions"
- heavy quark motion (drag, flow)
  - A. Adare et al. (PHENIX Collaboration): Phys. Rev. Lett. 98:092301, 2007
    - "Energy Loss and Flow of Heavy Quarks in Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV"

Heavy-Flavor in PHENIX

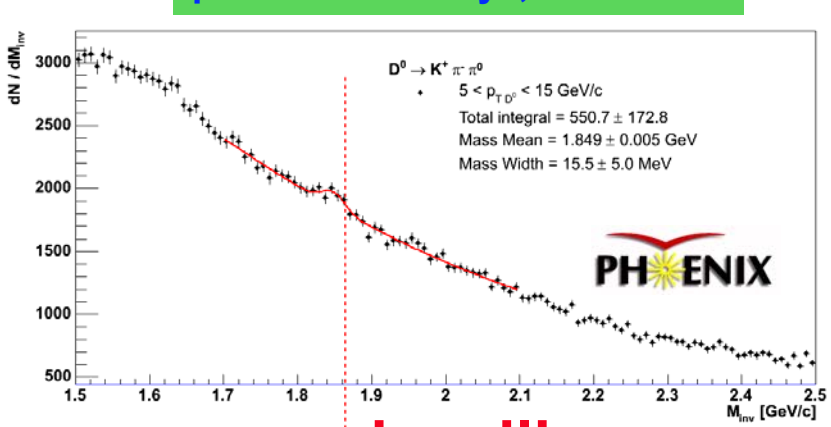


Meson	$D^{\pm}$ (D^0)
Mass	1.87 (1.87) GeV
BR D^0 --> $K\pi$	(3.85 ± 0.10) %
BR D --> e +X	17.2 (6.7) %
BR D --> μ +X	17.2 (6.6) %

- **current measurements**
  - **indirect via semileptonic heavy-flavor decays**
    - $e^{\pm}$: 6 PRL, 1 PRC papers
      - talk: Y. Morino
    - $\mu^{\pm}$: 1 PRC paper
      - talk: D. Hornback
    - e^+e^-: 1 PRL, 1 PLB submission
      - talk: A. Toia

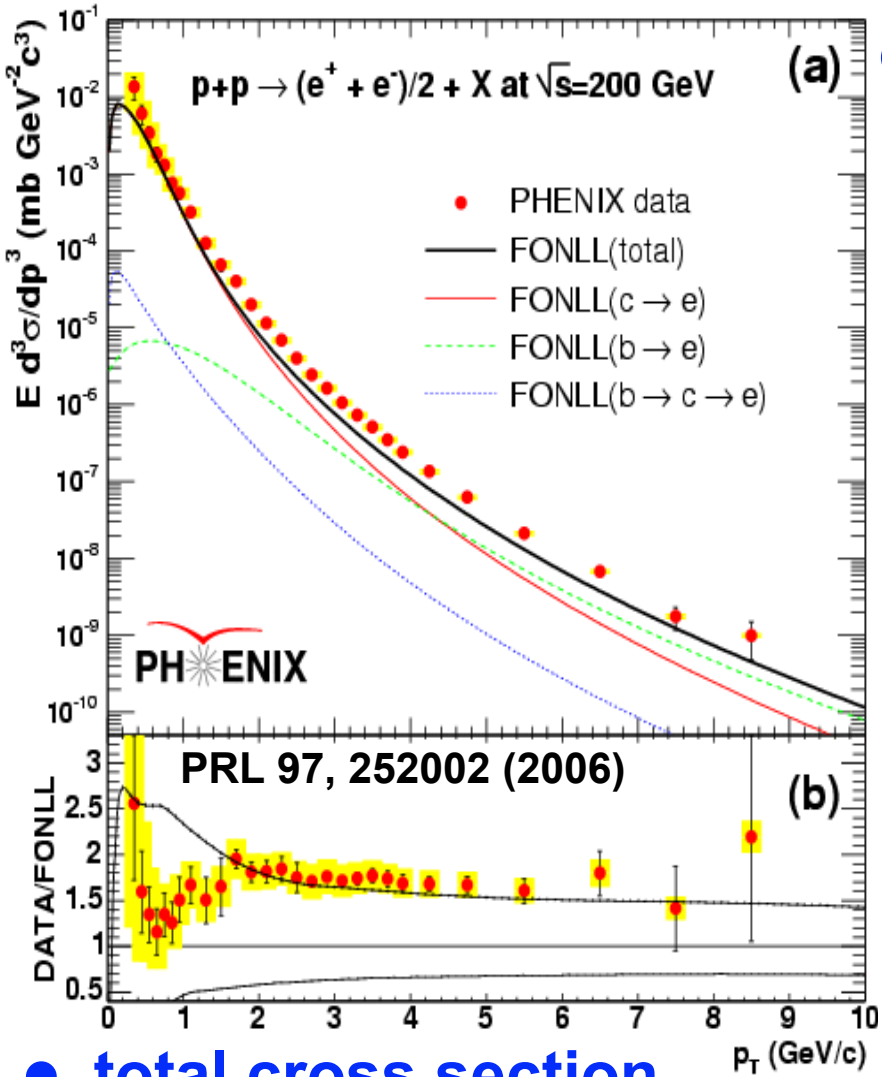
- **near future**
  - **reconstruction of hadronic decays**

posters: S. Butsyk, P. Shukla

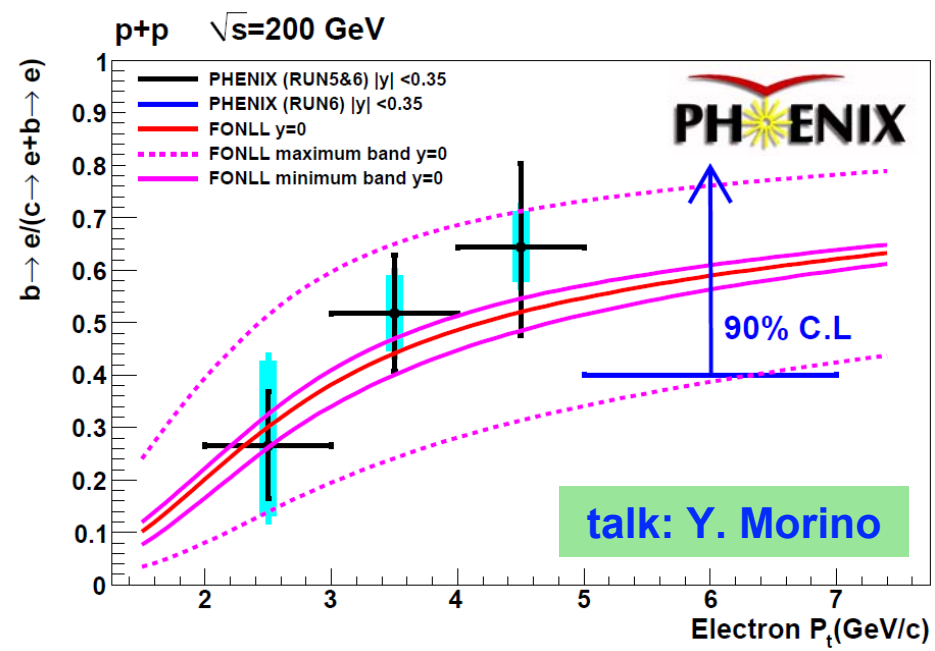


  - **upgrade: silicon vertex spectrometer**
    - talk: H. van Hecke

Baseline: p+p at √s = 200 GeV



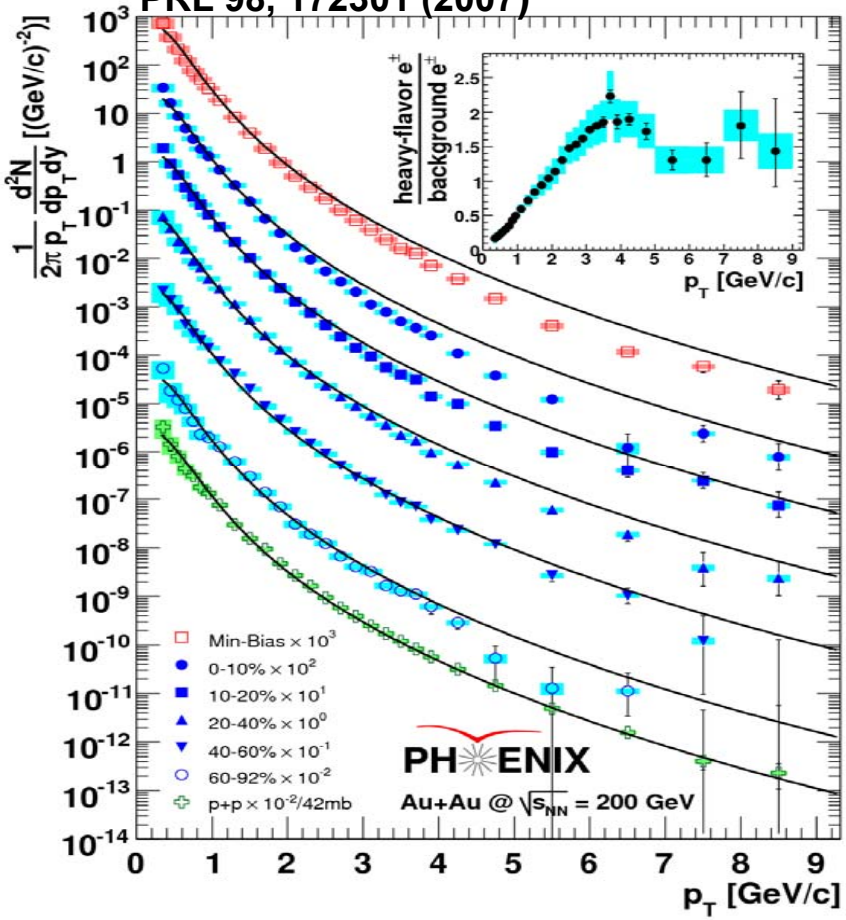
- heavy-flavor $e^{\pm}$ data
  - consistent with FONLL calculation: Fixed Order Next-to-Leading Log perturbative QCD
    (M. Cacciari, P. Nason, R. Vogt PRL95,122001 (2005))



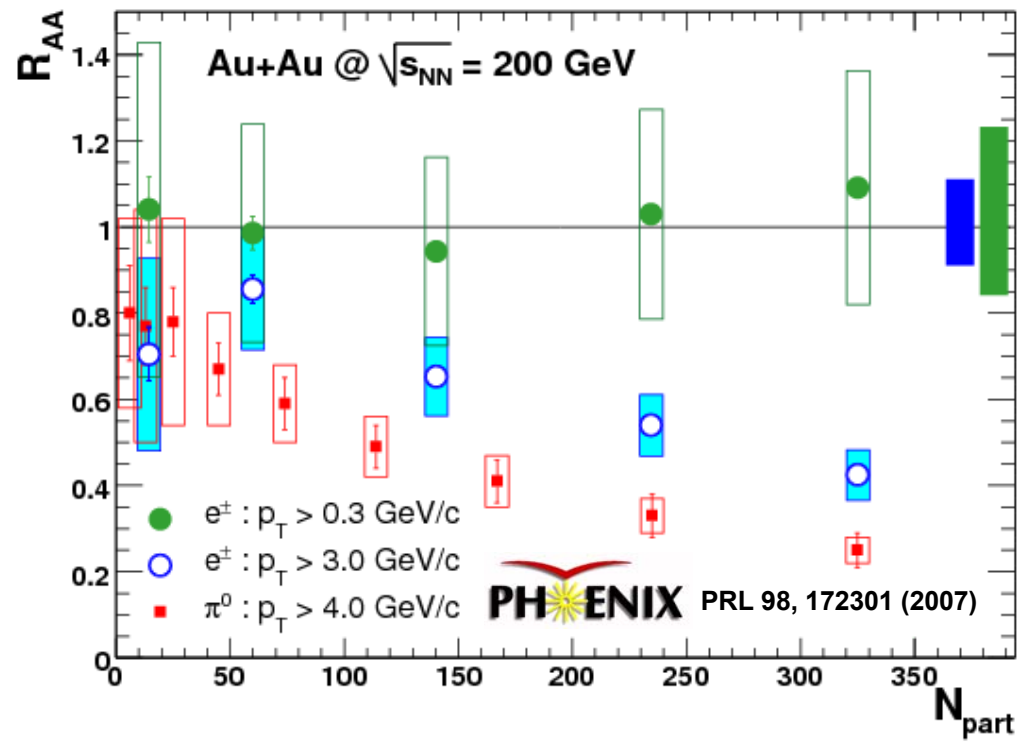
- total cross section
  - σ_{cc}= 567±57(stat)±224(sys) μb

Au+Au at $\sqrt{s_{NN}}$=200 GeV: Spectra

PRL 98, 172301 (2007)



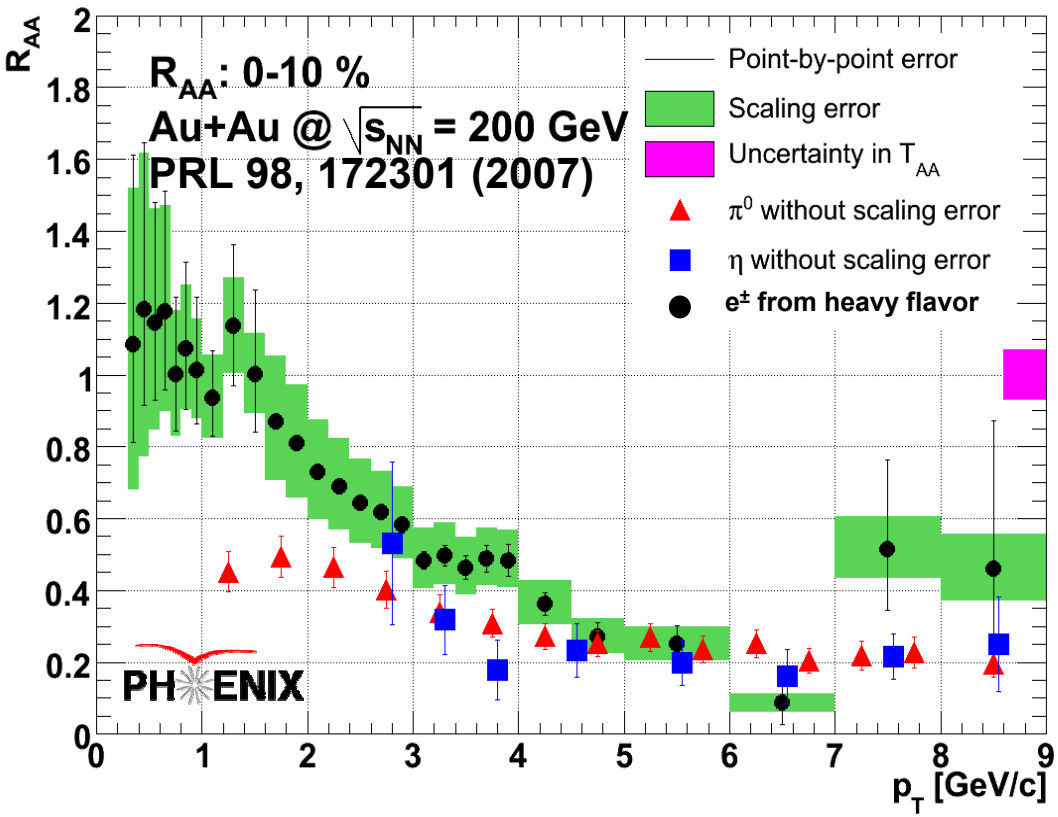
$$R_{AA} = \frac{Yield\ in\ Au+Au}{N_{binary} \times Yield\ in\ p+p}$$



- binary scaling of total e$^{\pm}$ yield from heavy-flavor decays
  - expected from heavy-quark production via hard scattering
- high p_T e$^{\pm}$ suppression increasing with centrality
  - footprint of medium effects

Nuclear Modification Factor R_{AA}

- R_{AA} $e^{\pm}$ from heavy-flavor decays

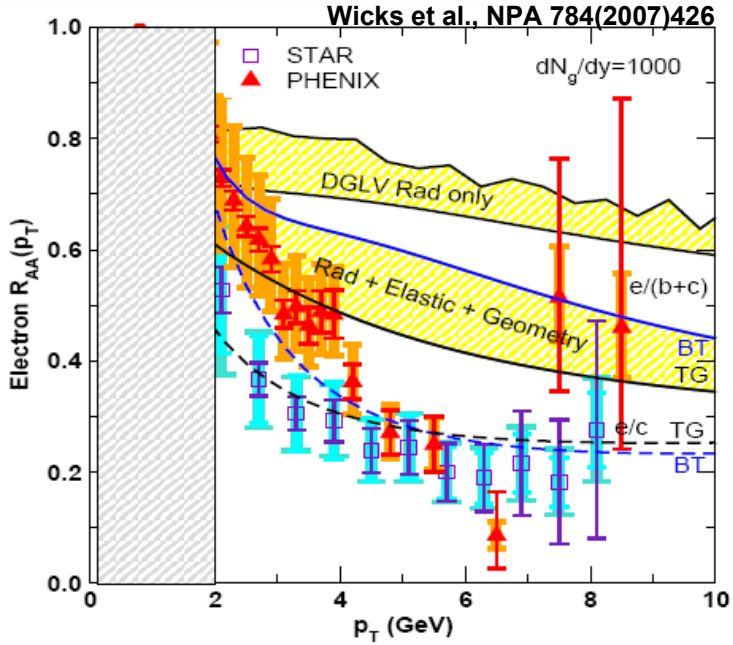


- very similar to light hadron R_{AA}
  - careful:
    - decay kinematics!
    - $p_T(e^{\pm}) < p_T(D)$
  - intermediate p_T
    - indication for quark mass hierarchy as expected for radiative energy loss (Dokshitzer and Kharzeev, PLB 519(2001)199)
  - highest p_T
    - $R_{AA}(e^{\pm}) \sim R_{AA}(\pi^0) \sim R_{AA}(\eta)$

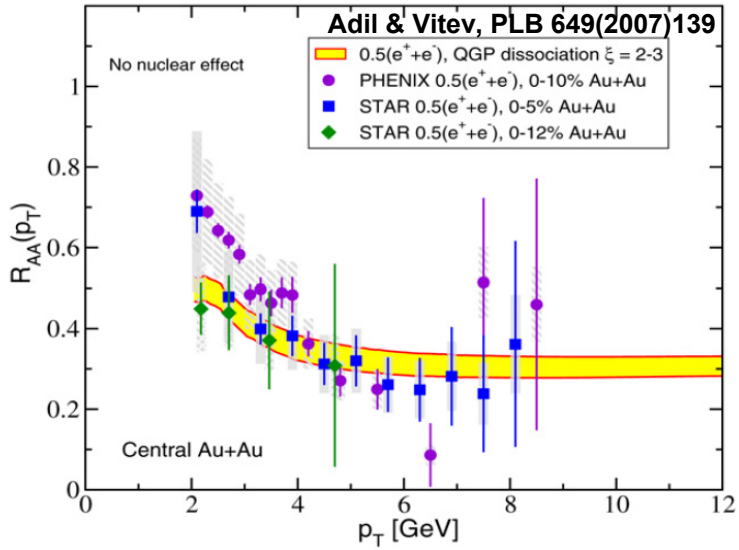
- crucial to understand: what is the bottom contribution?
- ideal: R_{AA} of identified charm and bottom hadrons

$e^{\pm}$ R_{AA}: a Challenge for Models

- testing ground for various parton energy loss (ΔE) models
  - radiative ΔE only
    - Djordjevic et al., PLB 632(2006)81
    - Armesto et al., PLB 637(2006)362)
  - collisional ΔE included
    - Wicks et al., NPA 784(2007)426
    - van Hees & Rapp, PRC 73(2006)034913)

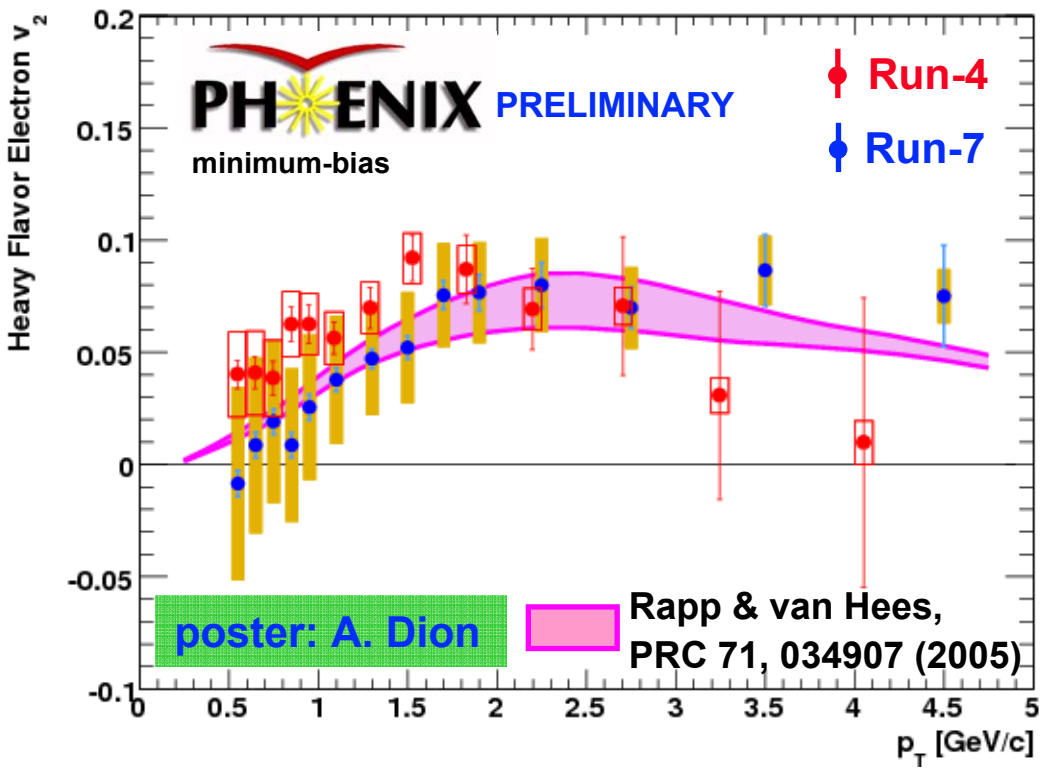


- or alternative approaches to interpret the suppression
  - collisional dissociation of heavy mesons (charm and bottom!)
    - Adil & Vitev, PLB 649(2007)139
  - contribution from baryon enhancement
    - Sorensen & Dong, PRC 74(2006)024902



Au+Au at $\sqrt{s_{NN}}$ = 200 GeV: Flow

- elliptic flow of $e^{\pm}$ from heavy-flavor decays
  - non-zero v_2 (RHIC Run-4)

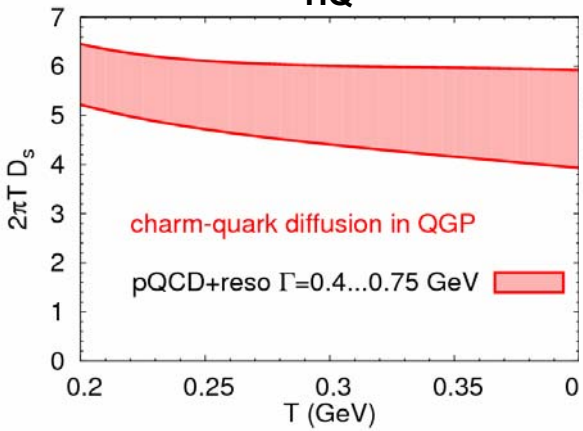


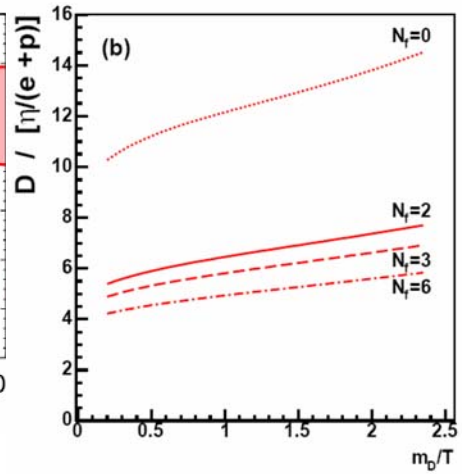
- progress in Run-7
  - improved reaction plane resolution
  - (increased statistics)
- data are consistent within uncertainties
- indication for non-zero v_2 at high p_T (charm vs. bottom)
- also available: v_2 vs. centrality

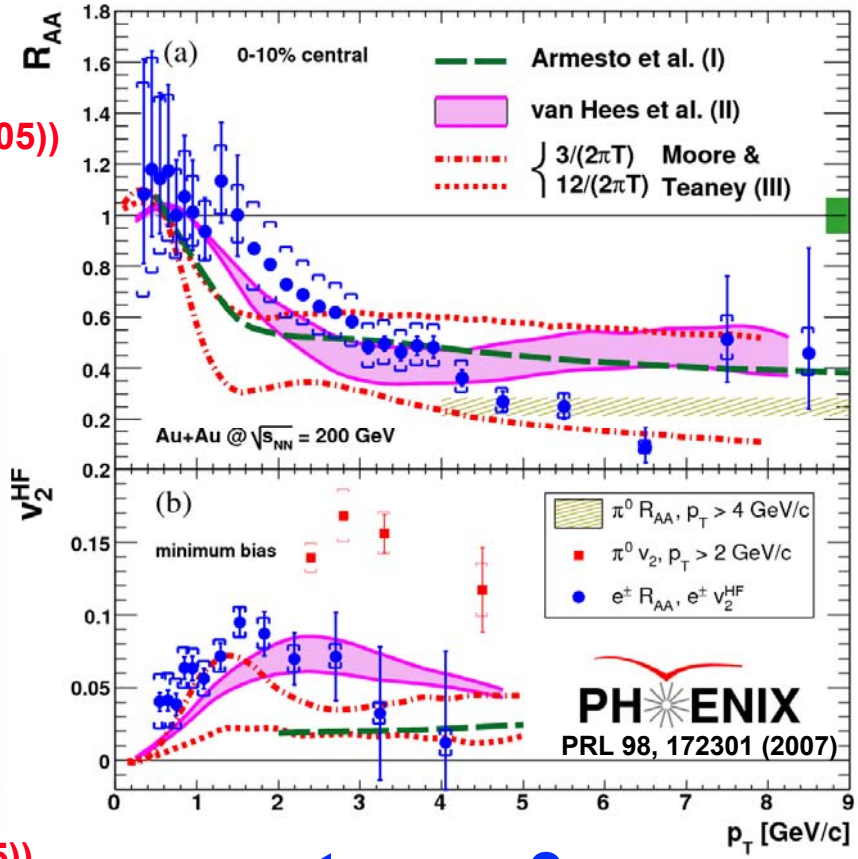
- good agreement with Langevin based transport calculation including resonant elastic scattering

Estimating η/s

- **transport models**
  - **Rapp & van Hees** (PRC 71, 034907 (2005))
    - diffusion coefficient required for simultaneous fit of R_{AA} and v_2
      - $D_{HQ} \times 2\pi T \sim 4\text{-}6$





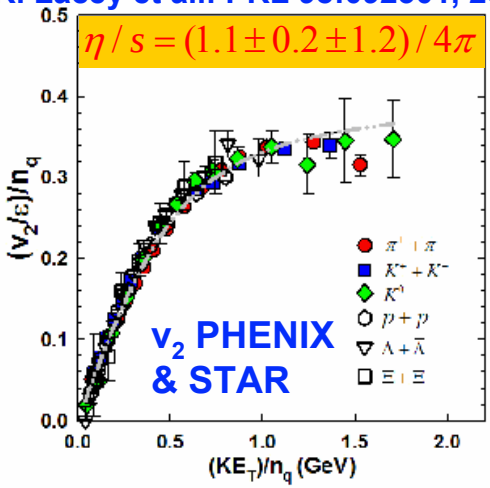


  - **Moore & Teaney** (PRC 71, 064904 (2005))
    - difficulties to describe R_{AA} and v_2 simultaneously
    - calculate perturbatively (and argue that plausible also non-perturbatively)
      - $D_{HQ} / (\eta/(\varepsilon+P)) \sim 6$ (for $N_f = 3$)

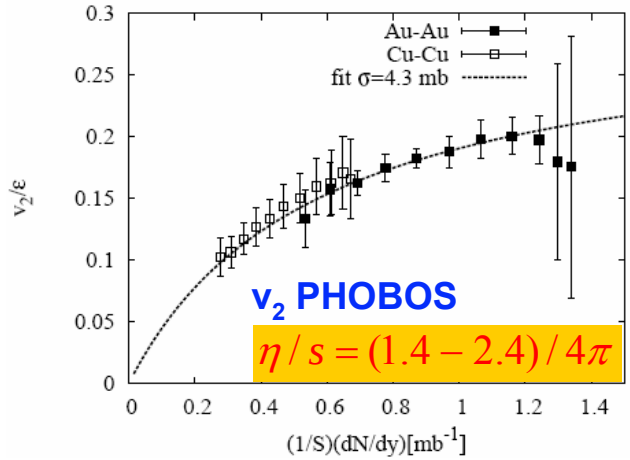
- **at $\mu_B = 0$**
  - $\varepsilon + P = Ts$
- **then**
  - $\eta/s = (1.3\text{-}2.0)/4\pi$

Comparison with other estimates

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

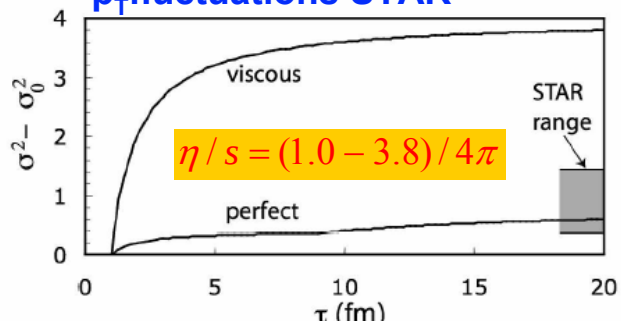


H.-J. Drescher et al.: arXiv:0704.3553

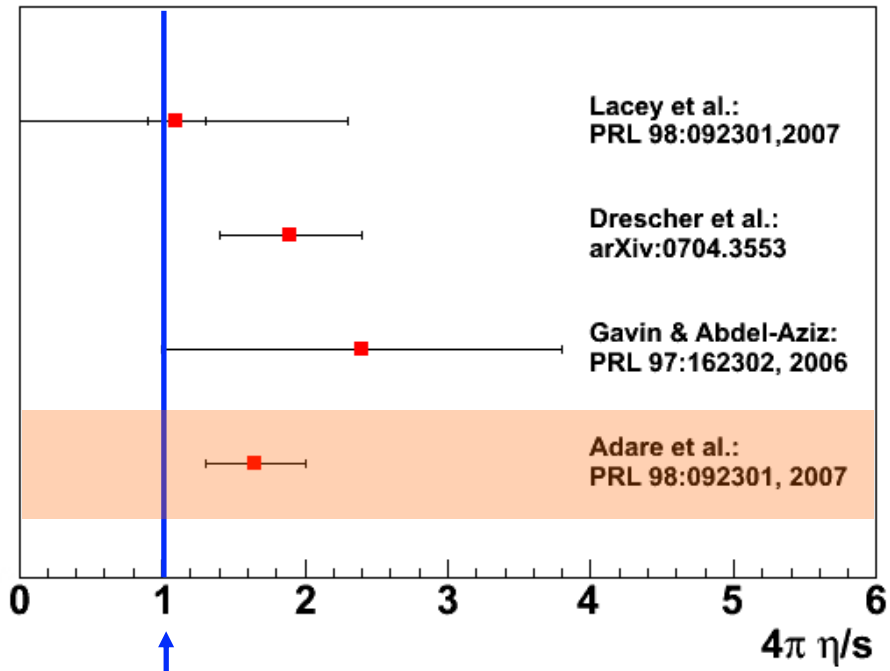


S. Gavin and M. Abdel-Aziz: PRL 97:162302, 2006

p_T fluctuations STAR



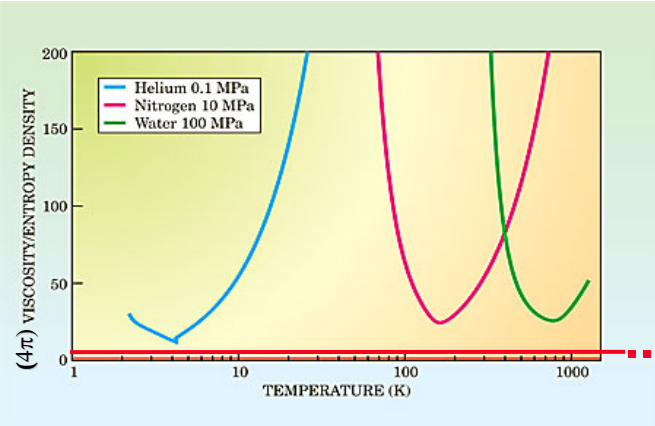
- estimates of η/s based on flow and fluctuation data
  - indicate small value as well
  - close to conjectured limit
  - significantly below η/s of helium (4πη/s ~ 9)



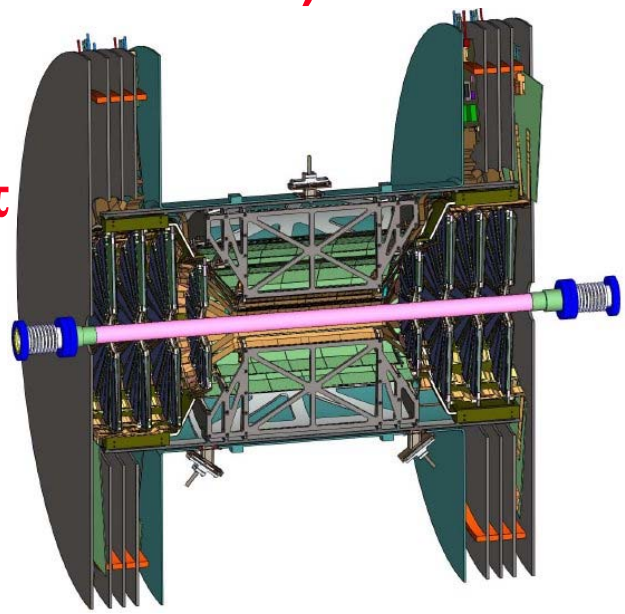
conjectured quantum limit

Summary

- ongoing quantitative studies of sQGP properties
  - heavy-flavor production is a crucial probe
- consistent η/s estimates from single electron production, flow, and fluctuation data
- "near perfect" fluid at RHIC, with η/s



- ~4 times smaller than η/s of helium (but at T ~ 10^{12} K)
- close to the conjectured limit $\eta/s = \hbar/4\pi$



- key for heavy-flavor physics in the future
  - silicon vertex tracking
  - full reconstruction of D/B mesons

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