Charm production at RHIC

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Charm 2007 Conference
Cornell University, Ithaca, NY
5 August 2007

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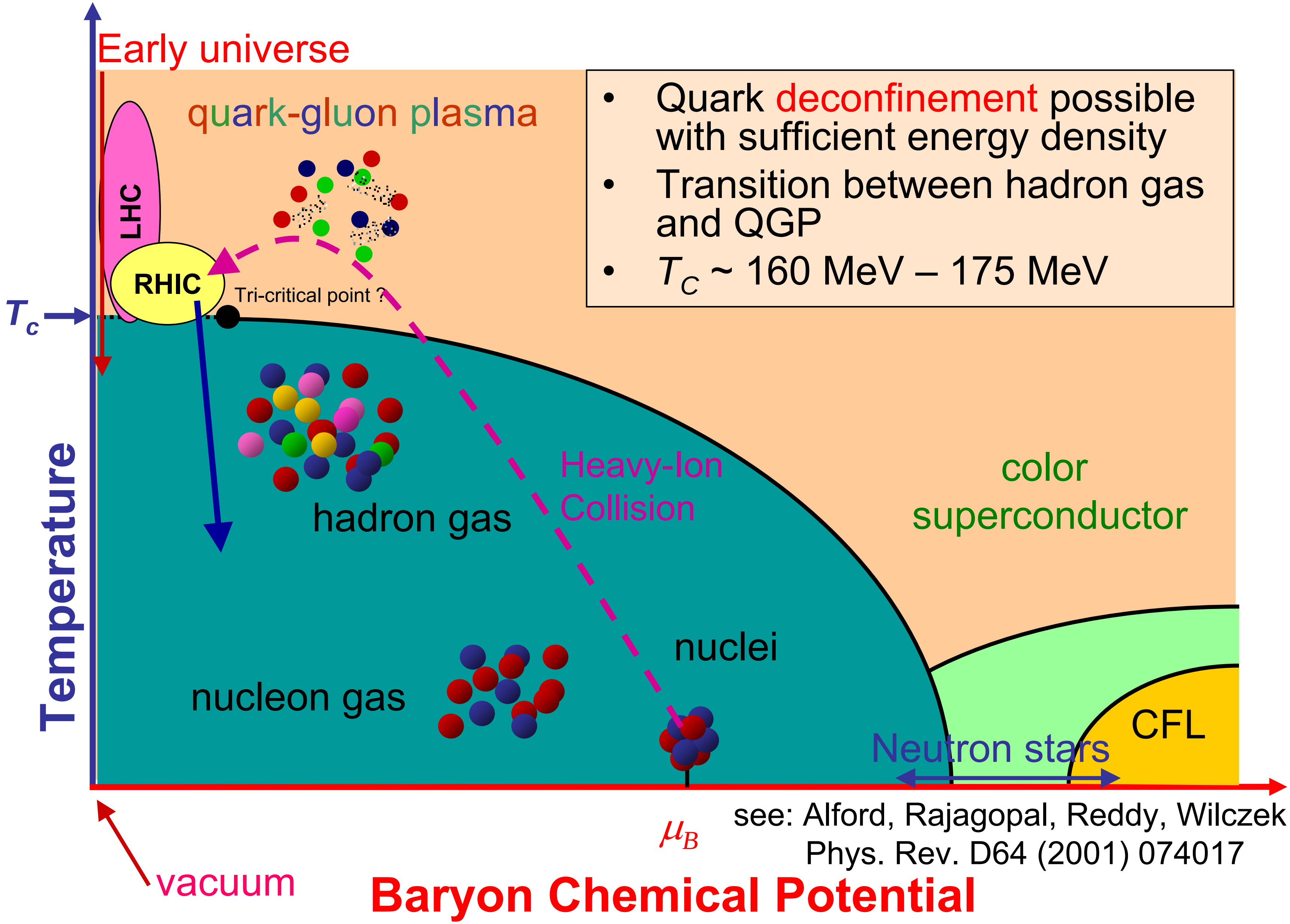
The Quark Gluon Plasma

- Quark deconfinement possible with sufficient energy density
- Transition between hadron gas and QGP
- T_C ~ 160 MeV – 175 MeV



see: Alford, Rajagopal, Reddy, Wilczek
Phys. Rev. D64 (2001) 074017

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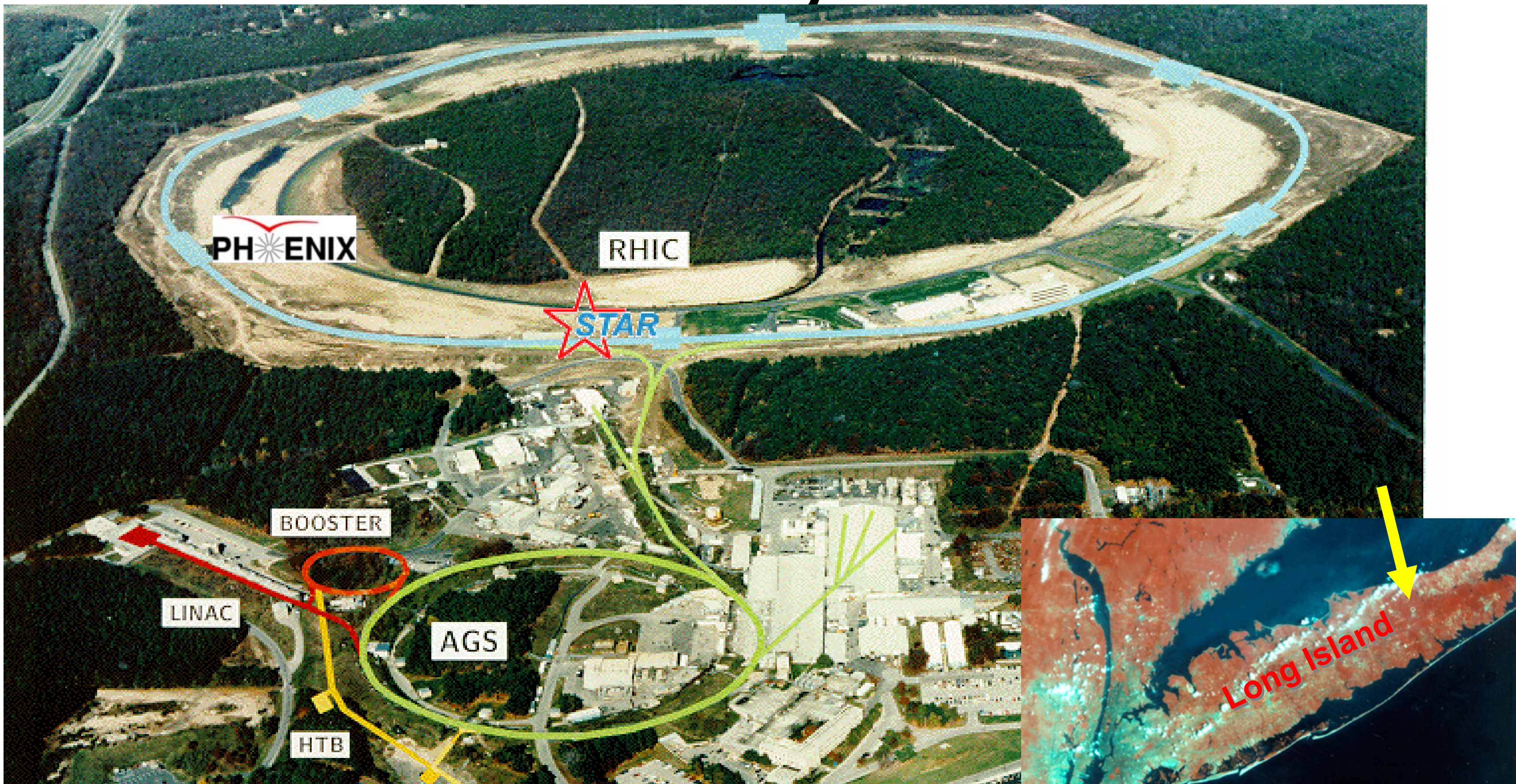
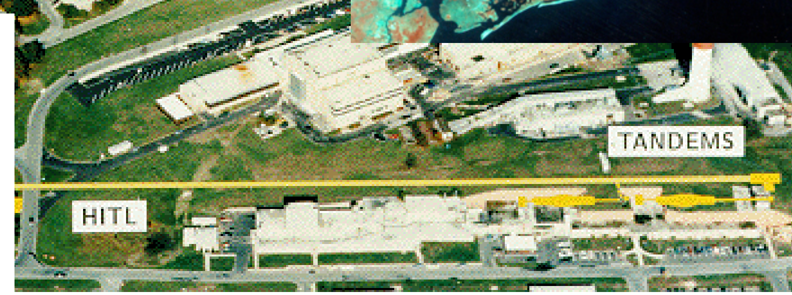
Relativistic Heavy Ion Collider





- 2 concentric rings
- 3.8 km circumference
- counter-circulating beams
- *p*, *p*↑: 5 GeV ≤ $\sqrt{s}$ ≤ 500 GeV
- *d*, Cu, Au: 5 GeV ≤ $\sqrt{s_{NN}}$ ≤ 200 GeV

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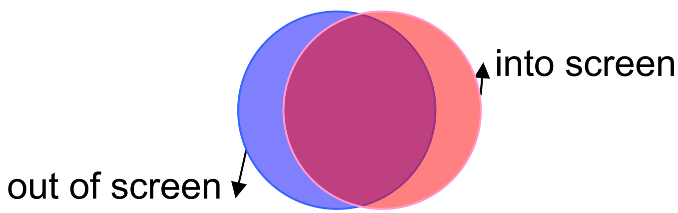
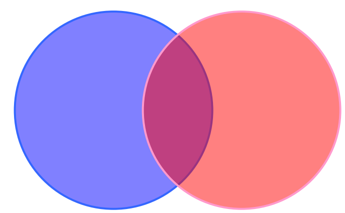
Collision Geometry

- Centrality: overlap between nuclei
  - N_{part}: number of participant nucleons
  - N_{bin}: number of binary collisions
    - $N_{bin} \geq N_{part}/2$
  - Measured through:
    - charged particle multiplicity (N_{ch})
    - number of spectator neutrons

(N_{part} and N_{bin} from Glauber model calculations)



"Central"
Small distance between centers of nuclei
N_{part}, N_{bin}, N_{ch} large



"Peripheral"
Large distance between centers of nuclei
N_{part}, N_{bin}, N_{ch} small

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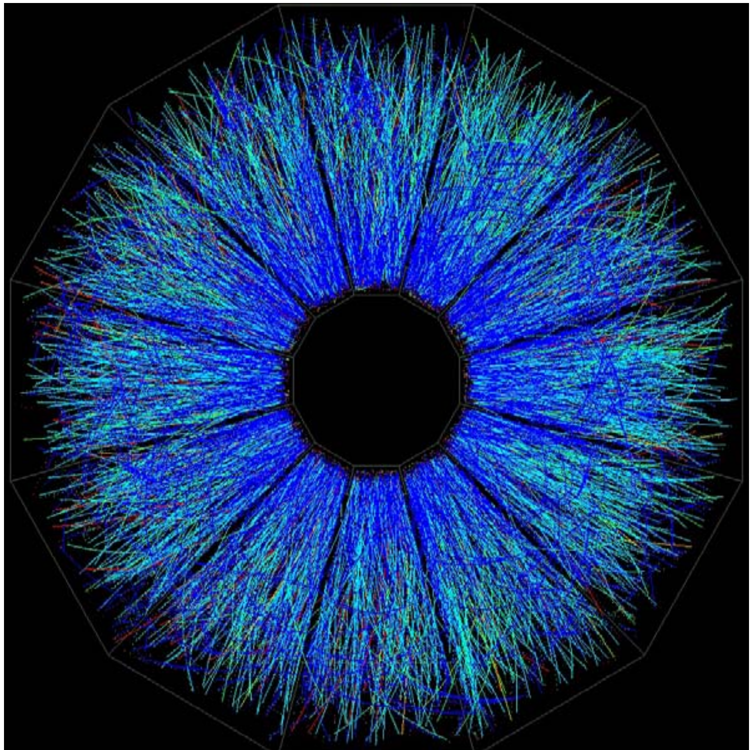
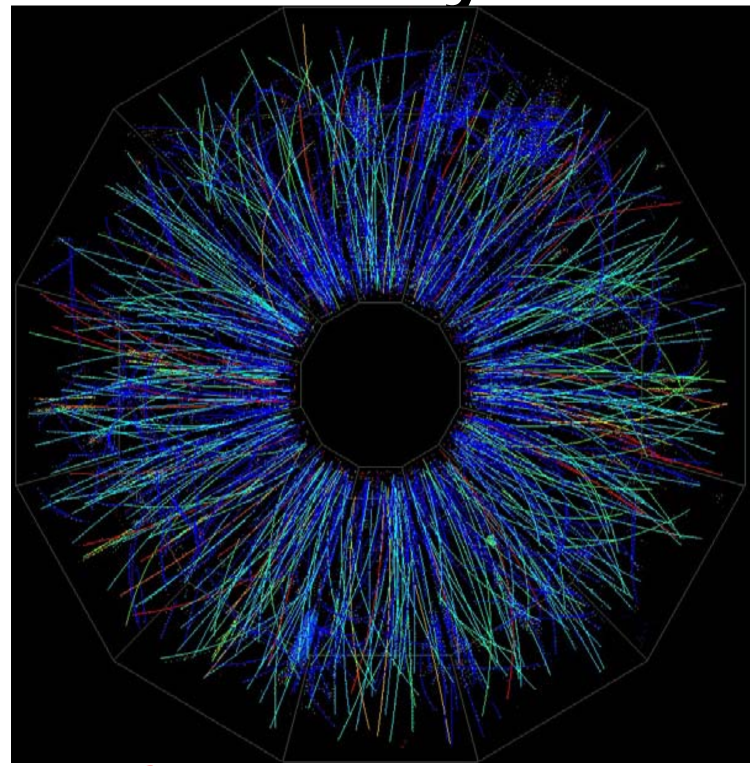
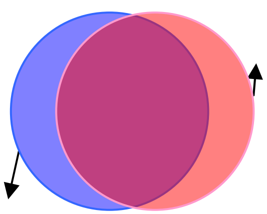
Collision Geometry





N_{ch} ~ 4000

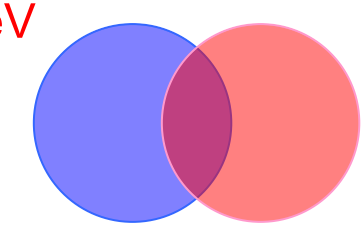
STAR: Au+Au 200 GeV



into screen

out of screen

"Central"
Small distance between centers of nuclei
N_{part}, N_{bin}, N_{ch} large



"Peripheral"
Large distance between centers of nuclei
N_{part}, N_{bin}, N_{ch} small

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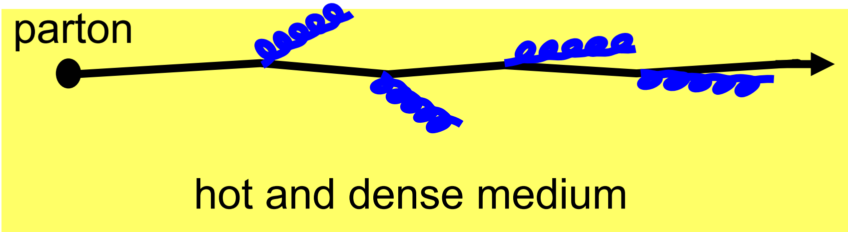
High-p_T Particle Suppression

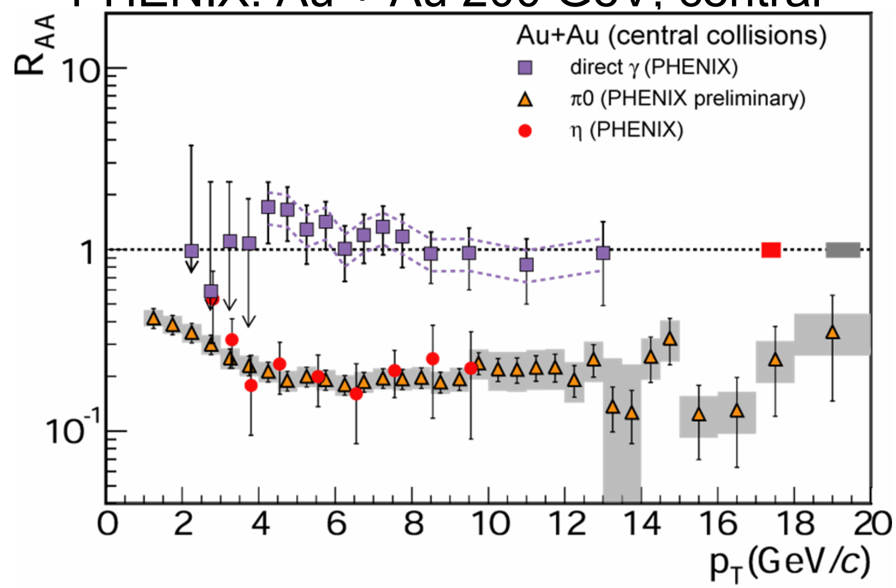
- Sensitive to medium properties
- Partons lose energy in medium
  - Gluon Radiation



  - High-p_T (> 2 GeV/c) particles suppressed
  - More suppression expected in central collisions
- Compare to p + p (no medium)
- Nuclear Modification Factor (R_{AA})
  - N_{bin}-scaled ratio of particle yields
  - No Medium Effect: R_{AA} = 1
    - (for p_T > 2 GeV/c)

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\cdot\langle N_{bin}\rangle}$$

PHENIX: Au + Au 200 GeV, central



- γ not suppressed
  - not strongly interacting
- Hadrons suppressed in central collisions
- Consistent with formation of QGP
- Other Tests: Jet Quenching, Elliptic Flow

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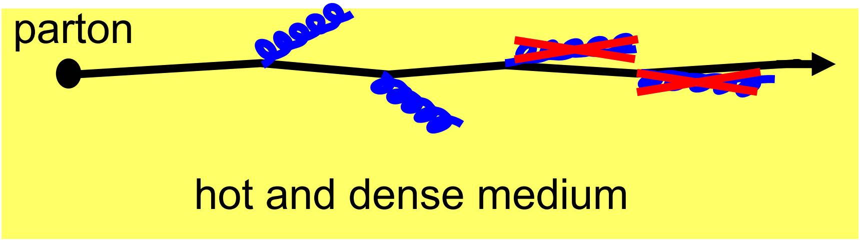
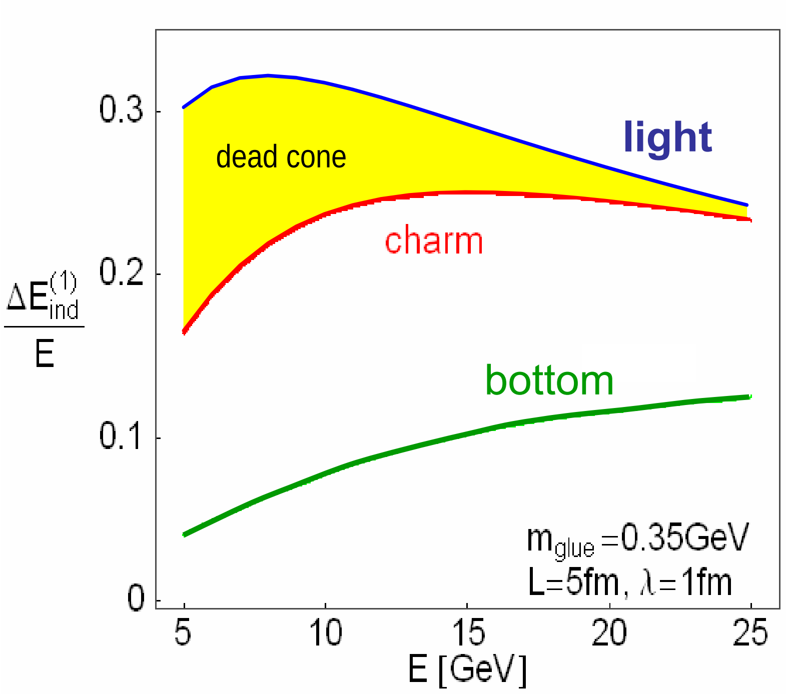
Heavy Flavor and the QGP

- Heavy quarks produced in initial hard scattering of partons
  - Dominant: *gg→QQ*
  - Production rates from pQCD
  - Sensitive to initial gluon distributions
- Heavy quark energy loss
  - Prediction: less than light quark energy loss (dead cone effect)



  - Sensitive to gluon densities in medium
- Quarkonium Suppression

ENERGY LOSS



M.Djordjevic PRL 94 (2004)

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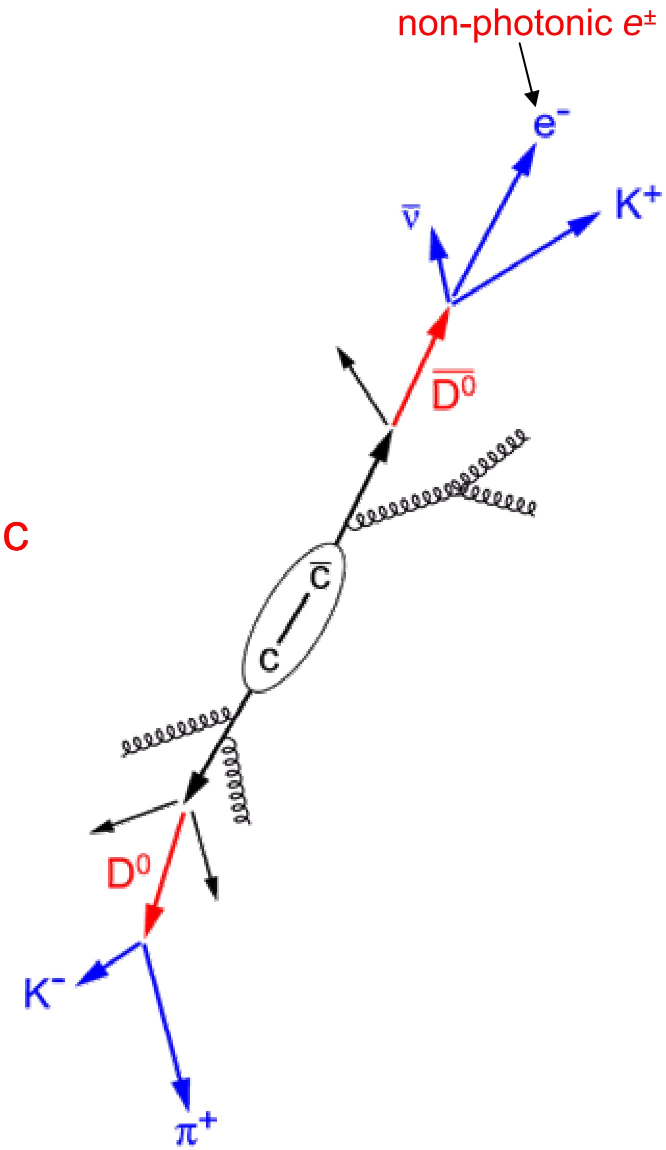
Measuring Heavy Flavor

- Study hadronic decays: $D^0 \rightarrow K\pi$, $D^* \rightarrow D^0\pi$, $D^{\pm} \rightarrow K\pi\pi$, $D_s^{\pm} \rightarrow \pi\phi$
- … and semileptonic decays:
  - $c \rightarrow \mu^+$ + anything (B.R.: ~7%)
  - $c \rightarrow e^+$ + anything (B.R.: 9.6%)
    - $D^0 \rightarrow e^+$ + anything (B.R.: 6.87%)
    - $D^{\pm} \rightarrow e^{\pm}$ + anything (B.R.: 17.2%)
  - $b \rightarrow e^+$ + anything (B.R.: 10.9%)
    - $B^{\pm}, B^0 \rightarrow e^{\pm}$ + anything (B.R.: 10.2%)
- Heavy flavor decays dominate non-photonic (single) $e^{\pm}$ spectrum; b decays dominate at high p_T
- Photonic $e^{\pm}$ background:
  - γ conversions ($\pi \rightarrow \gamma\gamma$, $\gamma \rightarrow e^+e^-$)
  - Dalitz decays of π^0, η, η'
  - ρ, ϕ, K_{e3} decays (small contributions)



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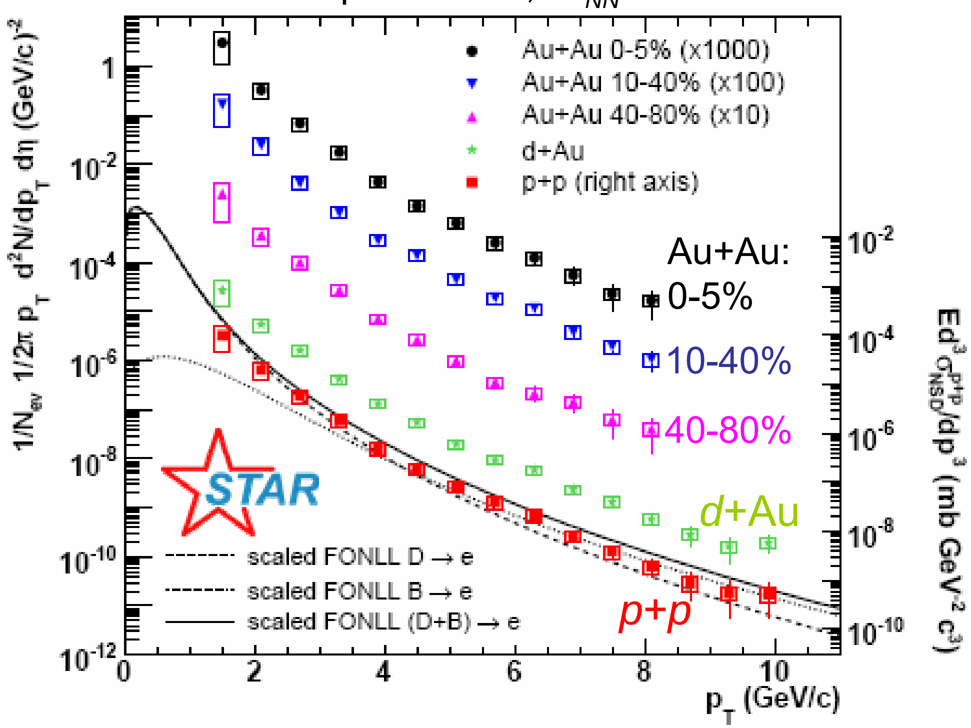
Non-photonic $e^{\pm}$

Remove Photonic $e^{\pm}$ Background

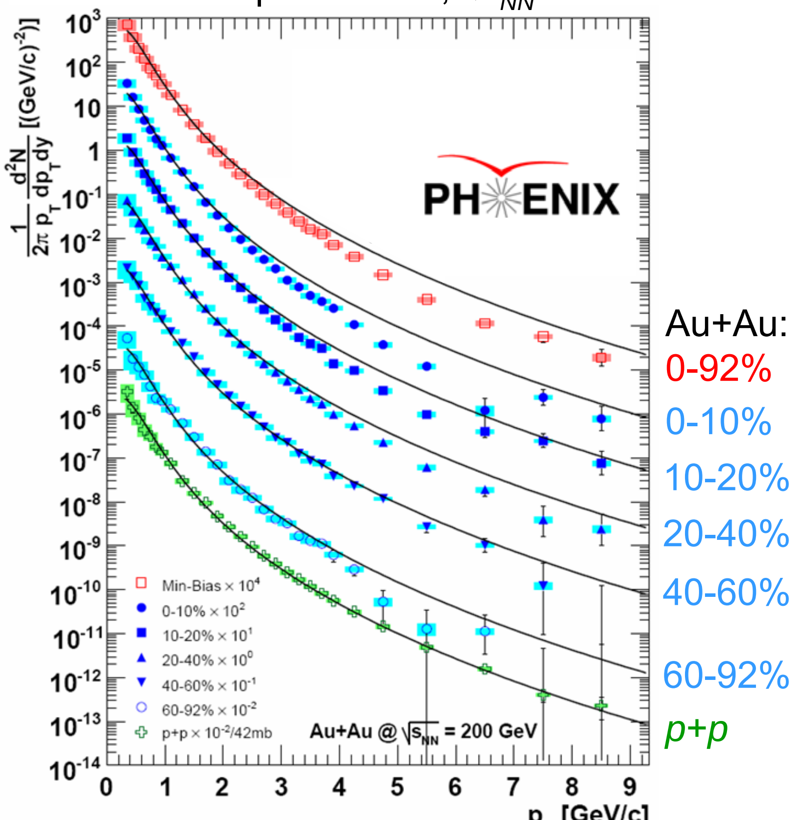
- Combine $e^{\pm}$ with oppositely charged tracks in same event; $e^{\pm}$ is background if M_{inv} < 150 MeV/c^2

STAR: Non-photonic $e^{\pm}$, $\sqrt{s_{NN}}$=200 GeV



- Simulate background $e^{\pm}$ from "cocktail" of measured sources (γ, π^0, η, etc.)
- Measure $e^{\pm}$ with converter, extrapolate to 0 background

PHENIX: Non-photonic $e^{\pm}$, $\sqrt{s_{NN}}$=200 GeV



STAR: B. I. Abelev *et al*, Phys. Rev. Lett. **98** (2007) 192301
PHENIX: A. Adare *et al*, Phys. Rev. Lett. **98**, 172301 (2007)

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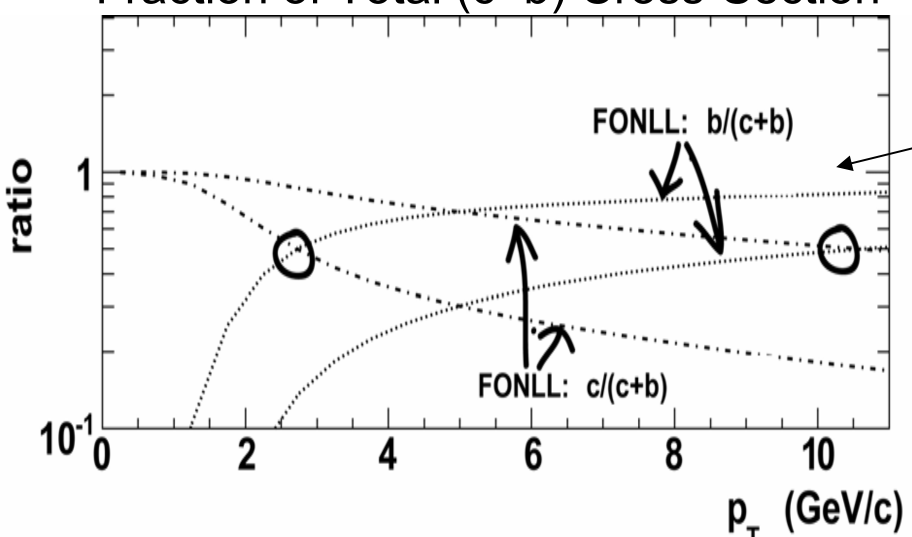
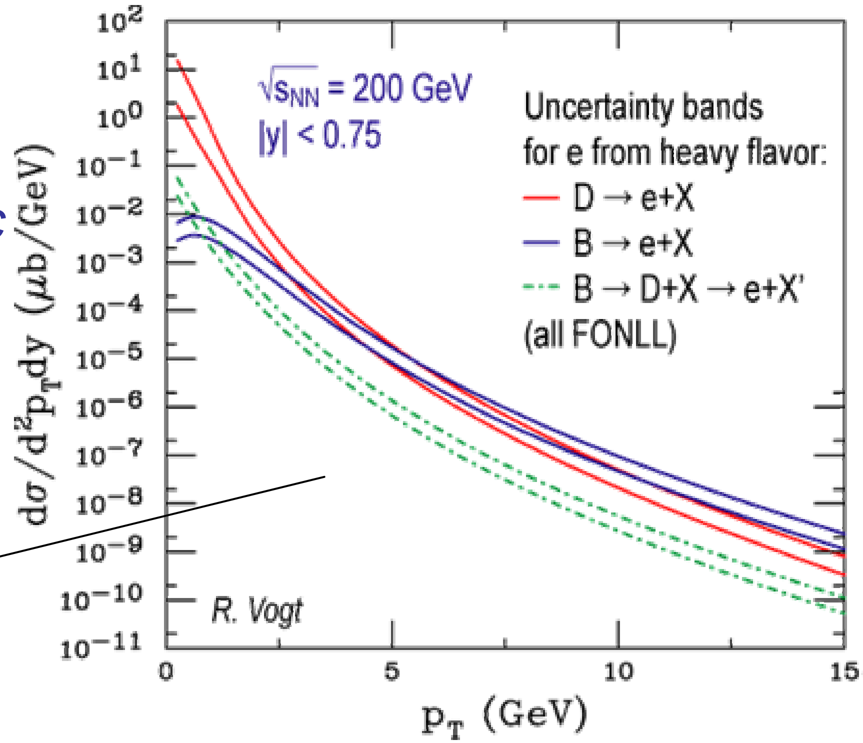
Perturbative Calculations

- Heavy quark production can be calculated perturbatively
- FONLL: Fixed-Order plus Next-Leading Log resummed
- At what p_T do b decays begin to dominate?
  - Within 3 GeV/c < p_T < 10 GeV/c
  - Most Likely Value: ~5 GeV/c

Fraction of Total (c+b) Cross-Section



FONLL: c and b decay contributions to non-photonic $e^{\pm}$ cross-section



Cacciari, Nason, and Vogt,
Phys. Rev. Lett. **95** (2005) 122001

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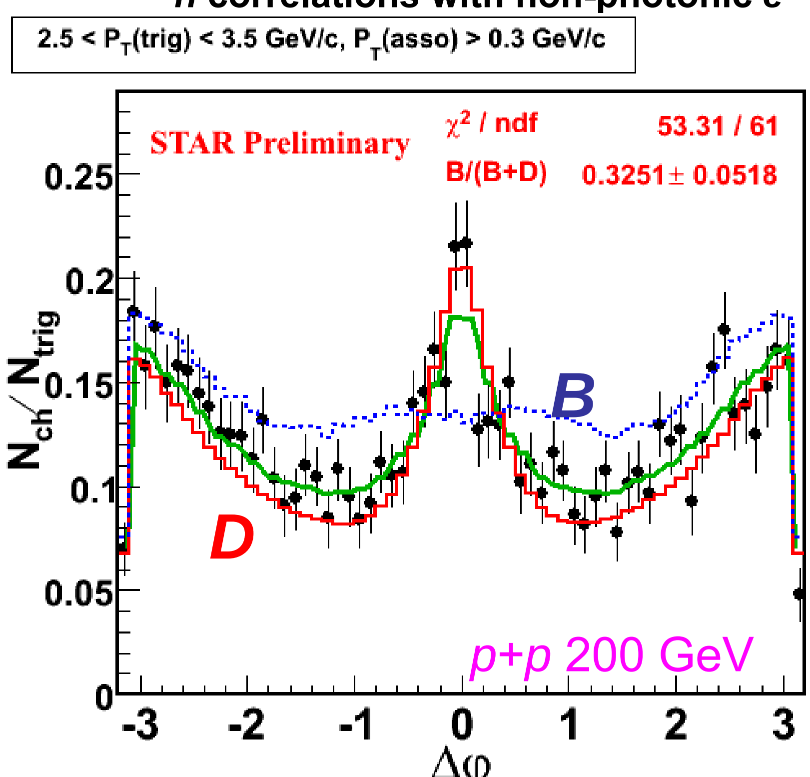
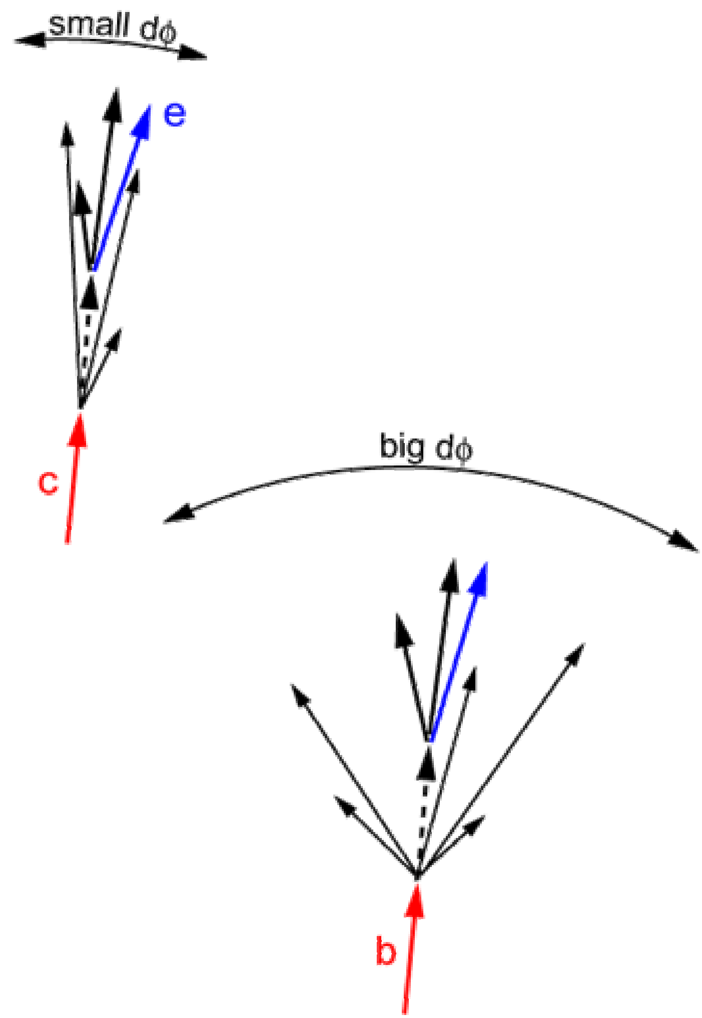
Disentangling Charm and Bottom

- Azimuthal distribution of hadrons w.r.t. non-photonic $e^{\pm}$
- $e^{\pm}$ can get bigger "kick" from *B* decay: broader same-side peak
- Also: $e^{\pm}$ correlation w/ identified D^0

h correlations with non-photonic e±





X. Lin, Strange Quark Matter Conference (2007)

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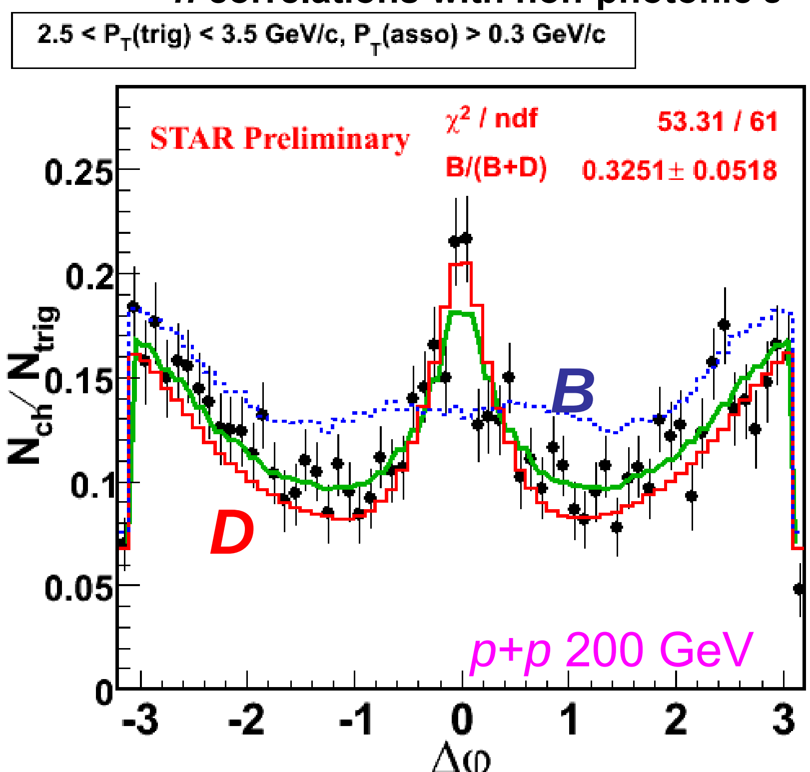
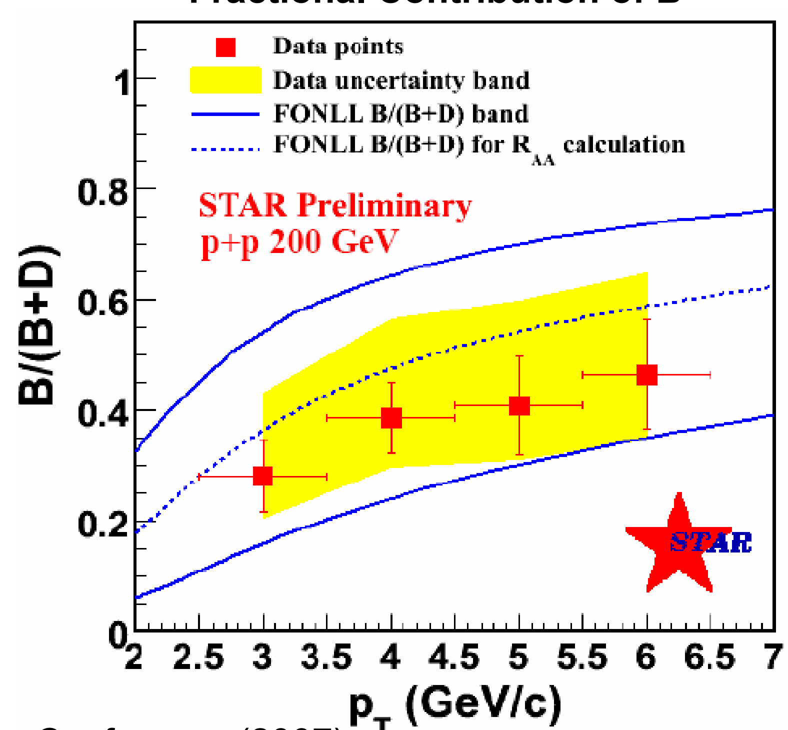


- PYTHIA Simulation: *D* and *B* contributions
- Fit determines *D* vs. *B*

$$\Delta\varphi_{fit} = (1-R)\Delta\varphi_D + R\cdot\Delta\varphi_B$$

- *B*-fraction consistent with FONLL

Fractional Contribution of B



X. Lin, Strange Quark Matter Conference (2007)

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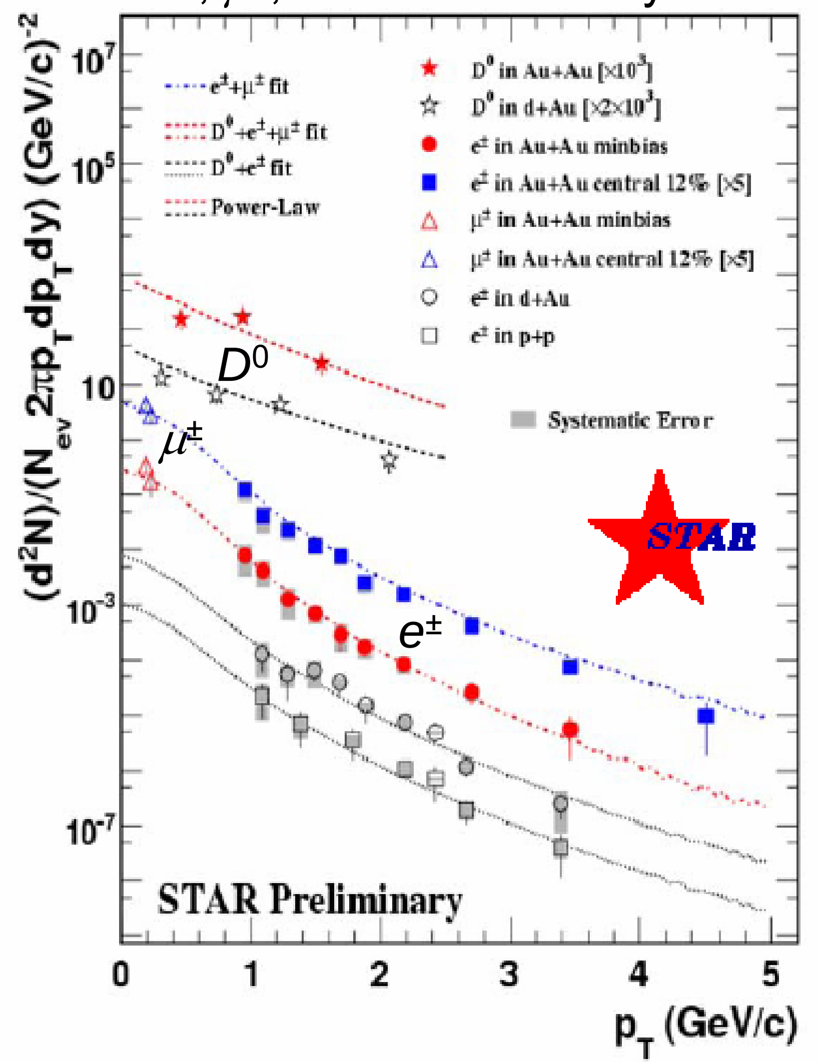
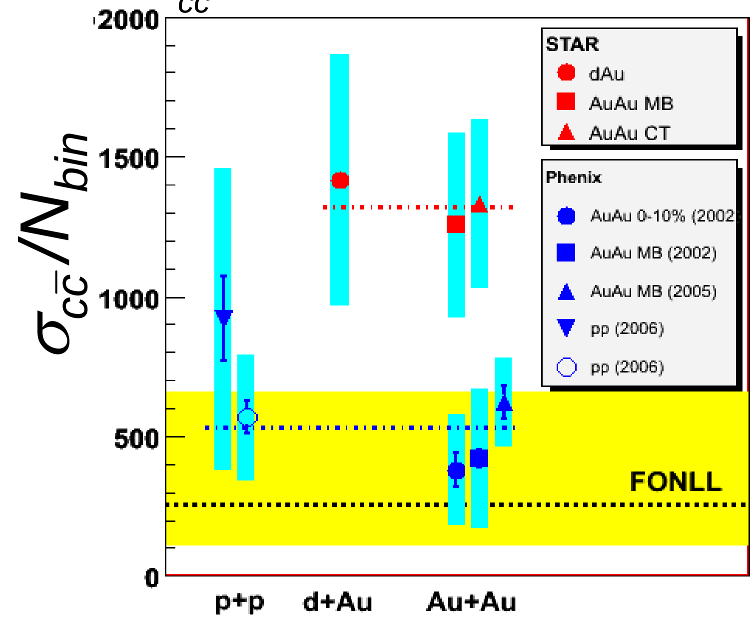
Charm Cross Section

D^0, $\mu^\pm$, and $e^\pm$ invariant yields



C. Zhong, J. Phys. G **34** (2007) S741-S744

- PHENIX: σ_{cc} from non-photonic $e^\pm$
- STAR: combined fit:
  - $D^0 \rightarrow K\pi$
  - $\mu^\pm$
  - non-photonic $e^\pm$ (TOF used)
  - covers ~95% of cross-section
- Scales with N_{bin}:
  - charm produced in initial hard scattering
  - No thermal production
- STAR σ_{cc} > FONLL calculation



A. Suaide, Quark Matter Conference (2006)

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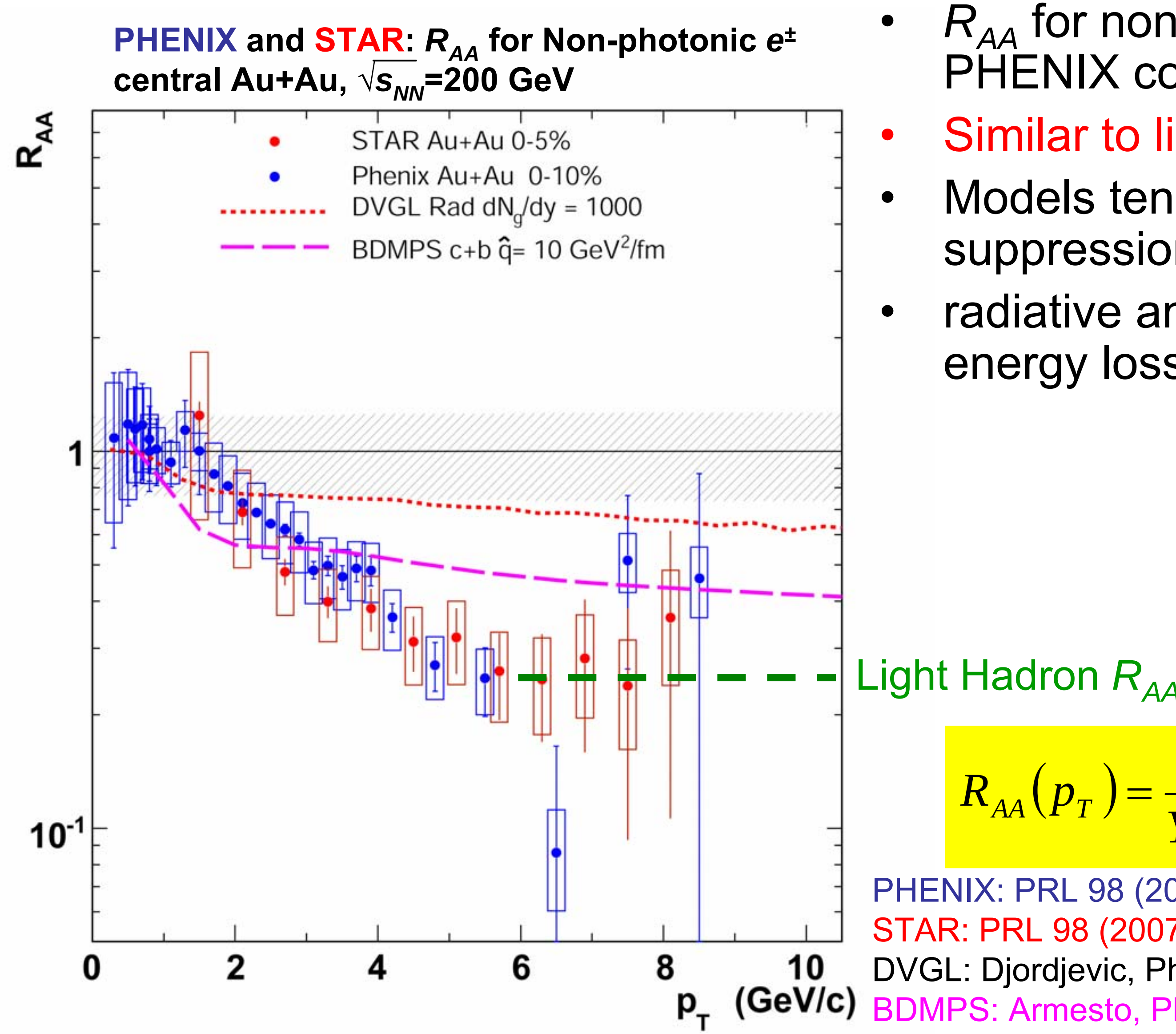
Nuclear Modification Factor



- R_{AA} for non-photonic $e^{\pm}$: PHENIX consistent with STAR
- Similar to light hadron R_{AA}
- Models tend to under-predict suppression
- radiative and/or collisional energy loss are insufficient

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\cdot\langle N_{bin}\rangle}$$

PHENIX: PRL 98 (2007) 172301
STAR: PRL 98 (2007) 192301
DVGL: Djordjevic, Phys. Lett. B 632 (2006) 81
BDMPS: Armesto, Phys. Lett. B 637 (2006) 362

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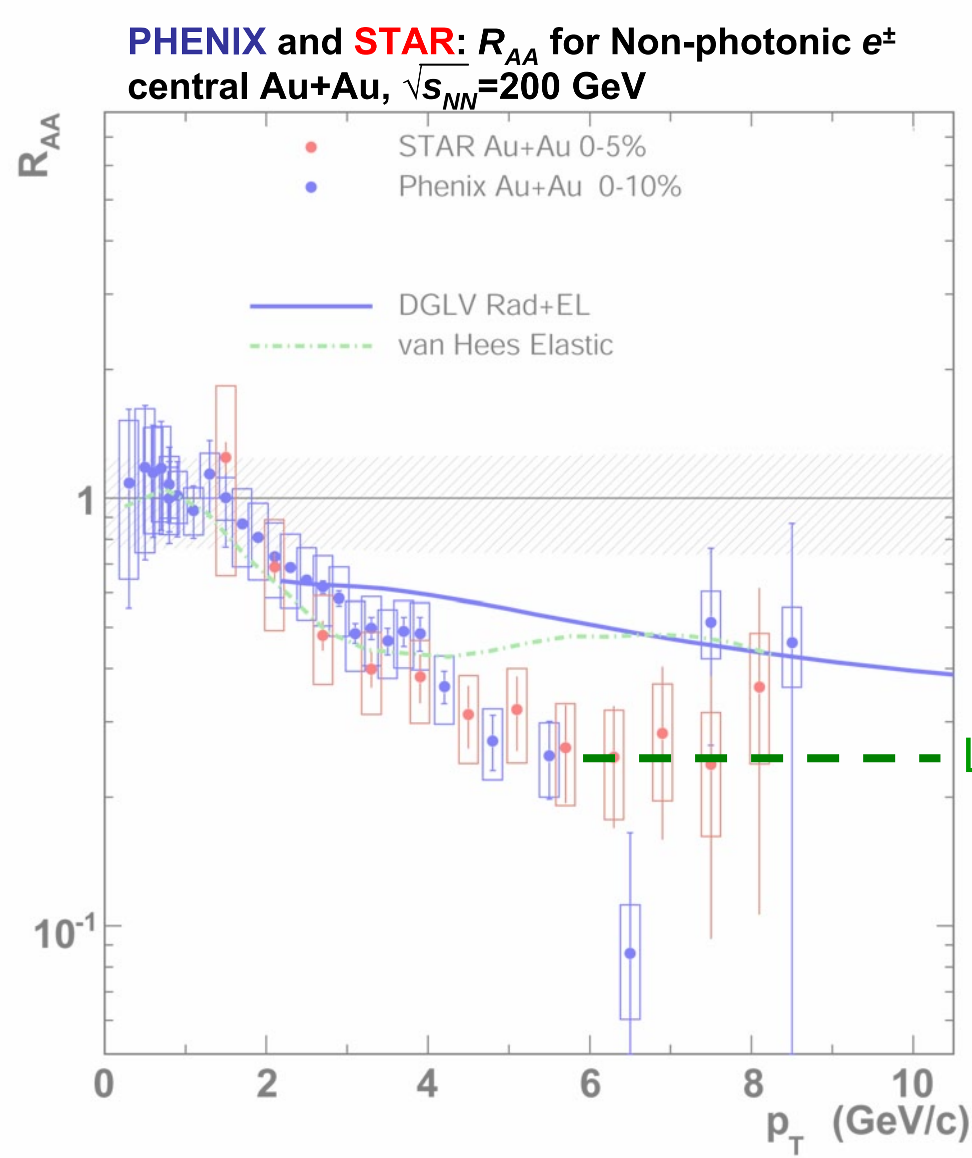
Nuclear Modification Factor



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PHENIX: PRL 98 (2007) 172301
STAR: PRL 98 (2007) 192301
DVGL: Wicks, nucl-th/0512076 (2005)
van Hees, Phys. Rev. C **73** 034913 (2006)

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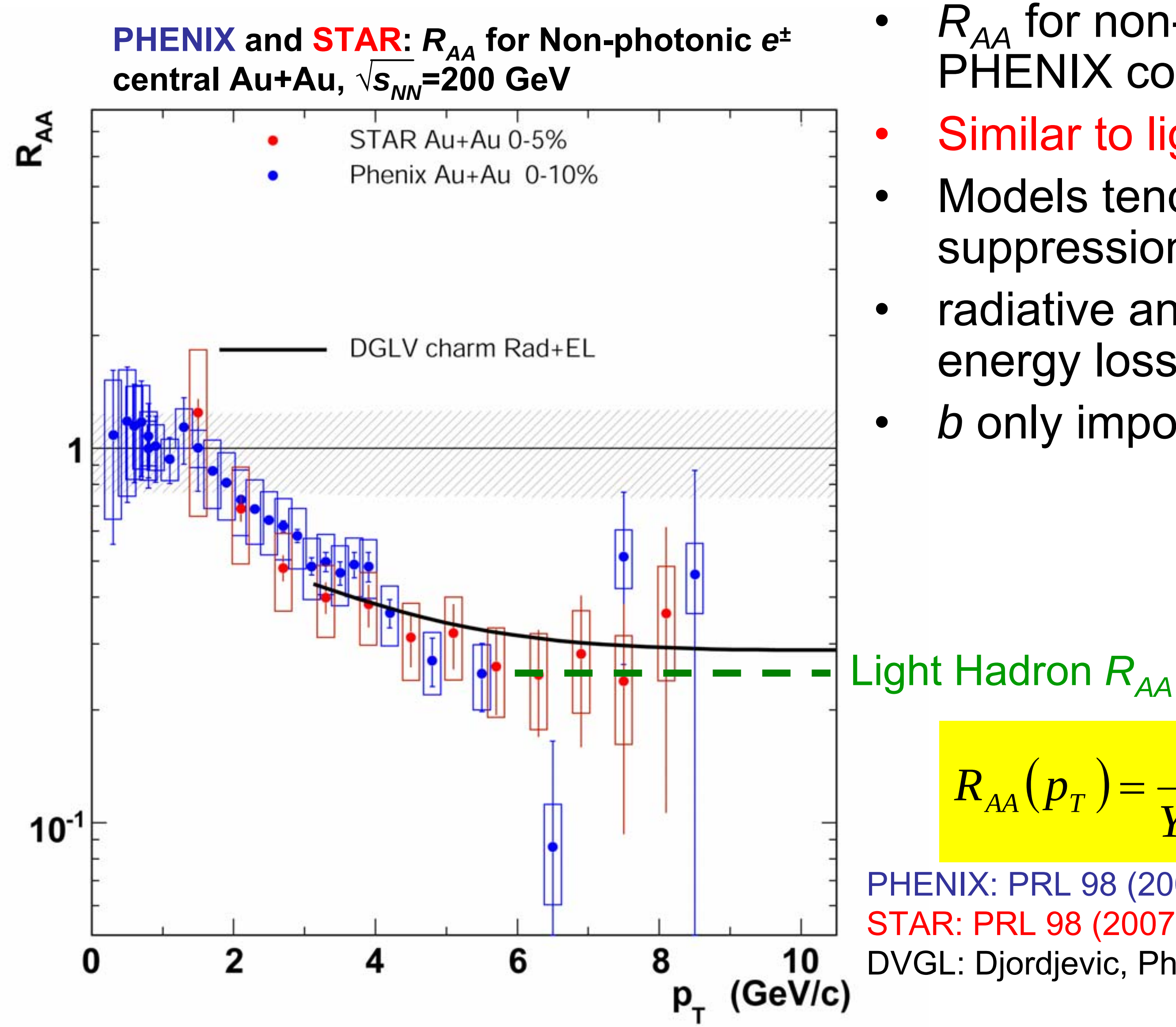
Nuclear Modification Factor



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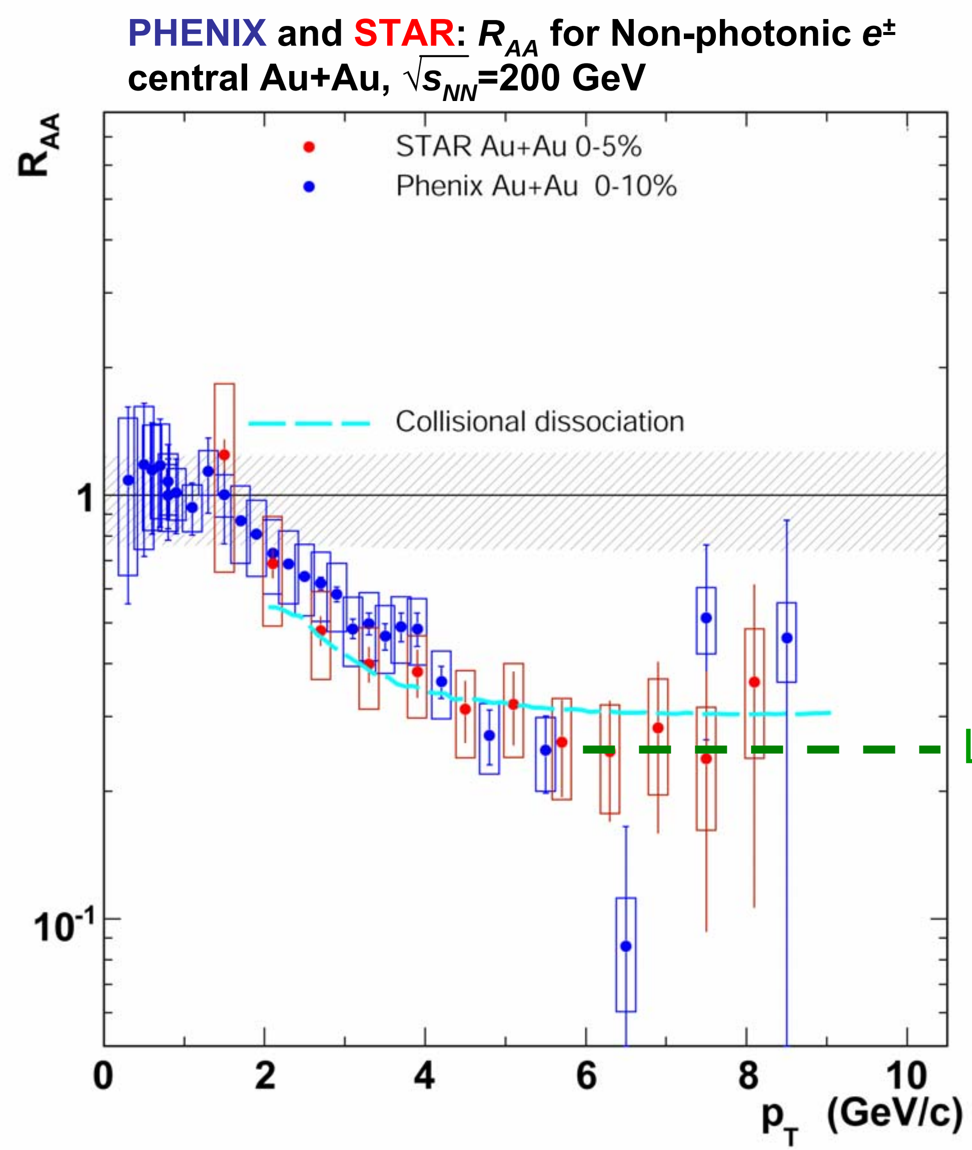

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- Similar to light hadron R_{AA}
- Models tend to under-predict suppression
- radiative and/or collisional energy loss are insufficient
- *b* only important at higher p_T?
- Collisional dissociation of heavy flavor mesons?
- Models still being refined

$$R_{AA}(p_T) = \frac{Yield(A+A)}{Yield(p+p)\cdot\langle N_{bin}\rangle}$$

PHENIX: PRL 98 (2007) 172301
STAR: PRL 98 (2007) 192301
Adil and Vitev, Phys. Lett. B 649 (2007) 139

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Summary and Outlook

- Charm Cross-Section
  - $c\bar{c}$ production scales as N_{bin}
    - Indicates charm production in initial state
  - STAR disagrees with PHENIX and FONLL calculations
- Non-photonic $e^{\pm}$ R_{AA}
  - Suppression similar to light hadrons
  - Difficult for models to describe
- $e^{\pm}$-h correlations
  - b-fraction consistent with FONLL

For more information about heavy-ion physics, visit **http://www.bnl.gov/RHIC/**

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- The Future at PHENIX
  - Hadron Blind Detector
- The Future at STAR
  - Low Material Run
    - Reduce photonic e+ bkg.
  - Improvements in data recording
- Improved Track Resolution Near Vertex
  - Better heavy flavor decay reconstruction
  - Disentangle charm and bottom
- The Future at RHIC
  - RHIC II Luminosity Upgrade

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Additional Material

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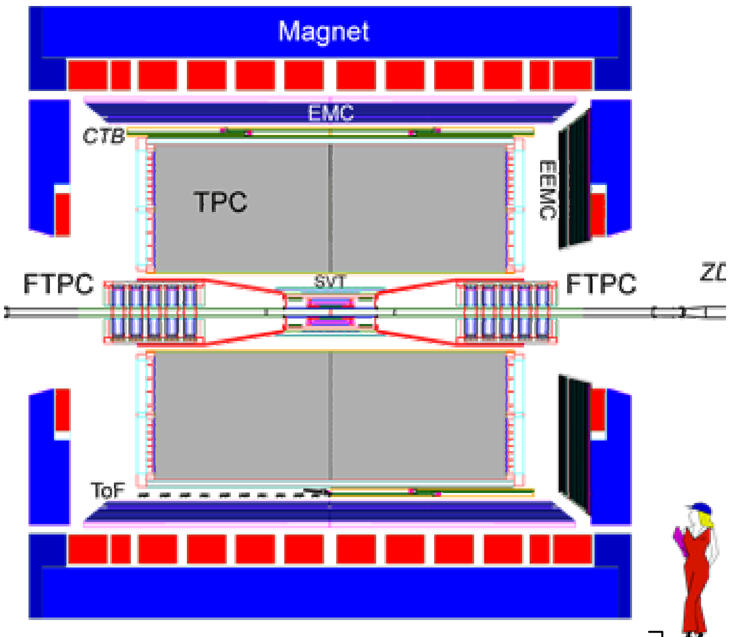
Experiments at RHIC

STAR

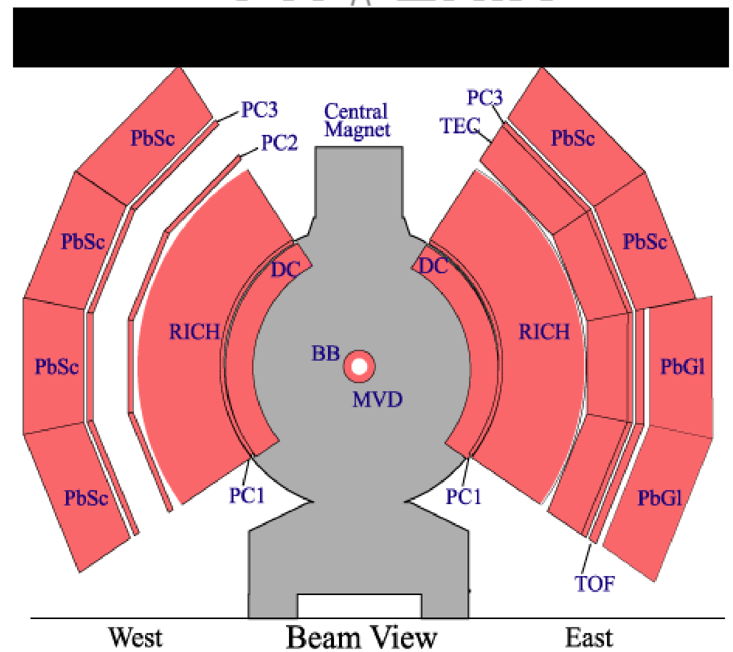


- Silicon Vertex Tracker ($|\eta| < 1$)
- Time Projection Chambers
  - ($|\eta| < 1.8$, $2.5 < |\eta| < 4$)
- EM Calorimeters ($-1 < \eta < 2$)

$\Delta\phi = 2\pi$

- Time-Of-Flight ($-1 < \eta < 0$, $\Delta\phi = \pi/30$)
- Covers large Ω
- ~500 Collaborators

PHENIX



- 2 central arms ($|\eta| < 0.35$)
  - Drift Chamber ($\Delta\phi = 90°\times2$)
  - Time Expansion Chamber ($\Delta\phi = 90°$)
  - RICH ($\Delta\phi = 90°\times2$)
  - EM Calorimeters ($\Delta\phi = 90°\times2$)
  - Time-Of-Flight ($\Delta\phi = 45°$)
- 2 forward arms ($\mu^{\pm}$ ID)
  - $-2.25 < y < -1.15$; $1.15 < y < 2.44$
- ~500 Collaborators

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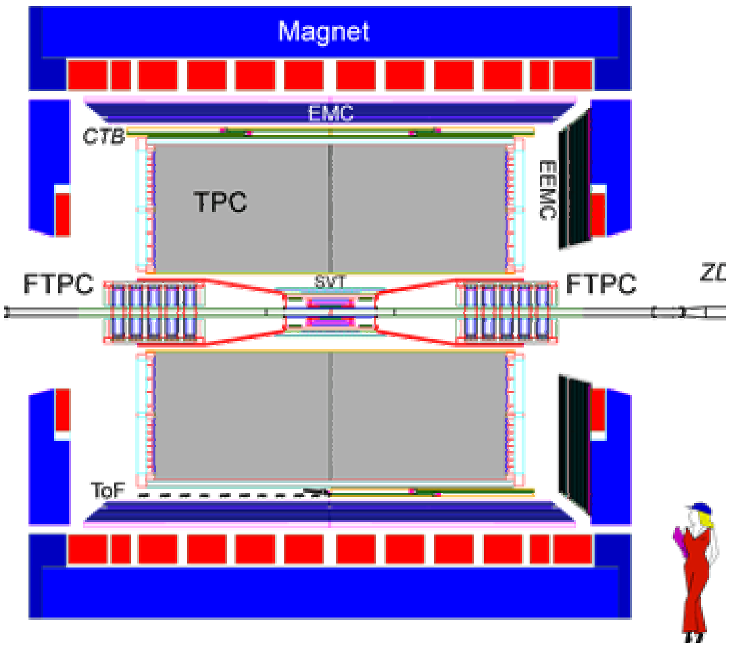
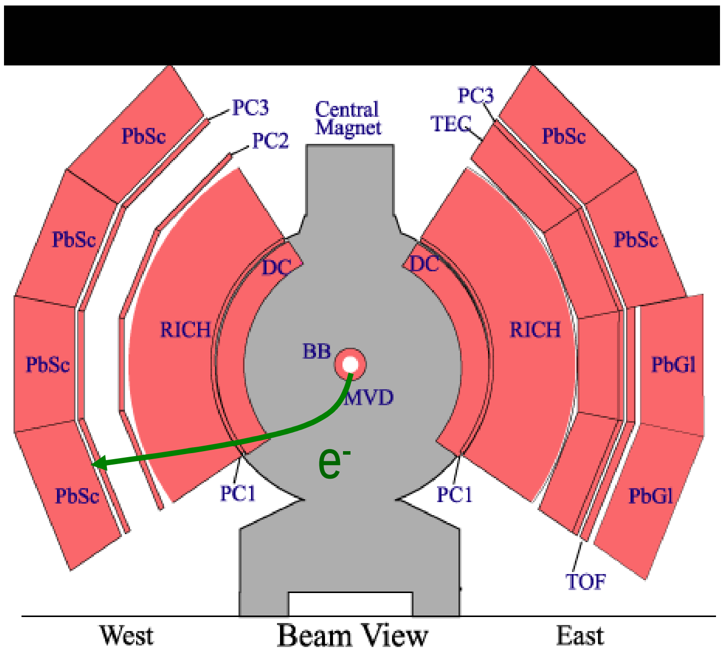
$e^{\pm}$ Identification





- EMC: $p/E < 2$
- SMD: cluster sizes ≥ 2
- TPC: 3.5 keV/cm < dE/dx < 5 keV/cm

- EMC: $E/p - 1 > -2\sigma$
- EMC: shower shape
- DC: tracks match EMC showers
- RICH: ≥ 3 associated hits

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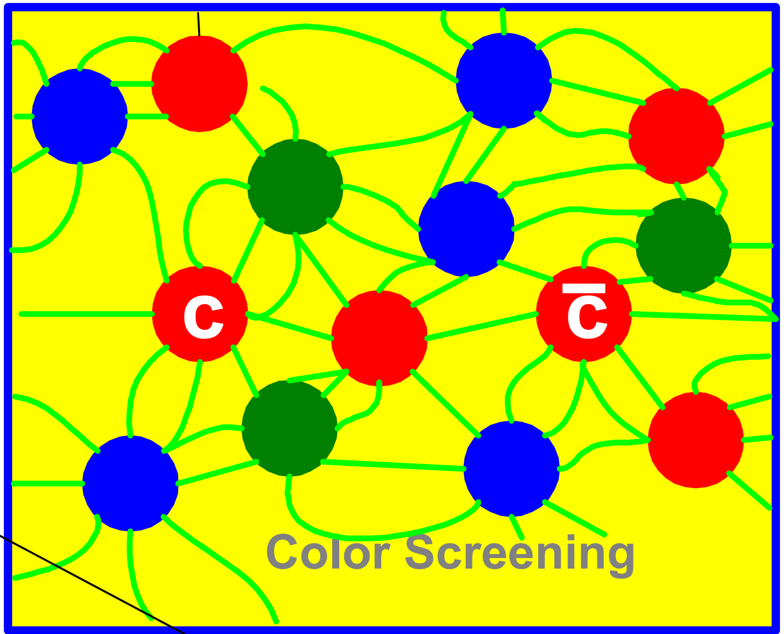
Quarkonium Suppression



- QGP Debye color screening → suppressed heavy quarkonia
- Different resonances may have different dissociation temperatures:
- Spectrum of quarkonia could be a thermometer for the medium (eventually)
- Suppression of heavier resonances (i.e. χ_c) can still suppress J/Ψ yield

Quarkonium Dissociation Temperatures
(Digal, Karsch, and Satz)

	T_d/T_c
$\Psi'(2s)$	1.12
$\chi_c(1p)$	1.16
$\Upsilon(3s)$	1.17
$\chi_b(2p)$	1.19
$\Upsilon(2s)$	1.60
$\chi_b(1p)$	1.76
J/Ψ	2.10
$\Upsilon(1s)$	>4.0

Just one calculation; others disagree

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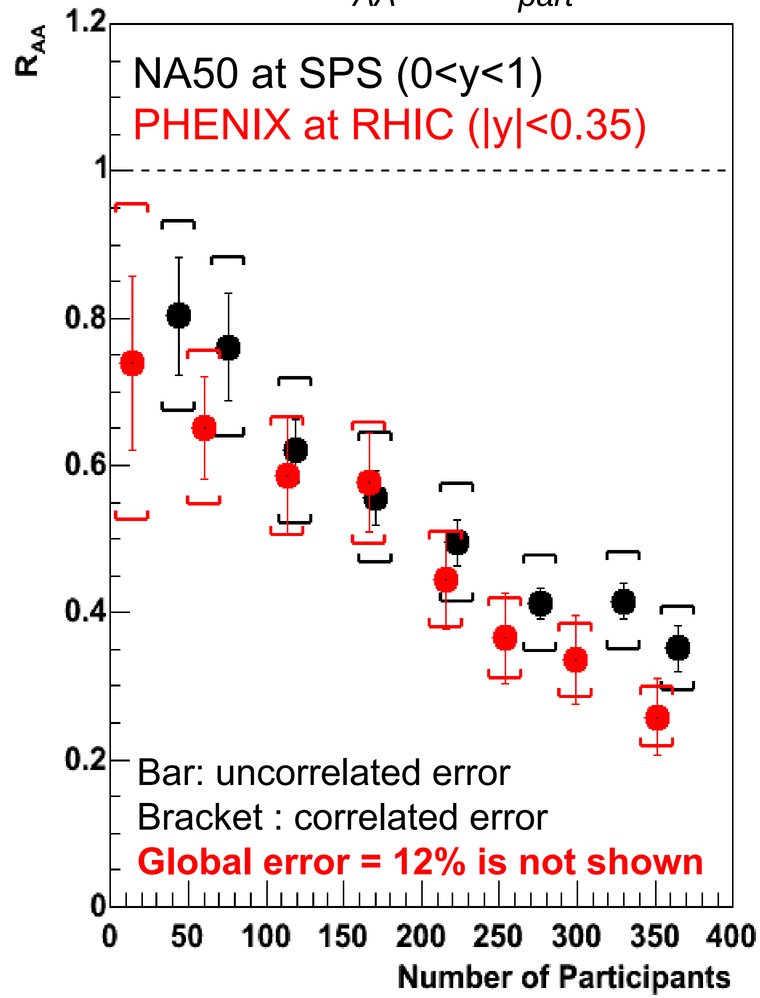
J/Ψ Suppression

- Suppression (R_{AA}) similar for:
  - NA50 (SPS) Pb + Pb, $\sqrt{s_{NN}}$=17.2 GeV
  - PHENIX Au + Au, $\sqrt{s_{NN}}$=200 GeV
- Suppression-only models:
  - describe SPS suppression well
  - over-predict RHIC suppression
- Regeneration of J/Ψ:
  - Gluon density at RHIC 2-3 times greater than at SPS
  - More $c\bar{c}$ pairs
  - Quarks from dissociated $c\bar{c}$ pairs can recombine into new pairs

J/Ψ R_{AA} vs. N_{part}



NA50: M. C. Abreu *et al*, Phys. Lett. B **477** (2000) 28
PHENIX: R. Averbeck, J. Phys. G **34** (2007) S567-S574

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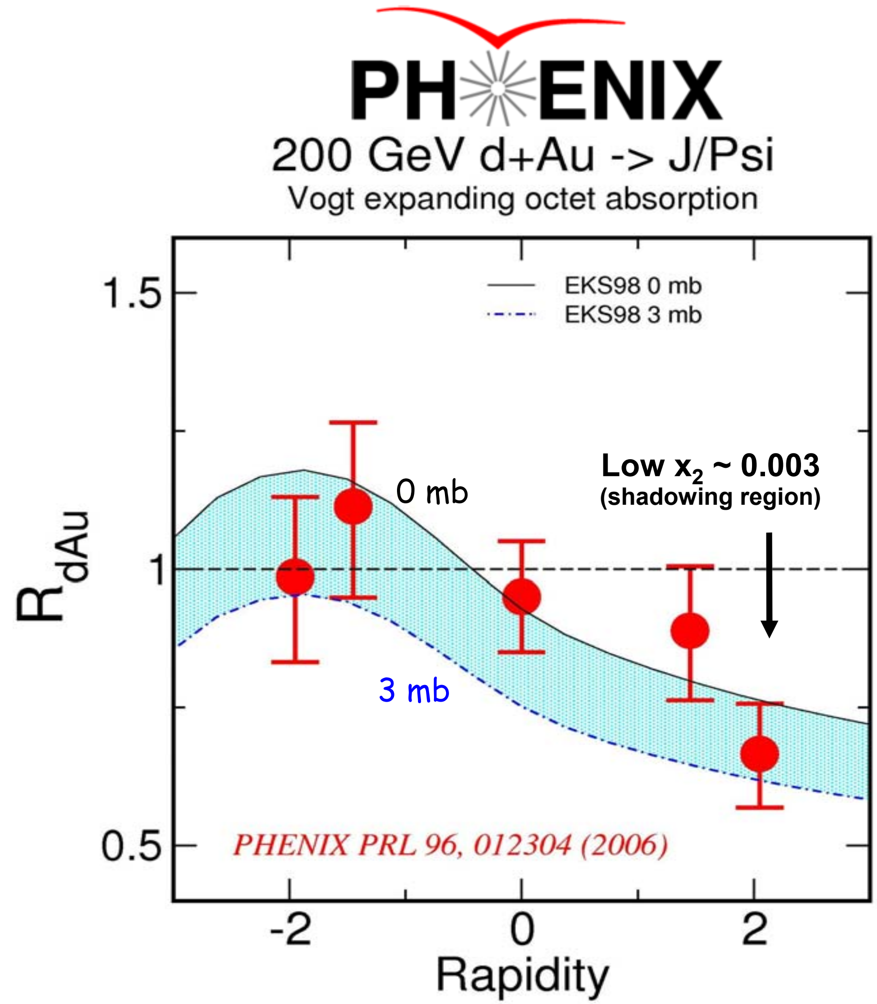
Cold Nuclear Matter Effects

- HOWEVER, J/Ψ also suppressed due to CNM effects
  - Dissociation/Absorption
  - Cronin Effect (multiple gluon scattering)
  - Shadowing (depletion of low-momentum gluons)
  - Gluon Saturation (Color Glass Condensate)
- d + Au: model (absorption + shadowing): σ_{abs} < 3 mb
- Need more *d* + Au data



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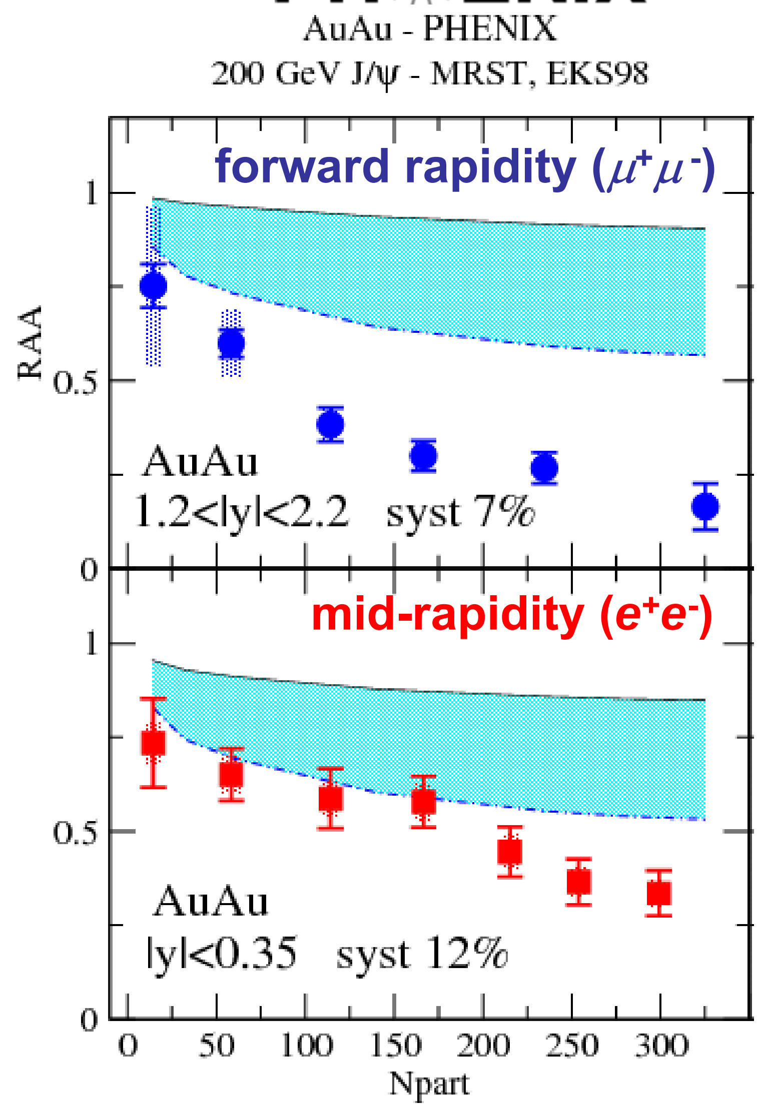
- Need more *d* + Au data
- Au + Au: same model under-predicts suppression
  - Need QGP?



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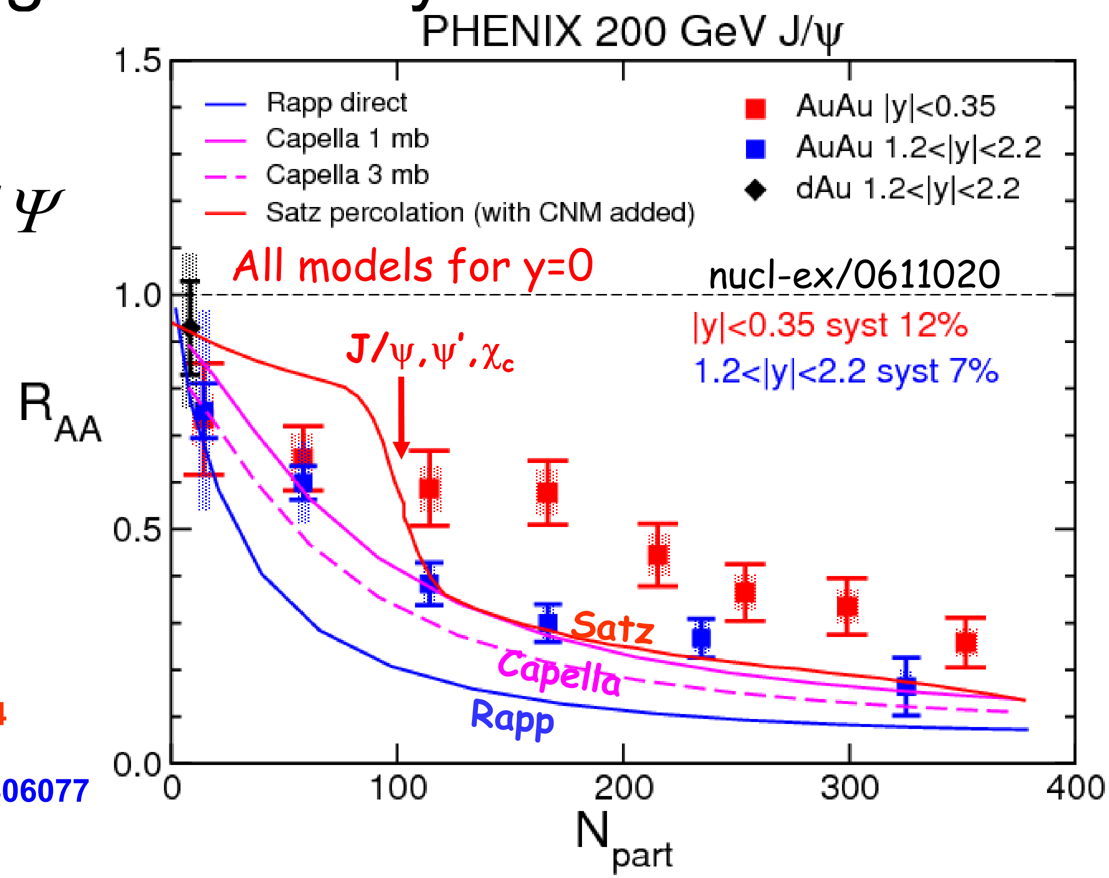
J/Ψ Suppression

- R_{AA} for Au + Au similar to SPS NA50 (Pb + Pb)
- Models describe SPS data well, but not RHIC
- 2-3 times greater gluon density at RHIC:
  - more $c\bar{c}$ pairs
  - pairs recombine
  - regeneration of J/Ψ



Digal, Fortunato, and Satz: hep-ph/0310354
Capella and Ferreiro: hep-ph/0505032
Grandchamp, Rapp, and Brown: hep-ph/0306077

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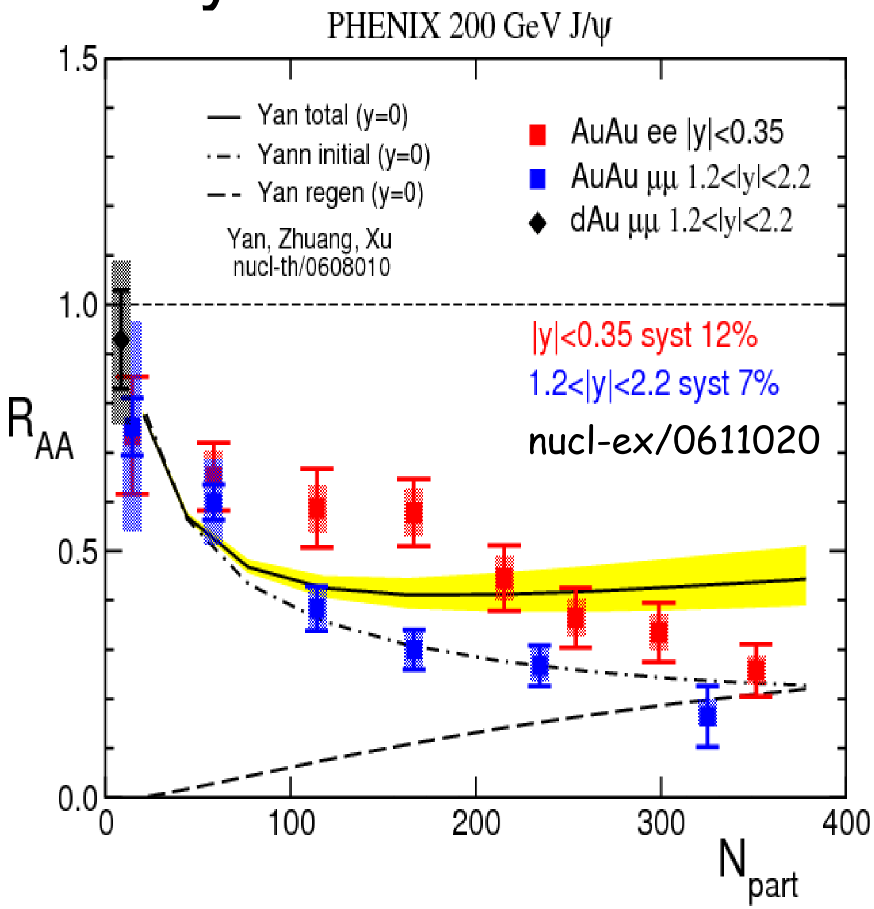
- Yan model shows less suppression
- Models: mid-rapidity suppression greater than forward



Yan, Zhuang, and Xu: nucl-th/0608010

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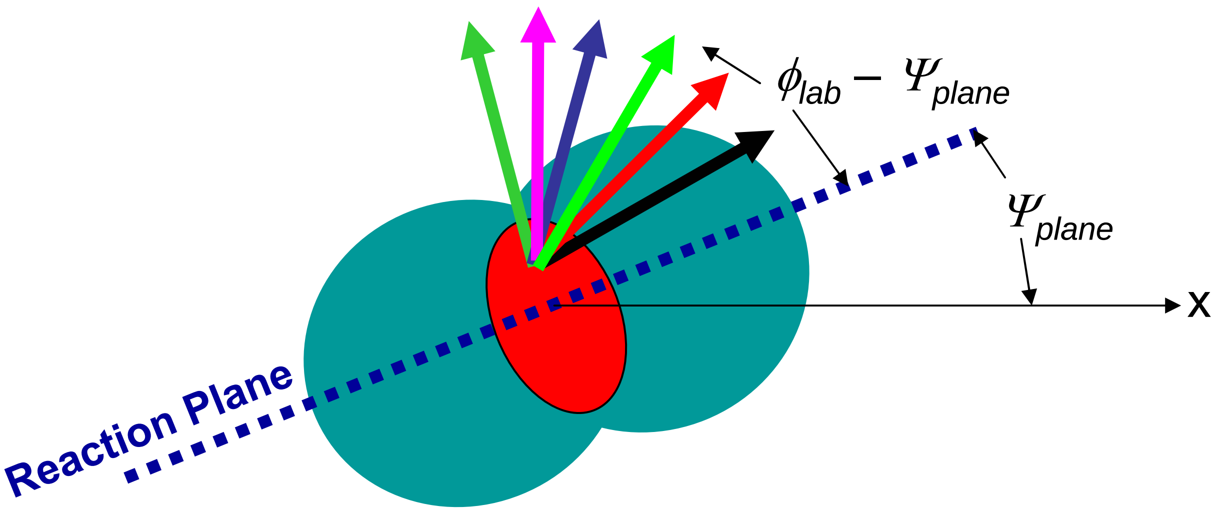
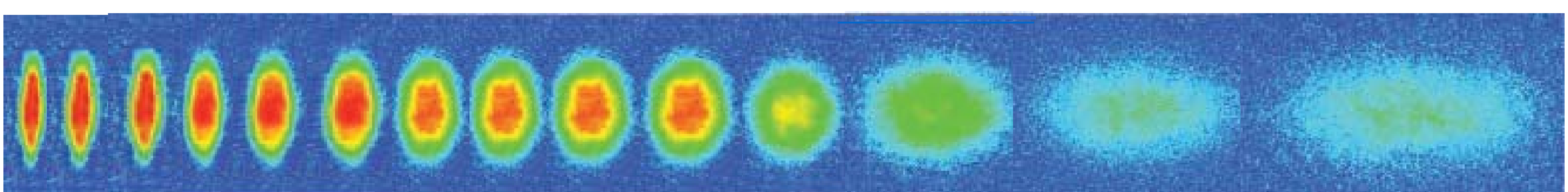
Elliptic Flow

- Yields depend on orientation w.r.t reaction plane
  - Azimuthal anisotropy in medium
  - Unequal pressure gradients in and out of reaction plane
- Measured by v_2 (from Fourier expansion)

$$Yield \propto 1 + v_2 \cos 2(\phi_{lab} - \Psi_{plane}) + v_4 \cos 4(\phi_{lab} - \Psi_{plane}) + \mathrm{K}$$





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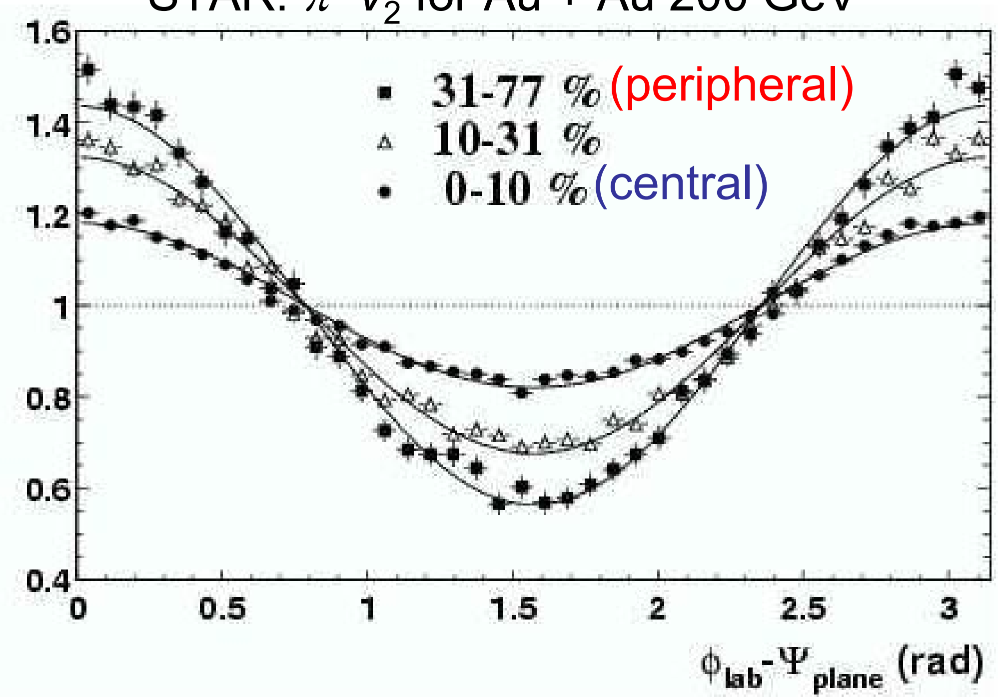
$$Yield \propto 1 + v_2 \cos 2(\phi_{lab} - \Psi_{plane}) + v_4 \cos 4(\phi_{lab} - \Psi_{plane}) + \ldots$$

- STAR observes large asymmetry

STAR: $\pi^{\pm}$ v_2 for Au + Au 200 GeV



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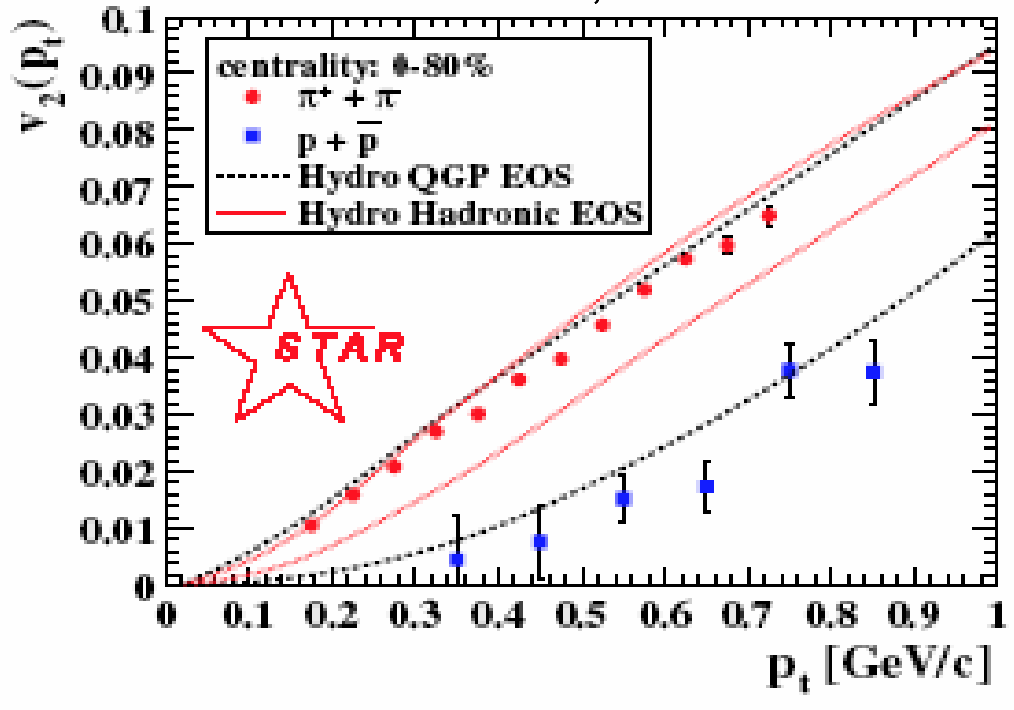
Elliptic Flow

- STAR: light hadron v_2 vs. p_T suggest QGP obeys ideal hydrodynamics (0 viscosity)
  - QGP is "perfect liquid"?

STAR: Au + Au 200 GeV, 0-80% most central



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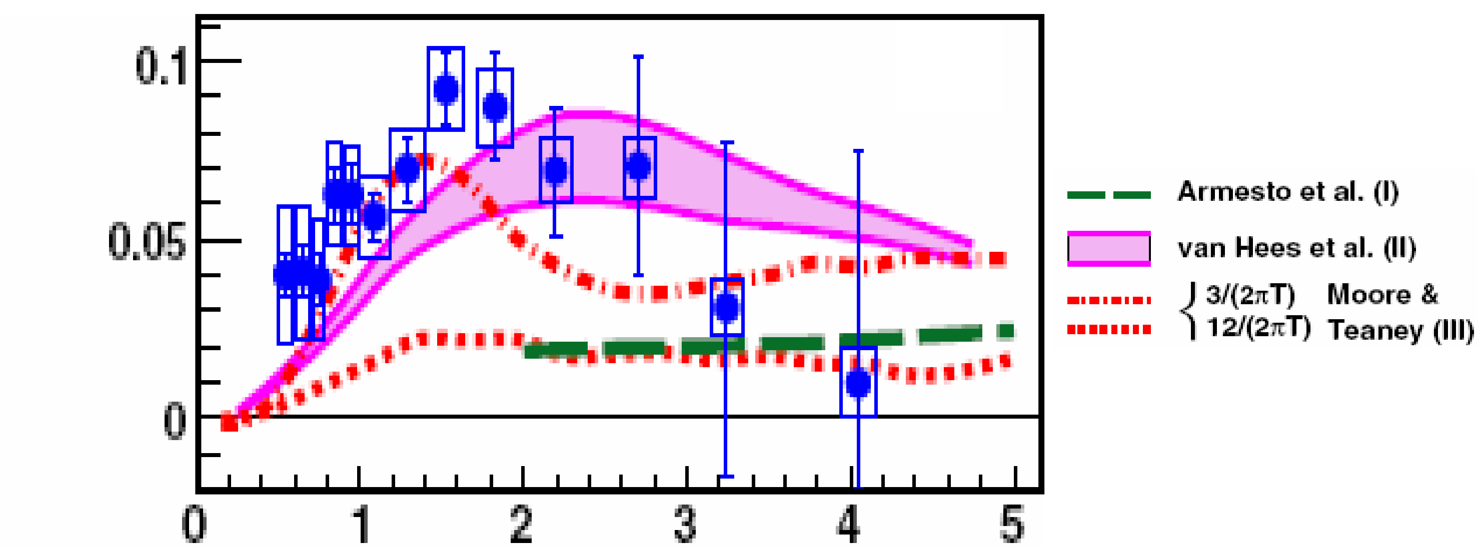
Elliptic Flow

- STAR: light hadron v_2 vs. p_T suggest QGP obeys ideal hydrodynamics (0 viscosity)
  - QGP is "perfect liquid"?
- PHENIX: flow of non-photonic $e^{\pm}$
- Data suggest low viscosity for charm

PHENIX: Au + Au 200 GeV, 0-10% most central



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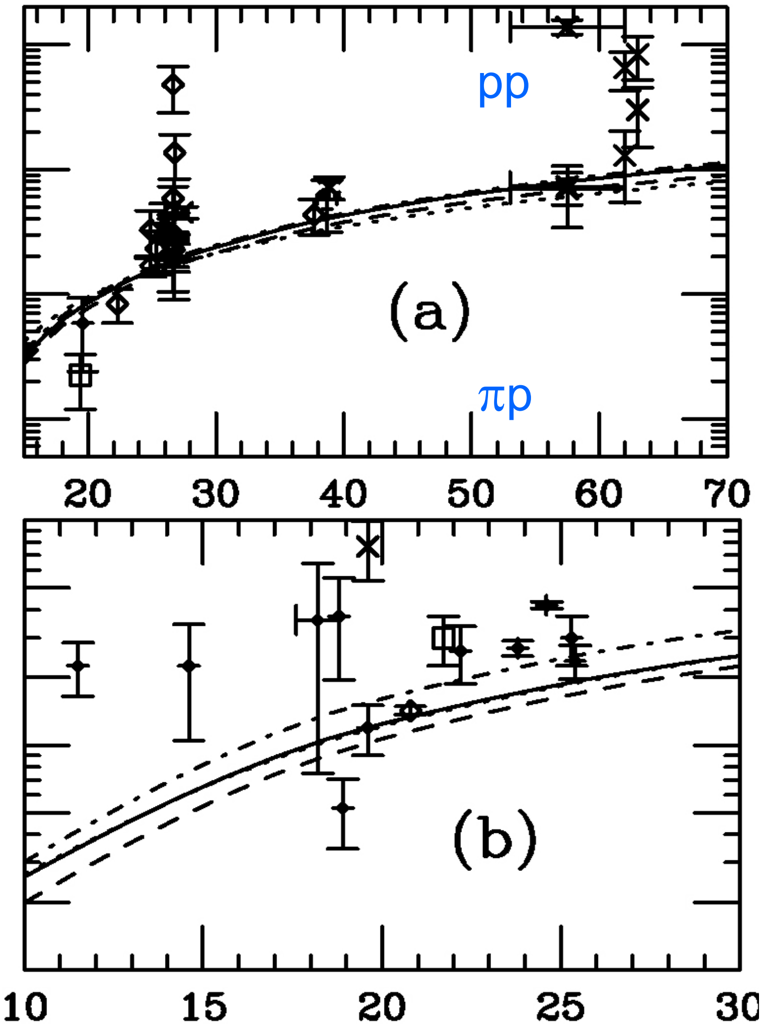
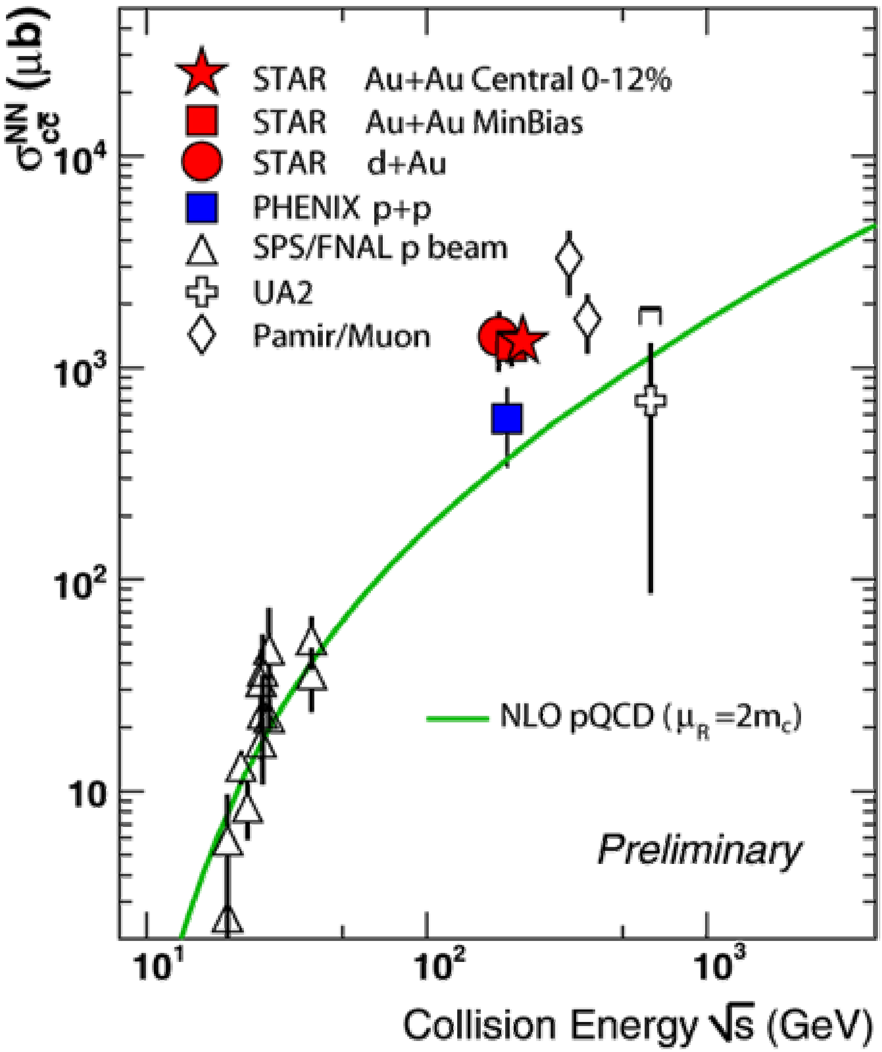
Charm Cross-Section





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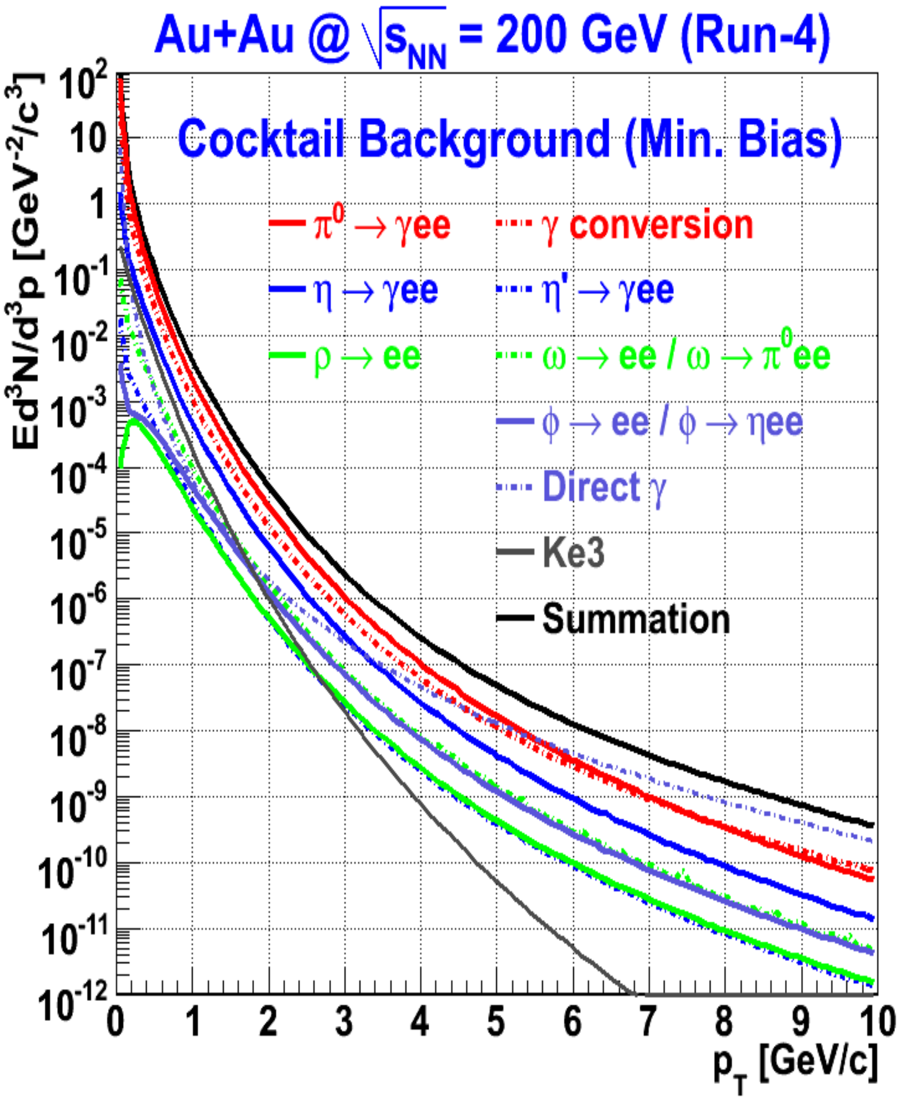
PHENIX Non-photnic $e^{\pm}$



F. Kajihara, Quark Matter Conference (2006)