Open charm production at RHIC

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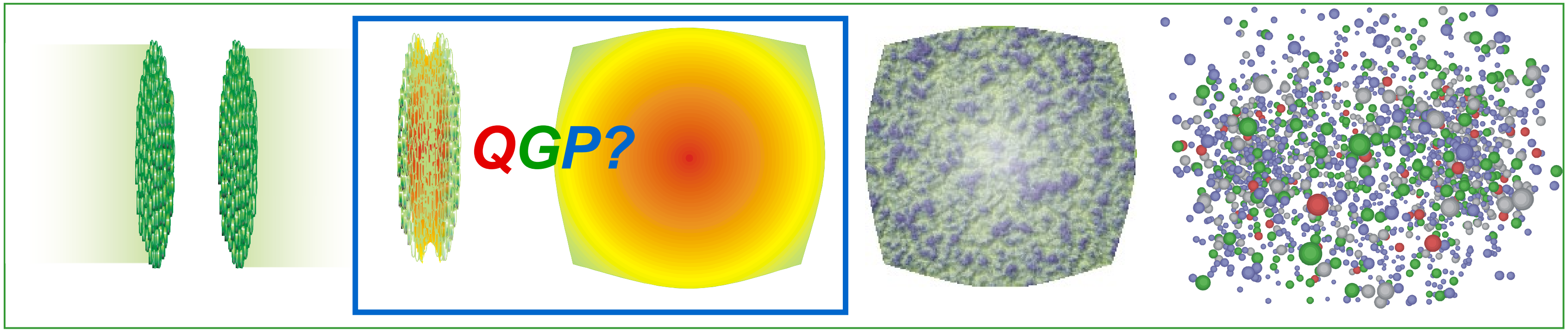
- Introduction
- Open charm production at RHIC
  - Charm production cross section
  - Charm quark ΔE in medium
  - Charm quark v_2
- Summary and outlook

Many Thanks to:
H. Huang, H. Ritter, K. Schweda, E. Sichtermann, P. Sorensen, N. Xu, Z. Xu, Y. Zhang
M. Djordjevic, L. Grandchamp, M. Gyulassy, J. Raufeisen, R. Vogt, X.-N. Wang

Heavy ion physics at RHIC

S. Bass



RHIC heavy ion program

Search and measure the ***QGP***

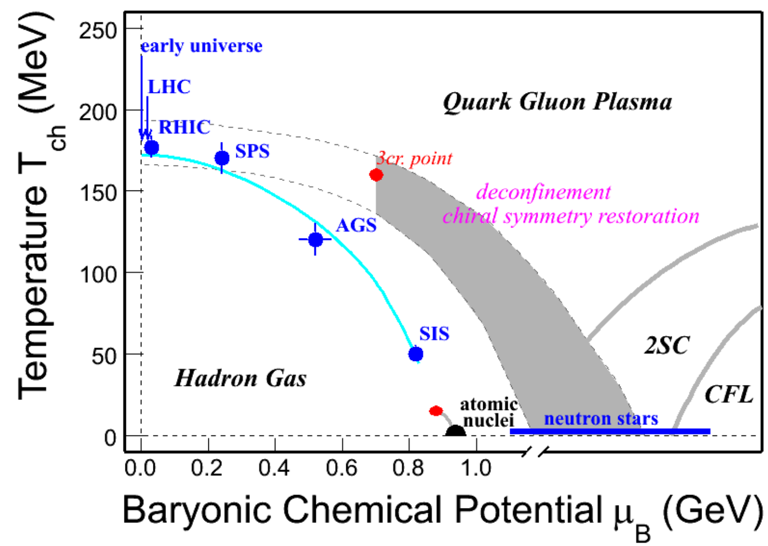
– matter with partonic EoS

Probes:

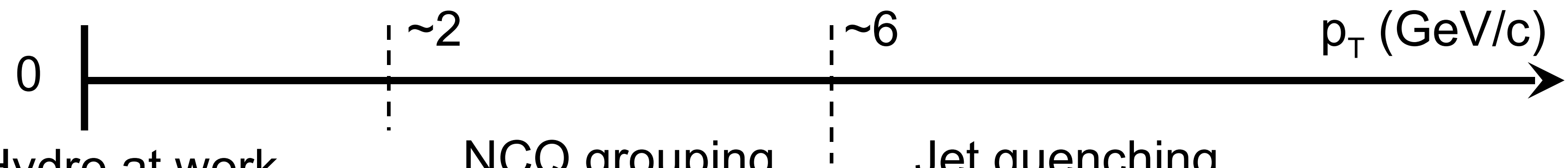
jets, direct photon, leptons,
heavy flavors, …

Measurements:

spectrum, flow (radial, elliptic …),
correlations, …



What we have learned at RHIC



Hydro at work
strong interactions
collectivity

NCQ grouping
partonic d.o.f

Jet quenching
high density matter

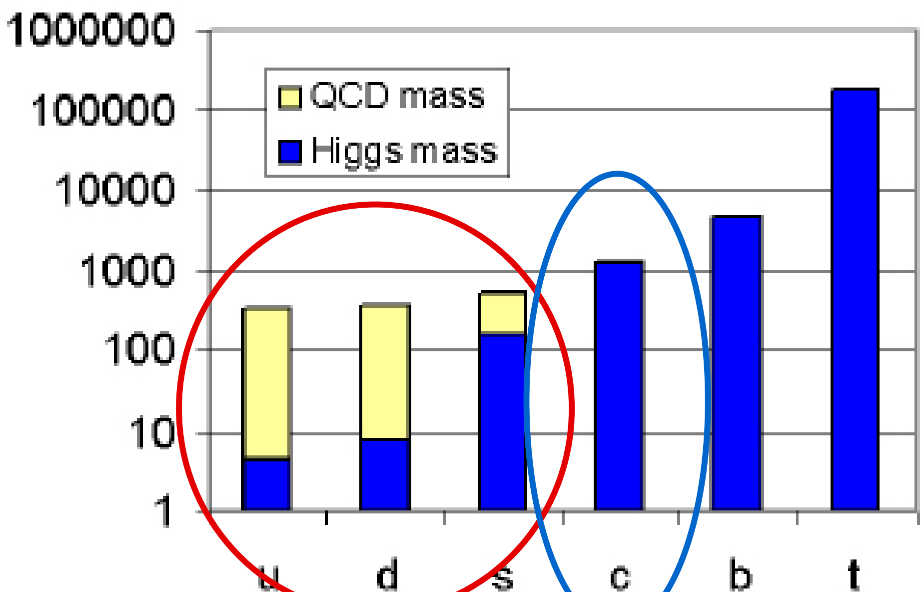
- Jet-quenching: high density medium created
- Large v_2 and β_T: partonic collectivity
- NCQ-grouping: partonic collectivity and deconfinement

A hot dense matter with partonic collectivity has been created at RHIC

Experimentally, future goals are:

- Looking for the evidence of early thermalization
- EoS
- Chiral symmetry restoration

Why Charm? – an ideal probe for studying QGP



B. Mueller, *nucl-th/0404015*

Heavy !

- Charm quarks created at early stage of HIC
  → total yields scaled by N_{bin}
- Sensitive to the partonic rescatterings
- Collectivity, flow
  → indication of light flavor thermalization (to some degree)

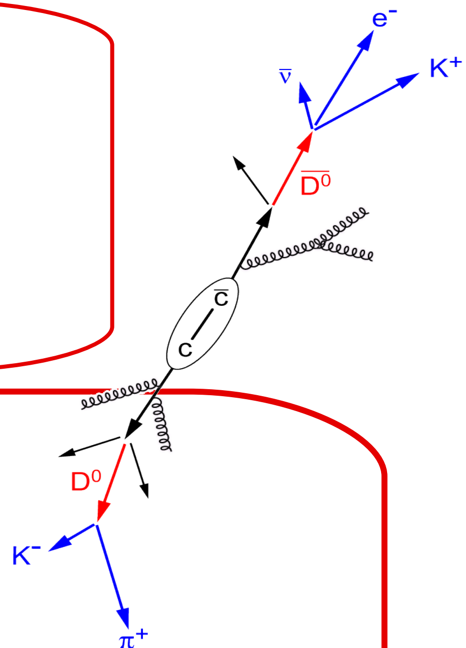
How to measure Charm?

Reconstruction from hadronic decay channels

$$D^0 \rightarrow K^-\pi^+(3.8\%) \qquad c\tau = 123\mu m$$

$$D^{*+} \rightarrow D^0\pi_s^+(68\%), D^0 \rightarrow K^-\pi^+(3.8\%)$$

$$\ldots$$



Semi-leptonic decay channels

$$D^0 \rightarrow e^+ + X \quad (6.9\%)$$

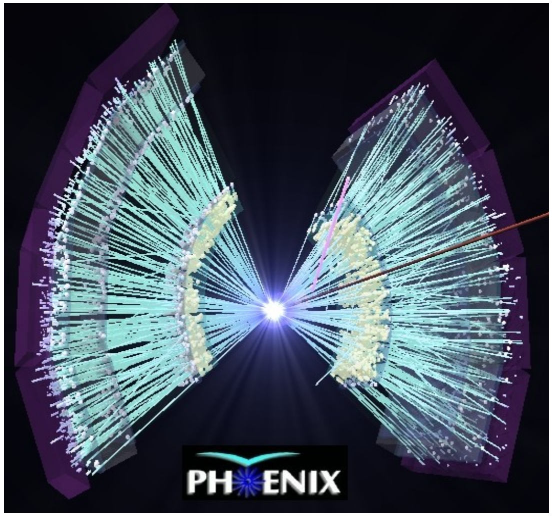
$$D^+ \rightarrow e^+ + X \quad (17.2\%)$$

Note: backgrounds (conversions and hadronic decays)

photon conversions (in detector)
π,η Dalitz decays
ρωφ (Dalitz) decays
} *Photonic bkgd*

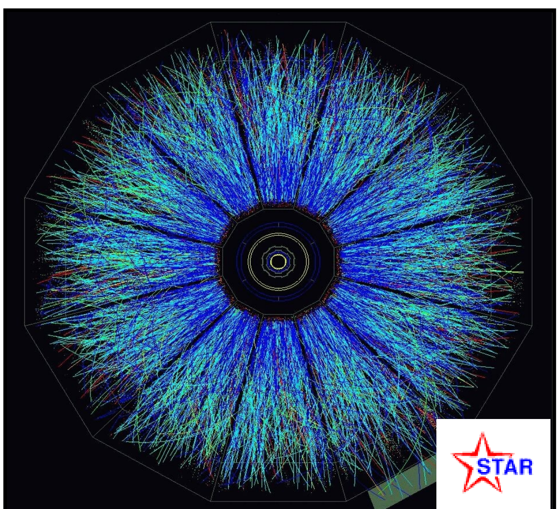
Heavy flavor (c, b) decays
Others (Drell-Yan etc)
} *Non-photonic signal*

Charm measurements at RHIC



- central arms --- electrons: $|\varphi|<2*\pi/2, |\eta|<0.35$
  DC (tracker), Ring Image Cherenkov (RICH), EMCal
- forward/backward arms --- muons: $1.5<|\eta|<1.8$
  muon tracker, muon identifier

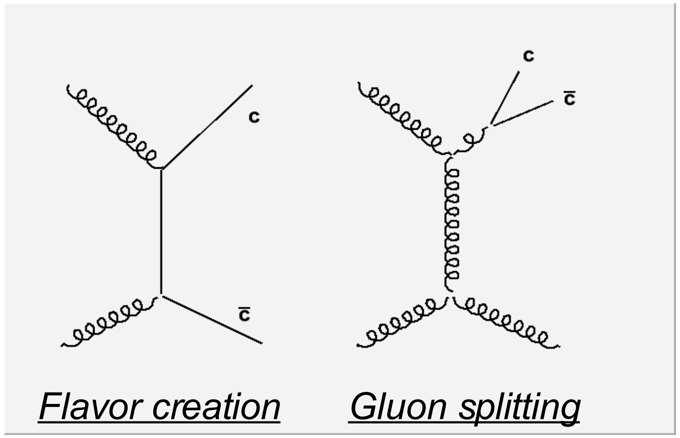
Advantages: **-- low material budget, clean environ.**
-- central, forward/backward coverage



- D recon. from hadronic decay channels:
  TPC (+TOF)
- electrons, *muons*:
  TPC, TPC+TOF, TPC+EMC

Advantages: **-- large acceptance $|\varphi|<2\pi, |\eta|<1$**
-- reconstruction from hadronic channel

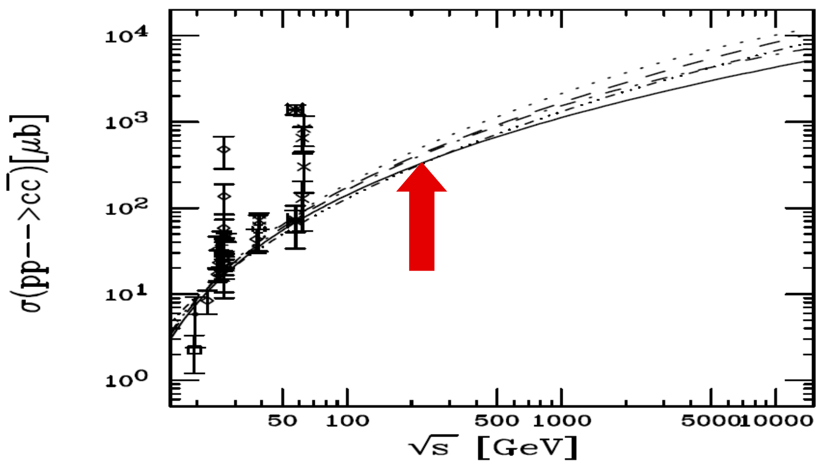
Heavy flavor in pQCD



Large Q value needed (>≈3GeV)

➔powerful test for pQCD calculation

$$\underbrace{\sigma_{pp}(s, m_Q^2)}_{ccbar} = \sum_{i,j=q,\bar{q},g} \int_{\frac{4m_Q^2}{s}}^{1} \frac{d\tau}{\tau} \delta(x_i x_j - \tau) \underbrace{f_{i/p}(x_i, \mu^2) f_{j/p}(x_j, \mu^2)}_{PDF} \underbrace{\hat{\sigma}_{ij}(\tau, m_Q^2, \mu^2)}_{pQCD}$$



NLO: ~ 300-500 μb

R. Vogt *Int. J. Mod. Phys.* ***E*** *12(2003)211*

FONLL: $256^{+400}_{-146}\,\mu b$

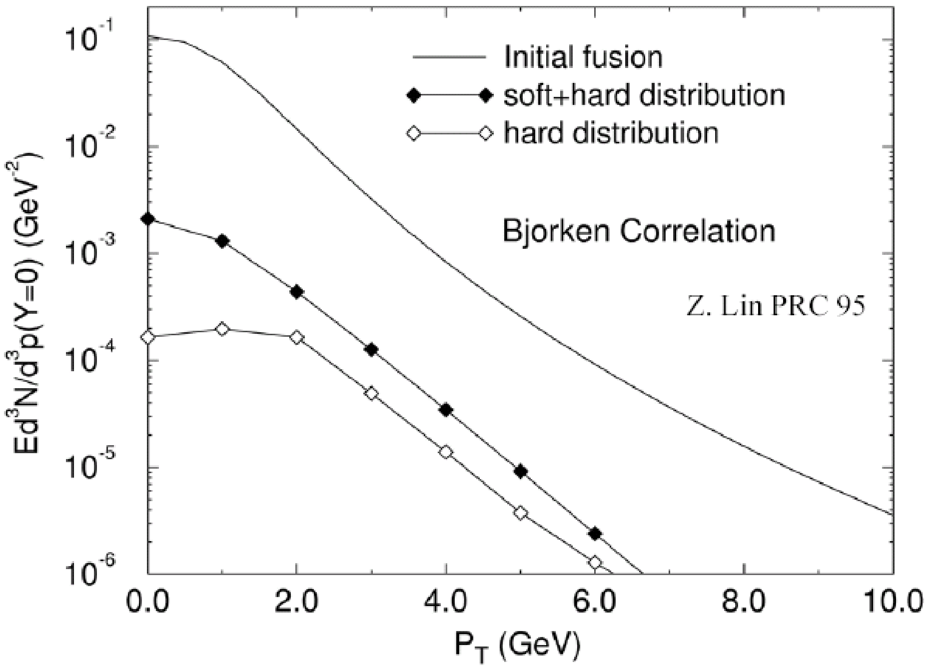
M. Cacciari *et al.*, *PRL 95 (2005) 122001*

Charm production in HIC at RHIC

Charm quark mostly produced from the initial fusion of partons (mostly gluons)

→ Charm quark cross section in heavy ion collisions should be scaled by the number of binary collisions

Z. Lin & M. Gyulassy, *PRC 51 (1995) 2177*

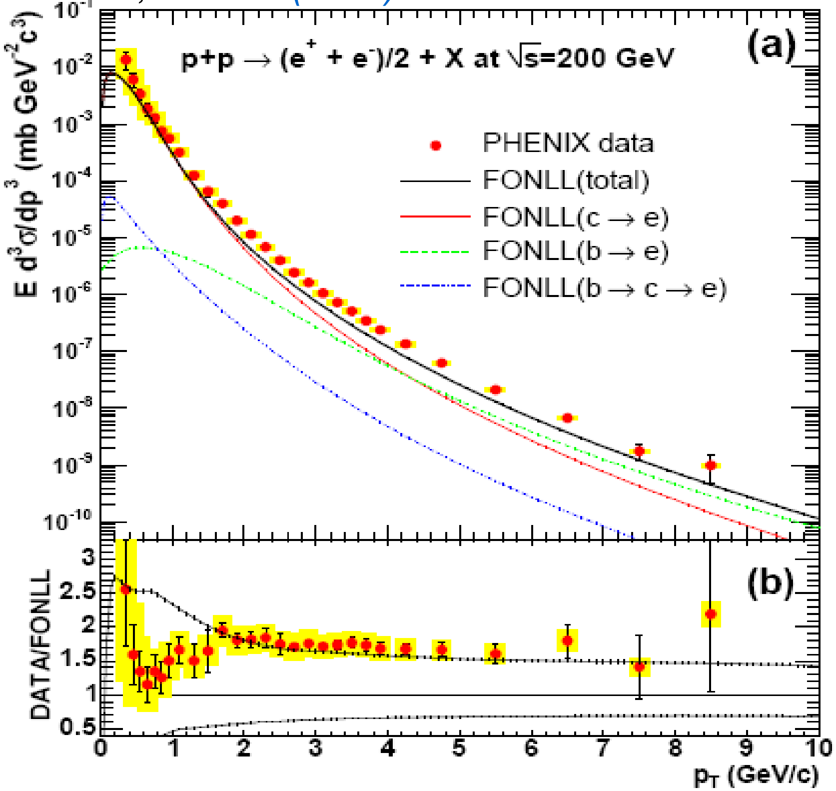


Nuclear shadowing effect?

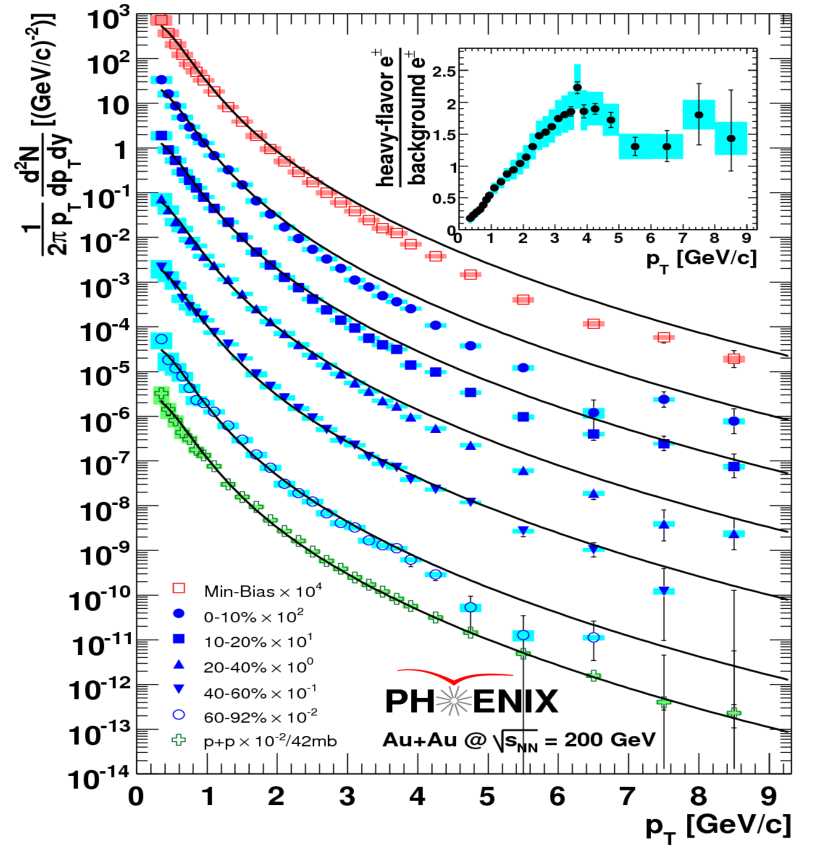
Charm cross section from PHENIX

Non-photonic electrons

PHENIX, PRL 97 (2006) 252002



PHENIX, PRL 98 (2007) 172301

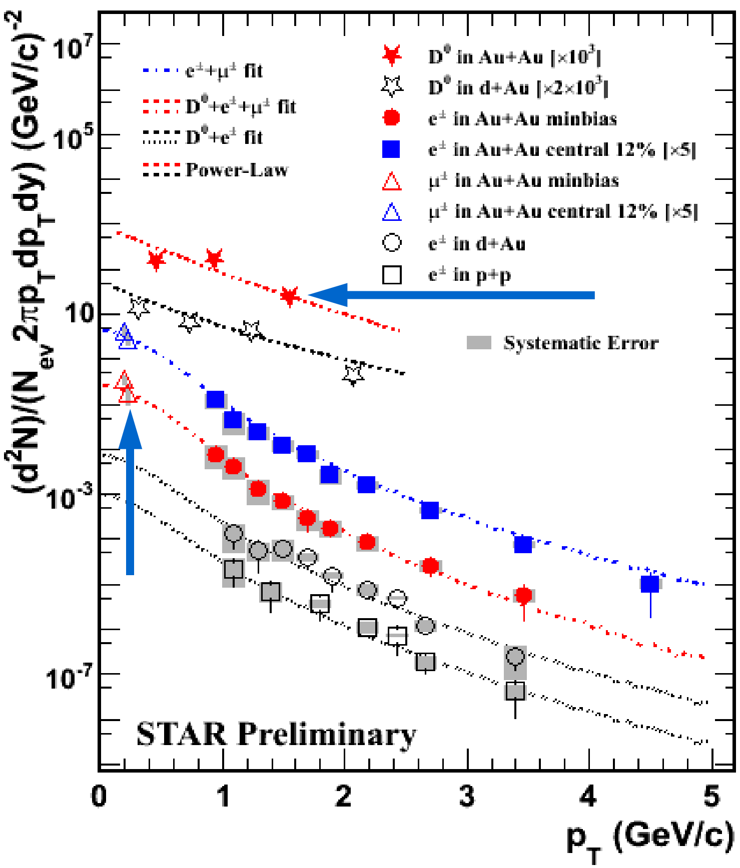


Non-photonic electron spectrum in p+p collisions is consistent with the FONLL calculations

Centrality dependence of charm production is consistent with N_{bin} scaling

Charm cross section from STAR

Y.F. Zhang (STAR), SQM06



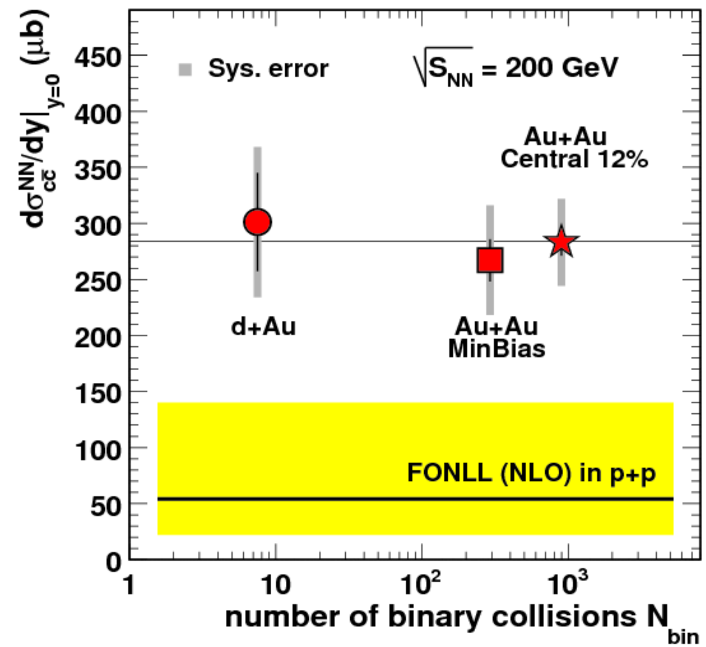
Three independent measurements

Three independent detector systems

1)Charm from hadronic channel

2)Charm from muon at low p_T (~0.2GeV/c)

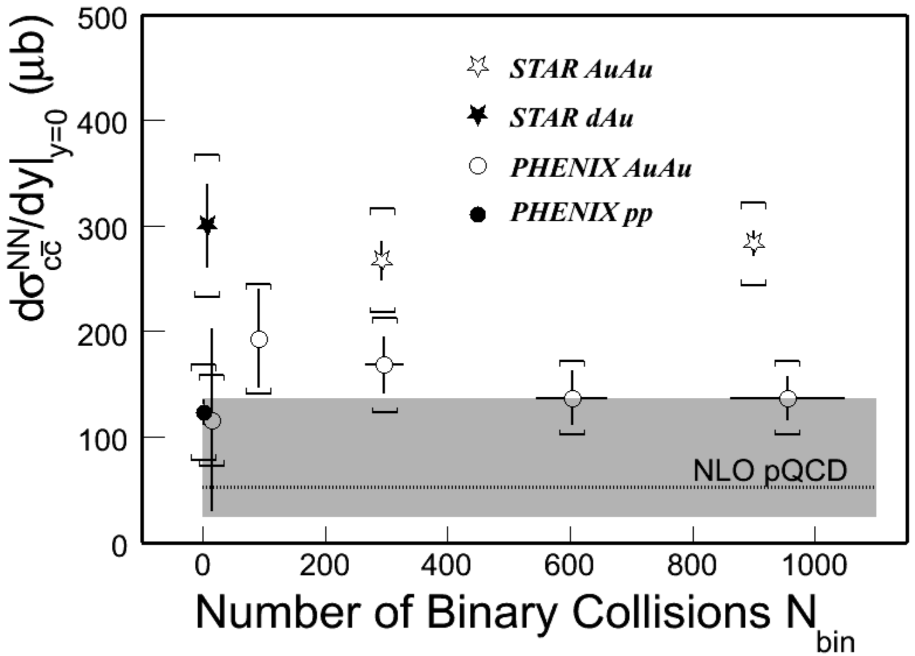
3)Charm from electrons



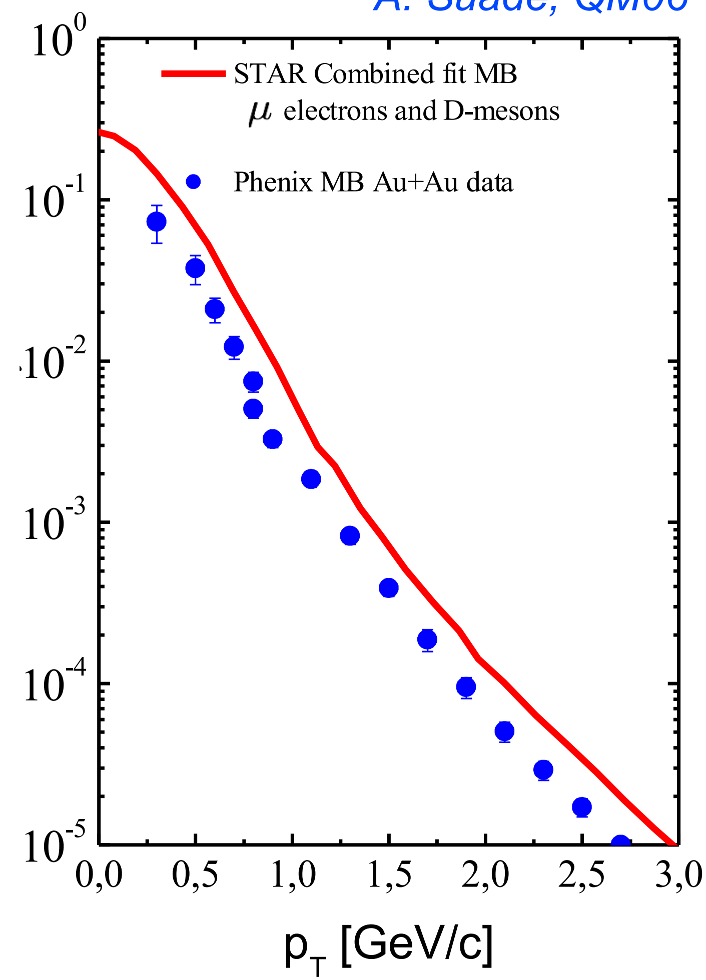
Charm yields are ~5x FONLL calculations

N_{bin} scaling preserved from d+Au to central Au+Au collisions

Comparisons between PHENIX and STAR



A. Suade, QM06



0) Approximate N_{bin} scaling from p+p to Au+Au central

1) Yields: STAR ~2x PHENIX

2) p_T shapes are consistent

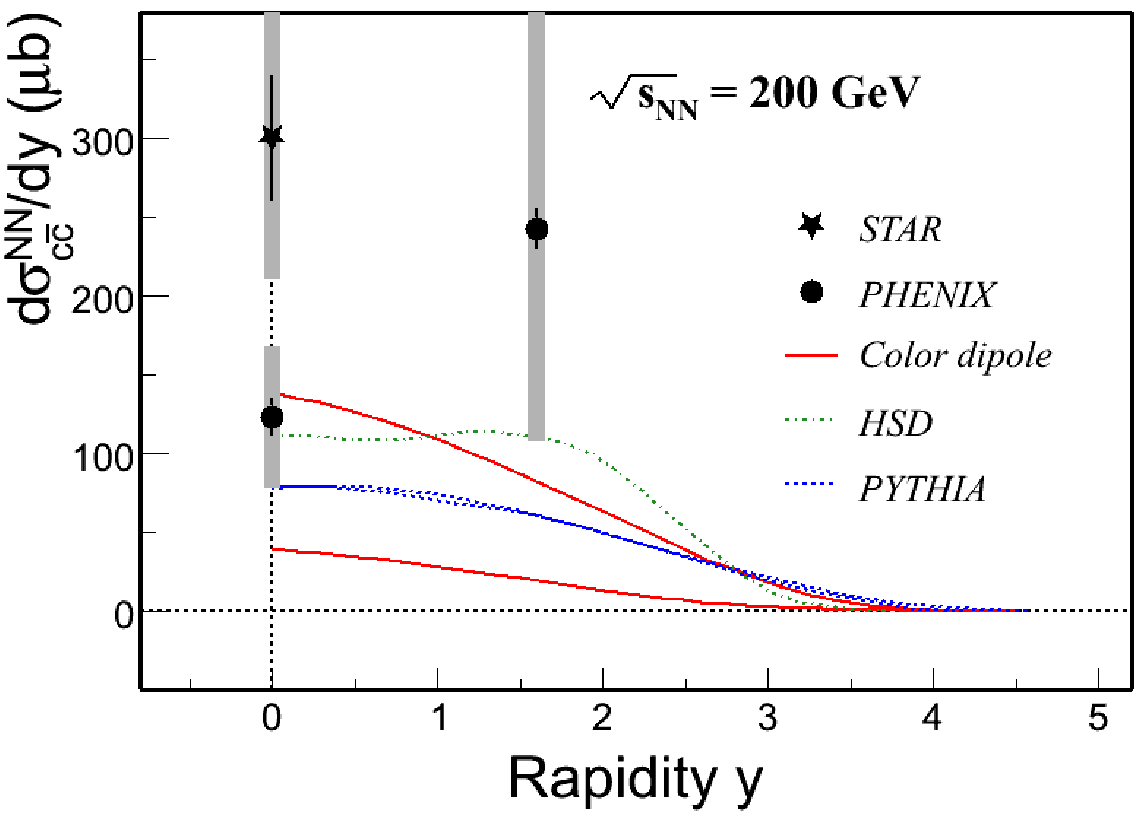
Next RHIC run: long d+Au run

STAR material reduced to <1%X_0

A good opportunity to solve the discrepancy between two experiments

Rapidity dependence

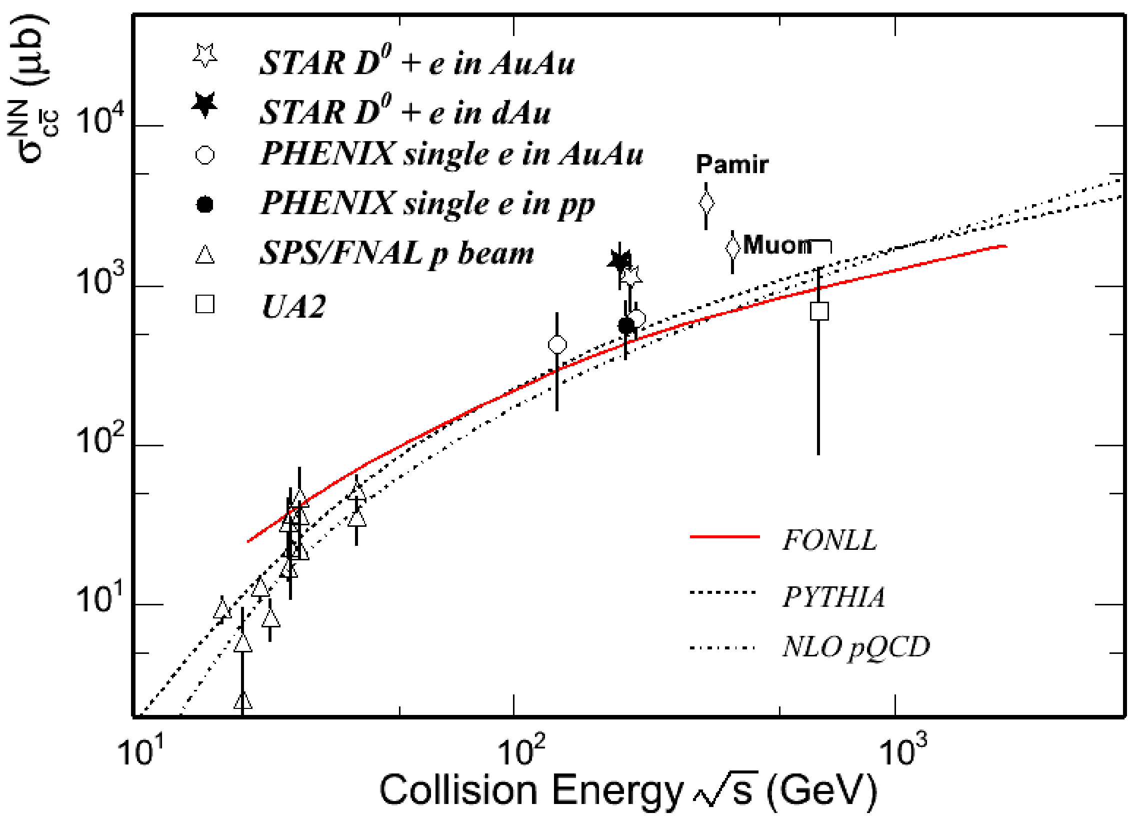
STAR *PRL 94 (2005) 062301* d+Au D^0+e measurement
PHENIX *PRL 97 (2006) 252002* p+p central arm electron measurement
PHENIX *nucl-ex/0609032* p+p forward arm muon measurement



E.L. Bratkovskaya et al, *PRC 67 (2003) 054905*
J. Raufeisen et al, *PRD 67 (2003) 054008*
R. Vogt *hep-ph/0203151*

In data, rapidity extrapolation uncertainty in X-sec for measurements at mid-rapidity is ~15%

Charm cross section vs energy



- STAR > pQCD
  PHENIX >~ pQCD
- Charm total cross section is a critical reference for J/ψ suppression /enhancement determination.
- Scales (μ_F and μ_R) may be energy dependent.

FONLL: $\mu_F = \mu_R = \mu = \sqrt{p_T^2 + m_c^2}, m_c = 1.2GeV/c^2$

PYTHIA: CTEQ5M1, MSEL=1

NLO: MRST $\mu = 2m_c, m_c = 1.2GeV/c^2$

Charmonium suppression/enhancement ?

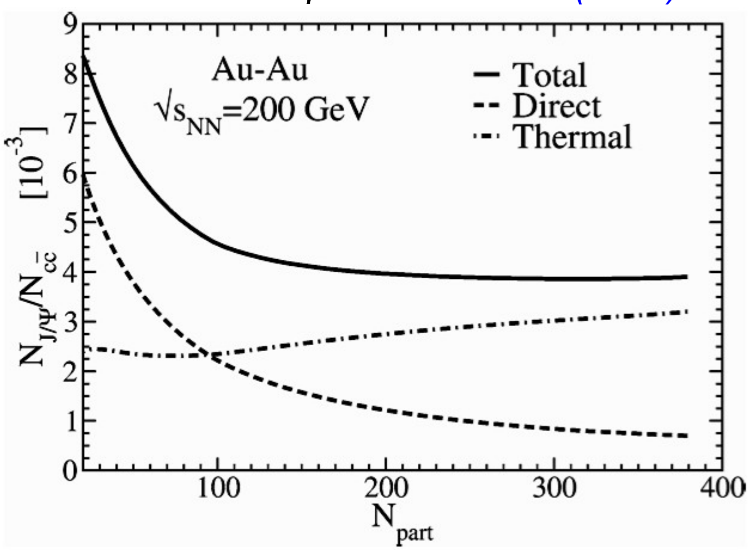
(1) direct pQCD production
(2) medium effect (chiral)
(3) absorption (color screening)

Central AuAu collisions at RHIC

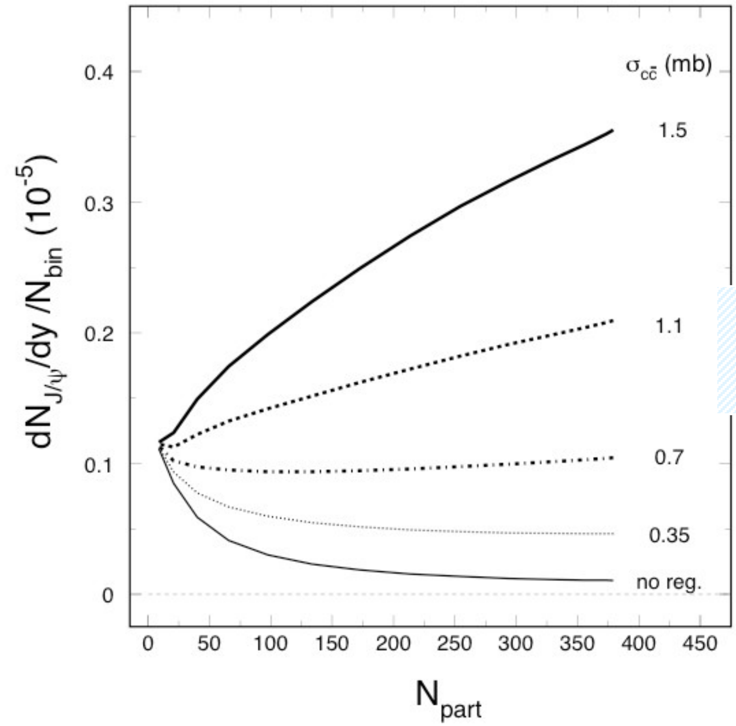
dN/dy(c$\bar{c}$) ~ 5-10

$$c + \bar{c} \rightarrow J/\psi + X$$

L.Grandchamp et al NPA 790 (2002) 415



L. Grandchamp, private comm.



Precise centrality dependence measurements on charm production cross section are important!

Charm energy loss

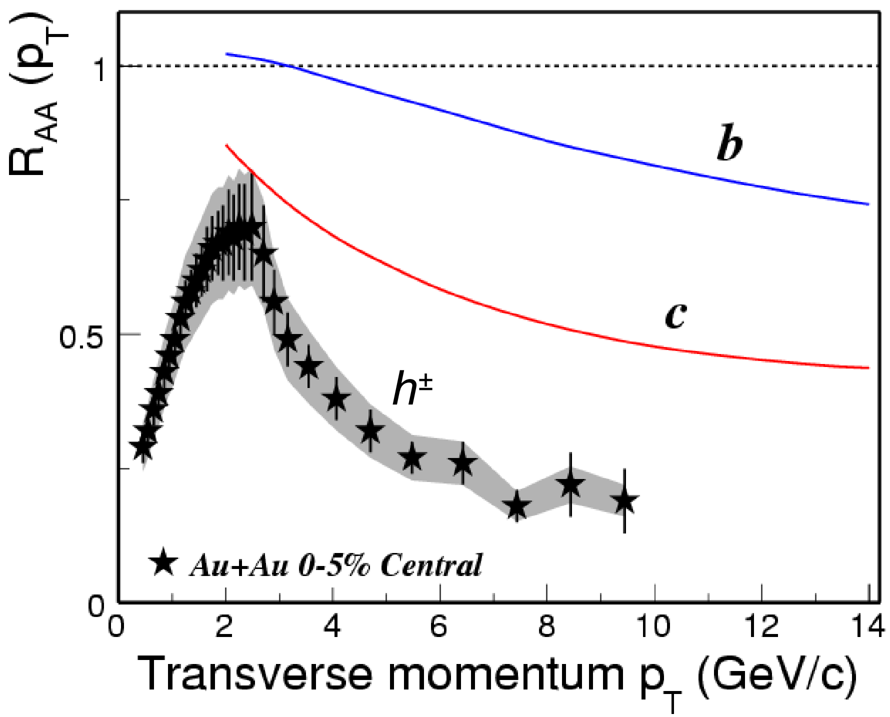
Heavy quark loss less energy due to suppression of small angle gluon radiation

"Dead Cone" effect

Y. Dokshitzer & D. Kharzeev PLB 519(2001)199

$$dP = \frac{\alpha_s C_F}{\pi} \frac{d\omega}{\omega} \frac{k_\perp^2 dk_\perp^2}{(k_\perp^2 + \omega^2\theta_0^2)^2} = \frac{dP_0}{(1+\theta_0^2/\theta^2)^2}$$

$$\theta_0 \equiv \frac{M}{E} \qquad \theta \equiv \frac{k_\perp}{\omega}$$



M. Djordjevic, et. al. PRL 94(2005)112301

B.W. Zhang et. al. PRL 93(2004)072301

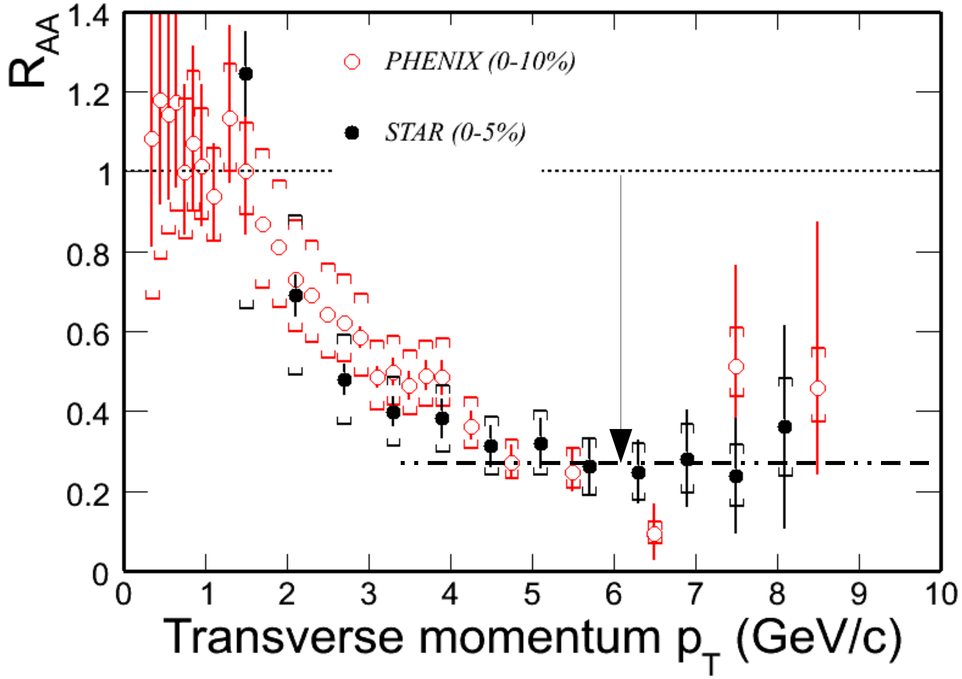
N. Armesto et. al. PRD 71(2005)054027

R. Rapp et. al. NPA 774 (2006) 685

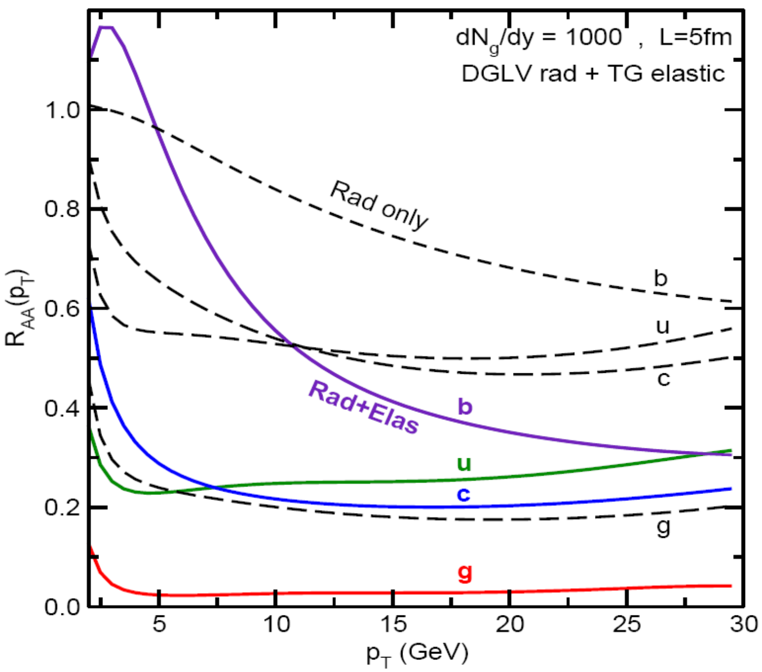
Energy loss of heavy quarks and light quarks

--- Probe the medium property the nature of parton interaction !

Challenge to radiative energy loss



PHENIX PRL 98 (2007) 172301
STAR PRL 98 (2007) 192301

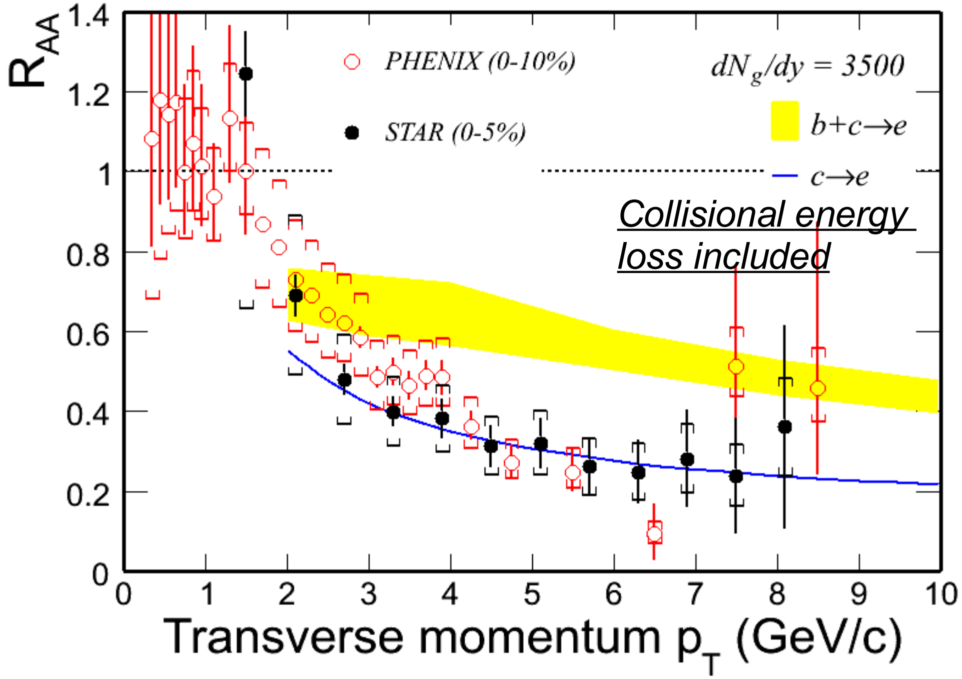


S. Wicks et al., NPA 784 (2007) 426

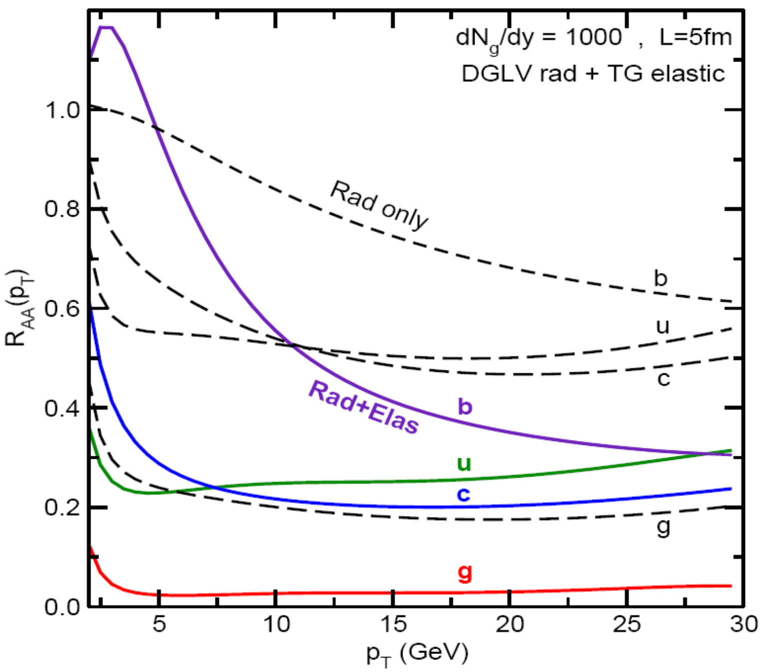
Radiative energy loss mechanisms can only account for part of strong suppression of R_{AA} for electrons.

Elastic collision energy loss becomes important at $\gamma\beta$ ~1

Challenge to radiative energy loss



PHENIX PRL 98 (2007) 172301
STAR PRL 98 (2007) 192301



S. Wicks et al., NPA 784 (2007) 426

Radiative energy loss mechanisms can only account for part of strong suppression of R_{AA} for electrons.

Elastic collision energy loss becomes important at $\gamma\beta$ ~1

Re-visit radiative energy loss in a dynamic medium

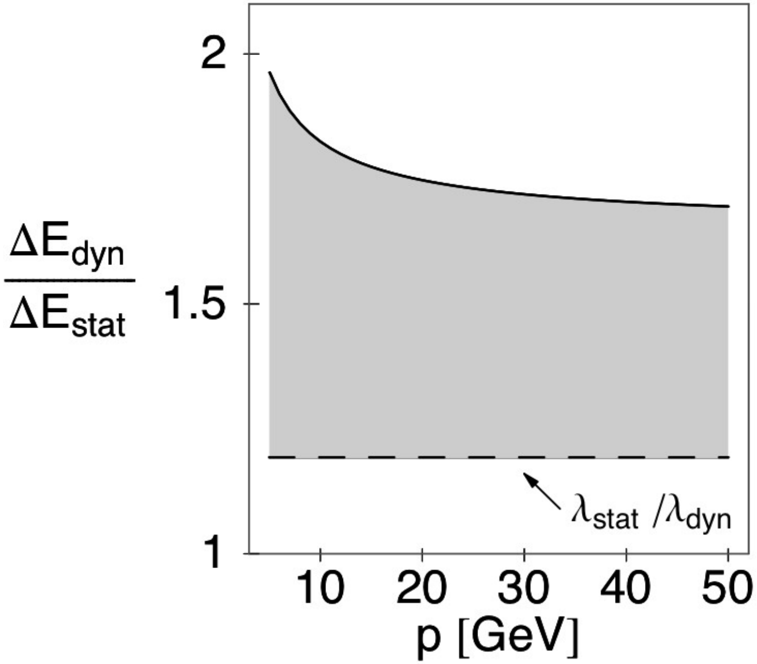
Previous radiative energy loss calculation is based on that the collisional energy loss is exactly 0 --- “static” medium.
→ Need recalculation if the collisional energy loss is not negligible.

First try: *M. Djordjevic and U. Heinz, arXiv:0705.3439*

Infinite and time-dependent QCD medium consist of dynamic components

$$\lambda_{\rm dyn} \Longleftrightarrow \lambda_{\rm stat} = \frac{\lambda_{\rm dyn}}{c(n_f)} \longrightarrow \sim 20\%$$

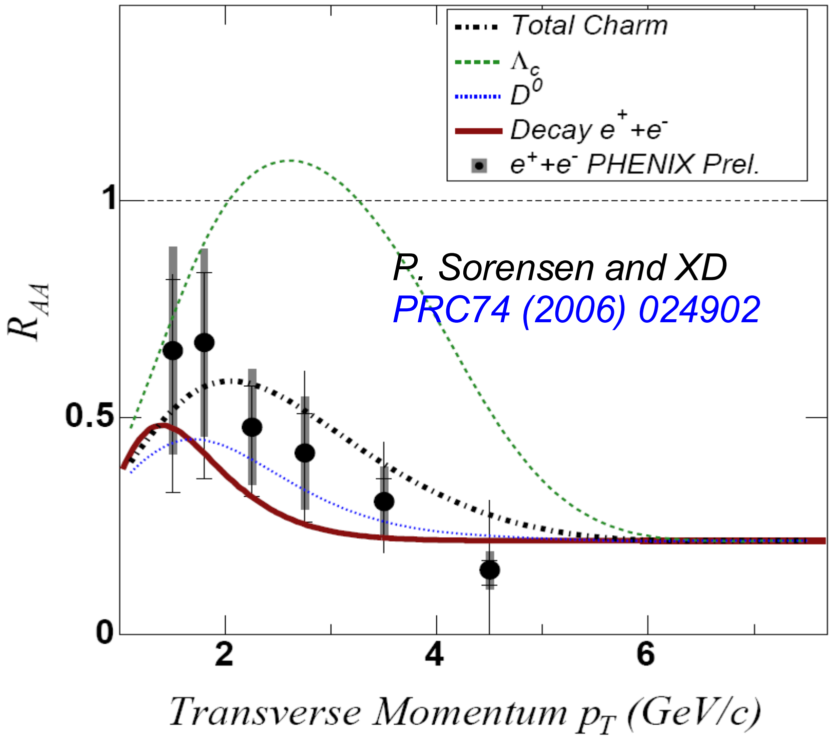
$$\left[\frac{\mu^2}{\boldsymbol{q}^2(\boldsymbol{q}^2+\mu^2)}\right]_{\rm dyn} \Longleftrightarrow \left[\frac{\mu^2}{(\boldsymbol{q}^2+\mu^2)^2}\right]_{\rm stat} \longrightarrow \sim 50\%$$

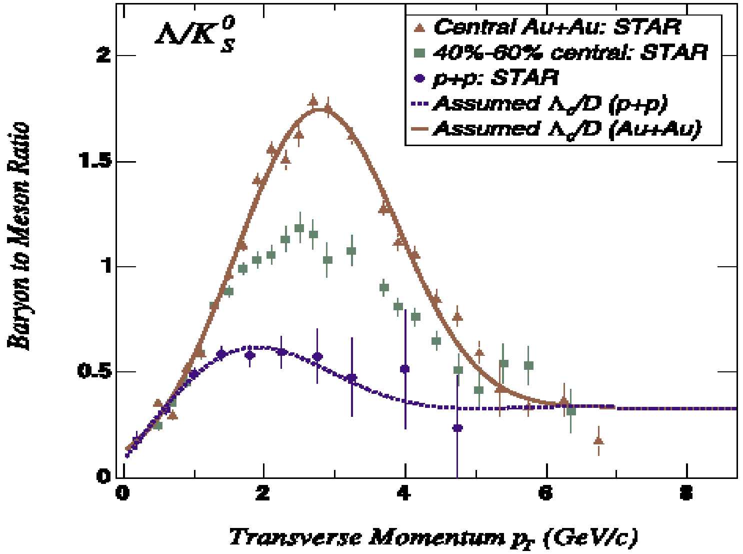


Further detail study on the energy loss in dynamic medium is called for!

Charm baryon contribution

$D^0 \to e^+ + X$ B.R. (6.87±0.28)%
$D^+ \to e^+ + X$ B.R. (17.2±1.9)%
$\Lambda_c^+ \to e^+ + X$ B.R. (4.5±1.7)%





S. Gadrat, *SQM07* *Another analysis*

- enhancement region for charm may at higher p_T region

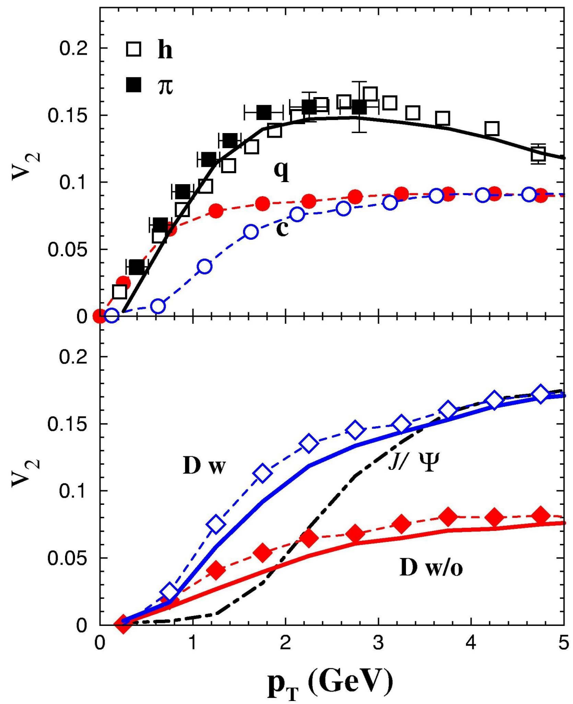
c/b energy loss prediction from Wick's paper

Need to measure charm mesons and baryons separately!

Charm elliptic flow

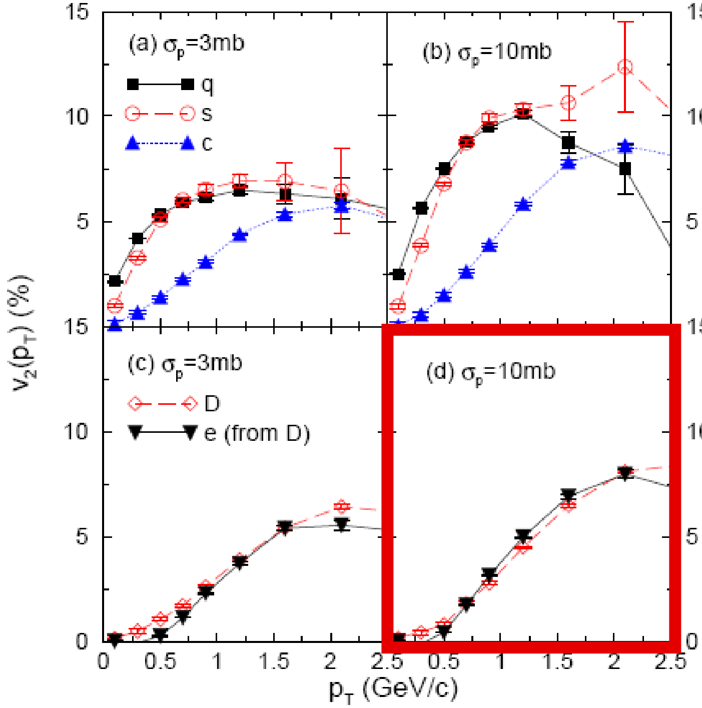
✓ Coalescence approach

V. Greco et al., PLB 595(2004)202



✓ AMPT transport model

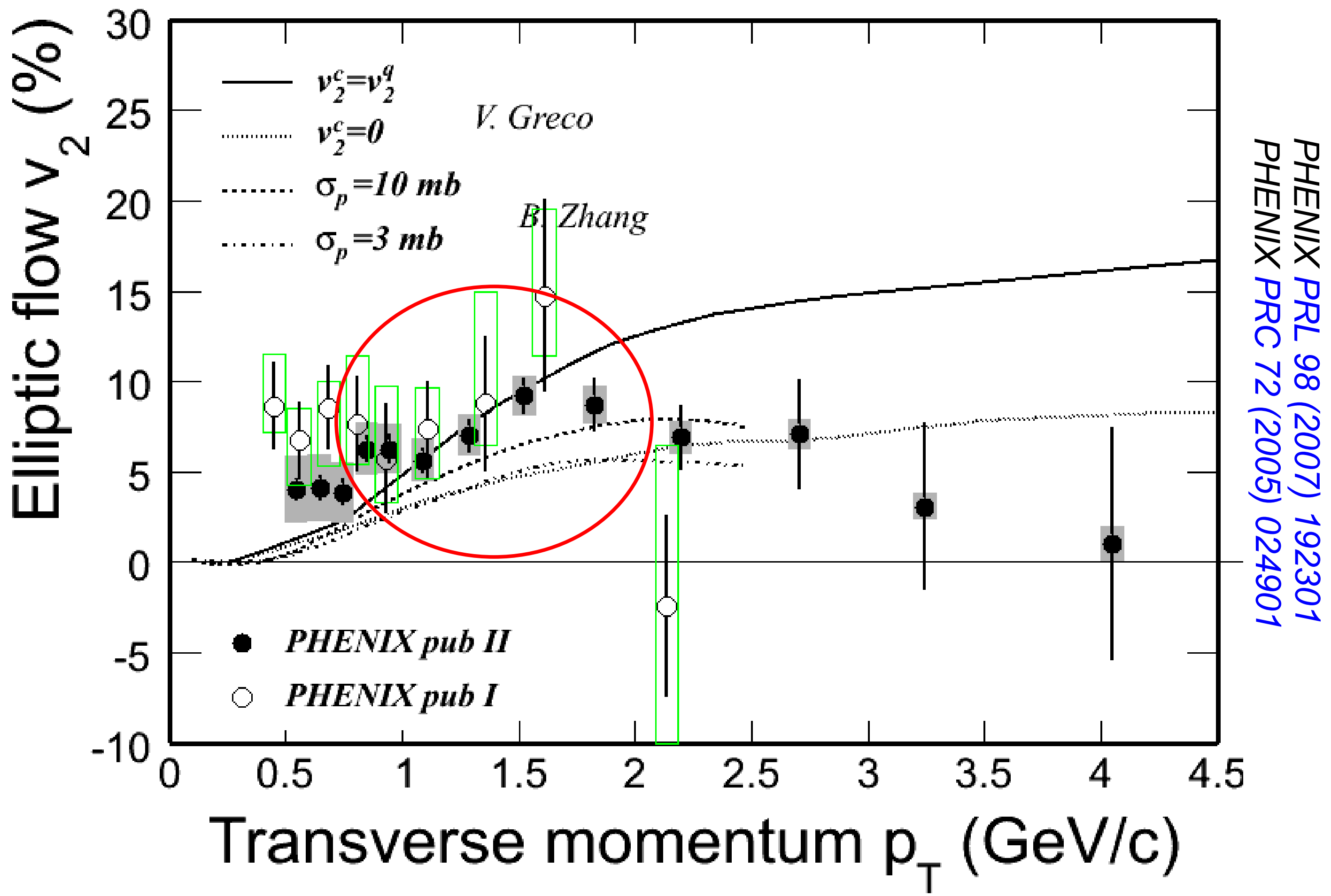
B. Zhang et al., PRC 72 (2005) 024906



Large cross section needed to reach high v_2 : Charm quark flows → Indication of light flavor thermal equilibrium!

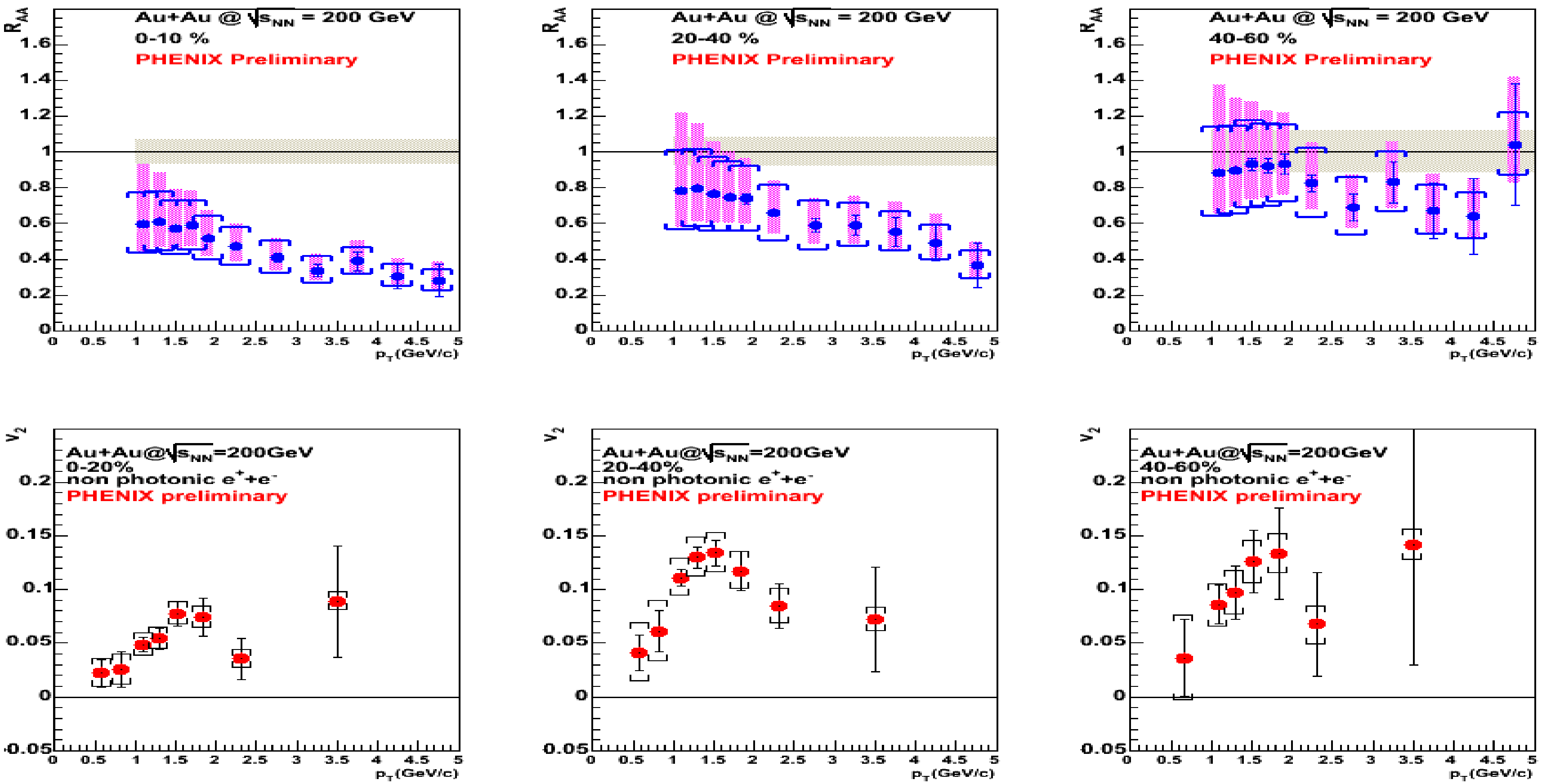
Is the large cross section realistic?

Non-photonic electron v_2



➢ $v_2(e)$ favors non-zero $v_2(c)$ at $p_T(e)$<2 GeV/c.

v_2 and R_{AA}



S. Sakai *(PHENIX), RHIC Users Mtg 06*

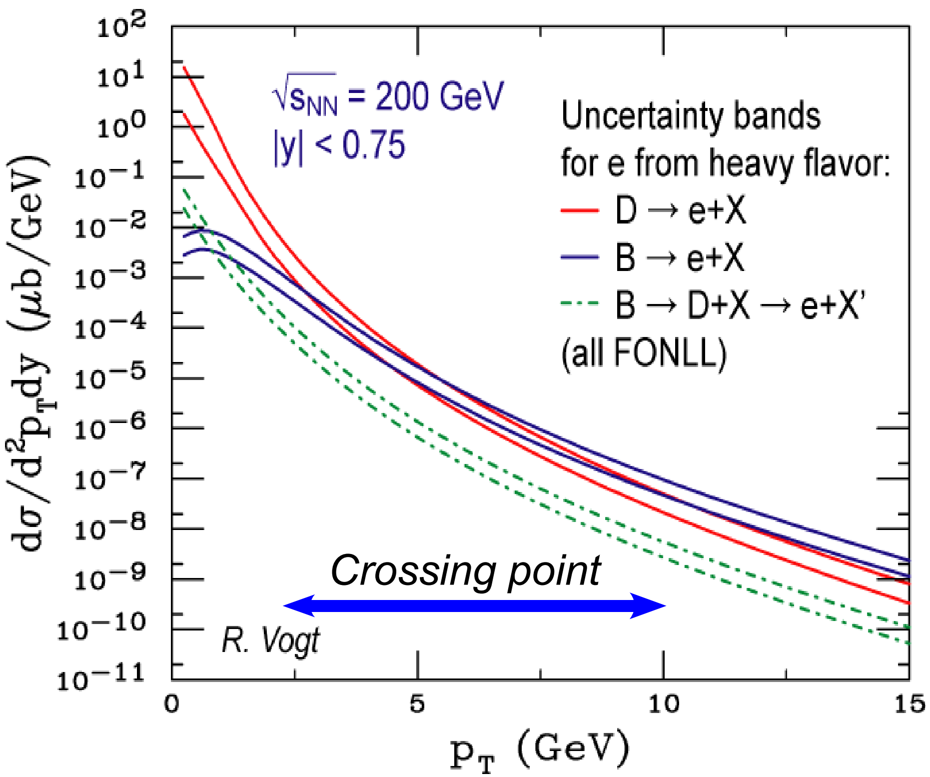
- R_{AA} ~ 1.0 @ peripheral collision but v_2 still non-zero
- *charm quarks* interact with *medium* not only in central but also in peripheral collisions

Bottom contribution

Non-photonic electrons:

- charm semi-leptonic decay
- bottom semi-leptonic decay
- others...

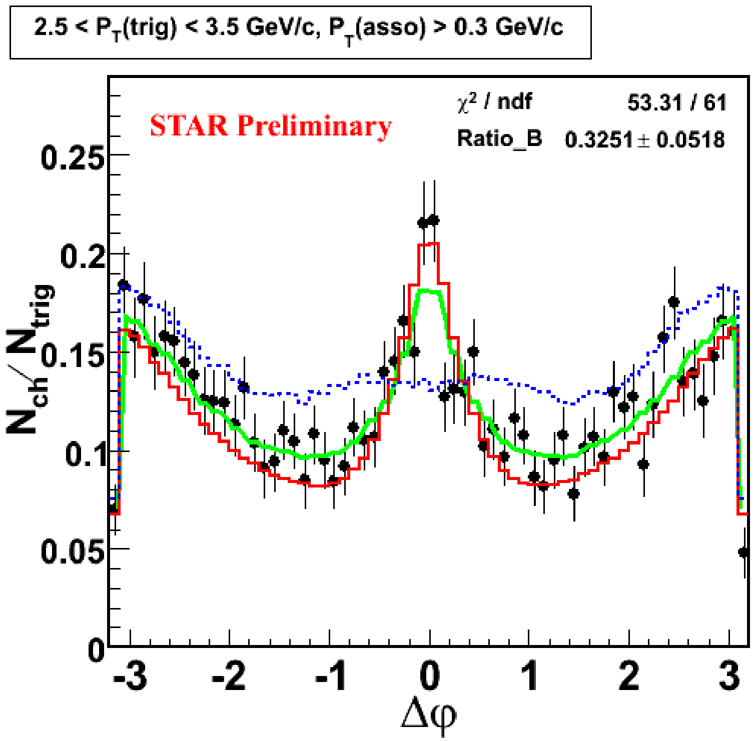
M. Cacciari *et al.*, *PRL 95 (2005) 122001*

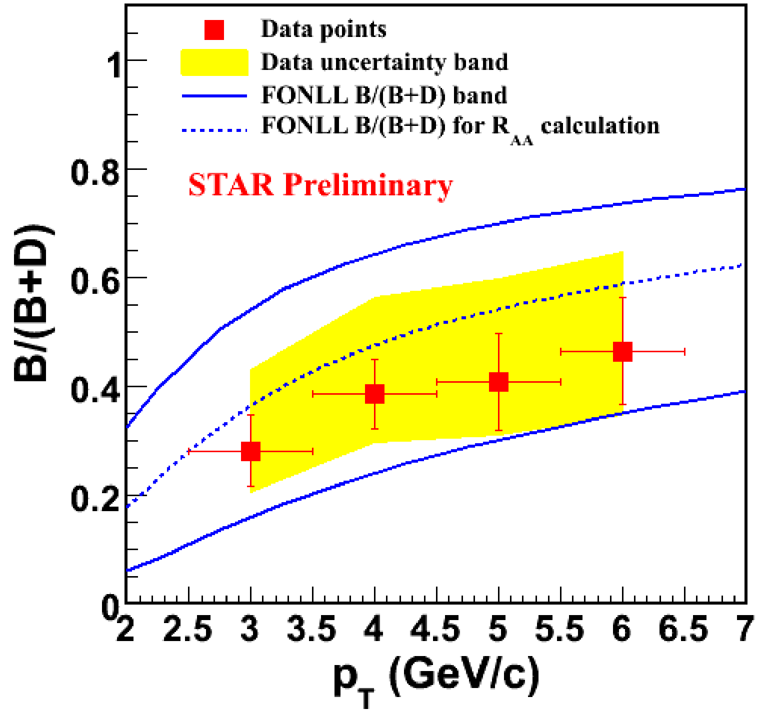


Theoretically, the bottom contribution to the total single electron spectrum has a big uncertainty. The crossing point of e(B) and e(D) spectra can vary from ***~3 GeV/c - ~10 GeV/c***

Bottom contribution

X. Lin *(STAR), QM06*





e-h correlation: which is different between e(D)-h and e(B)-h.

The result shows the bottom contribution to total non-photonic electrons is consistent with FONLL calculations within uncertainties.

Bottom contribution to non-photonic electrons is non-zero!

Summary

Achievements

Charm production cross sections in p+p, d+Au and AuAu

Strong suppression of non-photonic electron spectrum in central AuAu

Finite v_2 of non-photonic electrons in AuAu

Open issues

Measured X-sec > pQCD
Systematic difference between PHENIX and STAR
Large uncertainties

Bottom's contribution

Nature of parton interacting with medium

Charm quark collectivity

Much more precise measurements on heavy flavor are called for !

Summary

Electron approach experiences:

1) spectrum

low p_T: no distinguishing power

high p_T: bottom is largely uncertain

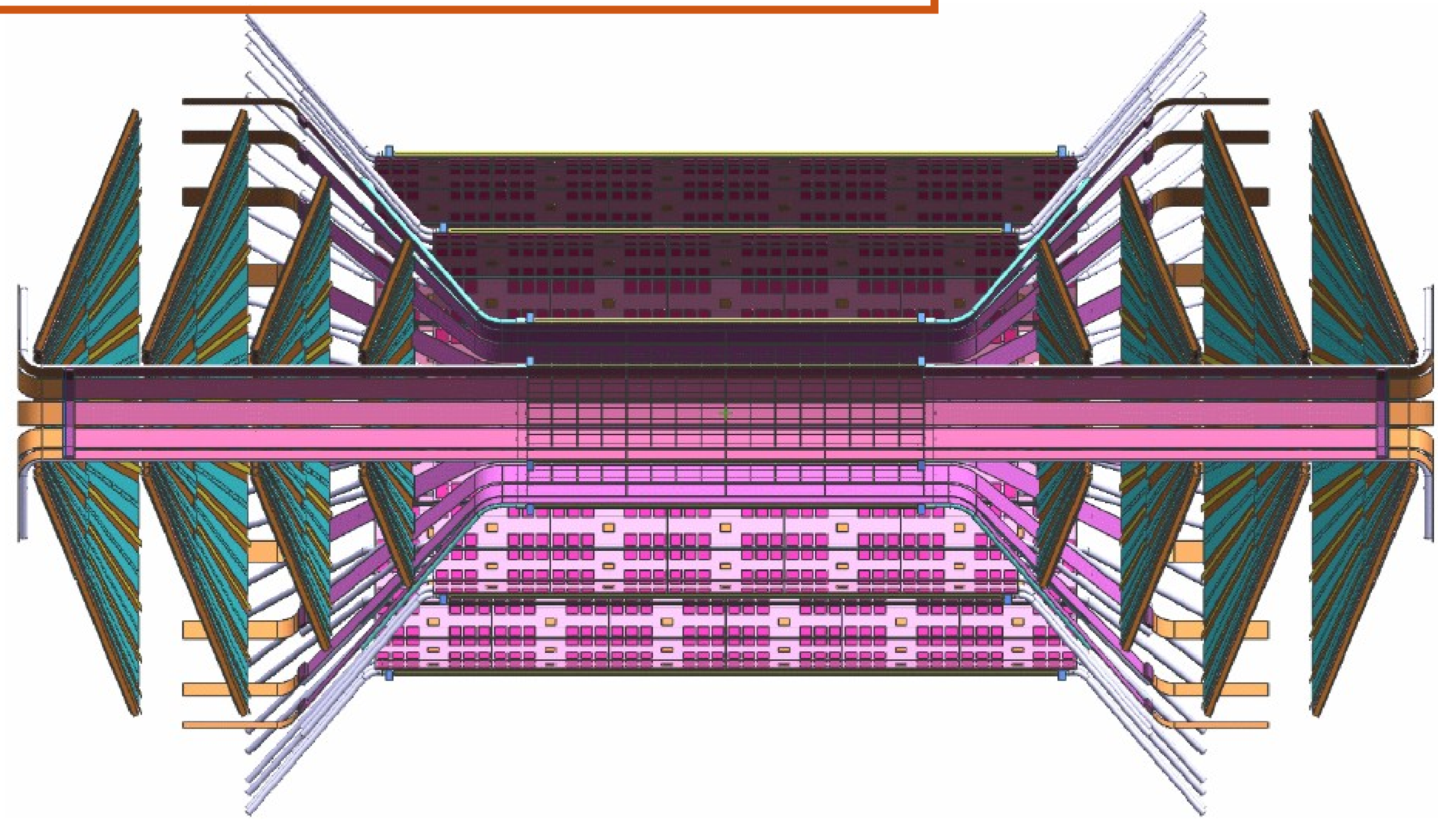
2) v_2

large statistical and systematical uncertainties

- ***Single electron approaches are placeholder.***
- ***Identified open charm (beauty) measurements are definitely necessary.***
- ***The upgrade programs in PHENIX and STAR are essential!***

Upgrade detectors at PHENIX

Barrel and Endcap Silicon Vertex Tracker

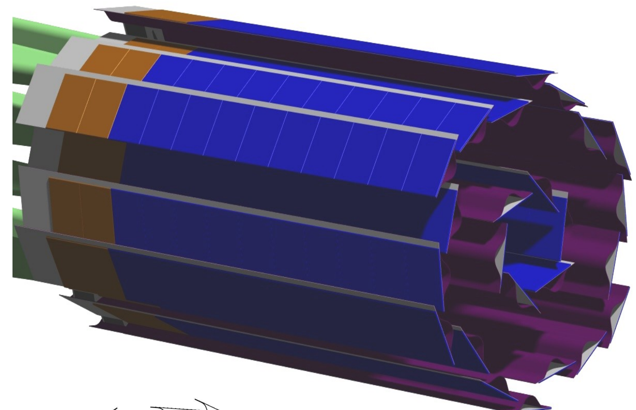


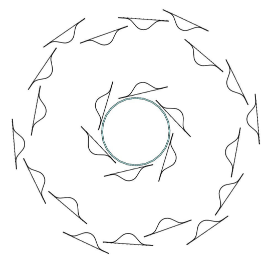
- Direct charm/beauty reconstruction: low p_T via e/μ, high p_T via Kπ

Upgrade detectors at STAR

Full Barrel MRPC - TOF

Heavy Flavor Tracker





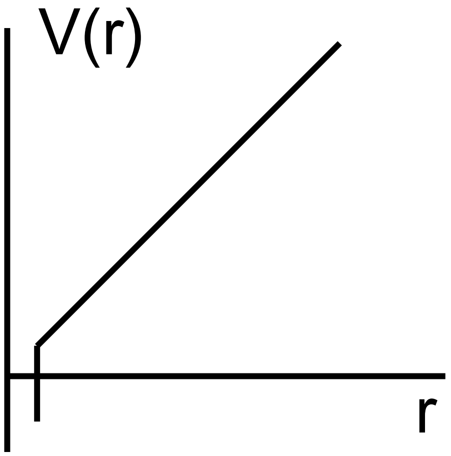
- Full open charm measurements
  - direct D-meson V_0 reconstruction
  - spectrum, v_2 (low → high p_T), correlations …

Back up

QCD in vacuum

Quark confinement

In vacuum, the potential increases linearly with the distance between quarks
➔ Quarks are confined

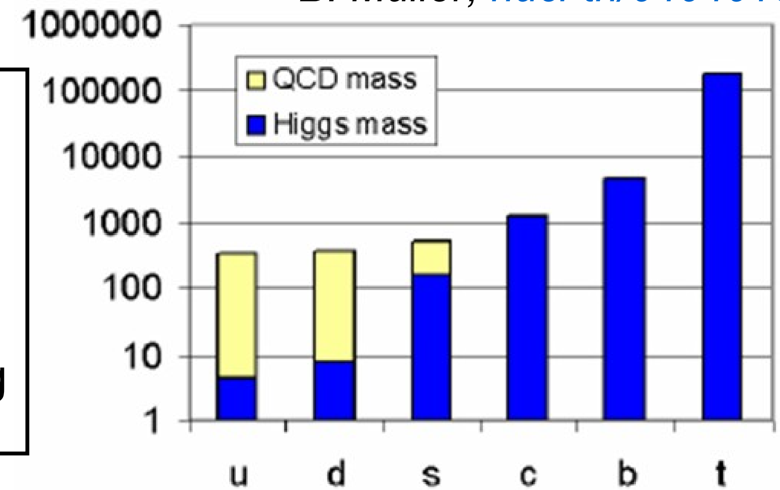


Mass origin

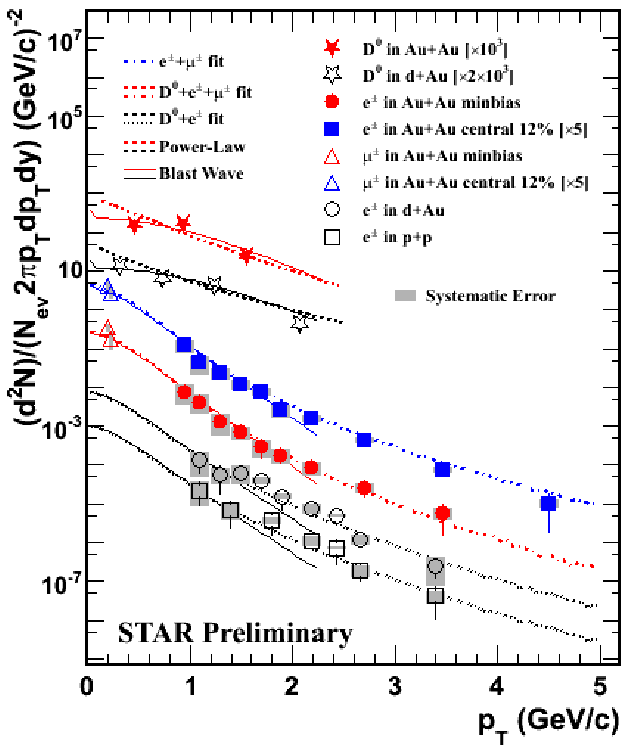
➢ Coupling with *electroweak* Higgs field
→ Higgs mass

➢ Coupling with quark-gluon condensates in vacuum (*Strong* coupling)
→ QCD mass / Chiral symmetry breaking

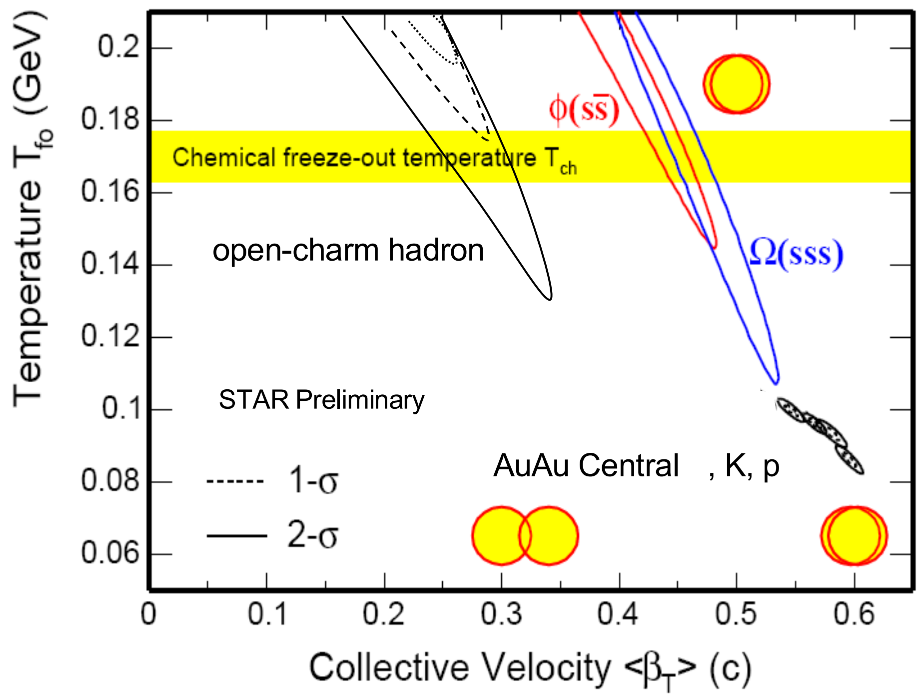
B. Müller, nucl-th/0404015



Charm collective motion



Y.F. Zhang (STAR), SQM06



Power-law and Blast Wave charm decay

D^0 + e fit in d+Au collisions.

D^0 + μ+ e fit in minbias Au+Au collisions.

μ+ e fit in central Au+Au collisions.

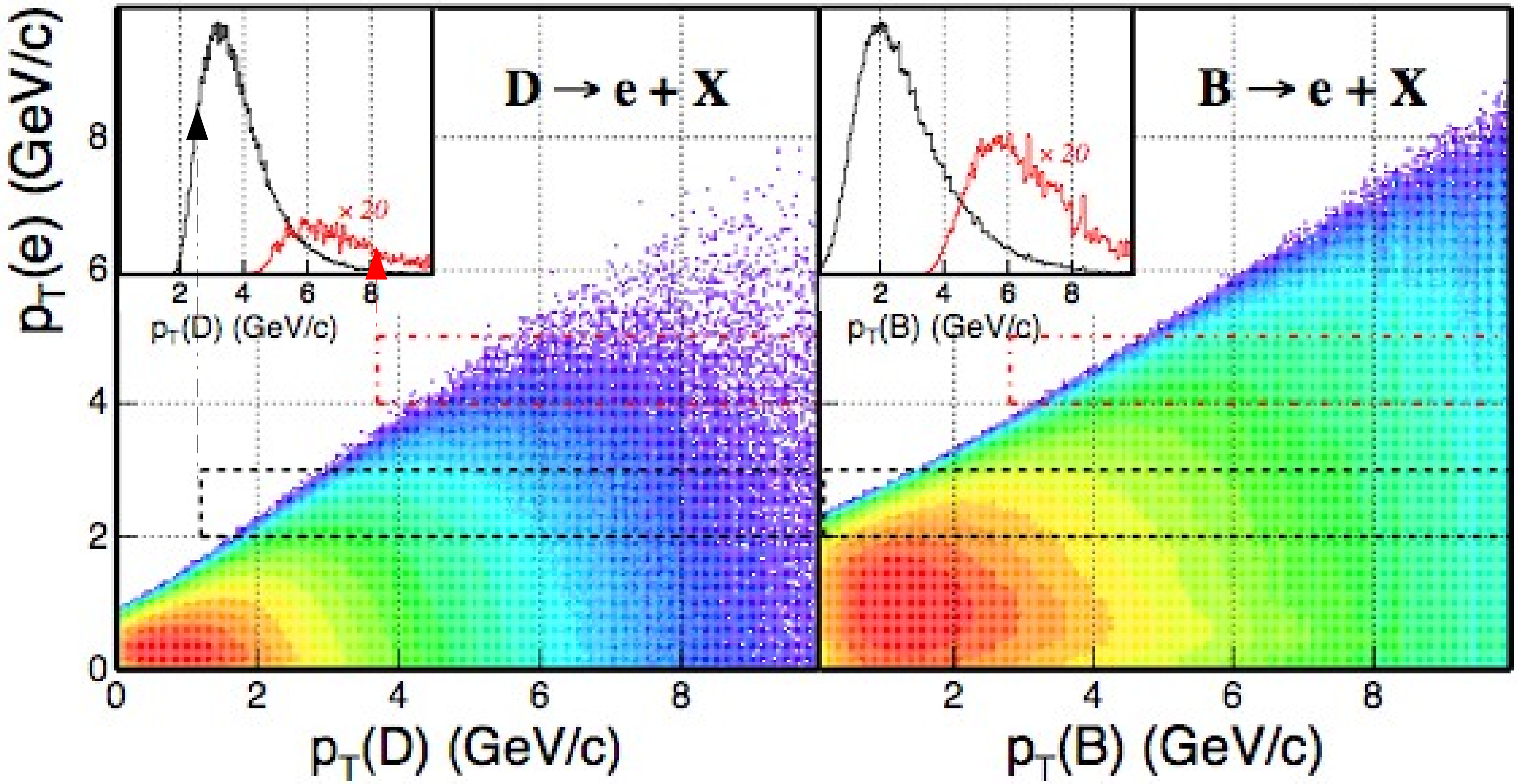
Expected to freeze out earlier

– T > 140 MeV

Collective velocity – charm flow?

$< \beta_T > < \phi\ , \Omega$

Correlations between electrons and D, B



The correlation between the decayed electrons and heavy-flavor hadrons is weak.