A Case For RHIC-II: Heavy Flavor Physics

Status Report of the RHIC-II Heavy Flavor Working Group

Thomas Ullrich for the HF Group

BNL Program Advisory Committee Meeting

November 3, 2005

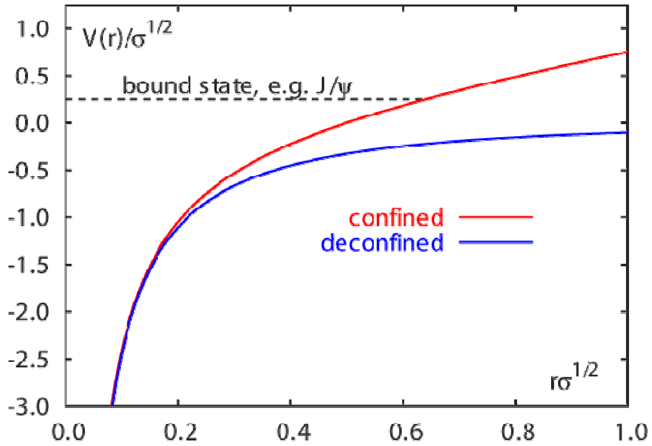
Heavy Flavor Group Conveners:
T. Frawley, R. Vogt, TU

Web site: http://rhicii-science.bnl.gov/heavy/

Why Quarkonia? – What Can We Learn?

Charmonia: J/ψ, Ψ', χ_c Bottomonia: ϒ(1S), ϒ(2S), ϒ(3S)

- Key Idea: Melting in the plasma
  - Color screening of static potential between heavy quarks:
    - J/ψ suppression: Matsui and Satz, *Phys. Lett. B* **178** (1986) 416
  - Suppression of states is determined by T_C and their binding energy



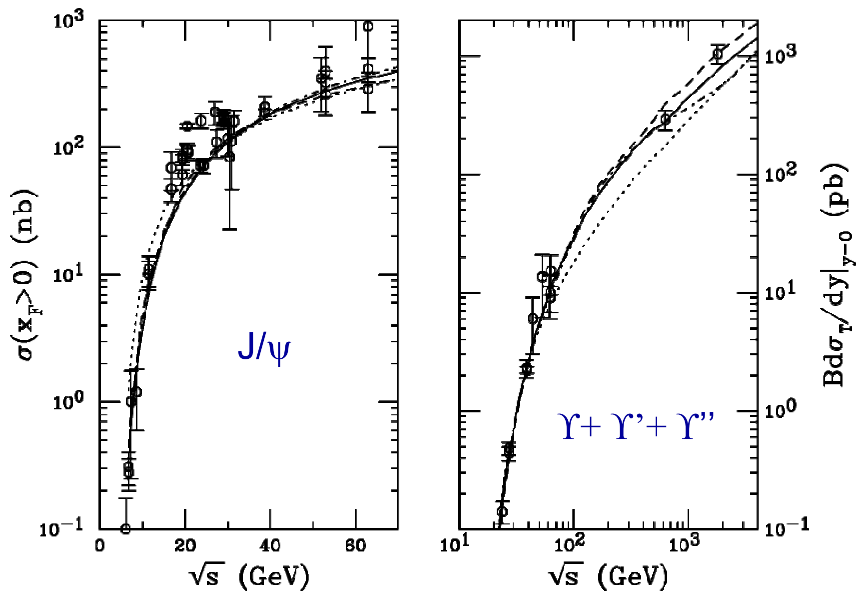
	$E_{binding}$ (GeV)
J/ψ	0.64
ψ'	0.05
χ_c	0.2
ϒ(1S)	1.1
ϒ(2S)	0.54
ϒ(3S)	0.31

- Sequential disappearance of states:
  - ⇒ Color screening ⇒ Deconfinement
  - ⇒ QCD thermometer ⇒ Properties of QGP

Quarkonia – Baseline Theory (pp/dA)

- Need properly "normalized" Quarkonia baseline
  - pp ⇒ production baseline
  - d+Au ⇒ cold matter effects (absorption, shadowing)
- pp
  - Color Evaporation Model (CEM)
  - Quarkonium production treated as fraction of all $\bar{Q}Q$ pairs below $\bar{H}H$ threshold
  - CEM taken to NLO (Gavai et al., G. Schuler and R.Vogt)
  - Parameters adjusted to existing data

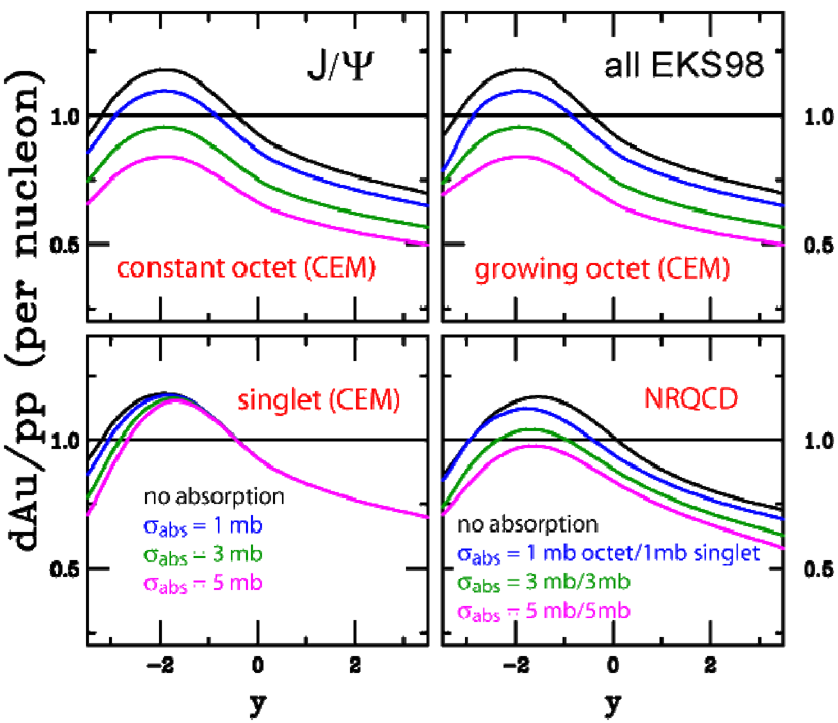
	Direct production ratio
J/ψ	0.62
ψ’	0.14
χ_{c1}	0.60
χ_{c2}	0.99
ϒ(1S)	0.52
ϒ(2S)	0.33
ϒ(3S)	0.20

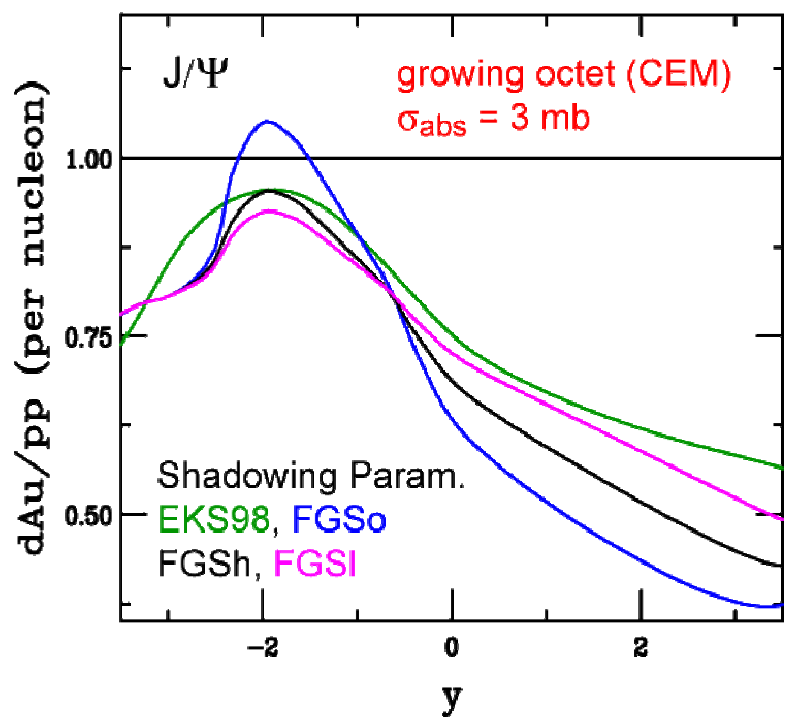


hep-ph/0412158

Quarkonia – Baseline Theory (pp/dA)

- pA
  - Nuclear Absorption
    - Breakup of quarkonia in the final state
    - Depends if produced as color singlet or octet
  - Shadowing
    - Modification of PDFs in the nucleus w.r.t. free nucleon
    - NB: y-distributions more sensitive than p_T



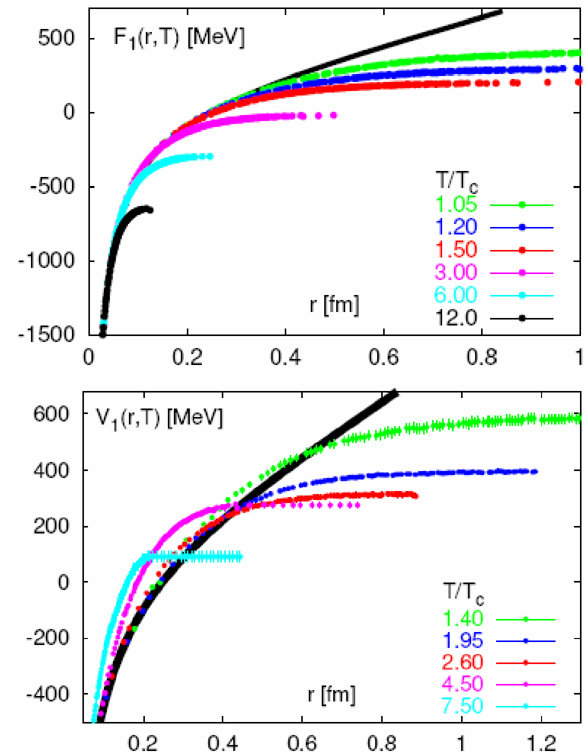


R. Vogt, RHIC-II Science Workshop

Quarkonia – Lattice QCD (AA)

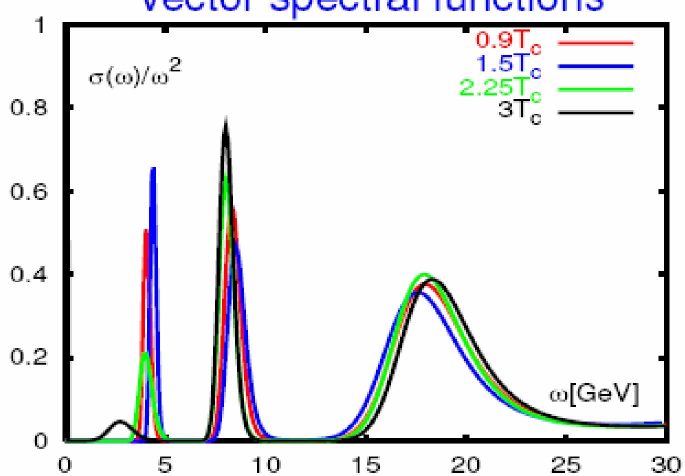
Recent developments:

- **Heavy Quark potential?**
  - Singlet free energy: F_1 (entropy term?)
  - Singlet energy: V_1
- **When do states really melt?**
  - Neither F_1 nor V_1 are potentials
  - $\Rightarrow$ spectral functions (results consistent with V_1)
  - $\Rightarrow$ J/ψ melts at 1.5-2.5 T_C
  - $T_{diss}(\psi') \approx T_{diss}(\chi_c) < T_{diss}(\Upsilon(3S)) < T_{diss}(J/\psi) \approx T_{diss}(\Upsilon(2S)) < T_{diss}(\Upsilon(1S))$



F. Karsch, RHIC-II Science Workshop

vector spectral functions



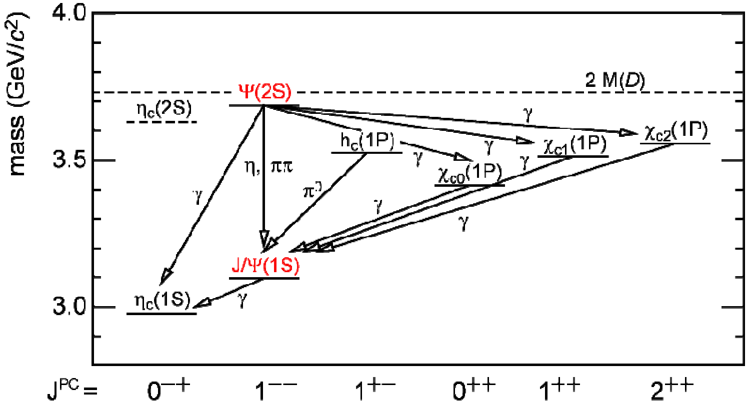
using F_1: S. Digal, P. Petreczky, H. Satz, Phys. Lett. B514 (2001) 57;

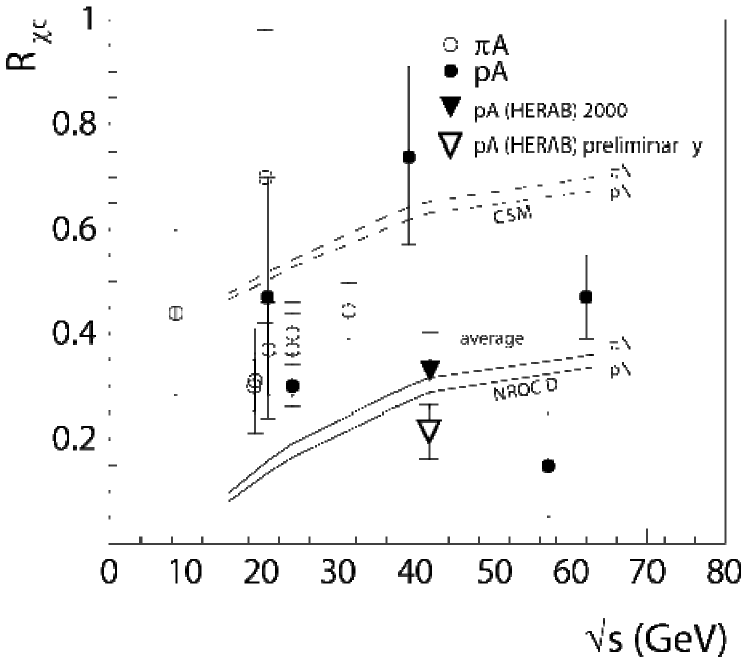
using V_1: C.-Y. Wong, hep-ph/0408020;

state	J/ψ	χ_c	ψ'	Υ	χ_b	Υ'	χ_b'	Υ''
E_s^i [GeV]	0.64	0.20	0.05	1.10	0.67	0.54	0.31	0.20
T_d/T_c	1.1	0.74	0.1 - 0.2	2.31	1.13	1.1	0.83	0.74
T_d/T_c	~ 2.0	~ 1.1	~ 1.1	~ 4.5	~ 2.0	~ 2.0	–	–

Collision with thermal gluons, $\langle p \rangle \sim 3\ T_c$ can lead to earlier dissociation: $dN_{J/\psi}/dt = -N_g \langle \sigma_{dis} \rangle$

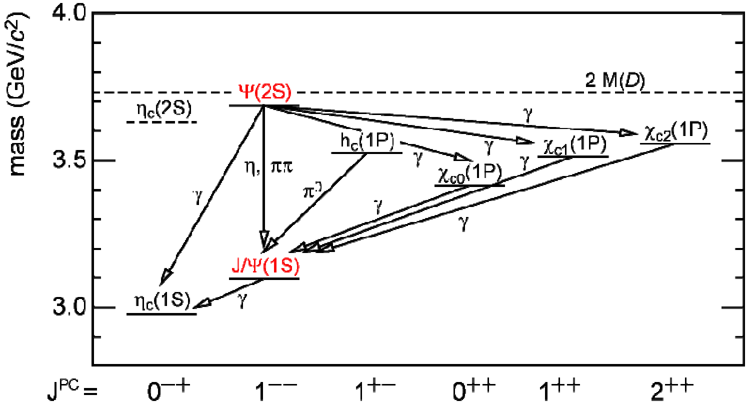
Quarkonia – Effects in AA

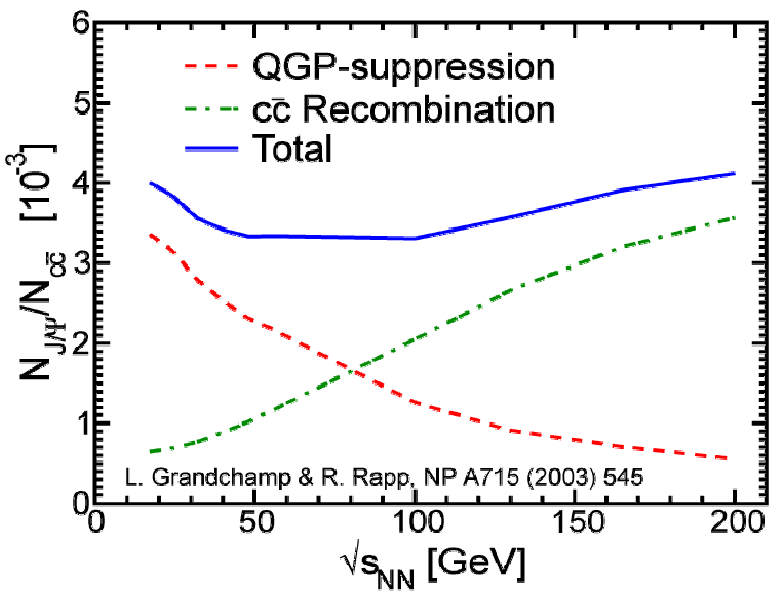




- Feed down:
  - Large from χ_c states (30-40% ?)
  - Not well measured in hadronic collisions
  - Unknown at RHIC energies

Quarkonia – Effects in AA





- Feed down:
  - Large from χ_c states (30-40% ?)
  - Not well measured in hadronic collisions
  - Unknown at RHIC energies
- Other sources of quarkonia production
  - Statistical coalescense (thermal production)
    - too small at RHIC – larger at LHC ?
  - Dynamic coalescence
    - coalescence: $\bar{c}+c \rightarrow J/\psi$
    - recombination: $J/\psi \rightarrow \bar{c}+c \rightarrow J/\psi$
    - $\Rightarrow$ narrower y and softer p_T distributions
- Quenching at high-p_T ($\Rightarrow$ discussed later)
- Comover absorption
  - $J/\psi + \pi\ (\rho) \rightarrow \bar{D}D$ (negligible for Υ)

Many effects that need to be understood to extract pure "suppression" mechanism

Open Heavy Flavor – What Can We Learn?

Open Heavy Flavor Mesons: D^0, D^*, $D^\pm$, D_s, B

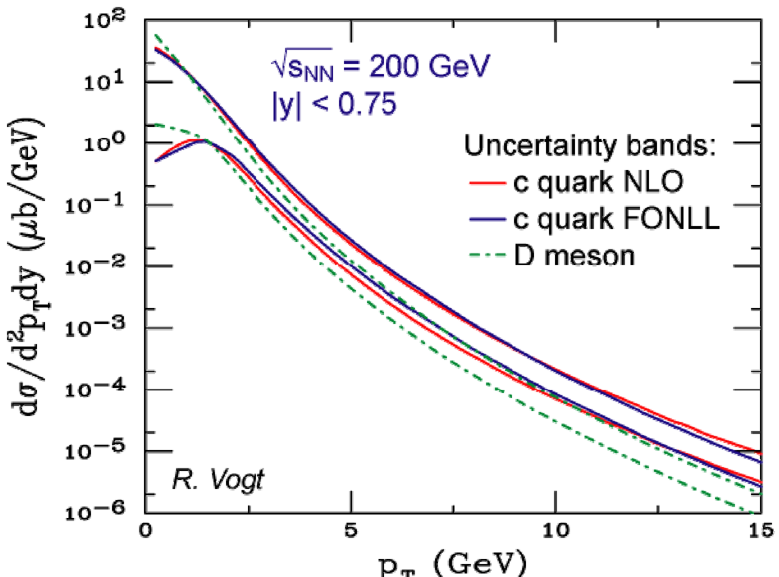
- Key Idea: Study interaction with hot and dense media
  - Yields
  - Spectra
  - Correlations
- High-p_T suppression $\Rightarrow$ Density of medium, E-Loss mechanism
- Low-p_T flow, spectra $\Rightarrow$ Thermalization ?
  $\Rightarrow$ Transport properties of the medium
- Charm-Charm, Charm-Hadron, J/ψ-Hadron Correlations:
  - Low-p_T $\Rightarrow$ Thermalization ?
  - High-p_T $\Rightarrow$ Tomography of medium

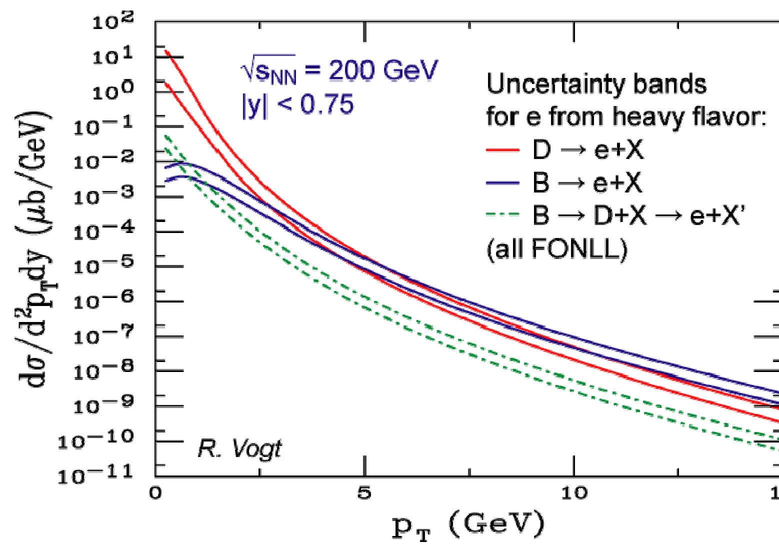
Study of heavy flavor $\Rightarrow$ Properties of QGP (Density, Thermalization)

Open Heavy Flavor – Baseline Theory (pp)

Heavy Quark production is a “hard” process ⇒ perturbative QCD

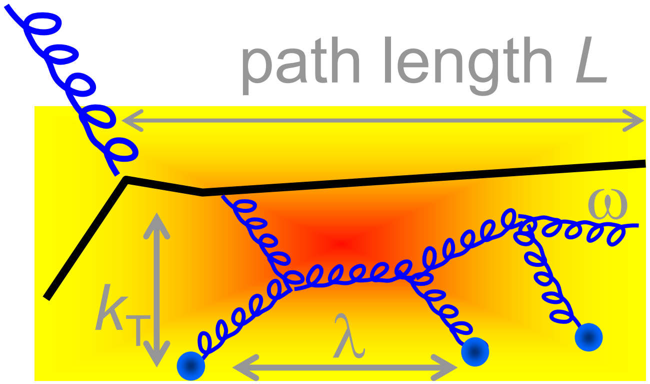
- Calculations on NLO (e.g. R. Vogt et al. hep-ph/0502203) depend on:
  - Quark mass m_c, m_b
  - Factorization scale μ_F (typically $\mu_F = m_T$ or 2 m_T)
  - Renormalization scale μ_R (typically $\mu_R = \mu_F$)
  - Parton density functions (PDF)
  - Fragmentation functions (FF) – plays important role
- Fixed-Order plus Next-to-Leading-Log (FONLL)
  - designed to cure large logs for $p_T >> m_q$ where mass is not relevant





M. Cacciari *et al.*, PRL 95:122001,2005

Open Heavy Flavor – Energy Loss in Medium

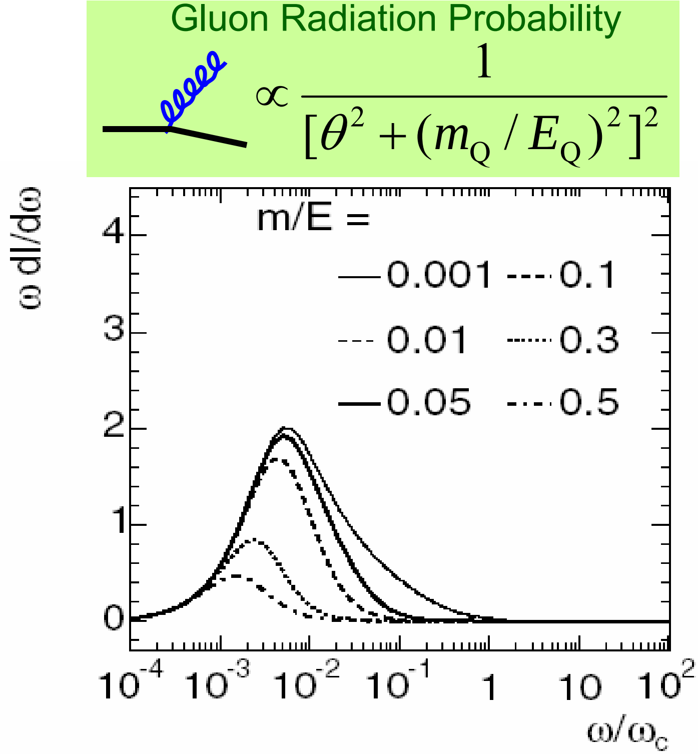


$$\Delta E \propto \hat{q} L^2$$

$\hat{q} \equiv$ transport coefficient

Various Models to describe E-loss in hot medium: BDMPS, GLV, …

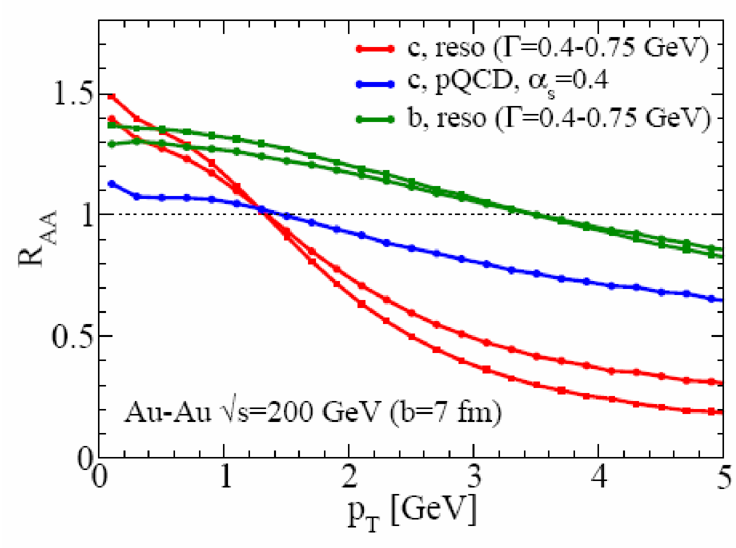
- In vacuum, gluon radiation suppressed at $\theta < m_Q/E_Q$
  - "dead cone" effect
  - implies lower energy loss (Dokshitzer-Kharzeev, '01)
  - energy distribution ω dI/dω of radiated gluons suppressed by angle-dependent factor
  - suppress high-ω tail
- Collisional E-loss: Qg → Qg, Qq → Qq
  - dE/dx ∝ ln p - considered small

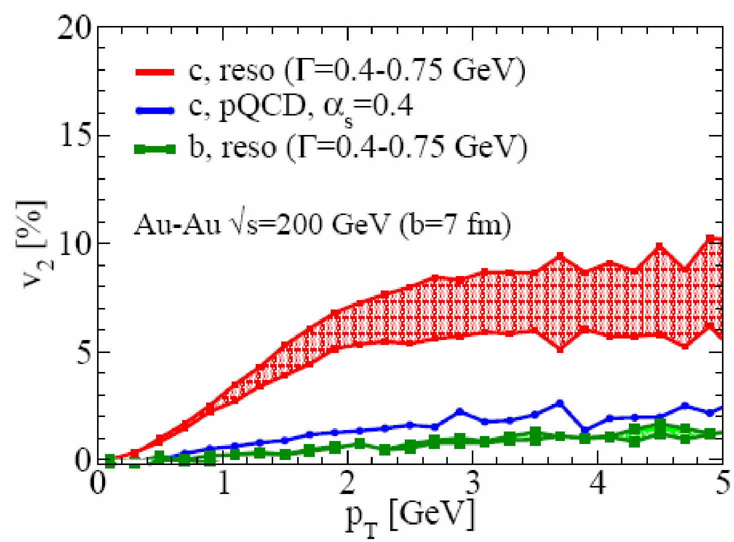


(Armesto, Salgado, Wiedemann, PRD 69 (2004) 114003)

Open Heavy Flavor – Elliptic Flow

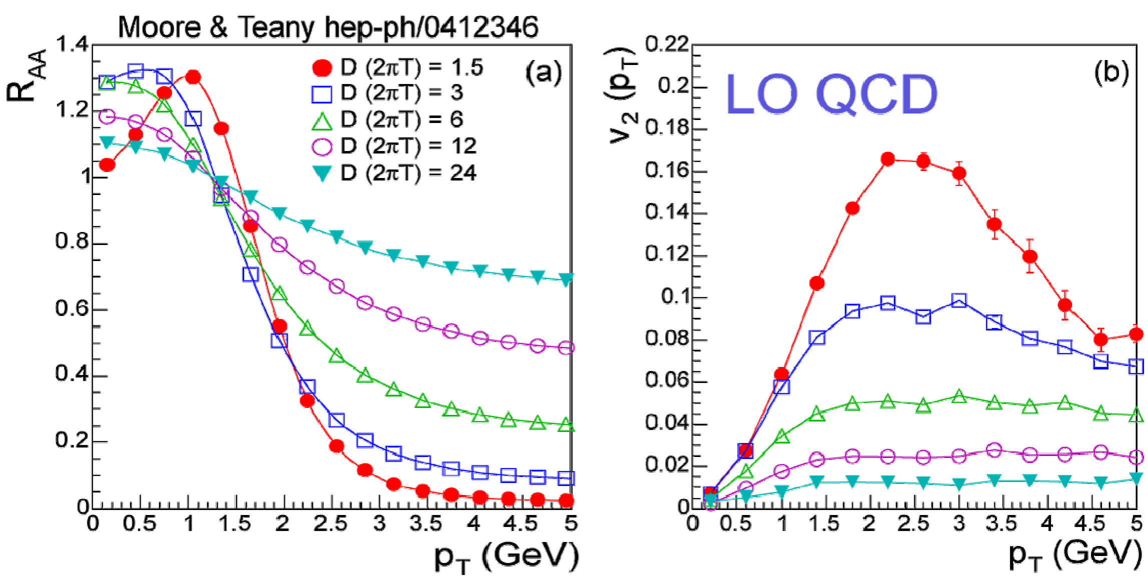
- Observed *large* elliptic flow of light/s quark mesons at RHIC
  - Strong evidence for thermalization
- What about charm?
  - Naïve kinematical argument: need m_q/T ~ 7 times more collisions to thermalize
  - v_2 of charm closely related to R_{AA}
- Examples: Van Hees & Rapp, PRC 71, 034907: resonant heavy-light quark scattering via scalar, pseudoscalar, vector, and axial vector D-like-mesons





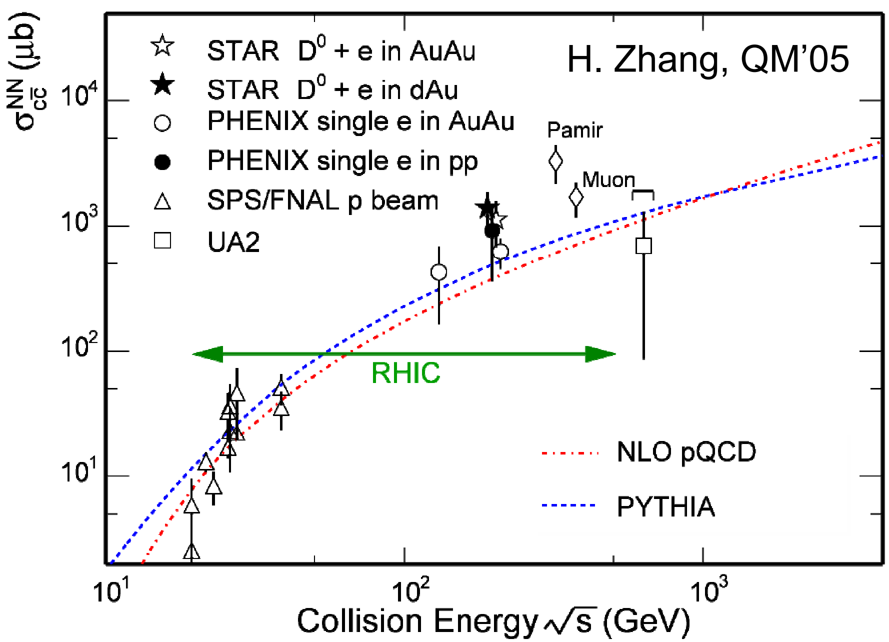
Open Heavy Flavor – Elliptic Flow

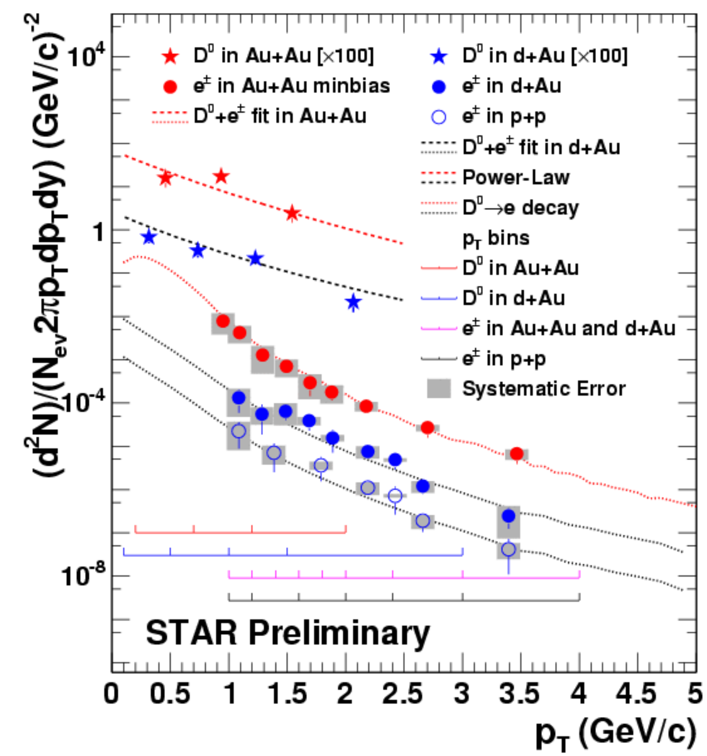
- Observed *large* elliptic flow of light/s quark mesons at RHIC
  - Strong evidence for thermalization
- What about charm?
  - Naïve kinematical argument: need m_q/T ~ 7 times more collisions to thermalize
  - v_2 of charm closely related to R_{AA}
- Examples: Moore & Teeny: Study of diffusion coefficient in QGP, $D = T/M\eta$ (η drag coefficient), using a Langevin model



RHIC Results – Charm Cross Section

- Study of D mesons (Kπ combinations/event mixing) and non-photonic single electrons (from semileptonic D decays)
  - Cross section 2-4 × larger than predictions from NLO



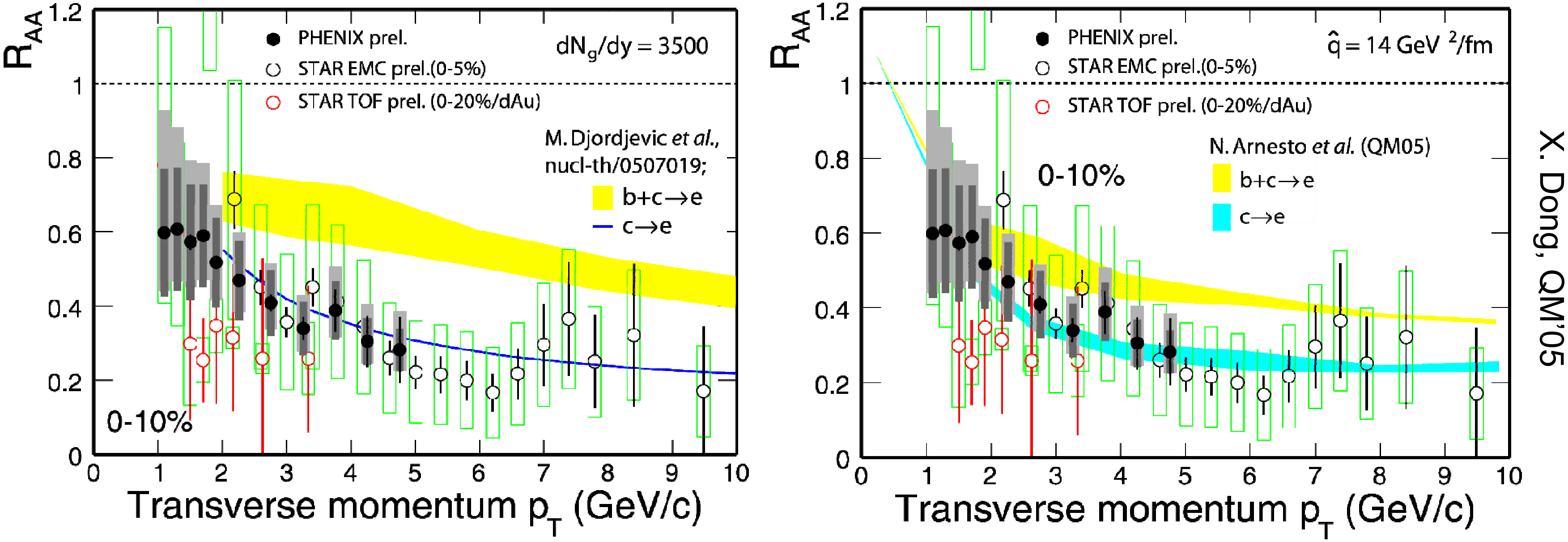


- Issues:
  - D mesons: large background
  - Non-photonic electrons: $\sigma_{measured}/\sigma_{cc}$ ~ 15%

⇒ Need direct measurement of D mesons (via K π)

RHIC Results – Charm Energy Loss

- Study of non-photonic single electrons (from semileptonic D decays)
  - First evidence of strong suppression of charm at high-p_T
  - Challenge to existing E-loss paradigm (collisional E-loss important?)

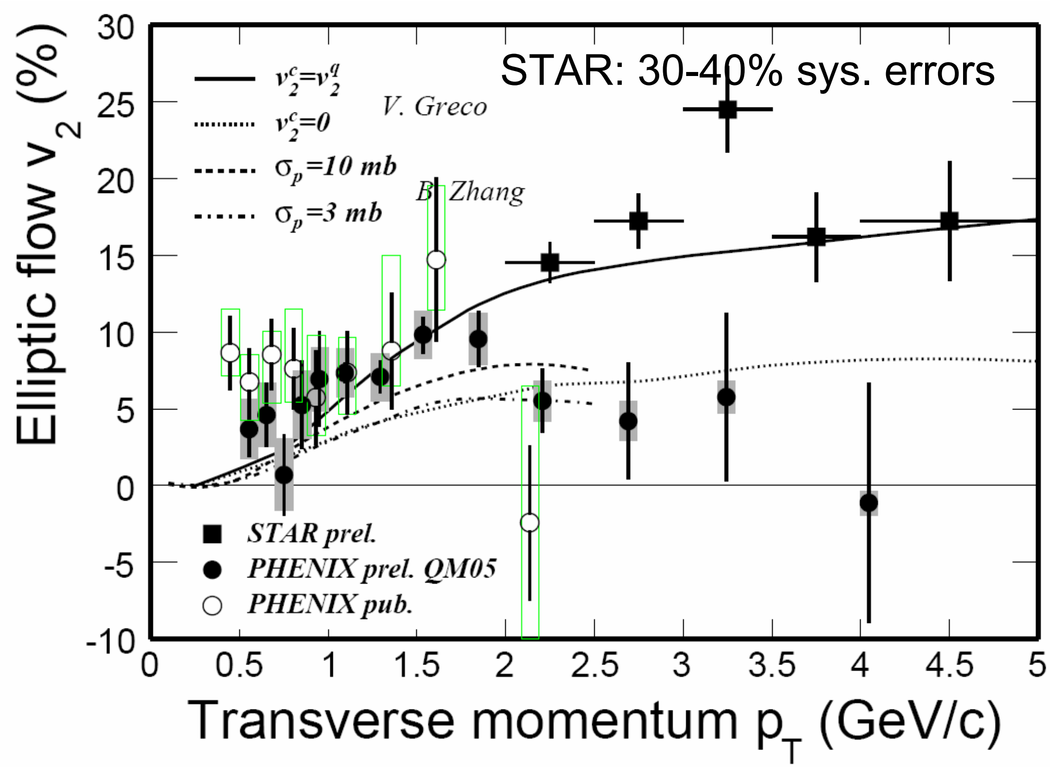


- Issues:
  - Statistics at high-p_T limited, uncertainties due to photonic background
  - Cannot deconvolute contributions from charm and bottom

⇒ Need direct measurement of high-p_T D mesons (via K π) and B mesons (via J/ψ)

RHIC Results – Charm Flow

- Study of non-photonic single electrons (from semileptonic D decays)
  - First hint of strong charm elliptic flow for p<2 GeV/c
  - Measurements from STAR & PHENIX deviate at higher p_T



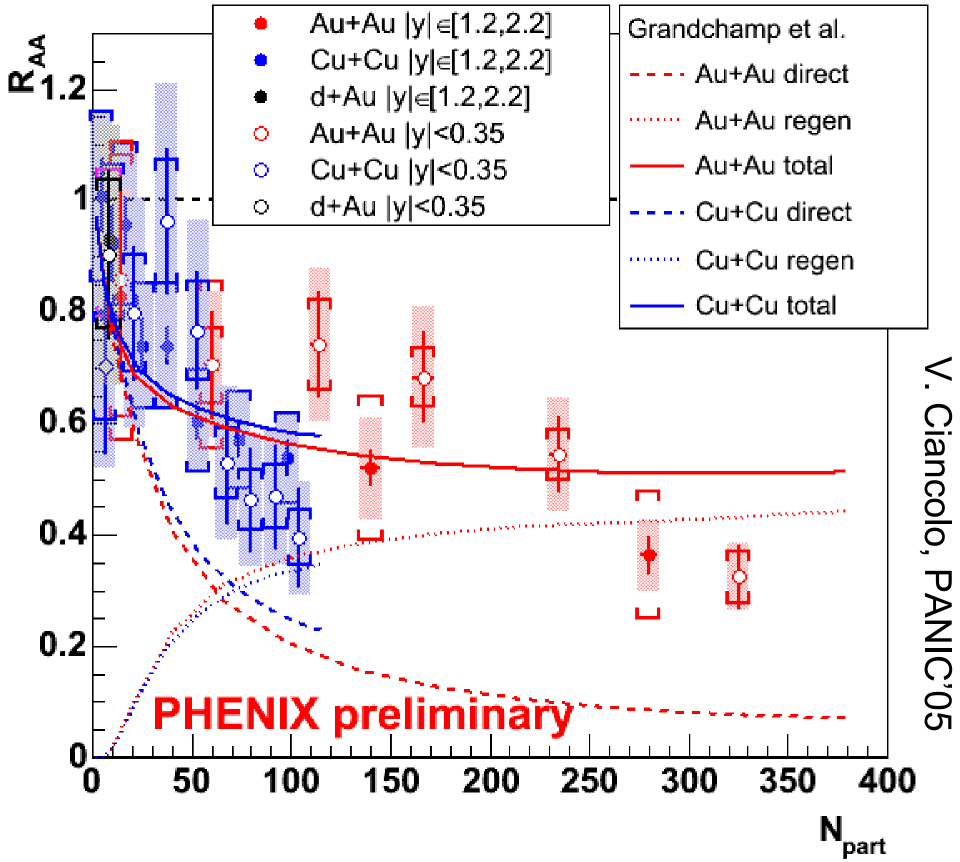
X. Dong, QM'05

- Issues:
  - Statistics limited
  - Uncertainties due to photonic background
  - Large sys errors
  - Cannot deconvolute contributions from charm and bottom
- Need direct measurement of D mesons (via K p) v_2

RHIC Results – J/ψ Suppression

- Study of J/ψ → ee and μμ in Au+Au and Cu+Cu
  - Yield is suppressed compared to that in p+p collisions
  - Suppression is larger for more central collisions.
  - Suppression beyond that of cold nuclear matter for most central collisions even if σ_{abs} ~ 3 mb.
  - Cold matter effects underpredict the suppression

J/ψ nuclear modification factor R_{AA}

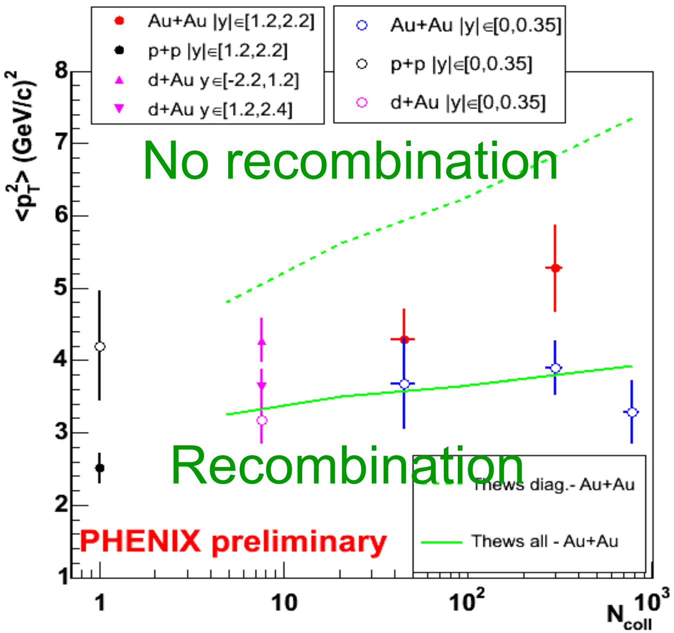


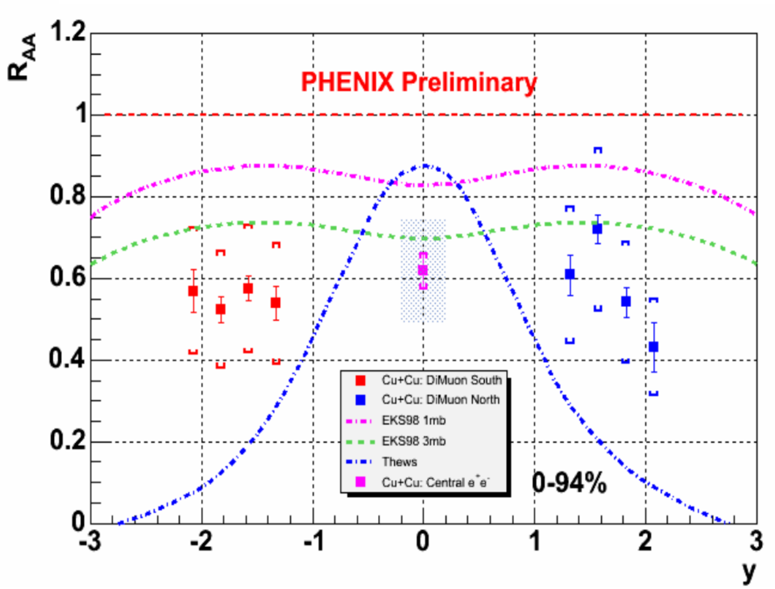
- Issues:
  - Lack of statistics
  - Only J/ψ measurement so far

⇒ Need more statistics and data on Ψ', χ_c, and ϒ states

RHIC Results – J/ψ Suppression

T. Gunji, PANIC'05





Recombination predicts narrow p_T and rapidity distribution:

- $\langle p_T^2 \rangle$ vs. $N_{collisions}$
  - Predictions of recombination model match better.
- R_{AA} vs. Rapidity
  - No significant change in rapidity shape compared to p+p result.

Recombination compensates suppression?

- Issues:
  - Charm rapidity distributions at RHIC are open questions
  - Require more data on √s, A dependence

Need more statistics, J/ψ v_2

Quarkonia – RHIC-II Goals and Requirements

Physics Motivation	Probes	Studies	Requirements
Baseline	J/ψ, ψ', ϒ(1S), ϒ(2S), ϒ(3S) through μμ and ee decay channels	Rapidity $y(x_F)$ and p_T spectra in AA, pA, pp as a function of A, $\sqrt{s}$	High luminosity and acceptance. High resolution to resolve ϒ states
Deconfinement & Initial Temperature	J/ψ, ψ', ϒ(1S), ϒ(2S), ϒ(3S)	Melting patterns of quarkonia states	Extract suppression mechanism taking into account: feed down, nuclear absorption, and recombination
Properties of the medium	High-p_T J/ψ	R_{AA}: Dissociation ↔ Quenching	High luminosity
Thermalization &Transport properties of the Medium	J/ψ	J/ψ flow (v_2) as a function of A, $\sqrt{s}$ Recombination: y and $\langle p_T^2 \rangle$	High luminosity to obtain good statistics in short time (A, $\sqrt{s}$ scans)

Quarkonia – RHIC-II Goals and Requirements

In order to extract the desired suppression signals the following measurements have to be achieved:

Topic	Studies	Requirements
Nuclear effects • shadowing • absorption	Quarkonia in pp, pA: • x_2, x_F dependence • A dependence • rapidity distributions over wide range	Large y coverage Forward coverage to high x_F
Suppression vs. Recombination	• charm production $d\sigma/dp_T dy$ • v_2 of J/ψ • p_T dependence of suppression	High resolution vertex detectors
Contribution from feed down	Measure χ_c at least in pp and pA	Photon detection at mid and forward rapidity, high luminosity, good energy & momentum resolution to minimize background
Quarkonium production	pA: χ_c / J/ψ A-dependence J/ψ polarization (?)	As above Large acceptance for $\cos \theta^*$

Open Heavy Flavor – RHIC-II Goals and Requirements

Physics Motivation	Probes	Studies	Requirements
Baseline	D/B mesons, non-photonic electrons	• Rapidity $y(x_F)$ and p_T spectra in AA, pA as a function of A, √s	High Luminosity High resolution vertex detectors ($c\tau(D) \sim 100$-300 μm) High-p_T PID ($D \to K\pi$)
Thermalization, Transport properties of the medium	D mesons, B? non-photonic electrons (D+B)	Elliptic flow v_2 p_T spectra	as above
Properties of the medium Initial conditions	D, B ($B \to J/\psi + X$) mesons, non-photonic electrons	$R_{AA}(p_T)$, R_{CP} of D , B as a function of p_T for various √s	as above
Properties of the medium Heavy Flavor Production	D mesons, non-photonic electrons	Correlations: • charm-charm • charm-hadron • J/ψ-hadron	**HIGH** luminosity (eff^2 !) Large coverage Trigger ?

RHIC-II - Facing the Challenge

- Addressing the requirements:
  - RHIC-II: increased luminosity (RHIC-II ≈ 40 × RHIC)
    - Note: collision diamond σ = 20 cm at RHIC and σ = 10 cm at RHIC II $\Rightarrow$ gain in usable luminosity is larger than "nominal" increase
  - PHENIX & STAR: more powerful upgraded detectors crucial to the Heavy Flavor physics program - completed in mid/near term ~5 years.
- STAR:
  - DAQ upgrade increases rate to 1 KHz, triggered data has ~ 0 dead time.
  - Silicon tracking upgrade for heavy flavor, jet physics, spin physics.
  - Barrel TOF for hadron PID, heavy flavor decay electron PID.
  - EMCAL + TOF J/ψ trigger useful in Au+Au collisions.
  - Forward Meson Detector
- PHENIX:
  - Silicon tracker for heavy flavor, jet physics, spin physics.
  - Forward muon trigger for high rate pp + improved pattern recognition.
  - Nose cone calorimeter for heavy flavor measurements.
  - Aerogel + new MRP TOF detectors for hadron PID.
  - Hadron-blind detector for light vector meson e^+e^- measurements.

RHIC-II – Open Heavy Flavor

- With detector upgrades (both PHENIX and STAR):
  - Dramatically reduce backgrounds for all open charm, open beauty signals using displaced vertex measurement.
  - Separate open charm and beauty statistically using displaced vertex.
  - Separate B $\rightarrow$ J/ψ from prompt J/ψ using displaced vertex.

- And with the luminosity upgrade:
  - Extend open charm and beauty R_{AA} measurements to high p_T. What is the energy loss well above the thermalization region?
  - Measure D & semileptonic charm and beauty decay v_2 to high p_T. See the transition from thermalization to jet energy loss for charm.
  - Measure open charm correlations with open charm or hadrons.

RHIC-II - Quarkonia

- With detector upgrades:
  - J/ψ from B decays with displaced vertex measurement (both).
  - Reduce J/$\psi \rightarrow \mu\mu$ background with forward μ trigger in PHENIX.
  - Improve mass resolution for charmonium and resolve Υ family.
  - See γ in forward calorimeter in front of muon arms (PHENIX) and in FMD in STAR

- And with the luminosity upgrade:
  - J/ψ R_{AA} to high p_T. Does J/ψ suppression go away at high p_T?
  - J/ψ v_2 measurements versus p_T. See evidence of charm recombination?
  - Υ R_{AA}. Which Upsilons are suppressed at RHIC?
  - Measure $\chi_c \rightarrow$ J/$\psi+\gamma$ R_{AA}. Ratio to J/ψ?
  - Measure Ψ' R_{AA}. Ratio to J/ψ?
  - Measure B $\rightarrow$ J/ψ using displaced vertex - independent B yield measurement, also get background to prompt J/ψ measurement.

RHIC-II - Heavy Flavor Yields

All numbers are first rough estimates (including trigger and reconstruction efficiencies) for 12 weeks physics run ($\int L_{eff}\,dt \sim 18\ nb^{-1}$)

Signal	RHIC Exp.	Obtained	RHIC I (>2008)	RHIC II	LHC/ALICE+
$J/\psi \to e^+e^-$	PHENIX	~800	3,300	45,000	9,500
$J/\psi \to \mu^+\mu^-$		~7000	29,000	395,000	740,000
$\Upsilon \to e^+e^-$	STAR	-	830	11,200	2,600
$\Upsilon \to \mu^+\mu^-$	PHENIX	-	80	1,040	8,400
$B \to J/\psi \to e^+e^-$	PHENIX	-	40	570	N/A
$B \to J/\psi \to \mu^+\mu^-$		-	420	5,700	N/A
$\chi_c \to e^+e^-\gamma$	PHENIX	-	220	2,900*	N/A
$\chi_c \to \mu^+\mu^-\gamma$		-	8,600	117,000*	N/A
$D \to K\pi$	STAR	$\sim 0.4\times10^6$ (S/B~1/600)	30,000**	30,000**	8000

* Large backgrounds, quality uncertain as yet

** Running at 100 Hz min bias

+ 1 month (= year), P. Crochet, EPJdirect A1, a (2005) and private comm.

T. Frawley, PANIC'05, RHIC-II Satellite Meeting

Summary & Conclusions

- Heavy Flavor Physics at RHIC teaches us about:
  - Deconfinement
  - Thermalization
  - Transport properties of the medium
- Heavy Flavor Physics at RHIC is just at the beginning
  - Already the first glimpses points to new physics
    - Charm suppression at high-p_T
    - J/ψ: suppression + recombination
    - Cross sections larger than NLO predictions
- RHIC-II luminosity & detector upgrades dramatically expand capabilities and thus our understanding
  - Study sequential suppression of many quarkonium states
  - Evaluate effects: feed down, absorption, recombination
  - Study D, B production and suppression in the medium
  - Study thermalization via charm and quarkonium flow
- Still challenging:
  - Correlation measurements, χ_b impossible?