Heavy Quarks and Heavy Quarkonia as Tests of Thermalization

2005-11 중이온 미팅 (HIM 2005-11)_

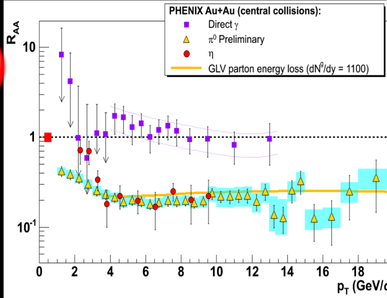
DongJo Kim
Yonsei University, Seoul Korea

Outline of Talk

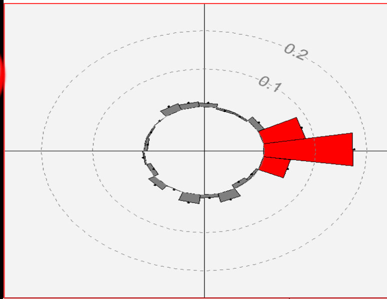
1. A short Overview of RHIC results.
   - ① RHIC history
   - ② Jet-Quenching (pion R_{AA}, Jet suppression)
   - ③ Flow (light hadrons, even heavier particles)
2. Extension from Light quarks to heavy quarks
3. How to measure Heavy flavor ?
   - ① Semi-leptonic heavy flavor decay (Cocktail/Converter)
   - ② J/Ψ
4. PHENIX heavy flavour measurement
   - ① Open charm Results(R_{AA} , charm flow)
     Radiative energy loss, bottom contribution
   - ② J/psi Results (R_{AA})
     Suppression (Screening) vs
     Enhancement (recombination)

5. Toward Precision heavy flavor measurement
6. Summary

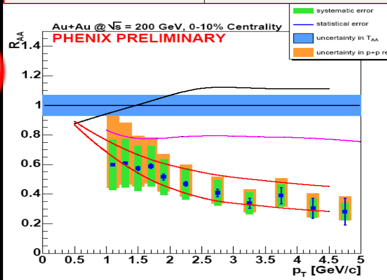
1-(2)



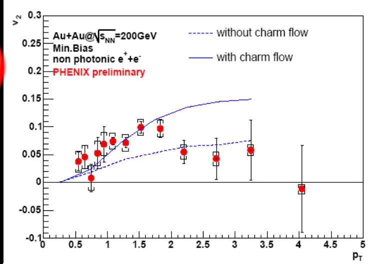
1-(2)



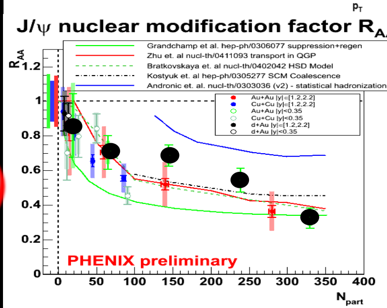
4-(1)



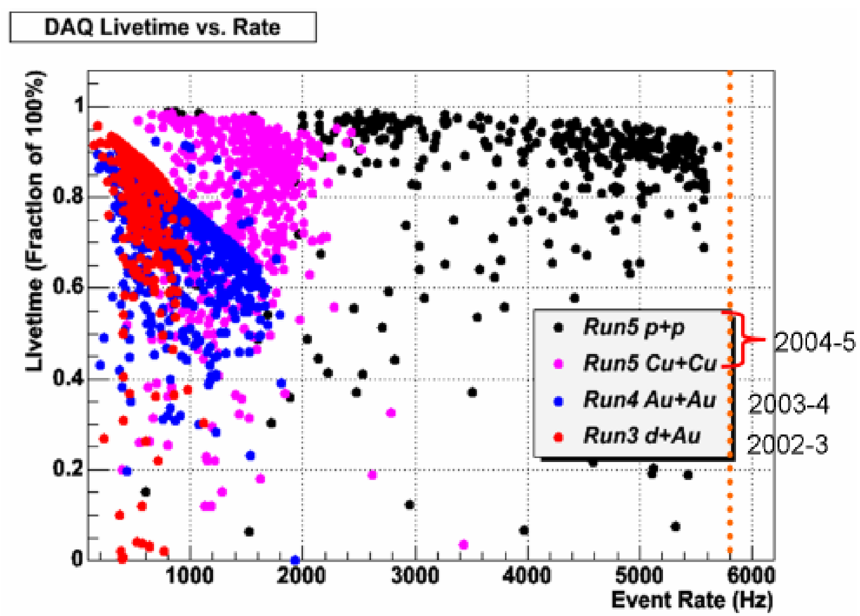
4-(1)

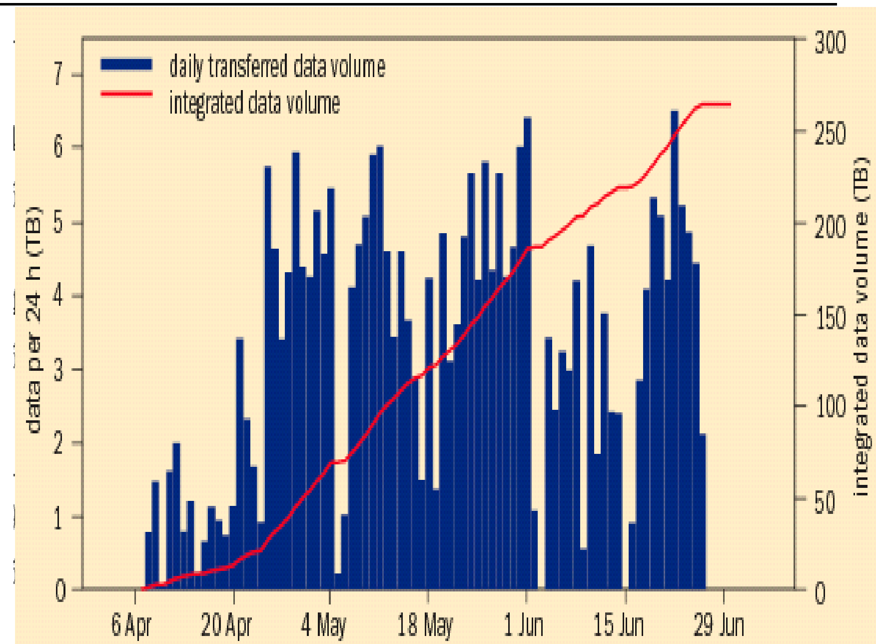


4-(2)



RHIC History





Run	Year	Species	$\sqrt{s_{NN}}$ (GeV)	$\int L\,dt$	N_{Tot}	p+p Equivalent	Data Size
05	2004/2005	Cu+Cu	200	3 nb^{-1}	8.6G	11.9 pb^{-1}	173 TB
		Cu+Cu	62.4	0.19 nb^{-1}	0.4G	0.8 pb^{-1}	48 TB
		Cu+Cu	22.5	2.7 μb^{-1}	9M	0.01 pb^{-1}	1 TB
		p+p	200	3.8 pb^{-1}	85G	3.8 pb^{-1}	262 TB

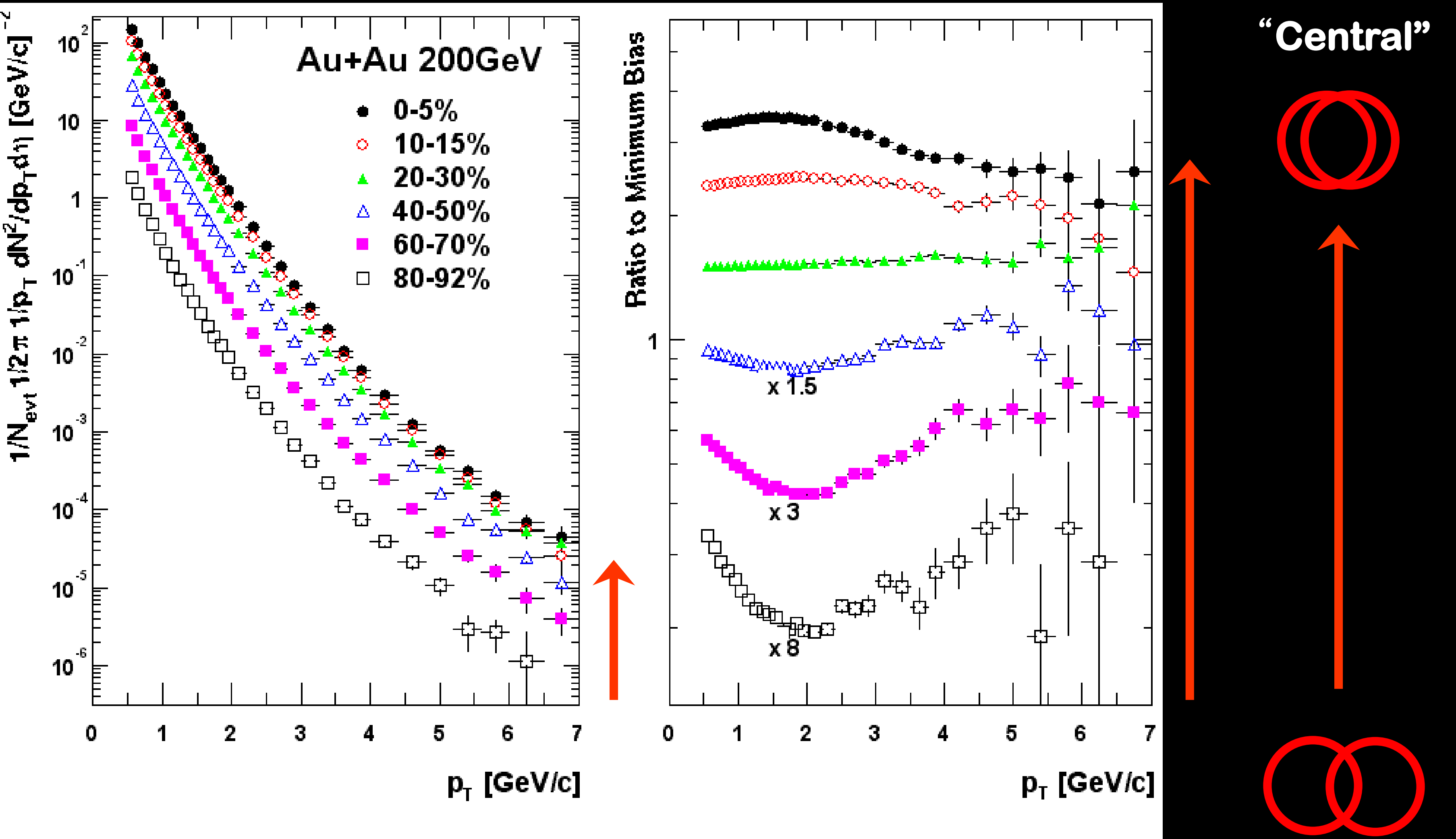
RHIC program is operating very successfully.
PHENIX online data transfer and reconstruction remarkable

Selected Results at RHIC

A. Jet suppression in central Au + Au collisions
   ① Suppression apparently flat for pt up to 10 GeV/c
   ② Absence of suppression in d+Au

B. Strong elliptic flow
   ① Scaling of v2 with eccentricity shows that a high degree of collectivity built up at a very early stage of collision – Evidence for early thermalization
   ② Data described by ideal hydrodynamic models→ fluid description of matter applies.

Particle Spectra Evolution



K. Adcox et al, Phys Lett B561 (2003) 82-92

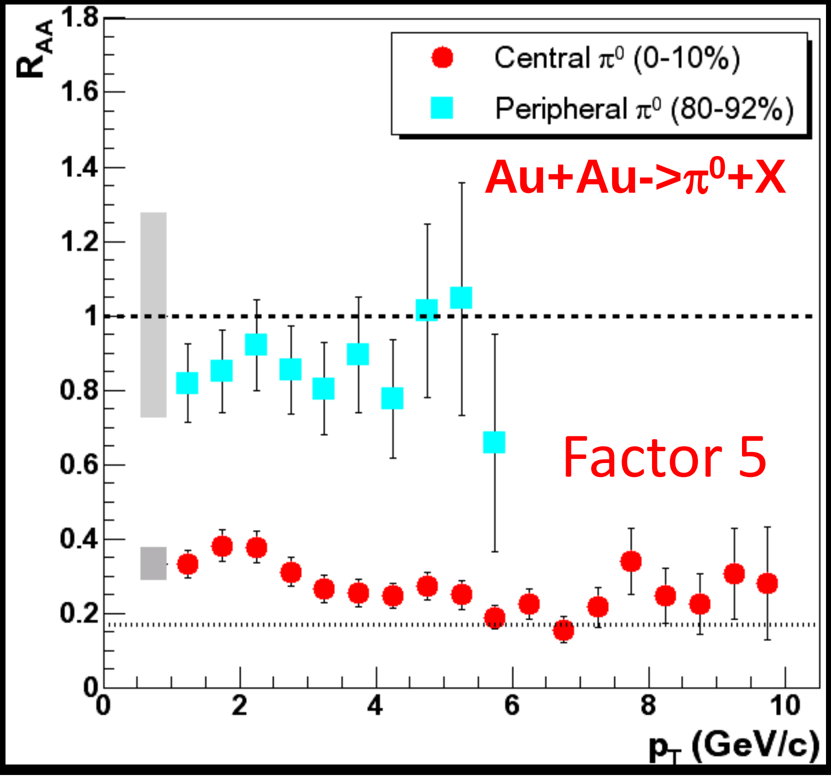
Nuclear Modification Factor: R_{AA}

PRL 91 (2003) 072301

- We define the nuclear modification factor as:

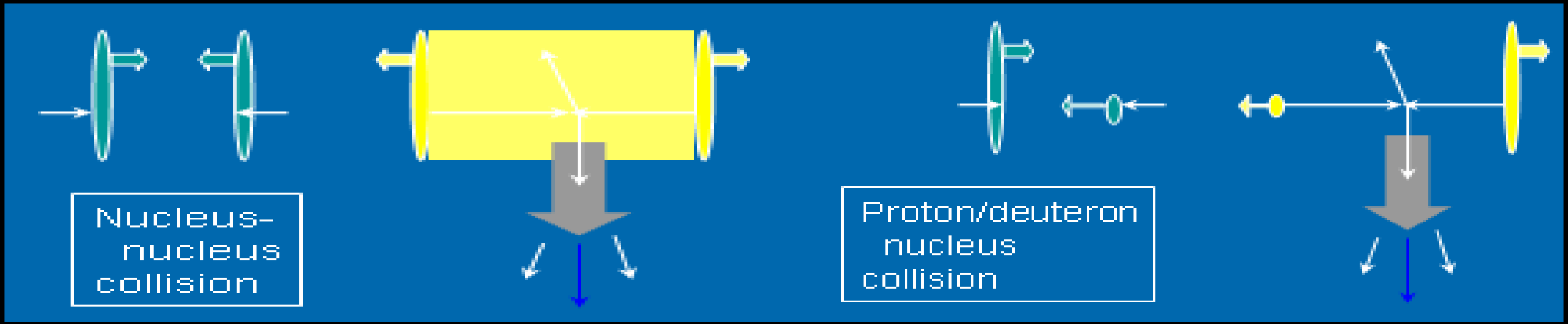
$$R_{AA}(p_T) = \frac{\frac{1}{N_{evt}} \frac{d^2N^{A+A}}{dp_T d\eta}}{\frac{<N_{binary}>}{\sigma_{inel}^{N+N}} \frac{d^2\sigma^{N+N}}{dp_T d\eta}}$$

- R_{AA} is what we get divided by what we expect.
- By definition, processes that scale with the number of underlying nucleon-nucleon collisions (aka N_{binary}) will produce R_{AA}=1.

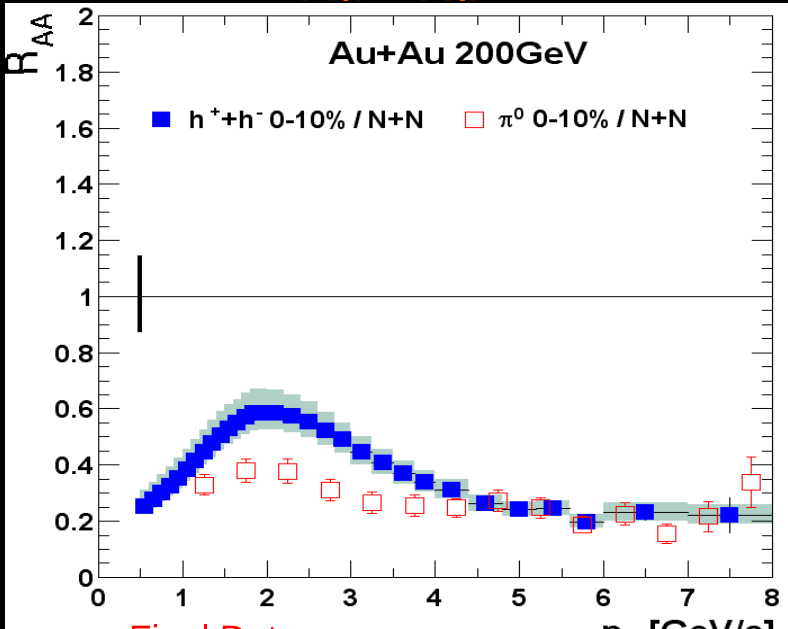


R_{AA} is well below 1 for both charged hadrons and neutral pions.

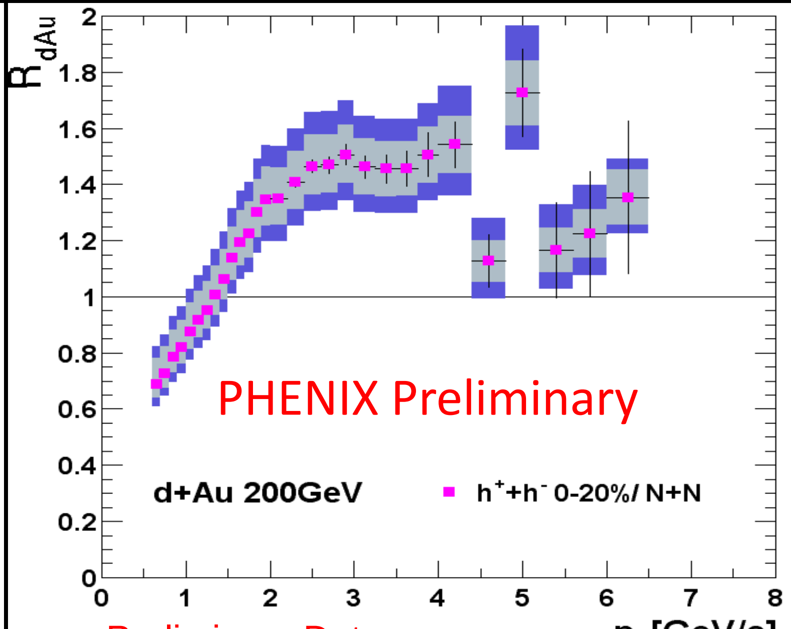
Initial State effects ruled out !



Initial + Final State Effects
Au + Au

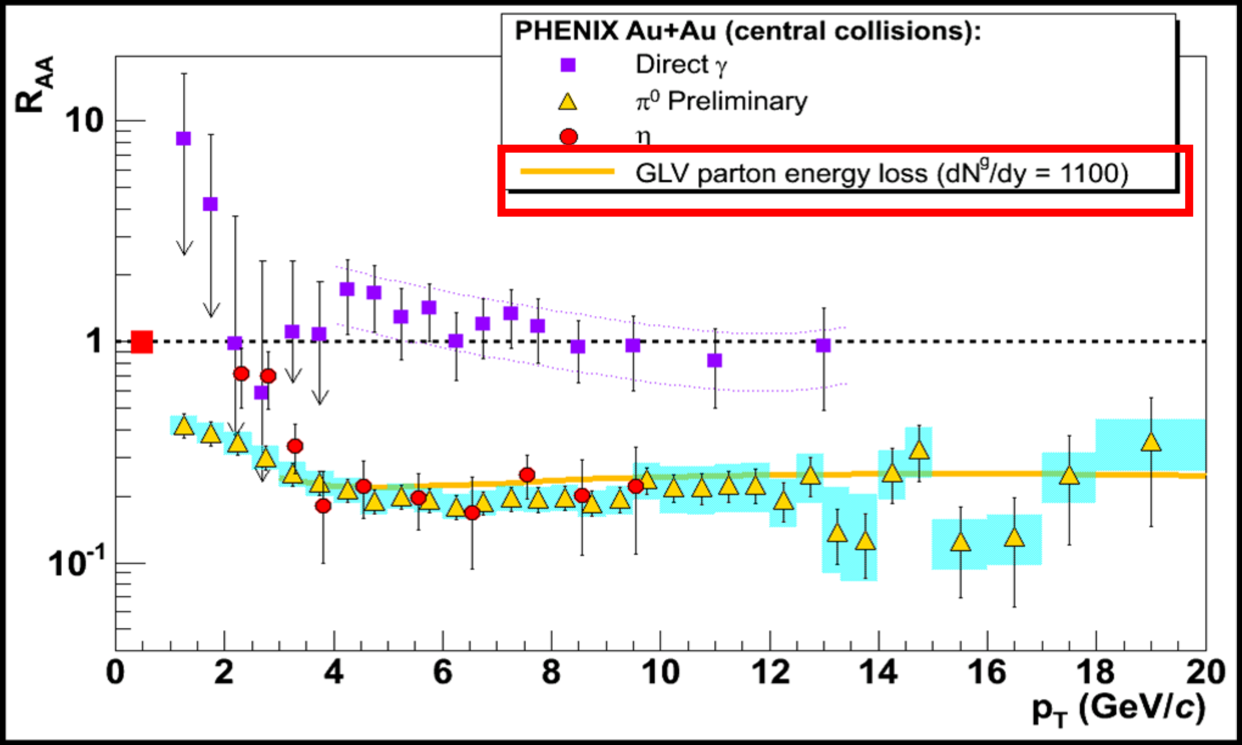


Initial State Effects Only
d + Au Control



- Dramatically different and opposite centrality evolution of Au+Au experiment from d+Au control.
- Jet Suppression is clearly a final state effect.

The matter is extremely opaque



Suppression is very strong (R_{AA}=0.2!) and flat up to 20 GeV/c

Energy loss of partons in dense matter

→ A medium effect predicted in QCD

(Energy loss by colored parton in medium composed of unscreened color charges by gluon bremsstrahlung : LPM radiation)

Gyulassy, Wang, Vitev, Baier, Wiedemann… See nucl-th/0302077 for a review.

Baier, Dokshitzer, Mueller, Peigne, Shiff, NPB483, 291(1997), PLB345, 277(1995), Baier hep-ph/0209038

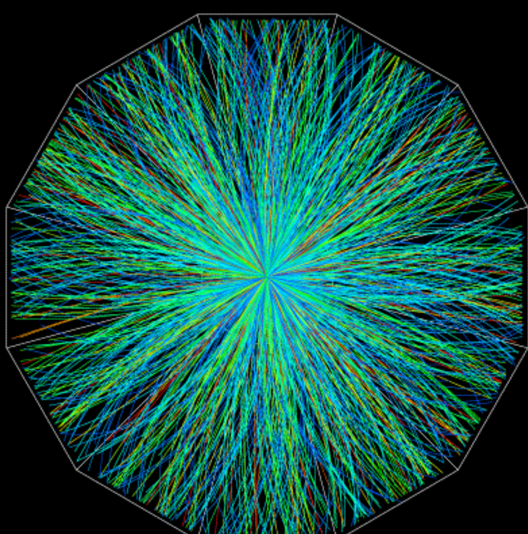
Jet Quenching !

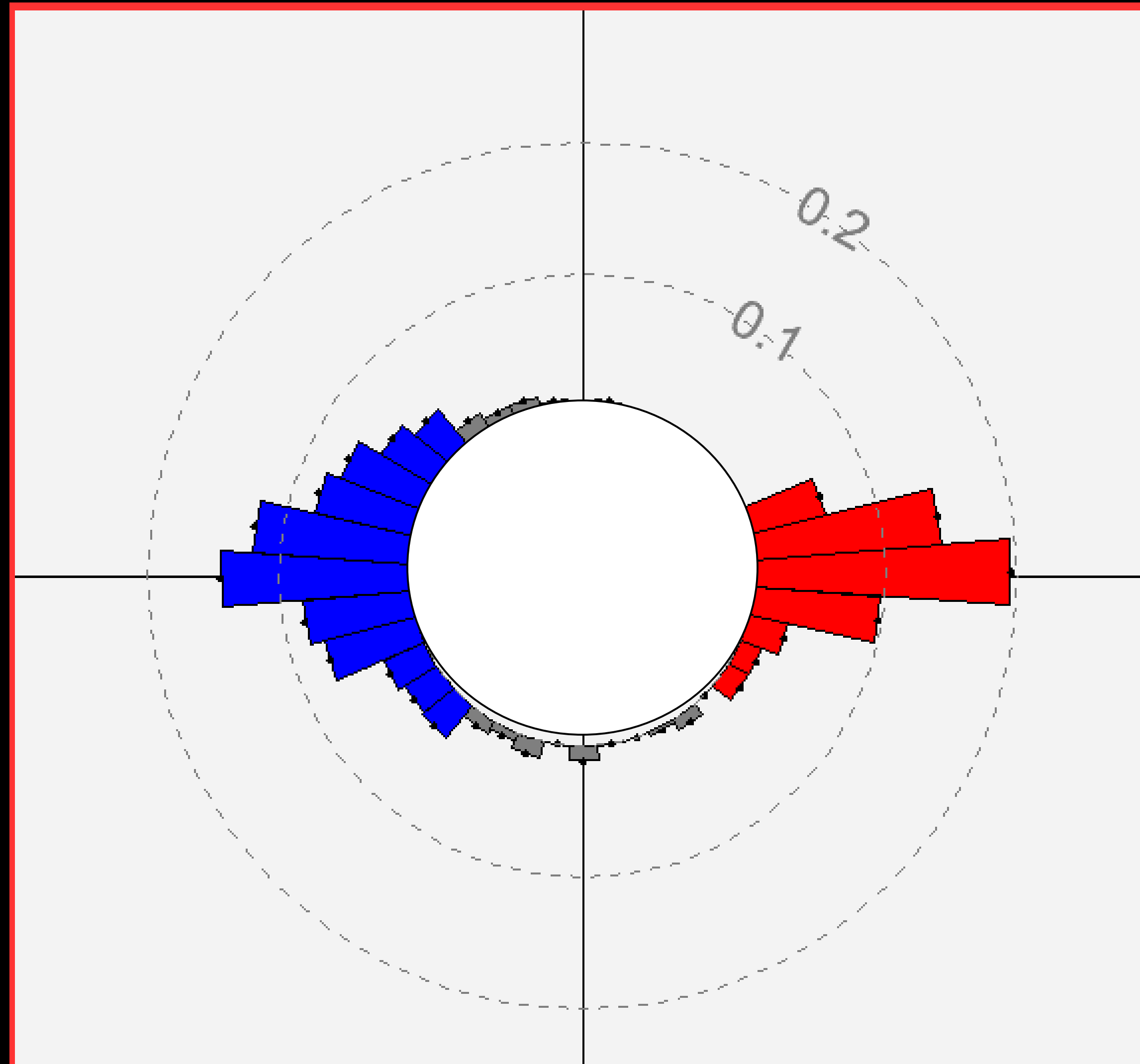
Jet correlations in proton-proton reactions.

Strong back-to-back peaks.

Jet correlations in central Gold-Gold.

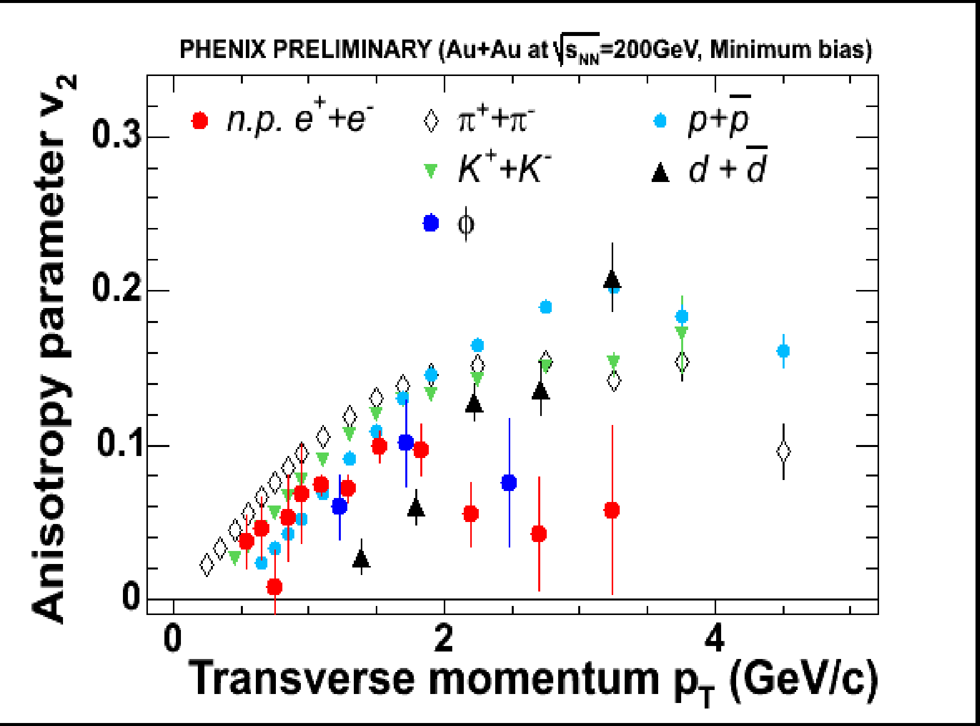
Away side jet disappears for particles $p_T > 2$ GeV

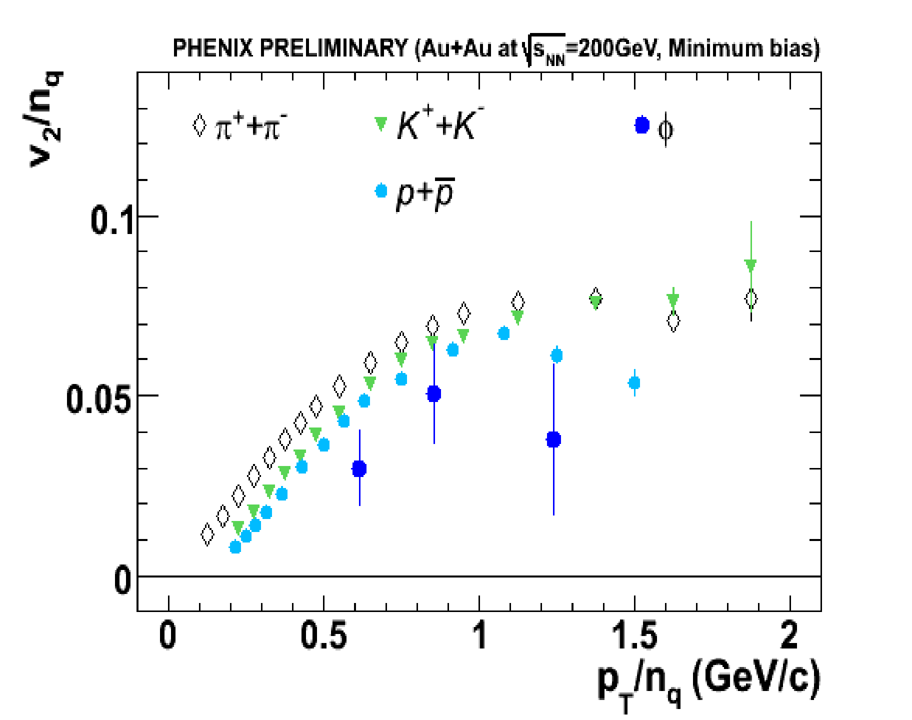




Azimuthal Angular Correlations

Collective Flow



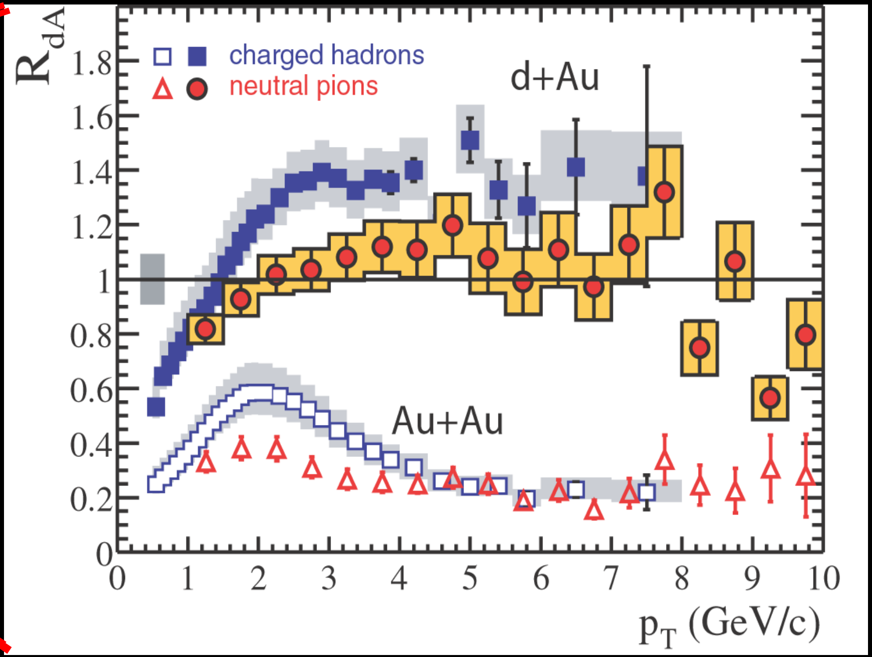


Identified charged hadron v2 indicates
① Early thermalization
② Constituent quark scaling → Partonic collectivity
Even Φ flows, within the errors consistent with other hadrons

Summary of RHIC results with light quarks

One of the central questions in high energy heavy ion physics is
whether a quark-gluon Plasma (QGP) has been discovered at RHIC.
(M.Gyulassy and L. McLerran, nucl-th/0405013, M.Gyulassy, nucl-th/0403032)

① Collective Flow and
Jet Quenching of light partons
strongly suggest that QGP is discovered.



Extension from light quarks to Heavy Quarks

One of the central questions in high energy heavy ion physics is
whether a quark-gluon Plasma (QGP) has been discovered at RHIC.
(M.Gyulassy and L. McLerran, nucl-th/0405013, M.Gyulassy, nucl-th/0403032)

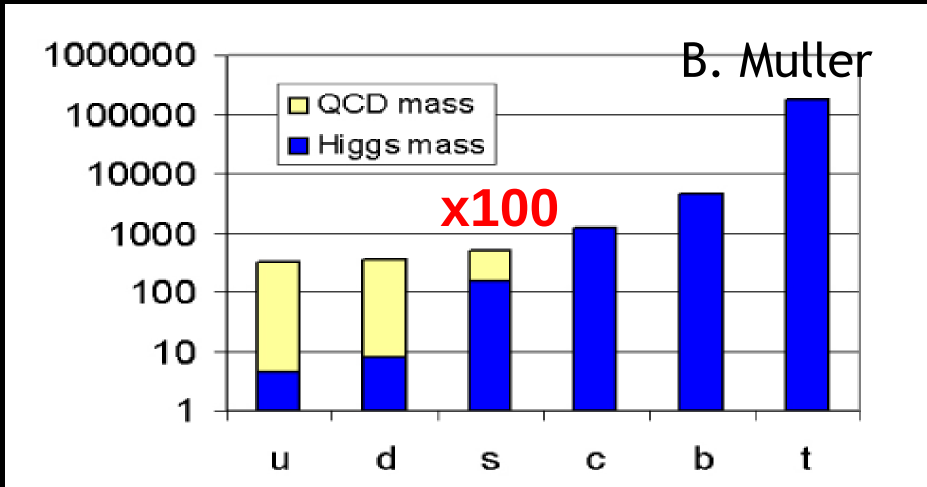
① Collective Flow and Jet Quenching of light partons strongly suggest that QGP is discovered.

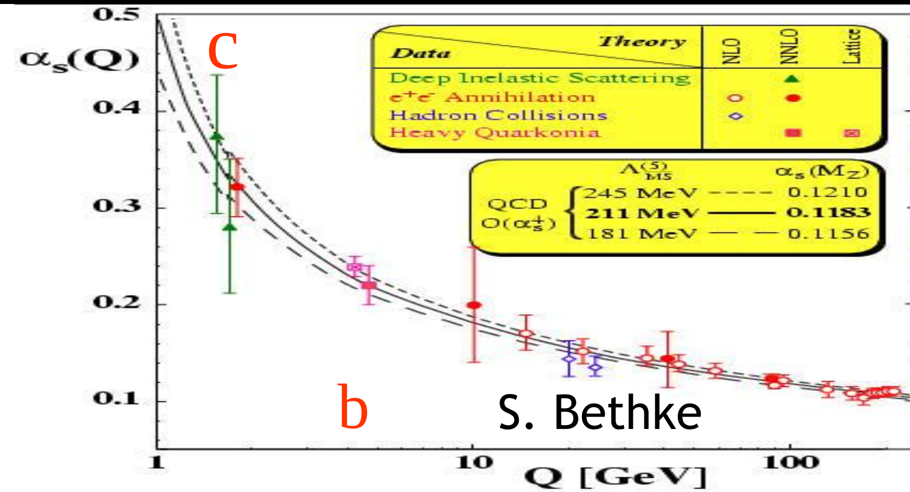
② Further detailed tests of jet tomography using heavy quarks could be decisive as a complementary test of the theory.

⌘ **Open charm suppression**, which can now be measured at RHIC by comparing pt distributions of D-mesons in *d-Au* and *Au-Au* collisions, is a **novel probe** of QGP dynamics.

⌘ **J/psi suppression or enhancement mechanism** should be nailed down with high statistical and systematical precision.

Why Heavy Quarks ?





- ➢ Heavy quarks (charm and beauty) - produced early in the collision. Live long enough to sample the plasma
- ➢ Intrinsic large mass scale allows precise calculations

What can we look in order to find out the characteristics or properties of the medium(QGP)

- ☹ **Yields of charm and beauty pairs compared to first principle lattice simulations determine the energy density and temperature**
  → J/Ψ suppression
- ☺ **Comparison between light and heavy quark suppression distinguishes between theoretical models of energy loss in the QGP**
  ➔ Charm vs Light quark energy loss (Jet-Quenching)
- ☺ **Mass dependence of diffusion of heavy quarks determines plasma properties, e.g. viscosity and conductivity ➔ Charm flow**

How to measure Heavy Flavor ?

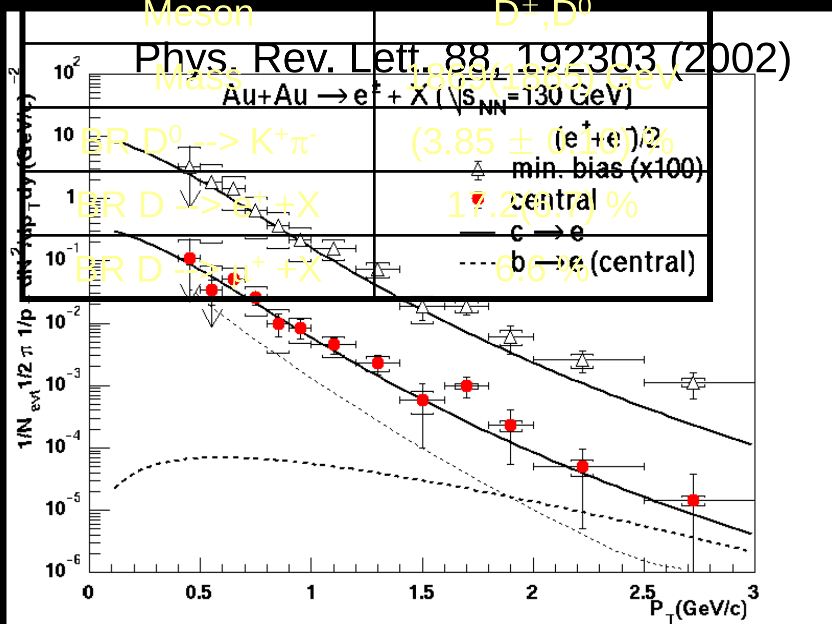
- Experimentally observe the decay products of Heavy Flavor particles (e.g. D-mesons)
  - Hadronic decay channels D→Kπ, $D^0 \to \pi^+ \pi^- \pi^0$
  - Semi-leptonic decays D→e(μ) K ν_e

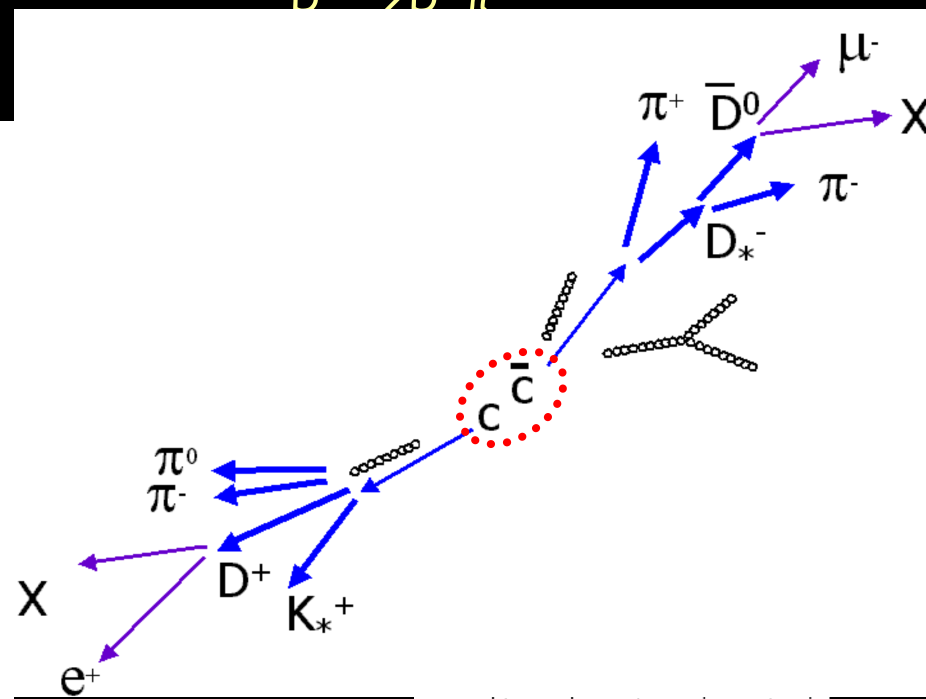
- PHENIX
  - Single electron measurements in p+p, d+Au, Au+Au $\sqrt{s_{NN}}$ = 130 200 62.4 GeV

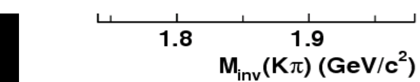
- STAR
  - Direct D mesons hadronic decay channels in d+Au
    - $D^0 \to K\pi$
    - $D^{\pm} \to K\pi\pi$
    - $D^{*\pm} \to D^0 \pi$

Meson	$D^{\pm}$,D^0
Mass	1869(1865) GeV
BR D^0 --> $K^+\pi^-$	(3.85 ± 0.10) %
BR D --> e^+ +X	17.2(6.7) %
BR D --> μ^+ +X	6.6 %

Phys. Rev. Lett. 88, 192303 (2002)







PHENIX detector at RHIC

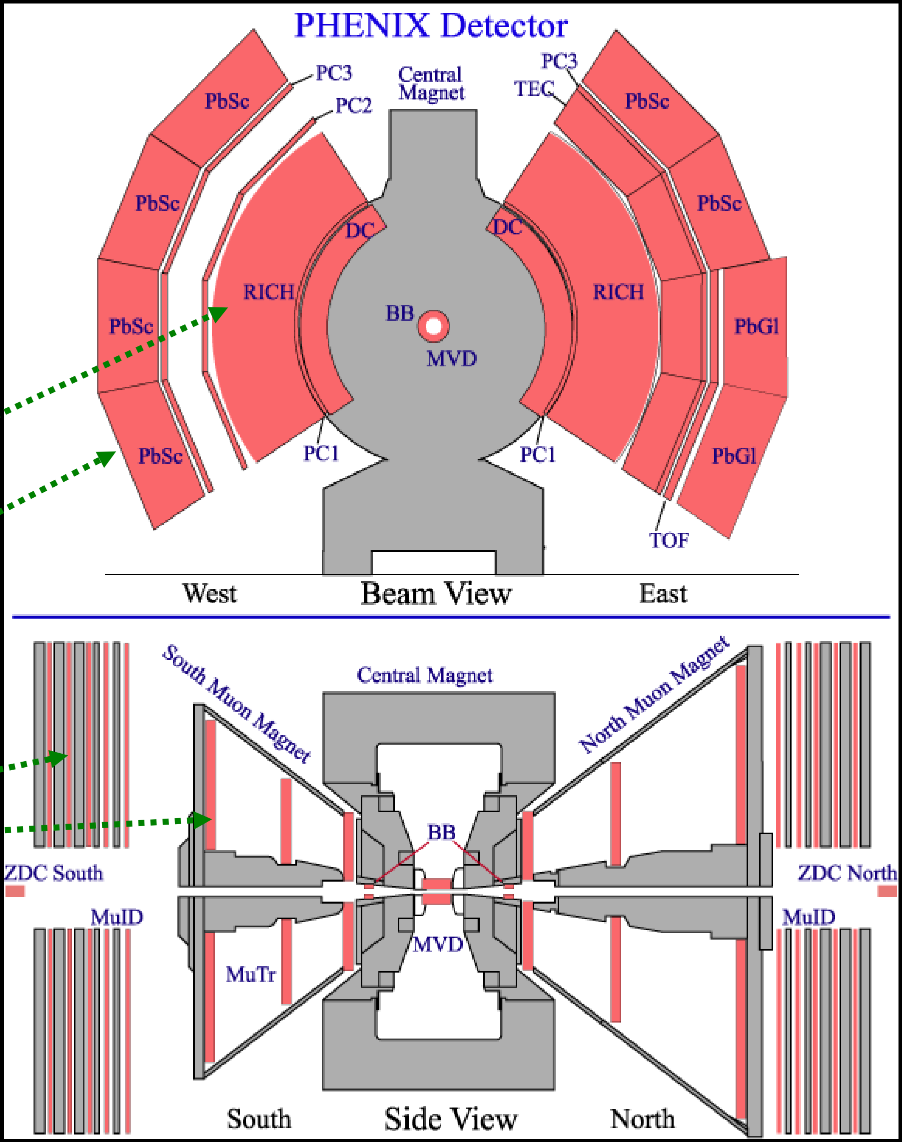
Designed to measure electrons, muons, photons and hadrons.

Key Parameters:

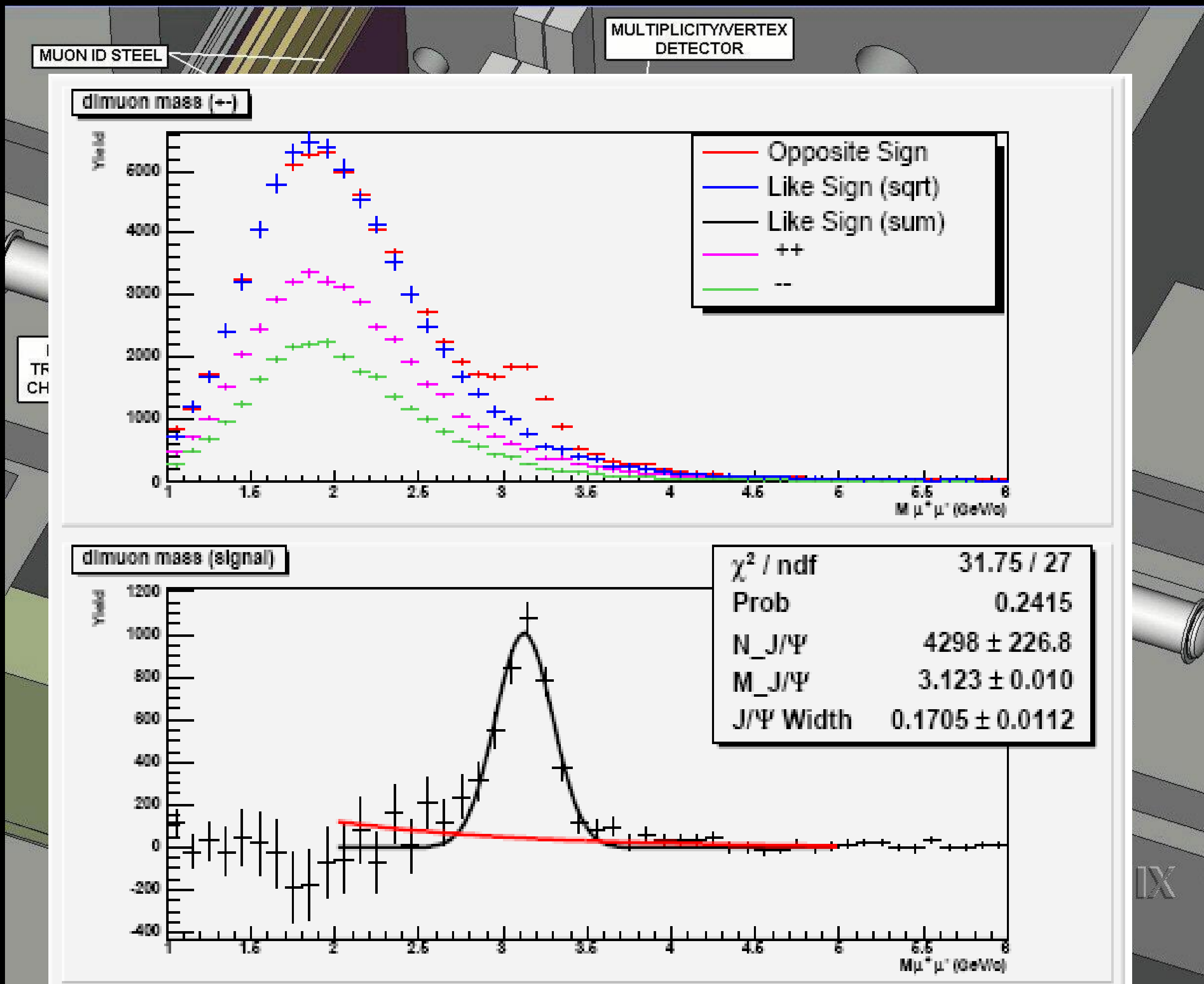
<u>Electrons:</u>
-0.35 < y < +0.35
Radiation Length < 0.4%
PID with RICH/EMC

<u>Muons:</u>
1.2 < |y| < 2.2

Very high data and trigger bandwidth



How does PHENIX see the J/Ψ ?



$J/\Psi \rightarrow e^+e^-$

identified in RICH and EMCal

- $|\eta| < 0.35$
- $p > 0.2$ GeV

$J/\Psi \rightarrow \mu^+\mu^-$

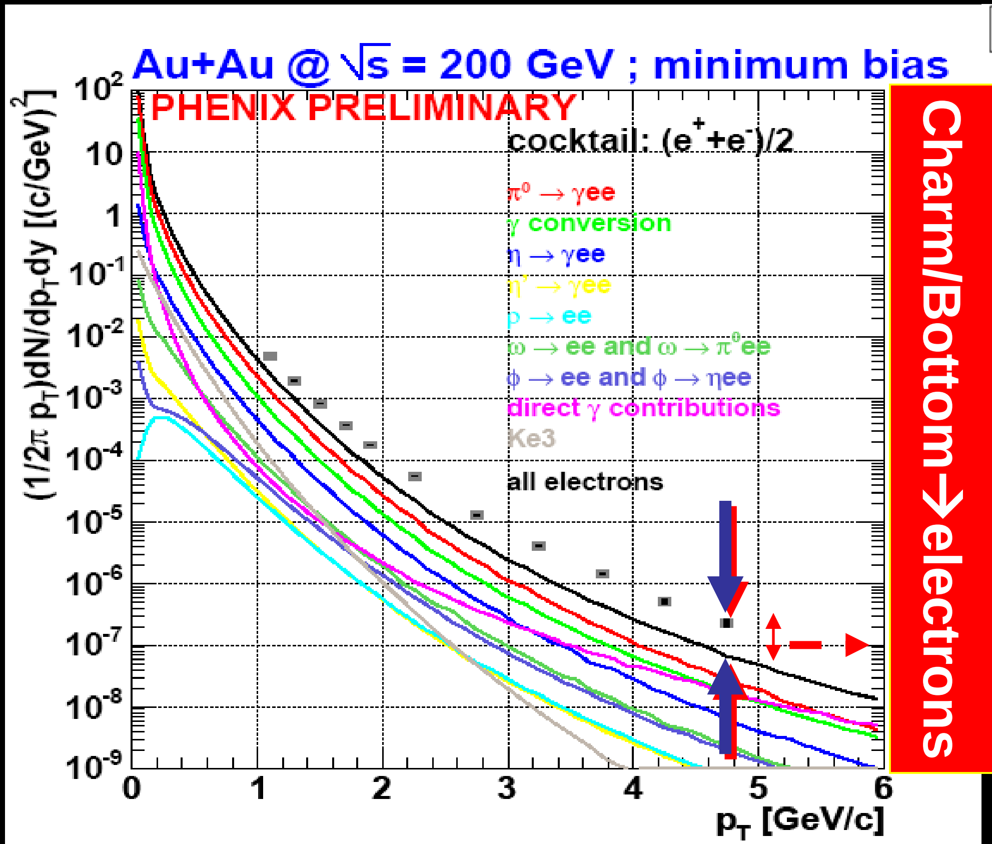
identified in 2 fwd spectrometers

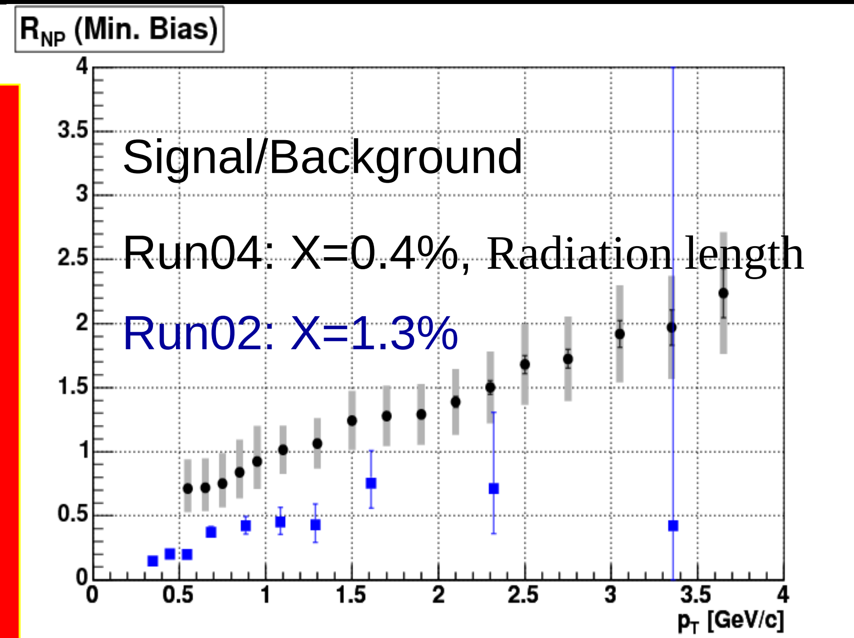
- $1.2 < |\eta| < 2.4$
- $p > 2$ GeV

Centrality and vertex given by

BBC in $3<|\eta|<3.9$

New Electron Results





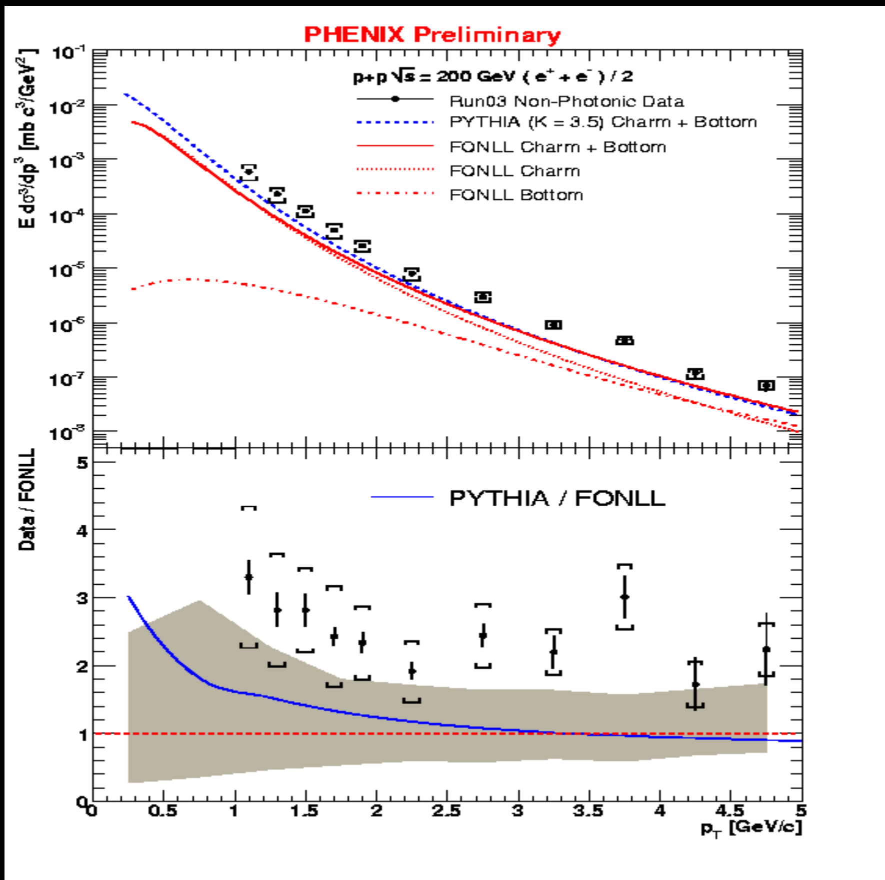
- S/B > 1 for p_T > 1 GeV/c

We use two different methods to determine the non-photonic electron contribution (Inclusive = photonic + non-photonic)

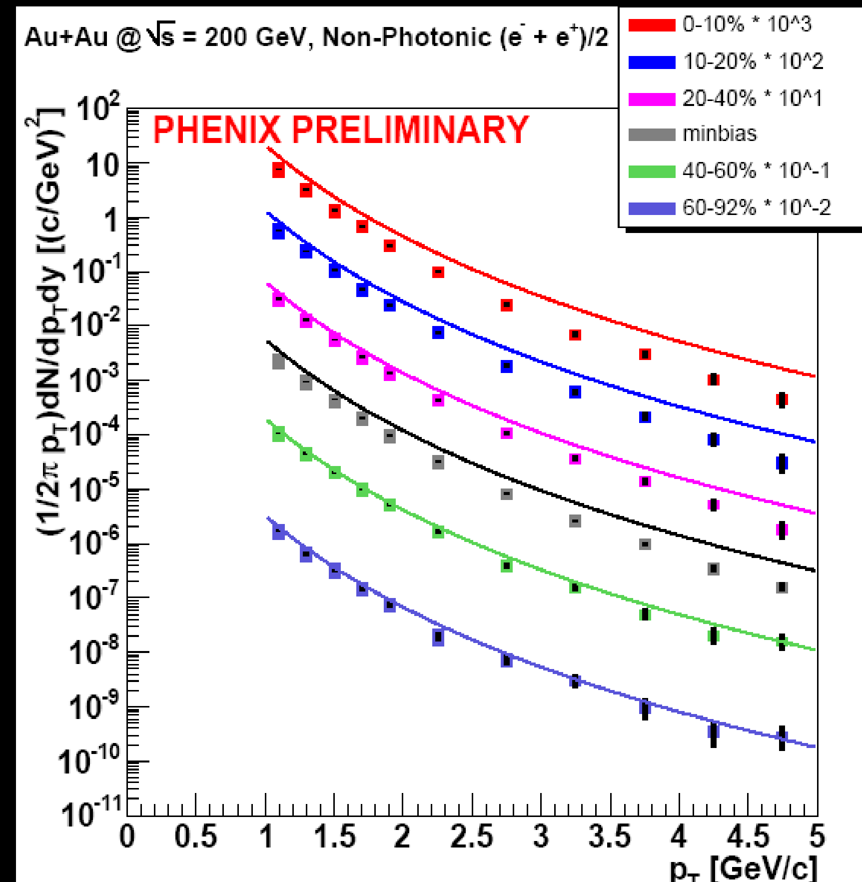
- Cocktail subtraction – calculation of "photonic" electron background from all known sources
- Converter subtraction– extraction of "photonic" electron background by special run with additional converter (X = 1.7%)

Non-Photonic Electron Spectra

Proton-Proton Baseline

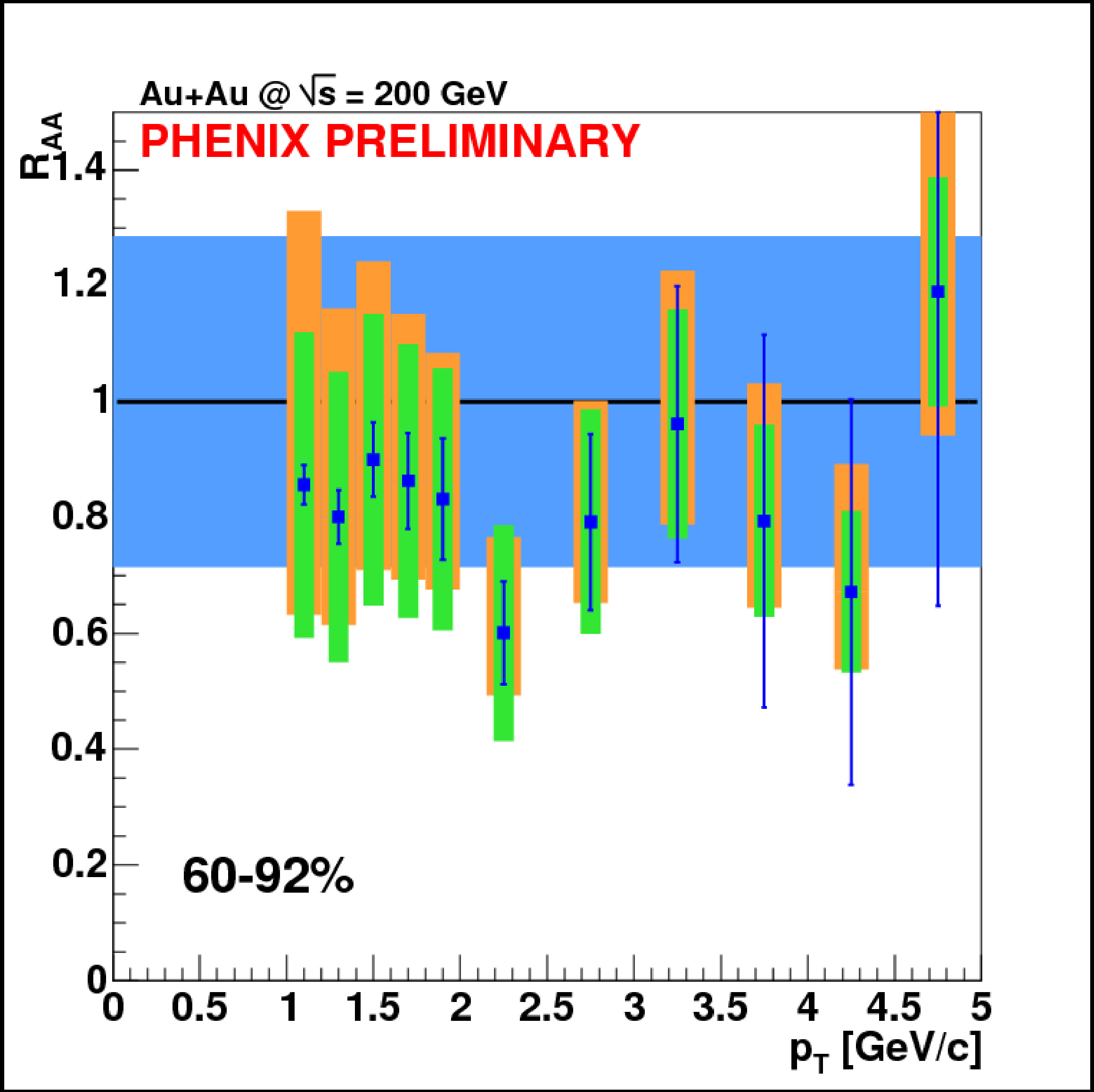


Gold-Gold Suppression



- Clear high pT suppression developing towards central collisions

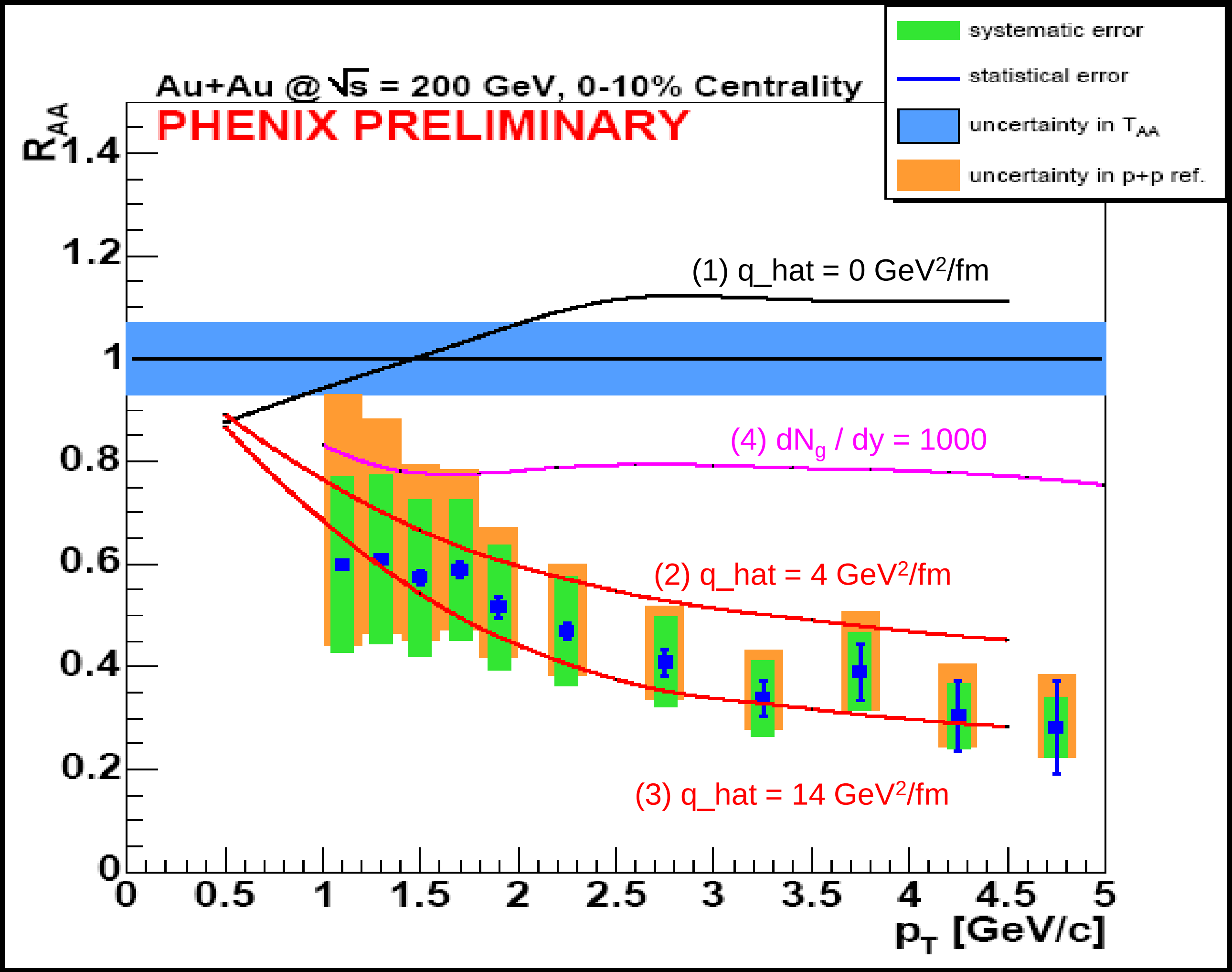
Suppression of High p_T Charm



$$R_{AA} = \frac{\left(\frac{d^3N}{dp^3}\right)_{AA}}{T_{AA} \cdot \left(\frac{d^3\sigma}{dp^3}\right)_{pp}}$$

Strong modification of the spectral shape in Au+Au central collisions is observed at high pT

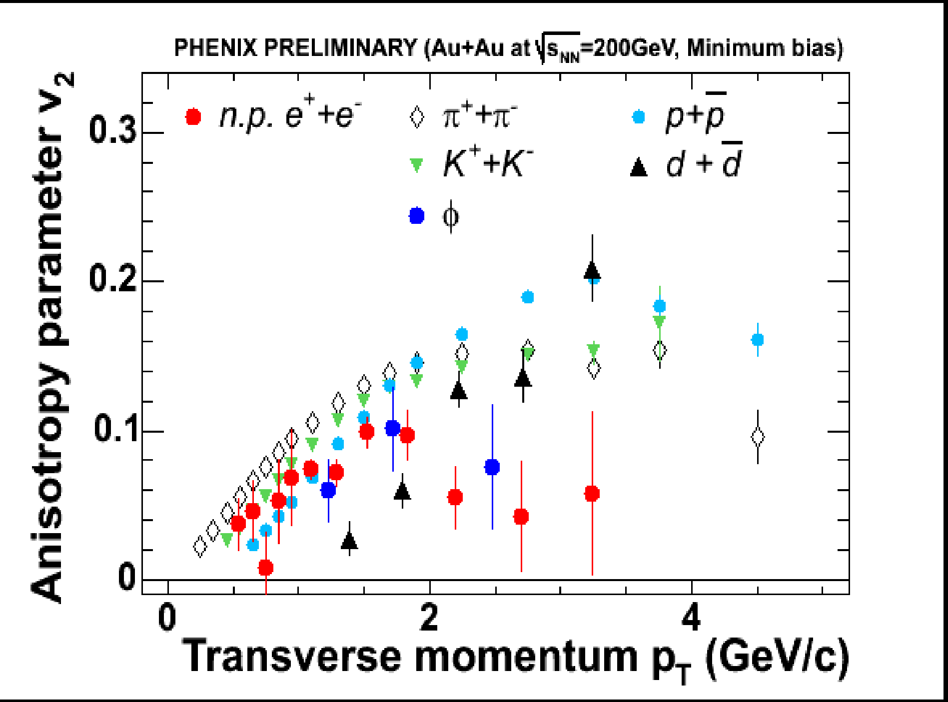
Theory Comparison

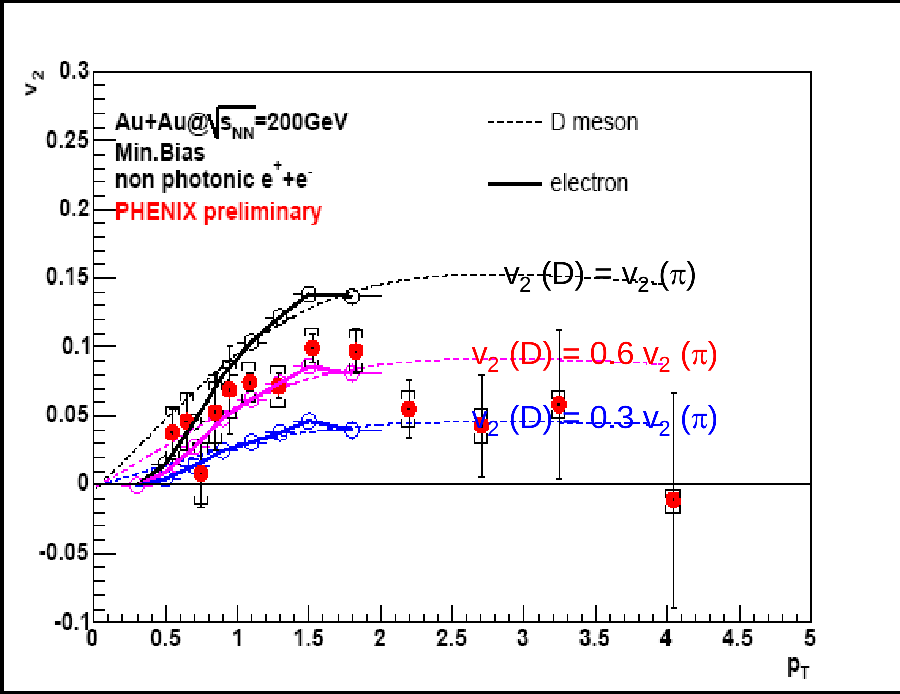


- Data favor models with large parton densities and strong coupling
- Main uncertainty:
  - Bottom contribution at high p_T

Theory curves
(1-3) from N. Armesto, *et al.*, hep-ph/0501225
(4) from M. Djordjevic, M. Gyulassy, S.Wicks, Phys. Rev. Lett. 94, 112301

Charm Flows ?





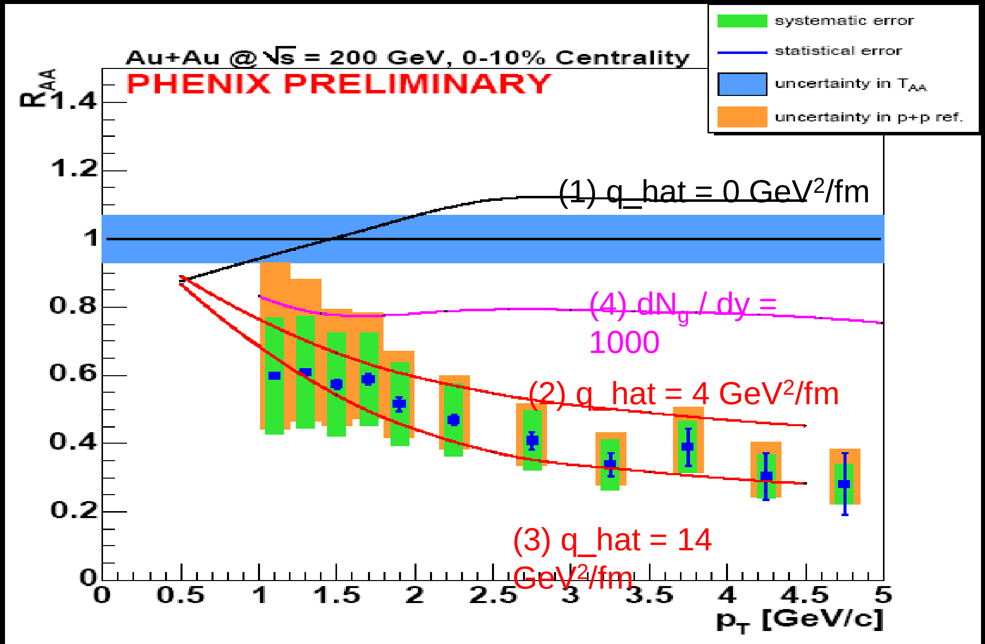
Charm quark exhibit a degree of thermalization

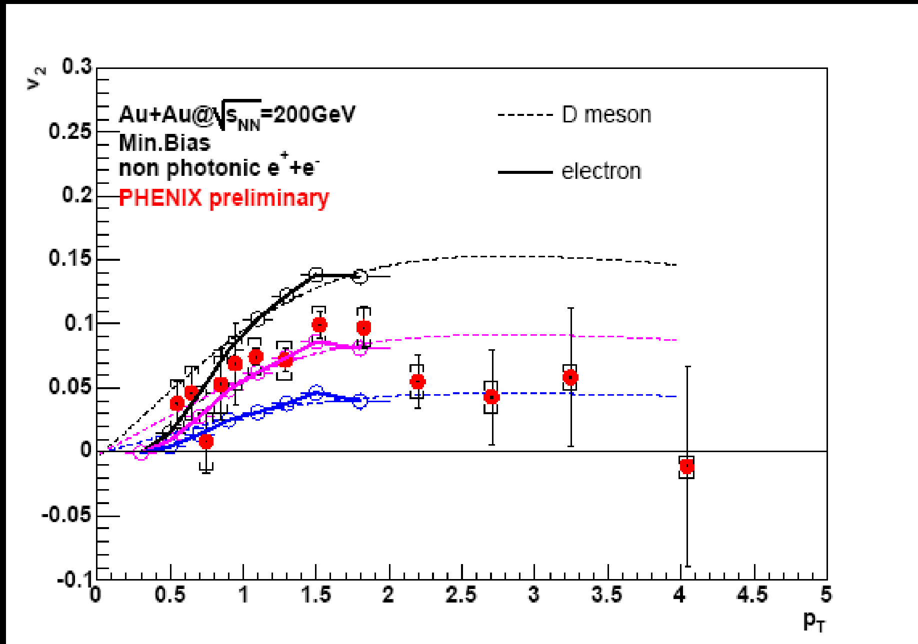
~ comparable to that of light partons

Theory curves from:
Greco, Ko, Rapp: Phys. Lett. B595 (2004) 202

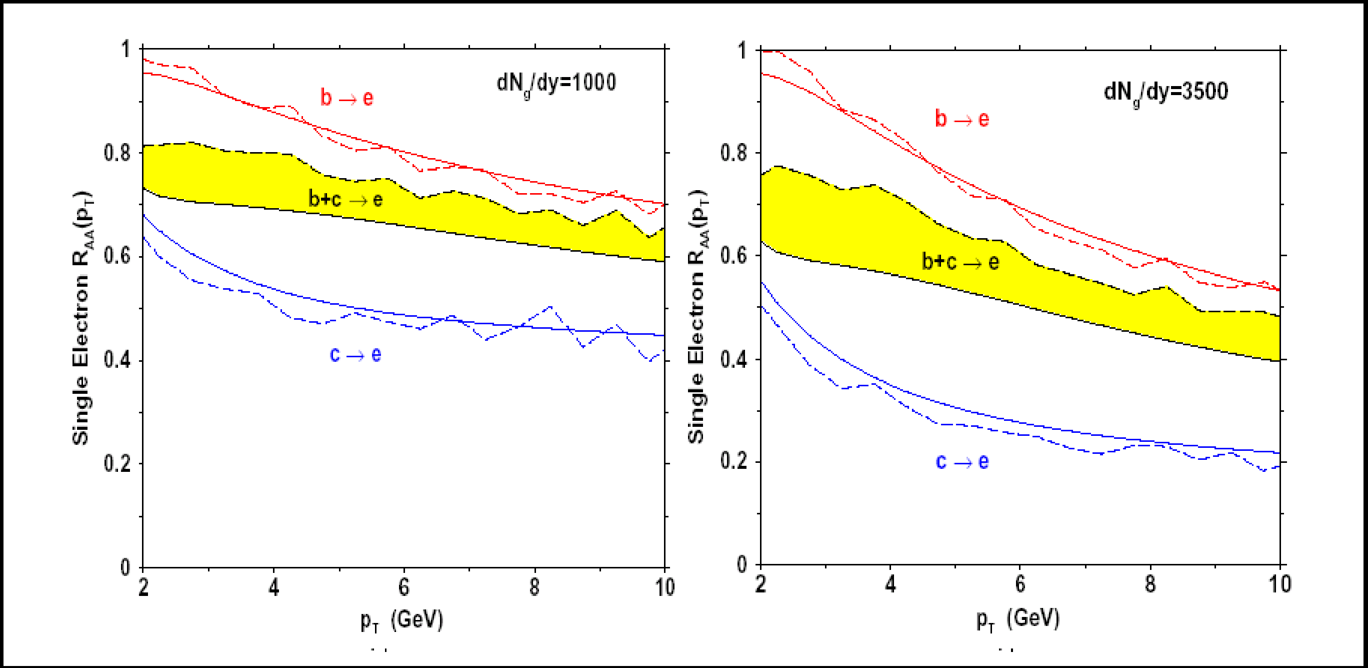
Charming? Summary

- Electrons from heavy flavor decays were measured at $\sqrt{s}$ = 200 GeV in Au+Au collisions at RHIC
- Nuclear modification factor R_{AA} shows a strong suppression of the electrons at high p_T in Au+Au collisions
- Observed R_{AA} favors models with large parton densities and strong coupling
- Charm flows! $v_2(D) \sim 0.6 \times v_2(p)$, indicating substantial coupling of the charm quarks to the bulk dynamics of the medium





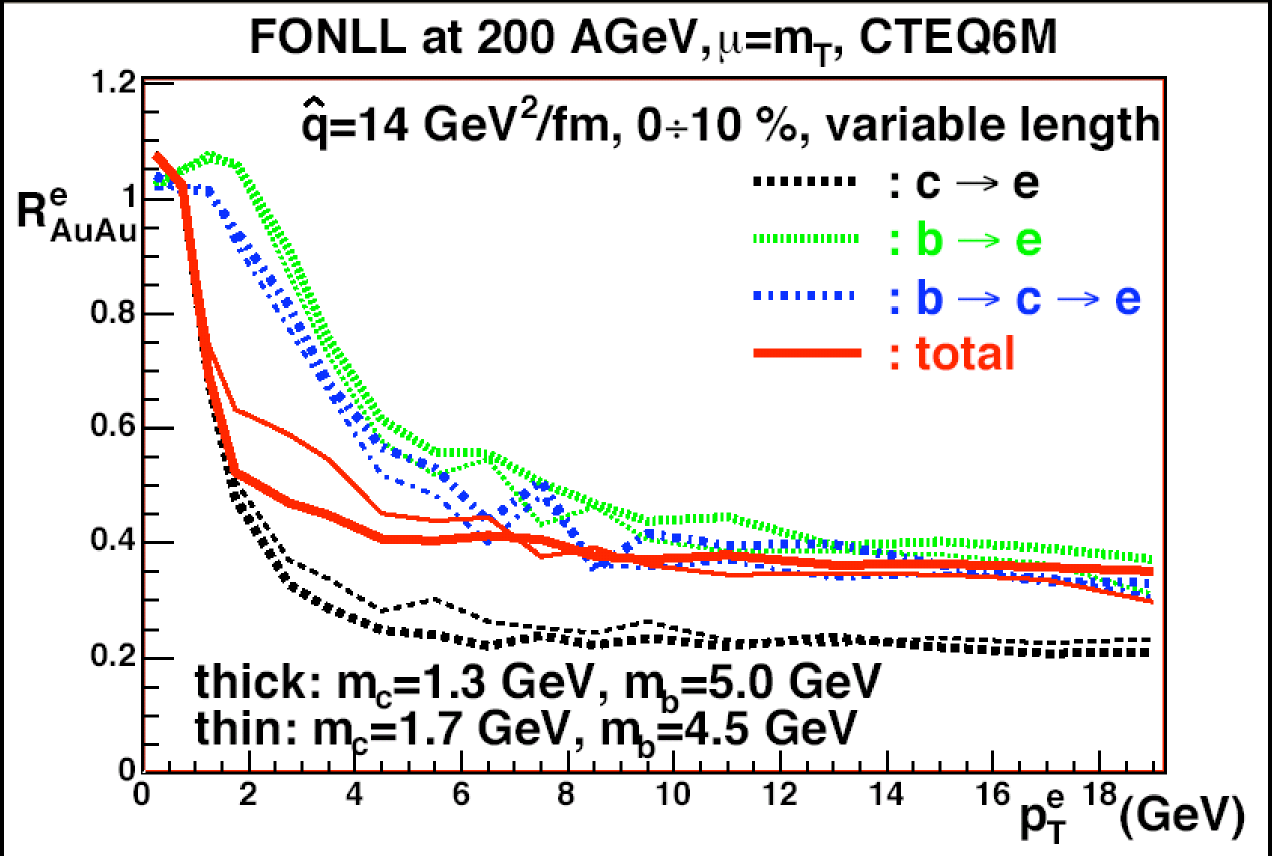
Beauty Limits Suppression Factor?



Therefore, if the preliminary PHENIX data suggesting $R_{AA}(e) < 0.5$ are confirmed, it will be a theoretical challenge to devise novel energy loss mechanisms that make the sQGP opaque to bottom quarks of $p_T \sim 10 - 20$ GeV without over-predicting the observed light hadron quenching in the $p_T \sim 10$ GeV range.

M. Djordjevic et al., nucl-th/0507019

Not All Theorists Agree



Now Armesto *et al.* also include beauty and can find consistent results with $R_{AA} = 0.4$

Charm suppression and Flow

In a calculation by Teaney and Moore (hep-ph/0412346), they calculate the expected elliptic flow (v2) and transverse momentum modifications for different charm quark diffusion coefficients(free parameter). The two effects go hand in hand.

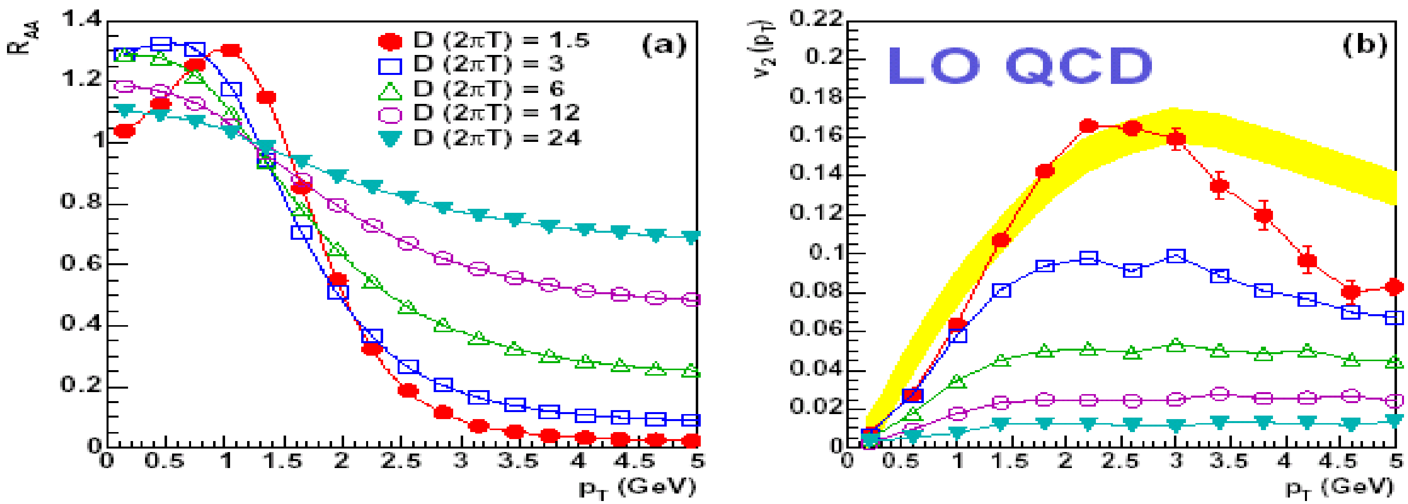
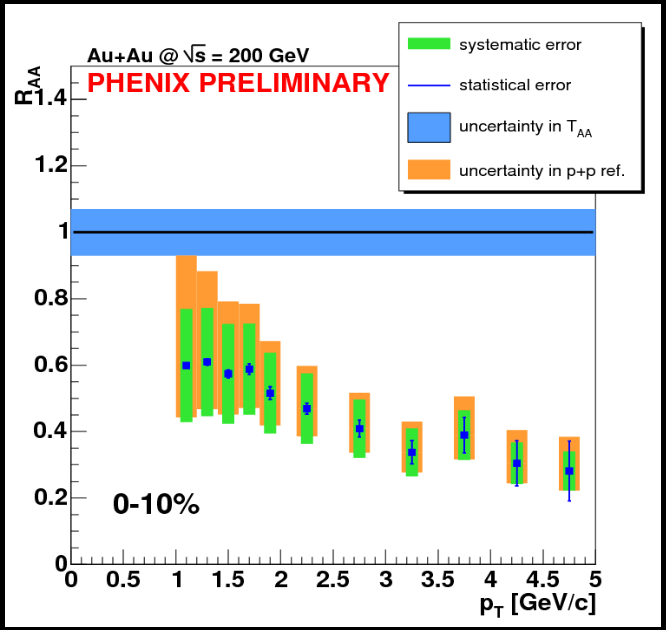
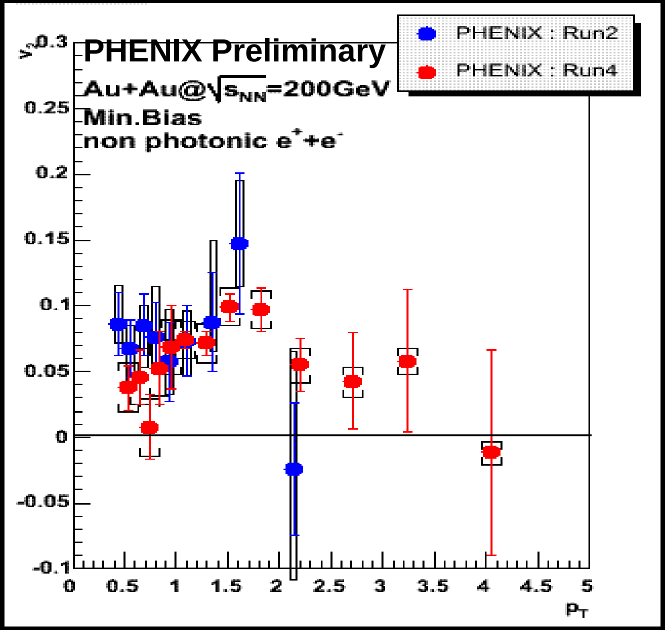
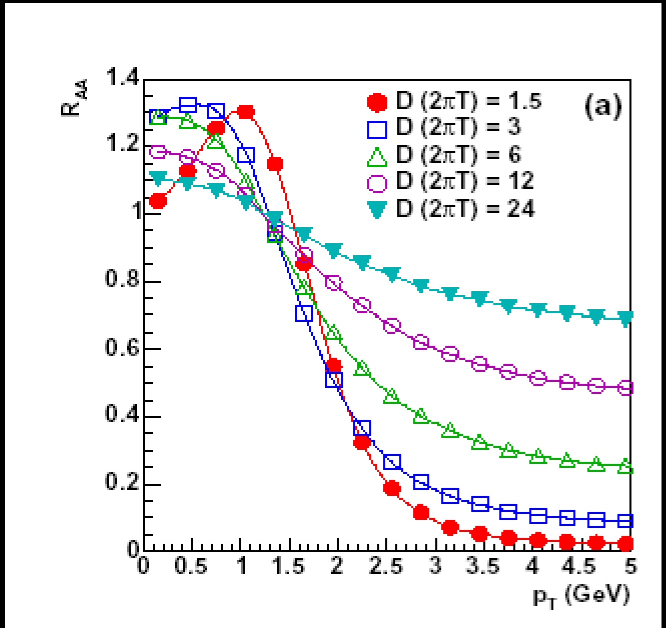


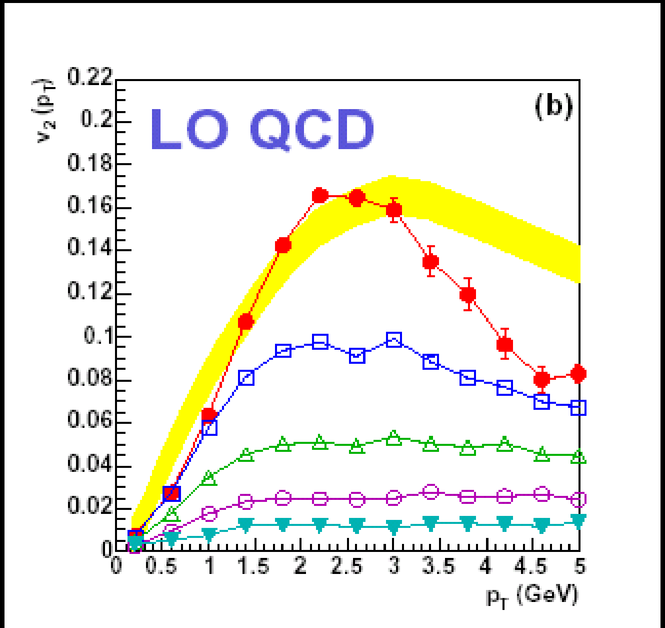
FIG. 4: (Color online) (a) The nuclear modification factor R_{AA} for charm quarks for representative values of the diffusion coefficient. (b) $v_2(p_T)$ for charm quarks for the same set of diffusion coefficients given in the legend in (a). In perturbation theory, $D \times (2\pi T) \approx 6\,(0.5/\alpha_s)^2$. The model for the drag and fluctuation coefficients is referred to as LO QCD in the text. The band estimates the light hadron elliptic flow for impact parameter $b = 6.5$ fm using STAR data [2].

"PHENIX Data: Results Speak for Themselves"



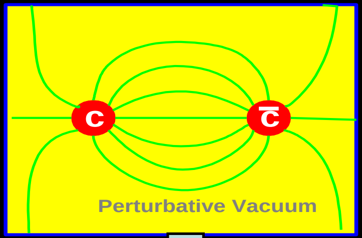


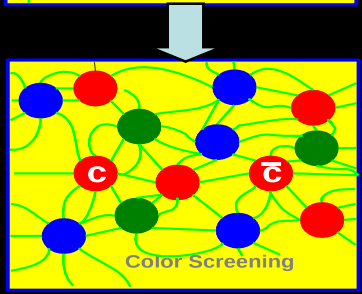




Heavy Quarkonia

A .Different predictions on J/Ψ behaviour when QGP is formed





① **Color screening** will lead to suppression of charmonium production in heavy ion collisions
(*T. Matsui, H. Satz, Phys. Lett. B178(1986)416*).

② **Lattice QCD** results show that the confining potential between heavy quarks is screened at high temperature. This screening should suppress bound states such as J/Ψ. However, recent lattice results indicate that the J/Ψ spectral functions only show modest modification near the critical temperature, and thus may not be suppressed until higher T.

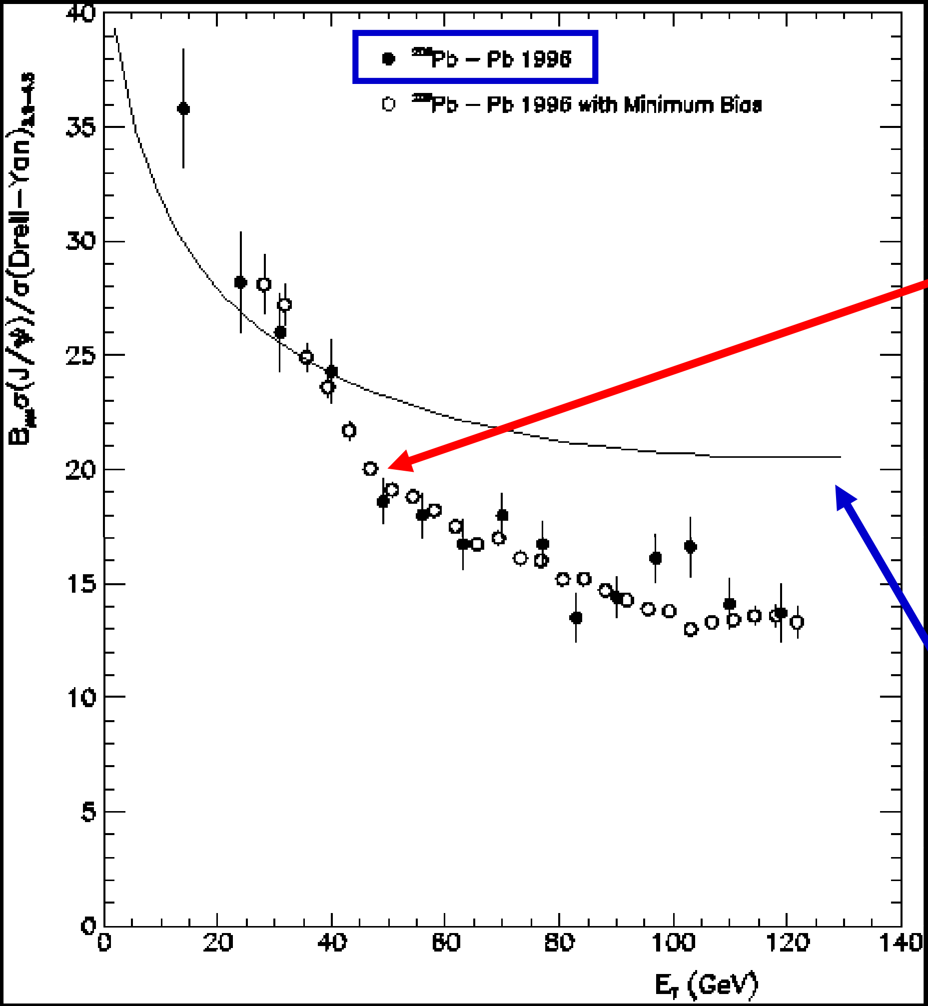
③ But after taken the **recombination** into account, much less suppression or even enhancement is predicted

A. Andronic, P.B. Munzinger et al., nucl-th/0303036
L. Grandchamp, R. Rapp, hep-ph/0103124
R.L. Thews et al., Phys. Rev. c63(2001)054905

B .Disentangle Normal nuclear effects

Gluon shadowing, Nuclear Absorption
Initial state energy loss , Cronin effect.

NA50 Conclusions



"A clear onset of the anomaly is observed. It excludes models based on hadronic scenarios since only smooth behavior with **monotonic derivatives** can be inferred from such calculations"

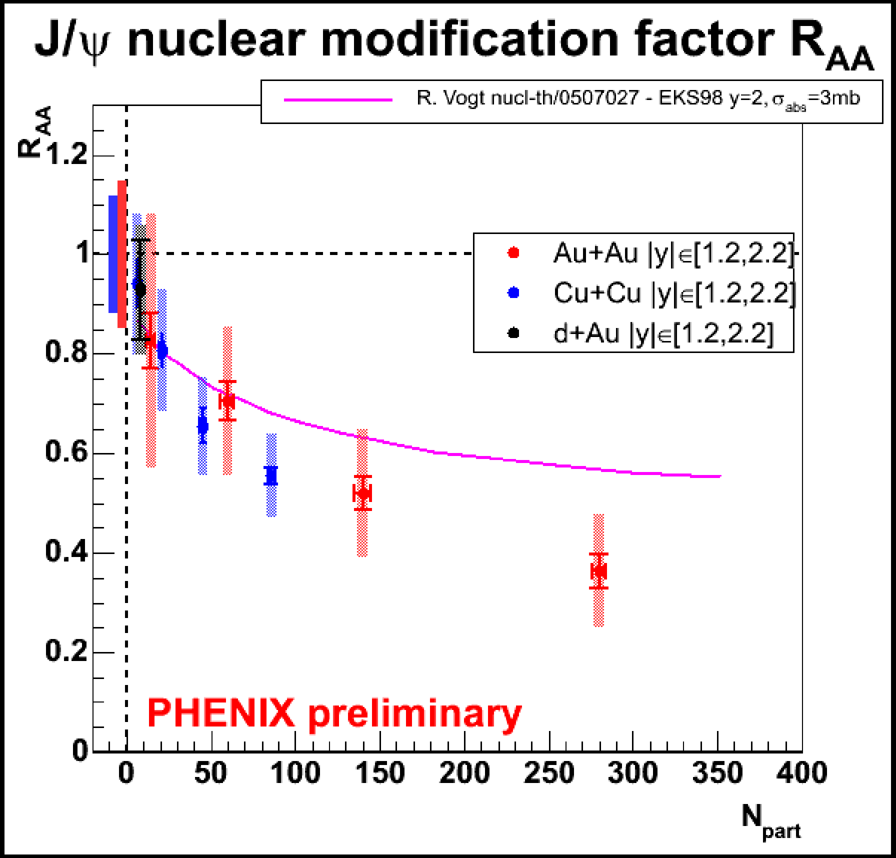
Phys. Lett. B 450, 456 (1999).

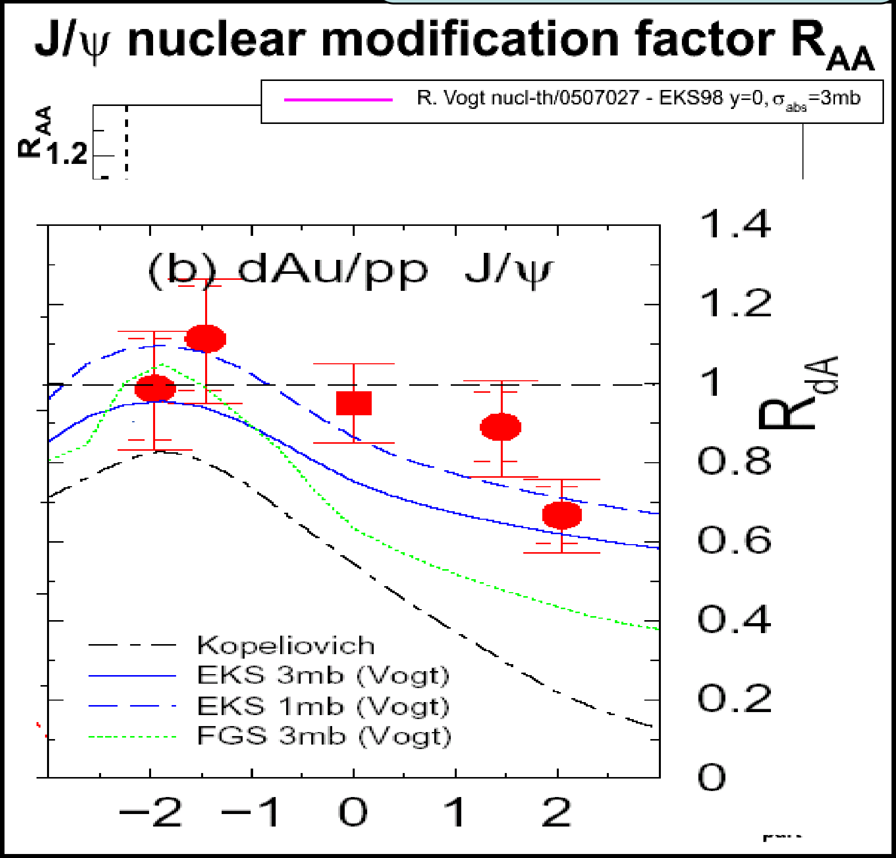
Model assuming:

- charm production scales as DY
- color octet c-c is absorbed by nucleons with a σ = 6.2 mb
- no absorption with comovers π,ρ

Normal Nuclear + Shadowing

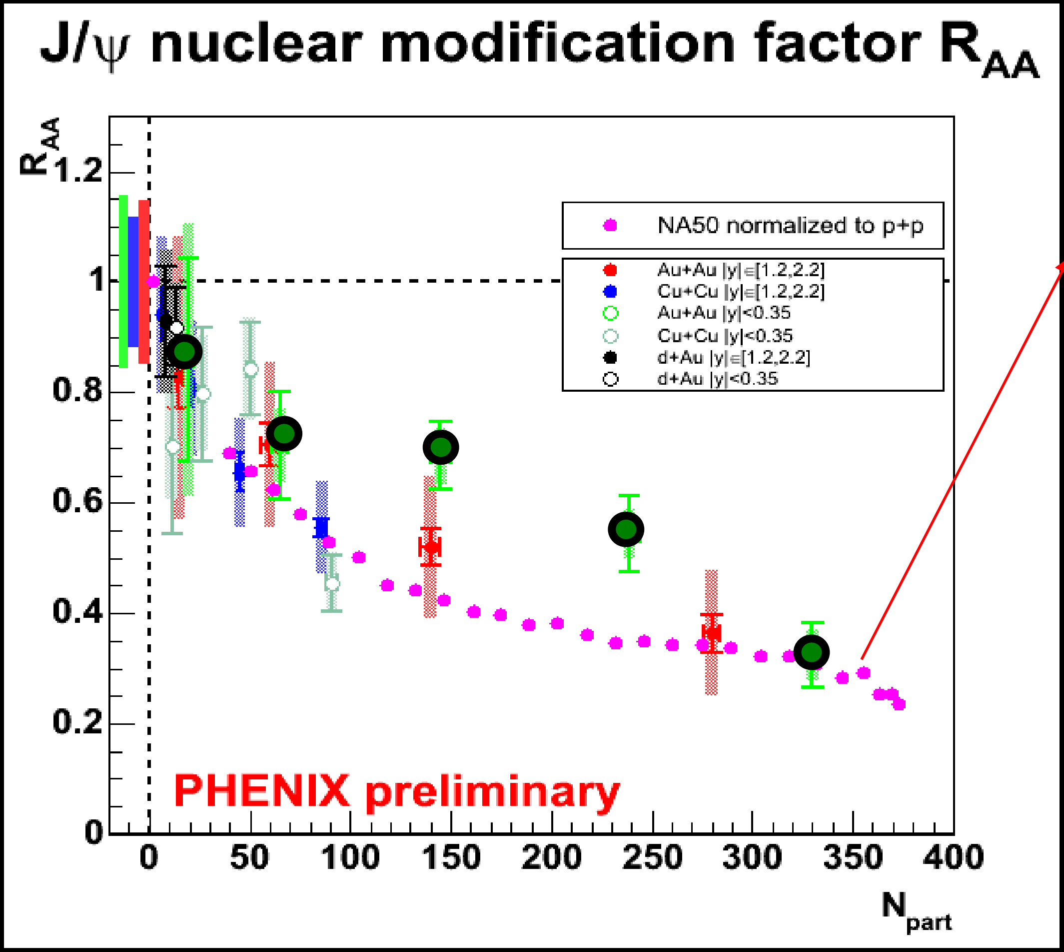
Theory Vogt:
nucl-th/0507027





Model of cold nuclear matter effects in agreement with dAu
Underpredicts suppression in AuAu and CuCu

Looks Like CERN Suppression?



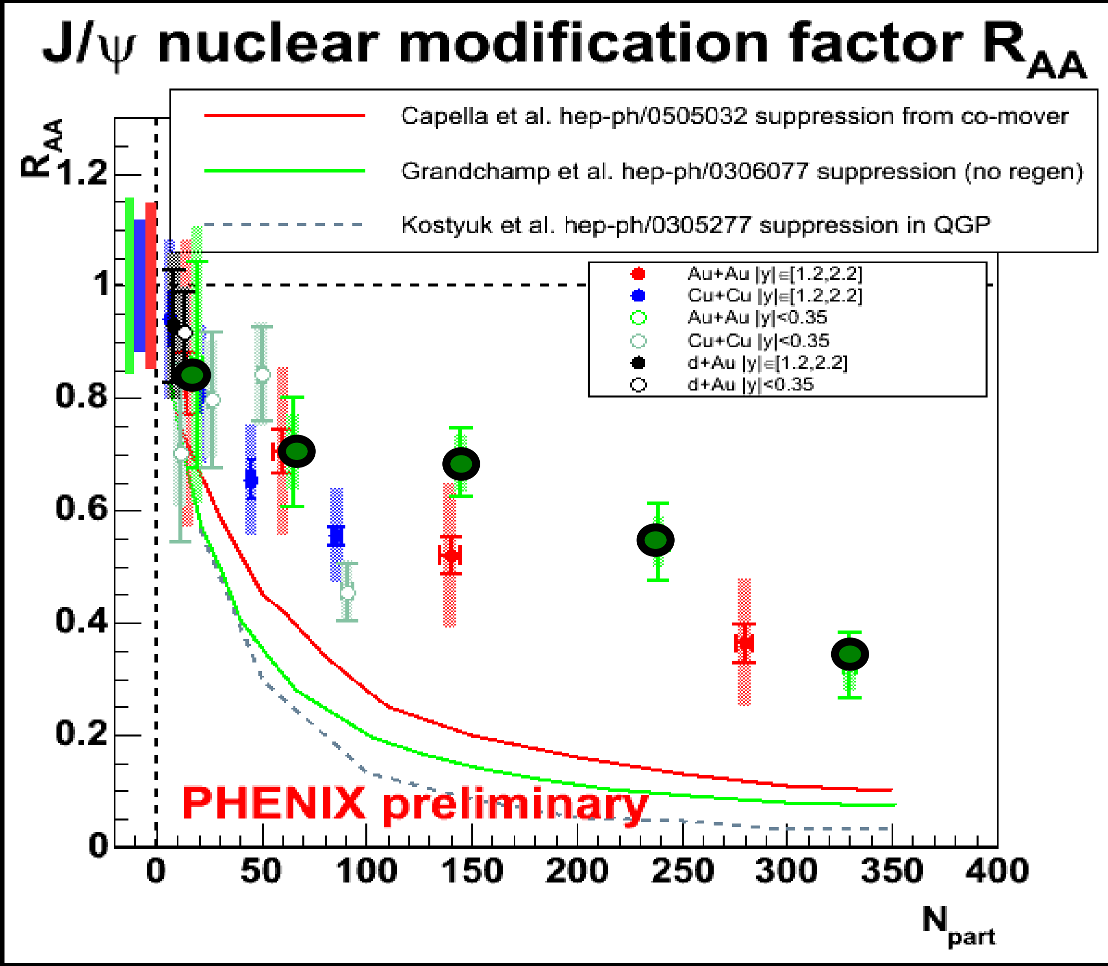
Comparison with NA50 data presented wrt Npart and normalized to NA50 p+p point.

Suppression level is similar between the two experiments, **but**

1) the collision energy is 10 times higher (200GeV wrt 17GeV)

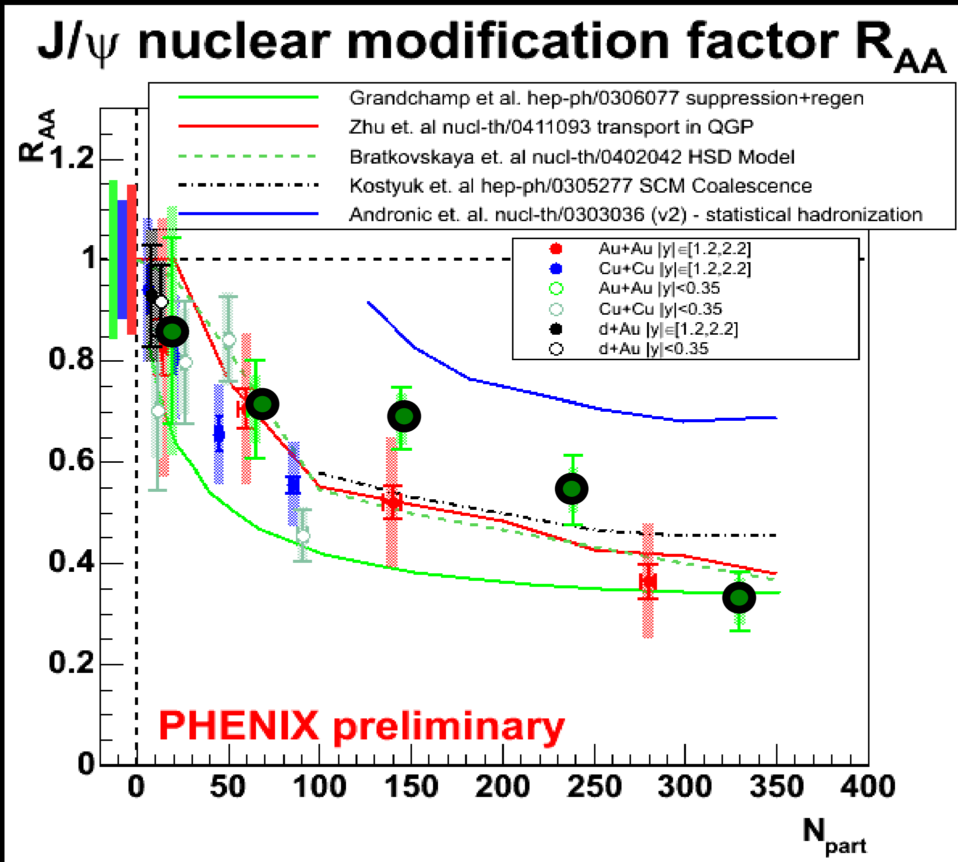
2) the rapidity window for NA50 is $|y| \in [0,1]$

Too Much Suppression in Theory!

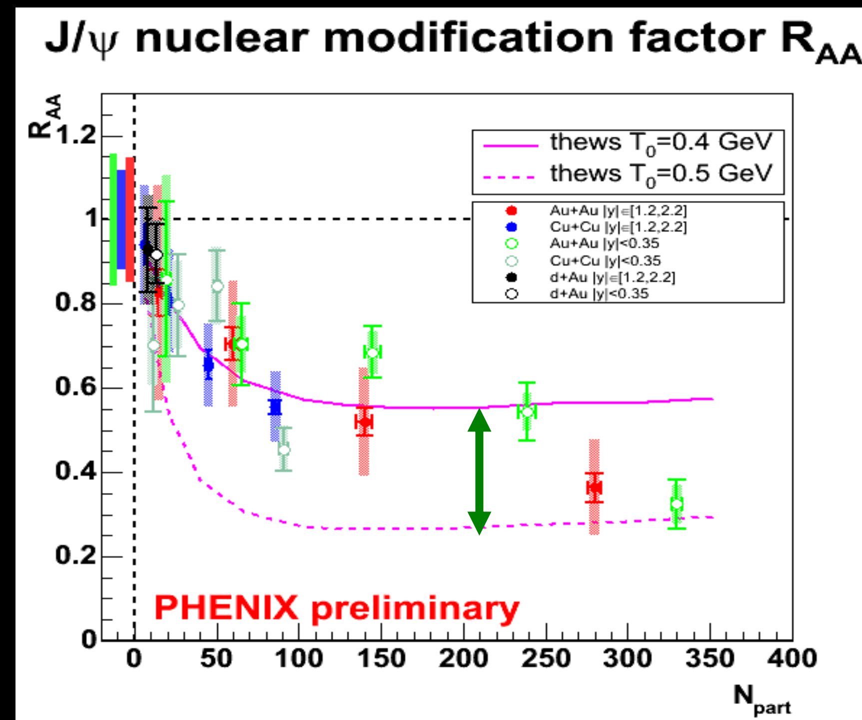


Models that were successful in describing SPS data fail to describe data at RHIC
➔ too much suppression

Regeneration



Uncertainty is large !



Implementing regeneration:

much better agreement with the data

At RHIC, Recombination compensates stronger QGP screening?

But still there are uncertainties in their calculations

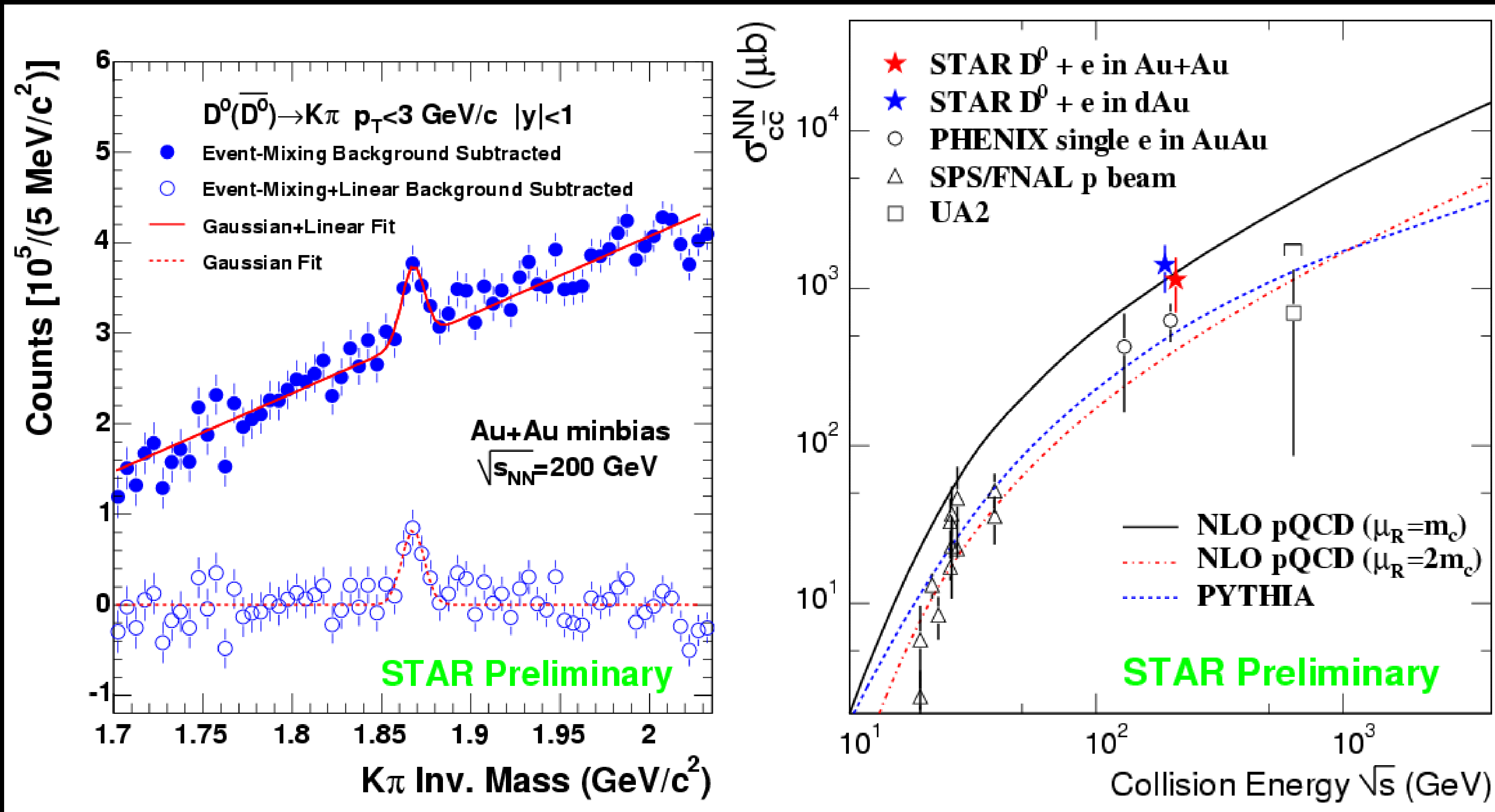
J/Ψ Summary

PHENIX J/ψ centrality dependence:

1) Models with only nuclear absorption don't quite have enough suppression
2) Models without recombination have too much suppression
3) Models with recombination are in reasonable agreement with the data

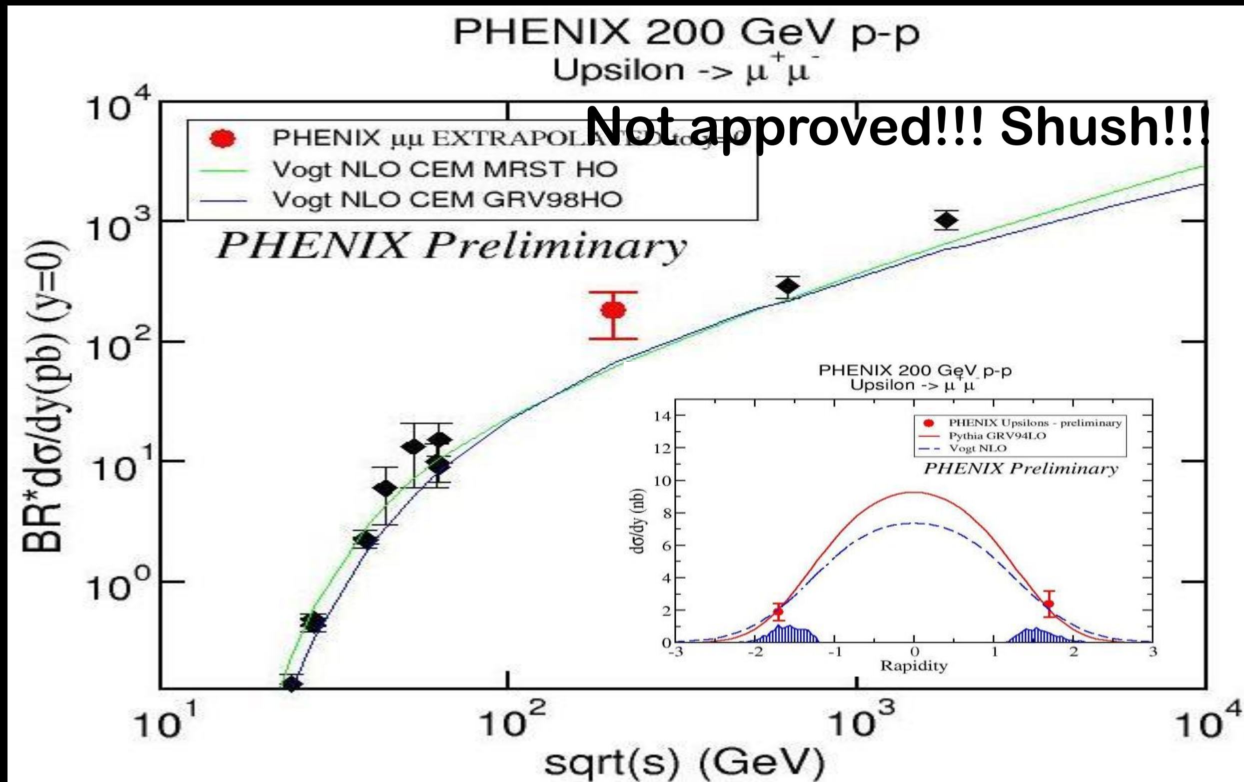
- Suppression for most central collisions is similar to NA50
- Energy density and gluon density at RHIC should be much higher (2-3 times, 200GeV vs 17GeV)?
- At RHIC:
  Recombination compensates stronger QGP screening?

Needed Input of Total Charm

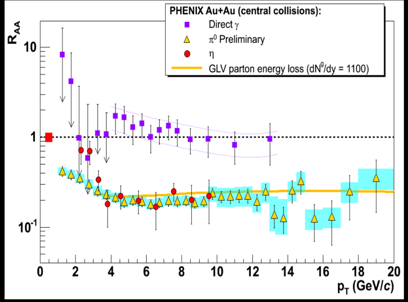


Input from both STAR and PHENIX is needed.

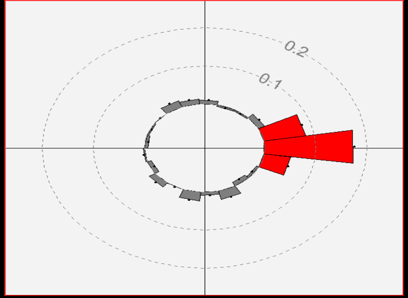
More in the Future...



- Reduce systematic errors and finalize CuCu and AuAu data.
- Improved statistics for baseline Run-5 Proton-Proton and future p-A or d-A
- Working on J/ψ v_2, but statistically very challenging with Run-4 and Run-5 data sets ➔ BUP06 Au-Au running !!!

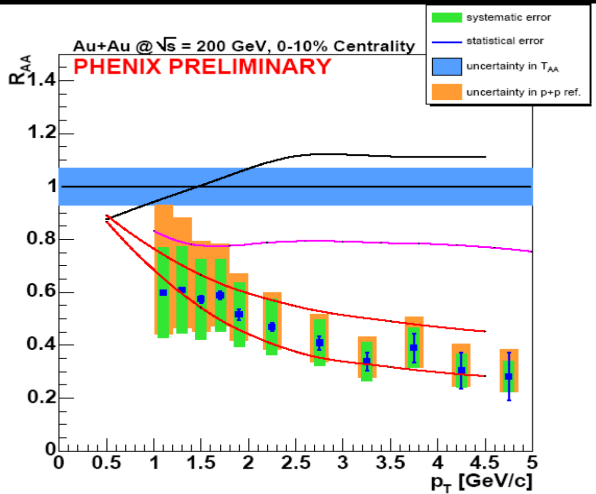


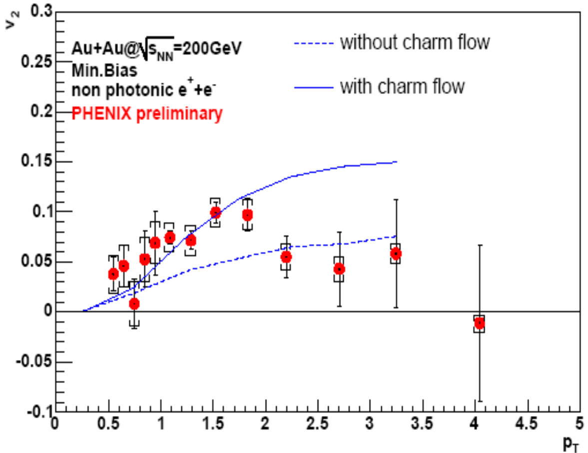
Summary

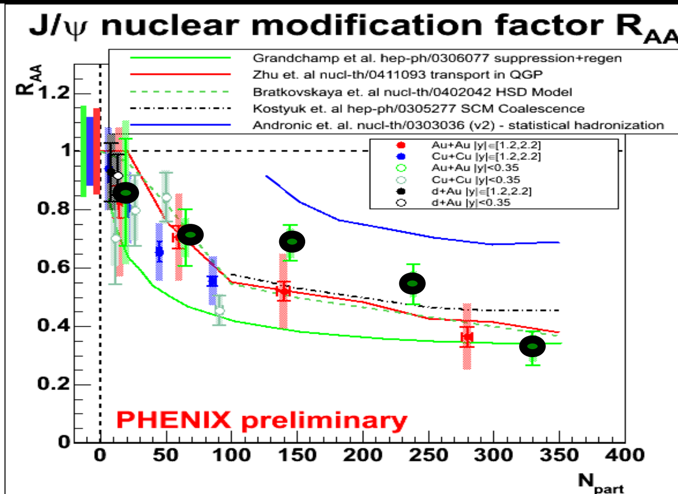


- A wealth of new PHENIX data on heavy quarks and heavy quarkonia.

- Charm is a very optimal probe of thermalization and properties of the medium, but the price for this may well be the loss of a probe via quarkonia for deconfinement.





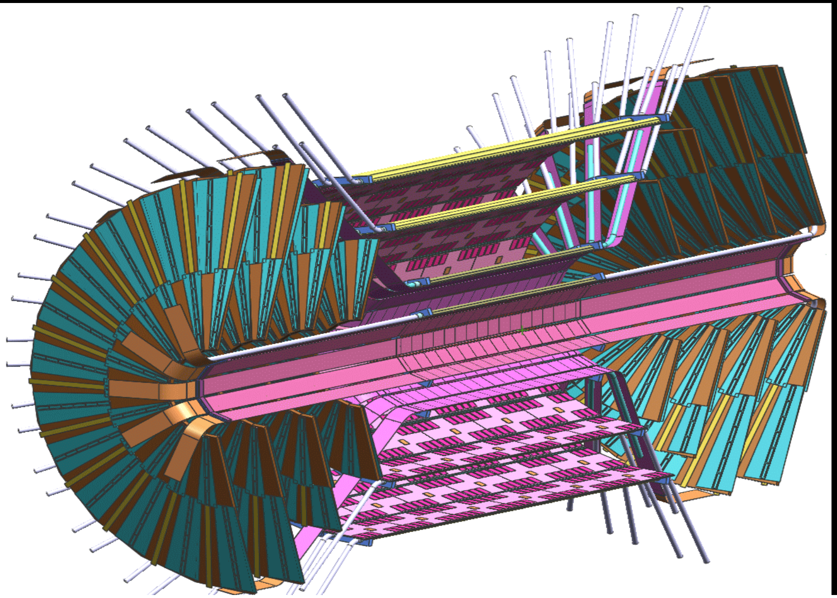


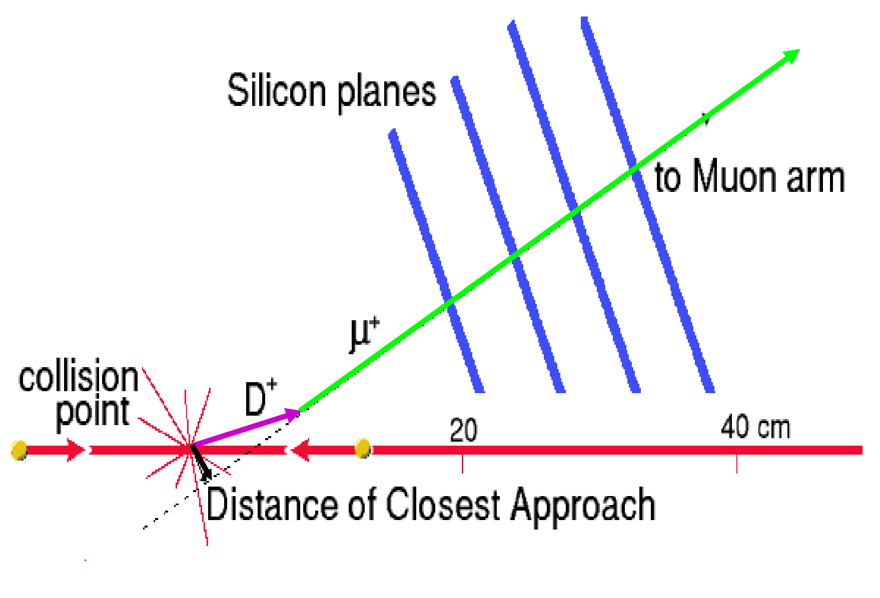
The precision Measurements

- Detector upgrade
  - Precise measurement of Displaced vertex
  - Onium measurements
  - Trigger
- RHIC II Luminosity

Silicon Vertex Detector

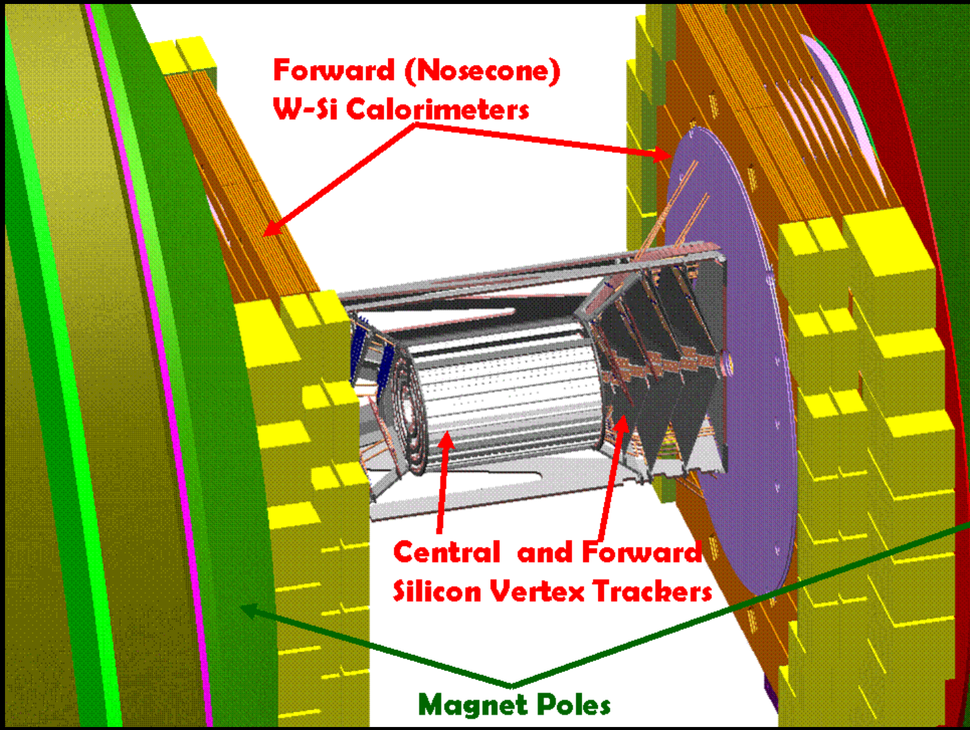
- Four barrel layers
  - Two ALICE pixel bus layers
  - Two strip-pixel layers
- Four end-cap pixel layers
- Displaced vertex (σ ~50 μm)
- Full azimuthal inner tracking $|\eta| <$ ~2.4
  - Improve acceptance for γ-jet correlations, $D \rightarrow K\pi$
- Connect to tracks in central and muon arms
  - Tag heavy flavor decays
    - $c,b \rightarrow e,\mu$
    - $B \rightarrow J/\Psi$
  - Improve onium resolution
  - Eliminate decay hadrons
  - Reduce high-p_T background





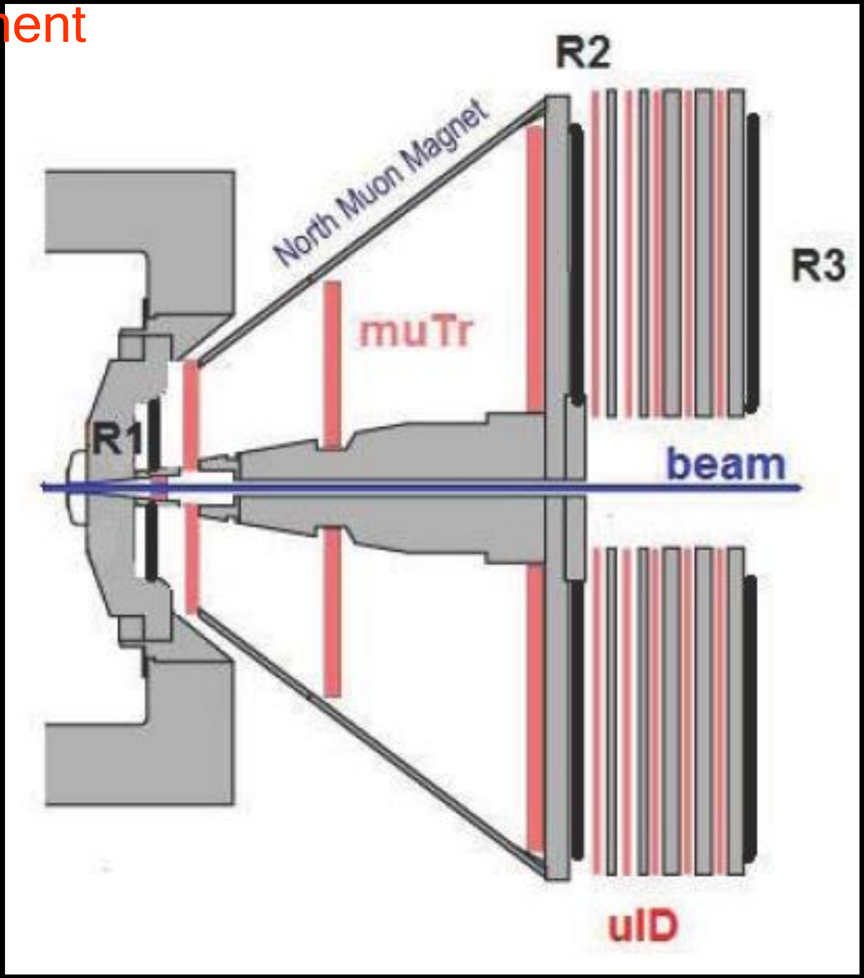
Nose Cone Calorimeter

- Replace central arm magnet nosecones (Cu) w/ tungsten-silicon calorimeters
- Coverage at forward/backward rapidity: $0.9 < |\eta| < 3.5$
  - γ/π^0 separation for $p_T < 30$ GeV/c
  - Jet identification
- γ identification gives good acceptance for $\chi_c \rightarrow J/\Psi + \gamma$



Muon Trigger Upgrade

- Three layers of RPCs with 2D (θ,φ) pad readout
- Provides online momentum measurement to improve Level-1 trigger rejection
  - Single-particle
    - p_T cut
    - *W* spin-measurements in *pp*
  - Two-particle
    - M_{inv} cut
    - onium measurements in AA
  - Necessary to take complete advantage of luminosity upgrades
- Provides improved high-multiplicity background rejection



RHIC II Luminosity – CAD Guidance

W. Fischer, T. Roser, I. Ben-Zvi, A. Fedotov, BNL C-AD, 16-Mar-2005

Classical proton radius [m] 1.53E-18

http://rhicii-heavy.bnl.gov/doc/RHIC_II_Luminosity_Roser.xls

Maximum Luminosity Estimates for RHIC II

Beams	unit	p	p	unit	Si	Cu	d	p	Au	unit	Au
Charge number Z	…	1	1	…	14	29	1	1	79	…	79
Mass number A	…	1	1	…	28	63	2	1	197	…	197
Relativistic γ	…	108	271	…	108	108	107	108	107	…	107
Revolution frequency	kHz	78.2	78.2	kHz	78.2	78.2	78.2	78	78.2	kHz	78.2
Normalised emittance, 95%, min	mm mrad	12	12	mm mrad	12	12	12	12	12	mm mrad	10
Ions/bunch, initial	10^9	200	200	10^9	10.7	5.2	150	200	1.0	10^9	1.0
Charges per bunch	$10^9 e$	200	200	$10^9 e$	150	150	150	200	80	$10^9 e$	80
No of bunches	…	110	110	…	110	110	110	110	110	…	110
Average beam current/ring	mA	275	275	mA	206	206	206	275	110	mA	110
Luminosity at one IP	**unit**	**p-p**	**p-p**	**unit**	**Si-Si**	**Cu-Cu**	**d-Au**	**p-Au**	**Au-Au**	**unit**	**Au-Au**
Beam-beam parameter per IP	…	0.0123	0.0123	…	0.0046	0.0043	0.0024 0.0036	0.0048 0.0048		…	0.0024
β*	m	1.0	0.5	m	1.0	1.0	2.0	2.0		m	0.5
Peak luminosity	10^{30} cm^{-2}s^{-1}	150	750	10^{28} cm^{-2}s^{-1}	42	10	28	37		10^{26} cm^{-2}s^{-1}	90
Peak / average luminosity	…	1.5	1.5	…	1.3	1.3	1.5	1.5		…	1.3
Average store luminosity	10^{30} cm^{-2}s^{-1}	100	500	10^{28} cm^{-2}s^{-1}	32	8	19	25		10^{26} cm^{-2}s^{-1}	70
Time in store	%	55	55	%	55	55	55	55		%	60
Luminosity/week	pb^{-1}	33	166	nb^{-1}	108	25	62	83		nb^{-1}	2.5
Luminosity/week, achieved	pb^{-1}	0.9		nb^{-1}		2.4	4.5			nb^{-1}	0.16

x 35 increase for pp

x 10 increase for CuCu

x 15 increase for dAu

x 15 increase for AuAu

RHIC II Yields - ADF, MJL Guidance

Machine	RHIC II	PHENIX
sqroot(s)	200 GeV	

Species 1 mass	1	p
Species 2 mass	1	p
luminosity/week	33 /pb/wk	
number of weeks	12	
PHENIX uptime	0.6	
Integrated luminosity	237.6 /pb	

RHIC II pp luminosity (average) 1 x 10^32

PHENIX chi_c acceptances from AN229
(muon arm acceptance is for south arm only, hence factor of 2)

PHENIX Jpsi and psi' acceptances from PPG038
PHENIX Upsilon acceptance from Axel Drees
Branch factors from PDG
Collision vertex sig SVTX covers +/- 10 cm
RF efficiency 80% (in central peak)

Signal	p+p dσ/dy	units	ref. dy	process / source	branch factor	nuclear scaling	collision vert cut	minbias trig eff	Level 1 trig eff	acceptance	reconstr efficiency	yield
Jpsi->ee	673000	pb	1	Jpsi ds/dy / PHENIX AN258	0.059	1	0.55	0.75	0.76	2.27E-002	0.82	55054
psi(2S)->ee	94220	pb	1	Psi/Jpsi ratio from hep-ph/9502270	7.60E-003	1	0.55	0.75	0.76	2.27E-002	0.82	993
chi_c0->gamma Jpsi->ee	6510000	pb	1	sigma(chi->gamma Jpsi->ee) AN229	3.90E-004	1	0.55	0.75	0.76	6.45E-004	0.82	100
chi_c1->gamma Jpsi->ee	2100000	pb	1	sigma(chi->gamma Jpsi->ee) AN229	1.62E-002	1	0.55	0.75	0.76	6.45E-004	0.82	1340
chi_c2->gamma Jpsi->ee	6950000	pb	1	sigma(chi->gamma Jpsi->ee) AN229	8.00E-003	1	0.55	0.75	0.76	6.45E-004	0.82	2190
Y(0,1,2)->ee	86	pb	1	Ups B*ds/dy / hep-ph/9502270	1	1	0.55	0.75	0.76	4.00E-002	0.82	210
Jpsi->mumu	451542	pb	2.2	Jpsi ds/dy / PHENIX AN255	0.059	1	0.55	0.75	0.8	1.28E-001	0.8	468741
psi(2S)->mm	63215.88	pb	2.2	Psi/Jpsi ratio from hep-ph/9502270	7.60E-003	1	0.55	0.75	0.8	1.28E-001	0.8	8453
chi_c0->gamma Jpsi->mn	6510000	pb	2	sigma(chi->gamma Jpsi->mm) AN22!	3.90E-004	1	0.55	0.75	0.8	1.20E-002	0.8	3822
chi_c1->gamma Jpsi->mn	2100000	pb	2	sigma(chi->gamma Jpsi->mm) AN22!	1.62E-002	1	0.55	0.75	0.8	1.20E-002	0.8	51215
chi_c2->gamma Jpsi->mn	6950000	pb	2	sigma(chi->gamma Jpsi->mm) AN22!	8.00E-003	1	0.55	0.75	0.8	1.20E-002	0.8	83702
Y(0,1,2)->mm	43	pb	2.2	Ups B*ds/dy / hep-ph/9502270	1	1	0.55	0.75	0.8	8.90E-002	0.8	528

- Assume CAD “Maximum Average” Luminosity Projection, 12 week runs, known PHENIX uptime (60%) to get Live Delivered Luminosity.
- Use measured values when possible to calculate *pp* σ’s, B.R.’s.
- Assume nuclear scaling - $(AB)^{\alpha}$, w/α=1 for Υ, α=0.92 for others.
- Use stated RF efficiency, diamond size to get vertex cut efficiency.
- Use measured PHENIX performance, assume PHENIX SiVTX, Nosecone Calorimeter, Muon Trigger upgrades to get acceptances, efficiencies.

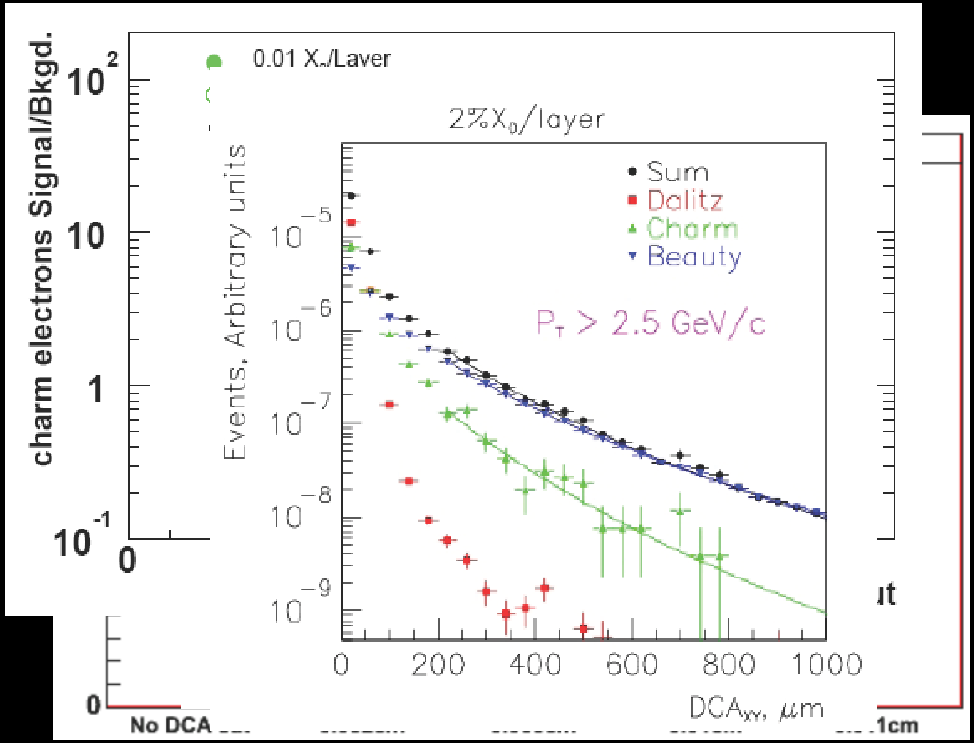
Onium Yields

Signal/System	pp (200 GeV)	pp (500 GeV)	CuCu (200 GeV)	AuAu (200 GeV)	dAu (200 GeV)
$J/\Psi \to ee$	55,054	609,128	73,921	44,614	29,919
$\Psi'(2S) \to ee$	993	10,985	1,333	805	540
$\chi\_c0 \to \gamma + J/\Psi \to ee$	100	2,578	134	81	54
$\chi\_c1 \to \gamma + J/\Psi \to ee$	1,340	40,870	1,800	1,086	728
$\chi\_c2 \to \gamma + J/\Psi \to ee$	2,190	59,296	2,941	1,775	1,190
$\Upsilon(0,1,2) \to ee$	210	3,032	547	397	184
$B \to J/\Psi \to ee$	1,237	41,480	4,567	3,572	1,085
$J/\Psi \to \mu\mu$	468,741	5,483,006	653,715	394,535	258,136
$\Psi'(2S) \to \mu\mu$	8,453	98,880	11,789	7,115	4,655
$\chi\_c0 \to \gamma + J/\Psi \to \mu\mu$	3,822	99,824	5,330	3,217	2,105
$\chi\_c1 \to \gamma + J/\Psi \to \mu\mu$	51,215	1,582,561	71,425	43,107	28,204
$\chi\_c2 \to \gamma + J/\Psi \to \mu\mu$	83,702	2,296,069	116,732	70,451	46,095
$\Upsilon(0,1,2) \to \mu\mu$	528	7,723	1,429	1,035	469
$B \to J/\Psi \to \mu\mu$	2079	76466	5756	3752	1824

- Precision measurements of the J/Ψ
- Exploratory measurements of the other onium states.
- Steep increase at $\sqrt{s}$ = 500 GeV illustrates the significant difficulties for measurements at lower energies.

Synergistic Benefits of Detector/Luminosity Upgrades for Open Heavy Flavor Measurement

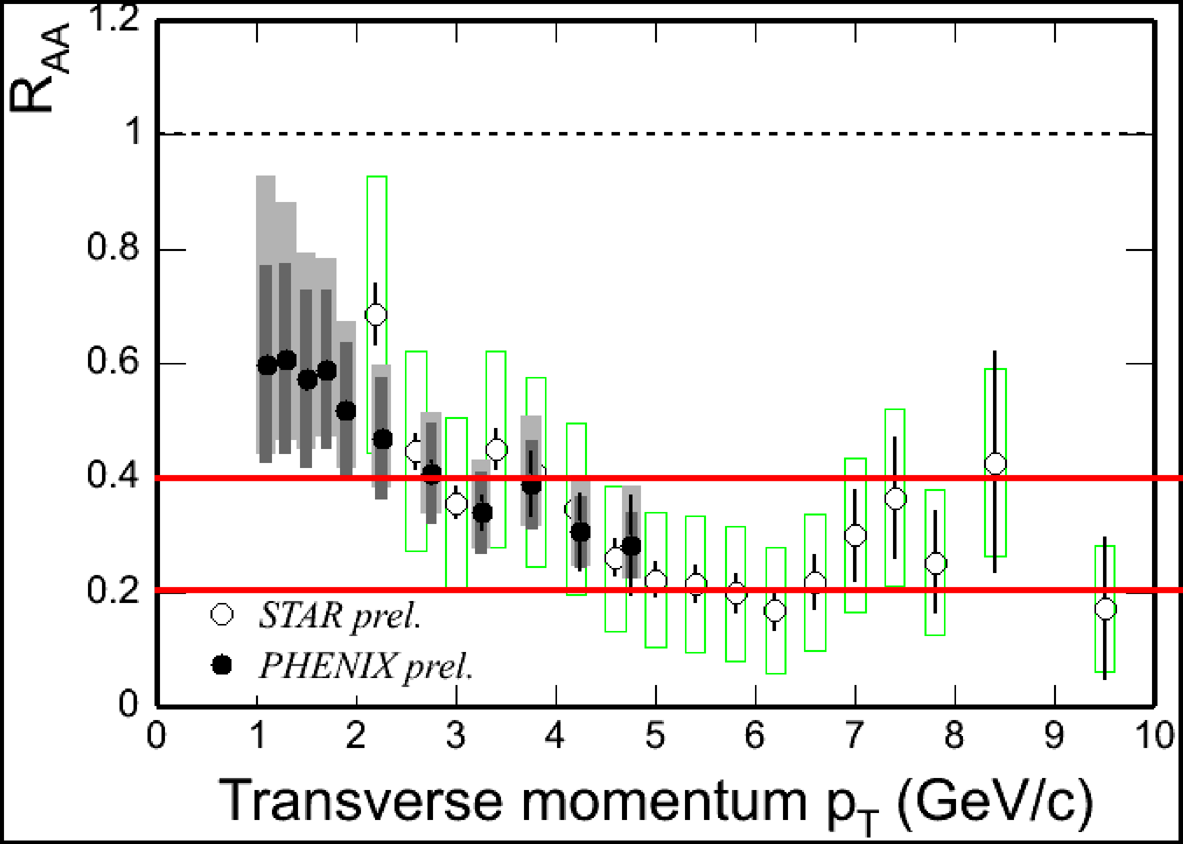
- Detector upgrades assist by determining **decay vertex**.
  - Allows direct measurement of charm via $D \to K\pi$
  - Reduces backgrounds at low-p_T
  - Allows statistical separation of *c/b* at high-p_T
  - Allows direct elimination of hadron decay muons.



- Luminosity upgrades extend p_T reach and allow reduction of **systematic errors**.
  - Additional special runs (*e.g.*, w/ different converter thicknesses and locations, different field configurations, etc.)
  - Finer binning of DCA dependence for *c/b* separation.
  - Better determination of punchthrough absorption.

Backup Slides

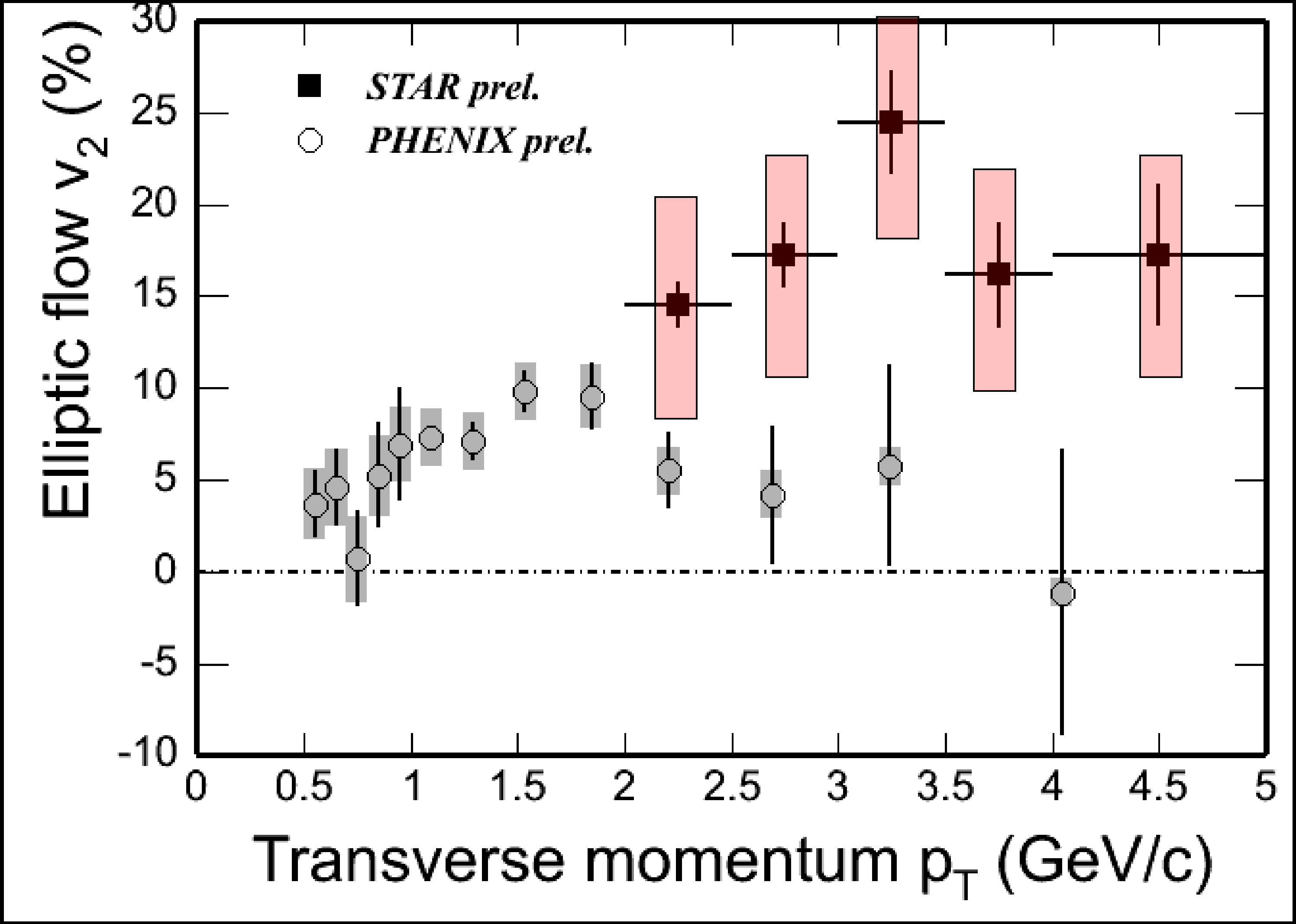
Not All Experiments Agree Either



R_{AA} agrees, but the proton-proton references are different by ~ 50%.

Also, can the theory resolve an R_{AA} suppression value of 0.2? Is the parton density then too high?

Comparison



Not shown were "30-40%" systematic errors.

NA50

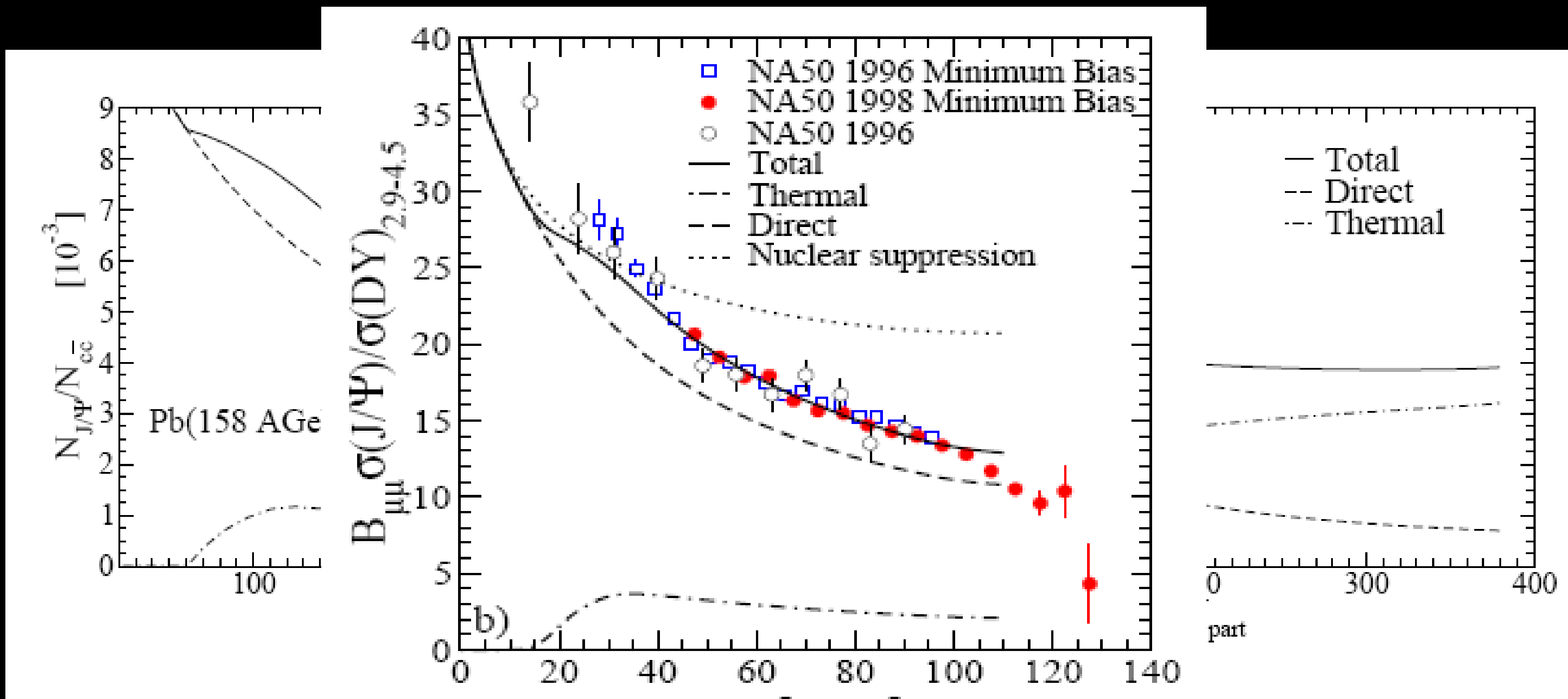
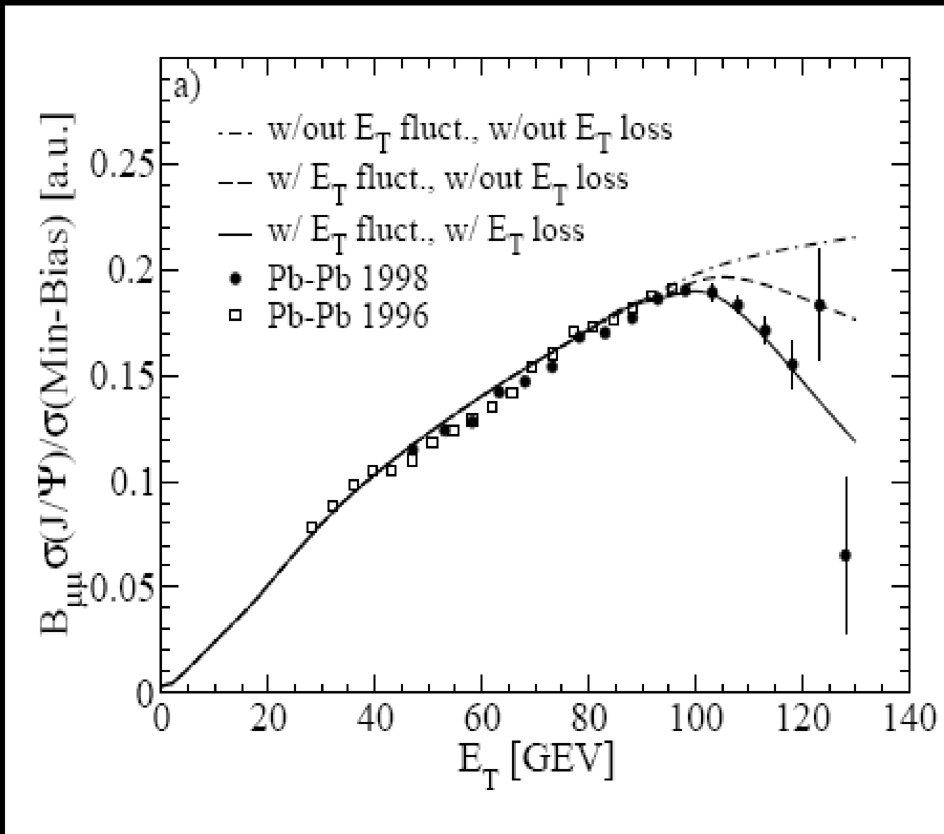
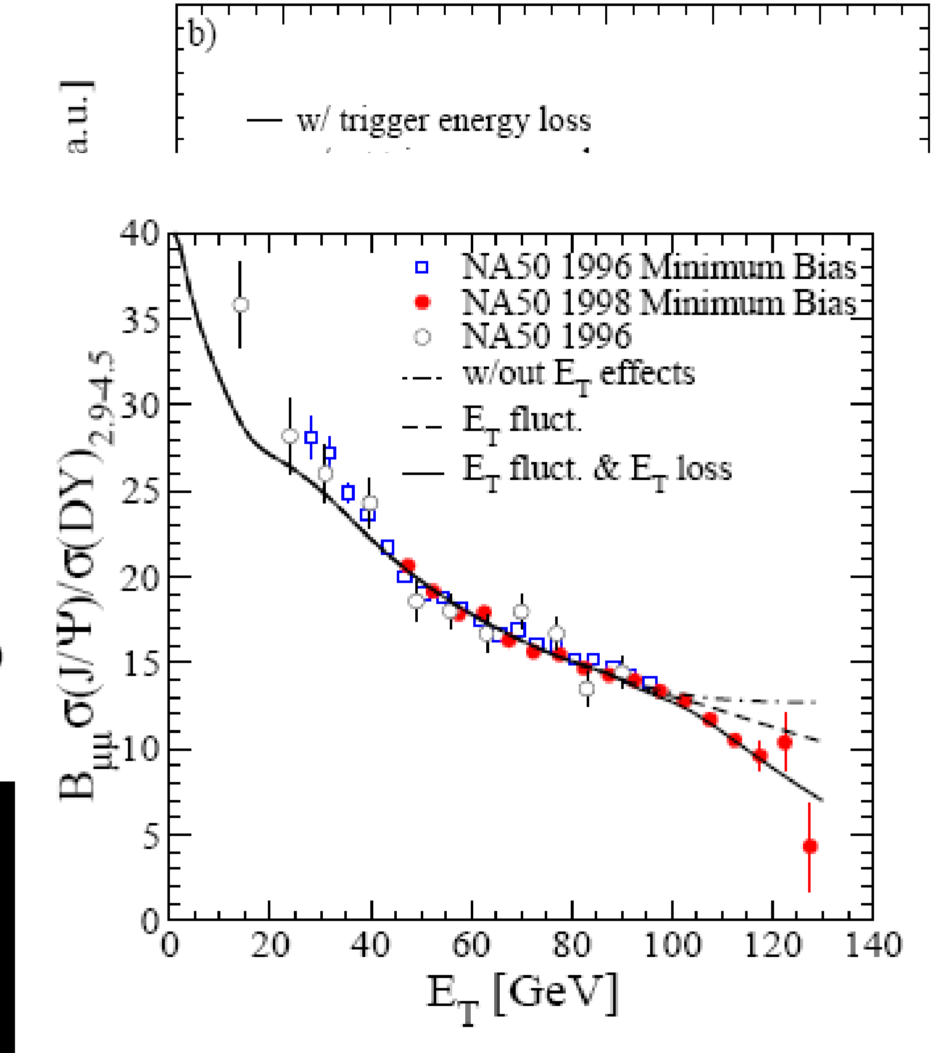


FIG. 10: Comparison of … energy (full line). The direct (thermal) contributions are shown separately, respectively in the dashed (dot-dashed) lines.

$$N_{J/\Psi} = N_{J/\Psi}^{dir} + N_{J/\Psi}^{th}$$

Regeneration

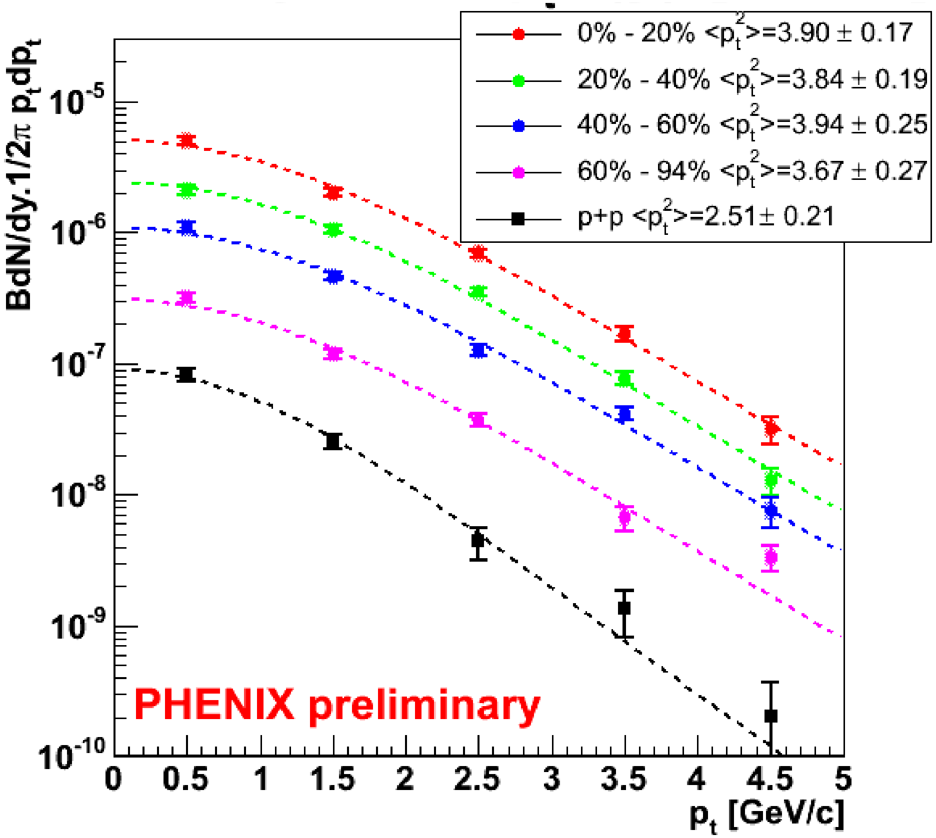




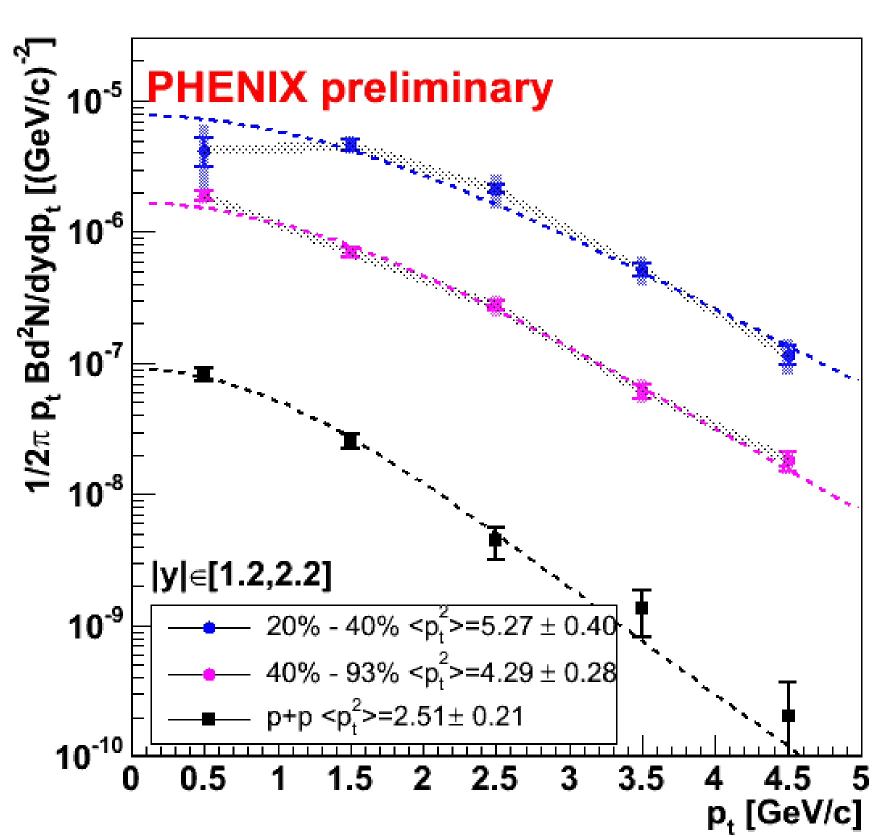
and 2) trigger energy loss

Transverse Momentum

Cu+Cu ($|y|\in[1.2,2.2]$)

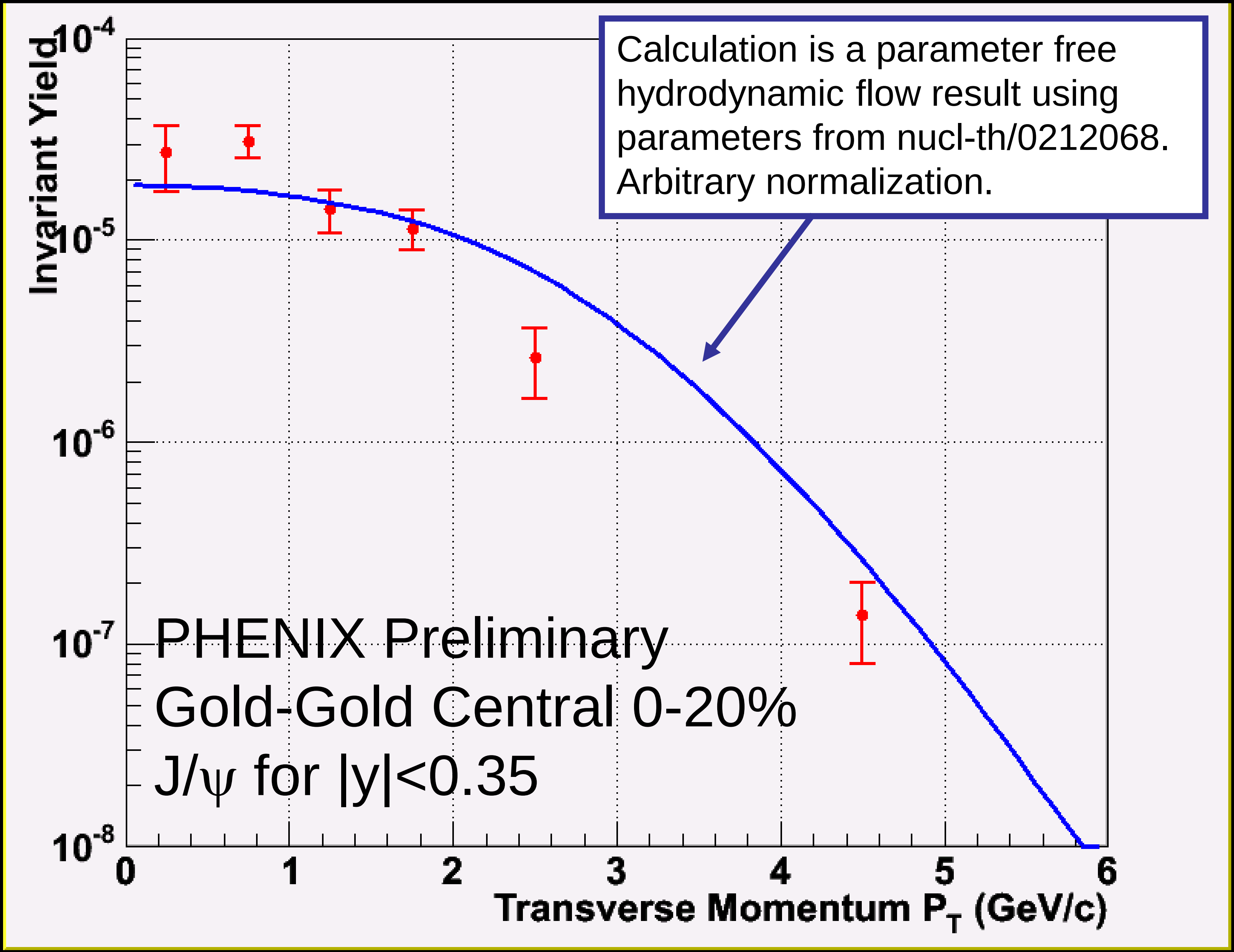


Au+Au ($|y|\in[1.2,2.2]$)

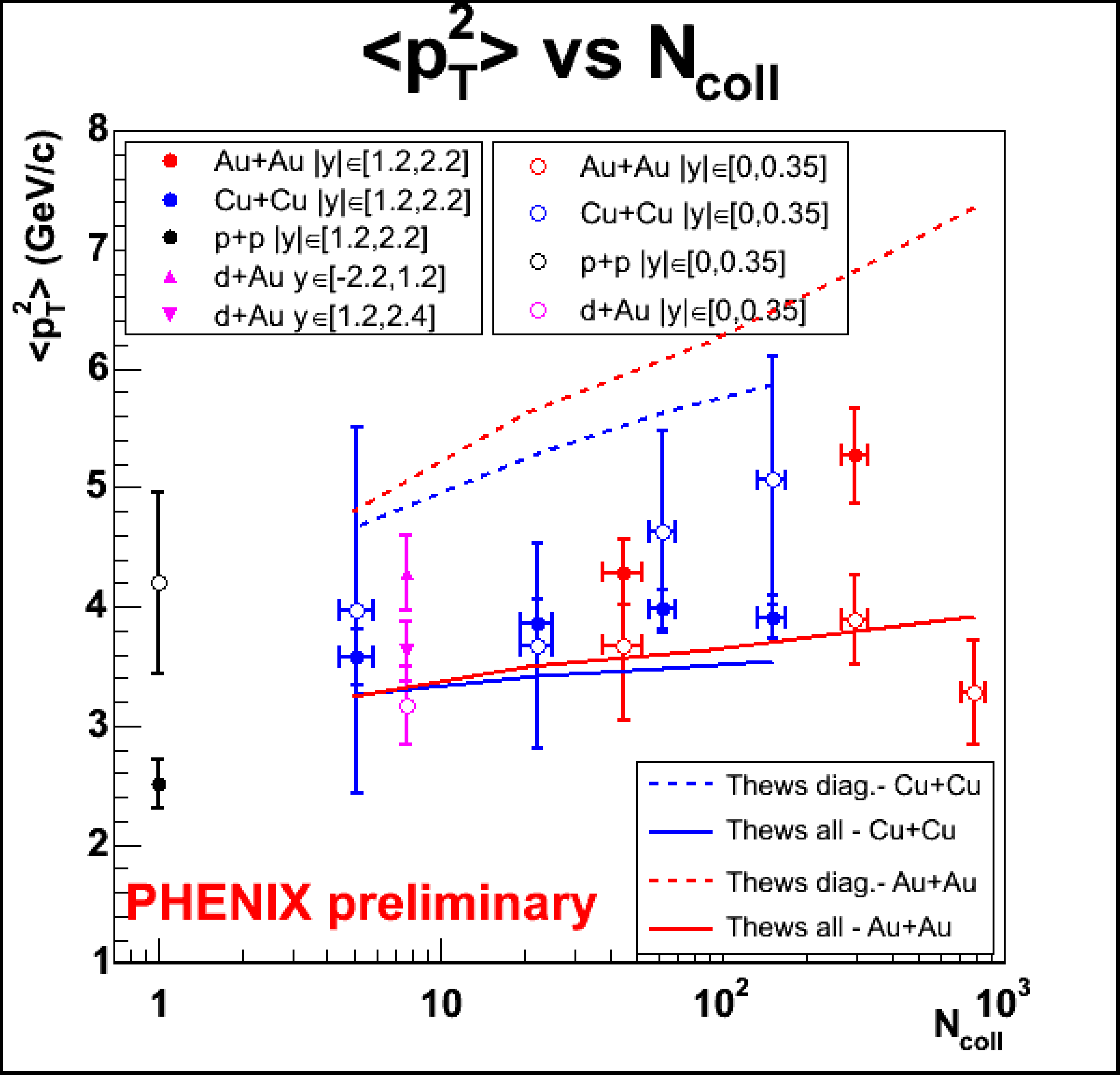


We fit the p_t spectrum using $A[1+(p_t/B)^2]^{-6}$ to extract $\langle p_t^2\rangle$

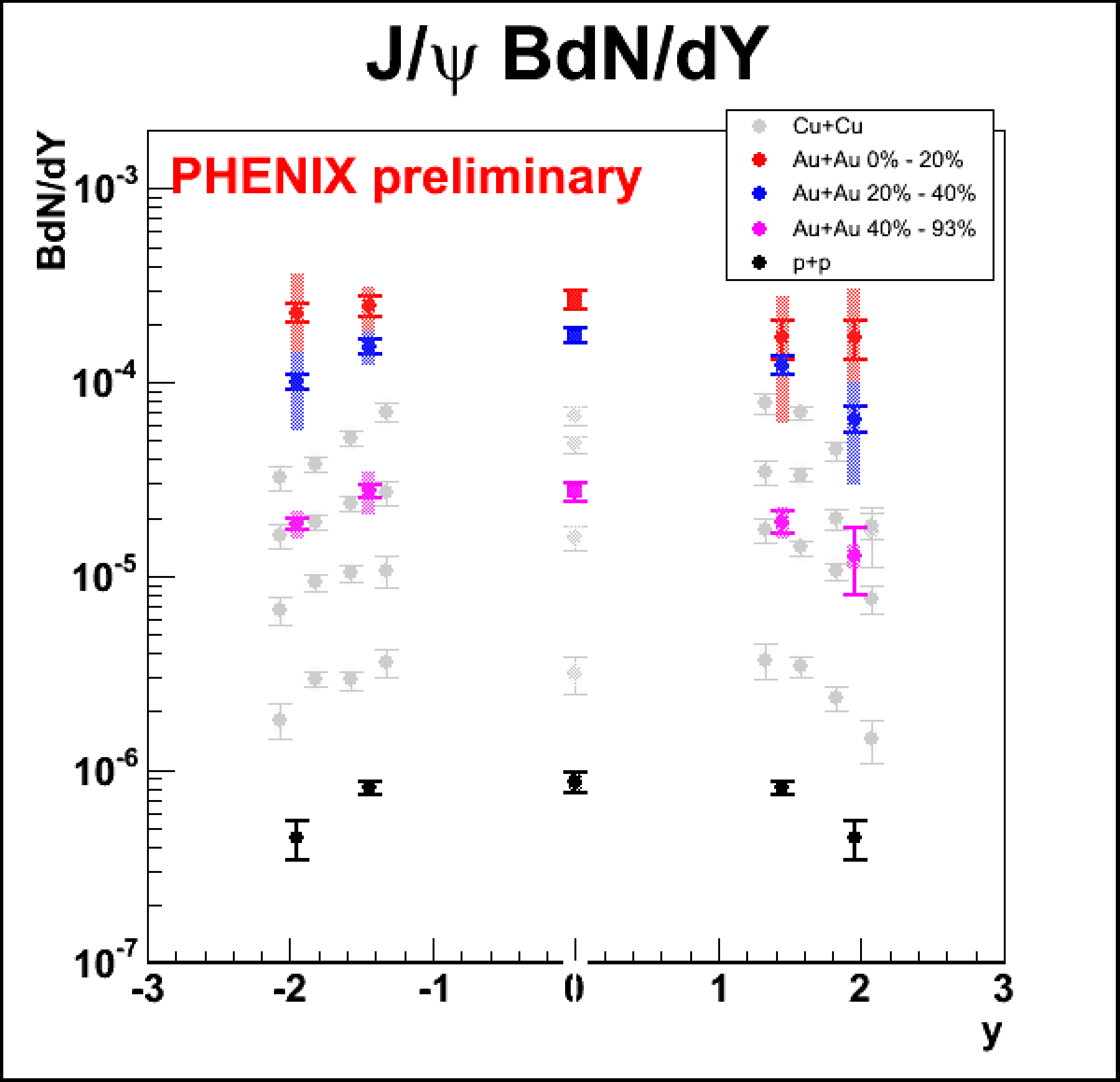
Hydrodynamic?



Balancing Effects



Rapidity Dependence



Common Feature: Rapidity Narrowing

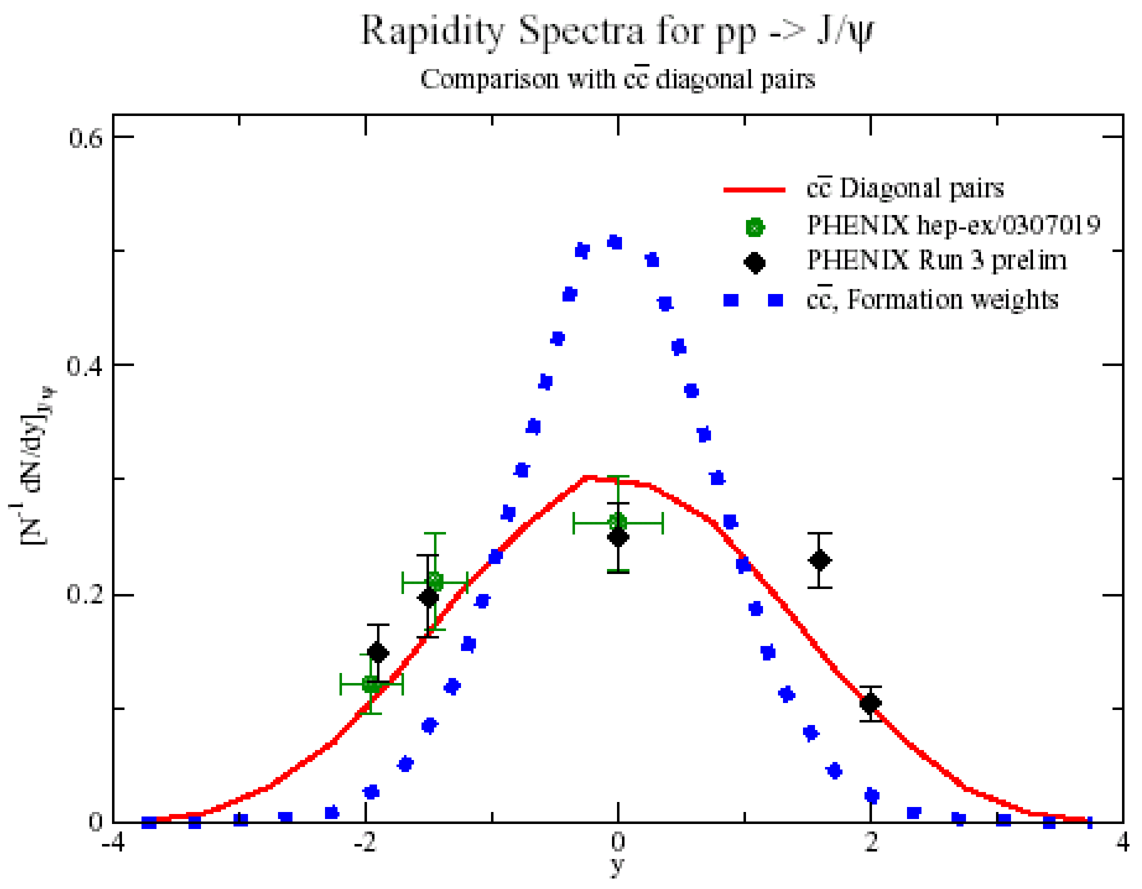


FIG. 19: Rapidity spectra of J/ψ production in pp interactions at 200 GeV.

See talk by Thews

What do the theorists Have to Say?

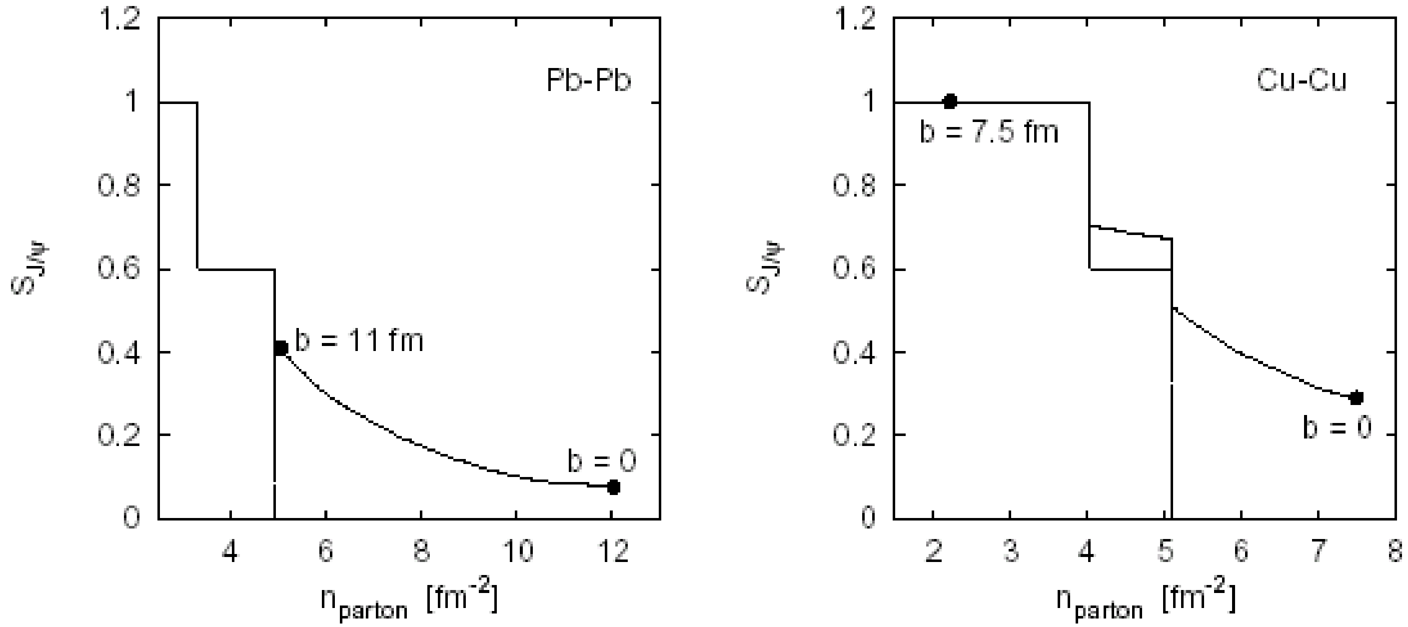
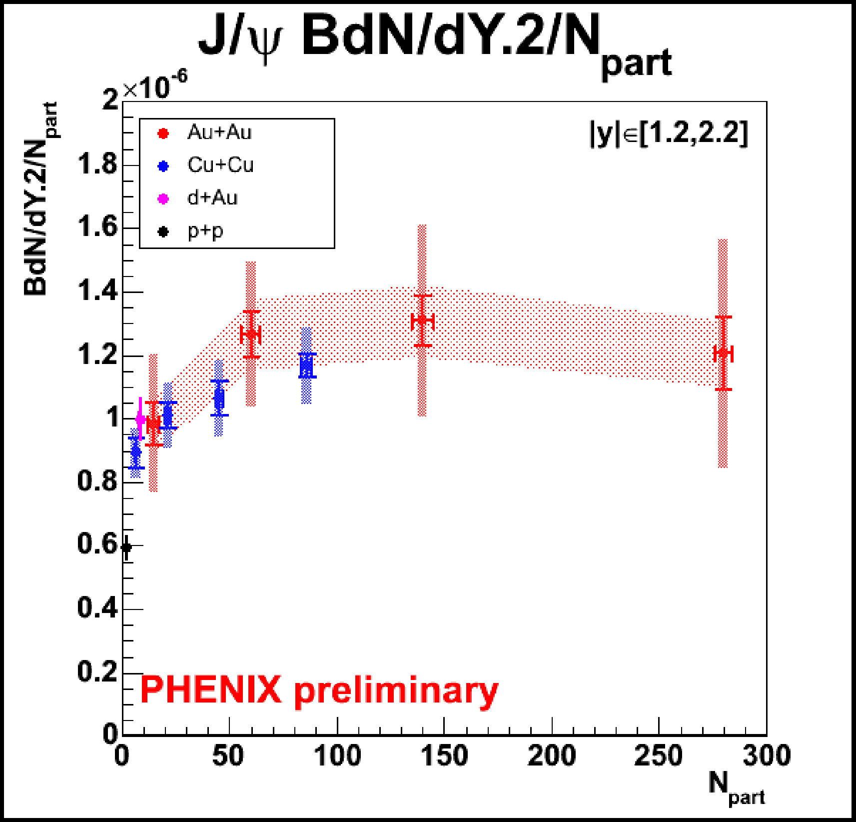
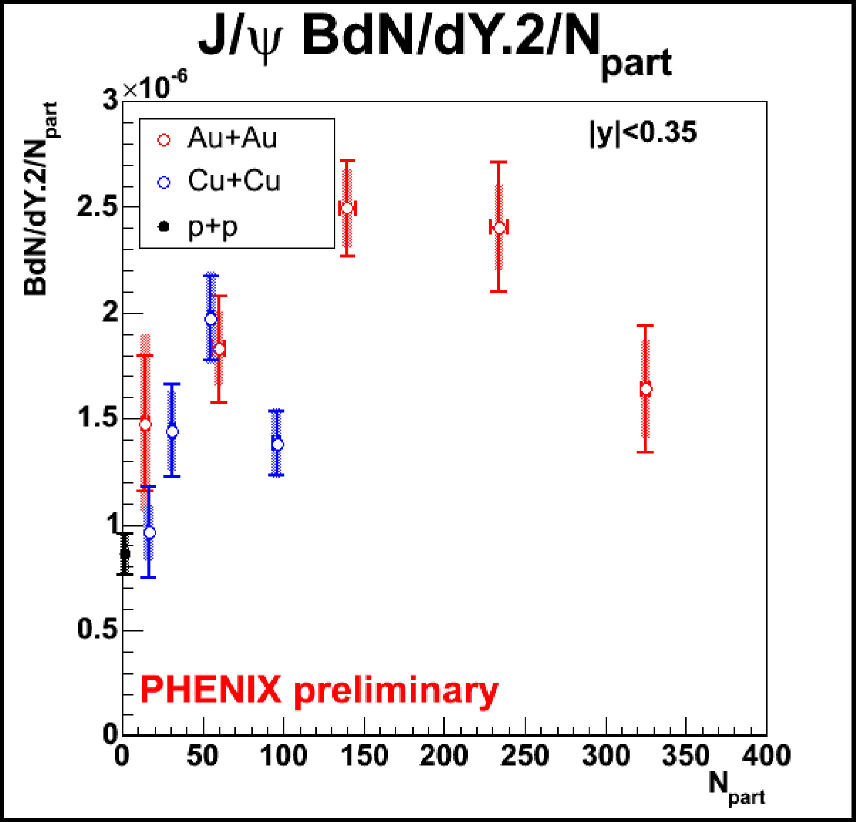


Figure 8. The J/ψ survival probability as function of the parton density for Pb–Pb (left) and for Cu–Cu (right) collisions at RHIC energy; the dotted line corresponds to a medium of uniform parton density, the solid line to collisions with parton densities determined by the profiles of the colliding nuclei.

trality at RHIC energy.

Participant Scaling?





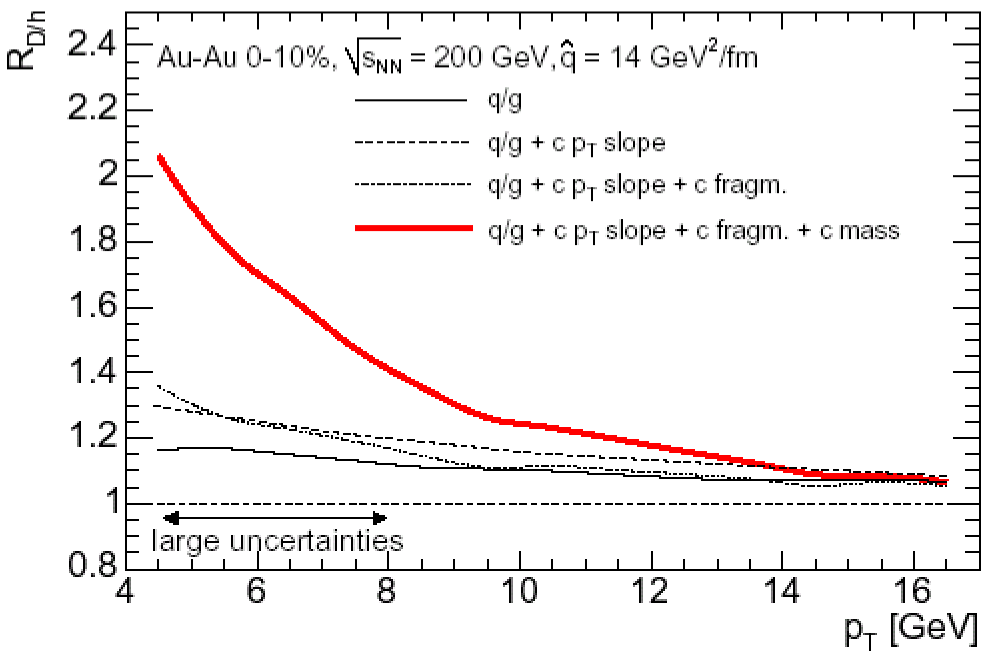


Fig. 3. Different contributions to the heavy-to-light ratio of D mesons in central (0–10%) Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV. Different curves correspond to the case in which the charm distribution is described i) with the same p_T spectrum, fragmentation function and parton energy loss as a light quark, ii) with a realistic charm p_T spectrum only, iii) with the charm p_T spectrum and fragmentation function of a realistic charm quark and iv) for the realistic case which includes the mass dependence of parton energy loss.

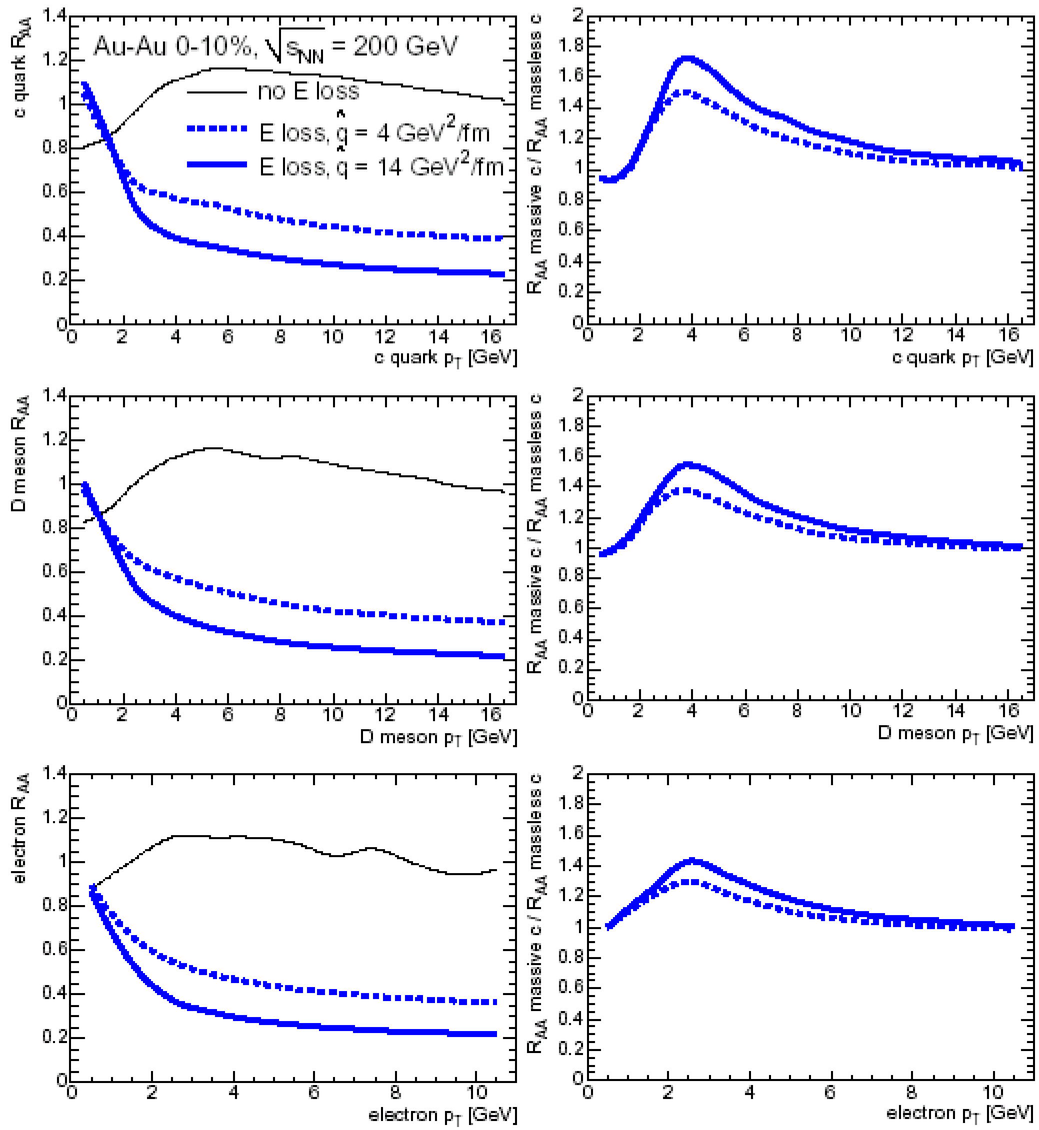


Fig. 2. LHS: Nuclear modification factors for c quarks, D mesons and their decay electrons in central (0–10%) Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV for different time-averaged strengths of the parton energy loss. RHS: The ratio of the nuclear modification factor plotted on the LHS, divided by the same factor calculated for a massless charm quark.

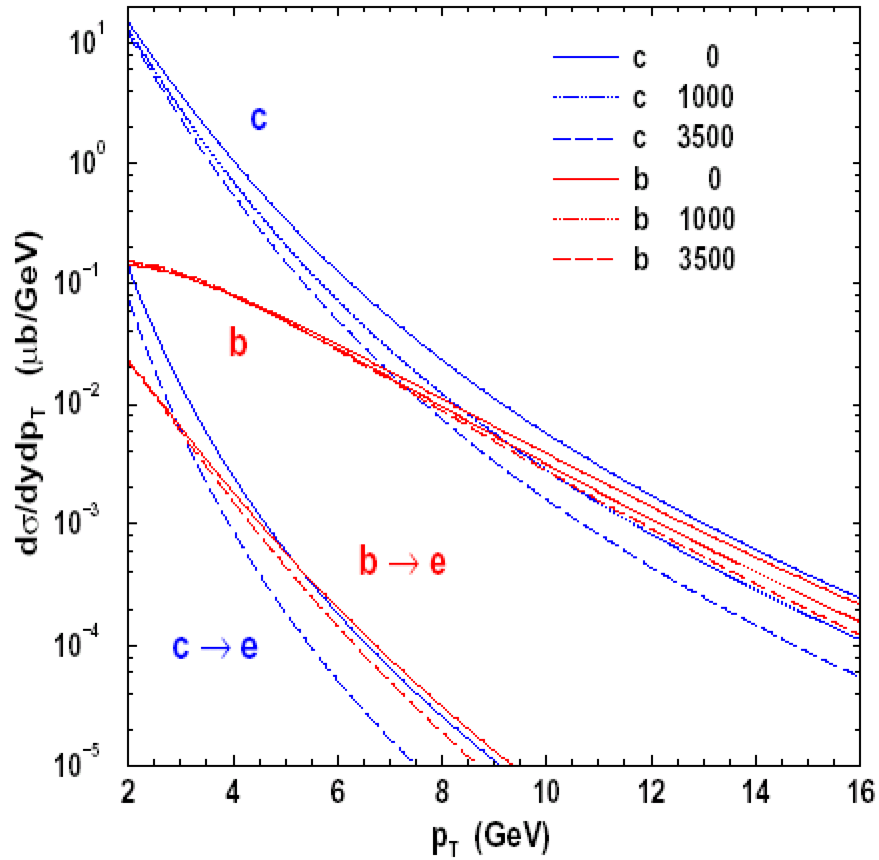


FIG. 1: The differential cross section (per nucleon pair) of charm (upper blue) and bottom (upper red) quarks calculated to NLO in QCD [34] compared to single electron distributions calculated with the fragmentation and decay scheme of Ref. [34]. The solid, dotted and long dashed curves show the

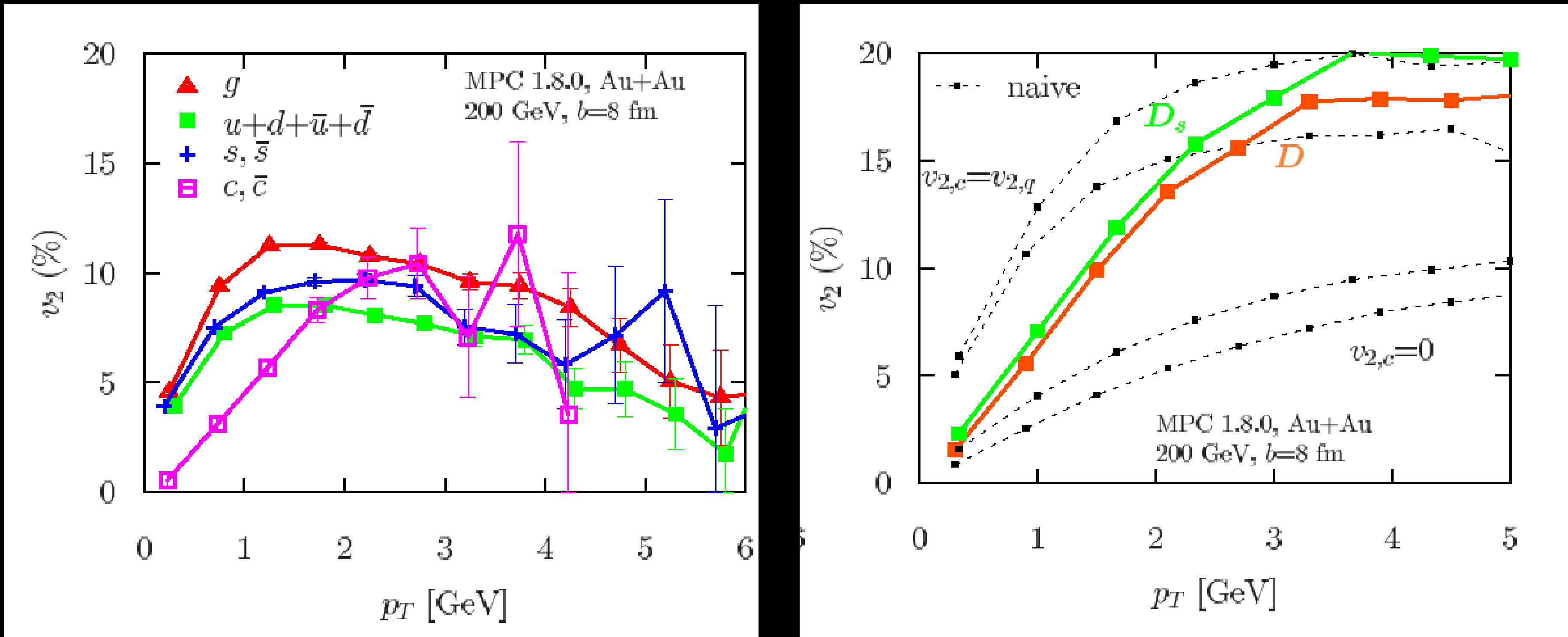
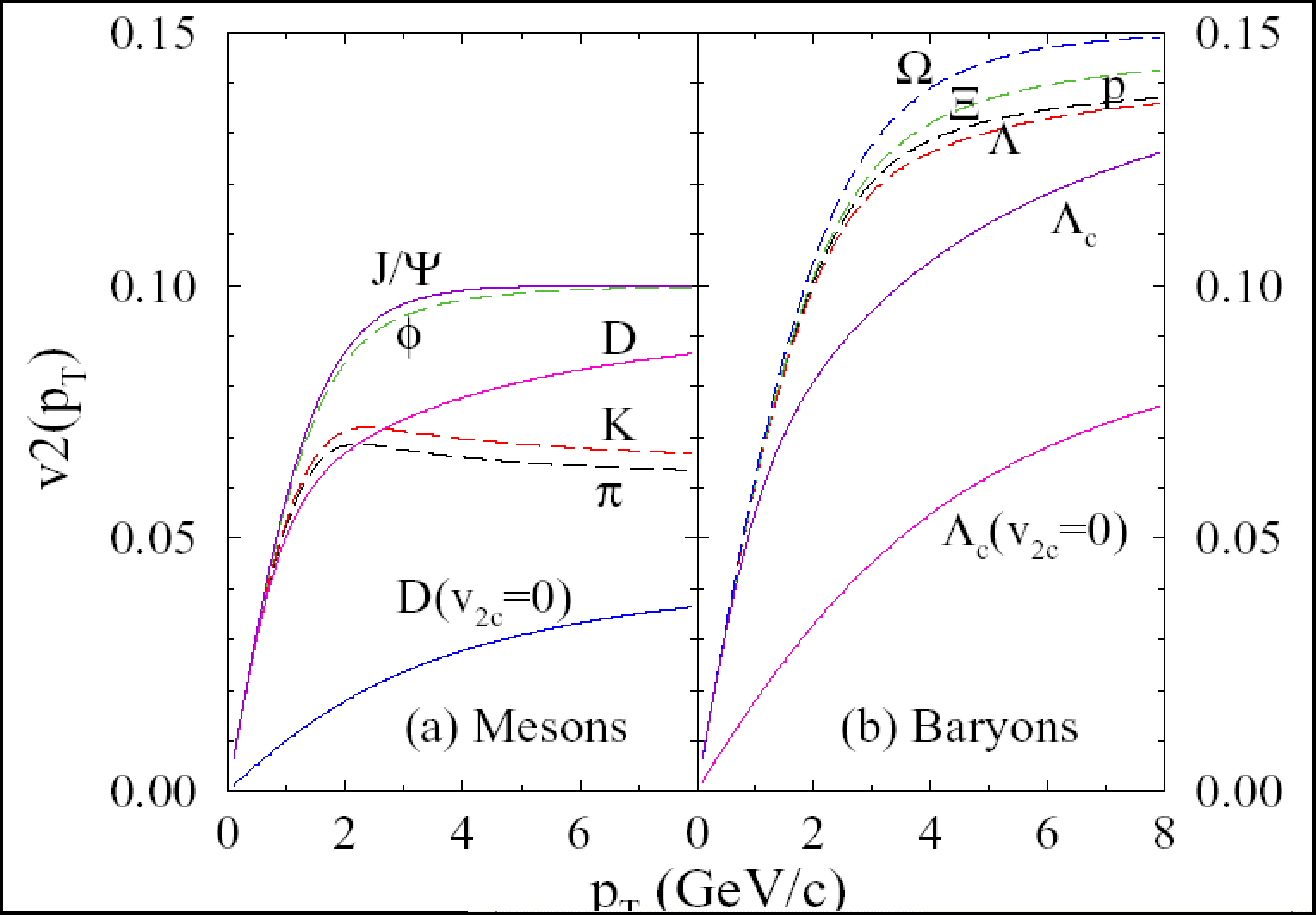
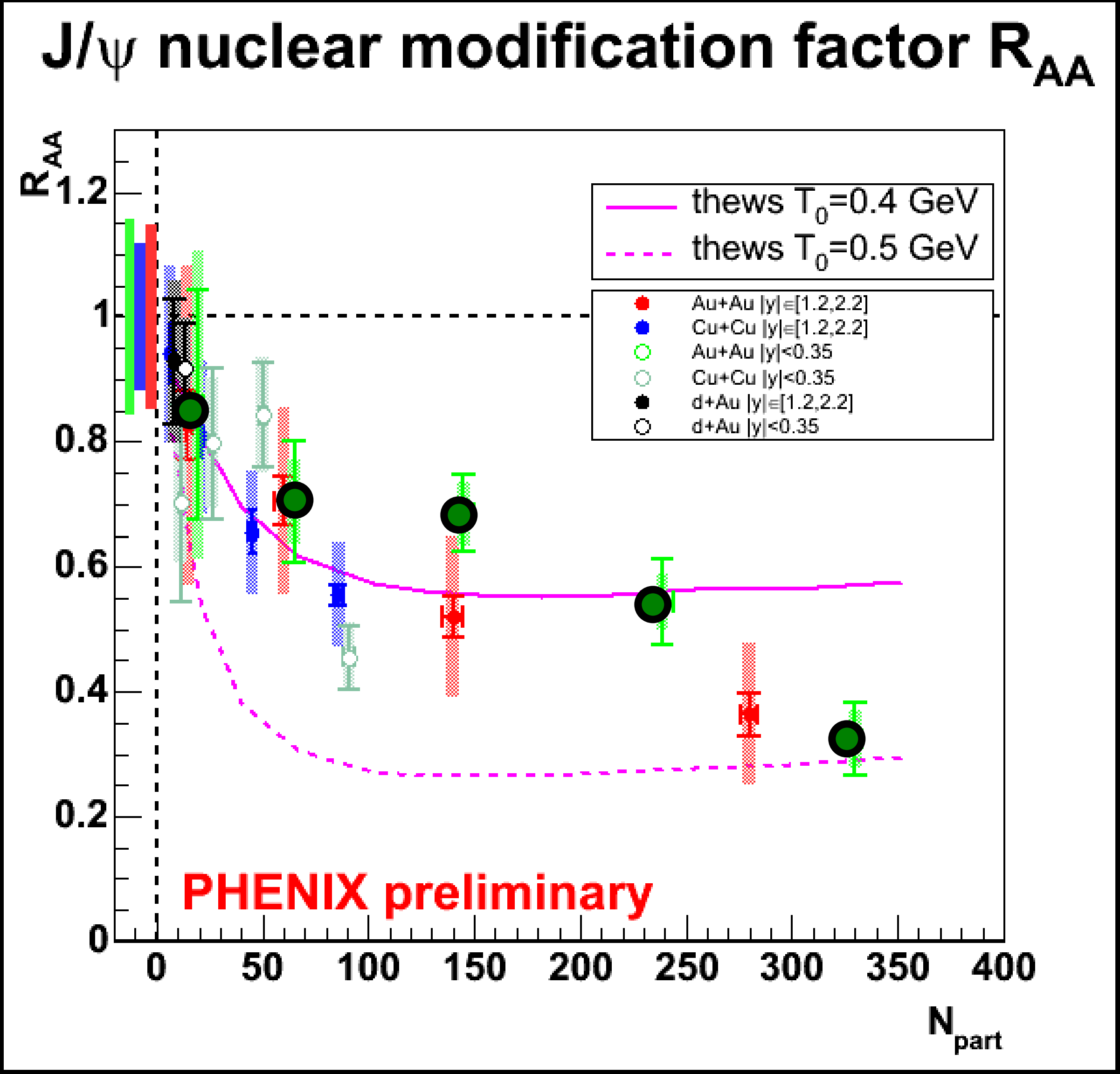


Figure 2. Final parton elliptic flows (left panel) and D meson elliptic flow (right panel) as a function of p_T in $Au + Au$ at $\sqrt{s_{NN}} = 200$ GeV with $b = 8$ fm at RHIC, computed using the transport model MPC [29]. The D meson v_2 was obtained from the parton flows via the quark coalescence formula in [13]. The dashed lines correspond to the two extreme scenarios in [13] (see text). For hadronization via independent fragmentation, charm hadron v_2 is approximately the same as the charm quark v_2.



0.15
0.10
0.05
0.00
v2(p_T)
J/Ψ
φ
D
K
π
D(v_2c=0)
(a) Mesons
Ω
Ξ
p
Λ
Λ_c
Λ_c(v_2c=0)
(b) Baryons
0 2 4 6 0 2 4 6 8
p_T (GeV/c)

More Regeneration



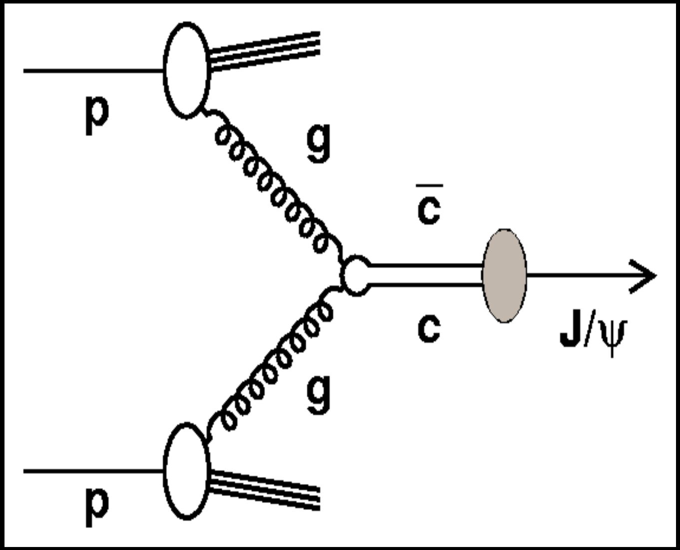
Super-Sensitive / Super-Complex

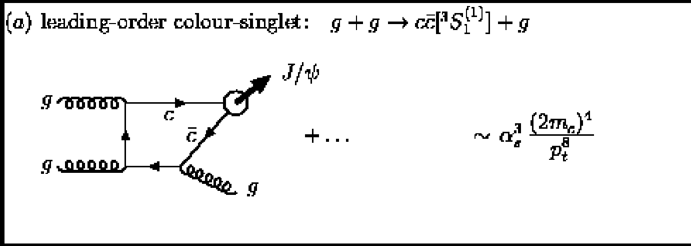
J/ψ by its heavy mass and direct coupling to incoming gluons at RHIC energies is sensitive to initial parton distribution functions (PDF).

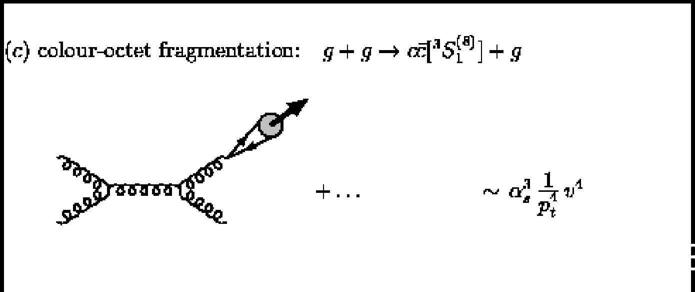
Modifications of these PDF's in nuclei will affect the initial production rate of charm-anticharm quark pairs.

Production of direct J/ψ is suppressed by the need for an additional radiated gluon to conserve quantum numbers, so another mechanism is needed.

Hadronic or pre-hadronic interactions can suppress J/ψ yields.







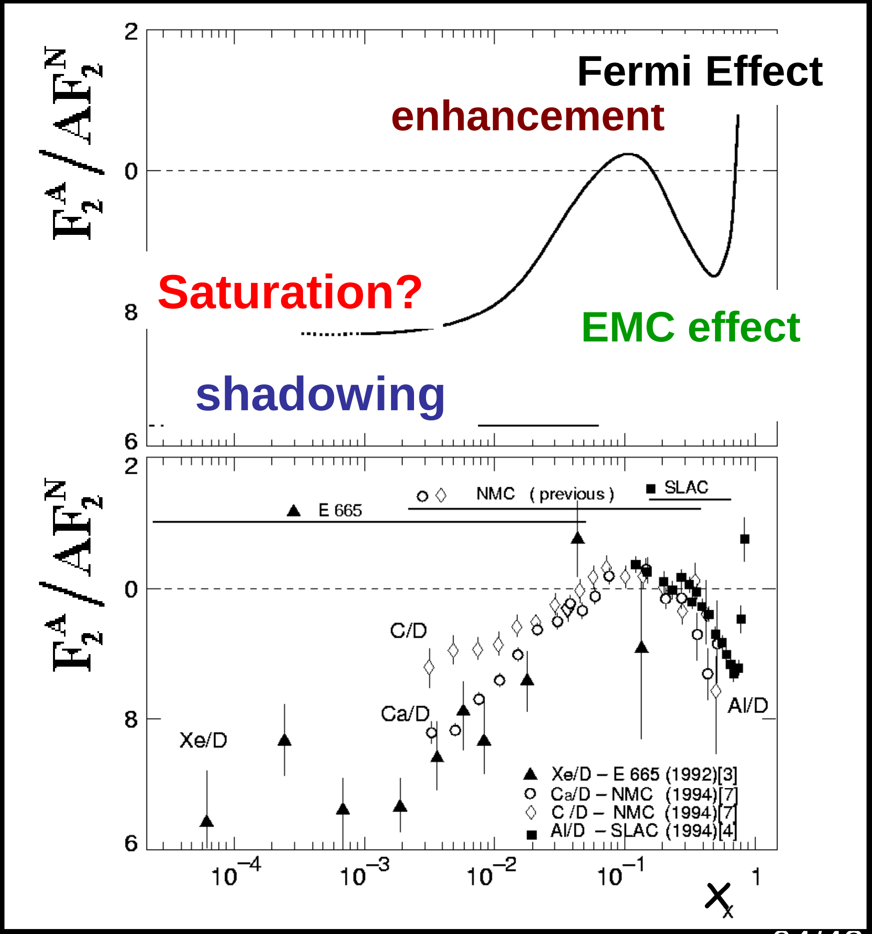
Nuclear Parton Distribution Functions

At low x ~ 10^{-2}, a suppression of partons is observed in the nuclear wavefunction (shadowing).

This suppressing any hard process coupling to those partons relative to point-like scaling (α = 1).

At high x ~ 10^{-1}, an enhancement (anti-shadowing) may enhance hard processes.

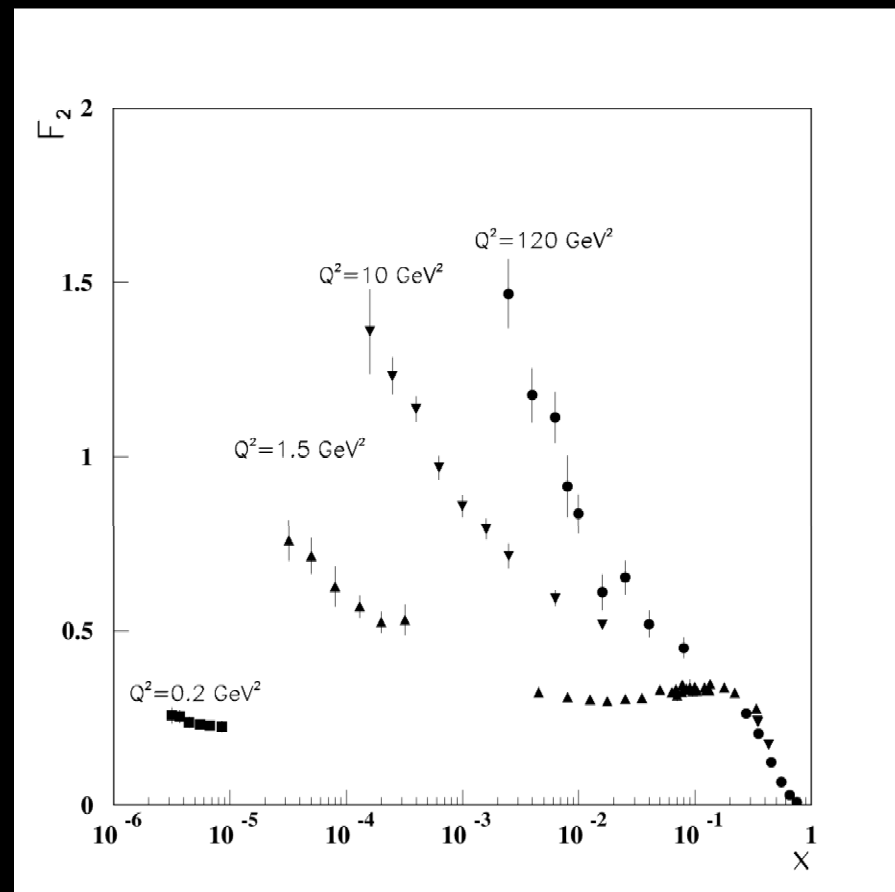
Color Glass Condensate or Saturation Physics gives a universal QCD explanation for low x shadowing.



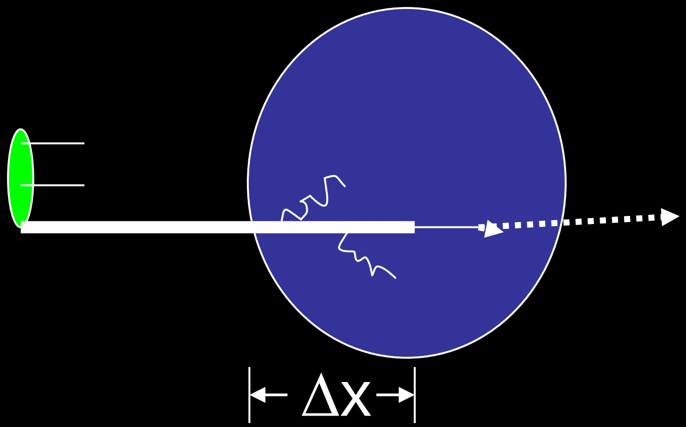
Evolution of Modified PDFs

As one probes a proton or nucleus at higher momentum transfer (shorter wavelength), there is an enormous growth of low x gluons.

Thus we might expect that saturation or shadowing effects will play a larger role in higher energy collisions sensitive to a similar range of x.

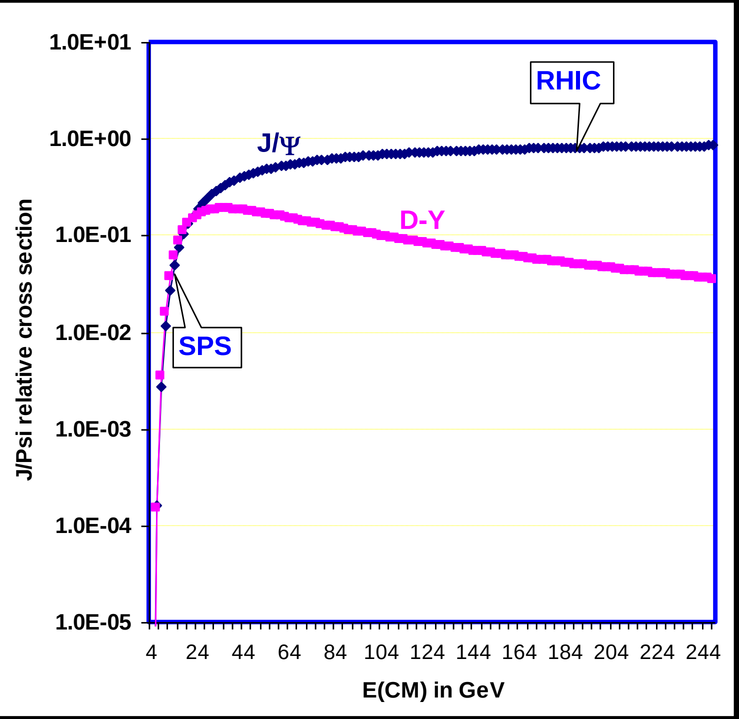


Initial Parton Energy Loss



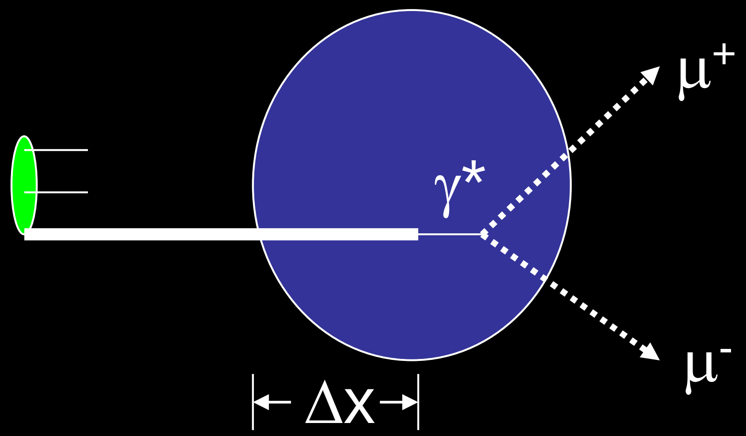
If the incoming hadron de-hadronizes as it interacts in the nucleus, an individual high-x parton starts to radiate (losing energy).

At lower energies (SPS, FNAL fixed target) where one is near J/ψ production threshold, a small energy loss can result in a strong suppression of production.



Parton Energy Loss

Drell-Yan production in proton-nucleus collisions is sensitive to parton energy loss..



Must carefully separate nuclear shadowing effects and energy loss effects both of which lead to suppression of Drell-Yan pairs.

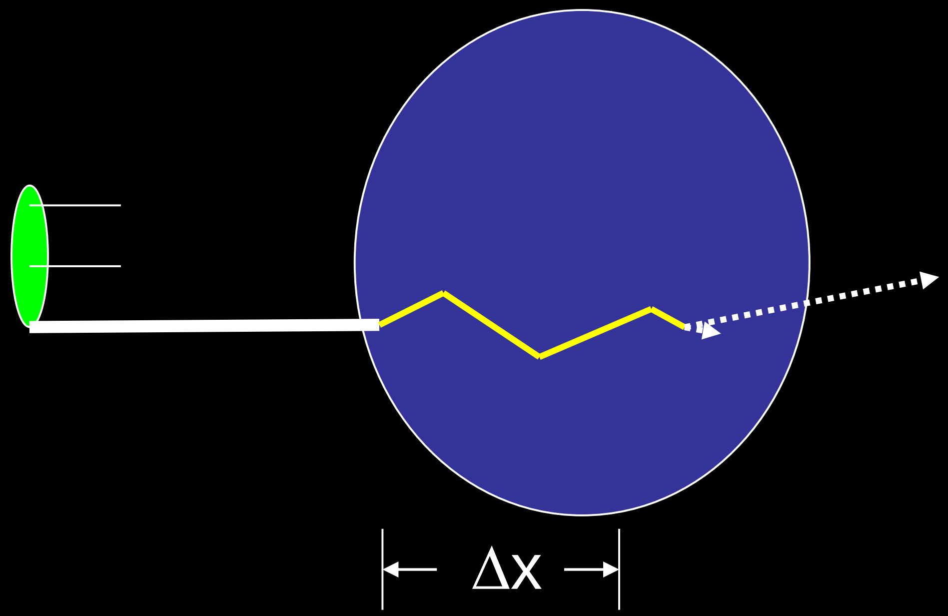
E772 and E866 at Fermilab

dE/dx = 2.73 ± 0.37 ± 0.5 GeV/fm (from hadronization due to confinement)
dE/dx ~ 0.2 GeV/fm (from gluon radiation due to nuclear environment)

"This is the first observation of a non-zero energy loss effect in such experiments."

Johnson, Kopeliovich, Potashnikova, E772 et al.
Phys. Rev.C 65, 025203 (2002) hep-ph/0105195
Phys. Rev. Lett. 86, 4487 (2001) hep=ex/0010051

Initial Parton Multiple-Scattering



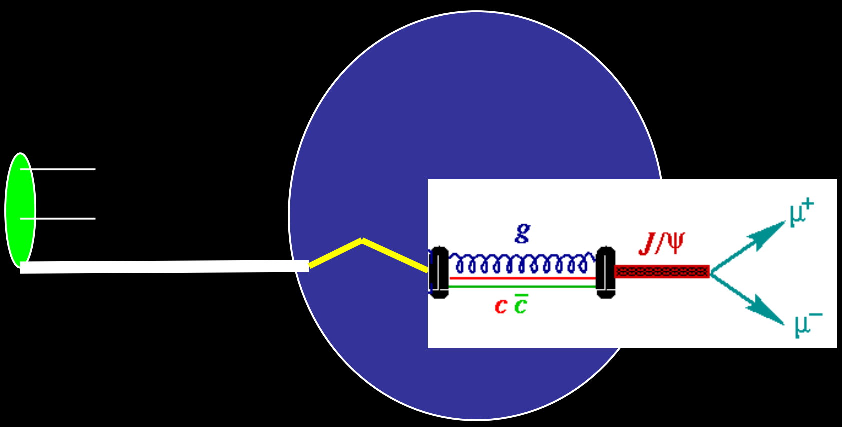
Initial state multiple-scattering of the parton leads to an enhancement in the p_T of the final J/ψ product.

This enhancement is often referred to as the "Cronin Effect." Despite the phenomenological success of incorporating this multiple scattering, there are still open questions about this mechanism.

Also, multiple scattering inherently leads to radiation.

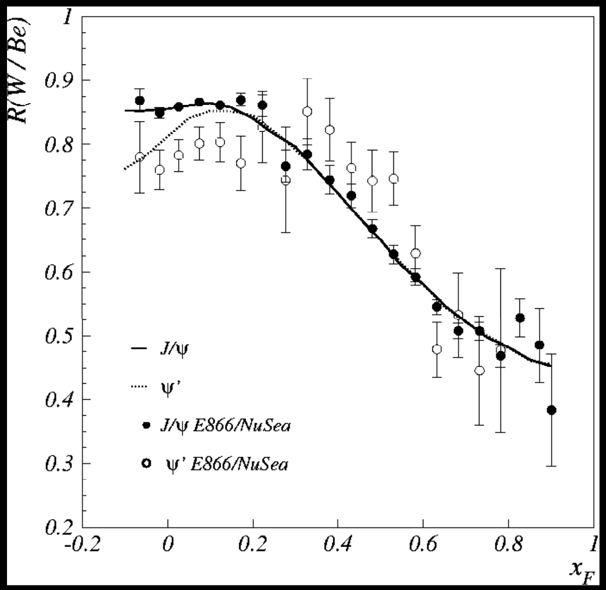
Re-Interactions

After production of the charm-anticharm pair, it may re-interact during its traversal of the remaining nuclear material.



These re-interactions may be of a pre-cursor to the J/ψ (color octet cc-g state) or of the physical J/ψ itself.[1]

In heavy ion reactions, the quarkonia state may be further suppressed due to color screening in medium.[2]



[1]Arleo, Gossiaux, Gousset, Aichelin, hep-ph/9907286
[2]Matsui, Satz, Phys. Lett. B178: 416 (1986).
[2]NA50 Phys. Lett. B521, 195 (2001)