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Overview of Charm Production – J/ψ's & Open Charm

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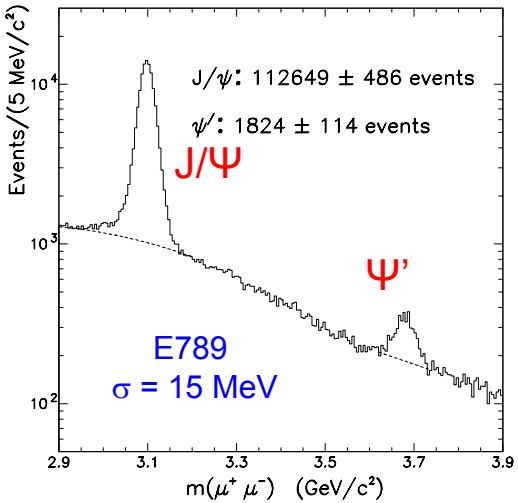
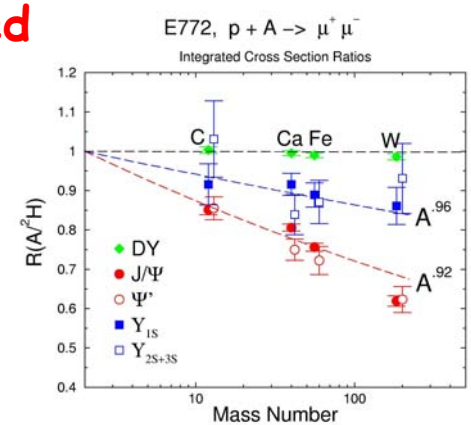
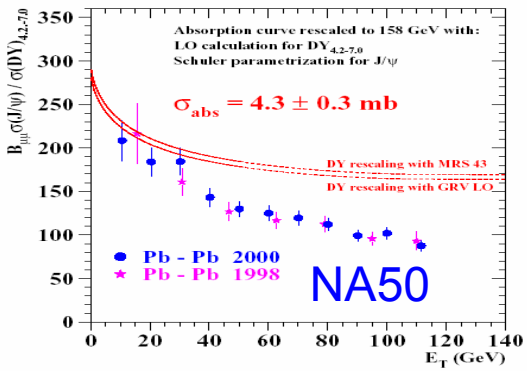
Quark Confinement & the Hadron Spectrum VI , 21-25 September 2004

- production
  - mechanisms
  - cross section & polarization
  - complications
- nuclear effects
  - shadowing
  - p_T broadening,
  - absorption
  - parton energy loss
  - contrasting open and closed charm
- hot-dense matter or QGP
  - color screening
  - recombination
- Summary







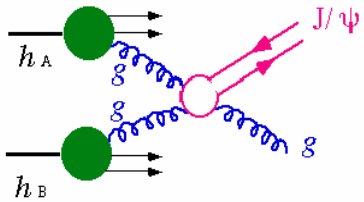
J/ψ & open-charm production, parton level structure & dynamics

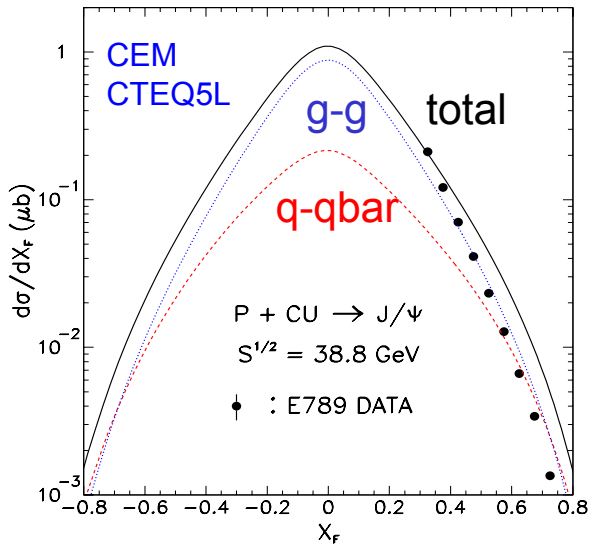
Production of heavy vector mesons, e.g. J/Ψ,Ψ' and ϒ

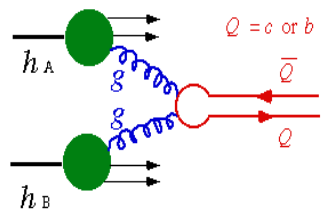
- gluon fusion dominates (NLO calculations add more complicated diagrams but still mostly with gluons)
- production: color singlet or octet $c\bar{c}$: absolute cross section and polarization?
- hadronization time (important for p*A* nuclear effects)
- complications due to substantial feed-down from higher mass resonances, e.g. from χ_c

Open charm

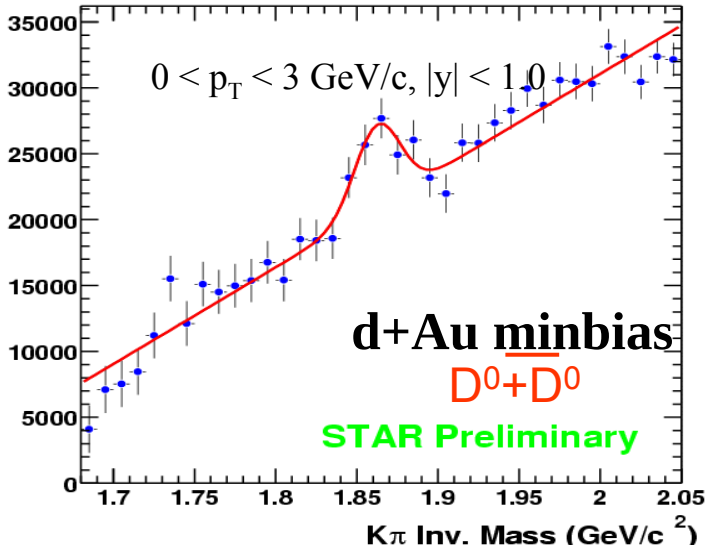
- shares sensitivity to gluon distributions and initial-state effects such as p_T broadening, initial-state energy loss
- but different hadronization and no feed-down





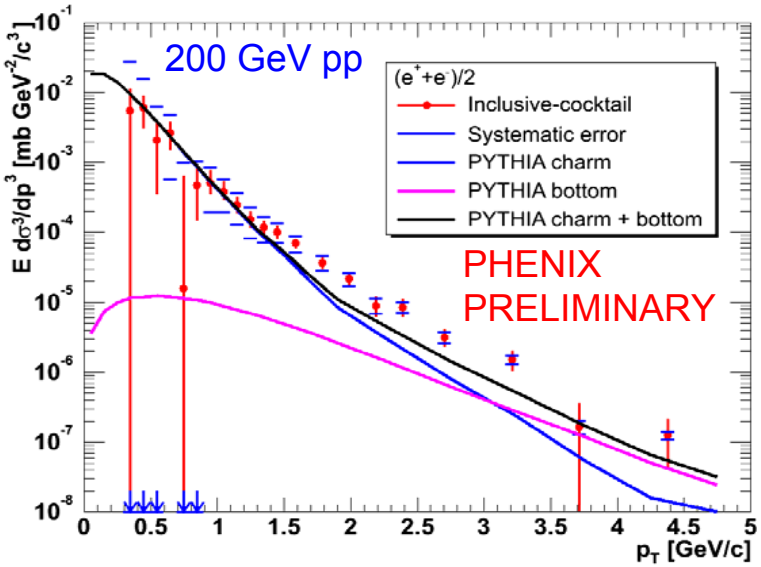


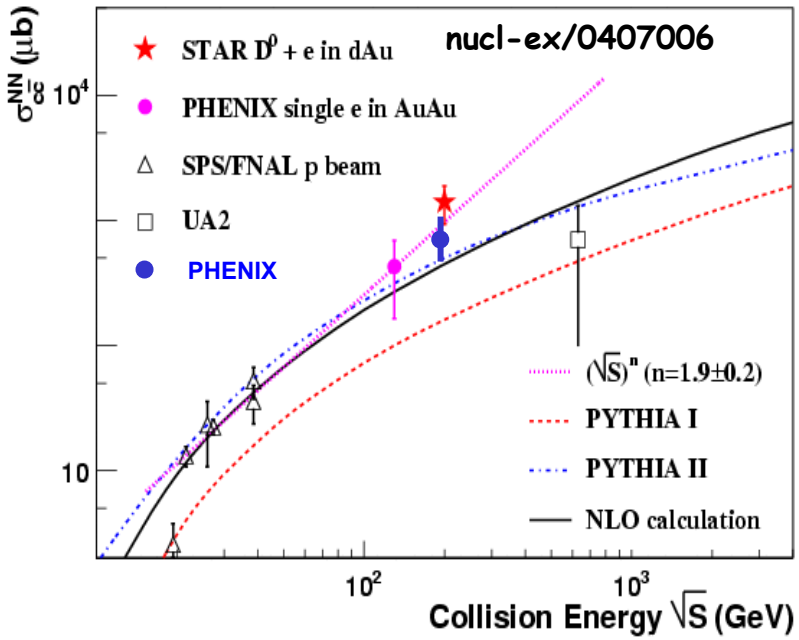
Open charm production at RHIC
cross sections & consistency of measurements



Consistency of 200 GeV measurements from STAR & PHENIX?

- **STAR: 1.2 ± 0.20 ± 0.4 mb from D→ Kπ**
- **STAR: 1.4 ± 0.20 ± 0.4 mb with both D→ Kπ & electrons**
- **PHENIX 0.709+-0.085+0.332-0.281 mb with electrons (preliminary)**





Production & Hadronization into J/ψ

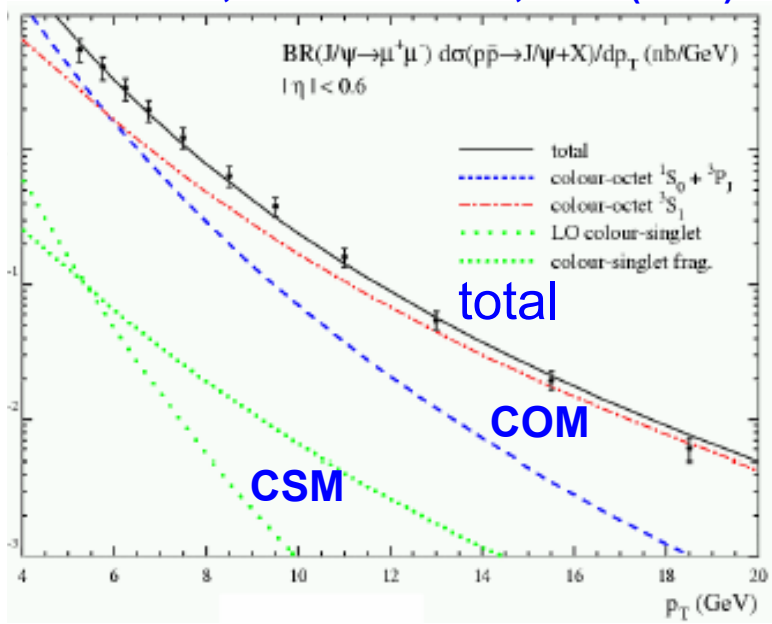
Various J/ψ hadronization models:

Color-singlet model (CSM)
- $c\bar{c}$ pair in color-singlet state, with same quantum numbers as J/ψ forms into J/ψ
- Predicts no polarization

Color-octet model (COM)
- J/ψ formed from $c\bar{c}$ color-octet state with one or more soft gluons emitted
- Color octet matrix elements expected to be universal
- Predicts transverse polarization at high p_T of J/ψ

Color-evaporation model (CEM)
- Assumes a certain fraction of $c\bar{c}$ (determined from experimental data) form J/ψ by emission of several soft gluons
- Predicts no polarization

hep-ph/0311048 &
Beneke, Kramer PRD 55, 5269 (1997)



CDF Data first uncovered short-comings of CSM

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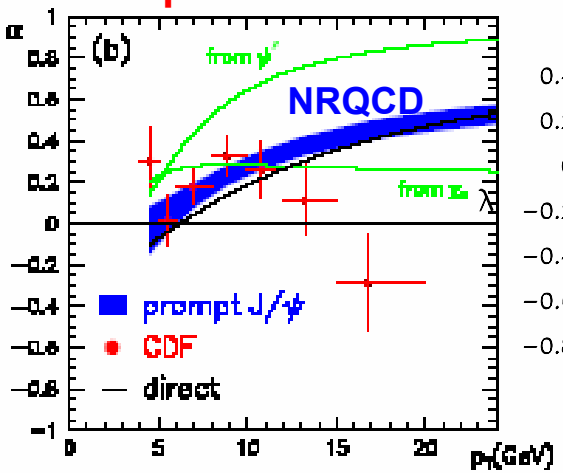
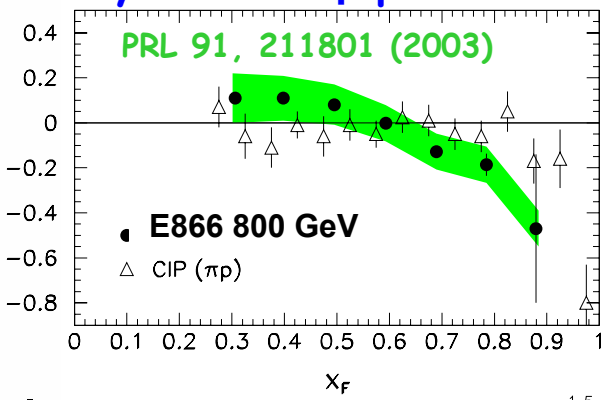
J/ψ Production—Polarization

Color Octet Model predicts J/ψ polarization at large p_T NOT SEEN in data

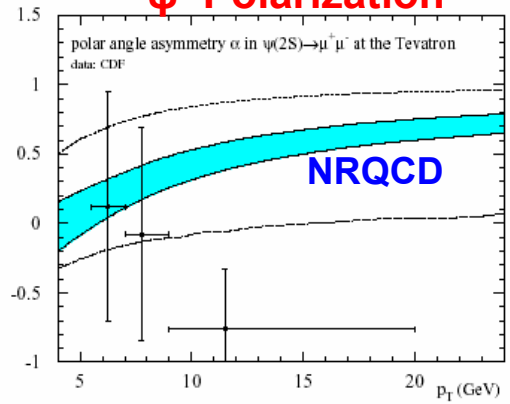
J/ψ Polarization



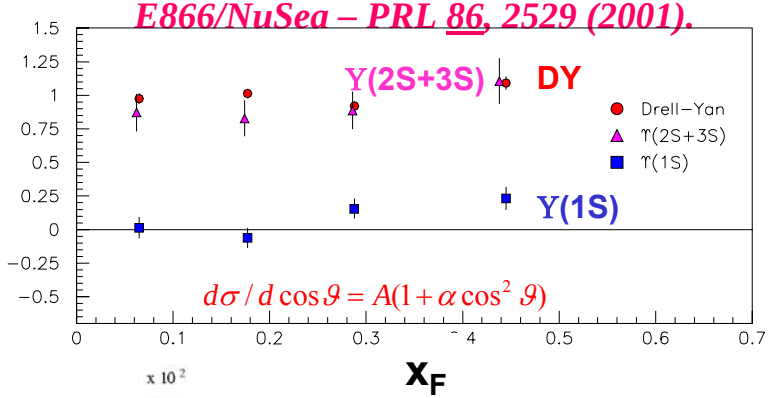
E866
very small J/ψ polarization



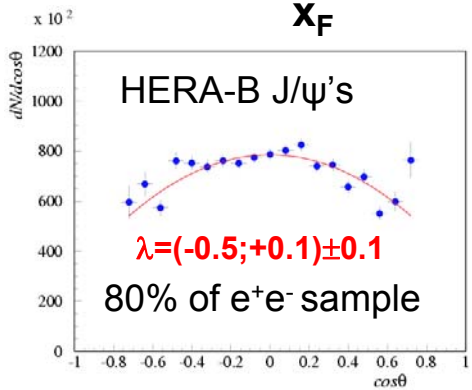
ψ' Polarization



E866/NuSea – PRL 86, 2529 (2001).



- CDF and Fermilab E866 data show little polarization of J/ψ - opposite trend from predictions
- ϒ polarized for (2S+3S) but not (1S)
- Is feed-down washing out polarization or something more?



not acceptance corrected

Feeding of J/ψ's from Decay of Higher Mass Resonances

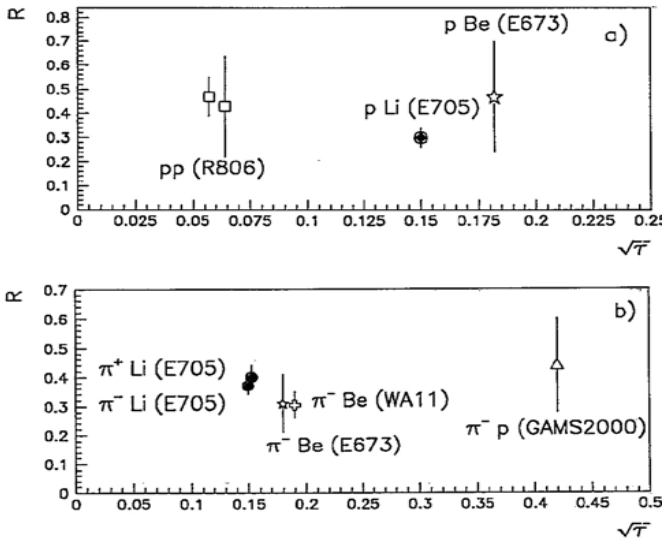
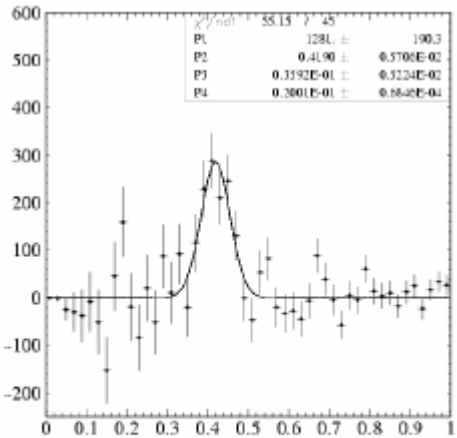


FIG. 3. Fraction of J/ψ produced via radiative χ in 300 GeV/c (a) proton and (b) $\pi^{\pm}$ ^{7}Li interactions.

E705 @ 300 GeV/c,
PRL 70, 383 (1993)

Large fraction of J/ψ's are not produced directly

	Proton	Pion
$\chi_{,1,2} \rightarrow J/\Psi$	30%	37%
$\Psi' \rightarrow J/\Psi$	5.5%	7.6%



HERA-B

$\chi_c/J/\psi$ = 0.21±0.05 from 15% of available statistics ($\sqrt{s_{NN}}$ = 42 GeV)

$\Delta m\ (GeV/c^2) = m_{\chi} - m_{J/\psi}$

Effect on Nuclear dependence:

- Nuclear dependence of parent resonance, e.g. χ_C is probably different than that of the J/Ψ
- e.g. in proton production ~30% of J/ψ's will have effectively stronger absorption because they were actually more strongly absorbed (larger size) χ_C's while in the nucleus

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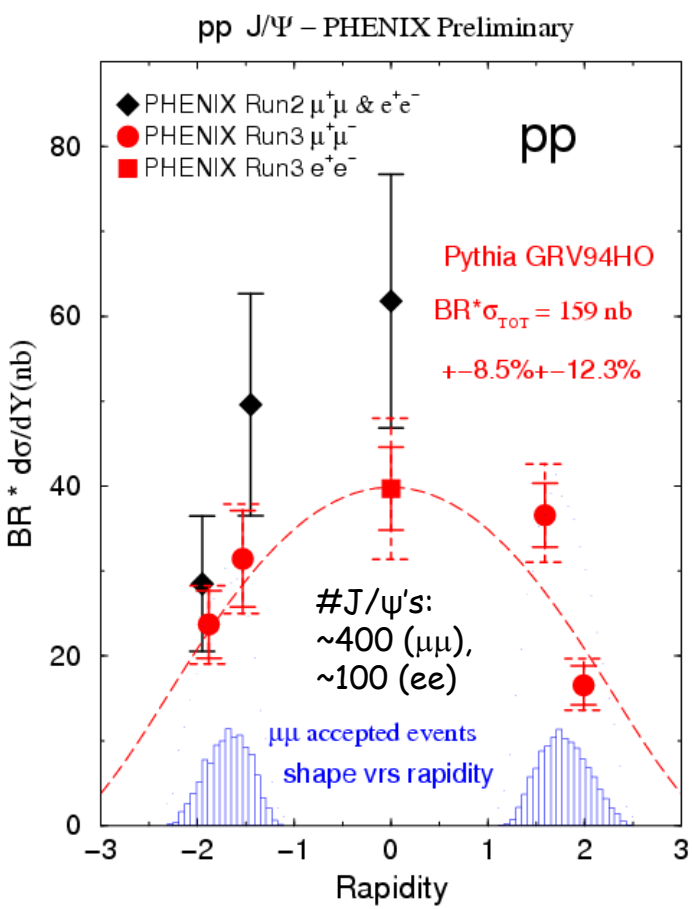
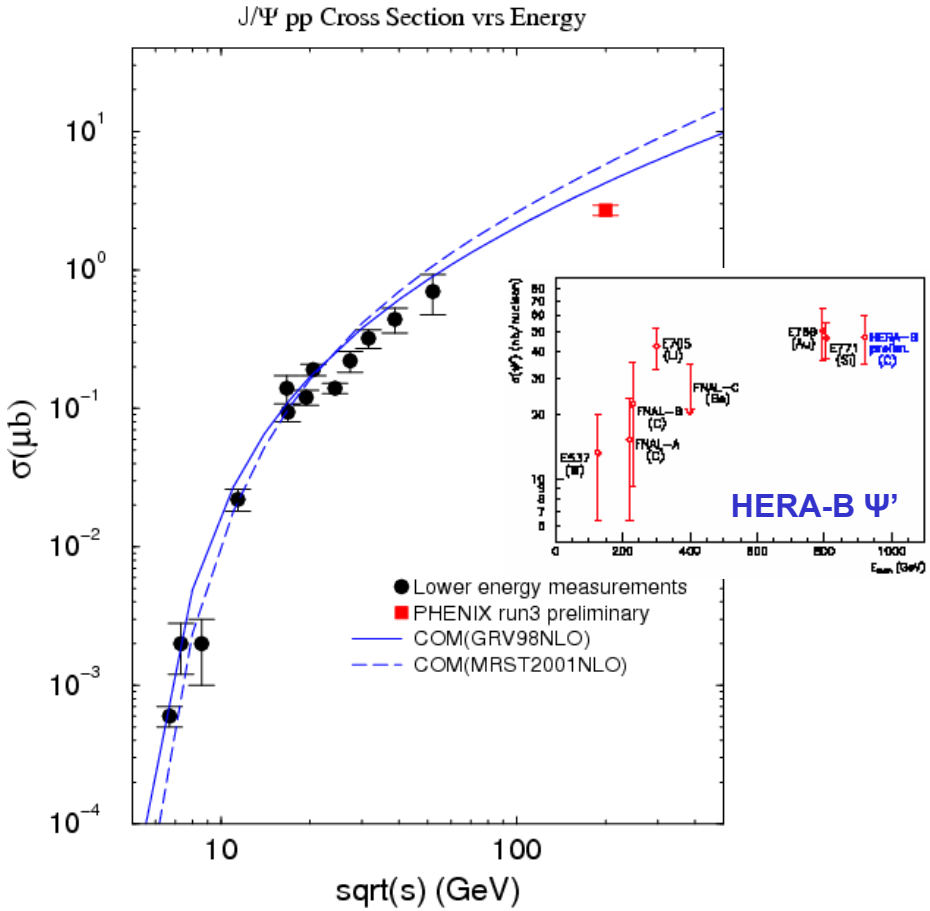
PHENIX - J/ψ cross section versus rapidity & √s

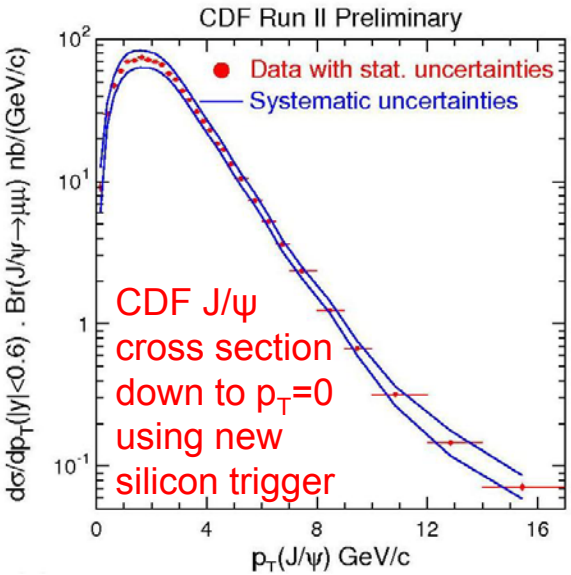


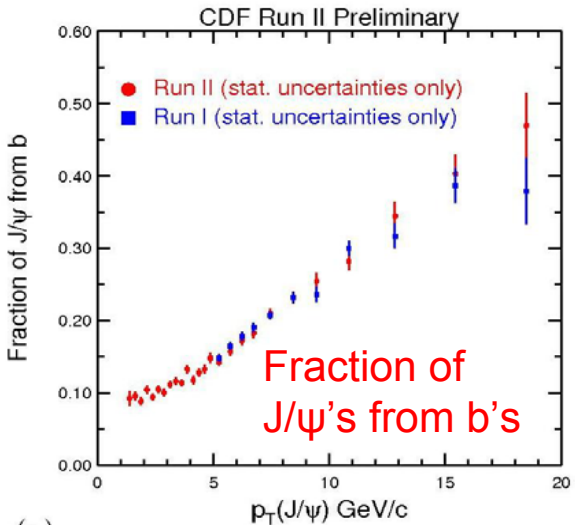


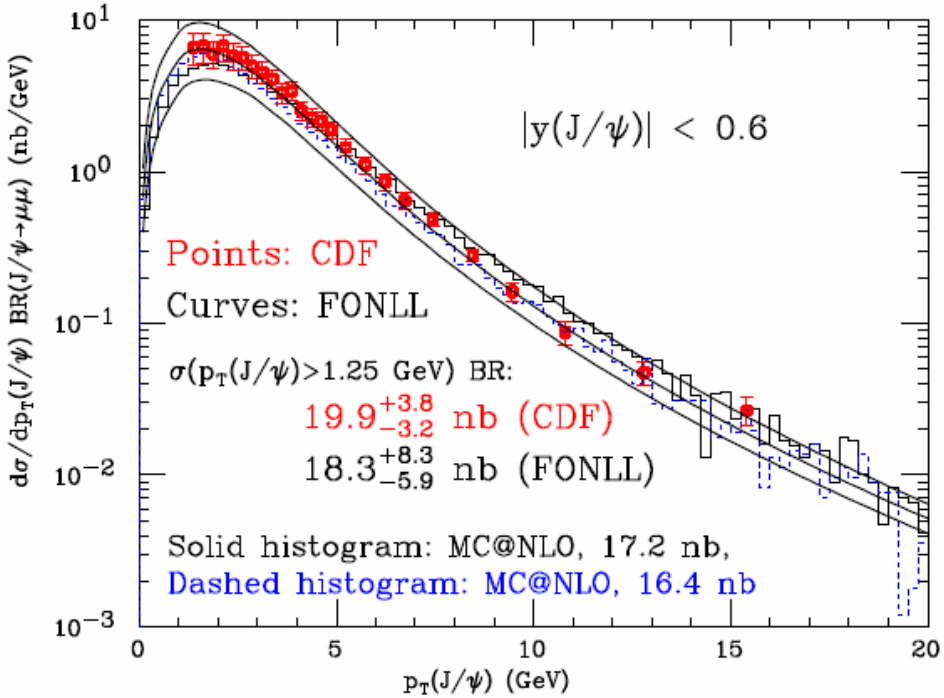
More pp J/ψ's coming from PHENIX 2004 run (~300/muon arm) + many more expected in 2005

(Ψ' so far out of reach with present RHIC luminosities)

CDF Run II J/Psi vrs p_T now down to p_T=0
hep-ex/0408020







Current NLO QCD calculations now able to describe observed CDF J/ψ cross sections!

Cacciari, Frixione, Mangano, Nason, Ridolfi, hep-ph/0312132 - FONLL or MC@NLO.

polarization?

Nuclear modification of parton level structure & dynamics

Modification of parton momentum distributions of nucleons embedded in nuclei

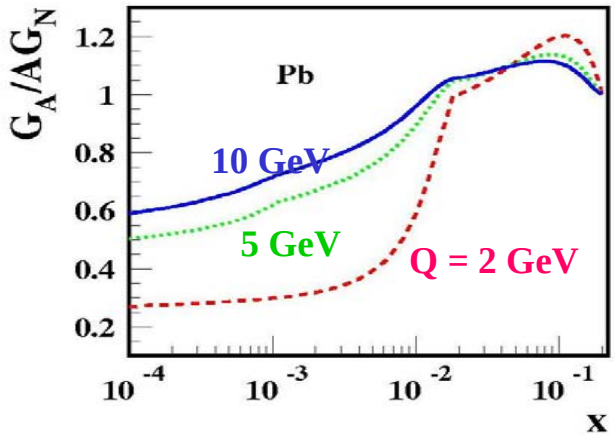
- e.g. shadowing – depletion of low-momentum partons (gluons)
- color glass condensate – specific/fundamental model that gives gluon shadowing in nuclei

Nuclear effects on parton "dynamics"

- energy loss of partons as they propagate through nuclei
- and (associated?) multiple scattering effects (Cronin effect)
- absorption of J/ψ on nucleons or co-movers; compared to no-absorption for open charm production

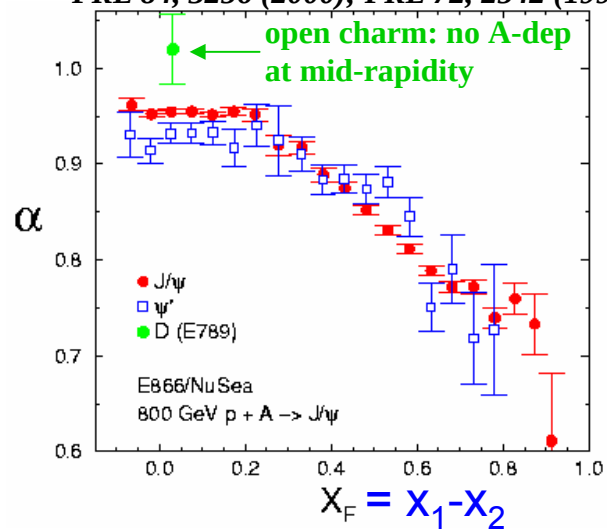
Gluon shadowing

Gerland, Frankfurt, Strikman, Stocker & Greiner (hep-ph/9812322)



800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$

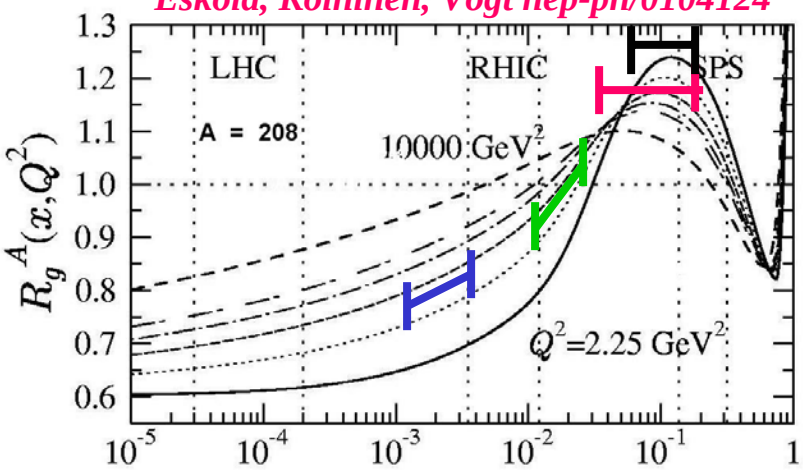
PRL 84, 3256 (2000); PRL 72, 2542 (1994)



Gluon Shadowing

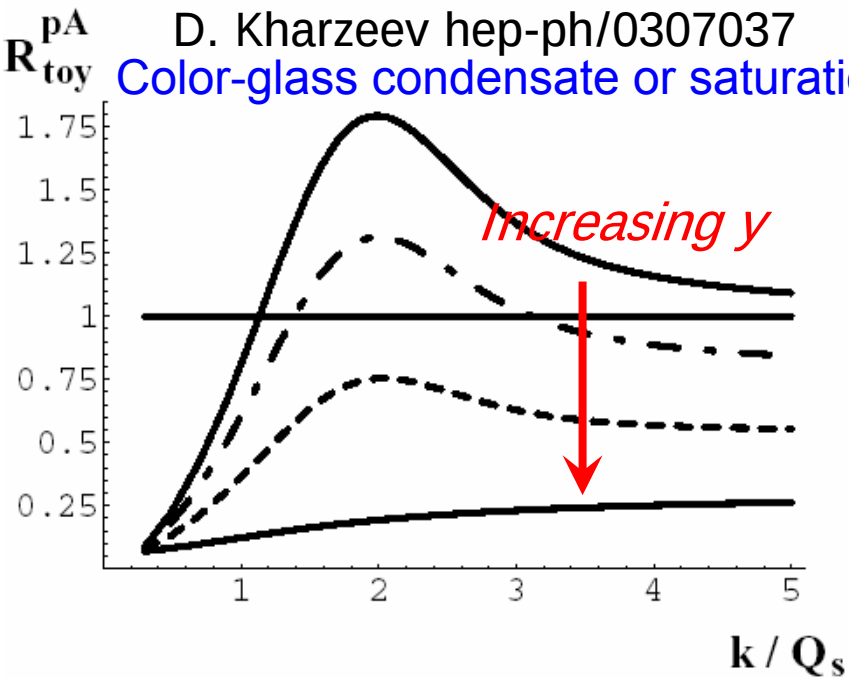
- **Shadowing** of gluons → depletion of the small x gluons
- Very low momentum fraction partons have large size, overlap with neighbors, and fuse; thus enhancing the population at higher momenta at the expense of lower momenta
- Or alternate but equivalent picture: coherent scattering resulting in destructive interference for coherence lengths longer than the typical intra-nucleon distance

Eskola, Kolhinen, Vogt hep-ph/0104124



D. Kharzeev hep-ph/0307037

Color-glass condensate or saturation



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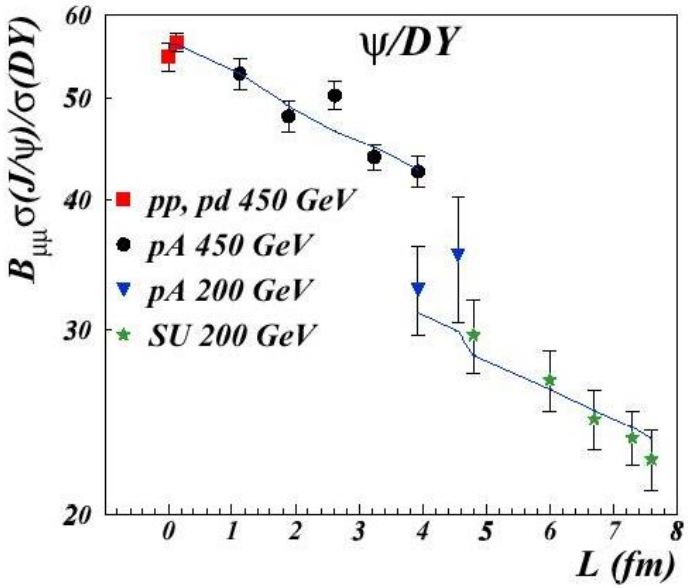
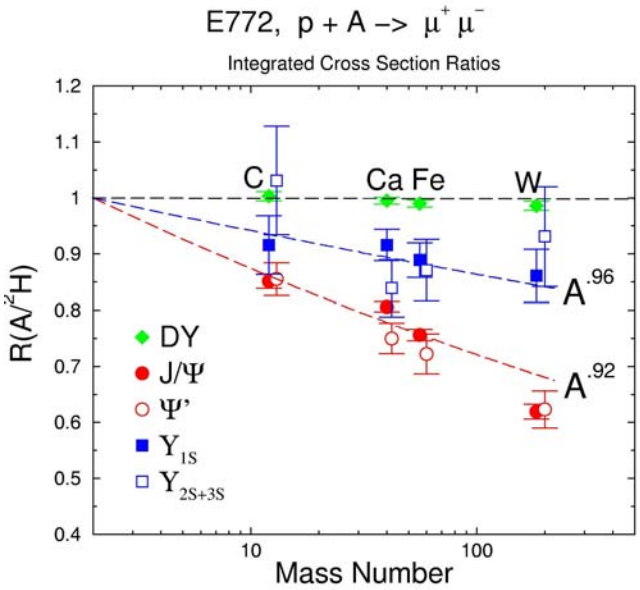
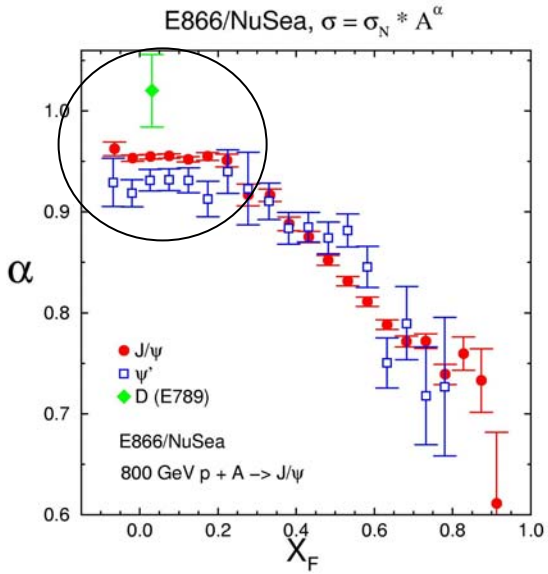
J/ψ at fixed target: Absorption at mid-rapidity





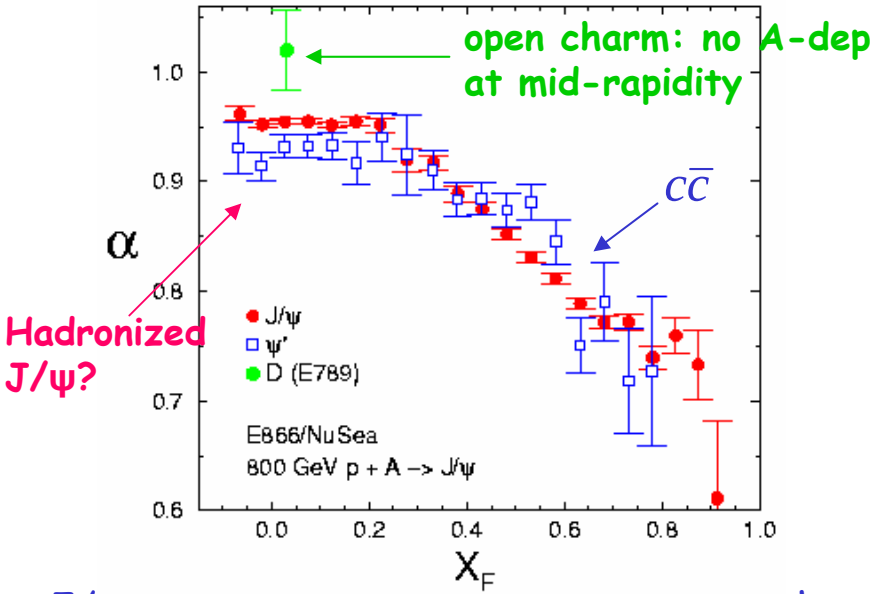


- Breakup by nucleus of J/**ψ or pre-J/ψ (cc) as it exits nucleus**
- Power law parameterization $s = s_N * A^a$
  - a = 0.92 (E772, PRL 66 (1991) 133) (limited p_T acceptance bias)
  - a = 0.919 ± 0.015 (NA38, PLB 444 (1998)516)
  - a = 0.954 ± 0.003 (E866 @ x_F=0. PRL 84 (2000),3258)
  - a = 0.941 ± 0.004 (NA50, QM2004)
- Absorption model parameterization
  - σ = 6.2 mb (NA38/50/51) to 4.3 ± 0.3 mb (NA50, QM2004)
- Small difference in a between J/ψ and ψ(2S) (E866)
  - a(J/**ψ**) – a(**ψ**(2S)) ~ 0.02-0.03 @ x_F = 0 (NA50 **$\sigma^{\psi'} - \sigma^{J/\psi}$ = 3.5** ± 0.7 mb)

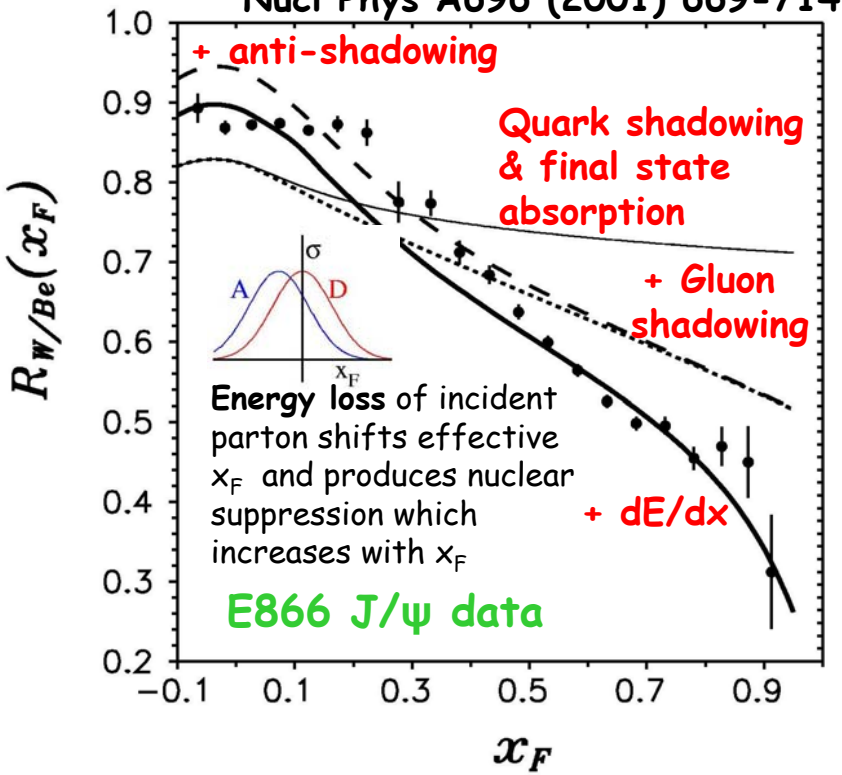
J/ψ suppression in pA fixed-target

800 GeV p-A (FNAL)

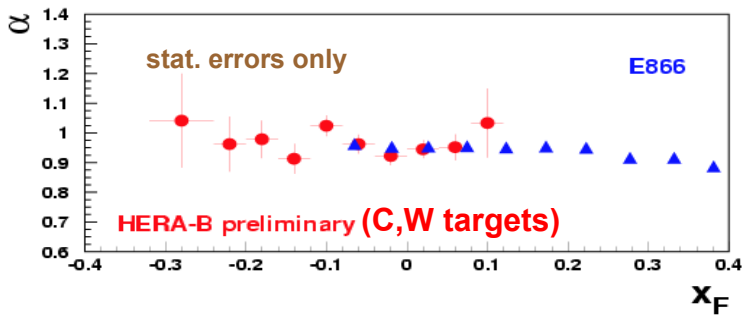
Leitch et al, PRL 84, 3256 (2000); PRL 72, 2542 (1994)



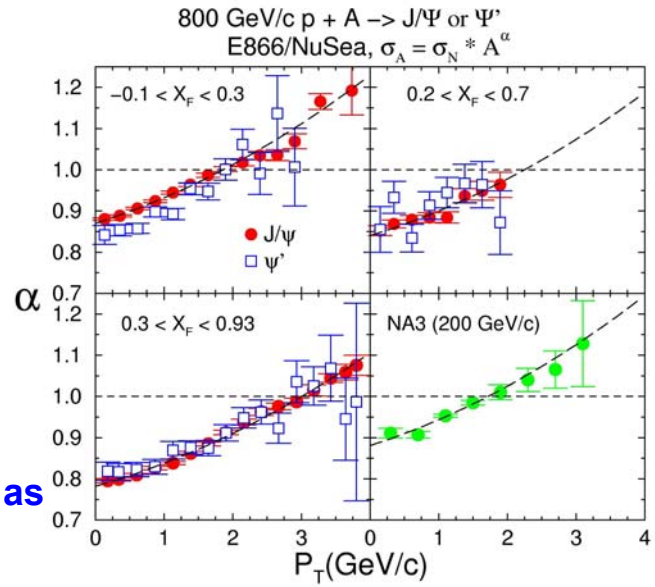
Kopeliovich, Tarasov, Hufner
Nucl Phys A696 (2001) 669-714



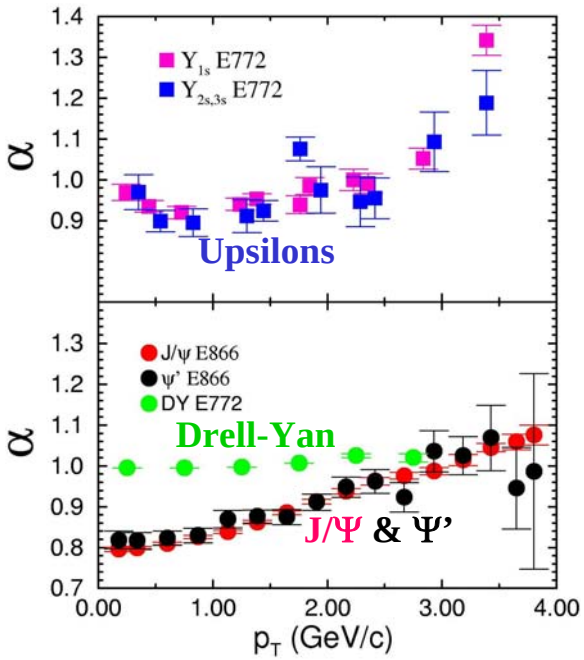
- J/Ψ and Ψ' similar at large x_F where they both correspond to a $c\bar{c}$ traversing the nucleus
- but Ψ' absorbed more strongly than J/Ψ near mid-rapidity (x_F ~ 0) where the resonances are beginning to be hadronized in nucleus
- open charm not suppressed (at x_F ~ 0)

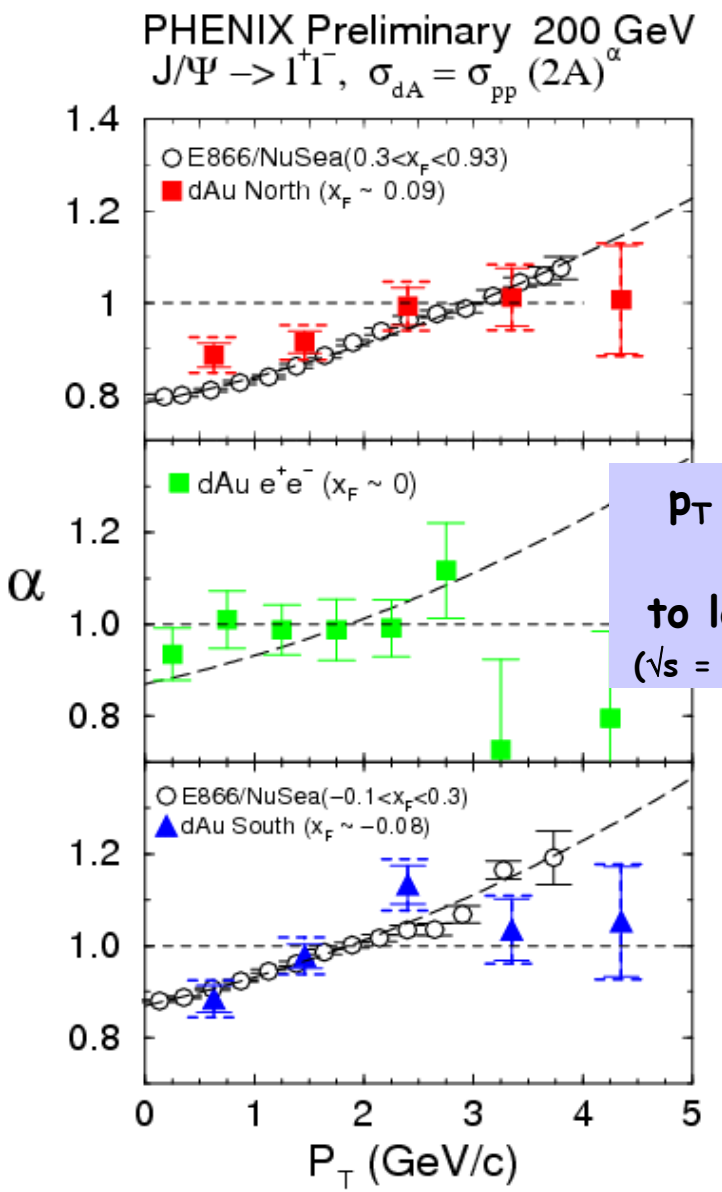


P_T Broadening for J/ψ's



Usually interpreted as initial-state multiple scattering





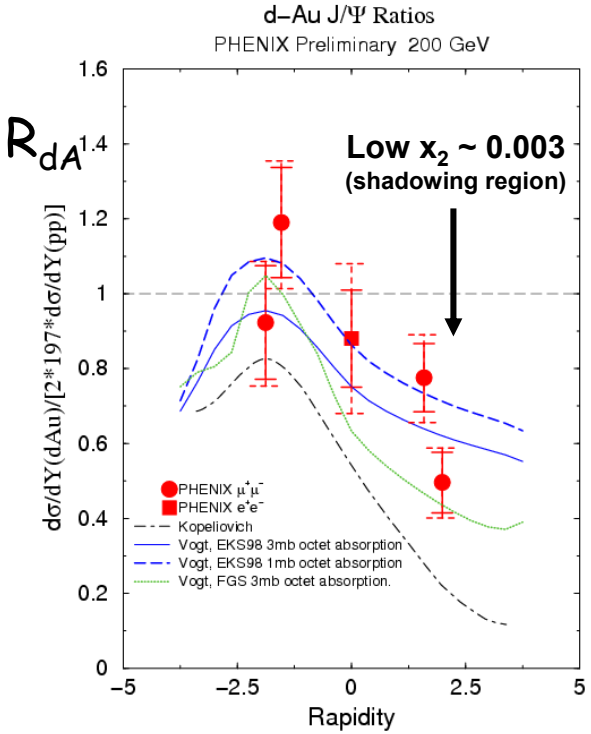
Low x_2 ~ 0.003

p_T broadening comparable to lower energy ($\sqrt{s}$ = 39 GeV in E866)

High x_2 ~ 0.09

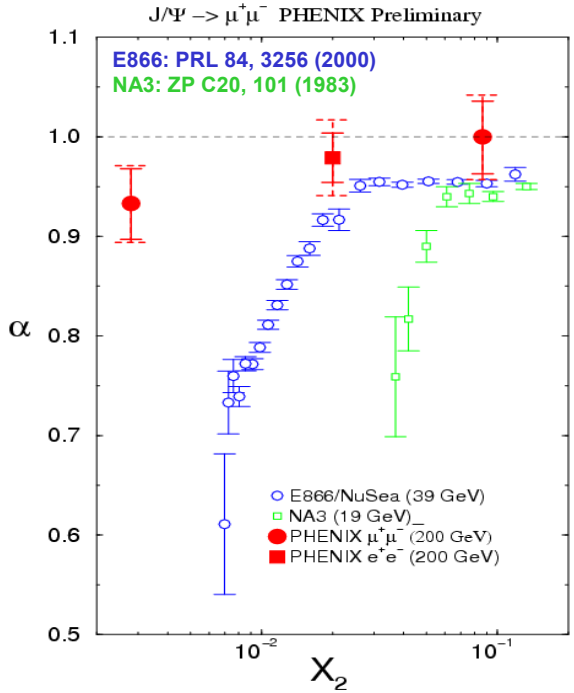
J/ψ nuclear dependence vrs rapidity & x_{Au}

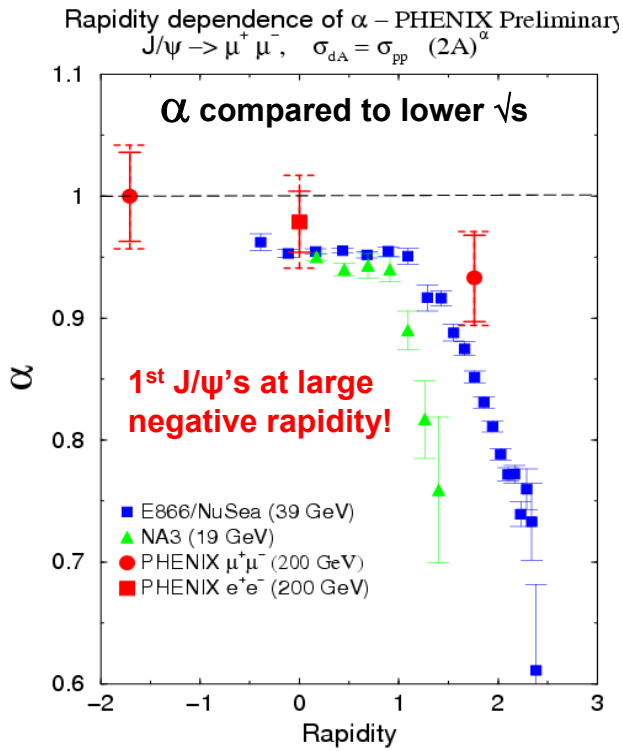
PHENIX compared to lower energy measurements



Klein,Vogt, PRL 91:142301,2003

Kopeliovich, NP A696:669,2001





Data favors (weak) shadowing + (weak) absorption (α > 0.92)

With limited statistics difficult to disentangle nuclear effects

Will need another dAu run! (more pp data also)

Not universal versus X_2 : shadowing is not the whole story.

Does scale with rapidity (and x_F)!

(Energy loss expected to be weak at RHIC energy)

Open Charm & J/ψ's

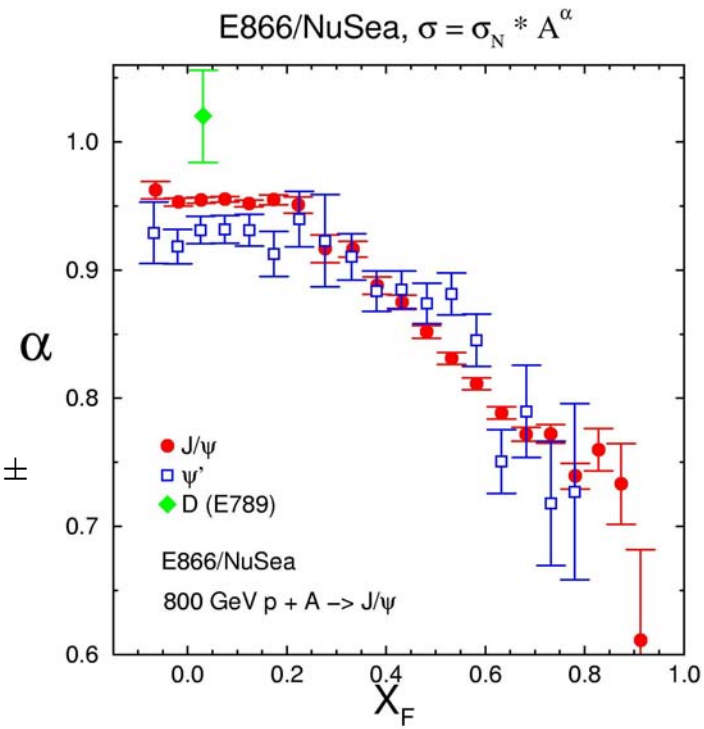
Charm production (D mesons) is complementary to J/ψ studies

- shares the same initial-state effects - production mechanism, shadowing, p_T broadening
- but is different in the final-state – e.g. absorption only for J/ψ, final-state p_T broadening…

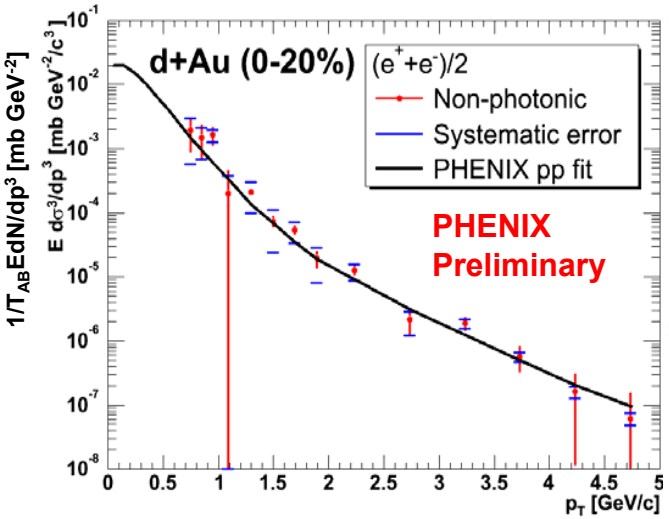
Open charm has little or no nuclear dependence in the mid-rapidity (non shadowing) region:

a = 1.00± 0.05	(E769 250GeV p+A)
a = 0.92 ±0.06	(WA82 340GeV p+A)
a = 1.02 ±0.03 ±0.02	(E789 800GeV p+A)

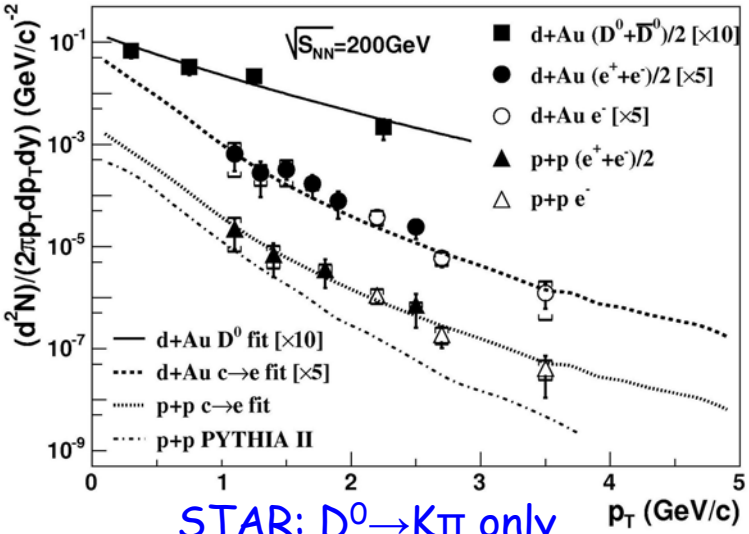
But significant nuclear suppression is reported in the large x_F (shadowing) region (WA78, a=0.81 ± 0.05) which could be due to nuclear shadowing.



Open charm in Cold Nuclear matter?

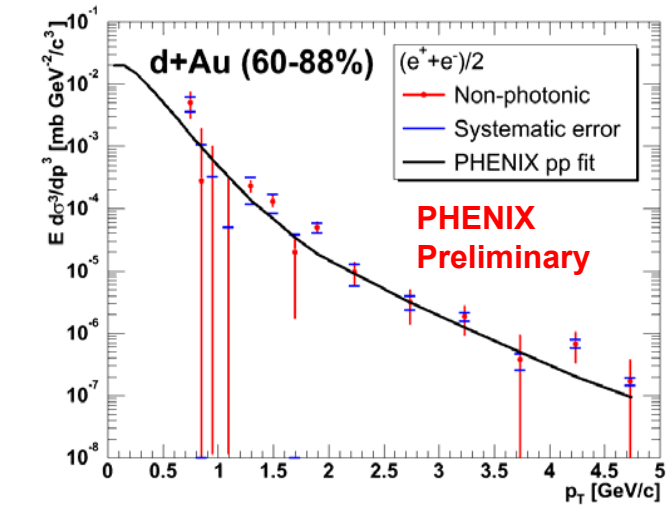


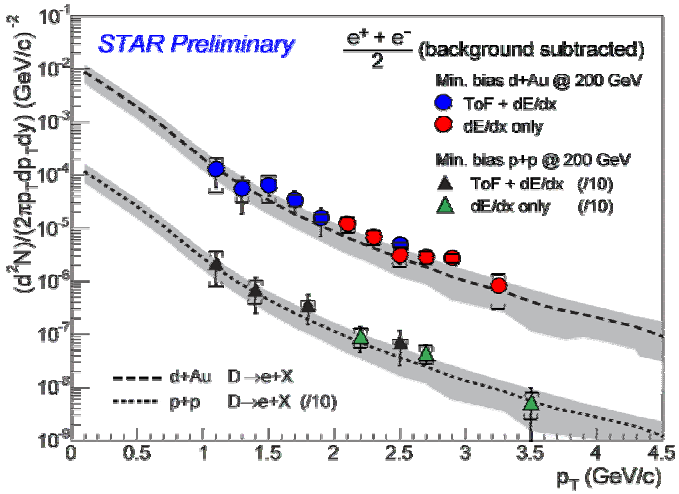
STAR – nucl-ex/0407006



STAR: $D^0 \rightarrow K\pi$ only

RdA = 1.3+-0.3+-0.3





- Scaling with Ncoll seems to indicate little energy loss.
- "dead-cone" effect (*Kharzeev et al., PL B519(2001)199-206*)?

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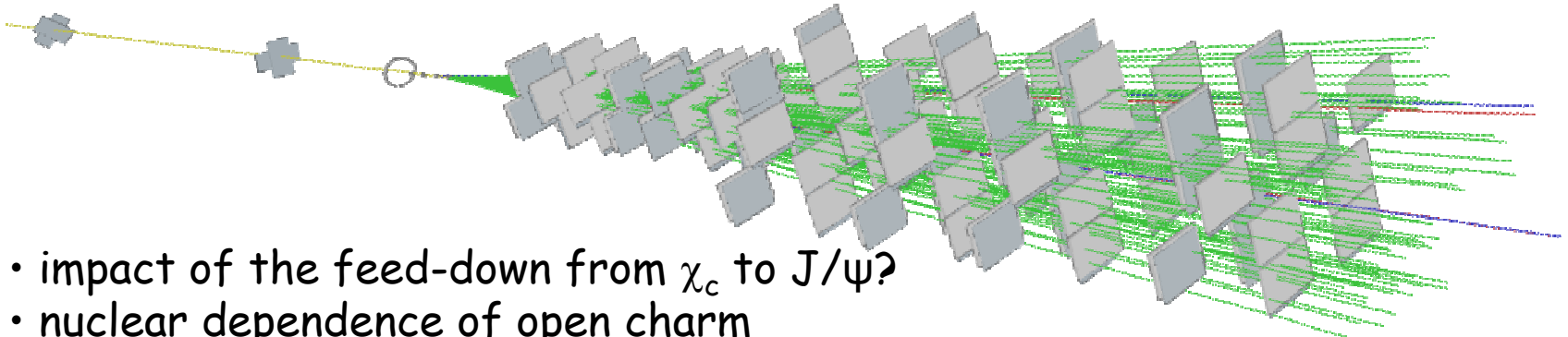
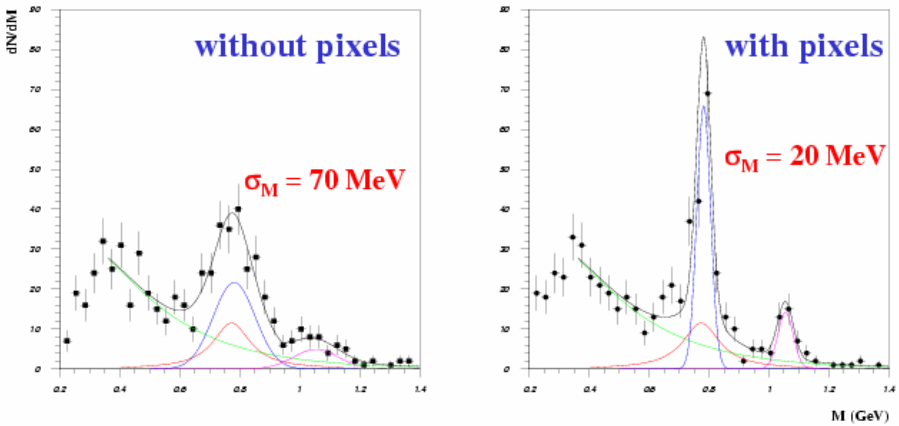
NA60: NA50 + silicon vertex



- impact of the feed-down from χ_c to J/ψ?
- nuclear dependence of open charm production in pA?
- is open charm enhanced in AA?
- low-mass charm pairs in AA?

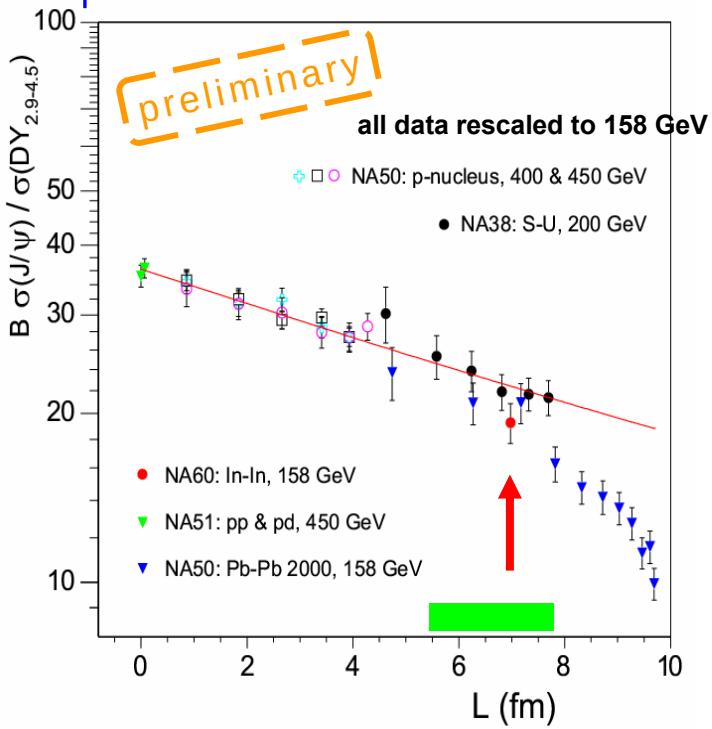
Improved J/ψ mass resolution with silicon !

NA60 test run - 450 GeV p+Be



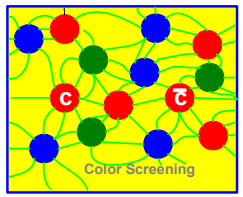
Arnaldi (NA60) Moriond 2004.

J/ψ / Drell-Yan in Indium-Indium collisions

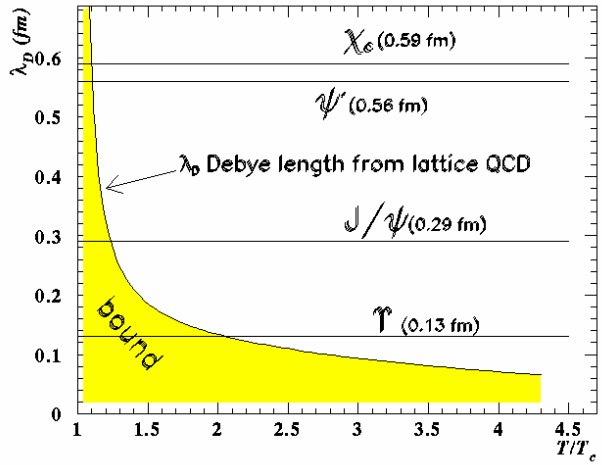


AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

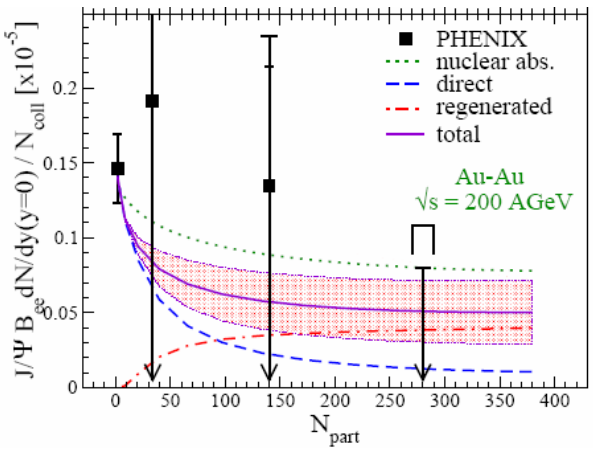
- Debye screening predicted to destroy J/ψ's in a QGP



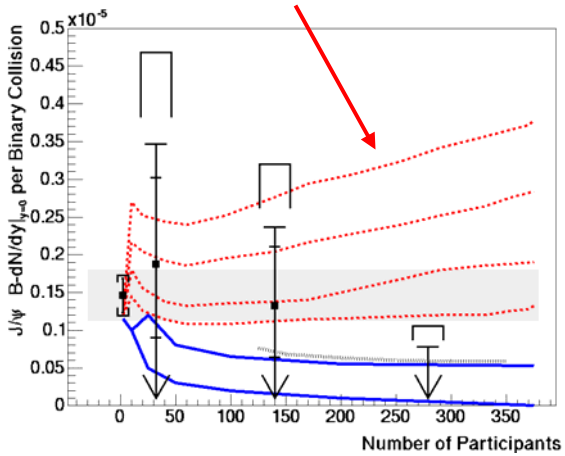
- Different states "melt" at different temperatures due to different binding energies.
- but recent charm recombination models might instead cause an enhancement?



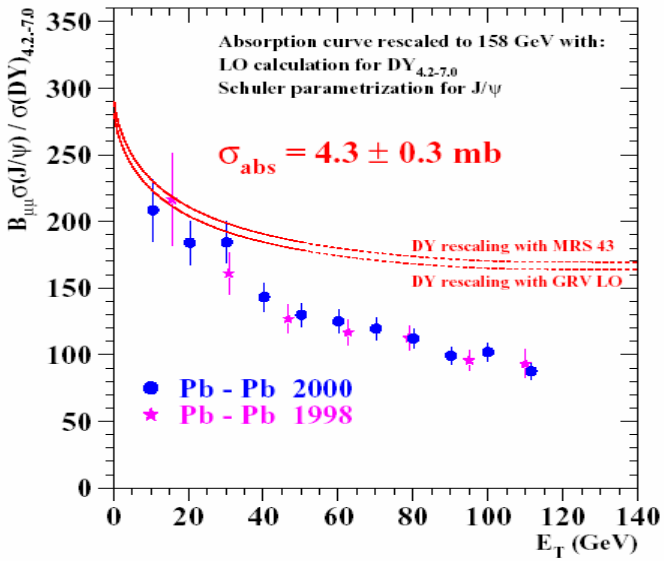
Grandchamp, Rapp, Brown hep-ph/0403204



R. L. Thews, M. Schroedter, J. Rafelski, Phys Rev C 63, 05490

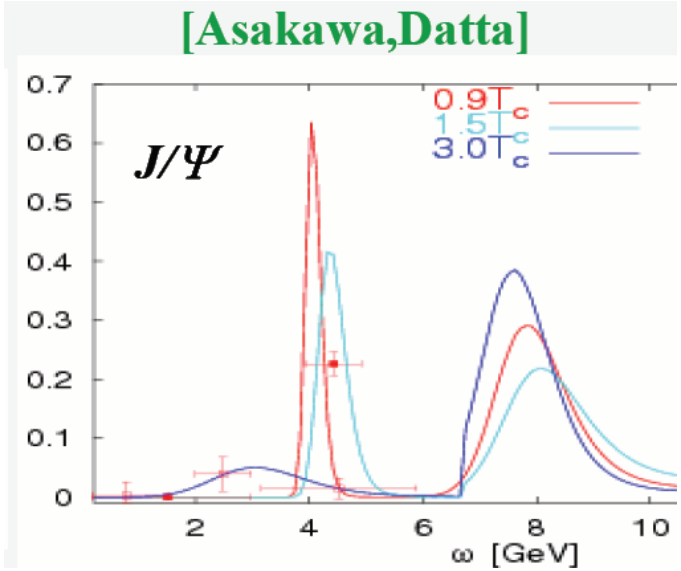


NA50



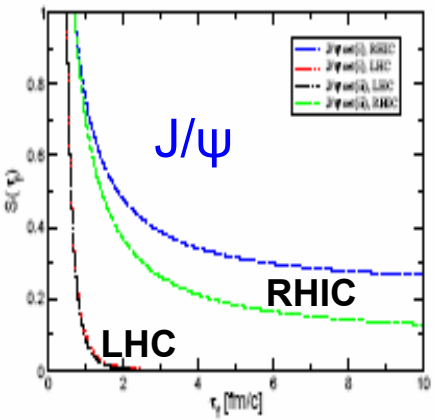
J/ψ ($c\bar{c}$) disassociation in hot-dense medium

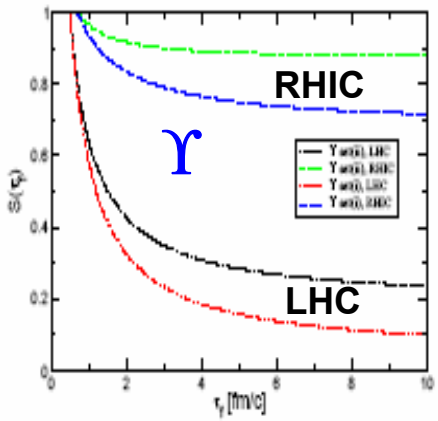
Recent lattice calculations
J/ψ disappears only above 1.5 T_c
Substantially higher than previously assumed!



Disassocation of J/ψ by higher momentum gluon field in a deconfined medium:

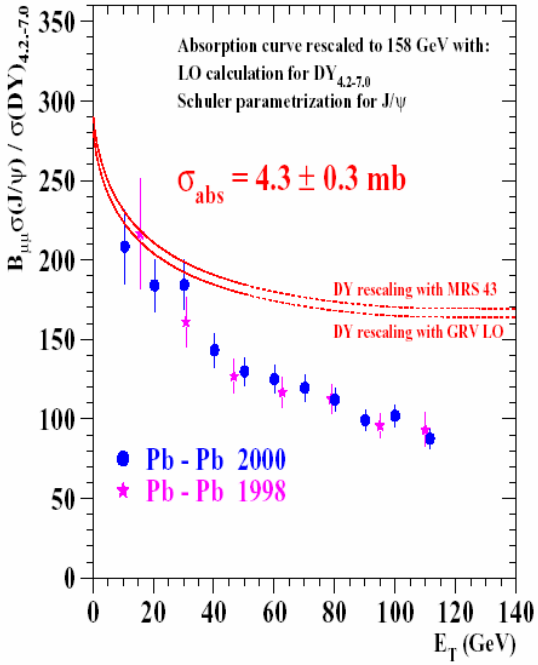
Survival probability of onium in expanding gluon plasma vrs plasma lifetime –(Blaschke et al. hep-ph/0311048)
(two different assumptions about binding energy and heavy quark masses)

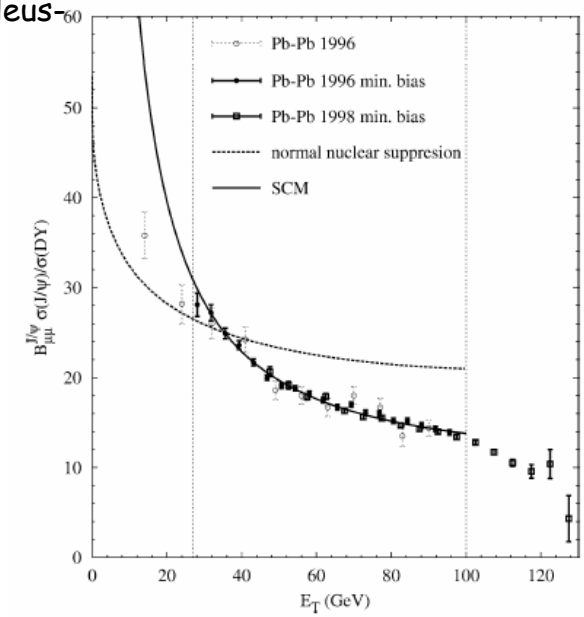




J/ψ Suppression in Pb-Pb at NA50

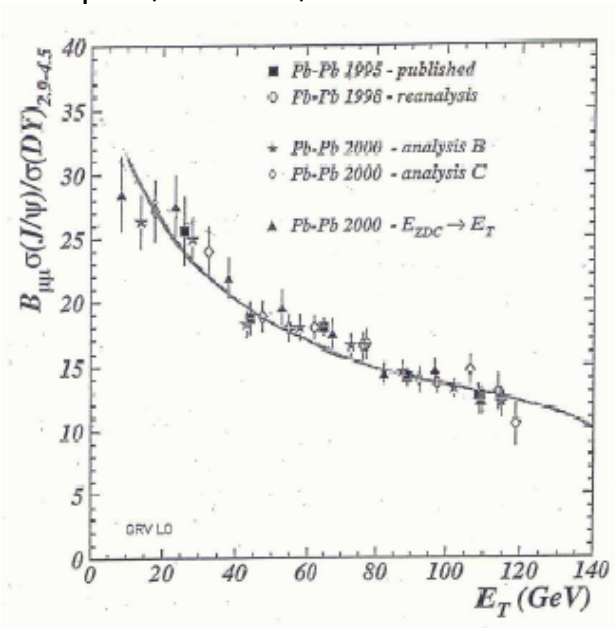
H. Santos, QM04, "Psi' production in nucleus-nucleus collisions at the CERN/SPS".





A.P.Kostyuk, M.I. Gorenstein, H. Stocker, W. Greiner, Phys. Lett B 531, 195-202

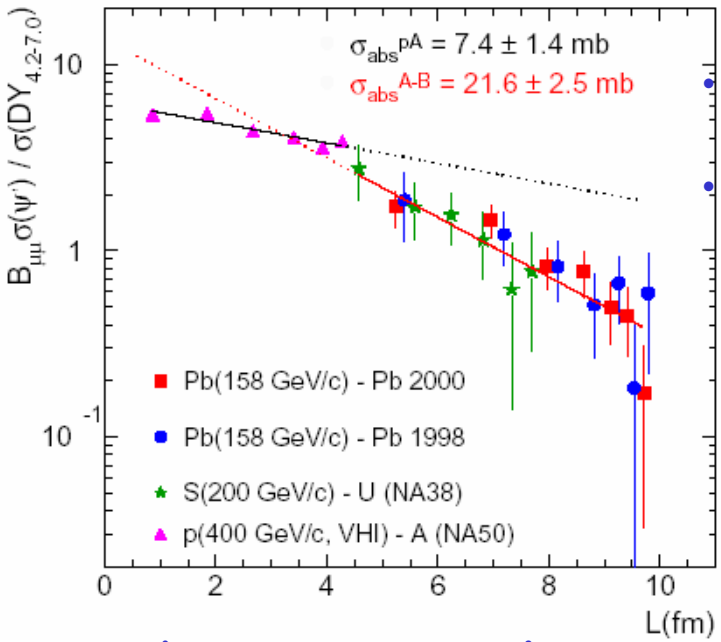
A. Capella, D. Sousa, nucl-th/0303055



- Suppression with respect to normal nuclear suppression expectations
- Theorists have produced various alternative models which also reproduce data:
  - Statistical coalescence model (also needs enhanced open charm)
  - Comovers
- RHIC data on J/ψ highly desired to give another data point(s) to compare to PbPb results and implied expectations

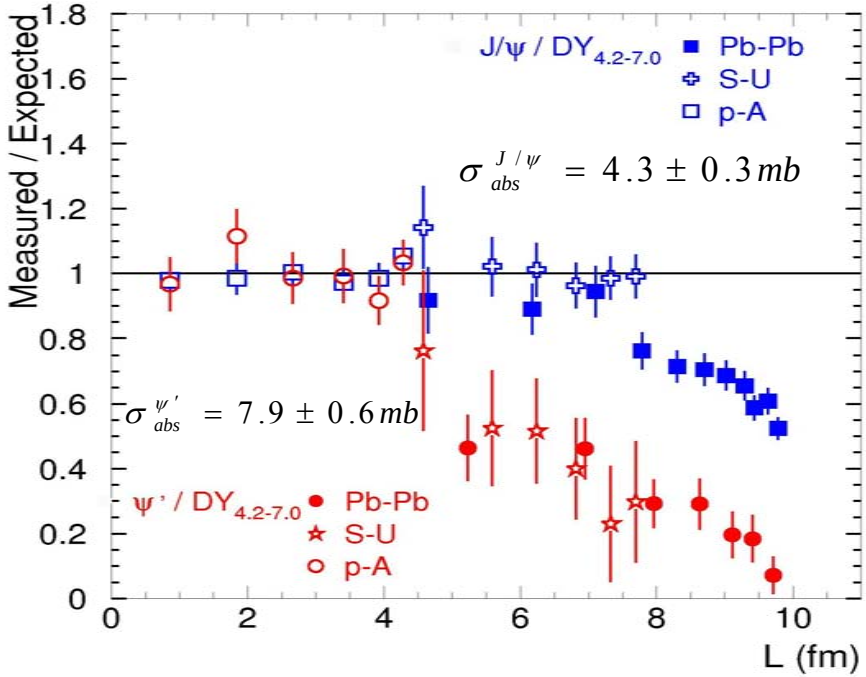
ψ' suppression at SPS/NA50

$$\sigma_0 e^{-<\rho L>\sigma_{abs}}$$



ψ' suppression relative to Drell-Yan & J/ψ increases with centrality in PbPb collisions

- ψ' absorption in pA is stronger than J/ψ absorption
- significantly stronger absorption in AA going from peripheral to central collisions
- no apparent difference in absorption pattern between SU and PbPb collisions



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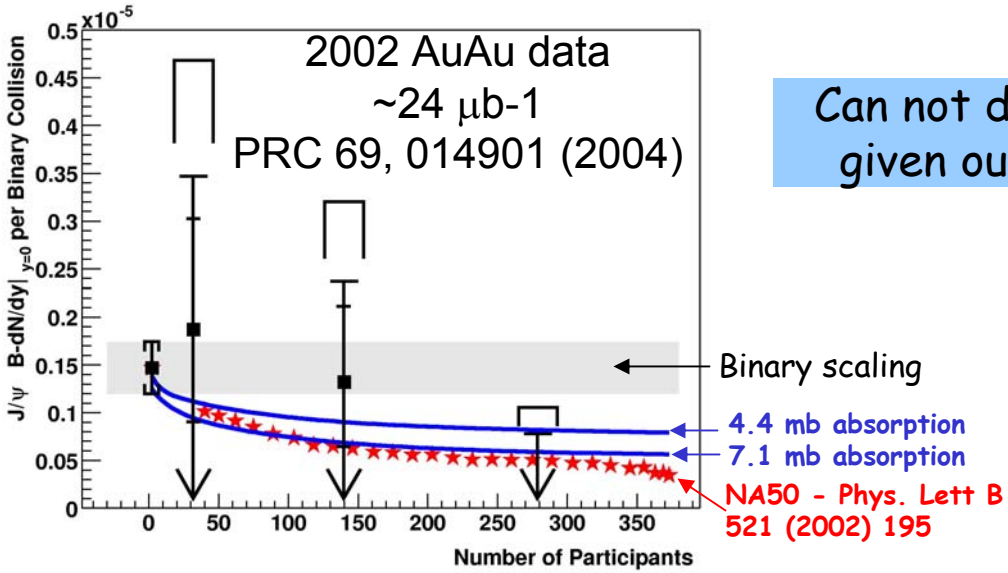
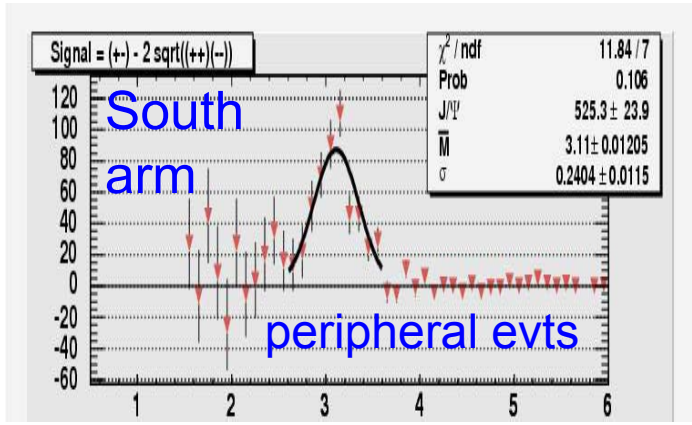
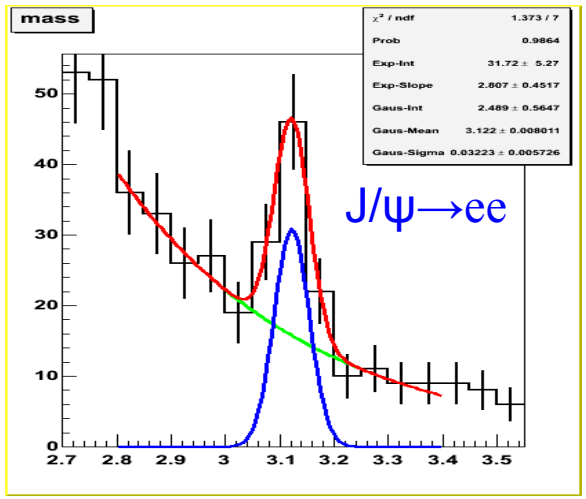
J/ψ's in 200 GeV AuAu collisions at PHENIX

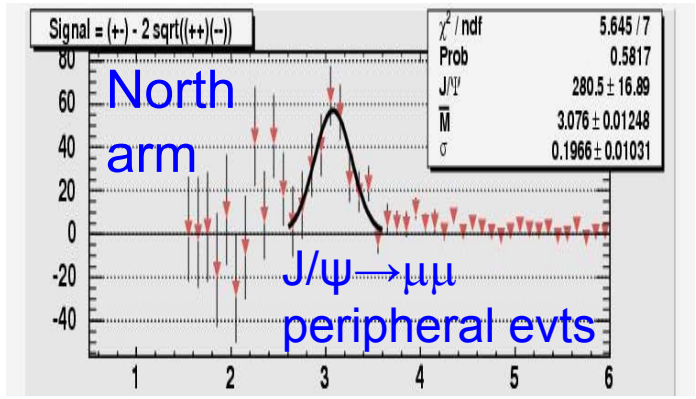


Can not discriminate between scenarios, given our present statistical accuracy

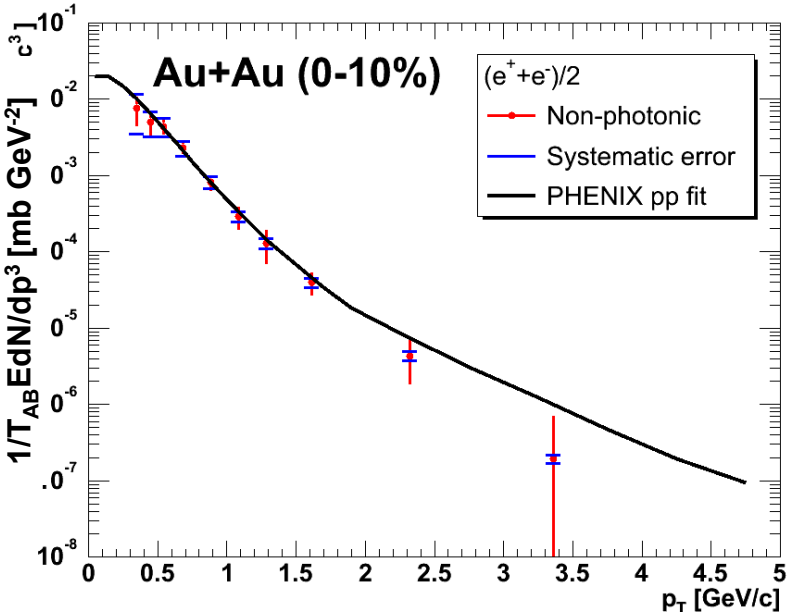


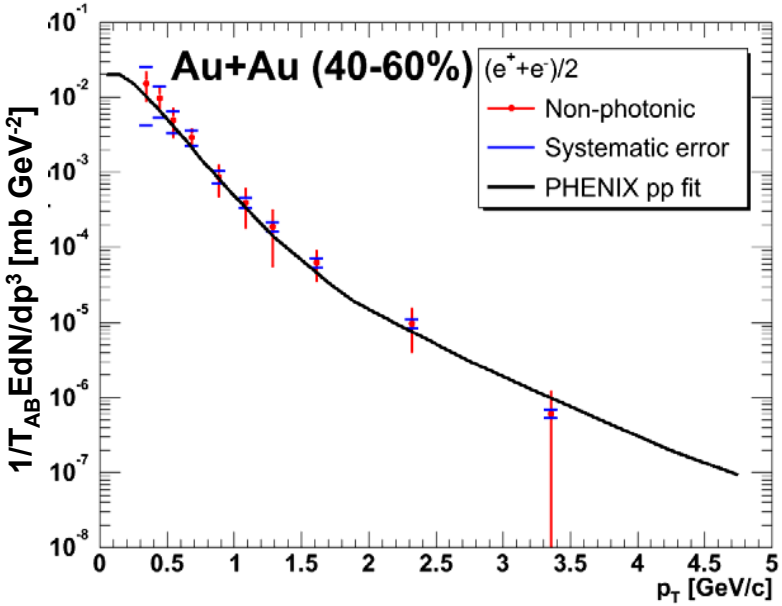


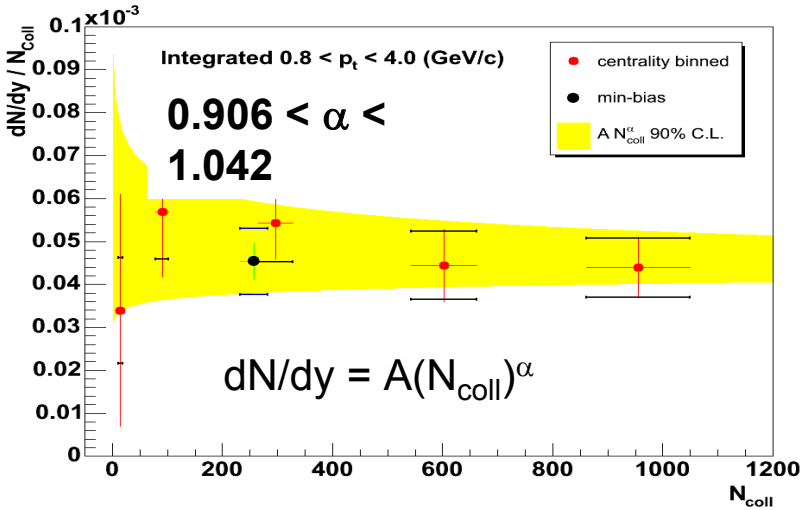
2004 AuAu data
~240 μb^{-1}
Clear J/ψ signal in both central and muon arms from a small fraction of analyzed filtered data.



Open charm in AuAu collisions







starving for statistics at high p_T!

binary scaling (almost?) seems to work!

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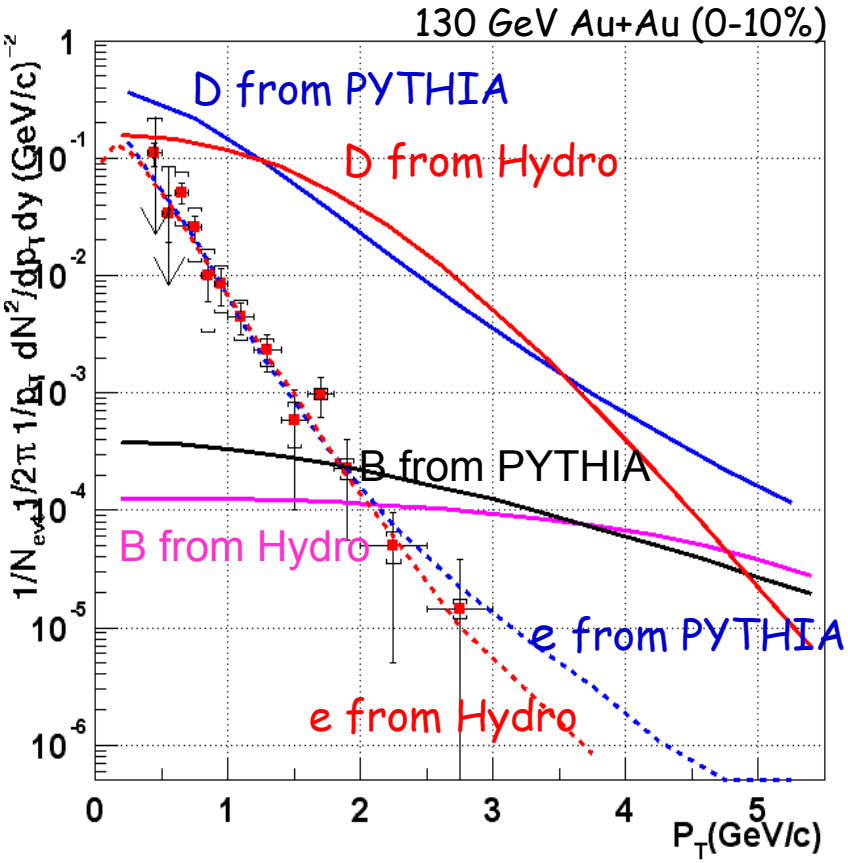
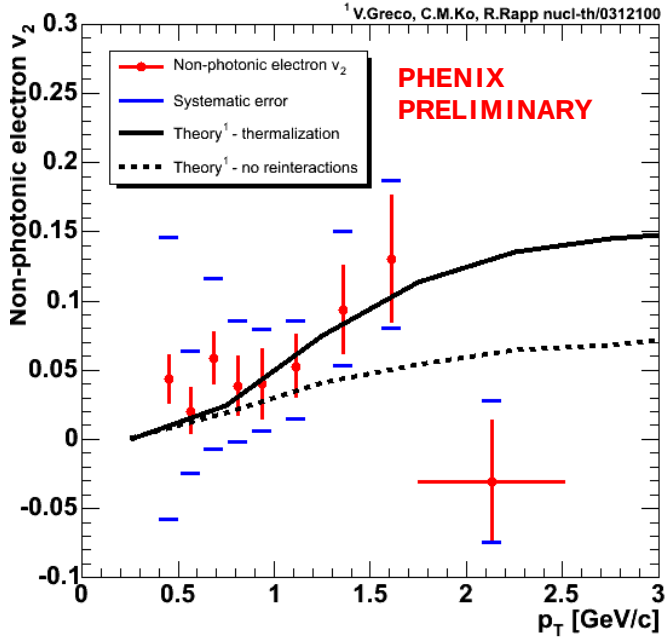
Dynamics of Charm In Media

Hydro & Pythia + dE/dx indistinguishable?



(S. Batsouli, S.Kelly, M.Gyulassy, J.Nagle) Phys.Lett. B557 (2003) 26-32

The measurement of v_2 of charm is a potential way to discriminate between these contrasting dynamical scenarios



Data too uncertain so far to indicate non-zero charm flow from run2

PHENIX accumulated a factor of 80 more statistics with better quality and less conversion background (0.3% instead of 1.4%)in RUN4. Expected to have much more clear answer.

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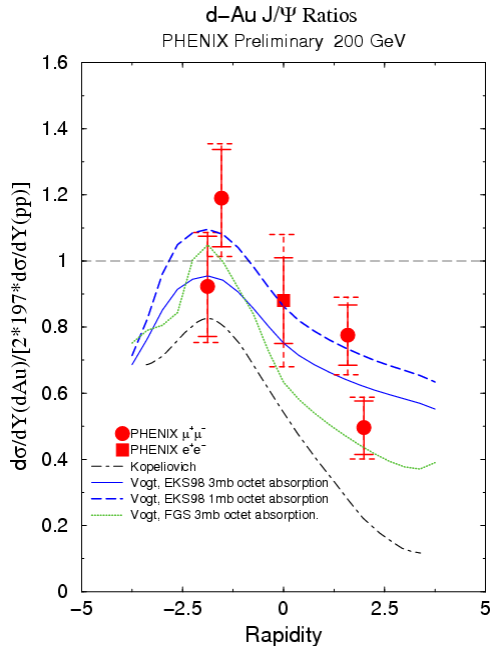
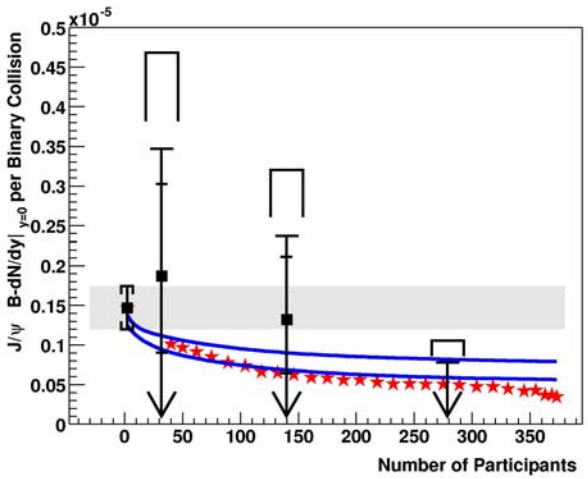
Summary & Comments

- Progress on charm production cross sections and polarizations but still doesn't seem to be well understood
  - also causes uncertainties in the understanding of nuclear effects (e.g. J/ψ absorption)
- Weak shadowing has been observed at RHIC for the J/ψ in dAu collisions but statistics in Au-Au collisions are not sufficient to learn much yet at RHIC
  - scaling with x_F (and not with x_2) is still a puzzle
- higher luminosity AuAu data with many more J/ψ's is being analyzed, and more d-Au is needed to:
  - show whether color screening effects or recombination wins out in AuAu collisions
  - better quantify cold-nuclear matter effects
- Complementary studies of open charm and of other onia are also critical
  - no apparent nuclear effects for open charm in d-Au
  - and, so far, no significant effect seen in Au-Au
  - upgrades to the RHIC detectors to allow exclusive measurements of open charm and beauty are critical for completing the physics puzzle





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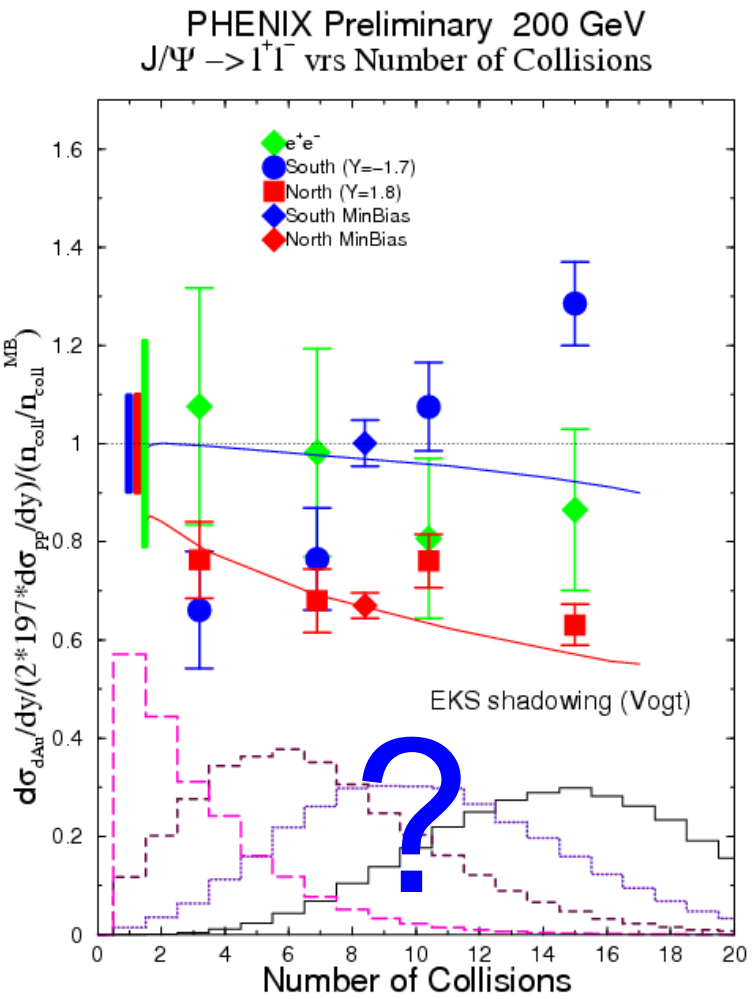
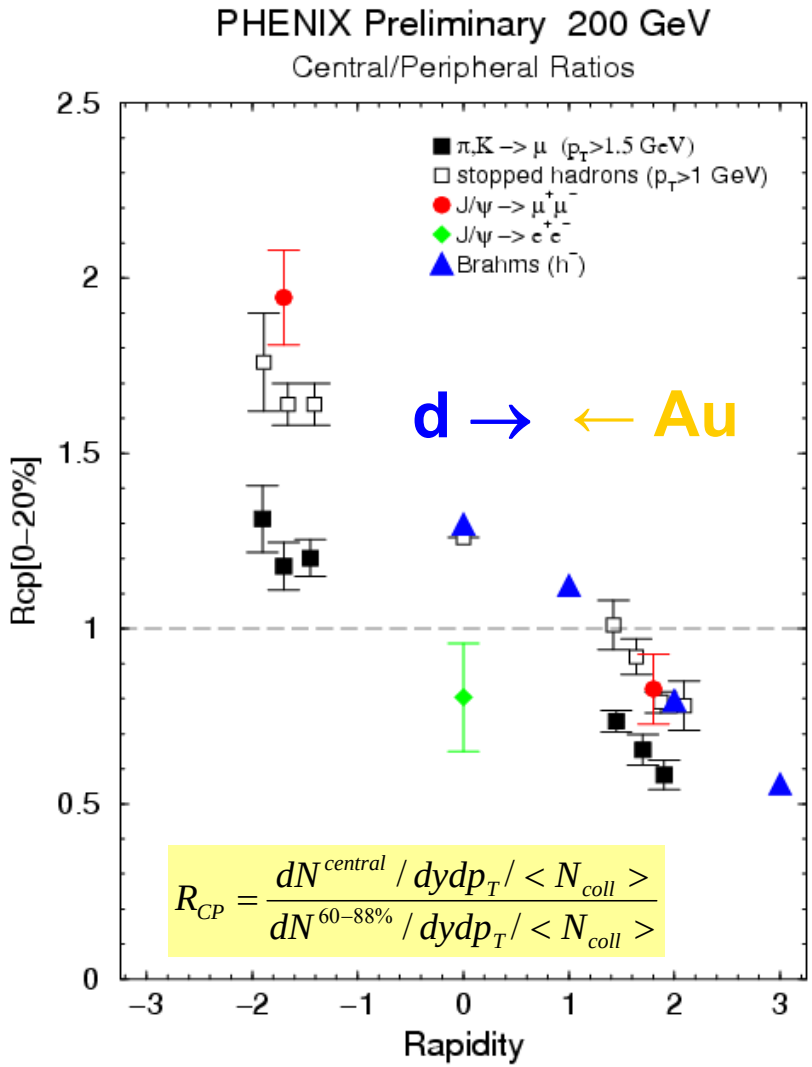
Centrality Dependence – new at RHIC





Current PHENIX Run Request

- An extensive program of luminosity and polarization development for p+p, with the goal of the earliest practicable measurement of DG
- Light-ion running, to investigate dependence on system size
- A reduced energy run, again with emphasis on obtaining highest possible integrated luminosity
- High integrated luminosities achieved via minimal variations in species and energies, as per CAD guidance

Table 2: The PHENIX Beam Use Proposal for 31 cryo weeks in Run-5, and 27 cryo weeks in latter years.

RUN	SPECIES	$\sqrt{s_{NN}}$ (GeV)	PHYSICS WEEKS	$\int \mathcal{L}dt$ (delivered)	p+p Equivalent
5	Cu+Cu	200	10	7.0 nb^{-1}	27.6 pb^{-1}
	p+p	200	11	13.1 pb^{-1}	13.1 pb^{-1}
6	Au+Au	62.4	9	111 μb^{-1}	4.3 pb^{-1}
	p+p	200	8	15.0 pb^{-1}	15.0 pb^{-1}
7	p+p	200	20	122 pb^{-1}	122 pb^{-1}
8	Au+Au	200	20	4140 μb^{-1}	161 pb^{-1}
9	p+p	500	20	359 pb^{-1}	359 pb^{-1}
10	d+Au	200	20	91.6 nb^{-1}	36 pb^{-1}

BELLE – Double Charm !

PRL 89, 142001 (2002).

$$\left.\frac{\sigma(e^+e^- \to J/\psi c\bar{c})}{\sigma(e^+e^- \to J/\psi X)}\right|_{P_{J/\psi}>2.0GeV/c} = \frac{0.5(N_{D^0} + N_{D^+} + N_{D_s^+} + N_{\Lambda_c^+}) + N_{(c\bar{c})_{rest}}}{N_{J/\psi}}$$

$$= 0.82 \pm 0.15 \pm 0.14$$

$\Rightarrow J/\psi c\bar{c}$ cross section is an order of magnitude larger than predictions and contradicts the NRQCD expectation that $J/\psi c\bar{c}$ is small (same for $J/\psi\eta_c$)

For e^+e^- collisions at the energy of the Upsilon(4S)

Check Form Fields and Comments...

Double charmonium production

Search for $e^+e^- \to J/\psi + (c\bar{c})$ production, where the additional $c\bar{c}$ pair fragments into either charmonium or charmed hadrons.

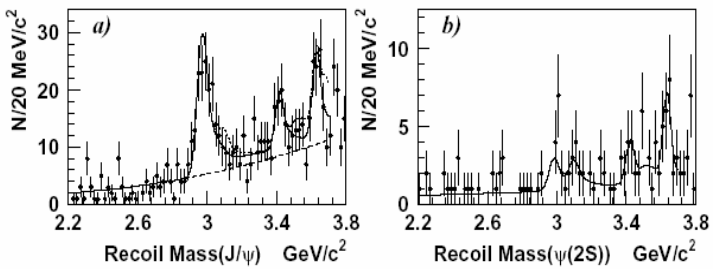
- PRL 89, 142001 (2002) with 46.2/fb
- LP03-274 (BELLE-CONF-0331) with 101.8/fb

Study J/ψ recoil mass spectrum around $M_{recoil} \sim 3$ GeV/c^2 :
$(M_{recoil} = ((E_{CMS} - E_{J/\psi})^2 - p^2_{J/\psi})^{1/2})$

- Constrain J/ψ into nominal mass to improve resolution
- Verify recoil mass scale using $e^+e^- \to \psi(2S)\gamma$, $(\psi(2S) \to J/\psi\pi^+\pi^-)$ for calibration : recoil mass bias < 3 MeV/c^2
- fit includes all known charmonium :
  $$\eta_c,\ J/\psi,\ \chi_{c0},\ \chi_{c1},\ \chi_{c2},\ \eta_c(2S),\ \psi(2S)$$
- Masses of η_c, χ_{c0}, $\eta_c(2S)$ free

Beauty 2003 – p.2/25

Double charmonium production

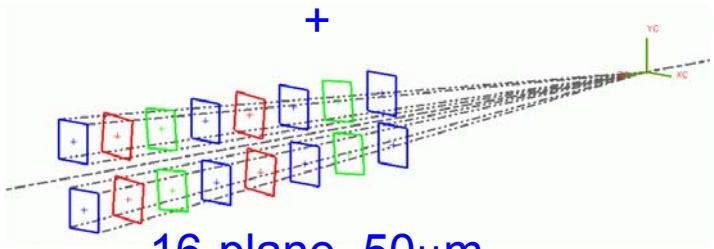


$(c\bar{c})_{rest}$	N (evts)	M [GeV/c^2]	σ	N (evts)	σ
η_c	175 ± 23	2.972 ± 0.007	9.9	15 ± 7	2.6
J/ψ	-9 ± 17	fixed	–	12 ± 7	–
χ_{c0}	61 ± 21	3.409 ± 0.010	2.9	18 ± 9	2.4
$\chi_{c1} + \chi_{c2}$	-15 ± 19	fixed	–	7 ± 9	–
$\eta_c(2S)$	107 ± 24	3.630 ± 0.008	4.4	31 ± 10	3.7
$\psi(2S)$	-38 ± 21	fixed	–	-4 ± 7	–

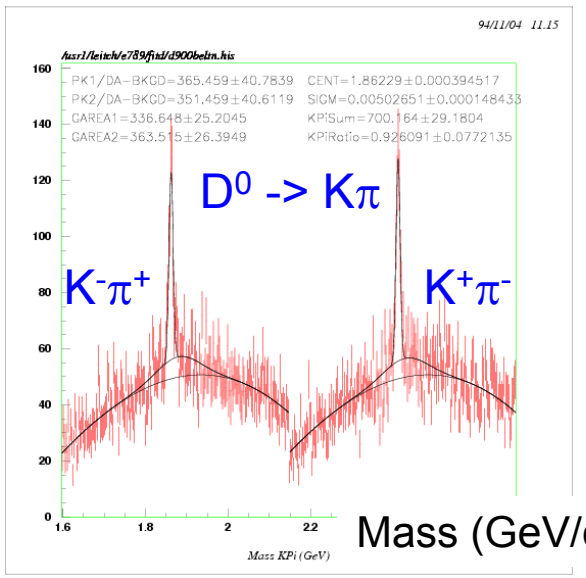
Fermilab E789: D^0 & B → J/ψ X (charm & beauty using silicon)

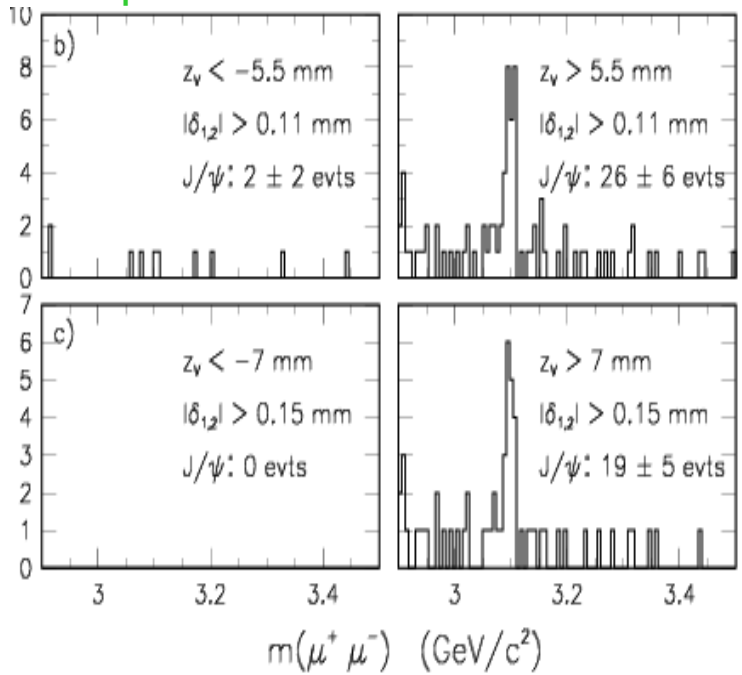
Dimuon spectrometer

+



16-plane, 50μm pitch/8.5k strip silicon vertex detector



Mass (GeV/c^2)

B -> J/ψ + X