Quarkonia Production in p-A Collisions

Mike Leitch - Los Alamos National Laboratory
leitch@lanl.gov

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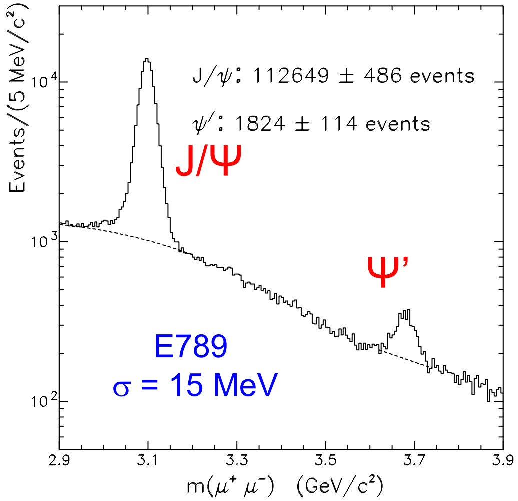
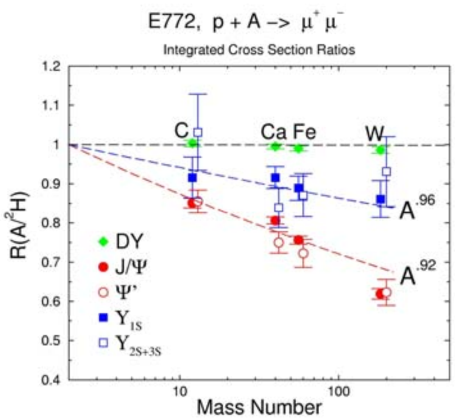
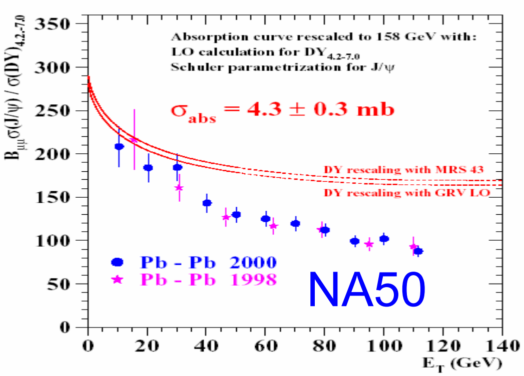
- production
  - mechanisms
  - cross section & polarization
  - complications
- nuclear effects
  - shadowing
  - p_T broadening
  - absorption
  - parton energy loss
  - contrasting open & closed charm
- Summary







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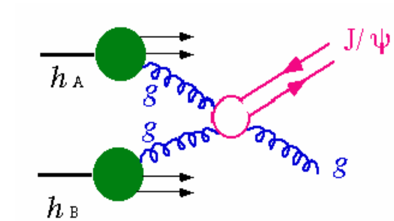
J/ψ & open-charm production, parton level structure & dynamics

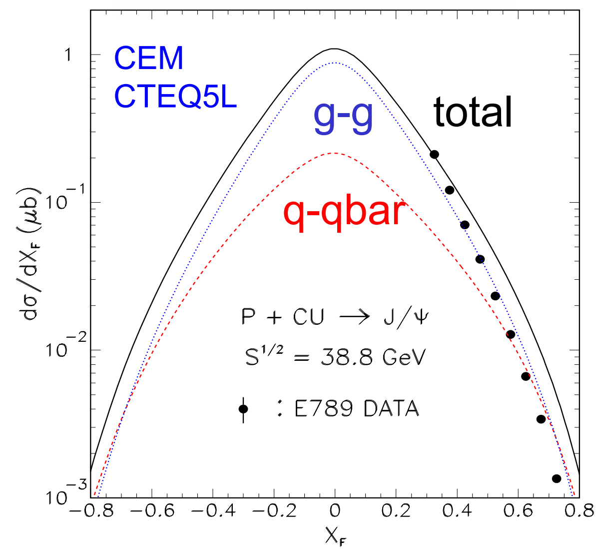
Production of heavy vector mesons, e.g. J/Ψ,Ψ' and ϒ

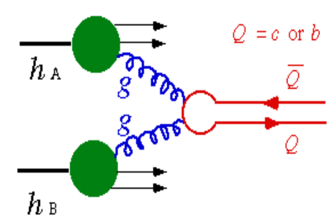
- gluon fusion dominates (NLO calculations add more complicated diagrams but still mostly with gluons)
- production: color singlet or octet $c\bar{c}$: absolute cross section and polarization?
- hadronization time (important for pA nuclear effects)
- complications due to substantial feed-down from higher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







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

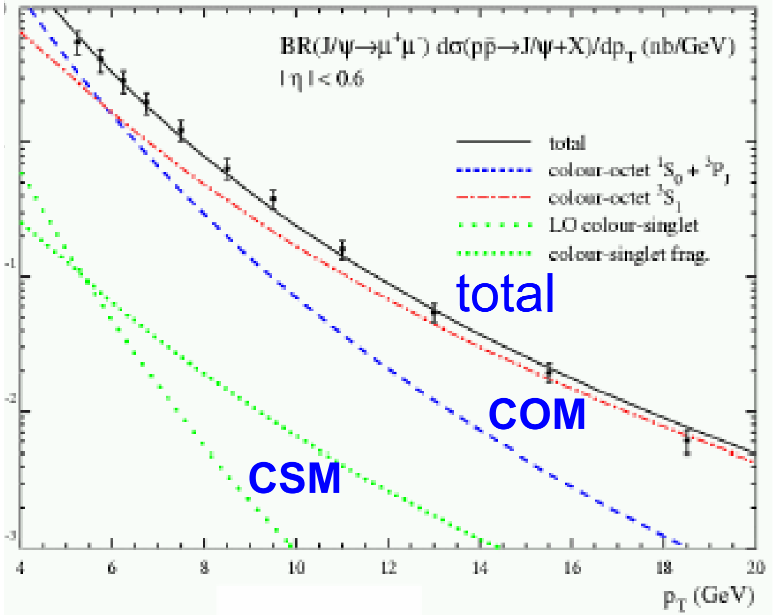
Color-octet model (COM)

- 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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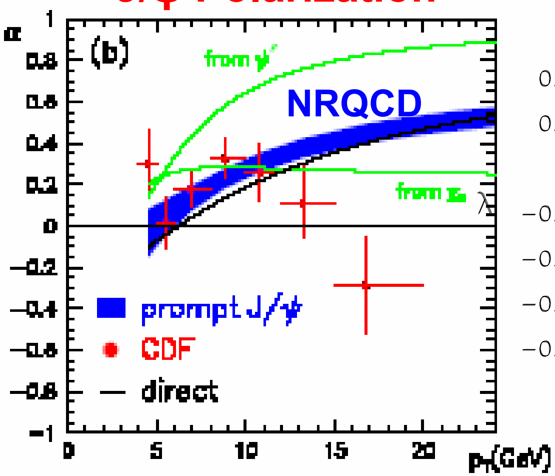
J/ψ Production—Polarization

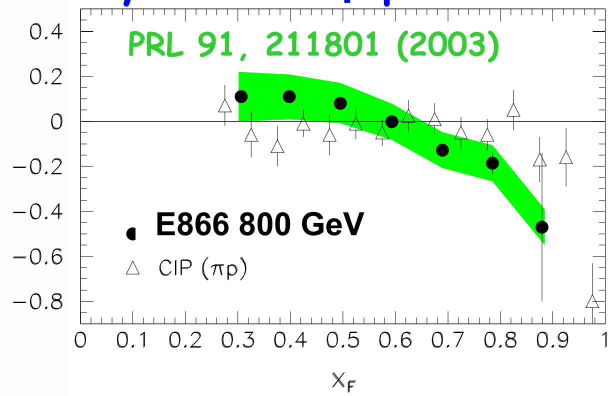
Color Octet Model predicts J/ψ polarization at large p_T - NOT SEEN in data

J/ψ Polarization

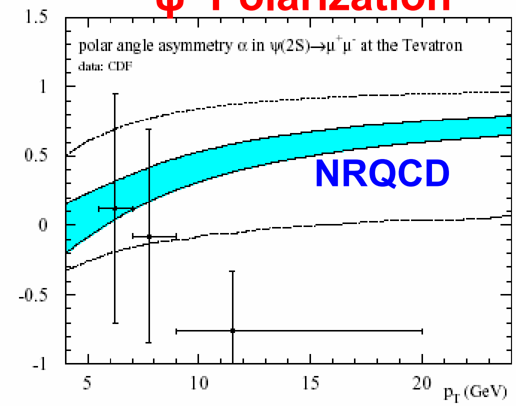


E866

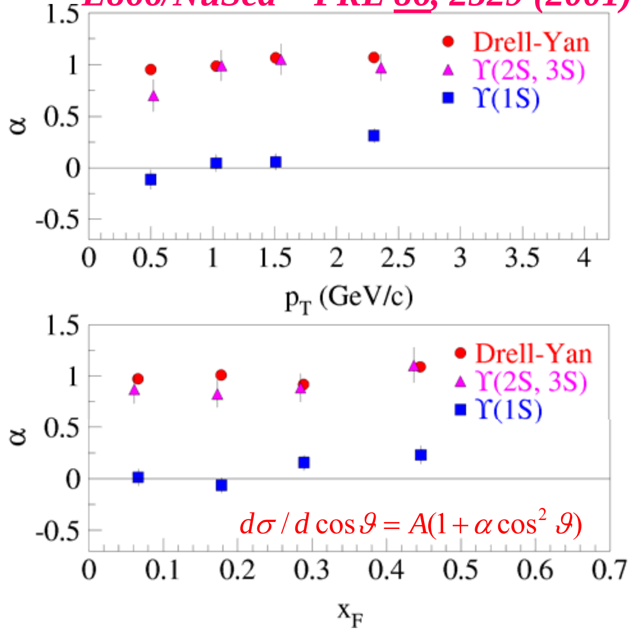
very small J/ψ polarization



ψ' Polarization



E866/NuSea – PRL 86, 2529 (2001)



- CDF and Fermilab E866 data show little polarization of J/ψ - opposite trend from predictions
- But ϒ maximally polarized for (2S+3S) but not (1S)
- Is feed-down washing out polarization?
- NRQCD predicts $0.25 < \lambda < 0.7$ (feed-down from χ states included).

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

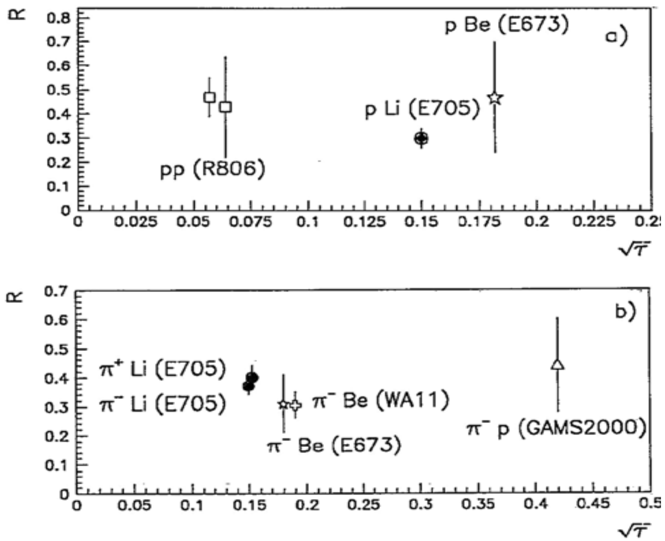
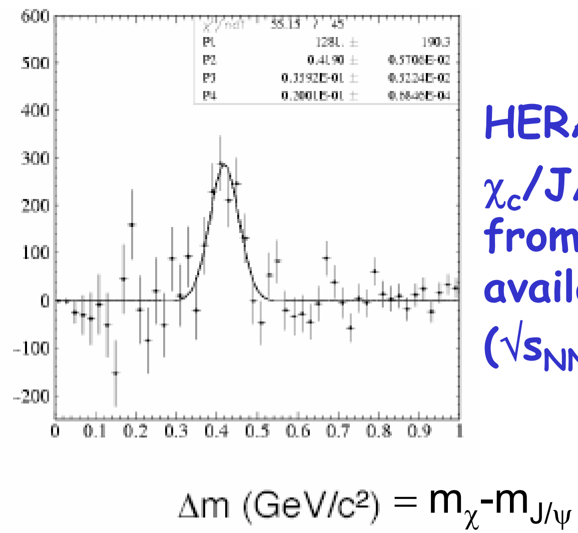


FIG. 3. Fraction of J/ψ produced via radiative χ in 300 GeV/c (a) proton and (b) $\pi^{\pm}$ ^{7}Li interactions.

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

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

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



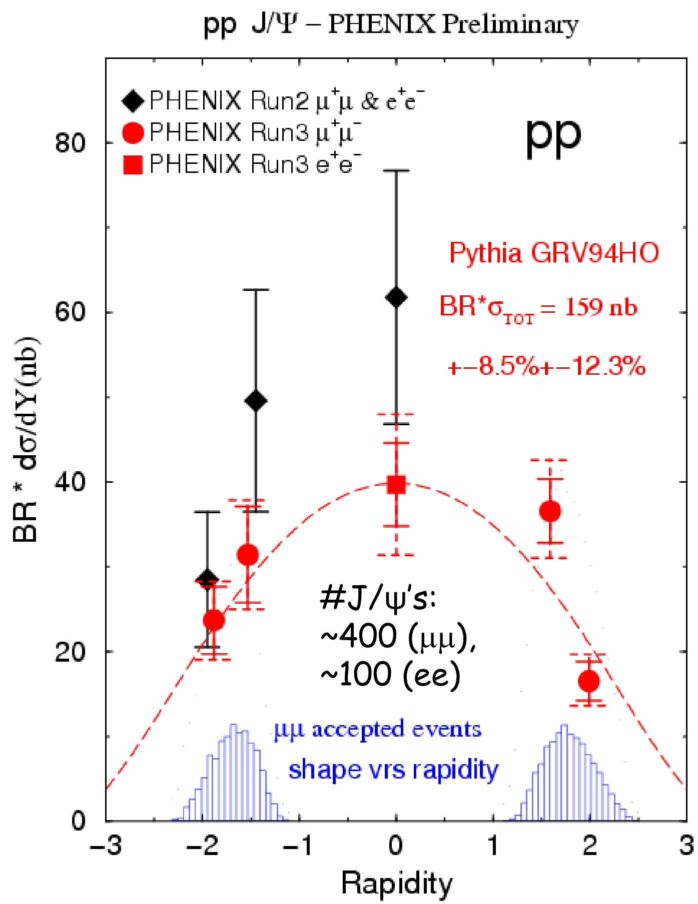
HERA-B

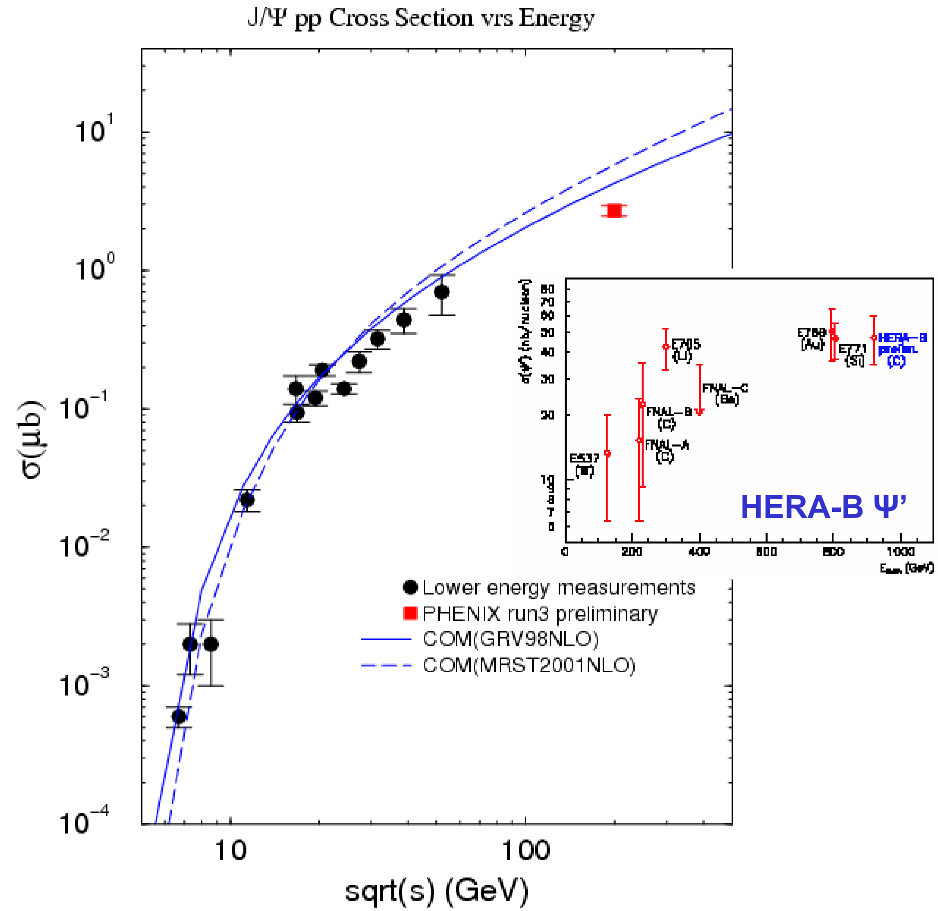
$\chi_c/J/\psi$ = 0.21±0.05 from 15% of available statistics ($\sqrt{s_{NN}}$ = 42 GeV)

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

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)

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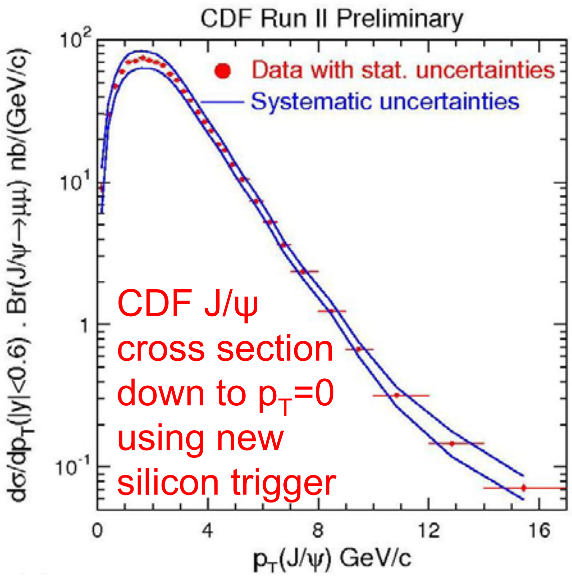
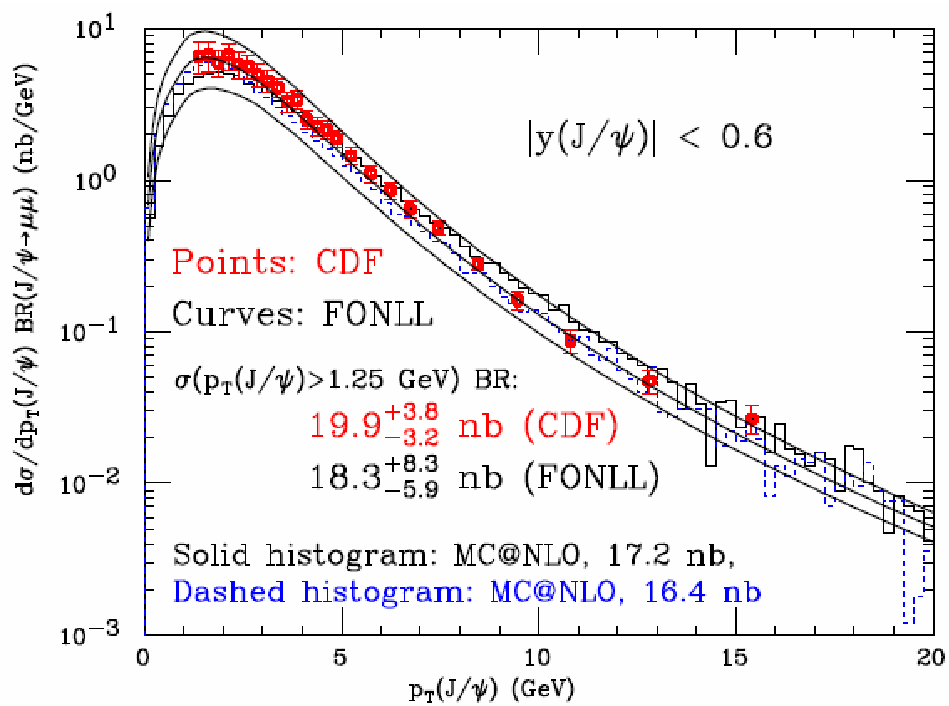
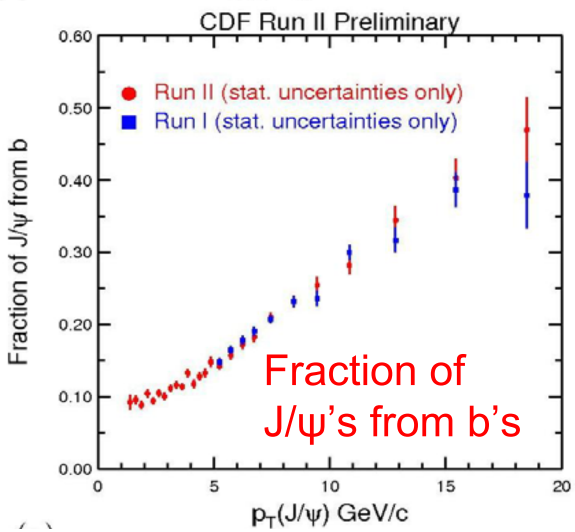
CDF Run II J/Psi vrs p_T now down to p_T=0

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.

- **but I guess they still don't get (lack of) polarization correct??**

Nuclear modification of parton level structure & dynamics

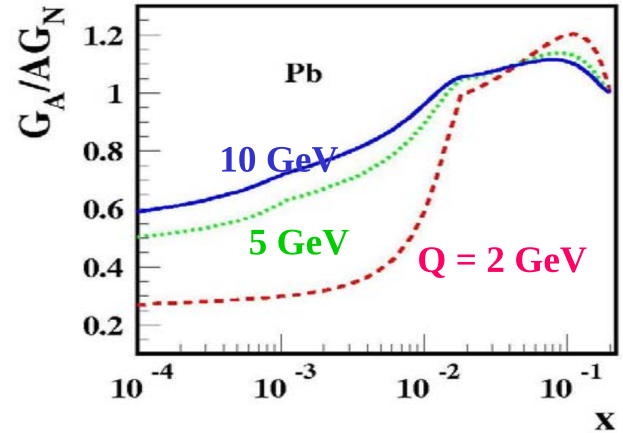
Modification of parton momentum distributions of nucleons embedded in nuclei

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

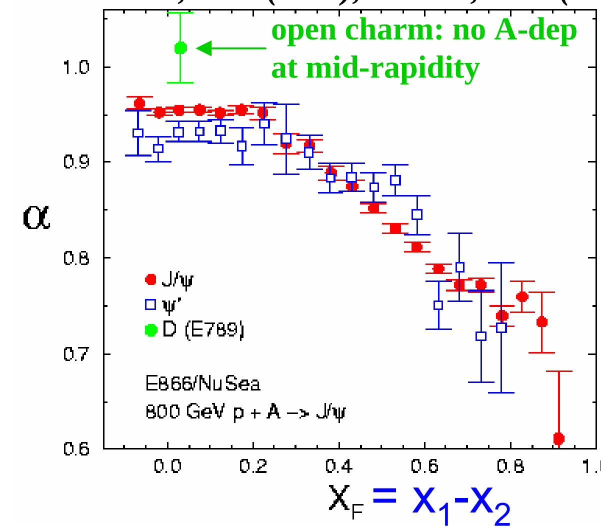
Nuclear effects on parton "dynamics"

- 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)

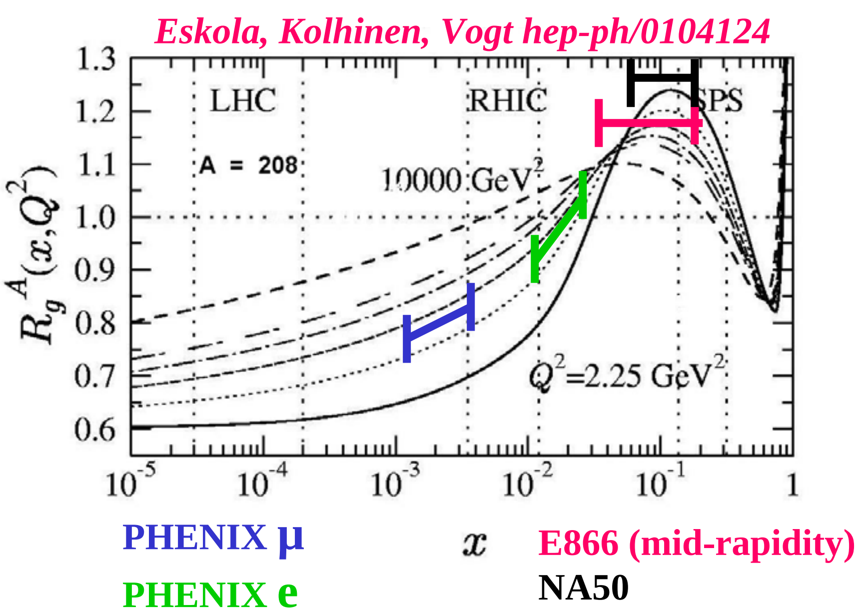


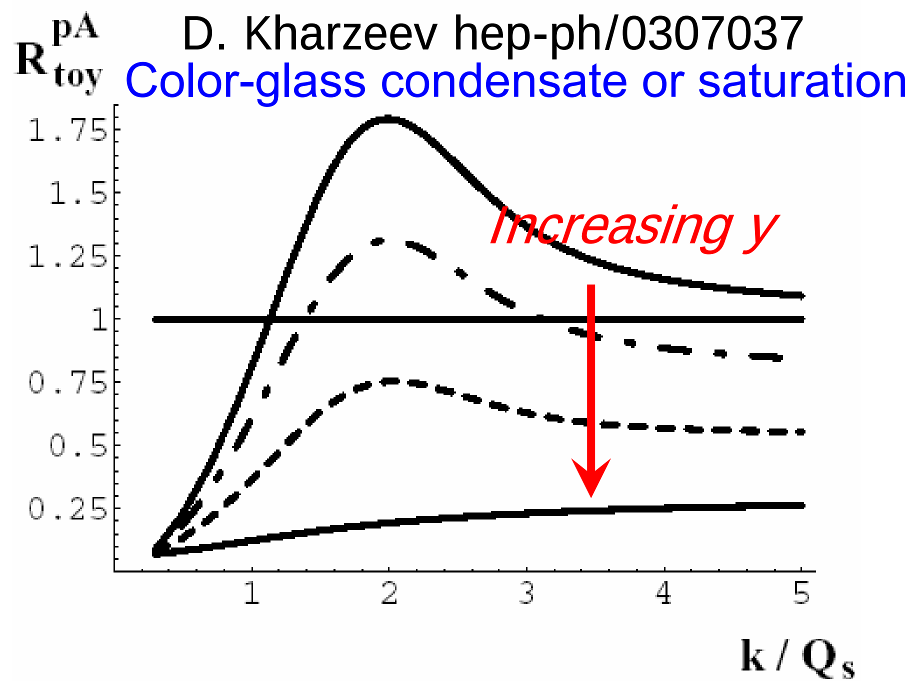
800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$
PRL 84, 3256 (2000); PRL 72, 2542 (1994)



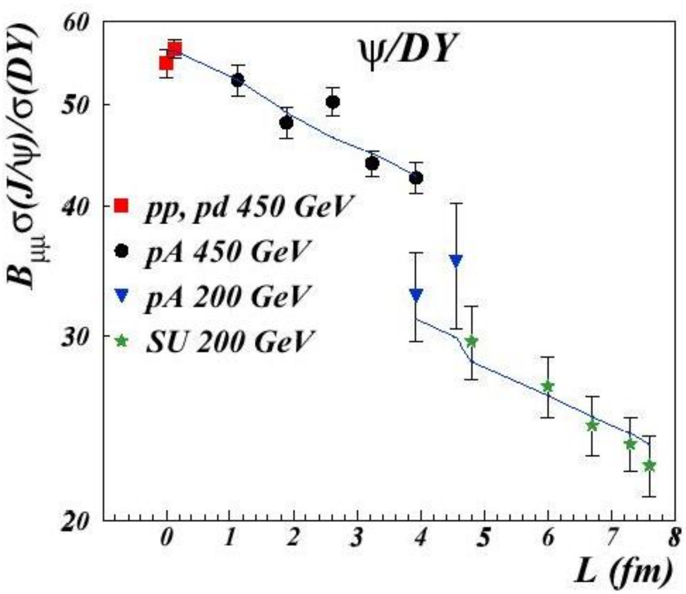
Gluon Shadowing

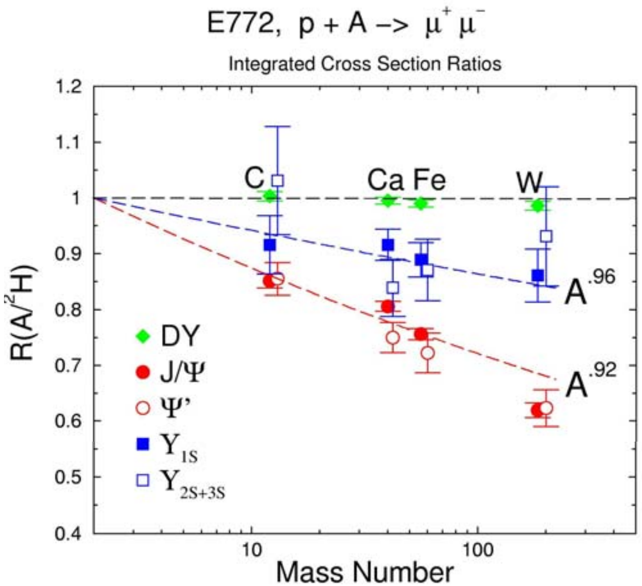
- **Shadowing** of gluons → depletion of the small x gluons
- Very low momentum fraction partons have large size, overlap with neighbors, and fuse; thus enhancing the population at higher momenta at the expense of lower momenta
- Or alternate but equivalent picture: coherent scattering resulting in destructive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

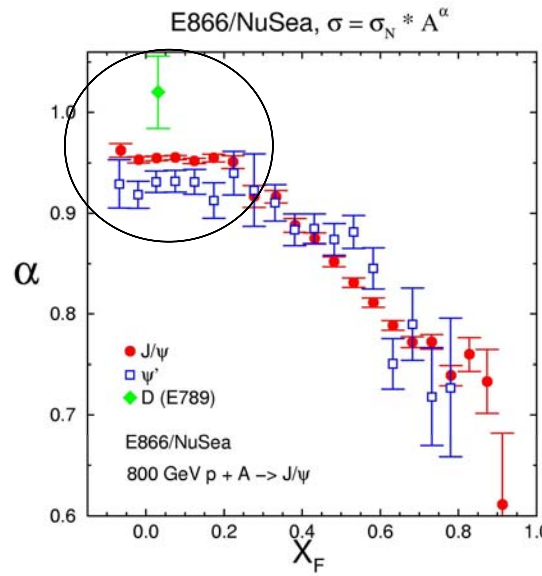




J/ψ at fixed target: Absorption at mid-rapidity





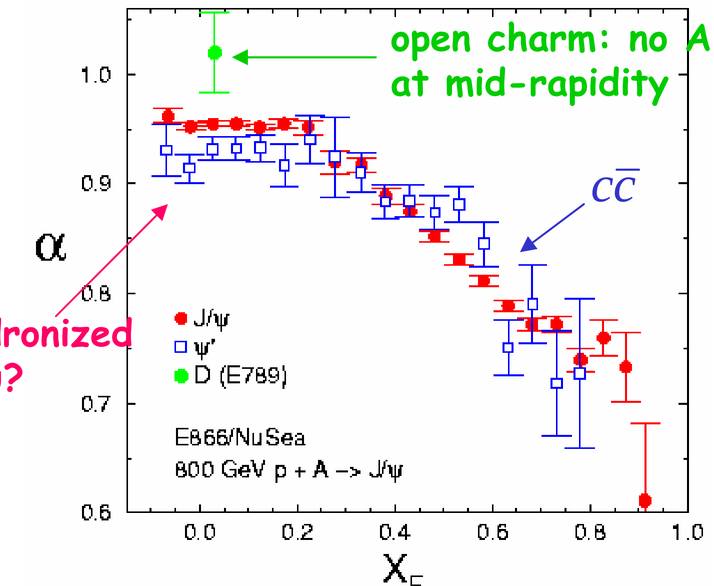


- Breakup by nucleus of J/ψ **or pre-J/ψ (cc) as it exits nucleus**
- Power law parameterization $s = s_N * A^a$
  - a = 0.92 (E772, PRL 66 (1991) 133) (limited p_T acceptance bias)
  - a = 0.919 ± 0.015 (NA38, PLB 444 (1998)516)
  - a = 0.954 ± 0.003 (E866 @ x_F=0. PRL 84 (2000),3258)
  - a = 0.941 ± 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

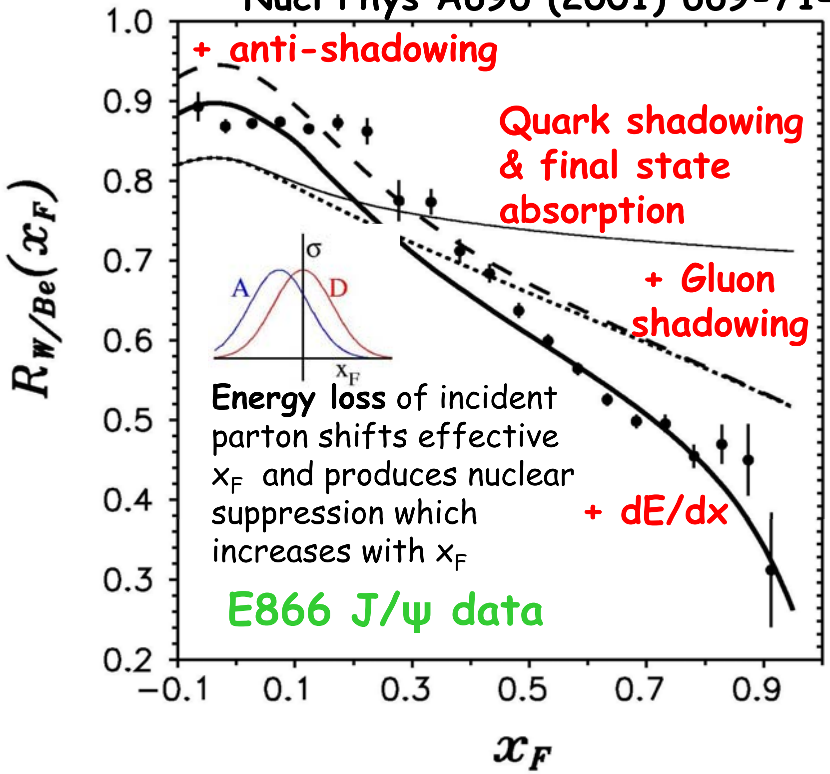
800 GeV p-A (FNAL)

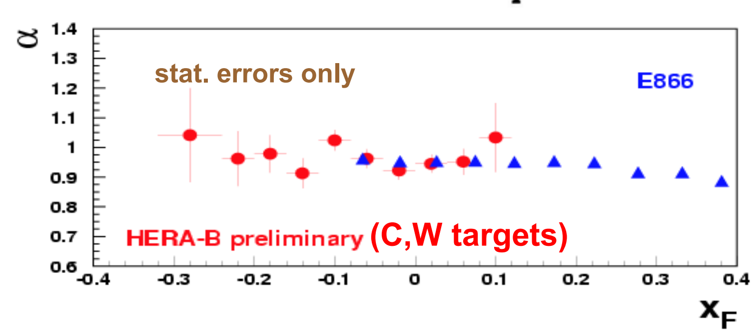
Leitch et al, PRL 84, 3256 (2000); PRL 72, 2542 (1994)



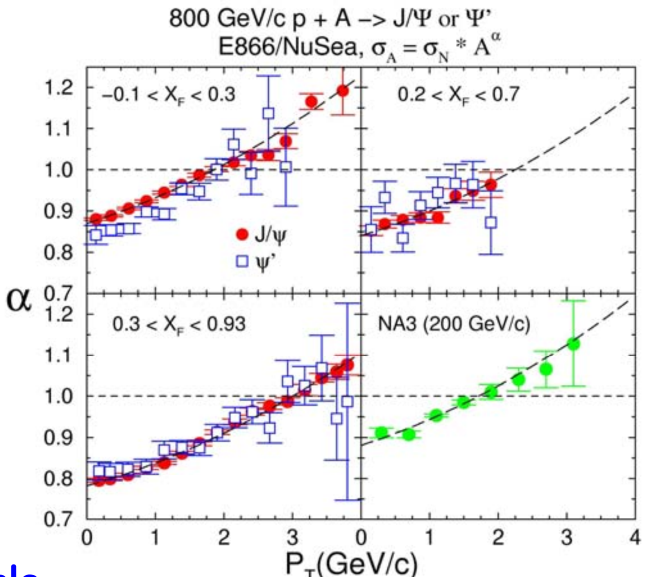
- J/Ψ and Ψ' similar at large x_F where they both correspond to a $c\bar{c}$ traversing the nucleus
- but Ψ' absorbed more strongly than J/Ψ near mid-rapidity ($x_F \sim 0$) where the resonances are beginning to be hadronized in nucleus
- open charm not suppressed at $x_F \sim 0$; what about at higher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

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

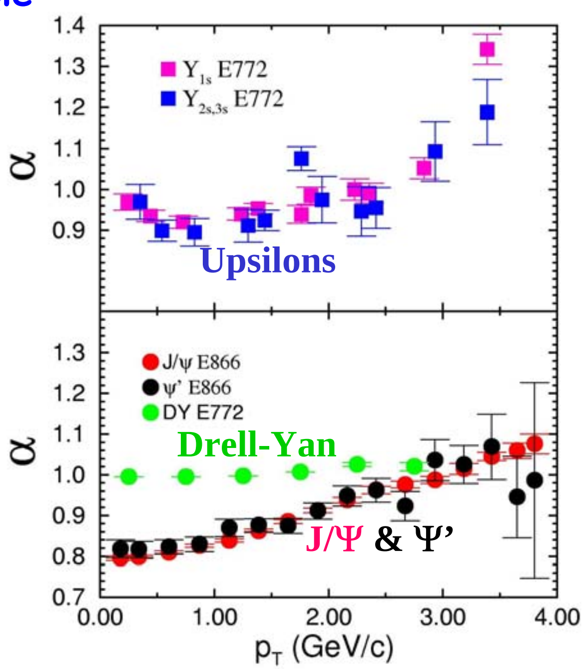


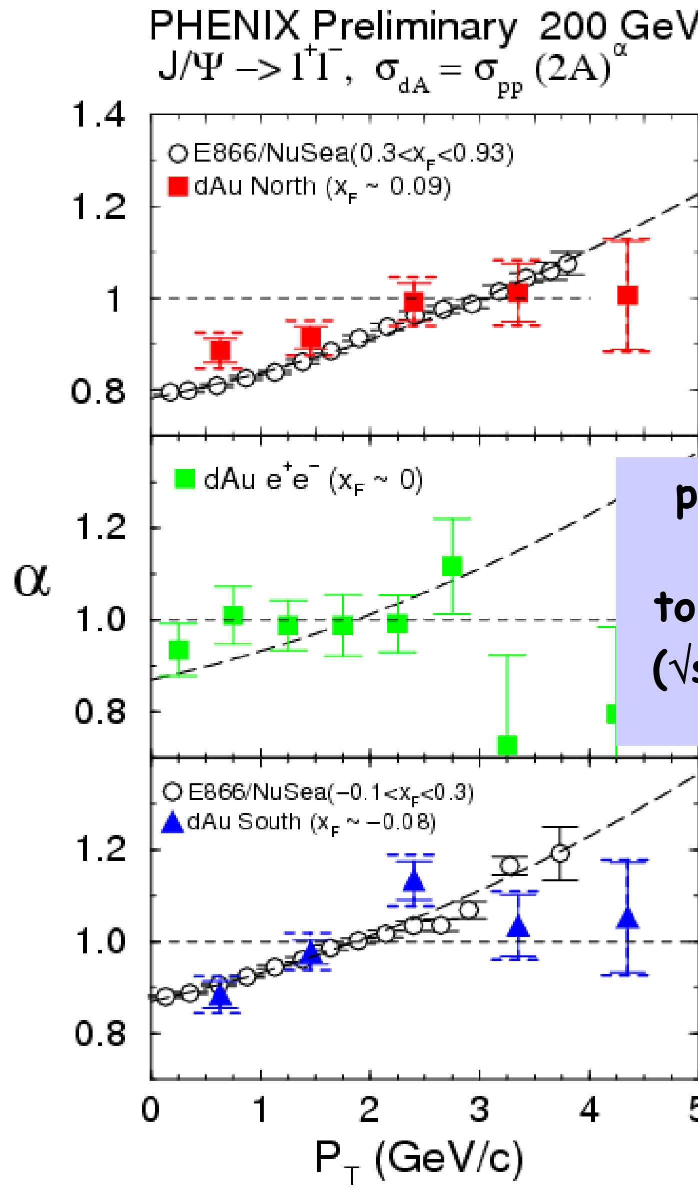


P_T Broadening for J/ψ's



Usually interpreted as initial-state multiple scattering



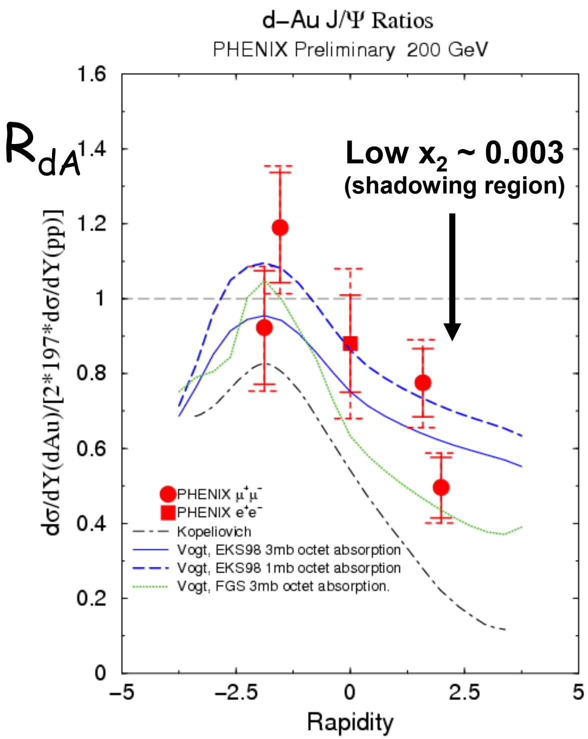


Low x_2 ~ 0.003

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

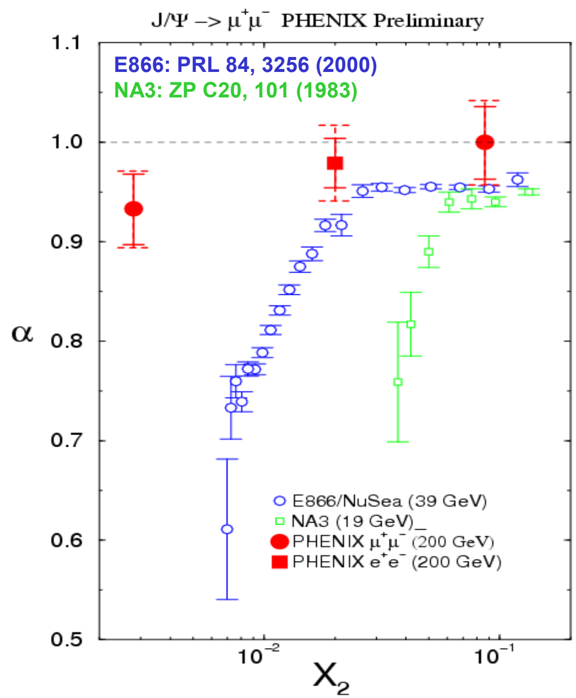
High x_2 ~ 0.09

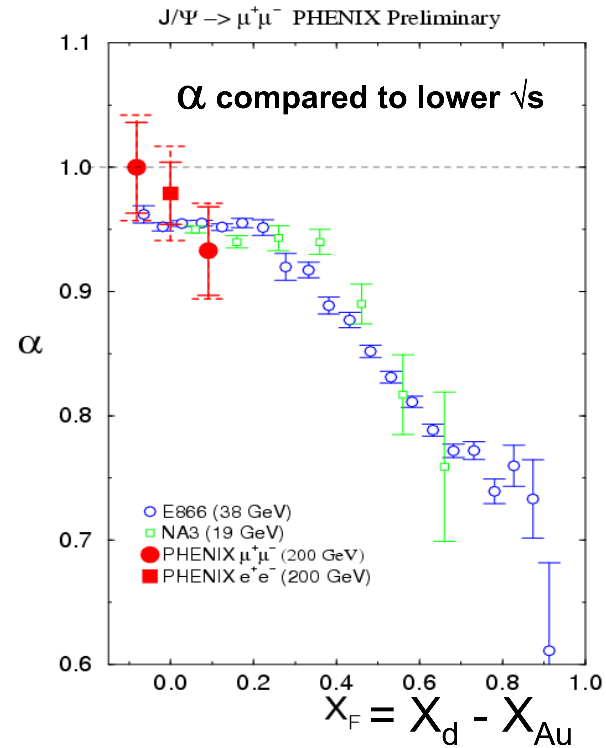
J/ψ nuclear dependence vrs rapidity & x_{Au}
PHENIX compared to lower energy measurements



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 story.

BUT does scale with x_F ! - why?

(Initial-state gluon energy loss -which goes as x1~xF - expected to be weak at RHIC energy)

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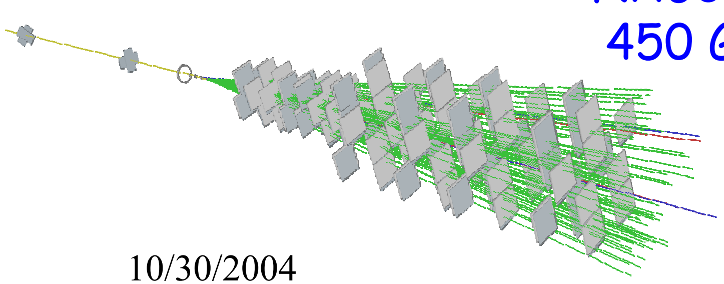
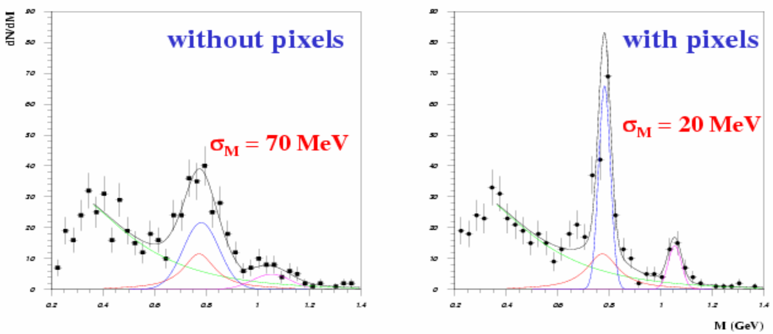
Some Critical Onia Physics Issues for NA60 to address

- Production & absorption
  - octet, singlet – absorption differences, polarization?
  - feed-down – dilution of polarization → need to de-convolute J/ψ, ψ', χ_C
  - mid-rapidity absorption is combination of physical and c-cbar states → need to understand both vrs x_F and √S
  - why J/ψ nuclear dependence scales with x_F & not with x_2?
  - why Υ_{2s+3s} polarized, but not Υ_{1s}, J/ψ? And what about ψ' polarization?
- If above is understood better, then:
  - can go after gluons and their nuclear modification (shadowing, initial-state energy loss)
  - have a firm baseline for A-A (QGP studies with onia)
- What can NA60 contribute?
  - excellent mass resolution, separation of Psi' (better for polarization since no feed-down) & add χ_C
  - high-precision, broad x_F, p_T coverage at several new √S. By comparisons with E866, Hera-B, NA3 - unravel scaling mystery, understand absorption, etc.
    - coverage up to $x_F \geq 0.5$ and $x_F < 0$ important → can be obtained by moving dimuon spectrometer back from target, and via Pb-Be collisions
  - problem – for clear physics comparisons, SPS & LHC both need pp, pA baseline at same √S as AA!

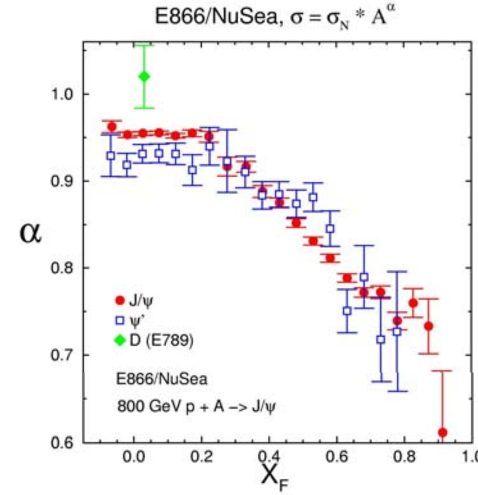


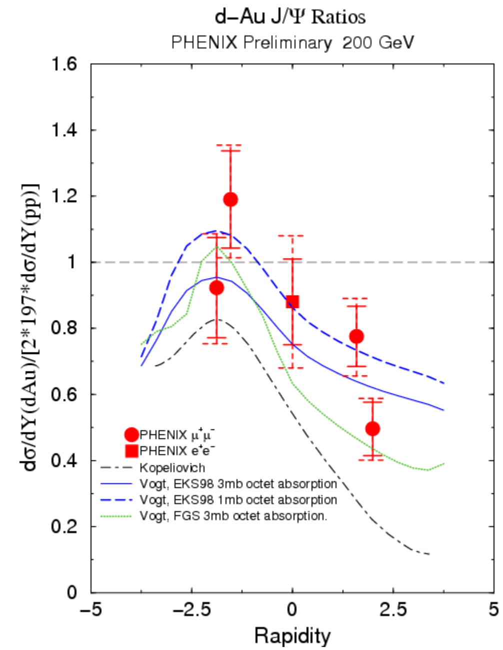
NA60 test run
450 GeV p+Be



Summary & Comments

- Progress on onia production cross sections and polarizations but still doesn't seem to be well understood
    - 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 need another dAu run
    - but scaling with x_F (and not with x_2) is still a puzzle
    - 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
    - upgrades to the RHIC detectors to allow exclusive measurements of open charm and beauty are critical for completing the physics puzzle
    - and NA60 can contribute now if priority is placed on pA (and Ap) measurements over broad ranges in x_F and p_T





Contrasting J/ψ's & Open Charm

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…

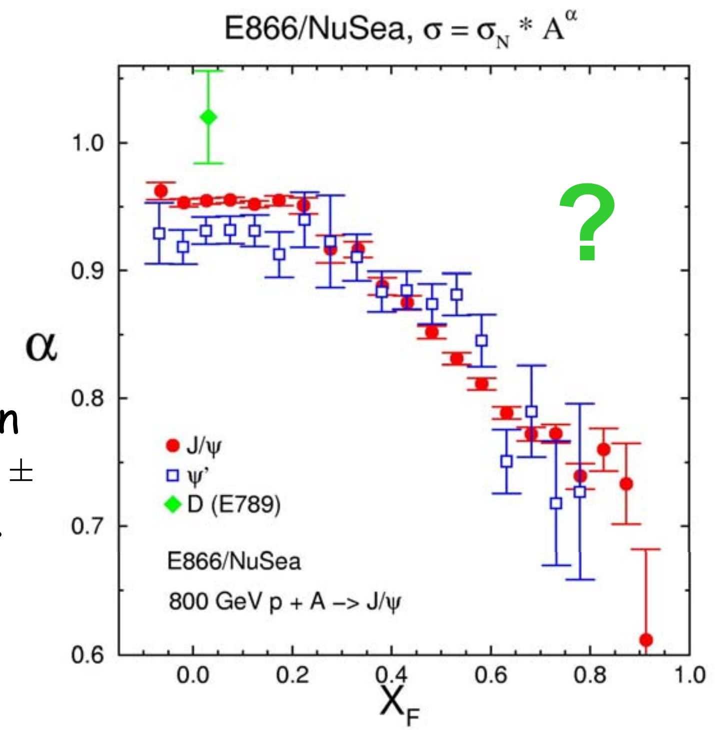
Open charm has little or no nuclear dependence in the mid-rapidity (non shadowing) region:

a = 1.00± 0.05 (E769 250GeV p+A)

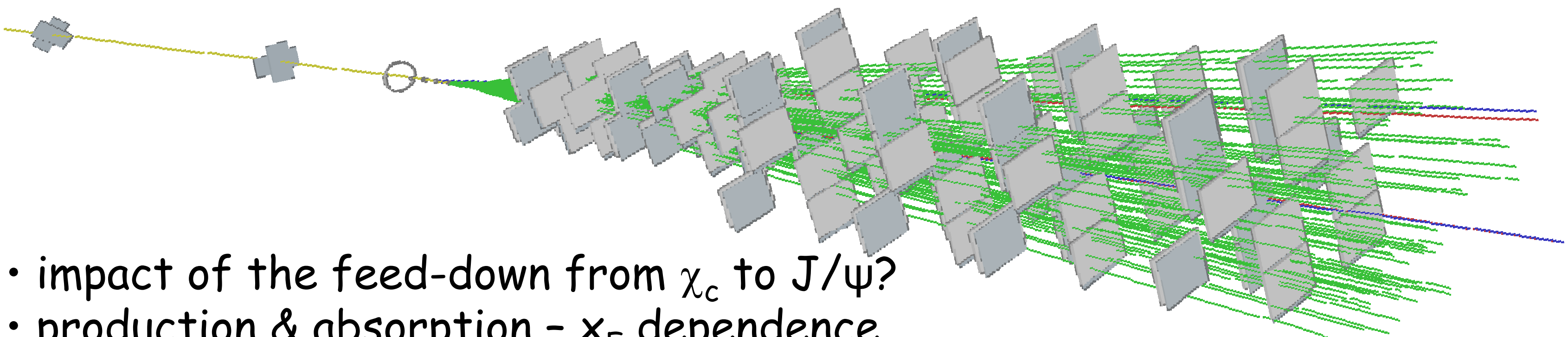
a = 0.92 ±0.06 (WA82 340GeV p+A)

a = 1.02 ±0.03 ±0.02 (E789 800GeV p+A)

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



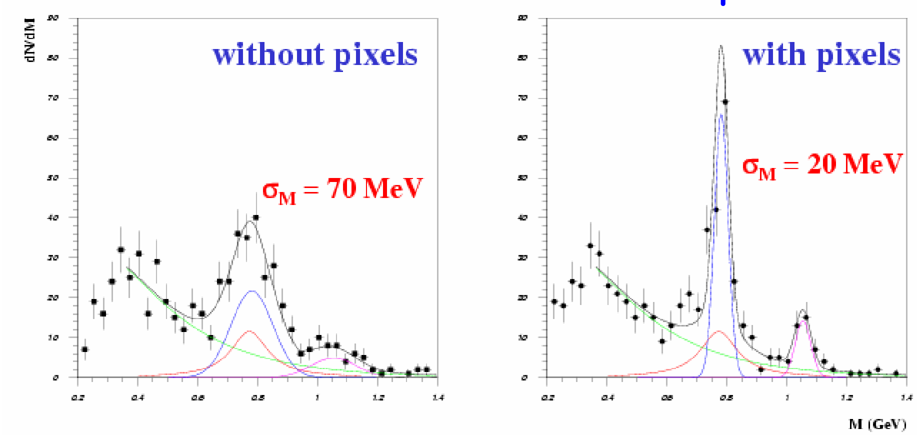
NA60: NA50 + silicon vertex



- impact of the feed-down from χ_c to J/ψ?
- production & absorption – x_F dependence and polarization
- nuclear dependence of open charm production in pA?

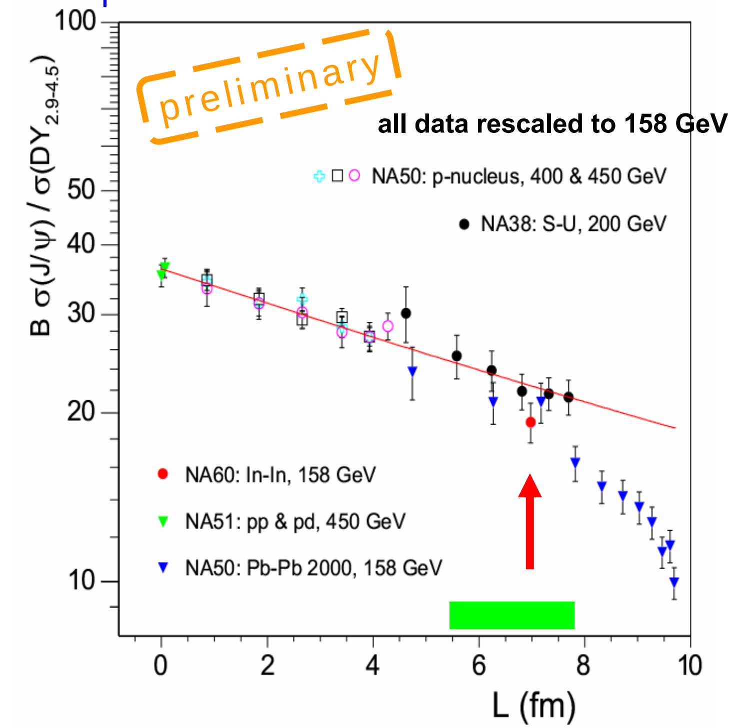
Improved J/ψ mass resolution with silicon !

NA60 test run - 450 GeV p+Be

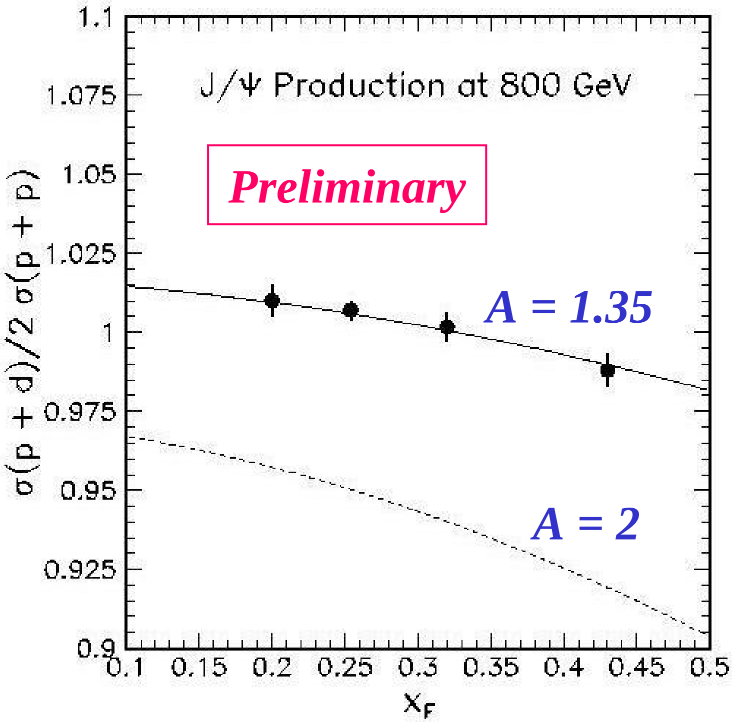


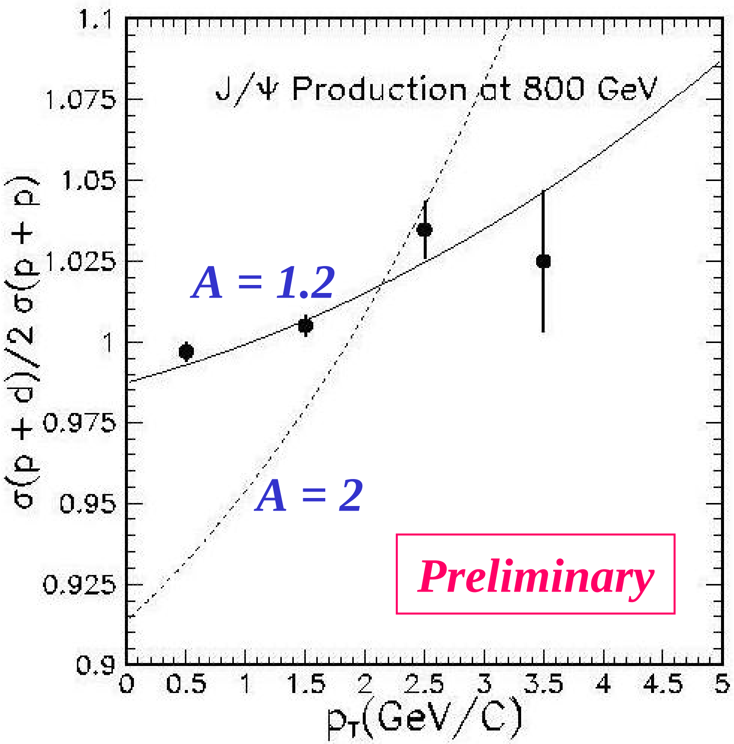
Arnaldi (NA60) Moriond 2004.

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



E866 - J/Ψ Nuclear dependence even for Deuterium/Hydrogen





Nuclear dependence in deuterium seems to follow the systematics of larger nuclei, but with an effective A smaller than two.

From fits to E866/NuSea p + Be, Fe, W data:

$$\alpha(x_F) = A*(1-.052x_F - .034x_F^2)$$
$$\alpha(p_T) = A*(1+.06p_T + .011p_T^2)$$

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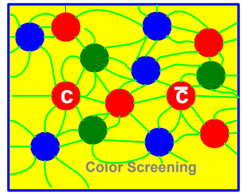
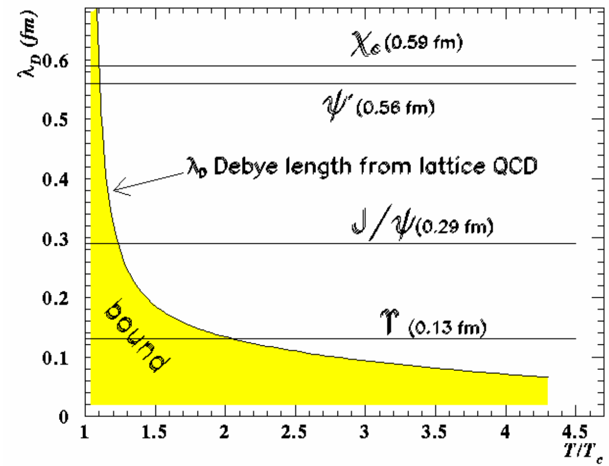
AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

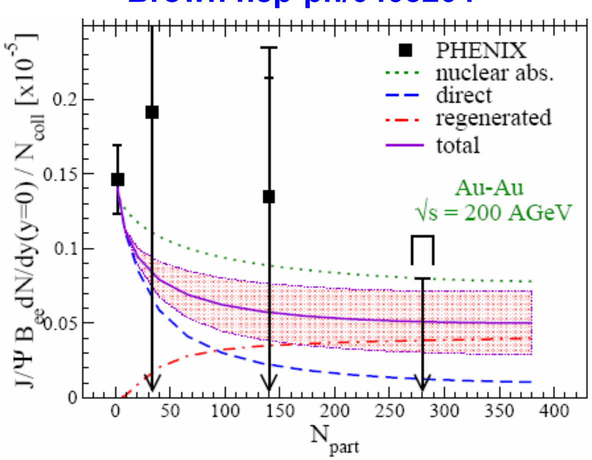
- Debye screening predicted to destroy J/ψ's in a QGP
- Different states "melt" at different temperatures due to different binding energies.
- but recent charm recombination models might instead cause an enhancement?



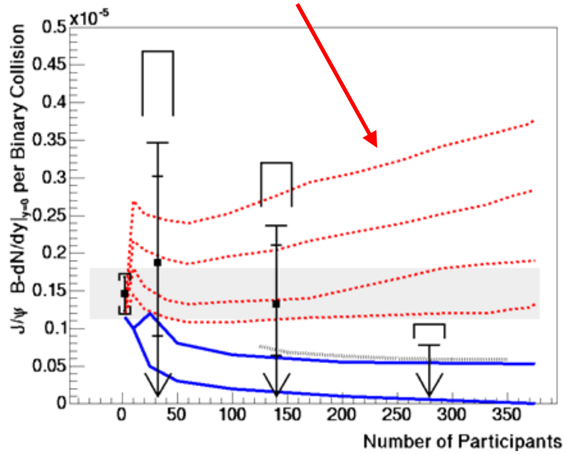


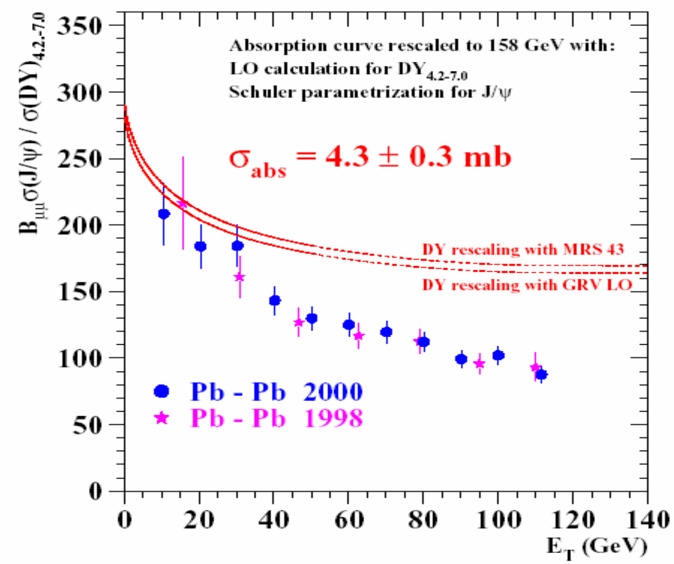
NA50

Grandchamp, Rapp, Brown hep-ph/0403204



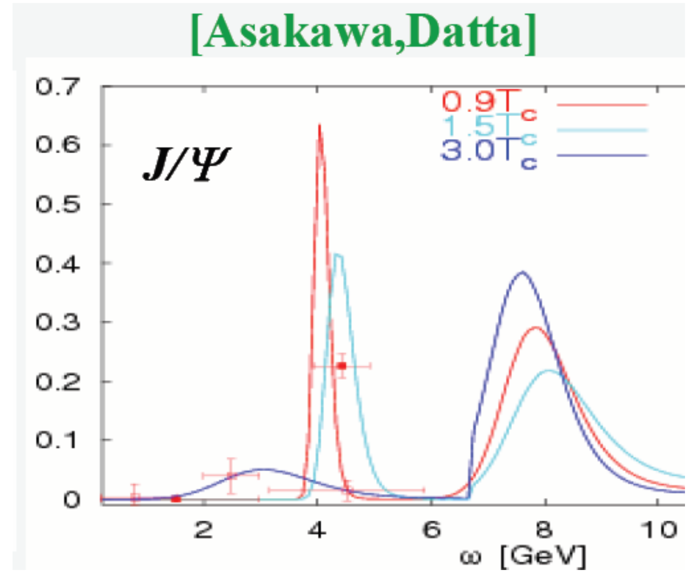
R. L. Thews, M. Schroedter, J. Rafelski, Phys Rev C 63, 05490!





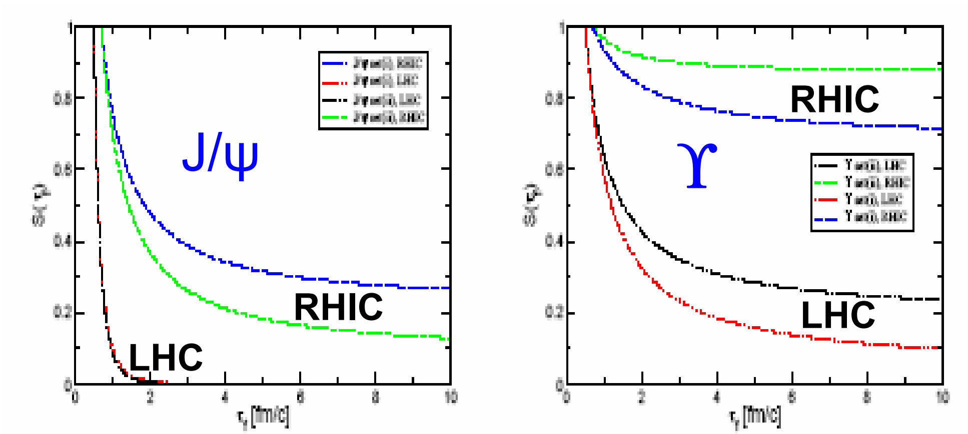
J/ψ ($c\bar{c}$) disassociation in hot-dense medium

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



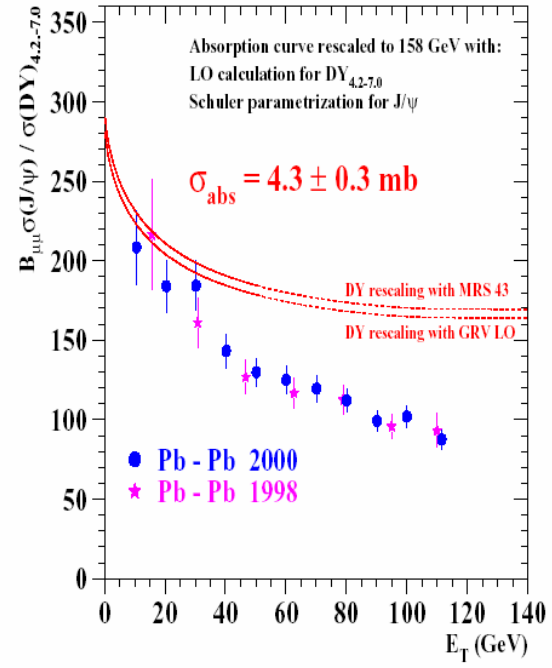
Disassocation of J/ψ by higher momentum gluon field in a deconfined medium:

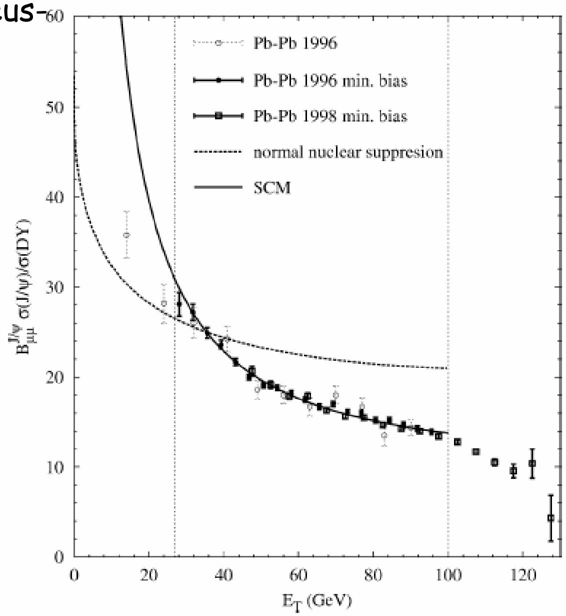
Survival probability of onium in expanding gluon plasma vrs plasma lifetime –(Blaschke et al. hep-ph/0311048)
(two different assumptions about binding energy and heavy quark masses)



J/ψ Suppression in Pb-Pb at NA50

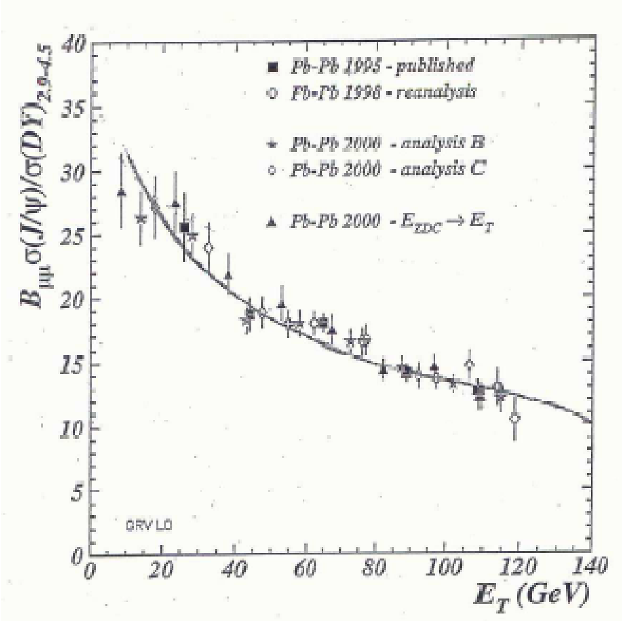
H. Santos, QM04, "Psi' production in nucleus-nucleus collisions at the CERN/SPS".





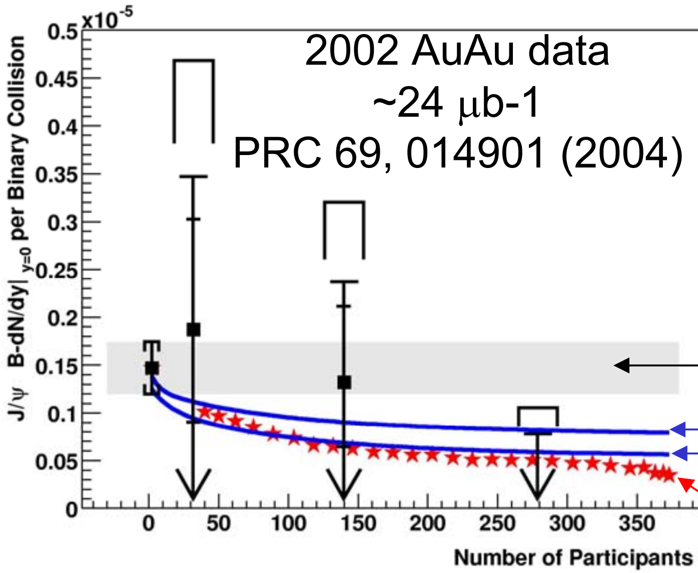
A.P.Kostyuk, M.I. Gorenstein, H. Stocker, W. Greiner, Phys. Lett B 531, 195-202

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

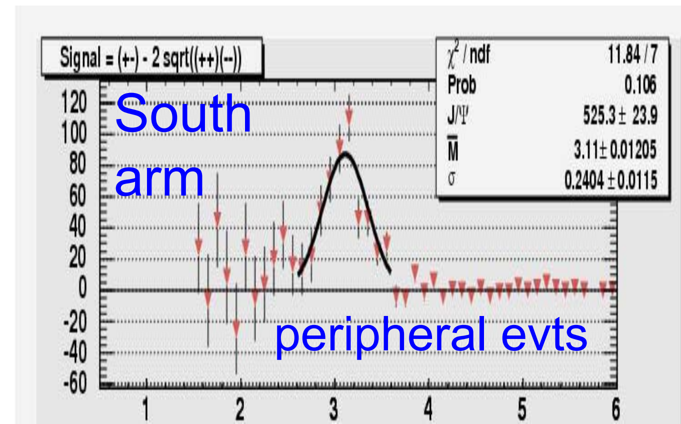


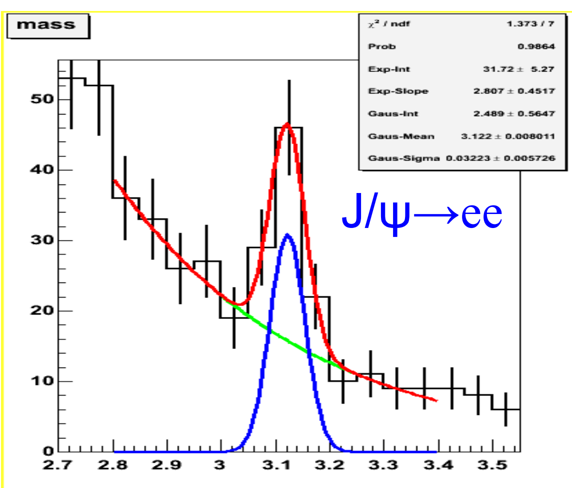
- Suppression with respect to normal nuclear suppression expectations
- Theorists have produced various alternative models which also reproduce data:
  - Statistical coalescence model (also needs enhanced open charm)
  - Comovers
- RHIC data on J/ψ highly desired to give another data point(s) to compare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

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



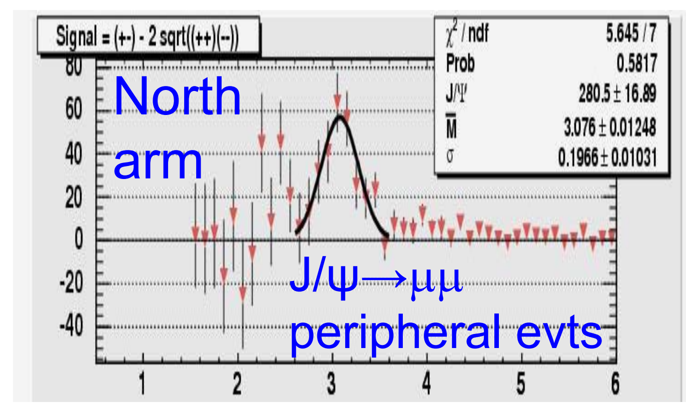
Can not discriminate between scenarios, given our present statistical accuracy



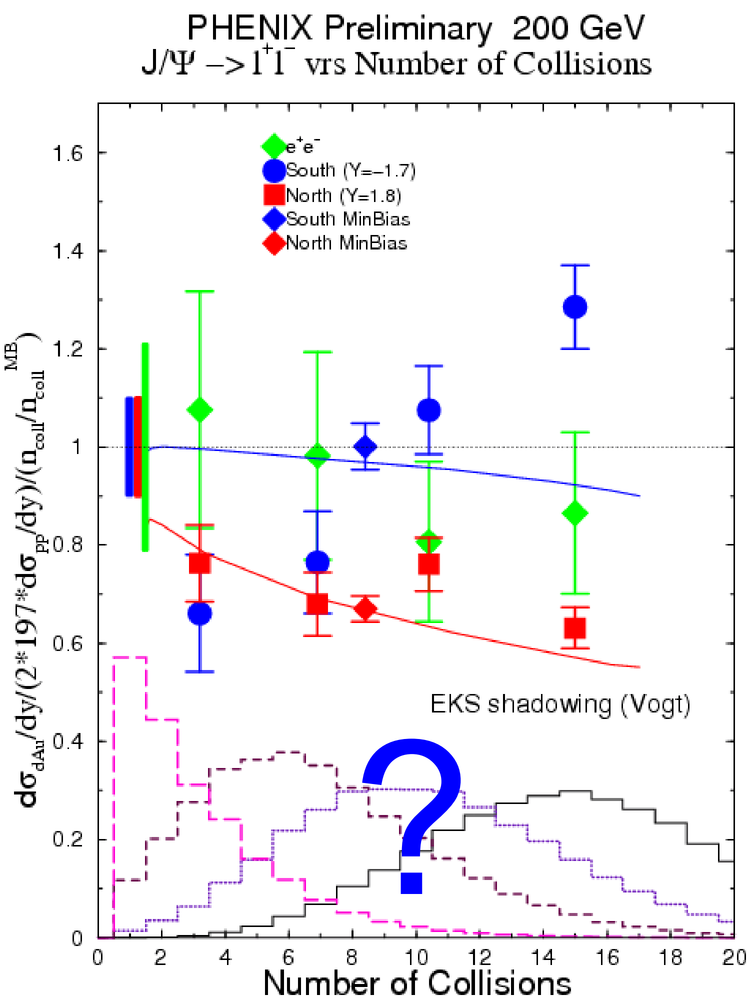


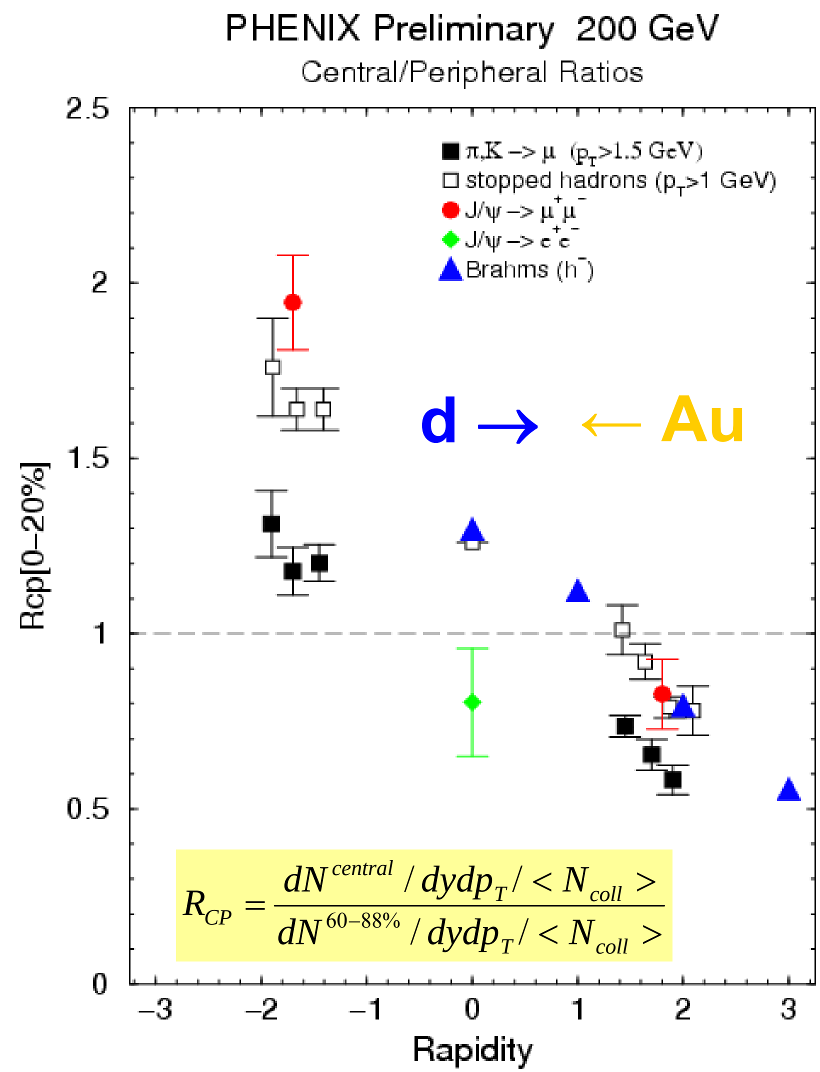
2004 AuAu data
~240 μb^{-1}

Clear J/ψ signal in both central and muon arms from a small fraction of analyzed filtered data.



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).

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

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

$\Rightarrow$ $J/\psi c\bar{c}$ 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.

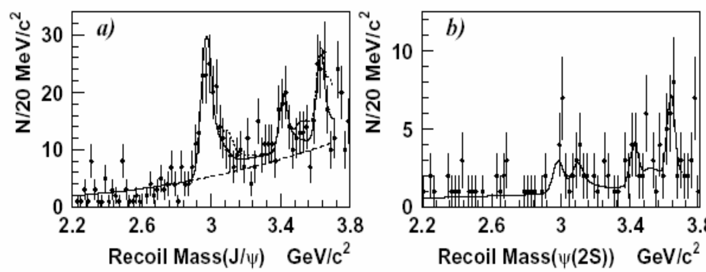
- PRL **89**, 142001 (2002) with 46.2/fb
- LP03-274 (BELLE-CONF-0331) with 101.8/fb

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 :
  η_c, J/ψ, χ_{c0}, χ_{c1}, χ_{c2}, $\eta_c(2S)$, $\psi(2S)$
- Masses of η_c, χ_{c0}, $\eta_c(2S)$ free

Beauty 2003 – p.2/25

Double charmonium production

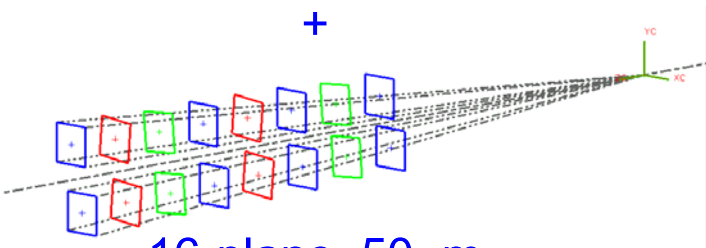


$(c\bar{c})_{res}$	N (evts)	M [GeV/c^2]	σ	N (evts)	σ
η_c	175 ± 23	2.972 ± 0.007	9.9	15 ± 7	2.6
J/ψ	-9 ± 17	fixed	–	12 ± 7	–
χ_{c0}	61 ± 21	3.409 ± 0.010	2.9	18 ± 9	2.4
$\chi_{c1} + \chi_{c2}$	-15 ± 19	fixed	–	7 ± 9	–
$\eta_c(2S)$	107 ± 24	3.630 ± 0.008	4.4	31 ± 10	3.7
$\psi(2S)$	-38 ± 21	fixed	–	-4 ±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

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

Dimuon spectrometer

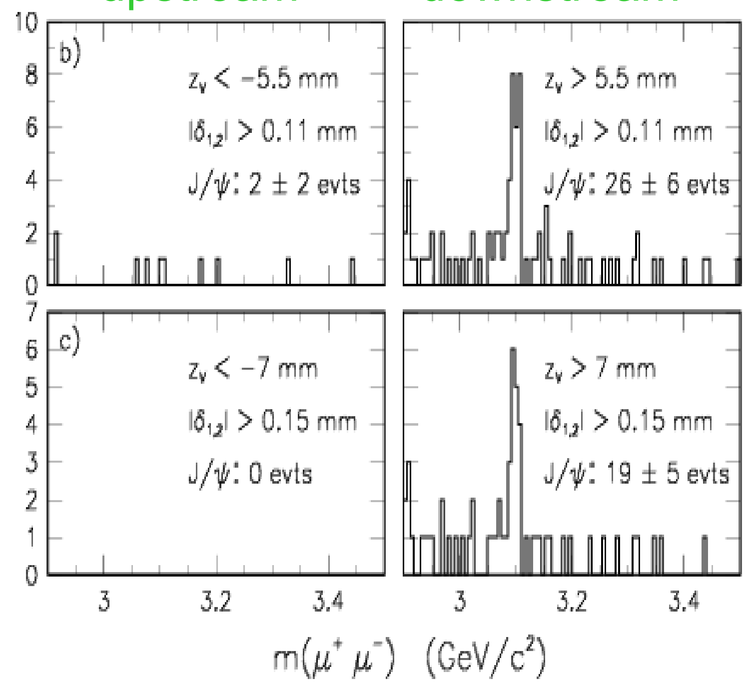
\+

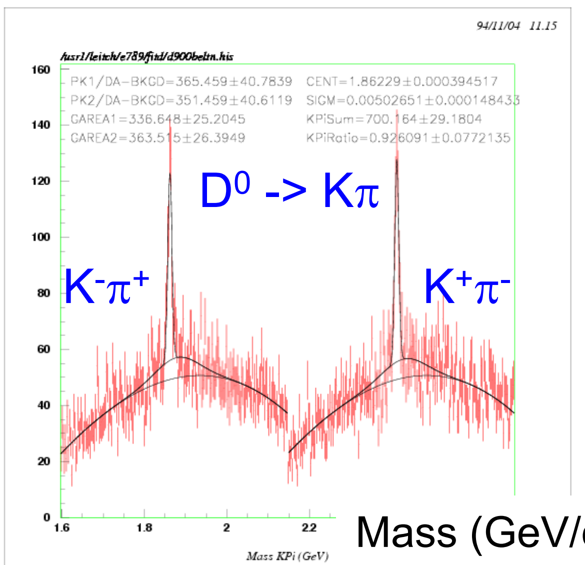


16-plane, 50μm pitch/8.5k strip silicon vertex detector

B -> J/ψ + X

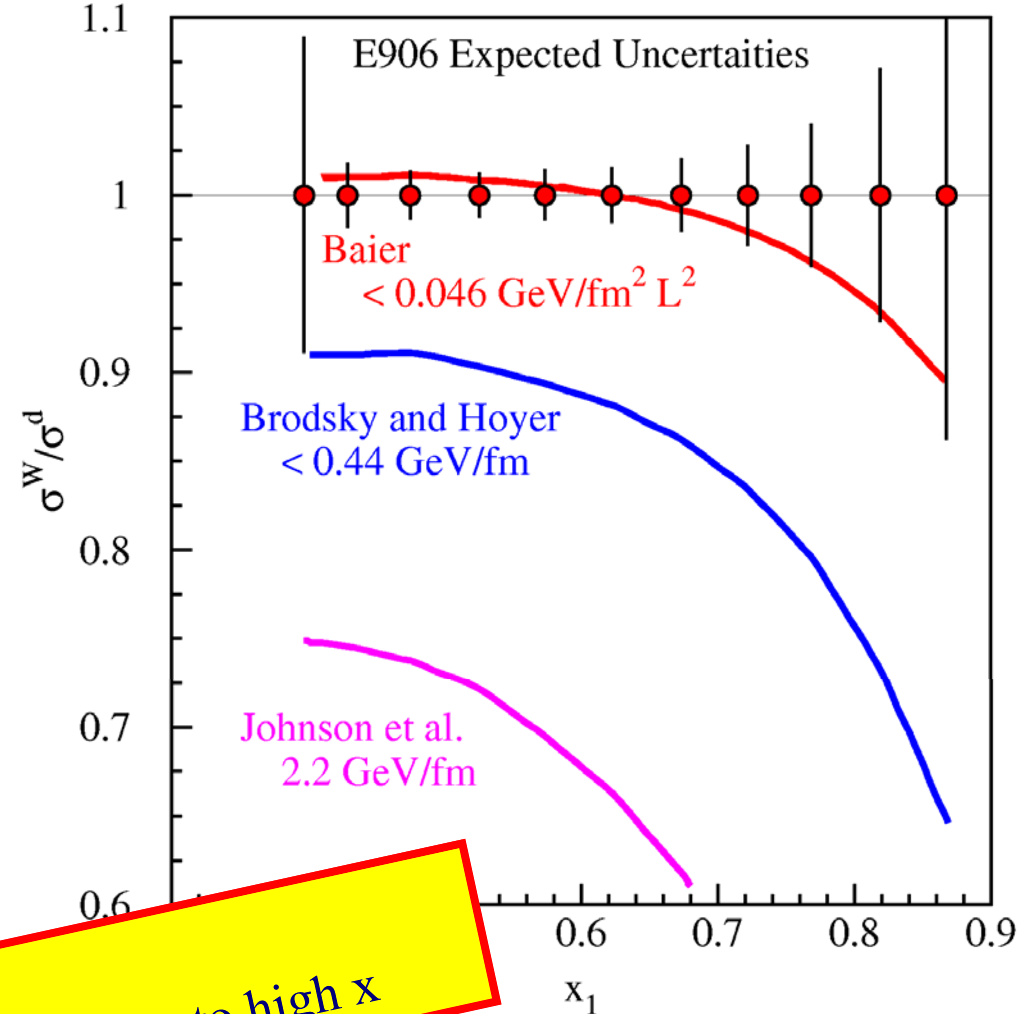
upstream downstream





Mass (GeV/c^2)

Parton Energy Loss



- Colored parton moving in strongly interacting media.
- Only initial state interactions are important—*no final state strong interactions*.
- *E866 Data are consistent wit*
- Treatment of pa … shadowing are critical
  Johnson e
- Energy loss … larger at 120 GeV
- Important to understand RHIC data.

Fermilab E906 will:
- Measure parton energy loss up to high x