Quarkonia Production in p-A Collisions

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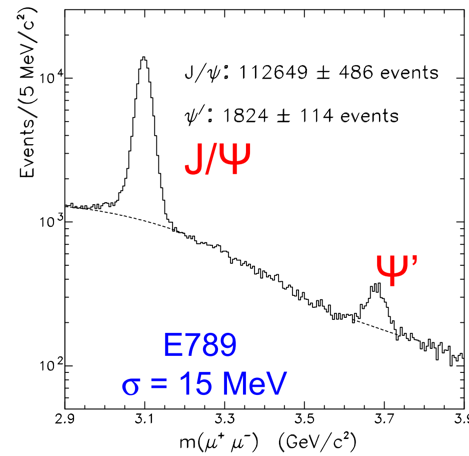
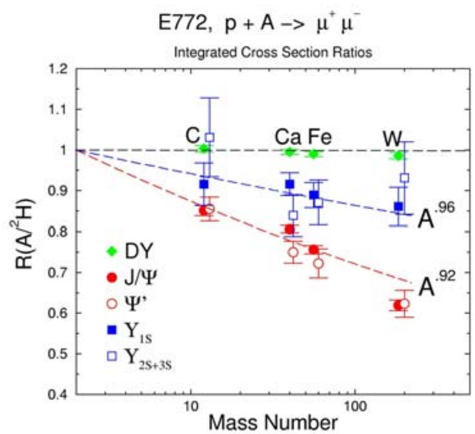
- production
  - mechanisms
  - cross section & polarization
  - complications
- nuclear effects
  - shadowing
  - p_T broadening
  - absorption
  - parton energy loss
  - contrasting open & closed charm
- summary





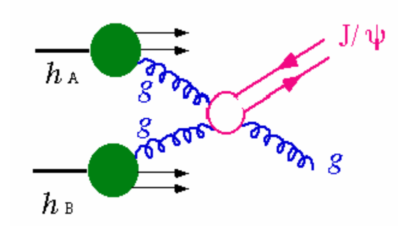
J/ψ & open-charm production, parton level structure & dynamics

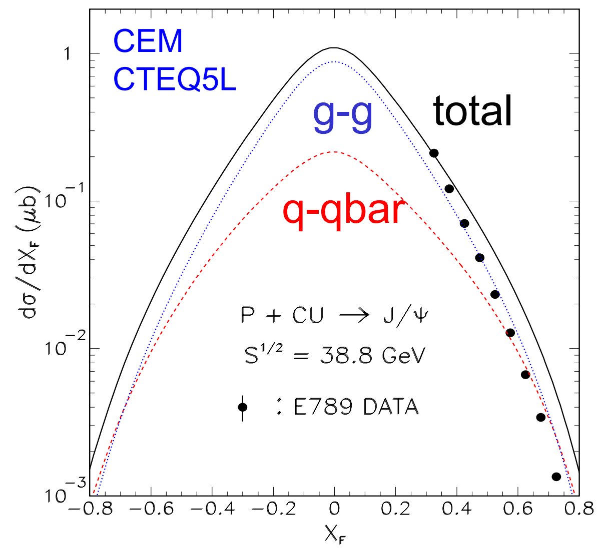
Production of heavy vector mesons, e.g. J/Ψ,Ψ' and ϒ

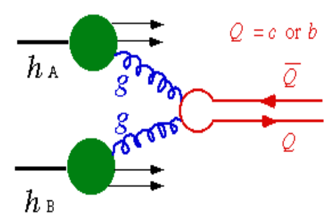
- gluon fusion dominates (NLO calculations add more complicated diagrams but still mostly with gluons)
- production: color singlet or octet $c\bar{c}$: absolute cross section and polarization?
- hadronization time (important for pA nuclear effects)
- complications due to substantial feed-down from higher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







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

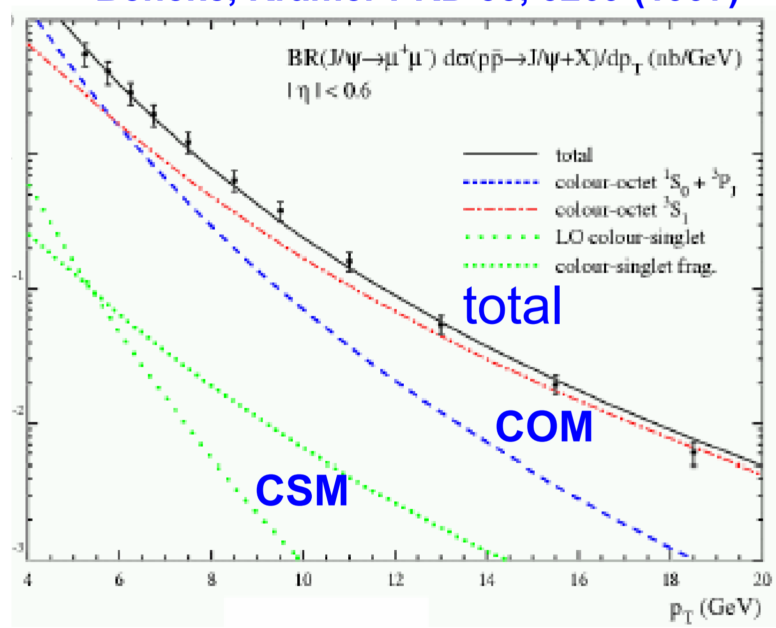
Color-octet model (COM)

- 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)

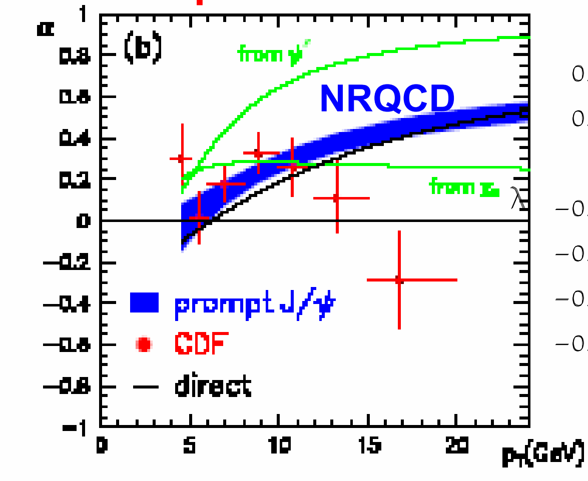


CDF Data first uncovered short-comings of CSM

J/ψ Production—Polarization

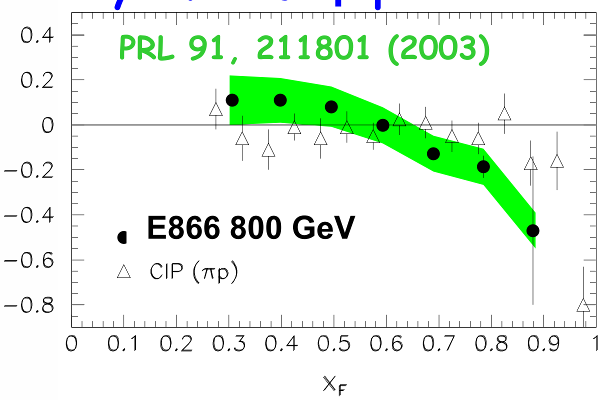
Color Octet Model predicts J/ψ polarization at large p_T - NOT SEEN in data

J/ψ Polarization

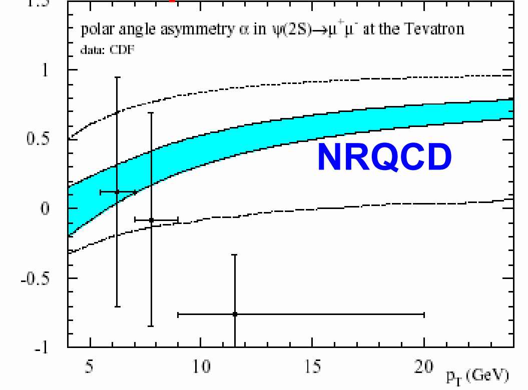


E866

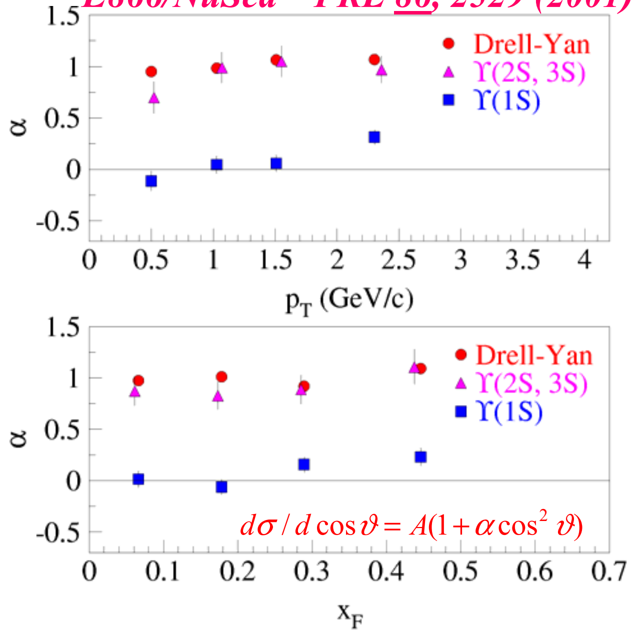
very small J/ψ polarization



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? (~50% of 1S from feed-down)
- NRQCD predicts $0.25 < \lambda < 0.7$ (feed-down from χ states included).

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

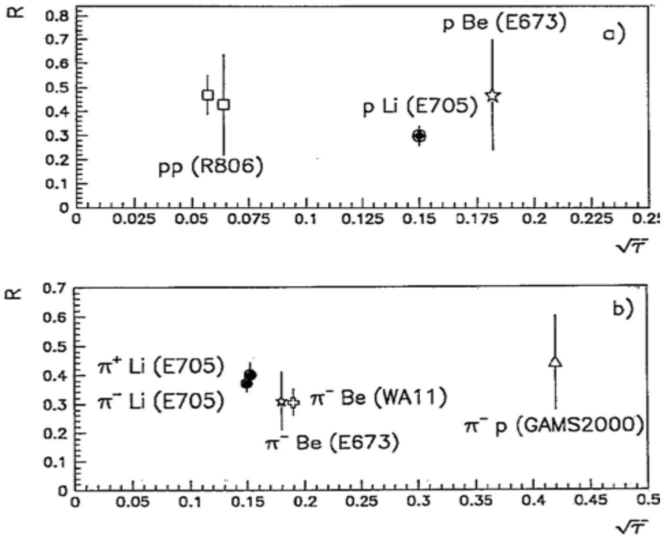
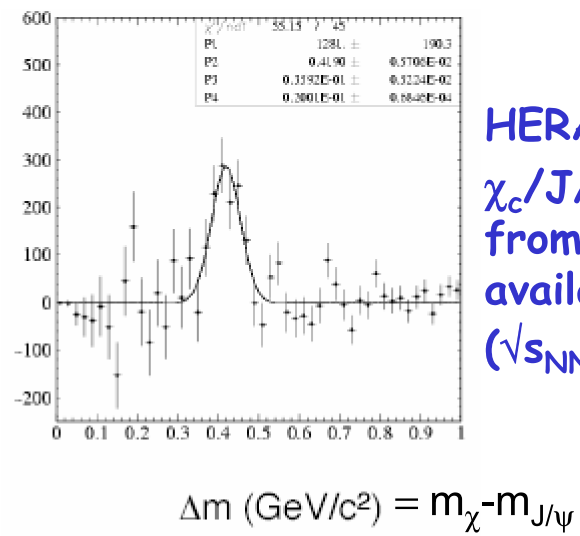


FIG. 3. Fraction of J/ψ produced via radiative χ in 300 GeV/c (a) proton and (b) $\pi^{\pm}$ ^{7}Li interactions.

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

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

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



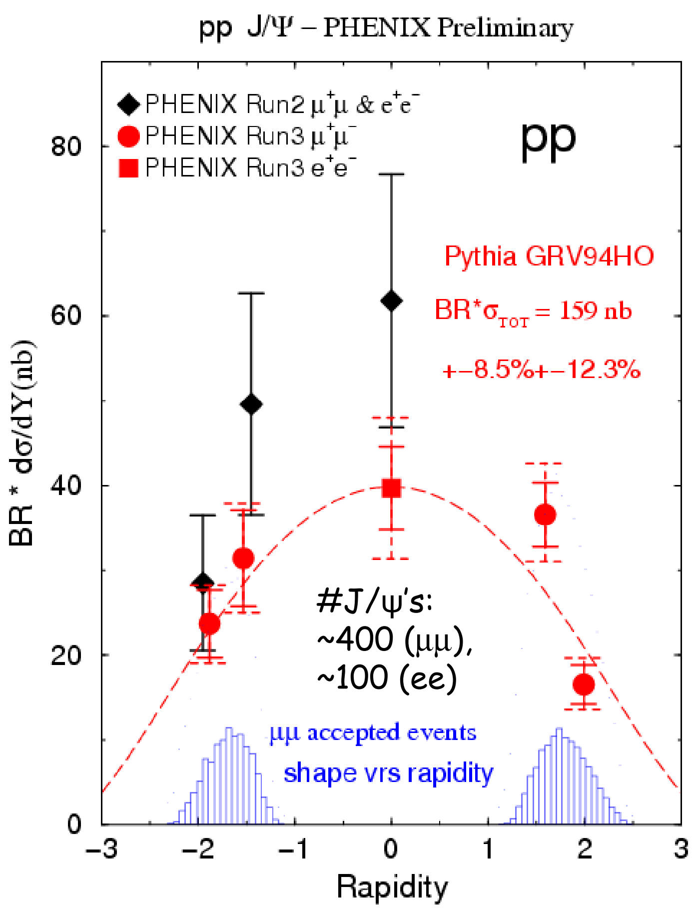
HERA-B

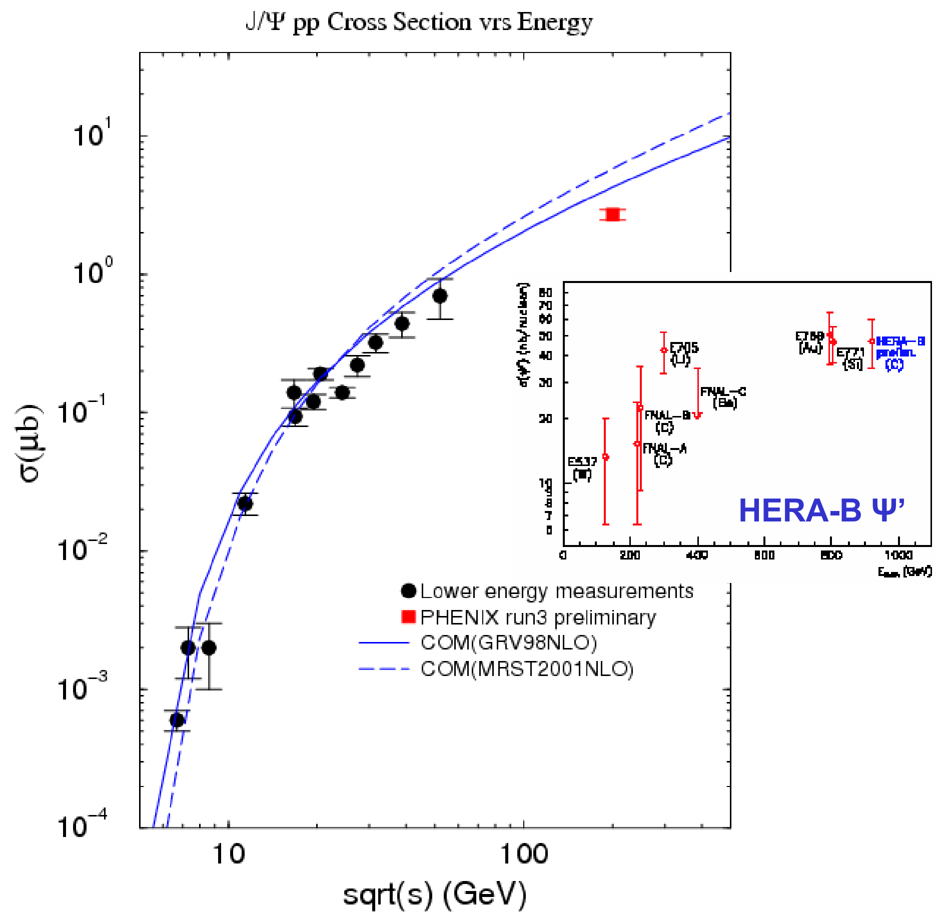
$\chi_c/J/\psi$ = 0.21±0.05 from 15% of available statistics ($\sqrt{s_{NN}}$ = 42 GeV)

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 ~21-30% 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

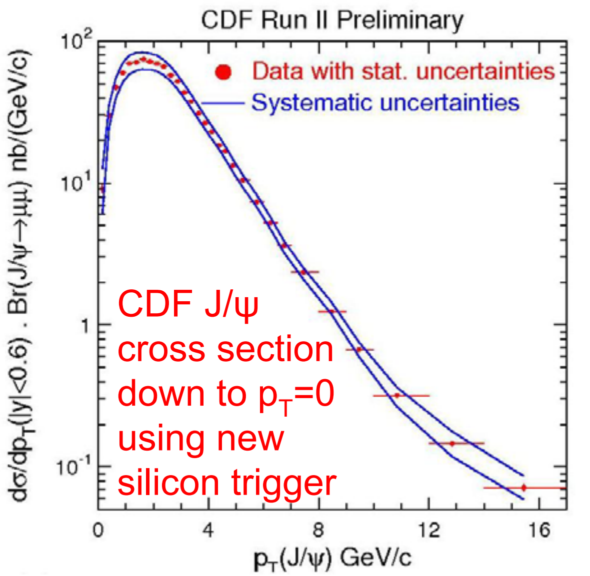


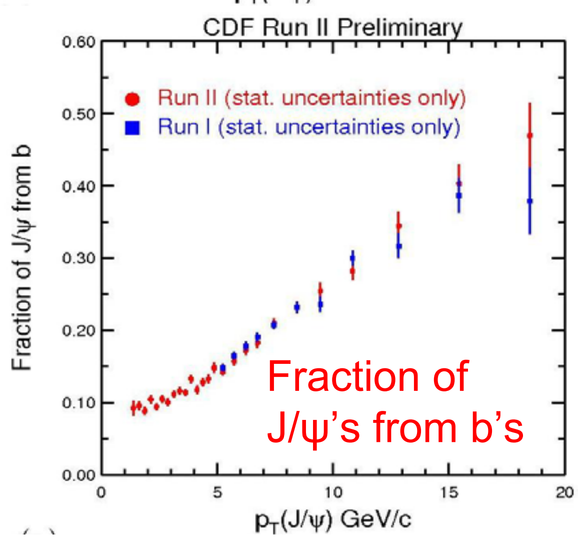


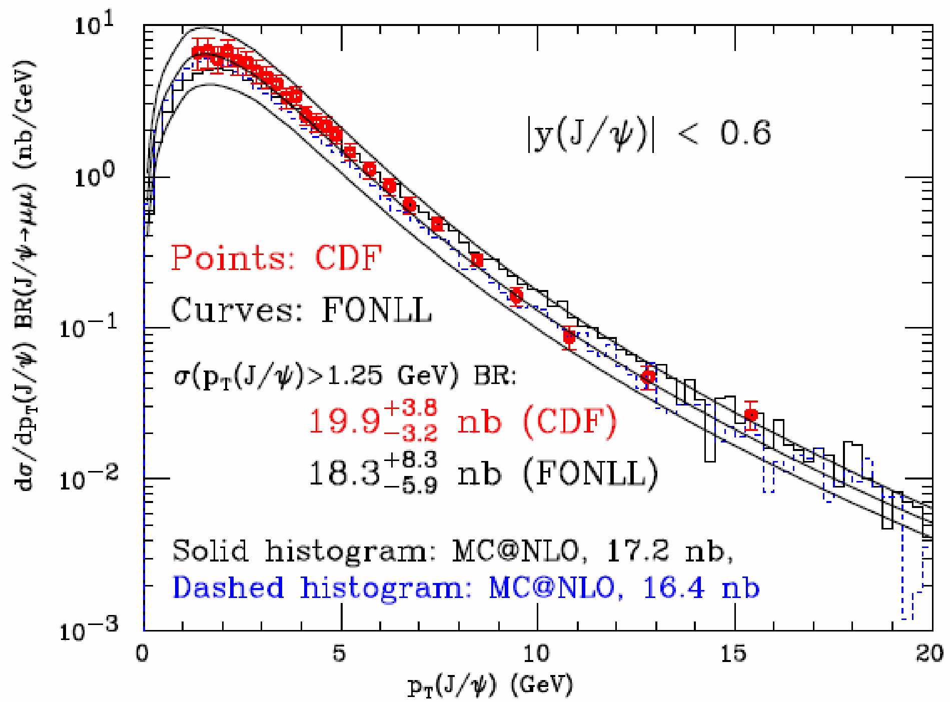
More pp J/ψ's coming from PHENIX 2004 run (~300/muon arm) + many more expected in 2005

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

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







Current NLO QCD calculations can 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

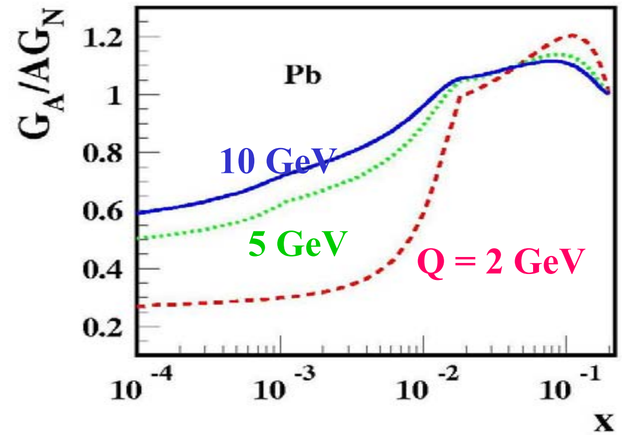
Modification of parton momentum distributions of nucleons embedded in nuclei

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

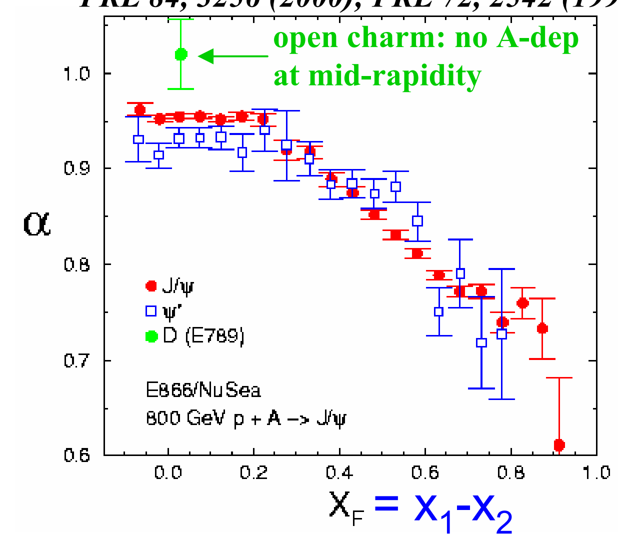
Nuclear effects on parton "dynamics"

- 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)



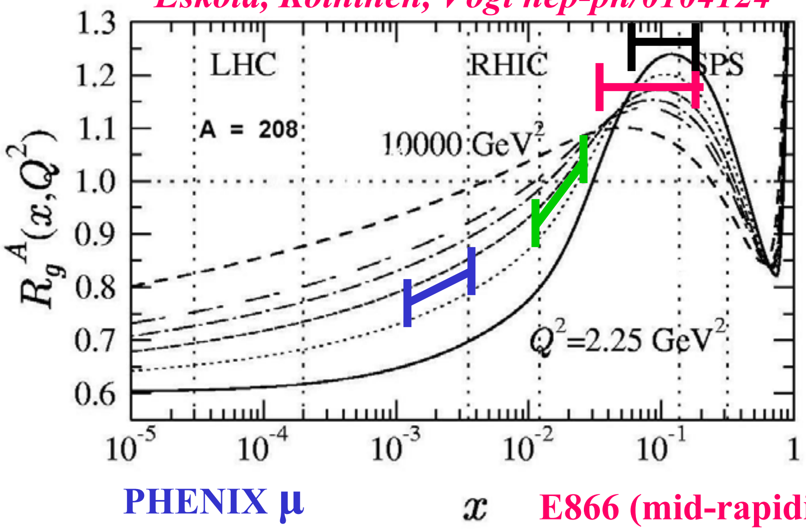
800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$
PRL 84, 3256 (2000); PRL 72, 2542 (1994)



Gluon Shadowing

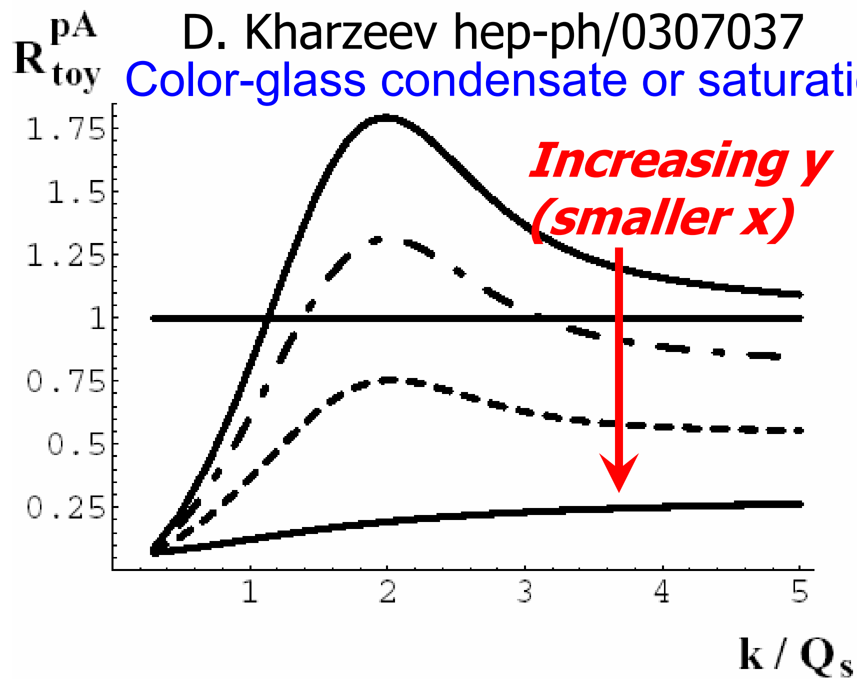
- **Shadowing** of gluons → depletion of the small x gluons
- Very low momentum fraction partons have large size & number density, overlap with neighbors, and fuse; thus enhancing the population at higher momenta at the expense of lower momenta
- Or alternate but equivalent picture: coherent scattering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

Eskola, Kolhinen, Vogt hep-ph/0104124

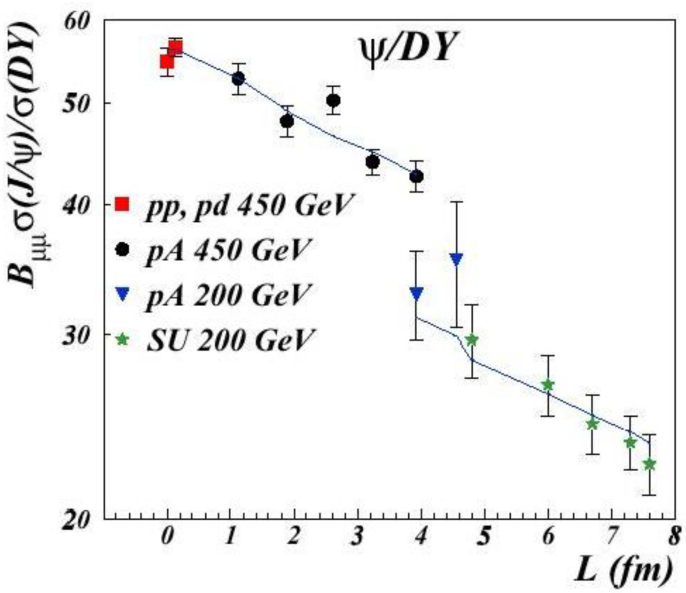


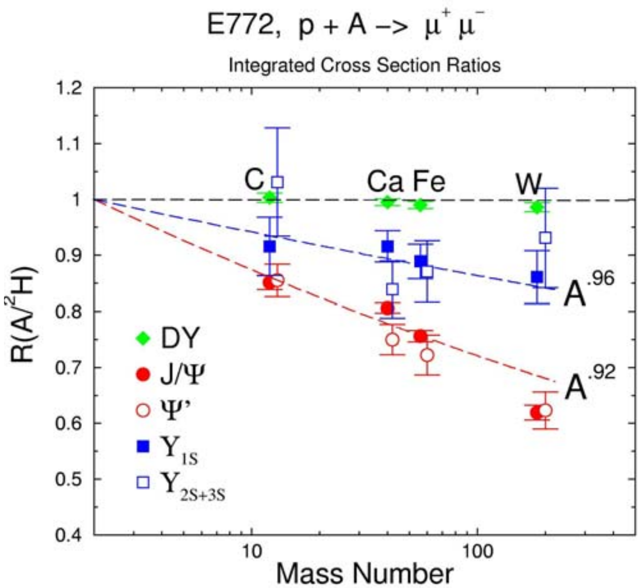
PHENIX μ
PHENIX e
E866 (mid-rapidity)
NA50

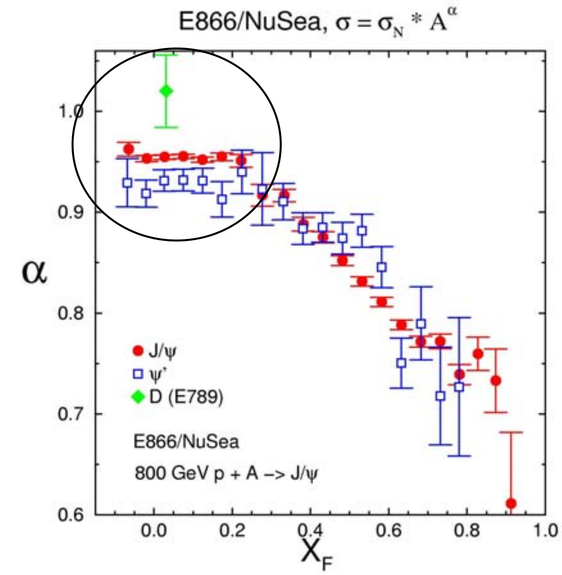
D. Kharzeev hep-ph/0307037
Color-glass condensate or saturation



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



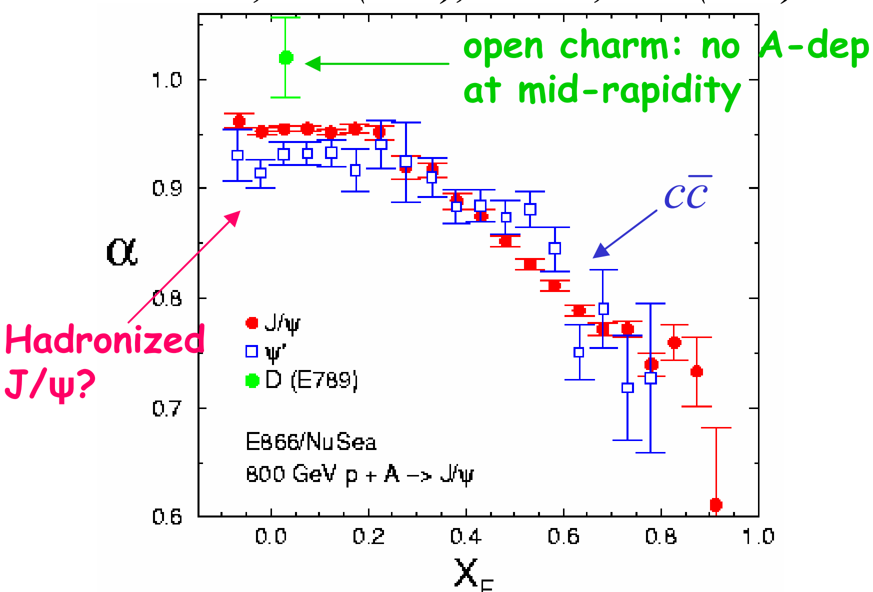




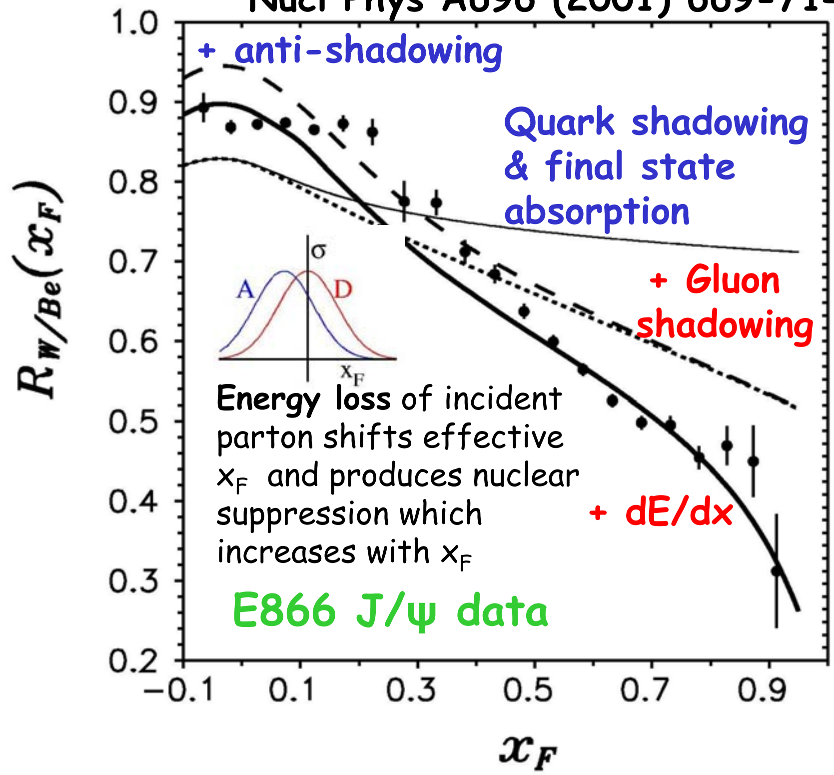
- Breakup by nucleus of J/**ψ or pre-J/ψ (ccbar) as it exits nucleus**
- Power law parameterization $\sigma = \sigma_N * A^\alpha$
  - $\alpha = 0.92$ (E772, PRL <u>66</u> (1991) 133) (limited p_T acceptance bias)
  - $\alpha = 0.919 \pm 0.015$ (NA38, PLB <u>444</u> (1998)516)
  - $\alpha = 0.954 \pm 0.003$ (E866 @ x_F=0. PRL <u>84</u> (2000),3258)
  - $\alpha = 0.941 \pm 0.004$ (NA50, QM2004)
- Absorption model parameterization
  - σ = 6.2 mb (NA38/50/51) to 4.3 ± 0.3 mb (NA50, QM2004)
- Small difference between J/ψ and ψ(2S) (E866)
  - $\alpha(J/\psi) - \alpha(\psi(2S))$ ~ 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

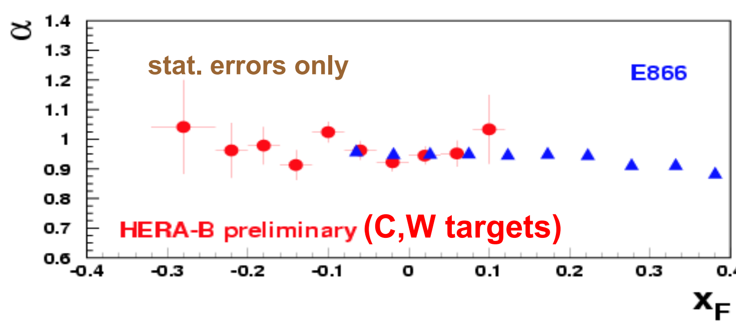
800 GeV p-A (FNAL)
PRL 84, 3256 (2000); PRL 72, 2542 (1994)



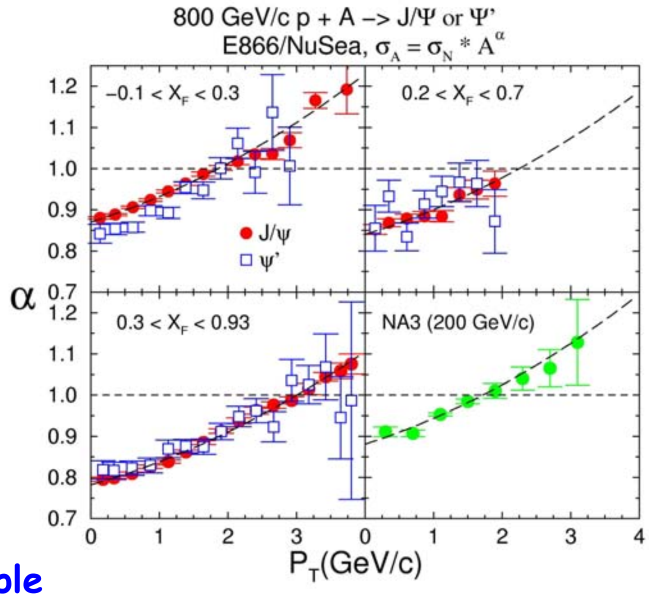
Kopeliovich, Tarasov, Hufner
Nucl Phys A696 (2001) 669-714



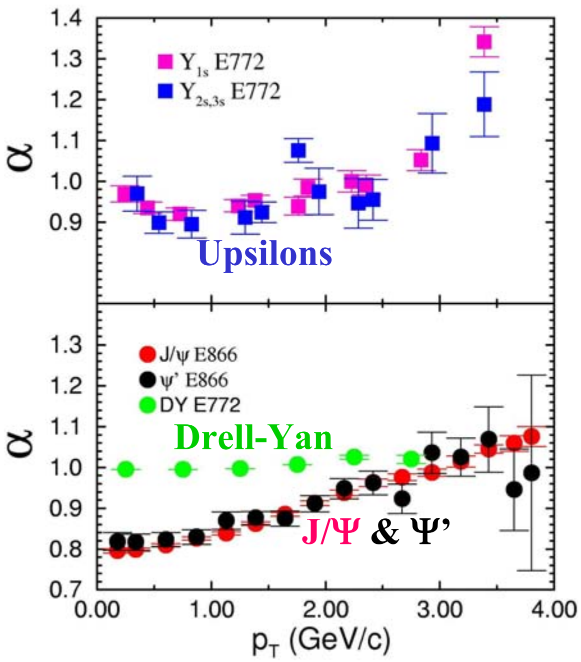
- J/Ψ and Ψ' similar at large x_F where they both correspond to a $c\bar{c}$ traversing the nucleus
- but Ψ' absorbed more strongly than J/Ψ near mid-rapidity (x_F ~ 0) where the resonances are beginning to be hadronized in nucleus
- open charm not suppressed at x_F ~ 0; what about at higher x_F?

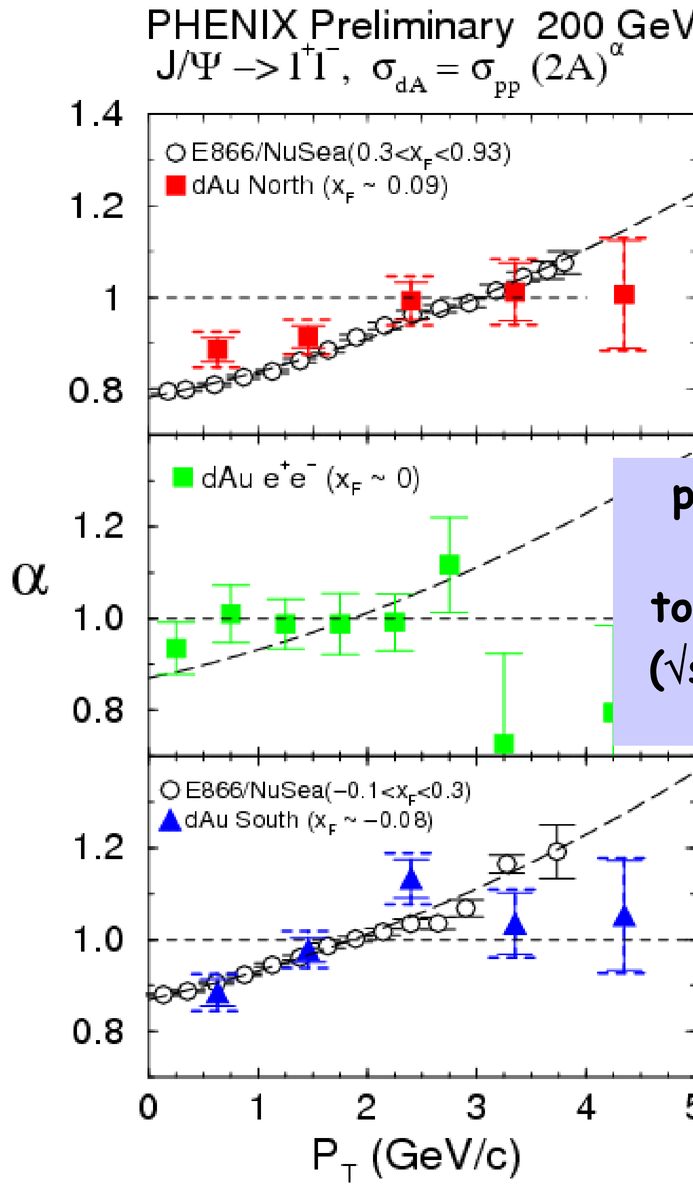


P_T Broadening for J/ψ's



Usually interpreted as initial-state multiple scattering



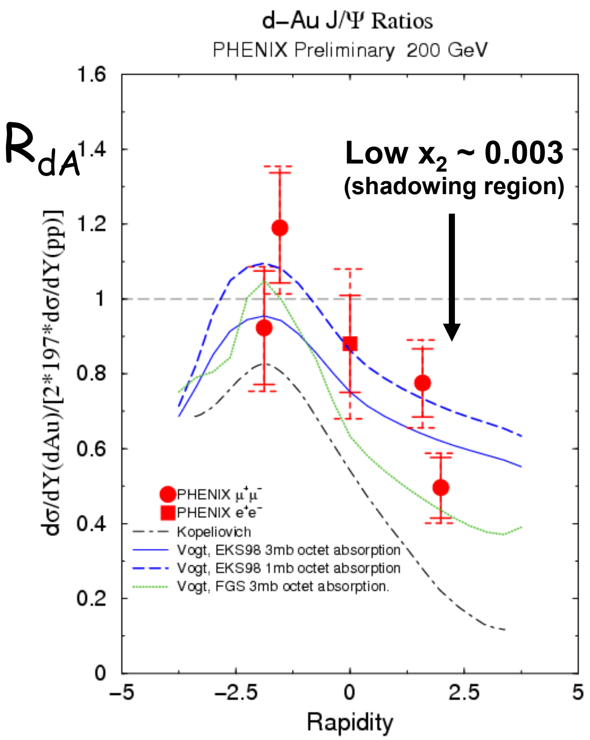


Low x_2 ~ 0.003

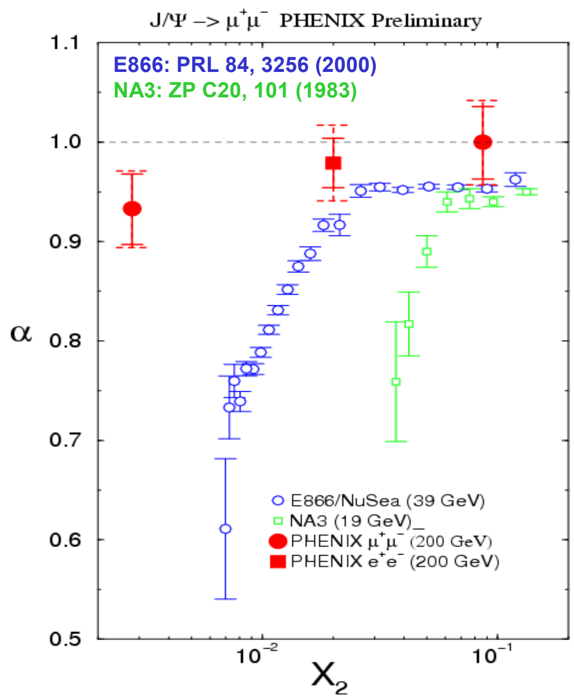
p_T broadening comparable to lower energy ($\sqrt{s}$ = 39 GeV in E866)

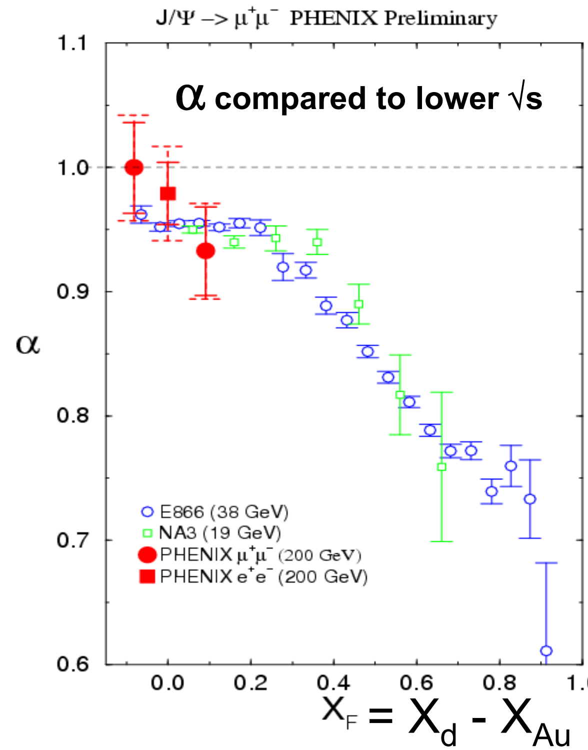
High x_2 ~ 0.09

J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F
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)

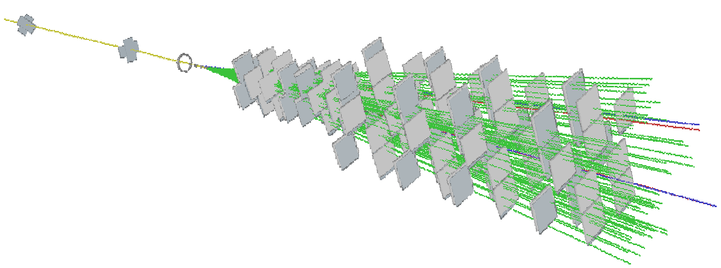
Not universal versus X_2 : shadowing is not the story.

BUT does scale with x_F ! - why?

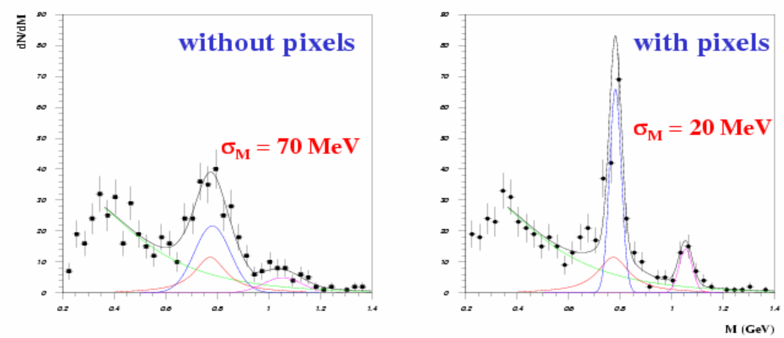
(Initial-state gluon energy loss -which goes as x1~xF - expected to be weak at RHIC energy)

Some Critical Onia Physics Issues

- 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 does J/ψ nuclear dependence scale with x_F (& not with x_2)?
  - why is Υ_{2s+3s} polarized, but not Υ_{1s} & J/ψ? And what about ψ' polarization?
- If above were 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 (from a non-NA60 member)?
  - excellent mass resolution, separation of ψ' (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!

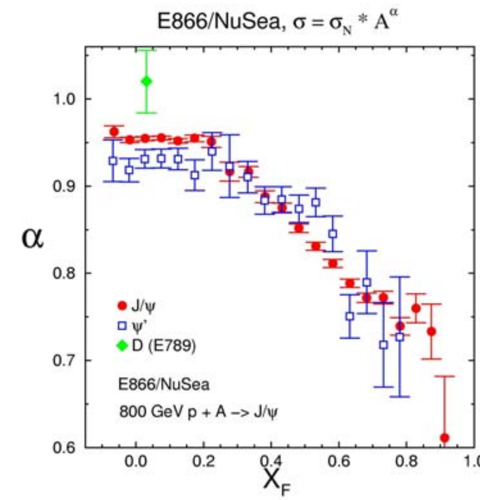


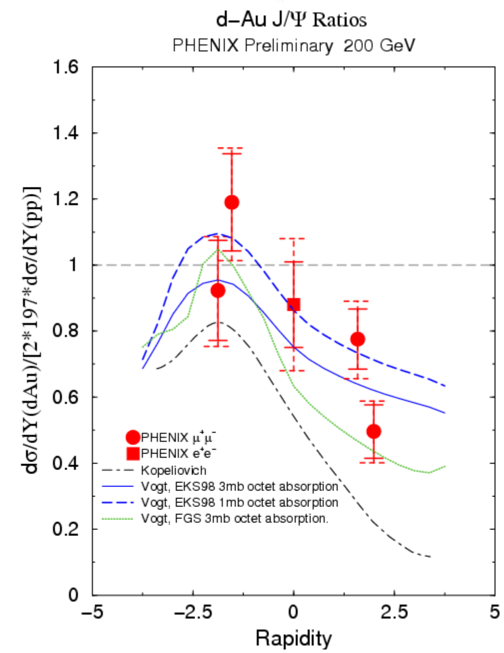
NA60 test run
450 GeV p+Be



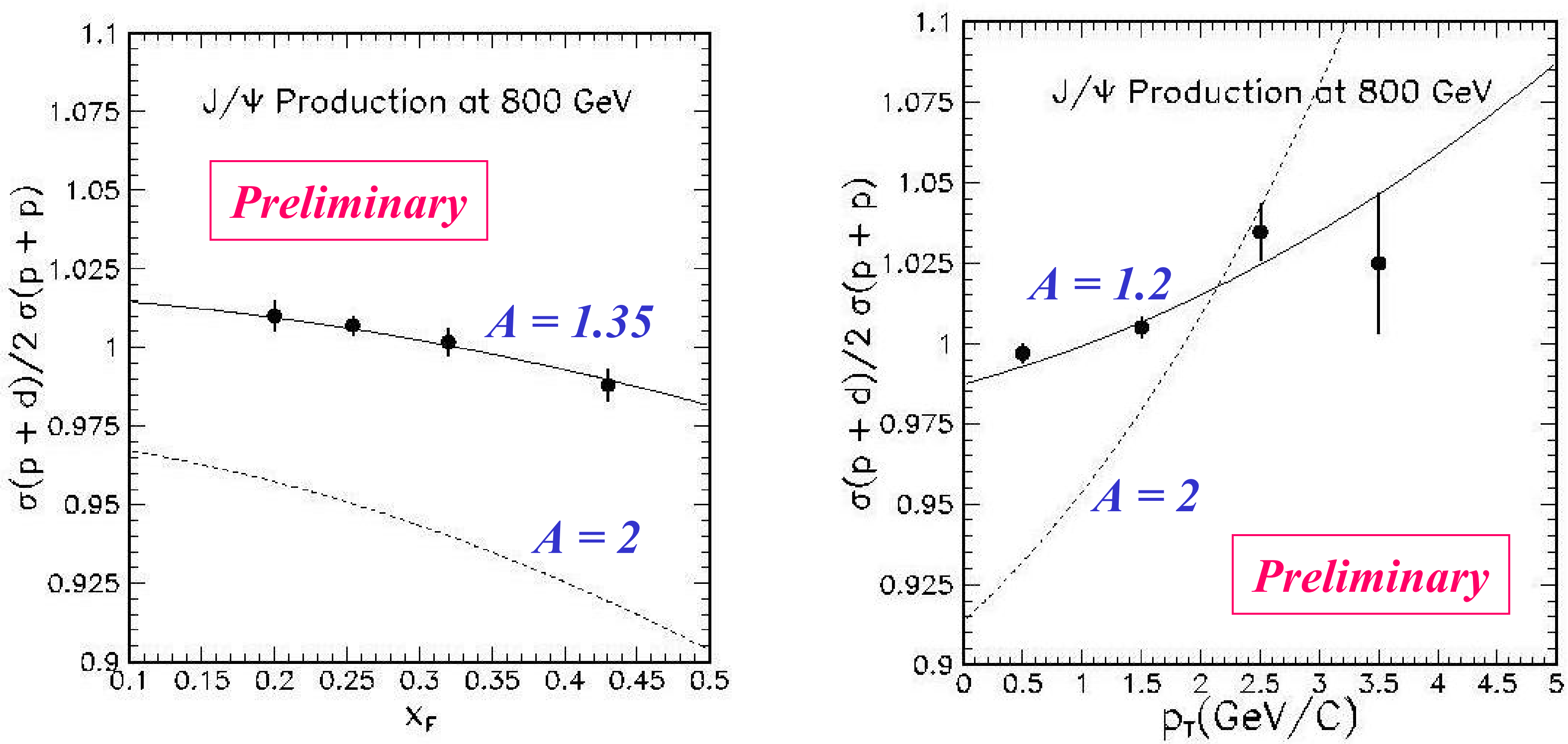
Summary & Comments

- 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 are low, so will need another dAu run
    - but scaling with x_F (and not with x_2) is still a puzzle!
- Complementary studies of open charm and of other onia are also critical
    - no apparent nuclear effects for open charm in d-Au (at mid-rapidity at least)
    - 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, particularly if priority is placed on pA (and Ap) measurements over broad ranges in x_F and p_T





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

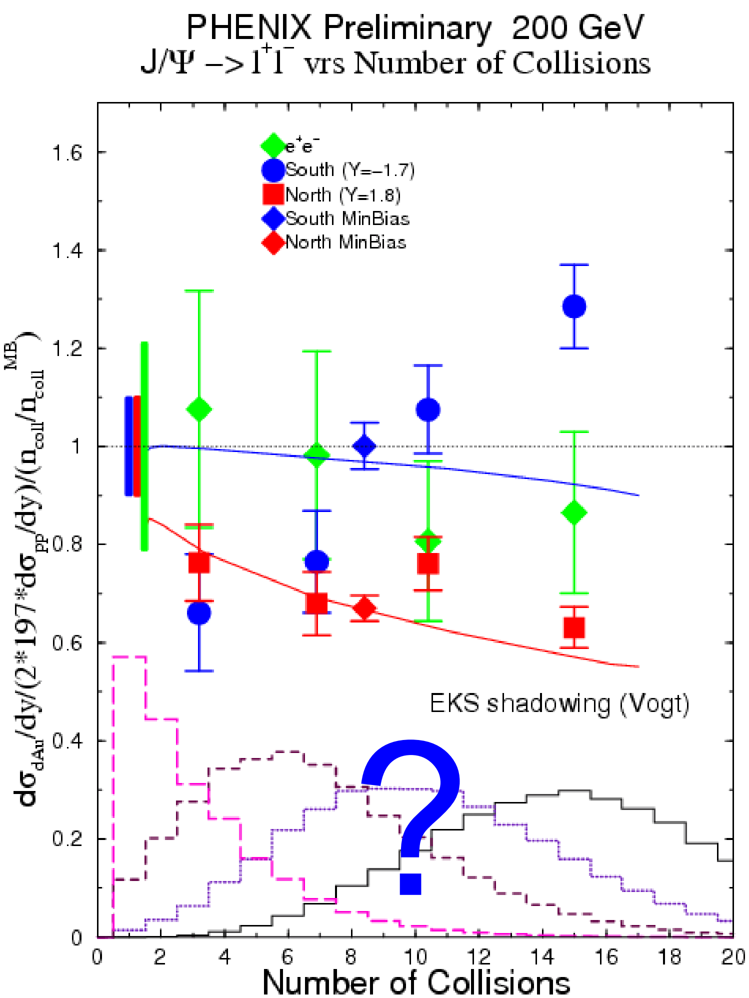


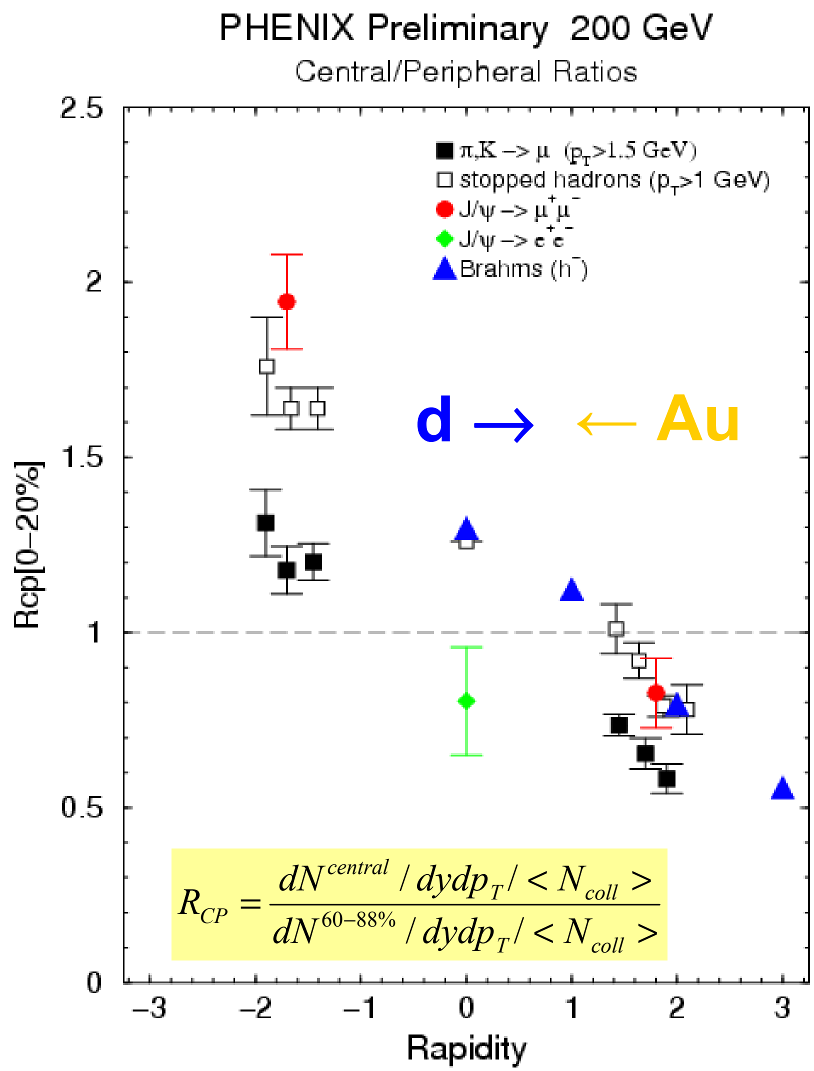
Nuclear dependence in deuterium seems to follow the systematics of larger nuclei, but with an effective A smaller than two.

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

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

Centrality Dependence – new at RHIC

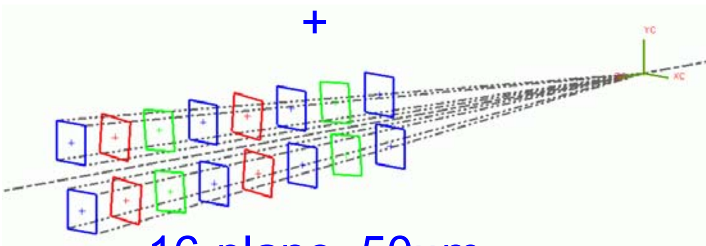




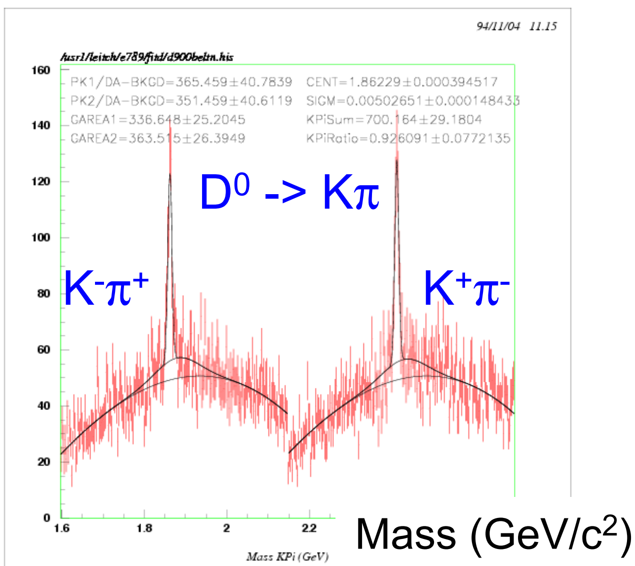
$$R_{CP} = \frac{dN^{central} / dydp_T / < N_{coll} >}{dN^{60-88\%} / dydp_T / < N_{coll} >}$$

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

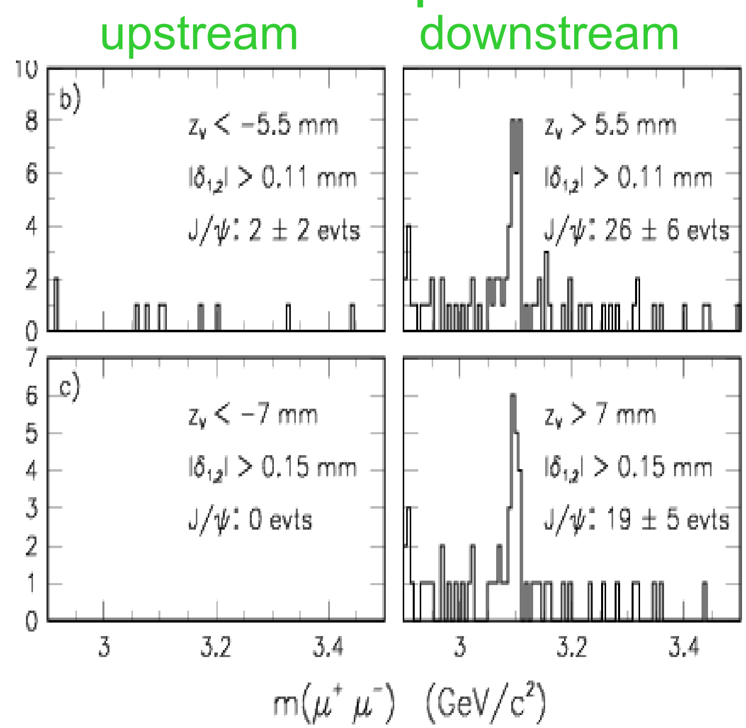
Dimuon spectrometer
+



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



B -> J/ψ + X



Los Alamos

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.

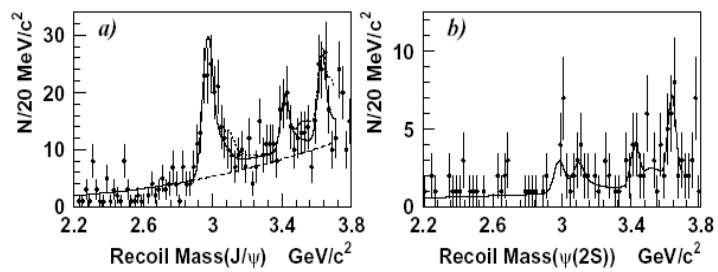
- PRL **89**, 142001 (2002) with 46.2/fb
- LP03-274 (BELLE-CONF-0331) with 101.8/fb

Study J/ψ recoil mass spectrum around $M_{recoil} \sim 3$ GeV/c² :
$(M_{recoil} = ((E_{CMS} - E_{J/\psi})^2 - p^2_{J/\psi})^{1/2})$

- 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/c²
- 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/c²]	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	–