Charmonium Production in p-A Collisions

Mike Leitch - Los Alamos National Laboratory

leitch@lanl.gov

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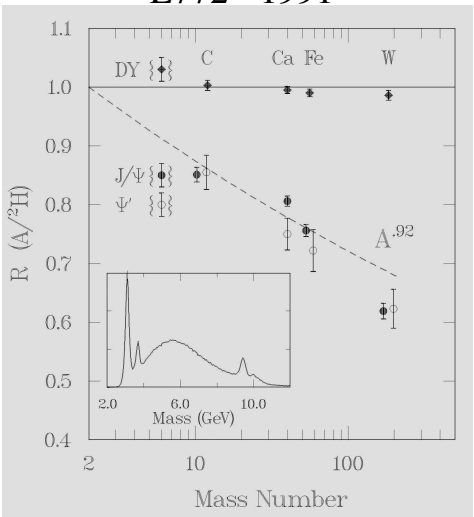
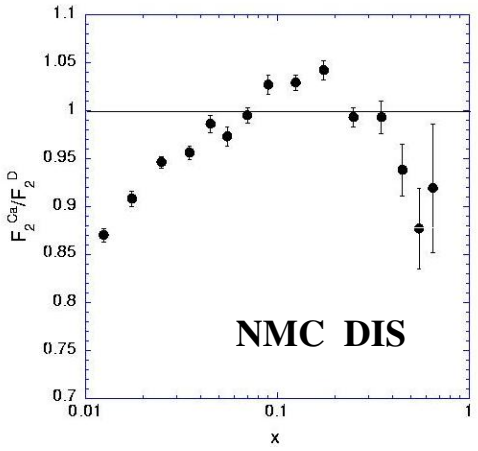
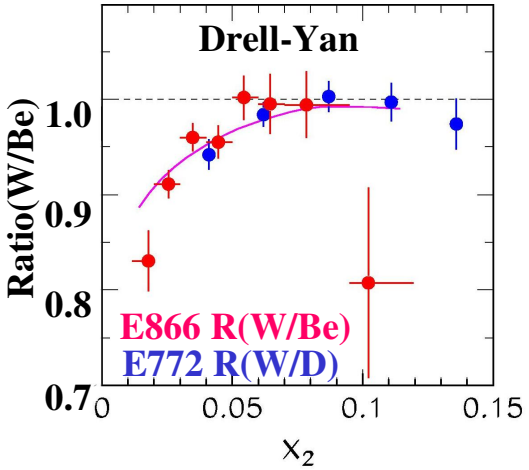
- Introduction to Physics of Charmonium suppression in nuclei
- E866/NuSea results for J/Ψ and Ψ'
- NA50 comparison & future at NA60 & HERA-B
- Prospects at PHENIX
- Summary

E772 - 1991

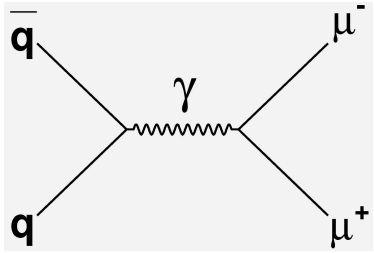


Nuclear modification of parton level structure & dynamics





Drell-Yan Process

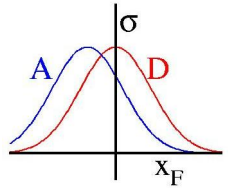


Modification of parton momentum distributions of nucleons embedded in nuclei

- e.g. shadowing – depletion of low-momentum partons. Process dependent?

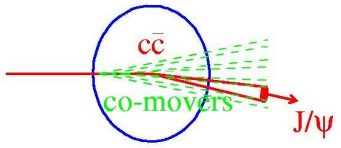
Nuclear effects on parton "dynamics"

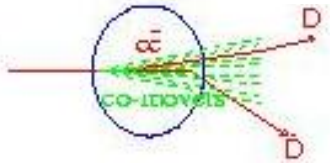
- energy loss of partons as they propagate through nuclei
- and (associated) multiple scattering effects

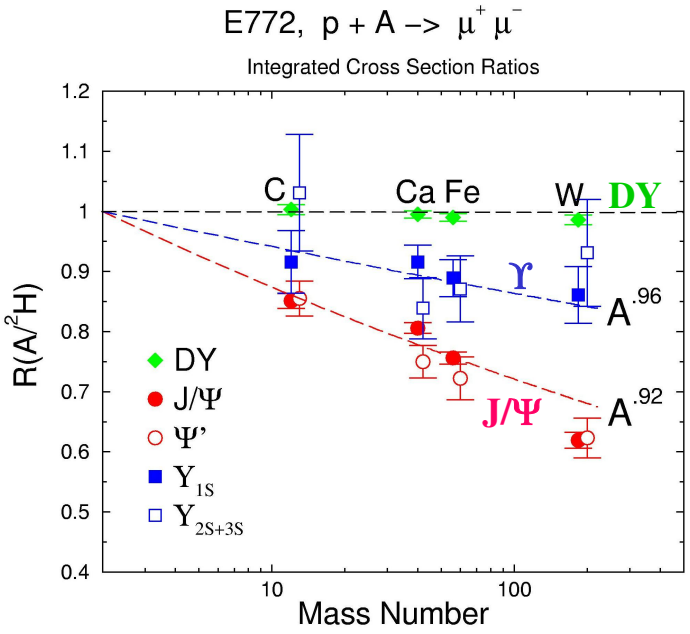


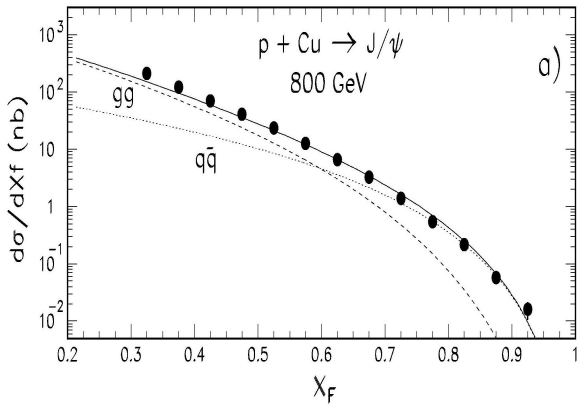
Production of heavy vector mesons, e.g. J/Ψ, Ψ ', ϒ

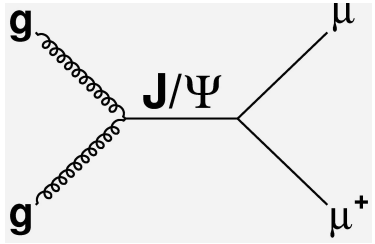
- production: color singlet or octet $c\bar{c}$ ($b\bar{b}$) and color neutralization timescale
- hadronization time: $l_H \approx 2E_{J/\Psi}/(m^2_{\Psi'} - m^2_{J/\Psi})$
- Coherence length for cc fluctuations: $l_C \approx 2E_{J/\Psi}/m^2_{J/\Psi}$
- absorption on nucleons or co-movers
- feed-down from higher mass resonances, e.g. χ_c











J/Ψ suppression – an effective signature of Quark-gluon plasma (QGP) formation?

- **Color screening in a QGP would destroy $c\bar{c}$ pairs before they can hadronize into charmonium**
- **But ordinary nuclear effects also absorb or modify J/Ψ's**
- **We need a comprehensive understanding of charmonium production in nuclei**
- **Competing effects may be identified in p-A collisions by their strong kinematic dependencies, together with complementary studies of Drell-Yan scattering and open-charm production**

FNAL E866/NuSea Collaboration

Abilene Christian University

Donald Isenhower, Mike Sadler, Rusty Towell, Josh Willis

Argonne National Laboratory

Don Geesaman, Sheldon Kaufman, Bryon Mueller

Fermi National Accelerator Laboratory

Chuck Brown, Bill Cooper

Georgia State University

Gus Petitt, Xiao-chun He, Bill Lee

Illinois Institute of Technology

Dan Kaplan

Los Alamos National Laboratory

Tom Carey, Gerry Garvey, Mike Leitch, Pat McGaughey, Joel Moss, Jen-Chieh Peng, Paul Reimer, Walt Sondheim

New Mexico State University

Mike Beddo, Ting Chang, Vassili Papavassiliou, Jason Webb

Oak Ridge National Laboratory

Paul Stankus, Glenn Young

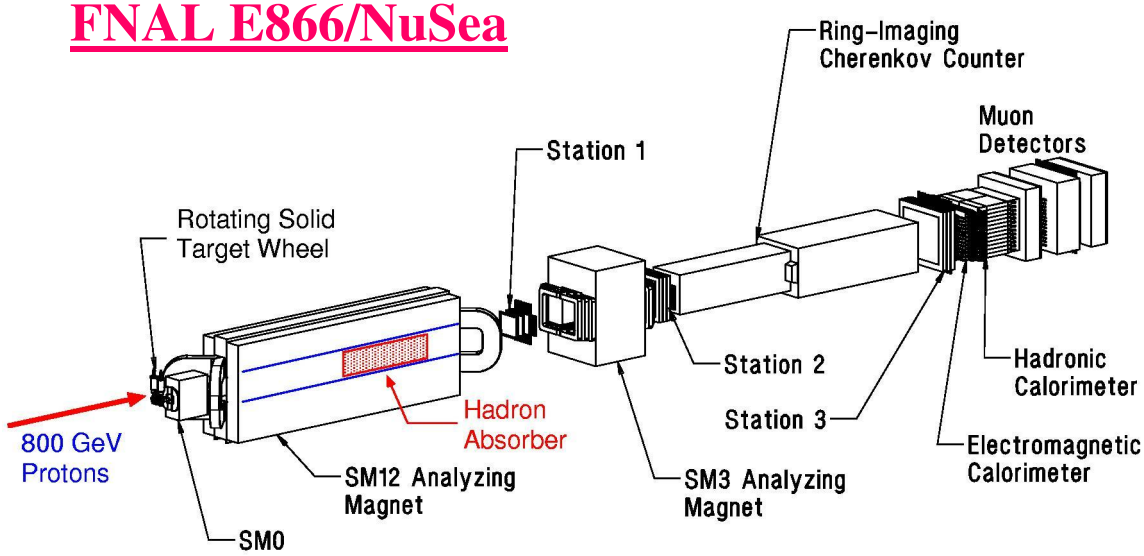
Texas A & M University

Carl Gagliardi, Bob Tribble, Eric Hawker, Maxim Vasiliev

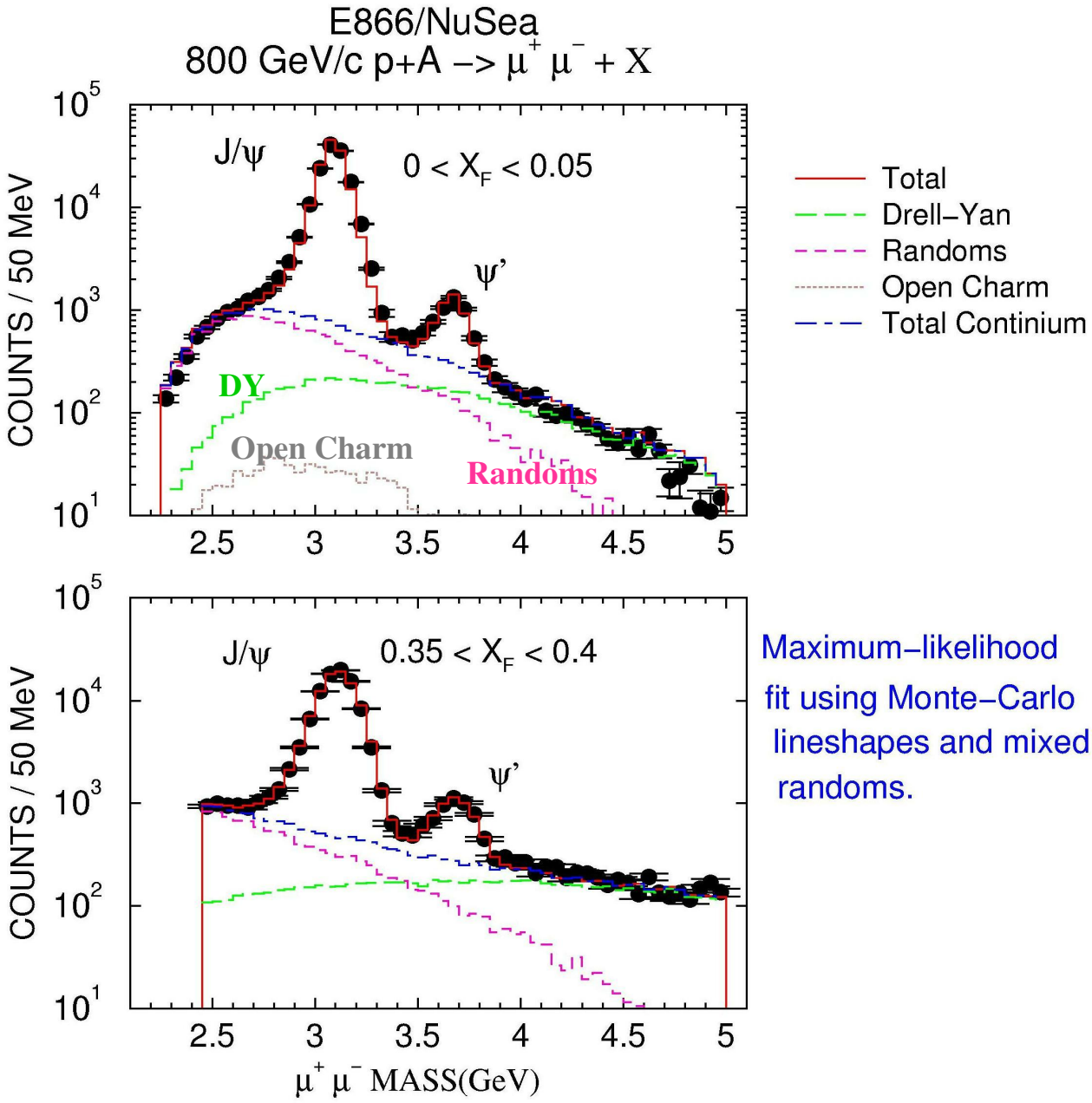
Valparaiso University

Don Koetke

FNAL E866/NuSea

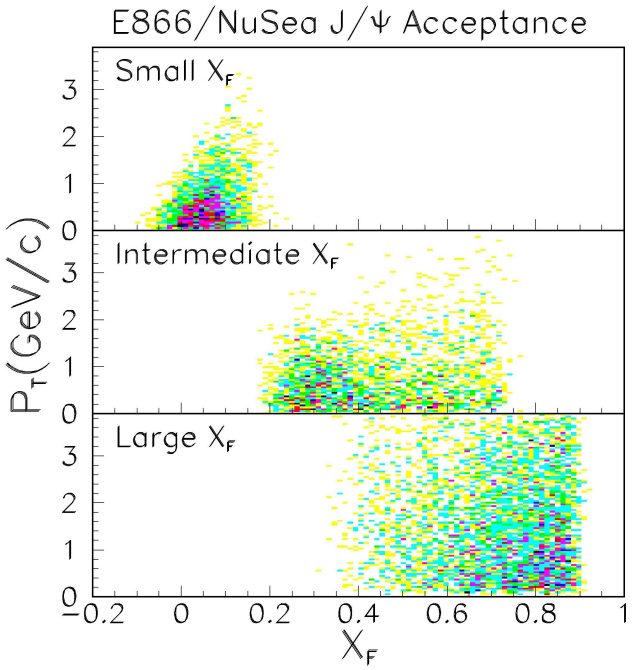


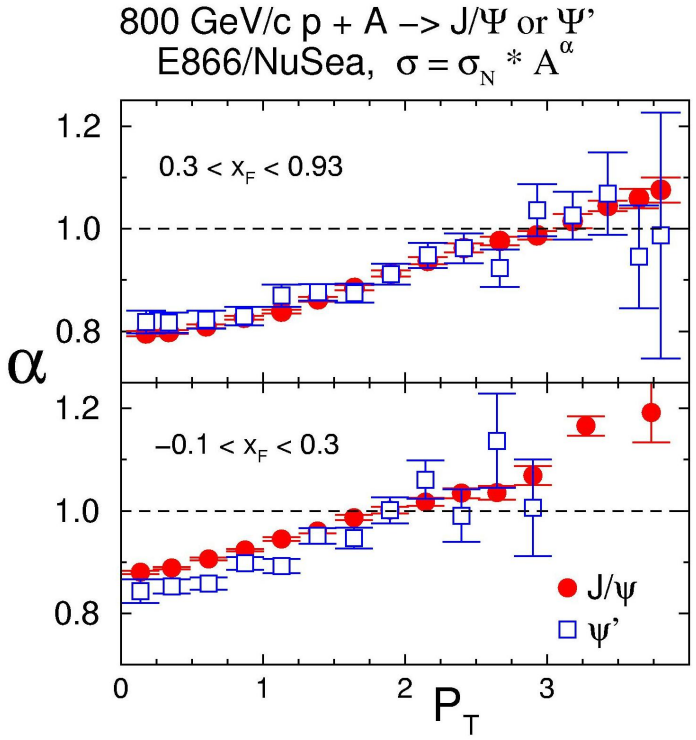
- Forward x_F, high-mass spectrometer
- Solid Be, Fe, W and empty targets
- Thick absorber wall to filter out all but μ's
- Two acceptance defining magnets
- Four tracking stations and one momentum analyzing magnet
- Scale 60m long, 3m x 3m at back



Maximum–likelihood fit using Monte–Carlo lineshapes and mixed randoms.

Effect of experimental p_T-acceptance on the measured J/Ψ suppression

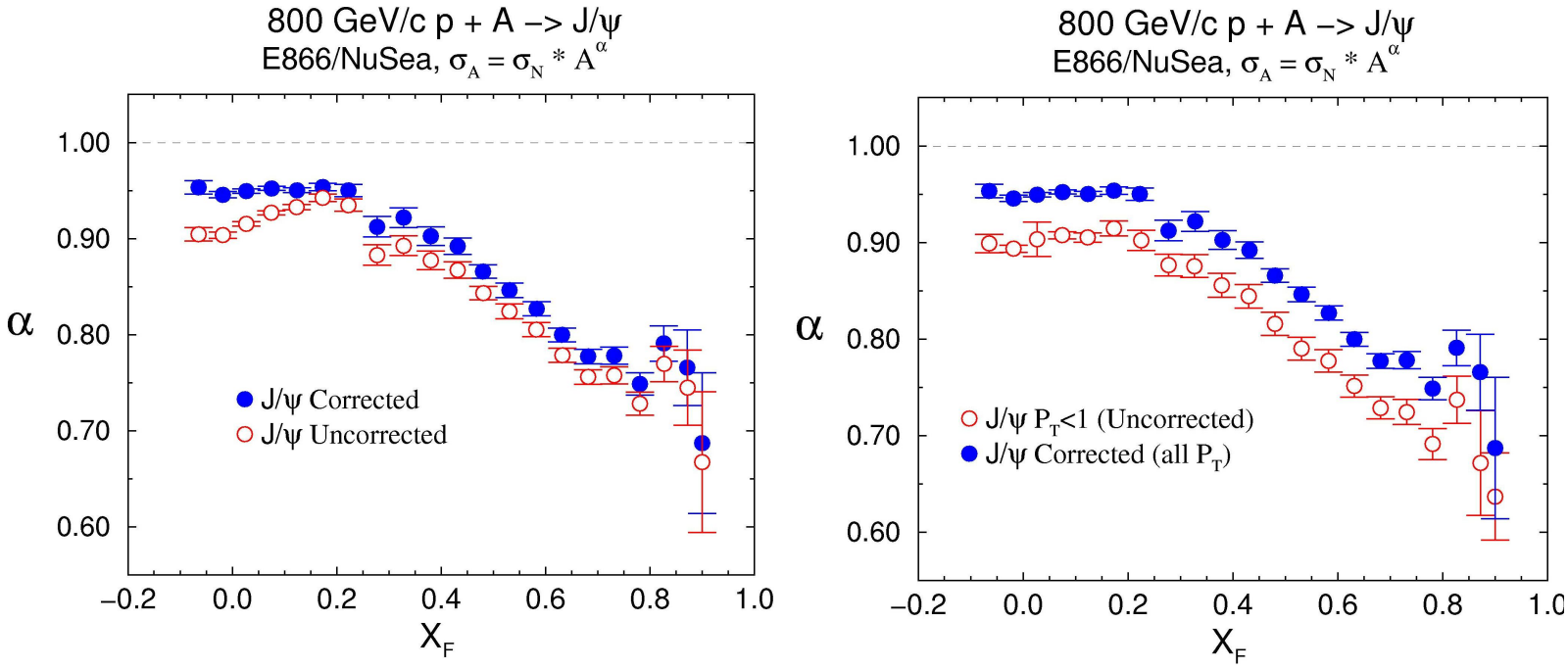




- Three E866/NuSea data sets
- At lowest x_F, p_T-acceptance is considerably narrowed
- Shown in terms of α, where $\sigma_A = \sigma_N * A^\alpha$ (α = 1 corresponds to NO suppression)

Correction to Nuclear Dependence for p_T Acceptance

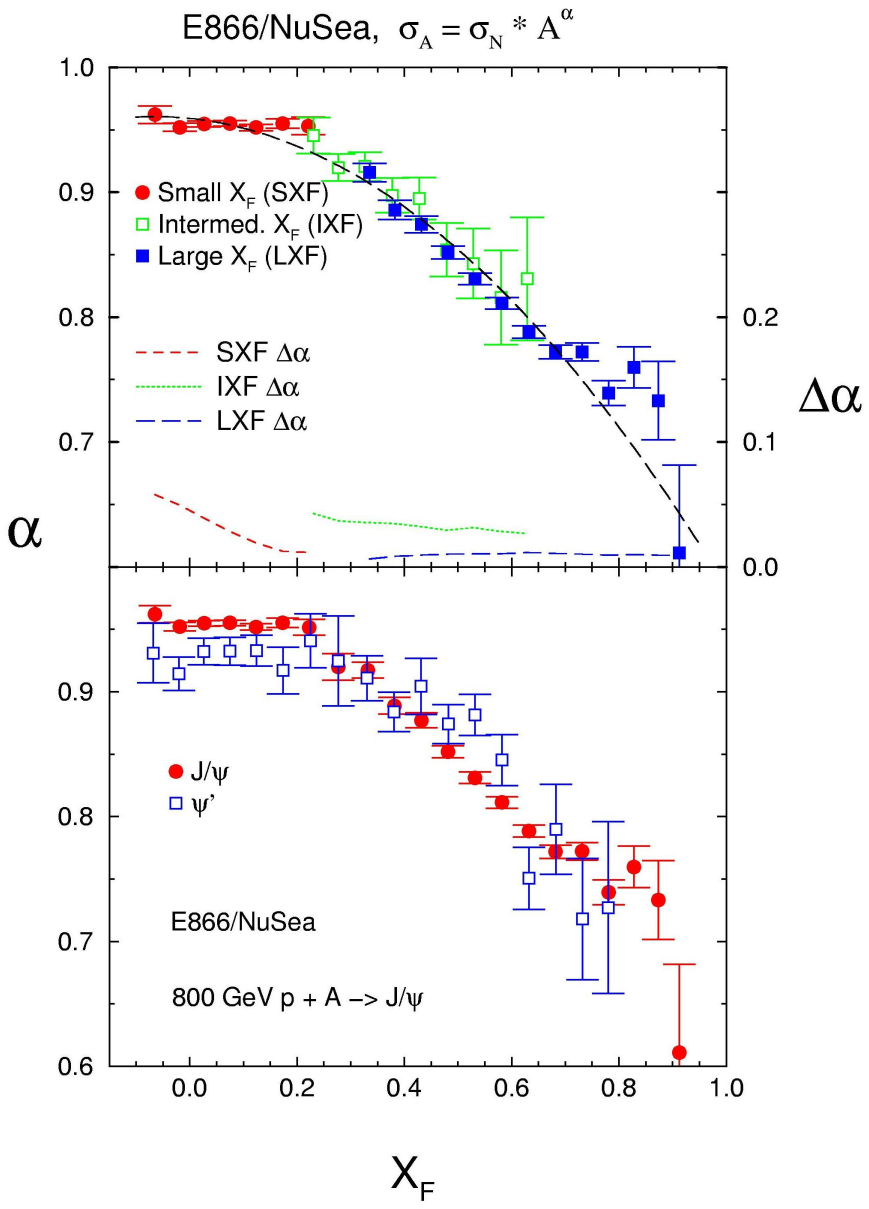
•**Incomplete coverage in p_T can distort J/Ψ suppression versus x_F**



•E866/NuSea p_T coverage is much better than previous experiment (e.g. E772) because of improved trigger

•Most significant effects are at lowest x_F where p_T is cut off near 1 GeV/c

•Use MC acceptance & $d\sigma/dp_T$ consistent with our data to correct for incomplete coverage



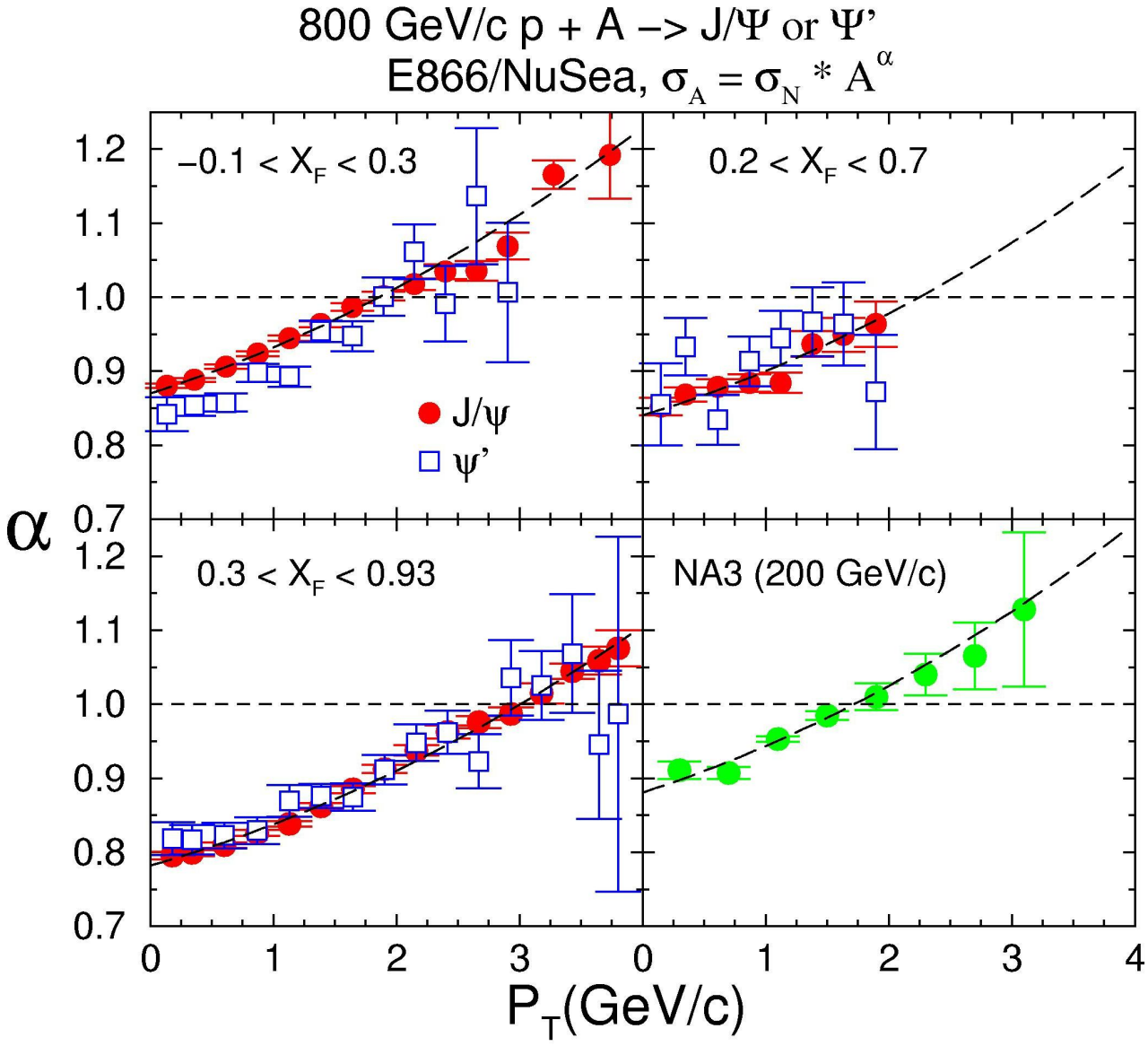
E866/NuSea

800 GeV p-A (Fermilab)

PRL 84, 3256 (2000)

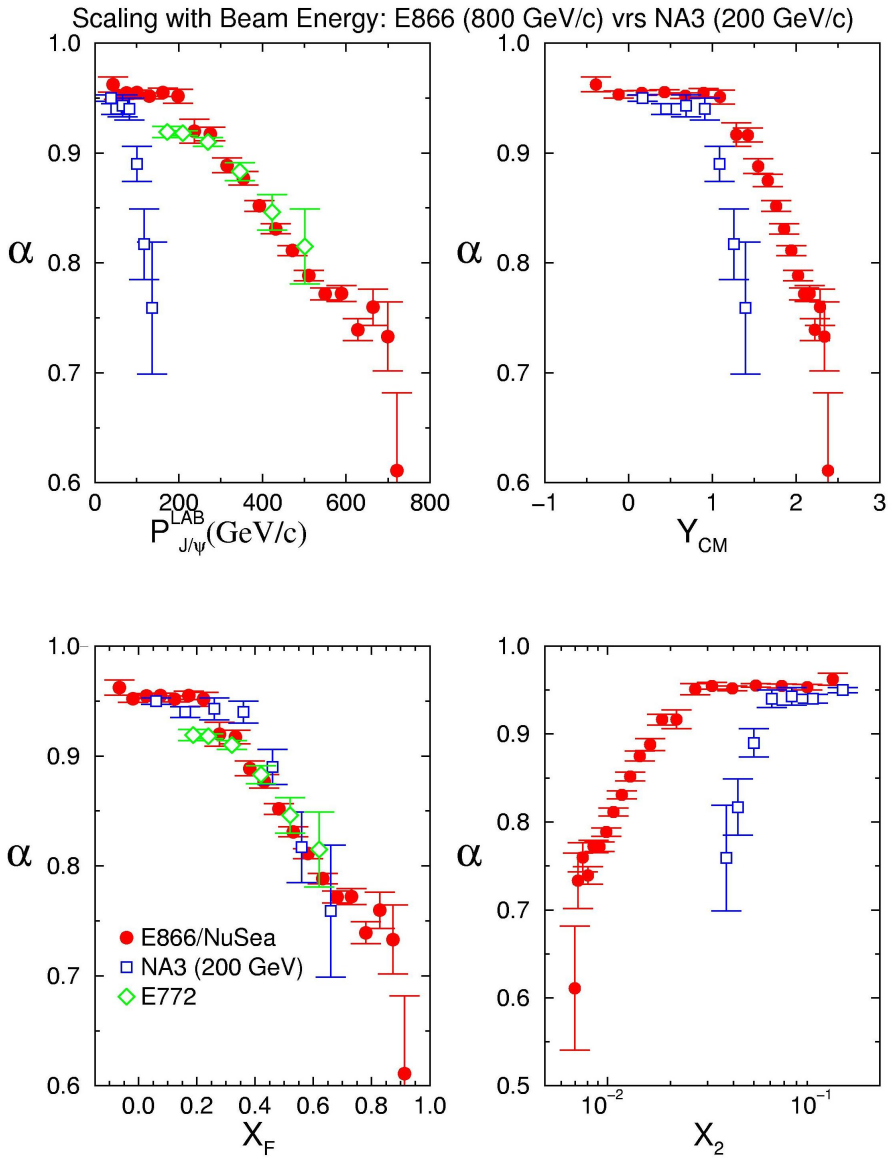
- Three magnet settings in E866 match up well
- Systematic errors shown at bottom of top panel

- J/Ψ and Ψ' similar at large x_F where they both correspond to a cc 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.


800 GeV/c p + A –> J/Ψ or Ψ'
E866/NuSea, σ_A = σ_N * A^α
–0.1 < X_F < 0.3
0.2 < X_F < 0.7
0.3 < X_F < 0.93
NA3 (200 GeV/c)
J/ψ
ψ'
α
P_T(GeV/c)

Scaling of J/Ψ Suppression?

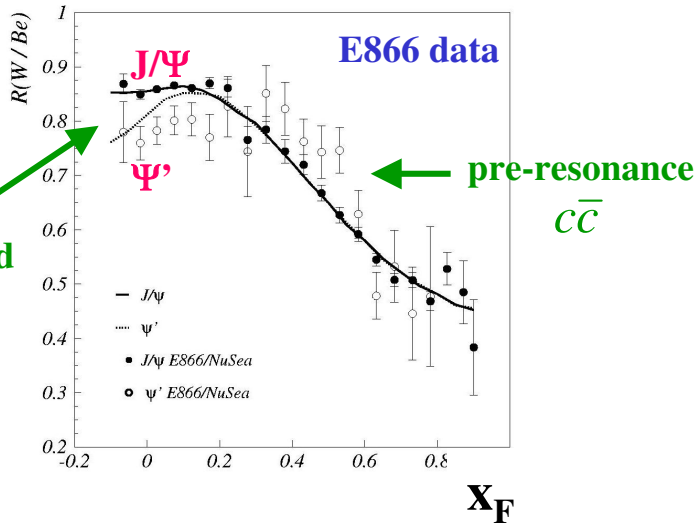
- Comparison of 800 GeV (E866) and 200 GeV (NA3)
- Appears to scale only with x_F



Arleo,Gossiaux,Gousset,Aichelin Model

(PRC 61, 054906 (2000) & hep-ph/0105047)

- **Absorption of color-octet or –singlet $c\bar{c}$ with color neutralizaton times**
- **J/Ψ, Ψ' & χ_c with feed-down**
- **Fit to E866/NuSea data with no shadowing & no dE/dx.**



p-Au at RHIC: Predictions

- **J/Ψ & Ψ' differences at negative rapidity**
- **Effect of dE/dx, also at negative rapidity**

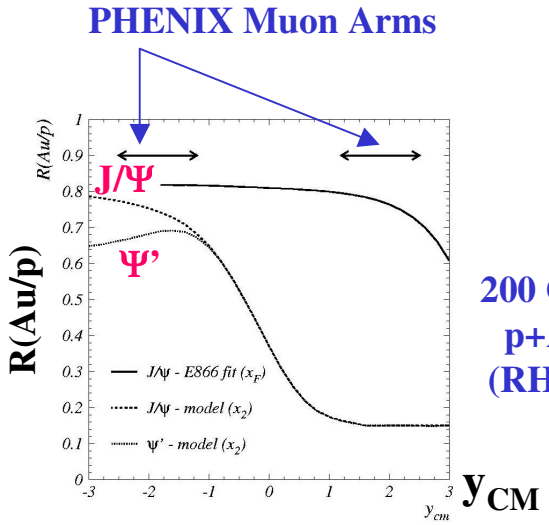


FIG. 1. Ratio R(Au/p) versus y_{cm} of produced J/ψ's within the E866/NuSea fit (solid line) in p(100 GeV)+ Au(100 GeV) collisions, assuming x_F scaling. The model prediction for J/ψ (dashed) and ψ' (dotted) production ratio is also shown. The arrows show the dimuon arm acceptance in the PHENIX experiment.

200 GeV p+Au (RHIC)

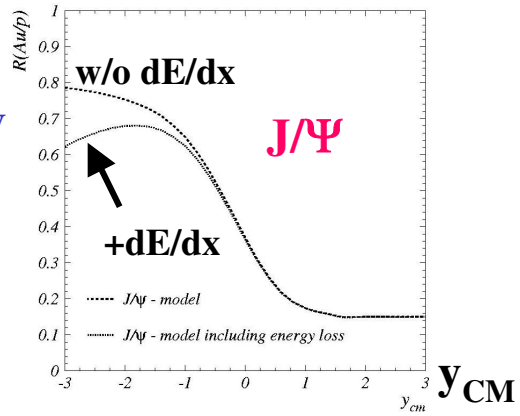


FIG. 2. Ratio R(Au/p) versus y_{cm} of produced J/ψ's in p(100 GeV)+ Au(100 AGeV) collisions predicted by the model with (*dotted*), and without (*dashed*), energy loss effects (see text for details).

Parton Energy Loss in Nuclei – Kopeliovich Model

Shadowing when coherence length,
$t_{coherence} = 2E_{J/\Psi} / 2M^2_{J/\Psi}$
is larger than nucleon separation

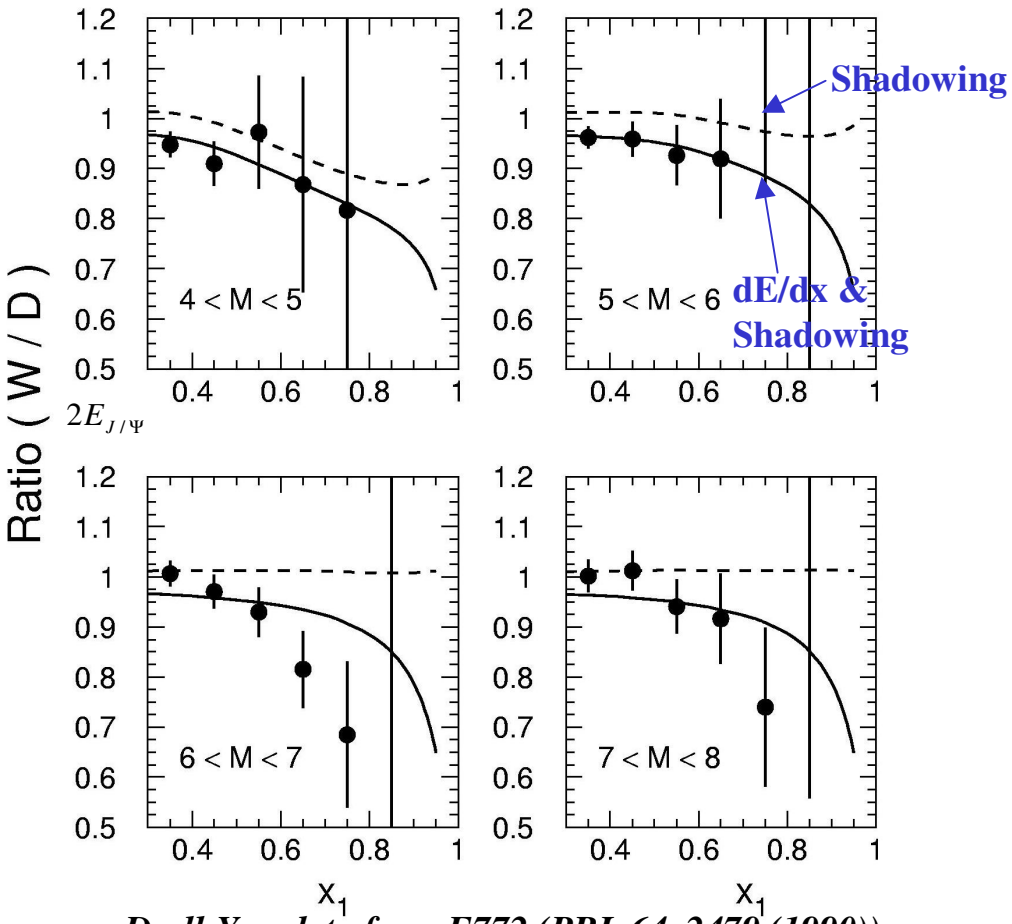
Three *dE/dx* mechanisms:

- **String breaking:** $dE/dz \sim K_s \sim 1$ GeV/fm
- **Multiple bremstrahlung:**
  $dE/dz \sim 3\alpha/\pi \langle k_T^2 \rangle \sim .8$ GeV/fm
- **Radiative gluon (BDMS):**
  $\Delta E \sim 3\alpha/8\, \Delta \langle p_T^2 \rangle \langle L \rangle \sim .075$ GeV/fm
  (since $\langle p_T^2 \rangle \sim 0.1$ GeV^2 from E772)

Total $\Delta E \sim 2$ GeV/fm expected from above

From E866 DY data with separation of shadowing & *dE/dx* via Mass dependence, gives $dE/dz \sim 3 \pm .6$ GeV/fm

Johnson, Kopeliovich et al., hep-ph/0105195



Drell-Yan data from E772 (PRL 64, 2479 (1990))

Kopeliovich, Tarasov, Hufner
hep-ph/0104256

Model:

- $c\bar{c}$ **absorption**
- **Dynamic calculation of shadowing and of energy loss**
- **Also gluon anti-shadowing from Eskola**

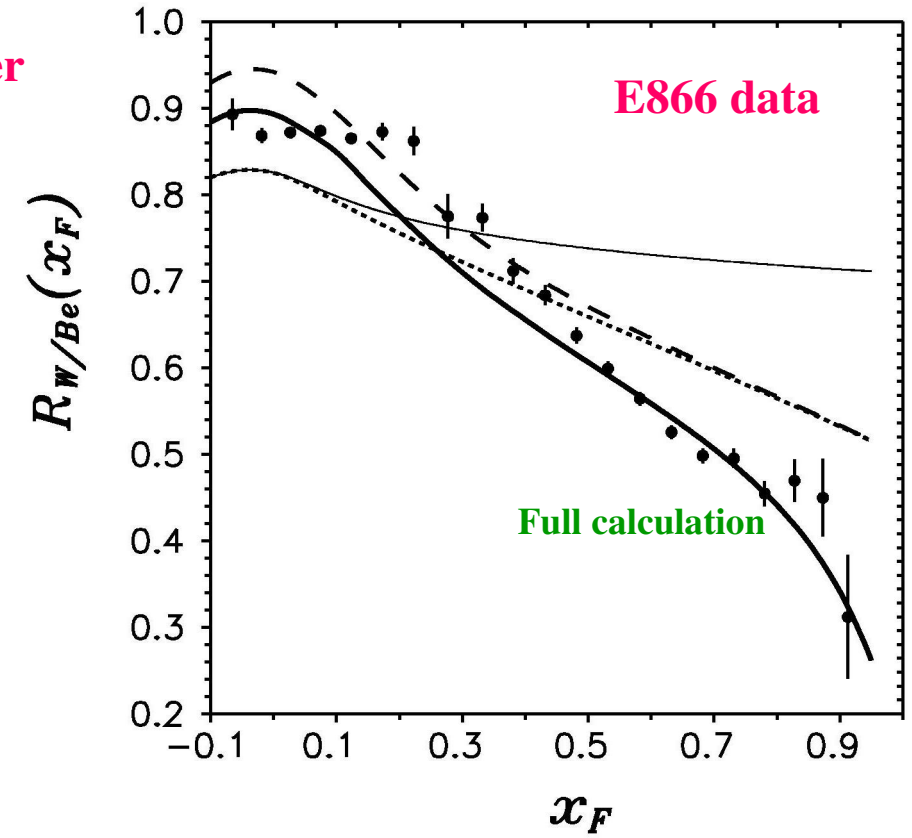


Figure 5: *Tungsten to beryllium cross section ratio as function of Feynman x_F for J/Ψ production at proton energy 800 GeV. The thin solid curve represents contribution of initial state quark shadowing and finals state $\bar{c}c$ attenuation for χ production. The dotted curve includes also gluon shadowing. The dashed curve is corrected for gluon enhancement at large x_2 (small x_F) using the prescription from [38]. The final solid curve is also corrected for energy loss and for $\chi \to J/\Psi\gamma$ decay. Experimental points are from the E866 experiment [3].*

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

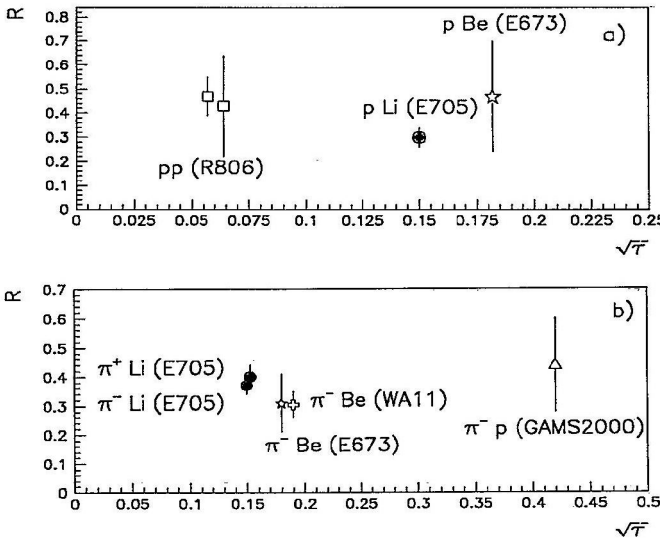


FIG. 3. Fraction of J/ψ produced via radiative χ in 300 GeV/c (a) proton and (b) $\pi^{\pm}$ ^{7}Li interactions.

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%

- 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

Meson	M(GeV)	R(Fm)	BE (MeV)
J/Ψ	3.1	.45	~640
Ψ′	3.7	.88	~52
χ_C	3.5	.70	

Open Charm Nuclear Dependence : x_F Dependence?

E769 250 GeV $\pi^{\pm}$ PRL 70,722 (1993)

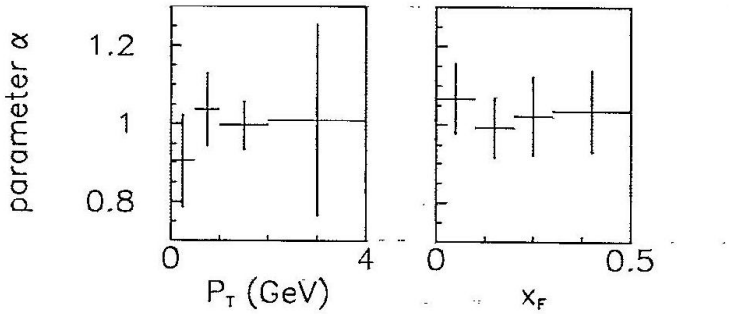


FIG. 4. Dependence of the parameter α on P_T and x_F for D^+ and D^0.

WA82 340 GeV π PRB 284,453 (1992)

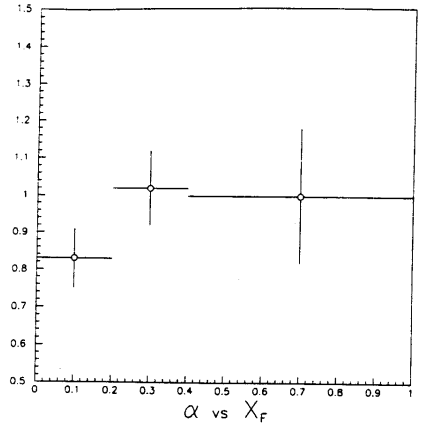
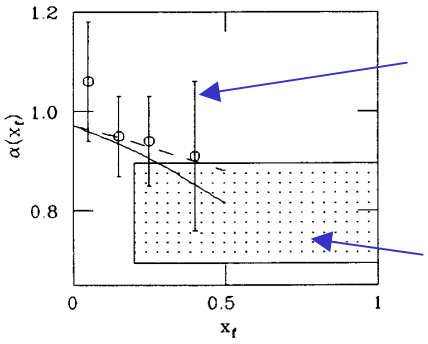


Fig. 4. The parameter α for charm production as measured in three x_F intervals.

Vogt et al., NP 383,643 (1992)

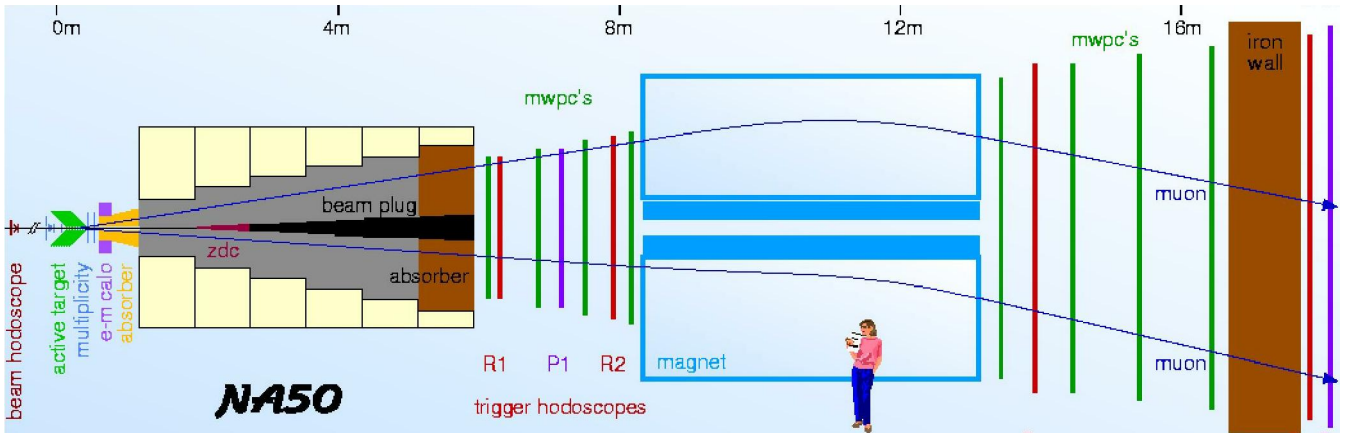


E769 250 GeV π

WA78 320 GeV π *(Beam dump)*

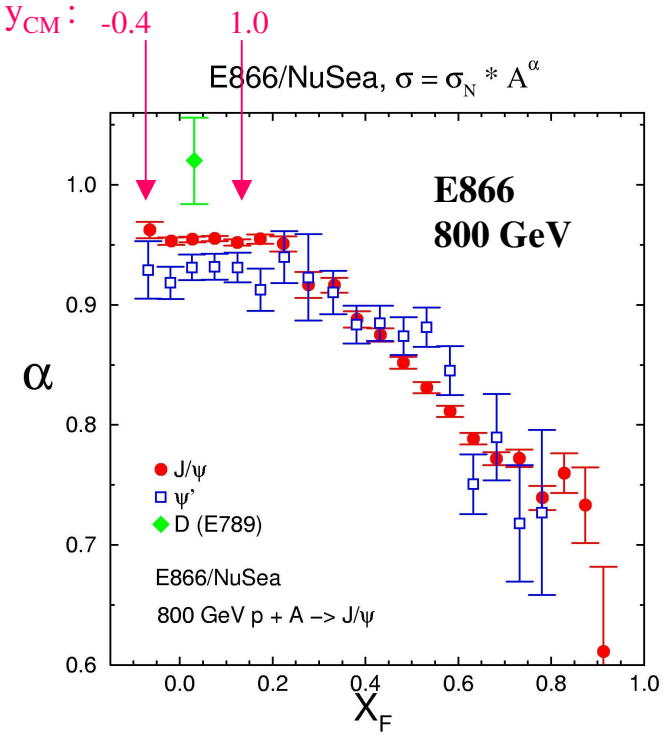
Fig. 14. We show $\alpha(x_f)$ for π^-A interactions at 300 GeV as calculated in our model. The dashed curve shows delta function fragmentation, the solid curve, the Peterson function. These results are compared to those for $D^{\pm}$ mesons produced by 250 GeV π^-A interactions [3] and the effective α found by the WA78 beam dump experiment [23], indicated by the band with $\langle x_f \rangle = 0.31$.

NA50 Spectrometer

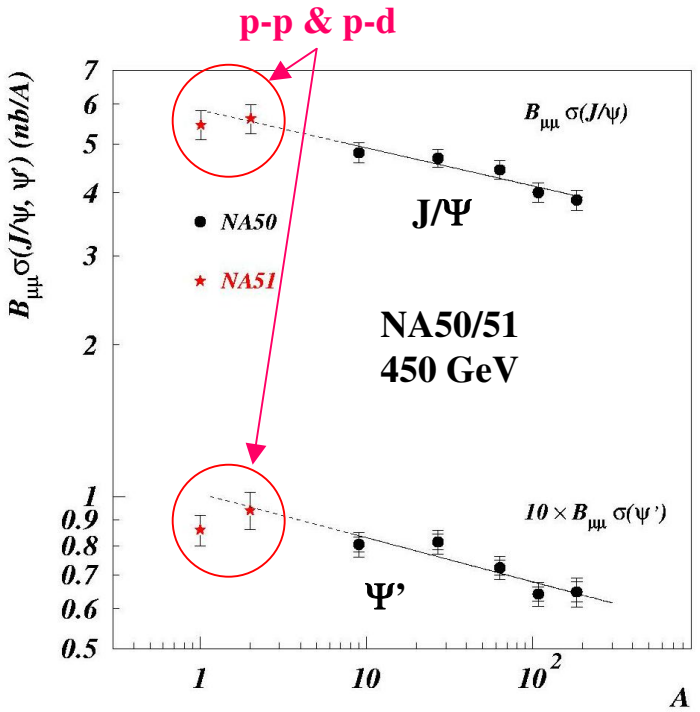


- Muon spectrometer: air-gap toroidal magnet with B ~ 2.1 Tm
- Covers $3 < y_{LAB} < 4$, $m_T >= 1.3$ GeV/c^2, $|cost_{CS}| < 0.5$ ($-0.1 < x_F < 0.1$)
- Good p_T coverage with constant acceptance up to 4 GeV/c
- Typically ~2e8 protons/(2.36s spill)
- Targets for 450 GeV/c runs: Be, Al, Cu, Ag, W
- NA50 (450 GeV/c); NA38 (200 GeV/c)

Comparison to NA50 J/Ψ Nuclear Dependence



$\sqrt{s}$



Charmonia cross sections from NA50/51 for p-A collisions at 450 GeV/c

$\alpha_{y\sim0}$ $\sqrt{s}$ dependence?

- **gluon shadowing?**
- **change in production, e.g. octet vrs singlet balance?**

(Both experiments have good p_T coverage, so strong p_T-dependence of α not the cause)

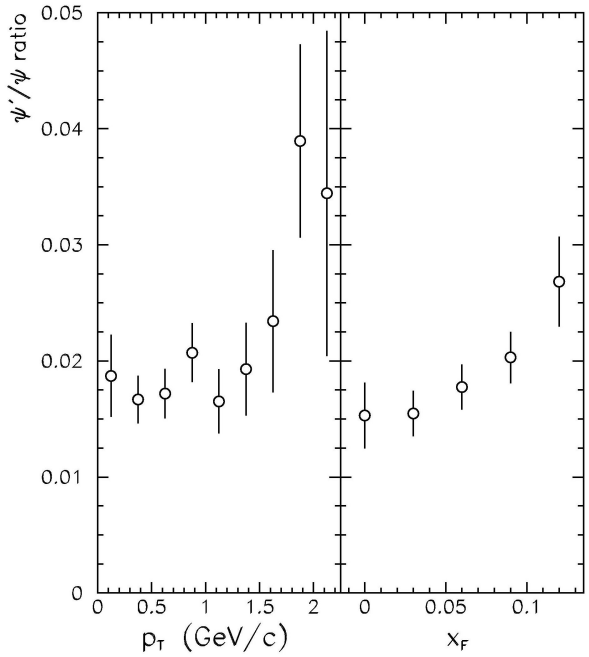
Expt.	E(GeV)	Y_{CM}	$\alpha_{J/\Psi}$	$\alpha_{J/\Psi} - \alpha_{\psi}$
E866	800	-0.4 to 1.0	.954 ± .001	.027 ± .006*
NA50	450	-0.4 to 0.6	.925 ± .018	.029 ± .014
NA38	200	0 to 1.0	.911 ± .034	

* mid-rapidity part of E866 data

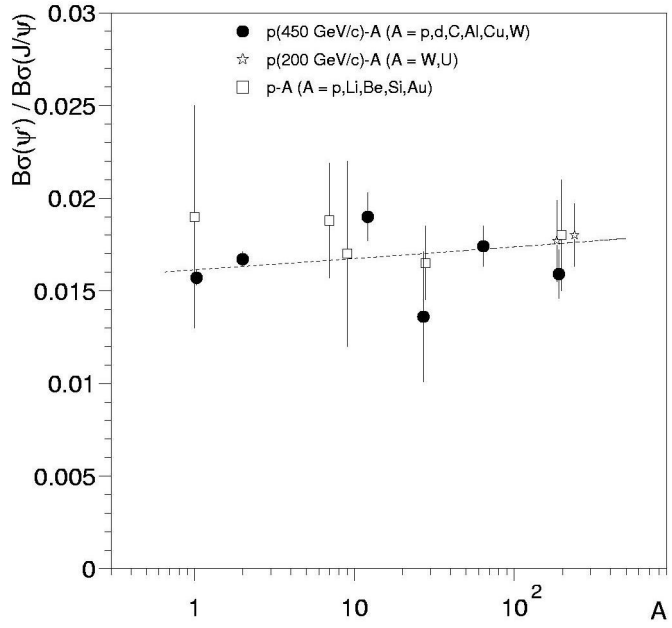
Ψ' to J/Ψ ratio (in $\mu^+\mu^-$ channel)

- Independent of $\sqrt{s}$ and rapidity?

E789 – 800 GeV p-Au
PRD52, 1307 (1995)

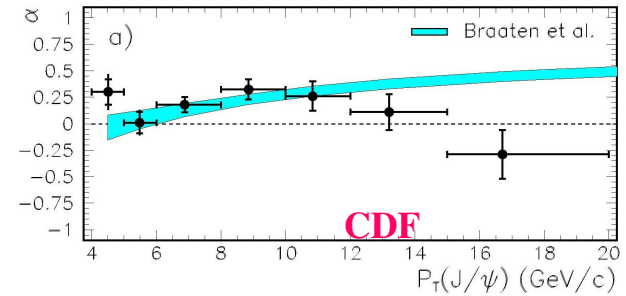


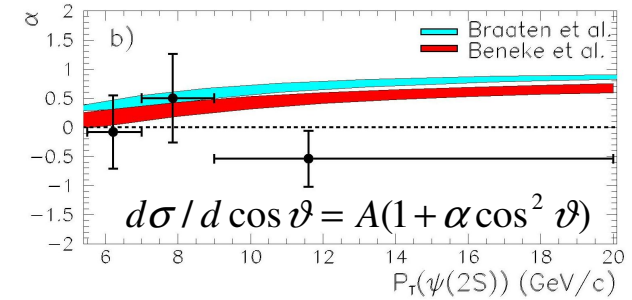
NA50 – 200 & 450 GeV p-A
PLB 444, 516 (1998)

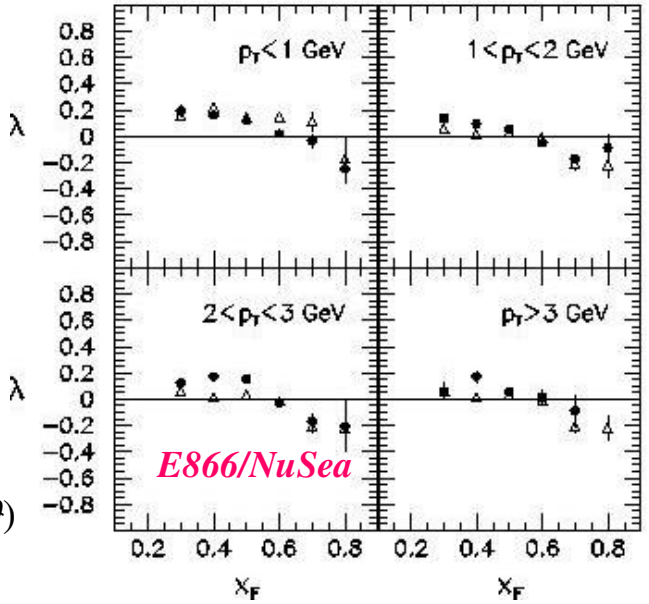


J/Ψ Polarization

- NRQCD based predictions *[Braaten & Fleming, PRL 74, 3327 (1995)]* necessary to explain CDF charm cross sections
- E866 measurement not in agreement with NRQCD based predictions *[Beneke & Rothstein, PRD 54, 2005 (1996)]* which give $0.31 < \lambda < 0.63$
- or with color-singlet models *[PRD 51, 3332 (1995)]*
- Complicated by feedown (~40%) from higher mass states.
- No clear information on production mechanism!





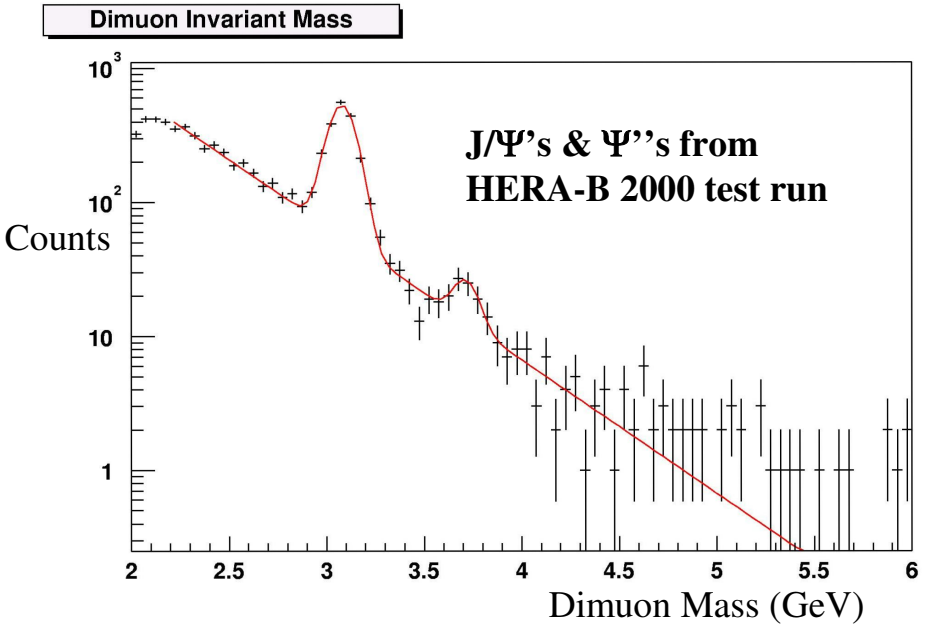


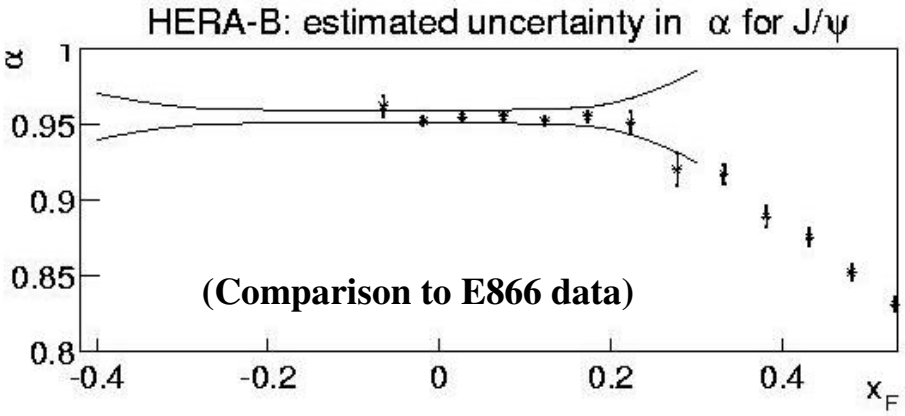
$$d\sigma/d\cos\vartheta = A(1+\lambda\cos^2\vartheta)$$

New Measurements of J/Ψ, Ψ ' and χ_C planned at HERA-B

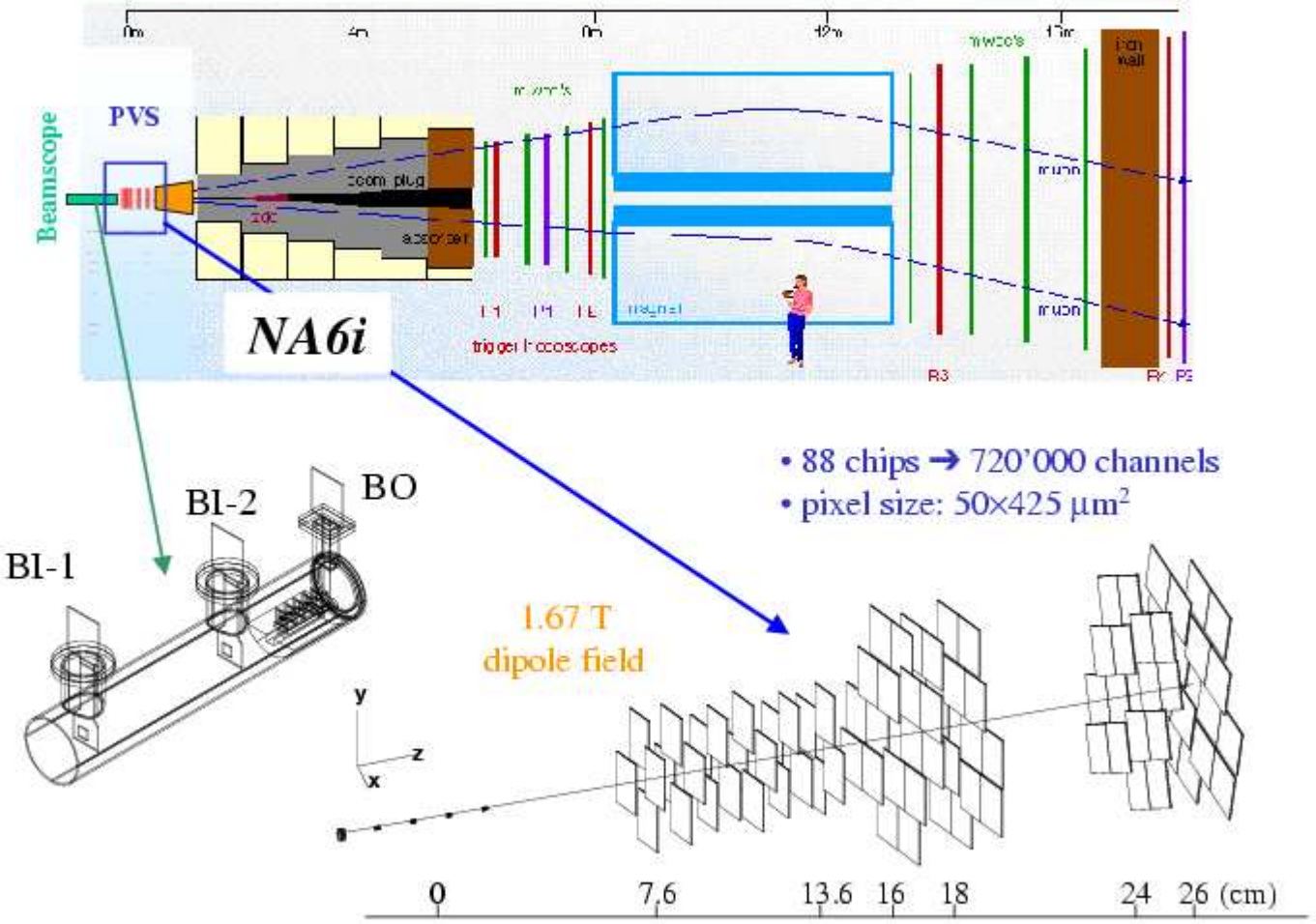
- **2002 run will measure charmonium nuclear dependence with 920 GeV protons on C, Ti, W targets**
- **covering $-0.3 < x_F < 0.2$, a region interestng in terms of formation time effects.**
- **Also would be first measurement (along with NA60) of χ_C**
- **Expect ~1.5M J/Ψ, 26k Ψ' & 100k χ_C**

- **Also will measure $\sigma_{b\bar{b}}$ via *B -> J/Ψ + X***



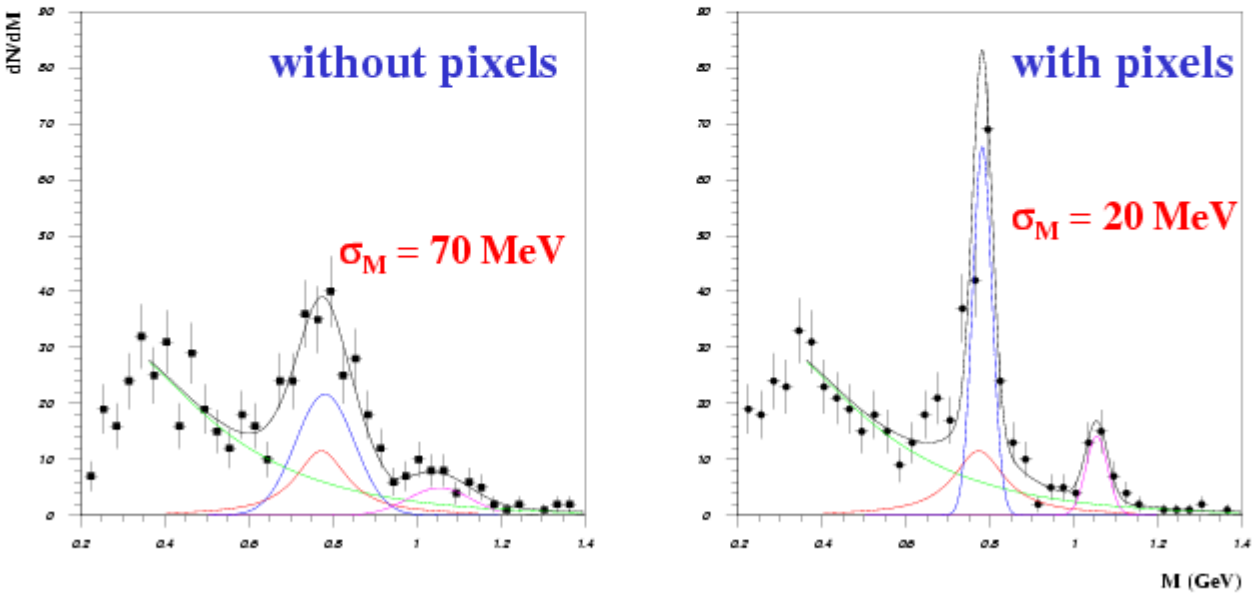


NA60 – (slide from Carlos Lourenço)



Test beam results: p-Be data

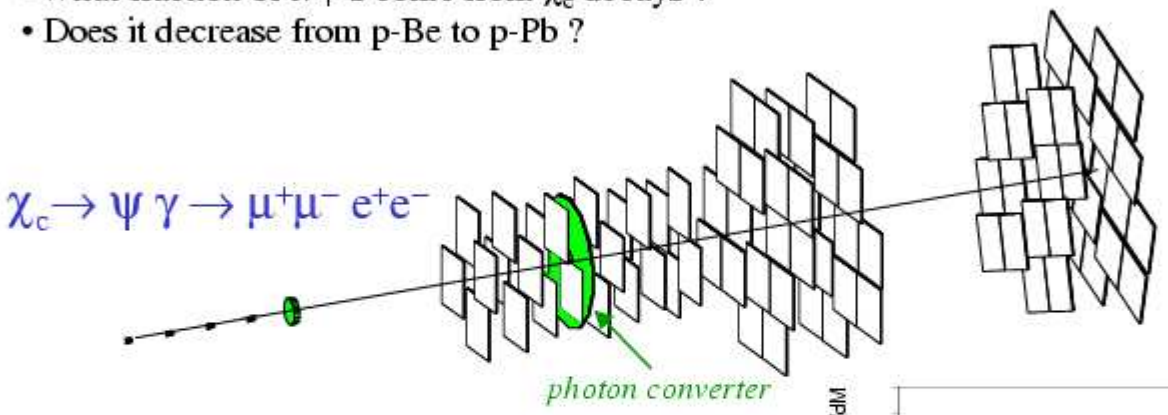
- 450 GeV protons, 10 mm Be target (5 % λ_{int})
- 3 days, ~ 10^{8} protons / burst
- bump-bonding + radiation damage : low detector efficiency



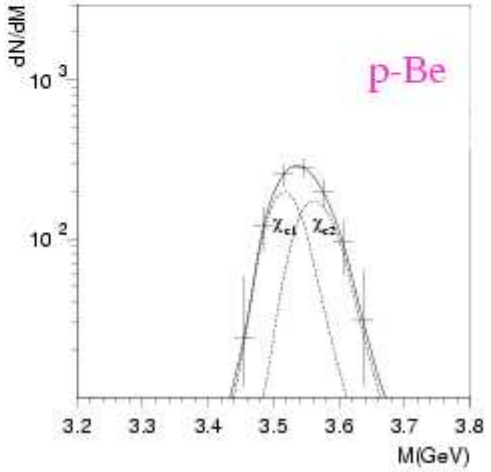
NA60 – (slide from Carlos Lourenço)

NA60 χ_c production in p-Be and p-Pb

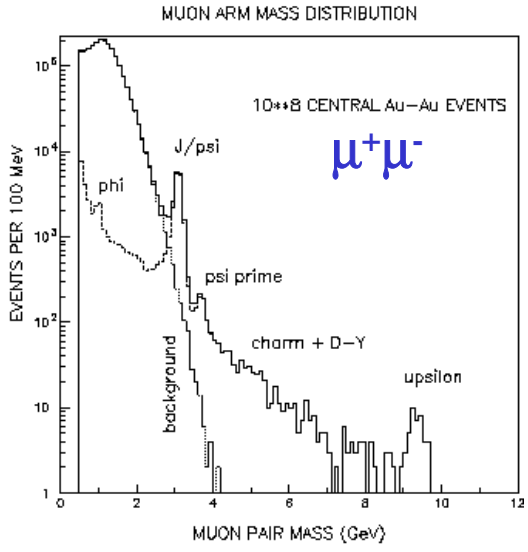
- What fraction of J/ψ's come from χ_c decays ?
- Does it decrease from p-Be to p-Pb ?

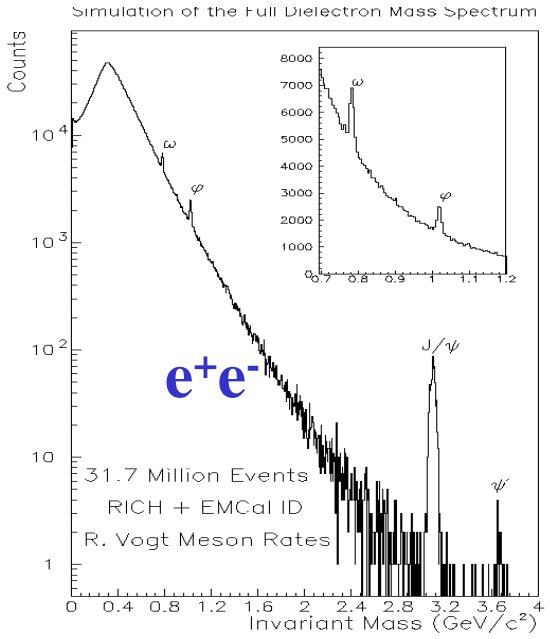


- 4 Be and 1 Pb targets; ~ 30 days of protons
- Dimuons with 2.9<M<3.3 GeV re-fitted imposing ψ mass
- Opposite-sign pairs re-fitted with common vertex in Pb target or disk and M = 2 m_e
- Background subtracted by mixing J/ψ and e^+e^- pairs from different events



NA60 – (slide from Carlos Lourenço)





Charmonium at PHENIX - Coming soon!

- **PHENIX: South Muon & Electrons taking first data now**
- **North Muon in 2003 (after shutdown)**
- **Au-Au collisions now; but d-A collisions hopefully coming soon.**

		PHENIX Muon South	PHENIX Muon North	PHENIX Electron	E866 NuSea**
$\sqrt{S}$ *(GeV)*		200	200	200	39
Y_{CM}		1.2 – 2.2	1.2 – 2.4	-0.35 – 0.35	-0.5 – 2.5
Acceptance	J/Ψ Ψ' ϒ	4.3% " 3.0%	4.3% " 3.0%	0.8% " ----	
Resolution σ*(MeV)*	J/Ψ Ψ' ϒ	110 " 250	110 " 200	20 " ----	100 " 125
Counts*	J/Ψ Ψ' ϒ	610k 10.5k 331	640k 11.5k 382	55k 900 ----	1.5M 60k 17k***

*** Min-bias/RHIC-year for α = .92 (Nagle & Brooks)**

**** E866 nuclear dependence data only *** Upsilons form E772**

J.C.Peng, LANL

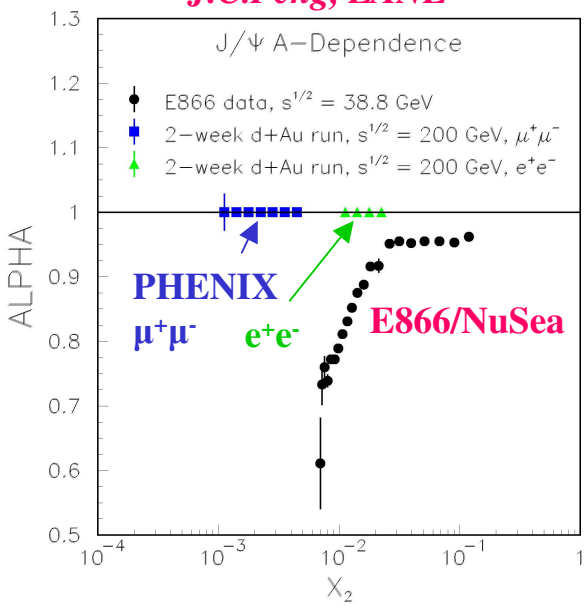
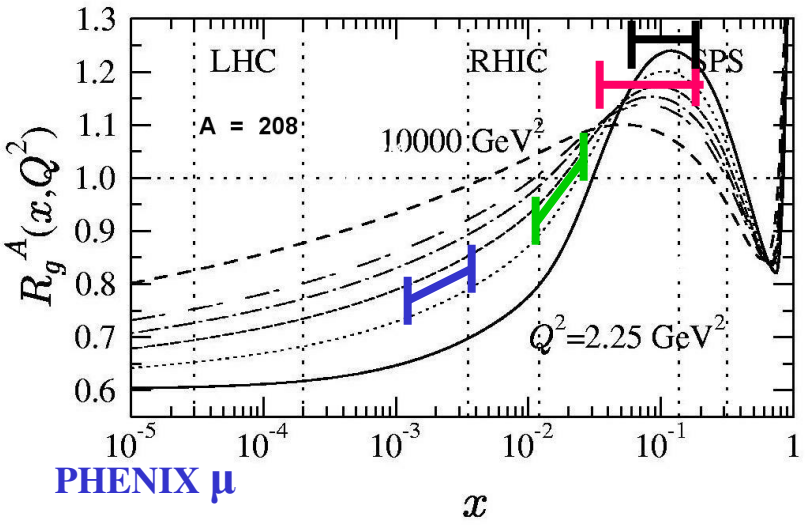


Figure 7: Expected statistical accuracy for measuring the nuclear dependence parameter α from a two-week d+Au run at PHENIX. Data from a fixed-target experiment [6] at $s^{1/2}$ = 38.8 GeV are also shown.

Eskola, Kolhinen, Vogt hep-ph/0104124



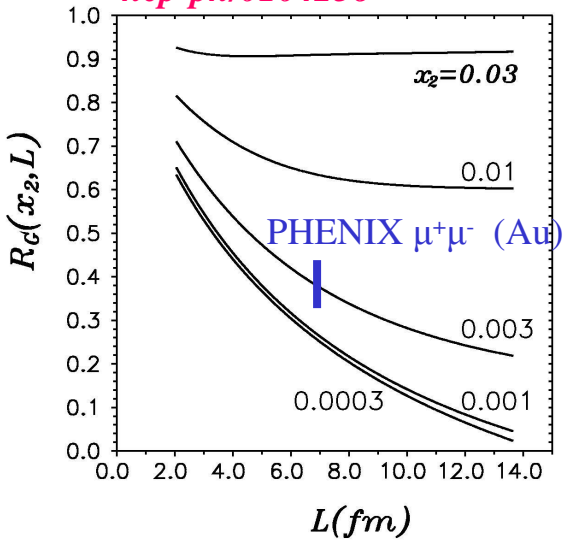
PHENIX μ

PHENIX e

E866 (mid-rapidity)

NA50

Kopeliovich, Tarasov, & Hufner hep-ph/0104256

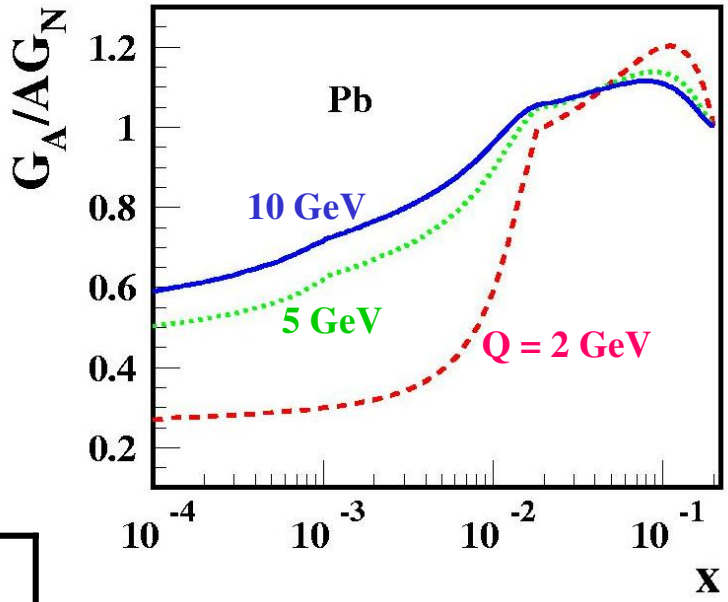


Gluon Shadowing for J/Ψ's

In PHENIX μ acceptance for Au-Au collisions?

- ***Eskola…* : ~ 0.8**
- ***Kopeliovich…* : ~ 0.4**
- ***Strikman… [hep-ph/9812322]* : ~ 0.4**

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



Change due to shadowing for PHENIX μ relative to NA50 for different models to the W/H ratio (*R*) and the resulting effective α.

"Model"	***R***	α
No shadowing difference from fixed-target expt.	1	.92
Eskola…	.66	.84
w/o anti-shadowing	.75	.87
Kopeliovich…	.4	.74

$$R \equiv \frac{R(W/H)_{PHENIX-\mu}}{R(W/H)_{NA50}}$$

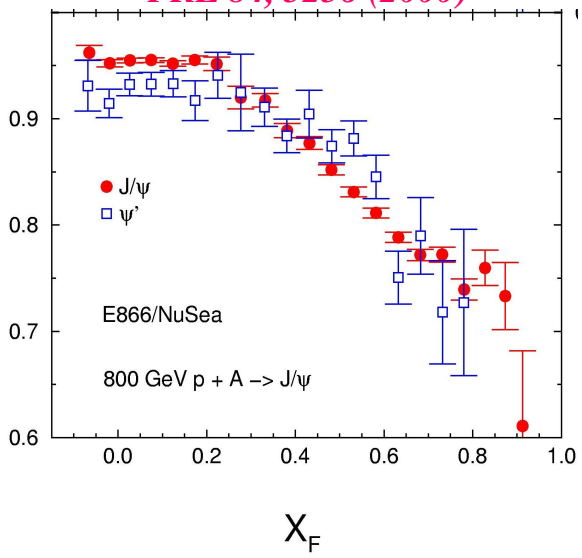
(Ratios due to gluon shadowing alone)

Summary:

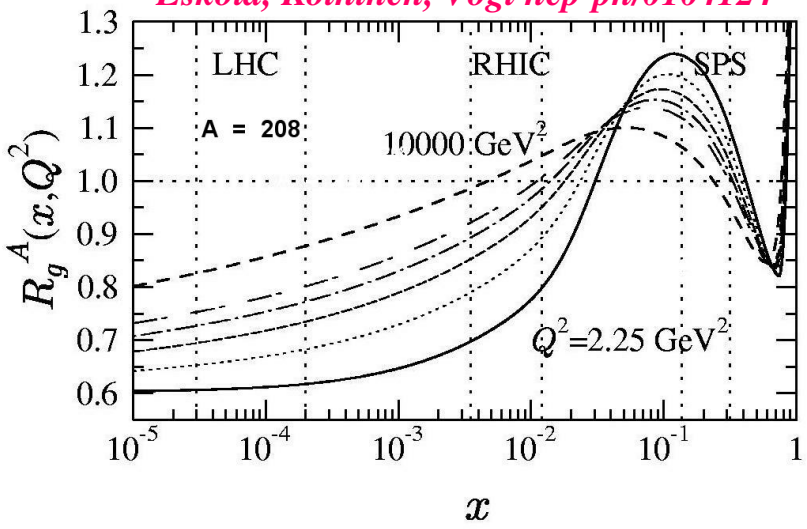
•Charmonium suppression involves a non-trivial interplay between different effects and involves several timescales including that for hadronizaton and for the coherence of a $c\bar{c}$ pair.

•It has large variations with x_F and p_T that help reveal the underlying mechanisms

PRL 84, 3256 (2000)



Eskola, Kolhinen, Vogt hep-ph/0104124

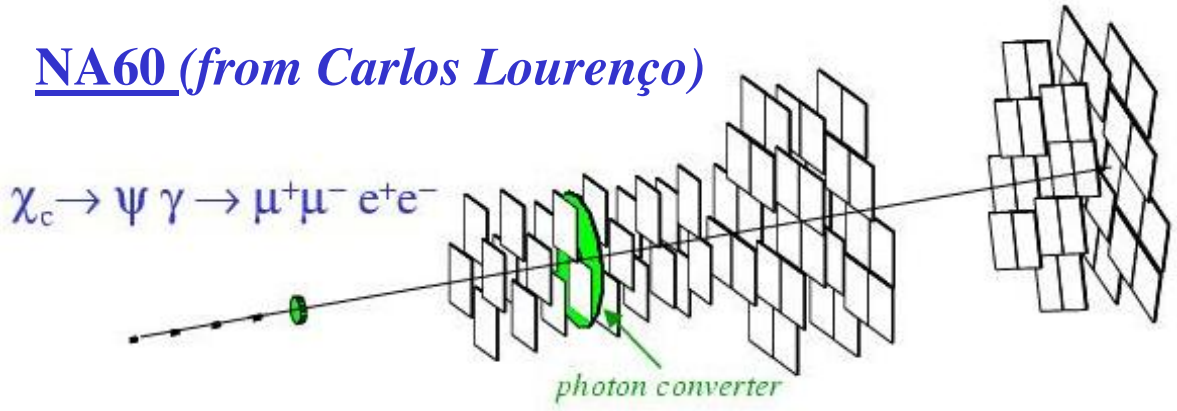


•p-A (or d-A) measurements serve as a basis for understanding what is seen in nucleus-nucleus collisions and are a must at RHIC.

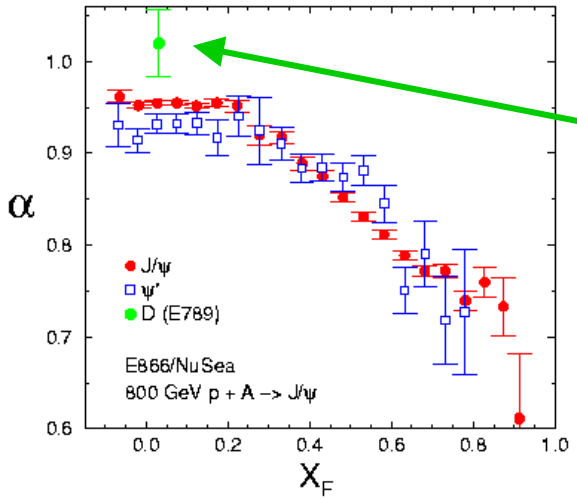
•Shadowing is certainly very important at RHIC and must be measured in d-A collisions as soon as possible

Summary - continued:

NA60 *(from Carlos Lourenço)*



- **Measurements of χ_c are also important both intrinsically and because they contribute through feed-down to the J/Ψ**



E789 D^0 Measurement

PRL 72, 2542 (1994)

- **as also are measurements of open charm which can reveal gluon structure function modifications and initial-state effects**