Quarkonia Production in p-p & p-A Collisions

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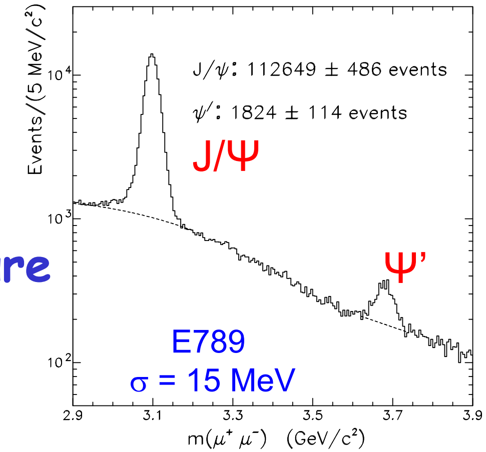
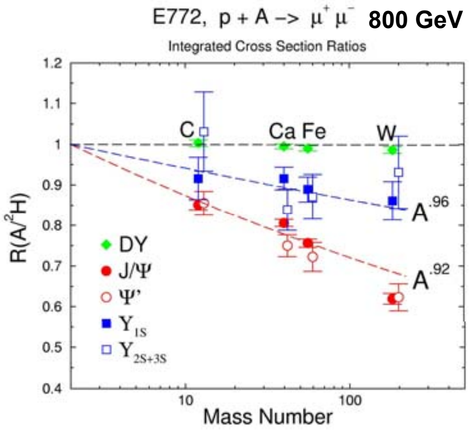
Probing QCD with High Energy Nuclear Collisions

Hirschegg, Austria -- 16-22 January 2005

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





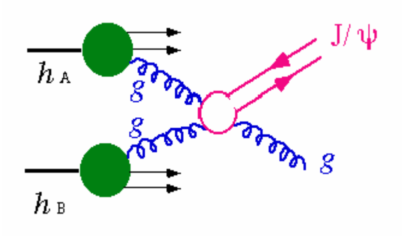
J/ψ & open-charm production, parton level structure & dynamics

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

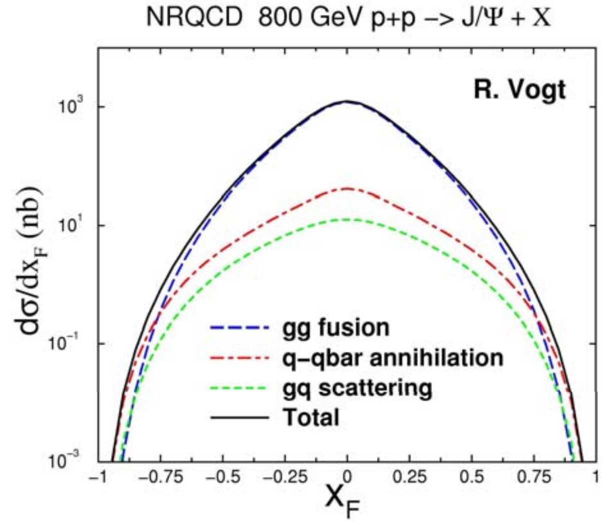
- gluon fusion dominates (NLO calculations add more complicated diagrams but still mostly with gluons)
- production: color singlet or octet $c\bar{c}$: absolute cross section and polarization?
- hadronization time (important for pA nuclear effects)
- complications due to substantial feed-down from higher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

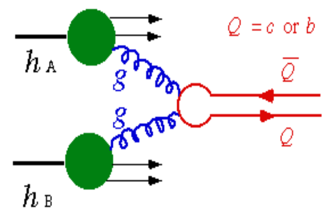
Open charm

- shares sensitivity to gluon distributions and initial-state effects such as p_T broadening, initial-state energy loss
- but different hadronization



Phys.Rev. C61 (2000) 035203





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)

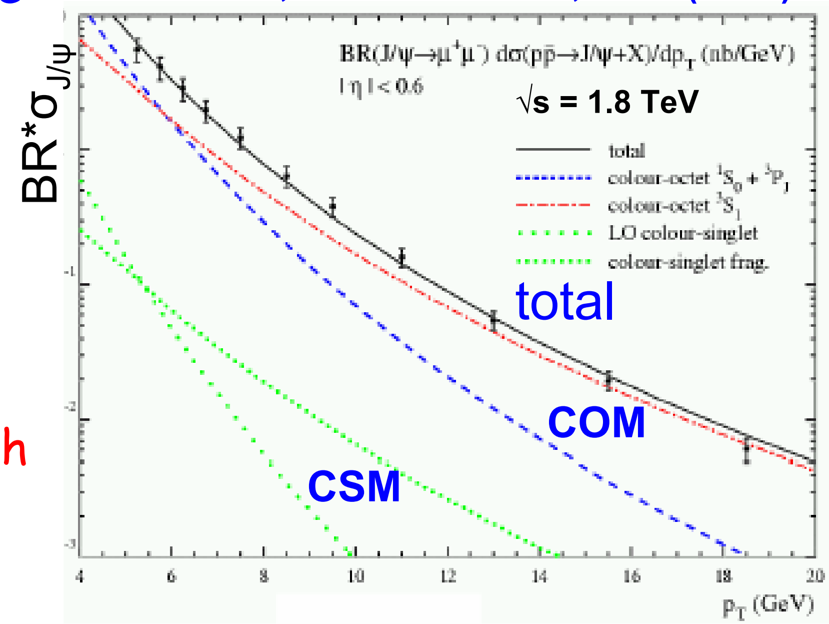
- J/ψ formed from $c\bar{c}$ color-octet state with one or more soft gluons emitted
- Color octet matrix elements should be universal (but are not)
- Predicts transverse polarization at high p_T of J/ψ

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

3-gluon mechanisms (discussed later)

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

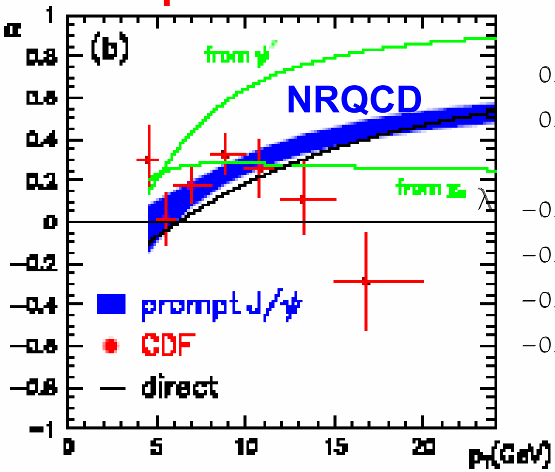


CDF Data first uncovered short-comings of CSM

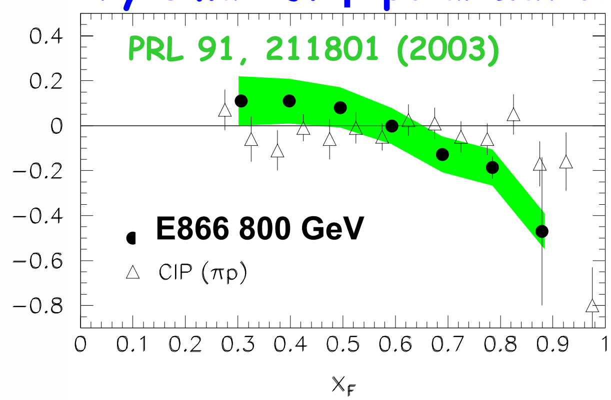
J/ψ Production—Polarization

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

J/ψ Polarization

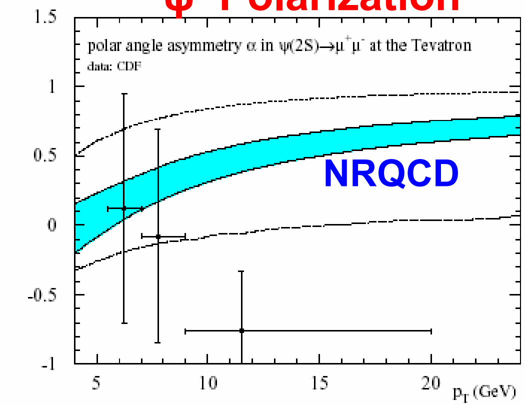


E866
very small J/ψ polarization

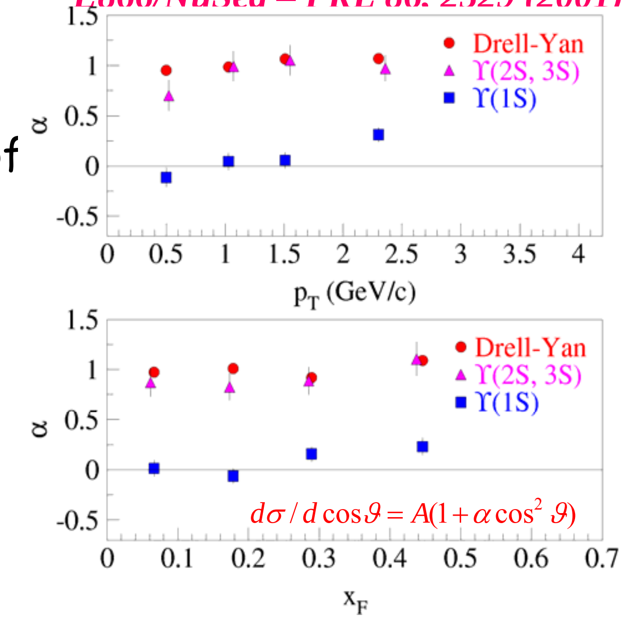


λ = +1 (transverse)
= -1 (longitudinal)

ψ' Polarization



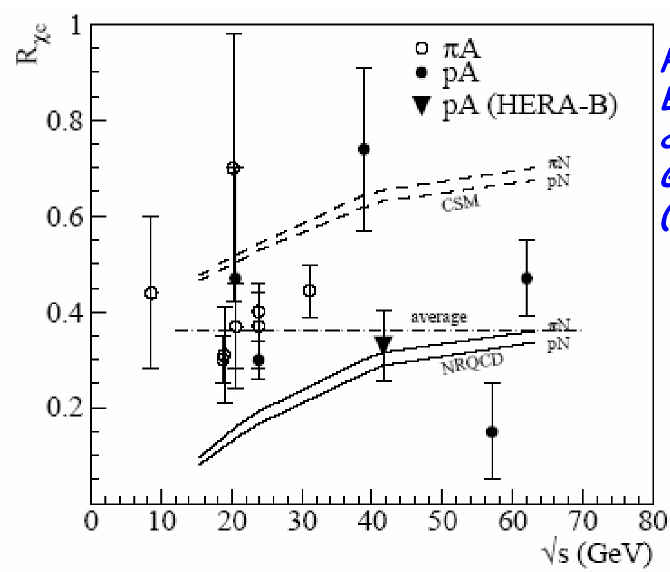
E866/NuSea – PRL 86, 2529 (2001)



- CDF and Fermilab E866 data show little polarization of J/ψ & opposite trend from predictions
  - NRQCD (with octet) predicts:

    $0.25 < \lambda < 0.7$ [Beneke & Rothstein, PRD 54, 2005 (1996)].
- But ϒ maximally polarized for (2S+3S), but NOT (1S)
- Is feed-down washing out polarization? (~50% of 1S from feed-down)

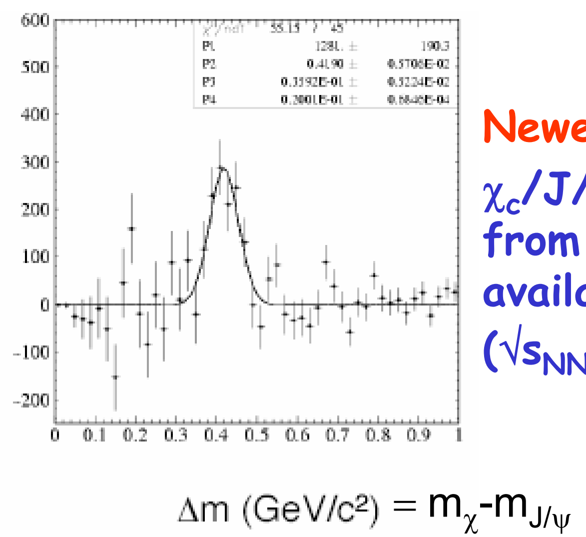
Feeding of J/ψ's from Decay of Higher Mass Resonances



HERA-B Phys.Lett. B561 (2003) 61-72 & 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%



Newer HERA-B

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

Effect on Nuclear dependence:

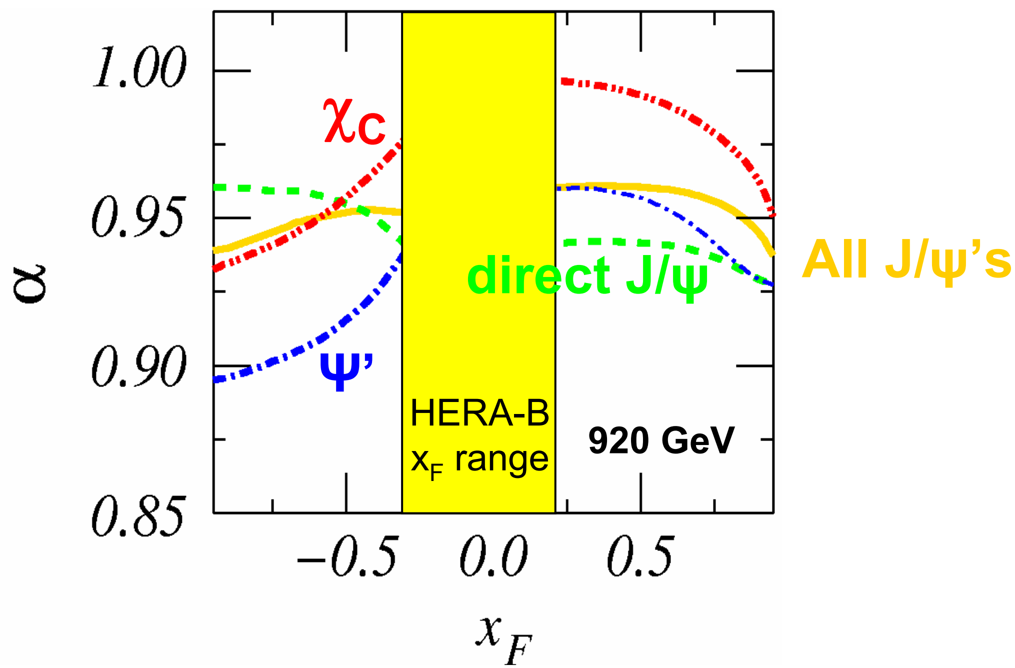
- Nuclear dependence of parent resonance, e.g. χ_c is probably different than that of the J/ψ
- e.g. in proton production ~21-30% of J/ψ's will have different effective absorption because they were actually χ_c's while in the nucleus

Effect of feed-down on nuclear dependence: χ_c, ψ'

- Contributes very significantly to the observed J/ψ yield
- Experimentally accessible (but not easy) through radiative decay $\chi_c \rightarrow J/\psi\ \gamma$
- New results from HERA-B soon

R. Vogt, NRQCD calculations

Nucl. Phys. A700 (2002) 539



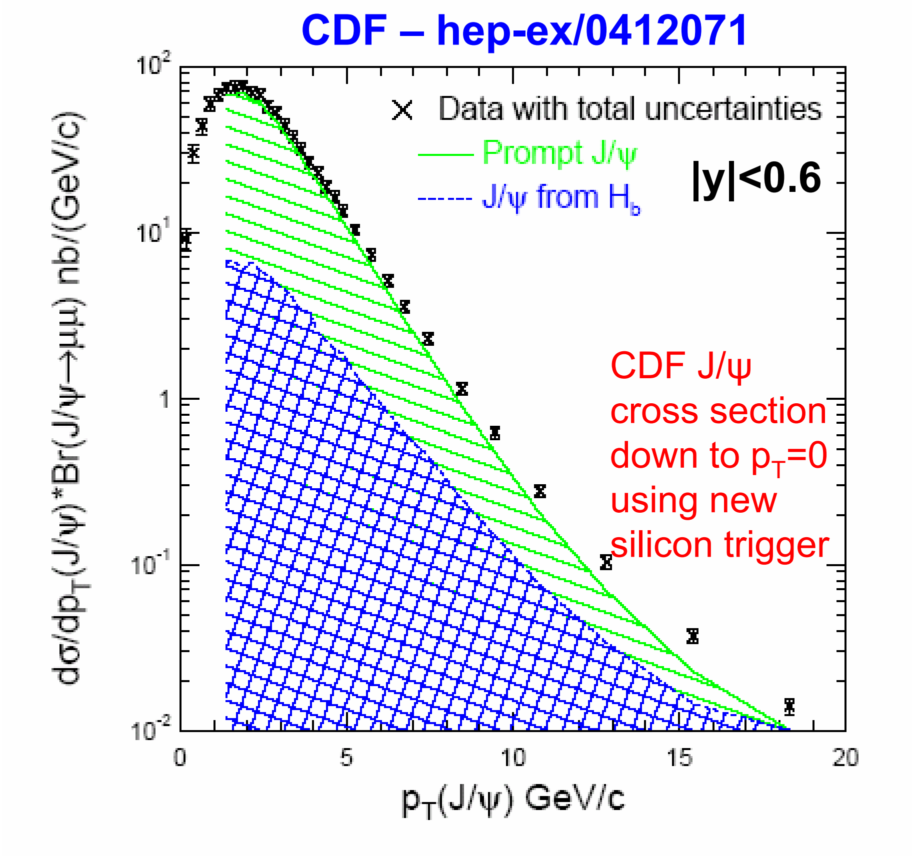
In NRQCD model

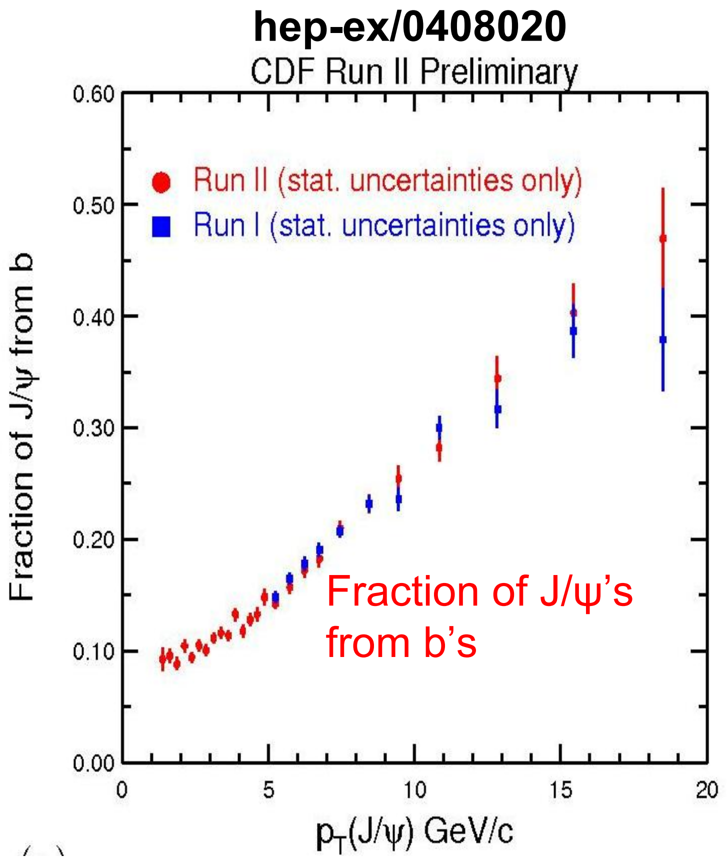
χ_c predominantly produced in a color singlet state

(J/ψ and ψ' in color-octet)

So χ_c expected to be less suppressed than the J/ψ

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

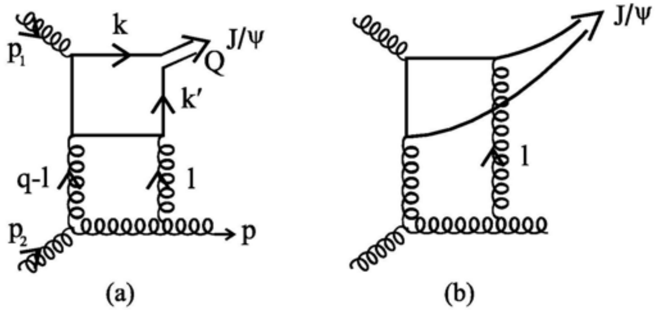


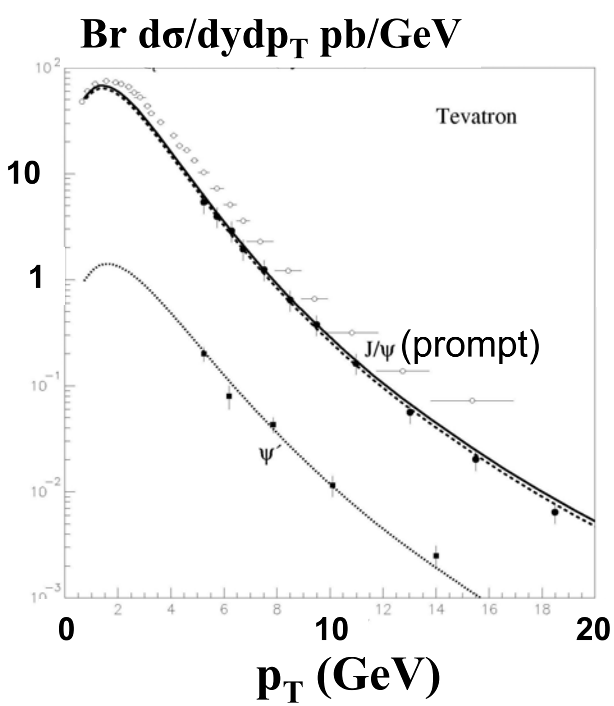


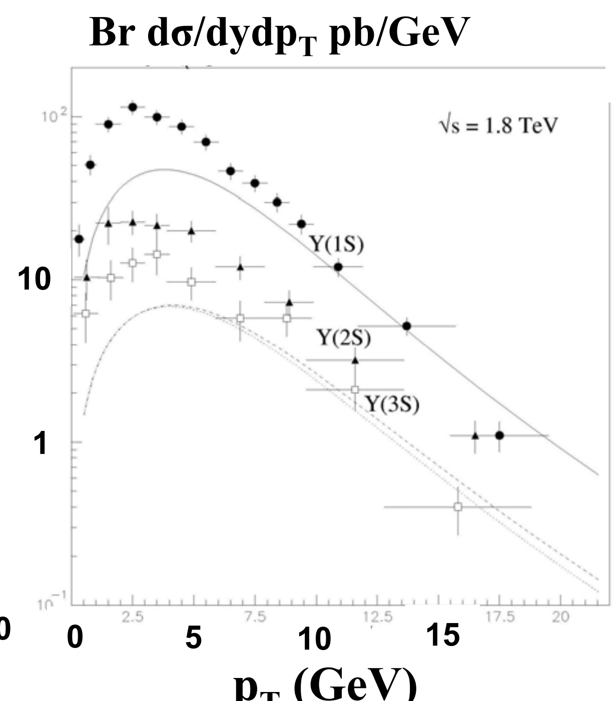
Khoze, Martin, Ryskin & Stirling, hep-ph/0410020

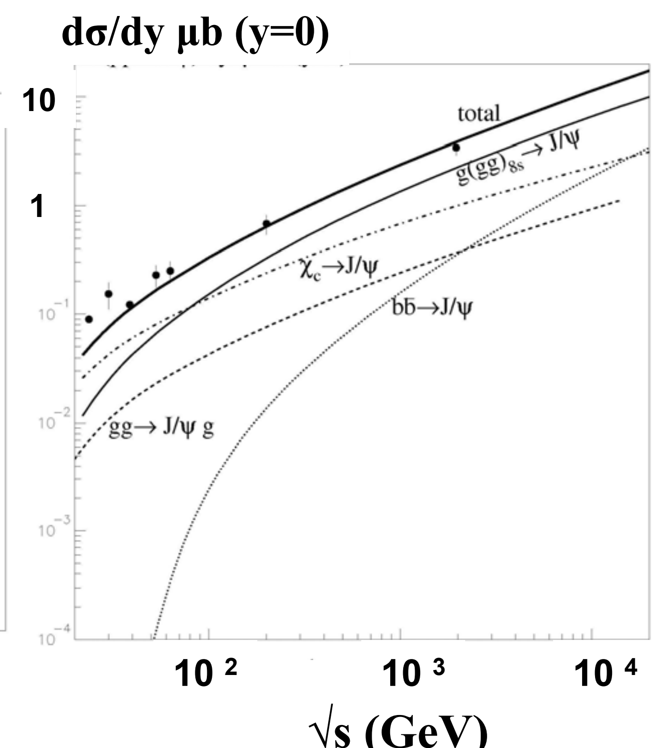
New pQCD calculations (no color-octet):

- 3-gluon diagrams: $g(gg)_{8s} \rightarrow J/\psi$
- agree with Tevatron J/ψ, ψ', Υ data
- predicts longitudinal polarization at large p_T (as seen by CDF and E866)!









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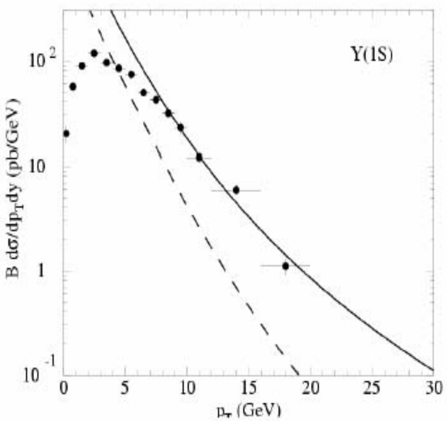
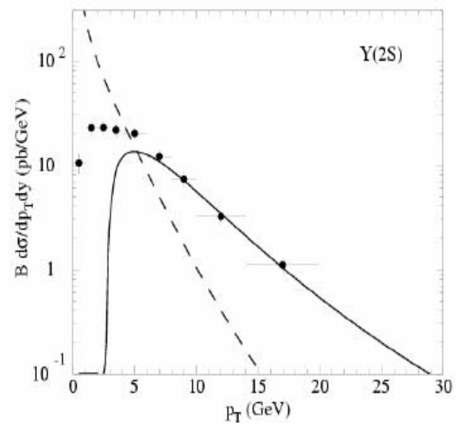
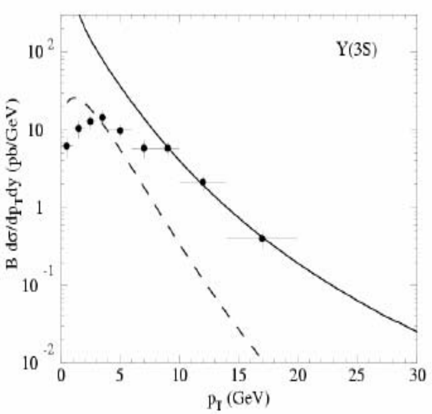
Υ's at CDF

Υ Cross Section at CDF

Run I:
PRL 88 (2002)161802







- smaller discrepancy with CSM but similar to $c\bar{c}$ result
- NRQCD CS+CO terms able to fit data with $p_T > 8$ GeV/c

March 3, 2004

Run I:
PRL 84 (2000) 2094

Direct Υ(1S): $(50.9 \pm 8.2 \pm 9.0)\%$

From $\chi_b(1P)$: $(27.1 \pm 6.9 \pm 4.4)\%$

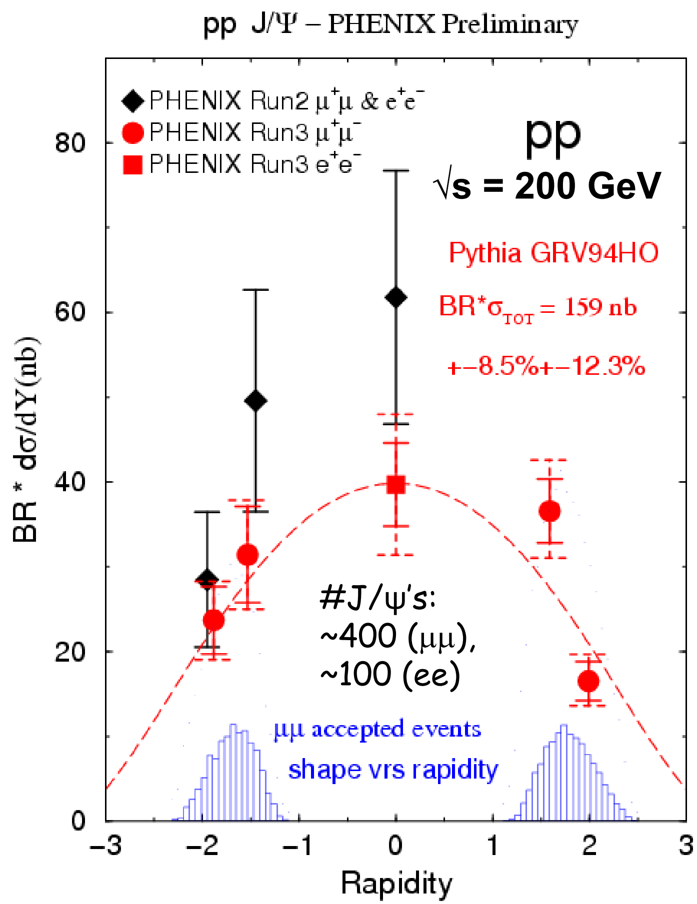
From $\chi_b(2P)$: $(10.5 \pm 4.4 \pm 1.4)\%$

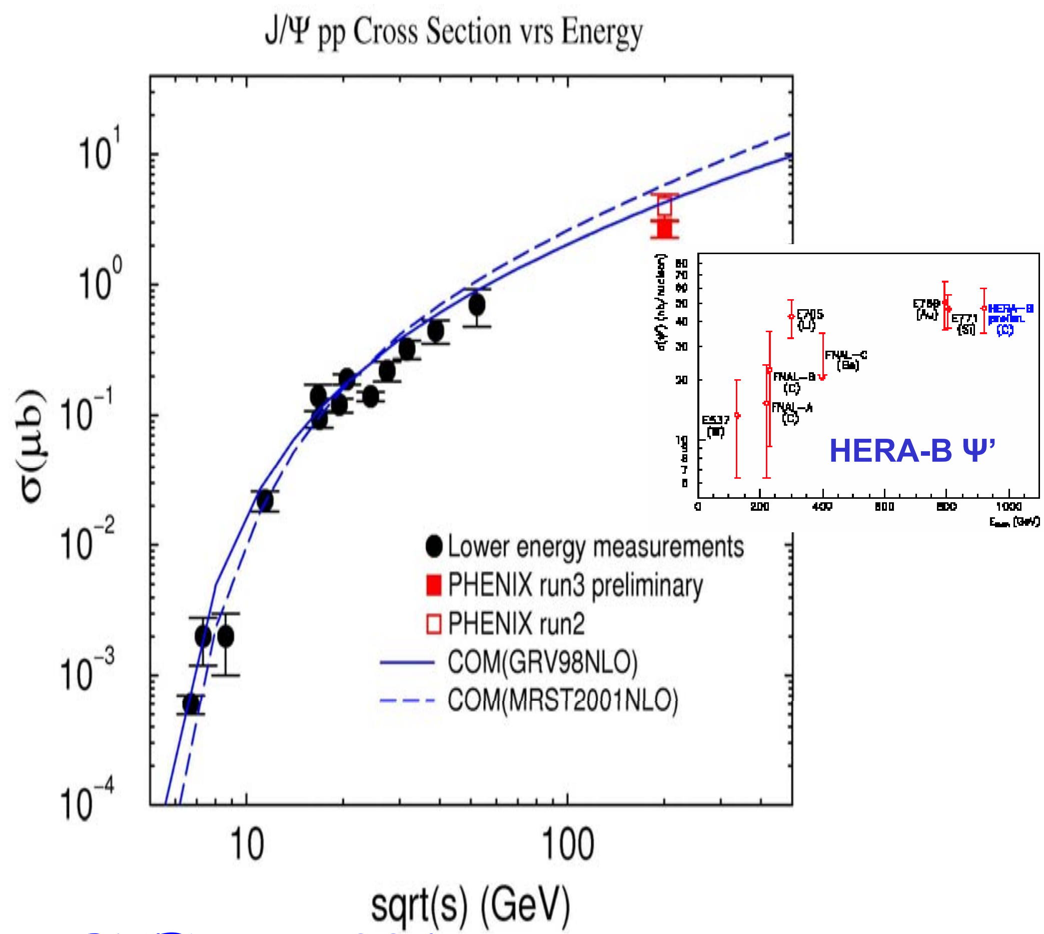
From Υ(2S) : $(10.7^{+7.7}_{-4.8})\%$

From Υ(3S) : $(0.8^{+0.6}_{-0.4})\%$

Input in theoretical calculations of Bottomonium cross sections

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

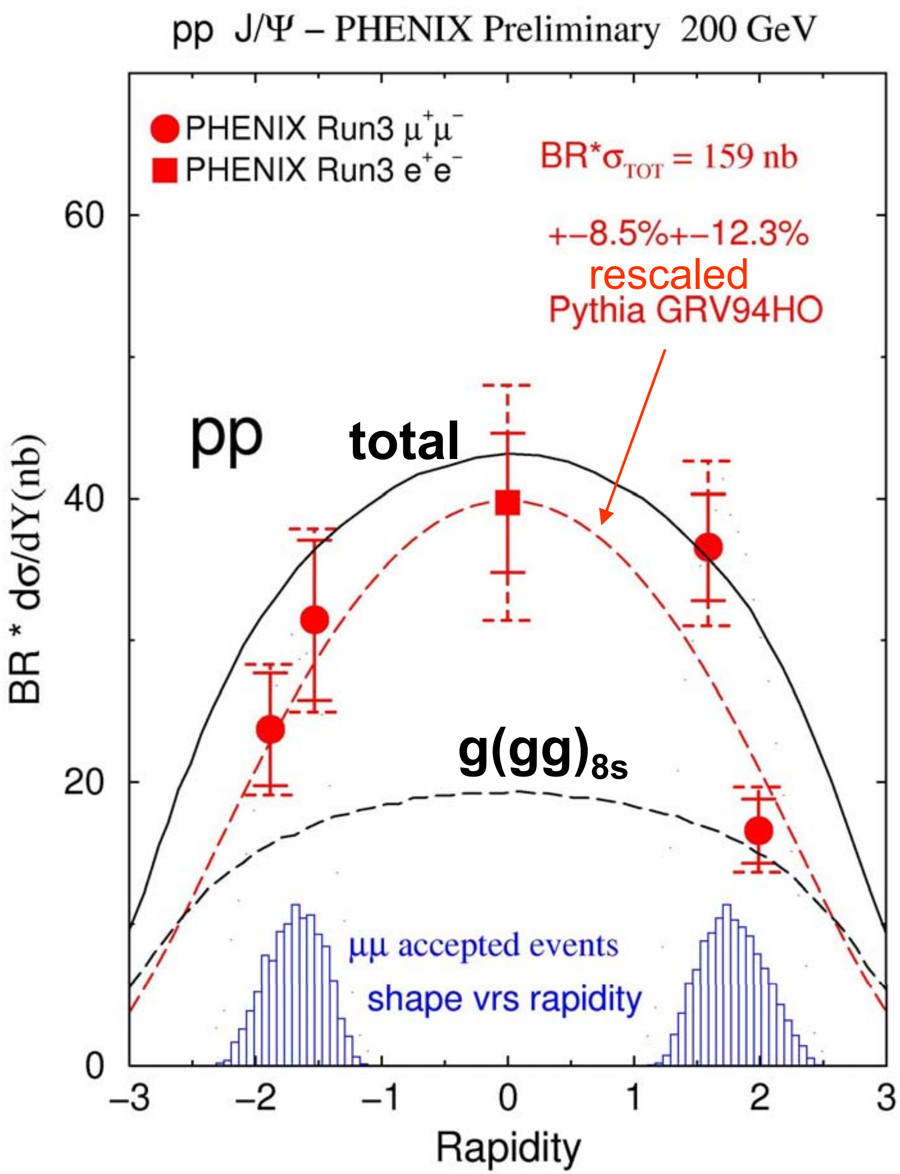




More pp J/ψ's coming from PHENIX 2004 run (~300/muon arm) + many more expected in 2005

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

Khoze, Martin, Ryskin & Stirling, hep-ph/0410020 & private communication

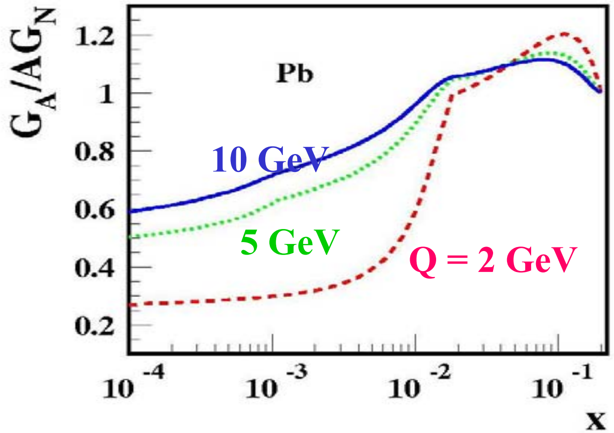


Nuclear modification of parton level structure & dynamics

Modification of parton momentum distributions of nucleons embedded in nuclei

- shadowing – depletion of low-momentum partons (gluons)
- coherence & dynamical shadowing
- gluon saturation – e.g. color glass condensate, a specific/fundamental model of gluon saturation which gives shadowing in nuclei

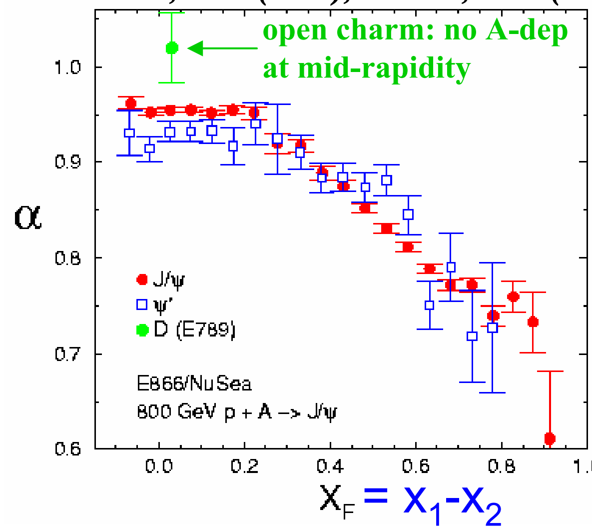
Gluon shadowing
Gerland, Frankfurt, Strikman, Stocker & Greiner (hep-ph/9812322)



Nuclear effects on parton "dynamics"

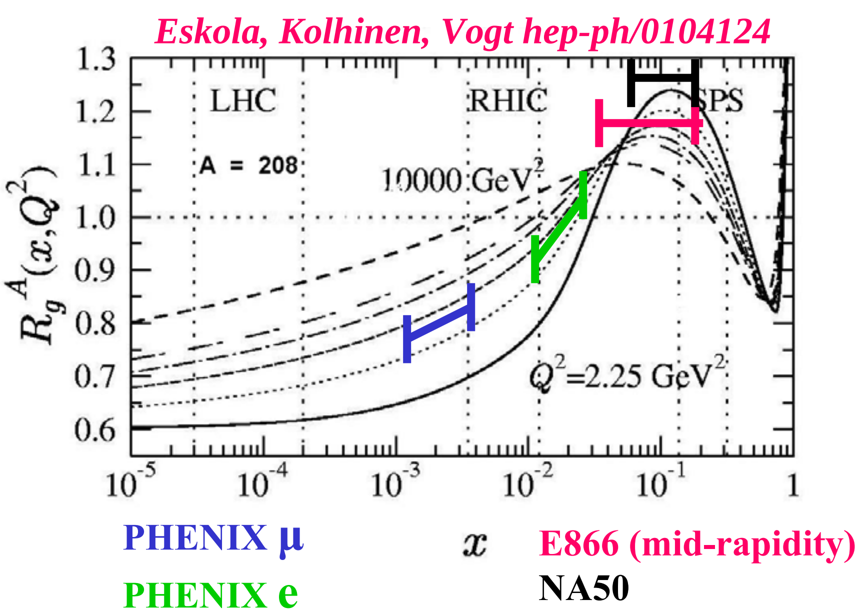
- energy loss of partons as they propagate through nuclei
- and (associated?) multiple scattering effects (Cronin effect)
- absorption of J/ψ on nucleons or co-movers; compared to no-absorption for open charm production

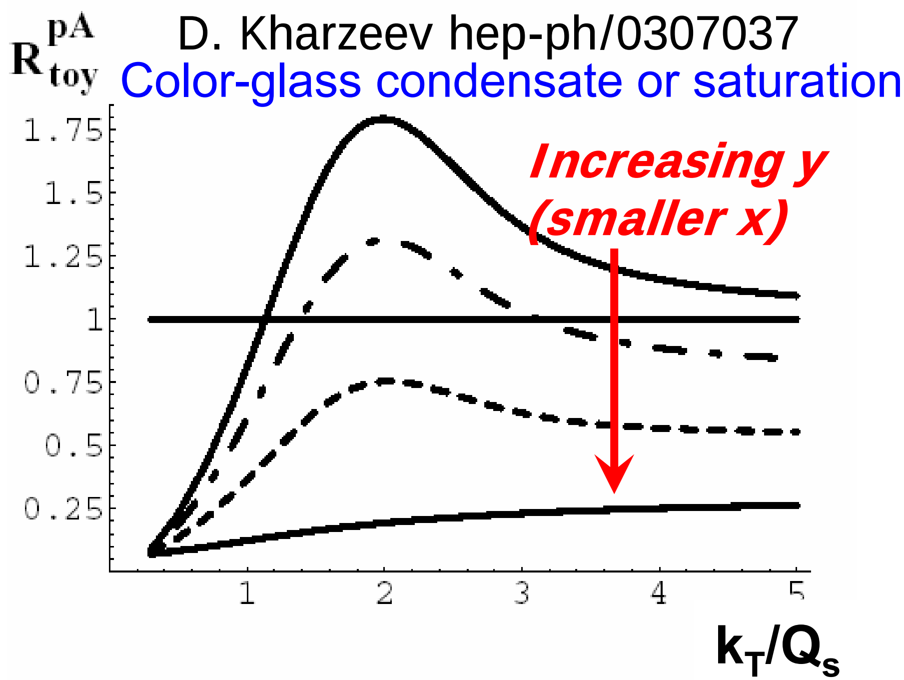
800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^{\alpha}$
PRL 84, 3256 (2000); PRL 72, 2542 (1994)



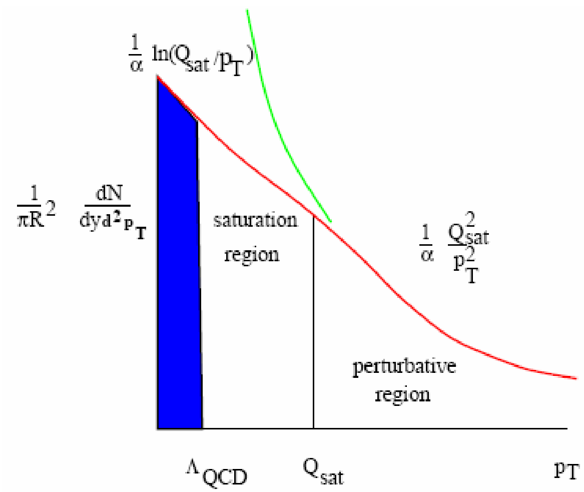
Gluon Shadowing

- **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





Gluon Saturation – the Color Glass Condensate (CGC)



- Gluons saturate and the distribution stops growing.
- Recently, a new way to look at this phenomena (McLerran, Venugopalan et al.)
- At low x there are so many gluons, that the quantum occupation numbers get so large that the situation looks classical.
- Can use renormalization group methods to do a calculation of this effect. Depends only on a "scale"
  $\Lambda_{CGC}^2 = (1/\pi R^2)(dN_{gluon}/dy) \sim$ 2-D gluon density

$$\Lambda^2{}_{CGC} = \frac{\left(\frac{dN_{gluon}}{dy}\right)_p}{\pi R^2{}_p} = \frac{\left(\frac{dN_{gluon}}{dy}\right)_A}{\pi R^2{}_A}$$

→ $dN/dy \sim R^3 \sim A$

- Nuclear amplification: $x_A G(x_A) = A^{1/3} x_p G(x_p)$, i.e. gluon density is ~6x higher in Gold
- Assume $xG(x) \sim x^{-\delta}$ with $\delta = 0.2$ to 0.4
- Saturation region around $x_p \sim 10^{-4}$

  (Golec-Biernat, Wusthoff PRD 59,014017, 1998)
- Need to reach $x_p \sim 10^{-4} \rightarrow x_{Au} \geq 10^{-2}$

(from Rich Seto & Raju Venugopalan)

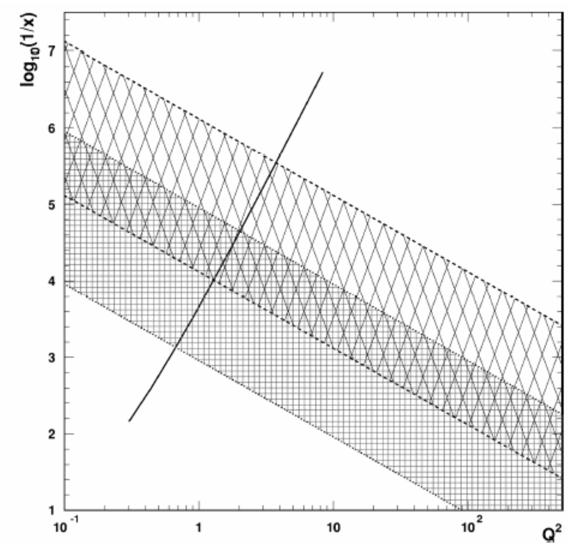
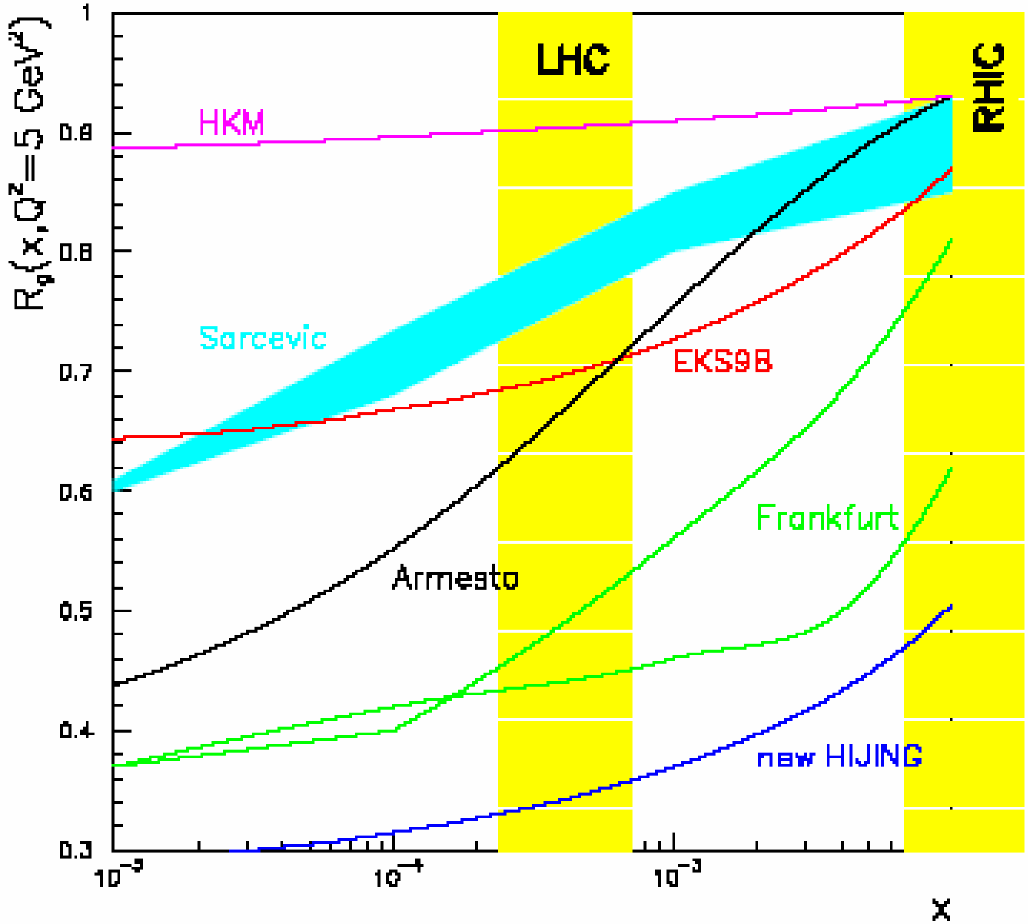


FIG. 5. The position of the critical line in the (x, Q^2)-plane. The narrow hatched area corresponds to the acceptance region of HERA. The wide hatched region indicates the range for a future 1 TeV *ep*-collider. The boundaries are lines of constant y.

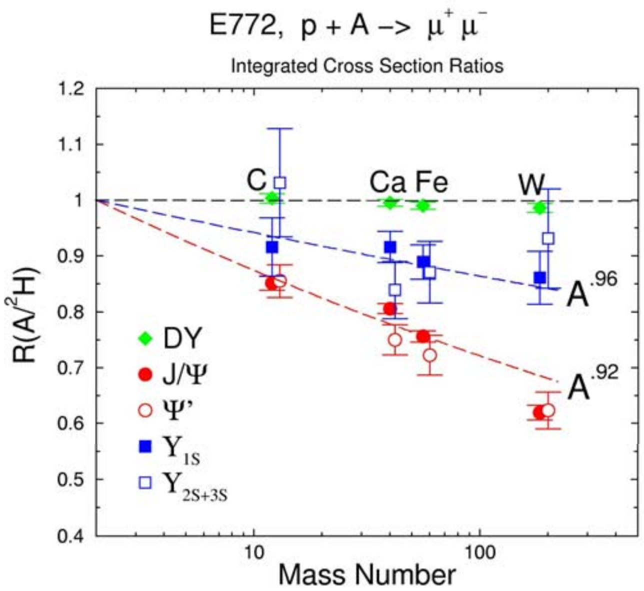
Large variations of predicted Gluon Shadowing!

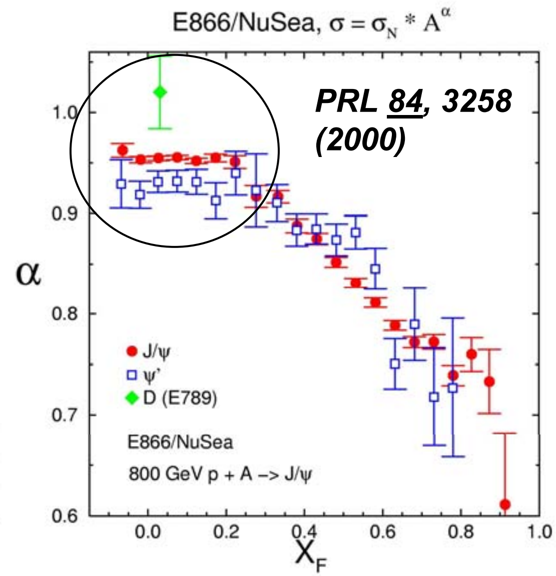


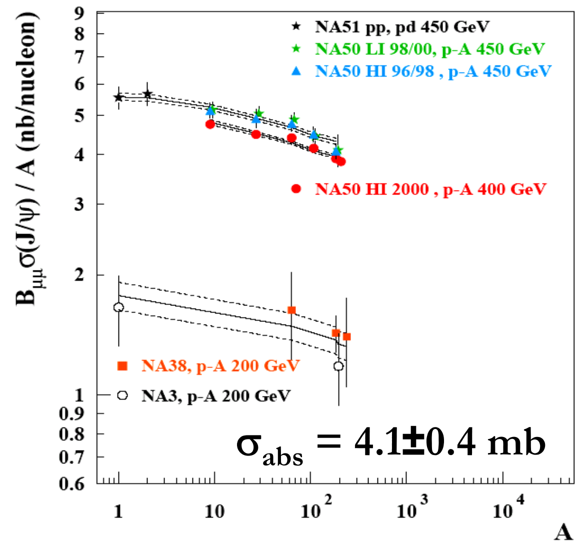
from
hep-ph/0308248
N. Armesto &
C. Salgado

Fig. 13: Ratios of gluon distribution functions from different models at $Q^2 = 5$ GeV^2; HKM refers to the results from Ref. [29], Sarcevic, Ref. [107], EKS98, Refs. [27, 28], Frankfurt, Ref. [103], Armesto, Refs. [89, 106] and new HIJING, Ref. [66]. The bands represent the ranges of $x = (Q/\sqrt{s})e^y$ for processes with $|y| \leq 0.5$, $Q^2 = 5$ GeV^2 at RHIC ($\sqrt{s} = 200$ GeV) and LHC ($\sqrt{s} = 5.5$ TeV).

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







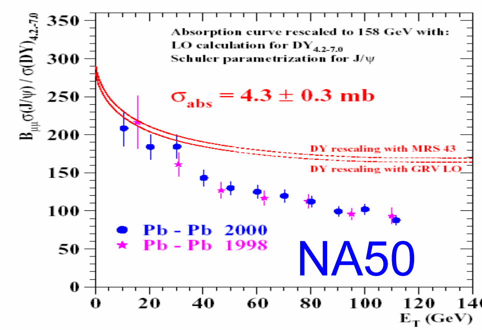
Breakup by nucleus of J/ψ or pre-J/ψ ($c\bar{c}$) as it exits nucleus

Power law parameterization $\sigma = \sigma_N * A^\alpha$

- $\alpha = 0.954 \pm 0.003$ E866/NuSea @ x_F=0.
- $\alpha = 0.941 \pm 0.004$ NA50, QM2004

Absorption model parameterization (from pA)

- $\sigma = 4.1 \pm 0.3$ mb NA38/50/51



Small difference between J/ψ and ψ(2S)

- $\alpha(J/\psi) - \alpha(\psi(2S)) \sim 0.02\text{-}0.03$ @ $x_F = 0$ (E866/NuSea)
- $\sigma_{abs}^{\psi'} = (7.9 \pm 0.6)$ mb (NA50) to be compared with $\sigma_{abs}^{J/\psi} = (4.1 \pm 0.4)$ mb
- $\alpha_{\psi'} = 0.858 \pm 0.017 \pm 0.008$ (NA50) → smaller than E866 (~0.92) → energy dependence?

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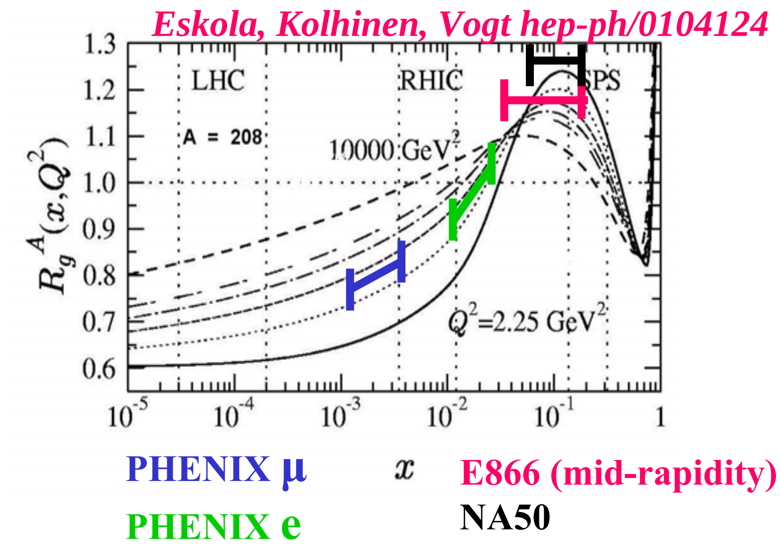
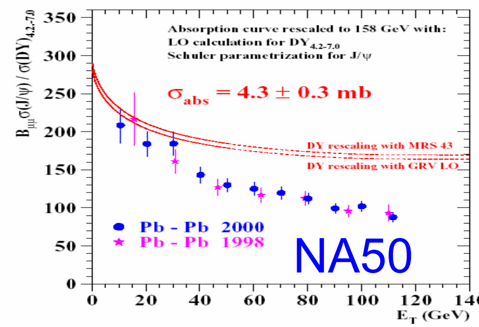
Absorption of J/ψ's not so simple?



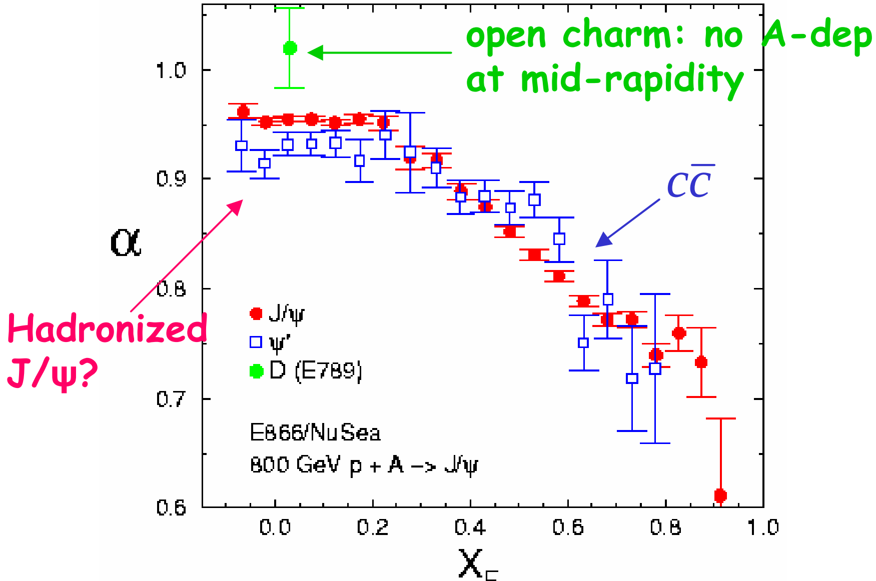
Set	P_{lab}	N_0 (nb)	σ_{abs} (mb)
NA50	450 GeV	5.6±0.1	4.1±0.4
NA50	400 GeV	5.1±0.1	
NA38 (corrected)	400 GeV	5.5±0.2	



- What really is $\sigma_{abs}^{J/\psi}$?
  - An effective quantity
  - What is crossing the nucleus and how does it evolve?
    - pre-resonant $c\bar{c}$ state, fully formed resonance?
  - Are we measuring primary J/ψ?
    - feed-down from ψ' and χ_c
    - will fraction of feed-down change in AA collisions?
  - Does anti-shadowing make absorption appear smaller than it is?

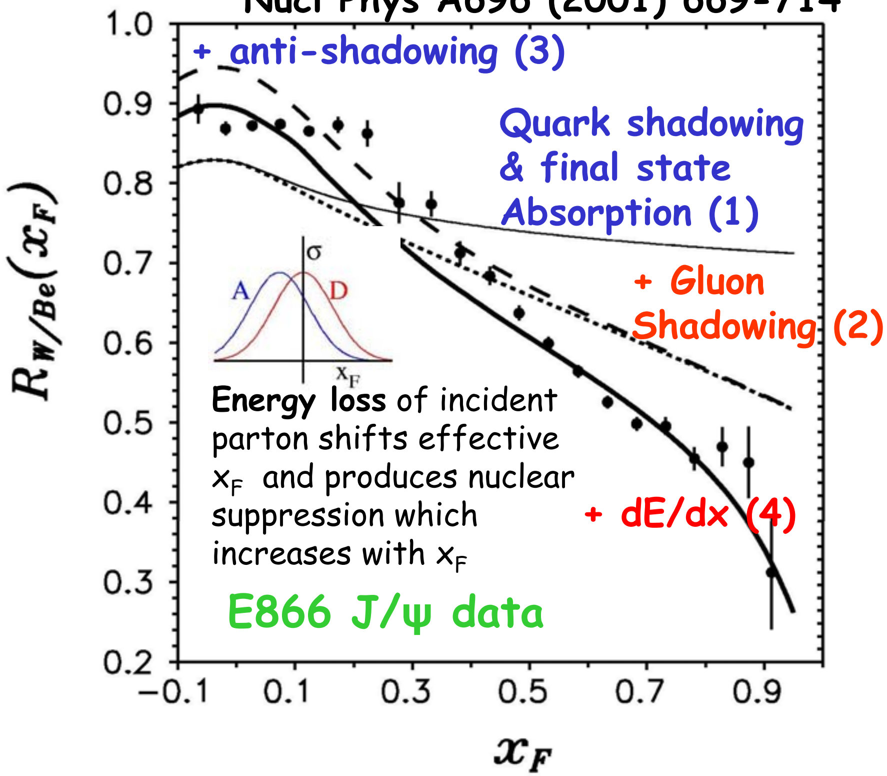
J/ψ suppression in pA fixed-target

800 GeV p-A (FNAL)
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?

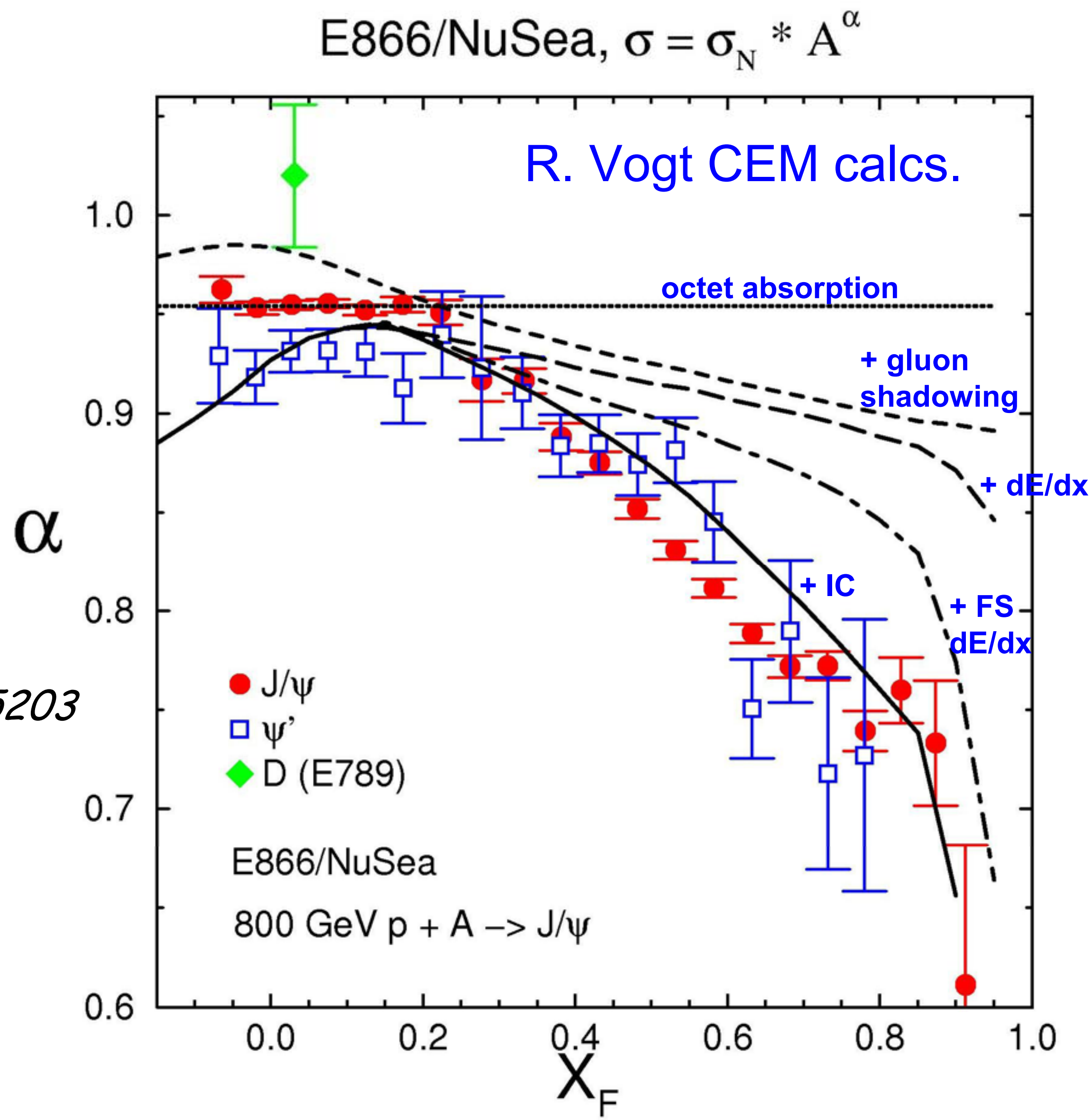
Kopeliovich, Tarasov, Hufner
Nucl Phys A696 (2001) 669-714



Another description of J/ψ nuclear dependence

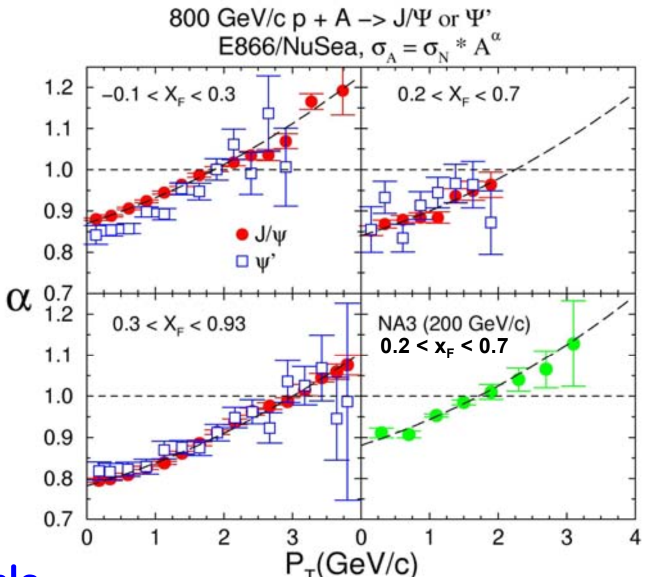
Many ingredients to explain the J/ψ nuclear dependence – R. Vogt

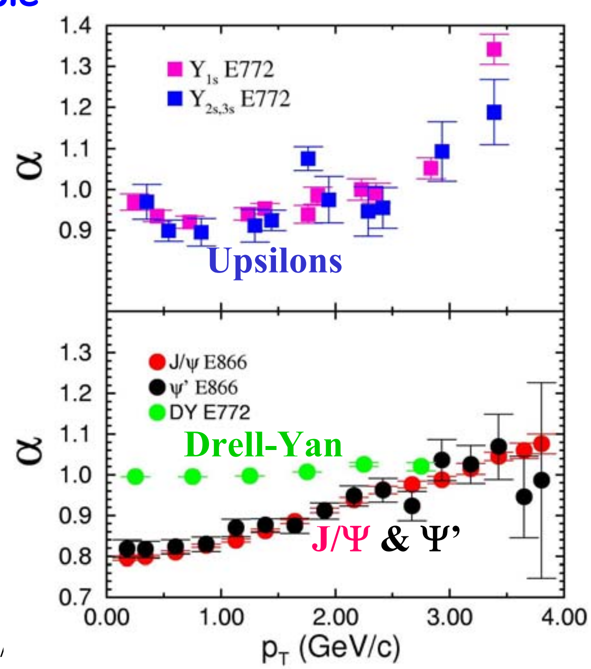
hep-ph/9907317 & Phys.Rev. C61 (2000) 035203

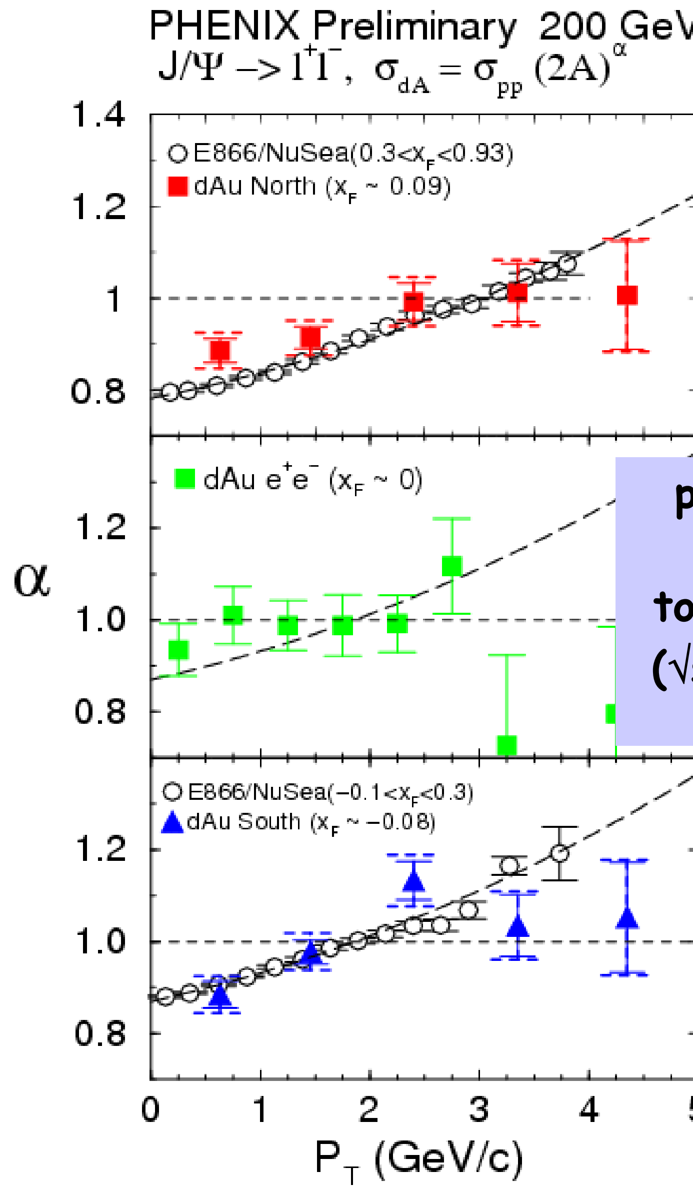


P_T Broadening for J/ψ's

Usually interpreted as initial-state multiple scattering





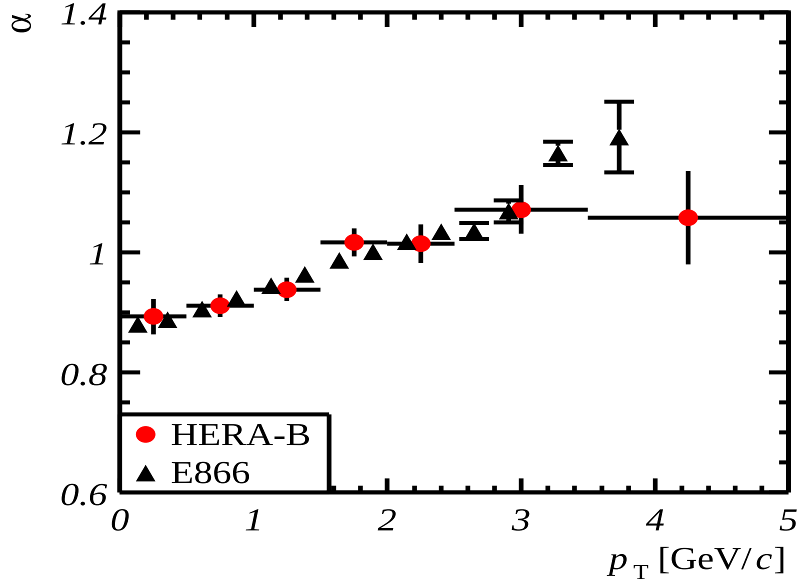


Low x_2 ~ 0.003

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

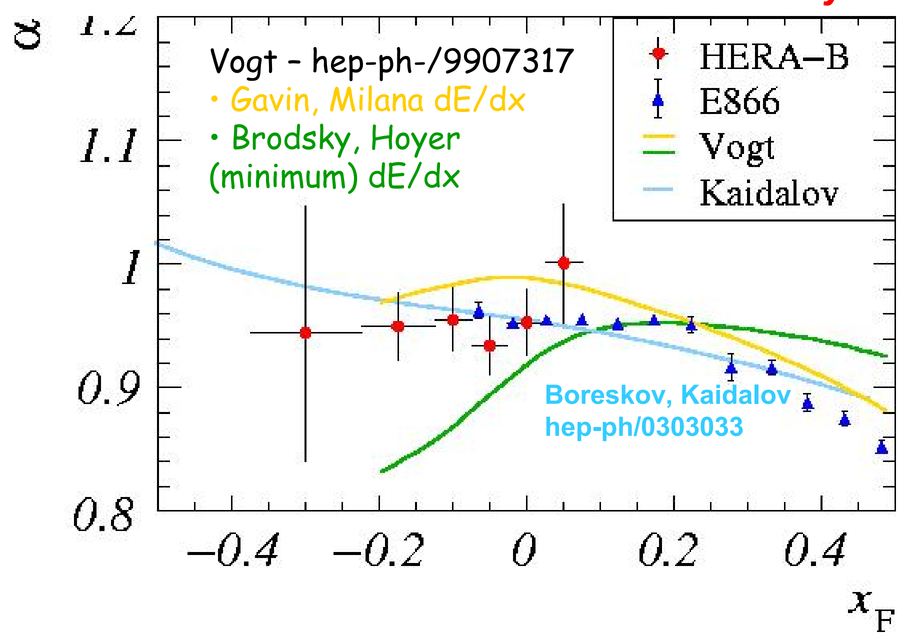
High x_2 ~ 0.09

HERA-B - J/ψ A dependence



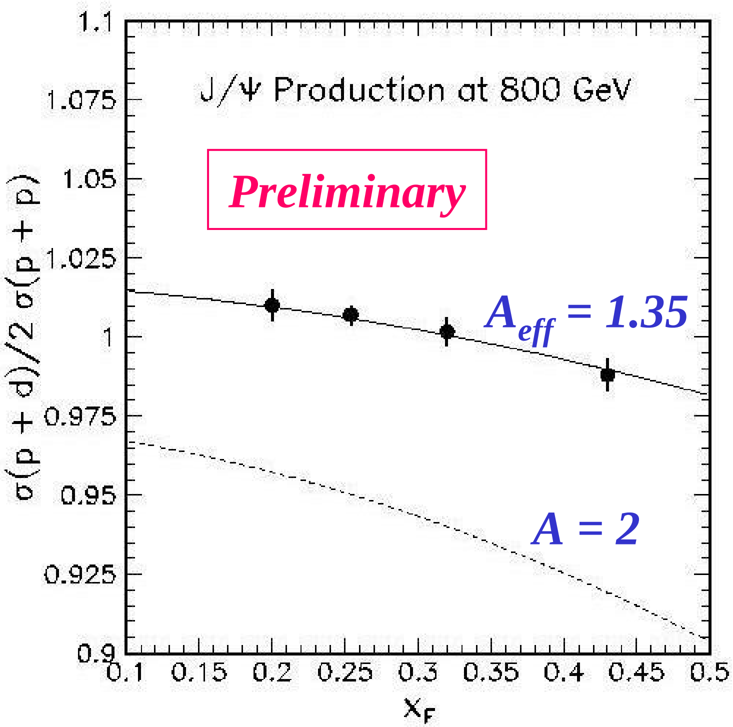
A. Zoccoli (HERA-B) – talk @ Hard Probes 2004

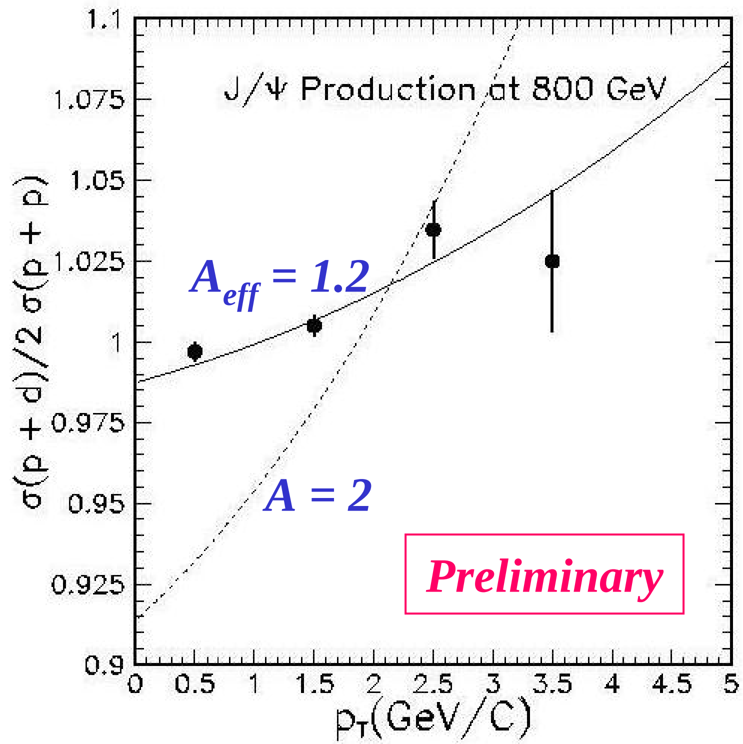
Preliminary



- Previous result of FNAL E866 extended to $x_F = -0.35$
- Result from 15% of full $\mu^+ \mu^-$ sample, statistical uncertainties only, similar results for e^+e^-
- Work on systematics ongoing. Complete the analysis on the full data sample.

J/ψ Nuclear dependence seen even for Deuterium/Hydrogen!



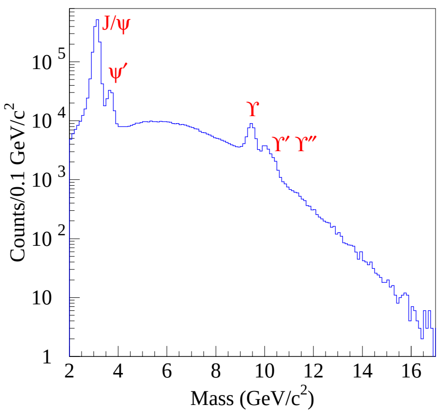


Nuclear dependence in deuterium seems to follow the systematics of larger nuclei, but with an effective A, A_{eff}, smaller than two.

From fits to E866/NuSea
p + Be, Fe, W data: $\sigma_{pA} \sim \sigma_{pp} A^{\alpha}$

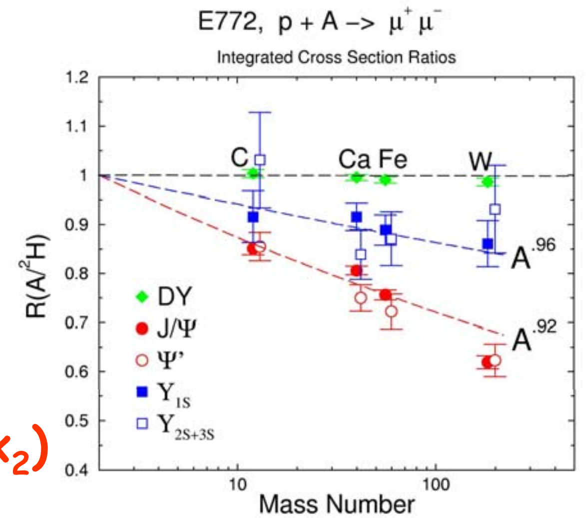
$$\alpha(x_F) \propto 1 - 0.052 x_F - 0.034 x_F^2$$
$$\alpha(p_T) \propto 0.06 p_T + 0.011 p_T^2$$

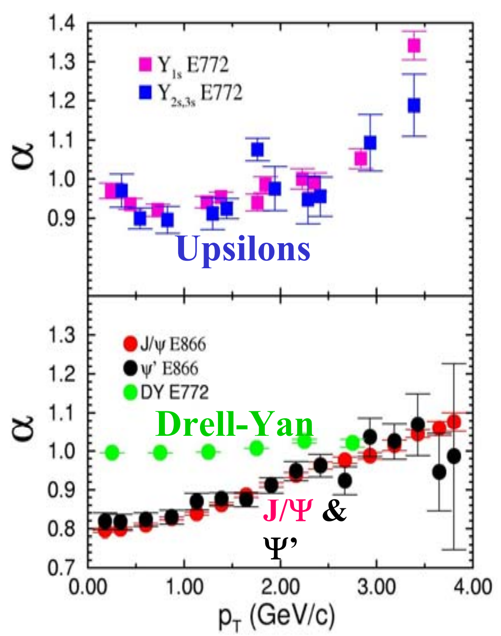
Contrasting ϒ's with J/ψ's

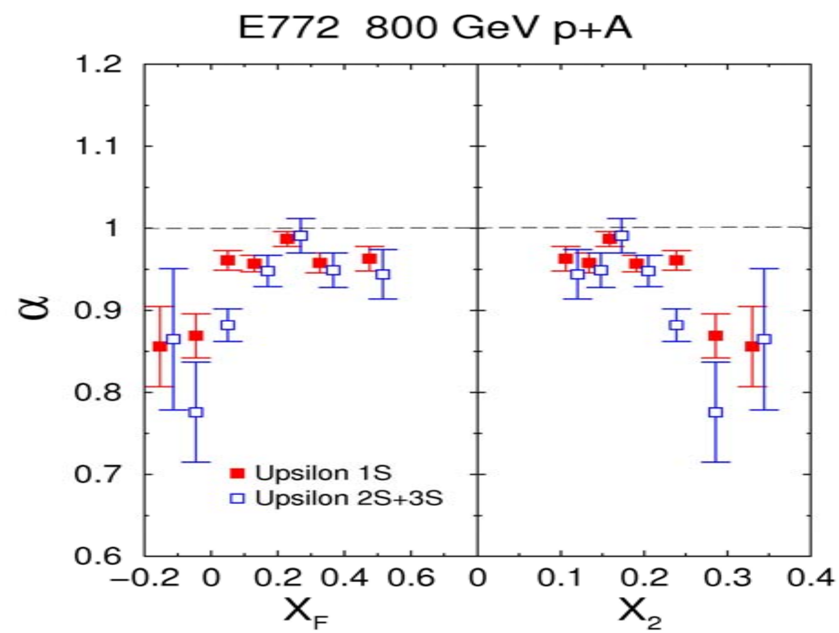


At √S = 39 GeV (E772/E866)

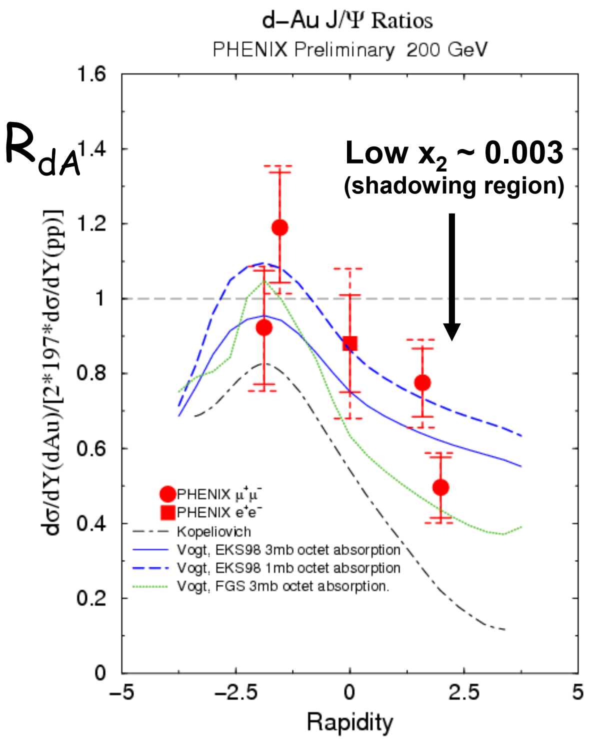
- less absorption
- similar p_T broadening
- Υ_{2S+3S} have large transverse polarization (unlike Υ_{1S} or J/ψ)
- not in shadowing region (large x_2)





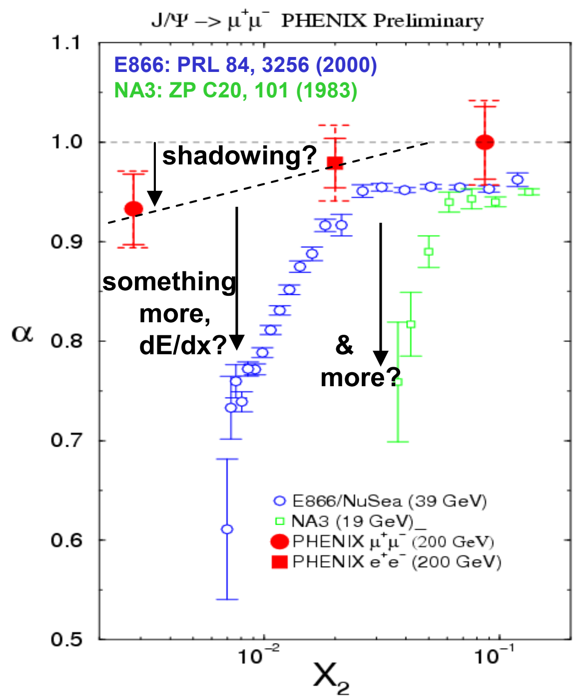


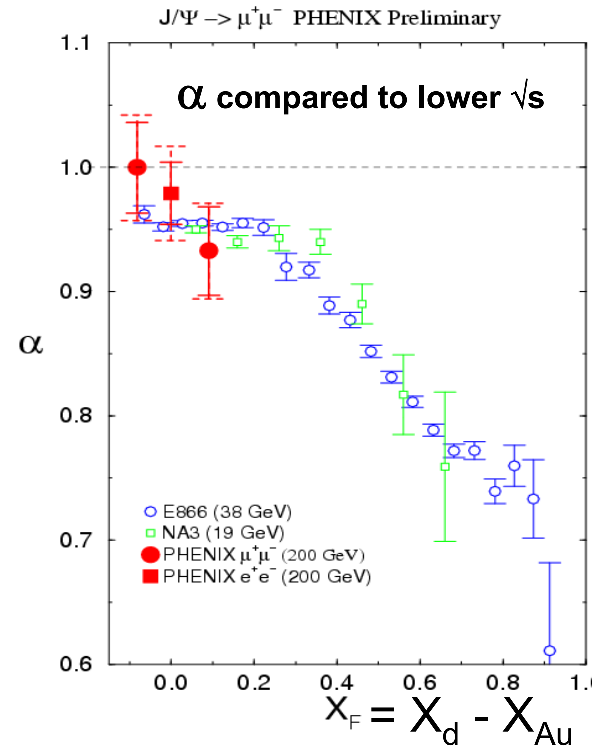
J/ψ nuclear dependence vrs rapidity, x_{Au}, x_F PHENIX compared to lower energy measurements



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 main story.

BUT does scale with x_F ! - why?

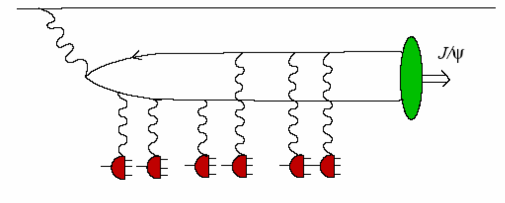
(Initial-state gluon energy loss -which goes as $x_1 \sim x_F$ - expected to be weak at RHIC energy)

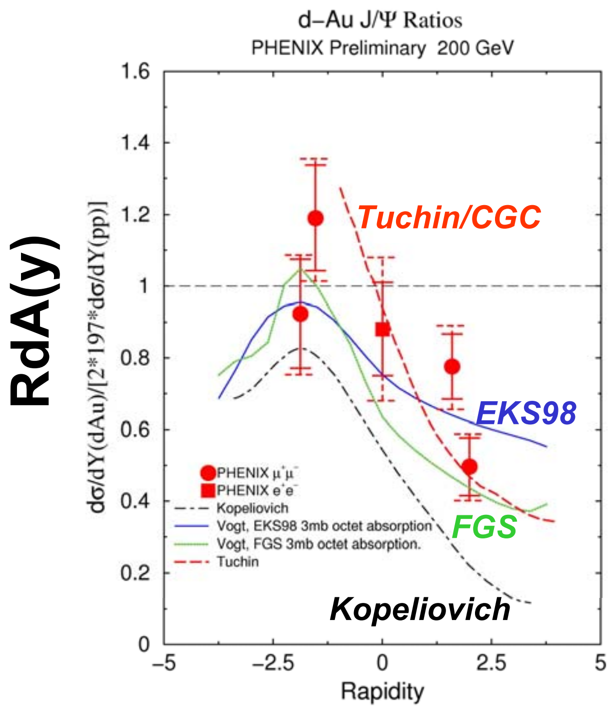
"Open and hidden charm production in d-A and A-A collisions"

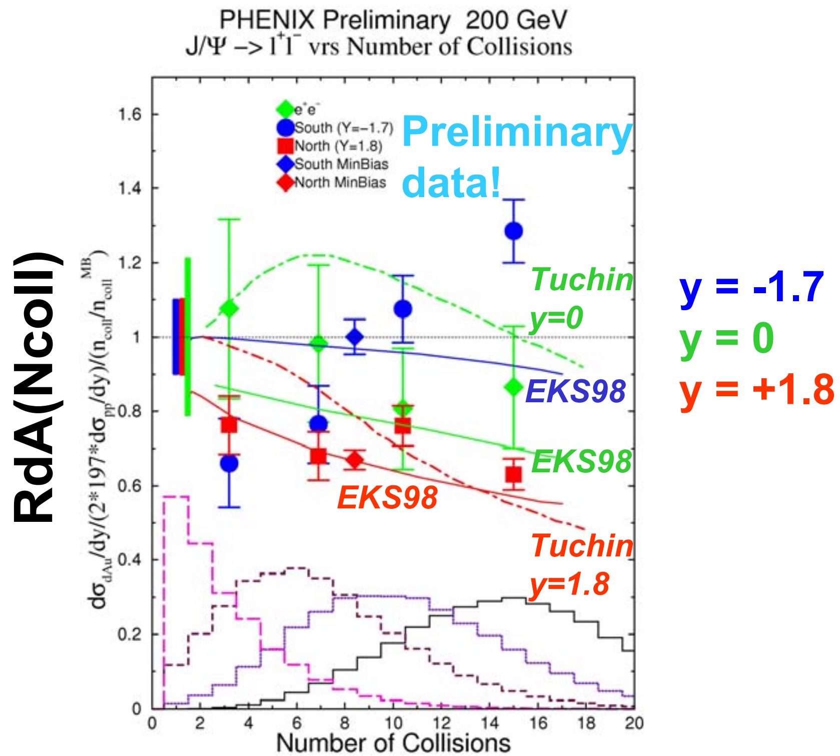
Kirill Tuchin, talk given at Hard Probes 2004

At large rapidity $c\bar{c}$ is produced coherently on whole nucleus and is suppressed due to gluon saturation ("color glass")

- two time scales:
  - production – $t_p \sim 7\ e^y$ fm
  - formation – $t_f \sim 42\ e^y$ fm
- give different scenarios for
  - coherence length and resulting shadowing
  - hadronization in or outside of nucleus

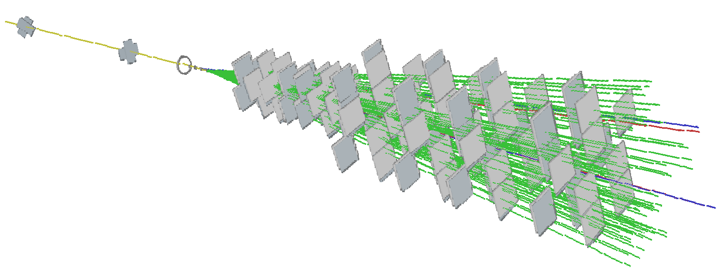




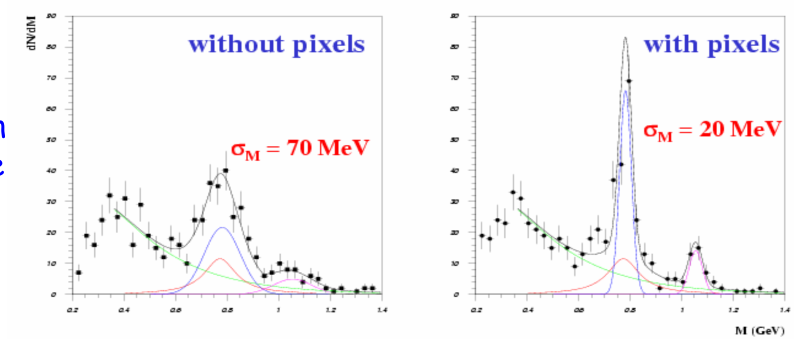


Some Critical Onia Physics Issues

- 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 $c\bar{c}$ 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 could 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

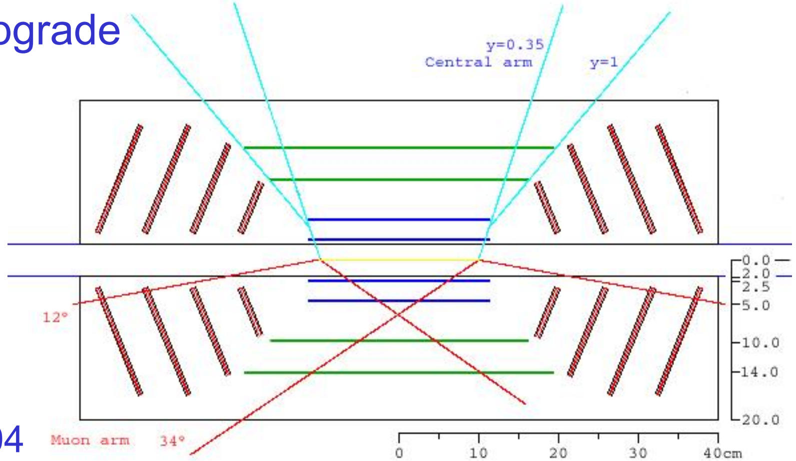


Some comments about the future at RHIC/PHENIX

- Present p-p in “Run5” is supposed to bring ~4.1 pb^{-1}
  - would give ~13k J/ψ, 400 ψ’, 6 ϒ (in 2 muon arms) & ~5k $J/\psi \to e^+e^-$
  - compared to ~0.2 pb^{-1} in Run3 with ~450 $J/\psi \to \mu^+\mu^-$
  - and ~0.2 pb^{-1} in Run4 with ~850 $J/\psi \to \mu^+\mu^-$ (?)
- A new higher luminosity d-Au run (by 2009?) needed
  - projected to give ~39 nb^{-1}
  - which would give ~50k $J/\psi \to \mu^+\mu^-$ & ~12k J/ψ→e+e-
  - compared to ~1.5 nb^{-1} in “Run3” which gave ~1.7k $J/\psi \to \mu^+\mu^-$ (~400 J/ψ→e+e-)
- Muon arm performance also is improved:
  - better efficiency with reduced beam backgrounds, by as much as a factor of two (see Run4 vrs Run3 pp above)
  - better mass resolution σ ~ 200 MeV → 150 MeV or better
- Silicon vertex upgrade to PHENIX will improve mass resolution further
- ϒ is tough without a luminosity (RHIC-II) upgrade

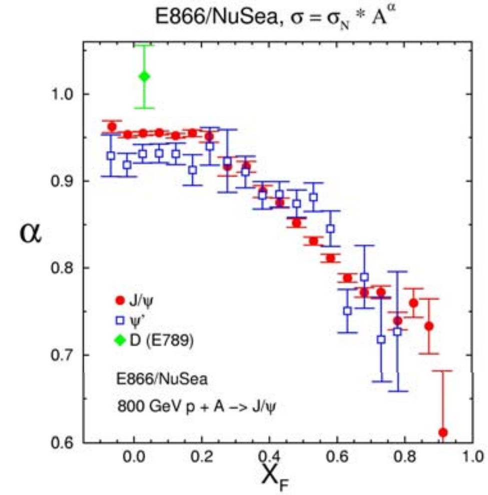
Vector meson	Lepton pair	1.5 nb^{-1} Au-Au	30 nb^{-1} Au-Au RHIC-II
ψ’	ee	100	2k
	μμ	1.4k	28k
ϒ	ee	8	155
	μμ	35	700

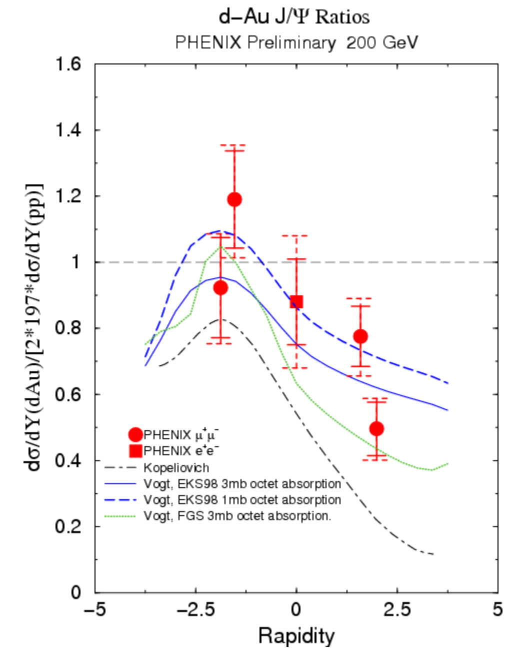
From Axel Drees CAARI 2004



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, particularly if priority is placed on pA (and Ap) measurements over broad ranges in x_F and p_T





Centrality Dependence – new at RHIC