J/Ψ & Heavy-Quark Production in E866 & PHENIX

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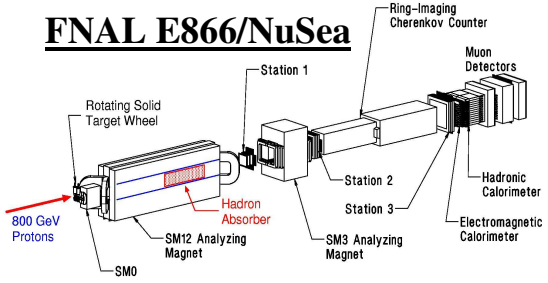
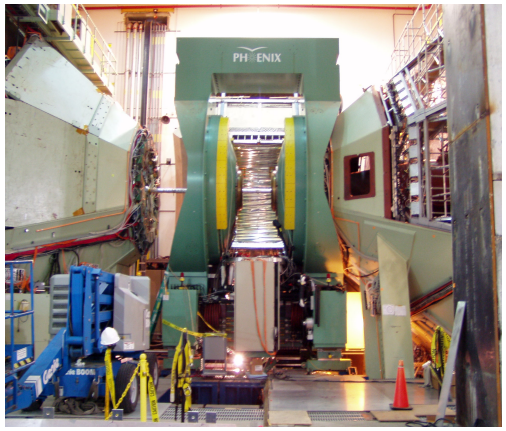
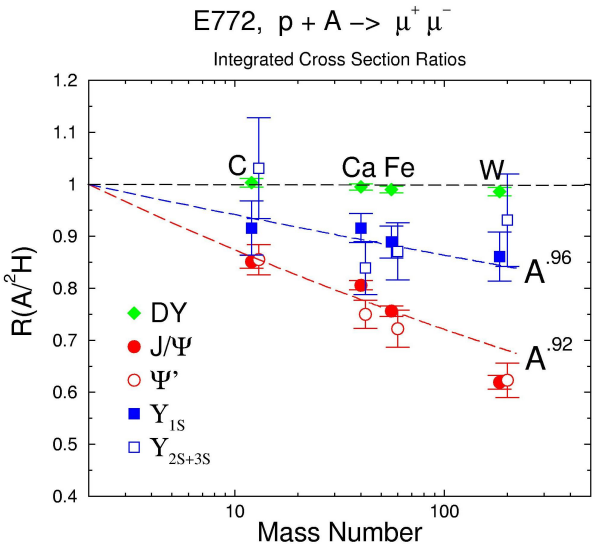
- Gluon shadowing & energy loss in nuclei
- J/Ψ production mechanisms & absorption
- Cronin effect (p_T broadening)
- PHENIX measurements and charm in d-Au
- Summary



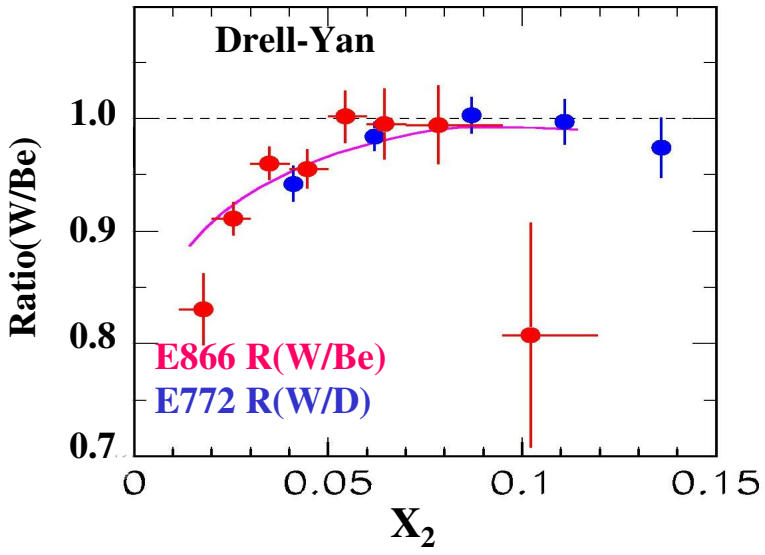




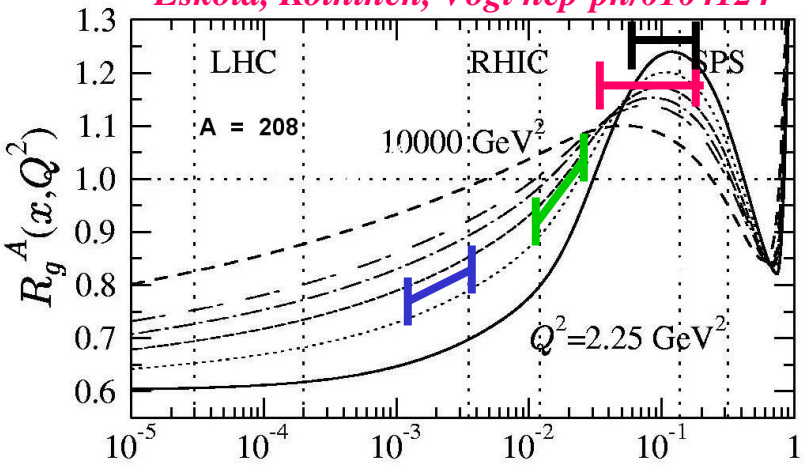
Physics Issues in heavy-quark production in nuclei - Shadowing

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

PRL 83, 2304 (1999) (hep-ex/9906010)



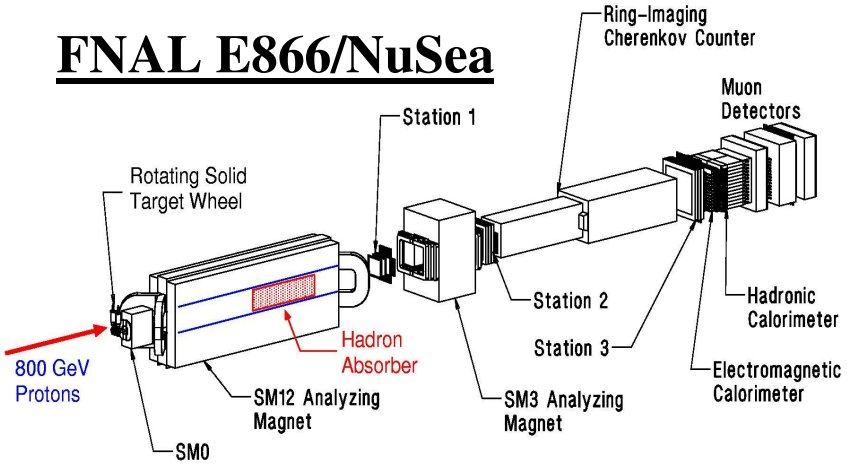
Eskola, Kolhinen, Vogt hep-ph/0104124



PHENIX μ
PHENIX e
E866 (mid-rapidity)
NA50

Nuclear Dependence of charm in E866

FNAL E866/NuSea



Donald Isenhower, Mike Sadler, Rusty Towell, Josh Willis ***Abilene Christian***

Don Geesaman, Sheldon Kaufman, Bryon Mueller ***ANL***

Chuck Brown, Bill Cooper ***FNAL***

Gus Petitt, Xiao-chun He, Bill Lee ***Georgia State***

Dan Kaplan ***IIT***

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

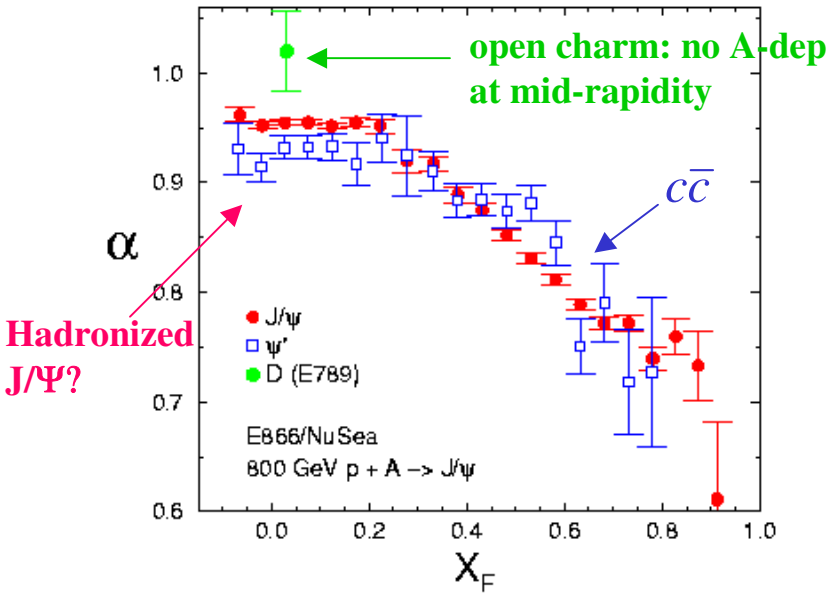
Mike Beddo, Ting Chang, Vassili Papavassiliou, Jason Webb ***New Mexico St.***

Paul Stankus, Glenn Young ***ORNL***

Carl Gagliardi, Bob Tribble, Eric Hawker, Maxim Vasiliev ***Texas A & M***

Don Koetke ***Valparaiso***

800 GeV p-A (FNAL)
PRL 84, 3256 (2000)

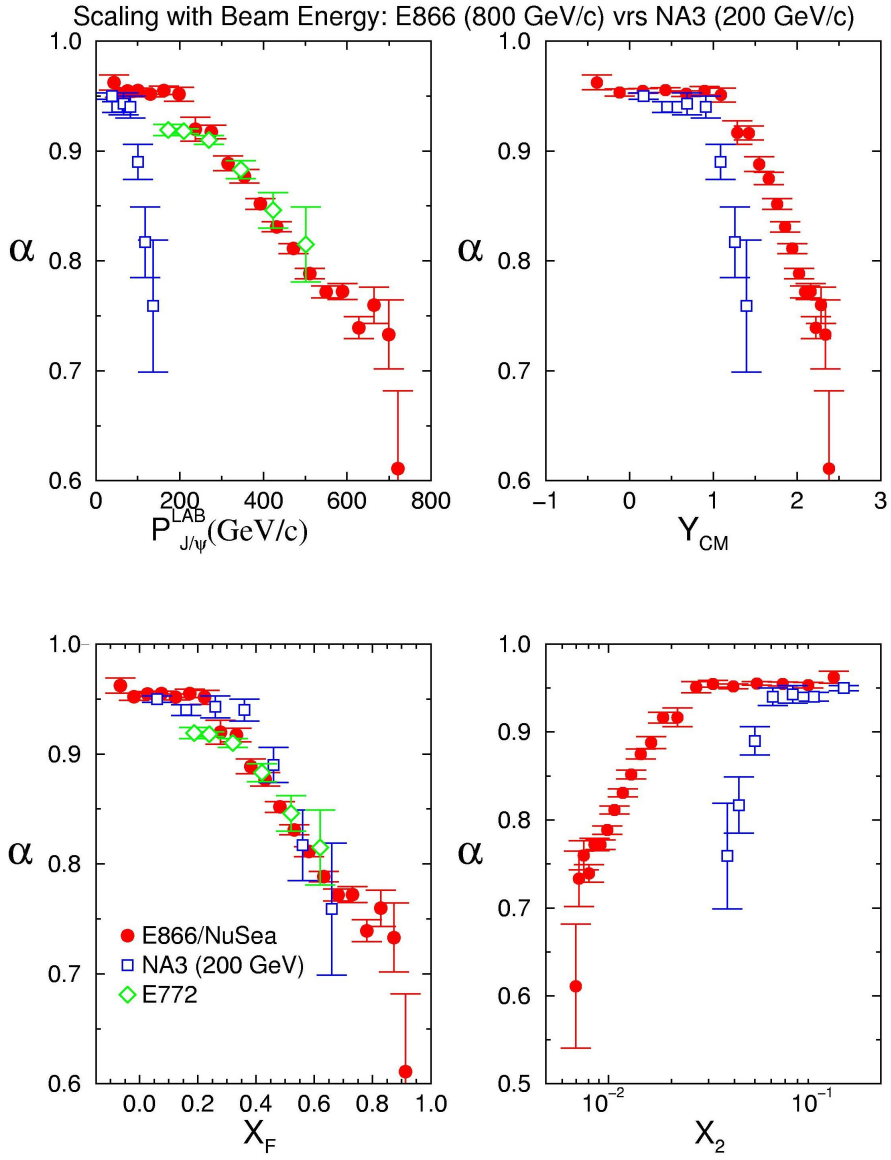


- J/Ψ and Ψ' similar at large x_F where they both correspond to a $c\bar{c}$ traversing the nucleus
- but Ψ' absorbed more strongly than J/Ψ near mid-rapidity ($x_F \sim 0$) where the resonances are beginning to be hadronized in nucleus
- open charm not suppressed (at $x_F \sim 0$)

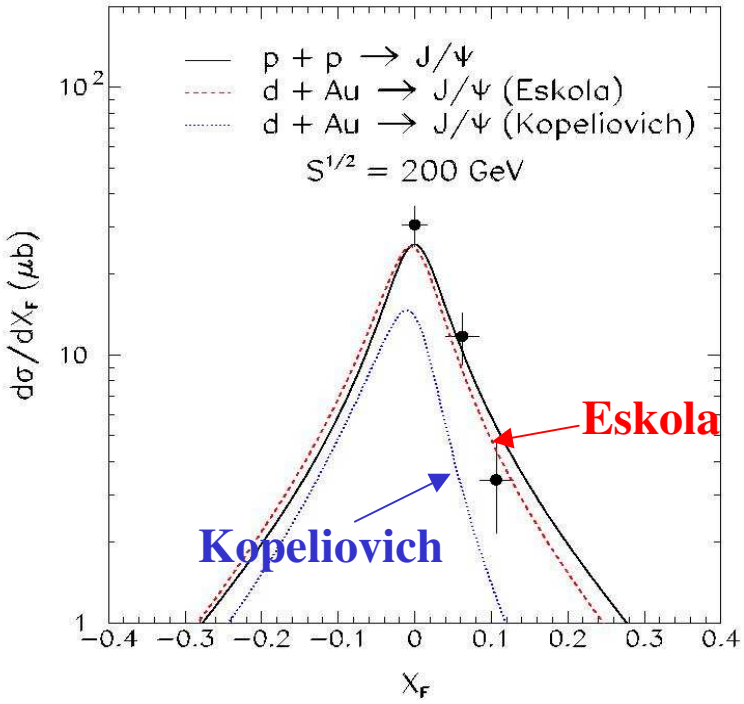
Scaling of J/Ψ Suppression?

- Shadowing and initial-state gluon energy loss thought to be main reasons for increasing suppression at larger x_F
- But this effect does not scale with x_2 as expected for shadowing between E866 at 800 GeV & NA3 at 200 GeV
- Although does scale with x_F which would be expected for energy loss
- Remains a puzzle…

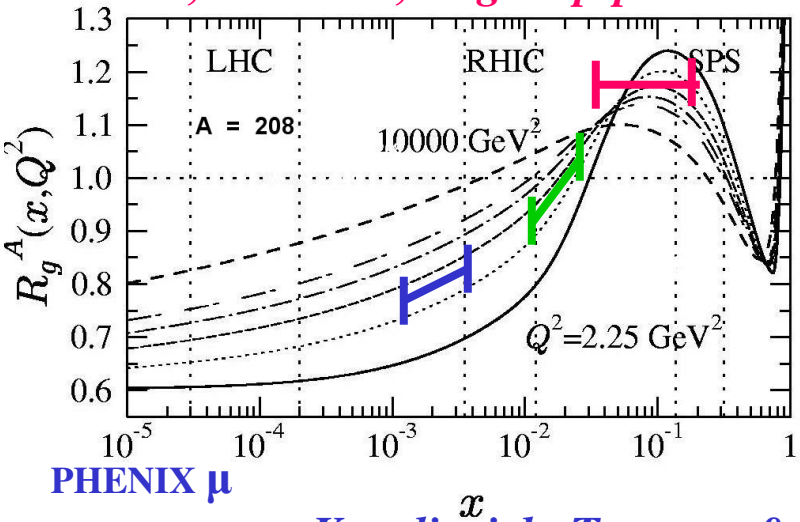
E866 - PRL 84, 3256 (2000) & NA3 - PRL84(2000),3258



Shadowing (only) for d+Au -> J/Ψ



Eskola, Kolhinen, Vogt hep-ph/0104124

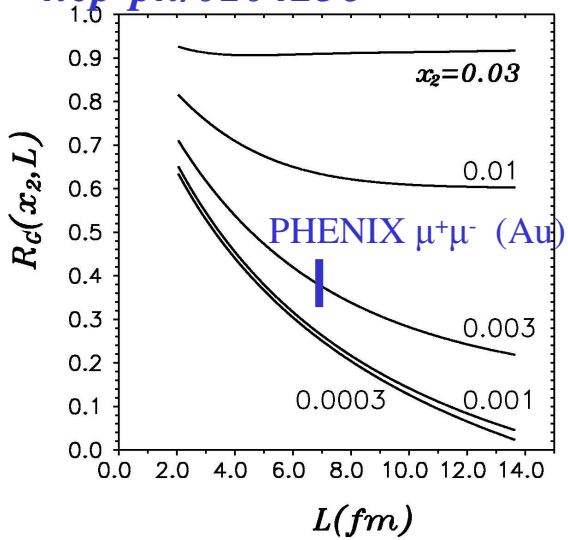


PHENIX μ

PHENIX e

E866 (*Y*~0)

Kopeliovich, Tarasov, & Hufner hep-ph/0104256

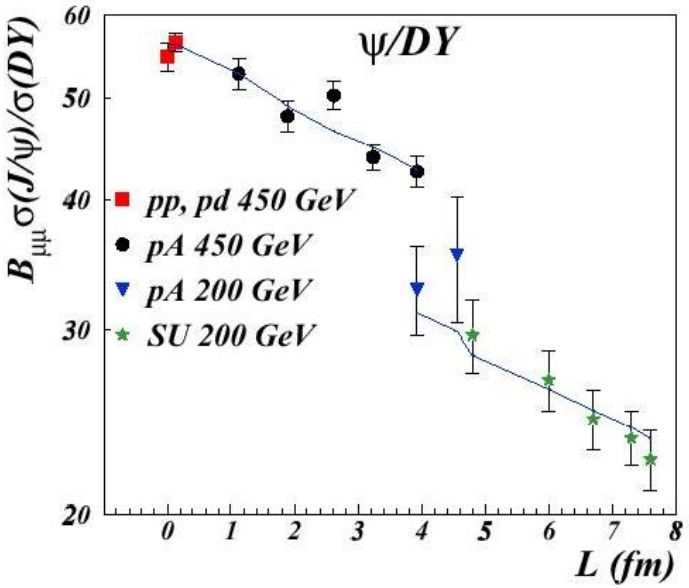


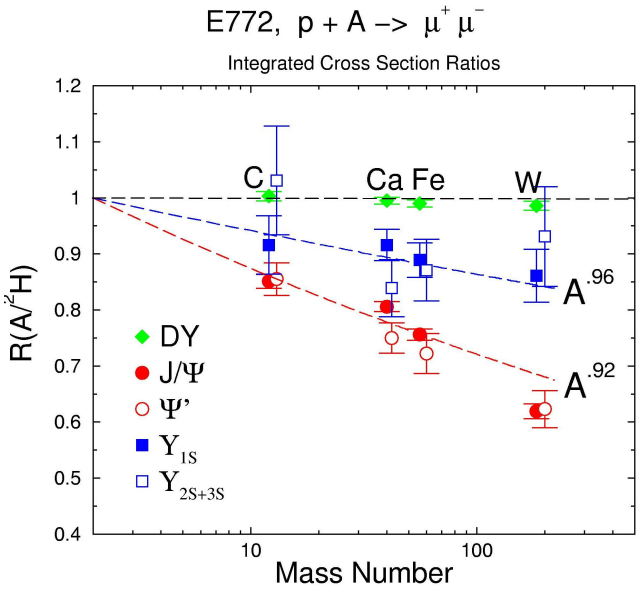
Gluon Shadowing – Largely Unknown

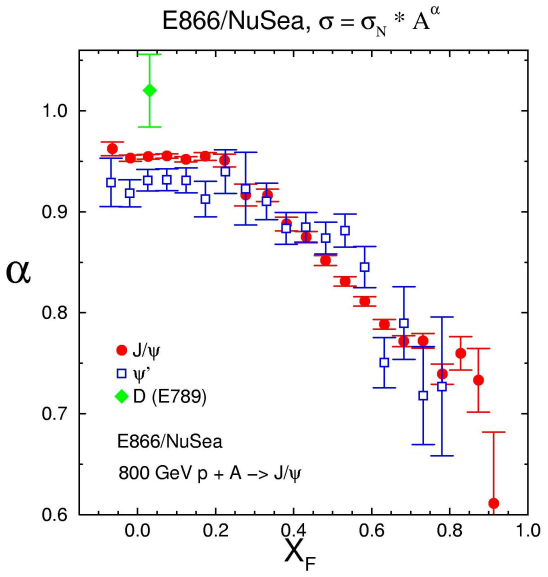
Gluon shadowing for J/Ψ's in PHENIX μ acceptance; large uncertainty:

- ***Eskola…* : ~ 0.8 vrs *Kopeliovich…* : ~ 0.4**
- **Must be measured**

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







- Significant nuclear dependence of cross section is observed
- Power law parameterization $\sigma = \sigma_N * A^{\alpha}$

  $\alpha = 0.92$ (E772, PRL 66 (1991) 133) (limited p_T acceptance bias)

  $\alpha = 0.919 \pm 0.015$ (NA38, PLB 444 (1998)516)

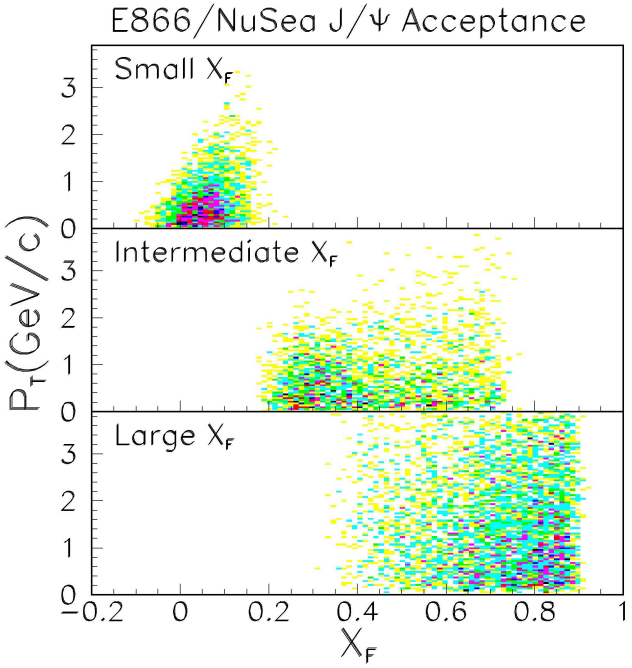
  $\alpha = 0.954 \pm 0.003$ (E866 @ x_F=0. PRL 84 (2000),3258)

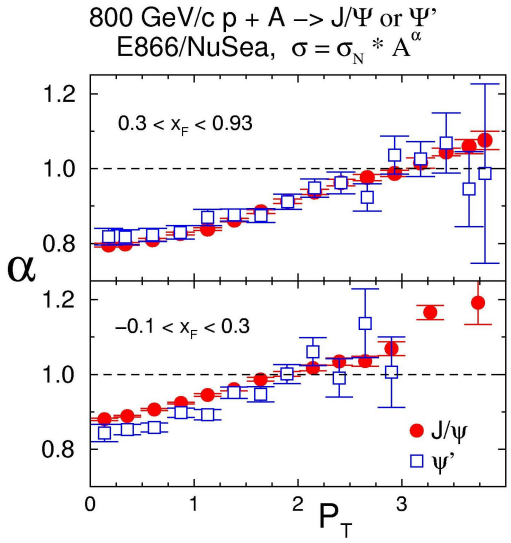
  $\alpha = 0.934 \pm 0.014$ (NA50, QM2001)
- Absorption model parameterization

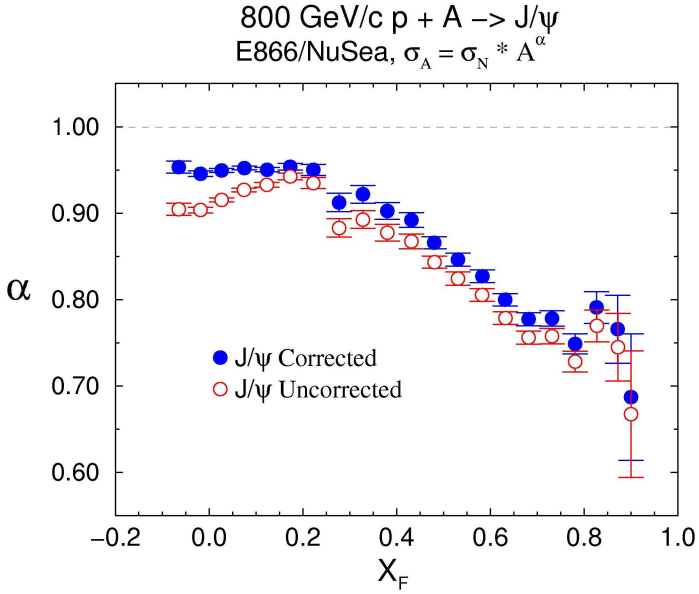
  σ = 6.2 mb (NA38/50/51) to 4.4 mb (NA50, QM2002)
- Small difference in α between J/Ψ and Ψ(2S) (E866)

  $\alpha(J/\Psi) - \alpha(\Psi(2S)) \sim 0.02\text{-}0.03$ @ $x_F = 0$

E866 - Correction to Nuclear Dependence for p_T Acceptance

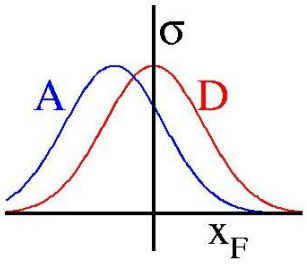






- Acceptance in p_T is considerably narrowed at low x_F
- Use MC acceptance & $d\sigma/dp_T$ consistent with our data to correct for incomplete coverage
- **This also is why E772 (which had stronger narrowing of p_T at small x_F) J/Ψ's got $\alpha \sim 0.92$**

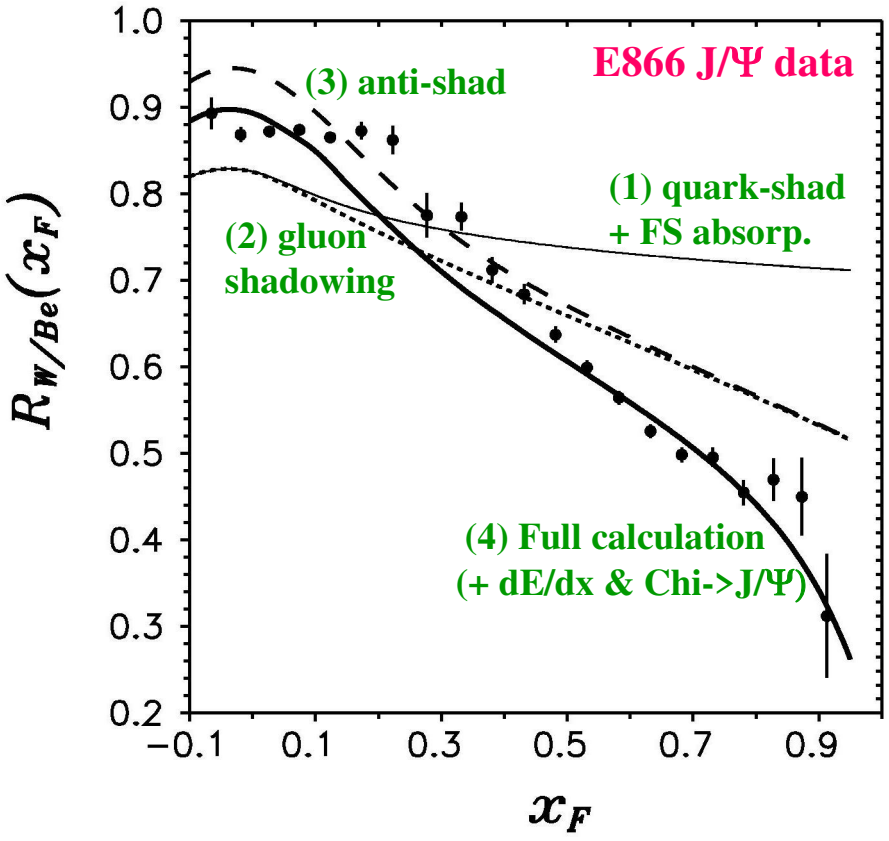
Energy loss of gluons in nuclei



Energy loss of incident parton shifts effective x_F and produces nuclear suppression which increases with x_F

Color-dipole model
Kopeliovich, Tarasov, Hufner
Nucl.Phys. A696 (2001) 669-714
(hep-ph/0104256)

1. $c\bar{c}$ absorption
2. dynamic calc. of gluon shadowing
3. anti-shadowing from Eskola
4. energy loss
5. Decay of $\chi \rightarrow$ J/Ψ (base calculation is for χ)



Parton Energy Loss in Nuclei for Drell-Yan – Kopeliovich Model

Shadowing when coherence length,

$$l_{coherence} \approx 1/2m_N x_2$$

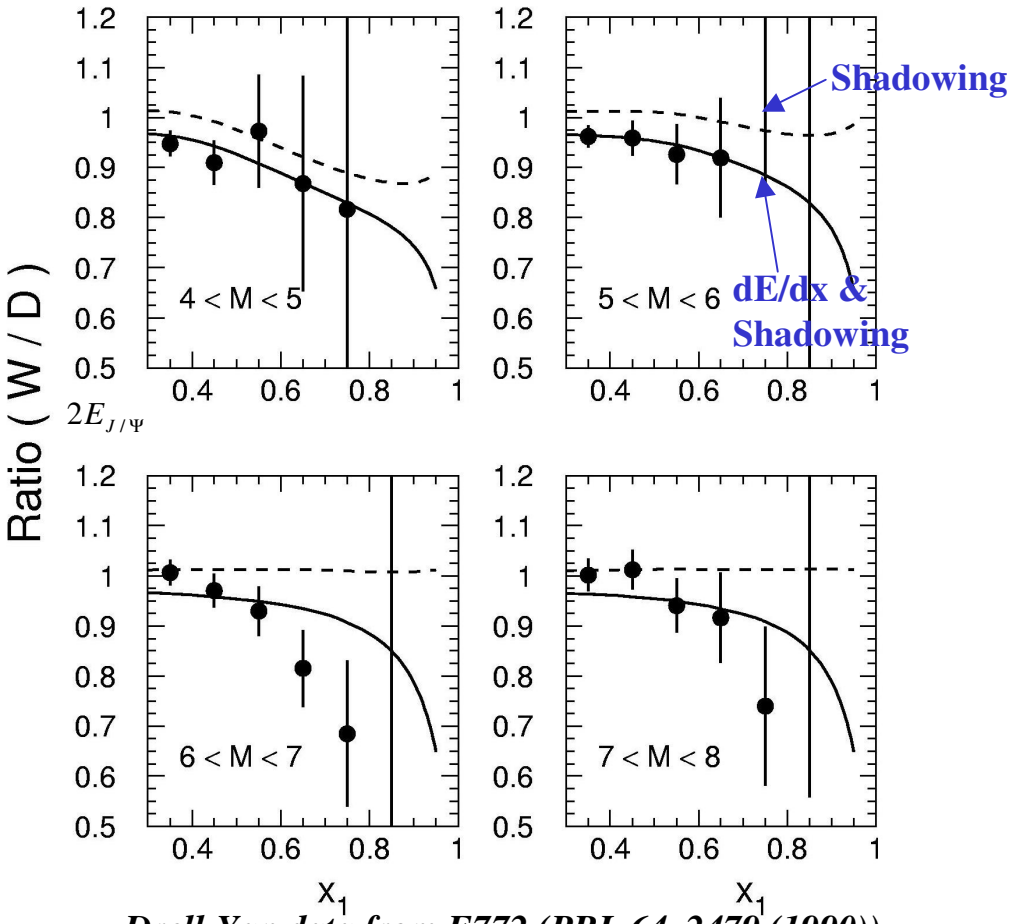
is larger than nucleon separation

- **From E772 & E866 Drell-Yan data**
- **With separation of shadowing & dE/dz via Mass dependence**
- **In the color-dipole model:**

dE/dz ~ -2.7 ± .4 ± .5 GeV/fm

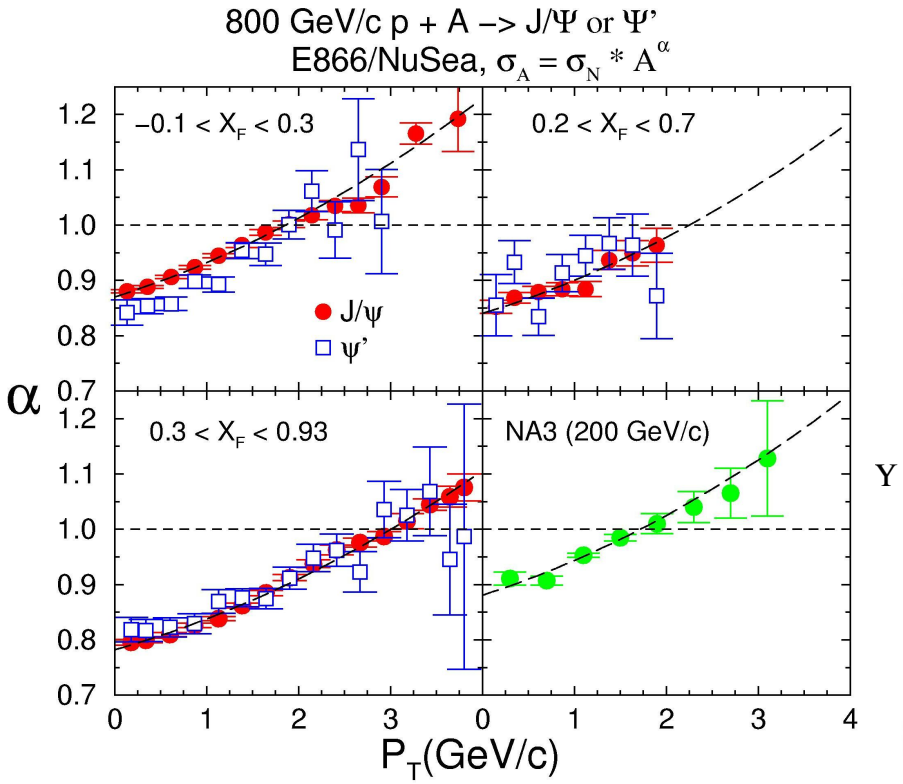
PRC 65, 025203 (2002)

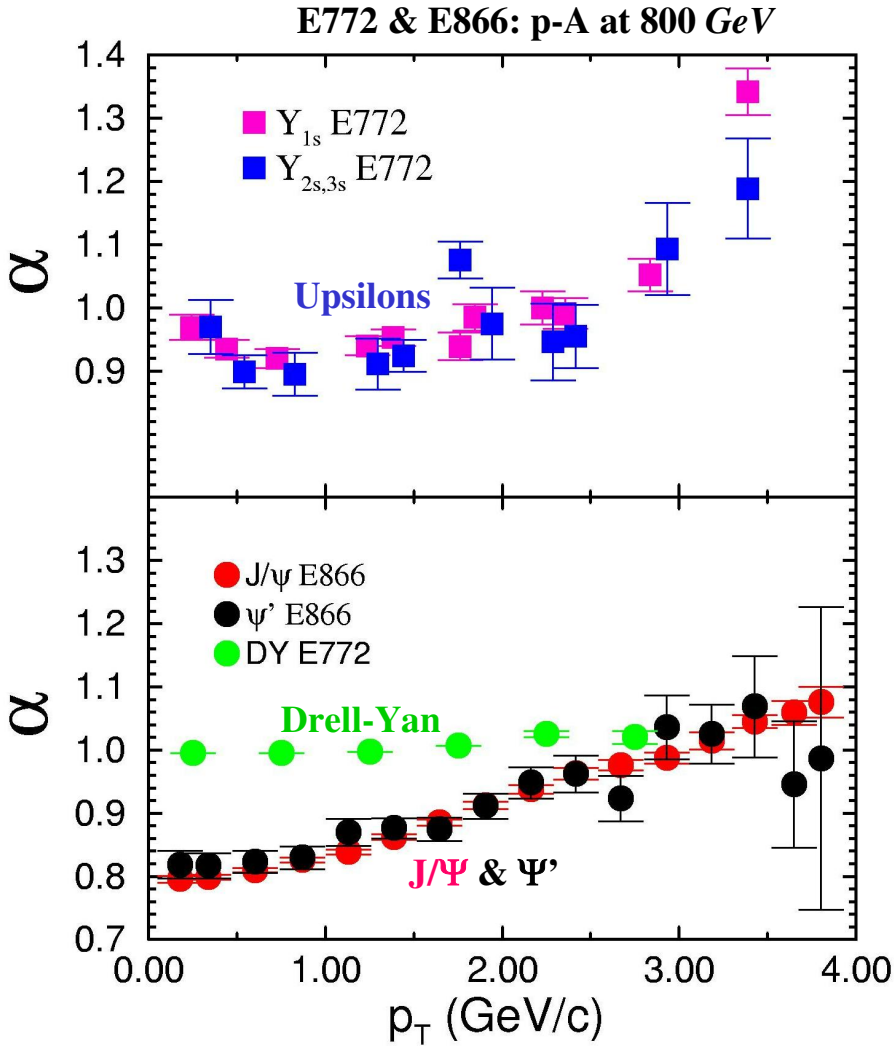
Johnson, Kopeliovich et al., hep-ph/0105195



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

P_T Broadening at 800 GeV

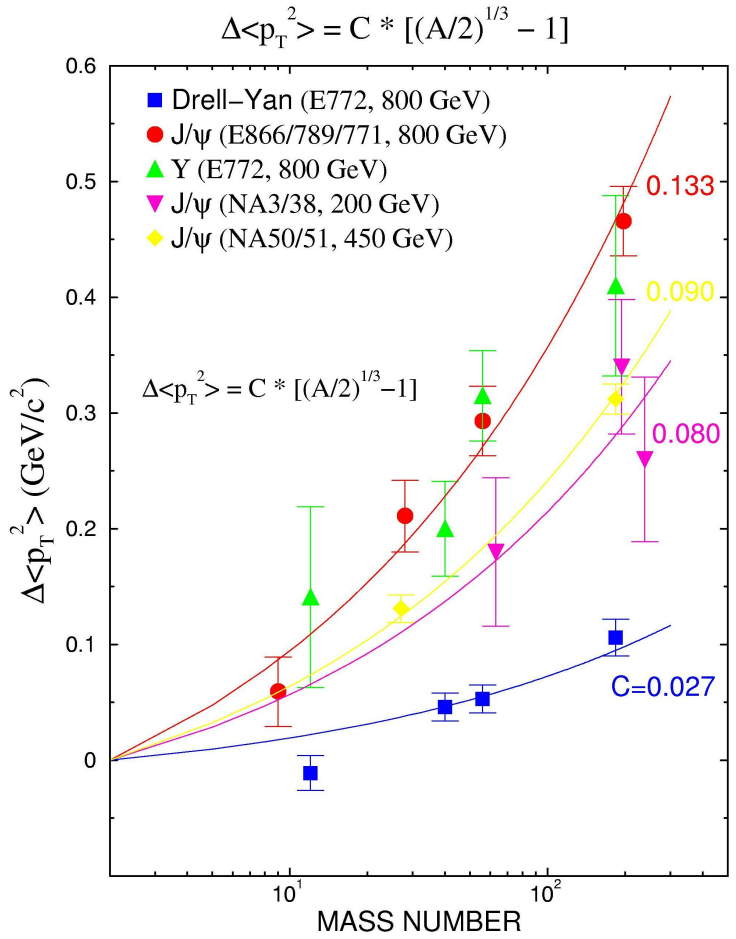


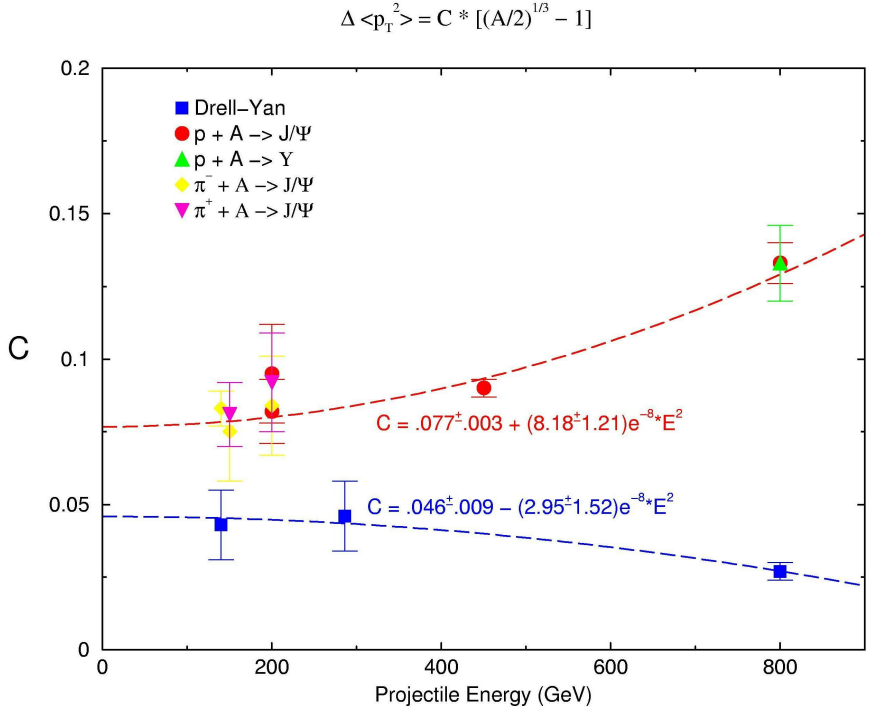


$\alpha(p_T)$ shape is independent of x_F & same for NA3 at a lower energy

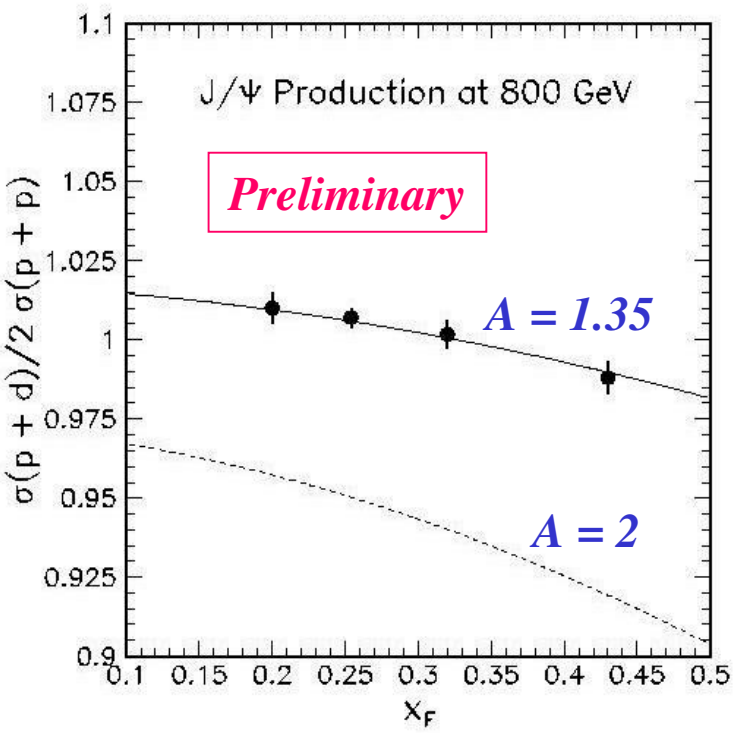
(curves are $\alpha(p_T) = A*(1+.06p_T+.011p_T^2)$ with A slightly different for each)

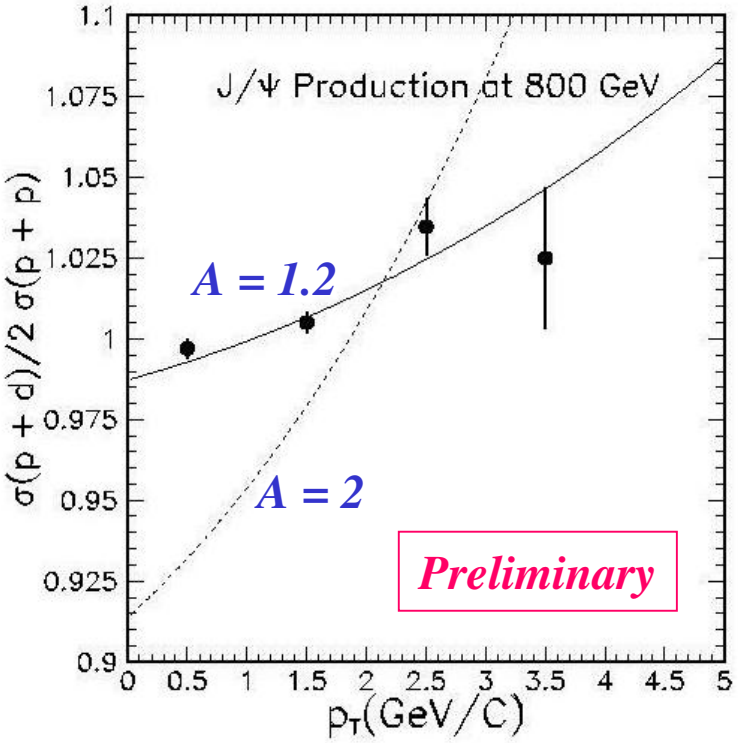
Systematics of P_T Broadening





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.

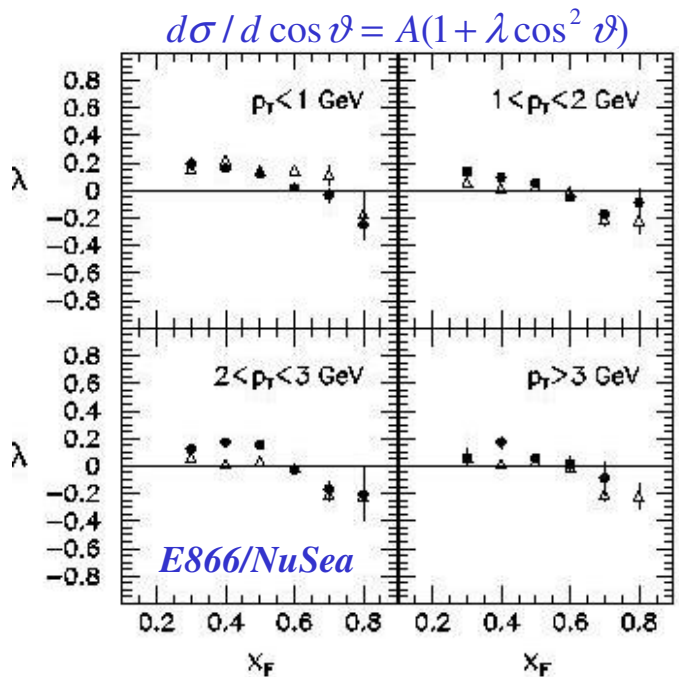
From fits to E866/NuSea p + Be, Fe, W data:

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

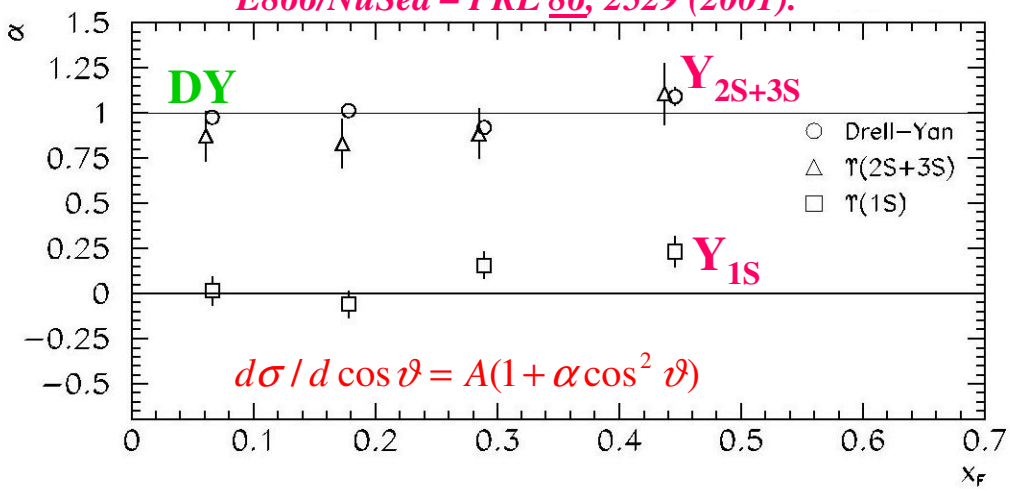
J/Ψ and Υ Polarization

- **NRQCD based predictions (color octet model) necessary to explain CDF charm cross sections**
- **E866 J/Ψ measurement not in agreement with NRQCD based predictions *[Beneke & Rothstein, PRD 54, 2005 (1996)]* which give $0.31 < \lambda < 0.63$**
- **J/Ψ complicated by feed-down (~40%) from higher mass states.**

However Υ(2S+3S), which should not suffer from feed-down, have maximal polarization consistent with the Octet model!



E866/NuSea – PRL 86, 2529 (2001).



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

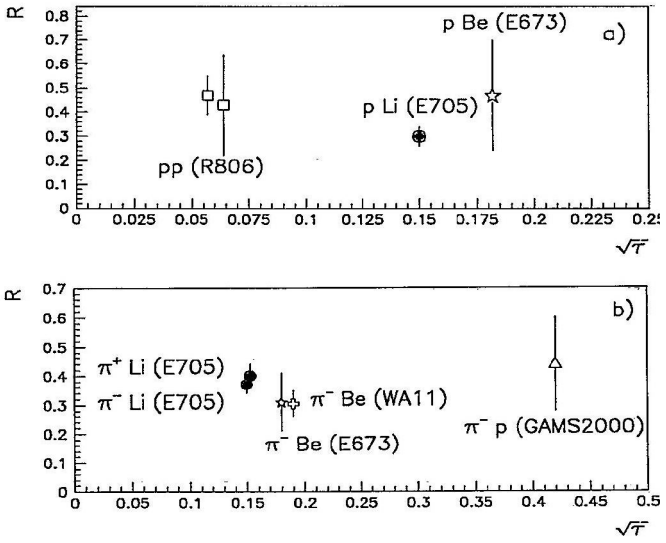


FIG. 3. Fraction of J/ψ produced via radiative χ in 300 GeV/c (a) proton and (b) $\pi^{\pm}$ ^{7}Li interactions.

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?

- Open charm has little or no nuclear dependence

  $\alpha = 1.00 \pm 0.05$ (E769 250GeV π+A)

  $\alpha = 0.92 \pm 0.06$ (WA82 340GeV π+A)

  $\alpha = 1.02 \pm 0.03 \pm 0.02$ (E789 800GeV p+A)
- This is consistent with that there being little nuclear shadowing in the x region probed by the fixed target charm experiments.
- Significant nuclear suppression is reported in large x_f region (WA78, α=0.81 $\pm$ 0.05). This could be due to nuclear shadowing in small x (large x_F), but this is not well understood.
- At RHIC, we can probe x values much smaller than for fixed target and may observe nuclear shadowing effect in charm production.

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

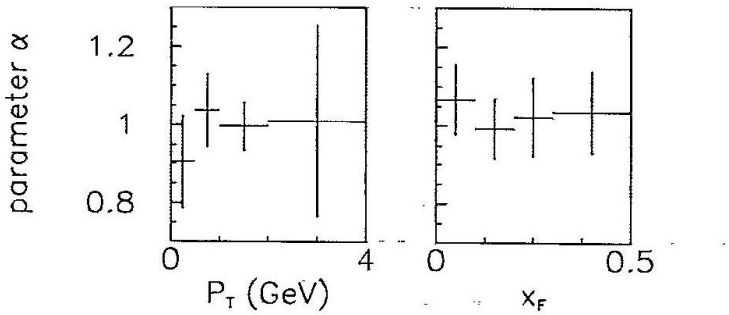


FIG. 4. Dependence of the parameter α on P_T and x_F for D^+ and D^0.

WA82 340 GeV π
PRB 284,453 (1992)

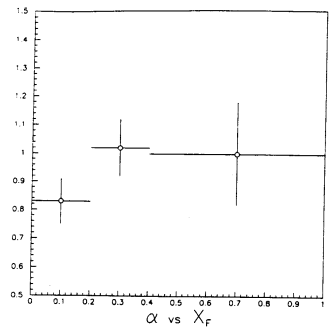
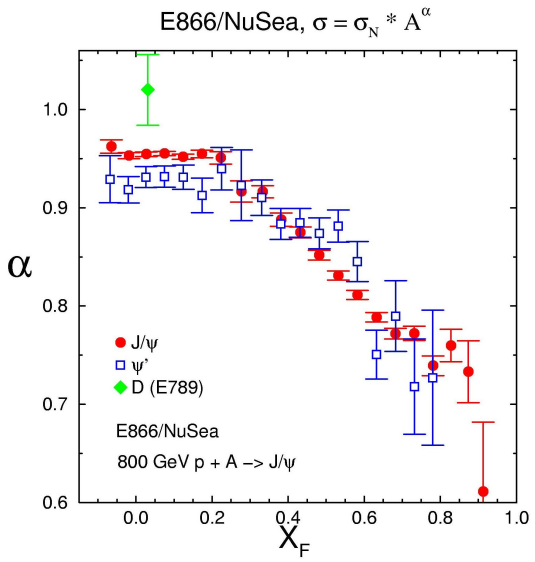


Fig. 4. The parameter α for charm production as measured in three x_F intervals.



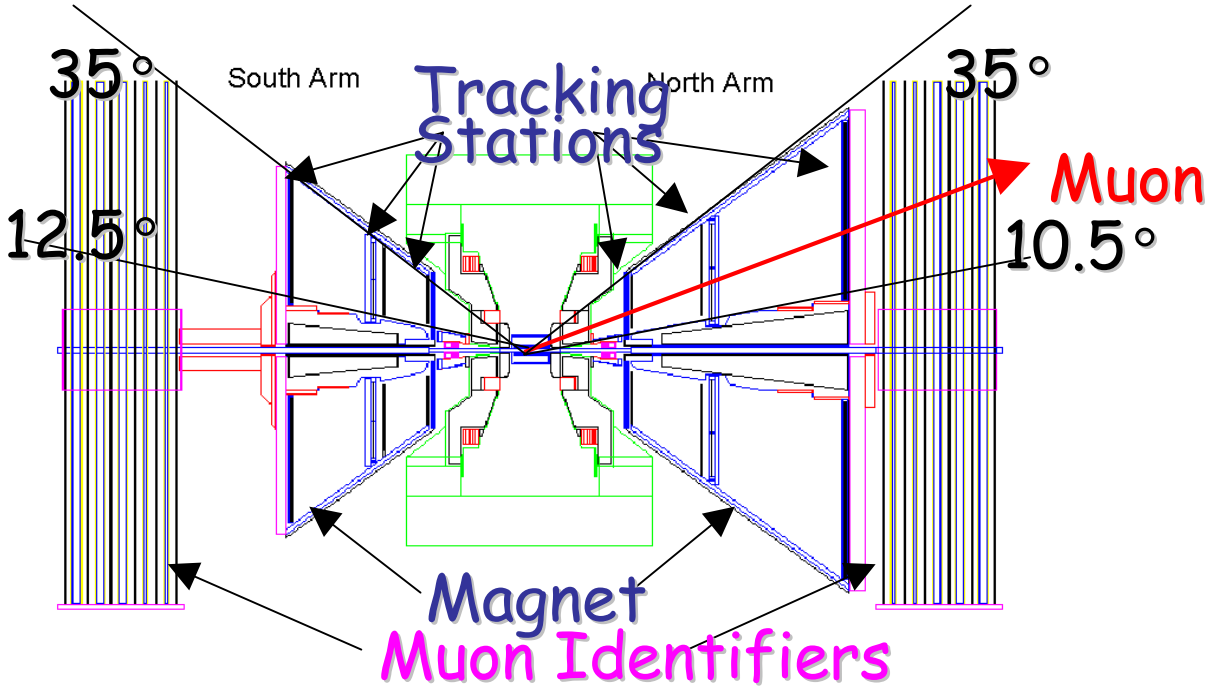
PHENIX Muon Arms

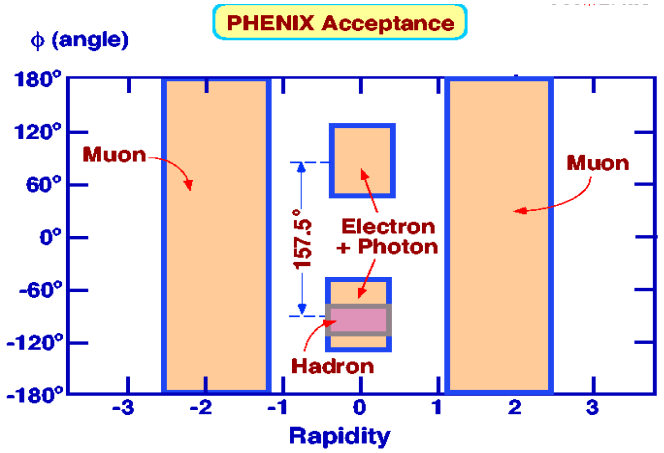
2 Muon Trackers =
2x3 stations
2 Muon Identifiers
= 2x5 planes

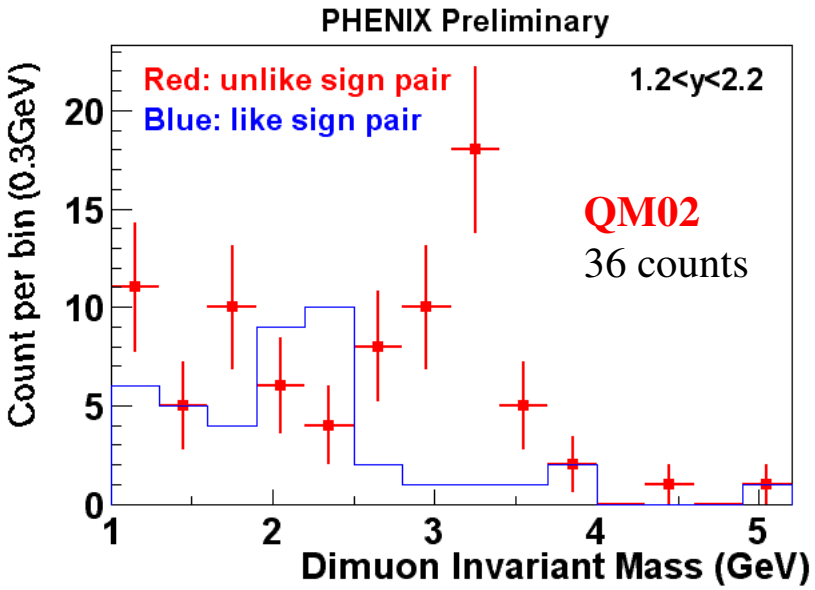
South Arm:
Began operations
in 2001-2002 run.

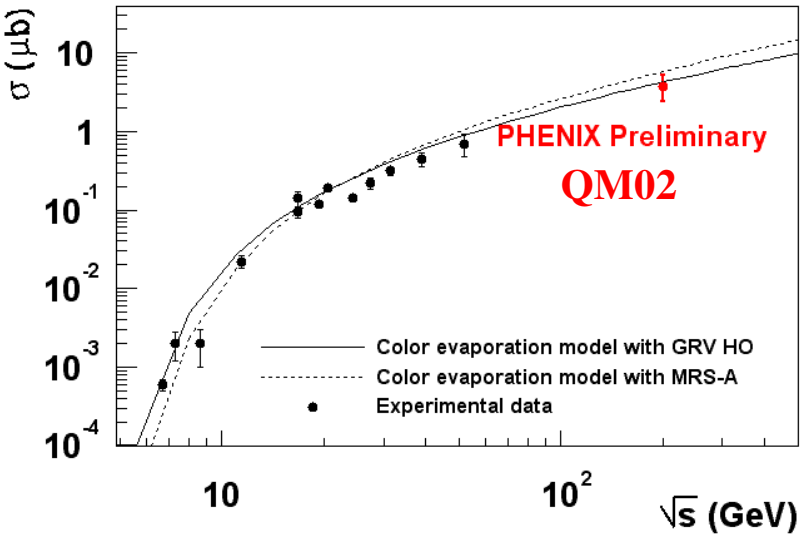
North Arm:
Installed in 2002.

Acceptance : $1.2 < |\eta| < 2.4$
$\Delta\Phi = 2\pi$
Muon minimum momentum ~ 2 GeV/c



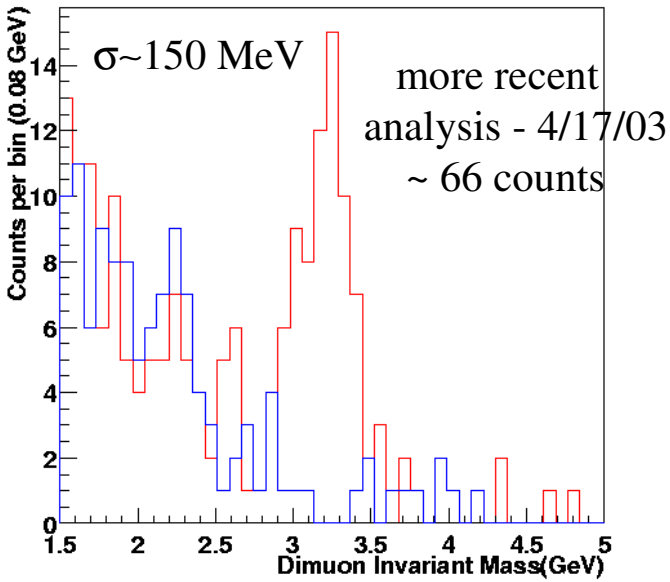




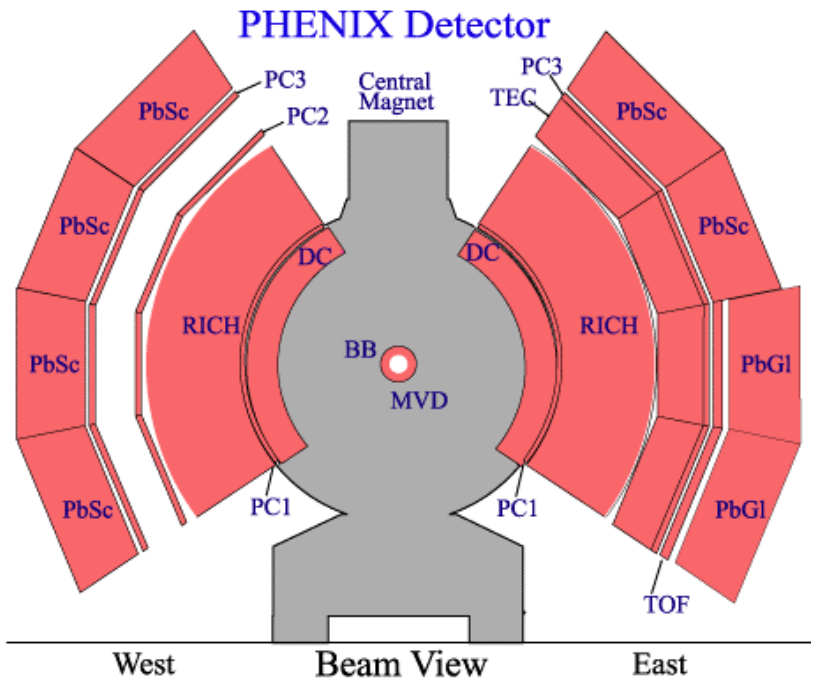


First J/Ψ → μ⁺μ⁻'s at RHIC

- 36 counts from South muon arm in 2001-2002 run as shown at Quark Matter last July (now 66 with tuned pattern recognition and analysis)
- Quark Matter cross section consistent with lower energy measurements extrapolated to RHIC energy by various theoretical models



Electron Measurement in PHENIX



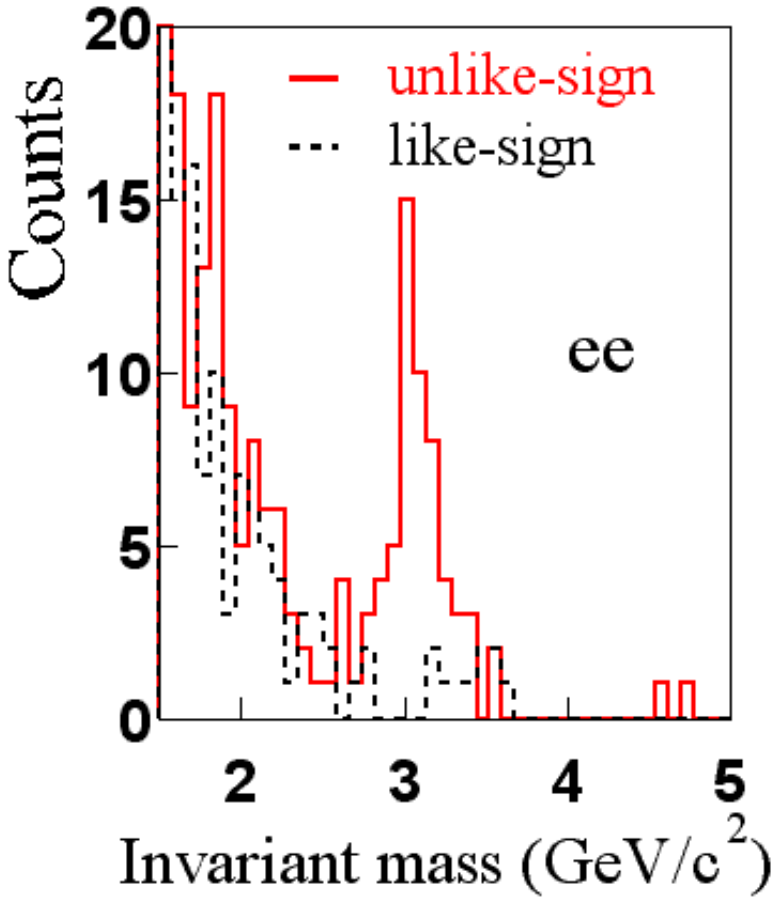
Measure electron between
$|\eta|<=0.35$ and mom>=0.2GeV

High resolution tracking and momentum measurement from Drift chamber.

Good electron identification from Ring Imaging Cherenkov detector (RICH) and Electromagnetic Calorimeter (EMCal).

High performance Level-1/Level-2 trigger

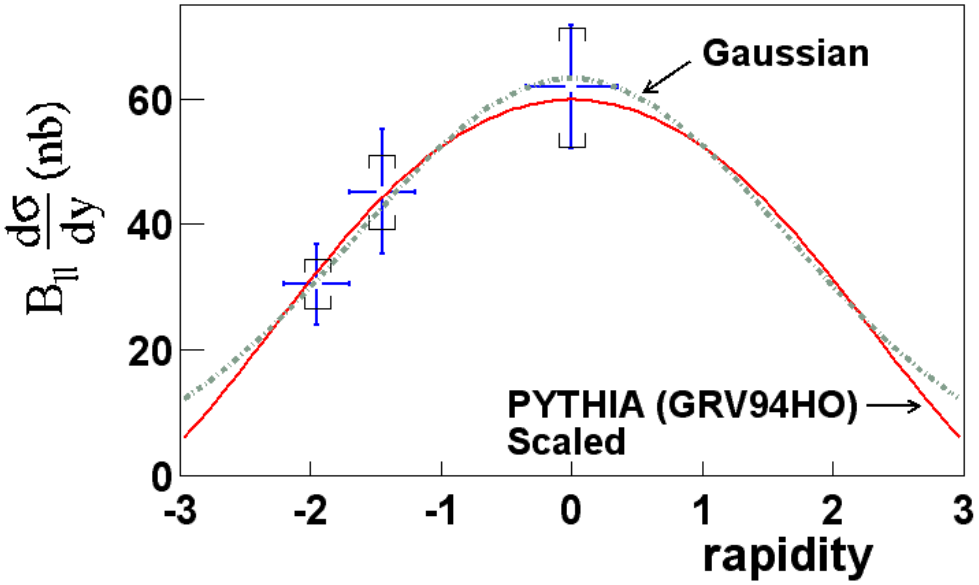
J/Ψ→ee in pp @ 200 GeV

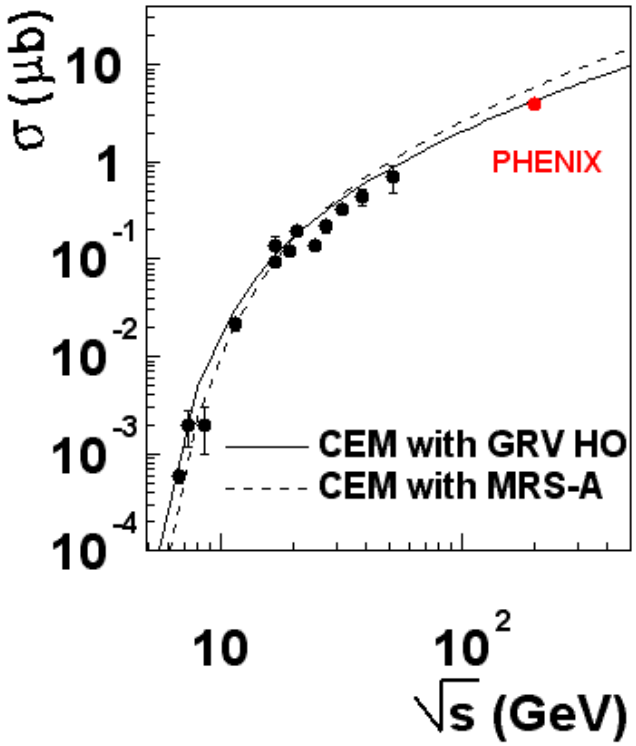


|y| <0.35 $N_{J/\Psi}$ = 24 ± 6 ± 4 (sys)

Bdσ/dy = 61.8 ±9.8 (stat) ± 9.4 (sys) ± 6.4 (abs) nb

pp→J/Ψ at RHIC



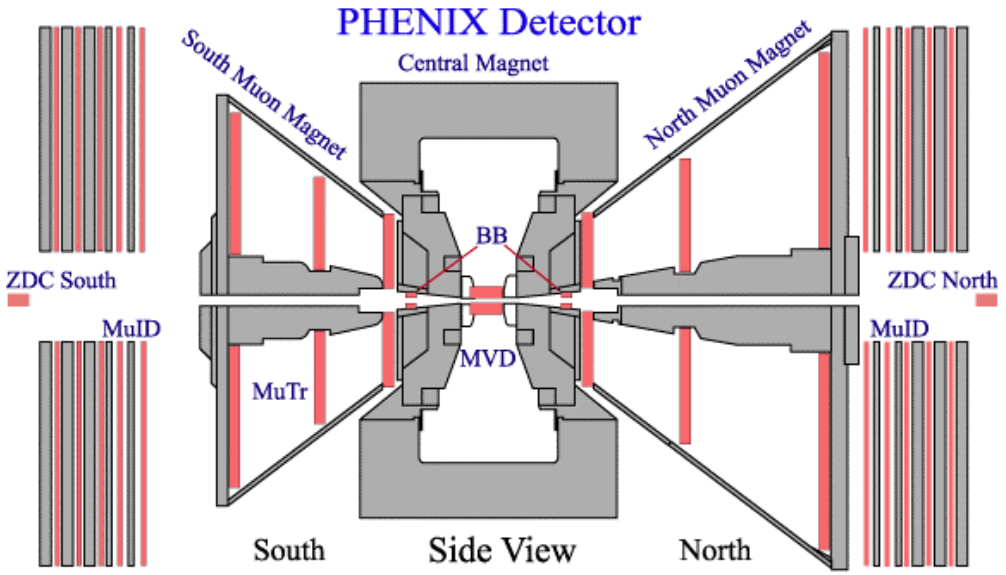


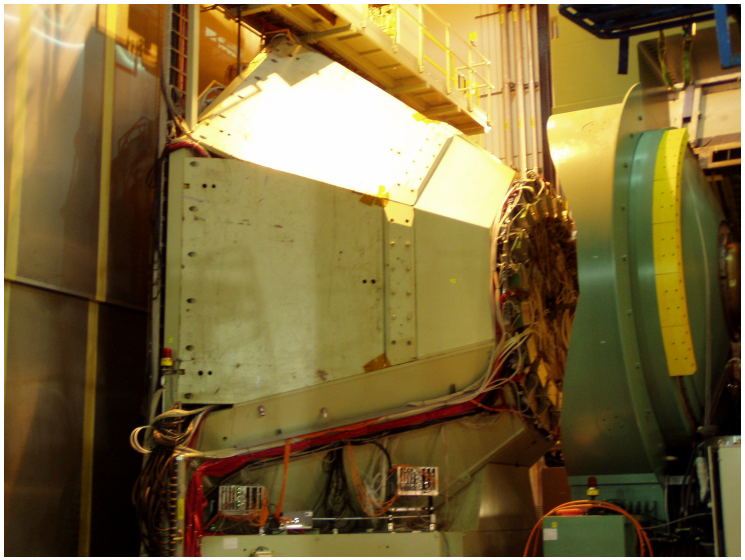
σ (p+p→J/ψX)

3.98 ± 0.62 (stat.) ± 0.56 (sys) ± 0.41 (abs) μb

- **PHENIX data agrees with the color evaporation model prediction at √s=200 GeV**

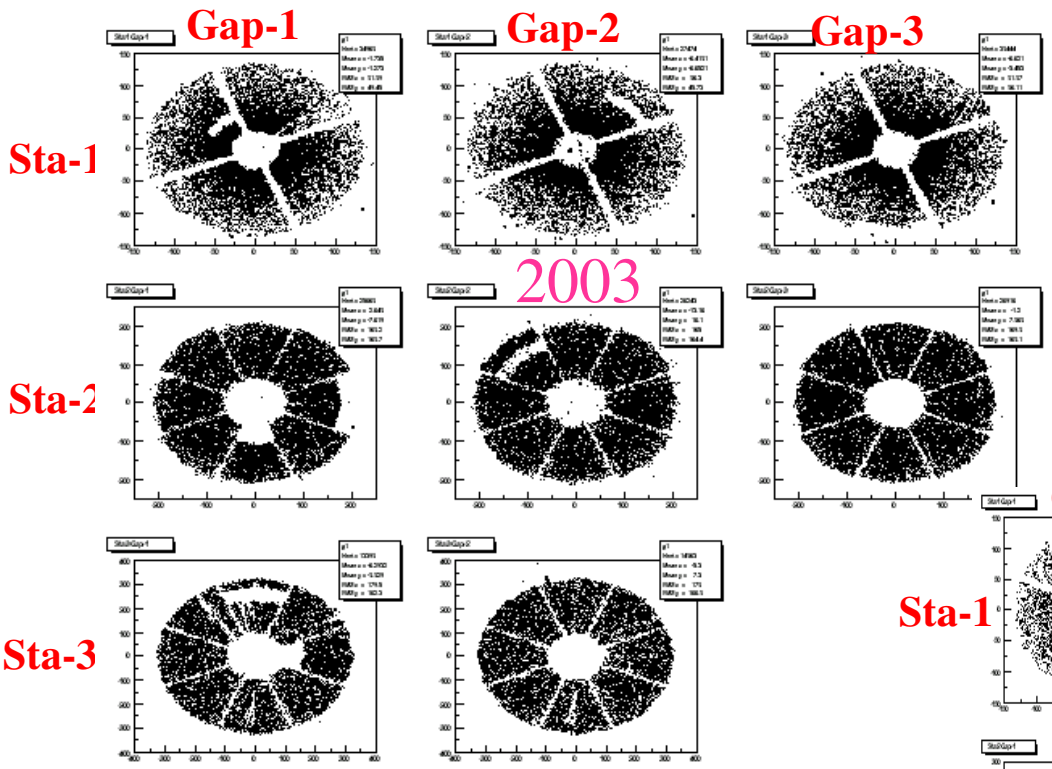
Both PHENIX Muon Arms Operational in Present d-Au Run





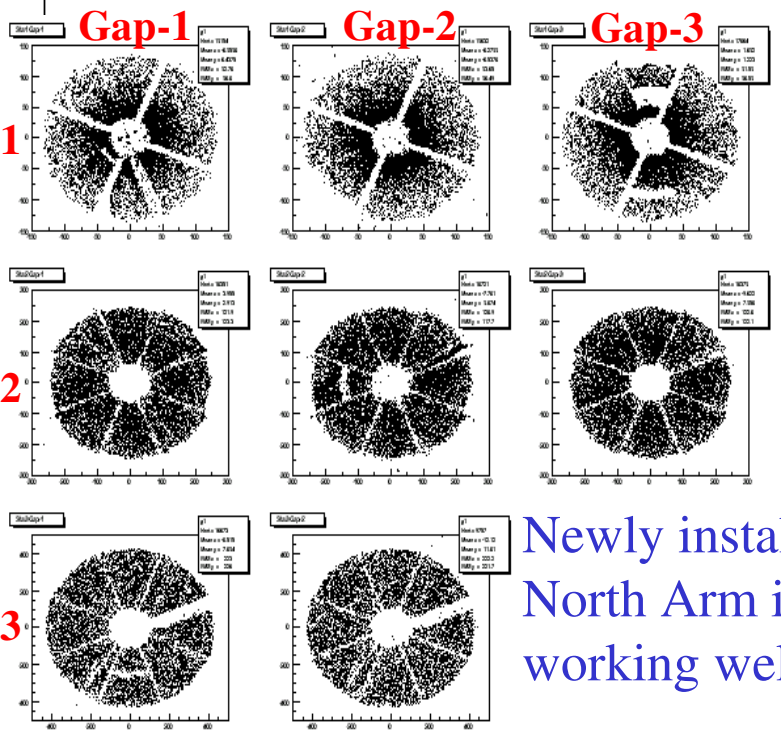
South Muon Arm

North Muon Arm



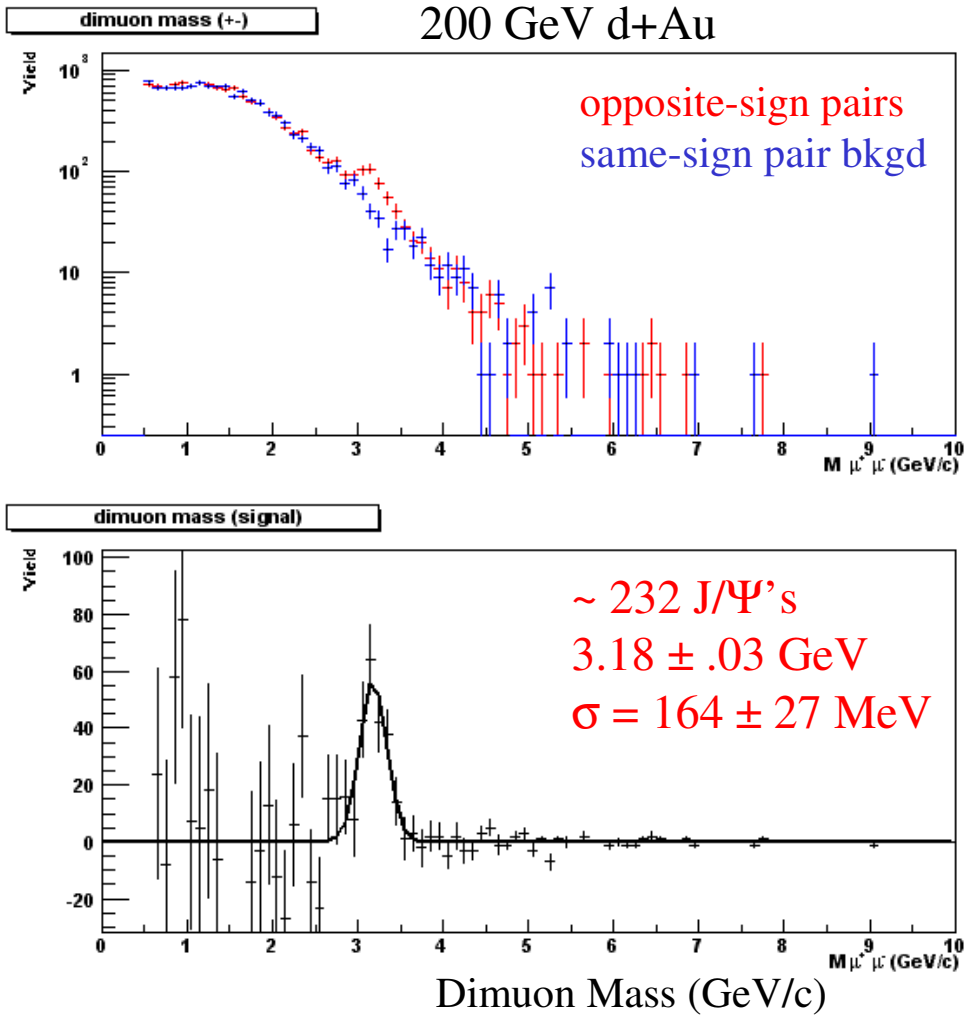
Radiographs of active area for South arm in run-II. (Three stations with 3 or 2 gaps each)

Vast improvement for present (run-III) after extensive repairs to electronics and HV during shutdown



Newly installed North Arm is working well

South PHENIX Muon Arm



South Arm operating at optimal level after extensive repair work during the shutdown before the d+Au run

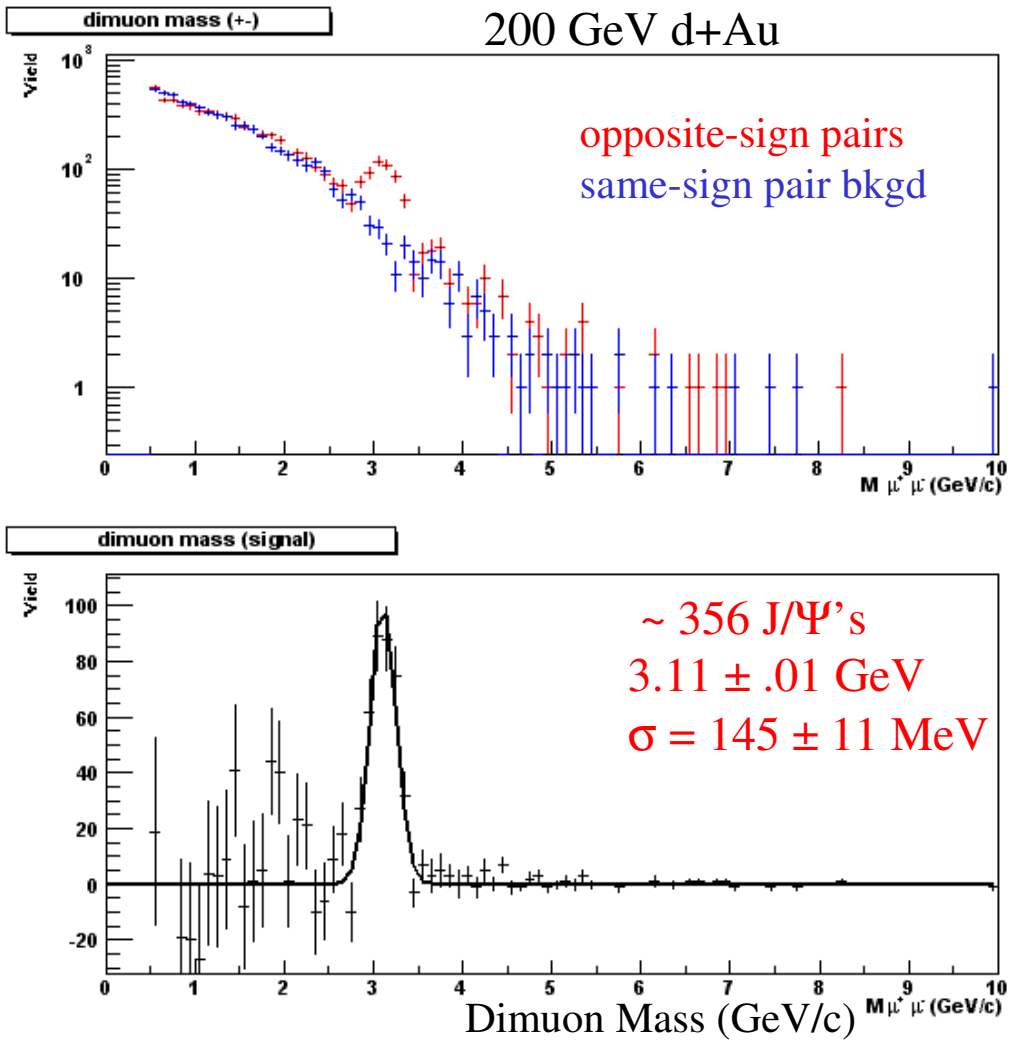
- less than 1/3 of d+Au data in this analysis
- trigger and other efficiencies still under study

Number of J/Ψ's expected from the $\int L \sim 2.7$ nb^{-1} d-Au run (w/o shadowing)

- ~ 1000/arm for $\mu^+\mu^-$
- ~ 400 for e^+e^-

Similar numbers for p-p run possible

North PHENIX Muon Arm

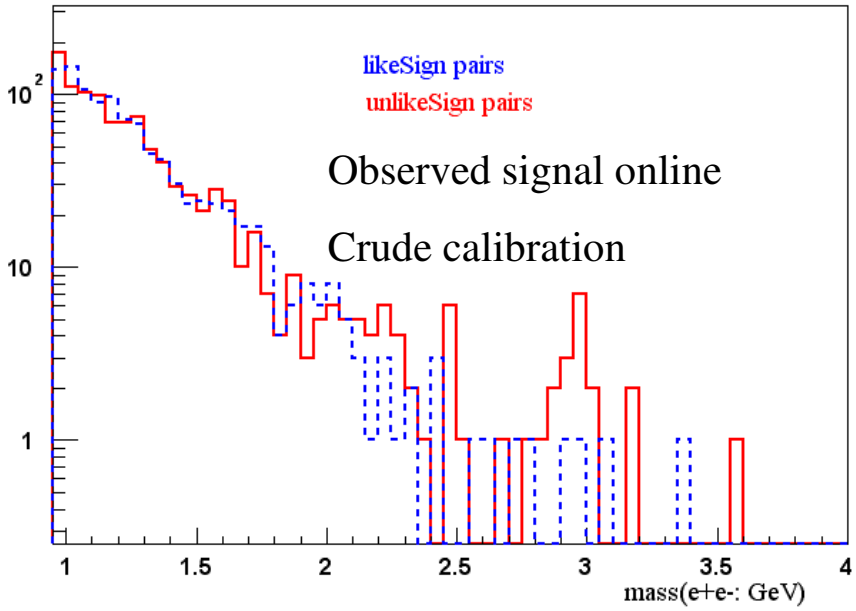


d+Au run is 1st for North Muon arm

- mass resolution already close to optimal even without final alignment constants
- this analysis from less than 1/3 of the d+Au data
- efficiencies, especially for the trigger, still largely unknown for this quick analysis

Comparison of North and South J/Ψ yields not instructive at this stage since we are only beginning to study efficiency issues which could have large effects and the data samples are not identical

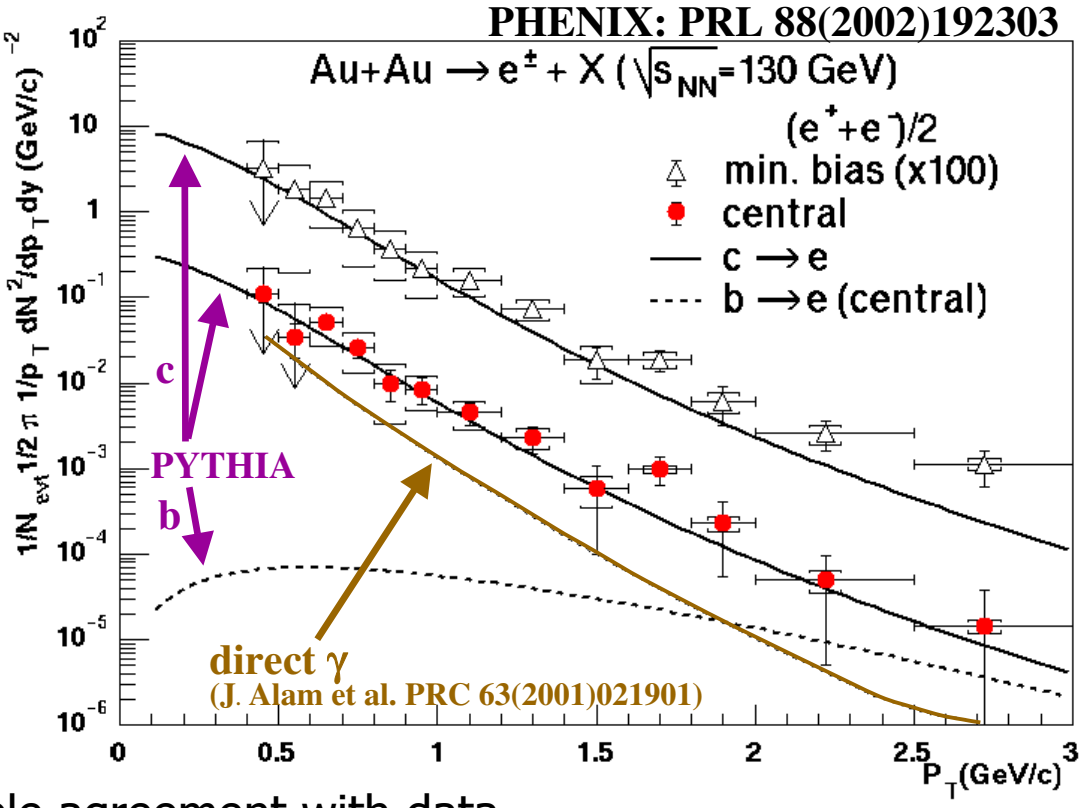
J/ψ->e^+e^- Signal in d-Au Collision



- With online calibration, we observed J/ψ->e^+e^- signal.
- The width of J/ψ is expected to be 60 MeV after good calibration.
- We expect to get a few hundred J/ψ->e^+e^- from the 2003 d-Au run.

Charm from High-p_T Electrons
Non-photonic Single Electron Spectra

- Single electron spectra, after background (photonic source) is subtracted, for central and M.B collisions at $\sqrt{s_{NN}}$=130GeV
- Electrons from charm and beauty decays calculated by PYTHIA
  -- PYTHIA tuned to fit low energy data
  -- & scaled to Au+Au using number of binary collisions.

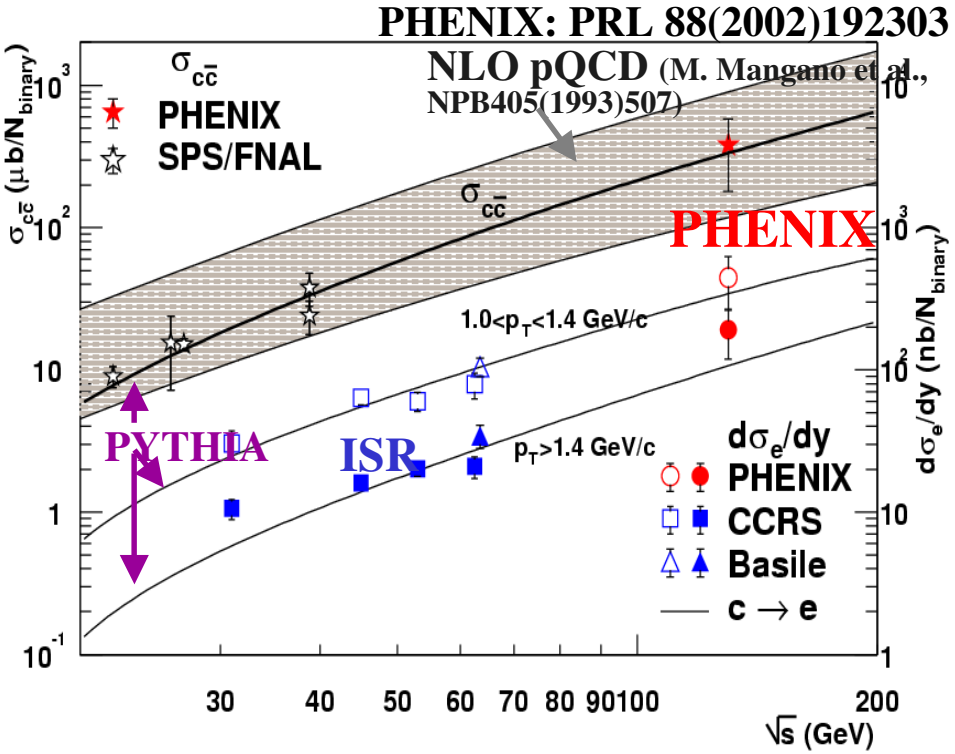


- Charm from PYTHIA in reasonable agreement with data (within relatively large uncertainty)
- The contribution from thermal dileptons and direct γ is neglected
  -- could mean we over-estimate the charm yield.

Charm Cross Section

- By fitting the PYTHIA electron spectrum to the data for pt>0.8 GeV/c, get the total charm yield N_{cc} per event.

$$\sigma_{c\bar{c}}^{0-10\%} = 380 \pm 60 \pm 200 \mu b \qquad \sigma_{c\bar{c}}^{0-92\%} = 420 \pm 33 \pm 250 \mu b$$



- Single electron cross section is compared with ISR data
- Charm cross section is compared with fixed target charm data.
  - Solid curve : PYTHIA
  - shaded Band : NLO pQCD

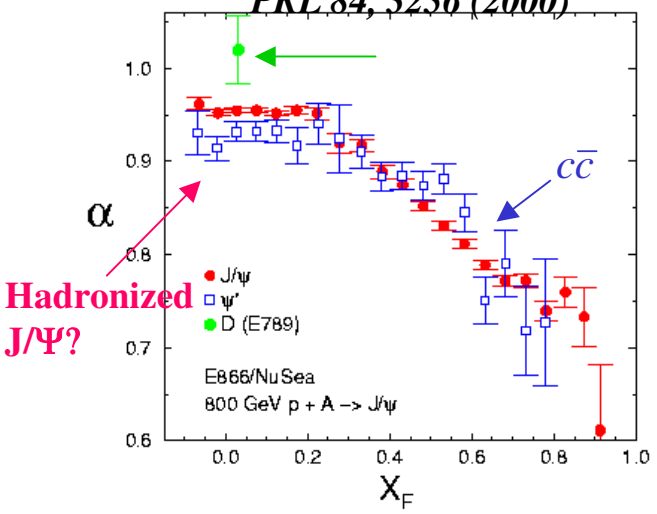
Assuming binary scaling,
PHENIX data are consistent with √s systematics (within large uncertainties)

Summary

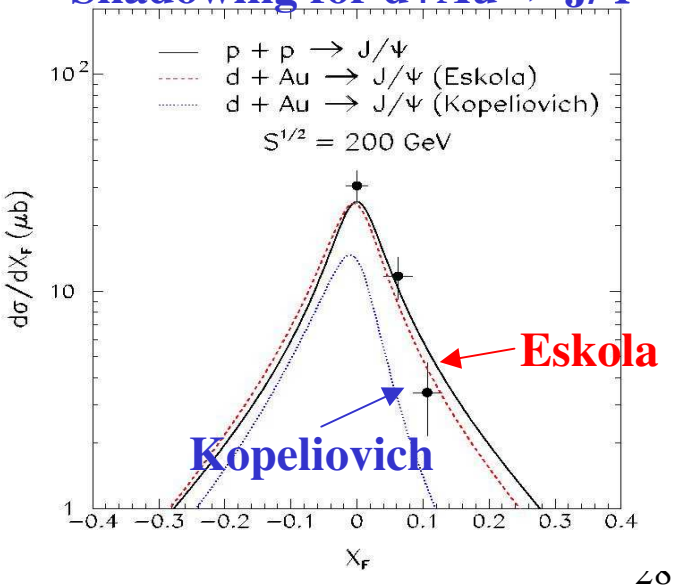
J/Ψ suppression has a rich variation with kinematic variables, i.e x_F and p_T

- gluon shadowing, absorption, parton energy-loss and p_T broadening all important
- J/Ψ is complicated by feed-down from higher mass resonances
- open-charm has no nuclear dependence at mid-rapidity (but this doesn't shed any light on shadowing at small x)
- Understanding J/Ψ suppression for normal nuclear matter is critical if the J/Ψ is to be used as a probe for hot high-density matter (QGP) in heavy-ion collisions
- At RHIC the effect of shadowing is very uncertain with predictions that vary by large factors. So it is quite important to measure shadowing at PHENIX

800 GeV p-A (FNAL)
PRL 84, 3256 (2000)



Shadowing for d+Au -> J/Ψ

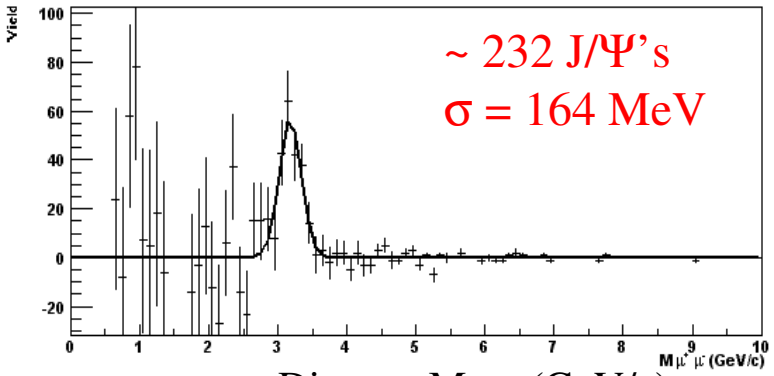


Summary-continued

New results from the PHENIX muon and electron arms for d-Au collisions are beginning to come out from this years data and should shed light on the question of shadowing for gluons, as well as provide a baseline for high-luminosity Au-Au measurements in the next RHIC run.

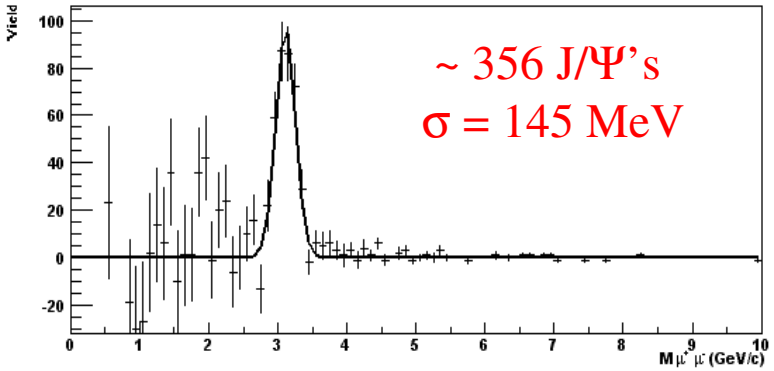
Comparison of North and South J/Ψ yields not instructive at this stage since we are only beginning to study efficiency issues which could have large effects and the data samples are not identical

South Muon Arm



Dimuon Mass (GeV/c)

North Muon Arm



Dimuon Mass (GeV/c)

PHENIX

Brazil	University of São Paulo, São Paulo
China	Academia Sinica, Taipei, Taiwan
	China Institute of Atomic Energy, Beijing
	Peking University, Beijing
France	LPC, University de Clermont-Ferrand, Clermont-Ferrand
	Dapnia, CEA Saclay, Gif-sur-Yvette
	IPN-Orsay, Universite Paris Sud, CNRS-IN2P3, Orsay
	LLR, Ecòle Polytechnique, CNRS-IN2P3, Palaiseau
	SUBATECH, Ecòle des Mines at Nantes, Nantes
Germany	University of Münster, Münster
Hungary	Central Research Institute for Physics (KFKI), Budapest
	Debrecen University, Debrecen
	Eötvös Loránd University (ELTE), Budapest
India	Banaras Hindu University, Banaras
	Bhabha Atomic Research Centre, Bombay
Israel	Weizmann Institute, Rehovot
Japan	Center for Nuclear Study, University of Tokyo, Tokyo
	Hiroshima University, Higashi-Hiroshima
	KEK, Institute for High Energy Physics, Tsukuba
	Kyoto University, Kyoto
	Nagasaki Institute of Applied Science, Nagasaki
	RIKEN, Institute for Physical and Chemical Research, Wako
	RIKEN-BNL Research Center, Upton, NY
	University of Tokyo, Bunkyo-ku, Tokyo
	Tokyo Institute of Technology, Tokyo
	University of Tsukuba, Tsukuba
	Waseda University, Tokyo
S. Korea	Cyclotron Application Laboratory, KAERI, Seoul
	Kangnung National University, Kangnung
	Korea University, Seoul
	Myong Ji University, Yongin City
	System Electronics Laboratory, Seoul Nat. University, Seoul
	Yonsei University, Seoul
Russia	Institute of High Energy Physics, Protovino
	Joint Institute for Nuclear Research, Dubna
	Kurchatov Institute, Moscow
	PNPI, St. Petersburg Nuclear Physics Institute, St. Petersburg
	St. Petersburg State Technical University, St. Petersburg
Sweden	Lund University, Lund

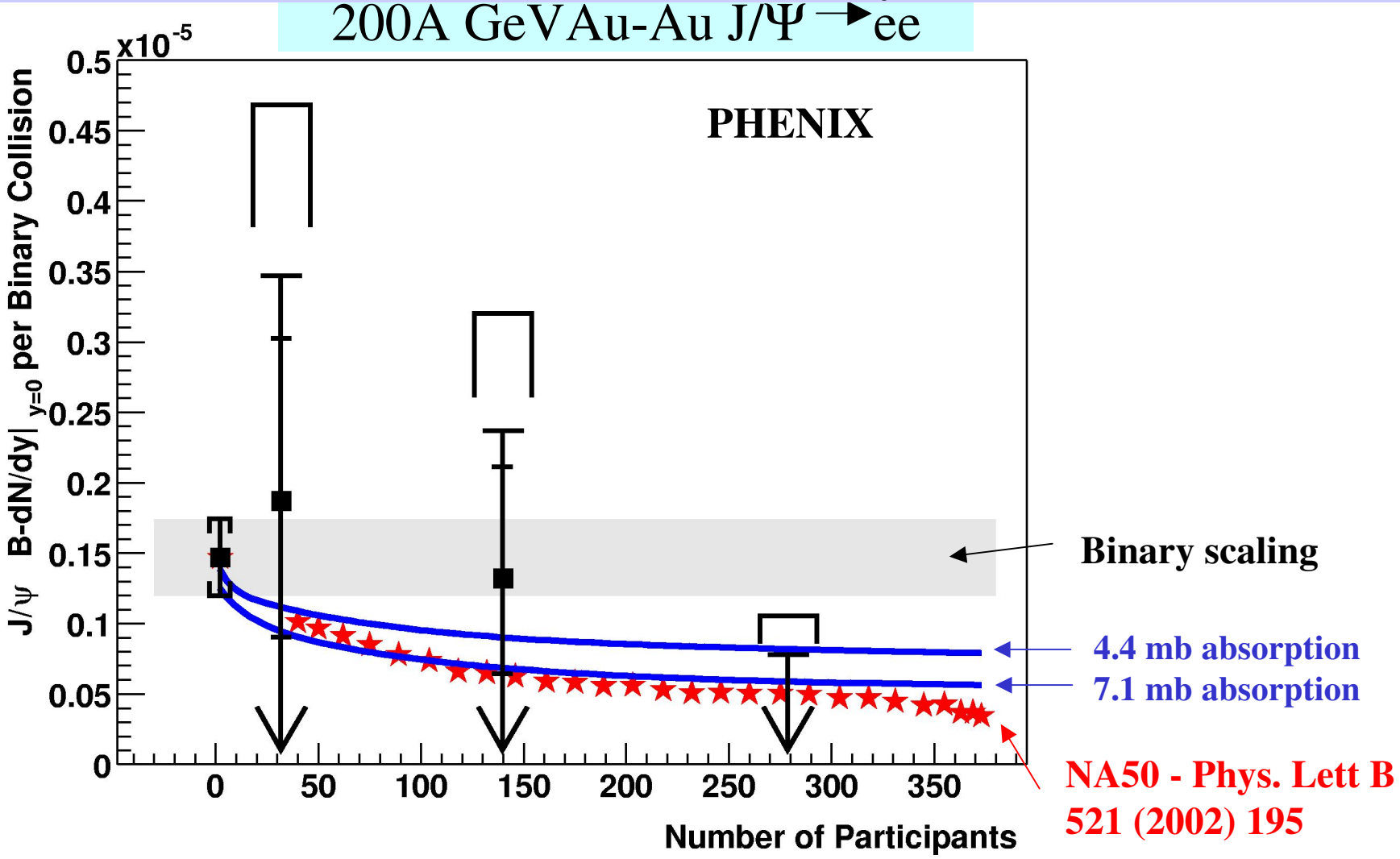
12 Countries; 57 Institutions; 460 Participants*

USA	Abilene Christian University, Abilene, TX
	Brookhaven National Laboratory, Upton, NY
	University of California - Riverside, Riverside, CA
	University of Colorado, Boulder, CO
	Columbia University, Nevis Laboratories, Irvington, NY
	Florida State University, Tallahassee, FL
	Georgia State University, Atlanta, GA
	University of Illinois Urbana Champaign, Urbana-Champaign, IL
	Iowa State University and Ames Laboratory, Ames, IA
	Los Alamos National Laboratory, Los Alamos, NM
	Lawrence Livermore National Laboratory, Livermore, CA
	University of New Mexico, Albuquerque, NM
	New Mexico State University, Las Cruces, NM
	Dept. of Chemistry, Stony Brook Univ., Stony Brook, NY
	Dept. Phys. and Astronomy, Stony Brook Univ., Stony Brook, NY
	Oak Ridge National Laboratory, Oak Ridge, TN
	University of Tennessee, Knoxville, TN
	Vanderbilt University, Nashville, TN

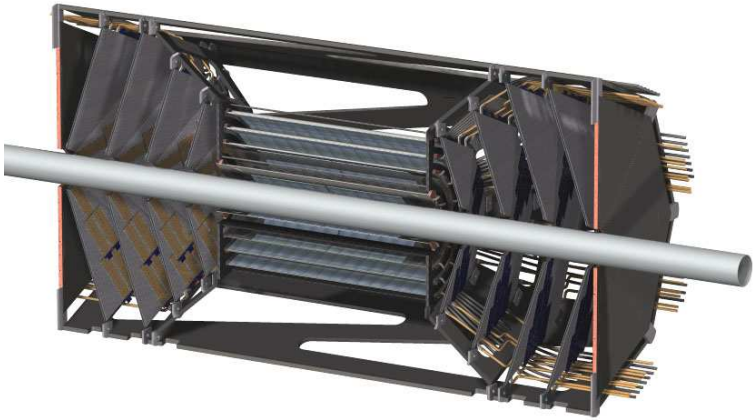
*as of July 2002

Backup slides

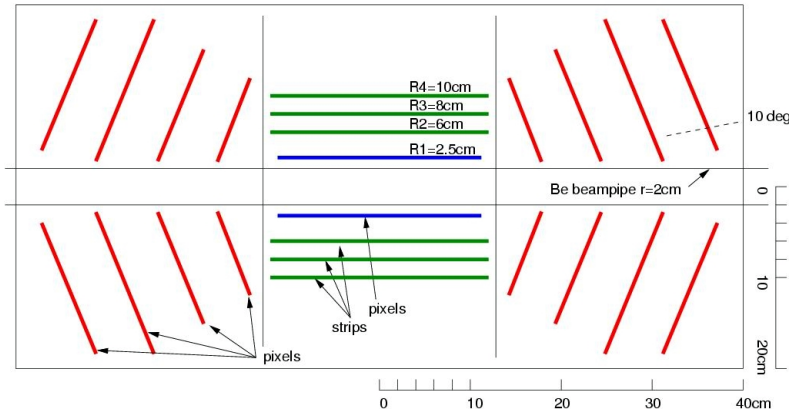
We can not discriminate between scenarios, given our present statistical accuracy

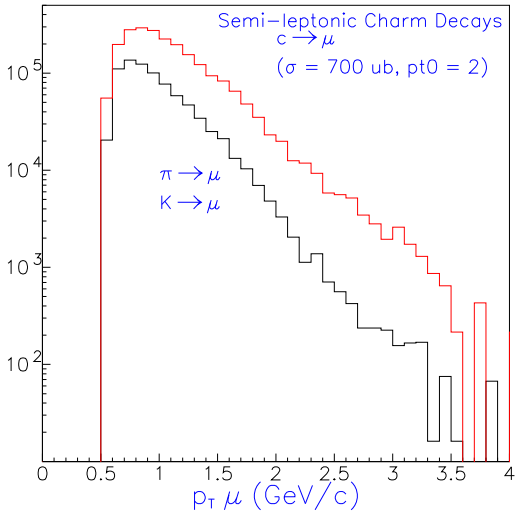


PHENIX Silicon Vertex Upgrade



A schematic cut-away mechanical drawing of the proposed vertex detector (from Hytec).

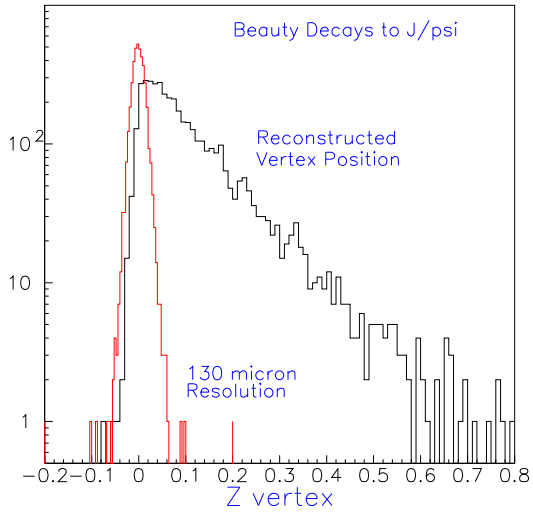




The pt distribution of muons that decay within 1cm of the collision vertex.

Physics Highlights:

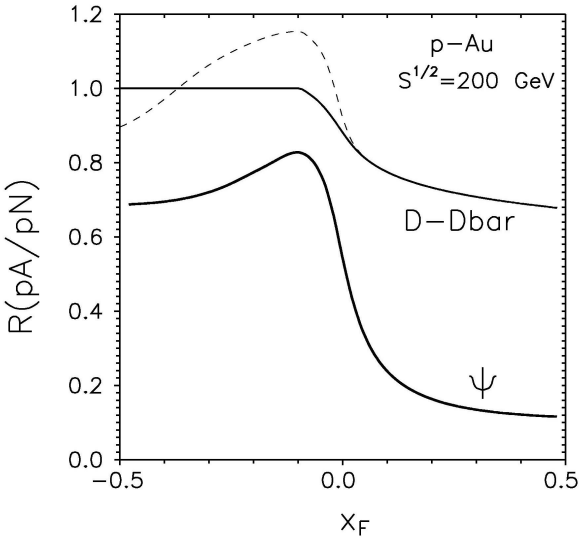
- **gluon shadowing & spin in the nucleon**
- **J/Ψ suppression & contrast to open-charm**
- **beauty**
- **heavy-quark energy loss**



The reconstructed Z-vertex distribution for the J/ψ from B decays (solid line) and the prompt J/ψ (dashed line).

Process Dependence of Shadowing?

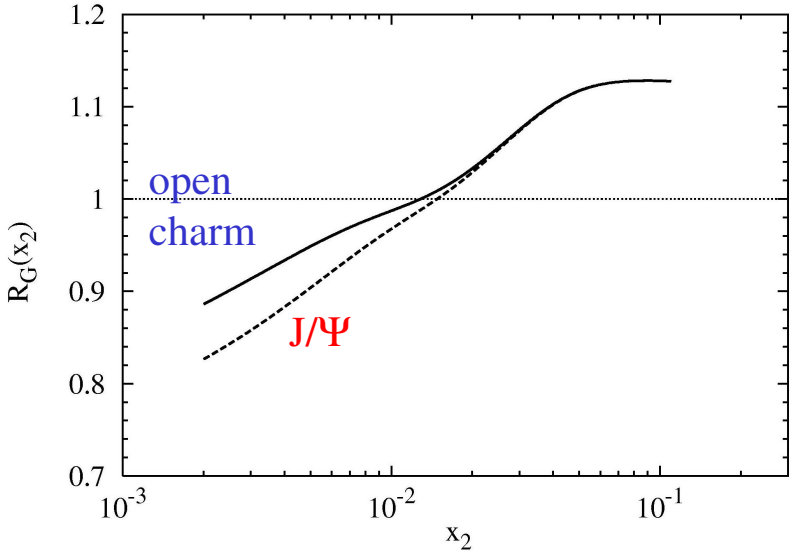
• Ordinary shadowing is process independent and is a "property" of the structure function in a nucleus



In the color-dipole model suppression at large x_F (small x_2) is much stronger for the J/Ψ than for open-charm

• but here much of the "shadowing" is "higher-twist final-state c-cbar interactions"

Kopeliovich et al hep-ph/0104256 & hep-ph/0205151



Jorg Raufeisen (private comm.)

• Gluon shadowing in the color-dipole model for Au

• here only the higher-twist shadowing causes the difference between open and closed charm

• (anti-shadowing from Eskola - ad hoc)

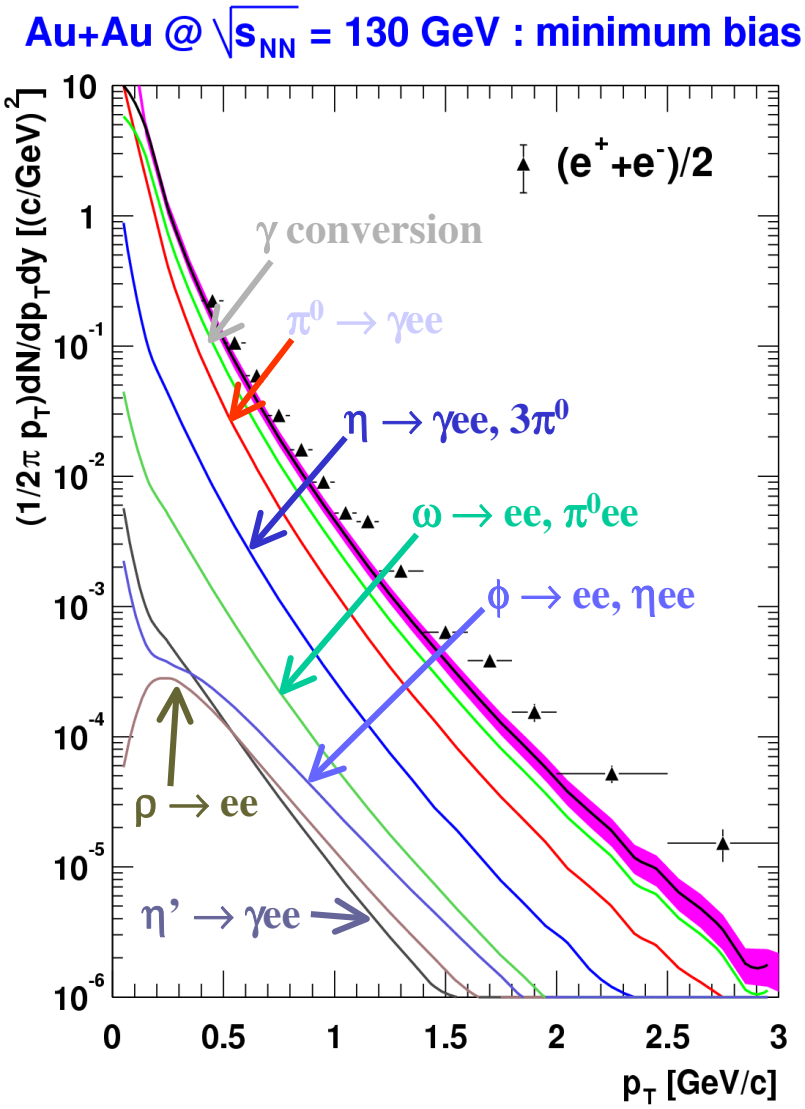
• also see, PRD 67, 054008 (2003)

PHENIX will look for this in d-Au measurements by comparisons of rapidity dependence of suppression between open- and closed-charm.

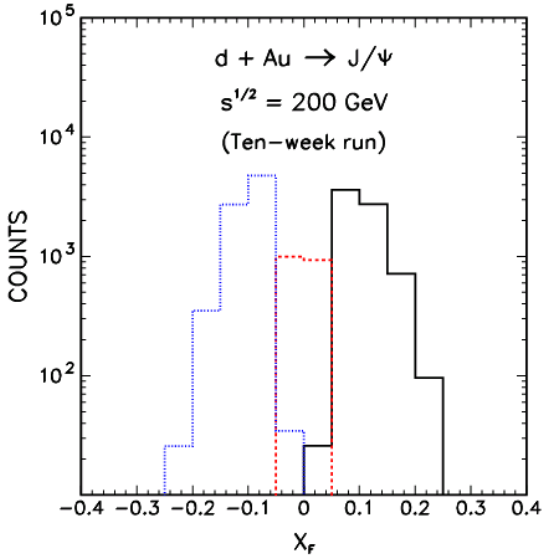
Cocktail Calculation

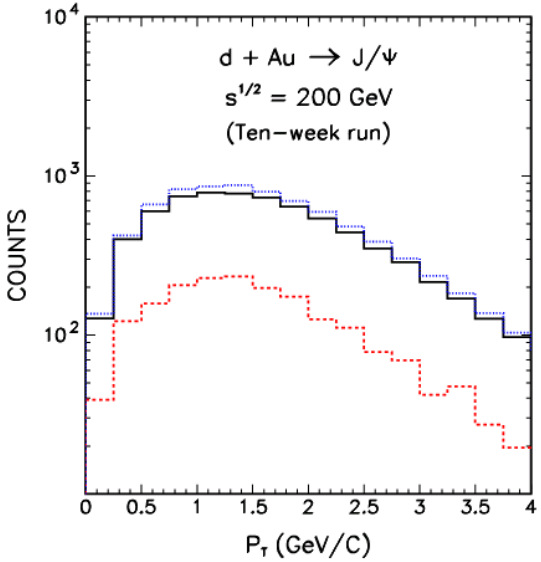
- p_T distribution of π^0 are constrained with PHENIX π^0 and $\pi^{\pm}$ measurement
- p_T slope of η, η' ρ and ω are estimated with m_T scaling
  $p_T = \mathrm{sqrt}(p_T^2 + M_{had}^2 - M_\pi^2)$
- Hadrons are relatively normalized by π^0 at high p_T from the other measurement at SPS, FNAL, ISR, RHIC
- Material in acceptance are studied for photon conversion

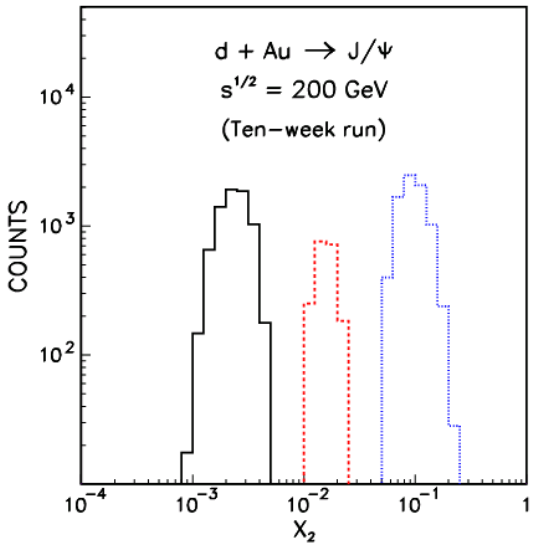
Signal above cocktail calculation can be seen at high p_T



J/Ψ Kinematic Coverage for present PHENIX d-Au (run-III)







PHENIX has very broad coverage in x_F, p_T and x_2 by combining

- North Arm
- Central Arm
- South Arm