Cold Nuclear Matter Effects

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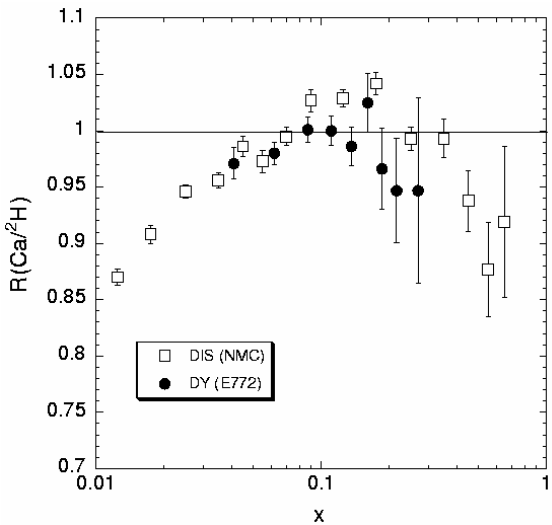
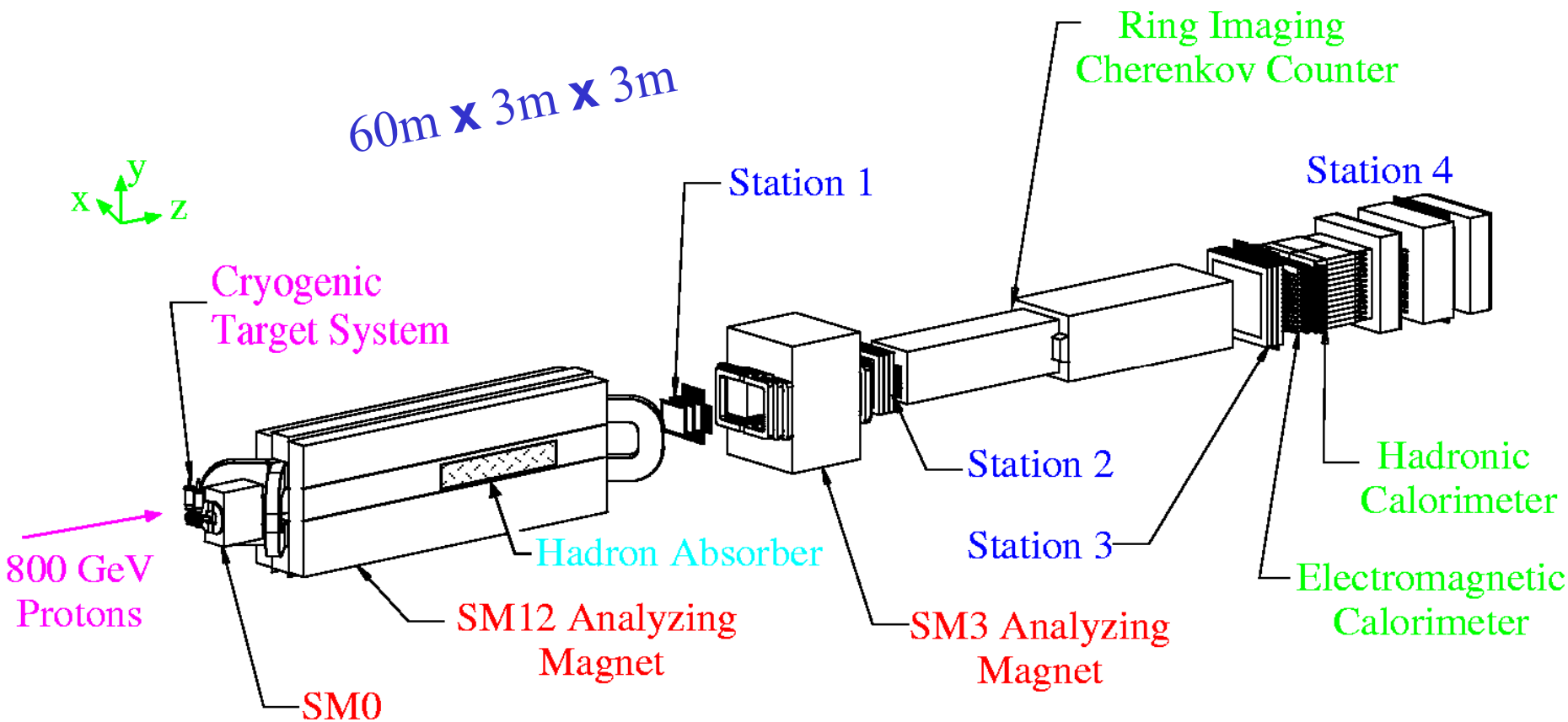
PHENIX Focus – 18 April 2006

- Spectrometers & definitions
- Deep Inelastic Scattering (DIS) & the EMC effect
- Drell-Yan
- Onia & cold nuclear matter effects
  - shadowing and/or saturation
  - p_T broadening
  - absorption
  - parton energy loss
  - contrasting open & closed charm
- Hadrons
- Upgrades at RHIC
- p(d)+A at RHIC-II and the LHC



800 GeV

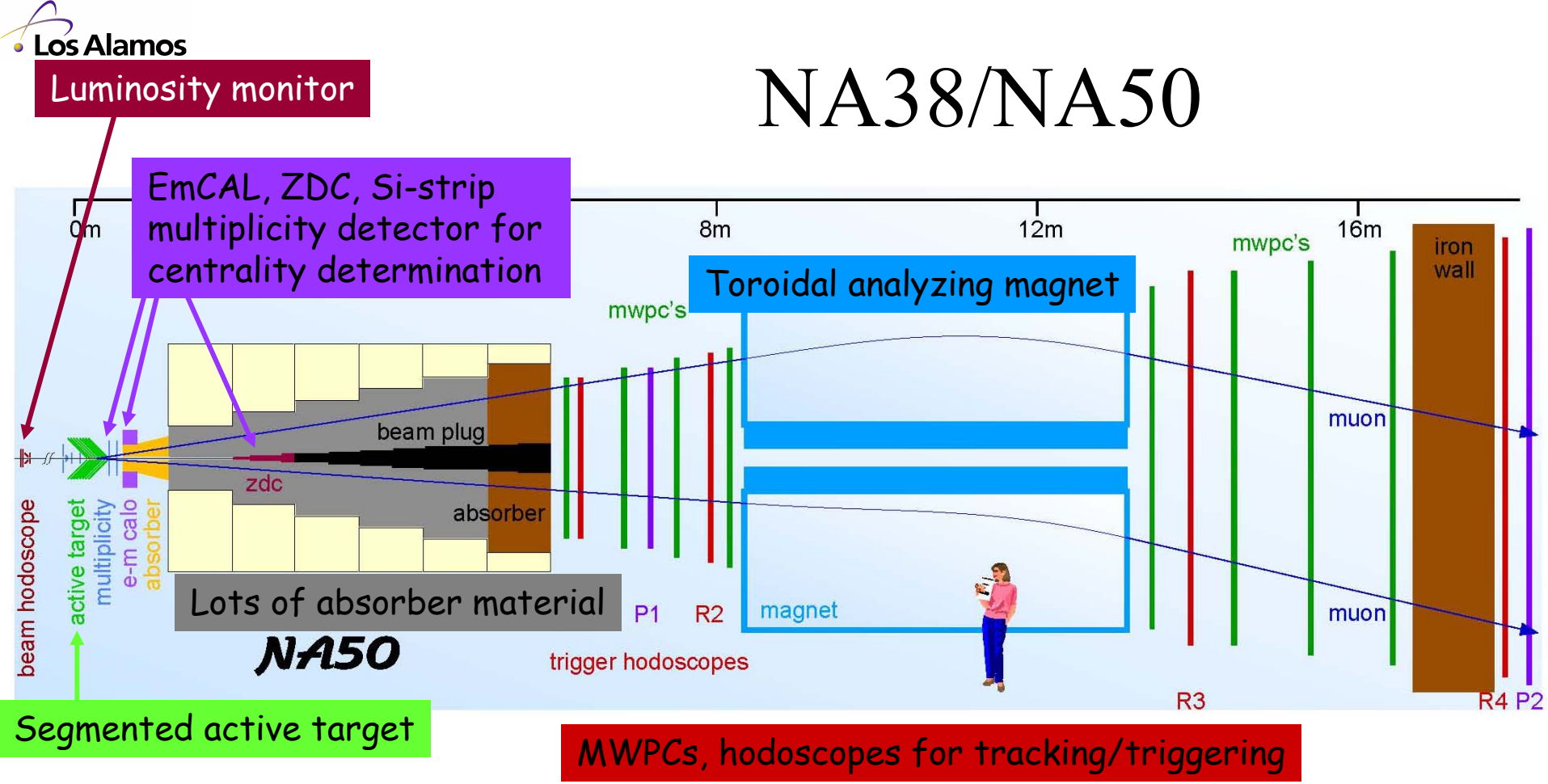
Fermilab E866/NuSea Detector



- Forward x_F, high mass μ-pair spectrometer
- Liquid hydrogen and deuterium targets
- Two acceptance defining magnets (SM0, SM12)

- Beam dump (4.3m Cu)
- Hadronic absorber (13.4 I_0-Cu, C, CH_2)
- Momentum analyzing magnet (SM3)
- Three tracking stations
- Muon identifier wall & 4th tracking

NA38/NA50



Note benefits of a fixed target experiment:

- Lots of luminosity.
- Boost in lab frame gives very high momentum particles, so resolution is improved and background can be greatly reduced by many meters of absorber.

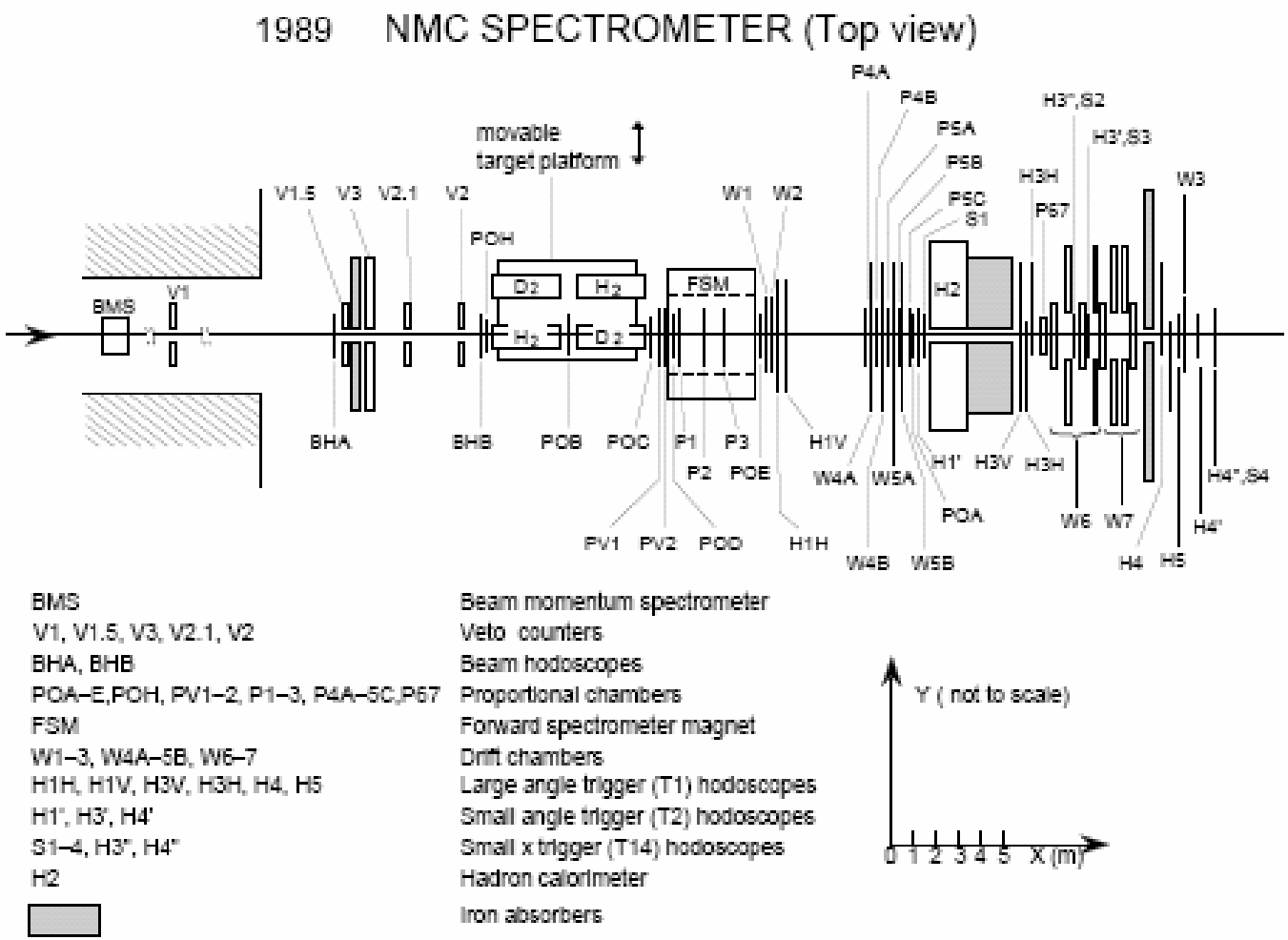
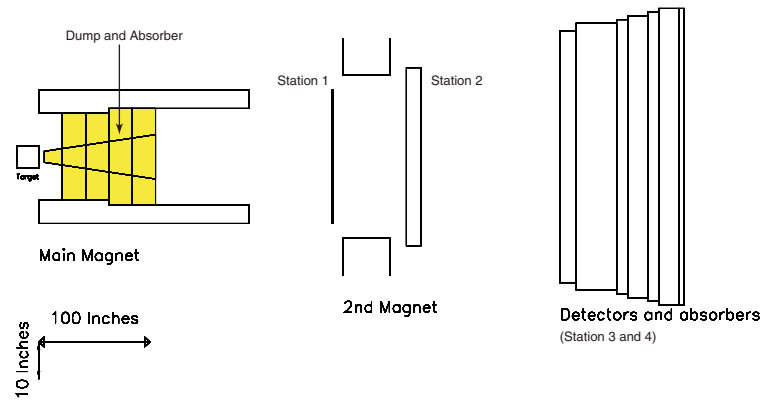


Figure 1: The NMC spectrometer for the 1989 data taking. The beam calibration spectrometer is located downstream and not shown.

Spectrometer for JPARC Dimuons

Schematic view in horizontal plane

- Two vertically bending magnets with p_T kick of 2.47 GeV/c and 0.5 GeV/c.
- "Closed geometry"
  - A tapered copper beam dump and Cu/C absorbers placed within the first magnet.
- Tracking is provided by three stations of MWPC and drift chambers.
- Muon id and tracking are provided.
- 2×10^{12} 50 GeV p/spill.



- Based on the Fermilab spectrometer for 800 GeV, the length can be reduced but the aperture has to be increased.

Representing Nuclear Dependences

Typical fixed-target measurement where centrality not measured e.g. E772,E866:

$$R(W/Be)=\frac{\left(\sigma(W)/A_W\right)}{\left(\sigma(Be)/A_{Be}\right)}$$

Power law representation of nuclear dependence when many nuclei are measured (especially useful when comparing different experiments that used different light and heavy targets):

$$\sigma_{pA}=\sigma_{pp}A^{\alpha}$$

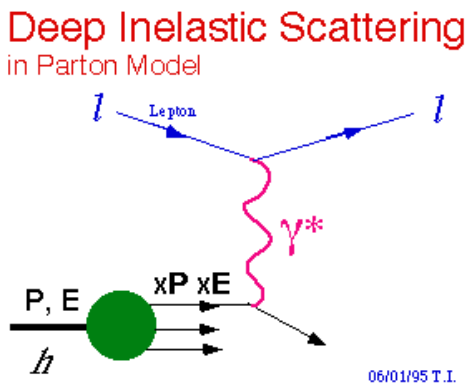
Nuclear Modification factor typically used at RHIC:

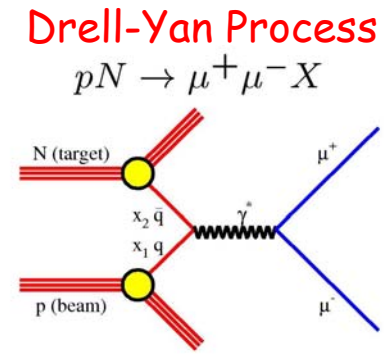
$$R_{dAu}=\frac{Yield_{inv}^{dAu}}{<N_{coll}^{dAu}>Yield_{inv}^{pp}}$$

Where, when looking at non-centrality binned results, the latter is equivalent to:

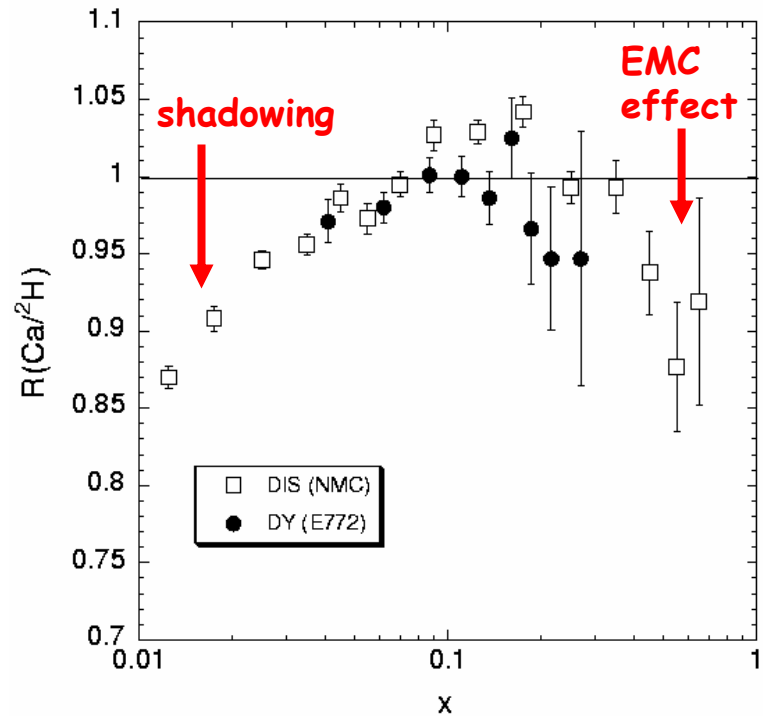
$$R_{dAu}=\frac{\sigma_{dAu}}{\left(2\times 197\right)\sigma_{pp}}$$

Deep Inelastic Scattering & the EMC Experiment



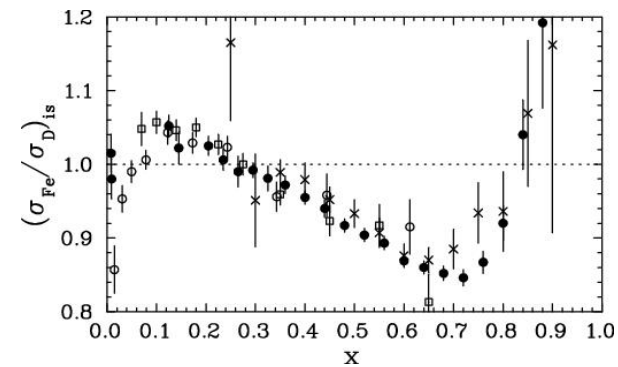


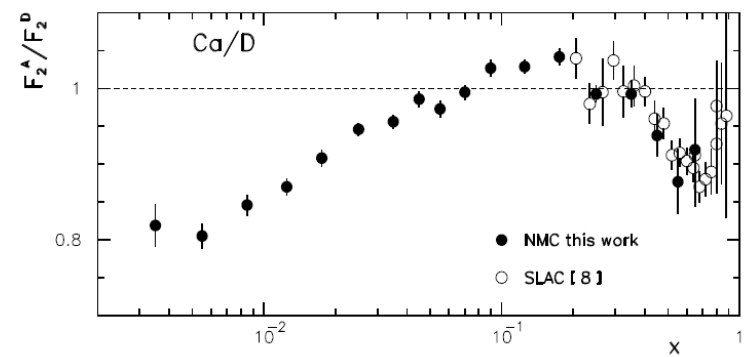
Nuclear effects on the nucleon's quarks or anti-quarks



The EMC Effect

- Measurements of F_2^A / F_2^D (EMC, SLAC, BCDMS) have demonstrated modification of quark distributions in nuclei
- Magnitude of effect depends on A, but not the shape





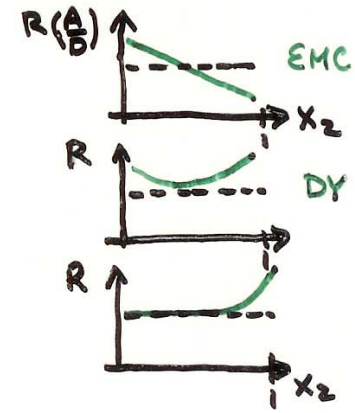
- Typically broken in 3 regions
  - x < 0.1: shadowing
  - 0.1 < x < 0.3: small enhancement (anti-shadowing)
  - x > 0.3: suppression -> "EMC Effect"
- Fourth region at x > 0.7 -> ratio increases, crosses 1.0
  - Attributed to Fermi momentum smearing

from Dave Gaskell
JLab E03-103

THEORETICAL MODELS

Nuclear Binding & Fermi Momentum (Ericson & Thomas, Bickerstaff & Thomas, Berger & Coester)

- excess π's (nuclear binding)
  - → loss of valence q momentum, enhanced sea (π's)
  - → π's have valence (large x) $\bar{q}$'s so $\bar{q}$ momentum enhanced
- Fermi motion spreads quark momentum to large x



Rescaling (Close et al.; Jaffe)

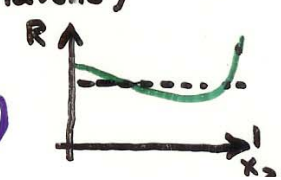
$$F_2^{Fe}(x,Q^2) \simeq F_2^{D}(x,\xi Q^2)\ ,\ \xi \sim 2$$

~15% phenomological increase in confinement scale

- overlapping nucleons (Close, Jaffe, ...)
  2-N correlation fn's
  → loss of valence q momentum

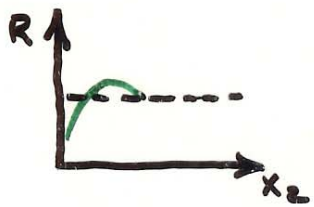
Multi-q Clusters (~16-30%) (Pirner & Vary, Carlson & Havens)

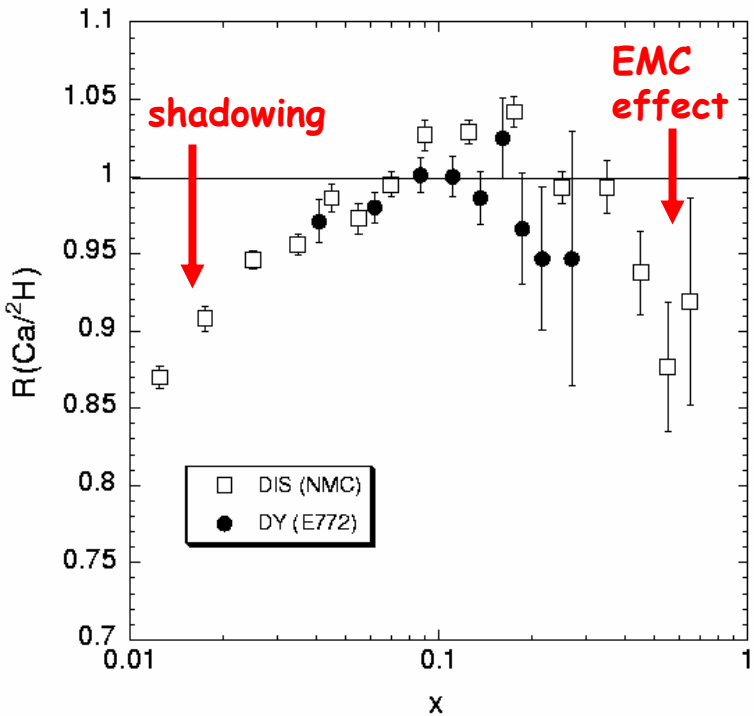
→ loss of valence q momentum, relative enhancement at x~1 (one q can have > nucleon momentum)



Shadowing depletion of low-mometum partons

- at low x partons from diff. nuclei overlap & interact (e.g. Miller & Qiu)
  → parton momenta redistributed
  → shadowing & anti-shadowing
- parton multiple scattering (Brodsky & Lu)

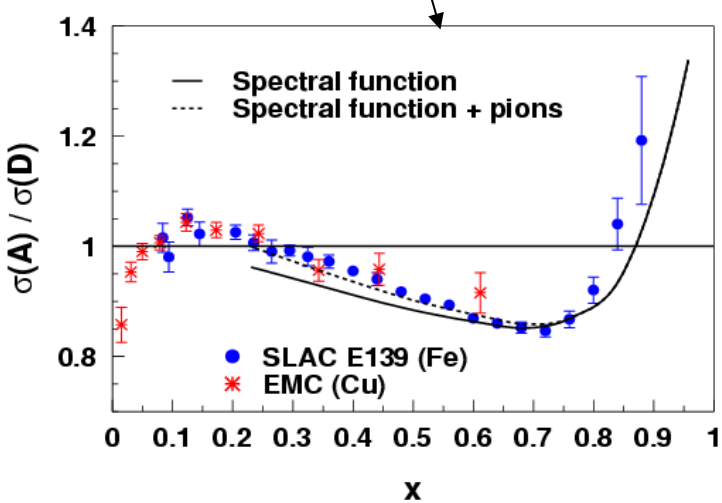




Explaining the EMC Effect

Conventional Models

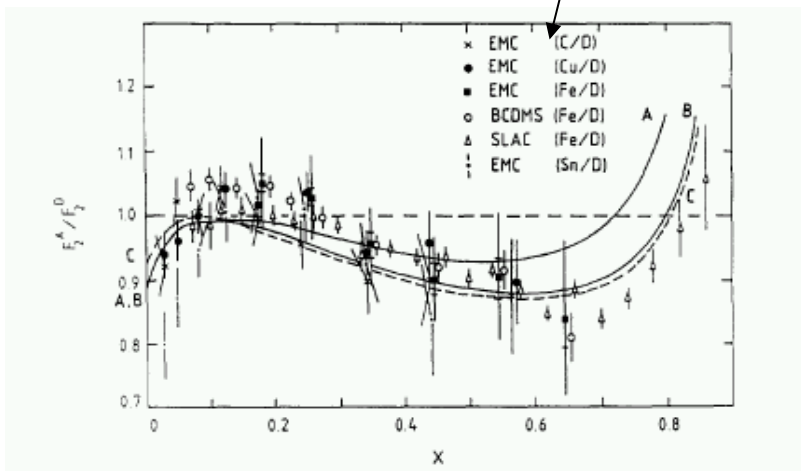
- Some combination of Fermi motion and binding
- Fermi motion + binding + nuclear pions



Benhar, Pandharipande, and Sick
Phys. Lett. B410, 79 (1997)

Exotic Models

- Dynamical rescaling
- Multiquark clusters

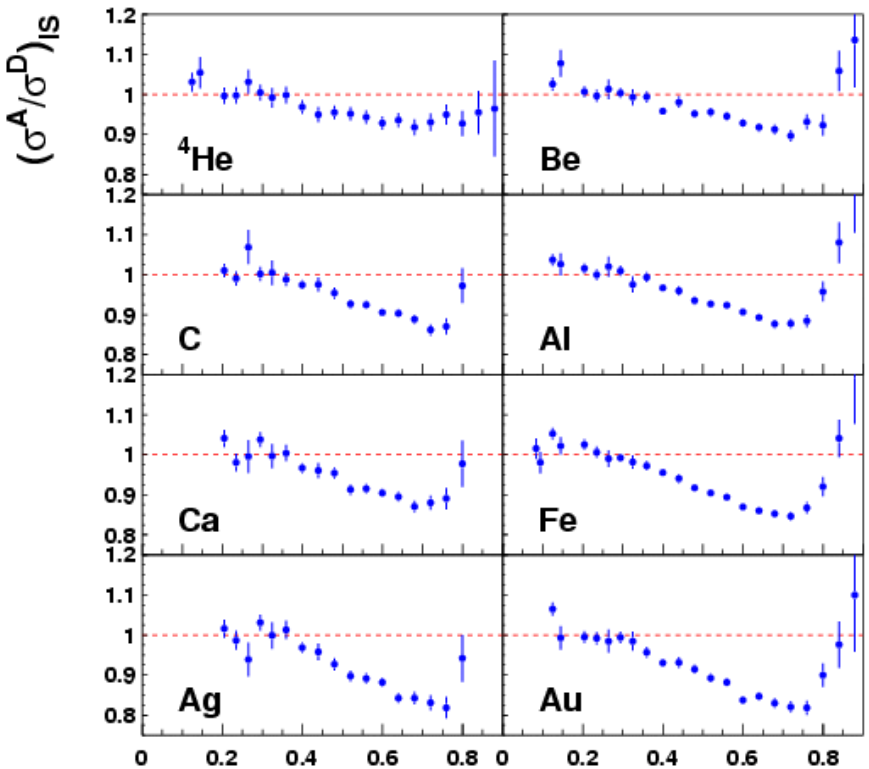


K.E. Lassila and U.P. Sakhatme
Phys. Lett. B209, 343 (1988)

from Dave Gaskell
JLab E03-103

Existing EMC Data

- SLAC E139 probably the most extensive data set for x>0.2
- Measured s_A/s_D for A=4 to 197
  - ^{4}He, ^{9}Be, C, ^{27}Al, ^{40}Ca, ^{56}Fe, ^{108}Ag, and ^{197}Au
  - Size at fixed x varies with A, but shape is nearly constant
- Data set could be improved with
  - Higher precision data for ^{4}He
  - Addition of ^{3}He data
  - Precision data at large x

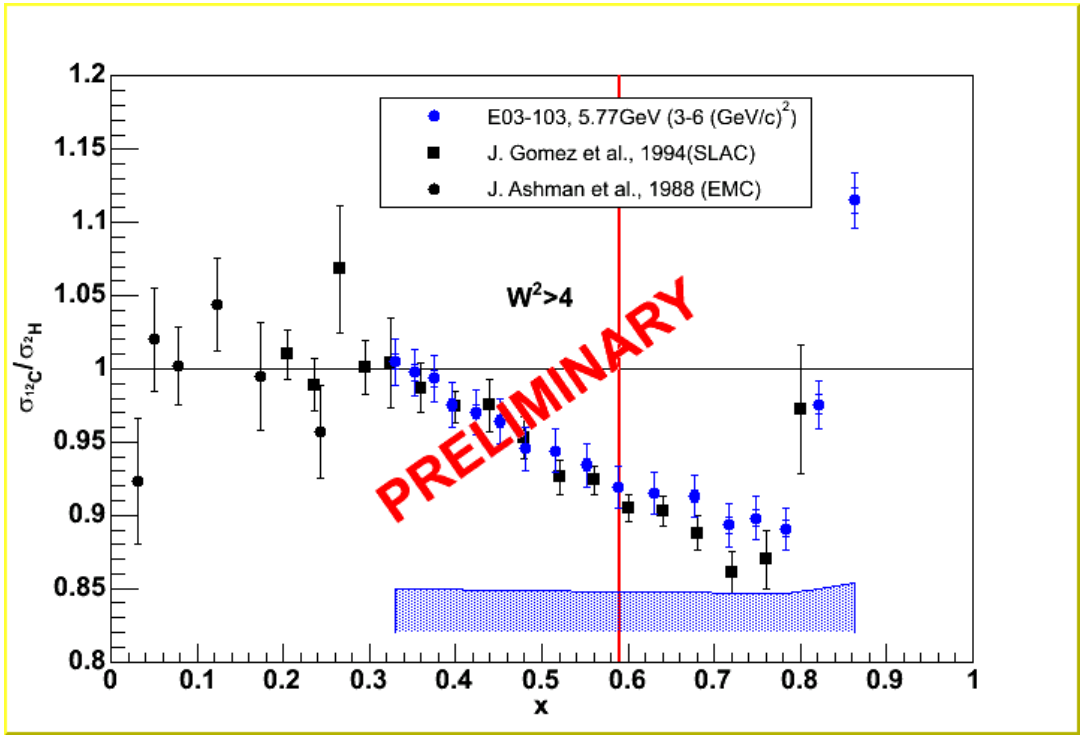


SLAC E139

x_{Bj}

from Dave Gaskell
JLab E03-103

Carbon EMC Ratio –JLab E03-103



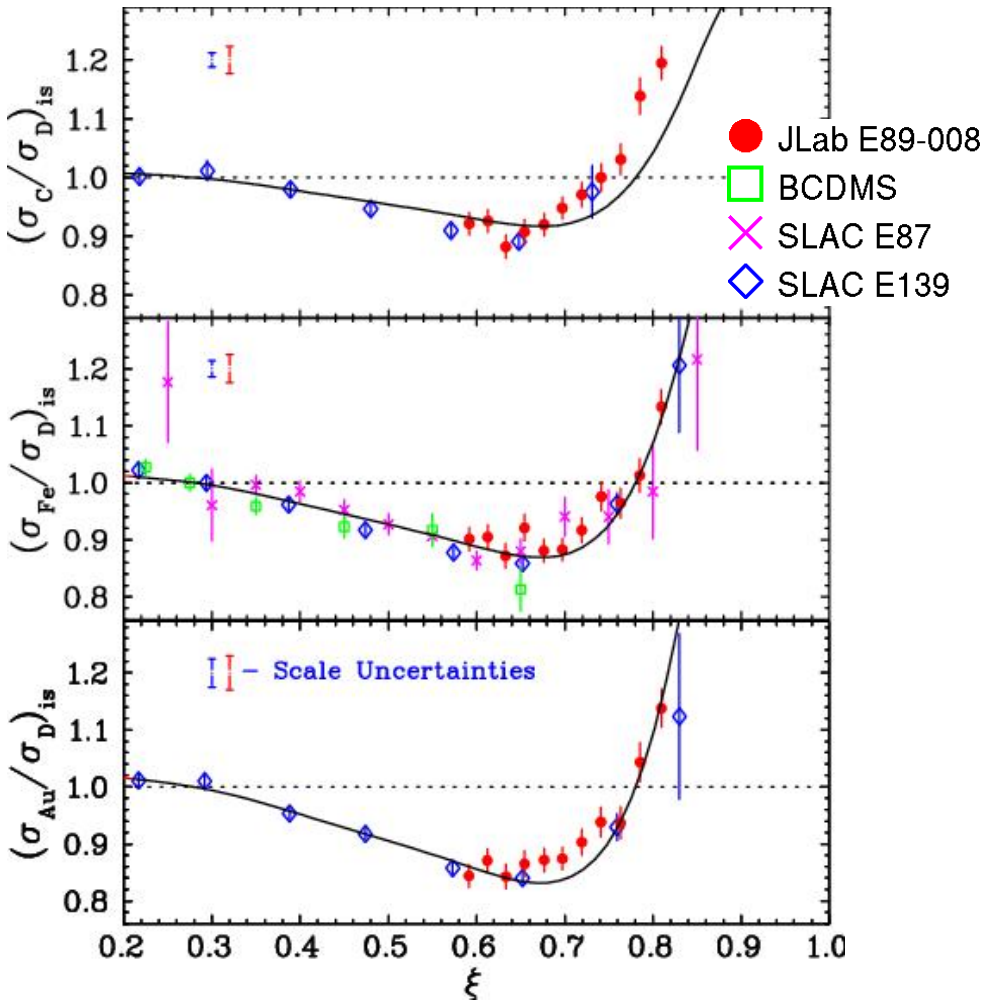
- Existing precision Carbon data serves as a nice cross-check
- Points include 1.5% point-to-point systematic uncertainty (radiative corrections, bin centering)
- 3% normalization uncertainty (target thickness, radiative and bin centering corrections)

from Dave Gaskell
JLab E03-103

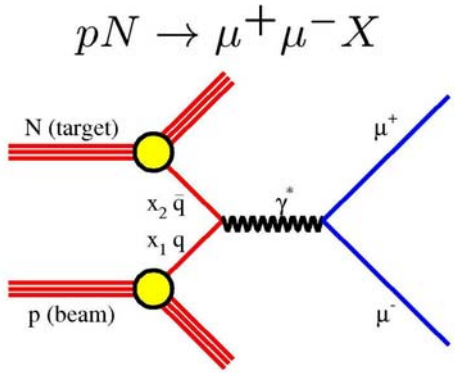
EMC Measurements at W<2 GeV

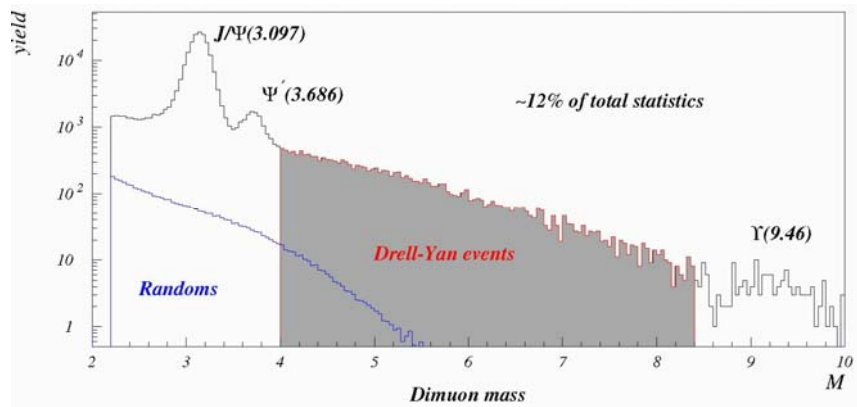
- EMC ratio extracted using resonance region data from E89-008
  - $1.2<W^2<3.0$ GeV^2 at $Q^2\approx4$ GeV^2
- Where there is overlap, JLab resonance data agrees well with SLAC (DIS) results
- E03-103 has data at $W^2>2$ GeV^2 at $Q^2=6$ GeV^2 (x=0.82)
- Data at smaller angles will allow us to put quantitative limits on deviation from scaling in the cross sections AND ratios

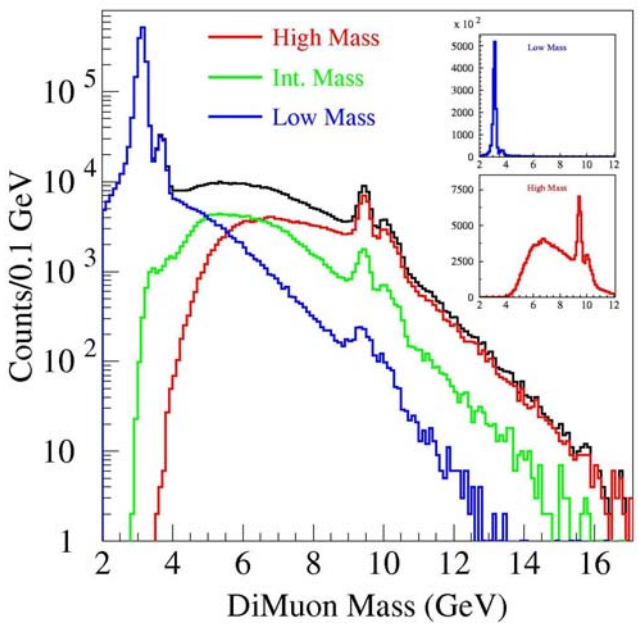
from Dave Gaskell
JLab E03-103

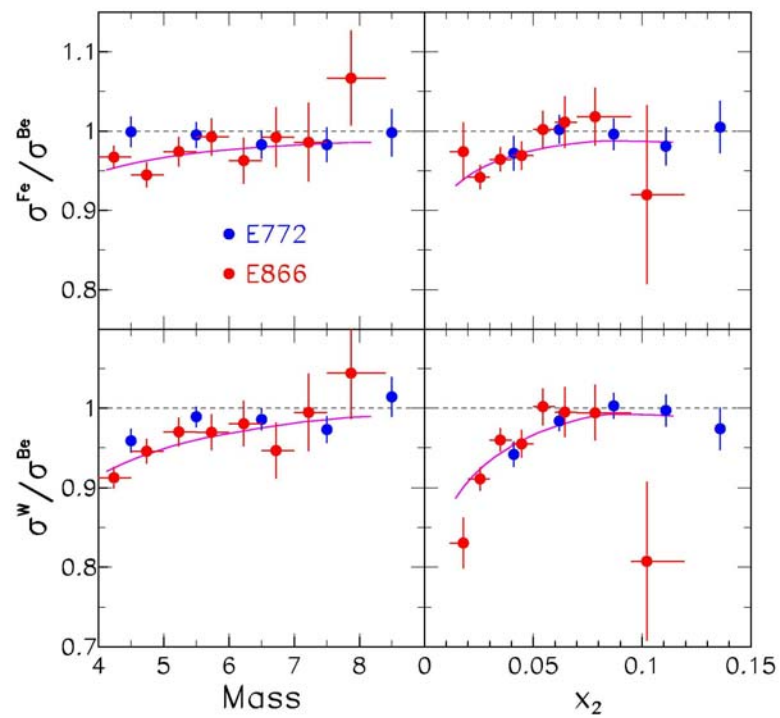


Drell-Yan and E772/E789/E866 at Fermilab



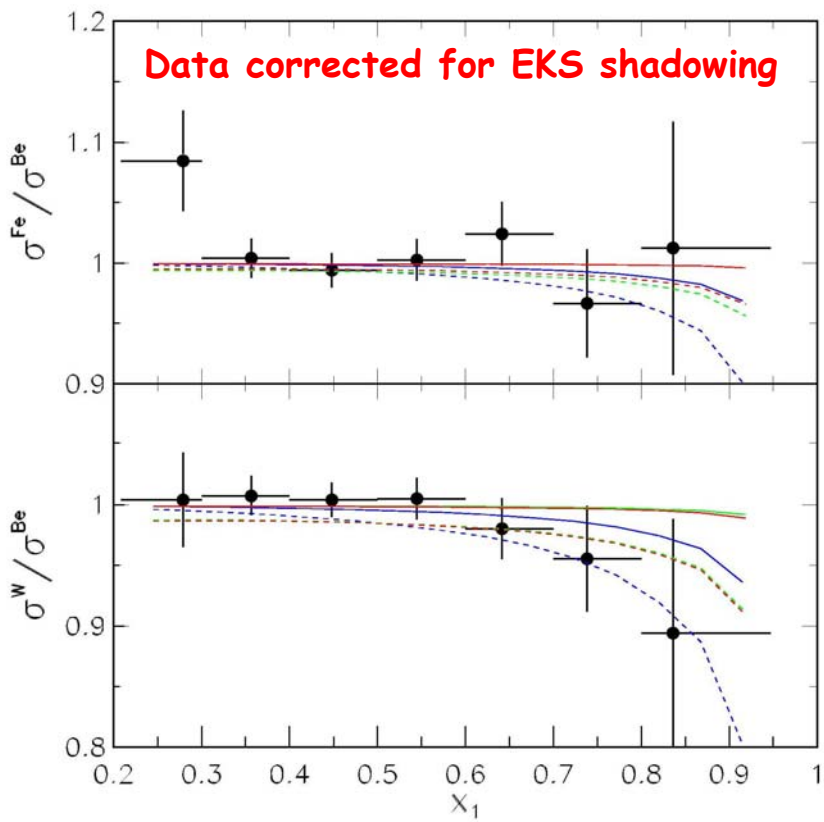






Quark Energy Loss from Drell-Yan data assuming EKS Shadowing

Parton energy loss limits



- Gavin and Milana $\Delta E < 0.14\,\%/\mathrm{fm}$
- Brodsky and Hoyer $\Delta E < 0.44\,\mathrm{GeV/fm}$
- Baier et al. $\Delta E < (0.046\,\mathrm{GeV/fm}^2) \times L^2$

- S.Gavin, J.Milana, Phys.Rev.Lett 68(1992)1834

$$\Delta x_1 = kCx_1 \left(\frac{Q_0}{Q}\right)^n A^{\frac{1}{3}}$$

$C = 4/3$ for quarks, $C = 3$ for gluons, $n =$ for "soft physics" Experimental fit: $\Delta x_1 = -k_1 x_1 A^{\frac{1}{3}}$

- S.Brodsky, R.Hoyer, Phys.Lett. B298(1993)165

$$|\Delta x_1| \leq \frac{< k_\perp > L_a}{2E}$$

Experimental fit: $\Delta x_1 = -\frac{k_2}{s} A^{\frac{1}{3}}$

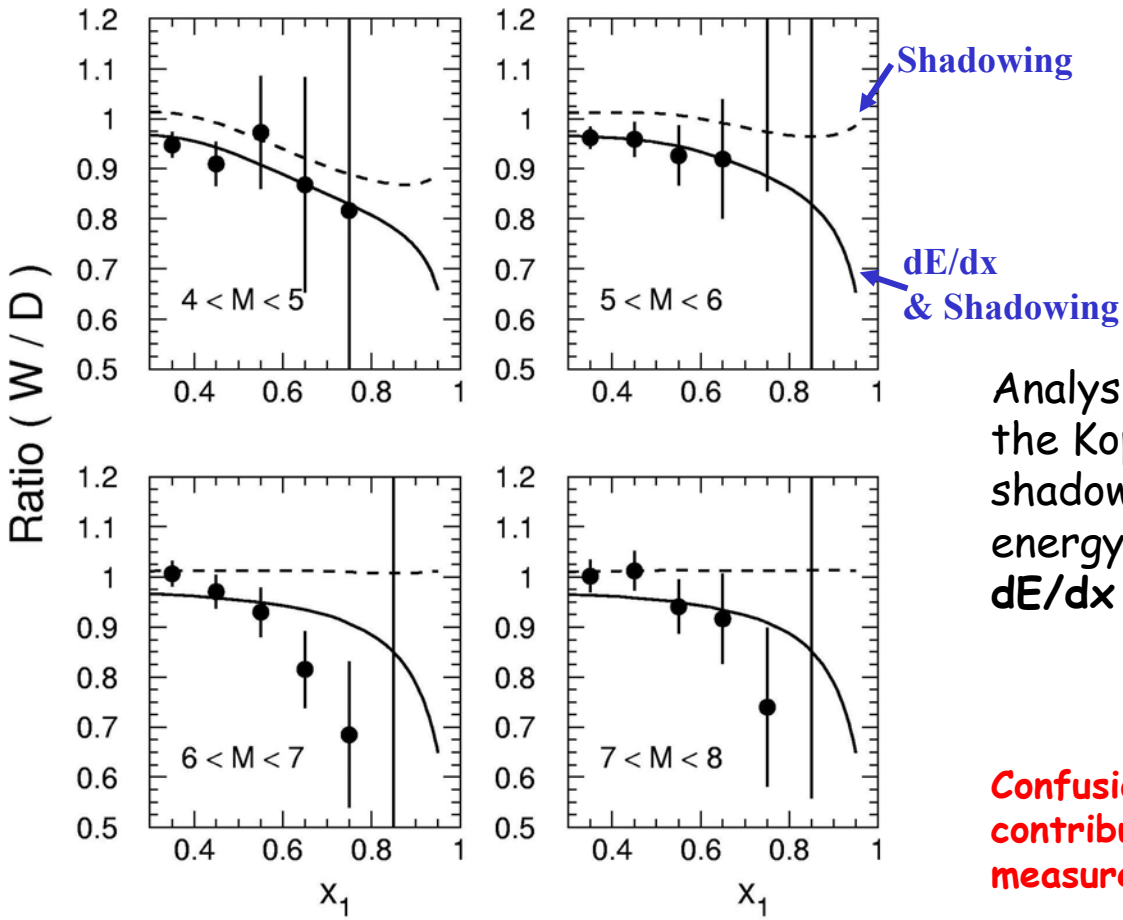
- R.Baier et al., Nucl.Phys. **B**484(1997)265
  R.Baier et al., Nucl.Phys. **B**531(1998)403

$$|\Delta x_1| = \frac{3\alpha_s}{2}\frac{m_p}{s} L_a < p_\perp^2 >$$

Experimental fit: $\Delta x_1 = -\frac{k_3}{s} A^{\frac{2}{3}}$

Quark Energy Loss from Drell-Yan data assuming Kopeliovich Shadowing

Johnson, Kopeliovich et al., PRL 86, 4483 (2001)



data from
E772 - PRL 64, 2479 (1990)

Analysis of our p-A Drell-Yan data using the Kopeliovich model. Dashed lines with shadowing only; solid lines with parton energy loss of

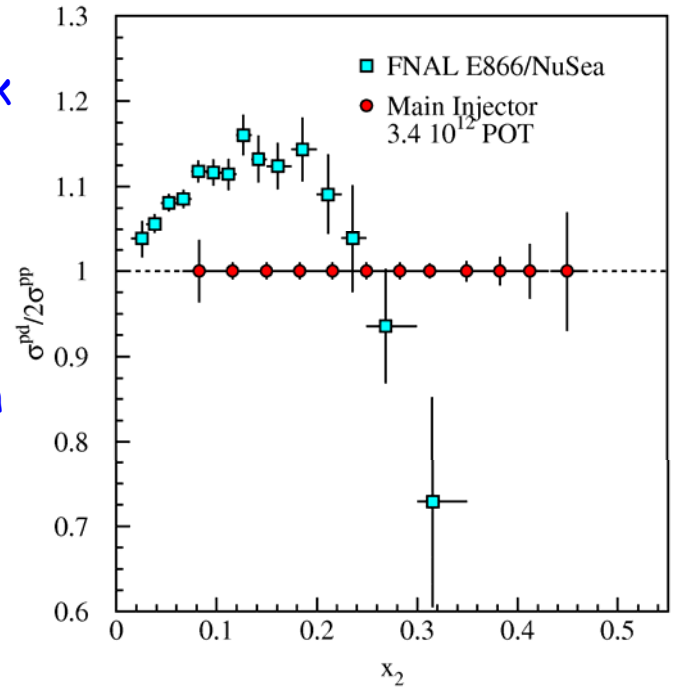
dE/dx = 2.32 ± 0.52 ± 0.5 GeV/fm

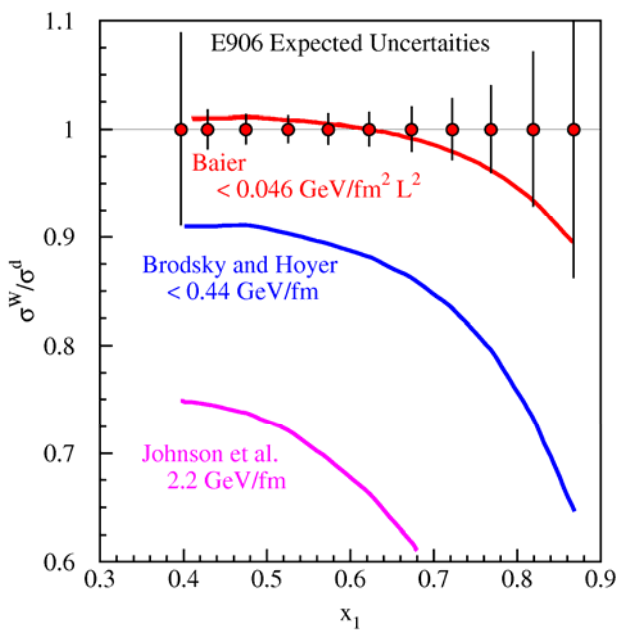
Confusion due to both shadowing and dE/dx contributing to Drell-Yan suppression for measurements at this energy

FNAL E906 – flavor asymmetry of the nucleon to larger x & quark energy loss in nuclei

dbar/ubar > 1 for x_2 < 0.25

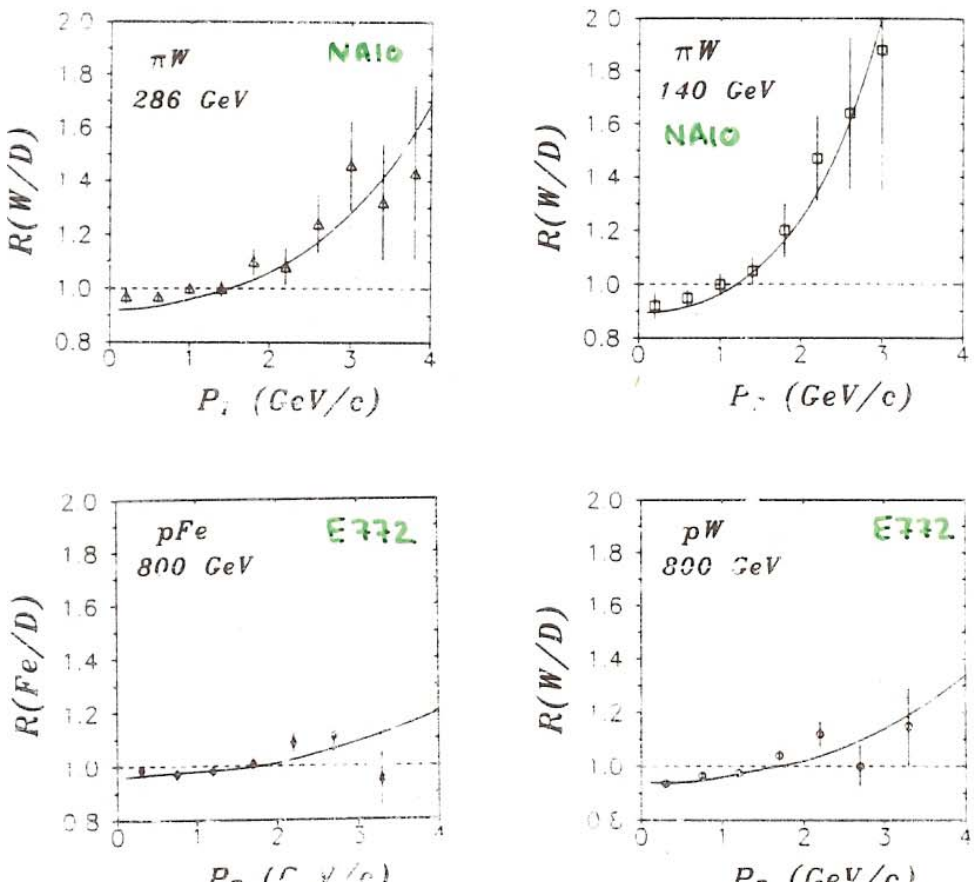
- probably due to meson cloud of proton, i.e. quark counting (p → n + π+ → n + dbar-u)
- does gluon splitting dominate at larger x_2 and give dbar=ubar?
- 120 GeV Drell-Yan D/H measurement needed to push to larger x_2!
- polarized p-p collisions at RHIC can explore spin structure of dbar/ubar with W's





At 800 GeV, the nuclear dependence of Drell-Yan on nuclear targets could not unambiguously separate shadowing and dE/dx effects at low x

- **for 120 GeV p-A Drell-Yan only quark dE/dx remains and can be isolated**
- **and is stronger, dE/dx ~ 1/s**
- **also would work at JPARC (50 GeV)**



Drell-Yan

P_T broadening

from
Dolejsi, Hufner, Kopeliovic
PL B312, 235 (1993)
data from E772
and
NA10 (PLB 193, 373 (1987))

Energy loss from p_T-broadening?

R.Baier et al., Nucl. Phys. B 484, 265(1997); R.Baier et. al., hep-ph/9804212 suggested:

$$-\frac{dE}{dz} = \frac{\alpha_s N_c}{4} \times \Delta < p_T^2 >$$

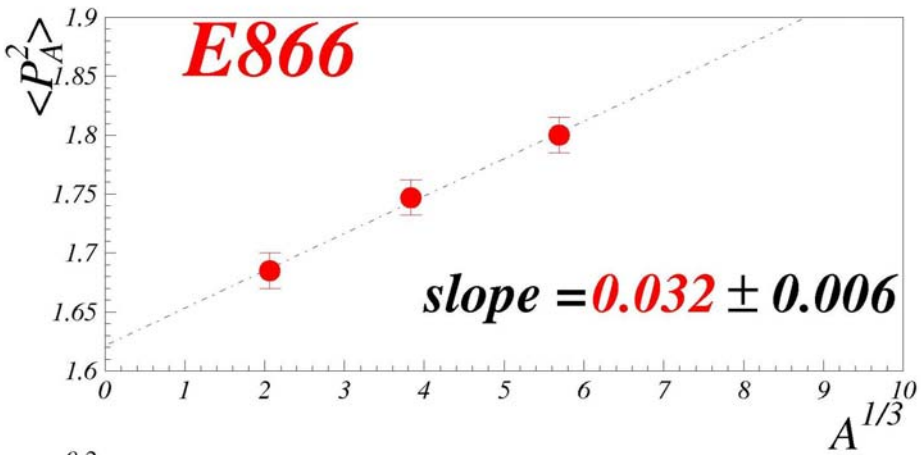
Can we find energy loss from it?

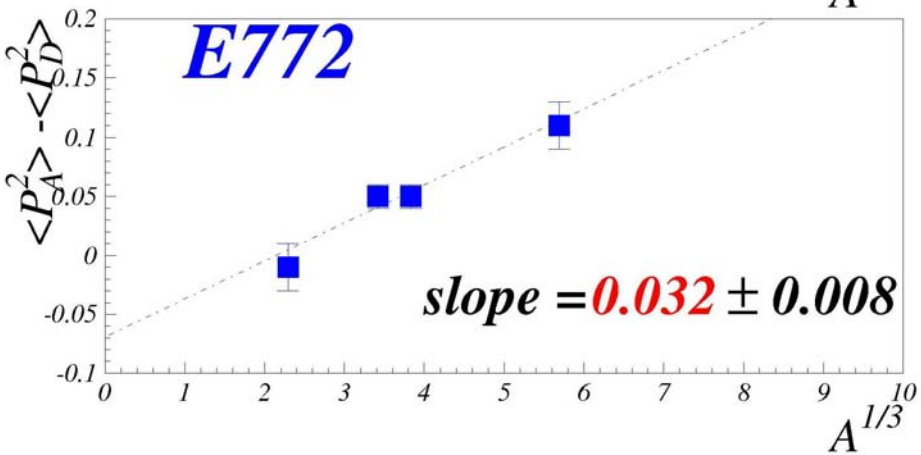
high statistics Monte-Carlo study of the p_T - acceptance for Drell-Yan pairs is necessary!
(Nearly finished)

$$\Delta < p_T^2 > = slope\ (A^{\frac{1}{3}} - 1)$$

$$\Delta E = \frac{dE}{dz} \times L = \frac{\alpha_s N_c}{4} \times slope\ (A^{\frac{1}{3}} - 1) \times L$$

$$\Delta E = \left(0.24 \times slope\ \frac{GeV}{fm^2}\right) \times L^2$$

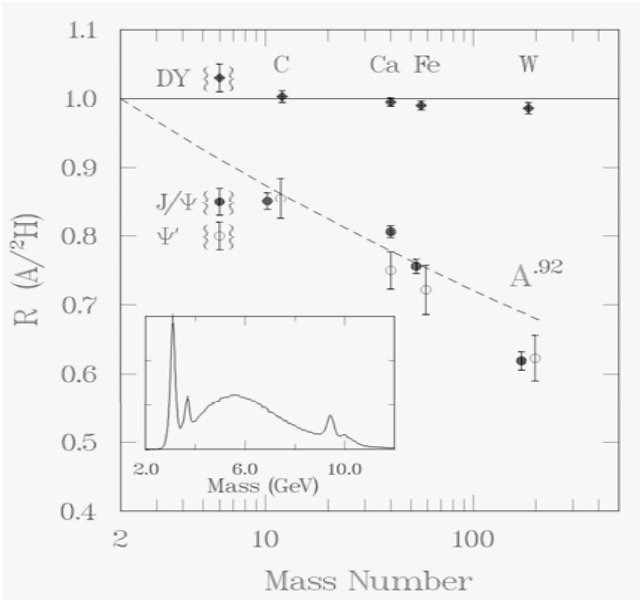


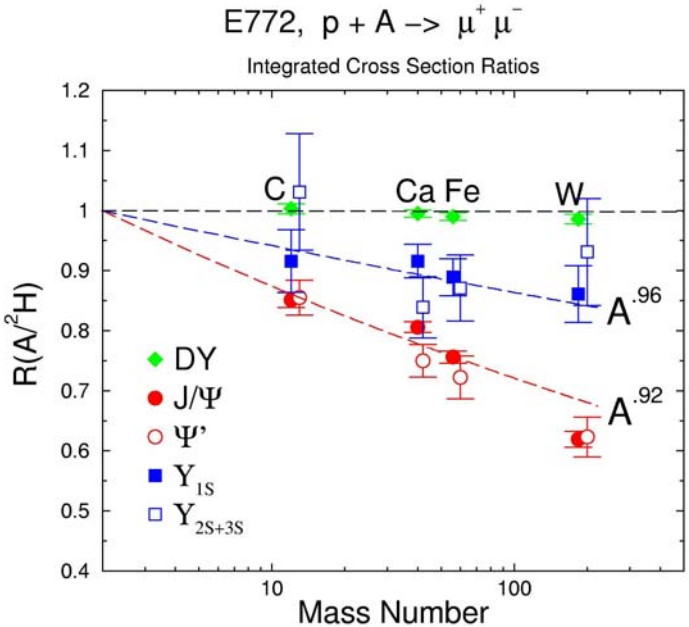


$$\Delta E = \left(0.008 \frac{GeV}{fm^2}\right) \times L^2$$

Onia at Fermilab – E772/E789/E866

E772 - 1991





Open Charm Nuclear Dependence : x_F Dependence?

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

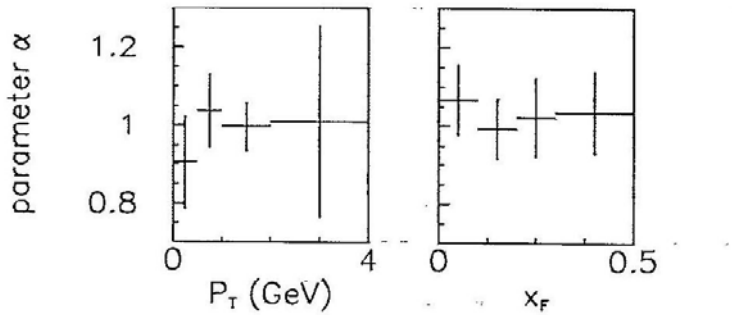


FIG. 4. Dependence of the parameter α on P_T and x_F for D^+ and D^0.

WA82 340 GeV π PRB 284,453 (1992)

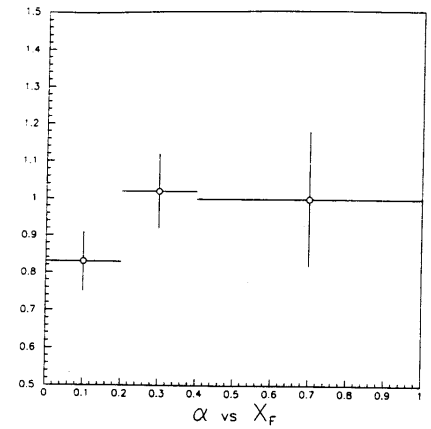


Fig. 4. The parameter α for charm production as measured in three x_F intervals.

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

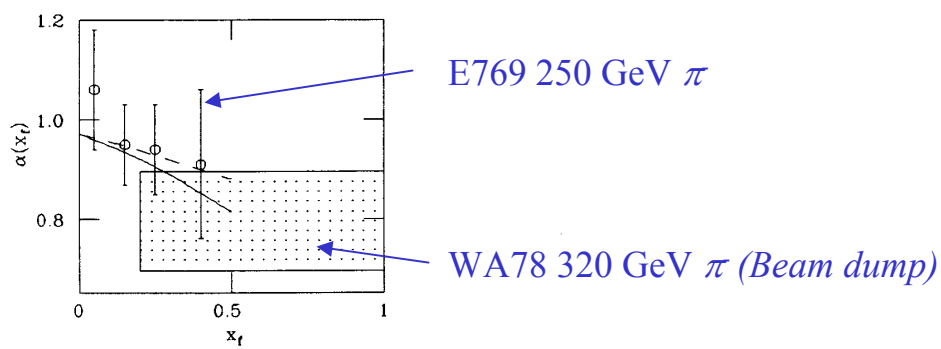
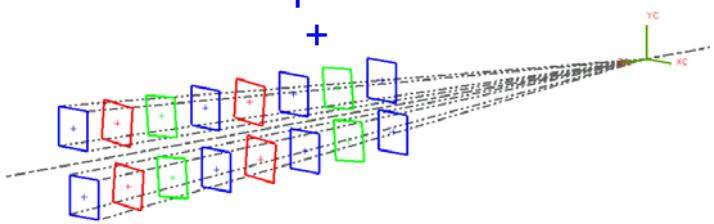


Fig. 14. We show $\alpha(x_f)$ for π^-A interactions at 300 GeV as calculated in our model. The dashed curve shows delta function fragmentation, the solid curve, the Peterson function. These results are compared to those for $D^{\pm}$ mesons produced by 250 GeV π^-A interactions [3] and the effective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

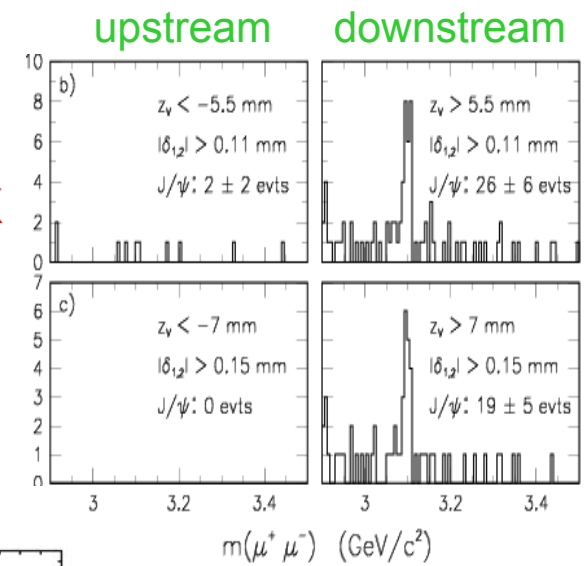
Fermilab E789: D^0 & $B \rightarrow J/\psi$ X
(charm & beauty using silicon)

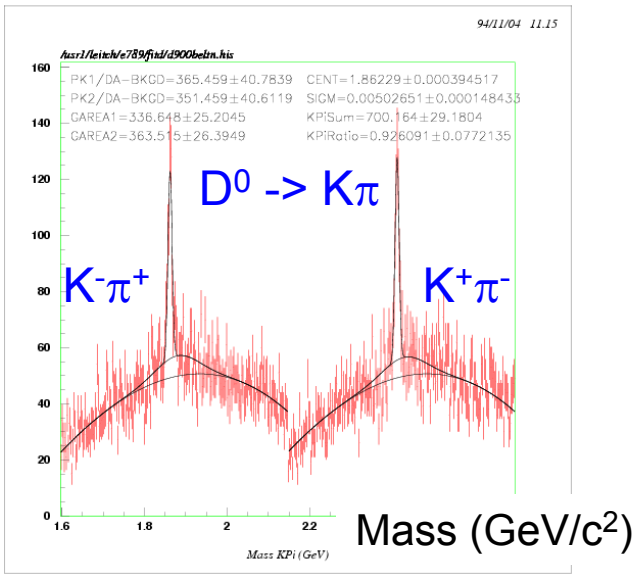
Dimuon spectrometer
+

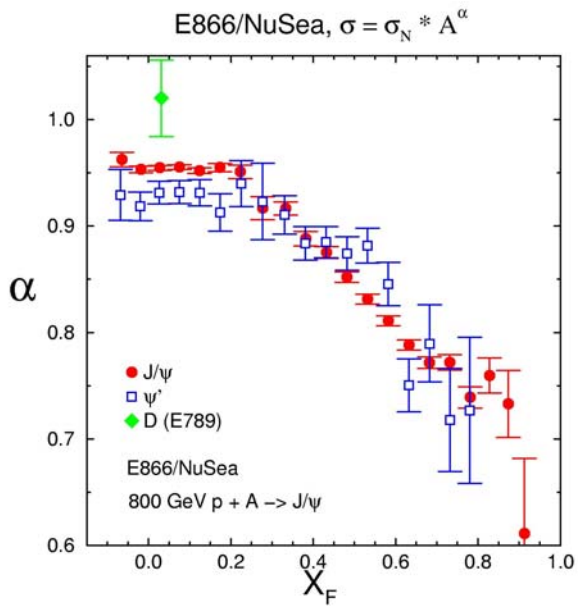


16-plane, 50μm pitch/8.5k
strip silicon vertex detector

B -> J/ψ + X







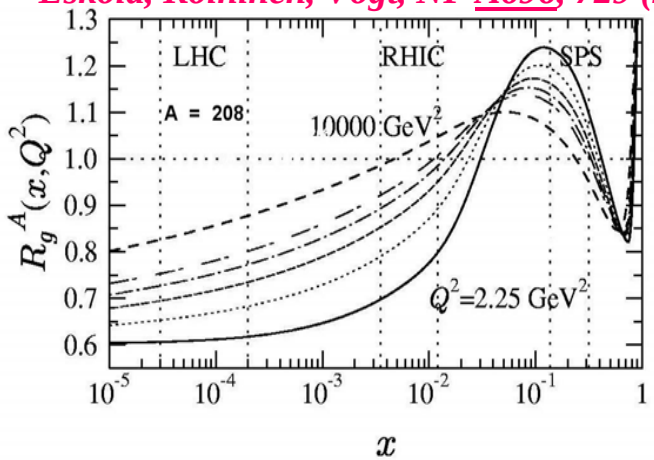
Now lets come back to my favorite cold nuclear matter effects i.e. those in Onia production

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 at small x – e.g. color glass condensate

Eskola, Kolhinen, Vogt, NP A696, 729 (2001)

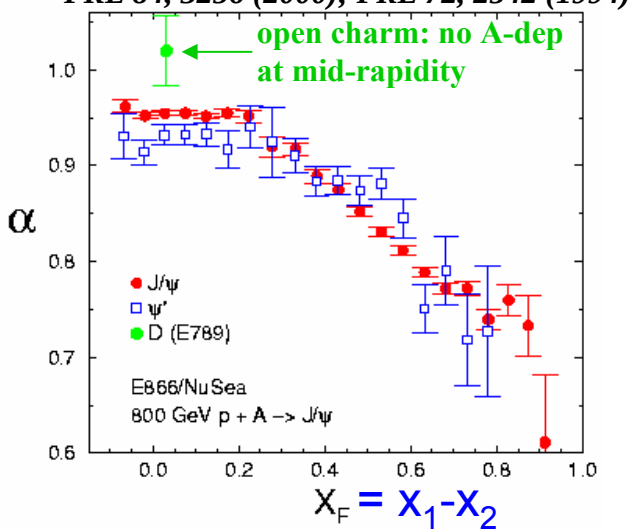


Nuclear effects on parton "dynamics"

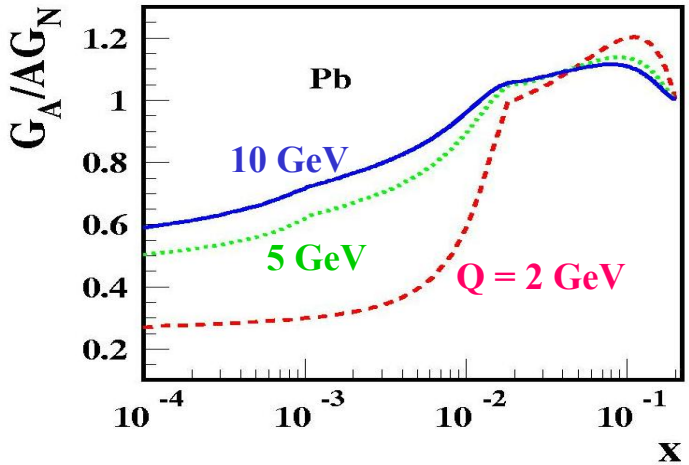
- absorption of J/ψ on nucleons or co-movers
- energy loss of partons as they propagate through nuclei
- multiple scattering effects (Cronin effect) causing p_T broadening

800 GeV p-A (FNAL) $\sigma_A = \sigma_p * A^\alpha$

PRL 84, 3256 (2000); PRL 72, 2542 (1994)



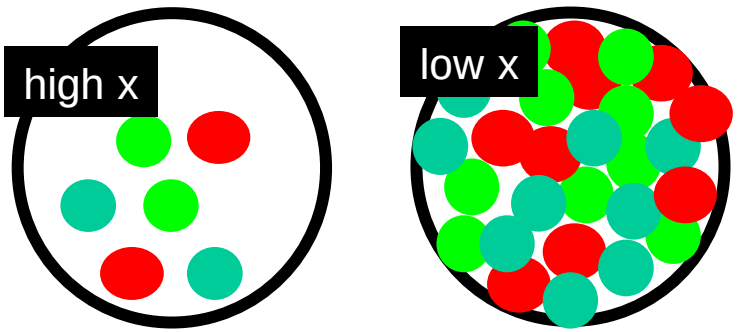
Gluon Shadowing and Saturation



Leading twist gluon shadowing, e.g.:

- Gerland, Frankfurt, Strikman, Stocker & Greiner - Eur. Phys. J A5, 293 (1999)
- phenomenological fit to DIS & Drell-Yan data, Eskola, Kolhinen, Vogt – Nucl. Phys. A696, 729 (2001).
- and many others

Amount of gluon shadowing differs by up to a factor of three between diff models!



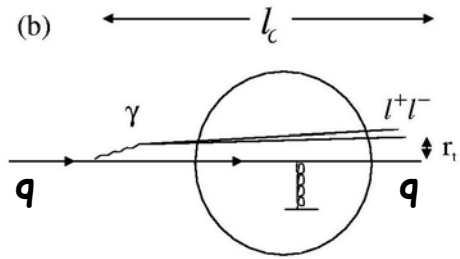
Saturation or Color Glass Condensate (CGC)

- At low-x there are so many gluons that $2 \rightarrow 1$ diagrams become important and deplete low-x region
- Nuclear amplification: $x_A G(x_A) = A^{1/3} x_p G(x_p)$, i.e. gluon density is ~6x higher in Gold than the nucleon

Coherence Effects & Shadowing

Johnson, Kopeliovich et al., PRL 86, 4483 (2001)

In target rest frame Drell-Yan can be described as,



$$q \rightarrow q\gamma^* \text{ and } \gamma^* \rightarrow l\bar{l}$$

And the coherence length of this fluctuation is,

$$l_c = \frac{1}{q_L} = \frac{2E_q}{M^2_{q\gamma^*} - m_q^2}$$

For $l_c << R_A$, i.e. short compared to nuclear size, the fluctuation appears for a very short time and therefore interacts with individual nucleons (no shadowing) and also has no (final-state) p_T broadening since it is just like on a free nucleon (but initial-state "Cronin" p_T broadening is still there)

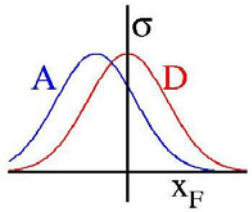
While for $l_c >> R_A$, the interaction is with the whole nucleus coherently and this can result in some nucleons being effectively hidden or shadowed and a nuclear dependence of $A^{2/3}$ (as the 2-D surface area)

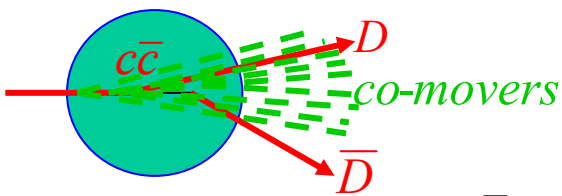
And for values in between, varying amounts of shadowing

The J/ψ - a Cold Nuclear Matter (CNM) Puzzle

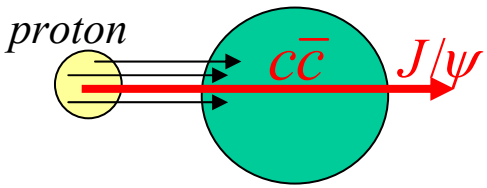
J/ψ suppression is a puzzle with possible contributions from **shadowing** & from:

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





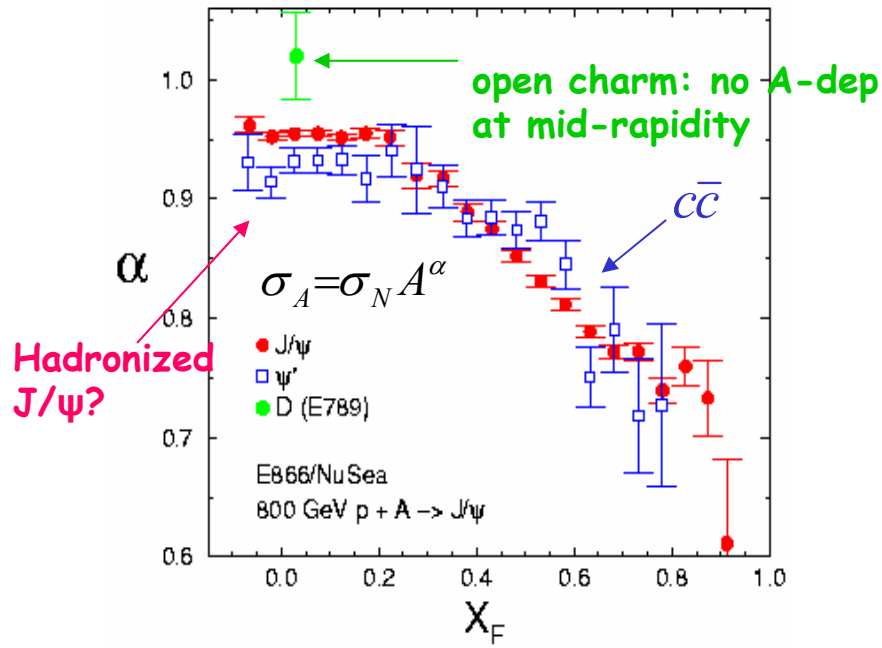
Absorption (or dissociation) of $c\bar{c}$ into two D mesons by nucleus or co-movers (the latter most important in AA collisions where co-movers more copious)



Intrinsic charm components of incident proton produce J/ψ at large x_F. $A^{2/3}$ dependence from surface stripping of proton's light quarks (Brodsky)

800 GeV p-A (FNAL)

PRL 84, 3256 (2000); PRL 72, 2542 (1994)

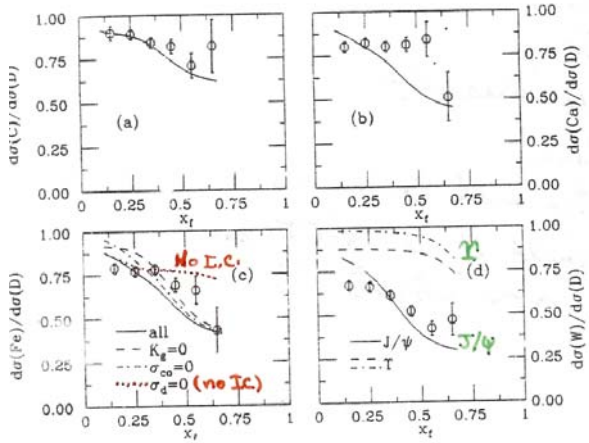


- J/Ψ and Ψ' similar at large x_F where they both correspond to a $c\bar{c}$ traversing the nucleus
- but Ψ' absorbed more strongly than J/Ψ near mid-rapidity (x_F ~ 0) where the resonances are beginning to be hadronized in nucleus
- open charm not suppressed at x_F ~ 0; what about at higher x_F?

INTRINSIC HEAVY QUARKS

At large x_F ($\gtrsim 0.5$) intrinsic $c\bar{c}$ or $b\bar{b}$ states in the projectile can dominate the production of heavy-quark pairs.
Can explain x_F dependence of J/ψ + Υ ??

(also includes nuclear absorption, comover scatteri initial-state shadowing)



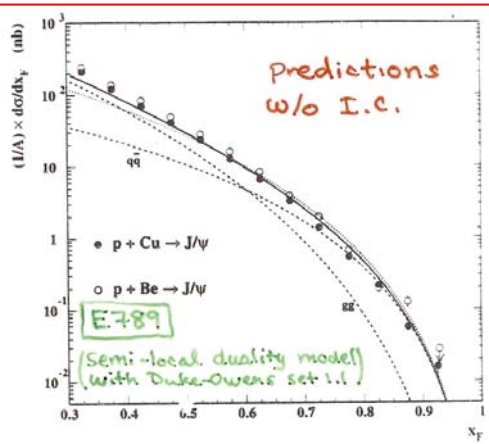
Vogt, Brodsky, Hoyer
NP B360, 67 (1991)

Intrinsic Charm (I.C.) model predictions

BUT E789 set limit on I.C. contribution to cross section of $< 2.3 \times 10^{-3}$ nb/nucleon

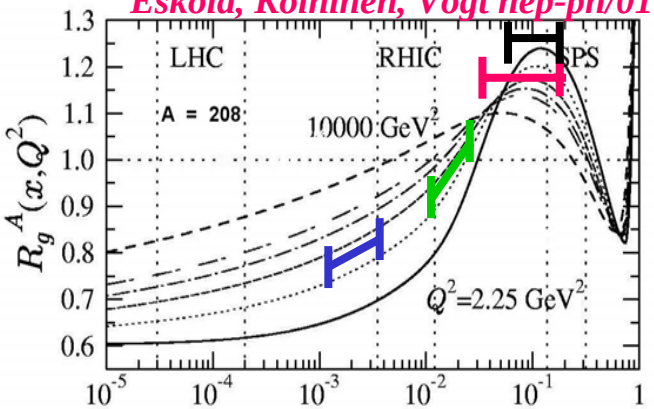
(1.8 nb/nucleon was predicted by model)

E789 PRL 72, 1318 (1994)



Absorption of J/ψ's - not so simple?

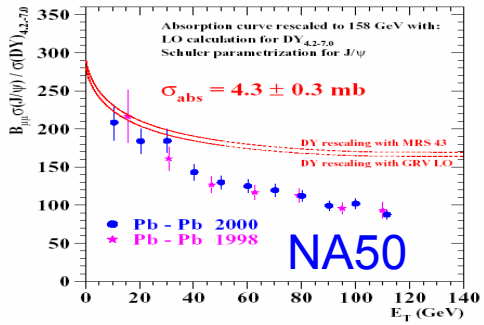
Eskola, Kolhinen, Vogt hep-ph/0104124



PHENIX μ — E866 (mid-rapidity)

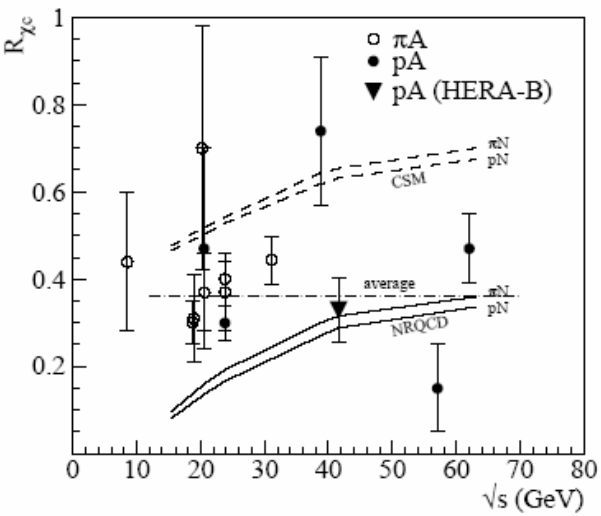
PHENIX e — NA50

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?

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

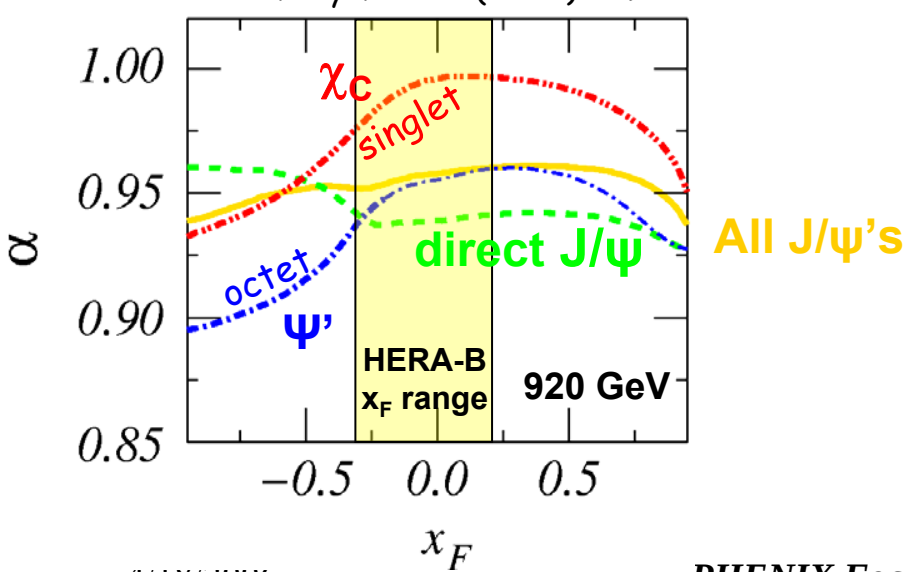


HERA-B Phys.Lett. B561 (2003) 61-72 & E705 @ 300 GeV/c, PRL 70, 383 (1993)

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%

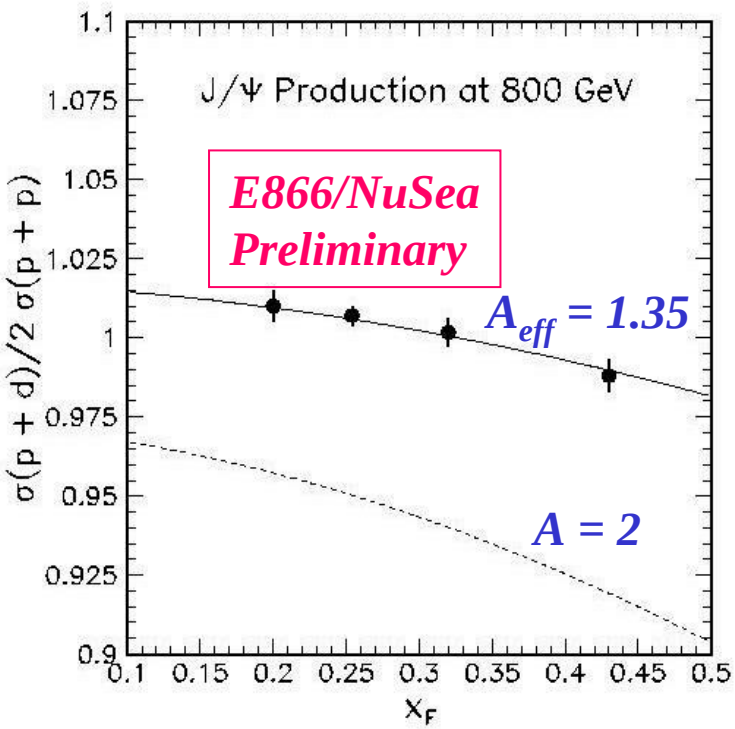
R. Vogt, NRQCD calculations
Nucl. Phys. A700 (2002) 539

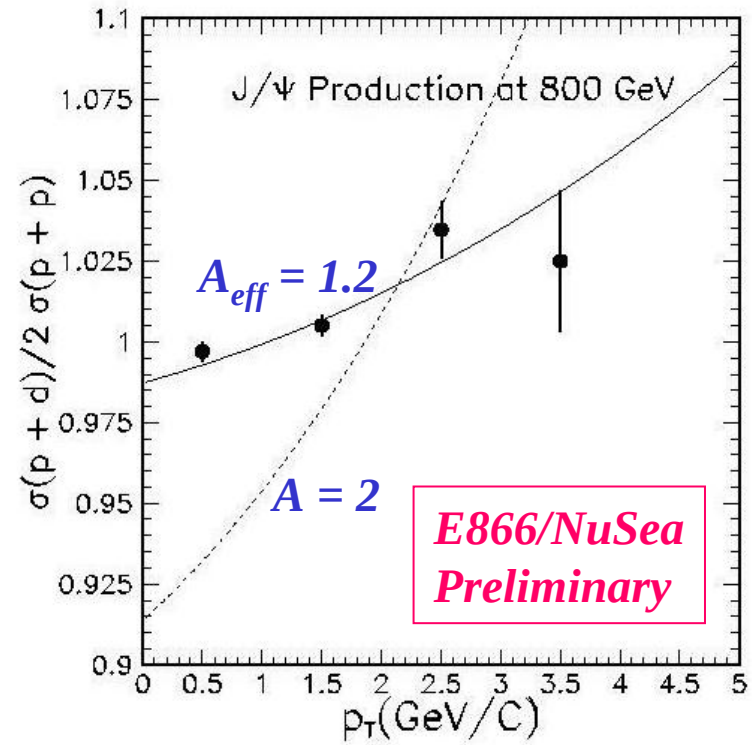


Effect on Nuclear dependence:

- 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

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





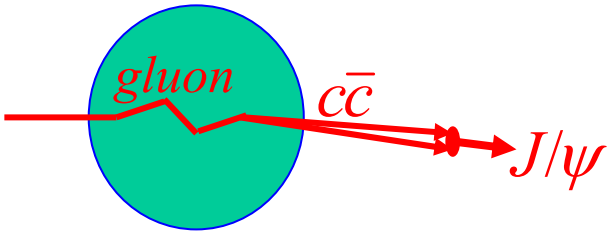
Nuclear dependence in deuterium seems to follow the systematics of larger nuclei, but with an effective A, A_{eff}, smaller than two.

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

$$\alpha(x_F) \propto 1 - 0.052 x_F - 0.034 x_F^2$$

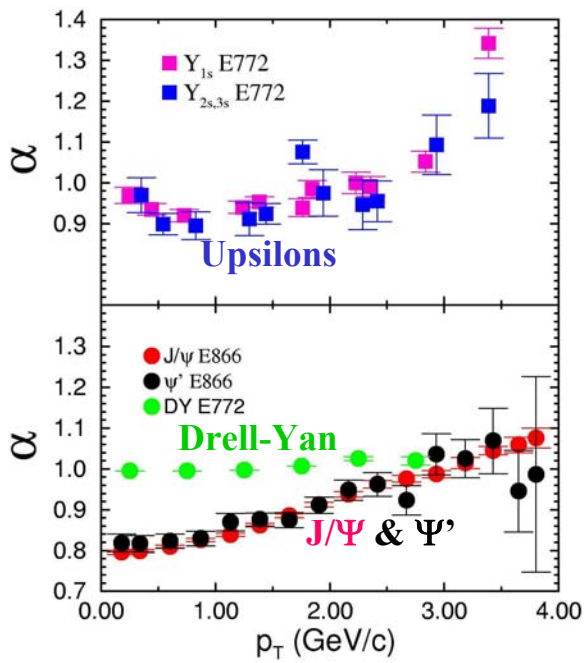
$$\alpha(p_T) \propto 0.06 p_T + 0.011 p_T^2$$

Transverse Momentum Broadening for J/ψ's

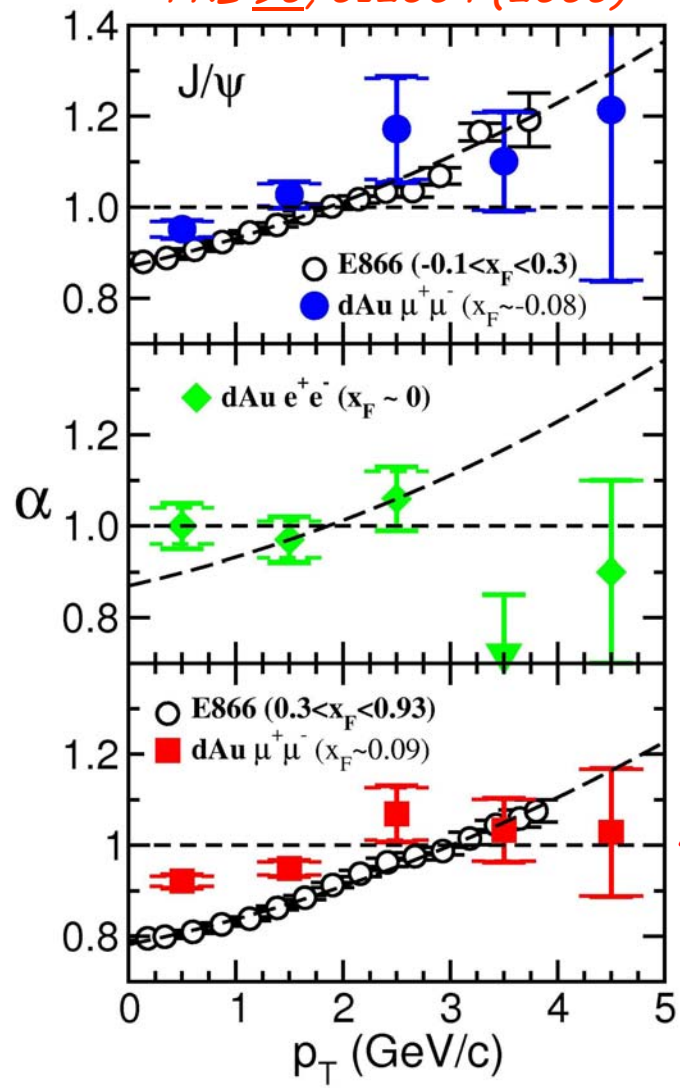


Initial-state gluon multiple scattering causes **p_T broadening** (or Cronin effect)

$$\sigma_A = \sigma_N A^{\alpha}$$



PRL 96, 012304 (2006)

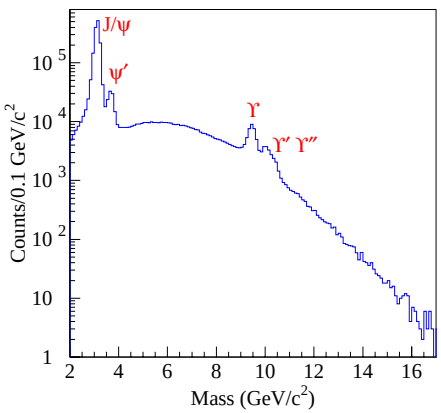


High x_2 ~ 0.09

PHENIX 200 GeV results show p_T broadening comparable to that at lower energy (√s=39 GeV in E866/NuSea)

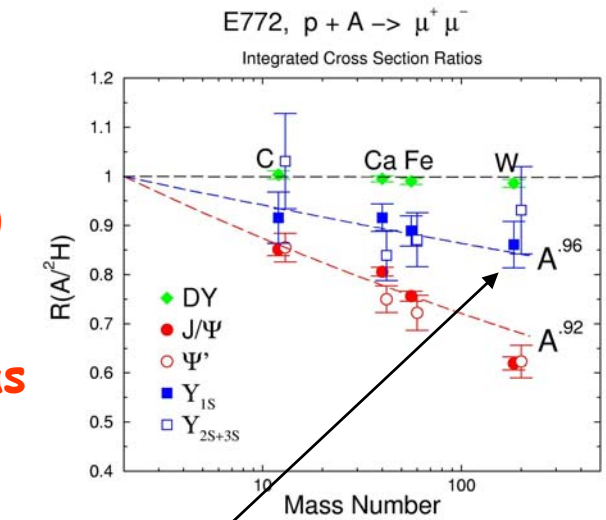
Low x_2 ~ 0.003

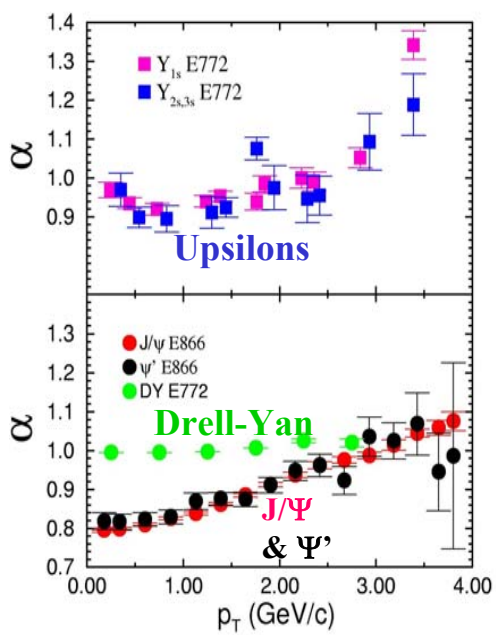
Contrasting ϒ's with J/ψ's



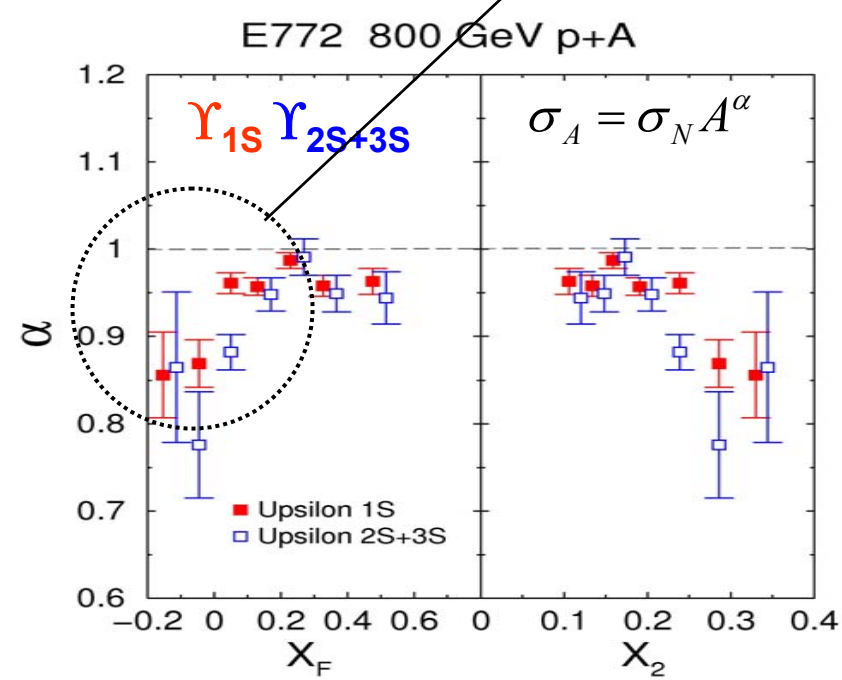
√S =39 GeV (E772 & E866)

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

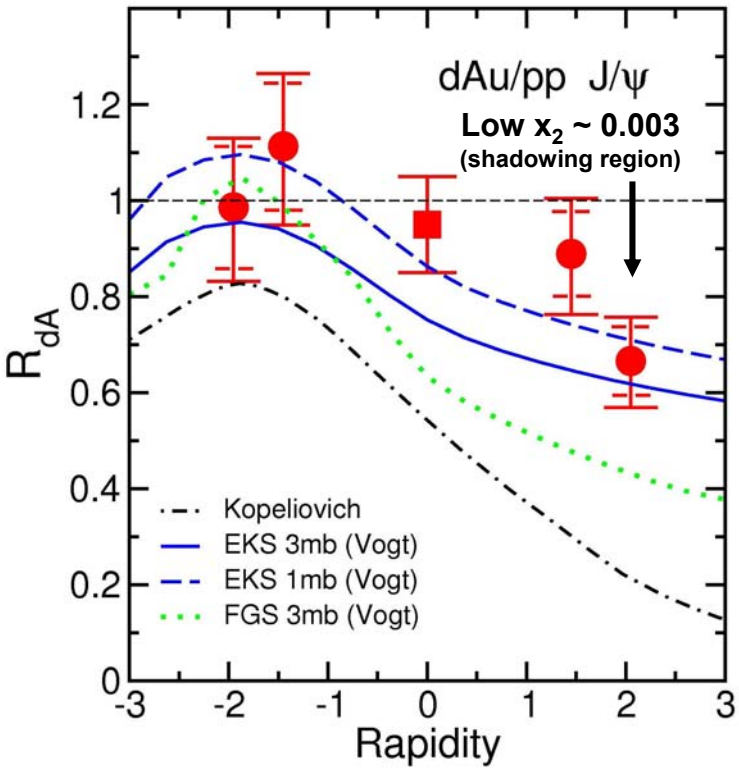




But careful: ϒ suppression is from data for x_F < 0 or x_2 > 0.2 (in the EMC region)

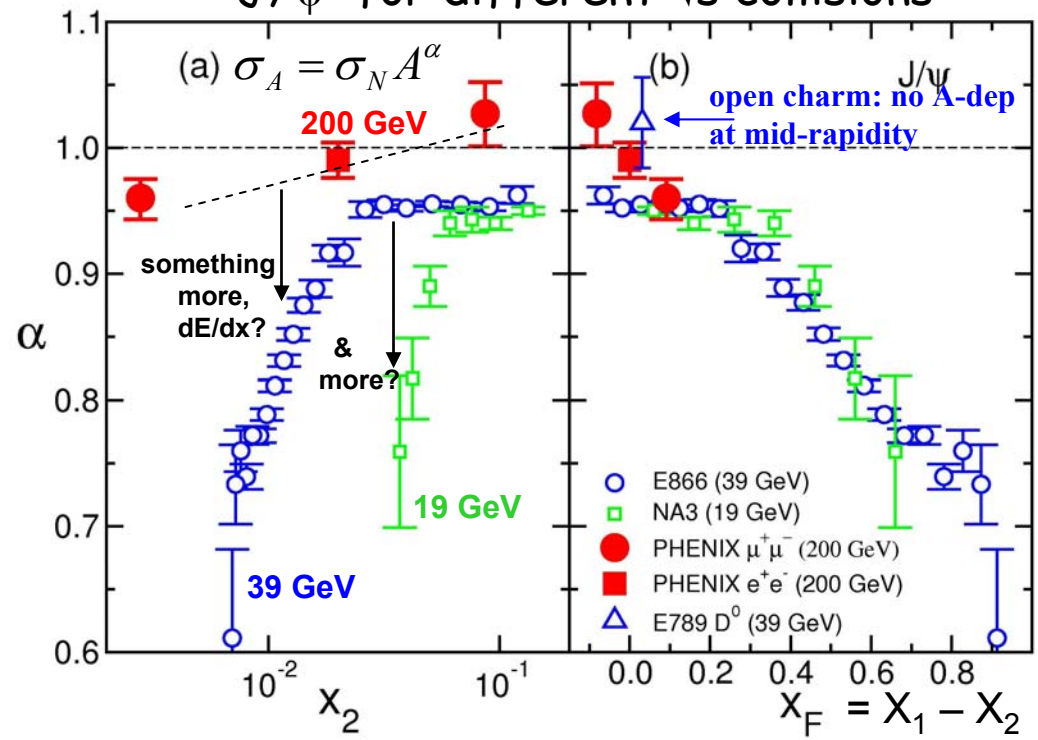


PHENIX J/ψ Nuclear Dependence for 200 GeV pp and dAu collisions – PRL 96, 012304 (2006)



Klein,Vogt, PRL 91:142301,2003
Kopeliovich, NP A696:669,2001

J/ψ for different √s collisions



Data favors weak shadowing & absorption

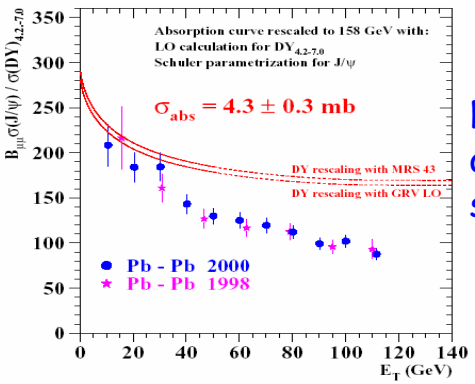
- With limited statistics difficult to disentangle nuclear effects
- Will need another dAu run! (more pp data also)

Not universal vs x_2 as expected for shadowing, but does scale with x_F, why?

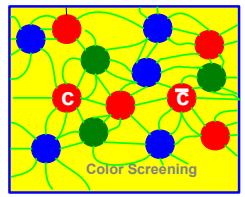
- initial-state gluon energy loss?
- Sudakov suppression (~energy conservation)?

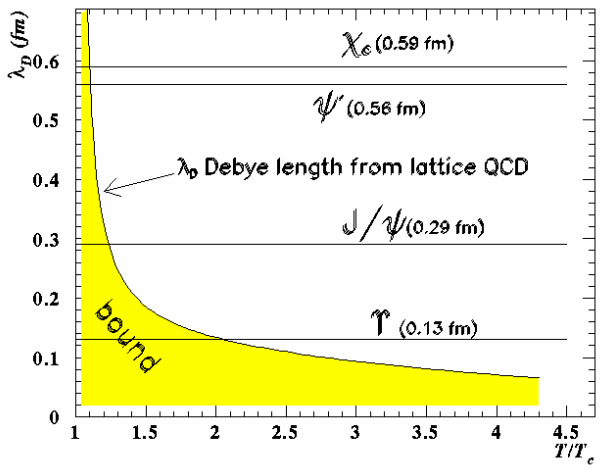
AuAu J/ψ's - Quark Gluon Plasma (QGP) signature?

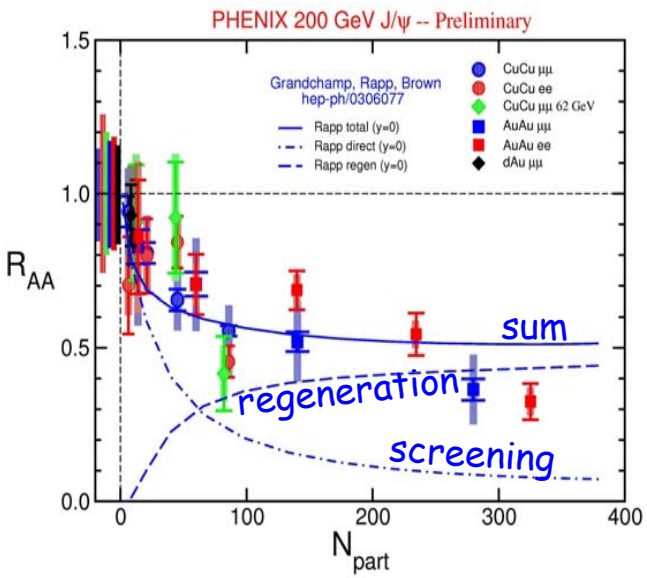
Debye screening predicted to destroy J/ψ's in a QGP with different states "melting" at different temperatures due to different binding energies.



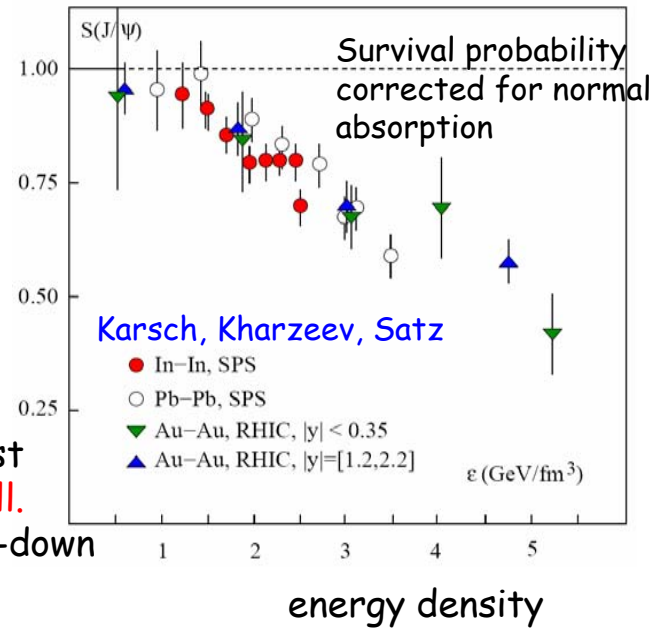
NA50 anomalous suppression





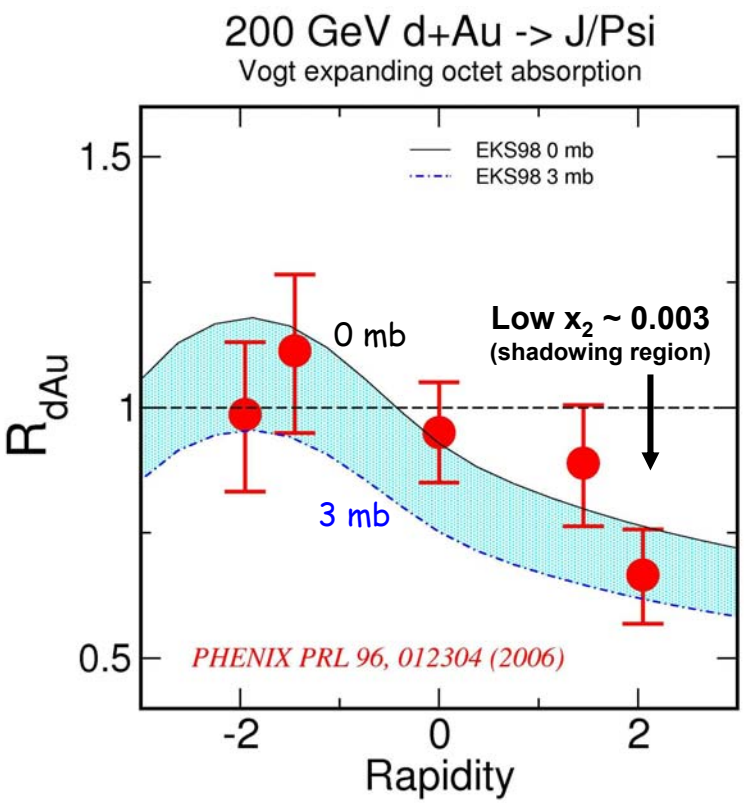


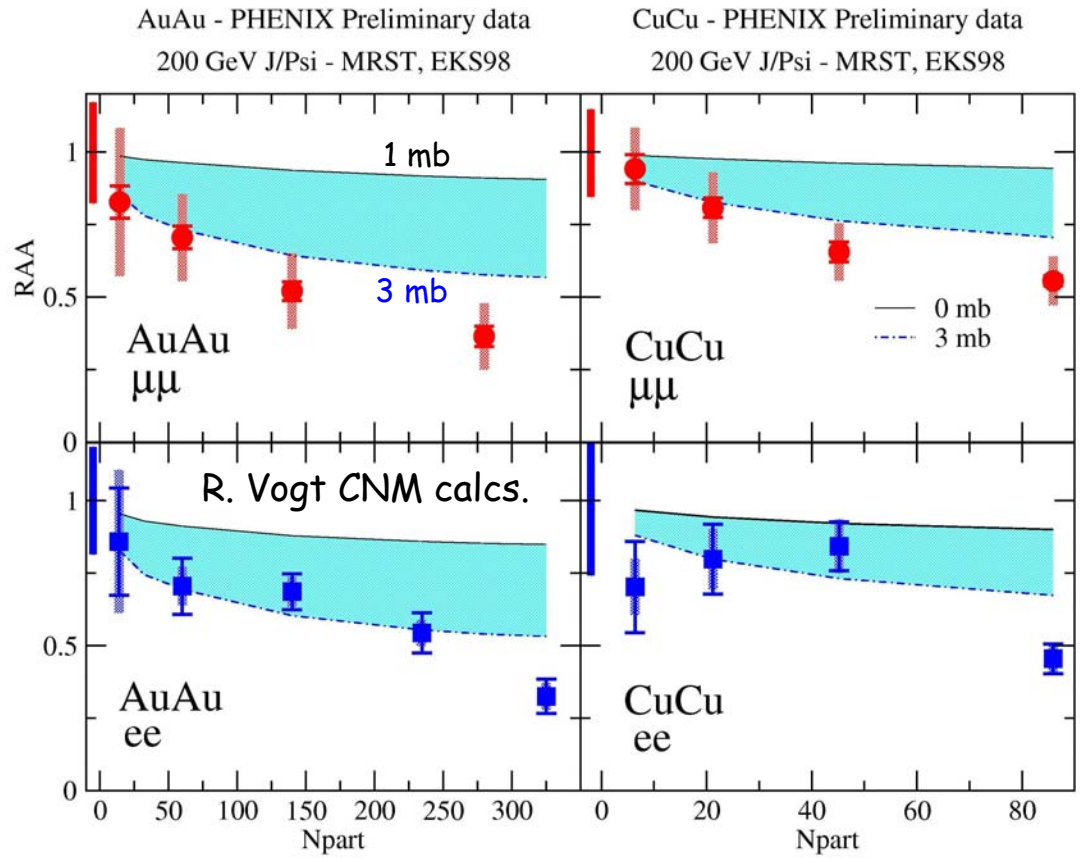
but recent regeneration models might give enhancement that compensates for screening?



on the other hand, recent lattice calculations suggest J/ψ not screened after all. Suppression only via feed-down from screened χ_c & ψ'

J/ψ suppression in AA collisions & CNM baseline





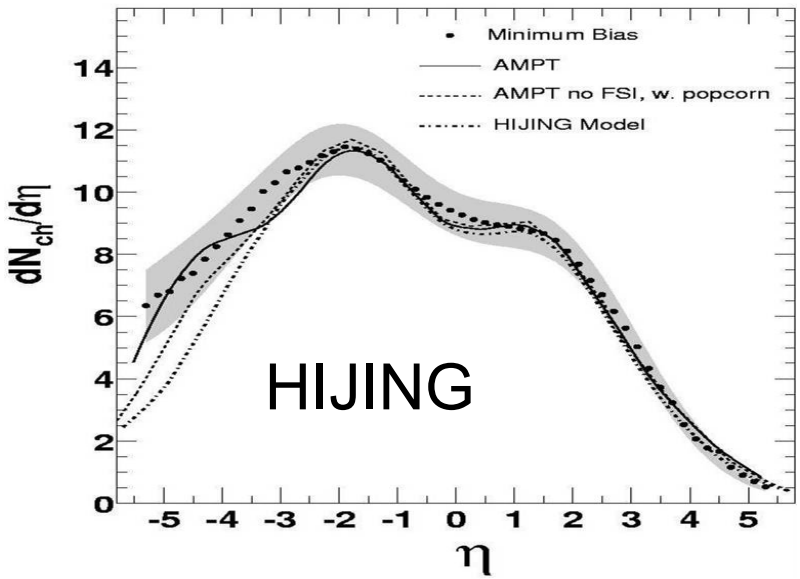
- CNM calculations with shadowing & absorption
- present dAu data probably only constrains absorption to: $\sigma_{ABS} \sim 1\text{-}3$ mb

- AA suppression is somewhat stronger than CNM calculations predict
- but really need more precise dAu constraint!

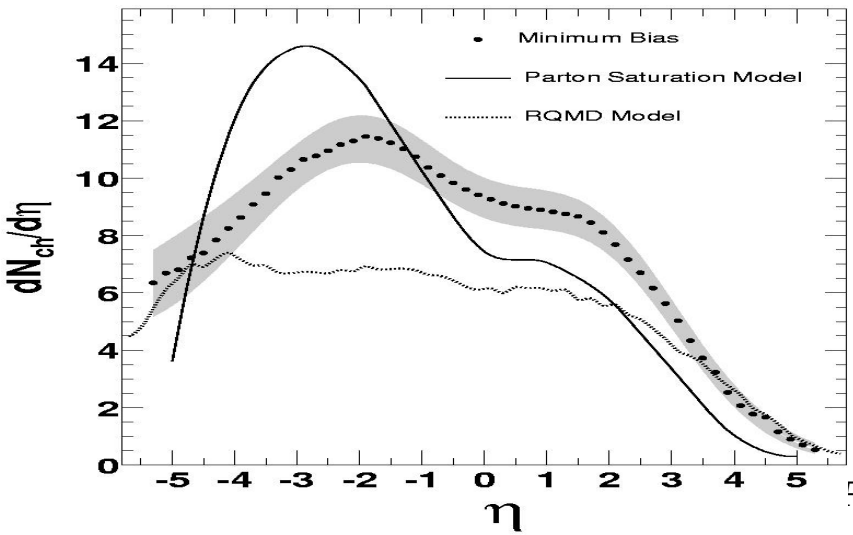
And finally – the cold nuclear matter effects you all know: hadrons

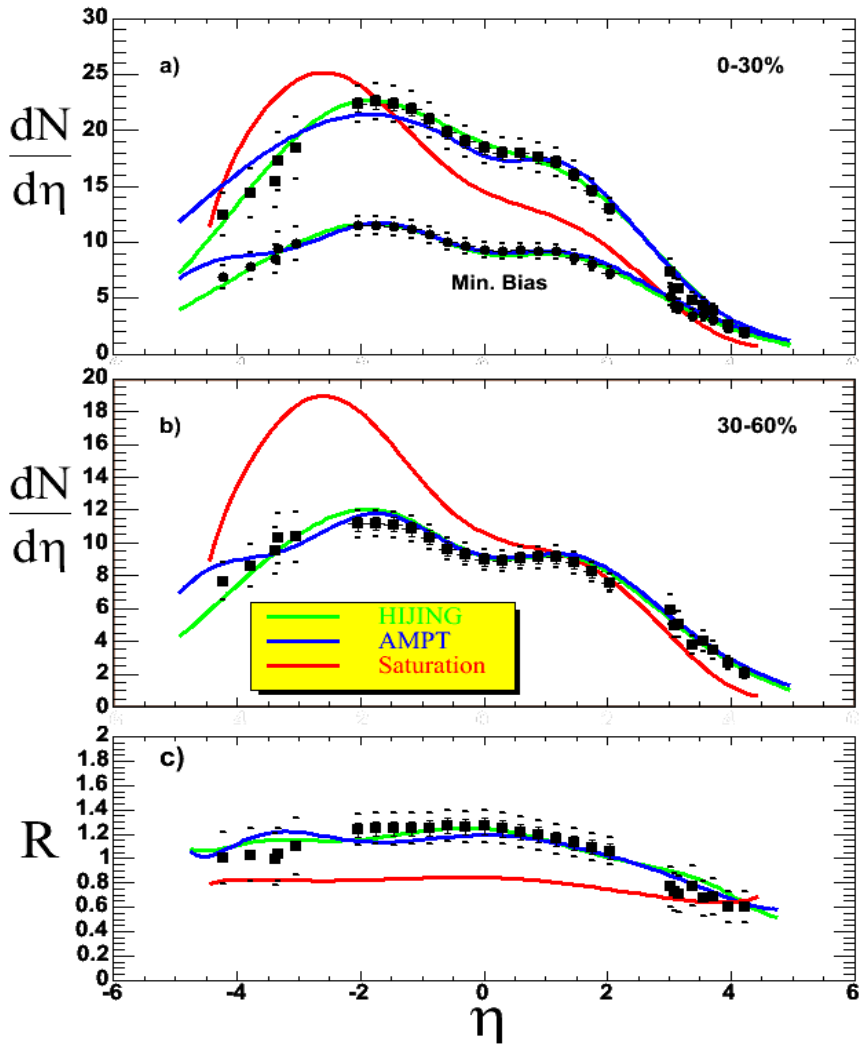
But I'll stop here

Hadron Rapidity Density



PHOBOS collab., Phys.Rev.Lett.



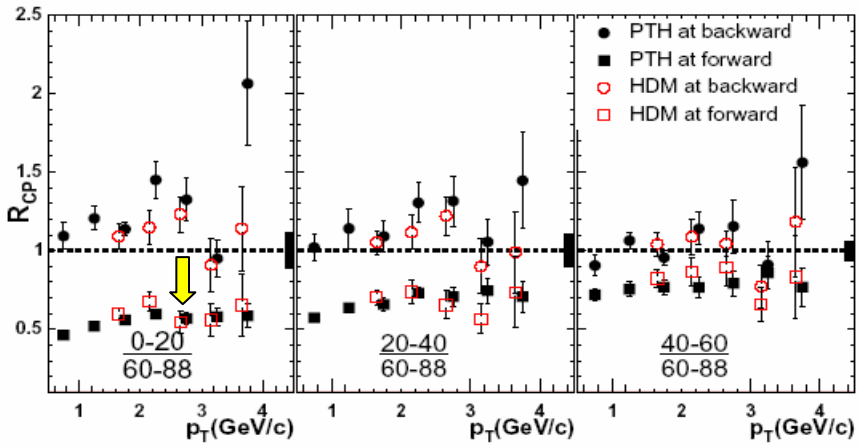


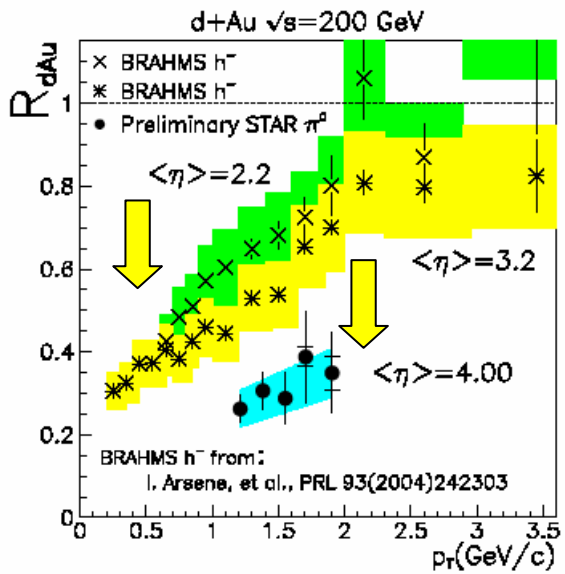
M.Murray, BRAHMS collaboration, QM 2004

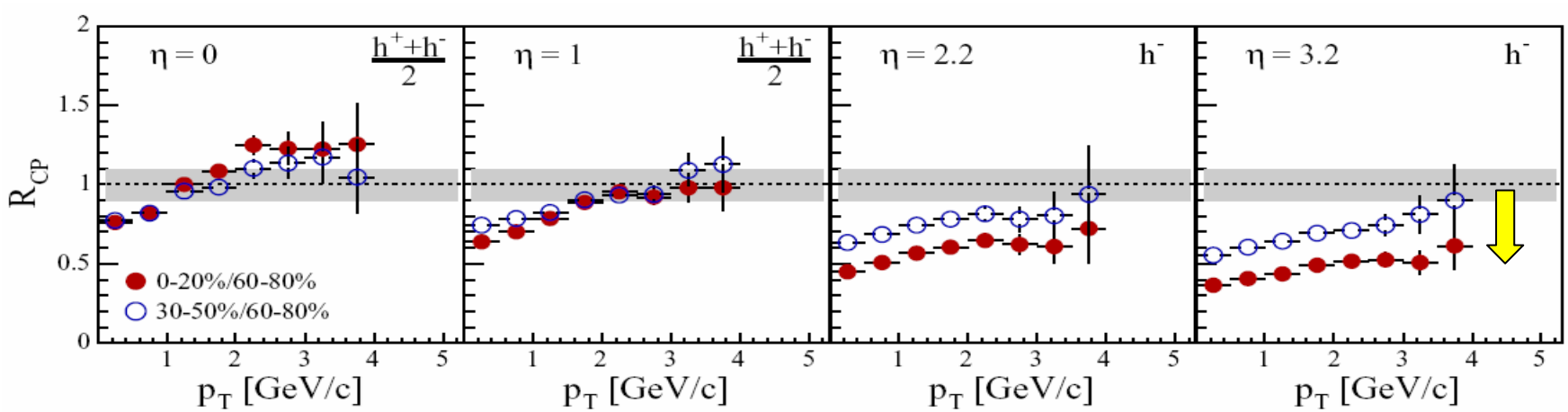
slide from Ivan Vitev

Forward Rapidity Suppression

$$R_{pA}(p_T) = \frac{d^2N^{pA}/dp_T d\eta}{T_{AA} d^2\sigma^{NN}/dp_T d\eta} = \frac{d^2\sigma^{pA}/dp_T d\eta}{N_{coll} d^2\sigma^{NN}/dp_T d\eta}$$



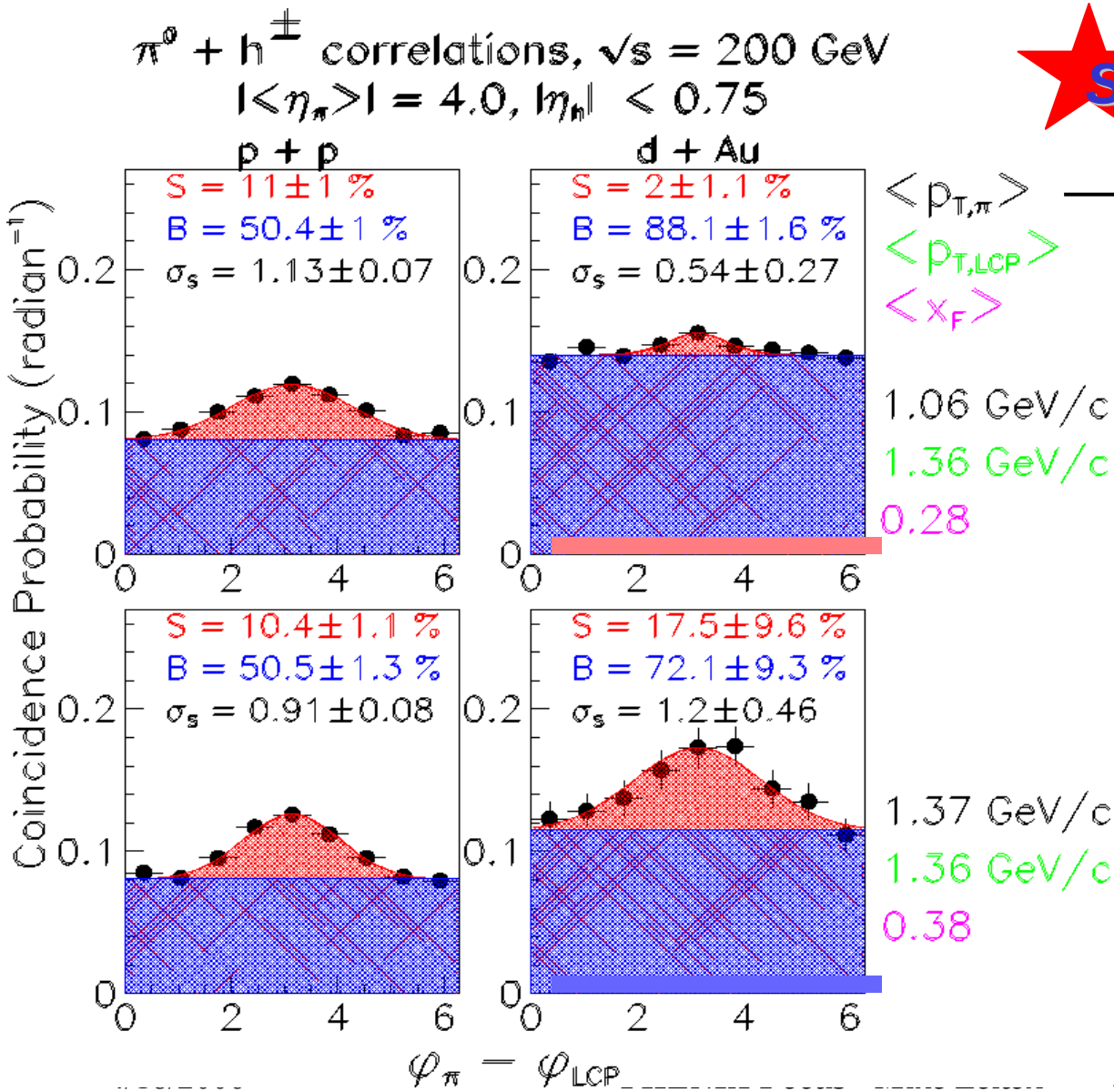




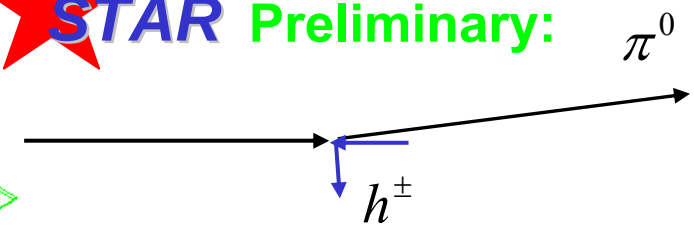
C/P = central to peripheral

slide from Ivan Vitev

Forward Correlations



STAR Preliminary:



- At p_T = 1.25 GeV hard scattering is **similar** in **p+p** and **p+A**
- There isn't **mono jettiness** or g-fusion
- I think that the p+A analysis has **under** and **over** estimated the **away-side** area

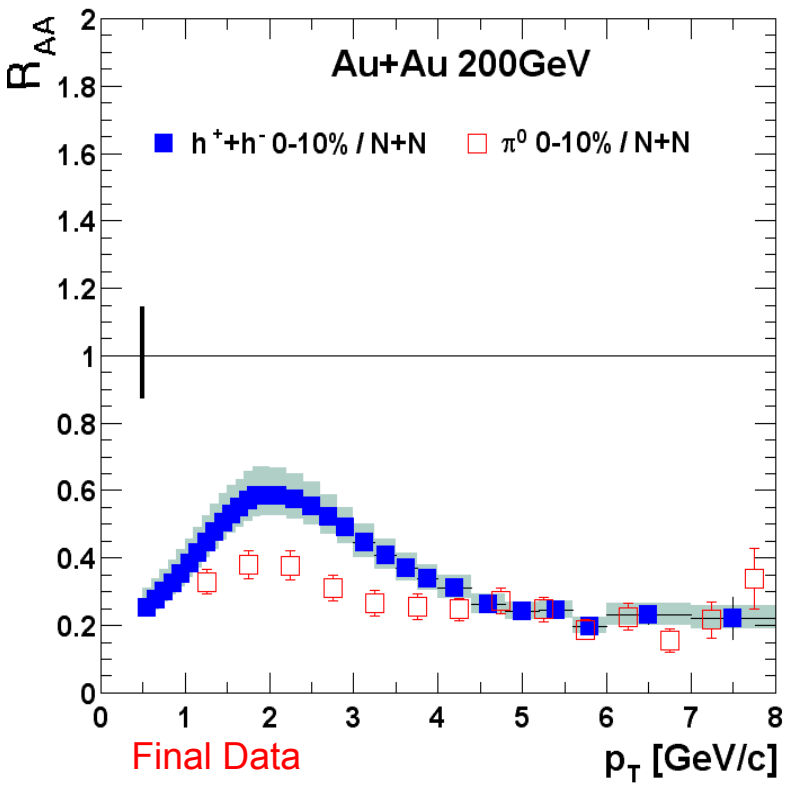
Statistical errors only

slide from Ivan Vitev

Jets: *AuAu* vs. *dAu* (PHENIX)

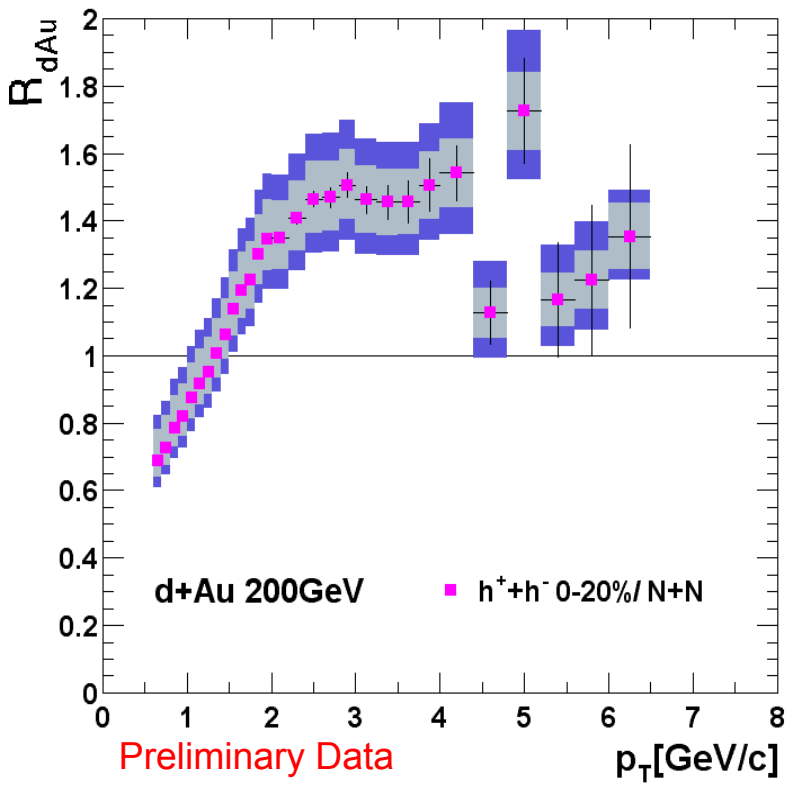
PPG028
Phys. Rev. Lett. **91**, 072303 (2003).

Au + Au Experiment



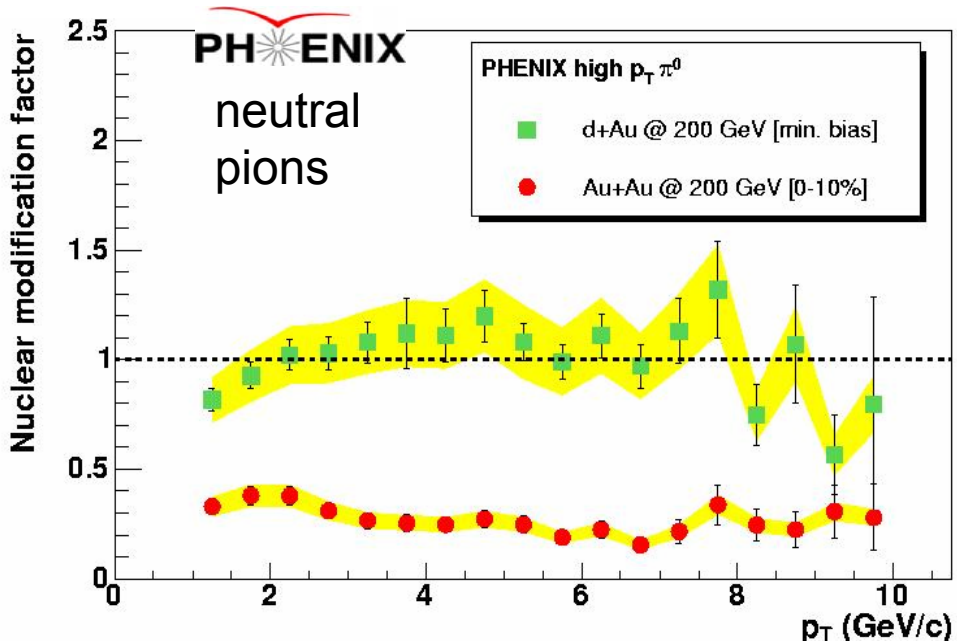
Final Data

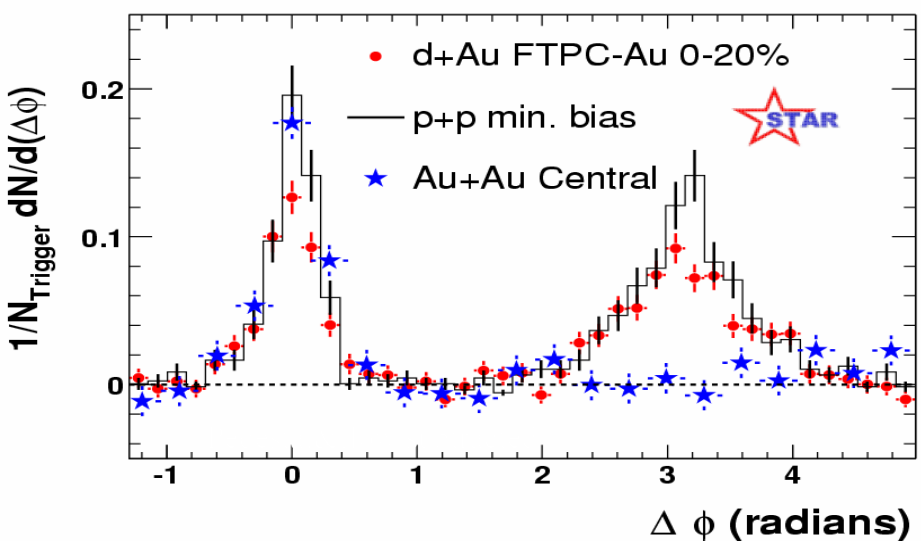
d + Au Control Experiment



Preliminary Data

Jet Quenching



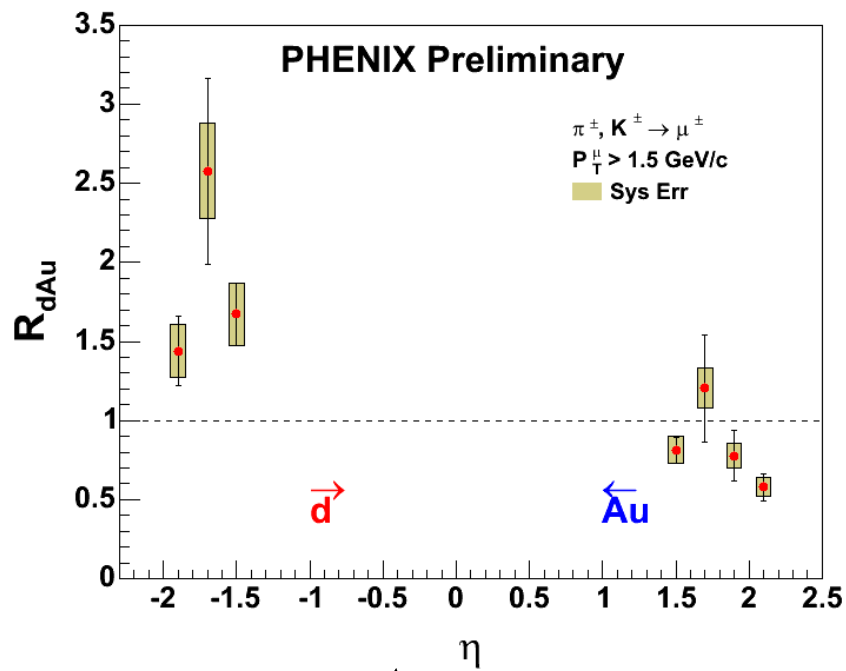


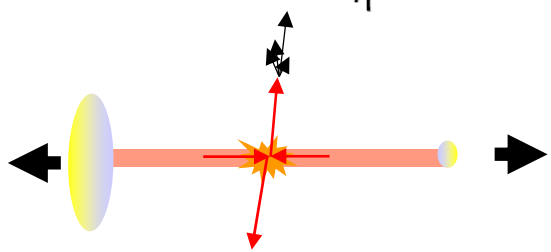
- d+Au @ RHIC shows "Cronin" p_T broadening as seen in lower $\sqrt{s}$ p+A
- Suppression in central Au+Au due to final-state effects -> 15x normal nuclear density
- back-to-back di-hadron correlations are very similar in p+p and d+Au
- but strongly suppressed in central Au+Au collisions at 200 GeV

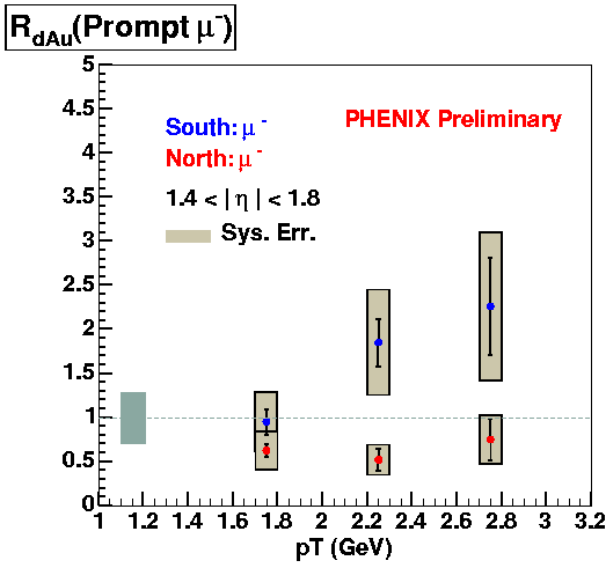
Single Muon Analysis of dAu data
dAu vs pp @ forward and backward

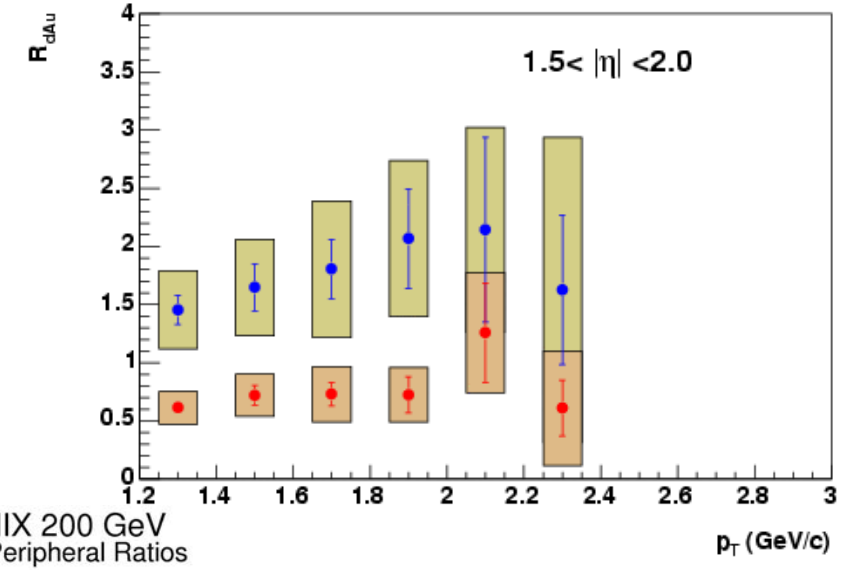
- R_{dAu} with muons from light meson decays
- Some theoretical models
  - Gluon saturation/CGC (Fwd)
  - Coherent scatterings (Fwd)
  - Parton recombination (Fwd & Bwd)
  - Breakdown of QCD factorization
- Open charm
  - Work in progress

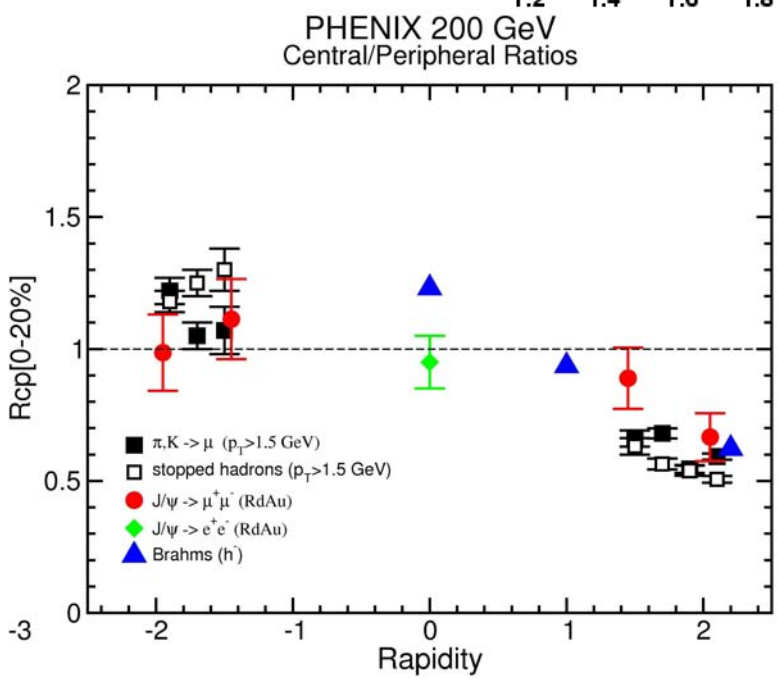
$$R_{dAu}(p_T, y) = \frac{d^2\sigma^{dAu} / dp_T dy}{< N_{coll} > d^2\sigma^{pp} / dp_T dy}$$






R_{dAu}(Prompt μ^-)
South: μ^-
North: μ^-
1.4 < | η | < 1.8
Sys. Err.
PHENIX Preliminary
pT (GeV)

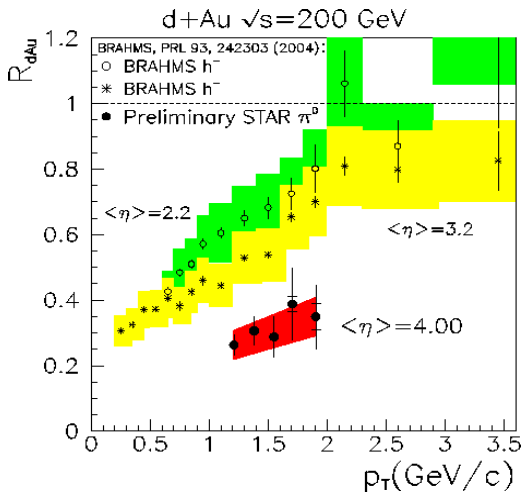

R_{dAu}
1.5< |η| <2.0
p_T (GeV/c)

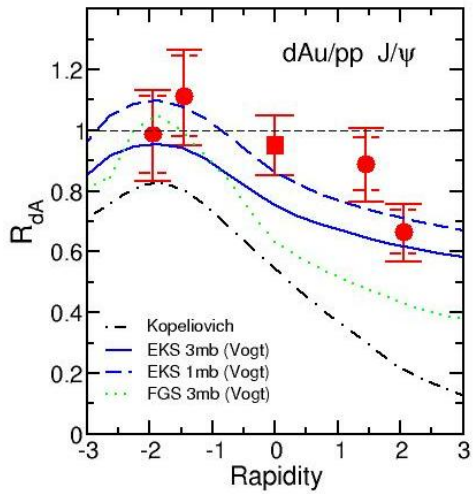

PHENIX 200 GeV
Central/Peripheral Ratios
Rcp[0-20%]
Rapidity
π,K -> μ (p_T>1.5 GeV)
stopped hadrons (p_T>1.5 GeV)
J/ψ -> $\mu^+\mu^-$ (RdAu)
J/ψ -> e^+e^- (RdAu)
Brahms (h`)

RHIC II Science - Forward & pA Physics

Conveners: Carl Gagliardi, Mike Leitch, Kirill Tuchin

- Small-x and shadowing in nuclei
  - leading twist, saturation, mass renormalization, etc.
  - contrast with LHC
  - forward hadrons
  - heavy quarks & onia
  - Sudakov suppr, limiting fragmentation
  - "mono"-jets
- Anti-quarks in the nucleon and nuclei
  - shadowing of sea anti-quarks
  - tagged Drell-Yan
- other forward-proton tagged reactions
- not discussed: direct photons; polarized pA (need theor. input), & …?
- Accelerator issues for pA





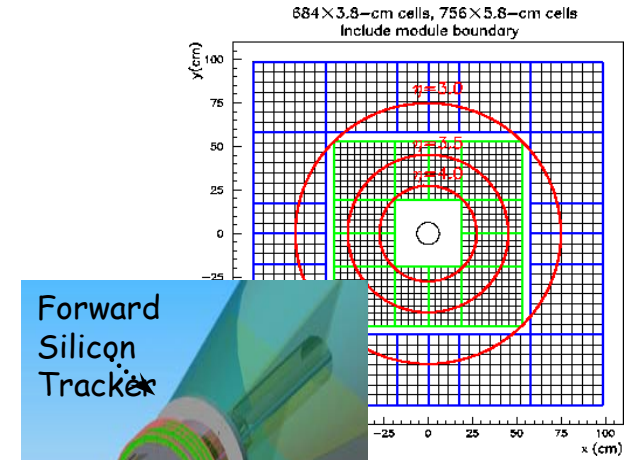
Upgrades

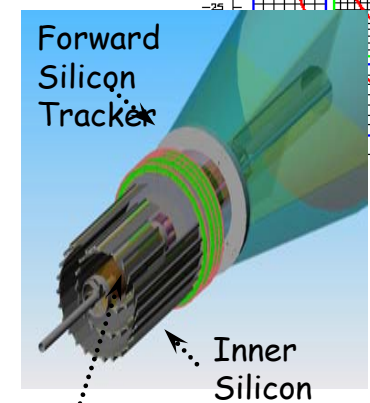
STAR

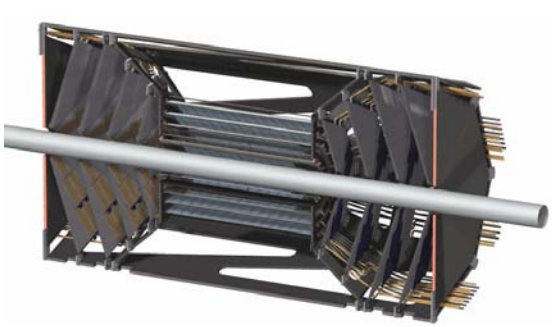
- Forward Meson Spectrometer
- Forward tracker upgrade (GEM)

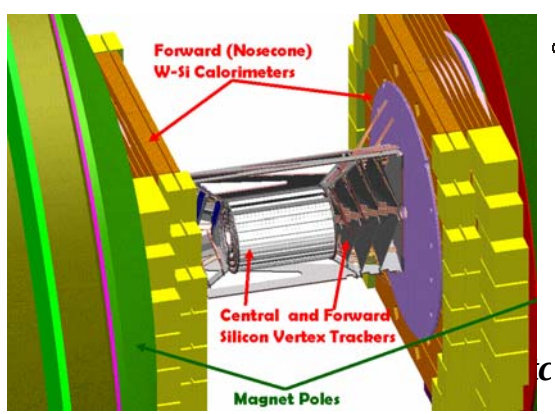
PHENIX

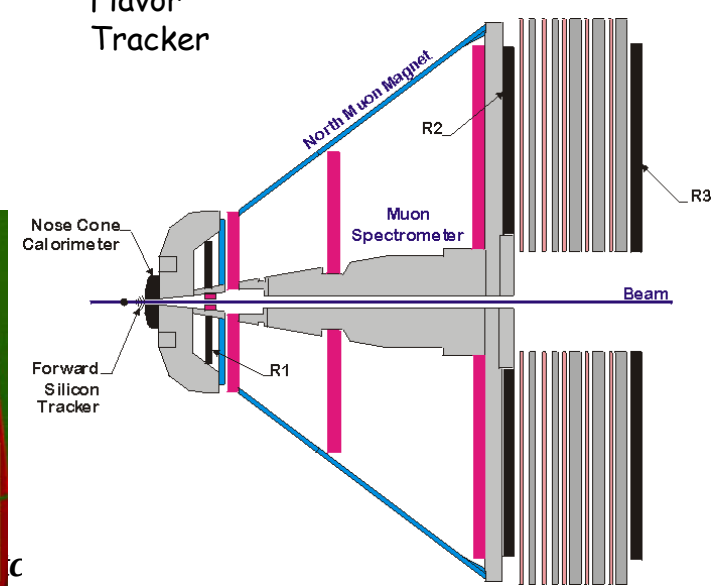
- Nosecone calorimeter (W-Si)
- forward muon trigger (RPC)
- Forward Silicon Vertex detector (mini-strips)







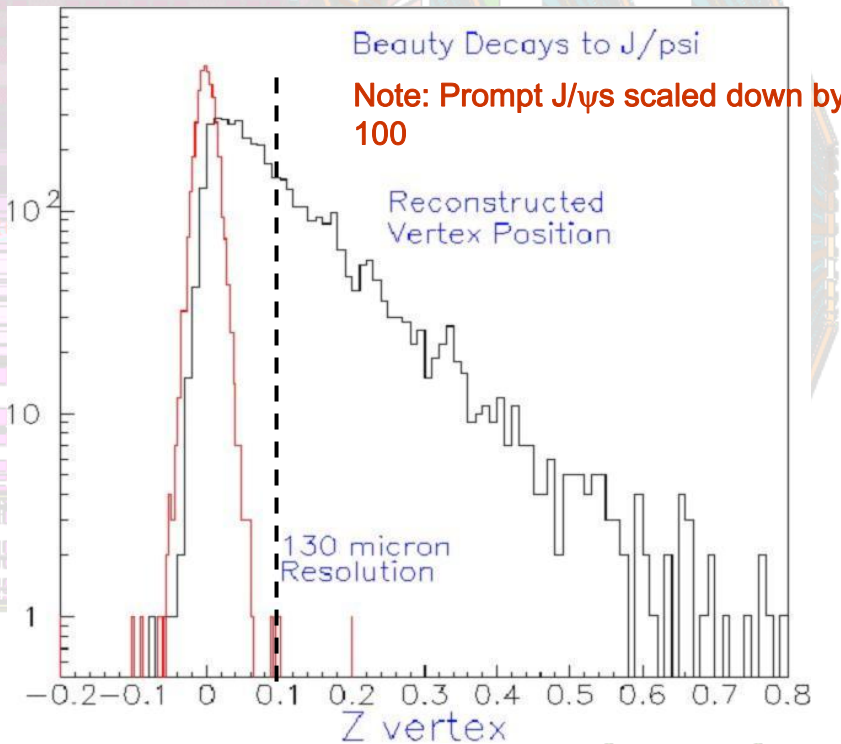




First Explicit Beauty Measurement Requires FVTX

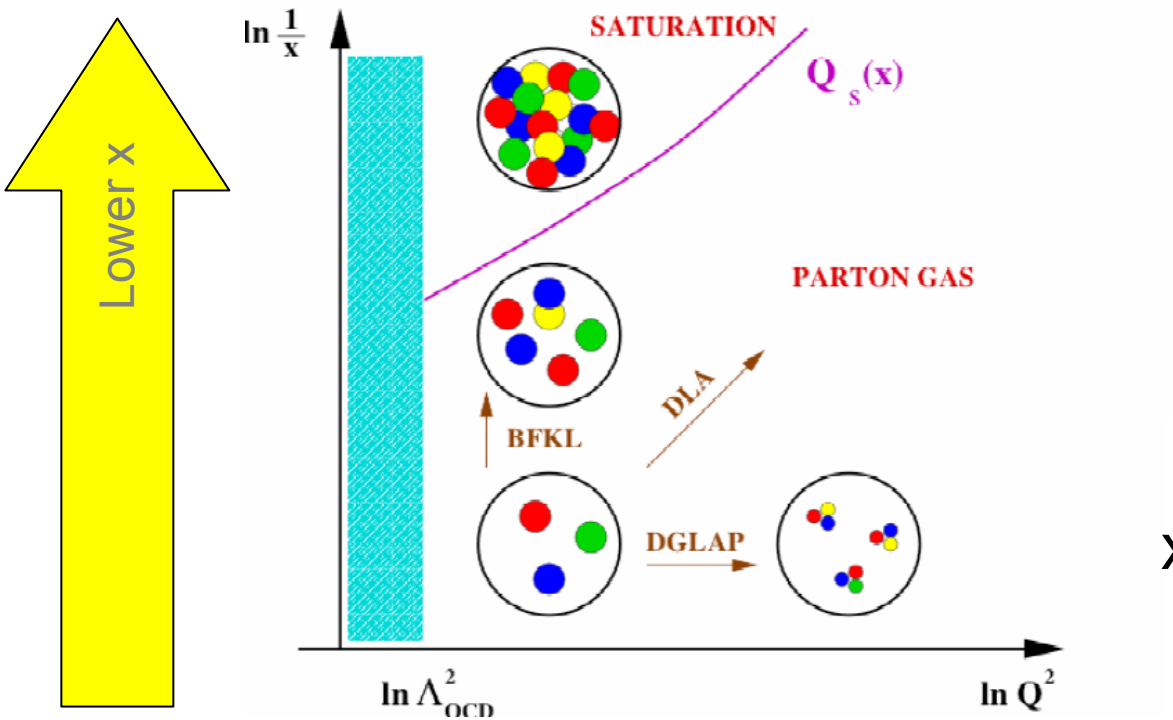
Observable	Counts per RHIC-I p+p week	Counts per RHIC-I Au+Au week	Counts per RHIC-II p+p week	Counts per RHIC-II Au+Au week
Luminosity	9.9 pb^{-1}	0.33 nb^{-1}	33 pb^{-1}	2.5 nb^{-1}
$B \rightarrow J/\psi X \rightarrow \mu \mu$	~200	~220	~650	~1.7k

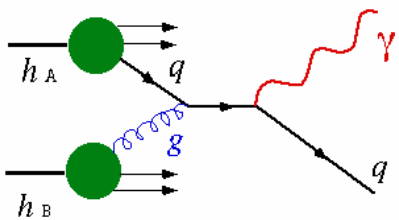
- Physics Motivation:
  - Open beauty measurement needed to separate charm and beauty components in single lepton measurements
- Only explicit measurement of open beauty
- Relatively free of background because prompt J/ψ AND displaced B-decay vertex J/ψ can be reconstructed
- Additionally, c and b may be separated by different lifetimes of D, B



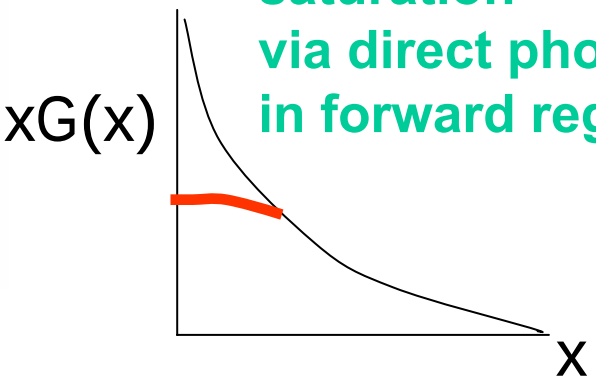
NCC - What is the Physics?

QCD: Proton Nucleus Physics and the Colored Glass Condensate





measure gluon saturation via direct photons in forward region



More saturation at Lower x

y~log(1/x)

Lower x ➔ forward rapidity

The Colored Glass Condensate: The Initial Condition for Heavy Ion Collisions?

Contrasting small-x physics at RHIC-II and the LHC

At RHIC/RHIC-II measurements explore the onset of shadowing or saturation, while at the LHC most measurements will be deep into the saturation region

- exploring the onset at RHIC-II will be key to understanding saturation
- studies at RHIC will be complimentary to those at the LHC

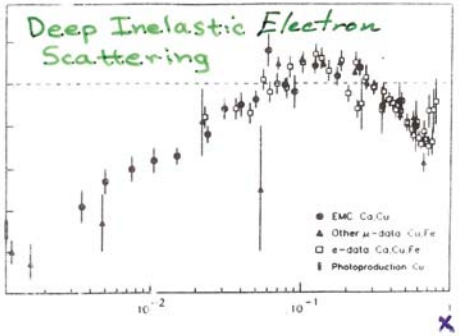
From the LHC pA Workshop: **(http://wwwth.cern.ch/pAatLHC/pAworkshop2.html)**

- p+A at the LHC is still officially an upgrade
- First year that LHC might run p+Pb: 2010
- Possible "target" luminosity: 10^{29} $cm^{-2}s^{-1}$ (RHIC-II: $2x10^{30}$ $cm^{-2}s^{-1}$ avg)
- Can't use the constant frequency solution that worked well at RHIC
- N-N CM not at lab y=0 (Δy=-0.46 for 8.8 TeV p+A)
- "Company line": no need for p+p reference. Will come from interpolation between Tevatron and 14 TeV
  - Probably okay for "really hard" processes
  - May be problematic for measurements focused on small-x saturation effects
  - If the accelerator turn-on goes well, even getting the 14 TeV reference data may be a challenge

Backup

Los Alamos

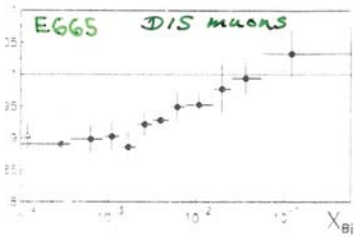
What About A-dependence of Drell-Yan??



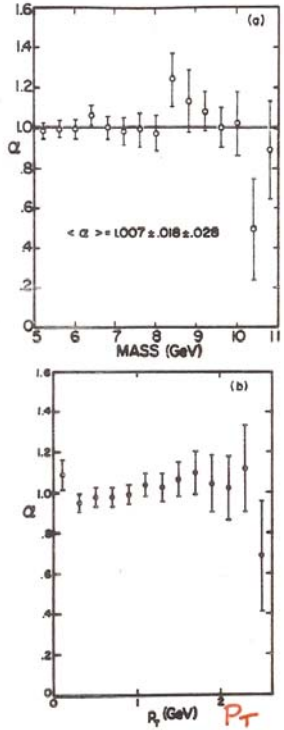
SHADOWING

X < 0.1 quarks suppressed in nuclei.

Gluons probably also suppressed.

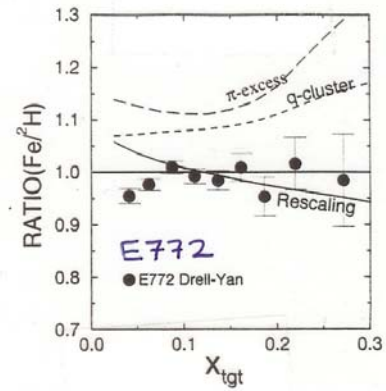


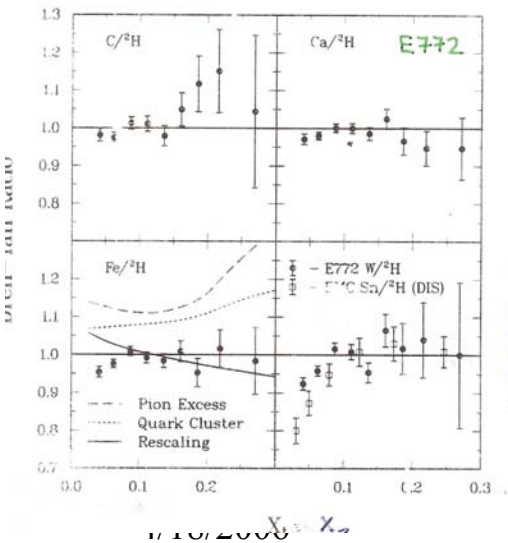
E665
Deep Inelastic Scattering
(470 GeV/c μ)
Z. Phys. C67, 403 (1995)



E288 – 400 GeV protons
PRD 23, 604 (1981).

NUCLEAR DEPENDENCE OF DRELL-YAN.



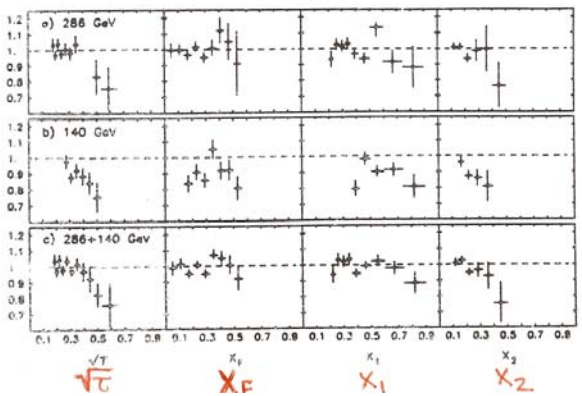


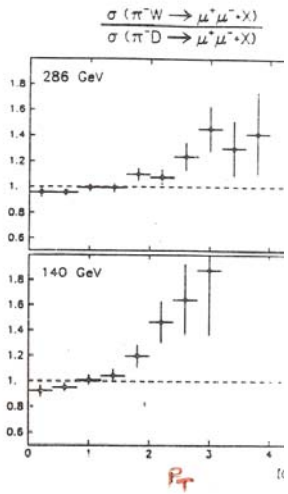
Explains low-x Drell-Yan

E772
p+A → μ⁺μ⁻
@ 800 GeV/c
PRL 64, 2479 (1990)

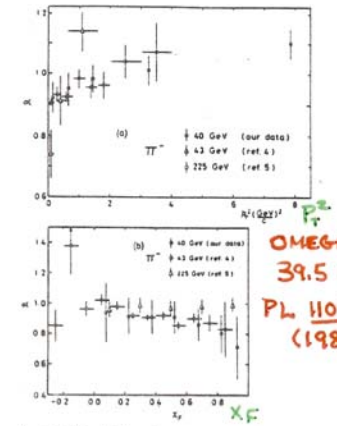
NA10 – 140 GeV/c & 288 GeV/c π^-
PL B 193, 368 (1987).

$$\frac{\sigma(\pi^- W \to \mu^+\mu^- + X)}{\sigma(\pi^- D \to \mu^+\mu^- + X)}$$





MORE J/ψ NUCLEAR DEP.



OMEGA Spectr.
39.5 GeV/c π^-
PL 110B, 415 (1982).

Fig. 3. Variation of A-dependence parameter α, $A^\alpha = \sigma(W)/\sigma(H_2)$, for π^- induced J/ψ as a function of p_T^2 and x_F. No corrections have been made for the effects of Fermi motion.

NA3
Z. Phys. 20, 101 (1983).
150 & 200 & 280 GeV/c

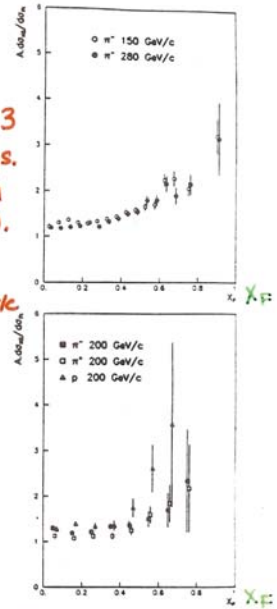
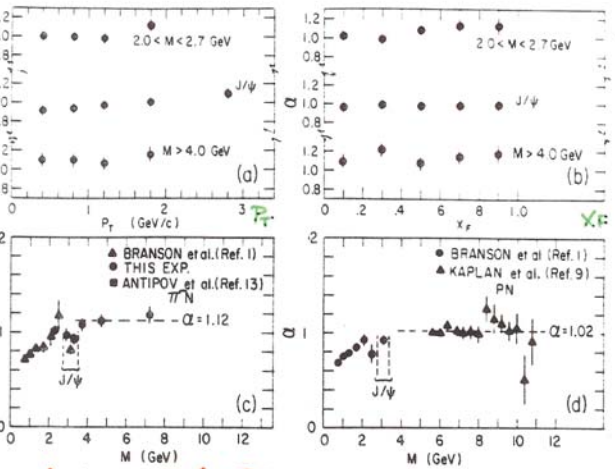
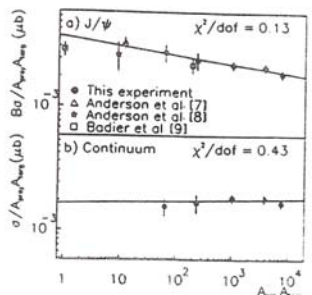


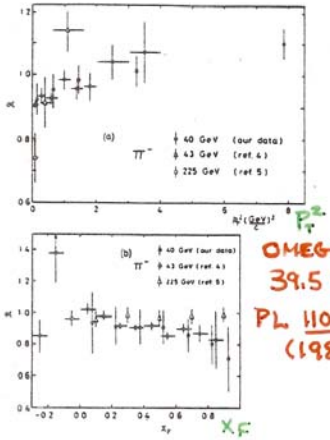
Fig. 2. Ratio of J/ψ cross sections on hydrogen and platinum $R(x_F) = A\frac{d\sigma(H_2)}{dx_F}\Big/\frac{d\sigma(Pt)}{dx_F}$ for the various π^+, π^-, p data of the experiment



Anderson et al. PRL 42, 944 (1979).
225 GeV/c $\pi^\pm$, $K^\pm$, $p^\pm$

NA38
PL 270, 105 (1991).





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39.5 GeV/c π^-
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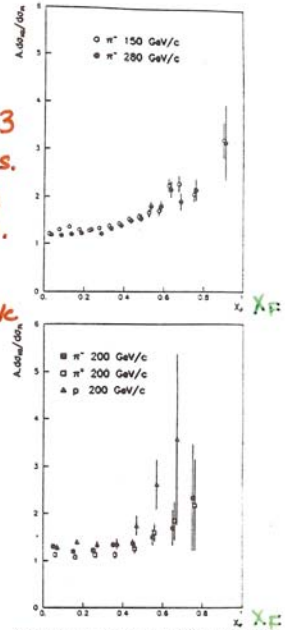
Fig. 3. Variation of A-dependence parameter α, $A^\alpha = \sigma(W)/\sigma(H_2)$, for π^- induced J/ψ as a function of p_T^2 and x_F. No corrections have been made for the effects of Fermi motion.

MORE J/ψ NUCLEAR DEP.

NA3
Z. Phys. 20, 101 (1983).
150 & 200 & 280 GeV/c



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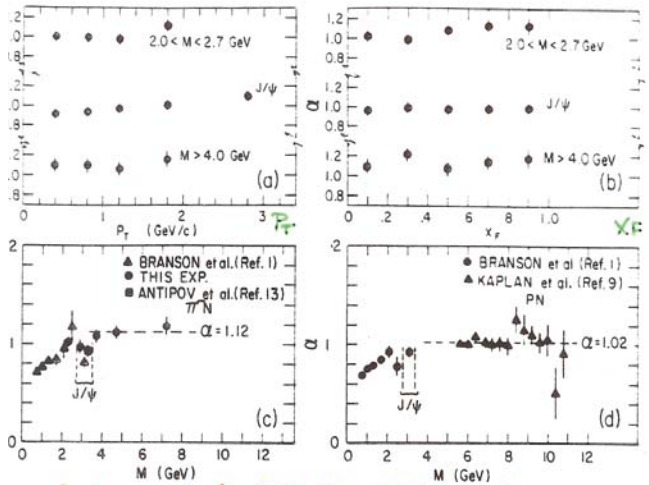
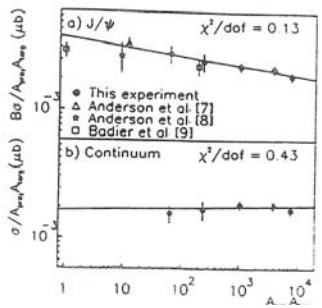
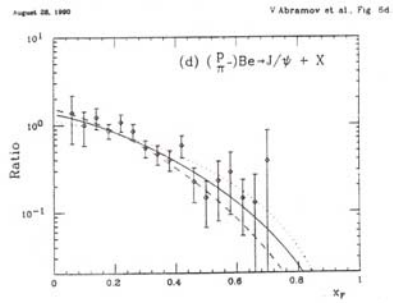


Anderson et al. PRL 42, 944 (1979).
225 GeV/c $\pi^\pm$, $K^\pm$, $p^\pm$

NA38
PL 270, 105 (1991).





NUCLEAR DEPENDENCE OF J/ψ PRODUCTION

E672/706
530 GeV/c π, p
(FNAL-Pub-91/62-E, FNAL-Conf-89/151-E)

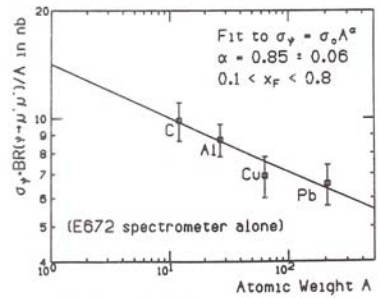
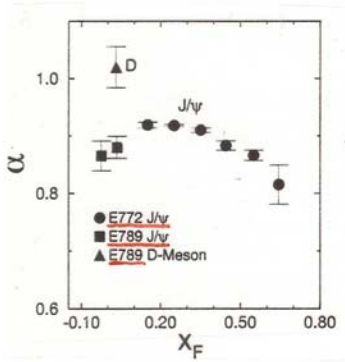
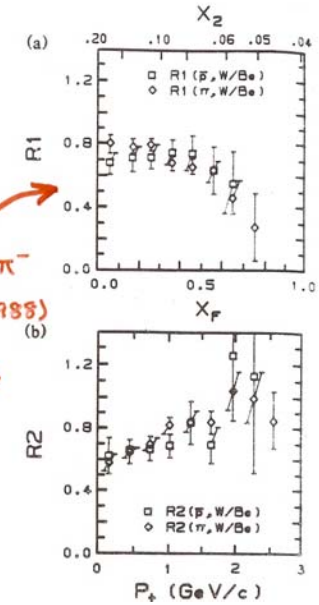


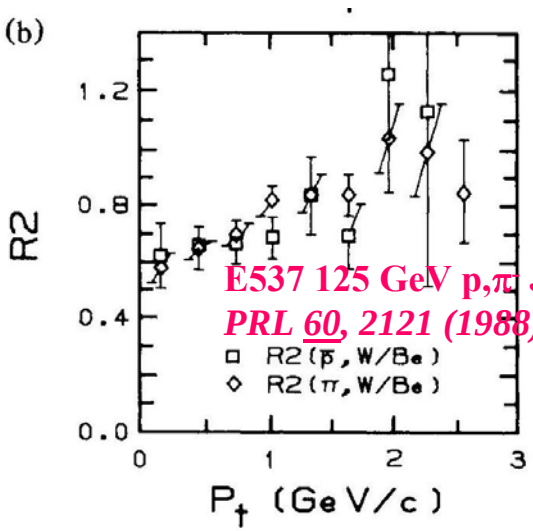
Fig. 7. The A-dependence of J/ψ Production



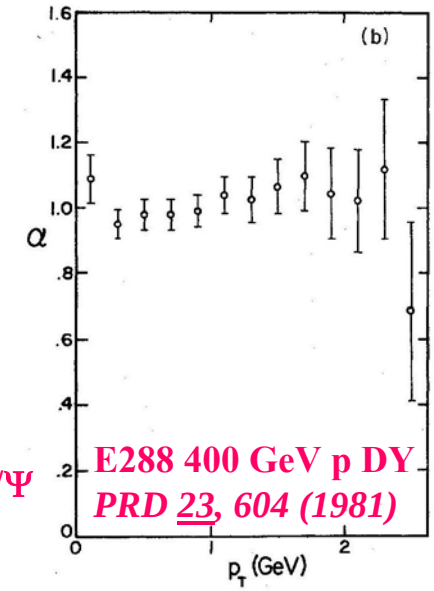
E537
125 GeV/c $\bar{p}, \pi^-$
PRL 60, 2121 (1988)



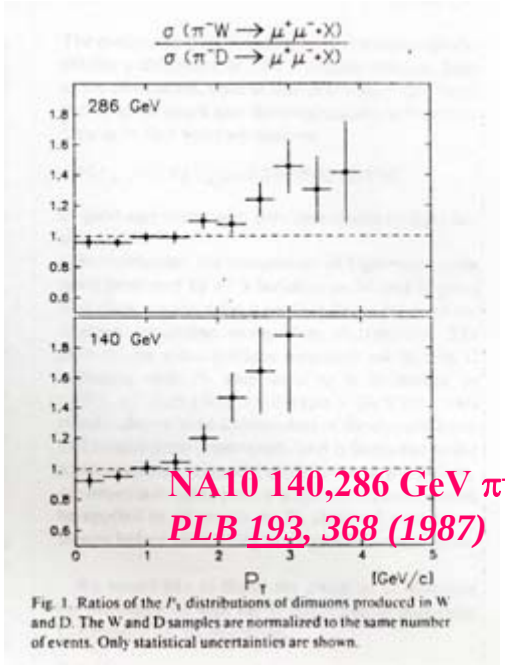
P_T Broadening for different energies and probes – other data



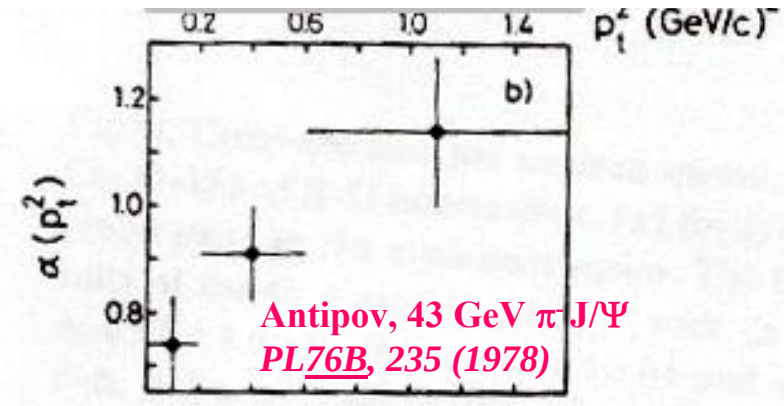
E537 125 GeV p,π^- J/Ψ
PRL 60, 2121 (1988)



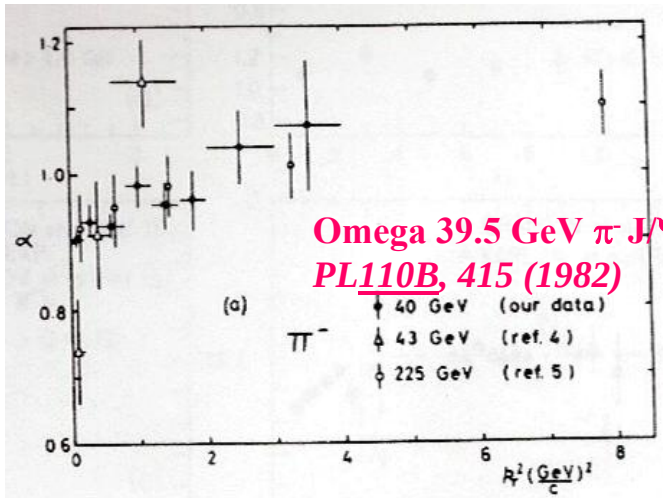
E288 400 GeV p DY
PRD 23, 604 (1981)



NA10 140,286 GeV π^- DY
PLB 193, 368 (1987)

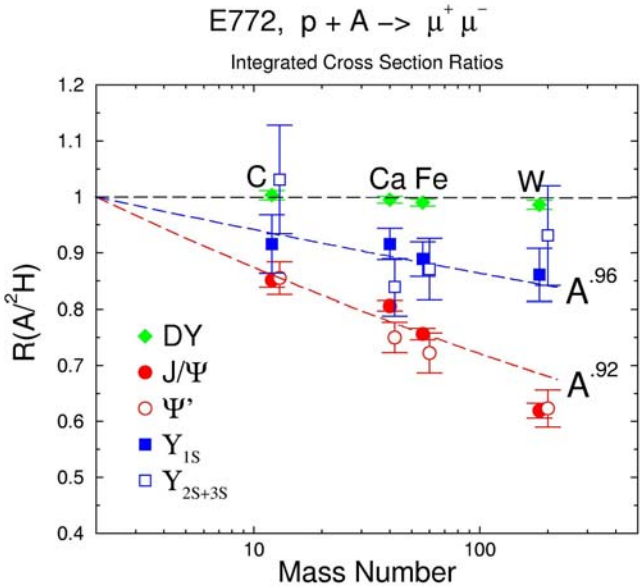


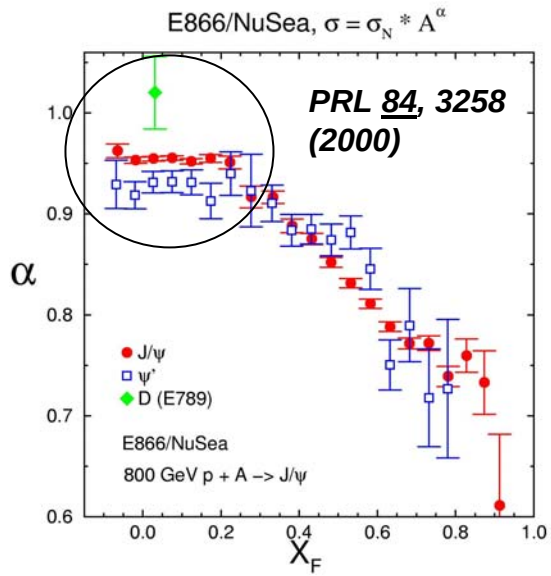
Antipov, 43 GeV π^- J/Ψ
PL76B, 235 (1978)



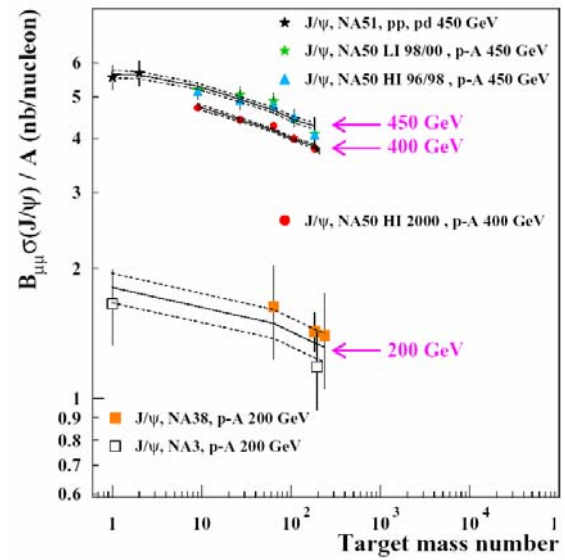
Omega 39.5 GeV π^- J/Ψ
PL110B, 415 (1982)

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





PRL 84, 3258 (2000)



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

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

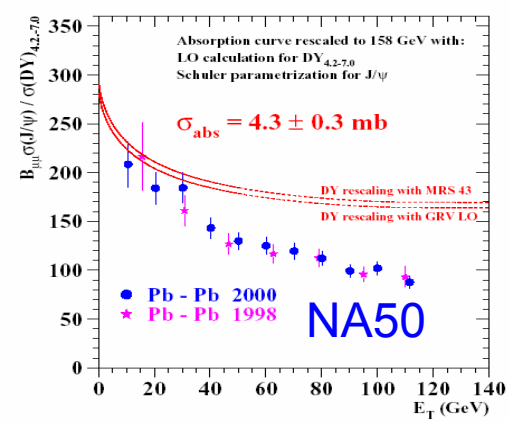
$\alpha = 0.954 \pm 0.003$ E866/NuSea @ x_F=0

$\alpha = 0.941 \pm 0.004$ NA50, QM04

Absorption model parameterization (from pA)

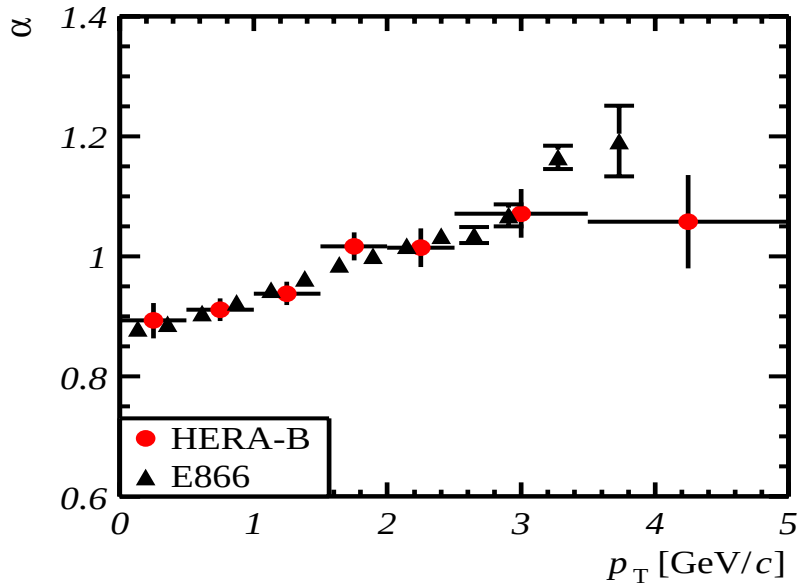
$\sigma_{J/\psi} = 4.18 \pm 0.35$ mb NA50 QM05

$\sigma_{\psi'} = 7.6 \pm 1.1$ mb

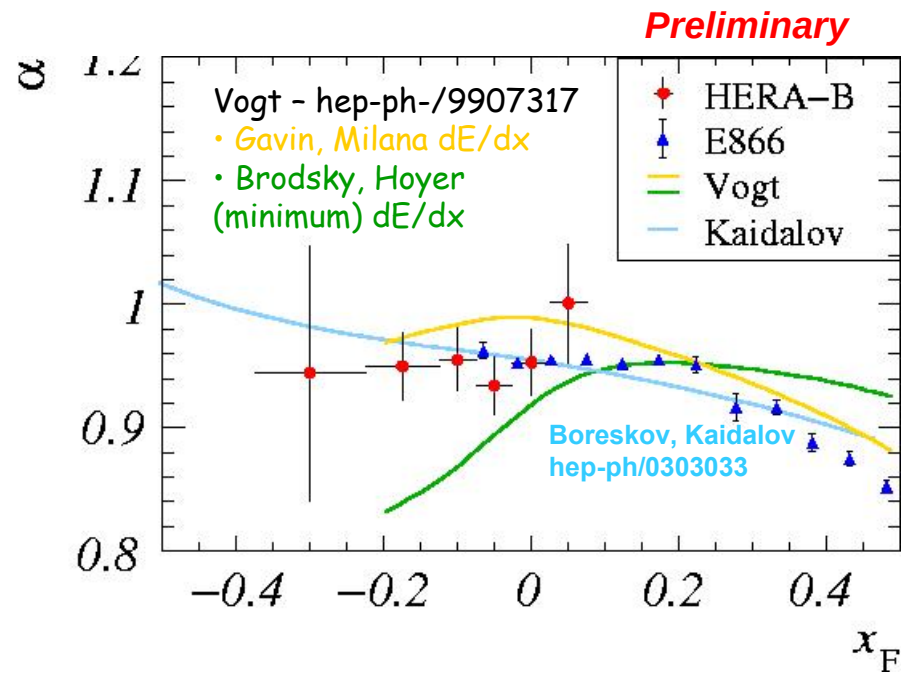


HERA-B - J/ψ A dependence

$$\sigma_A = \sigma_N A^{\alpha}$$



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



- 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.