What we have Learned from d+Au Collisions at RHIC

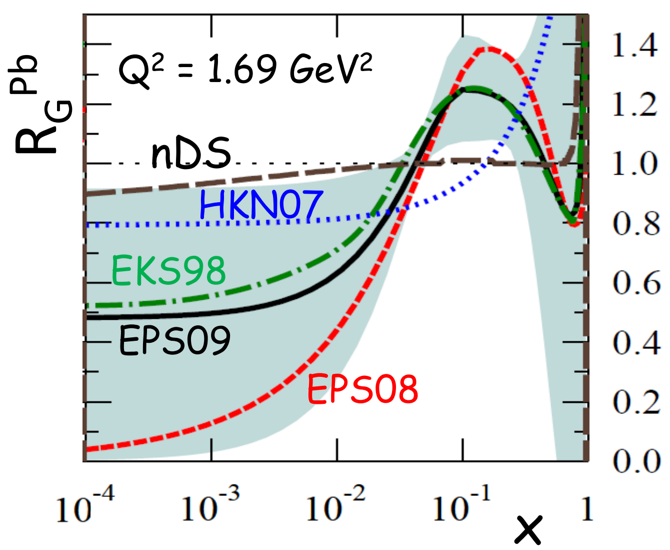
M.J. Leitch, LANL

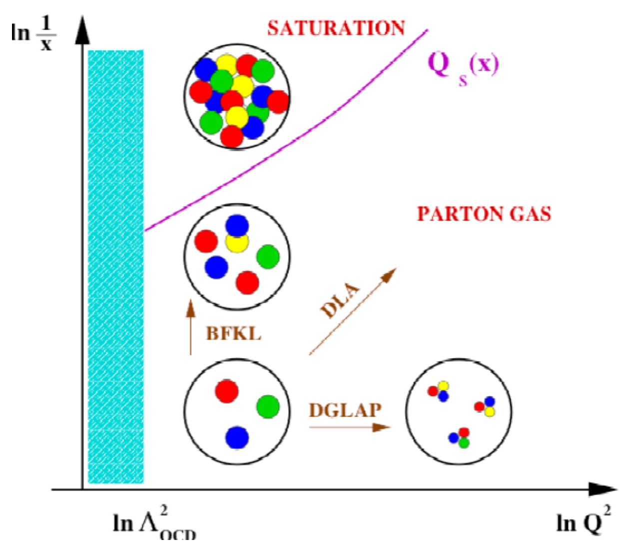
High Energy Hadron Physics with Hadron Beams

KEK, Tsukuba, Japan, 6-8 January 2010

Cold Nuclear Matter (CNM):

- Central Physics Questions
- What we have learned so far & Goals for the future



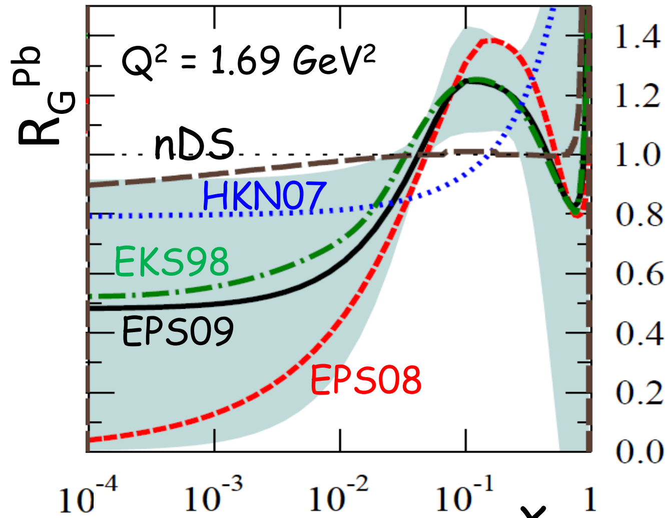


Saturation of Small-x Gluons or Shadowing

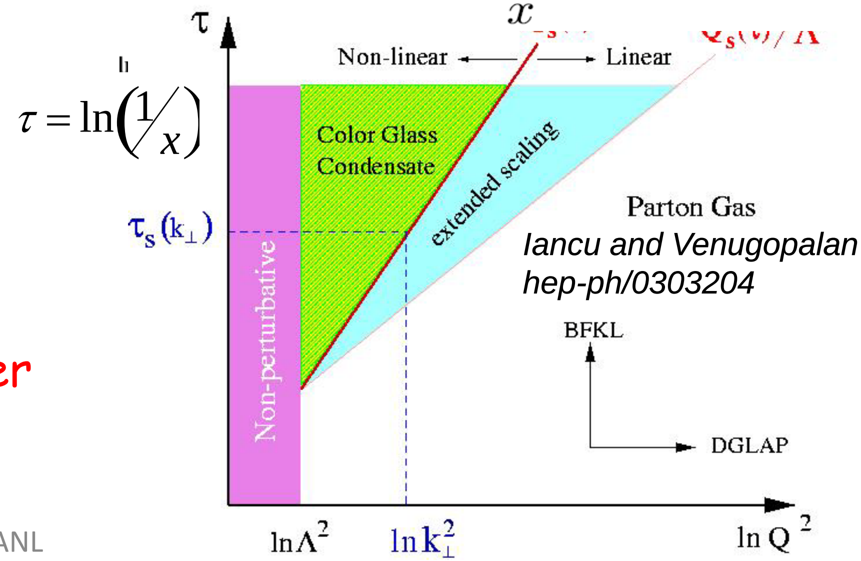
NSAC Milestone: DM8 – "Determine gluon densities at low x in cold nuclei via p + Au or d + Au collisions."

Leading twist gluon shadowing
- e.g. EPS09 - phenomenological fit to DIS & DY data with large uncertainties, arXiv:0902.4154

Also coherence models & higher-twist (HT) shadowing, e.g. Vitev PRC 75, 064906 (2007)



Small-x gluon saturation or Color Glass Condensate (CGC)
- At low-x there are so many gluons that 2→ 1 diagrams become important and deplete the 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

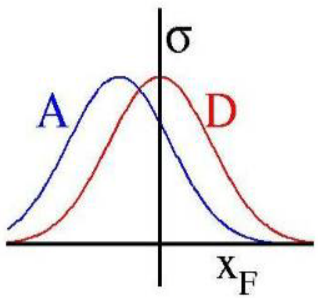


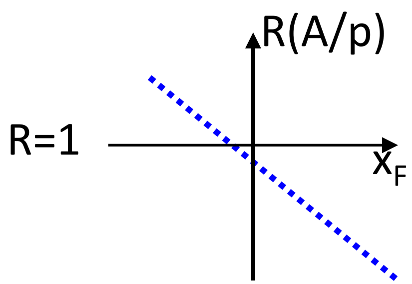
Iancu and Venugopalan hep-ph/0303204

Energy Loss of Partons in Nuclei

Related to NSAC Milestone: DM12 – "Measure production rates, high p_T spectra, and correlations in heavy-ion collisions at $\sqrt{s_{NN}}$ = 200 GeV for identified hadrons with heavy flavor valence quarks to constrain the mechanism for parton energy loss in the quark-gluon plasma."

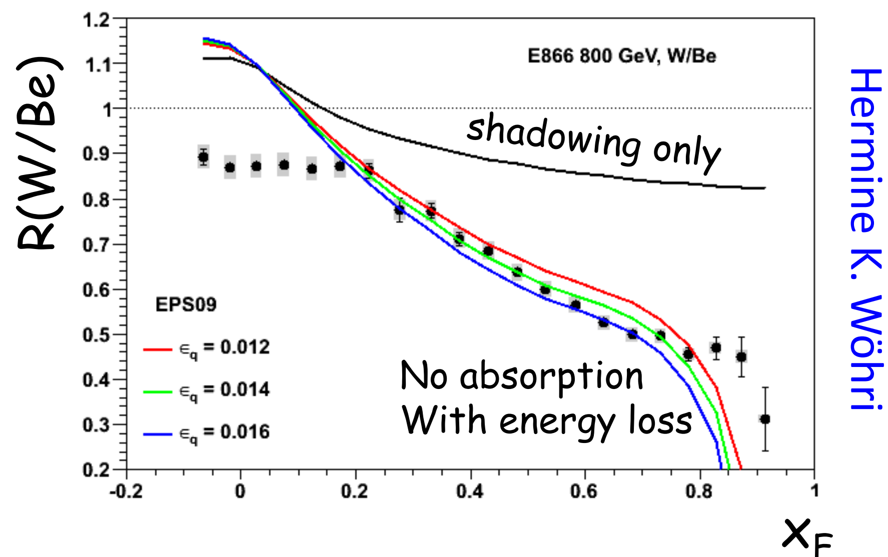
And what about energy loss in cold nuclear matter?





Initial-state energy loss

E866/NuSea, 800 GeV, J/Ψ p+W / p+Be ratio

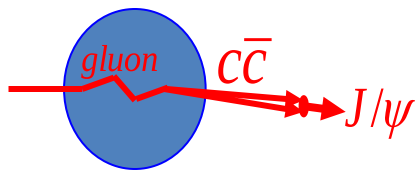


$$x_1' = x_1 (1 - \varepsilon_g)^{(Ncoll - 1)}$$

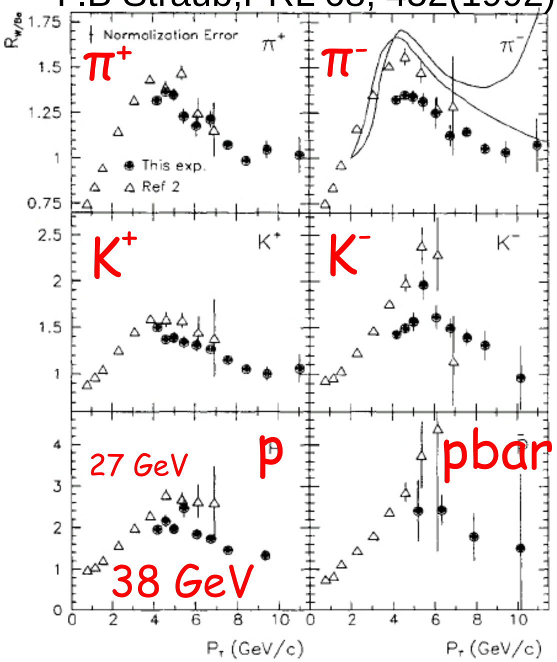
ε_q ~ 1.5% and $\varepsilon_g = 9/4\ \varepsilon_q$ ~ 3.3%

Cronin Effect in p(d)+A Collisions

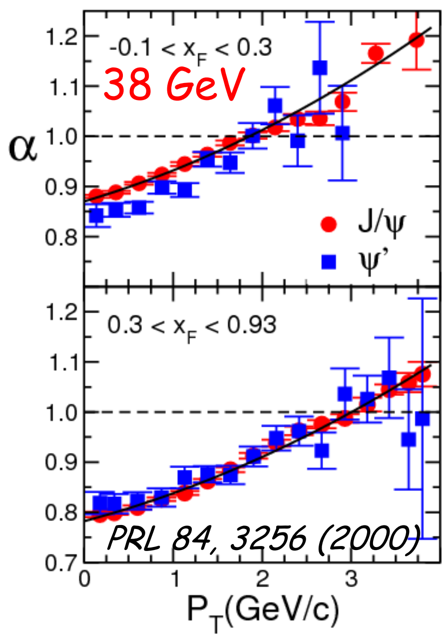
Cronin effect, or p_T broadening from soft initial-state pre-hard-interaction scatterings



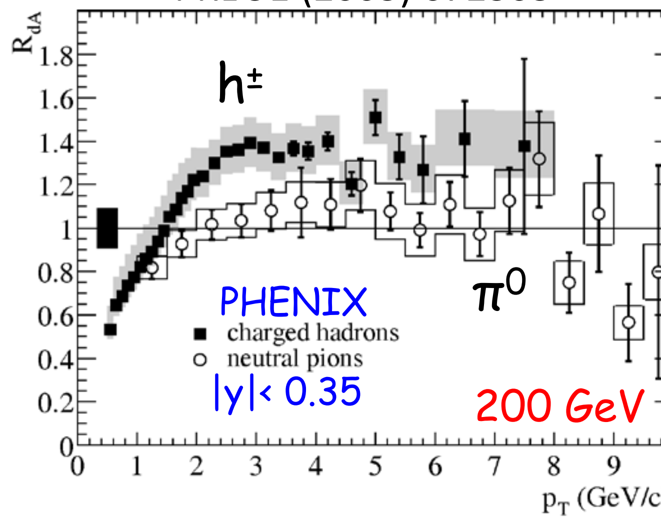
P.B Straub,PRL 68, 452(1992)

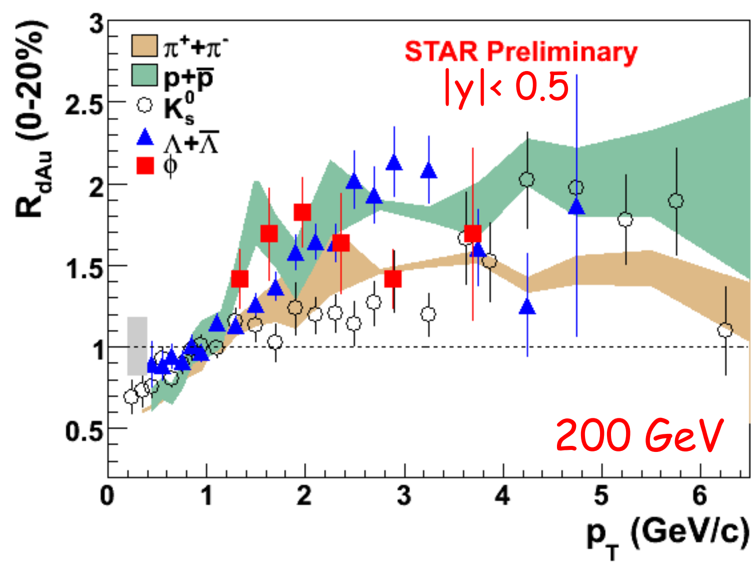


E866/NuSea 800 GeV p+A



PRL 91 (2003) 072303





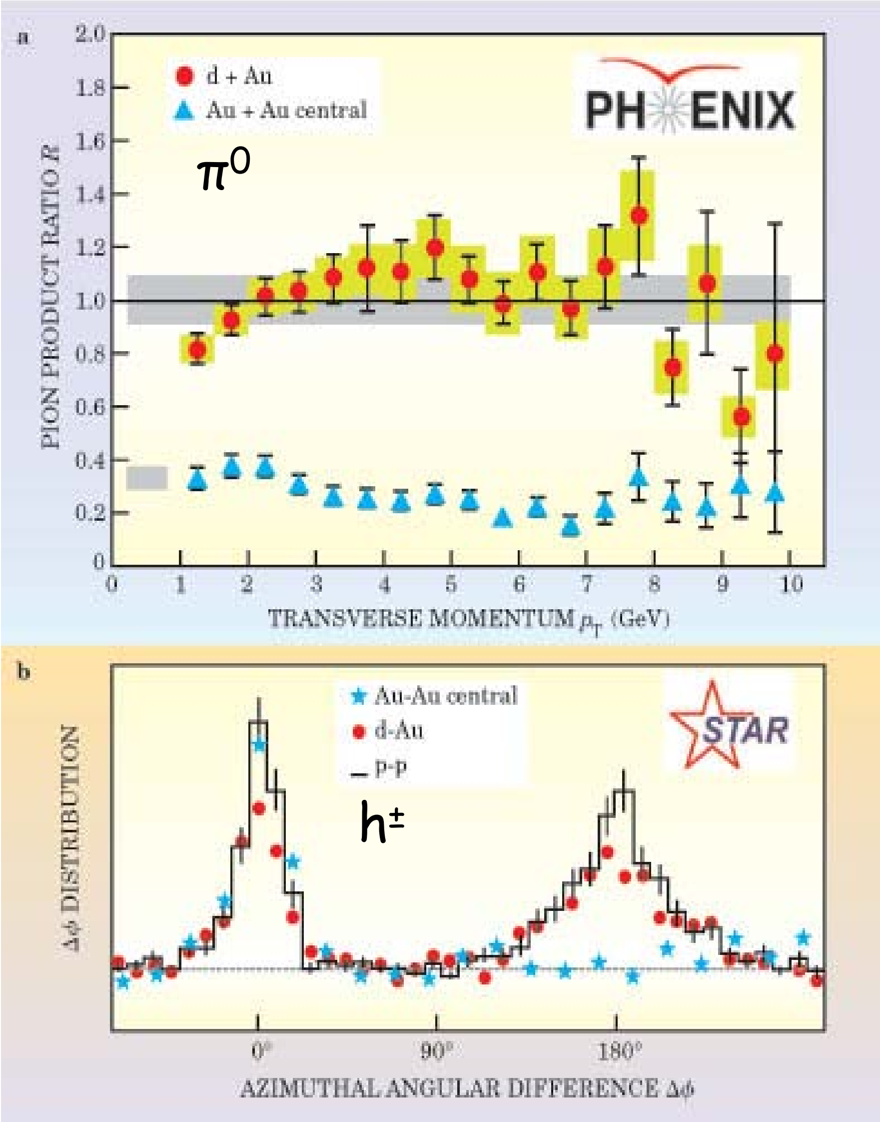
Jets – CNM Energy Loss & Jet Modification

Jets – CNM Energy Loss & Jet Modification

- Confirmation of the Cold Nuclear Matter (CNM) baseline from d+Au was essential for the jet quenching "discovery" in heavy-ion collisions

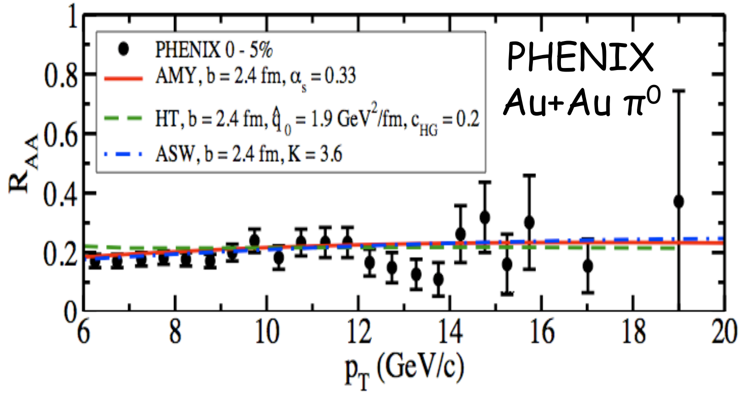
- Large energy loss in QGP medium is poorly understood – consistent description of quenching, flow, light and heavy quarks is complex

- Jet correlations unmodified in d+Au but strongly modified in A+A – another (even more complex) story



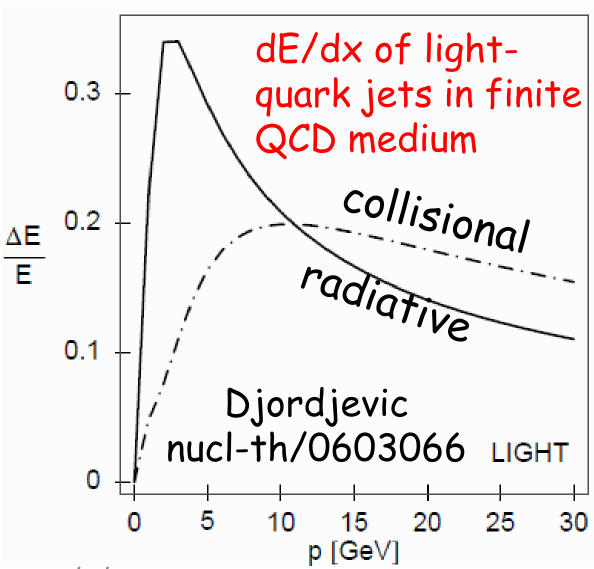
Jets – CNM Energy Loss & Jet Modification

S.Bass *et al* in arXiv:0808.0908

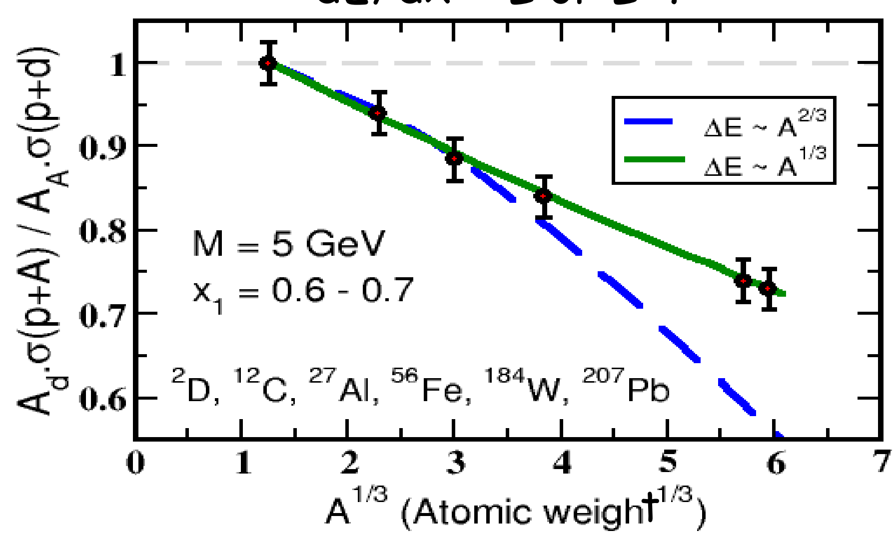


qhat_0 =4.1(AMY) , 2.3(HT), 10(ASW) GeV^2/fm
(no collisional dE/dx included here)

- Large energy loss observed in QGP medium, but complex to understand – radiative, collisional energy loss, etc.
- Need to measure & understand CNM energy loss as part of this puzzle
- Drell-Yan measurements at FNAL will measure incident-state quark energy loss (E906/SeaQuest)



dE/dx ~ L or L^2 ?

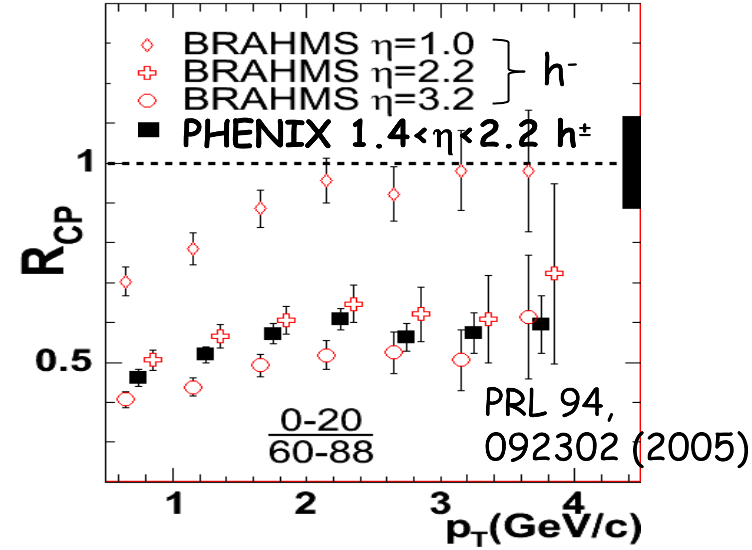


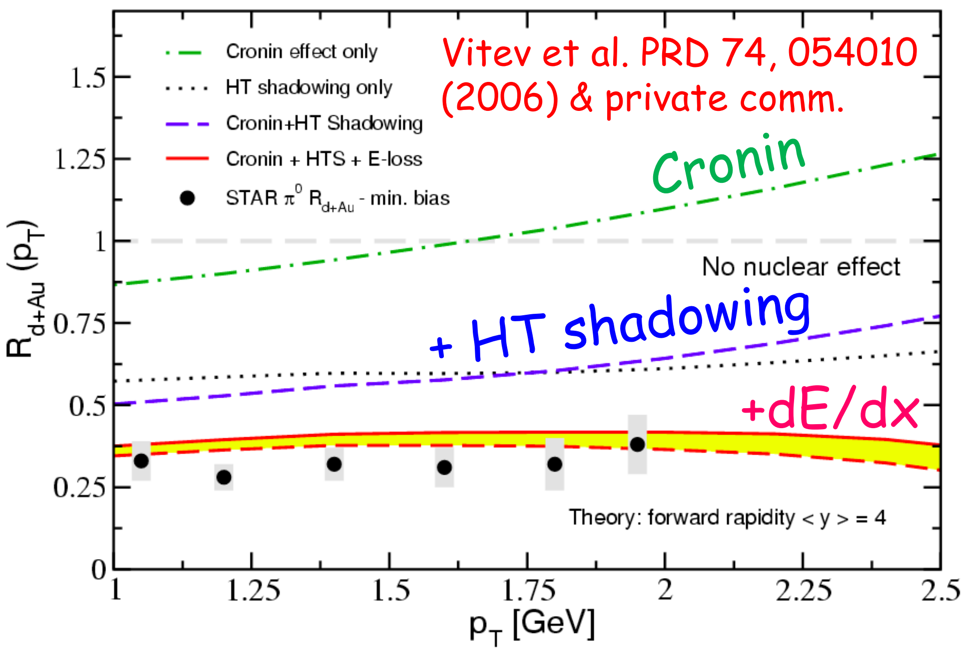
Hadrons and Correlations with Hadrons at Forward Rapidity

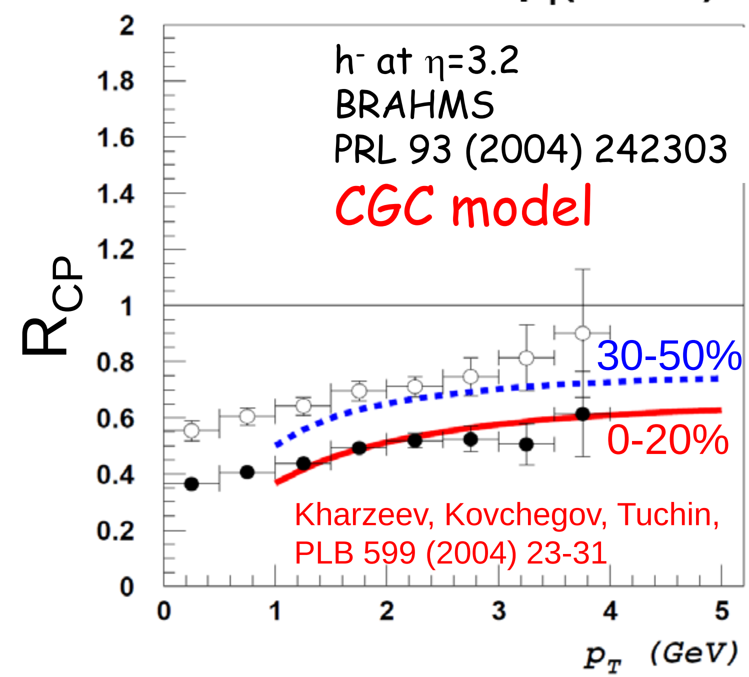
Forward Rapidity Hadrons in d+Au

Forward rapidity hadrons are suppressed in d+Au

- small-x shadowing region
- understanding in terms of pQCD effects or gluon saturation? (or are they equivalent?)

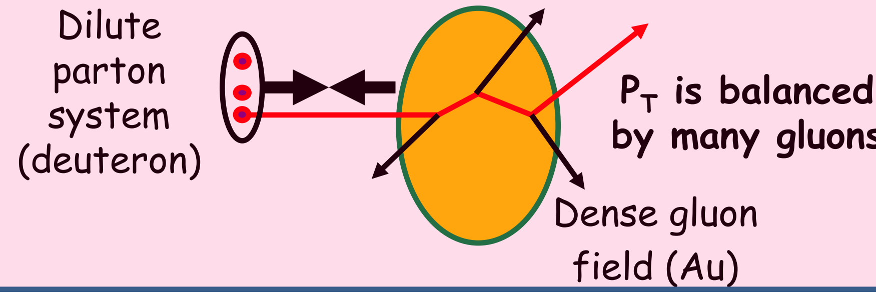




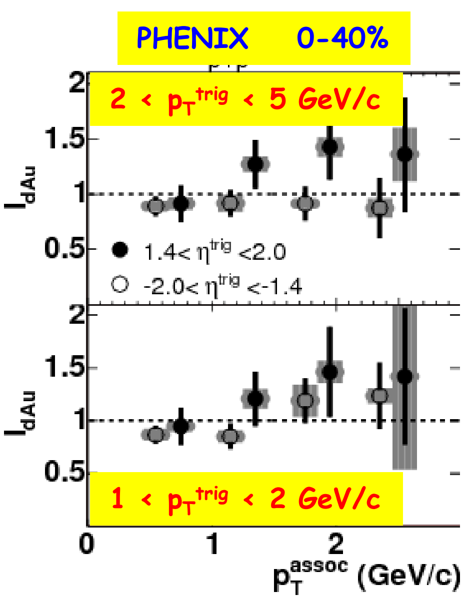


Rapidity-Separated Hadron Pairs in d+Au

Mono-jets in the gluon saturation (CGC) picture give suppression of pairs per trigger and some broadening of correlation
Kharzeev, NPA 748, 727 (2005)



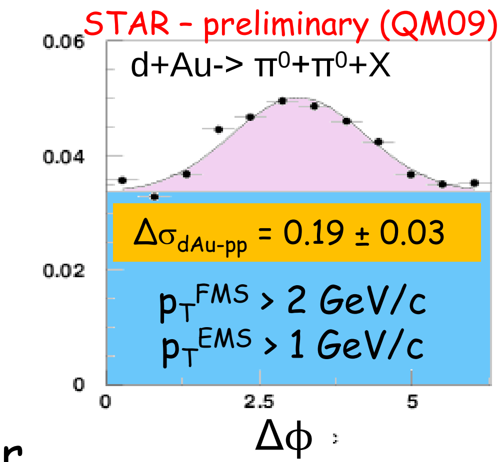
Tag on forward particle, look at pairs by adding mid-rapidity particle
- no substantial suppression & no broadening of correlation wrt p+p (within present uncertainties)
- no evidence for mono-jets (so far)

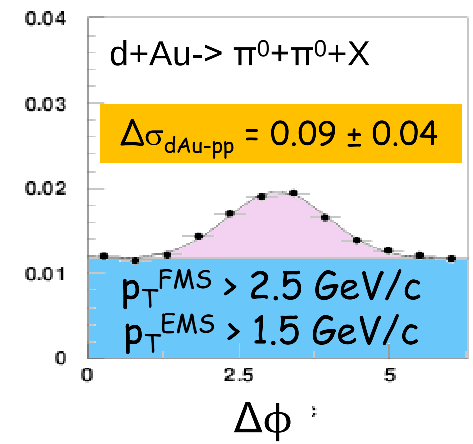


PHENIX:
No suppression or broadening

nucl-ex/0603017

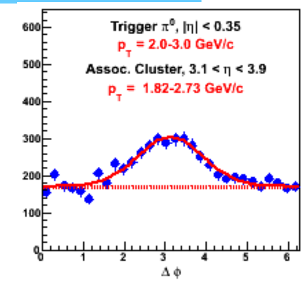
STAR/FMS:
Slightly more broadening for (slightly) higher p_T

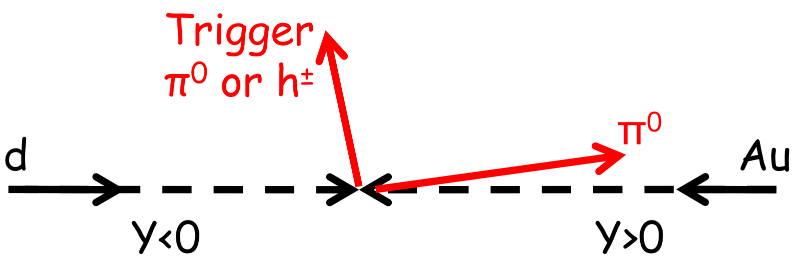




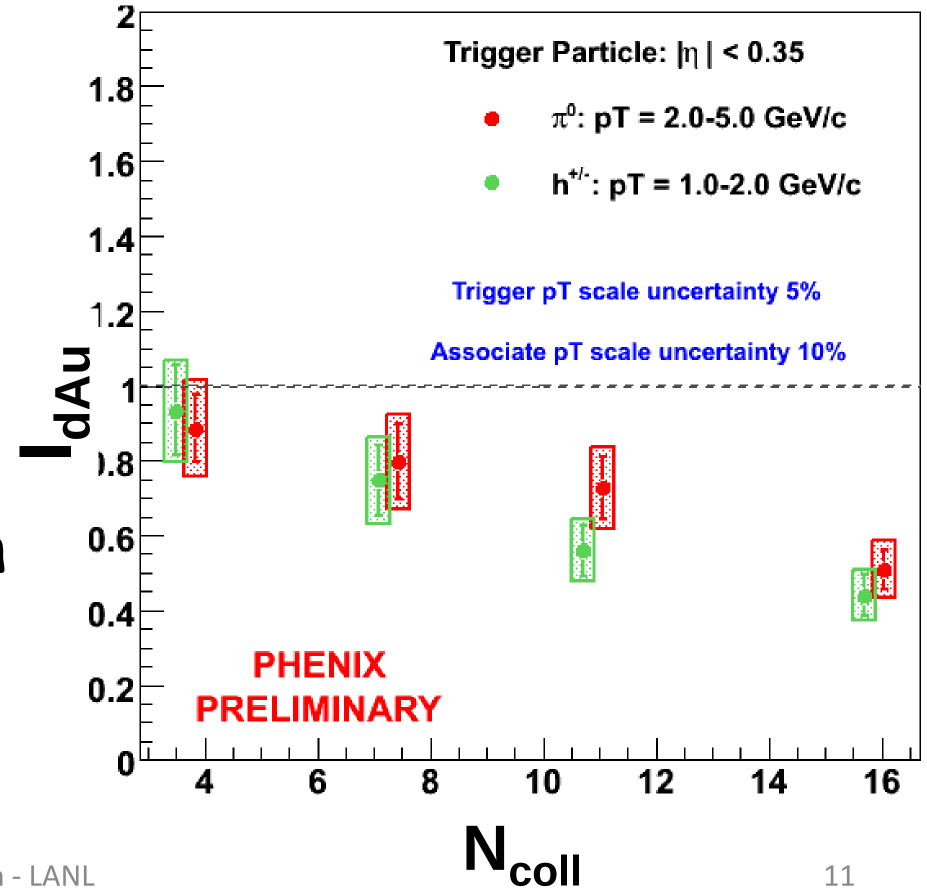
Rapidity-separated hadron correlations in d+Au

$$I_{dAu} = \frac{N^{pair}_{d+Au}\left[(\eta=3.5)+(\eta=0)\right] / N^{trig}_{d+Au}(\eta=0)}{N^{pair}_{p+p}\left[(\eta=3.5)+(\eta=0)\right] / N^{trig}_{p+p}(\eta=0)}$$





Associate π^0: $3.1<\eta<3.9$ p_T = 0.45-1.59 GeV



I_{dAu} suppressed at forward rapidity for more central collisions

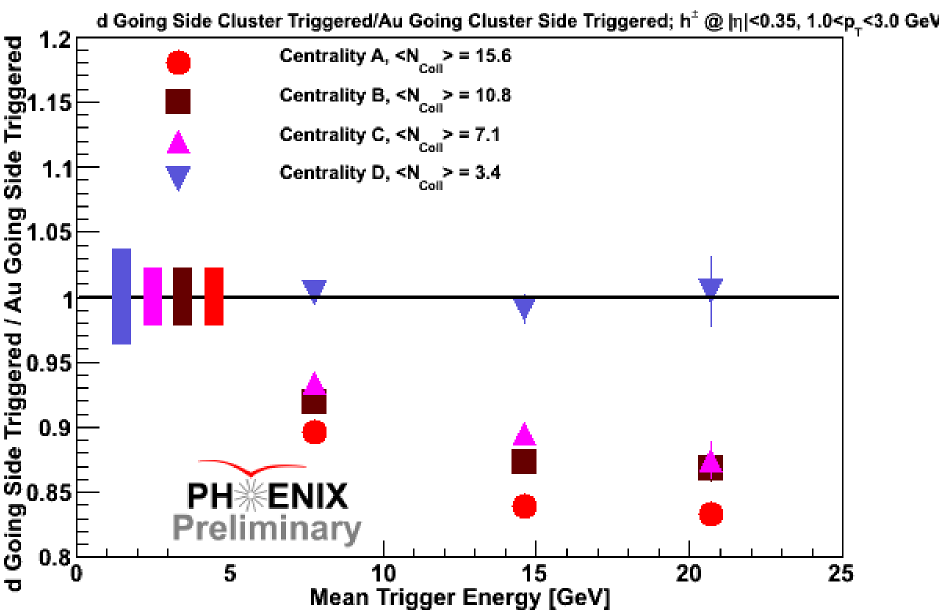
But no broadening seen within uncertainties

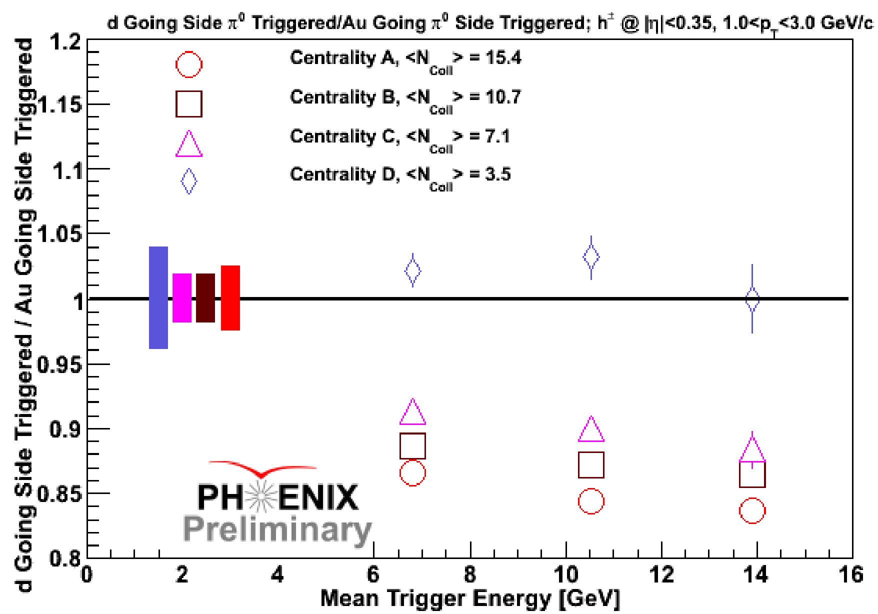
PHENIX, B. Meredith – QM09

Rapidity-Separated Hadron Pairs in d+Au using Forward Trigger

Mid-rapidity charged particle yields h are off-line "triggered" by MPC cluster or π^0

Ratio of forward (d) / backward (Au) triggered yields is shown:





Suppression increases with centrality & with trigger energy

PHENIX, Z. Citron, arXiv:0907.4796v3 [nucl-ex]

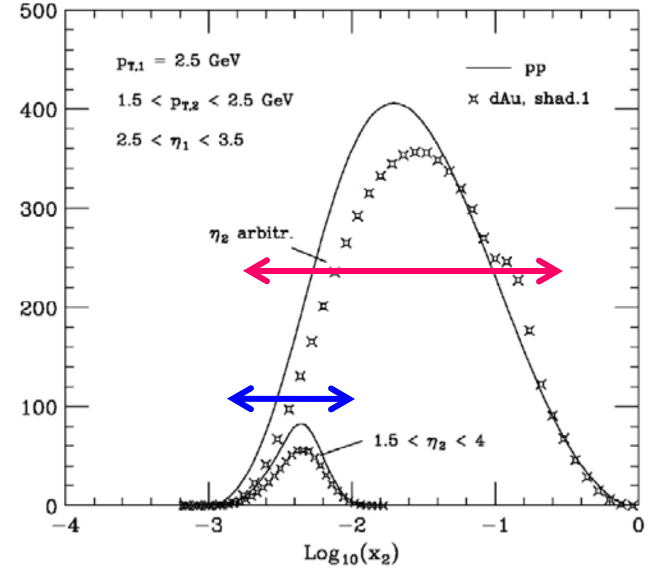
Forward-Forward d+Au $\Delta\Phi(\pi^0\pi^0)$

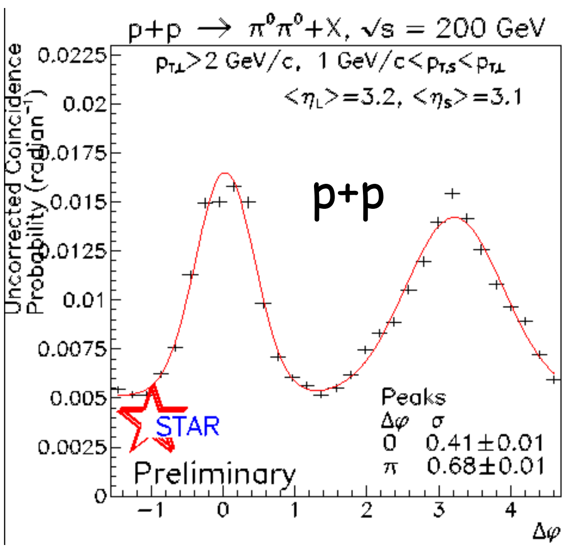
Two forward π^0's probe small x
- STAR preliminary data shows substantial reduction of away-side correlation peak

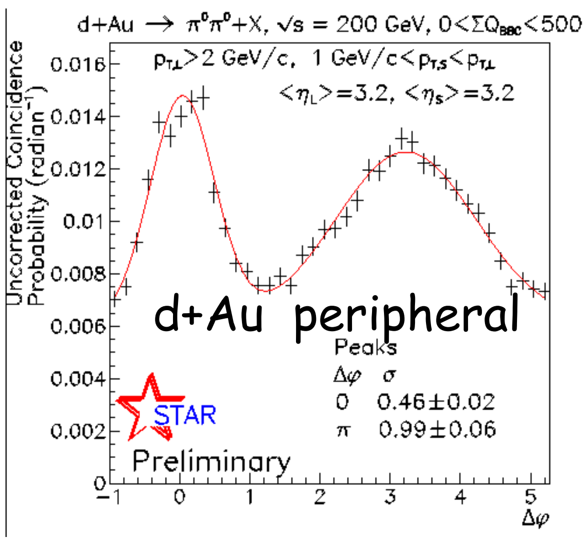
Broad range in x – when only one π^0 detected

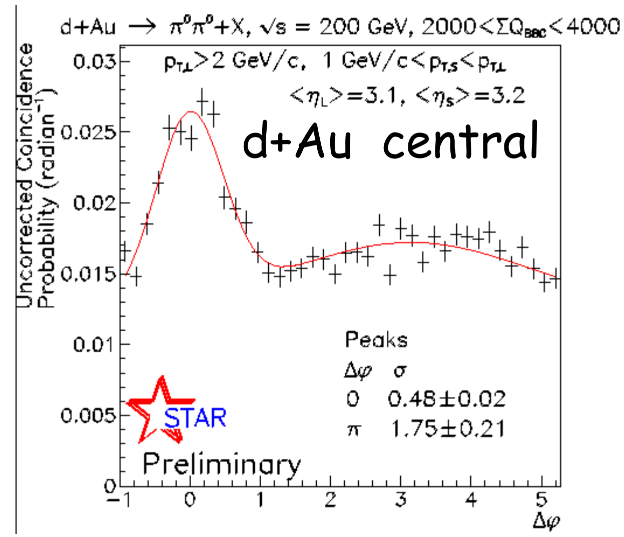
Small-x – when both π^0's detected at forward rapidity

Guzey, Strikman, and Vogelsang, PL B603, 173 (2004)









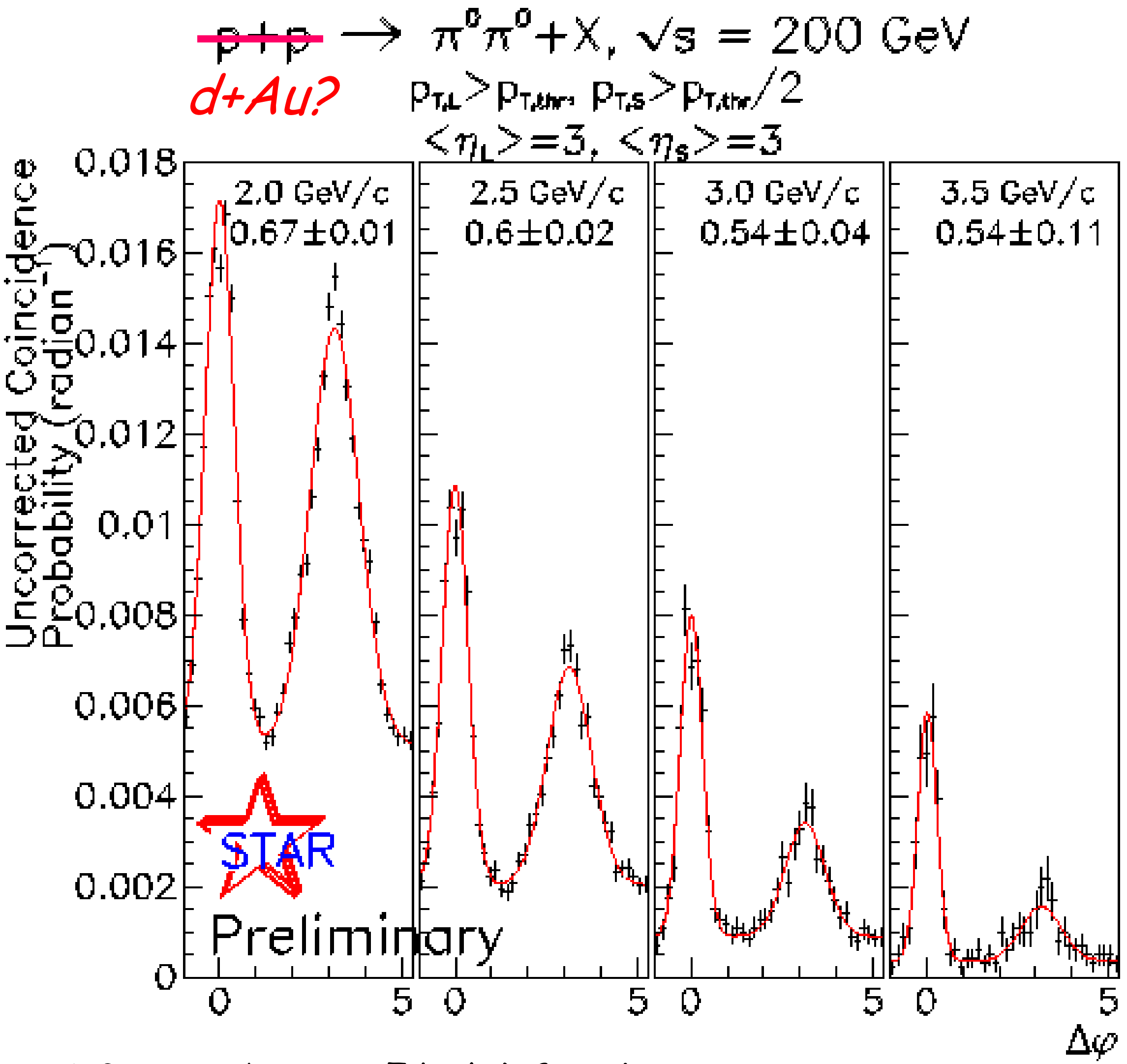
Akio Ogawa, STAR – Dec '09 - Scanning p_T

Normalized to number of events with leading $P_T(\pi^0) > 2.0$ GeV

No efficiency corrections (may have some ϕ dependence)

Away-side broadens & weakens for higher p_T

- *CGC predicts opposite trend , Marquet NPA796, 41 (2007)*
- *as would also be expected from soft physics?*

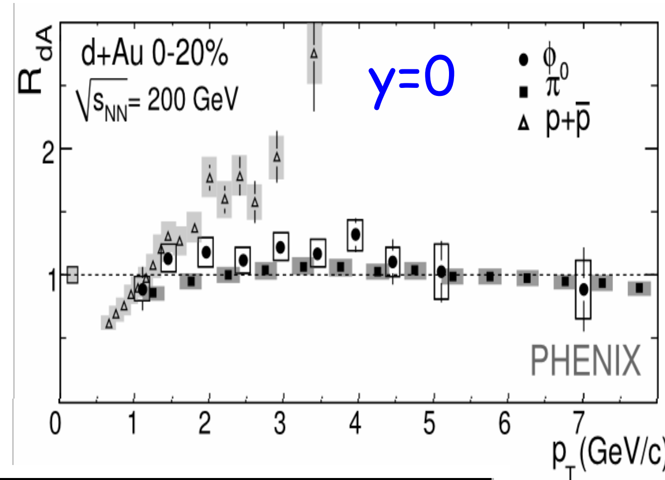


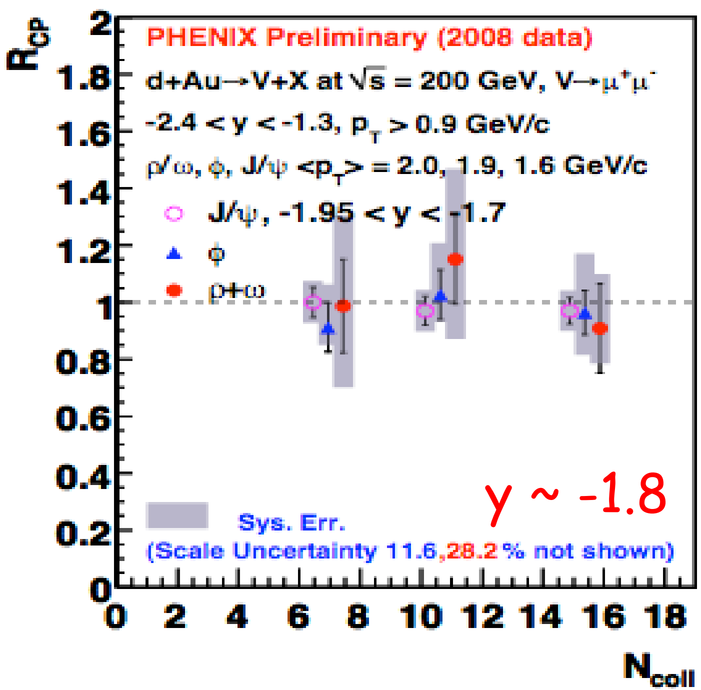
Wider range p_T scan (p_T^{Trig} =2.0 to 3.5 GeV, $p_T^{Asso} = p_T^{Trig}/2$) for dAu is coming

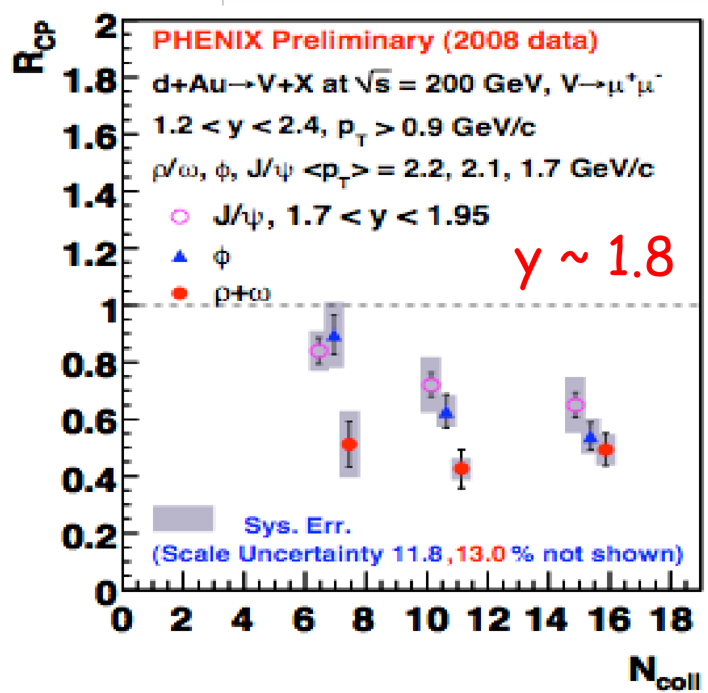
1^{st} $\phi \rightarrow \mu^+\mu^-$ measurement at RHIC

Lei Guo (LANL/PHENIX)

- d+Au nuclear dependence from 2008 data
- Strong suppression at forward rapidity (small-x) in d+Au
- no suppression at backward rapidity (nor at mid-rapidity from e^+e^- msmt)

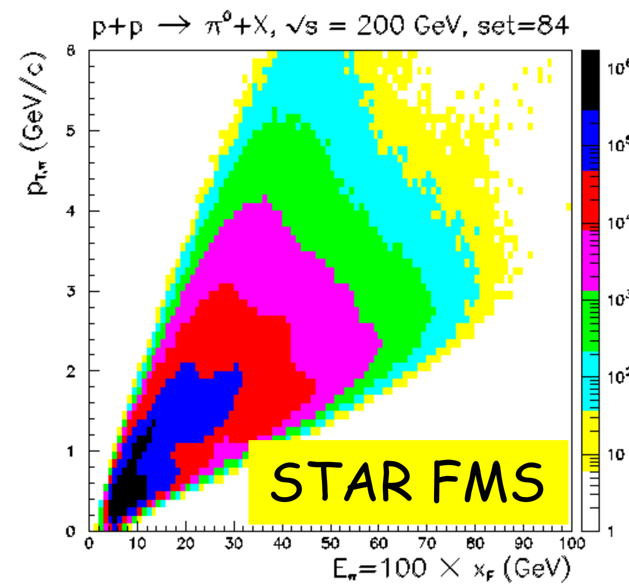


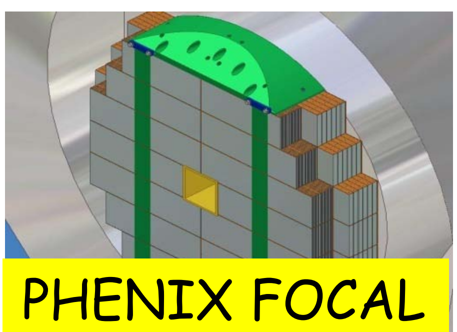




Outlook - Forward Hadrons in d+Au

- Hadrons are suppressed at forward rapidity but it is difficult to distinguish traditional or QCD coherence shadowing from gluon saturation (CGC)
- Mono-jets are a more unique signature of saturation, but no clear evidence seen so far
- Forward calorimeters in both PHENIX(MPC, FOCAL) & STAR (FMS) promise improved measurements soon



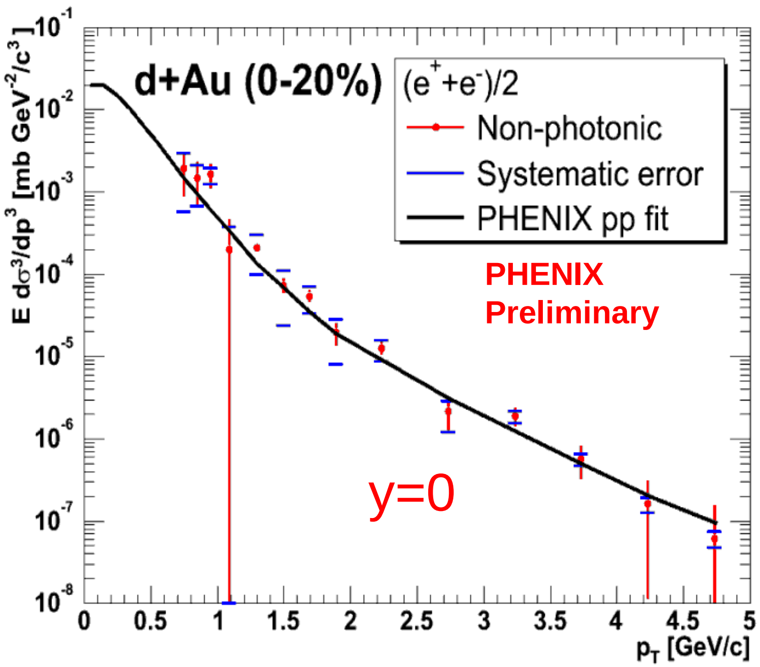


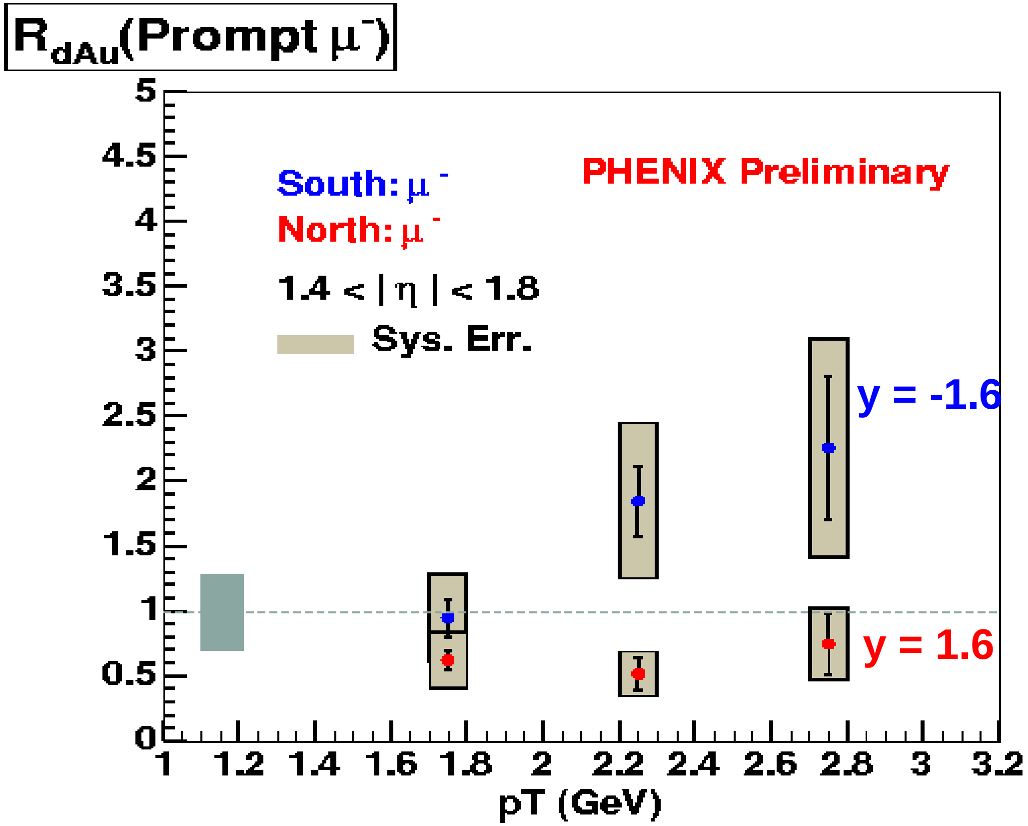
Heavy Quarks at Forward Rapidity

Heavy quarks in Cold Nuclear Matter?

Prompt muons from open charm & beauty:

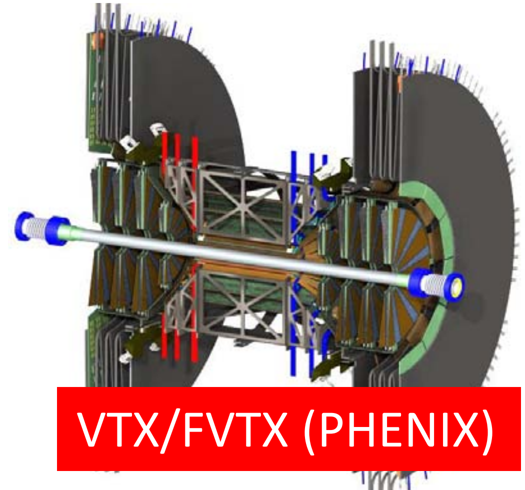
- unaltered at mid-rapidity
- suppressed at forward rapidity (in small-x shadowing region)
- enhanced at backward rapidity

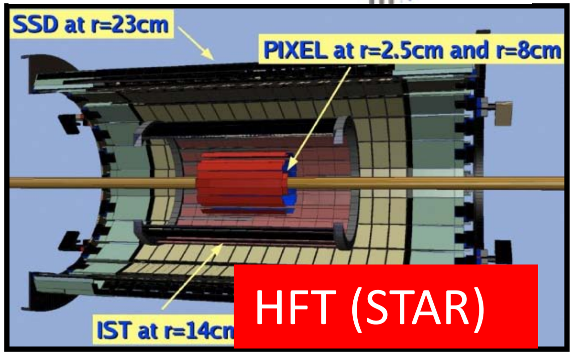


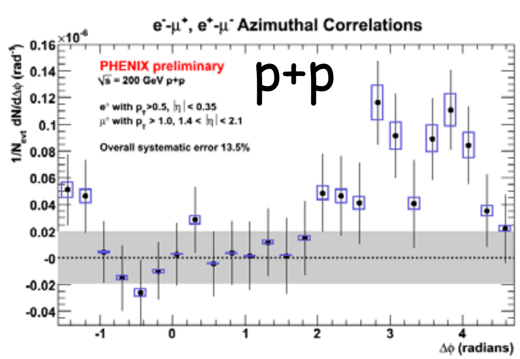


Outlook - Forward Heavy Quarks in d+Au

- Robust measurement of open-heavy at forward rapidity contrasted with complementary measurements at mid-rapidity using vertex detector upgrades - VTX/FVTX (PHENIX), HFT (STAR)
    - Charm & beauty via semi-leptonic decays, with separation via detached vertices
    - Exclusive measurements of beauty with $B \to J/\Psi$
    - $D^0 \to K\,\pi$ (HFT)
- Access to modified gluon structure functions in nuclei
- Separation of initial-state gluon energy loss using measurements at multiple energies (like E906)
- c-cbar correlations via e-μ measurements





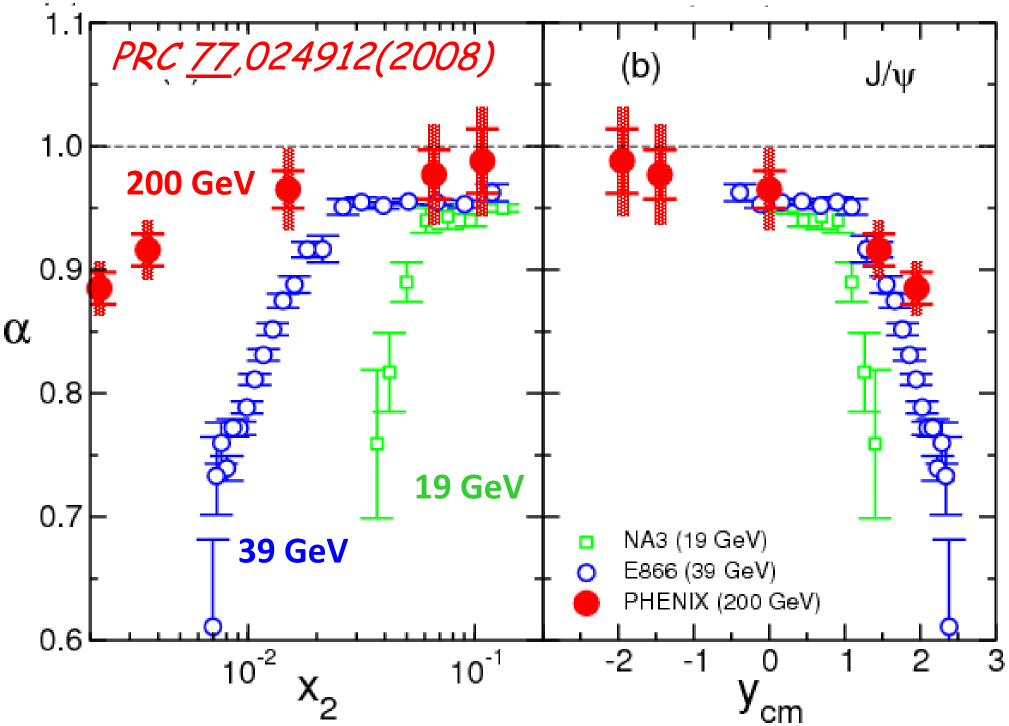


Quarkonia – J/Ψ, Ψ', χ_C, Υ's

J/ψ CNM Physics – PHENIX, E866, NA3 Comparison

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

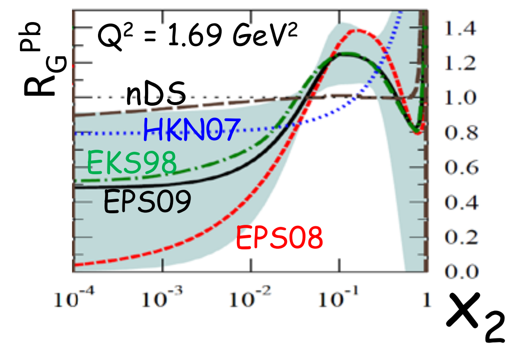
J/ψ α for different √s collisions
E866 p+A & lower-energy NA3 at CERN



(x_2 is x in the nucleus)

Scaling of E886 vs PHENIX better vs y_{cm}

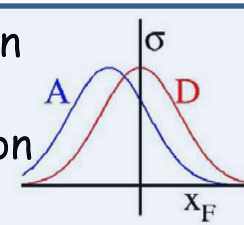
Suppression not universal vs x_2 as expected for shadowing



Closer to scaling with x_F or rapidity

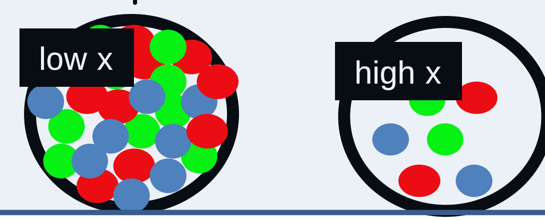
- initial-state gluon energy loss?

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



- or gluon saturation?

Gluon saturation from non-linear gluon interactions for the high density at small x; amplified in a nucleus.

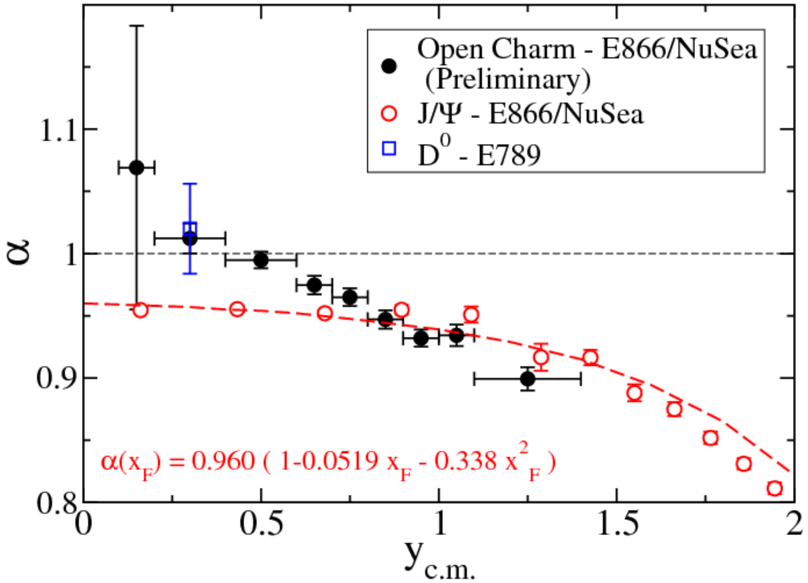


Comparing Open & Closed Charm
Isolating Initial-state Effects

E866/NuSea 800 GeV p+A

Open-charm p+A nuclear dependence (single-μ $p_T > 1$ GeV/c) – very similar to that of J/Ψ (Klinksiek, Peng, Reimer):

- implies that dominant effects are in the initial state
    - e.g. dE/dx, Cronin (since shadowing disfavored by lack of x_2 scaling)
- weaker open-charm suppression at y=0 attributed to lack of absorption for open charm



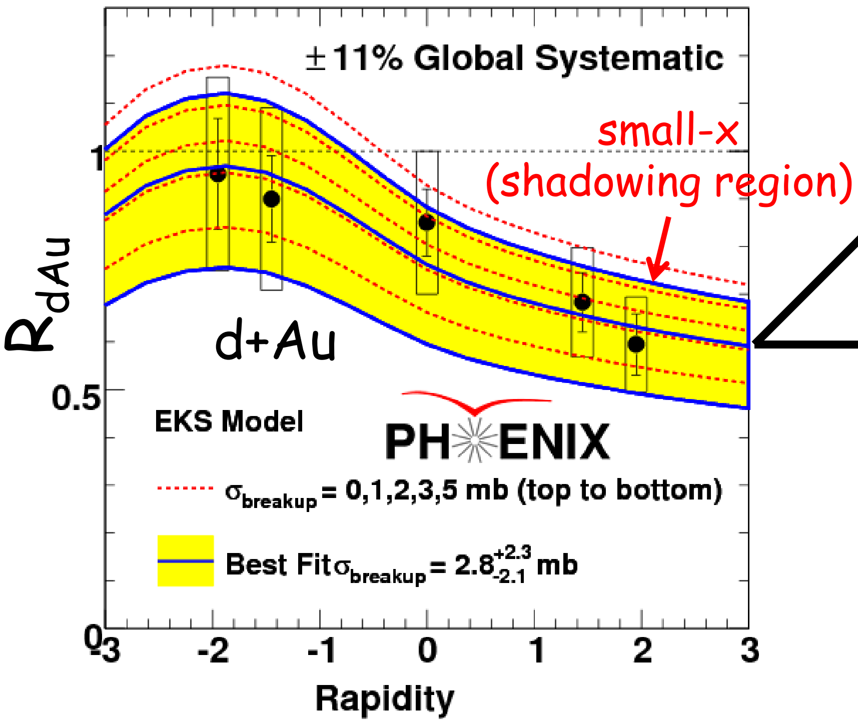
Need to follow this example at RHIC in d+Au collisions

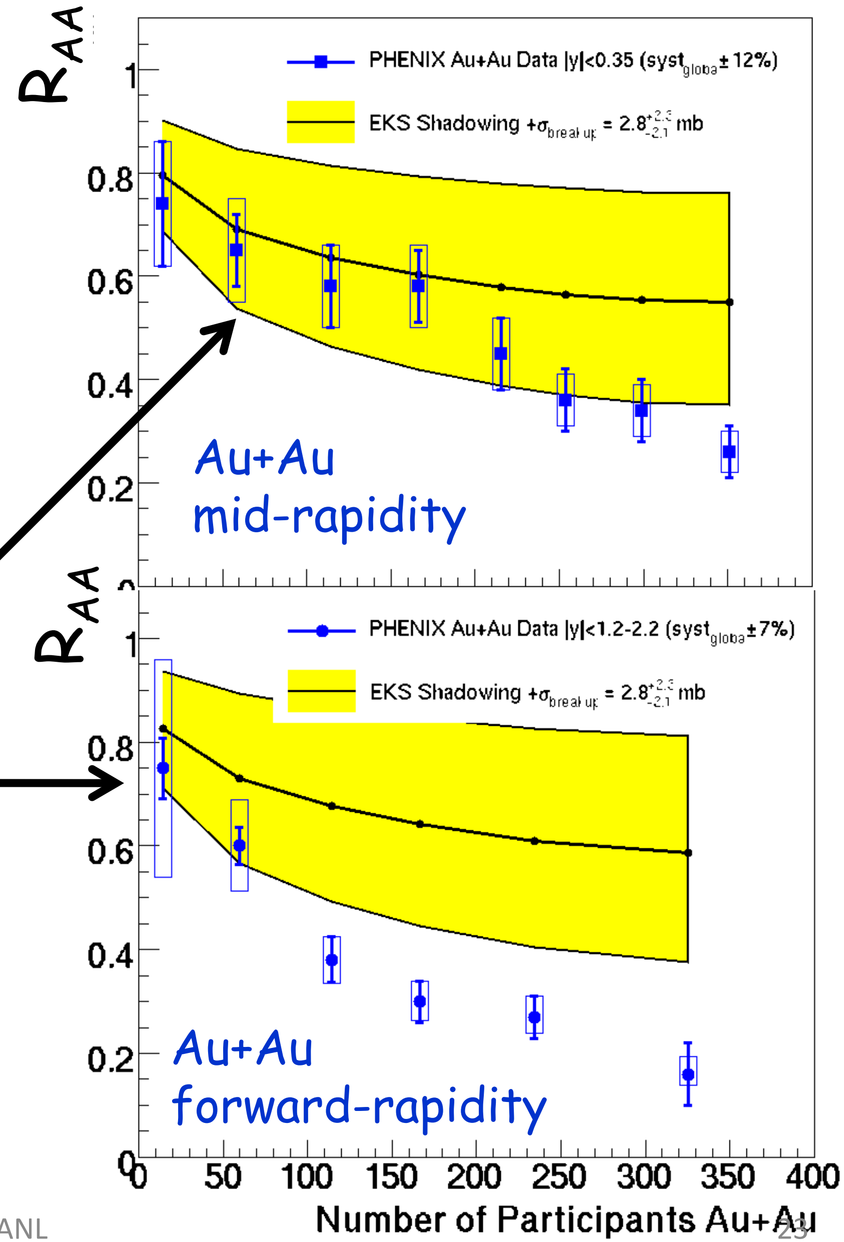
Will be enabled by Vertex detector upgrades

CNM Constraints from d+Au on A+A data

EKS shadowing + dissociation from fits to d+Au data (using R. Vogt theoretical calcs.)

PRC <u>77</u>, 024912(2008)
& Erratum: arXiv:0903.4845

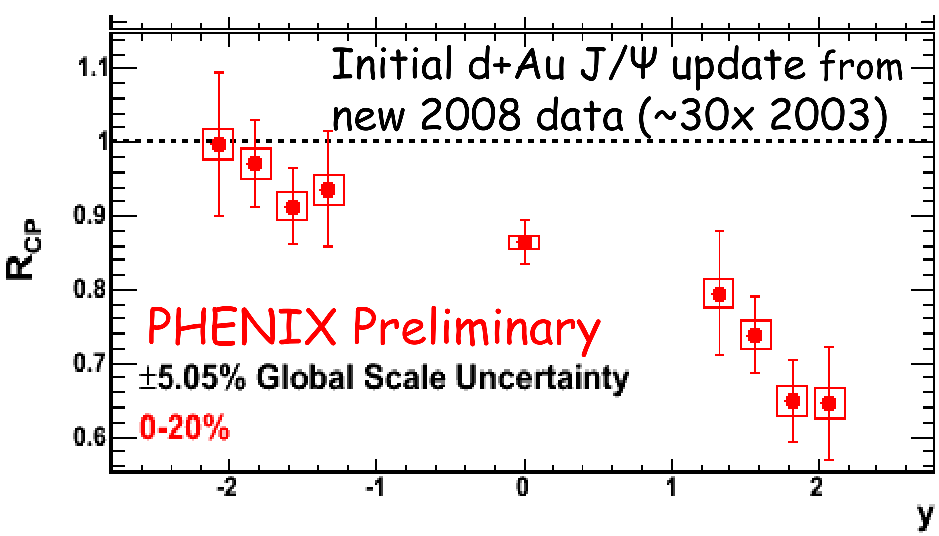


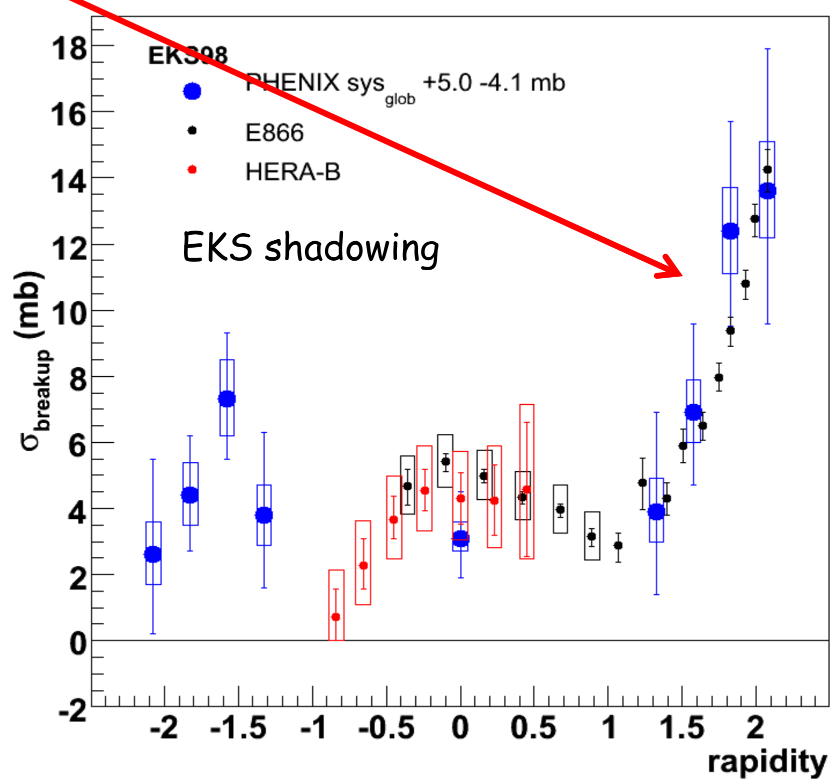


New CNM Constraints from d+Au on A+A data

New CNM fits using 2008 PHENIX d+Au Rcp - (Frawley, Vogt, MJL, others…)
- similar to before, use models with shadowing & absorption/breakup
- but allow effective breakup cross section to vary with rapidity to obtain good description of data
- large effective breakup cross section at large positive rapidity – probably indication of need to add initial-state dE/dx?

$$R_{CP}^{0-20\%} = \frac{N_{inv}^{0-20\%} / \langle N_{coll}^{0-20\%} \rangle}{N_{inv}^{60-88\%} / \langle N_{coll}^{60-88\%} \rangle}$$

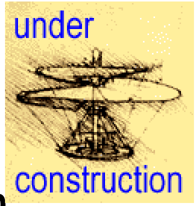




New J/Ψ CNM Constraints from d+Au on A+A data

Example of Comparison of Anomalous Suppression of RHIC & SPS in A+A Collisions (QGP) after dividing out d(p)+A baselines

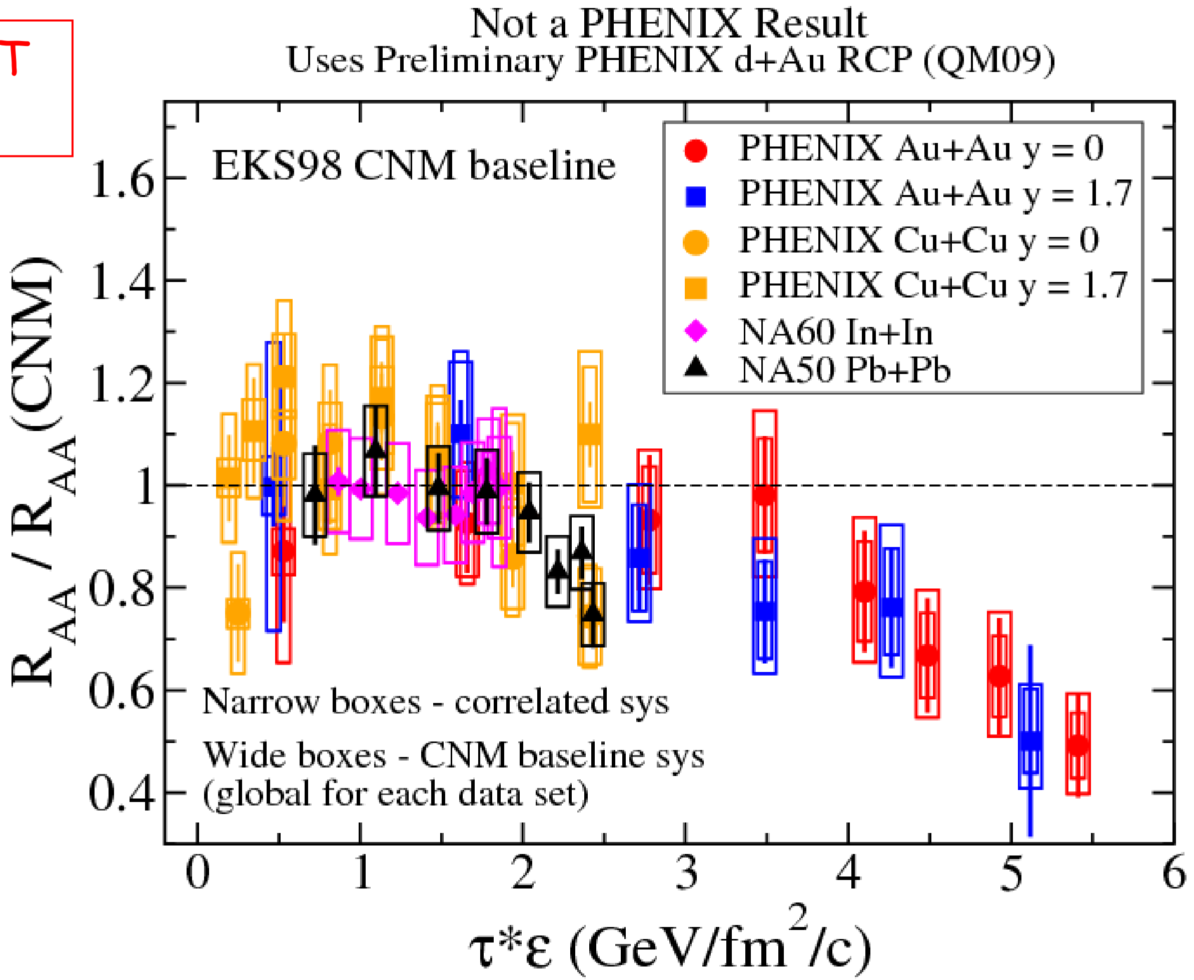
Plot by Leitch @ Seattle/INT Workshop – June 09



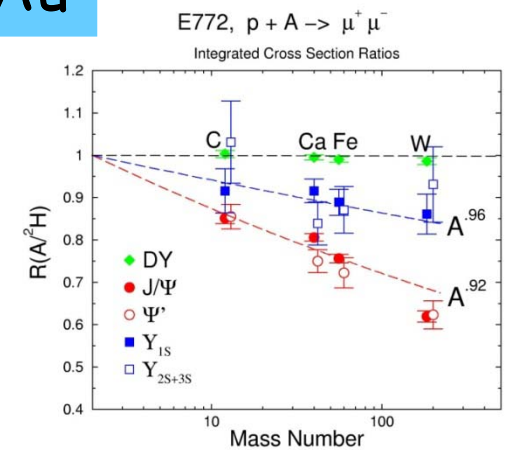
<u>Caution</u> - Many systematic uncertainties on relative (SPS vs RHIC) energy density scales:

Use tau*energy density scale

- but is τ same or different between SPS & RHIC energy??

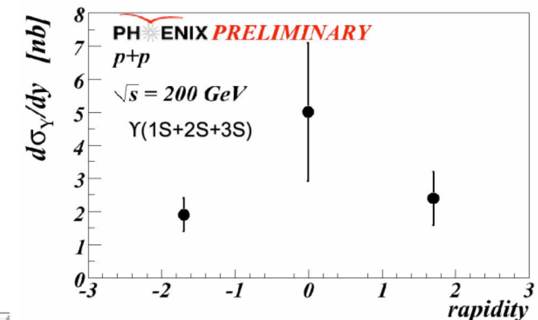


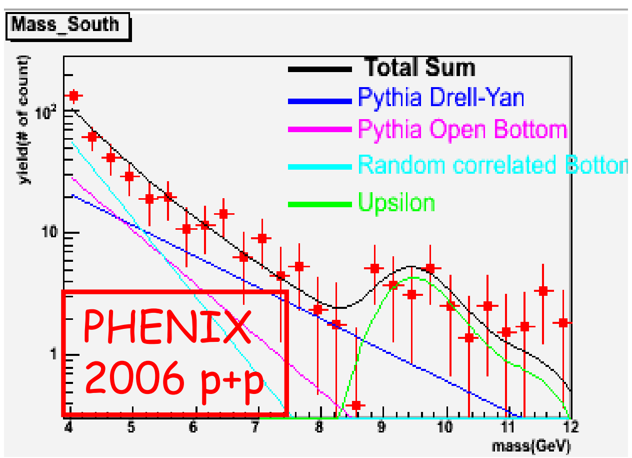
Upsilons (1S+2S+3S) in d+Au

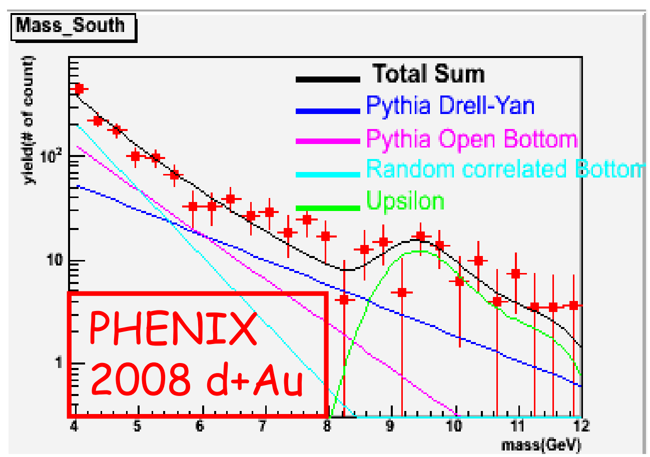


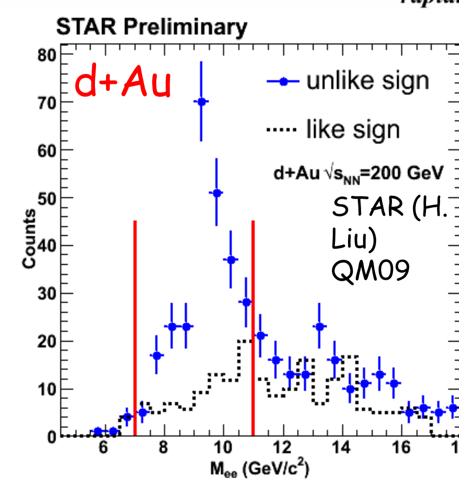
Just beginning to explore Upsilons at RHIC

- Enabled by increasing luminosities
- Known to have strong CNM effects from FNAL measurements
- PHENIX p+p Υ prelim. 2005
- PHENIX - Kwangbok Lee (Korea U.), working on 2008 d+Au & 2006 p+p Υ data (also working on χ_c using MPC)
- STAR – R_{dAu} = 0.98 ± 0.32 ± 0.28 (QM09)



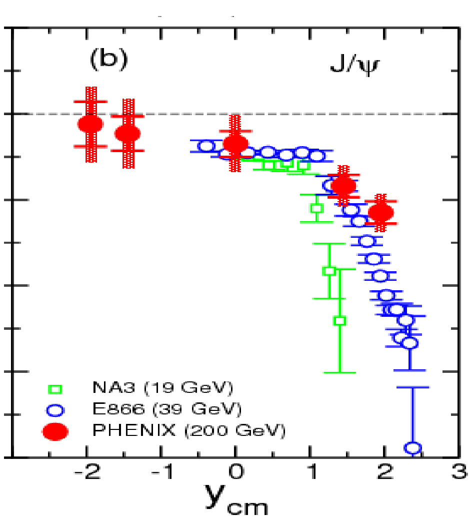


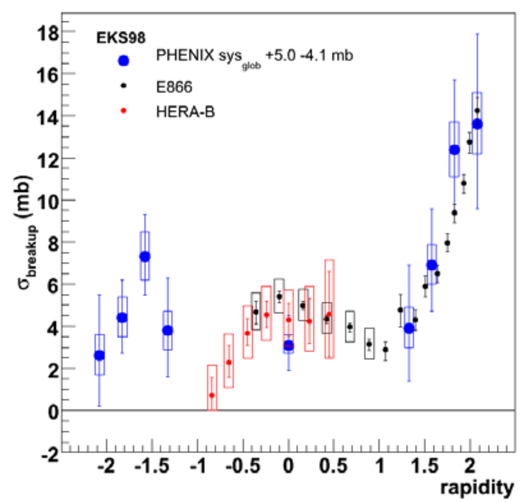


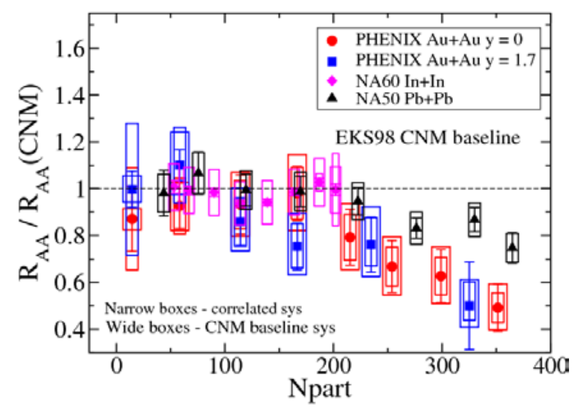


Outlook – Quarkonia in d+Au

- Increased accuracy of J/Ψ measurements via higher statistics and continuing efforts to beat down systematics
- Adding other pieces of the J/Ψ puzzle
  - Ψ' at forward rapidity separated via FVTX
  - χ_C with calorimeters + dileptons
  - Complementary open-charm measurements to separate initial-state and final-state effects
  - Better p+p measurements to clarify configuration of the c-cbar or b-bbar states that travel through CNM
- Increased luminosity for more useful yields of rarest states, e.g. the Upsilon

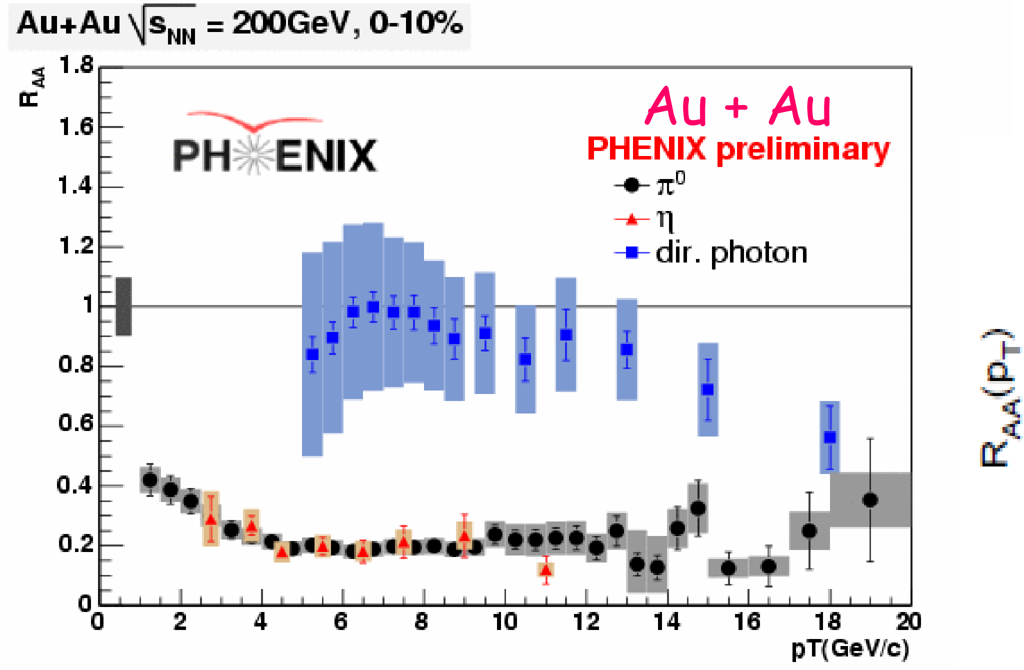




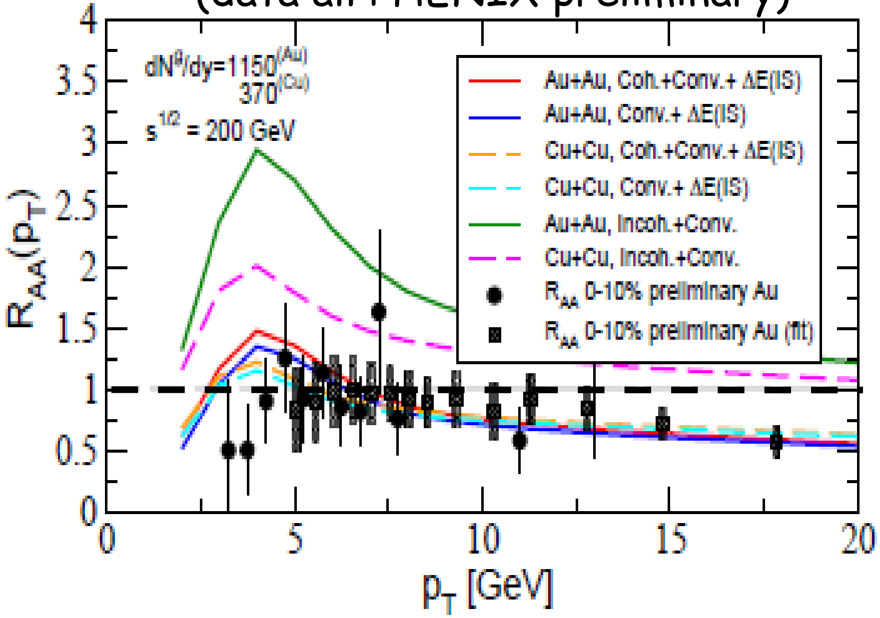


Photons & Gamma-jet – Probing the Gluon Structure Function at Small-x

Initial State with Direct Photons



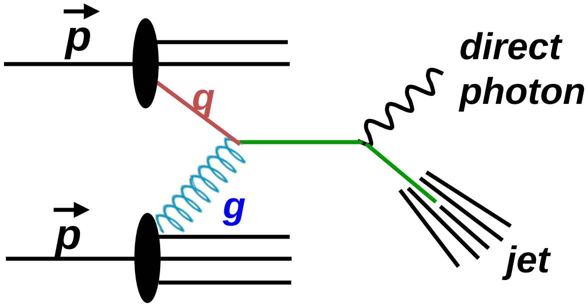
Isospin, Cronin, shadowing, dE/dx
Vitev, nucl-th/0810.3194v1
(data all PHENIX preliminary)

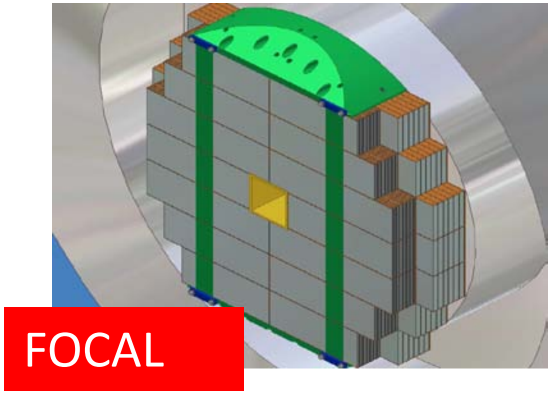


Au+Au photons have some modification at higher p_T, but may be just CNM effects – i.e. Cronin & neutron vs proton (isospin/charge) effects – need d+Au direct photon measurement!

Outlook – Direct Photons in d+Au

- Direct photon measurements at forward rapidity with forward calorimeters contrasted with same at mid-rapidity
- Gamma-jet measurements to access nuclear modifications of the gluon structure functions

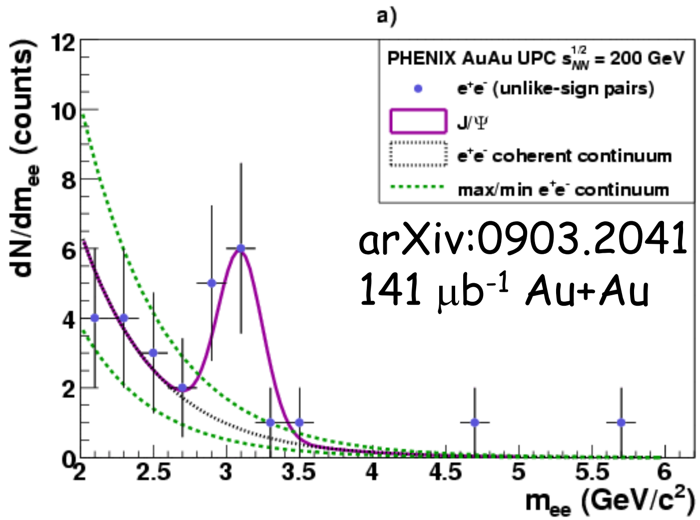




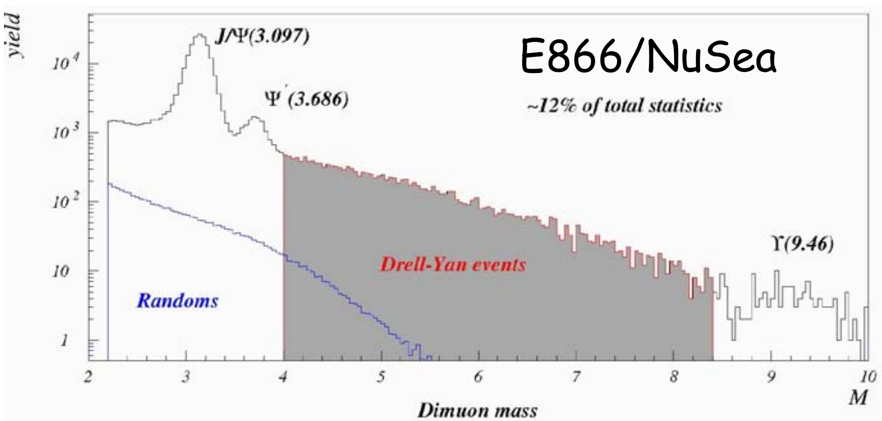
Other Physics at Forward Rapidity

(not covered here)

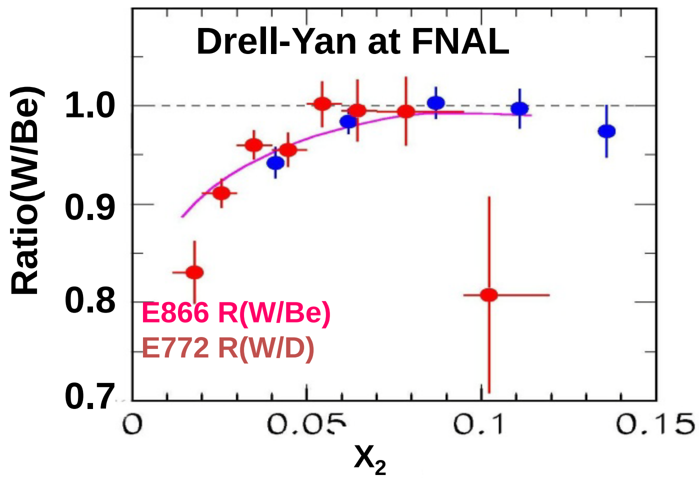
Ultra-peripheral A+A collisions
• quarkonia – nuclear gluons at small-x via electromagnetic probe



Drell-Yan probe of anti-quark sea distributions at small-x
• need vertex detectors to suppress backgrounds

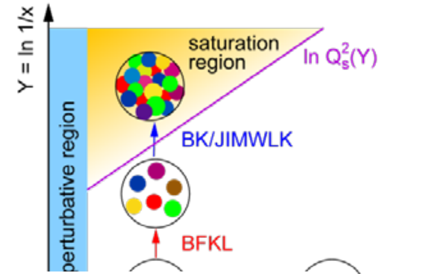


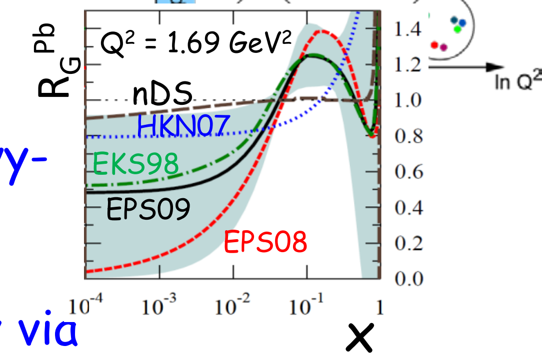
PRL 83, 2304 (1999) (hep-ex/9906010)

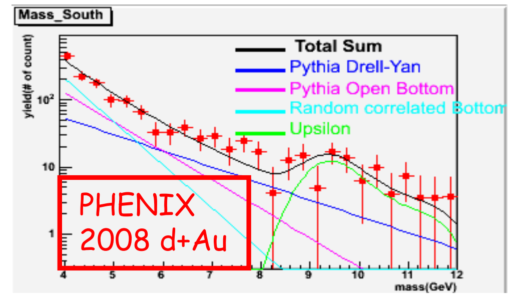


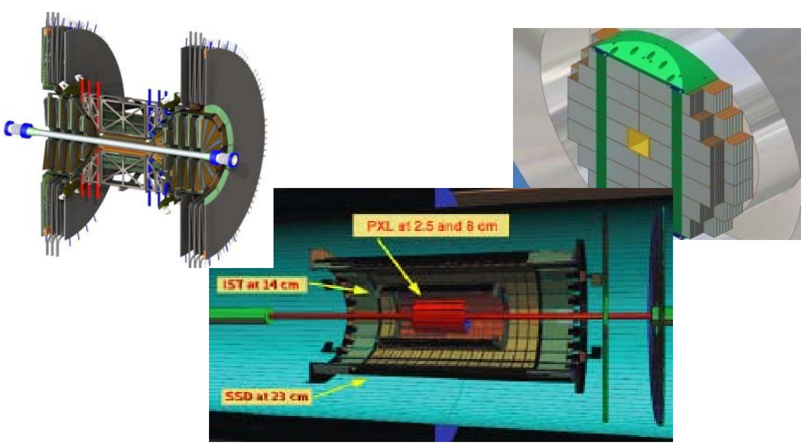
Summary/Outlook

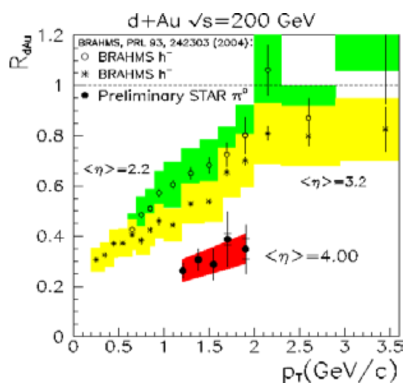
- How are gluons modified (saturated) at small-x in a nucleus?
  - what picture do we work with – pQCD or CGC?
- How do gluons and quarks lose energy in nuclear matter?
- Use forward calorimeter to look for mono-jets
- Robust measurements of charm & beauty to pin down heavy-quark energy loss and shadowing
  - lower energy runs to help separate these?
- Measure all the quarkonia with complementary open-heavy via increased luminosity & upgrade detectors
- Access gluon structure function modification at small-x via gamma-jet using forward calorimeters

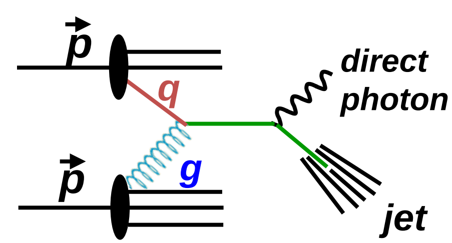






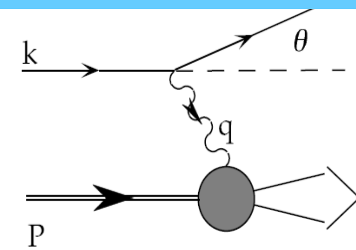


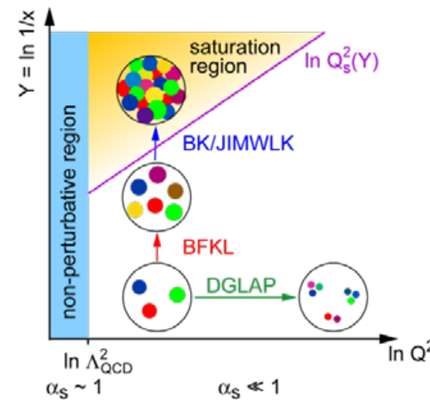


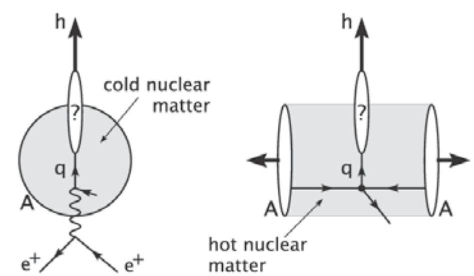


Backup Slides

Extending Gluon Saturation & Energy Loss Studies to EIC
(a few comments)







Gluon distributions in Nuclei

- DIS with wide x coverage & large luminosity
- ρ, ϕ, J/Ψ production on nuclei
- spatial dependence of distributions
- Forward γ production (DVCS)
- Diffractive interactions with (colorless) multi-gluon virtual excitations (Pomerons)

Energy loss & hadronization in CNM

- DIS hadron & heavy-quark production

Electron in e+A is clean well understood probe

- But d+Au is direct gluon probe, e+A is not

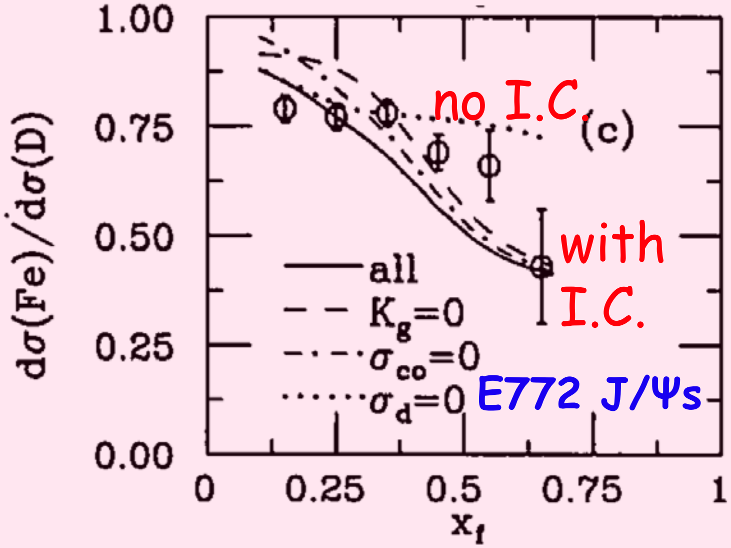
Synergism between e+A and RHIC/LHC

- Initial conditions for QGP - Small-x gluons? Glasma?
- Energy loss & hadronization – CNM vs hot-dense matter - consistent theoretical picture?

Other Physics that may Play a Role

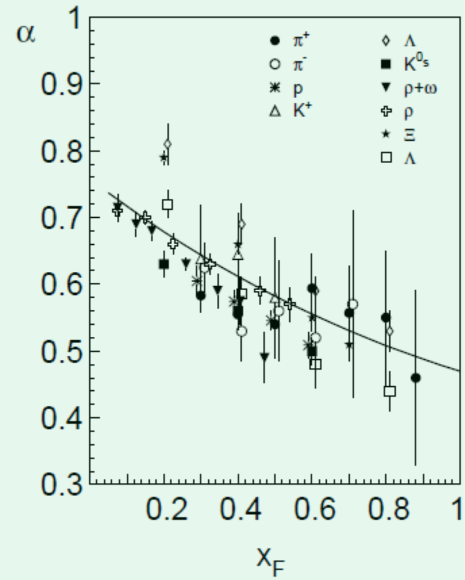
Intrinsic charm

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



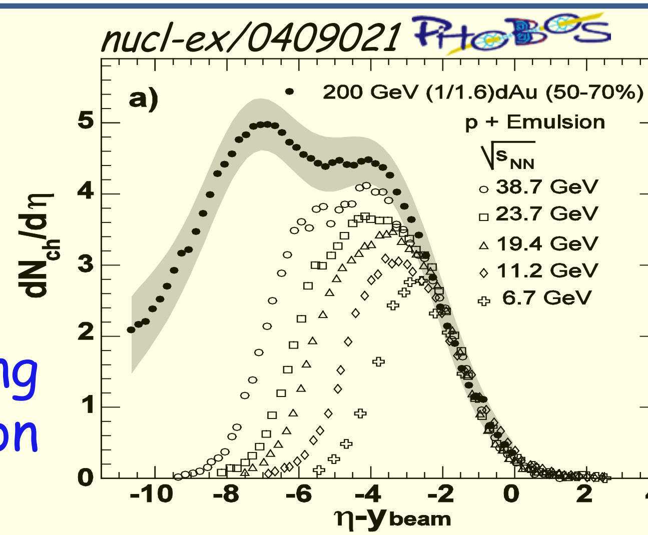
Sudakov suppression (energy conservation)

Kopeliovich et al, PRC 72, 054606 (2005)

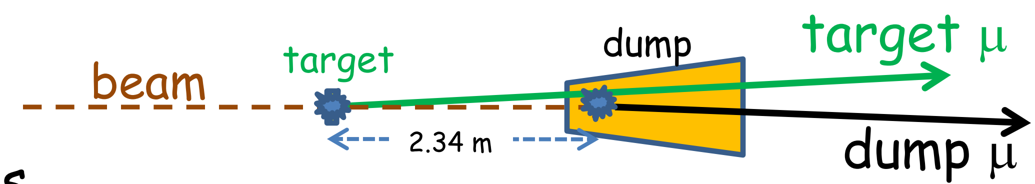


Limiting fragmentation

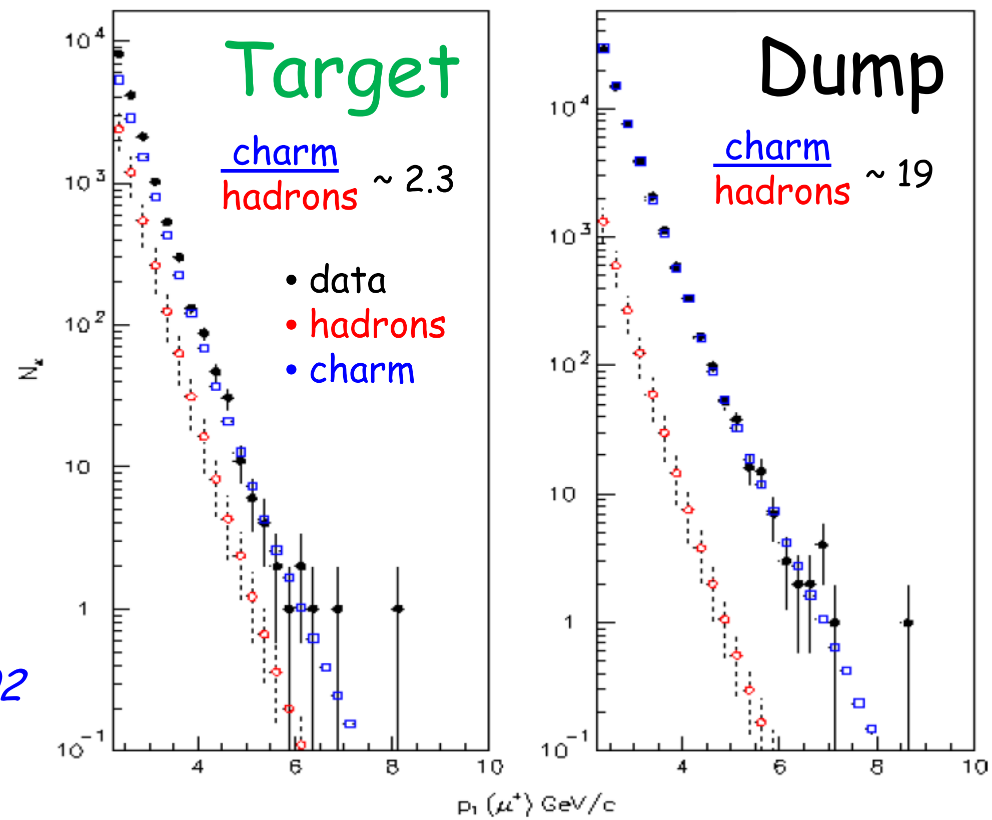
nucl-ex/0409021



E866/NuSea Open Charm Measurement

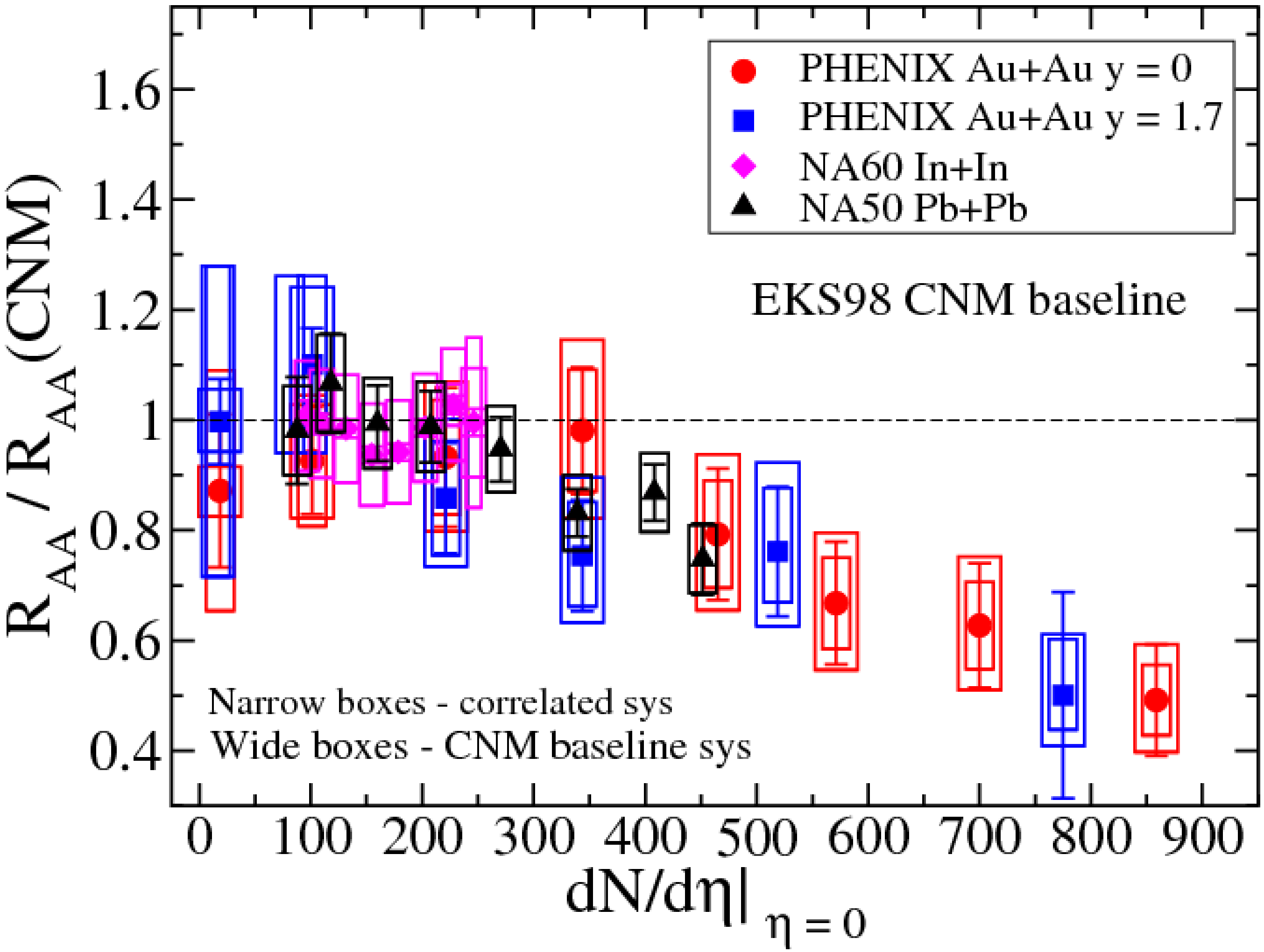


- hadronic cocktail explains ~30% of target & <5% of dump μ's
  - as expected since dump absorbs light hadrons before they can decay
- charm decays consistent between Cu target and Cu dump
- use same method for Be to get nuclear dependence

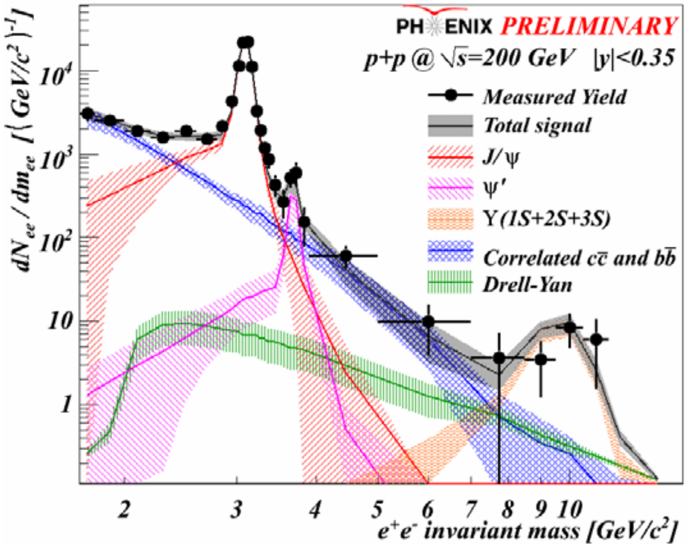


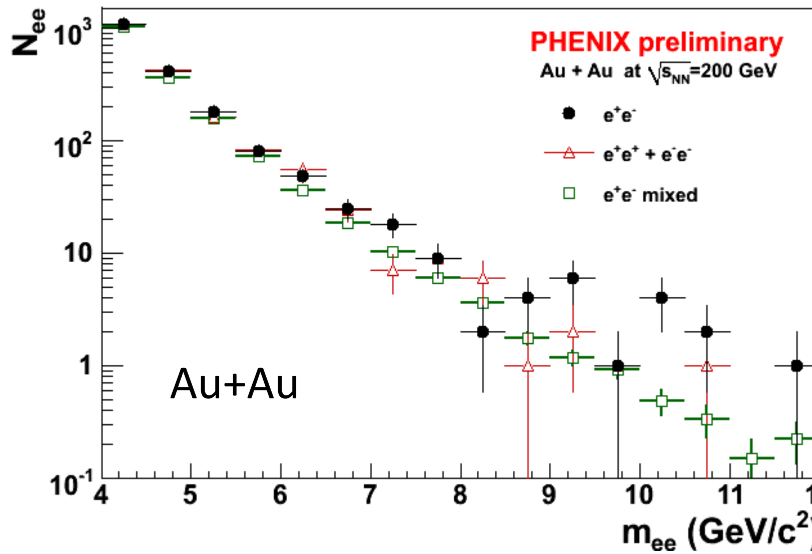
E866/NuSea 800 GeV p+A
- *S. Klinksiek thesis - hep-ex_0609002*
- *paper in preparation*

Anomalous Suppression vs $dN_{ch}/d\eta$

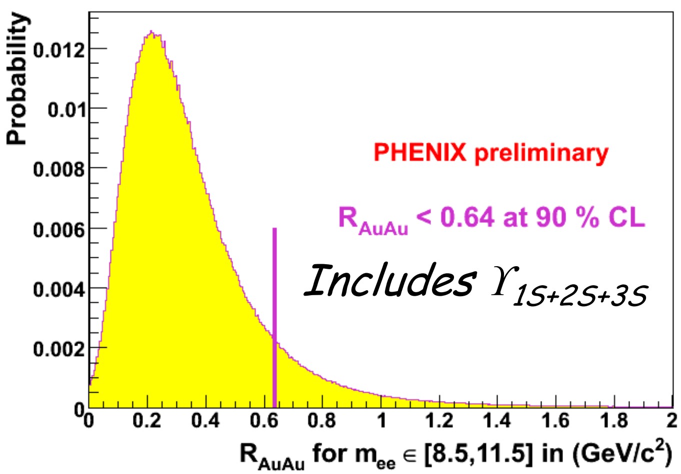


Upsilons Suppressed in Au+Au, what about d+Au

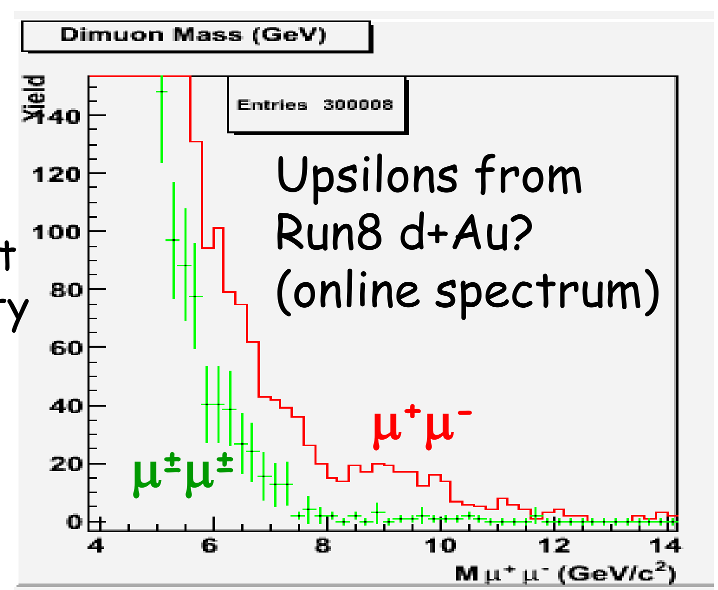




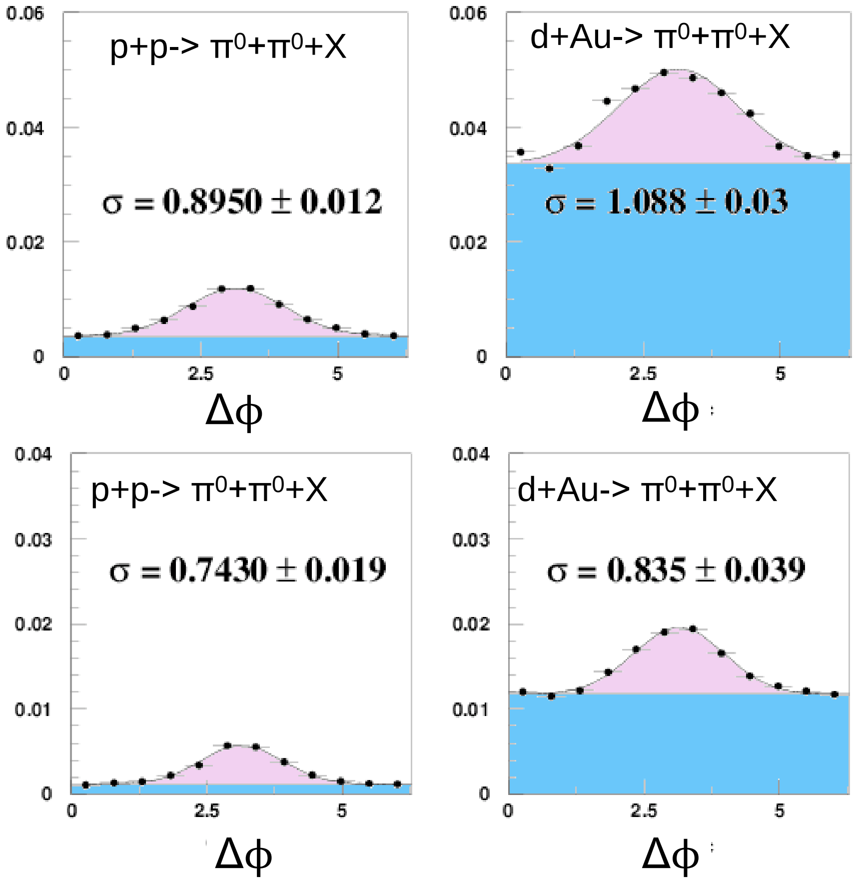
Z. Conesa del Valle, C. Silva,… – QM09



No d+Au measurement at forward rapidity yet, but…



STAR/FMS QM09 Results



lower p_T:

$p_T^{FMS} > 2$ GeV/c

$p_T^{EMS} > 1$ GeV/c

(slightly) higher p_T:

$p_T^{FMS} > 2.5$ GeV/c

$p_T^{EMS} > 1.5$ GeV/c

$$\Delta\phi = \phi_{\pi 0}^{FMS} - \phi_{\pi 0}^{EMC}$$

Broadening smaller for correlations of higher-p_T π^0's

$\Delta\sigma = 0.09 \pm 0.04$ (higher p_T) vs 0.19 ± 0.03 (lower p_T)