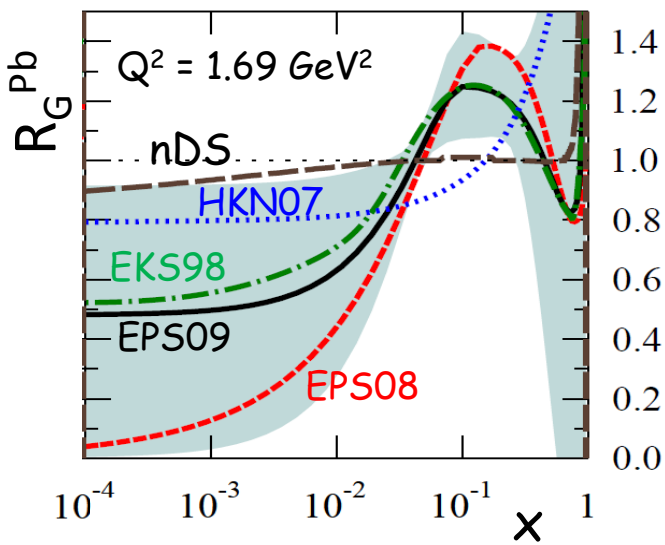
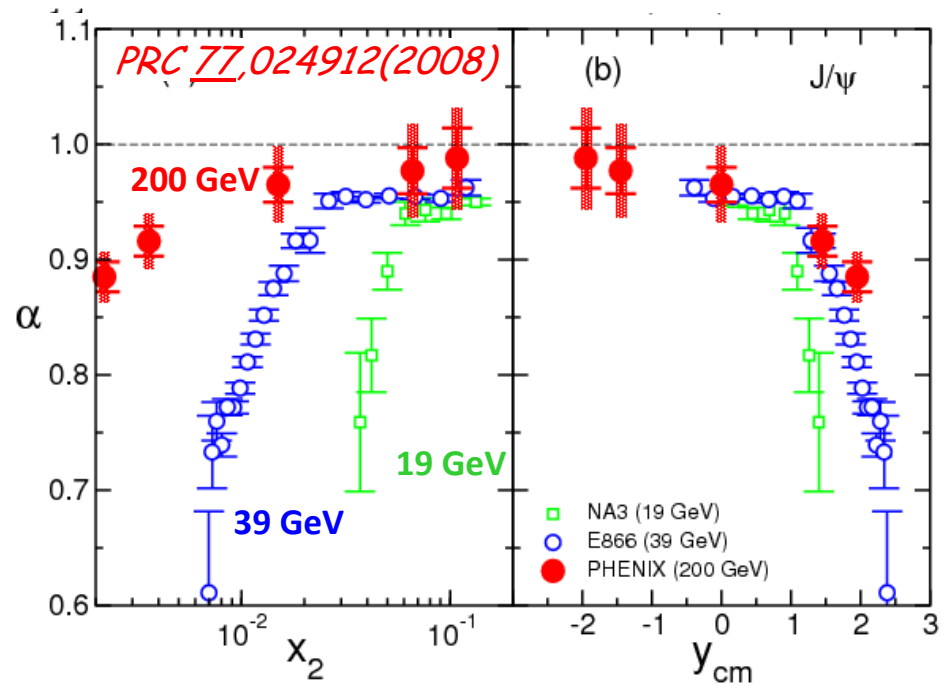
Solving the J/ψ Puzzle

M.J. Leitch, LANL

Seattle, 6-8 July 2010

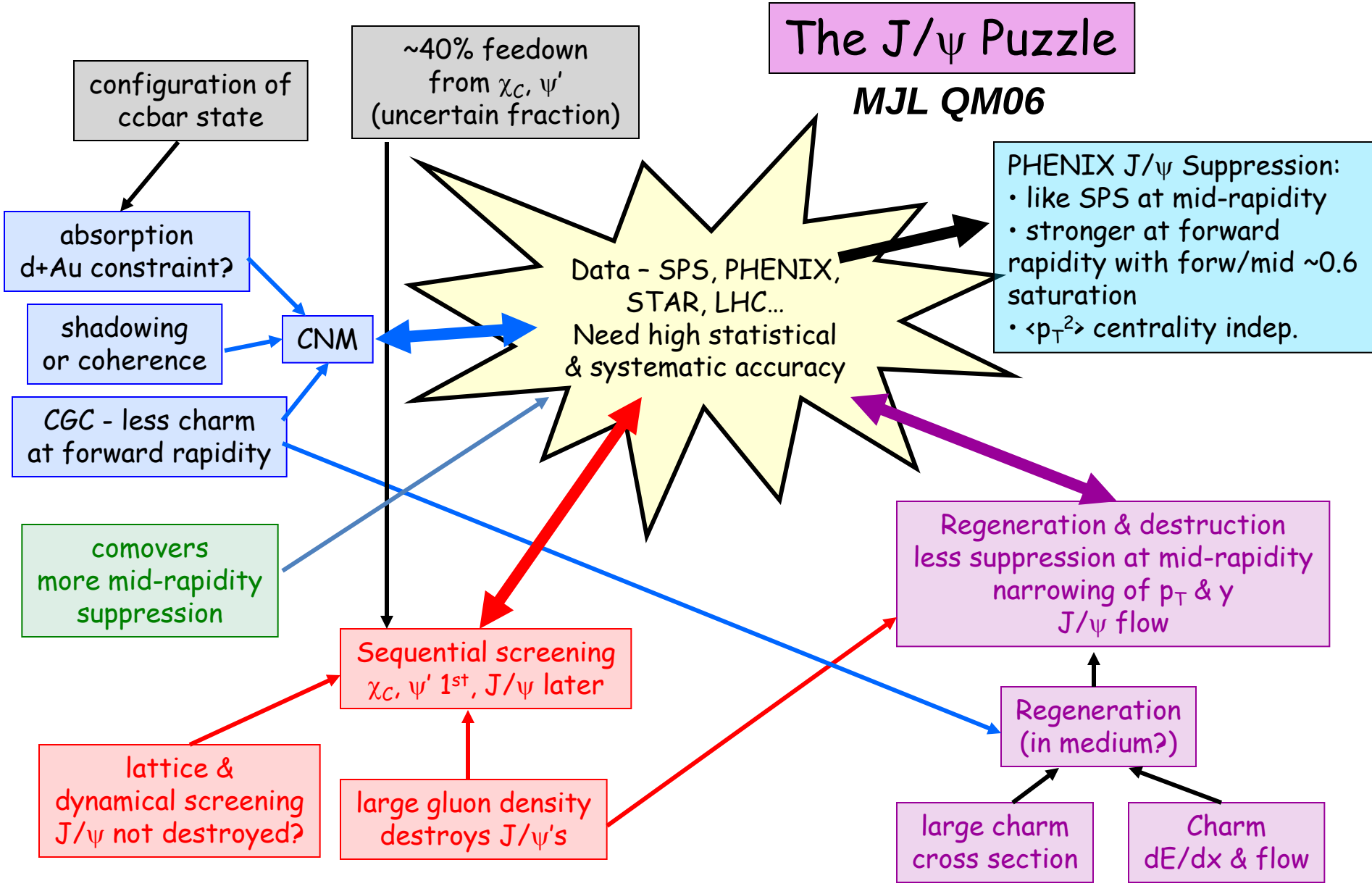
- The J/ψ Puzzle in Cold Nuclear Matter (CNM)
  - gluon saturation/shadowing; energy loss; absorption…
- The (large) CNM baseline in A+A collisions
  - towards an informed extrapolation of CNM to A+A





The J/ψ Puzzle

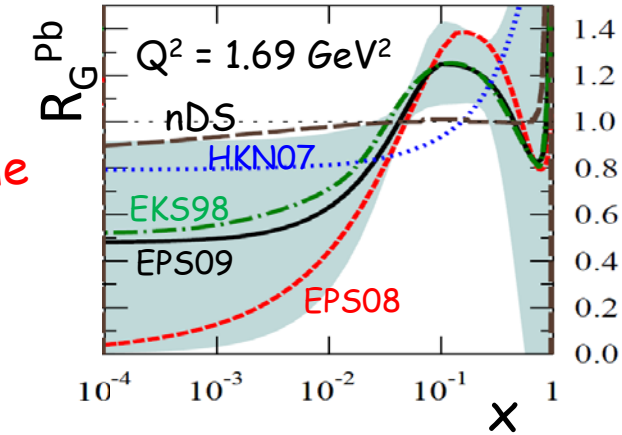
MJL QM06



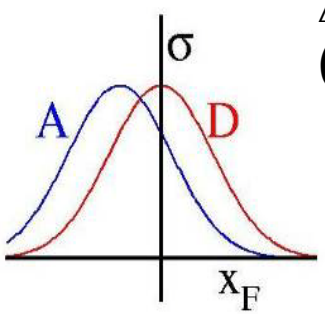
Fundamental Cold Nuclear Matter (CNM) Questions

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

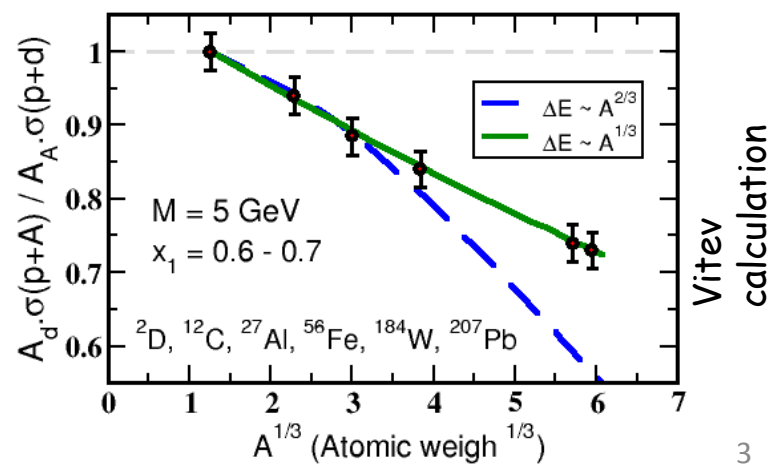
- Leading twist gluon shadowing
- Coherence models & higher-twist (HT) shadowing
- Gluon Saturation: at small-x, 2→ 1 diagrams become important and deplete the low-x region; amplified in a nucleus.



NSAC Milestone: DM12 – "…constrain the mechanism for parton energy loss in the quark-gluon plasma." And what about energy loss in cold nuclear matter?



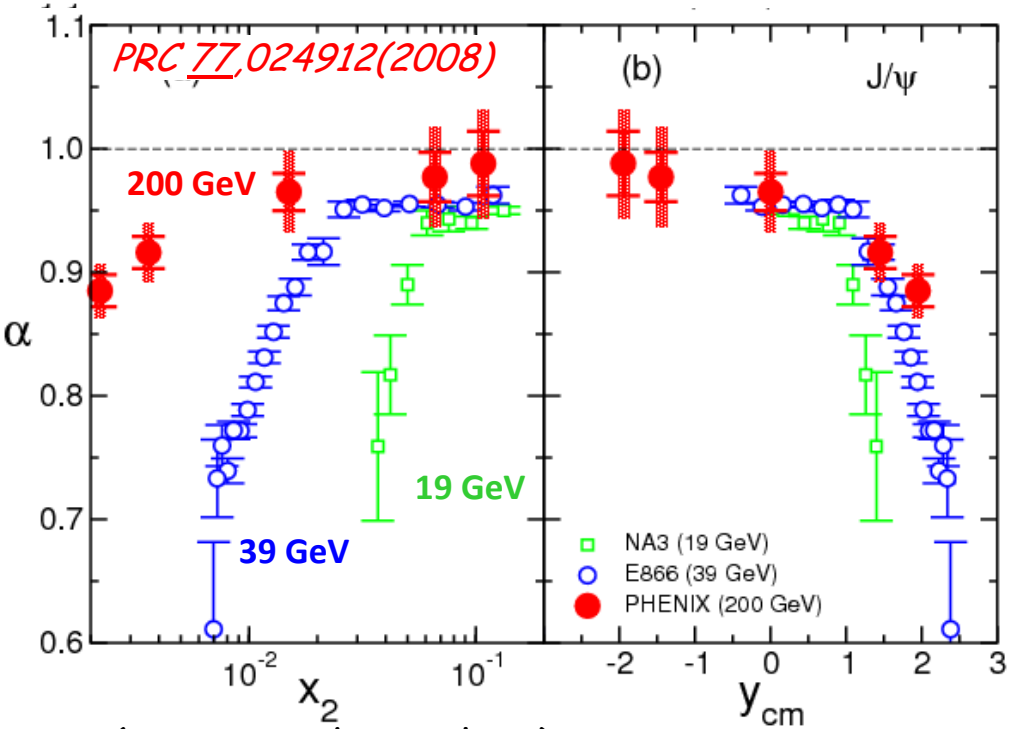
$\Delta E \sim L$ or L^2?
(collisional or radiative?)



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

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

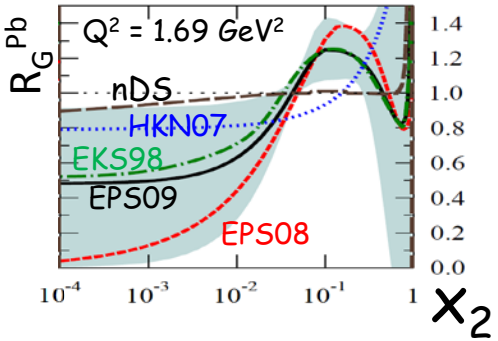
J/ψ α for different √s collisions
E866 p+A & lower-energy NA3 at CERN



(x_2 is x in the nucleus)

Scaling of E886 vs PHENIX better vs y_{cm}

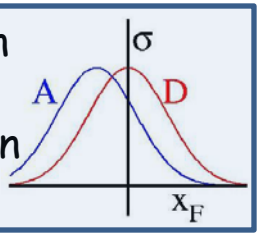
Suppression not universal vs x_2 as expected for shadowing



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



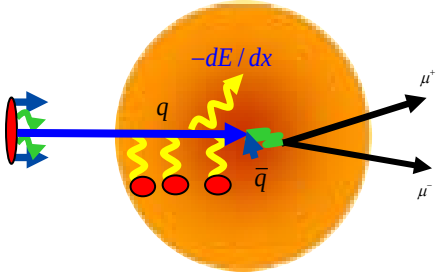
- or gluon saturation?

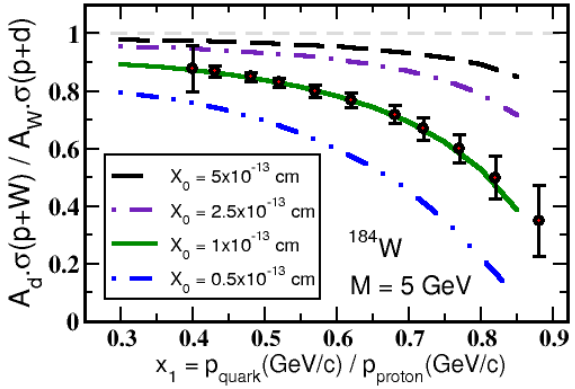
Gluon saturation from non-linear gluon interactions for the high density at small x; amplified in a nucleus.

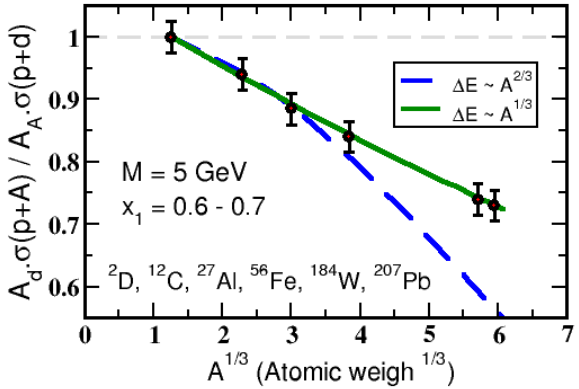
Solving the Puzzle – Constrain the Initial-state dE/dx
FNAL E906 – Drell Yan

In E906 at 120 GeV, nuclear suppression in Drell-Yan should only be from dE/dx (x_2 > 0.1)
(E866 at 800 GeV, could not unambiguously separate shadowing and dE/dx effects at low x)

Drell-Yan



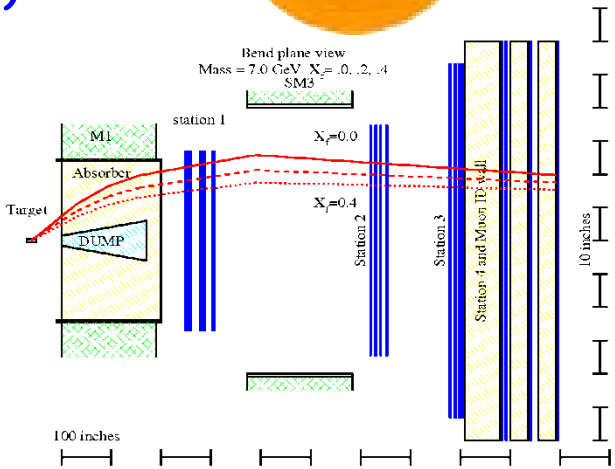




from Vitev

$$\frac{\Delta E}{E} \propto \frac{\mu^2 L^2}{\lambda_g} \frac{\ln E/Q_0}{E}$$

$$\frac{\Delta E}{E} \propto \frac{L}{\lambda_g} \ln \frac{E}{Q_0}$$



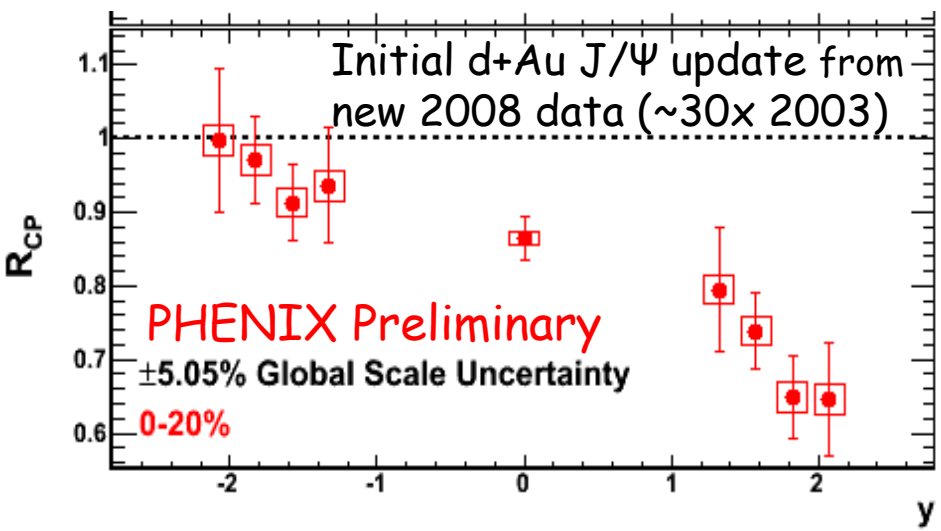
- Sensitivity ~ 20%
- Distinguish radiative from collisional (L^2 vs L)
- then "extrapolate" with theory to energy loss of gluons for quarkonia production

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

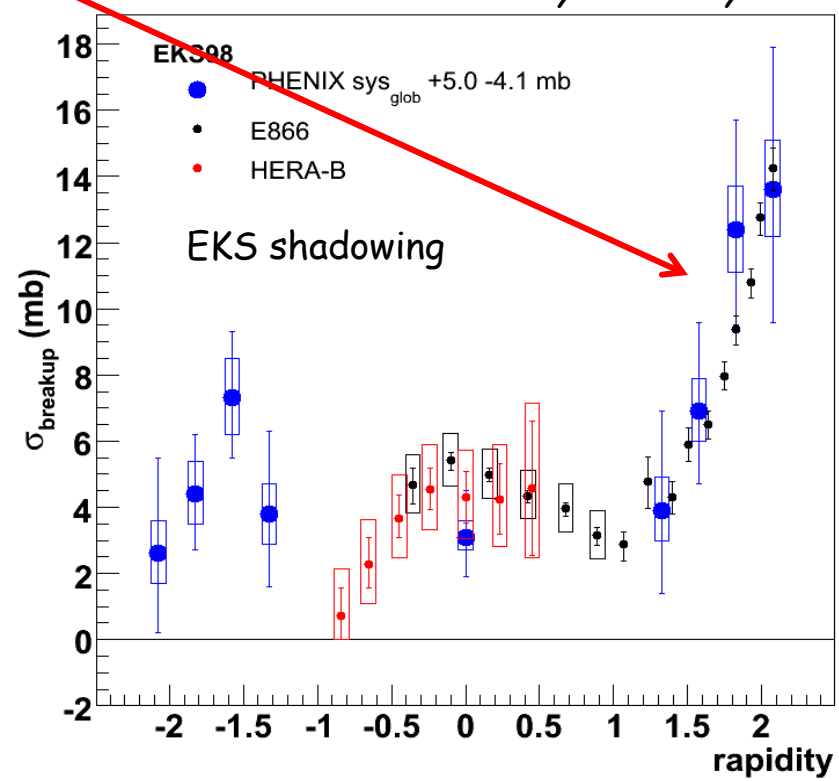
New CNM fits using 2008 PHENIX d+Au Rcp - (Frawley, Vogt, MJL, others…)

- 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?

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

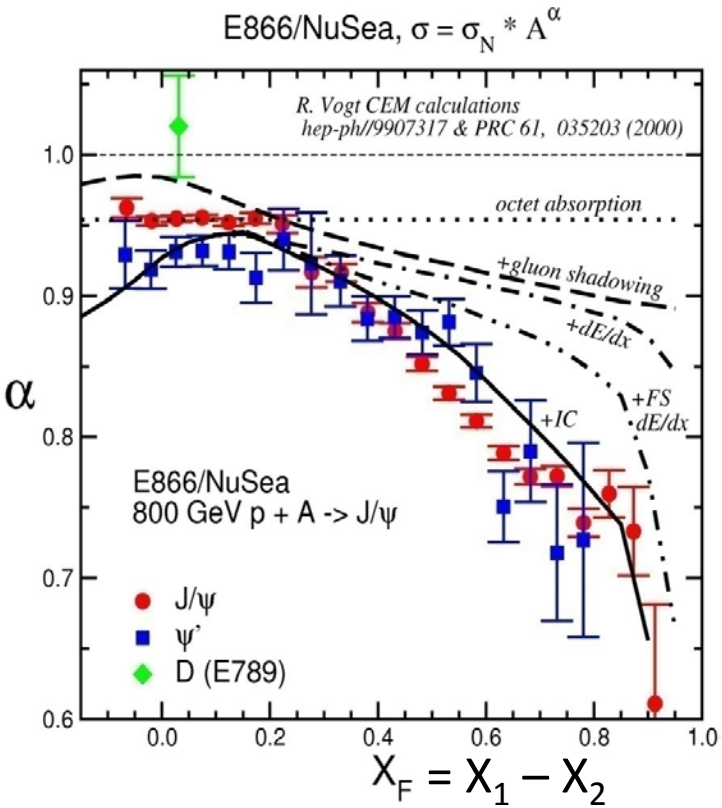


Tony Frawley



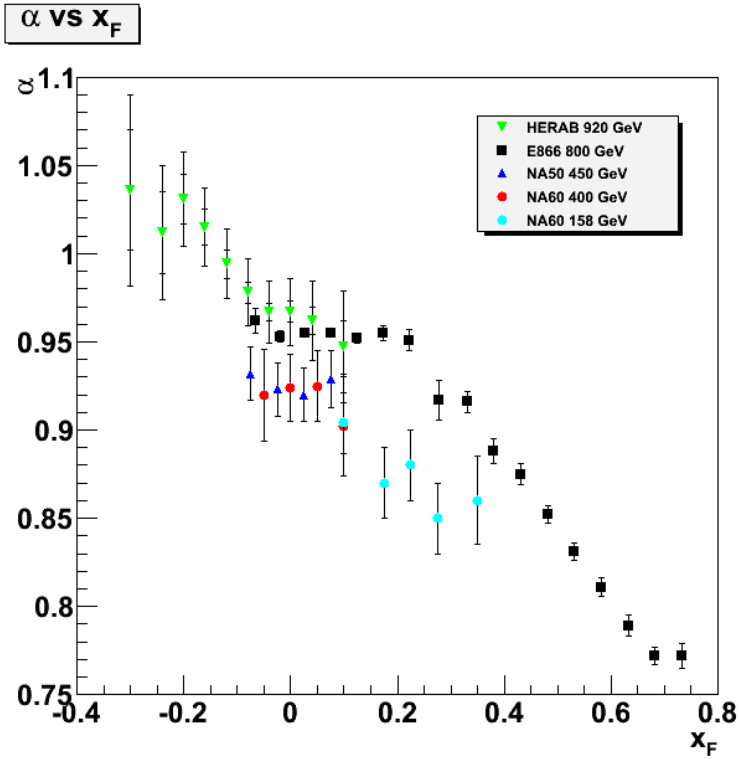
J/ψ suppression in p+A fixed-target

Many ingredients to explain the J/ψ nuclear dependence – R. Vogt (2000)



800 GeV p+A (FNAL)
PRL 84, 3256 (2000); PRL 72, 2542 (1994)

NA60 results at two energies appear to show similar trend with x_F; but systematically more suppression

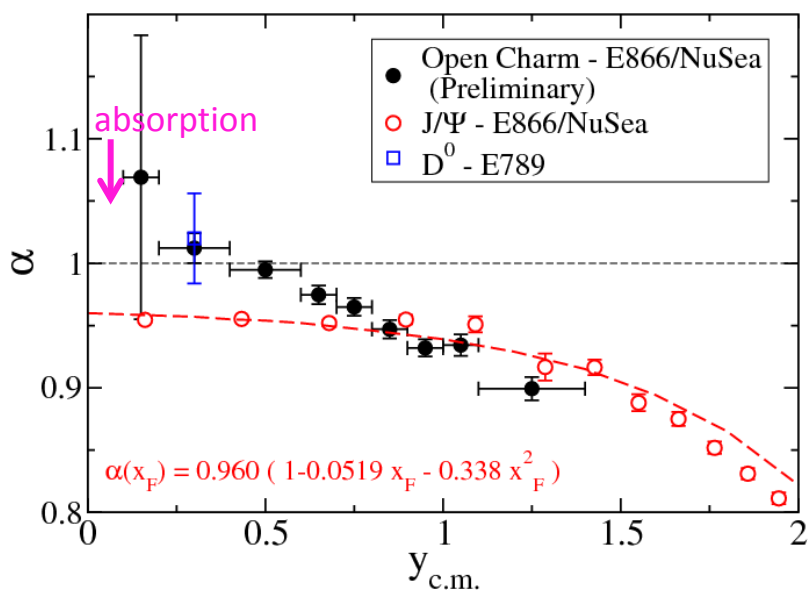


Solving the Puzzle – Isolate initial and final-state effects
Open-heavy with Vertex Detectors

Open-charm p+A nuclear dependence (single-μ $p_T > 1$ GeV/c) – very similar to that of J/Ψ (E866/NuSea):

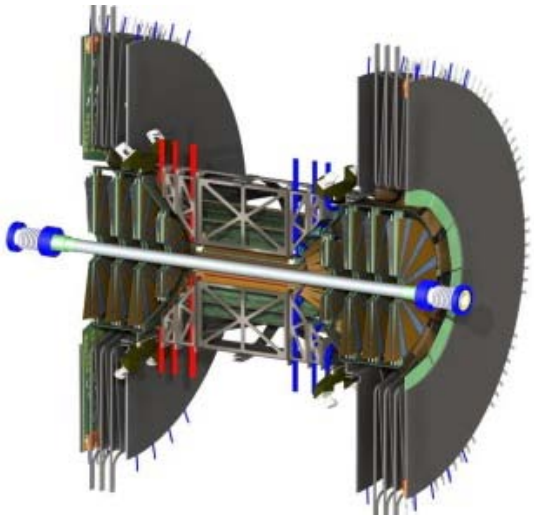
- implies that dominant effects are in the initial state
  - e.g. dE/dx, Cronin (since shadowing disfavored by lack of x_2 scaling)

include new c,b measurements with FVTX to isolate initial & final-state effects via comparisons with quarkonia



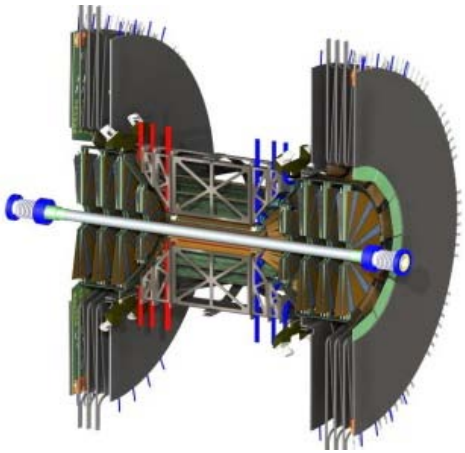
Need to follow this example at RHIC in d+Au collisions

Will be enabled by Vertex detector upgrades

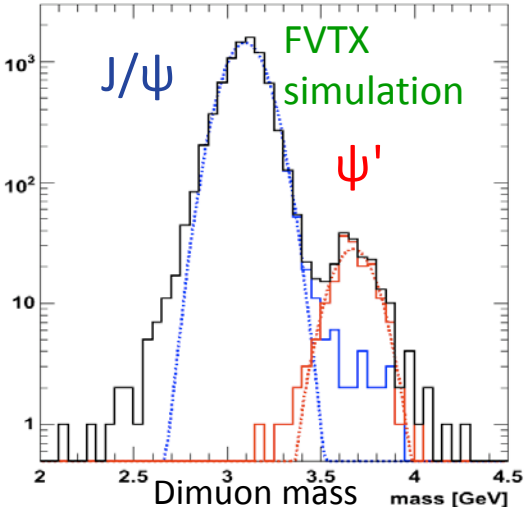


New Physics with FVTX at PHENIX

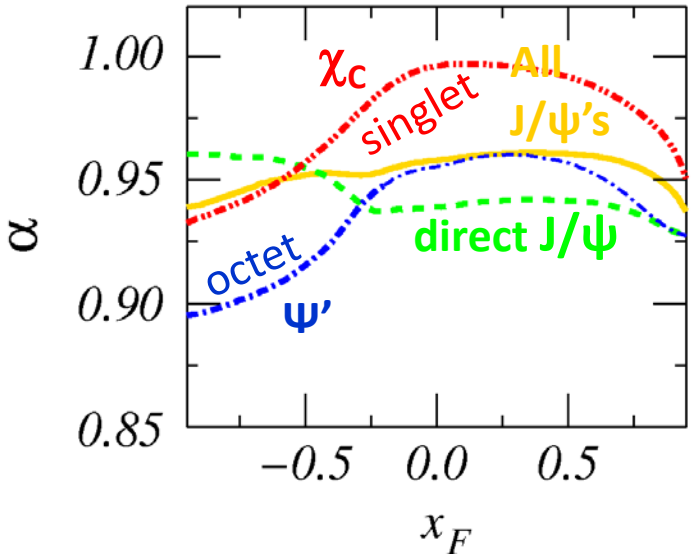
- Direct identification of D, B → μ + X and B → J/Ψ → energy loss and shadowing for D,B mesons; direct access to gluon structure
- Improved J/ψ and ψ′ mass resolution → enable use of ψ′ as a probe
- Reduced backgrounds by rejection of π and K → enable W and Drell-Yan measurements
- Installation in summer of 2011



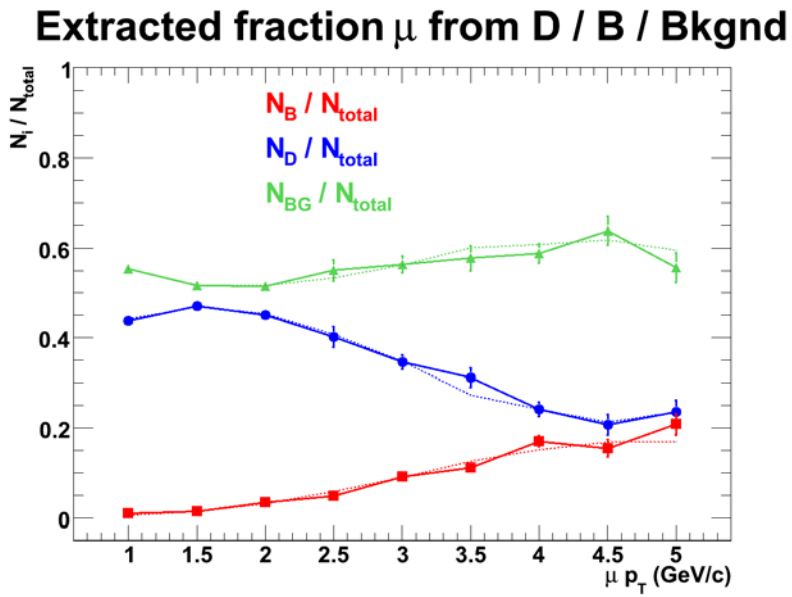
ψ′ separation possible

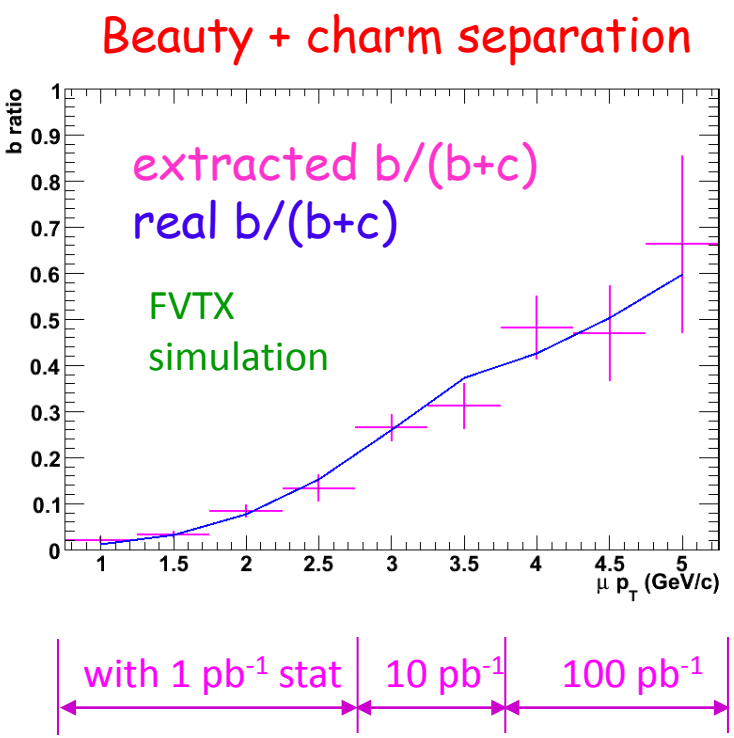


R. Vogt, NRQCD calculations
Nucl. Phys. A700 (2002) 539



Separation of beauty and charm with PHENIX Forward Vertex Detector (FVTX) - (Simulated Performance)

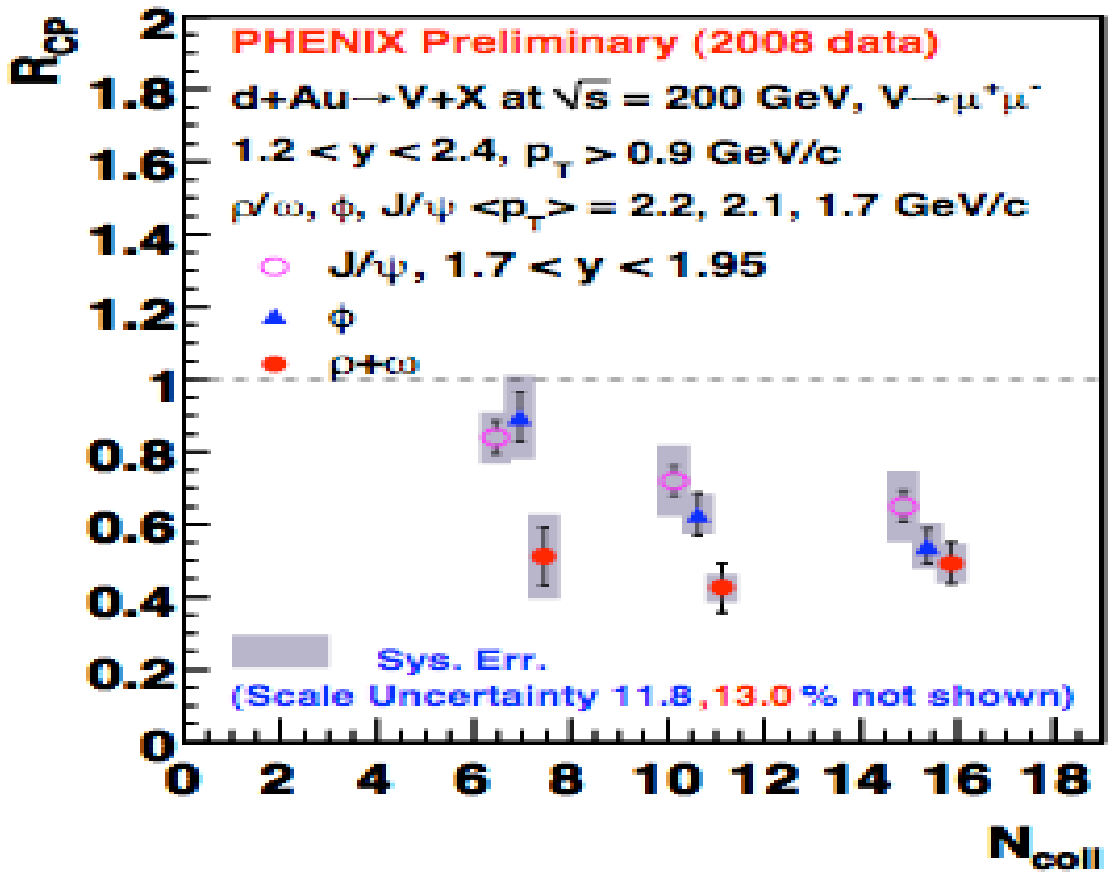




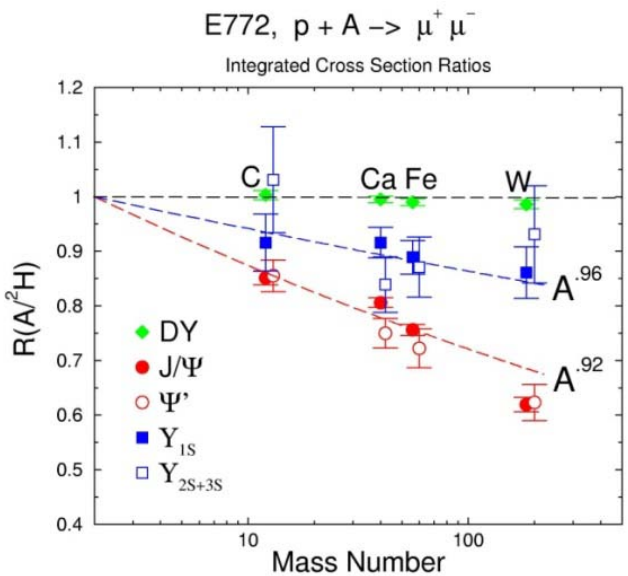
For p+p & available simulation statistics (as indicated)

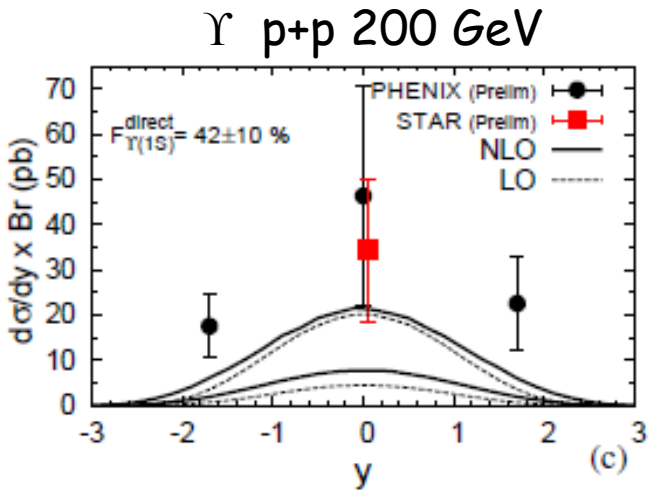
Solving the Puzzle
Adding other Quarkonia/Vector Mesons

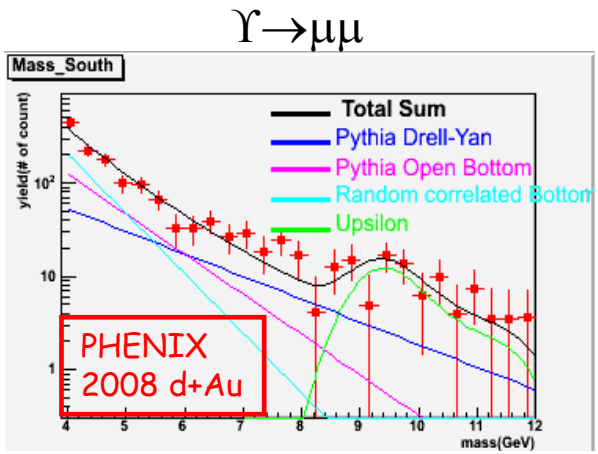
ρ,ω,ϕ

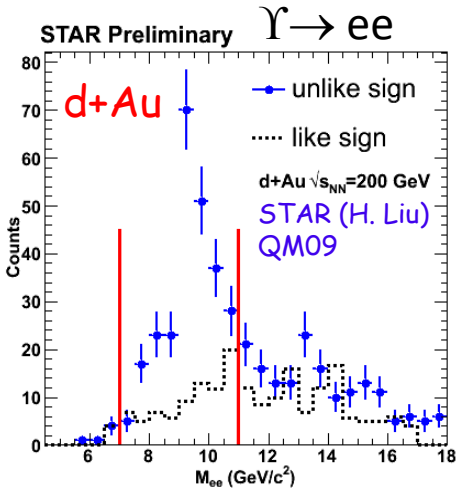


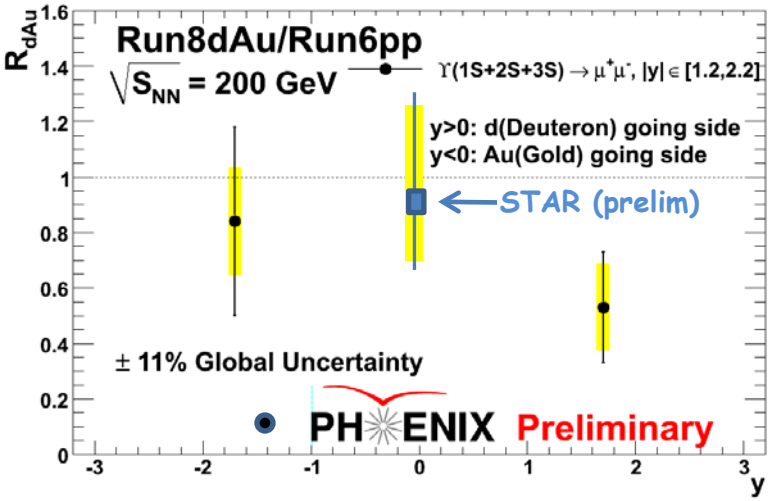
Solving the Puzzle - Adding Upsilons (1S+2S+3S)









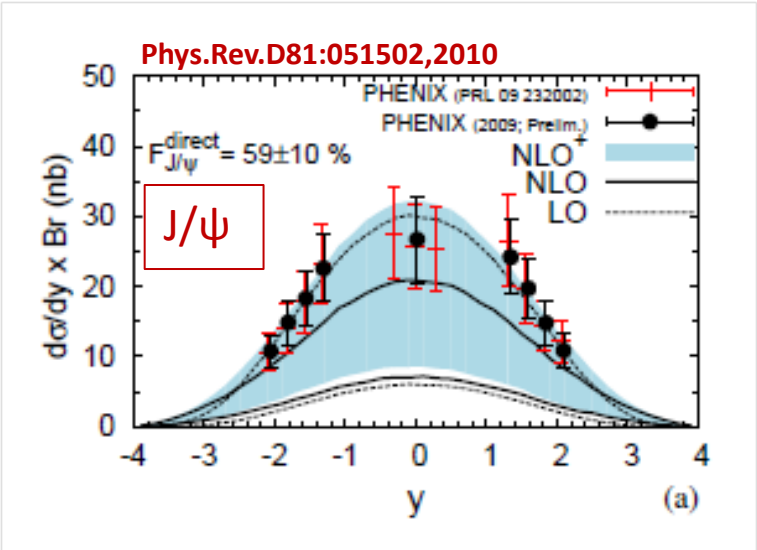


Solving the Puzzle - Production Physics?

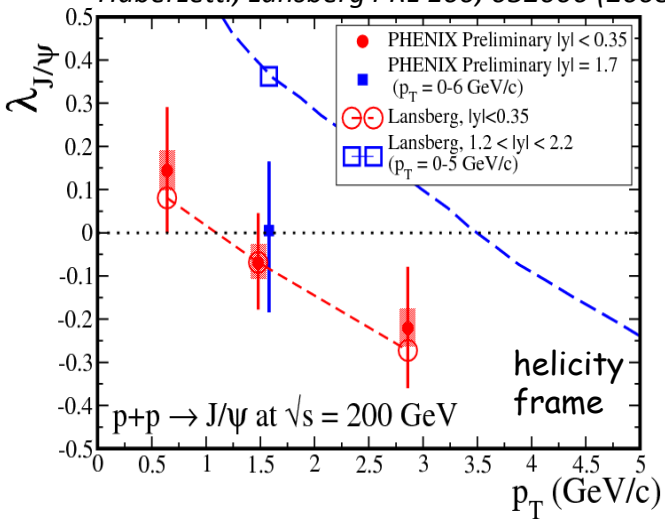
Need to know configuration of c-cbar (or b-bar) pre-hadronization state in order to describe the effect of the nucleus on its evolution

- What is $\sigma_{breakup}$ and how does it evolve?
- How are x_1 & x_2 related to x_F – extrinsic or intrinsic?

→ Precise measurements of production cross section & polarization

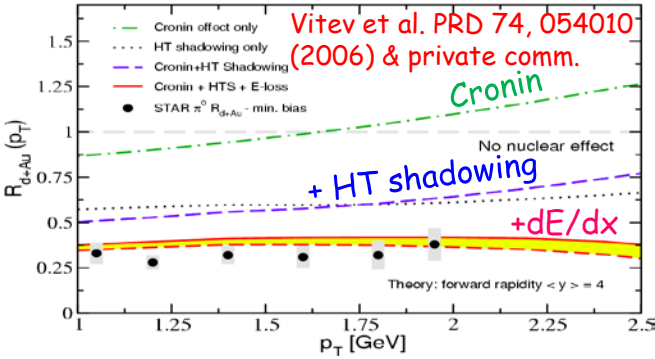


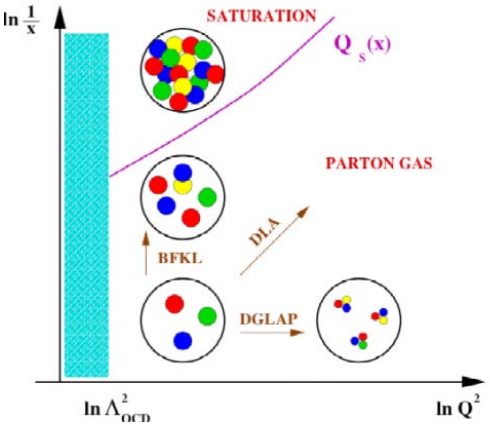
Haberzettl, Lansberg PRL 100, 032006 (2008)



Solving the Puzzle – Shadowing and/or Gluon Saturation

- pQCD in high-density (small-x) gluon region involves more complicated (NLO or higher-twist) processes, including $g+g \rightarrow g$
  - in principle can describe this region, but is very complicated
  - Larry says that a complete/correct pQCD calculation should be <u>equivalent</u> to the CGC (color glass condensate) picture
- CGC is a semi-classical picture for gluon saturation
  - it can describe ONLY the high-density region
  - this region is a "new" <u>extreme</u> state of QCD matter
  - but it does not describe things outside the saturation region
  - no consistent description of A+A processes that involve gluons both in and out of this region
  - not relevant for lower energy collisions (x not small) where large effects seen
- In any case, in my opinion – it seems more interesting to understand pQCD dynamics in this high-density region; rather than encapsulate it in a semi-classical theory (that has limited predictive power)

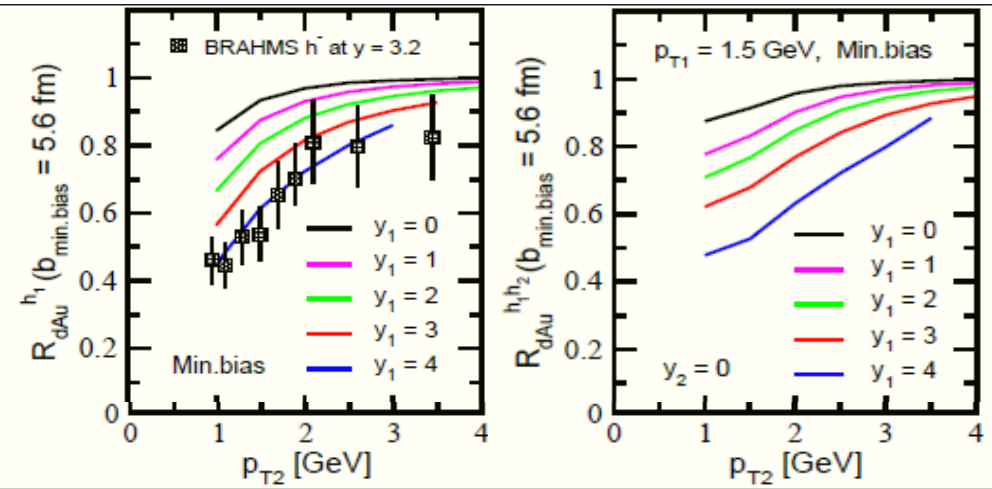




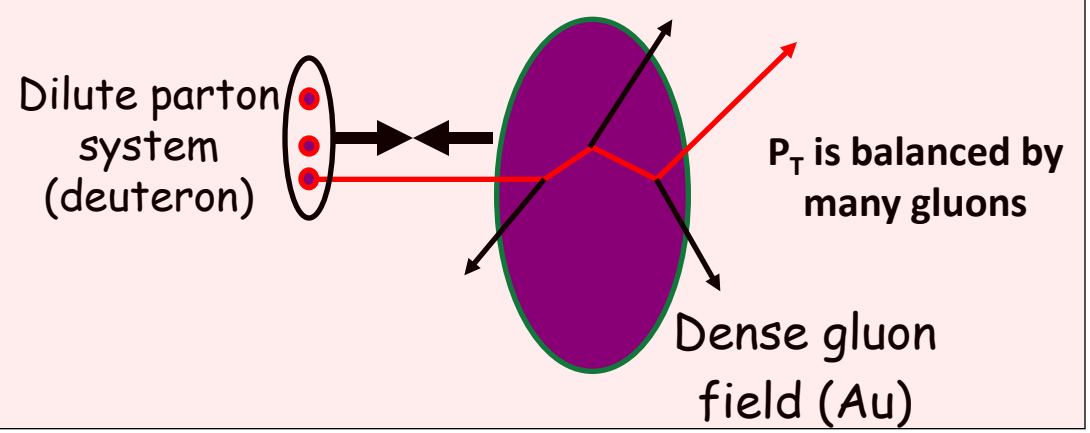
Rapidity-separated hadron correlations in d+Au

Two kinds of effects may give suppression in pairs that include a forward rapidity wrt mid-rapidity trigger hadron

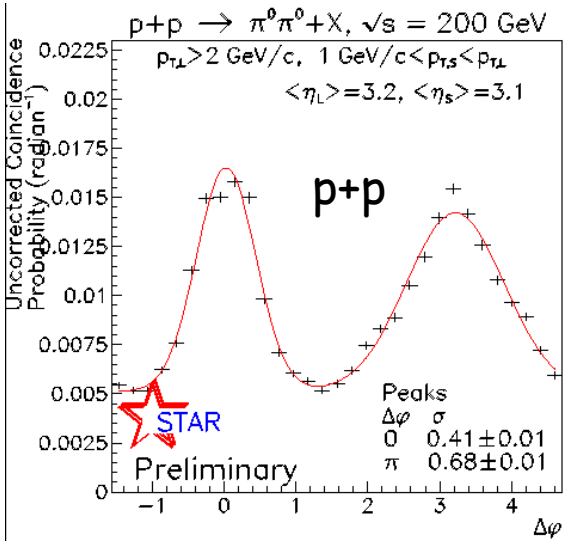
shadowing (non-LT) gives suppression of pairs wrt to singles
Vitev, hep-ph/0405068v2

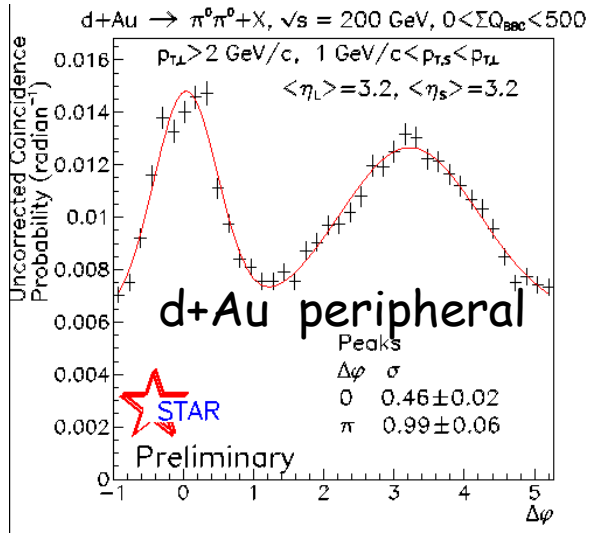


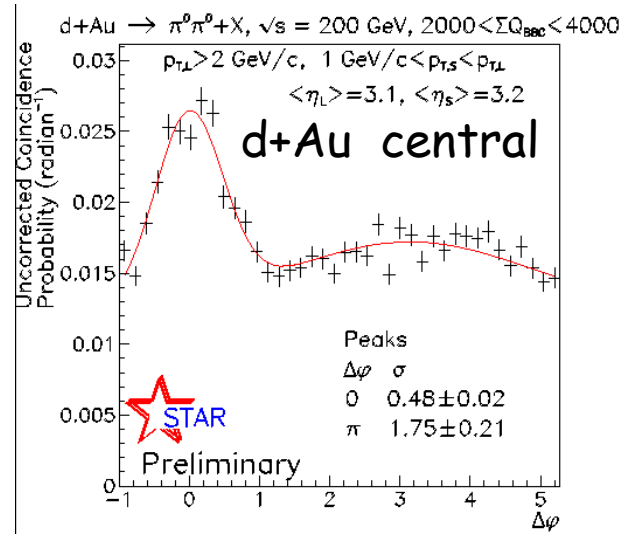
Mono-jets in the gluon saturation (CGC) picture give suppression of pairs per trigger and some broadening of correlation
Kharzeev, NPA 748, 727 (2005)

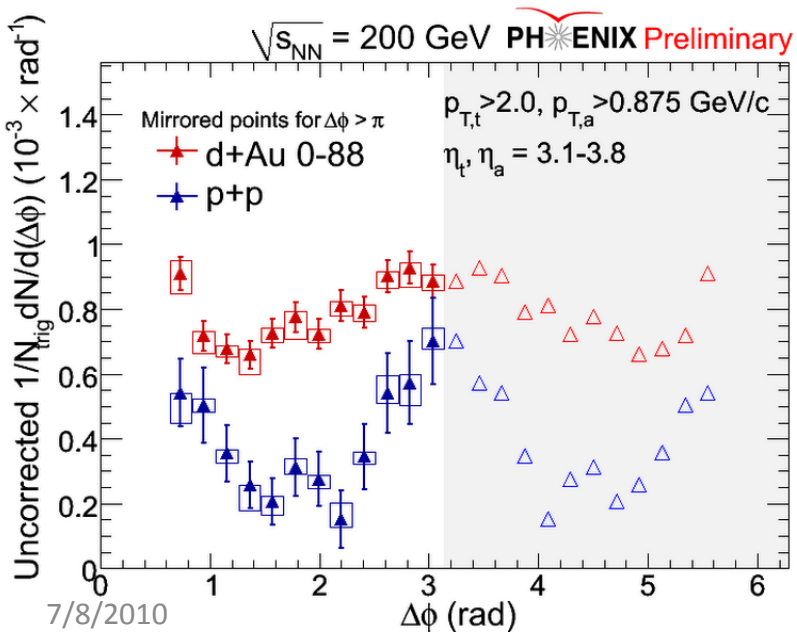


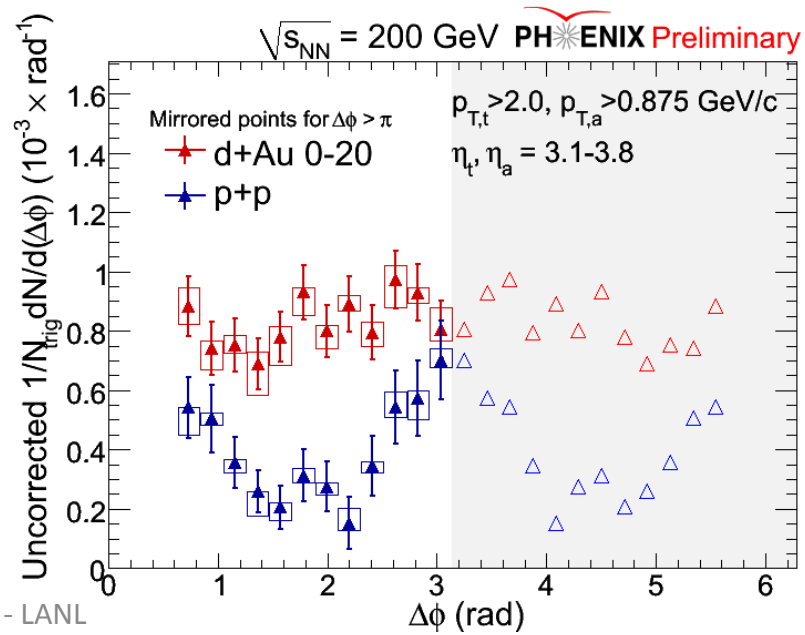
PHENIX Forward Rapidity CNM Physics
Ongoing and Near Future











Summary – Solving the J/ψ Puzzle

- Detailed theoretical analysis of d+Au J/Ψ to isolate shadowing and energy loss
  - input from quark dE/dx from E906; use theory to "extrapolate" this to gluon dE/dx
- Include new c and b measurements with FVTX to isolate initial & final-state effects via comparisons with quarkonia

- Add Υ, Φ; and add Ψ' with FVTX
- Need p+p measurements to pin down quarkonia production details & configuration of c-cbar (or b-bar) pre-hadronization state
  - differential cross section; polarization

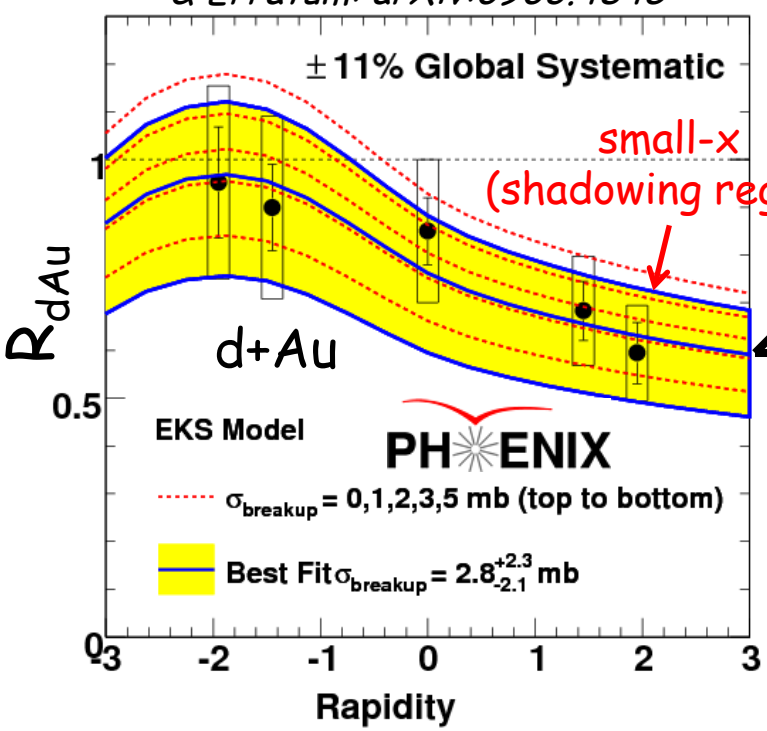
- Use systematics of quarkonia & open-charm measurements vs y & p_T at different sqrt(s) to try to constrain scaling of the gluon nPDF's (include dE/dx) & identify the correct theoretical description (i.e. CGC, QCD, …)

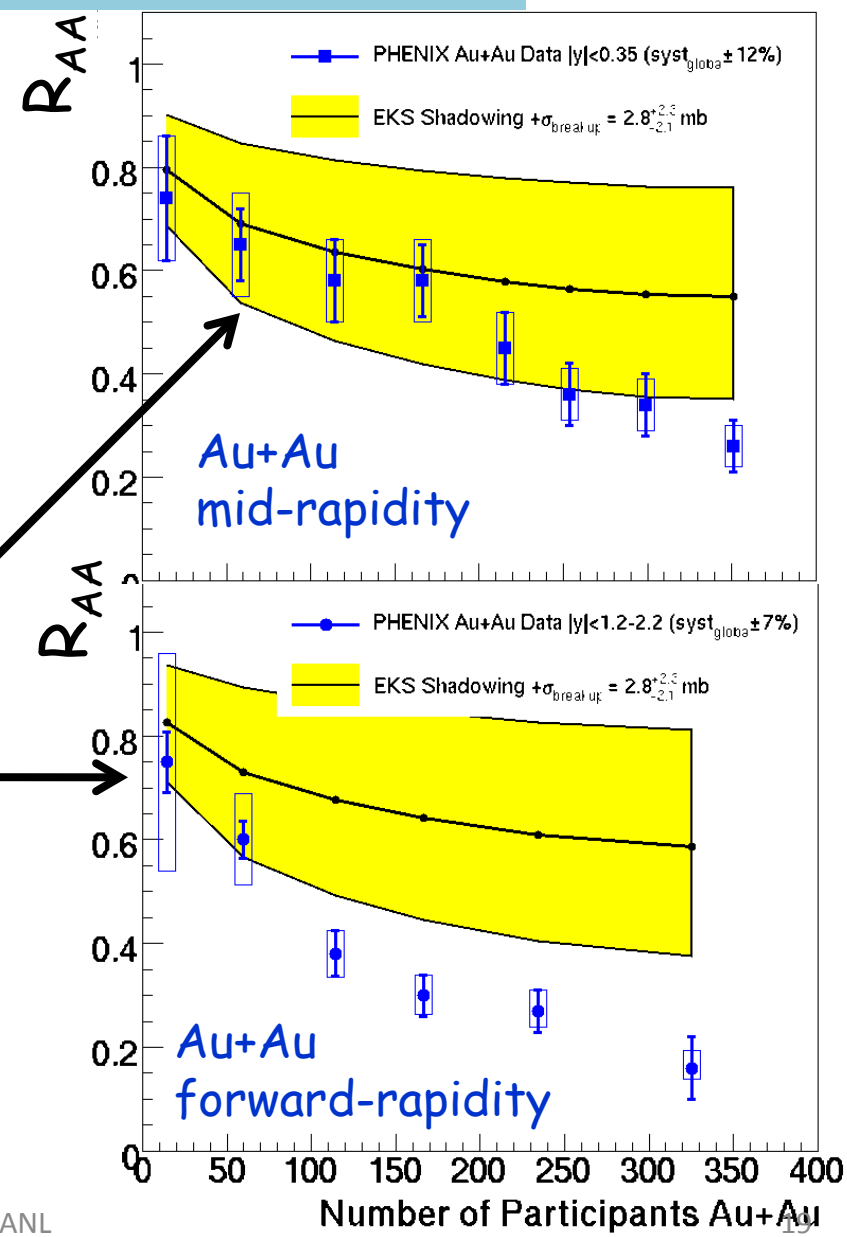
Backup Slides

Extrapolating CNM to A+A Collisions
CNM Constraints from 2003 d+Au

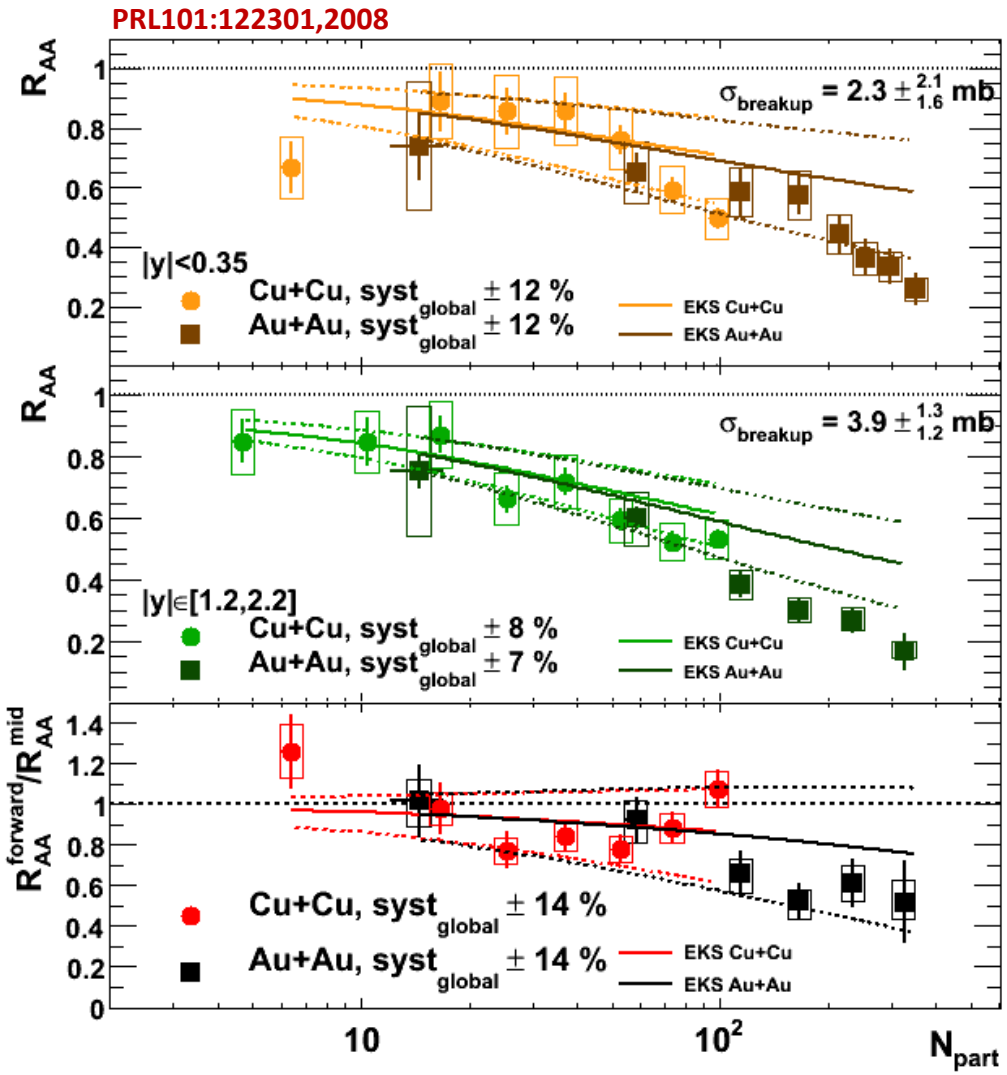
EKS shadowing + dissociation from fits to d+Au data (using R. Vogt theoretical calcs.)

PRC 77, 024912(2008)
& Erratum: arXiv:0903.4845





Extrapolating CNM to A+A Collisions
With (unphysical) rapidity-dependent $\sigma_{breakup}$



Data are from 2005 Cu-Cu and 2004 Au-Au.

Lines are cold nuclear matter effects extrapolated from 2003 d-Au data, using different $\sigma_{breakup}$ for mid and forward rapidity

Cu-Cu and Au-Au ratios match well where they overlap.
In Au+Au the suppression is larger than expected from CNM

There is (still) more suppression at forward rapidity than at mid-rapidity, but the difference can be absorbed by CNM

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

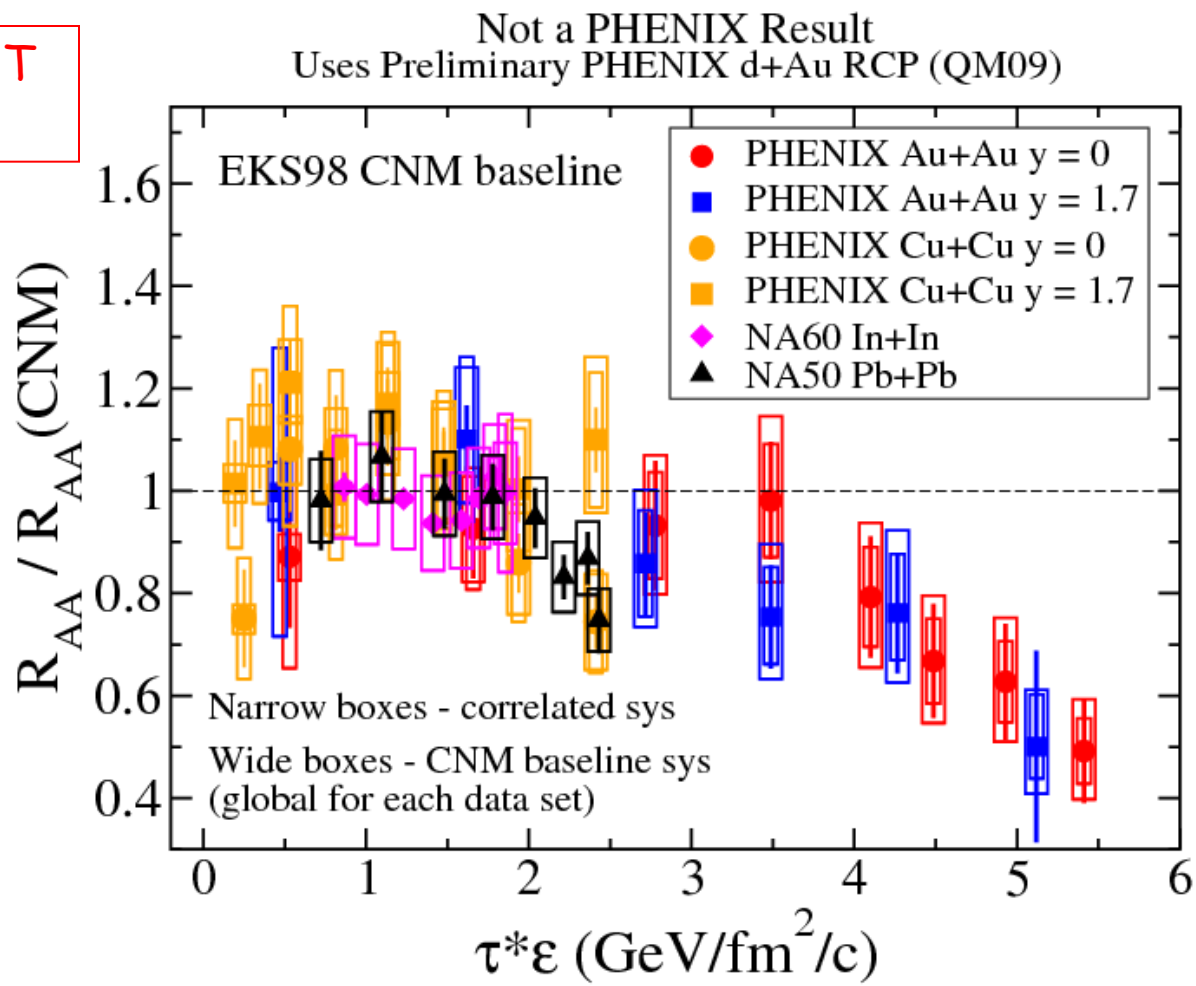
Example of Comparison of Anomalous Suppression of RHIC & SPS in A+A Collisions (QGP) after dividing out d(p)+A baselines

Plot by Leitch @ Seattle/INT Workshop – June 09

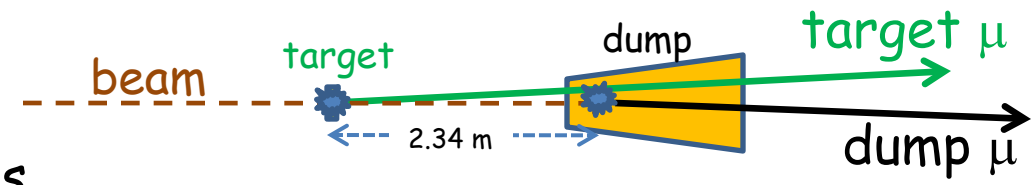
<u>Caution</u> - Many systematic uncertainties on relative (SPS vs RHIC) energy density scales:

Use tau*energy density scale

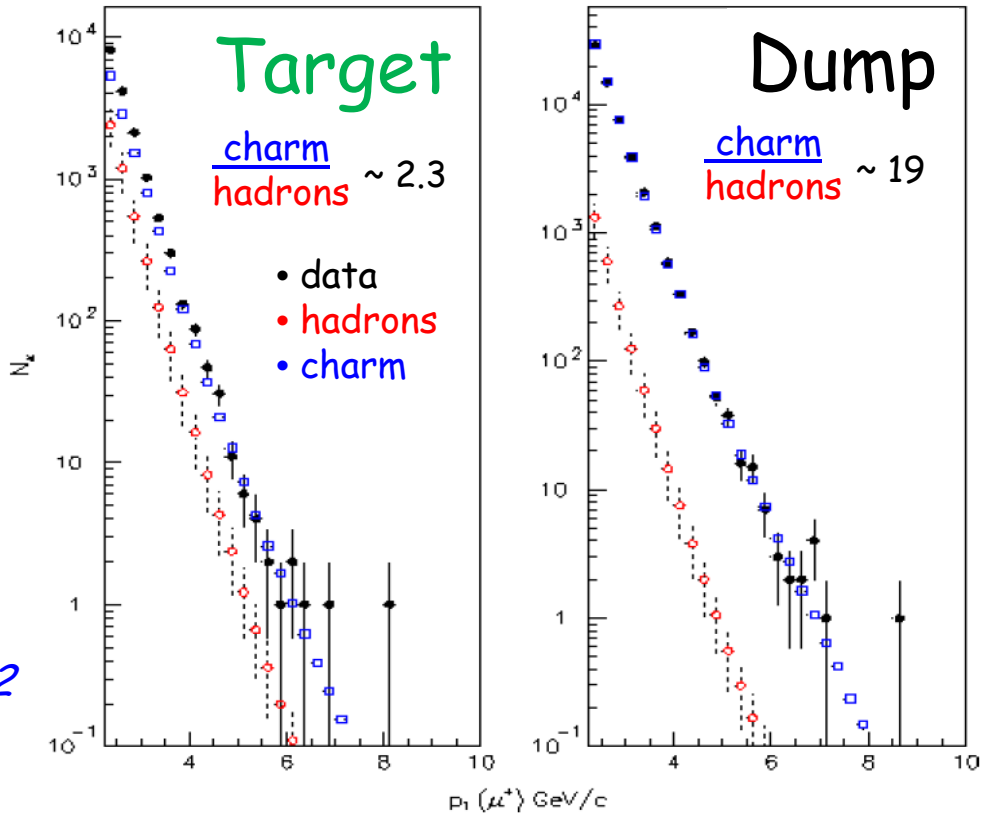
- but is τ same or different between SPS & RHIC energy??



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



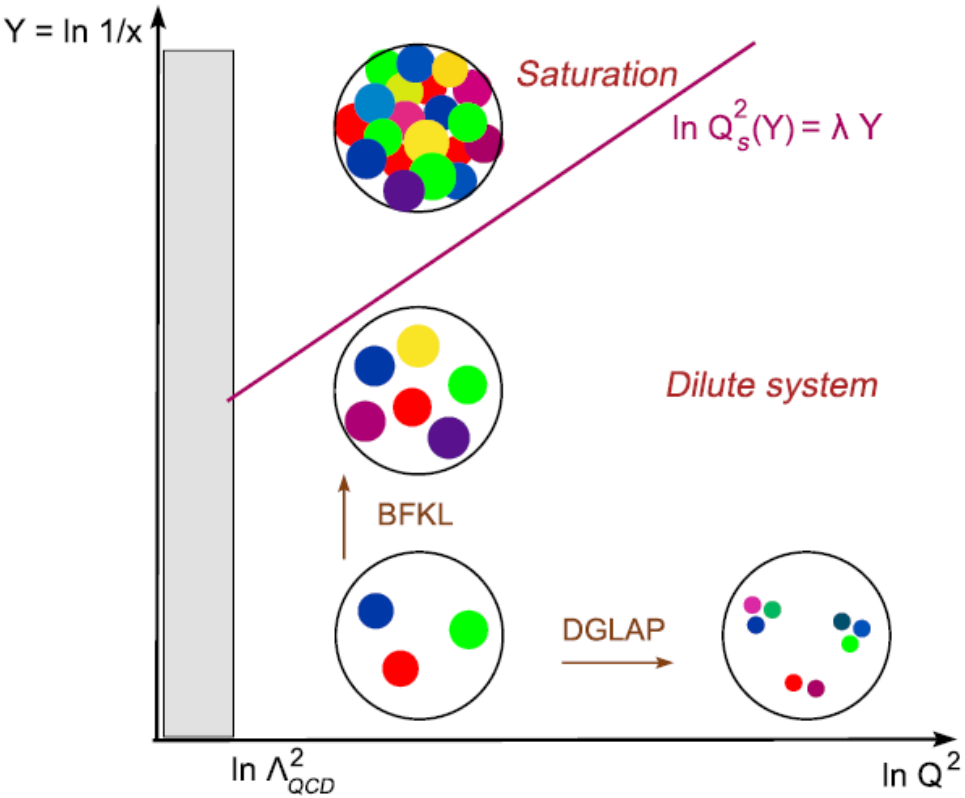
E866/NuSea 800 GeV p+A

- *S. Klinksiek thesis - hep-ex_0609002*
- *paper in preparation*

The Color Glass Condensate

(slide from Beau Meredith)

See Yu.V. Kovchegov, Phys. Rev. D 61, 074018 (2000).
For review, see F. Gelis, E. Iancu, J. Jalilian-Marian, R. Venugopalan, arXiv:1002.0333

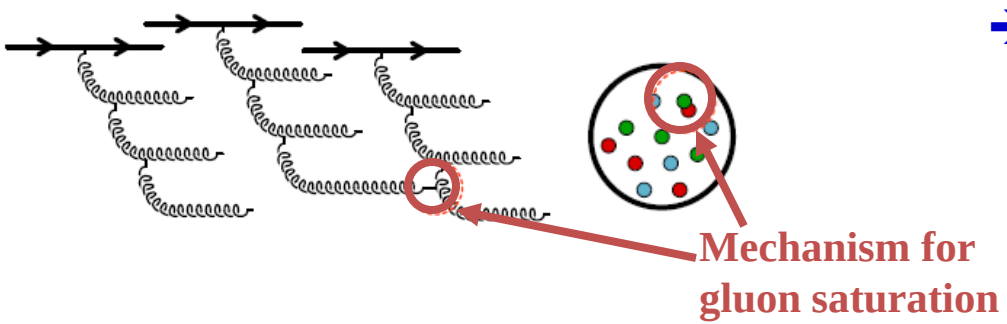


gluon density $n(Y, k_T)$ saturates for large densities at small x :

Non-linear evolution eqn.

$$\frac{\partial n}{\partial Y} \cong \underbrace{\lambda \alpha_s n}_{\text{g emission}} + \underbrace{\nu \alpha_s \partial_t^2 n}_{\text{diffusion}} - \underbrace{\mu \alpha_s^2 n^2}_{\text{g-g merging}}$$

g-g merging large if $\alpha_s n \propto 1$



➔saturation scale, Q_s

➔ nuclear enhancement ~ $A^{1/3}$

➔ increasing gluon density~ $1/x^{\lambda}$

$$Q_S \propto A^{1/3} / x^{\lambda}$$

CGC Effects at RHIC ($\sqrt{s_{NN}}$ = 200 GeV)

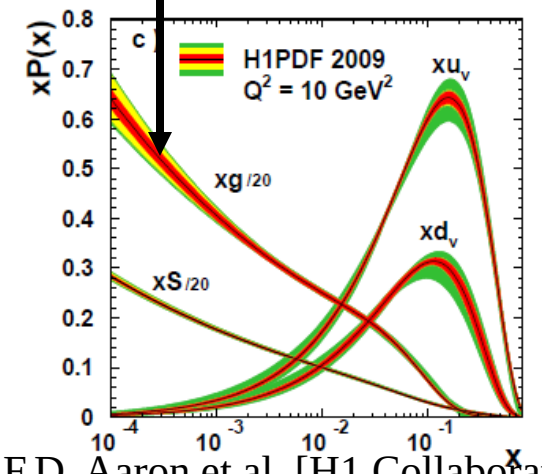
(slide from Beau Meredith)

- Probe low *x* gluons at **forward rapidities**

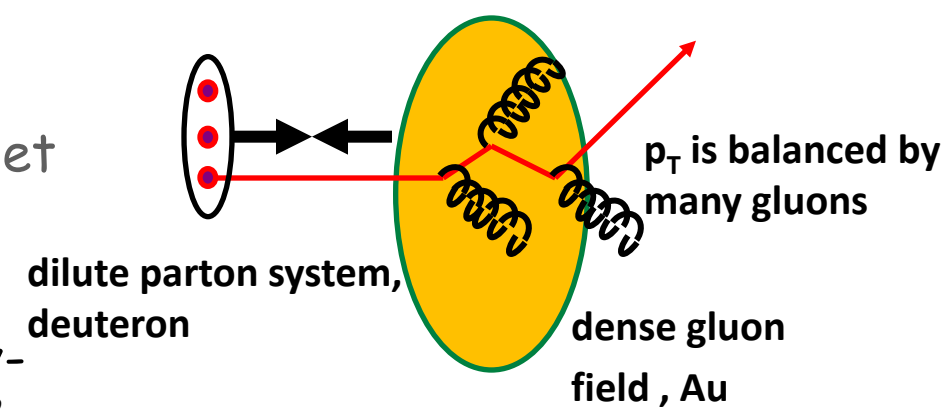
$$x_g = \frac{p_{T1}e^{-y_1} + p_{T2}e^{-y_2}}{\sqrt{s}}$$

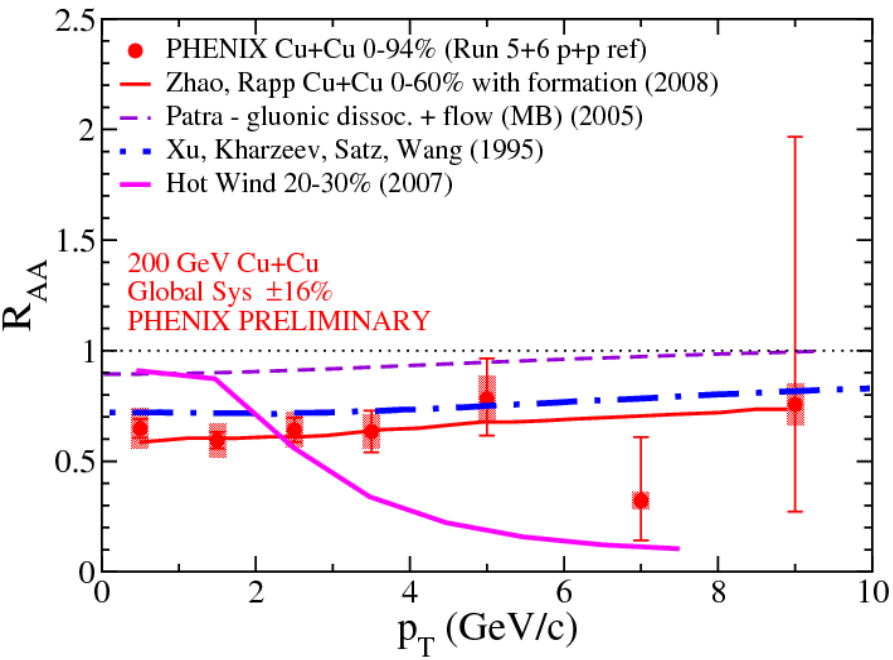
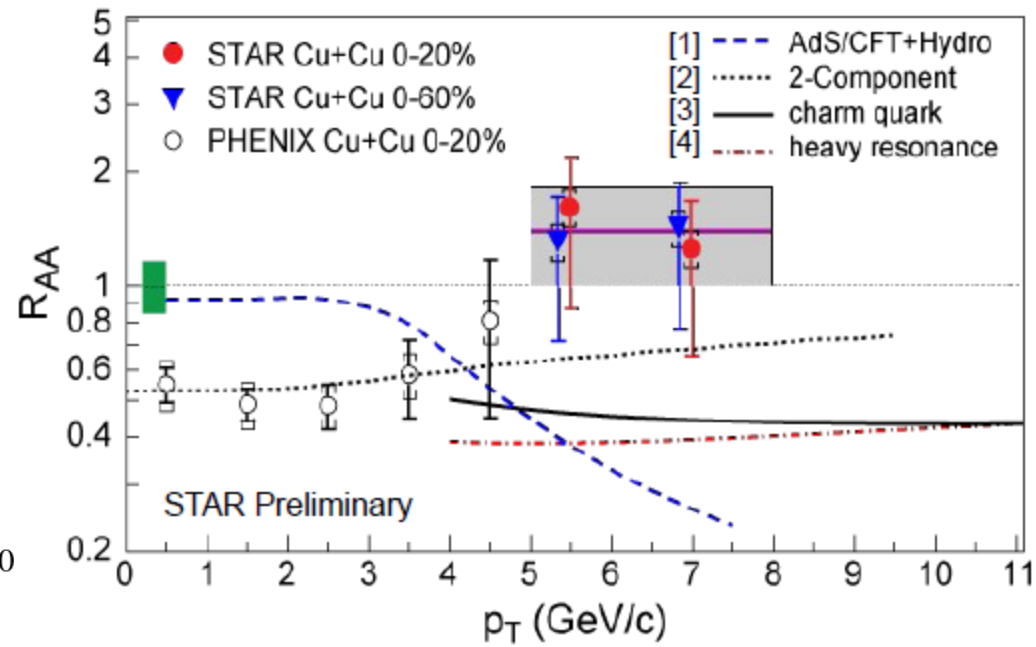
- Use **deuteron-gold (d+Au)** collisions vs **p+p**
  - Difference is nuclear enhancement factor in saturation scale, $A^{1/3}$
- Signatures of CGC
  - **suppression** of nuclear modification factors
  - **angular decorrelations** of di-jet signals (di-hadron $\Delta\Phi$ correlations)
    - Disappearance of the away-side peak in when $Q^2 \sim Q_s^2$

Gluon distribution function from HERA



F.D. Aaron et al, [H1 Collaboration] Eur. Phys. J. C 64, 561 (2009)



p_T dependence in Cu+Cu collisions

Need higher statistics at high-p_T to know whether R_{AA} maintains suppression or not for large p_T