dAu at PHENIX: Insights on the Cronin effect, shadowing and saturation

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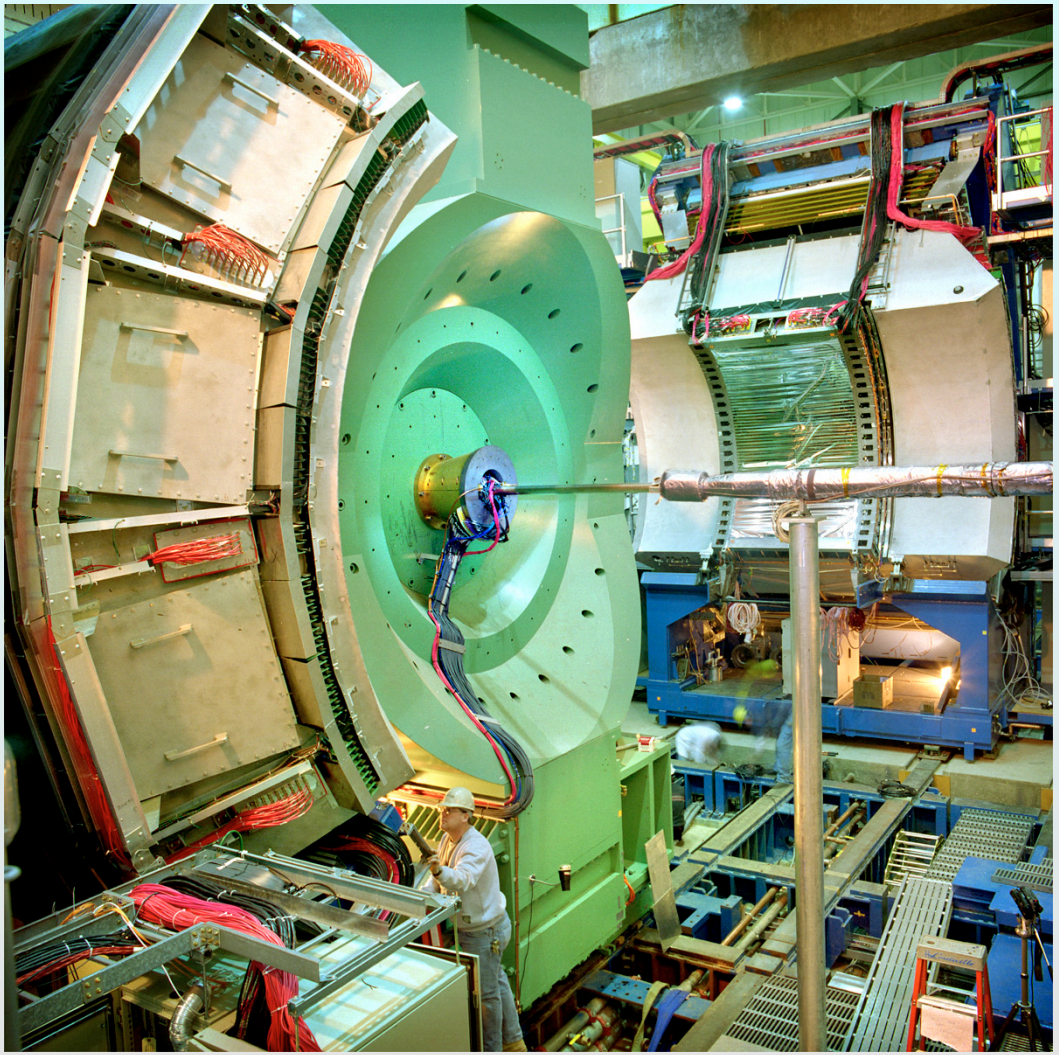
For the PHENIX Collaboration

pA Workshop, MIT

May 18, 2013



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BVJ history with Wit

- Began reading his papers in 1980's
  To guide first comparisons pp → pA → AA in HELIOS
- Met Wit at conferences
  Many discussions
  some even in Polish…
  Hung out together
  QM2002, 2005, etc.
  2002 KITP program on
  "QCD in the RHIC era"
- Workshop in Santa Fe
  In 1993

I always learned a lot!

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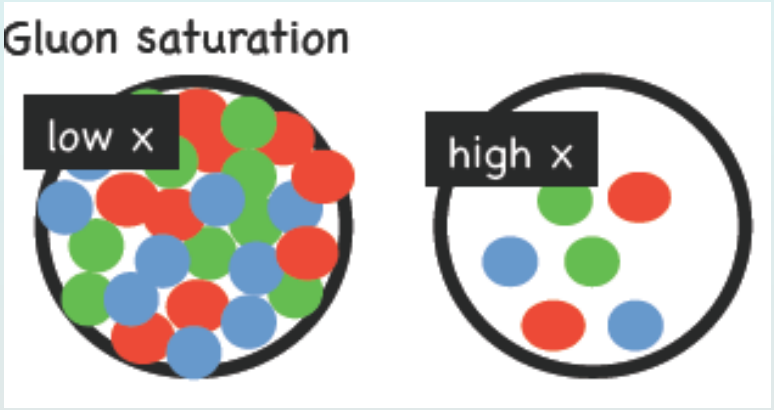
The big question in p+A physics

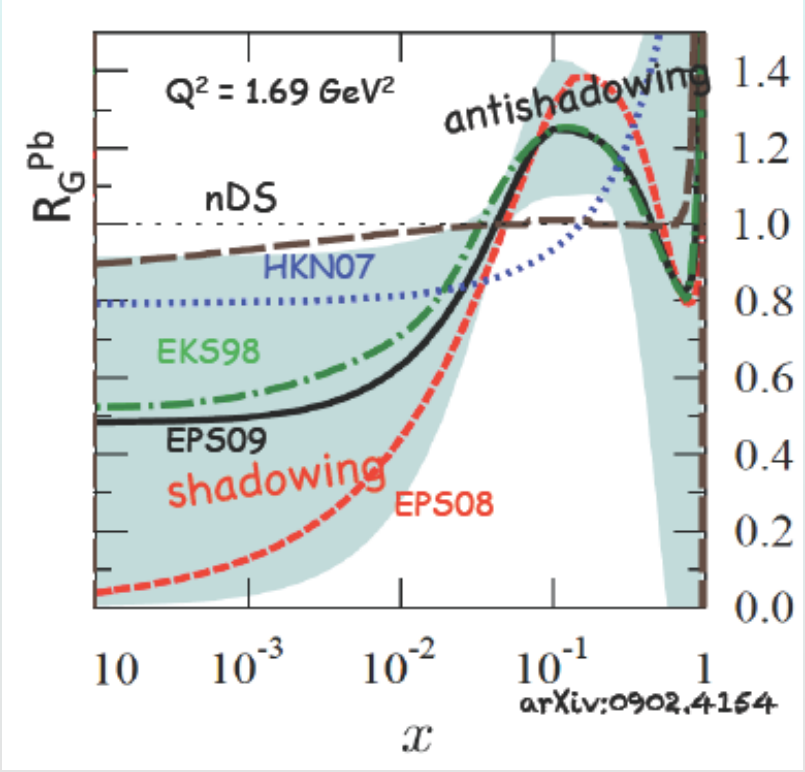
- **Then (the pre-RHIC era):**

  What do subsequent p-nucleon collisions in p+A have to do with one another?

- **Now (the RHIC and LHC era):**

  What do gluons at small x inside a nucleus have to do with one another?





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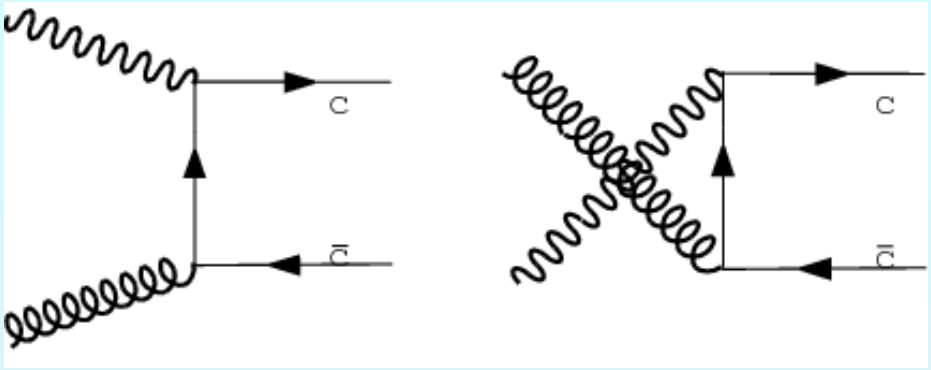
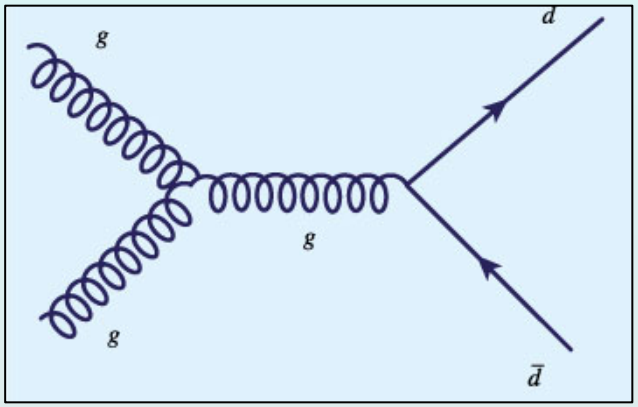
To answer this: PHENIX studies

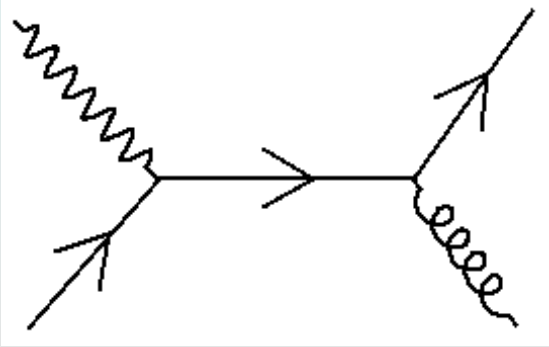
- **Heavy flavor production:**
  g+g → c + cbar



- **Jet and di-jet production:**
  g+g → di-jet



- **Direct photon production:**
  (QCD Compton process)
  q+g → γ + hadrons



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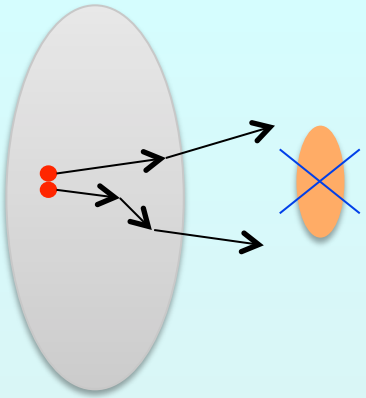
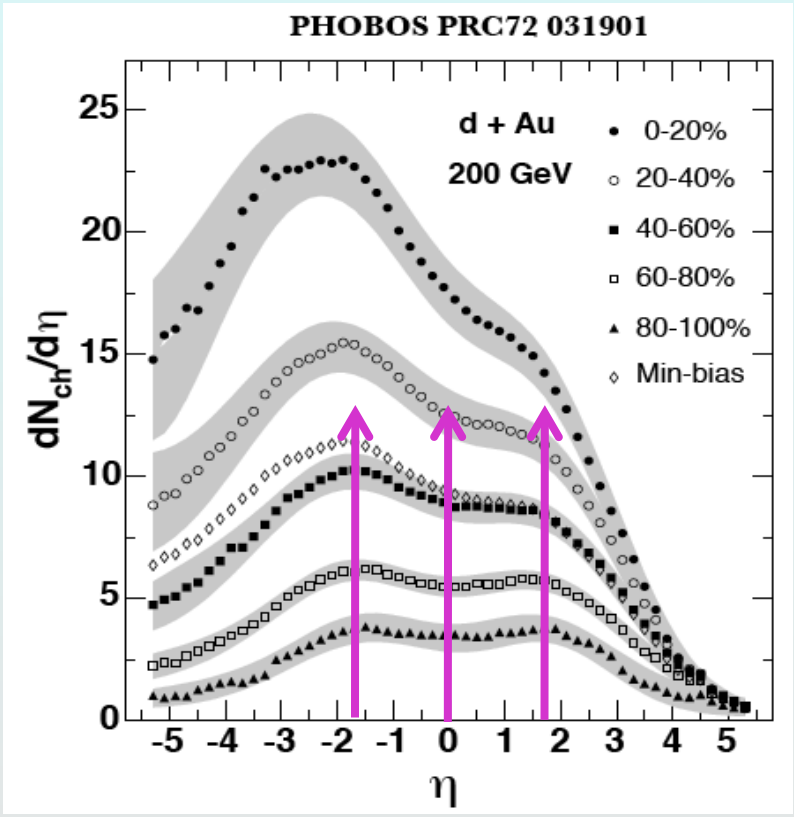
Heavy Flavor



- Production of c+cbar and b+bbar
  - Nuclear gluon distribution in d+Au
    - initial state effects:
      - saturation
      - shadowing, anti-shadowing
      - parton energy loss
      - parton (re)scattering
    - ❖ *quarkonia, open heavy flavor*

- Quarkonia survival probability
  - Sensitive to surrounding medium in d+Au
    - ❖ *J/ψ vs. ψ' vs. Υ*



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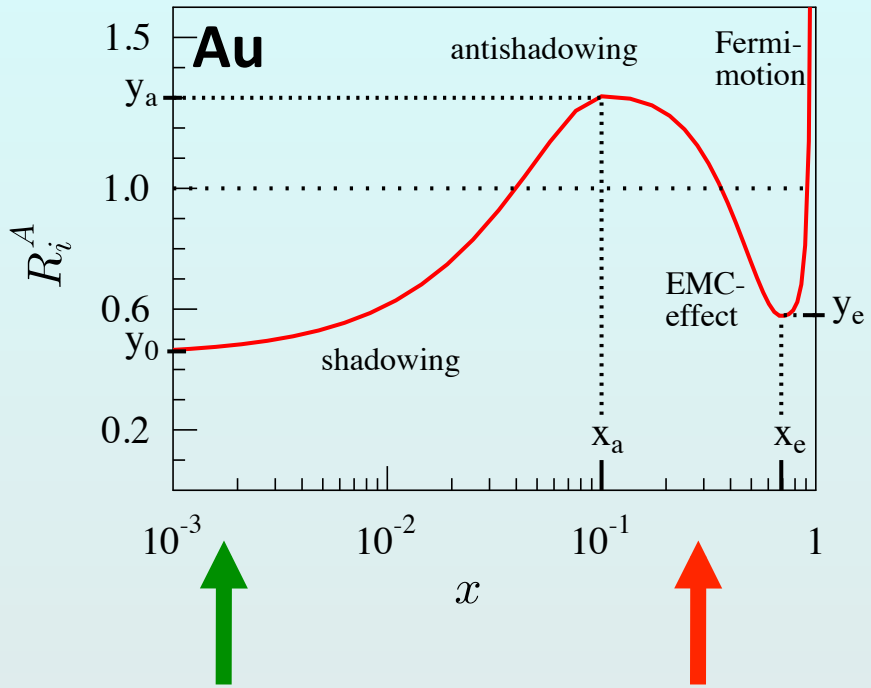
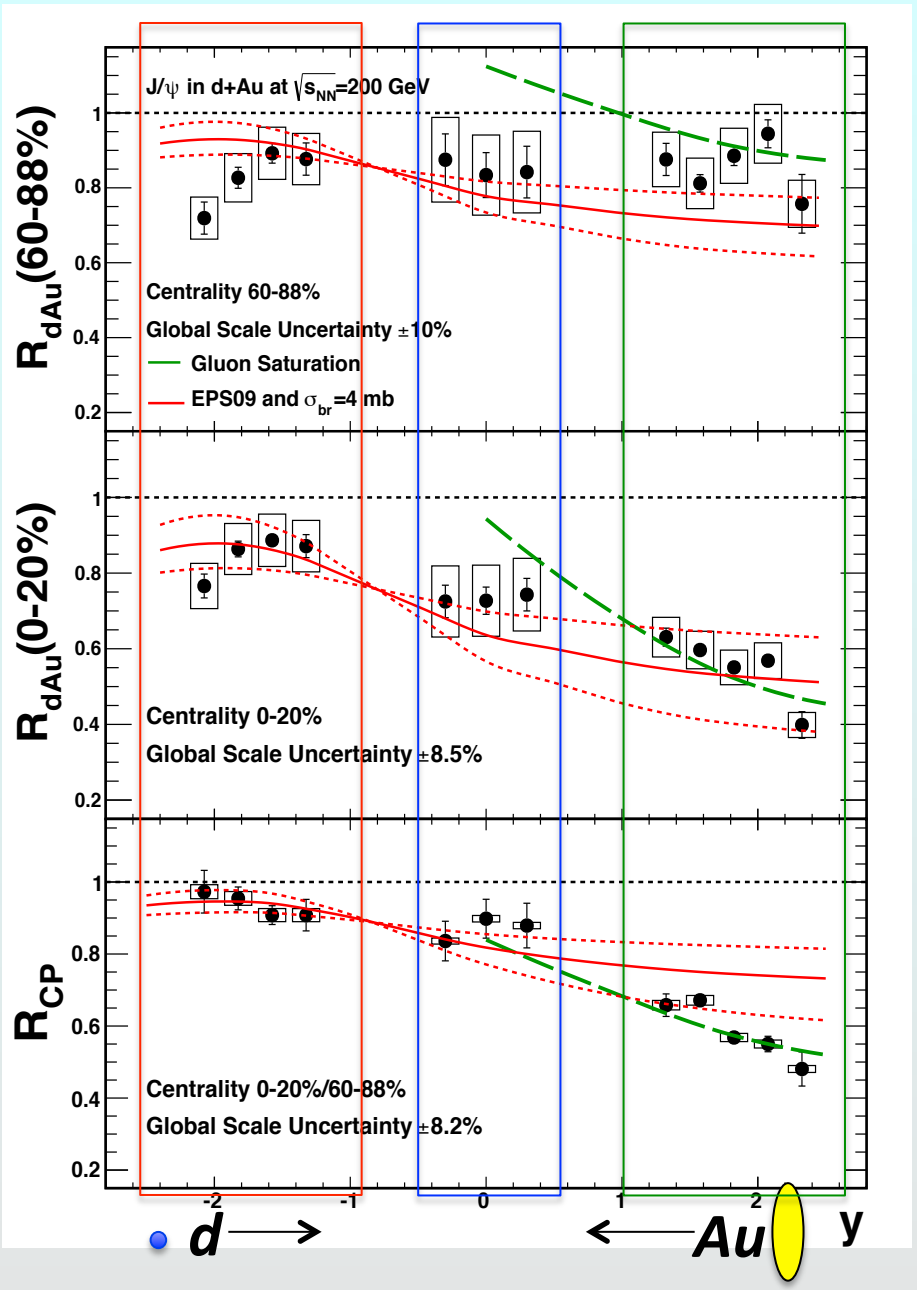
Initial State: what's where?



Forward
+ y
d-going

Backward
- y
Au-going



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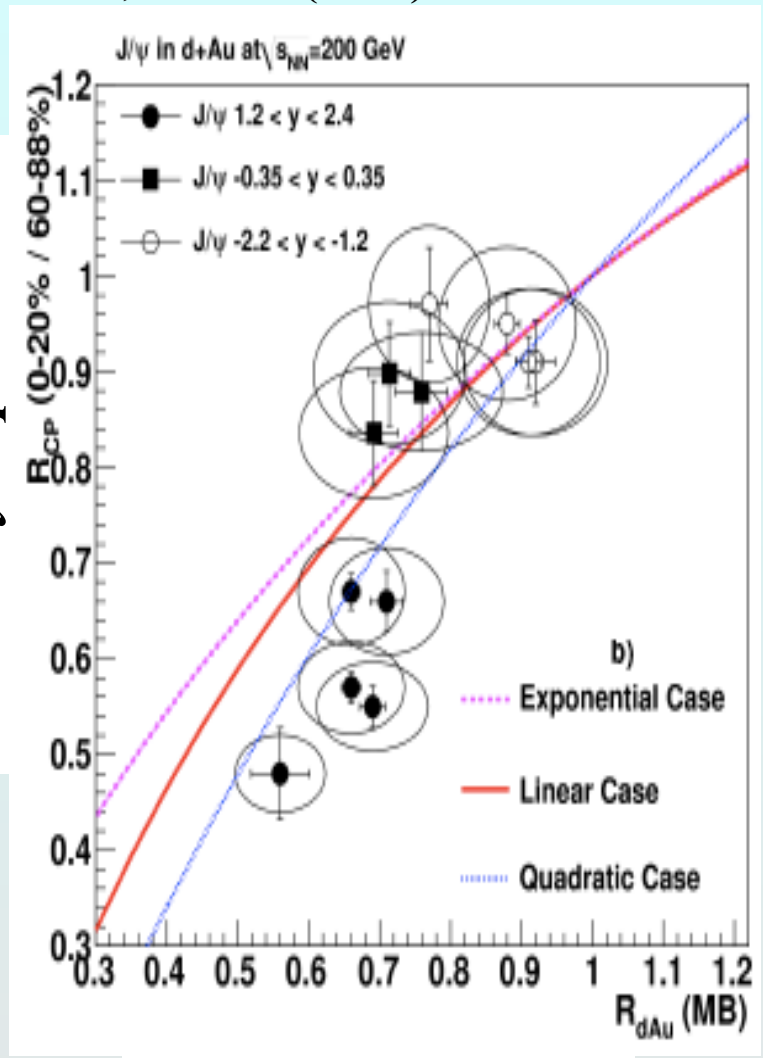
J/ψ in d+Au

PRL107, 142301 (2011)



Centrality dependence

Suppression level

forward rapidity probes low-x in Au

saturation predicts suppression

forward data: non-linear suppression vs. density weighted longitudinal thickness $\Lambda(r_T) \equiv \frac{1}{\rho_0}\int dz \rho(z, r_T)$

- **EPS09 nPDF's: linear**
- **break-up w/fixed σ_{br}: exponential**
- **data: ~quadratic**

increased suppression at forward rapidity also expected from initial state parton energy loss…

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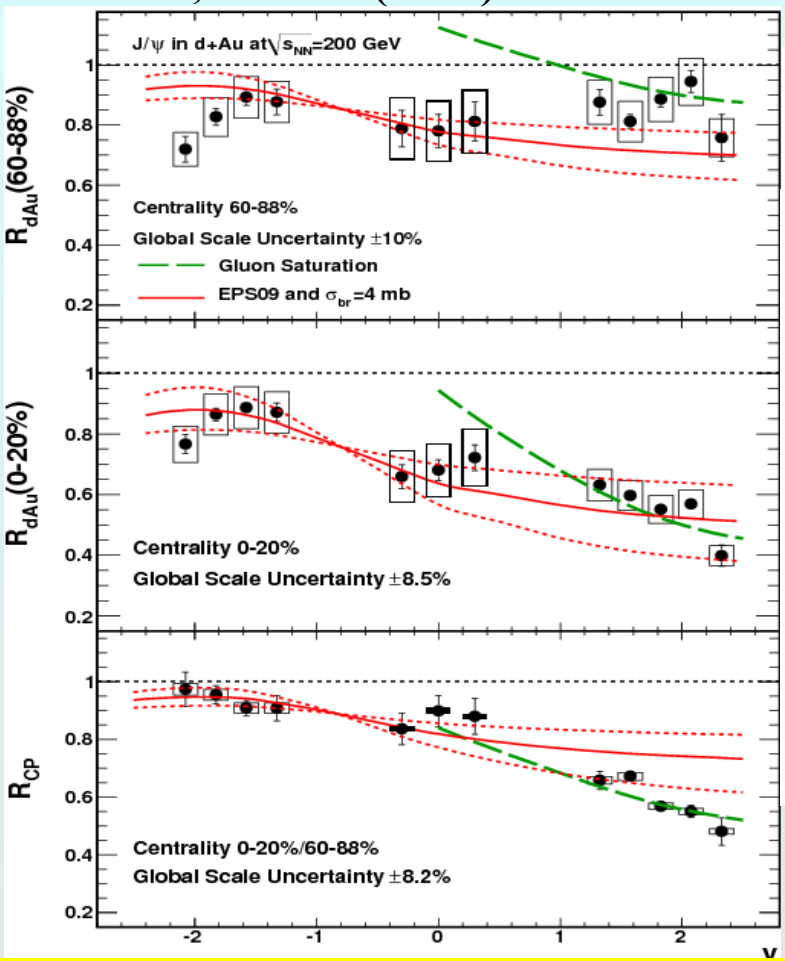
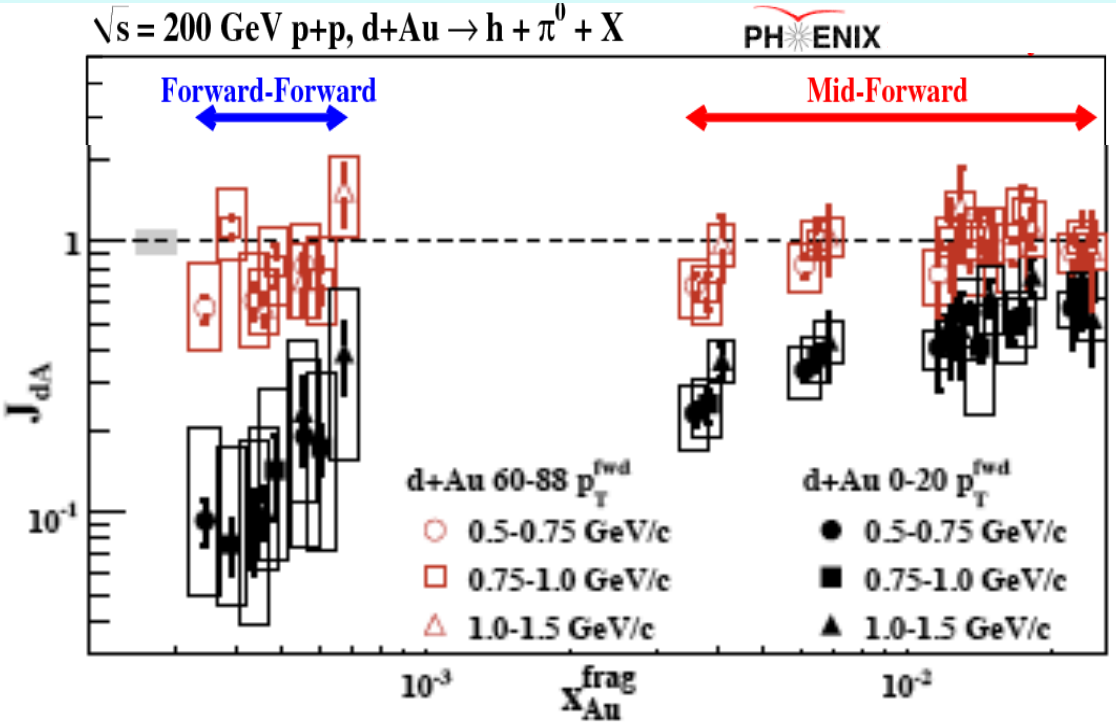
Dense gluonic matter effects observed

PRL107, 142301 (2011)



PRL107, 172301 (2011)



Shadowing/absorption stronger than linear w/nuclear thickness

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Di-hadron suppression at low x

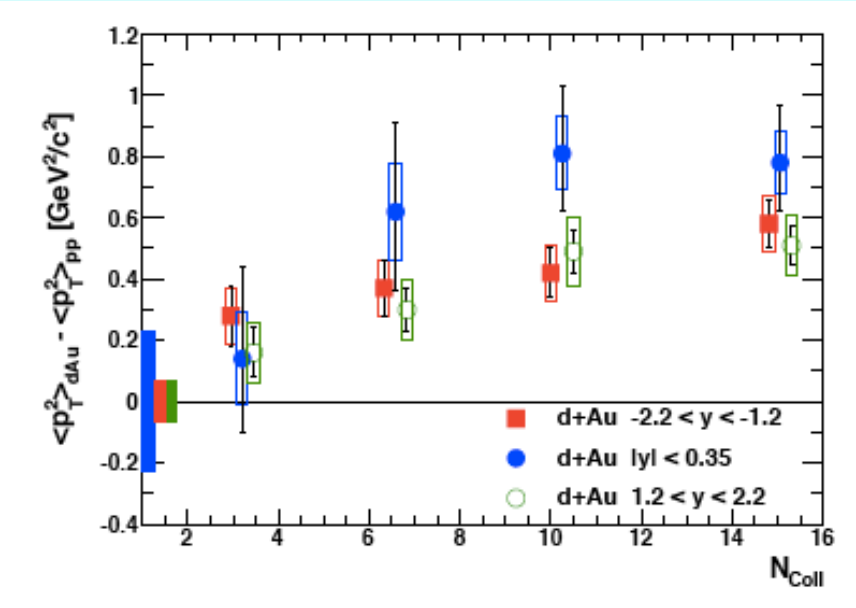
pocket formula (for 2➔2):

$$x_{Au}^{frag} = \frac{< p_{T1} > e^{-<\eta_1>} + < p_{T2} > e^{-<\eta_2>}}{\sqrt{s}}$$

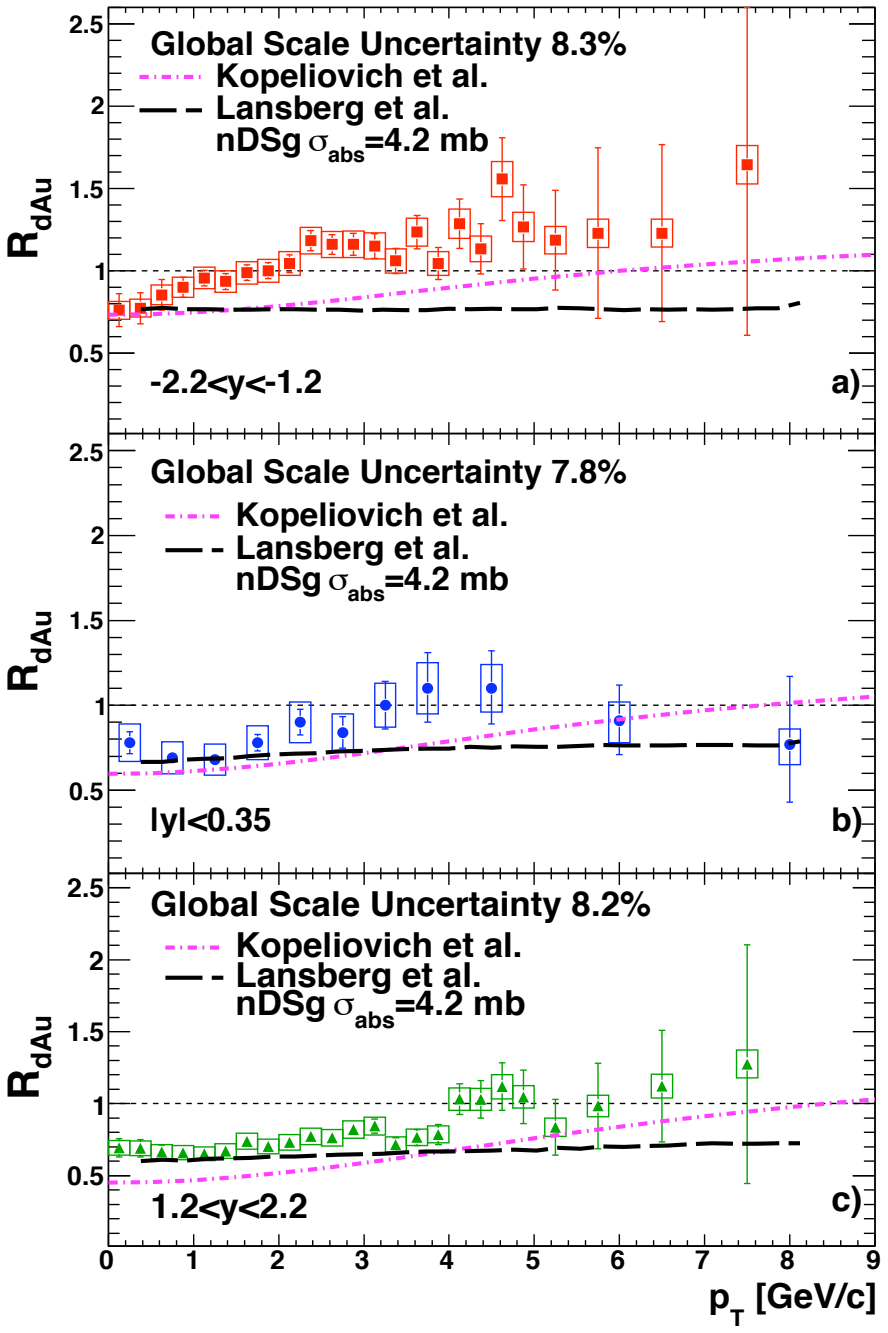
As expected for CGC …

Shadowing, breakup & Cronin effect

PRC87, 034911 (2013)



- p_T broadens (multiple scattering) w/N_{coll}; effect stronger at y=0
- J/ψ suppression to higher p_T @ mid & forward y (lower x in Au);
- R_{dA}>1 at high p_T backward (Cronin effect in Au nucleus)
- p_T, y, centrality dependence not reproduced by models



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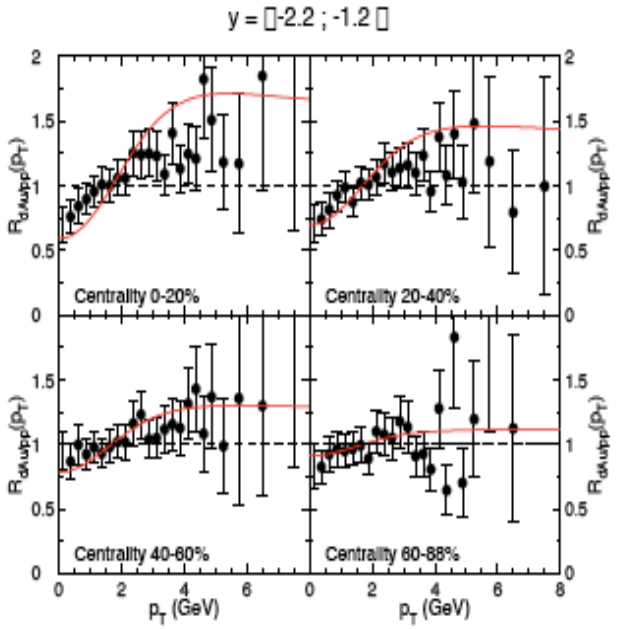
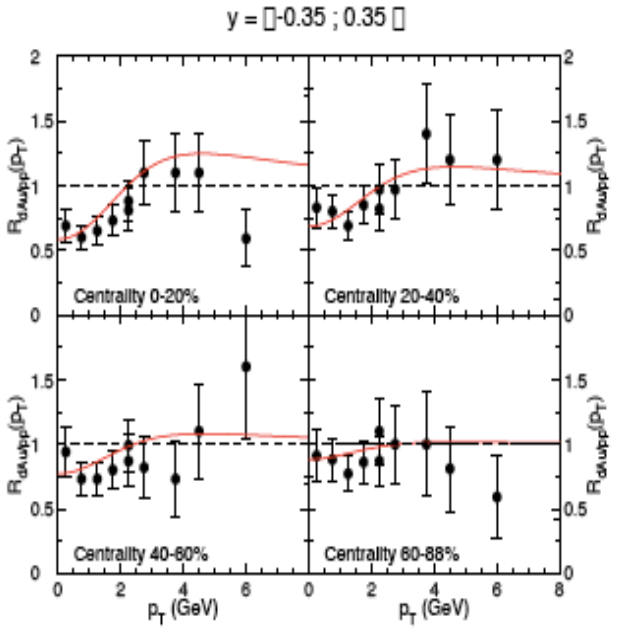
but

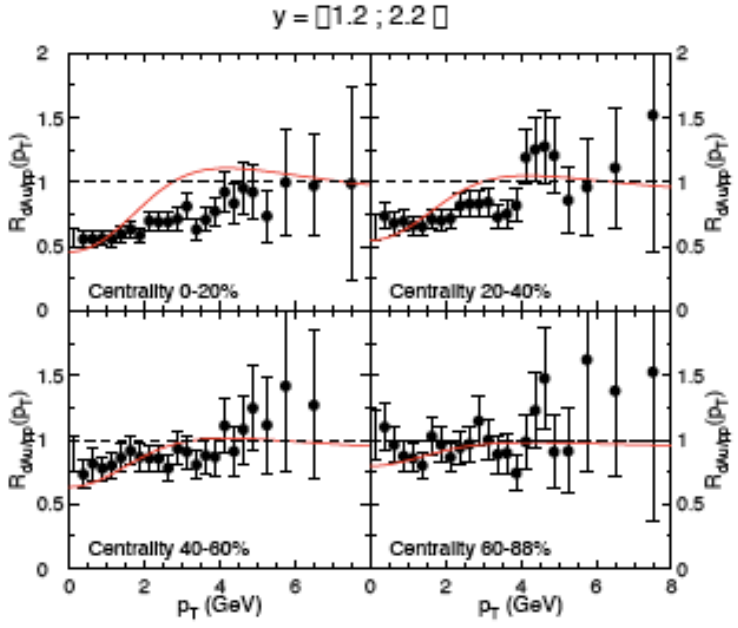




Parton p_T broadening and energy loss calculation (Arleo, et al 1304.0901)

consistent with the data!

shadowing+eloss or saturation?



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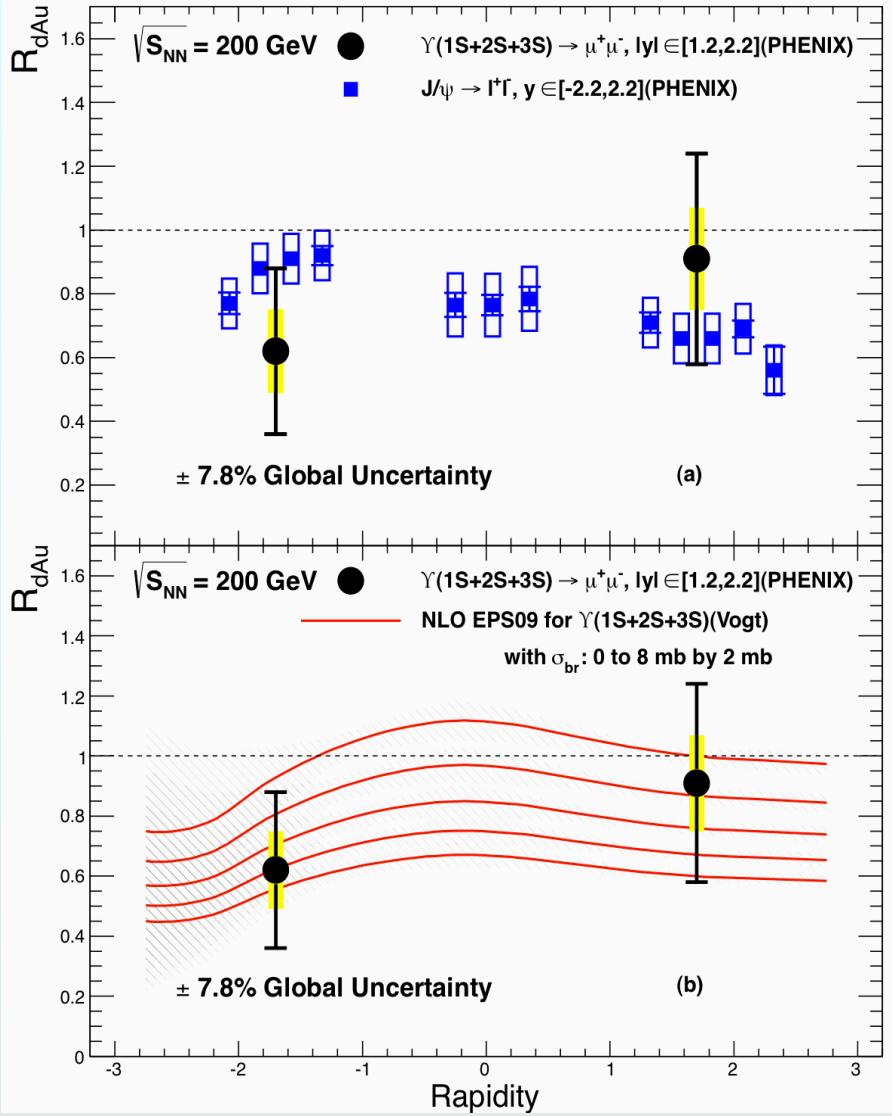
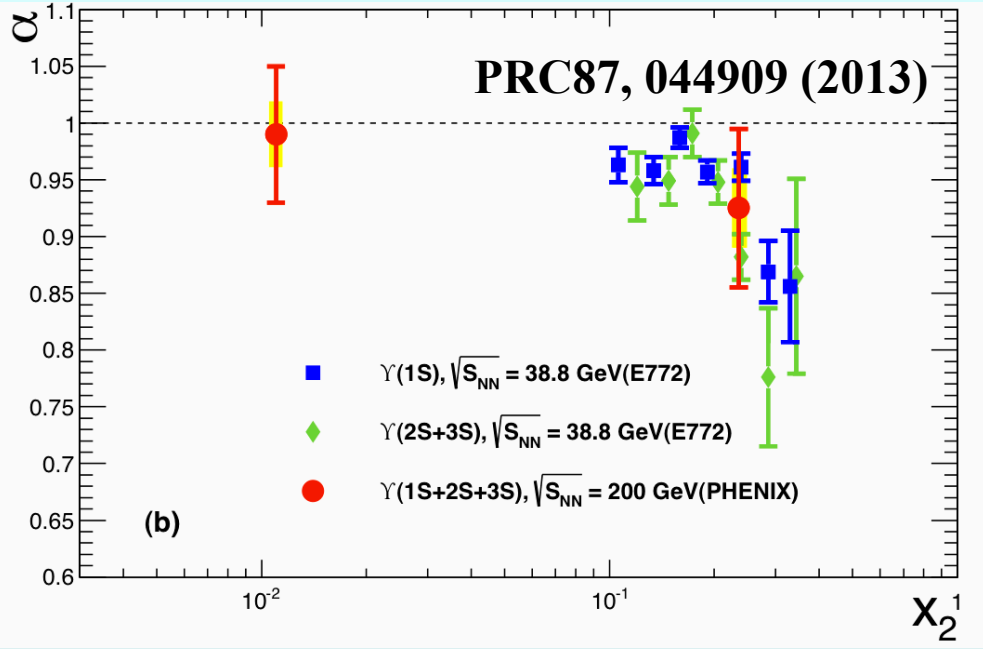
Smaller, more tightly bound probe





- Hard to quantify comparison Y in line with data at lower √s
- Consistent with EPS09 shadowing + some nuclear breakup (recall: backward rapidity = Au-going)

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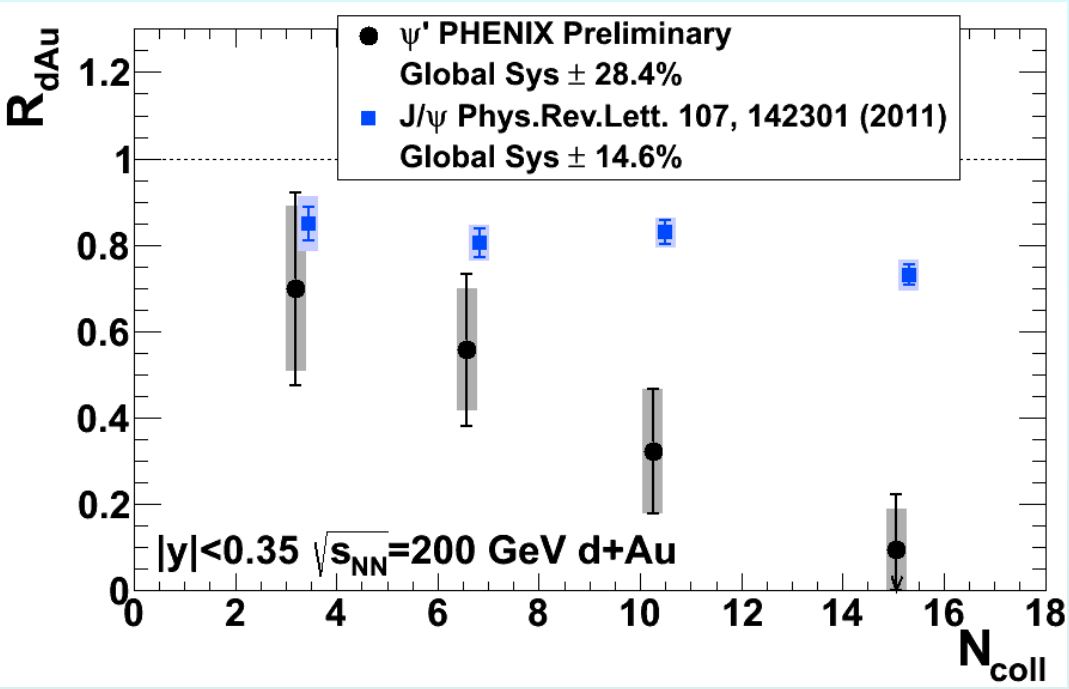
Larger, less tightly bound ψ'



- Clearly more suppressed than J/ψ
- Not shadowing or parton energy loss
  - These are initial state effects

- World data on ψ'/ J/ψ:
  - Decreases linearly with $dN_{ch}/d\eta$ (independent of √s)
- Supports: effect is not due to c-cbar production suppression
  - break-up of some kind: early or late?

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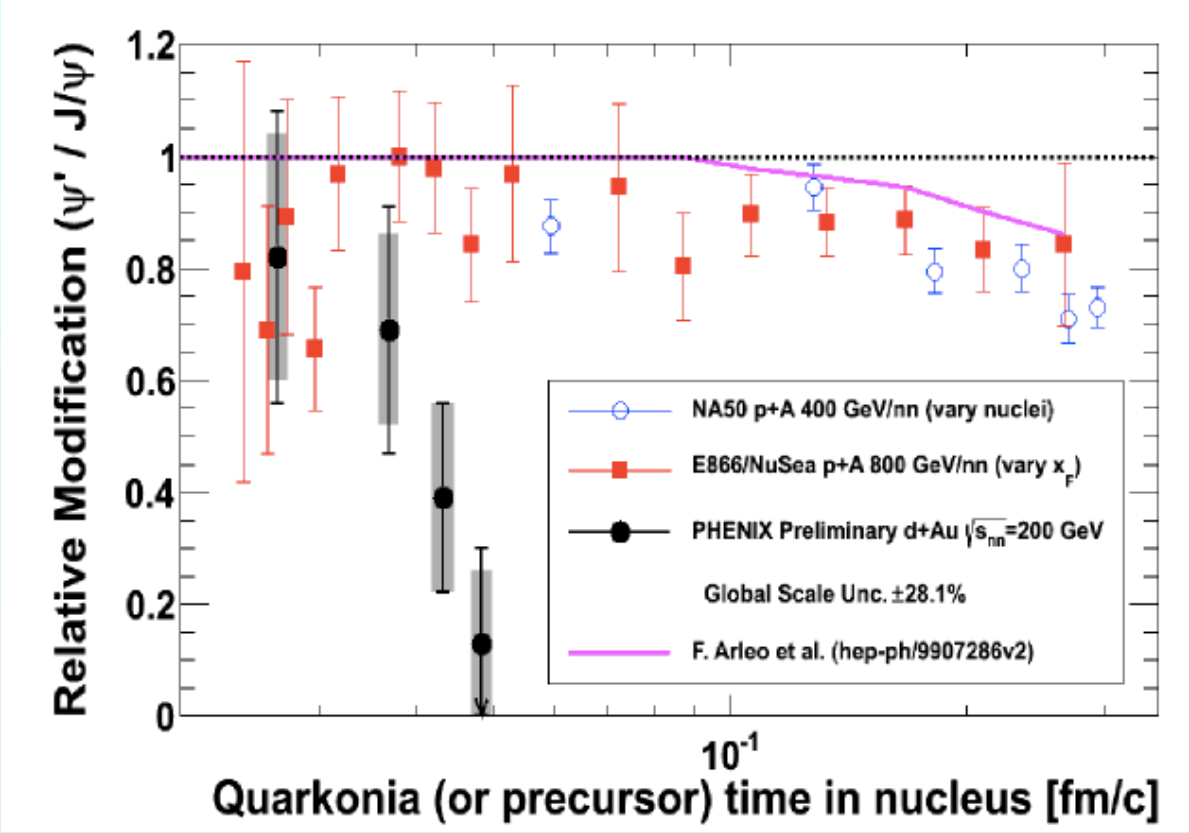
√s dependence is a key tool!



- Time in nucleus is short at √s = 200 GeV
  Shorter than bound state formation time! Late final state effect?
- Suppression vs. $dN_{ch}/d\eta$ suggests breakup by comoving hadrons?
  $dN_{ch}/d\eta$=15 in central d+Au; ψ' easier to break up than J/ψ (R. Vogt)

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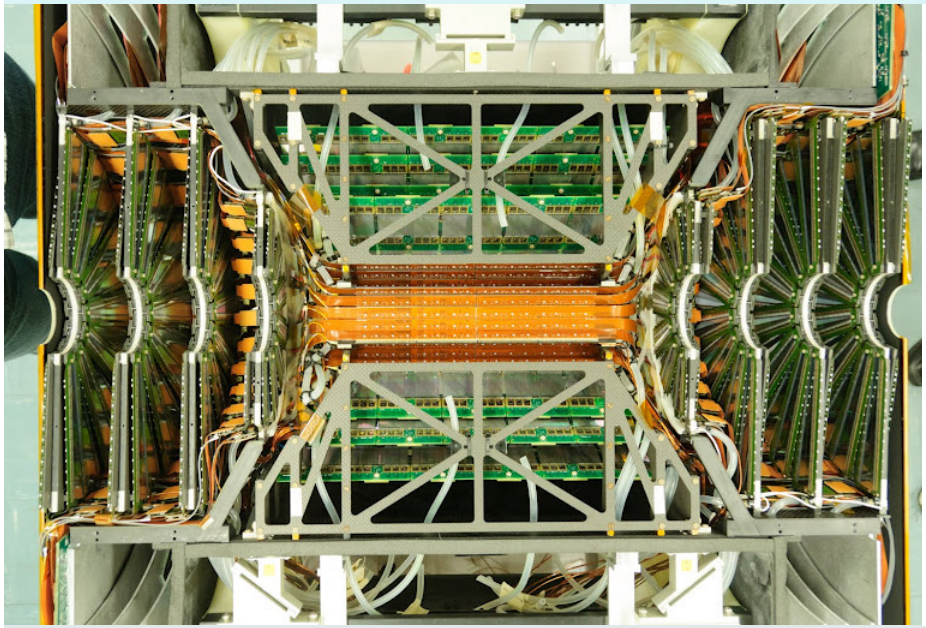
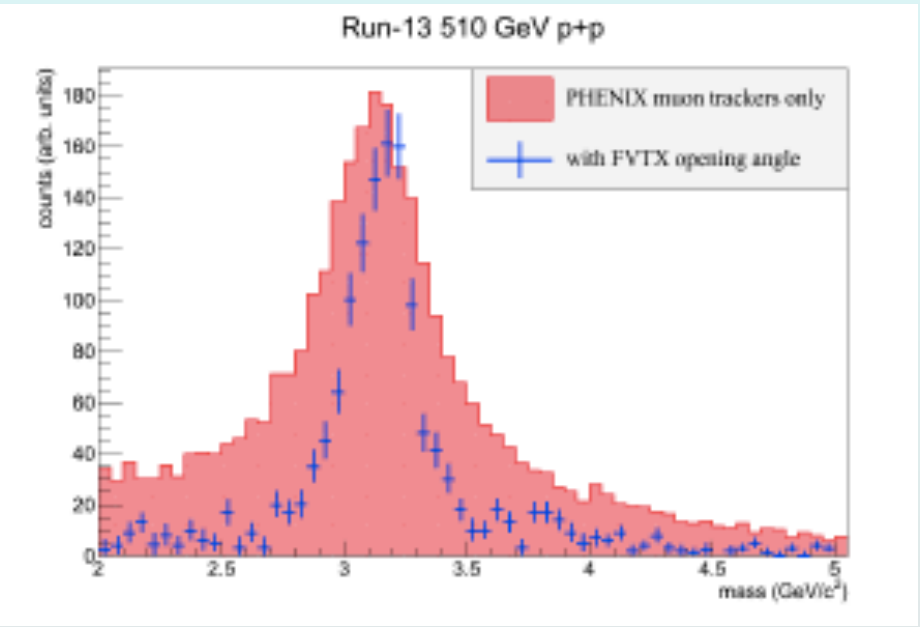
Rapidity dependence is coming

Forward vertex detector FVTX

improves mass resolution →

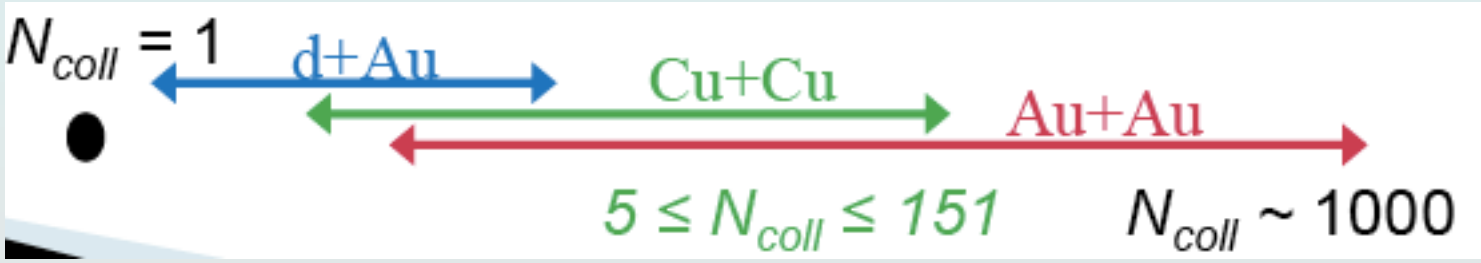
Ψ' at forward rapidity!





Open Heavy Flavor production in d+Au

- Leave aside the question of final state breakup
- Harder to measure the production cross sections
  - PHENIX approach is to use semi-leptonic decays
  - Measure non-photonic single leptons
  - Or intermediate mass lepton pairs
- ***PHENIX provides reach in rapidity and N_{coll}***



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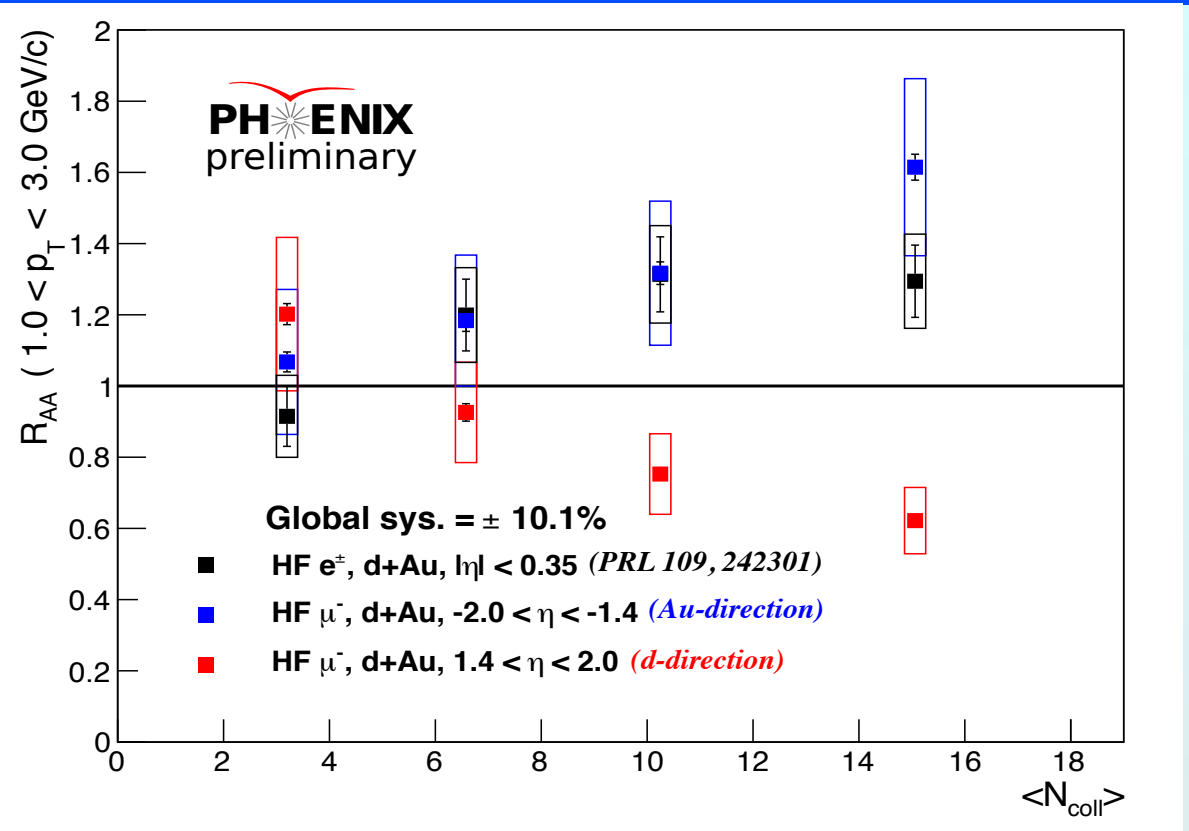
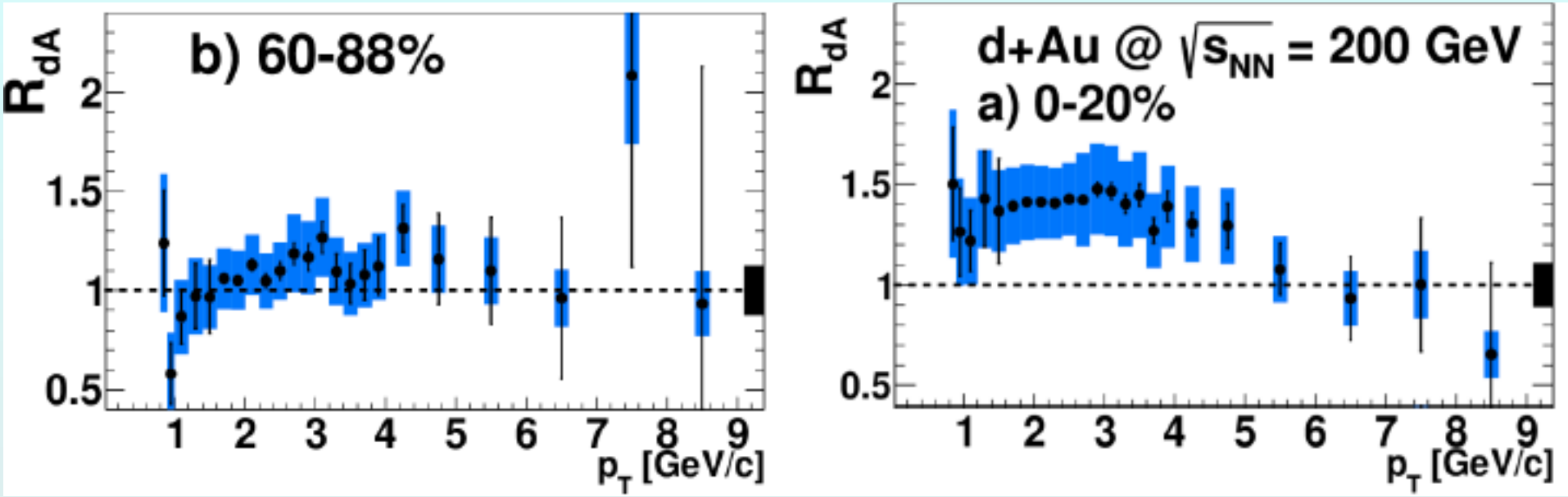
Open heavy flavor rapidity dependence



- Clear enhancement in Au-going direction sensitive to high-x in Au (*Anti-shadowing regime*)
- Suppression in d-going direction sensitive to low-x (*shadowing*)
- Enhancement also at mid-rapidity

At mid-rapidity

PRL109, 242301 (2012)



- R_{dA}=1 for peripheral collisions
- Enhancement at low p_T in central collisions
  - Recall J/ψ p_T evidence for parton multiple scattering
  - "classic" reason for Cronin Effect

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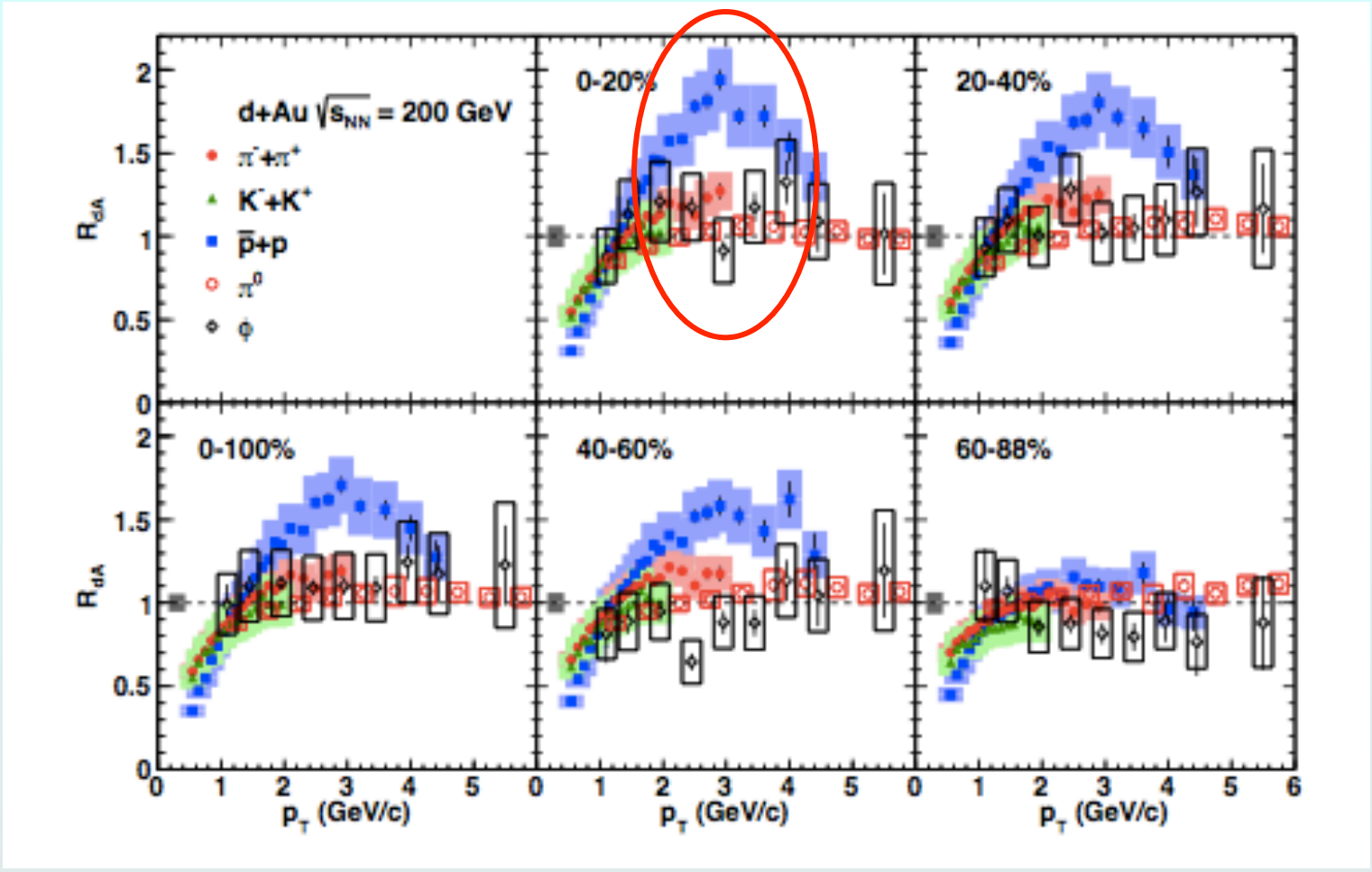
NB: Classic does not always mean right!



😈 "old" problem with "Cronin effect = parton multiple scattering"

How does the parton know it will produce a proton?

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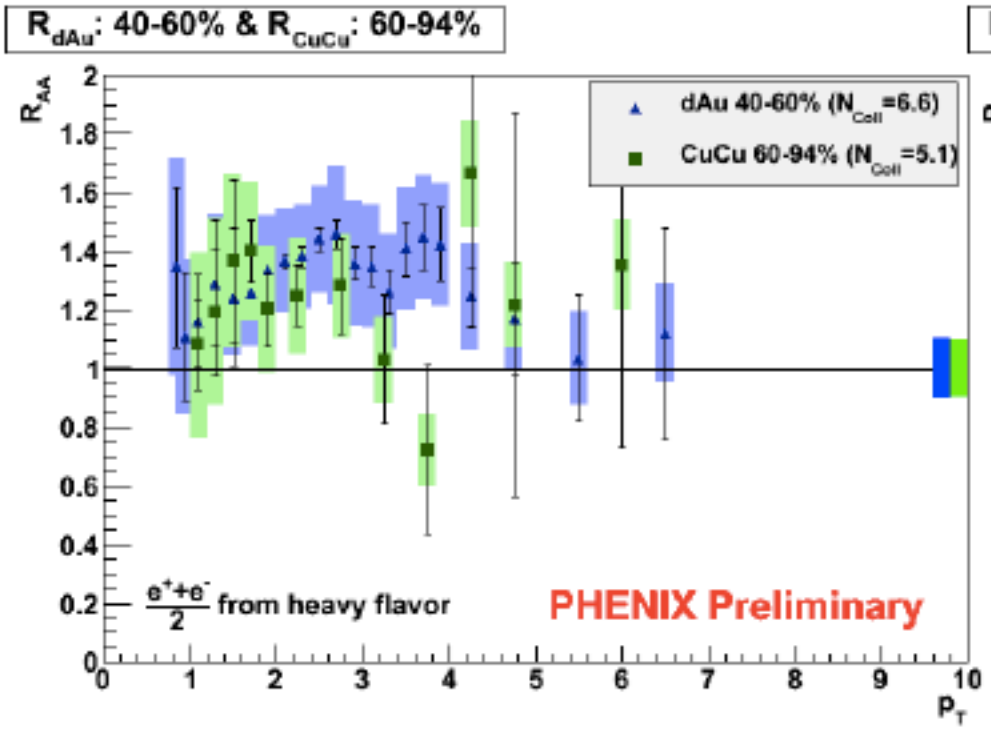
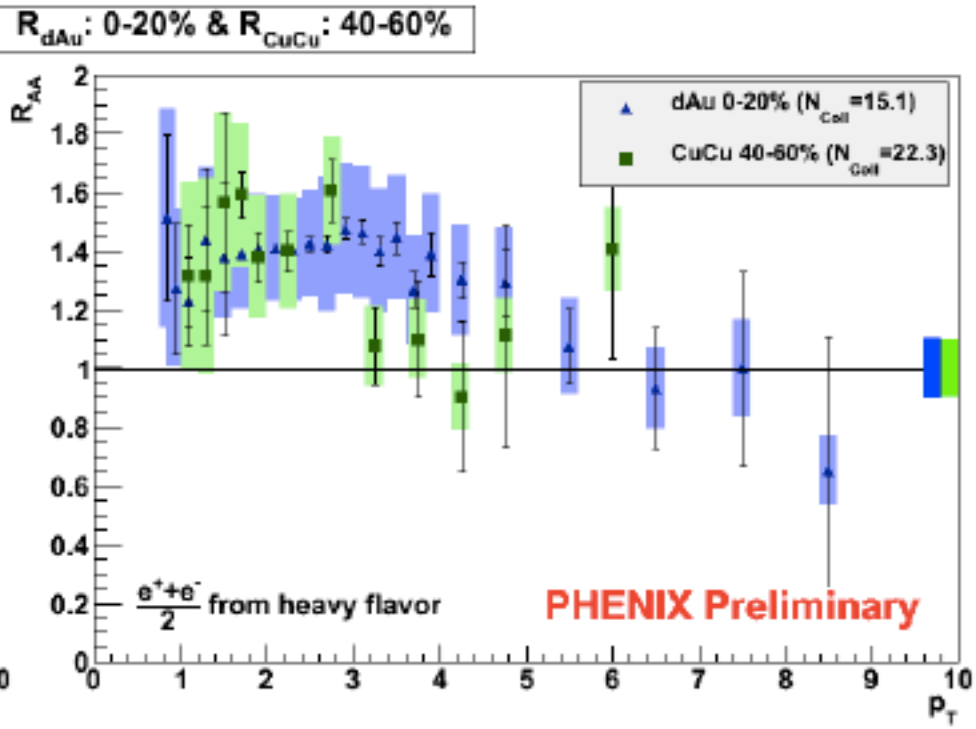
Heavy Flavor in d+Au: Electrons

- d+Au and Cu+Cu consistent in similar N_{coll} region

$\langle N_{coll}\rangle_{dAu} = 6.6$ & $\langle N_{coll}\rangle_{CuCu} = 5.1$
$\langle N_{part}\rangle_{dAu} = 7.7$ & $\langle N_{part}\rangle_{CuCu} = 6.4$

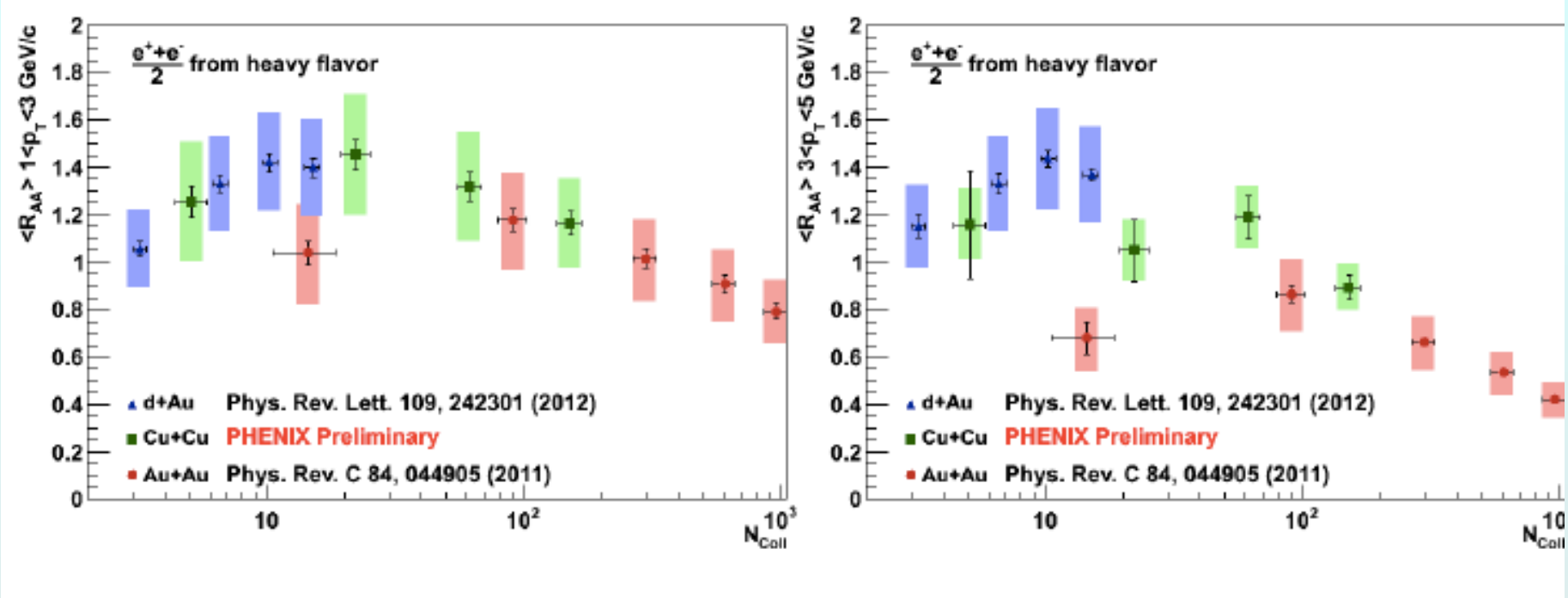
$\langle N_{coll}\rangle_{dAu} = 15.1$ & $\langle N_{coll}\rangle_{CuCu} = 22.3$
$\langle N_{part}\rangle_{dAu} = 15.6$ & $\langle N_{part}\rangle_{CuCu} = 21.2$





Phys. Rev. Lett. 109, 242301 (2012)

<R_{AA}> vs. Ncoll



- Enhancement in cold nuclear matter
- Then suppression in hot medium in A+A

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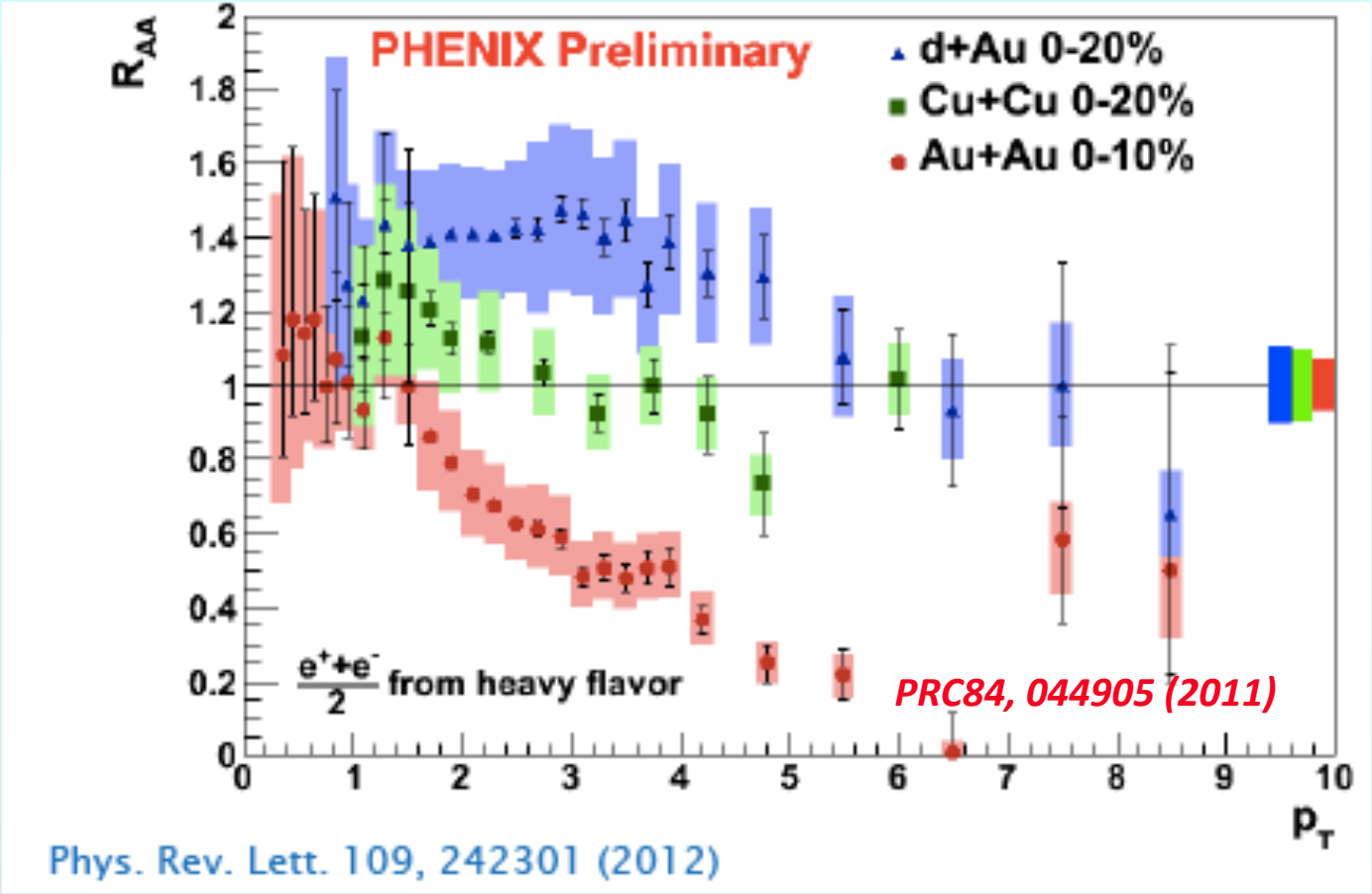
Should take both into account!



😈 **CNM baseline differs for π^0 & $e^{\pm}$**

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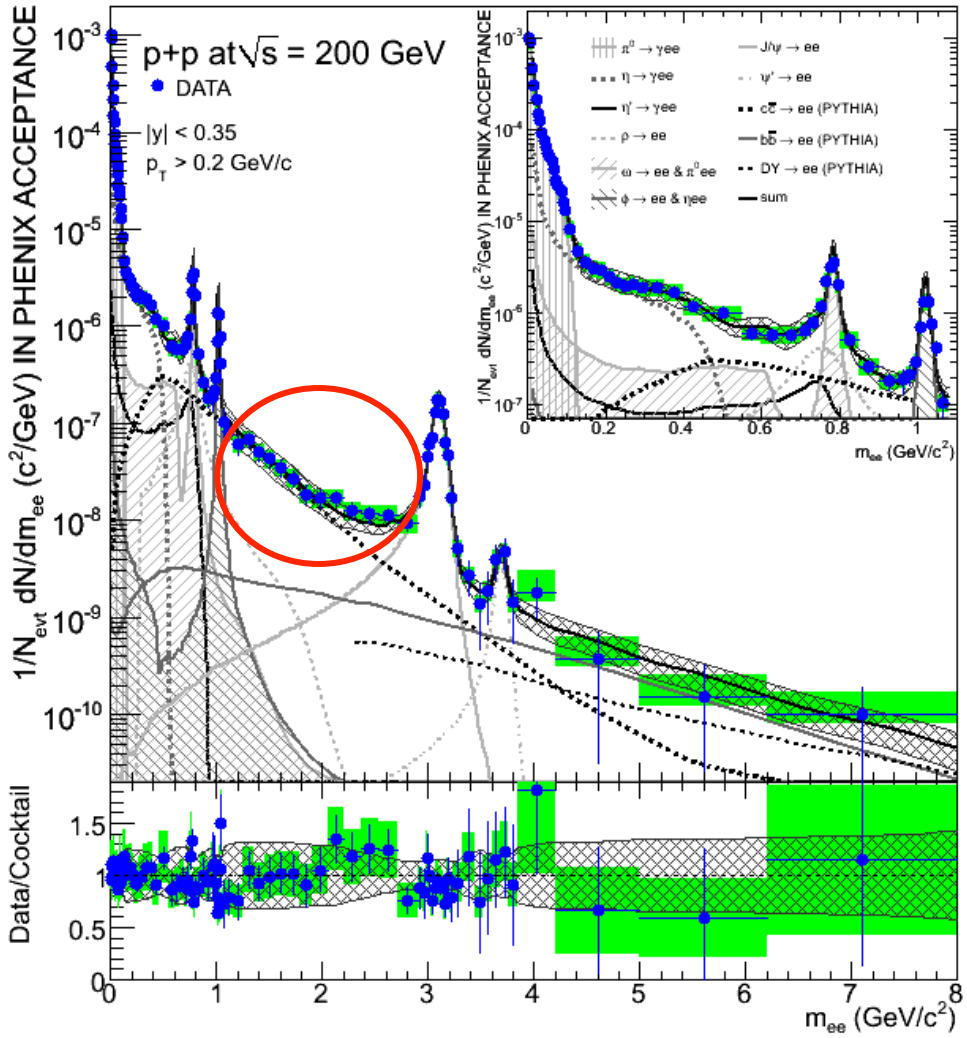
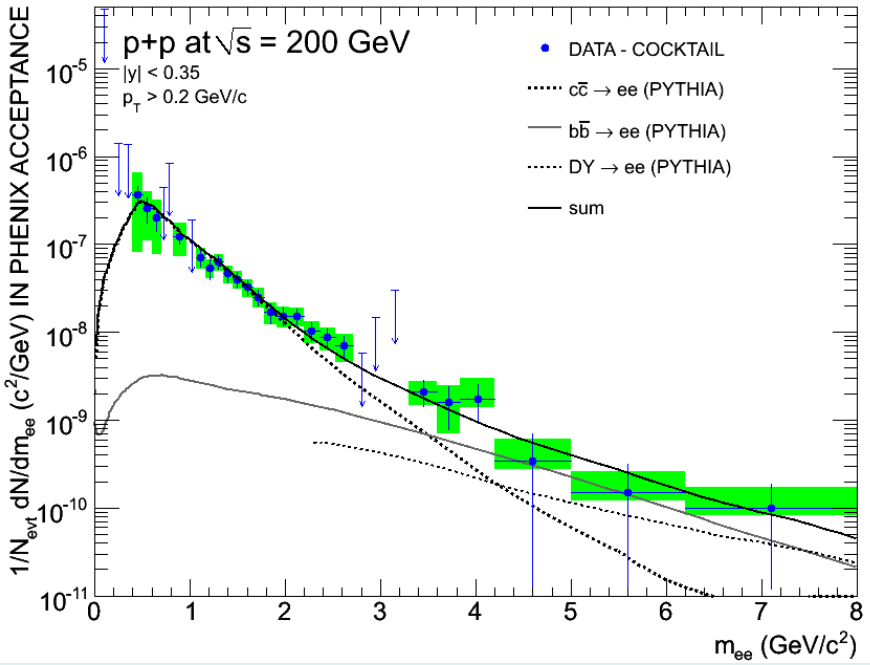
Another handle: di-electrons

PLB 670, 313 (2009) ***p+p***





σ_{charm} in p+p: 544μb ±39(stat) ±142(syst) ± 200 (model)

σ_{bot}: 3.9μb ±2.5(stat) $^{+3}_{-2}$(syst)

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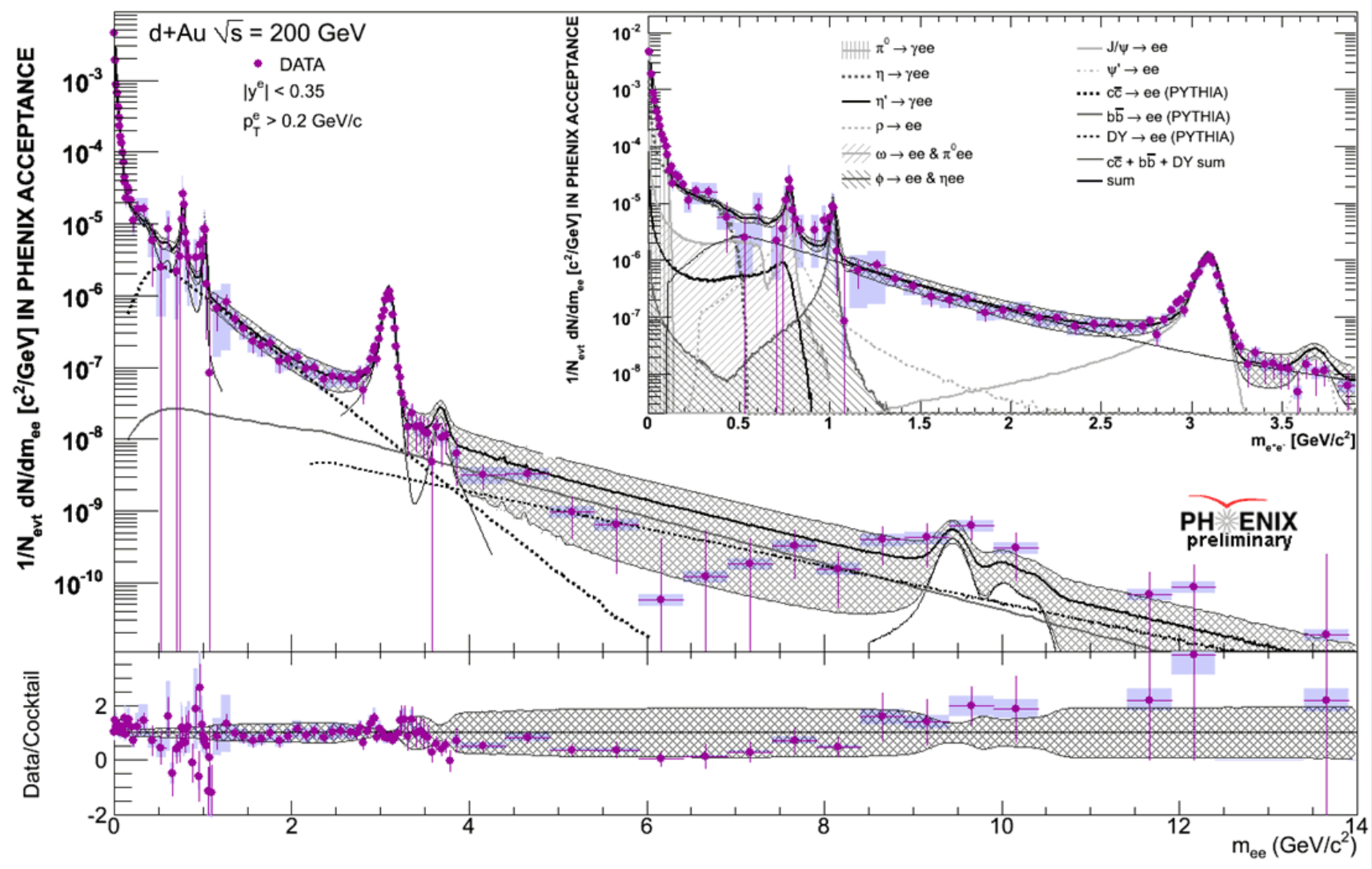
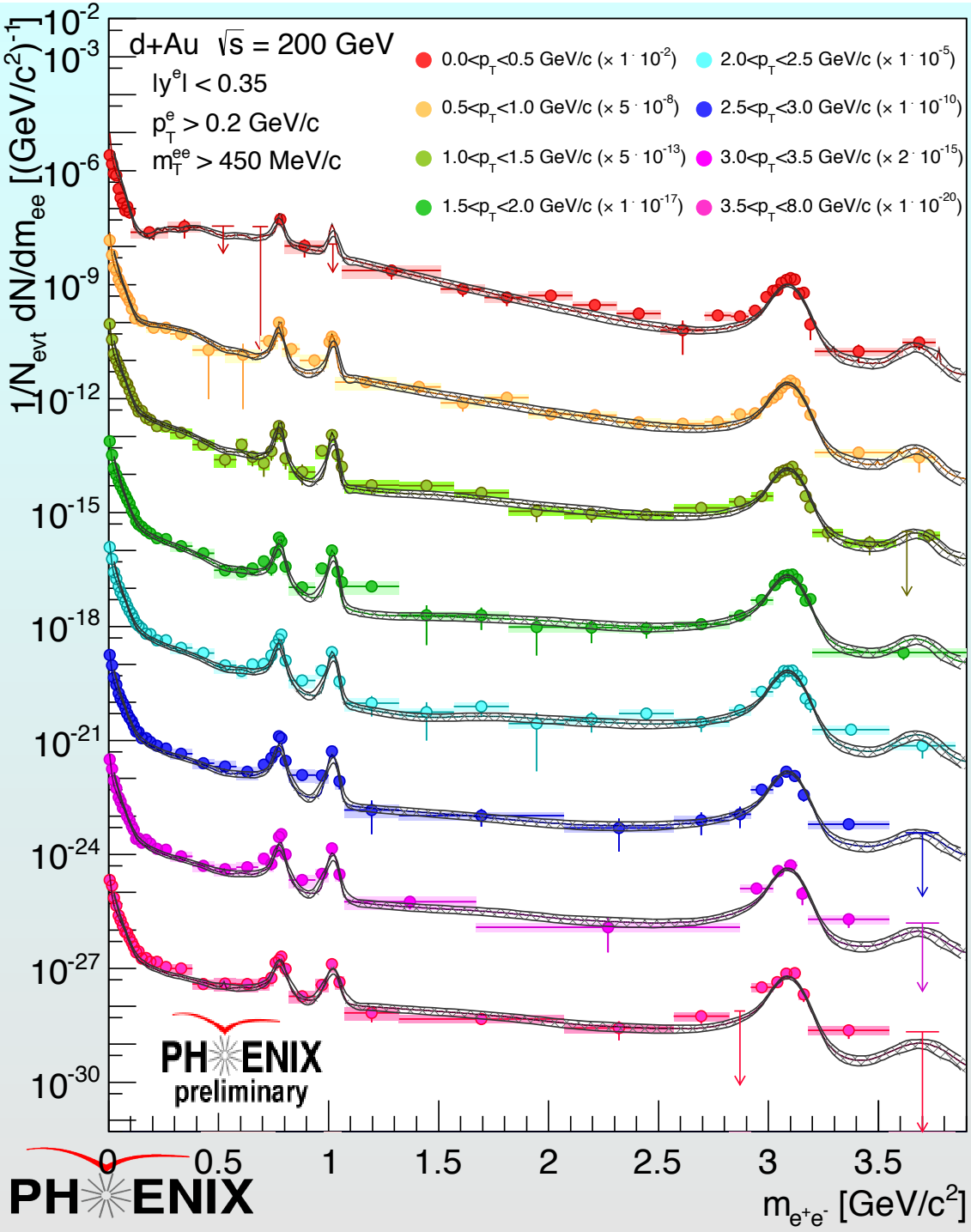
Di-electrons in d+Au



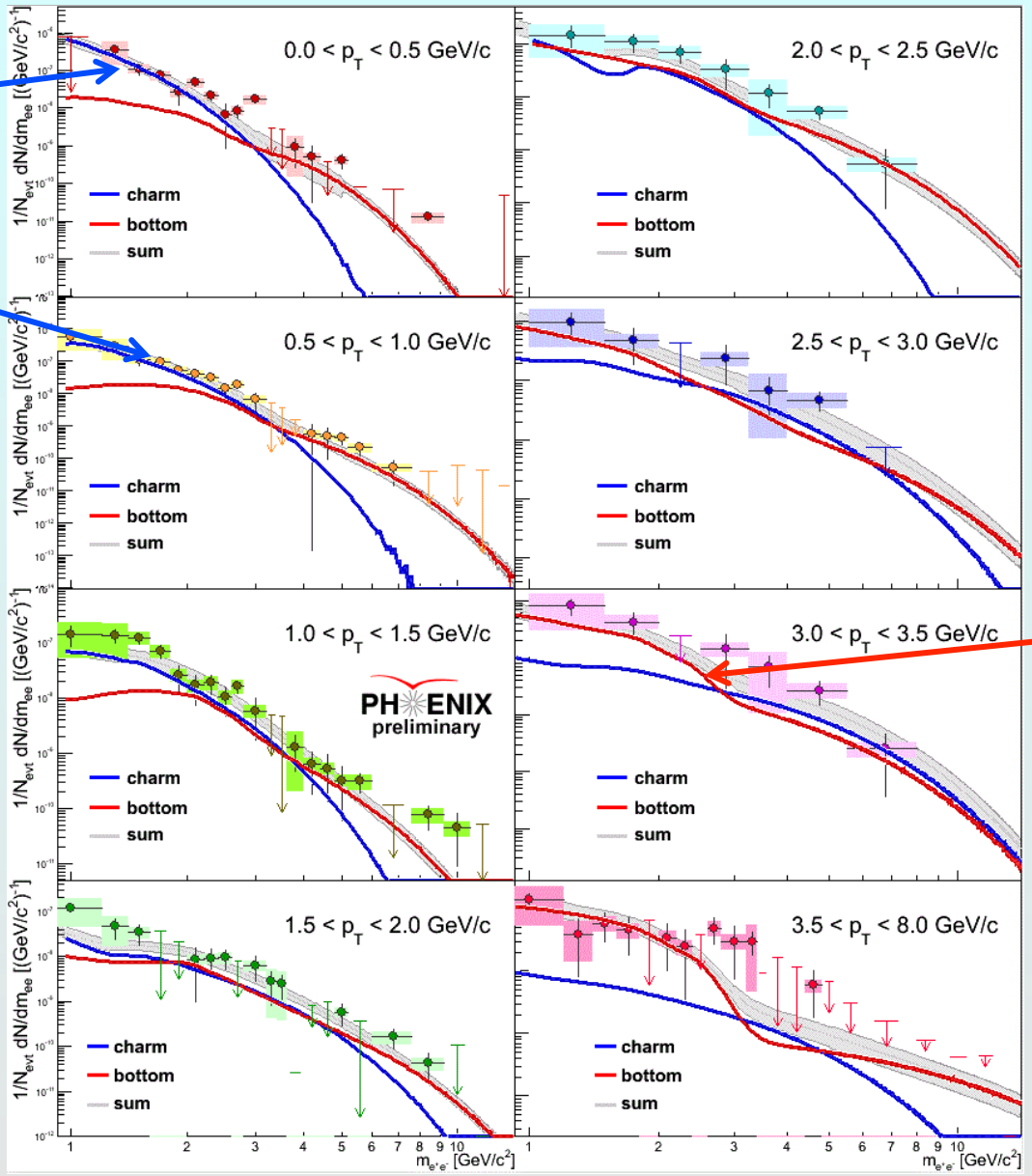


Good statistics in d+Au 2008 run

differential distributions in mass and p_T!

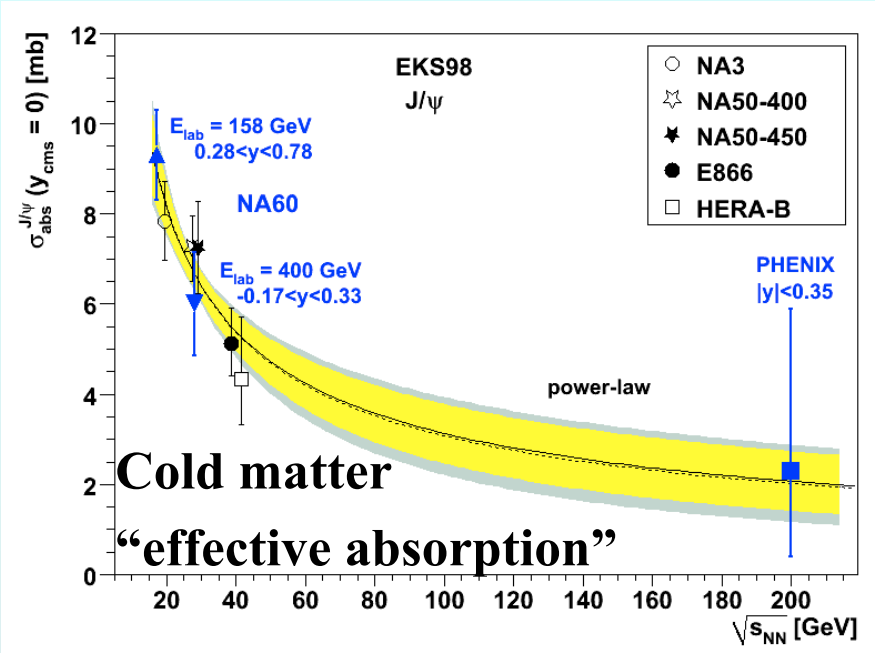
Separate charm and bottom

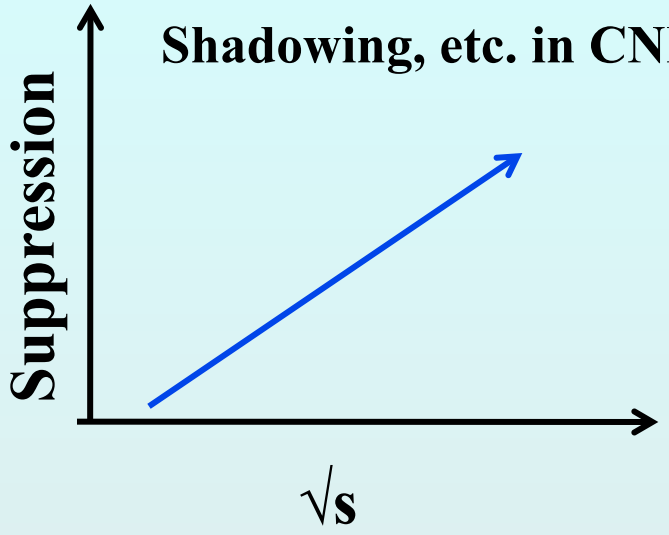
Charm dominates

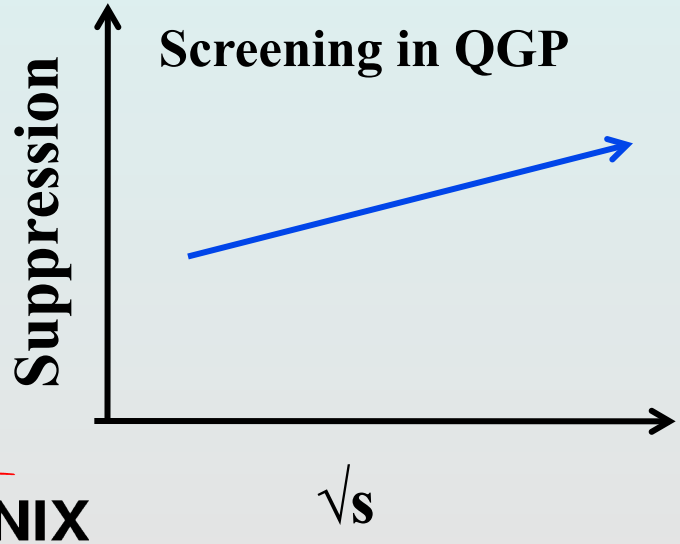


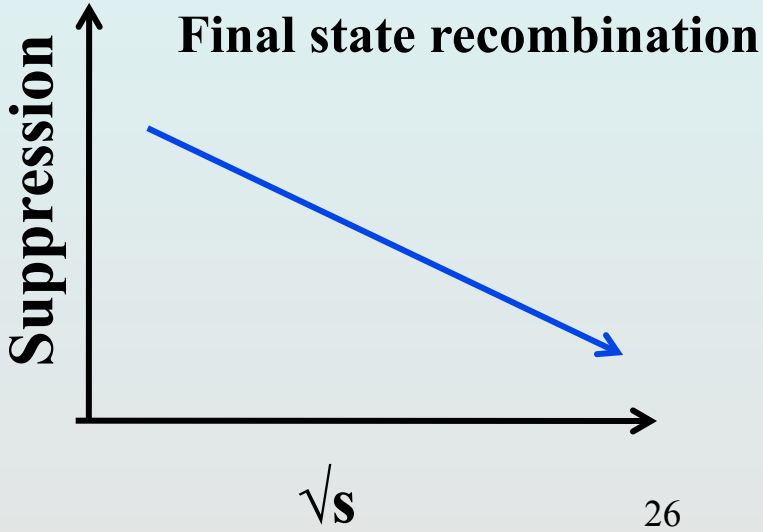
b dominates

NEED y, p_T, centrality, √s, species to sort it out!









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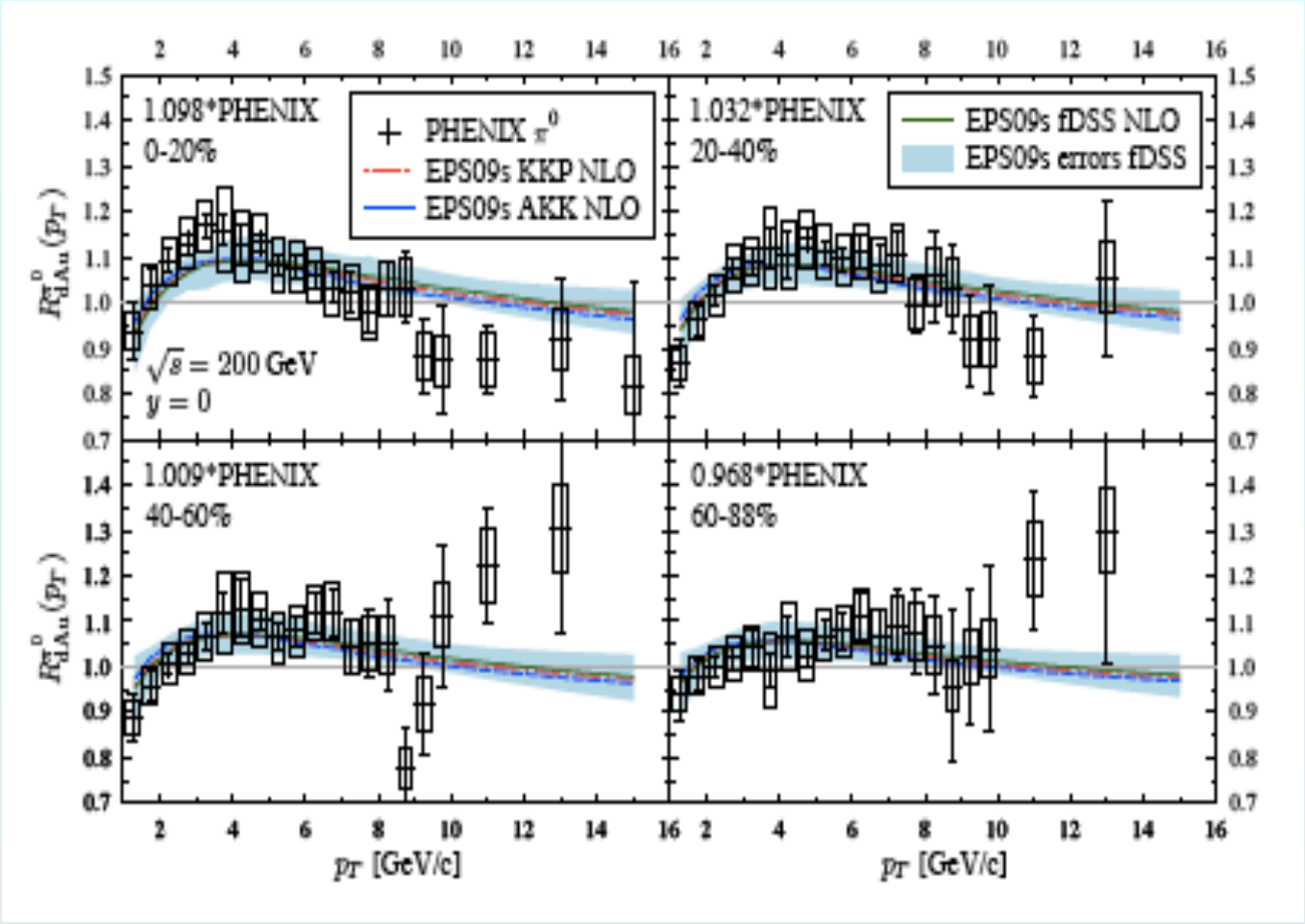
Turn now to jets and direct photons

arXiv 1205.5359

Hellenius, Eskola, et al

Fit data, including PHENIX π^0 R_{dAu}

Get b-dependent nPDFs



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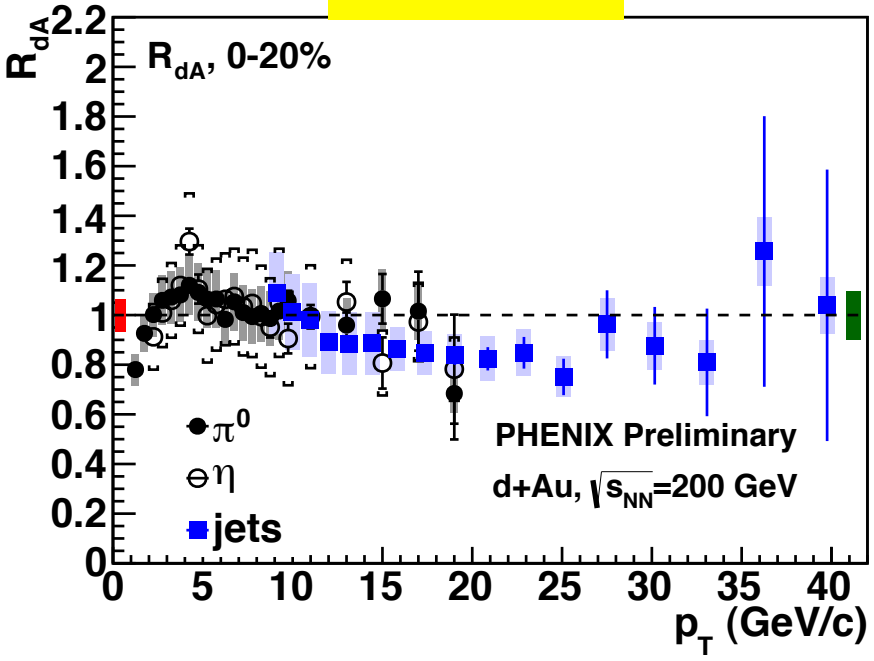
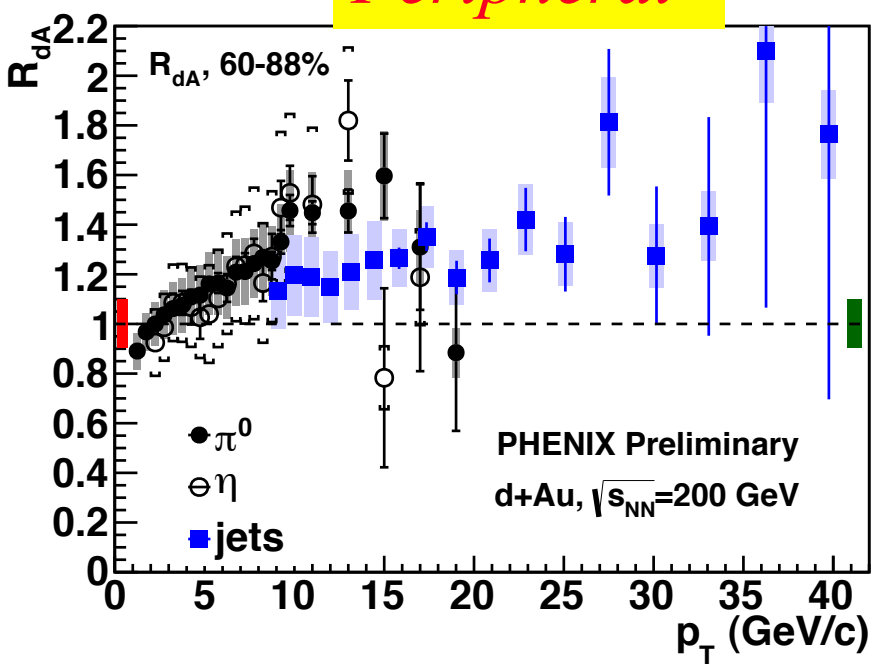
Suprising behavior of jets in d+Au

Central



Peripheral



- Enhancement in peripheral, slight suppression in central

  Surprisingly strong centrality dependence in nuclear PDFs
- Competing cold nuclear matter effects? Auto-correlations between high p_T processes & centrality measure?

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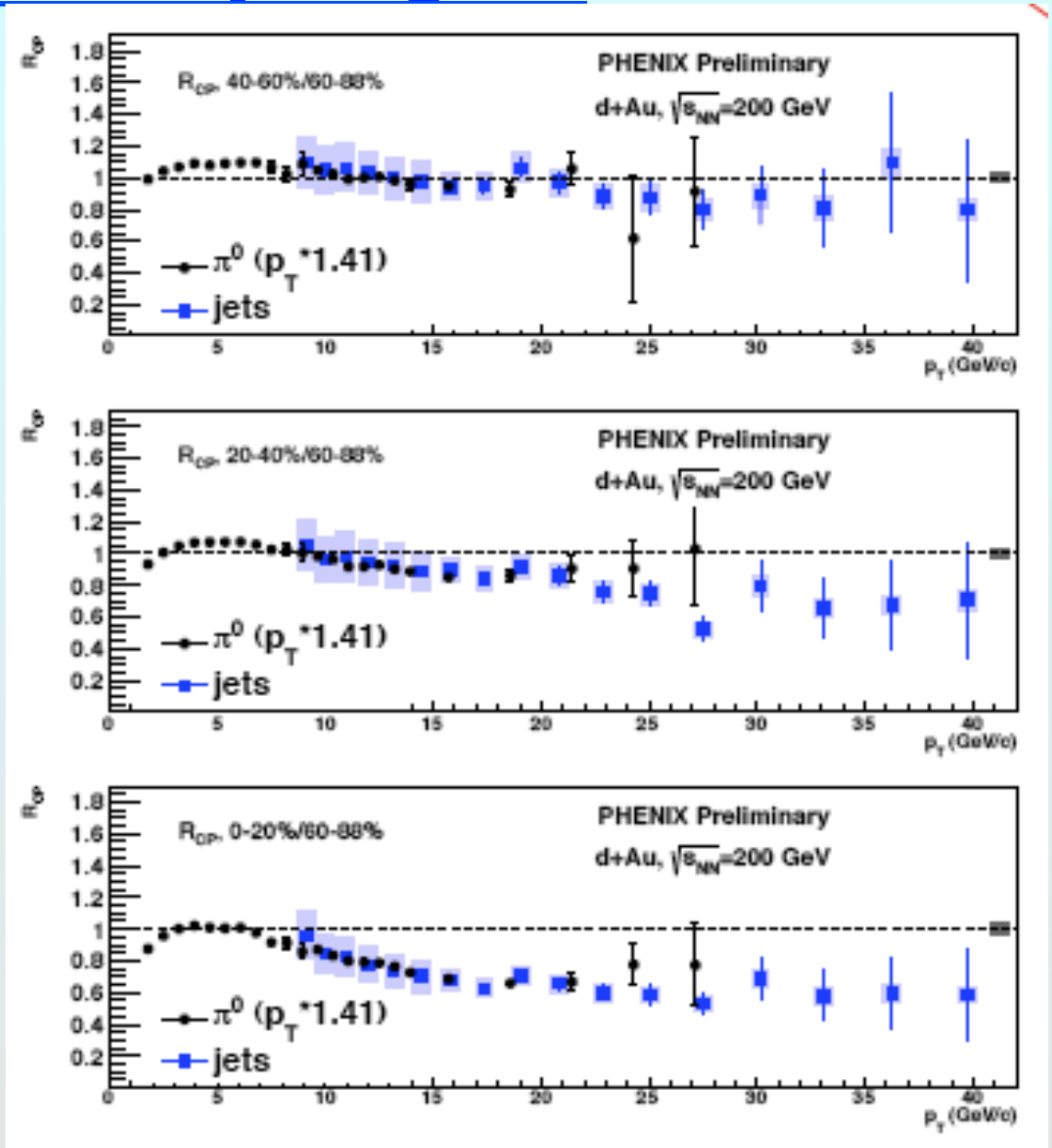
Do the π^0 and jets agree?

- Scale π^0 by 1/0.7
  i.e. $1/\langle Z_{leading} \rangle$
- Agreement is excellent

- R_{cp} shows strong centrality dependence

Autocorrelation?

How does the presence of a jet with p_T>10 GeV/c modify definition of a "peripheral d+Au collision"?



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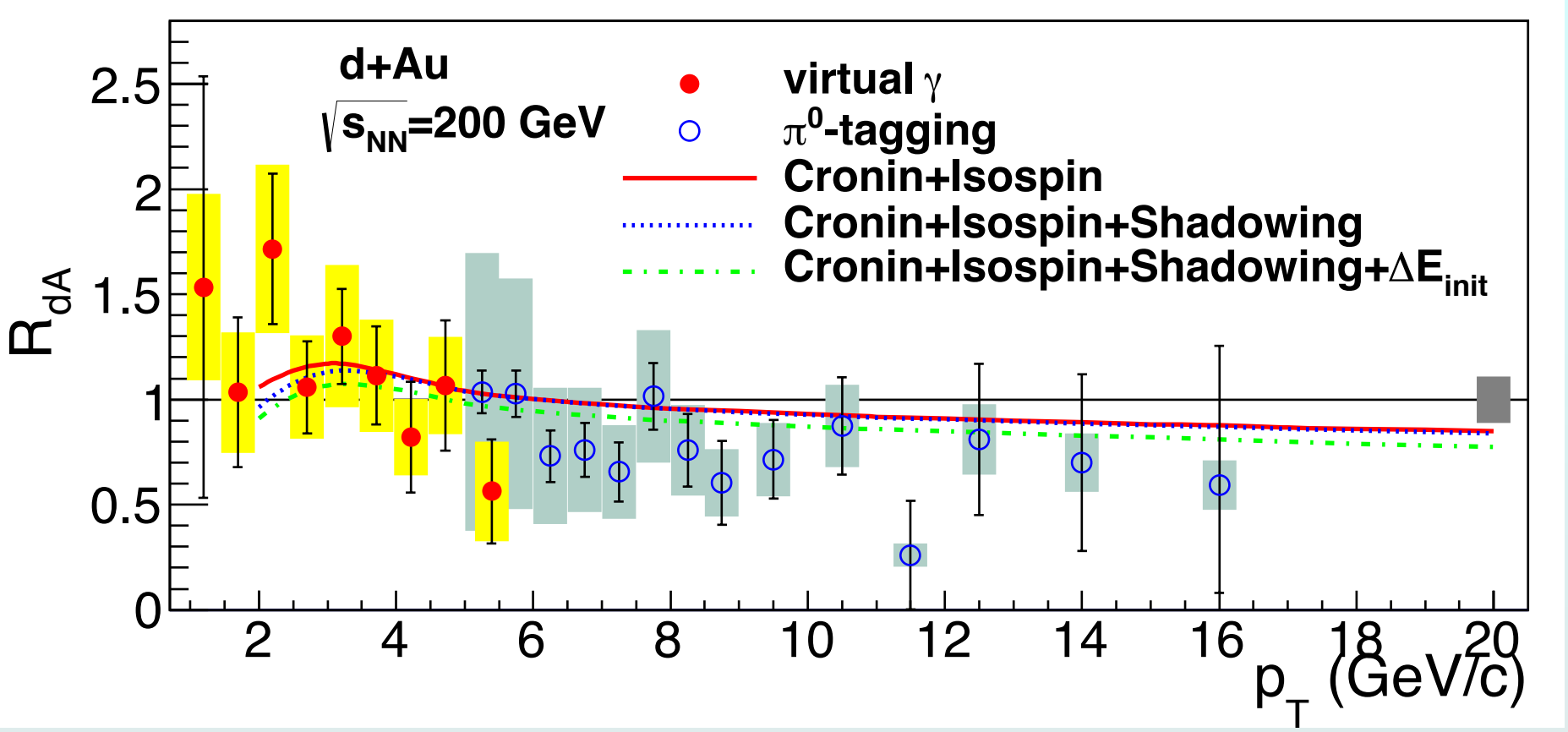
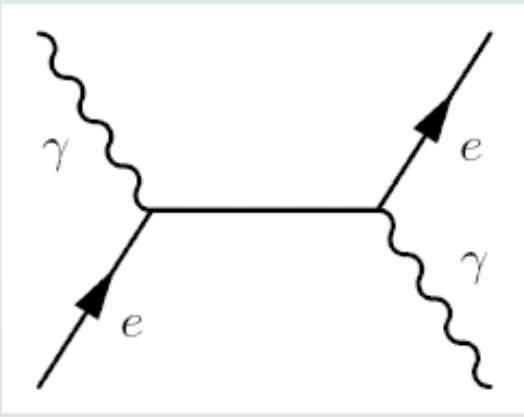
γ_{direct} in d+Au

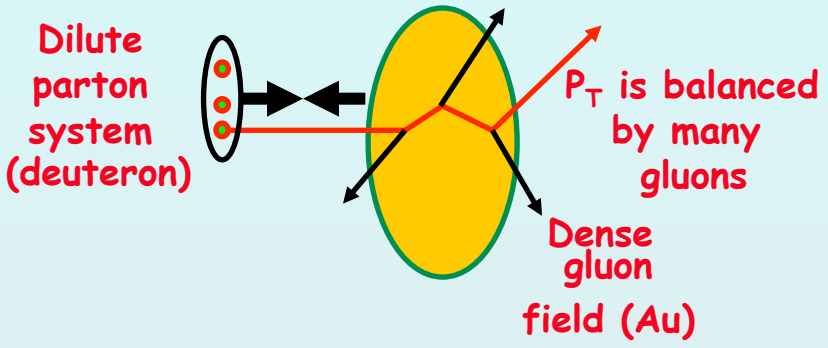


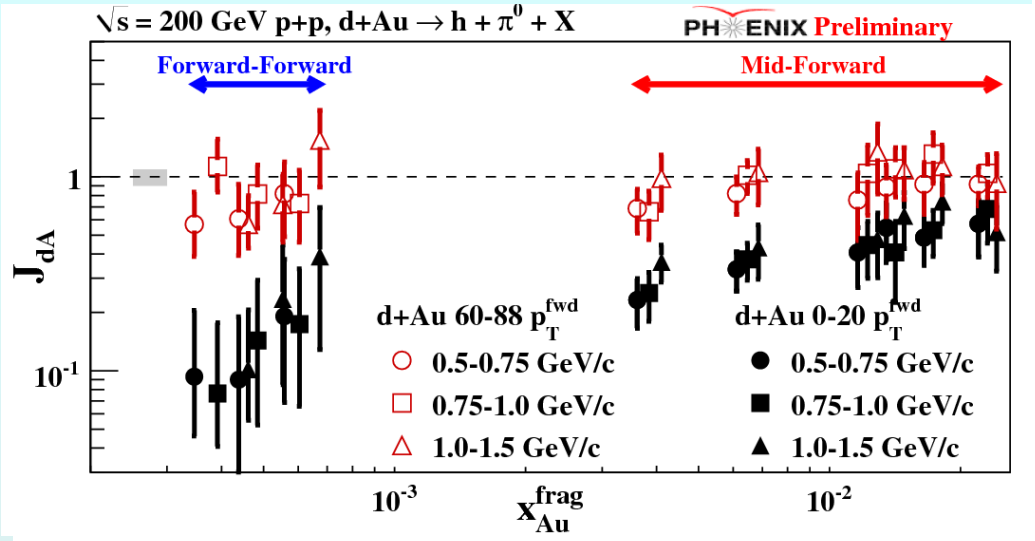
- No modification of direct photons in initial hard scattering and PDF compared to p+p at mid-rapidity

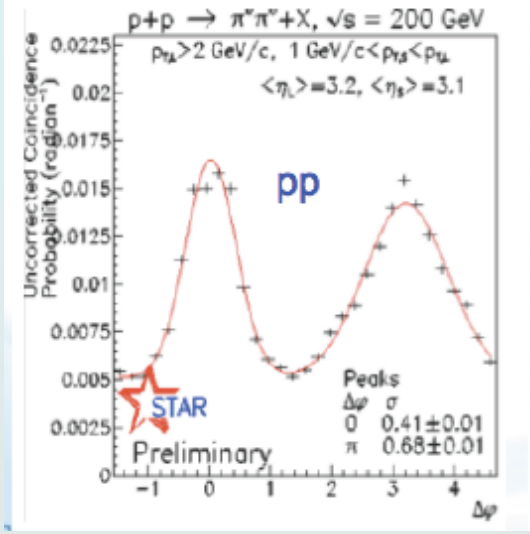


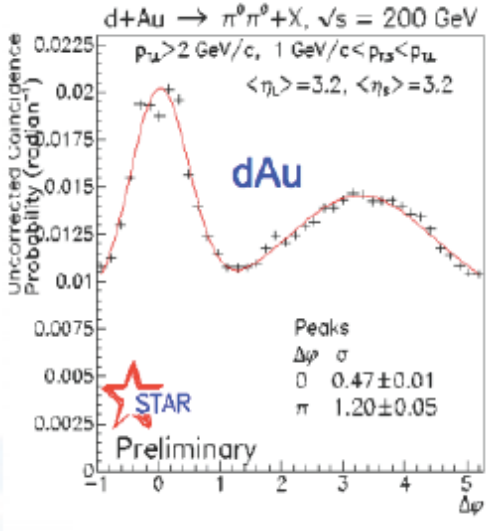
PHENIX

Initial State: shadowed or CGC?







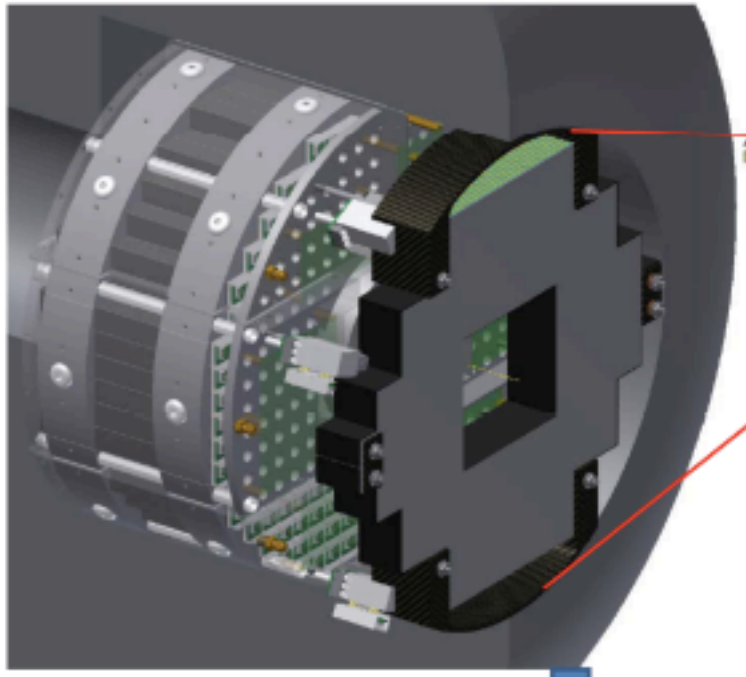


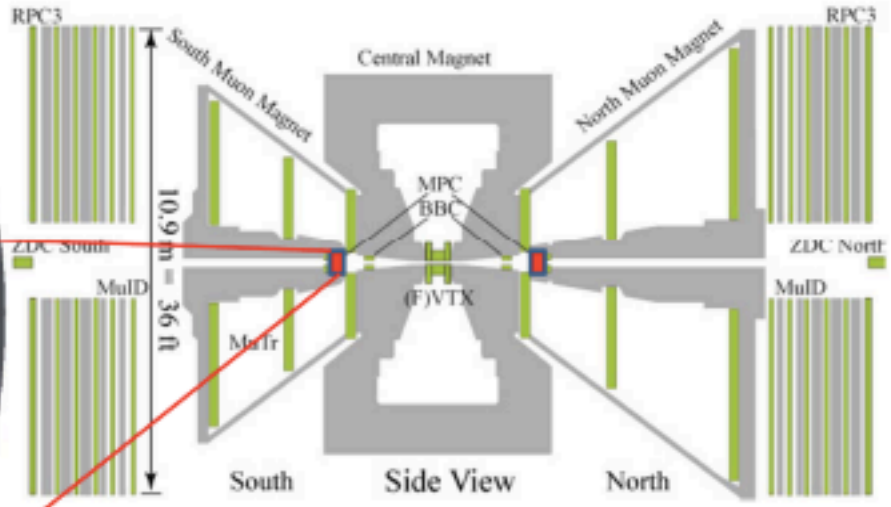
Use direct photons!

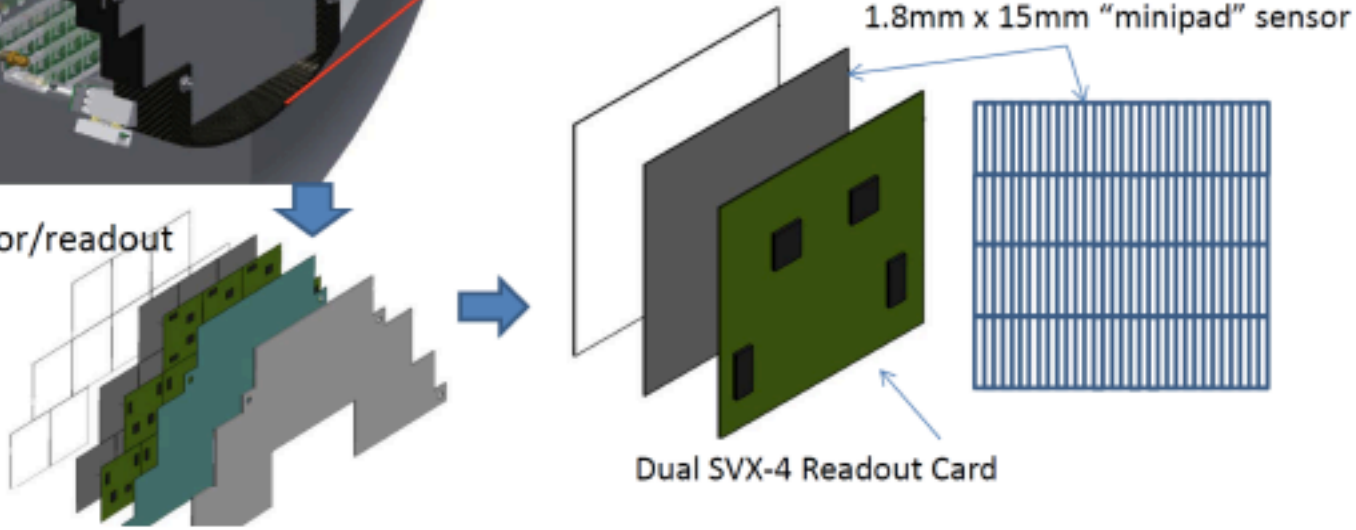
PHENIX

MPC-EX upgrade

$3.1 < \eta < 3.8$



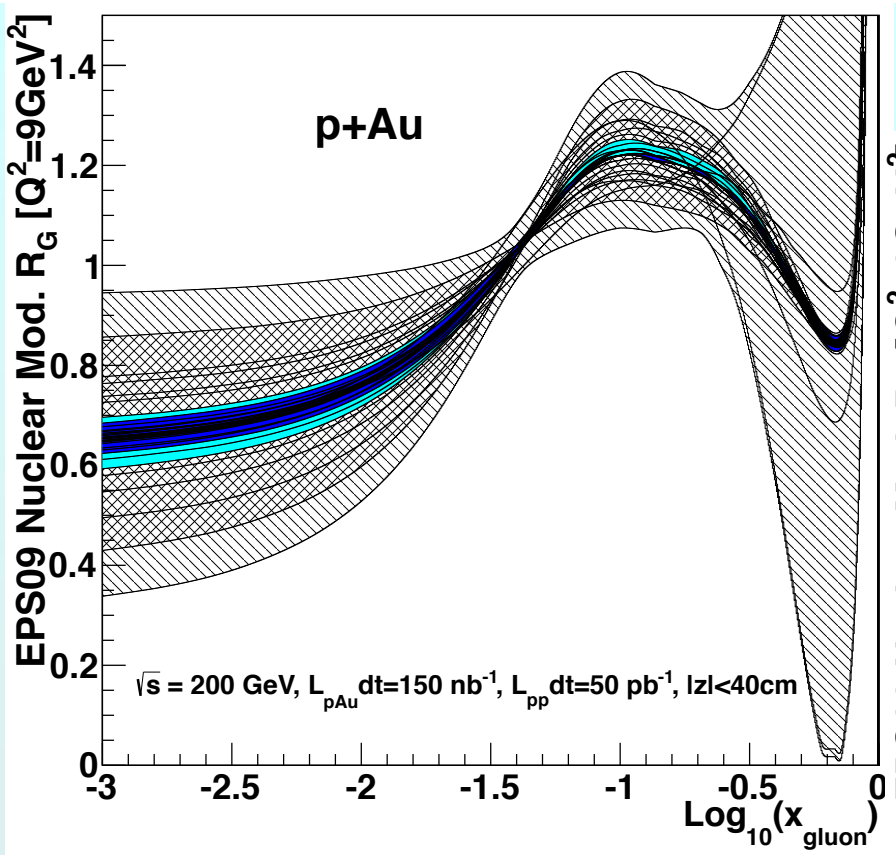


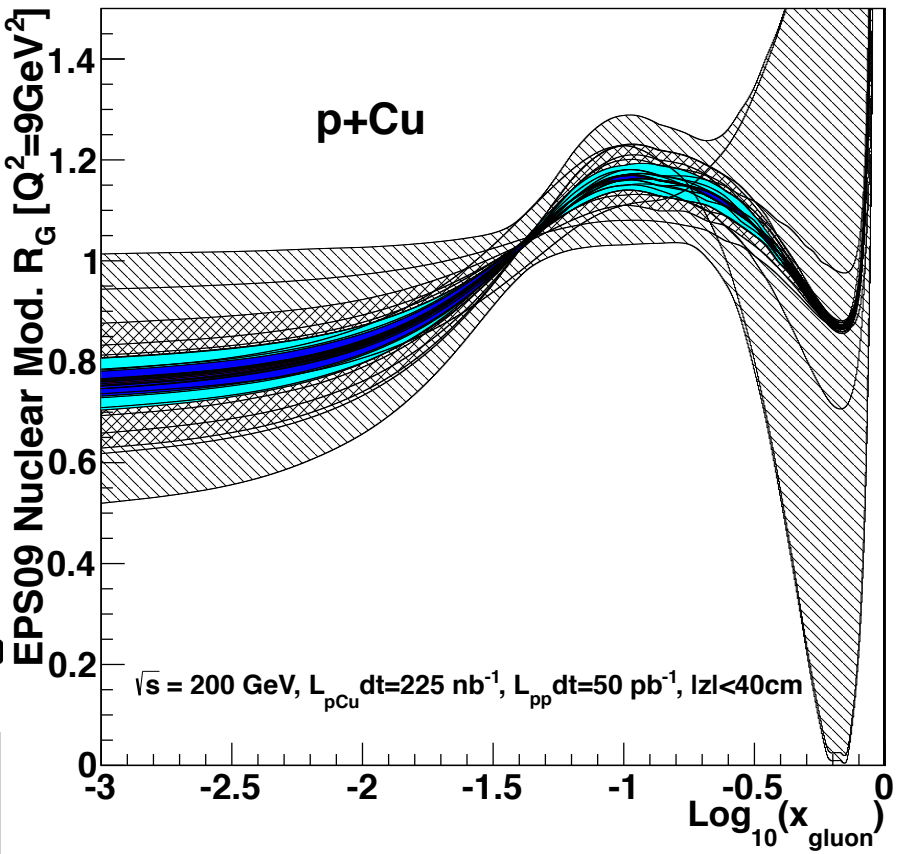


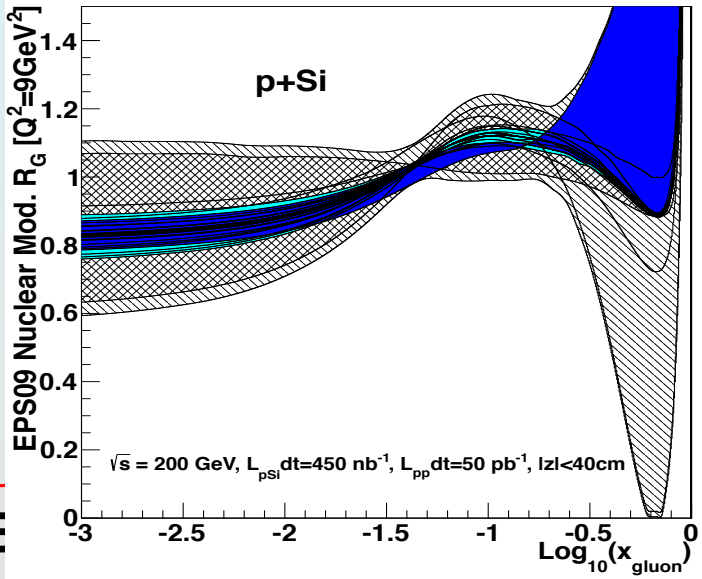
PHENIX

Reconstruct prompt γ and π^0 to 80 GeV: low & high x!

Will measure p+A in 2015







MPC-EX preshower: γ vs. π^0 decay

Substantially improve nPDFs!

to x ~ 10^{-3} and also at high x

2-4 weeks running per species

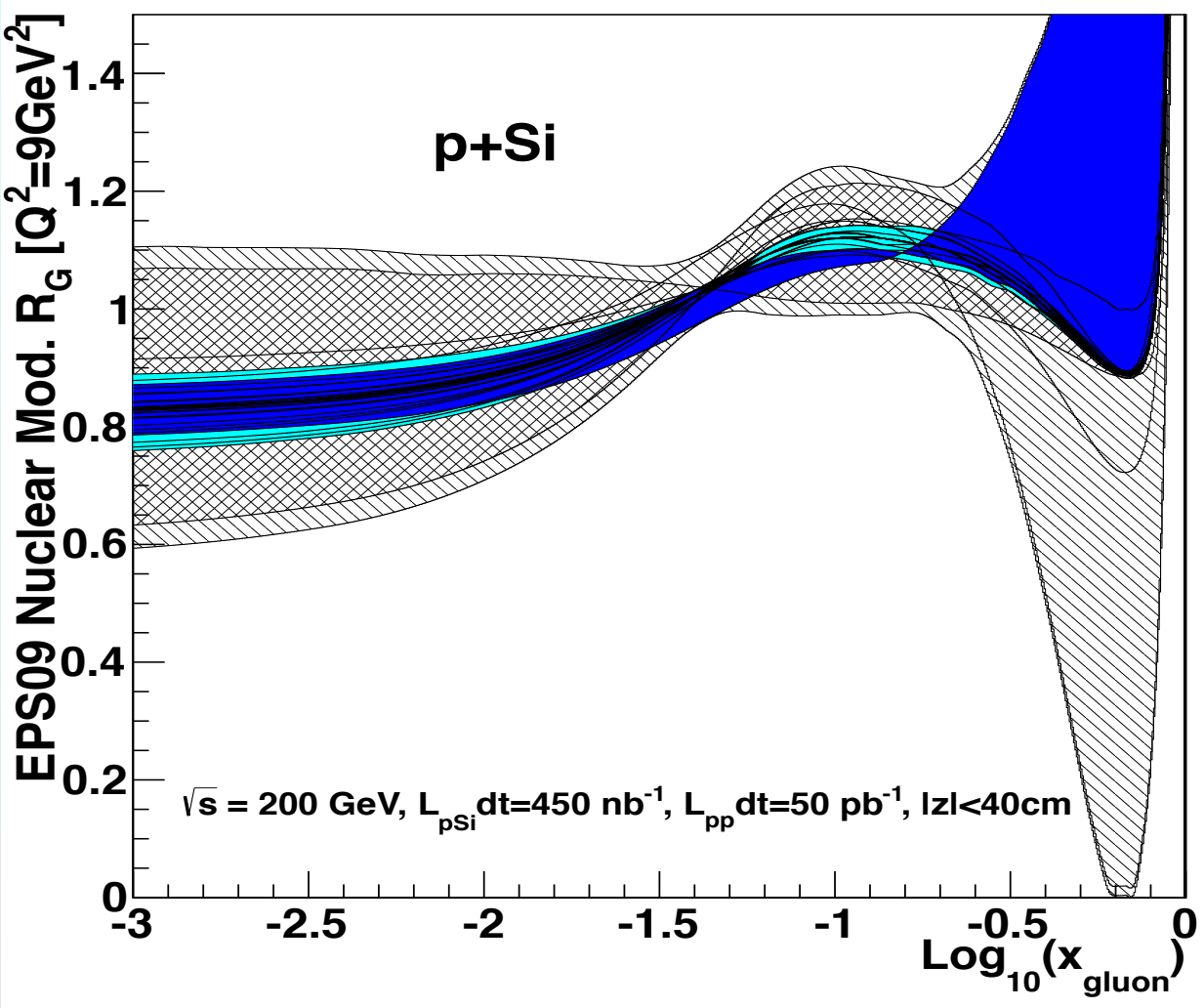
Conclusions

- Evidence for (expected) shadowing & antishadowing
  Suppression of J/ψ and di-h beyond shadowing at low x!!
- Heavy Flavor indicates
  parton multiple scattering (Cronin effect)
  parton energy loss; interplay w/other initial state effects?
  final state effects break up quarkonia, too
- Cronin effect: modifies charm suppression in A+A!
- Jet trend with centrality remains mysterious
  Need that "centrality" workshop – for RHIC+LHC!
- No strong evidence for direct photon modification at mid-y
  At least, not with current statistics
  Need forward rapidity to probe low-x and pin down nPDFs

NEED data vs. y, p_T, centrality, √s, species to sort it all out!

to Wit: still lots of fun to be had with p/d+Au!

- **Backup slides**


p+Si
EPS09 Nuclear Mod. R_G [Q^2=9GeV^2]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-3
-2.5
-2
-1.5
-1
-0.5
0
$\sqrt{s}$ = 200 GeV, $L_{pSi}dt$=450 nb^{-1}, $L_{pp}dt$=50 pb^{-1}, |z|<40cm
$Log_{10}(x_{gluon})$

PHENIX

VTX & FVTX