PHENIX d+Au insights

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For the PHENIX Collaboration

9th International Workshop on High p_T at the LHC

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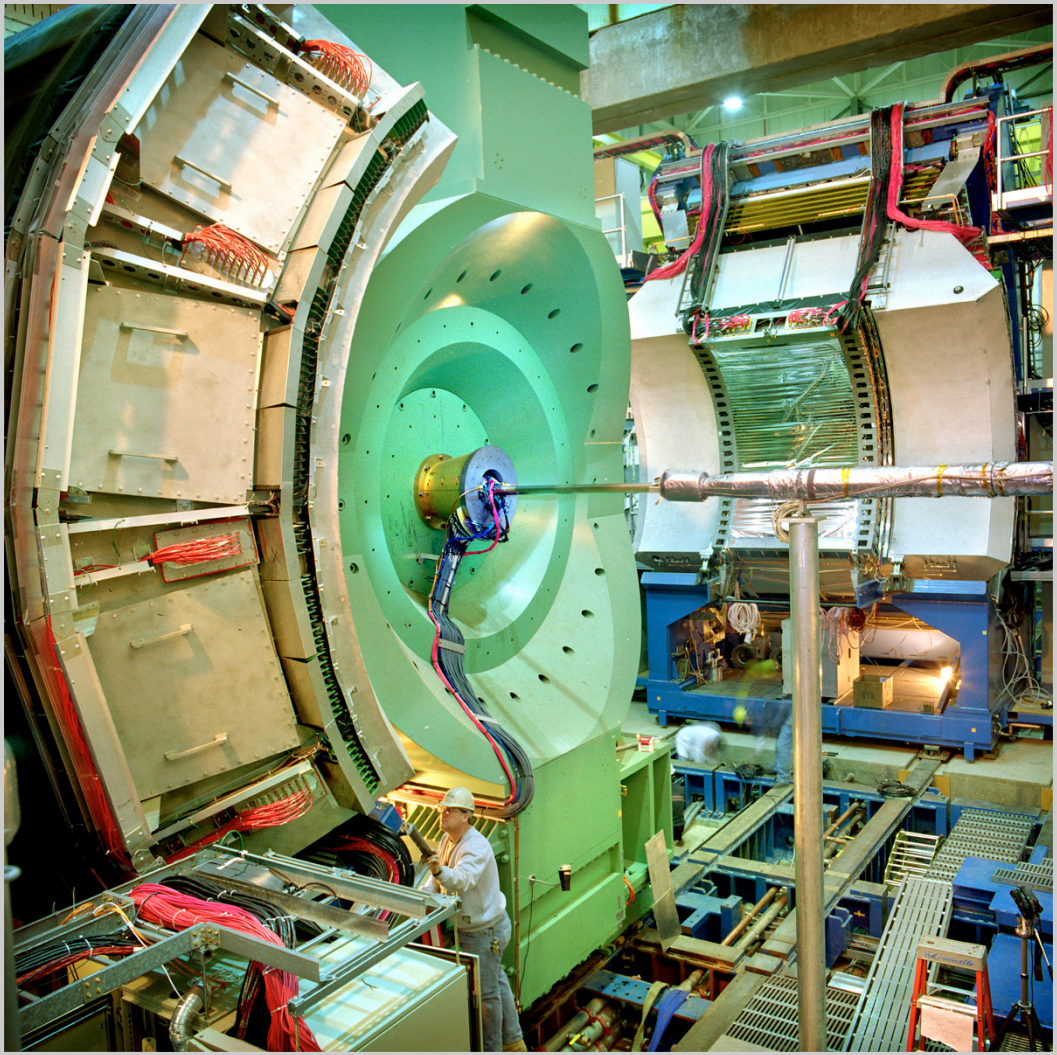

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Outline

- **Hadron correlations in d+Au**

  Flow in d+Au? What does this say about thermalization?

  Probe of initial conditions

- **Heavy flavor production**

  Quarkonia

  Open heavy flavor in Craig Ogilvie's talk

  Di-leptons

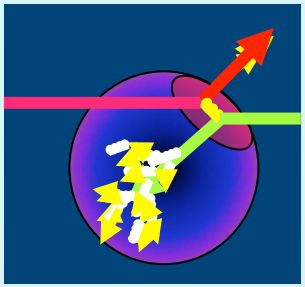
  Saturation, shadowing, anti-shadowing, parton energy loss, parton (re)scattering in cold nuclear matter

- **Direct photons**

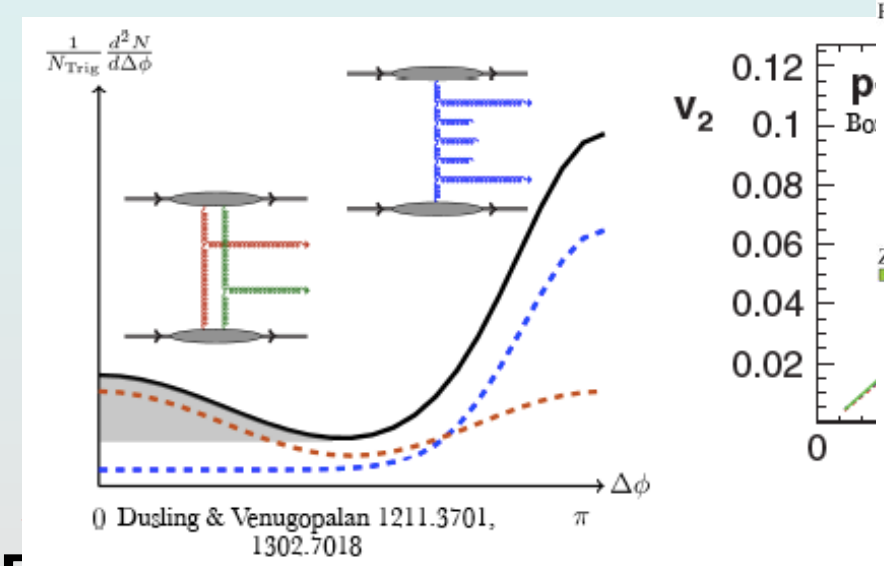
  Nuclear gluon distribution

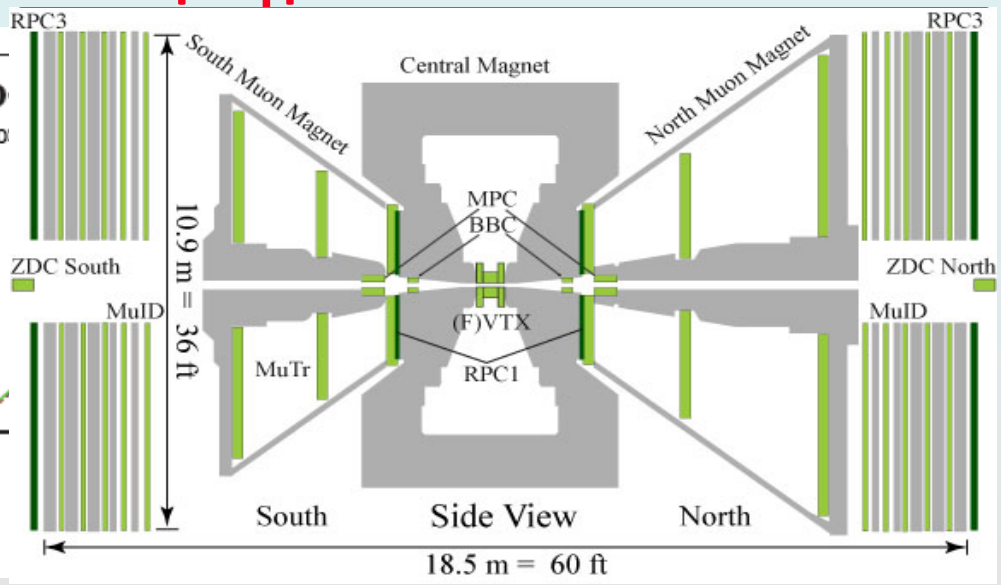
Di-hadrons in d+Au: initial or final state effect?

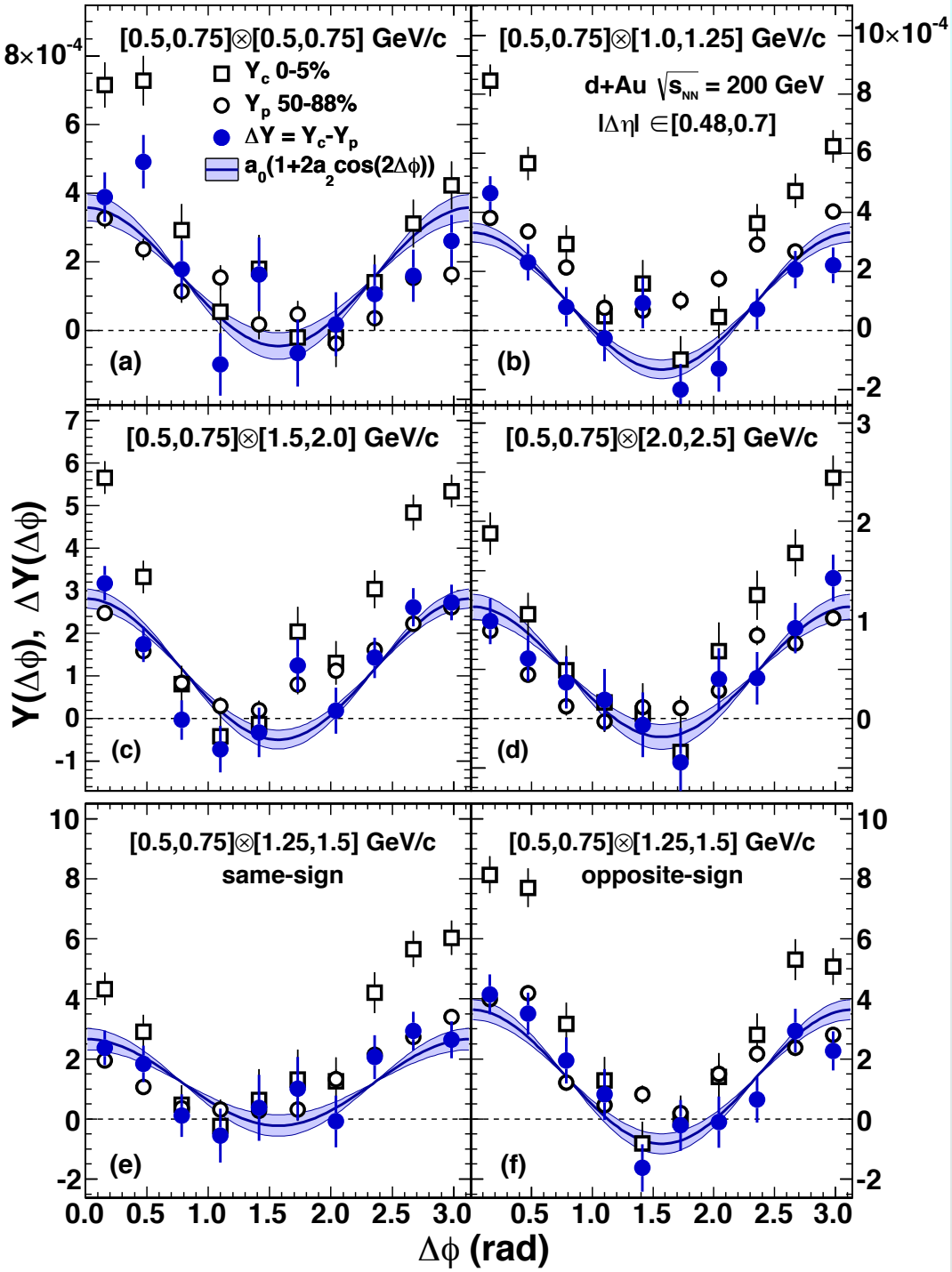
- **Jet correlations**
  - High p_T: maximize jet signal/minimize combinatorial bkgd
  - Near side/same jet produces small $\Delta\eta$ correlation



- **Correlations in underlying event**
  - ≥1 low p_T particle for sensitivity to underlying event
  - Select maximum $\Delta\eta$
    - In PHENIX central arms: $0.48 < |\Delta\eta| < 0.7$
    - MPC-central correlations: $3.0 < |\Delta\eta| < 4.0$







Di-hadrons in the central arms

$0.48 < |\Delta\eta| < 0.7$

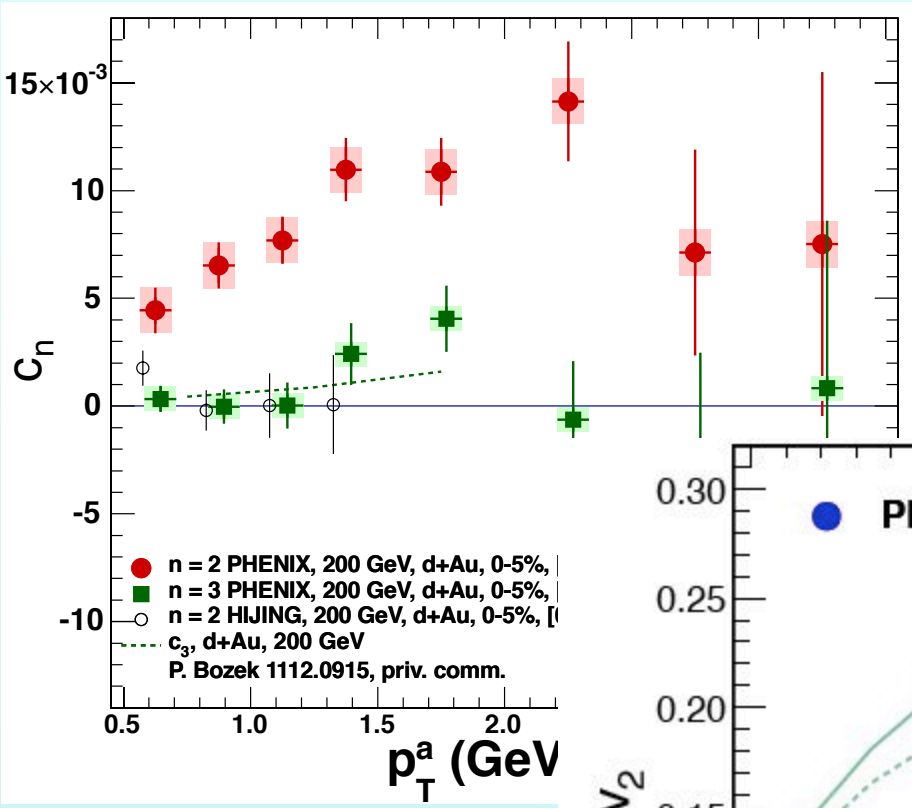
Central - peripheral to remove remaining jet

Looks awfully flow-like!

Opposite sign enhances jet contribution; subtraction works!

arXiv: 1303.1794

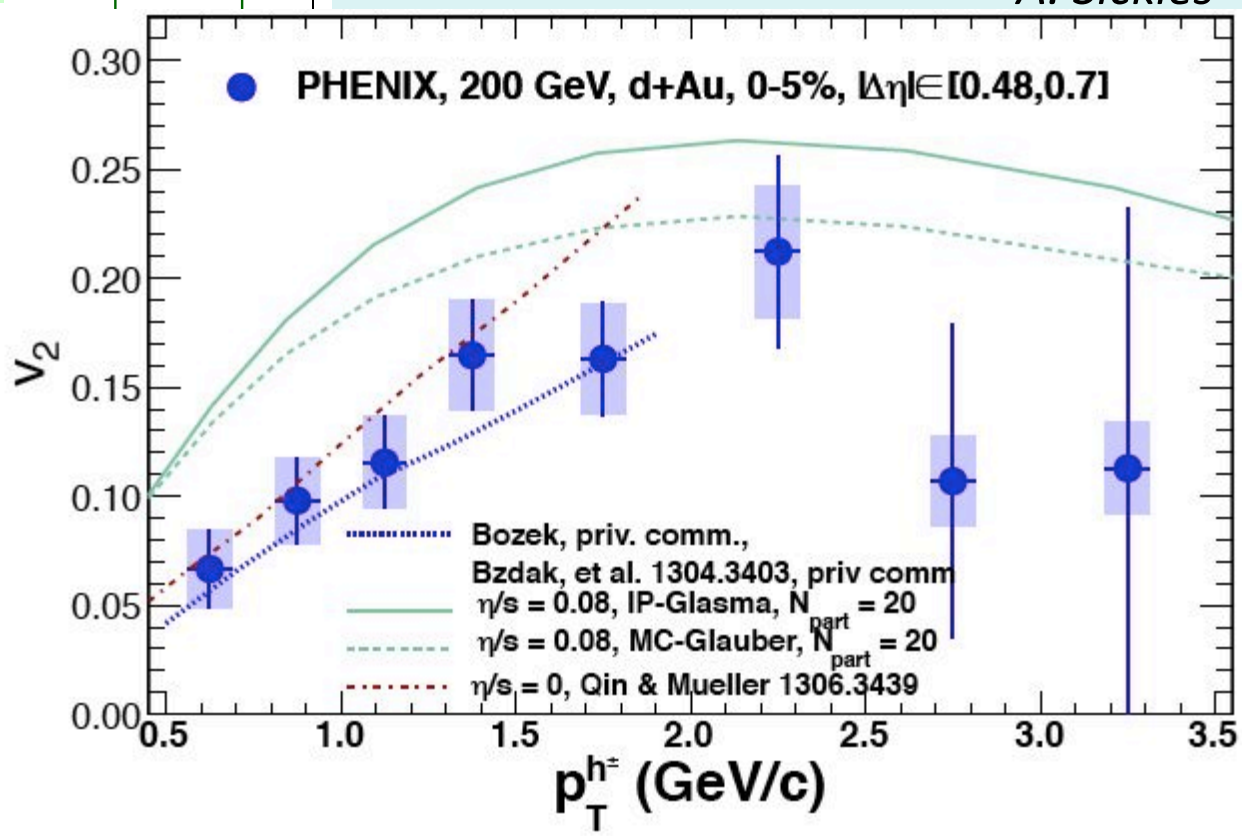
Fourier coefficients & v_2 value



Extract v_2 using factorization:

$$C_2(p_{Ta}, p_{Tb}) = v_2(p_{Ta})\, v_2(p_{Tb})$$

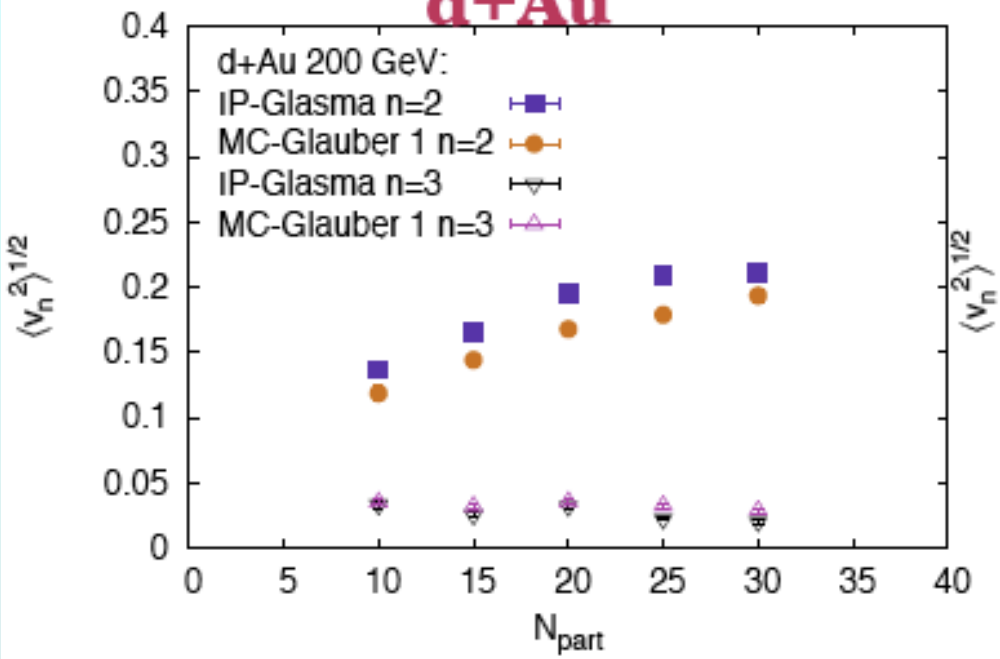
A. Sickles



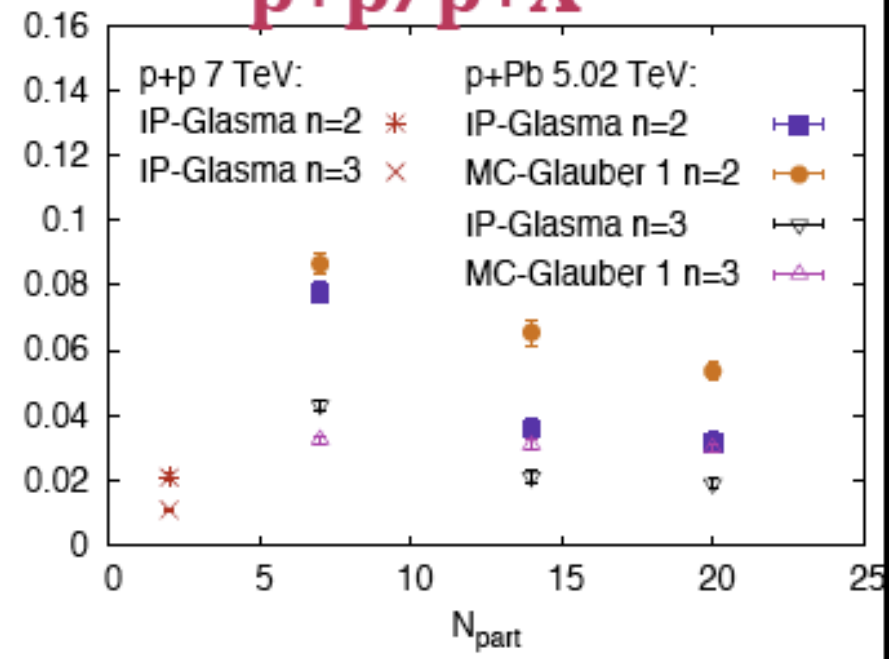
- $v_2 > v_2$ at LHC
- ε_2 d+Au > ε_2 p+Au
- v_2 agrees w/hydro
  - $\eta/s \leq 0.08$
- $v_3 \sim 0$

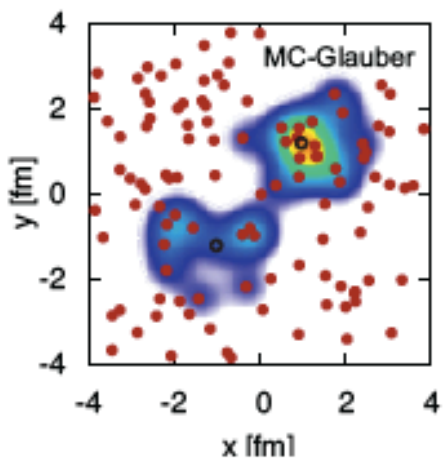
v_2 vs. v_3 in hydrodynamics

d+Au



p+p/p+A





depends on system and model of initial state

- **v2/v3 much larger in dAu than in pPb**

Sort out initial state for hard scatterings!

Bzdak et al: 1304.3403

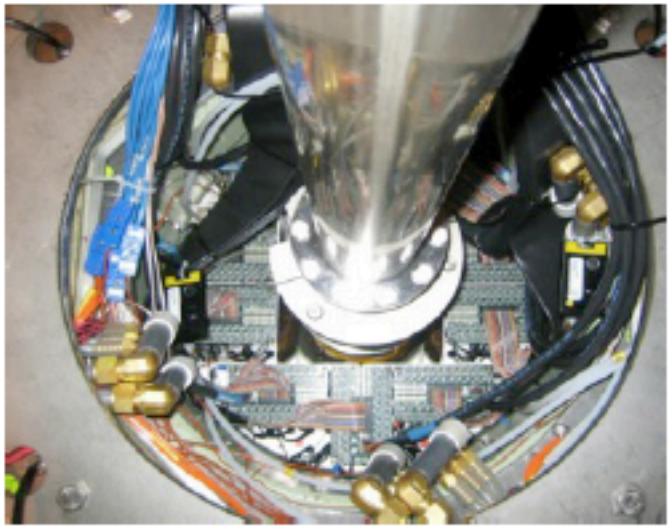
Use larger rapidity gap to ensure no jets

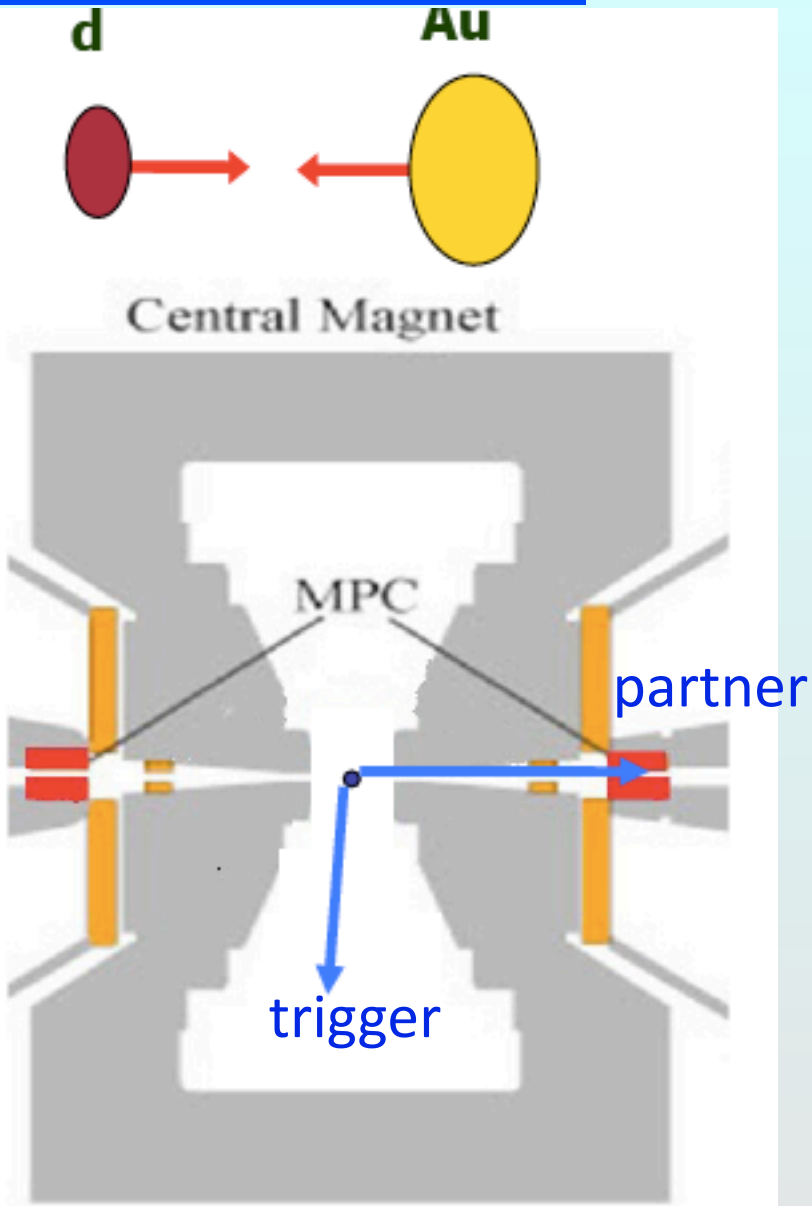
Muon Piston Calorimeters

both d-going & Au-going directions

$3 < |\eta| < 4$

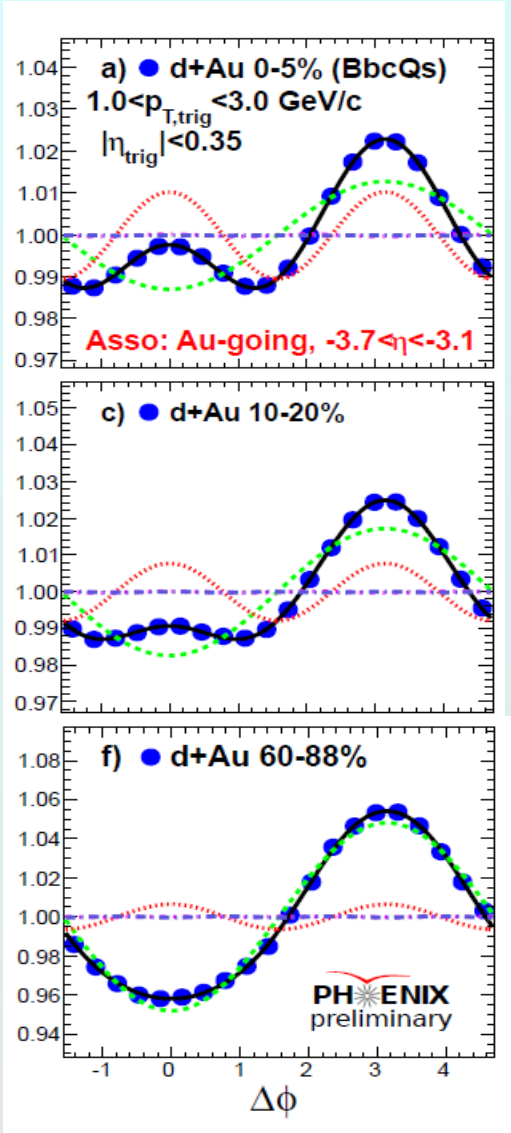
Look at $E_T \geq 300$ MeV/c clusters

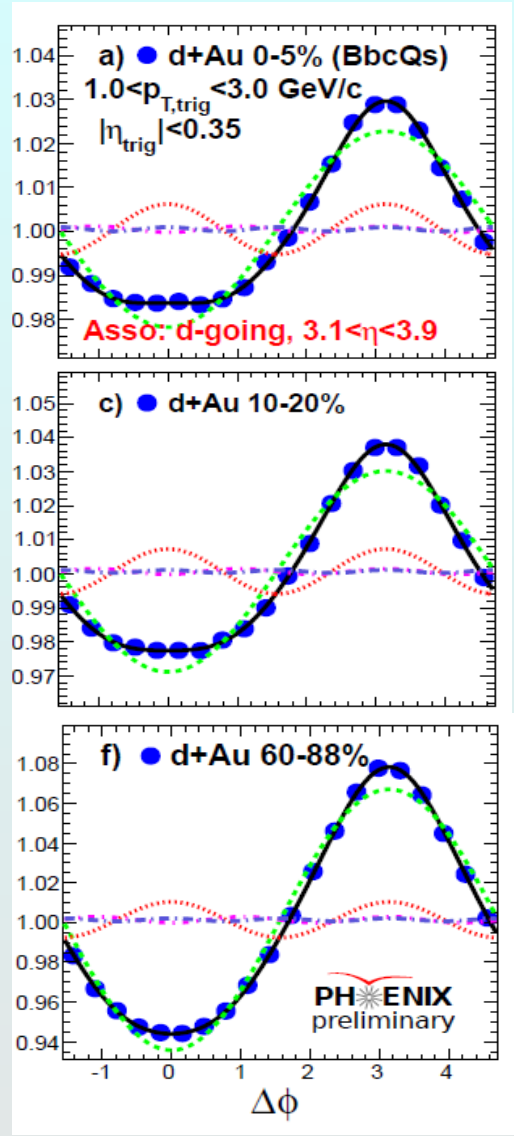




Long range correlations in d+Au at RHIC!

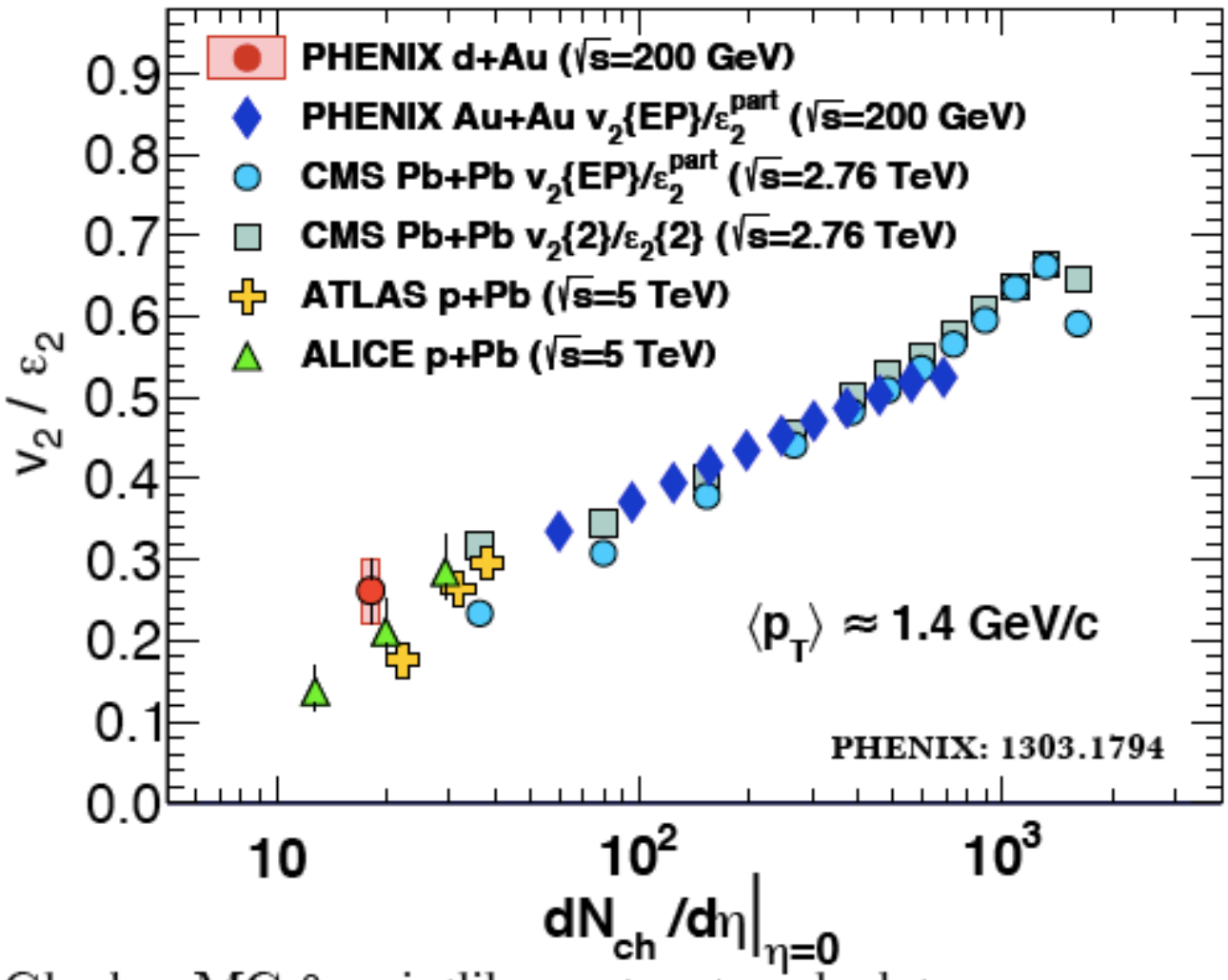
S. Huang





Ridge @ large η *NB: jets not removed; v_3 ~0*

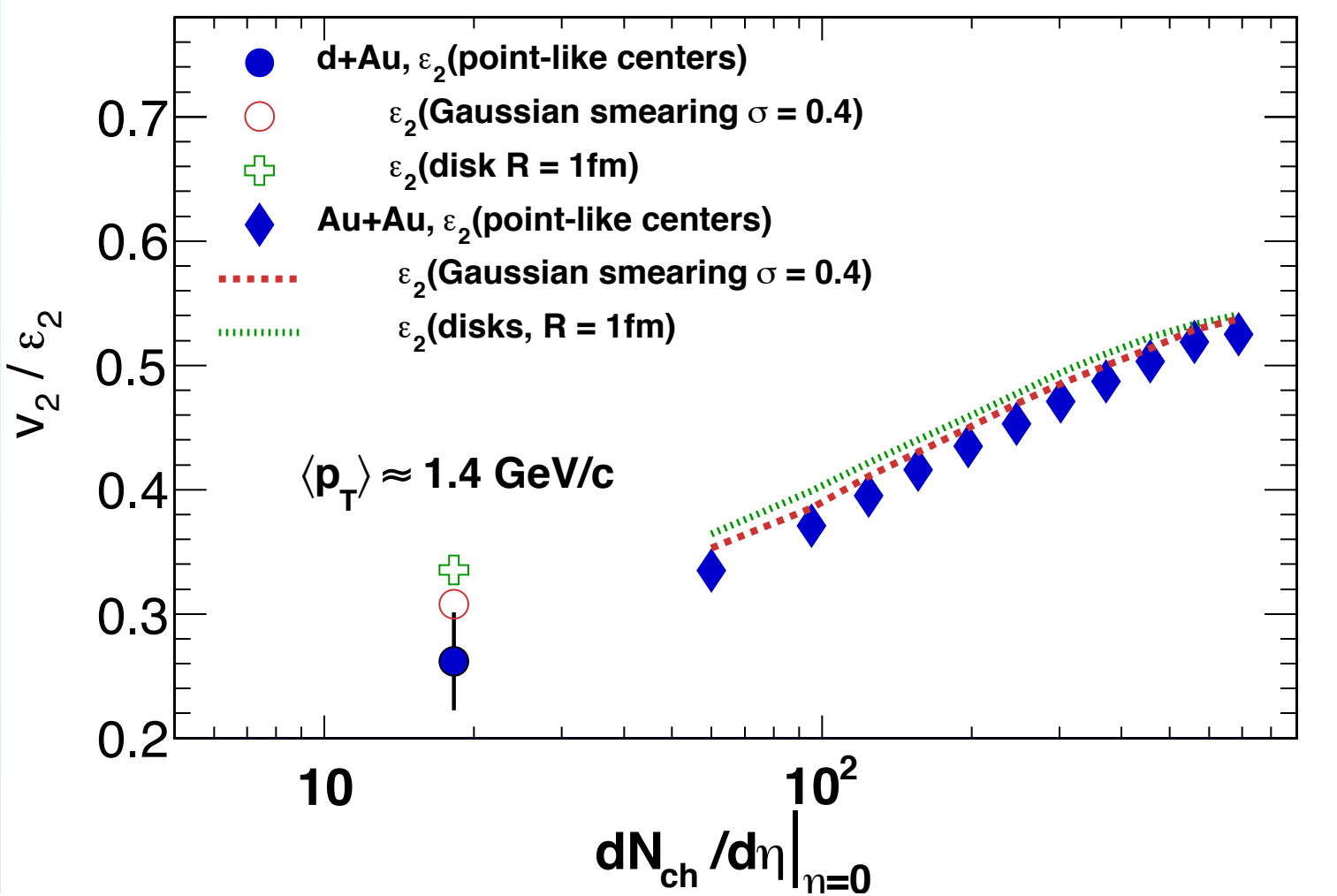
Returning to central-central: v_2/ε_2 vs multiplicity



- Glauber MC & pointlike centers to calculate ε_2
- → approximate scaling of v_2/ε_2 with $dN/d\eta$

a common relationship between geometry and v_2?

Might systematic effects confuse us?



BVJ: I'd expect difference in viscous effects in d+Au vs. Au+Au to modify the scaling. Data might have room for that?

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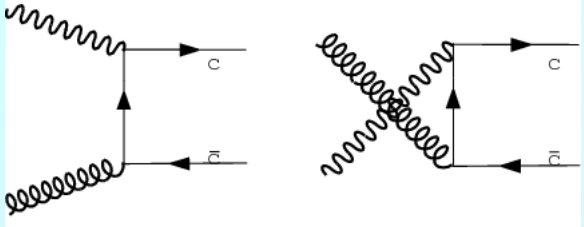
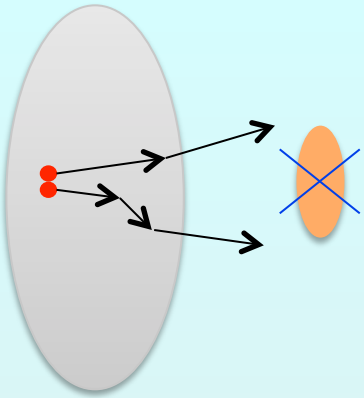
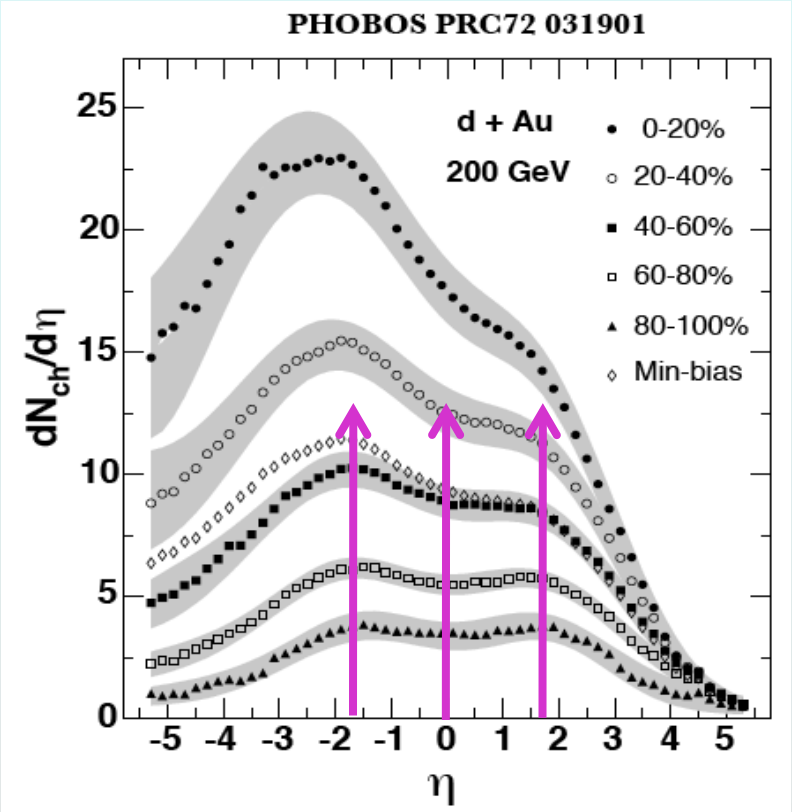


Heavy Flavor



- **Production of c+cbar and b+bbar**
  - **Probes 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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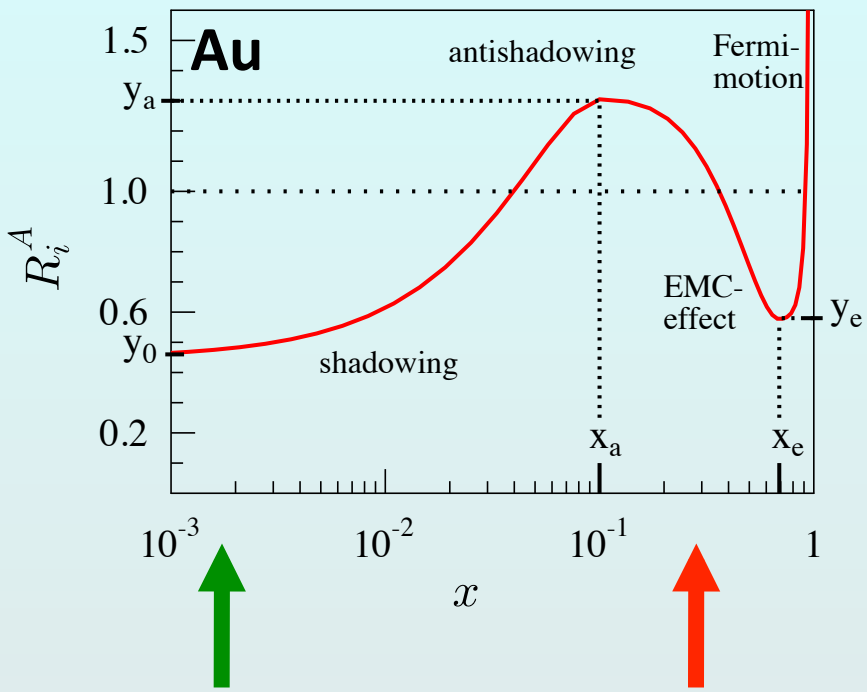
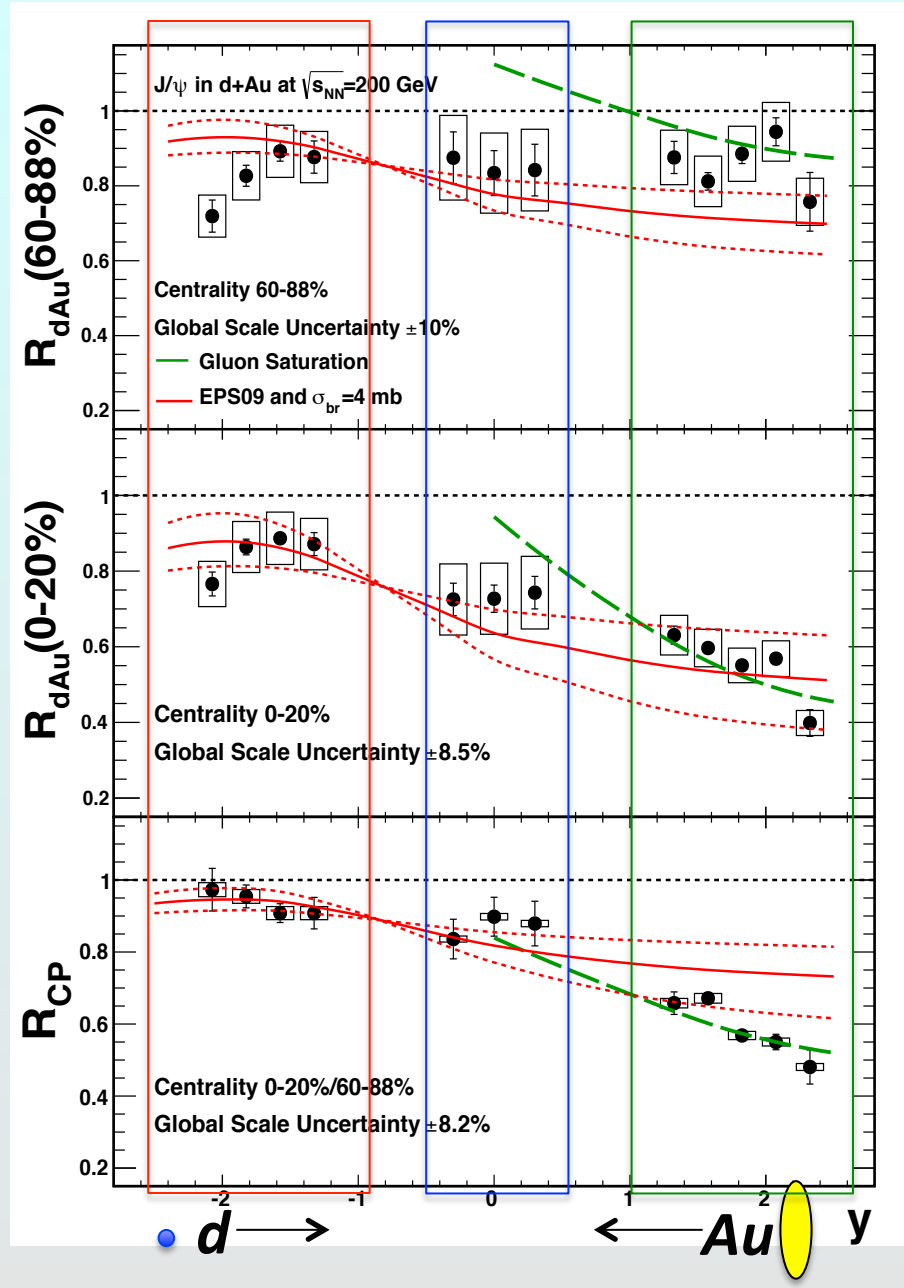
Initial State: what's where?



Forward
+ y
d-going

Backward
- y
Au-going



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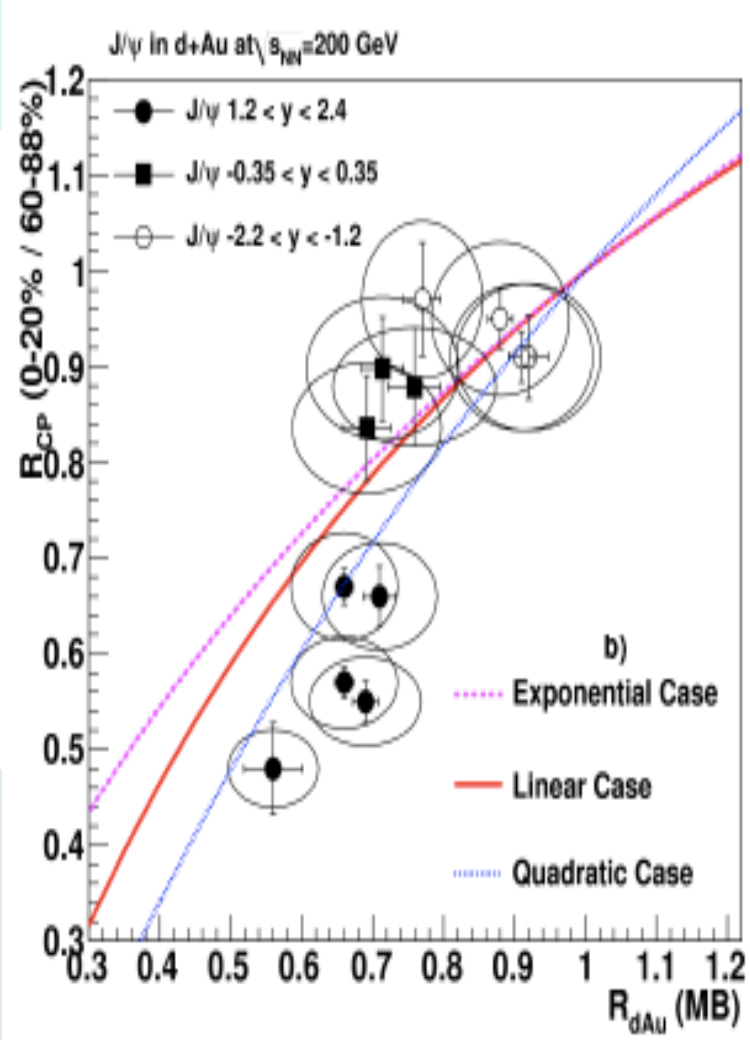
J/ψ in d+Au

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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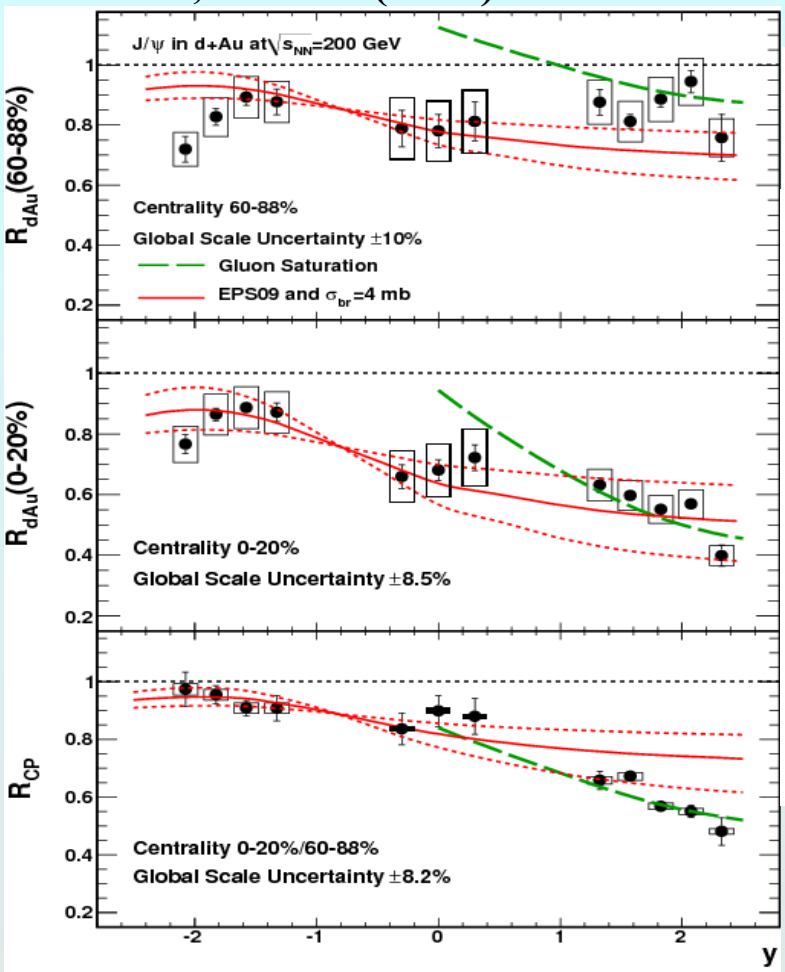
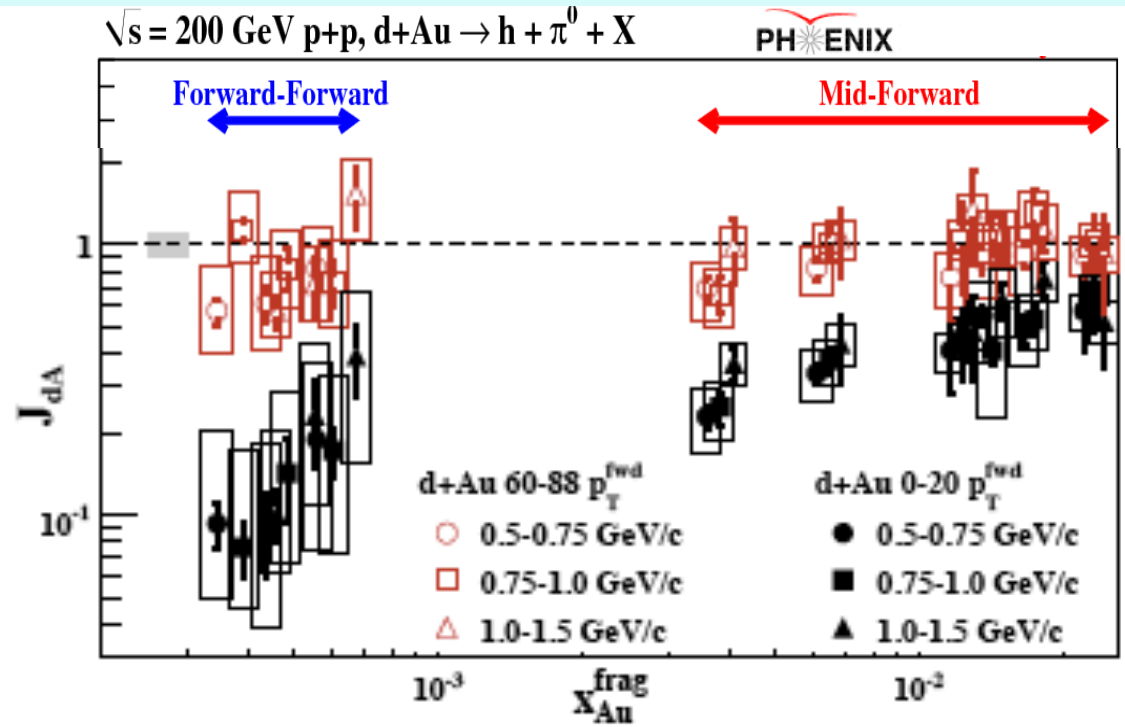
Dense gluonic matter effects observed

PRL107, 142301 (2011)



PRL107, 172301 (2011)



Shadowing/absorption stronger than linear w/nuclear thickness

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 …

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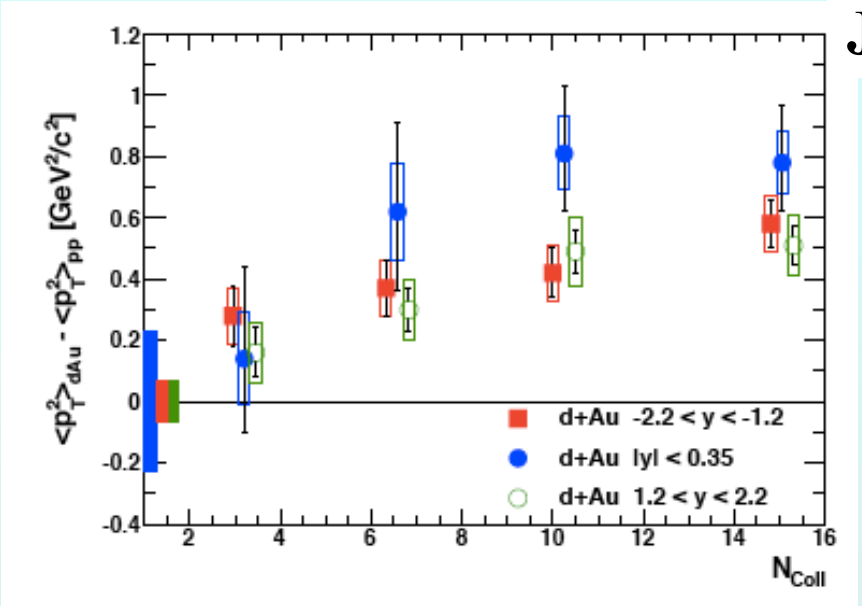
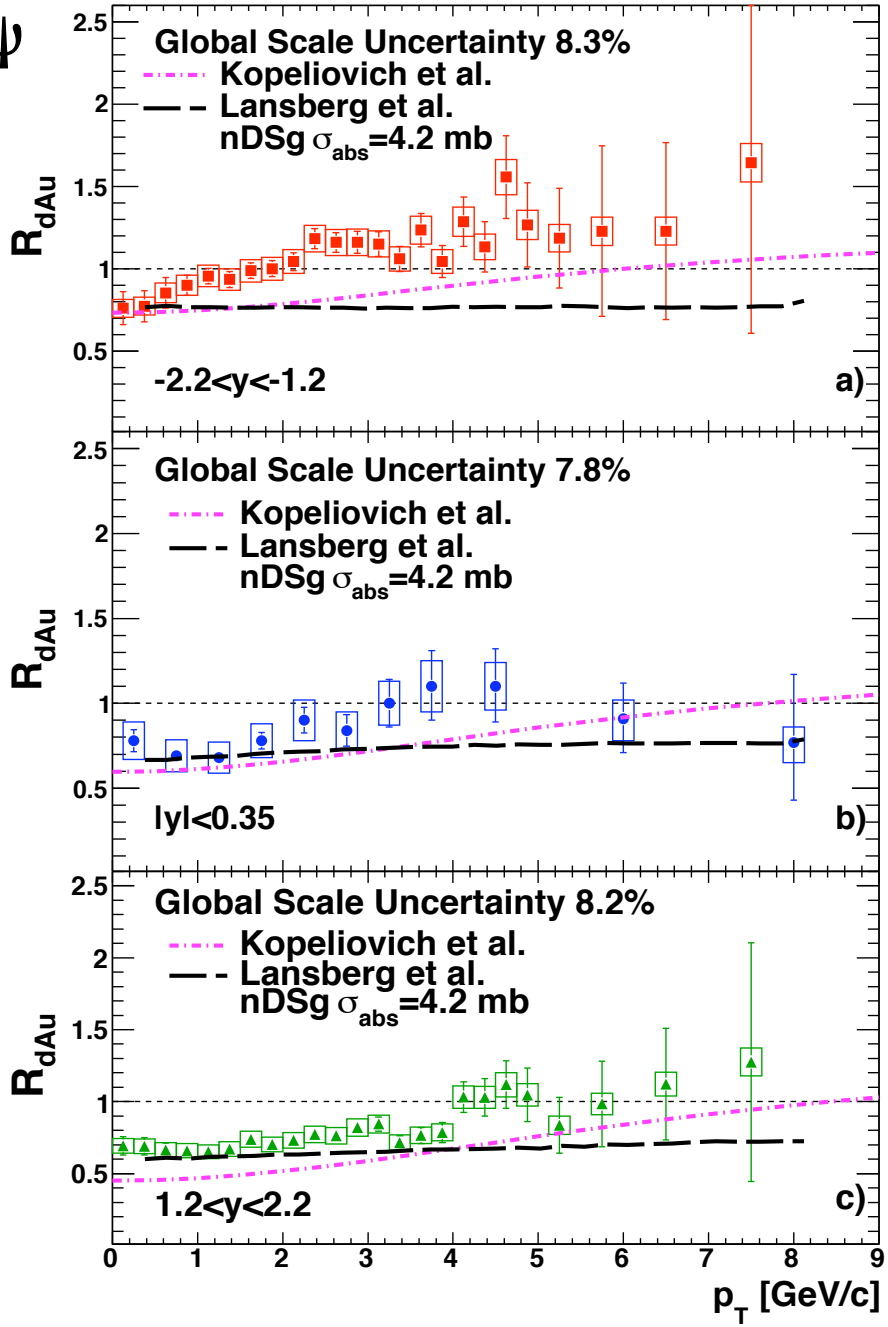
Shadowing, breakup & Cronin effect

PRC87, 034911 (2013)



J/ψ



- ✦ 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 was not reproduced by the models

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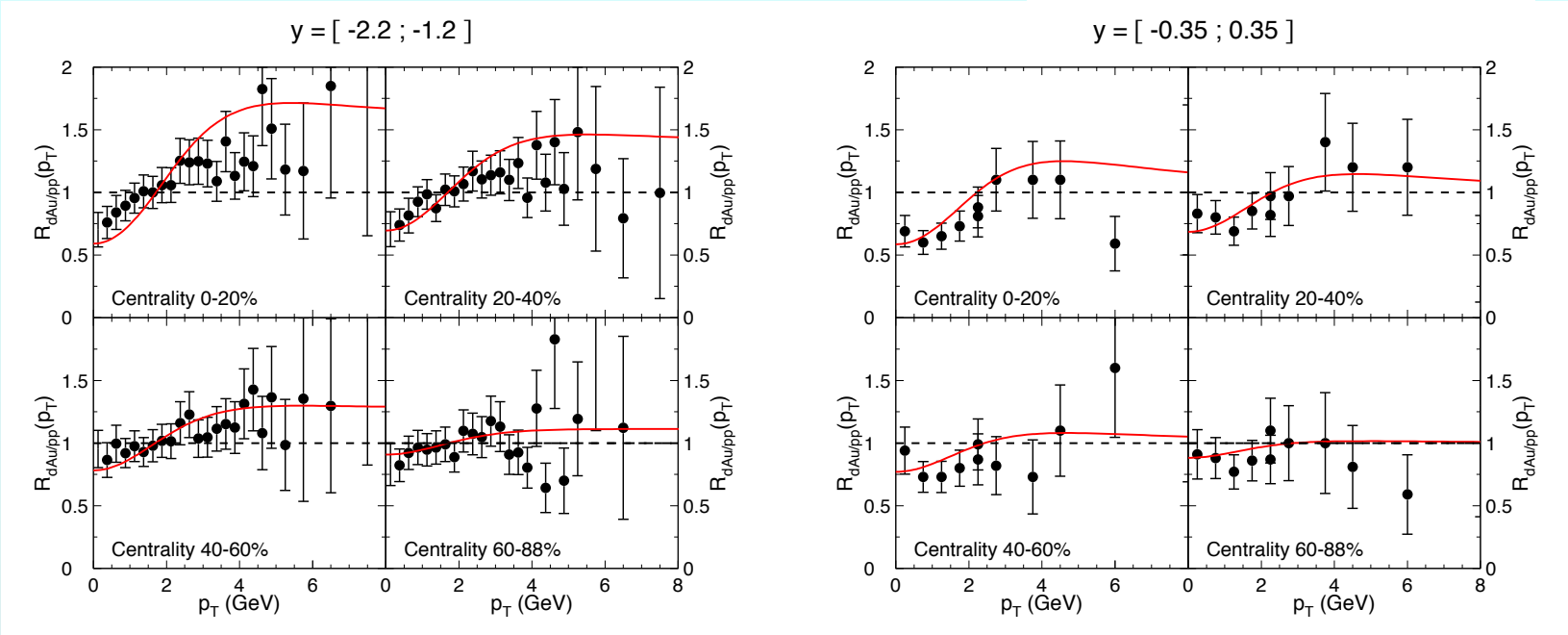
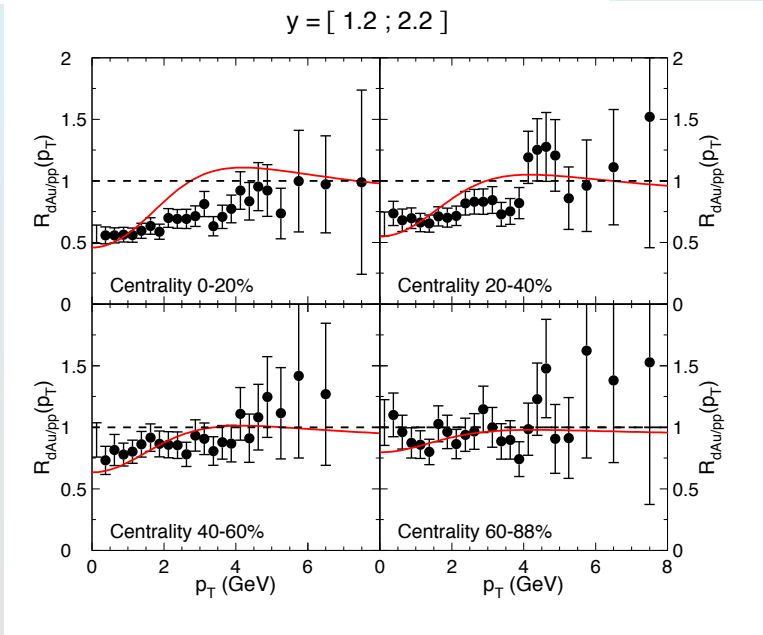
but

Arleo, et al 1304.090





coherent parton energy loss and p_T broadening is consistent with data!

$\hat{q}_0 = 0.075$ GeV^2/fm

Saturation: better rapidity dependence (for min bias, p_T integrated J/ψ)

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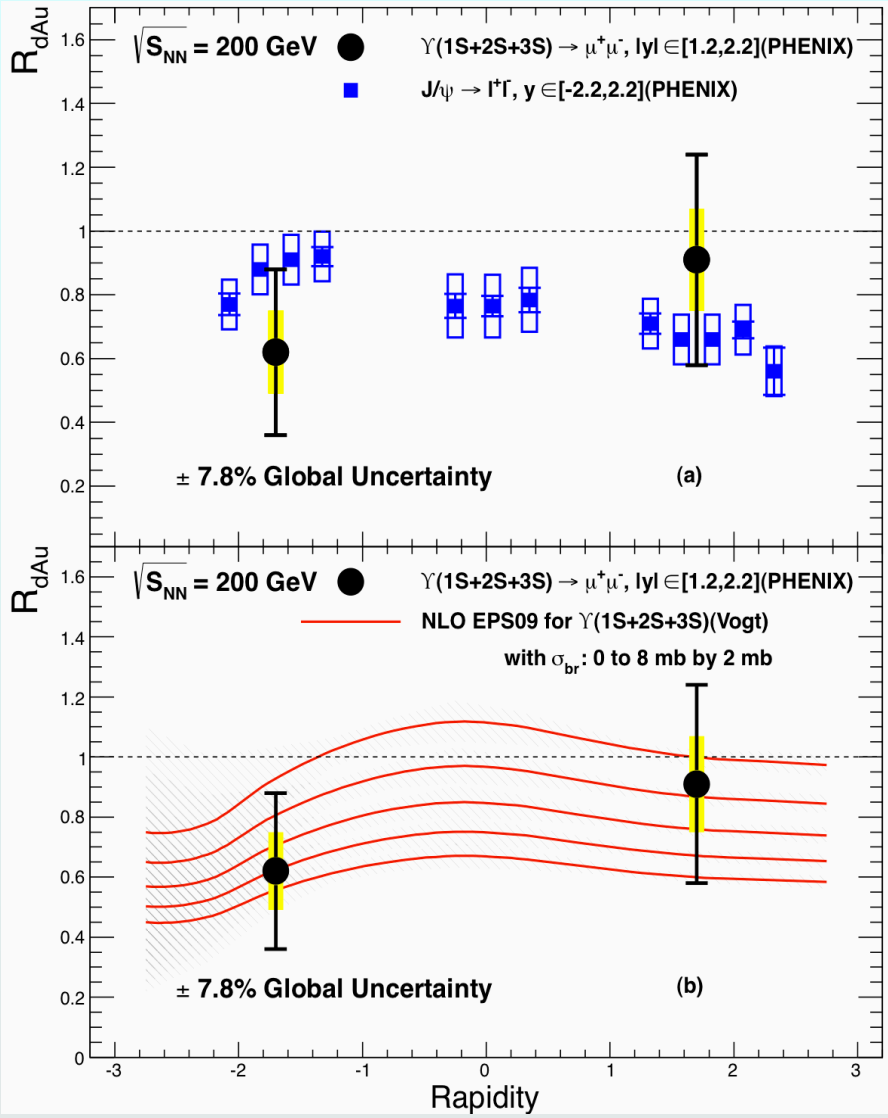
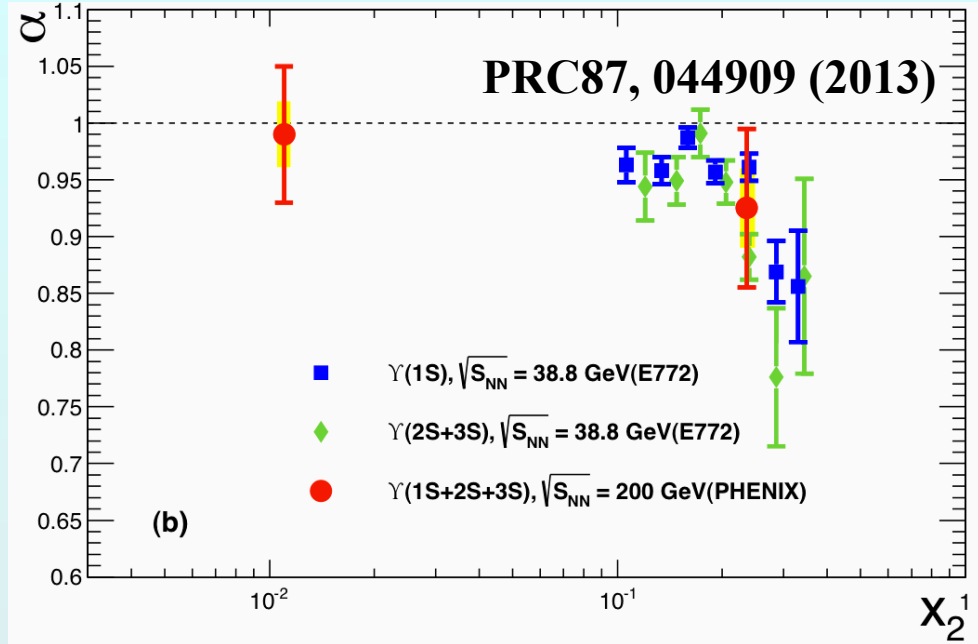
Smaller, more tightly bound probe





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

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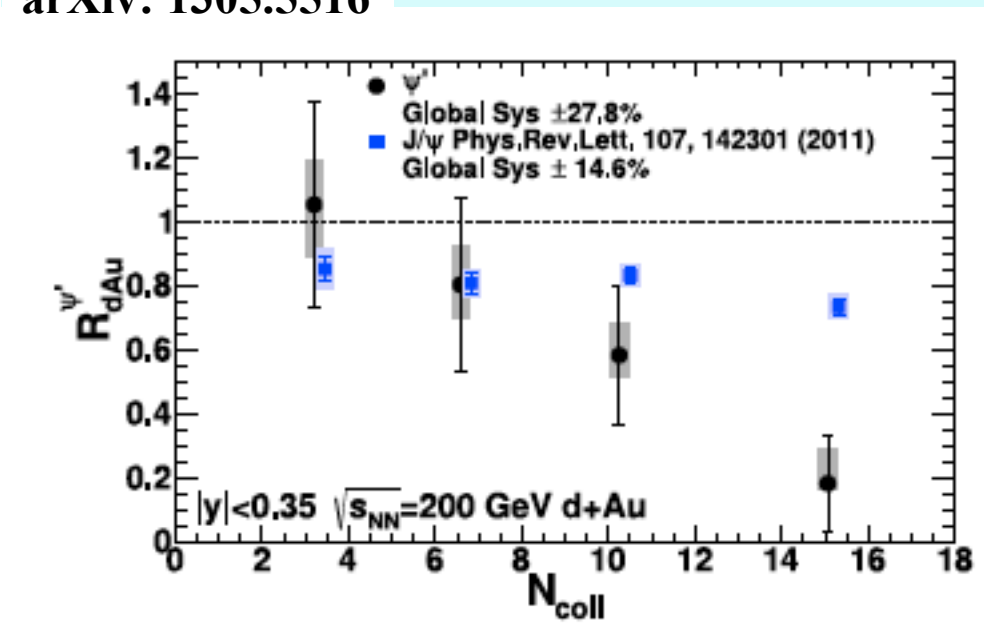
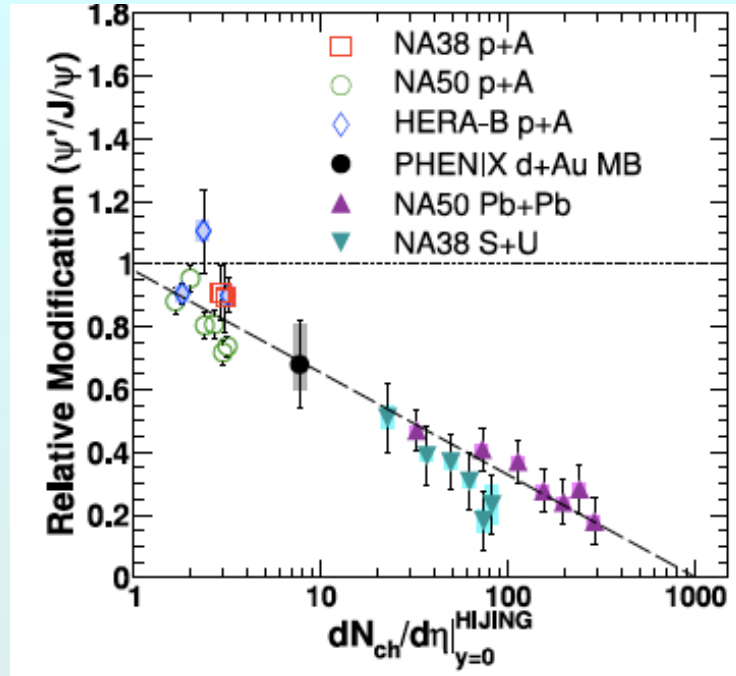
Larger, less tightly bound ψ'

arXiv: 1305.5516





- Clearly more suppressed than J/ψ
- Cannot be shadowing or parton energy loss

  These are initial state effects

- ψ'/ J/ψ decreases linearly with $dN_{ch}/d\eta$
- Break-up of some sort!

  early or late?

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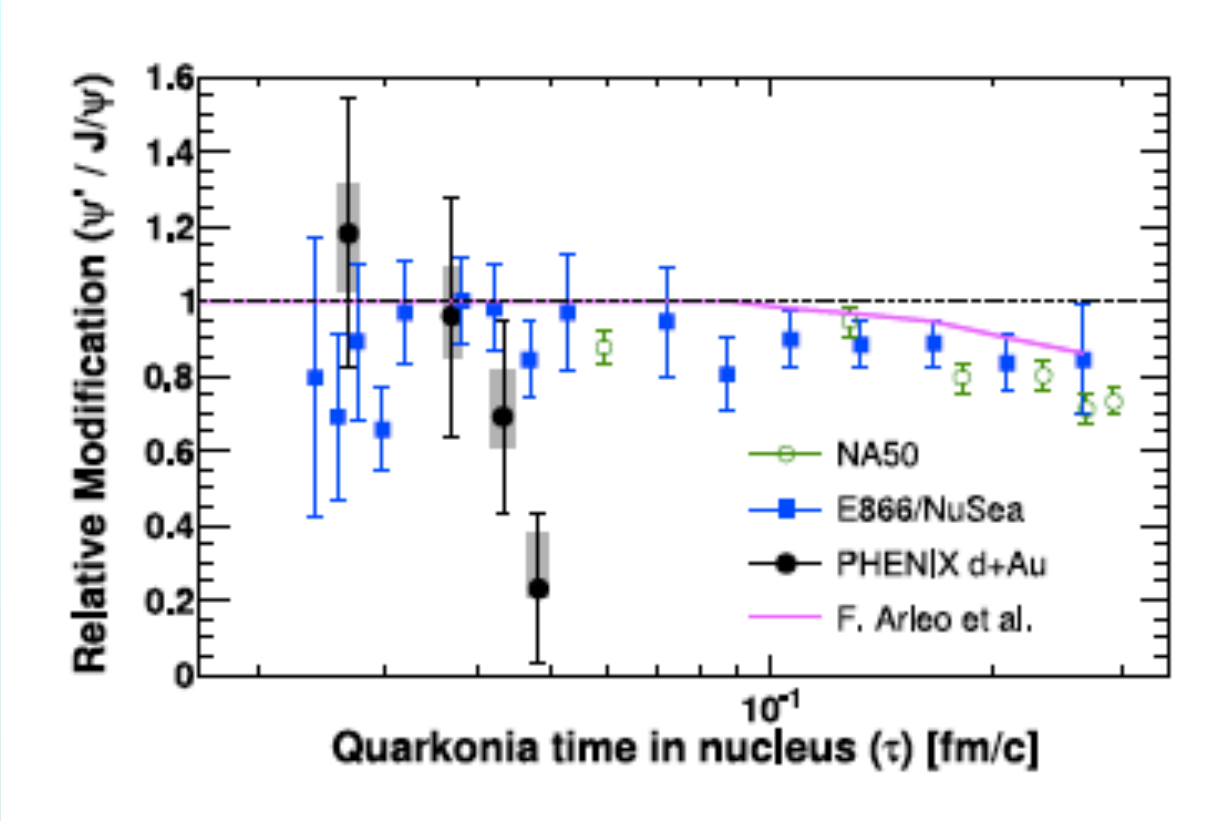
√s dependence is a key tool!



- 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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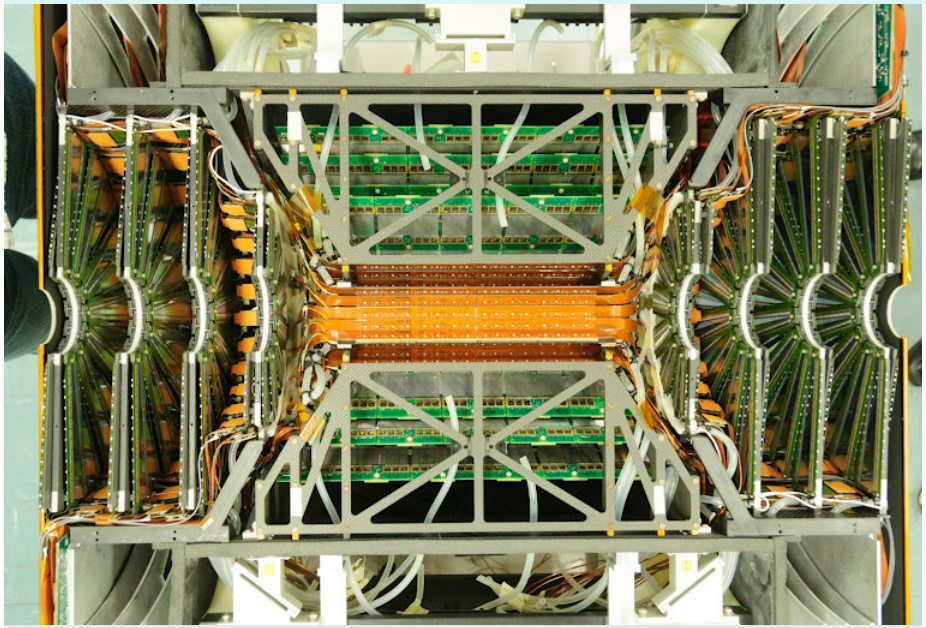
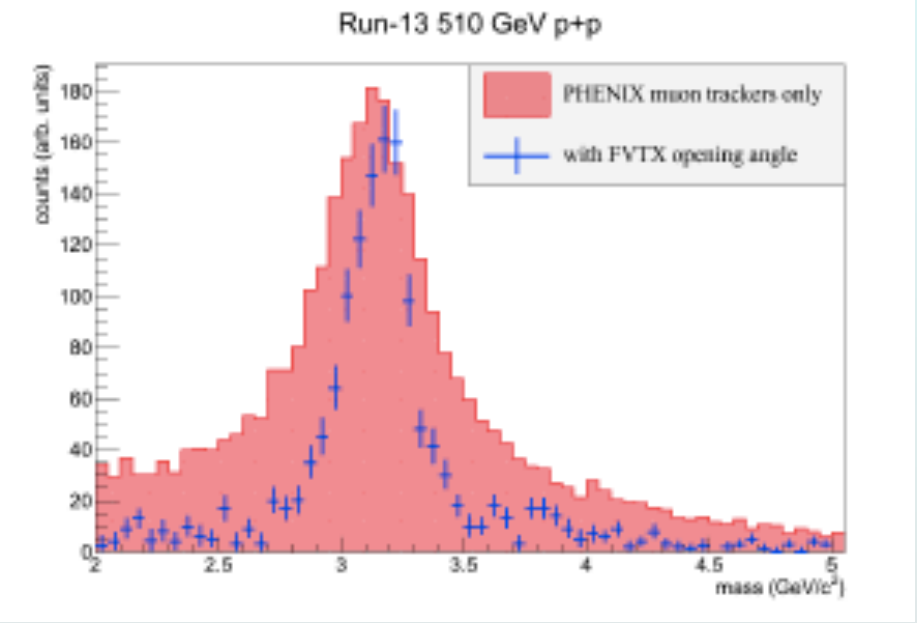
Rapidity dependence is coming

Forward vertex detector FVTX

improves mass resolution →

Ψ' at forward rapidity!





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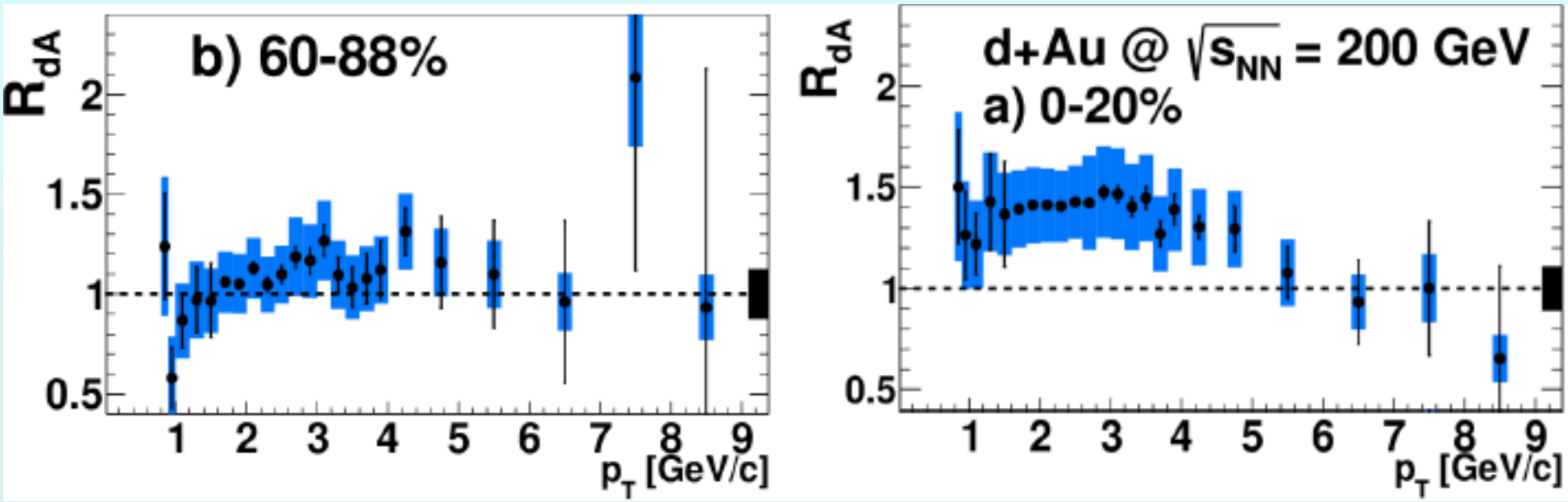
Open heavy flavor: mid-rapidity $e^{\pm}$

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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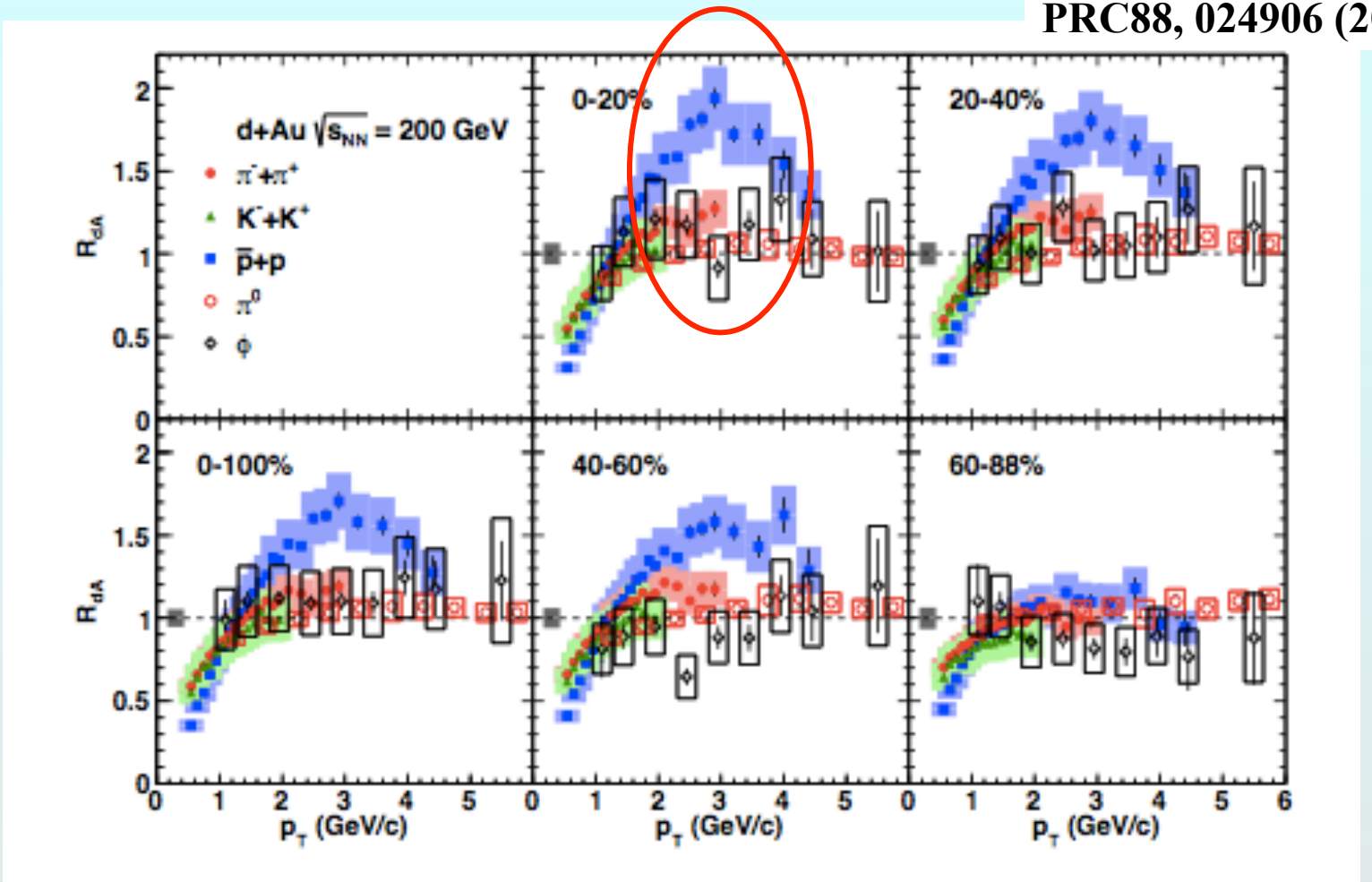
NB: Classic does not always mean right!

PRC88, 024906 (2013)



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

How does the parton know it will produce a proton?

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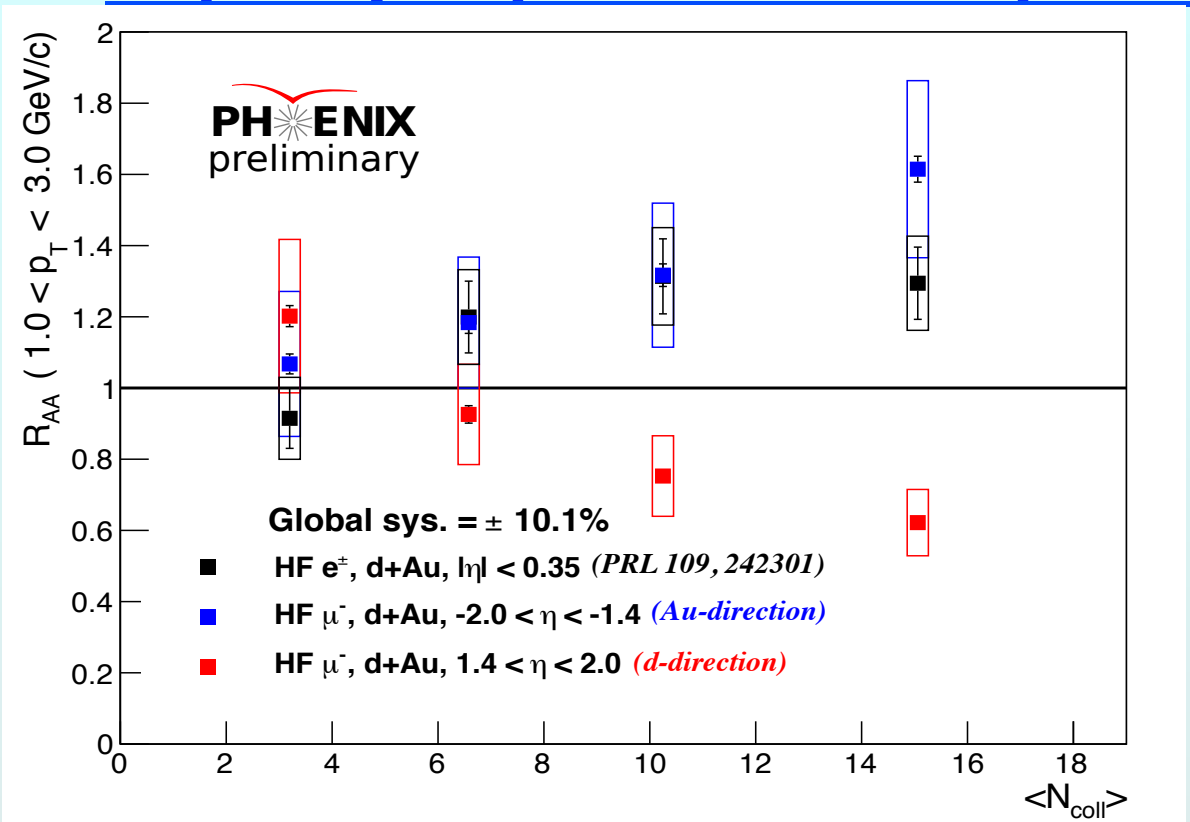
Rapidity dependence of open heavy flavor



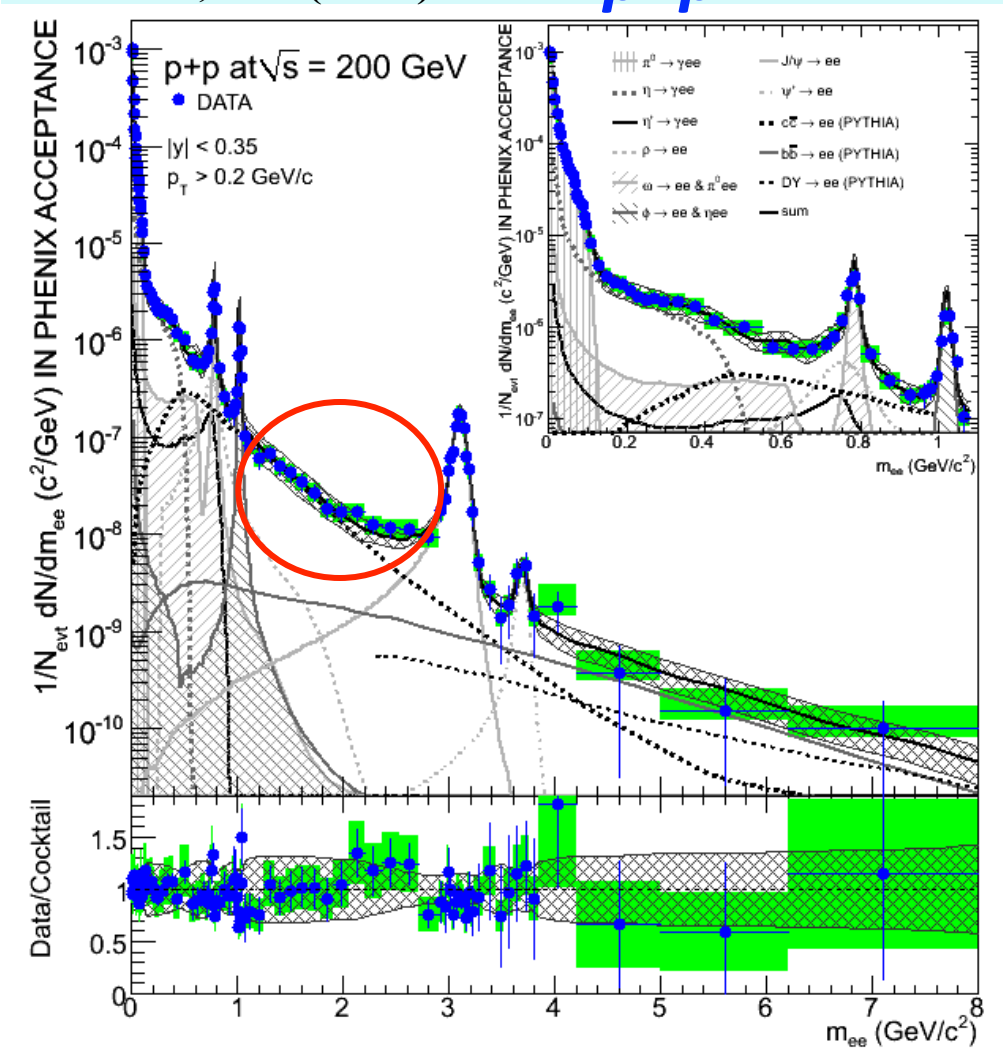
PHENIX measures:

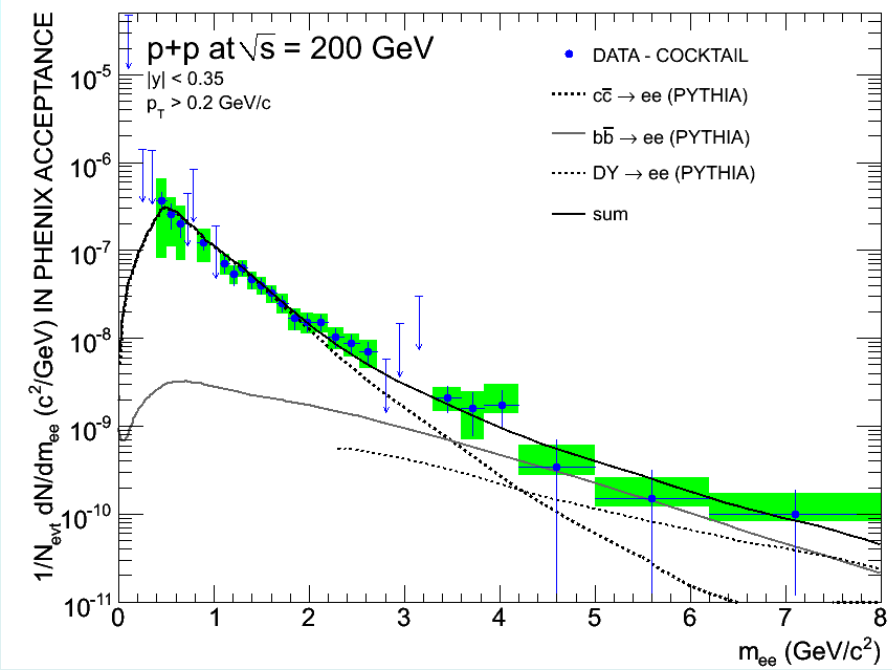
- ***non-photonic single leptons***
- ***also intermediate mass lepton pairs***

- **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 *(see C. Ogilvie's talk!)***

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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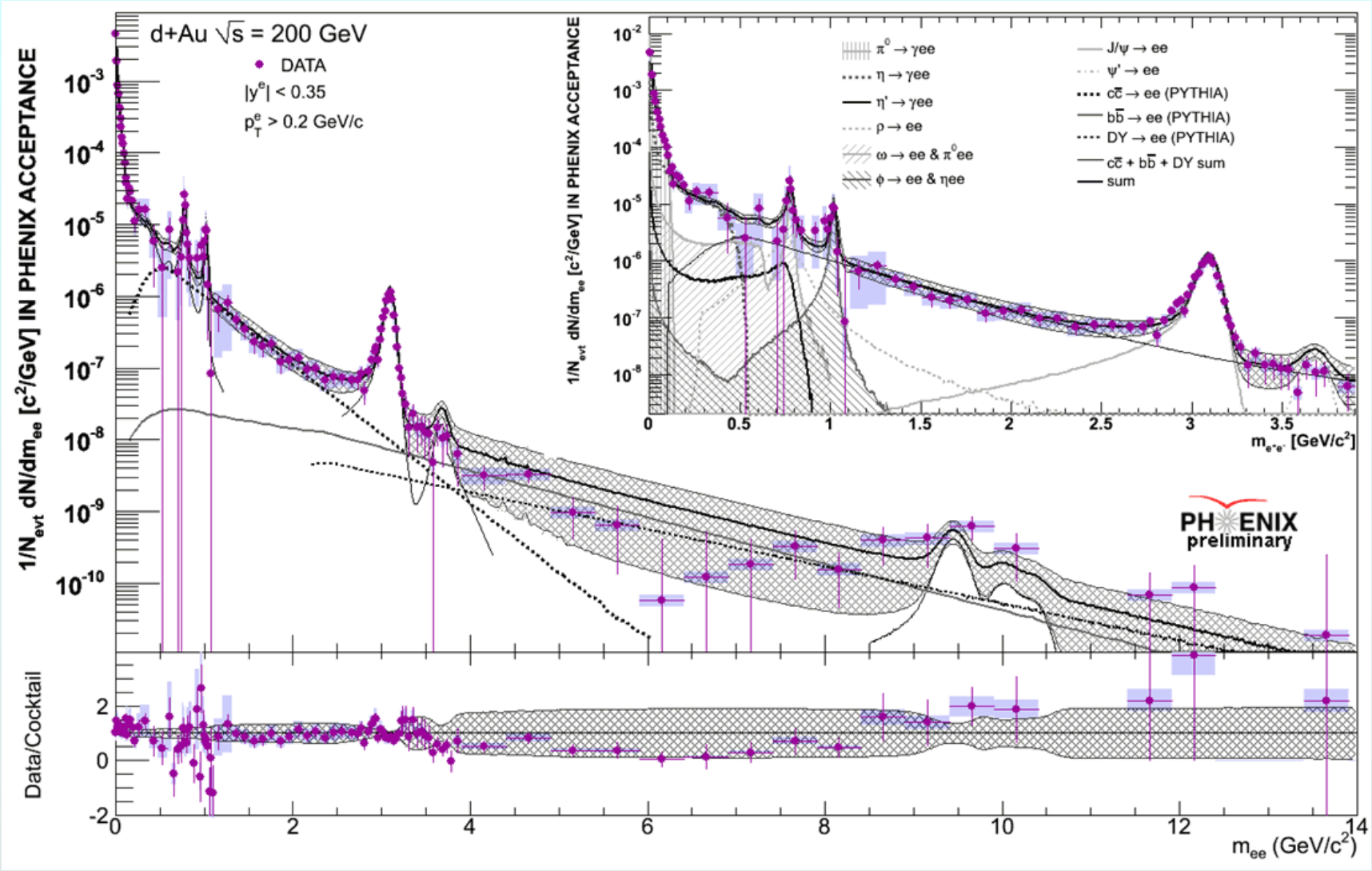
Di-electrons in d+Au



Note: no low mass enhancement in d+Au

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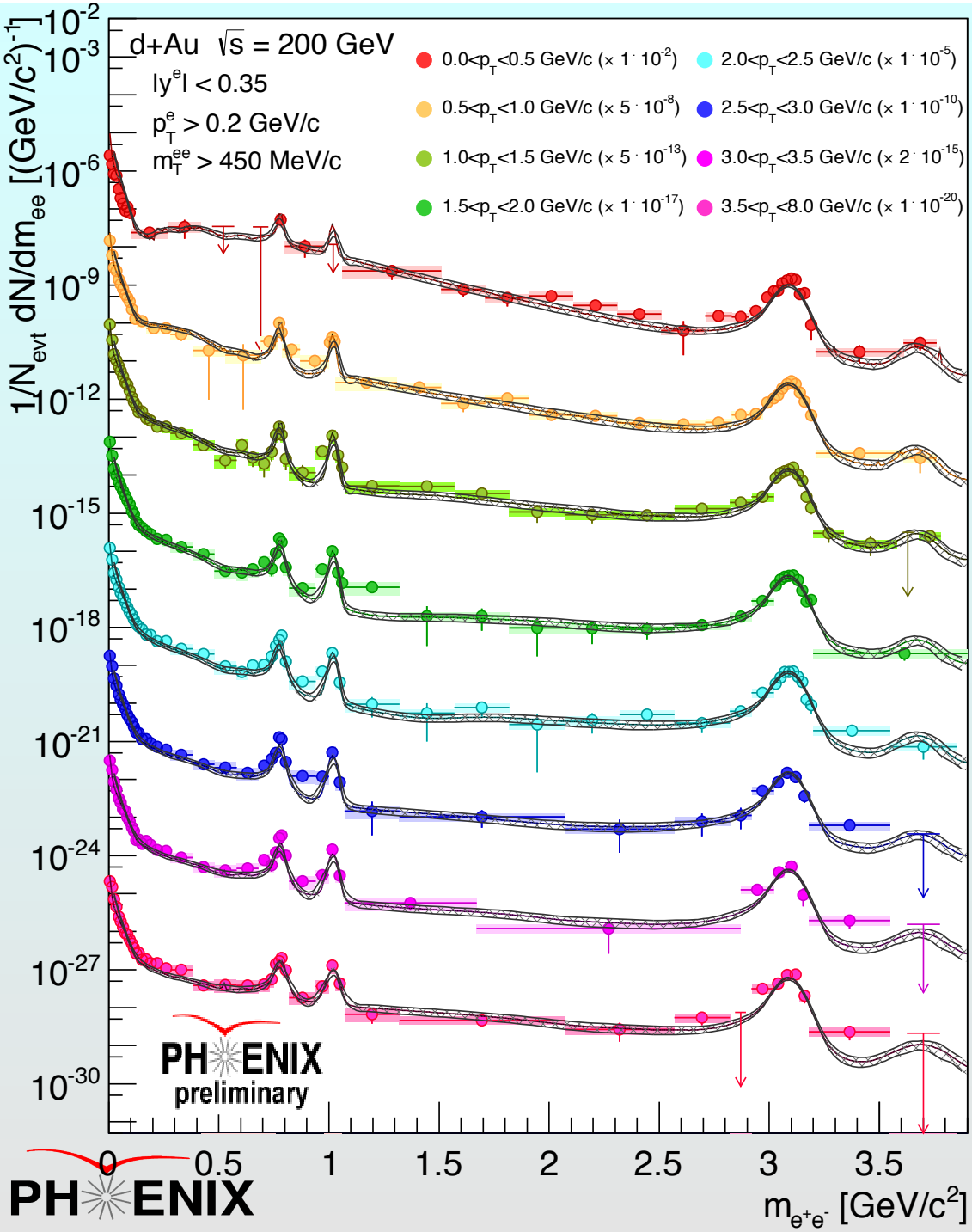
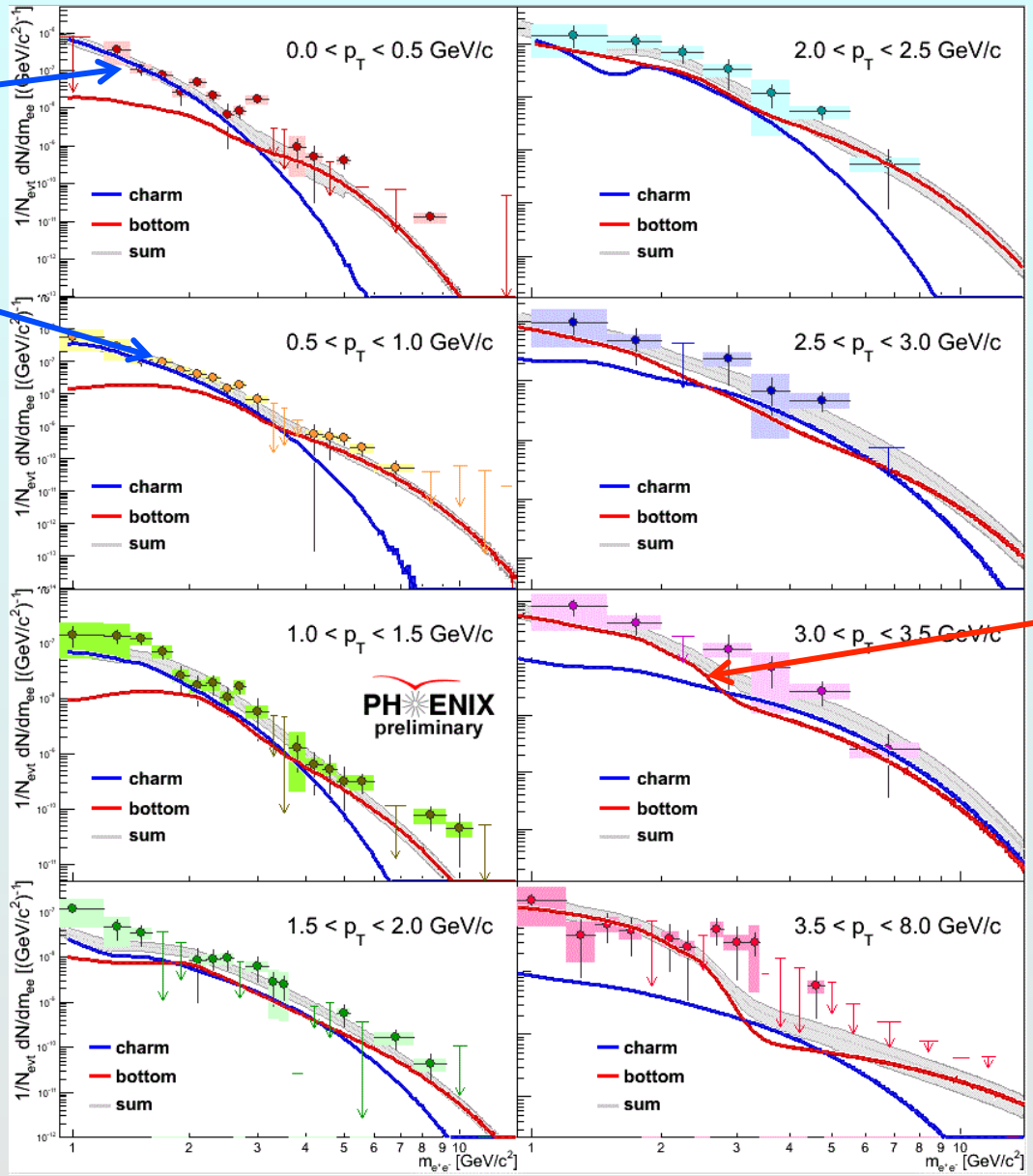


Good statistics in d+Au 2008 run

allows differential distributions in mass and p_T!

Separate charm and bottom

Charm dominates



B decays dominate at 1<m<3 GeV, statistics are reasonable!

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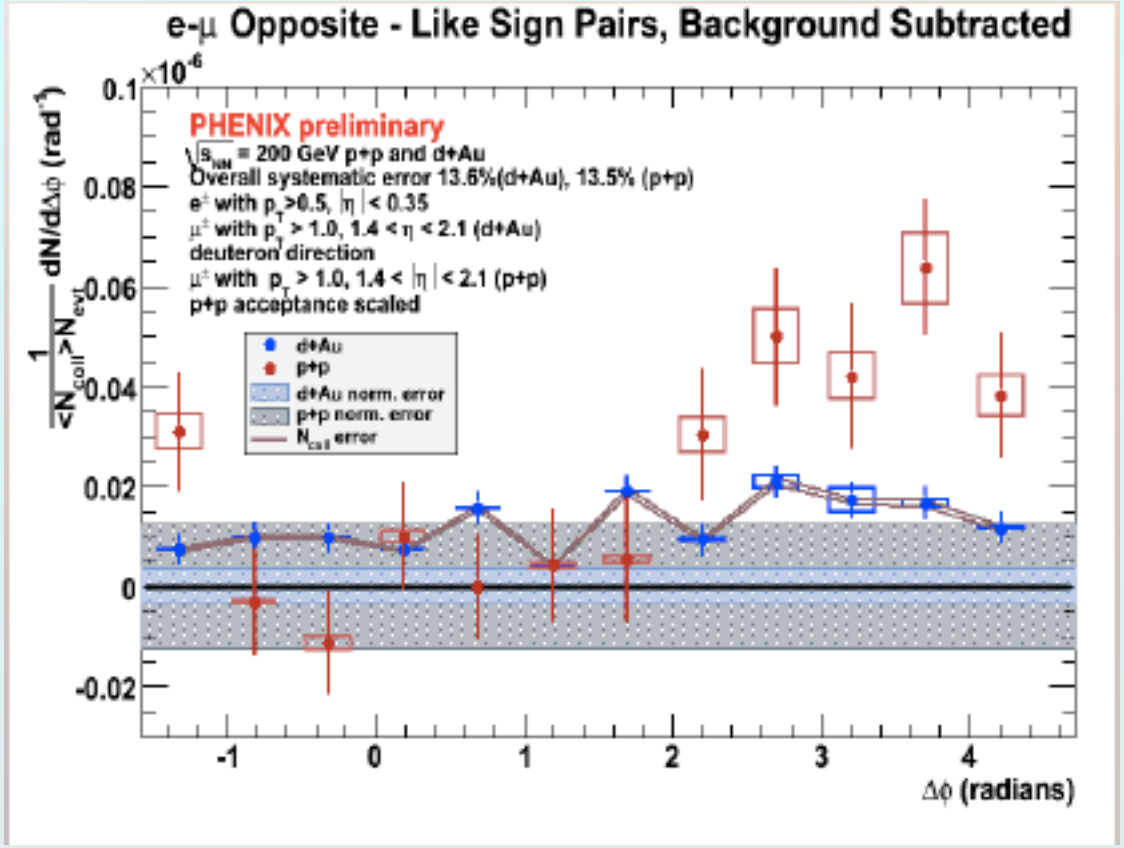
Opposite sign e-μ pairs for c-cbar



- ***Signal: e-μ @ Δφ ~ π***

From back-to-back c-$\bar{c}$ pairs

- ***No physics background***

No D-Y, resonances, thermal

Like-sign subtraction to remove combinatorial backgrounds

- **p+p (red): shape is consistent with NLO charm calculation**

  g radiation effects broaden Δφ around π

- **d+Au (blue) suppressed compared to p+p: CNM effects**

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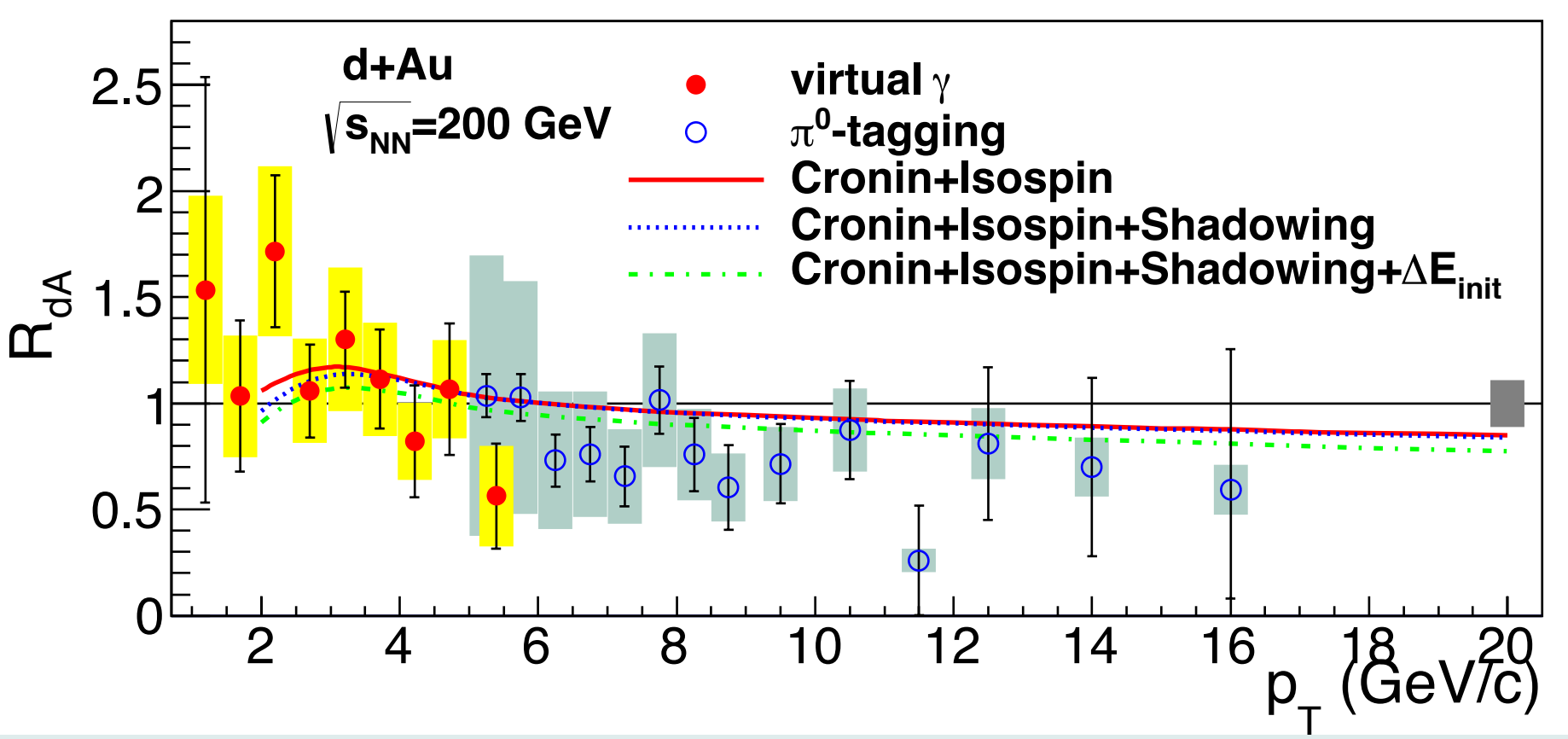
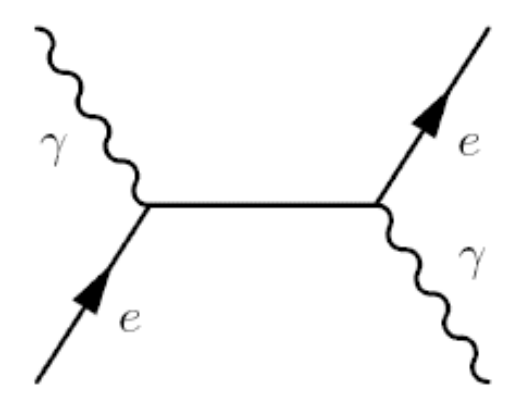
γ_{direct} in d+Au

arXiv: 1205.5533



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



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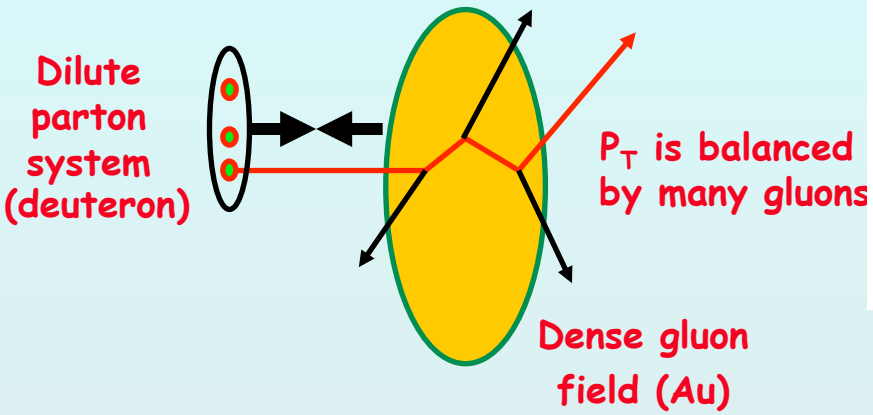
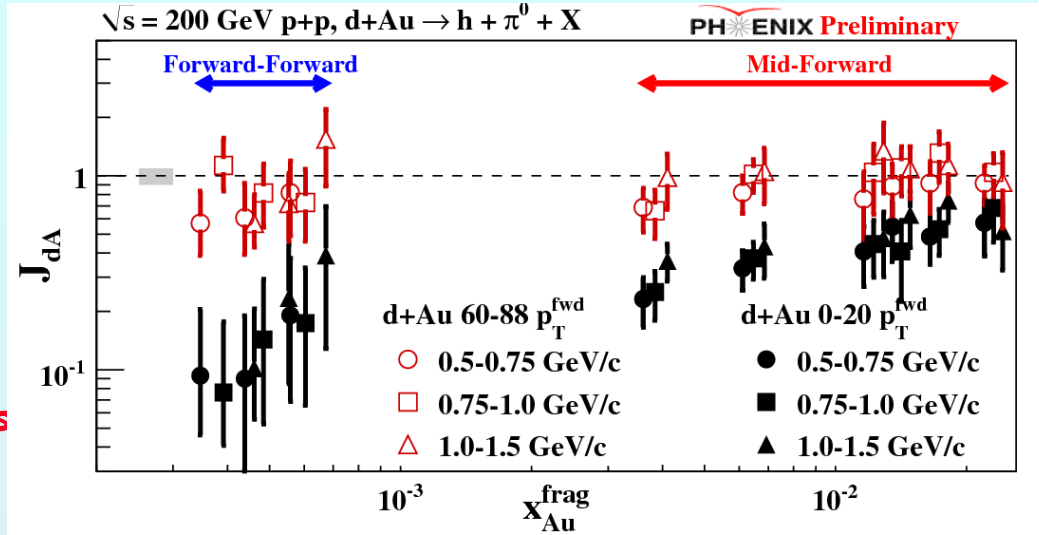
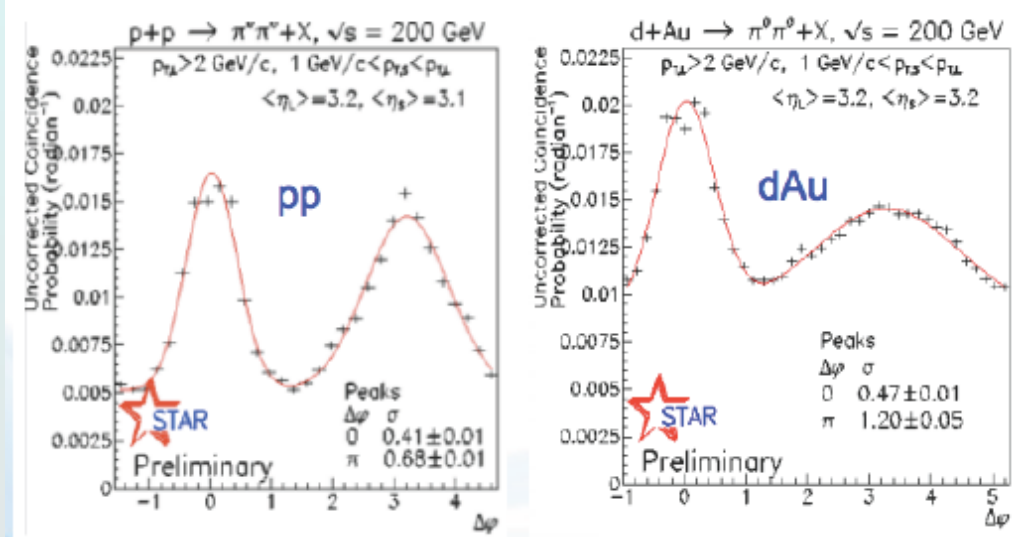
Initial State: shadowed or CGC?







Use direct photons!

Forward rapidity more sensitive than midrapidity

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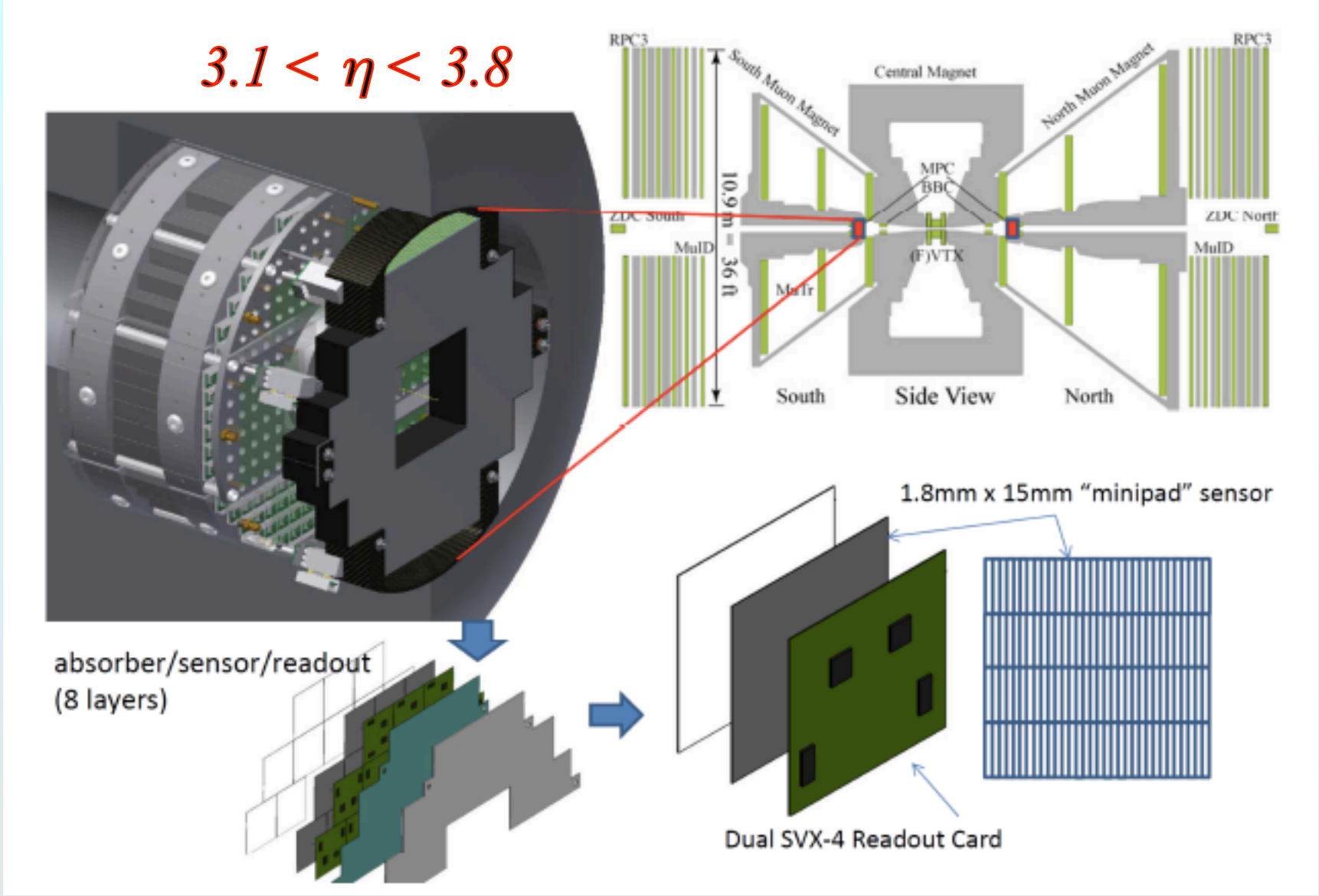
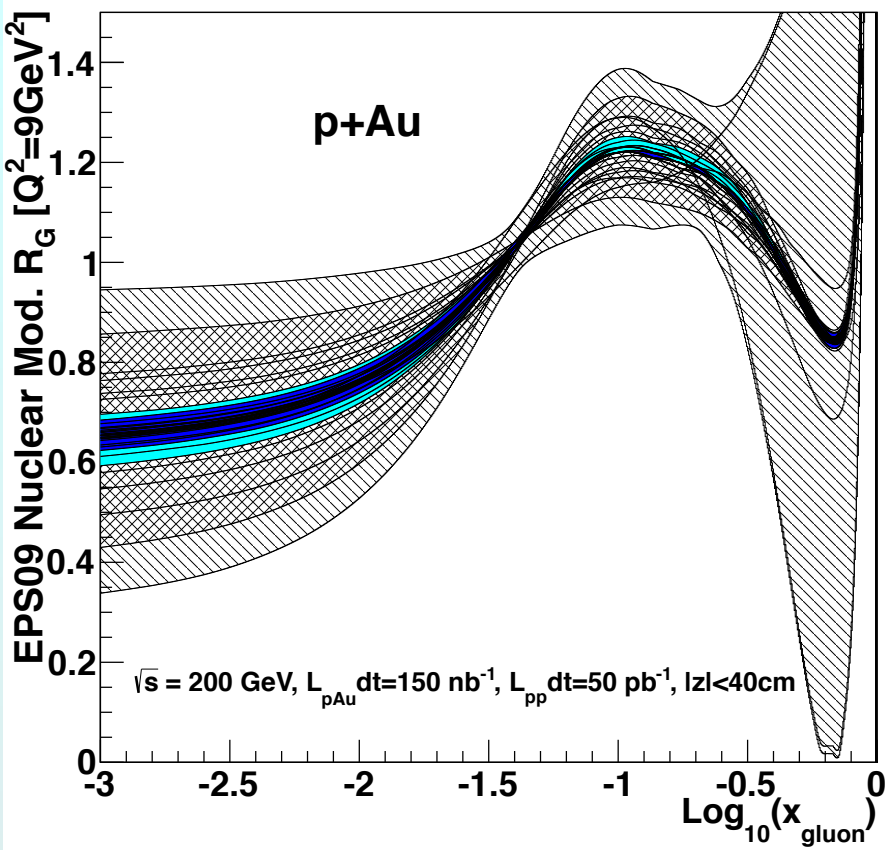
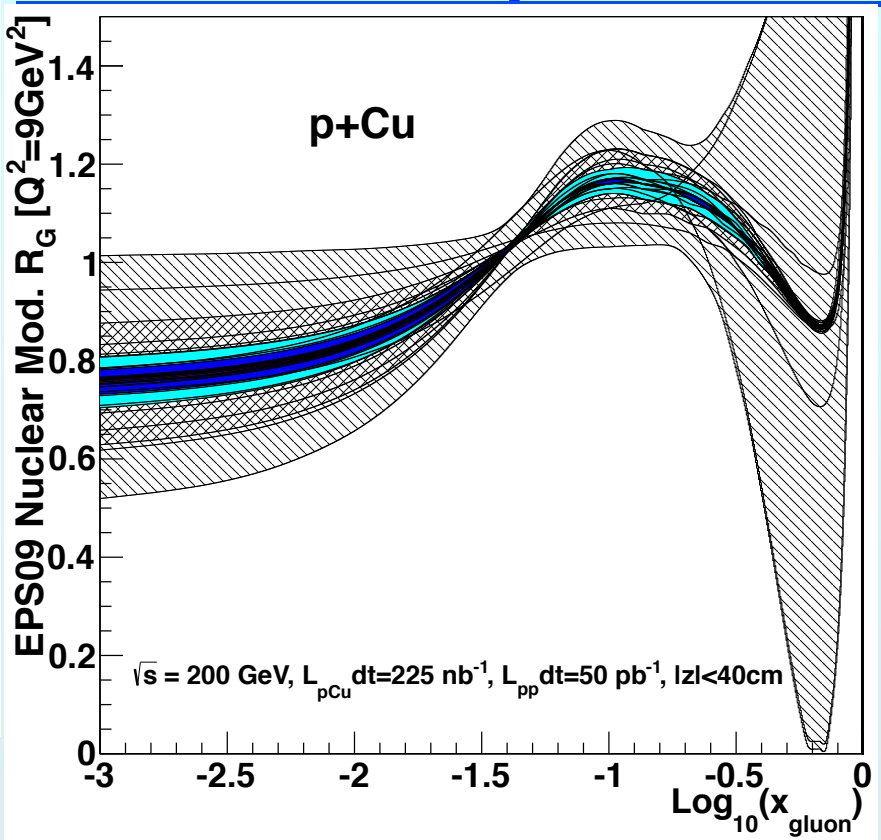
MPC-EX upgrade

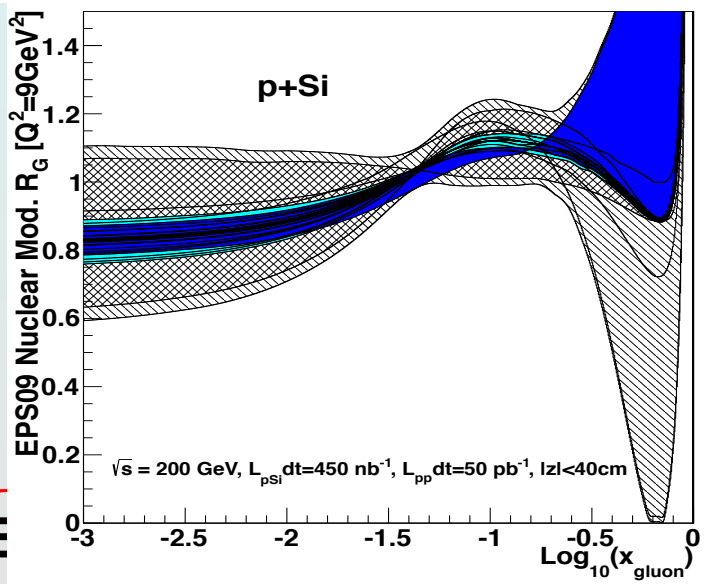


Reconstruct prompt γ and π^0 to 80 GeV: low & high x!

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

Possible to look at γ-h?

Conclusions

- Di-hadron correlations look hydrodynamic at RHIC
  As at LHC. v_2/ε_2 slope vs. dN/dy reflects viscous effects?
- 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?
  sensitivity to fluctuations?
  final state effects break up quarkonia, too
- No strong evidence for direct photon modification at mid-y
  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!

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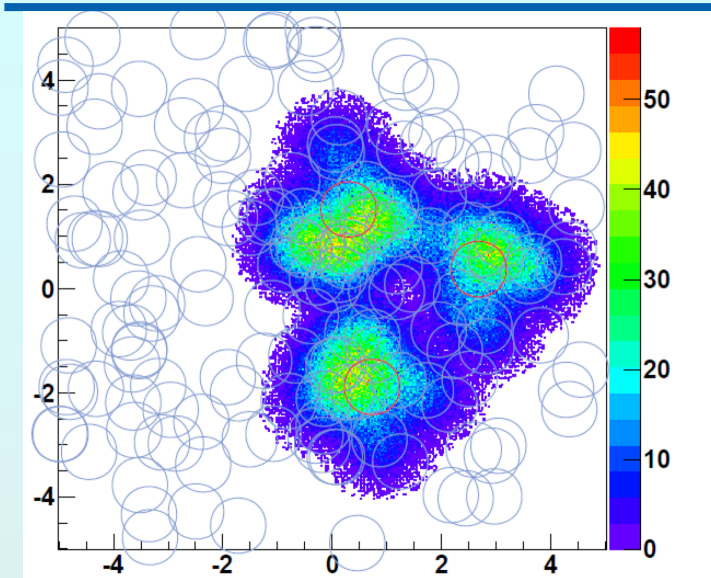
- **Backup slides**

Control the geometry: ^{3}He + Au

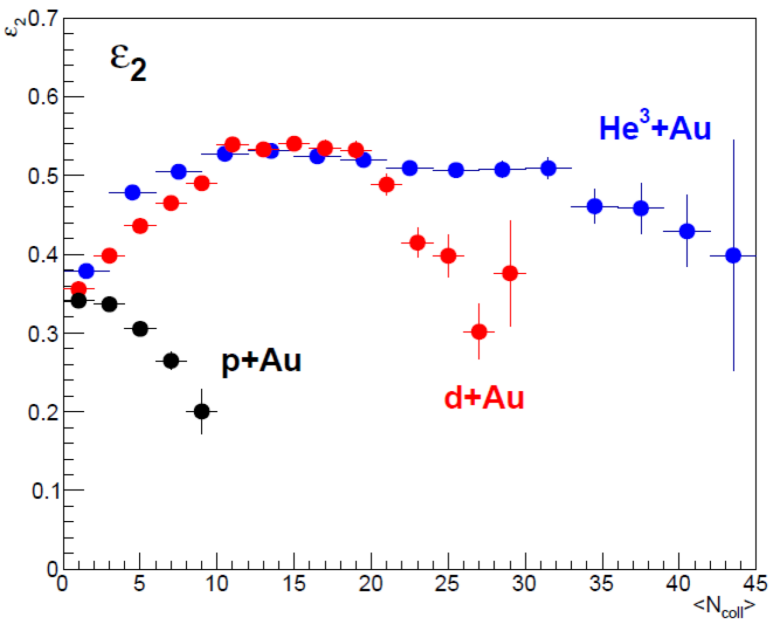


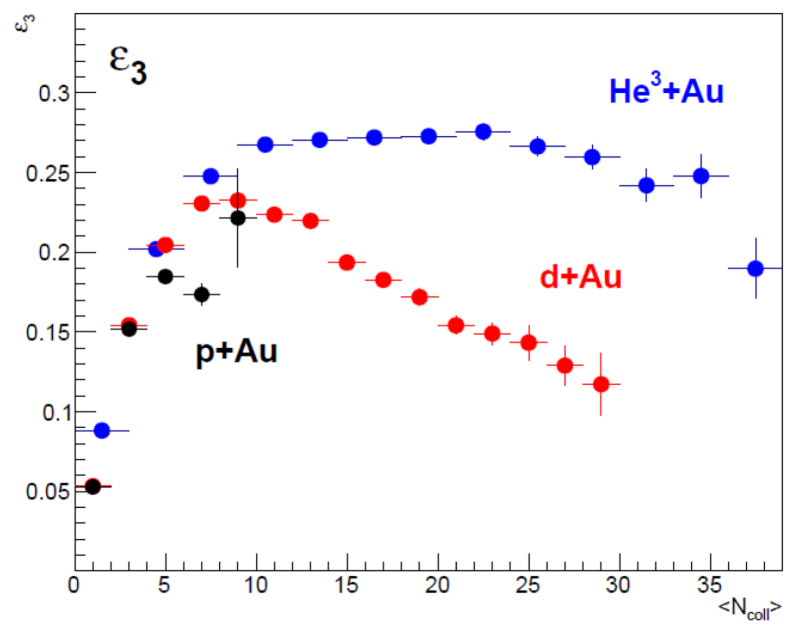
increase the triangularity of the initial state! what happens to v_3?

d+Au & He^3+Au in 2015

increased acceptance relative to previous d+Au run (VTX/FVTX)

compare with p+A





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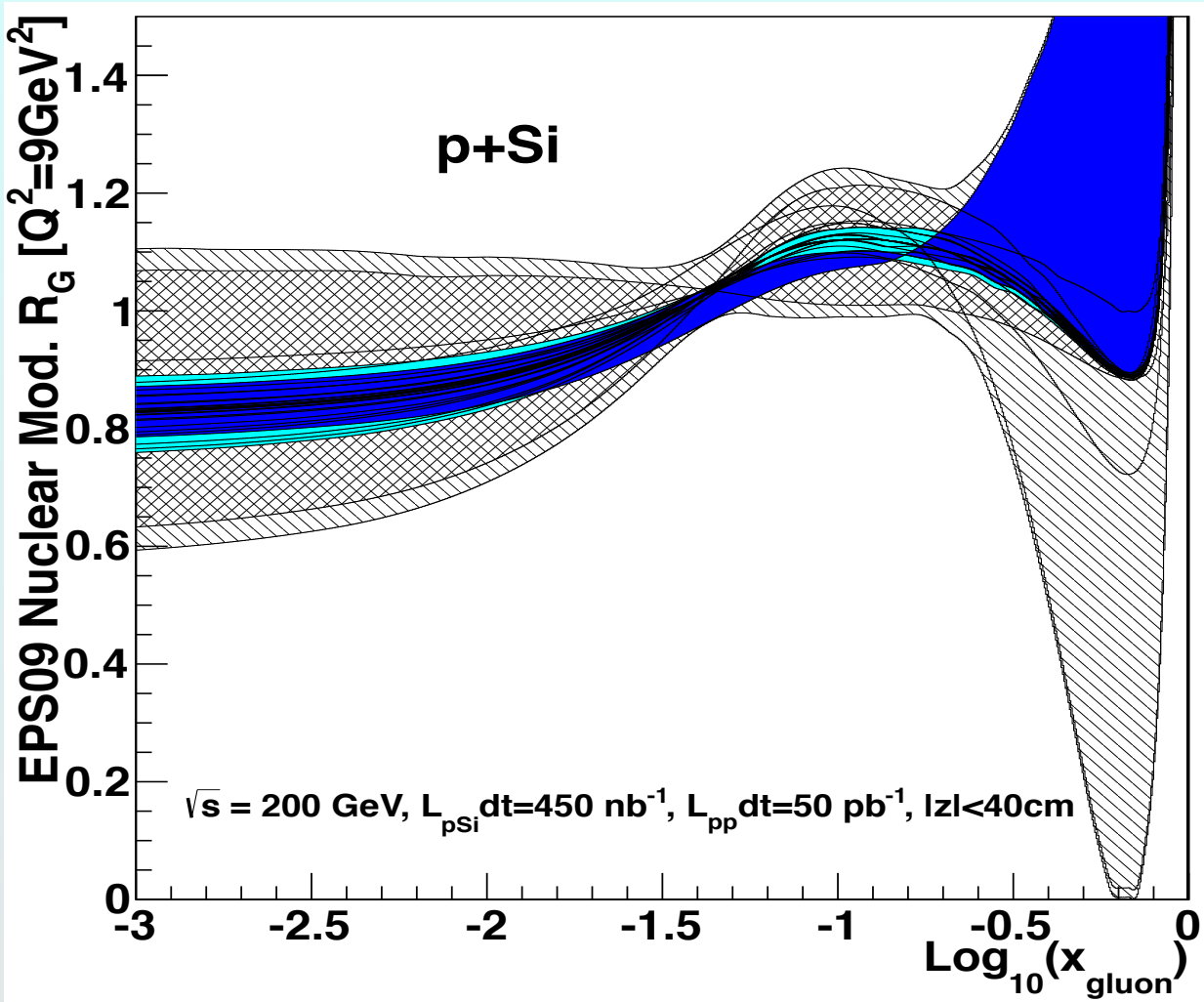
p+Si
EPS09 Nuclear Mod. R_G [Q^2=9GeV^2]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-3
-2.5
-2
-1.5
-1
-0.5
0
$\sqrt{s}$ = 200 GeV, $L_{pSi}dt$=450 nb^{-1}, $L_{pp}dt$=50 pb^{-1}, |z|<40cm
$Log_{10}(x_{gluon})$

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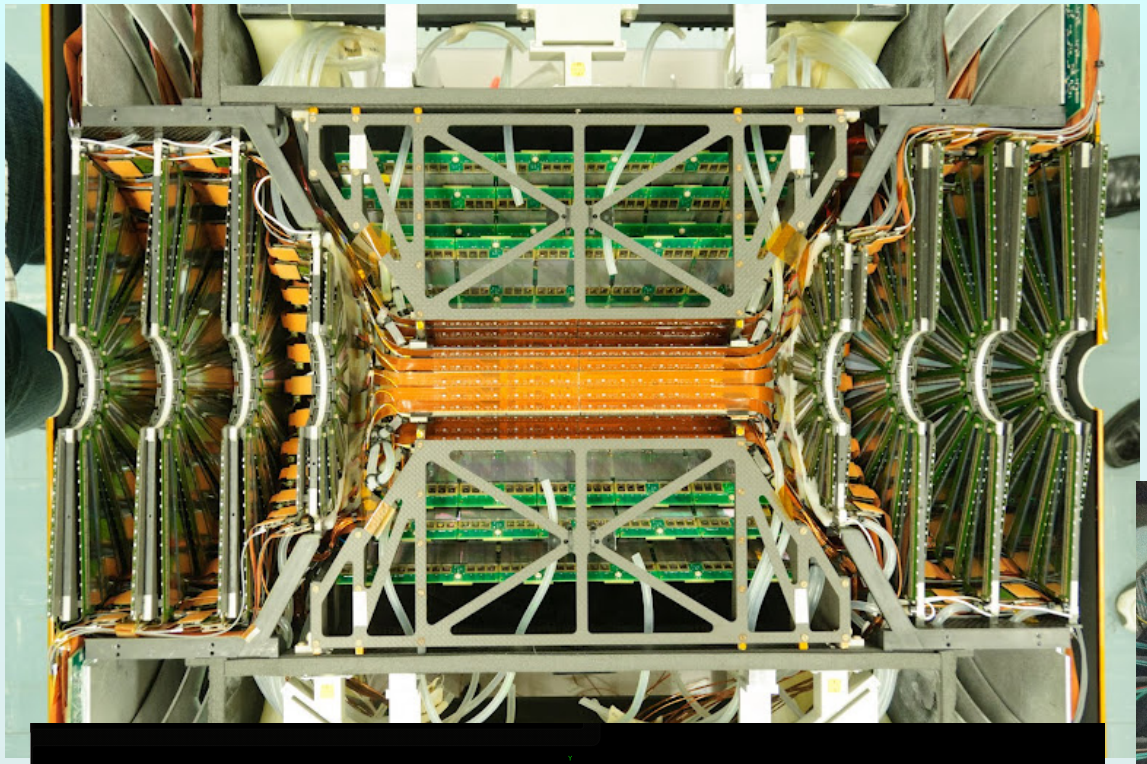
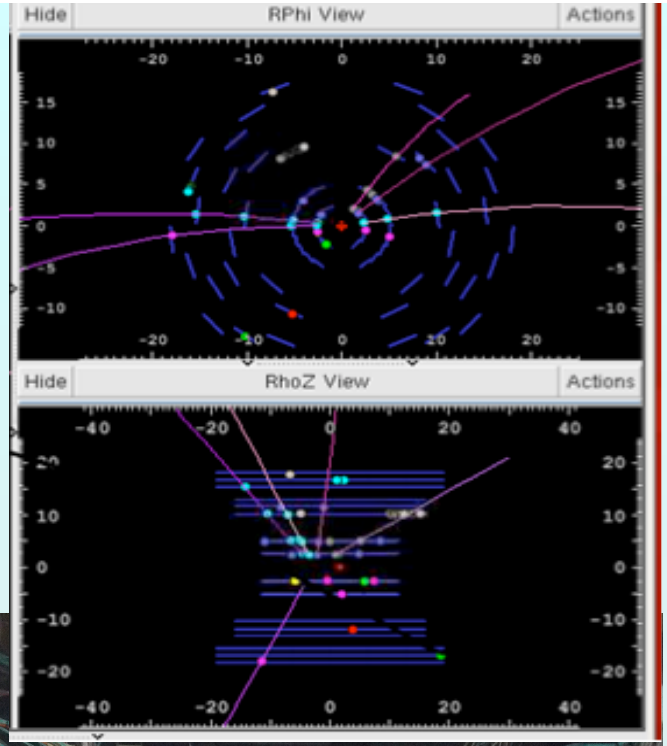
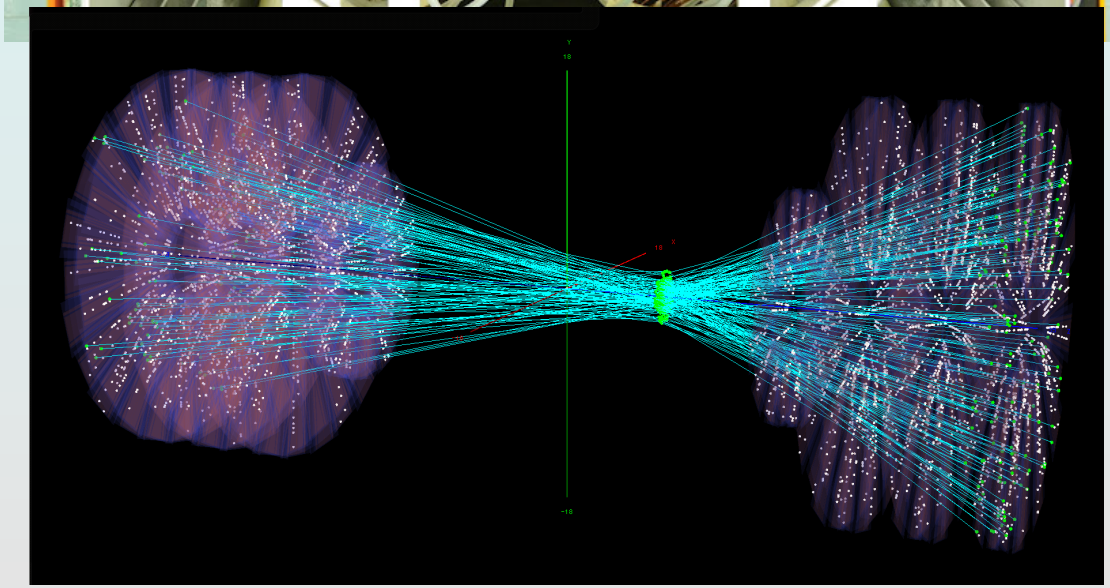
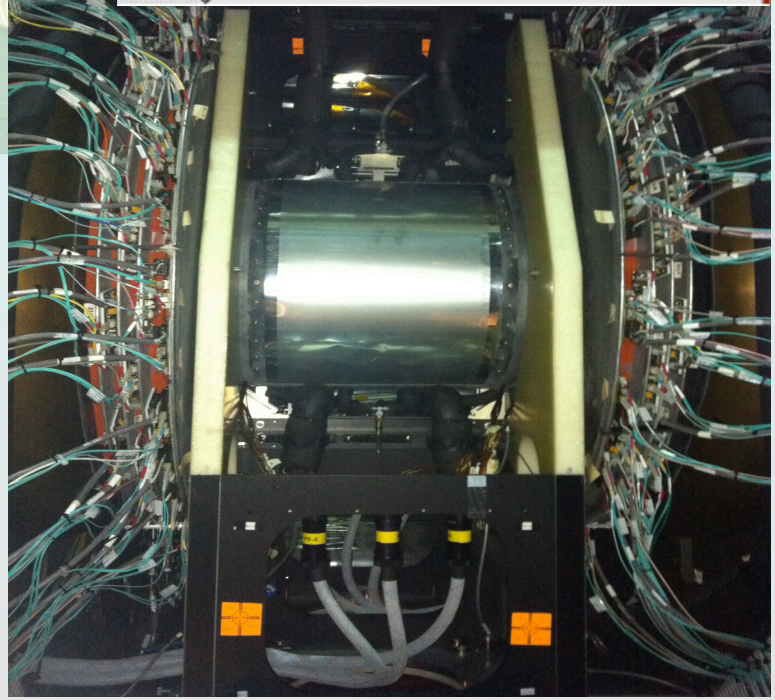
VTX & FVTX

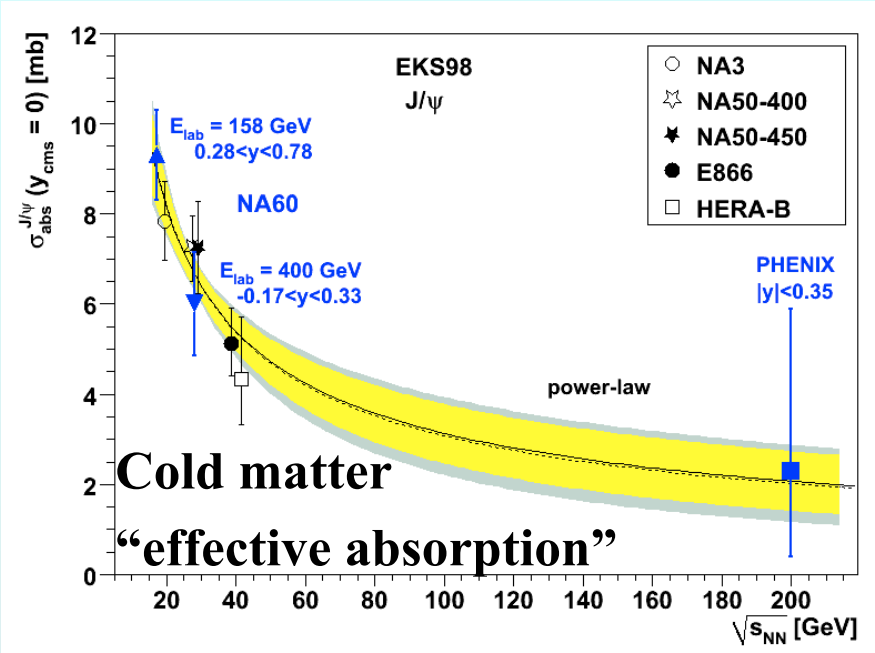


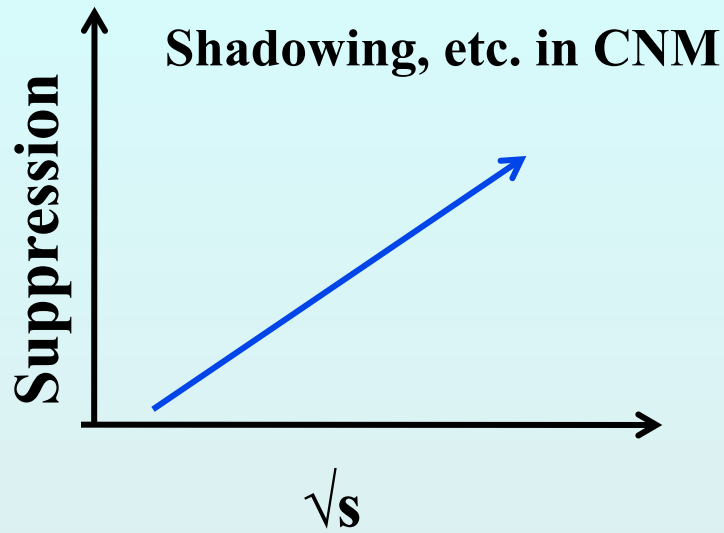


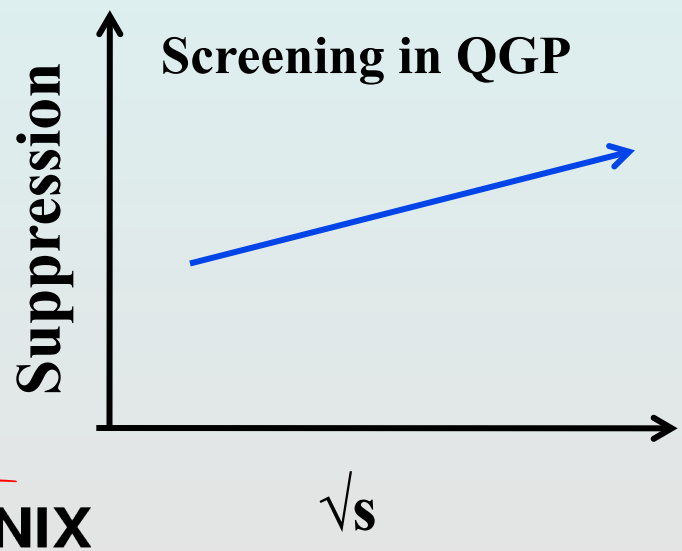


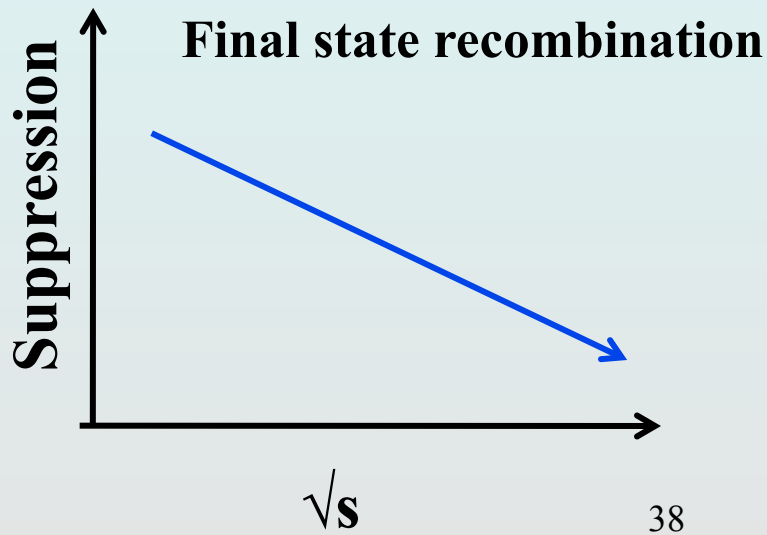


NEED y, p_T, b, √s, species to understand J/ψ









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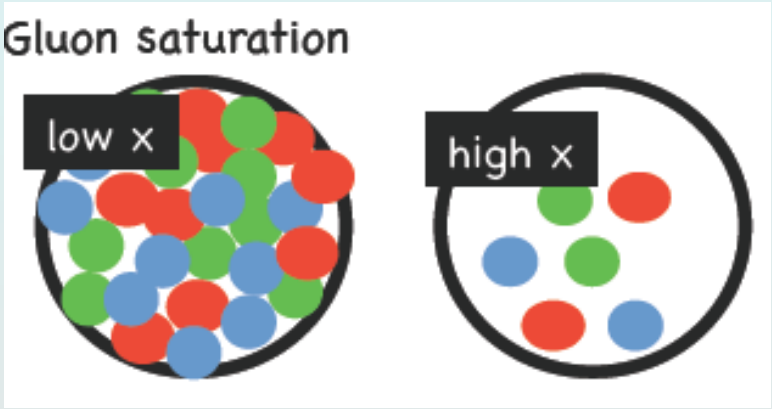
The big question in p+A physics

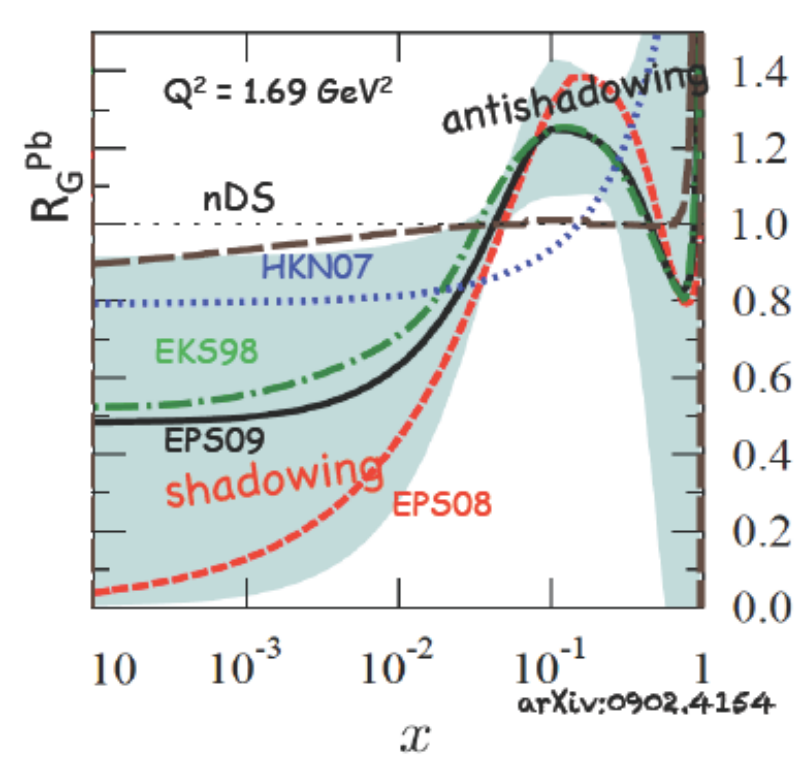
- **Then (the pre-RHIC era):**

  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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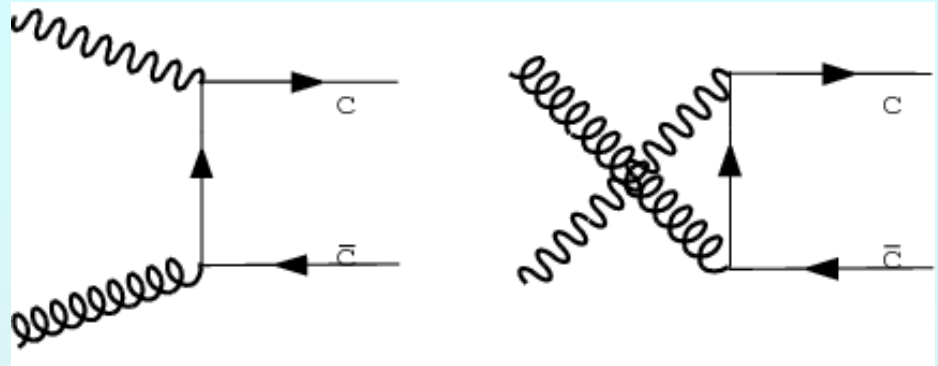
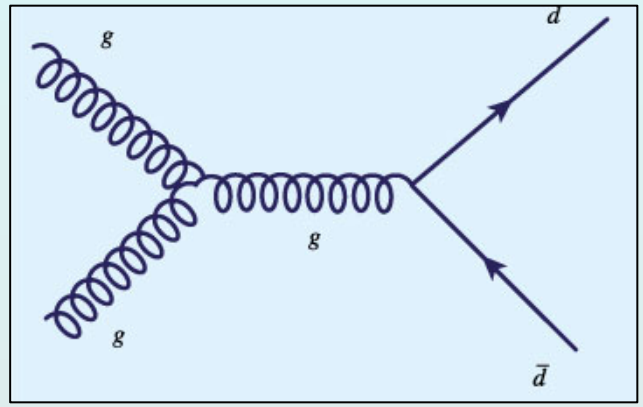
To answer this: PHENIX studies

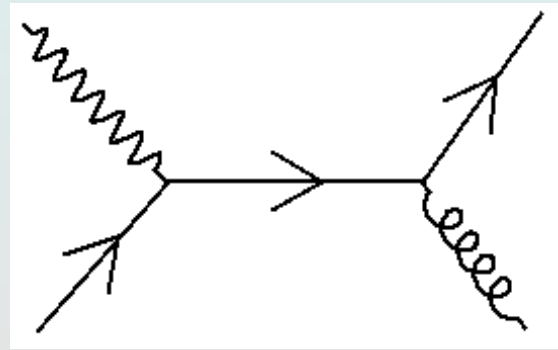
- **Heavy flavor production:**
  g+g → c + cbar



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



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



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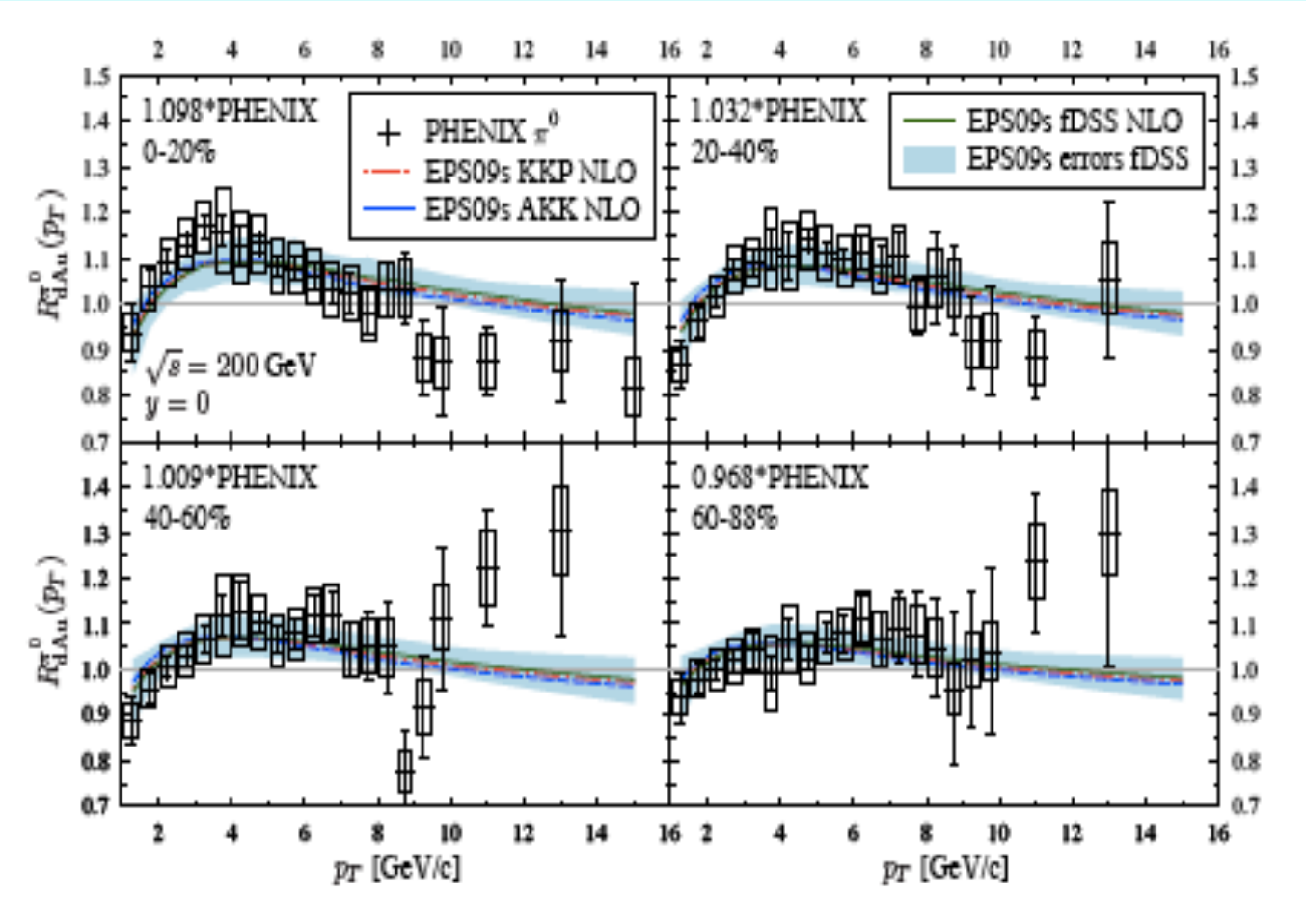
Turn now to jets and direct photons

arXiv 1205.5359

Hellenius, Eskola, et al

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

Get b-dependent nPDFs



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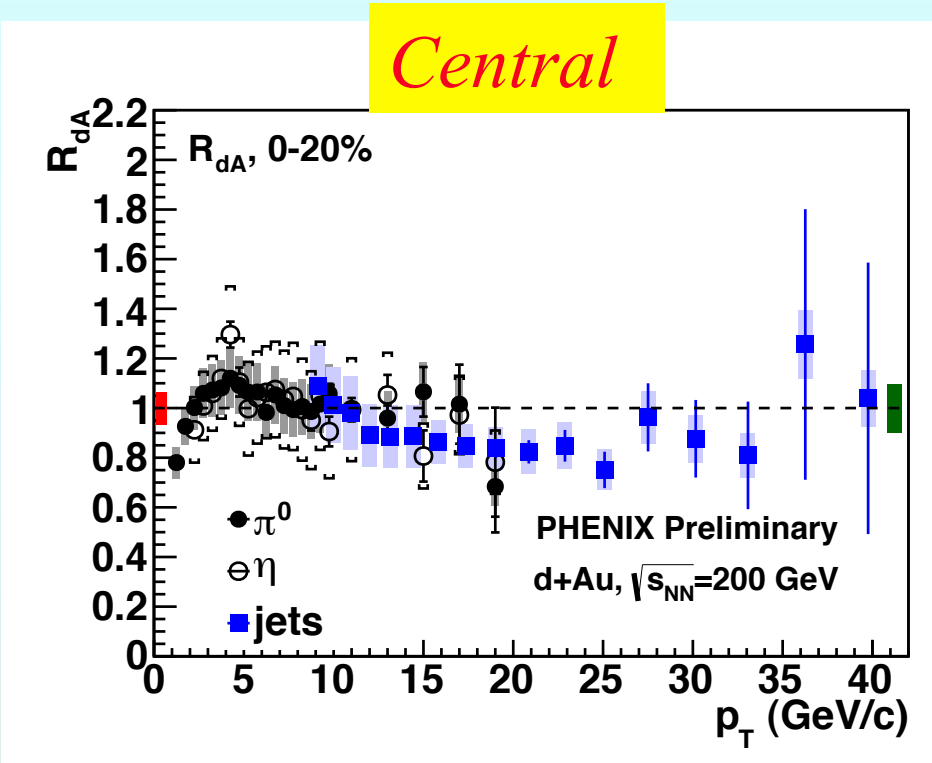
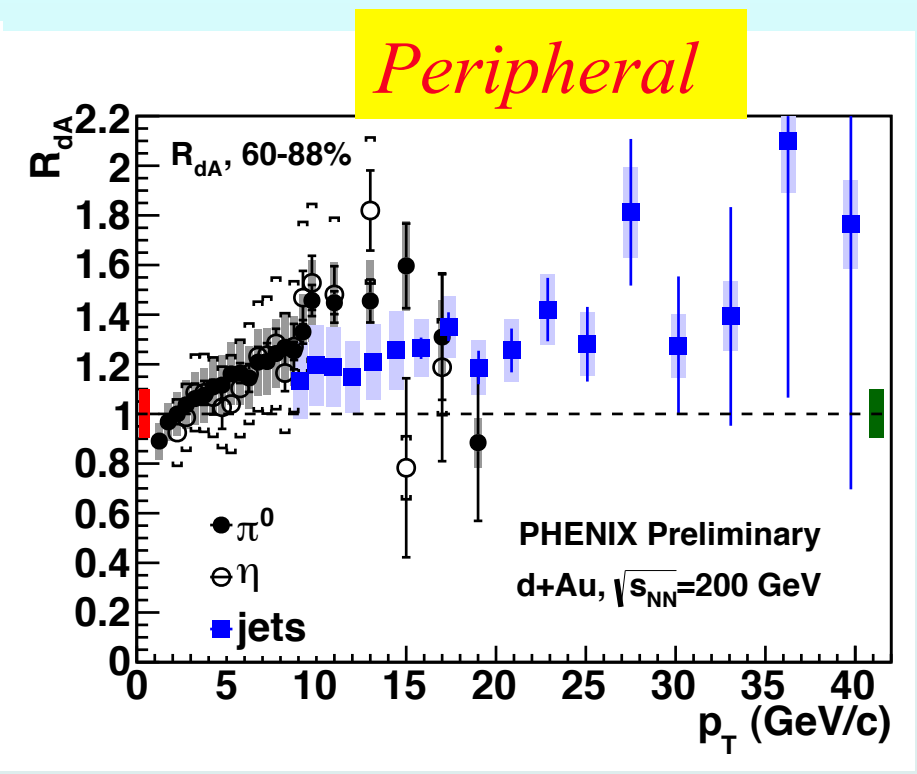
Suprising behavior of jets in d+Au





- 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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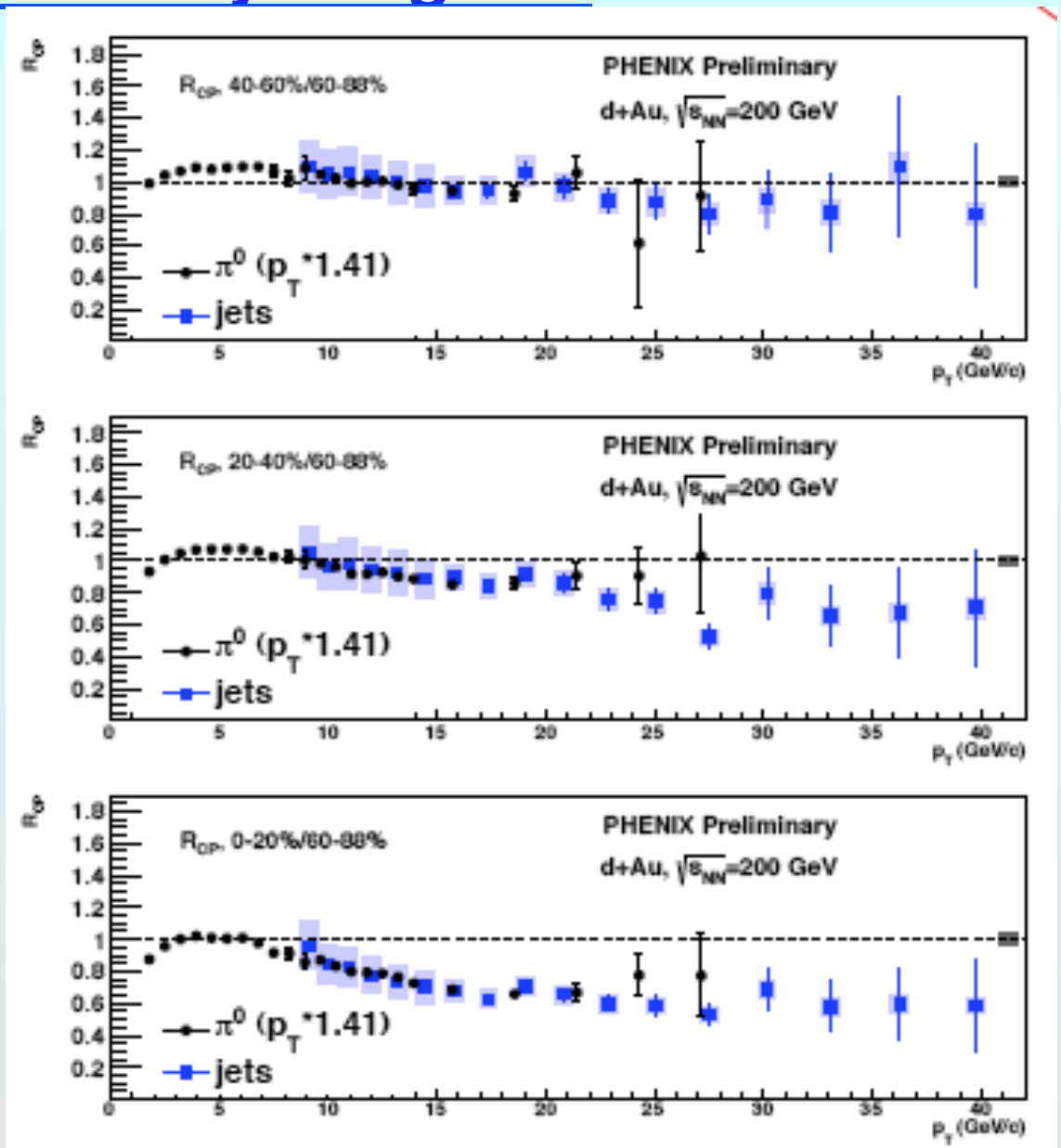
Do the π^0 and jets agree?

- 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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