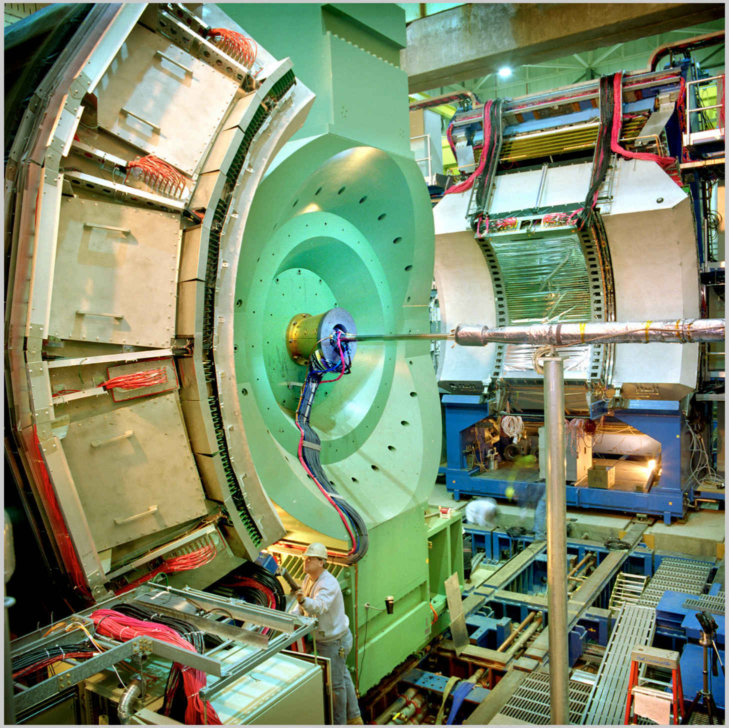
Insights from d+Au in PHENIX



Barbara Jacak

HEP 2013

December 19, 2013

PHENIX

Outline

- **Hydrodynamic flow in Au+Au and d+Au**

  Flow in d+Au?

  What does this say about thermalization?

- **Heavy quark production**

  Cold nuclear matter affects initial production

  Bound state suppessed by color screening in plasma

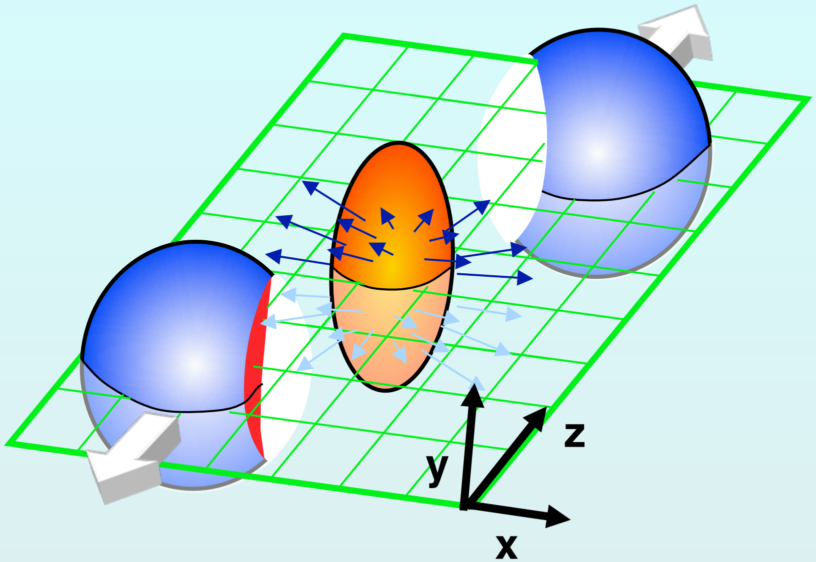
- **Direct photons**

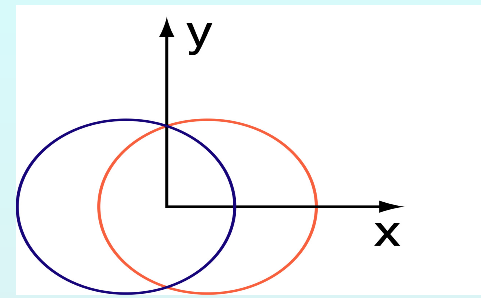
  Nuclear gluon distribution we start out with

  i.e. what does plasma thermalize *from*?

- **Future prospects**

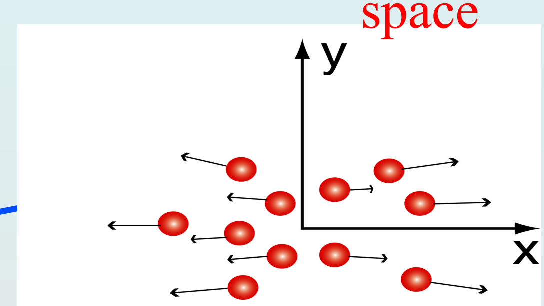
Measuring the collective flow (v_2) in A+A

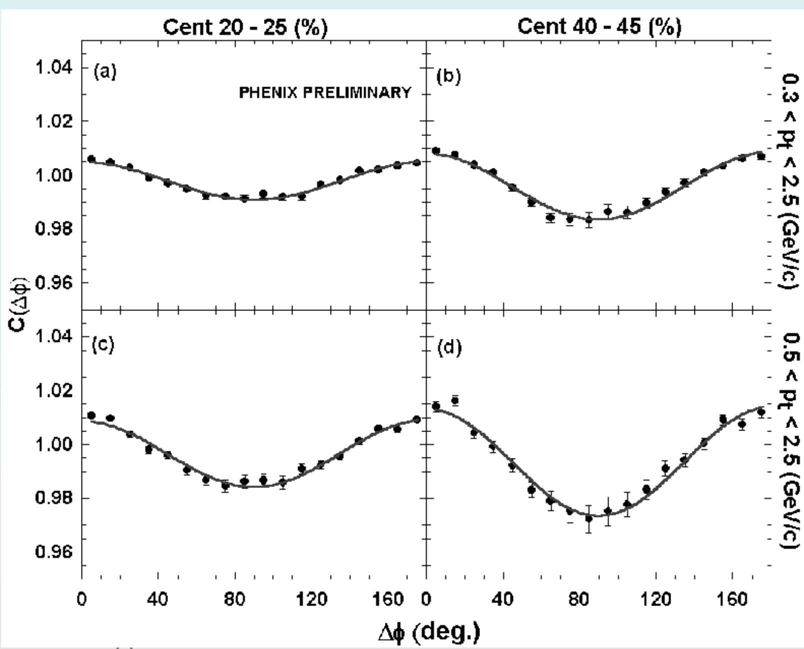




Almond shape overlap region in coordinate space

momentum space

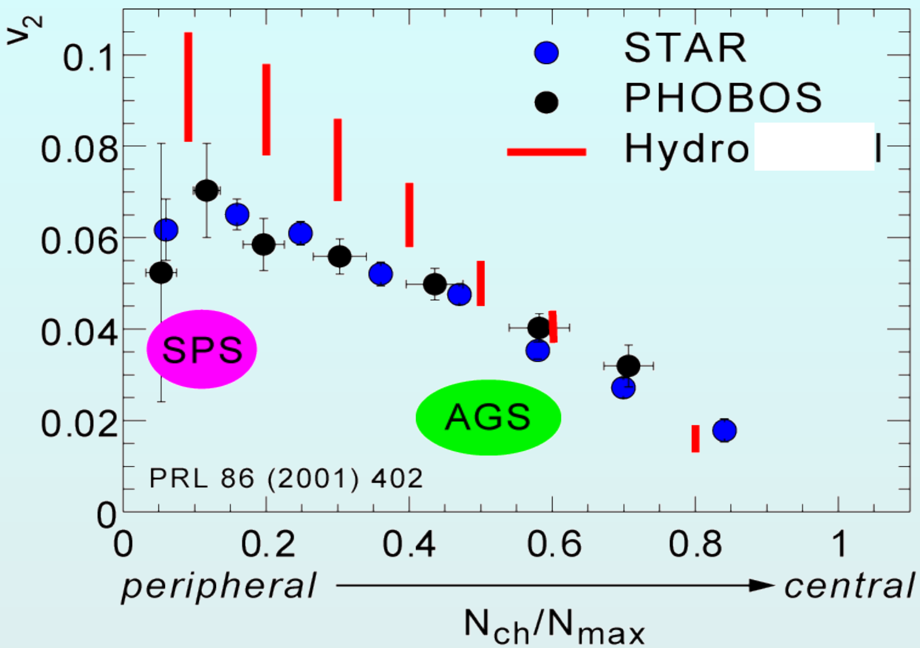




$dN/d\phi \sim 1 + 2\, v_2(p_T) \cos(2\phi) + \ldots$

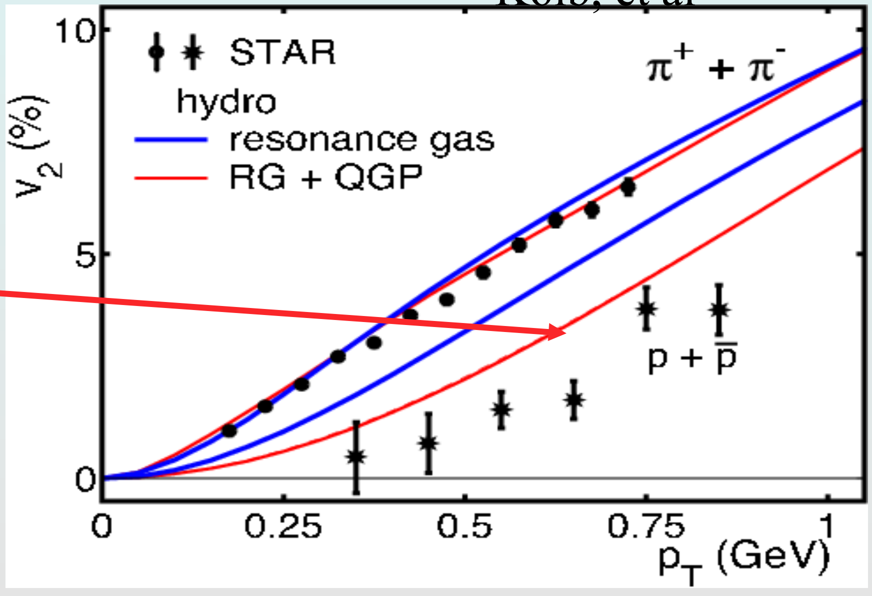
"elliptic flow"

Quark gluon plasma flows like a liquid



- huge pressure buildup
- large anisotropy → it all happens fast
- efficient equilibration mechanism??

Kolb, et al



Hydrodynamics reproduces elliptic flow of q-$\bar{q}$ and 3q states

Mass dependence requires

QGP - NOT gas of hadrons

Low viscosity/entropy ratio

D. Teaney, PRC68, 2003

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So how about p/d + A and p+p?

- Hydrodynamics needs approximate equipartition of particle momenta to be usable (~local equilibrium)
  And a system of sufficient volume to call it "matter"

- Can these conditions be satisfied in small systems?
  i.e. do they also evolve hydrodynamically?

- Until a few years ago, everyone thought "no"

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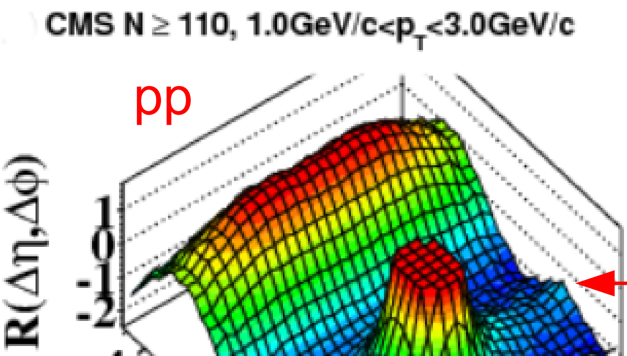
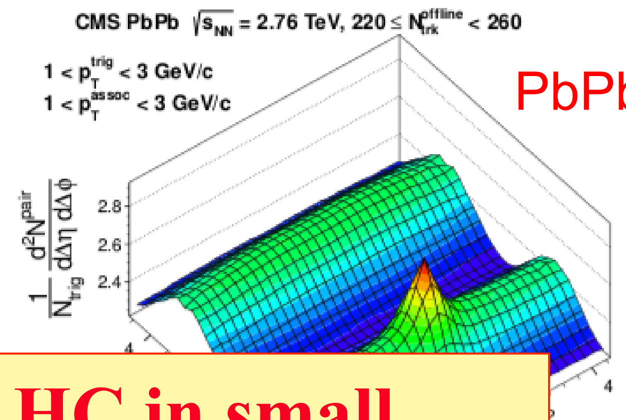
Two-particle angular correlations



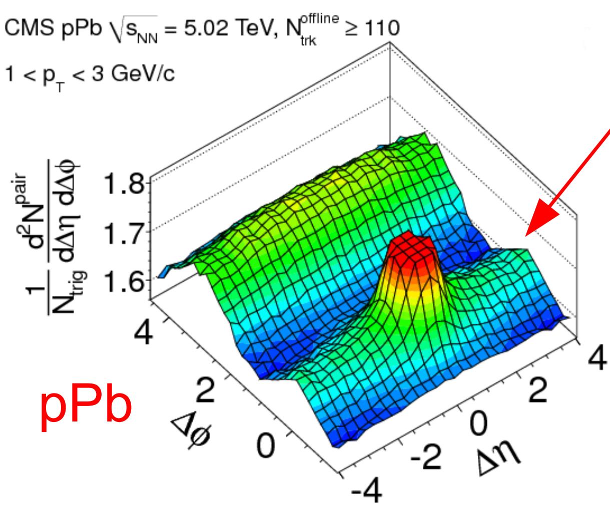
Near-side ridges apparent in high multiplicity events



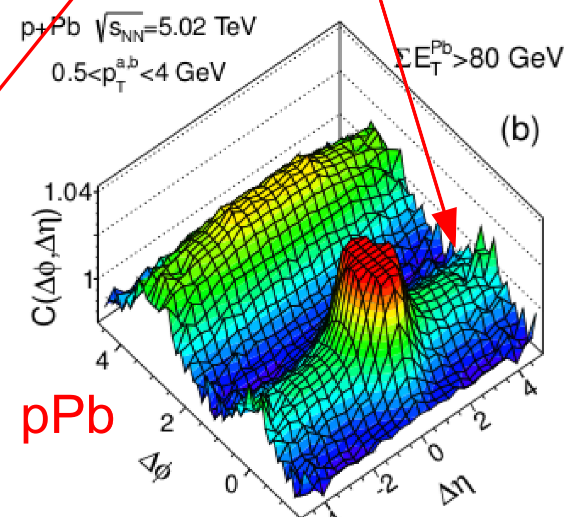
Looks like there might be flow at LHC in small systems when the number of final particles > 100

CMS, JHEP 1009 (2010) 91

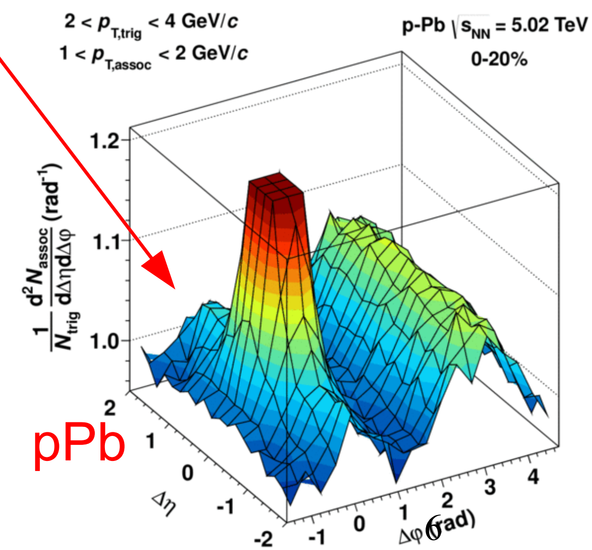
213



CMS, PLB 718 (2012) 795



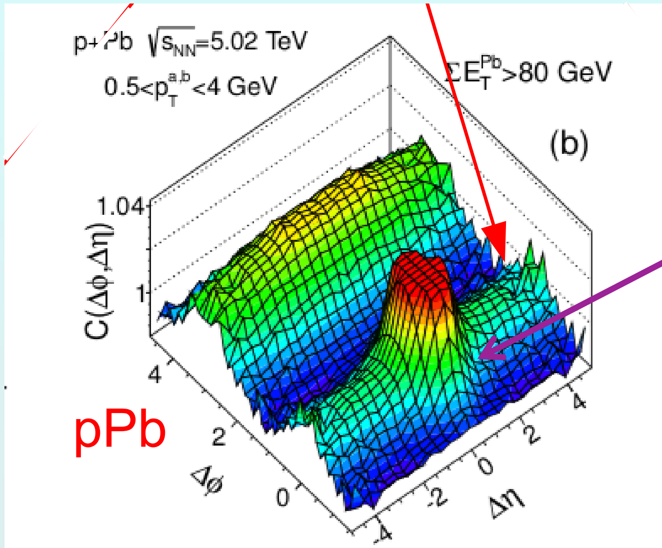
ATLAS, PRL 110 (2013) 182302

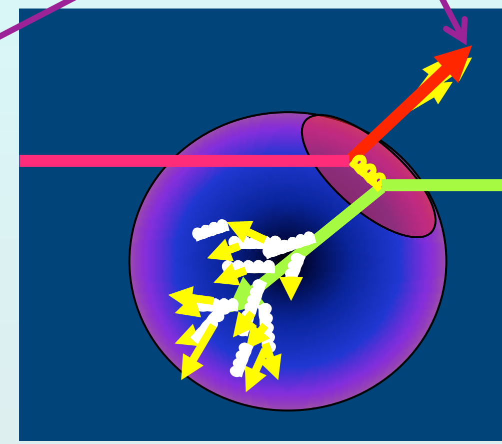


ALICE, PLB 719 (2013) 29

How about at RHIC?

- To quantify the Fourier expansion must remove the jet





- Do by subtraction: (central d+Au – peripheral d+Au)

  i.e. high multiplicity – low multiplicity

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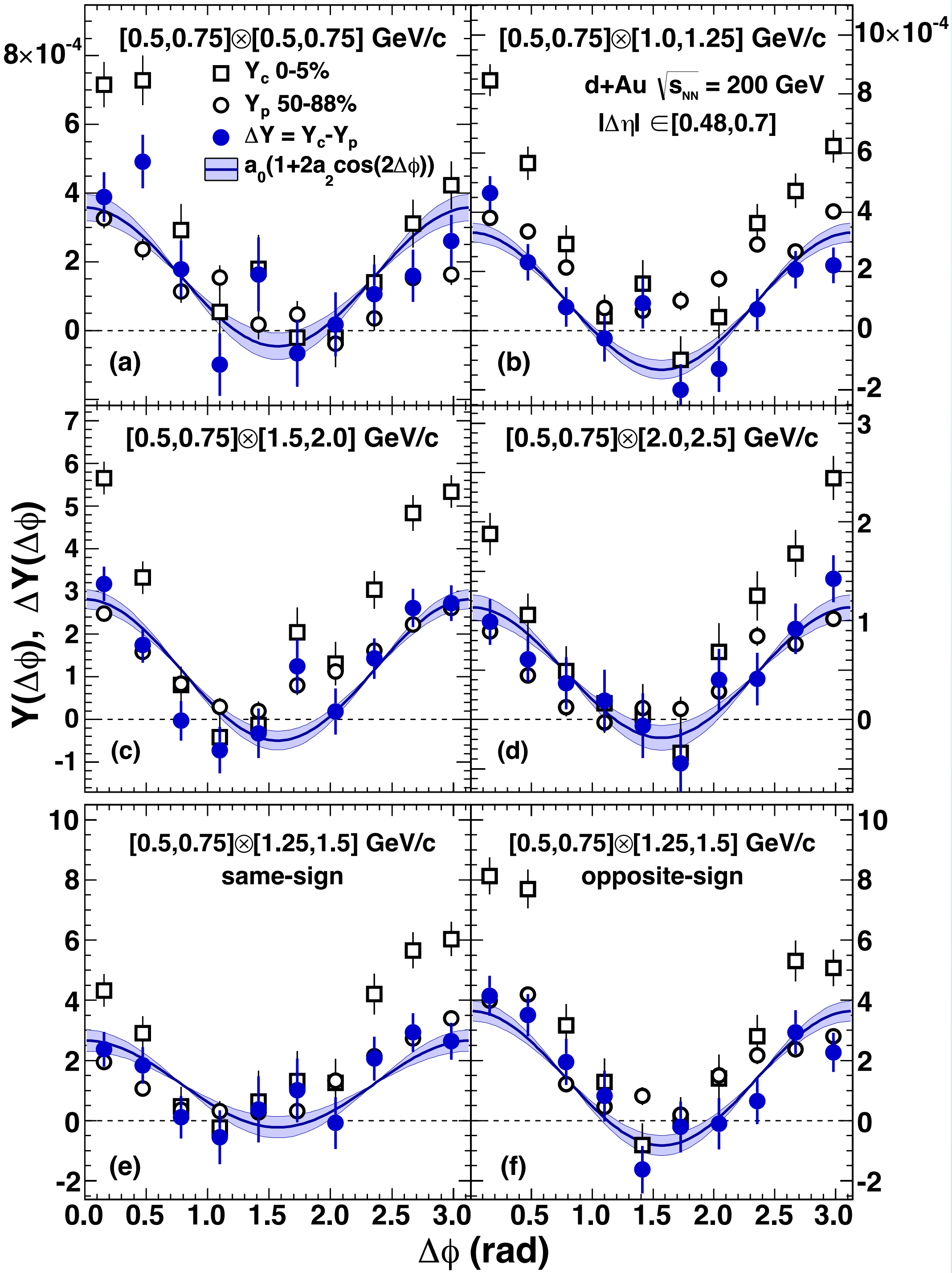
Di-hadrons in the PHENIX central arms

0.48 < |Δη| < 0.7



Central - peripheral to remove remaining jet

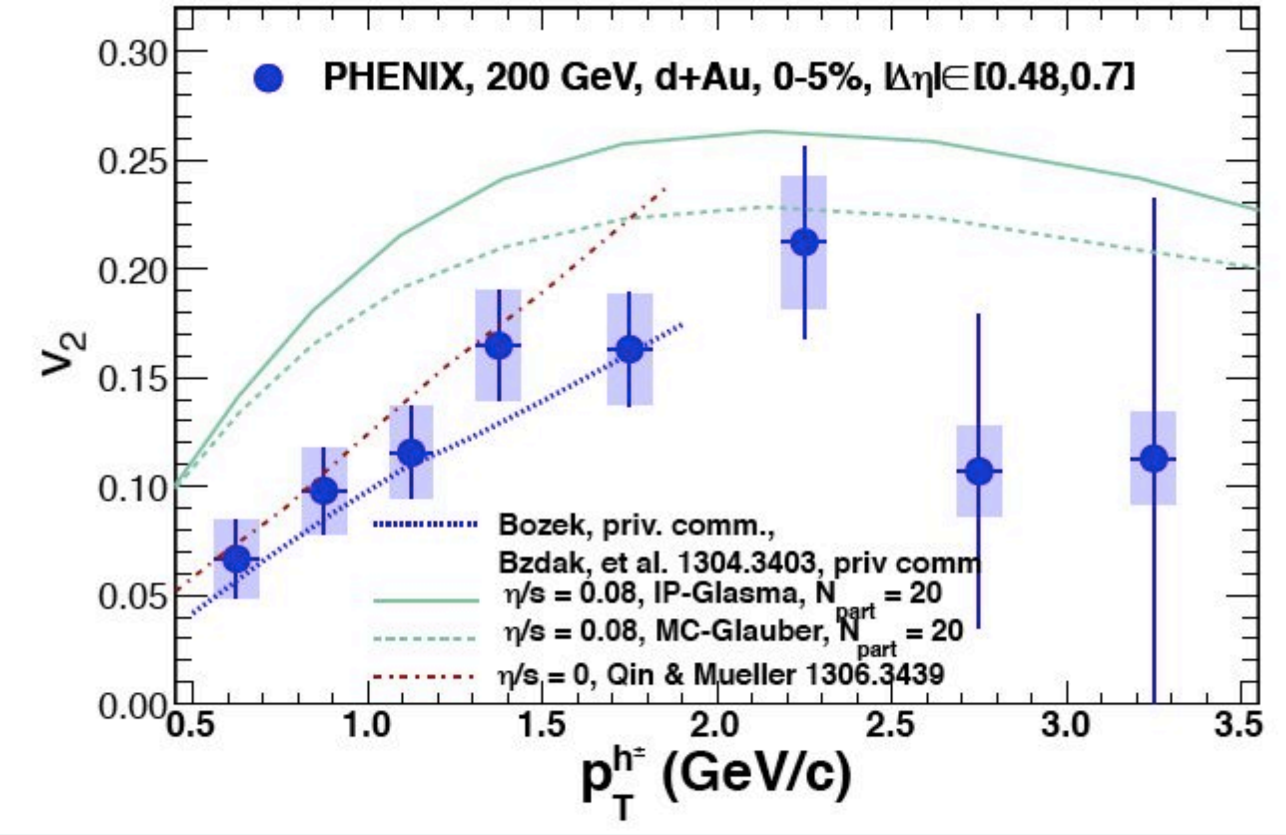
Looks awfully flow-like!

Opposite sign enhances jet contribution; subtraction works!

arXiv: 1303.1794

Accepted in PRL

v_2 value



arXiv:1303.1794

v_2 > v_2 at LHC, but note that ε_2 d+Au > ε_2 p+Au

v_2 agrees w/hydro if $\eta/s \leq 0.08$

v_3 ~ 0

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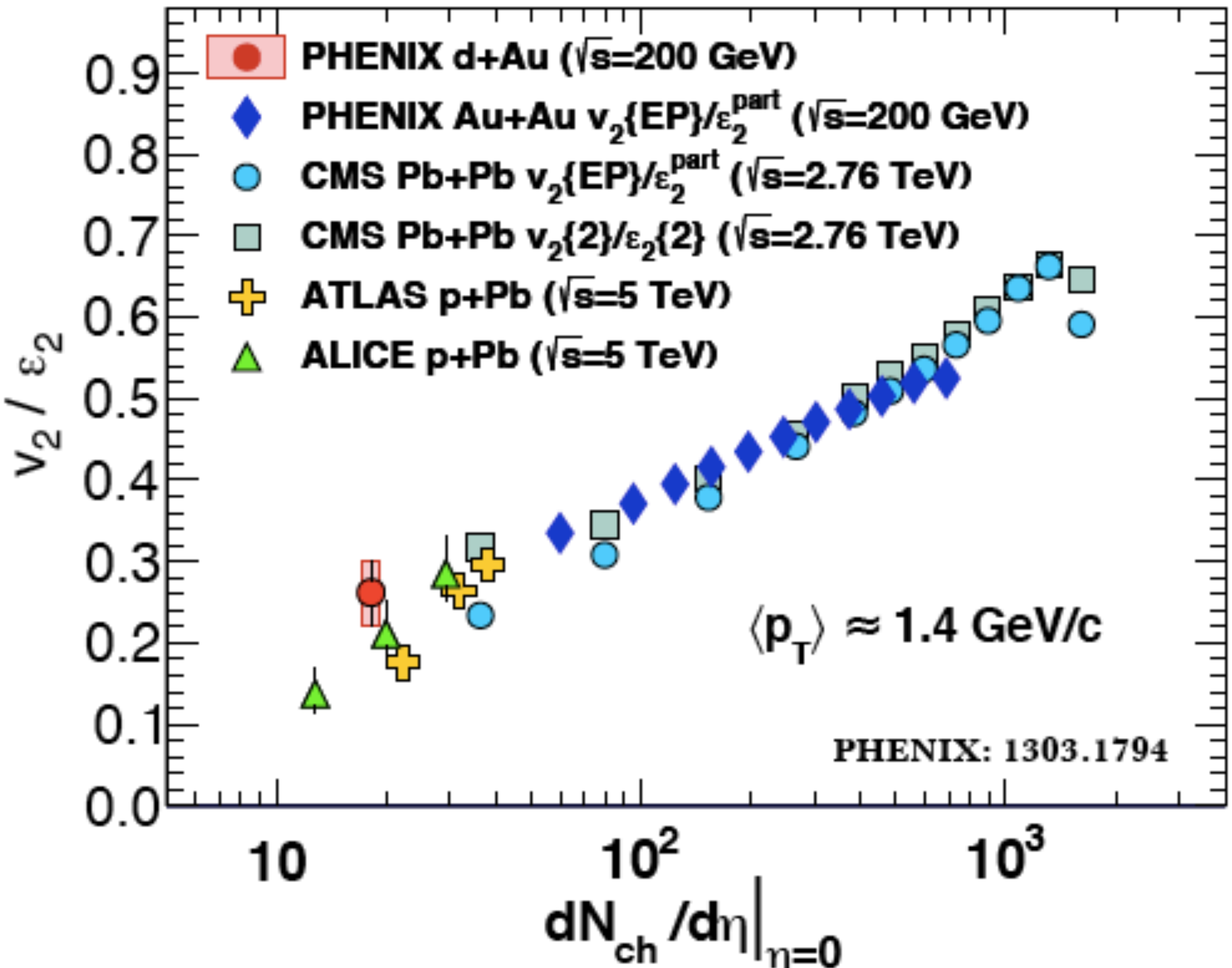
v_2/ε_2 vs multiplicity



- Glauber MC & pointlike centers to calculate ε_2
- → approximate scaling of v_2/ε_2 with dN/dη

a common relationship between geometry and v_2?

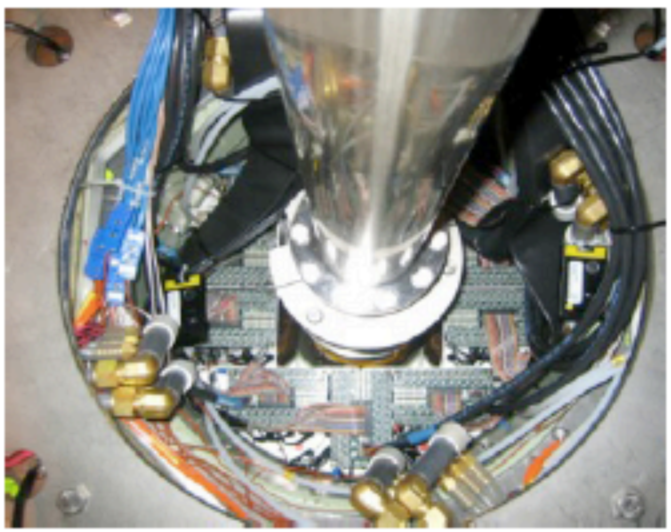
Larger rapidity gap reduces jet contribution

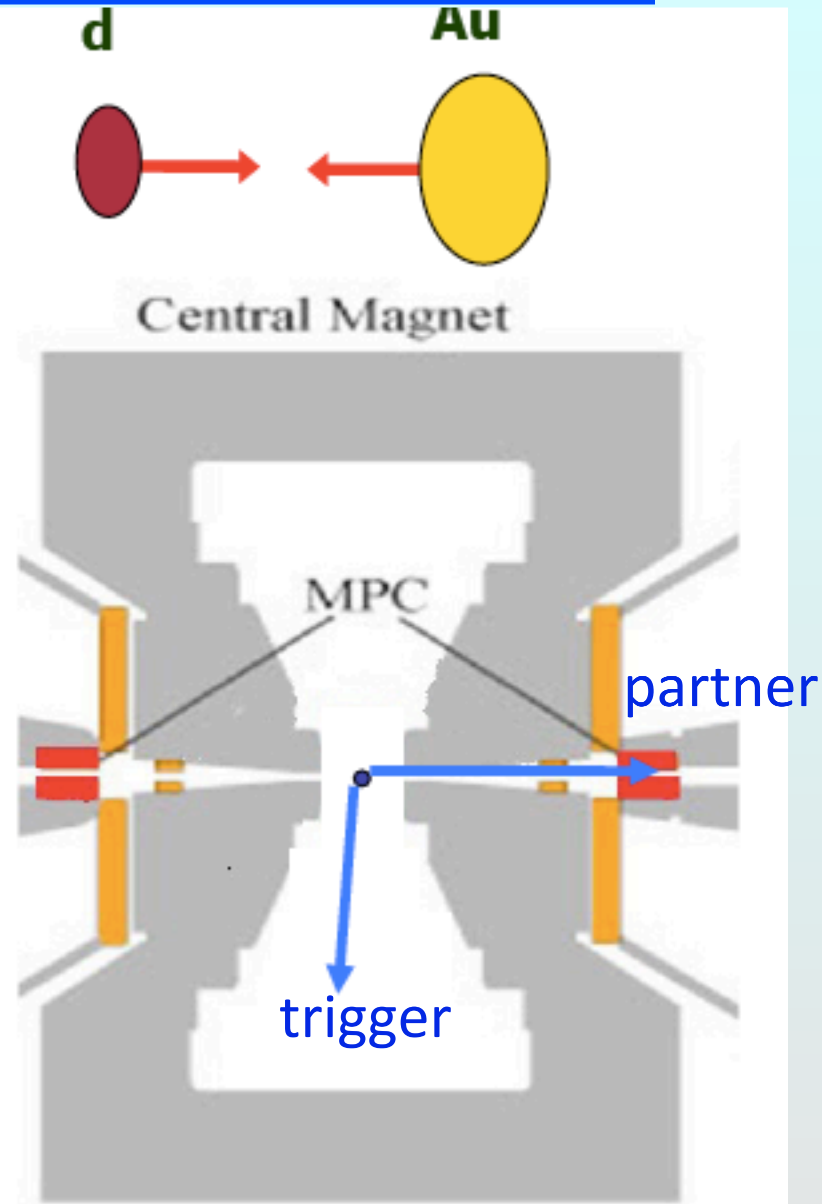
Muon Piston Calorimeters

both d-going & Au-going directions

$3 < |\eta| < 4$

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





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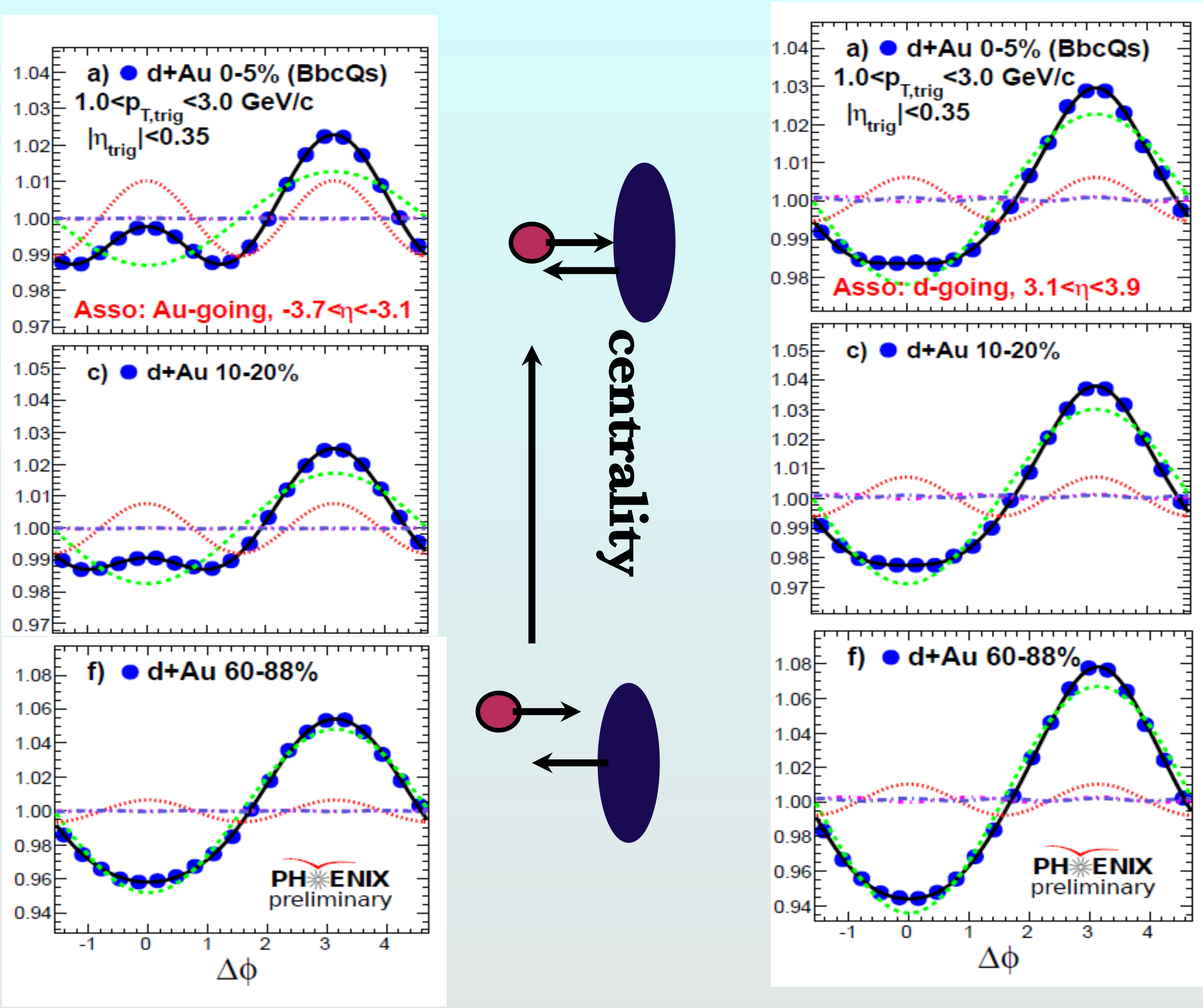
Long range correlations in d+Au at RHIC!

S. Huang



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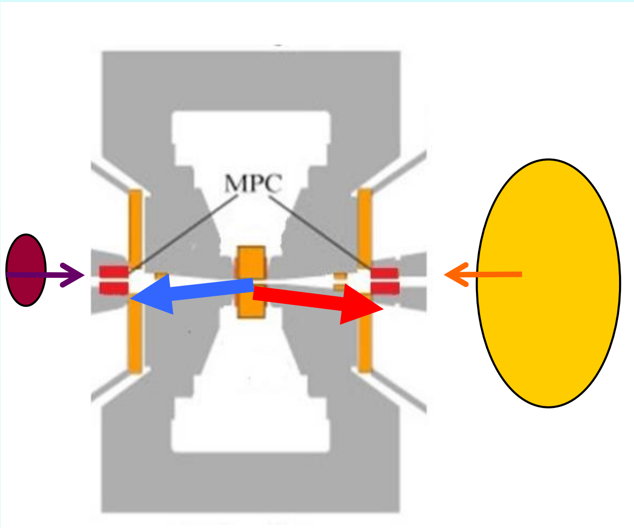
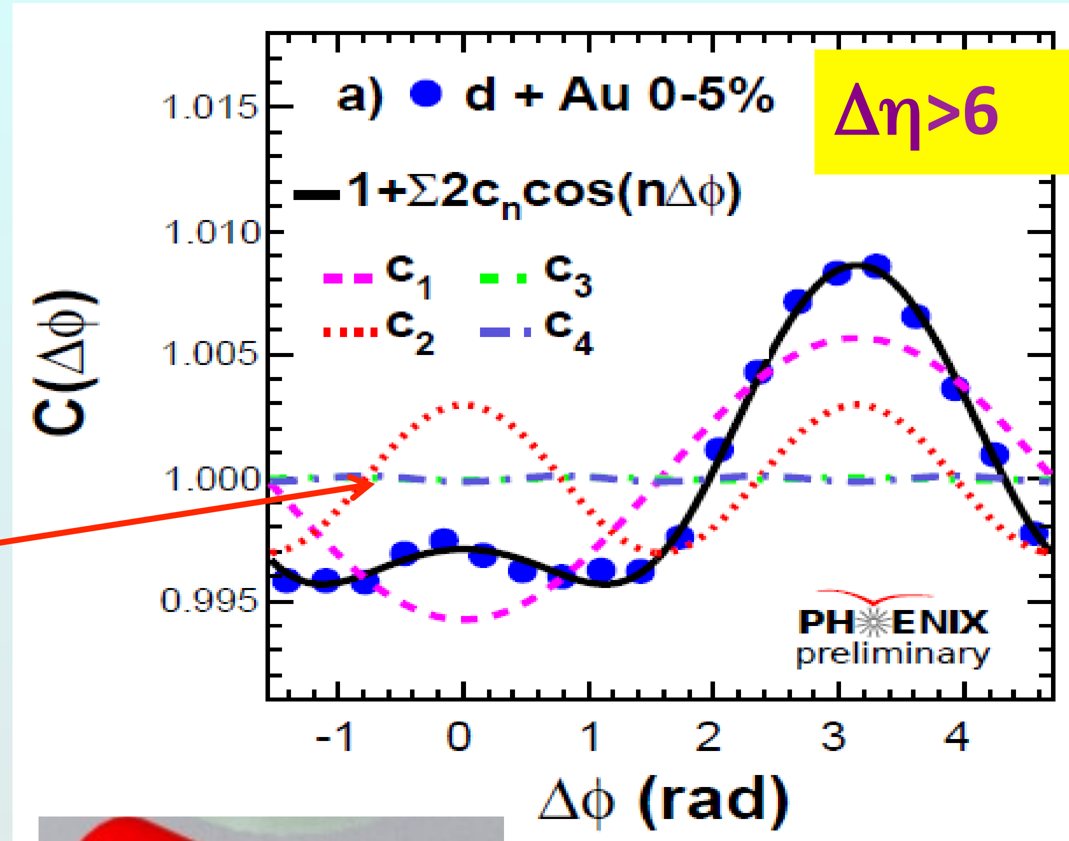
"ridge" @ large η ***NB: jets not removed; v_3 ~0***

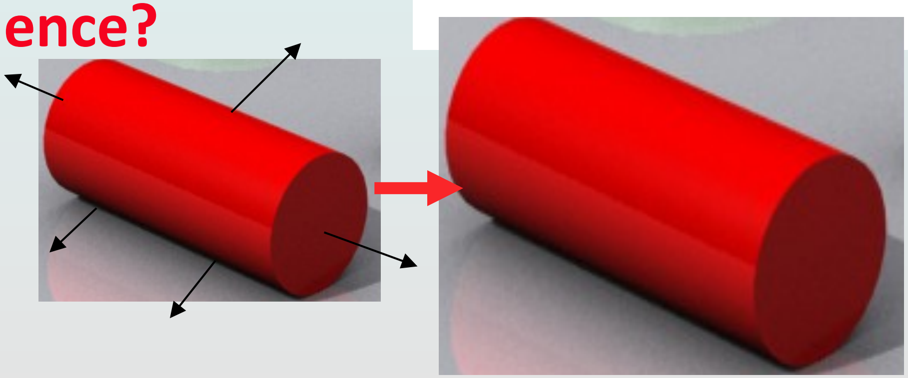
Even larger rapidity gap

S. Huang





- v_2 is still non-zero!
- Looks like hydrodynamic flow…
- Other evidence?



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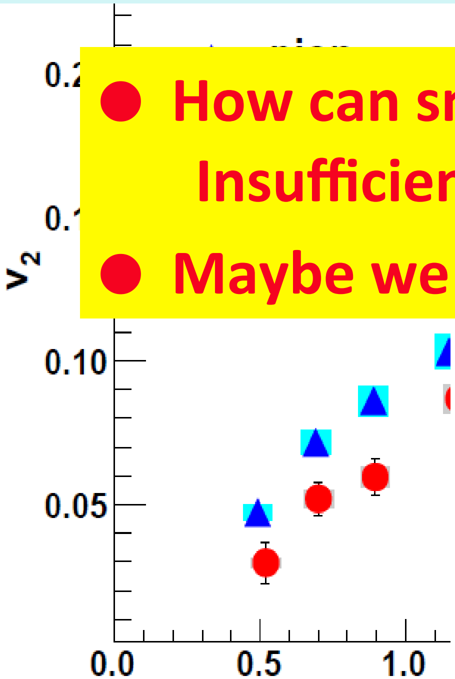
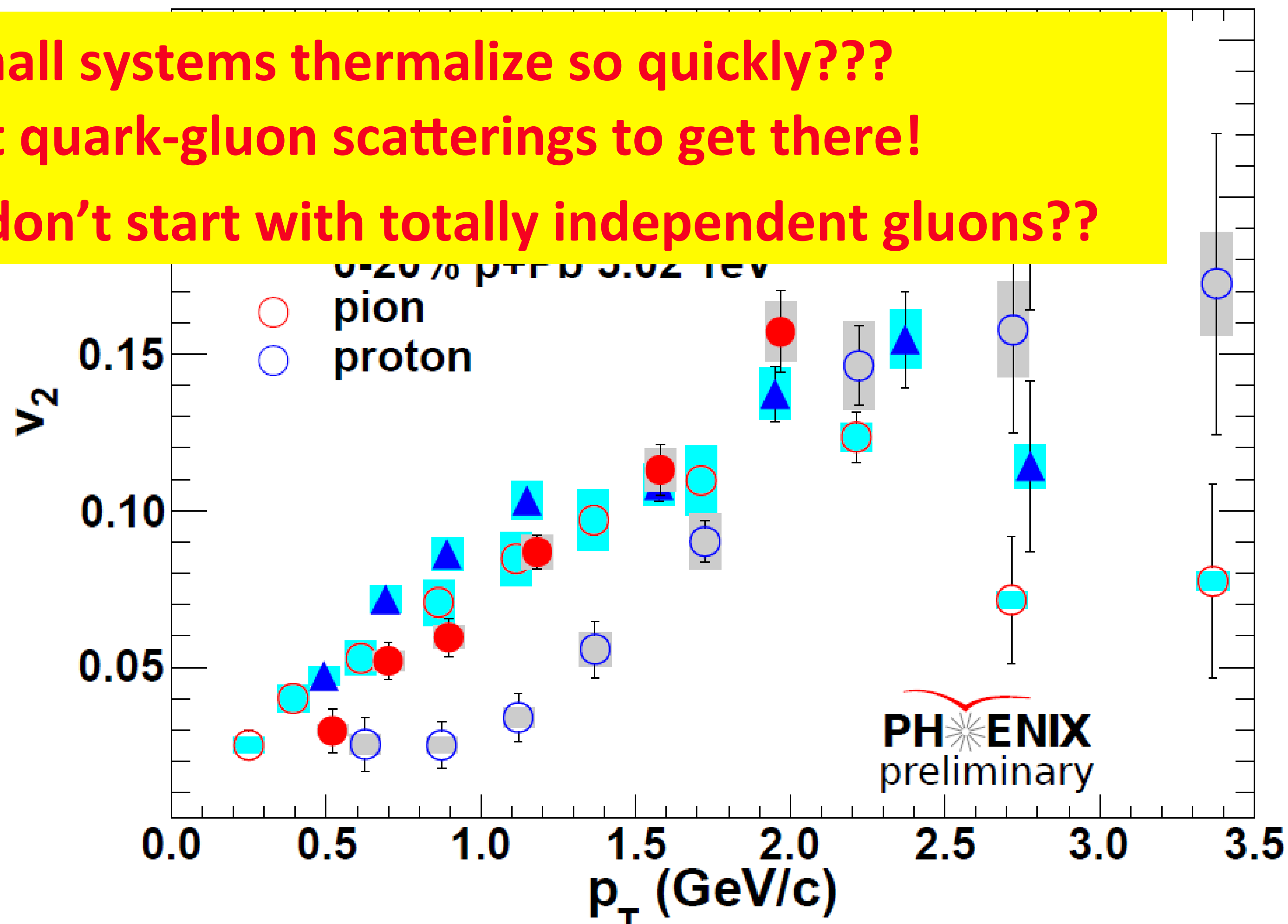
Should be radial expansion, too

- Radial velocity boost -> mass dependent momentum boost
- Mass splitting seen; smaller than at LHC… less dense & less flow

  Or maybe LHC p_T increase is not all due to radial flow?





- How can small systems thermalize so quickly???

  Insufficient quark-gluon scatterings to get there!

- Maybe we don't start with totally independent gluons??

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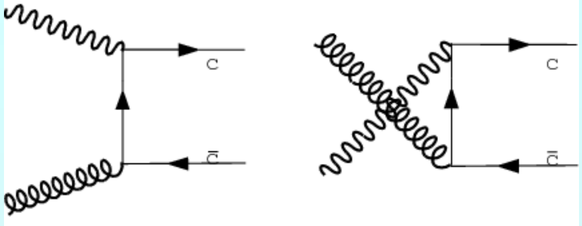
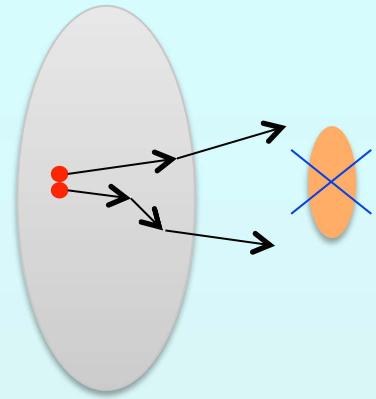
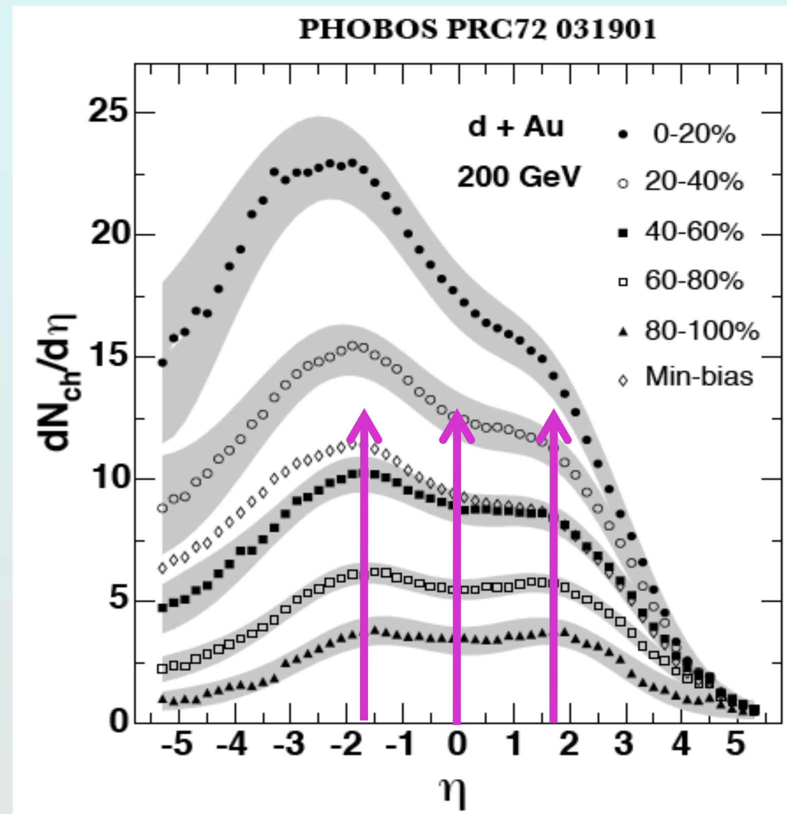


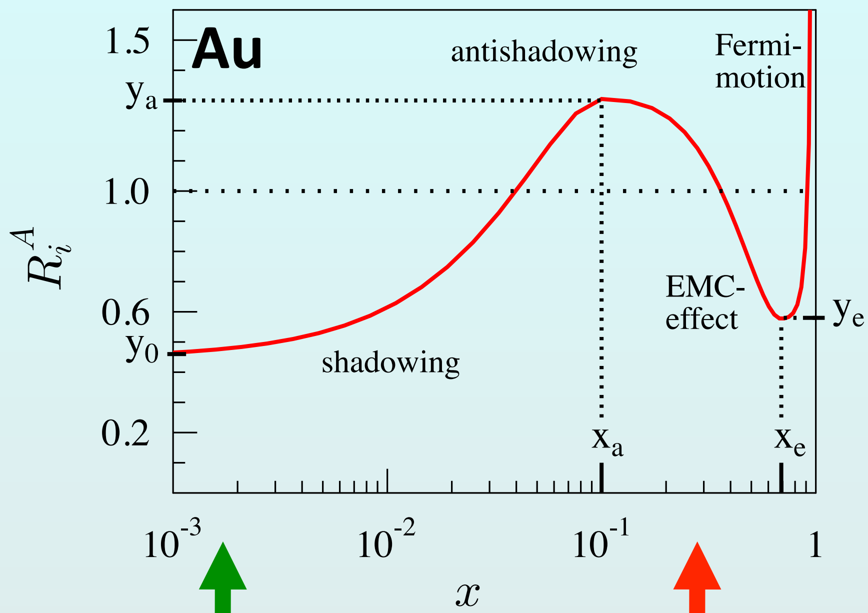
Heavy Flavor



- **Production of c+cbar and b+bbar**
  - **Probes nuclear gluon distribution in d+Au**
    - **initial state effects:**
      - **gluon saturation**
      - **shadowing, anti-shadowing**
      - **parton energy loss**
      - **parton multiple scattering**
  - ❖ ***quarkonia, open heavy flavor***
- **Quarkonia survival**
  - **Screening in QGP breaks them up**
  - **Sensitivity to medium in d+Au**
  - ❖ ***J/ψ vs. ψ' vs. Υ***
    different radius & binding energy



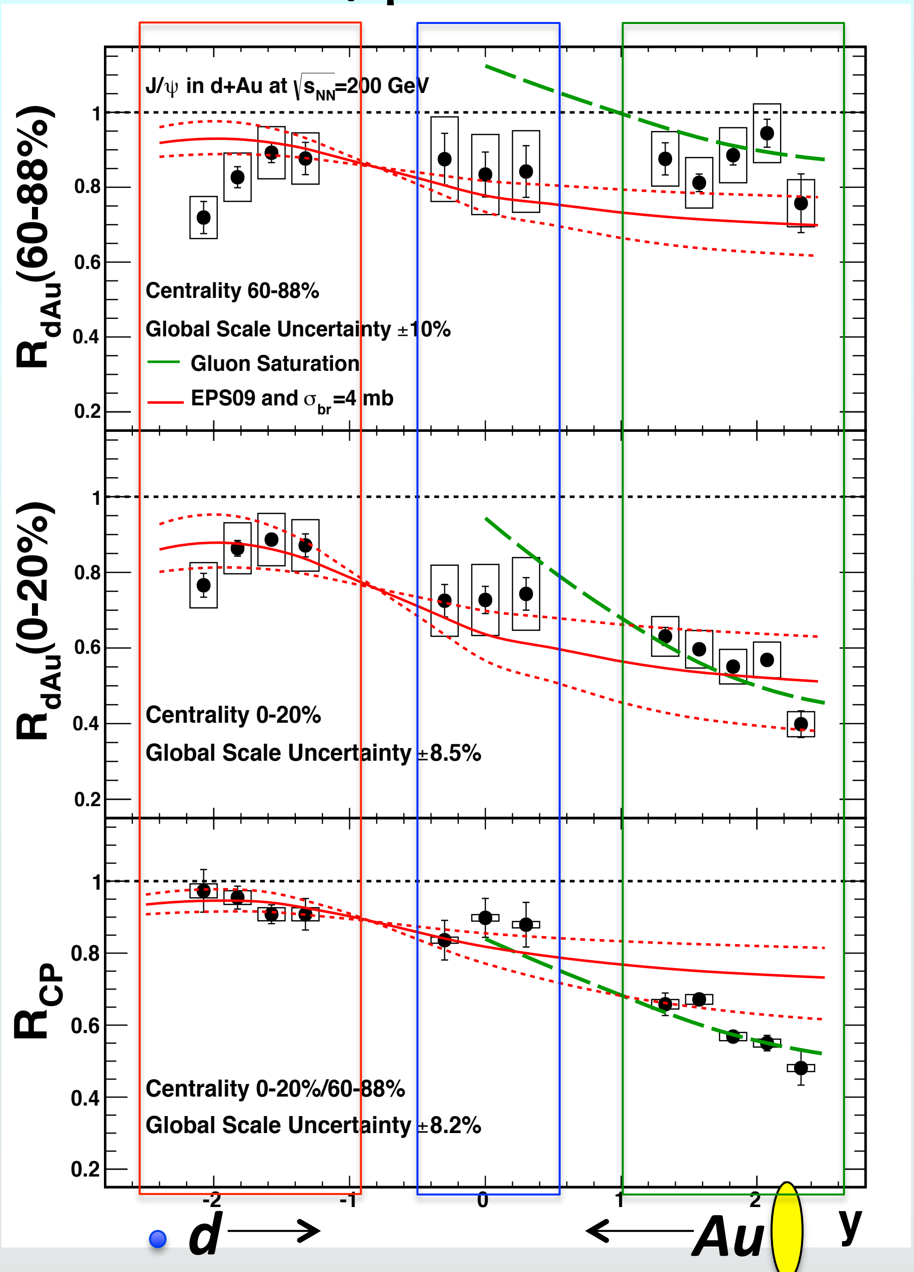
Initial State: what's where?



Forward
+ y
d-going

Backward
- y
Au-going

d+Au -> J/ψ from PHENIX



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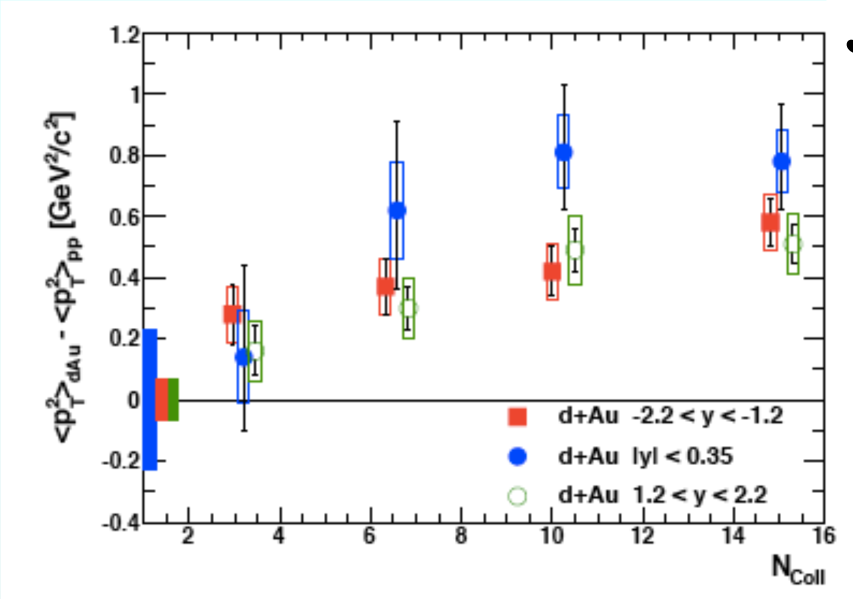
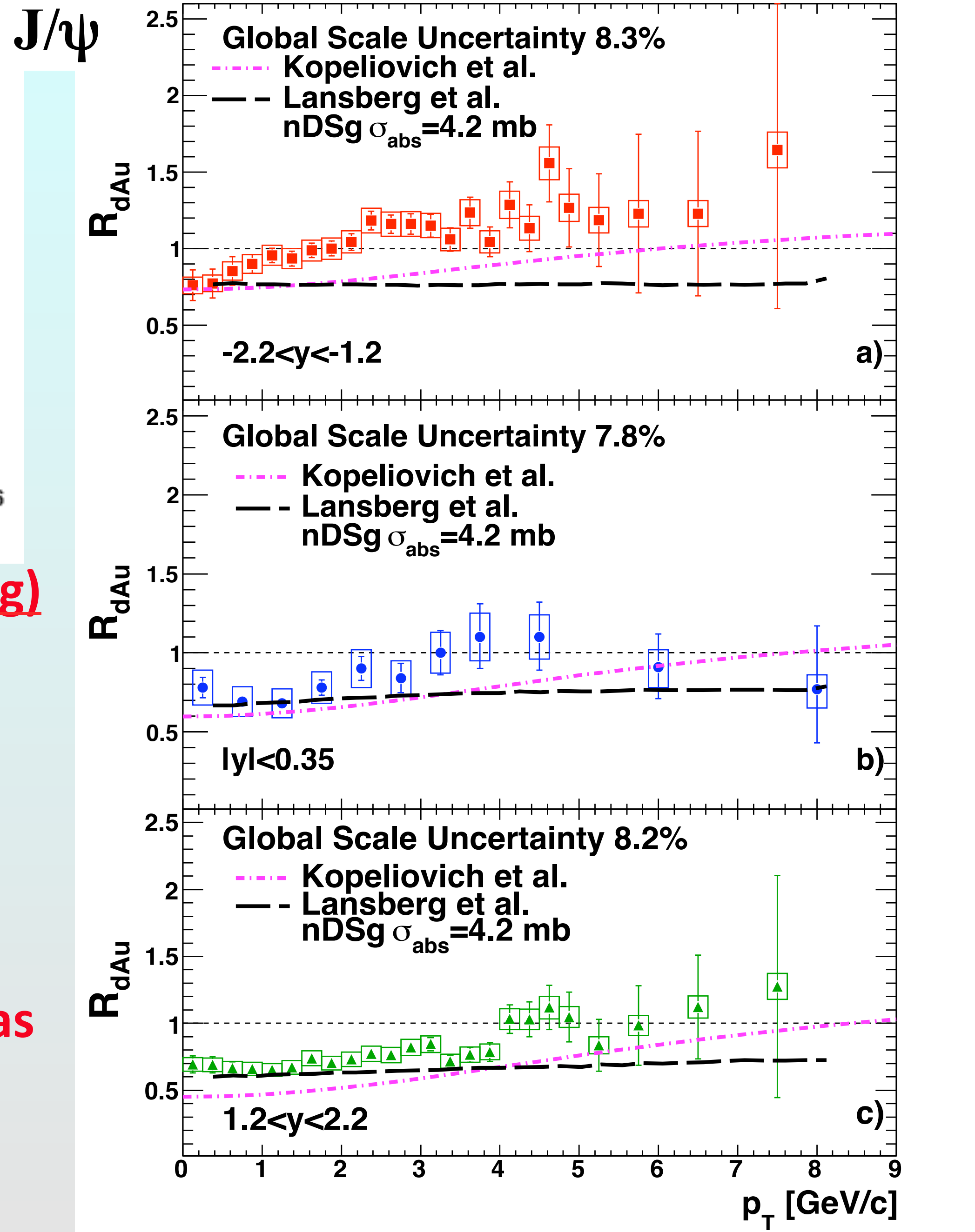
Shadowing, breakup & Cronin effect

PRC87, 034911 (2013)





- p_T broadens (multiple scattering) w/N_{coll}; effect stronger at y=0
- J/ψ suppressed 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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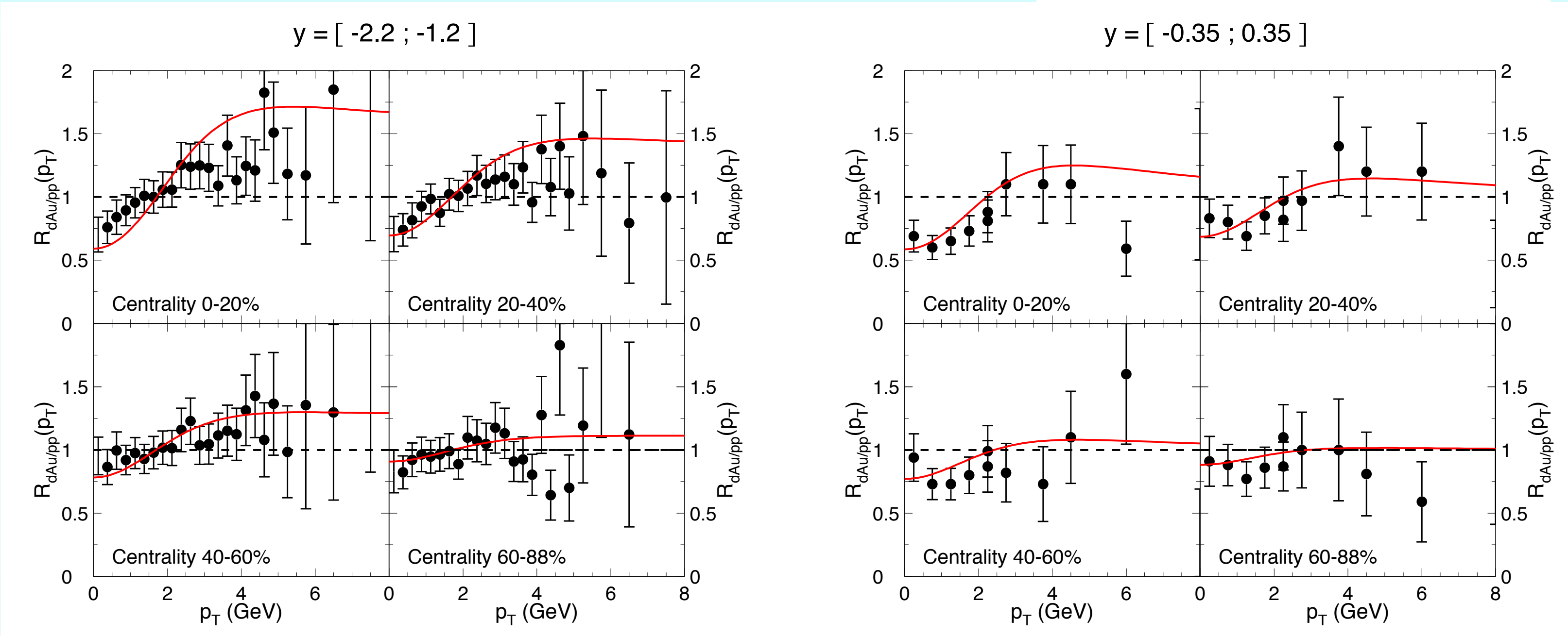
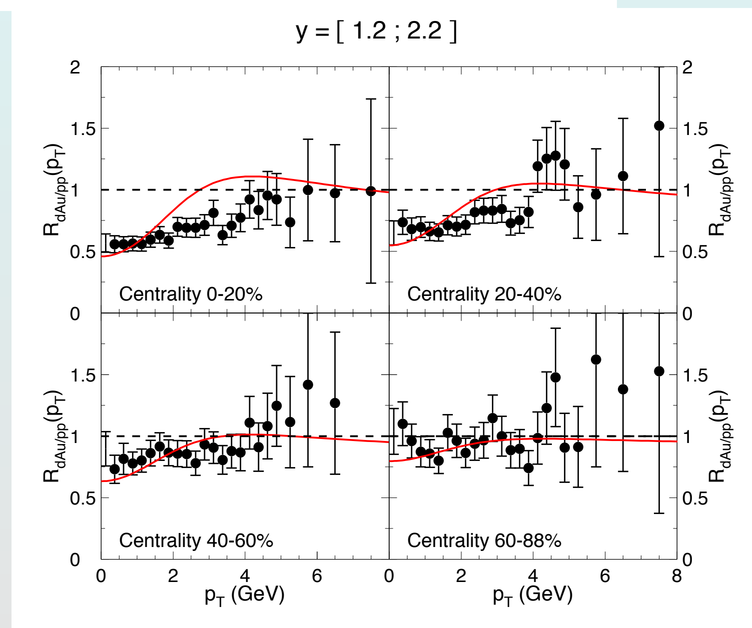
but

Arleo, et al 1304.090





coherent parton energy loss and p_T broadening from multiple scattering in the nucleus is consistent with data!

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

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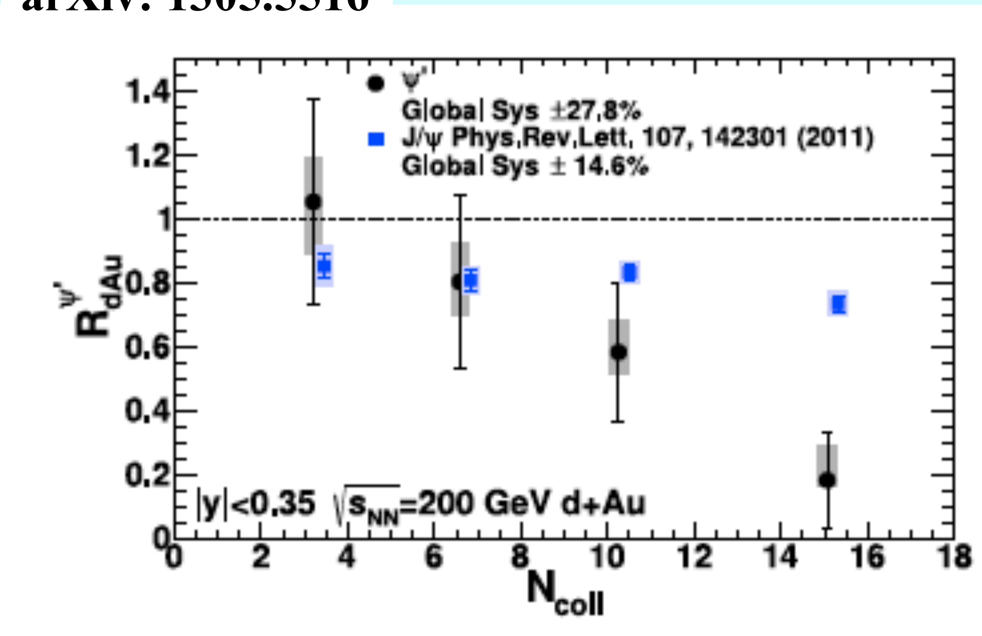
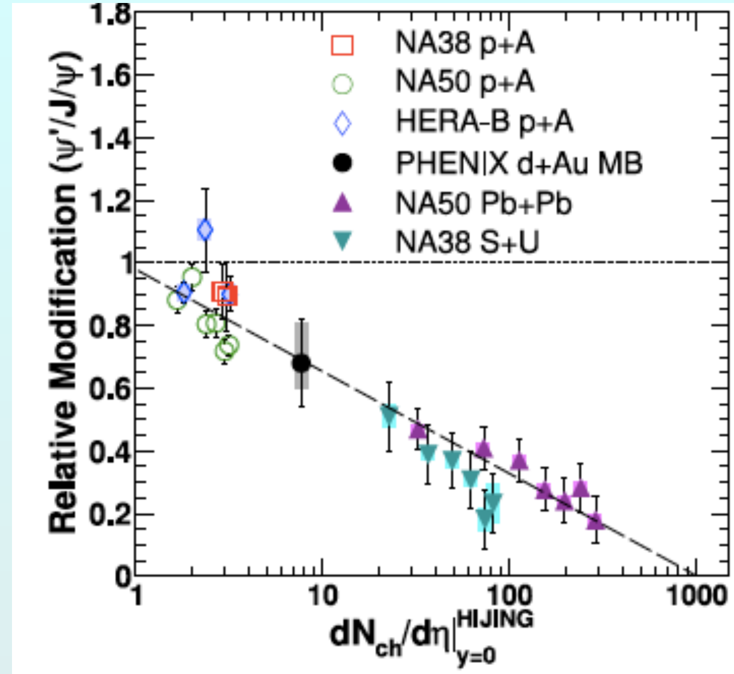
Larger, less tightly bound c-cbar: ψ'

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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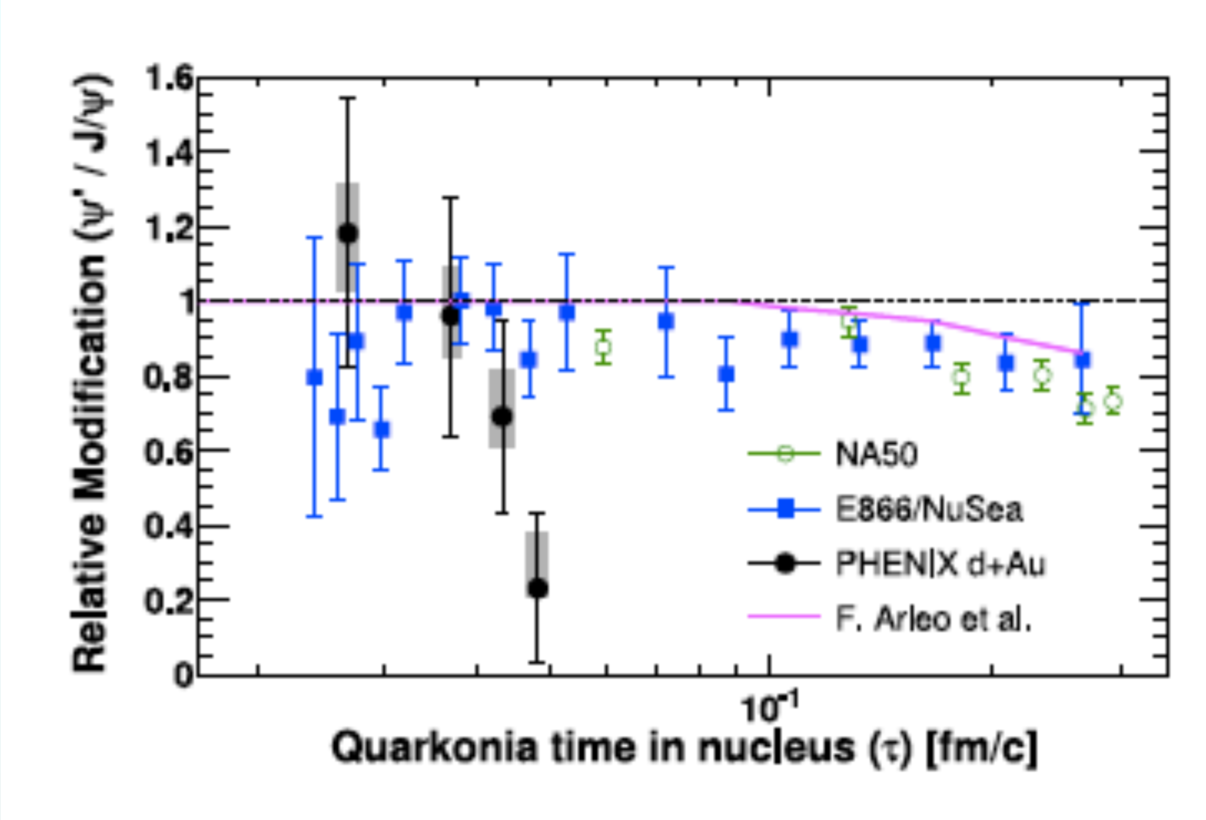
√s dependence is a key tool!



- 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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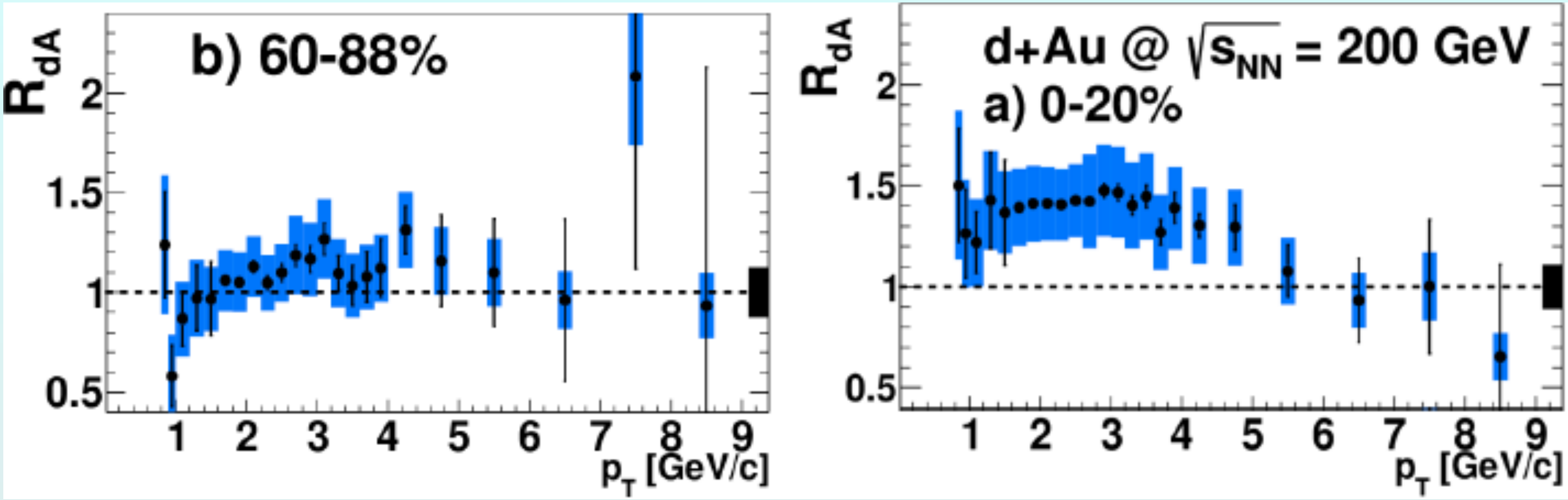
Open heavy flavor: mid-rapidity e±

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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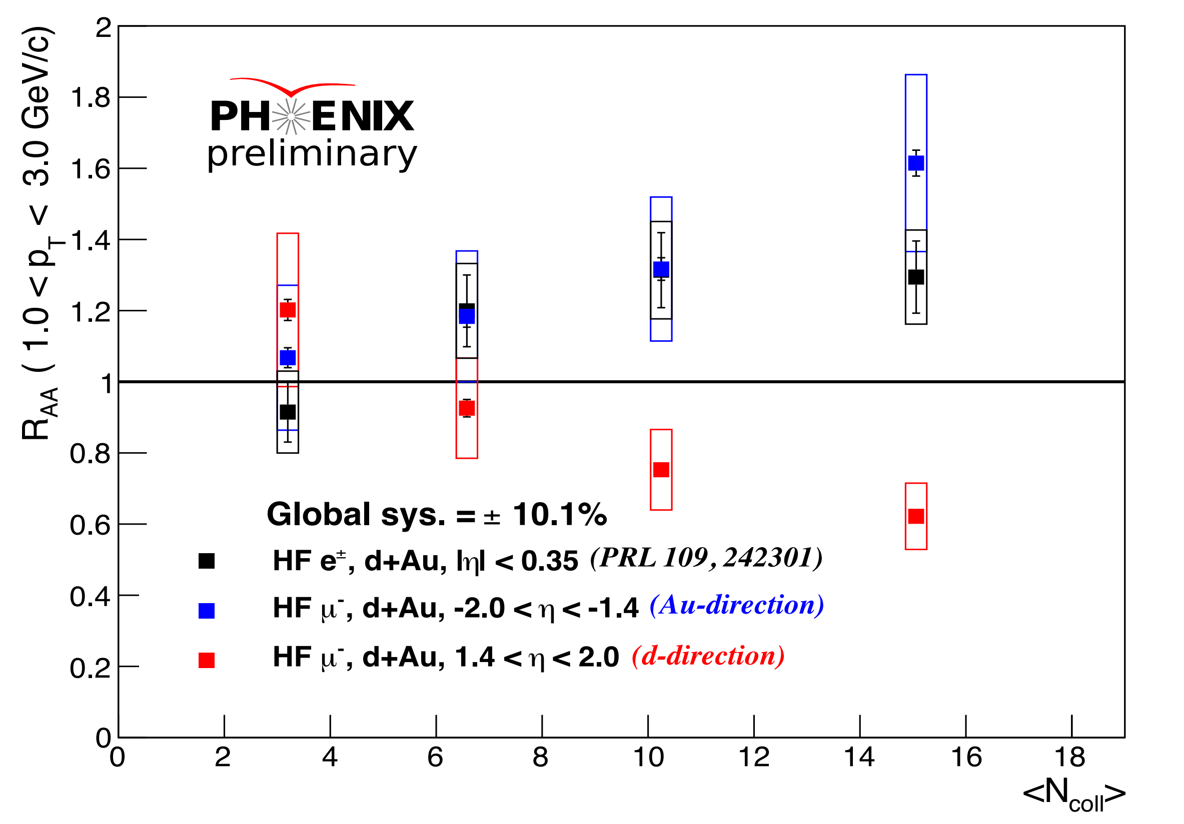
Rapidity dependence of open heavy flavor



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

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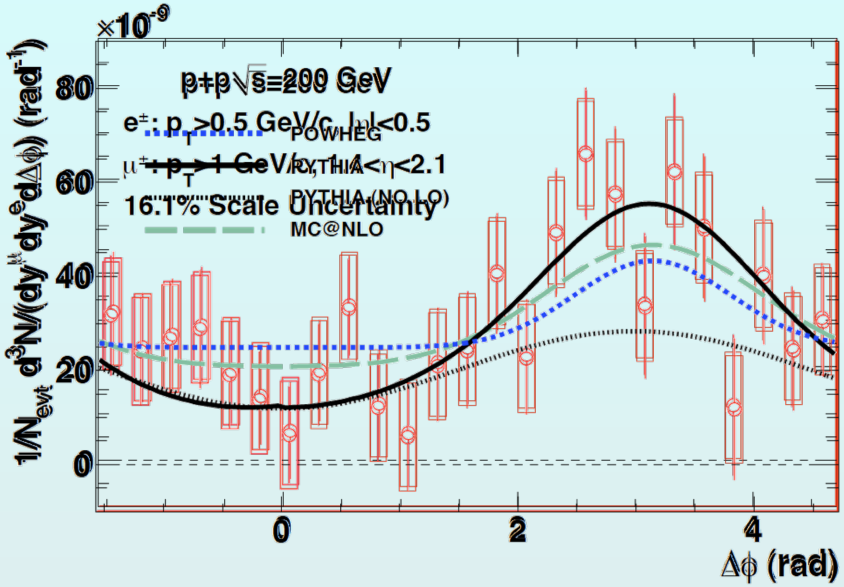
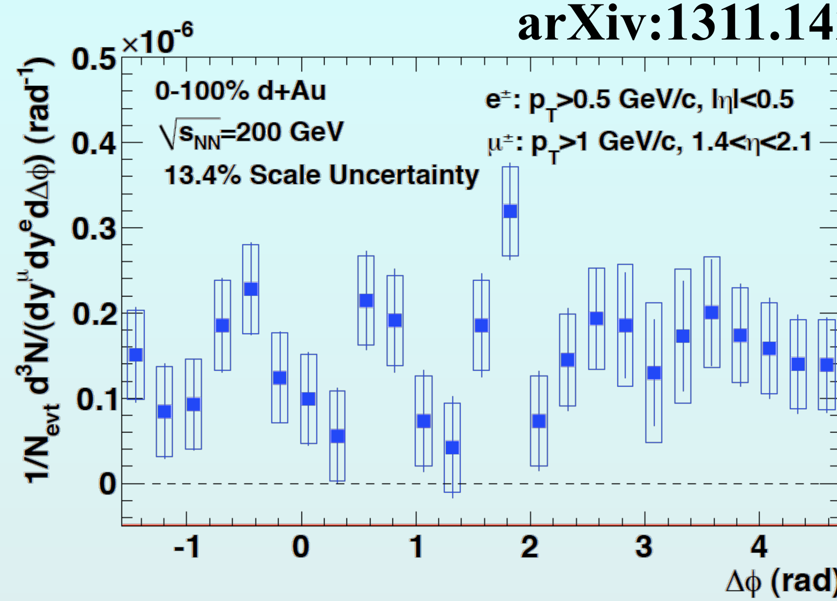
Los Alamos NATIONAL LABORATORY EST. 1943

HF e-μ pair yields

arXiv:1311.1427





Fit p+p yield with shapes from generators:

In d+Au, peak @ Δφ = π is GONE

PYTHIA: σ_{cc} = 340±29±114

POWHEG: σ_{cc} = 511±44±198

MC@NLO: σ_{cc} = 764±64±284
g radiation broadens Δφ

-Parton scattering/energy loss after cc production affects angular correlation

-Shadowing at forward y reduces charm yield

-Charmed baryon enhancement in dA reduces HF lepton yields

Consistent with previous measurements… NB: rapidity acceptance effects

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We've learned

- Gluons are suppressed at small x (deep in nucleus)
  Therefore *production* of heavy quarks also suppressed
  Scattering/energy loss before & after hard collision??
- At larger x no such suppression
  See effects expected from multiple scattering
  Shift particles to larger p_T…
- Some of the J/ψ suppression in Au+Au is due to Au nucleus
  Make fewer charm-anticharm pairs to begin with
  Gluons lose some energy *before* producing c-cbar pair
  Some J/ψ *break up* by colliding with surrounding particles
  Looser bound ψ' is more easily broken up
- What is the initial gluon distribution?

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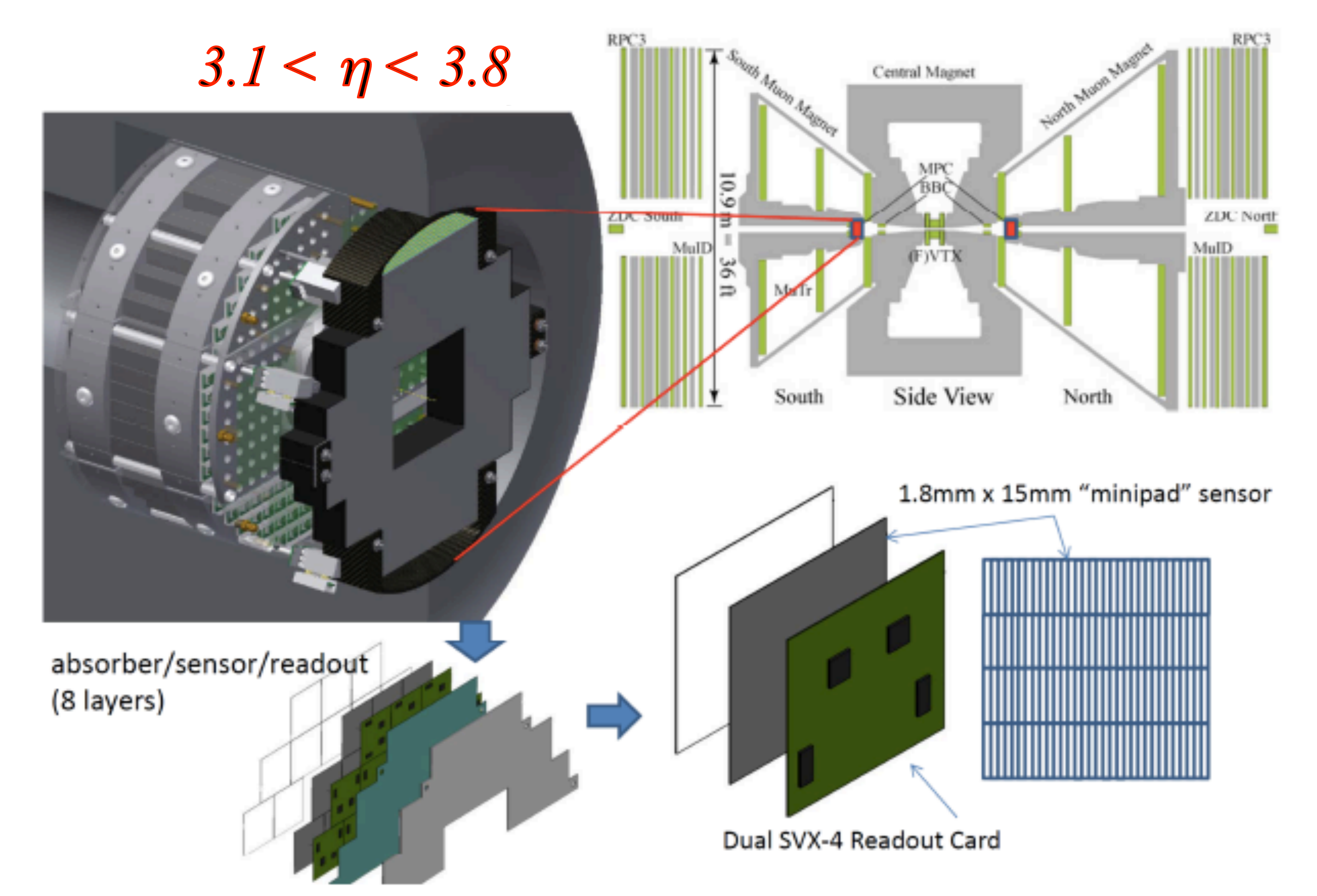
FUTURE PROSPECTS

Untangling the initial state

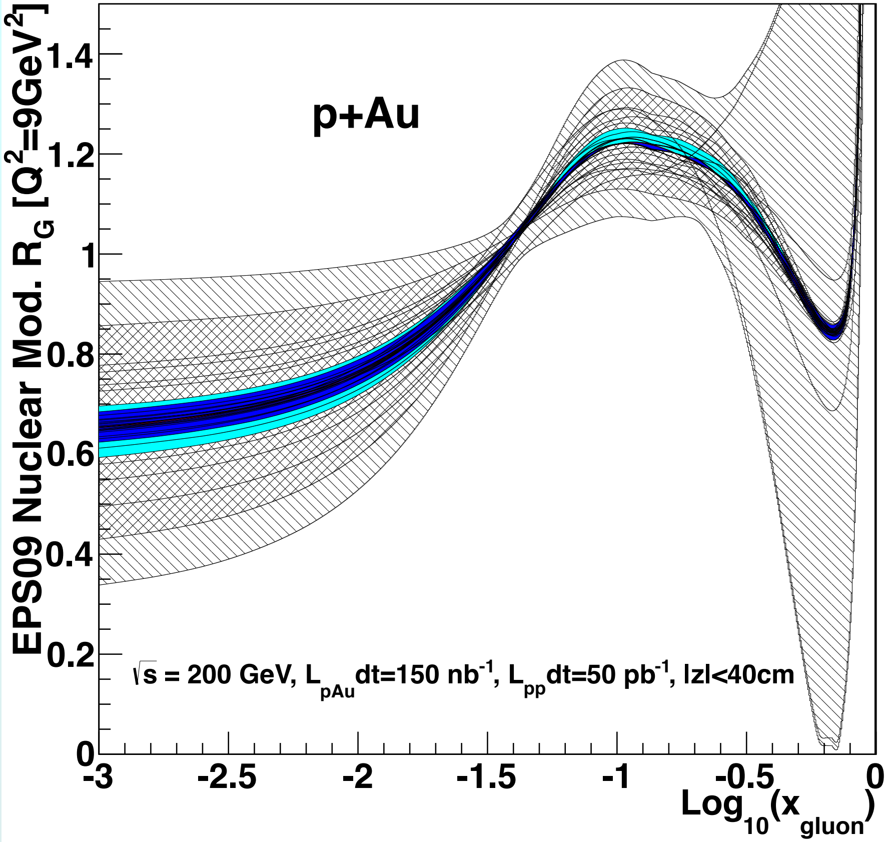
Quantifying properties of the quark gluon plasma

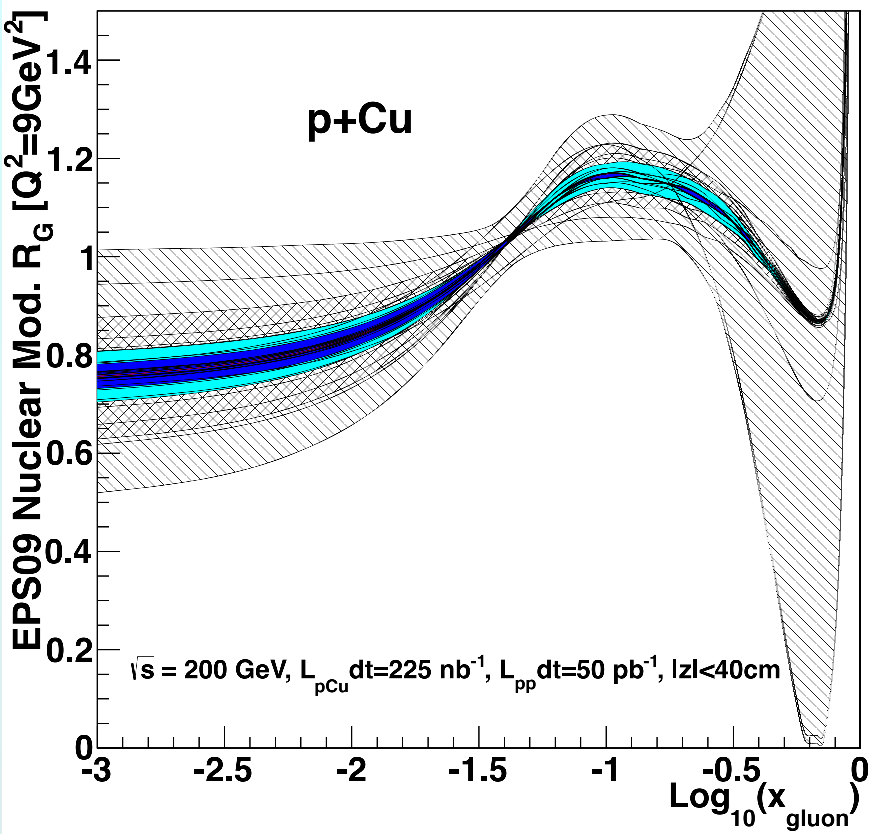
MPC-EX upgrade

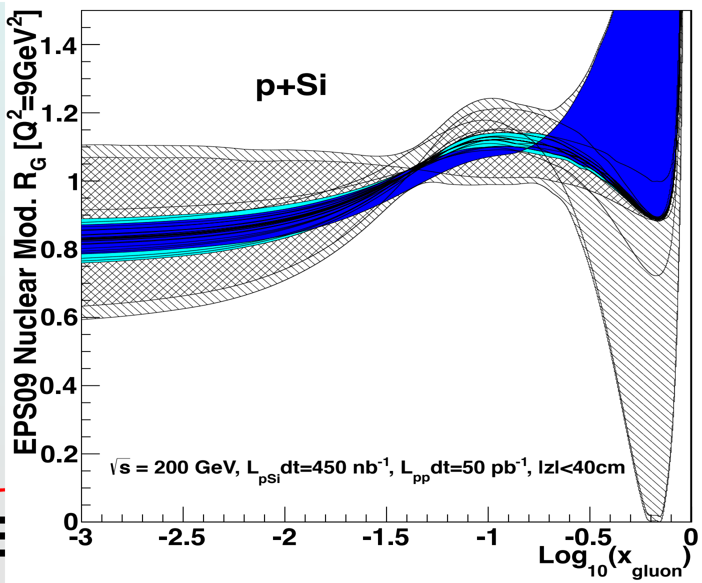


Reconstruct prompt γ and π^0 to 80 GeV: low & high x!

Will measure p+A in 2015







MPC-EX preshower: γ vs. π^0 decay

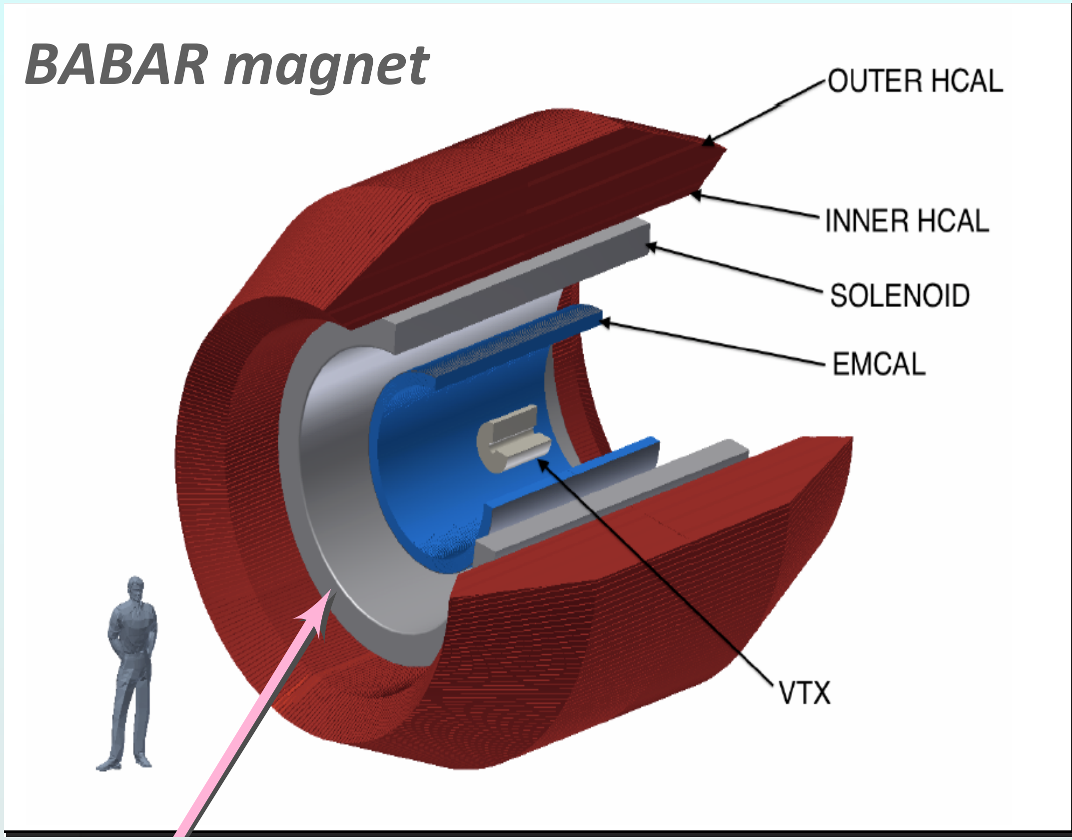
Substantially improve nPDFs!

to $x \sim 10^{-3}$ and also at high x

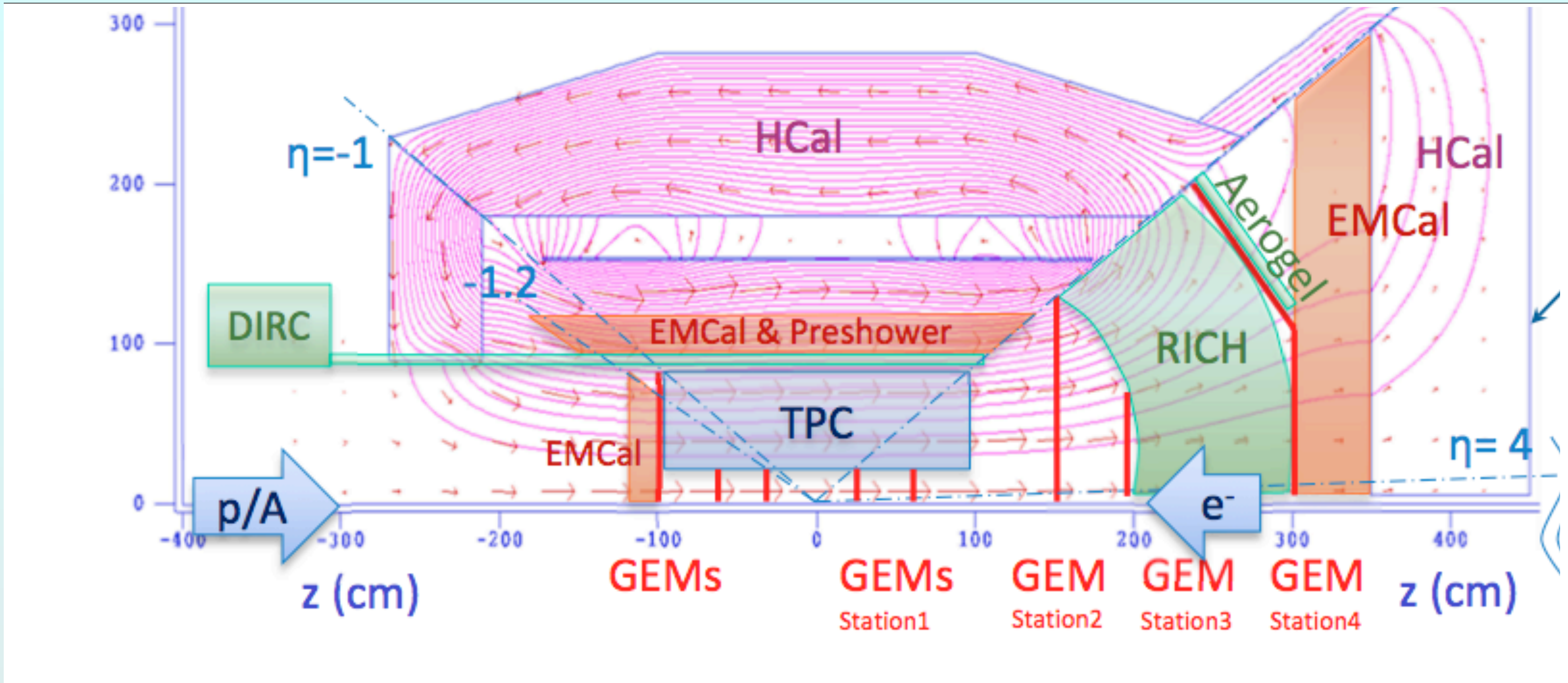
2-4 weeks running per species

sPHENIX upgrade

- **Jet, di-jet and γ-jet physics**
- Additional inner tracking (RIKEN)
  - ➔high-z fragmentation fn.
- Add pre-shower to EMCAL
  - ➔π^0 R_{AA} to 40 GeV/c; γ_{dir}
  - ➔eID for Υ states
  - ➔tag c,b jets
- Add forward detectors for p+A
- Fits on a truck!



Evolution: sPHENIX -> ePHENIX for eIC



- For p+A: add EM and hadron calorimeter endcap + tracking to sPHENIX barrel
- Further GEM trackers forward, TPC mid-y, and RICH/DIRC/ Aerogel for forward PID to produce "ePHENIX"

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e+A and e+p

- Cleanest way to study initial gluon & quark distribution deep inside the nucleus

  What is it that thermalizes so fast??

  Do we really need a tiny black hole to drive thermalization??

  (as expected in ∞ coupling approximation)

- Exciting opportunity to find spin carriers inside the proton

- Add electrons to RHIC (via an energy recovery linac)

  Or add hadrons to CEBAF

- Evolve sPHENIX to measure particles from e+A & e+p

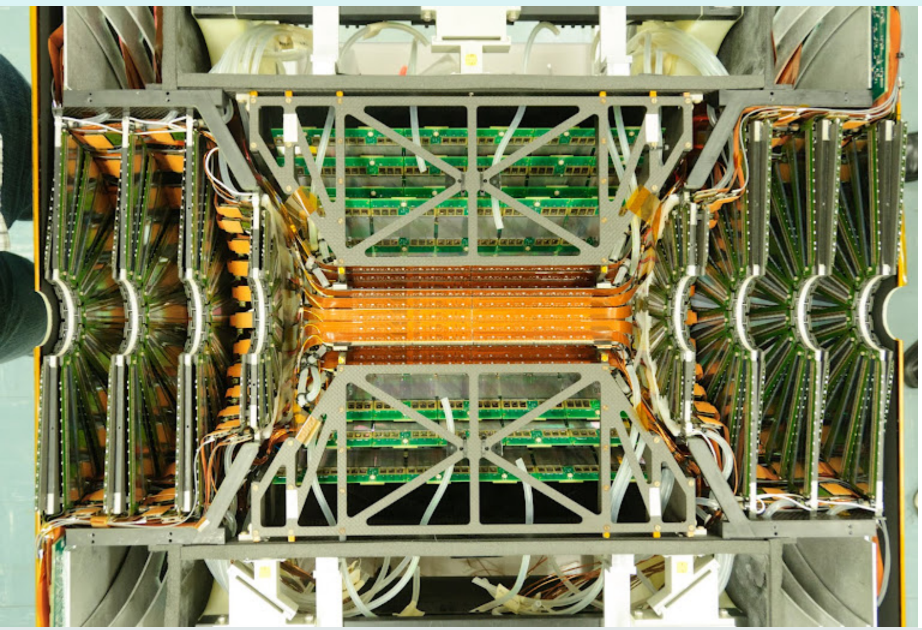
- **Backup slides**

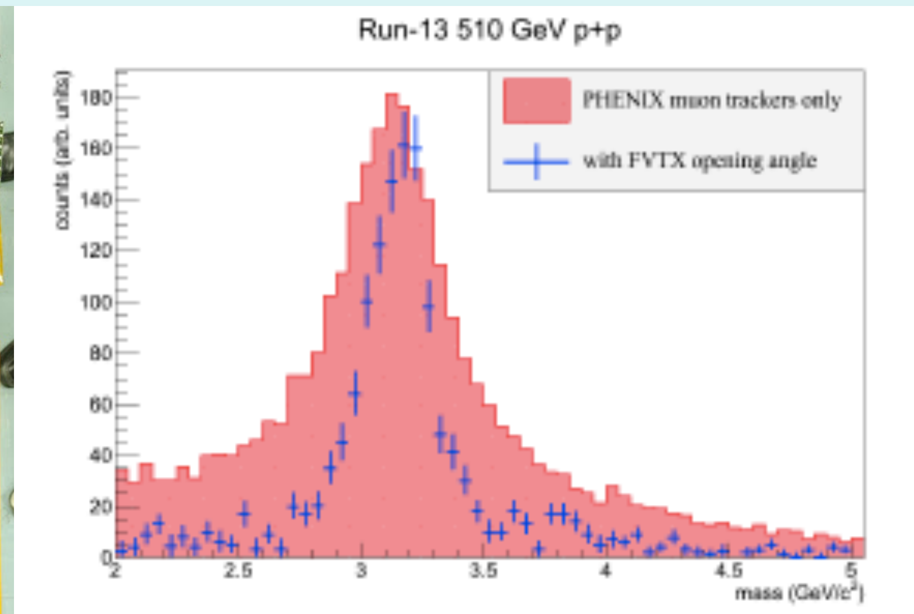
Rapidity dependence is coming

Forward vertex detector FVTX

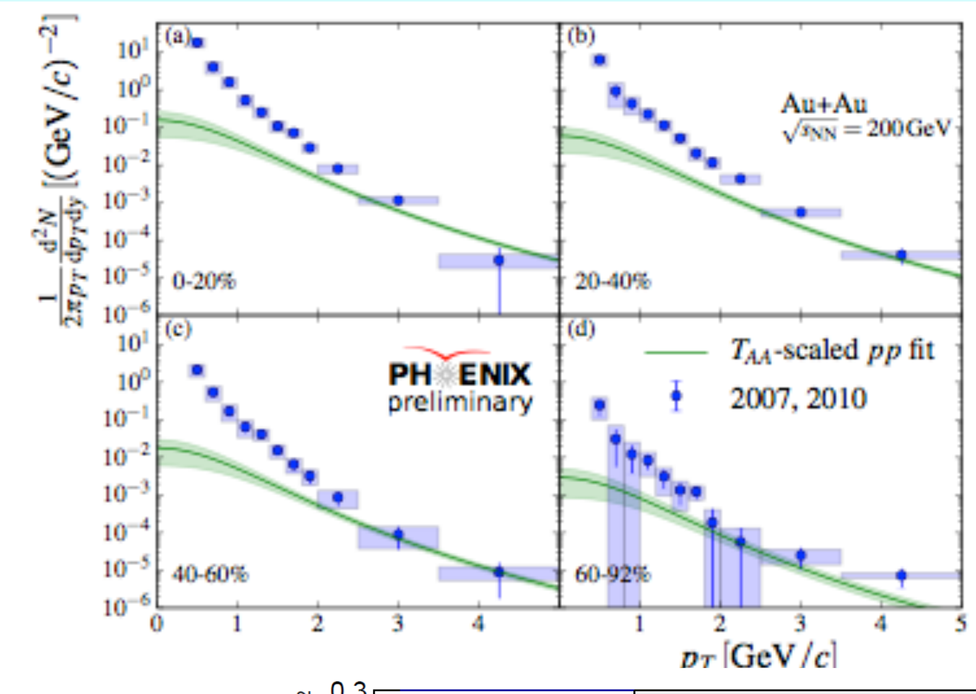
improves mass resolution →

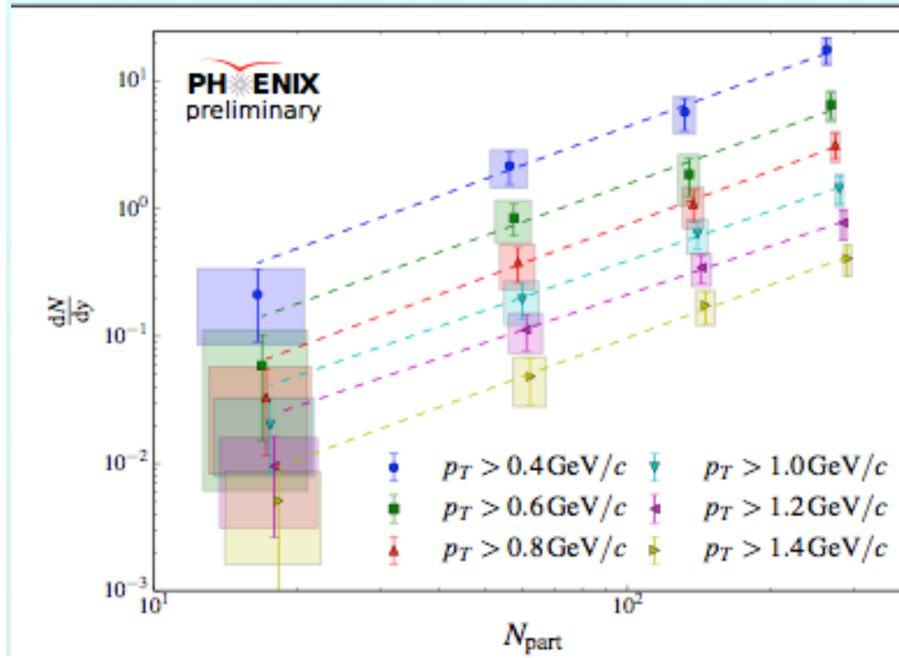
Ψ' at forward rapidity!

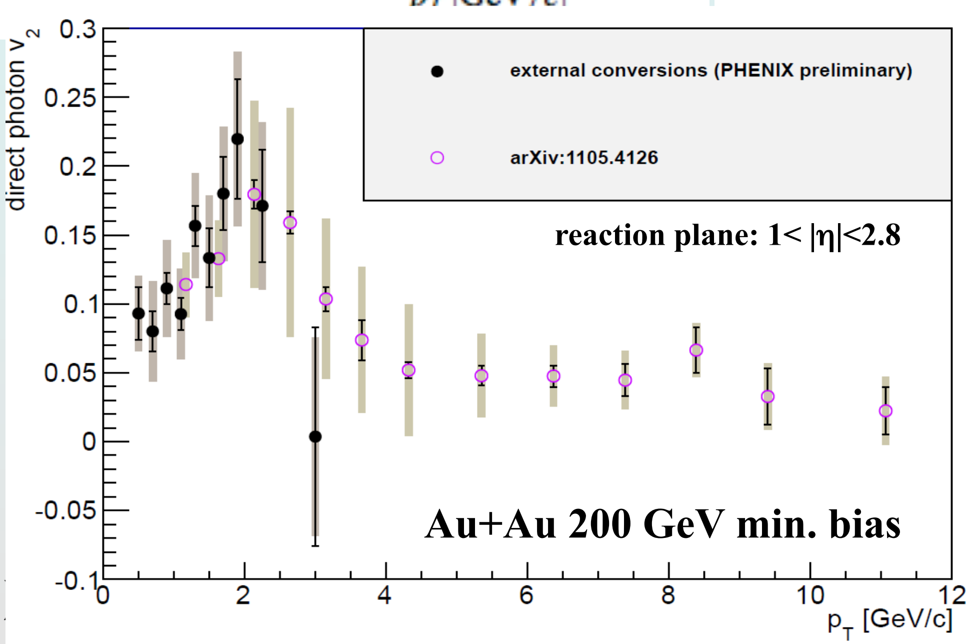




Di-electrons from thermal γ conversions in Au+Au



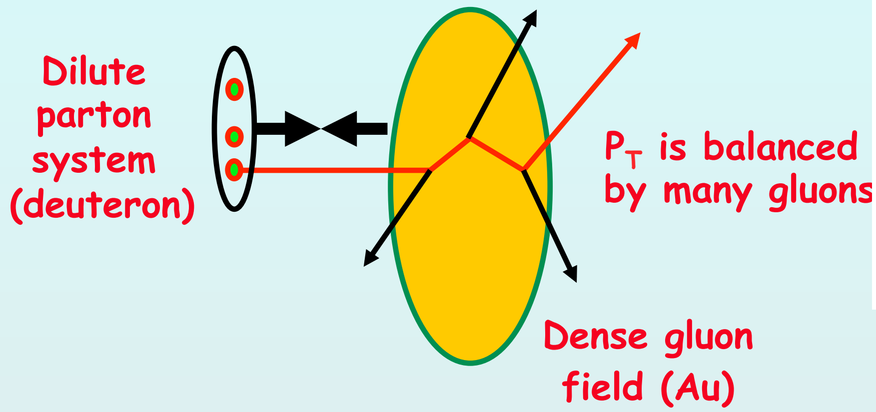


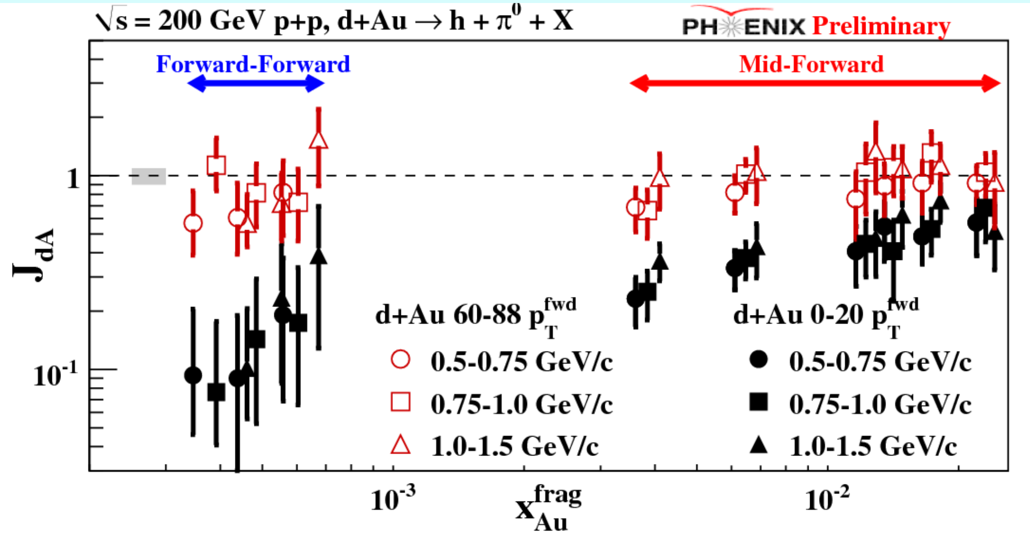


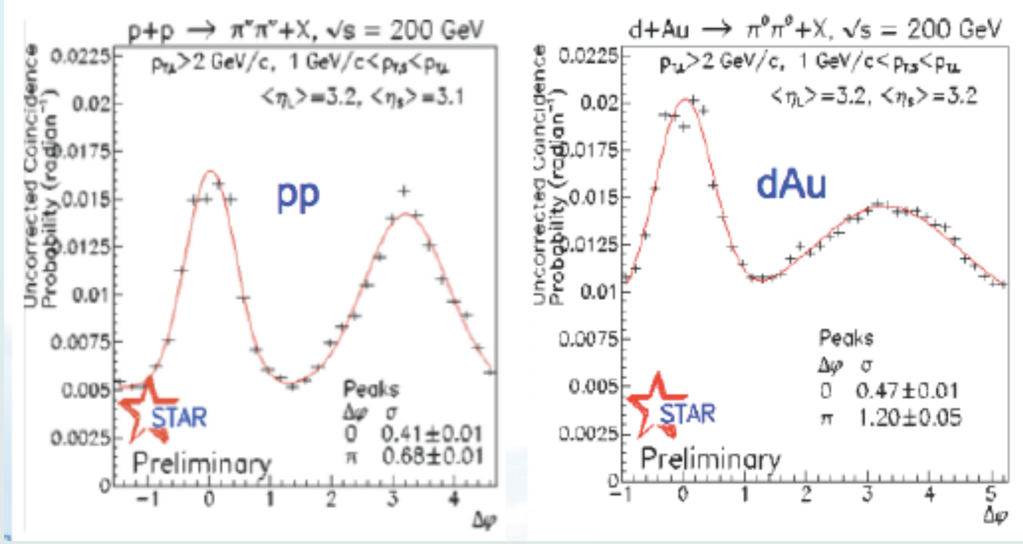
$dN_\gamma/dy \sim aN_{part}^{1.5}$
similar in hydro
(U. Heinz)

photons flow!
more than in hydro…

Initial State: are gluons shadowed or saturated?







Use direct photons (q+g)

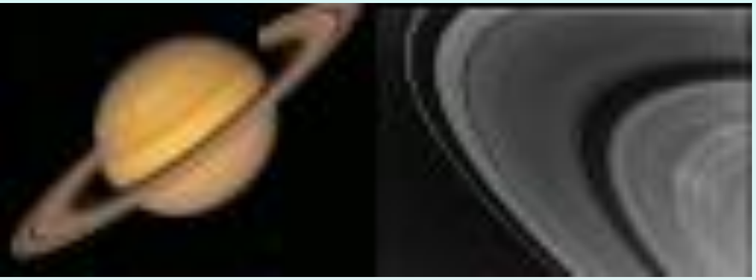
no final state effects on γ!

Forward rapidity to reach

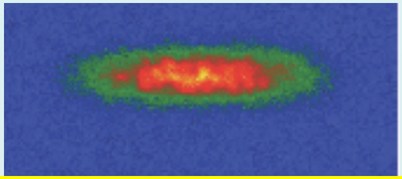
small x & high g density

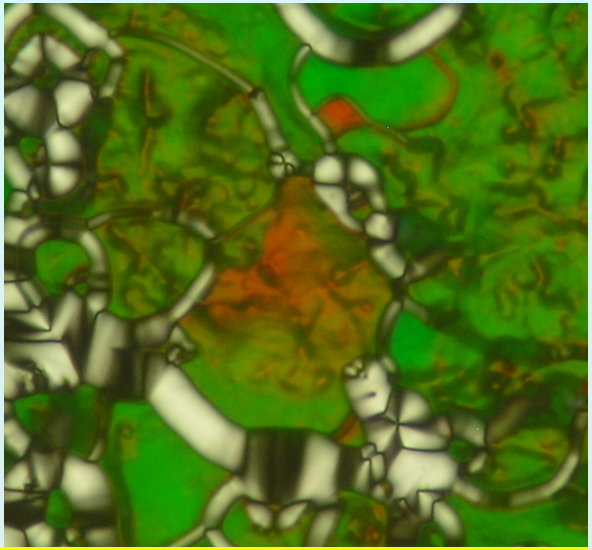
Many types of strongly coupled matter

Quark gluon plasma is like other systems with strong coupling
- all flow and exhibit phase transitions



Cold atoms: coldest & hottest matter on earth are alike!





Dusty plasmas &

In all these cases have a competition:

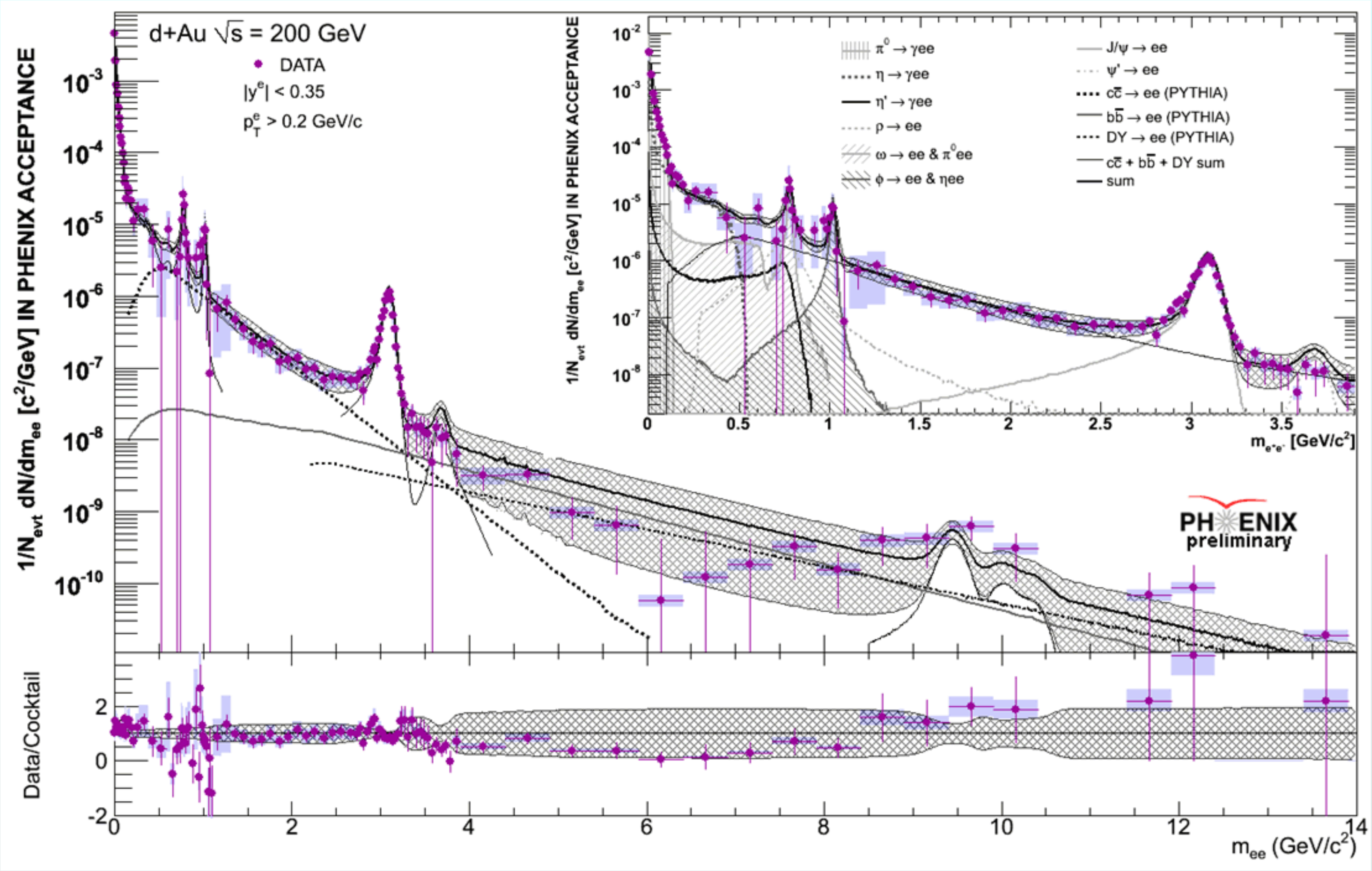
Attractive forces ⇔ repulsive force or kinetic energy

High T_c superconductors: magnetic vs. potential energy

Result: many-body interactions, not pairwise!

QCD is a great test lab: we *know* the Lagrangian!

Another handle on c & b: di-electrons



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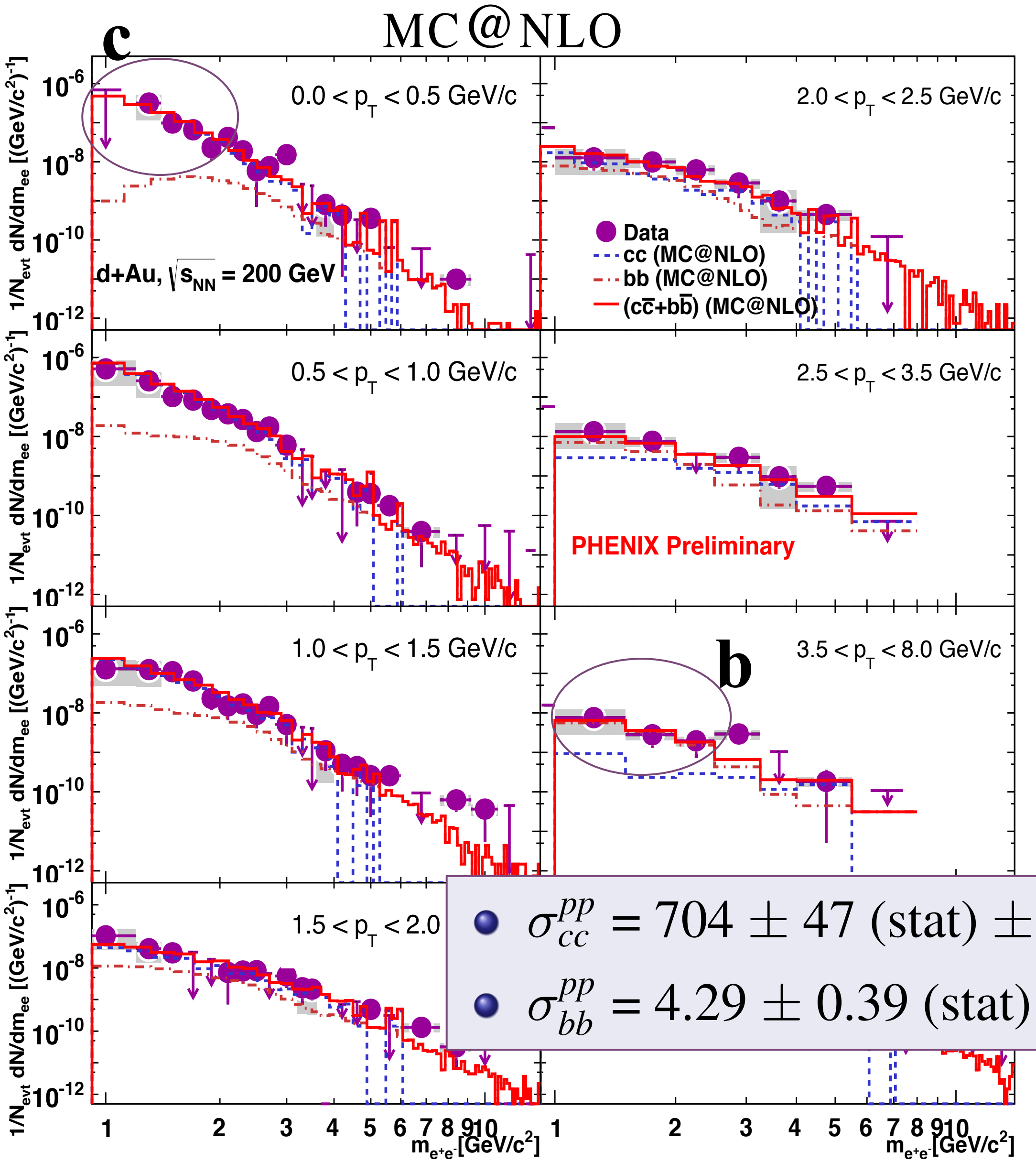
p_T vs. mass provides b/c separation



- Cocktail subtracted data
- MC@NLO charm, bottom
- Double differential analysis
- Charm dominant at
  Low mass, low p_T
- Bottom dominant at
  High p_T, but low mass
  Statistics still good!

- $\sigma_{cc}^{pp} = 704 \pm 47\ (\text{stat}) \pm 183\ (\text{syst}) \pm 40\ (\text{model})\ \mu\text{b}.$
- $\sigma_{bb}^{pp} = 4.29 \pm 0.39\ (\text{stat}) \pm 1.08\ (\text{syst}) \pm 0.11\ (\text{model})\ \mu\text{b}.$

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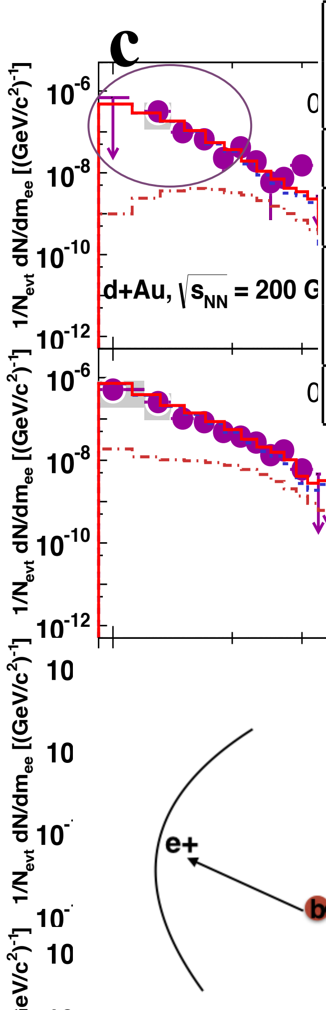
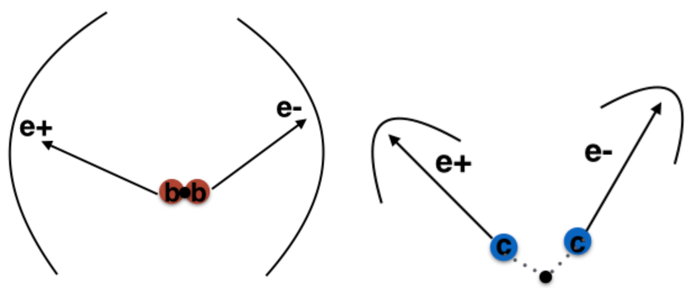
Sensitive to c-cbar opening angle

D. Sharma



Acceptance	PYTHIA e^+e^- pairs from $c\bar{c}$ $[F_{BR}^{c\bar{c}}\ ^{-1}]$	MC@NLO e^+e^- pairs from $c\bar{c}$ $[F_{BR}^{c\bar{c}}\ ^{-1}]$
4π	1	1
$\lvert y_{e+} \& y_{e-} \rvert < 0.5$	0.042	0.035
$\lvert y_{e+} \& y_{e-} \rvert < 0.5$ $m_{e+e-} > 1.16\text{GeV}/c^2$	0.0047	0.00022
$\lvert y_{e+} \& y_{e-} \rvert_{PHENIX}$	0.0023	0.0016

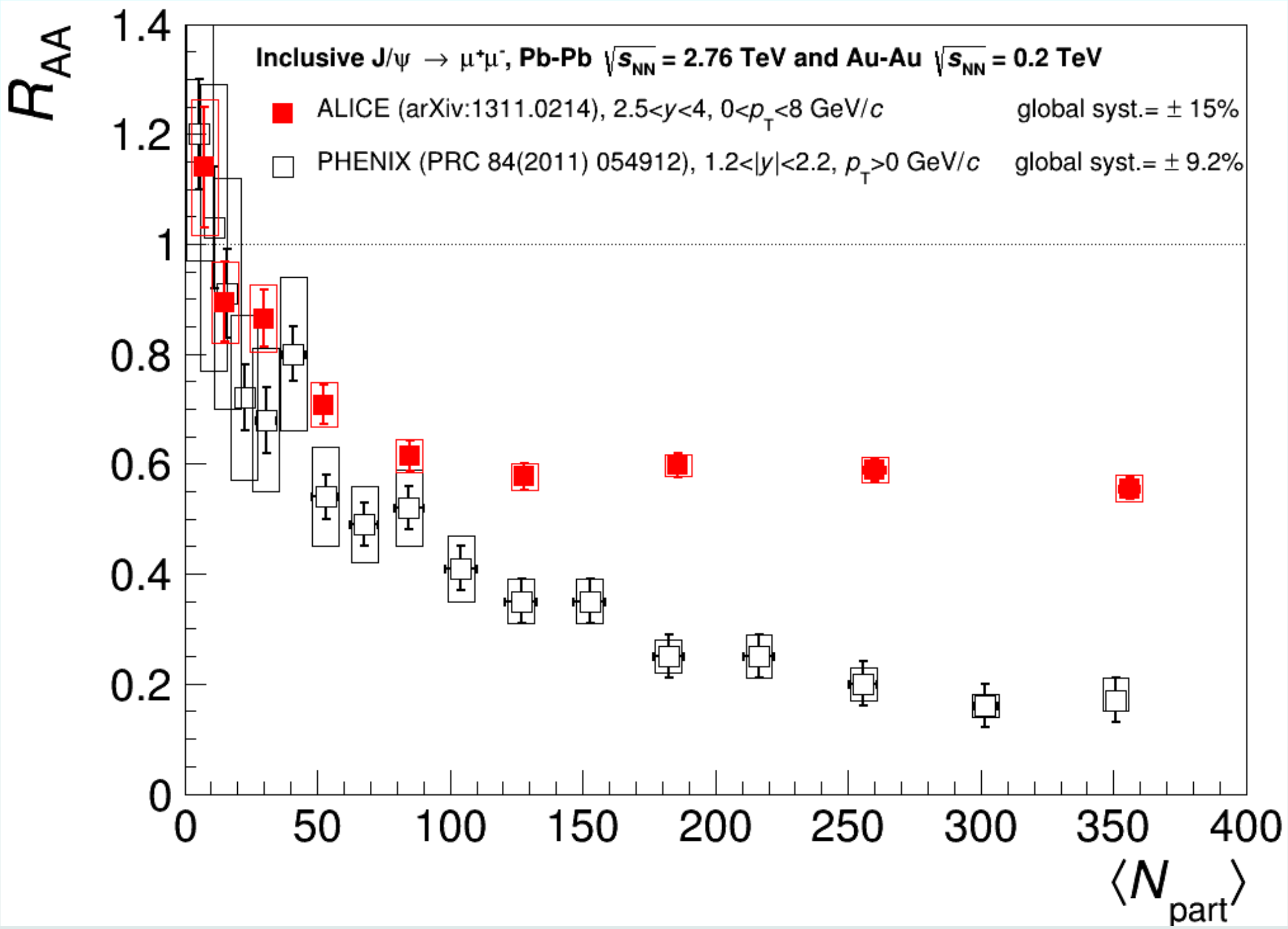
	PYTHIA e^+e^- pairs from $b\bar{b}$ $[F_{BR}^{b\bar{b}}\ ^{-1}]$	MC@NLO e^+e^- pairs from $b\bar{b}$ $[F_{BR}^{c\bar{c}}\ ^{-1}]$
$\lvert y_{e+} \& y_{e-} \rvert_{PHENIX}$	0.0084	0.0080



- If $m_q >> p$, the e^+e^- decay pair randomizes the correlation of $q\bar{q}$ pair.
- For a very heavy quark, the decay electron has no directional preference.

- The number of e^+e^- pairs from $c\bar{c}$ in 1 unit of rapidity differ by 1.2, that increases to 2.2 if one restricts the mass range above 1 GeVc^2.
- For $b\bar{b}$, the two simulations yield similar results within 5%.

J/ψ (c-cbar bound state) melts in QGP



Suppressed by ~ 5 at RHIC, less at LHC

how much is due to cold nuclear matter effects?

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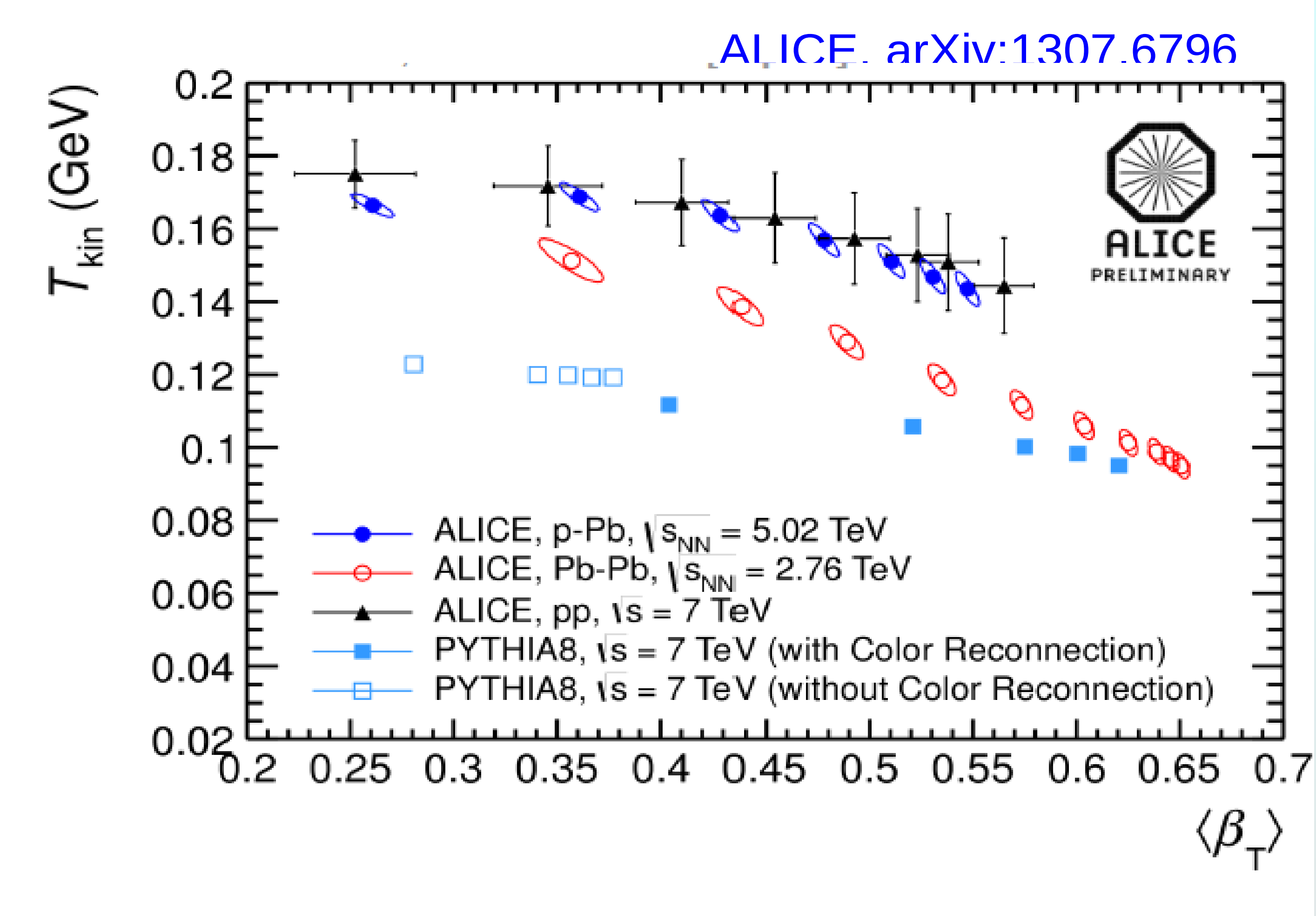
Analysis of spectra for flow at freezeout time



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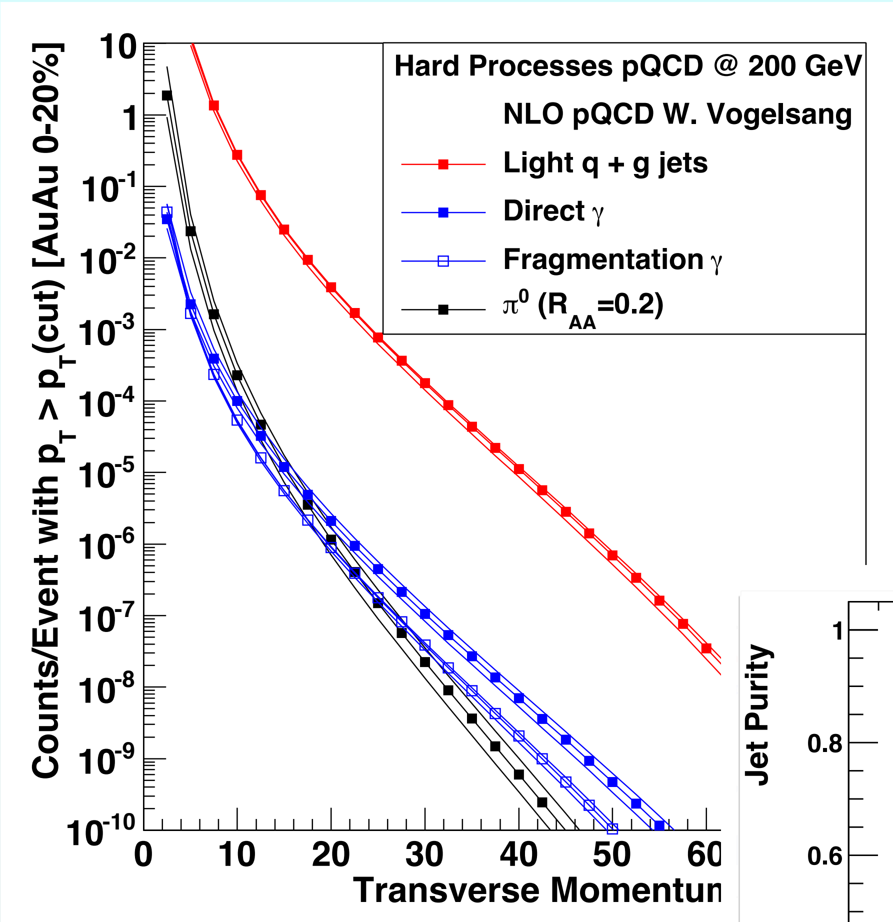
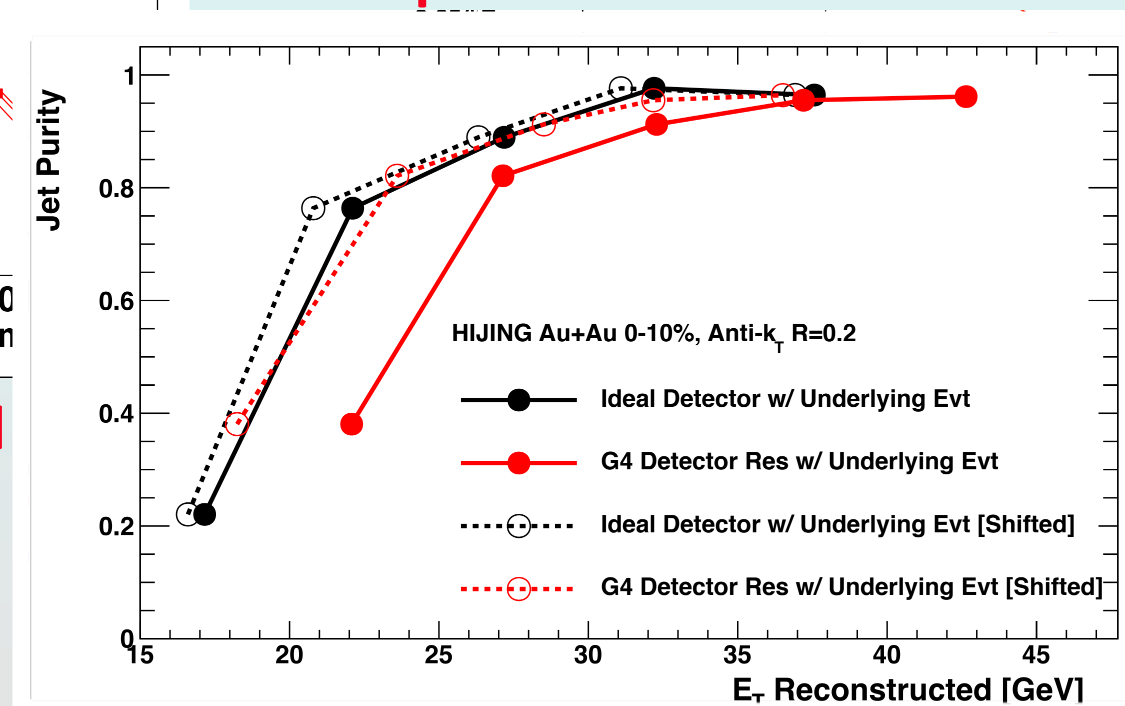
Study jets with strong medium interaction



- 30-50 GeV jet fragments at scale of QGP medium
  - Modified jets, di-jets , γ-jet
- High rate capability will provide
  - 10^6 jets above 30 GeV
  - 10^3 photons above 30 GeV



- Rates, performance good for Au+Au at 100 GeV
- studying b tagging

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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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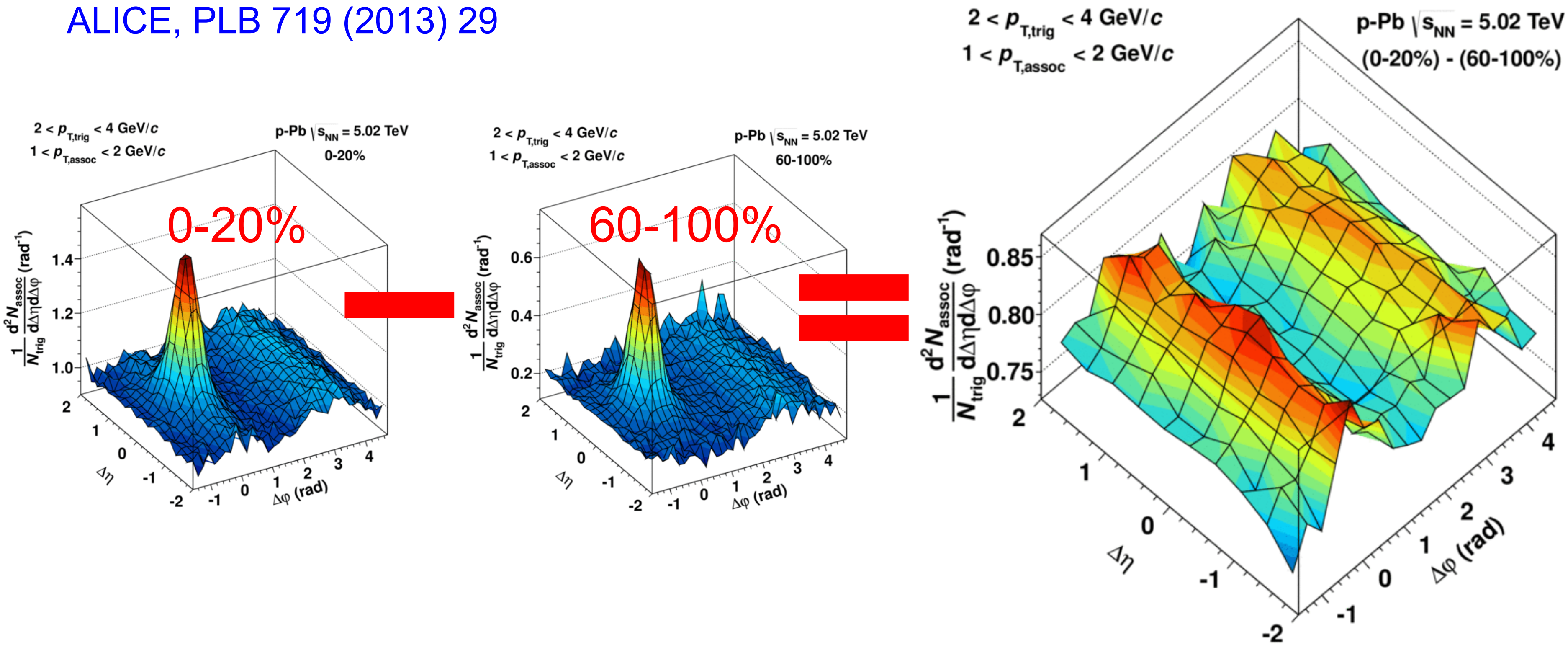
Extraction of double ridge structure

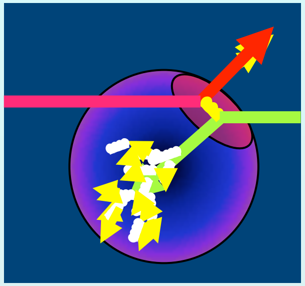
ALICE, PLB 719 (2013) 29

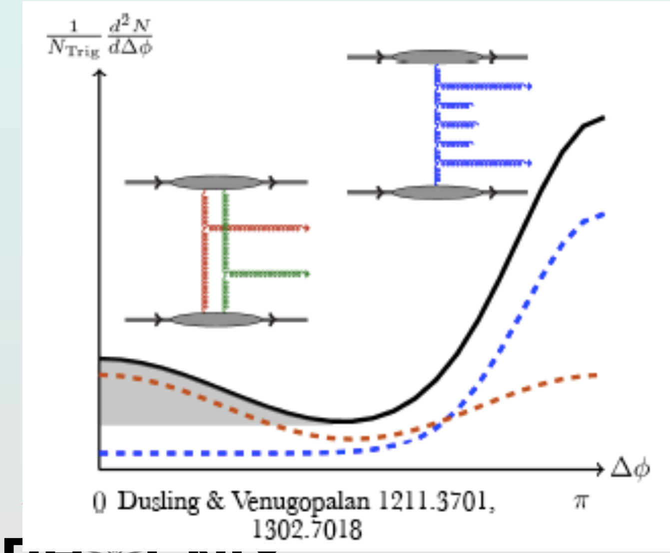


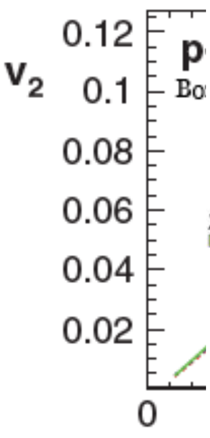
- Extract double ridge structure using a standard technique in AA collisions, namely by subtracting the jet-like correlations
  - It is assumed that the 60-100% class is free of non-jet like correlations
  - The near-side ridge is accompanied by an almost identical ridge structure on the away-side
  - Similar analysis strategy by ATLAS (PRL 110 (2013) 182302)

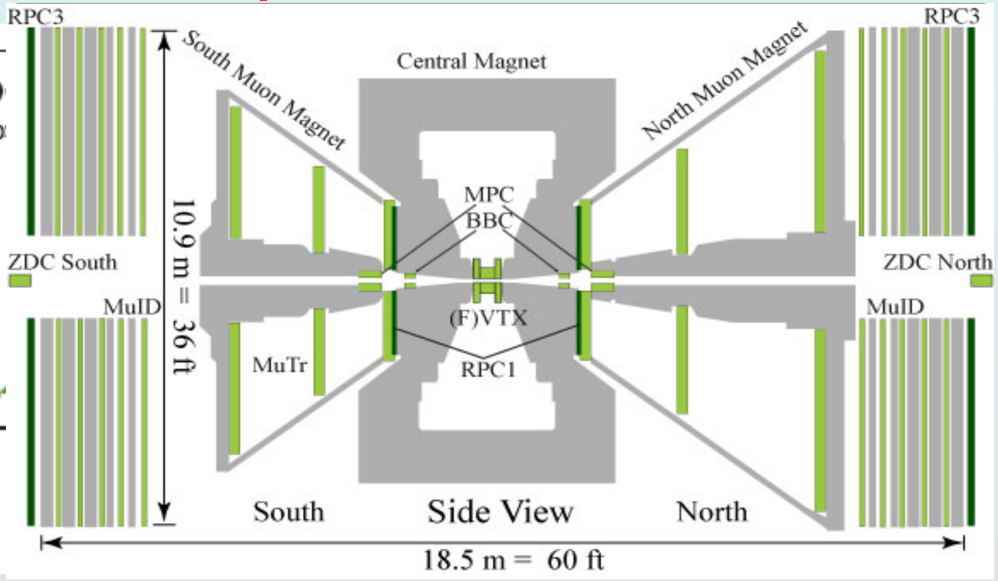
Di-hadrons in d+Au: initial or final state effect?

- **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: $3.0 < |\Delta\eta| < 4.0$

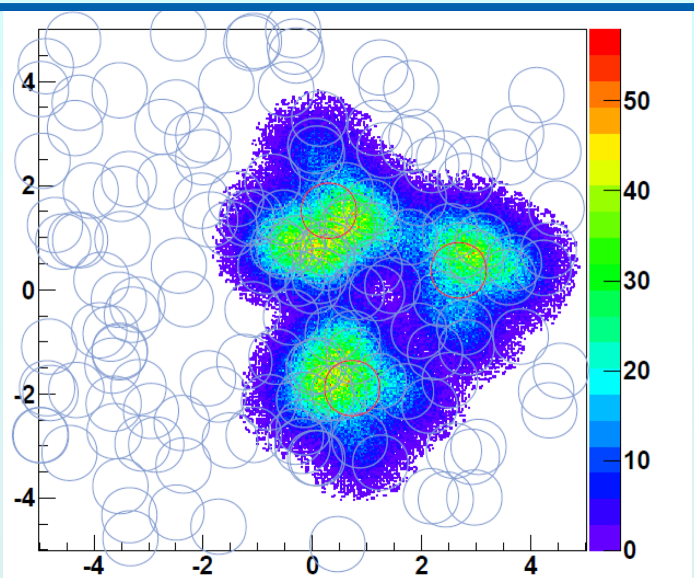








Control the geometry: ^{3}He + Au

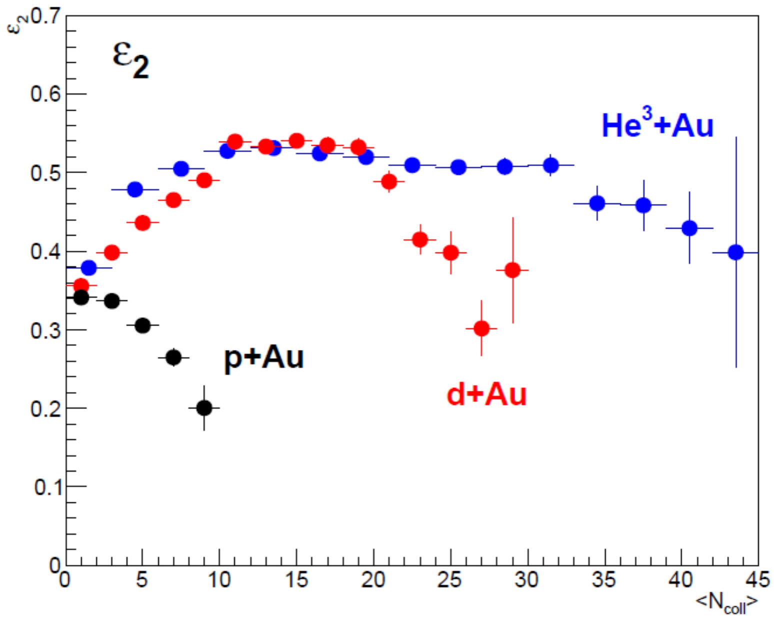


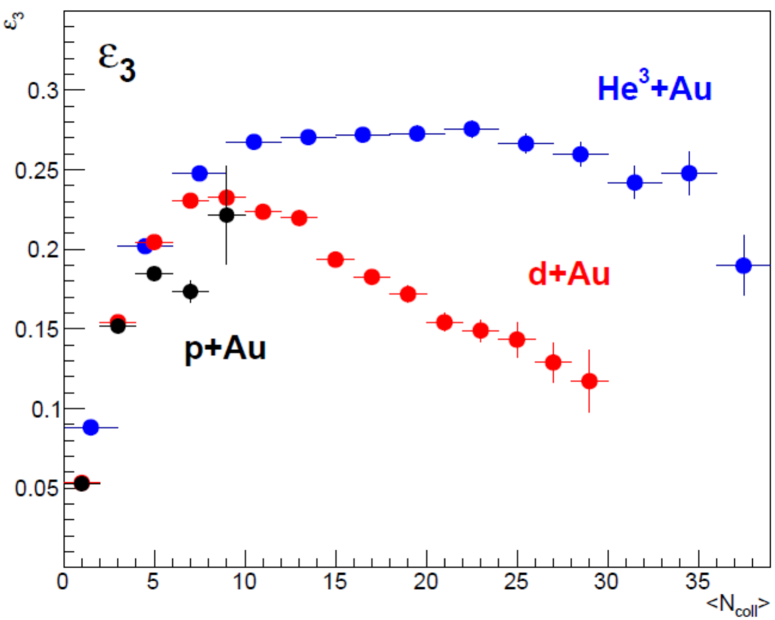
increase the triangularity of the initial state! what happens to v_3?

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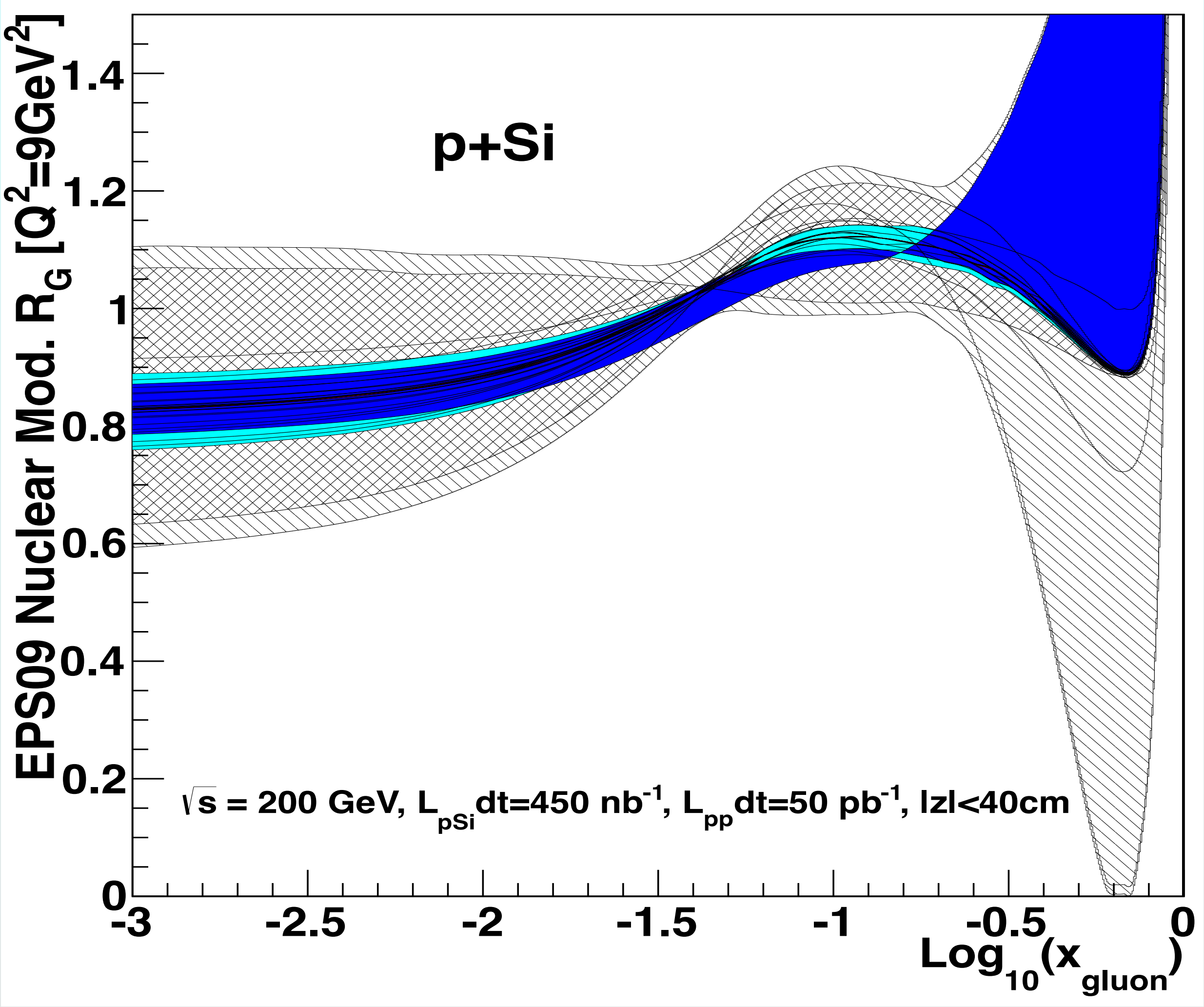
p+Si
EPS09 Nuclear Mod. R_G [Q^2=9GeV^2]
1.4
1.2
1
0.8
0.6
0.4
0.2
0
-3
-2.5
-2
-1.5
-1
-0.5
0
Log$_{10}$(x$_{gluon}$)
$\sqrt{s}$ = 200 GeV, L_{pSi}dt=450 nb^{-1}, L_{pp}dt=50 pb^{-1}, |z|<40cm

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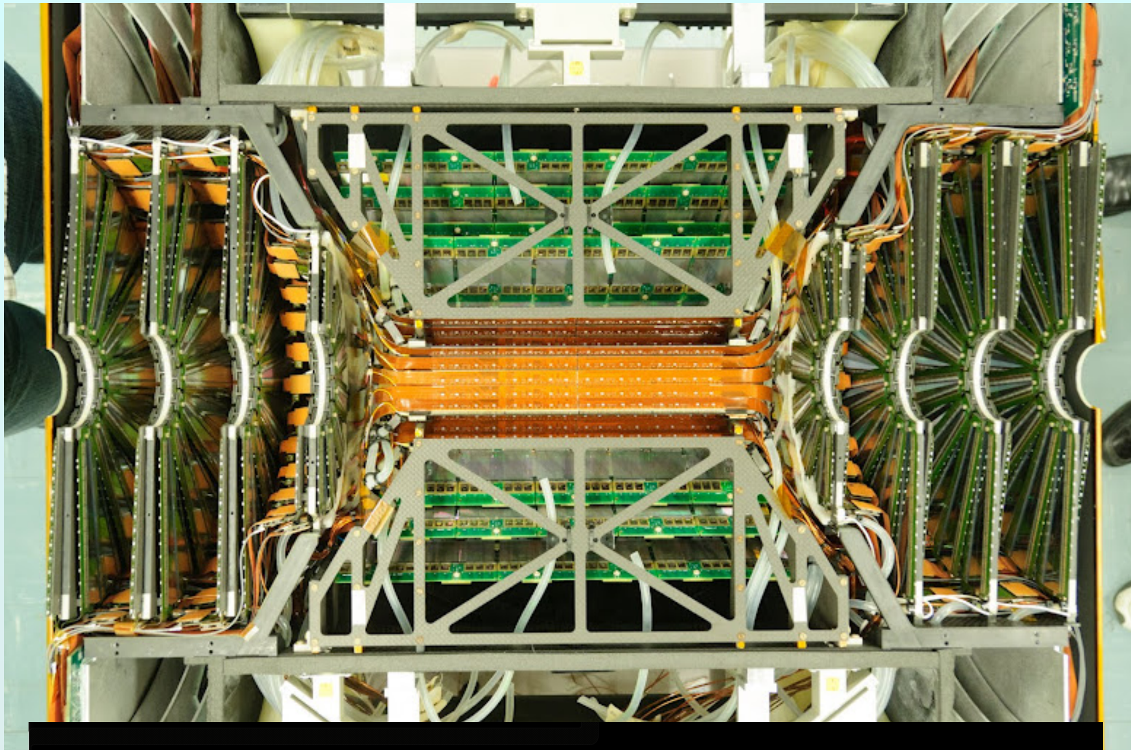
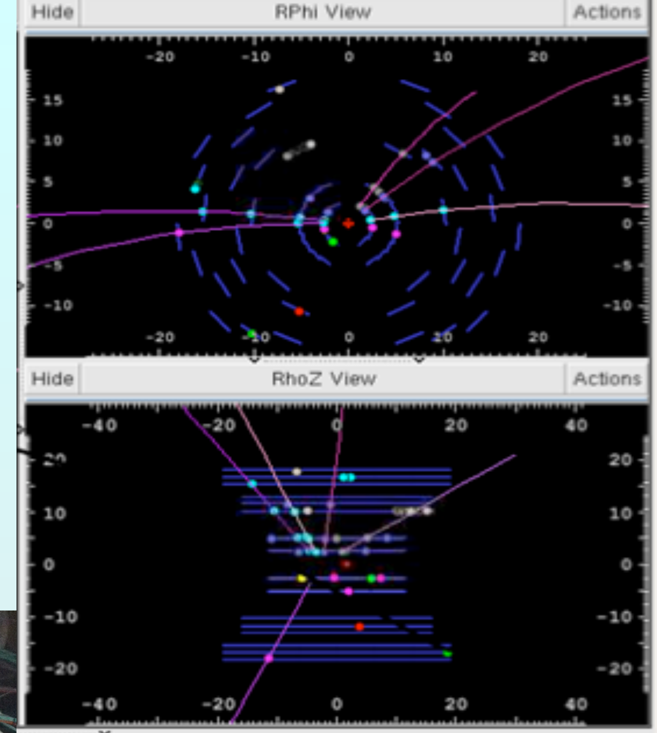
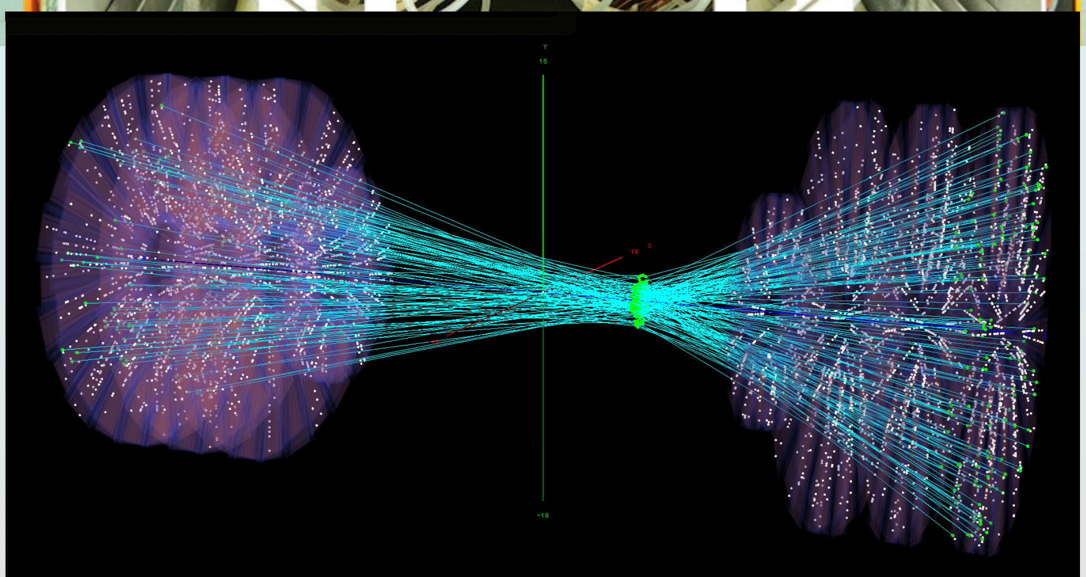
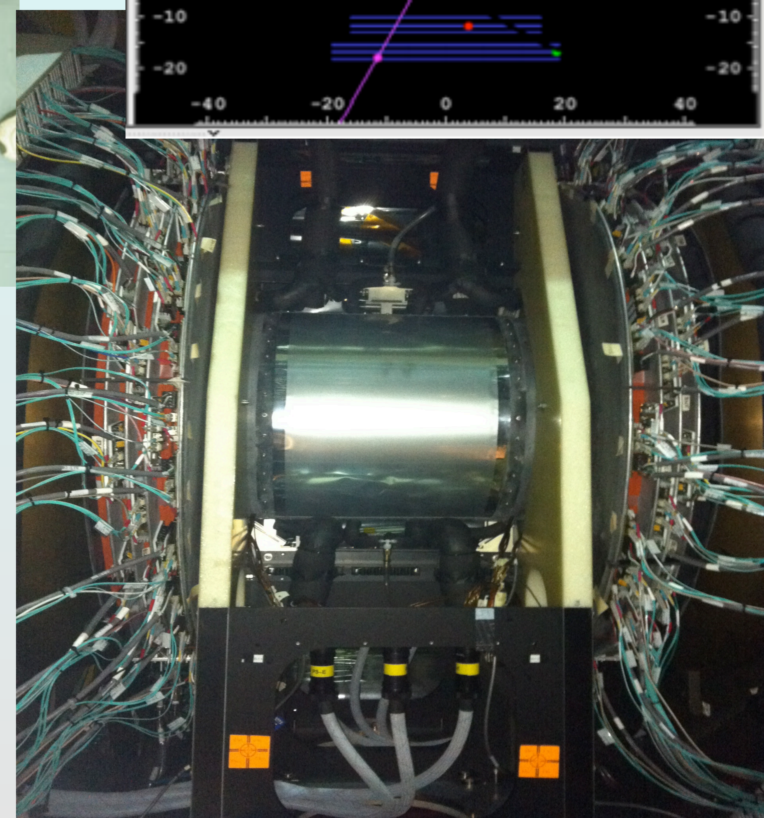
VTX & FVTX

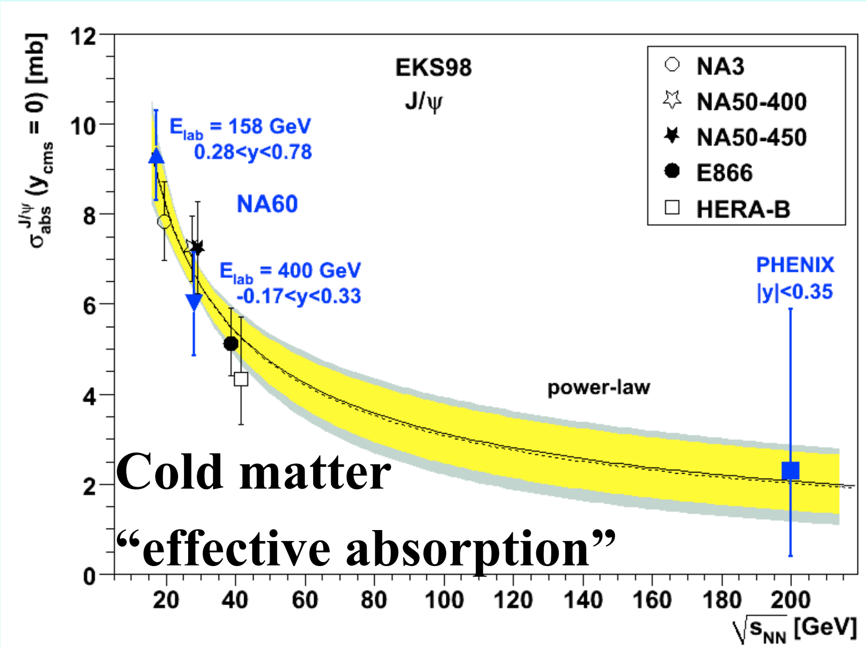


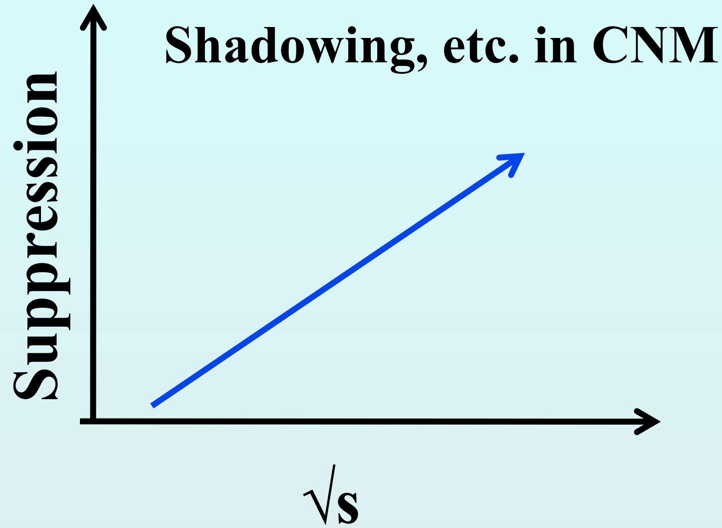


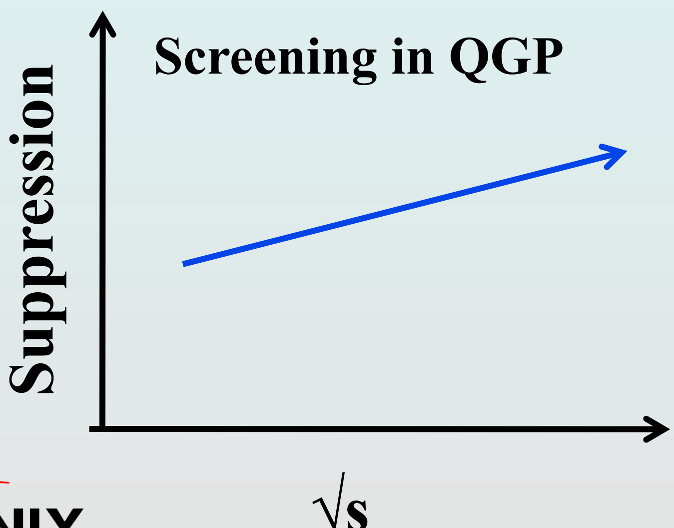


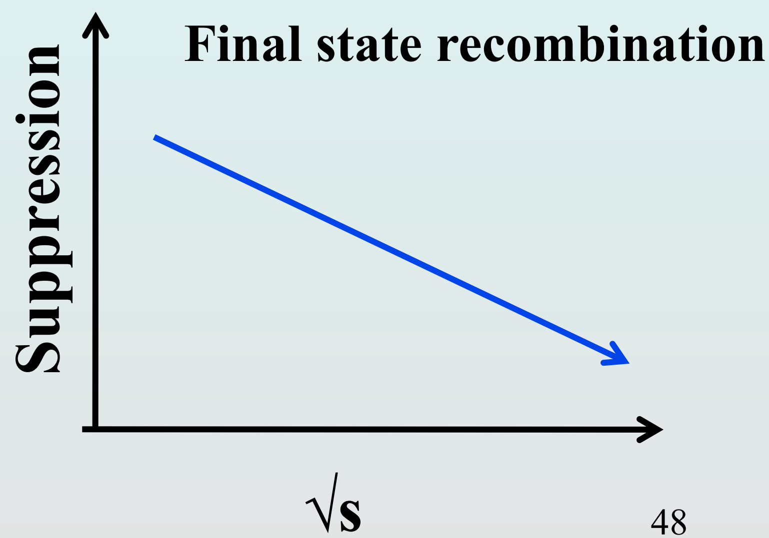


NEED y, p_T, b, √s, species to understand J/ψ









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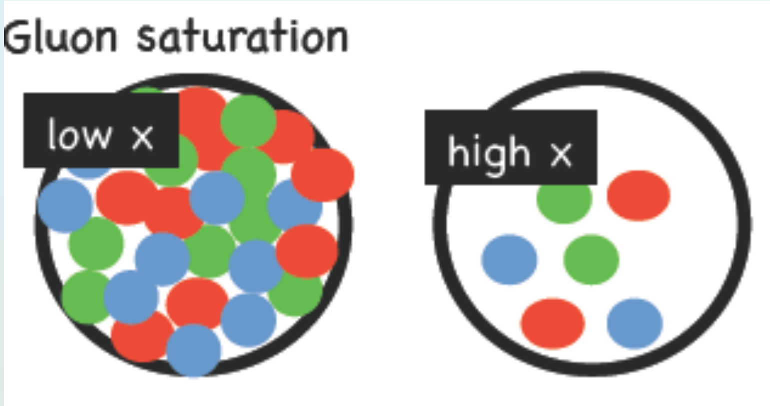
The big question in p+A physics

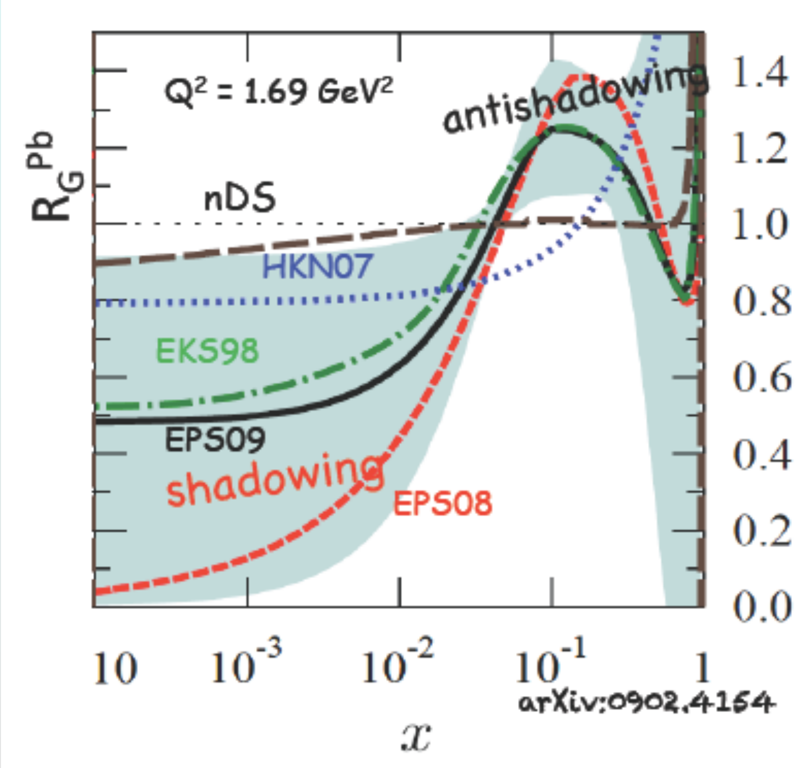
- **Then (the pre-RHIC era):**

  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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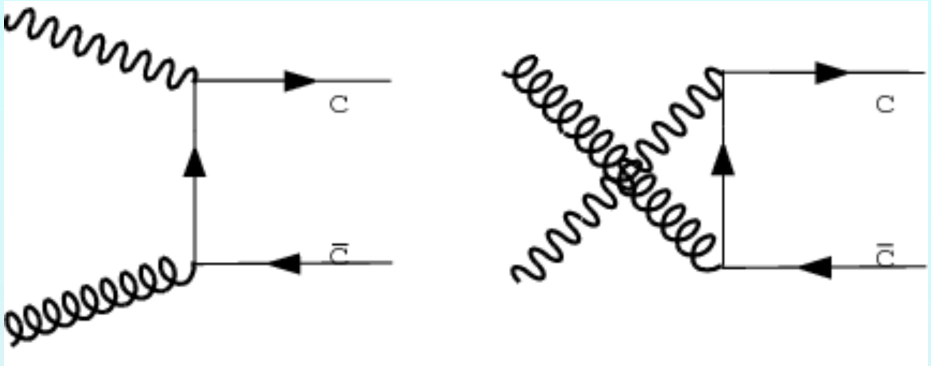
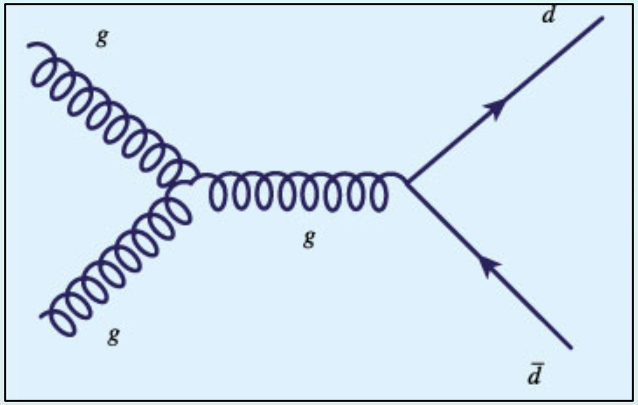
To answer this: PHENIX studies

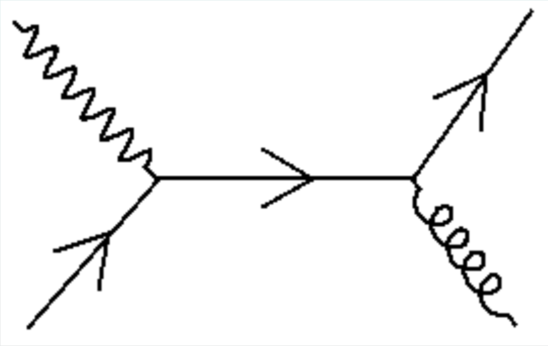
- **Heavy flavor production:**
  g+g ➔ c + cbar



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



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



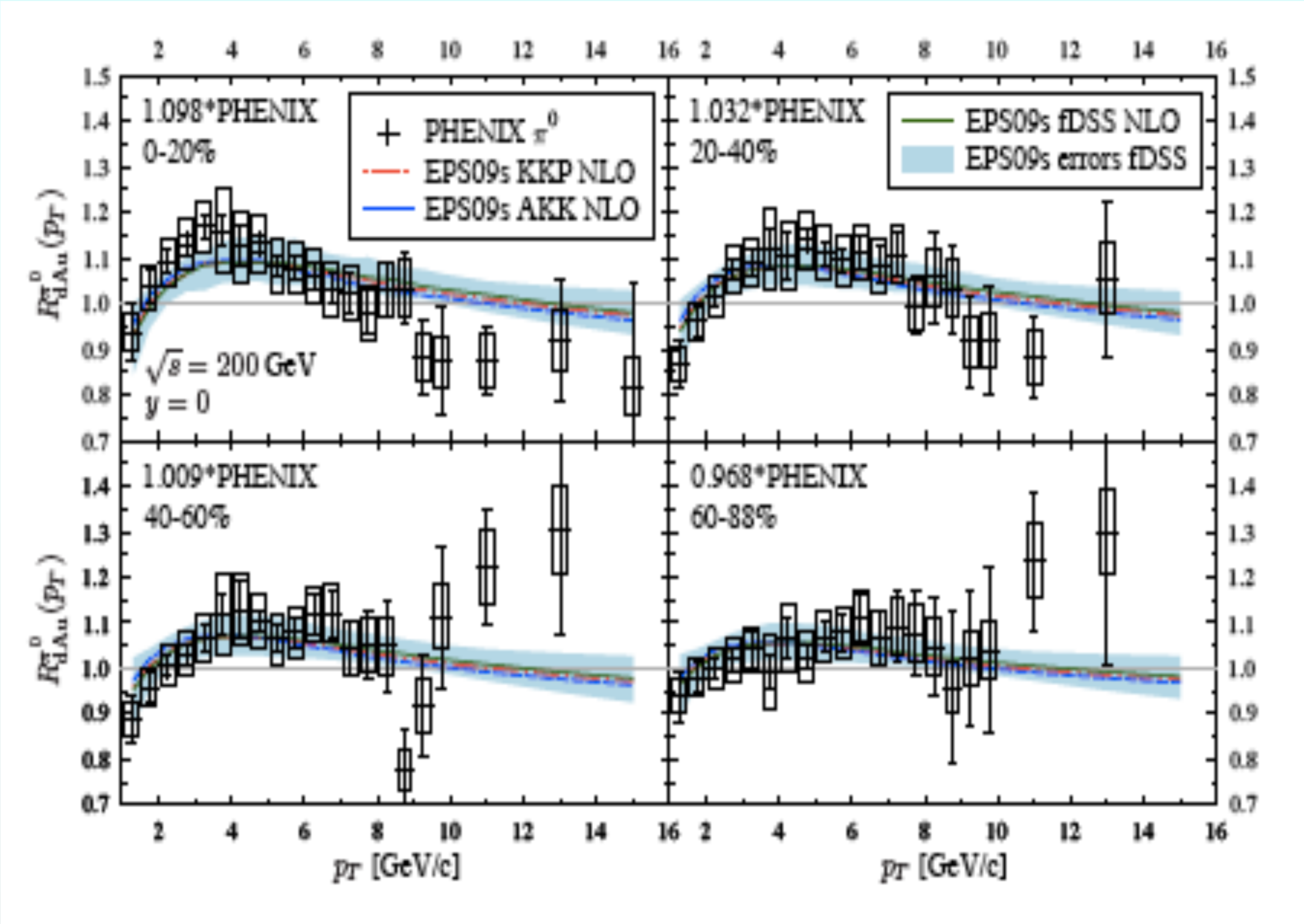
Turn now to jets and direct photons

arXiv 1205.5359

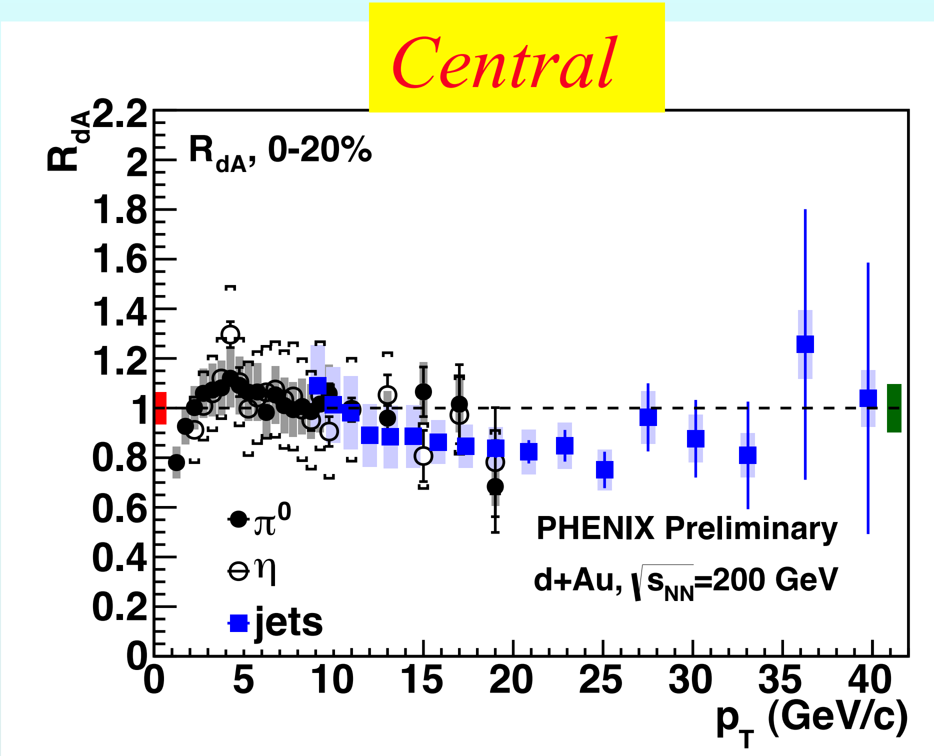
Hellenius, Eskola, et al

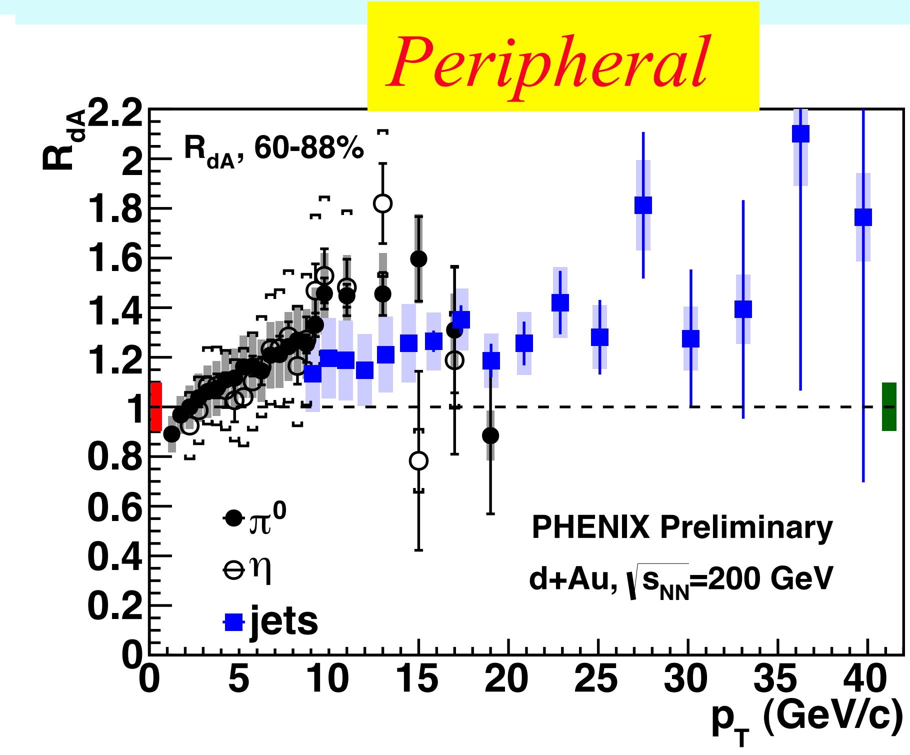
Fit data, including PHENIX π^0 R_{dAu}

Get b-dependent nPDFs



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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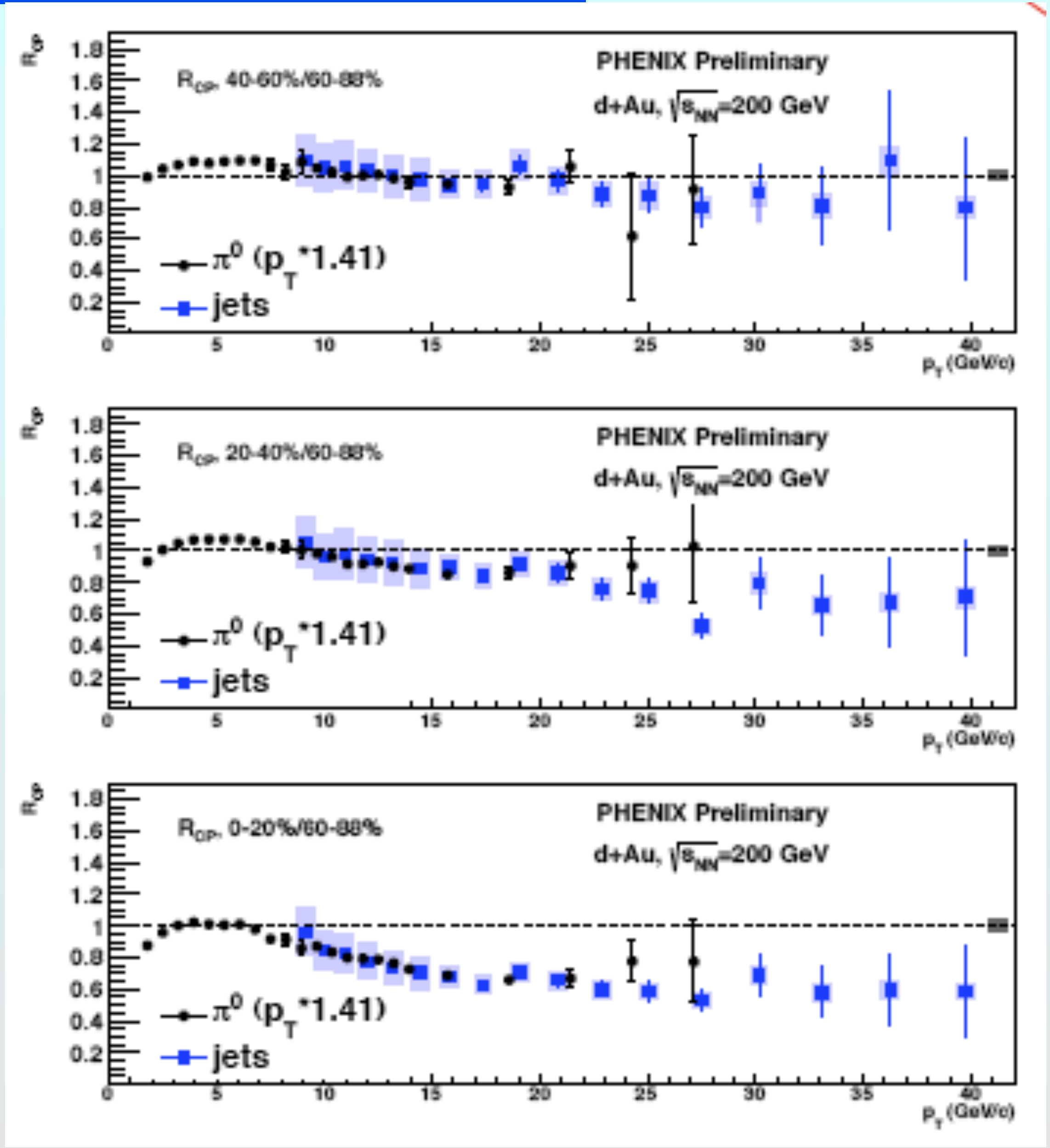
Do the π^0 and jets agree?

- Scale π^0 by 1/0.7
  i.e. 1/<$Z_{leading}$>
- 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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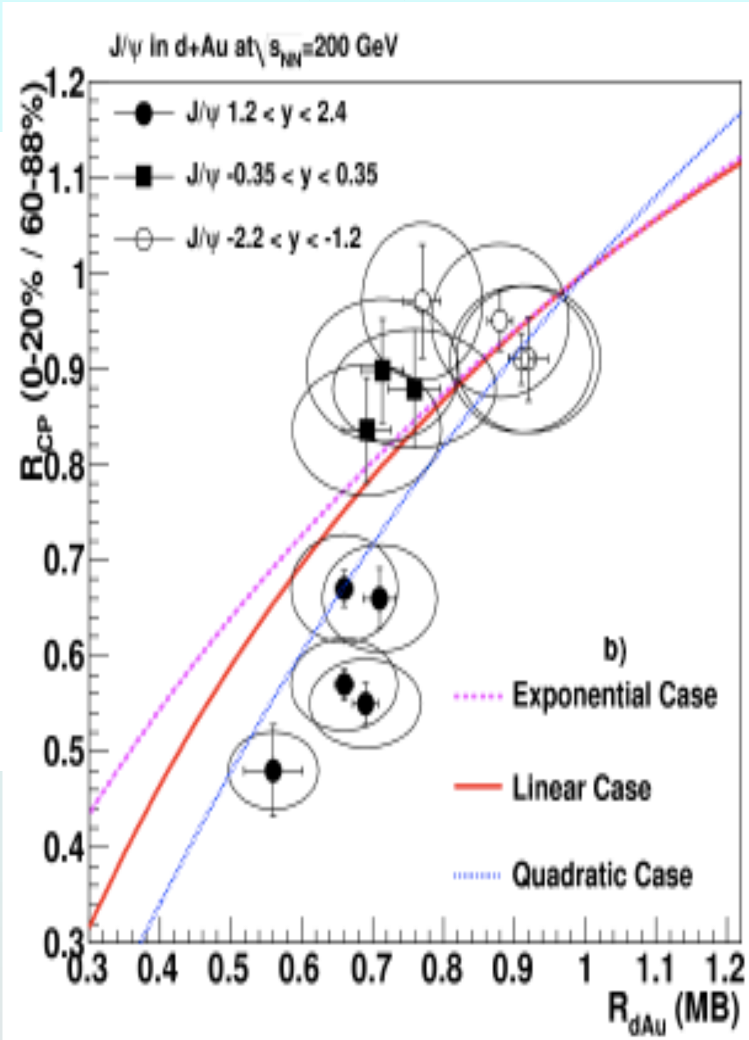
J/ψ in d+Au

PRL107, 142301 (2011)



Centrality dependence

Suppression level

forward rapidity probes low-x in Au

saturation predicts suppression

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

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

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

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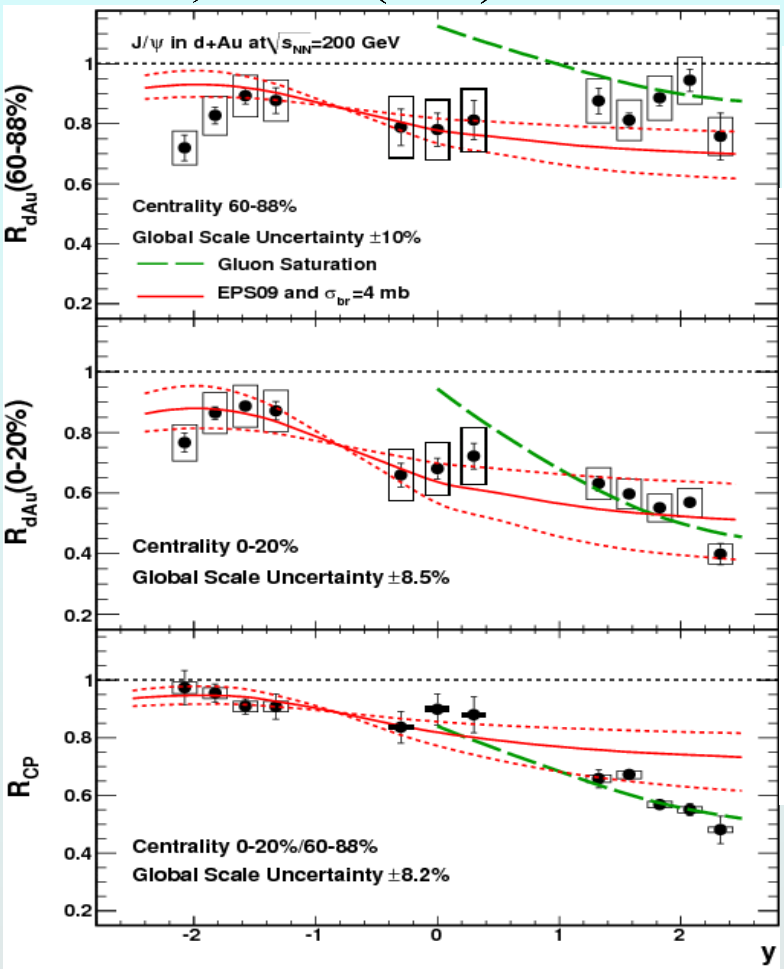
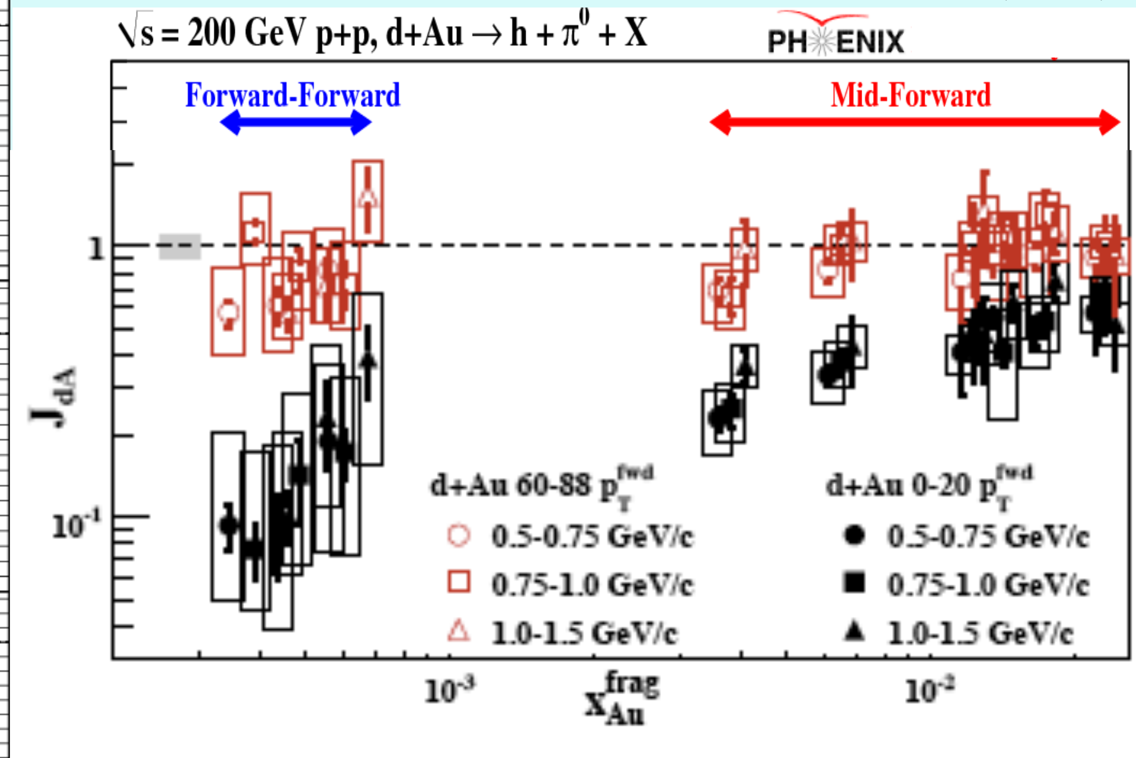
Dense gluonic matter effects observed

PRL107, 142301 (2011)



PRL107, 172301 (2011)



Di-hadron suppression at low x

pocket formula (for 2➔2):

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

Shadowing/absorption stronger than linear w/nuclear thickness

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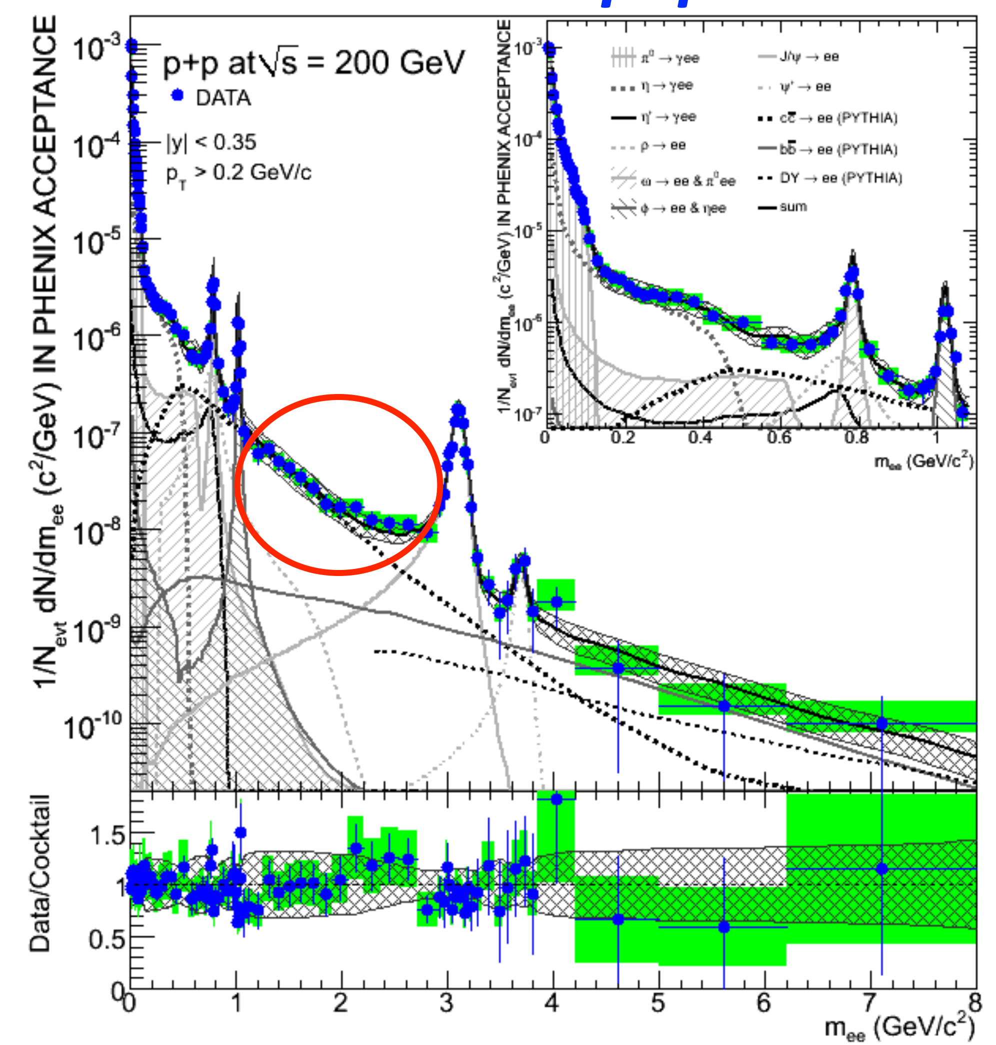
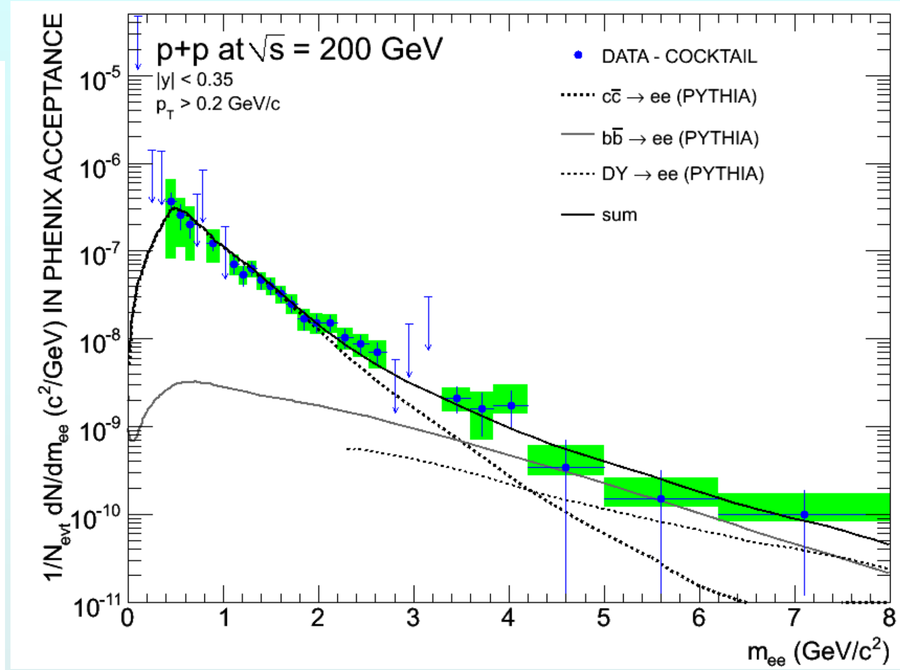
As expected for CGC …

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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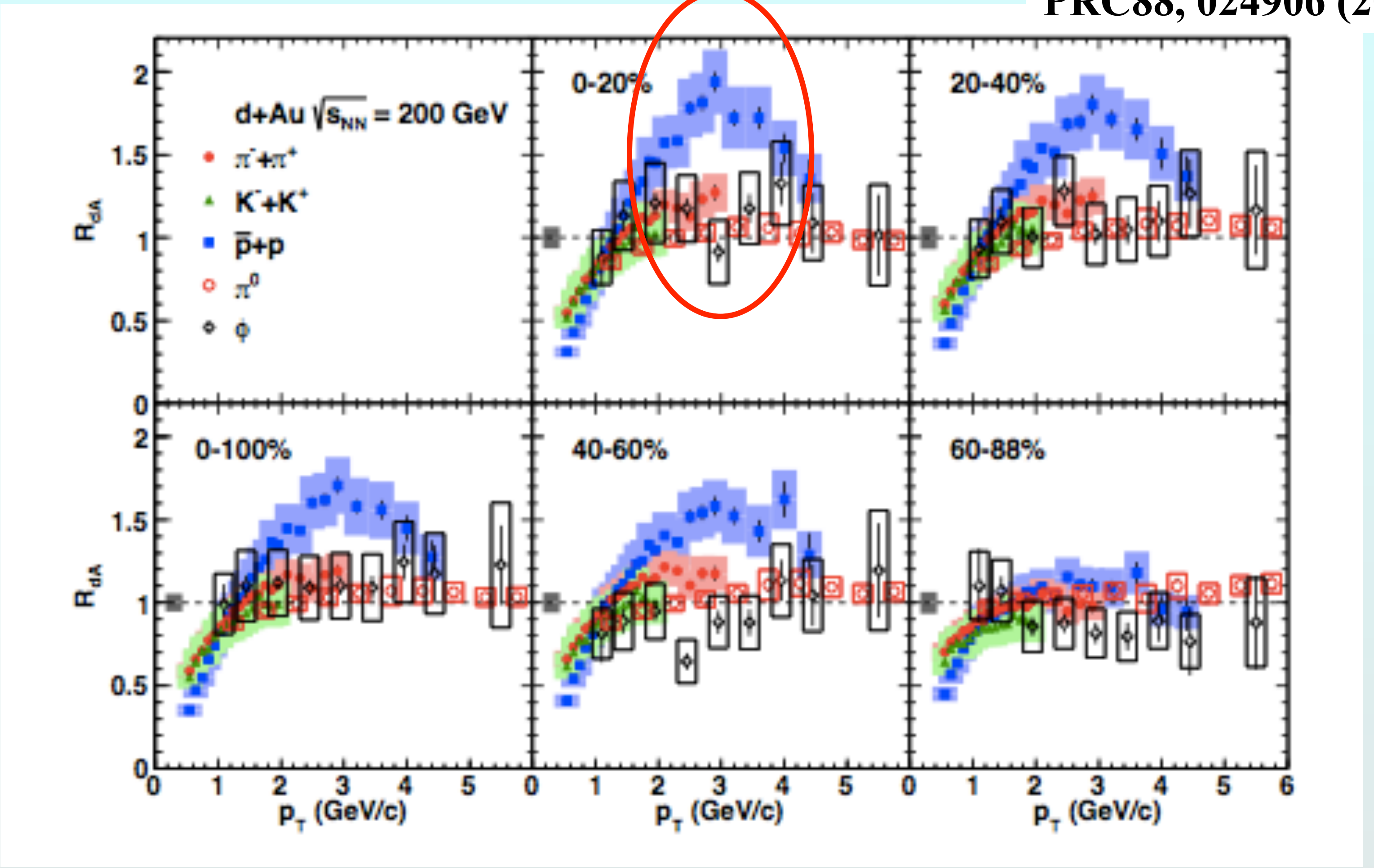
NB: Classic does not always mean right!

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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