Latest QCD and small-x physics results in p+p, d+Au and Au+Au collisions from PHENIX

Stefan Bathe

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For the PHENIX Collaboration

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RIKEN BNL Research Center

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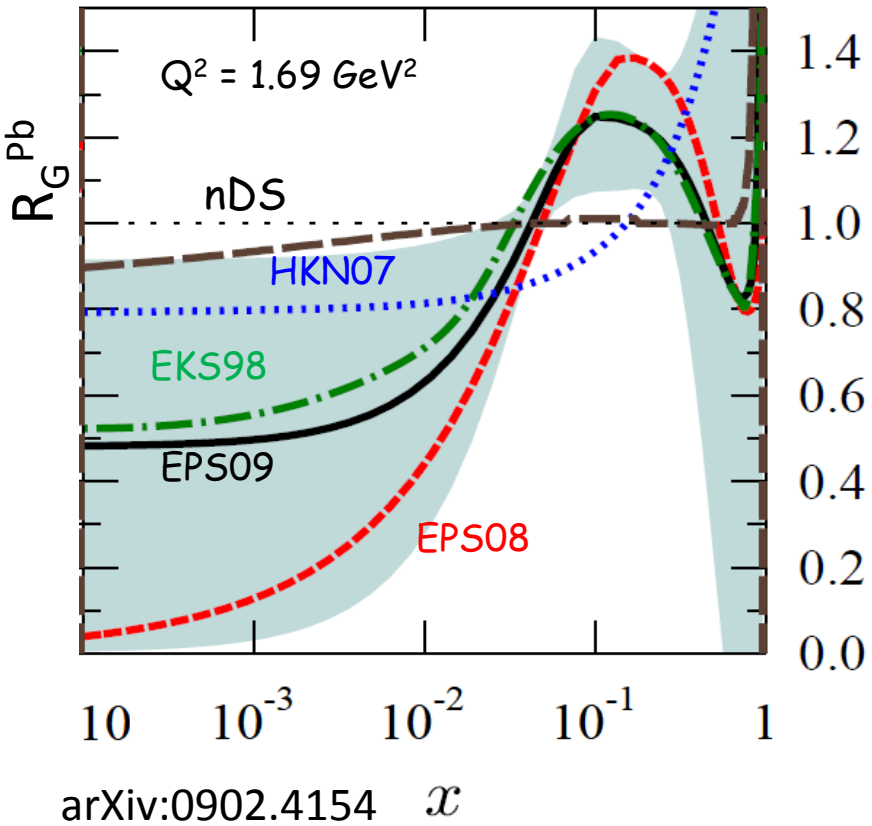
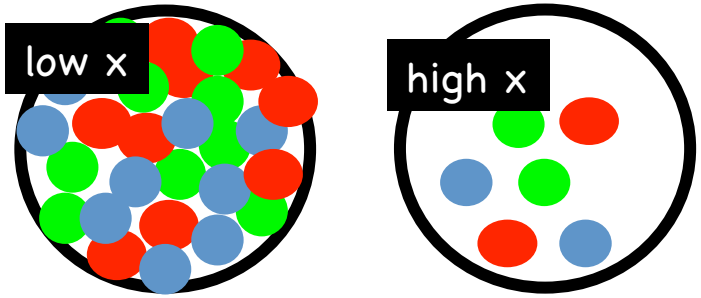
Cold Nuclear Matter



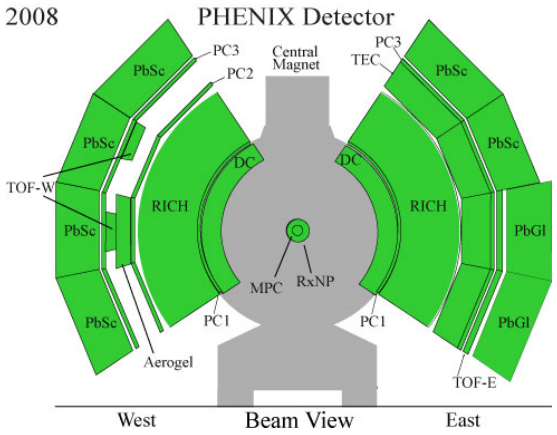
arXiv:0902.4154

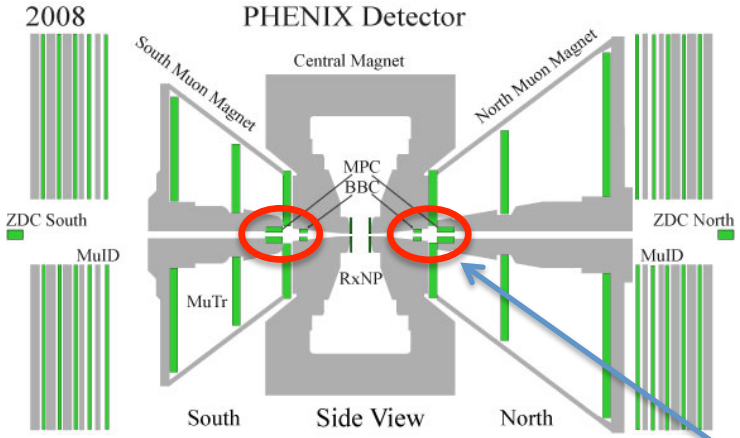


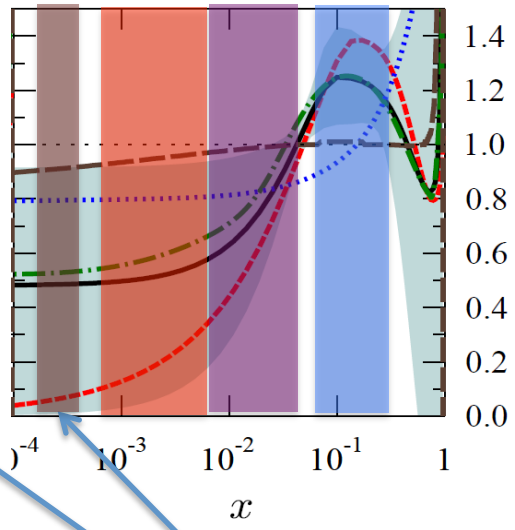
- Initial state effects
  - Modification of gluon distribution
    - shadowing
    - anti-shadowing
    - Gluon saturation
  - Energy loss and broadening
- Final state effects
  - Nuclear absorption
  - Coalescence?

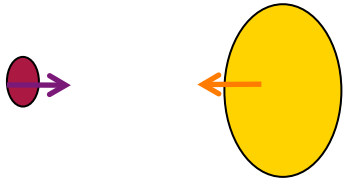
- Probes:
  - Photons, hadrons, jets, open and closed heavy flavor
  - Two-particle correlations

PHENIX Acceptance in d+Au



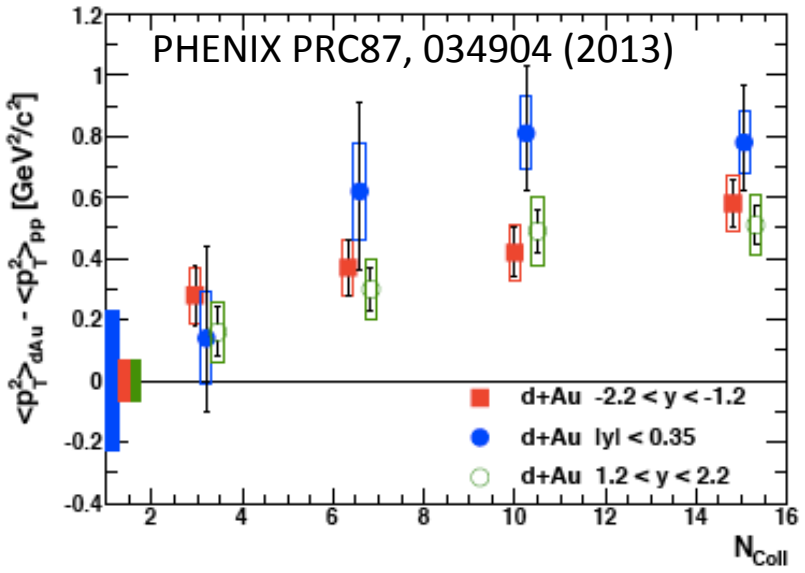






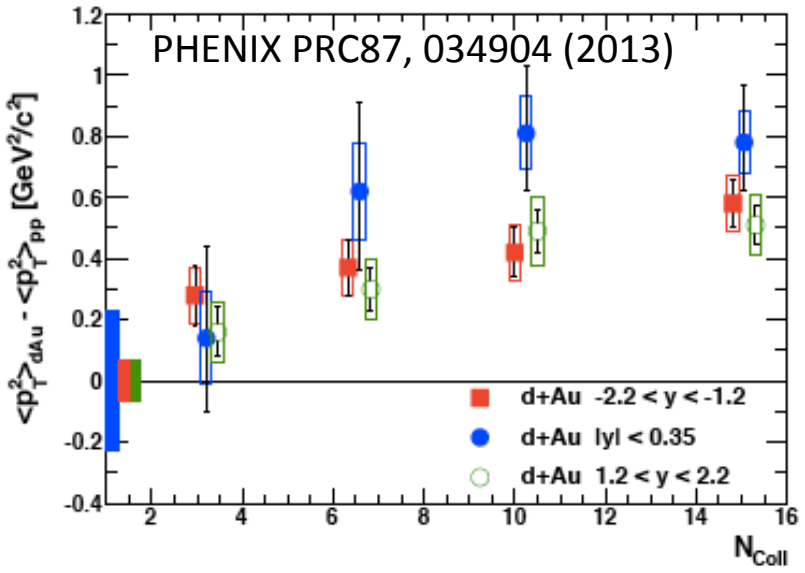
MPC-S	Sourth Muon Arm	Central Arms	North Muon Arm	MPC-N
$-3.8 < \eta < -3$	$-2.2<\eta<-1.2$	$\lvert\eta\rvert<0.5$	$1.2<\eta<2.2$	$3 < \eta < 3.8$
larger x in Au $10^{-1} < x < 10^{0}$ anti-shadowing	large x in Au $10^{-1} < x < 10^{0}$ anti-shadowing	medium x in Au $x\approx10^{-2}$ in Au	small x in Au $10^{-3} < x < 10^{-2}$ shadowing	smaller x in Au $10^{-4} < x < 10^{-3}$ saturation?

J/ψ

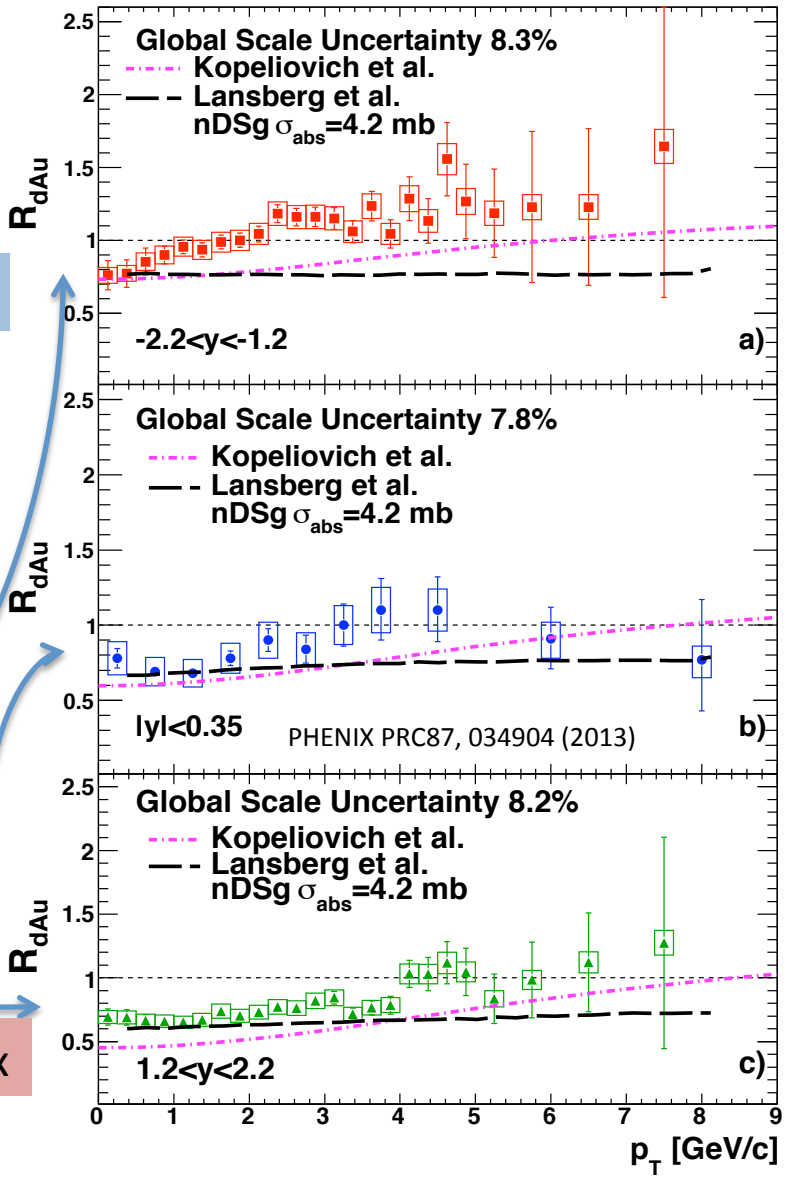


- p_T broadens (multiple scattering) w/ N_{coll}; effect stronger at y=0

J/ψ



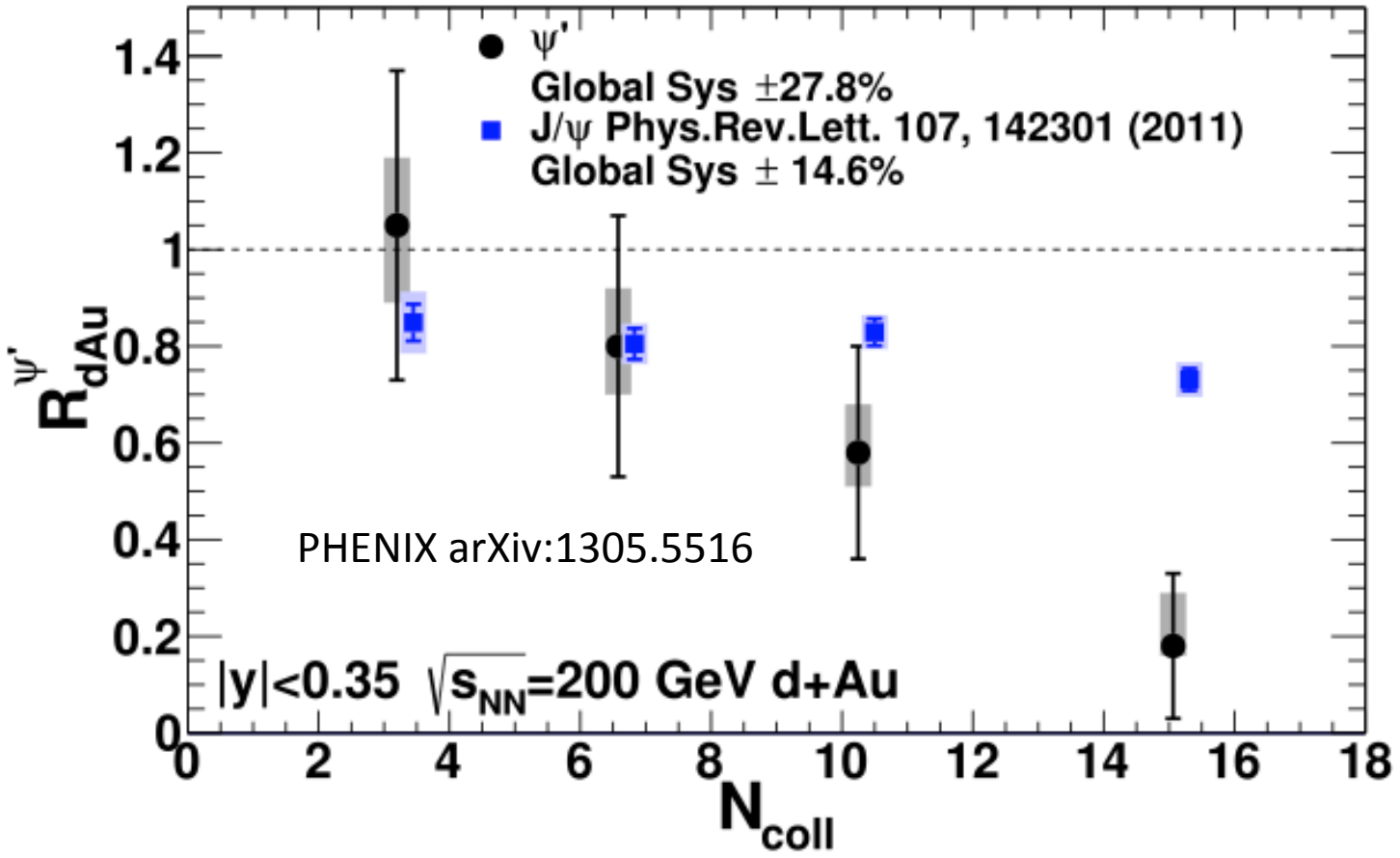
high x



low x

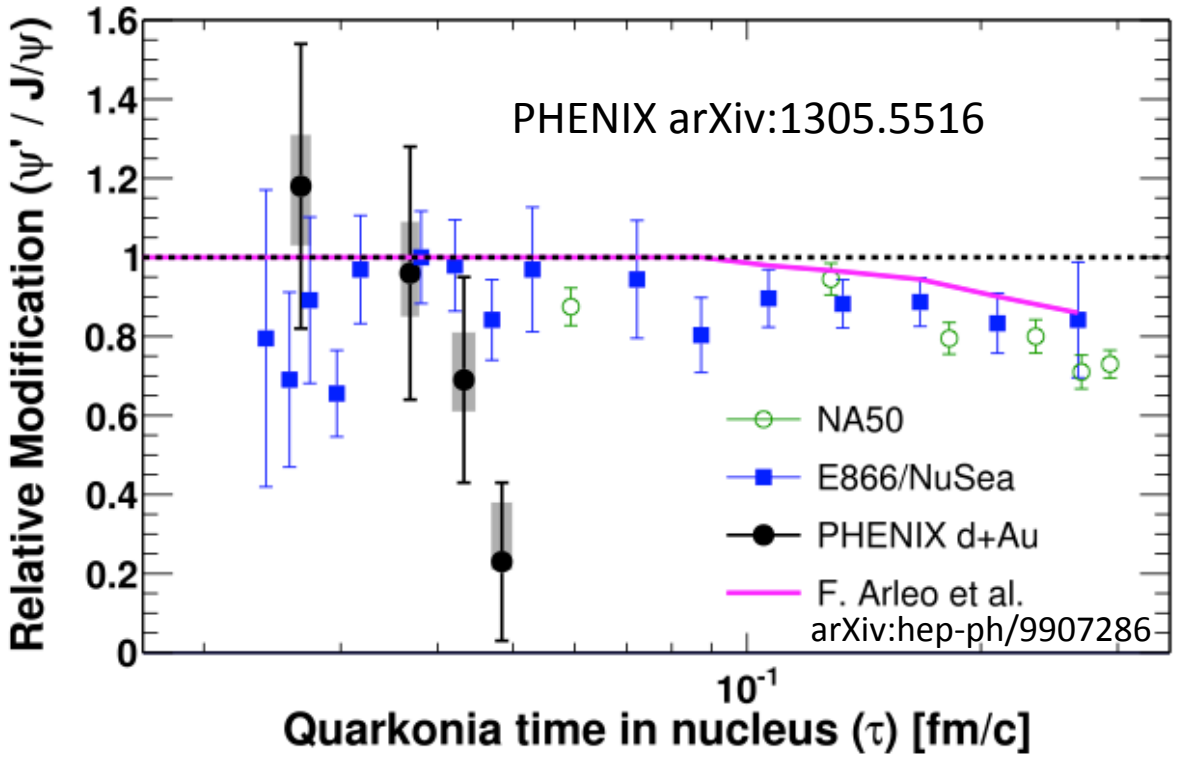
- p_T broadens (multiple scattering) w/ N_{coll}; effect stronger at y=0
- backward y:
  - only suppressed at lowest p_T
  - then rapid increase
- mid and forward y:
  - Much more gradual increase with p_T
  - Very similar in level and shape

ψ' R_{dAu}



- Less tightly-bound/larger ψ' more suppressed than J/ψ in dAu
- not initial state effect (parton level)
- Suggests final-state effect (hadron level)

ψ' time in nucleus



- Time in nucleus is short at √s = 200 GeV
- Shorter than bound state formation time! Late final state effect?

Open Heavy Flavor

- No issue of final break-up
- But x less constrained
- Harder to measure
  - non-photonic single leptons (from semi-leptonic decays)
  - no mass peak

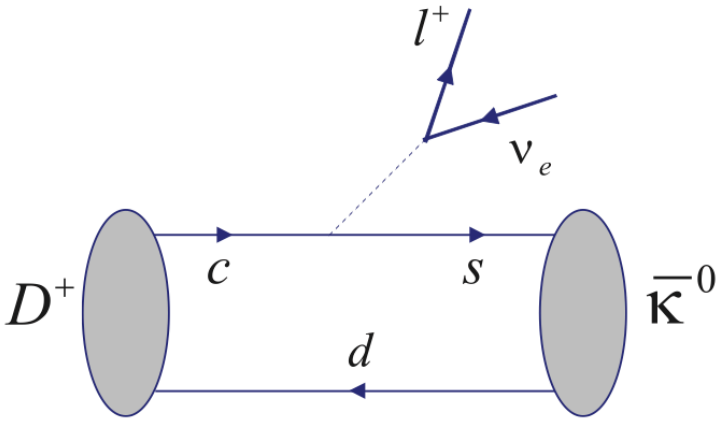
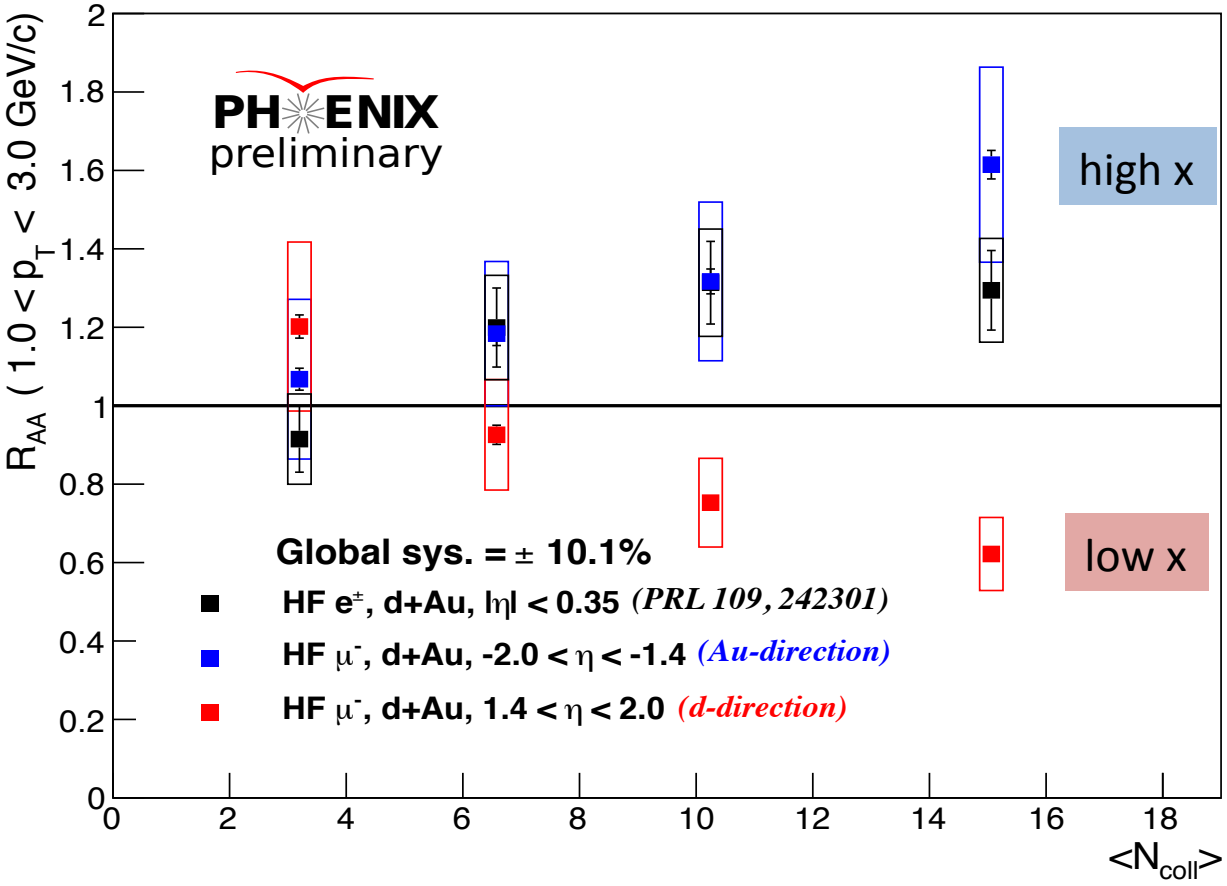


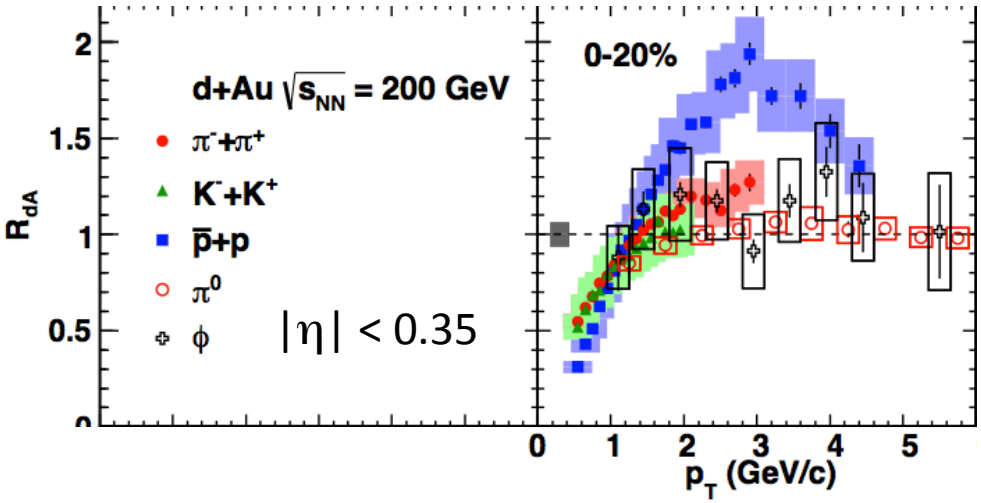
Figure from Phys.Lett. B608,69

Open heavy flavor

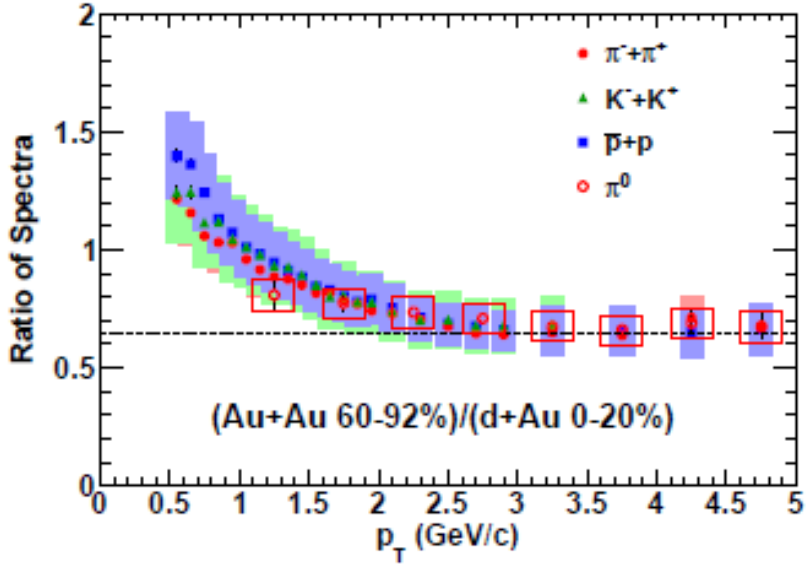


- Clear enhancement in Au-going direction sensitive to high-x in Au (anti-shadowing)
- Suppression in d-going direction sensitive to low-x (shadowing)
- Enhancement also at mid-rapidity

PID hadrons in dAu

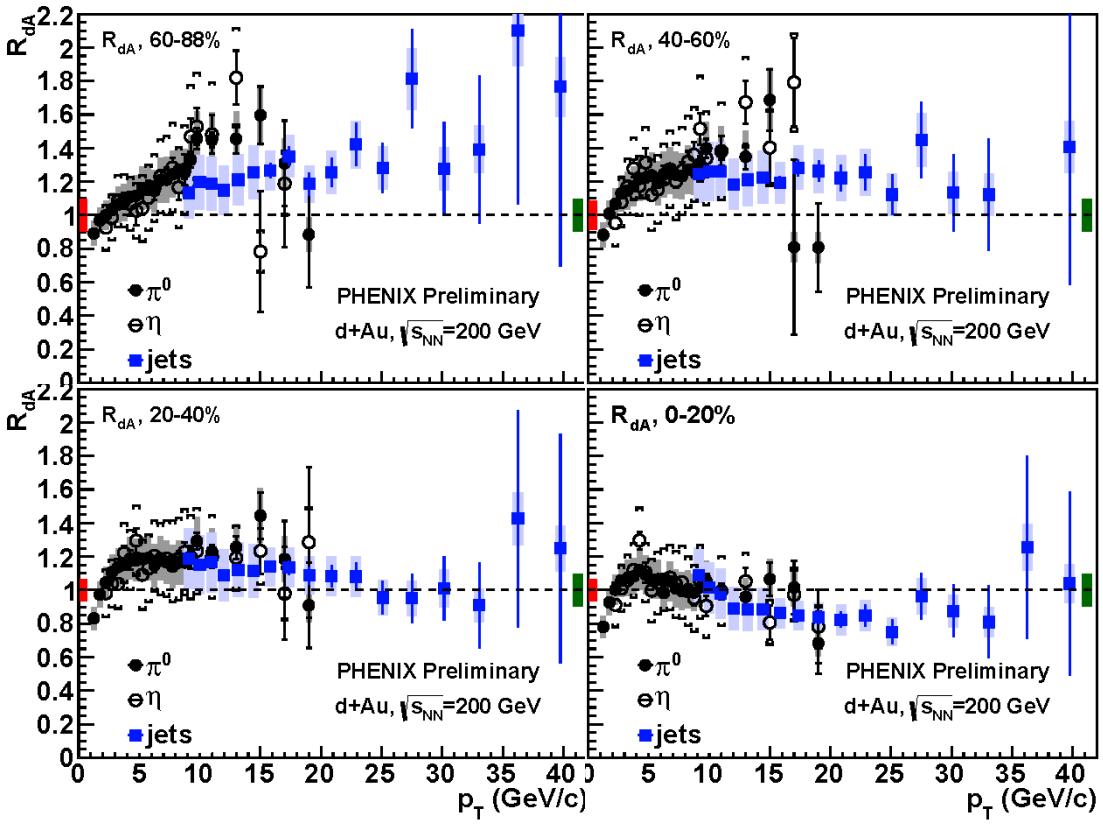


PHENIX arXiv:1304.3410



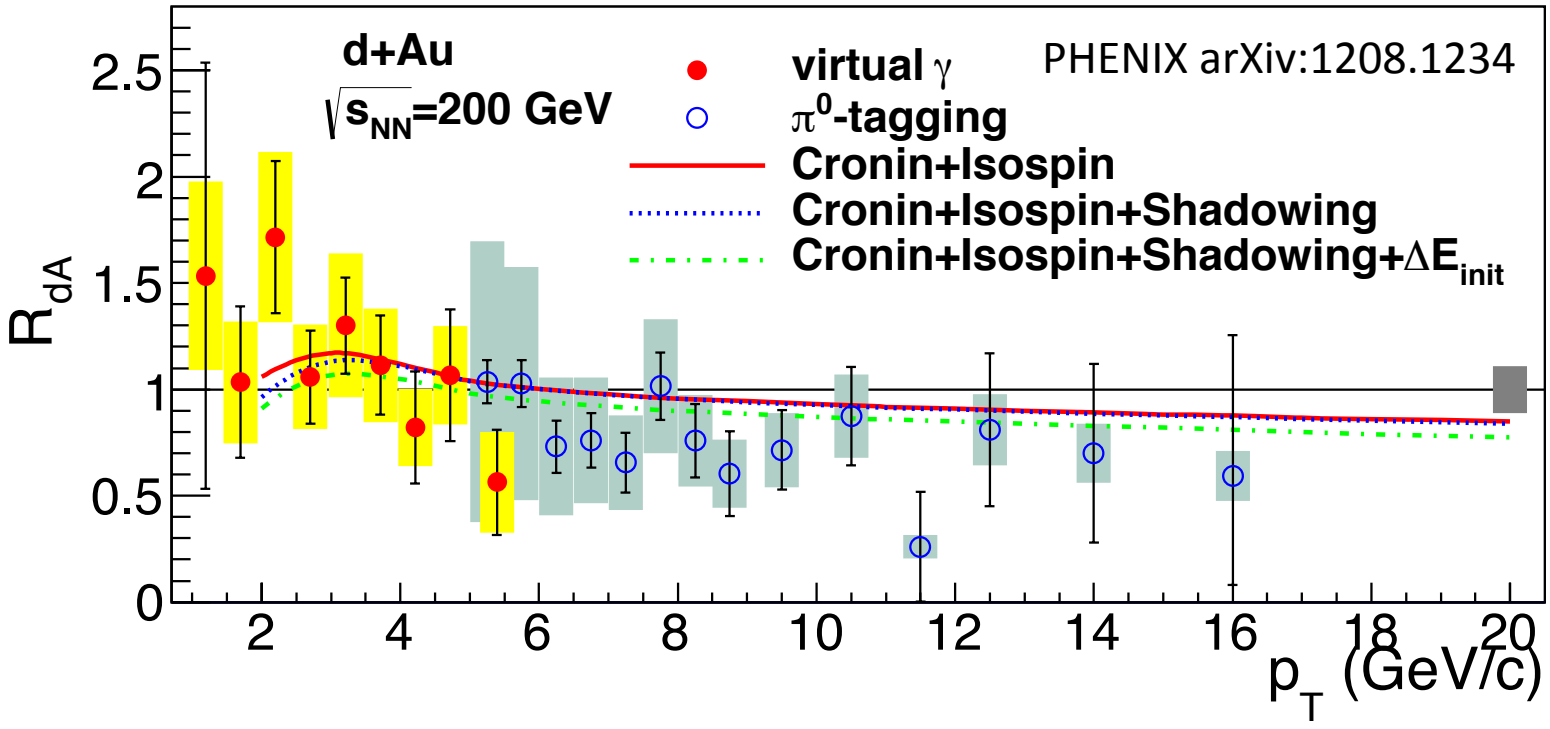
- Large R_{dA} for protons
  - Simple Cronin effect?
  - How does parton know it will produce a proton?
- No species dependence for AuAu/dAu ratio for same $N_{part, coll}$
  - Suggests common production mechanism in dAu and AuAu (coalescence?, flow?)
- Ratio < 1 at high pT
  - Energy loss in peripheral AuAu?
- Ratio > 1 at low pT
  - Participant asymmetry → rapidity shift?
- Possible effect from different pdf in dAu vs. AuAu

High p_T π^0 and jets

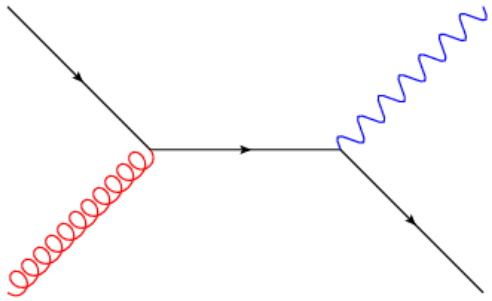


- Enhancement in peripheral, slight suppression in central
- Surprisingly strong centrality dependence
- Competing cold nuclear matter effects?
- Auto-correlations between high p_T processes & centrality measure?
- Cross check with p+Si (light ion): no centrality selection necessary (RHIC Run 2015)

Direct Photons



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

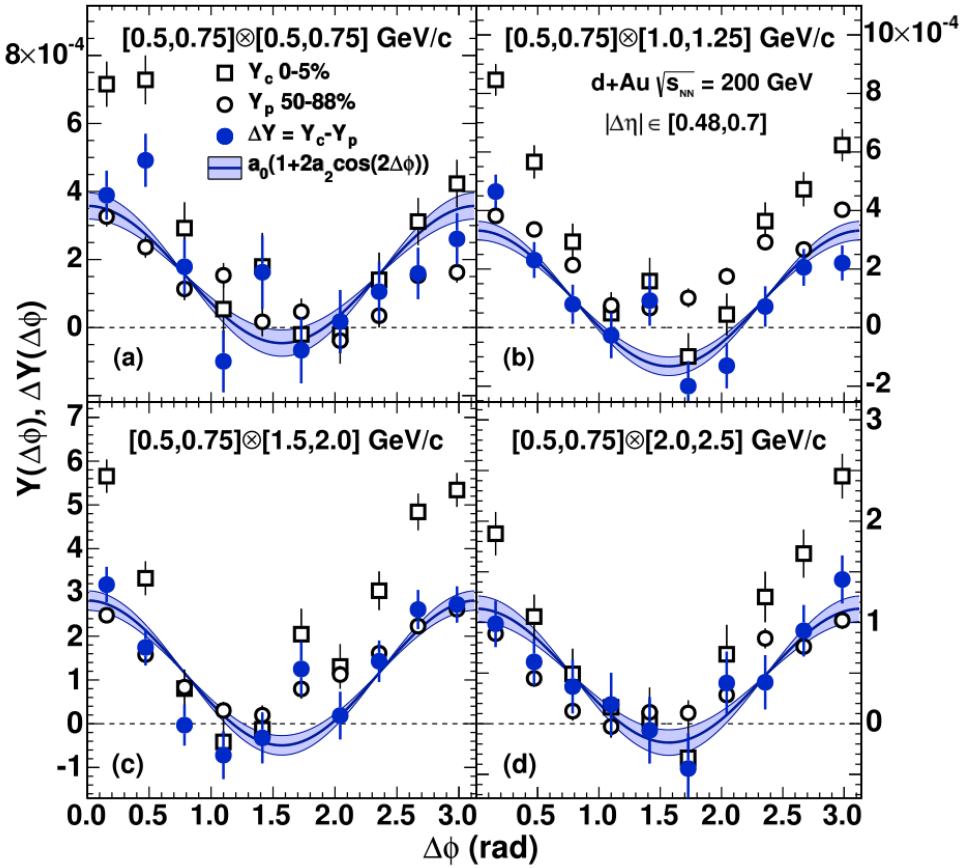


Two-Particle Correlations

- Sensitive to
  - Flow
  - Initial state correlations

Non-jet correlation in d+Au?

PHENIX arXiv:1303.1794

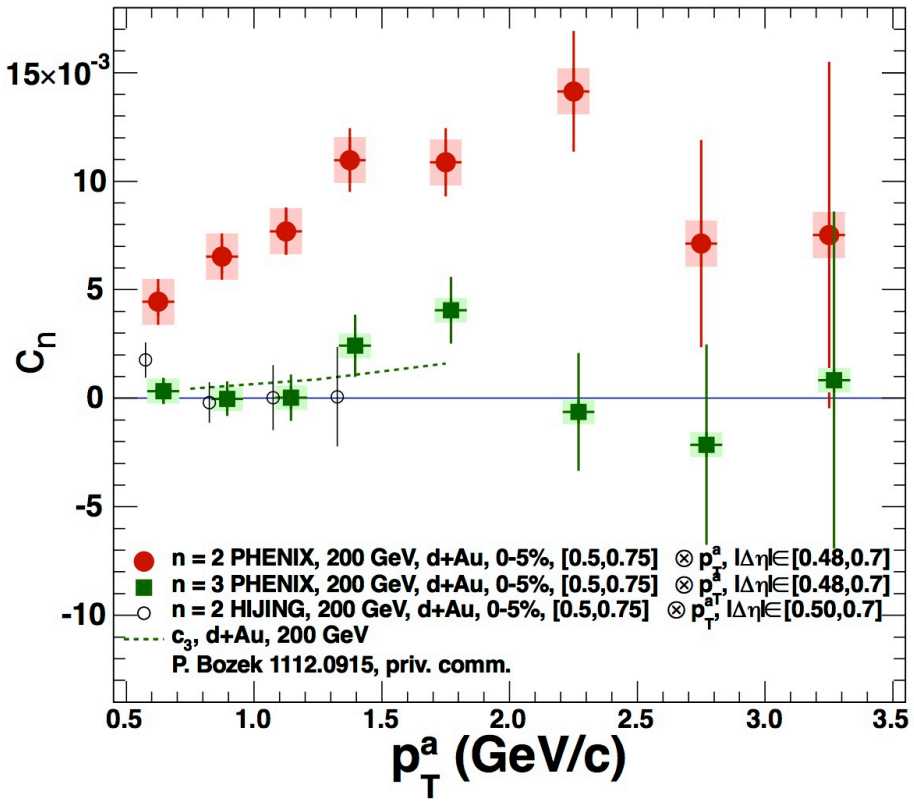


$$Y(\Delta\phi) \equiv \frac{1}{N^t}\frac{dN^{\text{pairs}}}{d\Delta\phi} - b_{\text{ZYAM}}$$

- mid-rapidity
- Per-trigger yield
- Eliminate jet correlations
  - Subtract peripheral from central
  - η gap ($\Delta\eta$>0.48)
- Symmetric, cosine-like correlation remains

Jet-Subtracted Fourier Moments

PHENIX arXiv:1303.1794



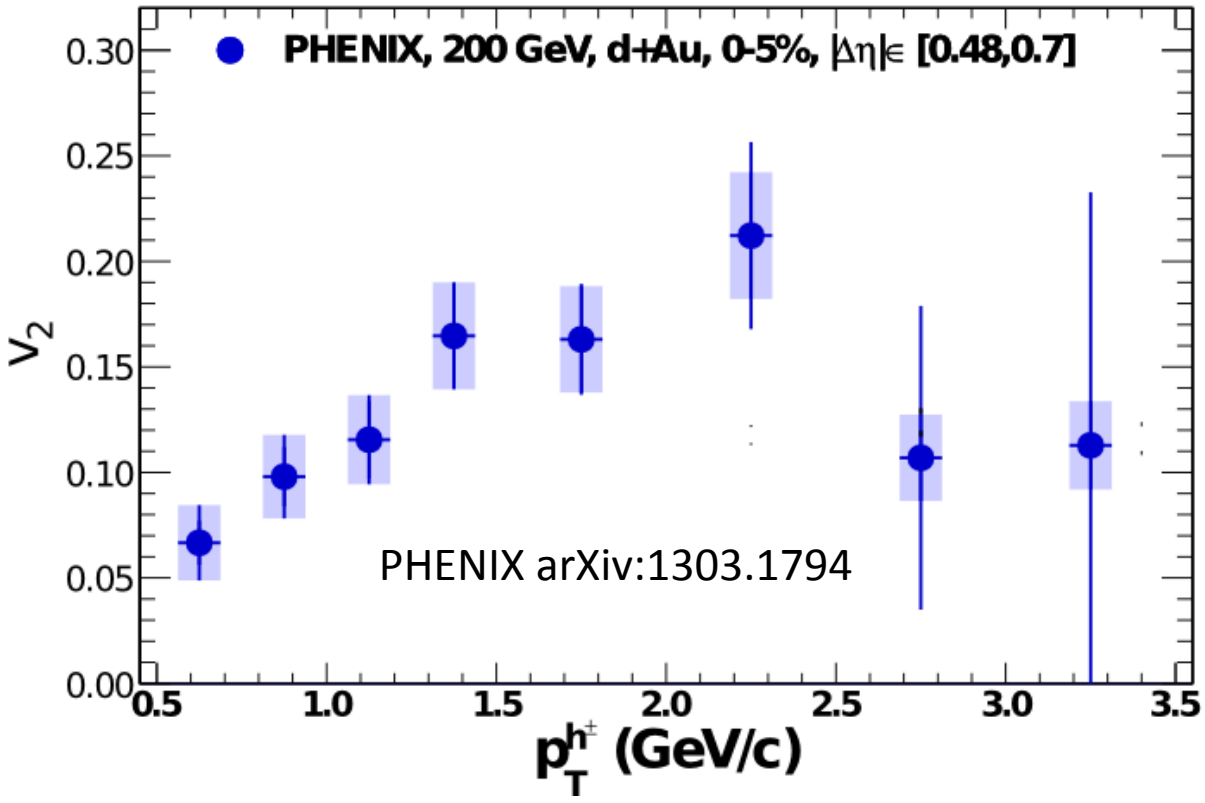
$$\Delta Y(\Delta\phi) \approx a_0 + 2a_2 \cos(2\Delta\phi)$$

$$c_n \equiv a_n / (b^c_{\mathrm{ZYAM}} + a_0)$$

- Fourier moments, c_n, of jet-subtracted distributions vs. associated p_T
- Significant c_2
- No significant c_3
- c_2 from HIJING small
- c_3 consistent with hydro

Fourier Moment v_2

$$c_2\left(p_T^t, p_T^a\right) = v_2\left(p_T^t\right) \times v_2\left(p_T^a\right)$$

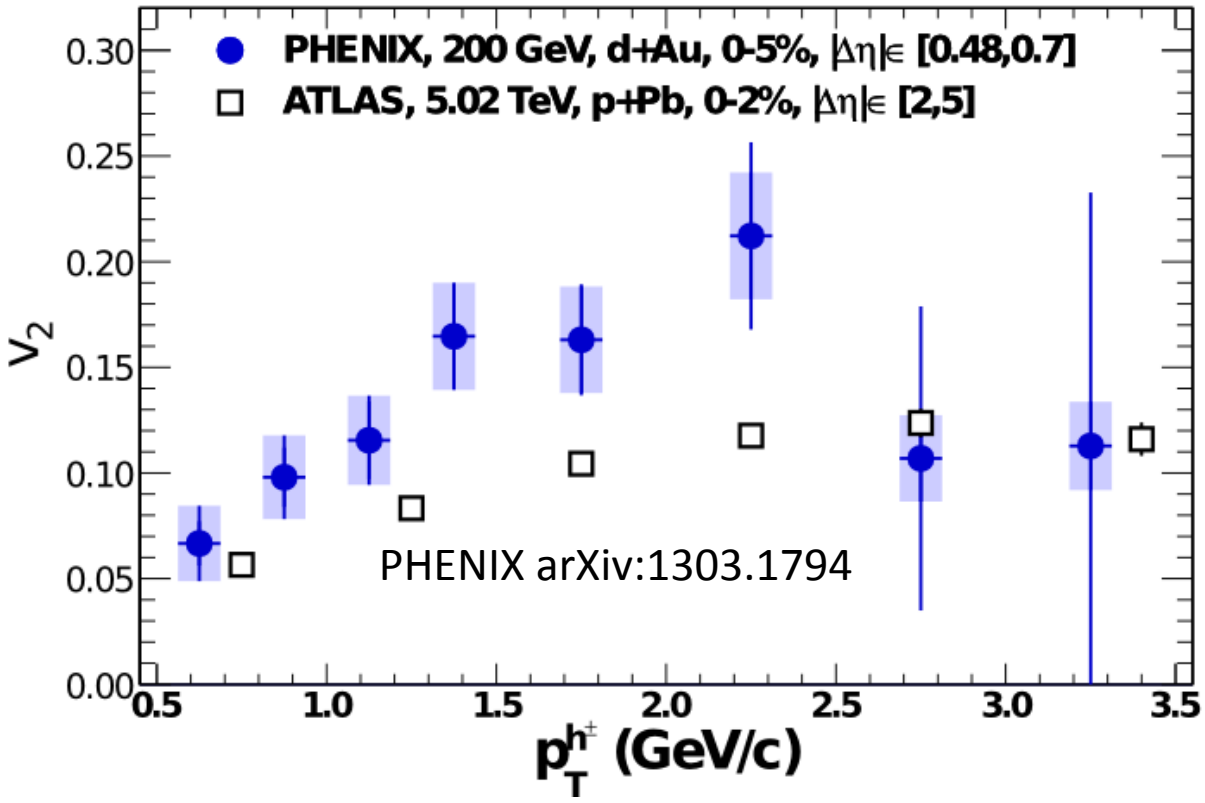


- Inferred quadrupolar anisotropy v_2 of h^{+-} vs. p_T

- significant v_2

Fourier Moment v_2

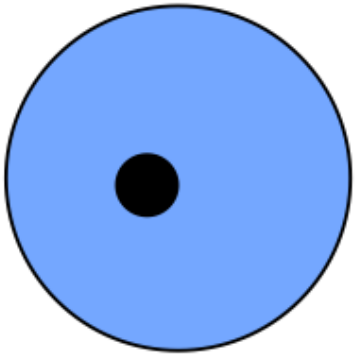
$$c_2\left(p_T^t, p_T^a\right) = v_2\left(p_T^t\right) \times v_2\left(p_T^a\right)$$

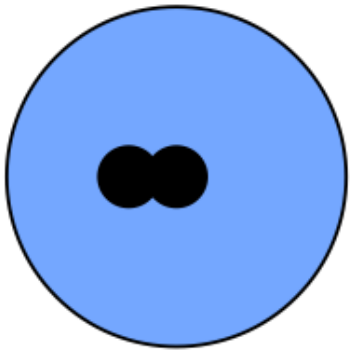


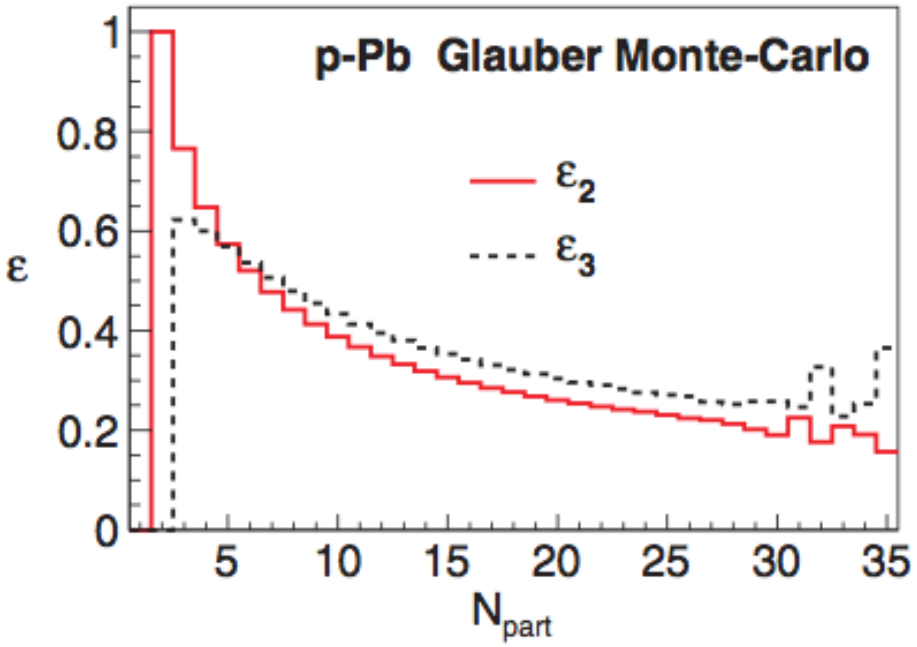
- Inferred quadrupolar anisotropy v_2 of h^{+-} vs. p_T

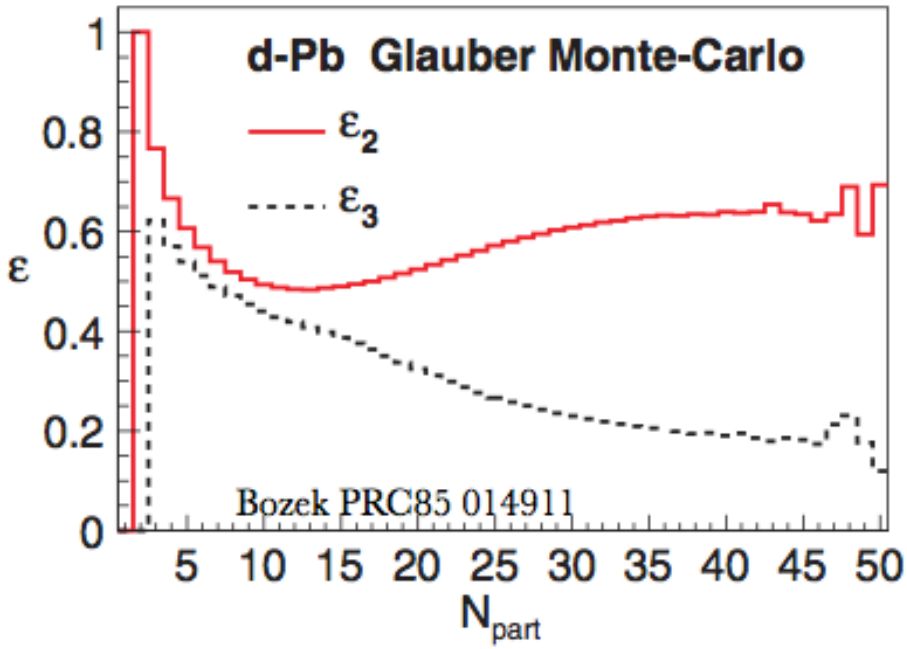
- v_2 d+Au > v_2 p+Pb

p+A vs. d+A

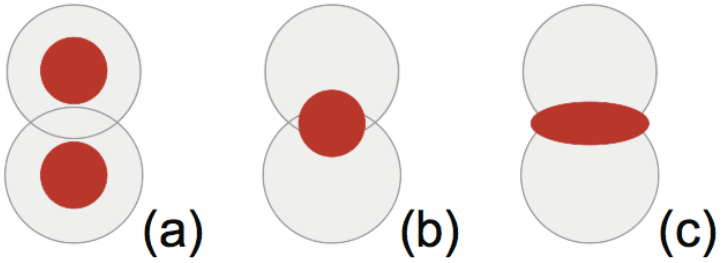




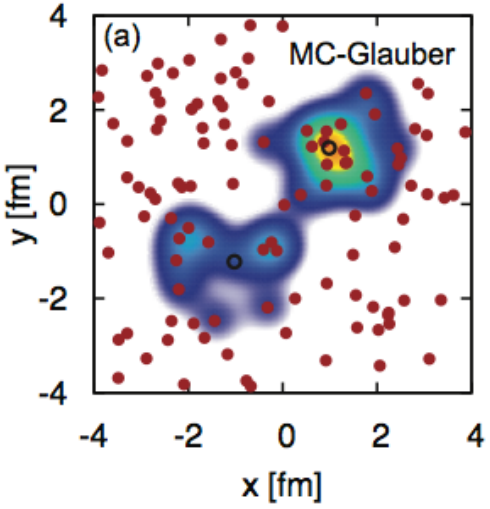

p-Pb Glauber Monte-Carlo
ε_2
ε_3
ε
N_{part}
0
0.2
0.4
0.6
0.8
1
5
10
15
20
25
30
35

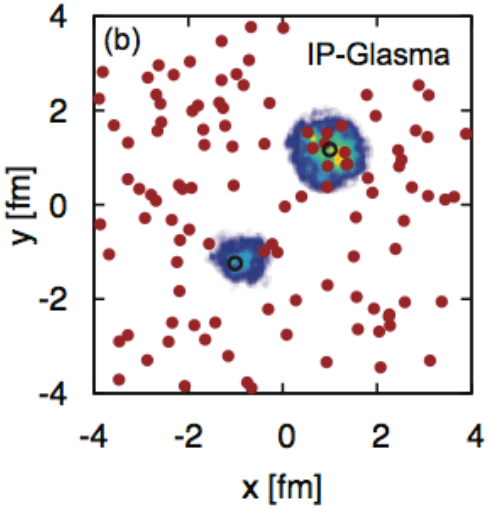

d-Pb Glauber Monte-Carlo
ε_2
ε_3
Bozek PRC85 014911
ε
N_{part}
0
0.2
0.4
0.6
0.8
1
5
10
15
20
25
30
35
40
45
50

Initial State Fluctuations



Energy deposition
a) nucleus center, $\varepsilon_2 = 1$
b) overlap region, $\varepsilon_2 = 0$
c) follow shape of overlap, $0 \leq \varepsilon_2 \leq 1$



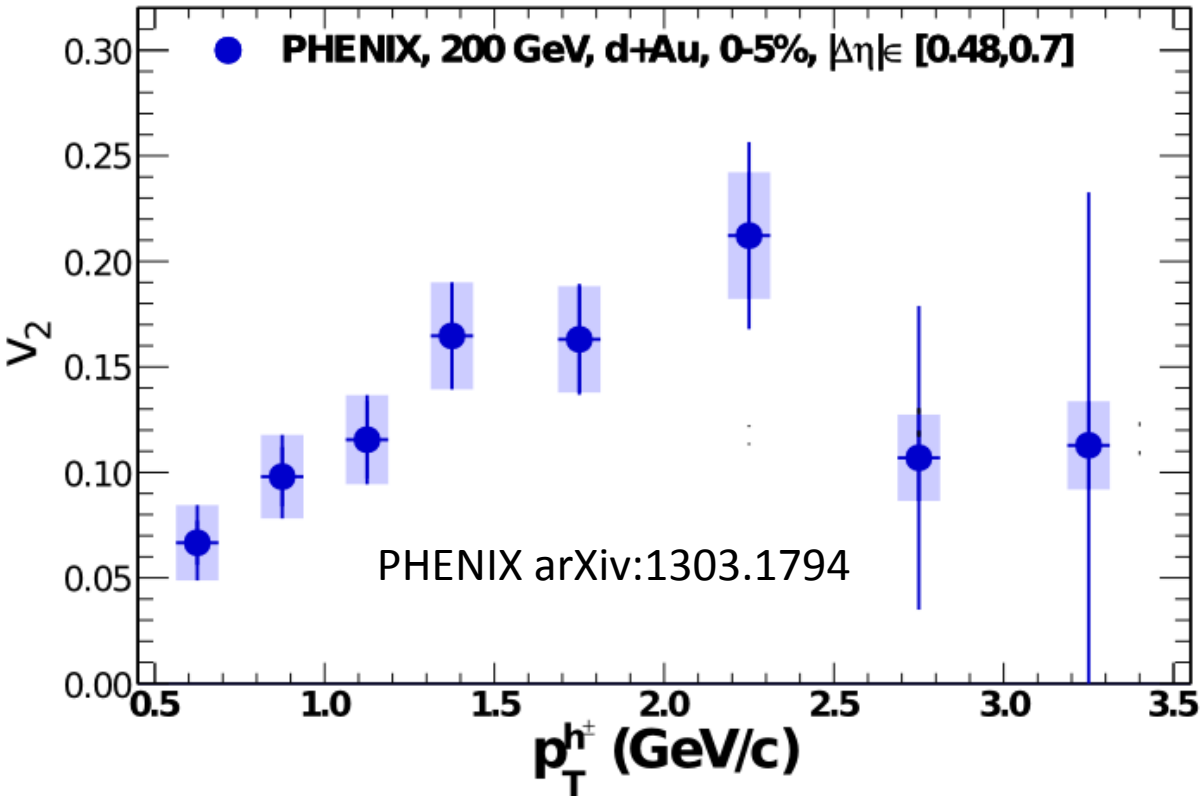


initial energy density distribution

Bzdak, Schenke, Tribedy, Venugopalan, 1304.3403

Fourier Moment v_2

$$c_2\left(p_T^t, p_T^a\right) = v_2\left(p_T^t\right) \times v_2\left(p_T^a\right)$$



- Inferred quadrupolar anisotropy v_2 of h^{+-} vs. p_T

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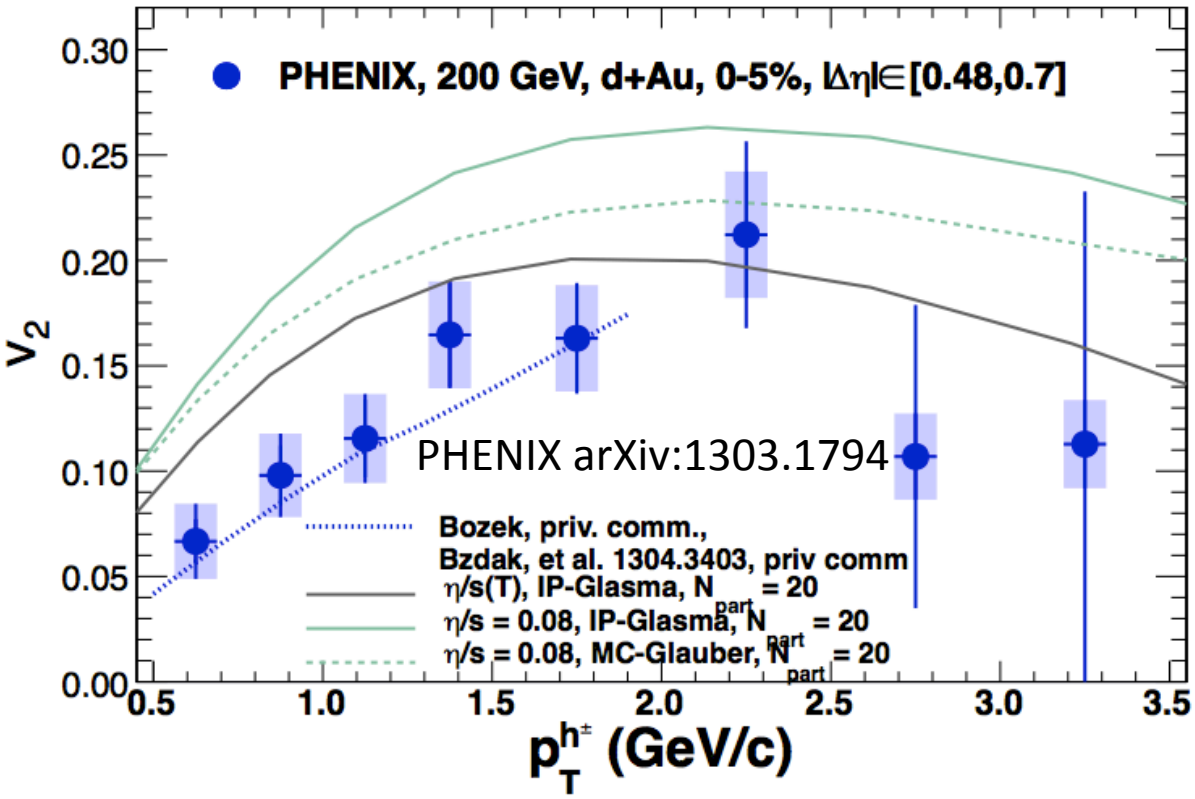
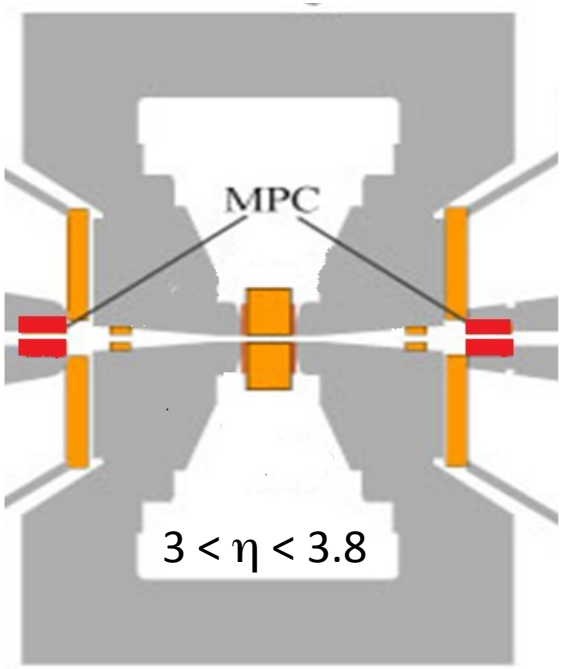
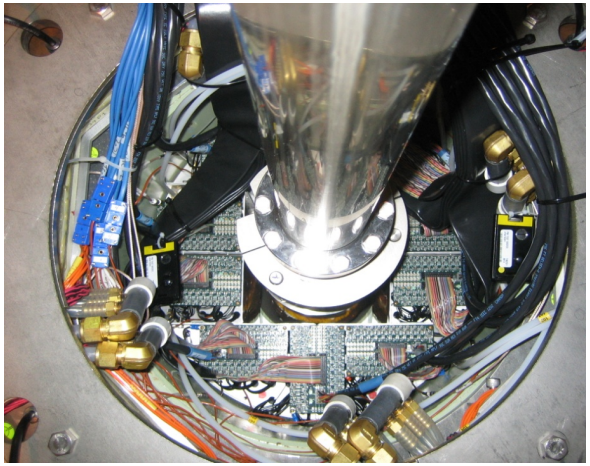


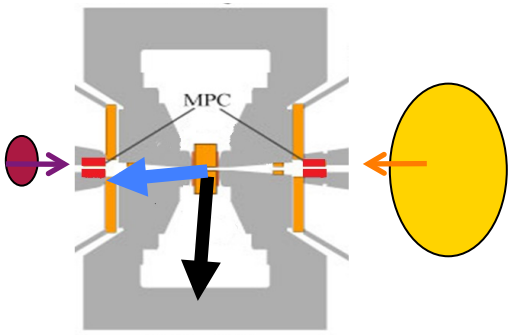
- Inferred quadrupolar anisotropy v_2 of h^{+-} vs. p_T

- v_2 consistent with hydro

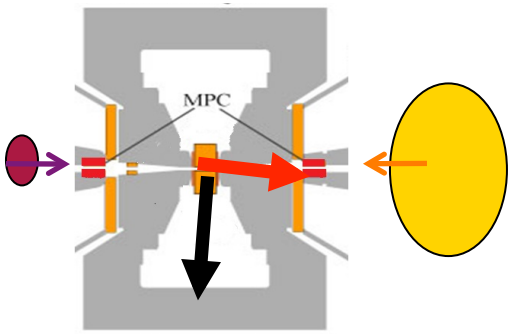
Extending to higher rapidities







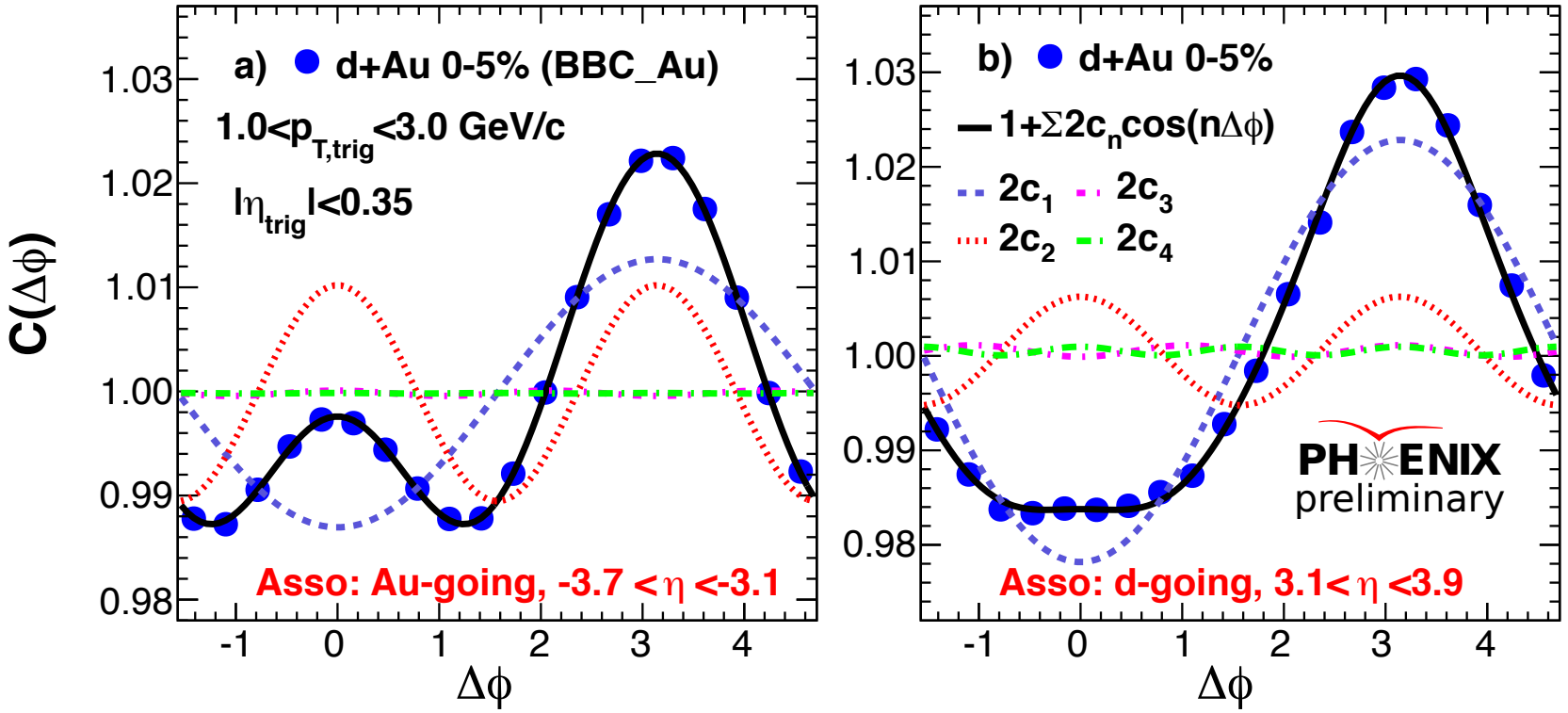
CNT-MPC Au-going
$\Delta\eta = 3.5$
high x in Au

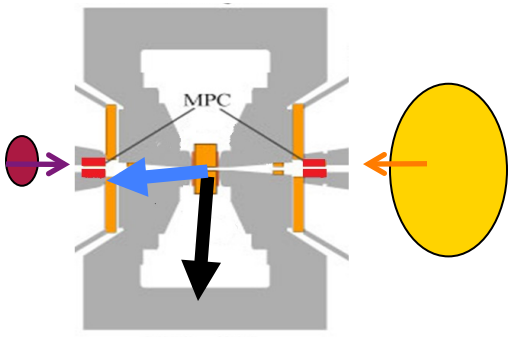


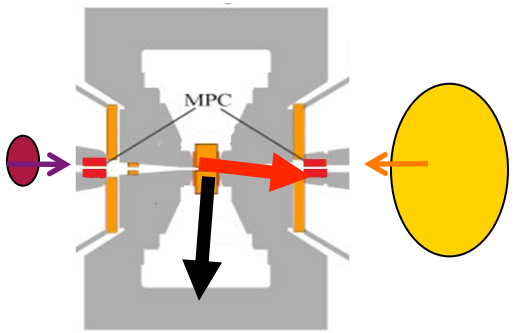
CNT-MPC d-going
$\Delta\eta = 3.5$
low x in Au

NEW!

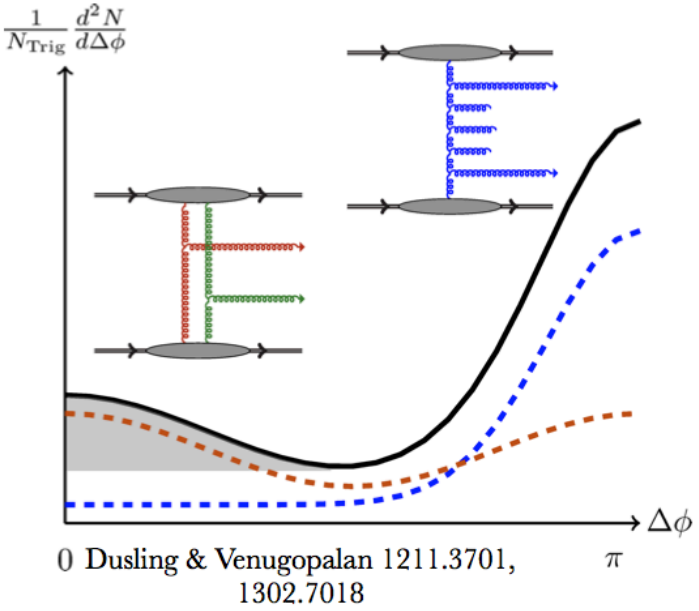
First evidence of long range ridge correlations in d+Au collisions at RHIC!

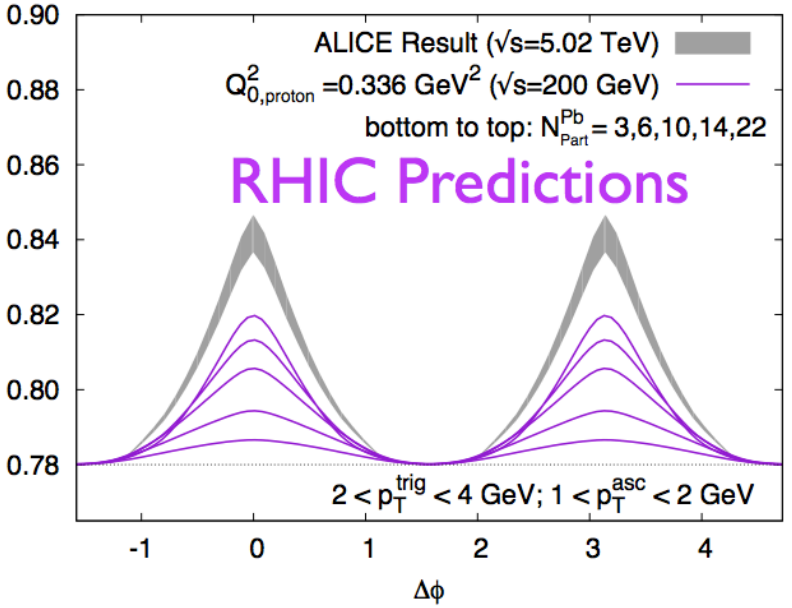






Correlations from Glasma Graphs

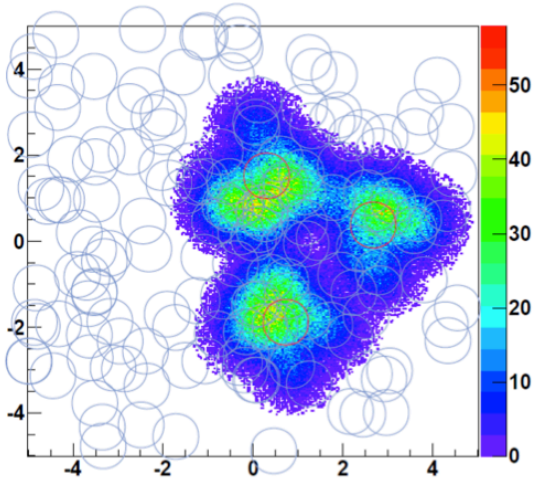




Dusling, Venugopalan, 1211.3701, 1302.7018, private communication

- Significant signal expected at RHIC
- No quantitative comparison at this point since data not corrected for absolute acceptance

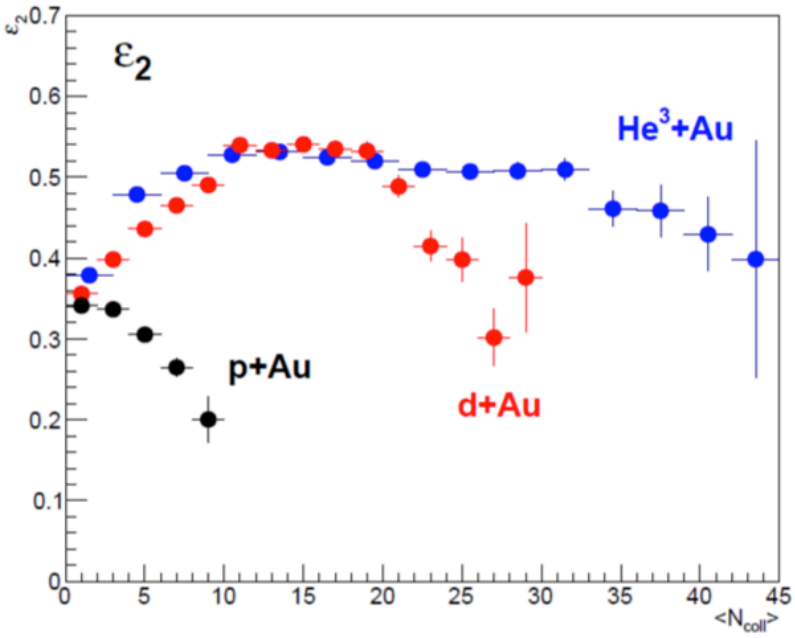
Hydro or Glasma Origin?

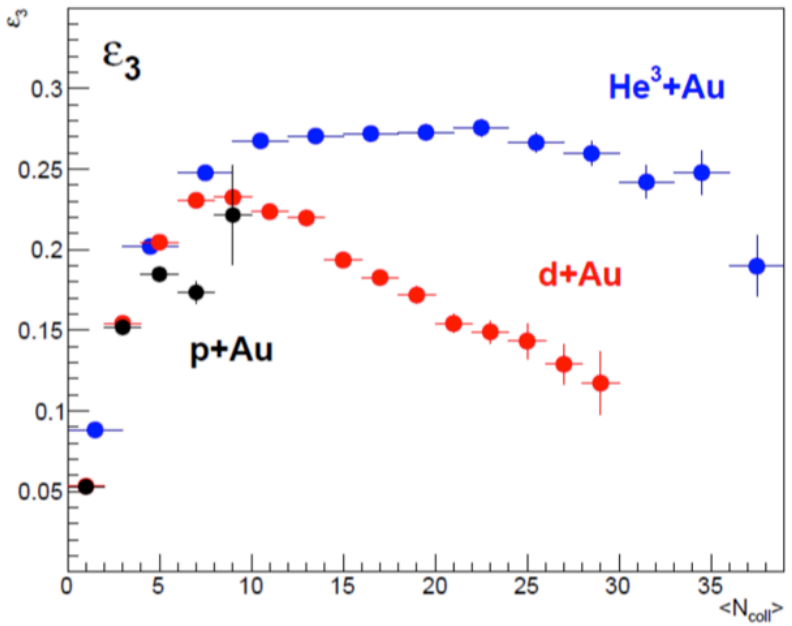


Glauber MC, Gaussian E distribution, σ = 0.4 fm

Eploit versatility of RHIC!

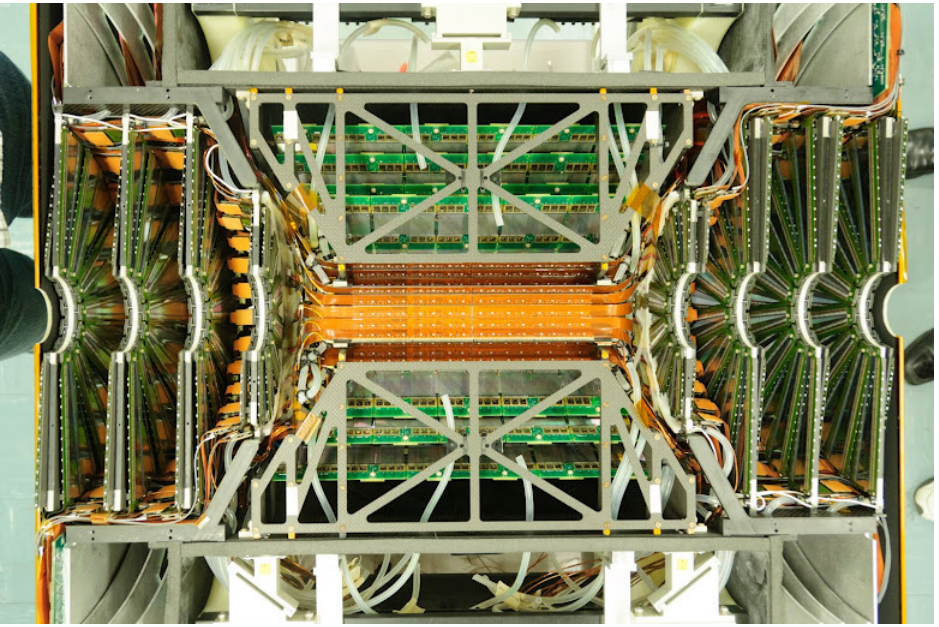
PHENIX requesting ^{3}He+Au, d+Au, p+Au in 2015 with increased acceptance (VTX+FVTX+MPC-EX)

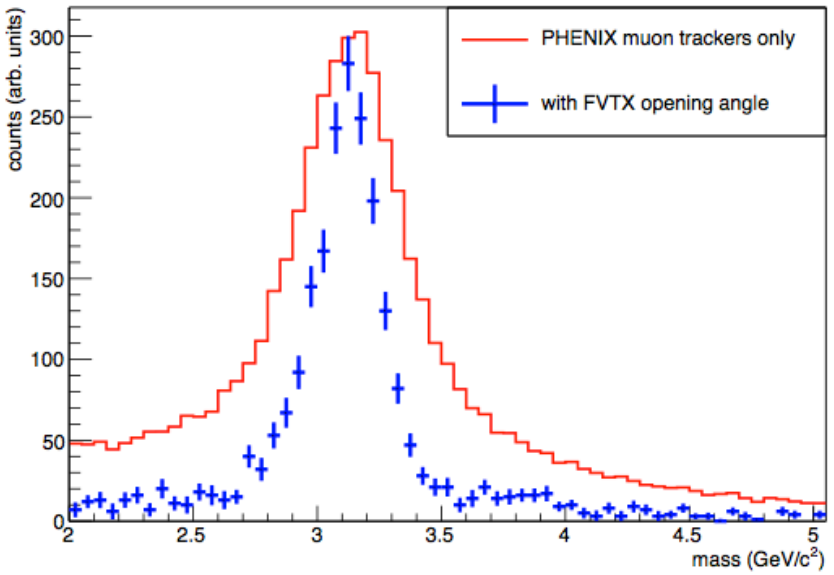




Upgrades

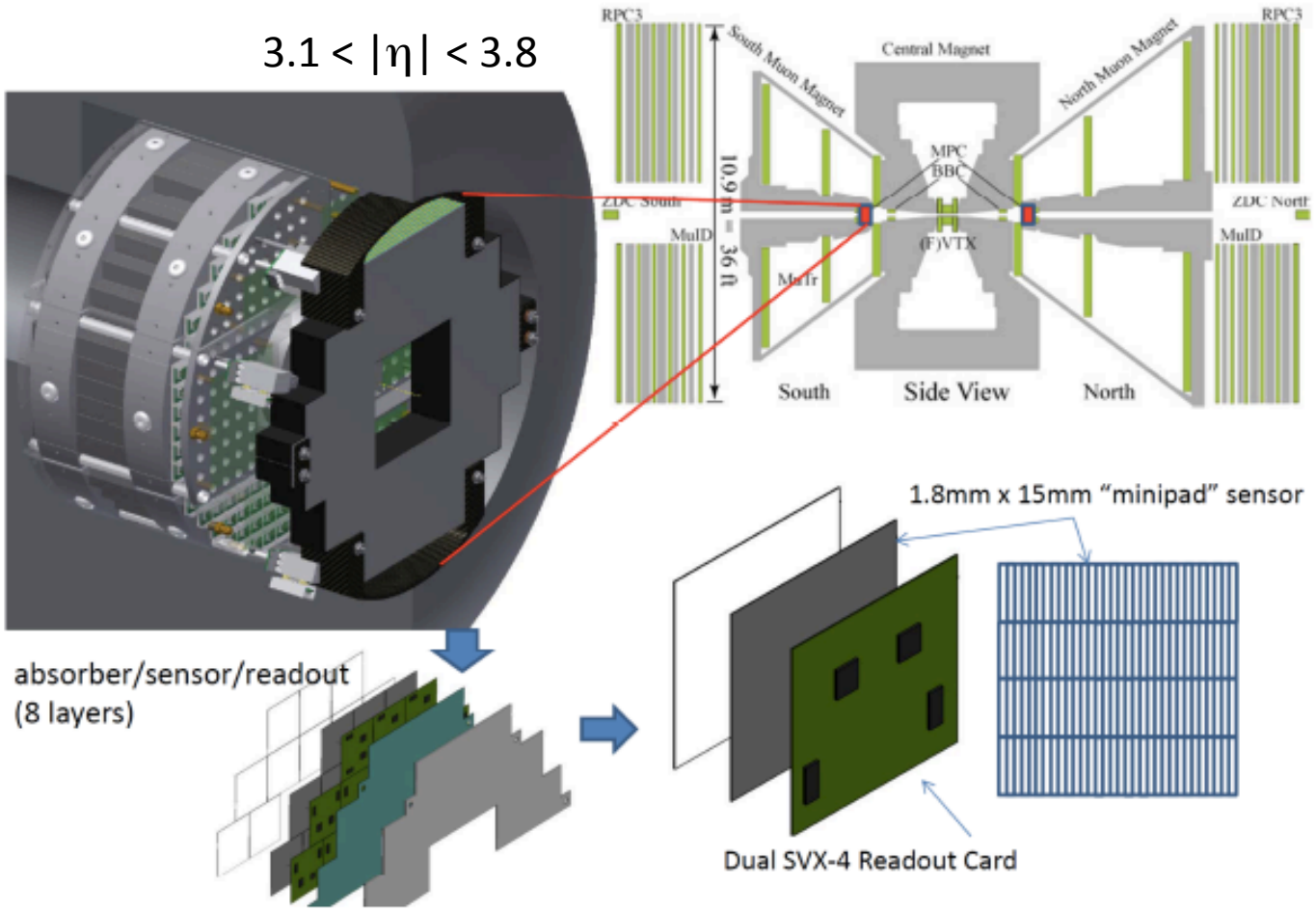
VTX+FVTX





- Improves mass resolution / suppresses background
- ψ' at forward/backward rapidity

MPC-EX Upgrade

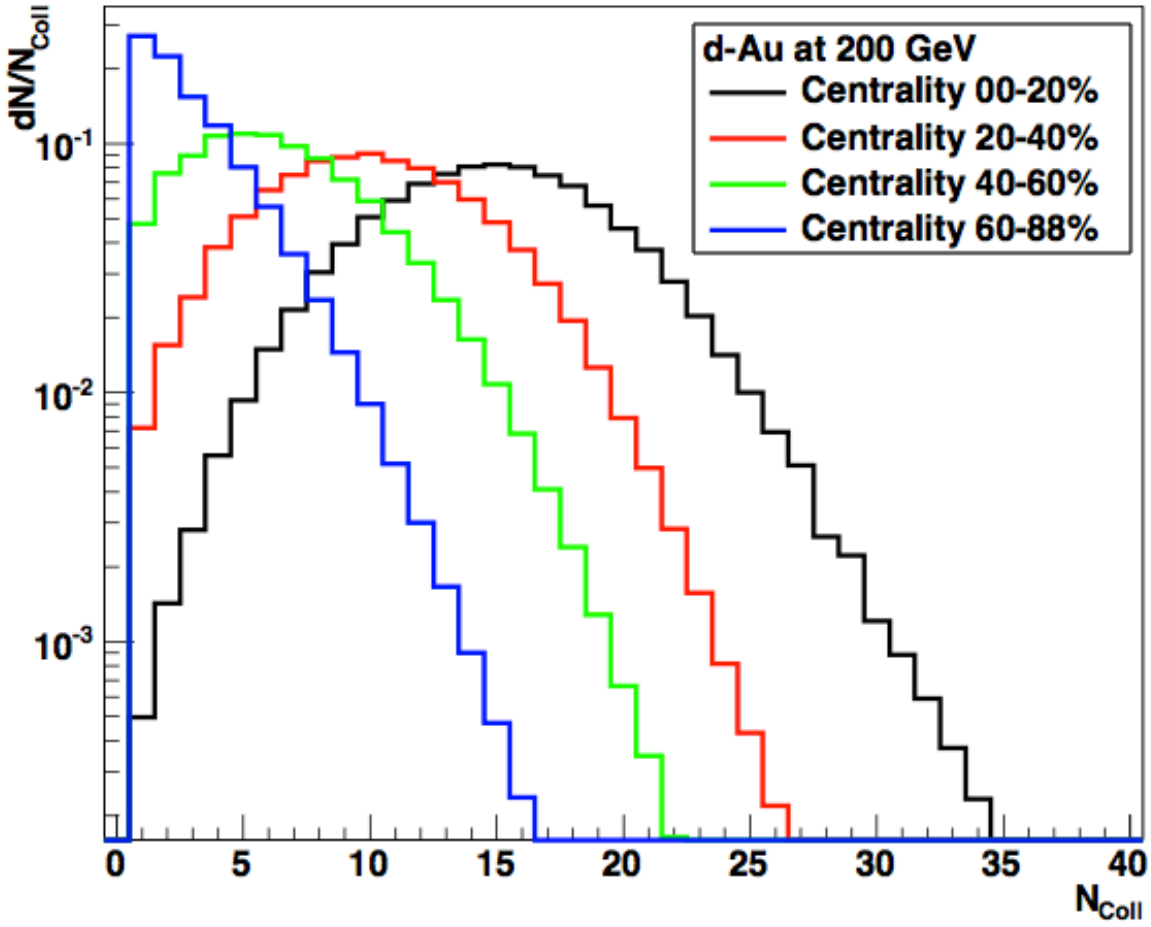


- Direct photons at low and high x in Run 2015

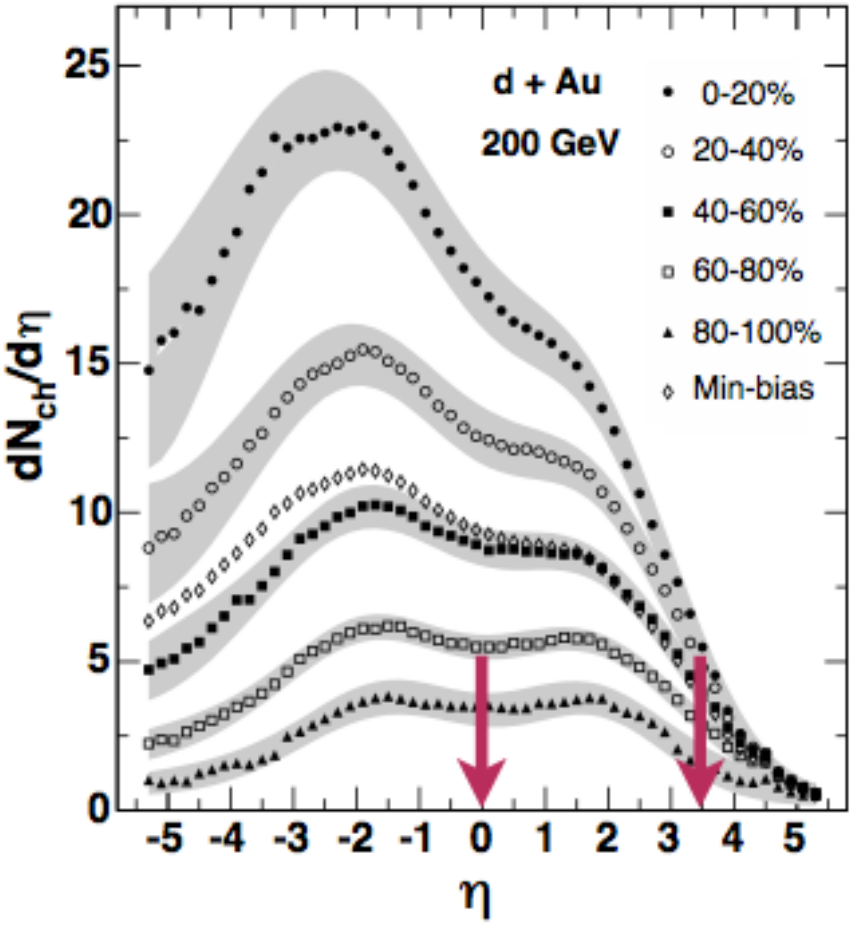
Conclusions and Outlook

- Quarkonia
  - evidence for (expected) shadowing & anti-shadowing
  - p_T dependence challenges models
  - ψ' break-up not simply size effect
  - FVTX upgrade for forward/backward y
- Heavy Flavor
  - parton multiple scattering (Cronin effect)
- PID hadrons
  - Large Cronin effect for protons
  - Species-independence of AA/pA ratio suggests common production mechanism
- π^0/jet trend with centrality remains mysterious
  - p + light ion in Run 2015
- No strong evidence for direct photon modification at mid-y
  - MPC-EX upgrade in Run 2015
- Two-particle correlations
  - Significant non-jet correlations
  - Correlations persist with very large η gap
  - Consistent with flow (question of applicability)
  - Correlations also expected from glasma graphs

d+Au N_{coll} distribution



d+Au $dN_{ch}/d\eta$



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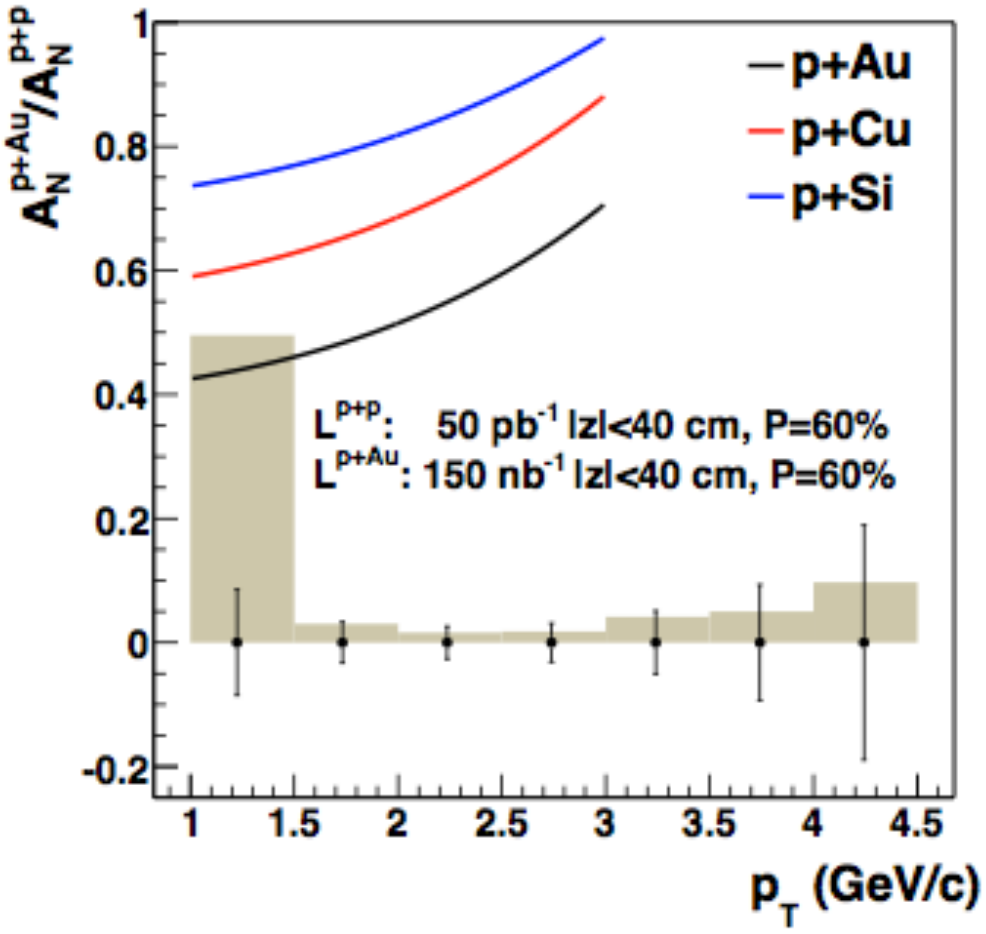
Polarized *p*+A: A_N^{p+Au}/A_N^{p+p}



Kang, Yuan, Phys.Rev., D84:034019, 2011

Outline

- J/y pT broadening:
  - larger at mid-rapidity
- y' suppression:
  - larger than for J/y
  - time in nucleus short
- open HF RdA
  - Enhanced at mid-rapidity and backward
  - Suppressed at forward rapidity
- PID hadrons
  - Large Cronin for p
  - Species-independent ratio of dAu/AuAu_peri
- P0, jets:
  - enhancement in peri
- Direct g
  - No modifiaction
- 2-p correlations at mid-rapidity
  - Double ridge
  - Large v2
- 2-p correlations large h gap
  - Double ridge