p+A, forward Physics
a bridge to the EIC

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UCR

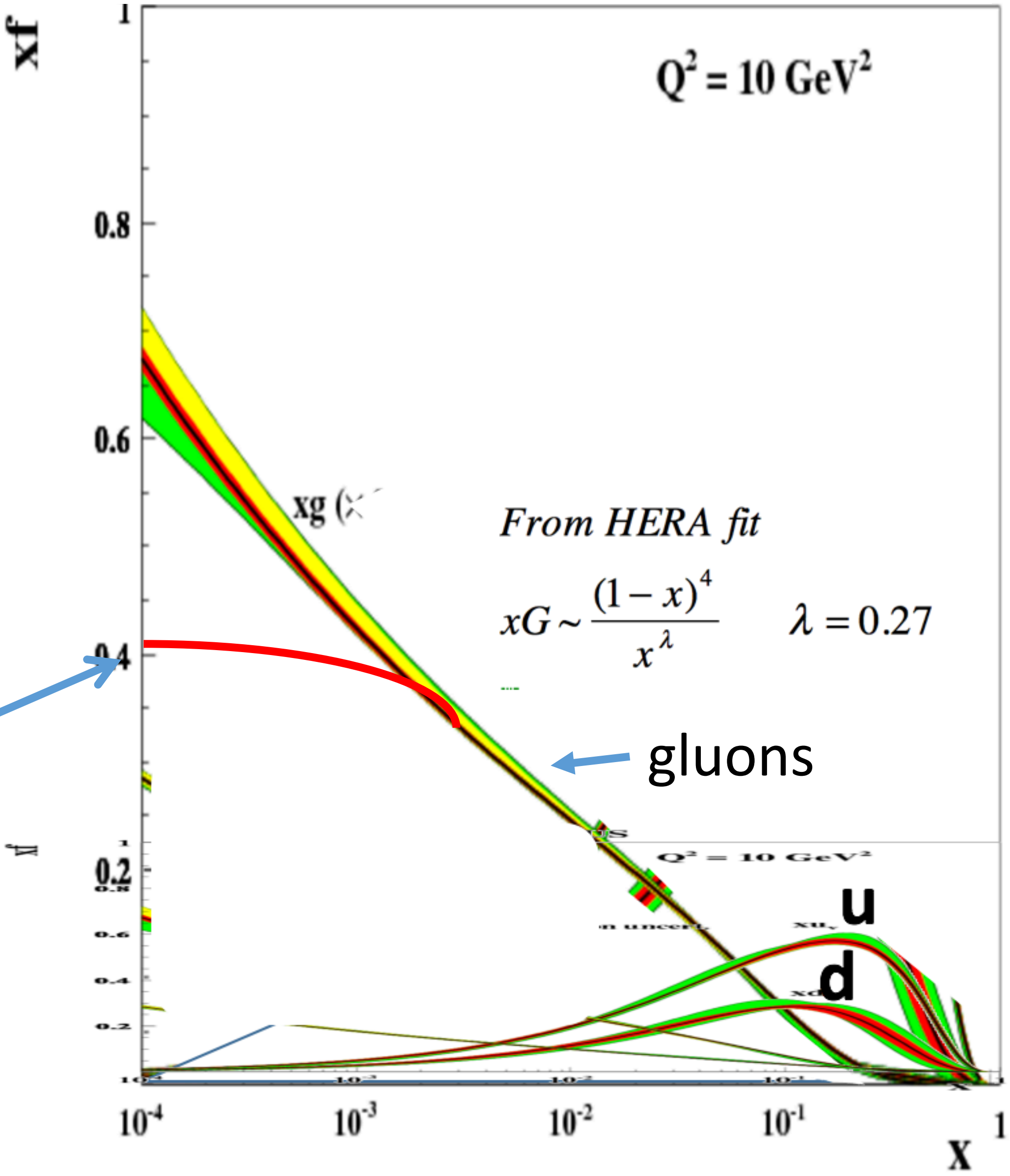
Outline

- What do gluons look like at low x?
  - Gluons and the problems of unitarity
  - The initial state of the QGP?
- Saturation and the Color Glass Condensate
  - Some finger physics: a Tutorial for the simple minded (like me)
  - Multiplicities, Correlations I: away side peak, Correlations II: near side ridge, Flow, A_N in p+A
- sPHENIX→fsPHENIX→EIC
- Physics of fsPHENIX: p+A
  - Saturation
  - Other
    - Onia
    - Heavy Quarks
    - Ultraperipheral and Diffration
  - Schedule and stuff
- Summary

Gluons and the problem of Unitarity

Gluon completely dominate the proton
At low x

Something has
To happen here



What is the initial state of the QGP?

QGP $T_i \sim 300$ MeV Note $\hbar c = .2$ GeV-fm

$\Rightarrow \varepsilon \simeq .45$ GeV $\sim \Delta pc$

$\Delta x \Delta p > h$ $\Delta x = \frac{\hbar c}{\Delta pc} \simeq \frac{.2 \text{ GeV fm}}{.45 \text{ GeV}} = 0.44$ fm

$R_{proton} = 0.87$ fm

proton $\Rightarrow$

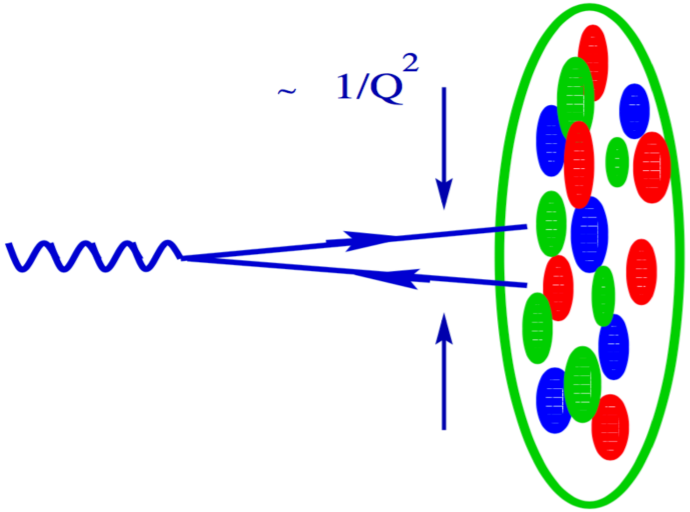
Some picture this as the
Recombination of gluons

Something like saturation
Must be going on in the formation
Of the QGP. Look closer

$\Rightarrow$ Limits Gluon Growth!

Kharzeev, Raufeisen, ArXiv:nucl-th/0206073 (2002)

What happens in A collision?



$\sigma \simeq \alpha_s \frac{1}{Q^2}$ (uncertainty again) [natural units $\hbar = c = 1$)

Nuclear "oompf" Factor ~ $A^{1/3}$

$\rho_A \simeq \frac{x G_A(x, Q^2)}{\pi R_A^2}$ $\quad R_A = 1.2\,\text{fm}\, A^{1/3}$ $\quad$ p + Au.

$\approx 7\,\text{fm}$

↗ density of gluons in transverse plane

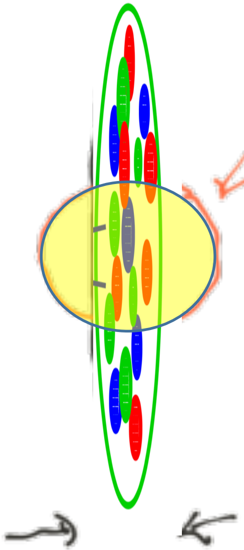
• $\sigma \rho_A \ll 1$ interacts < once

Saturation

- $\sigma \rho_A >> 1$ interact > once ; saturation

Reference frame of projectile.

Nuclear "oompf"
Factor ~ $A^{1/3}$



proton - interacts w/ all Au nucleons in transverse plane $\gamma = E/m = 100\,GeV / 1\,GeV = 100$

$L = \frac{2 \cdot 7\,fm}{100} = 0.14\,fm$

$L = 0.14\,fm$

Saturation Scale

Boundary of Saturation

$$\sigma \rho_A \sim \frac{\alpha_s}{Q_s^2} \frac{x G_A(x, Q_s^2)}{\pi R_A^2} \simeq 1$$

$$Q_s^2 \sim \alpha_s \frac{x G_A(x, Q_s^2)}{\pi R_A^2} \qquad \text{@ RHIC } Q_s \sim 1\text{-}2 \text{ GeV}^2$$

From here you can do some very simple minded calculations which I will not illustrate. For instance:

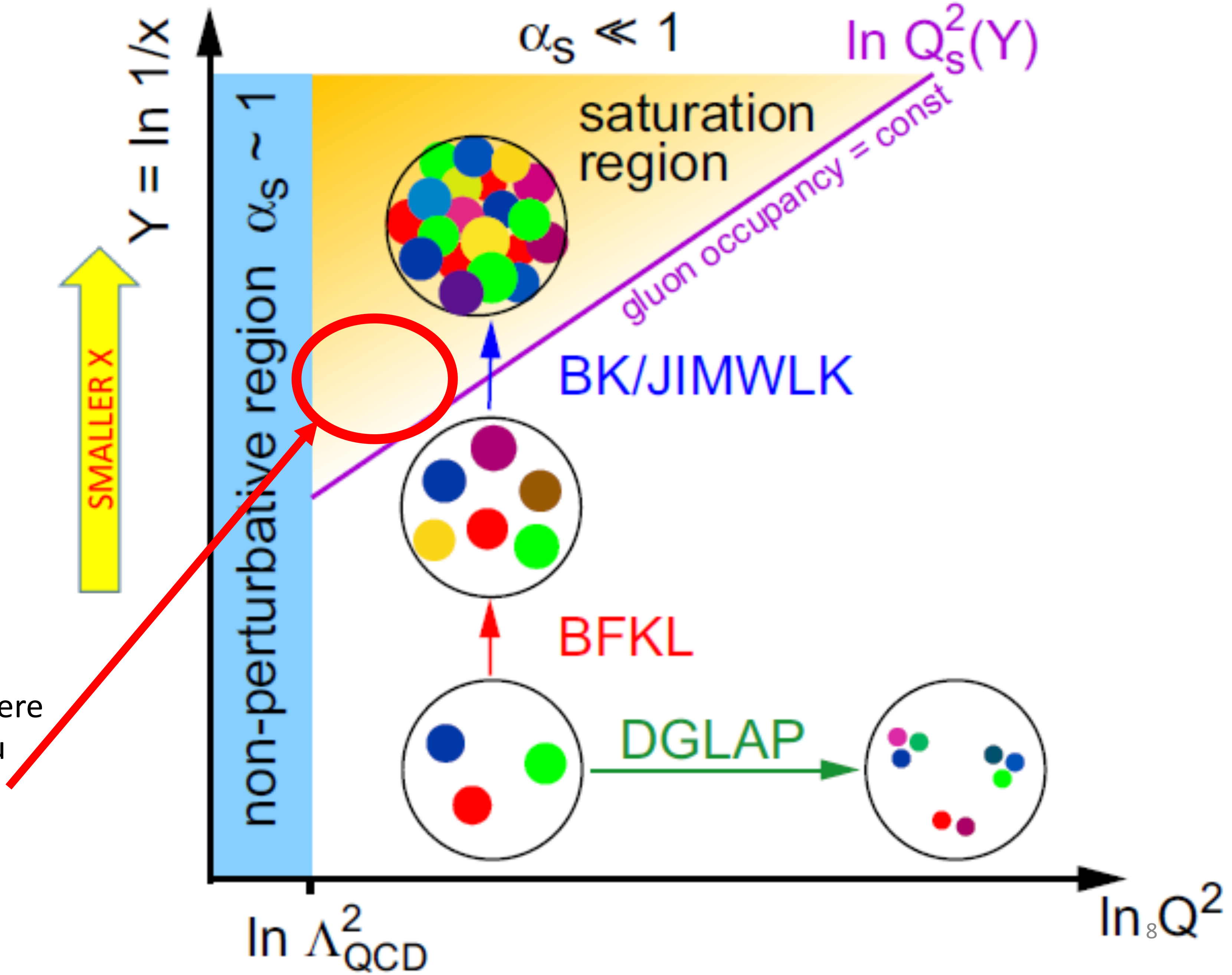
$$\frac{dN}{d\eta} = cN_{part} xG(x,Q_S^2) \quad xG(x,Q_S^2) \sim \ln\left(\frac{Q_S^2}{\Lambda_{QCD}^2}\right)$$

Where N_{part} is the number of participants at some centrality and c is a coefficient between the gluon and particle multiplicy. Note that Q_S^2 depends on N_{part} since it depends of the density of gluons in the transverse plane

The landscape of saturation.

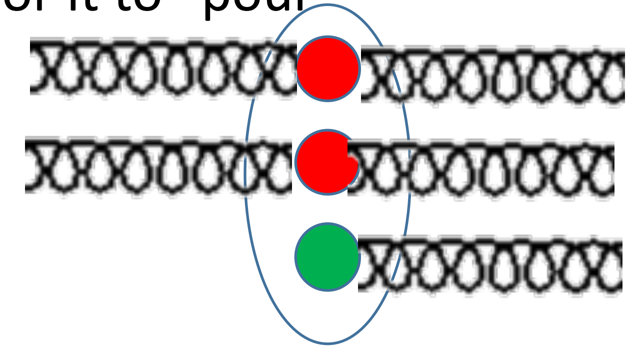
Where are we?

I think we are here
in forward p+Au
Q_S^2=1-2 GeV
X=10^{-3} – 10^{-2}



Why is it called a Color Glass Condensate?

- Color – it is QCD
- Condensate - not a BE condensate, but a saturated state – gluons are "condensed"
- Glass?
  - A glass is a material with long time scale
    - Think of Window glass, which is a liquid – but it takes years for it to "pour"
  - induced by "frustration"
    - E.g. Spin glass
  - In Color Condensate we have "relativistic frustration"
  - Model: Break Nucleus into Gluon Field, and Source
    - "Source" – quarks and gluons at high-x, ***Lorenz time dialated clock runs slow***
    - Gluon field at low-x. Clock runs fast, but motion is governed by "source", and a long time scale governs the motion of the gluons. They are "frustrated"



What is the status?
Are we in the saturation regime? The “Tests”

- dAu at forward rapidity
  - Singles spectrum
  - R_{dAu} – suppression in Cold Nuclear Matter?
  - Back to back particle distributions
    - vs x_{frag}
  - Multiplicities
    - vs centrality (Au+Au)
    - vs rapidity
  - SSA in pA
- dAu/AA- include evolution of the ”QGP”
  - Flow
    - Au+Au, v1-v5
    - p+Au, d+Au, He3+Au, v2 and v3

Saturation

- Saturation, or something like it has to true
- The question is not whether saturation is right, but whether we are in the saturation regime at RHIC
  - A second question: what model is correct? Is the CGC the right model?
  - Do other explanations work? e.g. twist-3. Are they just the same thing in a different language or realm of applicability?
- Saturation (e.g. the CGC) comes is a variety of guises: Recombination, the MV model, ..
  - Leads to various modeling tools, e.g. KLN, MC-KLN,rcBK, MC-rcBK, IP-Glasma
    - Which for example, treat the nucleus as a solid sphere, as a WoodsSaxon, sample it to add fluctuations
    - Need to take errors (or just the results from the spread in models/model parameters) seriously
- Must look at all the evidence, and collect data on a variety of observables
  - The right model must explain many signatures; free parameters should be consistent

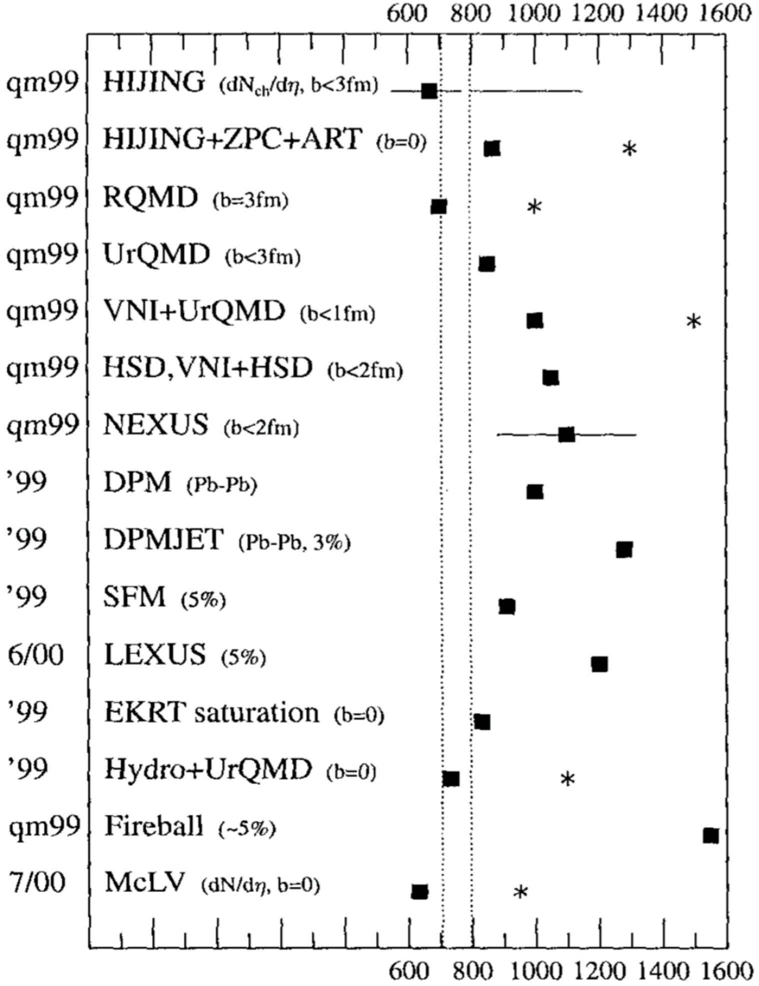
“Preponderance of evidence”

Note: the heavy ion community needs to know the answer to this questions

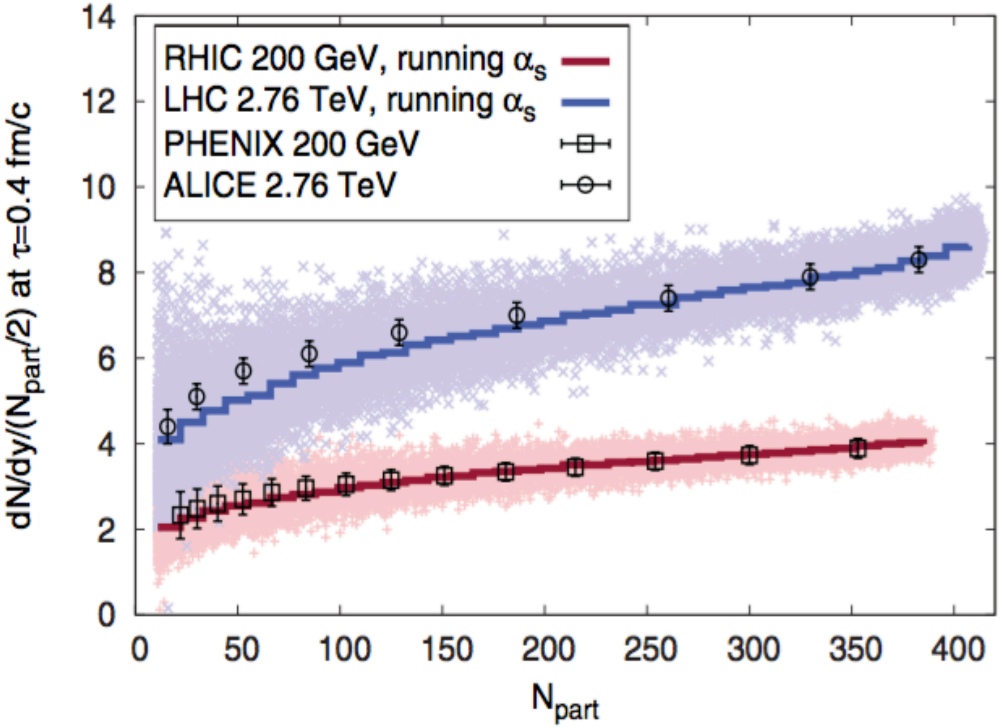
Test: Multiplicities

Physics I: QCD at extreme parton densities

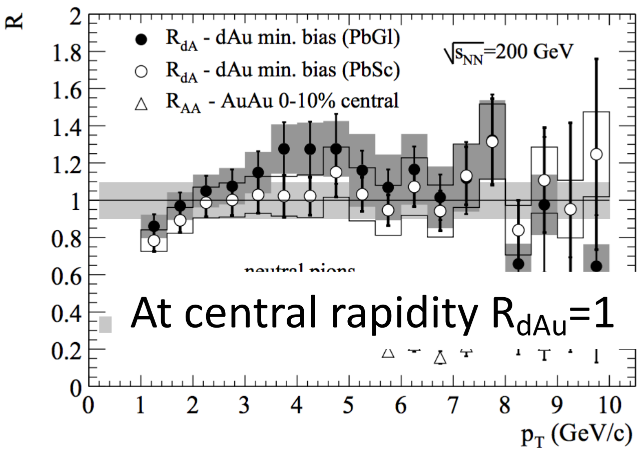
- What do we know?
- A fair amount (personal view)

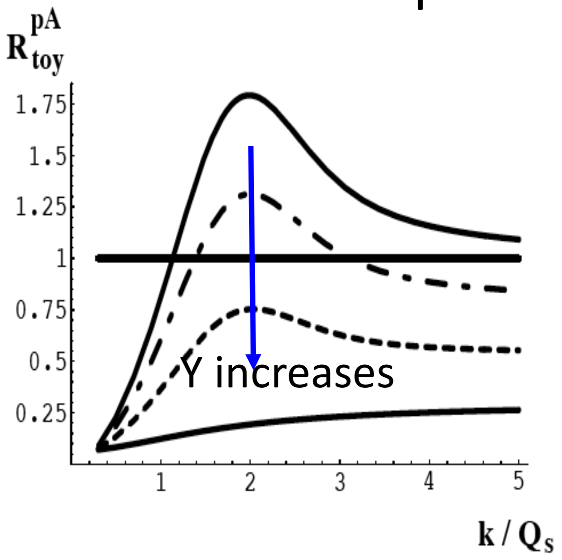


Day 1 Multiplicity distributions



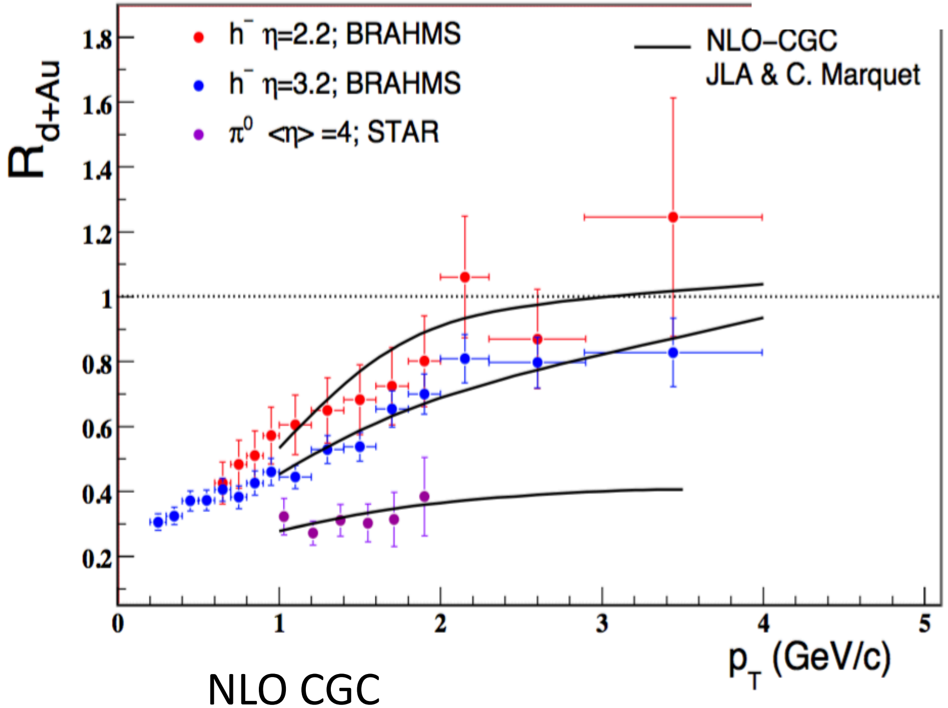
Test:CNM and Nuclear modification factors at forward rapidity (low x)





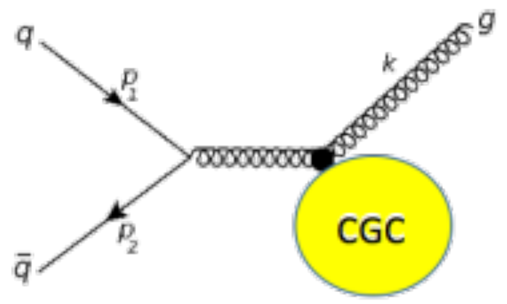
Expectation
At higher y
(smaller x)

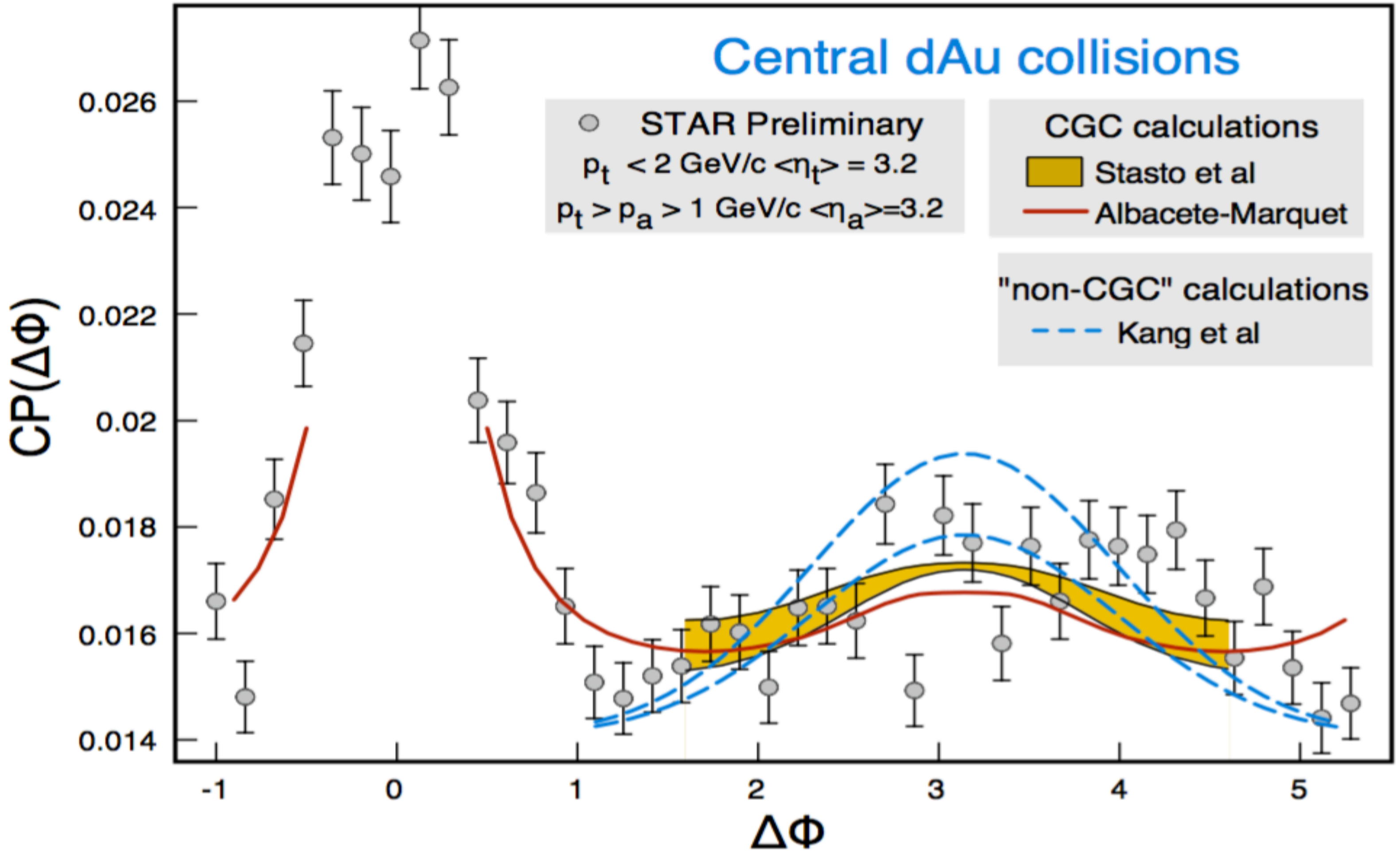
$$R_{dAu} = \frac{1}{N_{Coll}} \frac{dN^{dAu} / dp_T d\eta}{dN^{pp} / dp_T d\eta}$$



NLO CGC

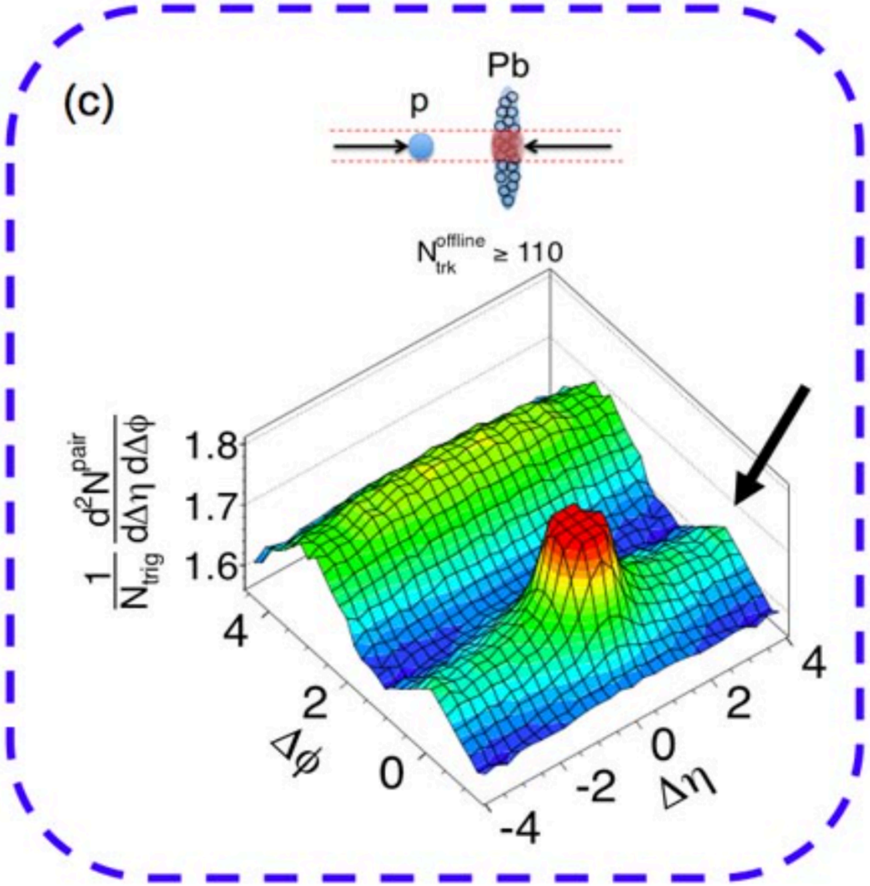
Test:Back to Back hadrons

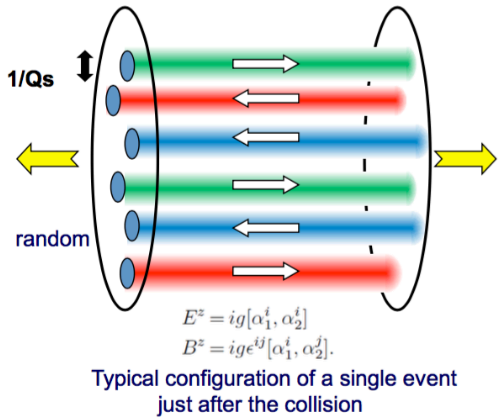




broadening of the opposite side “jet” peak

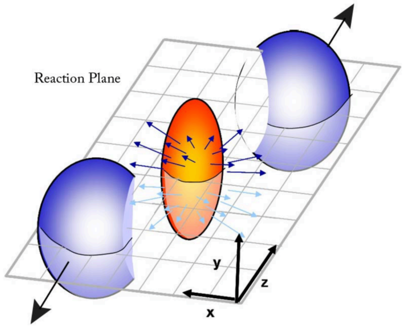
Saturation?:LHC: Near side ridge in p+A
An Explanation: Correlations from glasma flux tubes

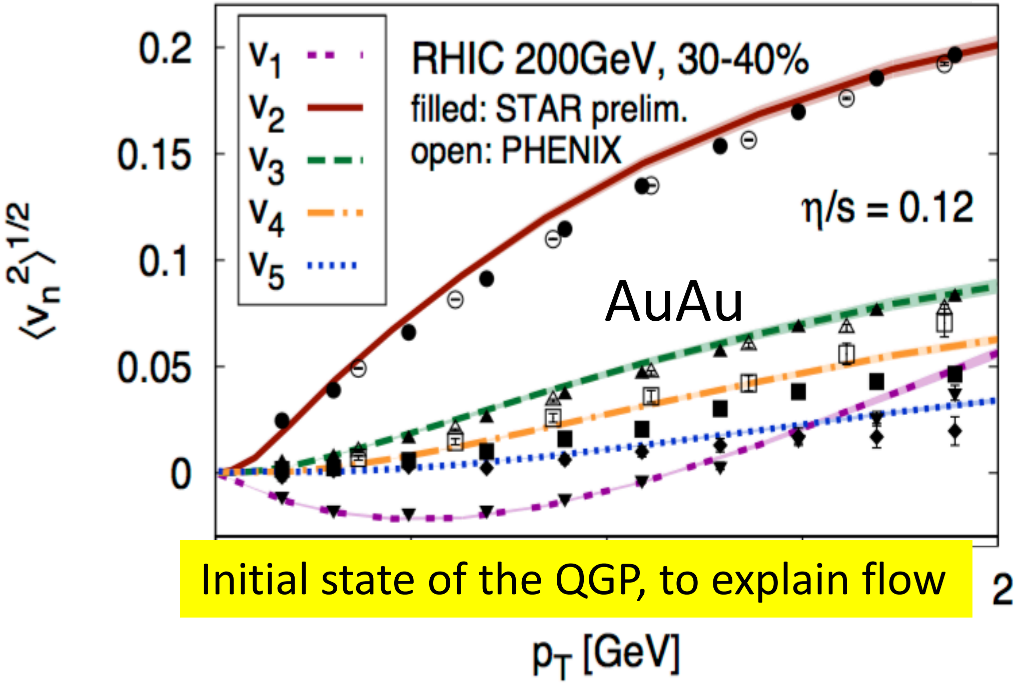




Due to CGC? (initial state)
Due to a QGP? (final state)
A combination?
Something else?

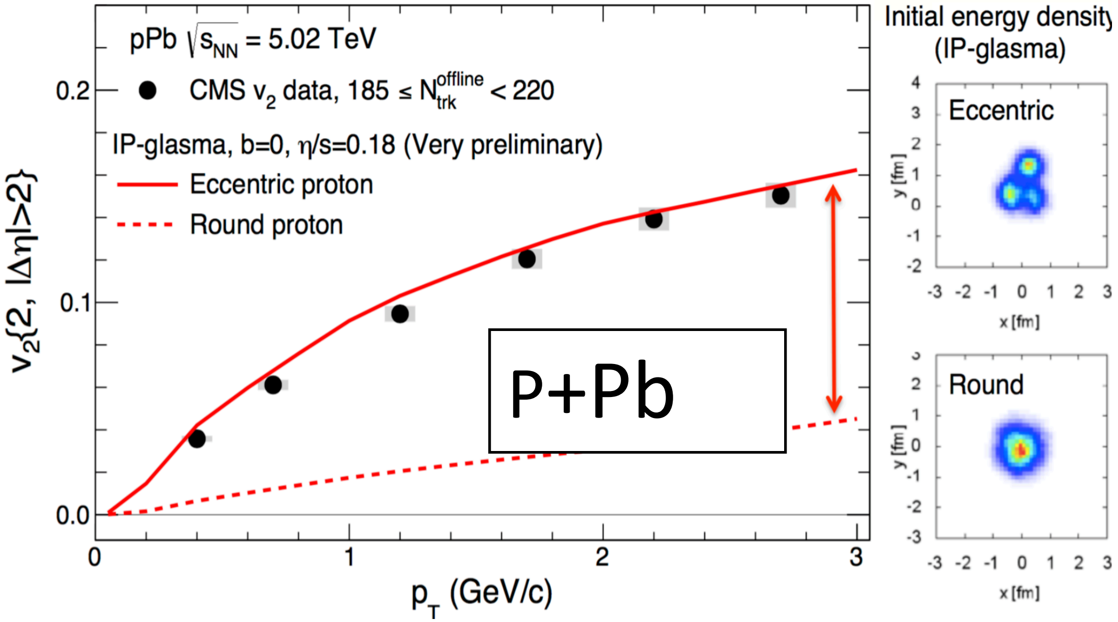
Saturation?:Flow: (as a follow on the the near side ridge





Initial state of the QGP, to explain flow

IP-Glasma

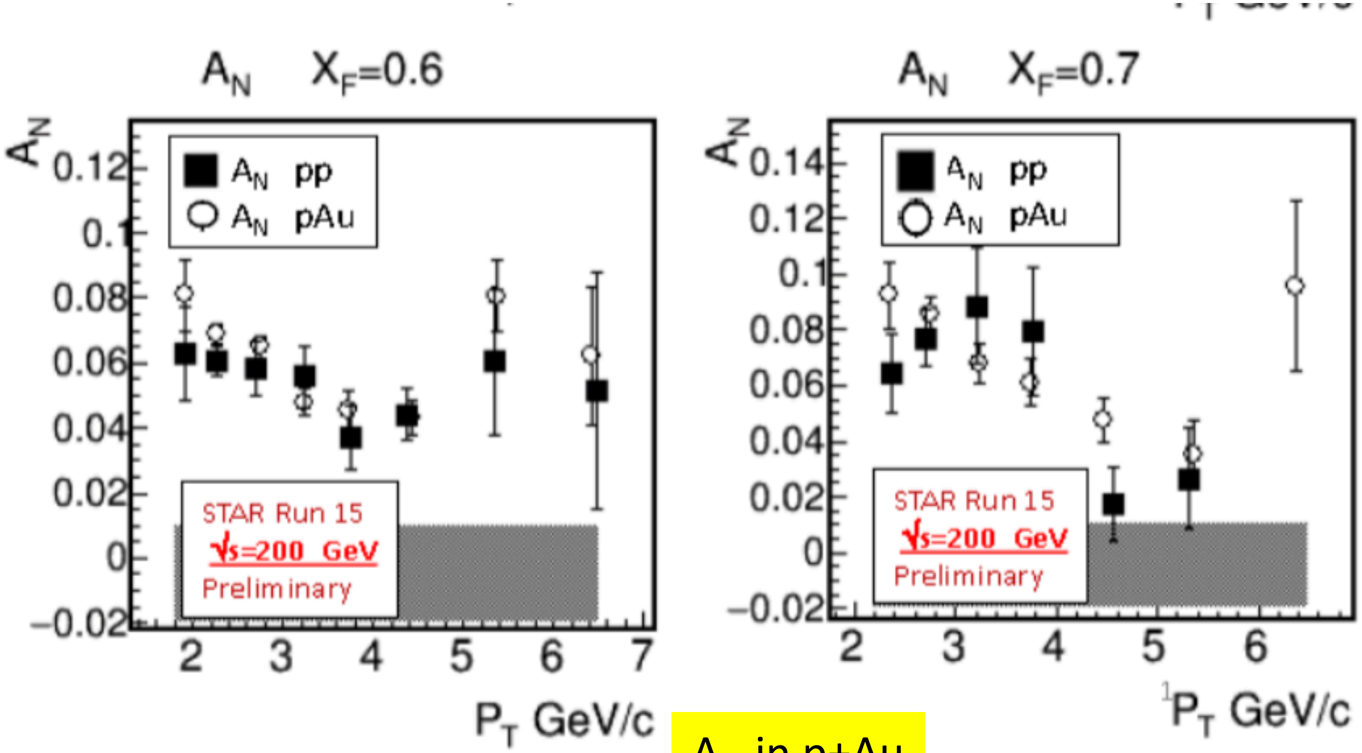


Initial state, for the explanation of p+Pb v_2:BUT needs proton structure

Test: Suppression of SSA in p+Au (from Collins)

$$\frac{A_N^{pA}}{A_N^{pp}} \sim \frac{Q_{sp}^2}{Q_{sA}^2} \sim \frac{1}{A^{1/3}} < 1\,. \quad (P_{hT} \lesssim Q_s)$$

Kang, Yuan (2011)



A_N in p+Au

Suppression of forward A_N looks small

BUT: More recently: from Sivers $\quad \frac{A_N^{pA}}{A_N^{pp}} \sim 1$

Hatta et al arXiv:1606.08640(June 2016)

Model dependence of pA. Need "preponderance (and stability) of signatures" Pretty good, but not definitive

signature	Saturation
Singles	Y
RdAu	Y
Back to back	Y
Back to back vs "x"	Y
SSA in pA	N??
Multiplicity vs centrality AA	Y
Multiplicity rapidity dAu	Y
Flow in AuAu	Y
Flow in dAu, v2 and v3	N, so far

Feb 2016

signature	Saturation
Singles	Y
RdAu	Y
Back to back	Y
Back to back vs "x"	Y
SSA in pA	Not inconsistent
Multiplicity vs centrality AA	Y
Multiplicity rapidity dAu	Y
Flow in AuAu	Y
Near side ridge	maybe
Flow in dAu, v2 and v3	Y, add proton structure

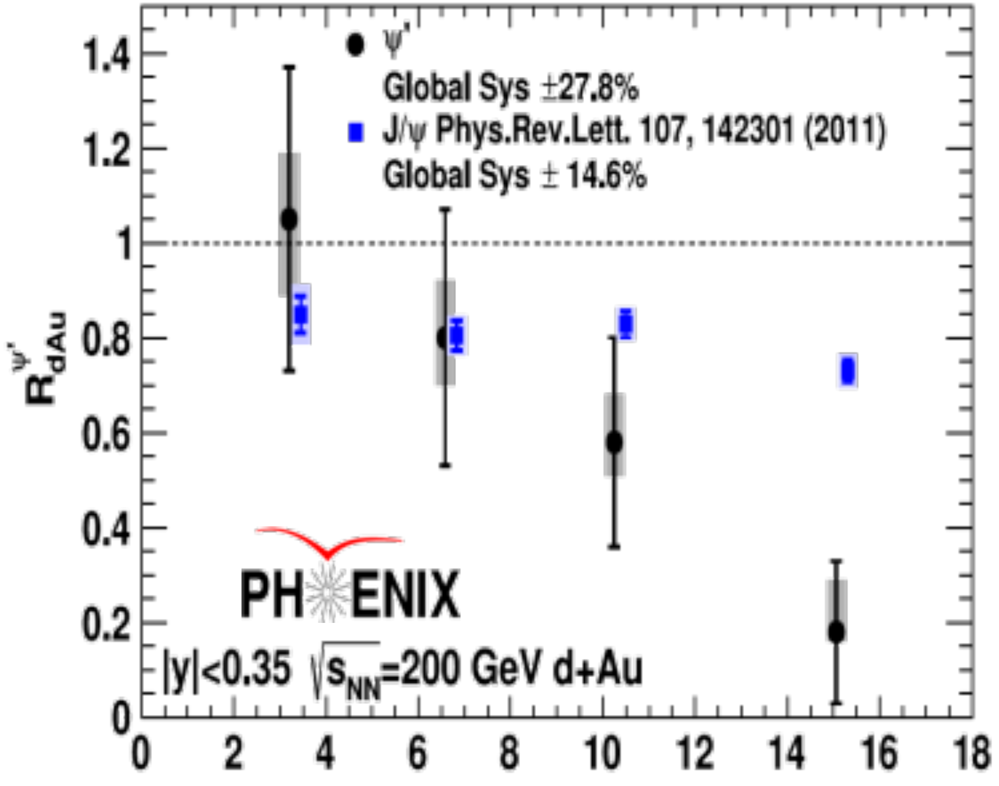
July 2016

Cold Nuclear Matter Effects, Onia

- Slides from Xuan Li
- FVTX results

Explore the CNM effect via J/ψ and ψ’

- Mid-rapidity ψ’ R_{dA} different magnitude of suppression versus N_{coll} then J/ψ. Note: Radius of ψ’ larger (easier to break up, melt etc)



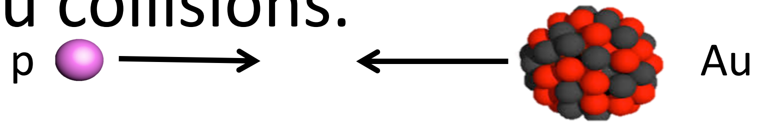
PRL 111, 202301 (2013)

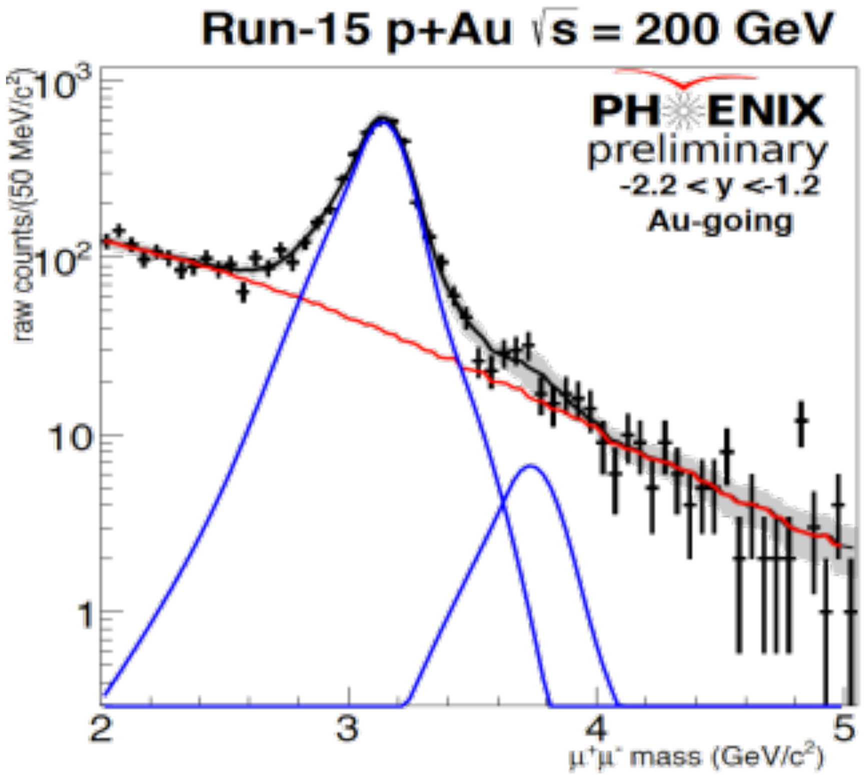
Number of binary nucleon-nucleon inelastic collision

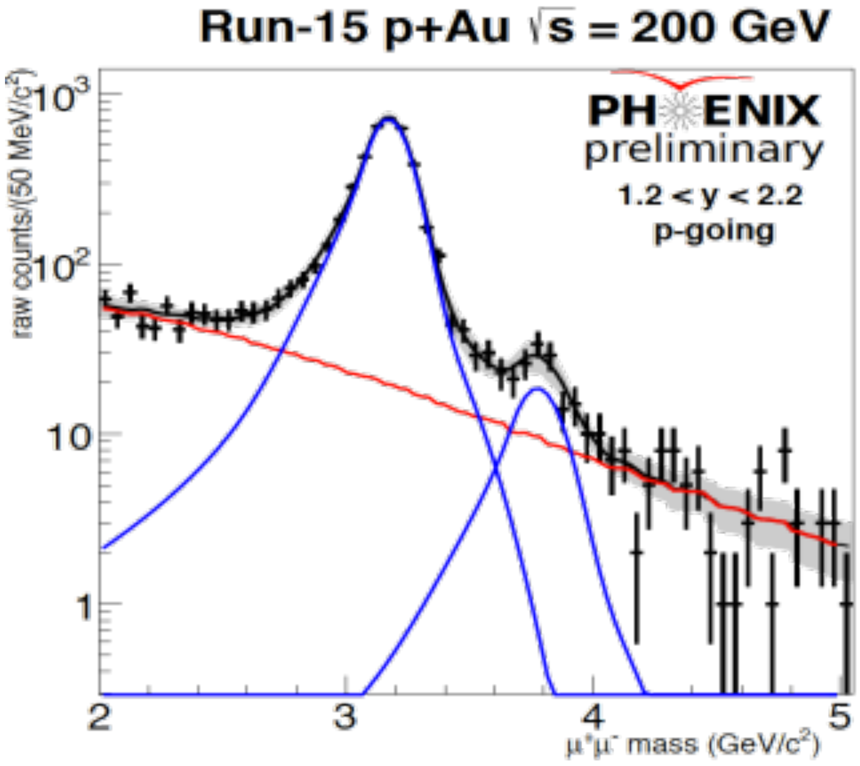
- Similar initial state effect
- final state effects cause the difference.
- Look forward/backward using FVTX

How about asymmetric nuclear collisions?

- In 200 GeV p+Au collisions.



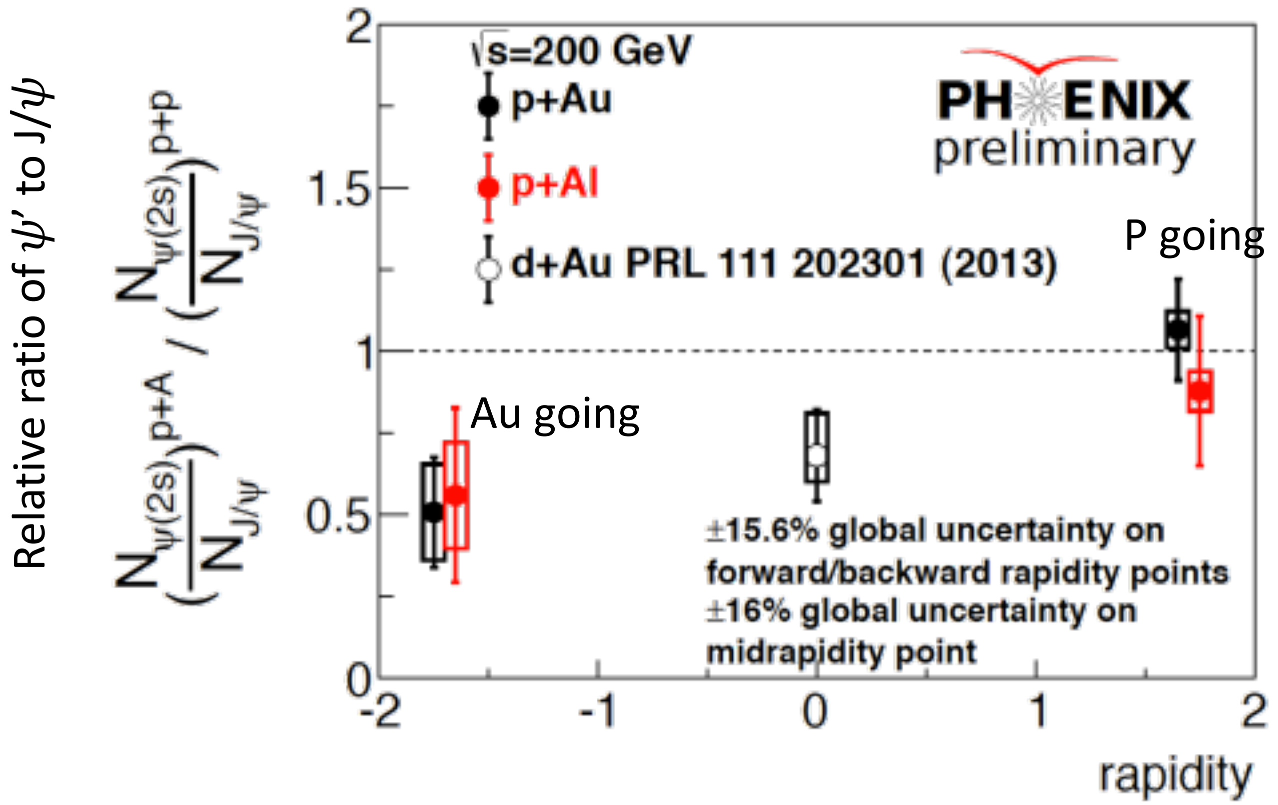




- Even with raw data, clearly the ψ’ yield is suppressed relative to J/ψ in the Au going direction as well.

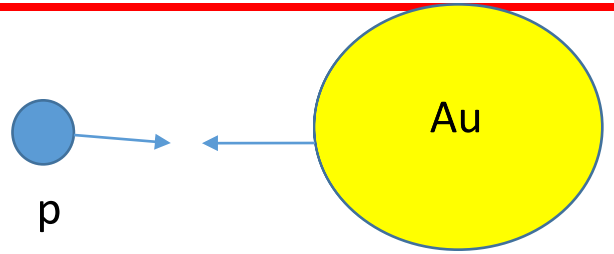
Relative ratio of ψ’ to J/ψ VS rapidity

- Centrality integrated relative ratio of ψ’ to J/ψ VS rapidity for p+Au, p+Al and d+Au (mid-rapidity).



Suppression at y>0 (p going)
is primarily Initial state

For y<0, (A going) it is probably final state
Note: comover model works



- The J/ψ and ψ’ have similar suppression at forward rapidity.
- Strong relative suppression is observed at back rapidity.

fsPHENIX Upsilon?

p+Nucleus collisions: A natural bridge to the EIC

- p+A (polarized p+p) will be available in the pre-EIC era
  - Very important to keep community (e.g spin, cold QCD) alive
  - Detectors can evolve into EIC stage I
    - Example: sPHENIX →fsPHENIX → ePHENIX (the names should be changed to protect the innocent)
  - p+A will add complementary data, and provide a base of support for many of the EIC scientific priorities

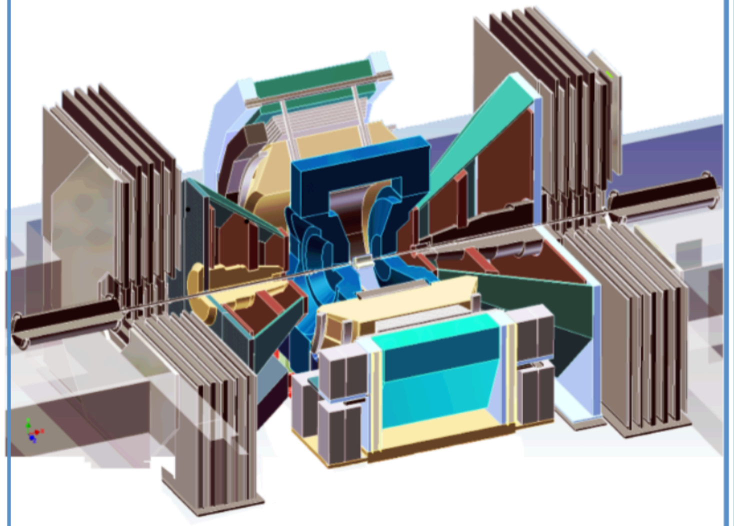
I am basing my thoughts on the current implementation of fsPhenix.
It is not clear that we want to limit ourselves to that

What makes it Hard: Detector design

- High particle densities, occupancies
  - Need high granularity
- High momenta
  - $\pi \rightarrow \gamma\gamma$ for direct photons
  - Consistent with sPHENIX, and a future EIC detector (e.g. PID Implemented later for EIC)
- Magnetic Fields for good momentum measurement difficult
  - Using Fringe field
    - Shape it
  - (Using separate magnet, which impedes continuous rapidity coverage)
- No money since everyone has used it already

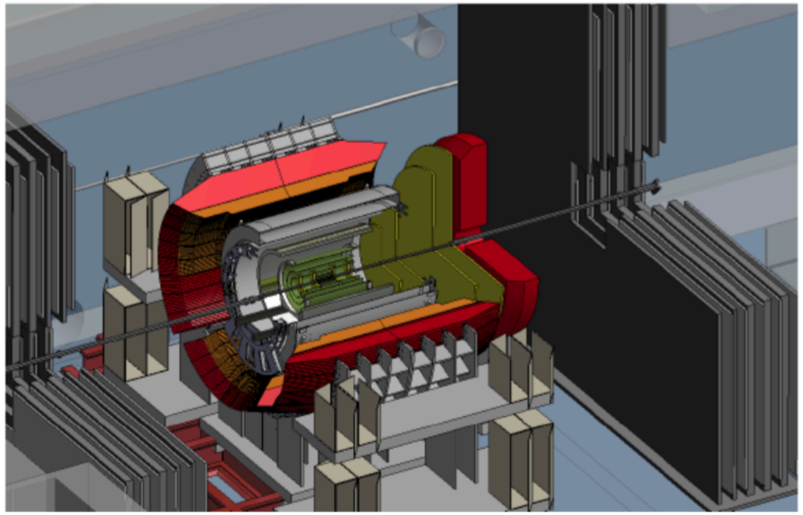
Current PHENIX

- PHENIX completed 2016
- 16y+ work
  100+M$ investment
- 130+ published papers to date



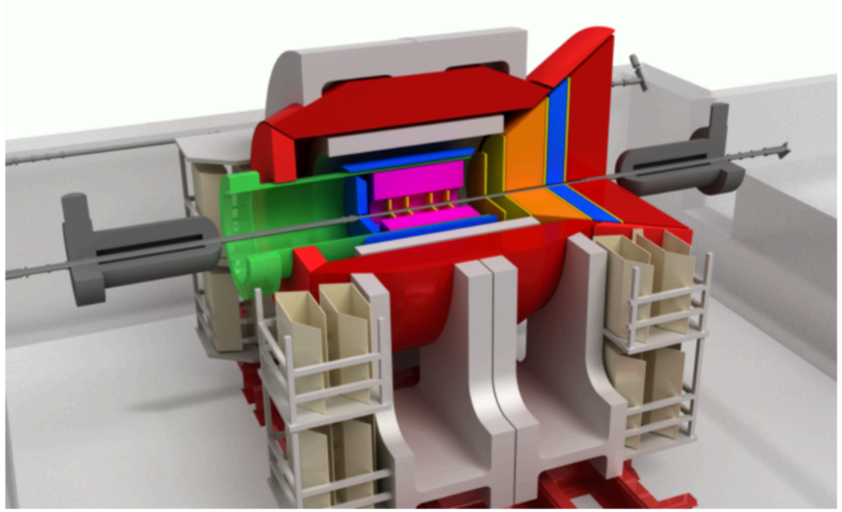
*f/s*PHENIX

- Comprehensive central upgrade based on BaBar magnet
- fsPHENIX: forward tracking, HCal and EMCAL
- Key study of transverse spin and CNM
- Vertexing for Heavy Quarks



An EIC detector

- Path of PHENIX upgrade leads to a capable EIC detector
- Large coverage of tracking, calorimetry and PID
- New collaboration/new ideas



~2000 — 2017→2022 — ~2025 — Time

RHIC: A+A, polarized p+p, polarized p+A

eRHIC: e+p, e+A

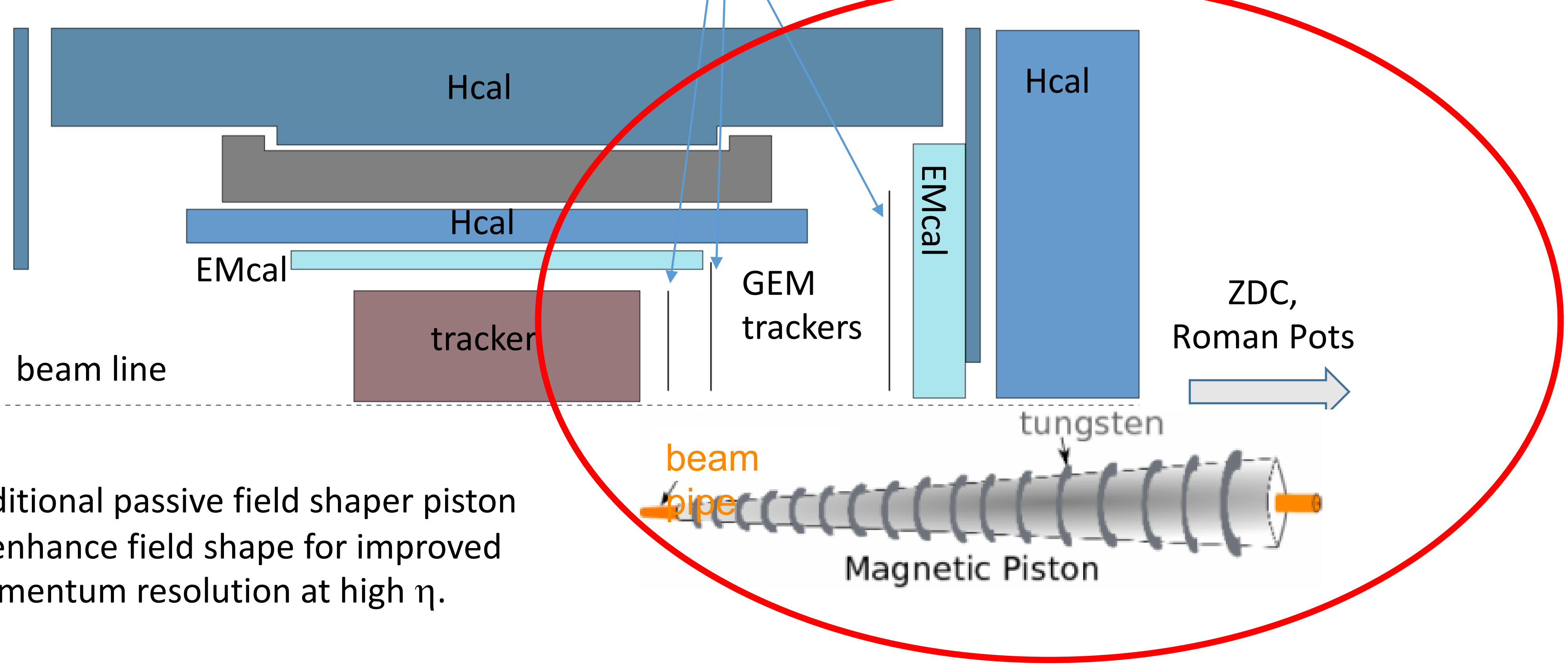
From Ken's
Talk at EIC
User's meeting

Forward instrumentation in sPHENIX (fsPHENIX)

Fits in 4.5m eRHIC IR constraint

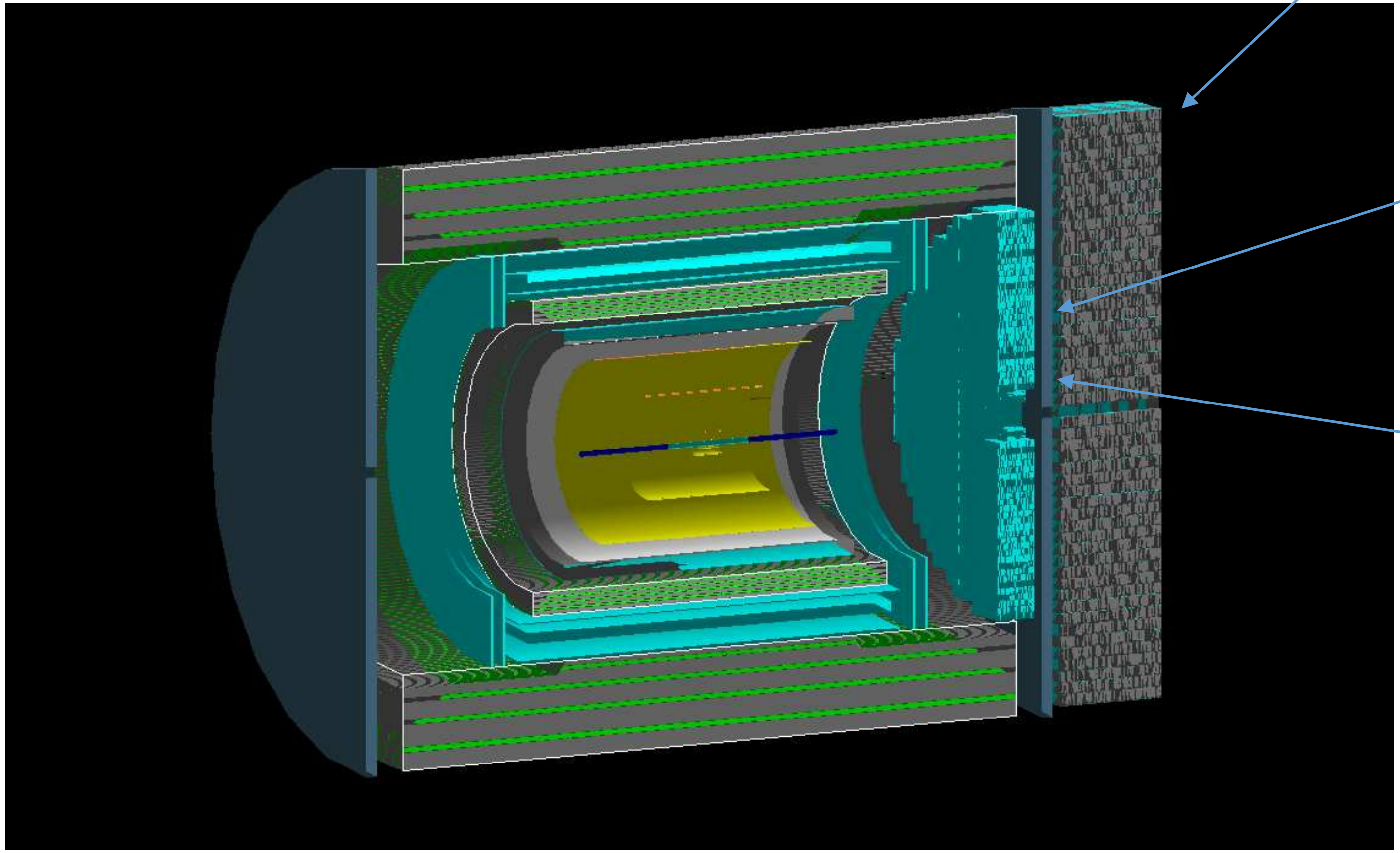
- Large area GEM tracking stations at z=120, 150, 275cm($1.45 < \eta < 4.0$)

$\Delta p/p$ ~0.3%p



Additional passive field shaper piston to enhance field shape for improved momentum resolution at high η.

Forward Calorimeters



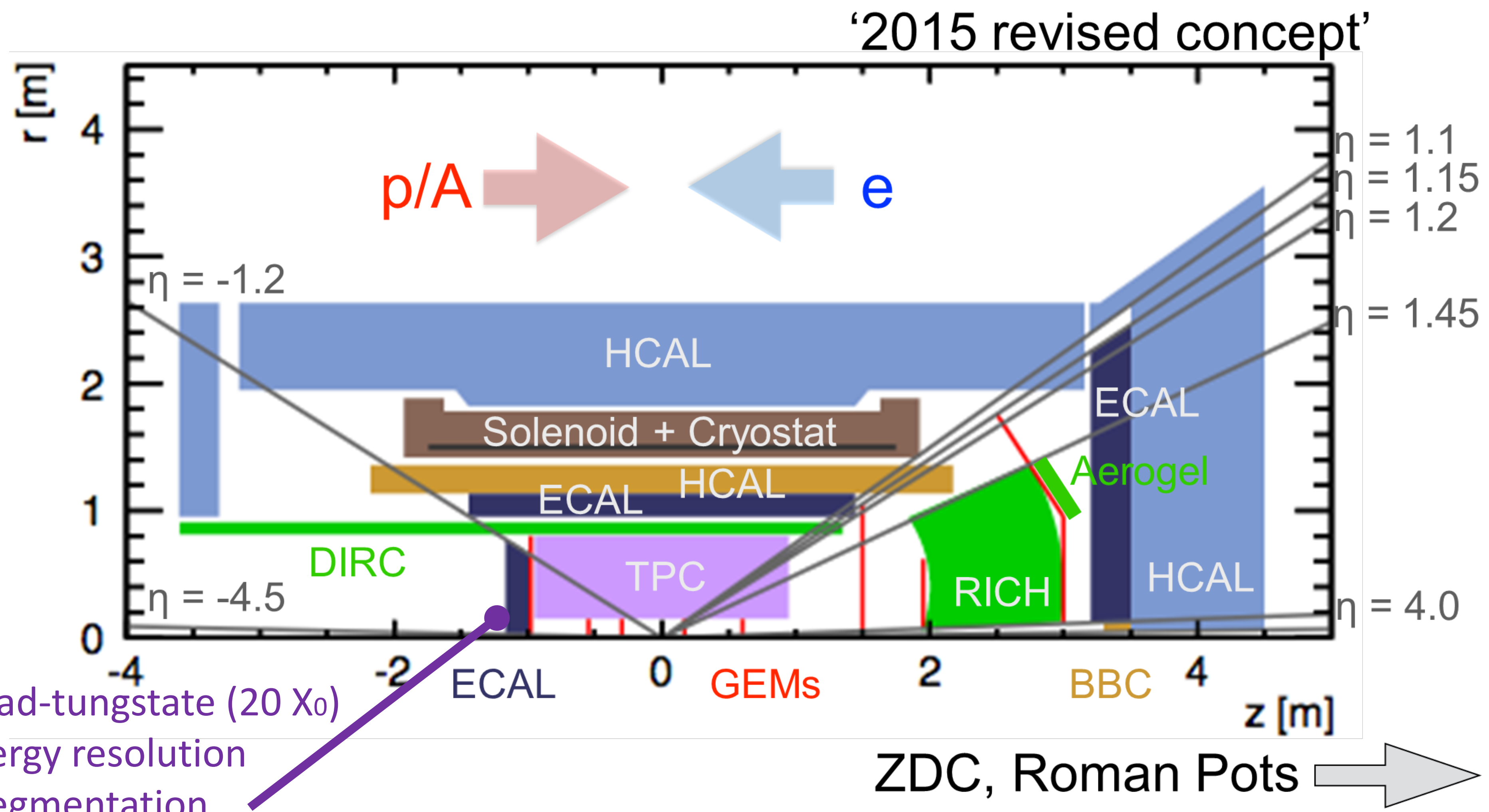
Pb/Sc sandwich HCAL (NEW)
($1.2 < \eta < 4.0$)
$\Delta E/E \sim 100\%/\sqrt{E}$

PHENIX PbSc EMCAL modules
($1.4 < \eta < 3.0\text{-}3.3$)
$\Delta E/E \sim 10\%/\sqrt{E}$

PbW (PHENIX MPC)
EMCal Crystals
$3.0\text{-}3.3 < \eta < 4.0$

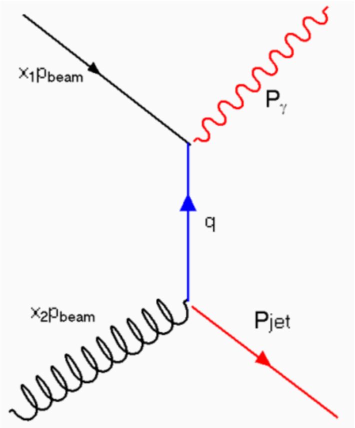
Reuse PHENIX Muon identification system ($1.2 < \eta < 2.4$)
+addition muID(to $\eta = 4$)

Day-1 EIC Detector



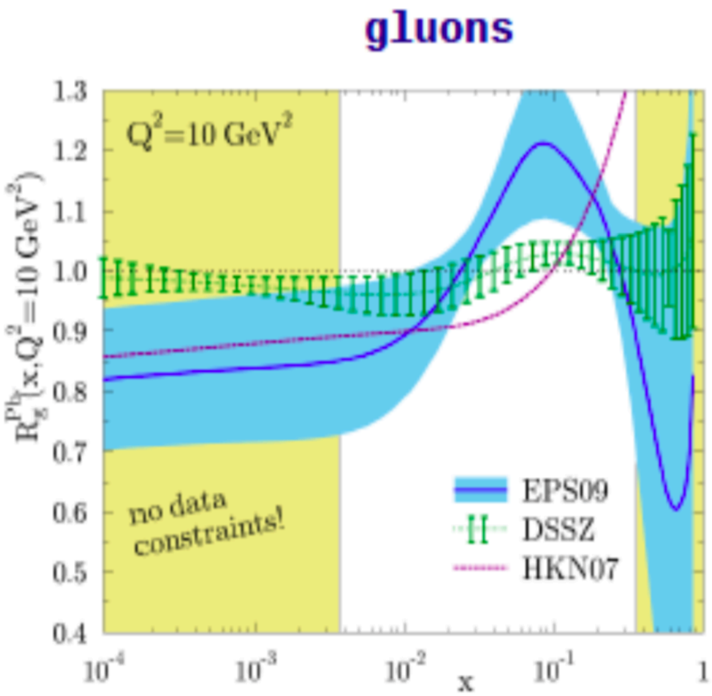
EMCal: Lead-tungstate (20 X_0)
2%/√E energy resolution
2x2 cm^2 segmentation
3mm/√E position resolution

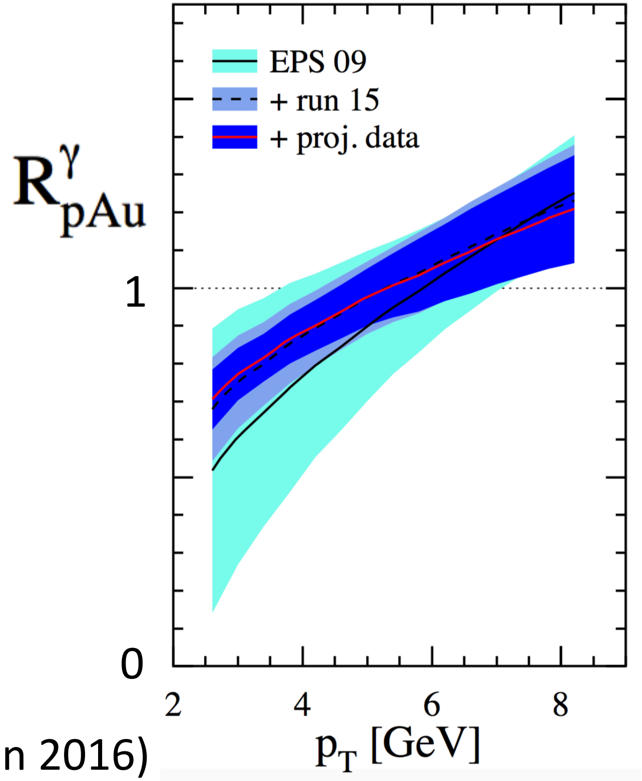
What can a new pA detector add?

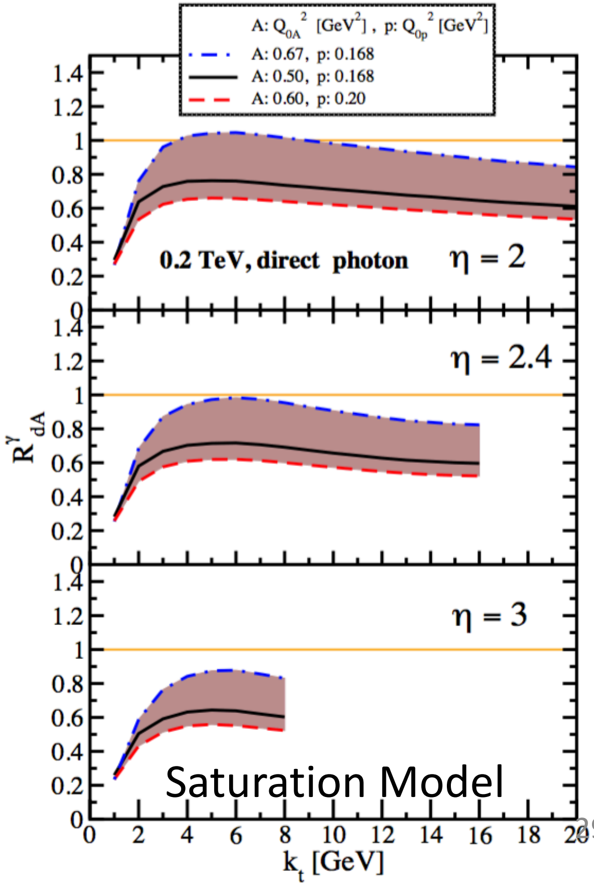


- Direct photons and DY at forward rapidities:
  - The FMS and MPC-EX will make first measurements, but these will have limited statistics.

Measurement of parton disribution functions







RHIC Cold QCD Plan for 2017 to 2013 (Jan 2016)

What about γ-jet?

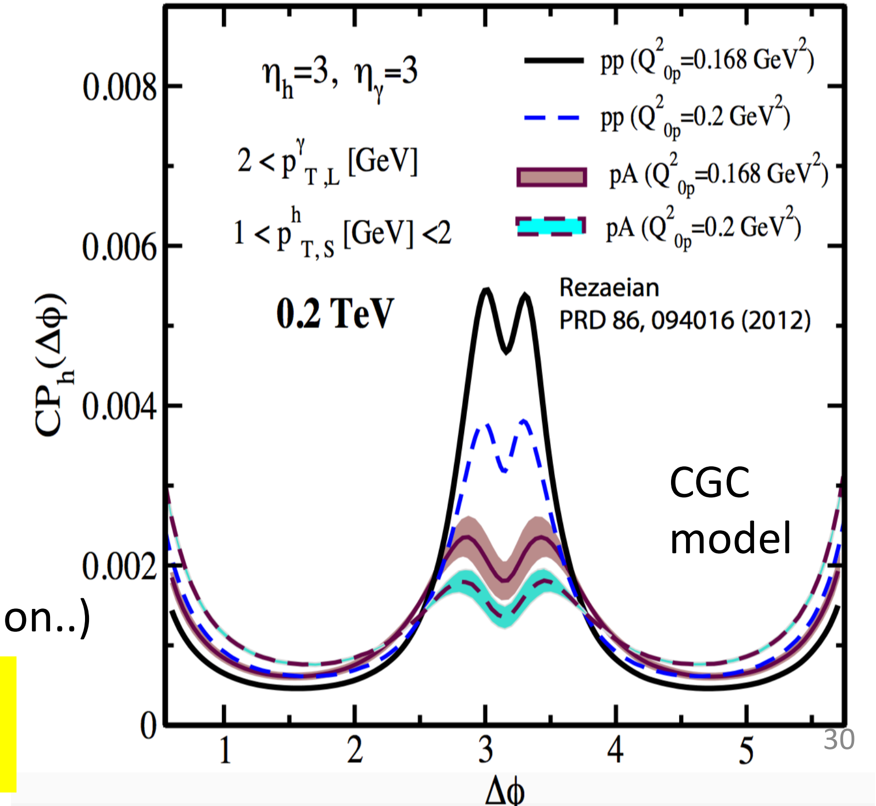
TMD factorization
In saturation region

Two gluon distributions

TABLE I. The involvement of these two-gluon distributions in high-energy processes.

	DIS and DY	SIDIS	hadron in pA	photon-jet in pA	Dijet in DIS	Dijet in pA
$xG^{(1)}$ (WW)	x	x	x	x	√	√
$xG^{(2)}$ (dipole)	√	√	√	√	x	√

- Not possible with present data
- Would need fsPHENIX



What would these measurements do?
Probably won't conclusively prove saturation (ala CGC) at RHIC
It will however, continue to add to the signatures, supportive or not
Expect the models to change

Different schemes (CGC, Twist 3, ….)

Different treatment of other effects (e.g. Fragmentation, evolution..)

However, these measurements will provide crucial information as
Model will be forced to explain many signatures in a consistent fashion

- PHYSICS II: Heavy Meson/Quark behavior in cold nucleus
- Complements Central Arm Physics
- We should look at correlation and flow measurements as well as yields
    - Suppression of Upsilon states
    - Onia flow (e.g. higher harmonics), excited Onia flow (“melts”, sensitive pressure build up at earlier times – e.g. a test for a QGP), χ_C (tough)
        - NOTE: needs very good momentum/energy resolution.
    - Heavy Quarks: Adding vertexing (possible using long MAPS tracker)
        - γ+c/b (energy loss of heavy mesons, to complement γ +pion correlations)
        - c/b-jets

PHYSICS III: Diffractive processes

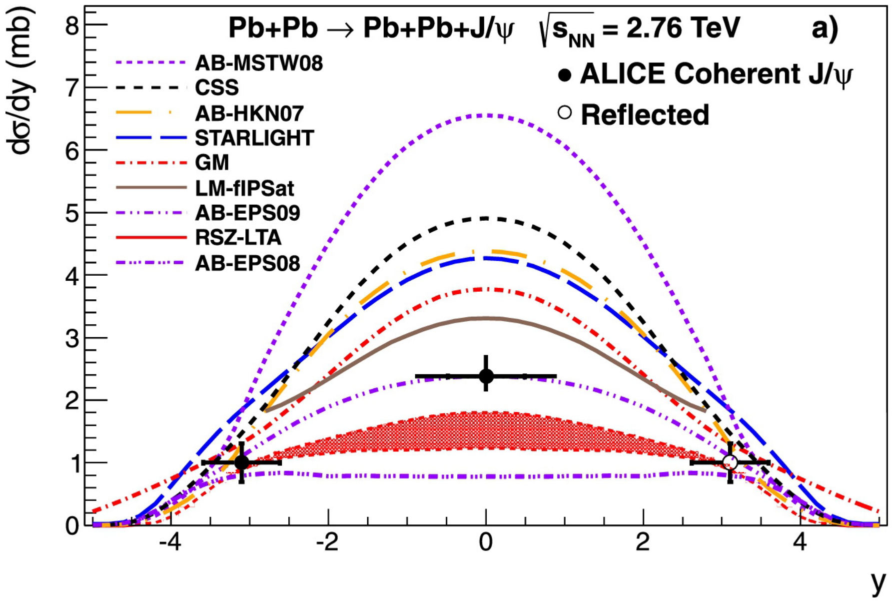
In eA collisions, this is an important signature of saturation

Official goal is to do this in p+p. Can this also be looked at in p+A?

Not much said in Cold-QCD white paper. Follow up?

Physics IV: Ultraperipheral vector meson production

Sensitivity to the gluon structure functions



Running schedule

p+A all in 2023

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD Eg	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR **None** **None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. **None** **None**
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. **None** Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. **None** Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity observables as in 2017 run	Yes Forward instrum. **None**
	202X	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

Table 1-2: Summary of the Cold QCD physics program propsed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.

Summary

- fSPHENIX is an ideal p+A precursor to Physics at the EIC (many topics in p+p as well). Measurements complement EIC measurements
  - Physics of high parton densities
  - Studying the detector possibilities for Onia and heavy quarks. (personal prejudice: I think we should push for these. They would make a very compelling case, given the recent pA correlation/flow results)
  - Important to keep the community alive
- fsPHENIX, is an ideal bridge to a day-1 detector at the EIC