pp/pA with MPC/MPC-EX at PHENIX

Workshop on Forward Physics and High-Energy Scattering at Zero Degrees

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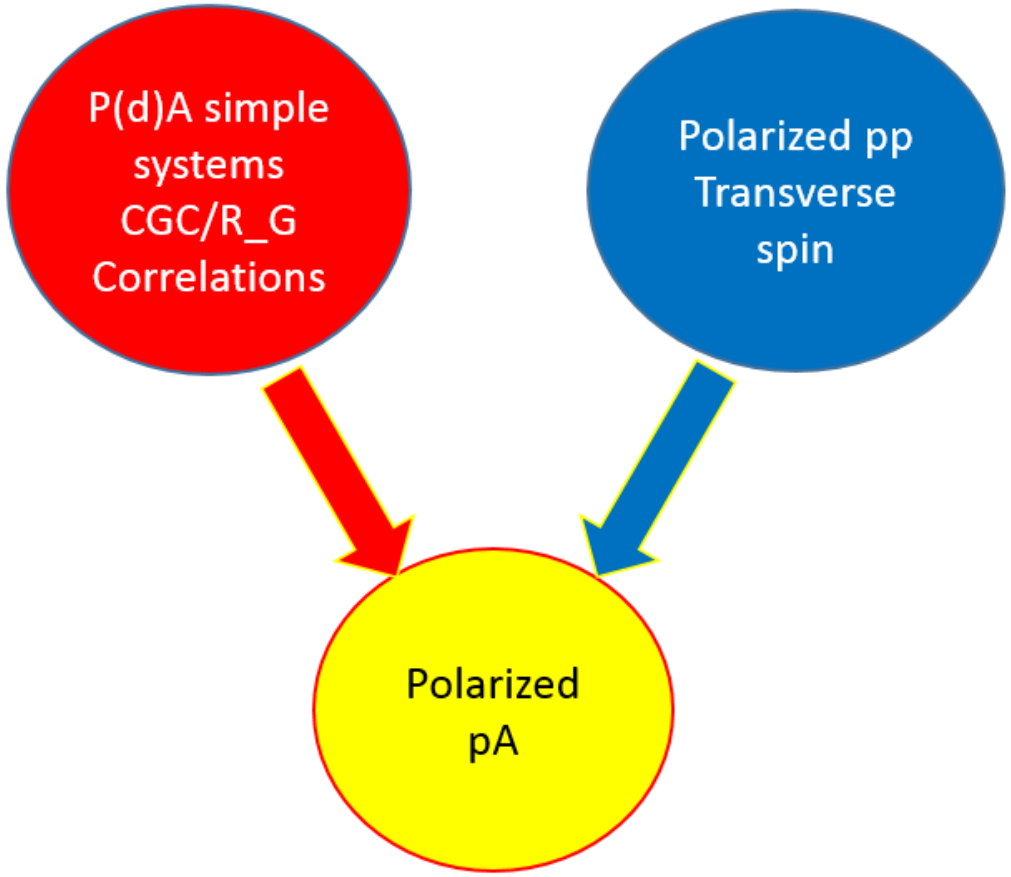
Nagoya, Sept 11, 2015

No AA, UPC, will show results from dAu

Outline

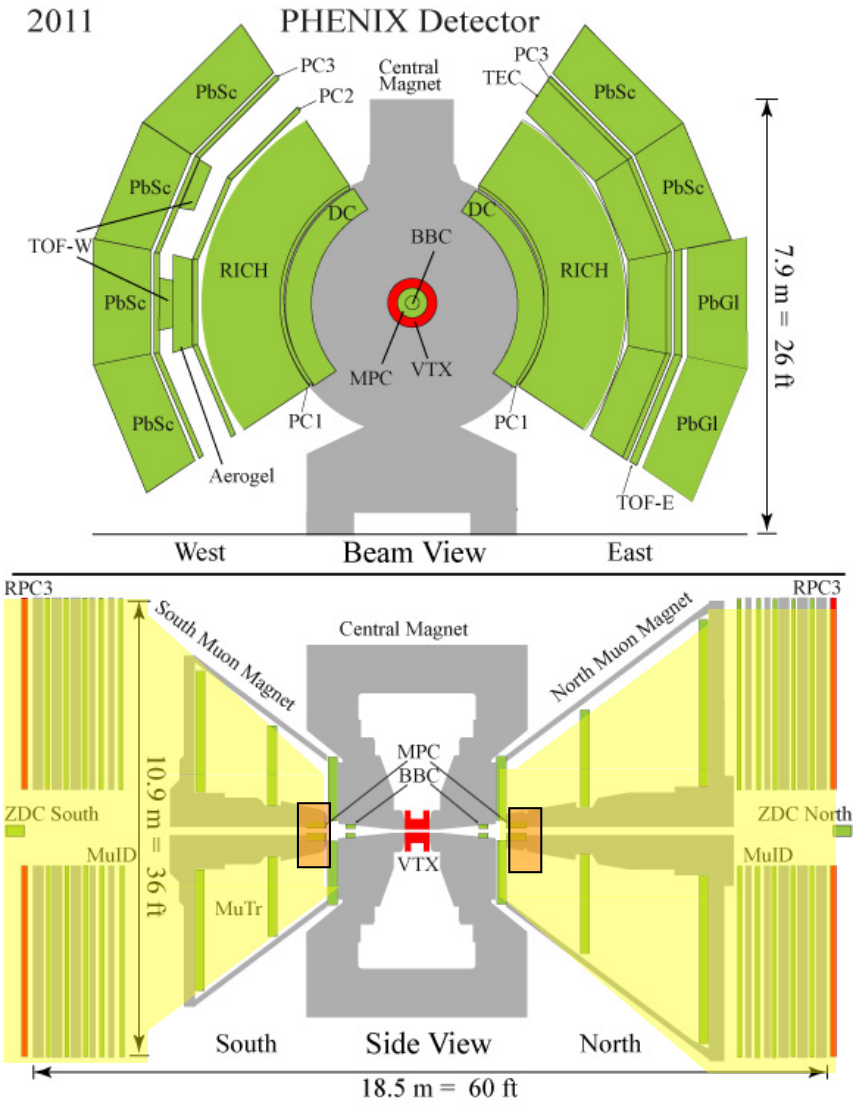
- MPC ← Will show results
- MPC-EX ← Data taken, projections only
  - Device
  - How it works
- Physics
  - Results
  - Projections

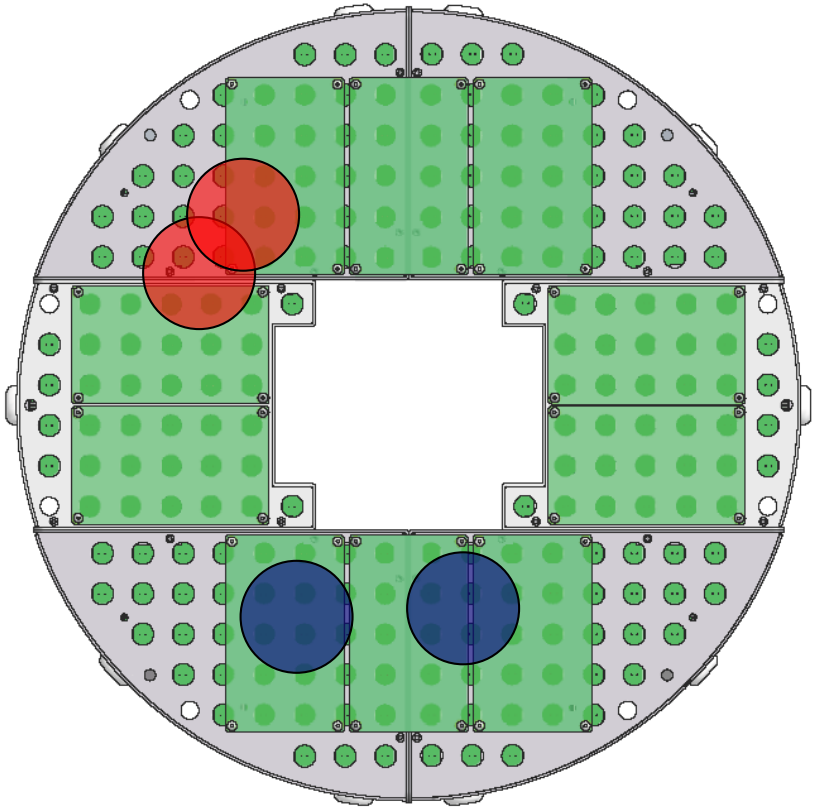


MPCs : lead tungstate calorimeters: π^0, η

Central arms
$|\eta|<0.35$

MPCs
$3.1<|\eta|<3.8$





Decay photon impact positions for low and high energy π^0's

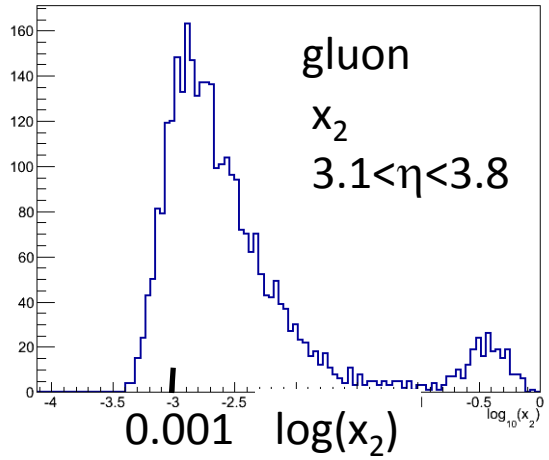
Direct Photons at Forward Rapidity

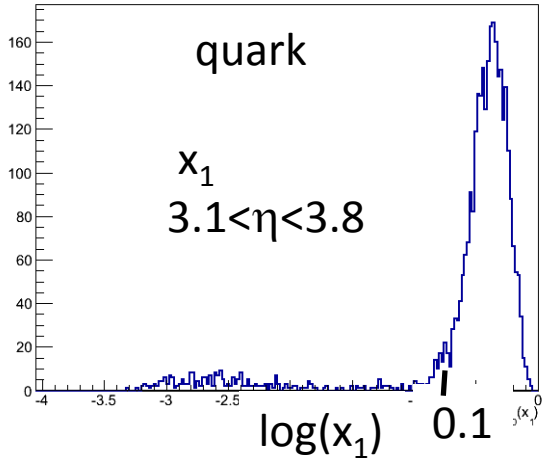
- Forward: qg→qγ dominates at low-x

$$R_\gamma = \frac{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Meas}}{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Sim}}$$

$$\gamma_{prompt} = \gamma_{Incl} * (1 - 1/R_\gamma)$$

Accurate π^0 measurement is crucial

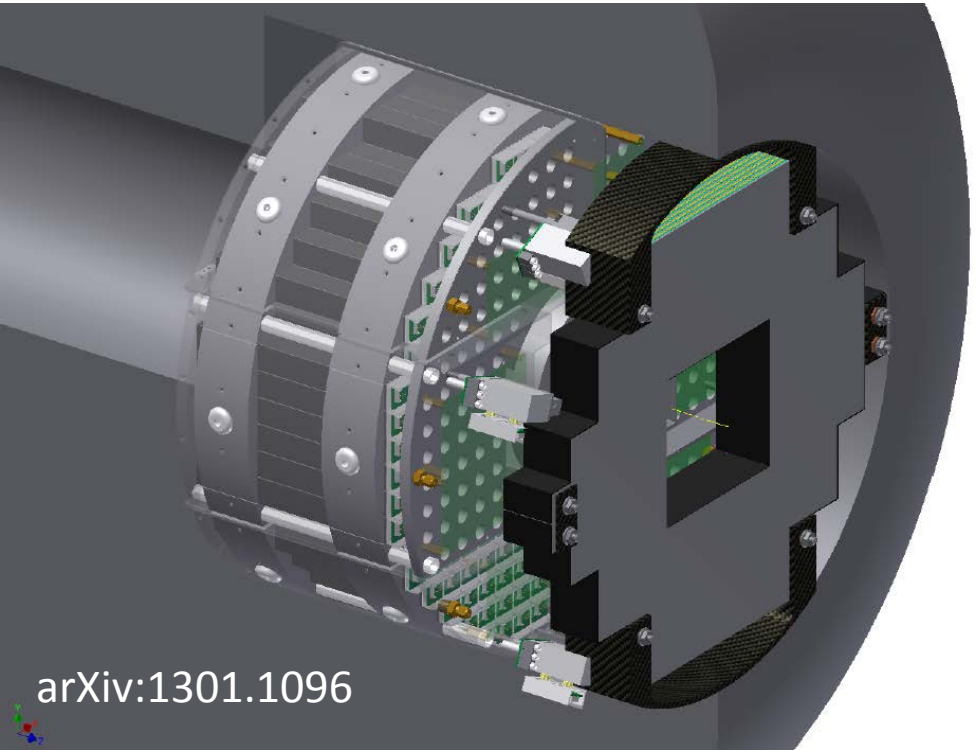




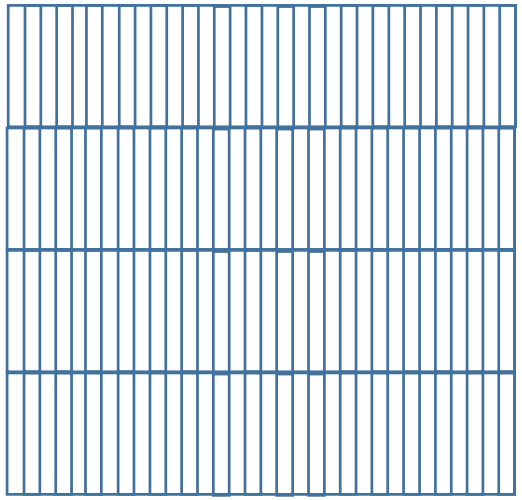
LARGE RAPIDITY:
p+A : low-x_2 gluons
p↑+p : high-$x_1$quarks

MPC-EX Preshower reconstruction of π^0s and γ_{direct} at forward rapidity

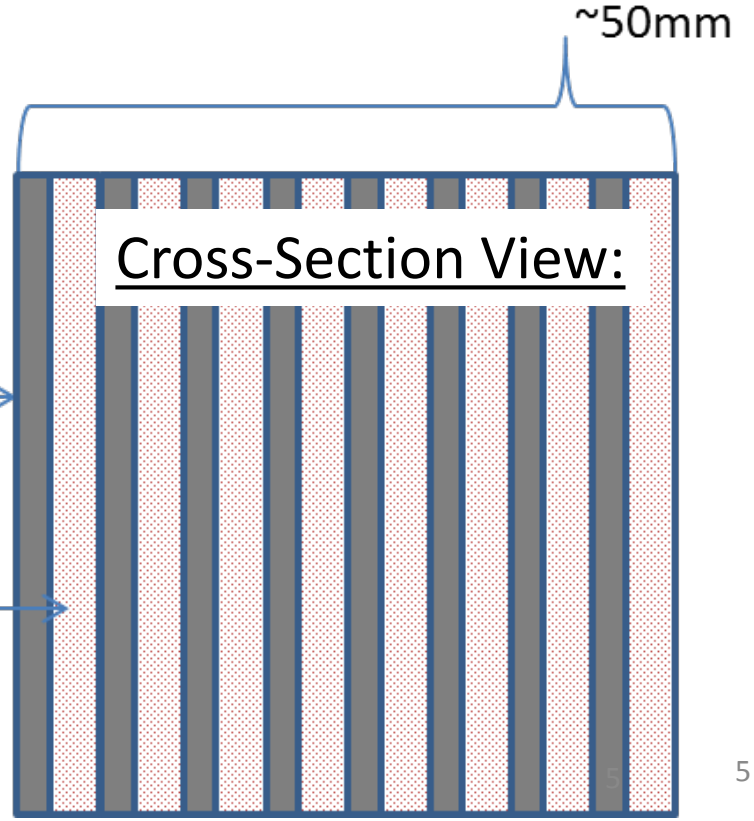
Installed prior to 2015 run



Silicon Tungsten Sandwich Calorimeter



1.8mm x 15mm
"minipad" Silicon sensor
SVX4 readout



2mm tungsten

Minipad Micromodules
(X or Y)

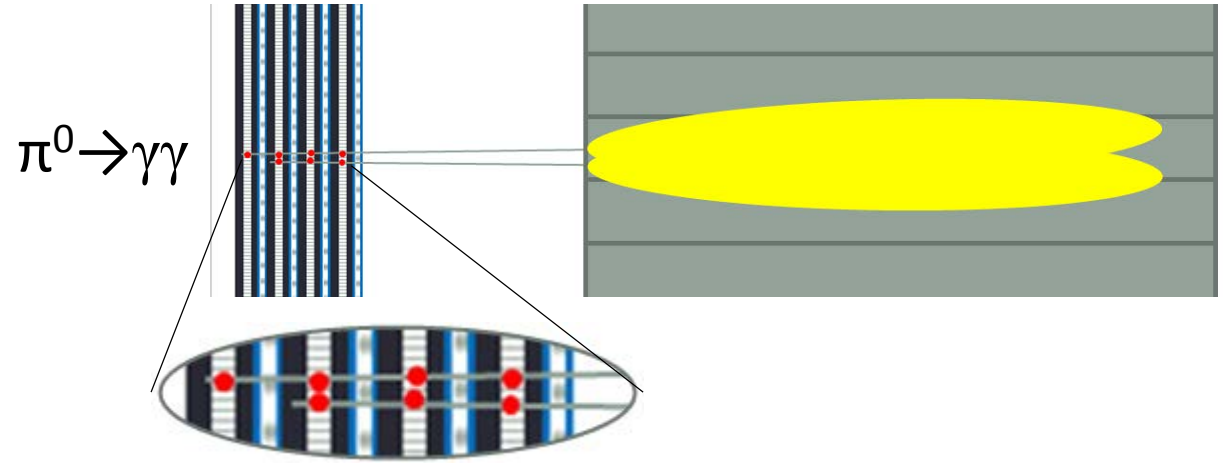
How does it work?

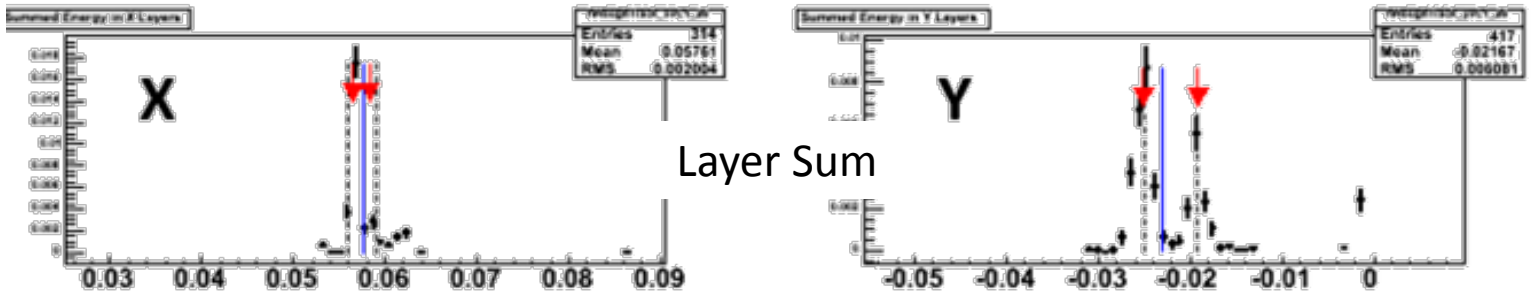
1) MPC: Shower energy

2) MPC-EX { Opening angle / Energy Sharing

➔ $\gamma\gamma$ invariant mass

$\pi^0 \rightarrow \gamma\gamma$

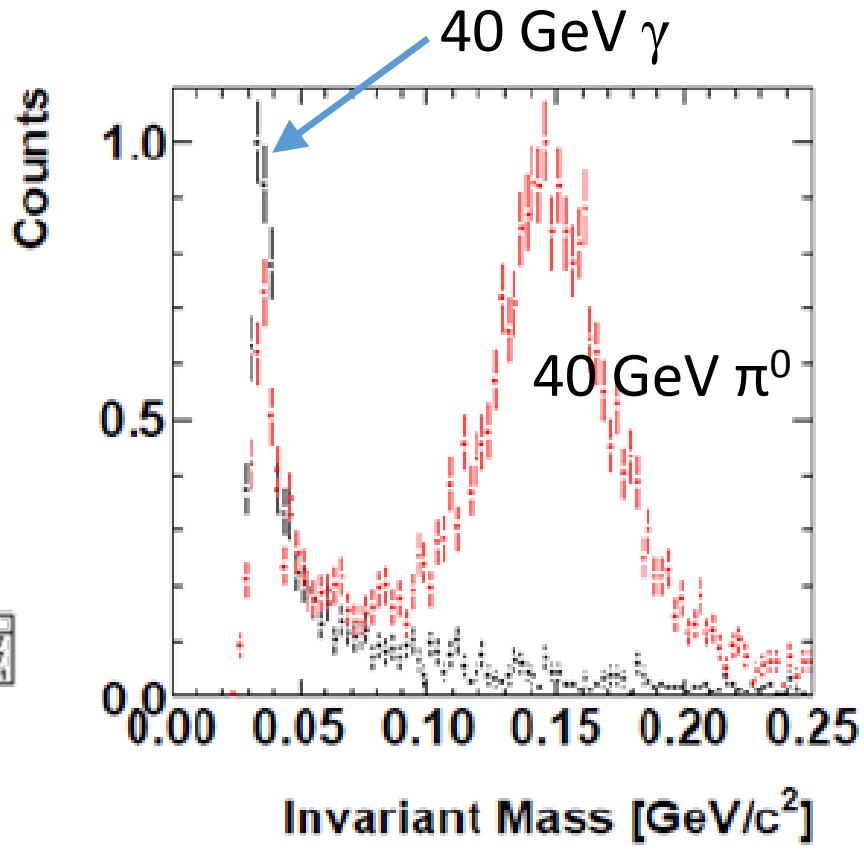


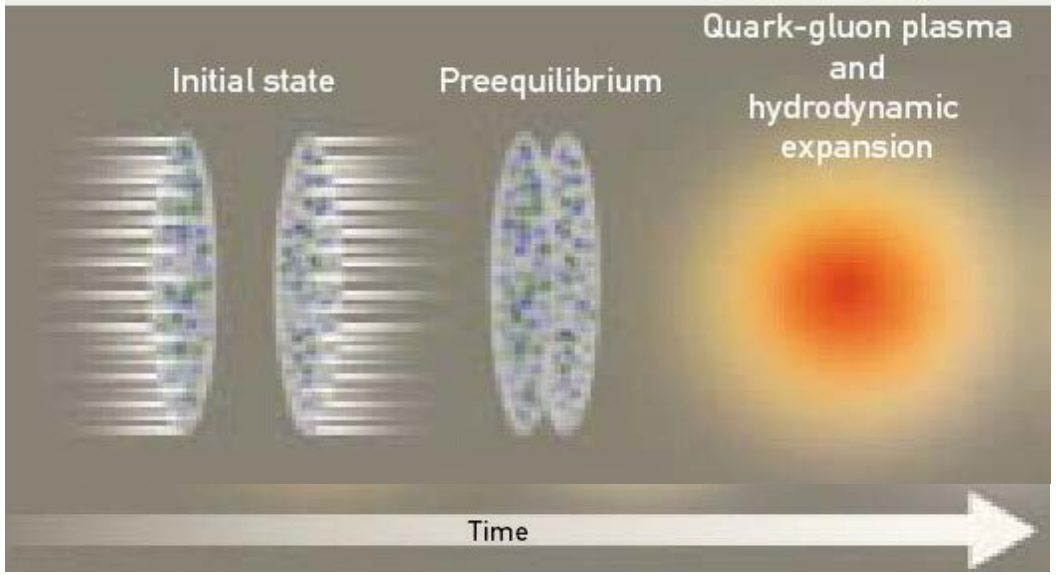


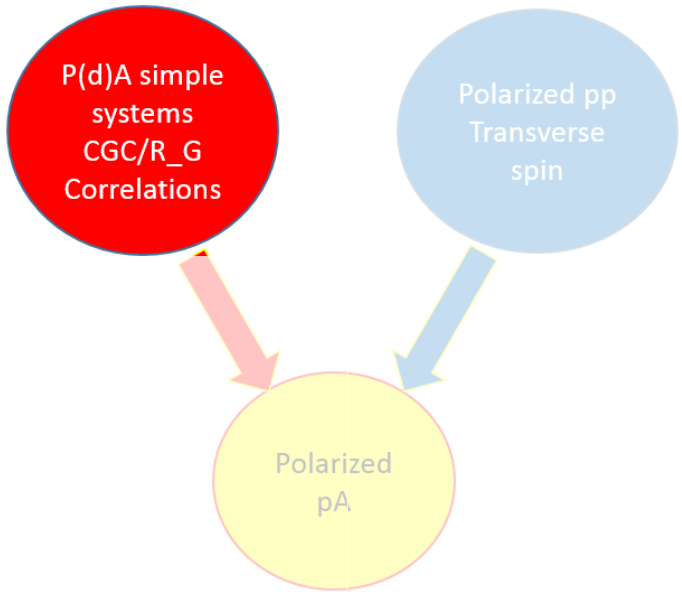
Layer Sum

Hough slope

Hough slope







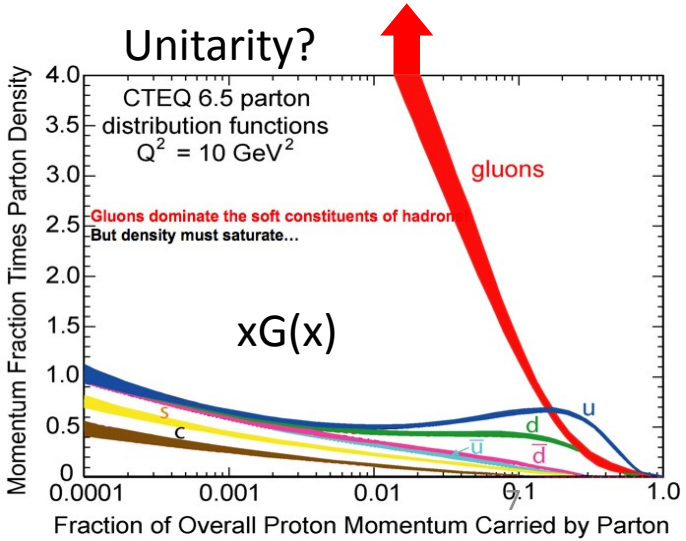
Simple systems: p, d+Au aka CNM (Cold Nuclear matter)

How is the QGP formed?

What is it's initial state?

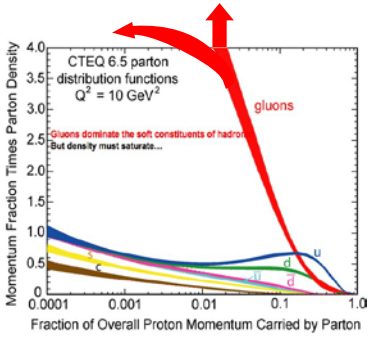
Can it be described by the saturation of gluons?

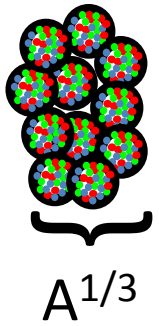
Is there a Quark Gluon Plasma
Formed in simple systems?



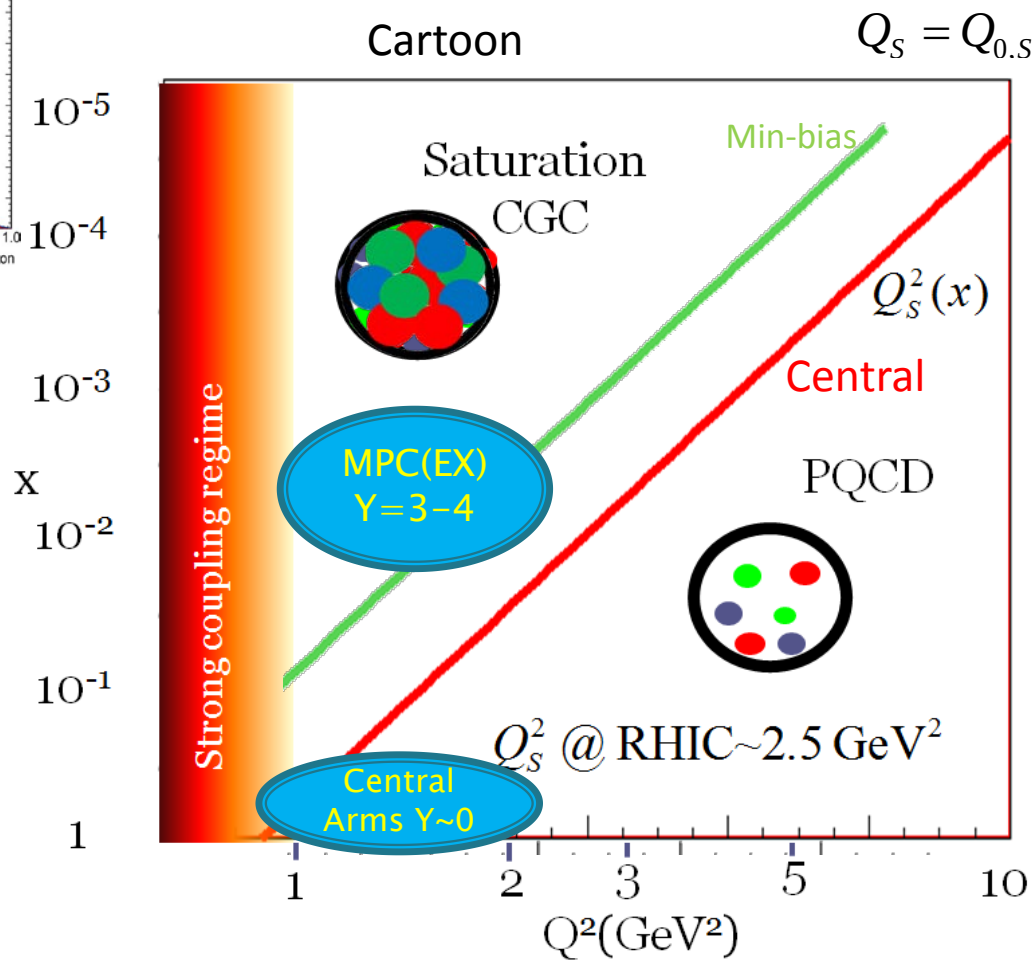
Descriptions of Cold Nuclear matter
The Color Glass Condensate (CGC) a dynamical theory

- Saturation of low-x gluons
  - high density
    - ⇨ Recombination of gluons,
    - ⇨ suppression @ low-x
  - Characterized by Q_S
  - Nuclear Amplification
    - ⇨ $xG_A = A^{1/3} xG_p$
      - We can exploit this behavior





$$Q_S = Q_{0.S}\left(\frac{x_0}{x}\right)^{\lambda}$$



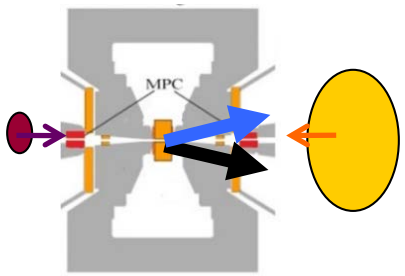
Look for suppression in pA/pp

Central: λ=.23 $Q_{0,S}^2 = 2.5\,GeV^2$ x_0 = .01 (Kharzeev, Levin private communication)

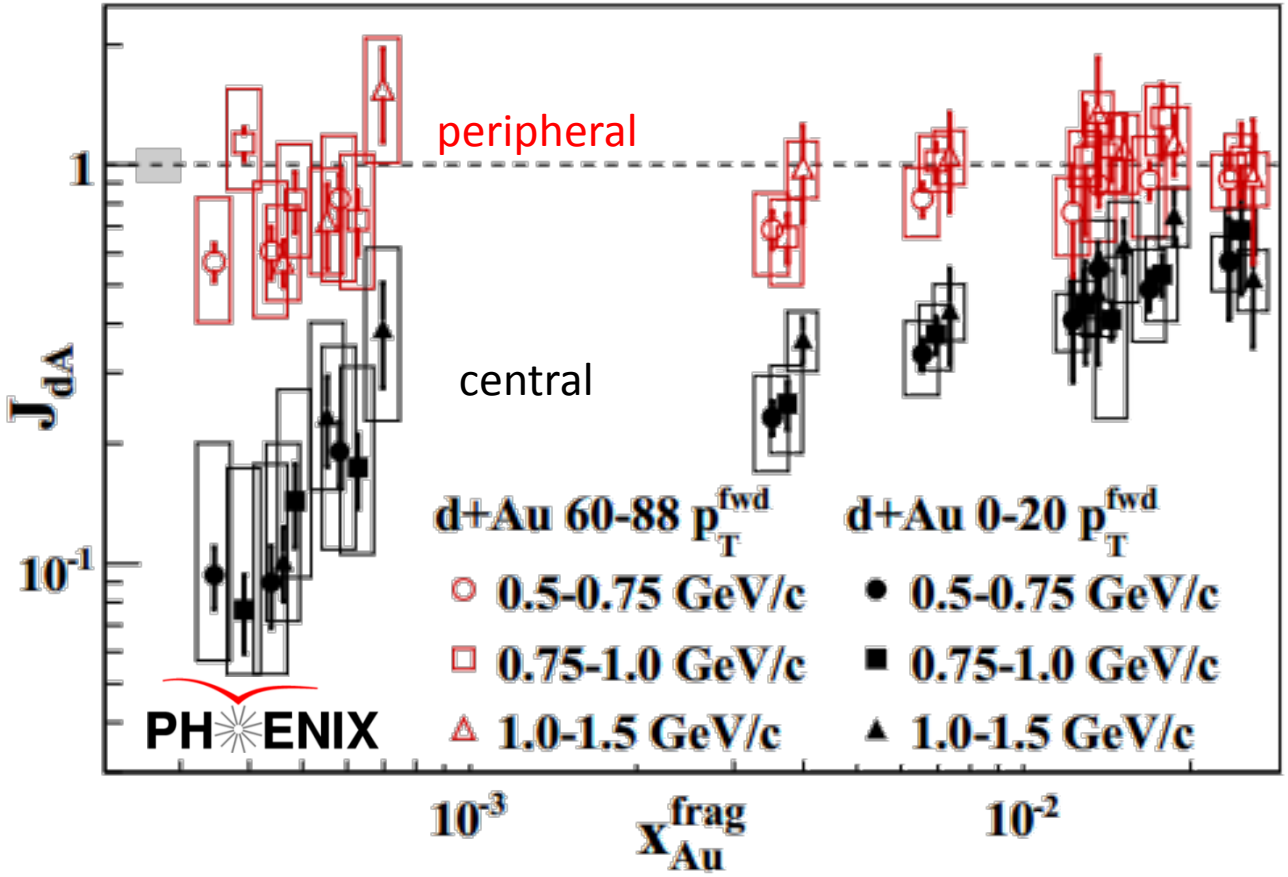
Min Bias: λ=.23 $Q_{0,S}^2 = 0.9\,GeV^2$ x_0 = .02 (Alacete,Marquet Phys.Lett.B687:174-179,2010)

Suppression low-x: d+Au/p+p

Getting to low-x:
Require 2 back to back
Forward particles in MPC



$$x_{Au}^{frag} = \frac{p_{T1}e^{-\eta_1} + p_{T2}e^{-\eta_2}}{\sqrt{s_{NN}}}$$



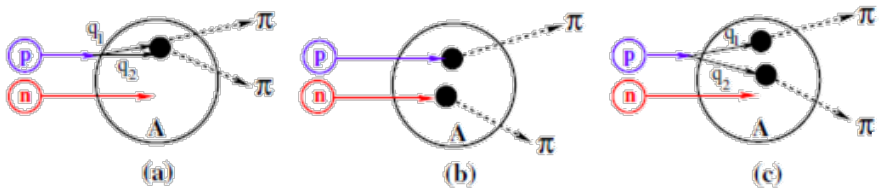
PRL 107, 172301(2011)

$$J_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{N_{d+Au}^{pair}}{N_{p+p}^{pair}} \sim \frac{xG_{Au}(x,Q^2)}{AxG_p(x,Q^2)}$$

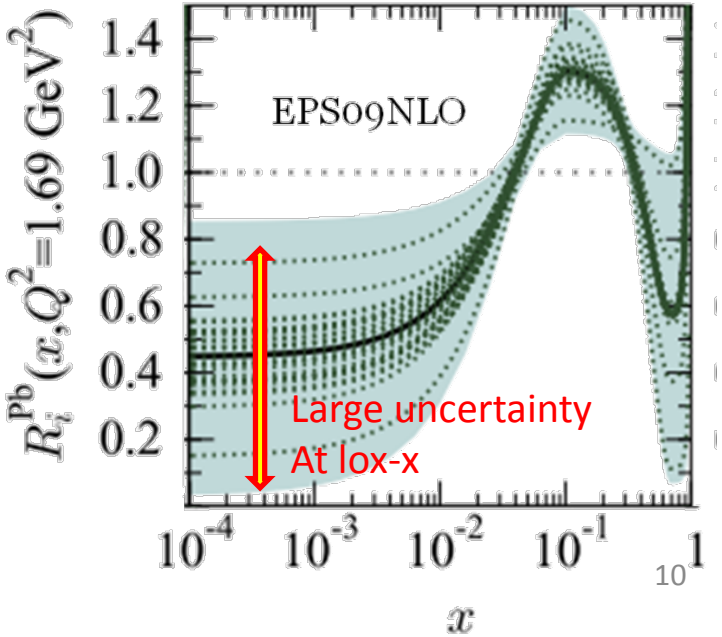
Low x gluon suppression, CGC?

Prompt photons as a measure of the gluon distribution

- Other pQCD inspired descriptions of data
  - pQCD shadowing: higher twist, coherence — Qiu, arXiv:0405068
  - Phenomenological models: Energy loss, multiple scattering — Dominquez, Marquet, Xiao and Yuan: TMD ↔ CGC
- dAu
  - Multiparton interactions — Vitev et al. PRD 74, 054010
  - Deuteron parton distribution at high x now well known — Strikman, Volgesang arXiv:1009.6123



$$R_G^{Pb}(x,Q^2) = \frac{xG_A(x,Q^2)}{AxG_p(x,Q^2)}$$



⇨ pA, direct photons : MPC-EX

Benchmark direct photon measurement of the gluon distribution: use empirical fit to data for PDF and nuclear shadowing

Direct Photon Simulations (π^0 cuts)

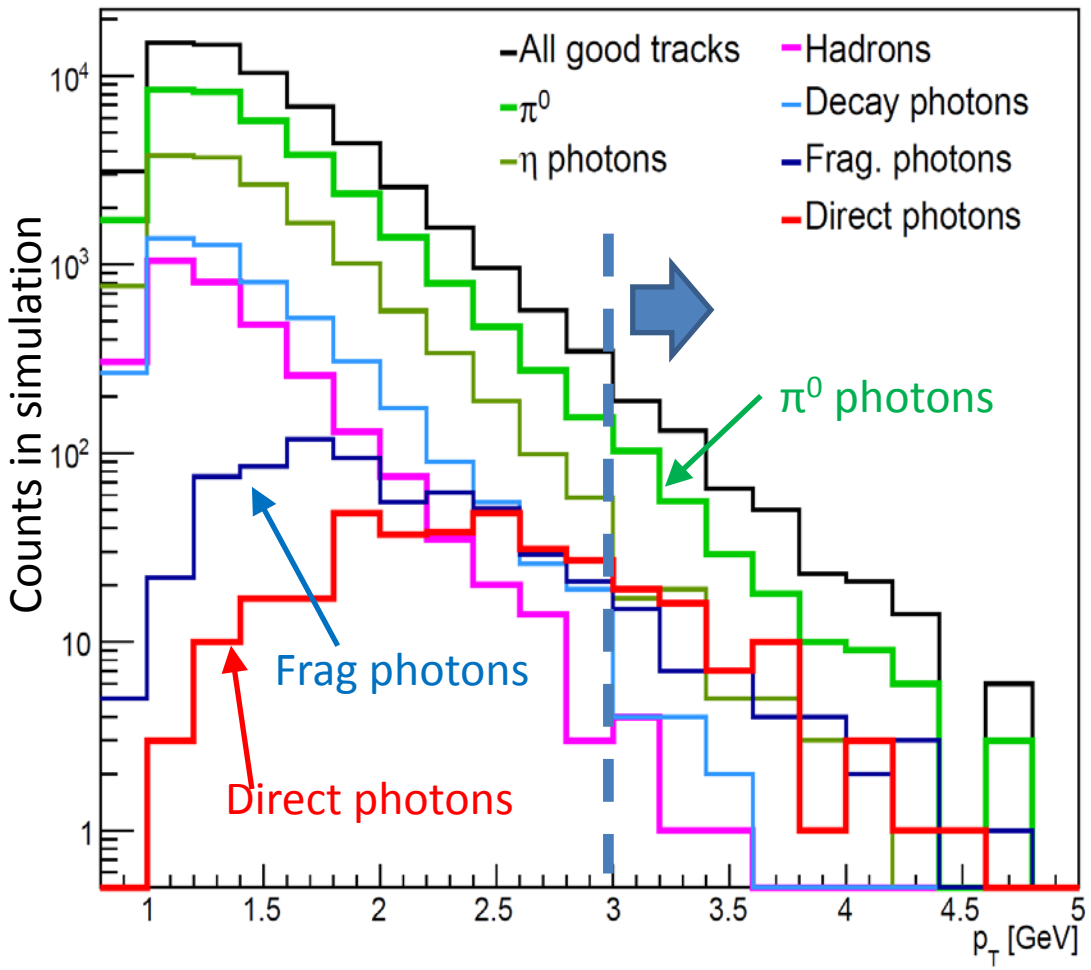
Basic cuts: remove π^0,η, charged hadrons

For p_T>3 GeV:

2.9% efficiency for π^0

31.2% efficiency for direct photons

dir/(frag+dir) = 57.4%



Simulation: 868M pythia MB events

~ 10^{-3} of expected sample

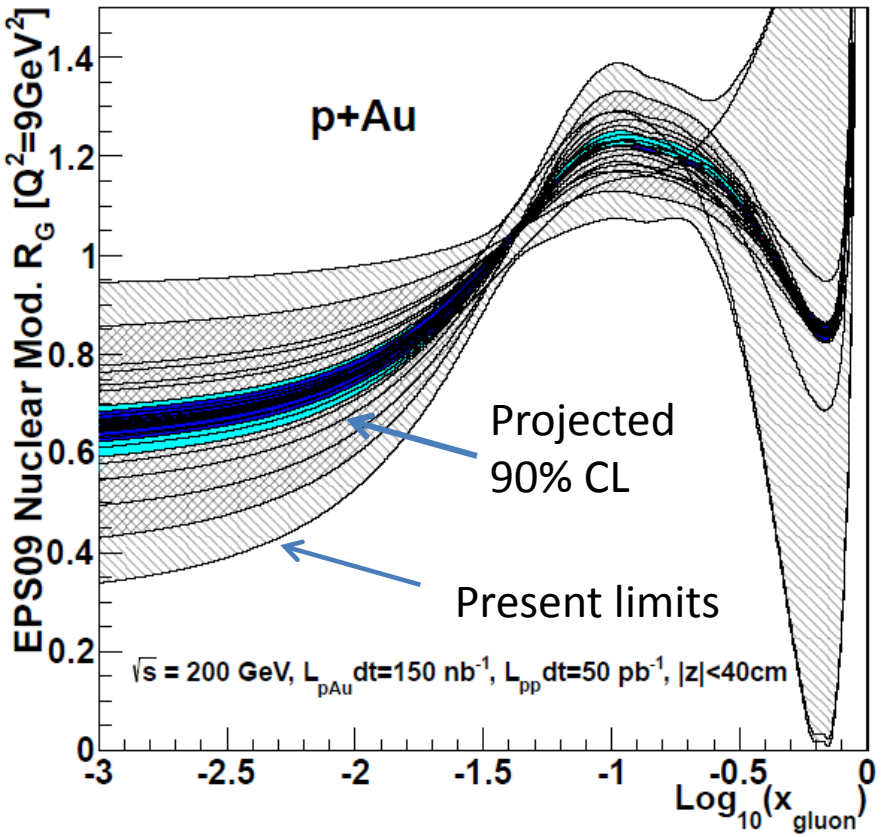
Systematic errors

$$R_\gamma = \frac{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Meas}}{\left(\frac{\gamma_{Incl}}{\pi^0}\right)_{Sim}}$$

$$R_{dAu} = \frac{1}{\langle N_{coll}\rangle} \frac{\gamma_{Incl}^{dAu} * (1 - 1/R_\gamma^{dAu})}{\gamma_{Incl}^{pp} * (1 - 1/R_\gamma^{pp})}$$

Quantity	value
R_γ	1.34
systematic error $\Delta R_\gamma / R_\gamma$ correlated between dAu and pp from knowledge of π^0 Cross section	7.2%
systematic error $\Delta R_\gamma / R_\gamma$ uncorrelated between dAu and pp Residual error from energy scale	1%
systematic error $\Delta\gamma_{Incl}/\gamma_{Incl}$ uncorrelated between dAu and pp Residual error from energy scale	2%
relative systematic error on $\langle N_{coll}\rangle$	3%

Projected γ_{dir} Measurement of nuclear gluon distribution as benchmark



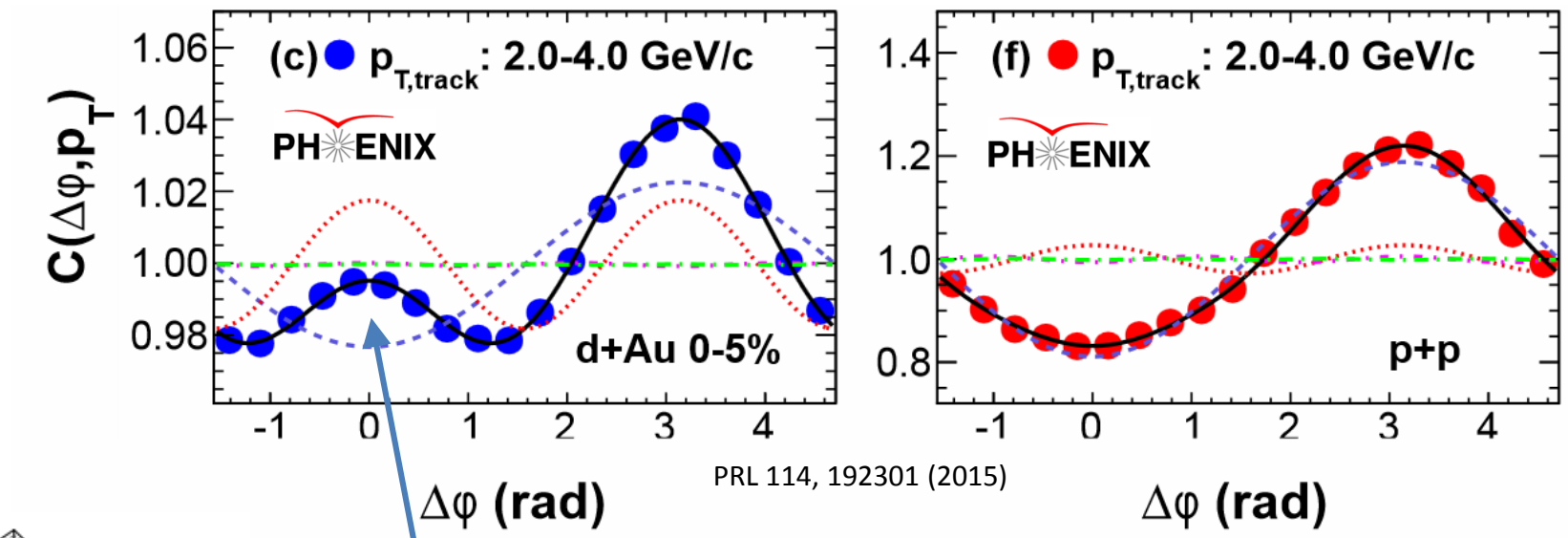
Prompt photons in MPC-EX → Precise Measurement of the Nuclear Gluon PDF

A measure of the initial state?…. BUT

A problem (?) with the simple system picture: “the same side Ridge”

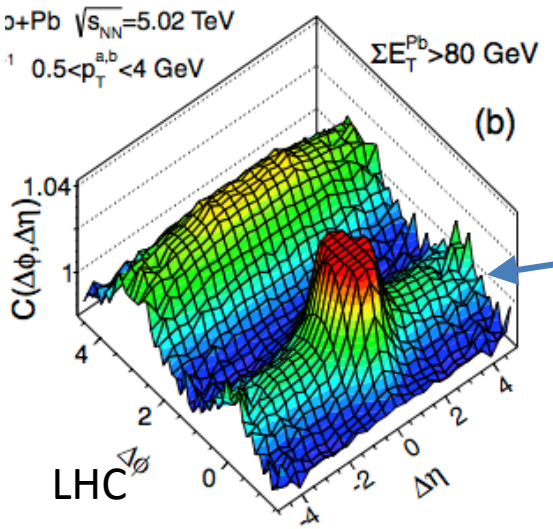
PHENIX Mid-Backward(MPC) Particle/Energy Correlations

CentralTrack
MPC Tower
Correlation



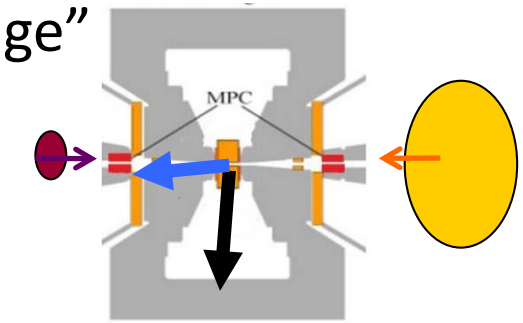
PRL 114, 192301 (2015)

Note: at the LHC same side “ridge” is seen in very high multiplicity p+p collisions. RHIC experiments are looking for them now



LHC

Same side “ridge”
⇨long range rapidity correlations

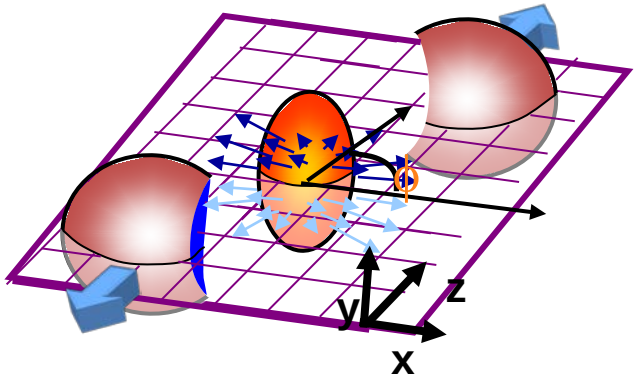


3<|Δη|<4

Explanation?

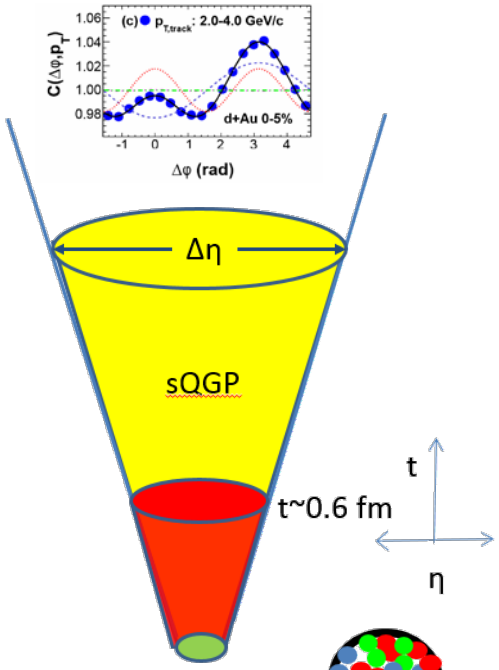
Effect is on Au going side

Hypothesis I: Flow (Hydro) in a (assumed) thermalized sQGP in small systems

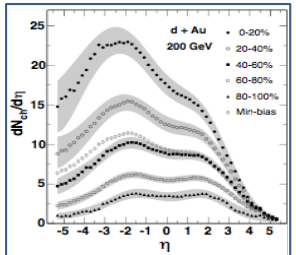


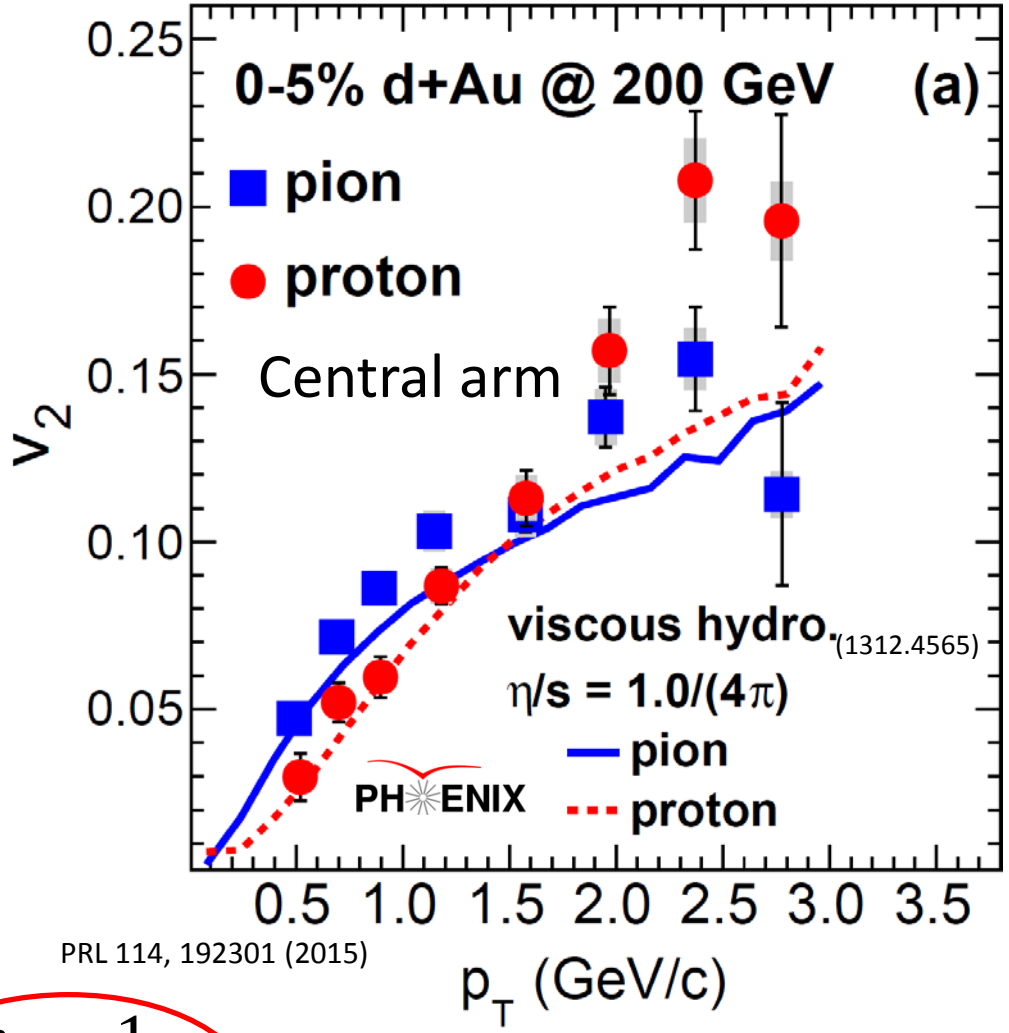
$$v_2 = \langle \frac{p_x^{\,2} - p_y^{\,2}}{p_x^{\,2} + p_y^{\,2}} \rangle$$

Initial state fluctuations also provide spatial asymmetries but thermalization is assumed



Initial state
Color Glass Condensate?
t=0.0 fm



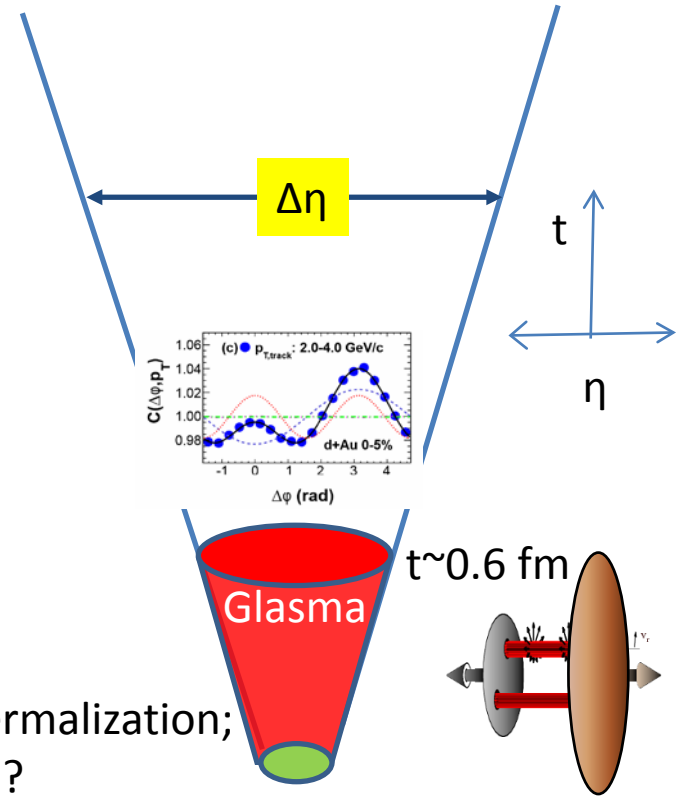


PRL 114, 192301 (2015)

$$\frac{\eta}{s} = \frac{1}{4\pi}$$

Lower limit set by Gauge-Gravity duality. Really?!

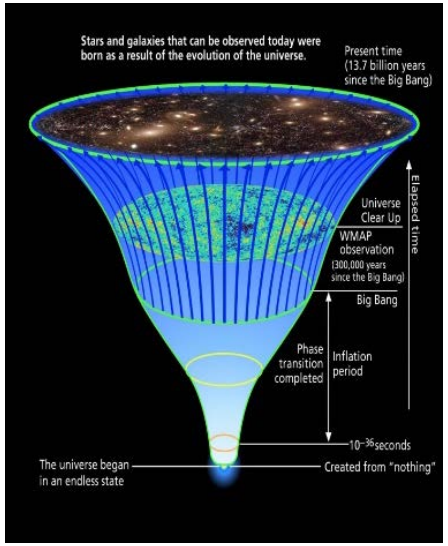
Hypothesis II: Initial state fluctuations "inflated" to long range correlations

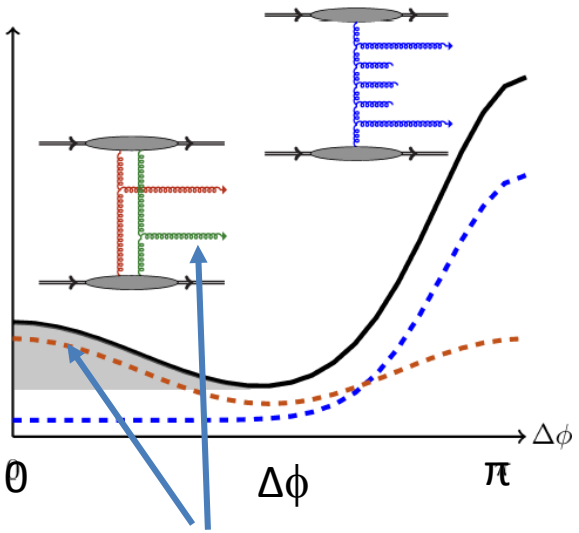


Pre-thermalization;
Glasma?

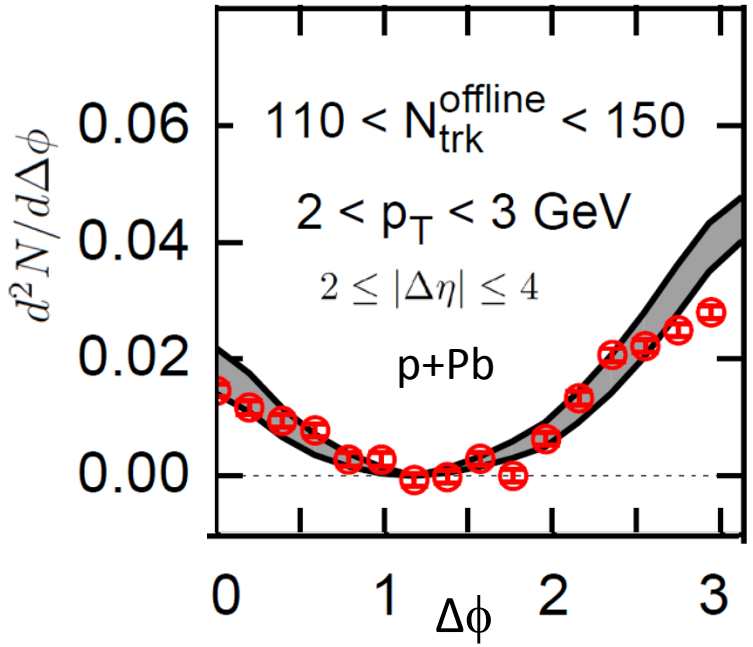
Initial state:
Color Glass Condensate?

arXiv:0804.3858 (2006)





Glasma contribution



CMS Data compared
To Glasma model
$Q_0^2(p)=0.504$ GeV^2
Dusling, Venugopalan

arXiv:1211.3701 (2012)
arXiv:1302.7081 (2013)

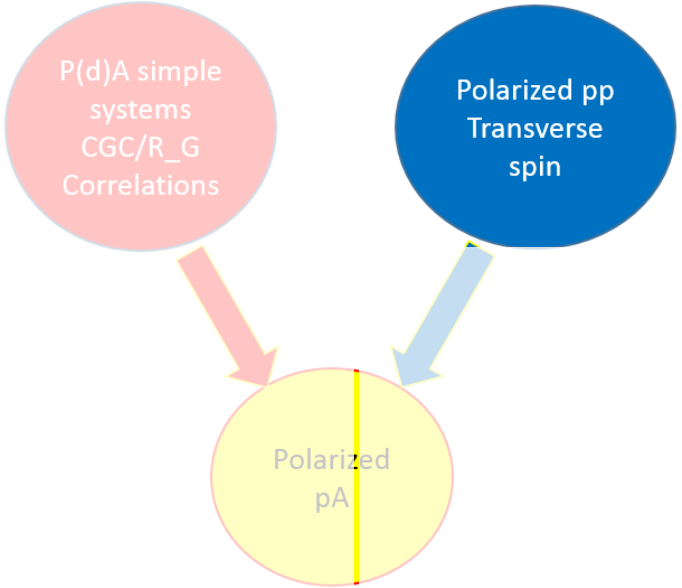
Other explanations exist:
e.g. Multiparton interactions

2015 data

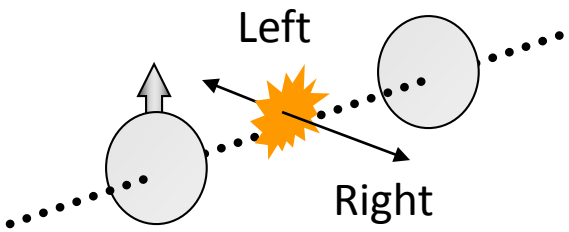
- Previous results were from d+Au collisions, which have a natural v_2 because of the geometry of the deuteron, hence pA
- Added high multiplicity trigger using Forward Vertex Detector (pp)
- Present Analysis on pp, pA:
  - Correlation analysis on pp, pA:
    - All combinations of central arm (including Central Barrel Vertex) and high rapidity detectors (Forward Vertex, Beam Beam Counters, Zero Degree Calorimeters, MPC-EX)
  - Reaction plane analysis is also progressing

Together with out measurements of the prompt photons, and the SSA in pA, we will need to assess whether we are measuring the true initial state, or some later stage in the evolution of the system. Prompt photons, should provide a powerful probe.

Single Spin Asymmetries (SSA) from the MPC
Plans for MPC-EX A_N Prompt γ measurement



Single Transverse Spin Asymmetries



$$A_N = \frac{1}{P}\frac{\sigma_L^\pi - \sigma_R^\pi}{\sigma_L^\pi + \sigma_R^\pi}$$

A_N ~ difference in cross-section between particles produced to the left and right

Theory Expectation:

Small asymmetries at high energies

(Kane, Pumplin, Repko, PRL 41, 1689–1692 (1978))

$$A_N \propto \frac{m_q}{\sqrt{s}}$$

A_N O(10^{-4}) Theory

Experiment:

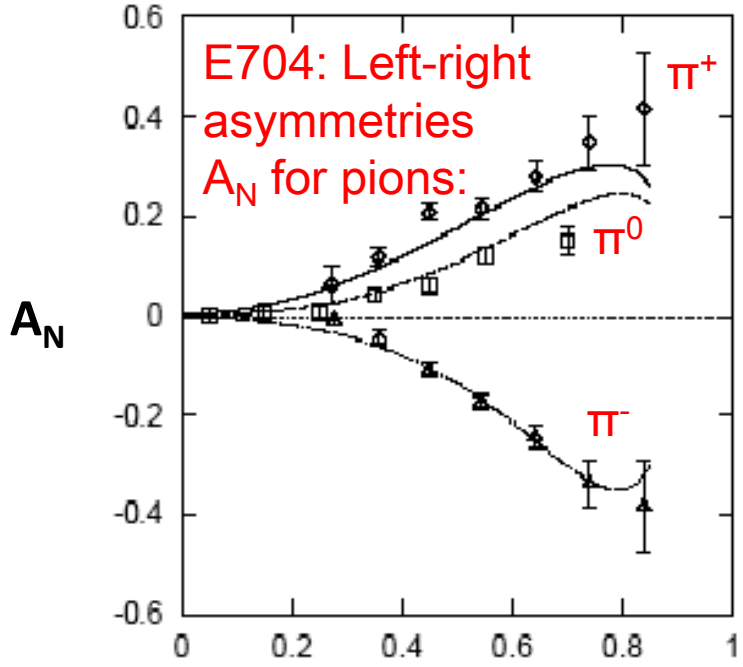
(E704, Fermi National Laboratory, 1991)

$$pp^\uparrow \rightarrow \pi + X$$

$$\sqrt{s} = 20\,\text{GeV}$$

A_N O(10^{-1}) Measured

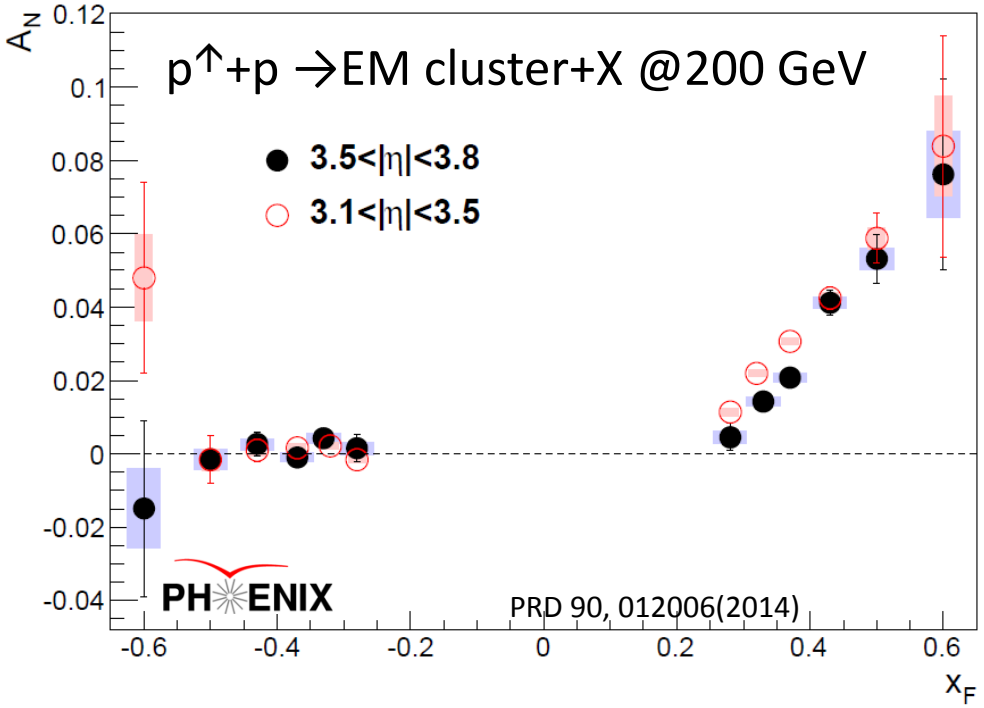
What happens at high energies?



$$x_F = \frac{2p_L}{\sqrt{s}}$$

MPC:EM clusters, π^0, η

$p^{\uparrow}$+p SSA@RHIC

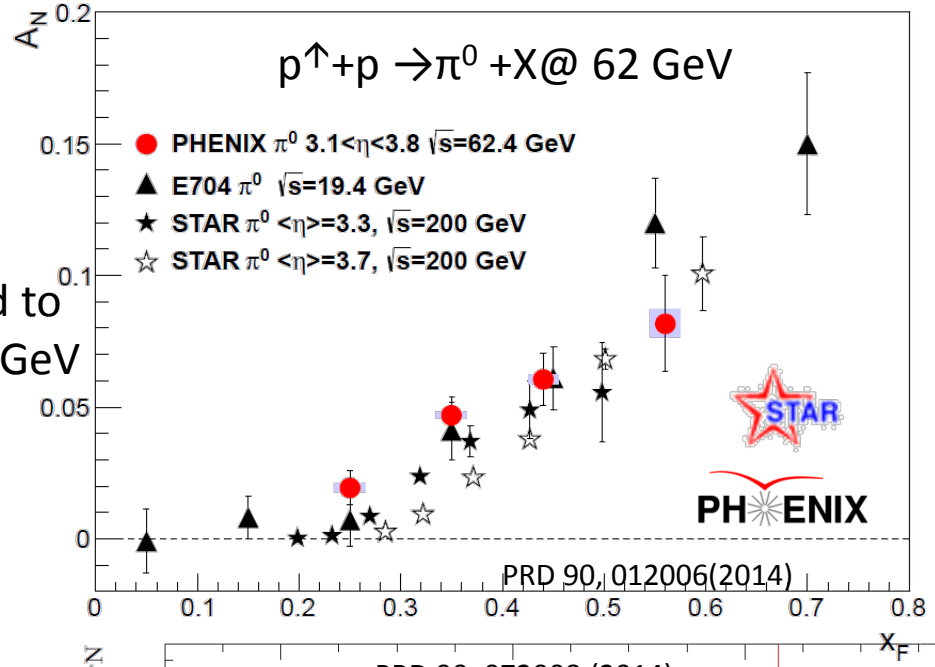


SSA's negligible at backward x_F

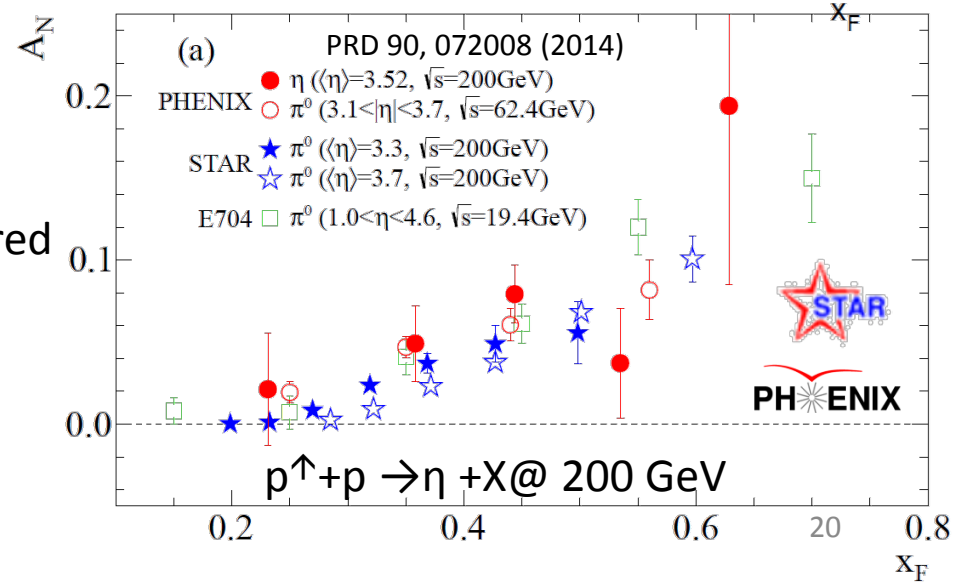
SSA's persist to RHIC energies
~Independent of energy

Qiu and Sterman PRL 67 (17) 2264 this is reasonable for twist 3

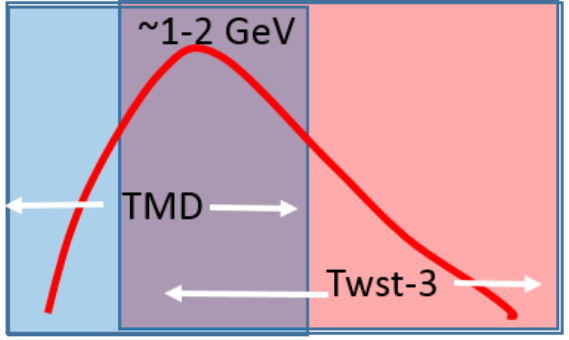
Compared to 19.4, 200 GeV



Compared to π^0s



Sources of Transverse SSA's



Note: TMD ⇔Twist3 ☺

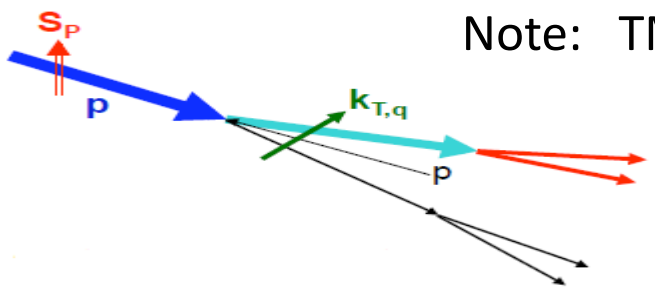
"initial state"

"Sivers effect"

TMD: Correlation between nucleon spin and parton k_T.

Phys. Rev. D **41**, 83 (1990)
Phys. Rev. D **43**, 261, (1991)

$$d\sigma^{\uparrow} \propto \underbrace{\bar{f}_{1T}^{\perp q}(x,k_\perp^2)}_{\text{Sivers distribution}} \cdot D_q^h(z)$$



Twist-3: Quark-gluon correlations in polarized hadron

Phys. Rev. D **59**, 014004 (1998)

$$\underbrace{gT_{q,F}(x,x)}_{\text{Qiu-Sterman function}} = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)$$

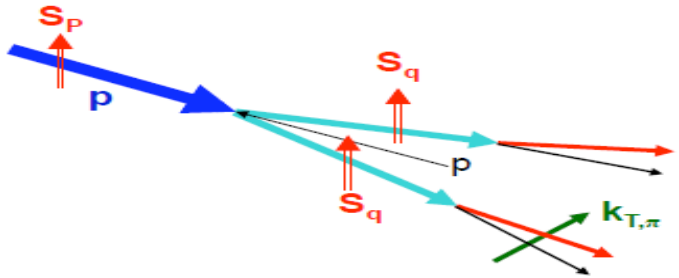
"final state" Fragmentation functions

"Collins effect"

TMD: Transversity distributions + Spin dependent fragmentation functions

Nucl. Phys. B 396, 161 (1993)

$$d\sigma^{\uparrow} \propto \underbrace{\delta q(x)}_{\text{Transversity}} \cdot \underbrace{H_1^{\perp}(z_2,\bar{k}_\perp^2)}_{\text{Collins FF}}$$

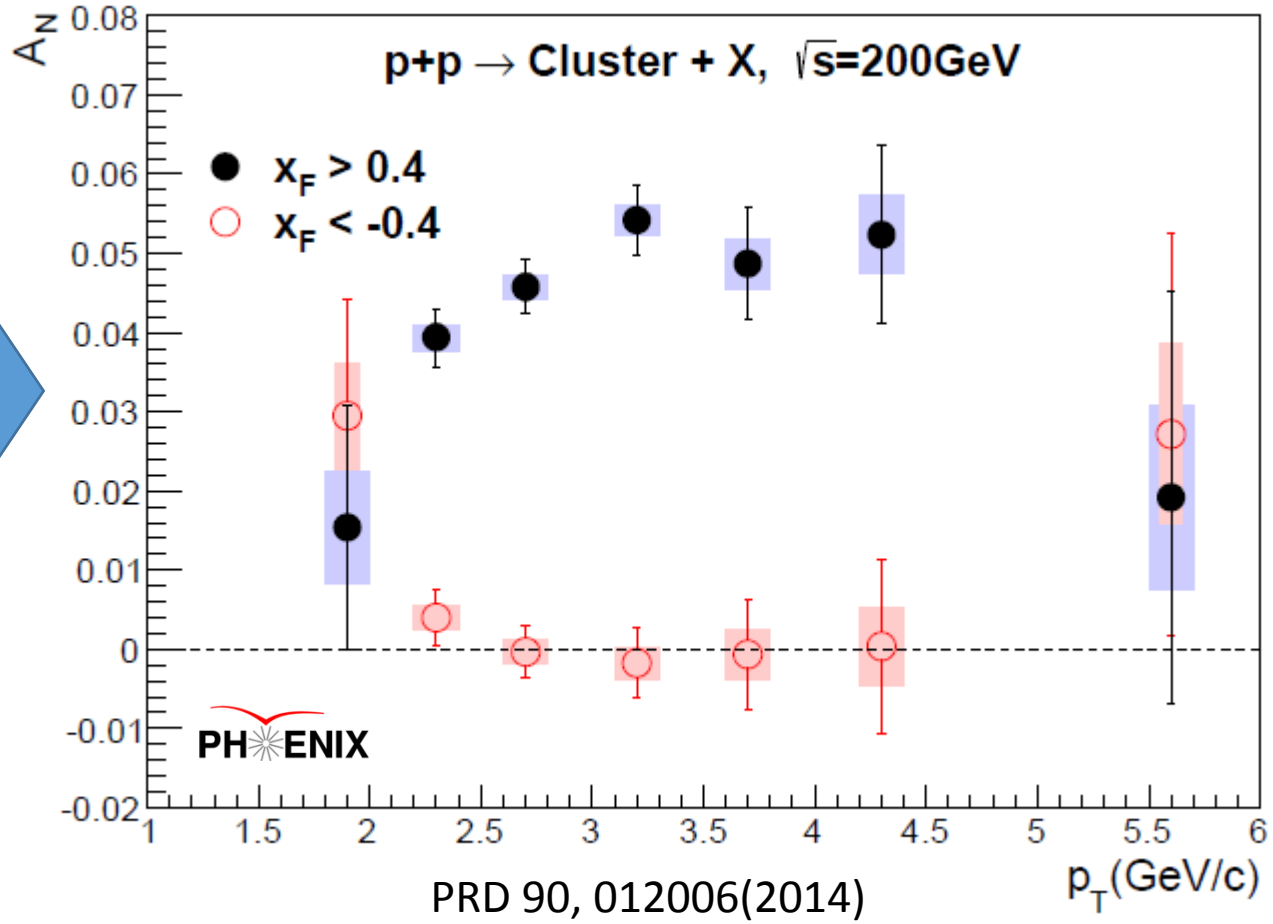


Twist-3: Transversity combined with twist-3 quark-gluon fragmentation function

Phys. Rev. D 89, 1115011 (2014)

MPC: EM cluster p_T Dependence

- Prediction: Collinear Higher Twist Calculations predict A_N is power suppressed in p_T
  - PRL97 082002 (2006)
  - PRD74 114013(2006)
- But we see no significant drop at high p_T up to 4 GeV
- Twist3 fragmentation functions are able to get this general behavior.
  - Kanazawa, Koike, Metz , Pitonyak PRD 89 111501(2014)



PRD 90, 012006(2014)

“Direct” photons

- More information to address the <u>source</u> of these asymmetries
  - Need more targeted measurements

➔ MPC-EX: SSA of direct photons : no final state contributions (Collins)

- Direct photons: Issues, Experimental and Theoretical
  - We measure prompt photons = direct + fragmentation photons. Fragmentation functions do have Collins
    - Theory: include fragmentation photons directly in calculations SSA
    - Experiment: Various cuts can change the direct/frag ratio
  - Experimental: Backgrounds from π, η→ γ also carry SSA

$$A_S = (1 + \frac{1}{r})A_{meas} - \frac{1}{r}A_B.$$

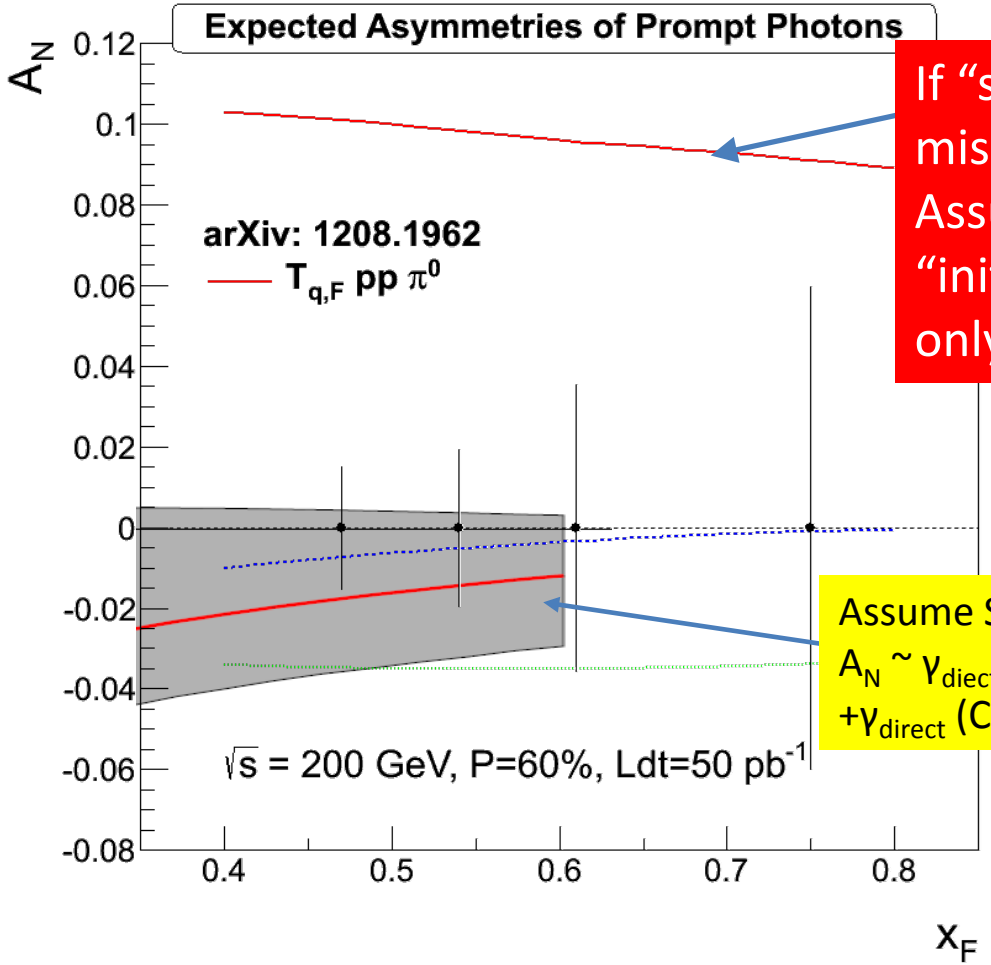
$r \equiv R_\gamma - 1 = {}^{S}/_{B} = 0.34$

    - In separate analysis:
      - Tune cuts to enhance π^0/η yield

      ⇒accurate measurement of δA_B (improve A_N^π A_n^η in the meantime)

      ⇒Minimize error in A_B

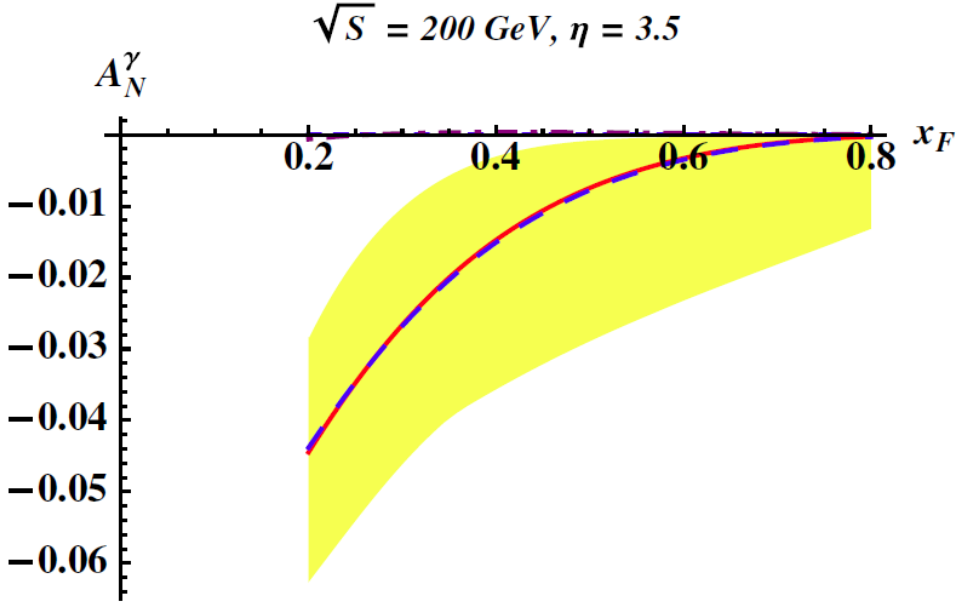
Prompt (Direct+Fragmentation) SSA projections



If "sign mismatch", Assumes Sivers "initial state" only

Assume SIDIS extraction $A_N \sim \gamma_{diect}$ (Sivers+Collins) $+\gamma_{direct}$ (Collins)

Kang, Qiu, Vogelsang and Yuan, Phys Rev. D 83 094001 (2011)
Gamberg and Kang, arXiv 1208.1962v1 (2012)

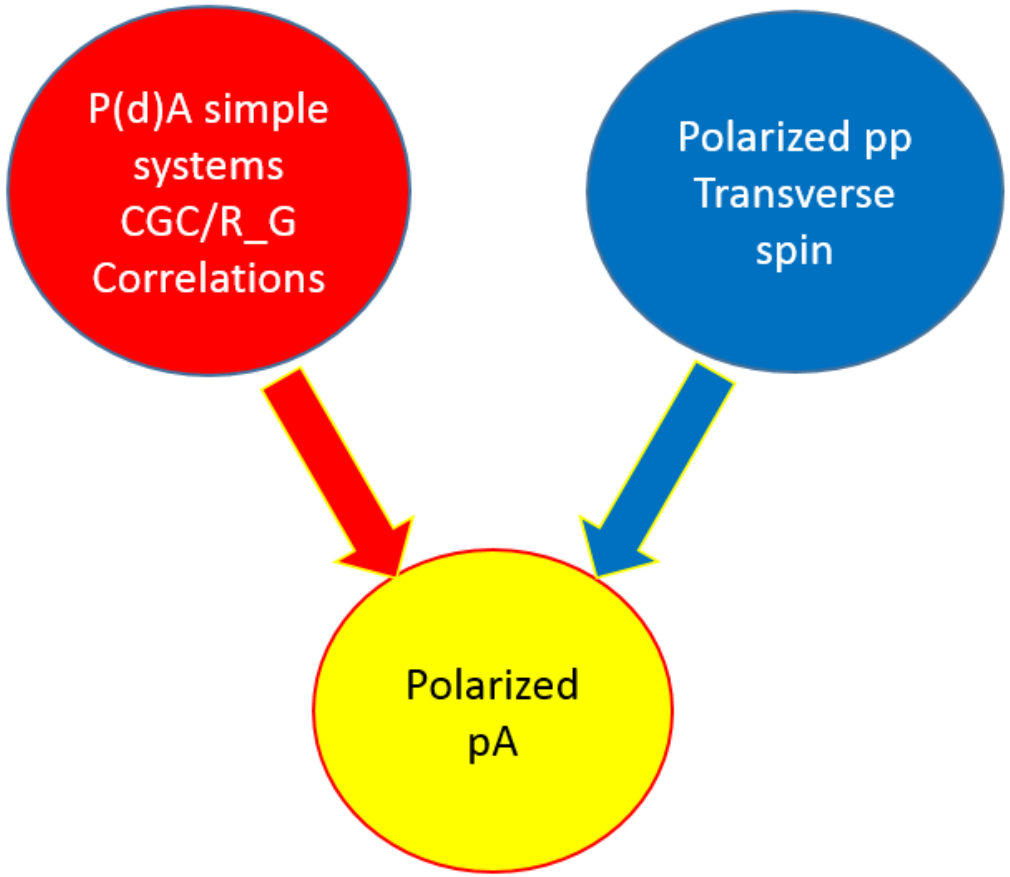


Kanazawa. Koike, Metz, Pitonyak, PRD 91 014013(2015)

There have been Issues in understanding SSAs such as the "sign mismatch" between the SIDIS extraction and the Twist -3 extraction.

A prompt photon measurement will add completely new information in understanding SSAs

A unique direction for RHIC: Polarized pA MPC-EX A_N to study Spin/Saturation



Spin Dependent Cross section in pA

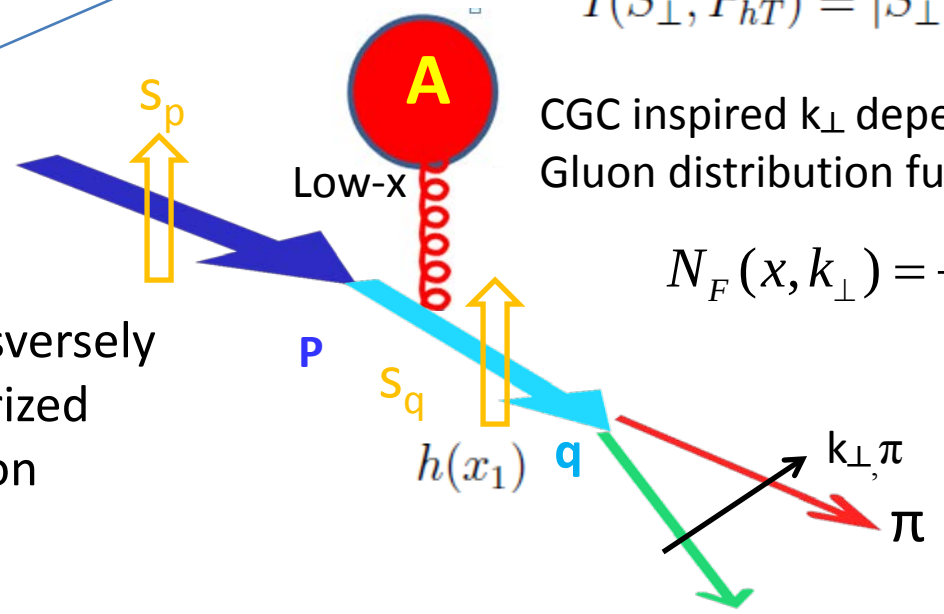
Kang, Yuan: PRD 84, 034019 (2011)

$$\frac{d\Delta\sigma}{dy_h d^2P_{h\perp}} = \frac{K}{(2\pi)^2}\int_{x_F}^{1}\frac{dz}{z^2}\int d^2P_{hT} I(S_\perp, P_{hT}) x_1 h(x_1) N_F(x_2, k_\perp)\delta\hat{q}(z, P_{hT})$$

$$\mathbf{P}_{h\perp} \approx z\,\mathbf{k}_\perp + \mathbf{P}_{hT}$$

Relative to Quark jet

$$I(S_\perp, P_{hT}) = |S_\perp||P_{hT}|\sin(\phi_h - \phi_s)$$



CGC inspired $k_\perp$ dependent unintegrated Gluon distribution function

$$N_F(x, k_\perp) = \frac{1}{Q_S^2} e^{-k_\perp^2/Q_S^2}$$

Transversely polarized proton

Collins Fragmentation Function

$$\delta\hat{q}(z, p_\perp^2) \sim \frac{1}{(\Delta^2 - \delta^2)^{3/2}} e^{-p_\perp^2/(\Delta^2-\delta^2)}$$

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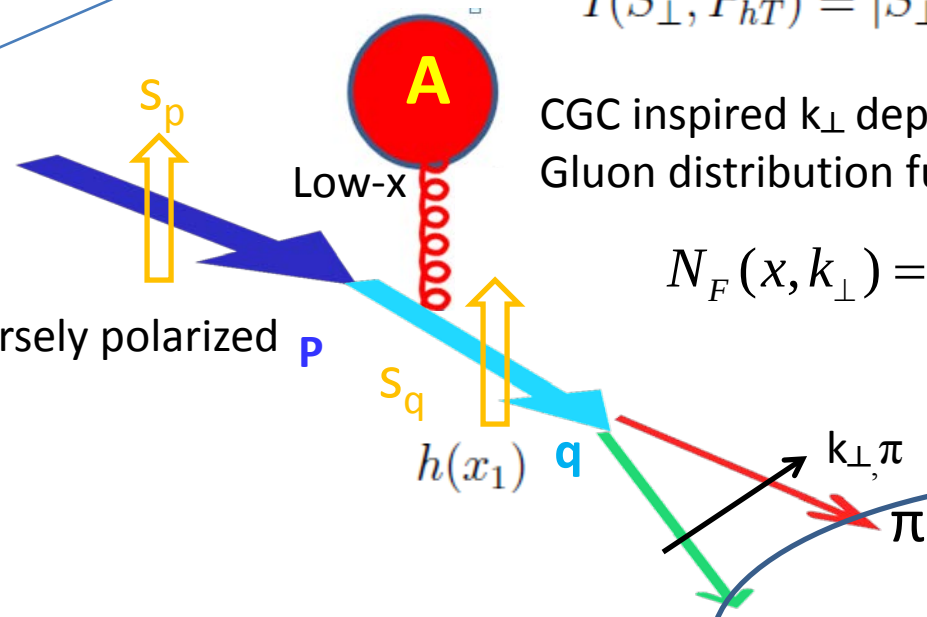

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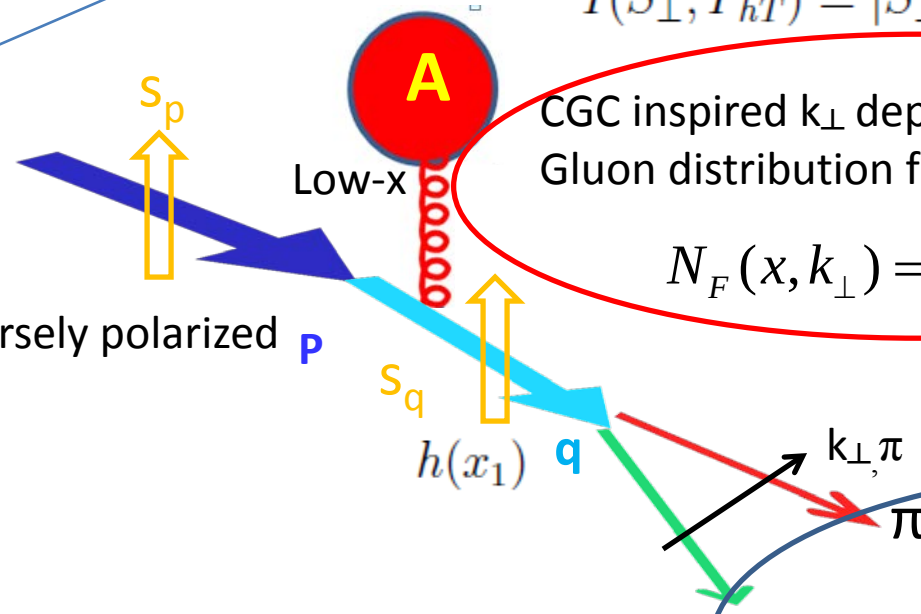

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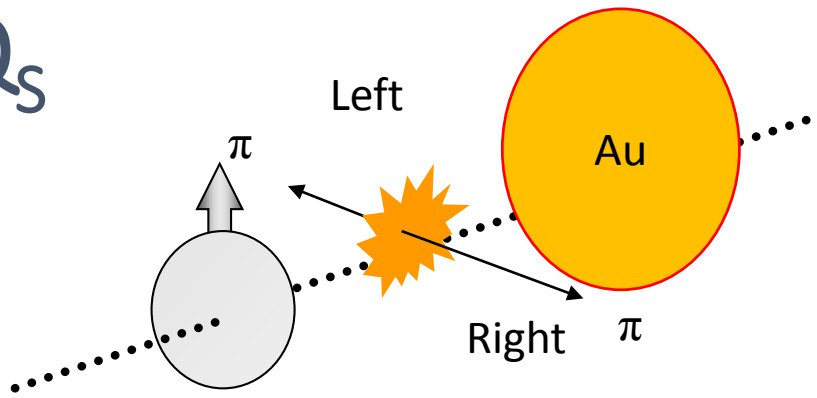
Polarized p+A Collisions as a measurement of Q_S



$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 << Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{P_{h\perp}^2 \delta^2 / Q_{sp}^2}$$

$$Q_{sat,A}^2 = cA^{1/3} Q_{sat,proton}$$

Kang, Yuan: PRD 84, 034019 (2011)

This is one mechanism. Others:
e.g. Sivers: see Boer et al. PRD 74, 074018
Kang-Xiao arXiv 1212.4309
Odderon (3 gluon)exchange: Kovchegov arXiv:1201.5890

- Dependence of Q_{sA} on *A, centrality*

➢ *Find* Q_S

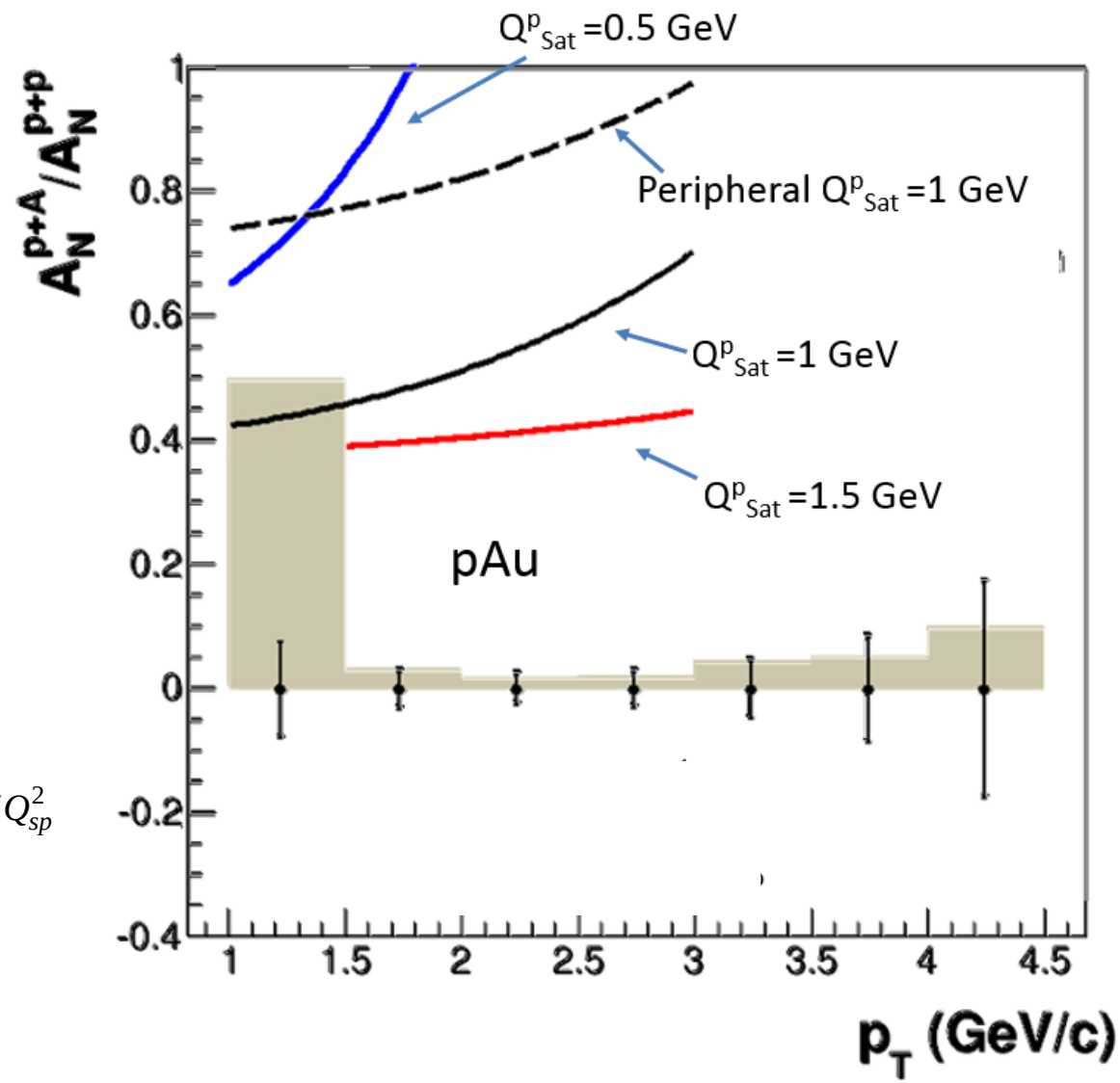
RHIC 2015 Polarized pA Run

- Dates: April 28- June 8 (45 days, 36 for physics)
- $\mathcal{L}$ (beginning of store) ~ $8.8 \times 10^{28}/cm^2$
- Pol = 55% (goal:60%)
- $\int \mathcal{L} dt$ = 198 nb^{-1} (goal: 190nb^{-1})
- reached pp goals as well

Projections for the 2015 data

L_{pAu}=190 nb^{-1}
L_{pp}=50 pb^{-1}
$|z|$<40 cm, P=60%

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 << Q_{sA}^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{P_{h\perp}^2 \delta^2 / Q_{sp}^2}$$



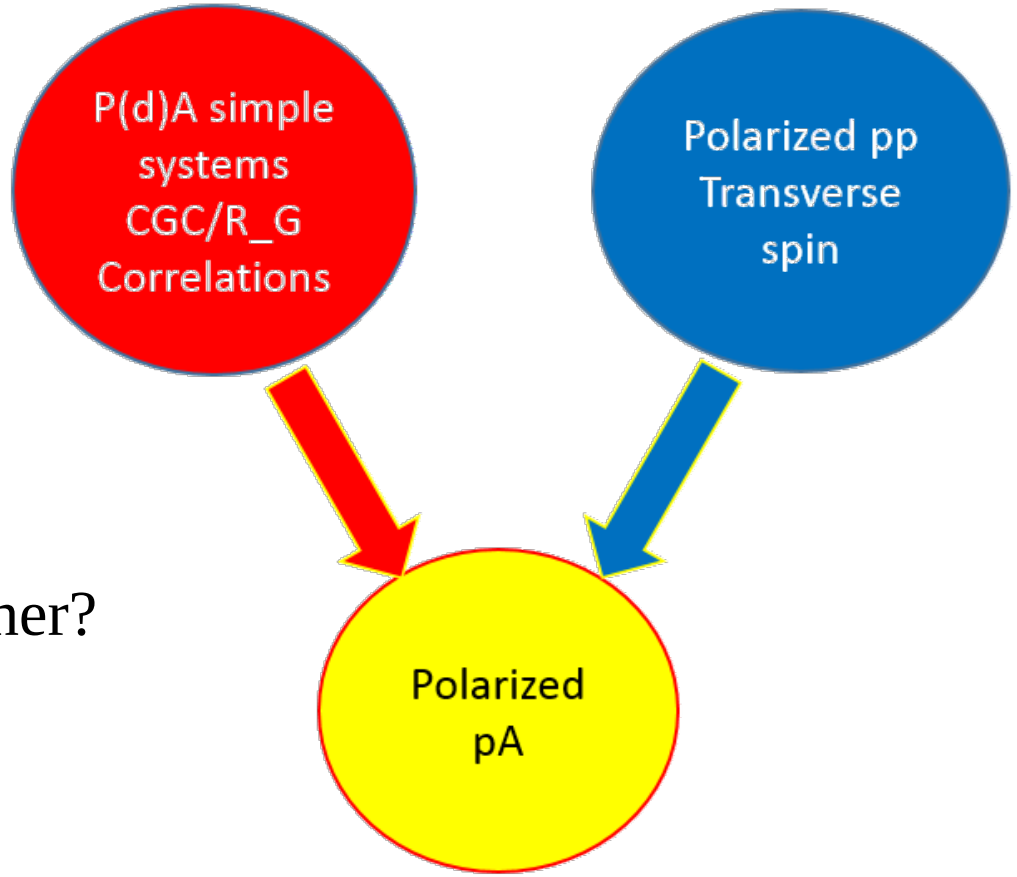
Kang and Yuan predict

$$\left.\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\right|_{P_{h\perp}^2 >> Q_{sA}^2} \to 1$$

Odderon mechanism (Kovchegov and Sievert) predicts → 0

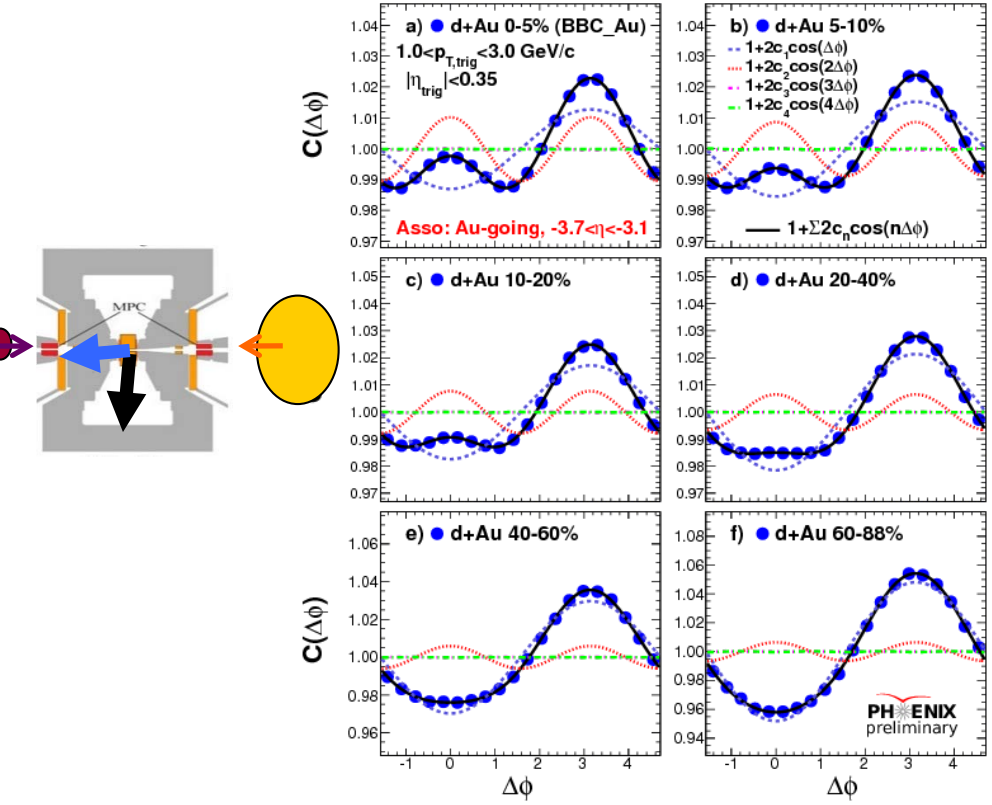
Summary: MPC/MPC-EX

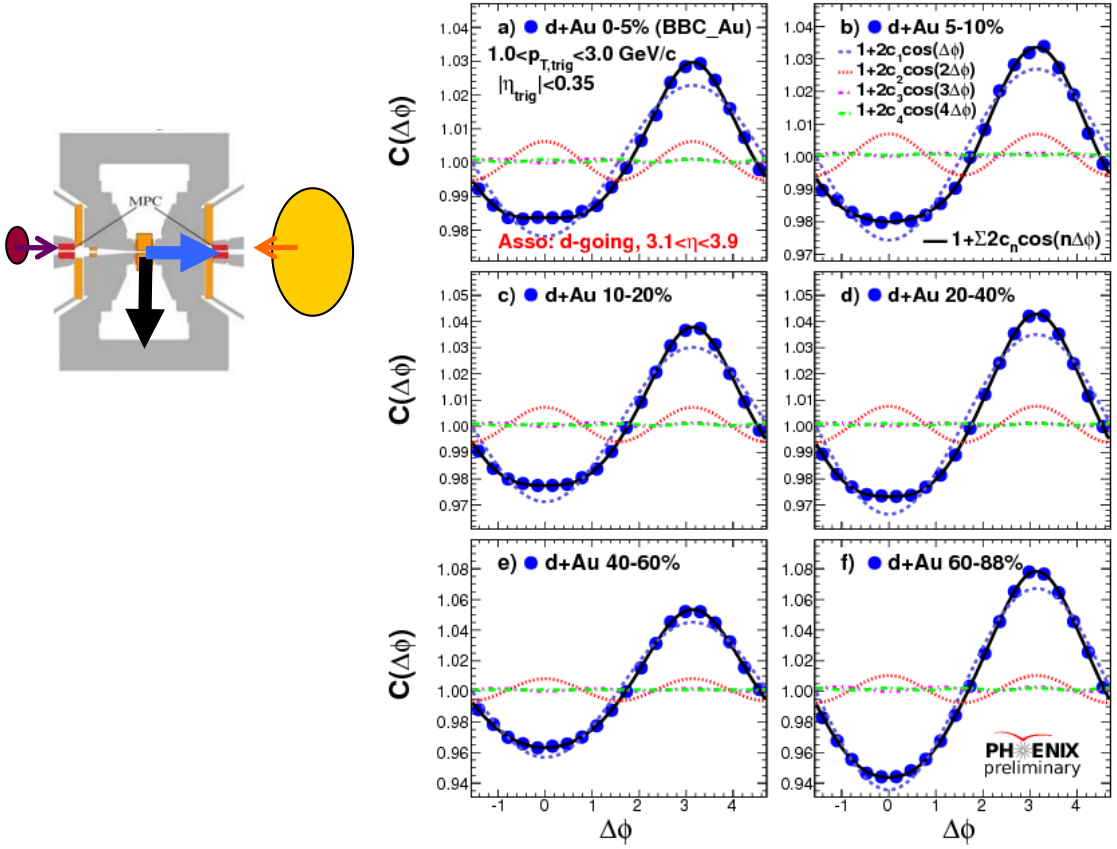
- pA, Simple systems
  - Saturation?
    - Suppression at low-x (yes)
    - γ at low-x
  - Long range correlations (QGP? CGC? Other?)
- Polarized pp, Understanding proton SSA
  - π^0, η SSA's exist at high energy? (yes)
  - Getting at the source: Sivers, Collins, both? other?
    - Behavior of A_N: p_T distribution, in hadron A_N (flat)
    - Prompt photon measurement
- polarized pA SSA
  - Getting at the saturation scale



Blue: first measurements done, more to do
Red: New measurements being done

Observations

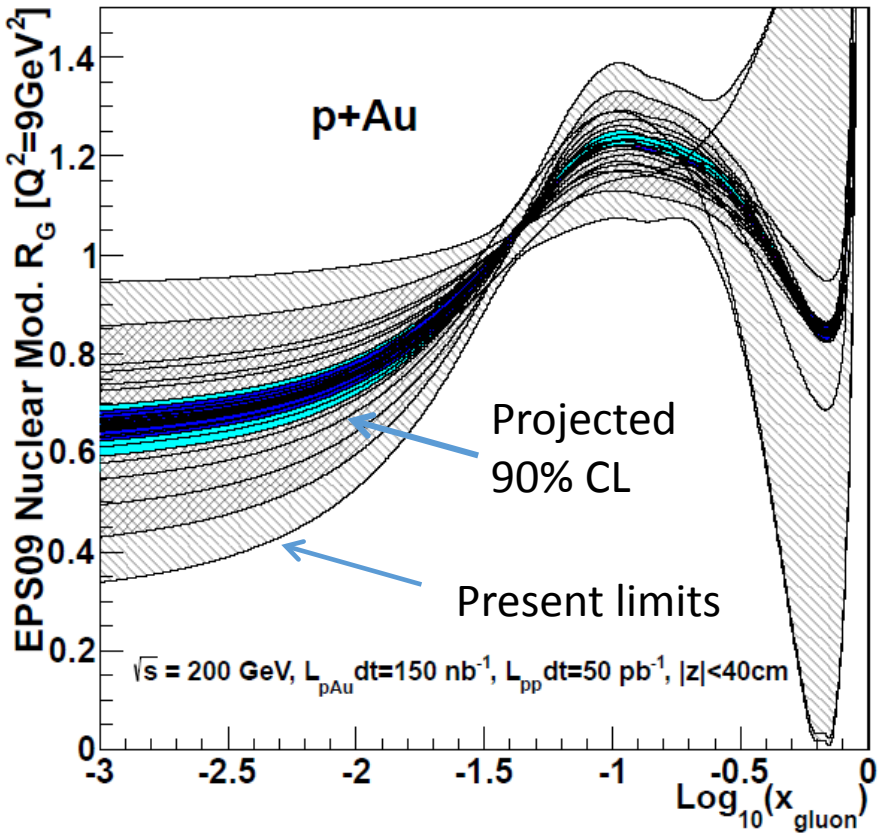




On Au going side
Centrality dependence as you might expect

On d going side, effect is weak

Projected γ_{dir} Measurement of nuclear gluon distribution as benchmark



- Weight events in x,Q^2 according to EPS09 to generate R_{dAu} for each curve
- Assume the R_{dAu} value we measure corresponds to the EPS09 baseline
- Vary R_γ^{pp}, R_γ^{dAu}, γ_{incl}^{dAu} and γ_{inc}^{pp} within 3σ systematic errors

$$R_{dAu} = \frac{1}{\langle N_{coll} \rangle} \frac{\gamma_{Incl}^{dAu} * (1 - 1/R_\gamma^{dAu})}{\gamma_{Incl}^{pp} * (1 - 1/R_\gamma^{pp})}$$

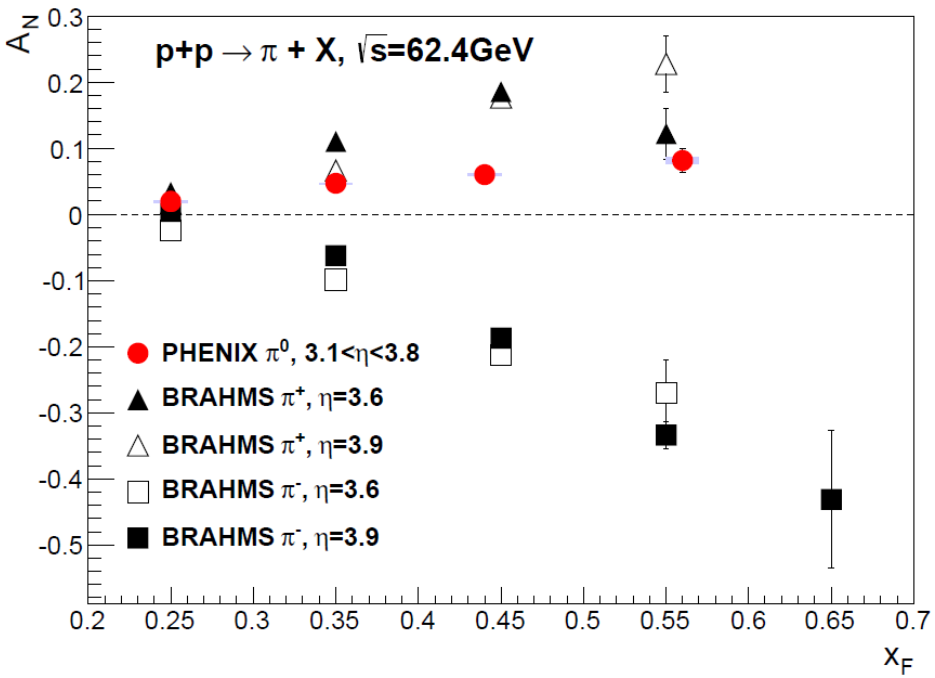
- Evaluate EPS09 curves to see which are consistent within 90% C.L.

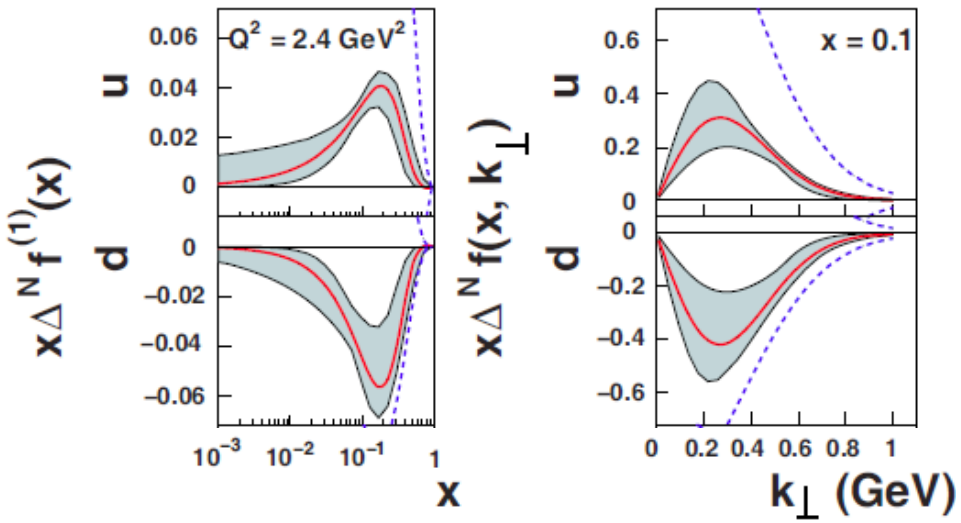
$$R_{dAu} \sim \text{Nuclear Mod. Factor } R_G = \frac{xG_{direct\,\gamma}^{pA}}{A\, xG_{direct\,\gamma}^{pp}}$$

Prompt photons in MPC-EX → Precise Measurement of the Nuclear Gluon PDF

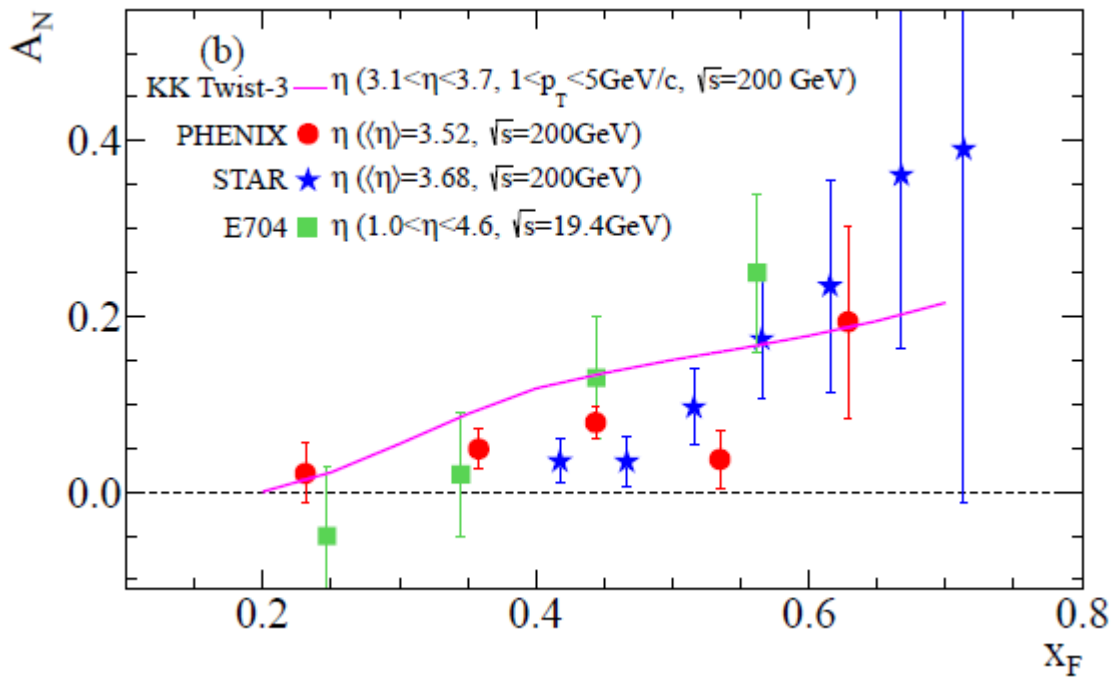
A measure of the initial state?….

Isospin comparison





Pythia:
Pi+ from u
Pi – from u and d
Pi0 from u, ¼ from d


(b)
KK Twist-3 η (3.1<η<3.7, 1<p_T<5GeV/c, √s=200 GeV)
PHENIX η (⟨η⟩=3.52, √s=200GeV)
STAR η (⟨η⟩=3.68, √s=200GeV)
E704 η (1.0<η<4.6, √s=19.4GeV)
A_N
0.4
0.2
0.0
0.2
0.4
0.6
0.8
x_F