Spin Physics with PHENIX Experiment's MPC-EX Calorimeter Upgrade

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- for RHIC Run-15 p+p and p+A collisions at $\sqrt{s}$=200 GeV .
  Covering: $3.1 < \eta < 3.8$, for high energy photon and π^0 detection.

New observables in p↑+p and p↑+A with MPC-EX, for example:

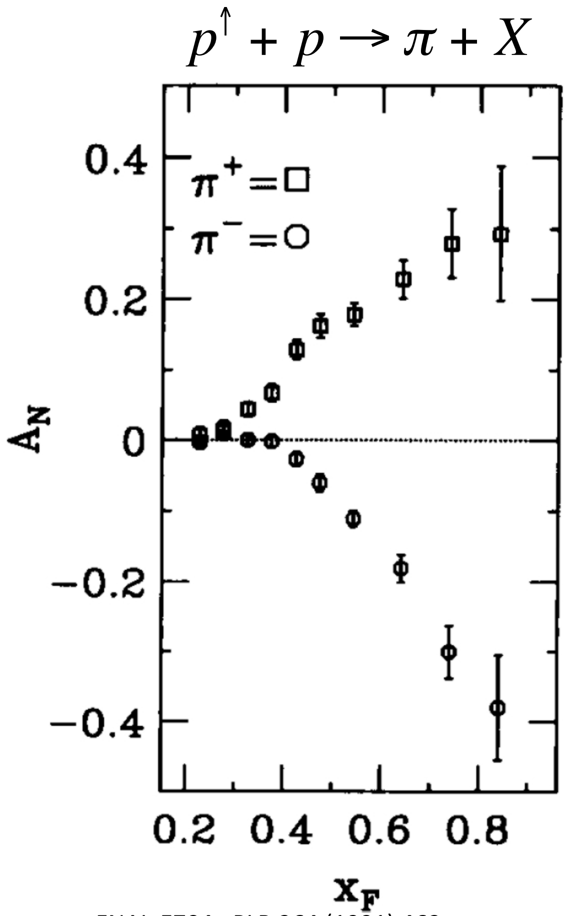
- In p↑+p, prompt photon A_N to access valence quark Sivers distribution and their feature of "process-dependency", resolving the issue of "Sivers function sign mismatch".

- In p↑+A, π^0 single-spin asymmetry, to access gluon saturation effects.

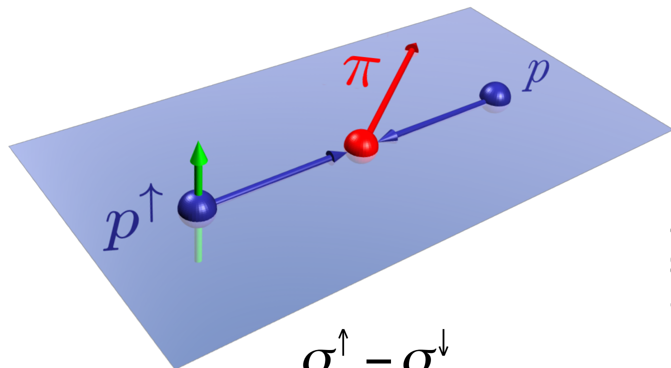
PHENIX

More details in: arXiv:1301.1096

Quarks can tell left-right in $p\, p^{\uparrow} \rightarrow \pi X$



FNAL-E704: PLB 264 (1991) 462.



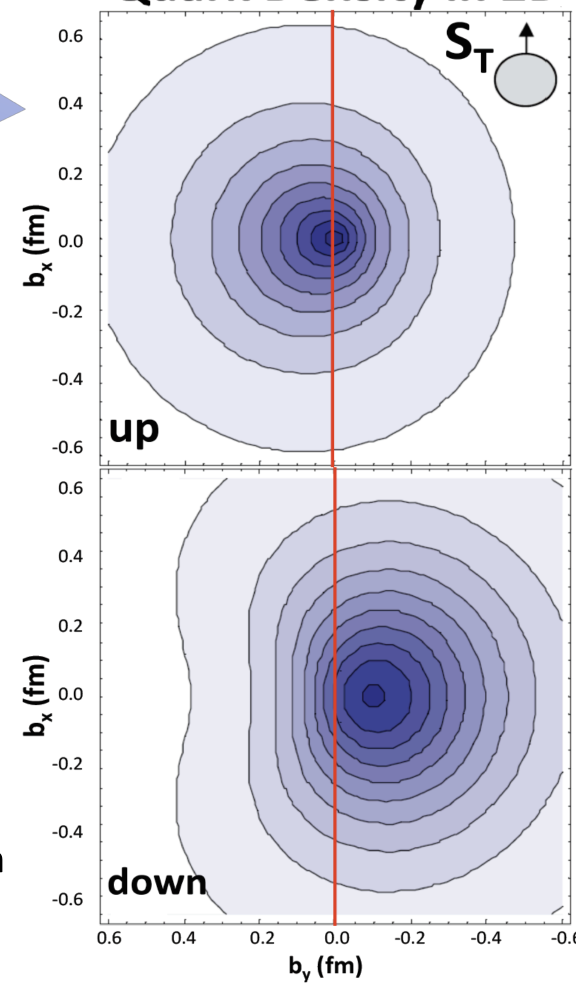
$$A_N = \frac{\sigma^{\uparrow} - \sigma^{\downarrow}}{\sigma^{\uparrow} + \sigma^{\downarrow}}$$

$\pi^+ (u\bar{d})$ favors left

$\pi^- (d\bar{u})$ favors right

One possible explanation (Sivers effect): quark's transverse motion generates a left-right bias.

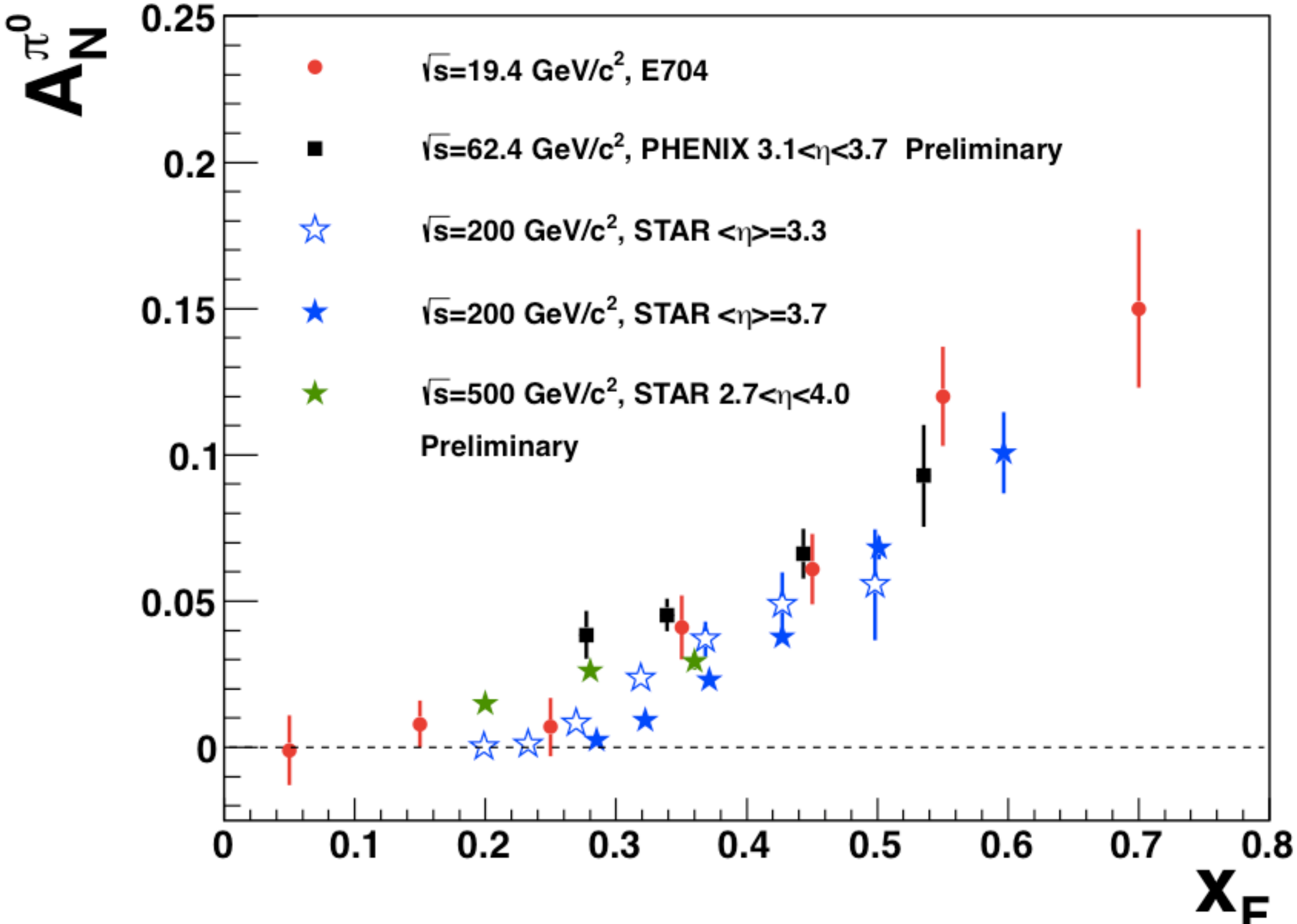
Quark Density in 2D



Lattice QCD PRL98:222001,2007.

up-quarks favor left (L_u>0), down-quarks favor right (L_d<0).

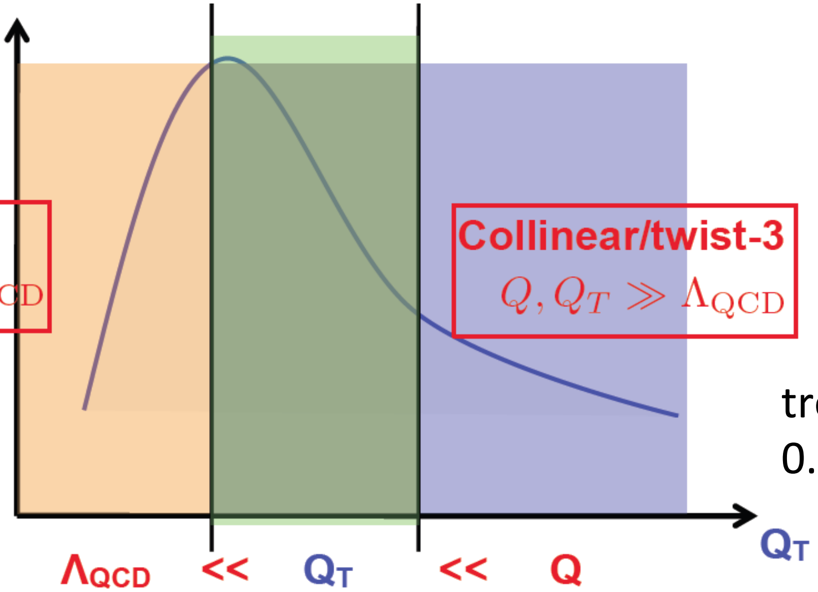
π^0 A_N in PHENIX (MPC) and STAR



- STAR/PHENIX have measured large SSA's for neutral pions and eta mesons
- Current measurements cannot address the <u>source</u> of these asymmetries
  - Need more targeted measurements

Two types of theoretical framework to describe SSA phenomena in SIDIS, and in p+p

TMD Factorization and Collinear Twist-3 Factorization



- Transversity
- Sivers distribution
- Collins fragmentation function
- Other spin-dependent frag. func…

linked

- Twist-3 quark-gluon correlation function (ETQS), tri-gluon correlation function …
- Twist-3 fragmentation functions…

One expects consistency of the two approaches, when gauge invariance is accounted:

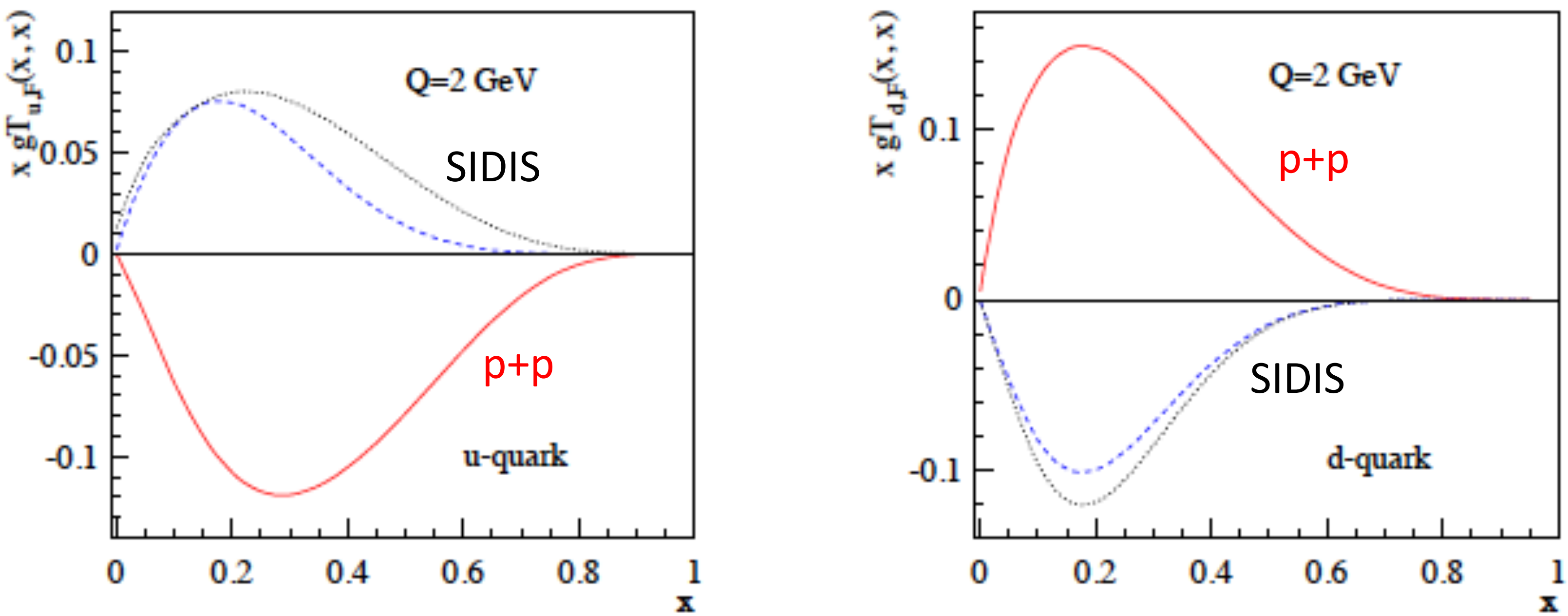
$$gT_{q,F}(x,x) = -\int d^2k_\perp \frac{|k_\perp|^2}{M} f_{1T}^{\perp q}(x,k_\perp^2)|_{\rm SIDIS}$$

ETQS

Sivers distribution

g: gauge line factor, process dependent

SIDIS vs p+p: Interpretation Disagree



SIDIS: final state interaction only.
p+p: both initial state and final state interactions.

Data covered different x-range. Sivers distribution has a rapid sign change at high-x ?
Major flaws in theory ? Unknown physics ?

MPC-EX: provide p+p data ($0.3<x<0.7$) to be compared with JLab-12GeV.

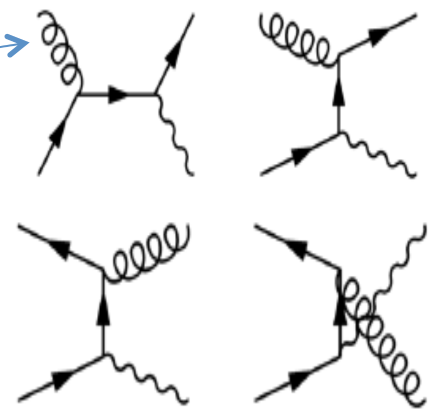
Inconsistencies and controversies will lead to discoveries.

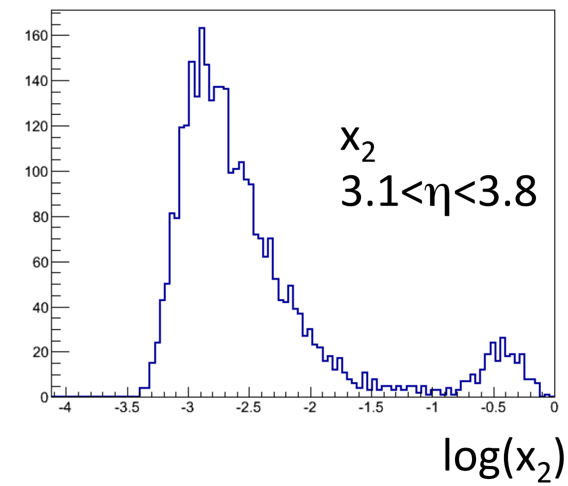
Prompt Photons at Forward Rapidity

a high-x valence quark from p↑ on a low-x gluon from p (or A).

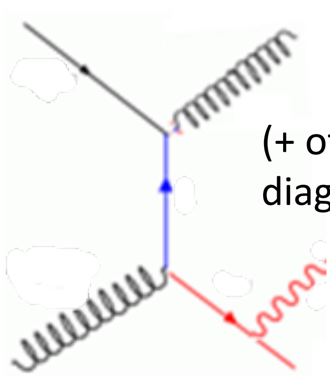
Direct Photons
Dominated by gluon Compton at forward rapidites

Same level of production in pythia and NLO calculations (within factor of ~2)



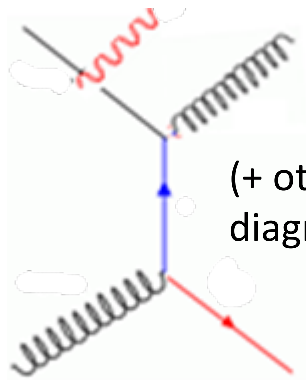


Fragmentation Photons
Comparable between pythia and NLO calculations

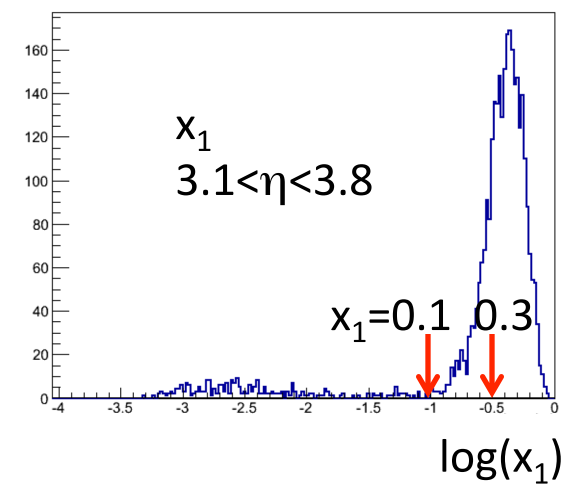


(+ other diagrams)

QED Radiation (initial state)
Production over-estimated in Pythia (Included in direct in NLO)

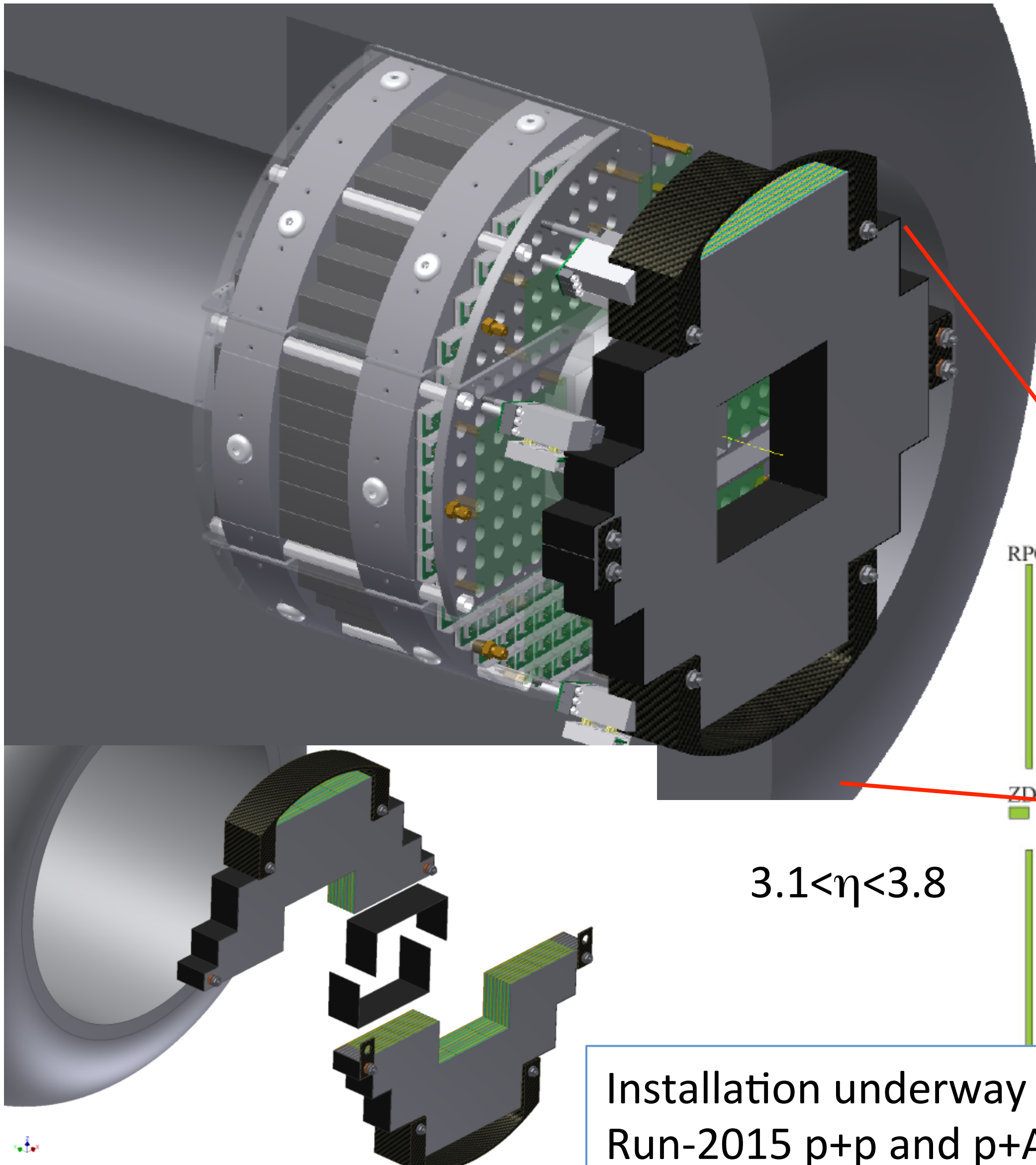


(+ other diagrams)



p↑+p : high-x quarks effects
p+A : low-x gluon effect

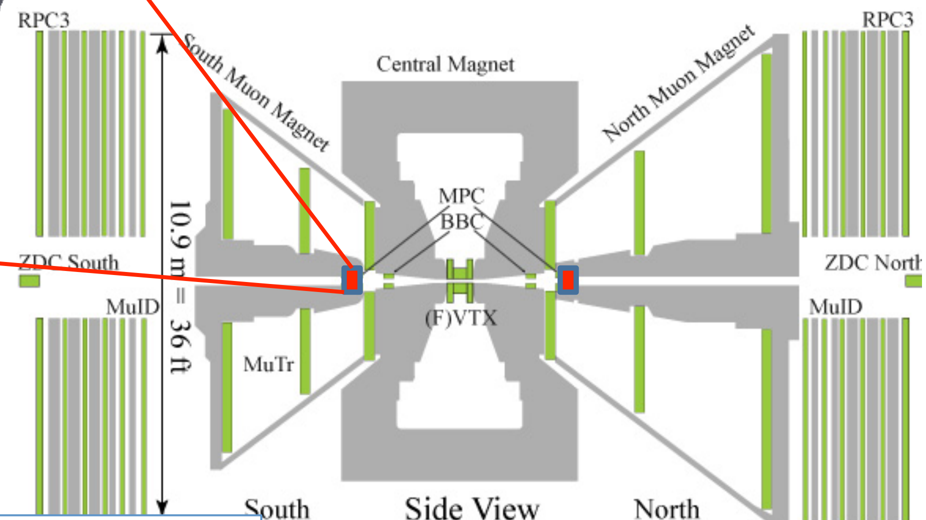
The MPC-EX Detector



A combined charged particle tracker and EM pre-shower detector – dual gain readout allows sensitivity to MIPs and full energy EM showers.

- π^0 rejection (direct photons)
- π^0 reconstruction out to >80GeV
- Charged track identification

$3.1<\eta<3.8$

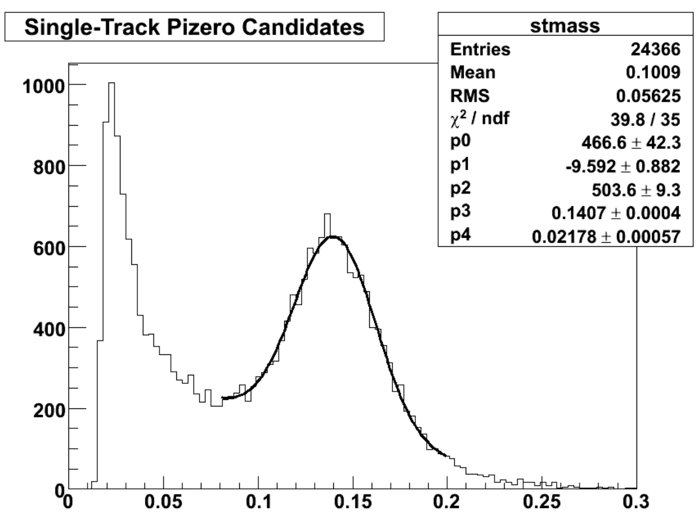


Installation underway for Run-2015 p+p and p+A run

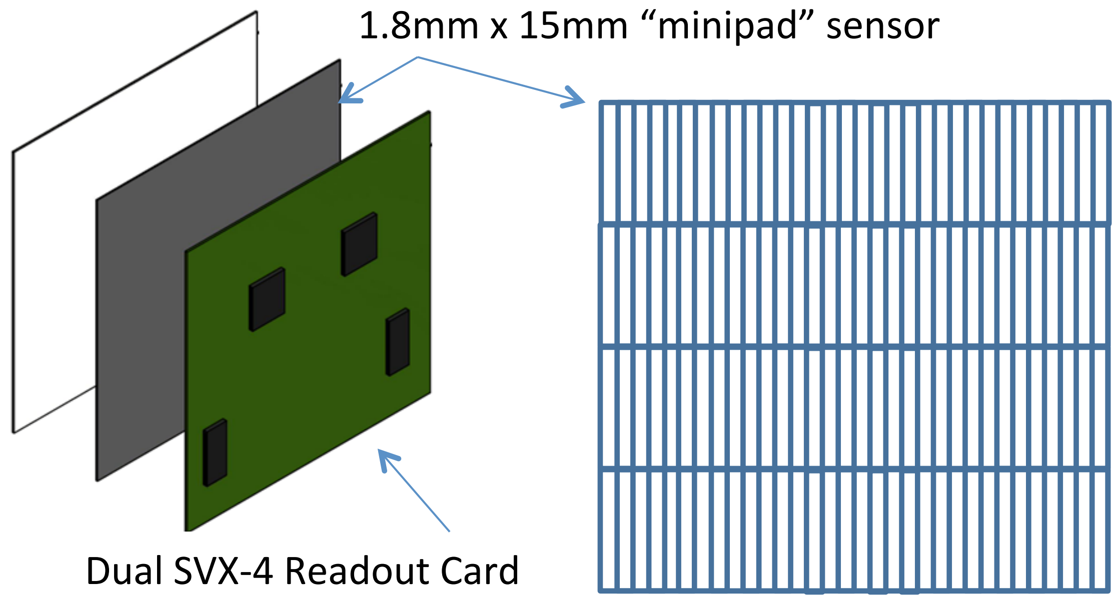
Minipad Sensors

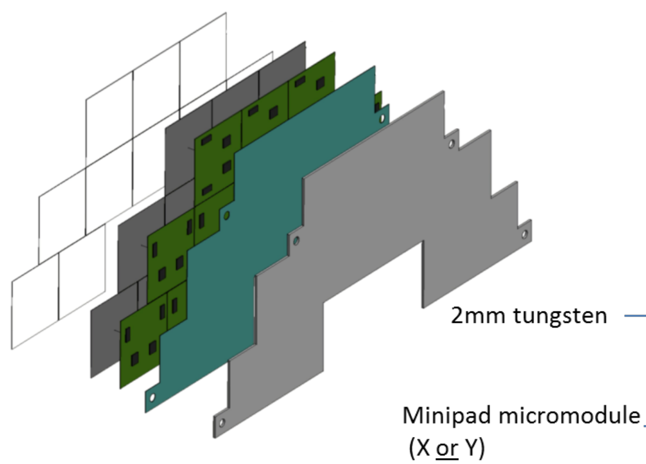
Detector elements are Si "minipad" detectors, one per tungsten gap, oriented in X and Y (alternating layers).

π^0 mesons reconstructed in p+p jet events (E>20GeV)

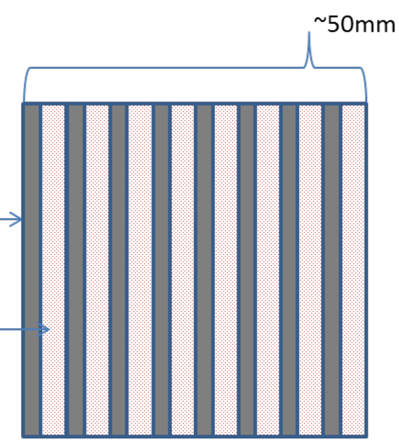


simulation



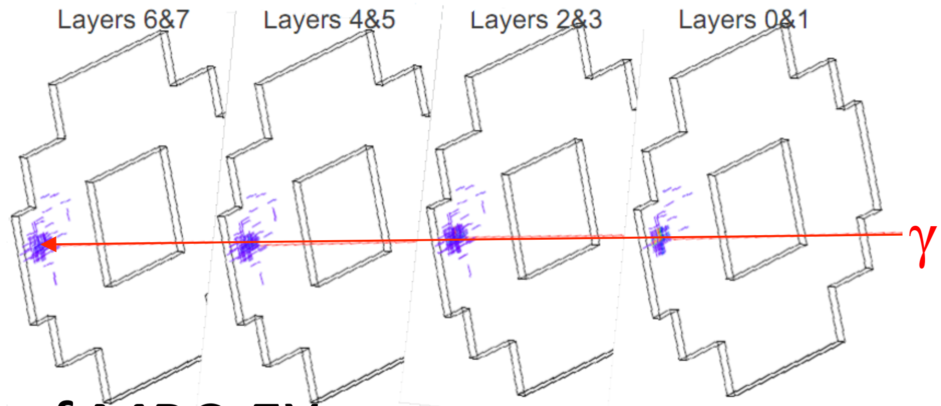


Cross-Section View:

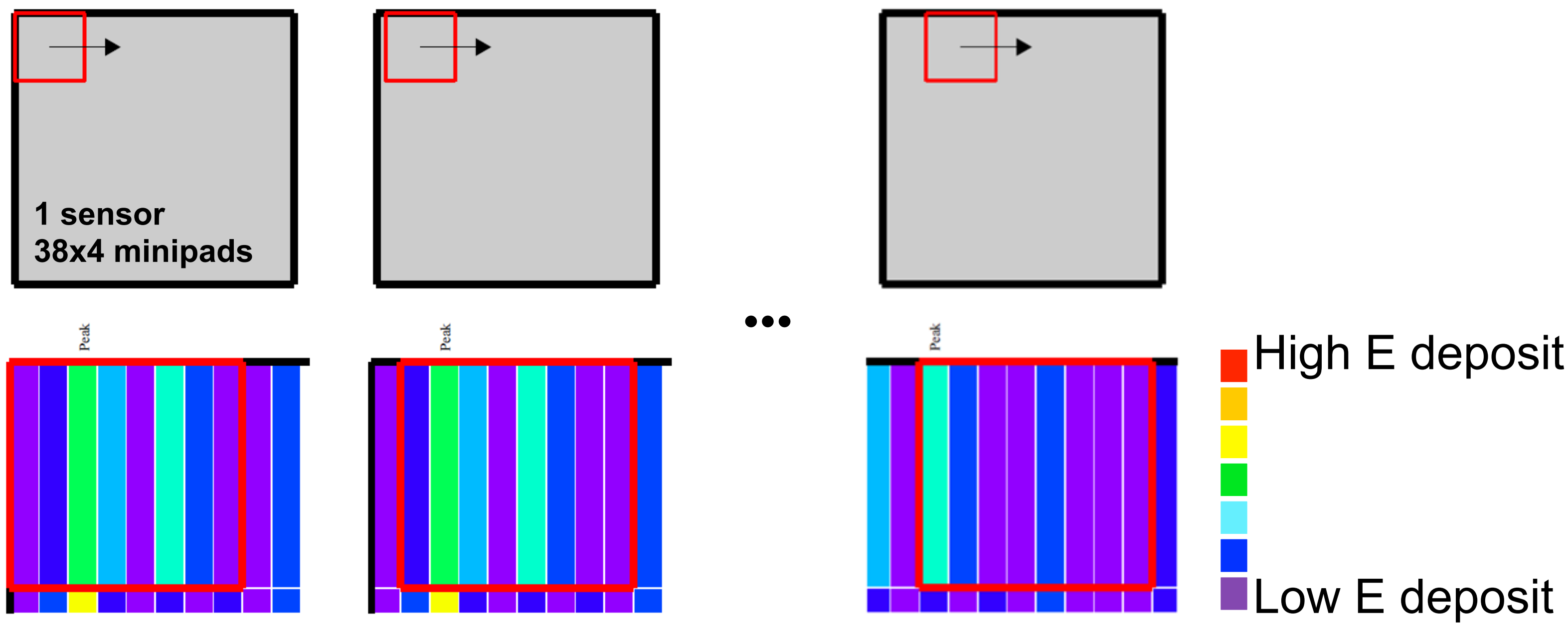


Cluster reconstruction

- Separately sum energy in x and y towers

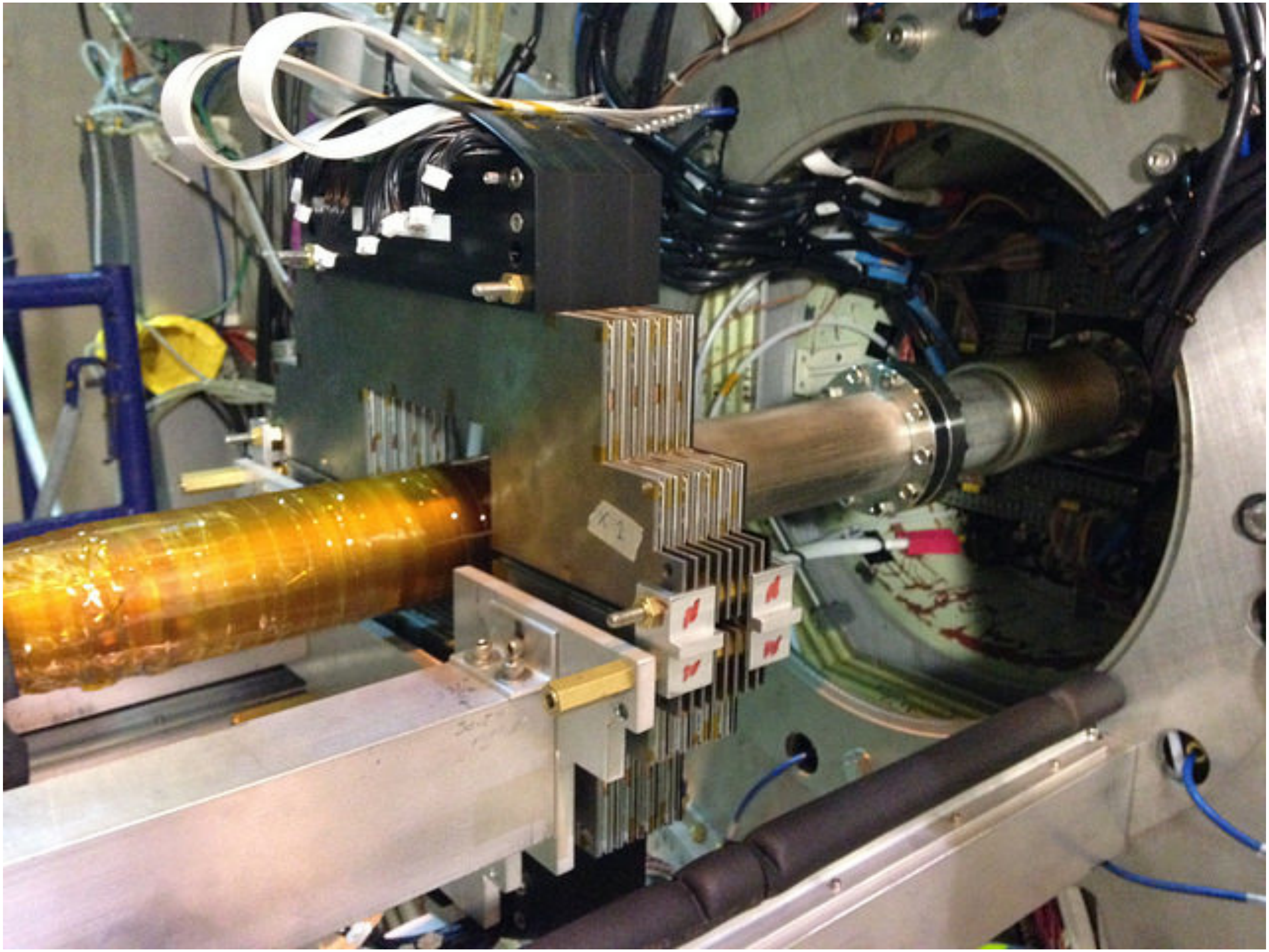


- Identify local maxima in scan of MPC-EX



  – Energy and position of clusters are found

North Side MPC-EX Installed Oct. 15th, 2014



The MPC-EX Physics Program

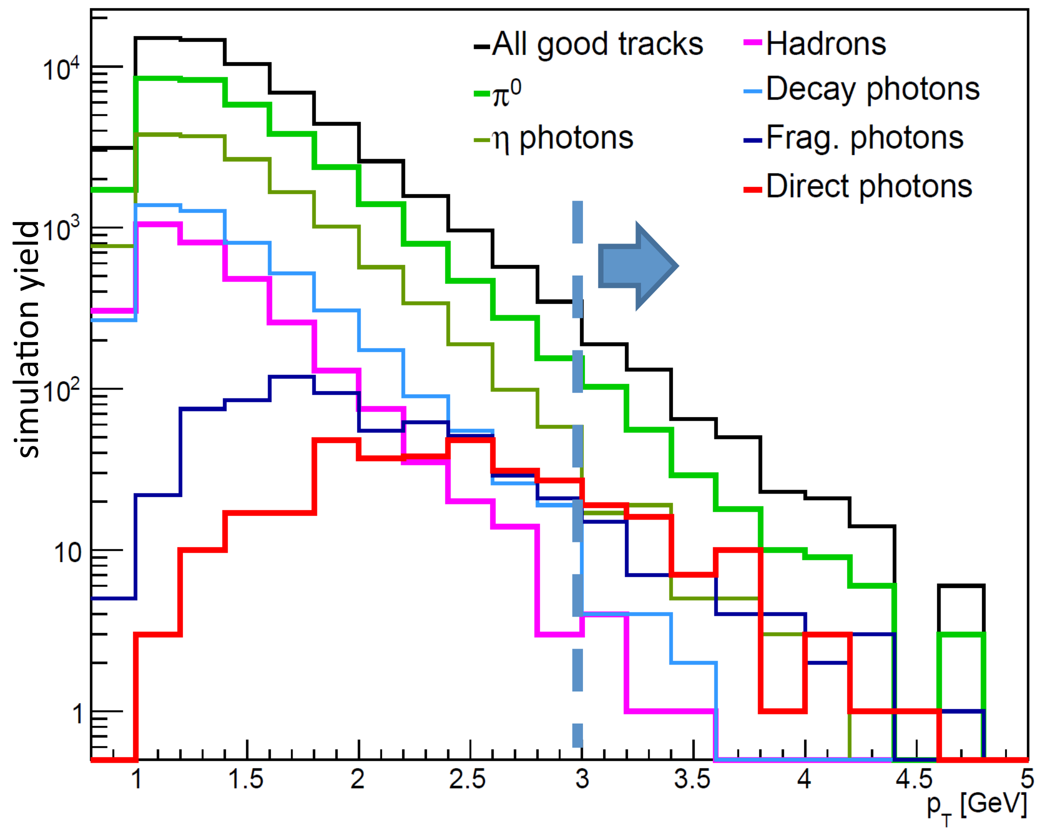
- **The Gluon Distribution in Cold Nuclear Matter at Low-x:**
  - Single π^0 production
  - π^0 pairs
  - **Prompt Photons**

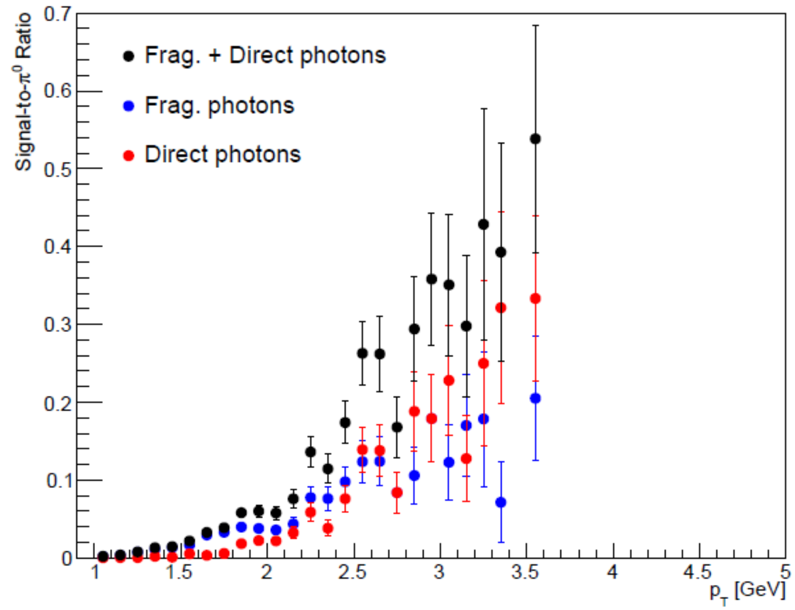
Extended kinematic range for existing measurements (p_T>1 GeV/c, E>20GeV)

- **Source of A_N in $p^{\uparrow}$+p Collisions:**
  - **Prompt Photon A_N**
  - **π^0 correlations with jet-like clusters**
    - "pioneering" measurement
  - A_N in "jet-like events".

Prompt Photon Simulations (π^0 cuts)

868M pythia MB+direct photon events





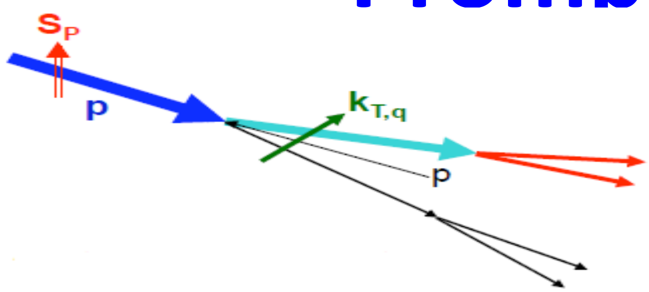
Basic cuts designed to remove π^0, charged hadrons and other backgrounds.

For p_T>3 GeV:

2.9% efficiency for π^0
31.2% efficiency for direct photons

dir/(frag+dir): 57.4%

Prompt Photon A_N (x_F>0)



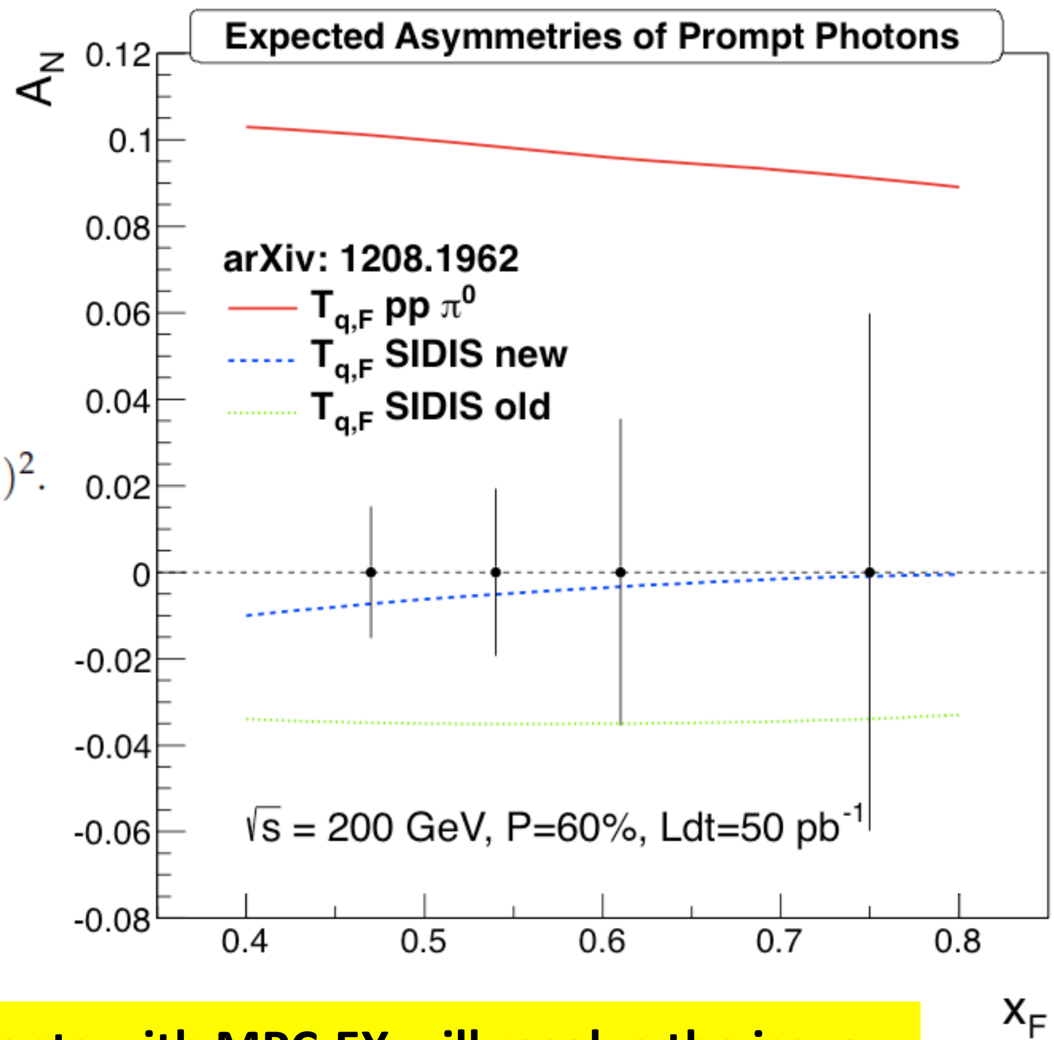
$$A_S = (1+\frac{1}{r})A_{meas} - \frac{1}{r}A_B.$$

r= S/B = 0.34

$$(\delta A_S)^2 = (1+\frac{1}{r})^2(\delta A_{meas})^2 + (\frac{1}{r})^2(\delta A_B)^2.$$

- Prompt Photon A_N
  - Excellent probe for Sivers
  - Projected error bars assume statistical errors, subtraction of π^0 and η photon asymmetry, and 60% polarization

Phys Rev. D 83 094001 (2011)



Prompt photon measurements with MPC-EX will resolve the issue.

Prompt Photon A_N (x_F<0)

Phys Rev. D 85 034030 (2012)

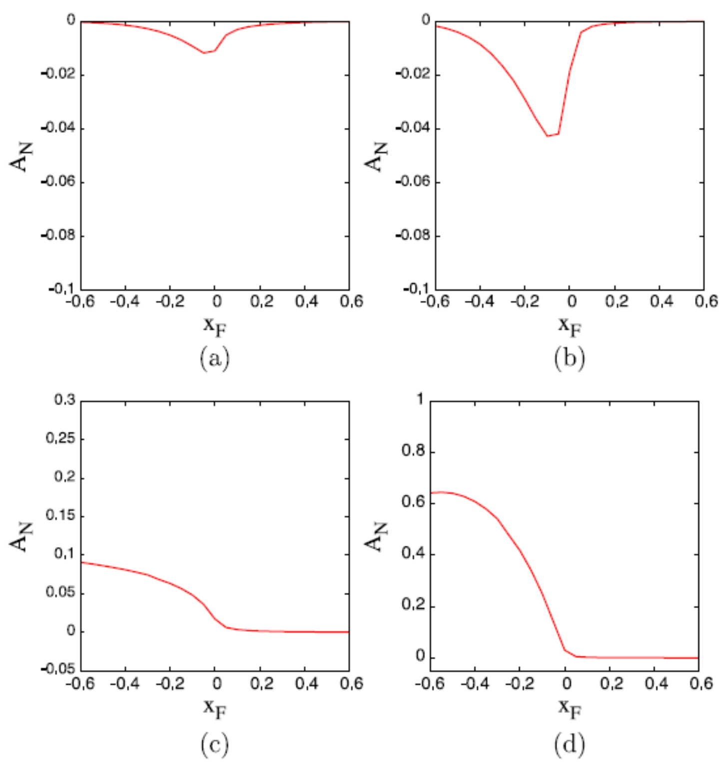
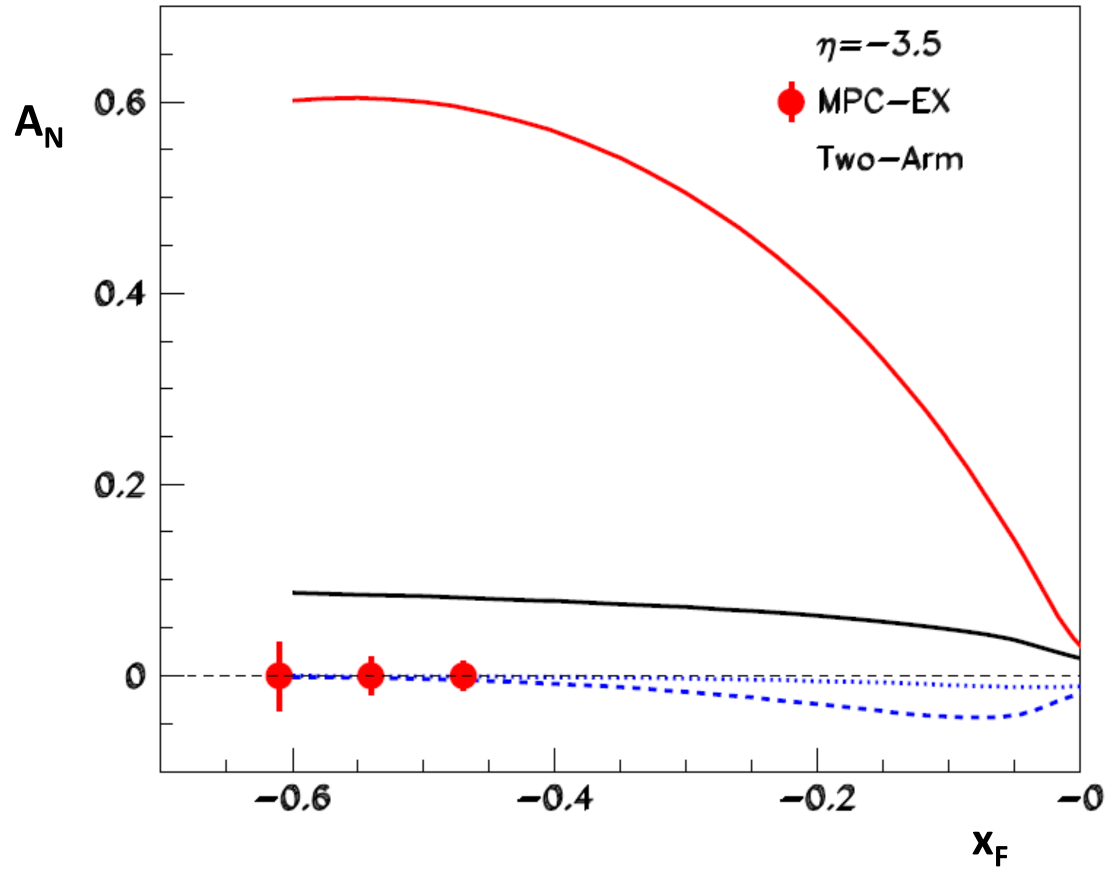
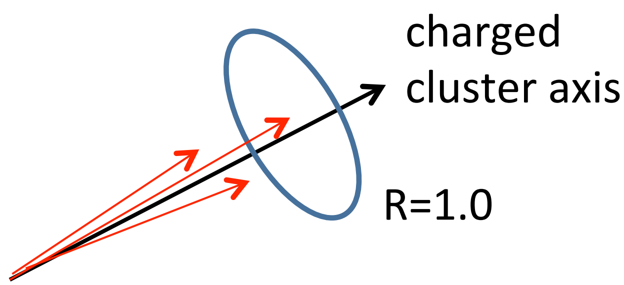


FIG. 3 (color online). A_N^γ as a function of x_F at the RHIC energy $\sqrt{S}$ = 200 GeV and q_T = 2 GeV. (a) A_N^γ for the case 1 with the model 1. (b) A_N^γ for the case 1 with the model 2. (c) A_N^γ for the case 2 with the model 1. (d) A_N^γ for the case 2 with the model 2.

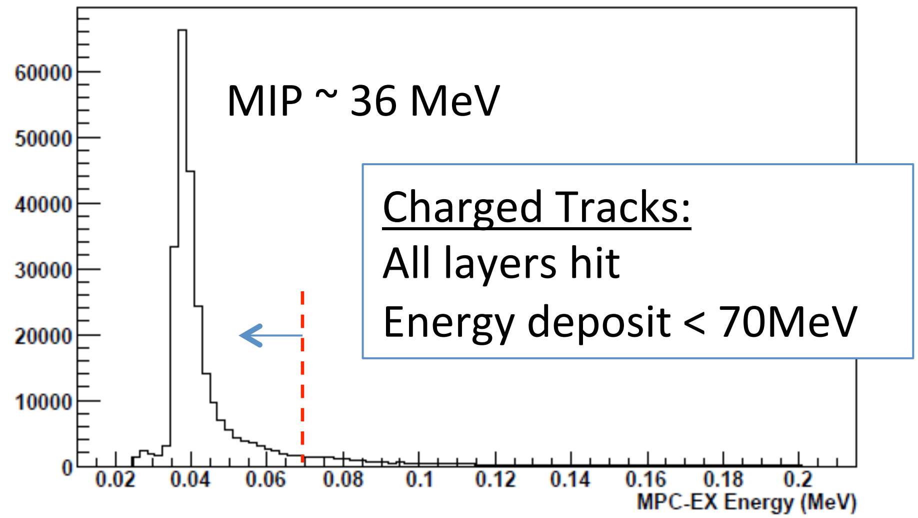


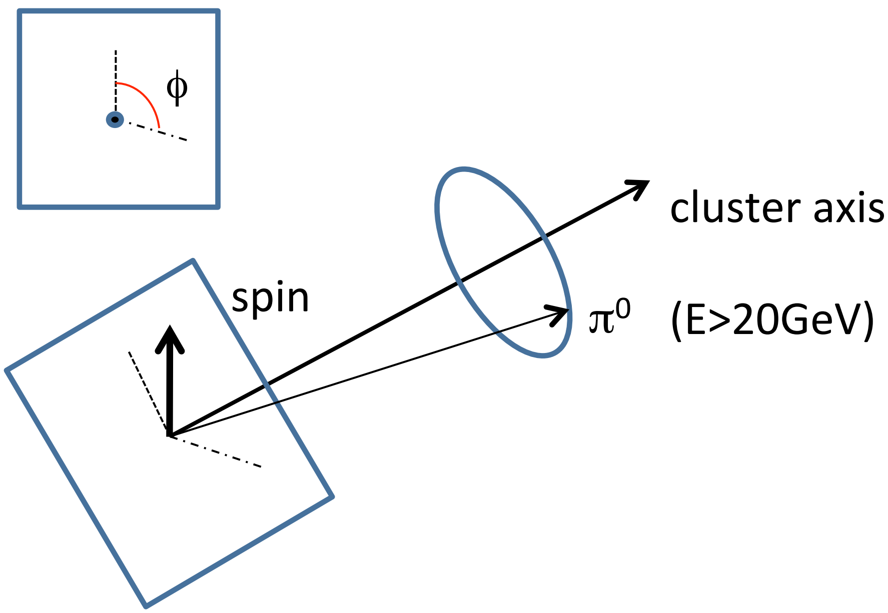
Prompt photon A_N for x_F<0 carries information about the tri-gluon correlation function.

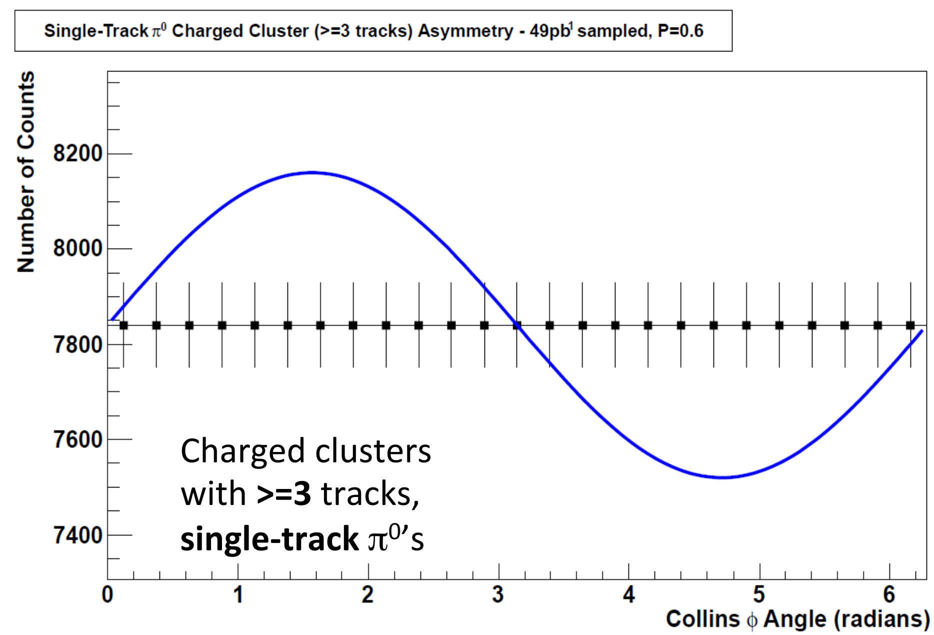
Collins Asymmetry in Jets



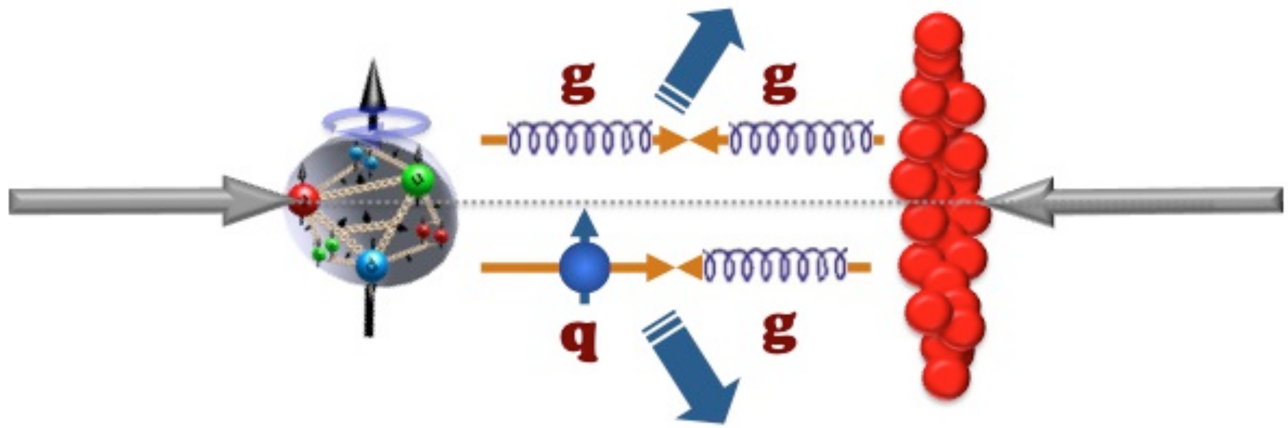
- All tracks given equal weight
- Select the cluster with highest number of tracks







p↑+A@RHIC and PHENIX with MPC-EX



- Recent developments on polarized p↑+p and p↑+A measurements for RHIC Run2015.
- Physics opportunities for PHENIX with MPC-EX in Run2015.

Back in Jan. 2013, a pA@RHIC workshop was held at BNL

- A dedicated workshop on polarized proton and ion collision at RHIC.
  - Goal was to explore the physics program as well as the feasibility of the RHIC collider
  - About 100 participants.
  - Presentations include:
    - Theory overviews (spin dependent and spin-independent observables).
    - LHC p+Pb results from 2012 test run.
    - Results from past p+A fixed target measurements (AGS and FNAL)
    - Machine and detector feasibility studies and practical issues.
    - Plans of detector upgrades (PHENIX and STAR) and new ideas (zero degree EM shower detectors).

Both STAR and PHENIX set p↑+p and p↑+A runs as the main goal for Run-2015.

pA@RHIC: Motivations

- p+A collision is an excellent probe to access the deep secrets of the nuclei, and to probe the gluon saturation effect as well as other nuclear effects
  - Gluon density distribution in a nuclei
  - Transvers momentum broadening.
  - Transverse spin effects through nuclear medium.
- LHC p+p and p+Pb pilot run has yielded many interesting results
  - for example, away side ridge was observed through correlations.

pA@RHIC Motivations: Single-Spin Asymmetry to probe gluon saturation effects in nuclei

- The possibility of polarized proton and ion collision opens a new territory beyond pA@LHC.
  - probing the source of transverse asymmetry
  - providing additional observables for the saturation physics study

$$\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2 \delta^2}{Q_{sp}^4}} \qquad \frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\gg Q_s^2} \approx 1$$

Kang, et al,

pA@RHIC vs. pA@LHC

- RHIC was designed to independent bending fields for two beams. LHC is a two-in-one dipole ring, i.e. identical bending field for the two beams
  – More ion species at RHIC than at LHC, which allows the measurement of saturation effect as function of A
    - from deuteron to Uranium
- RHIC can access the low energy part that is not available to LHC
- High energy polarized proton beams is absolutely unique to RHIC
  – Measure Single-Spin Asymmetries
  – More sensitive observable for saturation effects

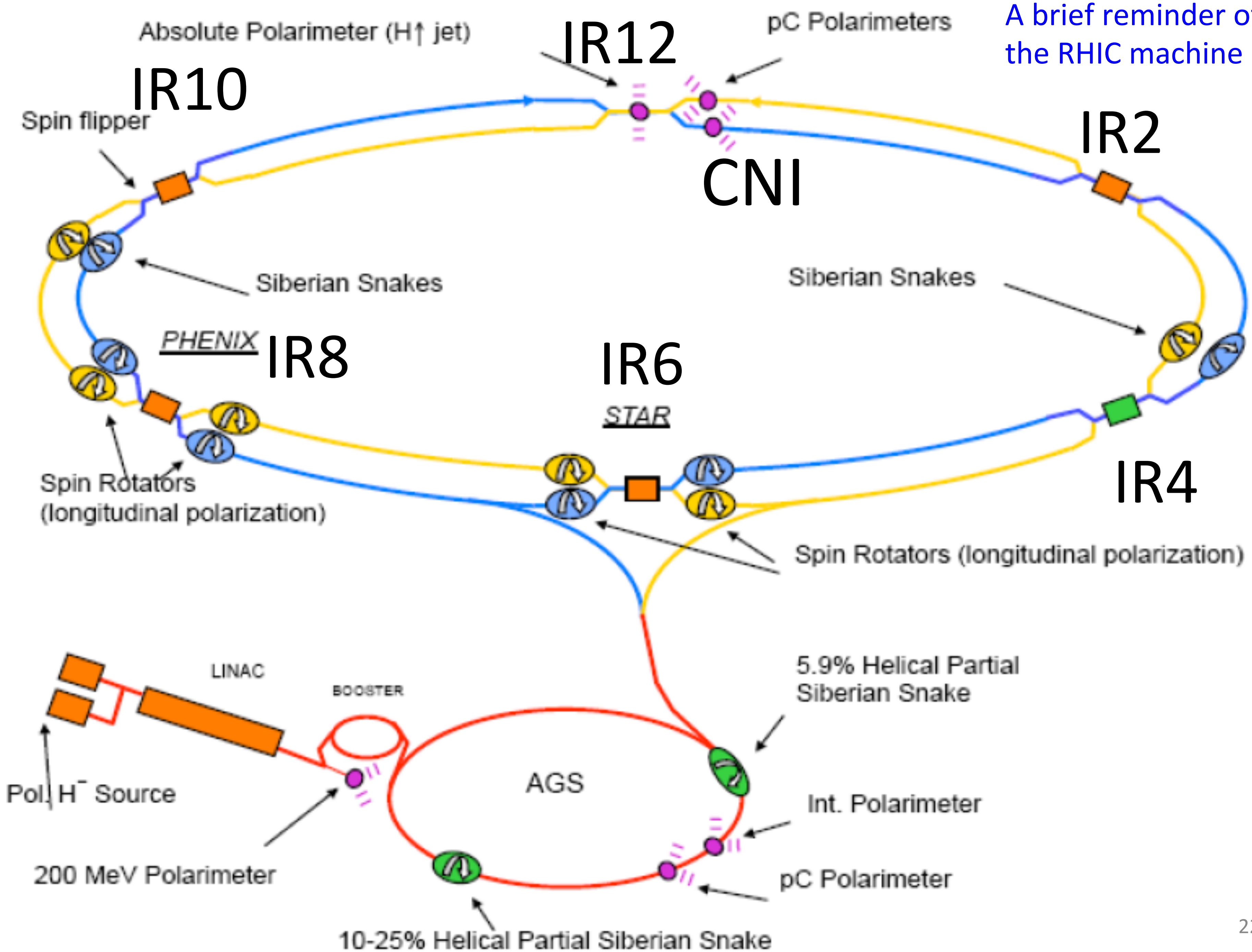
RHIC Machine Capabilities

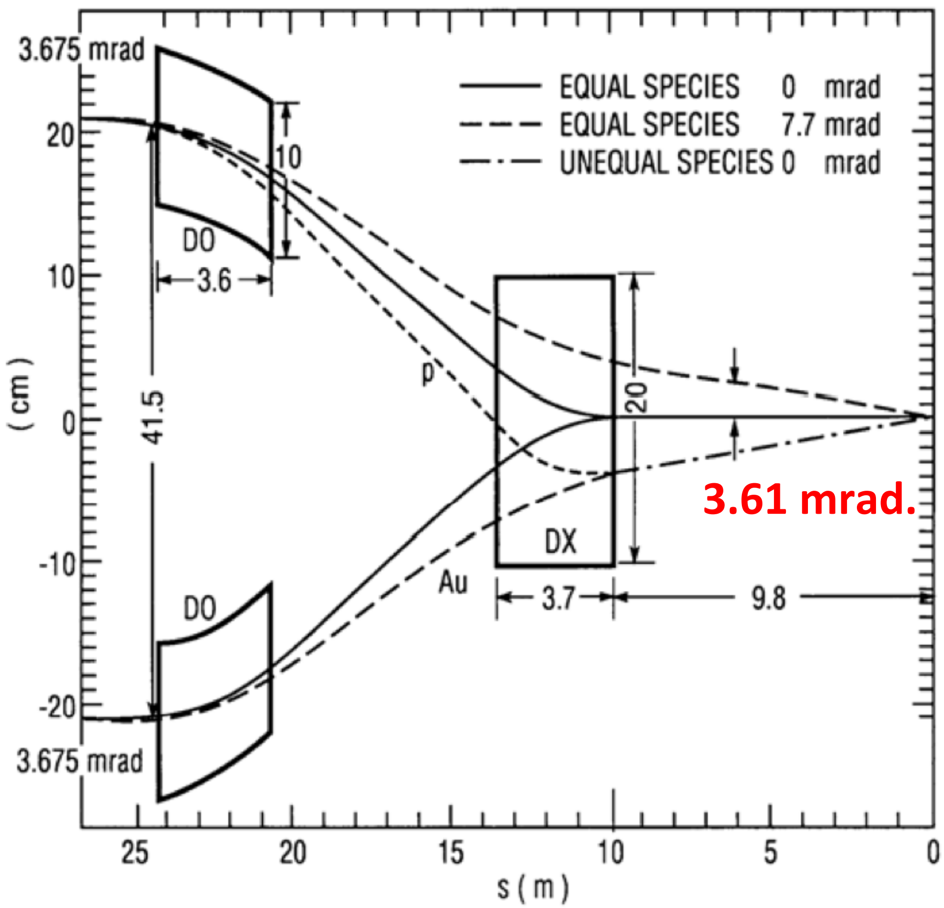
- RHIC was originally designed to accommodate asymmetric collision including p+A collisions.

Two independent rings, except for the DX magnets near collision points.

- – The DX magnets was designed to be moved sideways to center on the beam trajectory in the case of asymmetric collisions
- – The DX magnet was also designed to have adequate field uniformity in the case of asymmetric operation
- – d+Au collision has been part of RHIC operation since 2003.
- – In 2012 Cu+Au , in 2014 3He+Au collisions were also provided.
- – New EBIS source can also provide other ions (^{12}C, ^{14}N, ^{28}Si, ^{63}Cu, ^{197}Au, ^{208}Pb …Au beam with N_b = 2x10^9)

A brief reminder of the RHIC machine



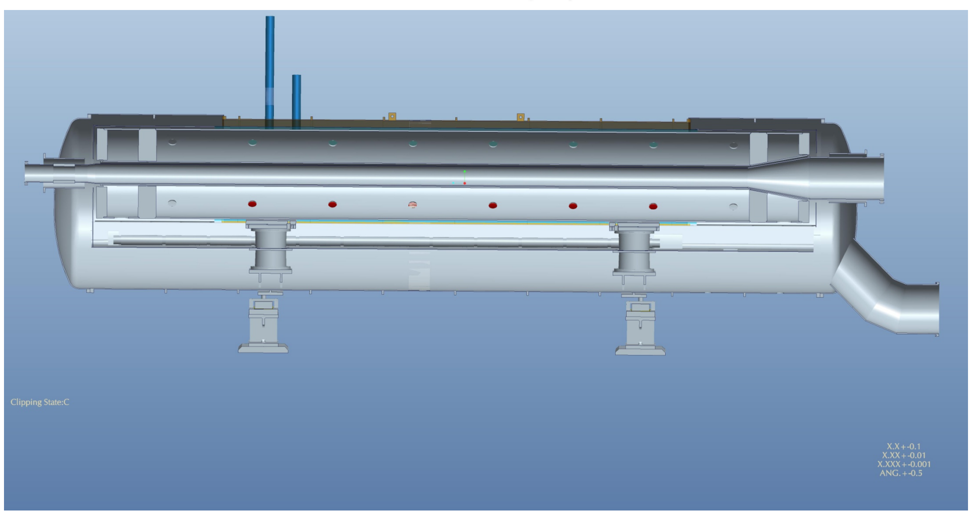


RHIC Interaction Region Layout

Beam split dipole DX magnet is first magnet on either side of IP

- L_{mag} = 3.7 m, B_{max} = 4.3 T
- large aperture (18 cm coil ID)

- Need to move DX magnets at STAR and PHENIX before switching to p+A. Collision head-on, with a common beam crossing angle of 3.61 mrad.



RHIC Machine Capabilities:
the proton beam is polarized

- Proton beam with N_b = 2x10^{11}, P = 55%.
  with upgrades (OPPIS): N_b = 3x10^{11}, P = 65%
- Vertical polarization is the natural spin orientation in the proton ring.
- Beam polarization is monitored by CNI (p+C elastic), and calibrated by polarized hydrogen jet (p+p elastic).

Note: in polarize p+A inclusive single-hadron single-spin asymmetry measurements, only transverse single-spin asymmetry is parity-allowed, longitudinal beam single-hadron SSA violates parity.

Jianwei Qiu's summary at the pA@RHIC workshop

Conclusions on physics opportunities of pA:

- Will produce a novel information on strong interactions in the high gluon density kinematics for fixed nuclear thickness as a function of energy: *parton , groups of partons propagation through media in soft and hard regime including spin effects*

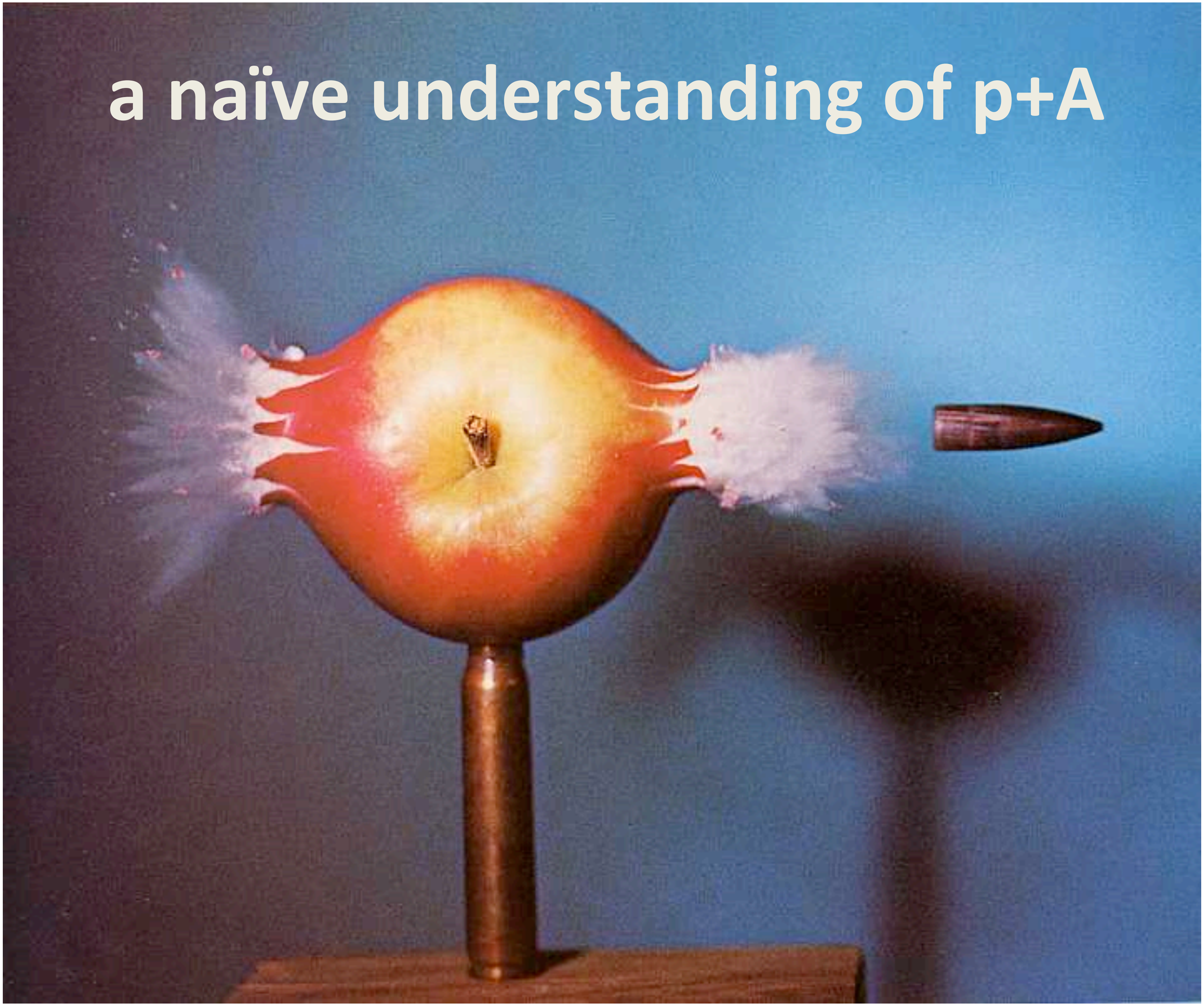
- Will complement pA run at LHC - critical for understanding how small x dynamics changes with energy

- Will allow to measure inelastic diffraction at the highest energy where it is still comparable/larger than e.m. contribution

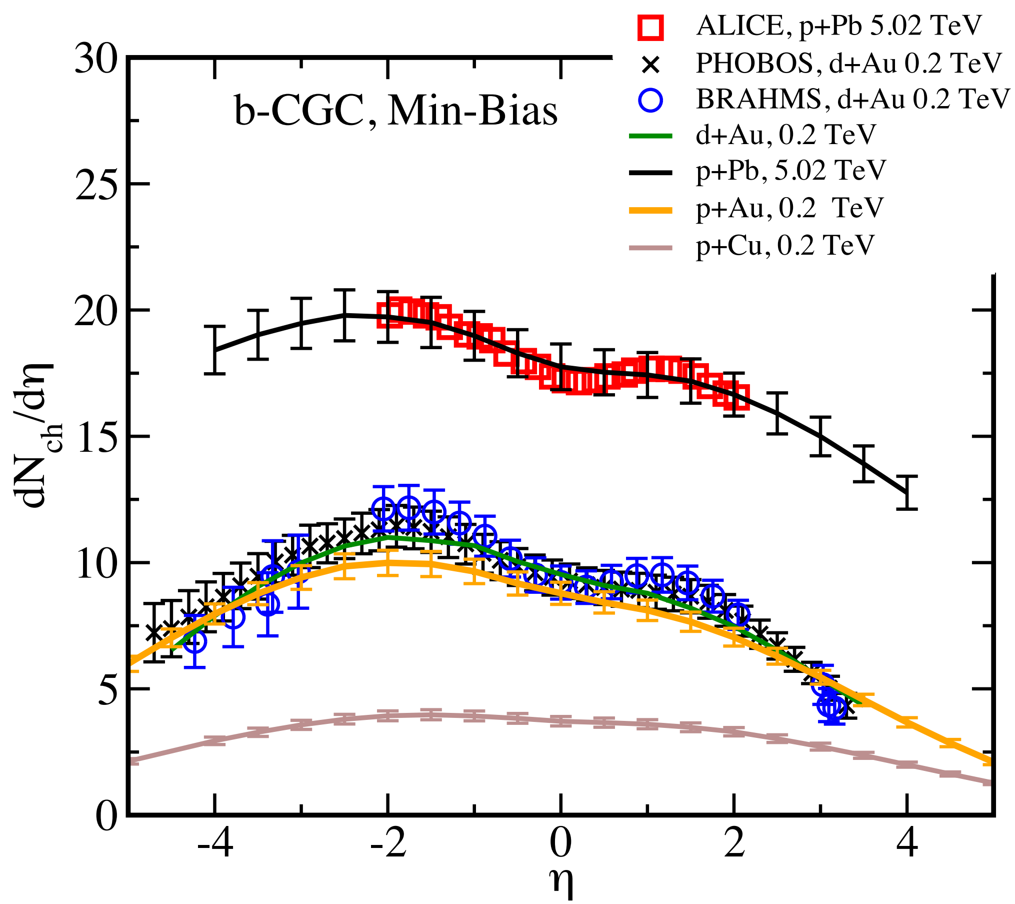
- Check the color fluctuation dynamics for generic inelastic pA collisions

Strikman

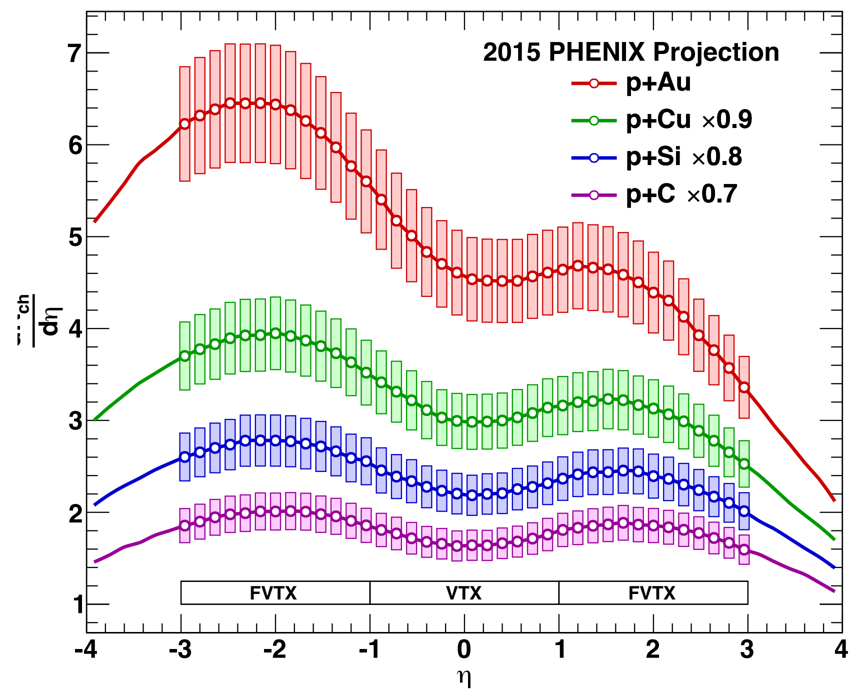
a naïve understanding of p+A



A. Rezaeian (2013).



Curves from HIJING with PHENIX projections, with 10% relative systematic uncertainties.



Need more theory guidance in details on the impacts of polarized observables for pA@RHIC.

- Polarized pA at RHIC provides a completely new testing ground for QCD

    Dynamics cannot be accessed by unpolarized x-section

    QCD is much richer than the leading power!

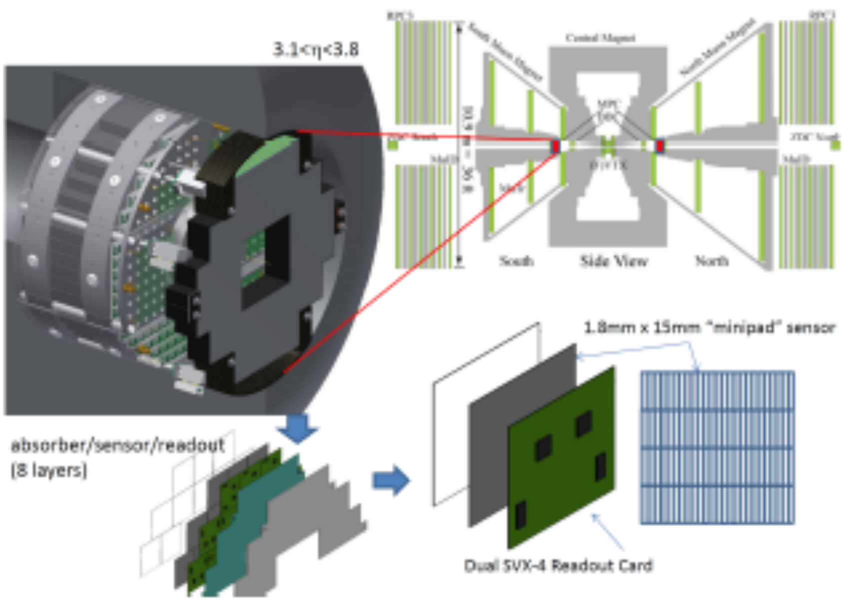
- SSA in pA is an excellent observable to study small-x physics in a nucleus

PHENIX Beam Use Proposal for Run-2015 p+A

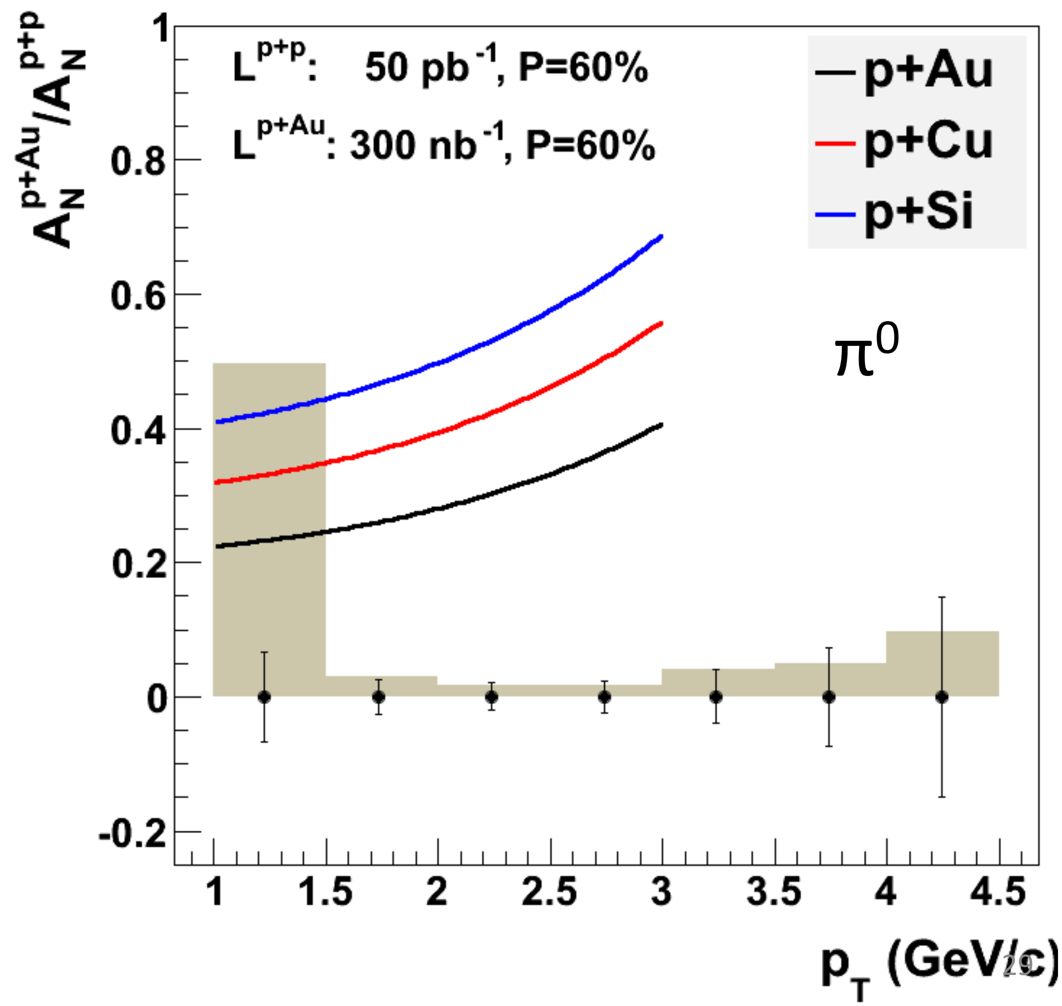
Single-Spin Asymmetry of forward π^0 through MPC-EX calorimeter

Ratios of SSA p+A vs p+p

$$\frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\ll Q_s^2} \approx \frac{Q_{sp}^2}{Q_{sA}^2} e^{\frac{P_{h\perp}^2\,\delta^2}{Q_{sp}^4}} \qquad \frac{A_N^{pA\to h}}{A_N^{pp\to h}}\Big|_{P_{h\perp}\gg Q_s^2} \approx 1$$

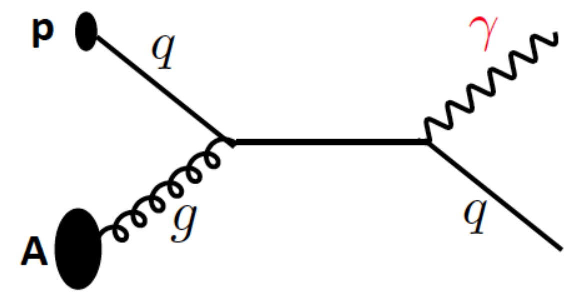


MPC-EX: forward EM calorimeter



Spin-independent observable:

Prompt photon in p+A to access gluon density in nuclei



PHENIX beam use proposal for run-2015

Address the basic scientific question: **What is the gluon density in nuclei ?**

- How much is it modified compared to a free proton ?
- Are there "smoking gun" evidences of the onset of gluon saturation ?

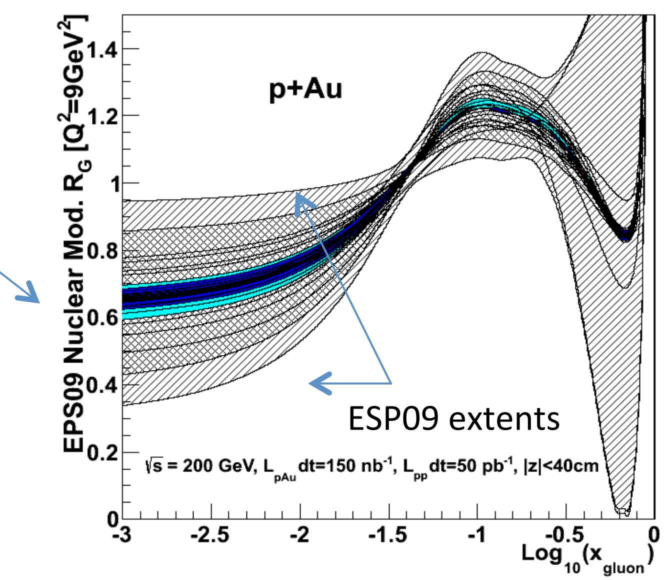
detect high energy prompt photons in p+A collisions with MPX-EX detector at PHENIX.

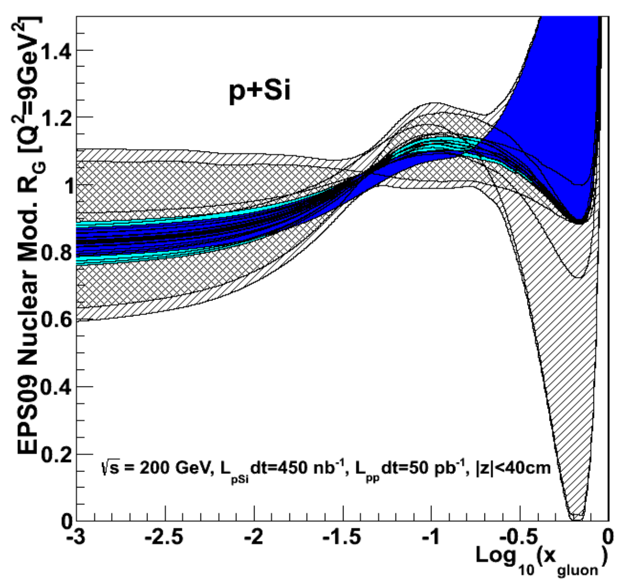
- Extract gluon density in several nuclei (A=^{28}Si, ^{63}Cu and ^{197}Au, for $A^{1/3}$ scaling check).

Experimental observable:

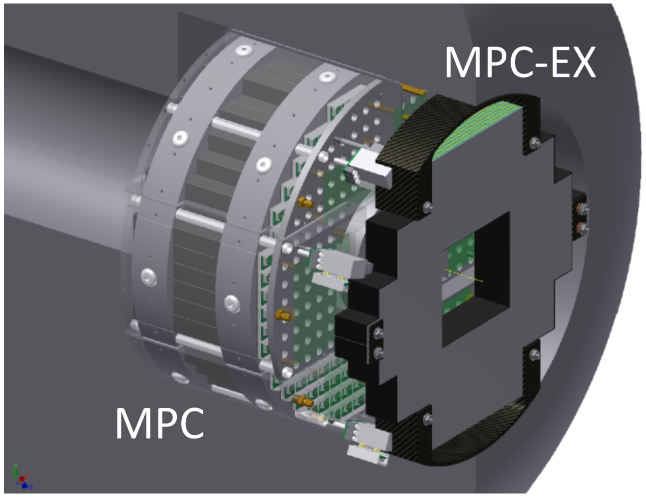
$$R^{\gamma}_{pA}(x_g,Q^2) = \frac{Photon\ Yield\ in\ p+A}{A \times (Photon\ Yield\ in\ p+p)} \propto \frac{f^A_g(x_g,Q^2)}{f^p_g(x_g,Q^2)}$$

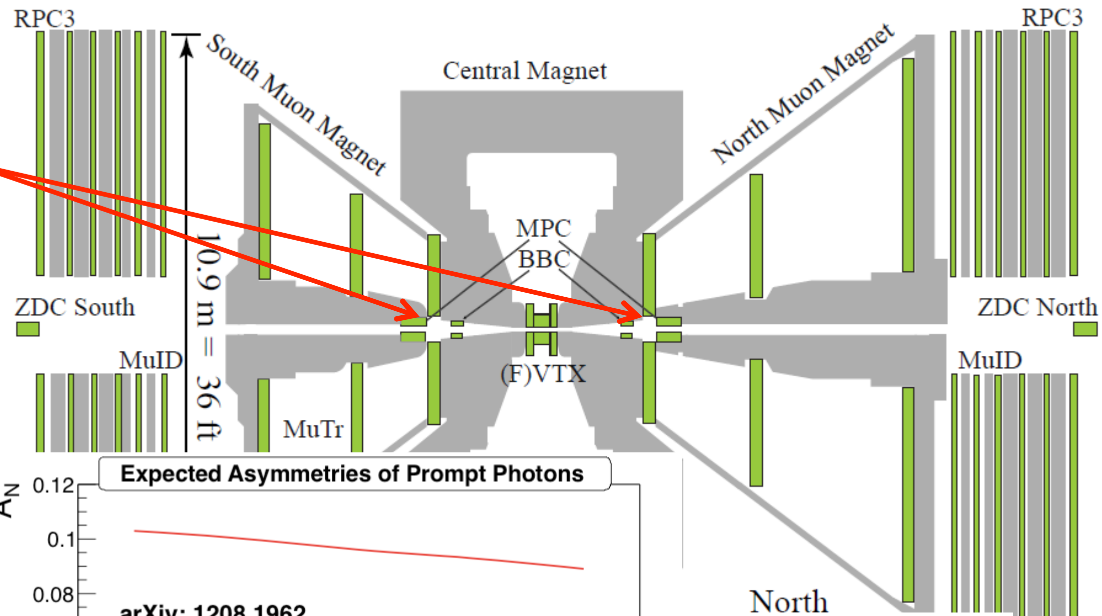
Colored band = range with MPC-EX direct photon data





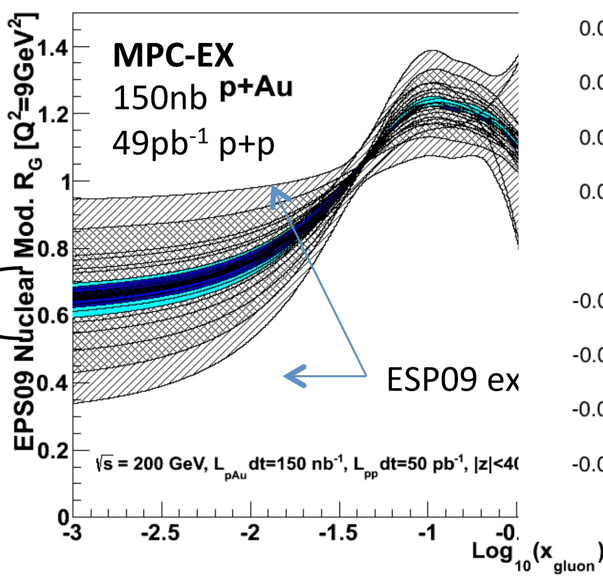
The PHENIX Muon Piston Calorimeter Extension (MPC-EX)

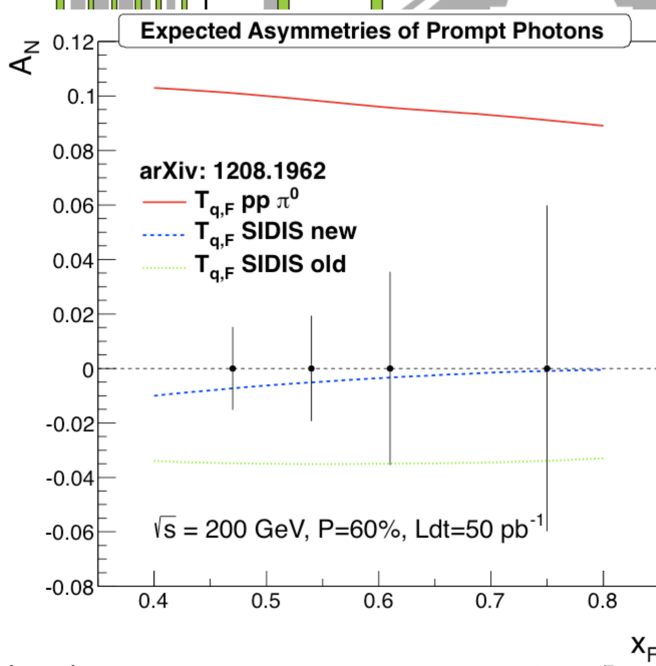




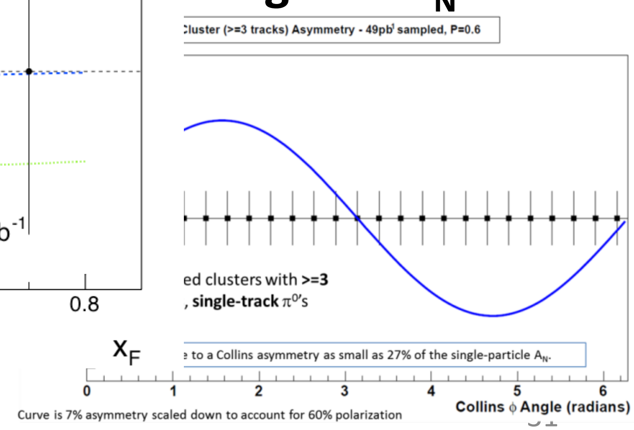
p+Au: Gluons in Nucle

Colored band = range with MPC-EX direct photon data





pol. protons: Origin of A_N



Summary

- **The MPC-EX is a novel detector that offers exciting new physics opportunities:**
  - Separate the sources of SSA's measured in transversely polarized p+p collisions
    - Deepen understanding of hadron structure
    - Enable continued progress in the application of fundamental QCD to p+p collisions
  - Measurement of the gluon distribution in cold nuclear matter
    - Further understanding saturation, shadowing, …
    - Set initial conditions for HI collisions at RHIC and LHC

- **Exciting new physics output from RHIC Run2015!**

What p↑+p and p↑+A@RHIC cannot do

(at least in the near future)

- Forward rapidity charged hadron production: $\pi^{\pm}$, $K^{\pm}$, ϕ, p, Λ, Ξ, pbar, anti-Λ etc.
  forward charged particle spin-correlations.
  STAR and PHENIX limited by the current magnets and detector design.

- Final state particle polarization at forward rapidity Λ, Ξ ect .
  spin-transfer, induced polarization etc.

- High statistic Drell-Yan measurements.
  - a clean access to sea quarks' density, helicity and angular motion without the complication of quark to hadron fragmentation functions.

Forward detector upgrade plans are under discussion.
See M. Liu fsPHENIX talk, Wednesday Morning, Session S11.

BACKUP

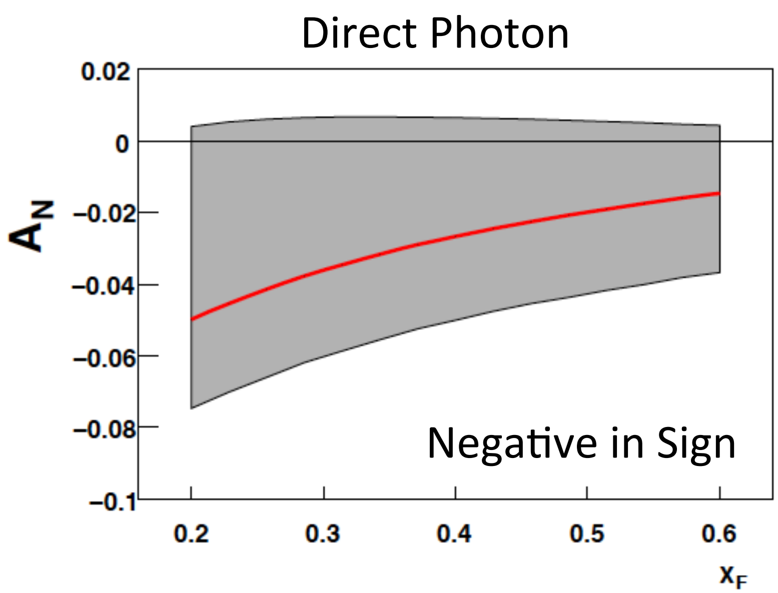
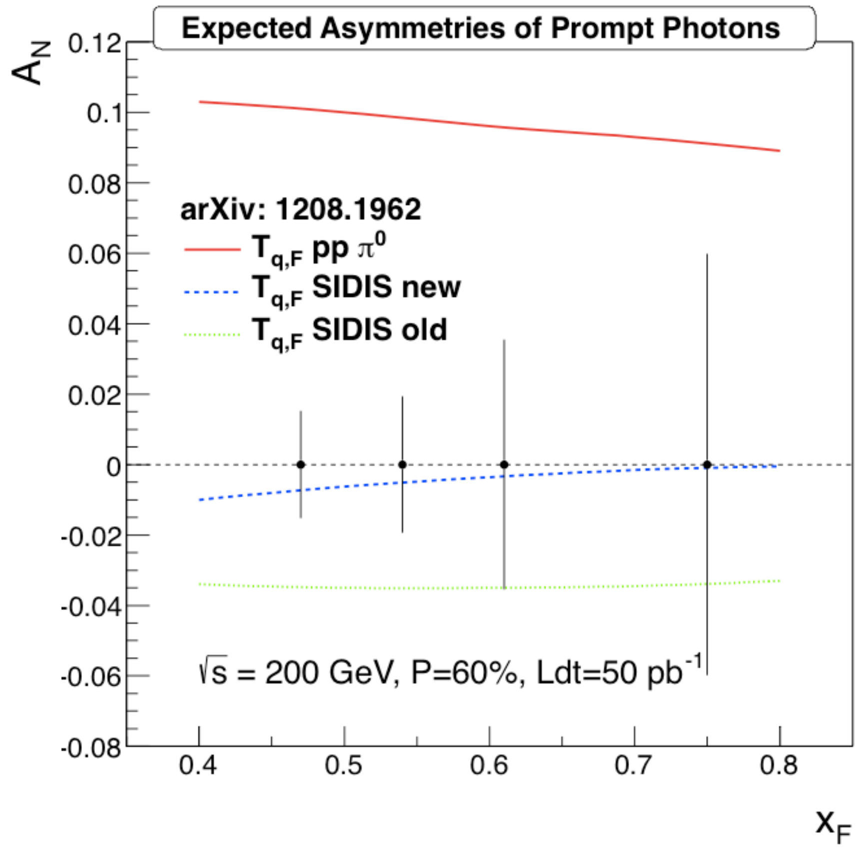


FIG. 4. Prediction of direct photon A_N in pp collisions at rapidity $y = 3.5$ and center-of-mass energy $\sqrt{s}$=200 GeV.

Gamberg, Kang, and Prokudin

Phys. Rev. Lett. 110, 232301 (2013)



Method and Systematic errors

Asymmetry of Signal (γ_{prompt})

Asymmetry of Background ($\pi^0/\eta \rightarrow \gamma$)

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

$$(\delta A_S)^2 = (1+\frac{1}{r})^2(\delta A_{meas})^2 + (\frac{1}{r})^2(\delta A_B)^2$$

Projected error bars assume

statistical errors, 50 pb^{-1}

60% polarization

Decay photon asymmetry subtraction ← Major source of error

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

⇨ factor of 10 to 30

⇨ accurate measurement of δA_B

⇨ assume $\delta A_B = \delta A_{meas}/2$

SSA's in polarized p+A Collisions

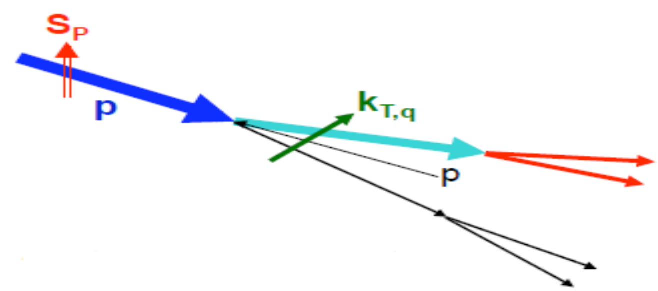
- Kang and Yuan, PRD 84, 034019

$$\left.\frac{A_N^{p+A\to h}}{A_N^{p+p\to h}}\right|_{P_{h\perp}^2 << Q_s^2} \approx \frac{Q_{s,p}^2}{Q_{s,A}^2} \cdot e^{\frac{P_{h\perp}^2 \cdot \delta^2}{Q_{s,p}^4}}, \quad \left.\frac{A_N^{p+A\to h}}{A_N^{p+p\to h}}\right|_{P_{h\perp}^2 >> Q_s^2} \approx 1$$

A systematic study of SSA's in spin-polarized p+A collisions would allow us to study the gluon saturation scale.

Two Approaches to explain Transverse SSA

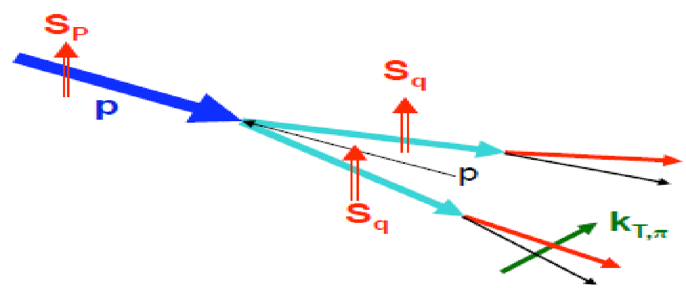
- In Transverse Momentum Dependent (TMD) approach , two competing effects at low p_T $(p_T \sim \Lambda_{QCD} \ll Q)$ as in semi-inclusive DIS
  - **Sivers effect:** Correlation between nucleon spin and parton k_T.



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

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

  - **Collins effect:** Transversity distributions + Spin dependent fragmentation functions



Nucl. Phys. B, 396, 161 (1993)

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

- In “twist-3 collinear factorization” approach at high p_T $(p_T \gg \Lambda_{QCD})$ as in p+p
  - Quark-gluon and gluon-gluon twist-3 correlation

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

In the overlapping p_T region, two approaches should be equivalent $(\Lambda_{QCD} \ll p_T \ll Q)$