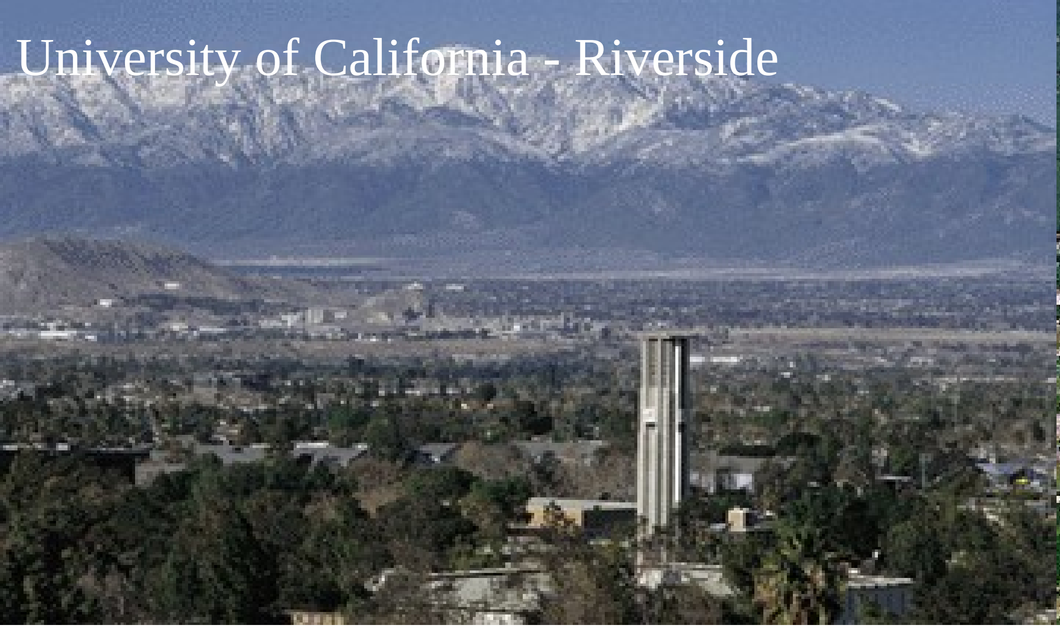
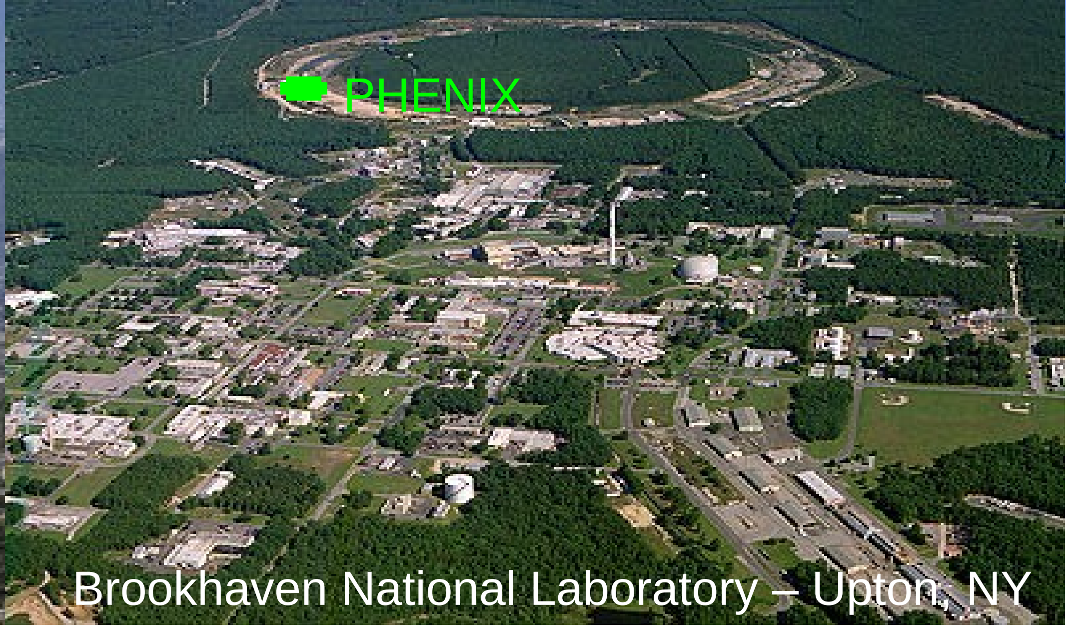




Transverse Single Spin Asymmetries and cross-sections at forward rapidity in PHENIX

David Kleinjan
University of California, Riverside
The PHENIX Collaboration

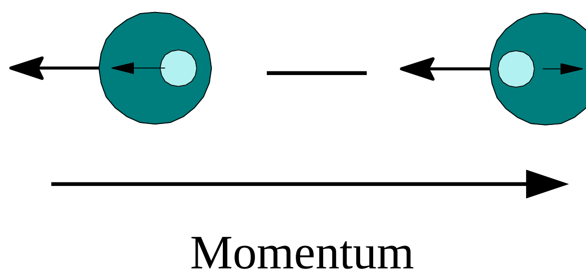
Outline

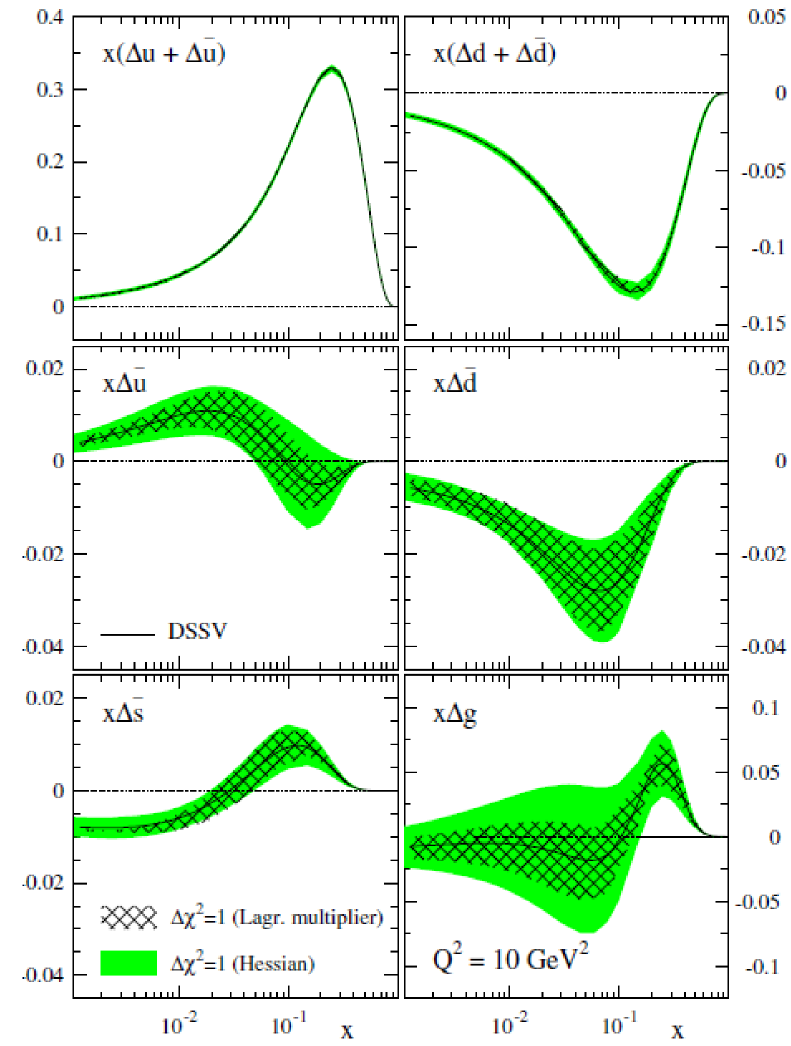
- Motivation
- Theoretical overview
- The PHENIX experiment and the MPC detector
- Forward A_N results using the MPC
- Forward Cross-section status using the MPC
  - Details of η meson cross-section analysis
- Outlook and Future

The Proton Spin Structure

$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta q + \Delta G + L_{q,g}$$

- Polarization Experiments
  - Helicity
    - Valence quarks
    - Sea quarks
    - Gluons

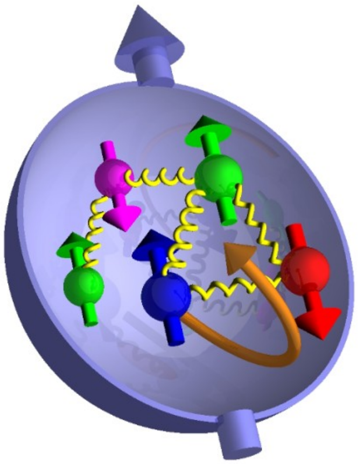


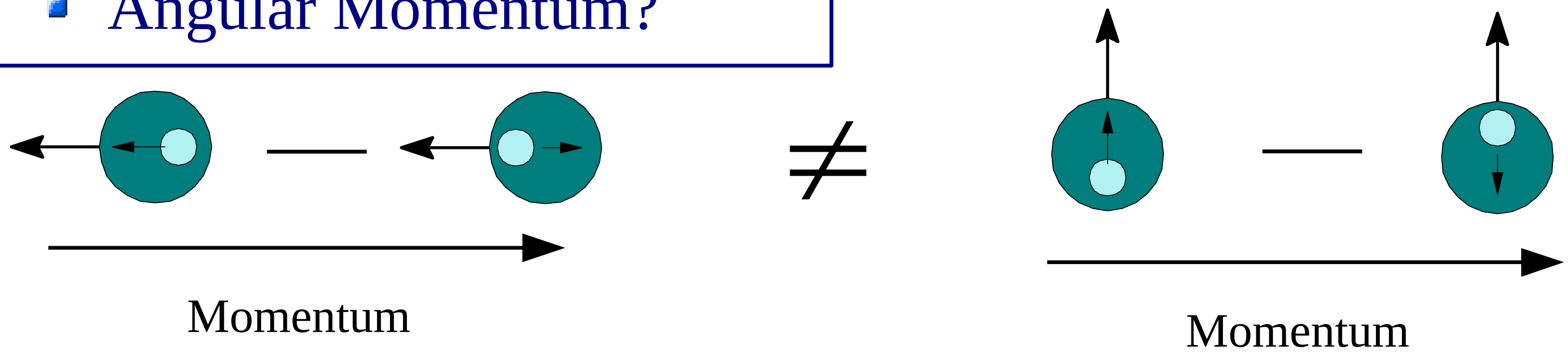


The Proton Spin Structure

$$S_{proton} = \frac{1}{2} = \frac{1}{2}\Delta q + \Delta G + L_{q,g}$$

- Polarization Experiments
  - Helicity
    - Valence quarks
    - Sea quarks
    - Gluons
  - Transversity
    - Angular Momentum?

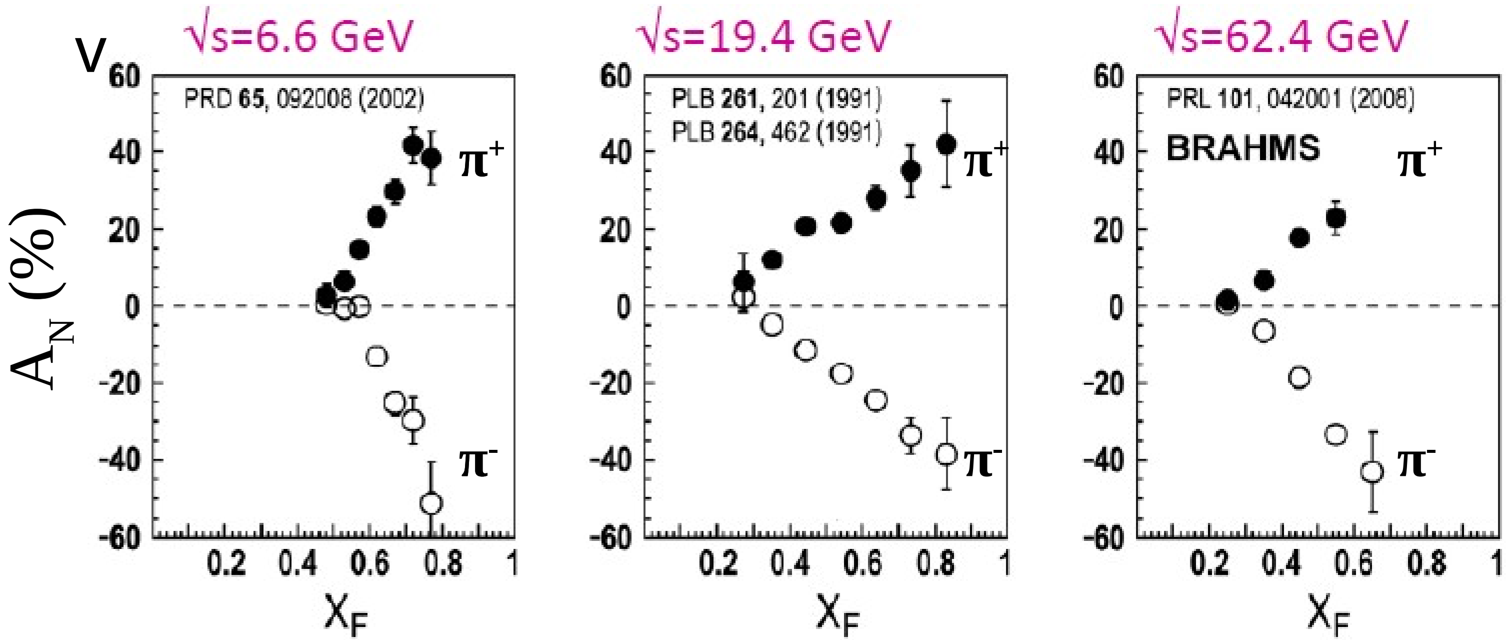




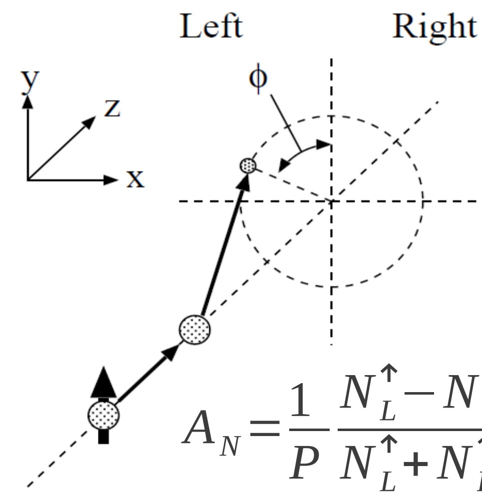
Motivation

A_N non-zero at various collision energies

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



i.e. fraction of proton energy given to forward momentum of hadron



$$A_N = \frac{1}{P}\frac{N_L^{\uparrow} - N_R^{\uparrow}}{N_L^{\uparrow} + N_R^{\uparrow}}$$

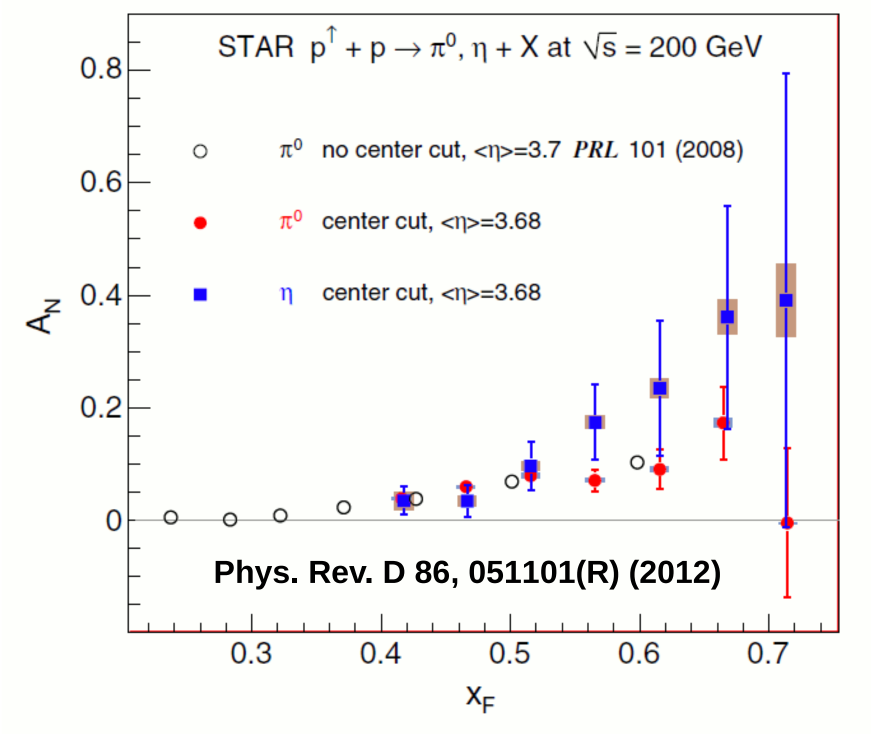
Collinear pQCD at leading twist interaction has small spin dependence, i.e. no asymmetry
Can initial or final state effects produce a nonzero asymmetry?

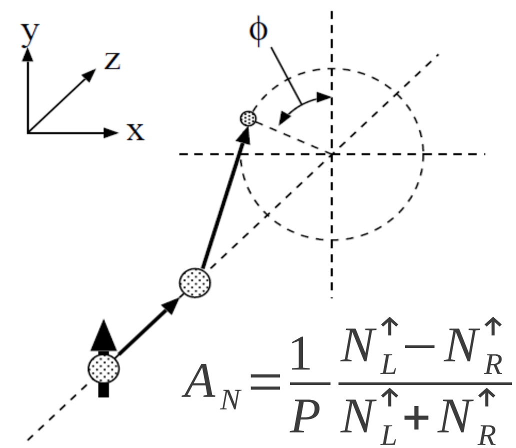
Motivation

A_N non-zero at various collision energies, various particles

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

i.e. fraction of proton energy given to forward momentum of hadron





$$A_N = \frac{1}{P}\frac{N_L^{\uparrow} - N_R^{\uparrow}}{N_L^{\uparrow} + N_R^{\uparrow}}$$

Collinear pQCD at leading twist interaction has small spin dependence, i.e. no asymmetry
Can initial or final state effects produce a nonzero asymmetry?

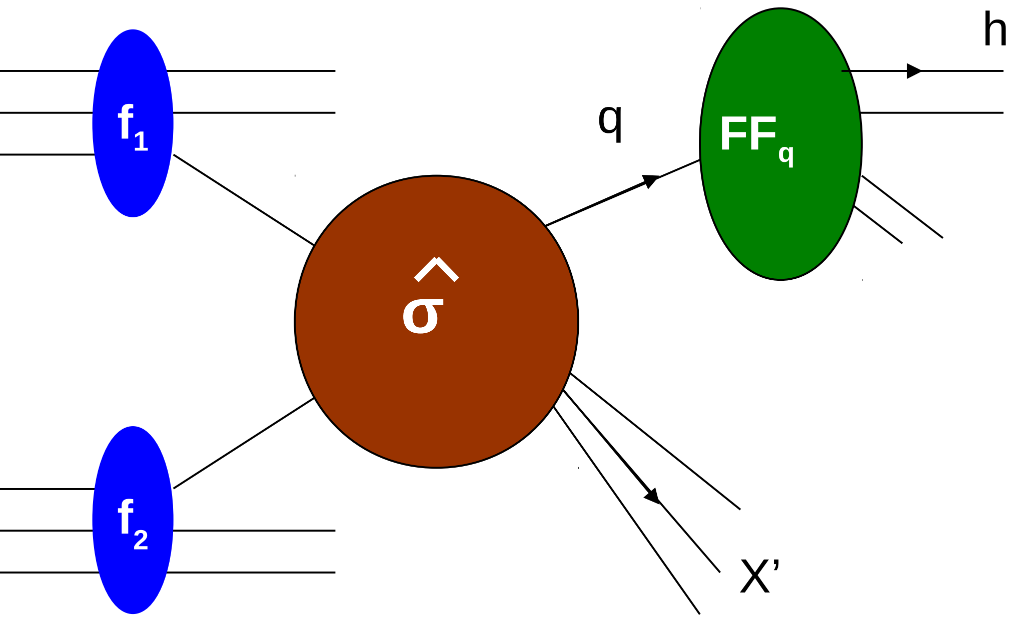
What is η meson A_N at √s = 200 GeV ? Larger than π^0 A_N?

Will measure π^0 and η meson A_N in PHENIX

Nucleon-Nucleon collisions: QCD factorization

Proton Structure | pQCD | Hard Scattering | Fragmentation Function

$$\frac{d^3\sigma(pp\rightarrow hX)}{dx_1\,dx_2\,dz} \propto q_1(x_1)\cdot q_2(x_2)\times \frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j\rightarrow q_k q_l)}{dx_1\,dx_2}\times FF_{q_k q_l}(z, p_{h,T})$$



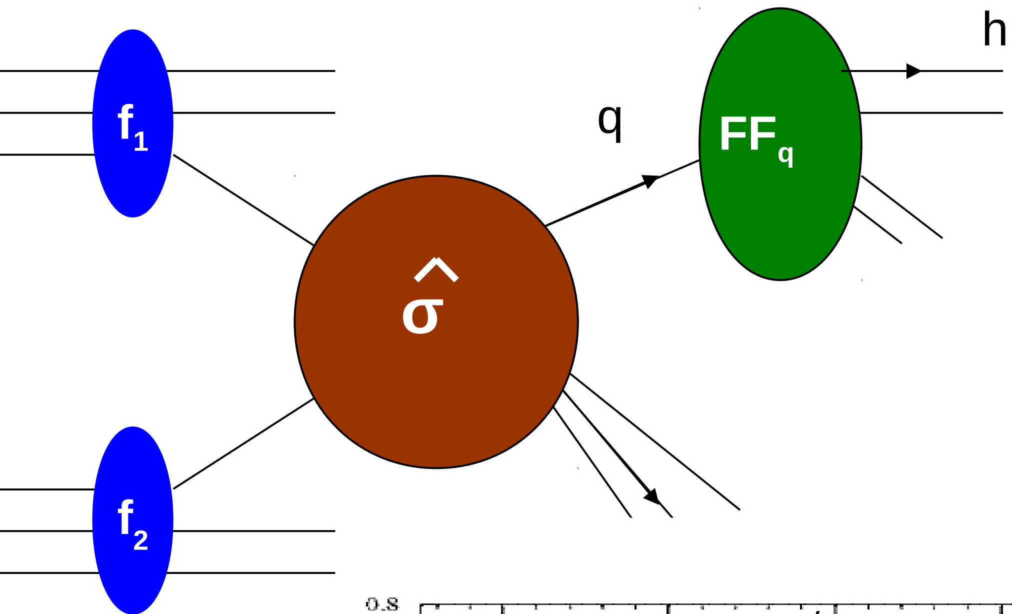
- **Two partons w/ respective momentum fraction interact**
- **Hard scattering of partons**
  - Small spin dependence
- **Hard scattering of partons produce Fragments (e.g. hadrons)**
  - Different partonic processes responsible for different $p_{h,T}$ ranges of measured hadrons

Nucleon-Nucleon collisions: QCD factorization

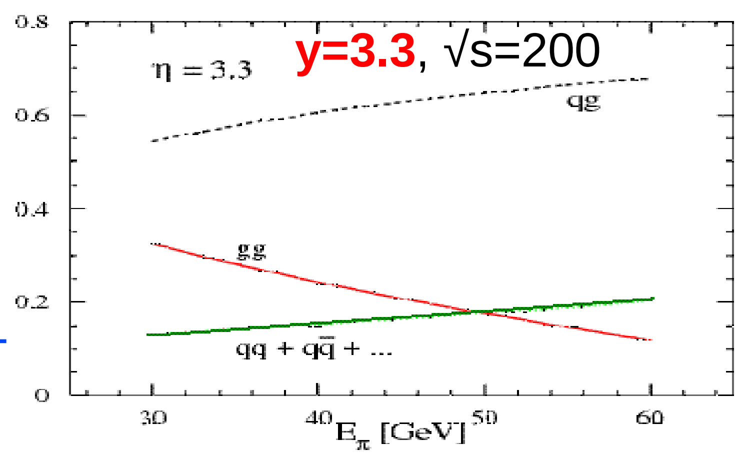
Proton Structure | **pQCD**

$$\frac{d^3\sigma(pp\to hX)}{dx_1\,dx_2\,dz} \propto q_1(x_1)\cdot q_2(x_2) \times \frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j \to q_k q_l)}{dx_1\,dx_2} \times FF_{q_k q_l}(z, p_{h,T})$$

Hard Scattering | **Fragmentation Function**



- **Two partons w/ respective momentum fraction interact**
- **Hard scattering of partons**
  - Small spin dependence
- **Hard scattering of partons produce Fragments (e.g. hadrons)**
  - Different partonic processes responsible for different $p_{h,T}$ ranges of measured hadrons
  - Dominated by quark-gluon scattering in the forward region



Possible Origins of Non-Zero A_N

Proton Structure — pQCD

$$\frac{d^3\sigma(pp\to hX)}{dx_1\,dx_2\,dz} \propto q_1(x_1)\cdot q_2(x_2)\times\frac{d^3\hat{\sigma}^{\uparrow}(q_i q_j\to q_k q_l)}{dx_1\,dx_2}\times FF_{q_k q_l}(z, p_{h,T})$$

Hard scattering — fragmentation function

- "Transversity" quark-distributions and Collins TMD fragmentation
  - Correlation between proton-spin and quark-spin and spin dependent fragmentation

$$A_N \propto h_1(x)\cdot H_1^{\perp}(z, p_{h,T}^2)$$

J. C. Collins, Nucl. Phys. **B396**, 161 (1993)

- Sivers distribution
  - Correlation between proton spin and transverse quark momentum

$$A_N \propto f_{1T}^{\perp q}(x, k_T^2)\cdot D_q^h(z)$$

D. Sivers, Phys. Rev. D **41**, 83 (1990)

- Higher Twist-3 effects
  - gg, qg correlators
  - Expectation: $A_N \sim 1/p_T$ at high p_T

Qiu, Wei, Sterman.Phys. Rev D **59**, 014001 (1998)

Kang, Qiu, Zhang..Phys. Rev D **81**, 114030 (2010)

Possible Origins of Non-Zero A_N

Proton Structure **pQCD**

$$\frac{d^3\sigma(pp\to hX)}{dx_1\,dx_2\,dz} \propto q_1(x_1)\cdot q_2(x_2)\times\frac{d^3\hat{\sigma}^{\uparrow}(q_iq_j\to q_kq_l)}{dx_1\,dx_2}\times FF_{q_kq_l}(z,p_{h,T})$$

Hard

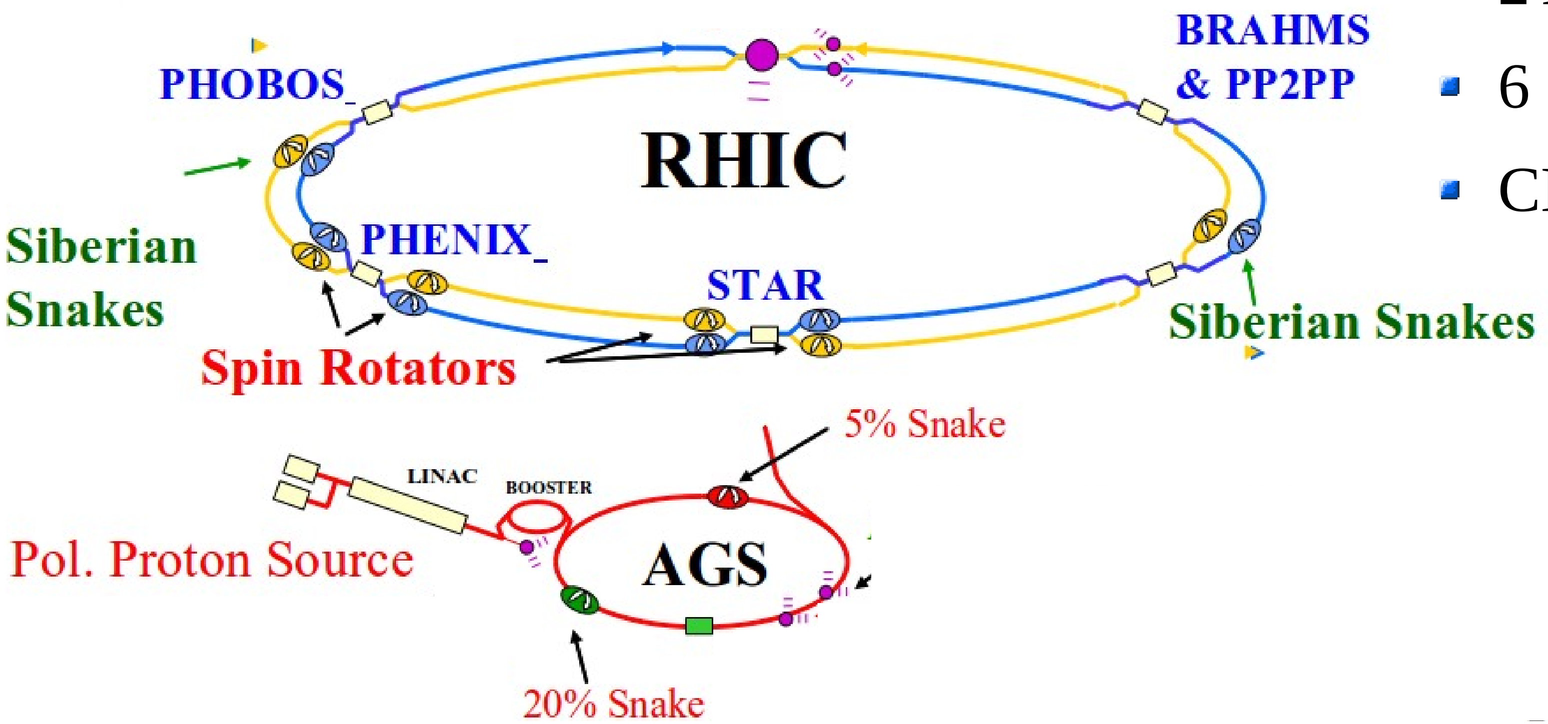
- “
  C
- S
- F

Collinear Factorization in unpolarized Cross section

- **π^0 and η meson cross section also measured**
  - Possibly improve uncertainty on fragmentation functions
- Caveat: Factorization not proven in TMD framework for p + $p^{\uparrow}$ → h + X
  - A_N a probe of underlying mechanisms

• gg, qg correlators
• Expectation: $A_N \sim 1/p_T$ at high p_T

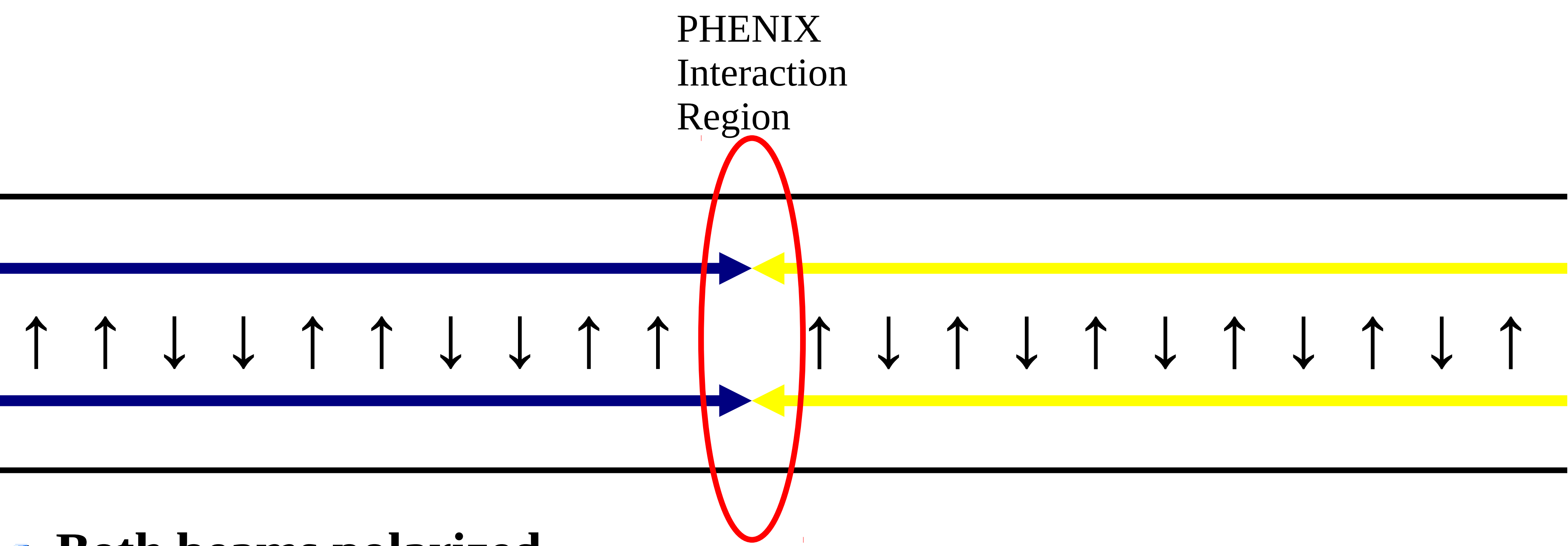
RHIC & AGS



- 3.83 km circumference
- 2 Accelerator Rings
- 6 collision points
- CNI Polarimeters

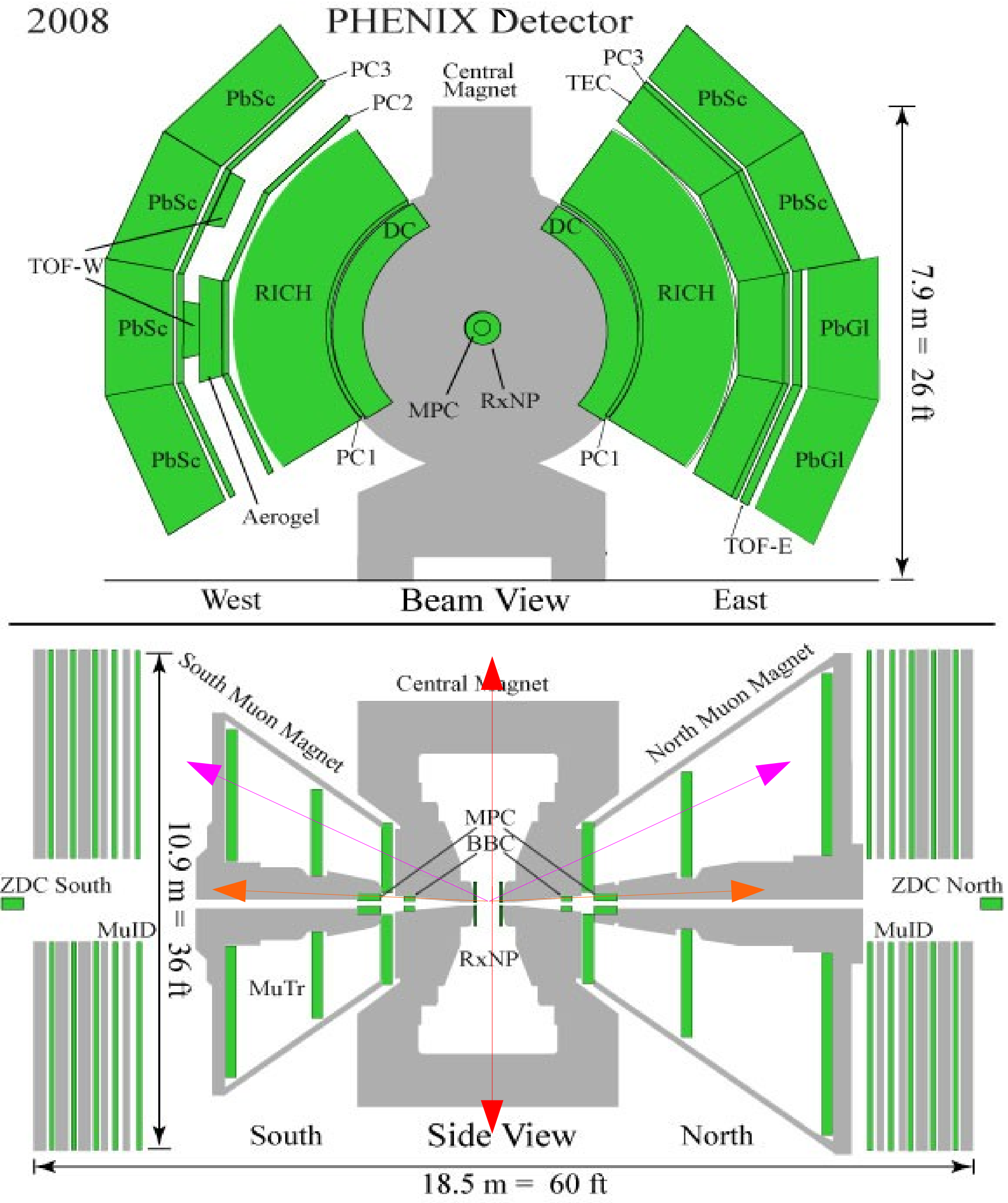
- Siberian Snakes: Depolarizing resonances of pp bunches averaged out by rotating spin 180 degrees at each Pass
- Versatile Polarization: Longitudinal or Transverse (measured w/ CNI polarimeters)
  - Energies probed so far in pp collisions √s=62GeV, 200GeV, 500GeV

Polarized Beams



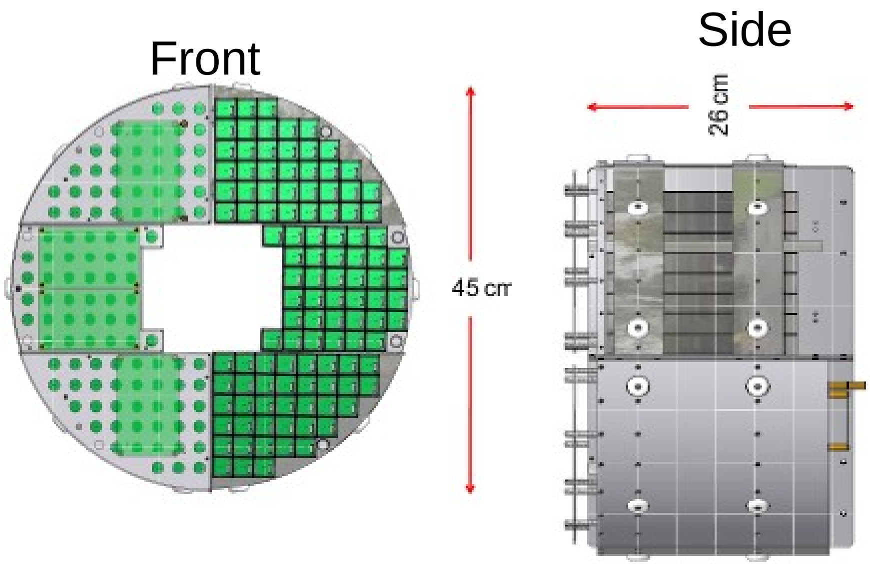
- **Both beams polarized**
- Variation of bunch polarization direction minimizes systematic uncertainties in measurement
- For transversely polarized beams, allows for two independent A_N measurements

PHENIX Detector (2008 schematic)

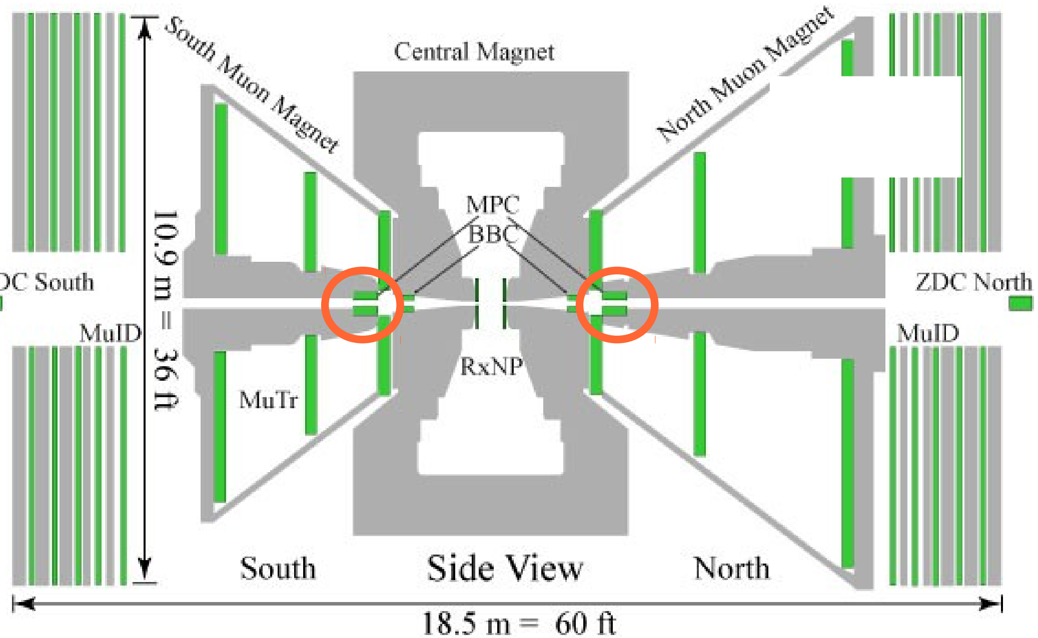


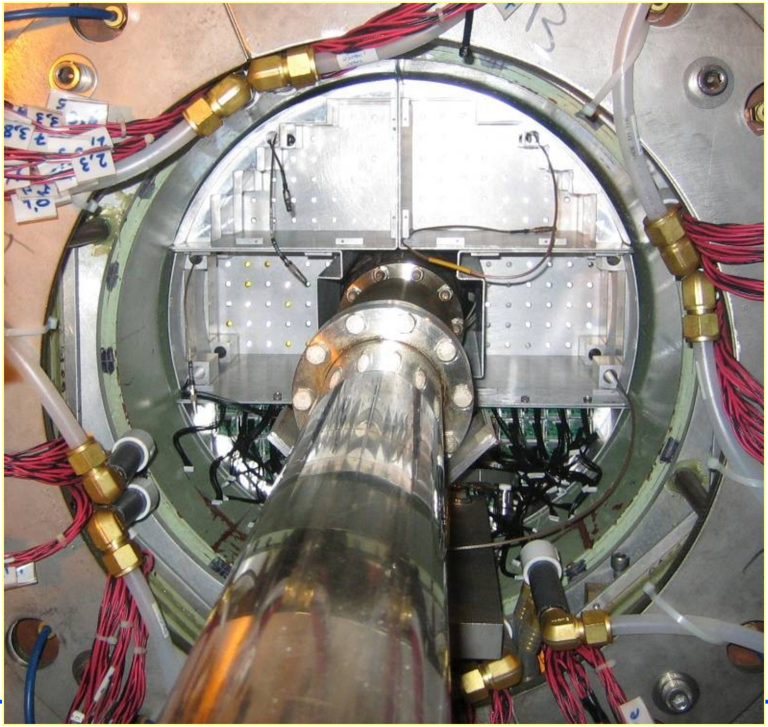
- 2 Central Arms $|\eta| < 0.35$ $\quad \eta = \ln \frac{|\vec{p}| + p_L}{|\vec{p}| - p_L}$
  - Identified charged hadrons
  - π^0,η mesons, direct photon
  - J/ψ, heavy flavor
- MPC $3.1 < |\eta| < 3.9$
  - π^0,η mesons
- 2 Muon Arms $2.1 < |\eta| < 2.4$
  - Unidentified charged hadrons
  - J/ψ, heavy flavor
- BBC,ZDC
  - Collision vertex, forward neutrons
- Sophisticated DAQ system allows high rate of data recorded by PHENIX

MPC detector in PHENIX

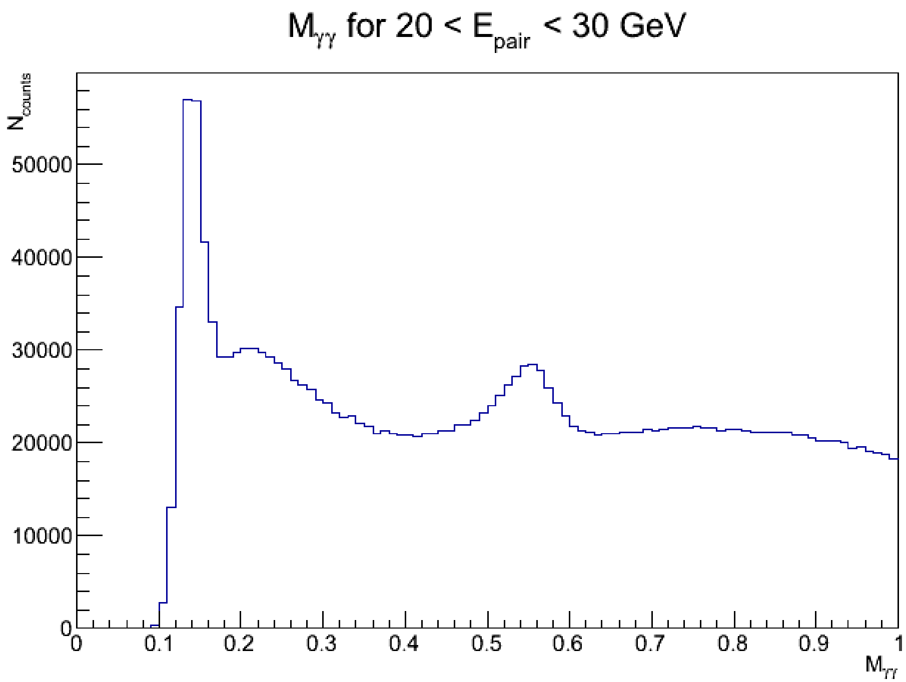


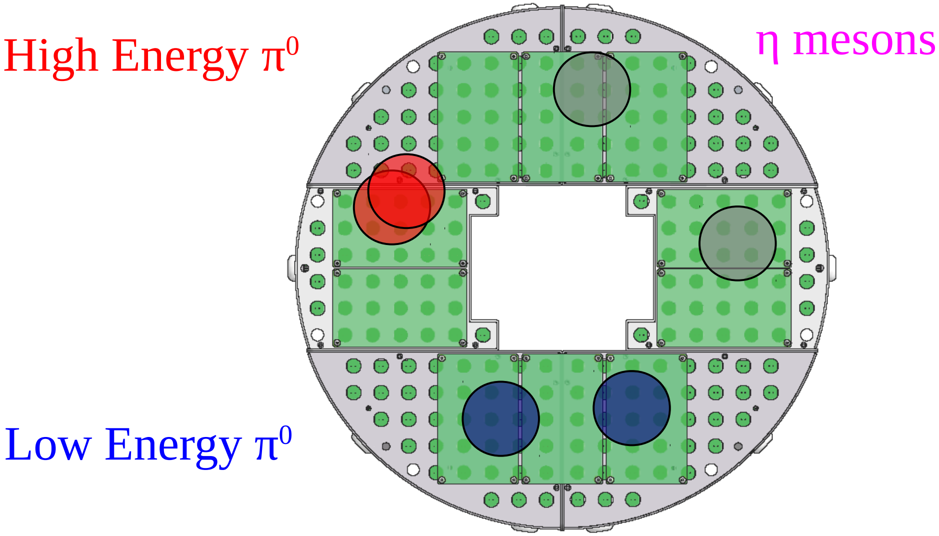
- MPC is forward E.M. Calorimeter
  - $2.2 \times 2.2 \times 18\ cm^3$ $PbWO_4$ crystal towers
  - 220 cm from nominal interaction point
  - $3.1 < |\eta| < 3.9$
  - 196(220) crystals in south(north) MPC



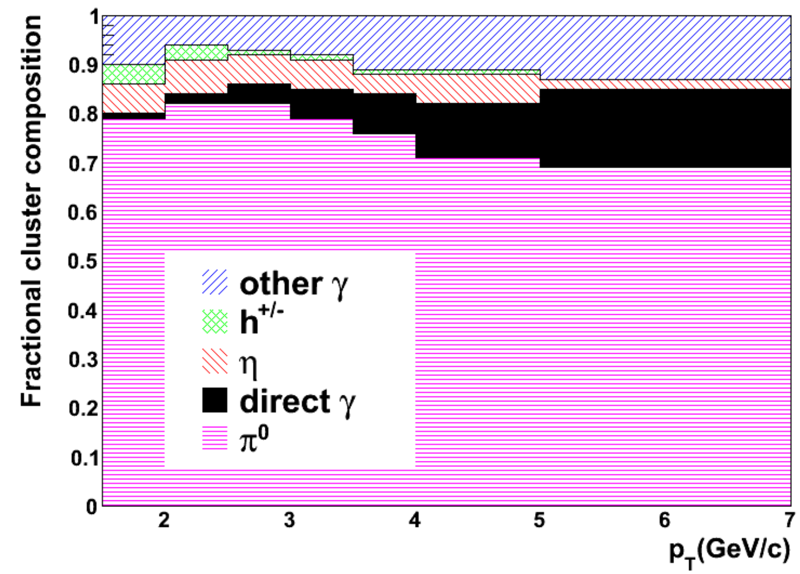


MPC detector in PHENIX

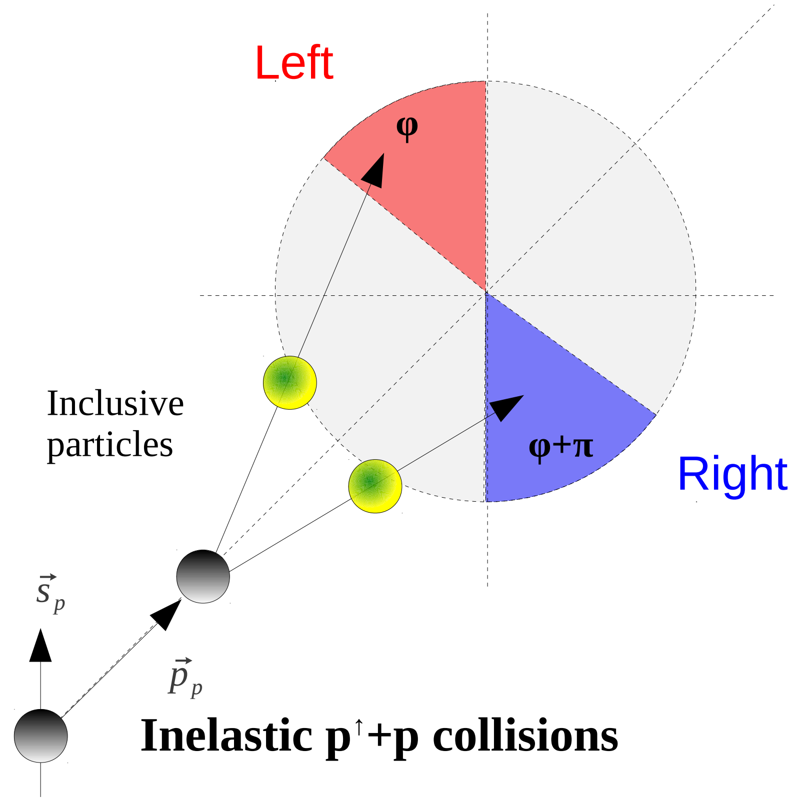




- Capable of reconstructing
  - η mesons (15 – 70 GeV)
  - Low Energy π^0 (7 - 20 GeV)
  - High Energy π^0 clusters (>20 GeV)
    - – ***Dominant cluster process at high p_T***



Measuring A_N for $p^{\uparrow}+p \rightarrow h+X$



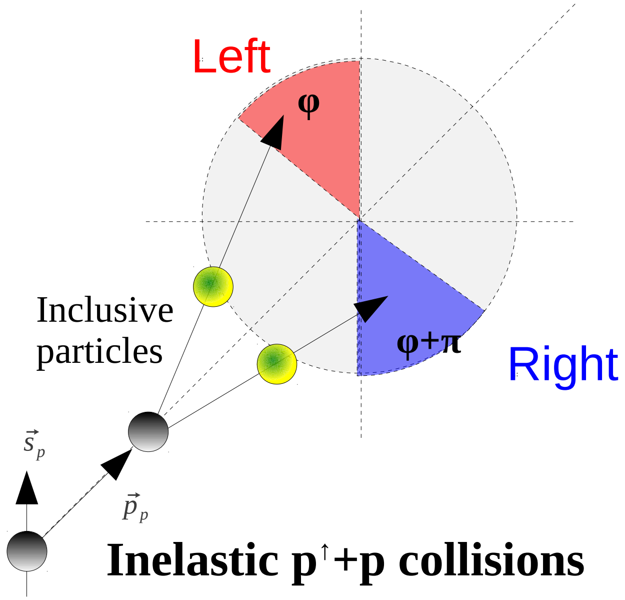
Inelastic $p^{\uparrow}+p$ collisions

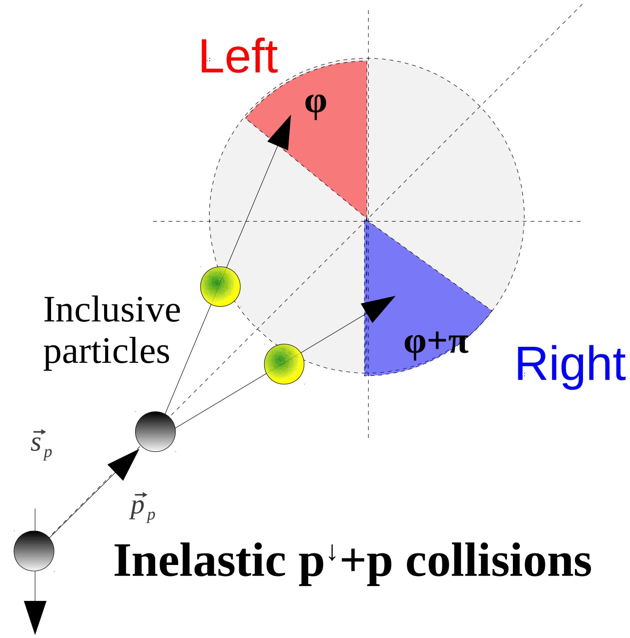
- **How do we measure A_N?**
- A_N is an azimuthal asymmetry of inclusive particle production *w.r.t.* incident proton spin
- Quantify the difference between particles produced to the "left vs right" *w.r.t.* proton spin

$$A_N = \frac{1}{P}\frac{\sigma_L^{\uparrow}(\varphi) - \sigma_R^{\uparrow}(\varphi+\pi)}{\sigma_L^{\uparrow}(\varphi) + \sigma_R^{\uparrow}(\varphi+\pi)}$$

Four cross section measurements AND their efficiencies?

Both Directions, Square-Root formula





$$A_N = \frac{1}{P}\frac{\sigma_L^{\uparrow}(\varphi)-\sigma_R^{\uparrow}(\varphi+\pi)}{\sigma_L^{\uparrow}(\varphi)+\sigma_R^{\uparrow}(\varphi+\pi)}$$

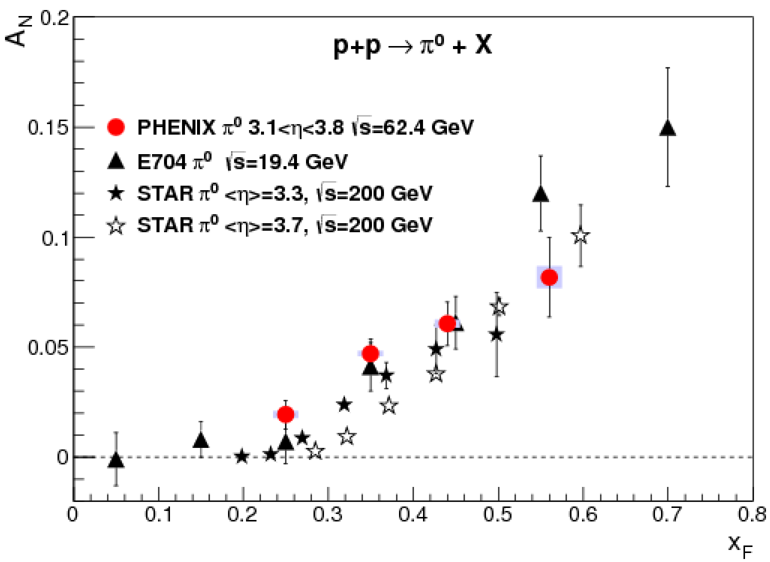
$$A_N = \frac{1}{P}\frac{\sigma_R^{\downarrow}(\varphi+\pi)-\sigma_L^{\downarrow}(\varphi)}{\sigma_R^{\downarrow}(\varphi+\pi)+\sigma_L^{\downarrow}(\varphi)}$$

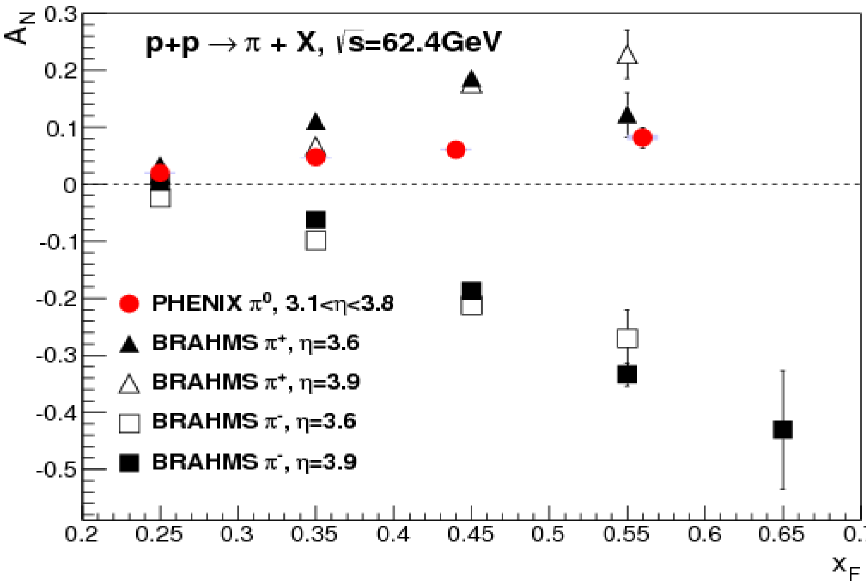
Geometric mean cancels out Luminosity, efficiency effects. Only need yields and Polarization

$$A_N = \frac{1}{P}\frac{\sqrt{N_L^{\uparrow}(\varphi)N_R^{\downarrow}(\varphi+\pi)}-\sqrt{N_R^{\uparrow}(\varphi+\pi)N_L^{\downarrow}(\varphi)}}{\sqrt{N_L^{\uparrow}(\varphi)N_R^{\downarrow}(\varphi+\pi)}+\sqrt{N_R^{\uparrow}(\varphi+\pi)N_L^{\downarrow}(\varphi)}}$$

Just submitted results for π^0 A_N

http://arxiv.org/abs/1312.1995



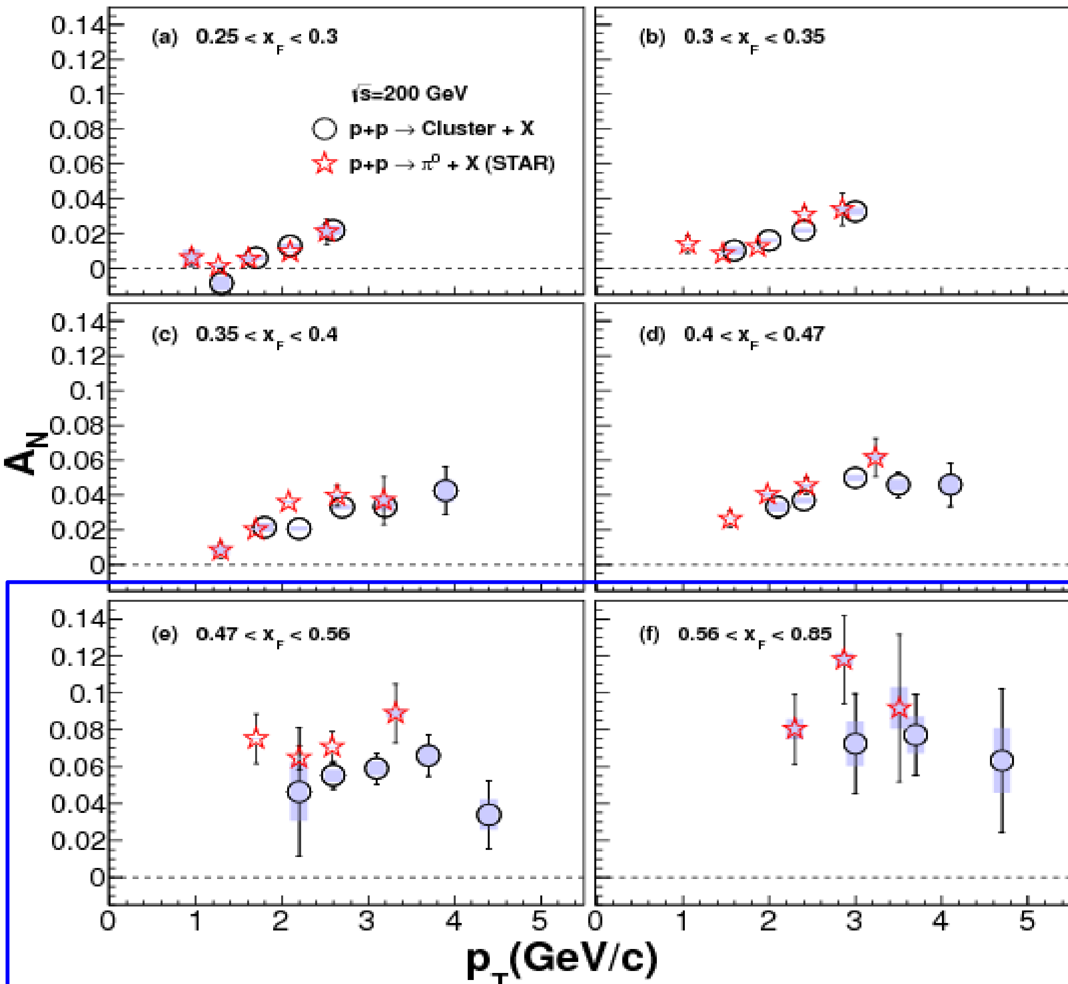


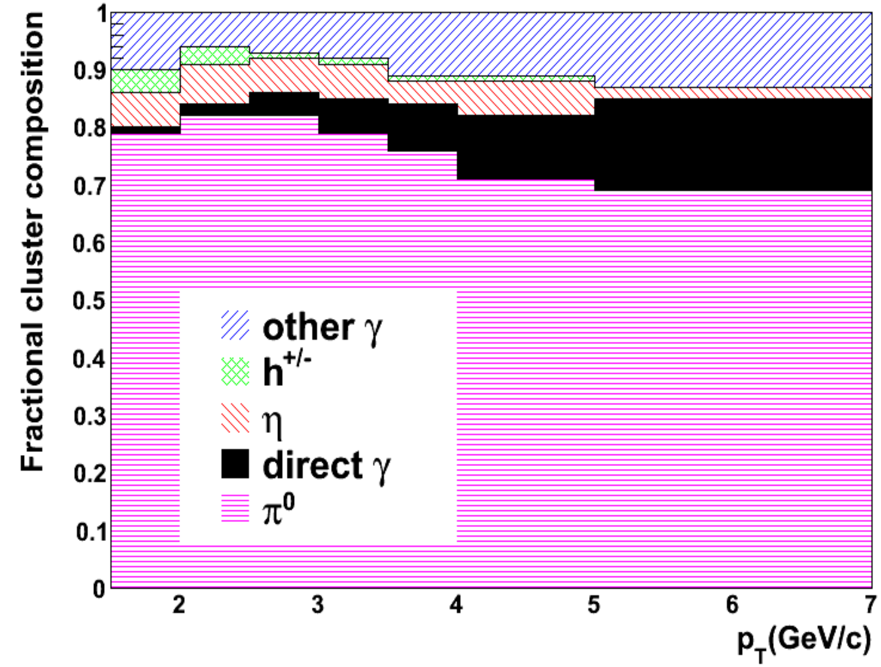
- Comparison to other neutral pion A_N measurements
  - A_N for neutral pions consistent across various energies
  - Not strongly dependent on Q^2

- Comparison to BRAHMS charged pion A_N
- Pion Isospin triplet FF studied in PYTHIA
  - $u \rightarrow \pi^+$ dominated
  - $d \rightarrow \pi^-$, $u \rightarrow \pi^-$ evenly
  - $d \rightarrow \pi^0$, $u \rightarrow \pi^0$ biased towards u quark
- Assuming u, d Sivers functions from SIDIS data
  - Eur. Phys. J. A 39, 89 (2009)
- ***Charge ordering for A_N suggests significant contributions from final state fragmentation***

And for Cluster A_N

http://arxiv.org/abs/1312.1995

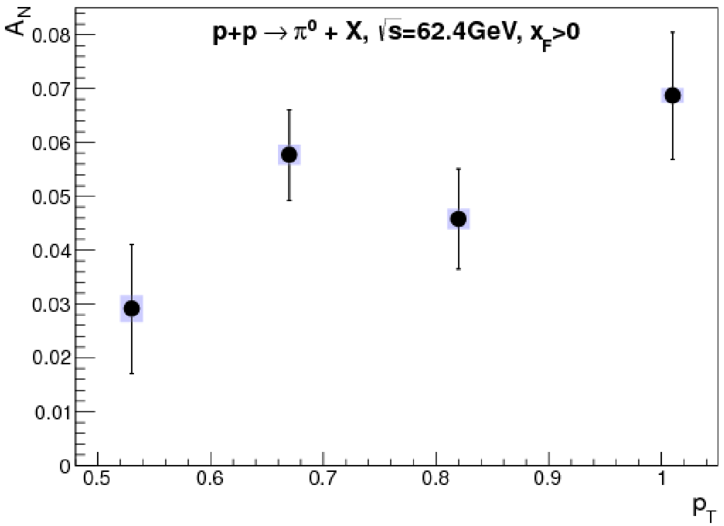


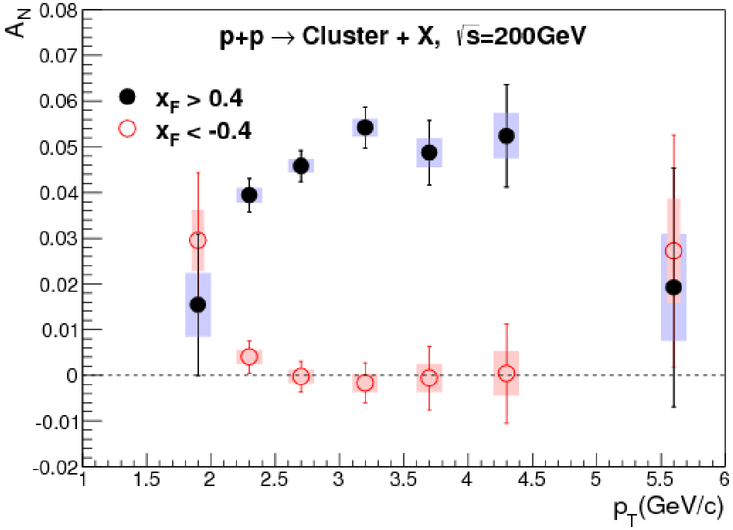


- Clear positive A_N at high x_F
  - Dominated by merged π^0 clusters
  - Consistent with STAR π^0, with exception to highest bins
    - *Direct photon A_N play non negligible role in Cluster A_N?*

A_N as a function of p_T

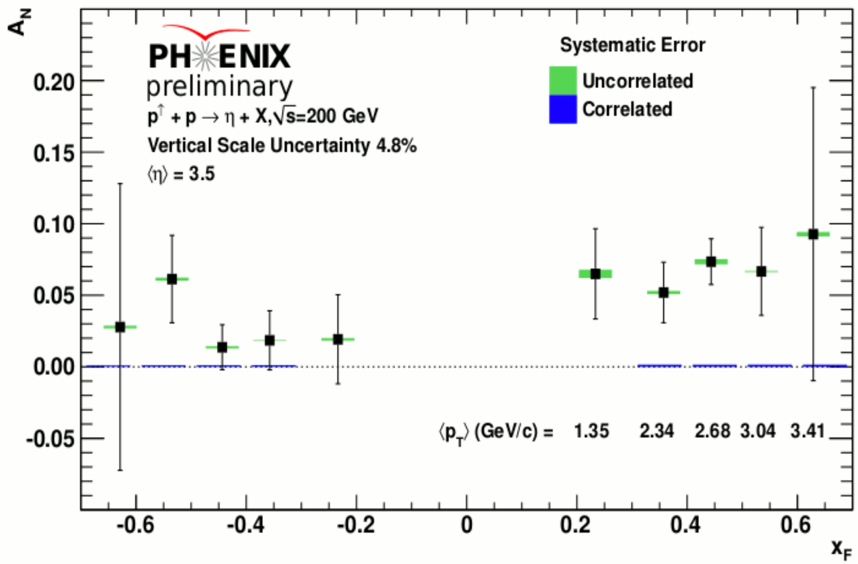
http://arxiv.org/abs/1312.1995

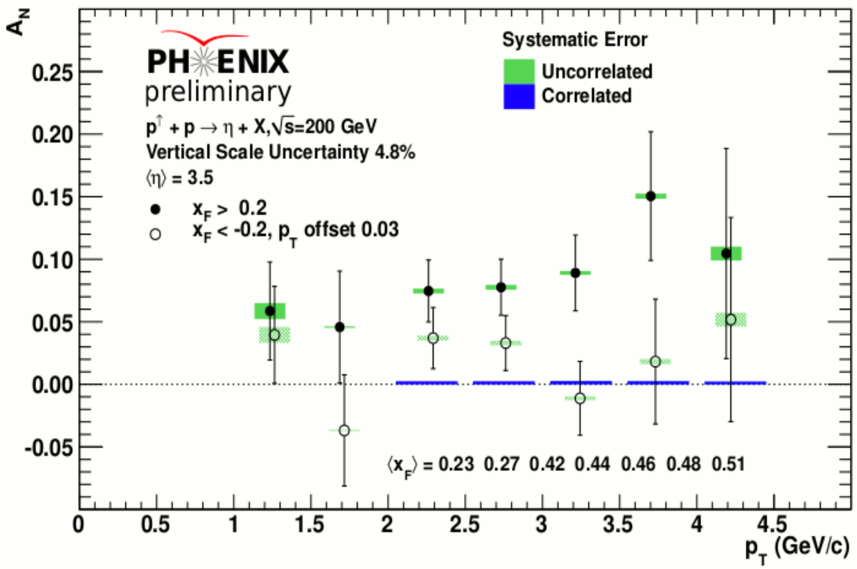




- No sign of decrease at high p_T within statistical uncertainty

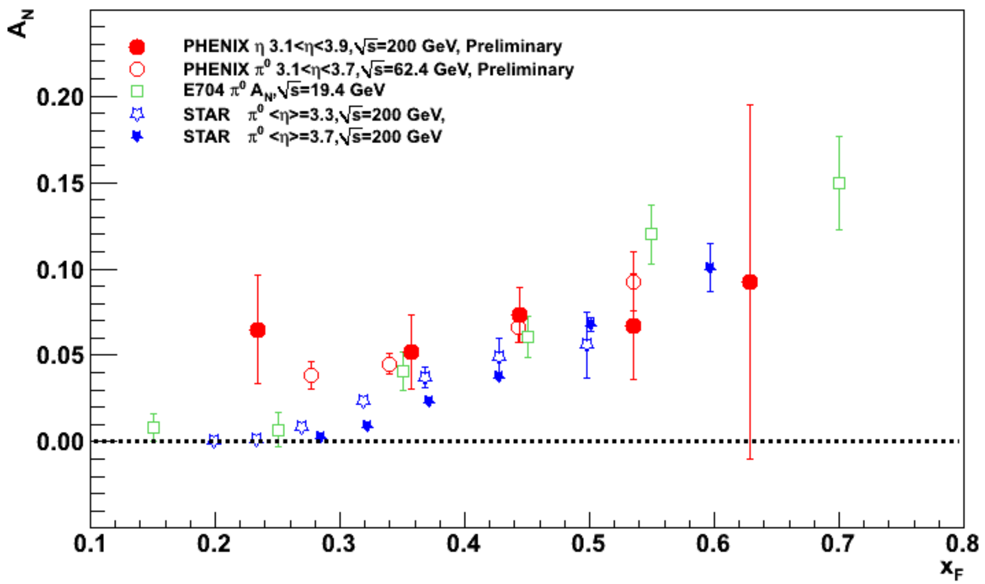
We also have η meson A_N

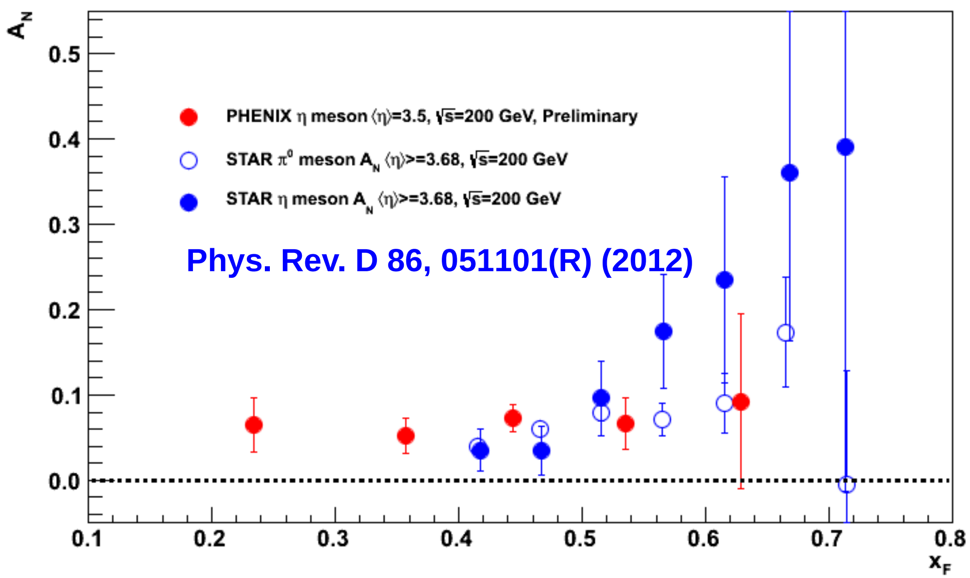




- There is a 5 to 10 percent positive A_N at forward x_F
- Consistent with zero at negative x_F
- Positive p_T dependent A_N for $x_F > 0.2$
  - No sign of high p_T decrease (Twist-3 effect) in this range

Comparison to other Forward A_N results





- Consistent with statistical uncertainty of previous π^0 meson A_N results
- No rise above 0.55 x_F as seen by STAR η meson A_N
  - Within statistical uncertainty
  - Different average <η> values

To measure the Cross-Section

- Three components
  - 1.) Integrated Luminosity
  - 2.) Measured Yield ΔN_η^{meas}
  - 3.) Efficiency of MPC to measure an η meson
    - a.) Reconstruction Efficiency
      - Is it geometrically accepted in detector?
      - Did the detector identify the particle?
    - b.) Trigger Efficiency
      - Did the Trigger fire?

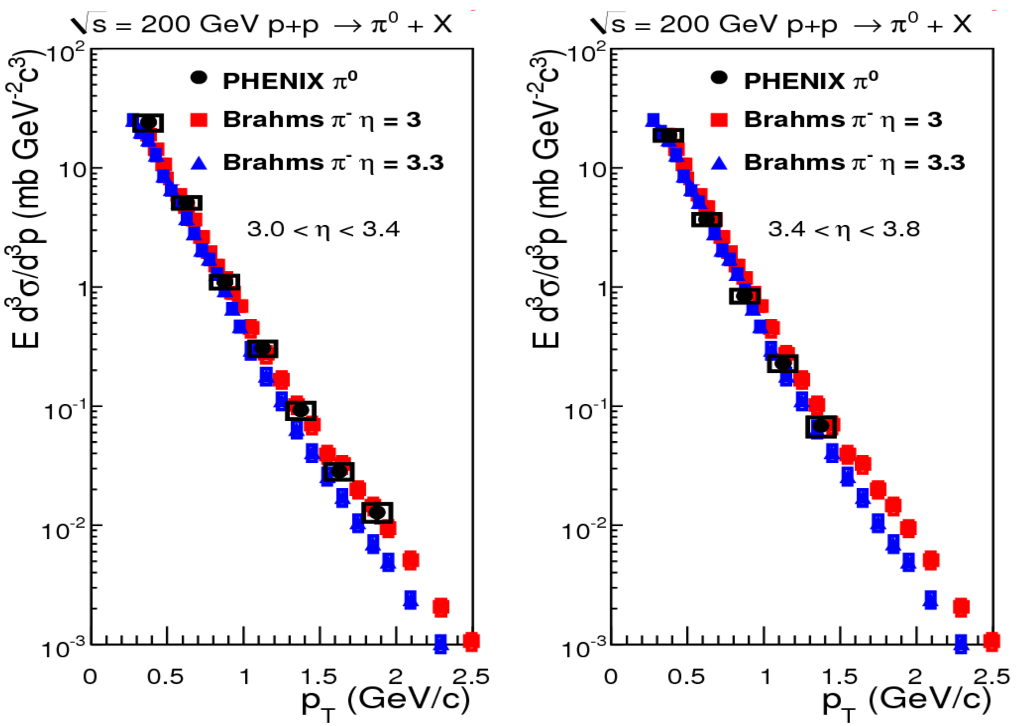
$$E\frac{d^3\sigma}{dp^3} = \frac{1}{2\pi p_T}\frac{1}{L}\frac{\Delta N_\eta^{meas}}{\epsilon \Delta\eta \Delta p_T}$$

$$N_\eta^{meas} = \epsilon N_\eta$$

$$\epsilon_\eta = \epsilon_{geo} \wedge \epsilon_{det} \wedge \epsilon_{trig} = \epsilon_{reco} \wedge \epsilon_{trig}$$

High precision measurement. Much care is needed.
Especially in efficiency corrections.

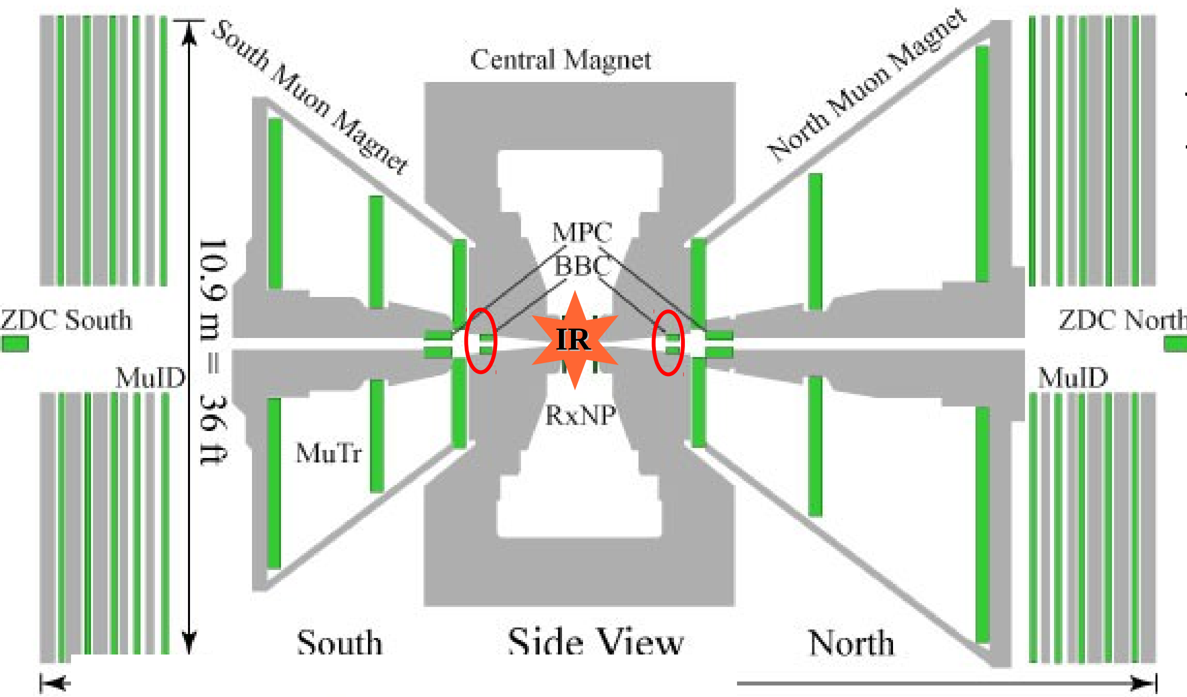
Neutral Pion Cross Section



Phys. Rev. Lett. 107, 172301 (2011)

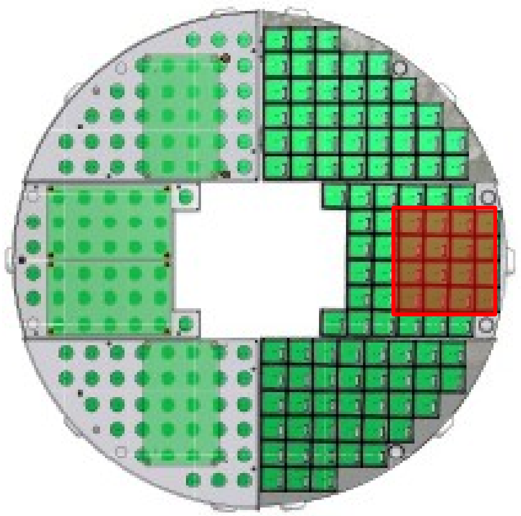
- Measured from $0.5 < p_T < 2.0$ GeV/c
- Close agreement with BRAHMS pion result
- **Status of η meson Cross Section**
  - Will measure from $0.5 < p_T < 5.0$ GeV/c
  - Compare η/π^0 ratio for $0.5 < p_T < 2.0$ GeV/c

Event Triggers



First Step: Record Data

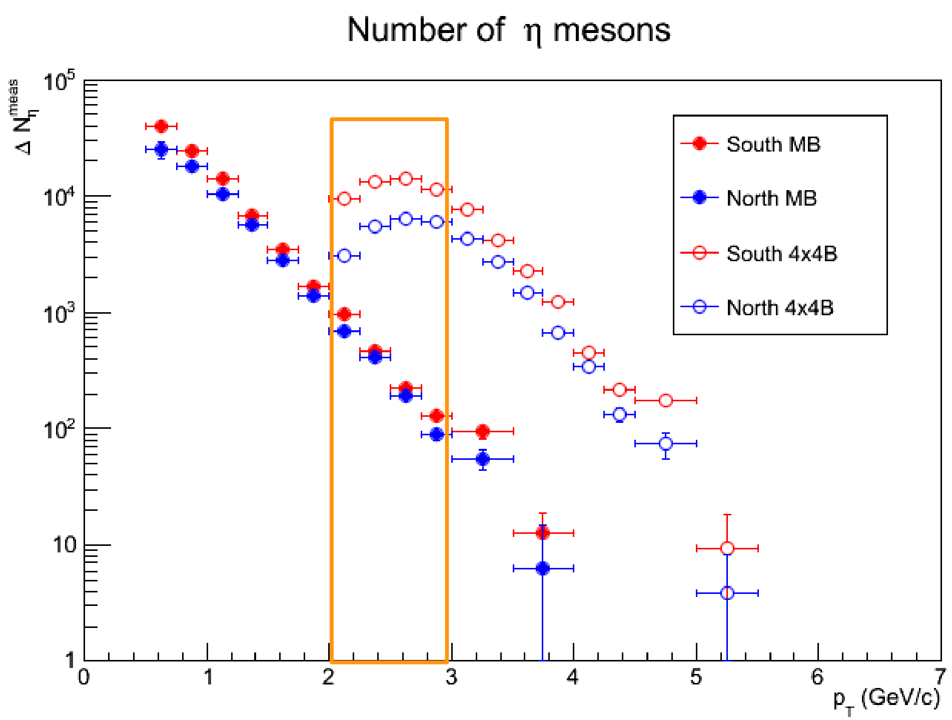
- Minimum Bias Trigger
  - BBCs measure inelastic pp collisions
  - Direct access to measure luminosity



- High-p_T MPC4x4B Trigger
  - 4x4 tower sums on MPC
  - E_{4x4} > 20 GeV on any 4x4 sum initiates readout of trigger

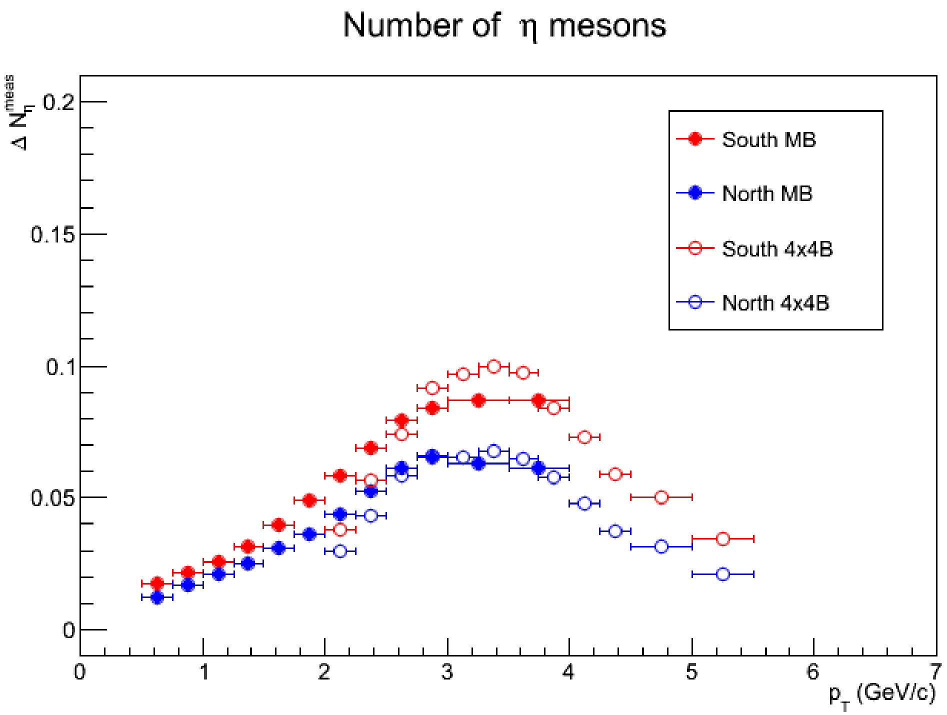
1.) Luminosity, 2.) Measured Spectra

- Minimum Bias
  - 0.018 pb^{-1}
- High-p_T, MPC4x4B
  - 3.86 pb^{-1}



- Measure signal peak above background in η meson Mass Region $N_\eta \pm 2\sigma_M$
- Same for both triggers
  - Minimum Bias trigger extraction
    - $0.5 < p_T < 4.0$ GeV/c
  - MPC4x4B Trigger extraction
    - $2.0 < p_T < 5.0$ GeV/c
- **Overlap region provides cross checks**

3a.) Reconstruction Efficiency



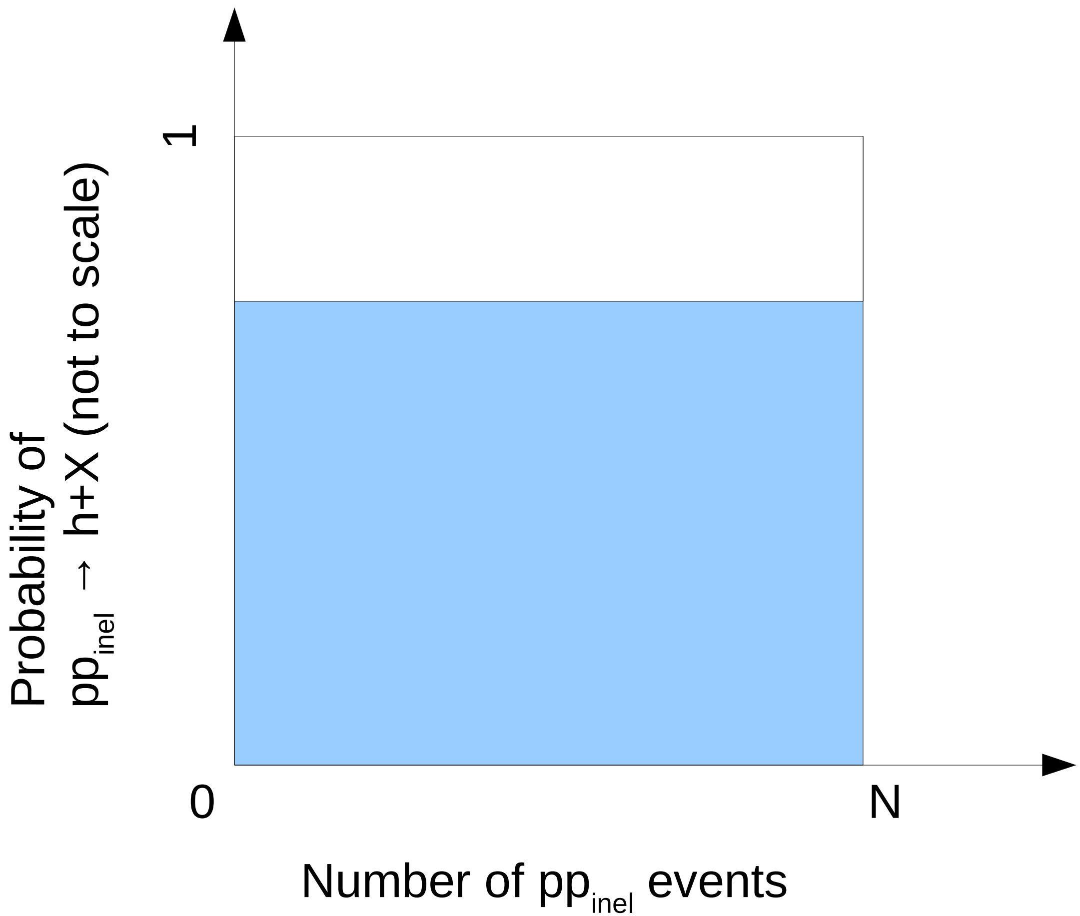
- Accounts for
  - Geometric effects
  - Detector efficiency
  - p_T, pseudo-rapidity smearing

$$\epsilon_{reco} = \frac{\Sigma[N_{reco}]}{\Sigma[N_{gen}]}$$

- Found using 80 Million Single η mesons ***generated*** using Pythia
- Single η mesons passed through full PHENIX GEANT simulation, embedded into real Minimum Bias events, and **reconstructed** using the same procedure as in the real data.
- Reconstruction Efficiency is found by taking the ratio of the number of η mesons reconstructed versus the number generated

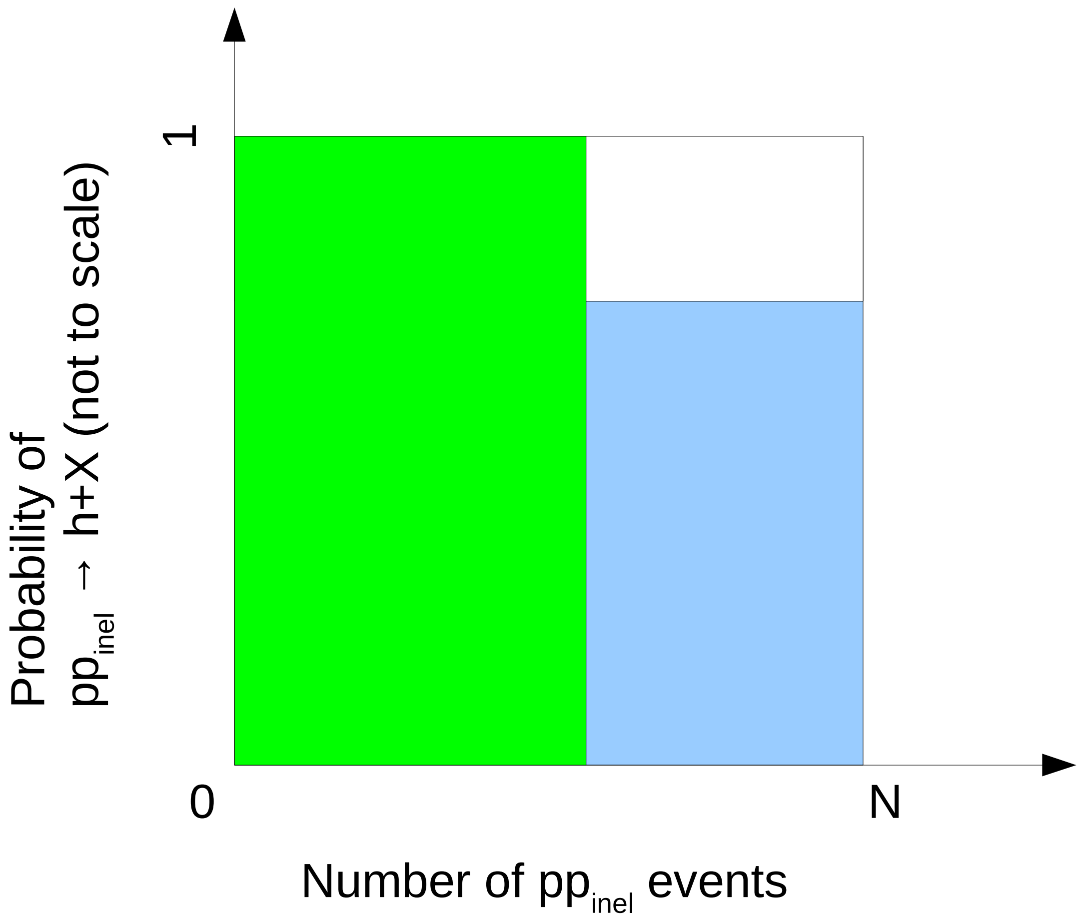
3b.) Minimum Bias η meson Trigger Efficiency

- We expect a pp_{inel} collision to produce inclusive particle h to some probability.



3b.) Minimum Bias η meson Trigger Efficiency

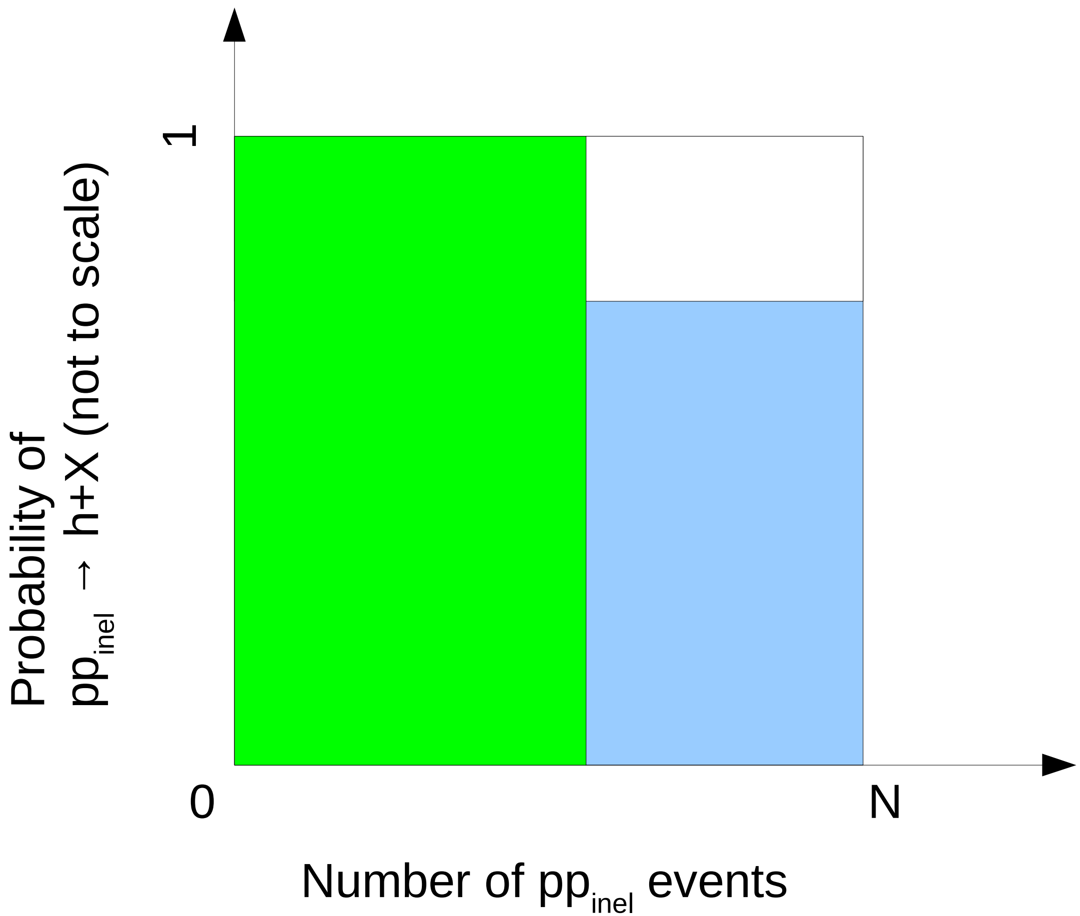
- However the BBCs only detect **~54%** of pp_{inel} collisions



- **h's** in **green** region are written to disc and can be measured
- But how do we account for missing **h's** in **blue** region?

3b.) Minimum Bias η meson Trigger Efficiency

- We look in dataset **w/out** BBC trigger requirement



- Use dataset that fires on produced **h's**, *not* on pp_{inel} collisions (*this analysis:* η mesons in MPC4x4B dataset)
- Get the yield of **η's** in MPC4x4B dataset when Minimum Bias also fires, and divide by the yield of **η's** in the MPC4x4B dataset by itself

$$\epsilon_{MB} = \frac{\Sigma\left[N_{\eta}^{MB} \wedge N_{\eta}^{MPC4\times 4B}\right]}{\Sigma N_{\eta}^{MPC4\times 4B}}$$

- **Still under study**

3b.) MPC4x4B η meson Trigger Efficiency

- The efficiency is Calculated in the Minimum Bias sample

$$\epsilon_{4x4B} = \frac{\Sigma\left[N_\eta^{MB} \wedge N_\eta^{4x4B}\right]}{\Sigma N_\eta^{MB}}$$

But not enough Statistics! Only to $p_T < 3.0$ GeV/c
High Stat. + Syst. Error in yield extraction in numerator

- Instead, Measure Cluster Efficiency and indirectly calculate η meson efficiency using Monte Carlo

$$\epsilon_{4x4B} = \frac{\Sigma\left[N_{reco} \times \Theta_\eta\left(\epsilon_{cl1}(E_{cl1}) \vee \epsilon_{cl2}(E_{cl2})\right)\right]}{\Sigma\left[N_{reco}\right]}$$

- Where

$$\Theta_\eta(E_1, E_2) = \begin{cases} 1, & \left[\epsilon_{cl1}(E_{cl1}) > \epsilon_{rand}\right] \vee \left[\epsilon_{cl2}(E_{cl2}) > \epsilon_{rand}\right] \\ 0, & \left[\epsilon_{cl1}(E_{cl1}) < \epsilon_{rand}\right] \wedge \left[\epsilon_{cl2}(E_{cl2}) < \epsilon_{rand}\right] \end{cases}, \quad 0 < \epsilon_{rand} < 1.0$$

3b.) MPC4x4B η meson Trigger Efficiency

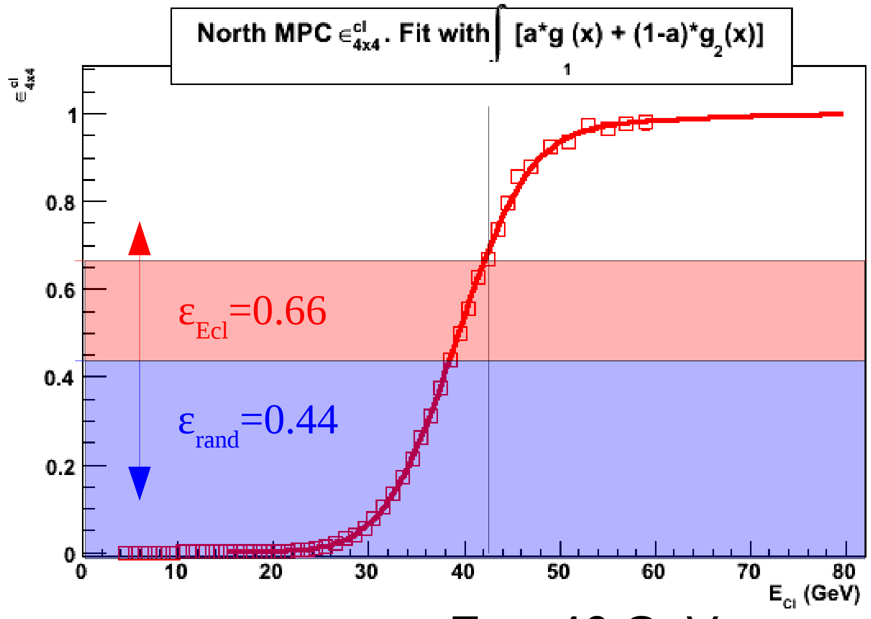
- Measure cluster efficiency as a function of cluster energy

$$\epsilon^{cl}_{4x4B} = \frac{\Sigma\left[N^{MB}_{cl} \wedge N^{4x4B}_{cl}\right]}{\Sigma N^{MB}_{cl}}$$

- Parametrize with Double Error Function
- Now Calculate

$$\epsilon_{4x4B} = \frac{\Sigma\left[N_{reco} \times \Theta_{\eta}\left(\epsilon_{cl1}(E_{cl1}) \vee \epsilon_{cl2}(E_{cl2})\right)\right]}{\Sigma\left[N_{reco}\right]}$$

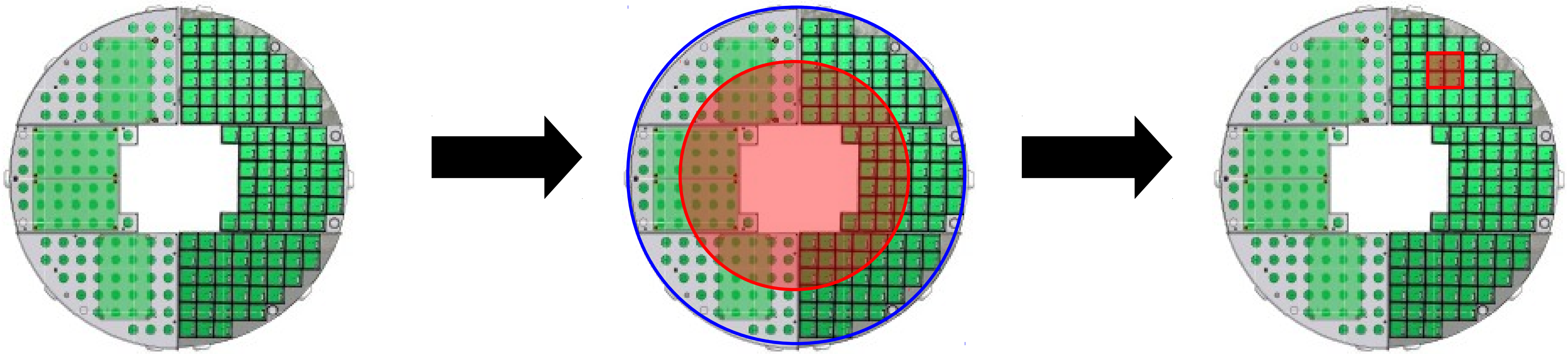
  - Step Function Θ_η:
    - Set Random efficiency between $0 < \varepsilon_{rand} < 1$
    - Evaluate cluster efficiency at cluster energy, E_{cl}
    - If($\varepsilon_{Ecl} > \varepsilon_{rand}$) (The trigger fired! In above example, it fired)
    - Done one cluster at a time



E_{cl} = 46 GeV

3b.) MPC4x4B η meson Trigger Efficiency

Choice of cluster efficiency in Θ_η

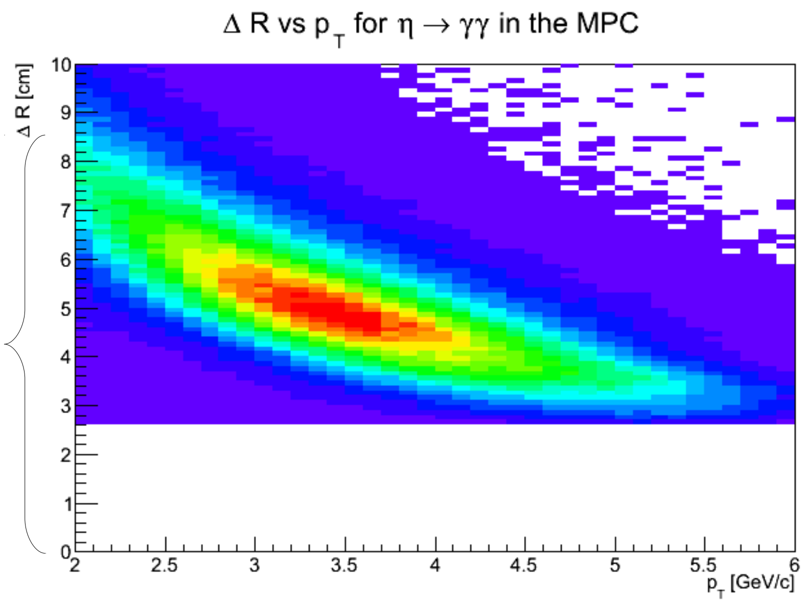


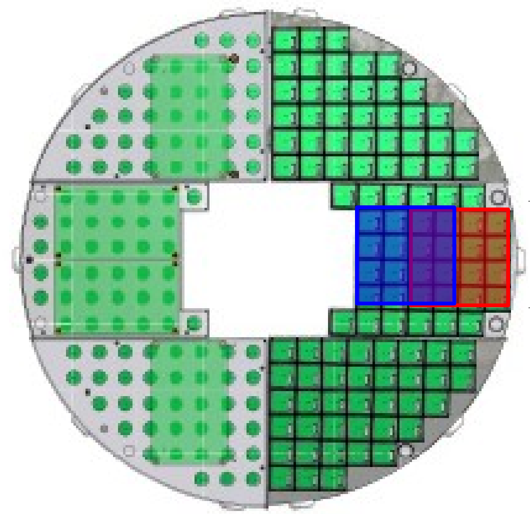
- First, we used cluster efficiencies in each MPC
  - Issues in p_T, pseudo-rapidity kinematics in inner vs outer MPC
- Second,we split MPC into inner and outer parts (above)
  - Issues with Non-uniformity in gain settings, and localized in MPC from tower to tower
- Third, split into MPC2x2ID efficiencies
  - 56 (61) efficiencies in the South (North) MPC

3b.) MPC4x4B η meson Trigger Efficiency

Choice of cluster efficiency in Θ_η

8.8 cm





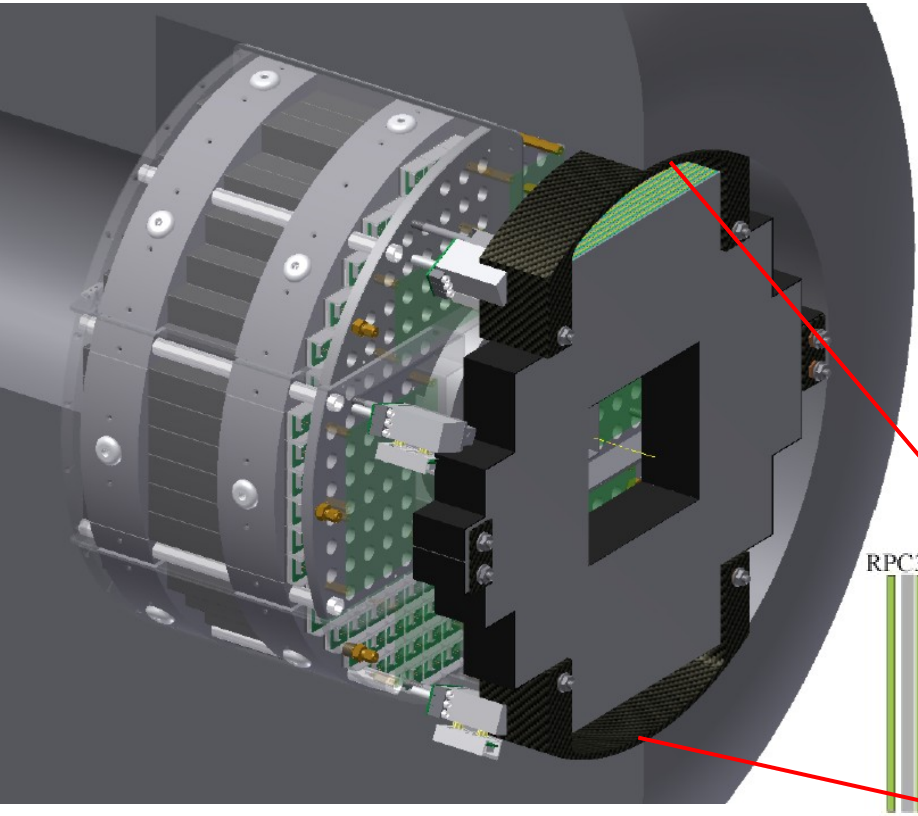
8.8 cm

- **Future:** look at underlying 4x4 tile efficiencies
  - Non-negligible effect from both photons η → γγ firing trigger
  - More complicated. 4X4 tiles overlap.

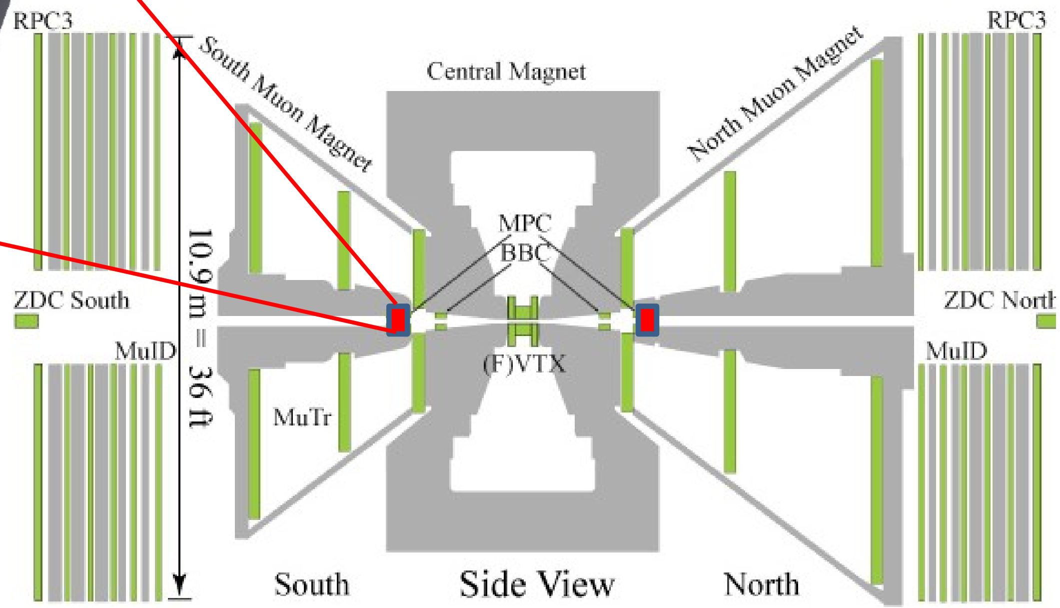
Outlook in the MPC

- Hope to finalize η meson A_N and Cross-section in the next few months
- Cluster Cross-section Measurement studies underway
  - More details of Cluster composition.
- 2012 dataset of $p+p^{\uparrow} \rightarrow \eta+X$ at $\sqrt{s}$ = 200 GeV
  - ~2.5 times Luminosity
  - New MPC electronics and trigger
    - To improve trigger purity
    - Measure up to all energies

Future: Direct γ with MPC-EX



- A combined charged particle tracker and detector
  - π^0 cluster rejection
  - Possible future Direct photon A_N and Cross-Section measurements

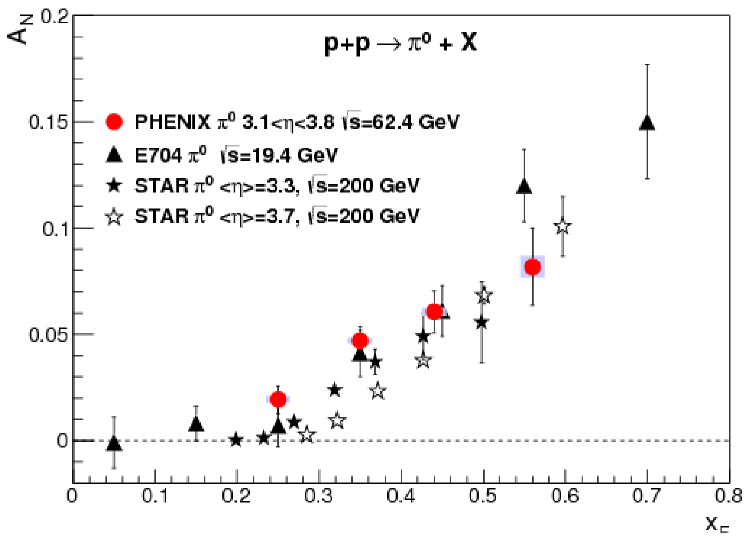


- Approved by BNL and DOE
  - First Commissioning in 2014
  - First Physics in 2015
    - p/d + Au Run

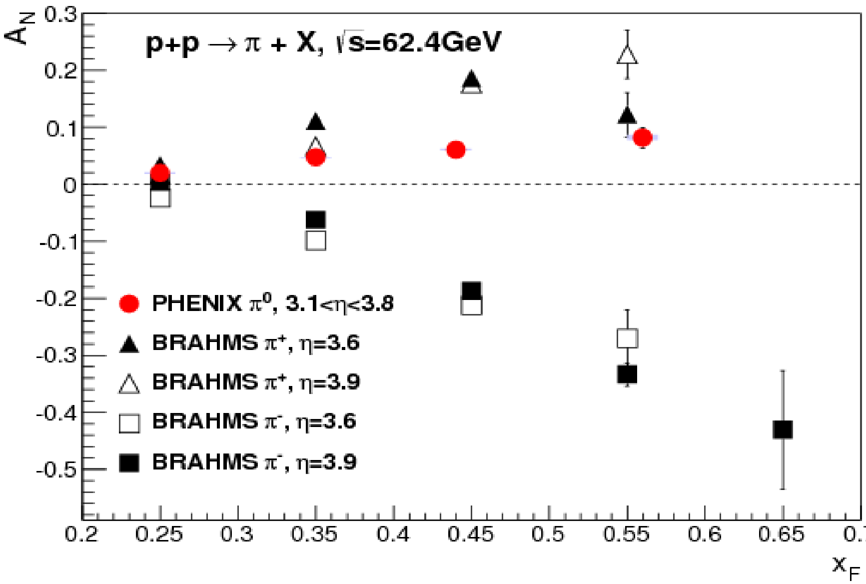
Conclusions

- MPC π^0 meson and single cluster A_N results consistent with previous π^0 A_N results
  - Single Cluster A_N shows possible hint of direct photon A_N at high x_F, p_T
- MPC η meson A_N consistent with other π^0 meson A_N
  - Consistent with STAR η meson A_N measurement within uncertainty
- Capable of measuring η meson Cross section
  - Will Compliment π^0 Cross Section

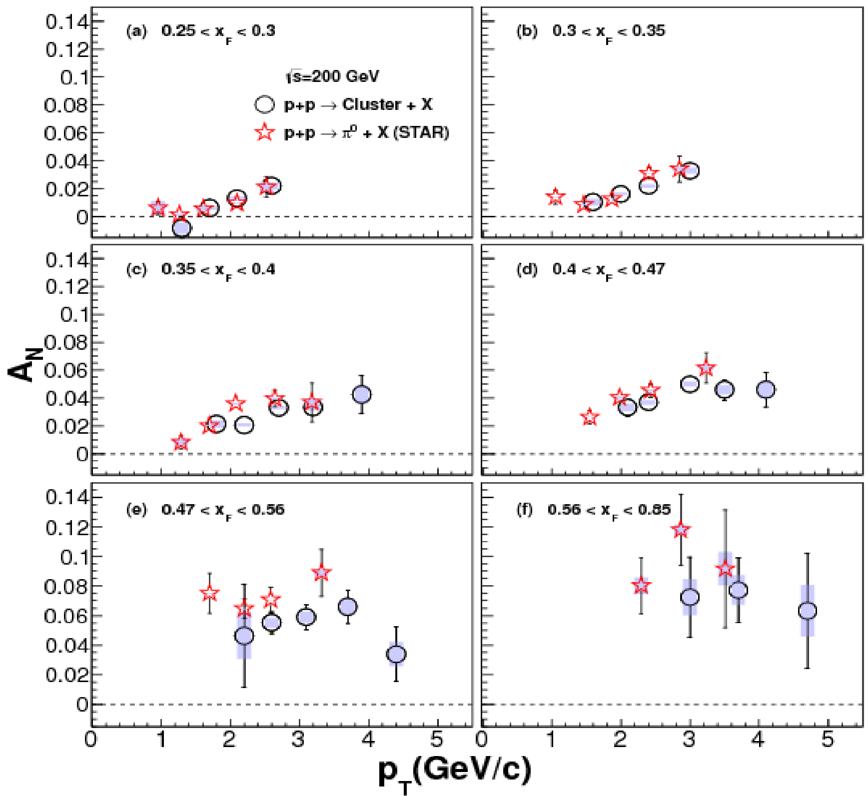
Thank you!



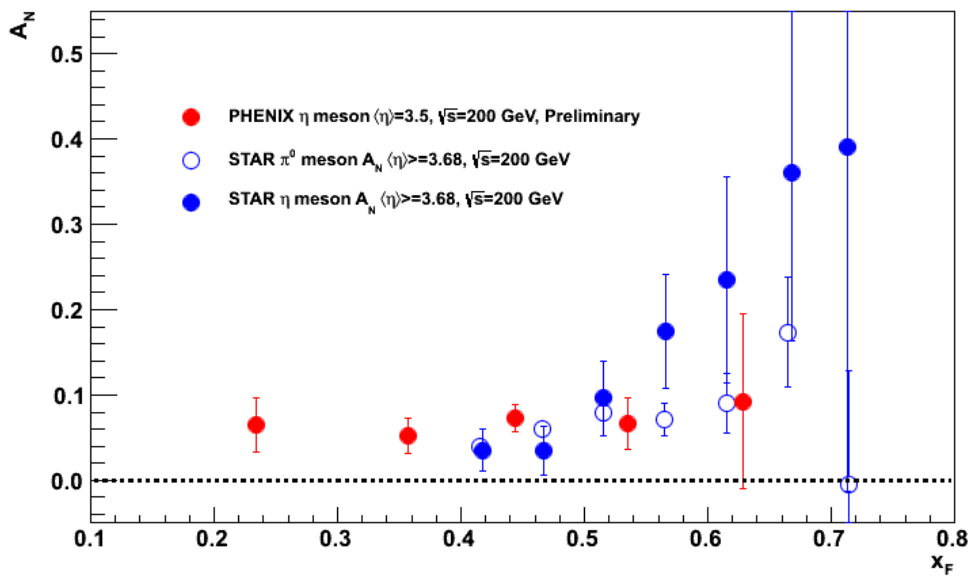
p+p → π⁰ + X
PHENIX π⁰ 3.1<η<3.8 √s=62.4 GeV
E704 π⁰ √s=19.4 GeV
STAR π⁰ <η>=3.3, √s=200 GeV
STAR π⁰ <η>=3.7, √s=200 GeV
A_N
x_F



p+p → π + X, √s=62.4GeV
PHENIX π⁰, 3.1<η<3.8
BRAHMS π⁺, η=3.6
BRAHMS π⁺, η=3.9
BRAHMS π⁻, η=3.6
BRAHMS π⁻, η=3.9
A_N
x_F



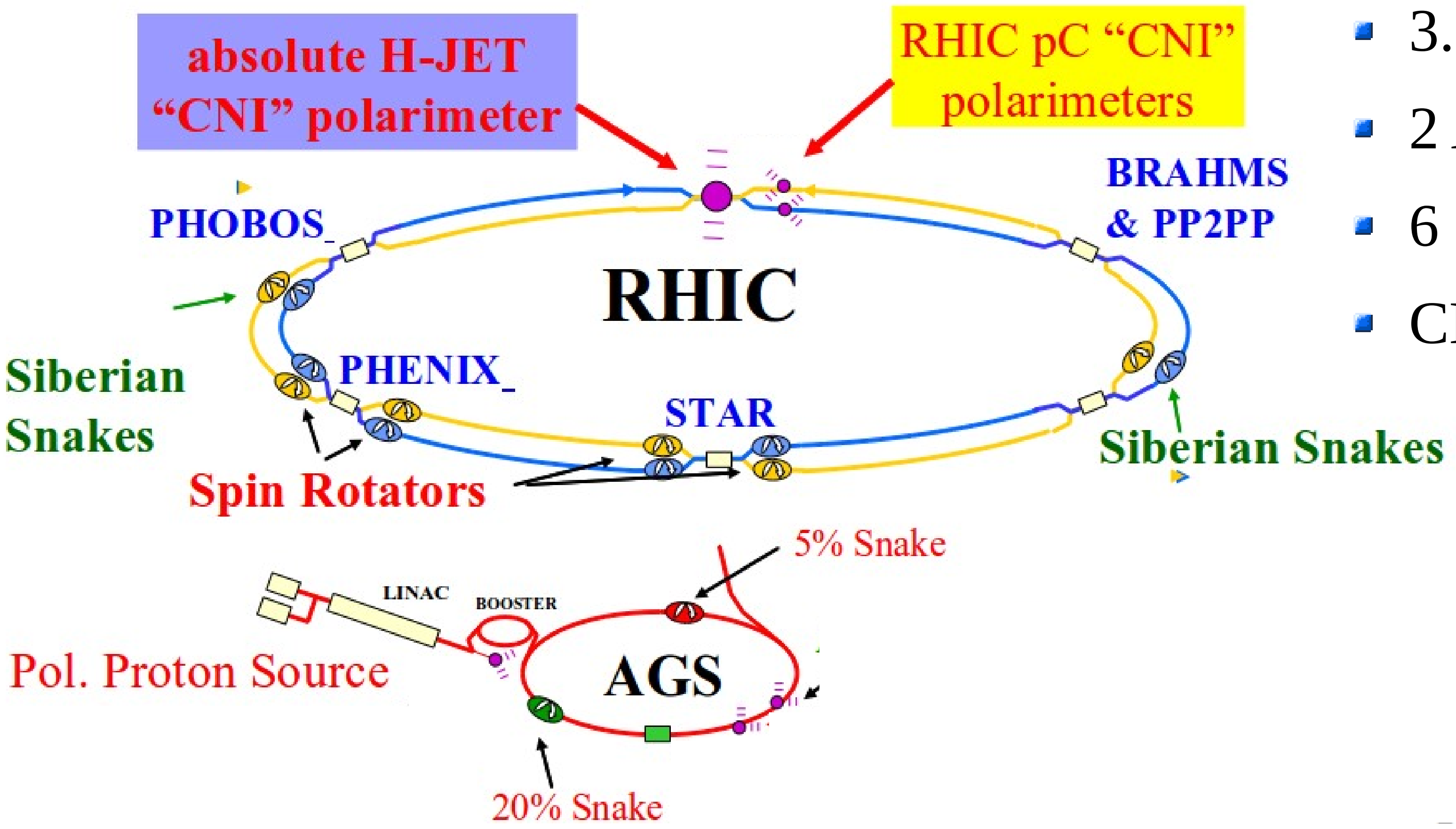
(a) 0.25 < x_F < 0.3
√s=200 GeV
p+p → Cluster + X
p+p → π⁰ + X (STAR)
(b) 0.3 < x_F < 0.35
(c) 0.35 < x_F < 0.4
(d) 0.4 < x_F < 0.47
(e) 0.47 < x_F < 0.56
(f) 0.56 < x_F < 0.85
A_N
p_T(GeV/c)



PHENIX η meson ⟨η⟩=3.5, √s=200 GeV, Preliminary
STAR π⁰ meson A_N ⟨η⟩>=3.68, √s=200 GeV
STAR η meson A_N ⟨η⟩>=3.68, √s=200 GeV
A_N
x_F

backup

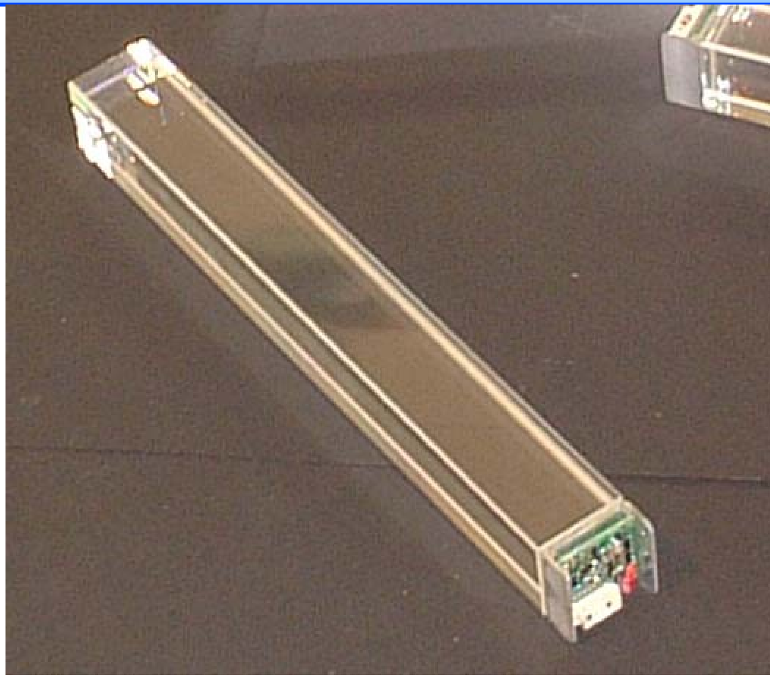
RHIC & AGS



- 3.83 km circumference
- 2 Accelerator Rings
- 6 collision points
- CNI Polarimeters

- H-JET Polarimeter: Allows for absolute normalization of polarizations
  - Slow measurement, but accurate
- Fast pC Polarimeter: Allows for online polarimetry measurements
  - Fast measurement, but must be calibrated offline after data taking

MPC detector in PHENIX



- MPC is forward E.M. Calorimeter
  - 2.2x2.2x18 cm^3 $PbWO_4$ crystal towers
  - 220 cm from nominal interaction point
  - **|3.1| < η < |3.9|**
  - 196(220) crystals in south(north) MPC

- Why use $PbWO_4$?
  - Close to beam pipe, IR
  - Need high density, homogeneous material
    - Short Radiation Length (0.89 cm)
    - Small Moliere Radius (2.0 cm)