Does the Gluon Carry Proton's Spin?

Hari Guragain, PhD.

February 19, 2016

PHENIX

UNIVERSITY OF VIRGINIA 1819

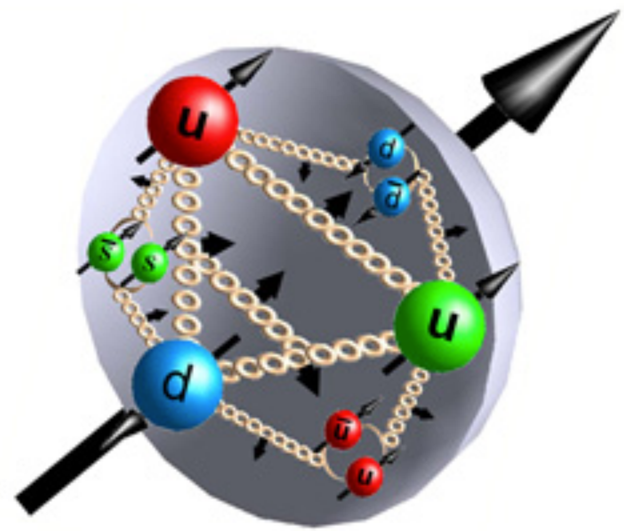
Georgia State University

Motivation

To understand the spin structure of the proton

Proton is composite particle:

- Two up and one down valence quarks
- Bound together by gluons
- Sea quarks (produced in pairs)



How do the properties of the proton arise from these constituents?

The Inner Life of Protons

- Charge: $+1 = 2/3 + 2/3 - 1/3$
  u u d

- Mass: Up and down quarks are almost massless ($m_u + m_u + m_d \approx 9$ MeV/c^2, total mass of proton $m_p \approx 938$ MeV/c^2)
  - Remaining mass is due to the kinetic energy of the quarks and **the energy of the gluon fields that binds the quarks together**.

Terminology Used

- Helicity: Projection of spin vector onto momentum
- Bjorken x: Momentum fraction carried by parton (quark or gluon) of hadron.
- Fragmentation function: Probability that a parton at a short distance fragments into a hadron with fraction z of the parent momentum x.
- Partonic cross section: Likelihood of interaction between particles.
- Spin dependent parton distribution function: The probability density for finding a particle with a certain longitudinal momentum fraction x at momentum transfer Q^2.

Momentum

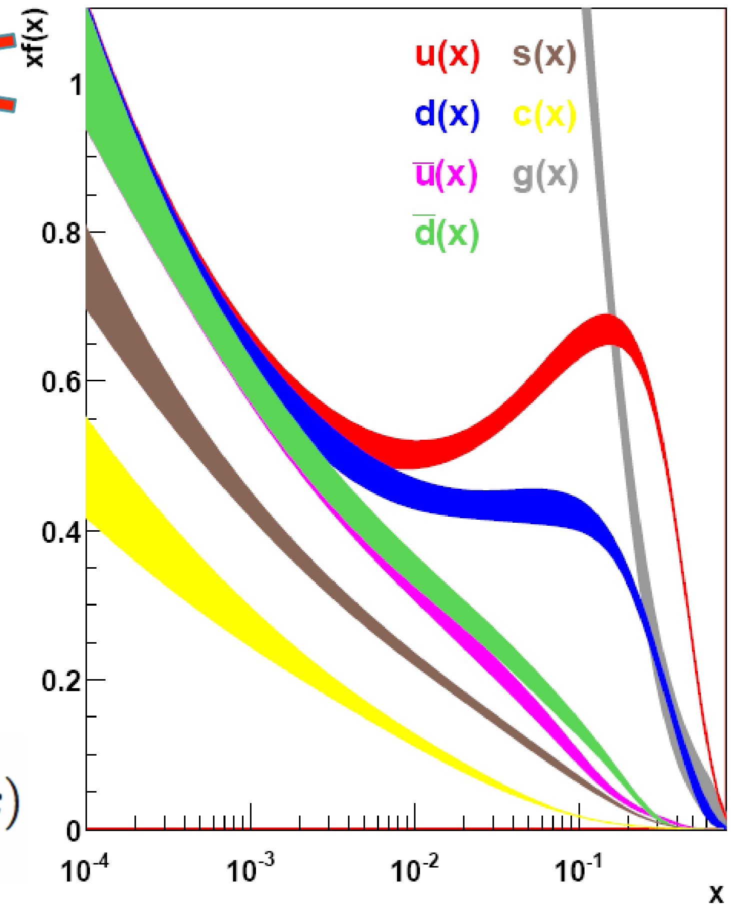
Initial thought:

- Momentum: I = ~~1/3 + 1/3 + 1/3~~

- The total momentum is not only contributed by the quarks but is smeared out due to continuously interchanging gluons

- Gluons themselves carry some momentum!

$$1 = \sum_q \int_0^1 x dx [q(x) + \bar{q}(x)] + \int_0^1 x dx g(x)$$



What about SPIN?

Spin Composition of the Proton

Initial thought:

- Spin is contributed only by quarks

$$\frac{1}{2} = \frac{1}{2} + \frac{1}{2} - \frac{1}{2}$$

- EMC results show only small fraction of spin is contributed by quarks ~ 30%[1]

PROTON SPIN CRISIS BEGIN

- What else could contribute?
  - Need to consider spin of sea quarks, gluon and orbital angular momentum

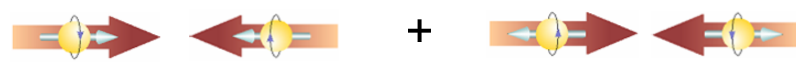
$$\frac{1}{2} = \frac{1}{2}(\underbrace{\Delta u_v + \Delta d_v + \Delta q_s}_{\Delta\Sigma}) + L_q + \Delta G + L_g$$

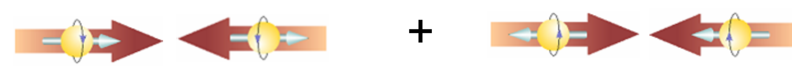
[1] S. D. Bass, Rev. Mod. Phys. 77, 1257 (2005)

Hunting ΔG

- Via Double Helicity Asymmetry

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{a,b,c=q,\bar{q},g} \Delta f_a \otimes \Delta f_b \otimes \Delta\hat{\sigma} \otimes D_{\pi/c}}{\sum_{a,b,c=q,\bar{q},g} f_a \otimes f_b \otimes \hat{\sigma} \otimes D_{\pi/c}}$$

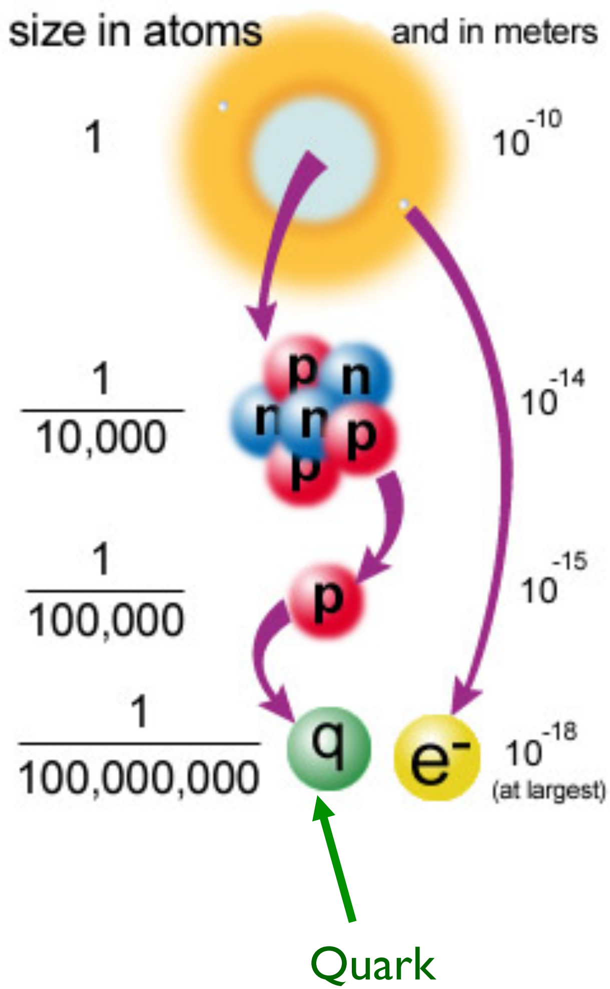
++ = Same helicity =


+ - = Opposite helicity =


- Δf(a/b) ≈ Δg: Spin dependent parton distribution function (Our Focus).
- $\Delta\sigma$: Hard scattering cross section.
- $D_{\pi/c}$ Fragmentation function(Cross section is used to get fragmentation function).

Taking a Look inside an Atom

- Rutherford's scattering experiment:
  - structure of atom
  - Energy is less to probe inside nucleus (Energy: 5.5 MeV)
- Similarly, scattering of electrons with protons at large angles (SLAC):
  - "hard" subcomponents in the proton
  - Little knowledge on nucleon (Energy: 1 – 10 GeV)
- Proton-proton scattering (RHIC):
  - deeper inside proton
  - reveals the structure of proton (Energy: up to 255 GeV)

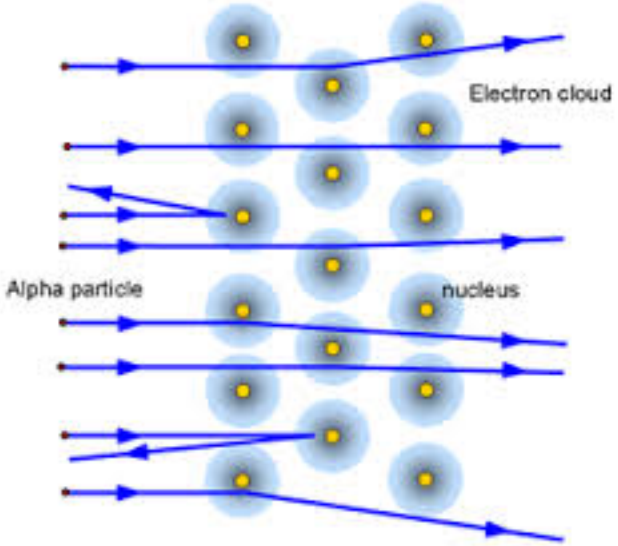


TOOLBOX

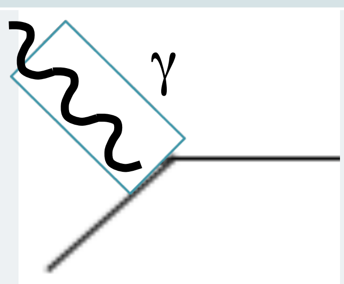
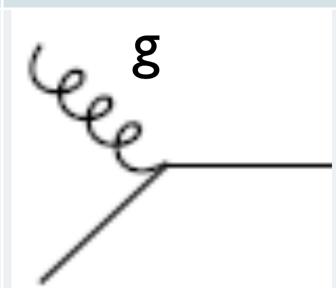
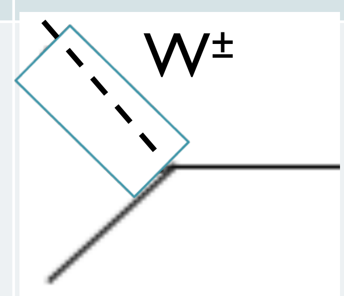
How can we study the proton?

- Can't use a microscope
  - Quantum Mechanics tells us that observation changes the system
- Instead, use some kind of probe to interact with what is inside
  - Basic technique is scattering

    Example: Rutherford scattering experiment with alpha particles
    - → Structure of Atom
  - Try the same thing, using electrons and protons (quarks and gluons)
- **But what kind of probes can we use?**

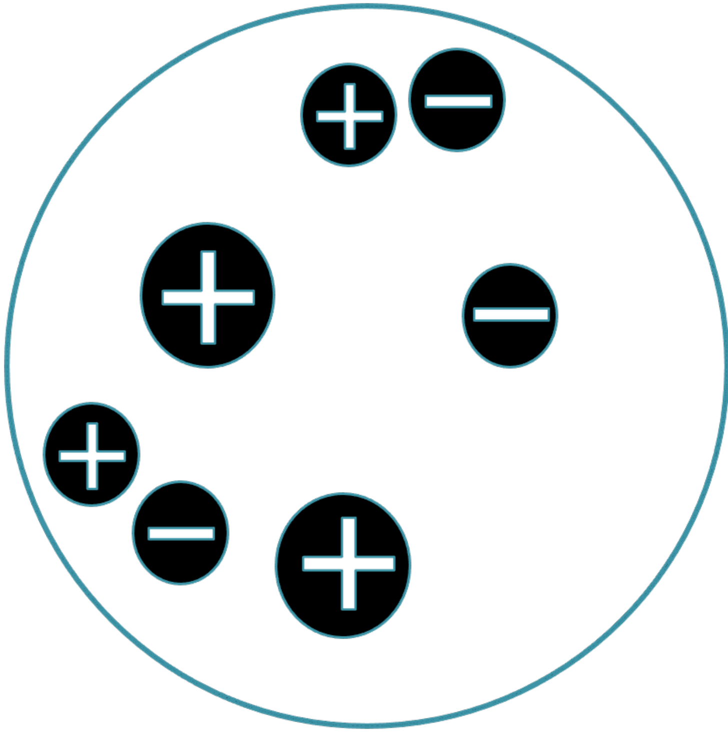


3 Forces → 3 Probes

Force	Electromag.	Strong Nuc.	Weak Nuc.
Carrier	photon	gluon	W^+, W^- (& Z) boson
Charge	+,-	color: r,g,b and anitcolor	weak charge: flavor
Relative Strength	1	100	10^{-11}
Standard (Feynman) symbol			

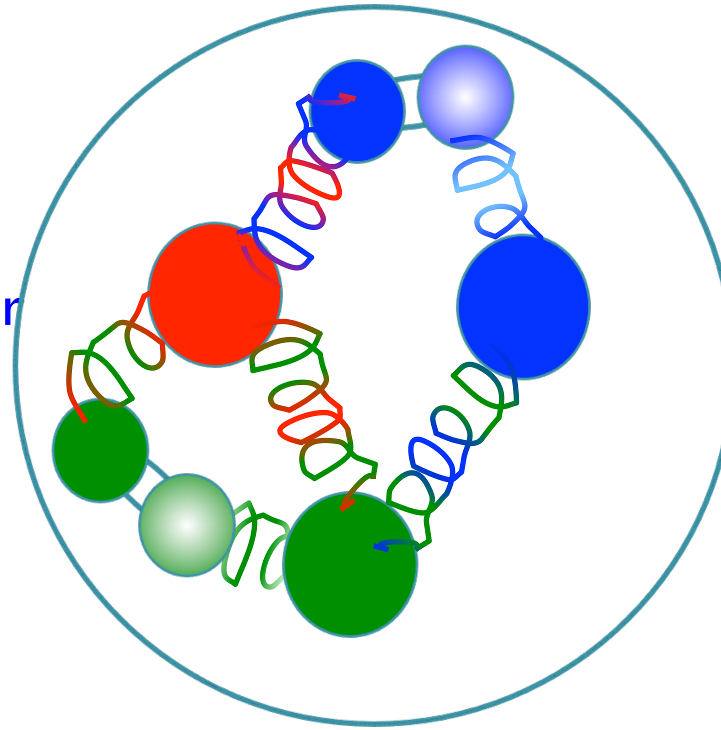
Electromagnetic: The Photon

- Only interact with charged particles, i.e. quarks
  - Limited direct information on gluons
- Very similar to X-ray scattering to study structure of crystals and other materials:
- In the case of protons, photon of (much high) energy Q^2 scatters off a quark with momentum xP, and we have a distribution of quarks $f(x,Q^2)$.



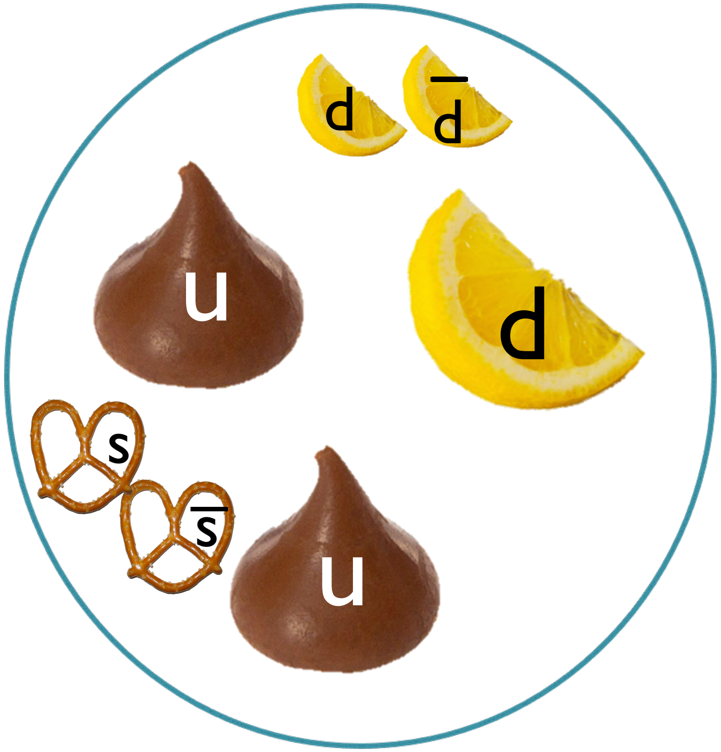
Strong Nuclear: The Gluon

- Gluons interact via "color" force.
  - Both quarks and gluons carry color charge, so can study both
  - Gluons are self interacting, unlike photons
  - Can directly access gluons

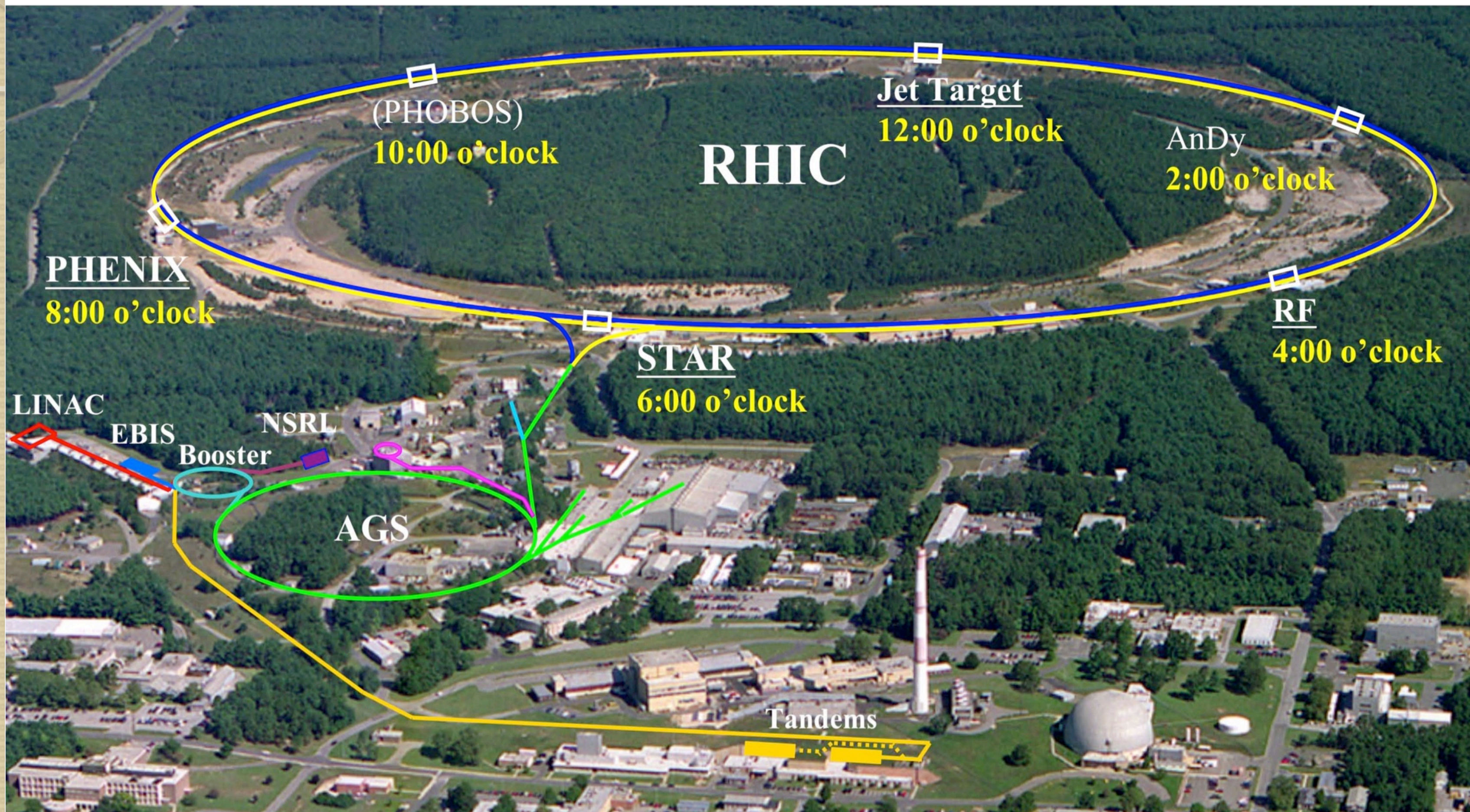


Weak Nuclear: The W & Z Bosons

- Weak force is sensitive to quark flavor
  - Explains neutron decay to proton
    - d → u + W → u + e + ν_e
- How can we get W's?
  - Can use neutrinos to study
    - Requires a lot of materials as neutrinos don't interact much
  - Also can annihilate quarks and anti-quarks to produce W's
    - What we do at RHIC



Studying Proton Structure in Lab: RHIC

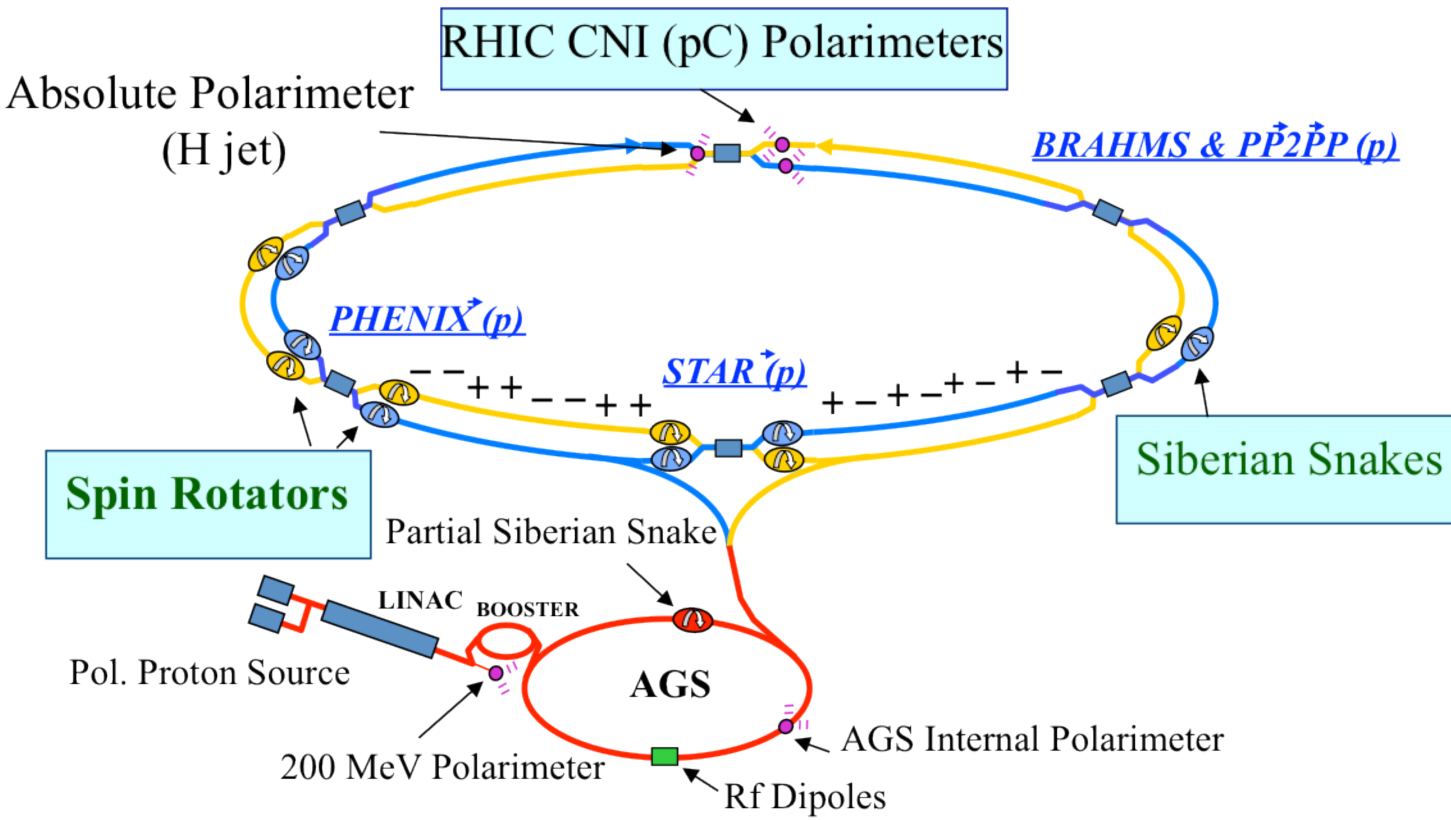


Relativistic Heavy Ion Collider (RHIC) can collide several species including the polarized protons

Spin Components at RHIC

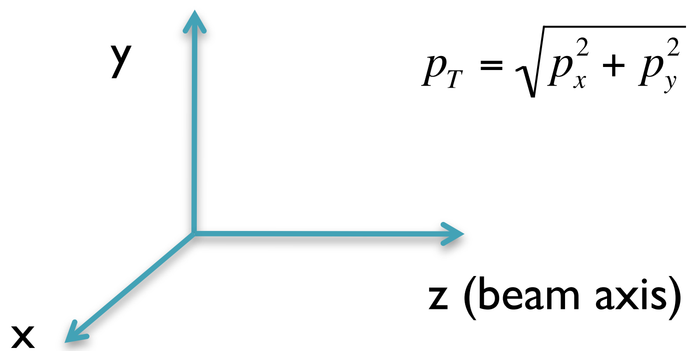
RHIC: The only polarized proton collider

- Up to $\sqrt{s}$=510 GeV
- P ~ 55% @ $\sqrt{s}$=510 GeV, P ~ 60% @ $\sqrt{s}$=200 GeV
- Transverse or longitudinal polarization



Kinematic Variables

Transverse Momentum



$$p_T = \sqrt{p_x^2 + p_y^2}$$

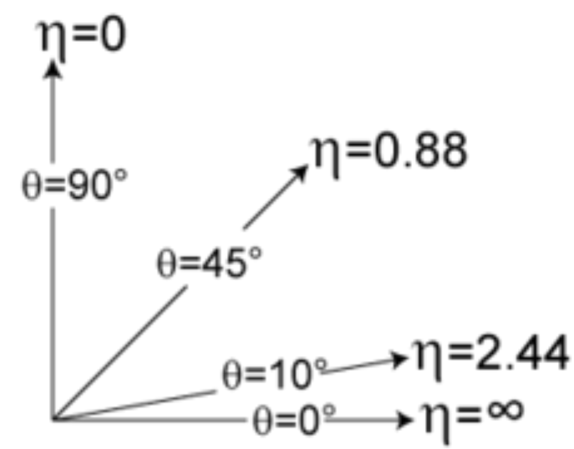
Invariant Mass

$$m_{\gamma\gamma} = \sqrt{E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2}$$

Rapidity

$$y = \frac{1}{2}\ln\frac{E + p_z}{E - p_z}$$

$$\approx \eta = -\ln[\tan(\theta/2)]$$



PHENIX Experiment:

Special Interest for spin:

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

Detectors Used:

1. Photon Identification:

Electromagnetic Calorimeter (EMCal):

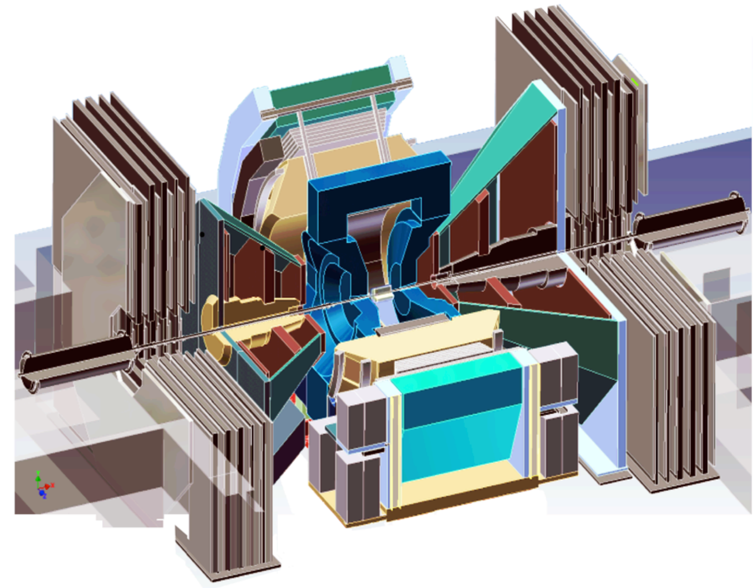
- 6 sectors PbSc with 64 layers of Pb and scintillator
- 2 sectors PbGl
- $|\Delta\eta| < 0.35$
- $\Delta\phi=\pi$ (2 arms x $\pi/2$)

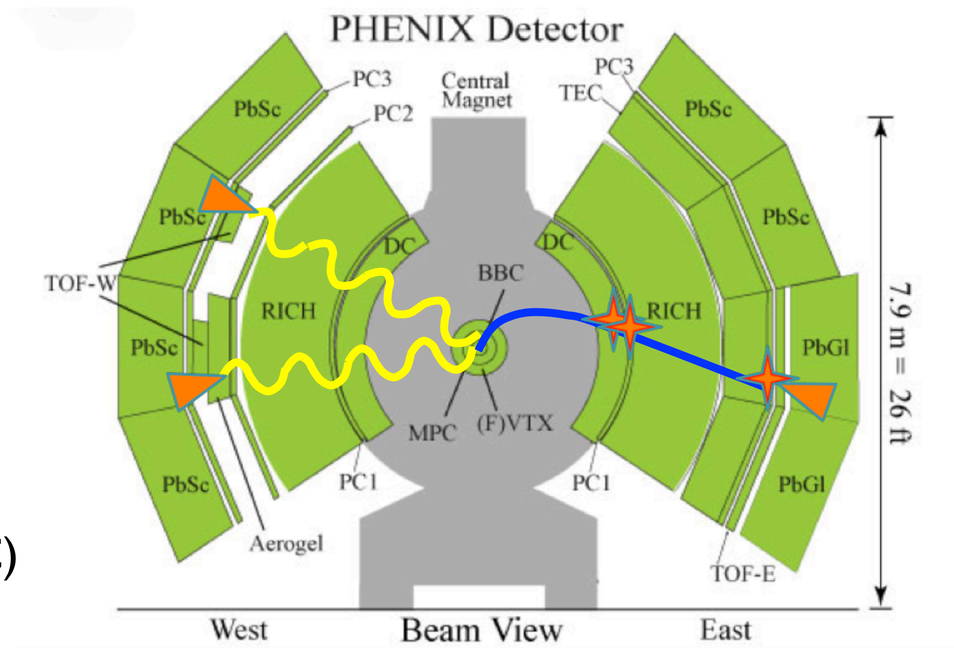
2. Hadron Identification:

Pad Chambers in front of EMCal.

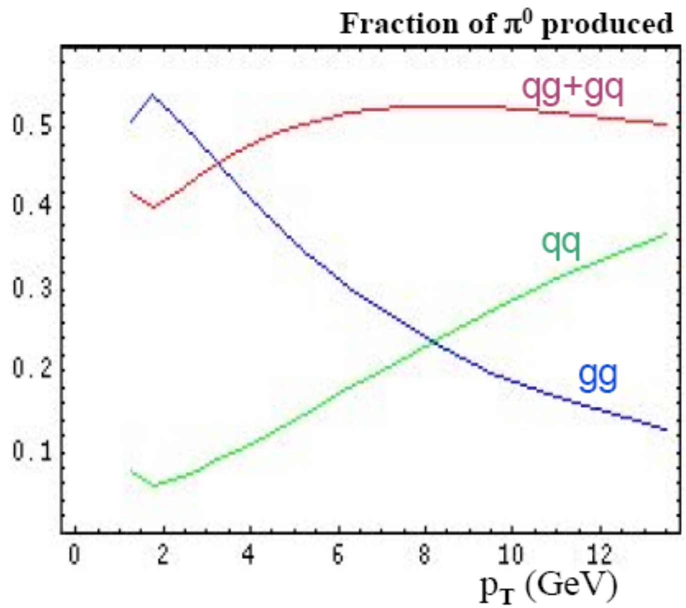
3. Relative Luminosity:

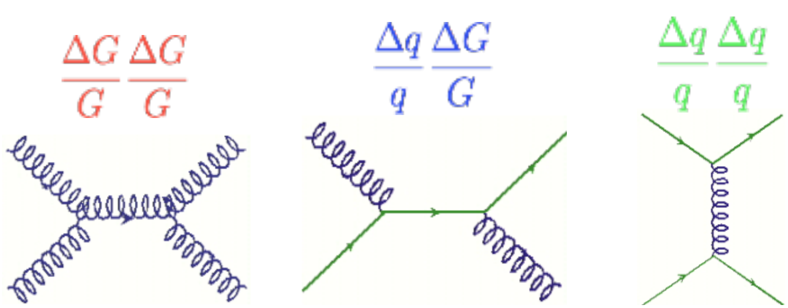
- Beam Beam Counter(BBC).
- Zero Degree Calorimeter(ZDC)





π^0 as a Probe for ΔG: Why π^0?

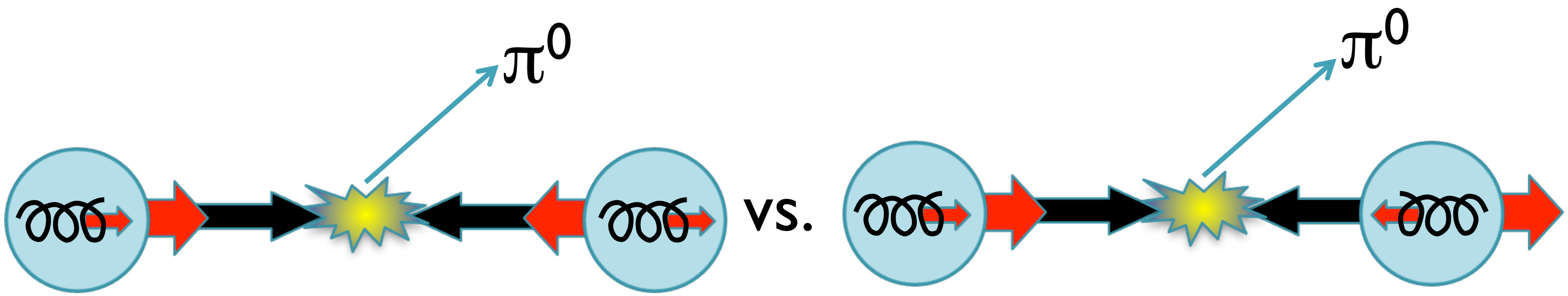




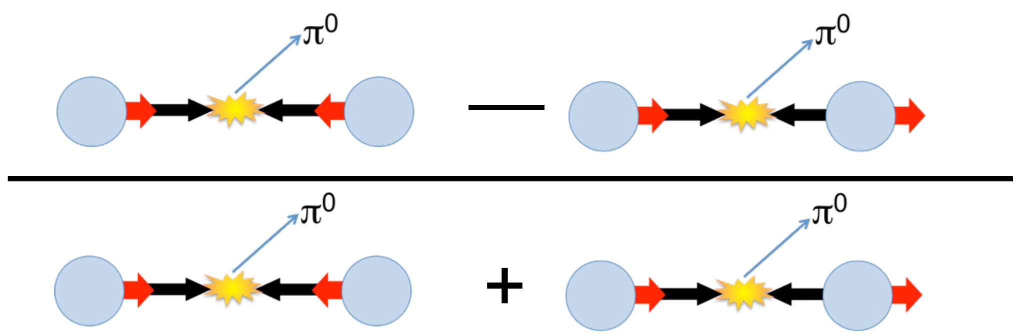
- π^0 is most dominantly produced particle observed in PHENIX detector
- processes that involve gluons are dominant in accessed kinematic range

What Exactly is Measured in this Experiment?

❖ We want to know how aligned the gluon spin is to the proton:

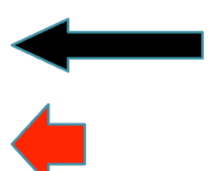


$A_{LL} =$



Mom.

Spin

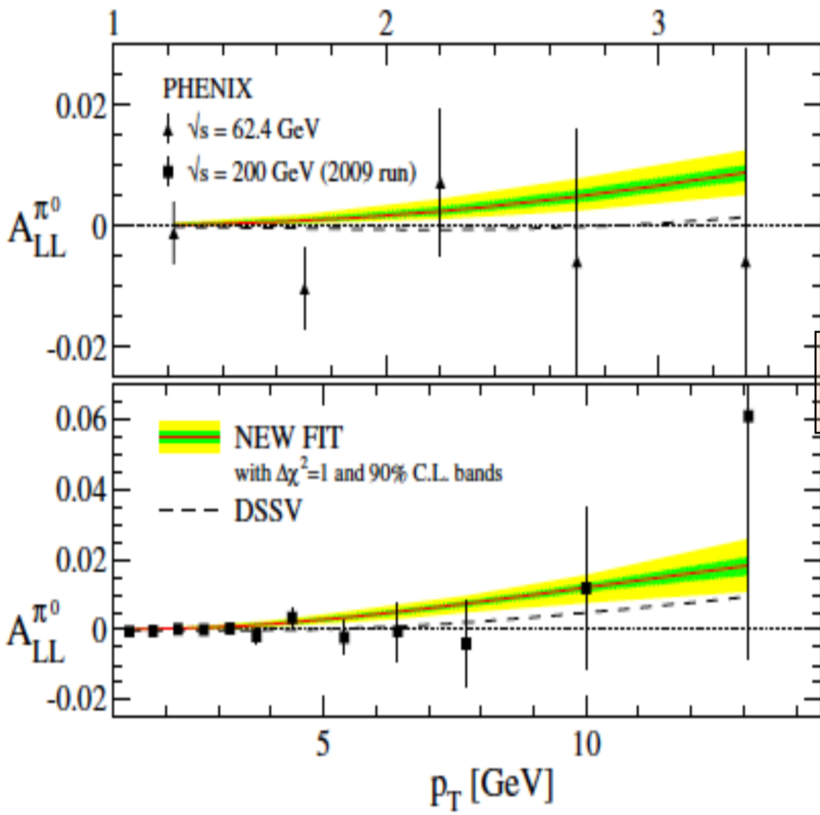


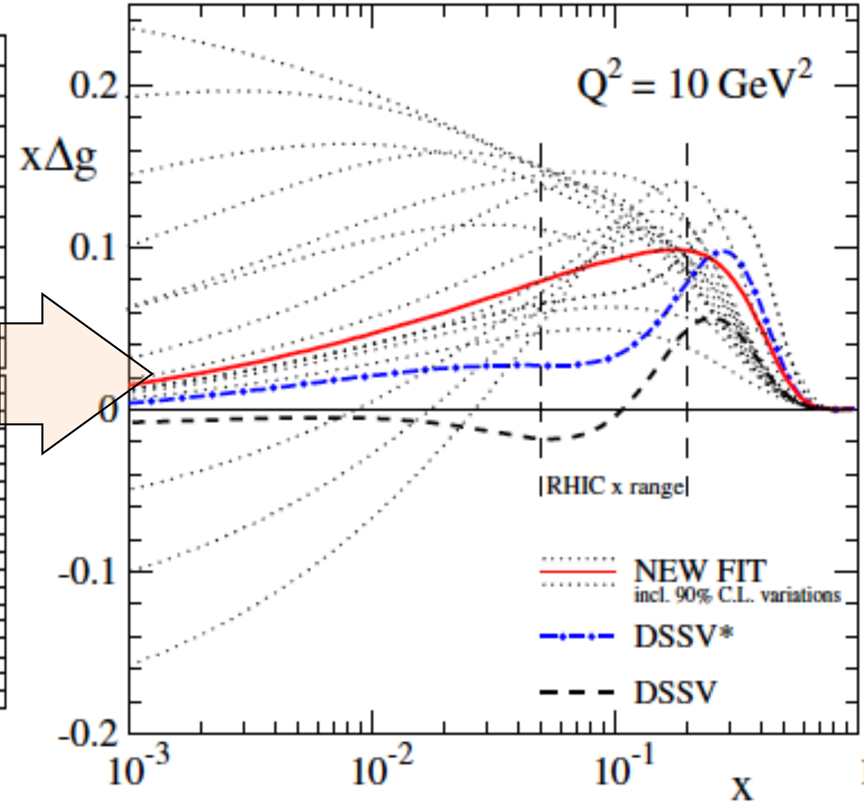
Necessary Ingredients for A_{LL}

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_b P_y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

- Helicity dependent particle yields (N)
  - π^0, π^+, π^-, η etc
- Beam polarization (P)
- Relative luminosity (R)

Current Status on: ΔG

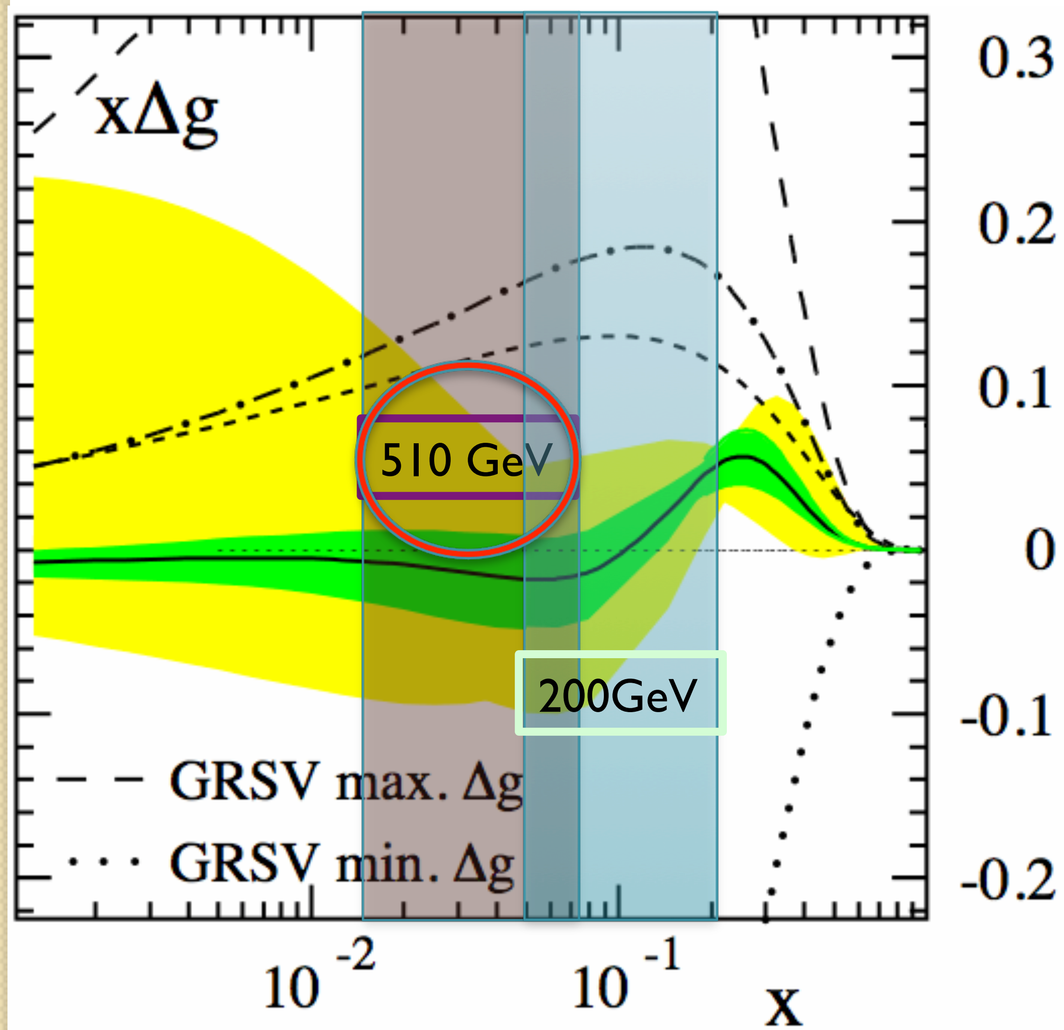




PHENIX √s =62.4 GeV (upper panel)
and 200 GeV (lower panel) data

PRL 113, 012001 (2014)

What is new in this analysis?

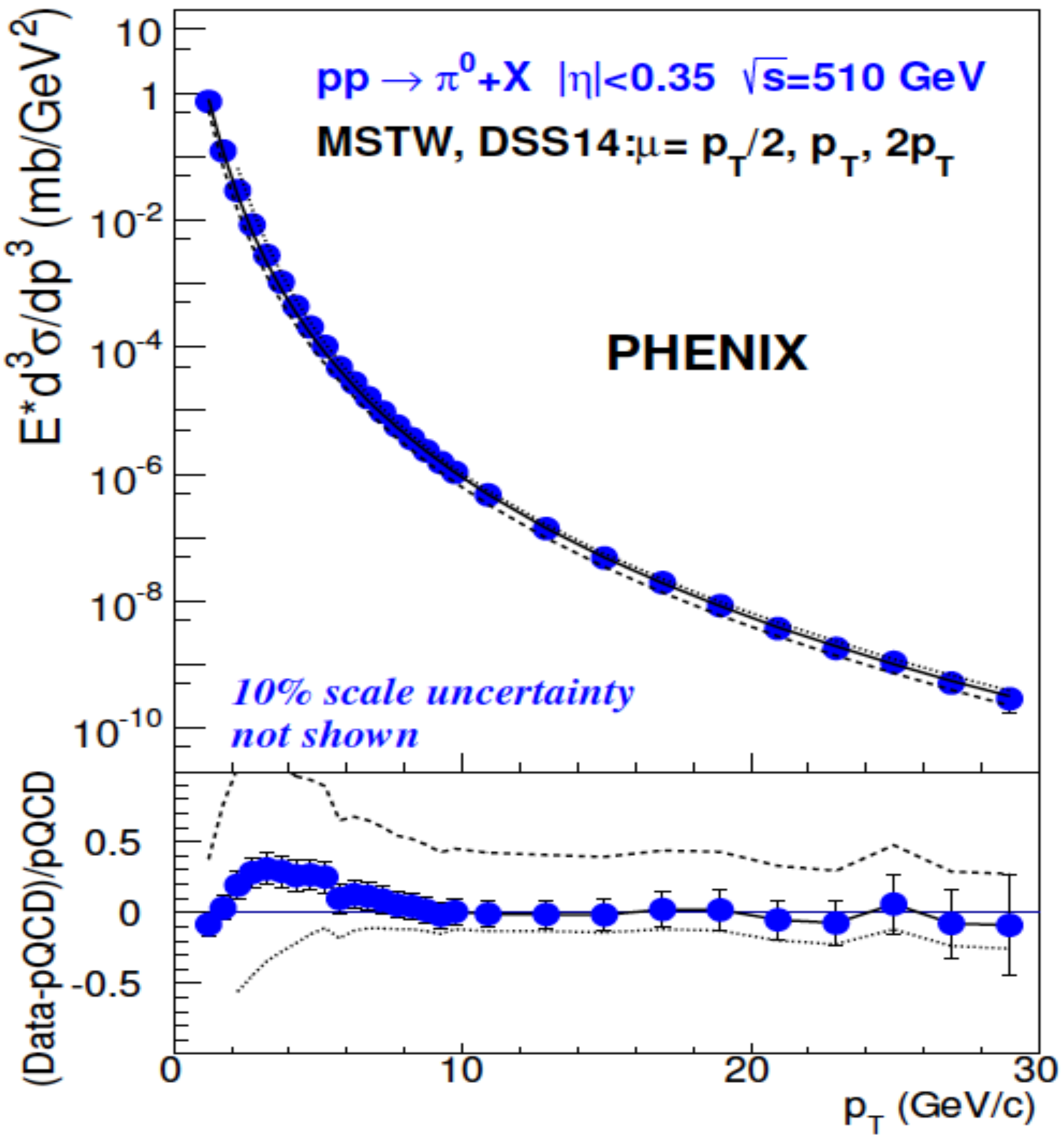


Δ g has larger uncertainty at small x region. Large lower region is still unexplored.

Data Selection

- Data was recorded in 2012 and 2013 (>312 hours) with the PHENIX central arm detectors
- Average polarization:
  - Blue: 0.55 ±0.02
  - Yellow: 0.56 ± 0.02
- An extensive QA analysis was performed
- Additional cuts were applied to improve the quality of the data
  - Total Luminosity (p + p collisions): 155 pb^{-1}
  - Luminosity (good data): 108 pb^{-1} (Run 13), 20 pb^{-1} (Run 12)

Cross-Section Results from 2013



Phys.Rev. D93 (2016) 1, 011501

- ❖ Comparison is made with theoretical calculation (pQCD)
- ❖ Theory agrees well with data

Basic Ingredients for A_{LL}

Recap

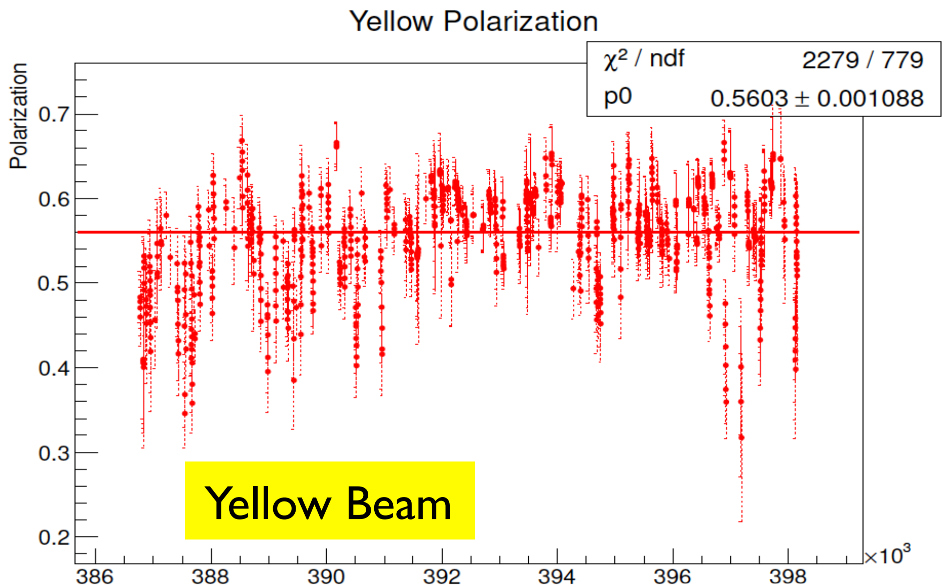
$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{P_b P_y} \frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

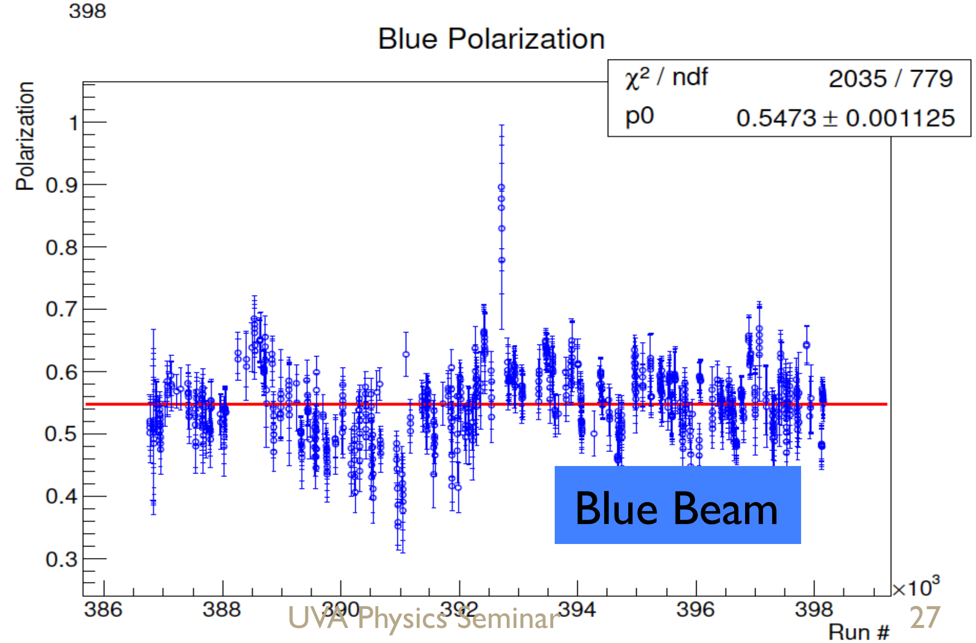
① Polarization information

② Yield from π^0 and

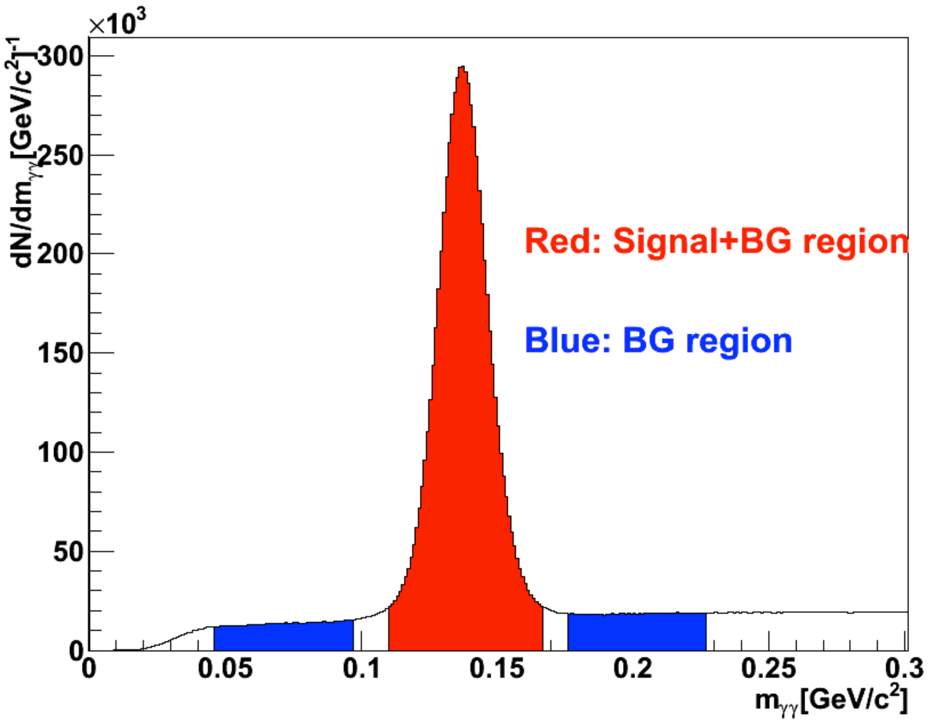
③ Relative luminosity

Polarization Results





π^0 Yield



- Invariant mass spectrum of π^0 reconstructed from associated di-photons in the detector in each event

$$m_{\pi^0} = \sqrt{E_1 E_2 - \vec{p}_1 \cdot \vec{p}_2}$$

- Red: signal + background region
- Blue: background regions

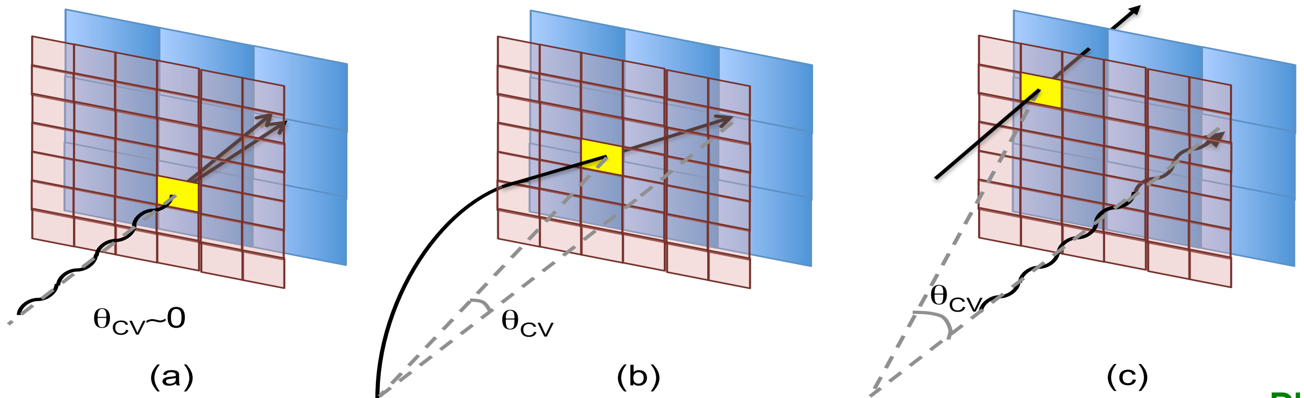
Major Sources of Background

- Charged hadrons
- Uncorrelated background

CHARGE VETO CUT

(REMOVING CHARGED HADRONS)

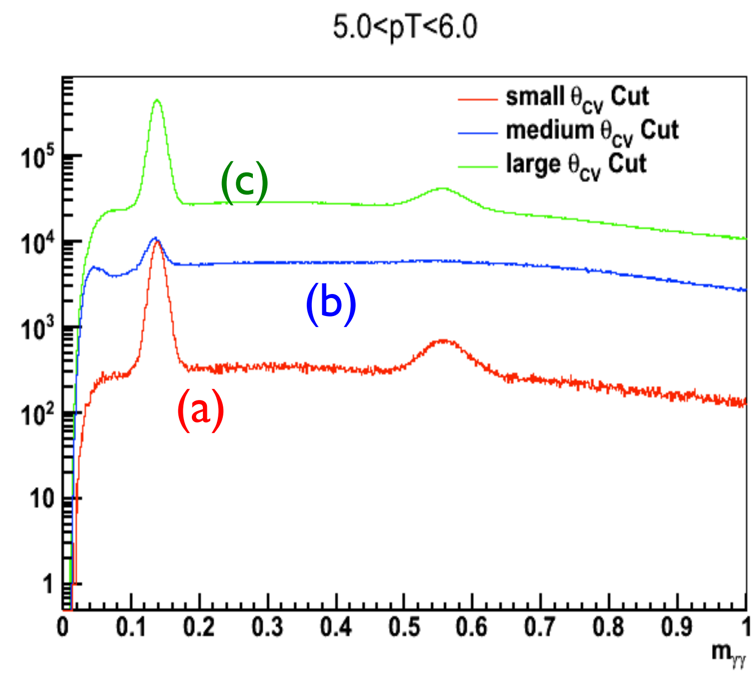
Veto Cut to Remove Charged Hadron



Conversion like

Hadron like

Photon like



Charge Veto:

- Use pad chamber in front of EMCal to tag charged hadrons
- Based on angle (θ_{CV}) between EMCal and Pad hit:
  - Exclude hadrons with moderate θ_{CV}
  - Retain conversion electrons with near zero θ_{CV}

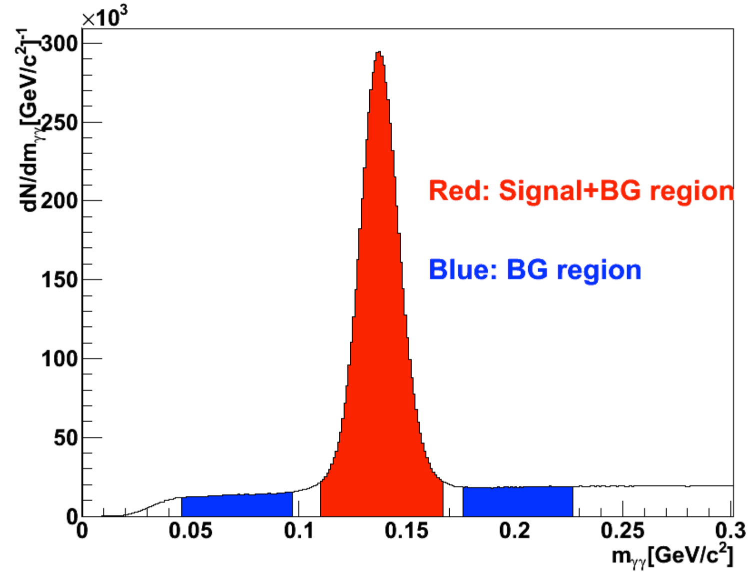
Uncorrelated background

- Random pair matching

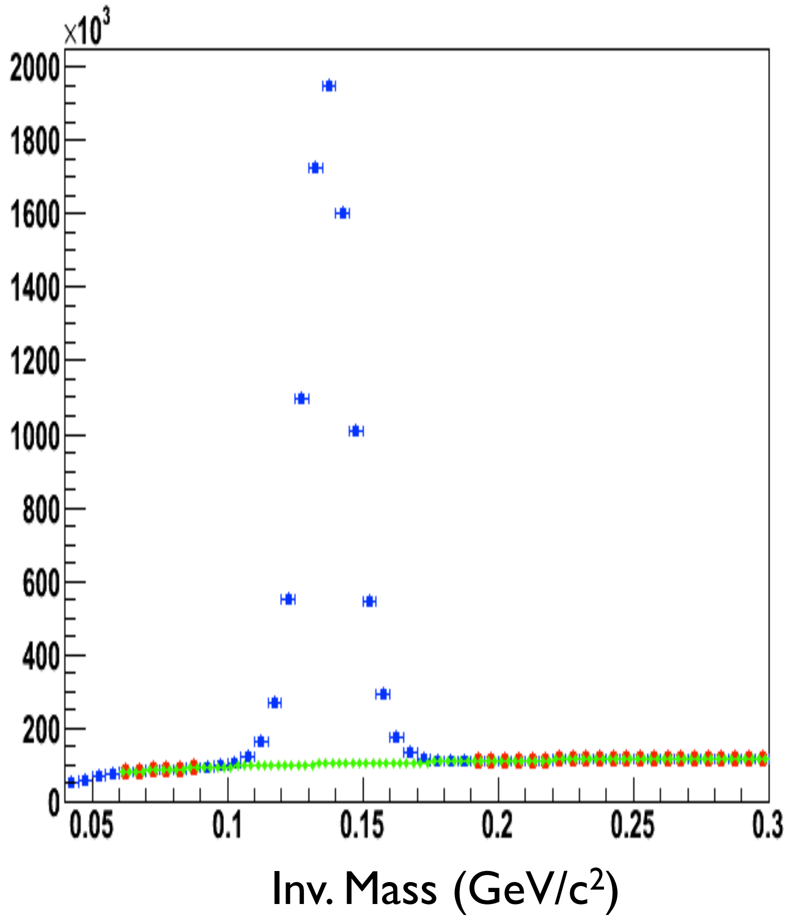
- Their effect can’t be reduced but can be estimated by calculating the background fraction

Background Fraction Calculation

- Ratio of number of counts in background region (blue area) and π^0s in signal region (red area)
- The π^0 in background region is calculated by using Gaussian Process Regression (GPR) method
- The π^0 in signal region is calculated by simply counting the yields from histograms



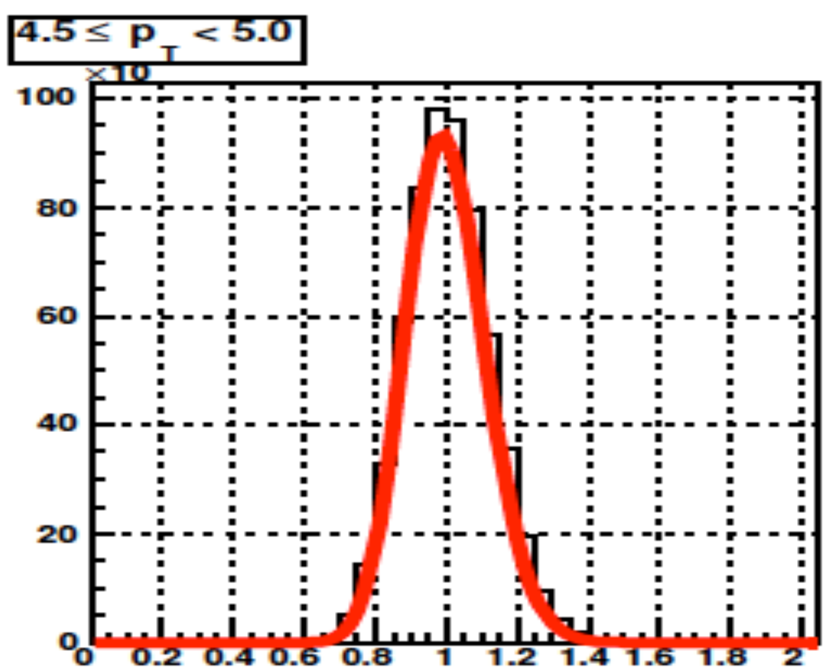
GPR Method for Estimation of Background Fraction



- Gaussian Process Regression(GPR) method is used to find the π^0 in the background region.
- Here, blue is our data, red is the fit by GPR and green is extrapolated values

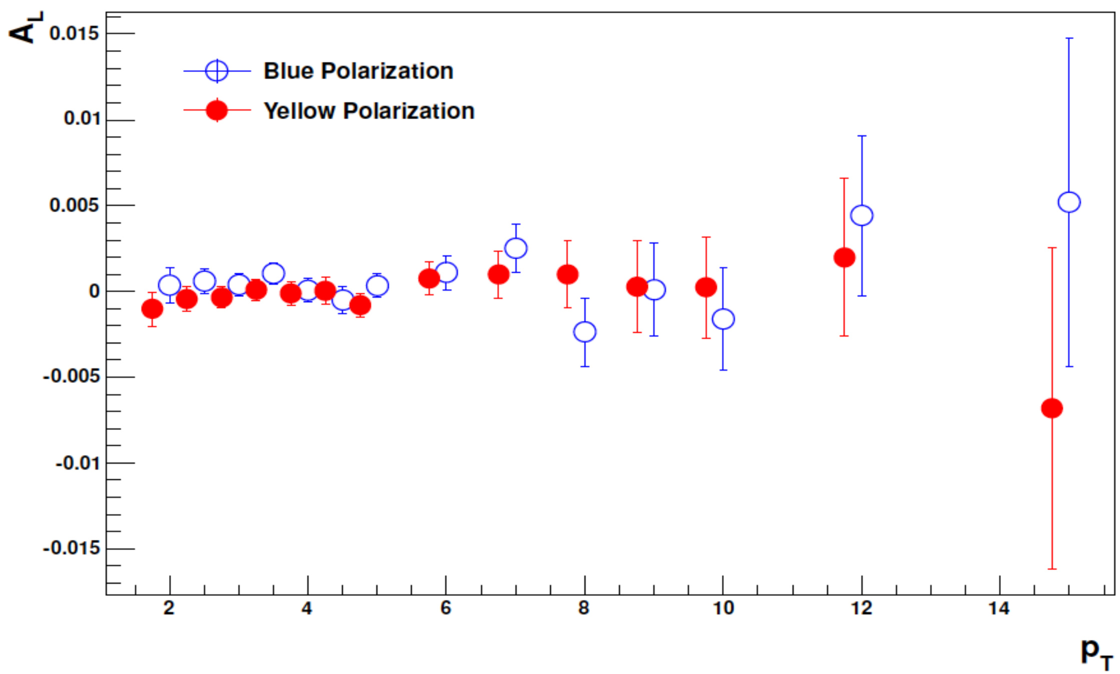
SYSTEMATIC UNCERTAINTY STUDIES

Bunch Shuffling (representative plots)



- Method to test if there is any systematic effect due to different bunches
- Randomly assign helicity for all bunches.
- Get A_{LL} for all fills in each p_T bin.
- Find χ^2/NDF for each sample.

Single Spin Asymmetry



- Parity violating property
- Strong interaction preserve the parity
- Small value of SSA is expected

(Strong interactions conserve parity)

RESULTS

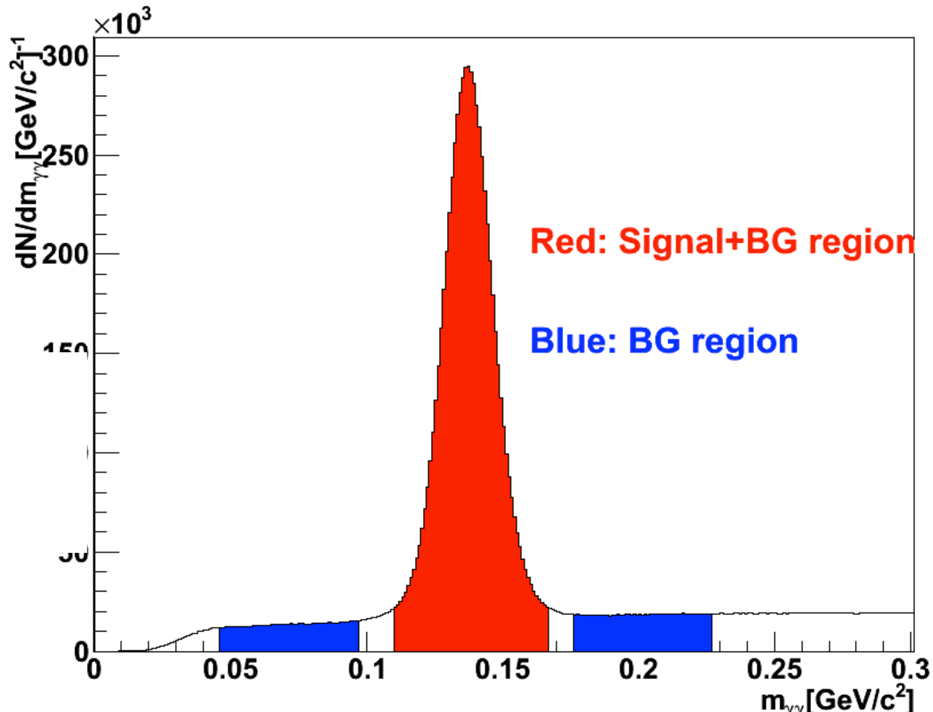
Double Helicity Asymmetry: A_{LL}

- Double helicity asymmetry for signal region (red region) and background region (blue) is calculated
- The background subtracted asymmetry is given by:

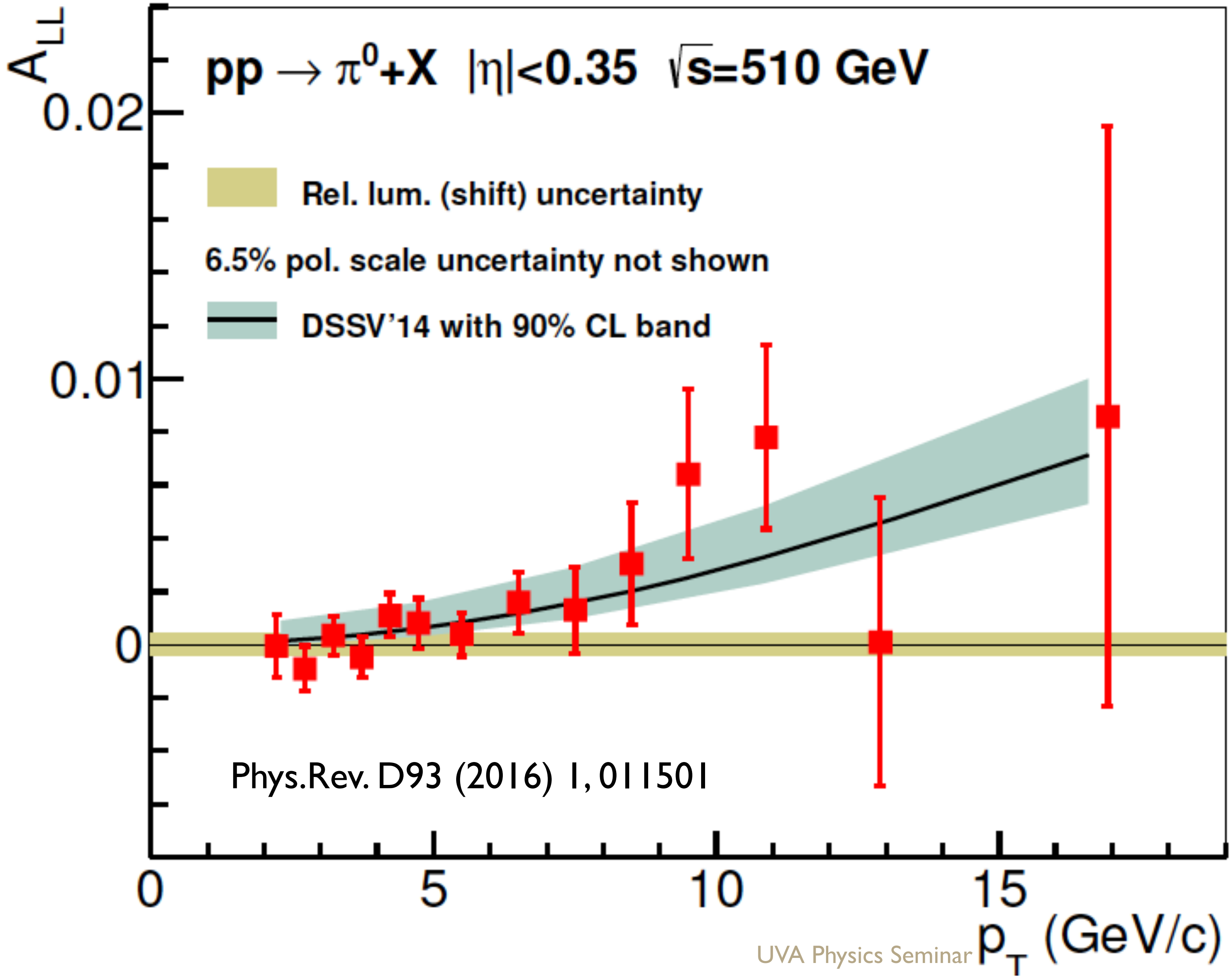
$$A_{LL} = \frac{A_{LL}^{\pi^0+BG} - r A_{LL}^{BG}}{1-r}$$

- r is given by:

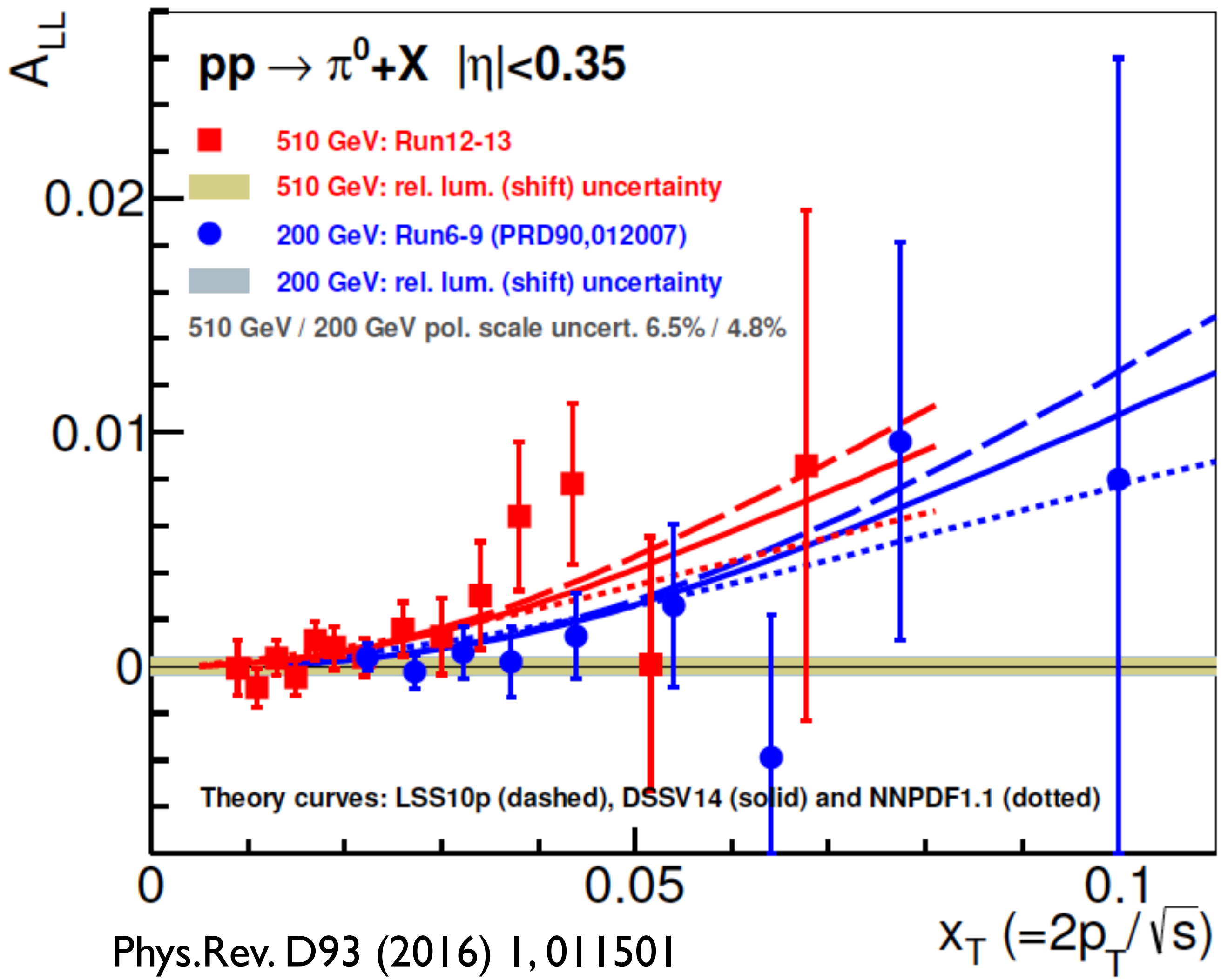
$$r = \frac{N^{BG}}{N^{BG+\pi^0}}$$



Double Helicity Asymmetry From 510 GeV Data



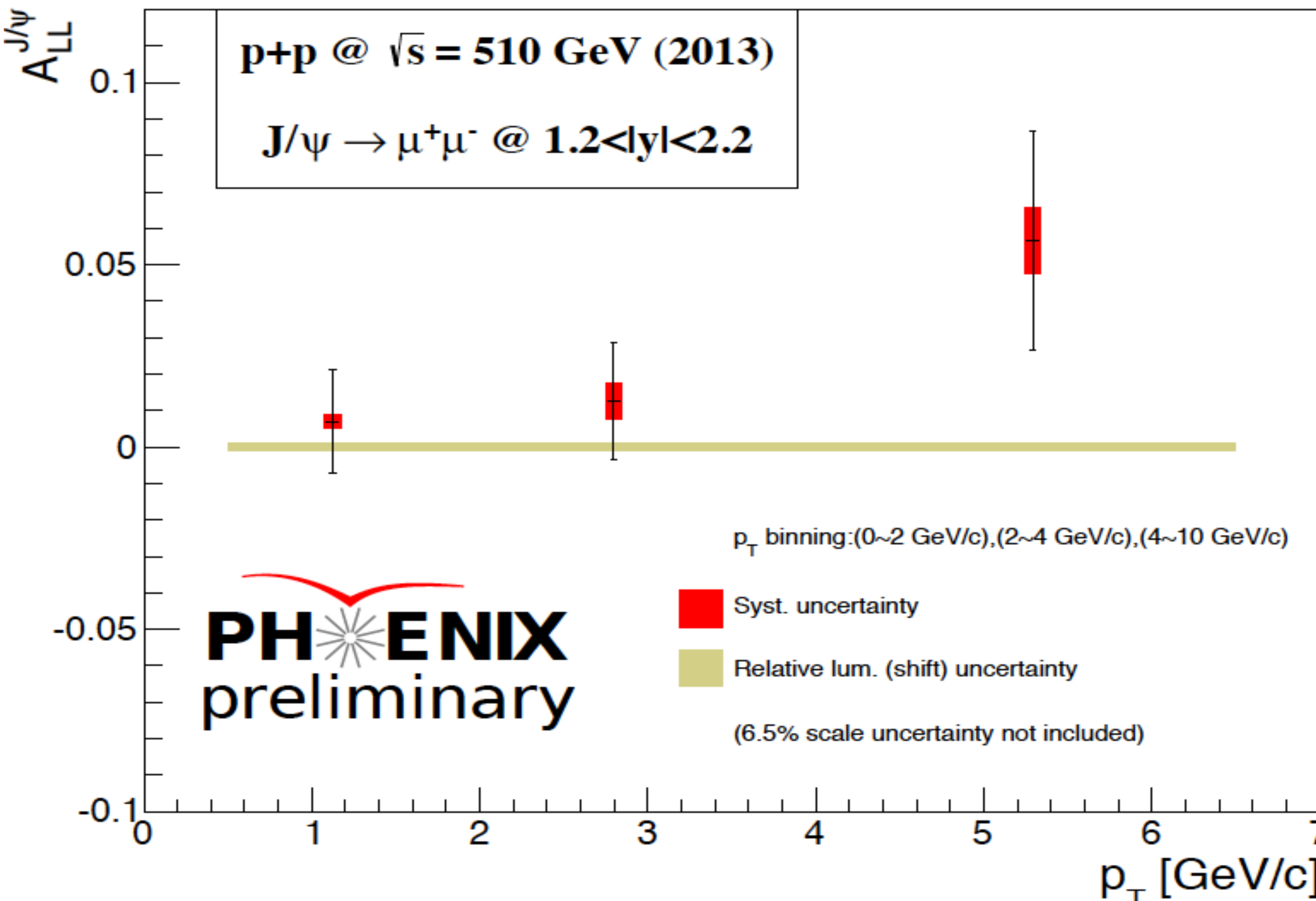
Comparison of Double Helicity Asymmetry at different center of mass energies



Phys.Rev. D93 (2016) 1, 011501

Preprint: arXiv:1510.02317

Double Helicity Asymmetry Results from J/ψ



Summary & Conclusion

- Cross-section and double helicity asymmetry from π^0 production at center of mass energy of 510 GeV is measured

- **For the first time in PHENIX, non-zero asymmetry is observed in π^0 production (Published in Phys.Rev. D93 (2016) 1, 011501)**

- Theory agrees very well with the measured cross-section

$\Rightarrow$ allows using the theory to interpret A_{LL} results

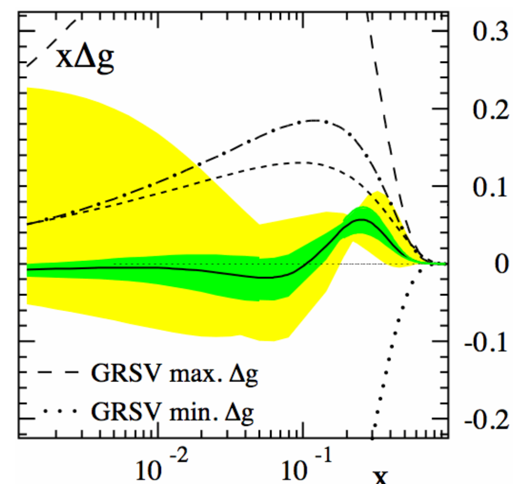
Future Prospects

- PHENIX has measured A_{LL} of π^0 production in several data sets ($\sqrt{s}$ = 62.4, 200 and 510 GeV). π^0 data was included in global analysis.
DSSV ++ indicates non-zero ΔG

$$\int_{0.05}^{1.0} \Delta g(x)dx = 0.2^{+0.06}_{-0.07}$$

- New data to be used in global fit

- Still large uncertainty at low Bjorken x region:
 Need to extend coverage to lower-x region



- Electron Ion Collider (EIC) is the ultimate solution for the complete understanding of gluon polarization as well as orbital angular momentum (OAM) of quarks and gluons

Finally, Answer to my Initial Question:

Does the Gluon Carry Proton's Spin?

Yes, indeed!!!

Understanding the Nucleon is like: (Elephant and 6 Blind People)

Thank You for Your Attention

Asymmetry Results from Fit

APPENDIX

Cross-Section of π^0 Meson

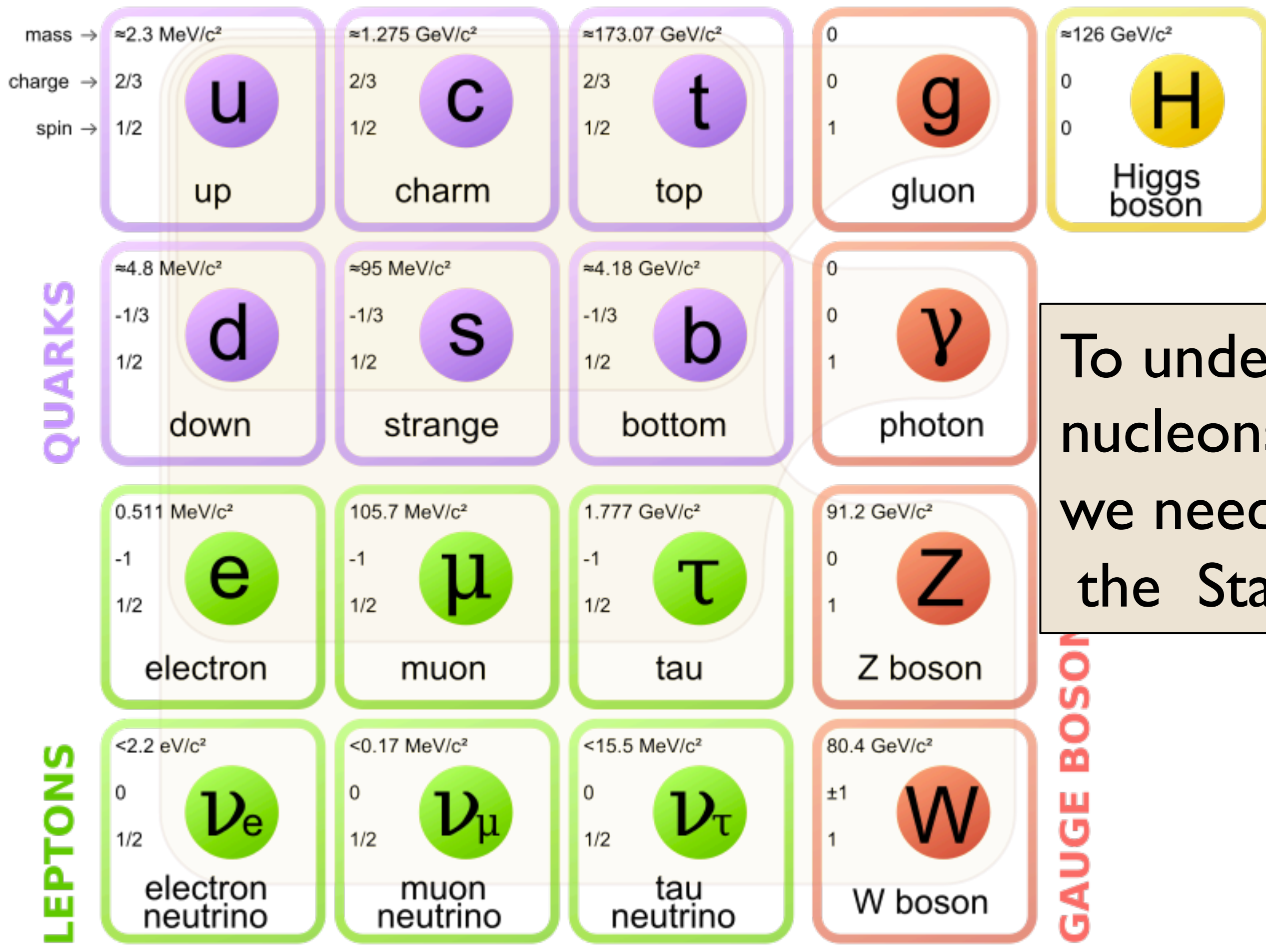
$$E\frac{d^3\sigma}{d^3p} = \frac{1}{2\pi p_T}\frac{1}{BR}\frac{1}{L}\frac{1}{A\epsilon_{trig}\epsilon_{rec}}\frac{N(\Delta p_T, \Delta y)}{\Delta p_T \Delta y}$$

- BR is the branching ratio~99%,
- L is the integrated luminosity ~N^{MB}/σ^{BBC} (σ^{BBC} = 32.5 mb),
- A is the acceptance calculated from simulation,
- ε_{trig} is the trigger efficiency,
- ε_{rec} is the reconstruction efficiency.
- N is the number of reconstructed π^0 mesons.

POLARIZATION MEASUREMENTS

Understanding the Spin Structure of Nucleon

What is a nucleon???



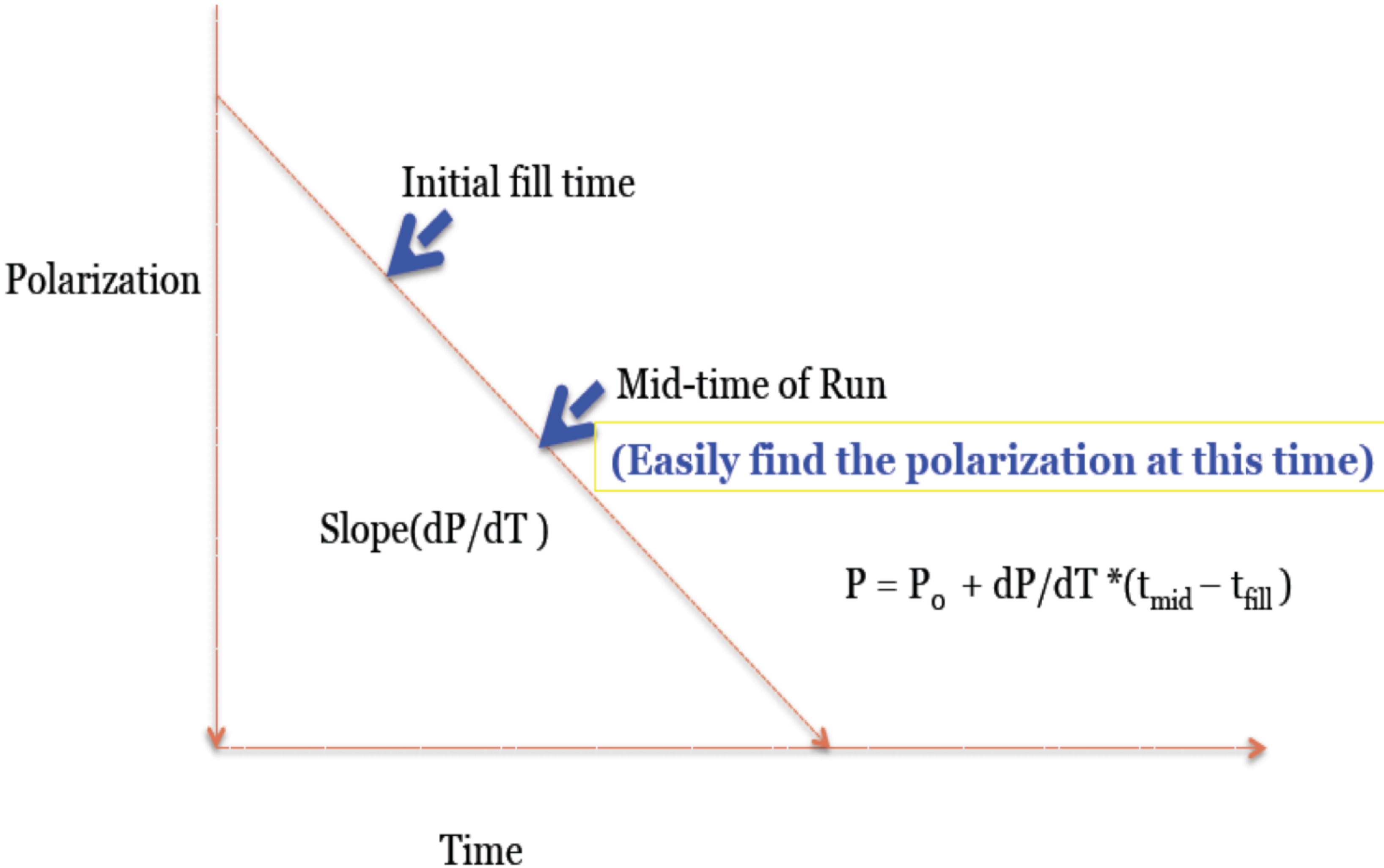
To understand nucleons,
we need to understand the Standard model.

Quest from last 30 Years

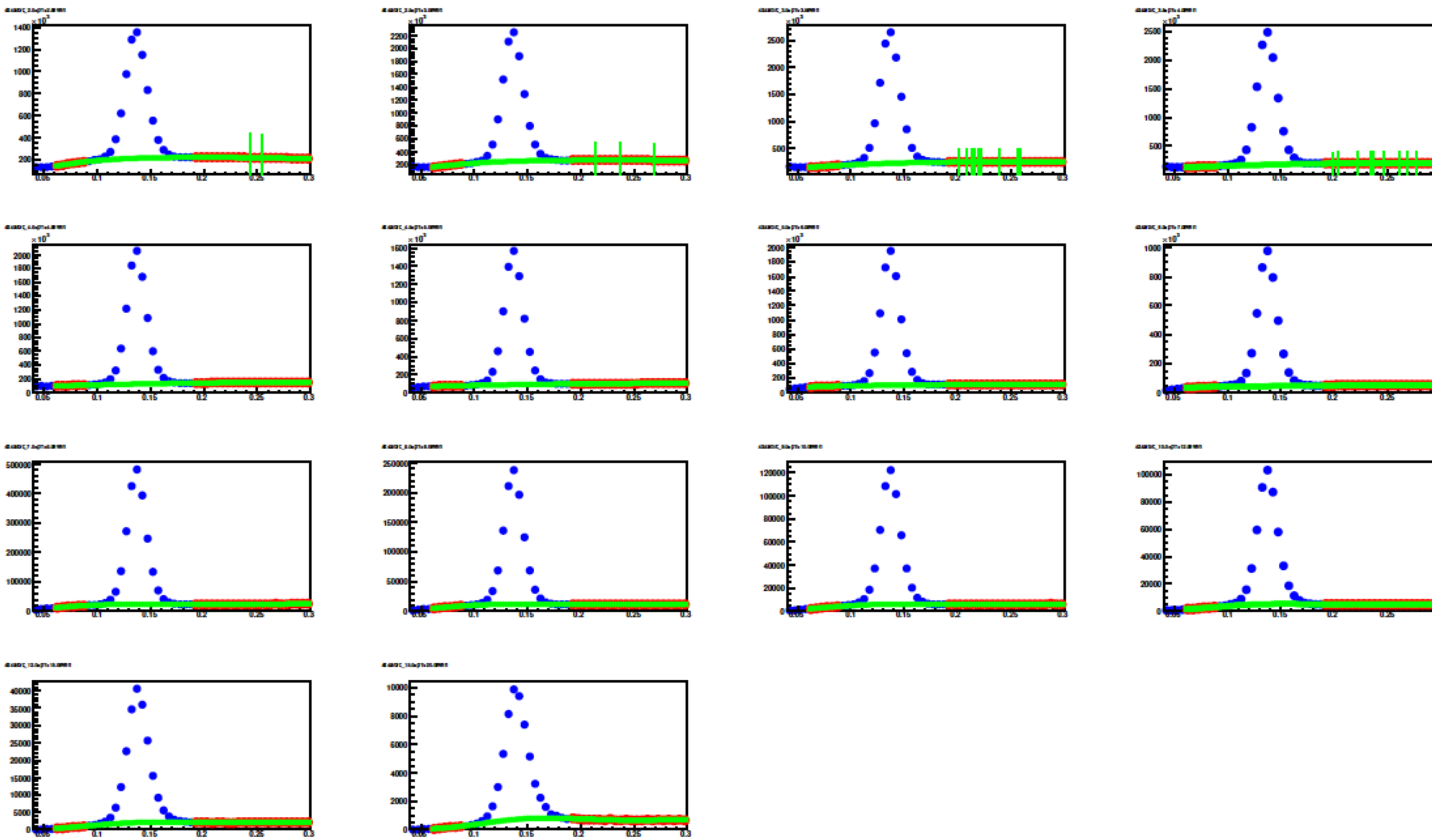
Polarization Measurements

- Fill-by-fill polarization values provided by the CNI group
- Change it to run-by-run values
  - Polarization values at beginning of each fill is known
  - Time stamp of each run is known
  - We find the mid-value of time
  - Calculate the polarization value at that particular time

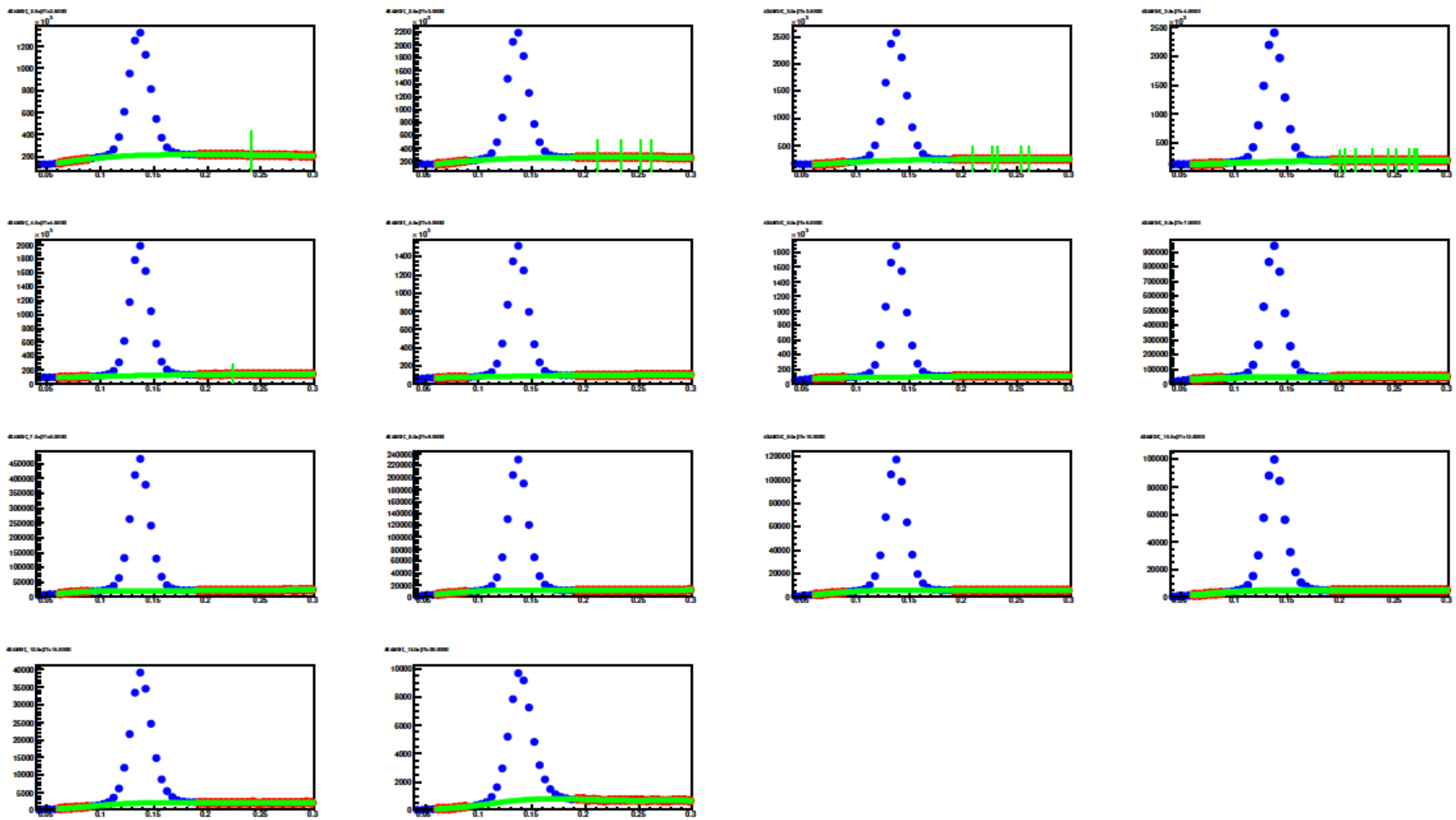
Polarization Calculations



Background Fraction Calculation (GPR method) Even Crossing



Background Fraction Calculation (GPR method) Odd Crossing



Bunch Shuffling: Procedure

- Generate 600000 random bunches
- Apply same set of cuts as was applied in the data analysis.
- Calculate A_{LL} fill by fill and find the mean from fit.
- Calculate the Chi Square per NDF and draw this distribution.

Bunch Shuffling

- Technique to ensure any systematic uncertainty from bunch to bunch or fill to fill is less than our statistical uncertainty.

Procedure:

- Randomly assign helicity for all bunches.
- Get A_{LL} for all fills in each pT bin.
- Find χ^2/NDF for each sample.

Getting Veto Parameters

- Upper edge: Large veto angle->Due to uncorrelated hits->Need to keep
- Middle part: Medium veto angle->Due to charged hadron->Need to throw
- Lower edge: Small veto angle->Due to photon conversion-> Need to keep