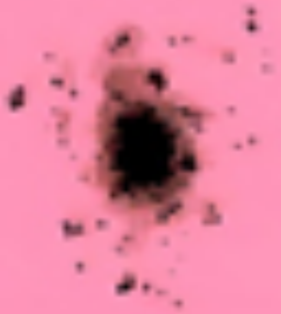
Measurements of $A_{LL}^{\pi^0}$ in p+p Collisions at $\sqrt{s}$ = 200 GeV and Their Impact on Determination of the Gluon Spin in the Proton

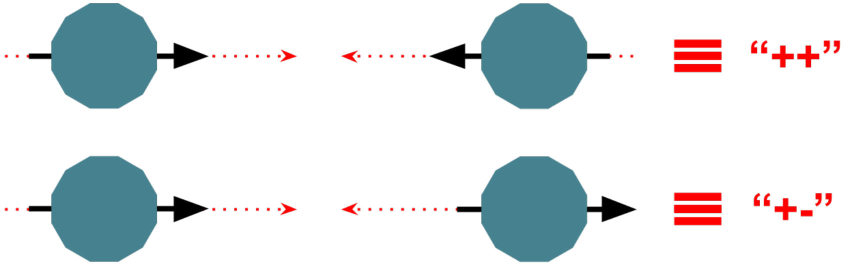


Andrew Manion
for the PHENIX Collaboration
21st International Symposium on Spin Physics
Beijing, China

X'ed Out - Charles Burns

Double Longitudinal Spin Asymmetries

- In p+p scattering:
  - proton spin parallel (positive helicity) or antiparallel with its momentum vector:



- "Double Longitudinal Spin Asymmetry" then defined in terms of cross-sections:

$$A_{LL} = \frac{(\sigma^{++} + \sigma^{--}) - (\sigma^{+-} + \sigma^{-+})}{(\sigma^{++} + \sigma^{--}) + (\sigma^{+-} + \sigma^{-+})}$$

- Ultimately want to connect to spin of proton constituents, e.g.:

$\equiv \Delta f_i$

Sum Rules

- Charge sum rule
    - assumes zero strangeness

$$Q_{proton} = 1 = \int_0^1 dx\ x \left(\frac{2}{3}[u(x) - \bar{u}(x)] - \frac{1}{3}[d(x) - \bar{d}(x)]\right)$$

- Momentum sum rule
    - quark term <50% of momentum
        - gluon contributes >50%

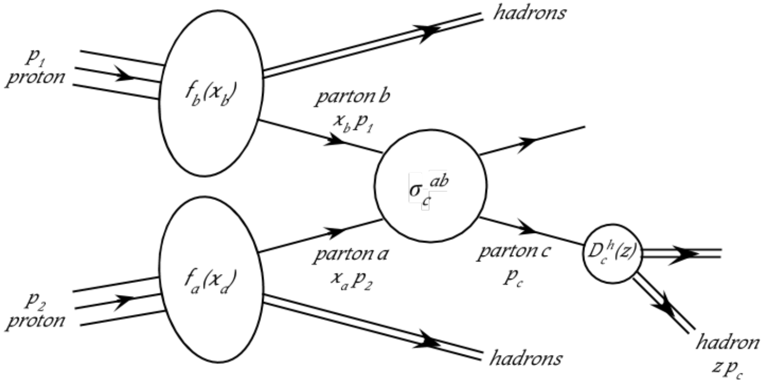
$$P_{proton} = P_{quark} + P_{gluon}$$
$$= \int_0^1 dx\ x\left([u(x) + \bar{u}(x)] + [d(x) + \bar{d}(x)] + [s(x) + \bar{s}(x)]\right) + \int_0^1 dx\ xg(x)$$

- Spin sum rule
    - quark spin, gluon spin, OAM
    - DIS experiments find quark spin contribution only 25-35%

$$S_{proton} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

$$\Delta G = \int_0^1 dx\ \Delta g(x), \quad \Delta\Sigma = \int_0^1 dx\ \left([\Delta u(x) + \Delta\bar{u}(x)] + [\Delta d(x) + \Delta\bar{d}(x)] + [\Delta s(x) + \Delta\bar{s}(x)]\right)$$

Factorization in p+p



- How to interpret A_{LL}?
- Known a priori:
  - parton-parton cross sections (calculable in pQCD)
  - *including gluon scattering!*
- Ingredients from other experiments:
  - Fragmentation functions (from e+e- scattering)
  - quark (p)PDFs
- Assume “factorization:”

$$A_{LL} = \frac{\sum_{abc} \Delta f_a(x_1, \mu_F^2) \otimes \boxed{\Delta f_b(}x_2, \mu_F^2) \otimes \Delta\sigma^{a+b\to c+X}(x_1, x_2, p_c, \mu_F^2, \mu_R^2, \mu_{FF}^2) \otimes D_c^h(z, \mu_{FF}^2)}{\boxed{\sum_{abc}} f_a(x_1, \mu_F^2) \otimes f_b(x_2, \mu_F^2) \otimes \boxed{\sigma^{a+b\to c+X}}(x_1, x_2, p_c, \mu_F^2, \mu_R^2, \mu_{FF}^2) \otimes \boxed{D_c^h}(z, \mu_{FF}^2)}$$

polarized PDF

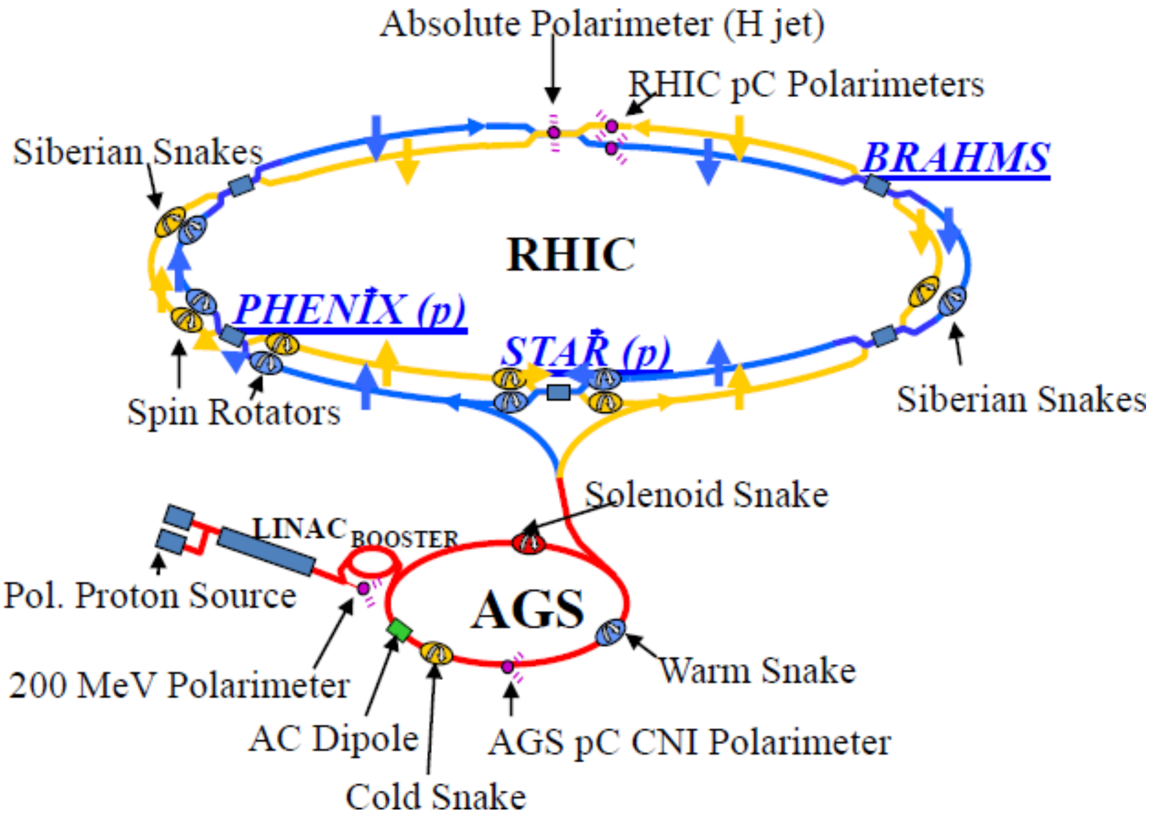
partonic reaction
a+b -> c

partonic x-sect

fragmentation function

- Factorization verified in each case by checking denominator against absolute x-section

RHIC: Relativisitic Heavy Ion Collider



- Variable$\sqrt{s}$: 62.4, $\boxed{200,}$ 500 GeV

most of this talk

Next talk

- Up to 120 proton bunches rotating in each ring
- Polarization can be chosen on a bunch-by-bunch basis, e.g.

+ − + − − + − +

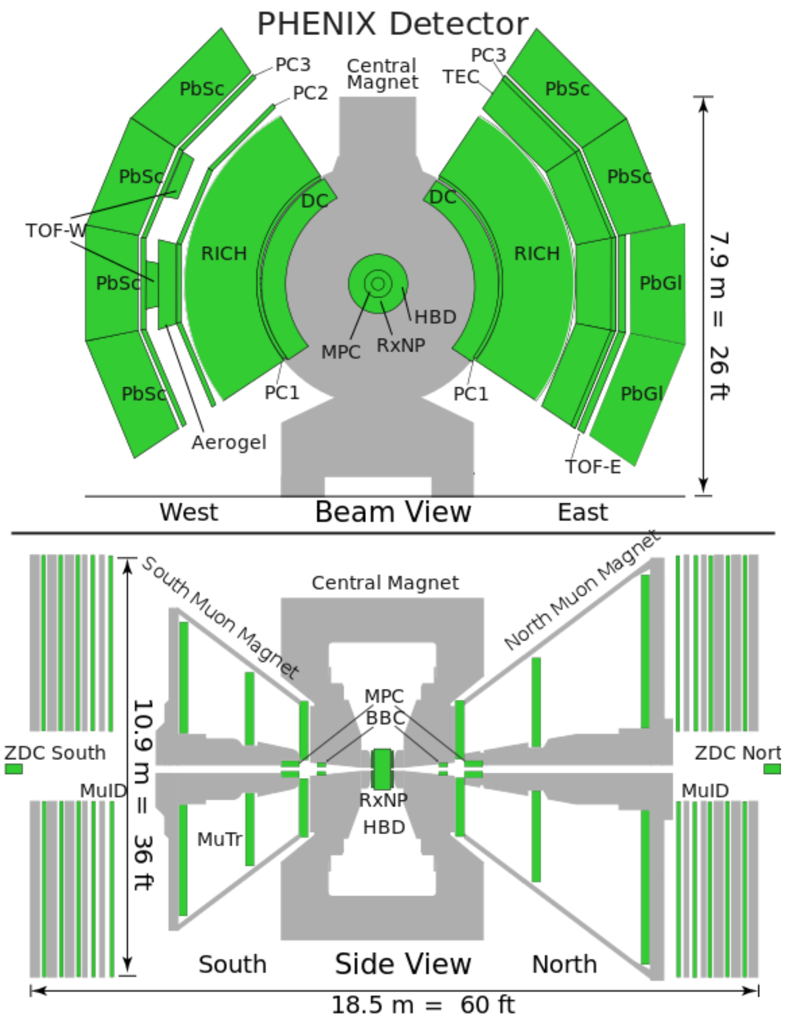
+ + − − + + − −

- Spin Rotators allow polarization axis to be made transverse, longitudinal, or radial at different experiments
- Overall polarization P_B, P_Y, measured precisely by pCarbon polarimeters, and normalized to accurate Hydrogen-jet polarimeter meas.
- Polarization axis must be measured individually at each experiment

The PHENIX Experiment at RHIC

- **Central arms**
  - |η| < 0.375, Δφ = (π/2) x 2
  - Tracking
    - **D**rift **C**hamber (Multi-Wire Proportional)
    - **P**ad **C**hambers
  - Particle ID
    - **R**ing **I**maging **Ch**erenkov detector
    - **H**adron **B**lind **D**etector (Gas Electron Multiplier) in ‘09 and ‘10
  - EM Calorimetry
    - Two separate technologies for cross-check
    - Lead-Scintillator (**PbSc**)
      - sampling calorimeter
    - Lead-Glass (**PbSc**)
      - Cherenkov radiation calorimeter

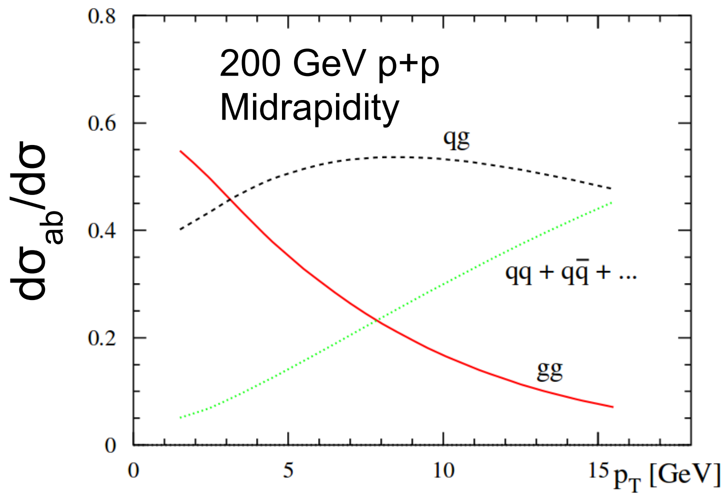
- **Forward arms**
  - Tracking, Calorimetry, Muon Identification
  - Minbias detectors
    - **Z**ero **D**egree **C**alorimeter:
    - Δη = ±(3.1 to 3.9), |z| = 18m
      - outside of bending field, sees neutrals
    - **B**eam-**B**eam **C**ounter: |Δη| = > 6, |z| = 1.4m
      - reconstruct collision z-vertex online with ~5cm resolution

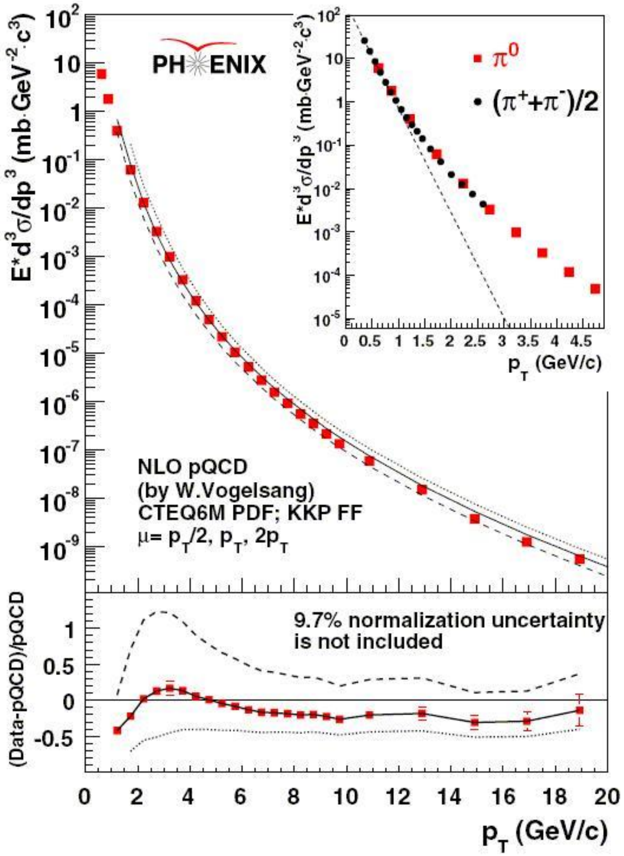


A_{LL} in π^0 Production

- π^0 is the highest statistics PHENIX central arm probe
  - decay photon separation out to p_T of 10GeV/c
- q-g and g-g sub-processes at low p_T

→ excellent constraint of ΔG





- Agreement with pQCD means we can use (unpolarized) factorization in interpreting our A_{LL}

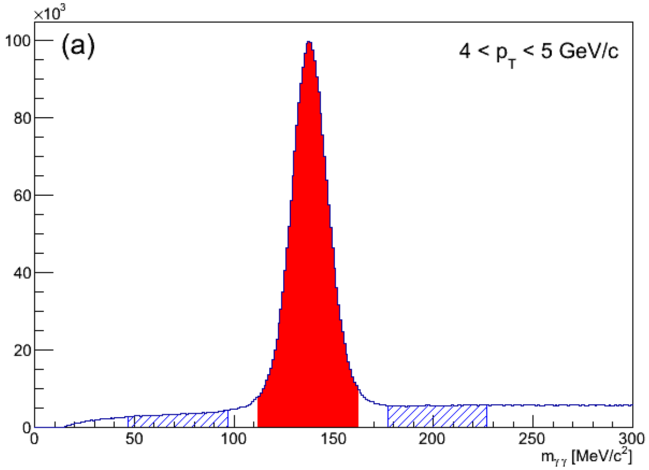
Analysis Technique

- Analyze through the ɣɣ decay channel
  - B.R. 99%for π^0
  - Can also analyze η meson, 39% B.R.
- Count signal region (red) and sideband region (blue) counts in ++ and +- helicity crossings:

$$A_{LL} = \frac{1}{P_B P_Y}\left(\frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}\right), \quad R \approx \frac{N^{++}_{BBC}}{N^{+-}_{BBC}}$$

- Relative Luminosity R is measured using minbias BBC scalars
  - largest systematic uncertainty from confidence that BBC sees zero asymmetry
- Interpolate combinatorial B.G. shape under peak to get background fraction “r”

$$A^{\pi^0}_{LL} = \frac{A^{signal}_{LL} - r A^{sides}_{LL}}{(1 - r)}$$



Advantage:

- mass peak -> directly count π^0s
- choose cuts to minimize total uncertainty

Systematic Uncertainties

- Polarization measurement
  - Scale uncertainty, mostly from molecular hydrogen contamination of H-jet target

- Event overlap in the EMÇal
  - creates non-zero BG asymmetry that can depend on mɣɣ
  - controlled by cuts/careful binning of analysis

- Relative Luminosity

$$A_{LL} = \frac{1}{P_B P_Y}\left(\frac{N^{++} - RN^{+-}}{N^{++} + RN^{+-}}\right) \quad R \approx \frac{N^{++}_{BBC}}{N^{+-}_{BBC}}$$

But is the BBC also sensitive to a physics A_{LL}?

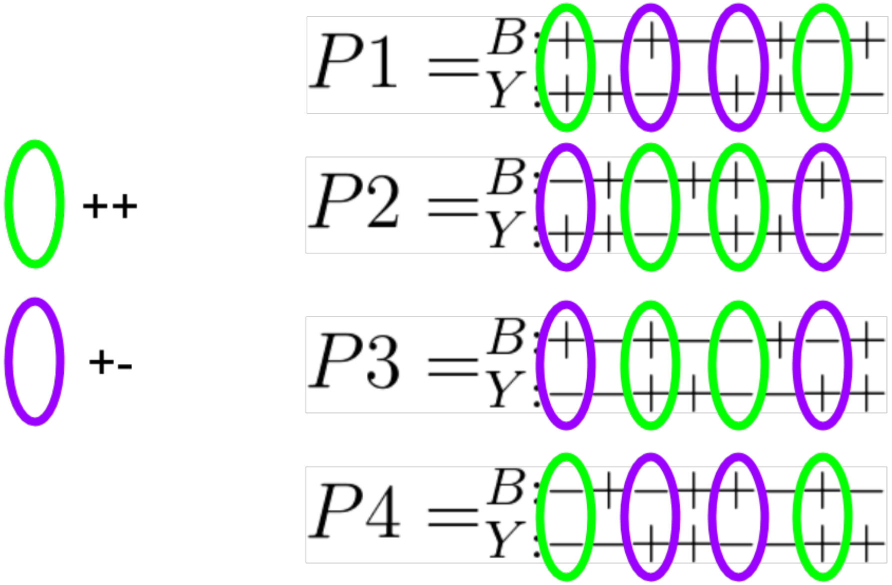
- Cross-check Asymmetries
  - Measurements of parity violating, 180 rotational asymmetries should be zero

Event Overlap in EMCal Readout

- Events from previous crossings contribute background to current crossing

- Certain spin patterns follow empty bunches
  - see less of this BG than other spin patterns
  - leads to false BG asymmetry
  - can have $m_{\gamma\gamma}$ dependence

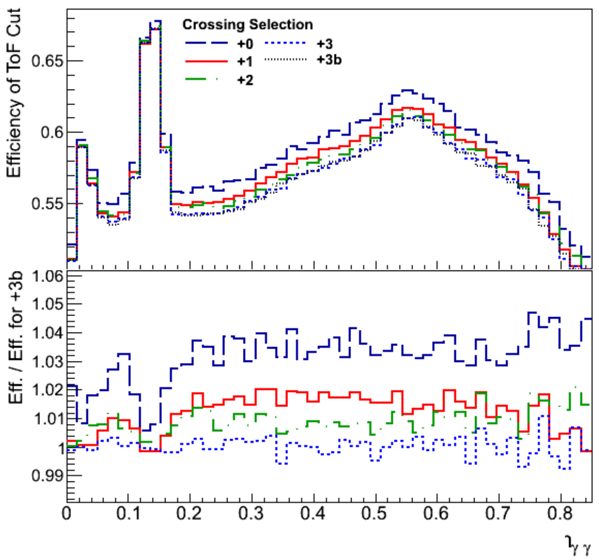
- Strategy:
  - cuts to eliminate $m_{\gamma\gamma}$ dependence
  - analyze spin patterns separately



Event Overlap in EMCal Readout

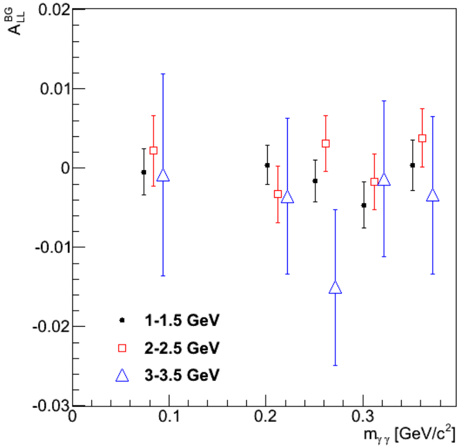
- Time of Flight cut
  - present crossing: σ_z
  - previous mixed crossing: $\sigma_z + \sigma_{t0}$

→ ToF cut more effective at removing this type of BG



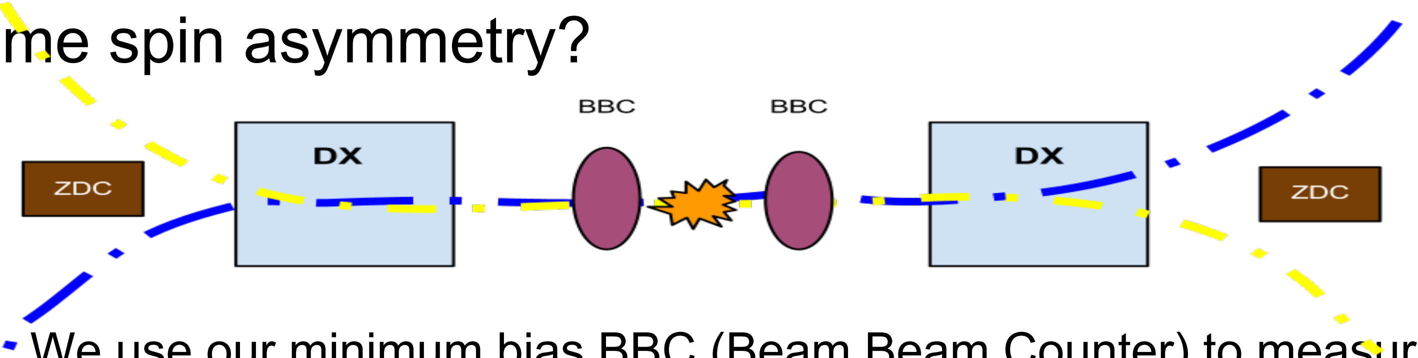
- Trigger requirement also helps (guarantees one photon of pair is in the current crossing)

- Check for remaining background A_{LL} dependence vs. mass to justify interpolation into peak region



Determination of Syst. Uncert. on RL

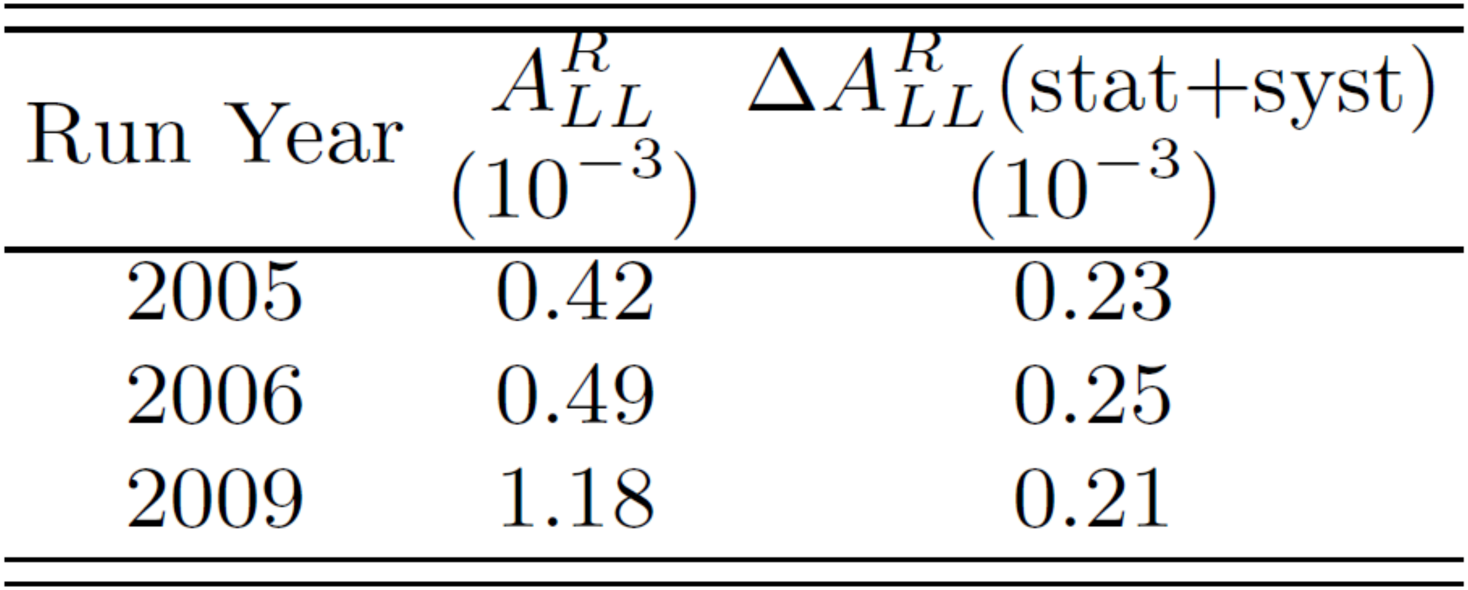
- i.e., what if our relative luminosity detector DOES see some spin asymmetry?



  - We use our minimum bias BBC (Beam Beam Counter) to measure R
  - ...and compare it with a detector past the DX magnetic field
    - ZDC: Zero Degree Calorimeter, no charged particles
  - We then assume the different physics they sample can't have the same asymmetry
    - so any non-zero asymm. in BBC should be apparent
  - Compare the two results to get the best estimate of systematic:

$$A_{syst} = \frac{1}{P_B P_Y} \frac{\left(\frac{N_{ZDC}}{N_{BBC}}\right)^{++} - \left(\frac{N_{ZDC}}{N_{BBC}}\right)^{+-}}{\left(\frac{N_{ZDC}}{N_{BBC}}\right)^{++} - \left(\frac{N_{ZDC}}{N_{BBC}}\right)^{+-}}$$

RL Syst. Throughout the Years

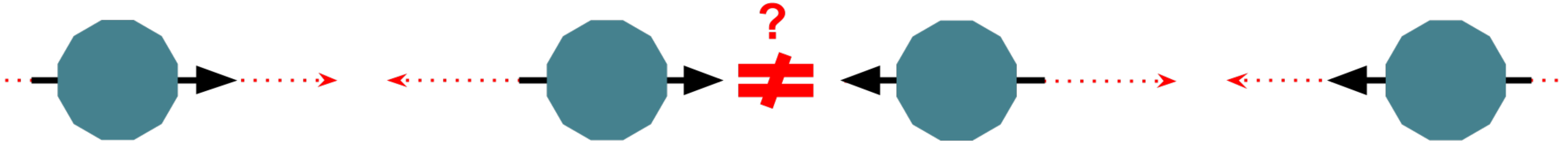


Run Year	A_{LL}^{R} (10^{-3})	ΔA_{LL}^{R}(stat+syst) (10^{-3})
2005	0.42	0.23
2006	0.49	0.25
2009	1.18	0.21

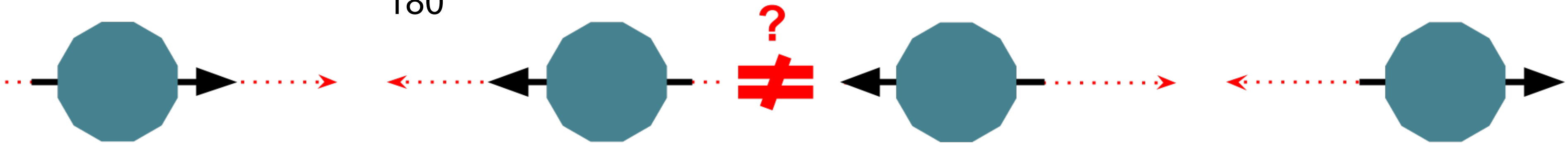
- Take maximum overlap in A_{LL}^{R} as correlated
- Take also uncertainty on A_{LL}^{R} as part of systematic
  - ○ 2009 total RL systematic uncertainty: $1.4e^{-3}$

Non-physical Asymmetries

- Non-physical “double-spin” asymmetries seen in longitudinal running between the BBC and ZDC:
    - 180° rotation of the experiment:



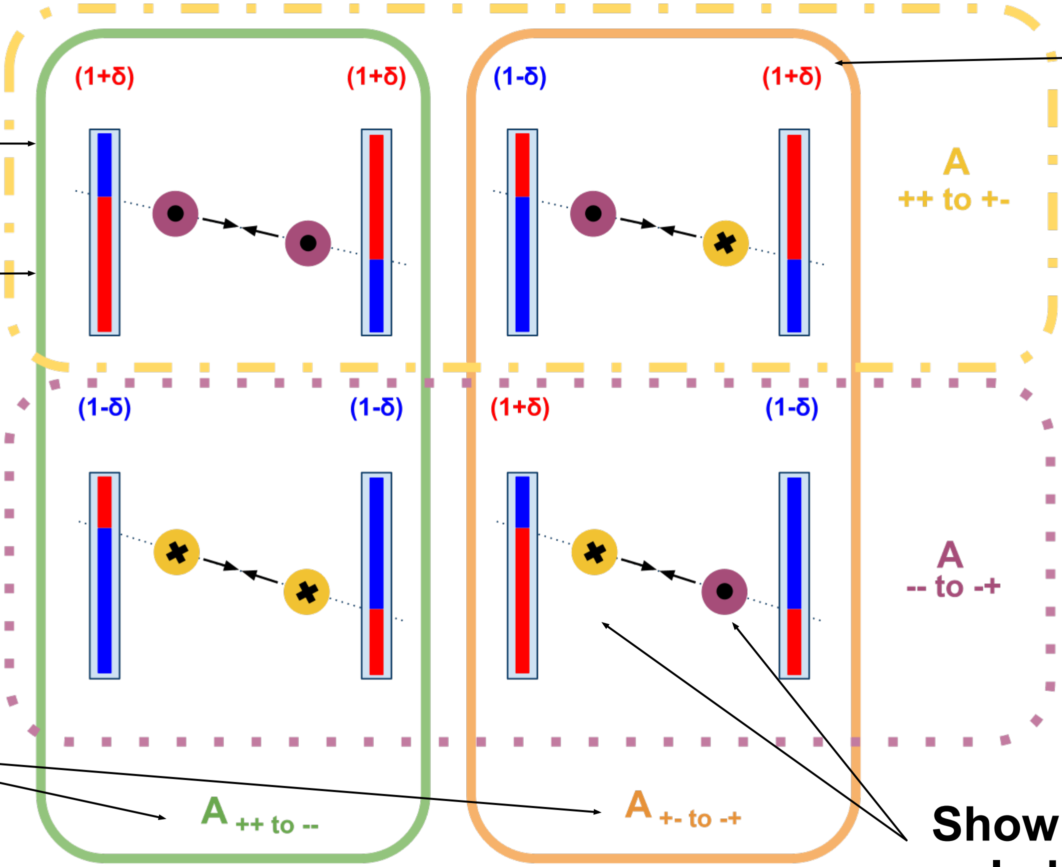
        - $A_{PV} = 1.4 \pm 0.1 \times 10^{-3}$ in 2009
    - Parity violating asymmetry:
        - $A_{180} = 82.3 \pm 0.1 \times 10^{-3}$ in 2009



Can these asymmetries be explained?

Model for Generation of Various False Asymmetries

- A left-right production asymmetry
- Coupled with a beam angle (or offset)
    - moves the high or low production side off the detector
    - generates a false asymmetry



Fewer
-or-
More
Particles
(from A_N)

Acceptance modification factor

Different Asymmetries

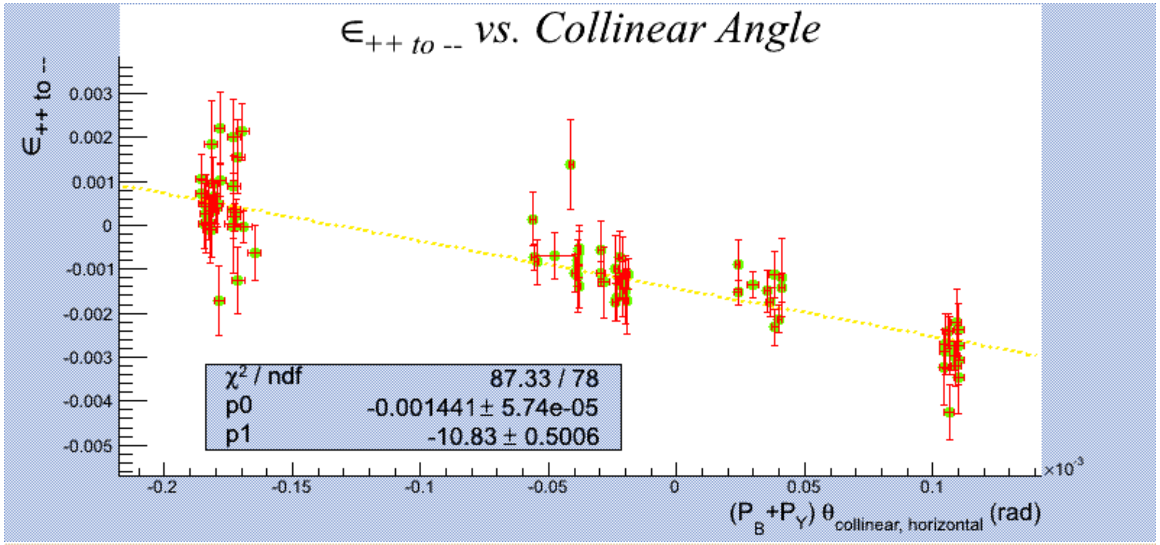
Show transverse pol. direction

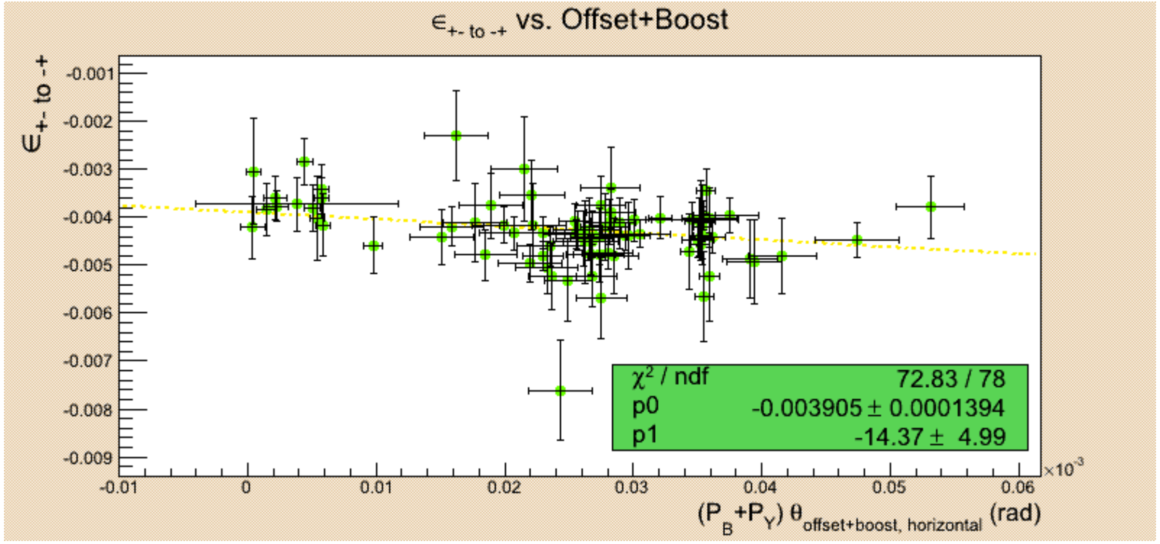
Predictions of Model

	$\epsilon_{++\text{ to }--}$	$\epsilon_{+-\text{ to }-+}$	$\epsilon_{++\text{ to }+-}$	$\epsilon_{--\text{ to }-+}$
Collinear Angle	$= (P_B + P_Y)\ \delta$	$= 0$	$= P_Y\ \delta$	$= -P_Y\ \delta$
Offsets	$= 0$	$= (P_B + P_Y)\ \varepsilon$	$= -P_Y\ \varepsilon$	$= P_Y\ \varepsilon$
Boosts	$= 0$	$= (P_B + P_Y)\ \varepsilon$	$= -P_Y\ \varepsilon$	$= P_Y\ \varepsilon$

- Key Feature: linear dependence on polarization
- δ, ε: acceptance modification factors, functions of angle, offset, or boost
- Important point: cross-check asymmetries which should be zero can be large under this effect!
  - failure to understand them would lead to additional systematic uncertainties

Run 2012 Collinear Beam Angle Scan

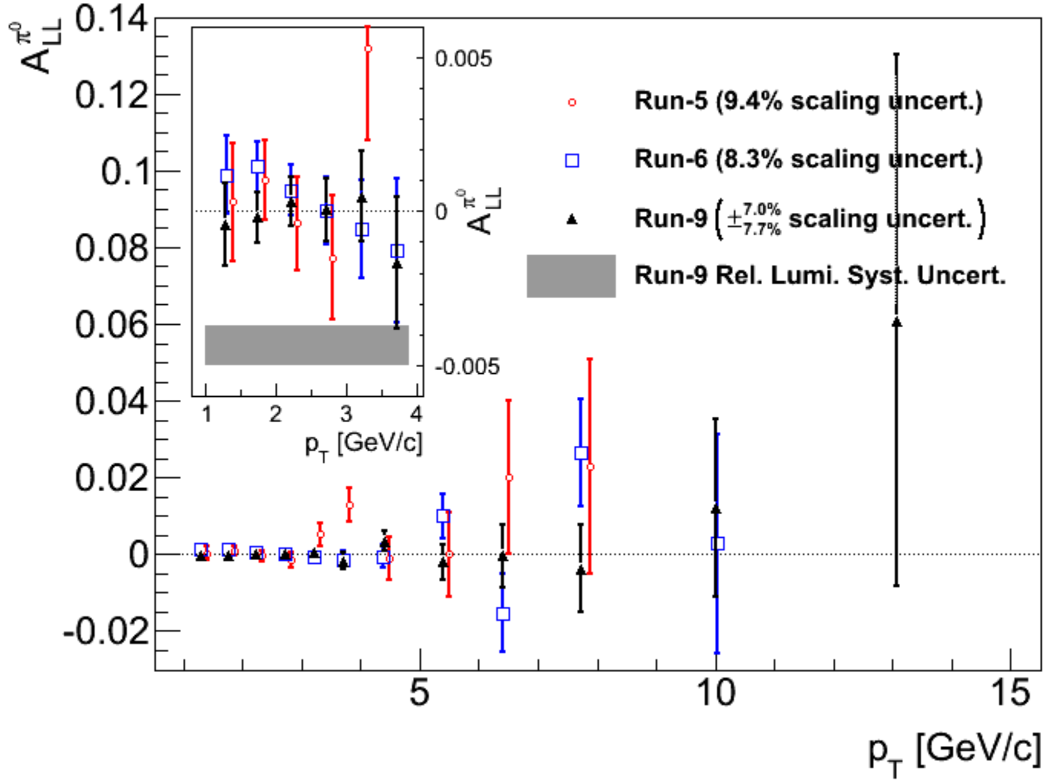




- Predicted to have largest variation in the Run12 scan of collinear beam angles
- Slope about ½ of simulation prediction

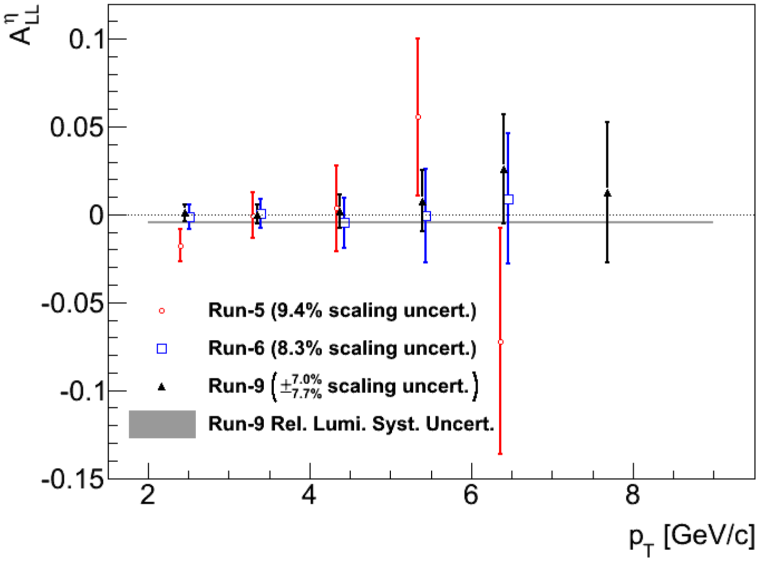
- Should not have changed much during scan
    - its dependence is on boosts and offsets

The End Result(s)



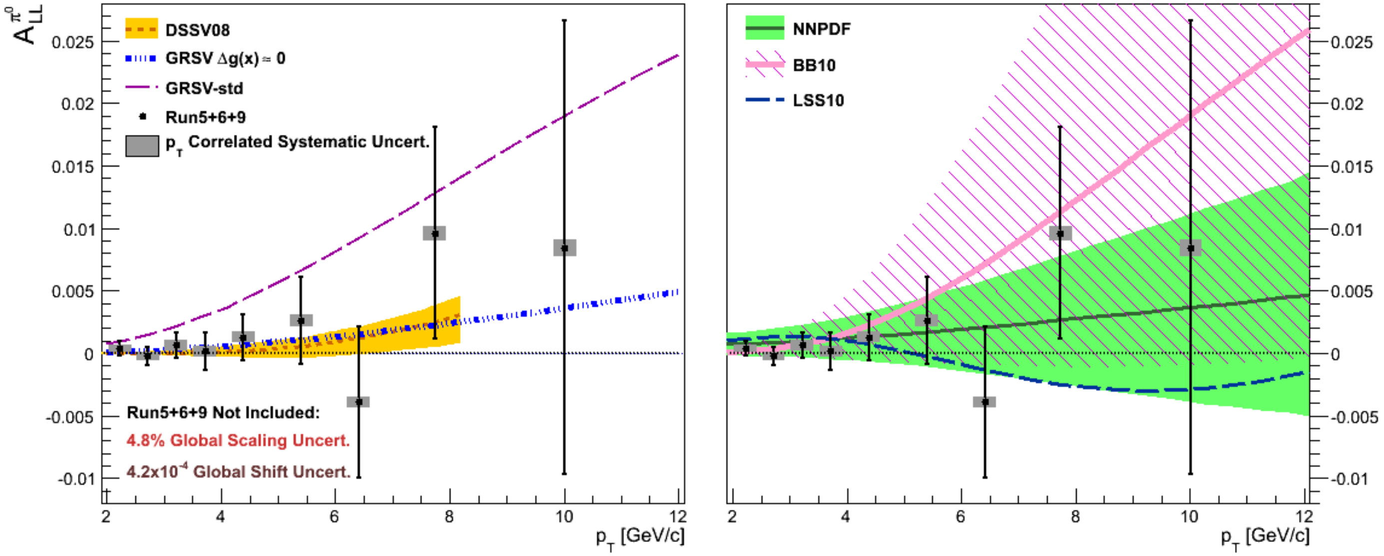
- 2009 measurement doubles existing statistics for η and π^0 asymmetries
- RL syst. larger than in previous runs
- η not included in global analysis

- **PRD90 (2014) 012007**
- **arXiv:1402.6296**



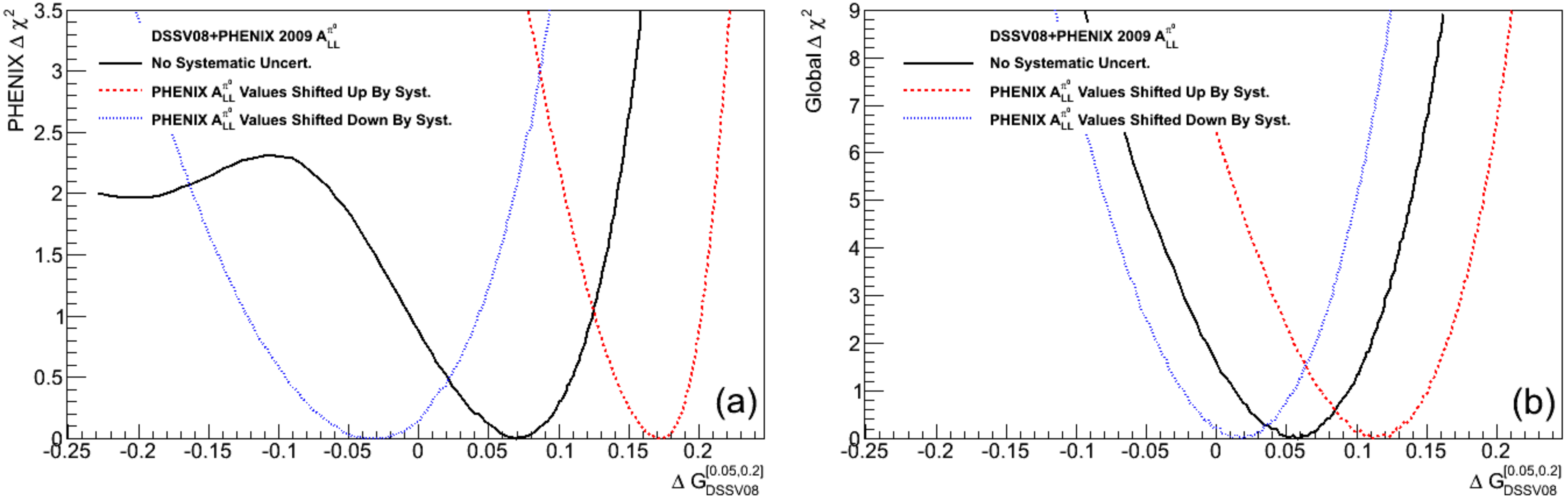
Comparison to Global Analyses

- Combined PHENIX results alongside various global analyses
  - DSSV08: DIS + SIDIS + PHENIX + STAR (up to 2006)
    - constrains $\Delta G^{[0.05,0.2]}_{DSSV08} = 0.005^{+0.129}_{-0.164}$
  - GRSV: older DIS-only analysis
  - BB10: DIS-only analysis
  - NNPDF: DIS + prelim. STAR W A_L
    - uses neural networks instead of PDF functional form
  - LSS10: DIS+SIDIS analysis

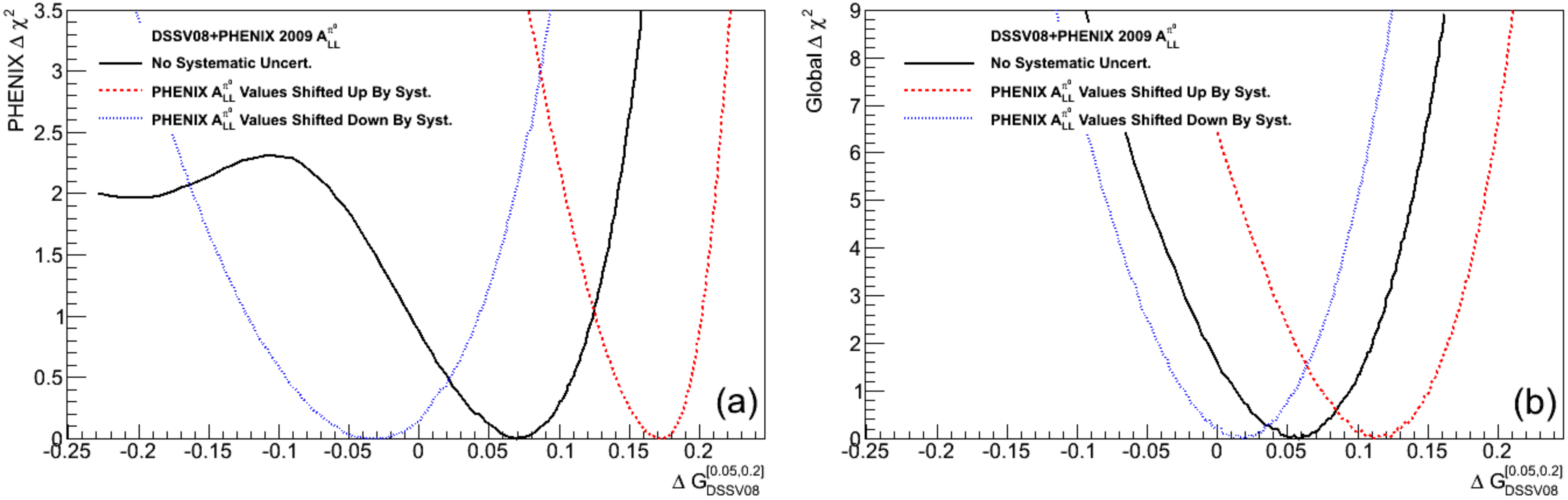


Adding 2009 PHENIX Data, Effect of RL Systematic Uncert.

- Added 2009 PHENIX π^0 A_{LL} to the DSSV08 analysis
    - along with updates of some prelim data to final
- DSSV08 global analysis did not include systematic uncertainties from the experiments
- Effect of shifting only PHENIX π^0 A_{LL} up or down by its total systematic uncertainty
    - dominated by systematic uncertainty on relative luminosity



Adding 2009 PHENIX Data, Effect of RL Systematic Uncert.



- Results of adding 2009 PHENIX π^0 A_{LL} to the DSSV08 analysis
  - along with updates of some prelim data to final:

$$\Delta G^{[0.05,0.2]} = 0.06^{+0.11}_{-0.15}$$

0.02

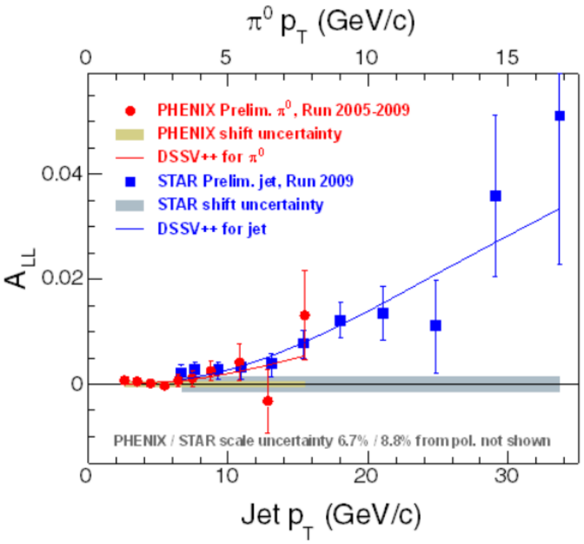
0.12

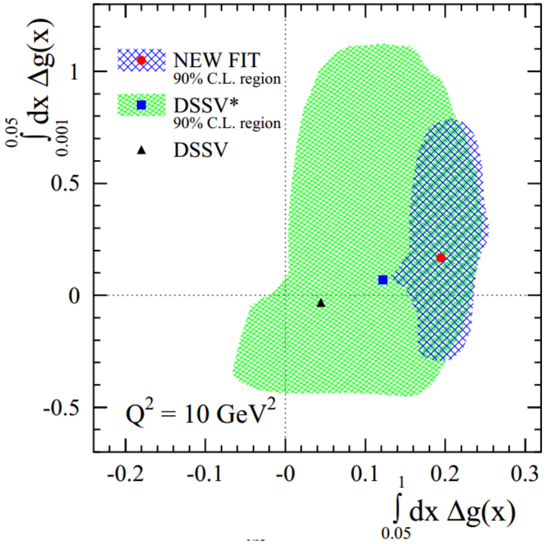
  - vs. previously: $\Delta G^{[0.05,0.2]}_{DSSV08} = 0.005^{+0.129}_{-0.164}$

Conclusions

- 2009 PHENIX and STAR final data already swiftly included in the DSSV global analysis
    - important to fully treat experimental systematic uncertainties to get the full picture (plus theoretical uncertainties)
    - Other final states + 500 GeV datasets (I. Yoon, next talk) also currently available or under analysis
        - Not only gives us more information on ΔG, but our best test of factorization

bnl.gov/npp/docs/RHIC-Spin-WriteUp-121105.pdf



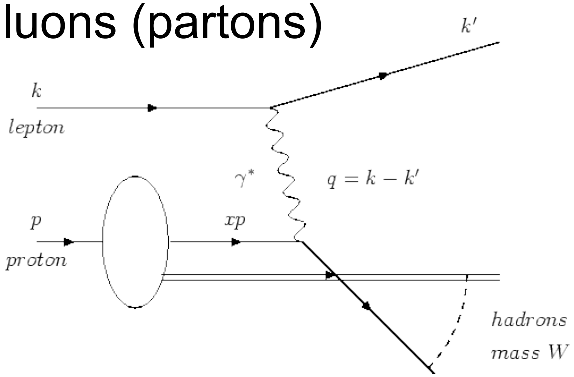


arXiv:1404.4293

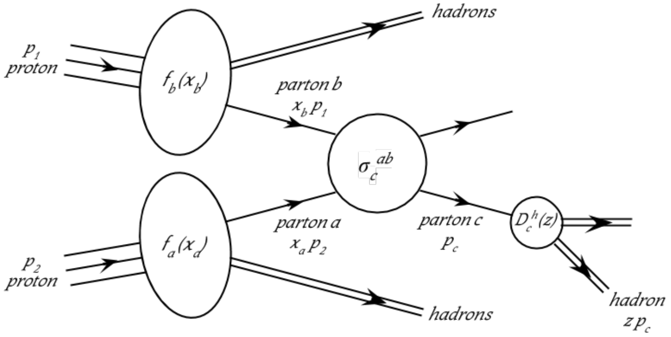

backup

Proton Sub-Structure & Parton Scattering

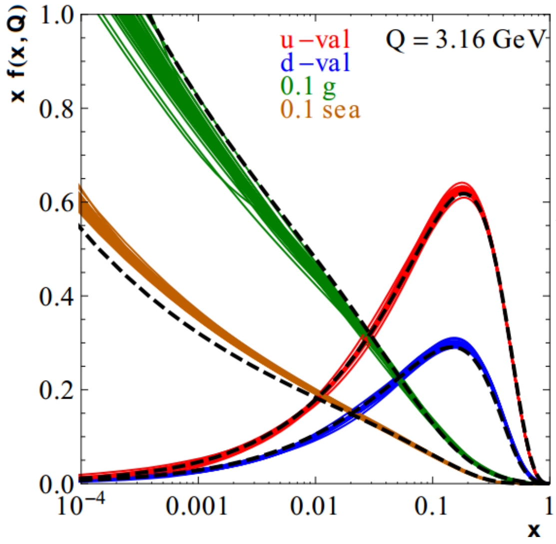
- High energy scattering with a nucleon (proton) probes the sub-structure
  - scattering with individual quarks, antiquarks, and gluons (partons)
- DIS:



- p+p:



- Parton Distribution Functions (PDFs), $f_i(x)$
  - describe statistical distribution of partons with momentum fraction x

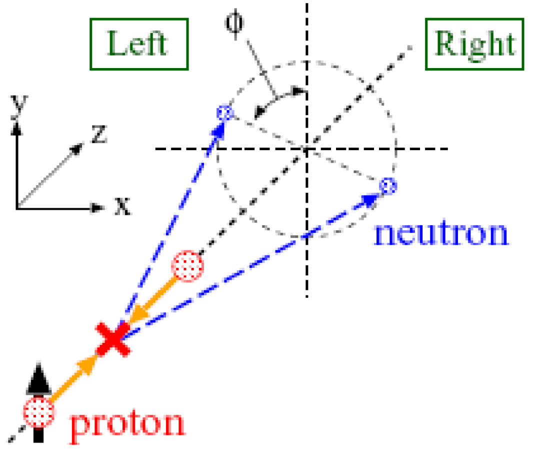


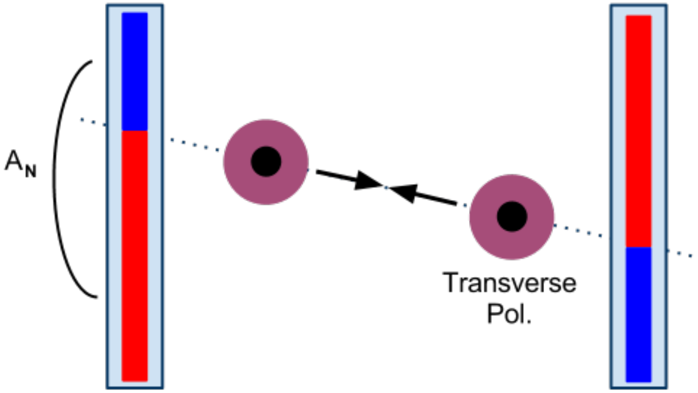
CT10 NNLO, arXiv:1302.6246

- *polarized* PDFs, $\Delta f_i(x)$
  - take into account spin along proton's spin axis

Transverse Spin Asymmetry A_N

- No physics A_{LL}s we are familiar with in the ZDC or BBC
- But we do know of a transverse, phi-dependent, forward, single-spin asymmetry in NEUTRON PRODUCTION
  - transverse: Goes away for longitudinally polarized beams (local polarimetry)
  - phi-dependent: integrates out over all of phi
  - forward: backward asymmetry 0; polarization of other beam irrelevant
  - single-spin: scales as polarization P (compared to P^2 for double spin asymmetries like A_{LL})

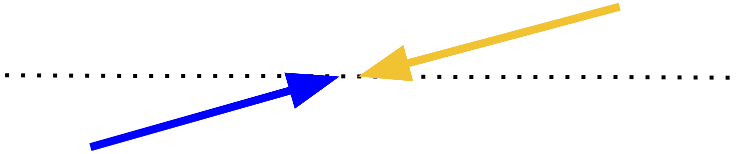




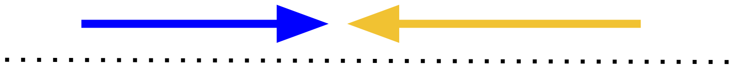
+ Beam Geometry

- Beams traverse IRs in "zero" magnetic field region
  - straight paths
- Intersection geometry of beams can be decomposed into three components (x 2 planes)

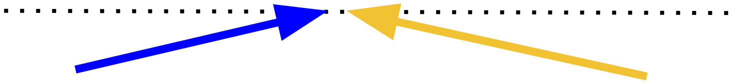
  - Collinear Angle:



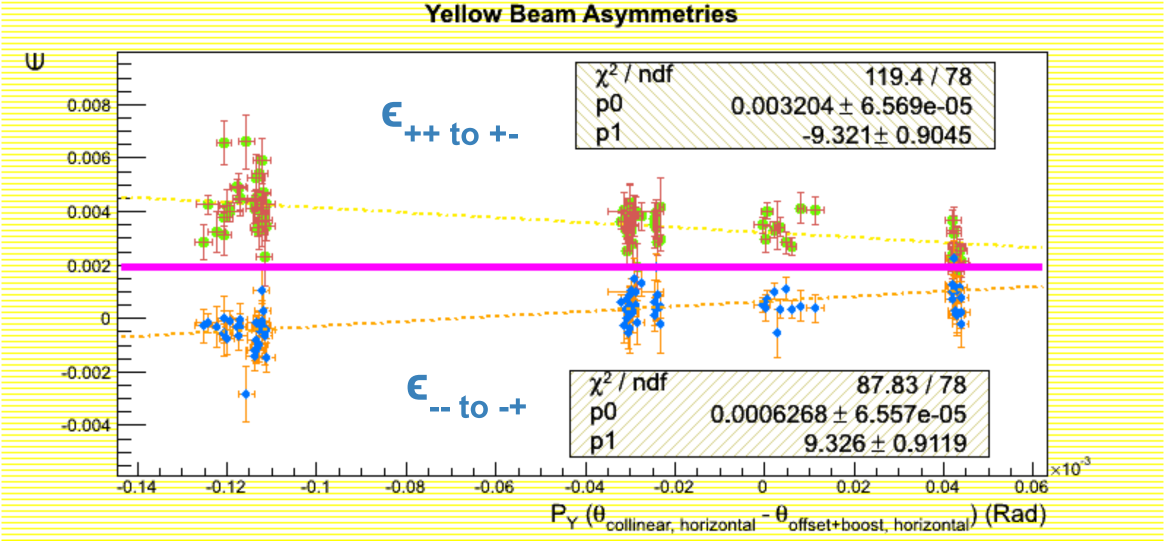
  - Offset:

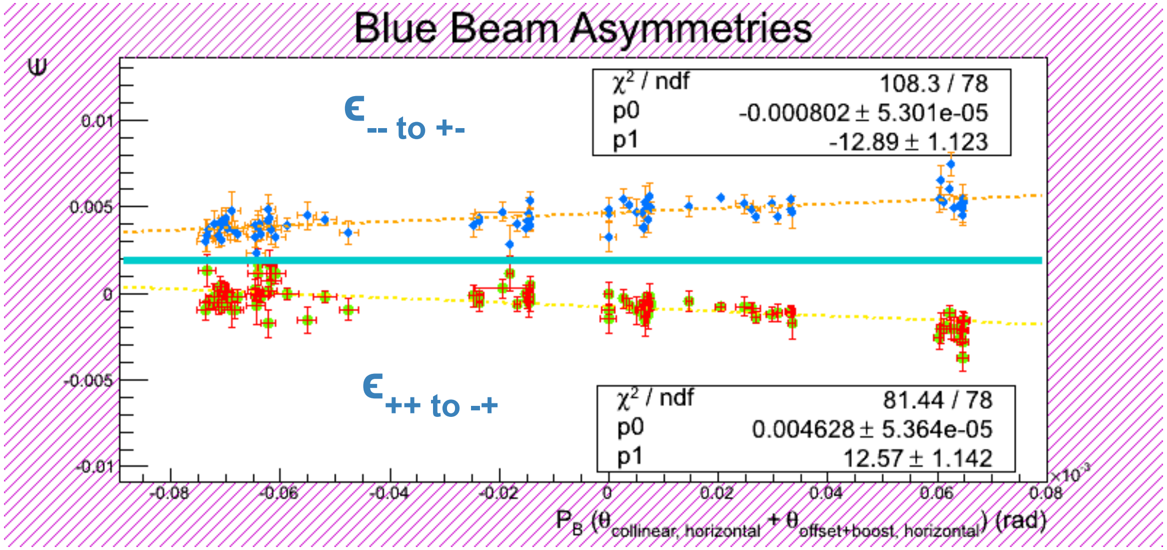


  - Boost:



Run 12 Collinear Beam Angle Scan





- Under model, these two yellow beam asymmetries should be equal and opposite
- Slopes equal and opposite, but not intercepts

- Same logic applies to blue beam asymmetries
- both yellow and blue asymmetries average to ~2e-3