# Getting at the Gluon: The High Statistics $\pi^0$ $A_{LL}$ Measurement at PHENIX With Investigations of a Major Systematic Uncertainty

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# Proton Spin

- Spin of the Proton

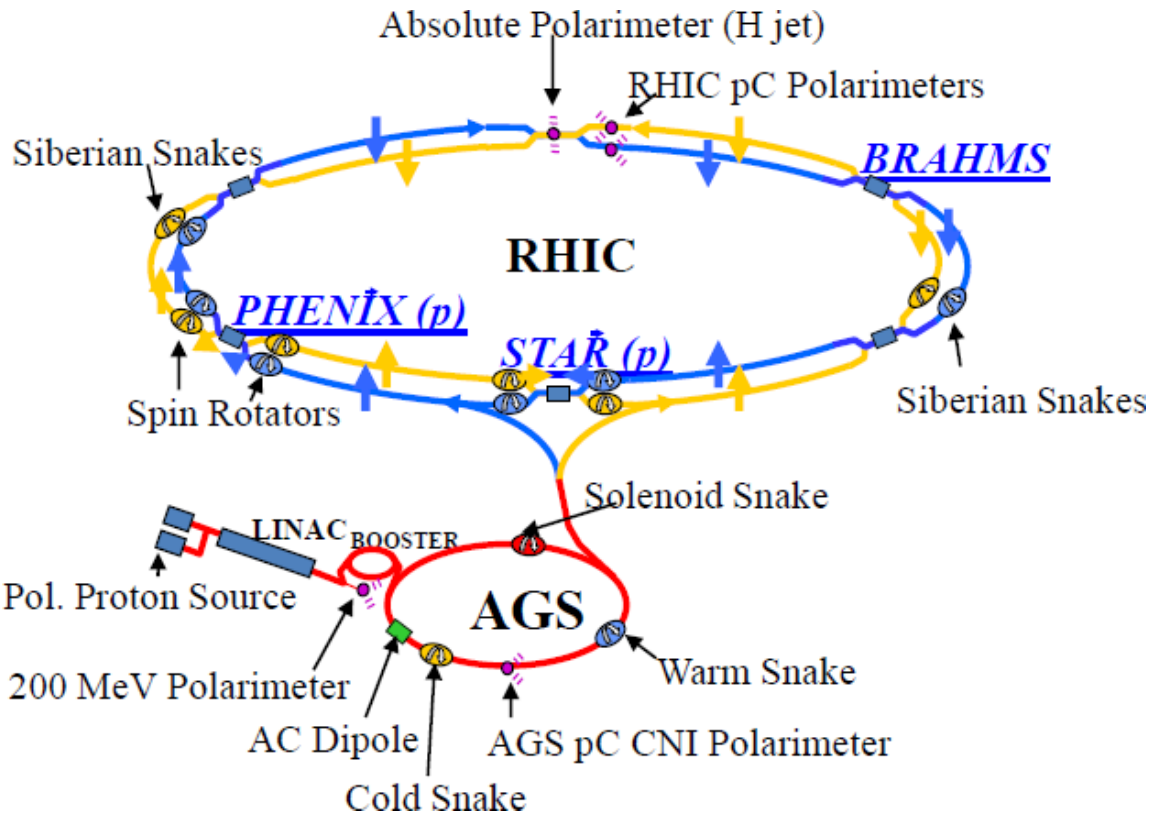
$$S_p = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

- RHIC SPIN program
  - Polarized p+p to constrain $S_p$, starting with focus on ΔG
    - √s = 200, 500, 62.4 GeV

$$\Delta G = \int_0^1 dx \Delta g = \int_0^1 dx [g_+(x, \mu^2) - g_-(x, \mu^2)]$$

- Some other measurements to constrain various components of $S_p$:
  - forward transverse single-spin asymmetries
  - parity violating W-boson asymmetries

# RHIC



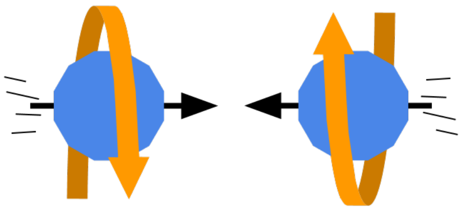

- Up to 120 proton bunches rotating in each ring
- Polarization can be chosen on a bunch-by-bunch basis, e.g.

+ − + − − + − +

+ + − − + + − −

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

# Experimental Formula for $A_{LL}$



- e.g., in collisions with longitudinal spin (helicity), we measure asymmetries in the production of a particle

$$A_{LL} = \frac{1}{P_B P_Y} \left( \frac{N_{\pi^0}^{same} - R N_{\pi^0}^{opposite}}{N_{\pi^0}^{same} + R N_{\pi^0}^{opposite}} \right), R = \frac{L^{same}}{L^{opposite}}$$

- This formula differentiates colliding bunches with the "same" ("++" and "--"), or "opposite" ("+-" and "-+") helicity
- P's are the polarizations of the two beams
- R is the relative luminosity
  - because it is a ratio, we can construct it from measured counts in any detector that sees no spin asymmetry

# 2009 PHENIX $\pi^0$ $A_{LL}$ Preliminary Results

○ $\sqrt{s}$ = 200 GeV

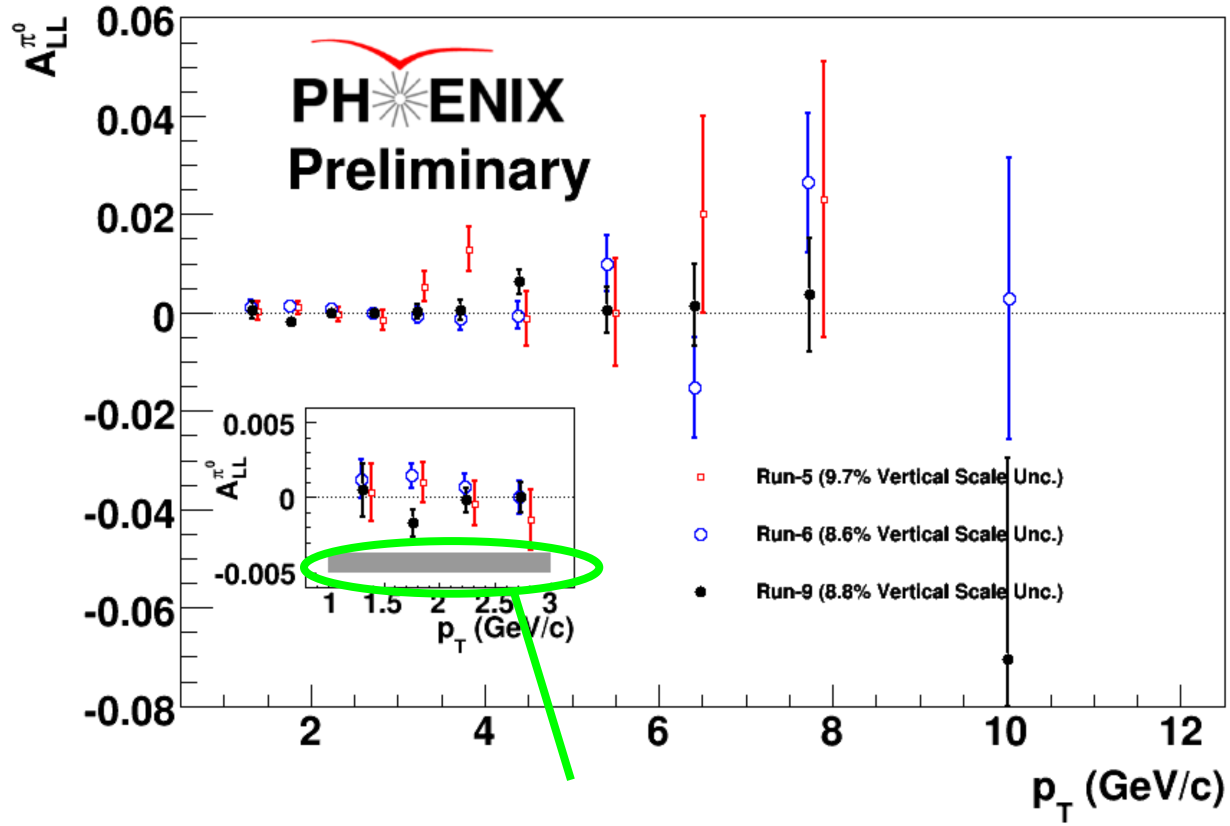
○ Lowest bin error-bar larger in '09 because of increased minimum-energy cut

  ○ To to mitigate background effects due to increased collision rates

○ Highest bin affected by conservative quality cuts for prelim.

In progress for final:

- Additional BG cut: Charged particle veto
- Measurement in 12-15 GeV bin




- Systematic uncertainty due to relative luminosity
- Along with polarization measurement, only significant source of systematic uncertainty

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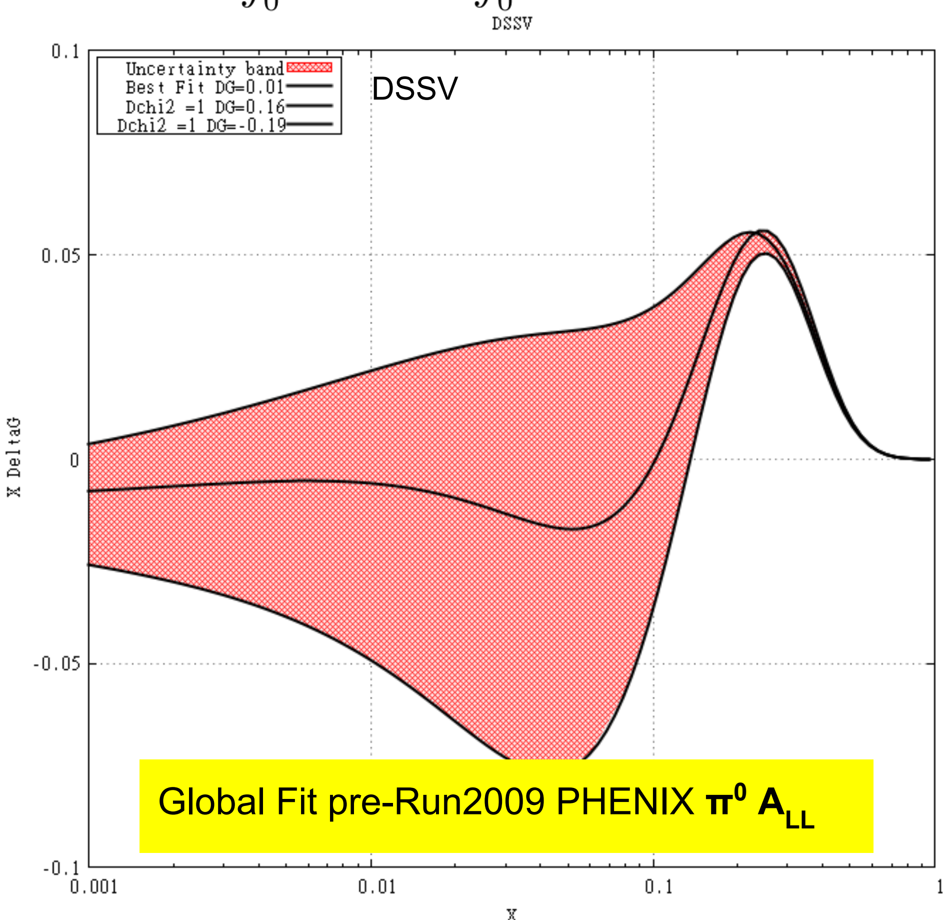
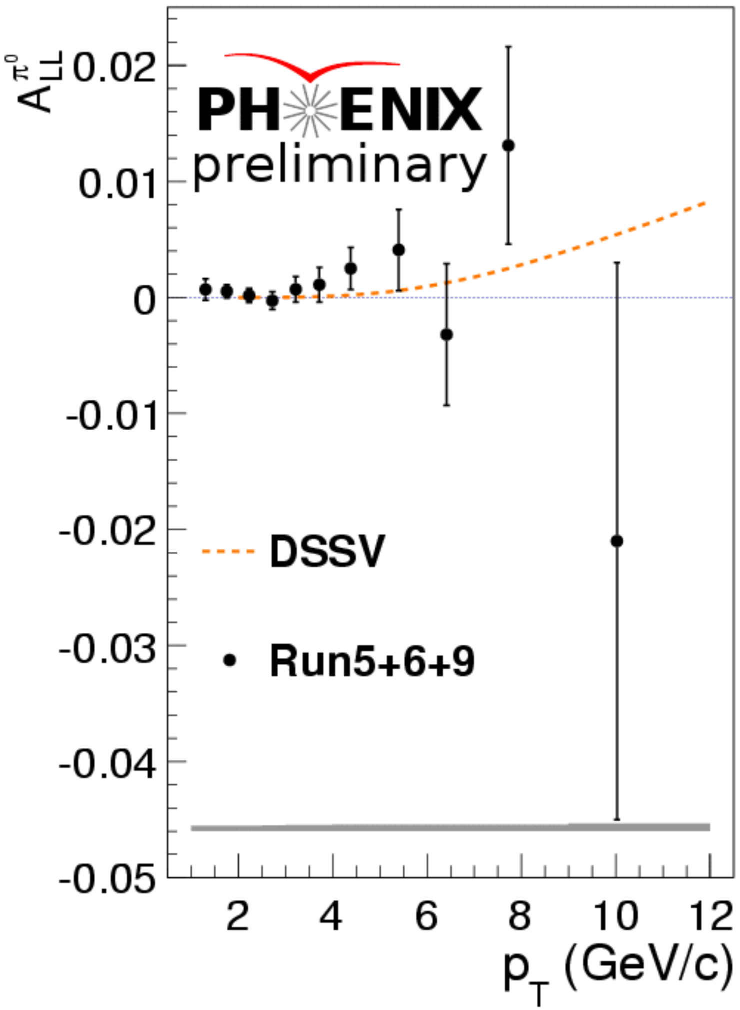
# PHENIX $\pi^0$ $A_{LL}$ and Its Impact on the Global Fit

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

$$\Delta G = \int_0^1 dx \Delta g = \int_0^1 dx [g_+(x,\mu^2) - g_-(x,\mu^2)]$$



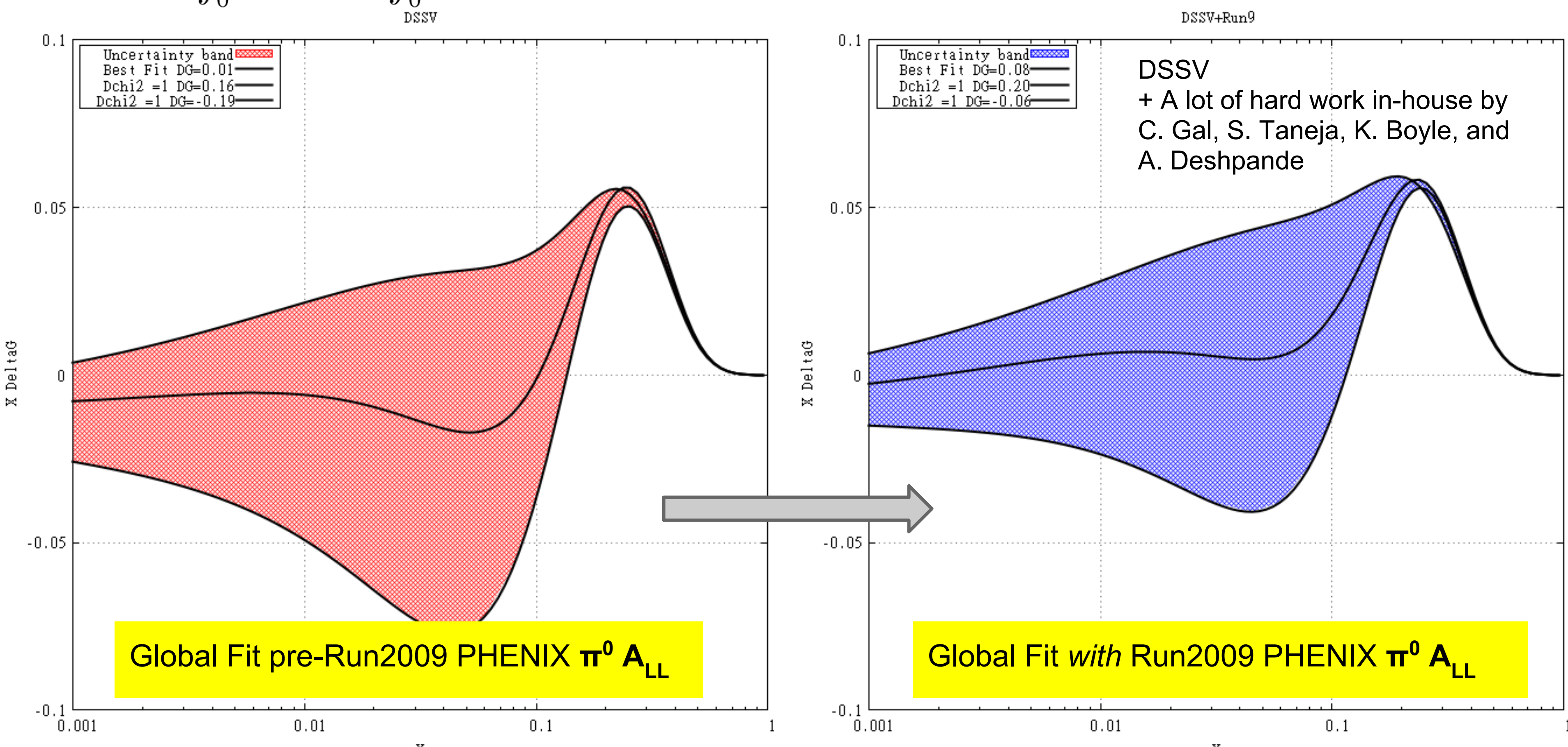



# PHENIX $\pi^0$ $A_{LL}$ and Its Impact on the Global Fit

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

$$\Delta G = \int_0^1 dx \Delta g = \int_0^1 dx[g_+(x,\mu^2) - g_-(x,\mu^2)]$$

- The impact is clear
- Integral of mean value increases
- This version does not have systematics




Global Fit pre-Run2009 PHENIX $\pi^0$ $A_{LL}$

Global Fit *with* Run2009 PHENIX $\pi^0$ $A_{LL}$

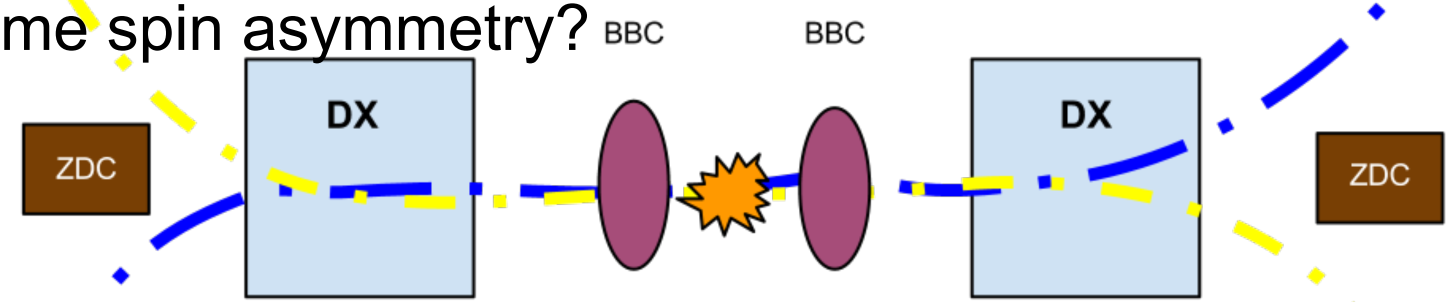
# Relative Luminosity Systematic, Historically

| Run, $\sqrt{s}$ | $\sigma_{stat}$ $\pi^0$ $A_{LL}$ smallest uncert. $p_T$ bin | $\sigma_{syst}$ RL |
|---|---|---|
| 2005, 200 GeV | 13e-4 | 2.5e-4 |
| 2006, 200 GeV | 8.2e-4 | 7.5e-4 |
| 2009, 200 GeV | 8.2e-4 | 14e-4 |

If this is due to a physics asymmetry, it should be constant year to year.
Typical uncertainty on this number ~2.5e-4, so it is not consistent.

# How Do We Measure the Systematic Uncertainty on Relative Luminosity?

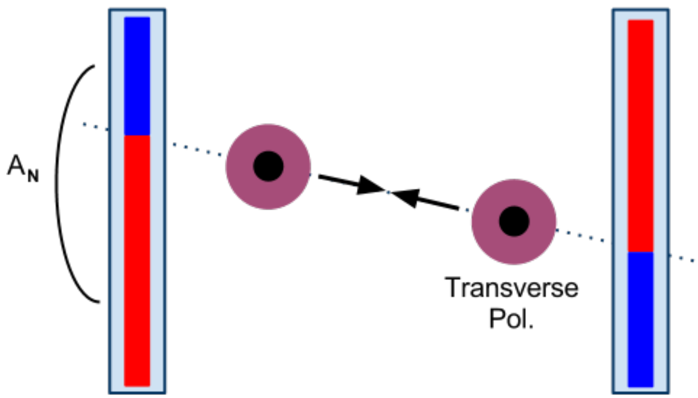
- i.e., what if our relative luminosity detector DOES see some spin asymmetry?

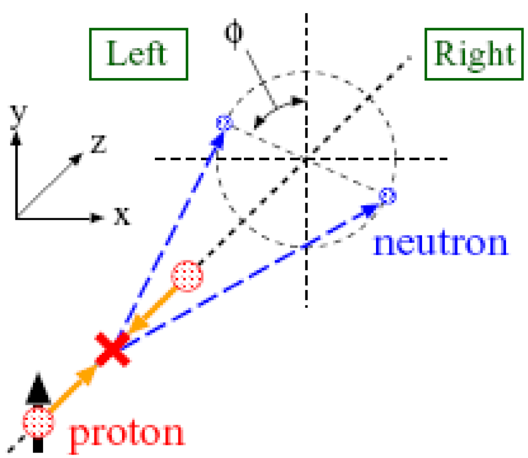



  - We use our minimum bias BBC (Beam Beam Counter) to measure R
  - ...and compare it with a detector past the DX magnetic field
    - ZDC: Zero Degree Calorimeter, no charged particles
  - We then assume the different physics they sample can't have the same asymmetry
  - Compare the two results to get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

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

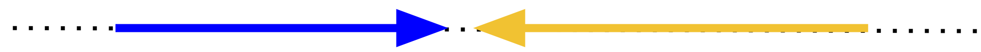
# RL Studies in Transverse Pol Running



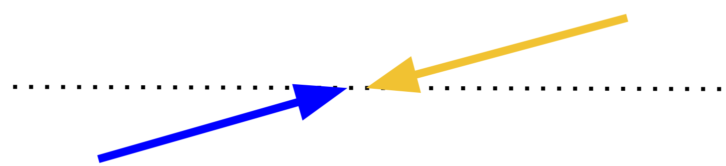




- Even our longitudinally polarized beams have some small transverse component
  - Transverse running in 2012 gave us an opportunity to test a hypothesis: Maybe $A_N$ coupled with some geometric effect could be faking other asymmetries.
- We angled the beam through the PHENIX IR and calculated our typical BBC/ZDC asymmetries

# Beam Geometry Components

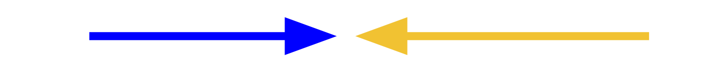


- Beams traverse IRs in "zero" magnetic field region
  - straight paths
- Intersection geometry of beams can be decomposed into three components (x 2 planes)
  - Collinear Angle:

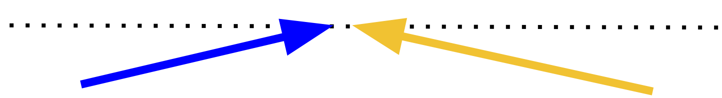


studied in Run12!

  - Offset:



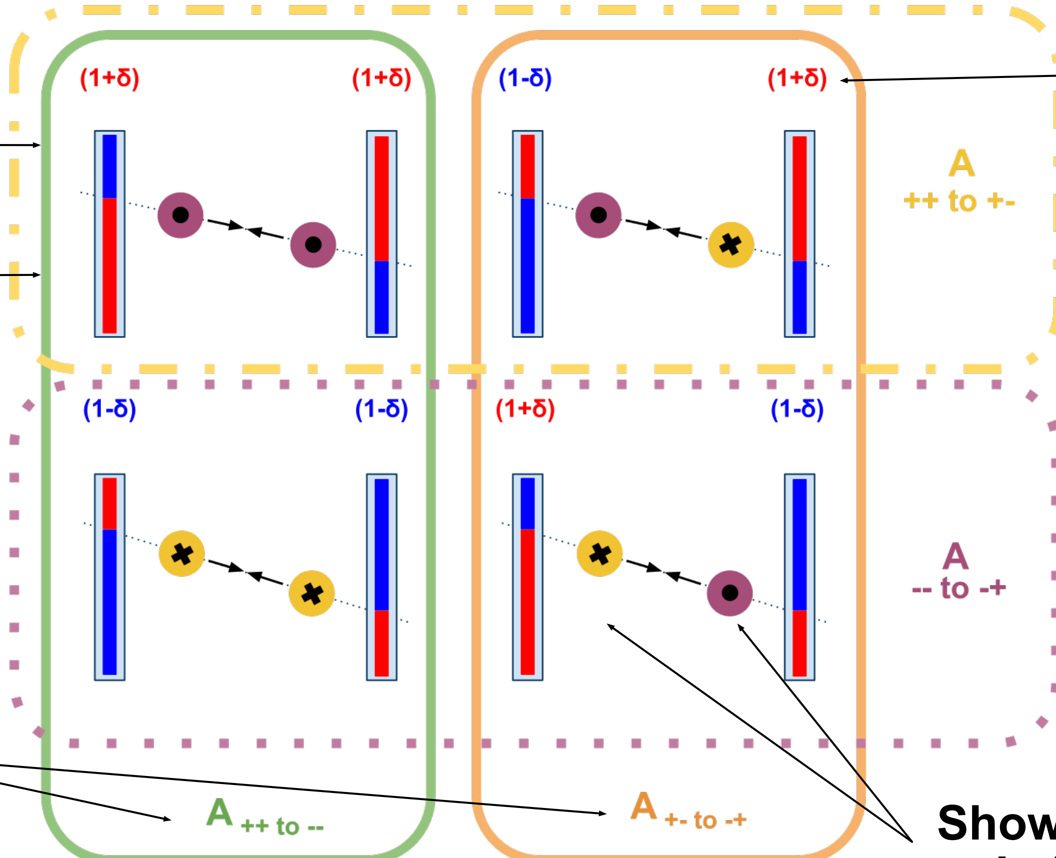
  - Boost:



# Model: Case of Collinear Beam Angle

**Fewer** -or- **More** Particles (from $A_N$)

Acceptance modification factor




**Different Asymmetries**

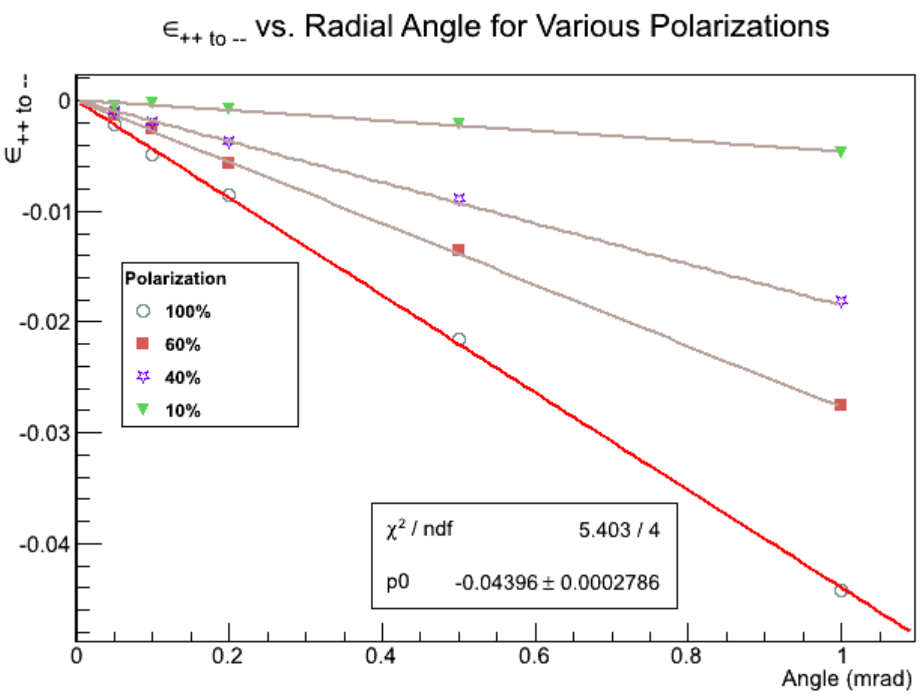
**Show transverse pol. direction**

# 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
- $\delta$, $\varepsilon$: acceptance modification factors, functions of angle, offset, or boost
- Important point: cross-check asymmetries which should be zero can be large under this effect!

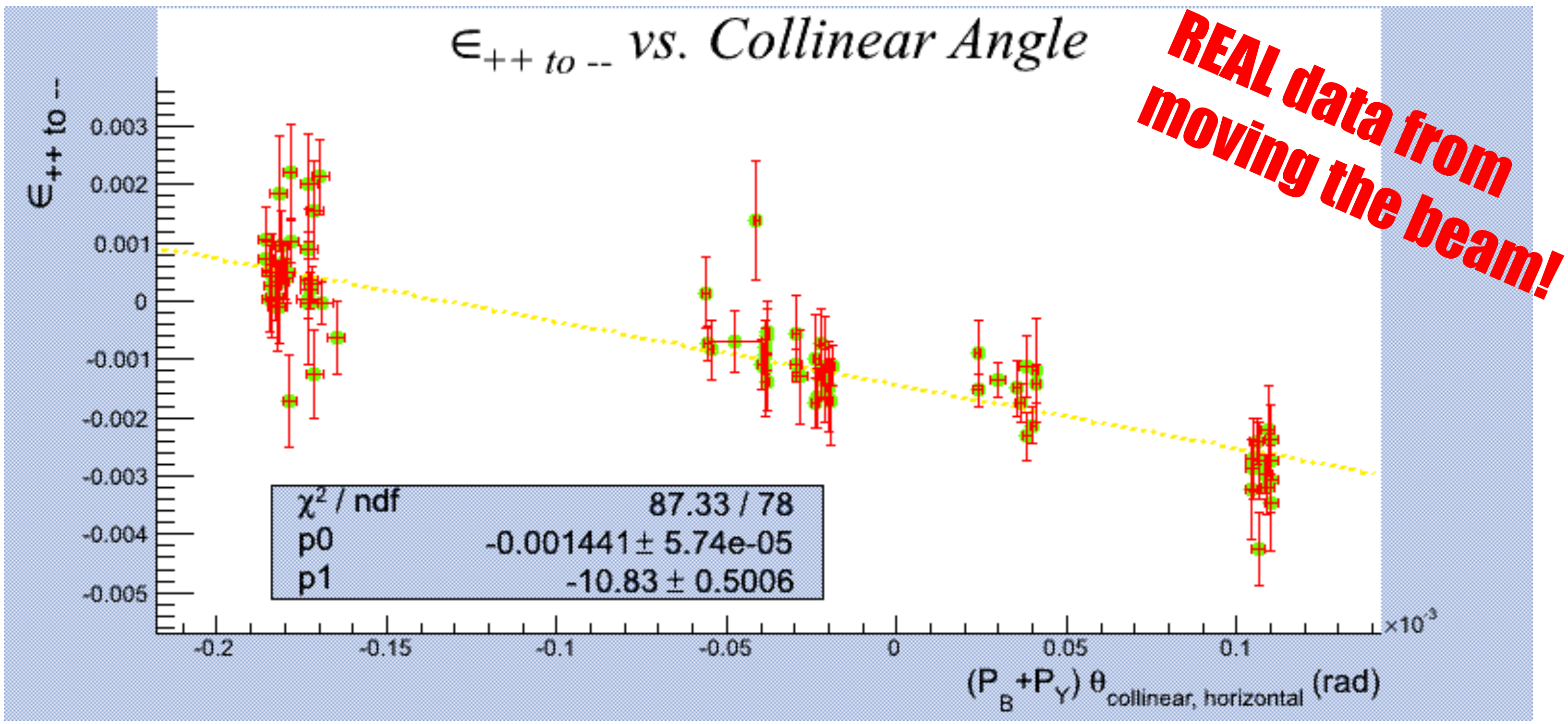
# Predictions of Toy MC Simulation (Collinear Beam Angle)




- Key prediction:
  - linear relationship between asymmetry and angle/offset/boost
- Linear dependence on pol confirmed
  - only red line is fit, rest are scaled by input polarization

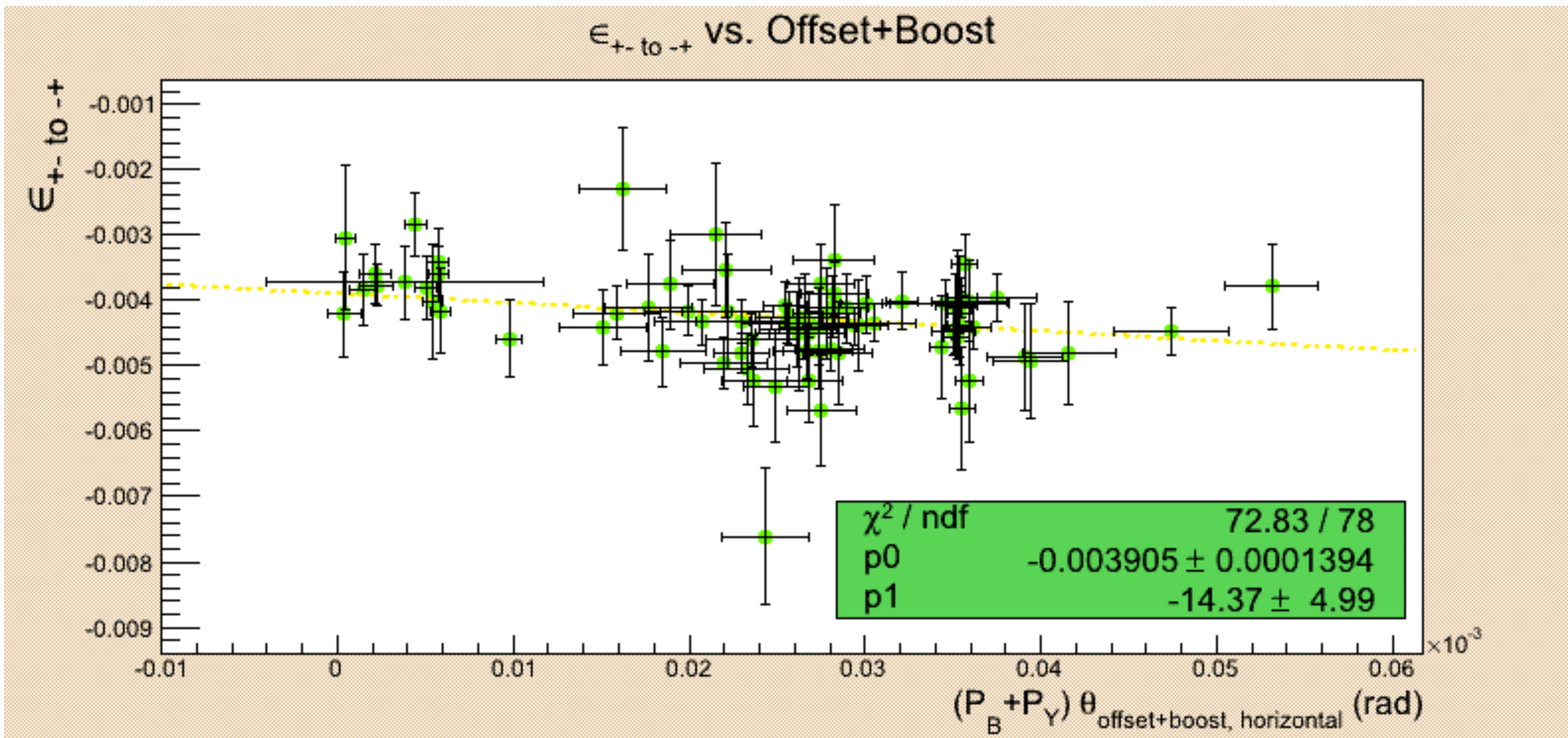
# Run12 Result: $\epsilon_{++ \text{ to } --}$ ("Parity Violating")

- Note slope and compare with rest



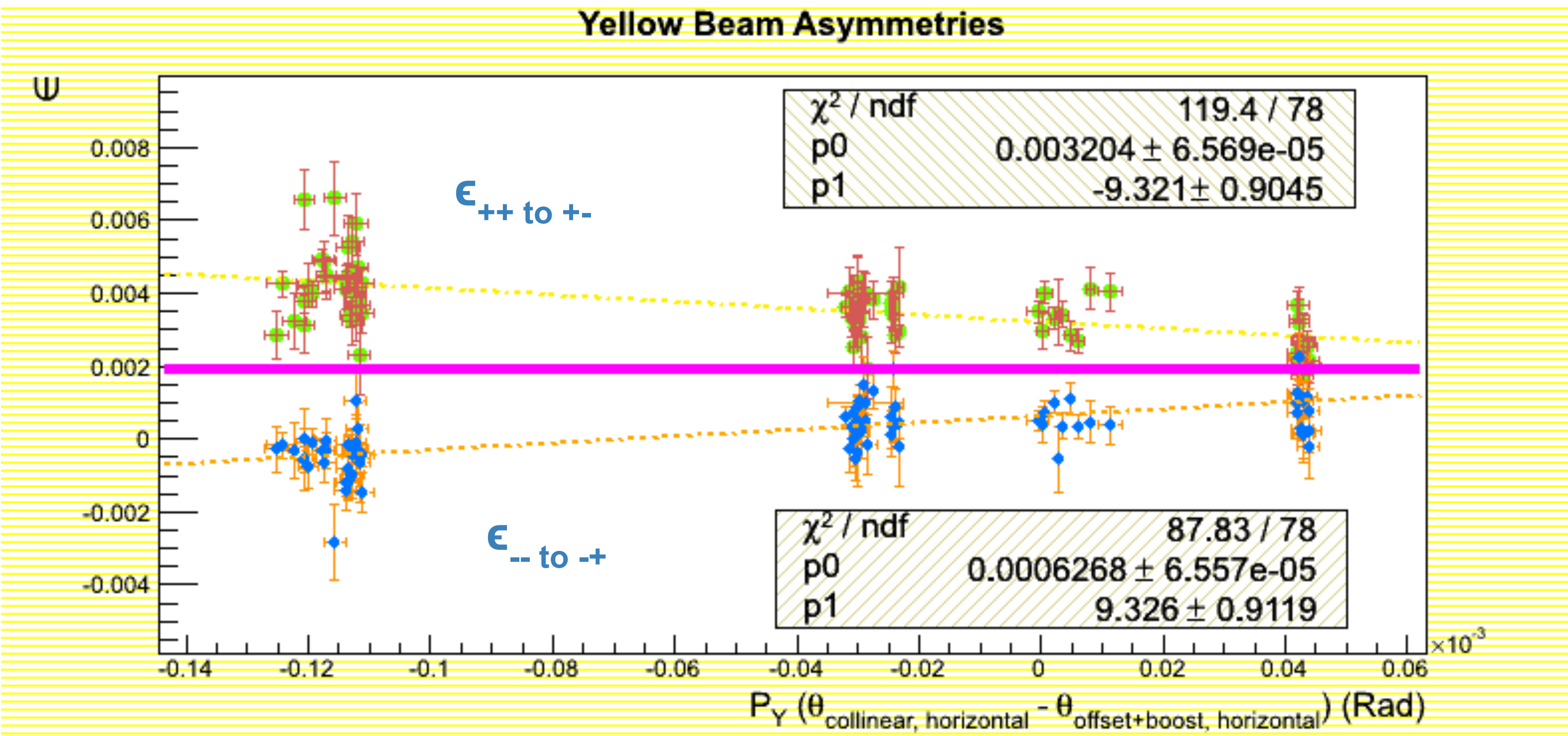
# Result: $\epsilon_{+- \text{ to } -+}$ ("A 180° Rotation")

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



# Result: Yellow Beam Asymmetries ($\epsilon_{++\ to\ +-}$, $\epsilon_{--\ to\ -+}$)

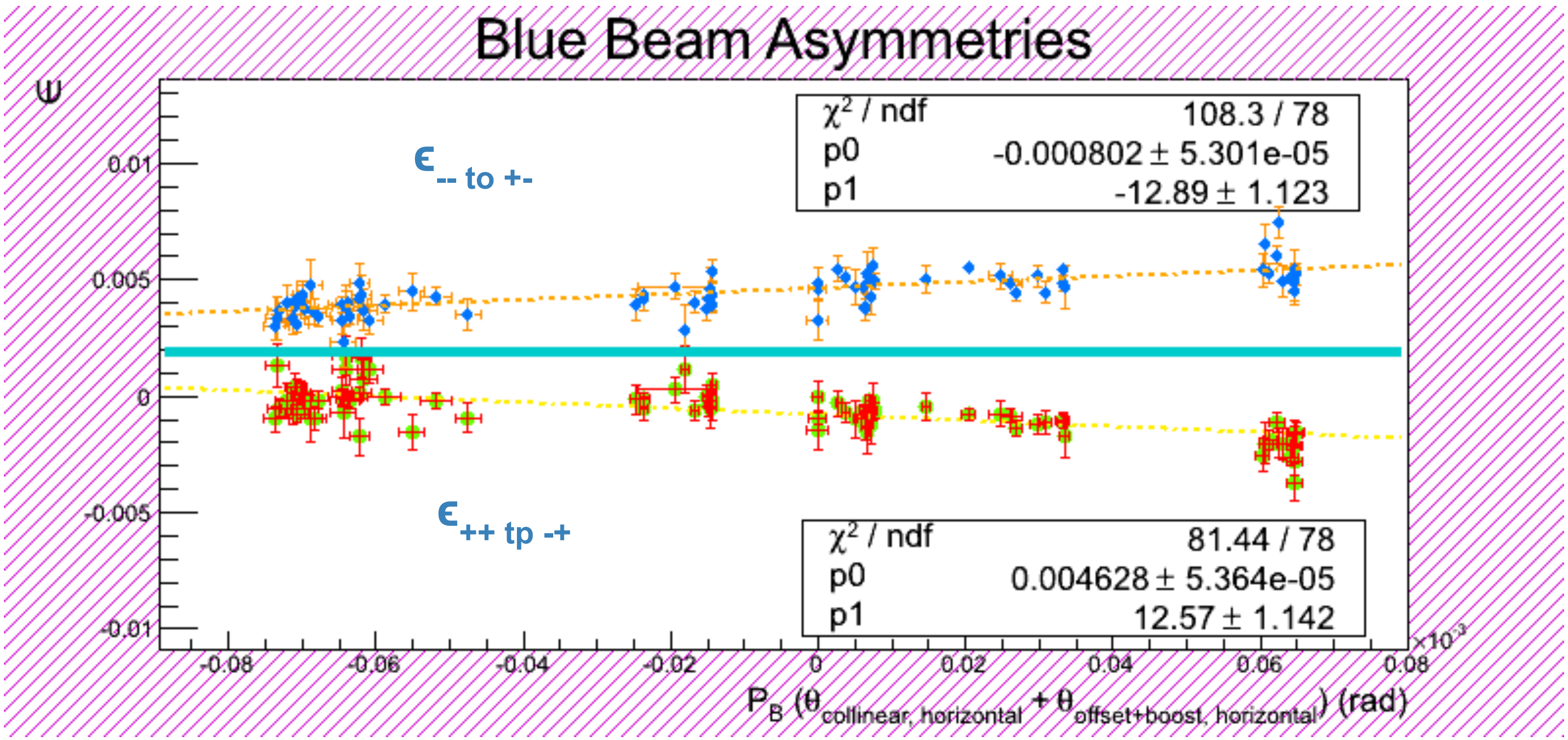
- Under model, should be equal and opposite




- Slopes equal and opposite, but not intercepts

# Result: Blue Beam Asymmetries ($\epsilon_{++\text{ to }-+}$, $\epsilon_{--\text{ to }+-}$)

- Under model, should be equal and opposite




- Slopes equal and opposite, but not intercepts
  - as in yellow, average ~2e-3

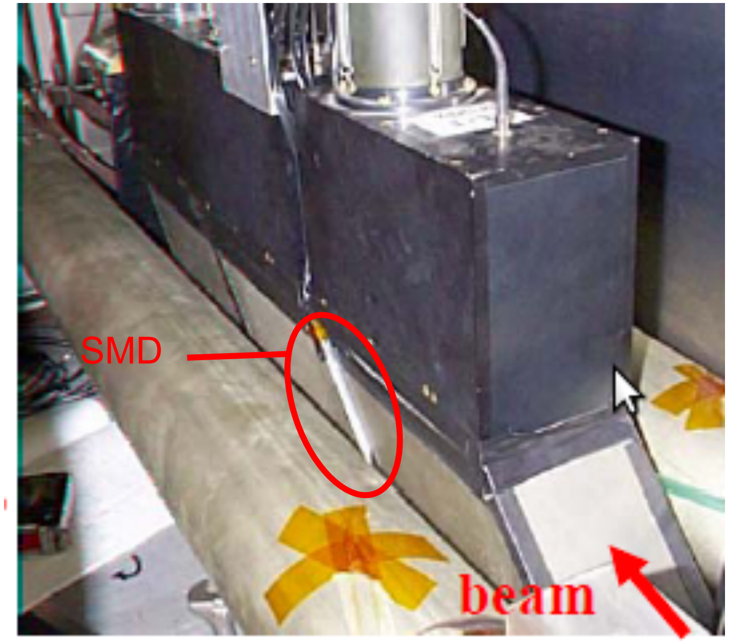
# Possible Future Beam Studies

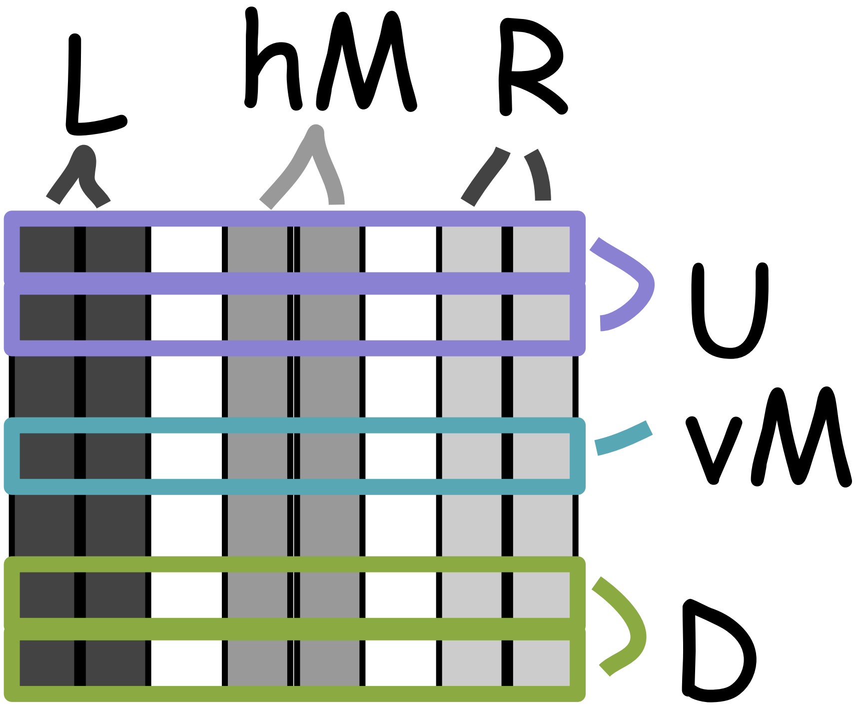
- *offset* scan (especially in vertical direction)
  - Our ZDC detector shifted 1.2 cm in vertical w.r.t the nominal beam axis
  - 1.2 cm at the 18m ZDC translates to 666 μrad angle
    - angle scan had a range of about +/-150 μrad
    - could be in a non-linear region for this effect
- Check for effects in the BBC
  - can be done by combining offsets (which move on BBC and ZDC equally) and angles (negligible at the BBC)
- Measure $A_{TT}$
- But beam time is precious....

# Hardware Based Study: Segmented SMD Readout

- SMD (Shower Maximum Detector) sits behind the first layer of the Zero Degree Calorimeter) ZDC, which sits at |η|>6
- Has strips that are read out individually
- Idea: Count hits on individual strips/groups of strips in ***scalers***

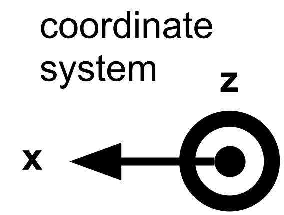
ZDCs (x3 layers)

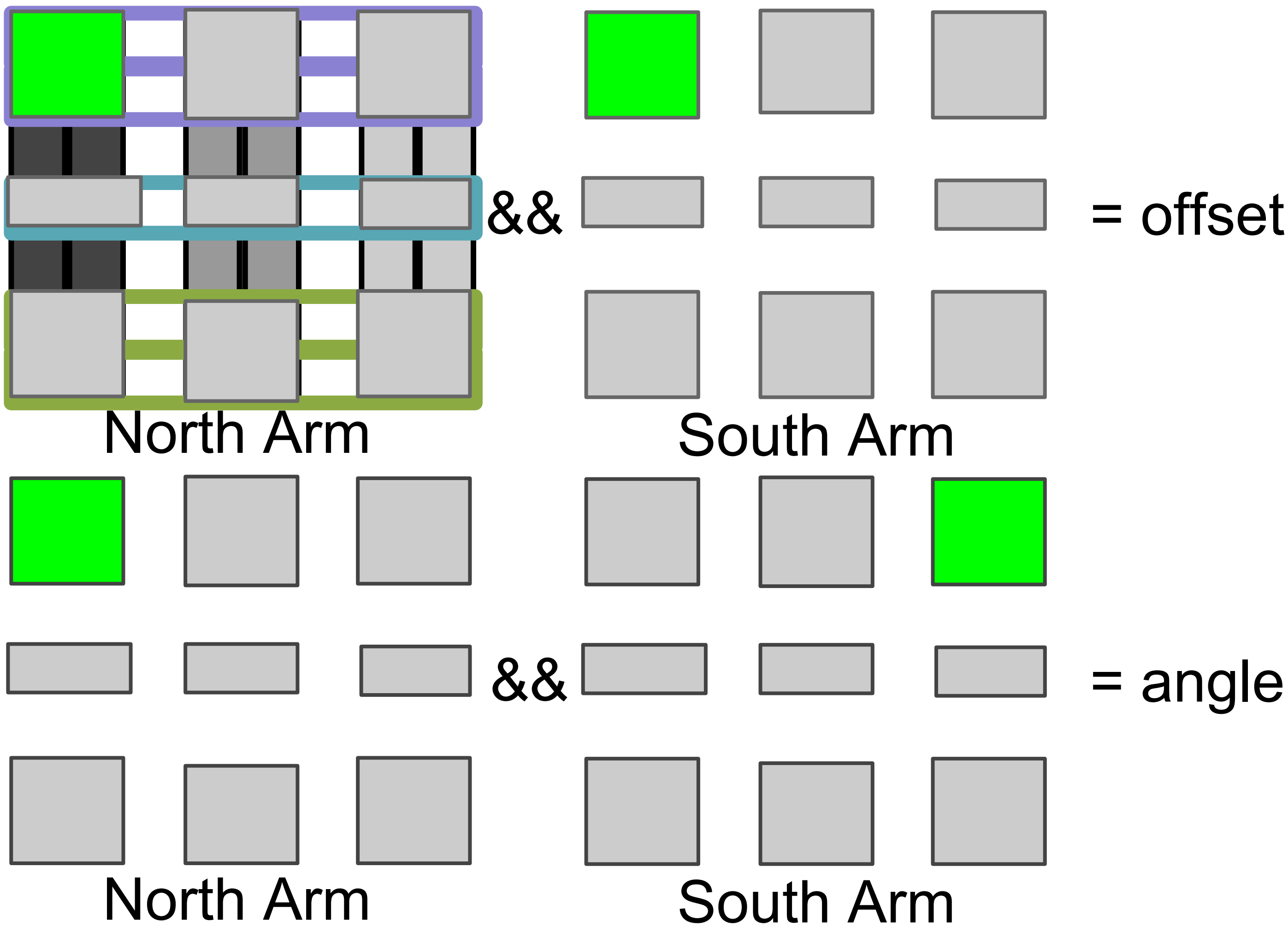


# How Do We Move to Angles/Offsets?

- After making our choice, make coincidences between north and south detectors
- e.g.:



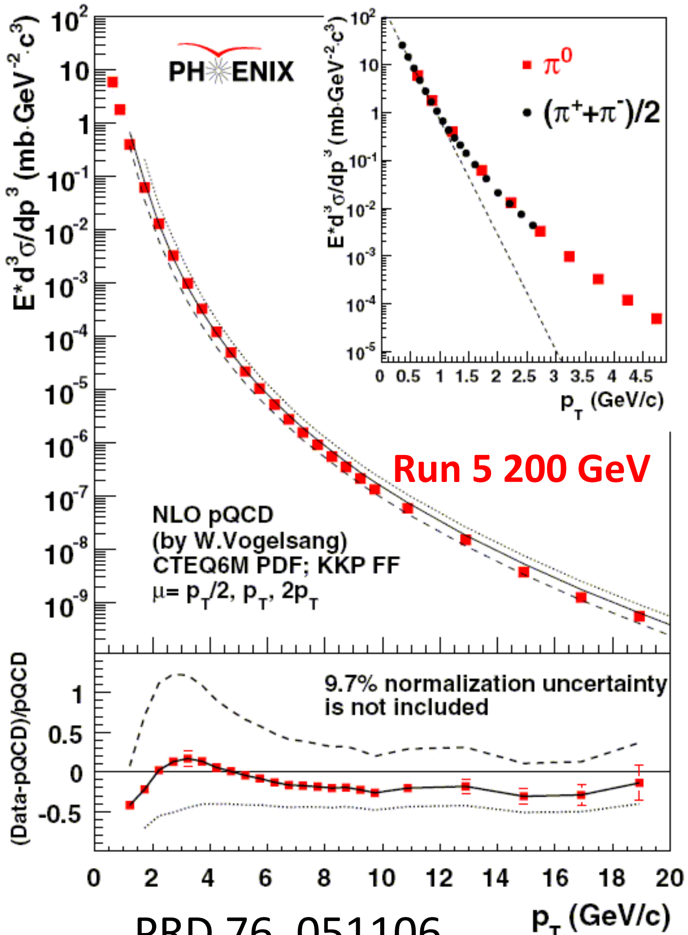
# Conclusions

- Measurements at RHIC (including Run09 $\pi^0$ $A_{LL}$!) have put significant constraints on ΔG, and continue to contribute to understanding the spin of the proton
  - but systematics have started to limit us

- In particular, ongoing longitudinal-spin program at sqrt(s) = 500 GeV would benefit from reduction in RL systematics
  - Important for $A_{LL}$ measurements at central and forward
- Run12 angle scan gives us insight into some RL asymmetries
  - Can explain seemingly non-physical (180 degree rotational) and fantastical (large parity violating) asymmetries in longitudinal running with a transverse beam component + $A_N$
  - but not giving us the full story
- More beam dynamic tests should be done
  - beam offsets, in particular vertical beam movement
  - hardware-based tests (may happen in 2013)

# Backup

# 200 GeV $\pi^0$ Cross-section

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- Previous results have shown that pQCD along with measured parton "Fragmentation Functions" and "Parton Distribution Functions"

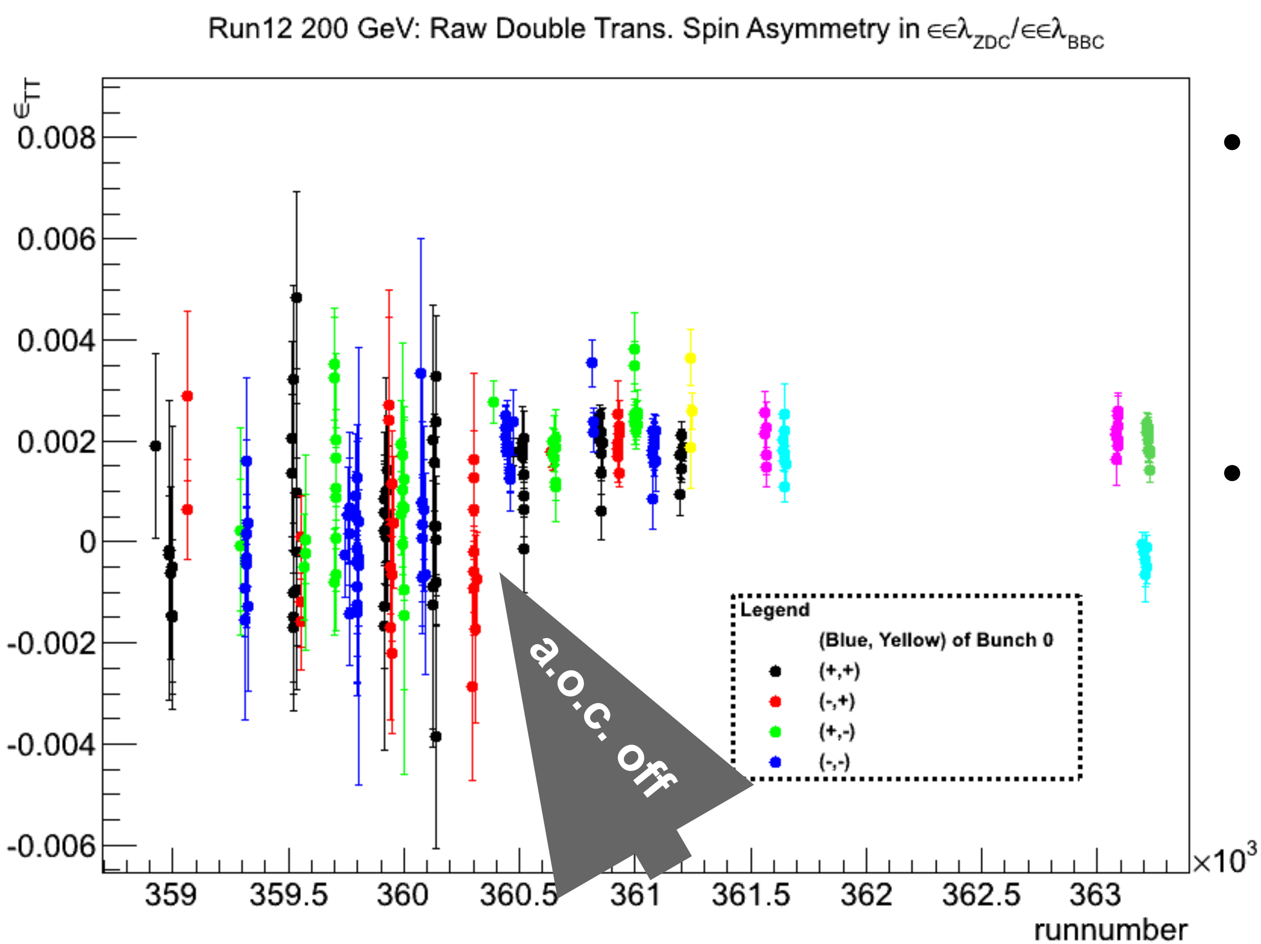
- Thus we can use theory and fragmentation functions to extract more intricate "*Polarized* PDFs"

$$\Delta G = \int_0^1 dx \Delta g = \int_0^1 dx[g_+(x,\mu^2) - g_-(x,\mu^2)]$$

using asymmetry observables such as

$$A_{LL} \equiv \frac{\{d\sigma_{++} + d\sigma_{--}\} - \{d\sigma_{+-} + d\sigma_{-+}\}}{\{d\sigma_{++} + d\sigma_{--}\} + \{d\sigma_{+-} + d\sigma_{-+}\}} = \frac{d\Delta\sigma}{d\sigma}$$

# Automatic Orbit Correction: Evidence of Beam Geometry Effects




- Accelerator physicists implemented automatic orbit correction for beams to help maintain polarization
- ***increase*** **in average asymmetry/*****decrease*** **in fluctuations coinciding with automatic orbit correction being turned off**

# Simulation Details

- Toy Monte Carlo of colliding beams
  - Charged particles for the BBC produced according to previously measured distributions
  - Neutrons for the ZDC according to previously measured distributions AND $A_N$
  - Collided at any angle/offset/boost

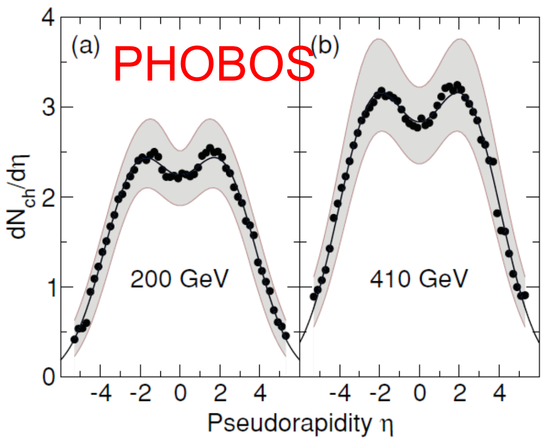
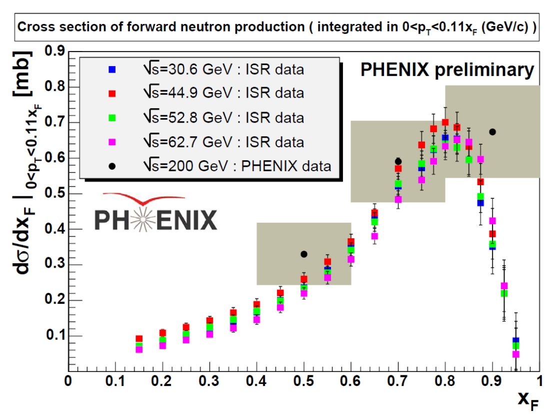
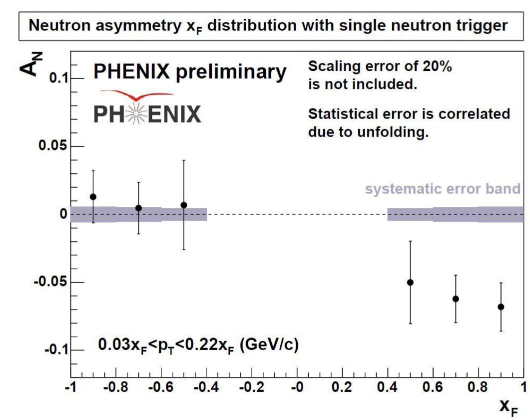
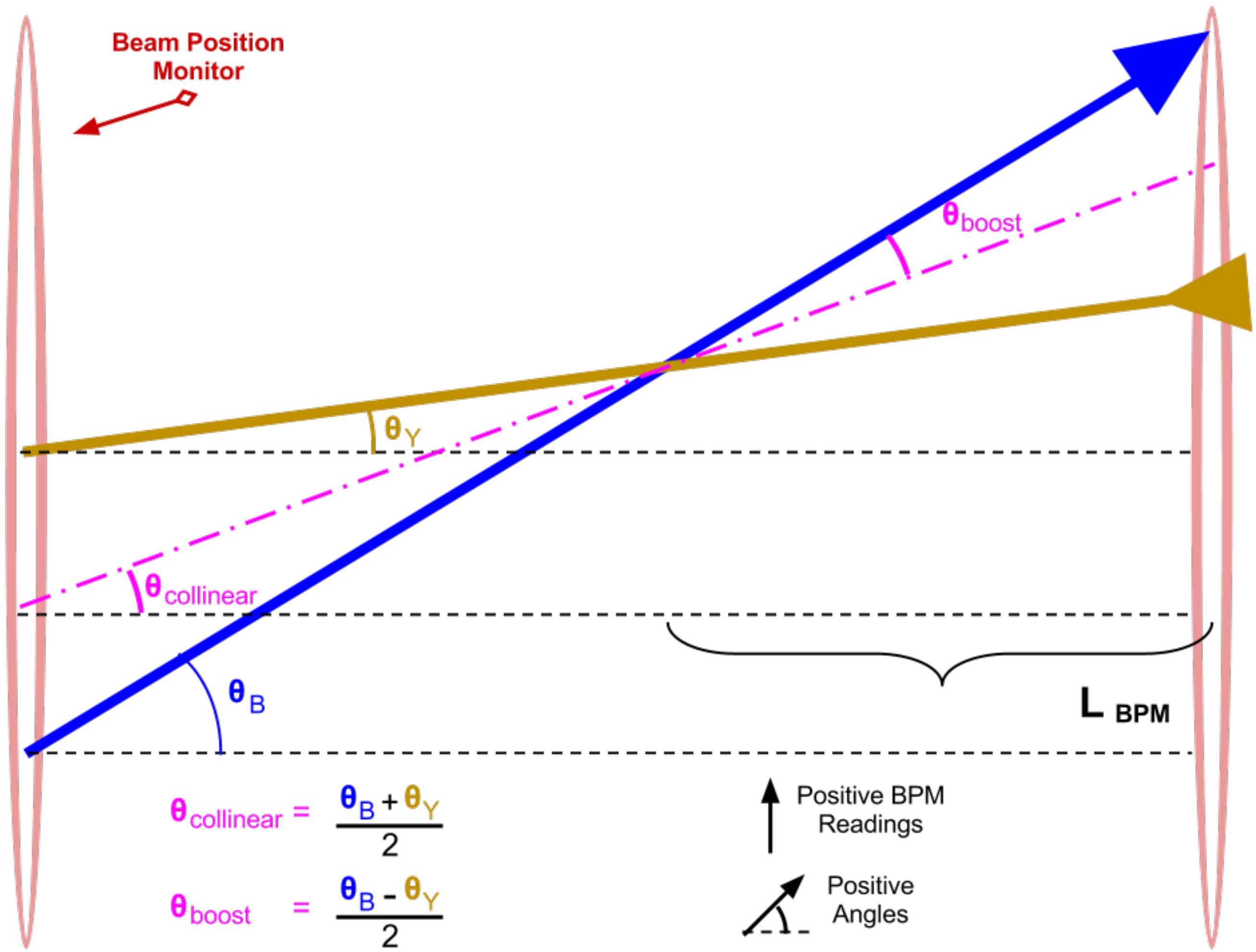



FIG. 29. (Color online) Charged-particle multiplicity $dN_{ch}/d\eta$ shown for 200-GeV (a) and 410-GeV (b) $pp$ inelastic collisions.



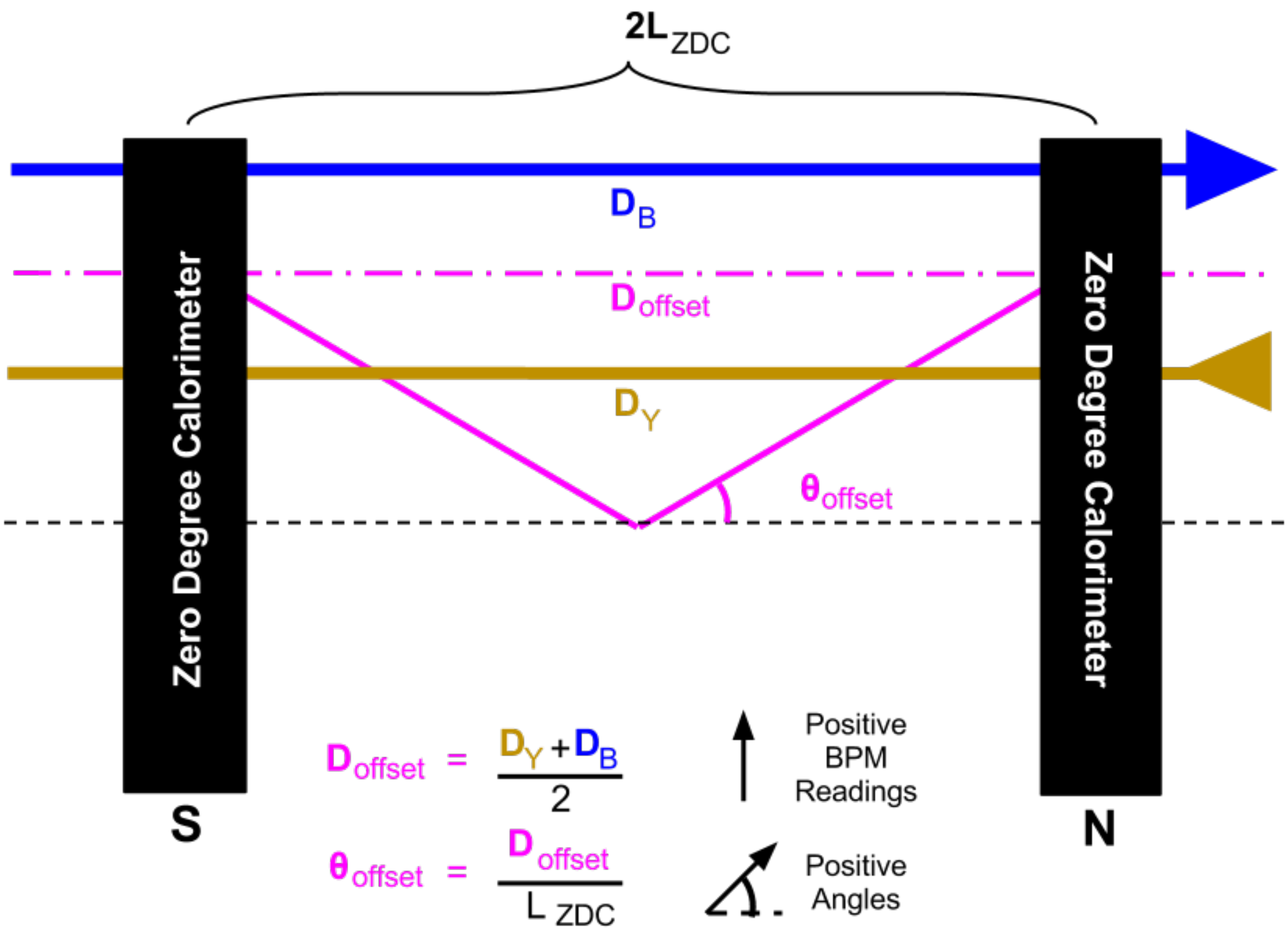
# Precise Angle Definitions - Collinear/Boost




$$\theta_{collinear} = \frac{\theta_B + \theta_Y}{2}$$

$$\theta_{boost} = \frac{\theta_B - \theta_Y}{2}$$

# Precise Angle Definitions - Offset



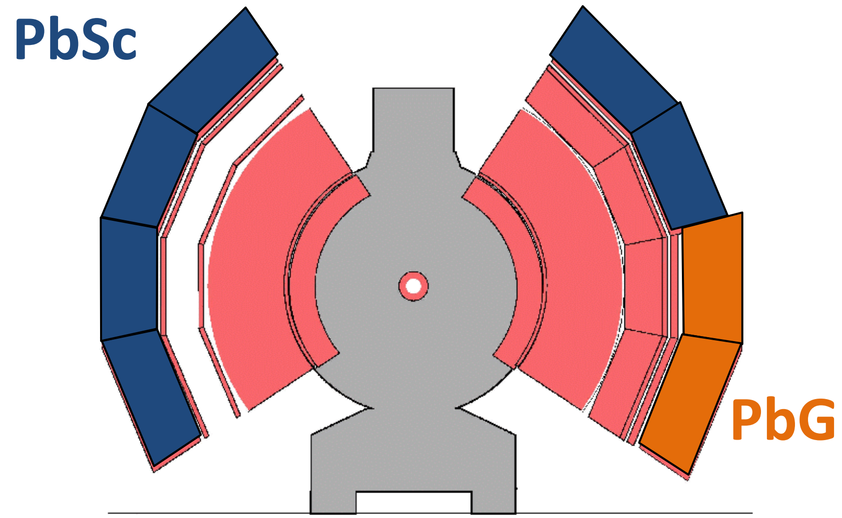

$$D_{offset} = \frac{D_Y + D_B}{2}$$

$$\theta_{offset} = \frac{D_{offset}}{L_{ZDC}}$$

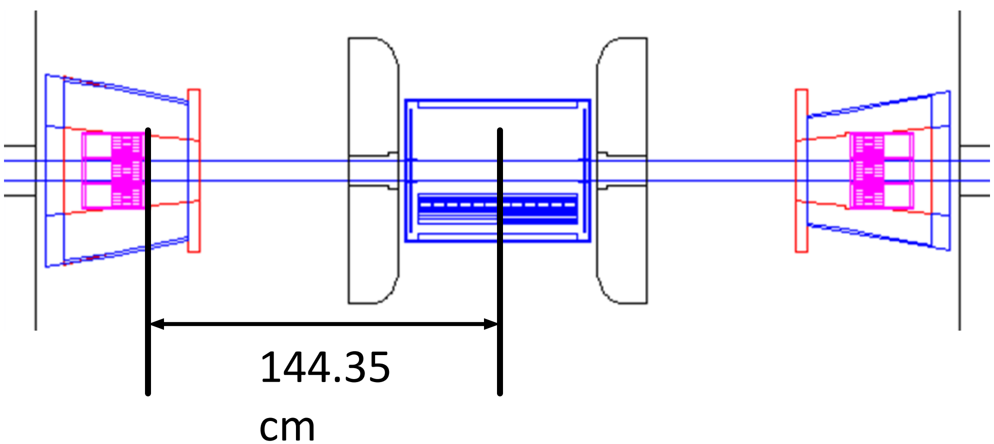
# Measuring di-Photons ($\pi^0$s) and Luminosity: EMCal and BBC

**Electromagnetic Calorimeter (EMCal)**

- Six sectors Pb-Scintillator sampling calorimeter
- Two sectors Pb-Glass Cherenkov radiator
- Good energy, timing, and spatial resolution
- Measures photon energy *and* position to reconstruct $\pi^0$s
- $|\eta| < 0.375$, $\Delta\varphi = (\pi/2) \times 2$
- Different systematics in PbSc and PbGl allow for cross checks




**Beam-Beam Counters (BBCs)**




- Two arrays of 64 elements, each a quartz Cherenkov radiator with PMT
- $\Delta\eta = \pm(3.1 \text{ to } 3.9)$, $\Delta\varphi = 2\pi$
- Used for relative luminosity measurement:

$$R = \frac{L^{++}}{L^{+-}} \approx \frac{N_{BBC}^{++}}{N_{BBC}^{+-}}$$

- Also used for collision vertex measurement and as MB trigger

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