PHENIX Local Polarimetry

RADIATION LAB. STUDENT SEMINAR

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Contents

- Motivation
  - Run13 experiment at RHIC
  - Experimental condition
  - Local polarimetry for systematic uncertainty
- Measurement
  - Physics
  - Detectors
  - Procedure
- Result
- Discussion & Conclusion
- Summary

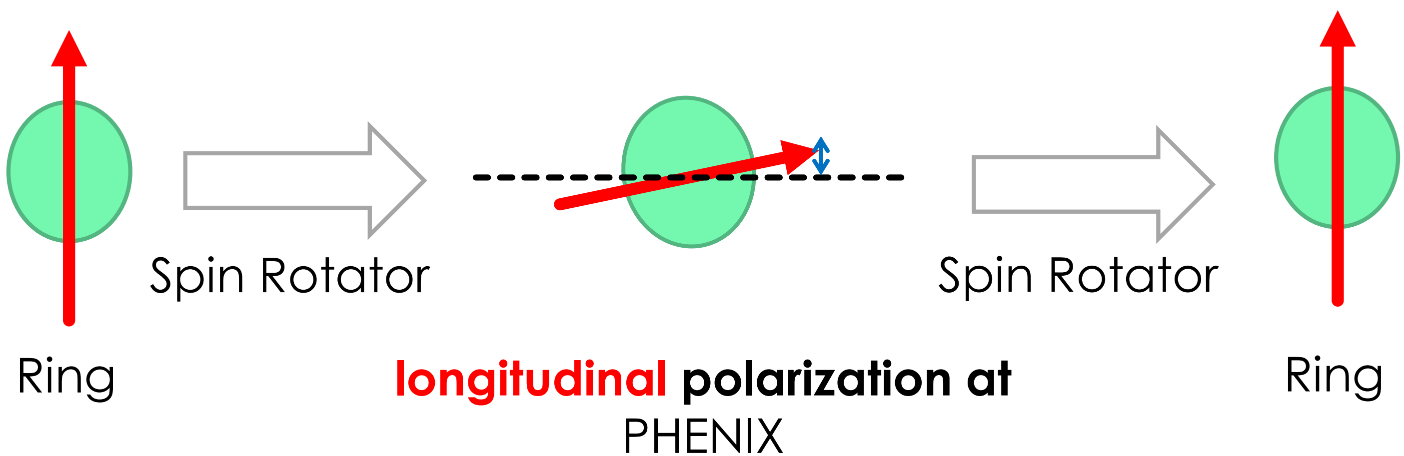
Run13 PHENIX Experiment at Relativistic Heavy Ion Collider

Run13 (in 2013):
Longitudinally polarized p+p collisions at $\sqrt{s} =$ 510 GeV to study **helicity distribution of partons**

In the Brookhaven National Lab, NY

Experimental Condition

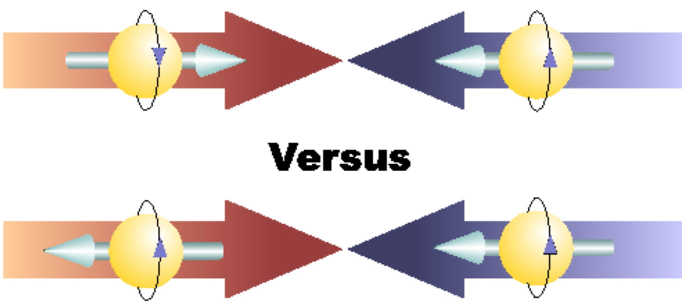
The **stable beam polarization direction** in the RHIC rings : **vertical**

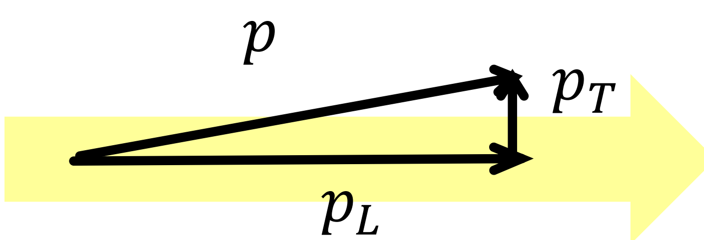


↕ **<u>Transverse component of polarization, p_T may remain!</u>**

Systematic Uncertainty from p_T

$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}}$
measurement for gluon polarization





$$A_{LL}^{measured} \equiv \frac{1}{p^Y}\frac{1}{p^B}\frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$
$$\cong \frac{1}{p^Y}\frac{1}{p^B}(p_L^Y p_L^B A_{LL} + p_T^Y p_T^B A_{TT})$$

Yellow, Blue: two colliding beam

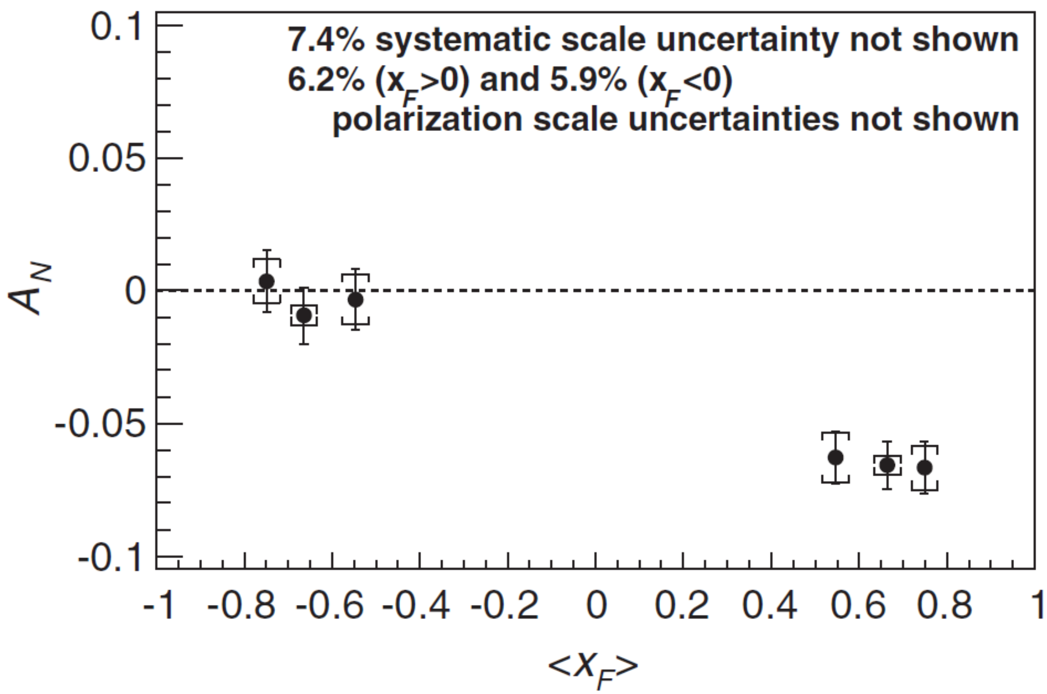
A_{LL} *is very small* (measured up to $O(10^{-4})$, ~A_{TT} prediction)

-> $\frac{p_L}{p}$ & $\frac{p_T}{p}$ *measurement,* ***"Local" Polarimetry, necessary!!***

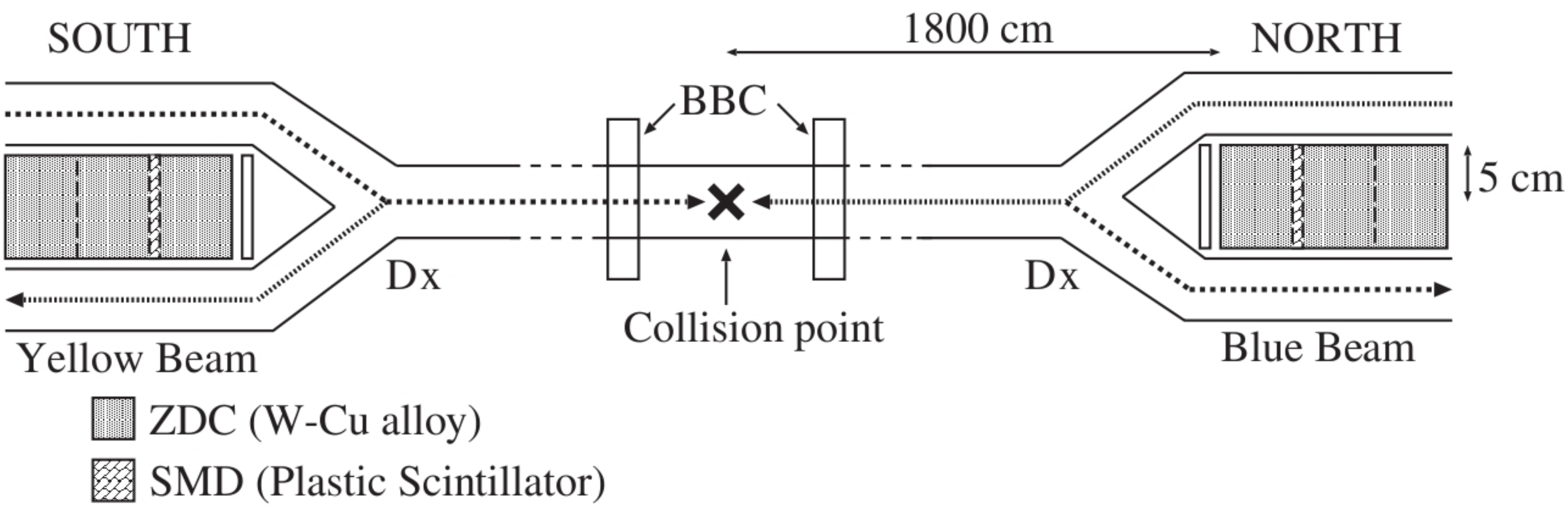
Physics for PHENIX Local Polarimetery

Use large Transverse Single Spin Asymmetry (Left-Right Asymmetry) of forward neutron production

$$A_N \equiv \frac{\sigma_L^{\uparrow}-\sigma_L^{\downarrow}}{\sigma_L^{\uparrow}+\sigma_L^{\downarrow}} = \frac{\sigma_L^{\uparrow}-\sigma_R^{\uparrow}}{\sigma_L^{\uparrow}+\sigma_R^{\uparrow}}$$



Detector layout



- **Z**ero **D**egree **C**alorimeter : Neutron energy measurement
- **S**hower **M**ax **D**etector : Reconstruct a neutron X-Y position using shower profile
- **B**eam **B**eam **C**ounters : Provide collision triggers

Zero Degree Calorimeter & Shower Max Detector

10 cm x 10 cm transverse coverage

ZDC:

- W-Cu alloy + PMMA based optical fibers
- Collect cherenkov light produced by charged secondary particles from neutron showers

SMD:

- X-Y plastic scintillator strip hodoscope
- Between the 1st & 2nd ZDC modules - approx. shower max location
- Position calculation

$$x, y = \frac{\sum_i^{SMD\ strips\ with\ hit} energy\ (i) \times strip\ position(i)}{\sum_i^{SMD\ strips\ with\ hit} energy\ (i)}$$

Measurement Procedure

0. $\boldsymbol{A_N^{Eff}} \equiv \frac{\boldsymbol{e_N}}{\boldsymbol{p_T}} = \frac{1}{f_{detector}} A_N$ ($f_{detector}$: assumed to be constant)

1. Transversely polarized beam $(p = p_T)$: get A_N^{Eff}

$$A_N^{Eff} = \frac{e_N}{p} \equiv \frac{e_N^{Tran}}{p^{Tran}}$$

2. Longitudinally polarized beam : calculate $\frac{p_T}{p}, \frac{p_L}{p}$

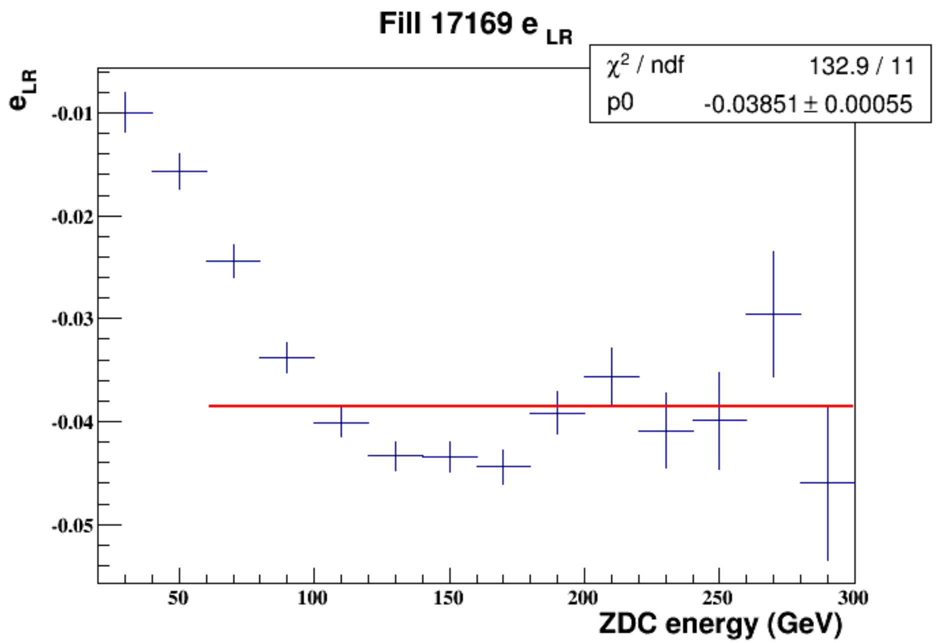
$$\frac{p_T}{p} = \frac{1}{p} \frac{e_N}{A_N^{Eff}} = \frac{p^{Tran}}{p} \frac{e_N}{e_N^{Tran}}$$

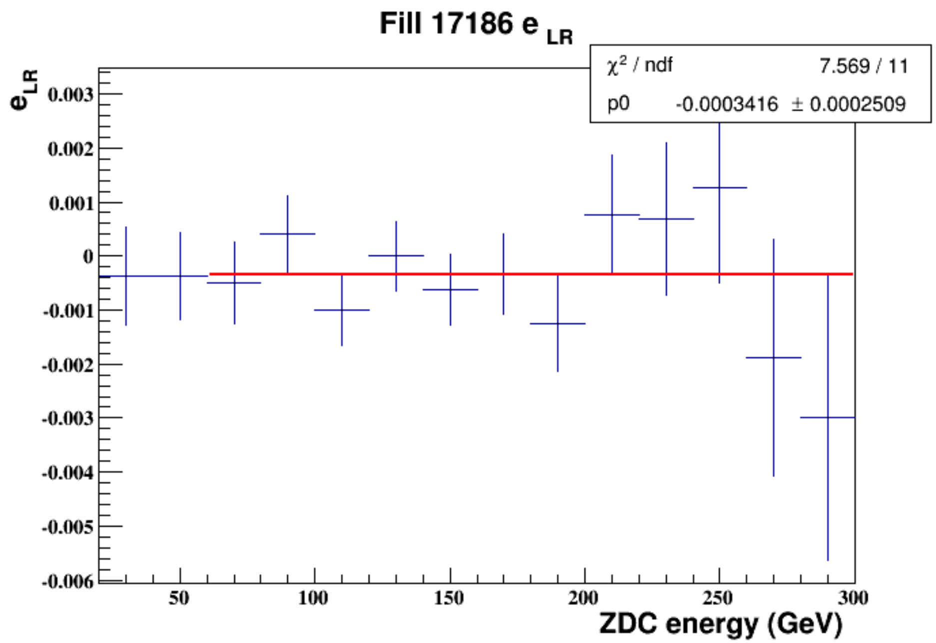
$$\frac{p_L}{p} = \sqrt{1 - \left(\frac{p_T}{p}\right)^2}$$

e_N : observed asymmetry
- Local Polarimeter

p : absolute polarization
- RHIC Polarimeter
~50% in average

Observed Asymmetry Result

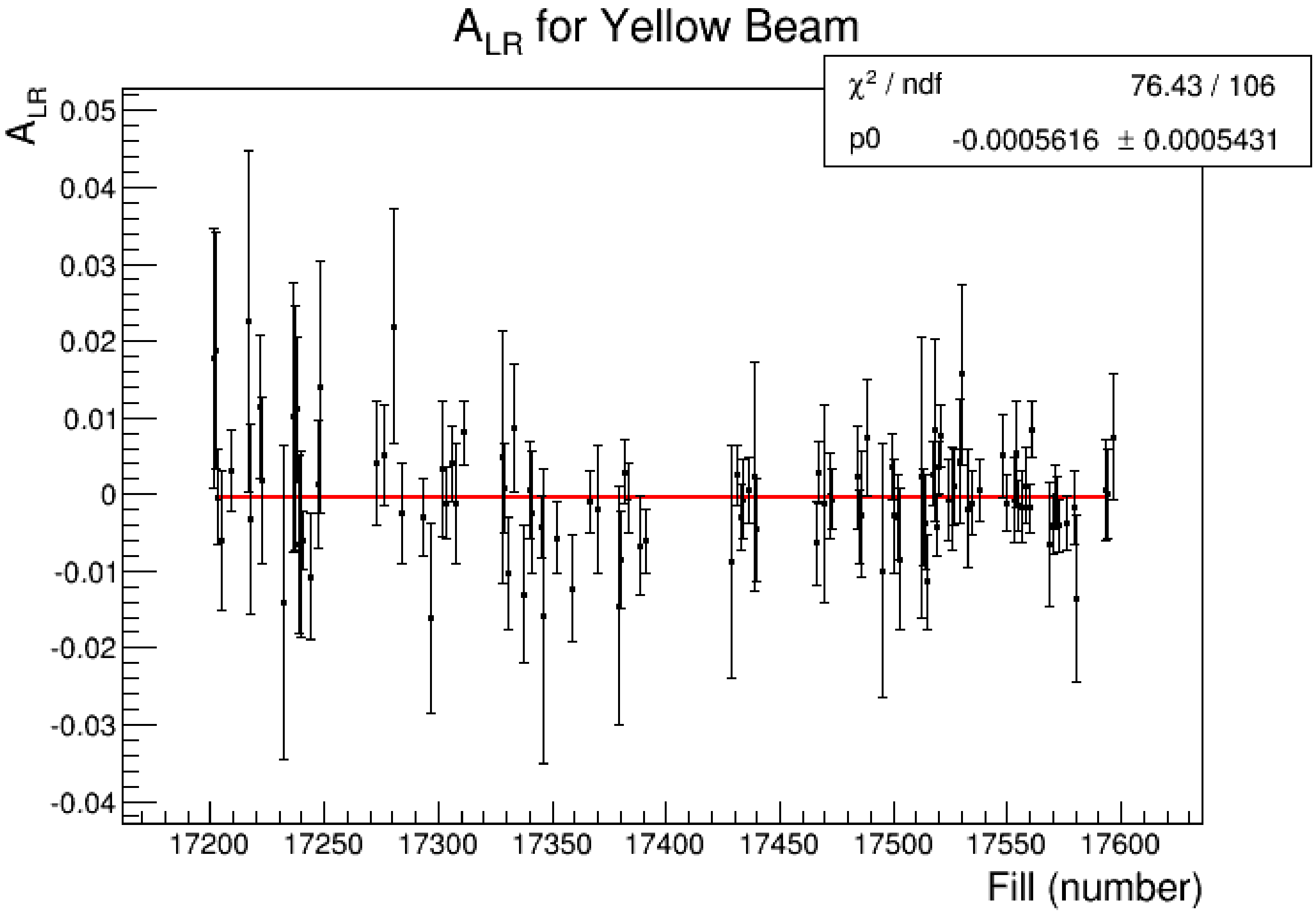




Transversely polarized beam:
$e_{LR} = -0.03851 \pm 0.00055$

Longitudinaly polarized beam:
$e_{LR} = -0.0003416 \pm 0.0002509$

$\frac{e_N}{p}$ of Longitudinal Fills Result



$\frac{p_T}{p}$ & $\frac{p_L}{p}$ of Run13

Yellow beam:

$$\frac{p_T}{p} = 0.007327^{+0.004423}_{-0.007327}(stat.)^{+0.005279}_{-0.000000}(syst.bc) + 0.001158(syst.e)$$

$$\frac{p_L}{p} = 0.999973^{+0.000027}_{-0.000038}(stat.)^{+0.000000}_{-0.000043}(syst.bc) - 0.000008(syst.e)$$

Blue beam:

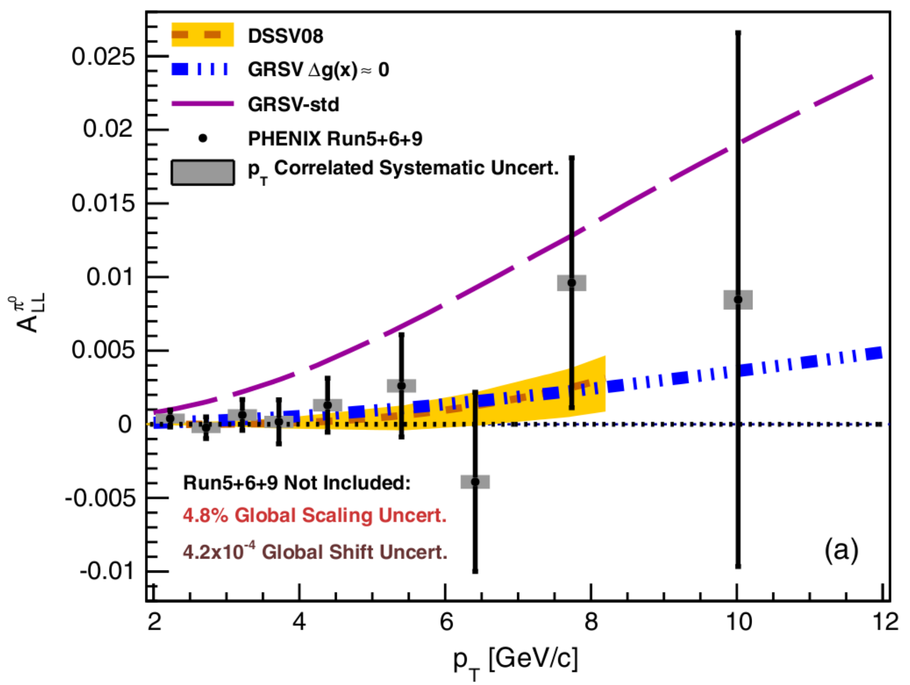
$$\frac{p_T}{p} = 0.048686^{+0.008164}_{-0.008736}(stat.)^{+0.000000}_{-0.006180}(syst.bc) \pm 0.003292(syst.e)$$

$$\frac{p_L}{p} = 0.998814^{+0.000386}_{-0.000436}(stat.)^{+0.000334}_{-0.000000}(syst.bc) \pm 0.000155(syst.e)$$

$$\frac{p_T^Y}{p^Y}\frac{p_T^B}{p^B} \sim 0.001\ , \quad \frac{p_L^Y}{p^Y}\frac{p_L^B}{p^B} \cong 0.999$$

Discussion & Conclusion

- A_{LL} measurement done up to $O(10^{-4})$
- $A_{TT} \sim 10^{-4}$ by theoretical prediction
- $A_{LL}^{measured}$
  $\cong \frac{1}{p^Y}\frac{1}{p^B}(p_L^Y p_L^B A_{LL} + p_T^Y p_T^B A_{TT})$
  $\cong 0.999 A_{LL} + O(10^{-7})$



-> ***p_T is small enough*** *not to contribute relatively large systematic uncertainty in A_{LL} measurement*

Summary

- Run13: longitudinally polarized p+p experiment
- A_{LL} measurement for gluon helicity distribution
- Local polarimetry is necessary for A_{LL} systematic uncertainty estimation
- Run13 Local polarimetry analysis: gives $O(10^{-7})$ accuracy on one of the systematic error of A_{LL}. Transverse component of beam polarization is small enough for A_{LL} measurement.

Backup

Origin of Proton Spin

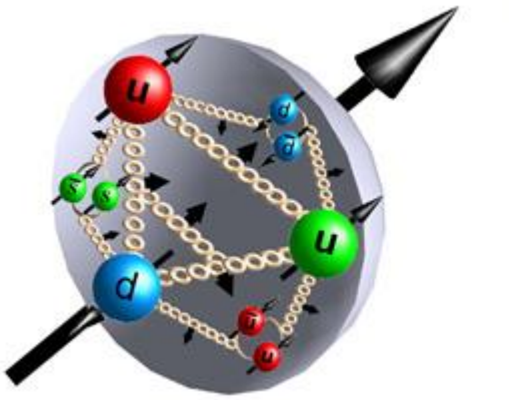
Naive spin model (static quark model):

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma$$

($\frac{1}{2}\Delta\Sigma$: quark polarization)

In DIS experiment:

$$\frac{1}{2}\Delta\Sigma \approx 30\%$$



Proton longitudinal spin sum rule in QCD:

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

$\boldsymbol{\Delta G = \int_0^1 dx\, \Delta g(x)\,,\ \Delta g(x) = g^{\uparrow}(x) - g^{\downarrow}(x)}$ **-> Not well measured**

$L_{q(g)}$: orbital angular momentum of quarks (gluons) -> Not measured yet

Spin Asymmetry Definitions

Longitudinal asymmetries

$$A_{LL} \equiv \frac{\sigma^{++} - \sigma^{+-}}{\sigma^{++} + \sigma^{+-}}$$

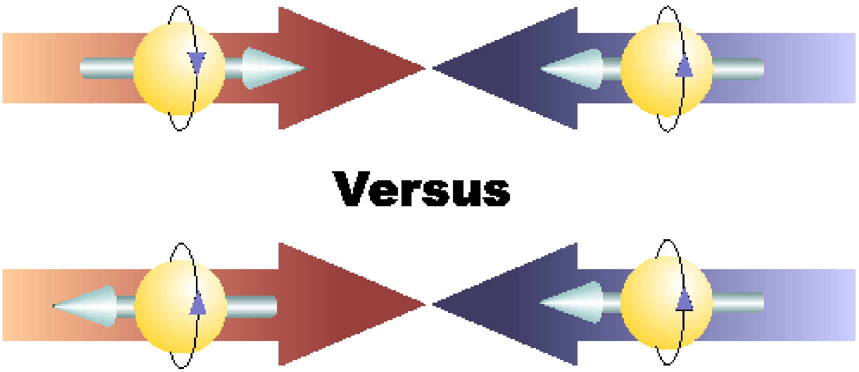
$$A_{L} \equiv \frac{\sigma^{+0} - \sigma^{-0}}{\sigma^{+0} + \sigma^{-0}}$$

Transverse asymmetries

$$A_{N} \equiv \frac{\sigma_L^{\uparrow 0} - \sigma_L^{\downarrow 0}}{\sigma_L^{\uparrow 0} + \sigma_L^{\downarrow 0}}$$

$$A_{TT} \equiv \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}}$$

For A_{LL}



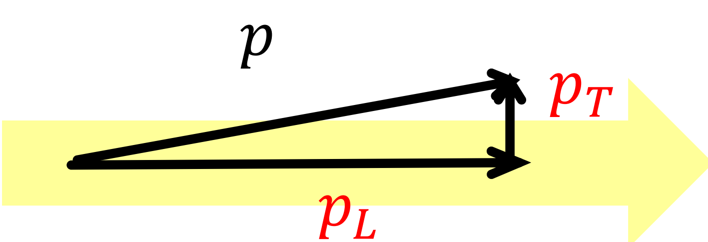
- ++ : same helicity
- +- : opposite helicity
- ↑ (↓) : spin up (down)
- 0 : unpolarized

Necessity of **Local Polarimetry** on A_{LL} measurement

Ideal longitudinal polarization

$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{1}{p^Y}\frac{1}{p^B}\frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}}$$

Real Longitudinal polarization



$$\frac{1}{p^Y}\frac{1}{p^B}\frac{N_{++} - RN_{+-}}{N_{++} + RN_{+-}} = A_{LL}^{measured} \cong \frac{1}{p^Y}\frac{1}{p^B}\left(p_L^Y p_L^B A_{LL} + p_T^Y p_T^B A_{TT}\right)$$

$p^{Y(B)}$: yellow(blue) beam polarization

$R = \frac{L^{\uparrow}}{L^{\downarrow}}$: relative luminosity

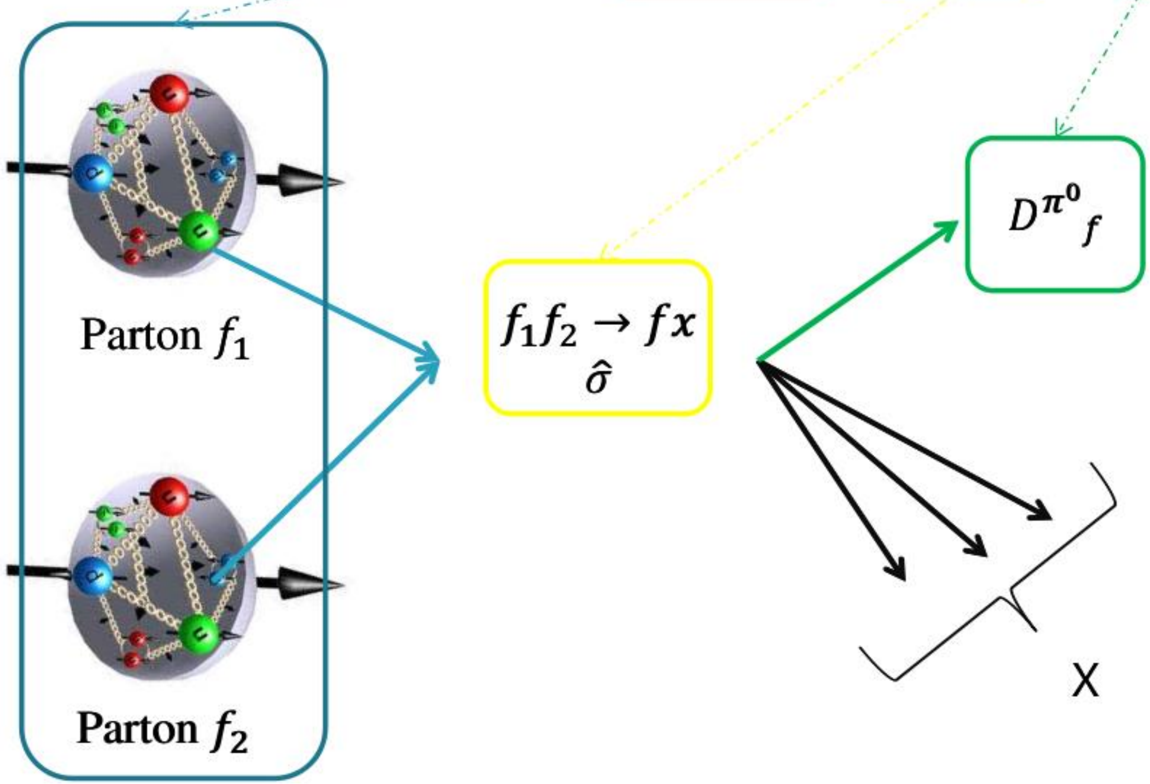
- Only $p^{Y,B}$ measured by RHIC polarimeters
- Very small A_{LL} in ΔG measurement
- π^0 production, $A_{TT} \cong 10^{-4}$ (theoretical prediction)

Local Polarimetry

$\frac{p_L}{p}, \frac{p_T}{p}$ measurement necessary!!

$A_{LL}^{\pi^0}$ measurement for ΔG

$$A_{LL}{}^{\pi^0} = \frac{\sigma^{\pi^0}{}_{++} - \sigma^{\pi^0}{}_{+-}}{\sigma^{\pi^0}{}_{++} + \sigma^{\pi^0}{}_{+-}} = \frac{\sum_{f_1,f_2,f} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D^{\pi^0}{}_f}{\sum_{f_1,f_2,f} f_1 \otimes f_2 \otimes \hat{\sigma}^{f_1 f_2 \to fX} \otimes D^{\pi^0}{}_f}$$



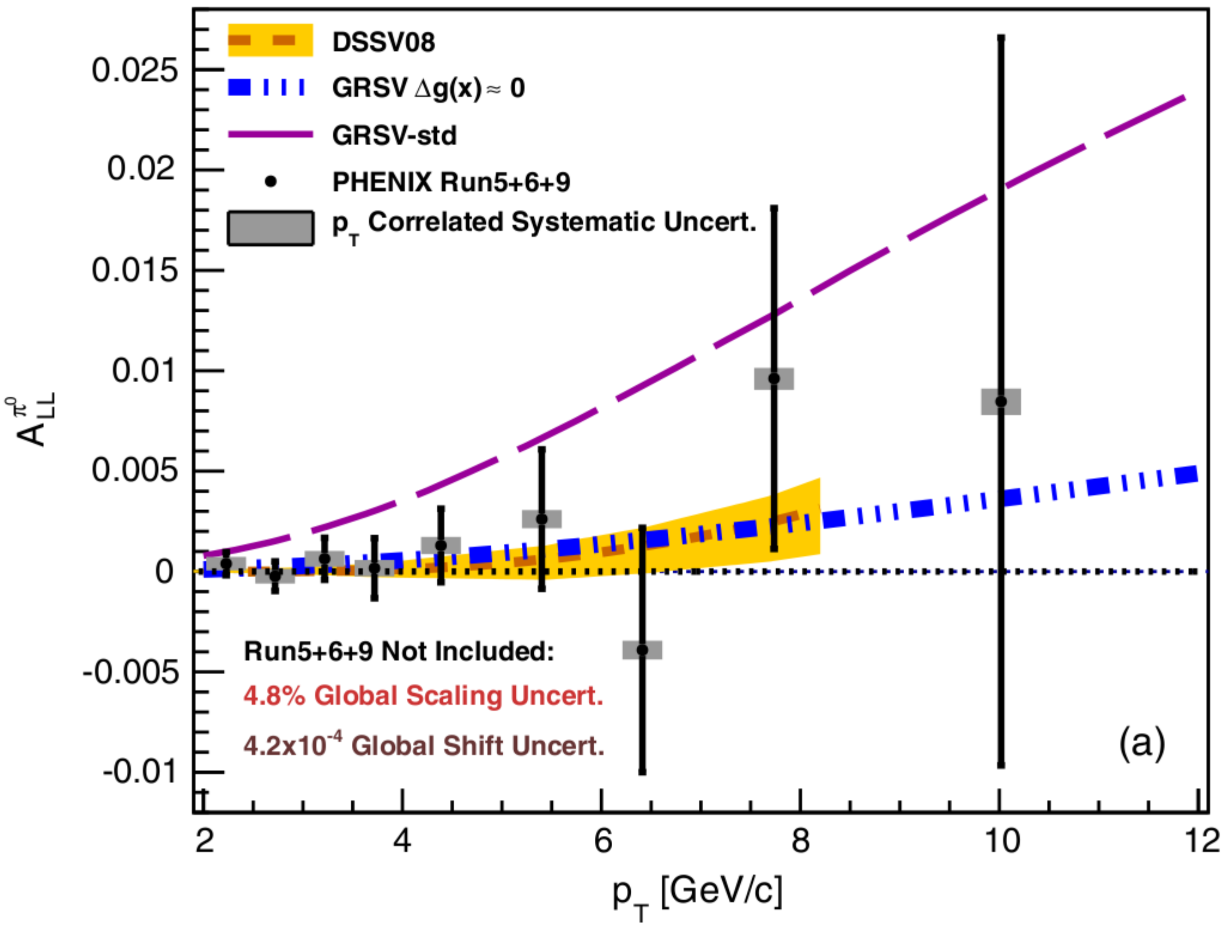
$f_{1,2}$, Δf_q: DIS data

$\Delta f_{\bar{q},g}$: theoretical predictions

$\sigma^{\{f_1 f_2 \to fX\}}$, $d\sigma^{\{f_1 f_2 \to fX\}}$: pQCD

$D_f^{\pi^0}$: $e^+ + e^-$ collision data

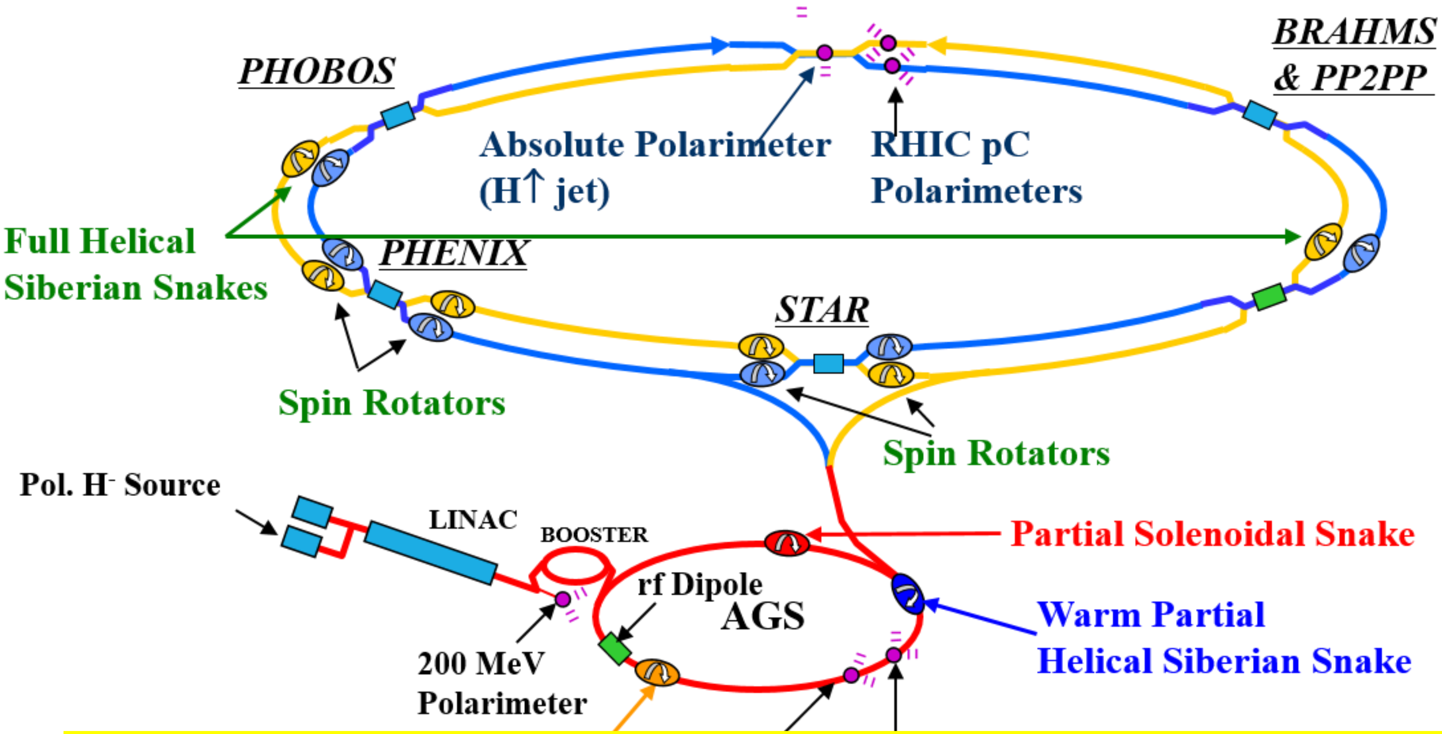
$A_{LL}^{\pi^0}$ measurement at PHENIX



$$\Delta G^{[0.05,0.2]}_{PHENIX} = 0.07^{+0.05}_{-0.08}$$

ΔG is not well measured because of **smallness of A_{LL}**

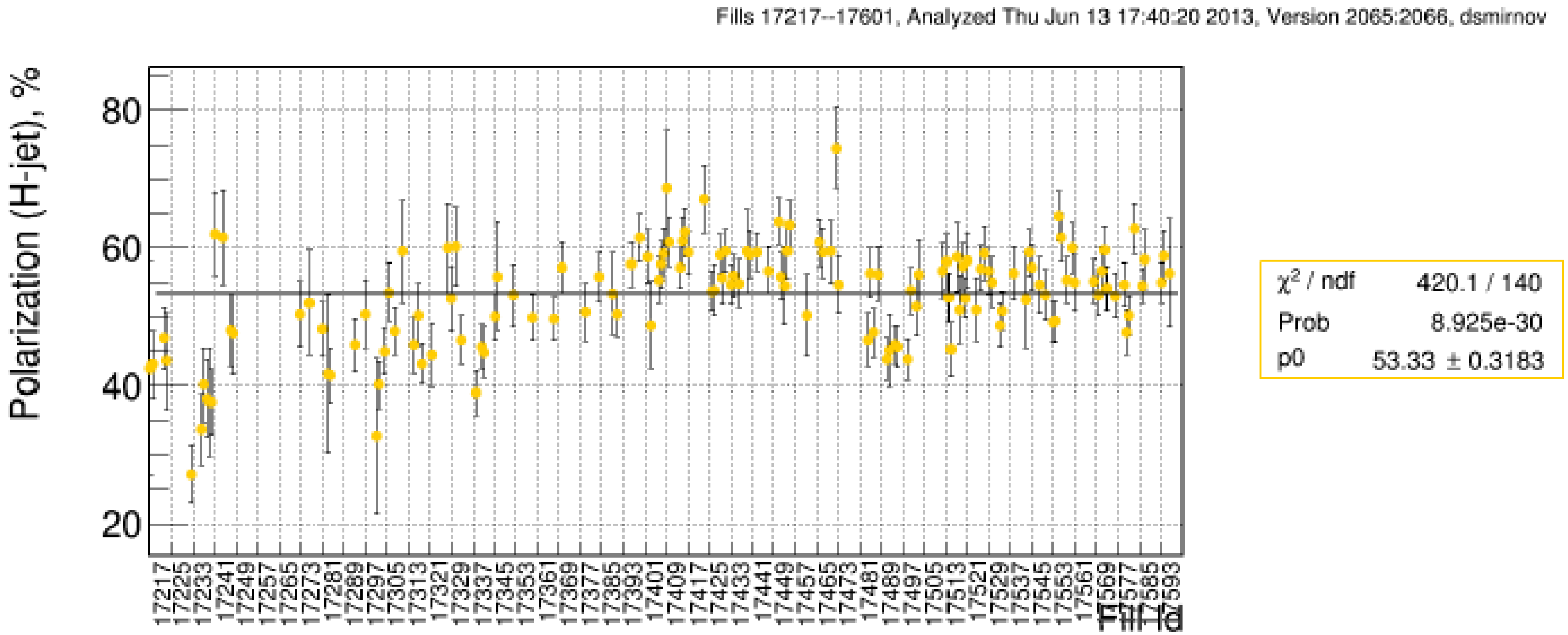
RHIC complex

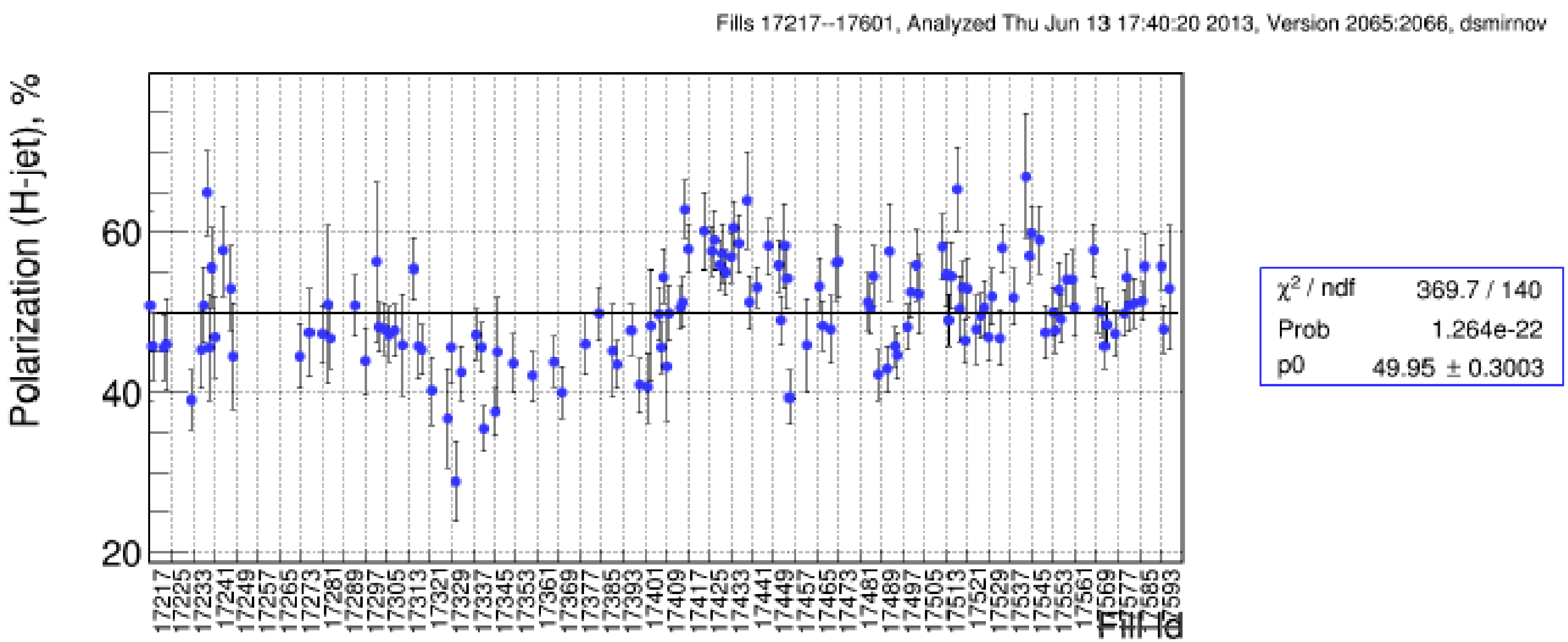


Stable beam polarization direction: vertical

->longitudinal polarization

only at the experimental halls


Fills 17217--17601, Analyzed Thu Jun 13 17:40:20 2013, Version 2065:2066, dsmirnov
Polarization (H-jet), %
80
60
40
20
17217 17225 17233 17241 17249 17257 17265 17273 17281 17289 17297 17305 17313 17321 17329 17337 17345 17353 17361 17369 17377 17385 17393 17401 17409 17417 17425 17433 17441 17449 17457 17465 17473 17481 17489 17497 17505 17513 17521 17529 17537 17545 17553 17561 17569 17577 17585 17593
Fill Id
χ² / ndf 420.1 / 140
Prob 8.925e-30
p0 53.33 ± 0.3183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Fill Id
χ² / ndf 369.7 / 140
Prob 1.264e-22
p0 49.95 ± 0.3003

Zero Degree Calorimeter & Shower Max Detector

10 cm x 10 cm transverse coverage

ZDC:

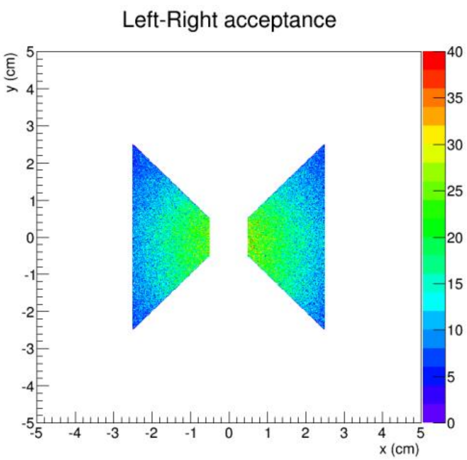
- Collect cherenkov light produced by charged secondary particles from neutron showers

SMD:

- X-Y plastic scintillator strip hodoscope
- Between the 1st & 2nd ZDC modules - approx. shower max location
- Position calculation

$$x, y = \frac{\sum_i^{SMD\ strips\ with\ hit} energy\ (i) \times strip\ position(i)}{\sum_i^{SMD\ strips\ with\ hit} energy\ (i)}$$

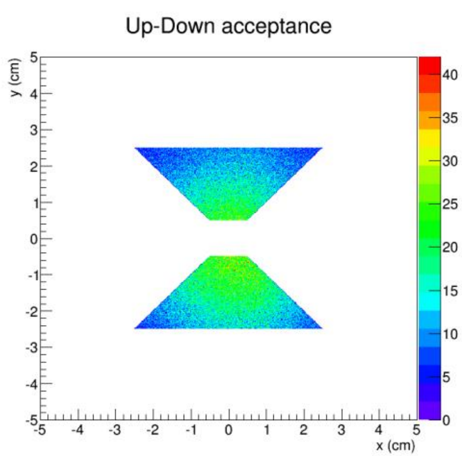
Asymmetry Definitions



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

By rotational symmetry-> $\sigma_L^{\uparrow(\downarrow)} = \sigma_R^{\downarrow(\uparrow)}$. L, R: left, right

$$e_{LR} = \frac{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} - \sqrt{N_R^{\uparrow} N_L^{\downarrow}}}{\sqrt{N_L^{\uparrow} N_R^{\downarrow}} + \sqrt{N_R^{\uparrow} N_L^{\downarrow}}} \quad , \quad e_{UD} = \frac{\sqrt{N_U^{\uparrow} N_D^{\downarrow}} - \sqrt{N_D^{\uparrow} N_U^{\downarrow}}}{\sqrt{N_U^{\uparrow} N_D^{\downarrow}} + \sqrt{N_D^{\uparrow} N_U^{\downarrow}}},$$



($N_{area}^{\uparrow(\downarrow)}$: neutron yield)

$$A_{LR} = \frac{e_{LR}}{p} \, , \, A_{UD} = \frac{e_{UD}}{p}$$

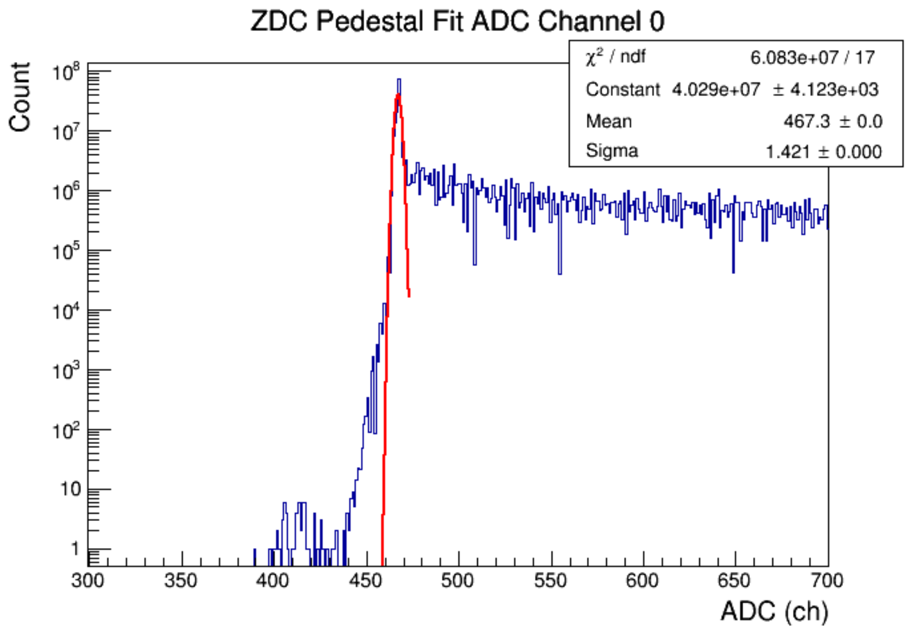
$A_N^{Eff} = -\sqrt{A_{LR}^2 + A_{UD}^2}$ of transverse fill

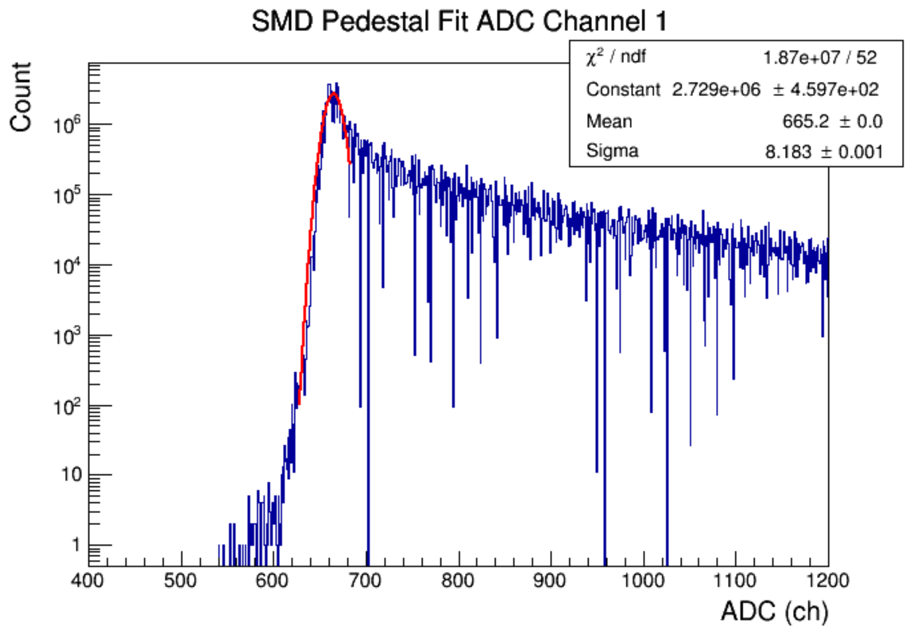
Analysis Basics

- Data samples
  - local pol trigger
- Run QA
  - bad ADC distribution, spin pattern problem run rejected
- Calibration
  - ZDC/SMD pedestal : offline fitting
  - ZDC gain : 100 GeV neutron peak in peripheral heavy ion collision, HV adjustment by LED signal for p+p run
  - SMD gain: Fit ADC distribution with two exponential function
- Event selection
  - SMD shower cut : #hit SMD ≥ 2 each coord., reject photon event
  - Acceptance cut edge : $-4.5\ cm \leq x, y \leq 4.5\ cm$, avoid shower leakage
  - Acceptance cut center : $-0.5\ cm \leq x - x_{center}, y - y_{center} \leq 0.5\ cm$, avoid falsely measured Left-Right
  - Energy cut : take 60-300 GeV, 60 GeV- gate signal threshold (beam scraping background rejected); 300 GeV – 255 GeV + 20% ZDC energy resolution

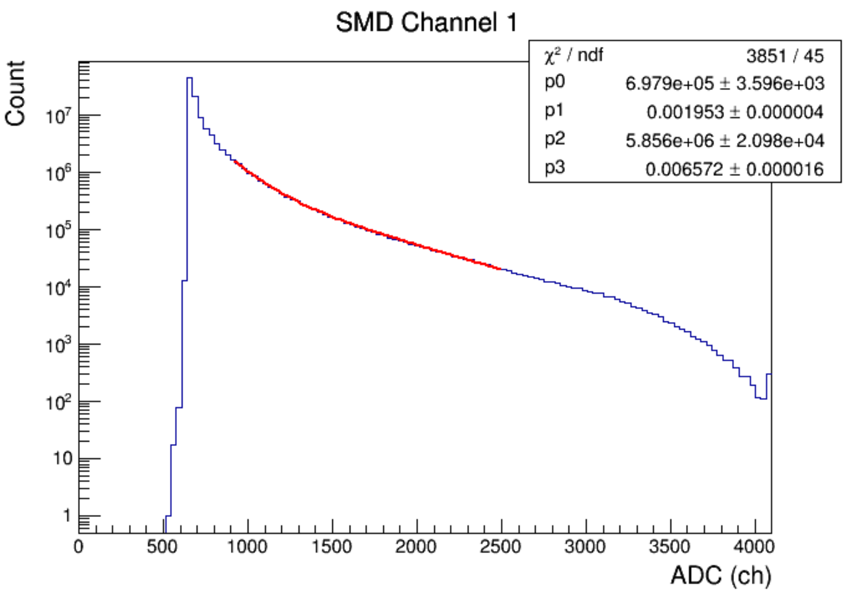
Calibration - Pedestal

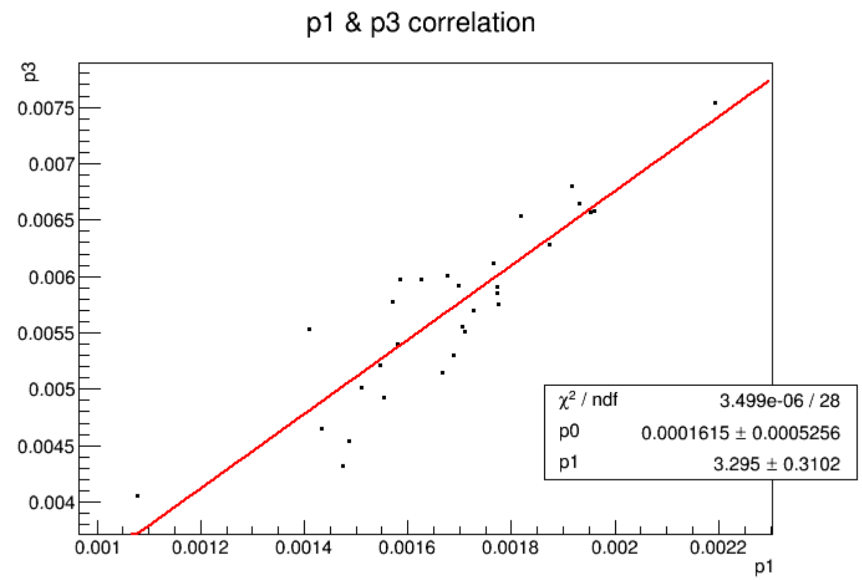
Gaussian fit





Calibration – SMD Gain





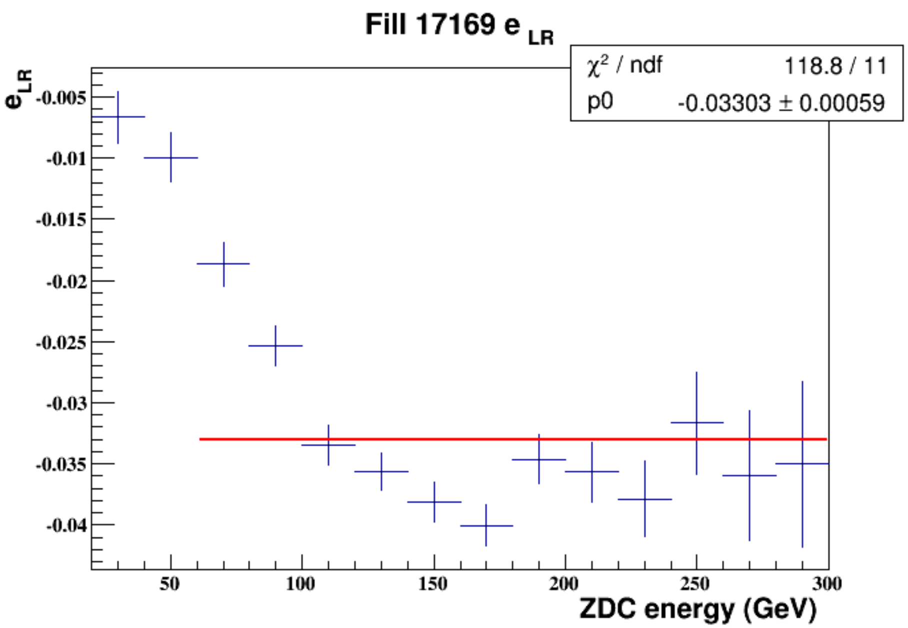
Fit function: $p0\exp(p1 * (x - pedestal)) + p2\exp(p3 * (x - pedestal))$

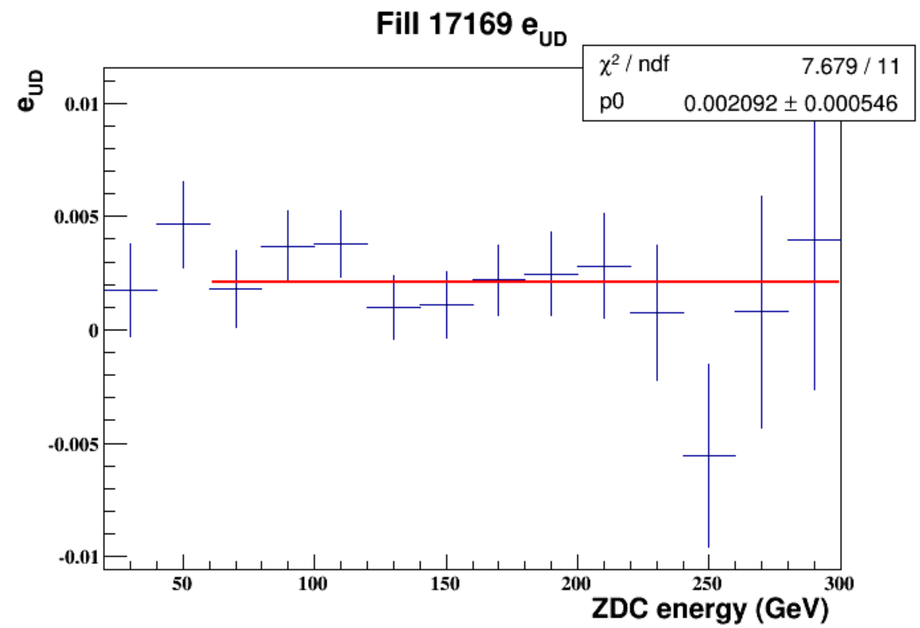
Gain: $p1$

$p1$ & $p3$ correlate

$p3$ for systematic error study from gain calibration -> no significant effect

Yellow beam raw asym

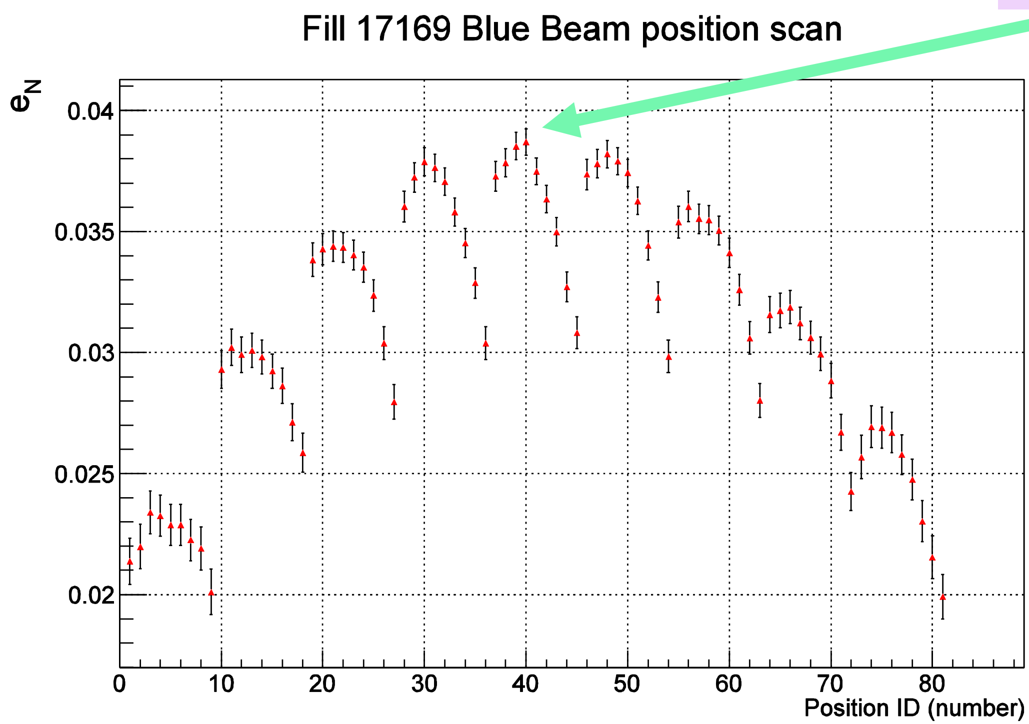


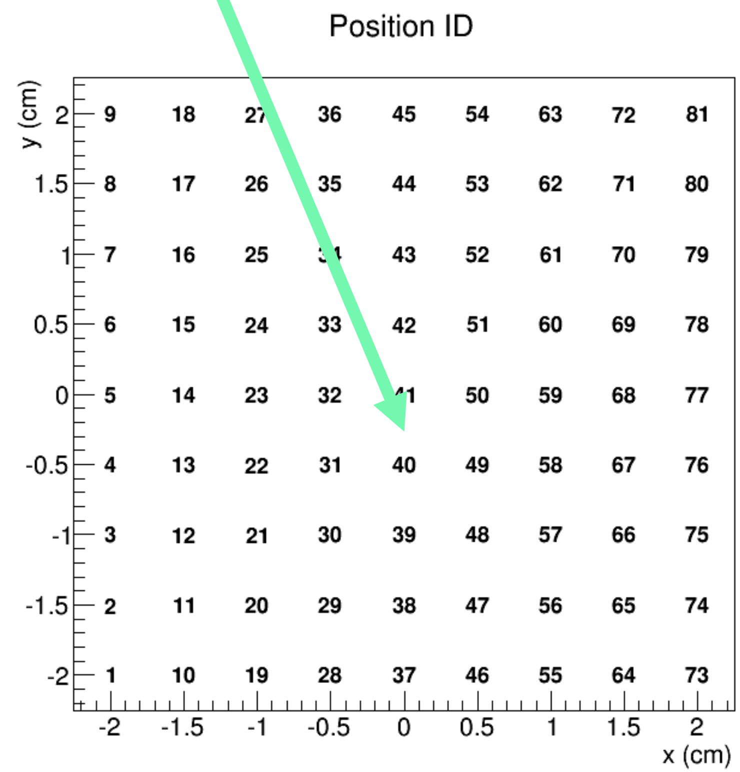


Beam center

Center: Largest e_N

Center: (0.0 cm, -0.5 cm)





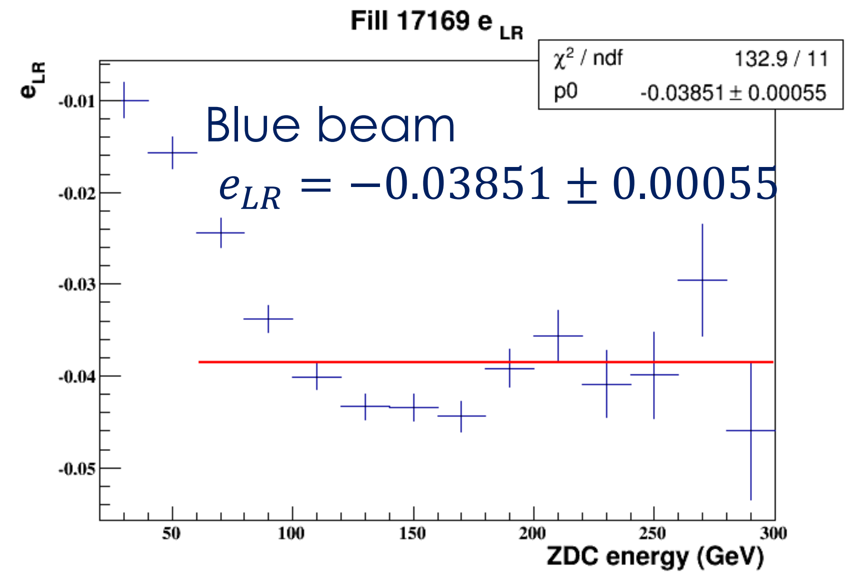
A_N^{Eff} from a Transverse Fill

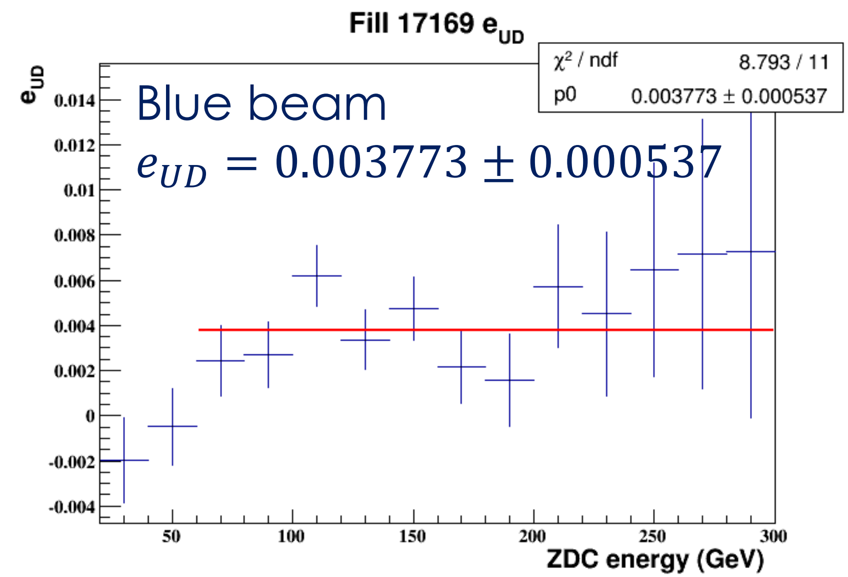
Calculated e_{LR} & e_{UD} of each energy bin (20 GeV interval), then took average of 60-300 GeV

$$A_{LR(UD)} = \frac{e_{LR(UD)}}{p}$$

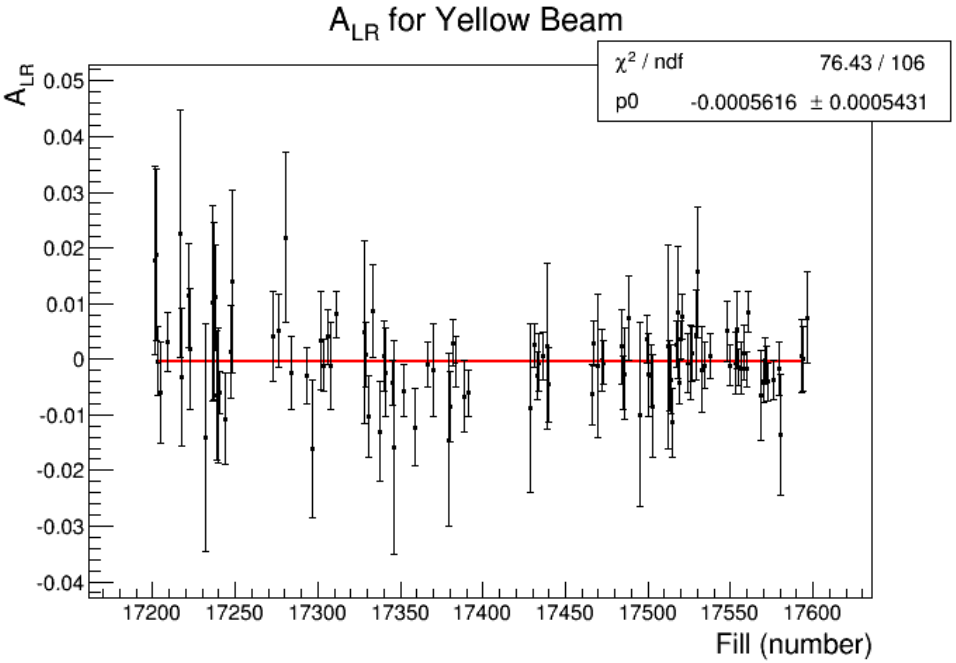
$$p^Y = 0.3688 \pm 0.0608$$
$$p^B = 0.5022 \pm 0.0544$$

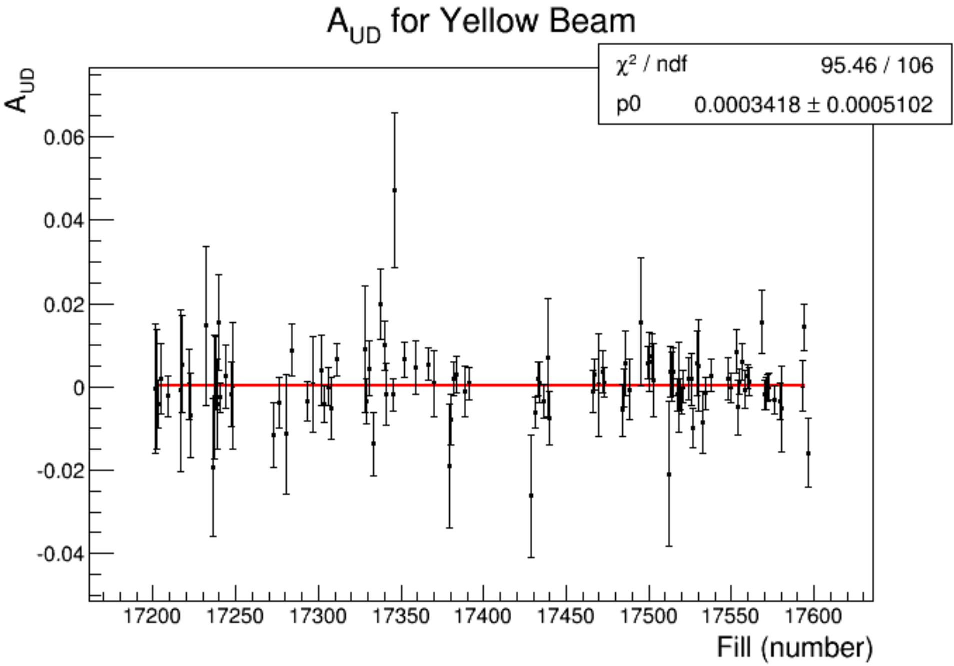
$$A_N^{Eff} = -\sqrt{A_{LR}^2 + A_{UD}^2}$$
$$= -0.07706 \pm 0.008340 \text{ Blue beam}$$
$$-0.08973 \pm 0.01482 \text{ Yellow beam}$$





$A_{LR,UD}$ of Longitudinal Fills - Yellow

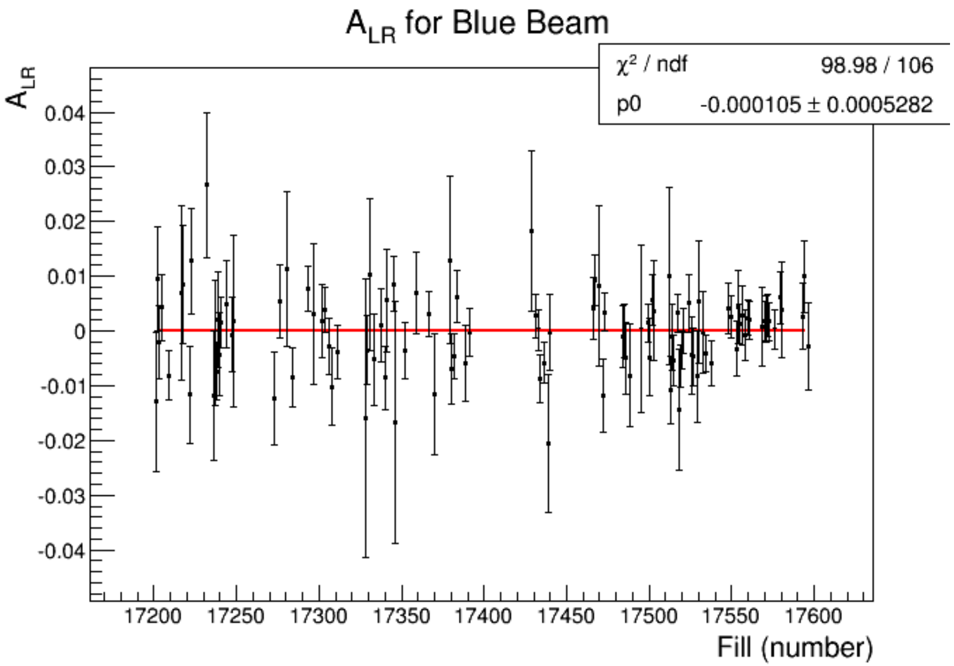


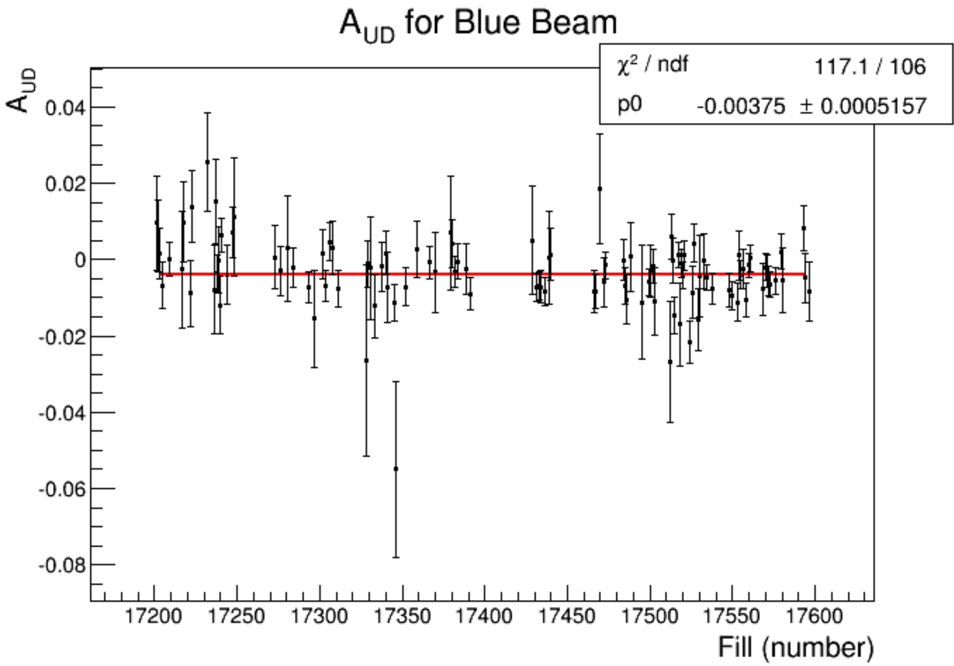


Yellow beam:

$$A_{LR} = -0.0005616 \pm 0.0005431$$
$$A_{UD} = -0.0003418 \pm 0.0005102$$

$A_{LR,UD}$ of Longitudinal Fills - Blue





Blue beam:

$$A_{LR} = -0.000105 \pm 0.0005282$$
$$A_{UD} = -0.000375 \pm 0.0005157$$

Statistical Uncertainty (1)

A_{LR}, A_{UD} close to 0, order of statistical uncertainty

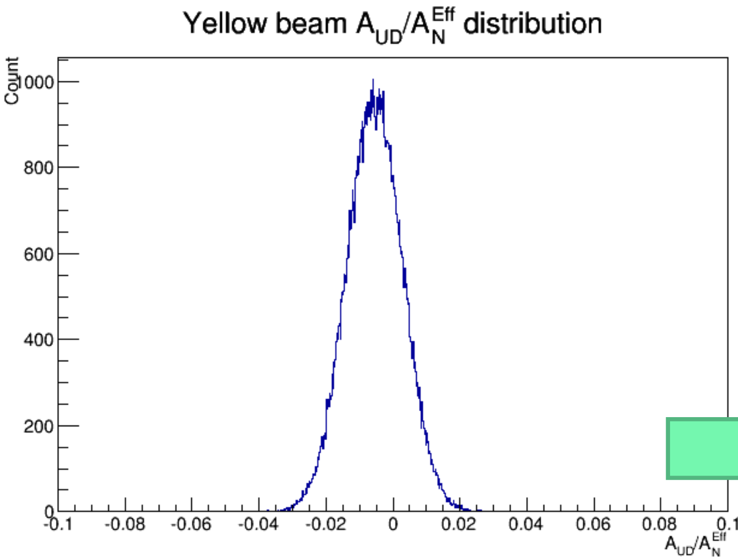
$\frac{p_T}{p}, \frac{p_L}{p}$ has limitation : [0,1]

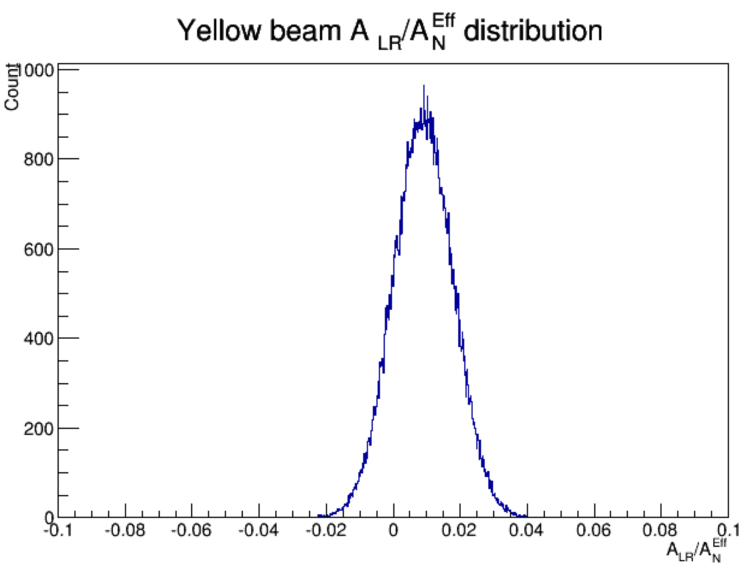
-> Error propagation not work

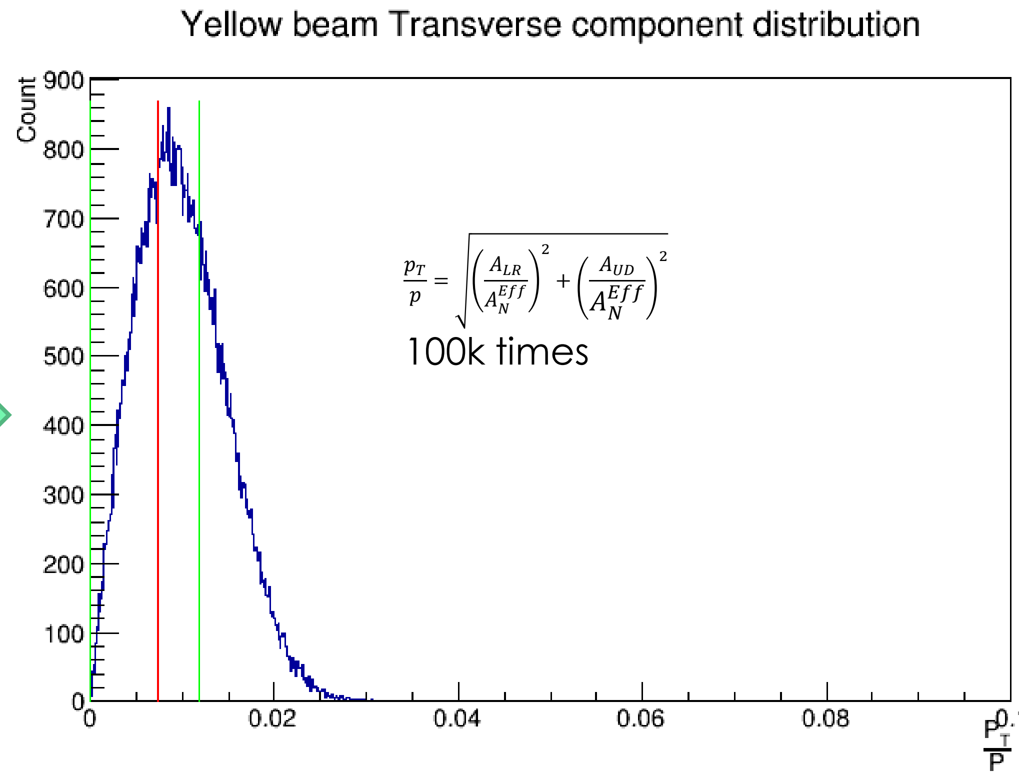
Solution:

1. make random Gaussian distribution of $\frac{A_{LR}}{A_N^{Eff}}, \frac{A_{UD}}{A_N^{Eff}}$
2. Sample 100k event to make $\frac{p_T}{p}, \frac{p_L}{p}$ distribution

Statistical Uncertainty (2)





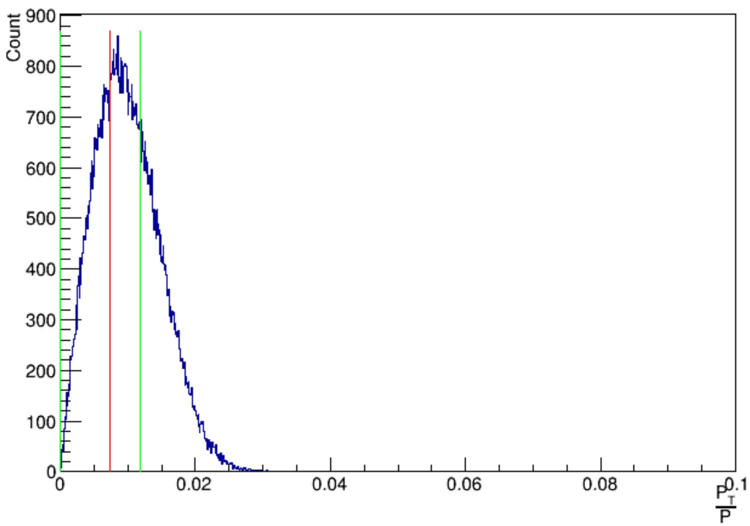


Result w/ stat. : (Yellow beam, Blue beam)

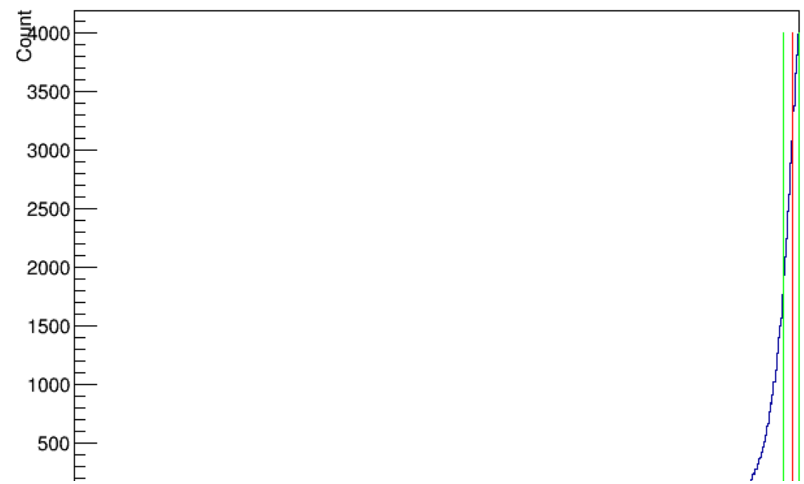
$$\frac{p_T}{p} = 0.007327^{+0.004423}_{-0.007327}, \quad \frac{p_L}{p} = 0.999973^{+0.000027}_{-0.000038}$$

$$\frac{p_T}{p} = 0.048686^{+0.008164}_{-0.008736}, \quad \frac{p_L}{p} = 0.998814^{+0.000386}_{-0.000436}$$

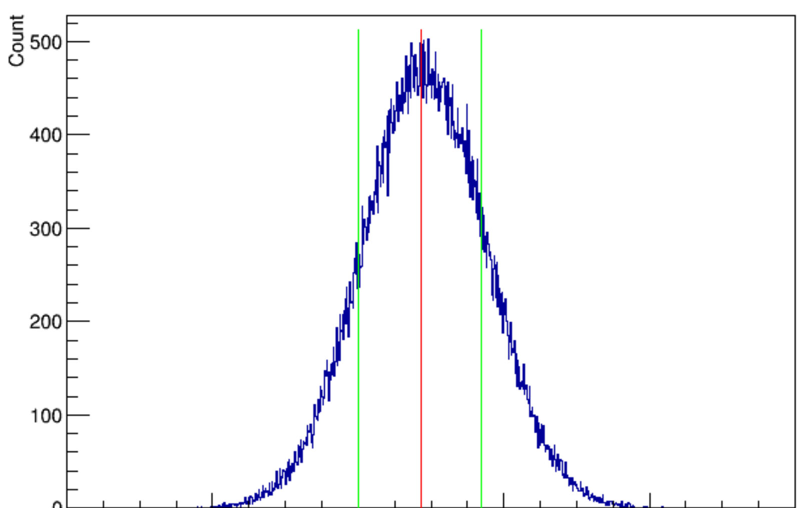
Yellow beam Transverse component distribution



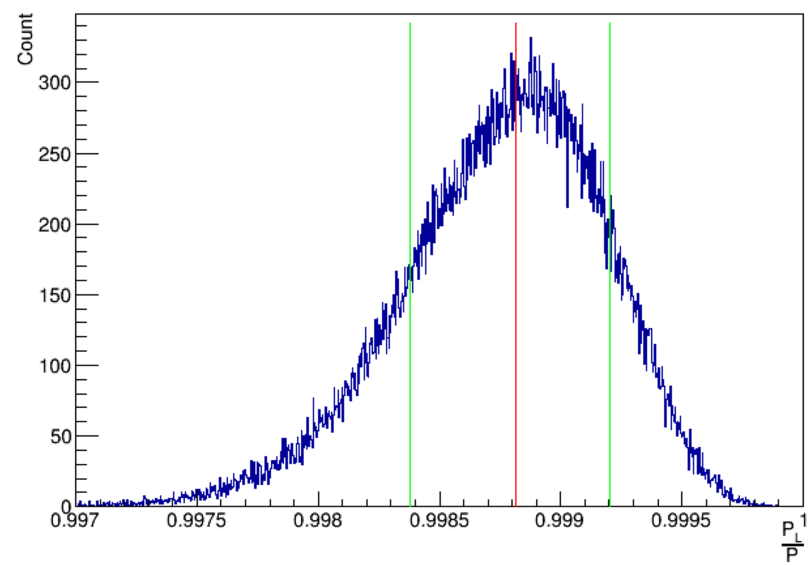
Yellow beam Longitudinal component distribution



Blue beam Transverse component distribution



Blue beam Longitudinal component distribution



Systematic Uncertainty

1. SMD gain calibration

   - Compare results using p1 and p3 -> Not significant

2. Beam center uncertainty

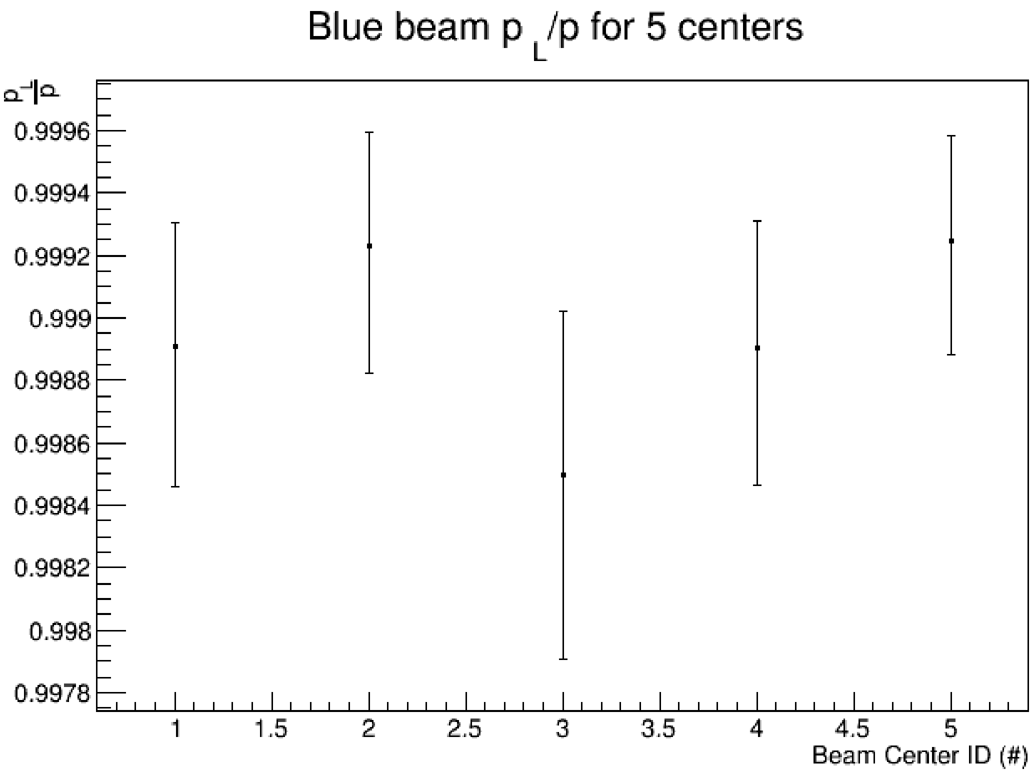
   - Estimated beam shift during the run: 2~3 mm

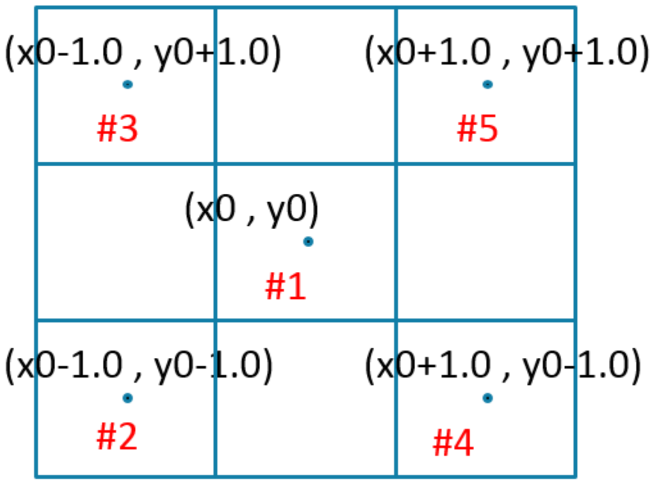
   - Conservatively assigned by results at $\pm$1 cm from the determined center

3. Energy fitting range uncertainty

   - Conservatively assigned by result using 100-300 GeV fitting range

Beam center uncertainty





#1 : center
(values in cm)

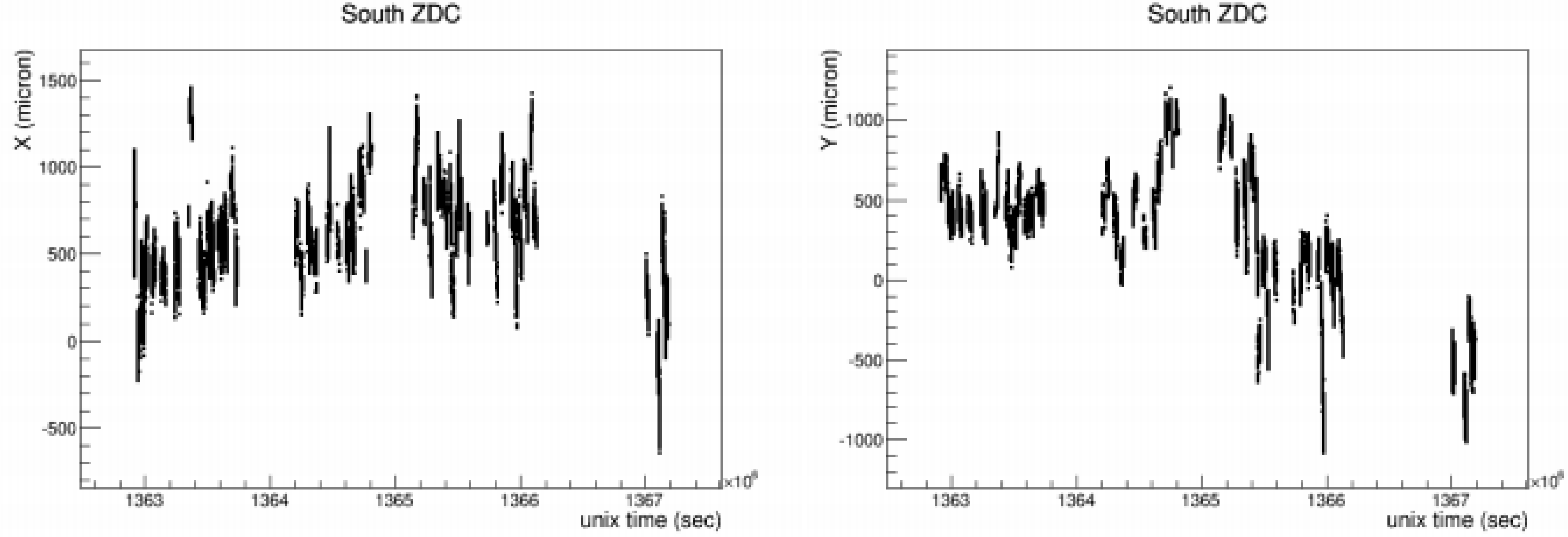


Figure 25: Beam center at the south ZDC represented in BPM's coordinate system.

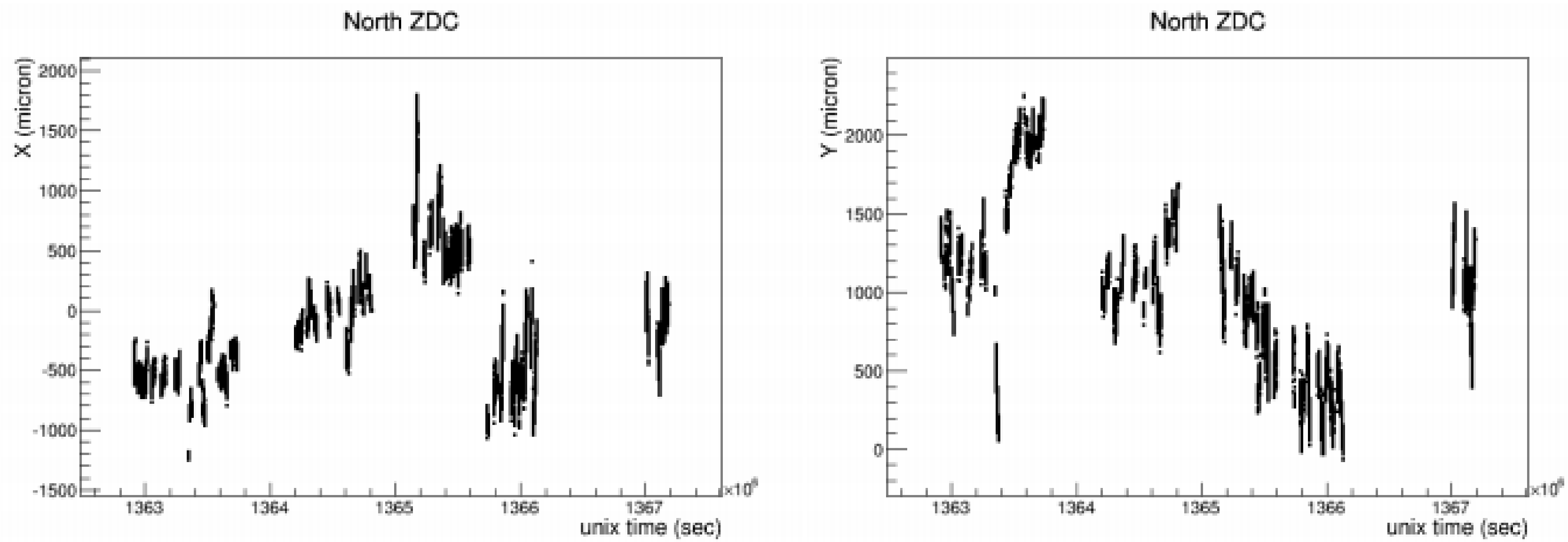


Figure 26: Beam center at the north ZDC represented in BPM's coordinate system.