Measurement of Transverse Single Spin Asymmetry (A_N) of Neutral pions ($\pi°$) using $\sqrt{s}$ = 200 GeV Transversely polarised *pp* collisions at STAR

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Outline

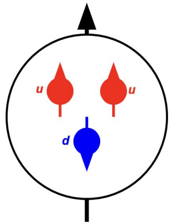
Motivation

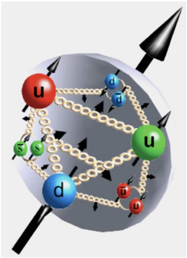
The Proton Structure:
What is the proton made of and how these components interact

1960s : Quark model + Parton Model
Parton Distribution Function

1970s : Quantum Chromodynamics
Gluons, Sea Quarks and their interactions

1980s and after : Spin Polarised Structure

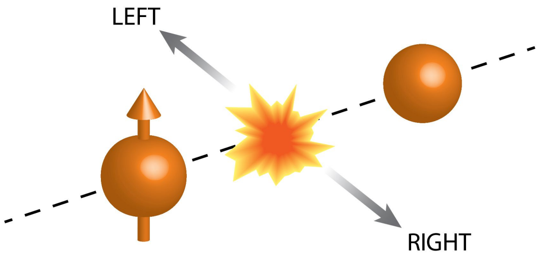




The "Proton Spin Crisis" - Quarks contribute to only ~ 30 % of the proton spin!

Motivation - Transverse Single Spin Asymmetry (A_N)

Experimental Measurement : Transverse Single Spin Asymmetry - TSSA (A_N)

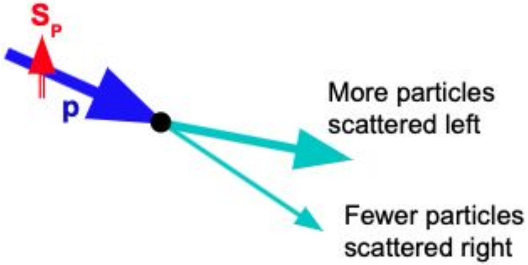


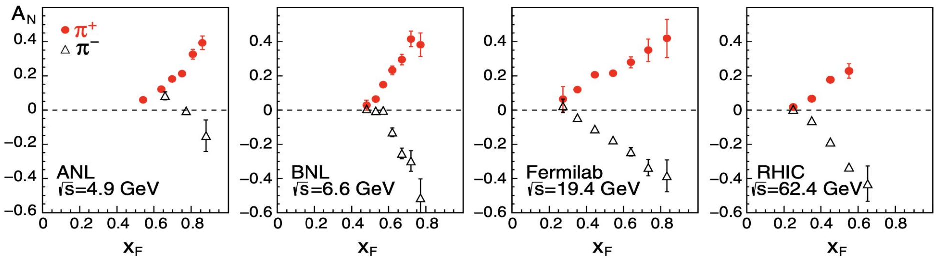
Collisions of transversely polarised proton beam with unpolarised proton beam

"Left-Right" Asymmetry of Scattered Particles

$$A_N = \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

Perturbative QCD predicts AN ~ 0.0001



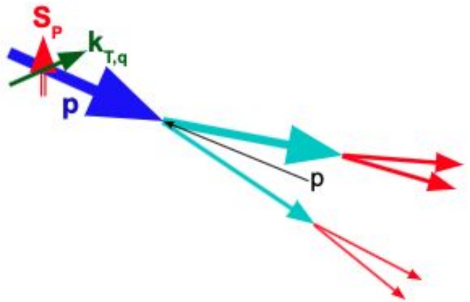


Rev. Mod. Phys. 85, 655 (2013)

However, experimental measurements show that there are large asymmetries!
Such large asymmetry cannot be generated by traditional Collinear Model

Motivation : Sivers Effect and Collins Effect

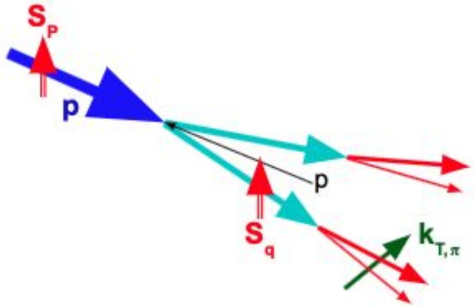
Sivers Function : Describes the Transverse Momentum Distribution of unpolarised partons inside a transversely polarised hadron (proton)



Sivers Effect : ***Initial State Effect***

Correlation between initial parton and proton spin. Leads to a distortion in u/d quark k_T distribution => left-right asymmetry

Collins Fragmentation Function : Describes the azimuthal hadron distribution correlated with the outgoing quark transverse polarisation vector



Collins Effect : ***Final State Effect***

Observed for charged pions and hadron jets

Twist - 3 Effect : Incorporates higher-order correlations, specifically quark-gluon-quark correlations. Multi-parton correlators encode spin–momentum correlations

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TSSA is the combined result of BOTH Sivers and Collins effects, as well as Twist-3 effects.
Experimental data is very important in validating the factorizations and constraining the distribution functions

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Observed for charged pions and hadron jets

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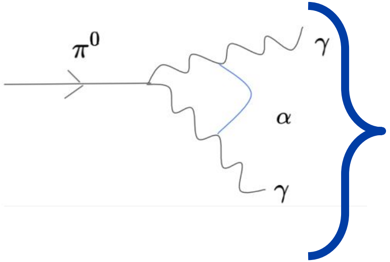
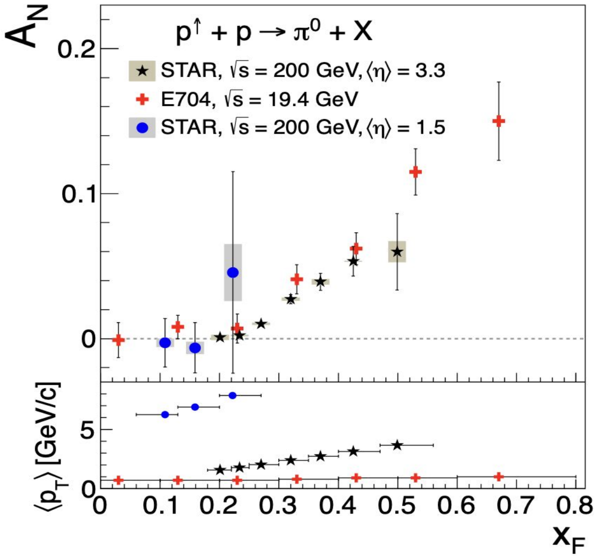
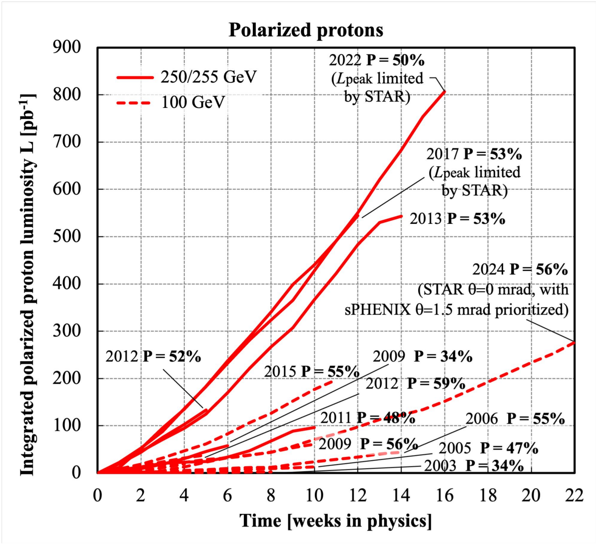
Motivation : Previous Measurements of TSSA (A_N)

Neutral Pion A_N measurements have been done at mid- and forward rapidities at RHIC.
Run 2015 with the Electromagnetic Endcap Calorimeter (EEMC) provides higher luminosity data at an intermediate rapidity range for better understanding of the asymmetry distribution



Final particles detected: di-photons from pion decay channel





Previous measurements at the EEMC using Run 2006 data
Ref : STAR, PRD 89, 012001

This analysis uses Run 2015 data at the EEMC, which provides 17 times higher luminosity than Run 2006

Experimental Setup - RHIC & STAR

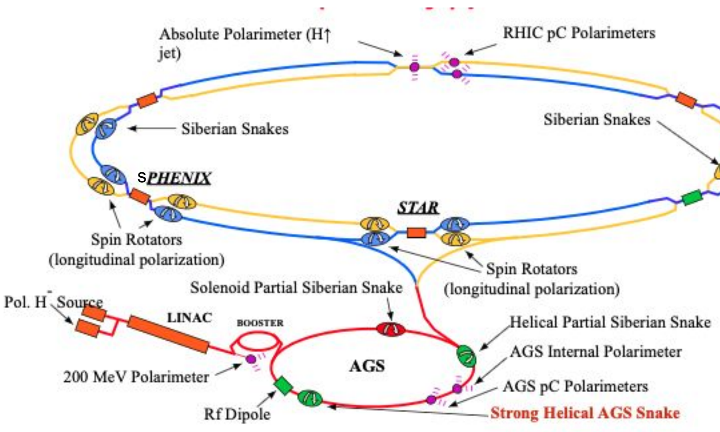
Relativistic Heavy Ion Collider (RHIC)

RHIC is world's only polarised proton-proton collider

Polarisation of protons maintained by Siberian Snakes

Spin pattern changes from fill to fill

Spin rotators provide choice of spin orientation



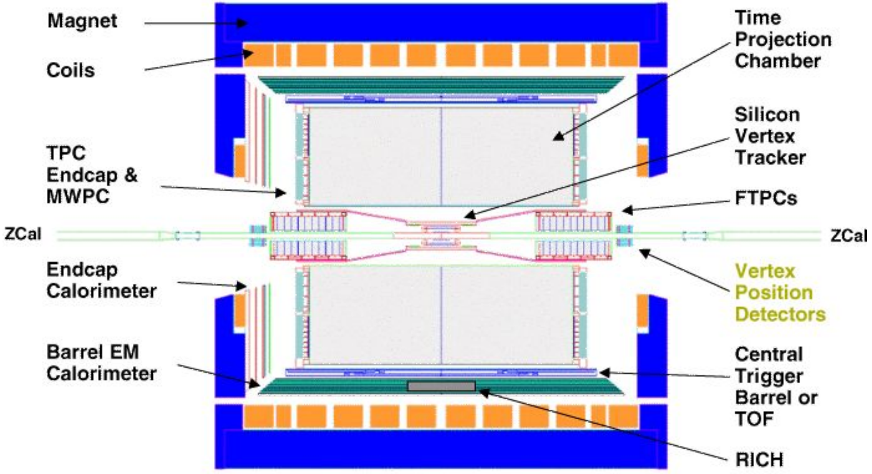
The Solenoidal Tracker At RHIC (STAR)

Located at 6 o' clock position of the RHIC Ring

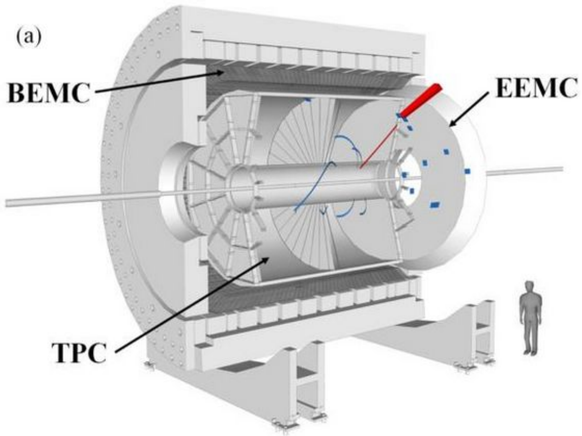
High precision tracking with the TPC

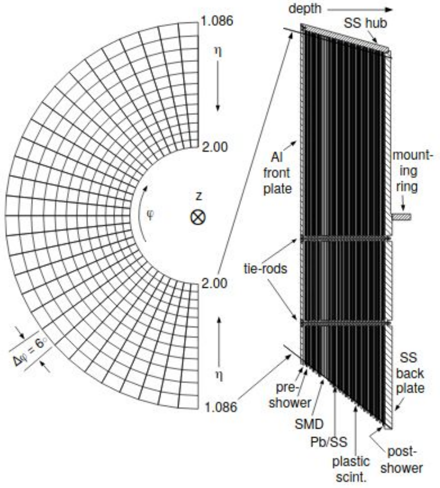
Electromagnetic calorimetry with the BEMC, EEMC, and FMS

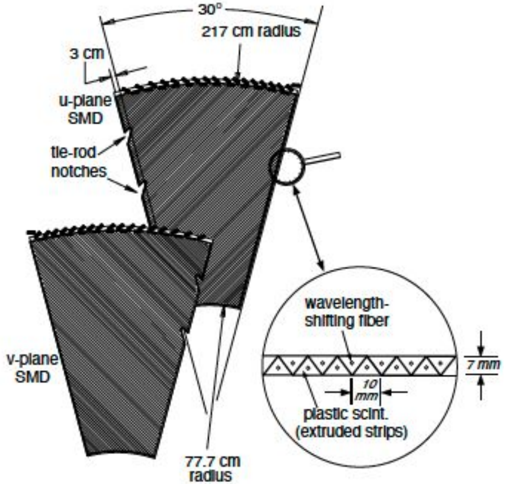
VPD, ZDC, and BBC detectors for relative luminosity, local polarimetry, and minimum bias triggering



Electromagnetic Endcap Calorimeter (EEMC)





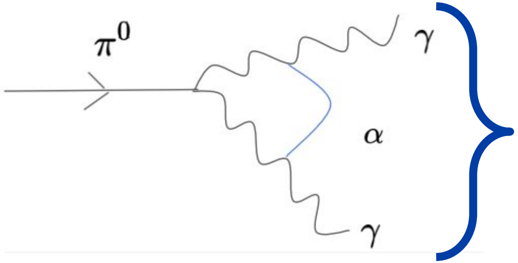


- Located at the west end of STAR detector. Pseudorapidity $1.086<\eta<2.0$, azimuth $0<\varphi<2\pi$
- The full annulus ring is divided into 12 sectors of 30° in φ and 12 η bins.
- 5 towers in each sector of 6° φ coverage each => 720 towers in total.

- EEMC Towers record **hits**
- Shower Maximum Detector (SMD) ~ 5 X deep - help in reconstruction of **clusters**
- Clusters and Hits at the EEMC towers and SMD layers passing kinematic cuts are considered as photon candidates

Analysis : Pion Reconstruction from Photons

Photon candidates from clusters and hits are used to reconstruct the neutral pions



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

Final particles detected - di-photons from pion decay channel

The invariant mass of the pion is related as:

$$m_{\pi^0}^2 = 4E_{\gamma_1}E_{\gamma_2}\sin^2(\alpha/2)$$

Where α is the opening angle between the two photons.
Only consider pions for which $Z_{\gamma\gamma} < 0.8$ where,

$$Z_{\gamma\gamma} = \frac{E_{\gamma_1} - E_{\gamma_2}}{E_{\gamma_1} + E_{\gamma_2}}$$

- **Dataset :**

STAR Run15, Energy 200 GeV

Integrated Luminosity = 48 pb^{-1}

- **Event Selection Cuts :**

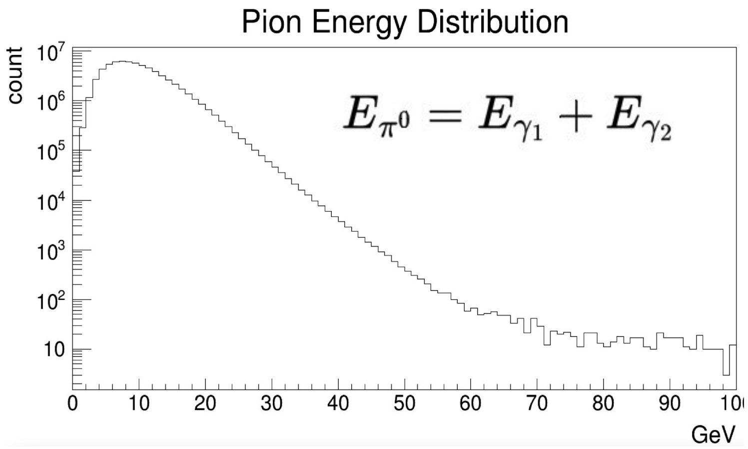
E_T > 6.0 GeV for π^0 (Transverse energy to cross the trigger threshold)

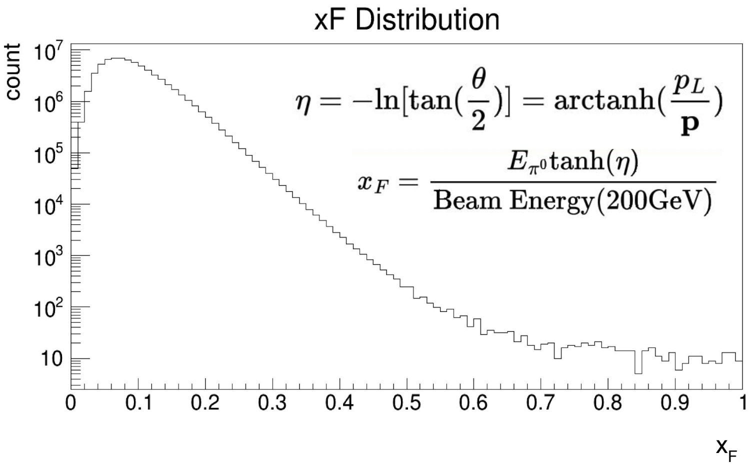
$Z_{\gamma\gamma}$ < 0.8 (Energy asymmetry between two photons)
Inv Mass < 1.0 GeV/c^2

- **Trigger : High Tower Level 0 Trigger**

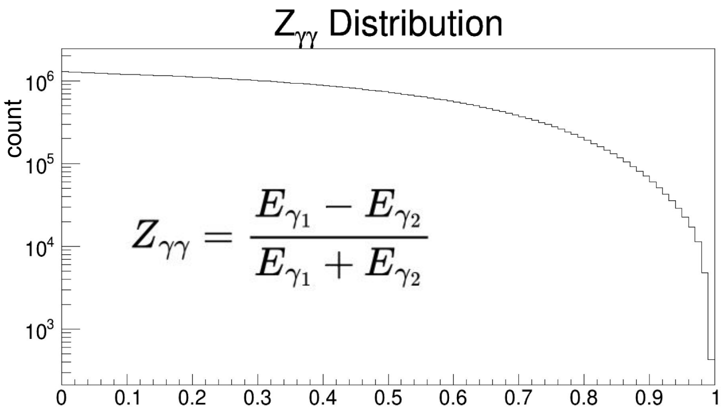
Trigger records a particle candidate as photon when there is a very high E_T recorded in a tower (threshold ~ 5.9 GeV)

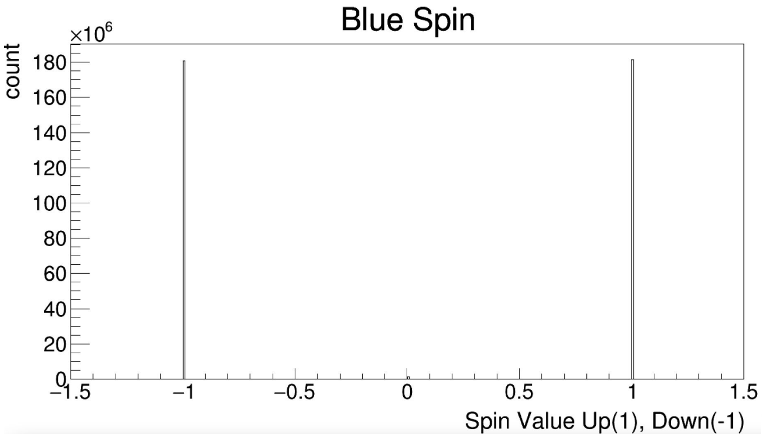
Analysis : QA plots

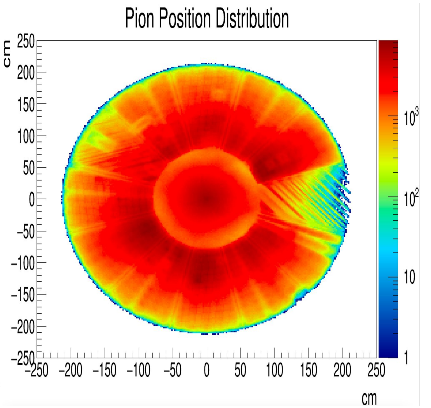




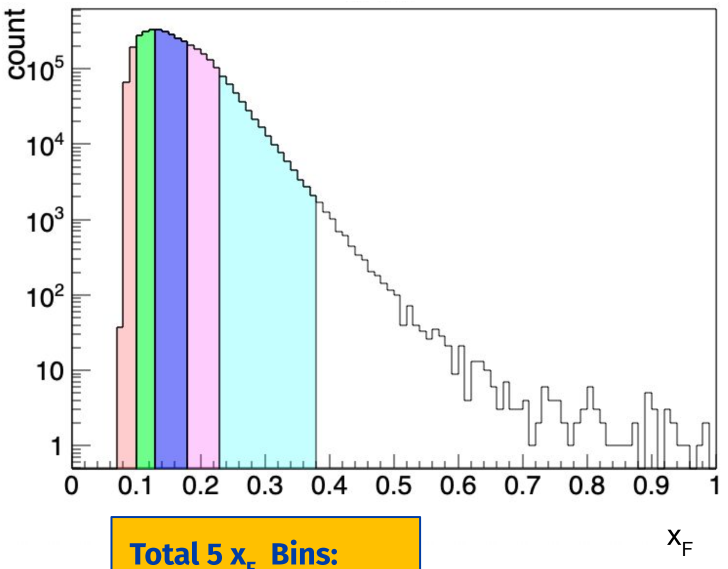
The bad sector at the EEMC are excluded for the A_N analysis





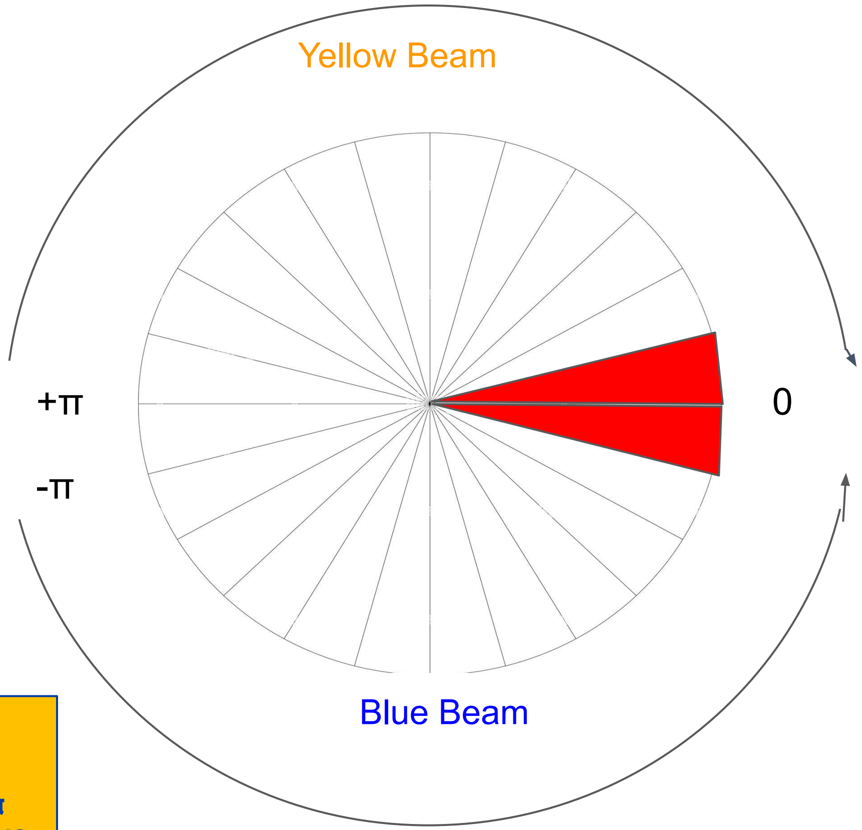


Run 2015 Data division for this Analysis - x_F bins and phi bins



Total 5 x_F Bins:

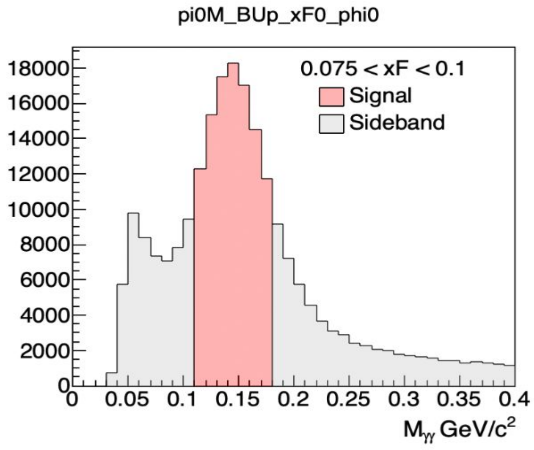
$0.075 < x_F < 0.1$
$0.1 < x_F < 0.125$
$0.125 < x_F < 0.175$
$0.175 < x_F < 0.225$
$0.225 < x_F < 0.375$

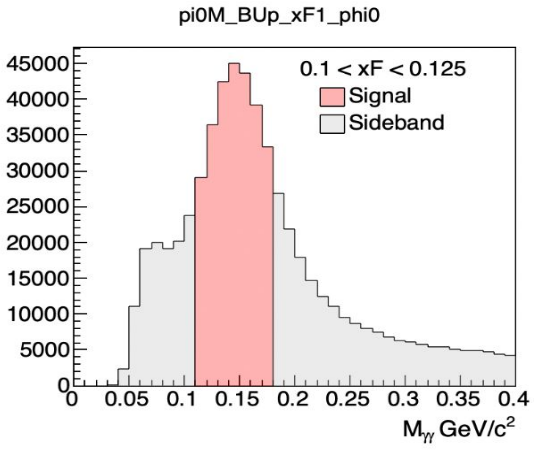


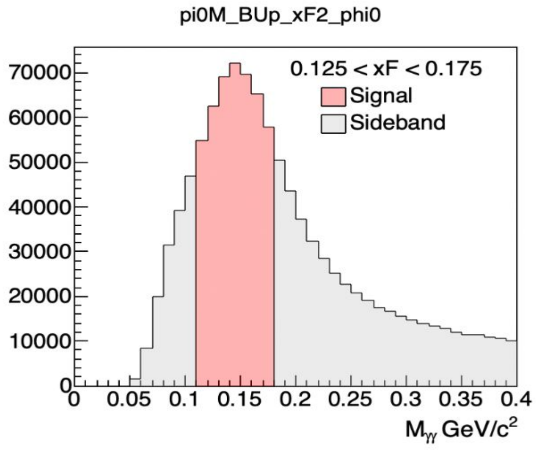
ϕ Bins:

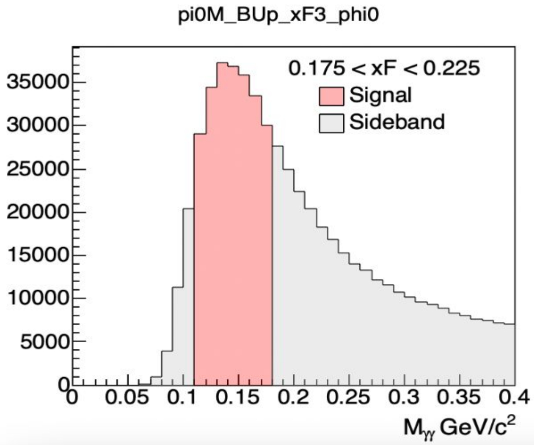
24 bins : -π to +π
1 bin : 15 deg, π/12

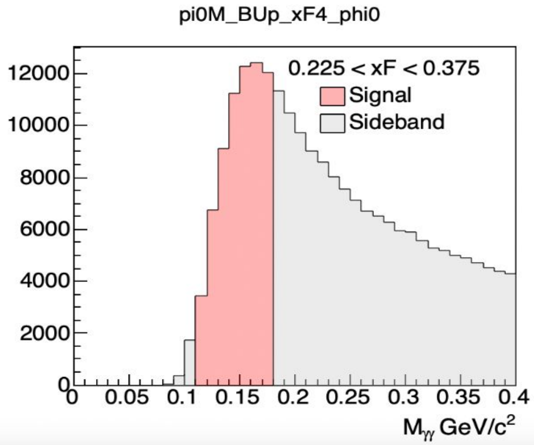
Diphoton Invariant Mass Histograms Signal-Sideband region for all x_F Bins











Signal Region : 0.11 - 0.18
Low Mass SB : 0.0 - 0.11
High Mass SB: 0.18 - 0.4
(in Gev/c^2)

Analysis : Calculation of Raw (Inclusive) A_N

The Relative Luminosity Method will be used for the Inclusive A_N measurement

$$pol.\, A_N^{raw}.\phi = \frac{N^{\uparrow}(\phi) - RN^{\downarrow}(\phi)}{N^{\uparrow}(\phi) + RN^{\downarrow}(\phi)}$$

where, N = π° yields

↑ = Beam spin polarised vertically upward in the lab frame

↓ = vertically downward

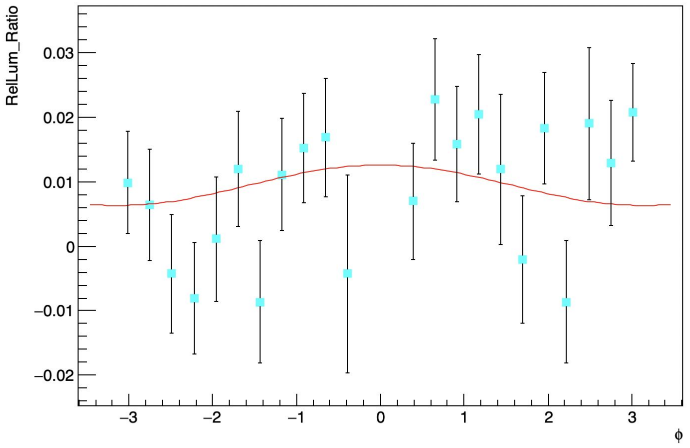
P = average Polarisation

R = Relative Luminosity

Calculating these quantities for the 5 different xF bins using all the bins, and fitting them to : $p0 + p1 * cos(\phi)$

The fit parameter "p1" divided by the avg. polarisation (P) is the raw A_N

Raw A_N = p1/<P>



Relative Luminosity Ratio vs. ϕ fitted with $p0 + p1 * cos(\phi)$

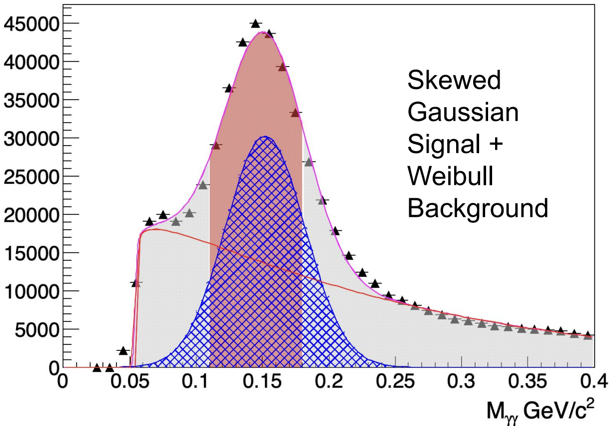
Analysis : Extraction of $\pi°$ A_N

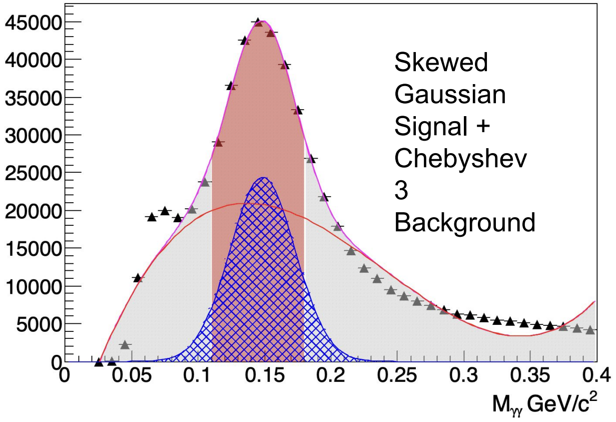
$\pi°$ A_N is extracted by fitting the invariant mass histograms with signal and background functions and calculating the fraction of signal in signal region, as well as sideband region

$$A_N^{\mathrm{raw}_{sig}} = f_{\mathrm{sig}_{sig}} * A_N^{\pi^0} + (1 - f_{\mathrm{sig}_{sig}}) * A_N^{bkg}$$

$$A_N^{\mathrm{raw}_{sb}} = f_{\mathrm{sig}_{sb}} * A_N^{\pi^0} + (1 - f_{sig_{sb}}) * A_N^{bkg}$$

For the $\pi°$ signal, a Skewed Gaussian Distribution is used.
Three different functions are selected for describing the background :
Weibull Distribution, Chebyshev Third Order Polynomial and Levy Distribution





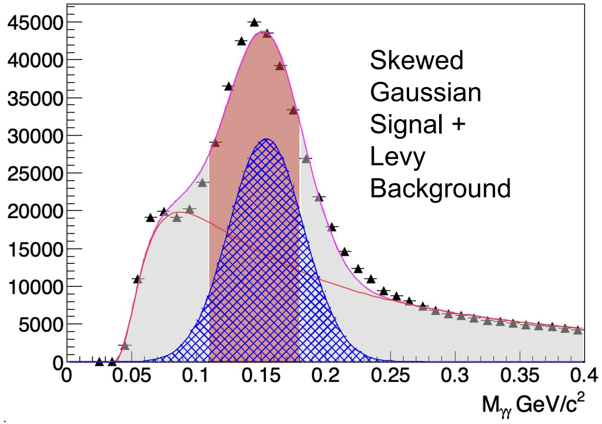
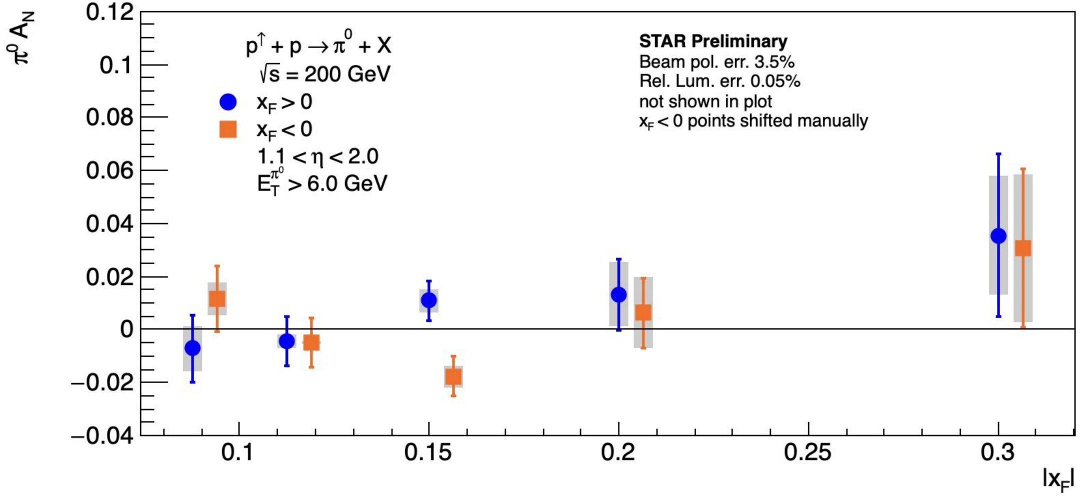


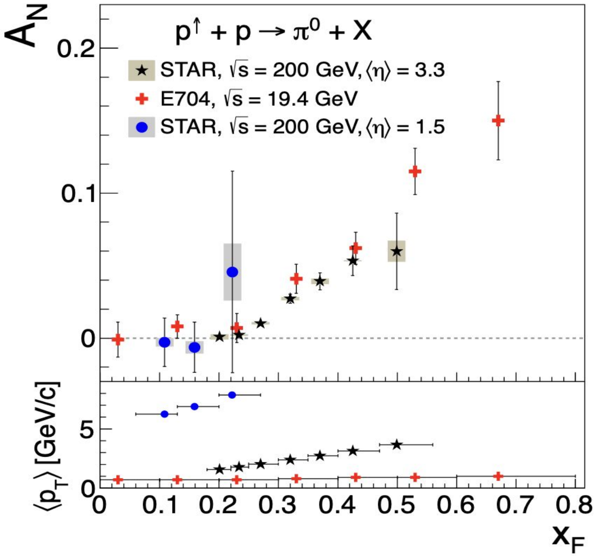
Fig Left : Sig + Weibull ; Middle : Sig + Chebyshev ; Right : Sig + Levy Fits for invariant histogram in the 0.1 < xF < 0.125 range

Analysis : Systematics Studies

- **Systematics for measuring Relative Luminosity ~ 0.05% from scalers**
- **Systematics for measuring Average Polarisation Error ~ 3.5% for Run 2015 transversely polarised *pp* collisions**
- **Systematics for measuring neutral pion yields - mainly comes from background estimation.**
- **Weibull Distribution considered as the baseline function for describing the background. Deviation of measurement using the other two background functions gives point-to-point systematic uncertainty.**

Preliminary Results :





Current A_N measurement with Run 2015, $\sqrt{s}$ = 200 GeV *pp* collisions with EEMC

Previous A_N measurement with Run 2006, $\sqrt{s}$ =200 GeV *pp* collisions with EEMC

Current A_N Analysis at EEMC using Run 2015 data has significantly lower error bars than the previous A_N measurement

Similar trend in A_N observed in both measurements. Results are consistent with very small A_N values

Summary :

- Previous A_N Analysis using the EEMC was done with Run 2006 data
- Run 2015 data has 17 times larger luminosity than Run 2006
- This is reflected in the smaller error bars in the A_N measurement for neutral pions
- Improvement on systematic studies will be made
- Further studies on the A_N measurement will be done using transversely polarised proton beams at $\sqrt{s}$ = 510 GeV using STAR Run 2017 data


THANK YOU

Back-Up Slides

Beam Polarisation Calculation

- Calculate P for an event : $P(t) = P_0 + \frac{dP}{dt}t$

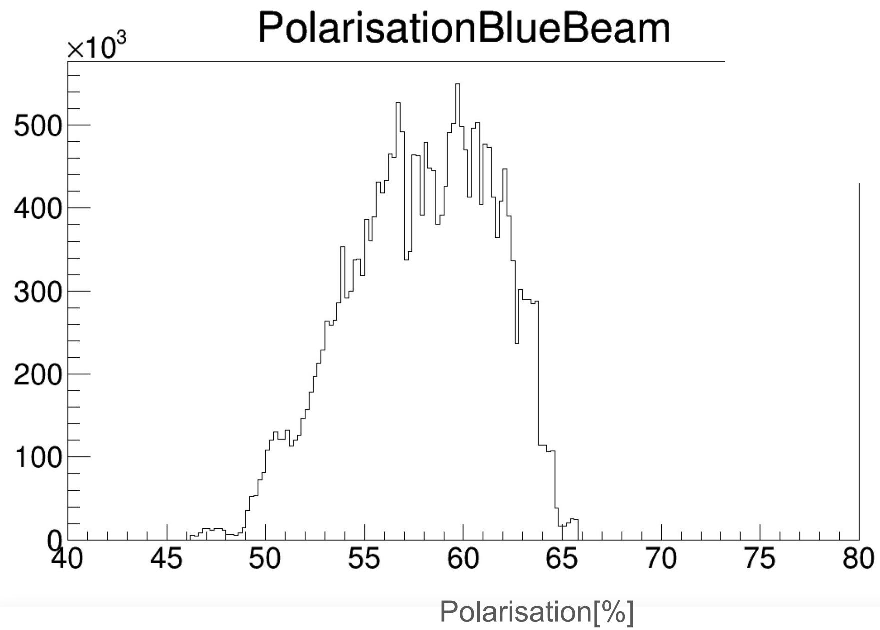
  Use $t = (t_{event} - t_0)$ where

  $t_{event} =$ event time from MuDst

  $t_0 =$ Start time for the fill

  (from spin group table)

- Calculate for every event accepted
- Plot over entire dataset
- Following this approach,



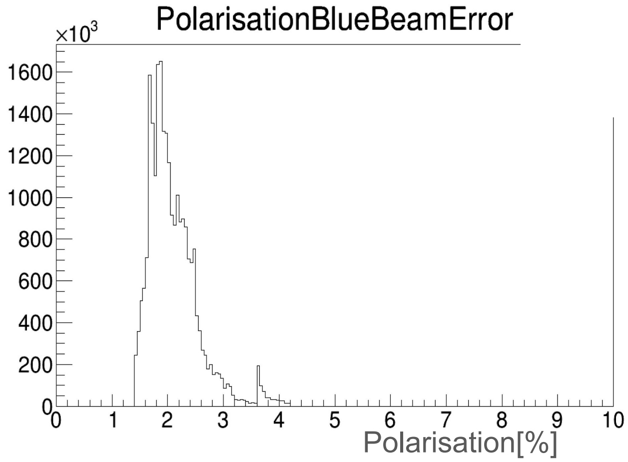
Beam Polarisation Error Calculation - Blue Beam

$$\sigma(P_{set}) = P_{set} \cdot \frac{\sigma(scale)}{P} \oplus \sigma_{set}(fill - to - fill) \oplus P_{set} \cdot \frac{\sigma(profile)}{P}$$

$$\sqrt{1 - \frac{M}{N}} \frac{\sum_{fill} L_{fill} \sigma(P_{fill})}{\sum_{fill} L_{fill}}$$

$$\sigma(P_{fill}) = \sigma(P_0) \oplus \sigma(\frac{dP}{dt}) \cdot (\frac{\sum_{run} t_{run} L_{run}}{L_{fill}} - t_0) \oplus \frac{\sigma(fill - to - fill)}{P} \cdot P_{fill}$$

- $\sqrt{1 - \frac{M}{N}}$ is the correction for over-counting



Ref. 1: RHIC Polarization for Runs 9 - 17 By W.B. Schmidke

Ref. 2: Example Calculation of fill-to-fill polarization By Z. Chang

Motivation : Twist - 3 Effects

- Collinear Factorization : Hard Scattering part convoluted with non-perturbative PDFs
- Twist - 3 : Incorporates higher-order correlations, specifically quark-gluon-quark correlations

$$A_N \sim \frac{1}{p_T} \frac{T_F(x) \circledast f(z) \circledast H(x,z)}{g(x) \circledast H}$$

where $T_F(x)$: Twist-3 PDF

$f(z)$: Fragmentation Function

$H(x,z)$: Hard Scattering Kernel

$g(x)$: unpolarised quark and helicity distributions