Transverse Spin Asymmetries in the $p^{\uparrow}p \rightarrow p\pi^{0}X$ Process at STAR

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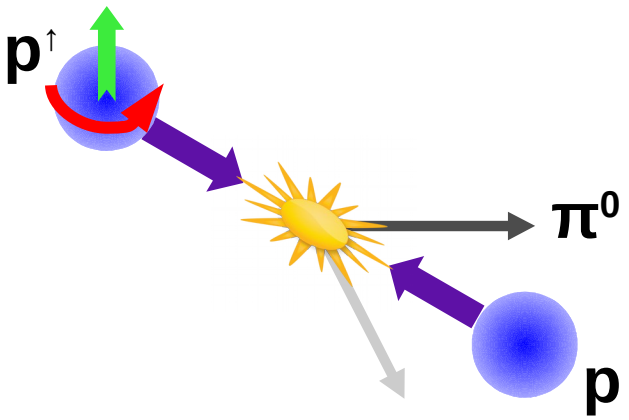
DIS 2019 – April 2019

Transverse Single Spin Asymmetry A_N

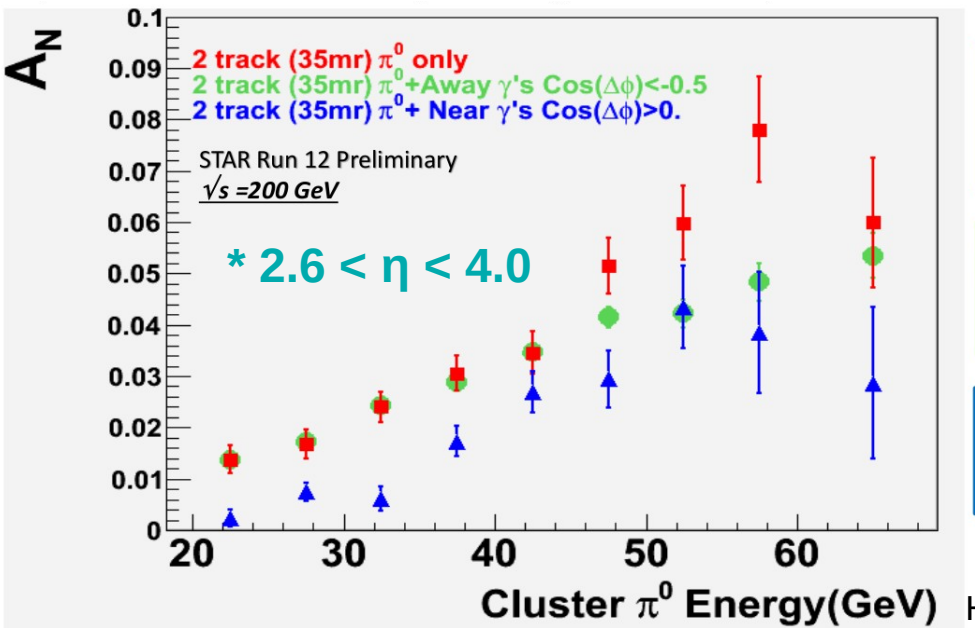


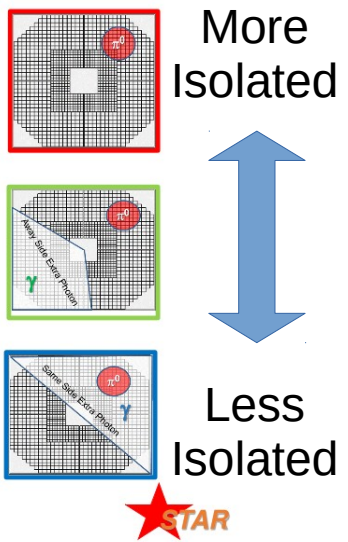
$$A(\phi) = \frac{d\sigma^{\uparrow}(\phi) - d\sigma^{\downarrow}(\phi)}{d\sigma^{\uparrow}(\phi) + d\sigma^{\downarrow}(\phi)} \sim A_N \cdot \cos\phi$$

If $A_N > 0$:

- Spin-up proton tends to produce more π^0s to the left, than to the right
- Spin-down: vice versa

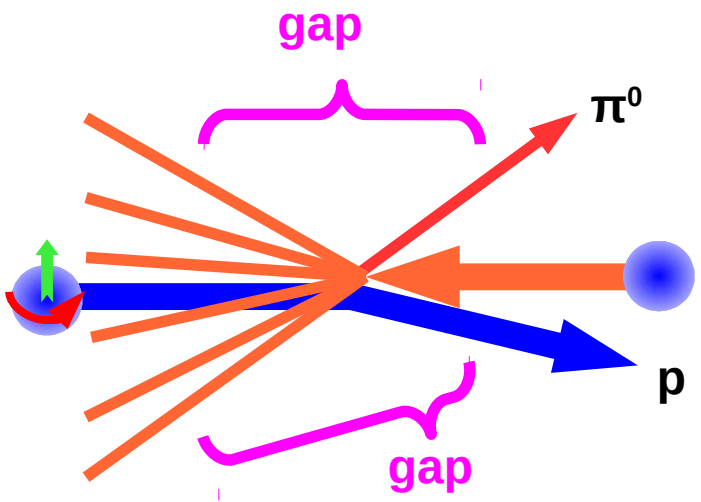
- Forward* π^0 A_N is positive, rising with $x_F = 2E / \sqrt{s}$
- A_N is also **event topology dependent**:
- Forward **isolated pions** have larger A_N than those with **nearby EM energy deposits**



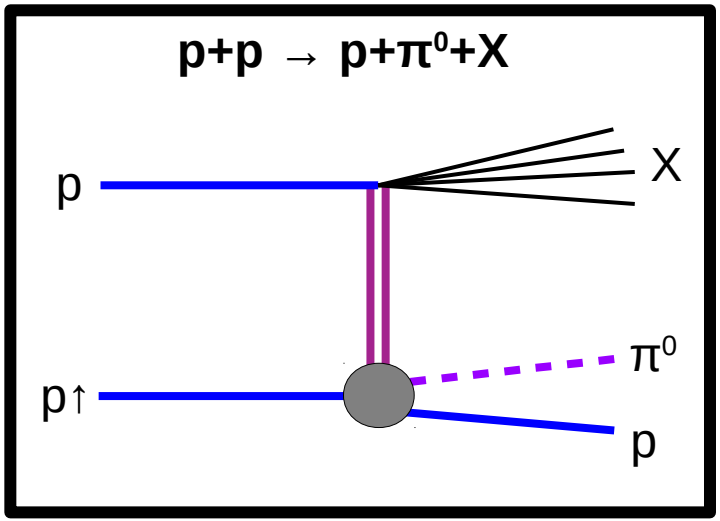


Heppelmann, DIS 2013

Example of Isolated Pion Production

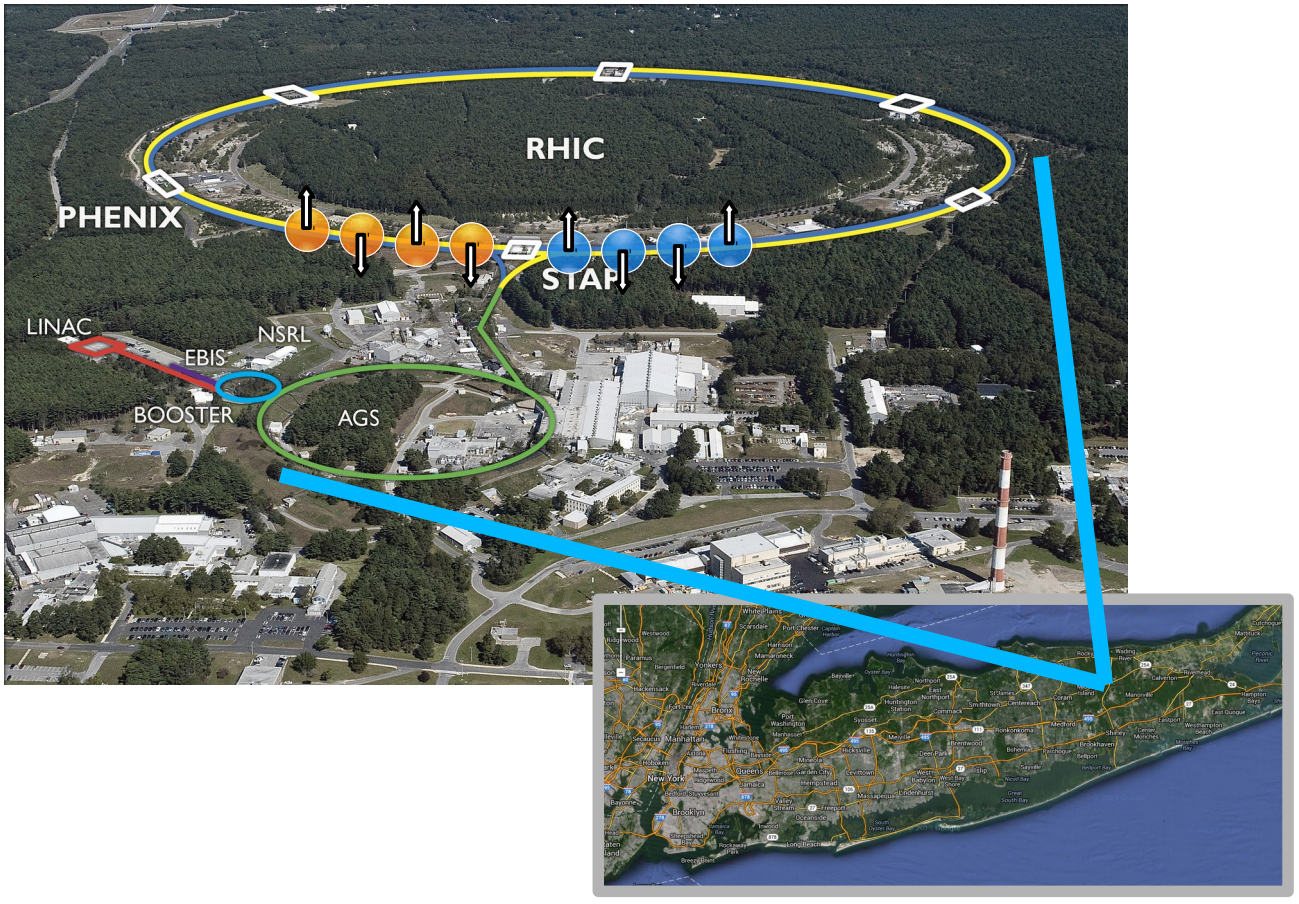


- One possible channel for isolated pions is the process $p^{\uparrow}p \rightarrow p\pi^0X$
- Although this is a relatively rare process to observe, the STAR experiment at RHIC sees evidence of it, despite acceptance limitations



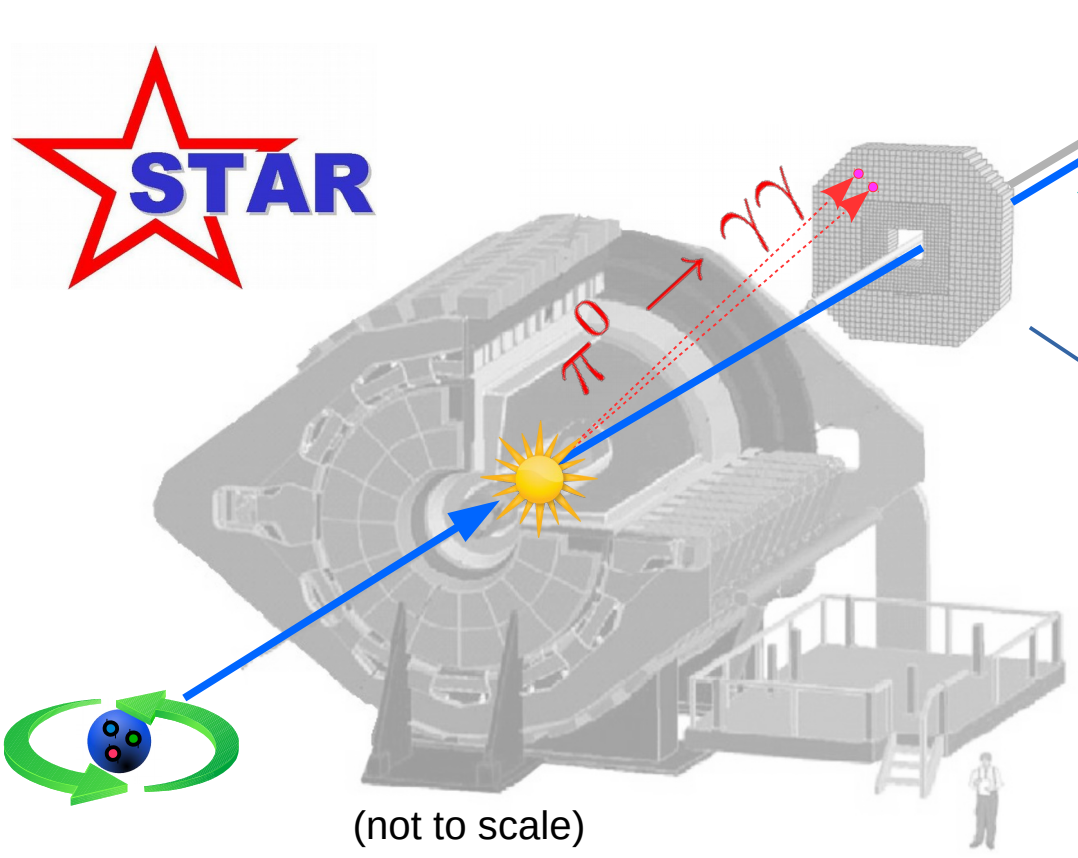
- Possible Model: Incident polarized proton may fluctuate into a proton+pion pair, which then interacts with the opposing proton
- Incident proton transverse spin may be correlated with proton+pion angular momentum
- Goal: study asymmetries modulated by proton and pion azimuthal angles

RHIC: Relativistic Heavy Ion Collider



Brookhaven National Laboratory
Long Island, NY

Detectors and Orientation



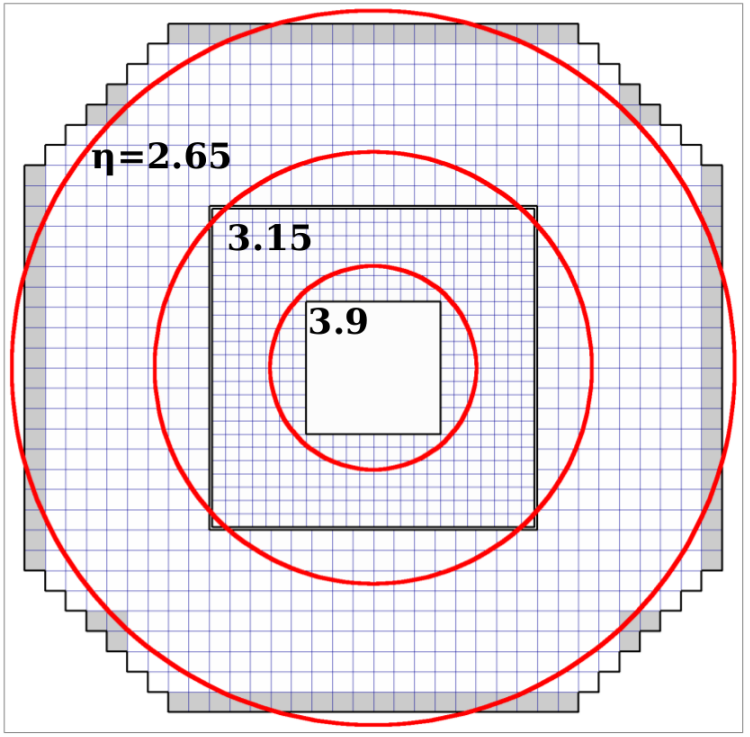
RP Roman Pots

FMS Forward Meson Spectrometer

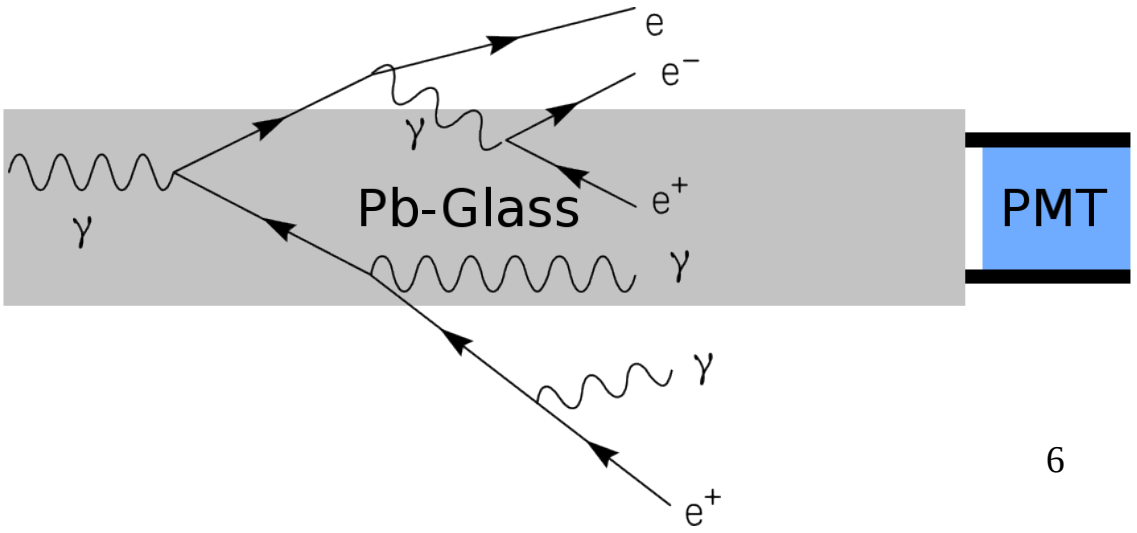
Transversely polarized pp collisions at √s=200 GeV

[RHIC 2015 Run]

FMS: Forward Meson Spectrometer

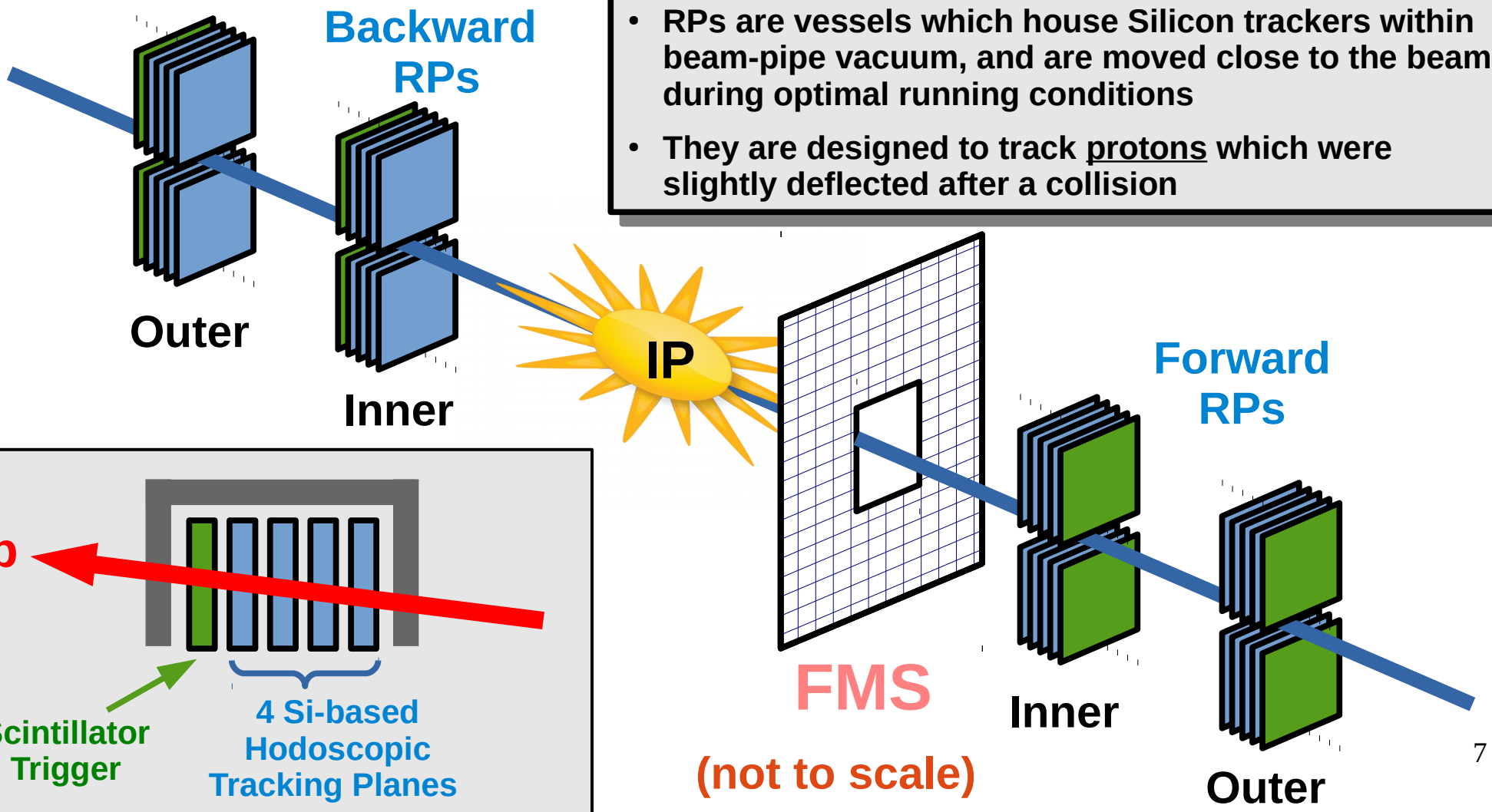


- Lead-Glass Electromagnetic Calorimeter
- Forward Pseudorapidity: $2.65 < \eta < 3.9$
- Array of ~1200 Pb-glass cells coupled to Photomultiplier Tubes (PMTs)
- γ, e^-, e^+ → EM shower
- Primary observable: $\pi^0 \rightarrow \gamma\gamma$



RP: Roman Pot Detectors

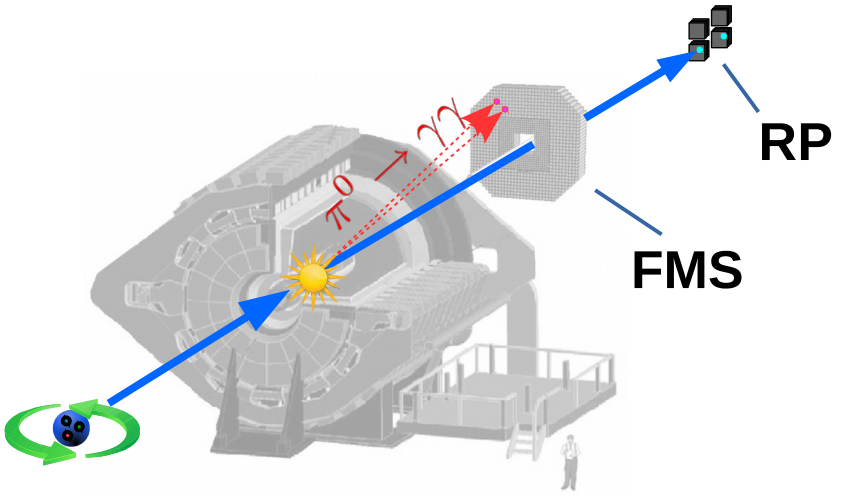
- RPs are vessels which house Silicon trackers within beam-pipe vacuum, and are moved close to the beam during optimal running conditions
- They are designed to track <u>protons</u> which were slightly deflected after a collision



Pion and Proton Cuts

Pions

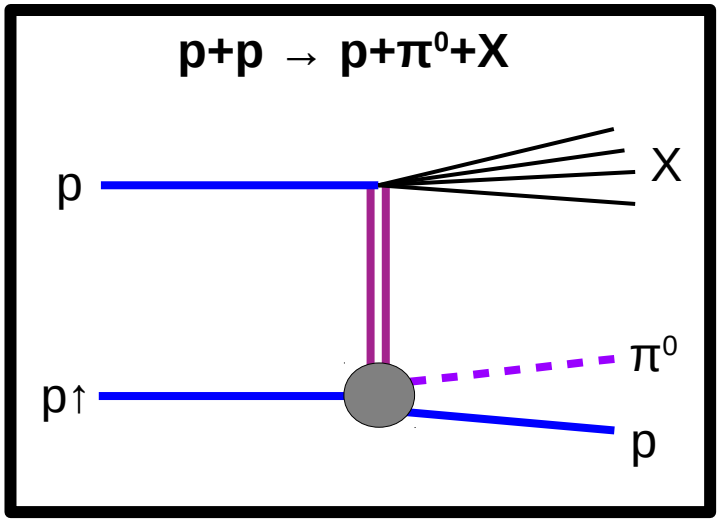
- Event triggered on Pion
- Highest energy pair in the event
- Mass within π^0 mass window
- $12 < E < 70$ GeV
- $Z = | E_1 - E_2 | / E < 0.8$
- p_T trigger threshold cut



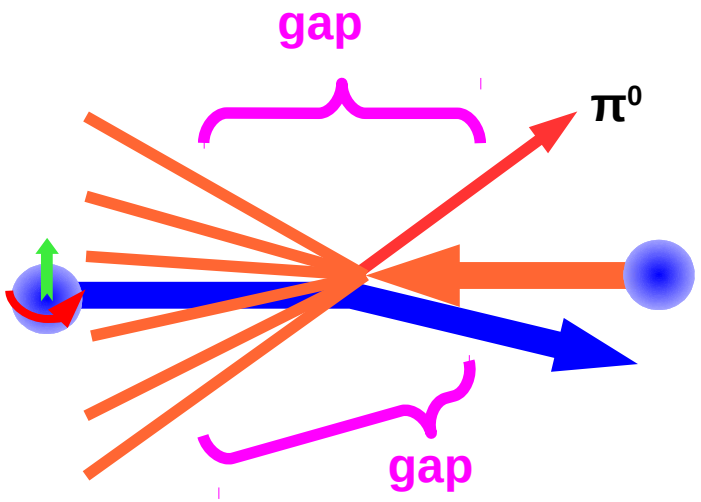
Protons

- Hits in both inner and outer forward Roman Pots
- Track within geometric acceptance
- Hit at least 7 of 8 tracking planes
- No activity on backward Roman Pots

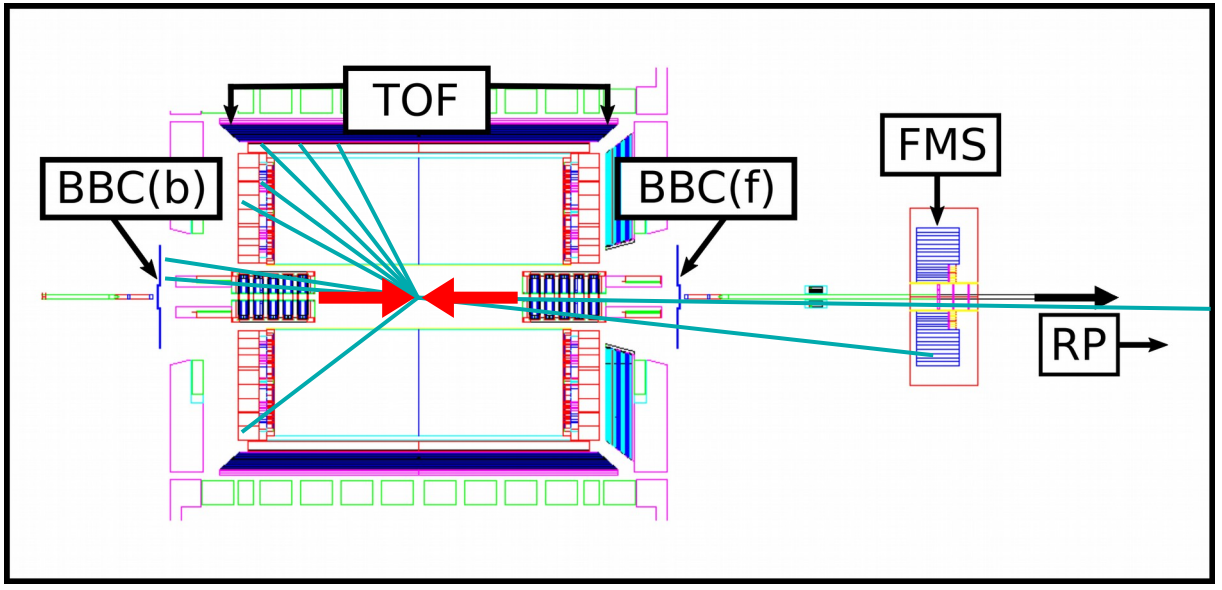
Properties of $p^{\uparrow}p \rightarrow p\pi^0X$ at STAR



- **E**(scattered proton) + **E**(pion) = **E**(initial proton) = 100 GeV
- $\mathbf{p_T}$(proton) ~ 0.2 GeV/c
- $\mathbf{p_T}$(pion) ~ 2 GeV/c
- Evidence of recoil proton breakup



Additional Cuts



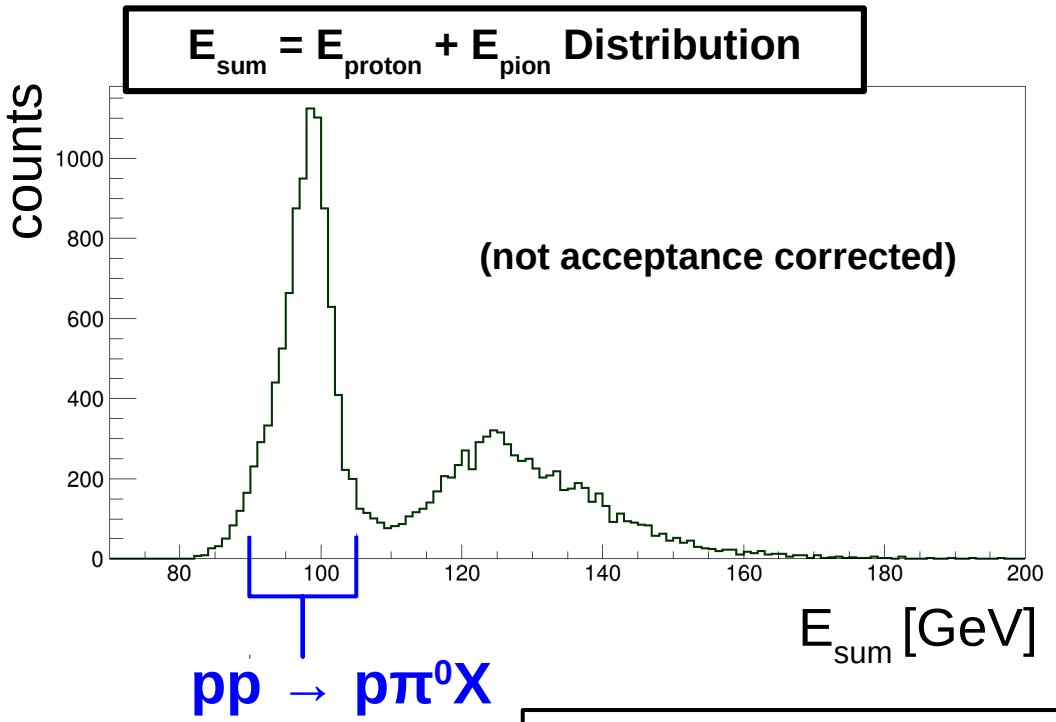
Forward BBC: 2.1 < η < 5

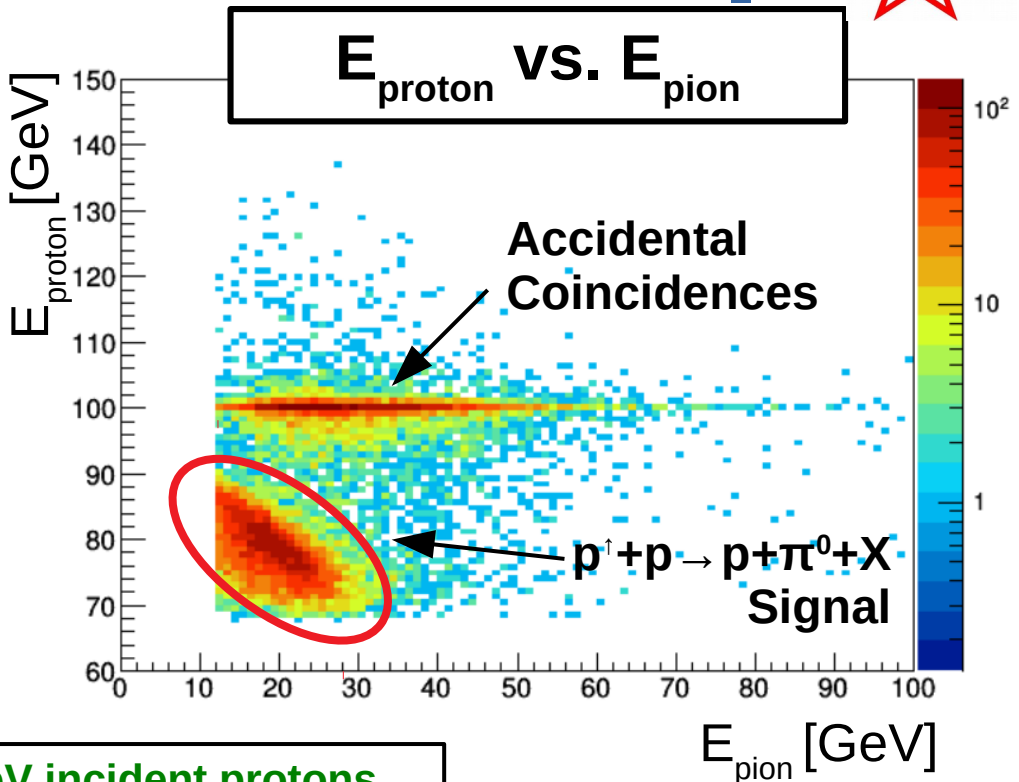
- Scintillator that spans FMS η range
- Cut on BBC hits to reduce events from accidental coincidences with a second interaction in the same bunch crossing
- Cut level set to minimize impact on $pp \rightarrow p\pi^0X$ events, since some π^0s are observed in the BBC

TOF: –1 < η < 1 Backward BBC: –2.1 > η > –5

- Evidence of recoil proton remnants X
- Require sum of TOF and Backward BBC hits to be nonzero
- Only 5 out of ~9000 events do not satisfy this requirement

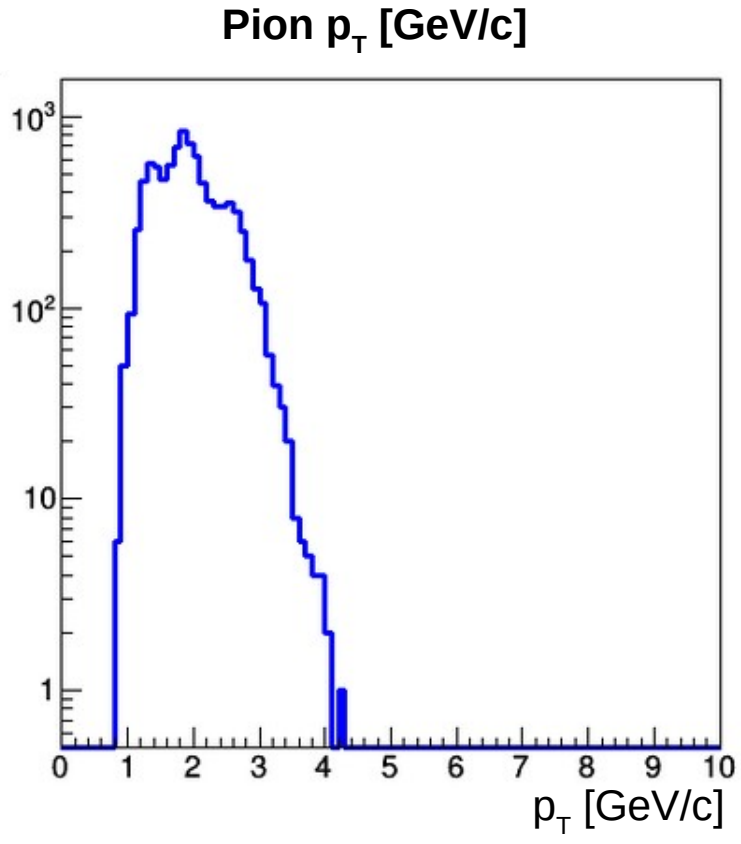
Selecting $p^{\uparrow}+p \rightarrow p+\pi^0+X$ Events

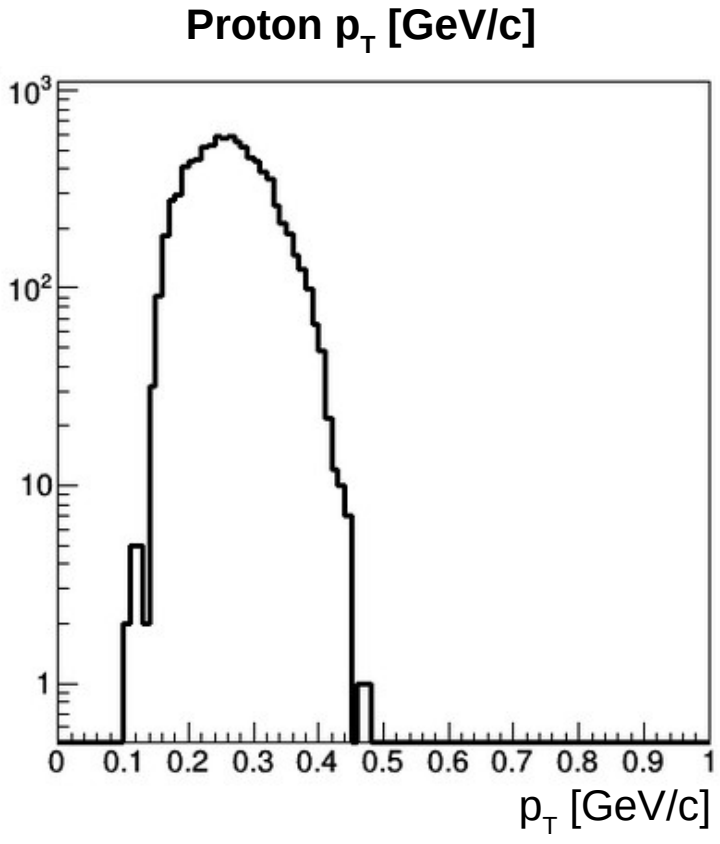




- $\sqrt{s}$ = 200 GeV → 100 GeV incident protons
- E_{sum} ~ 100 GeV indicates $p^{\uparrow}p \rightarrow p\pi^0X$
- Event Cut: $90 < E_{sum} < 105$ GeV
- 8,870 $pp \rightarrow p\pi^0X$ events

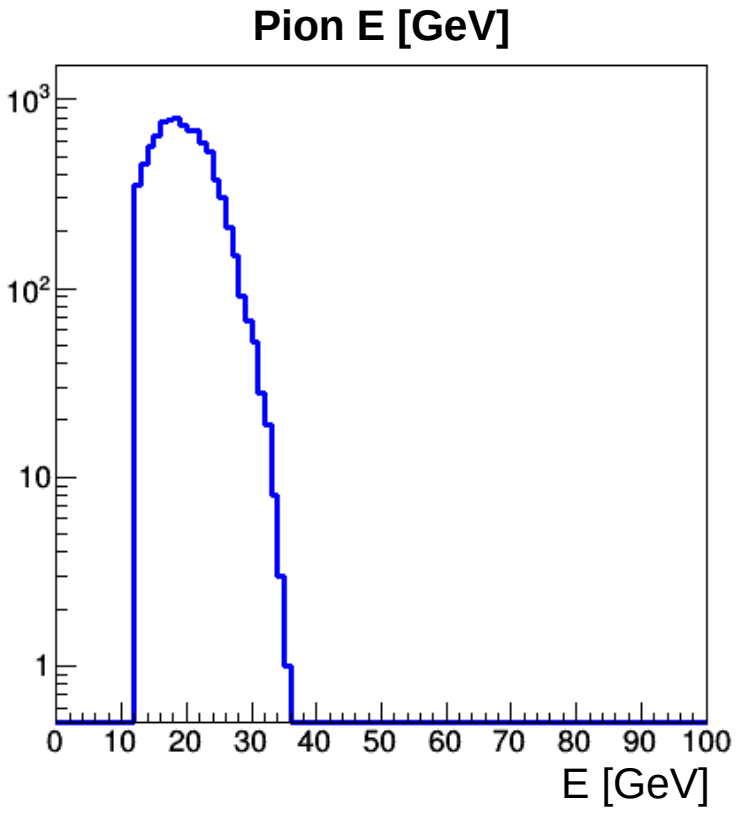
Transverse Momentum

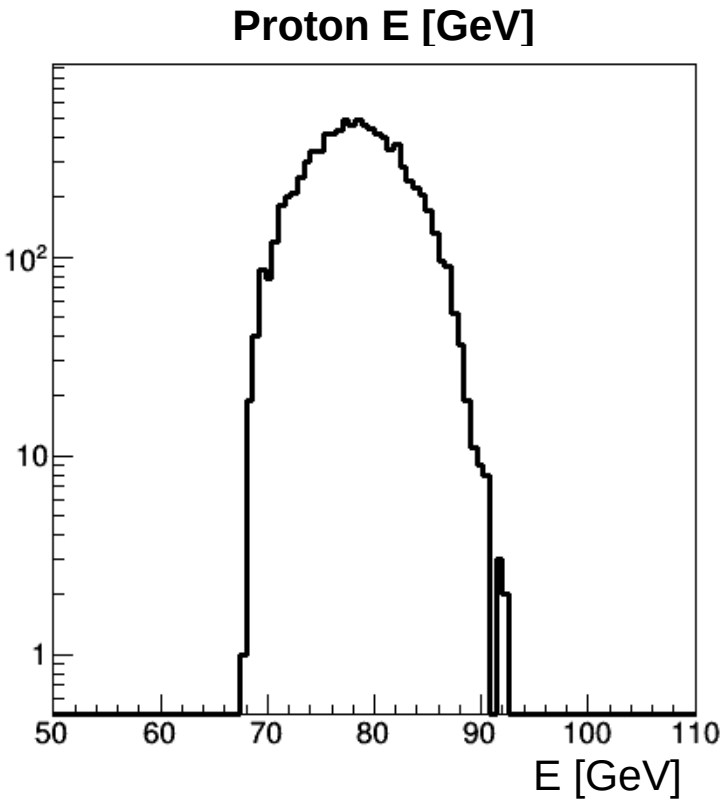




- **Pion p_T range: 1 – 4 GeV/c**
- **Proton p_T range: 0.1 – 0.45 GeV/c**

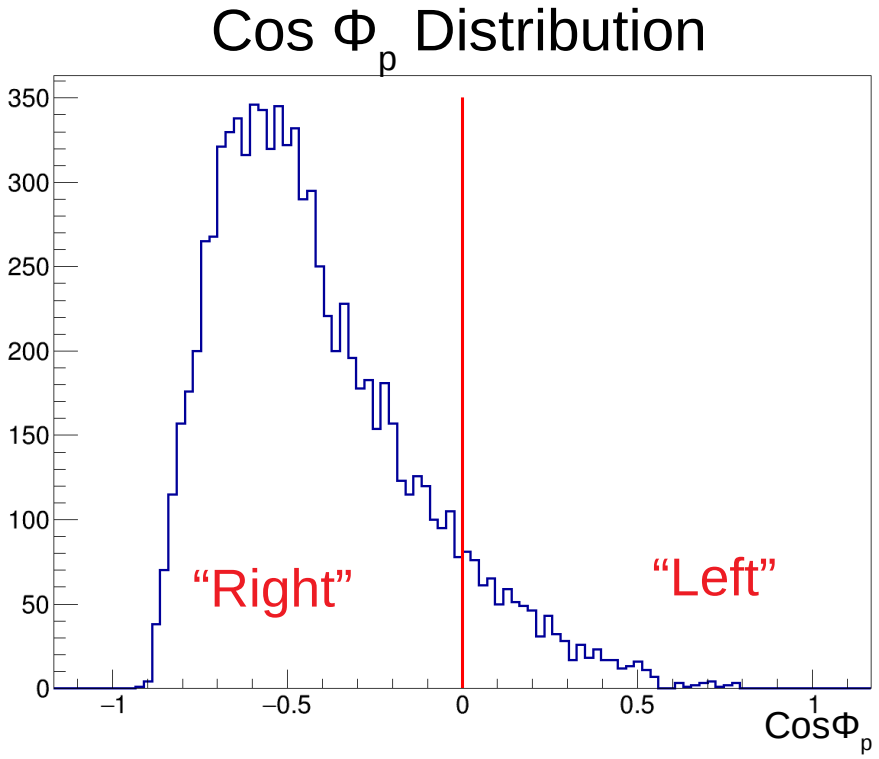
Energy



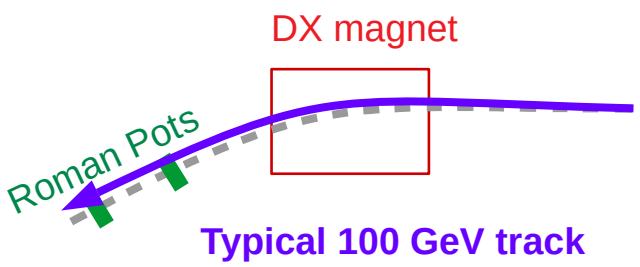


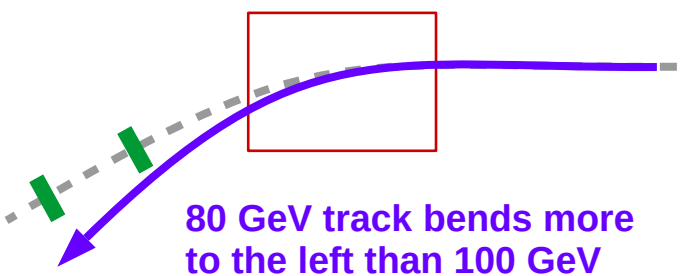
- **Pion E range: 12 – 35 GeV**
- **Proton E range: 68 – 90 GeV**

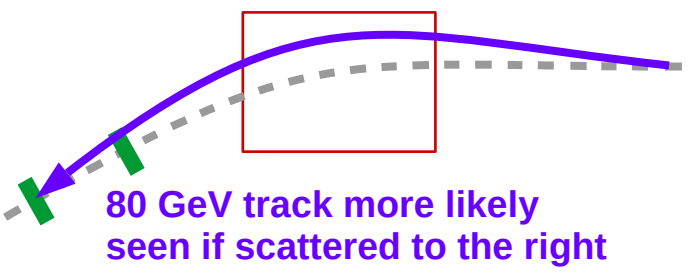
Proton Azimuth



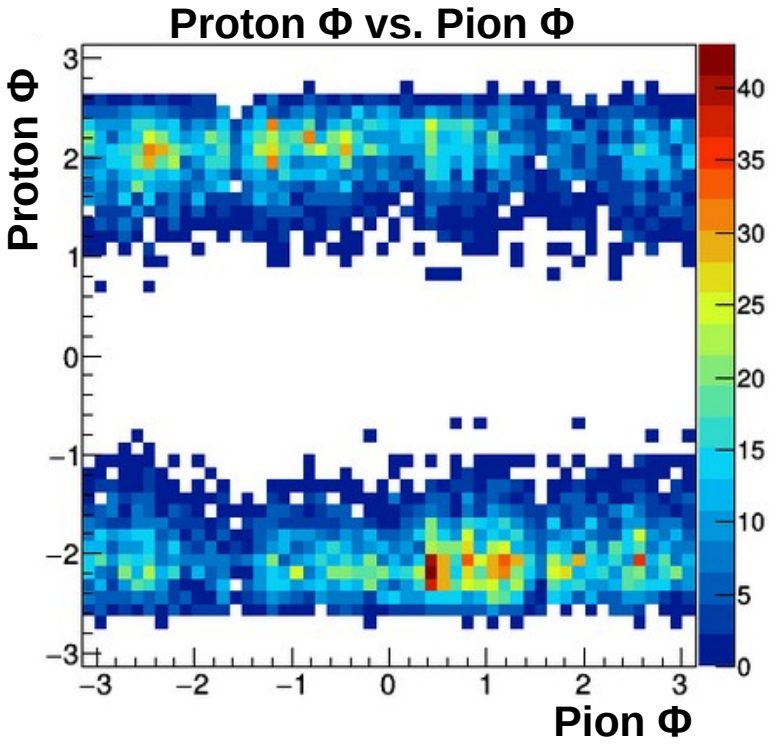
- A beam magnet (STAR DX magnet) bends the outgoing proton beam to the left before passing between the Roman Pots
- Scattered protons with E<100 GeV are bent to the left more than those with E~100 GeV
- Consequently, there is a bias of observing protons which scattered to the right

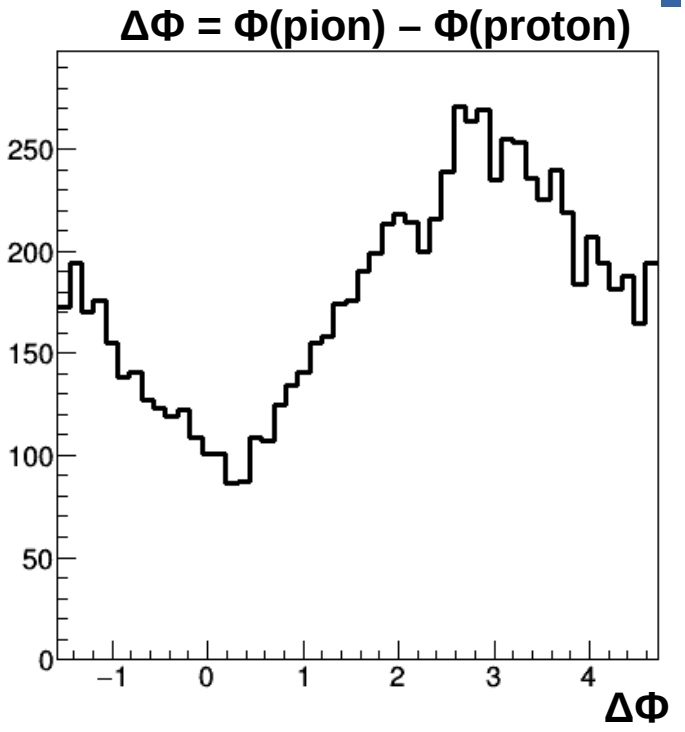






Azimuthal Correlations





- Proton azimuth Φ_p is limited by acceptance: ~90% events have proton momentum to the right ($\pi/2 < |\Phi| < \pi$)
- Pion azimuth Φ_π spans full 2π azimuth
- $pp \rightarrow p\pi^0X$ events favor back-to-back proton and pion

Constructing Asymmetries

Beam momentum vector: $Z = (0,\ 0,\ E_B)$

Recoil proton momentum vector: $P = (p_T \cos\phi_p,\ p_T \sin\phi_p,\ p_L)$

Pion momentum vector: $\Pi = (\pi_T \cos\phi_\pi,\ \pi_T \sin\phi_\pi,\ \pi_L)$

Spin pseudovector (m=±1/2): $S = (0,\ m,\ 0)$

- Geometric products of these objects can represent physically-allowed asymmetry azimuthal modulations
- They must be:
  - Scalar → parity conserving
  - Invariant under rotations of π radians
  - Dependent on spin → linear in *m*

pseudovector, ~cosΦ

$$\underbrace{(Z \times \Pi)}_{\text{pseudovector, } \sim\cos\Phi} \cdot S \quad \propto m \cos\phi_\pi \rightarrow \text{Pion Single-Spin Asymmetry}$$

$$(Z \times P) \cdot S \quad \propto m \cos\phi_p \rightarrow \text{Proton Single-Spin Asymmetry}$$

Constructing Asymmetries

Beam momentum vector: $Z = (0,\ 0,\ E_B)$

Recoil proton momentum vector: $P = (p_T \cos\phi_p,\ p_T \sin\phi_p,\ p_L)$

Pion momentum vector: $\Pi = (\pi_T \cos\phi_\pi,\ \pi_T \sin\phi_\pi,\ \pi_L)$

Spin pseudovector (m=±1/2): $S = (0,\ m,\ 0)$

- Geometric products of these objects can represent physically-allowed asymmetry azimuthal modulations
- They must be:
  - Scalar → parity conserving
  - Invariant under rotations of π radians
  - Dependent on spin → linear in *m*

scalar, ~cosΔΦ

$$\Delta\phi = \phi_\pi - \phi_p$$

$$[(Z \times P) \cdot (Z \times \Pi)]\ (Z \times \Pi) \cdot S \propto m \cos\phi_\pi \cos\Delta\phi$$

$$[(Z \times P) \cdot (Z \times \Pi)]\ (Z \times P) \cdot S \propto m \cos\phi_p \cos\Delta\phi$$

With two observables, modulations involving the azimuthal angles of *both* of them may be explored

Hypothesized by S. Heppelmann

Constructing Asymmetries

The observed asymmetry seems to be modulated by $\cos\phi_p \cos\Delta\phi$

Alternative modulations, such as $\cos\phi_\pi \cos\Delta\phi$ have been explored, but their asymmetries are consistent with zero

$$A_{p\pi} \propto \cos\phi_p \cos\Delta\phi$$

$A_{p\pi}$ magnitude is large when:

- Spin up/down proton scatters left/right
- Pion is within the scattering plane of the observed proton

Although this modulation may not be the true physics asymmetry, especially given limited statistics, it seems to describe the data well

Systematic Uncertainties

Polarization Scale Uncertainty on Asymmetries

Average beam polarization: $\langle P \rangle = 56.5\% \pm 1.73\%$

Scale systematic uncertainty on asymmetries: $\sigma / \langle P \rangle = 3.1\%$

Shift Uncertainty on Asymmetries

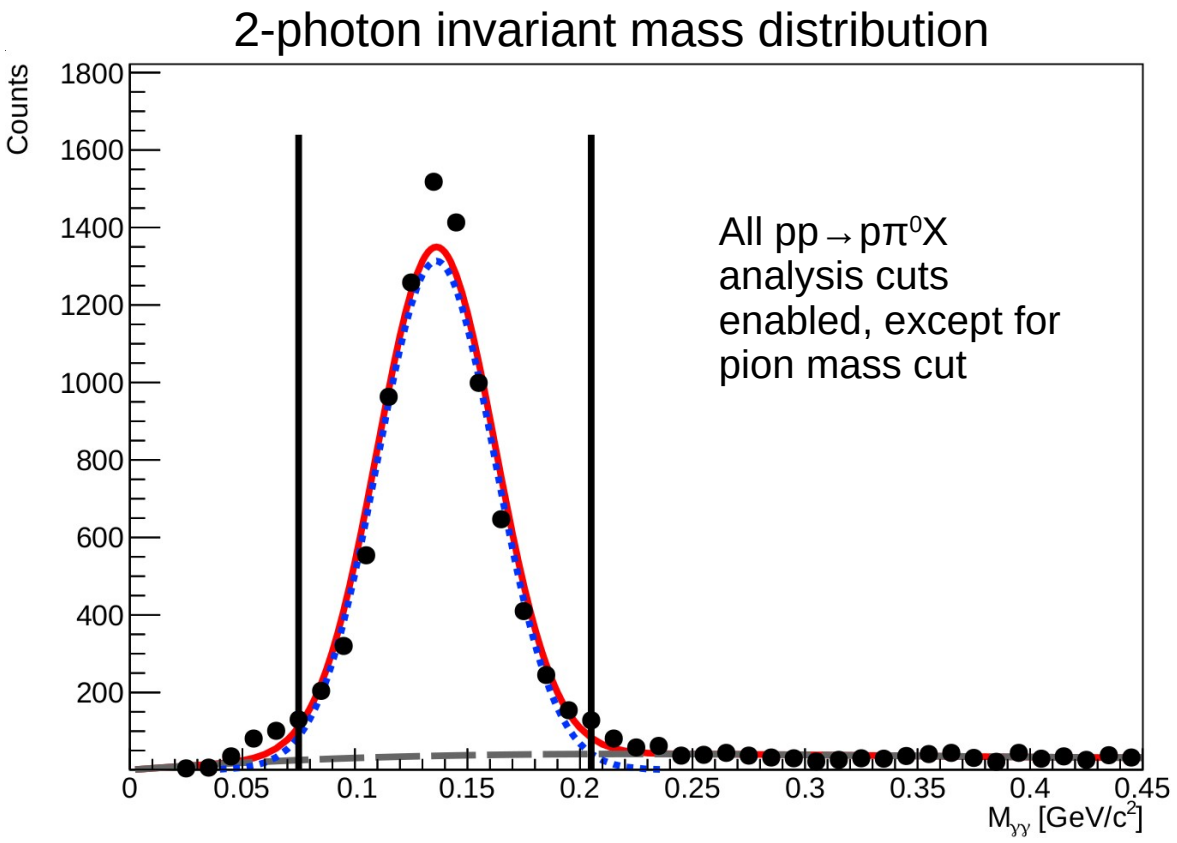
With ~9,000 events, statistical uncertainties are vastly dominant over any asymmetry shift systematic uncertainties

Azimuth Uncertainty

Used a simple Monte Carlo to propagate FMS and RP position uncertainties to an overall uncertainty on $\mathrm{Cos}\Phi_p\mathrm{Cos}\Delta\Phi$

- Pion azimuth uncertainty: 0.009 rad
- Proton azimuth uncertainty: 0.010 rad
- **Uncertainty on $\mathrm{Cos}\Phi_p\mathrm{Cos}\Delta\Phi$: 0.007**

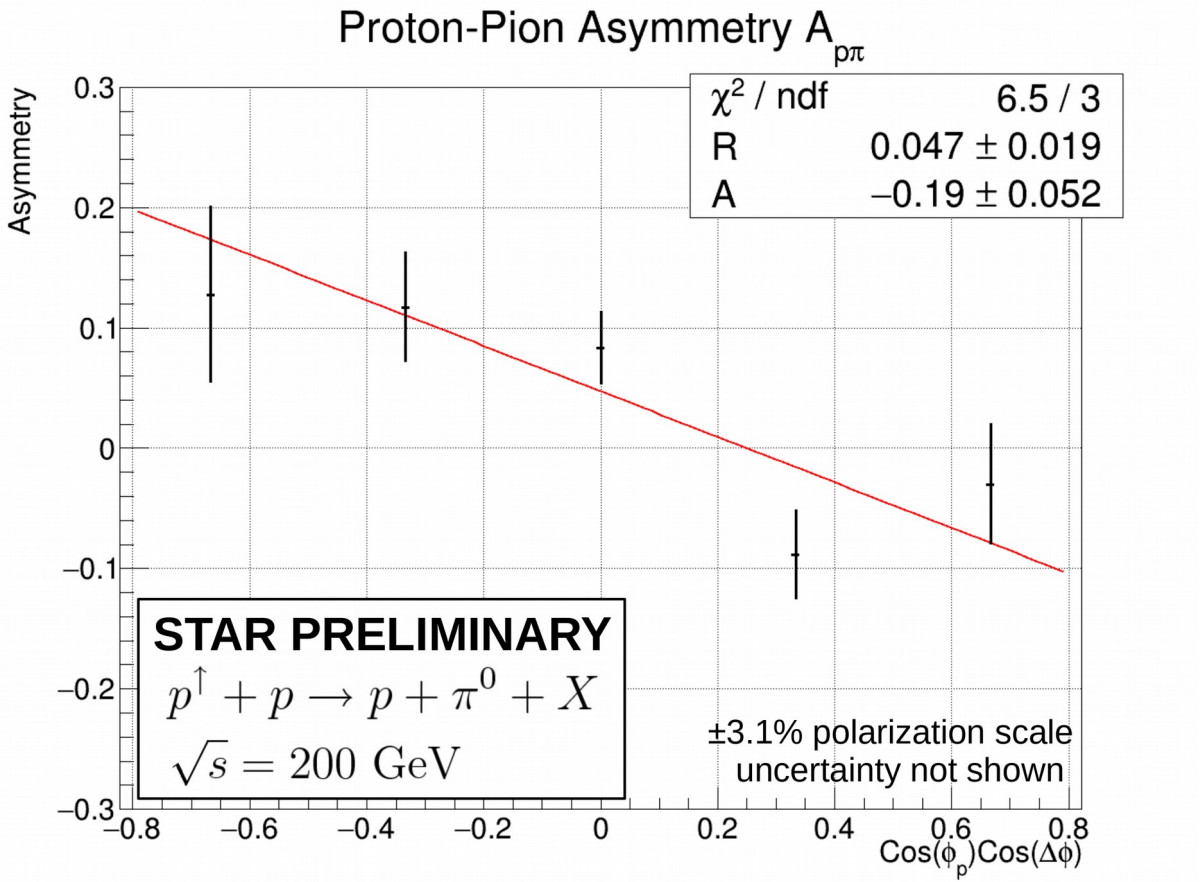
Background Estimate



Pion purity: 94.8% +/- 1.2%

Determined via the fraction of data histogram that is background, according to the grey-dashed background fit (3-polynomial)

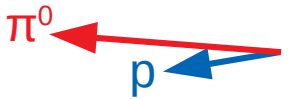
Cos(Φ_p)Cos(ΔΦ) Asymmetry



- **–19% Asymmetry (~4σ)**
- Vertical error bars are statistical uncertainties
- Horizontal error bars are propagated from FMS and RP position uncertainties
- 5% background under π^0 mass peak
- 3.1% scale uncertainty from polarization
- This asymmetry is *not* sensitive to the bias of protons scattered to the right

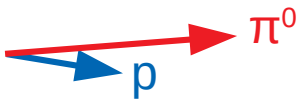
Fit Function: $\frac{1}{\langle P \rangle} \frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}} = R + A \cos\phi_p \cos\Delta\phi$

$Cos(\Phi_P)Cos(\Delta\Phi)$ Asymmetry Interpretation

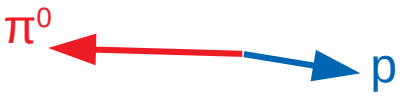


Negative Asymmetry

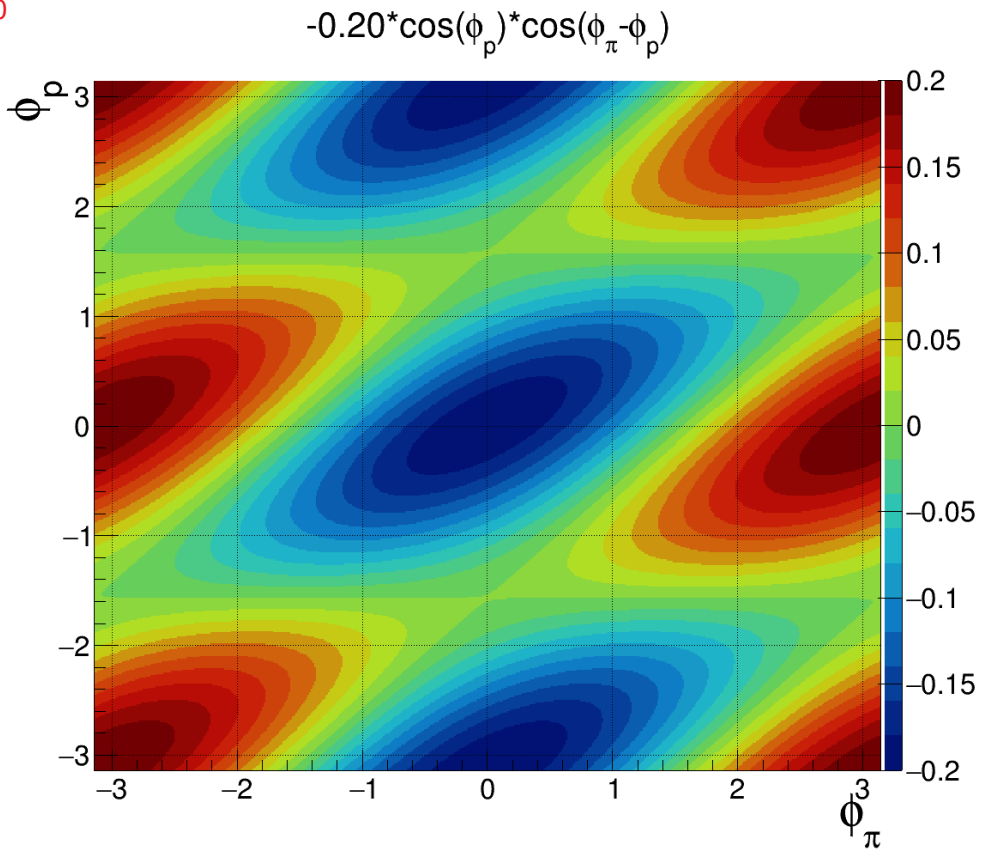
Positive Asymmetry



Positive Asymmetry



Negative Asymmetry

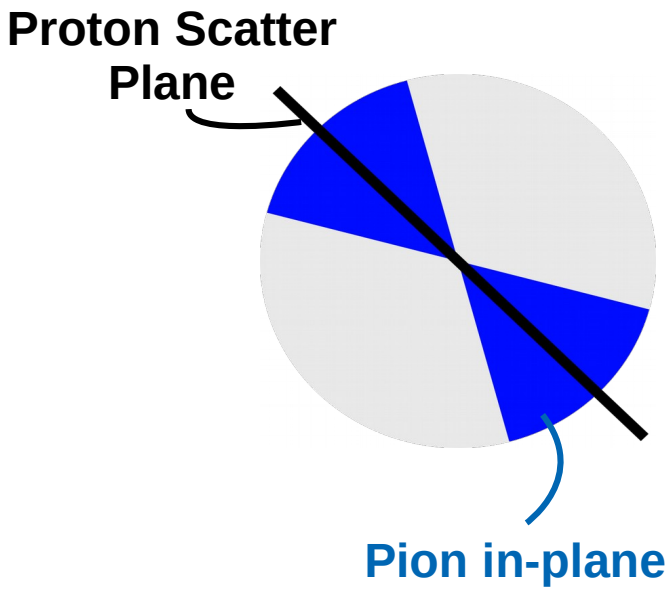


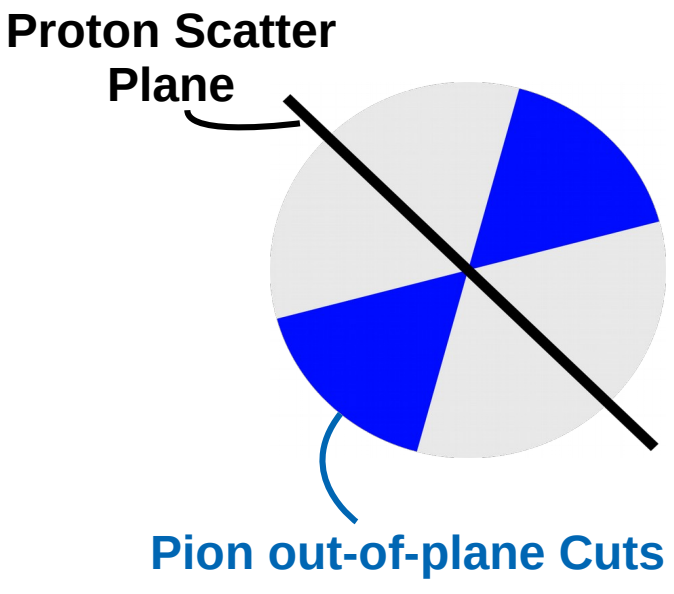
This is a pion asymmetry, in the scattering plane of the proton

(see backup slides for surface plots from various viewpoints)

$Cos(\Phi_P)Cos(\Delta\Phi)$ Asymmetry Interpretation

Test: use cuts on ΔΦ to select for in-plane / out-of-plane pions

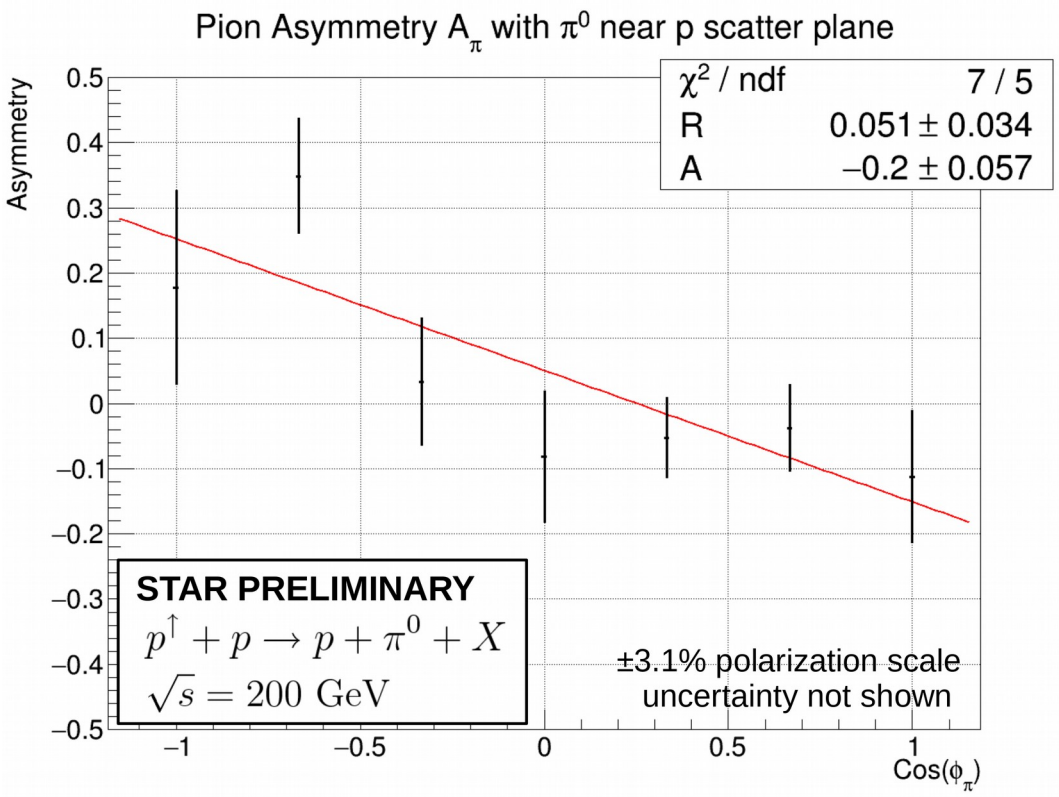


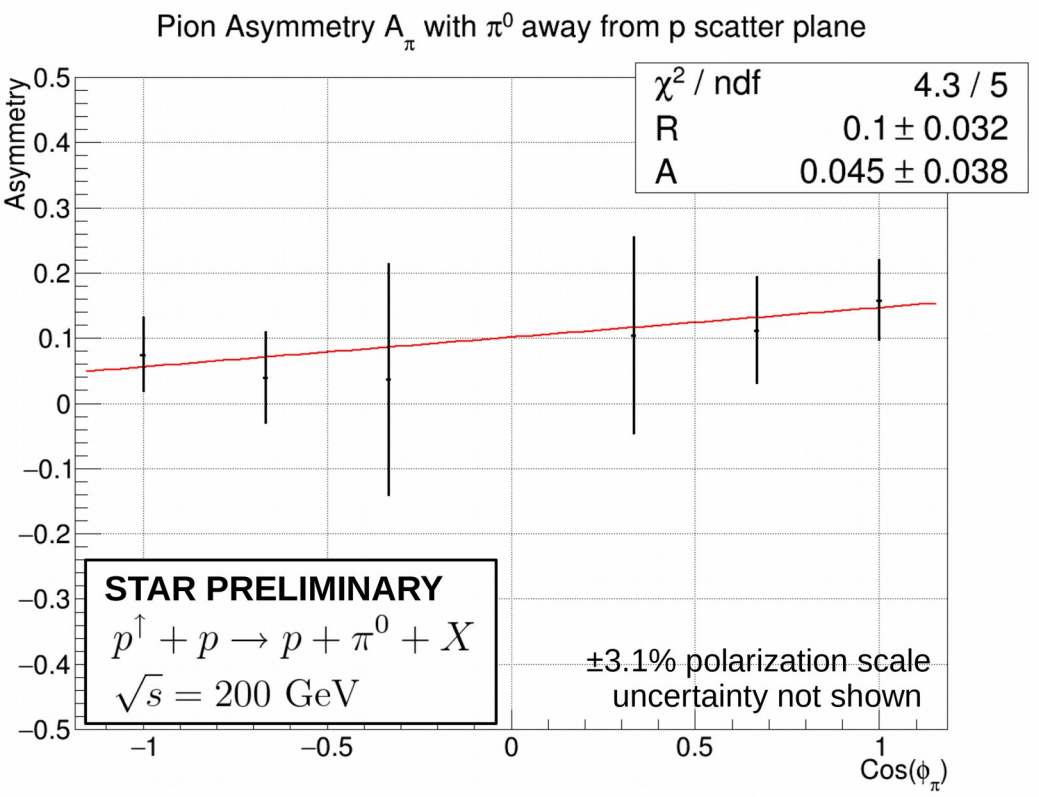


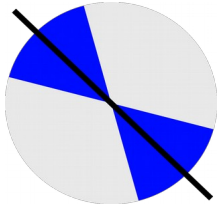
$$\Delta\phi \in \left(-\frac{\pi}{6},\ +\frac{\pi}{6}\right) \cup \left(\pi - \frac{\pi}{6},\ \pi + \frac{\pi}{6}\right)$$

$$\Delta\phi \in \left(\frac{\pi}{2} - \frac{\pi}{6},\ \frac{\pi}{2} + \frac{\pi}{6}\right) \cup \left(-\frac{\pi}{2} - \frac{\pi}{6},\ -\frac{\pi}{2} + \frac{\pi}{6}\right)$$

Pion Asymmetries for in-plane vs. out-of-plane

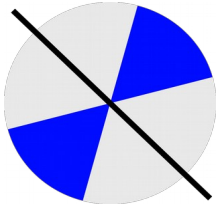






–20% (4σ) pion single-spin asymmetry for in-plane pions

(fit to $R + A\cos\phi_\pi$)



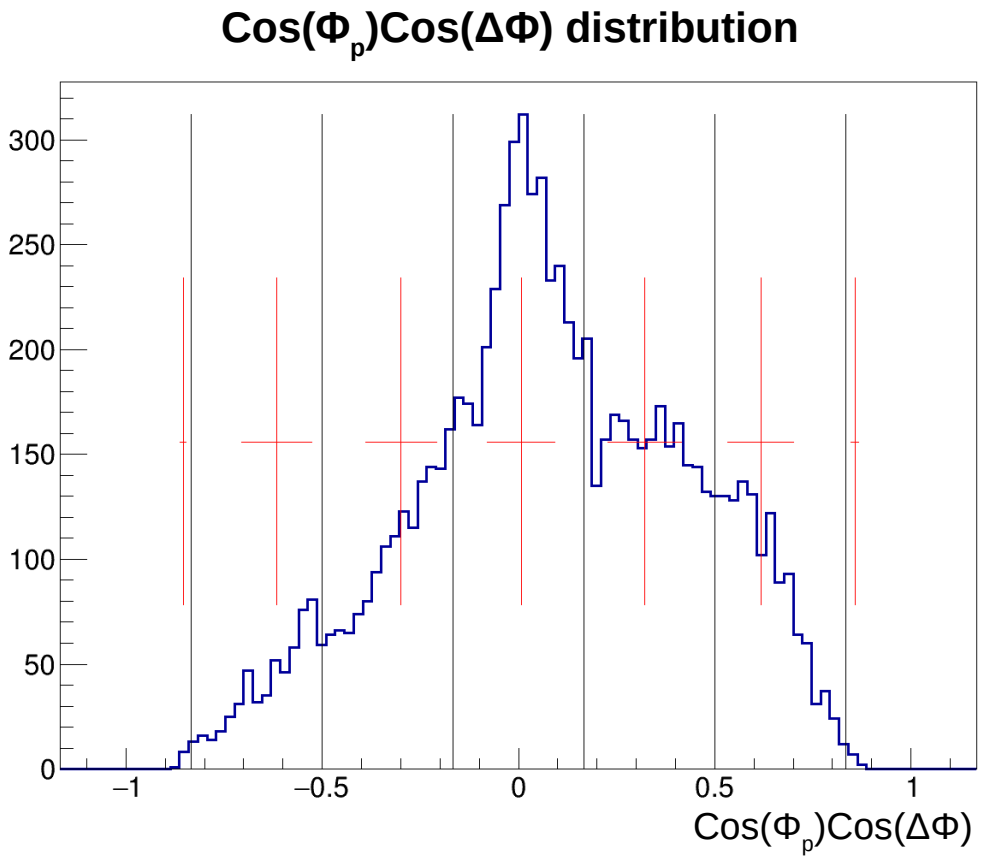
Out-of-plane pion asymmetry consistent with zero

Summary

- The $\mathbf{p^{\uparrow}+p \rightarrow p+\pi^0+X}$ **process** has been observed at **STAR**
- The **proton** and **pion** have transverse momenta of **~0.2** and **~2 GeV/c**, respectively
- Asymmetries dependent on the proton and pion azimuthal angles have been explored
- The most noteworthy asymmetry appears to be modulated by $\mathbf{\cos\Phi_p \cos\Delta\Phi}$, measuring **– 19% ± 5%**
- A large pion asymmetry is seen for pions that scatter *near* the proton scattering plane; on the other hand, for pions that scatter *away* from the proton scattering plane, the pion asymmetry is consistent with zero
- Note that the pion-in-plane asymmetry is *opposite* in sign to the positive ~1% asymmetry seen in forward inclusive pions
- **The mechanism remains open to interpretation**

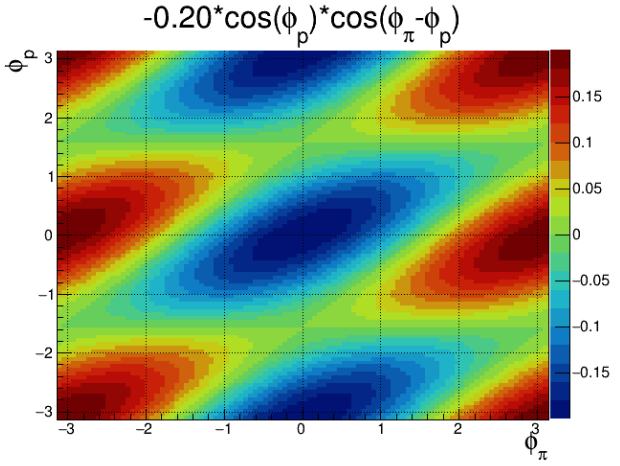
backup

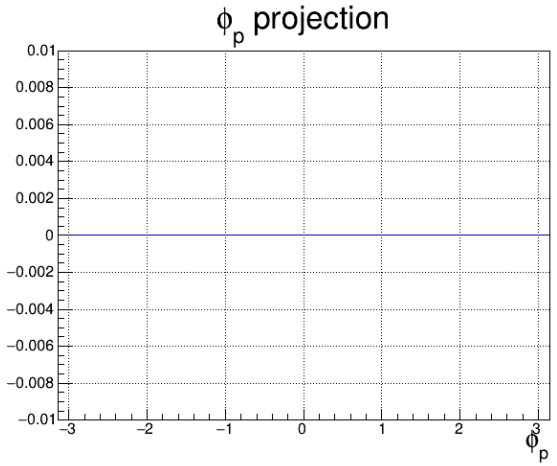
$Cos(\Phi_p)Cos(\Delta\Phi)$ Distribution

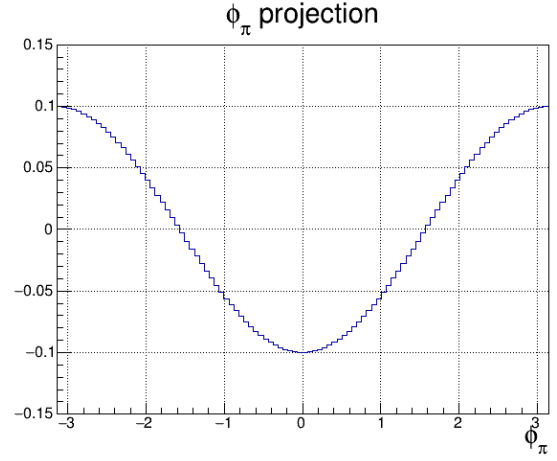


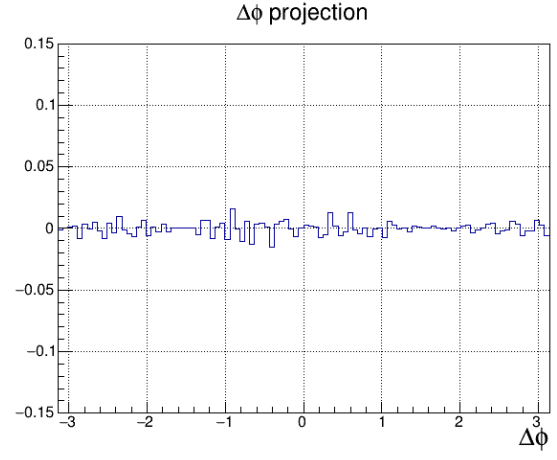
- Data divided into 7 equally-spaced bins, indicated by vertical black lines
- Outermost bins centered on ±1 omitted from asymmetry
- Asymmetry points plotted at bin means, given by horizontal position of vertical red lines
- Length of horizontal red lines denotes bin RMSs

Limited Proton Acceptance Studies



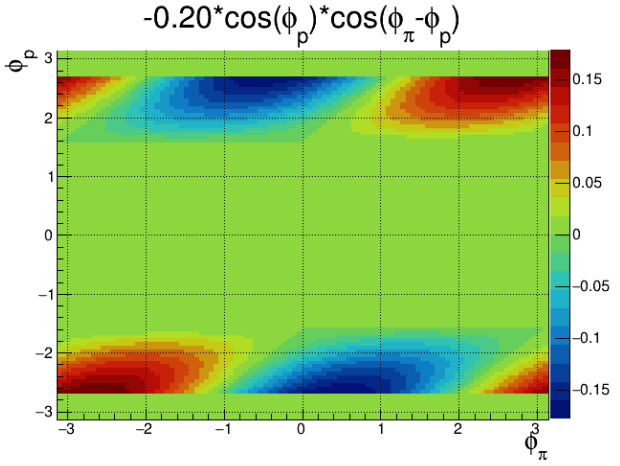


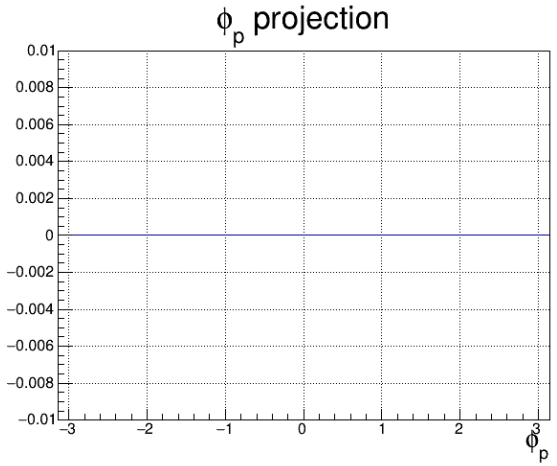


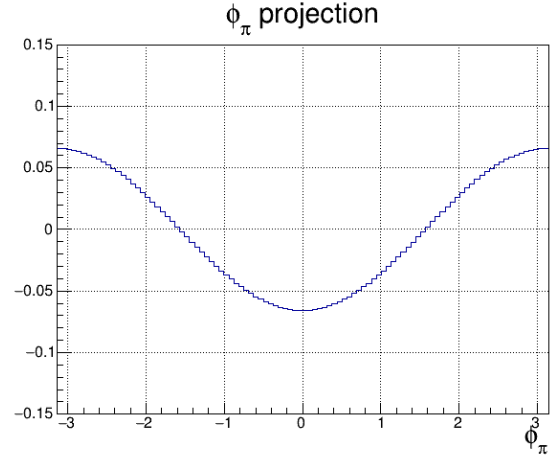


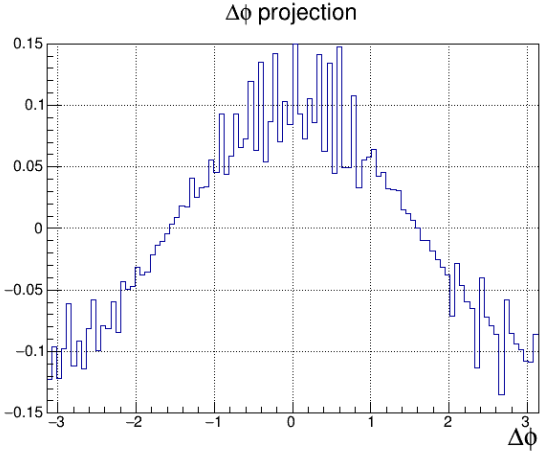
- This is a plot of the $A_{p\pi}$ asymmetry, assuming an amplitude of –20% (upper-left), and its projection to proton azimuth (upper-right), pion azimuth (lower-left), and ΔΦ (lower-right)
- This assumes full azimuthal acceptance for both the proton and pion
- There is no proton single-spin asymmetry
- There is a –10% pion single spin asymmetry
- There is no ΔΦ asymmetry

Limited Proton Acceptance Studies









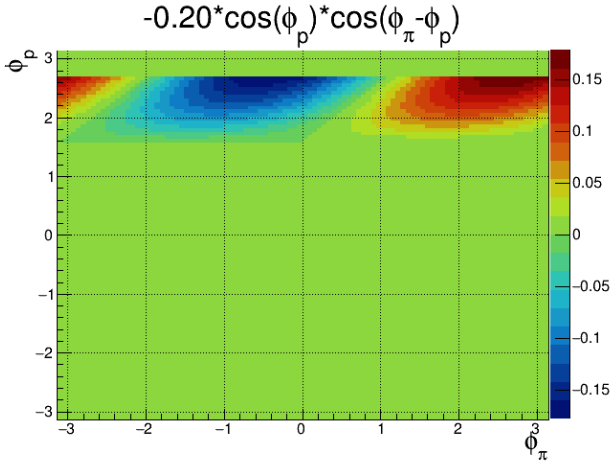
- Now implement the approximate proton azimuthal acceptance limit:

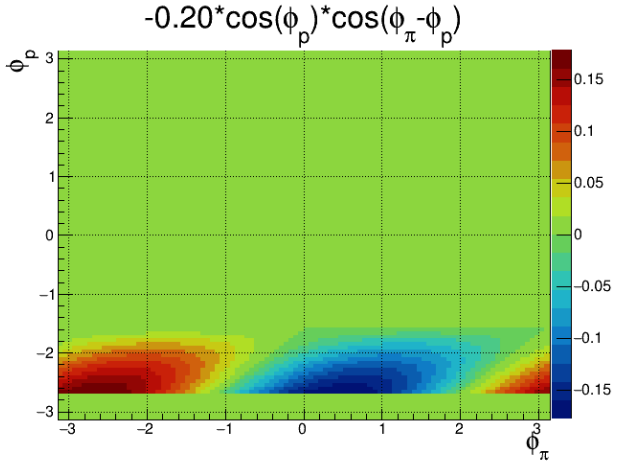
  $\pi/2 < |\Phi_p| < 2.7$

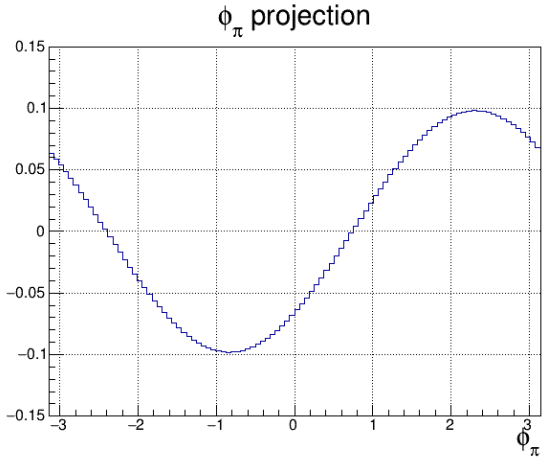
- Still no proton single-spin asymmetry, in agreement with data*
- Pion single-spin asymmetry drops to –6%; this agrees with the data*
- There is now a +10% ΔΦ asymmetry, which is a nonphysical modulation since this angle does not correlate back to proton spin; it also agrees data* and is a pure acceptance effect

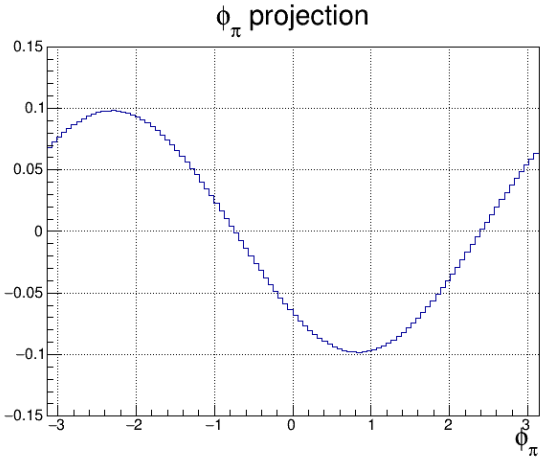
* asymmetry data plot not included in this presentation

Limited Proton Acceptance Studies





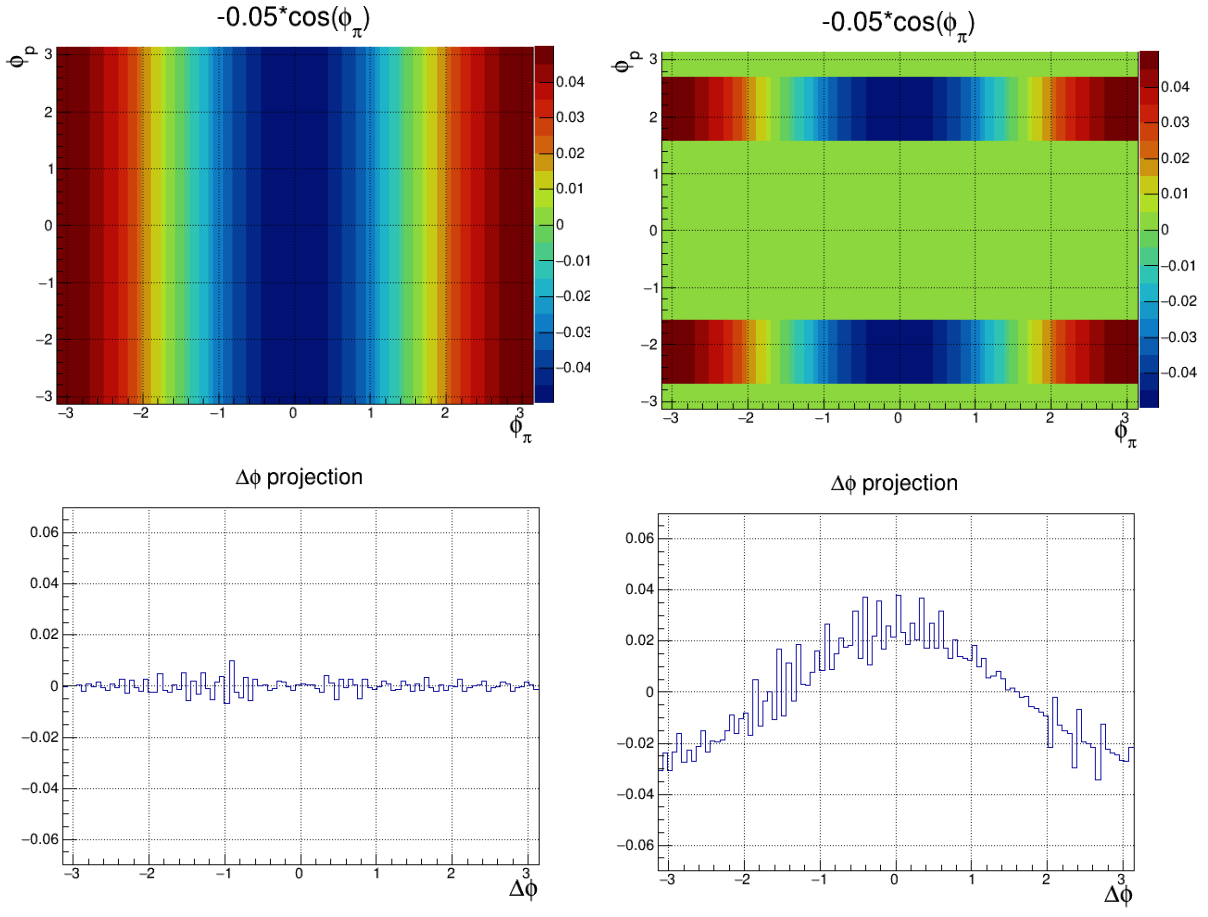




- Keeping the proton azimuthal acceptance limit, now select on protons going either upward (left column plots) or downward (right column plots)
- The pion single spin asymmetry is shown, which also matches data*

* asymmetry data plot not included in this presentation

Limited Proton Acceptance Studies



- Assume the asymmetry is *just* a –5% pion asymmetry
- Left column shows this, with full proton azimuthal acceptance; right column is with limited proton azimuth
- With the limited proton azimuth, a ΔΦ asymmetry does appear, but it is too small relative to the pion asymmetry, in disagreement with the data

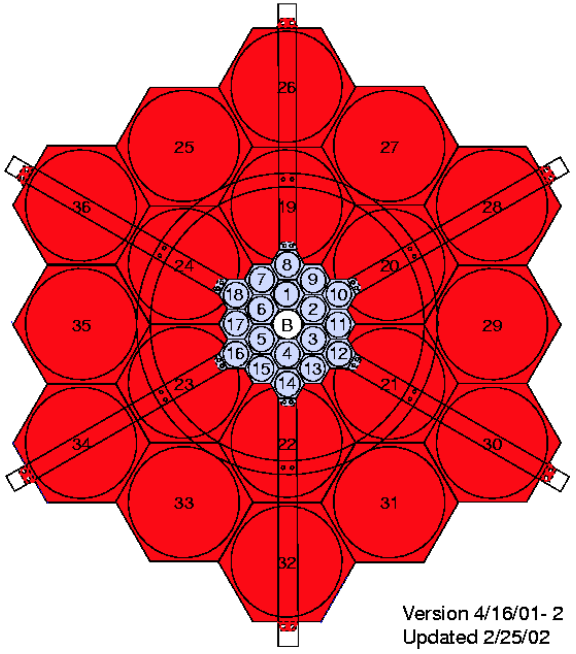
Forward BBC Cuts

Additional cuts for selecting p+p → p+π0+X:

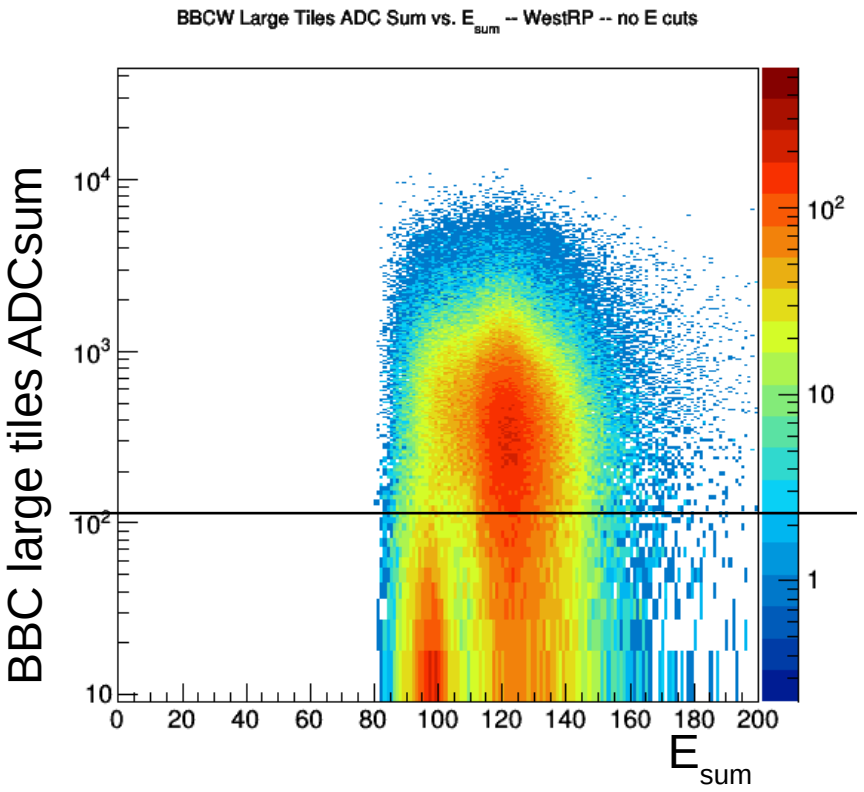
- One good track in forward RP, and no activity in backward RP
- Rudimentary rapidity gap cut using BBC (Beam Beam Counter), a scintillator spanning 2.1 < η < 5:

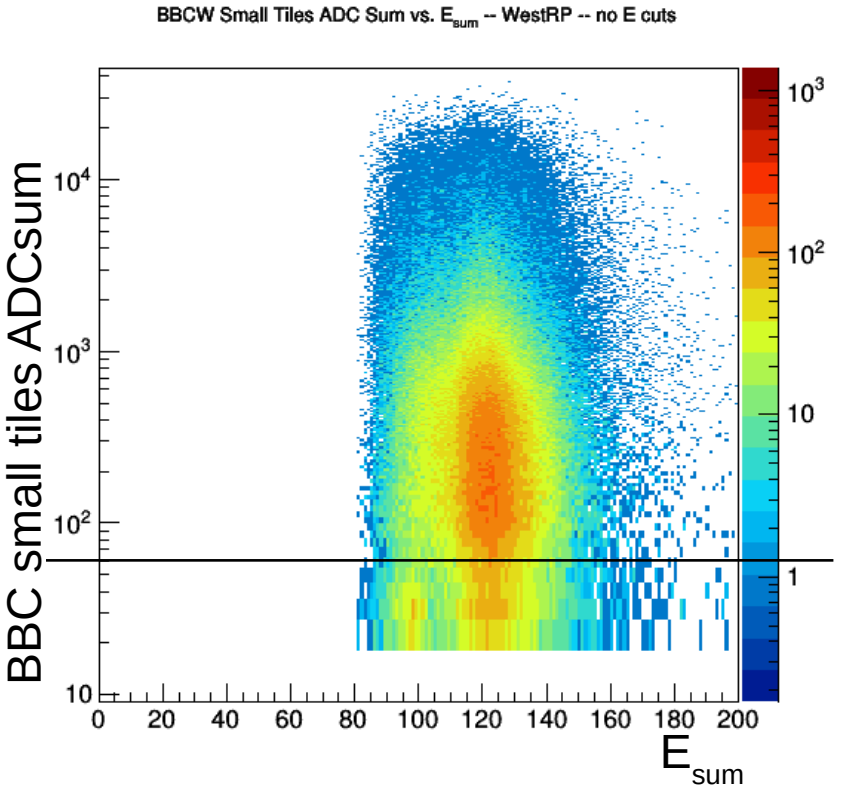
Goals of BBC cuts:

- Reduce events from accidental coincidences with other diffractive / elastic / etc. collisions
- Minimize impact on $pp \rightarrow p\pi^0X$ events, since some π^0s are observed in the BBC



BBC(f) Counts vs. $E_{sum} = E_{proton} + E_{pion}$



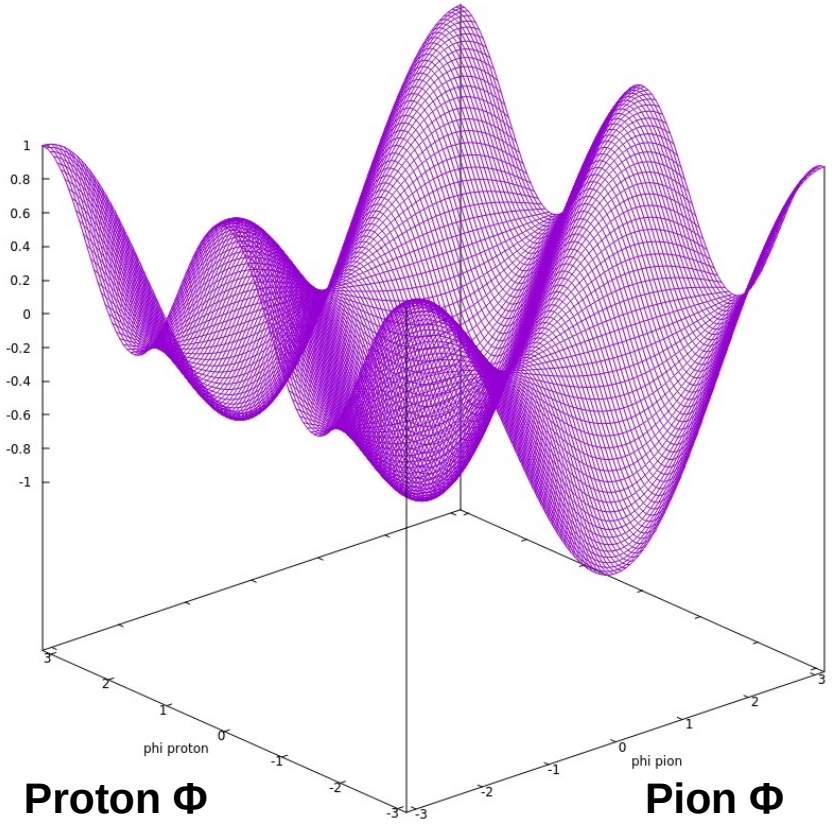


- Some FMS pions are seen in the BBC
- The BBC cuts are set so that these pions are included in the analysis
- Requring, e.g., BBC large tiles ADCsum == 0, is too draconian: it removes ~90% of the data

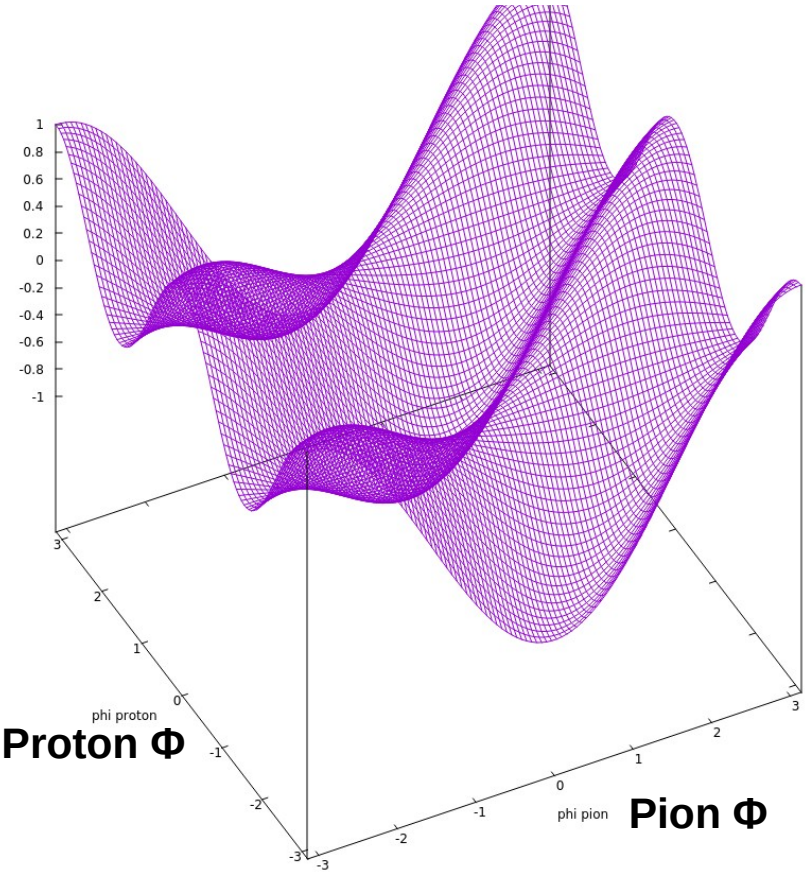
BBC Cuts:

- Large tile ADC sum < 110 counts
- Small tile ADC sum < 60 counts

Plots of $-\mathrm{Cos}(\Phi_p)\mathrm{Cos}(\Delta\Phi)$

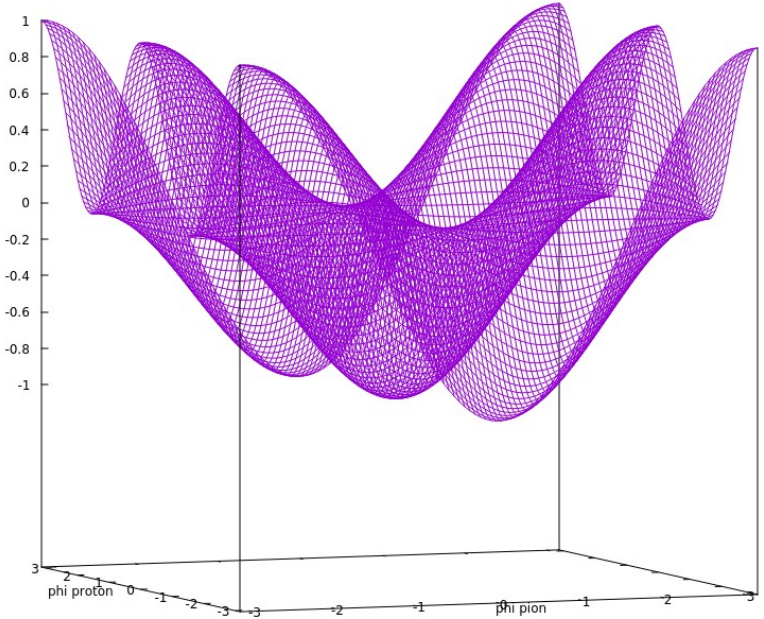


Proton Φ **Pion Φ**



Proton Φ **Pion Φ**

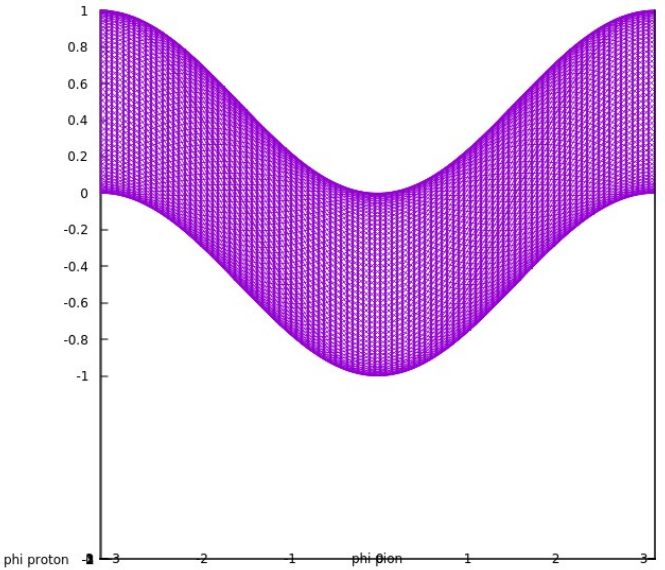
Plots of $-Cos(\Phi_P)Cos(\Delta\Phi)$



Proton Φ

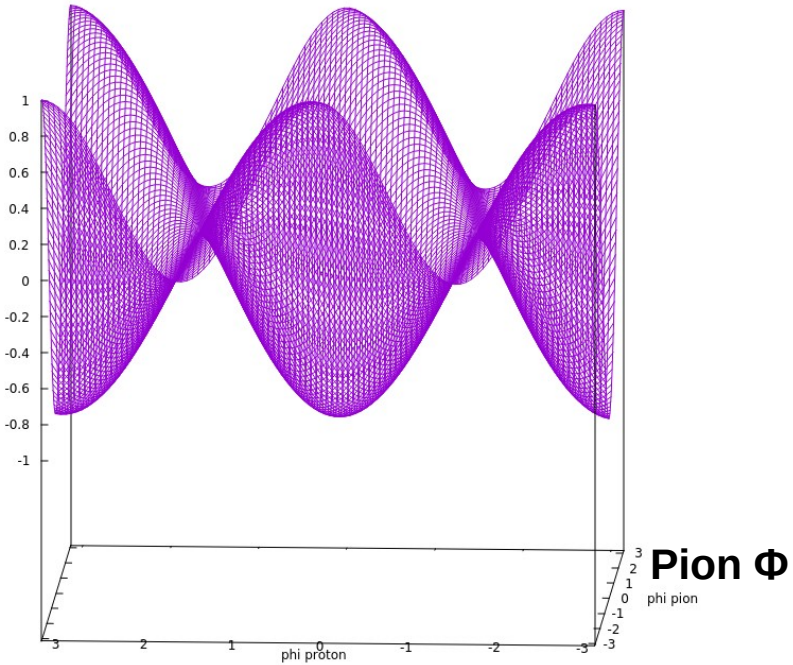
Pion Φ

Pion Φ View



Pion Φ

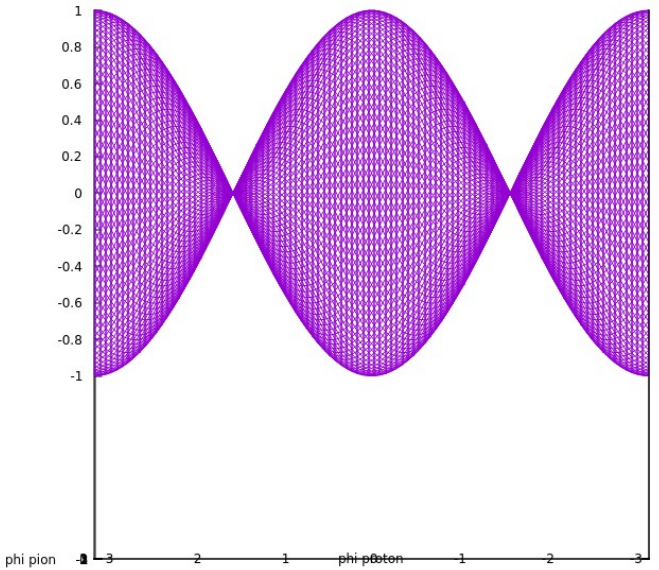
Plots of $-Cos(\Phi_p)Cos(\Delta\Phi)$



Pion Φ

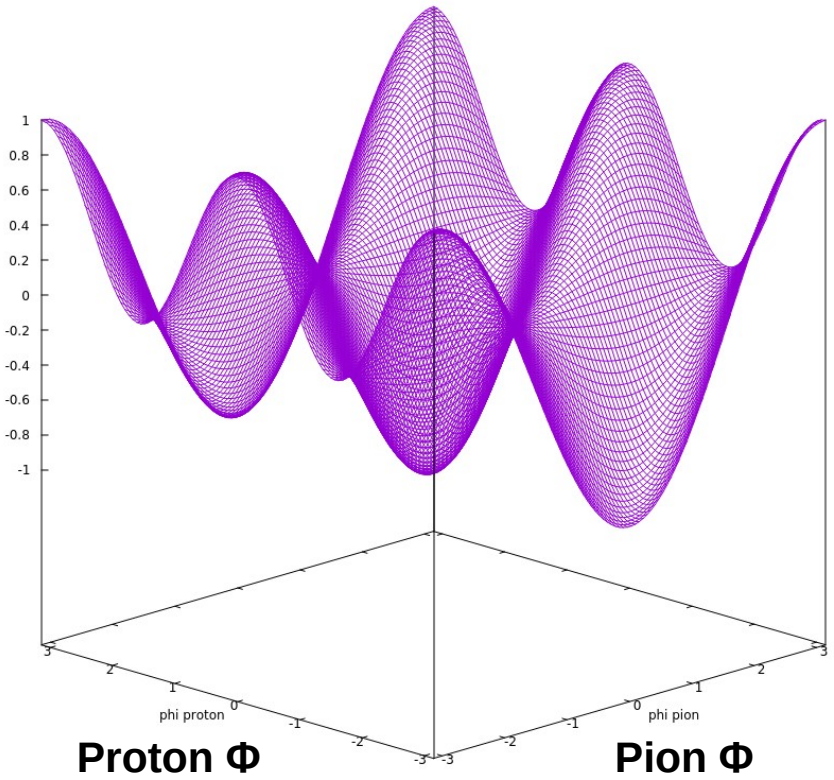
Proton Φ

Proton Φ View



Proton Φ

Plots of $-Cos(\Phi_p)Cos(\Delta\Phi)$



ΔΦ View