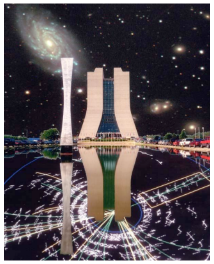
University of Virginia

Search for CP Violation in Hyperon Decays with the Hyper*CP* Spectrometer at Fermilab

Chad J Materniak
for the HyperCP Collaboration

SESAPS 2006

HyperCP (FNAL E871) Collaboration



Chan, Y.C. Chen, C. Ho, P.K. Teng
Academia Sinica Taiwan
W.S. Choong, Y. Fu, G. Gidal, P. Gu, T. Jones, K.B. Luk, B. Turko, P. Zyla
University of California at Berkeley and Lawrence Berkley National Laboratory
C. James, J. Volk
Fermilab
R. Burnstein, A. Chakravorty, D. Kaplan, L. Lederman, W. Luebke, D. Rajaram,
H. Rubin, N. Solomey, Y. Torun, C. White, S. White
Illinois Institute of Technology
N. Leros, J.P. Perround
Universite de Lausanne
R.H. Gustafson, M. Longo, F. Lopez, H.K. Park
University of Michigan
C.M. Jenkins, K. Clark
University of South Alabama
C. Dukes, C. Durandet, T. Holmstrom, M. Huang, L.C. Lu, K. Nelson
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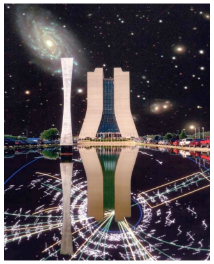
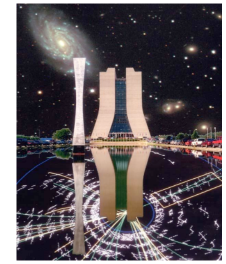
Motivation for CP Violation Studies



- **Mystery**: Why didn't all the matter and antimatter annihilate leaving nothing but an empty universe? What caused the asymmetry?
- **Sakharov's ingredients**: Proposed in 1967
  1) Baryon number violation - a way to get rid of matter (or antimatter) without annihilation.
  2) Violation of both C and CP - allow for different particle/antiparticle decay rates.
  3) Departure from thermal equilibrium when antimatter was turning into matter.
- CP violation has been observed in the K and B systems.
- However, the observed CP violation is insufficient to explain the asymmetry!

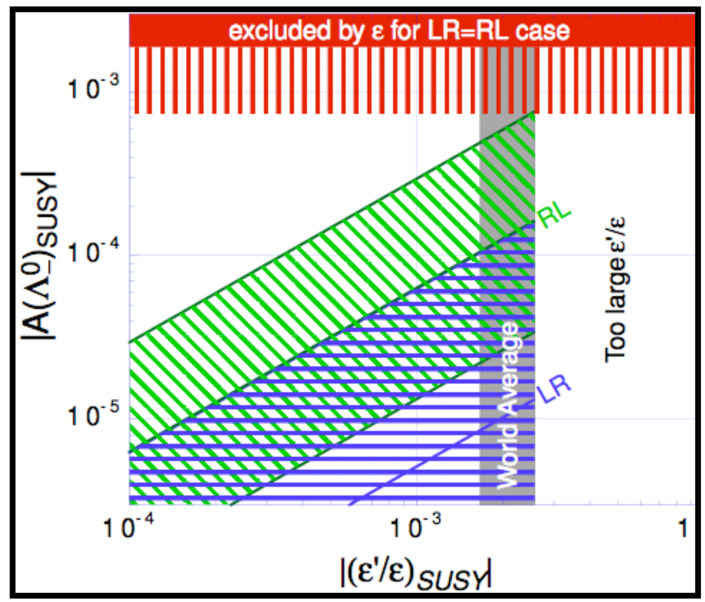
Studies of CP violation may help us understand the matter-antimatter asymmetry and may lead to new physics

Why Search for CP Violation in Hyperon Decays?



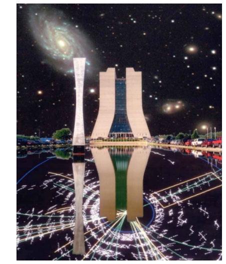
- Hyperons are sensitive to sources of CP violation that kaons are not.
  - Possible CP violation in hyperons is not constrained by kaon sector measurements of ε'/ε
- Many scenarios for new physics allow for large CP asymmetries in Hyperons.
- SM prediction for CP asymmetries are small so any signal strongly suggests new physics.
- Hyperons are experimentally accessible.
  - No new accelerators needed
  - Experimental apparatus is modest in scope and cost.

Calculation of constraints on A_Λ from ε'/ε measurements for various SUSY models.



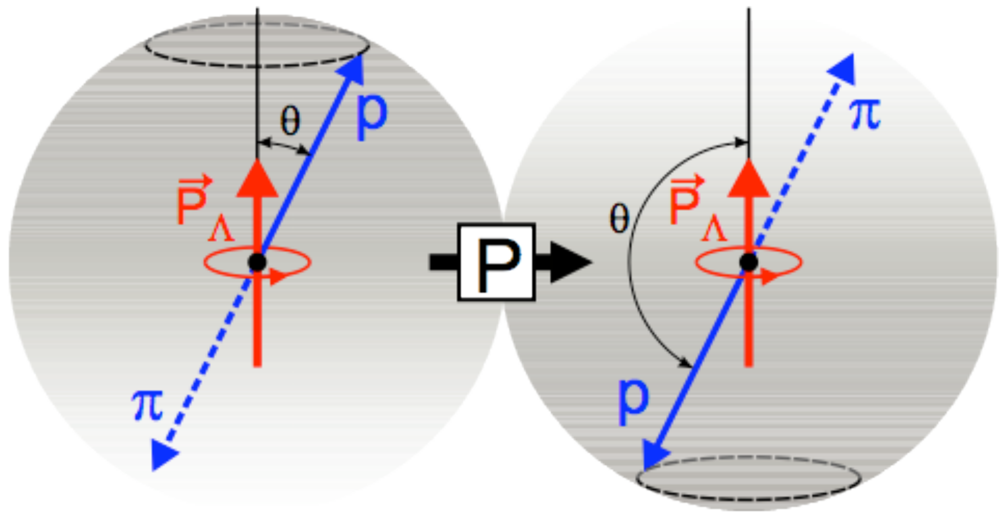
He et al., PRD 61 (2000) 071701(R)

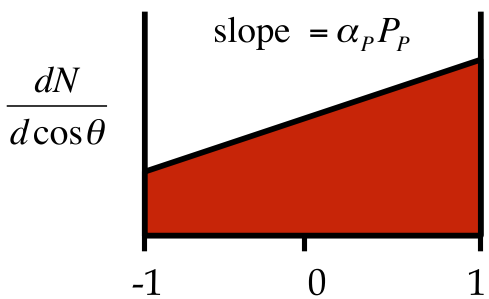
Parity Violation in Hyperon Decays



- Decay modes are two-body non-leptonic.
- Daughter particle decay distributions are anisotropic $\Rightarrow$ parity violating.
- The slope of the daughter baryon $\cos\theta$ distribution is given by $\alpha_P P_P$.
- Magnitudes of parity violation, i.e the α parameters, are generally large.

E.g. $\Lambda \to p\pi^-$

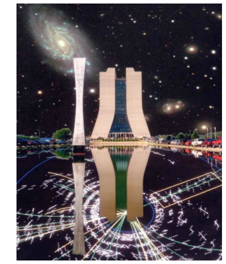




Anisotropic proton decay distribution:

$$\frac{dN}{d\cos\theta} = \frac{N_0}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta)$$

Parity Violation in Hyperon Decays



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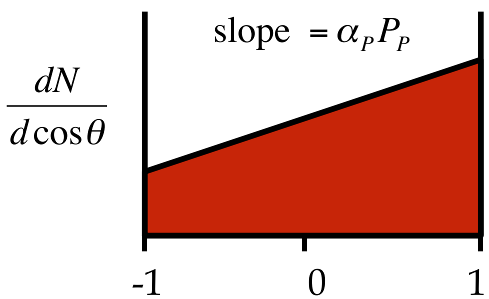
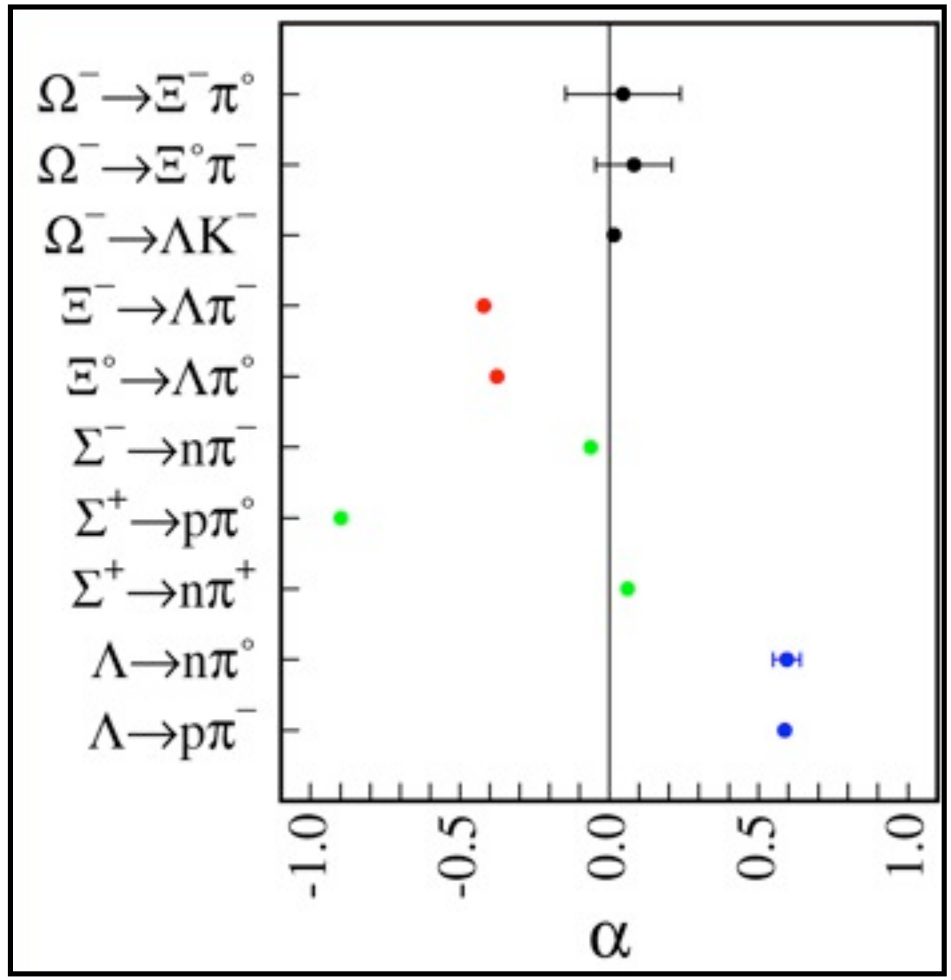
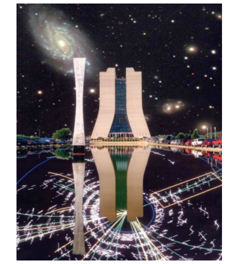


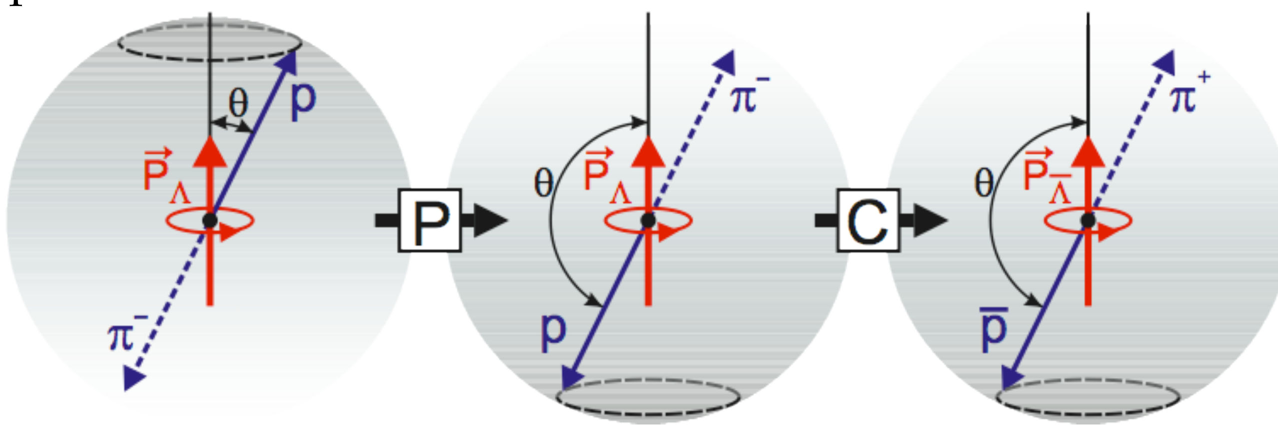


CP Violation in Hyperon Decays



E.g. $\Lambda \rightarrow p\pi^-$

The daughter baryon preferentially decays in the direction of the parent particles polarization.

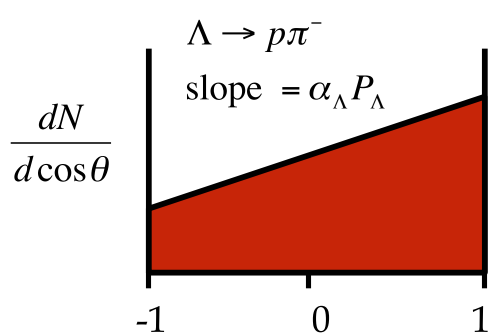


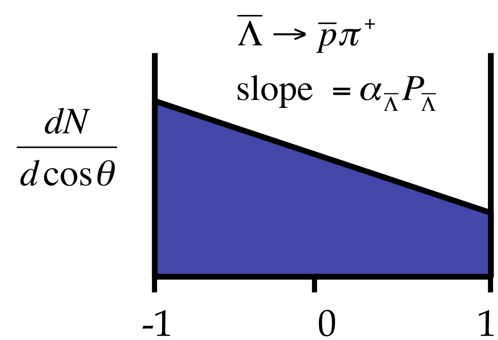
If CP is conserved:

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$$

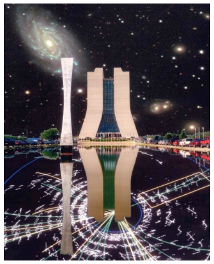
$$\frac{dN(p)}{d\cos\theta} = \frac{N_p}{2}(1 + \alpha_\Lambda P_\Lambda \cos\theta)$$

$$\frac{dN(\bar{p})}{d\cos\theta} = \frac{N_{\bar{p}}}{2}(1 + \alpha_{\bar{\Lambda}} P_{\bar{\Lambda}} \cos\theta)$$





Producing Λ's with Known Polarization



We produce Λ's of known polarization through unpolarized Ξ decays. Targeting at zero degrees insures that our produces Ξ's are unpolarized.

$$\Xi^- \to \Lambda \pi^- \qquad \overline{\Xi}^+ \to \overline{\Lambda} \pi^+$$

If the Ξ is produced unpolarized, then the Λ is found in a helicity state.

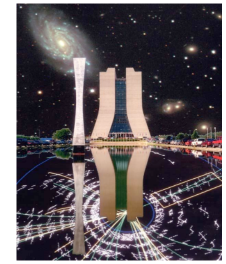
$$\vec{P}_\Lambda = \alpha_\Xi \hat{p}_\Lambda \qquad \vec{P}_{\overline{\Lambda}} = \alpha_{\overline{\Xi}} \hat{p}_{\overline{\Lambda}}$$

$$\frac{dN(p)}{d\cos\theta} = \frac{N_p}{2}(1 + \alpha_\Lambda \alpha_\Xi \cos\theta) \qquad \frac{dN(\overline{p})}{d\cos\theta} = \frac{N_{\overline{p}}}{2}(1 + \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}} \cos\theta)$$

If CP is good, then $\alpha_\Lambda \alpha_\Xi = \alpha_{\overline{\Lambda}} \alpha_{\overline{\Xi}}$

If CP is conserved, the slopes of the proton and antiproton $\cos\theta$ distributions are equal!

Producing Λ's with Known Polarization



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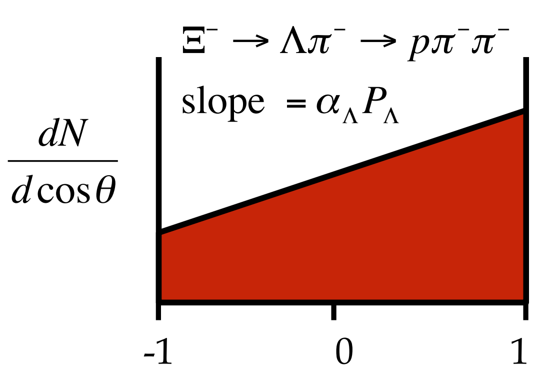
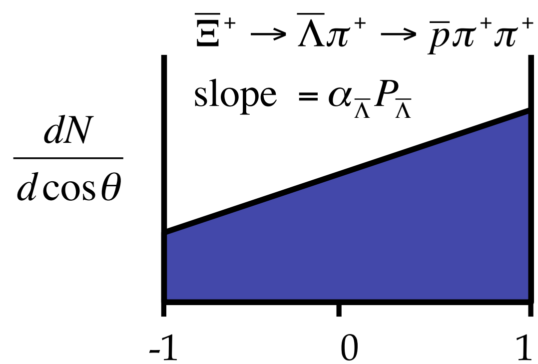




If CP is good, then $\alpha_\Lambda\alpha_\Xi = \alpha_{\overline{\Lambda}}\alpha_{\overline{\Xi}}$

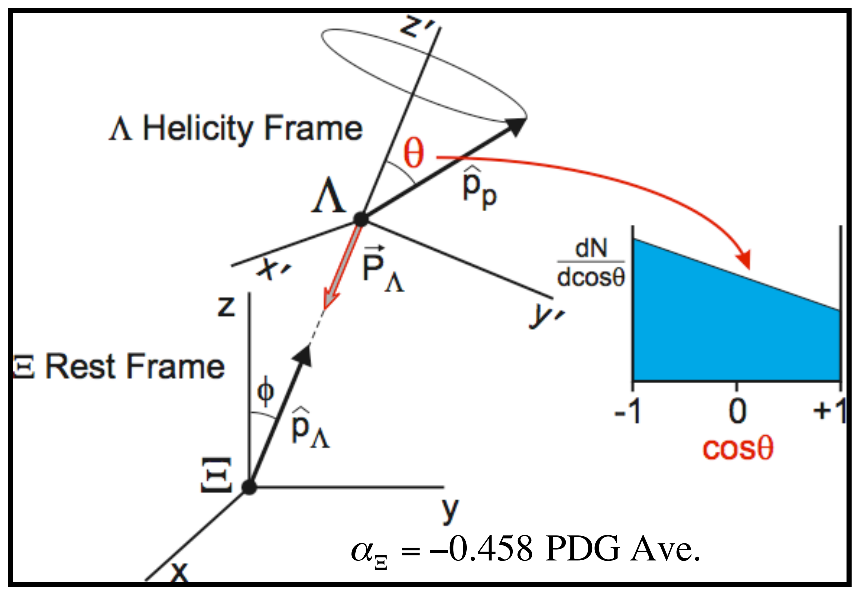
If CP is conserved, the slopes of the proton and antiproton $\cos\theta$ distributions are equal!

CP Violating Asymmetry: $A_{\Xi\Lambda}$

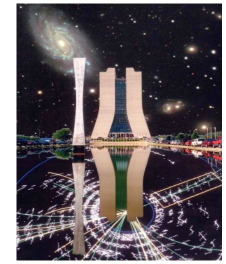
From the $\cos\theta$ distributions we seek to extract the asymmetry parameter $A_{\Xi\Lambda}$.

$$A_{\Xi\Lambda} = \frac{\alpha_{\Xi}\alpha_{\Lambda} - \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}}{\alpha_{\Xi}\alpha_{\Lambda} + \alpha_{\overline{\Xi}}\alpha_{\overline{\Lambda}}} \approx A_{\Lambda} + A_{\Xi} \quad \text{where,} \quad \begin{cases} A_{\Xi} = \dfrac{\alpha_{\Xi} + \alpha_{\overline{\Xi}}}{\alpha_{\Xi} - \alpha_{\overline{\Xi}}} \\ A_{\Lambda} = \dfrac{\alpha_{\Lambda} + \alpha_{\overline{\Lambda}}}{\alpha_{\Lambda} - \alpha_{\overline{\Lambda}}} \end{cases}$$

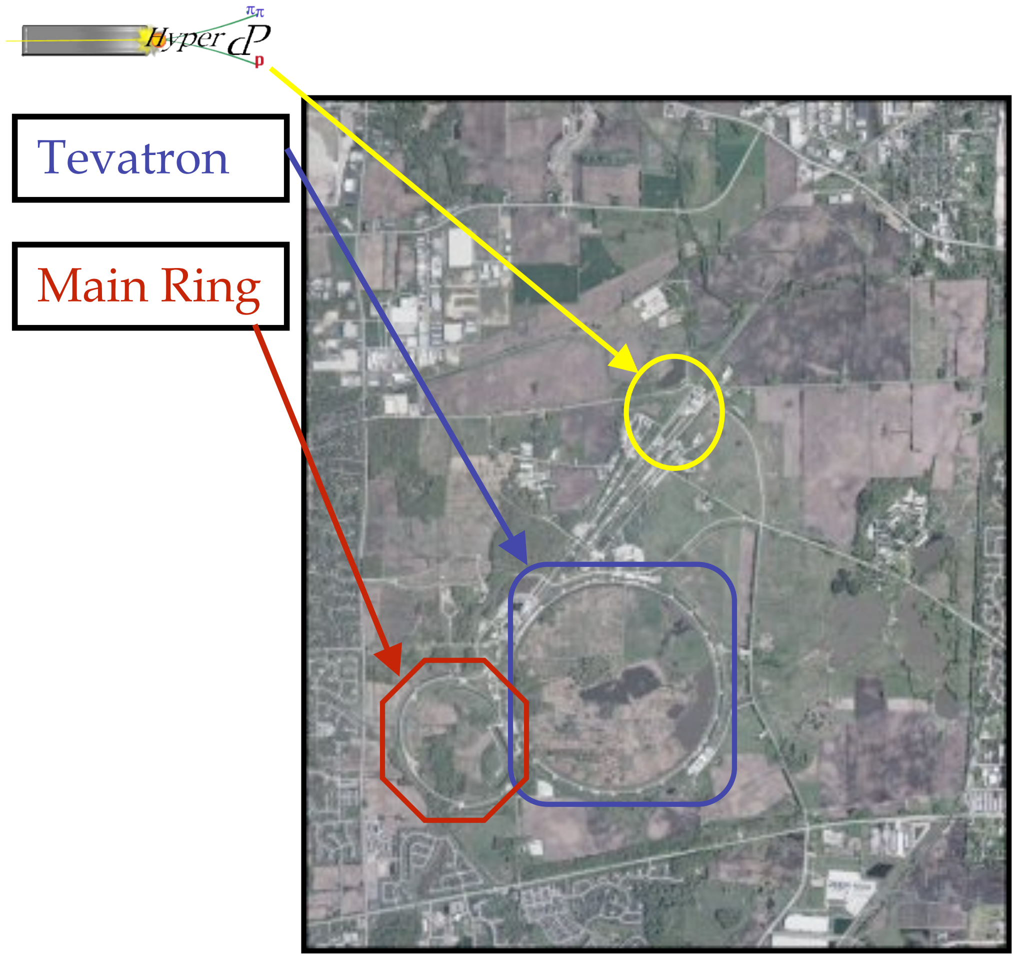
The slope is measured in the Λ rest frame where the orientation of the polar axis is defined by the Λ momentum in the Ξ rest frame.



Hyper*CP* Spectrometer at Fermilab



- Spectrometer sat in Fermilab's meson line.
- Data taking runs completed in 1997 & 1999.
- Spectrometer specifications:
  - 800 GeV incident proton beam
  - 167 GeV secondary beam
  - High rate DAQ (100k evts/s)
  - High rate, narrow pitch wire chambers for tracking
  - Two hodoscopes and hadron calorimeter at rear for triggering



Designed to minimize bias when switching from Ξ^- to Ξ^+ modes.

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A look up the Meson Line

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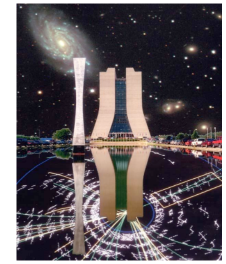

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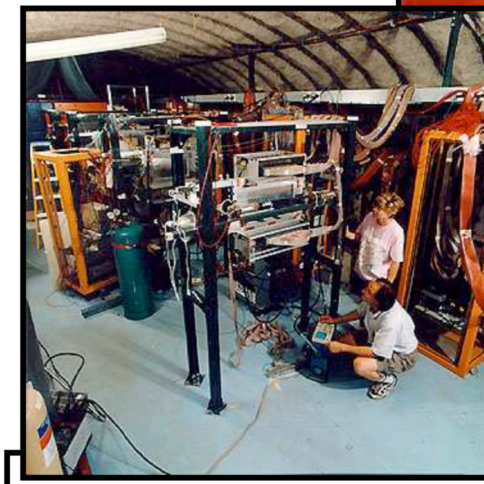
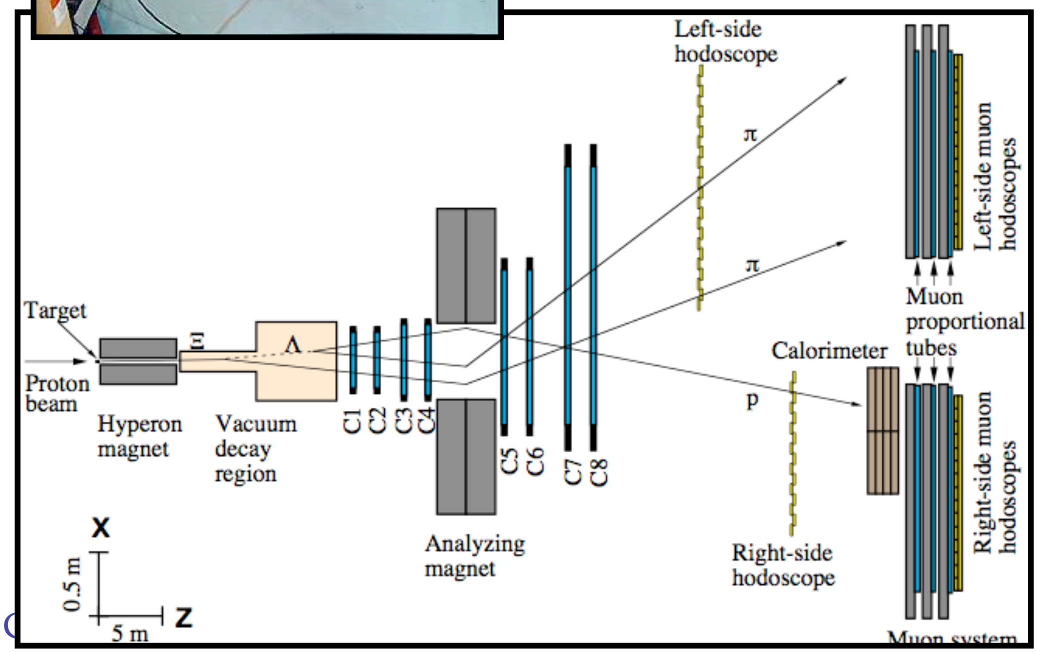
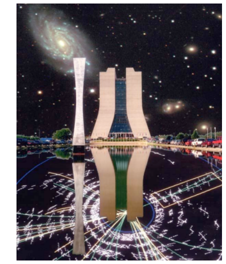


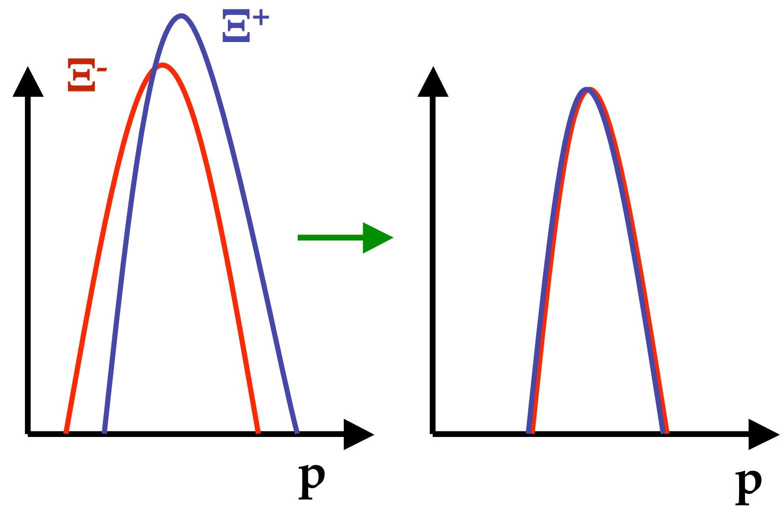


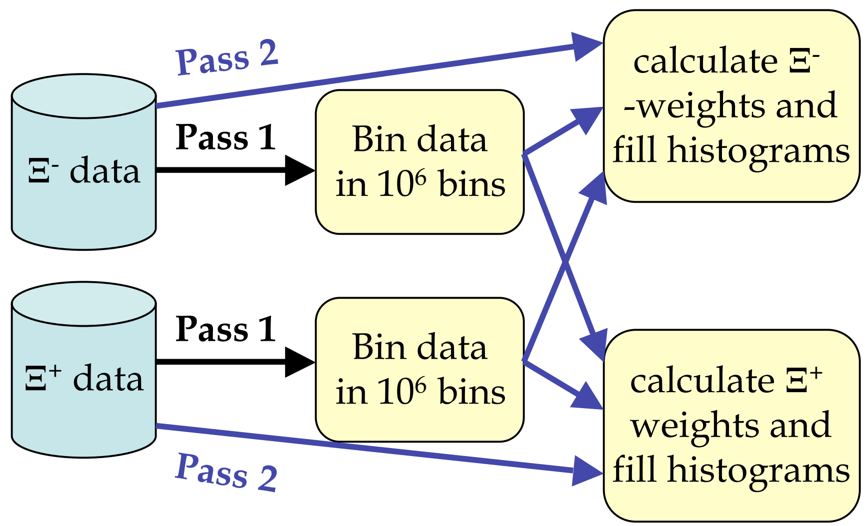
Accounting for Ξ⁻,Ξ⁺ Acceptance Differences



- Differences in production mechanisms for the Ξ^- and Ξ^+ lead to spectrometer acceptance differences.
- **Fix**: Weight Ξ^- and Ξ^+ momentum distributions and force them to be identical.
  - Weight the Ξ's momentum dependent parameters at exit of the collimating magnet.
  - 10^6 total bins.
  - Perform measurement of $\cos\theta$ distribution.

This method equalizes acceptance between Ξ^- and Ξ^+ events





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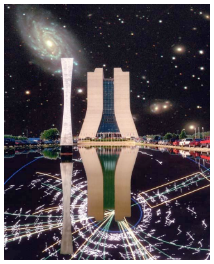

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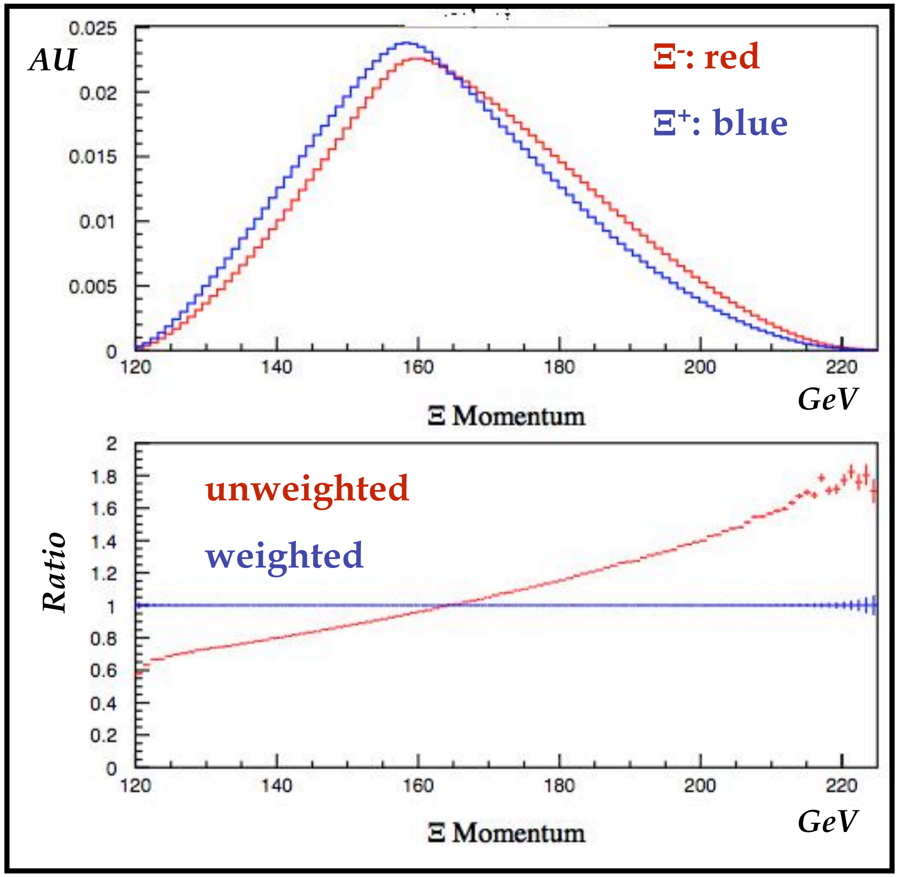

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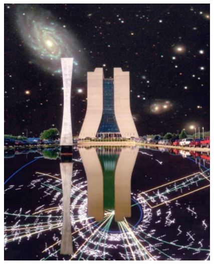

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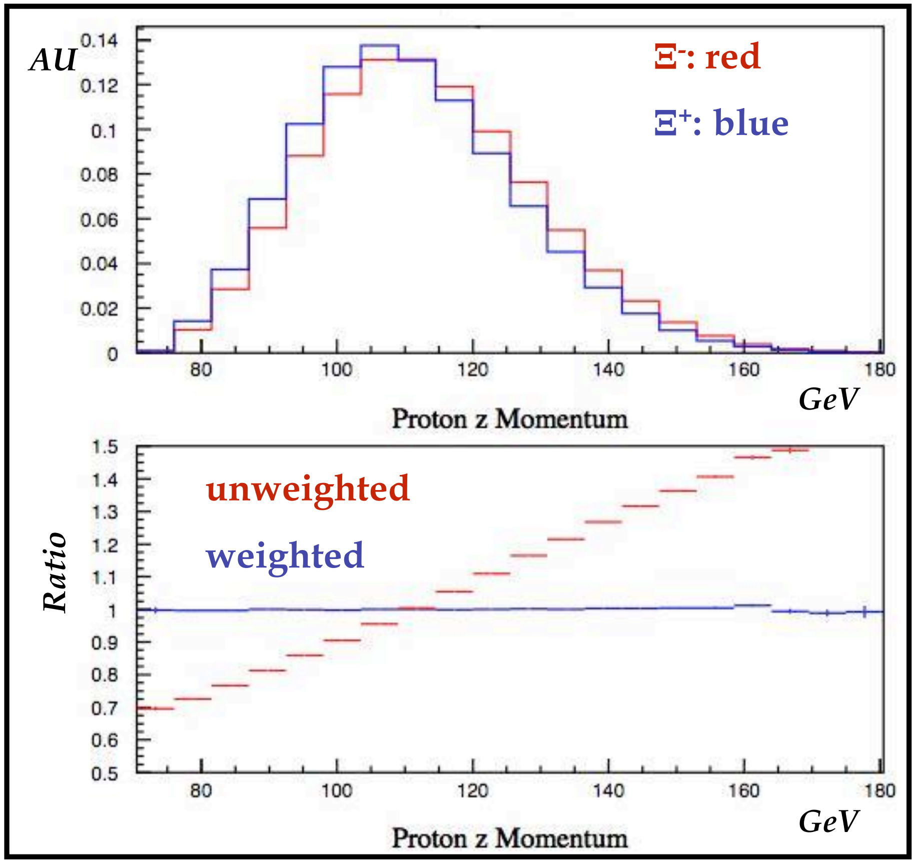
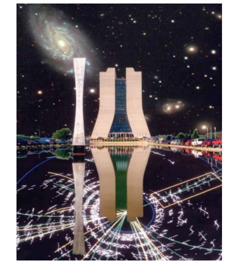


Extracting the CP Asymmetry from Data



- The $\cos\theta$ ratios for the proton and antiproton are:

$$\frac{dN(p)}{d\cos\theta} = \frac{N_p}{2}(1+\alpha_\Lambda\alpha_\Xi\cos\theta)$$

$$\frac{dN(\bar{p})}{d\cos\theta} = \frac{N_{\bar{p}}}{2}(1+\alpha_{\bar{\Lambda}}\alpha_{\bar{\Xi}}\cos\theta)$$

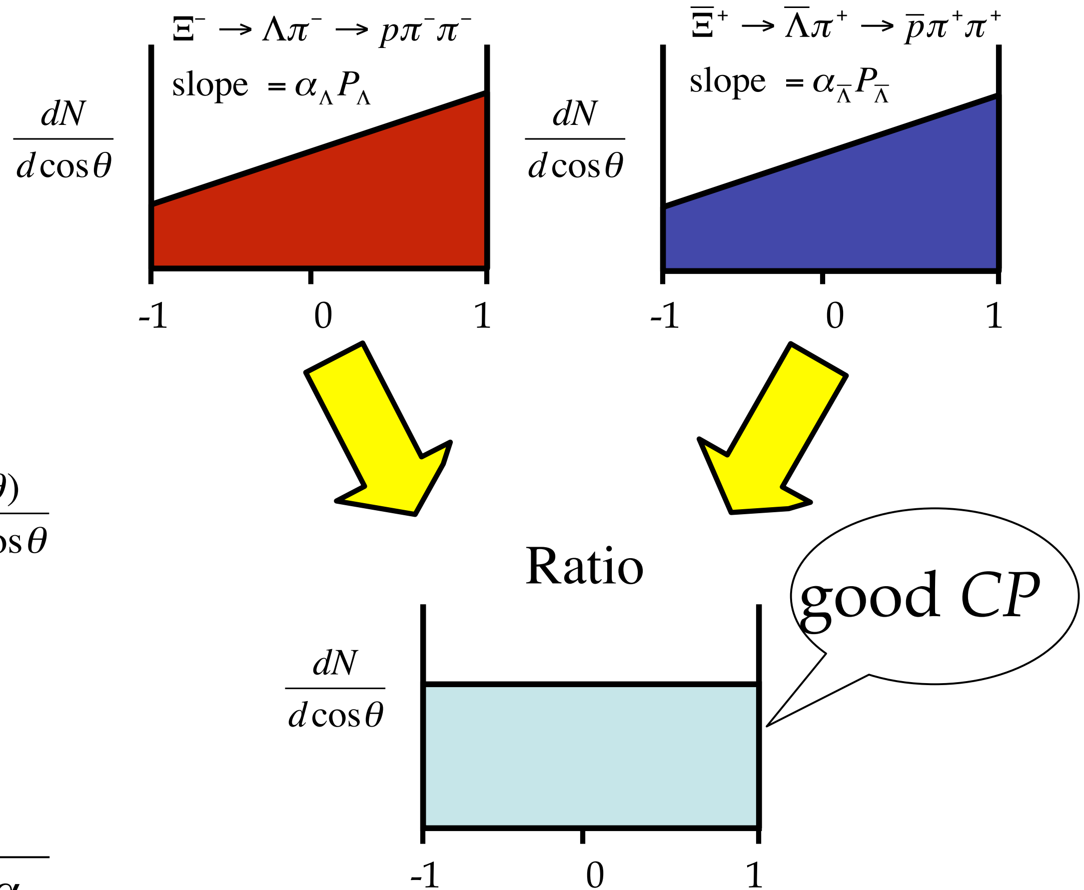
- We fit the ratios to:

$$R(\cos\theta,\delta) = \frac{N_p}{N_{\bar{p}}}\frac{(1+\alpha_\Xi\alpha_\Lambda\cos\theta)}{1+(\alpha_\Xi\alpha_\Lambda-\delta)\cos\theta}$$

$$\delta \equiv \alpha_\Xi\alpha_\Lambda - \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}$$

- Then we extract the asymmetry.

$$A_{\Xi\Lambda} = \frac{\delta}{\alpha_\Xi\alpha_\Lambda + \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}} \approx \frac{\delta}{2\alpha_\Xi\alpha_\Lambda}$$



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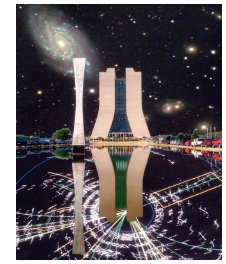

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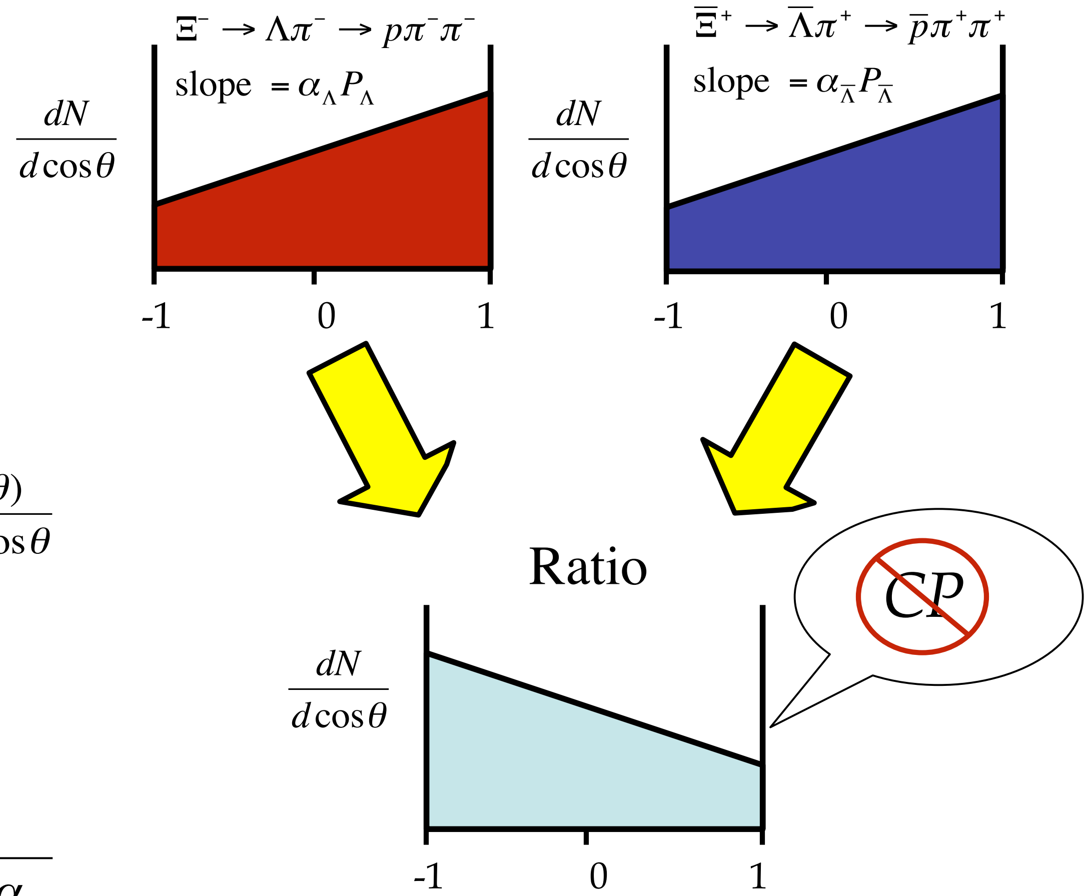
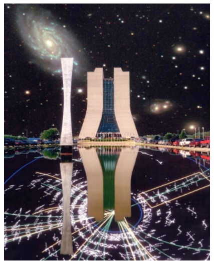


No MC necessary to extract result!

Published Result

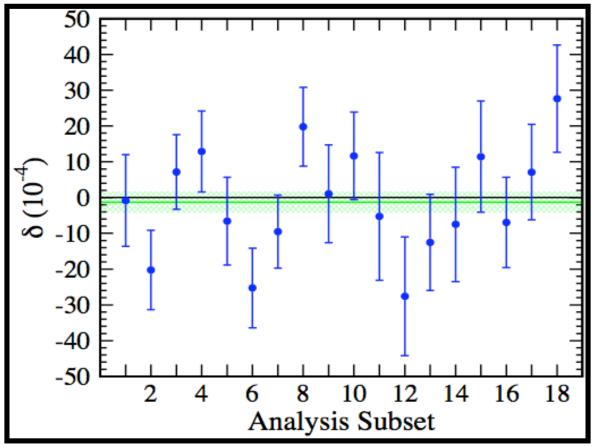


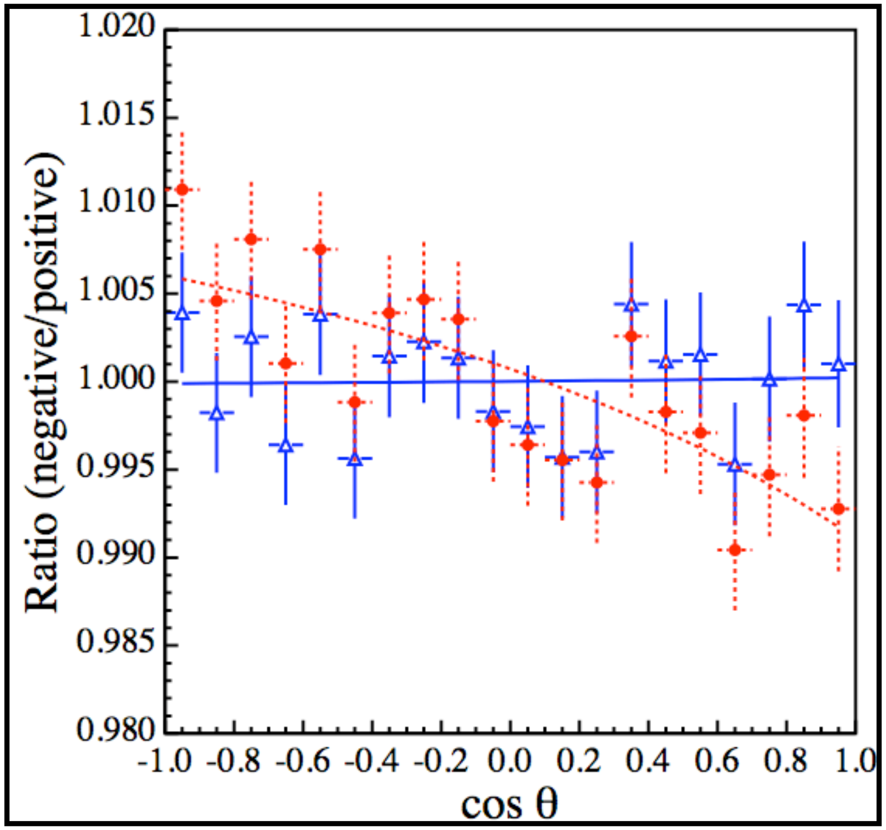
- Approximately 10% of data broken into 18 analysis subsets and analyzed.
- δ extracted for each data subset and $A_{\Xi\Lambda}$ calculated from:

$$A_{\Xi\Lambda} = \frac{\delta}{\alpha_{\Xi}\alpha_{\Lambda} + \alpha_{\bar{\Xi}}\alpha_{\bar{\Lambda}}} \approx \frac{\delta}{2\alpha_{\Xi}\alpha_{\Lambda}}$$

- The weighted average from the 18 measurements is (BKG subtracted):

$$A_{\Xi\Lambda} = [0.0 \pm 5.1(stat) \pm 4.4(syst)] \times 10^{-4}$$ (*)

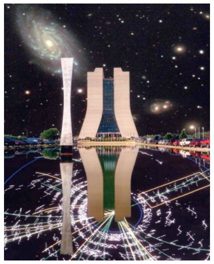




Proton/antiproton cosθ ratio before (•) and after (Δ) weighting.

(*) PRL 31 Dec. 2004

Published Result



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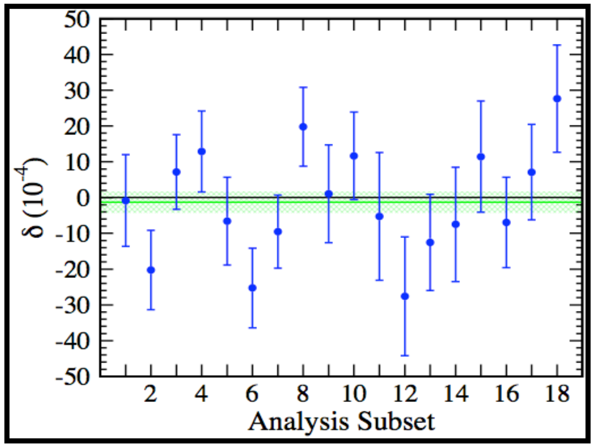

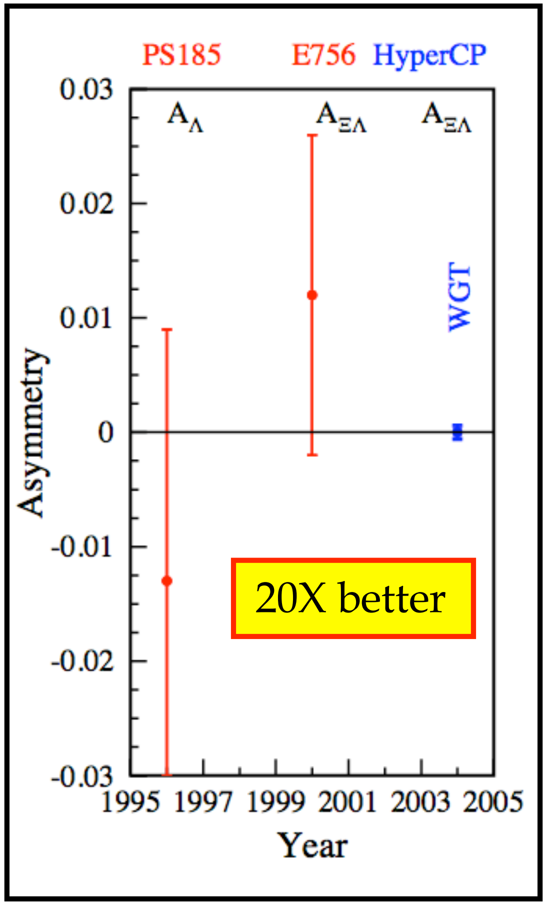

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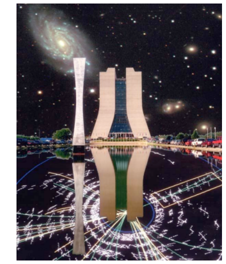

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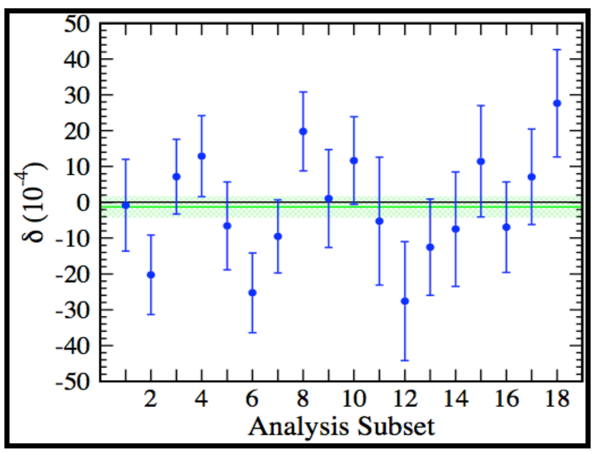
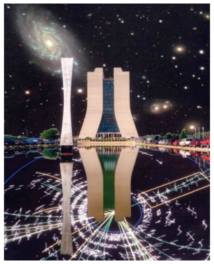


Systematic	Method	$\delta A_{\Xi\Lambda}(10^{-4})$
Analyzing Magnets field uncertainties	Data	2.4
Calorimeter inefficiency uncertainty	Data	2.1
Validation of analysis code	CHMC	1.9
Collimator exit x slope cut	Data	1.4
Collimator exit x position cut	Data	1.2
PWC inefficiency uncertainty	CHMC	1.0
Hodoscope inefficiency uncertainty	Data	0.3
Particle/antiparticle interaction differences	MC	0.9
Momentum weights bin size	Data	0.4
Background subtraction uncertainty	Data	0.3
Error on $\alpha\alpha_{PDG}$	Data	0.03
Polarization	MC	negligible
Earth's magnetic field	CHMC	negligible
Total systematic error		4.4

- MC only used to validate the analysis technique.
- Most systematic uncertainties can be reduced with the analysis of the full data set.

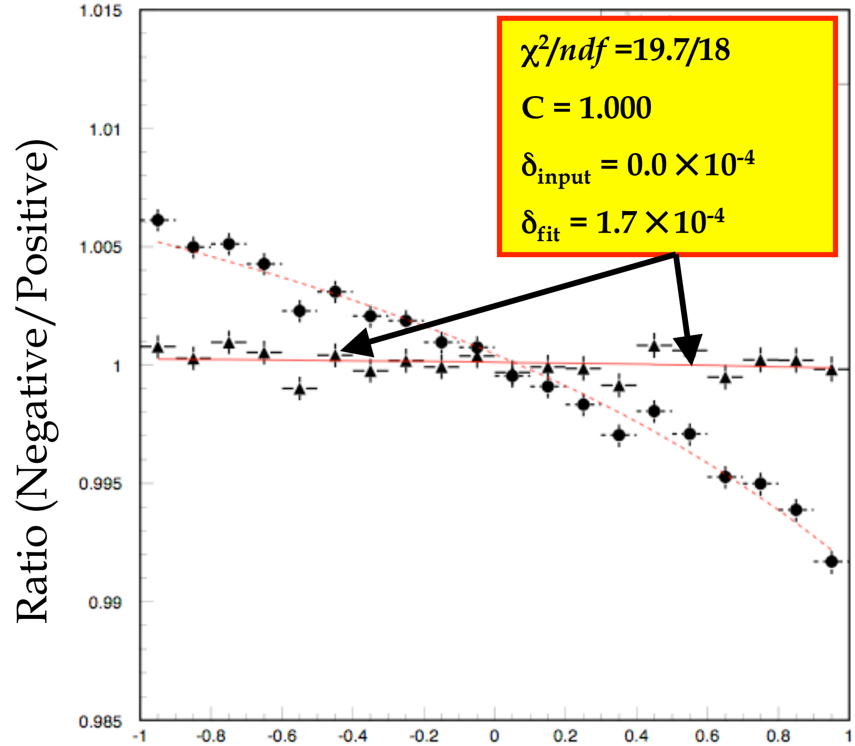
Expanding the Analysis to the Full Data Set



- Approx 1 billion Ξ decays separated into 10 analysis sets using the entire 1999 Hyper*CP* data sample.
- 10 billion MC events generated at Fermilab in order to verify the analysis technique.
- Expect sensitivity better than $\delta A_{\Xi\Lambda} = 2 \times 10^{-4}$.

Detailed systematic error studies underway.

MC Data: 0.5B events



Proton/antiproton cosθ ratio before (•) and after (Δ) weighting.

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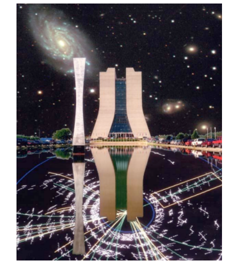

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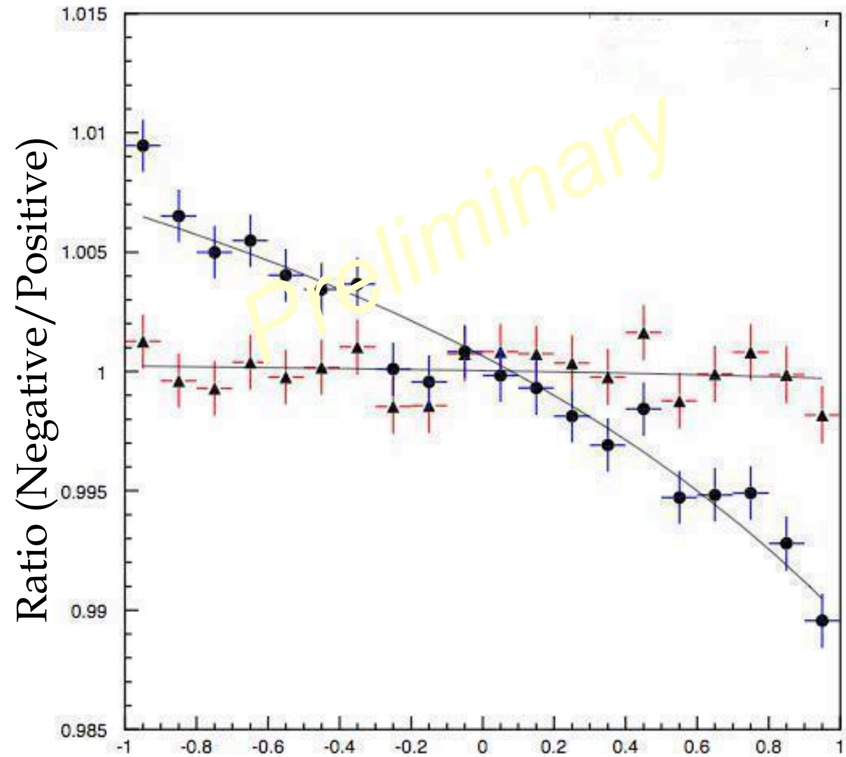
Real Data: >100M events



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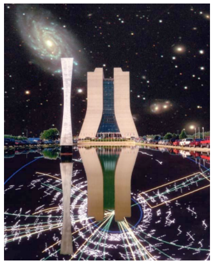

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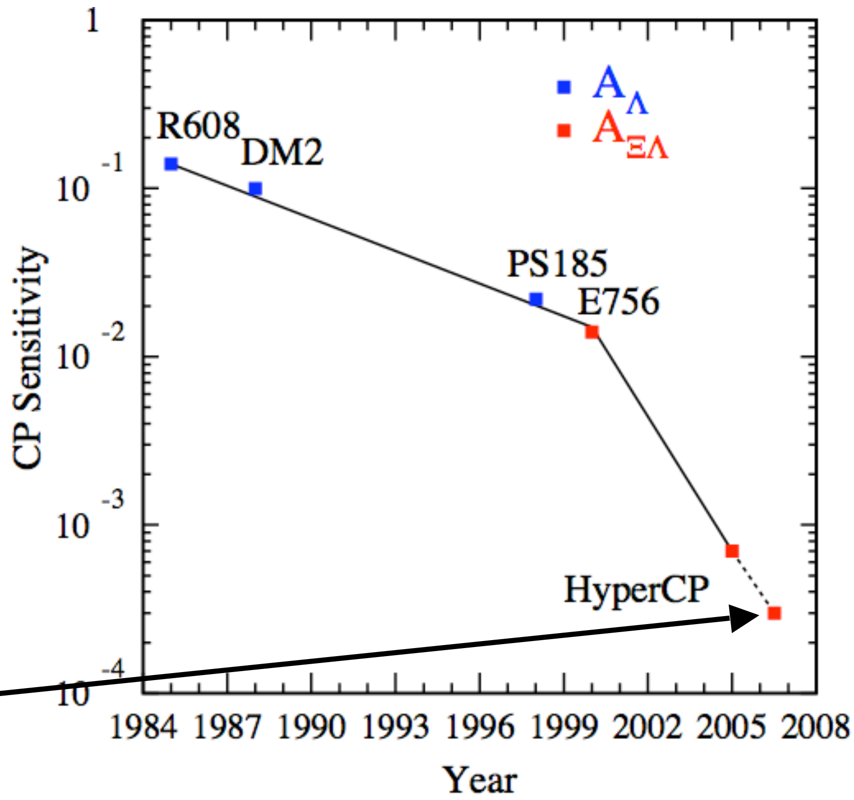
Future CP Sensitivity



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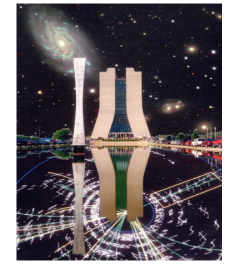

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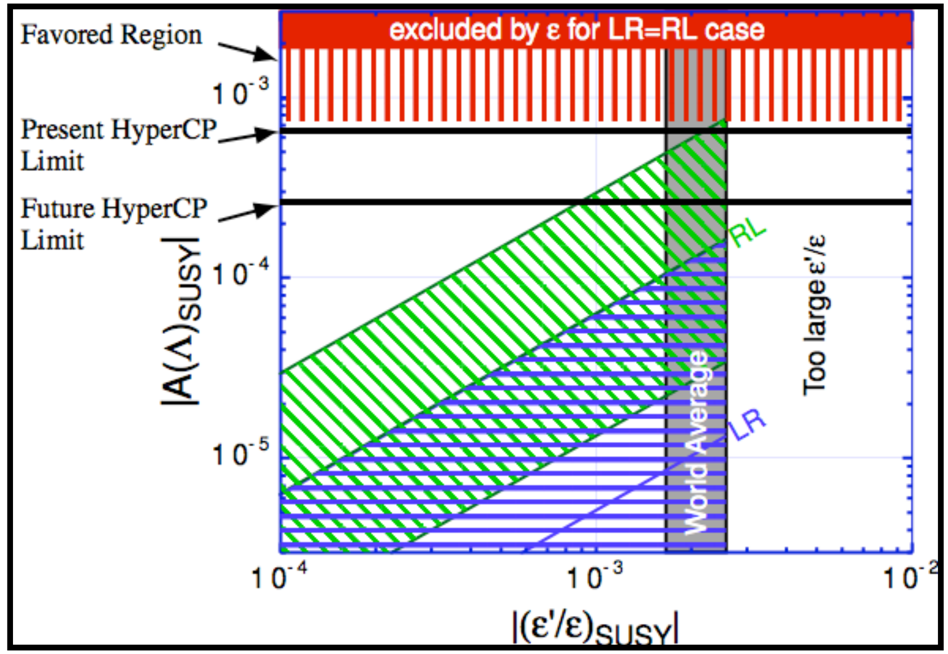
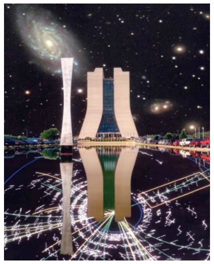


Detailed systematic error studies underway.

Results already constrain upper SUSY limits.

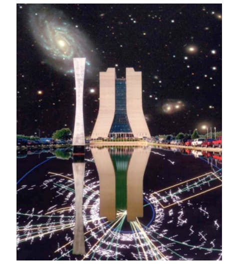
Conclusions and Outlook



- Using the largest sample of hyperon decays ever amassed by an experiment, the Hyper*CP* collaboration is making a precision search for CP violation from exotic sources.
- Measurements are complementary to those carried out in the K and B sectors.
- Thus far we have found no evidence of CP violation in $\Xi^{\pm}$ and Λ decays
  - $\delta A_{\Xi\Lambda} = [0.0 \pm 5.1(stat) \pm 4.2(syst)] \times 10^{-4}$
- Analysis of the entire 1999 data sample is underway.
  - MC running on Fermilab Grid
  - Weighting technique working
  - Systematic studies in progress
  - Shortly we will push our uncertainty to our statistical limit and reach an uncertainty $\delta A_{\Xi\Lambda} \sim 2 \times 10^{-4}$.

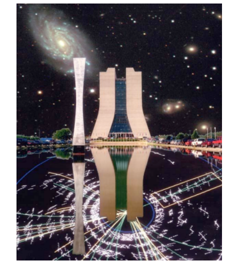
Backup Slides

Hyper*CP* Experimental Goals



- Primary goal:
  - Search for CP violation in $\Xi^{\pm} \to \Lambda\pi^{\pm} \to p\pi^{\pm}\pi^{\pm}$ decays.
- Secondary goals:
  1) Search for CP violation in $\Omega^{\pm} \to \Lambda K^{\pm}$.
  2) Lepton number violation in $\Xi^{-} \to p\mu^{-}\mu^{-}$.
  3) Flavor changing neutral currents in hyperon and charged kaon decays:
     $\Sigma^{+} \to p\mu^{+}\mu^{-}$, $K^{\pm} \to \pi^{\pm}\mu^{+}\mu^{-}$.
  4) $\Delta S > 1$ decays: $\Xi^{-} \to p\pi^{-}\pi^{-}$, $\Omega^{-} \to \Lambda\pi^{-}$
  5) Search for θ^{+} pentaquark.
- Measurement of hyperon production and decay parameters:
  1) $\Xi^{\pm}$ and $\Omega^{\pm}$ polarization.
  2) β decay parameter in Ξ^{-} decays $\Rightarrow$ $\Lambda\pi$ strong phase shift.
  3) α decay parameter in $\Omega^{\pm} \to \Lambda K^{\pm}$.
  4) Hyperon production cross sections.

Phenomenology of CP Violation in Hyperon Decays



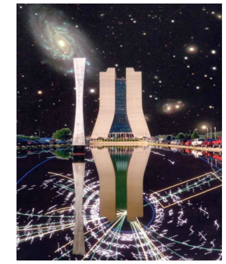
- CP violation is manifestly direct with $\Delta S = 1$.
- Three ingredients are necessary to get a non zero asymmetry:
  1) At least two channels in the final state: S- and P-wave amplitudes.
  2) The CP violating weak phases must be different for the two channels
  3) There must be unequal final state strong phase shifts.

$$A_\Xi = (\alpha_\Xi + \bar{\alpha}_\Xi)/(\alpha_\Xi - \bar{\alpha}_\Xi) \cong -\tan(\delta_P - \delta_S)\sin(\phi_P - \phi_S)$$

$$A_\Lambda = (\alpha_\Lambda + \bar{\alpha}_\Lambda)/(\alpha_\Lambda - \bar{\alpha}_\Lambda) \cong -\tan\underbrace{(\delta_P - \delta_S)}_{\text{strong phases}}\sin\underbrace{(\phi_P - \phi_S)}_{\text{weak phases}}$$

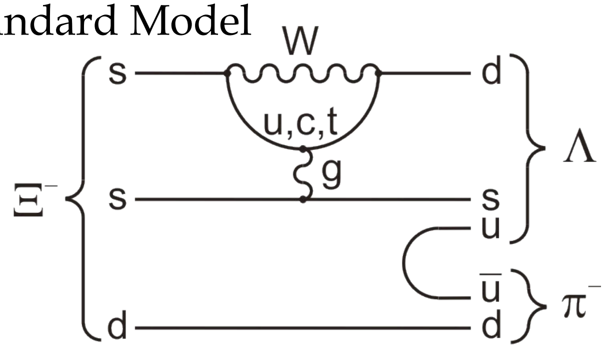
- Asymmetry greatly reduced by strong phase shifts.
  - Strong phases shift measured by HyperCP!

Comparison of A_{Ξ}, A_{Λ} with ε'/ε



A_{Ξ}, A_{Λ}

- Thought to be due to Penguin diagram in Standard Model



- Expressed through a different *CP*-violating phase in *S*- and *P*-wave amplitudes
- Probes parity-violating and parity-conserving amplitudes

ε'/ε

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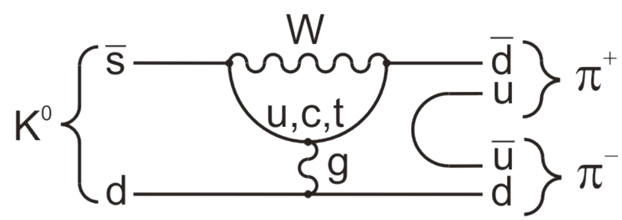

- Expressed through a different CP-violating phase in *I=0* and *I*=2 amplitudes
- Probes parity-violating amplitudes

"Our results suggest that this measurement is complementary to the measurement of ε'/ε, in that it probes potential sources of CP violation at a level that has not been probed by the kaon experiments."

He and Valencia, PRD 52 (1995), 5257.

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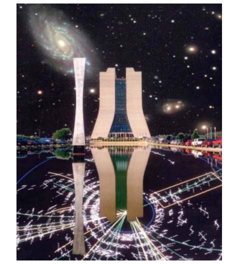

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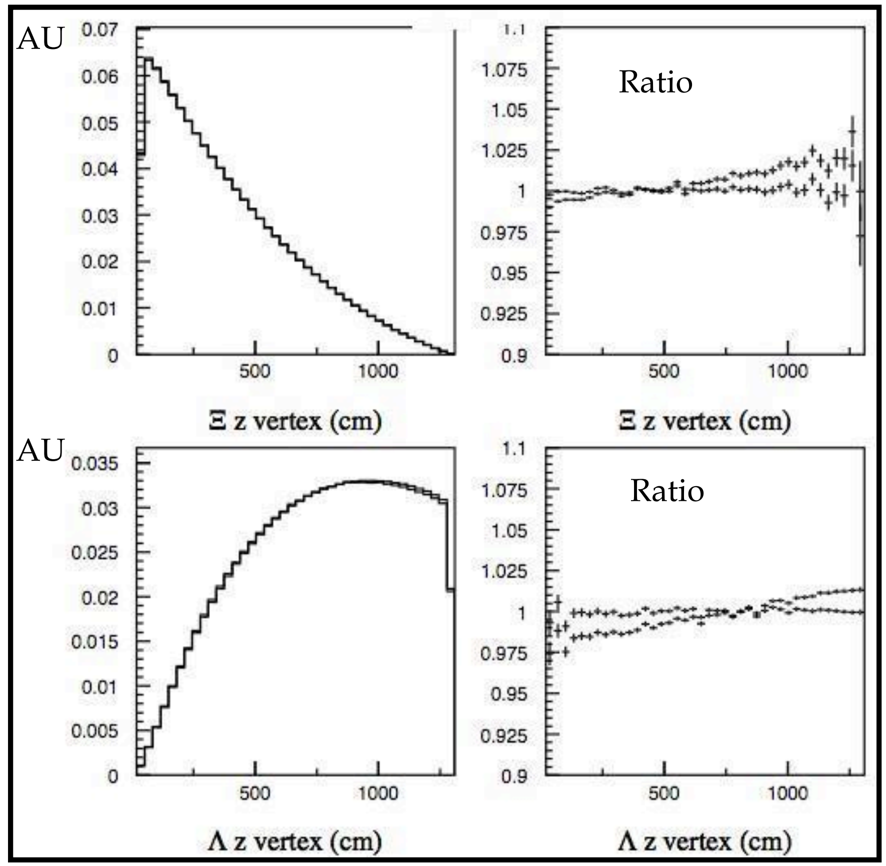
Weighted vs. unweighted ratios



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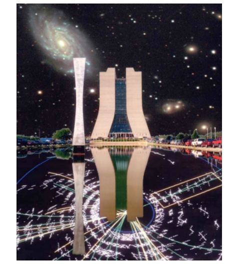

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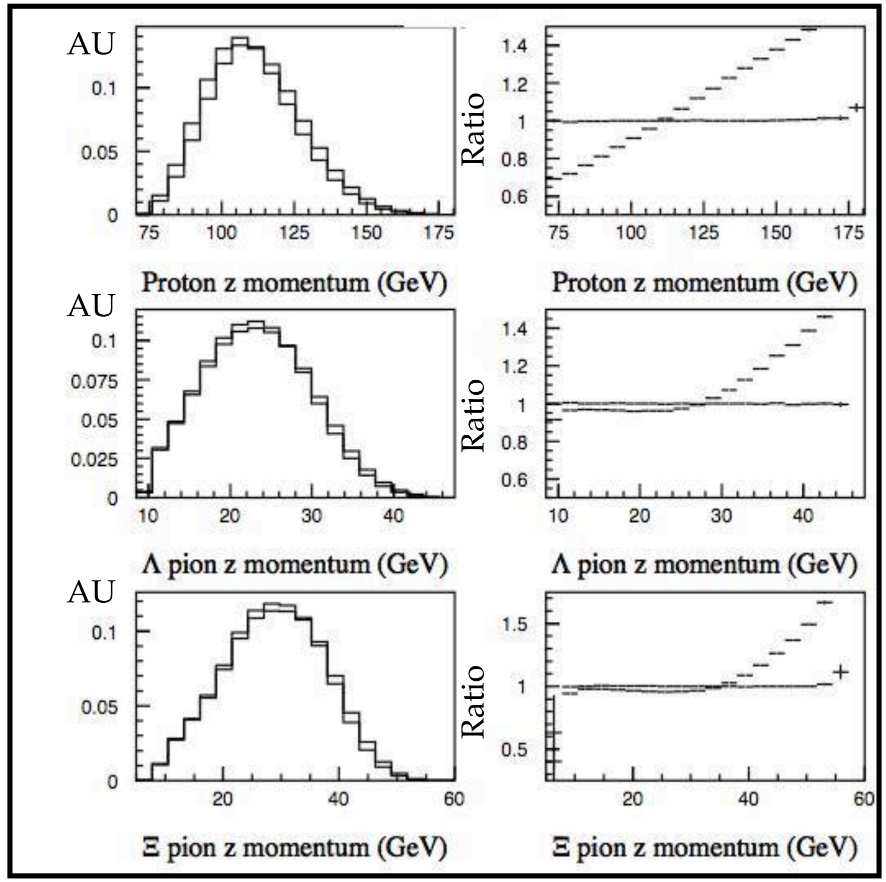
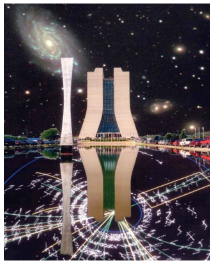
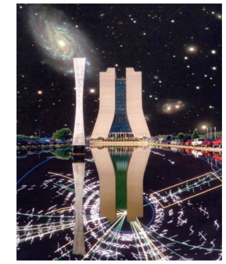


Hyper*CP* Publications



- *Observation of Parity Violation in the $\Omega^- \rightarrow \Lambda K^-$ Decay.*
  Phys. Lett. B **617**, 11 (2005)
- *Search for the Lepton-Number-Violating Decay $\Xi^- \rightarrow p\mu^-\mu^-$.*
  Phys. Rev. Lett. **94**, 181801 (2005)
- *HyperCP*: *A high-rate spectrometer for the study of charged hyperon and kaon decays.*
  Nucl. Instrum. Methods A **541**, 516 (2005)
- *Search for ΔS=2 Nonleptonic Hyperon Decays.*
  Phys Rev. Lett. **94**, 101804 (2005)
- *Measurement of the α Asymmetry Parameter for the $\Omega^- \rightarrow \Lambda K^-$ Decay.*
  Phys. Rev. D **71**, 051102(R) (2005)
- *Evidence for the Decay $\Sigma^+ \rightarrow p\mu^+\mu^-$.*
  Phys. Rev. Lett. **93**, 262001 (2005)
- *Search for CP Violation in Charged-Ξ and Λ Hyperon Decays.*
  Phys. Rev. Lett. **93**, 262001 (2005)

Hyper*CP* Publications II



- *High Statistics Search for the θ^+ Pentaquark State.* Phys. Rev. D **70**, 111101(R) (2004)
- *New Measurement of $\Xi^- \rightarrow \Lambda\pi^-$ Decay Parameters.* Phys. Rev. Lett. **93**, 011802 (2004)
- *Tripling the Data Set for the HyperCP Experiment.* IEEE Trans. Nucl. Sci. 49:568-576, 2002
- *Observation of the Decay $K^- \rightarrow \pi^- \mu^+ \mu^-$ and Measurements of the Branching Ratios for $K^\pm \rightarrow \pi^\pm \mu^+ \mu$.* Phys. Rev. Lett. **88**, 111801 (2002)
- *Upgraded DAQ System for the HyperCP Experiment.* Nucl. Intrum. Methods A **474**, 67 (2001)
- *A High-Throughput Data Acquisition System for the HyperCP Experiment.* Nucl. Instrum. Methods A **455**, 424 (2000)