The Search for New Physics in Hyperon Decays: Results from the HyperCP Experiment

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HyperCP Collaboration

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Heavy Quarks and Leptons 2006

HyperCP: Fermilab experiment searching for rare and forbidden charged hyperon decays

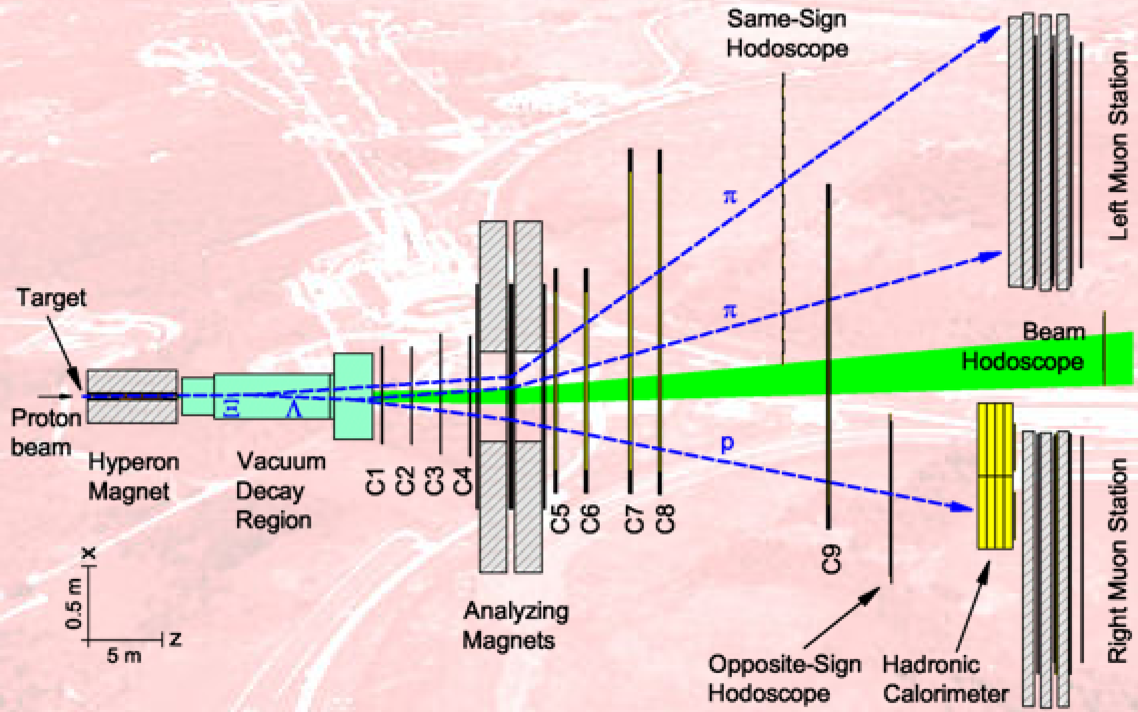
Primary Goal:

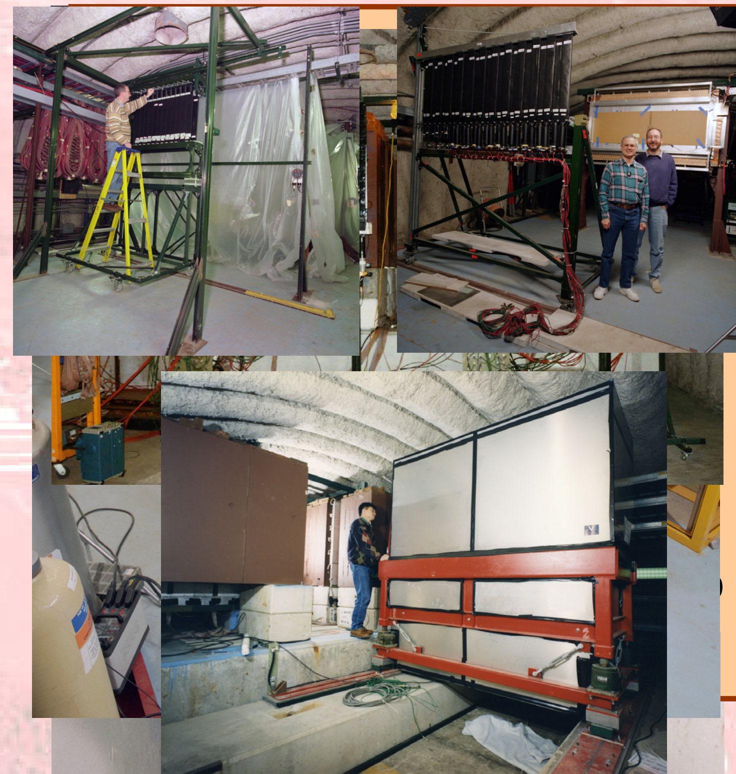
- Search for exotic sources of CP violation in $\Xi^{\pm}\rightarrow\Lambda\pi^{\pm}\rightarrow p\pi^{\pm}\pi^{\pm}$ decays

Secondary Goals

- Search for CP violation in $\Omega^{\pm}\rightarrow\Lambda K^{\pm}$
- Make precision measurement of hyperon decay parameters:
  - α, β, and γ decay parameters in $\Xi^{-}\rightarrow\Lambda\pi^{-}$ decays
  - α decay parameter in $\Omega^{\pm}\rightarrow\Lambda K^{\pm}$
- Search for rare and forbidden charged hyperon (and kaon) decays
  - lepton-number violation: $\Xi^{-}\rightarrow p\mu^{-}\mu^{-}$
  - FCNC: $K^{\pm}\rightarrow\pi^{\pm}\mu^{+}\mu^{-}$
  - $\Delta S > 1$ decays: $\Xi^{-}\rightarrow p\pi^{-}\pi^{-}$, $\Omega^{-}\rightarrow\Lambda\pi^{-}$
  - Search for θ^{+} pentaquark
  - $\Sigma^{+}\rightarrow p\mu^{+}\mu^{-}$

New hyperon beam and high-rate spectrometer built





Charged Secondary Beam

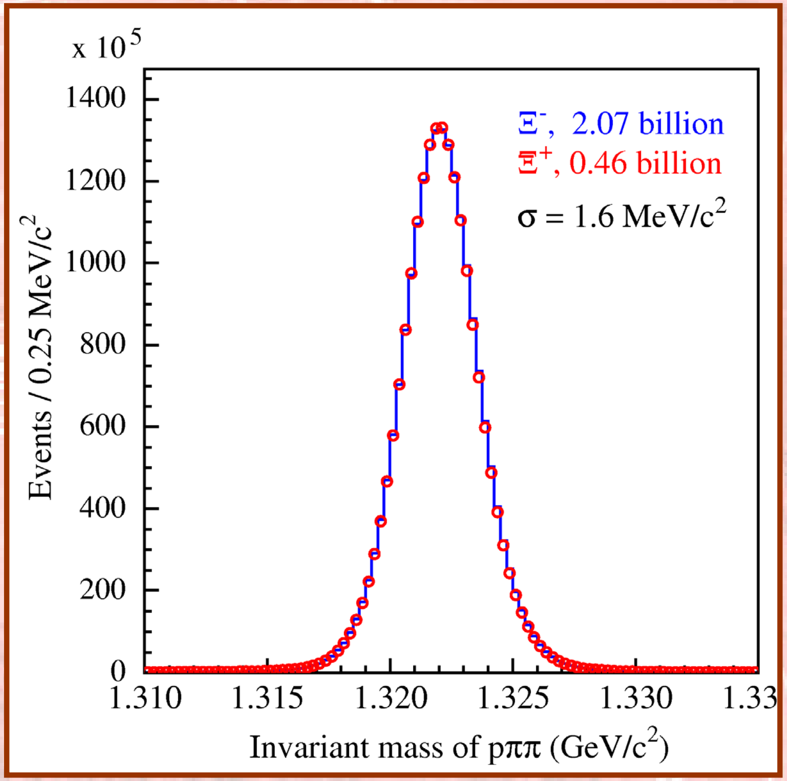
- 800 GeV protons on 2x2mm^2 target
- mean momentum: 167 GeV/c
- rate: 10-15 MHz
- alternate +/- beam polarity

High-Rate Magnetic Spectrometer

- 8 high-rate, narrow-pitch MWPCs
- left and right muon stations: only pid
- simple hyperon decay trigger
- dimuon and single-muon triggers
- very high-rate DAQ: 100,000 evts/s to tape

HyperCP Yields

- In 12 months of data taking HyperCP recorded one of the largest event sample ever
  - 231 billion events
  - 29,401 tapes
  - 120 TB
- Entire WWW as of end of data taking (Jan 2000) ~5 TB



Reconstructed Events

	Channeled beam polarity		
Type	+	−	Total
$\Xi \to \Lambda\pi$	458×10^6	$2\,032 \times 10^6$	$2\,490 \times 10^6$
$K \to \pi\pi\pi$	391×10^6	164×10^6	555×10^6
$\Omega \to \Lambda K$	4.9×10^6	14.1×10^6	19.0×10^6

Why Search for *CP* Violation in Hyperon Decays?

- After 40 years of intense effort – and many beautiful experiments – we still no little about *CP* violation: the origin of *CP* violation remains unknown and though nicely accommodated by the Standard Model it is not explained by the Standard Model
- The importance of *CP* violation to our understanding of particle physics, indeed the universe, cannot be overstated
- The asymmetry in hyperon decays can be relatively large: up to $O(10^{-2})$
- The price is modest:
  - No new accelerators needed
  - Apparatus is modest in scope and cost
- Hyperons are sensitive to sources of *CP* violation that, for example, kaons are not
- Almost all scenarios for New Physics produce large *CP* asymmetries

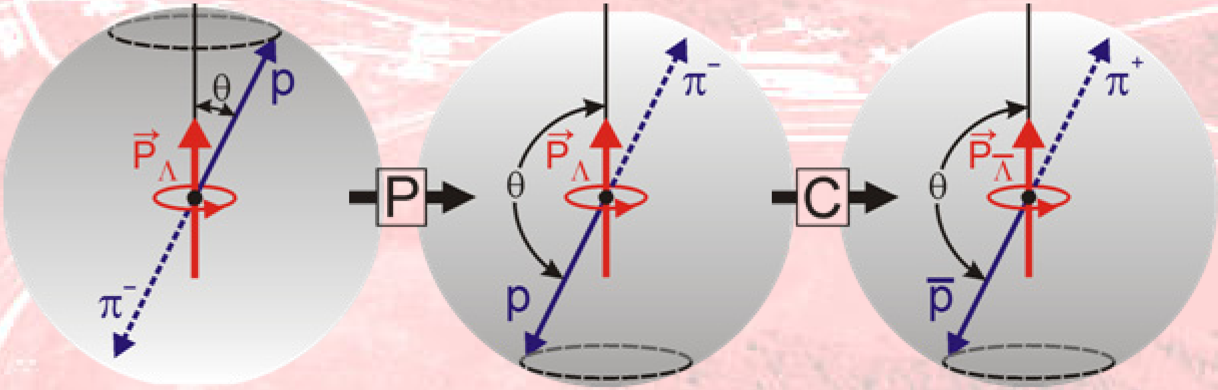
> "We are willing to stake our reputation on the prediction that dedicated and comprehensive studies of *CP* violation will reveal the presence of New Physics"
>
> Bigi and Sanda, *CP Violation*

How to Search for CP Violation in Λ Decays

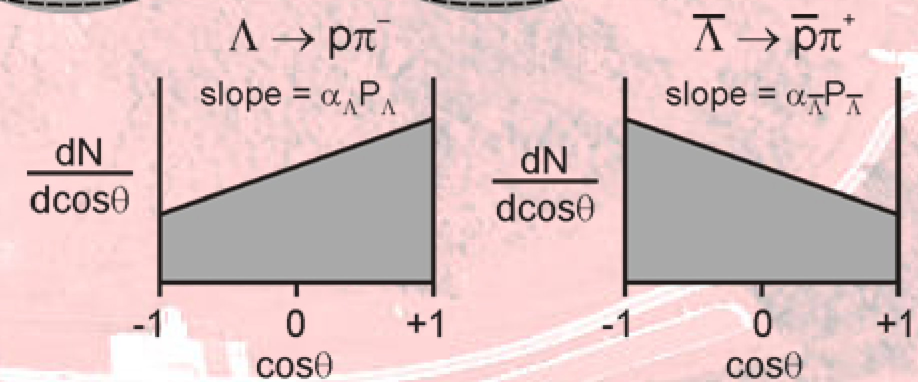
Due to parity violation the proton likes to go in the direction of the Λ spin:

$$\Lambda \to p\pi^- \qquad \frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}\left(1+\alpha_\Lambda P_\Lambda \cos\theta\right) \qquad \alpha_\Lambda = \frac{2\mathrm{Re}(S^*P)}{|S|^2+|P|^2} = 0.64$$

Under CP violation that antiproton prefers the go opposite to the direction of the anti-Λ spin



$$\alpha_\Lambda \overset{CP}{\leftrightarrow} \bar{\alpha}_\Lambda = -\alpha_\Lambda$$



Problem: to extract α_Λ ($\bar{\alpha}_\Lambda$) the Λ ($\bar{\Lambda}$) polarizations must be precisely known

Problem: Producing Λs of Known Polarization

Λs and anti-Λs of known polarization can be produced through $\Xi^{\pm}$ decays

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

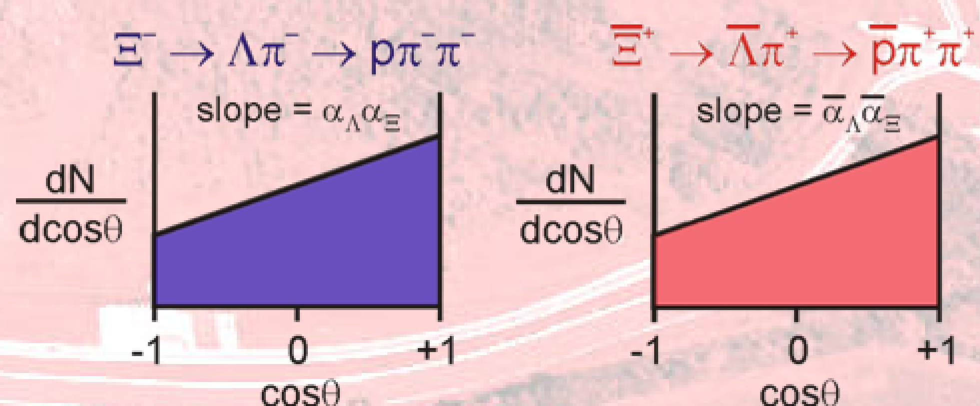
If the Ξ is produced unpolarized – which can simply be done by targetting at 0° – then the Λ is produced in a helicity state.

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

$$\frac{dN(p)}{d\cos\theta} = \frac{N_0}{2}\left(1 + P_\Lambda \alpha_\Lambda \cos\theta\right) \qquad\qquad \frac{dN(\overline{p})}{d\cos\theta} = \frac{N_0}{2}\left(1 + \overline{P}_\Lambda \overline{\alpha}_\Lambda \cos\theta\right)$$

If CP is good the slopes of the proton and antiproton cosθ distributions are identical.

$$\alpha_\Xi \alpha_\Lambda = \overline{\alpha}_\Xi \overline{\alpha}_\Lambda$$



We are Sensitive to CP in both Ξ and Λ Decays

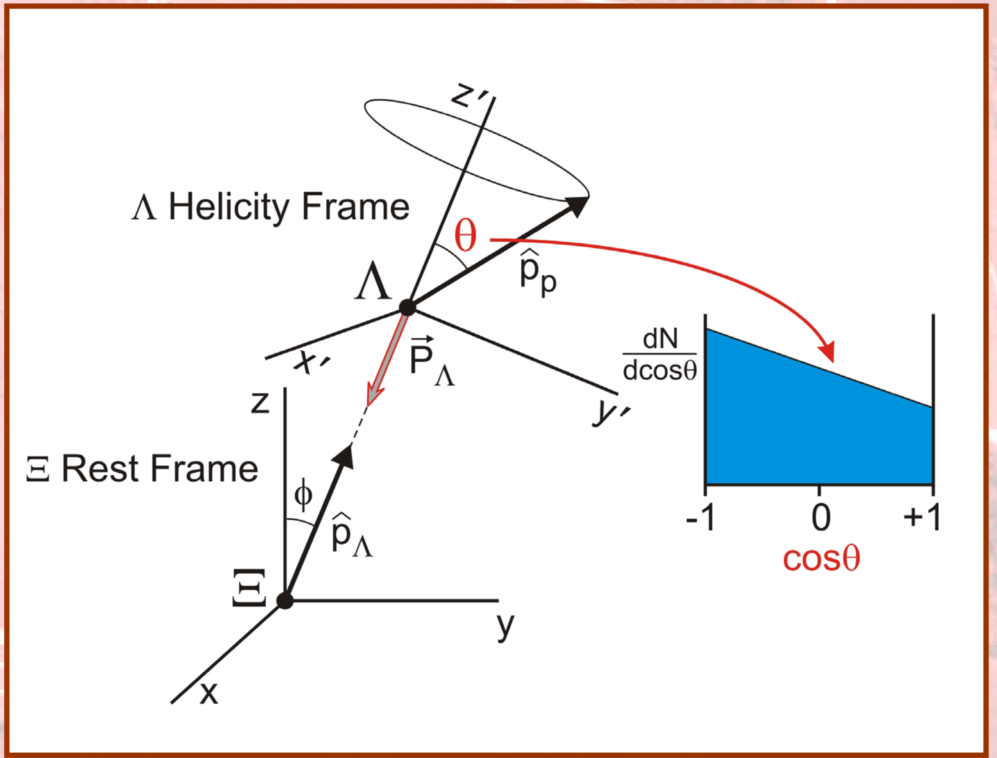
$$A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \overline{\alpha}_\Xi \overline{\alpha}_\Lambda}{\alpha_\Xi \alpha_\Lambda + \overline{\alpha}_\Xi \overline{\alpha}_\Lambda} \approx A_\Xi + A_\Lambda$$

where

$$A_\Xi = \frac{\alpha_\Xi + \overline{\alpha}_\Xi}{\alpha_\Xi - \overline{\alpha}_\Xi}$$

$$A_\Lambda = \frac{\alpha_\Lambda + \overline{\alpha}_\Lambda}{\alpha_\Lambda - \overline{\alpha}_\Lambda}$$

- What we experimentally measure is the slope of the proton (antiproton) cosθ distribution in the rest frame of the Λ ($\overline{\Lambda}$).
- We do this in a special Λ rest frame called the Lambda Helicity Frame in which the Λ direction in the Ξ rest frame defines the polar axis.



Bad News: SM Theoretical Predictions Small

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

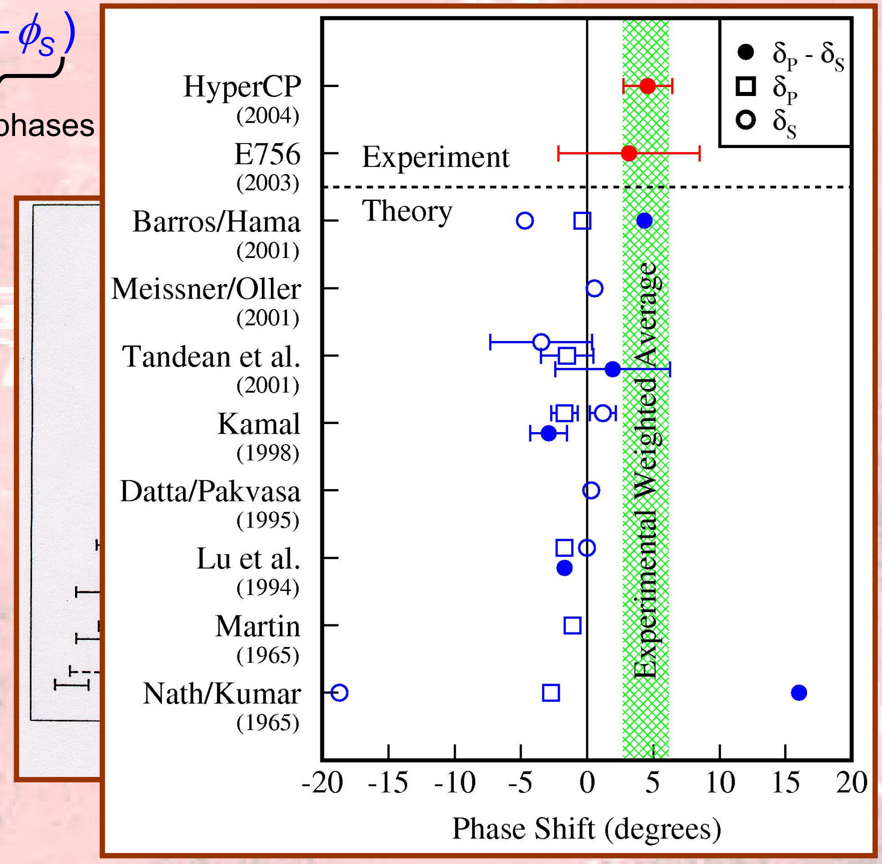
$$A_\Xi = (\alpha_\Xi + \bar{\alpha}_\Xi)/(\alpha_\Xi - \bar{\alpha}_\Xi) \cong -\tan(\underbrace{\delta_P - \delta_S}_{\text{strong phases}})\sin(\underbrace{\phi_P - \phi_S}_{\text{weak phases}})$$

- Much enthusiasm a decade ago as theory predictions were relatively large and experimentally accessible
- Standard Model predictions have slowly fallen since then to

$$-0.5\times10^{-4} \le A_{\Xi\Lambda} \le +0.5\times10^{-4}$$

(Tandean and Valencia, 2003)

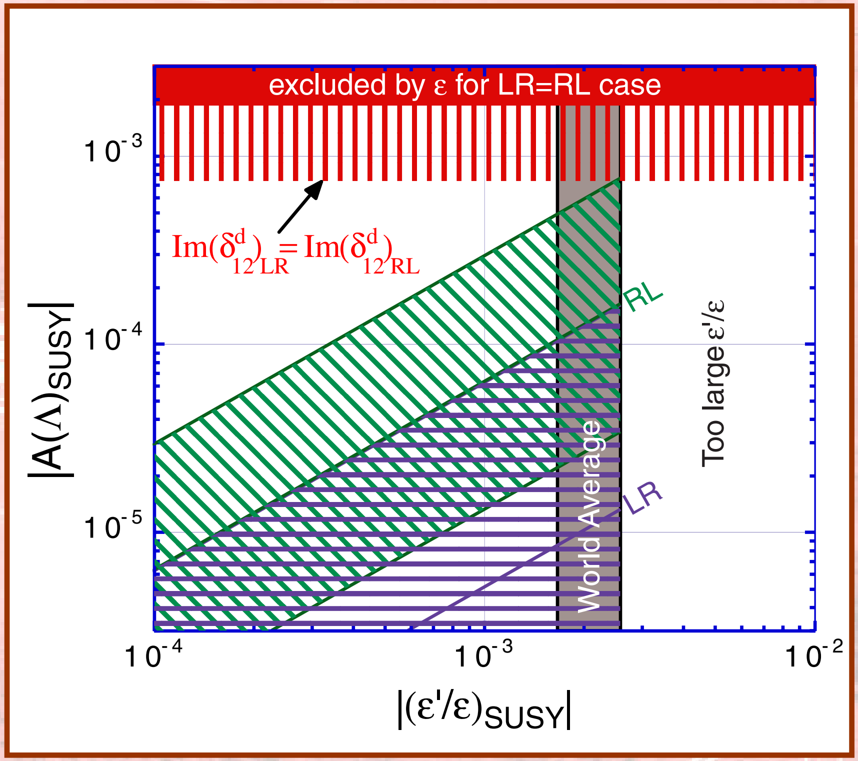
mainly because of the smaller size of the $\Lambda\pi$ strong phase shift



Note: no unambiguous connection between $\delta_{CKM} \Leftrightarrow A_\Xi$, A_Λ

Good News: SM Theory Predictions are Small

- Most beyond-the-standard-model theories predict new and large CP-violating phases
- These predictions are often not well constrained by kaon CP measurements as hyperon CP violation probes both parity conserving and partiy violating amplitudes
- A paper by Tandean (2004) shows that the upper bound on $A_{\Xi\Lambda}$ from ε'/ε and ε measurements is $O(10^{-2})$.
- For example, some supersymmetric models that do not generate ε'/ε, can lead to A_Λ of $O(10^{-3})$.



He, Murayama, Pakvasa, Valencia, PRD 61, 071701 (2000).

Any CP-violation signal will almost certainly indicate New Physics

High Energy Physics University of Virginia

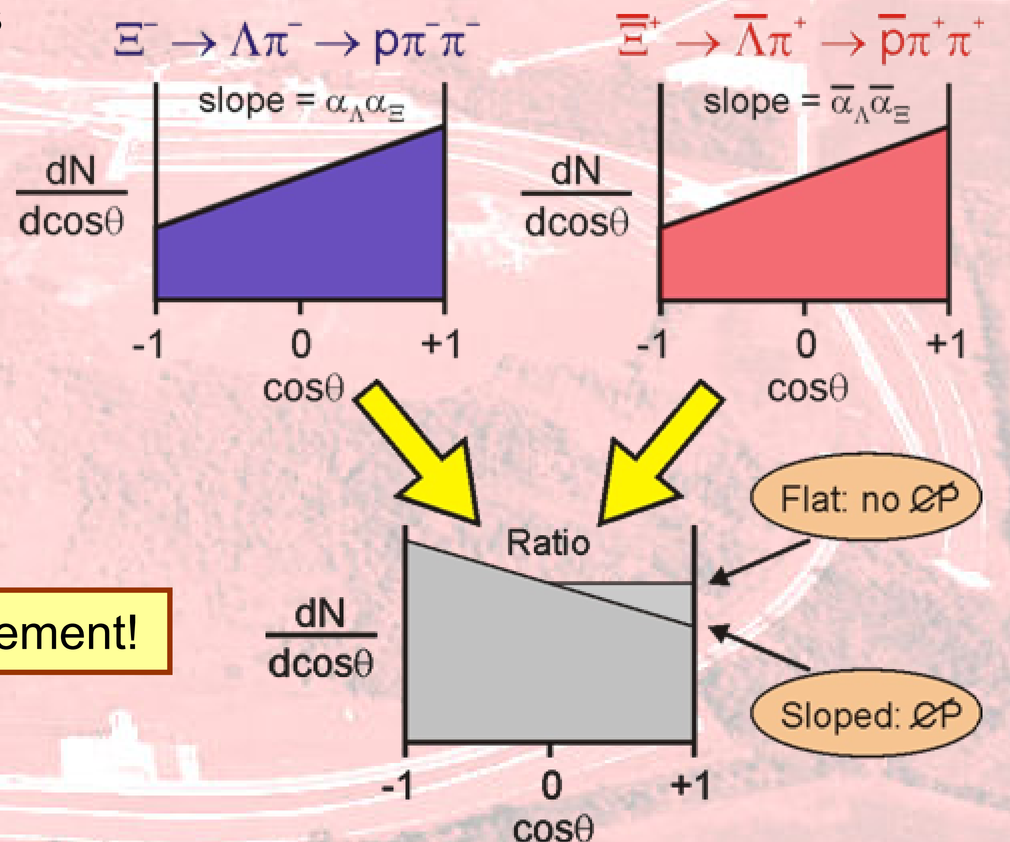
Extracting the *CP* Asymmetry

- If CP is good then the proton and antiproton $\cos\theta$ distributions are identical

$$\frac{dN_-}{d\cos\theta} = A_- \frac{N_-}{2}\left(1+\alpha_\Xi\alpha_\Lambda\cos\theta_-\right)$$

$$\frac{dN_+}{d\cos\theta} = A_+ \frac{N_+}{2}\left(1+\bar{\alpha}_\Xi\bar{\alpha}_\Lambda\cos\theta_+\right)$$

  - Take the ratio of the two distributions to extract $A_{\Xi\Lambda}$: if not flat CP is violated



Note: No Monte Carlo used in measurement!

The *CP* Asymmetry

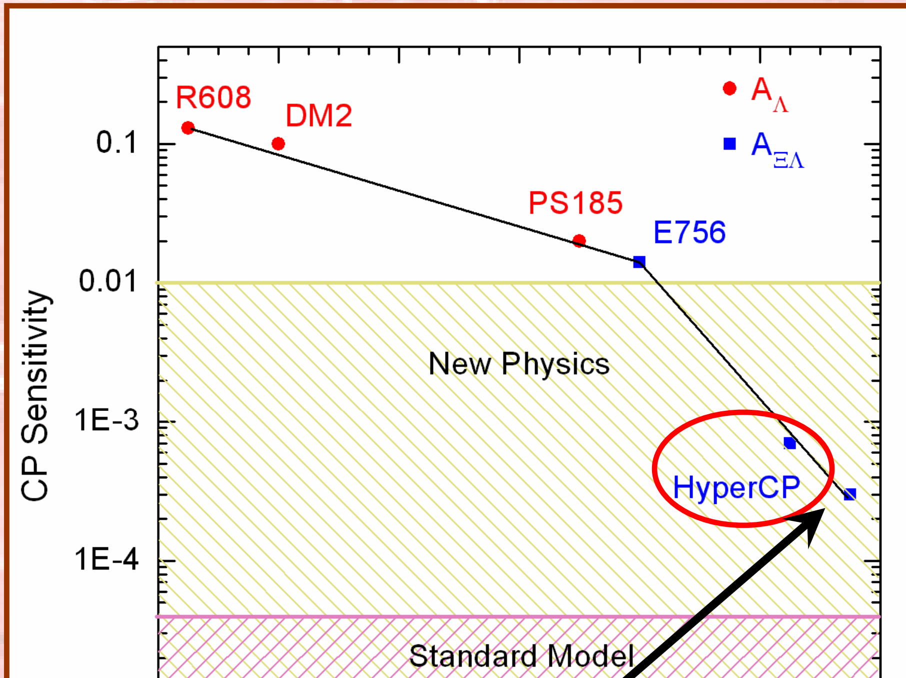
- ~10% of data sample: 119 million Ξ^-, 42 million $\overline{\Xi}^+$
- Apply no acceptance corrections: however we do weight the Ξ^- and $\overline{\Xi}^+$ events by their momentum-dependent variables to equalize distributions
- Subtract background asymmetry:

$$\left.\begin{array}{l}\Xi^- : 0.43\% \\ \hline \overline{\Xi}^+ : 0.41\%\end{array}\right\} 0.43\sigma \text{ effect}$$

- Estimate systematic errors
- With no efficiency corrections:

$$A_{\Xi\Lambda} = \frac{\alpha_\Xi \alpha_\Lambda - \overline{\alpha}_\Xi \overline{\alpha}_\Lambda}{\alpha_\Xi \alpha_\Lambda + \overline{\alpha}_\Xi \overline{\alpha}_\Lambda}$$
$$= [0.0 \pm 5.1(\text{stat}) \pm 4.4(\text{syst})] \times 10^{-4}$$

- Factor of 20 improvement in sensitivity over previous limit



Variable	# cells	Cell size
Ξ momentum	100	2.25 GeV/c
y position at collimator	100	0.013 cm
y slope at collimator	100	0.08 mrad

Expect ... 1 billion events analyzed in about a year with factor of ~3 improvement in sensitivity

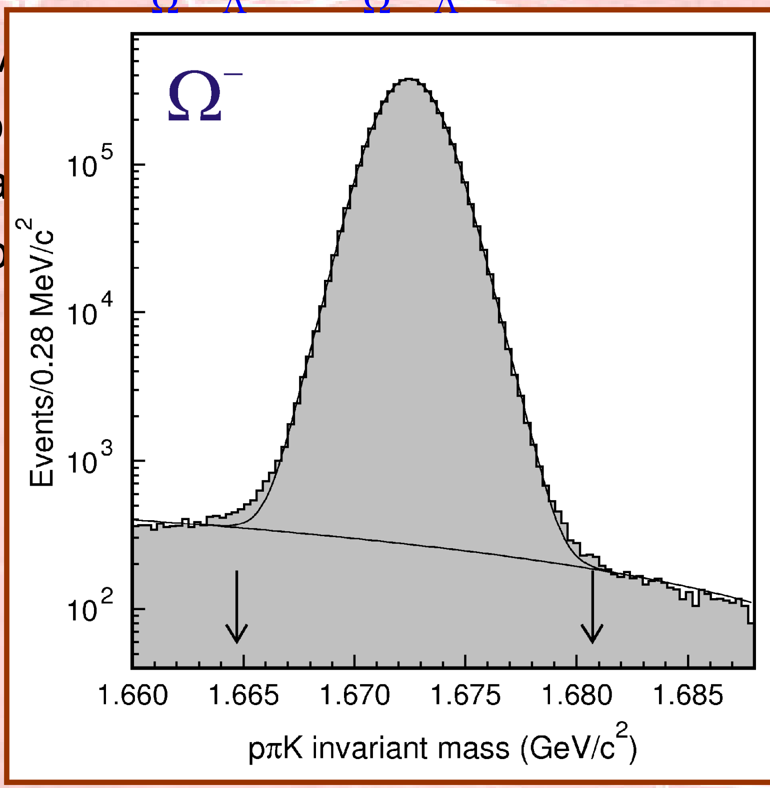
One million weights used!

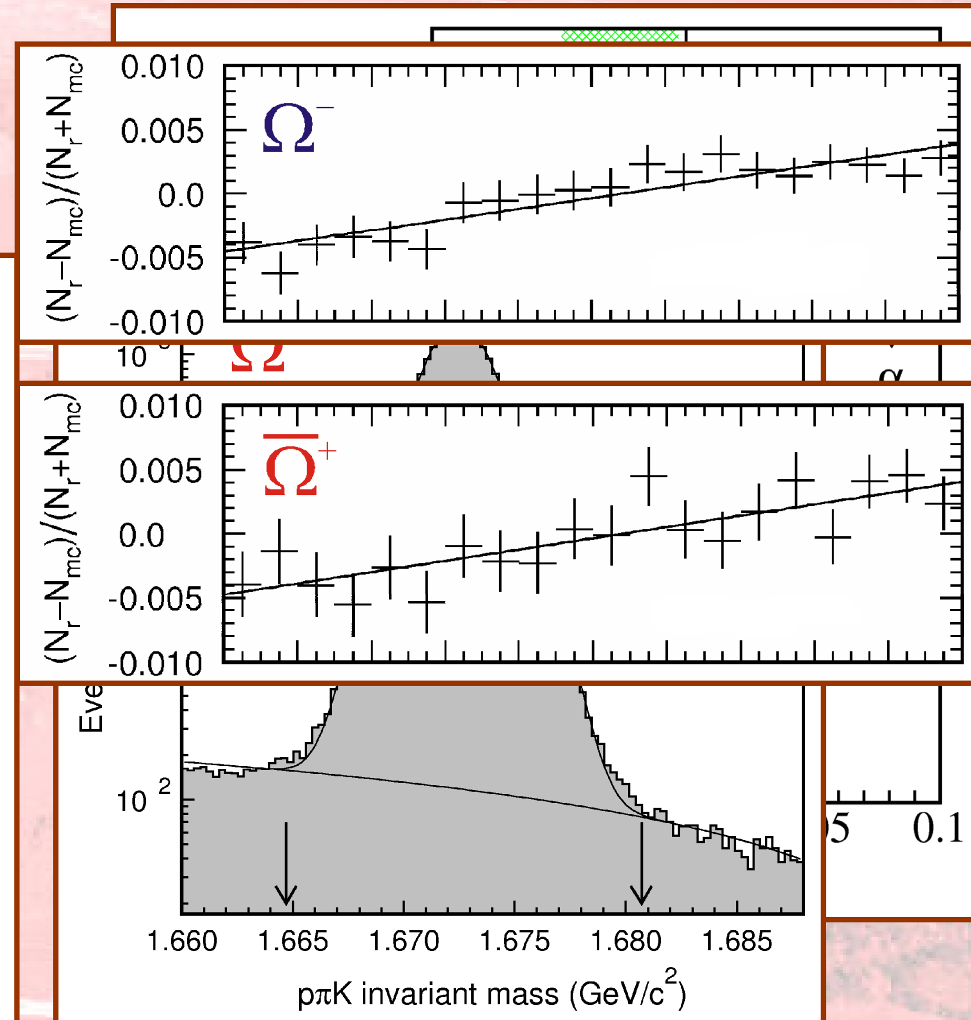
CP Violation Search in $\Omega \to \Lambda K$ Decays

- HyperCP has:
  - 4.5 million $\Omega^- \to \Lambda K^- \to p K^- \pi^-$
  - 1.5 million $\Omega^+ \to \Lambda K^+ \to p K^+ \pi^+$
- Separately measure products

  $\alpha_\Omega \alpha_\Lambda \qquad \overline{\alpha}_\Omega \overline{\alpha}_\Lambda$

- *P* v
- No
  ma
- Mo

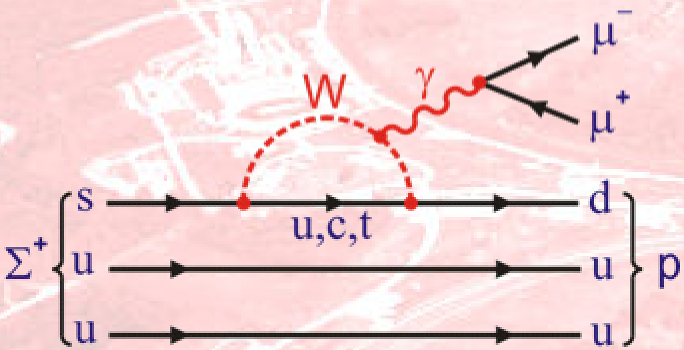


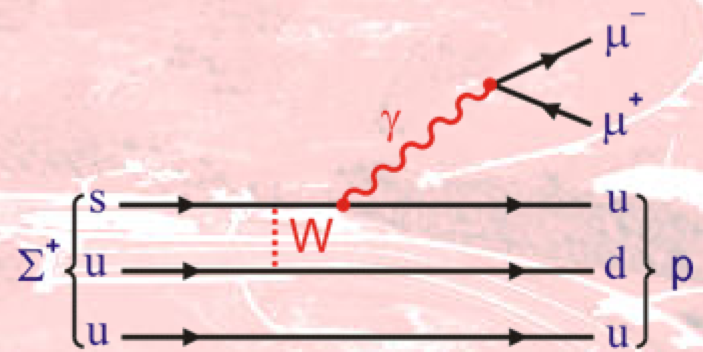


Hints of New Physics in the Decay $\Sigma^+ \to p\mu^+\mu^-$

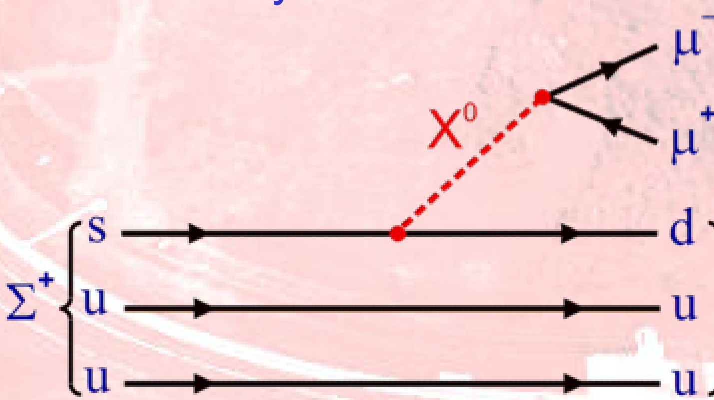
Motivation

In SM $\Sigma^+ \to p\mu^+\mu^-$ highly suppressed → leading diagrams FCNC and WR decays

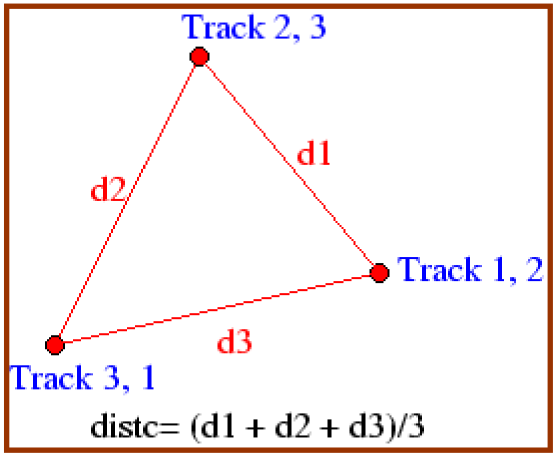




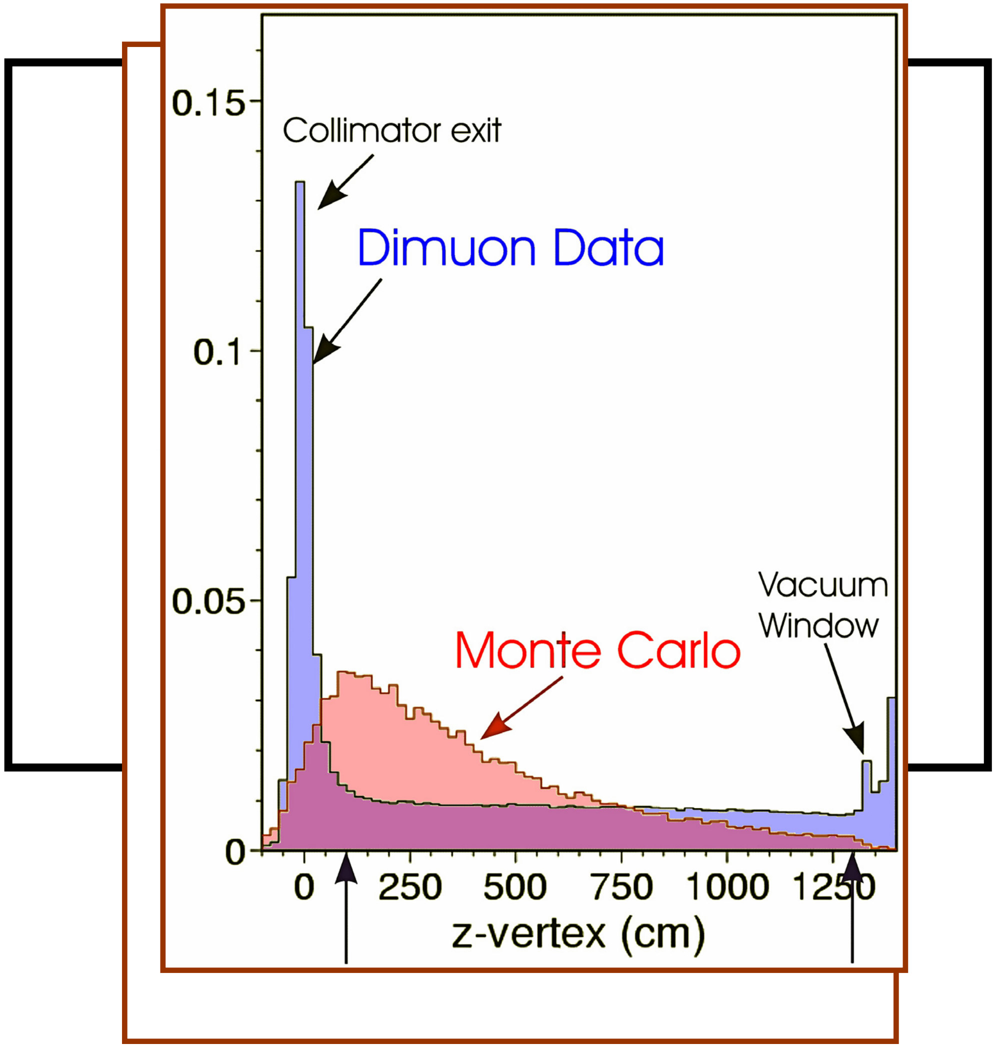
Hence sensitive to New Physics



FCNC at tree level



Track 2, 3
d1
d2
Track 1, 2
d3
Track 3, 1
distc= (d1 + d2 + d3)/3



0.15
0.1
0.05
0
Collimator exit
Dimuon Data
Monte Carlo
Vacuum Window
0
250
500
750
1000
1250
z-vertex (cm)

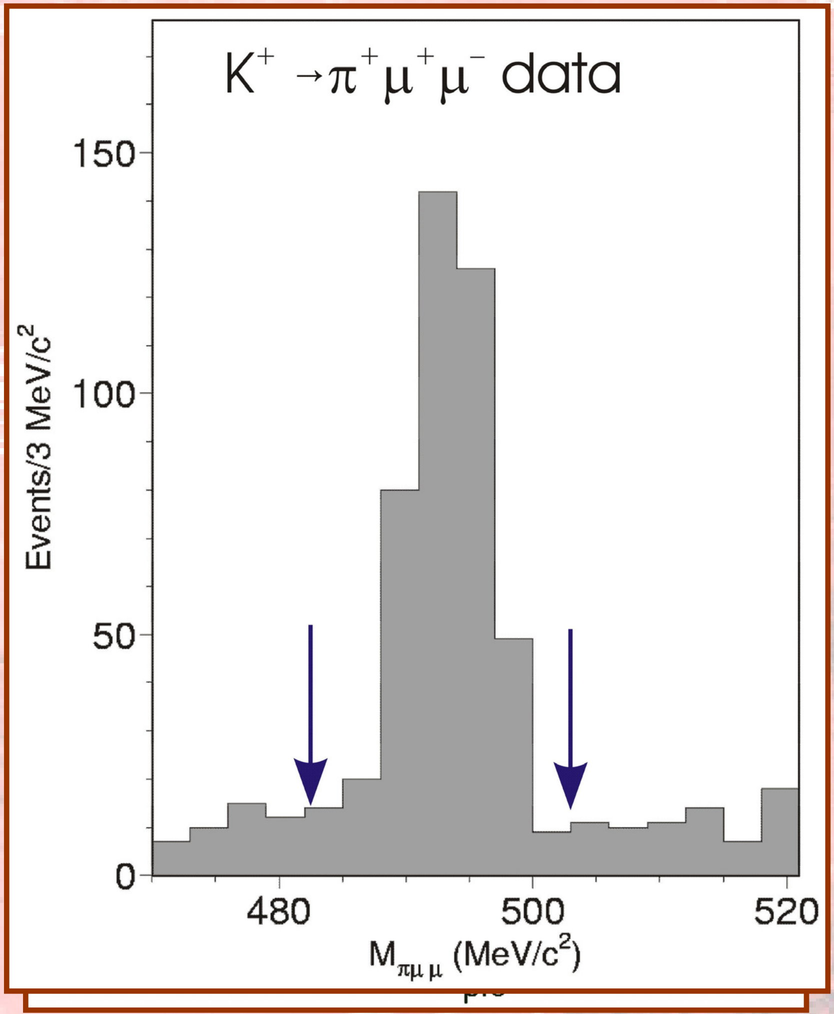
Two further Kaon removal cuts

- Huge K^+ background:
  - ~0.5 billion $K^+ \to \pi^+\pi^-\pi^+$
  - ~1,000 $K^+ \to \pi^+\mu^+\mu^-$
- In $\Sigma^+ \to p\mu^+\mu^-$ proton carries most momentum $\Rightarrow$ require

$$f_{hadron} = \frac{\text{"baryon" momentum}}{\text{total "}\Sigma\text{" momentum}} \geq 0.68$$

- After f_{hadron} cut, MC studies show *K*-decay background negligible

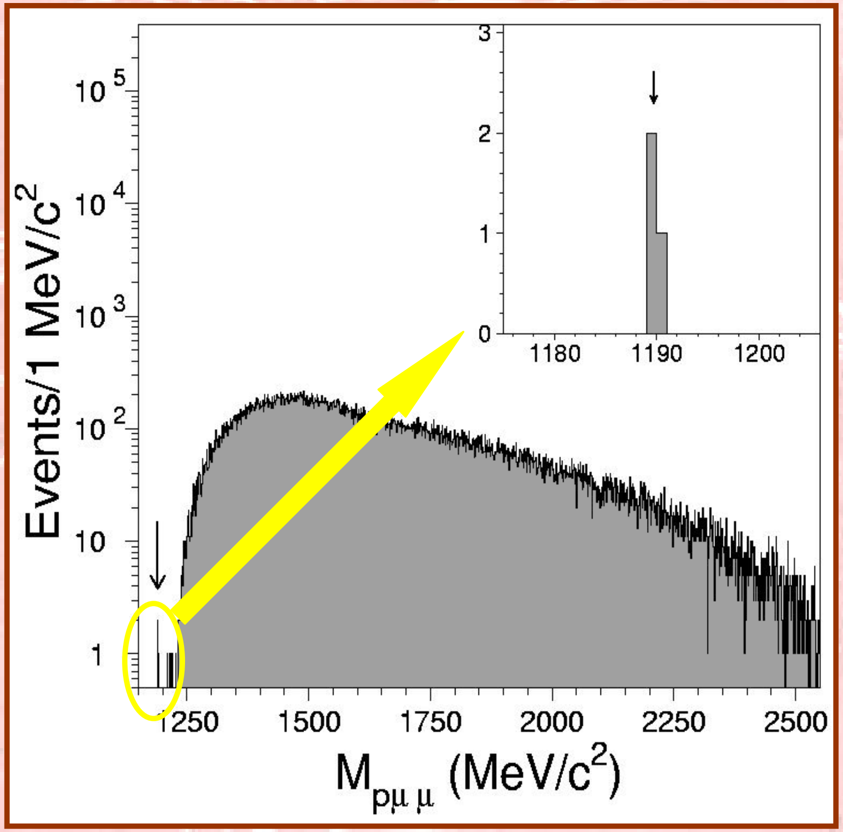
Decay Mode	Branching Ratio	ε(%)
$K^+ \to \pi^+\pi^-\pi^+$	5.6%	0.0
$K^+ \to \pi^+\pi^-\mu^+\nu_\mu$	1.4×10^{-5}	~0.0
$K^+ \to \pi^+\mu^+\mu^-$	8.1×10^{-8}	0.4



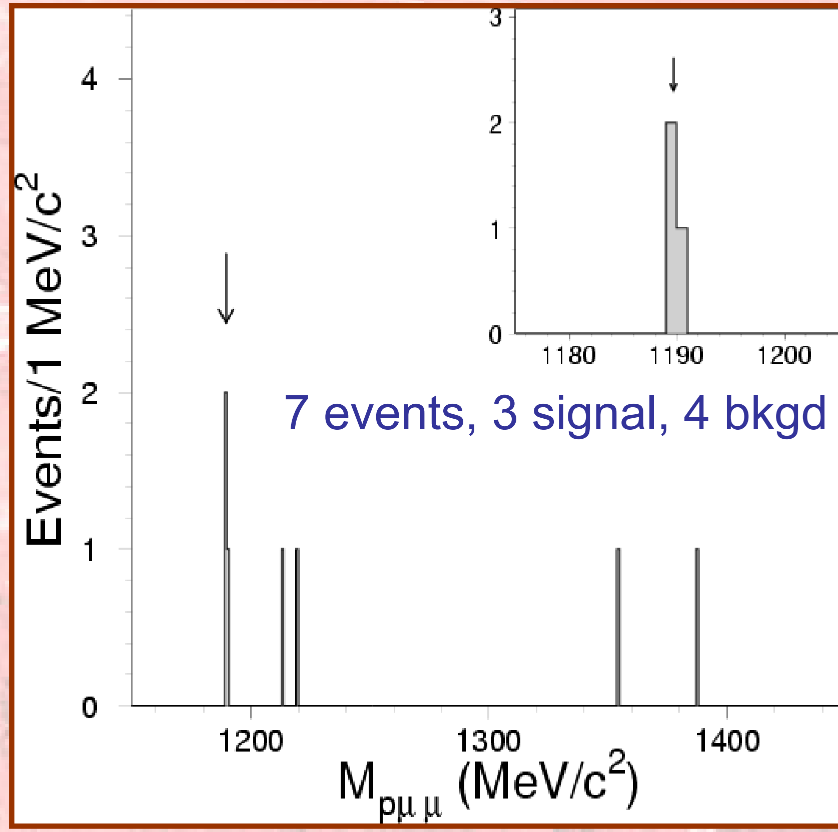
- Second cut removes events with $\pi^+\mu^+\mu^-$ mass within ±10 MeV (3σ) of K^+ mass

Three $\Sigma^+ \to p\mu^+\mu^-$ decays survive all cuts

Basic selection cuts



Basic + kaon removal cuts



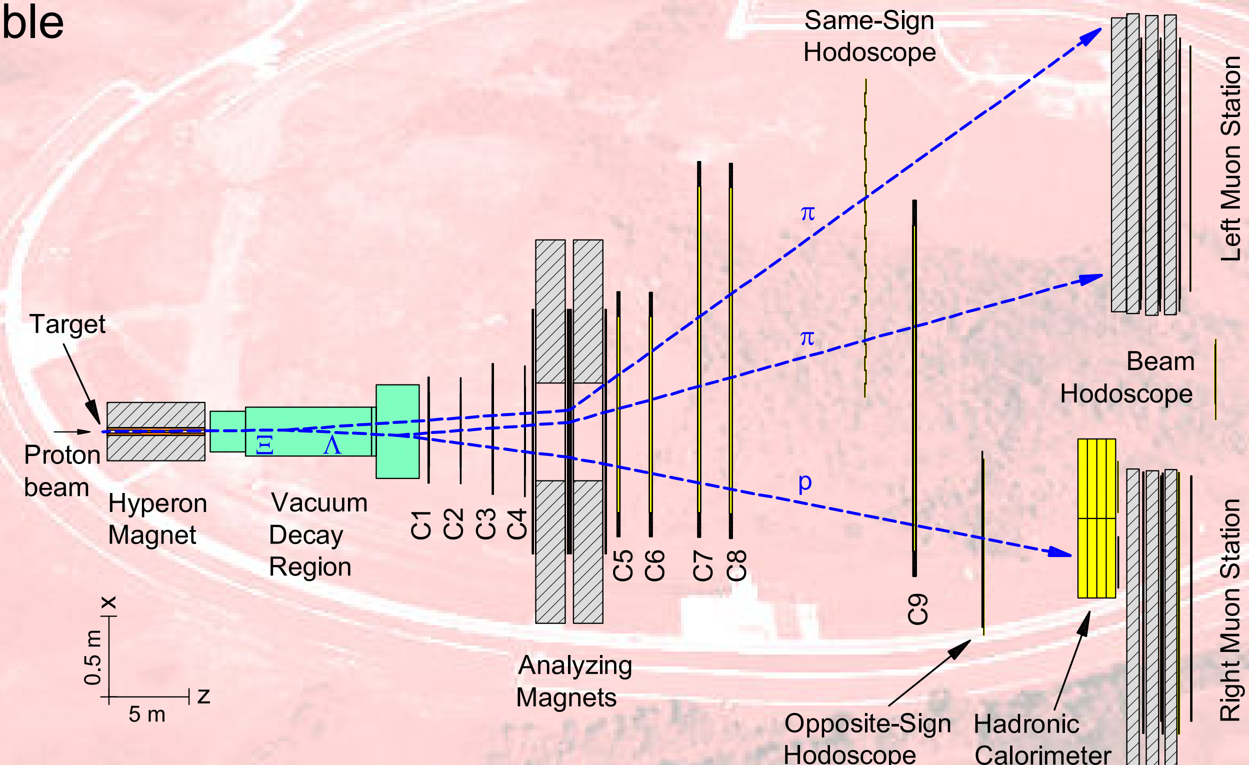
- Observe 3 events with 1σ of the Σ mass (1189 MeV)
- Backgrounds 20σ away from Σ mass
- f_{hadron} and $K^+ \to \pi^+\mu^+\mu^-$ cuts get rid of all but 7 events

Backgrounds: other hyperon decays

- No other positively charged hyperon
- Anti-hyperons have a different decay topology:
  - an opposite-sign highest momentum track
  - like-sign π or *K*'s whose decays-in-flight produce same-sign dimuons

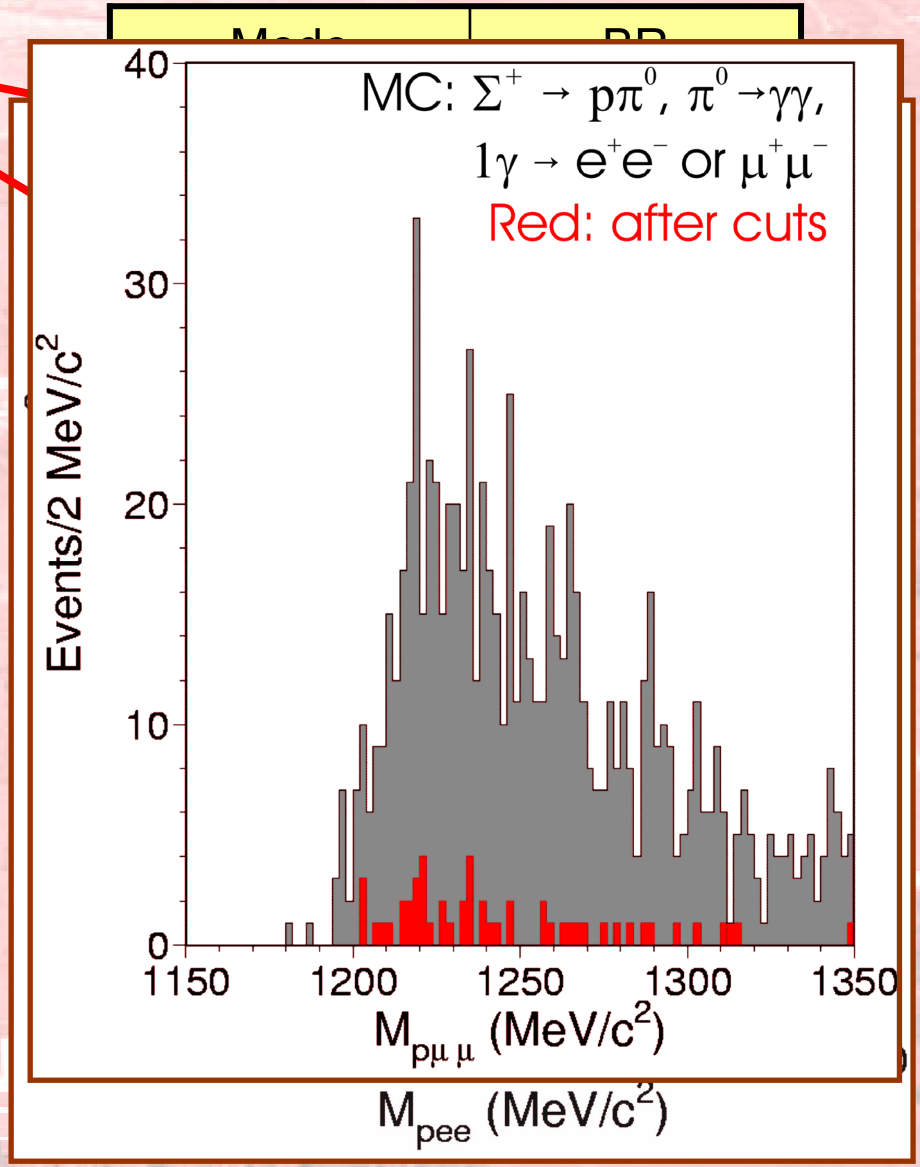
⇒ Negligible

$$\overline{\Xi}^+ \to \overline{\Lambda}\pi^+ \to \overline{p}\pi^+\pi^+$$
$$\overline{\Sigma}^+ \to \overline{n}\pi^+$$
$$\overline{\Omega}^+ \to \overline{\Lambda}K^+ \to \overline{p}\pi^+K^+$$
$$\to \overline{\Xi}^0\pi^+ \to \overline{\Lambda}\gamma\gamma\pi^+ \to \overline{p}\pi^+\pi^+\gamma\gamma$$
$$\to \overline{\Xi}^+\pi^0 \to \overline{\Lambda}\pi^+\gamma\gamma \to \overline{p}\pi^+\pi^+\gamma\gamma$$



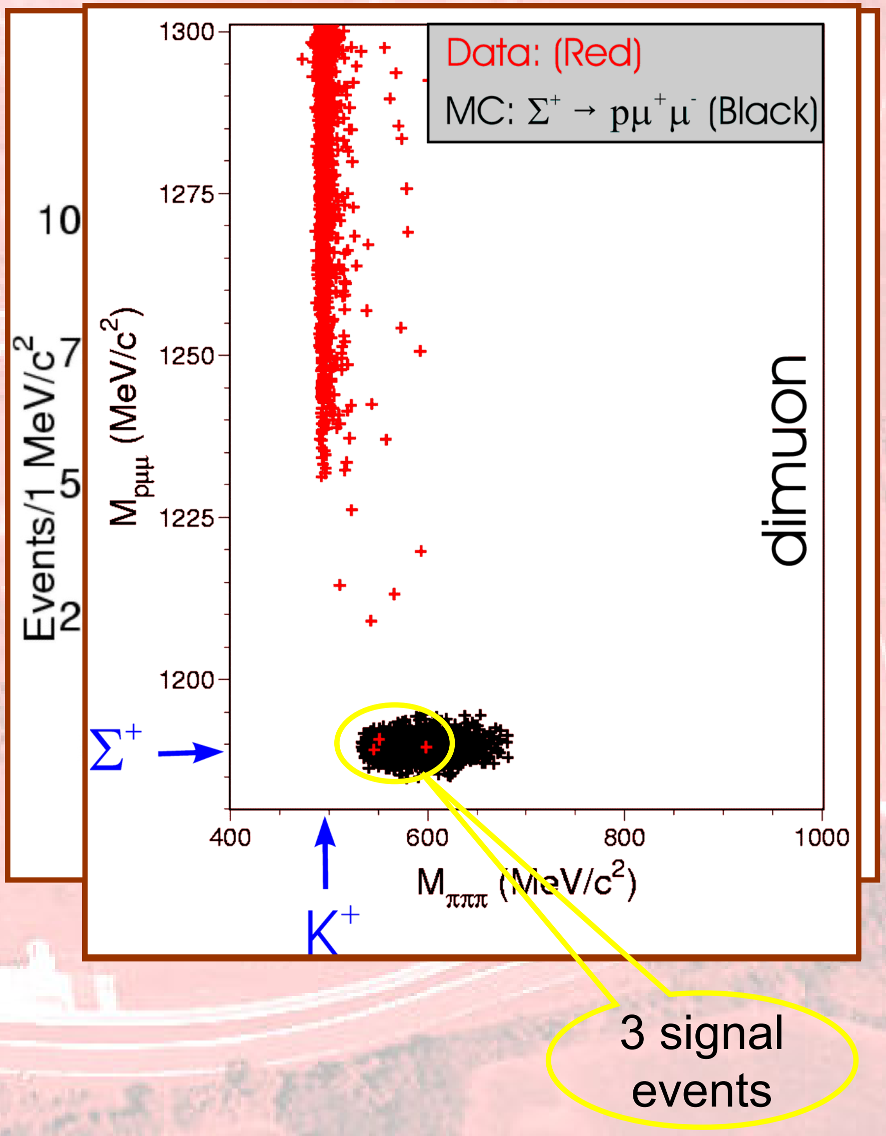
Backgrounds: other Σ^+ decays

- Only possible problems come from radiative decays with gamma conversion: $\gamma \rightarrow \mu^+\mu^-$
- Probability of a photon conversion to $\mu^+\mu^-$ in the vacuum pipe window (0.21% X_0 upstream, 0.15% X_0 downstream) ~ 10^{-7}
- Monte-Carlo studies of $\Sigma^+ \rightarrow p\pi^0$ and $\Sigma^+ \rightarrow p\gamma$ conversion backgrounds, with 100-1,000 times the expected level, show no background
- No evidence of much larger $\Sigma^+ \rightarrow pe^+e^-$ rate if photon conversions were a problem ($\gamma \rightarrow e^+e^-$ 10^5x $\gamma \rightarrow \mu^+\mu^-$)
- Proton momentum not consistent with $\Sigma^+ \rightarrow p\gamma$ two-body decay



Backgrounds: Look at Data

- MC indicates backgrounds not a problem but with ~1x10[10] K⁺ decays non-gaussian tails can be a problem
- Look at data:
  - Negative polarity data sample
    - about ½ size of positive polarity sample
    - Note: anti-Σ^+ production down by ~10X
    - no events below 1230 MeV
  - Single muon trigger sample
    - 30X larger: more background
    - prescaled by 10X: expect no events
    - no events below 1205 MeV



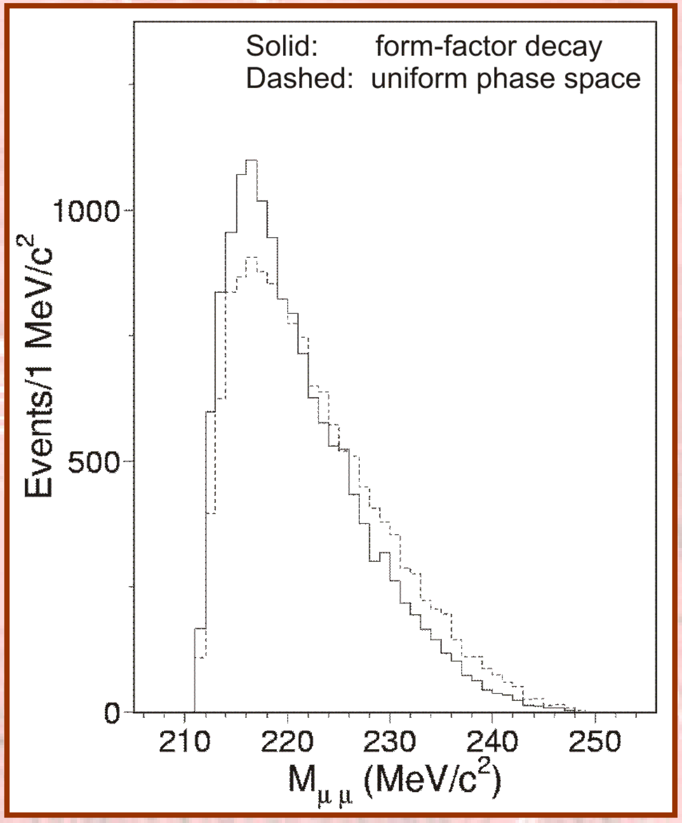
Extracting the branching ratio

- Since our acceptance is not perfect we need to know the form factors
- Four form factors: a, b, c, d
  - a and b (at $q^2 = 0$) come from WR decay $\Sigma^+ \to p\gamma$
  - c and d limited by on $B(\Sigma^+ \to pe^+e^-) < 7\times10^{-6}$

$$B(\Sigma^+ \to p\mu^+\mu^-) = \left[13^{+10}_{-8} \pm 7\right]\times10^{-8} \text{ (uniform decay)}$$

$$B(\Sigma^+ \to p\mu^+\mu^-) = \left[8.6^{+6.6}_{-5.4} \pm 5.5\right]\times10^{-8} \text{ (form factor)}$$

- smallest branching ratio ever measured for a baryon



What does theory say?

- Bergström, Safadi and Singer, ZPC 37, 281 (1988)

$B(\Sigma^+ \to p\mu^+\mu^-) \sim 10^{-8}$

- Updated calculation by He, Tandean, and Valencia, PRD 72, 074003 (2005)

$1.6\times10^{-8} \leq B(\Sigma^+ \to p\mu^+\mu^-) \leq 9.0\times10^{-8}$

- HyperCP result consistent with theory, albeit a bit high.

$$B(\Sigma^+ \to p\mu^+\mu^-) = \left[13^{+10}_{-8} \pm 7\right]\times10^{-8} \text{ (uniform decay)}$$
$$B(\Sigma^+ \to p\mu^+\mu^-) = \left[8.6^{+6.6}_{-5.4} \pm 5.5\right]\times10^{-8} \text{ (form factor)}$$

So far nothing terribly exciting about this result

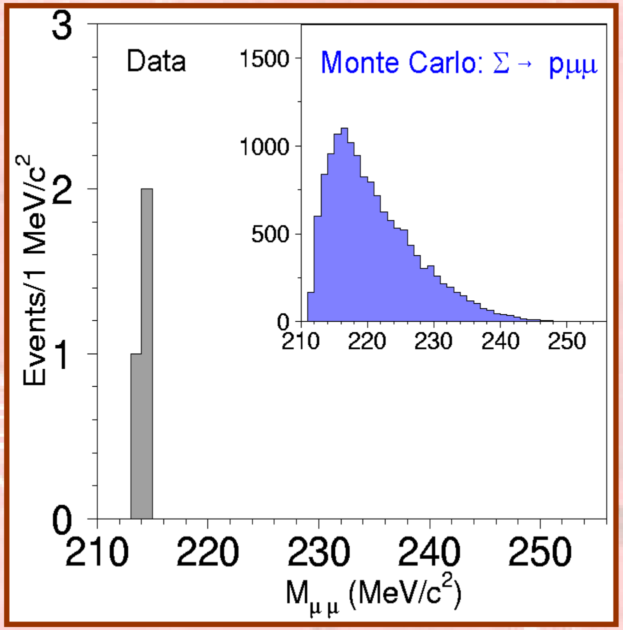
Until you look at the $\mu^+\mu^-$ mass

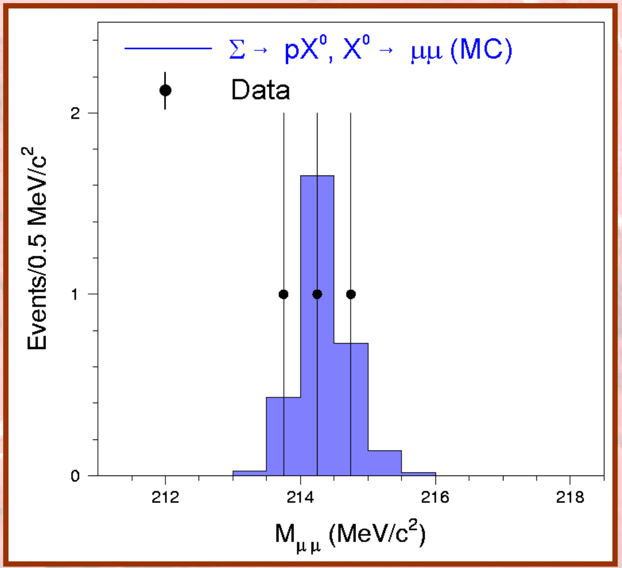
- The dimuon masses of all 3 events are within 1 MeV of each other!
- This is the mass resolution of the HyperCP spectrometer
- Suggests that the decay proceeds via an intermediate state, X^0

$$\Sigma^+ \to pX^0,\ X^0 \to \mu^+\mu^-$$

$$M_{X^0} = (214.3 \pm 0.5)\,\mathrm{MeV}/c^2$$

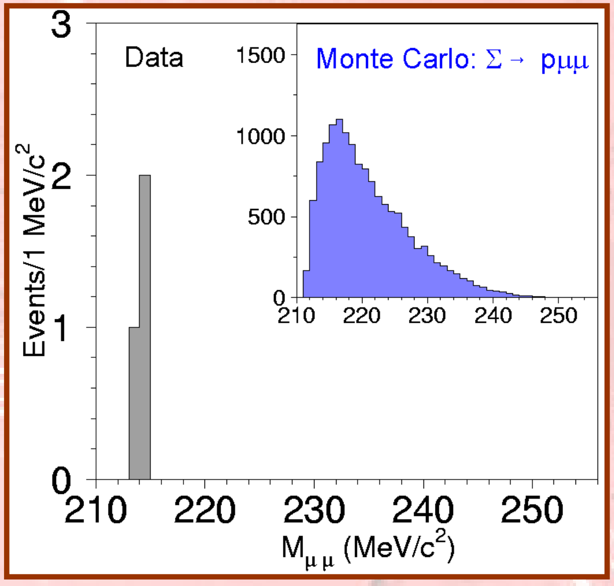
$$B(\Sigma^+ \to pX^0,\ X^0 \to \mu^+\mu^-) = [3.1 \pm^{2.4}_{1.9} \pm 1.5] \times 10^{-8}$$





Can this be real?

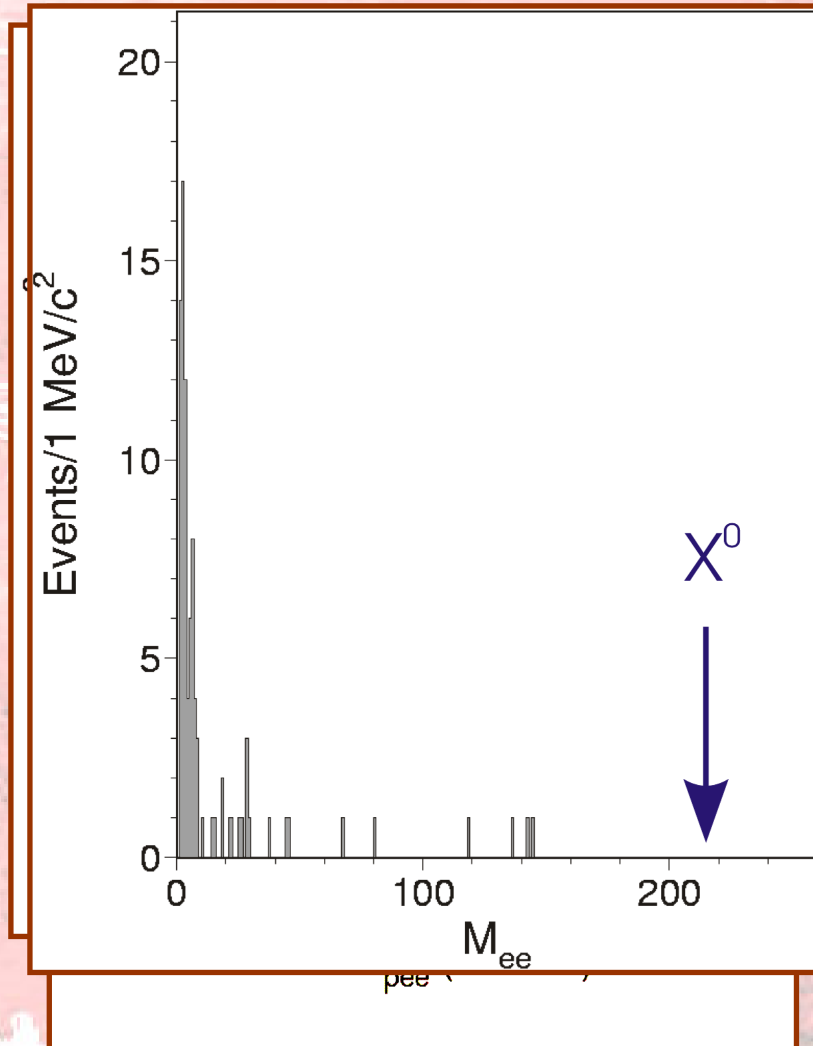
- Is it a statistical fluctuation?
  - Probability of 3 events having $\mu^+\mu^-$ mass within 1 MeV of each other anywhere in the kinematically allowed range is ~1%
  - Form factors can't be fudged to increase that probability by much
- Is it muonium? Not likely: it is 3.0 MeV (6.0 σ) above $2m_\mu$
- Is it $\Sigma^+ \to p\gamma$, $\gamma \to \mu^+\mu^-$? Probability is negligible and if true we would see loads of events in the e^+e^- mode.
- Is it another hyperon decay? All of the charged hyperons have the wrong decay topology
- Is it the analysis or detector? We've looked hard, but we don't see anything wrong.



What about $\Sigma^+ \to p e^+ e^-$?

- Much more difficult than $\Sigma^+ \to p\mu^+\mu^-$
  - no electron identification
  - trigger prescaled by 100X, although SM BR expected to be ~100X larger
  - WR decay background a problem: $\Sigma^+ \to p\gamma,\ \gamma Z \to e^+e^-$
- Clear Σ^+ peak
- Most of the events appear to be $\Sigma^+ \to p e^+ e^-$, but extracting $\Sigma^+ \to p\gamma,\ \gamma Z \to e^+e^-$ background difficult
- No sign of X^0, but we don't expect to see it

$$\frac{B(X^0 \to e^+e^-)}{B(X^0 \to \mu^+\mu^-)} \approx 1 - 10^{-4}$$

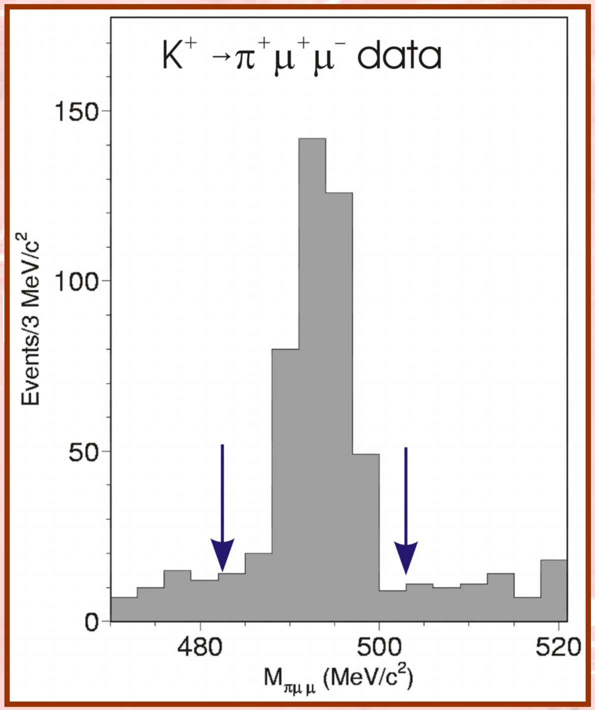


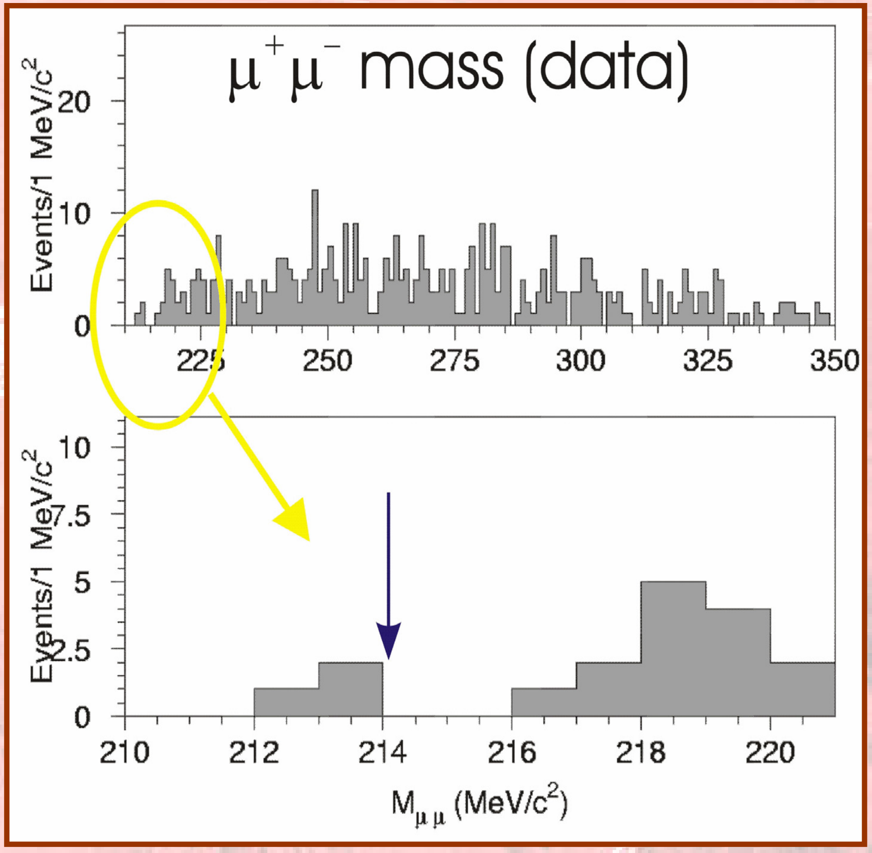
Suppose X^0 is real

- What properties does it have?
  - HyperCP can say little on this subject
    - know its mass
    - lifetime: not a resonance and not super long-lived
    - don't know its spin
    - don't know branching ratios: however $X^0 \to \mu^+\mu^-$ must be large
- Why wasn't it seen before?
- Is there any theoretical context for such a particle?
- Where else can we look for it?

Kaon searches eliminate all but a parity-conserving pseudoscaler or axial vector

- If either parity violating, or scalar or vector, HyperCP and others would have seen it in $K^+ \to \pi^+\mu^+\mu^-$ at several orders of magnitude more than the $(8.1\pm1.4)\times10^{-8}$ BR
- **However: existing constraints on parity-conserving pseudoscalar or axial vector weak**





Theoretical context: Supersymmetry?

- Sgoldstino: superpartner to the goldstino, the longitudinal component of the gravitino
- Properties: Spin: 0, all other properties ill-determined:
  - Unknown, but expected to be light
  - Lifetime: can be long or short lived
  - Should be two: scalar (S) and pseudoscalar (P)
  - Can have flavor conserving and flavor violating interactions
  - Interactions with quarks may or may not conserve parity: however theoretical motivation for parity-conserving interaction
  - Branching ratio to dimuons can be large if light ($< 2m_\pi$)

"Parity conservation in sgoldstino interactions with quarks and gluons may not be accidental…It is likely that sgoldstino interaction will conserve parity in supersymmetric versions of other models designed to solve the strong CP problem without introducing light axion."

Gorbunav and Rubakov,PRD 64, 054008 (2001)

$B(P\to e^+e^-)$	0.001%	0.01%
$c\tau$(cm)	0.02	0.003

1 TeV (SUSY breaking scale)

~100 GeV (order of photino mass)

A_l: soft-mass term

Where to look for parity-conserving pseudoscalar

Expected BRs based on HyperCP BR (with $X^0 \to \mu^+\mu^-$)

$K^+ \to \pi^+\pi^0 X^0$	$\sim 10^{-12}$
$K_L \to \pi^0\pi^0 X^0$	$\sim 10^{-8}$
$\to \pi^+\pi^- X^0$	$\sim 10^{-13} - 10^{-9}$
$K_S \to \pi^0\pi^0 X^0$	$\sim 10^{-11}$
$\to \pi^+\pi^- X^0$	$\sim 10^{-16} - 10^{-12}$
$\Omega^- \to \Xi^- X^0$	$\sim 10^{-6}$
$D^+ \to \rho^+ X^0$	$\sim 10^{-9} - 10^{-6}$
$B^+ \to K^{*+} X^0$	$\sim 10^{-9} - 10^{-6}$

Gorbunov and Rubakov, He, Tandean and Valencia, Deshpande, Eilam and Jiang, Gorbunov and Demidov

- Four-body kaon decay limits weak
- No data on $K \to \pi\pi\mu\mu$
- $K_L \to \pi^+\pi^- e^+e^- = 3.1\times10^{-7}$
- $K_L \to \pi^0\pi^0 e^+e^- < 6.6\times10^{-9}$
- If X^0 sgoldstino then $X^0 \to \mu^+\mu^- > X^0 \to e^+e^-$
- B and D limits getting to upper range of predictions

Only other hyperon mode accessible.
SM BR $\sim 10^{-8}$

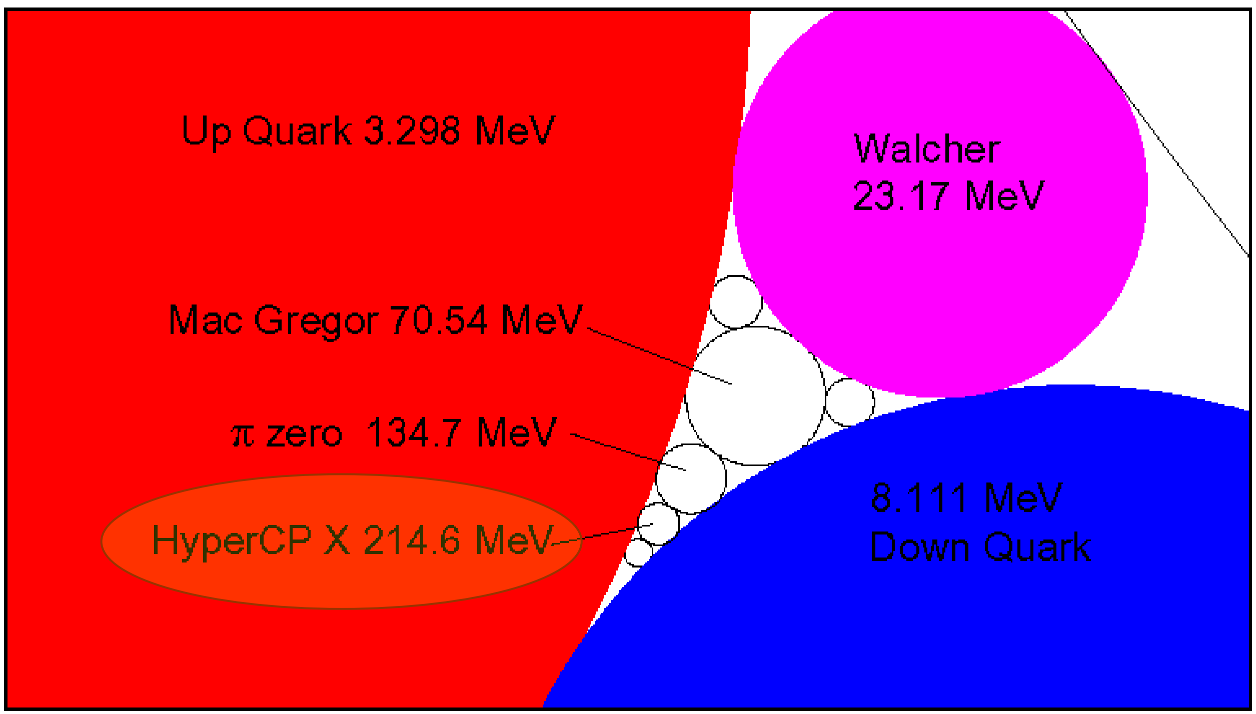
HyperCP is looking for $\Omega^- \to \Xi^-\mu^+\mu^- \to \Lambda\pi^-\mu^+\mu^- \to p\pi^-\pi^-\mu^+\mu^-$

At best we expect 1 or 2 events

There are more exotic explanations!

Diether and Inopin, physics/0601110

> To this date, no one has been able to successfully explain the mass spectrum of all the known particles. We don't pretend that we can fully explain it either but we expect the solution to be a geometrical one of some fashion. Our 2D Spin Matrix geometry is our first attempt for a geometrical solution and it has some promising features that warrant further investigation. Starting with the rest mass energy of the electron or positron, our geometry generates energy states that can be applied to the up and down quarks, pi zero mesons, the new HyperCP particle and many others. We have to stress that our scheme is parameter-free.



Conclusions and Outlook

- With one of the largest data samples ever taken HyperCP has pioneered high-sensitivity searches in hyperon decays
- This program is complementary to those carried out in other sectors, and often more sensitive
- Our CP-violation search is probing limits not constrained by Kaon, B, or EDM measurements

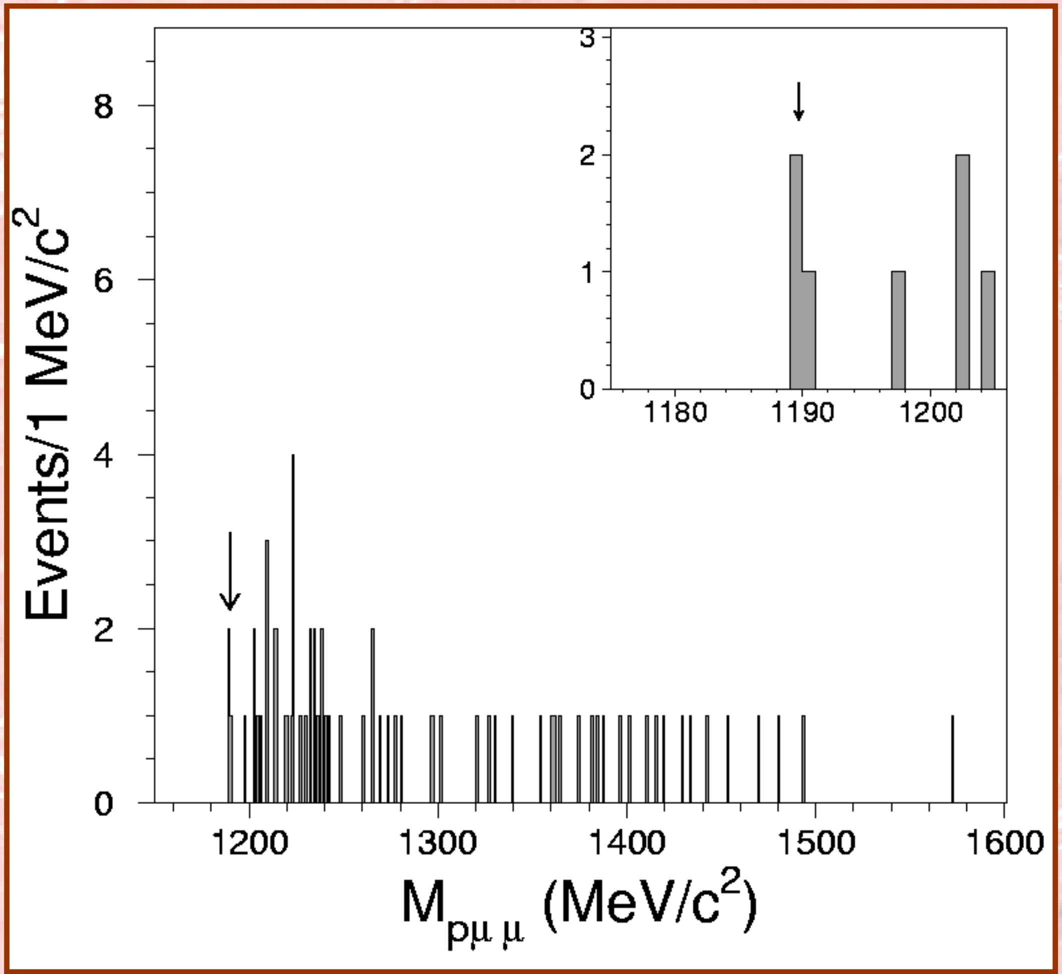
> "…we can then conclude that the available preliminary measurement by HyperCP has already begun to probe the parity even contributions better than ε does."
>
> Tandean, 2004

- Our $\Sigma^+ \rightarrow p\mu^+\mu^-$ result is intriguing and begs to be confirmed
- Mounting an experiment with 10X the statistics of HyperCP would be easy
- Unfortunately, the Tevatron no longer available for fixed-target physics at Fermilab, so it may be some time before we will learn more about these rare hyperon decays

Background Slides

Backgrounds: Relaxed Cuts

- Relax all basic selection cuts by ~1σ
- No events within 8σ



Searches for light boson

- Many experiments have searched for a light boson
- Few searches for a short-lived boson of mass ~200 MeV/c^2

Decay Mode	Exp. Limit	Range S=short lived, L=long lived
$K^+ \to \pi^+ X^\circ$	$< 4.5\times10^{-8}$ to 10^{-11}	$0 < m_{X^\circ} <$ 300 MeV (L)
$K^+ \to \pi^+ X^\circ$, $X^\circ \to \gamma\gamma$	$< 5.0\times10^{-8}$	$0 < m_{X^\circ} <$ 100 MeV (S)
$K^+ \to \pi^+ X^\circ$, $X^\circ \to \mu^+\mu^-$	$< 1.5\times10^{-7}$	$220 < m_{X^\circ} <$ 300 MeV (S)
$K^+ \to \pi^+ X^\circ$	$< 2\times10^{-5}$	$5 < m_{X^\circ} <$ 300 MeV (S & L)
$\eta \to \gamma X^\circ$	$< 6\times10^{-5}$	$200 < m_{X^\circ} <$ 525 MeV (L)
$\Upsilon \to \gamma X^\circ$	$< 1.3\times10^{-5}$	$m_{X^\circ} <$ 5 GeV (L)
$\Upsilon \to X^\circ X^\circ$	$< 1\times10^{-3}$	$m_{X^\circ} <$ 3.1 GeV (L)