Evidence for New Physics in the Decay $\Sigma^+ \to p\mu^+\mu^-$

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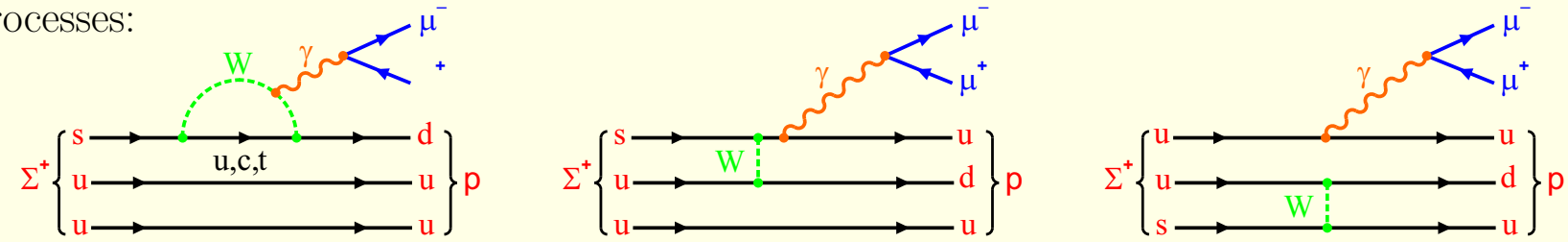
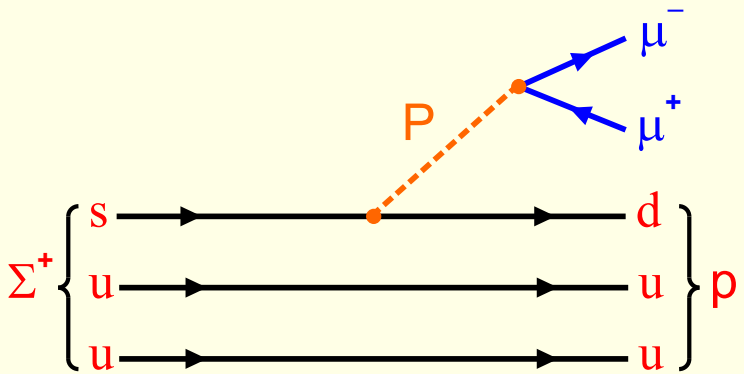
Motivation

- In SM $\Sigma^+ \to p\mu^+\mu^-$ is suppressed: leading diagrams are FCNC and Internal Conversion processes:



- Hence decay is sensitive to **New Physics**.
- **In particular, to light parity-conserving pseudoscalar sgoldstino decays.**

> "...if the sgoldstino is sufficiently light, the hyperon decays into baryon and sgoldstino are kinematically allowed and searches for these decays are very sensitive to sgoldstino couplings in models with light pseudoscalar sgoldstino and parity conservation."
>
> D.S. Gorbunov



- Such decays are constrained by kaon searches at only the $10^{-3} - 10^{-4}$ level.
- Collider searches only sensitive to high masses $m > 20$ GeV.
- Probes the scale of supersymmetry breaking as large as $10^3 - 10^4$ TeV.

Standard Model Predictions

- **Theory** "prediction" (L. Bergstroöm, R. Safadi, and P. Singer, Z. Phys. C **37**, 281 (1988)):

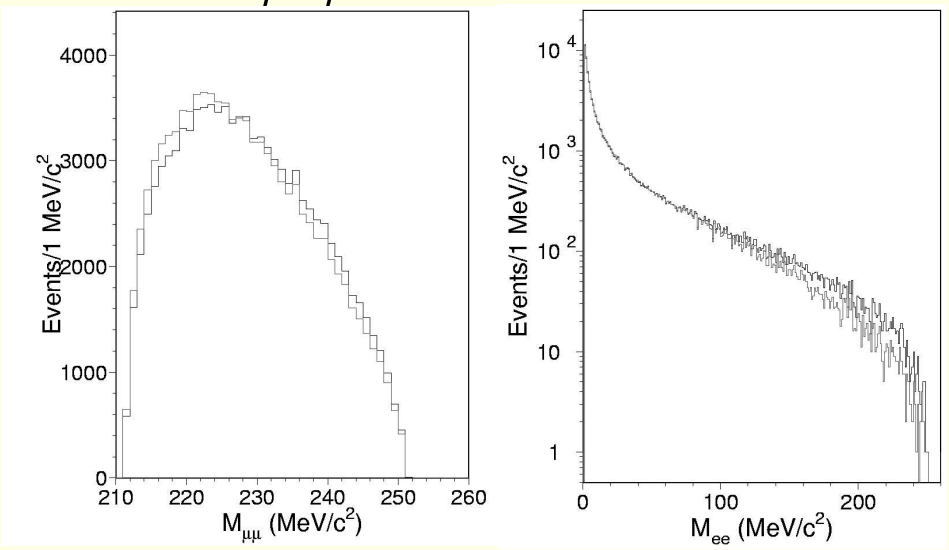
$$B(\Sigma^+ \to pe^+e^-) \sim B(\Sigma^+ \to p\gamma)\cdot\alpha_e \sim 10^{-6}$$
$$B(\Sigma^+ \to p\mu^+\mu^-) \leq \frac{1}{100}B(\Sigma^+ \to pe^+e^-) \leq 10^{-8}$$

- **Experimental** results: only an upper limit on $\Sigma^+ \to pe^+e^-$: $B(\Sigma^+ \to pe^+e^-) < 7\times10^{-6}$
- Hadronic matrix element described by 4 form factors: b_1, b_2, c_1, c_2. b_1 and b_2 extracted from known rate and asymmetry parameter in $\Sigma^+ \to p\gamma$:

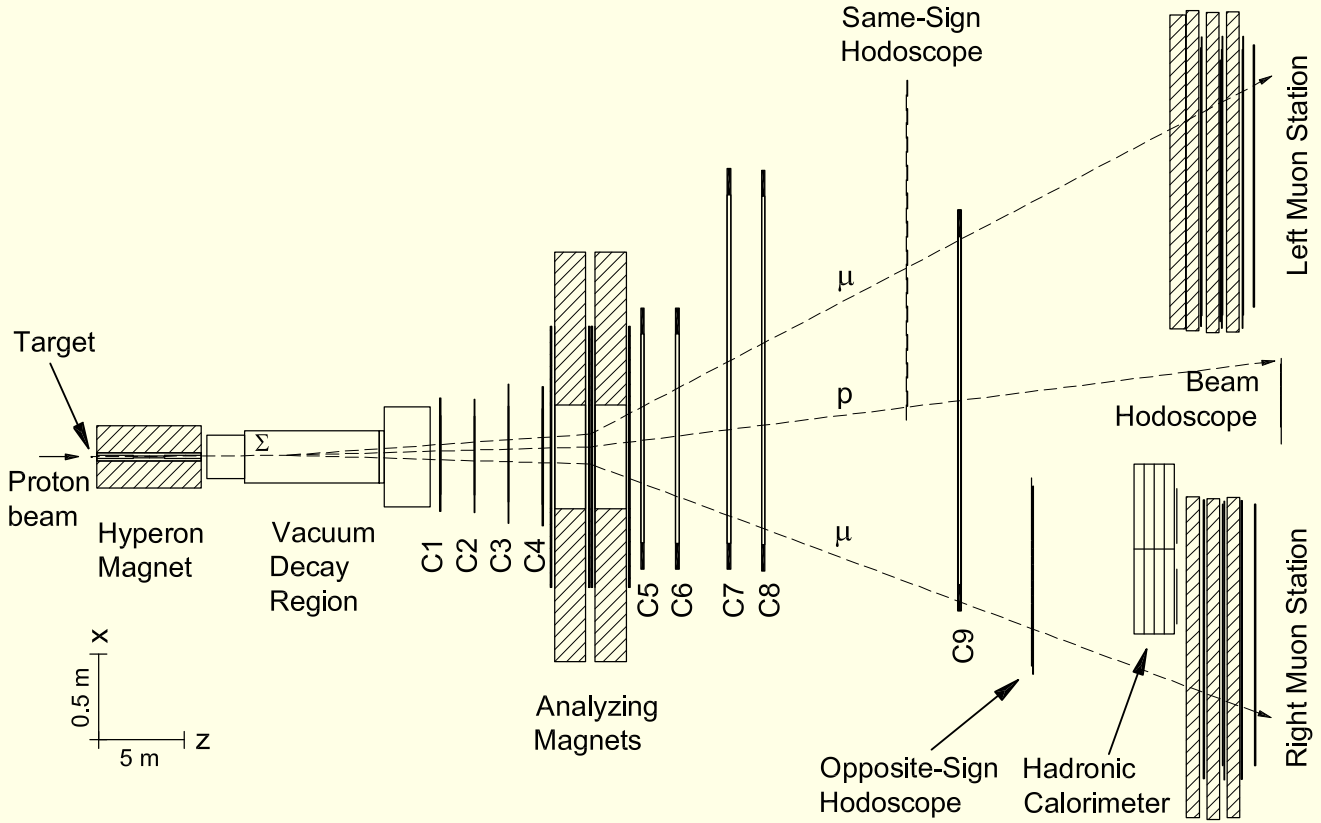
$$\Gamma(\Sigma^+ \to p\gamma) \sim |b_1|^2 + |b_2|^2$$
$$\alpha = \frac{2\mathrm{Re}(b_1 b_2^*)}{|b_1|^2 + |b_2|^2}$$
$$\frac{b_2(0)}{b_1(0)} = -0.46\pm0.07$$
$$|b_1(0)| = 6.8\pm0.2\mathrm{MeV}$$

- Limits on c_1 and c_2 are determined by the upper limit for $\Sigma^+ \to pe^+e^-$.

$\Sigma^+ \to \mu^+\mu^-$ $\Sigma^+ \to e^+e^-$



High Rate Spectrometer Built for *CP*-Violation Search



- Alternate + and − running.
- 800 GeV/c incident proton beam.
- 10–15 MHz, 167 GeV/c charged beam.
- High-rate, narrow-pitch wire chambers.
- High-rate DAQ: ∼100,000 evnts/s.
- Muon system only particle ID detector.
- Two stations on left and right side.
- Three layers of 80-cm thick steel.
- Three layers of x and y proportional tubes.
- Hodoscopes at rear for triggering.
- μ trigs. 2μ: L·R muon hodoscopes
  1μ: L (prescale 10), R (prescale 5).

HyperC^P Yields

- In 12 months of data taking *HyperC*^{P} recorded one the largest data samples ever by a particle physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB data.

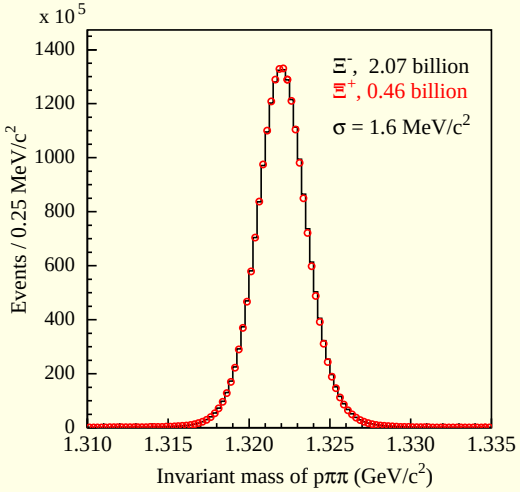
Reconstructed Events

	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

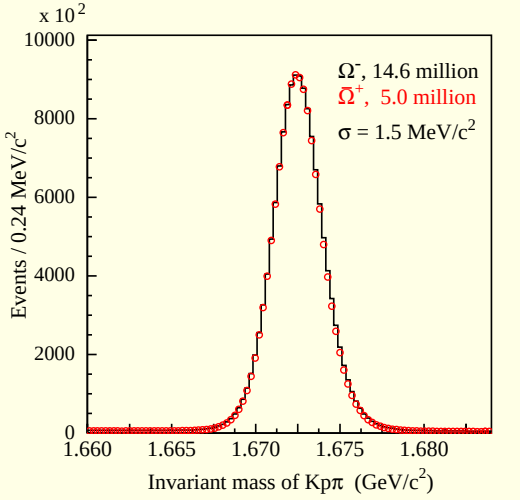
→ Largest hyperon samples ever taken

→ $\sim 10^{10}$ Σ^+ decays.

$\Xi^\pm \to \Lambda\pi^\pm$ [1]

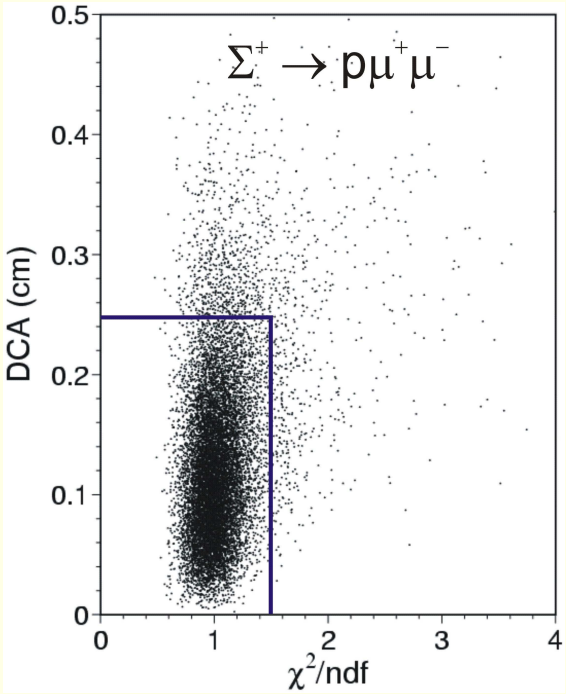


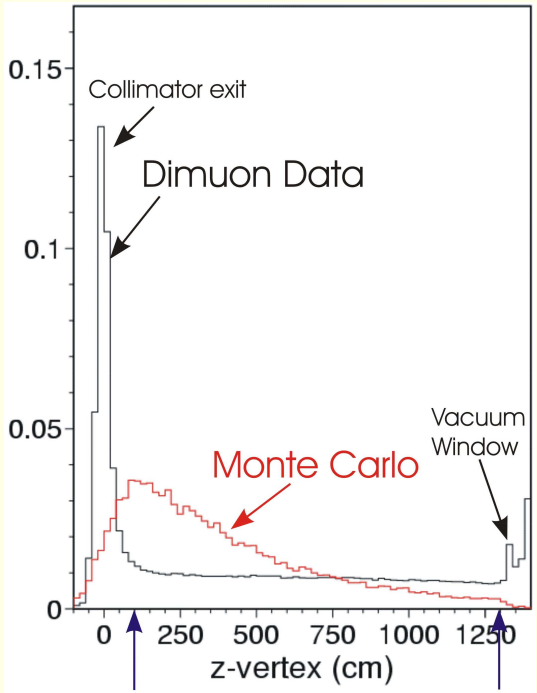
$\Omega^\pm \to \Lambda K^\pm$

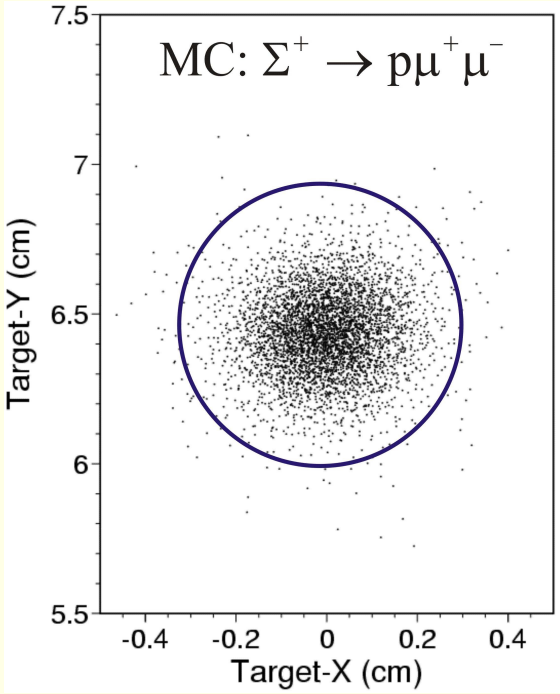


Simple yet Powerful Cuts for Event Selection

- Note: 1) only muon id; 2) decay has very little Q (40 MeV)
- Two unlike-sign muons.
- Muon id: good hits in 2/3 muon PWCs and muon hodoscopes.
- Good vertex: DCA < 2.5 mm; $\chi^2 < 1.5$.
- Decay vertex well within Vacuum Decay Region.
- Target pointing: $R < 3.5$ mm.

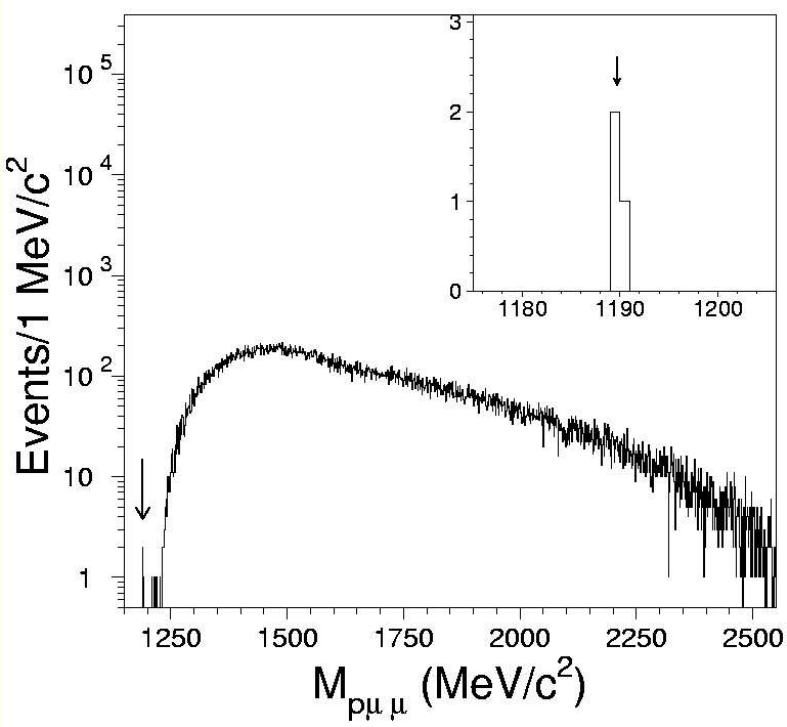




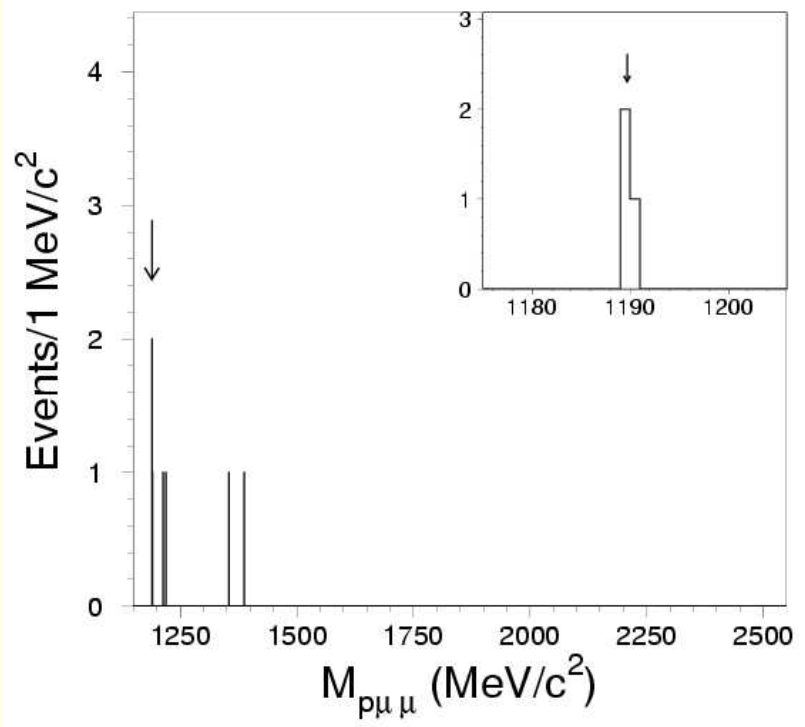


Three $\Sigma^+ \to p\mu^+\mu^-$ Decays Survive Selection Cuts

Basic Selection Cuts



Basic Selection Cuts + $f_{\rm had} > 0.68$



- **Observe 3 events all within $1\,\sigma$ of the the Σ^+ mass (1189 MeV).**
- Do not see any events in the negative data.
- Backgrounds $20\,\sigma$ away from Σ^+ mass.

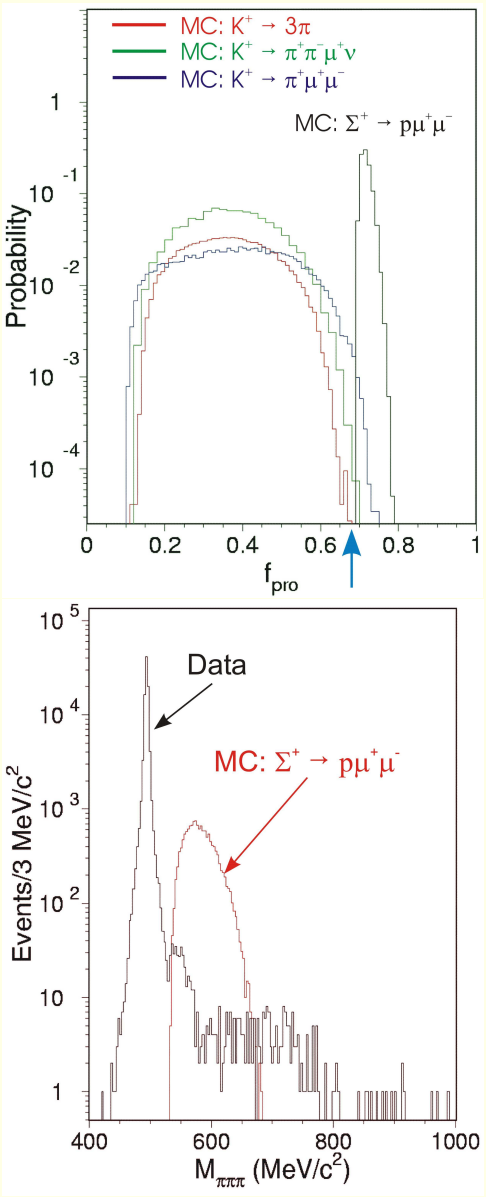
Removing Kaon Background

- Heavier decay daughters carry more momentum.
- Require:

$$f_{\rm had} = \frac{\text{hadron momentum}}{\text{total momentum}} > 0.68$$

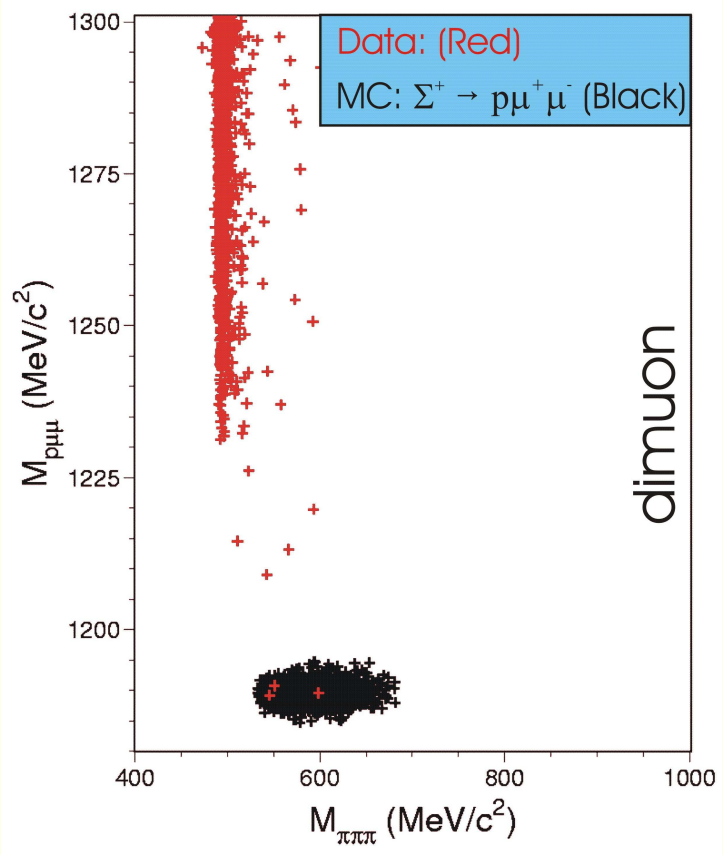
Decay Mode	BR	$\epsilon(\%)$
$K^+ \to 3\pi$	5.6%	0.0
$K^+ \to \pi^+\pi^-\mu^+\nu_\mu$	1.4×10^{-5}	$\sim$0.0
$K^+ \to \pi^+\mu^+\mu^-$	8.1×10^{-8}	0.4

- MC studies show no kaon decays are serious sources.
- Non-gaussian tails difficult to simulate. Look at data.

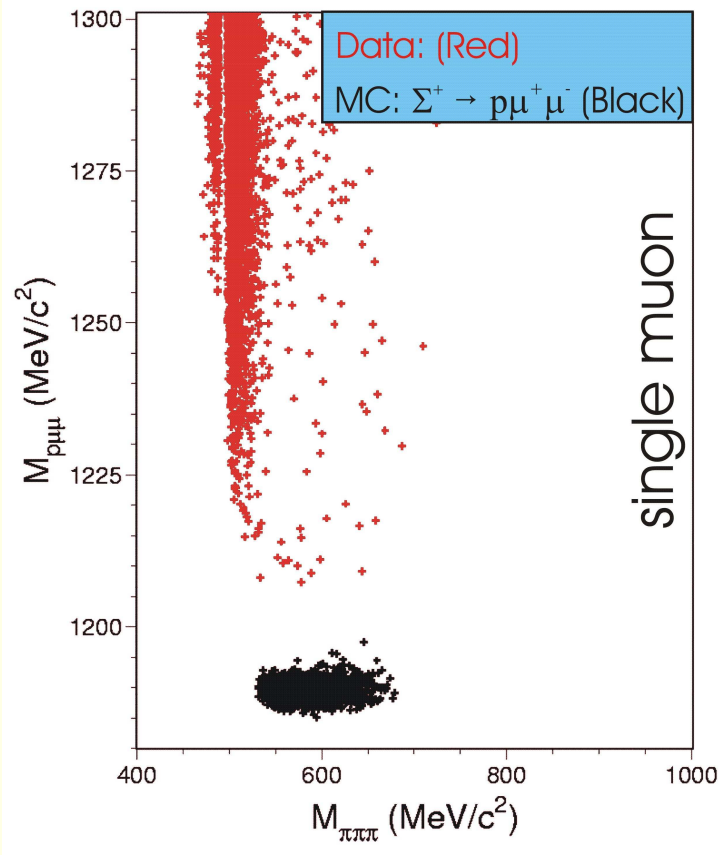


Background: Single-Muon Sample

Dimuon trigger sample

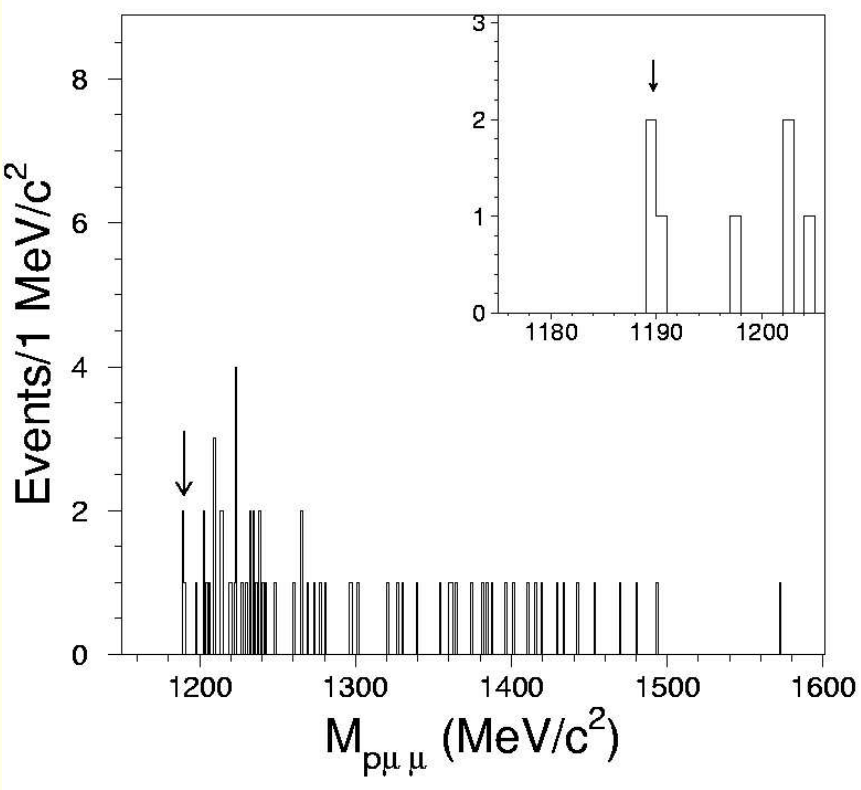


Single muon trigger sample



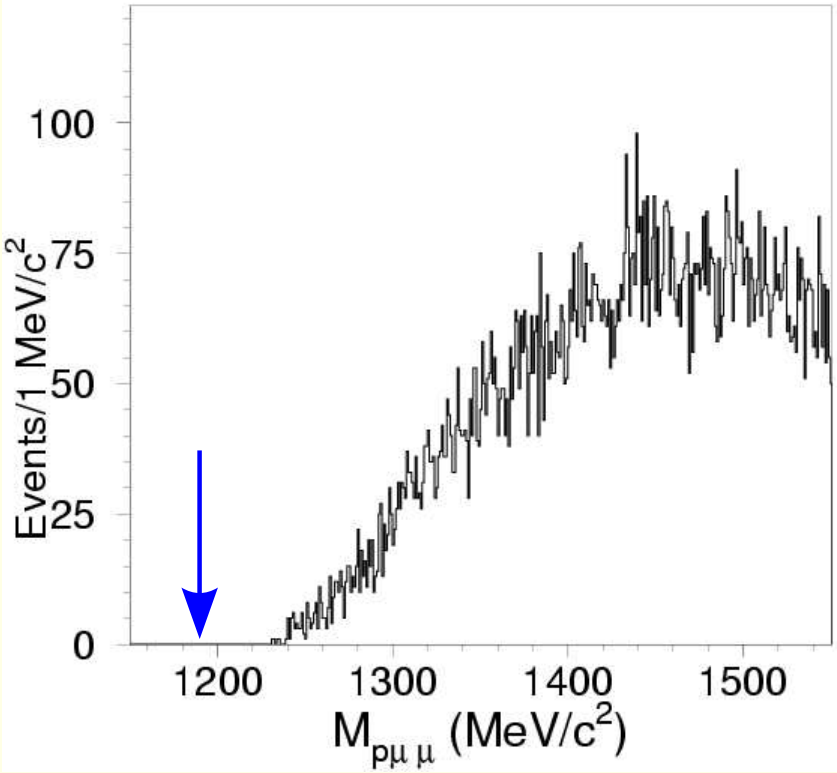
- Single-muon sample: 30 $\times$ larger.
- No events below 1200 MeV/c^2.

Dimuon Sample with Relaxed Cuts



- Increased the background but still no events with $8\,\sigma$ of the Σ^+ mass.

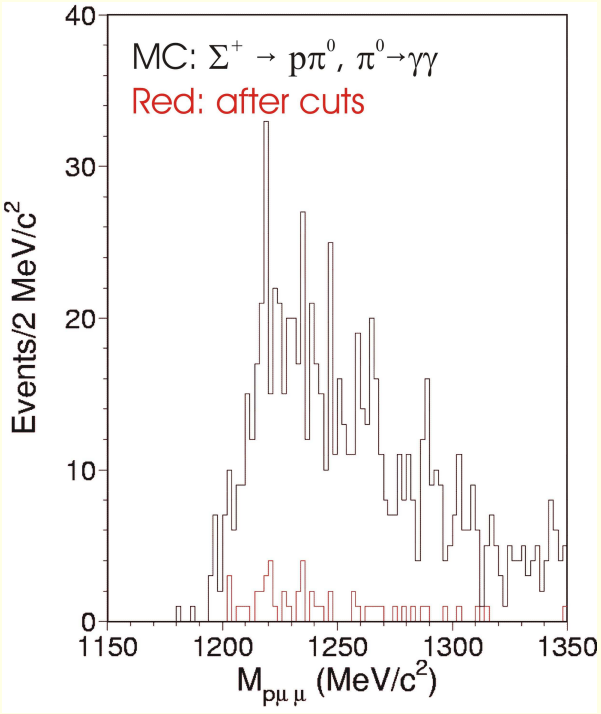
Negative-polarity Dimuon Sample

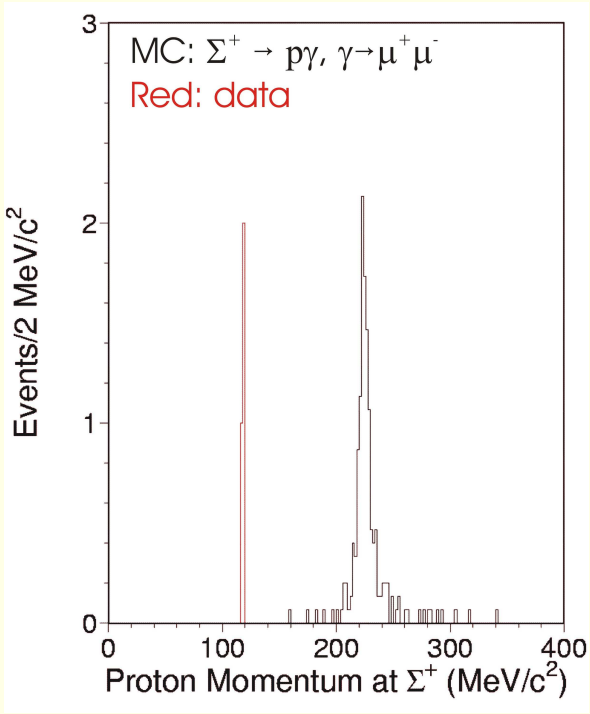


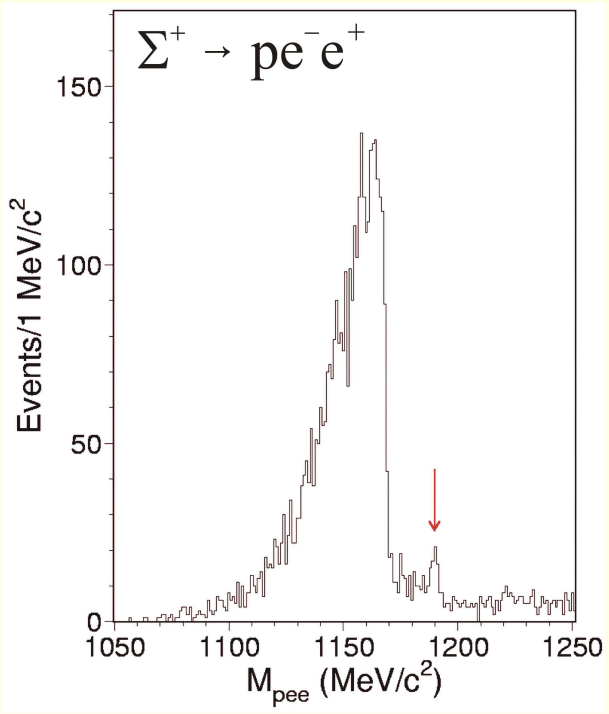
- Negative-beam sample one half the size of the positive beam.
- Note: $\overline{\Sigma^+}$ production decreased by $\sim$10 $\times$.

Background: Photon Conversions

- Probability of γ conversion in decay pipe window 10^{-7}.
- Monte Carlo studies of $K^+ \to \pi^+\pi^\circ$, $K^+ \to \pi^+\gamma\gamma$, $\Sigma^+ \to p\pi^\circ$, $\Sigma^+ \to p\gamma$, with 100–1,000 times expected level show no background.
- No evidence of much larger $\Sigma^+ \to pe^+e^-$ rate if e^+e^- were from γ conversions.







Measuring the Branching Ratio

- No EM calorimetery: use $\Sigma^+ \to p\pi^\circ \to pe^+e^-\gamma$ for normalization.

$$B(\Sigma^+ \to p\mu^+\mu^-) = \frac{N^{\rm obs}_{\rm signal}}{100{\cdot}N^{\rm obs}_{\rm norm}} \frac{A_{\rm norm}}{A_{\rm signal}} \frac{\epsilon_{\rm norm}}{\epsilon_{\rm signal}} \frac{B(\Sigma^+ \to p\pi^\circ){\cdot}B(\pi^\circ \to e^+e^-\gamma)}{\epsilon_{\mu^+\mu^-}{\cdot}\epsilon^{\rm trig}_{rel}}$$

- If 3 candidates are $\Sigma^+ \to p\mu^+\mu^-$ decays:

$$B(\Sigma^+ \to p\mu^+\mu^-)$$

$$= [1.3^{+1.0}_{-0.8} \pm 0.7] \times 10^{-7} (\text{uniform decay})$$

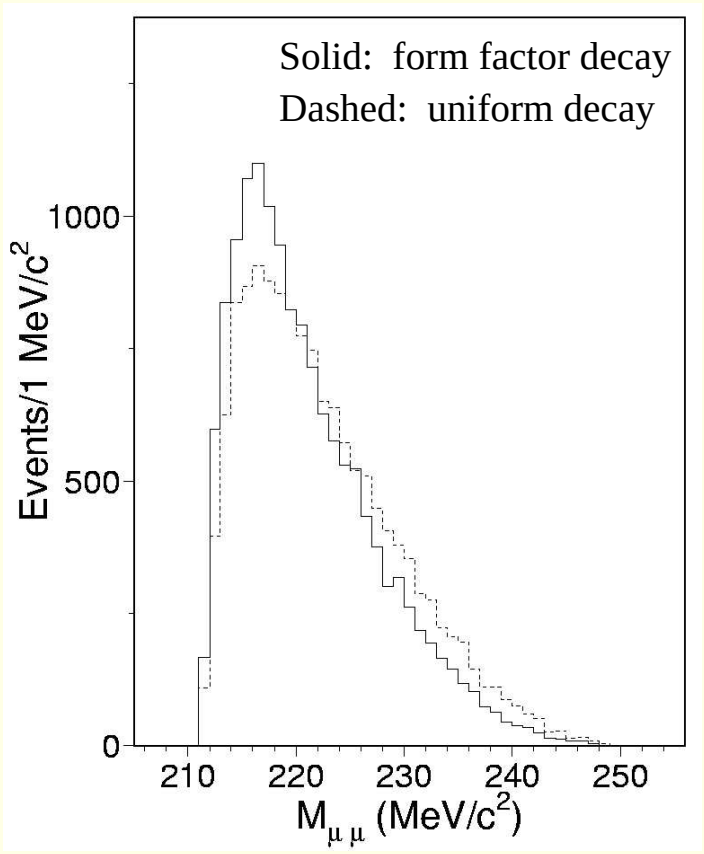
$$= [0.9^{+0.7}_{-0.5} \pm 0.6] \times 10^{-7} (\text{form factor decay})$$

- If 3 candidates are some unknown background:

$$B(\Sigma^+ \to p\mu^+\mu^-)$$

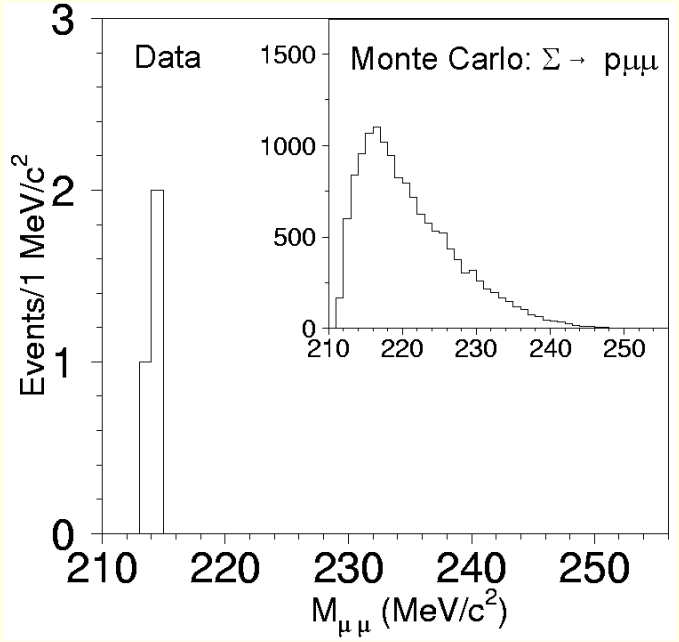
$$< 5.2 \times 10^{-7} (\text{uniform decay})$$

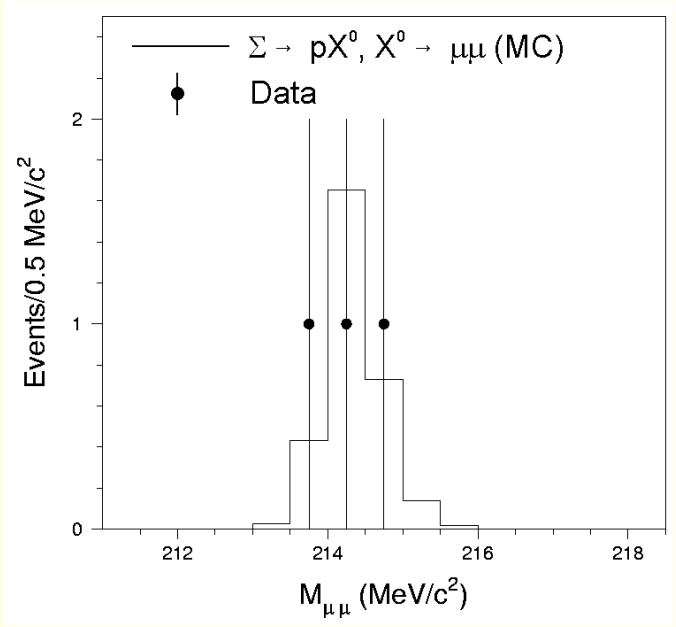
$$< 3.4 \times 10^{-7} (\text{form factor decay})$$



Dimuon Mass Suggests Intermediate State

- **The dimuon masses of the 3 events are all within 1 MeV/c^2 of each other!**





- **Probability of the 3 events all having a mass within 1 MeV/c^2 anywhere in the allowed kinematic range is $\sim$0.8 %!**
- Suggests decay proceeds through an intermediate state:

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

$$\mathrm{M}_{X^\circ} = (214.3 \pm 0.5)\,\mathrm{MeV}/c^2$$

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

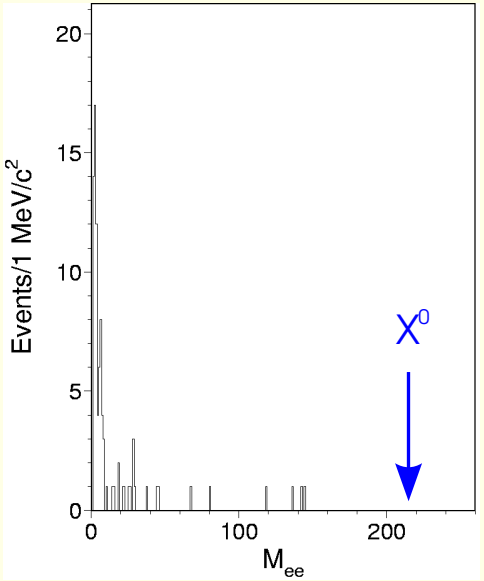
Could the X° be a Vector Particle?

- Impossible to tell from our data.
- If X° **vector particle**:

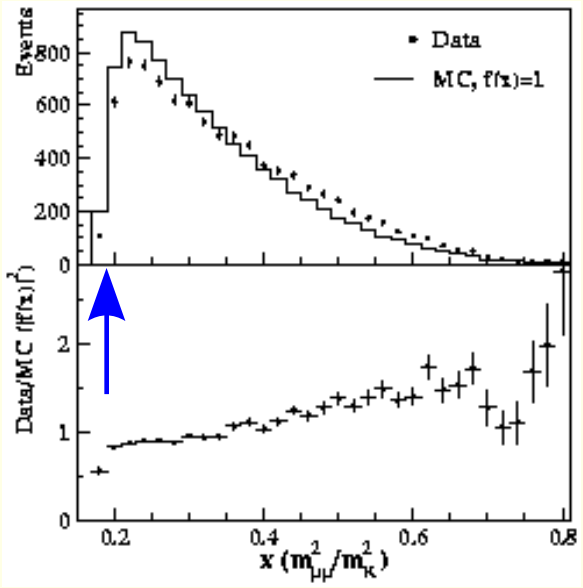
$$\frac{B(X^\circ \to e^+e^-)}{B(X^\circ \to \mu^+\mu^-)} \sim 2 \Rightarrow B(\Sigma^+ \to pX^\circ \to pe^+e^-) \sim 6\times10^{-8}$$

- If X° **scalar particle** $X^\circ \to e^+e^-$ is helicity suppressed:

$$\frac{B(X^\circ \to e^+e^-)}{B(X^\circ \to \mu^+\mu^-)} \sim 10^{-4} \Rightarrow B(\Sigma^+ \to pX^\circ \to pe^+e^-) \sim 6\times10^{-12}$$



- In either case we expect to see < 1 e^+e^- events.



- Vector possibility ruled out by $K_L \to \gamma\mu^+\mu^-$:
  - KTeV found 9327 decays.
  - $B(K_L \to \gamma\mu^+\mu^-) = (3.62\pm0.04\pm0.08)\times10^{-7}$
  - Don't see: $K_L \to \gamma X^\circ$, $X^\circ \to \mu^+\mu^-$.

Can X° be a Sgoldstino?

Sgoldstino:

- Sgoldstino is the superpartner to the goldstino, which is the longitudinal component of the gravitino.
- Spin 0.
- Massless at tree level, obtains mass from the Kähler potential. In general light.
- Should be two: scalar (S) and pseudoscalar (P).
- Can have flavor conserving and flavor violating interactions.
- Interactions with quarks and gluons may, or may not, conserve parity.
- Branching ratio to dimuons can be large:

	$A_l = 100\,\text{GeV}$	$A_l = 1000\,\text{GeV}$
$B(P \to \gamma\gamma)$	91.3%	9.5%
$B(P \to \mu^+\mu^-)$	8.7%	90.5%
$B(P \to e^+e^-)$	0.001%	0.01%
$c\tau$ (cm)	0.02	0.002

$\sqrt{F} = 1$ TeV

$M_{\gamma\gamma}$: order of photino mass ($\sim$100 GeV)

A_l : soft mass term

- $B(\Sigma^+ \to pX^\circ) < 10^{-3} - 10^{-6}$ (Gorbunov)

Previous Searches for a Light Boson

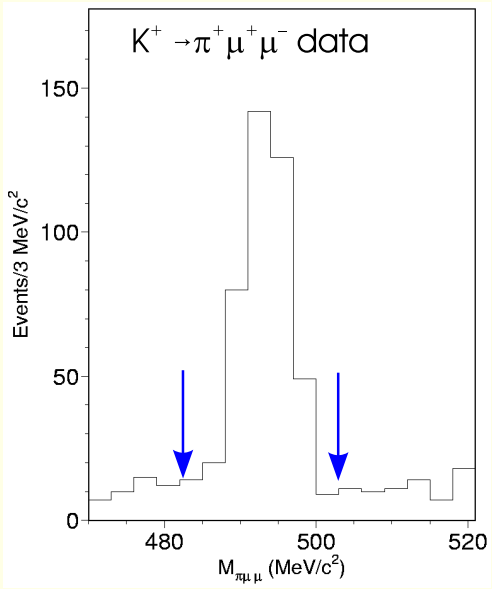
- A short-lived X° of mass $214\,\mathrm{MeV}/c^2$ has not been well searched for.

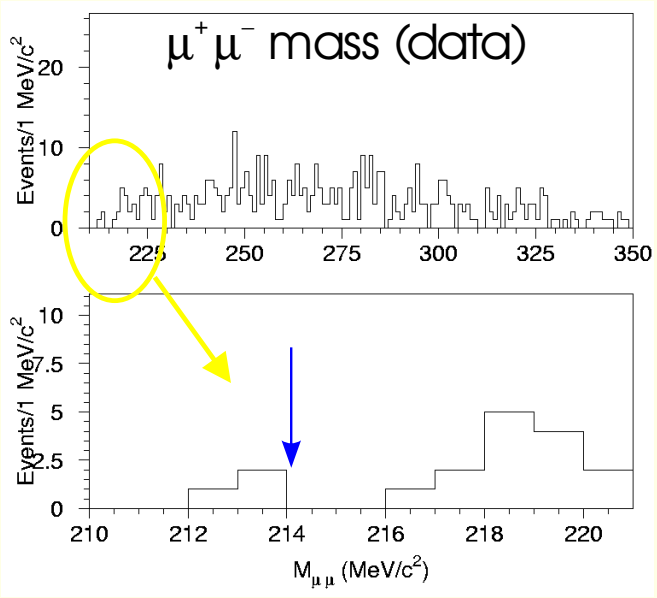
Decay Mode	Exp. Limit	Range S=short lived, L=long lived
$K^+ \to \pi^+ X^\circ$	$< 4.5\times10^{-8}$ to 10^{-11}	$0 < m_{X^\circ} <$ 300 MeV (L)
$K^+ \to \pi^+ X^\circ$, $X^\circ \to \gamma\gamma$	$< 5.0\times10^{-8}$	$0 < m_{X^\circ} <$ 100 MeV (S)
$K^+ \to \pi^+ X^\circ$, $X^\circ \to \mu^+\mu^-$	$< 1.5\times10^{-7}$	$220 < m_{X^\circ} <$ 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)

- Two-body decays in general do **not** probe **parity-conserving pseudoscalar** sgoldstinos.

Kaon Searches Eliminate Parity Violating or Scalar Boson

- If either parity violating or scalar then HyperCP would have seen it in $K^+ \to \pi^+\mu^+\mu^-$ at the $\sim 10^{-10}$ level:





- Existing constraints on **parity-conserving pseudoscalar** boson weak.
- Theoretical motivation for a **parity-conserving pseudoscalar sgoldstino** interaction.

> "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."
>
> Gorbonov and Rubakov, PRD **64**, 054008 (2001)

Conclusions and Outlook

- We have observed 3 events consistent with the decay $\Sigma^+ \to p\mu^+\mu^-$.
- This is the rarest decay of a baryon yet observed: $B = [8.6^{+6.6}_{-5.4} \pm 5.5] \times 10^{-8}$
- The narrow ranges of dimuon masses indicates that the decay proceeds via a hitherto unobserved neutral intermediate state:

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

$$\mathrm{M}_{X^\circ} = 214.3 \pm 0.5\,\mathrm{MeV}/c^2$$

$$B = [3.1^{+2.4}_{-1.9} \pm 1.5] \times 10^{-8}$$

- This state is consistent with a **pseudoscalar sgoldstino** with a **parity-conserving interaction**.
- Further searches are needed!
- Note: this work recently published: Phys. Rev. Lett. **94**, 021801 (2005).

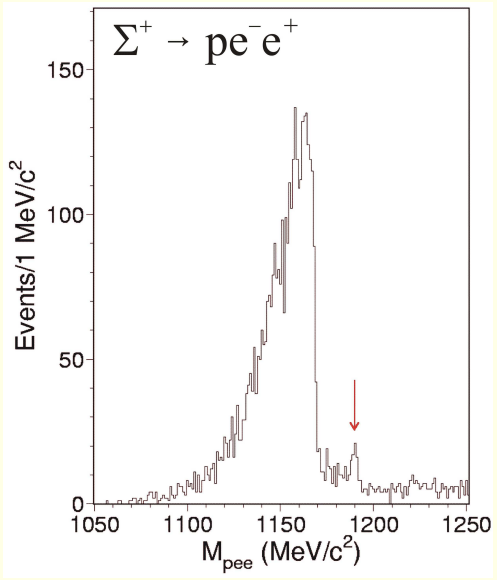
Backup Slides

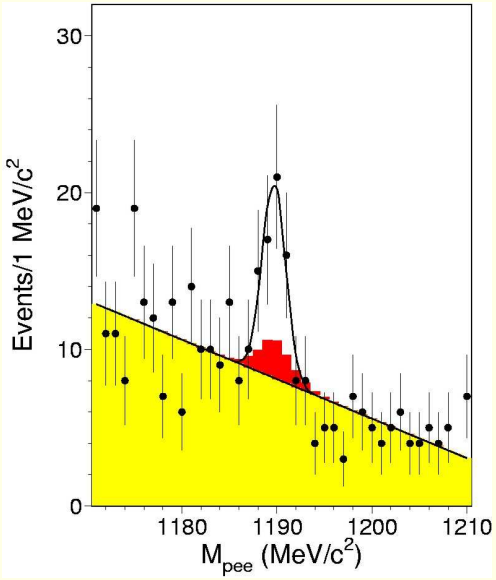
Where to Look for Parity-Conserving Pseudoscalar

- In general you want three-body meson decays.

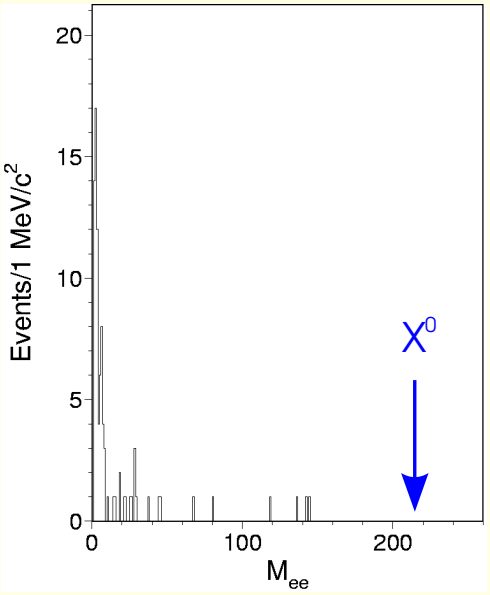
	Range	
Decay Mode	General	Re $h_{12}^{(D)} = 0$
$K_L \to \pi^+\pi^- P$, $\pi^\circ\pi^\circ P$	$< 10^{-3}$	10^{-6}
$K^+ \to \pi^+\pi^\circ P$	$< 10^{-6}$	10^{-4}
$K_S \to \pi^+\pi^- P$, $\pi^\circ\pi^\circ P$	very small	10^{-3}
$\phi(1020) \to K^+\pi^- P$		
$\Omega^- \to \Xi^- P$		
$D^+ \to \pi^-\pi^\circ P$		
$B^+ \to K^+\pi^\circ P$		

Search for $\Sigma^+ \to pe^+e^-$ Decays





- **Note: No EM calorimeter or particle id!**
- Observe peak at Σ^+ mass.
- Peak is consistent with $\Sigma^+ \to pe^+e^-$ decays with a little $\Sigma^+ \to p\gamma$, $\gamma \to e^+e^-$.
- See no evidence of X°, nor do we expect to given statistics, irrespective of whether it is a scalar or a vector particle.



Systematic Errors

	$\Sigma^+ \to p\mu^+\mu^-$	$\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-$
	uniform decay (form factor)	
Source	σ_B/B (%)	σ_B/B (%)
Normalization	14.7 (14.7)	14.7
Modeling of Σ^+ production	52.1 (54.3)	44.6
Beam targeting	11.5 (11.1)	8.7
Magnetic field	3.8 (2.2)	3.9
Trigger efficiency	1.5 (1.5)	1.5
Muon identification	0.3 (0.3)	0.3
$\Sigma^+_{p\mu\mu}$ decay model	(8.8)	
π^0 form factor	1.8 (1.8)	1.8
$B(\Sigma^+ \to p\pi^0)$	0.6 (0.6)	0.6
$B(\pi^0 \to ee\gamma)$	2.7 (2.7)	2.7
MC statistics	1.3 (1.3)	1.3
Total	55.6 (58.2)	48.1

- Main source of error is modeling the Σ^+ momentum.