Evidence for the Sgoldstino in the Decay $\Sigma^+ \to p\mu^+\mu^-$ from the HyperCP Experiment

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for the HyperCP Collaboration

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University of Durham
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Outline:

1. Motivation
2. The HyperCP Experiment
3. Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$
4. Interpretation of results
5. Conclusions

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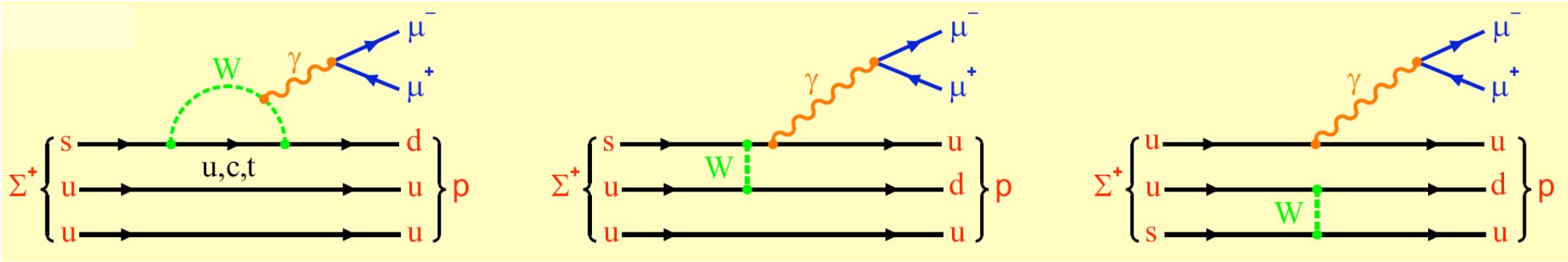
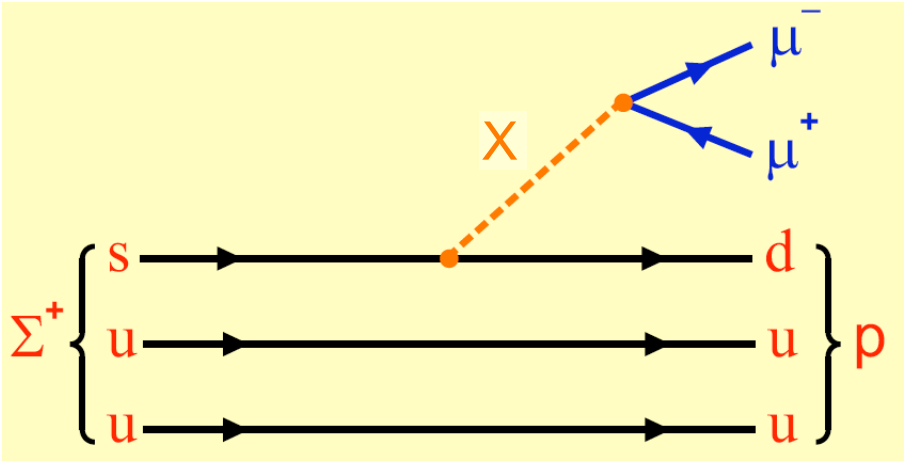
Physics Motivation

- In the SM, the decay $\Sigma^+ \to p l^+ l^-$ ($l = e,\ \mu$) is suppressed:
  - leading diagrams are FCNC (penguin) and Internal Conversion processes:

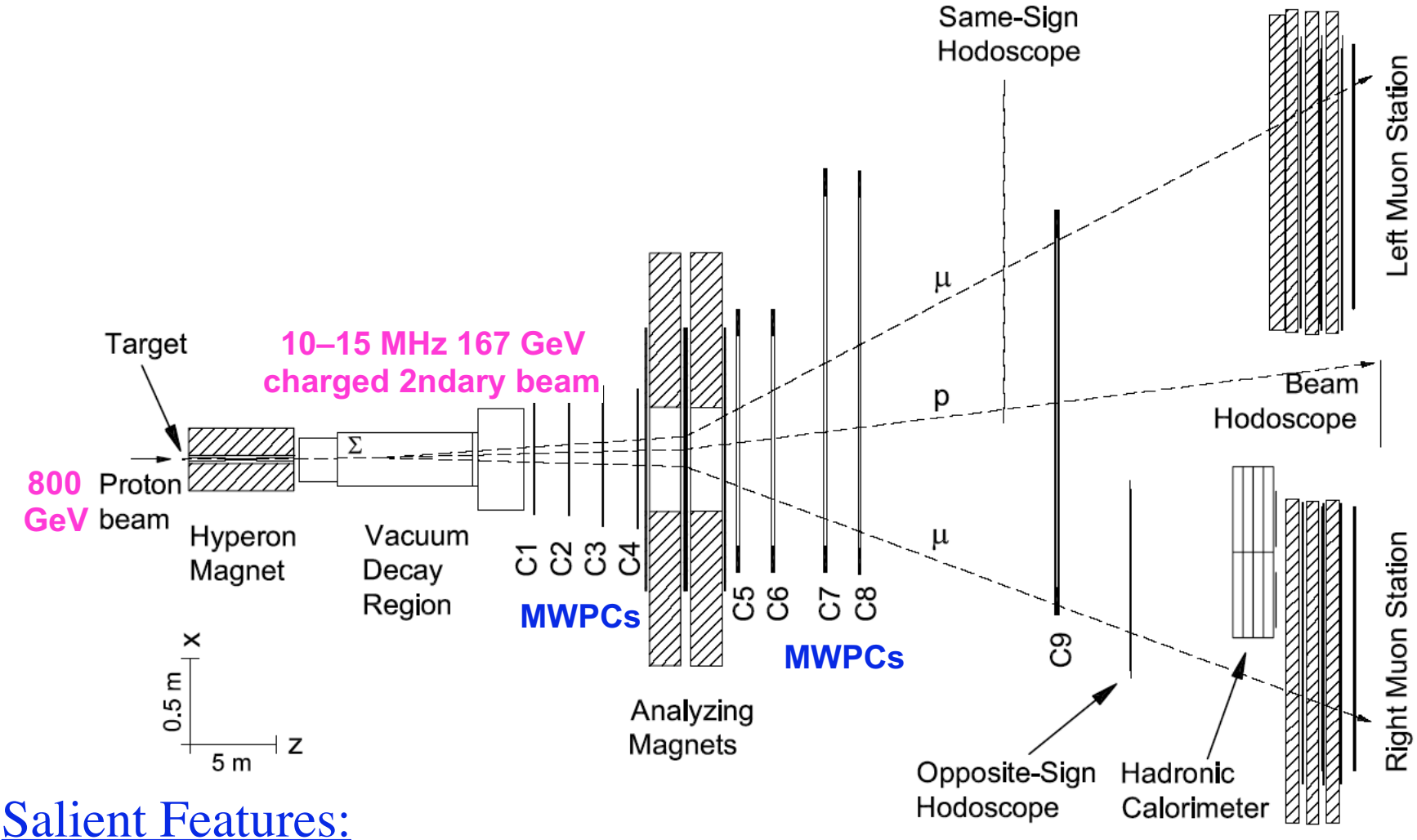


- Hence decay potentially sensitive to **New Physics**
- E.g., new light scalar or vector particle:
  - could mediate tree-level FCNC processes
  - in practice, unconstrained by kaon rare-decay searches if, e.g., a parity-conserving process



- Collider searches sensitive only to high masses $m_X > 20$ GeV.
- Can probe scale of supersymmetry breaking as high as $10^3 - 10^4$ TeV.

HyperCP Spectrometer (built for hyperon *CP*-violation search)



Salient Features:

- High-rate detectors & DAQ (100k evts/s)
- Alternating "+" & "–" running (with reversed B fields) to minimize systematics
- Simple, low-bias triggers based on hodoscope coincidences
- Muon-ID system:
  - 3 layers 80-cm-thick steel
  - 3 layers *x* & *y* proportional tubes
  - hodoscopes for triggering
  - μ triggers: 2μLR, 1μL ÷ 10, 1μR ÷ 5
- No other particle ID

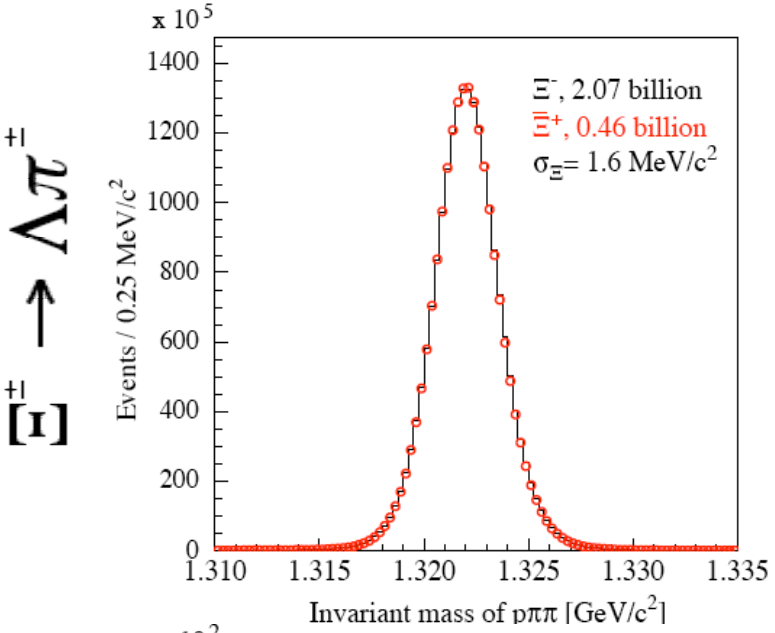
HyperCP Event Yields

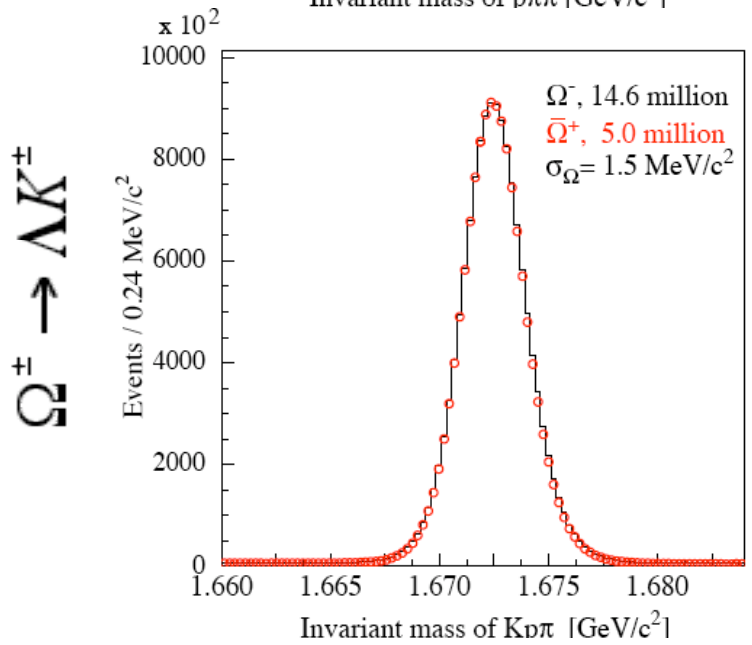
- In 12 months of data taking in 1997–99, HyperCP recorded one the largest data samples ever by a particle-physics experiment: 231 billion events, 29,401 tapes, and 119.5 TB of data

Reconstructed Events			
Mode	+	–	Total
$\Xi \to \Lambda\pi$	0.458×10^9	2.032×10^9	2.490×10^9
$K \to \pi\pi\pi$	0.391×10^9	0.164×10^9	0.555×10^9
$\Omega \to \Lambda K$	4.9×10^6	14.1×10^6	19.0×10^6

Largest hyperon samples ever taken!

include $\sim 10^{10}$ Σ^+ decays

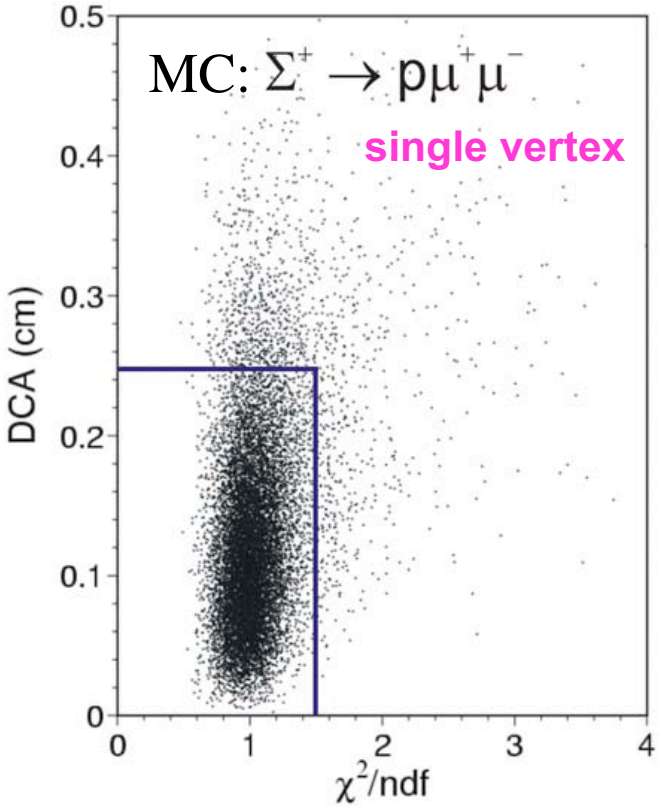


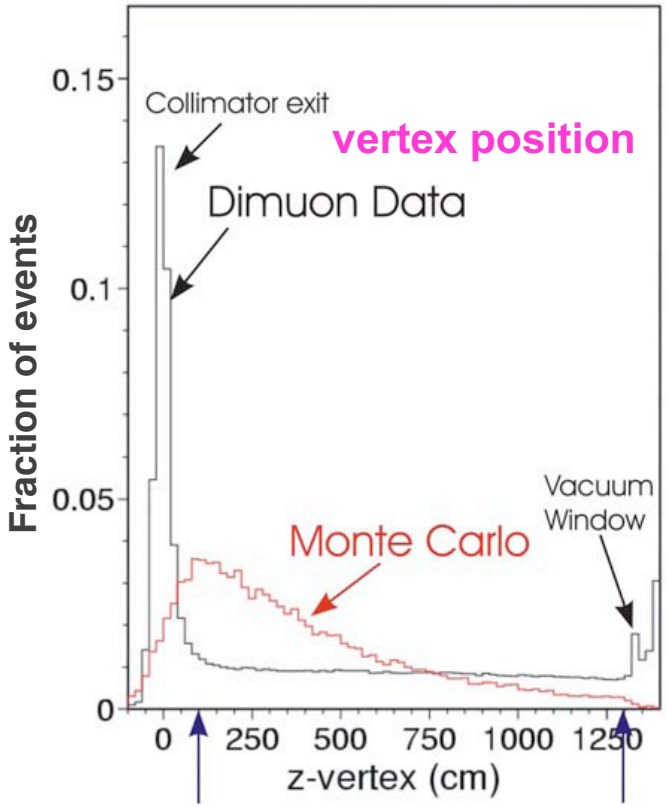


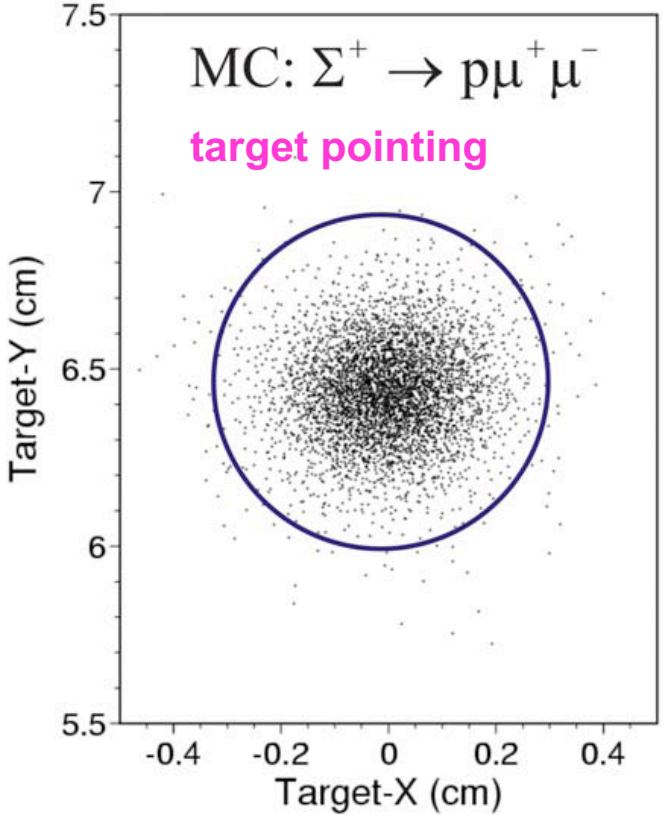
Search for $\Sigma^+ \rightarrow p\mu^+\mu^-$

[H. K. Park *et al.*, "Evidence for the Decay $\Sigma^+ \rightarrow p\mu^+\mu^-$," Phys. Rev. Lett. **94**, 021801 (2005)]

- Basic selection cuts:
  - 2 opposite-sign muons plus higher-momentum positive track
    - muon-ID: good hits in 2 of 3 μ prop tubes plus μ hodos
  - Single vertex: χ^2/ndf < 1.5, DCA < 2.5 mm
  - Vertex within decay vacuum: 100 cm < z_v < 1300 cm
  - Target pointing: r_t < 3.45 mm
  - Total momentum: 120 < p < 240 GeV/c
- Monte Carlo studies show: these cuts are efficient for signal events:



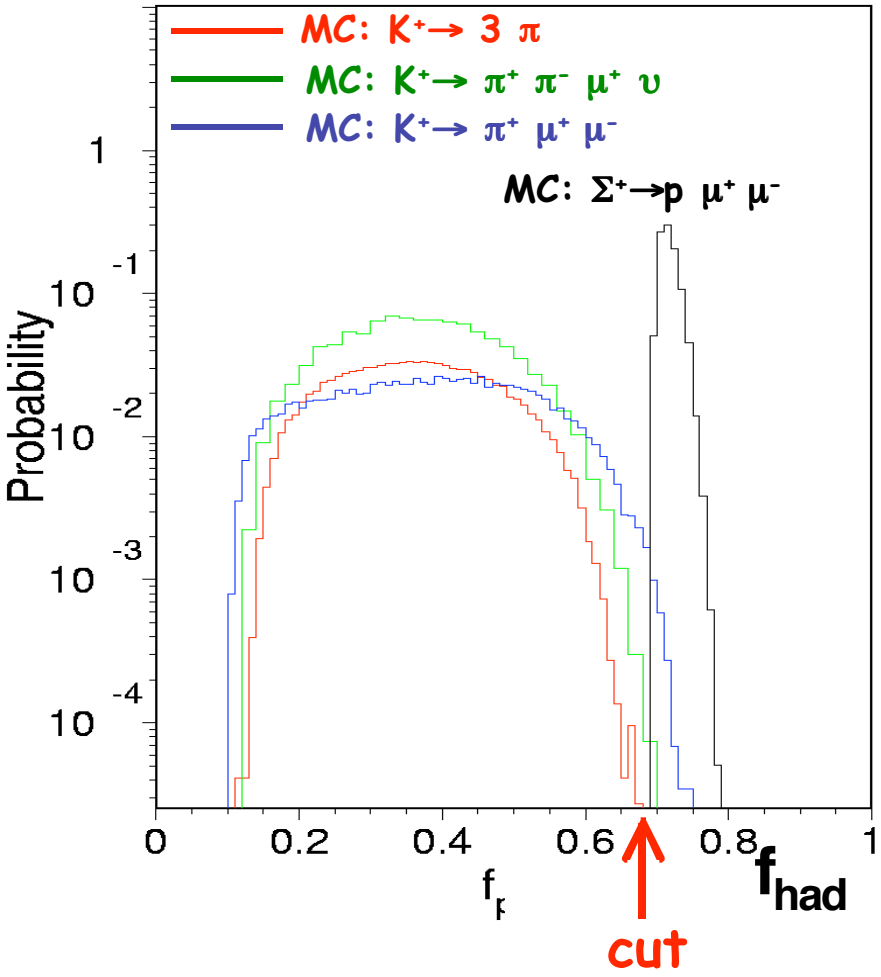




Search for $\Sigma^+ \to p\mu^+\mu^-$

- Additional cut:
  - $f_{had} \equiv \dfrac{\text{hadron momentum}}{\text{total momentum}} > 0.68$
  - suppresses $K \to 3\pi$ since heavier decay daughters carry more momentum in lab frame
- MC studies show
  - f_{had} cut preserves 100% of signal
  - strongly rejects K^+ backgrounds:

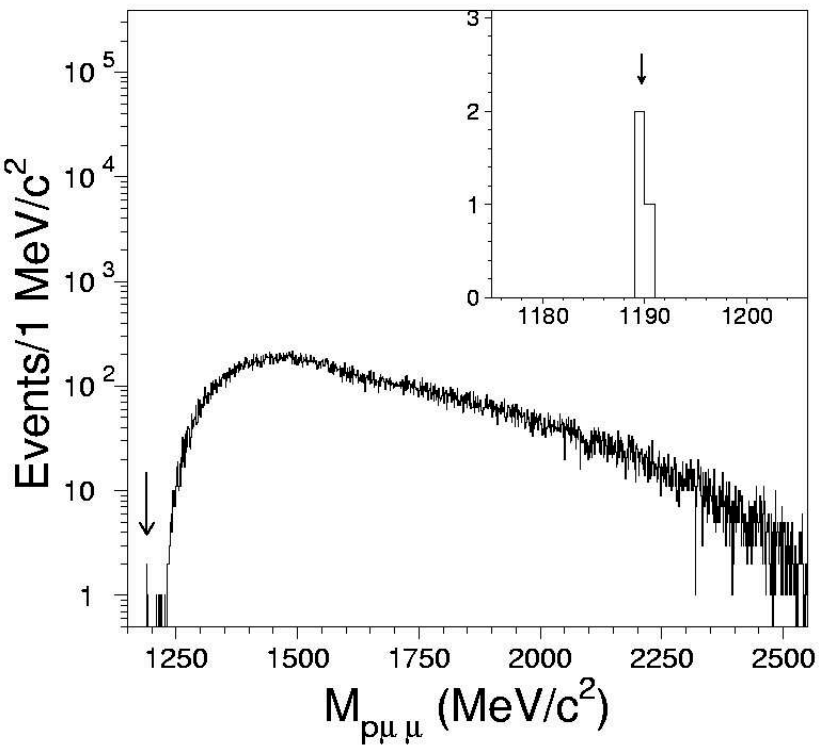
Decay Mode	ϵ (%)
$B(K^+ \to 3\pi) = 5.6\%$	0.0
$B(K^+ \to \pi^+\pi^-\mu^+\nu_\mu) = 1.4 \times 10^{-5}$	~0.0
$B(K^+ \to \pi^+\mu^+\mu^-) = 8.1 \times 10^{-8}$	0.4



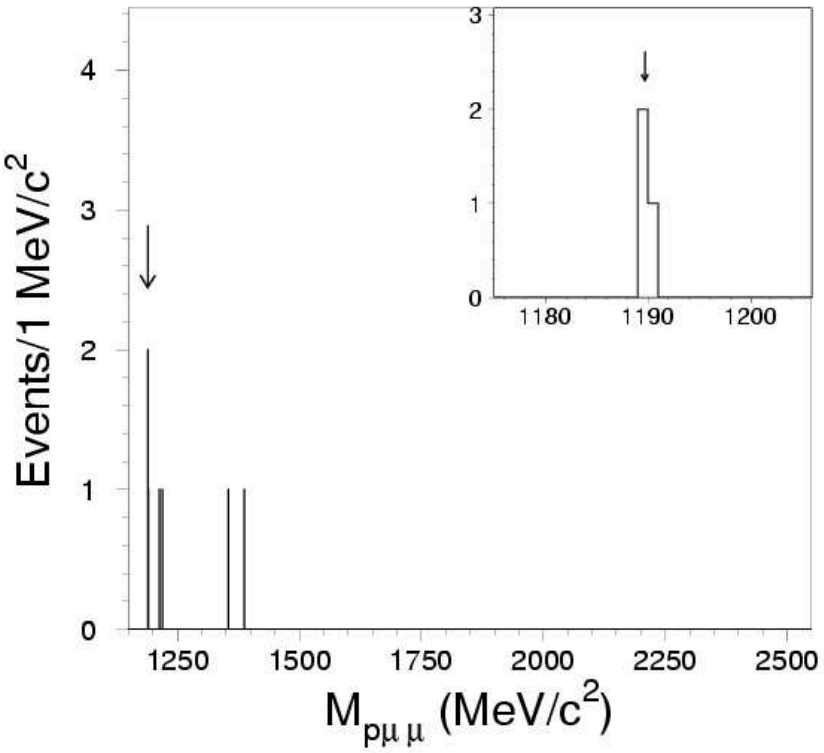
Search for $\Sigma^+ \to p\mu^+\mu^-$

- Data after cuts:

Basic selection cuts



Basic selection cuts & $f_{had} > 0.68$



- 3 signal candidates clustered within 1σ in mass; nearest bkg evt >20σ away
- Note signal mode is inherently clean
  - very little Q (40 MeV) $\Rightarrow \Sigma^+ \not\to p\pi^+\pi^-$, so no pion decay-in-flight background
- Also, $\bar{\Xi}^+ \to \bar{\Lambda}\pi^+ \to \bar{p}\,\pi^+\pi^+$ not a background (nor is $\bar{\Omega}^+ \to \bar{\Lambda}K^+$)
  - antiproton does not decay in flight $\Rightarrow$ no substantial source of μ^-
  - no stiff positive particle
  - fails single-vertex cuts

Interpreting the Signal

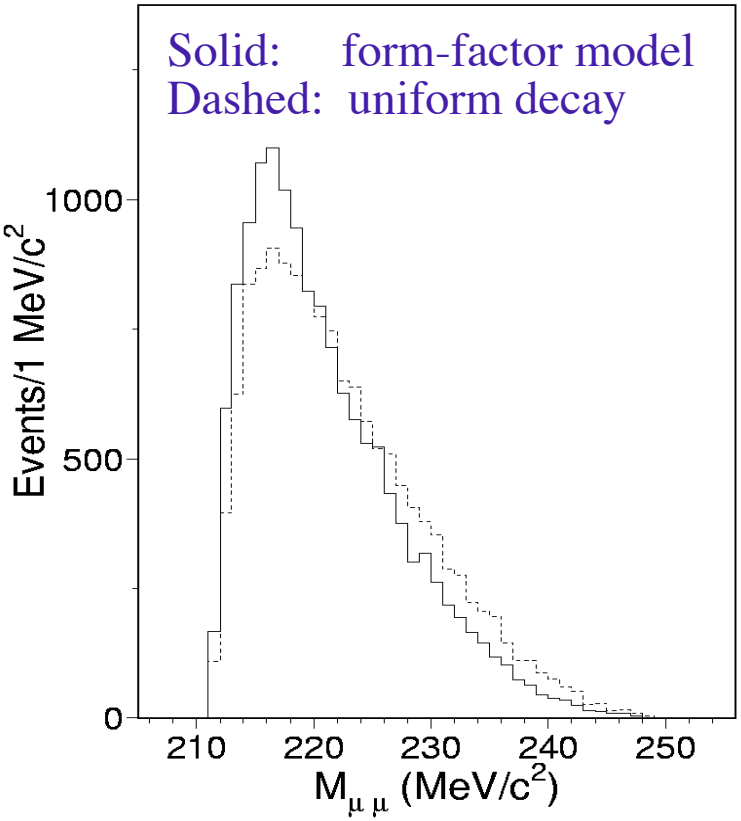
- Decay model for $\Sigma^+ \to p l^+ l^-$:
  - 4 form factors: b_1, b_2, c_1, c_2
  - b_1 and b_2 extracted from known rate and asymmetry parameter of $\Sigma^+ \to p\gamma$:

$$\Gamma(\Sigma^+ \to p\gamma) \sim |b_1|^2 + |b_2|^2$$

$$\alpha = \frac{2\mathrm{Re}(b_1 b_2^*)}{|b_1|^2 + |b_2|^2}$$

$$\Rightarrow \quad \frac{b_2(0)}{b_1(0)} = -0.46 \pm 0.07$$

$$|b_1(0)| = 6.8 \pm 0.2 \mathrm{MeV}$$



  - c_1 and c_2 determine $B(\Sigma^+ \to p e^+ e^-)$
    - chosen to minimize $B(\Sigma^+ \to p e^+ e^-)$ so as to agree with PDG limit $B(\Sigma^+ \to p e^+ e^-) < 7 \times 10^{-6}$

- If the 3 candidates are indeed $\Sigma^+ \to p\mu^+\mu^-$ decays, then

$$\mathrm{B}(\Sigma^+ \to \mathrm{p}\mu^+\mu^-) = [1.3^{+1.0}_{-0.8} \pm 0.7] \times 10^{-7} \text{ (uniform decay)} \quad \text{or}$$

$$\mathrm{B}(\Sigma^+ \to \mathrm{p}\mu^+\mu^-) = [8.6^{+6.6}_{-5.4} \pm 5.5] \times 10^{-8} \text{ (form factor)}$$

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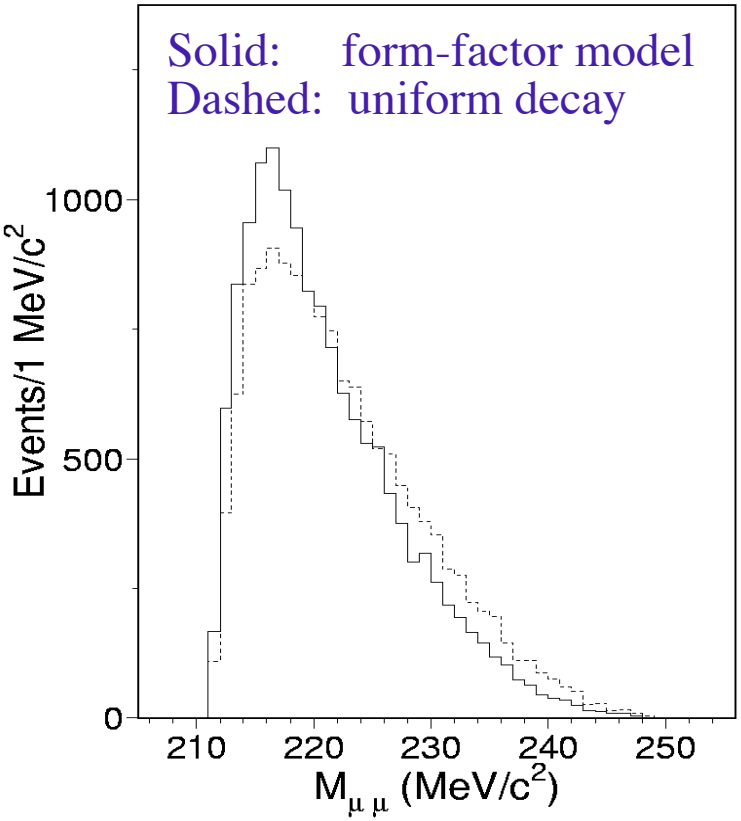

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→ This is the smallest branching ratio ever measured for a baryon.

Interpreting the Signal

- In a recent preprint, He, Tandean, and Valencia [hep-ph/0506067] point out that long-distance contributions dominate over penguin and box diagrams, for both $\Sigma^+ \to p\gamma$ and $\Sigma^+ \to p l^+ l^-$
- Form-factor treatment still valid
- They allow that New Physics could be contributing to both $B(\Sigma^+ \to p\gamma)$ and $B(\Sigma^+ \to p\gamma)$, although not yet definitively established

$\to$ In SM, preferred range for $B(\Sigma^+ \to p\mu^+\mu^-)$ is $\approx 1\text{–}3 \times 10^{-8}$

$\Rightarrow$ If not a statistical fluctuation, HyperCP's large observed value,

$\mathrm{B}(\Sigma^+ \to \mathrm{p}\mu^+\mu^-) = [8.6^{+6.6}_{-5.4} \pm 5.5] \times 10^{-8}$, is hard to reconcile with SM

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... but that's not the only problem...

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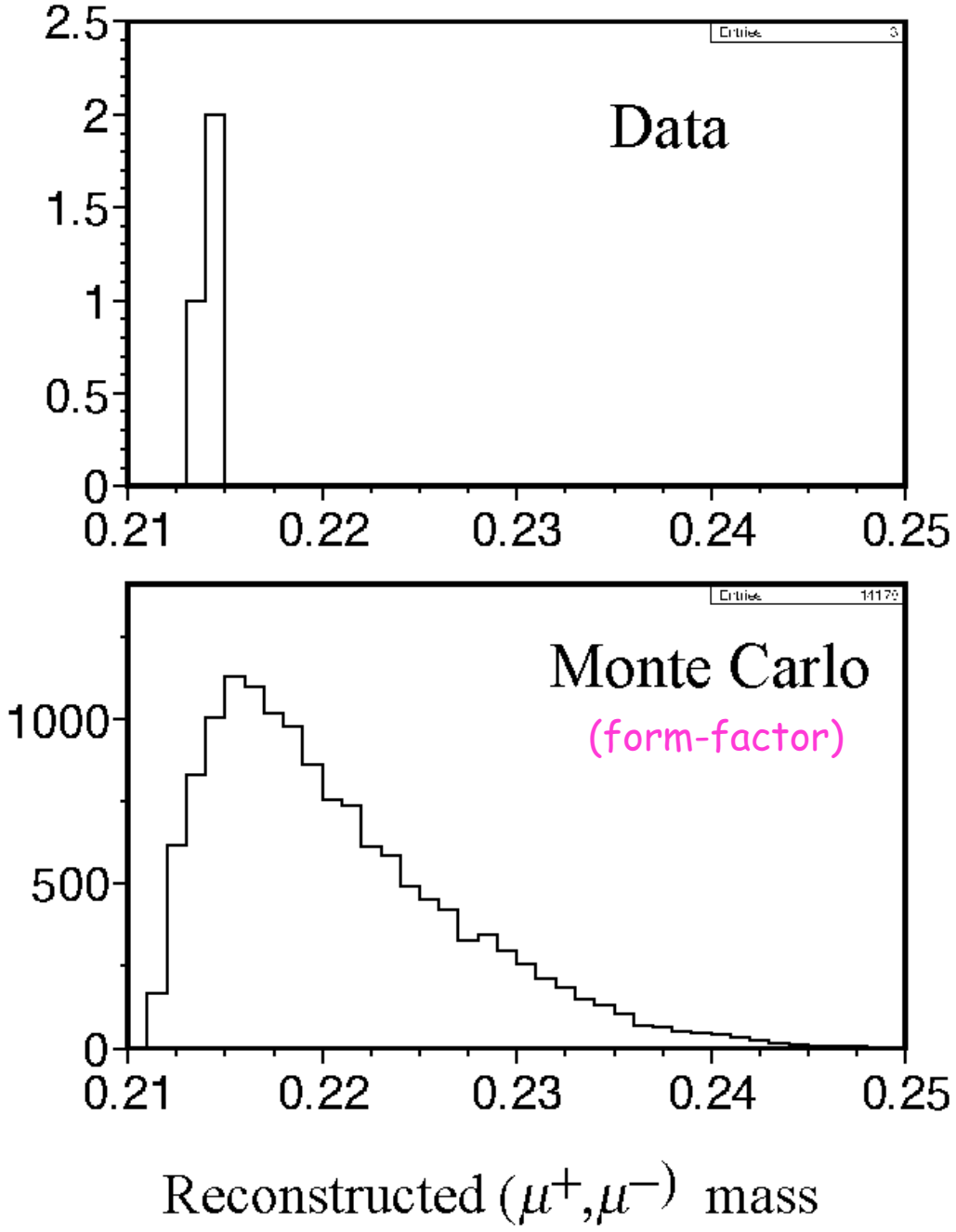

A surprise: The narrow dilepton-mass distribution!

- The dimuon masses for the 3 candidate events are clustered within ≈1 MeV/c^2, which is consistent with the experimental dimuon mass resolution

- Probability that dimuon masses of 3 events, chosen at random from form-factor distribution, fall within 1 MeV for $\Sigma^+ \to p\mu^+\mu^-$ in SM is 0.8% or less for reasonable form factors

- This suggests a two-body decay:

$$\Sigma^+ \to p X^0, \quad X^0 \to \mu^+\mu^- \quad \text{with}$$

$$m_{X^0} = 214.3 \pm 0.5 \text{ MeV}/c^2$$

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

Is there a theoretical model that suggests an X^0?

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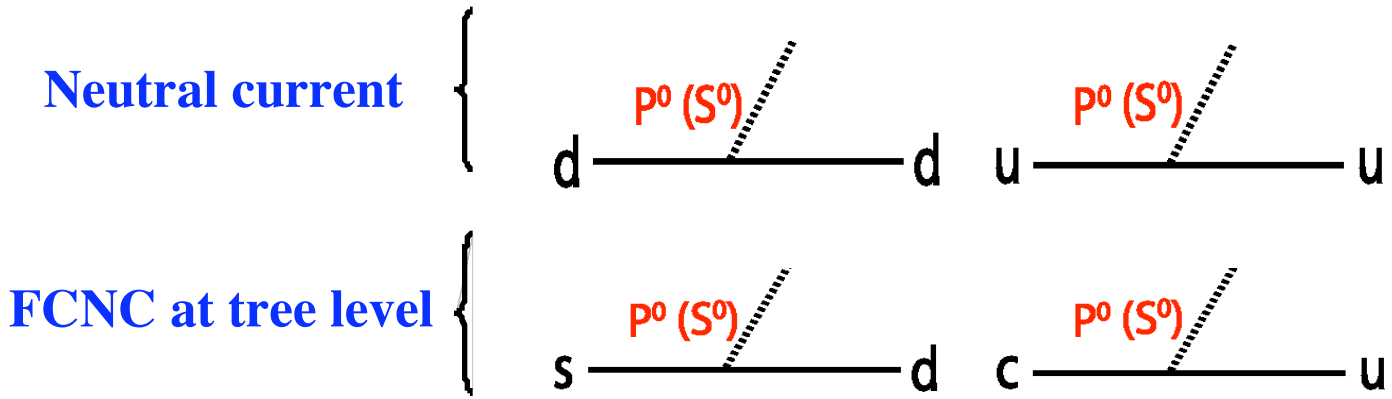
[see e.g. Gorbunov & Rubakov, PRD **64**, 054008 (2001)]

- In SUSY, spontaneous SUSY breaking generates Goldstone fermion (Goldstino), which gives the longitudinal component of the gravitino
- There should exist superpartners of the Goldstino: sgoldstinos, with a pseudoscalar P^0 and scalar S^0
- Their masses are generally arbitrary, perhaps < a few GeV or a few MeV
- P^0 and S^0 can couple with SM particles, quarks, leptons and gauge bosons.
- Interactions of sgoldstinos P^0 and S^0 with quarks given by



Is there a theoretical model that suggests an X^0?

- If the masses of P^0 and S^0 are less than $2m_\pi$, they can decay into photon or lepton pairs [D.S. Gorbunov, Nucl. Phys. B602 (2001) 213]:

$$\Gamma(P^0(S^0) \to \gamma\gamma) = \frac{m^3_{s^0(p^0)} M_{\gamma\gamma}}{32\pi F^2}, \qquad \Gamma(P^0 \to l^+l^-) = \frac{m^3_{p^0} A_l^2}{16\pi F^2} \frac{m_l^2}{m^2_{p^0}} (1 - \frac{4m_l^2}{m_p^2})^{1/2}$$

where

F : SUSY breaking scale $\sqrt{F} \geq 217$ GeV by CDF, PRL 85, 1378 (2000)
$M_{\gamma\gamma}$: order of photino mass (~100 GeV)
A_l : "soft" mass term (~100 GeV)

- Typical parameter choices:

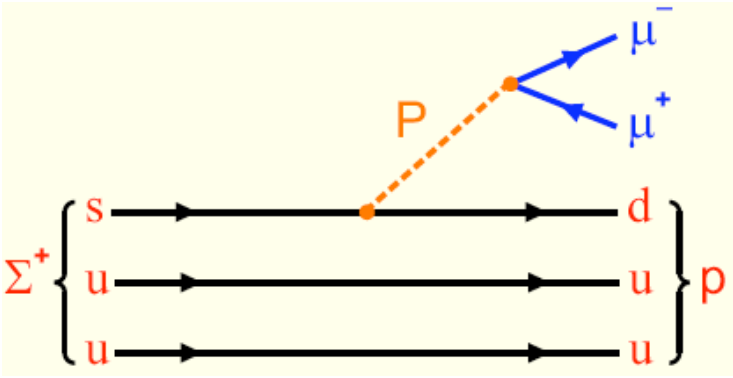
$m_{P^0} = 214.3$ MeV $\sqrt{F} = 1$ TeV	$M_{\gamma\gamma} = 100\ GeV$ $A_l = 100\ GeV$	$M_{\gamma\gamma} = 100\ GeV$ $A_l = 1000\ GeV$	$M_{\gamma\gamma} = 1000\ GeV$ $A_l = 100\ GeV$
$B(P^0 \to \gamma\gamma)$	92.5%	11.0 %	99.9 %
$B(P^0 \to \mu^+\mu^-)$	7.5 %	88.9 %	0.1 %
$B(P^0 \to e^+e^-)$	10^{-3} %	0.01 %	10^{-5} %
$c\tau$ (cm)	0.02	0.002	0.0002

- All 3 cases give short-lived sgoldstino, consistent with single-vertex constraint in HyperCP $\Sigma^+ \to p\mu^+\mu^-$ analysis
- P^0 branching ratio to muon pairs can be appreciable

Is there a theoretical model that suggests an X^0?

⇒ The observed signal is a possible candidate for sgoldstino in SUSY:

"...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, Proc. Quarks-2004, Pushkinskie Gory, Russia, May 24–30, 2004

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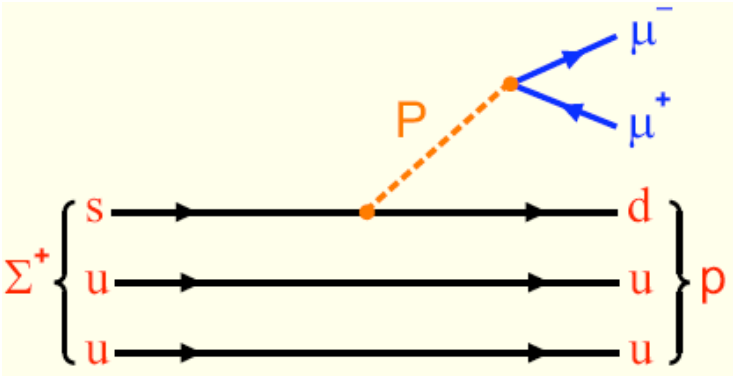

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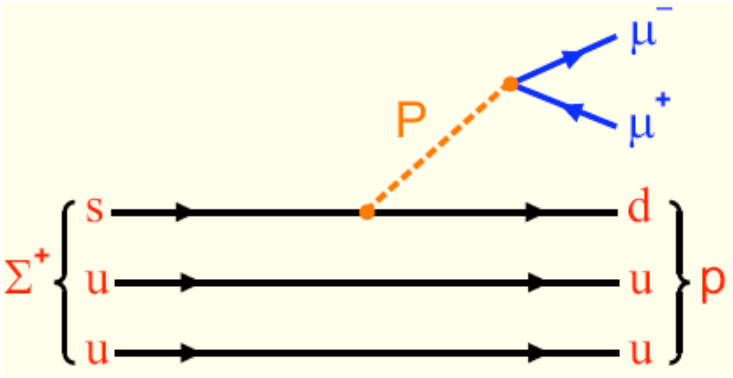

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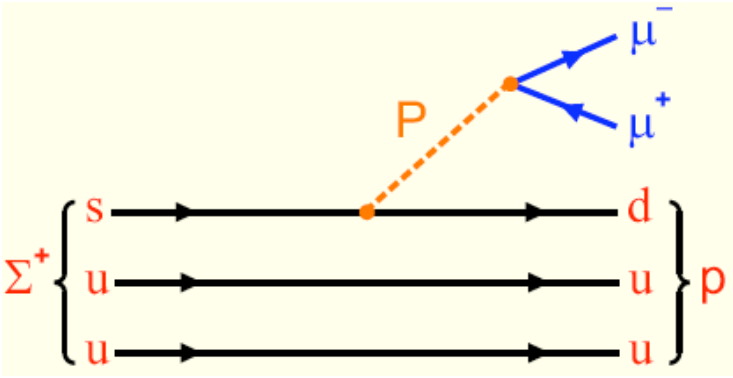

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Prospects for Low-Energy Antiproton Running at Fermilab

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LEAP05
GSI-Bonn
17 May 2005

Hyperon ~~*CP*~~, rare decays, charm/-onium physics, etc. – see hep-ex/0507015

Conclusions

- In a sample containing ~10^{10} Σ^+ decays, HyperCP has seen 3 events consistent with $\Sigma^+ \to p\,\mu^+\mu^-$
- With a form-factor decay model we obtain
  $B(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4} \pm 5.5] \times 10^{-8}$
- Large branching ratio and narrow dimuon mass spectrum suggest decay via $\Sigma^+ \to p\,X^0$, $X^0 \to \mu^+\mu^-$, with $m_{X^0} = 214.3 \pm 0.5$ MeV/c^2
- X^0 is a candidate for a sgoldstino (superpartner of Goldstino)
- If confirmed, this could be first observation of a supersymmetric particle
- A followup (e.g., low-energy $\bar{p}p$ fixed-target) experiment is called for to pursue this further
- Note: now published, H. K. Park *et al.*, Phys. Rev. Lett. **94**, 021801 (2005)