Recent Results On Hyperon Decays

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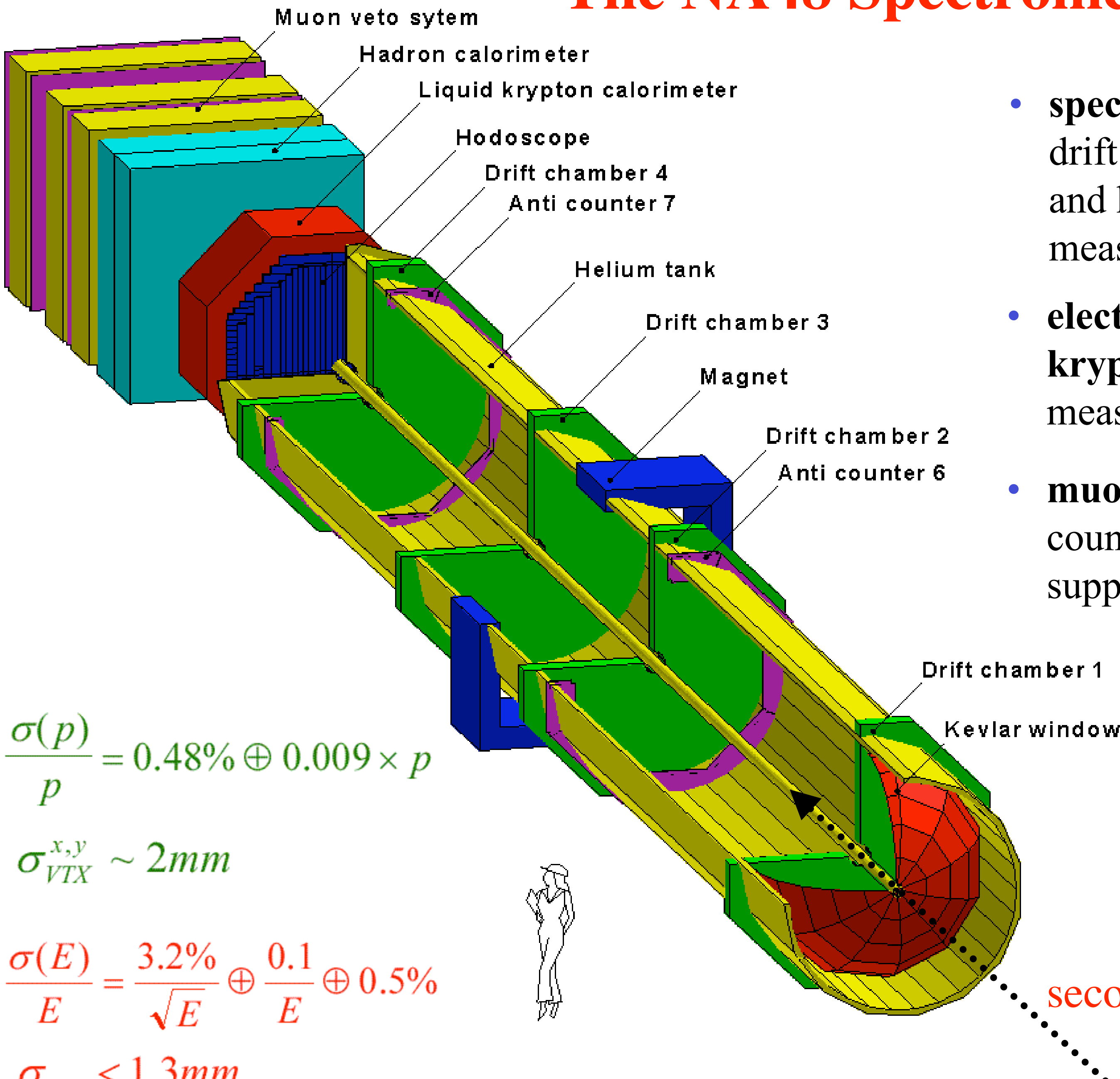
Contents:

- Some experiments
- Decay parameter α and Direct CP violation
- Phase-shift difference of $\Lambda\pi^-$
- Radiative decays
- Weak radiative decay
- Semi-leptonic decay
- Observation of $\Sigma^+ \to p\mu^+\mu^-$
- Search for $\Xi^- \to p\mu^-\mu^-$
- Search for $\Delta S=2$ non-leptonic decays

The NA48 Spectrometer



- **spectrometer** (consisting of 4 drift chambers and a magnet) and hadron calorimeter for measuring charged particles
- **electromagnetic liquid-krypton calorimeter** for measuring neutral particles
- **muon detector** and anti-counters for background suppression

$$\frac{\sigma(p)}{p} = 0.48\% \oplus 0.009 \times p$$

$$\sigma_{VTX}^{x,y} \sim 2mm$$

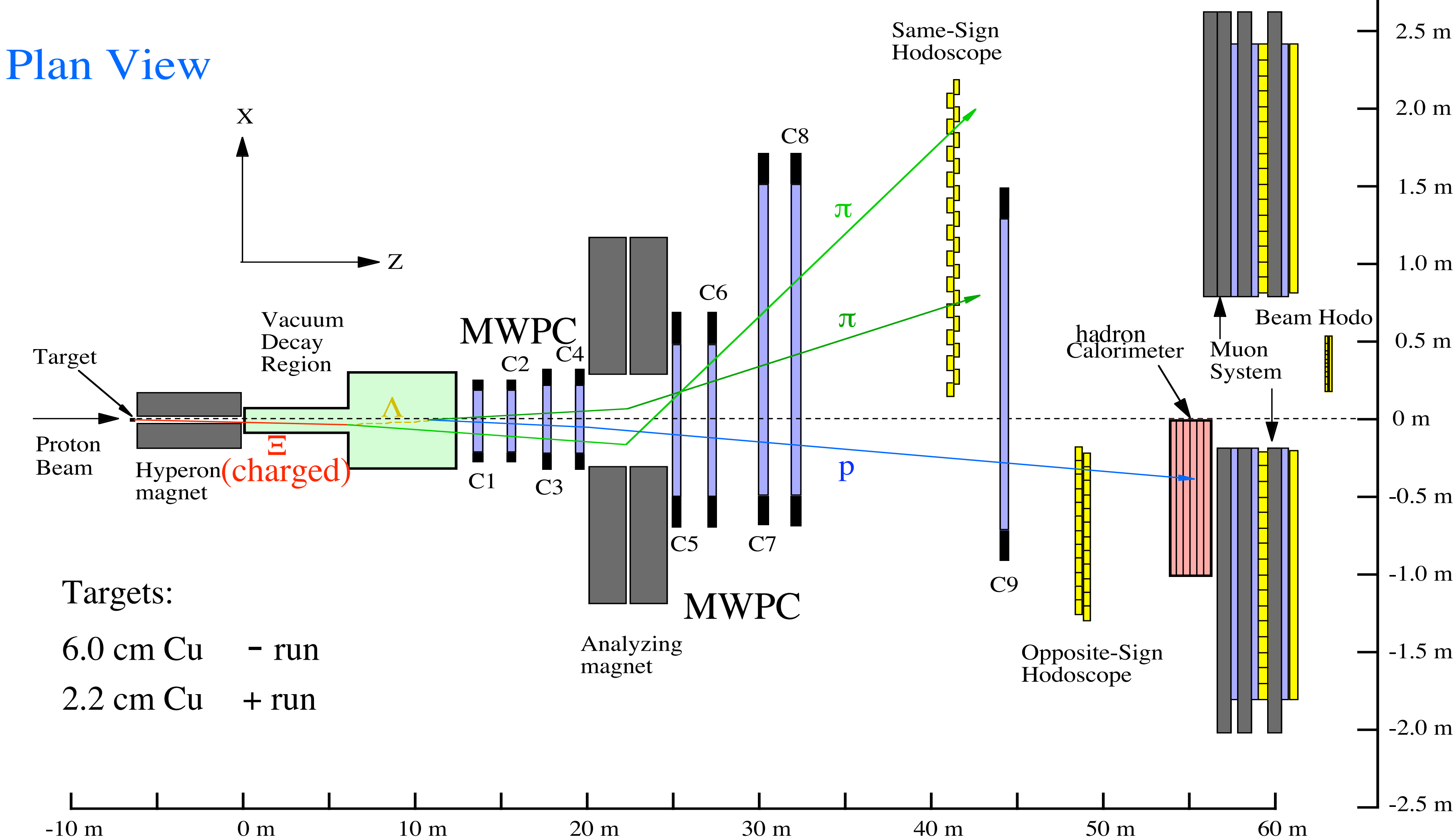
$$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{0.1}{E} \oplus 0.5\%$$

$$\sigma_{x,y} < 1.3mm$$

The HyperCP Spectrometer

- Protons on target = (7-8) GHz
- Sec. beam inten. = (10-15) MHz
- Total triggers = (50-80) kHz

Trigger = SS(≥1)·OS (≥1)·Cal(E ≥ 40 GeV)

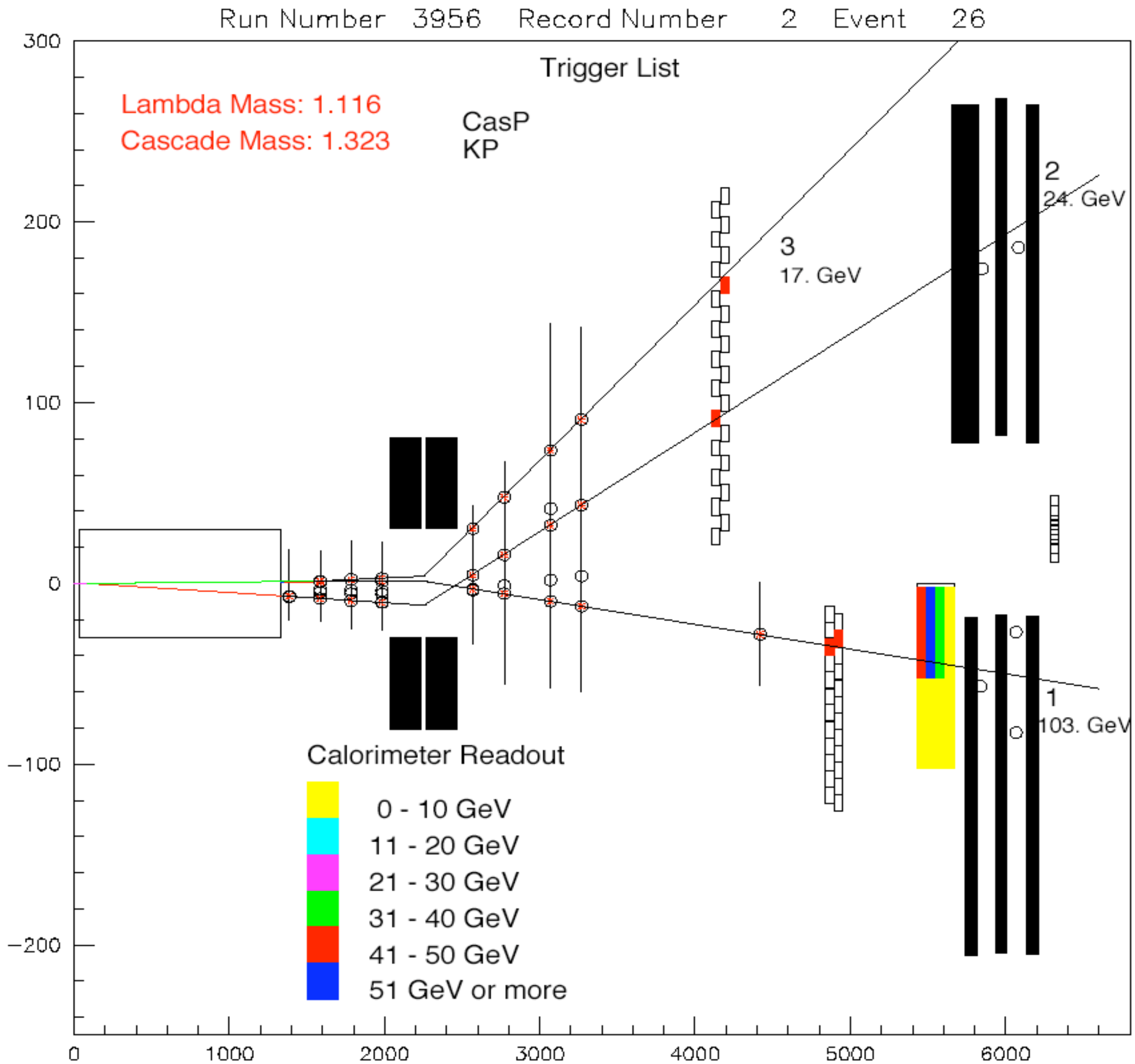


Targets:

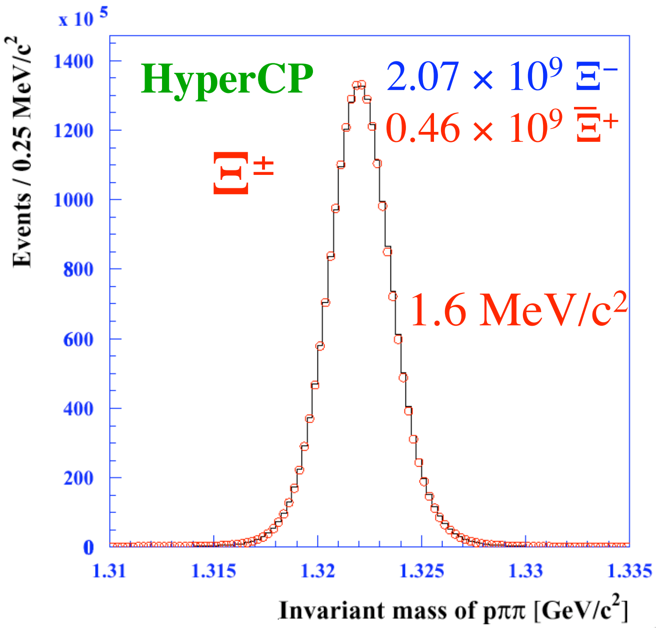
6.0 cm Cu - run

2.2 cm Cu + run

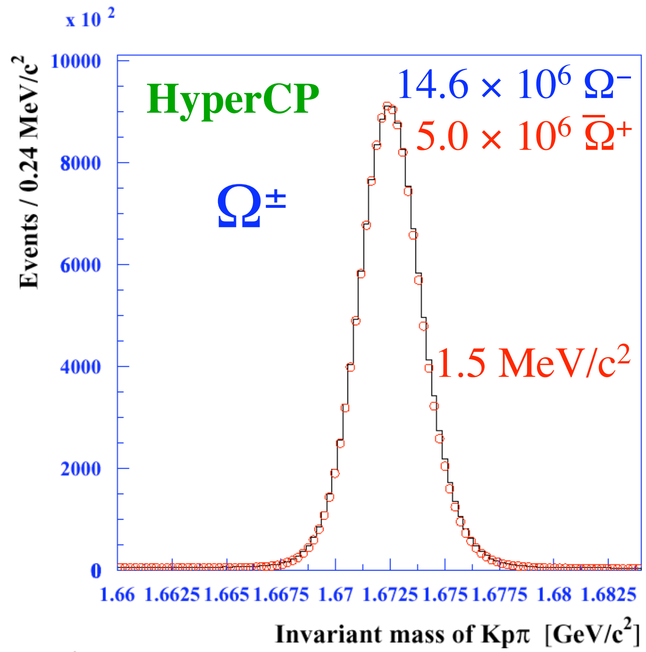
Event Display of HyperCP

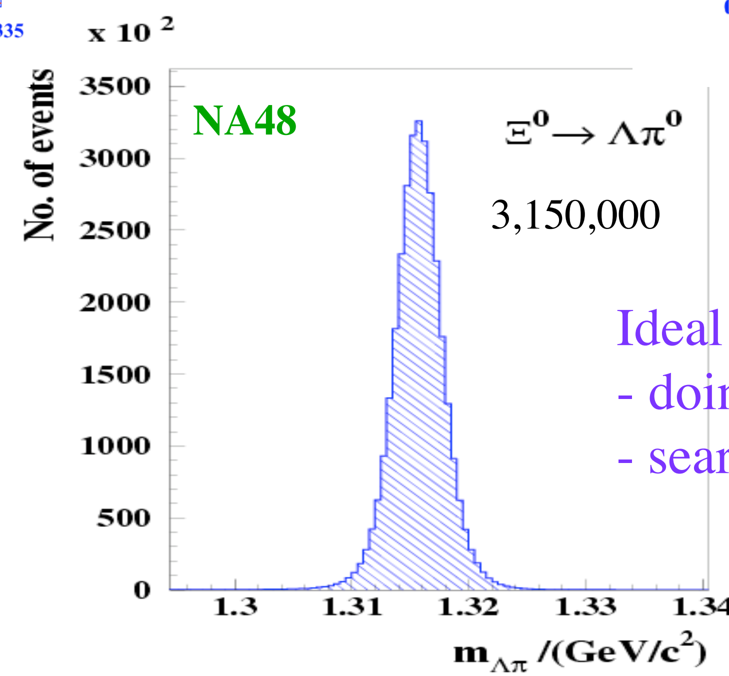


High-Statistic Samples of Hyperons



- Low background
- Excellent mass resolution





Ideal for:
- doing precise measurements
- searching for rare processes

Non-leptonic Decay of Hyperon

- Consider the weak decay

$$\Lambda \rightarrow p\, \pi$$

the decay matrix element is:

$$M(\Lambda \rightarrow p\pi) \propto \chi_p^\dagger (S + P\vec{\sigma}\cdot\hat{q}_p)\chi_\Lambda$$

where

S - parity-violating amplitude of the S-wave of the final state
P - parity-conserving amplitude of the P-wave of final state
$\hat{q}_p$- unit vector along the proton momentum
χ - two-component spinors

- Decay parameters:

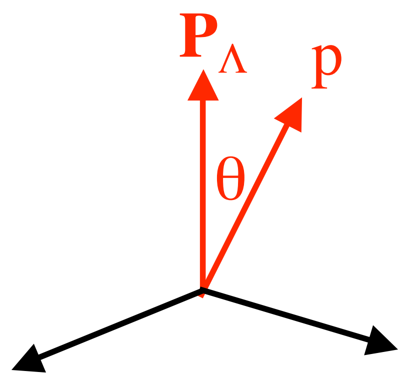
$$\alpha_\Lambda = \frac{2Re(S^*P)}{|S|^2+|P|^2} \qquad \beta_\Lambda = \frac{2Im(S^*P)}{|S|^2+|P|^2} \qquad \gamma_\Lambda = \frac{|S|^2-|P|^2}{|S|^2+|P|^2}$$

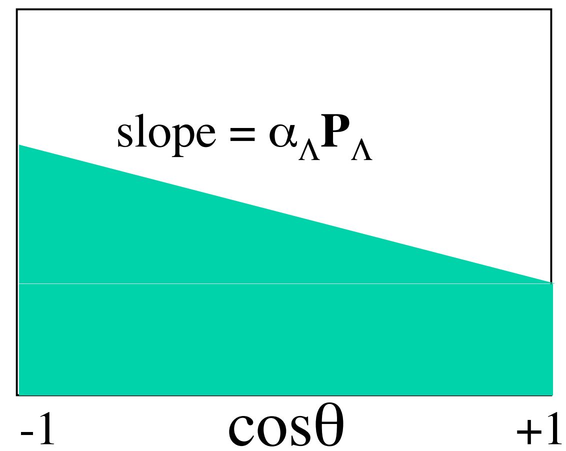
with:

$$\alpha_\Lambda^2 + \beta_\Lambda^2 + \gamma_\Lambda^2 = 1$$

Non-leptonic Decay of Hyperon (cont.)

- In the rest frame of the decaying Λ the angular distribution of the proton is:





$$\frac{dN_p}{d\cos\theta} = \frac{N_0}{2}\left(1 + \alpha_\Lambda \mathbf{P}_\Lambda \cos\theta\right)$$

where $\alpha_\Lambda = 0.642 \pm 0.013$

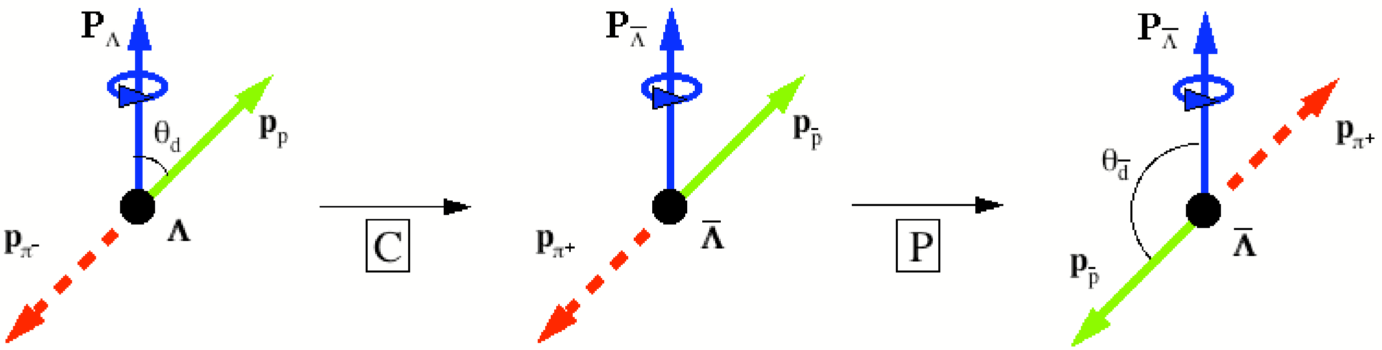
$\mathbf{P}_\Lambda$ is the polarization of Λ

θ is the angle between $\mathbf{P}_\Lambda$ and the proton momentum

- Polarization of Λ produced in the decay of polarized $\Xi \rightarrow \Lambda\pi$ is:

$$\vec{\mathrm{P}}_\Lambda = \frac{(\alpha_\Xi + \vec{\mathrm{P}}_\Xi \cdot \hat{\mathrm{q}}_\Lambda)\hat{\mathrm{q}}_\Lambda + \beta_\Xi \vec{\mathrm{P}}_\Xi \times \hat{\mathrm{q}}_\Lambda + \gamma_\Xi \hat{\mathrm{q}}_\Lambda \times (\vec{\mathrm{P}}_\Xi \times \hat{\mathrm{q}}_\Lambda)}{(1 + \alpha_\Xi \vec{\mathrm{P}}_\Xi \cdot \hat{\mathrm{q}}_\Lambda)}$$

Direct CP Violation in Ξ-Λ Non-leptonic Decays



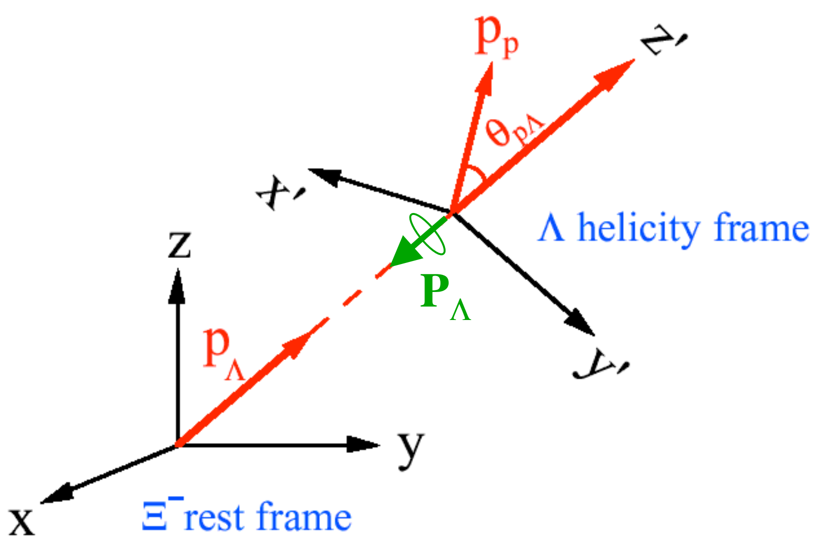
CP conservation:

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

- Get longitudinally polarized Λ from **unpolarized** $\Xi \rightarrow \Lambda\pi^-$ decay:

$$\mathbf{P}_\Lambda = \alpha_\Xi\, \mathbf{p}_\Lambda \qquad \text{with } \alpha_\Xi = -0.458 \pm 0.012$$

- In the Λ helicity frame, the angular distribution of the proton is:



$$\frac{dN_p}{d\cos\theta_{p\Lambda}} = \frac{N_0}{2}\left(1 + \alpha_\Lambda \alpha_\Xi \cos\theta_{p\Lambda}\right)$$

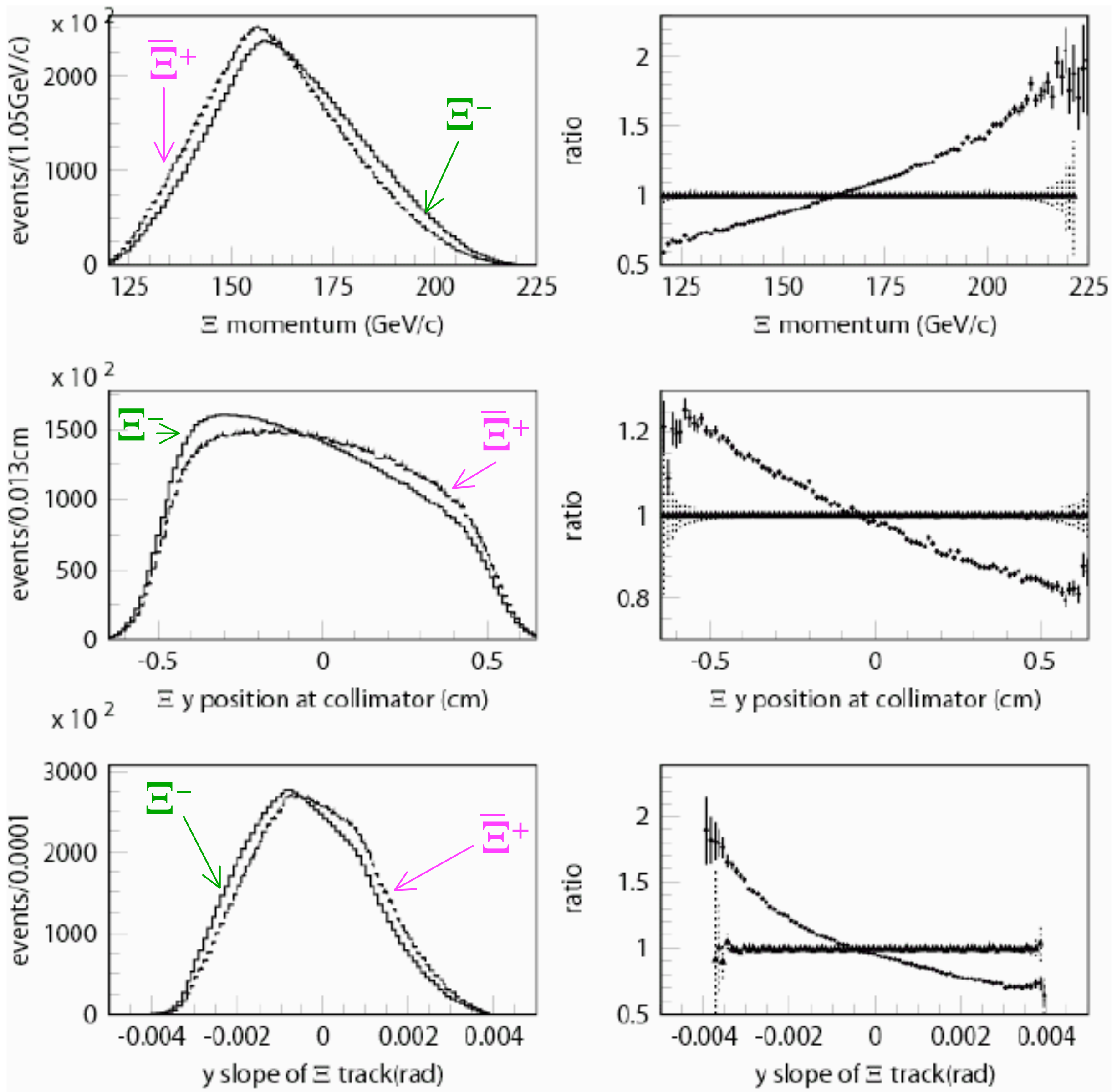
identical distribution for the $\bar p$ from $\bar\Xi$-$\bar\Lambda$ decay if CP is conserved.

Define CP-asymmetry parameter:

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

Measuring $A_{\Xi\Lambda}$ With Direct Weighting Method

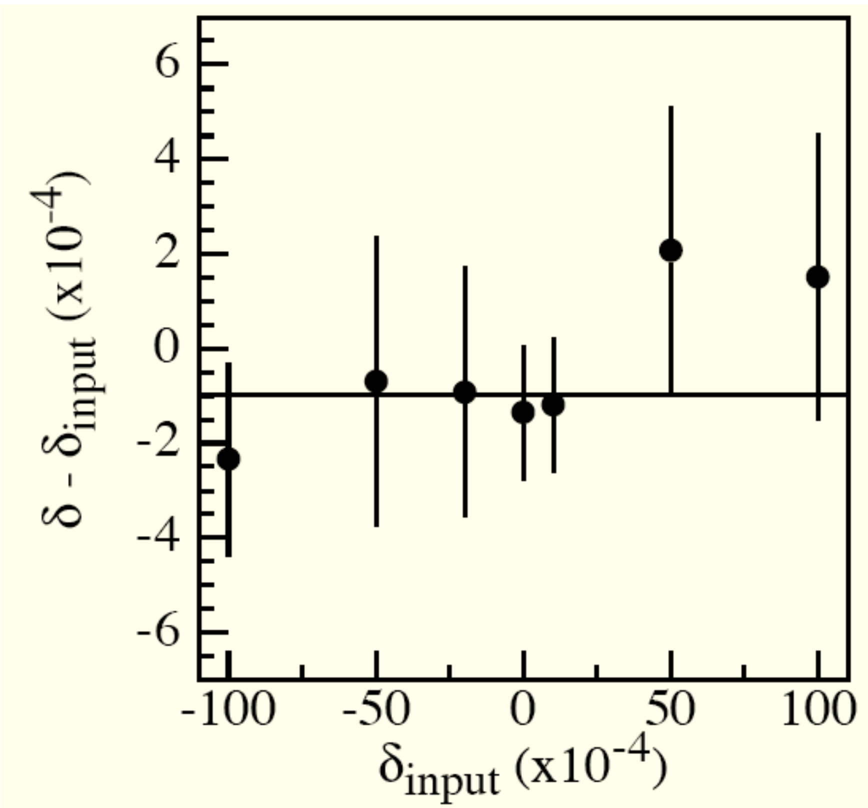
- **HyperCP** analysed 118.6×10^6 Ξ^- and 41.9×10^6 $\bar{\Xi}^+$ near the end of the 1999 run.
- Matched by weighting **momentum magnitude, y slope, and y coordinate of Ξ at the exit of the hyperon channel**.



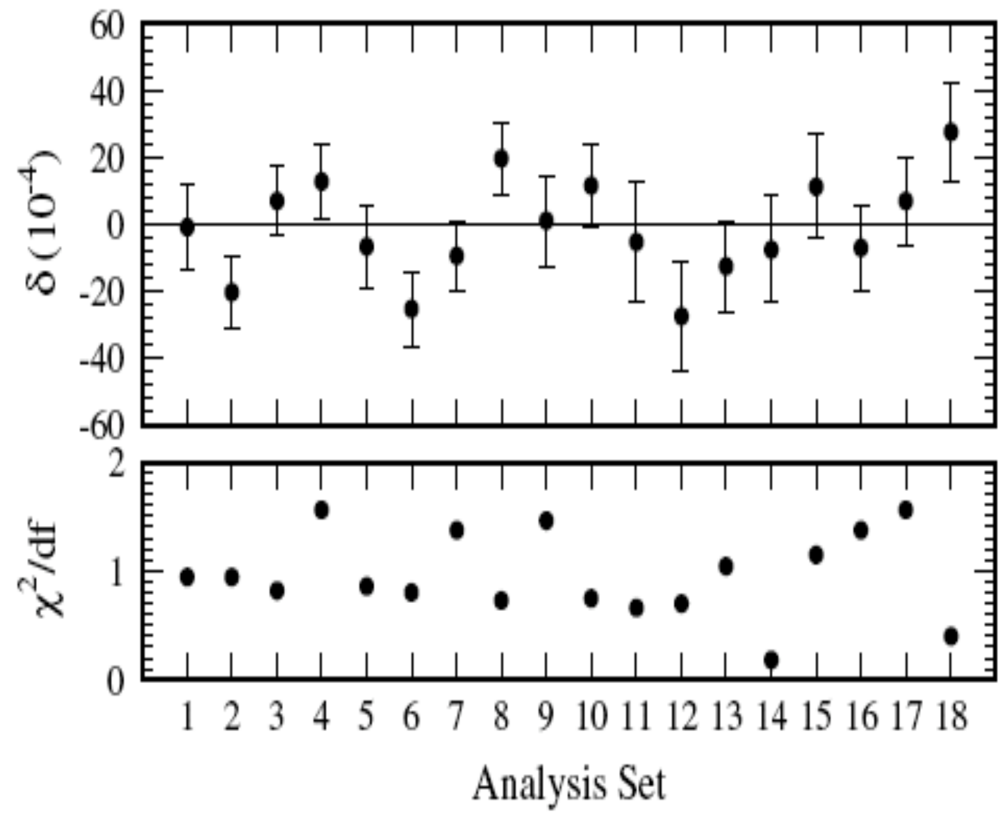
Measuring $A_{\Xi\Lambda}$ With Direct Weighting Method (cont.)

- Use MC samples with different input

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



- Method works to a precision of 1.4×10^{-4} for $\delta_{input} = 0$.



- **Result:** $A_{\Xi\Lambda} = (0.0 \pm 5.1_{stat} \pm 4.4_{syst}) \times 10^{-4}$
- About 20 times better than the previous best limit
- Begin to test beyond-the-standard model predictions

β_Ξ, γ_Ξ and Λ-π Strong Phase-Shift Difference

- The CP asymmetry of $\Xi \rightarrow \Lambda\pi$ is

$$A_\Xi \approx - \tan(\delta_P - \delta_S)_\Xi \sin(\phi_P - \phi_S)_\Xi$$

where δ's are the strong phase-shifts, and ϕ's are the weak CP phases.

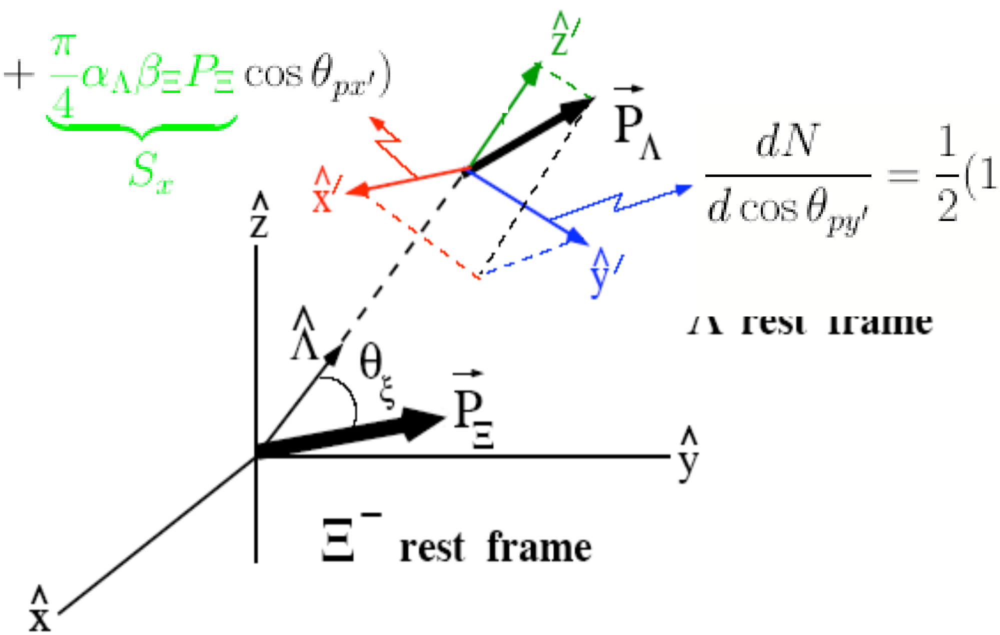
- Determine the strong phase-shift difference

$$\beta_\Xi / \alpha_\Xi = - \tan(\delta_P - \delta_S)_\Xi$$

- Require studying the proton distributions with **polarized** Ξ-Λ decays:

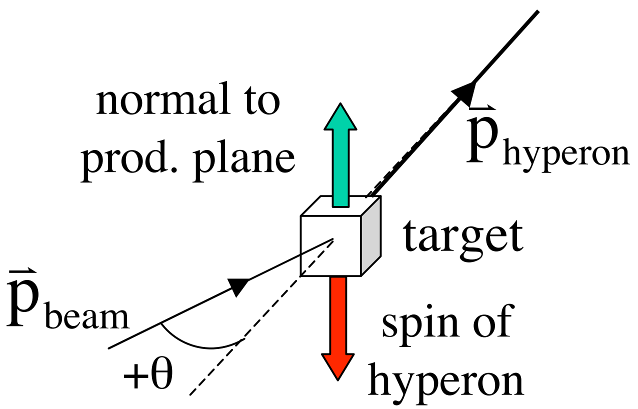
$$\frac{dN}{d\cos\theta_{px'}} = \frac{1}{2}(1 + \underbrace{\frac{\pi}{4}\alpha_\Lambda \beta_\Xi P_\Xi}_{S_x} \cos\theta_{px'})$$

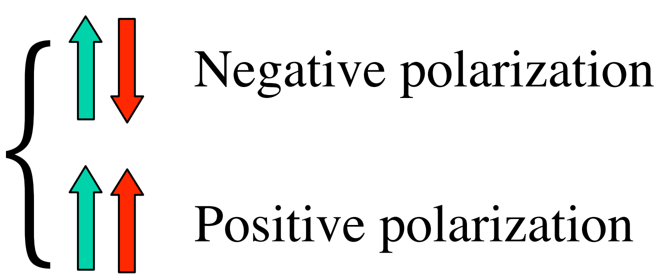
$$\frac{dN}{d\cos\theta_{py'}} = \frac{1}{2}(1 + \underbrace{\frac{\pi}{4}\alpha_\Lambda \gamma_\Xi P_\Xi}_{S_y} \cos\theta_{py'})$$



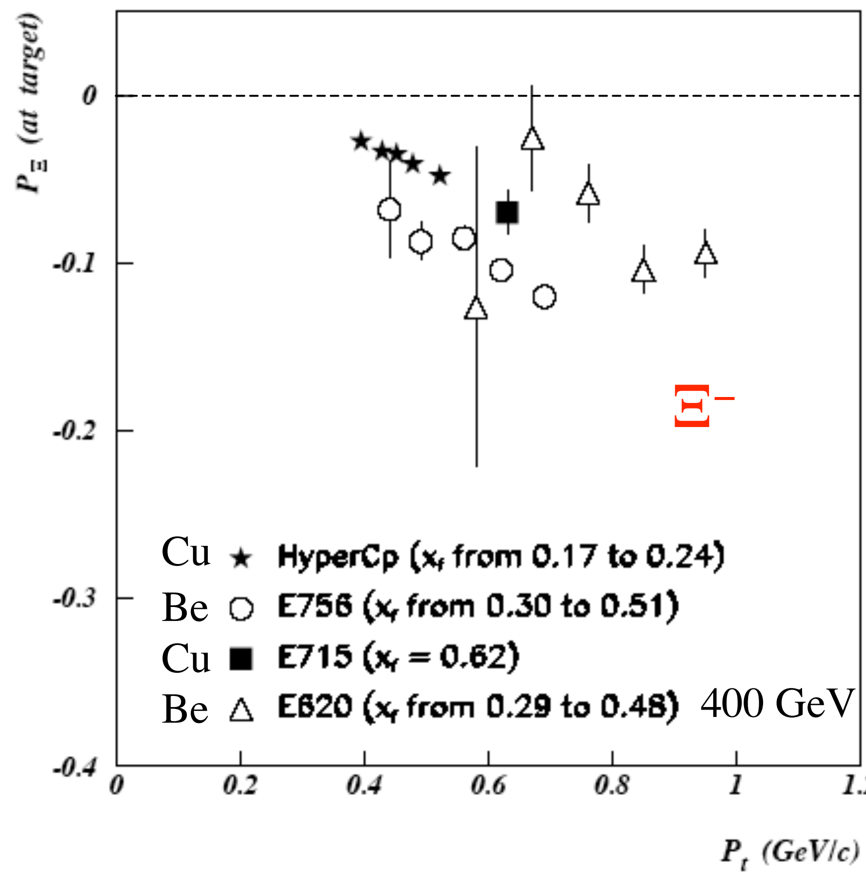
Polarization at Production

Hyperons can be polarized when they are produced by **unpolarized** protons on a **unpolarized** target:



Convention: 

HyperCP, PRL **93**, 011802 (2004)



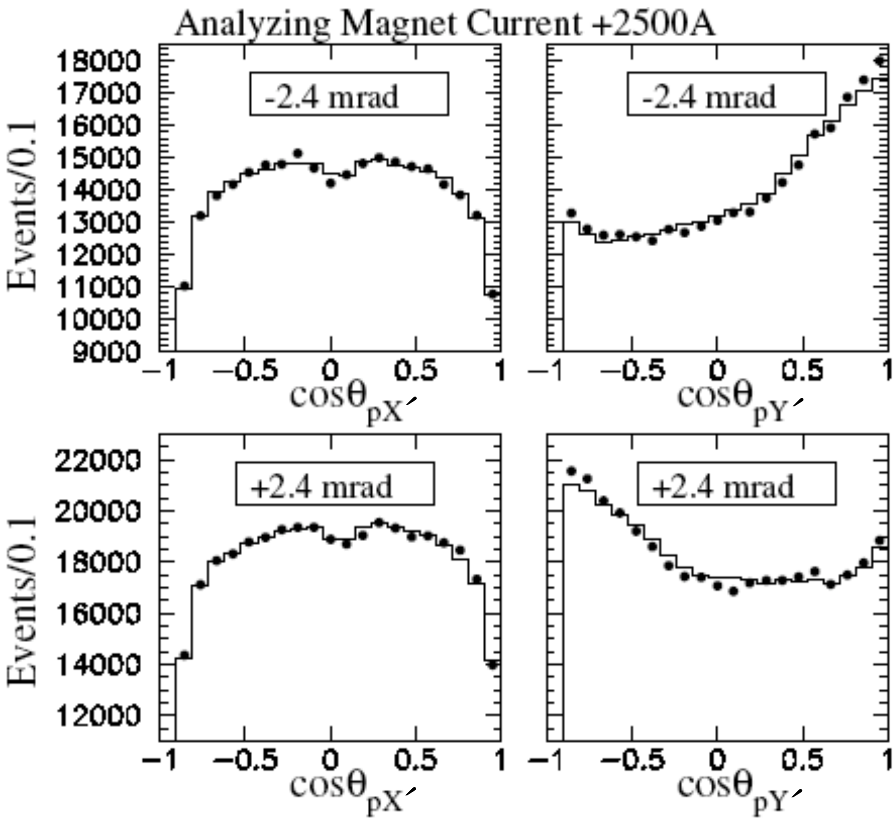
• Polarization grows with p_t up to ~1 GeV/c

β_Ξ, γ_Ξ and Λ-π Strong Phase-Shift Difference (cont.)

- In practice,

$$\tan\phi_\Xi = \frac{\beta_\Xi}{\gamma_\Xi} = \frac{S_x}{S_y}$$

$$\beta_\Xi = \sqrt{1-\alpha_\Xi^2}\sin\phi_\Xi, \quad \gamma_\Xi = \sqrt{1-\alpha_\Xi^2}\cos\phi_\Xi$$



E756, PRL **91**, 031601 (2003)

- **E756** analyzed 1.35 × 10^6 polarized $\Xi^- \to \Lambda\pi^-$ decays and determined

ϕ_Ξ = -1.61°± 2.66° ± 0.37°

β_Ξ = –0.025 ± 0.042 ± 0.006

γ_Ξ = +0.889 ± 0.001 ± 0.007

and found **Λ-π strong phase-shift difference** to be

$\delta_P - \delta_S$ = 3.17°± 5.28° ± 0.73°

indicating the difference is likely small.

β_Ξ, γ_Ξ and Λ-π Strong Phase-Shift Difference (cont.)

HyperCP used 132 millions polarized $\Xi^- \rightarrow \Lambda\pi^-$ decays to obtain:

HyperCP, PRL **93**, 011802 (2004)

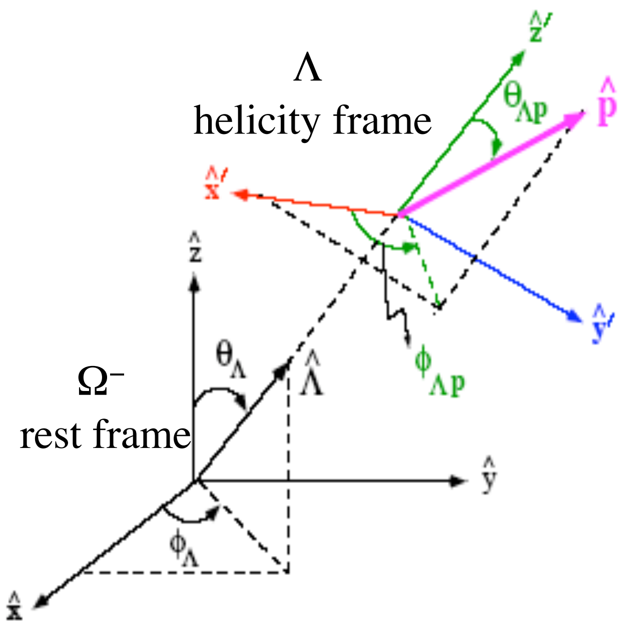
p_Ξ (GeV/c)	S_x	S_y	ϕ_Ξ (degree)
139	-0.00037 ± 0.00047	0.01191 ± 0.00041	-1.77 ± 2.28
152	-0.00046 ± 0.00047	0.01447 ± 0.00038	-1.81 ± 1.88
162	-0.00038 ± 0.00041	0.01557 ± 0.00035	-1.39 ± 1.49
173	-0.00074 ± 0.00040	0.01880 ± 0.00036	-2.26 ± 1.22
191	-0.00123 ± 0.00040	0.02109 ± 0.00040	-3.33 ± 1.08
Average			$-2.39 \pm 0.64 \pm 0.64$

$$\beta_\Xi = -0.037 \pm 0.011_{stat} \pm 0.010_{syst} \,,$$
$$\gamma_\Xi = 0.888 \pm 0.0004_{stat} \pm 0.006_{syst} \,,$$
$$\delta_p - \delta_s = 4.6° \pm 1.4°_{stat} \pm 1.2°_{syst}$$

which is comparable to the p-π strong phase-shift difference, and small, indicating CP-odd effects in Ξ and Λ decays are tiny.

Decay Parameter α_Ω of $\Omega \to \Lambda K$ Decay

- Predict the decay is predominantly parity-conserving (P-wave dominant).
- The D-wave amplitude is thus small; hence α is expected to be close to 0.



- For the decay sequence

$$\Omega^- \to \Lambda K^-$$
$$\hookrightarrow p\pi^-$$

proton distribution in the Λ helicity frame is:

$$\frac{dN}{d\cos\theta_{\Lambda p}} = \frac{N_0}{2}\left(1 + \alpha_\Omega \alpha_\Lambda \cos\theta_{\Lambda p}\right)$$

- **HyperCP obtained final results:**

$\alpha_\Omega\alpha_\Lambda = [1.33 \pm 0.32_{stat} \pm 0.52_{sys}] \times 10^{-2}$ (1997)

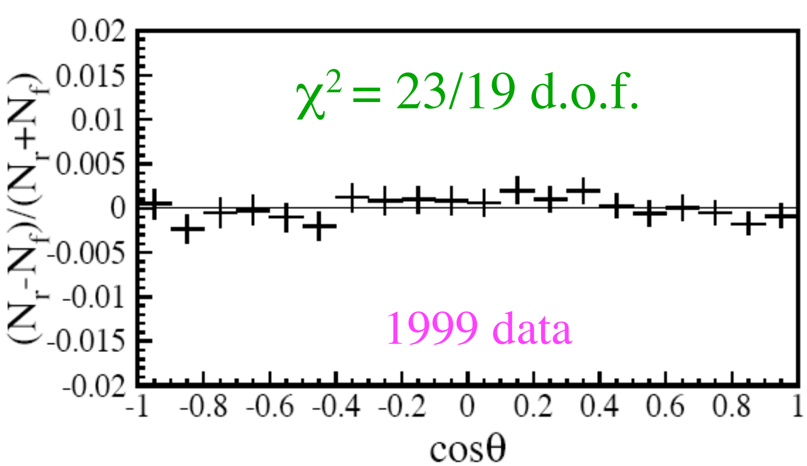
$\alpha_\Omega\alpha_\Lambda = [1.14 \pm 0.12_{stat} \pm 0.10_{sys}] \times 10^{-2}$ (1999)

Using $\alpha_\Lambda = 0.642 \pm 0.013$,

$\alpha_\Omega = [2.07 \pm 0.50_{stat} \pm 0.81_{sys}] \times 10^{-2}$ (1997)

$\alpha_\Omega = [1.78 \pm 0.19_{stat} \pm 0.16_{sys}] \times 10^{-2}$ (1999)

confirming theoretical predictions.



Decay Parameter α_Ω of $\Omega \rightarrow \Lambda K$ Decay (cont.)

- Using the same code and event-selection requirements, based on 1.9×10^6 $\overline{\Omega}^+ \rightarrow \overline{\Lambda} K^+$, $\overline{\Lambda} \rightarrow \overline{p}\pi^+$ events, **HyperCP extracted a preliminary value**:

$$\alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}} = [1.16 \pm 0.18_{stat} \pm 0.16_{syst}] \times 10^{-2}$$

Using $\alpha_{\overline{\Lambda}} = -0.642 \pm 0.013$,

$$\alpha_{\overline{\Omega}} = [-1.81 \pm 0.28_{stat} \pm 0.25_{syst}] \times 10^{-2}$$

- **Test of CP symmetry in $\Omega \rightarrow \Lambda K$ decay:**

  From the measured values of $\alpha_\Omega \alpha_\Lambda$ and $\alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}$, the CP asymmetry is determined to be

$$\delta_{\Omega\Lambda} = \alpha_\Omega\alpha_\Lambda - \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}} = [-0.02 \pm 0.22(\text{stat}) \pm 0.19\ (\text{syst})] \times 10^{-2}$$

or

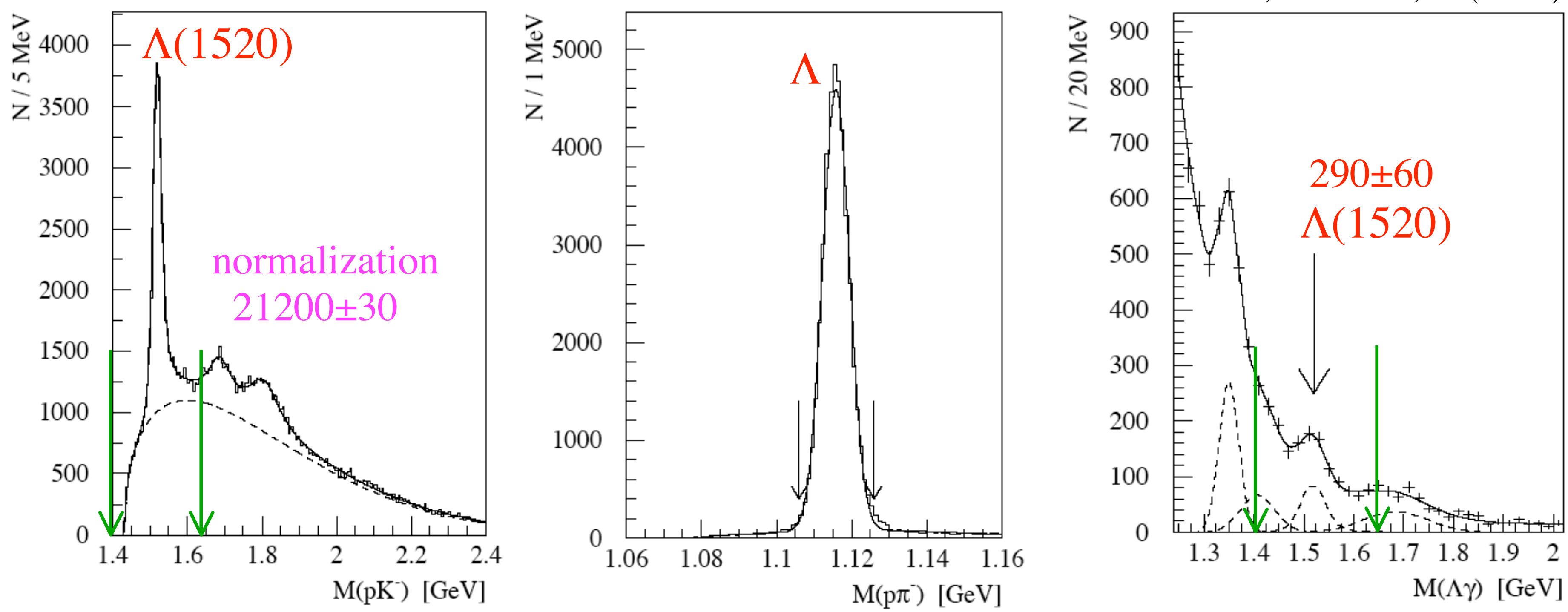
$$A_{\Omega\Lambda} = \frac{\alpha_\Omega\alpha_\Lambda - \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}}{\alpha_\Omega\alpha_\Lambda + \alpha_{\overline{\Omega}}\alpha_{\overline{\Lambda}}} = \left[-0.87 \pm 9.41(stat) \pm 8.20(syst)\right] \times 10^{-2}$$

Radiative Decay

- Width of Λ(1520) → Λγ is predicted to be between 30 keV and 215 keV
- Predictions are sensitive to the SU(3) structure of the wave function of Λ(1520)

- **SPHINX** studied the 70 GeV p + N → Λ(1520)K⁺ + N reaction to look for Λ(1520) → Λγ decays.

SPHINX, PLB **604**, 22(2004)



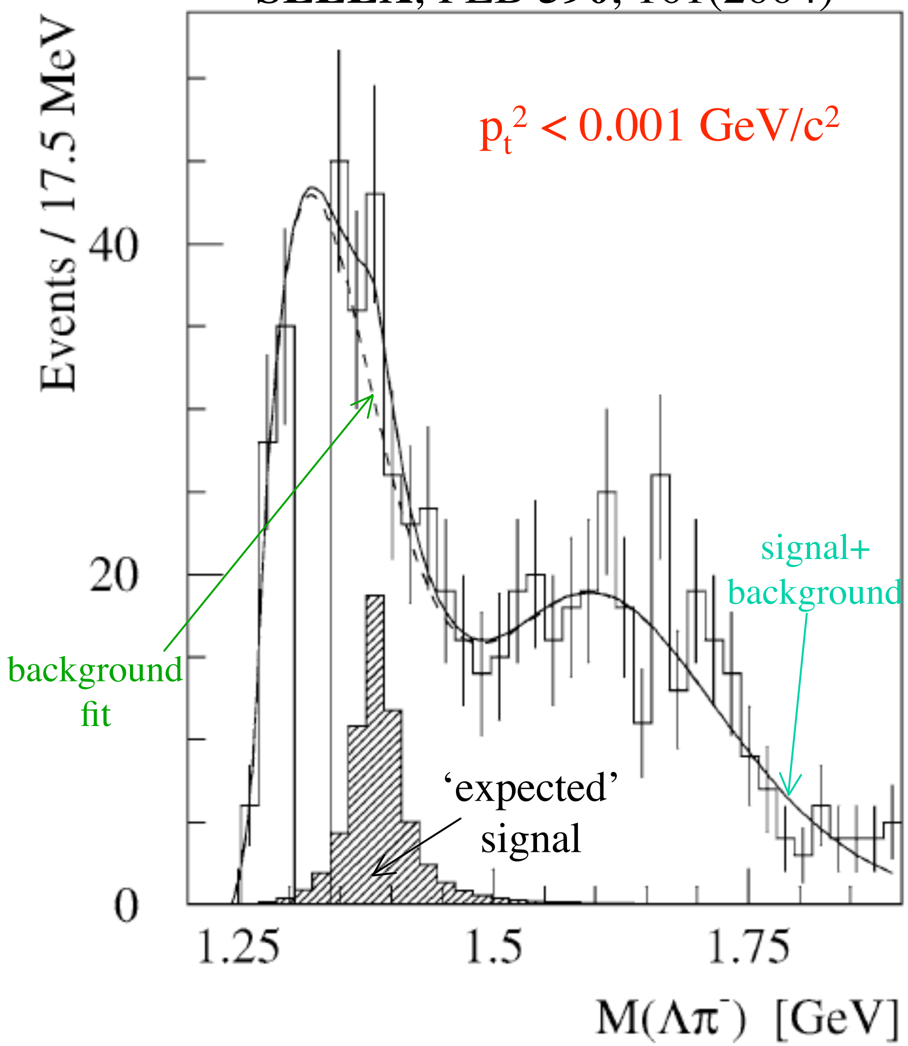
Obtained: **Br[Λ(1520) → Λγ] = $(1.02 \pm 0.21_{stat}) \times 10^{-2}$,**
Γ[Λ(1520) → Λγ] = $(159 \pm 35_{stat})$ keV

Radiative Decay (cont.)

SELEX looked for

$$\Sigma^- + Pb \rightarrow \Sigma(1385)^- + Pb$$
$$\quad \hookrightarrow \Lambda\pi^-$$

SELEX, PLB **590**, 161(2004)



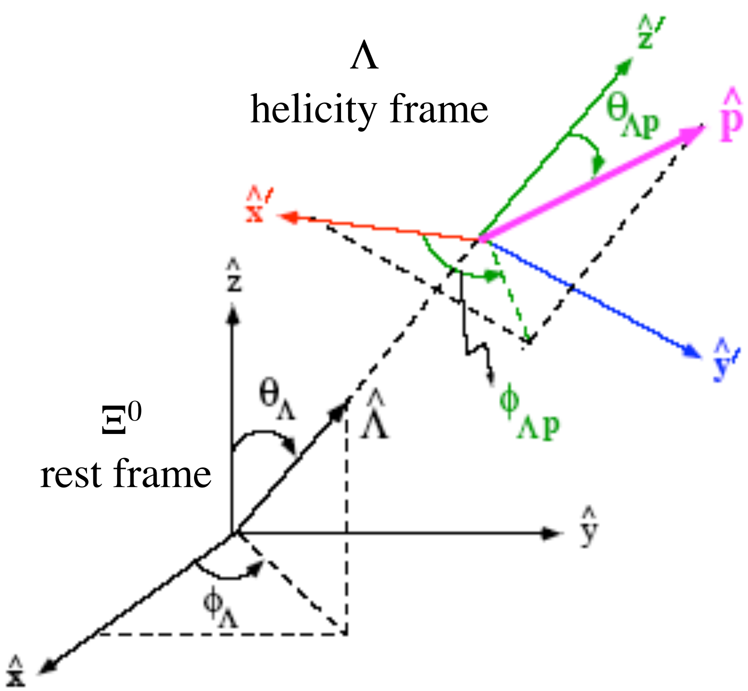
- Did not find any strong evidence of $\Sigma(1385)^- \rightarrow \Lambda\pi^-$ decays.
- Established:

$\mathbf{\Gamma[\Sigma(1385)^- \rightarrow \Sigma^-\gamma\ ] < 9.5\ keV}$ (90% c.l.)

right at the upper edge of theoretical predictions, and 2.5 times better than the previous best measurement.

Weak Radiative Decay: $\Xi^0 \to \Lambda\gamma$

- The decay is completely described by the decay rate, and three decay parameters $\alpha_{\Xi\Lambda\gamma}$, $\beta_{\Xi\Lambda\gamma}$, $\gamma_{\Xi\Lambda\gamma}$ such that $\alpha^2 + \beta^2 + \gamma^2 = 1$.
- Theoretical predictions vary widely:
  - pole models, χPT (satisfying the *Hara theorem*): α is negative
  - vector-meson-dominance models, quark model: α is positive



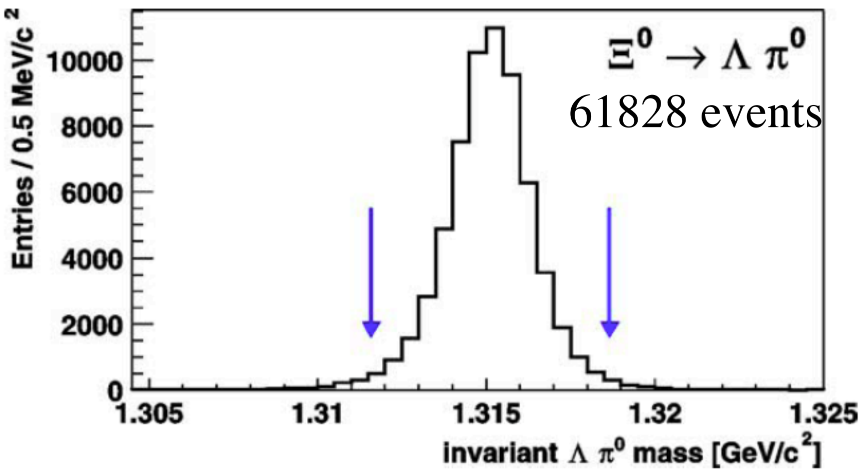
For the decay sequence

$$\Xi^0 \to \Lambda\gamma$$
$$\hookrightarrow p\pi^-$$

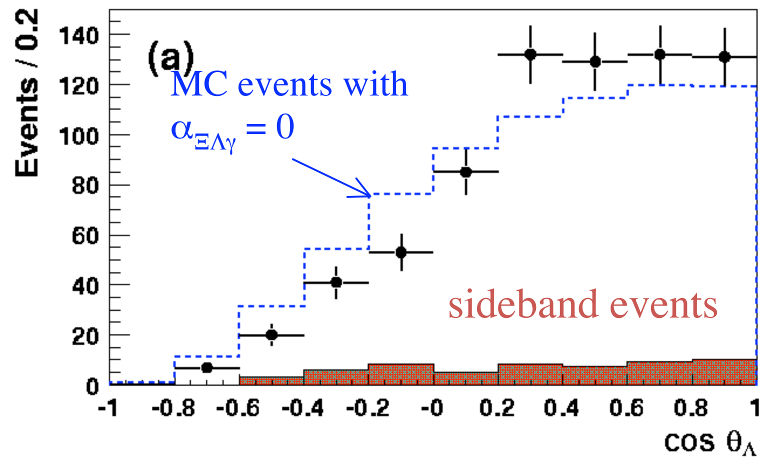
the proton distribution in the Λ helicity frame is:

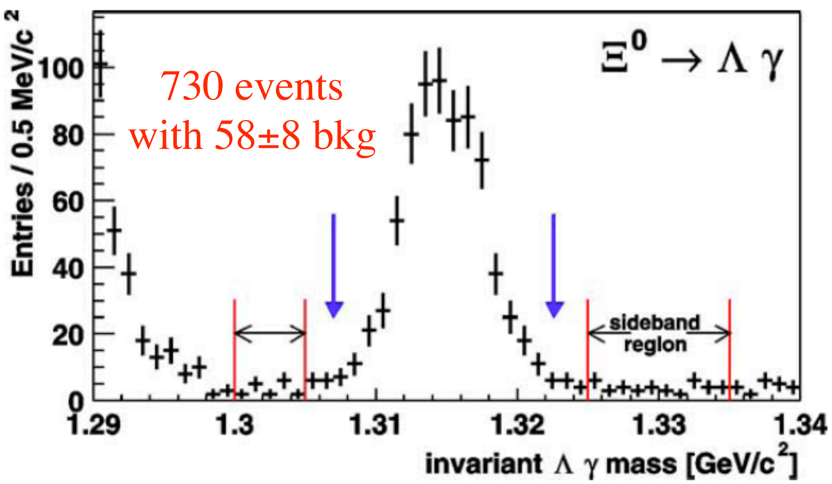
$$\frac{dN}{d\cos\theta_{\Lambda p}} = \frac{N_0}{2}\left(1 - \alpha_{\Xi\Lambda\gamma}\,\alpha_{\Lambda}\cos\theta_{\Lambda p}\right)$$

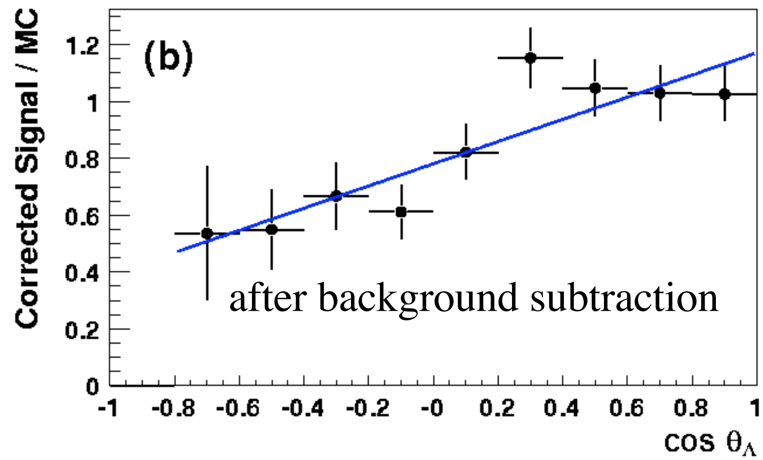
Weak Radiative Decay: $\Xi^0 \rightarrow \Lambda\gamma$ (cont.)



NA48, PLB **584**, 251(2004)







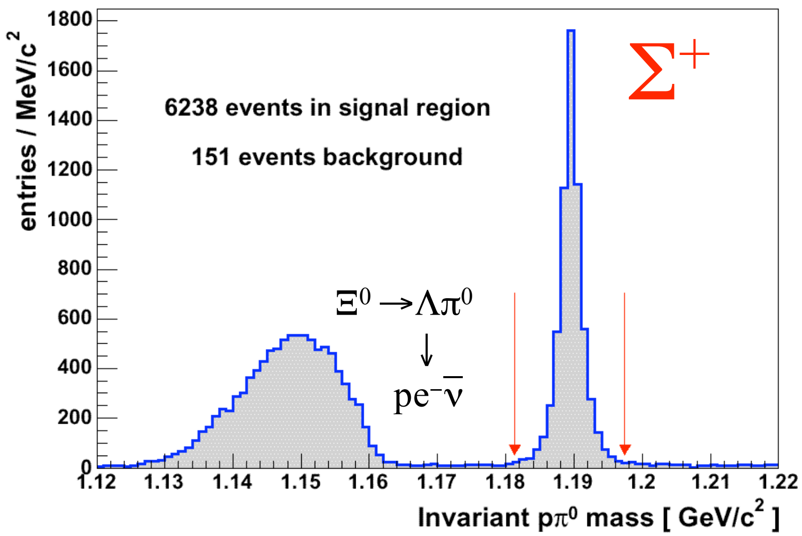
- **NA48** determined:

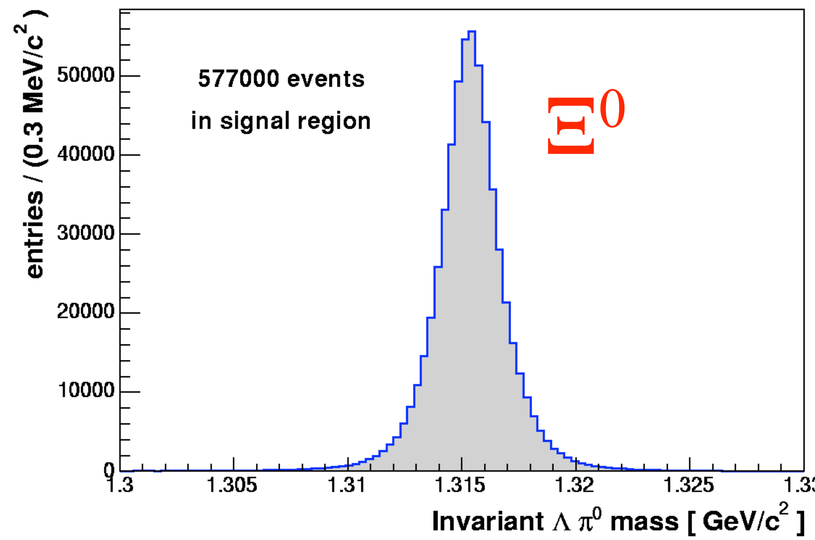
$$Br(\Xi^0 \rightarrow \Lambda\gamma) = (1.16 \pm 0.05_{stat} \pm 0.06_{sys}) \times 10^{-3}$$

$\alpha_{\Xi\Lambda\gamma} = -0.78 \pm 0.18_{stat} \pm 0.06_{sys}$, supporting Hara theorem.

Semi-leptonic Decay: $\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$

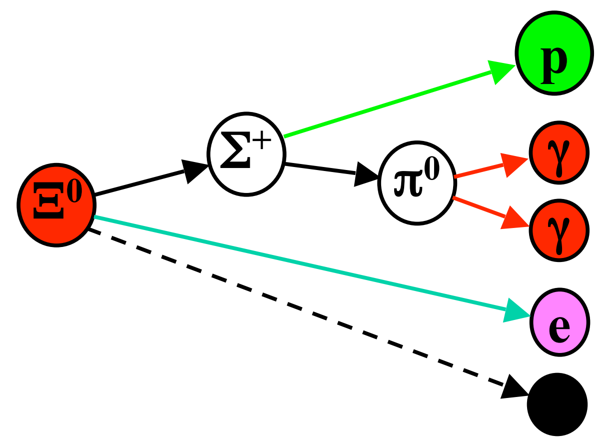
- Can be used to extract $|V_{us}|$.





From NA48:

- reconstruct $\Sigma^+ \to p\, \pi^0$ candidate
- require an additional electron
- background subtraction from mass sidebands



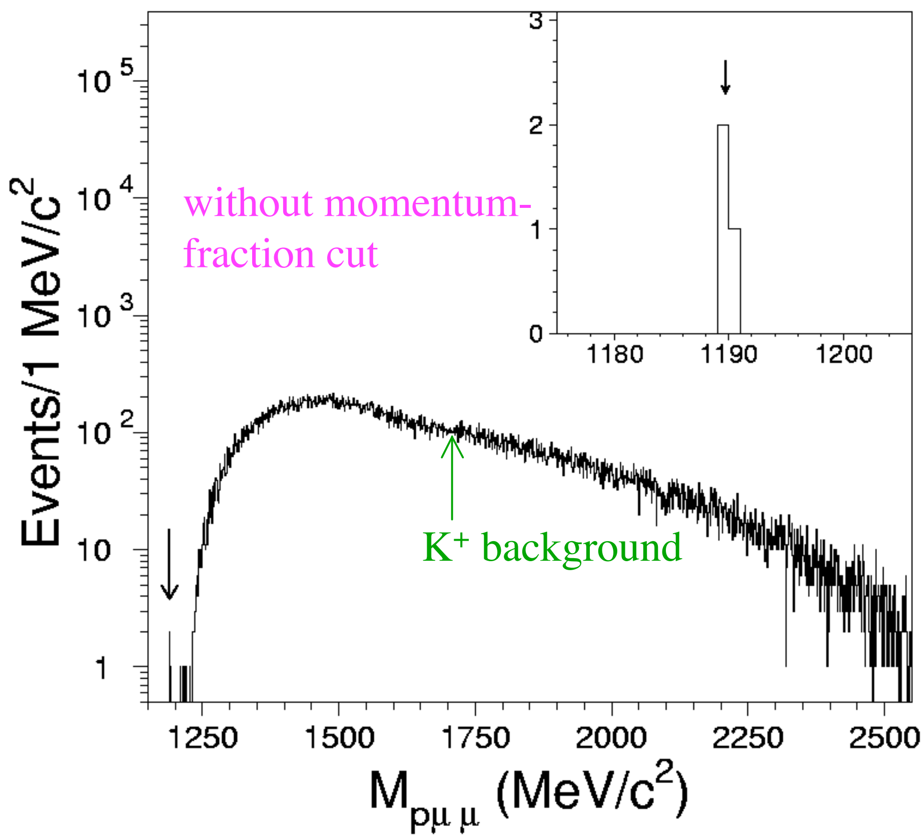
Preliminary result for the branching ratio:

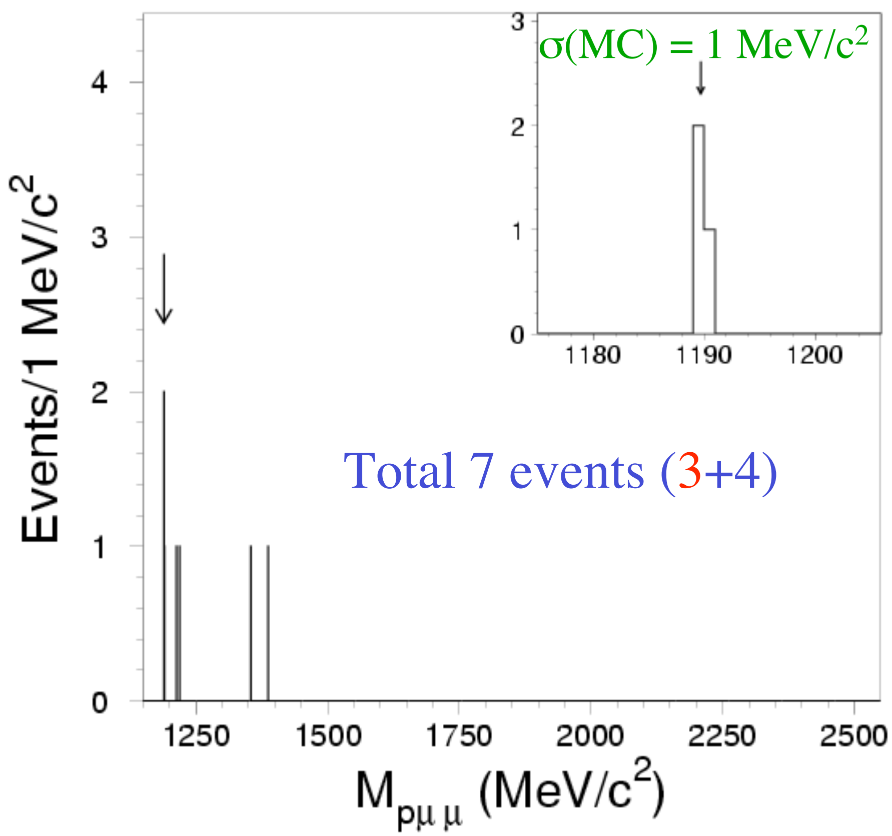
$$Br(\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e) = (2.51 \pm 0.03_{stat} \pm 0.11_{sys}) \times 10^{-4}$$

for comparison: $(2.71 \pm 0.38) \times 10^{-4}$ **KTeV** published (1999)

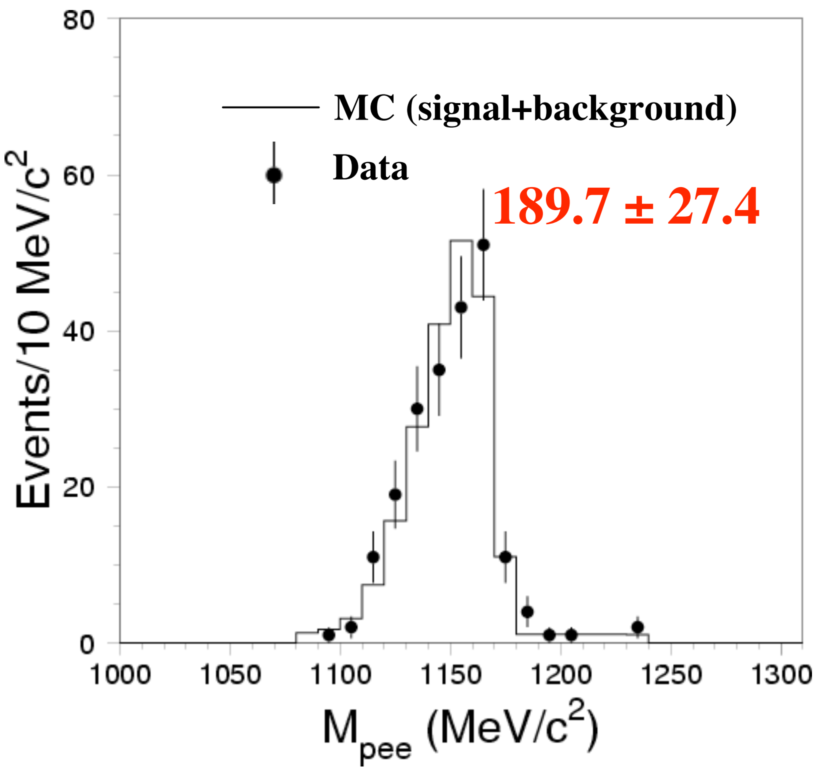
Observation of $\Sigma^+ \to p\mu^+\mu^-$ Events

- **HyperCP** hunt for FCNC through $\Sigma^+ \to pl^+l^-$ decays.
- Look for events with
  - three charged tracks of which two are tagged as muons
  - a good decay vertex within the decay region
  - the decaying particle coming from the target
  - proton carries at least 0.68 of the total momentum





Observation of $\Sigma^+ \to p\mu^+\mu^-$ Events (cont.)



- Look for

$$\Sigma^+ \to p\pi^0$$
$$\hookrightarrow e^+e^-\gamma$$

for normalization.

- Number of Σ^+ decays in the 1999 run is $(2.14 \pm 0.31) \times 10^{10}$

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

$$B(\Sigma^+ \to p\mu^+\mu^-) = [8.6^{+6.6}_{-5.4} \pm 5.0] \times 10^{-8} \quad \text{(uniform decay)}$$

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

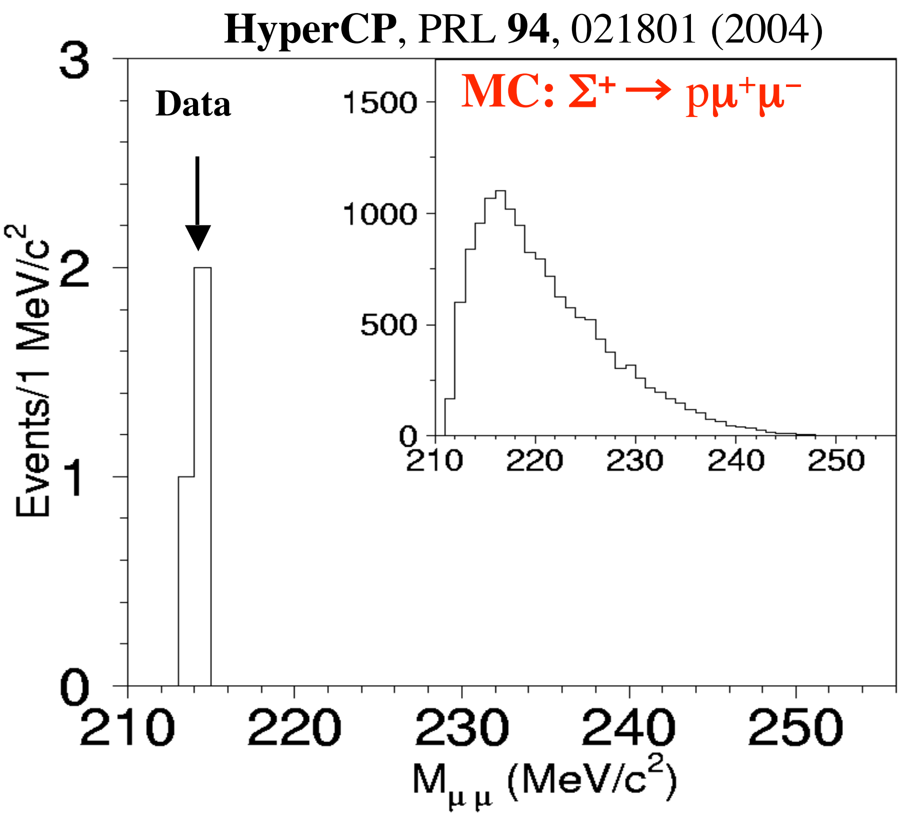
- If they are background events,

$$B(\Sigma^+ \to p\mu^+\mu^-) < 1.1 \times 10^{-7} \quad \text{(uniform decay), @ 90\% C.L.}$$

$$B(\Sigma^+ \to p\mu^+\mu^-) < 1.6 \times 10^{-7} \quad \text{(form factor), @ 90\% C.L.}$$

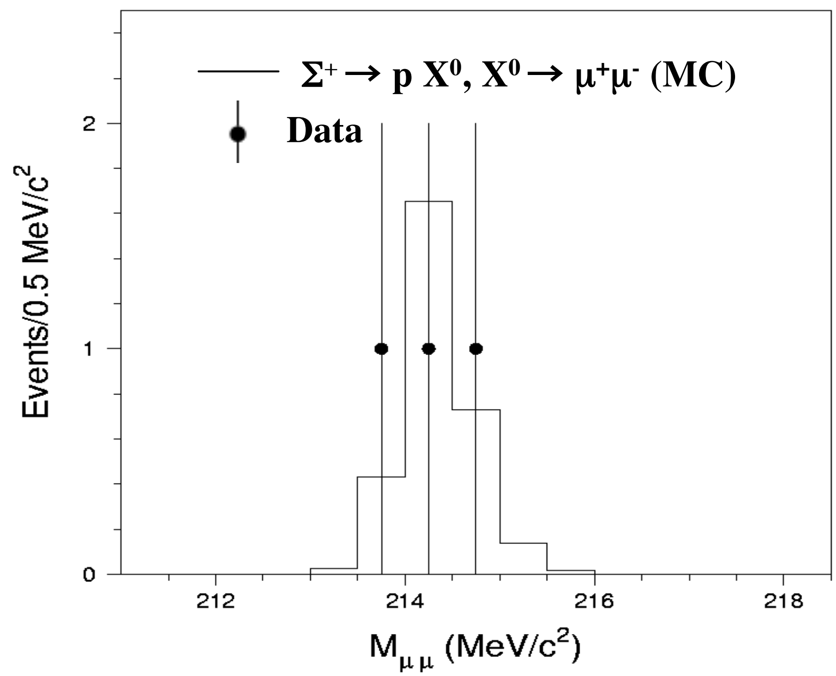
Observation of $\Sigma^+ \to p\mu^+\mu^-$ Events (cont.)

- Dimuon masses for 3 candidates are clustered within ~ 1 MeV/c^2:



- Probability for dimuon masses of 3 events to be within 1 MeV/c^2 for $\Sigma^+ \to p\mu^+\mu^-$ decays in SM is less than 1%.

- The $\mu^+\mu^-$ of the 3 events could come from the decay of a new particle X^0:



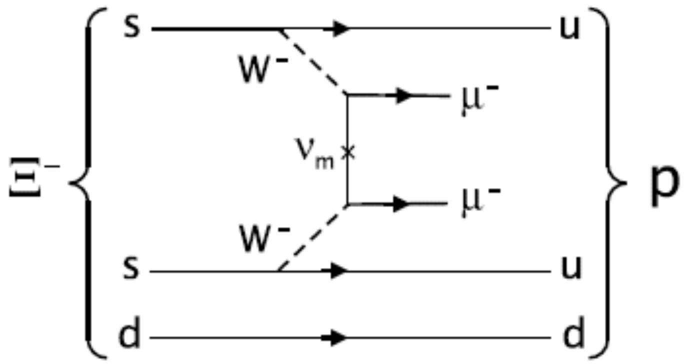
- For $\Sigma^+ \to pX^0$, $X^0 \to \mu^+\mu^-$:

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

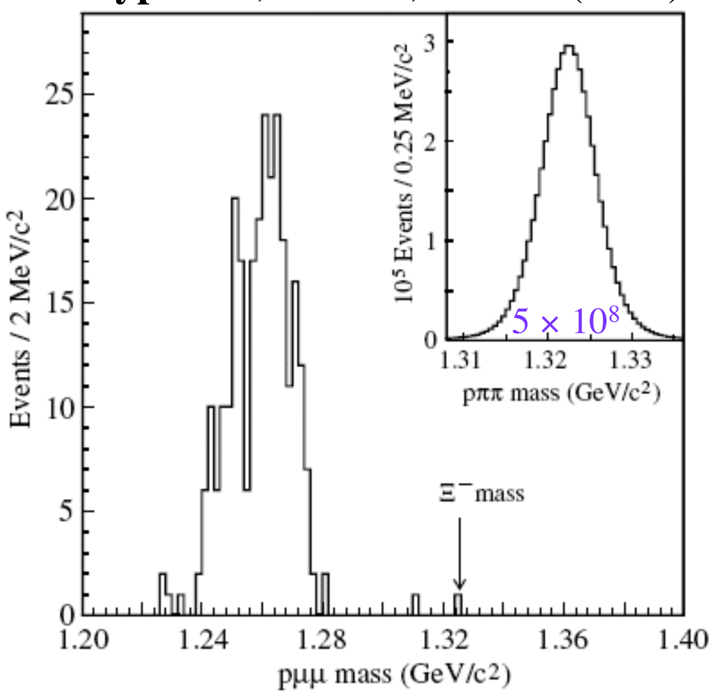
$$Br(\Sigma^+ \to pX^0, X^0 \to \mu^+\mu^-) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$$

Search For $\Xi^- \to p\mu^-\mu^-$ Decay

- It is a $\Delta L = 2$ process mediated by a Majorana neutrino:



HyperCP, PRL **94**, 181801 (2005)



- Based on a sample of $\sim 10^9$ Ξ^-, **HyperCP** set a limit on

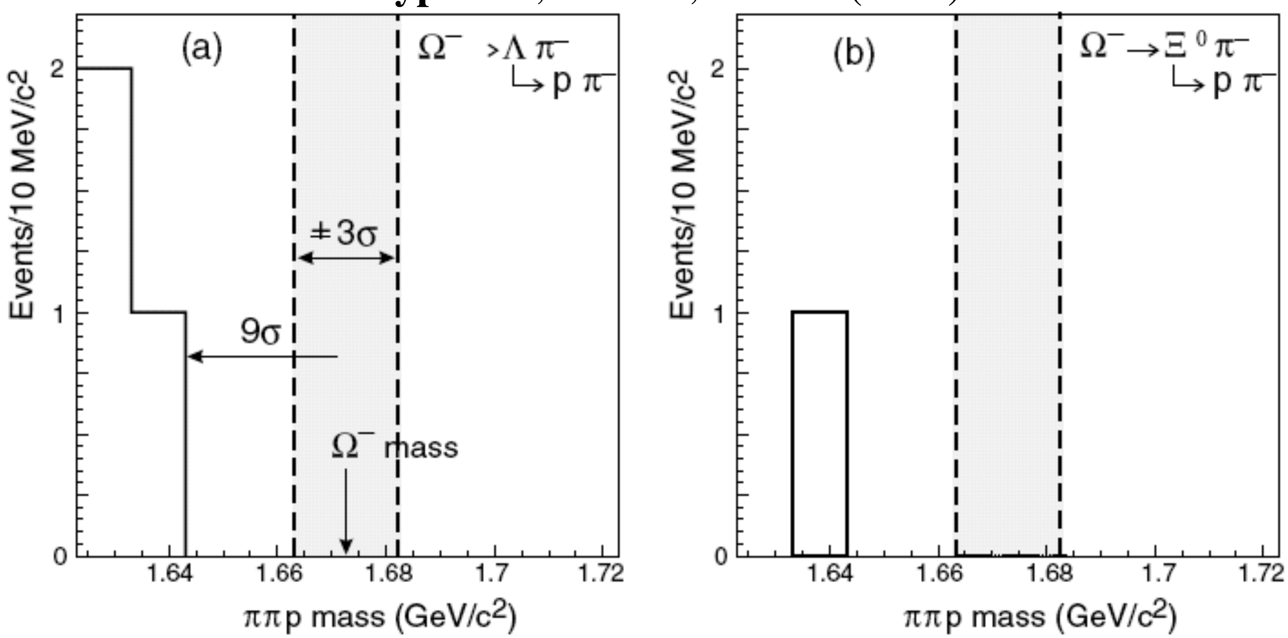
$$Br(\Xi^- \to p\mu^-\mu^-) < 4.0 \times 10^{-8} \text{ at } 90\% \text{ c.l.}$$

which is four orders of magnitude better than the previous best limit, but is still very far away from any theoretical predictions.

Search For ΔS=2 Non-leptonic Decays

- A second-order weak process that has only been observed in K^0-$\bar{K}^0$ mixing.
- Such process could be enhanced in hyperon decays via new parity-odd mechanism (He and Valencia).
- Using about a data set containing ~3 ×10^6 $\Omega^- \rightarrow \Lambda K^-$ decays, **HyperCP** look for $\Omega^- \rightarrow p\pi^-\pi^-$ events:

HyperCP, PRL **94**, 101804 (2005)



$Br(\Omega^- \rightarrow \Lambda\pi^-) < 2.9 \times 10^{-6}$ at 90% c.l.

$Br(\Xi^0 \rightarrow p\pi^-) < 8.2 \times 10^{-6}$ at 90% c.l.

Summary

- Current generation of dedicated experiments for studying strange particles have collected large samples of hyperons for precision measurements and for high-sensitivity searches.

- Many results are consistent with theoretical predictions.

- There is no sign of direct CP violation in the Ξ–Λ decays yet, down to the $\sim 6 \times 10^{-4}$ level.

- **HyperCP** has observed three $\Sigma^+ \rightarrow p\mu^+\mu^-$ events that call for further investigation.