New Results on Ξ^0 Hyperon Decays

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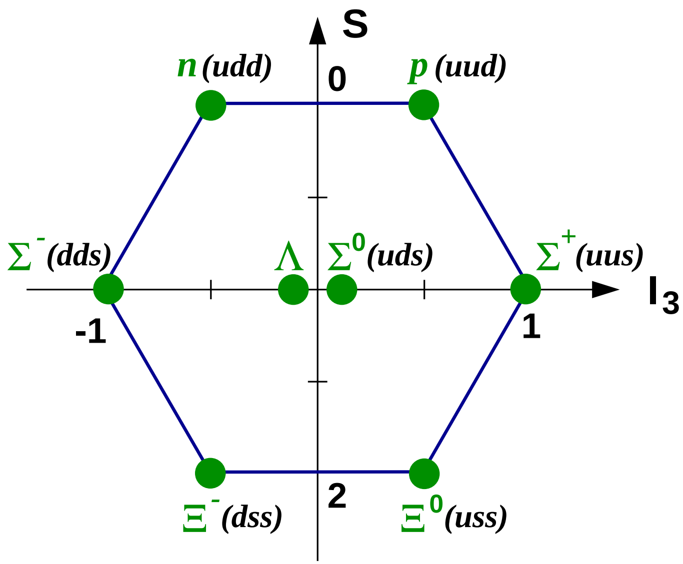
Why investigate Hyperons?

- Understanding of $\mathbf{SU(3)_f}$ **symmetry** and symmetry breaking.
- Possible $|\mathbf{V_{us}}|$ **measurement,** complementary to kaons.
- Deeper understanding of baryon structure and decays.

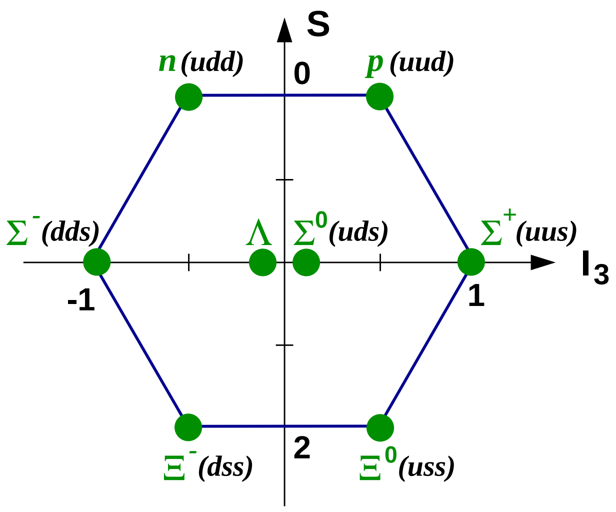


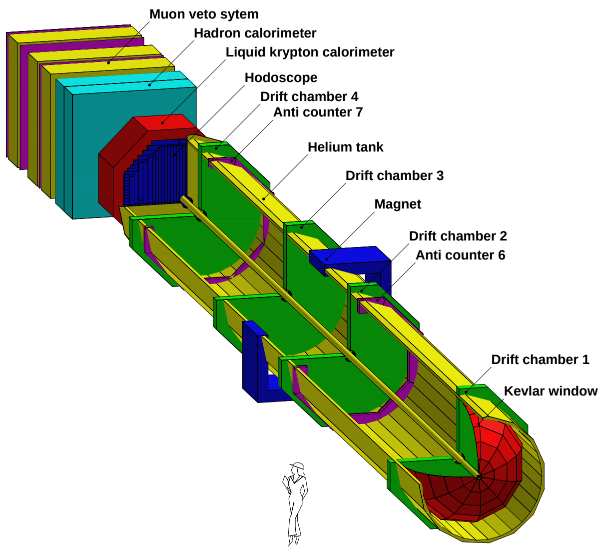
Many new data on neutral hyperons!

- Most previous data were still from the 60's and 70's.
- $\mathbf{\Lambda}$ and $\mathbf{\Xi^0}$ have similar lifetimes & decay lengths than K_S mesons.
  $\Longrightarrow$ Recent high statistics kaon experiments provide large samples of neutral hyperons!
- **This talk:** New results on $\mathbf{\Xi^0}$ **decays** from **NA48/1** and **KTeV.**

Overview

- Introduction
- Experimental Set-up
- Ξ^0 Beta Decay and $|V_{us}|$
- $\Xi^0 \rightarrow \Sigma^+ \mu \nu_\mu$
- Ξ^0 Lifetime
- Ξ^0 Decay Asymmetries
- Summary

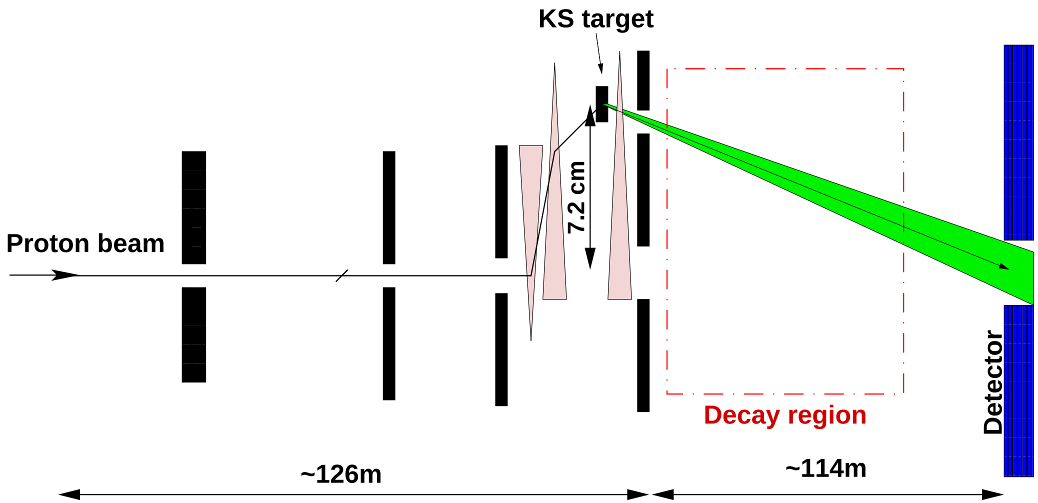




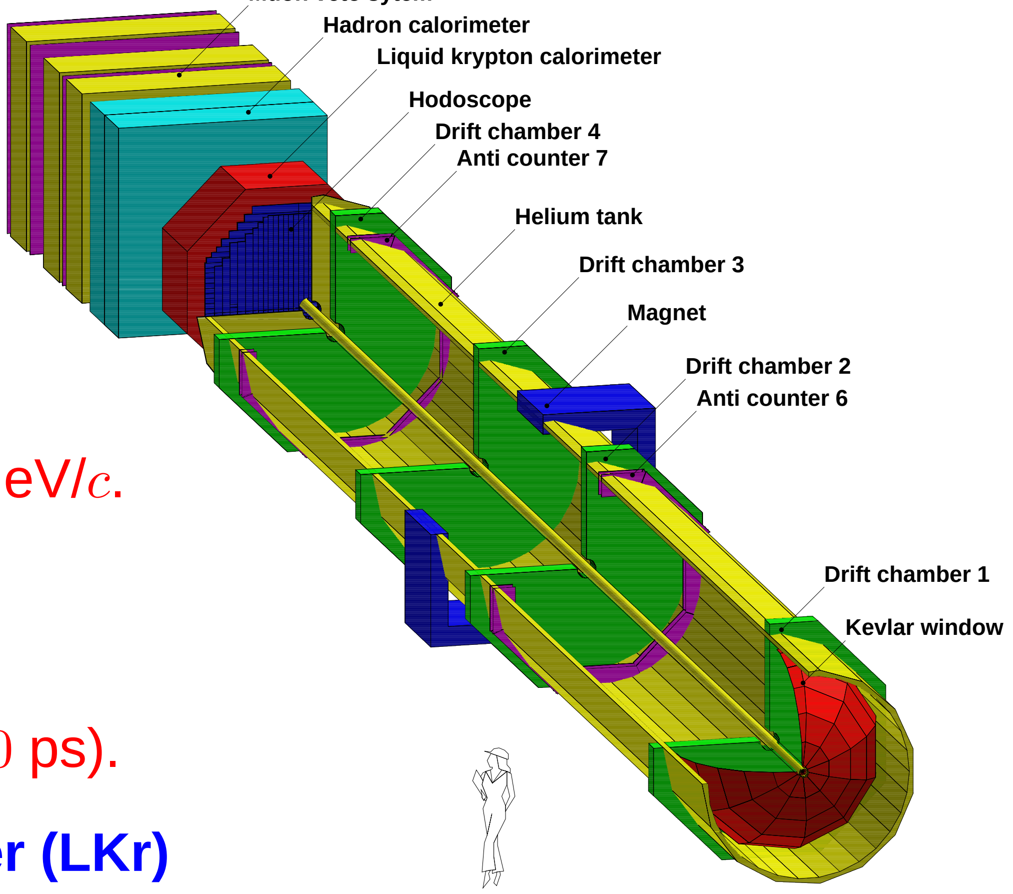
K_S *and* Ξ^0 *Decays:*
The NA48/1 Experiment at CERN

Data taking in 2002: *(NA48/1 experiment)*

- **Purpose:** Measurement of very rare K_S decays and neutral Hyperon decays.
- Neutral beam with target close decay region.
  (K_S target from ϵ'/ϵ measurement, but $200\times$ intensity.)
- **Total statistics:** **K_S flux:** $\sim \mathbf{3.5 \times 10^{10}}$
  Ξ^0 flux: $\sim \mathbf{2.4 \times 10^{9}}$ in the decay region.



The NA48 Detector



Detector components:

- **Magnet spectrometer**

  4 sets of drift chambers.

  $\Delta p/p \approx 0.5\%$ for $p = 20$ GeV/c.

- **Hodoscopes:**

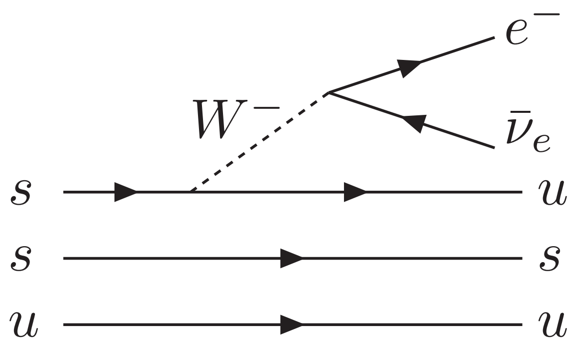
  Fast trigger, precise time measurement ($\sigma_t = 150$ ps).

- **Liquid Krypton Calorimeter (LKr)**

  $\Delta E/E \approx 1.0\%$ for $E_{e,\gamma} = 20$ GeV/c.

- **Hadron calorimeter, photon vetos, muon counters**

$\Xi^0 \rightarrow \Sigma^+ e^- \overline{\nu}_e$ decay:



- Ξ^0 hyperon (uss) strange partner of the neutron (udd).

  $\Longrightarrow$ $\Xi^0 \rightarrow \Sigma^+ e^- \overline{\nu}_e$ decay similar to neutron β-decay.

  $\Longrightarrow$ **Determination of $|\mathbf{V_{us}}|$** possible!

- **Decay rate:**

$$\Gamma = \frac{\mathrm{Br}(\Xi^0 \rightarrow \Sigma^+ e^- \overline{\nu}_e)}{\tau_{\Xi^0}} \approx G_F^2 |V_{us}|^2 \frac{\Delta m^5}{60\pi^3} [(1 - \tfrac{3}{2}\beta)(|f_1|^2 + 3|g_1|^2)]$$

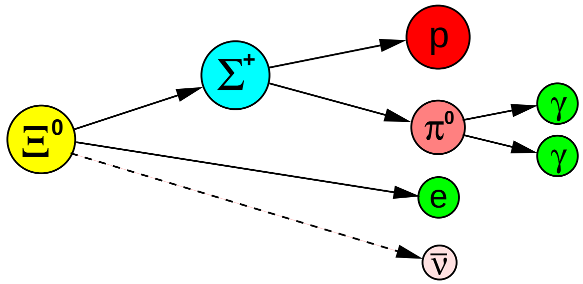
$(\Delta m = m_{\Xi^0} - m_{\Sigma^+}, \beta = \frac{\Delta m}{m_{\Xi^0}})$

Form factors $f_1, g_1, \ldots$ = neutron form factors in $SU(3)_f$ symmetry.

- Only one published measurement (KTeV, 1999) with 176 events.
  (+ preliminary result with 626 events.)

Ξ^0 *Beta Decay: Event Selection*

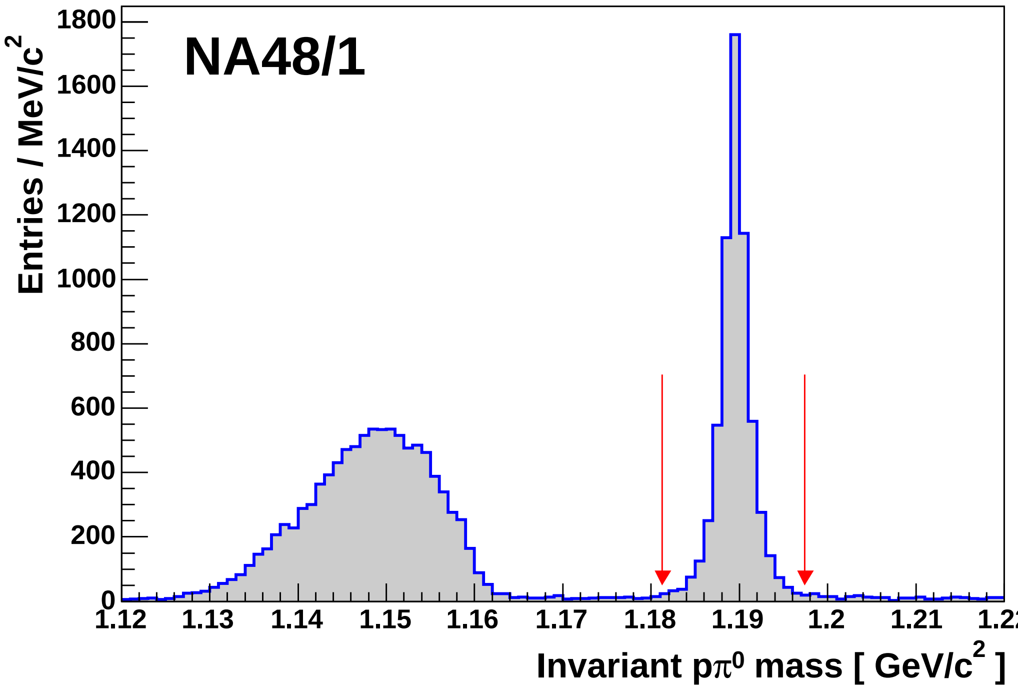
Event selection of $\Xi^0 \to \Sigma^+ e^- \overline{\nu}_e$:



- Reconstruct Σ^+ by its decay to $p\pi^0$.
- Require an additional electron ($E/p > 0.9$).

NA48/1:

- Ξ^0 beta decay is only source of Σ^+ in neutral beam.
- **6316 candidates**
- Background: ≈ 140 events (2.2%) (estimated from mass side-bands.)



Ξ^0 *Beta Decay:*
Monte Carlo Simulation

Monte Carlo simulation:

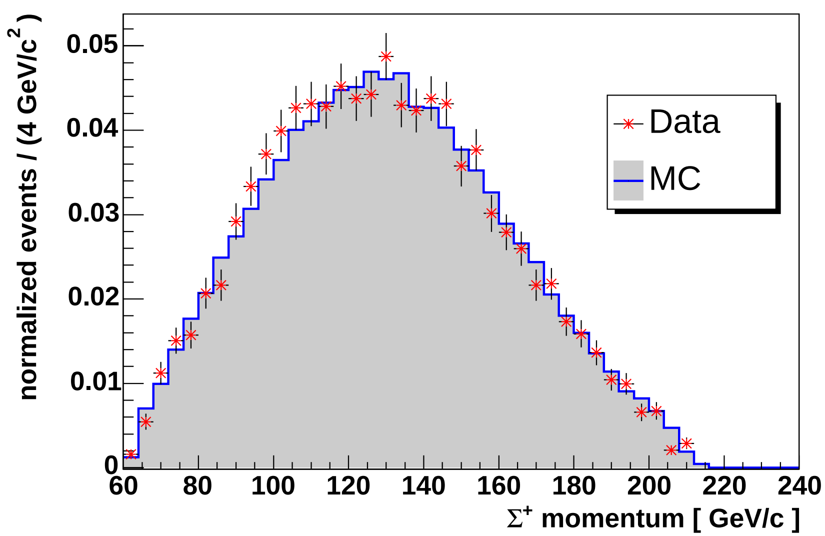
- Experimental challenge of Hyperon decays:

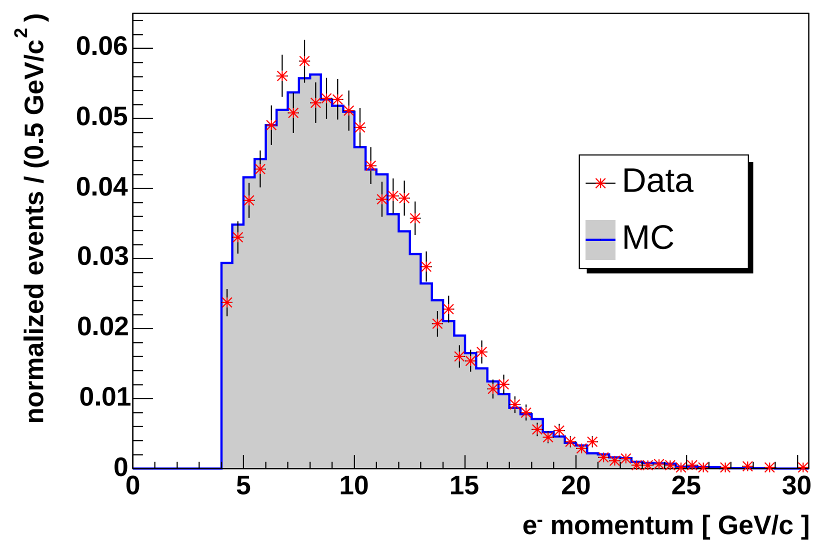
  Leading proton takes most of the original hyperon momentum.

  $\Longrightarrow$ Proton line-of-flight very close to the beam pipe.

  $\Longrightarrow$ Low acceptances, high sensitivity to detector geometry.

- Monte Carlo simulation elaborately tuned to correct detector geometry and inefficiencies.





Ξ^0 *Beta Decay: Result*

- **NA48/1 result** on 6316 Ξ^0 β-decay candidates:

$$\mathbf{Br}(\Xi^0 \to \Sigma^+ e^- \bar{\nu}) = (2.51 \pm 0.03_{\text{stat}} \pm 0.09_{\text{syst}}) \times 10^{-4}$$

- **Systematics:**

Source	$\sigma_{\text{syst}}/\text{Br}$
Trigger efficiency	$\pm 2.2\%$
Detector acceptance	$\pm 1.0\%$
Ξ^0 form factors g_1, f_2	$\pm 1.6\%$
Ξ^0 polarization	$\pm 1.0\%$
Normalization	$\pm 1.0\%$
Others (MC stat., bkg., τ_{Ξ^0})	$\pm 1.0\%$
Total systematics	$\pm \mathbf{3.4\%}$

- Measured also $\overline{\Xi^0}$ β**-decay:** (555 events)

$$\Longrightarrow \mathbf{Br}(\overline{\Xi^0} \to \overline{\Sigma^+} e^+ \nu) = (2.55 \pm 0.12_{\text{stat}} \pm 0.10_{\text{syst}}) \times 10^{-4}$$

$|V_{us}|$ *from* Ξ^0 *Beta Decay*

- Use Ξ^0 lifetime (PDG06) for computation of decay rate:

$$\Gamma(\Xi^0 \to \Sigma^+ e^- \nu) = (8.66 \pm 0.31_{\text{exp}} \pm 0.27_{\Xi^0\text{ lifetime}}) \times 10^5\ \text{s}^{-1}$$

- For $|\mathbf{V_{us}}| \cdot \mathbf{f_1(0)}$ have to use form factors as input:

KTeV, 2001 (494 events): $g_1/f_1 = 1.32^{+0.22}_{-0.18}$, $f_2/f_1 = 2.0 \pm 1.3$

(And assume $SU(3)_f$ symmetry for f_1.)

$\Longrightarrow$ $$|\mathbf{V_{us}}| = \mathbf{0.209} \pm \mathbf{0.005}_{\text{exp}} \ {}^{+\mathbf{0.022}}_{-\mathbf{0.028}\,\text{form factors}}$$

$\Longrightarrow$ Good agreement with $|V_{us}| = 0.2257 \pm 0.0021$ from Kaon decays, but uncertainty from form factors still large.

- **Turn it around instead:** Determination of $\mathbf{g_1/f_1}$ using $|V_{us}|$!

$\Longrightarrow$ $$\mathbf{g_1/f_1 = 1.20 \pm 0.04_{\text{exp}} \pm 0.03_{\text{ext}}}$$

(Compare with $g_1/f_1 = 1.267$ neutron decay + $SU(3)$ symmetry!)

$\Xi^0 \to \Sigma^+ \mu^- \nu$

Semimuonic decay $\Xi^0 \to \Sigma^+ \mu^- \nu_\mu$:

- Phase-space suppressed, prediction:

  $\text{Br} \approx \frac{1}{114} \times \text{Br}(\Xi^0 \to \Sigma^+ e^- \nu)$

  $\approx 2.2 \times 10^{-6}$

- **First observation: KTeV, 2005**

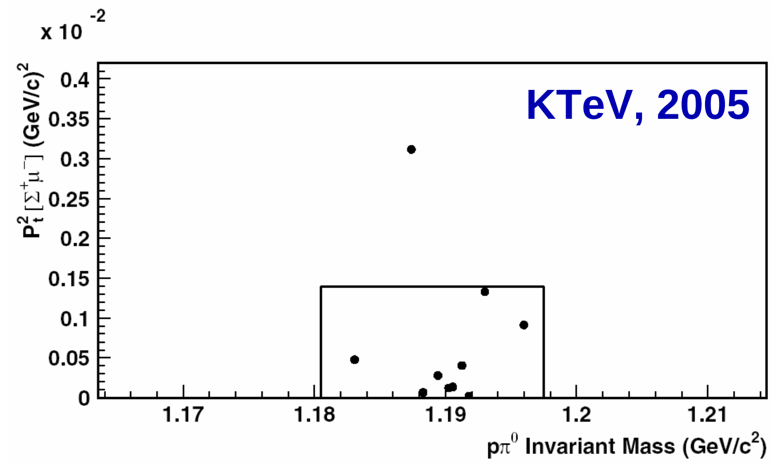
  8 signal events (negligible bkg).

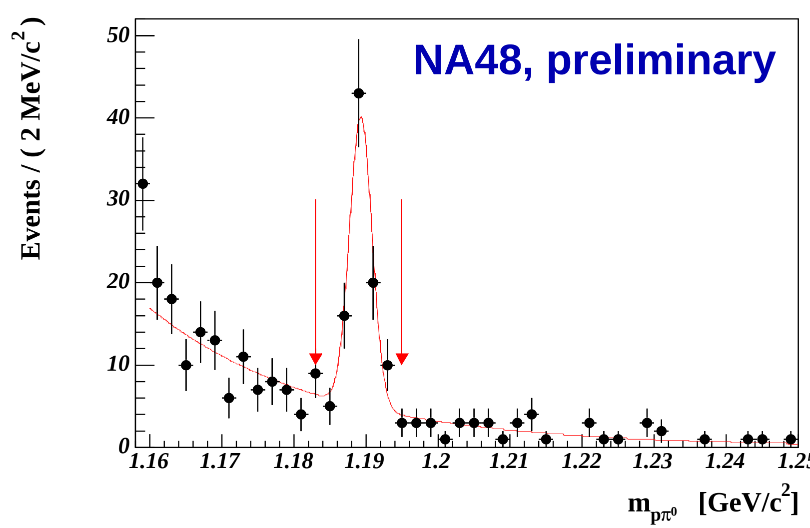
  $$\textbf{Br} = (4.7^{+2.0}_{-1.4} \pm 0.8) \times 10^{-6}$$

- **NA48/1, preliminary:**

  99 signal events ($\approx$ 30 bkg events).

  $$\textbf{Br} = (2.2 \pm 0.3 \pm 0.2) \times 10^{-6}$$



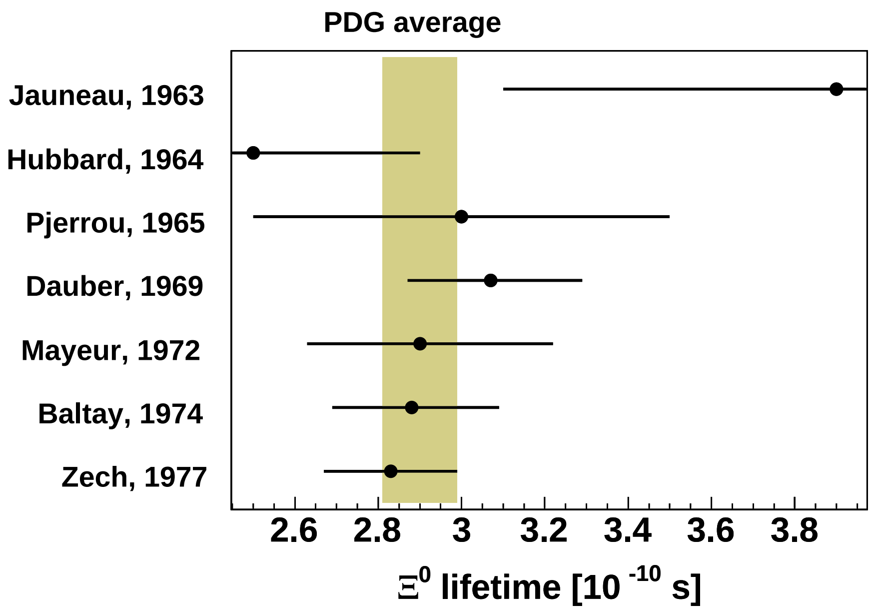


Ξ^0 Lifetime:

- Important input for other measurements (e.g. $|V_{us}|$ from Ξ^0 β-decays).
- Currently known to less than 3% accuracy:

$$\tau_{\Xi^0}(\text{PDG}) = (2.90 \pm 0.09) \times 10^{-10}\ \text{s}$$

Last measurement almost 30 years old!



Ξ^0 Lifetime

NA48/1 Measurement:

- Use $\Xi^0 \rightarrow \Lambda\pi^0$ events taken with minimum bias trigger (downscaled by 100).

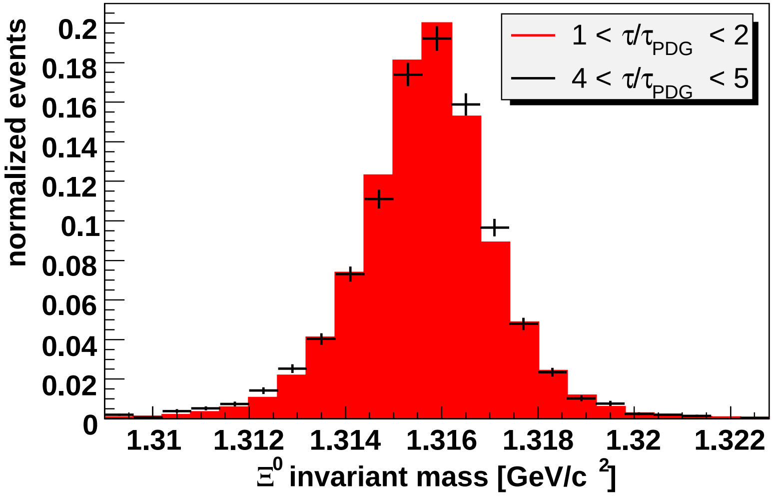
  $\Longrightarrow$ $\sim$ **260 000 events**
  (virtually background-free)

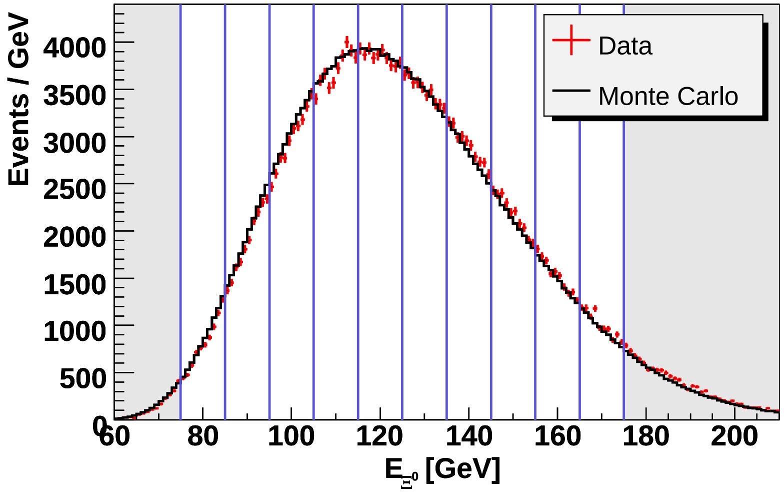
- Fit in separate energy bins.

  $\Longrightarrow$ No spectrum dependency.

- Fit region well separated from collimator position.

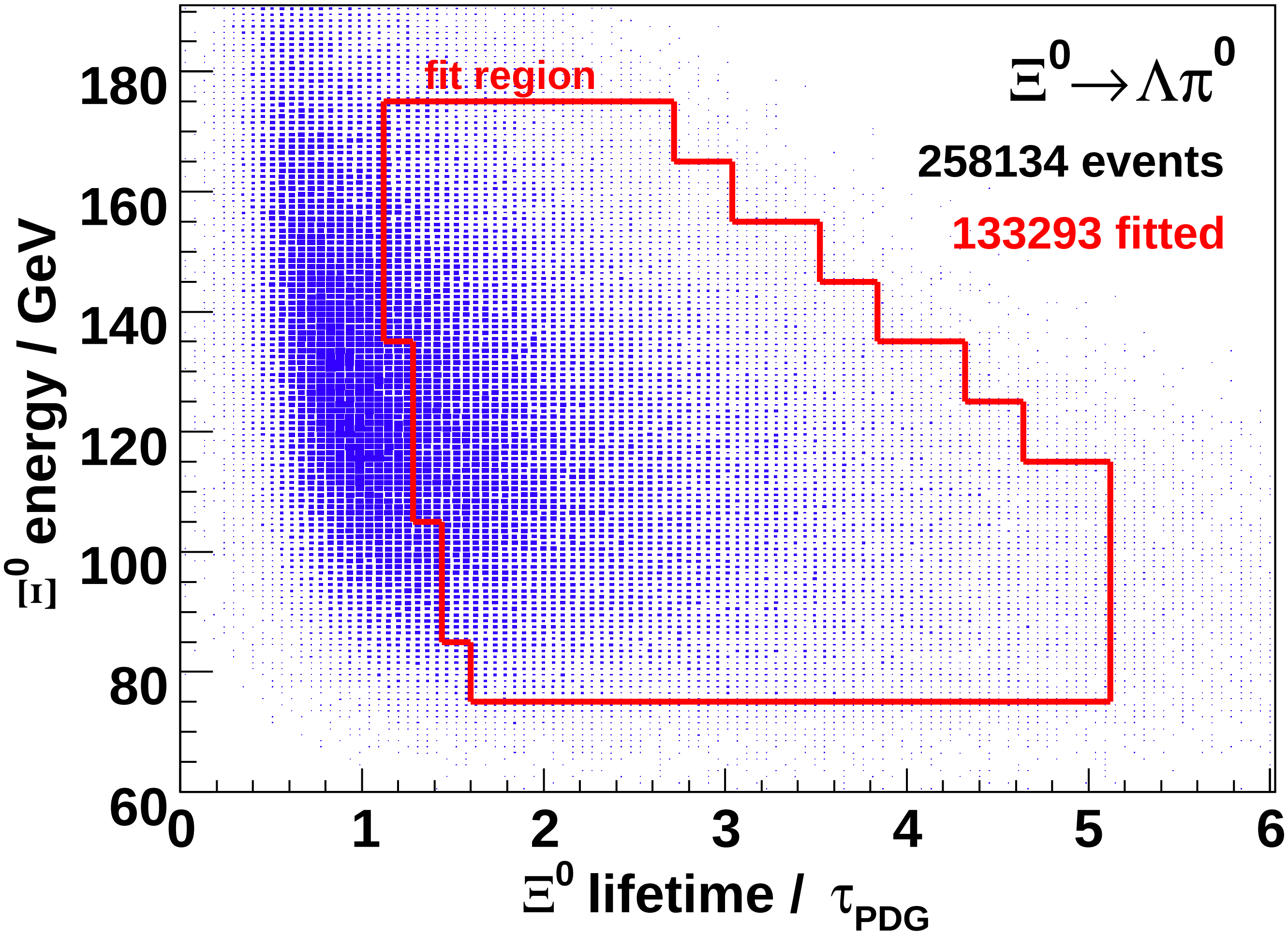
  $\Longrightarrow$ No effects from detector resolution.





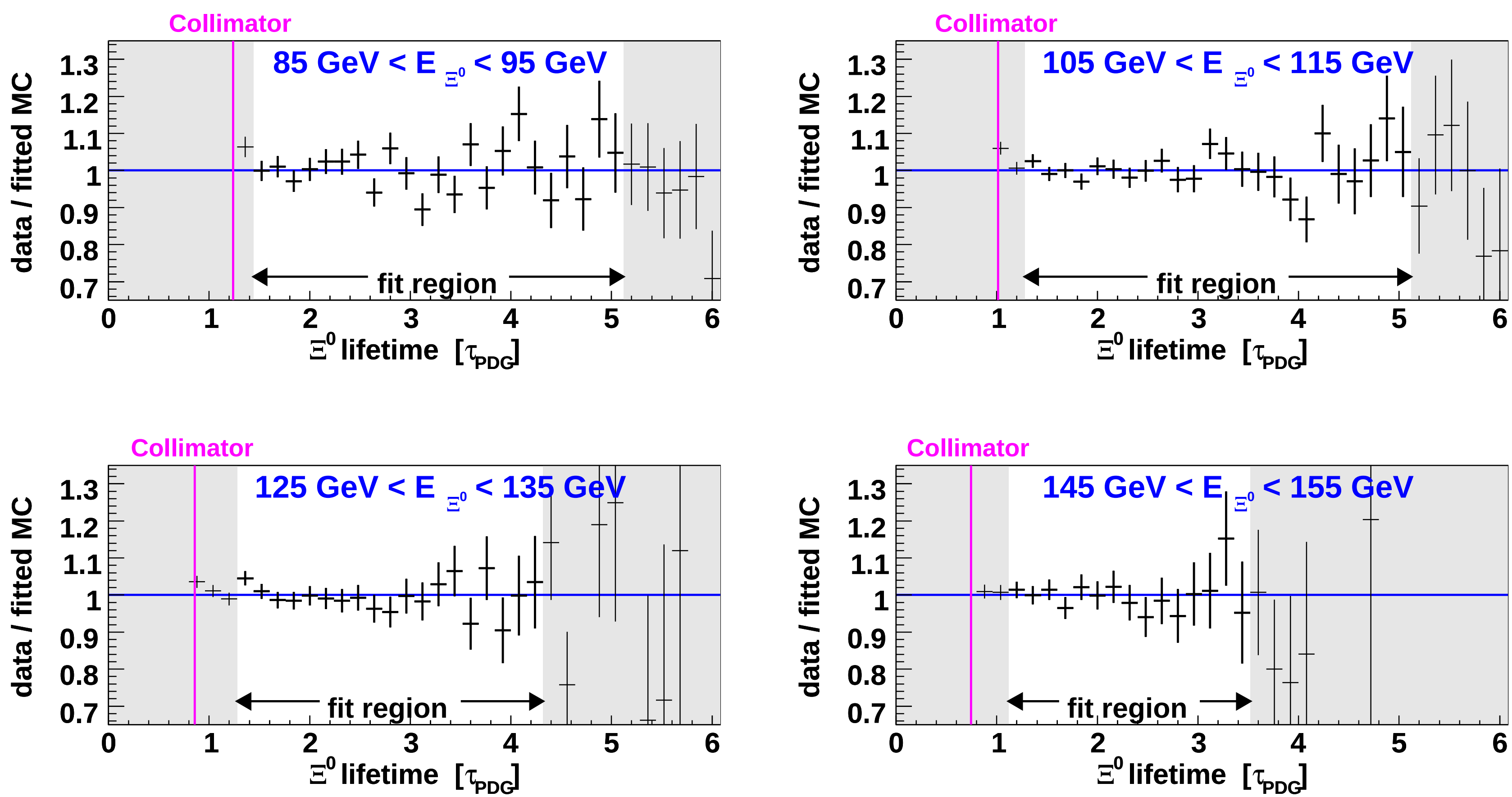
Ξ^0 *Lifetime*

Fit region:

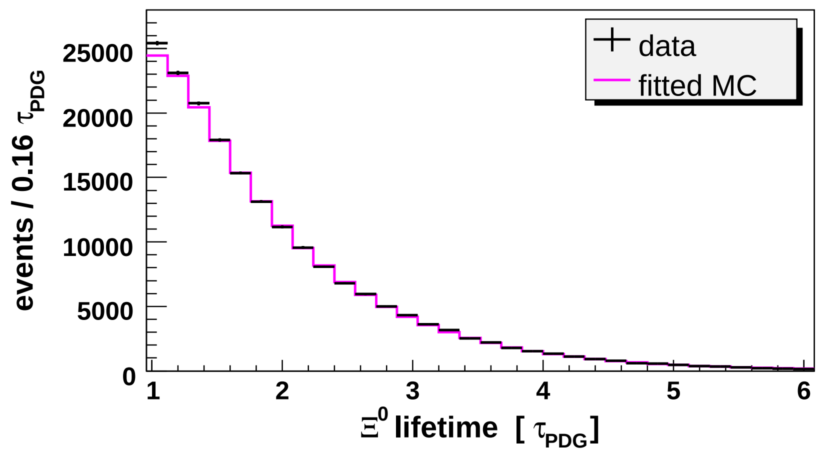


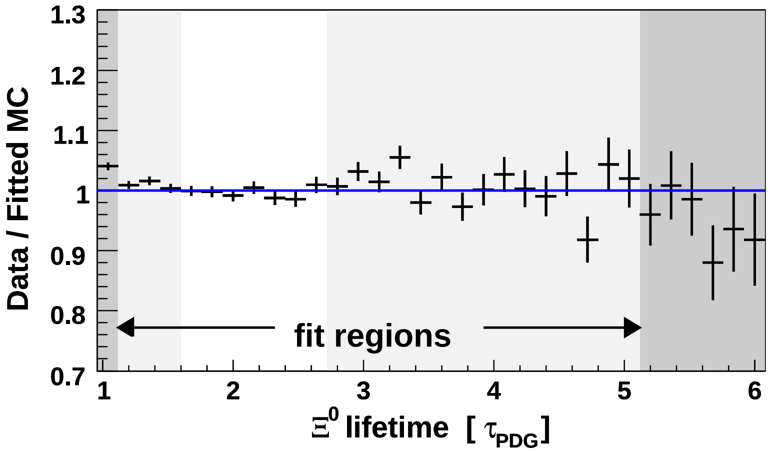
Ξ^0 *Lifetime*

Data/MC agreement in single energy bins:



Ξ^0 Lifetime



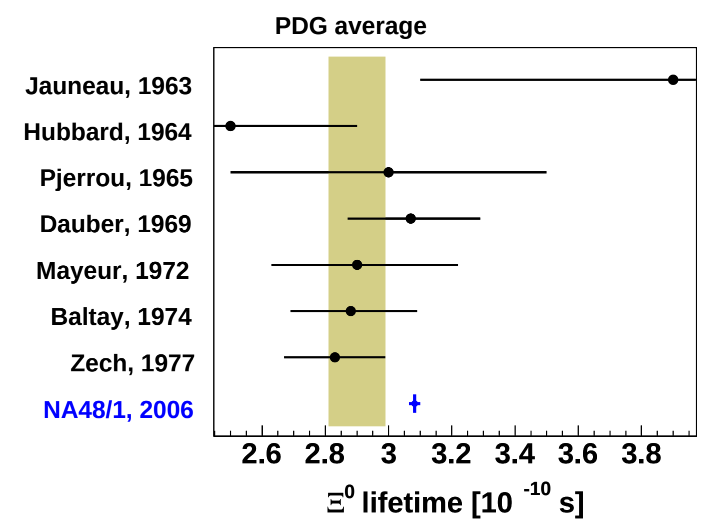


Fit result: *(preliminary)*

$$\tau_{\Xi^0} = (3.082 \pm 0.013 \pm 0.012) \cdot 10^{-10}\ \mathrm{s}$$

Systematics:

Detector accept.	$\pm 0.30\%$
Vertex resolution	$\pm 0.08\%$
LKr energy meas.	$\pm 0.17\%$
Ξ^0 polarisation	$\pm 0.15\%$
Ξ^0 mass	$\pm 0.20\%$

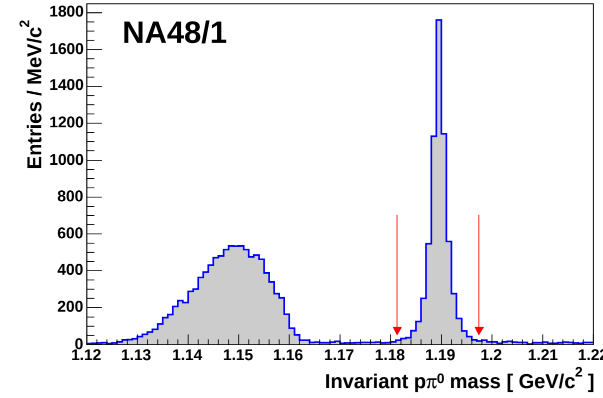


$\Longrightarrow$ About $2\,\sigma$ above PDG 2004 average, and five times more precise.

$|V_{us}|$ *with new* Ξ^0 *lifetime*

- NA48/1 measurement of Ξ^0 β-**decay:**

  $\text{Br} = (2.51 \pm 0.09) \times 10^{-4}\ \text{s}^{-1}$



- Use **new Ξ^0 lifetime** for decay rate:

(preliminary)

$$\boldsymbol{\Gamma(\Xi^0 \to \Sigma^+ e^- \nu)}$$
$$\boldsymbol{= (8.14 \pm 0.29_{\text{exp}} \pm 0.05_{\tau(\Xi^0)}) \cdot 10^5\ \text{s}^{-1}}$$

- Same computation as before. . .

(preliminary)

$$\Longrightarrow \quad \boldsymbol{|V_{us}| = 0.203 \pm 0.004_{\text{exp}}\ {}^{+0.22}_{-0.27}}\ \text{form factors}$$

- **Outlook:** Measurement of g_1/f_1 from same data sample.

Weak Radiative Ξ^0 Decays

Weak Radiative Hyperon Decays: $(\Xi^0 \to \Lambda\gamma,\ \Xi^0 \to \Sigma^0\gamma,\ \ldots)$

- All interactions (weak, strong, e.m.) involved.
- Several competing theoretical models
  (pole models, quark models, VMD, . . .)

Decay Asymmetry in Hyperon Decays:

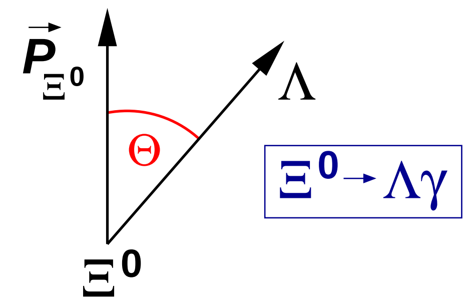
$$\frac{dN}{\cos\Theta} = N_0(1 + \alpha\,|\vec{P}_{\Xi^0}|\cos\Theta)$$

- **Asymmetry α:**
  Interference of s-wave (P conserving) and p-wave (P violating) amplitudes.

$$\alpha = \frac{2\,\mathrm{Re}(\mathbf{A_s}\,\mathbf{A_p^\star})}{|\mathbf{A_s}|^2 + |\mathbf{A_p^\star}|^2}$$

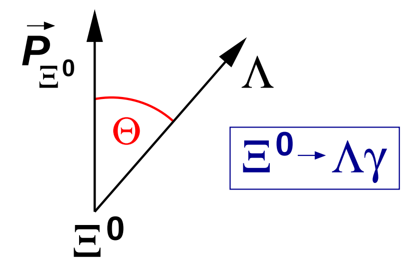
- Very different theoretical predictions for decay asymmetries:

sign of α	$\Sigma^+ \to p\gamma$	$\Lambda \to n\gamma$	$\Xi^0 \to \Lambda\gamma$	$\Xi^0 \to \Sigma^0\gamma$
pole	$-$	$-$	$-$	$-$
QM, VMD	$-$	$+$	$+$	$-$



Weak Radiative Ξ^0 Decays

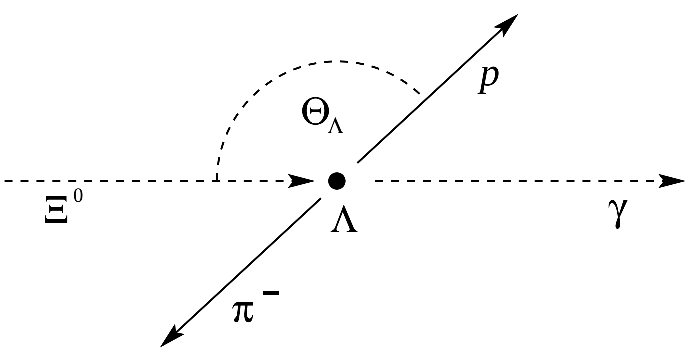
Measurement of the $\Xi^0 \to \Lambda\gamma$ Decay Asymmetry:



- For using $\frac{dN}{\cos\Theta} \propto 1 + \alpha\,|\vec{P}_{\Xi^0}|\cos\Theta$
  the Ξ^0 polarization $\vec{P}_{\Xi^0}$ is too small ($\approx 10\%$).

- **Better:** Use subsequent $\Lambda \to p\pi^-$ decay!
  The Λ is polarized by the Ξ^0 asymmetry: $\vec{P}_\Lambda = \alpha_{\Xi^0} \cdot \vec{n}_{\Xi^0}$

- Use $\Lambda \to p\pi^-$ asymmetry α_Λ and
  measure $\cos\boldsymbol{\Theta}_{\boldsymbol{\Lambda}}$ between Ξ^0 and p:



$$\Longrightarrow \quad \frac{\mathbf{dN}}{\cos\boldsymbol{\Theta}_{\boldsymbol{\Lambda}}} \propto \mathbf{1} - \alpha_{\boldsymbol{\Lambda}}\,\alpha_{\boldsymbol{\Xi}^{\mathbf{0}}}\cos\boldsymbol{\Theta}_{\boldsymbol{\Lambda}}$$

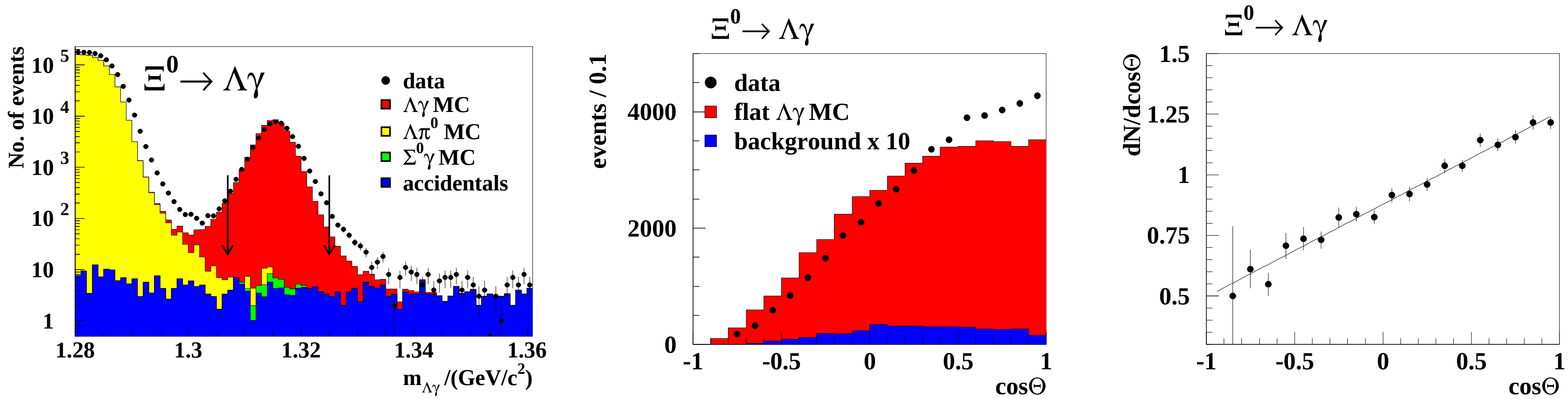
(Independent from Ξ^0 polarisation!)

- $\boldsymbol{\Xi}^{\mathbf{0}} \to \boldsymbol{\Sigma}^{\mathbf{0}}\gamma \to (\boldsymbol{\Lambda}\gamma)\gamma$:
  Build product $\cos\boldsymbol{\Theta}_{\boldsymbol{\Xi}\to\boldsymbol{\Sigma}\gamma} \cdot \cos\boldsymbol{\Theta}_{\boldsymbol{\Sigma}\to\boldsymbol{\Lambda}\gamma}$.

$\Xi^0 \to \Lambda\gamma$ *Decay Asymmetry*

$\Xi^0 \to \Lambda\gamma$ **from NA48/1:** **43814 decay candidates.**

Background: 0.8% ($\Xi^0 \to \Lambda\pi^0$, accid. overlaps)



- Fit result: $\alpha_{\Xi^0\to\Lambda\gamma} \cdot \alpha_{\Lambda\to p\pi} = -0.439 \pm 0.013_{\text{stat}} \pm 0.038_{\text{syst}}$

  (Systematics mainly from energy dependence, trigger efficiency.)

- Use $\alpha_{\Lambda\to p\pi} = 0.642 \pm 0.013$ [PDG]:

(NA48/1 preliminary)

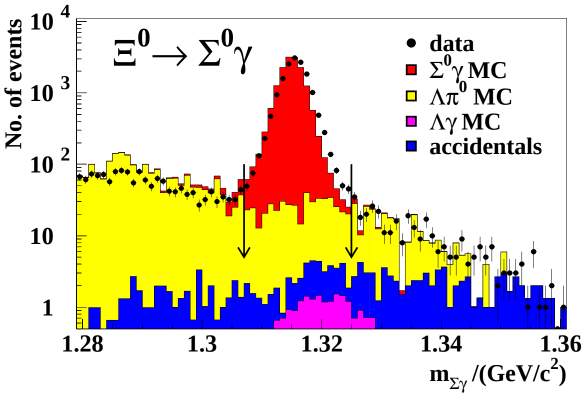
$$\boldsymbol{\alpha_{\Xi^0\to\Lambda\gamma} = -0.684 \pm 0.020_{\text{stat}} \pm 0.061_{\text{syst}}}$$

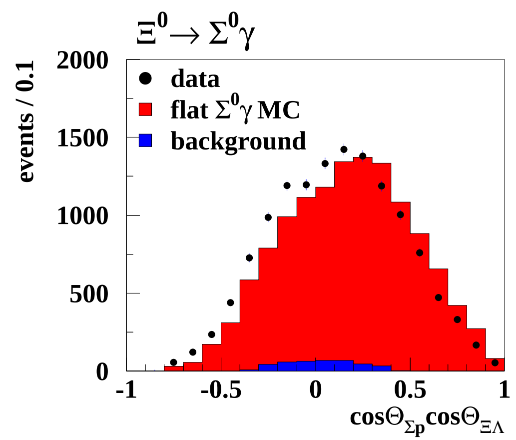
(Previous measurement: $\alpha = -0.78 \pm 0.19$ [NA48, 2003])

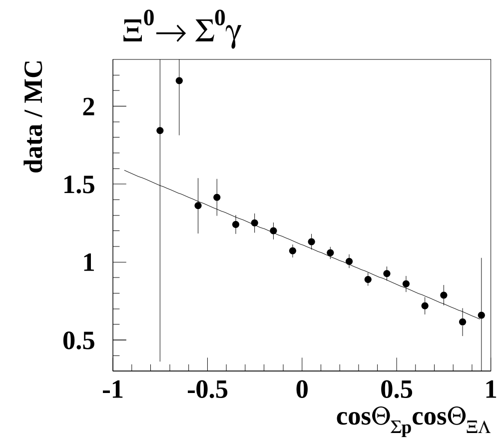
$\Xi^0 \to \Sigma^0\gamma$ *Decay Asymmetry*

$\Xi^0 \to \Sigma^0\gamma$ **from NA48/1:** **13068 decay candidates.**

Background: $\approx 3\%$ (Mainly $\Xi^0 \to \Lambda\pi^0$)







- Fit result: $\alpha_{\Xi^0\to\Sigma^0\gamma} \cdot \alpha_{\Lambda\to p\pi} = -0.438 \pm 0.020_{\text{stat}} \pm 0.041_{\text{syst}}$

  (Again systematics mainly from energy dependence, trigger efficiency.)

- Use $\alpha_{\Lambda\to p\pi} = 0.642 \pm 0.013$ [PDG]:

(NA48/1 preliminary)

$$\alpha_{\Xi^0\to\Sigma^0\gamma} = \mathbf{-0.682 \pm 0.031_{\text{stat}} \pm 0.065_{\text{syst}}}$$

(Previous measurement: $\alpha = -0.63 \pm 0.09$ [KTeV, 2001])

Summary

- **NA48/1 result** on 6316 Ξ^0 β-decay events:

$$\text{Br}(\Xi^0 \to \Sigma^+ e^- \bar{\nu}) = (2.51 \pm 0.03_{\text{stat}} \pm 0.09_{\text{syst}}) \times 10^{-4}$$

- First observations of $\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}$ by **KTeV** and **NA48/1.**
- New very precise **NA48/1** measurement of the Ξ^0 **lifetime:**

$$\tau_{\Xi^0} = (3.082 \pm 0.013 \pm 0.012) \cdot 10^{-10}\ \text{s}$$ *(prel.)*

- Use beta decay and lifetime results for $|V_{us}|$:

$$|V_{us}| = 0.203 \pm 0.005_{\text{exp}}\ {}^{+0.22}_{-0.27}{}_{\text{form factors}}$$ *(prel.)*

- Precise measurements of $\Xi^0 \to \Lambda/\Sigma^0\gamma$ **decay asymmetries:**

$$\alpha_{\Xi^0 \to \Lambda\gamma} = -0.684 \pm 0.020_{\text{stat}} \pm 0.061_{\text{syst}}$$
$$\alpha_{\Xi^0 \to \Sigma^0\gamma} = -0.682 \pm 0.031_{\text{stat}} \pm 0.065_{\text{syst}}$$ *(prel.)*