New Results on Hyperons from NA48/1

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Hyperons

Hyperons – Why?

Hyperon decays are under investigations since more than 50 years.

Why are they still interesting ?

- All interactions (e.m., weak, strong) are involved in hyperon decays
  $\Rightarrow$ Hyperons are a powerful tool to test models
- A lot of their features are still not understood, e.g.
  - Decay asymmetries of non-leptonic and radiative decays
  - Polarization at production in nucleon-nucleon-collisions
- Semileptonic decays allow determination of $|V_{us}|$
  $\Rightarrow$ Check $|V_{us}|$ from kaon decays
- For the first time large data samples ($O(10^4)$ events) of semileptonic and radiative Ξ^0 decays are available (KTeV and NA48)
  $\Rightarrow$ Precise measurements

Hyperons

... still interesting!

Outline

- The NA48 experiment
- Hyperons at NA48/1
- Ξ^0 Lifetime
- Decay asymmetries of $\Xi^0 \to \Lambda\gamma$ and $\Xi^0 \to \Sigma^0\gamma$
- Branching ratios of semileptonic decays and $|V_{us}|$
- Conclusions

The NA48 Experiment

The NA48 Experiments

NA48

1997 ε'/ε run $K_L + K_S$

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1999 ε'/ε run $K_L + K_S$ | K_S Hi. Int.

2000 K_L only | K_S High Intensity | *NO Spectrometer*

2001 ε'/ε run $K_L + K_S$ | K_S High Int.

⇒ direct CP-violation in neutral kaons, K_L and K_S decays

NA48/1

2002 K_S High Intensity

⇒ rare K_S and neutral hyperon decays

this talk

NA48/2

2003 $K^{\pm}$ High Intensity

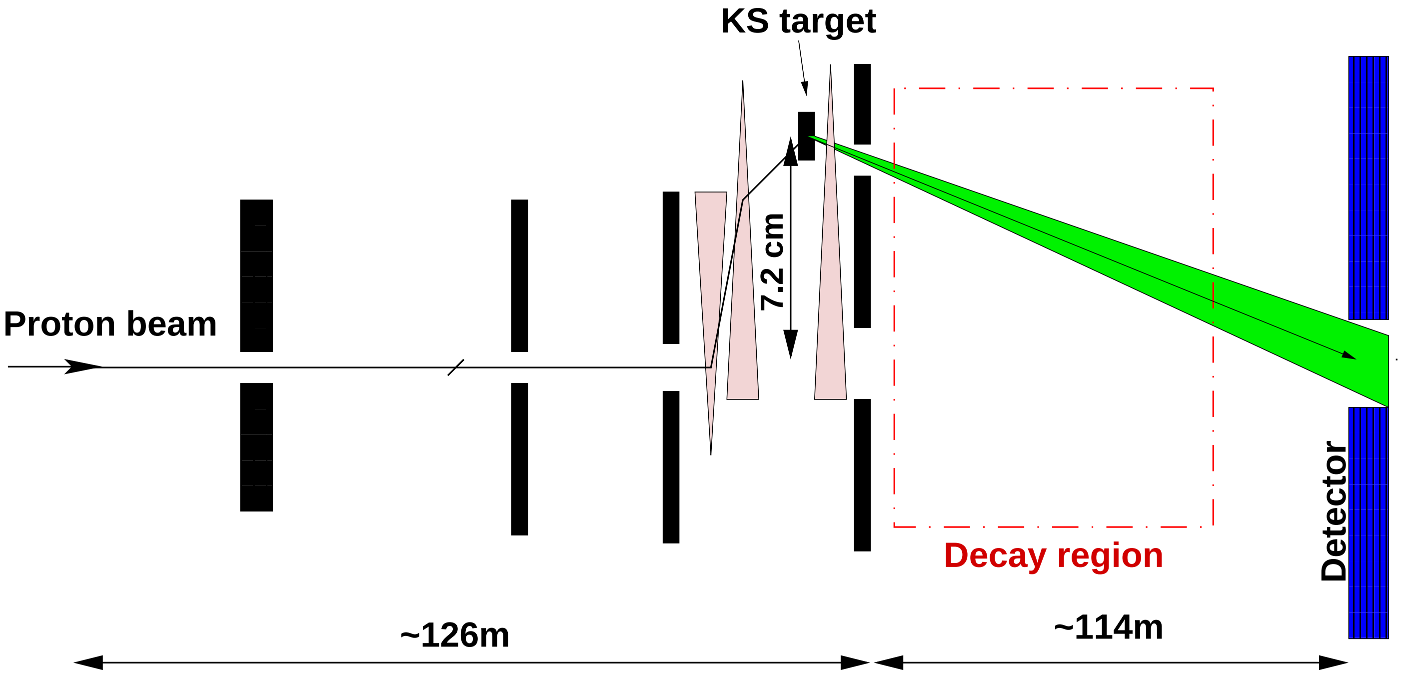
2004 $K^{\pm}$ High Intensity

⇒ charged kaon decays

previous talks

The NA48/1 Experiment in 2002

- 80 days data taking with $\sim 200\times$ intensity of ε'/ε runs
- Neutral beam: mainly kaons and hyperons (Ξ^0 and Λ)
- Total flux: $3.5 \cdot 10^{10}\ K_S$ and $2.4 \cdot 10^{9}\ \Xi^0$ in decay region
- Production angle: -4.2 mrad $\Rightarrow$ polarized hyperons! ($\sim 10\%$ polarization)



The NA48 Detector

- **Magnet spectrometer**

  with 4 drift chambers

  $$\frac{\sigma(p)}{p} = 0.48\% \oplus 0.015p \quad (p \text{ in GeV/c})$$

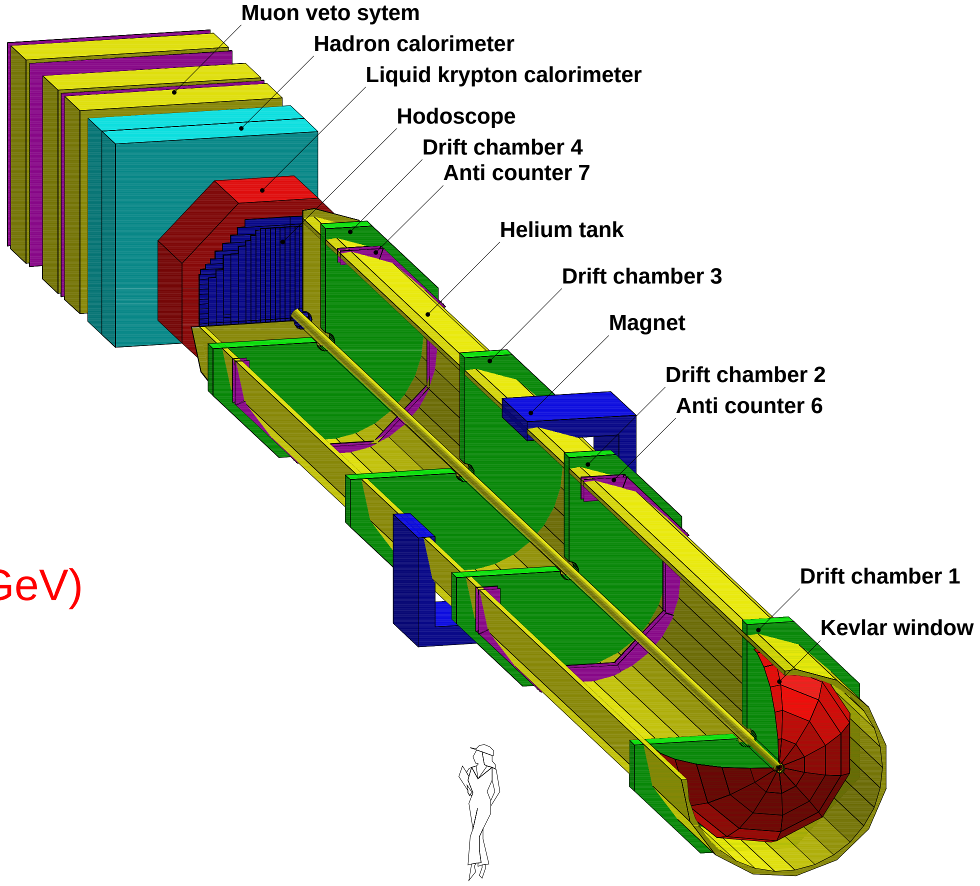
- **Liquid Krypton Calorimeter**

  with ~ 13300 cells

  $$\frac{\sigma(E)}{E} = \frac{3.2\%}{\sqrt{E}} \oplus \frac{9\%}{E} \oplus 0.42\% \quad (E \text{ in GeV})$$

- **Scintillator hodoscope**

  $\sigma(t) \approx 200$ ps



Hyperon Decays at NA48/1

- Only the neutral hyperons Ξ^0 and Λ can reach the decay region
  $(\tau_{\Xi^0}, \tau_\Lambda \approx \tau_{K_S})$

decay	events	analyses (presented here)
Non-leptonic and radiative Ξ^0 decays:		
$\Xi^0 \to \Lambda\pi^0$	$3 \cdot 10^6$	lifetime, mass, decay asymmetry
$\Xi^0 \to \Lambda\gamma$	$44 \cdot 10^3$	BR, decay asymmetry
$\Xi^0 \to \Sigma^0\gamma$	$13 \cdot 10^3$	BR, decay asymmetry
Semileptonic Ξ^0 decays:		
$\Xi^0 \to \Sigma^+ e^- \overline{\nu}_e$	$6.2 \cdot 10^3$	BR, form factors
$\Xi^0 \to \Sigma^+ \mu^- \overline{\nu}_\mu$	99	BR
Rare Ξ^0 decays:		
$\Xi^0 \to \Lambda e^+ e^-$	$O(10^2)$	first measurement
$\Xi^0 \to p\pi^-$	?	search

Typical signature of hyperon decays

- **Non-leptonic and radiative Ξ^0 decays:**
  - $\Xi^0 \rightarrow \Lambda\pi^0$ with $\pi^0 \rightarrow \gamma\gamma$
  - $\Xi^0 \rightarrow \Lambda\gamma$
  - $\Xi^0 \rightarrow \Sigma^0\gamma$ with $\Sigma^0 \rightarrow \Lambda\gamma$

  (first two) $\} \Rightarrow$ always one Λ and one or two photons

  - photon = cluster in LKr without associated track in spectrometer
  - Λ is identified via the decay $\Lambda \rightarrow p\pi^-$

- **Semileptonic Ξ^0 decays:**
  - $\Xi^0 \rightarrow \Sigma^+ e^- \overline{\nu}_e$
  - $\Xi^0 \rightarrow \Sigma^+ \mu^- \overline{\nu}_\mu$

  $\} \Rightarrow$ always one Σ^+ and a charged lepton

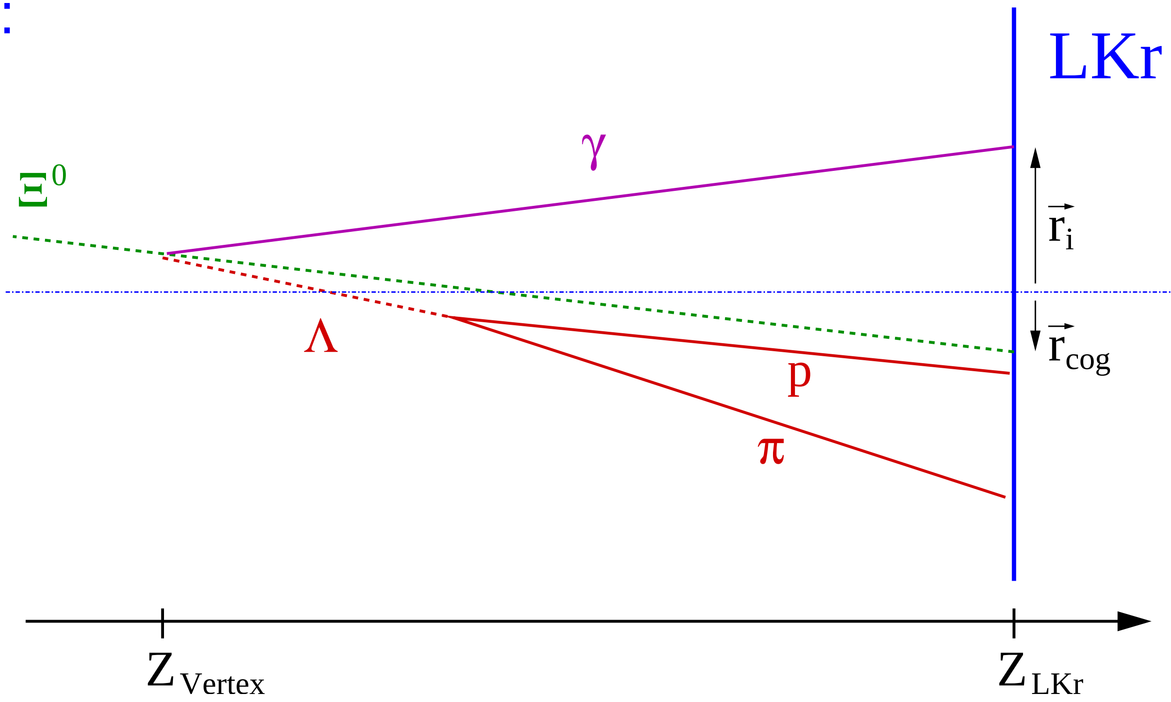
  - Σ^+ is identified via the decay $\Sigma^+ \rightarrow p\pi^0$ and $\pi^0 \rightarrow \gamma\gamma$

$\Rightarrow$ All decays: 2 charged particles (spectrometer) + 1 or 2 photons (LKr)

Reconstruction of Hyperon Decays

- Reconstruction of $\Lambda \rightarrow p\pi^-$ (mass, decay vertex, line of flight, ...) is straightforward due to known momenta $\vec{p}_p$, $\vec{p}_{\pi^-}$ from spectrometer
- Photons: only energies and positions in LKr are known

⇒ Reconstruction of Ξ^0 decay:



- Build Ξ^0 line of flight with target and center of gravity

$$\vec{r}_{cog} = \frac{\sum E_i \vec{r}_i}{\sum E_i}$$

- Ξ^0 + Λ line of flight ⇒ Ξ^0 decay vertex
- Ξ^0 decay vertex + positions in LKr ⇒ full momenta $\vec{p}_\gamma$

Ξ^0 Lifetime

Ξ^0 Lifetime – Motivation

Motivation:

- Last and best measurement 1977 with 6300 events.

  $\Rightarrow$ **Current accuracy only 3%**

  (PDG average $\tau_{\Xi^0,PDG} = (2.90 \pm 0.09) \cdot 10^{-10}$ s)

- Direct input for other measurements:

  e.g. $|V_{us}|$ from semilep. Ξ^0 decays

- Indirect input for all Ξ^0 measurements :

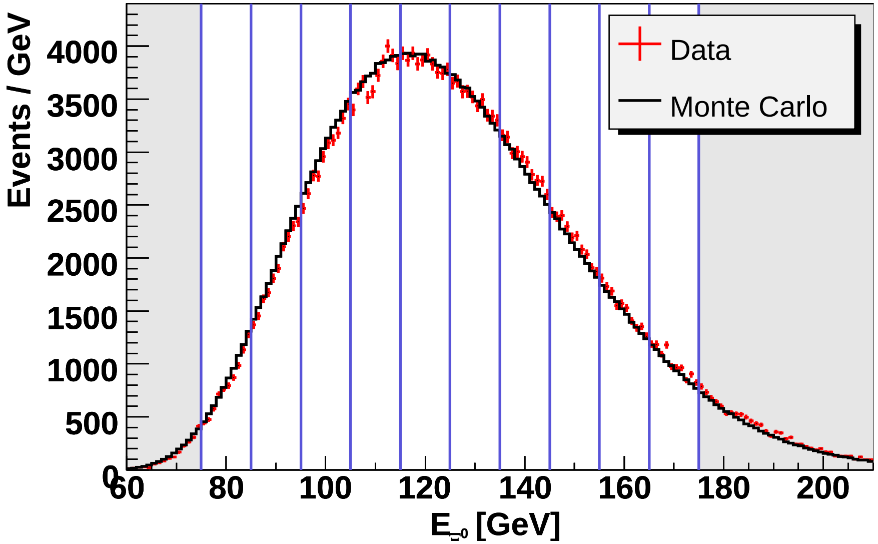
  e.g. detector simulation

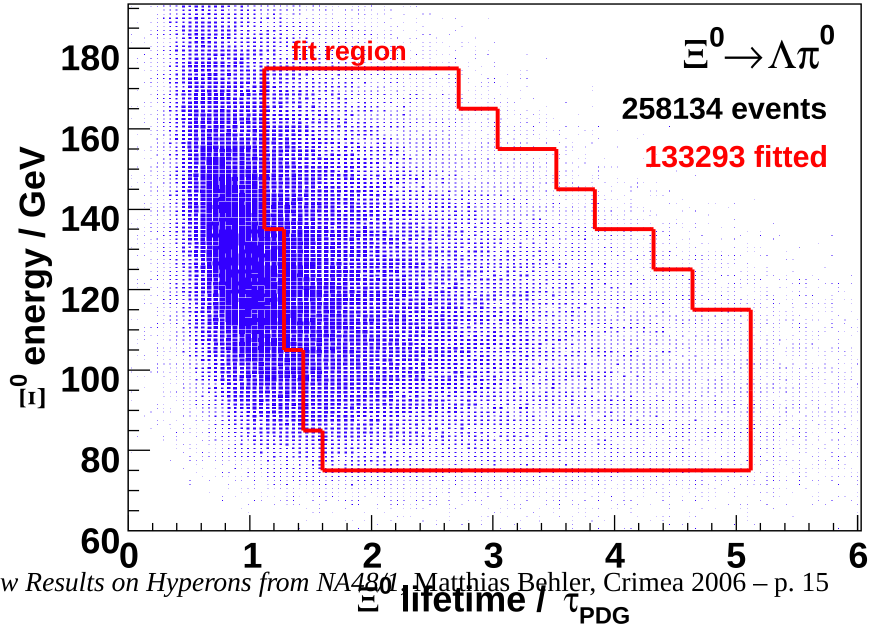
$\Rightarrow$ **Better measurement needed**

Ξ^0 Lifetime – Measurement

NA48/1 Measurement:

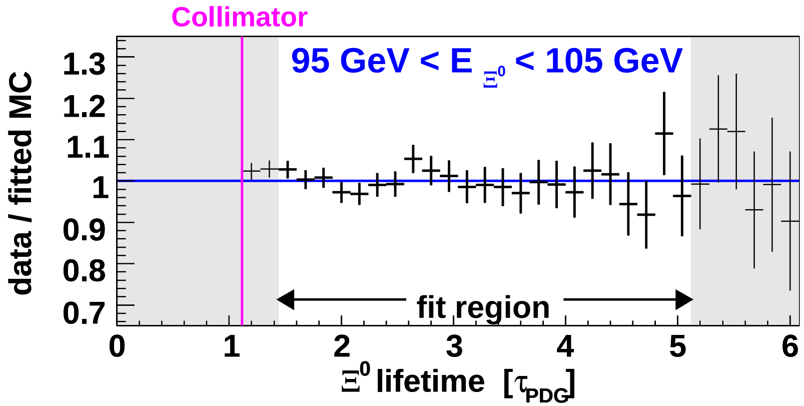
- *Minimum bias* trigger
  (very efficient: $\varepsilon_{L1} = (99.56 \pm 0.02)\%$, but down scaled)
- $\sim$ 260,000 $\Xi^0 \to \Lambda\pi^0$ decays
  with $\lesssim 0.1\%$ background
- Analysis in 10 energy bins,
  simultaneous fit to all energy bins
- Fit region well separated from final collimator

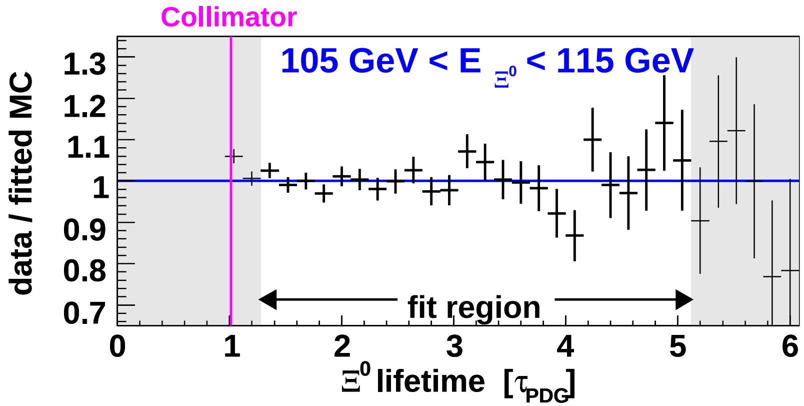


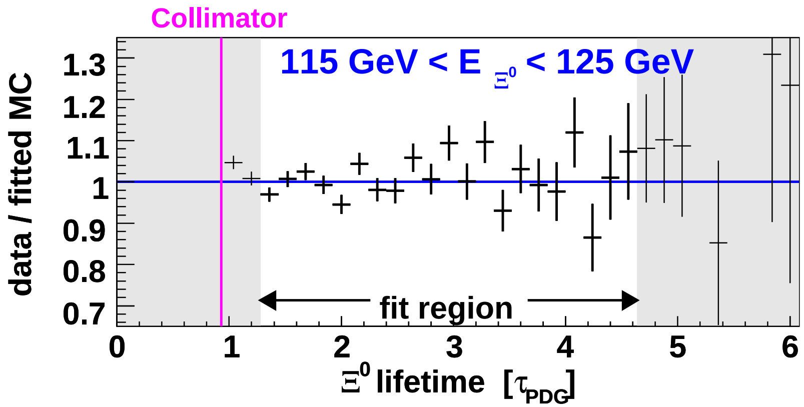


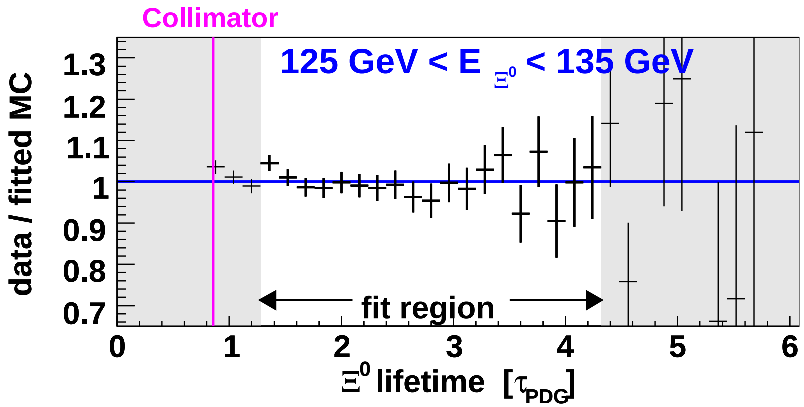
Ξ^0 Lifetime – Fit

- MC with $\tau_{PDG} = (2.90 \pm 0.09) \cdot 10^{-10}$ s is used for the fit:







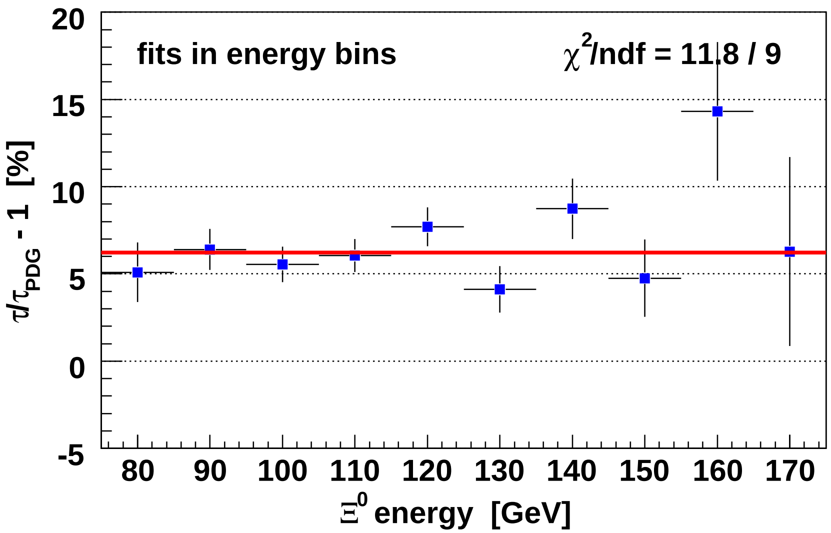


$$\Rightarrow \quad \boxed{\frac{\tau_{data}}{\tau_{PDG}} = 1.0626 \pm 0.0044_{stat} \pm 0.0043_{syst}}$$

Ξ^0 Lifetime – Systematic Checks

- **Several systematic checks were performed:**

10 single fits are in good agreement with the global fit:



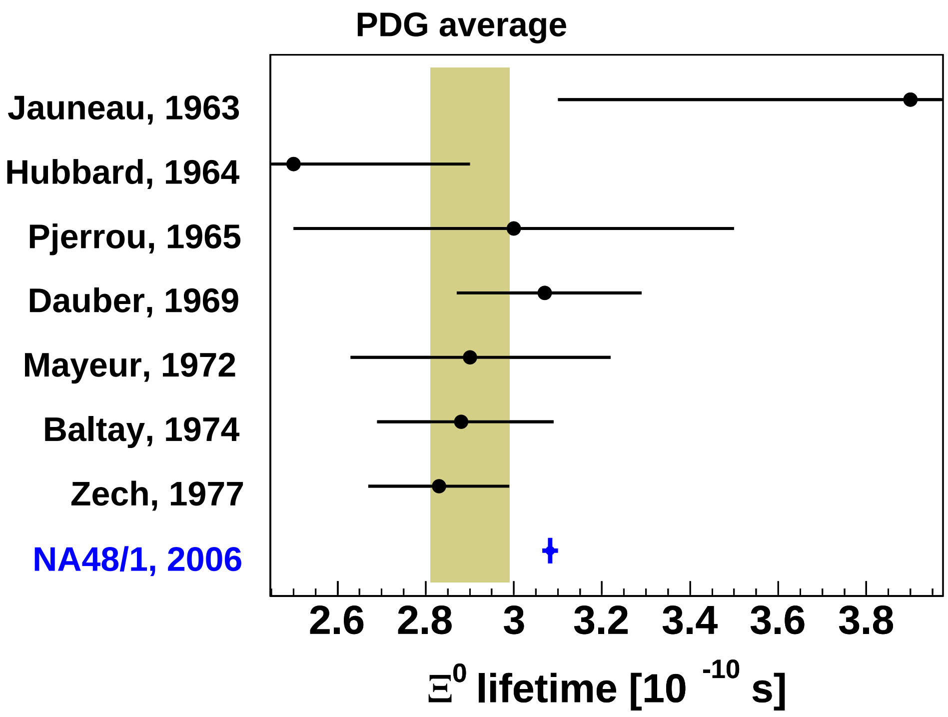
Source	$\Delta_{syst}/\tau_{PDG}(\%)$
Detector acceptance	±0.30
Vertex resolution	±0.08
Energy scale	±0.14
Energy non-linearities	±0.09
Ξ^0 polarization	±0.15
Ξ^0 mass	±0.20
Λ lifetime	±0.04
Total systematics	±0.43
Statistical uncertainty	±0.44

Ξ^0 Lifetime – Result

- Our result: $$\frac{\tau_{data}}{\tau_{PDG}} = 1.0626 \pm 0.0044_{stat} \pm 0.0043_{syst}$$

NA48 preliminary

$$\Rightarrow \quad \tau_{\Xi^0} = (3.082 \pm 0.013_{stat} \pm 0.012_{syst}) \cdot 10^{-10}\ \text{s.}$$



$\sim 2\sigma$ above the PDG average

5 × smaller uncertainty

Decay Asymmetries

Decay Asymmetry

Decay asymmetry α:

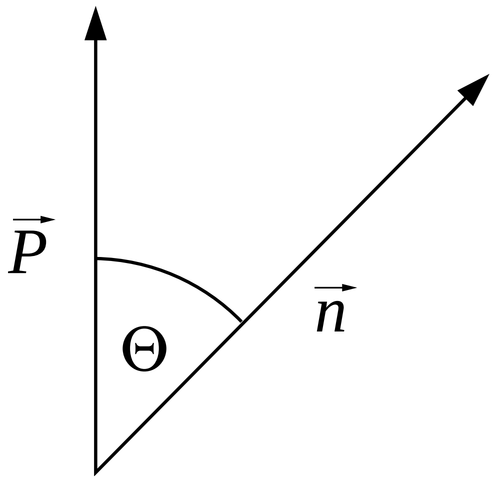
- Two possible final states allowed for non-leptonic and radiative hyperon decays: a s-wave ($l = 0$) and a p-wave ($l = 1$)
    - Decays asymmetry due to interference of both amplitudes A_s and A_p:

$$\alpha = \frac{2\Re(A_s A_p^*)}{|A_s|^2 + |A_p|^2}$$

    - Angular distribution :

$$\frac{dN}{d\cos\Theta} \propto \ 1 + \alpha\vec{P} \cdot \vec{n} = 1 + \alpha|\vec{P}|\cos\Theta$$

$\vec{P}$: initial polarization,
$\vec{n}$: outgoing baryon direction



Decay Asymmetry – Theory

- First prediction of decay asymmetries for radiative decays by Hara (*Hara-theorem, 1964*)
  - α of $\Sigma^+ \to p\gamma$ and $\Xi^- \to \Sigma^-\gamma$ should vanish in exact $SU(3)_f$
  - Measured: $\alpha_{\Sigma^+ \to p\gamma} = -0.76 \pm 0.08$ [PDG])

$\Rightarrow$ Conflict between Hara-theorem and experimental data unsolved

- Many theoretical models: pole-models, quark-models, VMD, ...
- But none can explain all decays (BR, asymmetries) simultaneously

Sign of α	$\Sigma^+ \to p\gamma$	$\Lambda \to n\gamma$	$\Xi^0 \to \Lambda\gamma$	$\Xi^0 \to \Sigma^0\gamma$
Pole models	$-$	$-$	$-$	$-$
Quark models, VMD	$-$	$+$	$+$	$-$

- **$\boldsymbol{\Xi^0 \to \Lambda\gamma}$ asymmetry provides a good test**

Decay Asymmetry – $\Xi^0 \rightarrow \Lambda\gamma$

- Could use $\frac{dN}{d\cos\Theta} \propto \ 1 + \alpha|\vec{P}|\cos\Theta$ to measure the asymmetry α but the Ξ^0 polarization is small ($\sim 10\%$)
- More sensitivity using the Ξ^0 and Λ decay:

⇒ **For $\Xi^0 \rightarrow \Lambda\gamma$:**

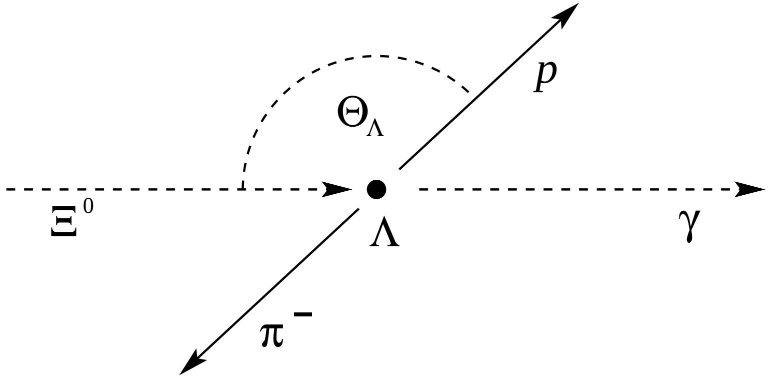
- In the Λ rest frame the Λ is polarized by the Ξ^0 asymmetry :

  $\vec{P}_\Lambda = \alpha_{\Xi^0}\vec{n}_{\Xi^0}$

- Using the $\Lambda \rightarrow p\pi^-$ asymmetry

  $\frac{dN}{d\cos\Theta} \propto \ 1 + \alpha_\Lambda\vec{P}\cdot\vec{n}_p$

  one finds

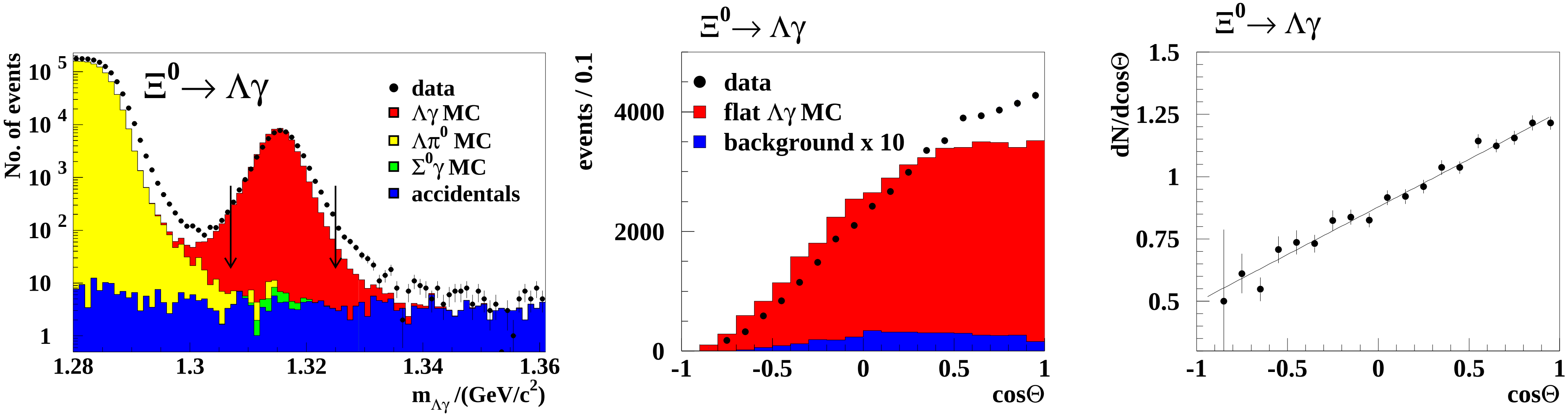


$$\boxed{\frac{dN}{d\cos\Theta_\Lambda} \propto \ 1 - \alpha_\Lambda\alpha_{\Xi^0}\cos\Theta_\Lambda}$$

(Also valid in case of polarized Ξ^0s)

Decay Asymmetry – $\Xi^0 \rightarrow \Lambda\gamma$ Result

- **43814 $\Xi^0 \rightarrow \Lambda\gamma$ candidates with 0.8% background:**



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

- With $\alpha_{\Lambda\rightarrow p\pi^-} = 0.642 \pm 0.013$ [PDG]:

$$\Rightarrow \boxed{\alpha_{\Xi^0\rightarrow\Lambda\gamma} = -0.684 \pm 0.020_{stat} \pm 0.061_{syst}}$$

NA48 preliminary

(NA48, testrun 1999, with 730 events: $\alpha_{\Xi^0\rightarrow\Lambda\gamma} = -0.78 \pm 0.19$)

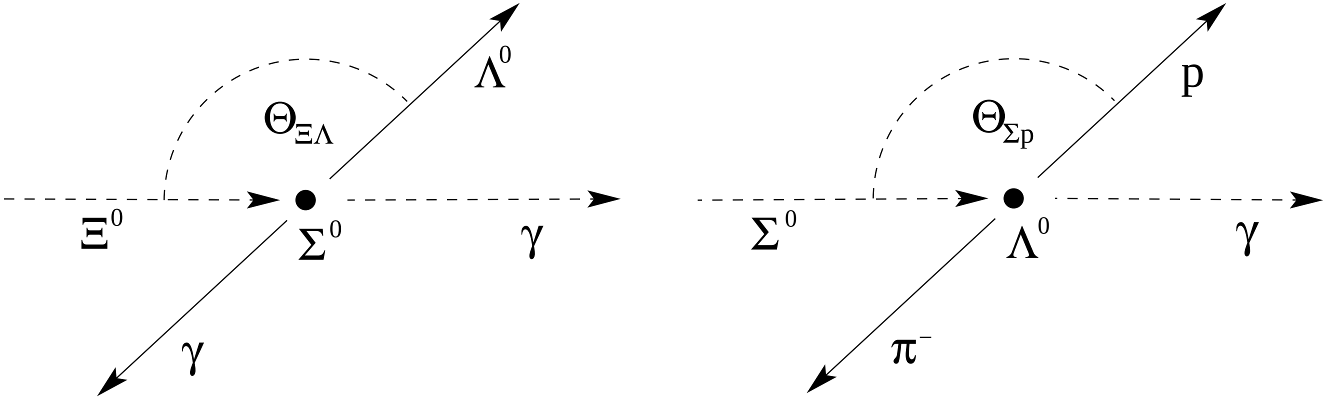
Decay Asymmetry – $\Xi^0 \to \Sigma^0\gamma$

⇒ **For $\Xi^0 \to \Sigma^0\gamma$:**

- Same method as for $\Xi^0 \to \Lambda\gamma$, but one additional decay: $\Sigma^0 \to \Lambda\gamma$

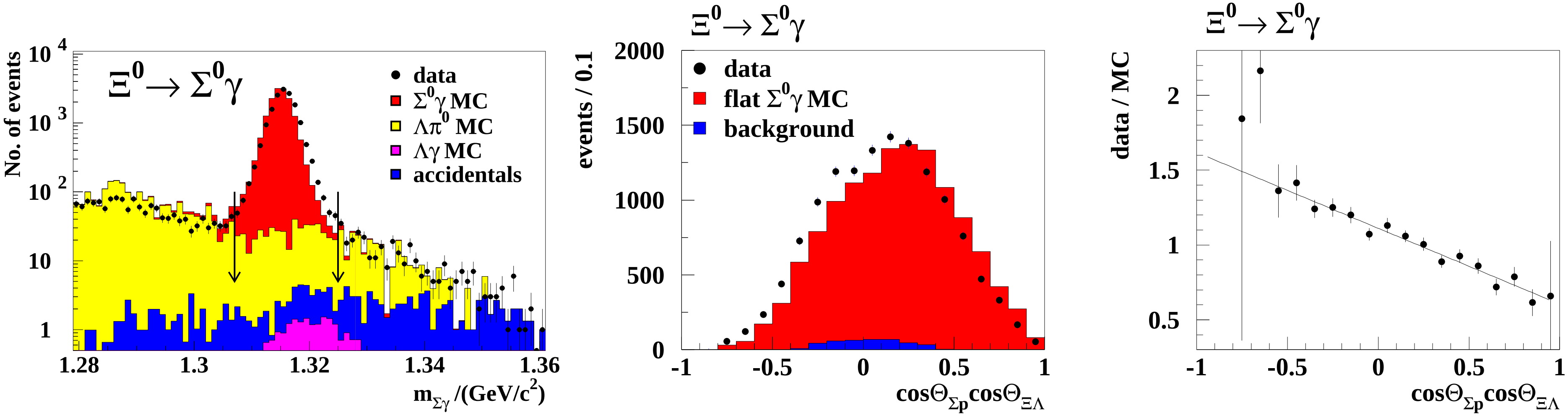
  ⇒ Two decay angles to describe the full cascade:

$$\boxed{\frac{\mathrm{d}^2 N}{\mathrm{d}\cos\Theta_{\Xi\Lambda}\,\mathrm{d}\cos\Theta_{\Sigma p}} \propto 1 + \alpha_{\Xi^0\to\Sigma^0\gamma}\alpha_{\Lambda\to p\pi^-}\cos\Theta_{\Xi\Lambda}\cos\Theta_{\Sigma p}}$$



Decay Asymmetry – $\Xi^0 \rightarrow \Sigma^0\gamma$ Result

- **13068 $\Xi^0 \rightarrow \Sigma^0\gamma$ candidates with $\approx 3\%$ background:**



- Fit:

$$\boxed{\alpha_{\Xi^0\rightarrow\Sigma^0\gamma}\cdot\alpha_{\Lambda\rightarrow p\pi^-} = -0.438 \pm 0.020_{stat} \pm 0.041_{syst}}$$

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$$\Rightarrow \quad \boxed{\alpha_{\Xi^0\rightarrow\Sigma^0\gamma} = -0.682 \pm 0.031_{stat} \pm 0.065_{syst}}$$

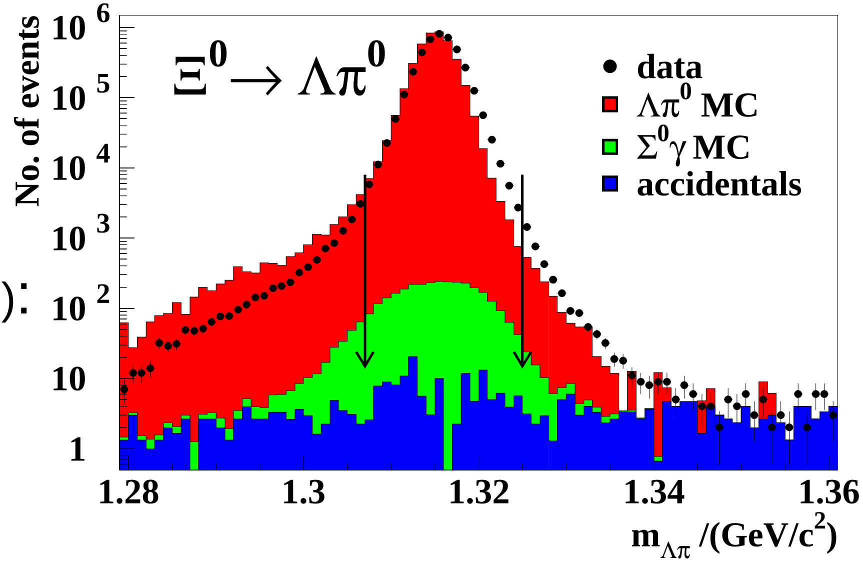
(KTeV, 2001, with 4045 events: $\alpha_{\Xi^0\rightarrow\Sigma^0\gamma} = -0.63 \pm 0.09$)

Decay Asymmetry – $\Xi^0 \rightarrow \Lambda\pi^0$

Important cross check for systematic uncertainties:

- Measurement of the well known $\Xi^0 \rightarrow \Lambda\pi^0$ asymmetry ($\alpha_{\Xi^0\rightarrow\Lambda\pi^0} = -0.411 \pm 0.022$ [PDG])
  - $3 \cdot 10^6$ $\Xi^0 \rightarrow \Lambda\pi^0$ candidates with 0.1% background:
  - Angular distribution (similar to $\Xi^0 \rightarrow \Lambda\gamma$):

$$\boxed{\frac{dN}{d\cos\Theta} \propto 1 + \alpha_\Lambda \alpha_{\Xi^0} \cos\Theta_\Lambda}$$



  - Fit:

$$\boxed{\alpha_{\Xi^0\rightarrow\Lambda\pi^0} \cdot \alpha_{\Lambda\rightarrow p\pi^-} = -0.282 \pm 0.003_{stat} \pm 0.028_{sys}}$$

NA48 preliminary

$$\Rightarrow \boxed{\alpha_{\Xi^0\rightarrow\Lambda\pi^0} = -0.439 \pm 0.004_{stat} \pm 0.045_{syst}}$$

Decay Asymmetries – Systematic Checks

- **Other checks and uncertainties:**

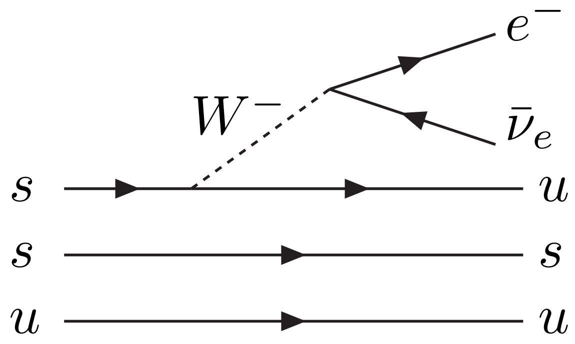
	$\Delta(\alpha_\Xi \alpha_\Lambda)$		
	$\Xi \to \Lambda\gamma$	$\Xi \to \Sigma^0\gamma$	$\Xi \to \Lambda\pi^0$
Trigger eff.	0.016	0.024	0.001
Ξ^0 polarization	—	—	0.002
Detector geometry / selection	0.021	0.021	0.012
Ξ^0 energy dependence	0.025	0.025	0.025
Ξ^0 mass	0.011	0.004	0.005
Ξ^0 lifetime	0.001	0.007	0.003
$\Lambda\pi^0$ background	0.001	—	—
Total systematics	0.038	0.041	0.028
Statistical error (data+MC)	0.013	0.020	0.003

Semileptonic Decays

Semileptonic Decays

- $\Xi^0 \to \Sigma^+ e^- \overline{\nu}_e$ decay similar to neutron β-decay ($SU(3)_f$)

  $\Rightarrow$ Check $SU(3)_f$ breaking



- Semileptonic decay allows determination of $|V_{us}|$

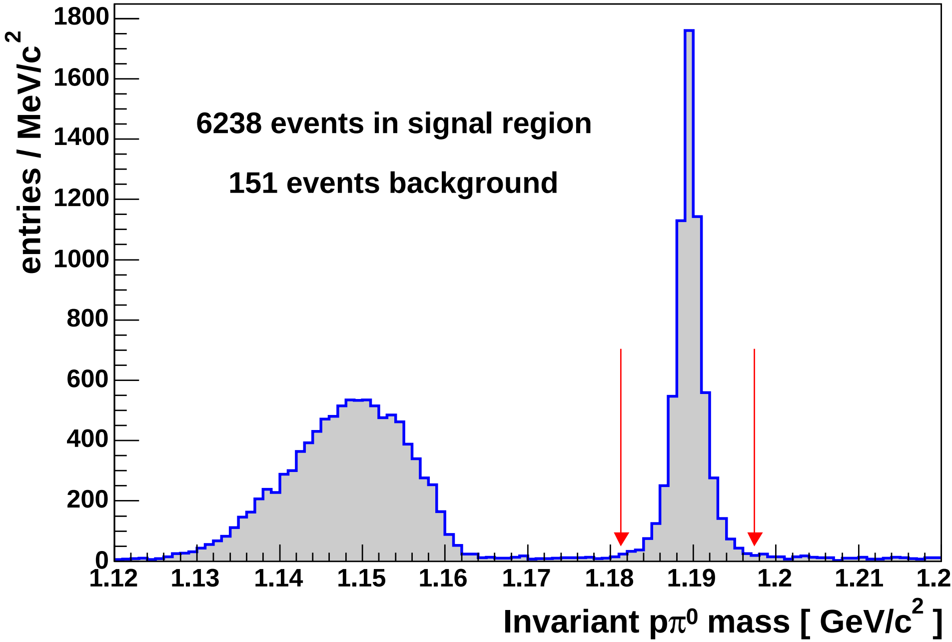
  $\Rightarrow$ Decay rate

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

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

Semileptonic Decays – $\Xi^0 \to \Sigma^+ e^- \overline{\nu}_e$

- Identification of semileptonic decays via $\Sigma^+ \to p\pi^0$ and a charged lepton
- $\Xi^0 \to \Sigma^+ e^- \overline{\nu}_e$:
  - **6238 candidates with 2.4% background**
  - Normalization channel: $\Xi^0 \to \Lambda\pi^0$



6238 events in signal region

151 events background

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$$\Rightarrow \quad \boxed{BR(\Xi^0 \to \Sigma^+ e^- \overline{\nu}_e) = (2.51 \pm 0.03_{stat} \pm 0.11_{syst}) \cdot 10^{-4}}$$

(KTeV, 1999, with 176 events: $BR(\Xi^0 \to \Sigma^+ e^- \overline{\nu}_e) = (2.7 \pm 0.4) \cdot 10^{-4}$)

Semileptonic Decays – $|\mathrm{V}_{\mathrm{us}}|$

- $|\mathrm{V}_{\mathrm{us}}|$ **from** $\Xi^0 \rightarrow \Sigma^+ \mathrm{e}^- \overline{\nu}_{\mathrm{e}}$**:**

$$\boxed{|V_{us}| = 0.214 \pm 0.006_{exp} \; {}^{+0.030}_{-0.025}{}_{\,syst}}$$

NA48 preliminary

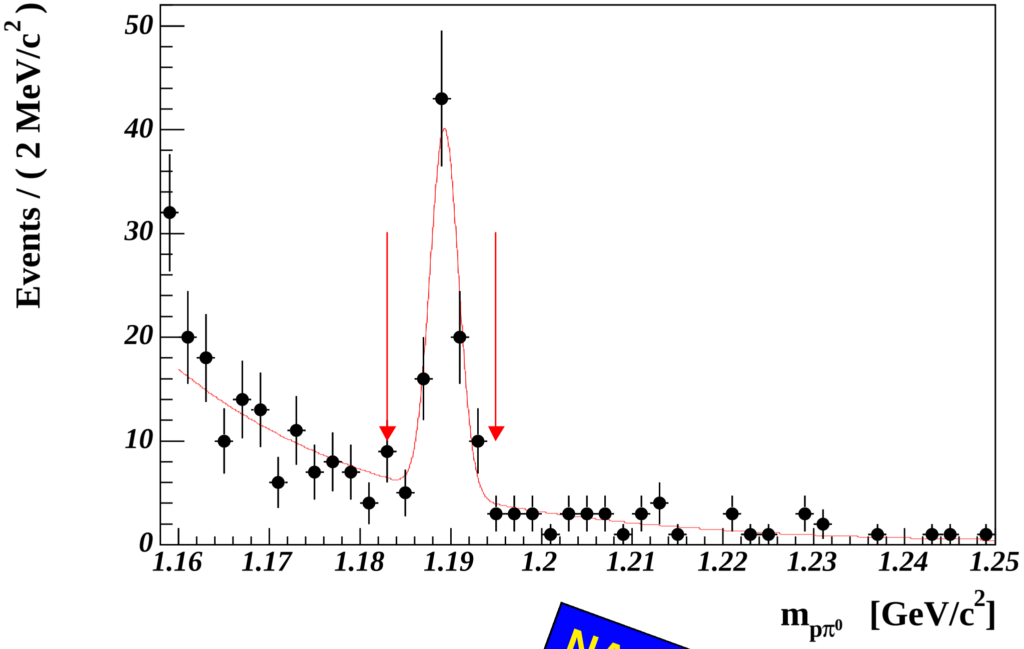
Systematic uncertainties dominated by form factor

$$\frac{g_1}{f_1} = 1.32^{+0.21}_{-0.17} \pm 0.05$$

(from kaon decays [PDG]: $|V_{us}| = 0.2257 \pm 0.0021$)

Semileptonic Decays – $\Xi^0 \rightarrow \Sigma^+\mu^-\overline{\nu}_\mu$

- $\mathbf{\Xi^0} \rightarrow \Sigma^+\mu^-\overline{\nu}_\mu$:
  - 99 candidates with 31% background
  - Normalization channel: $\Xi^0 \rightarrow \Sigma^+e^-\overline{\nu}_e$



$$\Rightarrow \quad \boxed{BR(\Xi^0 \rightarrow \Sigma^+\mu^-\overline{\nu}_\mu) = (2.2 \pm 0.3_{stat} \pm 0.2_{syst}) \cdot 10^{-6}}$$

(KTeV, 2005, with 9 events: $BR(\Xi^0 \rightarrow \Sigma^+\mu^-\overline{\nu}_\mu) = (4.9^{+2.1}_{-1.6}) \cdot 10^{-6}$)

Conclusions

- Decay asymmetries of $\Xi^0 \rightarrow \Lambda\gamma$ and $\Xi^0 \rightarrow \Sigma^0\gamma$:

$$\boxed{\alpha_{\Xi^0 \rightarrow \Lambda\gamma} = -0.684 \pm 0.020_{stat} \pm 0.061_{syst}}$$

$$\boxed{\alpha_{\Xi^0 \rightarrow \Sigma^0\gamma} = -0.682 \pm 0.031_{stat} \pm 0.065_{syst}}$$

- Ξ^0 lifetime:

$$\boxed{\tau_{\Xi^0} = (3.082 \pm 0.013_{stat} \pm 0.012_{syst}) \cdot 10^{-10} \text{ s.}}$$

- Branching ratios of semileptonic Ξ^0 decays:

$$\boxed{BR(\Xi^0 \rightarrow \Sigma^+ e^- \overline{\nu}_e) = (2.51 \pm 0.03_{stat} \pm 0.11_{syst}) \cdot 10^{-4}}$$

$$\boxed{BR(\Xi^0 \rightarrow \Sigma^+ \mu^- \overline{\nu}_\mu) = (2.2 \pm 0.3_{stat} \pm 0.2_{syst}) \cdot 10^{-6}}$$

- Several other measurements are in progress