Hyperon nonleptonic decays in χPT, revisited

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Nonleptonic decays

Transition amplitude

$$\mathcal{M}(B_i \to B_f \pi) = G_F m_{\pi^+}^2 \bar{u}_f (A^{(S)} + A^{(P)} \gamma_5) u_i$$

Dimensionless l-wave amplitudes

$$\text{parity-violating: } A^{(S)} \equiv S$$

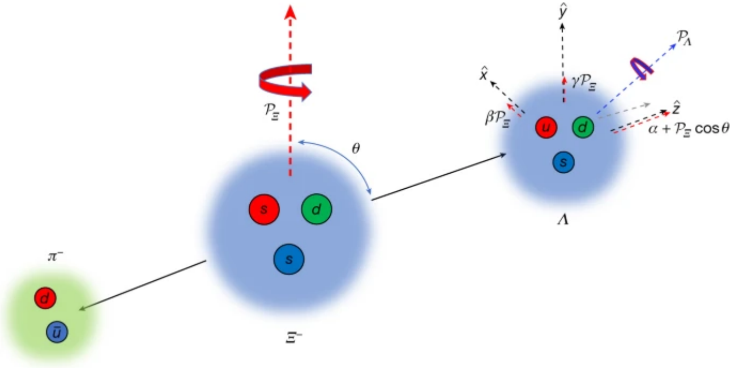
$$\text{parity-conserving: } A^{(P)} \equiv \frac{|\vec{\mathbf{p}}_f|}{E_f + m_f} P$$

Decay observables

$$\alpha = \frac{2\Re(S^* P)}{|S|^2 + |P|^2} \qquad \beta = \frac{2\Im(S^* P)}{|S|^2 + |P|^2} = \sqrt{1 - \alpha^2} \sin\phi$$

$$\Gamma = \text{kin}(|\vec{\mathbf{p}}_f|, E_f, m_f)(|S|^2 + |P|^2)$$

Baryon polarization



$\Xi^- \to \Lambda(\to p\pi^-)\pi^-$ decay [Nature 606, 6469 (2022)]

Produced $B(\bar{B})$ at e^+e^- colliders (e.g. BESIII) are **inherently** polarized.

$$\mathbf{P}_\Lambda \cdot \hat{\mathbf{z}} = \frac{\alpha_\Xi + \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}}{1 + \alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}}, \qquad \mathbf{P}_\Lambda \times \hat{\mathbf{z}} = |P_\Xi|\sqrt{1-\alpha_\Xi^2}\,\frac{\sin\phi_\Xi \hat{\mathbf{x}} + \cos\phi_\Xi \hat{\mathbf{y}}}{1 + \alpha_\Xi \mathbf{P}_\Xi \cdot \hat{\mathbf{z}}},$$

Motivation: new data landscape

nature physics

LETTERS

https://doi.org/10.1038/s41567-019-0494-8

Polarization and entanglement in baryon–antibaryon pair production in electron–positron annihilation

The BESIII Collaboration*

[Nature Phys. 15, 631 (2019)]

Article | Open Access | Published: 01 June 2022

Probing CP symmetry and weak phases with entang double-strange baryons

The BESIII Collaboration

Nature **606**, 64–69 (2022) | Cite this article

11k Accesses | **7** Citations | **96** Altmetric | Metrics

[Nature 606, 6469 (2022)]

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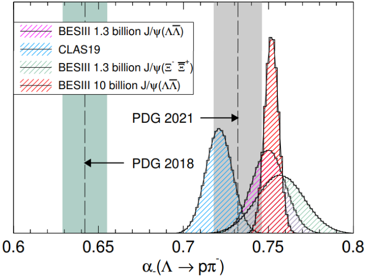
Precise Measurements of Decay Parameters and *CP* Asymmetry with Entangled Λ–$\bar{\Lambda}$ Pairs

M. Ablikim *et al.* (BESIII Collaboration)

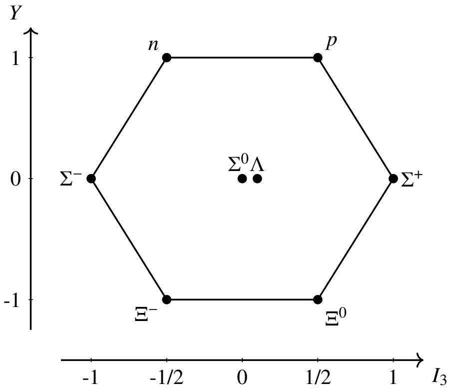
Phys. Rev. Lett. **129**, 131801 – Published 22 September 2022

[Phys.Rev.Lett. 129, 131801 (2022)]



Subject of study

- $\Delta S = 1$ transitions:
  - $\Sigma^+ \to n\pi^+$
  - $\Sigma^- \to n\pi^-$
  - $\Lambda \to p\pi^-$
  - $\Xi^- \to \Lambda\pi^-$



$$\sqrt{2}A(\Sigma^+ \to p\pi^0) - A(\Sigma^+ \to n\pi^+) + A(\Sigma^- \to n\pi^-) = 0$$

$$A(\Lambda \to p\pi^-) + \sqrt{2}A(\Lambda \to n\pi^0) = 0$$

$$A(\Xi^- \to \Lambda\pi^-) + \sqrt{2}A(\Xi^0 \to \Lambda\pi^0) = 0$$

Measurable parameters

Summary of nonleptonic hyperon decays properties [PRD105, 116022 (2022)]

	$\mathcal{B}$	α	ϕ [rad]	Γ [$G_F^2 m_{\pi^+}^4$GeV]
$\Sigma^+ \to n\pi^+$	48%	0.068(13)	2.91(35)	0.0769(02)
$\Sigma^+ \to p\pi^0$	52%	−0.994(04)	0.63(59)	0.0821(02)
$\Sigma^- \to n\pi^-$	100%	−0.068(08)	0.17(26)	0.0861(01)
$\Lambda \to p\pi^-$	64%	0.755(03)	−0.113(61)	0.0310(02)
$\Lambda \to n\pi^0$	36%	0.692(17)	−−	0.0174(01)
$\Xi^- \to \Lambda\pi^-$	100%	−0.379(04)	−0.042(16)	0.0778(01)
$\Xi^0 \to \Lambda\pi^0$	100%	−0.345(08)	0.36(21)	0.0438(01)

Next step

Use α, γ, Γ data to extrapolate updated experimental L-wave amplitude values.

Extrapolate data points

L-wave amplitude extraction: assuming CP conservation, $\Delta I = 1/2$

$$L = \sum_j L_j \exp(i\delta_j^L), \;\; j \in \{2\Delta I, 2I\}$$

and final-interaction phase shifts [PRD105, 116022 (2022)]

	$\lvert\mathbf{q}\rvert$ [MeV/c]	δ_1^S [°]	δ_3^S [°]	δ_1^P [°]	δ_3^P [°]
$\Lambda \to N\pi$	103	6.52(9)	−4.60(7)	−0.79(8)	−0.75(4)
$\Sigma \to N\pi$	190	9.98(23)	−10.70(13)	−0.04(33)	−3.27(15)

Relative sign between amplitudes fixed by Lee-Sugawara relation

$$\frac{3}{\sqrt{6}} A^{(S)}(\Sigma^- \to n\pi^-) + A^{(S)}(\Lambda \to p\pi^-) + 2A^{(S)}(\Xi^- \to \Lambda\pi^-) = 0$$

Extrapolate data points

New reference values extracted from data compared to [NPB 375 (1992)]:

aditionalForm=

	S_{comp}	S_{real}	S_{Jenkins}	P_{comp}	P_{real}	P_{Jenkins}
$\Sigma^+ \to n\pi^+$	$0.09 + 0.24\,i$	0.06	0.06	$1.70 + 0.00\,i$	1.81	1.81
$\Sigma^+ \to p\pi^0$	$-1.37 + 0.08\,i$	−1.38	−1.43	$1.25 - 0.00\,i$	1.24	1.17
$\Sigma^- \to n\pi^-$	$1.85 - 0.35\,i$	1.88	1.88	$-0.06 + 0.00\,i$	−0.06	−0.06
$\Lambda \to p\pi^-$	$1.36 + 0.16\,i$	1.38	1.42	$0.63 - 0.01\,i$	0.63	0.52
$\Lambda \to n\pi^0$	$-1.02 - 0.12\,i$	−1.03	−1.04	$-0.42 + 0.01\,i$	−0.41	−0.39
$\Xi^- \to \Lambda\pi^-$	−1.99	−1.99	−1.98	0.39	0.39	0.48
$\Xi^0 \to \Lambda\pi^0$	1.52	1.52	1.52	−0.27	−0.27	−0.33

Previous values extracted on the assumption of real-valued amplitudes: comparison with complex-valued l-waves on most recent data.

Framework

- At low-energy regime, α_s too large for a perturbative description of hadron interactions from QCD.
- χPT: EFT with hadrons as DF parametrizes meson-baryon interactions [Physica A 96 (1979) 1-2, 327-340], [Annals Phys. 158 (1984) 142].

Weak nonleptonic hyperon decays previously studied in

Nuclear Physics B261 (1985) 185–198
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ON THE VALIDITY OF CHIRAL PERTURBATION THEORY FOR WEAK HYPERON DECAYS*

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Hyperon non-leptonic decays in chiral perturbation theory

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Non-leptonic hyperon decays in chiral perturbation theory

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Starting point

Computing 1-loop corrections using *Heavy-Baryon* χPT (nonrelativistic approach):

1. [Nucl.Phys.B 261 (1985) 185-198]:
   - baryon decuplet not included as internal states; terms up to $O(M_K^2 \log M_K)$.
2. [Nucl.Phys.B 375 (1992) 561-581]:
   - inclusion of decuplet, 3-meson vertex h_π; terms up to $O(M_K^2 \log M_K)$.
3. [Eur.Phys.J.C 6 (1999) 85-107]
   - decuplet not included, 3-meson vertex h_π; terms up to $M_K^2(a + b \log M_K)$.
4. [Phys. Rev. D 61, 114014 (2000)]:
   - same as 2, contradicting results in h_π terms.

General conclusions

- LO chiral corrections to S-waves are in good agreement with experiment;
- P-waves are not well-described;
- Results from simultaneous fitting are unsatisfactory.

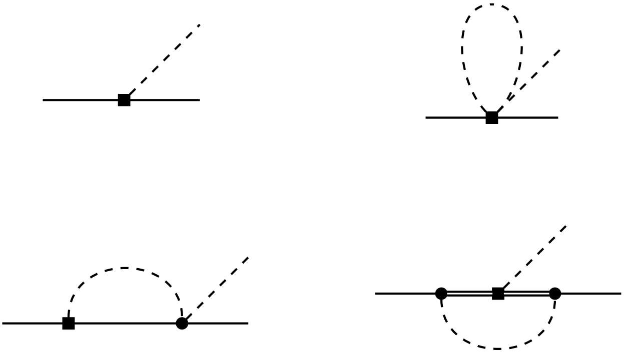
Procedure

Compute 1-loop corrections from relativistic LO Lagrangian

$$\mathcal{L}^{\mathrm{s}}_{\phi B} + \mathcal{L}^{\mathrm{w}}_{\phi B}$$

$$\mathcal{L}^{\mathrm{w}}_{\phi B} = h_D \ \mathrm{tr}\bar{B}\{\xi^\dagger h \xi, B\} + h_F \ \mathrm{tr}\bar{B}[\xi^\dagger h \xi, B] + h_C \ \mathrm{tr}\, \bar{T}^\mu (\xi^\dagger h \xi) T_\mu$$

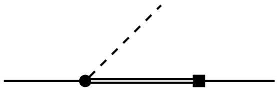
E.g. S-wave contributions:



Procedure

Inclusion of lower-lying $\frac{1}{2}^{\pm}$ resonances [Phys. Rev. D 59, 094025 (1999)]

$$\mathcal{L}^{\rm w}_{\rm res} \propto d^* \left[\mathrm{tr}(\bar{R}^+\{\xi^\dagger h\xi, B\}) + \mathrm{tr}(\bar{B}\{\xi^\dagger h\xi, R^+\})\right] + f^* \left[\mathrm{tr}(\bar{R}^+[\xi^\dagger h\xi, B]) + \mathrm{tr}(\bar{B}[\xi^\dagger h\xi, R^+])\right]$$
$$+ i w_d \left[\mathrm{tr}(\bar{R}^-\{\xi^\dagger h\xi, B\}) - \mathrm{tr}(\bar{B}\{\xi^\dagger h\xi, R^-\})\right] + i w_f \left[\mathrm{tr}(\bar{R}^-[\xi^\dagger h\xi, B]) - \mathrm{tr}(\bar{B}[\xi^\dagger h\xi, R^-])\right]$$



The resulting amplitudes:

$$S_{\rm theory},\ P_{\rm theory} = l.c.(h_{D,F,C},\ w_{d,f},\ d^*,\ f^*)$$

Goal

To fit $L_{\rm theory}$ to $L_{\rm expt}$ using least squares method to obtain LEC's values.

Previous work result

TABLE 2

Predicted S-wave amplitudes for parameter values $h_D = -0.35$, $h_F = 0.86$, and $h_C = -0.36$

Decay	s_{expt}	s_{theory}	s_{tree}	Δs_{loop}	Δs_{octet}	Δs_{decup}
$\Sigma^+ \to n\pi^+$	0.06	−0.09	0.00	−0.09	0.13	−0.22
$\Sigma^+ \to p\pi^0$	−1.43	−1.41	−0.85	−0.55	−0.04	−0.51
$\Sigma^- \to n\pi^-$	1.88	1.90	1.21	0.69	0.18	0.51
$\Lambda \to p\pi^-$	1.42	1.44	0.91	0.53	0.16	0.37
$\Lambda \to n\pi^0$	−1.04	−1.02	−0.64	−0.37	−0.11	−0.27
$\Xi^- \to \Lambda\pi^-$	−1.98	−2.04	−1.19	−0.84	−0.14	−0.71
$\Xi^0 \to \Lambda\pi^0$	1.52	1.44	0.84	0.60	0.10	0.50

[Nucl.Phys.B 375 (1992) 561-581]

- Good agreement with experiment.
- h_C not well determined by 1-loop fit ($h_C = -0.36(65)$). 3-meson h_π terms are negligible. Quark model prediction $h_D/h_F = -1/3$ is favored.
- Octet correction is small, while decuplet contribution is sizable.
- P-waves are poorly reproduced when using S-wave fit LEC's.

Preliminary results

Resonance saturation S-wave fit ($h_D = -1/3\ h_F$)

LEC	$[G_F m_\pi^2 \sqrt{2} f_\pi]$
h_F	0.994 ± 0.012
h_C	-11.01 ± 0.11
w_f	11.00 ± 0.11
w_d	-22.77 ± 0.13
χ^2	123.5
$\tilde{\chi}^2$	61.77

	s_{expt}	s_{theory}	s_{tree}	Δs_{loop}	Δs_{res}
$\Sigma^+ \to n\pi^+$	0.09	−−	−−	−−	−−
$\Sigma^+ \to p\pi^0$	−1.37	−1.37	−0.94	−0.44	−2.15
$\Sigma^- \to n\pi^-$	1.85	1.85	1.32	0.52	3.23
$\Lambda \to p\pi^-$	1.36	1.37	1.08	0.29	2.42
$\Lambda \to n\pi^0$	−1.02	−1.00	−0.76	−0.23	−1.70
$\Xi^- \to \Lambda\pi^-$	−1.99	−2.02	−1.35	−0.66	−10.79
$\Xi^0 \to \Lambda\pi^0$	1.52	1.27	0.96	0.31	7.40

S-waves

- Corrections to LO χPT are large, for most channels coming from the resonances (also tree-level): confirmed importance of resonances.
- Good agreement with experiment and convergent behavior recovered.
- h_C is large, h_F is even close to Jenkins'. Large cancellation between resonance and loops.

Preliminary results

Resonance saturation *P*-wave fit ($h_D = -1/3\ h_F$)

LEC	$[G_F m_\pi^2 \sqrt{2} f_\pi]$
h_F	0.696 ± 0.005
h_C	0.527 ± 0.007
d^*	0.69 ± 0.04
f^*	-4.190 ± 0.031
χ^2	68.66
$\tilde{\chi}^2$	22.89

	p_{expt}	p_{theory}	p_{tree}	Δp_{loop}	Δp_{res}
$\Sigma^+ \to n\pi^+$	1.70	1.73	−0.03	1.76	1.88
$\Sigma^+ \to p\pi^0$	1.25	1.22	−0.70	1.92	1.14
$\Sigma^- \to n\pi^-$	−0.06	−0.10	0.97	−1.06	0.31
$\Lambda \to p\pi^-$	0.63	0.63	−0.33	0.95	0.76
$\Lambda \to n\pi^0$	−0.42	−0.46	0.24	−0.70	−0.56
$\Xi^- \to \Lambda\pi^-$	0.39	0.39	0.12	0.27	−1.31
$\Xi^0 \to \Lambda\pi^0$	−0.27	−0.29	−0.09	−0.20	0.89

P-waves

- Tree level is not dominant. “True” loops dominate in some decay channels: not a coherent picture.
- Good agreement with experiment, loss of convergent behavior.
- LEC’s size is closer to previous works.

Preliminary results

Resonance saturation combined s- and p-wave fit

LEC	$[G_F m_\pi^2 \sqrt{2} f_\pi]$
h_D	0.3362 ± 0.0022
h_F	0.8887 ± 0.0028
h_C	2.260 ± 0.006
w_d	17.60 ± 0.09
w_f	-1.022 ± 0.011
d^*	-12.480 ± 0.027
f^*	-5.553 ± 0.016
χ^2	4971
$\tilde{\chi}^2$	828.5
h_D/h_F	0.378

	α_{expt}	α_{theory}	Γ_{expt}	Γ_{theory}	s_{expt}	s_{theory}	p_{expt}	p_{theory}
$\Sigma^+ \to n\pi^+$	0.07	0	0.08	0.07	0.09	0	1.70	−1.78
$\Sigma^+ \to p\pi^0$	−0.98	−1.00	0.08	0.09	−1.37	1.34	1.25	−1.35
$\Sigma^- \to n\pi^-$	−0.07	0.07	0.09	0.05	1.85	−1.37	−0.06	−0.05
$\Lambda \to p\pi^-$	0.76	0.74	0.03	0.03	1.36	1.43	0.63	0.63
$\Lambda \to n\pi^0$	0.69	0.75	0.02	0.02	−1.02	−1.00	−0.42	−0.46
$\Xi^- \to \Lambda\pi^-$	−0.38	−0.40	0.08	0.08	−1.99	0.43	0.39	−2.07
$\Xi^0 \to \Lambda\pi^0$	−0.36	−0.42	0.04	0.04	1.52	−0.32	−0.27	1.43

Combined fit

- Poor agreement with data, loss of convergent behavior for S-waves.
- LEC's size is inconsistent with other results.
- Quadratic relation in α and Γ disregards relative signs between amplitudes: too much freedom. Switch to fit separately to L-waves together (future).

Relativistic chiral LO Lagrangian

Meson-baryon LO Lagrangian

$$\mathcal{L}^{\mathrm{s}}_{\phi B} = i\ \mathrm{tr}\ \bar{B}\not{D}B - m_B\ \mathrm{tr}\ \bar{B}B + D\ \mathrm{tr}\ \bar{B}\gamma^\mu\gamma_5\{A_\mu, B\} + F\ \mathrm{tr}\ \bar{B}\gamma^\mu\gamma_5[A_\mu, B] - i\ \bar{T}^\mu\not{D}T_\mu$$
$$+ m_T\ \bar{T}^\mu T_\mu + C\left(\bar{T}^\mu A_\mu B + \bar{B}A_\mu T^\mu\right) + \mathcal{H}\ \bar{T}^\mu\gamma_\nu\gamma_5 A^\nu T_\mu + \frac{f^2}{4}\ \mathrm{tr}\ \partial_\mu\Sigma\partial^\mu\Sigma^\dagger$$

Inclusion of $\frac{1}{2}^\mp$ resonances [PRD59, 094025 (1999)]

$$\mathcal{L}^{\mathrm{s}}_{RB} = 2s_d\left[\mathrm{tr}(\bar{R}\gamma_\mu\{A_\mu, B\}) - \mathrm{tr}(\bar{B}\gamma_\mu\{A_\mu, R\})\right]$$
$$+ 2s_f\left[\mathrm{tr}(\bar{R}\gamma_\mu[A_\mu, B]) - \mathrm{tr}(\bar{B}\gamma_\mu[A_\mu, R])\right]$$

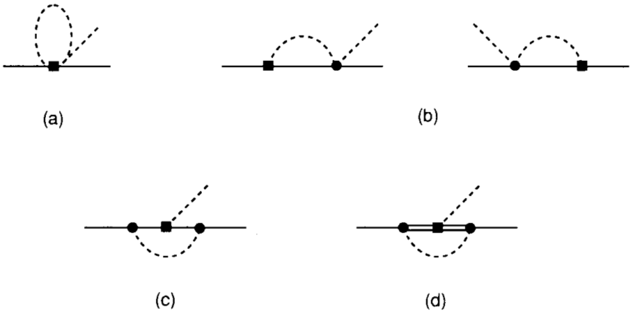
$$\mathcal{L}^{\mathrm{s}}_{B^*B} = \frac{D^*}{2}\left[\mathrm{tr}(\bar{B}^*\gamma_\mu\gamma_5\{A_\mu, B\}) + \mathrm{tr}(\bar{B}\gamma_\mu\gamma_5\{A_\mu, B^*\})\right]$$
$$+ \frac{F^*}{2}\left[\mathrm{tr}(\bar{B}^*\gamma_\mu\gamma_5[A_\mu, B]) + \mathrm{tr}(\bar{B}\gamma_\mu\gamma_5[A_\mu, B^*])\right]$$

$$V^\mu = \frac{1}{2}\left(\xi\partial^\mu\xi^\dagger + \xi^\dagger\partial^\mu\xi\right), \quad A^\mu = \frac{i}{2}\left(\xi\partial^\mu\xi^\dagger - \xi^\dagger\partial^\mu\xi\right)$$

$$\xi = \exp\frac{i\pi}{f}, \quad \Sigma = \xi^2 = \exp\frac{2i\pi}{f}$$

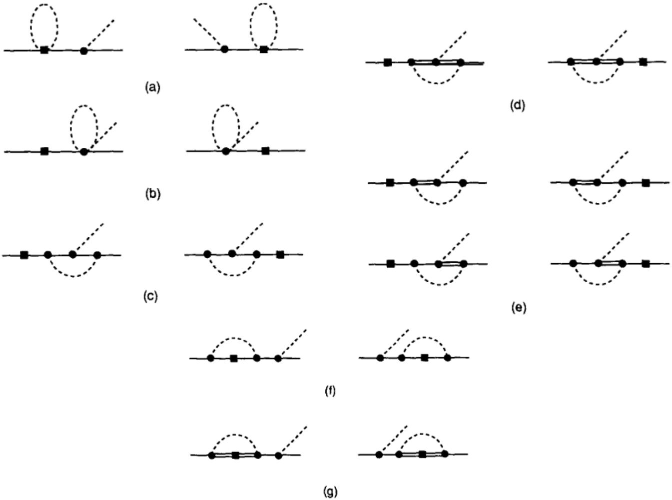
S-wave diagrams

S-wave 1-loop corrections [Nucl. Phys. B 375 (1992)]



P-wave diagrams

P-wave 1-loop corrections, [Nucl. Phys. B 375 (1992)]



Preliminary results

Resonance saturation s-wave fit

LEC	$[G_F m_\pi^2 \sqrt{2} f_\pi]$
h_D	7.5 ± 0.9
h_F	-2.7 ± 0.4
h_C	-38.5 ± 3.2
w_f	25.7 ± 1.7
w_d	-91 ± 8
$\chi^2 = \tilde{\chi}^2$	82.86
h_D/h_F	-2.792

	s_{expt}	s_{theory}	s_{tree}	Δs_{loop}	Δs_{res}
$\Sigma^+ \to n\pi^+$	0.09	$--$	$--$	$--$	$--$
$\Sigma^+ \to p\pi^0$	-1.37	-1.37	7.20	-8.57	-7.39
$\Sigma^- \to n\pi^-$	1.85	1.85	-10.18	12.03	9.18
$\Lambda \to p\pi^-$	1.36	1.35	-0.23	1.57	7.49
$\Lambda \to n\pi^0$	-1.02	-1.05	0.16	-1.21	-5.26
$\Xi^- \to \Lambda\pi^-$	-1.99	-2.01	6.35	-8.36	-27.72
$\Xi^0 \to \Lambda\pi^0$	1.52	1.33	-4.49	5.82	19.08

Preliminary results

Resonance saturation p-wave fit

LEC	$[G_F m_\pi^2 \sqrt{2} f_\pi]$
h_D	-0.286 ± 0.008
h_F	0.10 ± 0.08
h_C	-0.79 ± 0.18
d^*	3.6 ± 0.4
f^*	-1.93 ± 0.32
χ^2	16.76
$\tilde{\chi}^2$	8.38
h_D/h_F	-2.91

	p_{expt}	p_{theory}	p_{tree}	Δp_{loop}	Δp_{res}
$\Sigma^+ \to n\pi^+$	1.70	1.70	-0.25	1.95	1.78
$\Sigma^+ \to p\pi^0$	1.25	1.25	-0.29	1.54	1.30
$\Sigma^- \to n\pi^-$	-0.06	-0.06	0.15	-0.21	-0.02
$\Lambda \to p\pi^-$	0.63	0.63	0.11	0.52	0.31
$\Lambda \to n\pi^0$	-0.42	-0.46	-0.08	-0.39	-0.23
$\Xi^- \to \Lambda\pi^-$	0.39	0.39	-0.20	0.59	-0.48
$\Xi^0 \to \Lambda\pi^0$	-0.27	-0.28	0.15	-0.43	0.33

Preliminary results

Resonance saturation combined s- and p-wave fit

	s_{expt}	s_{theory}	s_{tree}	Δs_{loop}	Δs_{res}	p_{expt}	p_{theory}	p_{tree}
$\Sigma^+ \to n\pi^+$	0.09	−−	−−	−−	−−	1.70	−1.78	0.58
$\Sigma^+ \to p\pi^0$	−1.37	1.34	−0.39	1.73	1.18	1.25	−1.35	−0.42
$\Sigma^- \to n\pi^-$	1.85	−1.37	0.55	−1.92	−0.98	−0.06	−0.05	1.20
$\Lambda \to p\pi^-$	1.36	1.43	1.23	0.20	−0.99	0.63	0.63	−0.80
$\Lambda \to n\pi^0$	−1.02	−1.00	−0.87	−0.14	0.69	−0.42	−0.46	0.59
$\Xi^- \to \Lambda\pi^-$	−1.99	0.43	−0.95	1.38	2.05	0.39	−2.07	0.70
$\Xi^0 \to \Lambda\pi^0$	1.52	−0.32	0.67	−0.99	−1.43	−0.27	1.43	−0.51