Narodowe Centrum Nauki

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# Weak nonleptonic hyperon decays in relativistic $\chi$PT

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Technische Universität Darmstadt

Uniwersytet Śląski w Katowicach

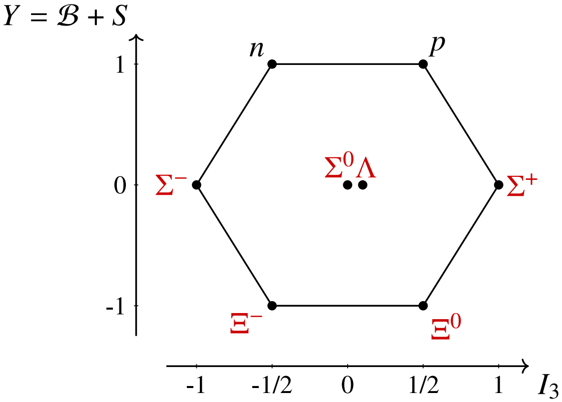
Uppsala Universitet

GSI

NCBJ Świerk

# Subject of study

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




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

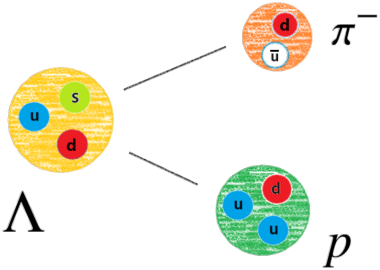
# Nonleptonic decays

Transition amplitude

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

From angular momentum conservation:

$$J(1/2) = S_b(1/2) + S_\pi(0) + L_{b\pi}$$
$$S(L_{b\pi} = 0), \quad P(L_{b\pi} = 1)$$



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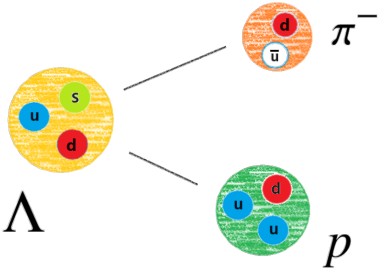
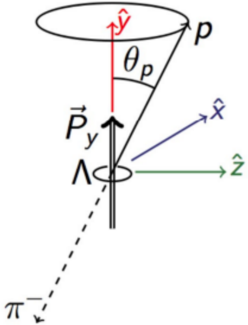
Dimensionless $l$-wave amplitudes

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



# Nonleptonic decay parameters

From partial waves to observables:



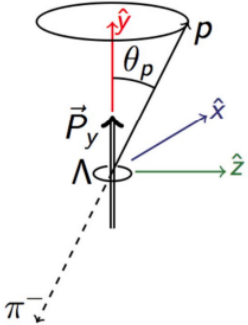

$\Lambda \to p\pi^-$ decay

# Nonleptonic decay parameters

From partial waves to observables:

- Angular distribution $\frac{d\Gamma}{d\Omega} \propto 1 + \alpha \, \mathbf{P}_\Lambda \cdot \hat{\mathbf{n}}$

$$\alpha = \frac{2\Re(S^* P)}{|S|^2 + |P|^2}$$

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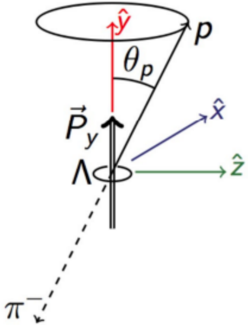
- Spin $\mathbf{s}_\Lambda \to \mathbf{s}_p$ rotation

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

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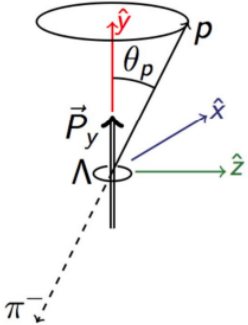
- Decay width

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




$\Lambda \to p\pi^-$ decay

# 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**

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[Nature 606, 6469 (2022)]

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

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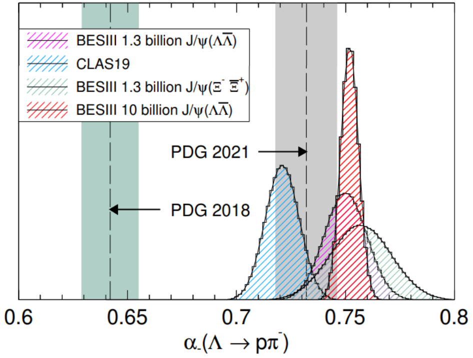

# Extrapolate data points

## Next step

Use $\alpha$, $\phi$, $\Gamma$ data to extrapolate updated experimental $L$-wave amplitude values.

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

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

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and final-interaction phase shifts [NS et al., PRD105, 116022 (2022)]

| | $\lvert\mathbf{q}\rvert$ [MeV/c] | $\delta_1^S$ [°] | $\delta_3^S$ [°] | $\delta_1^P$ [°] | $\delta_3^P$ [°] |
|---|---|---|---|---|---|
| $\Lambda \to N\pi$ | 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) |

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Relative sign between amplitudes fixed by Lee-Sugawara relation

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

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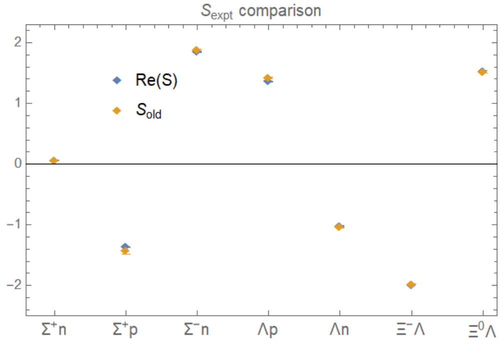
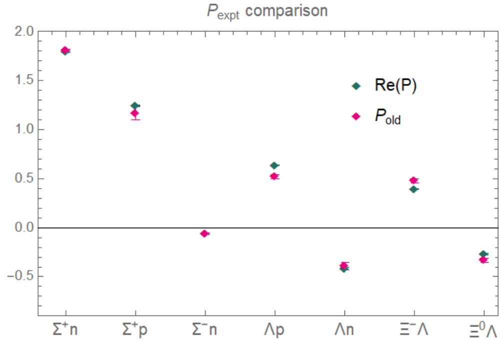
New reference values extracted from current data compared to [E. Jenkins, NPB 375 (1992) 561-581]:




Previous values extracted on the assumption of real-valued amplitudes:
updated to complex-valued $l$-waves on most recent data.

# Framework

- At low-energy regime, $\alpha_s$ too large for a perturbative description of hadron interactions from QCD.
- $\chi$PT: EFT with hadrons as DF parametrizes meson-baryon interactions
  [S. Weinberg, Physica A 96 (1979) 1-2, 327-340], [J. Gasser & H. Leutwyler, Annals Phys. 158 (1984) 142].

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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***

J BIJNENS[1], H SONODA and Mark B WISE[2]

*California Institute of Technology, Pasadena, CA 91125, USA*

Received 23 January 1985
(Revised 14 June 1985)

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**Non-leptonic hyperon decays in chiral perturbation theory**

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NUCLEAR PHYSICS B

Hyperon non-leptonic decays in chiral perturbation theory

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*Department of Physics 0319, University of California, San Diego, 9500 Gilman Drive, La Jolla, CA 92093-0319, USA*

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# Starting point

Computing 1-loop corrections using *Heavy-Baryon* $\chi$PT (nonrelativistic approach):

| Ref. | $\mathcal{O}$(trunc) | 10 | $h_\pi$ | $B^*$ |
|---|---|---|---|---|
| Bijnens, Sonoda & Wise [NPB 261 (1985) 185-198] | $M_K^2 \log M_K$ | ✗ | ✗ | ✗ |
| Jenkins [NPB 375 (1992) 561-581] | ‖ | ✓ | ✓ | ✗ |
| Abd El-Hady & Tandean [PRD 61, 114014 (2000)] | ‖ | ✓ | ✓[1] | ✗ |
| Borasoy & Holstein [EPJC 6 (1999) 85-107] | $M_K^2 (a + b \log M_K)$ | ✗ | ✓ | ✗ |
| Borasoy & Holstein [PRD 59, 094025 (1999)] | $M_K^2$ | ✗ | ✓ | ✓ |

[1]Contradicting previous results.

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## General conclusions

- LO chiral corrections to *S*-waves are in good agreement with experiment. *P*-waves are not well-described.
- A tree-level fit suggests **resonance exchange** is relevant.
- Results from simultaneous fitting are presumed unsatisfactory: **yet unexplored**.

[1] Contradicting previous results.

# Relativistic $\chi$PT and EOMS

- Dimensional regularization + modified minimal subtraction do not work for baryons;
- inclusion of baryon masses breaks power-counting for the loop diagrams.

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## Previous approach: HB$\chi$PT Jenkins & Manohar [PLB 255 (1991) 558-562]

- Expansion of the Lagrangian in powers of $1/m_B$ in the chiral limit.
- Power-counting is manifest, but Lorentz invariance is not.
- Issues with analyticity (reproducing the correct positions of poles).

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**Extended On-Mass-Shell ren. scheme** Gegelia & Japaridze [PRD 60 (1999) 114038]

- Subtract the power-counting-violating terms, i.e. choosing appropriate renormalization conditions.
- Manifest Lorentz invariance: the standard approach for B$\chi$PT nowadays.

# Procedure

Compute 1-loop corrections from relativistic LO Lagrangian

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

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

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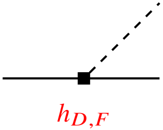
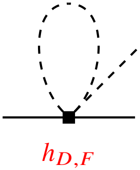
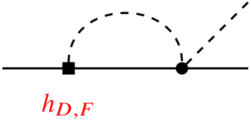
E.g. $S$-wave contributions:

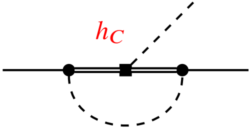



$= O(M_K^0)$




$= O(M_K^2 \log M_K^2)$



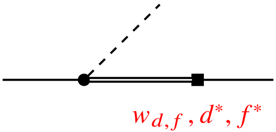




$= O(M_K^2 (a + b \log M_K^2))$

# Resonance saturation

Inclusion of lower-lying $\frac{1}{2}^{\pm}$ resonances [Borasoy & Holstein, PRD 59, 094025 (1999)][1]

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



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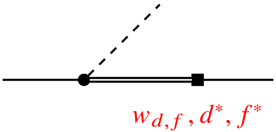


The resulting amplitudes:

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

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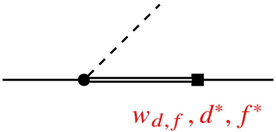


Update for Roper multiplet

| LEC | **SL new fit** | Ref. [1] |
|---|---|---|
| $D^*$ | $0.72 \pm 0.11$ | $0.60 \pm 0.41$ |
| $F^*$ | $0.36 \pm 0.05$ | $0.11 \pm 0.41$ |

The resulting amplitudes:

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

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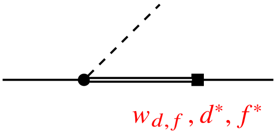



Update for Roper multiplet

| LEC | **SL new fit** | Ref. [1] |
|---|---|---|
| $D^*$ | $0.72 \pm 0.11$ | $0.60 \pm 0.41$ |
| $F^*$ | $0.36 \pm 0.05$ | $0.11 \pm 0.41$ |

The resulting amplitudes:

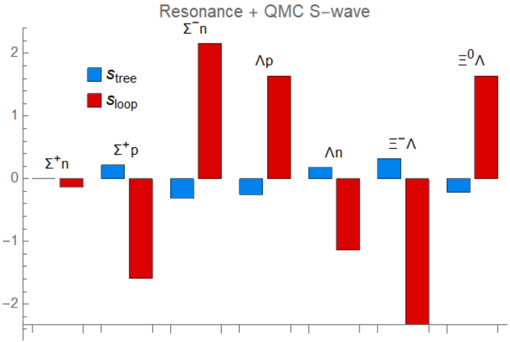
$$S_{\mathrm{theory}},\ P_{\mathrm{theory}} = l.c.(h_{D,F,C},\ w_{d,f},\ d^*,\ f^*)$$

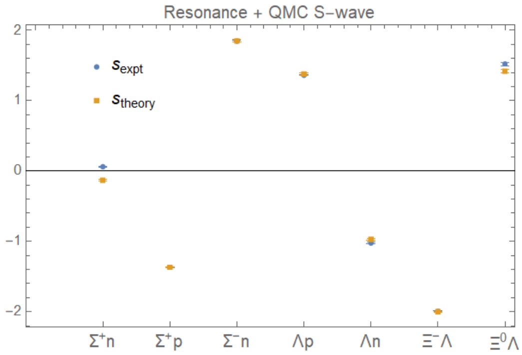
**Goal**

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

# Preliminary results – *S*-waves

LECs extracted from fit to ***S*-waves only**:




| **LEC** | $[G_F m_\pi^2 \sqrt{2} f_\pi]$ |
|---|---|
| $h_D$ | $-1/3 h_F$ |
| $h_F$ | $-0.233 \pm 0.007$ |
| $h_C$ | $1.99 \pm 0.04$ |
| $w_f$ | $4.63 \pm 0.07$ |
| $w_d$ | $-14.72 \pm 0.11$ |

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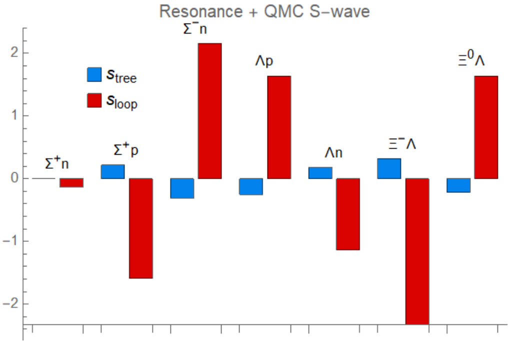


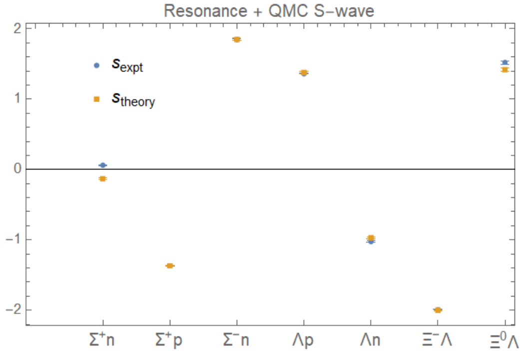


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## EOMS + resonances

- Good agreement with experiment.
- Corrections to LO are large.

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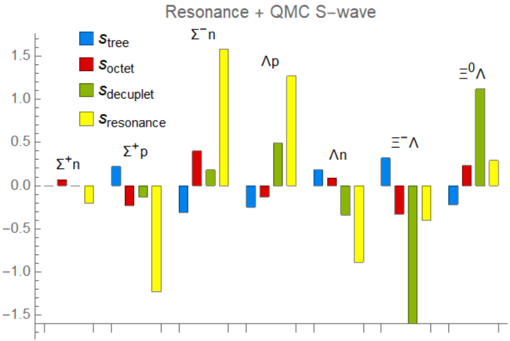


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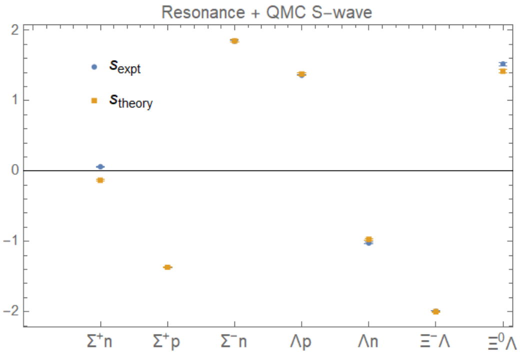
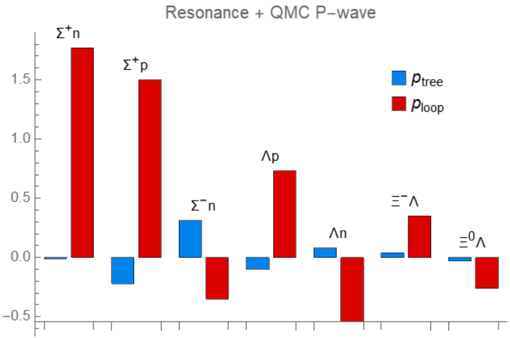


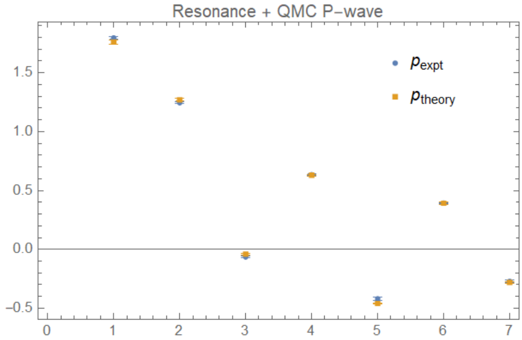

## EOMS + resonances

- Good agreement with experiment.
- Corrections to LO are large.
- The importance of 10 and $B^*$ is confirmed.

# Preliminary results – $P$-waves

LECs extracted from fit to ***P*-waves only**:




| LEC | $[G_F m_\pi^2 \sqrt{2} f_\pi]$ |
|---|---|
| $h_D$ | $-1/3 h_F$ |
| $h_F$ | $0.221 \pm 0.002$ |
| $h_C$ | $0.095 \pm 0.003$ |
| $d^*$ | $1.61 \pm 0.04$ |
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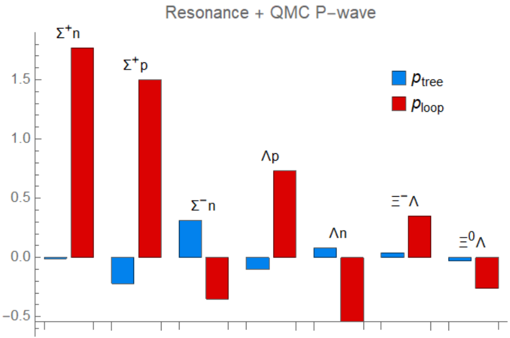


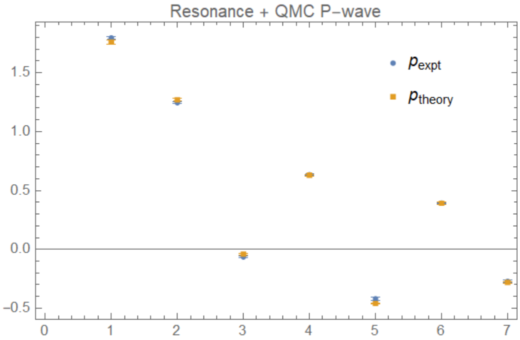


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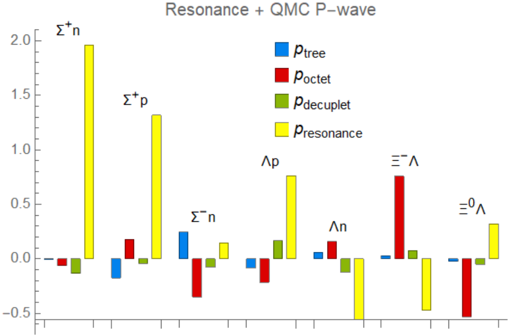


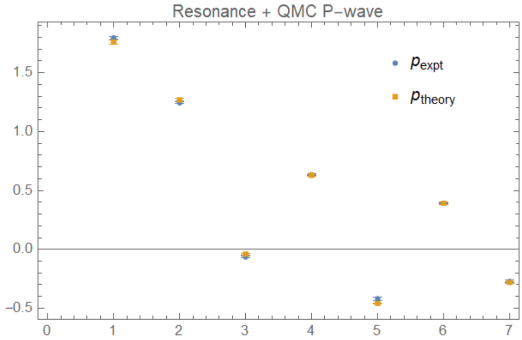


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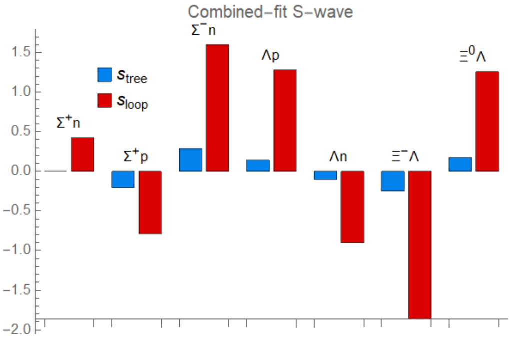
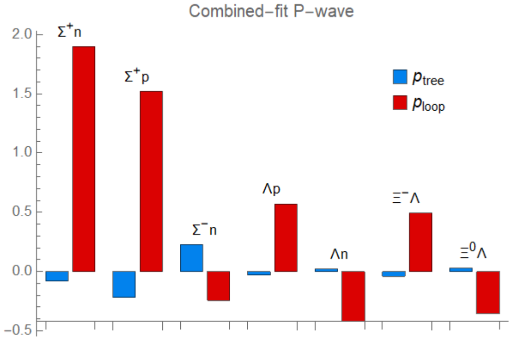
## EOMS + resonances

- Agreement with experiment better than in *S*-waves.
- Similar resonance-to-tree-level relative size as in *P*-waves.

# Preliminary results – Combining $S$ and $P$

LECs extracted from fit to **combined $S$- and $P$-waves**:



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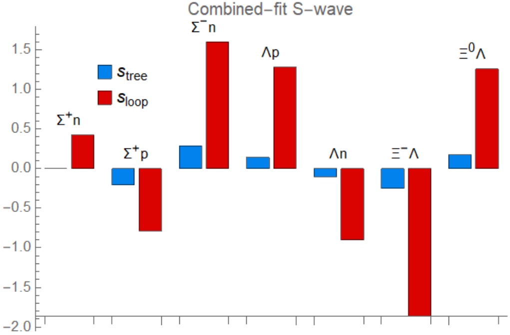


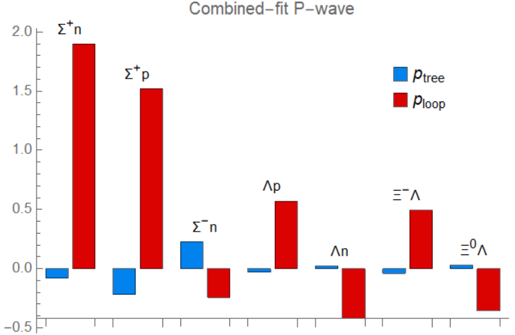


## EOMS + resonances

- LEC's size somewhat consistent with other results.

| LEC | $[G_F m_\pi^2 \sqrt{2} f_\pi]$ | LEC | $[G_F m_\pi^2 \sqrt{2} f_\pi]$ |
|---|---|---|---|
| $h_D$ | $-0.192 \pm 0.004$ | $w_d$ | $-9.73 \pm 0.06$ |
| $h_F$ | $0.186 \pm 0.002$ | $w_f$ | $7.71 \pm 0.02$ |
| $h_C$ | $-0.136 \pm 0.008$ | $d^*$ | $2.72 \pm 0.05$ |
| | | $f^*$ | $-2.83 \pm 0.04$ |

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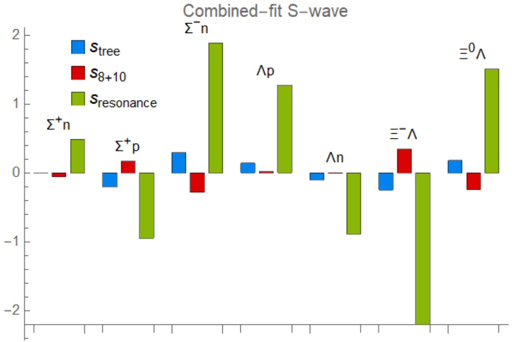


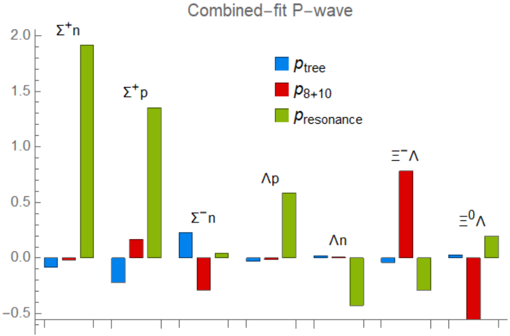


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- LEC's size somewhat consistent with other results.
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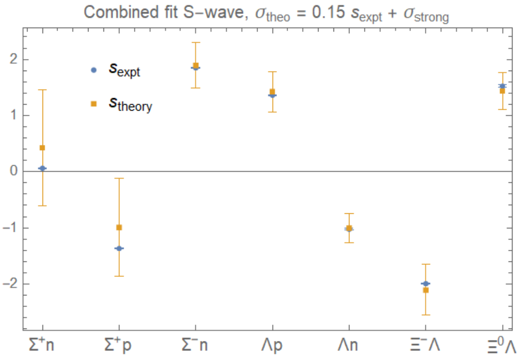


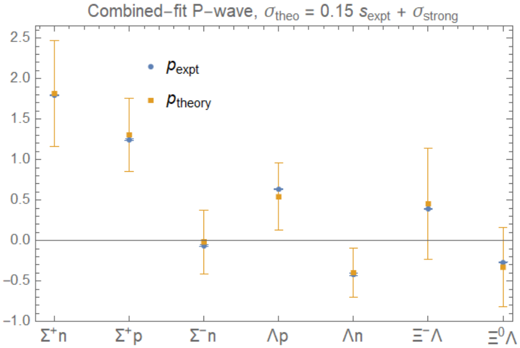


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- $S$ agreement with experiment slightly worse, $P$ remains good.

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|---|---|---|---|
| $h_D$ | $-0.13 \pm 0.23$ | $w_d$ | $-7.3 \pm 1.3$ |
| $h_F$ | $0.16 \pm 0.09$ | $w_f$ | $7.7 \pm 1.3$ |
| $h_C$ | $0.0 \pm 0.4$ | $d^*$ | $1.1 \pm 1.8$ |
| | | $f^*$ | $-2.3 \pm 1.5$ |

# In short

## Conclusions

- Hyperon nonleptonic decays were never studied in relativistic $\chi$PT: following previous attempts in HB$\chi$PT and updated measurement of $\alpha_\Lambda$ from BESIII (2019).

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- Perform a comparison fit using 8 independent $\Delta I = 1/2$ amplitudes to circumvent isospin relations.
- Outlook: two-loops, $\Lambda(1405)$ as hadron molecular state, resonances included as DF...


Thank You for your attention.
Any questions?
(this is the part where you run)
someecards
user card

# 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 $\frac{1}{2}^{\pm}$ resonances [B. Borasoy & B. Holstein, PRD 59, 094025 (1999)]

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

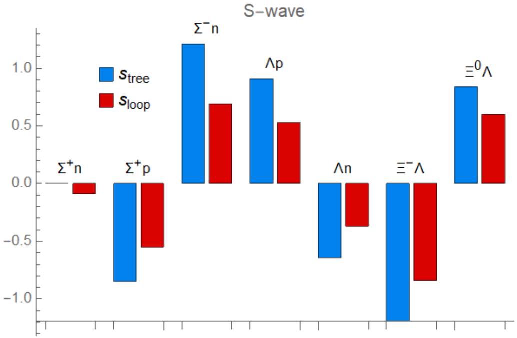
$$\mathcal{L}^{\mathrm{s}}_{B^*B} = \frac{D^*}{2}\left[\mathrm{tr}(\bar{B}^*\gamma_\mu\gamma_5\{A_\mu, B\}) + \mathrm{tr}(\bar{B}\gamma_\mu\gamma_5\{A_\mu, B^*\})\right]$$
$$+ \frac{F^*}{2}\left[\mathrm{tr}(\bar{B}^*\gamma_\mu\gamma_5[A_\mu, B]) + \mathrm{tr}(\bar{B}\gamma_\mu\gamma_5[A_\mu, B^*])\right]$$

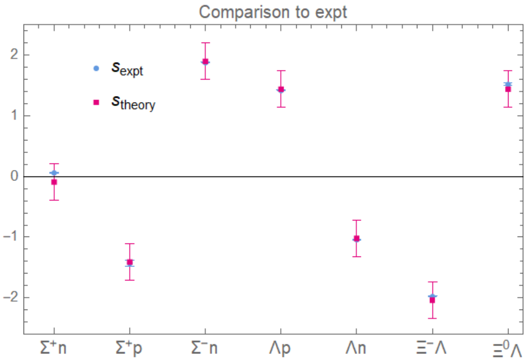
$$V^\mu = \frac{1}{2}\left(\xi\partial^\mu\xi^\dagger + \xi^\dagger\partial^\mu\xi\right), \quad A^\mu = \frac{i}{2}\left(\xi\partial^\mu\xi^\dagger - \xi^\dagger\partial^\mu\xi\right)$$

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

# Previous work results – *S*-waves

LECs extracted from fit to ***S*-waves only**:




| **LEC** | $[G_F m_\pi^2 \sqrt{2} f_\pi]$ |
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| $h_D$ | $-0.35 \pm 0.09$ |
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[NPB 375 (1992) 561-581]

- Good agreement with experiment.

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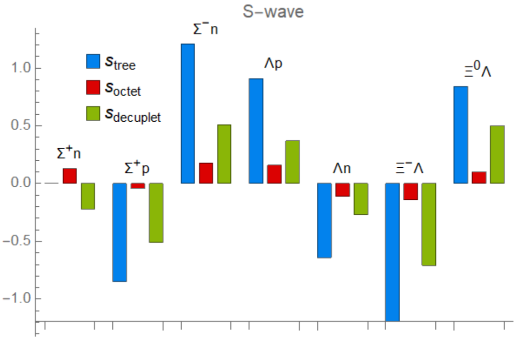


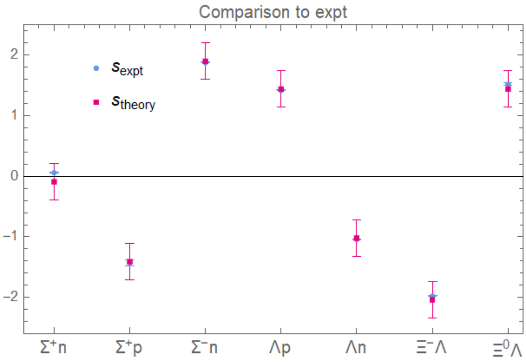


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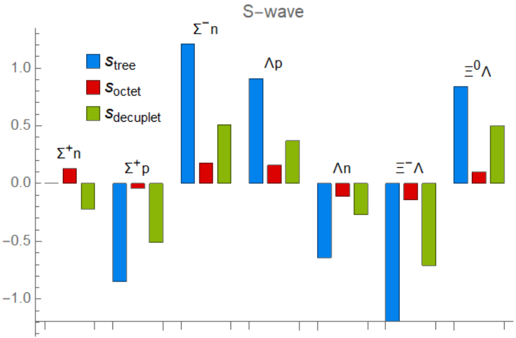


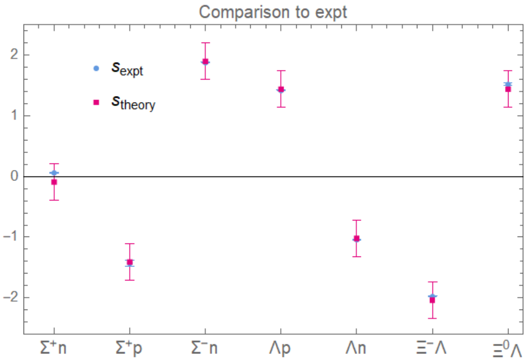


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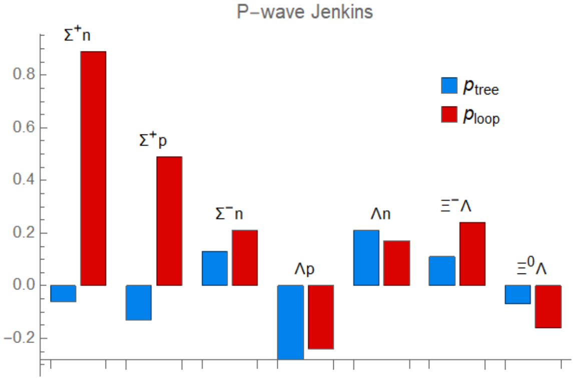
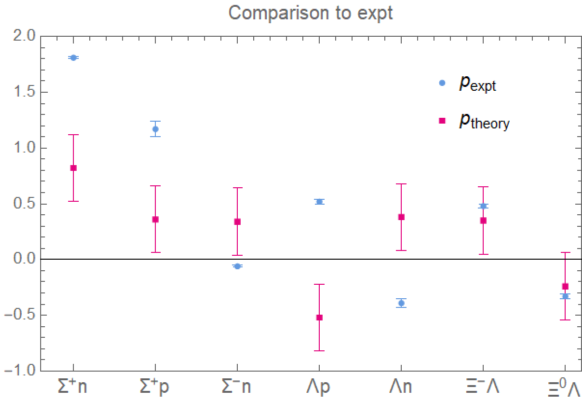
[NPB 375 (1992) 561-581]

- Good agreement with experiment.
- Decuplet contribution dominates over octet.
- $h_C$ not well determined by 1-loop fit.

# Previous work results – *P*-waves

Using the LECs from *S*-wave fit:

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- *P*-waves are poorly described.
- Simultaneous fitting seems unfeasible.