$\not{C}\!P$ in $\Lambda^0 \to p\pi^-$

SM vs "New Physics"

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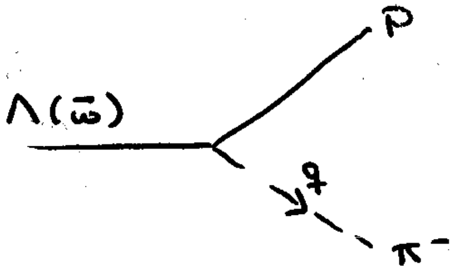
Decay $\Lambda^0 \to p\pi^-$: polarized Λ, p polarization NOT observed



- s, p waves
- $\Delta I = 1/2, 3/2$

Observables $\quad \Gamma \sim |s|^2 + |p|^2 \qquad B = 63.9\,\%$

$$\frac{d\Gamma}{d\Omega} \sim 1 + \underline{\alpha}\, \bar{q}\cdot\bar{\omega} \qquad \alpha = 0.64 \quad \text{(PDB)}$$

Notation

$$s = s_1 e^{i\delta_1^s} + s_3 e^{i\delta_3^s} \qquad s_3/s_1 = 0.026$$

$$p = p_1 e^{i\delta_1^p} + p_3 e^{i\delta_3^p} \qquad p_3/p_1 \simeq 0.03 \pm 0.03$$

Strong phases: πN scattering at $\sqrt{s} = M_\Lambda$

$$\delta_1^s \sim 6^\circ \qquad \delta_1^p \sim -1^\circ$$

$$\delta_3^{s,p} \sim 1^\circ \text{ (large errors)}$$

$\not{C}\not{P}$: Weak phases $s_i \to s_i e^{i\phi_i^s}$

$p_i \to p_i e^{i\phi_i^p}$

compare to $\bar{\Lambda} \to \bar{p}\pi^+$ decay:

CP predicts: $\bar{\Gamma} = \Gamma$

$\bar{\alpha} = -\alpha$

$\not{C}\not{P}$ observables:

$$\Delta \equiv \frac{\Gamma - \bar{\Gamma}}{\Gamma + \bar{\Gamma}} \sim \sqrt{2}\,\frac{s_3}{s_1}\,\sin(\delta_3^s - \delta_1^s)\,\sin(\phi_3^s - \phi_1^s)$$

- $\Delta I = 1/2$ vs $\Delta I = 3/2$ interference
- suppressed by $s_3/s_1 \sim 0.03$

$$A \equiv \frac{\alpha + \bar{\alpha}}{\alpha - \bar{\alpha}} \sim -\sin(\delta_1^p - \delta_1^s)\,\sin(\phi_1^p - \phi_1^s)$$
$$\sim 0.12 \sin(\phi_1^p - \phi_1^s)$$

- S-wave vs P-wave interference
- dominated by $\Delta I = 1/2$ sector $\gg \Delta$
- qualitatively different from ϵ'/ϵ

Also: $\Xi \to \Lambda\pi$ is very similar except strong phases are not known

Additional Observable:

If the polarization of both B, B' in $B \to B'\pi$ are observed:

$$\frac{d\Gamma}{d\Omega} \sim \ldots + \beta \langle \sigma_B \rangle \cdot \left(\langle \sigma_{B'} \rangle \times \hat{q} \right)$$

CP predicts: $\bar{\beta} = -\beta$

$\cancel{CP}$ observable: $\mathcal{B} \equiv \dfrac{\beta + \bar{\beta}}{\beta - \bar{\beta}} \sim \dfrac{\sin(\phi_i^p - \phi_i^s)}{\tan(\delta_i^p - \delta_i^s)}$

Expect: $\mathcal{B} \gg A \gg \Delta$

BUT:
- $\mathcal{B}$ is very hard to measure (both polarizations)
- $\mathcal{B}$ normalization is misleading

AND: Δ could be larger in $\Omega \to \Xi \pi$

Experiment: E871 (hypercp) at Fermilab

- to have polarized Λ with known polarization
  they do $\Xi^- \to \Lambda\pi^- \to (p\pi^-)\,\pi^-$

- Measure: $A(\Lambda^0_-) + A(\Xi^-_-)$
- weak phases in Ξ^-_- $\sim 1/2$ as in Λ^0_- (?)
- strong phases in Ξ^-_- $\sim 1/5$ as in Λ^0_-

$$\therefore \quad A(\Lambda^0_-) + A(\Xi^-_-) \sim A(\Lambda^0_-)$$

- Expect sensitivity 10^{-4}
- so far 0.012 ± 0.014 from E756

How do $A(\Lambda^0_-)$ and $A(\Xi^-_-)$ compare?

- weak phases similar (?) signs(?)
- strong phases ? ([redacted])

Strong Phases

1) $\Lambda \to N\pi$

Watson's thm $\to$ same as $N\pi$ scattering at $E_{cm} = M_\Lambda$

For $A(\Lambda^0_-)$ need δ for $I = 1/2$, S, P waves

- measured and small: $\delta_S^{1/2} \sim 6^\circ$

$$\delta_P^{1/2} \sim -1.1^\circ$$

- errors ? $\pm 1^\circ$?

2) $\Xi \to \Lambda\pi$ $(\Omega \to \Xi\pi)$

Watson's thm: $\Lambda\pi$ $(\Xi\pi)$ scattering at $E_{cm} = M_\Xi$ (M_Ω)

- not measured

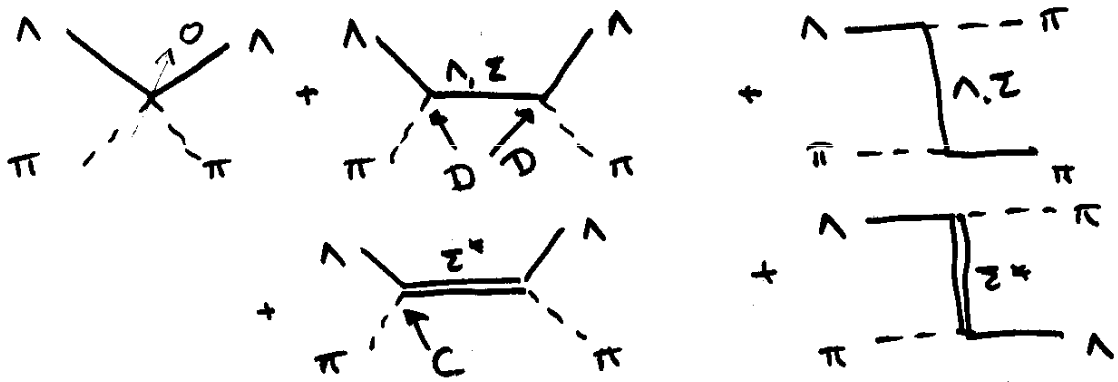
Old model: Nath, Kumar Nuov. Cim. 36 (1965) 669

$$\Xi \to \Lambda\pi \qquad \delta_S^{I=1} \sim -20^\circ \quad \underline{\text{large}}$$

New χPT: small

Λ-π scattering

Lu, Wise, Savage
Datta, Pakvasa
J. Tandean, G.V.



Again, χPT a la Jenkins, Manohar

Again, depends on $\underbrace{D\ (F)}_{0.5\ -\ 0.8}$, $\underbrace{C}_{1.2\ -\ 1.6}$ and 20-30% kinematic dependence

at $E_{cm} = M_\Xi$

$$\delta_p = \frac{-|k|^3 M_\Lambda}{24\pi f_\pi^2 M_\Xi}\left[\frac{2D^2}{M_\Xi - M_\Sigma} + \frac{2/3\ D^2}{M_\Xi - 2M_\Lambda + M_\Sigma} - \frac{2/3\ C^2}{M_\Xi - 2M_\Lambda + M_{\Sigma^*}}\right]$$

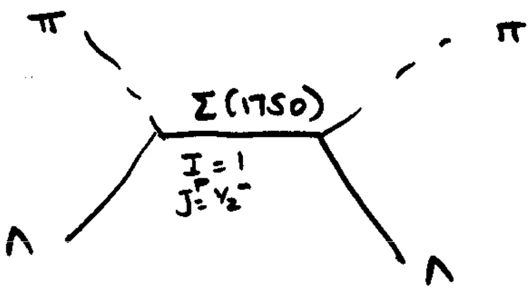
$\sim -1.8°$

$\delta_s = 0$

at Next order in χPT $\delta_s \neq 0$ (Lu, Savage, Wise)

- relativistic corrections $\sim 1°$ (Kamal)
- $\Sigma\pi$ threshold (?) in progress

Datta + Pakvasa : look for resonance in the $J = 1/2$ $\not{P}$ channel



use $\Sigma \to \Lambda\pi$ decay as unknown and

Γ: $60 \text{ MeV} \leq \Gamma \leq 160 \text{ MeV}$

Note $M_\Xi = 1319$ MeV

Find $\delta_s \lesssim \underline{0.5^\circ}$

<u>Ultimate resolution</u> : measure $(\delta_s - \delta_p)$

a) $\Xi \to \Lambda\pi e\nu$

b) Ignore CP then in $\Xi \to \Lambda\pi$ $\beta/\alpha \propto \tan(\delta_s - \delta_p)$

Weak Phases

SM: $H_{eff}^{\Delta S=1} = \frac{G_F}{\sqrt{2}} V_{ud}^* V_{us} \sum c_i(\mu) Q_i(\mu) \quad + h.c.$

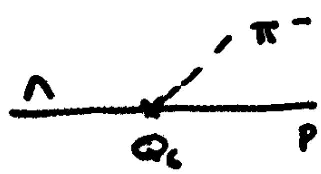
- well known – $K \to \pi\pi$
- need $\langle \pi^- p | O_i(\mu) | \Lambda \rangle$

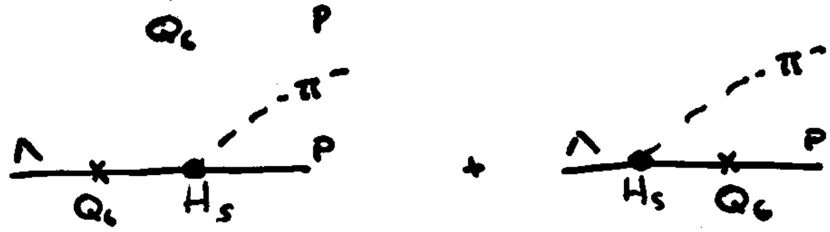
- Assume CP small – take $\left\{ \begin{array}{l} Re\,(s) \\ Re\,(p) \end{array} \right. \to$ experiment

- Calculate $Im\,(s), Im\,(p)$ or $Im \langle \pi^- p | c_i Q_i | \Lambda \rangle$
  - dominated by penguin : $y_6 Q_6 A^2 \lambda^4 \eta$
  - note ϵ'/ϵ controversy B_6, B_8

Model

- Get  in Bag model : Donoghue et al.
  (lattice ultimately ?)
- Use leading order χPT

S-wave 

P-wave 

Estimate of Uncertainty

I. • Compare with CP conserving amplitude

H_W also an $(8_L, 1_R)$ operator as Q_6

S-wave 

P-wave 

 Fit to data or Bag model

Results: in some units

$S_{exp} = 1.47 \pm 0.01$ vs $S_{Th} = 1.5$

$P_{exp} = 9.98 \pm 0.24$ vs $P_{Th} = 10.4$

P waves for Σ, Ξ do not work

II. • – compute size of a higher order term

S - wave  factorization ~ lowest order

P- wave  ~ 30% of lowest order

∴ - overall factor 2 for S, P

- extra 30% in P relative to S

∴

$$\boxed{A(\Lambda^0_-)_{SM} = (-3.0 \pm 2.6) \times 10^{-5}}$$

Beyond SM

- early estimates in specific models not too promising
    - very hard to distinguish from SM
- model independent analysis

  Consider all dim 6 operators consistent with SM

  $$H_{eff}^{\Delta S=1} = \left(H_{eff}^{SM} + \sum_i \lambda_i Q_i^{New}\right)^{\Delta S=1}$$

  Calculate $A(\Lambda^0_-)$, ϵ, ϵ'/ϵ with model for matrix elements

- General Result

$$Q_i^{New}$$

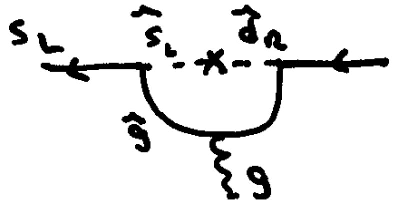
P-even	P-odd
• $\phi_P \neq 0$	• $\phi_S \neq 0$
• $\epsilon \neq 0$, $\epsilon'/\epsilon = 0$	• $\epsilon'/\epsilon \neq 0$, $\epsilon = 0$

- stronger bounds on P-odd
- $A(\Lambda^0_-) \sim \underline{\underline{5 \times 10^{-4}}}$ is possible.

Specific Example

$$H_{new} = \left[a_{LR}\, \bar{d}\, \sigma_{\mu\nu} t^a (1+\gamma_5) s + a_{RL}\, \bar{d}\, \sigma_{\mu\nu} t^a (1-\gamma_5) s\right] G^{a\mu\nu}$$

- occurs in Weinberg model
- occurs in SUSY models



$+ \cdots$

Roughly:

$$\epsilon \sim \mathrm{Im}(a_{LR} + a_{RL}) \qquad \text{P-even}$$

$$\epsilon'/\epsilon \sim \mathrm{Im}(a_{LR} - a_{RL}) \qquad \text{P-odd}$$

$$A(\Lambda^0_-) \sim \mathrm{Im}(0.3\, a_{LR} + 3.6\, a_{RL})$$

- Recent interest in SUSY (Masiero, Murayama)
  - a_{LR} can naturally give $\epsilon'/\epsilon \sim 10^{-3}$ level
    - this was Weinberg model → not too large $A(\Lambda^0_-)$
  - a_{RL} can give larger A (no s-p cancellation)
  - The P-even case can give huge Λ (no ϵ' constraint)
    - motivated by $\lambda = \sqrt{m_d/m_s}$ (Barbieri, Dvali, Hall)

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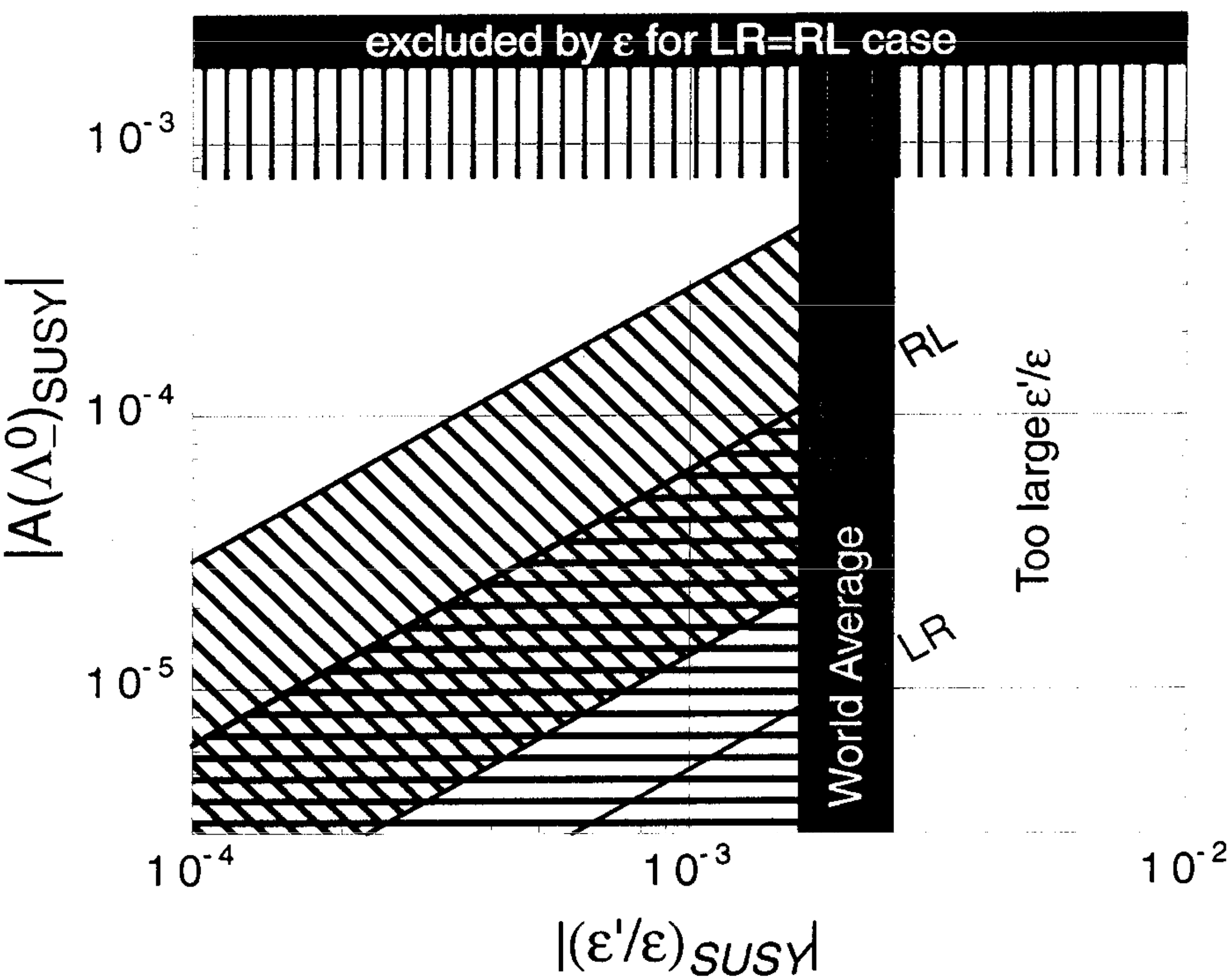

Conclusion

$A(\Lambda^0_-)$ is an additional $\not{CP}$ observable that does not receive much attention

- Future (near) E871 results should be very interesting at the 10^{-4} level since

$$A(\Lambda^0_-)_{SM} \simeq (-3 \pm 2.6) \times 10^{-5}$$

$$A(\Lambda^0_-)_{New} \leq 10^{-3} \quad \text{(bound from } \epsilon\text{)}$$

- E871 can rule out interesting scenarios with a measurement that <u>COMPLEMENTS</u> ϵ'/ϵ

- A non-zero result at 10^{-4} → Non SM

- A non-zero result at 10^{-5} → ?? similar to current ϵ'/ϵ
  - can be SM
  - can be something else
  - parameters (ρ, η etc) → ?? hadronic unc.

- A zero result at 10^{-6} → won't rule out SM without significant improvement in matrix elements.