Radiative and weak decays of decuplet baryons

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Outline

1. Chiral Perturbation Theory
2. Radiative two-body decays: $B^*(J = 3/2) \to B\gamma$
3. Radiative three-body decays: $B^*(J = 3/2) \to B\gamma\pi$
4. Weak three-body decays: $B^*(J = 3/2) \to Be\bar{\nu}$

Chiral symmetry

- The QCD mass term is not chirally invariant

$$\bar{q}\mathcal{M}q = \bar{q}_R\mathcal{M}q_L + \bar{q}_L\mathcal{M}q_R \tag{1}$$

- But, the three lightest quarks are approximately massless on a hadronic scale

$$\begin{pmatrix} m_u \\ m_d \\ m_s \end{pmatrix} \ll 1\,\mathrm{GeV} \leq \begin{pmatrix} m_c \\ m_b \\ m_t \end{pmatrix} \tag{2}$$

- $SU(3)_V \times SU(3)_A \times U(1)_V$ symmetry in chiral limit
- Symmetry is spontaneously broken to $SU(3)_V \times U(1)_V$

$\rightsquigarrow$ 8 Goldstone bosons $\Rightarrow$ pseudoscalar meson octet

- Good starting point for low-energy QCD

Chiral perturbation theory (χPT)

- An effective field theory

$$\mathcal{L} = \mathcal{L}^{(1)} + \mathcal{L}^{(2)} + \mathcal{L}^{(3)} + \cdots \tag{3}$$

- Neglect irrelevant degrees of freedom
- Expand in powers of momenta and quark masses
- Rely on symmetries to construct the effective Lagrangian

$\rightsquigarrow$ Chiral symmetry heavily reduces number of terms!

- A power counting scheme determines the relevance of each diagram
- Predictive power once low energy constants (LECs) are known
- External sources are naturally introduced: v^{μ}, a^{μ}, s, p

Radiative decays $B^*(J = 3/2) \to B\gamma$

- Interactions with photons can be studied by

$$v^\mu \to eA^\mu \begin{pmatrix} \frac{2}{3} & 0 & 0 \\ 0 & -\frac{1}{3} & 0 \\ 0 & 0 & -\frac{1}{3} \end{pmatrix} . \tag{4}$$

- At next to leading order (NLO), only one term contributes

$$\mathcal{L}_{\text{int}}^{(2)} = i c_M \epsilon_{ade} \bar{B}_c^e \gamma_\mu \gamma_5 (f_+^{\mu\nu})_b^d T_\nu^{abc} + \text{h.c.} \tag{5}$$

⇝ Vector transition form factor related to the LEC c_M.

- The partial decay width at tree level is

$$\Gamma_{B^* \to \gamma B} = \frac{c^2}{6\pi} p_{\text{cm}}^3 \frac{E_B + m_{B^*}}{m_{B^*}} . \tag{6}$$

Radiative decays $B^*(J = 3/2) \to B\gamma$

We can fit c_M to data and make predictions

Decay	$c/(c_M e)$	BR [%]	$\lvert c_M \rvert$ [GeV^{-1}]
$\Delta \to N\gamma$	$2/\sqrt{3}$	0.60±0.05	2.00±0.03
$\Sigma^{*+} \to \Sigma^+\gamma$	$-2/\sqrt{3}$	0.70±0.17	1.89±0.08
$\Sigma^{*-} \to \Sigma^-\gamma$	0	< 0.024	—
$\Sigma^{*0} \to \Sigma^0\gamma$	$1/\sqrt{3}$	**0.18±0.01**	—
$\Sigma^{*0} \to \Lambda\gamma$	-1	1.25±0.13	1.89±0.05
$\Xi^{*0} \to \Xi^0\gamma$	$-2/\sqrt{3}$	**4.0±0.3**	—
$\Xi^{*-} \to \Xi^-\gamma$	0	< 4	—

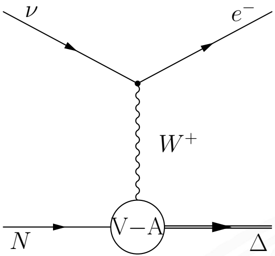
$\Sigma^{*-} \to \Sigma^-\gamma$, $\Xi^{*0} \to \Xi^0\gamma$ vanishes due to flavour symmetry (U-spin)

(predictions in boldface)

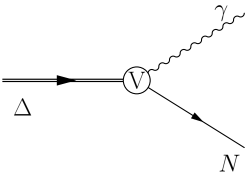
Holmberg, M. & Leupold, S. Eur. Phys. J. A (2018) 54: 103

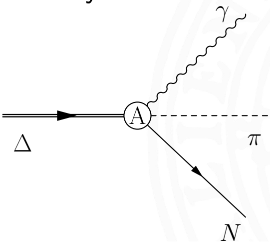
Axial-vector transition form factors

- Interesting for scattering neutrino-nucleon to electron-Delta
- Low energies: want to know deviation from LO result $\rightsquigarrow$ LEC c_E



- Vector and axial-vector transition form factors contribute also to $\Delta \to N\gamma$ and $\Delta \to N\pi\gamma$, respectively

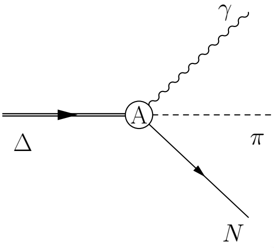




Axial-vector TFFs and three-body decays

Problems:

- Needs to be disentangled from bremsstrahlung
- Hard to measure for broad Delta



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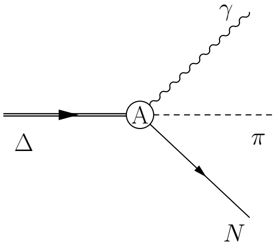
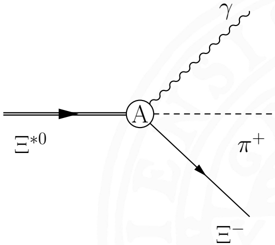
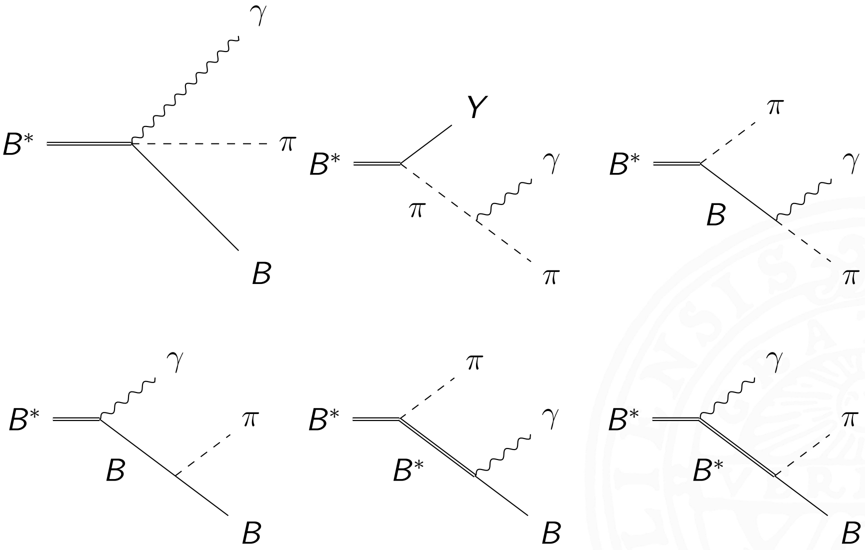


$\hookrightarrow$ Get some clue from radiate three-body decays of hyperons, e.g. cascades



Three body decays $B^*(J = 3/2) \to B\gamma\pi$



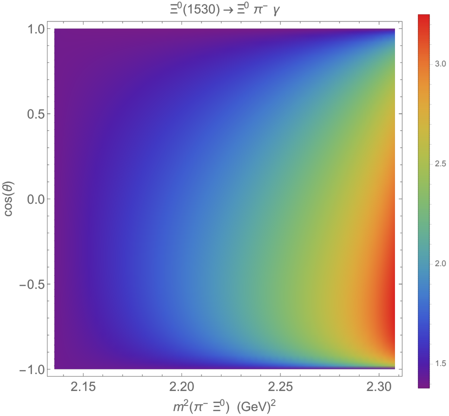
Three body decays $B^*(J=3/2) \to B\gamma\pi$

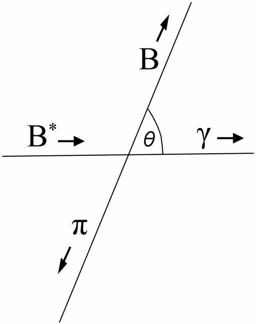
Preliminary predictions (none of these are measured!)

Decay	BR	Decay	BR
$\Sigma^{*+} \to \Sigma^+\pi^0\gamma$	1.1×10^{-6}	$\Xi^{*-} \to \Xi^-\pi^0\gamma$	7.9×10^{-6}
$\Sigma^{*+} \to \Sigma^0\pi^+\gamma$	3.6×10^{-5}	$\Xi^{*-} \to \Xi^0\pi^-\gamma$	1.3×10^{-3}
$\Sigma^{*+} \to \Lambda\pi^+\gamma$	—	$\Xi^{*0} \to \Xi^-\pi^+\gamma$	1.1×10^{-3}
$\Sigma^{*-} \to \Sigma^-\pi^0\gamma$	6.0×10^{-7}	$\Xi^{*0} \to \Xi^0\pi^0\gamma$	1.8×10^{-6}
$\Sigma^{*-} \to \Sigma^0\pi^-\gamma$	4.3×10^{-5}	$\Delta^{++} \to p\pi^+\gamma$	1.7×10^{-3}
$\Sigma^{*-} \to \Lambda\pi^-\gamma$	—	$\Delta^+ \to p\pi^0\gamma$	6.6×10^{-5}
$\Sigma^{*0} \to \Sigma^+\pi^-\gamma$	5.7×10^{-5}	$\Delta^+ \to n\pi^+\gamma$	7.4×10^{-4}
$\Sigma^{*0} \to \Sigma^-\pi^+\gamma$	3.2×10^{-5}	$\Delta^0 \to p\pi^-\gamma$	1.0×10^{-3}
$\Sigma^{*0} \to \Sigma^0\pi^0\gamma$	2.5×10^{-8}	$\Delta^0 \to n\pi^0\gamma$	7.2×10^{-6}
$\Sigma^{*0} \to \Lambda\pi^0\gamma$	3.5×10^{-6}	$\Delta^- \to n\pi^-\gamma$	2.3×10^{-3}

(Photon energy cut at 25 MeV)

Three body decays $B^*(J = 3/2) \to B\gamma\pi$



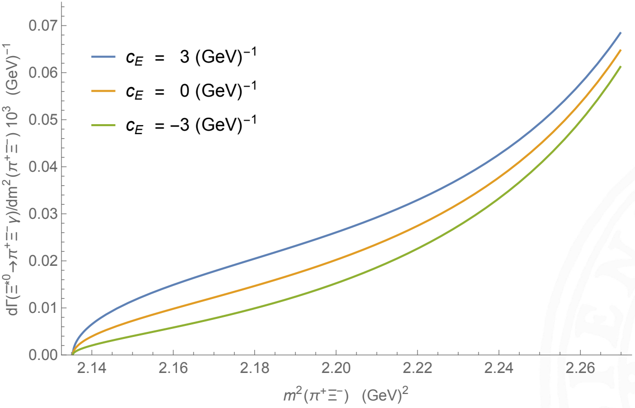


- Blows up when photon energy approaches zero

$$m^2(\pi B) = M_{B^*}^2 - 2M_{B^*}E_\gamma \quad (7)$$

Three body decays $B^*(J = 3/2) \to B\gamma\pi$

- Consider $\Xi^{*0}(1530) \to \Xi^-\pi^+\gamma$



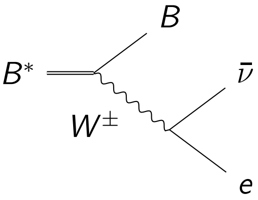
- Branching ratio $1.3 \cdot 10^{-3}$ (cut off photon energy at 25 MeV)

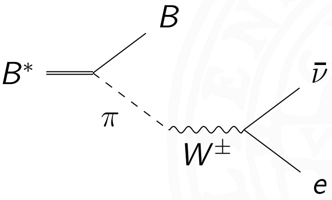
Weak decays $B^*(J = 3/2) \to Be\bar{\nu}$

- Interactions with the W-boson obtained by

$$l_\mu = v_\mu - a_\mu \to -\frac{g_W}{\sqrt{2}} W_\mu^+ \begin{pmatrix} 0 & V_{ud} & V_{us} \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix} + \text{h.c.} \qquad (8)$$

- At NLO, decay depends on 3 LECs (c_M, c_E, h_A)

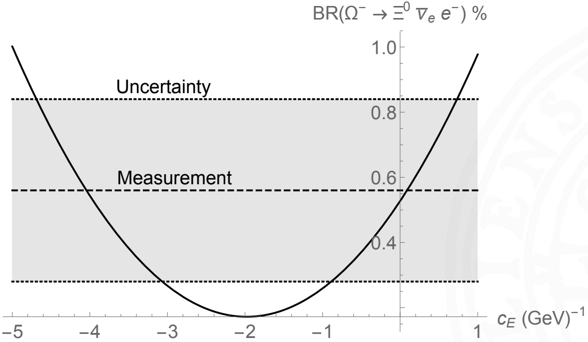




Decay $\Omega^- \to \Xi^0 \bar{\nu}_e e^-$

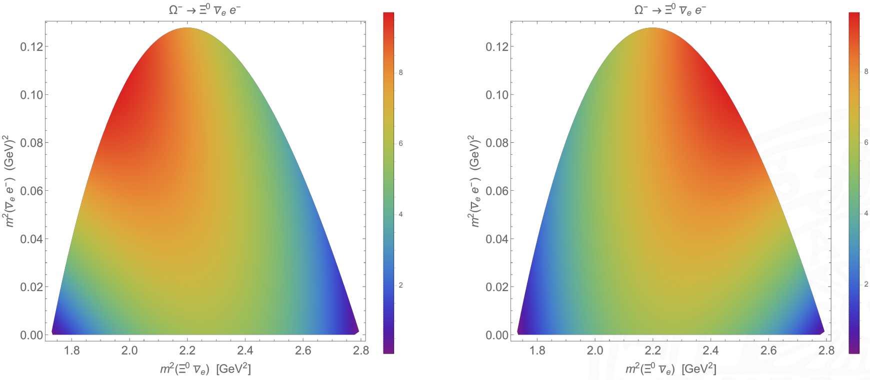
- The BR of $\Omega^- \to \Xi^0 \bar{\nu}_e e^-$ is known: $(0.56 \pm 0.28)\%$
- Two solutions of the LEC c_E

$$\frac{\Gamma_{\Omega^- \to \Xi^0 \bar{\nu}_e e^-}}{\Gamma_{\text{tot}}} = \alpha h_A^2 + \beta {c_M}^2 + \gamma {c_E}^2 + \delta h_A c_E \tag{9}$$



Decay $\Omega^- \to \Xi^0 \bar{\nu}_e e^-$

The Dalitz plot distinguishes between the two solutions of c_E



Summary

- χPT is a versatile tool for describing low-energy QCD
- Predicts a 4% BR of $\Xi^{*0} \to \Xi^0\gamma$
- Radiative three-body decays can be used to learn more about several LECs

$\hookrightarrow$ Interesting for neutrino physics

$\hookrightarrow$ However, BR are generally small, especially for neutral final states

- The BR of $\Xi^{*-} \to \Xi^0\,\pi^-\,\gamma$, $\Xi^{*0} \to \Xi^-\,\pi^+\,\gamma$ are of order 10^{-3}

$\hookrightarrow$ Can be used to pin down c_E

- The weak decay $\Omega^- \to \Xi^0 e^- \bar{\nu}_e$ can also be used to pin down c_E

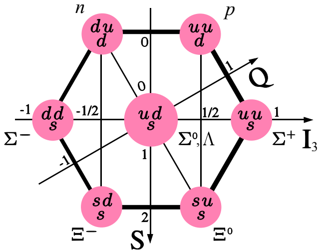
$\hookrightarrow$ Need higher quality measurements

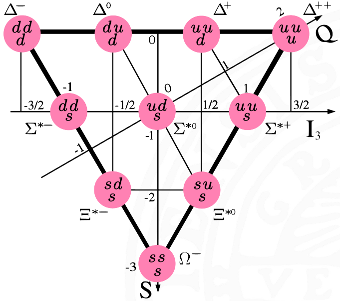
Backup slide: U-spin

No explicit flavor breaking at NLO, as $\mathcal{M} \sim m_G^2 \sim \mathcal{O}(p^2)$

U-spin, which interchanges d and s quarks, is conserved

Need $\mathcal{O}(p^4)$ terms $\rightarrow$ N^{3}LO at tree level or N^{2}LO loops





Backup slide: Dalitz plot $B^*(J = 3/2) \to B\gamma\pi$