Weak decays of Ω^- dibaryons

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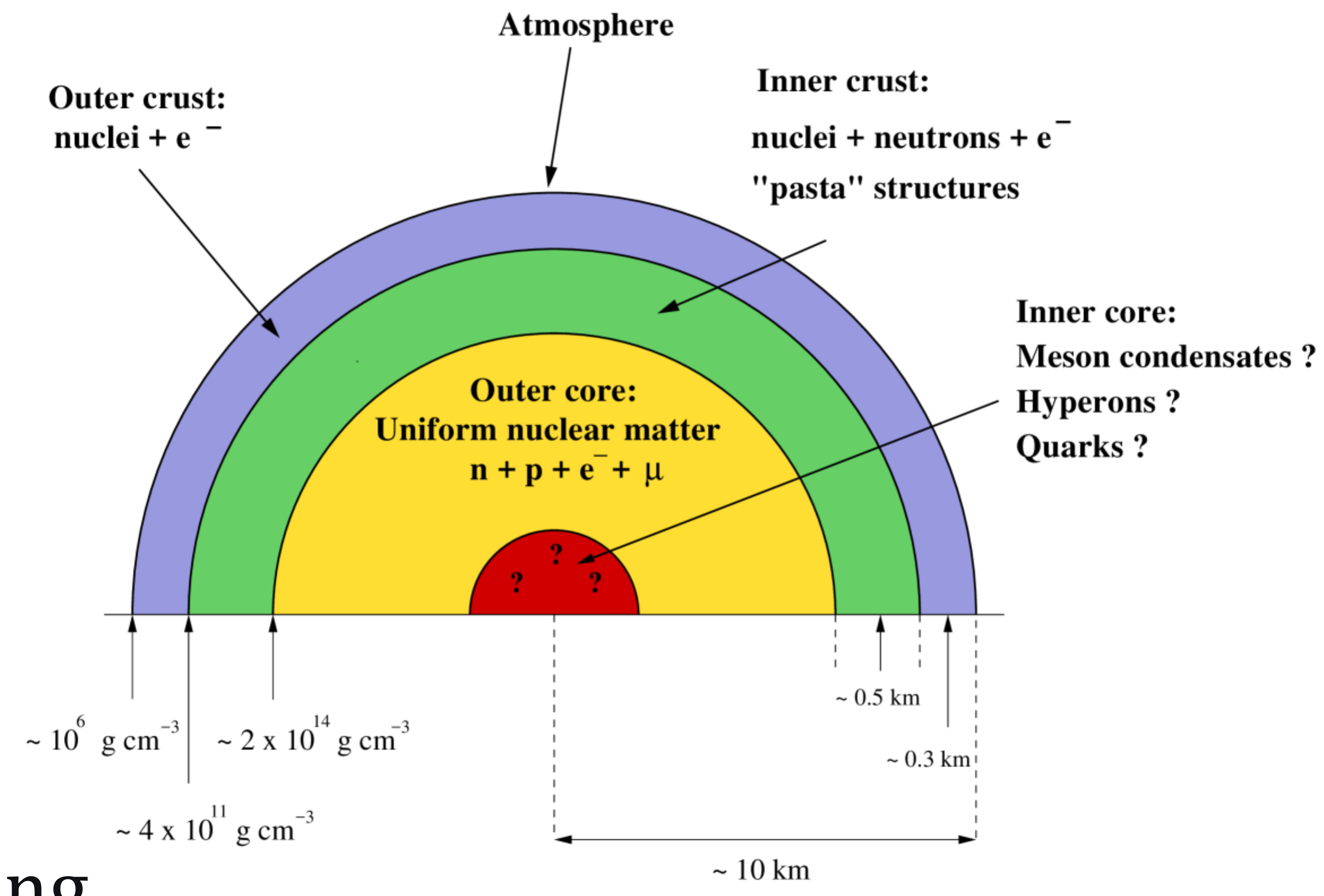
Motivation for studying Ω^- Dibaryons

- **Neutron stars:** Extreme environments to study ultra-dense matter.
- **At >2–3 ρ_0:** Exotic particles like hyperons or dibaryons may appear.
- **Ω^- dibaryon :** Key to understanding hyperon–hyperon interactions.
- **Experimental Challenge & Opportunity:** short lifetime and specific decay topologies make them challenging but promising candidates for discovery in heavy-ion collision experiments



Vidaña, I. (2018). *A short walk through the physics of neutron stars*. arXiv:1805.00837 [nucl-th].

What are Hyperons and Hypernuclei?

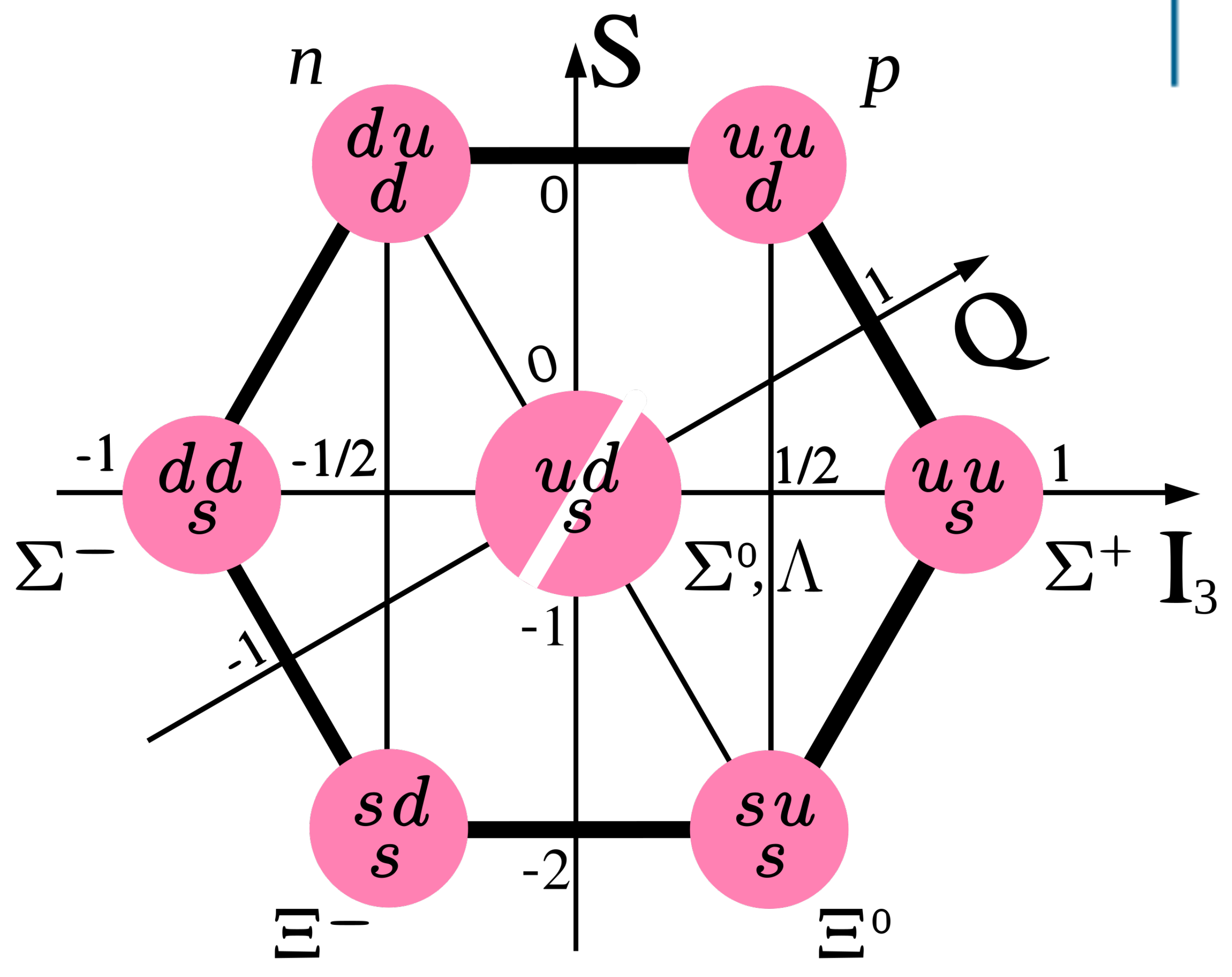
hyperon: baryon containing one or more strange quarks

- Hyperons from Baryon Octet (Spin ½): $\Sigma^{-}, \Sigma^{0}, \Sigma^{+}, \Lambda, \ \Xi^{-}, \Xi^{0}$

- Hyperons from Baryon Decuplet (Spin 3/2): $\Sigma^{*-}, \Sigma^{*0}, \Sigma^{*+}, \Xi^{*-}, \Xi^{*0}, \boldsymbol{\Omega^{-}}$

→ baryon mass increases with strangeness (number of s-quarks)

hypernuclei: nucleus with one or more hyperons



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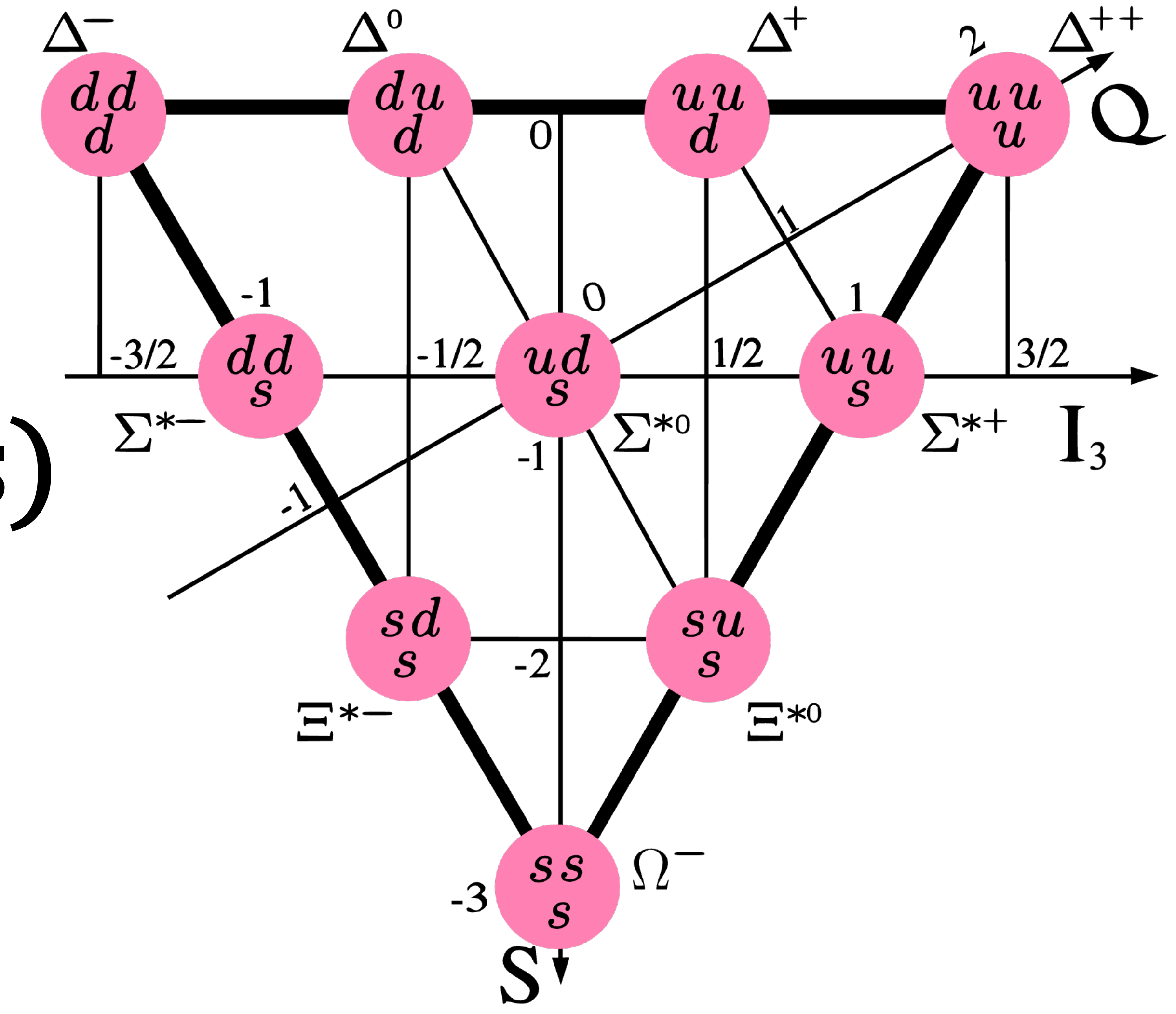


Holdsworth, J. (2007). *Baryon-decuplet-small.svg* [SVG-Grafik]. Wikimedia Commons.https://commons.wikimedia.org/wiki/File:Baryon-decuplet-small.svg

Hyperon decays

- Hyperons and Hypernuclei decay mainly weakly

- conserve baryon number and charge but violate strangeness, with $|\Delta S| = 1$.

- Examples : $\Xi^0 \rightarrow \Lambda + \pi^0$

  $\Xi^- \rightarrow \Lambda + \pi^-$

  $\Omega^- \rightarrow \Lambda + K^- \ (67.7\%)$

  $\Omega^- \rightarrow \Xi^0 + \pi^- \ (24.3\%)$

  $\Omega^- \rightarrow \Xi^- + \pi^0 \ (8.55\%)$

→ approximate lifetime: $\tau \approx 10^{-10} s$

Dibaryons

- **Definition:** Exotic, composite particles made of two baryons
- **Composition:** Can be combinations of nucleons (p, n) and/or hyperons (Λ, Σ, Ξ).
- **Key Property:** carry **strangeness**.
- **Lifetime:** order of the weak decay of a free Λ hyperon (cτ = 8 cm).

$-S\backslash Z$	-2	-1	0	+1	+2
0			nn	np	pp
1		$\Sigma^- n$	$\Lambda\, n$	$\Lambda\, p$	$\Sigma^+ p$
2	$\Sigma^-\Sigma^-$	$\Xi^- n$	$\Lambda\Lambda$	$\Xi^0 p$	$\Sigma^+\Sigma^+$
3	$\Xi^-\Sigma^-$	$\Xi^-\Lambda$	$\Xi^0\Lambda$	$\Xi^0\Sigma^+$	
4	$\Xi^-\Xi^-$	$\Xi^0\Xi^-$	$\Xi^0\Xi^0$		
5	$\Xi^-\Omega^-$	$\Xi^0\Omega^-$			
6	$\Omega^-\Omega^-$				

(J. Schaffner, C.Greiner, Stöcker 1992, J. Schaffner, Dover, Gal, Millener, C.Greiner, Stöcker 1993, 1994)

Dibaryon Decay Modes

Dibaryons decay via the weak force :

A. Mesonic Decays

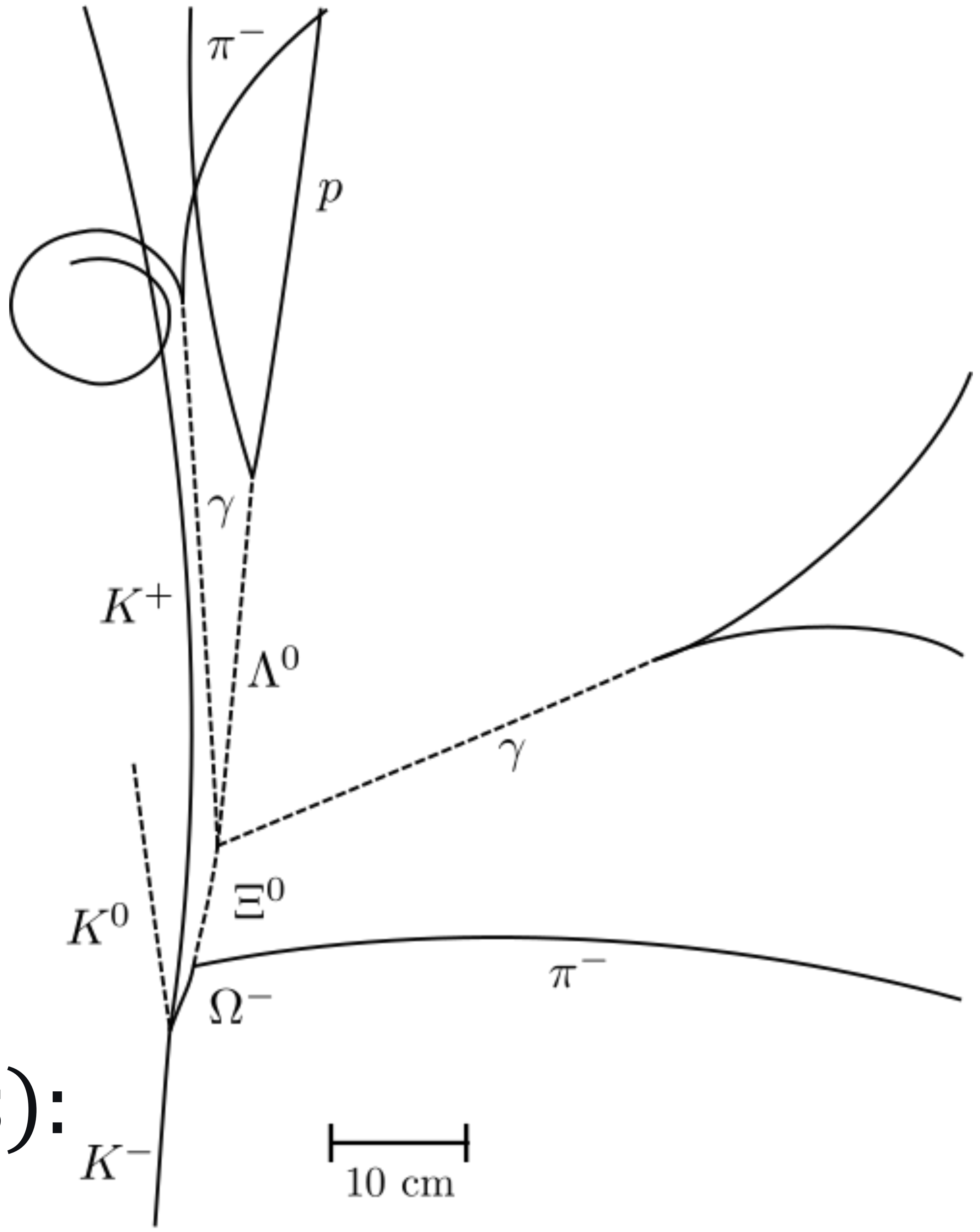
Example: $(\Xi^{-}\Lambda)_{b} \rightarrow \Lambda + \Lambda + \pi^{-}$

→ Branching ratios are similar to those of free hyperons.

B. Non-Mesonic Decays

These become dominant if the dibaryon is deeply bound.

- **Two-Body Charged Final States** (Ideal for TPC detectors):
  - $(\Sigma^{+}p)_{b} \rightarrow p + p$
  - $(\Xi^{0}p)_{b} \rightarrow p + \Lambda$
  - $(\Xi^{0}\Lambda)_{b} \rightarrow \Lambda + \Lambda$ *(Particularly interesting for experiments)*



Barnes, V.E. et al. *Observation of a Hyperon with Strangeness Minus Three* Phys. Rev. Lett. 12, 204 (1964)

Ω^- – Dibaryons

- Candidates for Dibaryons:

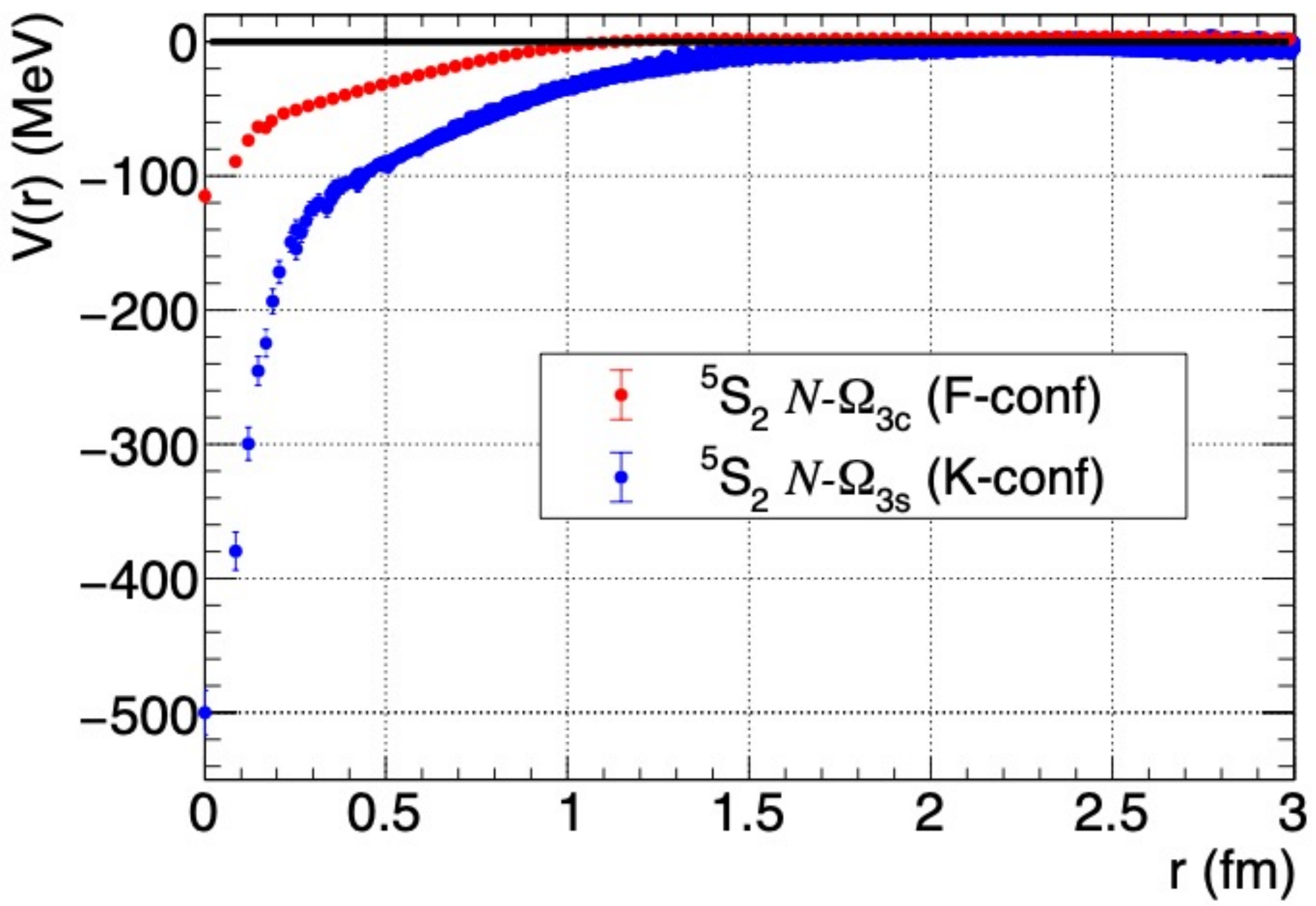
$$\Omega^-\Xi^-$$
$$\Omega^-\Xi^0$$
$$\Omega^-\Omega^-$$

- **ΩΩ dibaryon** is a unique six-quark state made purely of s - quarks.

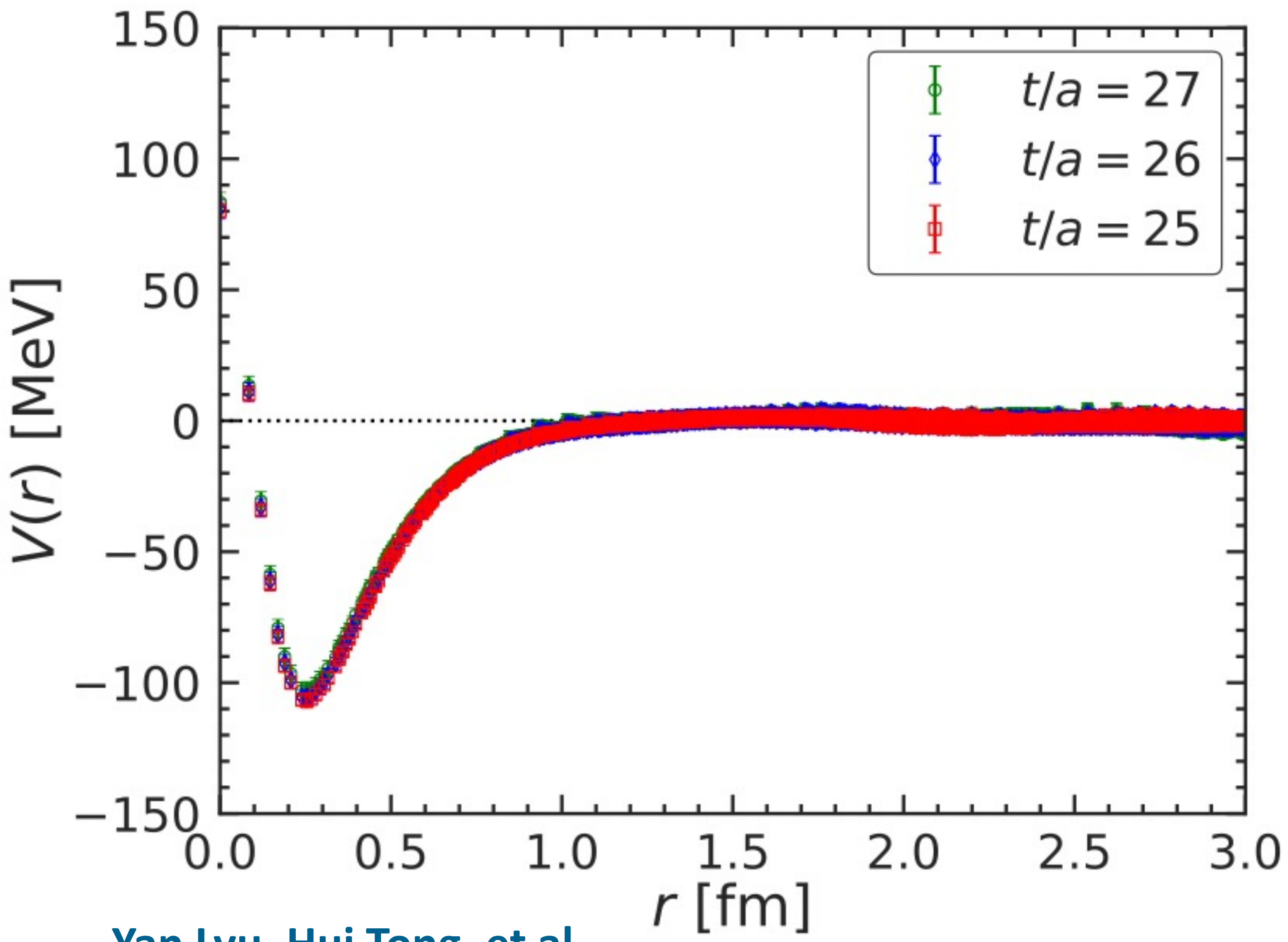
- **predicted** by theory (Lattice QCD) to be a weakly **bound state.**

- **Ω^- Properties:**
  - 3 strange quarks (sss)
  - Spin (J) = 3/2
  - Strangeness (S) = -3
  - Electric Charge = -1

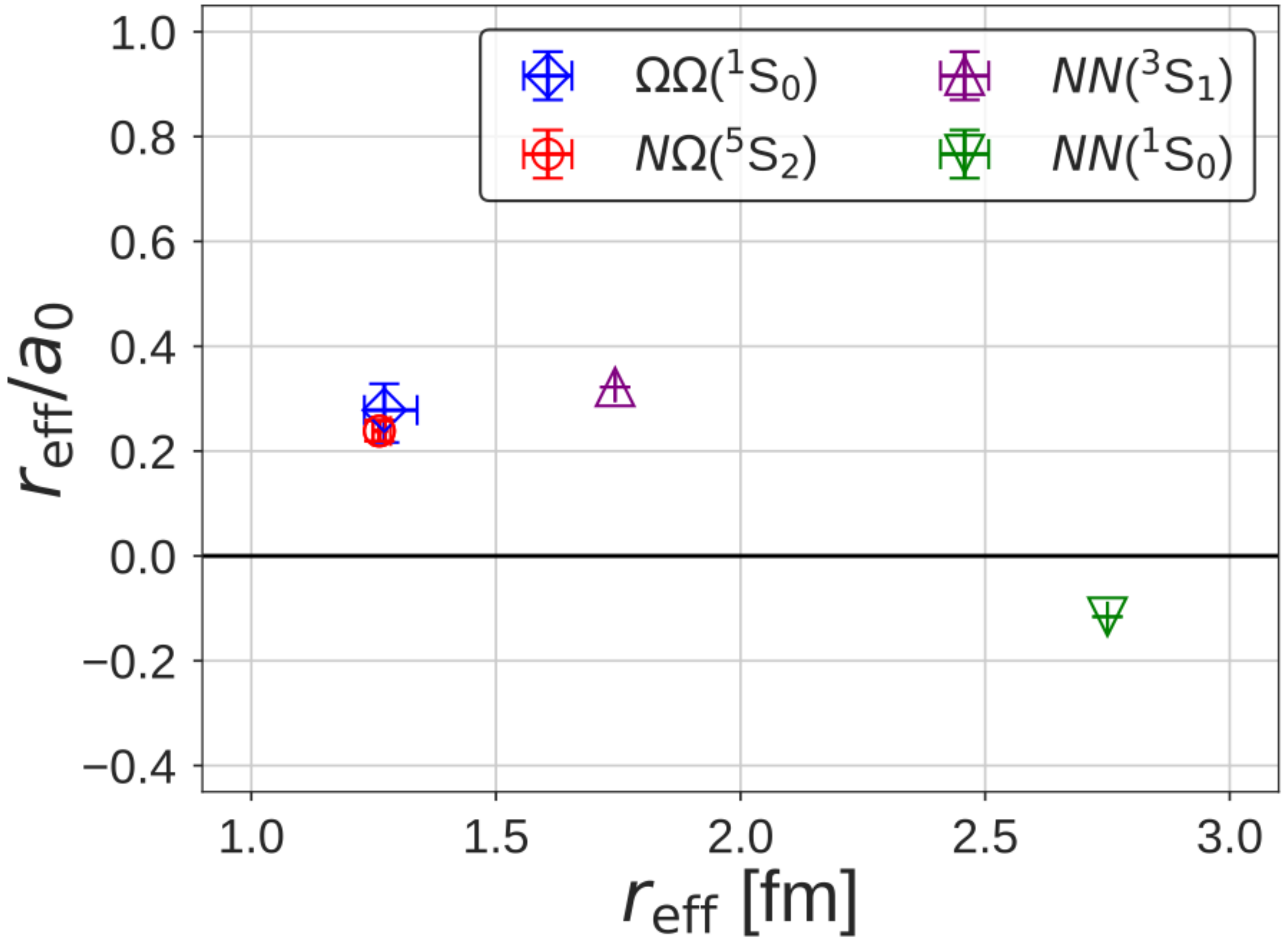
Lattice QCD for N−Ω_{3c} and Ω_{3c}−Ω_{3c}potential in the S-wave



L. Zhang, T. Doi, Y. Lyu et al., HAL QCD Collaboration, Phys. Rev. D 108, 054504 (2025)



Yan Lyu, Hui Tong, et al.
"Dibaryon with highest charm number near unitarity from lattice QCD"
arXiv:2102.00181 [hep-lat] (2021)



(Iritani et al., HAL QCD Collaboration, Phys. Rev. D 107, 094502 (2019))

SU(3) model & Pole model for hyperon weak decays

A) Weak mesonic decay :

Ansatz: Dibaryons decay mesonically like free hyperons

Matrix element of mesonic decay $B \rightarrow B' + \pi/K$:

$$\mathcal{A}(\Omega^- \rightarrow \mathcal{B}_i\phi_j) = \bar{u}_{\mathcal{B}_i}\left\{A_{ij}^{(P)}q_\mu + B_{ij}^{(D)}\gamma_5 q_\mu\right\}u^\mu_{\Omega^-} \qquad (1)$$

q_μ: four − momentum of outgoing π/K
$\bar{u}_{B_i}$ & $u^\mu_{\Omega^-}$: baryon spinors

$A_{ij}{}^{(P)}$: Parity conserving p − wave amplitude
$B_{ij}{}^{(D)}$: Parity violating d − wave amplitude → phase-space suppressed

(1) (Borasoy & Holstein, arXiv:hep-ph/9905398 (1999))

SU(3) model & Pole model for hyperon weak decays

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Effective Lagrangian in CHPT :

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{strong}} + \mathcal{L}_{\text{weak}} \tag{1}$$

Strong Lagrangian:

$$\mathcal{L}_{\text{strong}} = \frac{h_A}{2\sqrt{2}} \left(\epsilon^{ade} \overline{T}^{\mu}_{abc} (u_\mu)^b_d B^c_e + \epsilon_{ade} \overline{B}^c_e (u^\mu)^d_b T^{abc}_\mu \right) \tag{2}$$

with vertex factor involving any spin-1/2 baryon, spin-3/2 baryon or meson :

$$\mathcal{V}^{T\to\Phi B}_\mu = \underbrace{\frac{h_A}{2\sqrt{2}F_\pi}}_{g_{\Omega^-\Xi^-\overline{K}^0}} \mathcal{C}^{T\to\Phi B}_{nij} \, p^\Phi_\mu \tag{3}$$

(2) (Mommers & Leupold, arXiv:2208.11931 [hep-ph] (2022))

SU(3) model & Pole model for hyperon weak decays

Weak Lagrangian in ChPT

$$\mathcal{L}^{(0)}_{\text{weak}} = h_C\, \bar{T}^{\mu}_{abc}[u(h+h^\dagger)u^\dagger]^c{}_d T^{abd}_{\mu} + h_D\,\mathrm{tr}\big(\bar{B}\{u(h+h^\dagger)u^\dagger, B\}\big) + h_F\,\mathrm{tr}\big(\bar{B}[u(h+h^\dagger)u^\dagger, B]\big)$$
$$+ \tfrac{1}{4} h_\pi F_\pi^2\, \mathrm{tr}\big[u(h+h^\dagger)u^\dagger u_\mu u^\mu\big]\ . \qquad (4)$$

- $h + h^\dagger \rightarrow \lambda_6$ Gell − Mann matrices ensures hypercharge violation
- h describes s→d transitions ($\Delta I = 1/2$ rule)

Parameters: $h_c = 5.1 \cdot 10^{-8}\,\mathrm{GeV}$, $h_D = 0.44 \cdot 10^{-7}\,\mathrm{GeV}$, $h_F = -0.5 \cdot 10^{-7}\,\mathrm{GeV}$
$h_\pi = 3.2 \cdot 10^{-7}$, $F_\pi \simeq 0.0924\,\mathrm{GeV}$

(2) (Mommers & Leupold, arXiv:2208.11931 [hep-ph] (2022))

Weak decay Amplitudes of Ω^-- Dibaryons

Pole model calculations:

$\Omega^- \rightarrow \Lambda + K^-$:

$$A^{(P)}_{\Lambda K} = \frac{h_A}{2\sqrt{6}F_\pi}\left(\frac{d-3f}{M_\Lambda - M_{\Xi^0}} + \frac{h_c}{M_\Omega - M_{\Xi^*}}\right) = -3.75 \cdot 10^{-9}\ \mathrm{MeV}^{-1} \quad (1)$$

$\Omega^- \rightarrow \Xi^0 + \pi^-$:

$$A^{(P)}_{\Xi^0\pi^-} = \frac{C}{\sqrt{2}F_\pi}\left(\frac{h_c}{3(M_\Omega - M_{\Xi^*})} + \frac{h_\pi m_\pi^2}{2(m_K^2 - m_\pi^2)}\right) = 8.28 \cdot 10^{-10}\ \mathrm{MeV}^{-1} \quad (2)$$

$\Omega^- \rightarrow \Xi^- + \pi^0$:

$$A^{(P)}_{\Xi^-\pi^0} = \frac{C}{2F_\pi}\left(\frac{h_c}{3(M_\Omega - M_{\Xi^*})} + \frac{h_\pi m_\pi^2}{2(m_K^2 - m_\pi^2)}\right) = 5.76 \cdot 10^{-10}\ \mathrm{MeV}^{-1} \quad (3)$$

Experimental values:

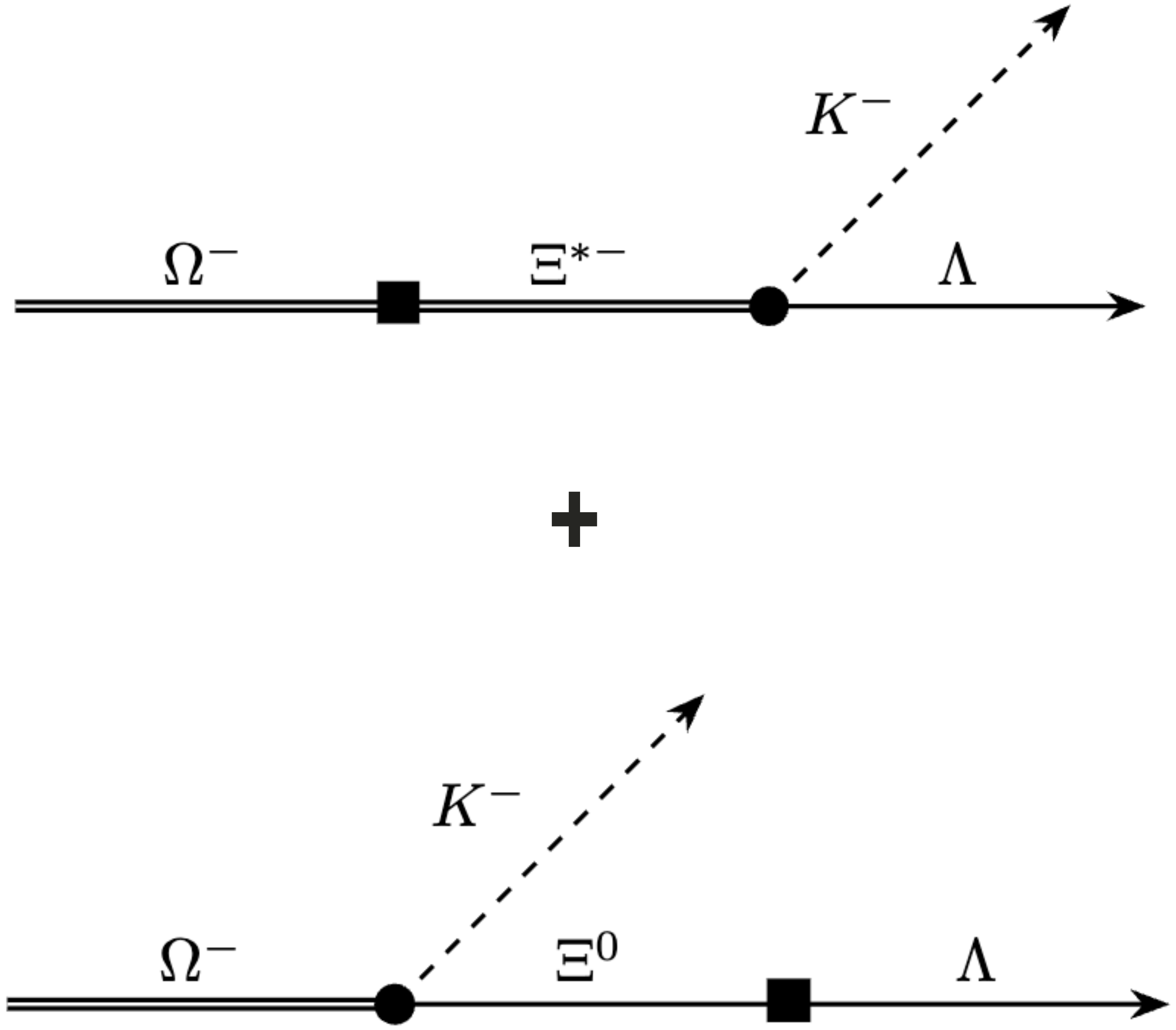
$$\mathrm{A}^{(\mathrm{P})}_{\Lambda\mathrm{K}} = 4.02 \cdot 10^{-9}\mathrm{MeV}^{-1}$$

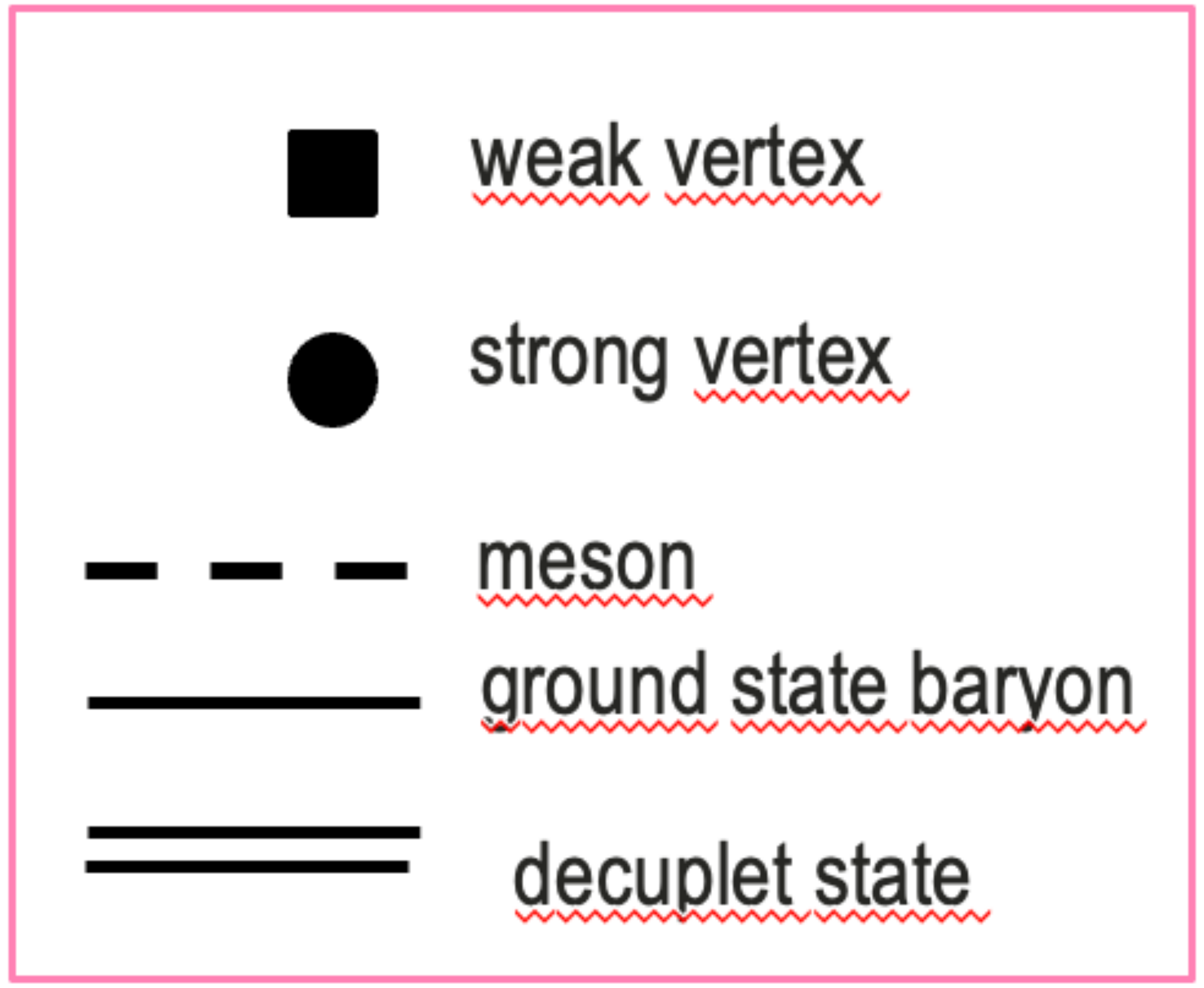
$$\mathrm{A}^{(\mathrm{P})}_{\Xi^0\pi^-} = 13.3 \cdot 10^{-10}\mathrm{MeV}^{-1}$$

$$\mathrm{A}^{(\mathrm{P})}_{\Xi^-\pi^0} = 8.18 \cdot 10^{-10}\mathrm{MeV}^{-1}$$

Strong and weak vertex decays (mesonic Polemodel)

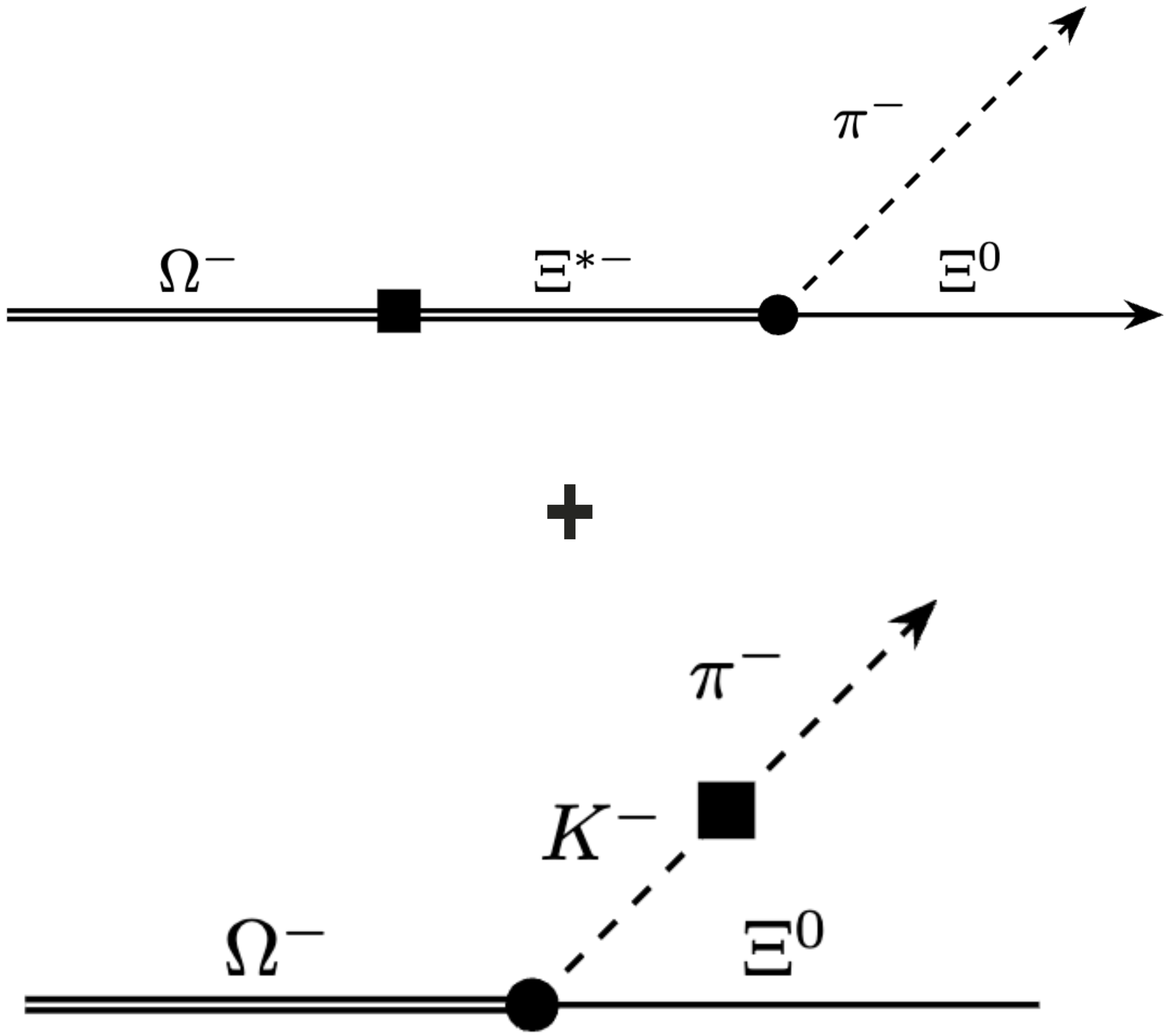
(1)

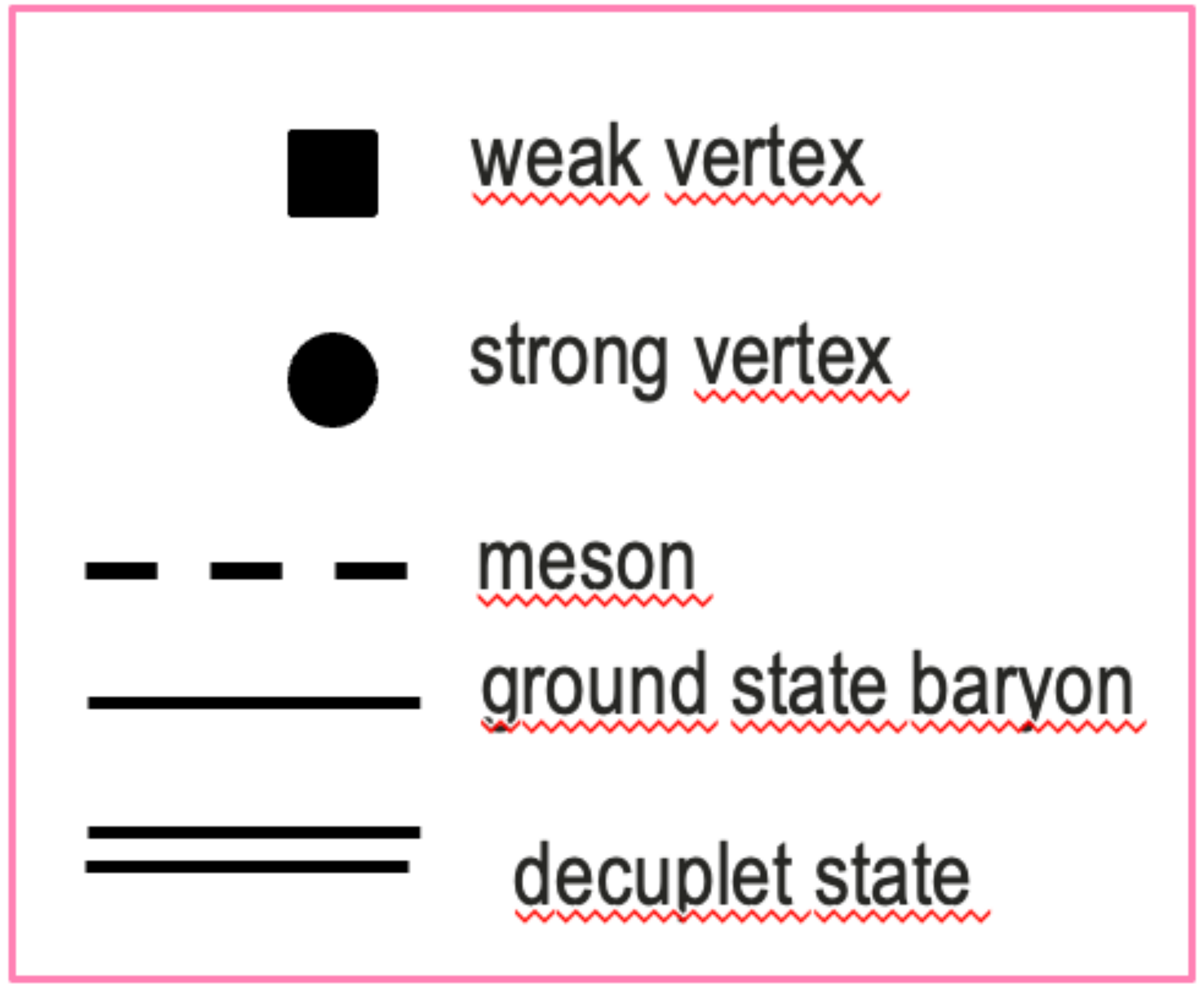




Strong and weak vertex decays (mesonic Polemodel)

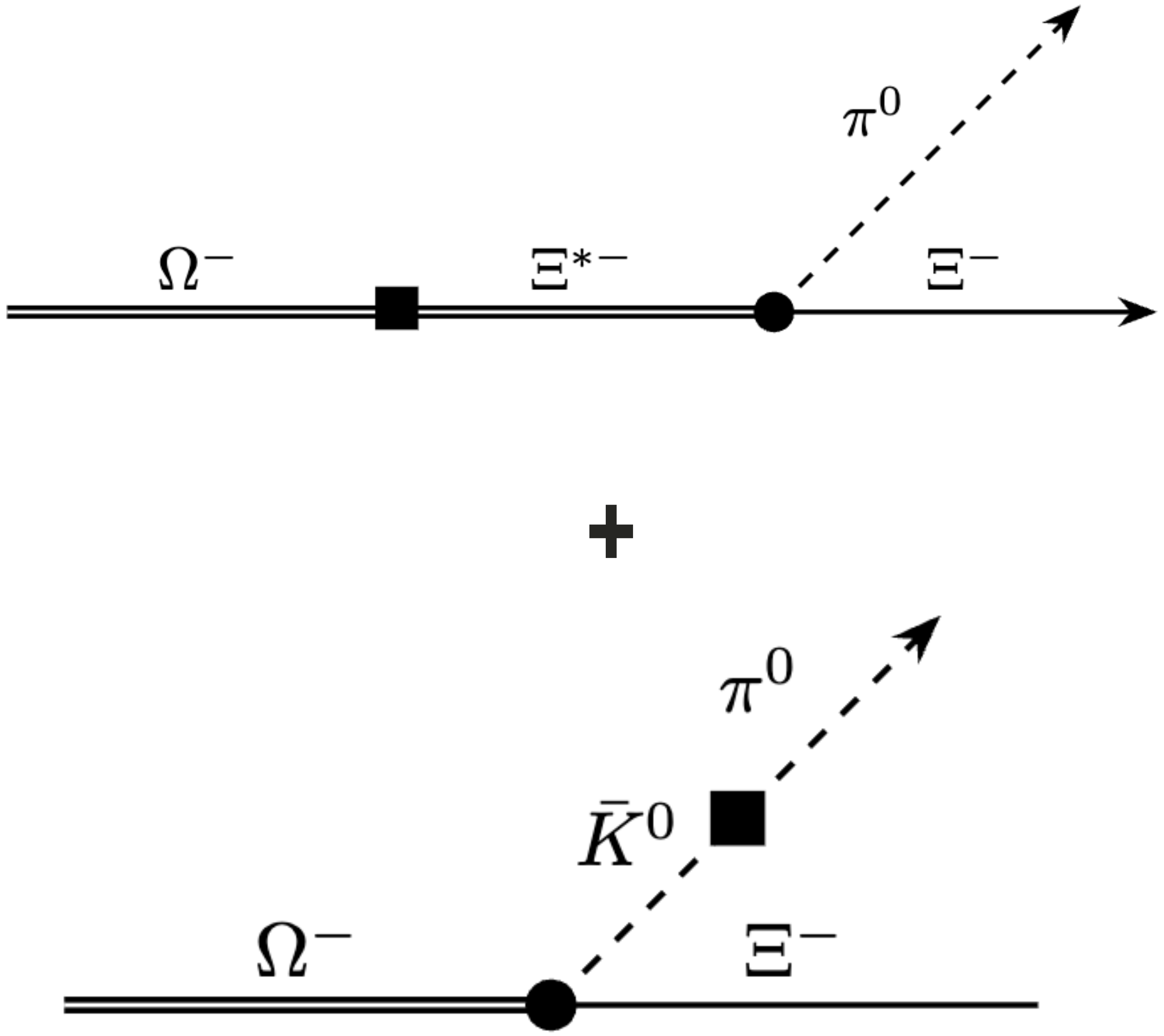
(2)

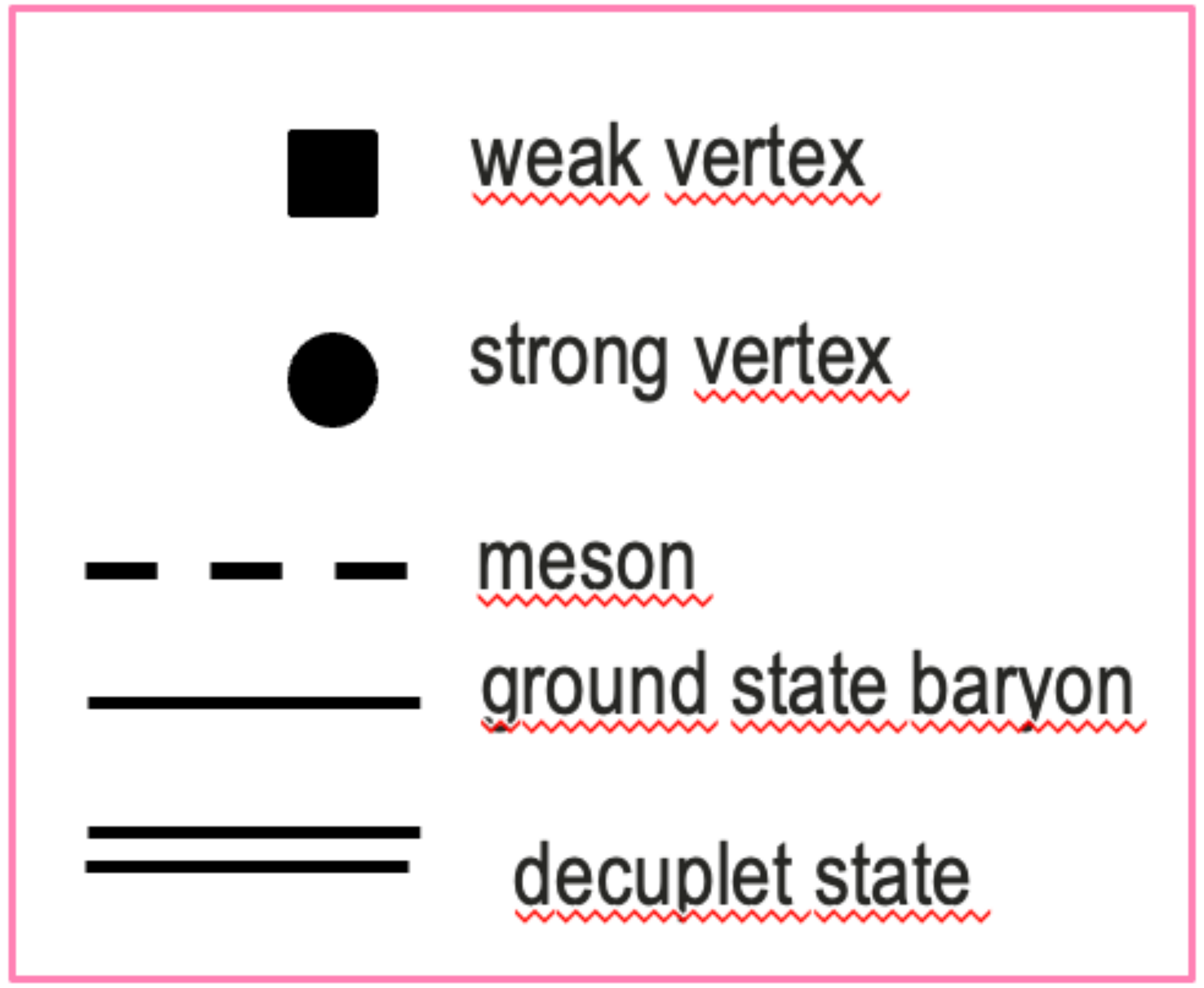




Strong and weak vertex decays (mesonic Polemodel)

(3)





SU(3) model for nonmesonic decay

B) Non-mesonic decay:

$$(B_1 B_2) \rightarrow B_1' + B_2'$$

- strong interaction vertex described through one-boson exchange approach
- weak interaction vertex based on weak hyperon decay
- A deuteron-like wavefunction, as parameterized by Krivoruchenko and Shchepkin (1982)
- one adjustable parameter: binding energy of the dibaryon states

Non mesonic decay of Ω^-

- Possible non mesonic decay channels:

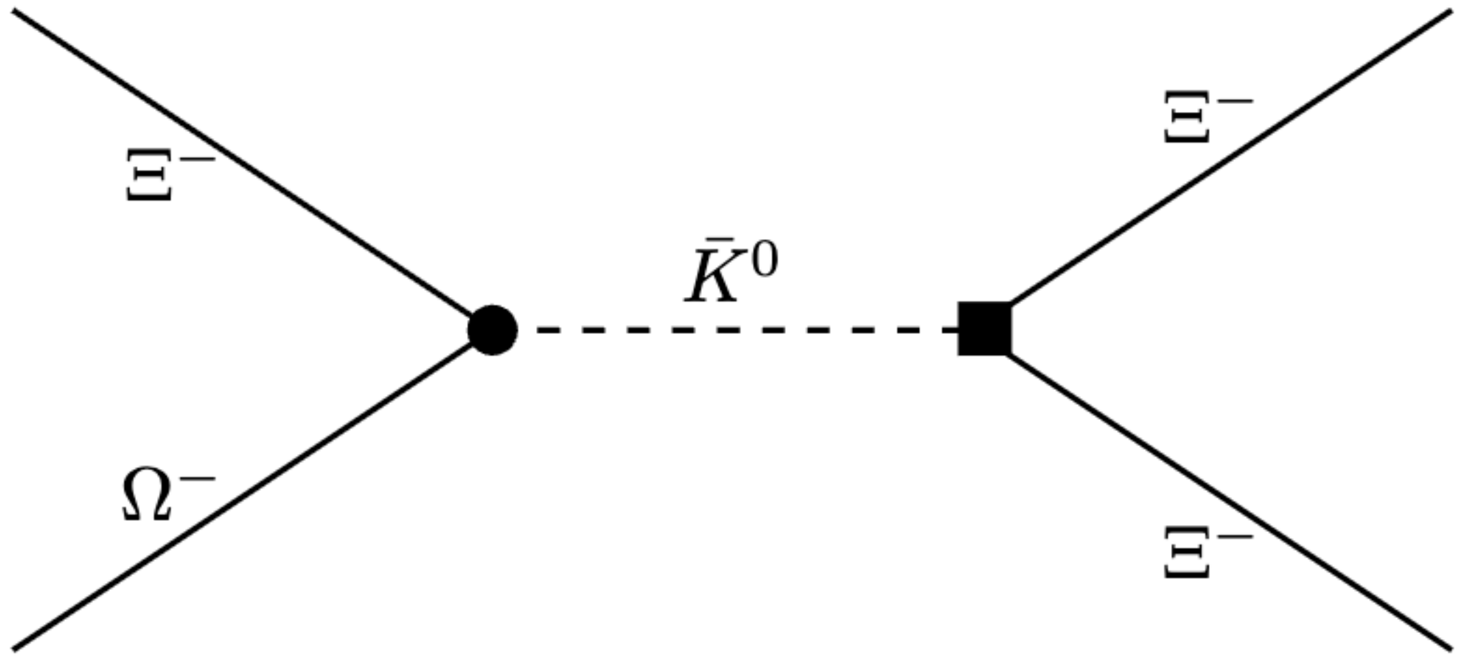
1) $\Omega^-\Xi^- \rightarrow \Xi^- + \Xi^-$

2) $\Omega^-\Xi^- \rightarrow \Omega^- + \Sigma^-$

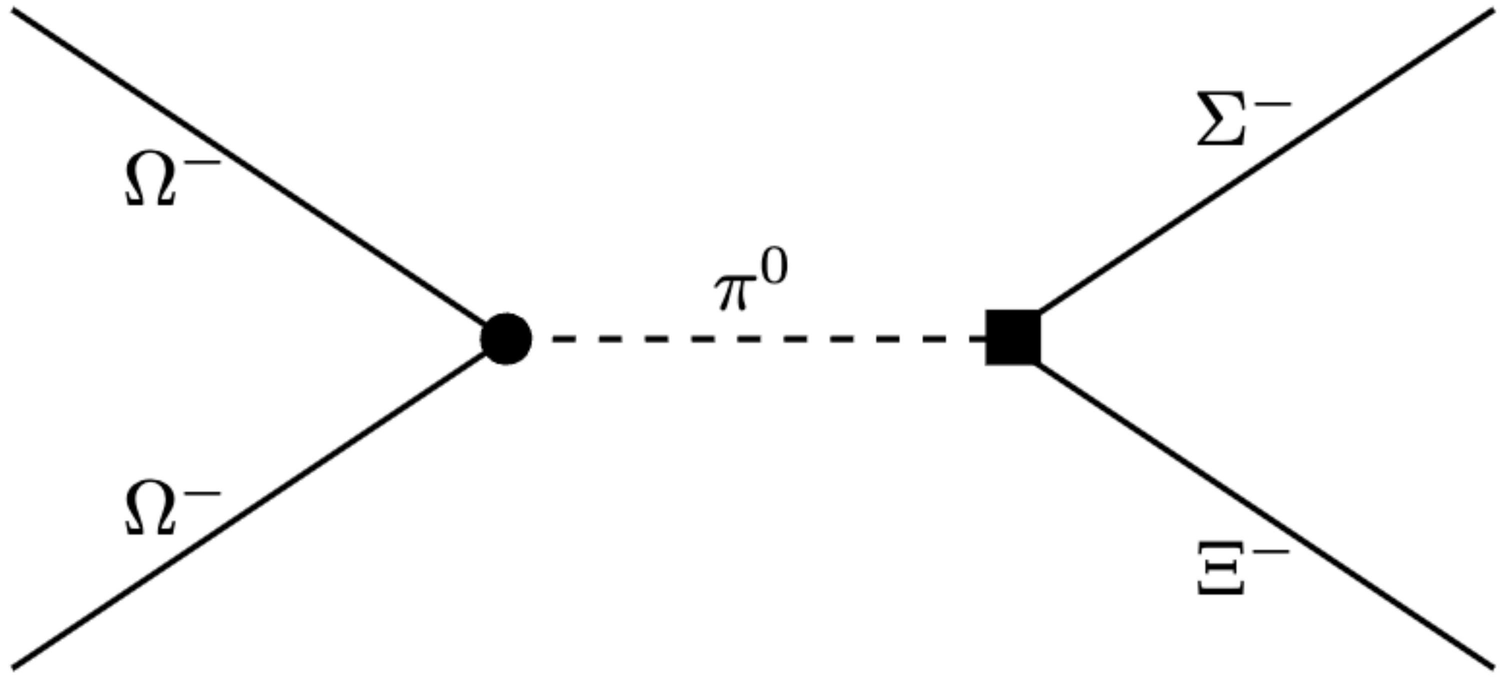
3) $\Omega^-\Xi^0 \rightarrow \Xi^- + \Xi^0$

4) $\Omega^-\Xi^0 \rightarrow \Omega^- + \Sigma^0$

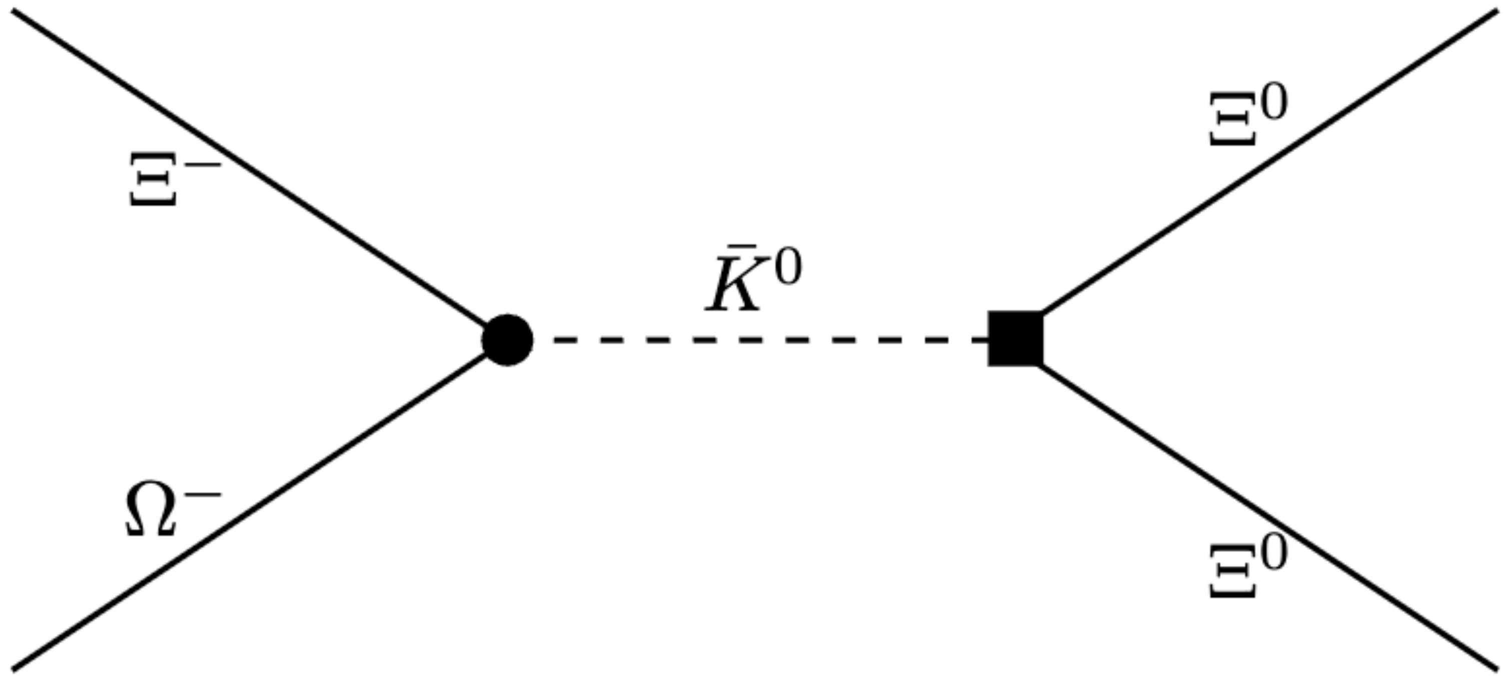
5) $\Omega^-\Omega^- \rightarrow \Xi^- + \Omega^-$



1)



2)



3)

Non mesonic decay of Ω^-

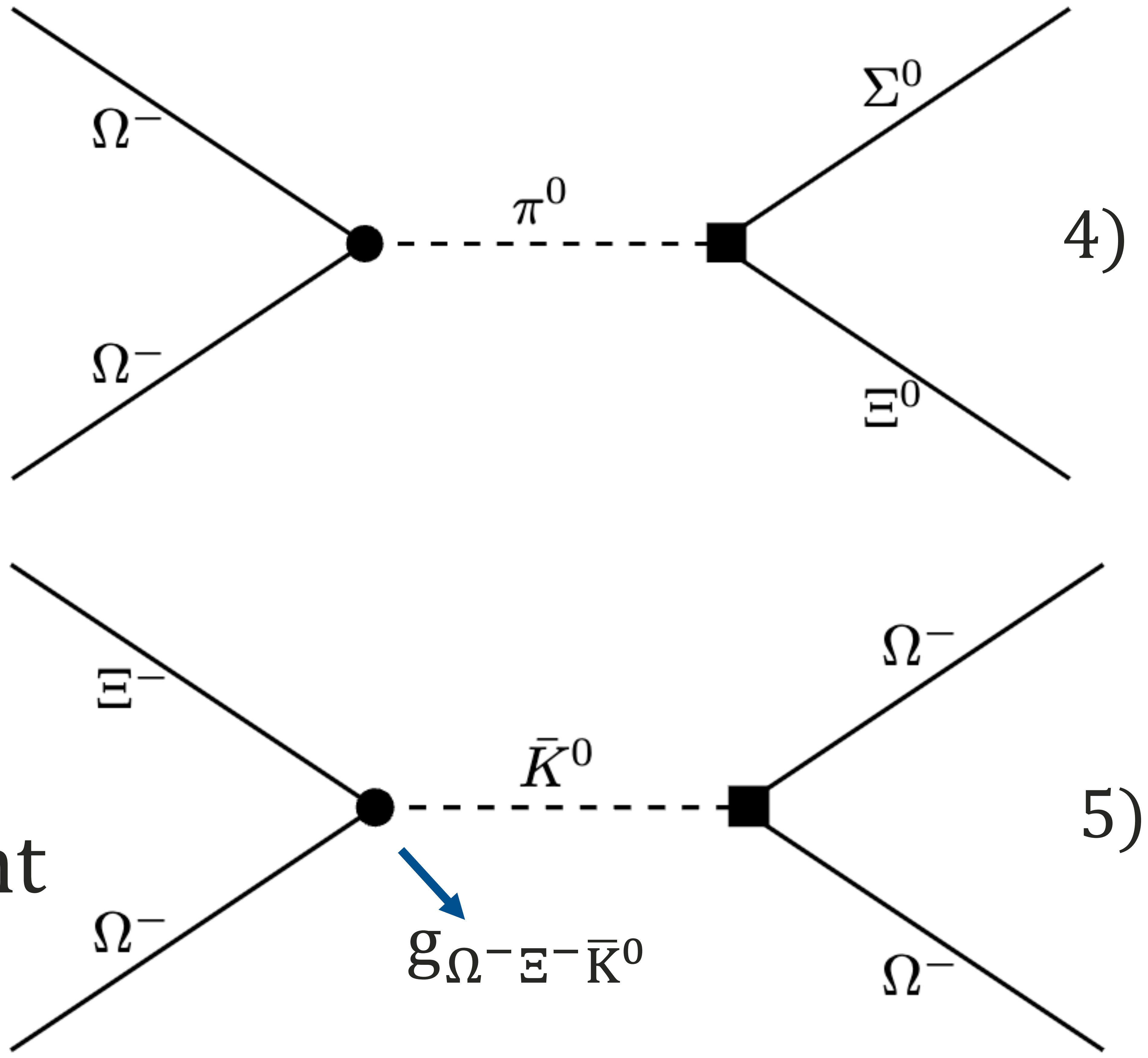
Coupling constants:

$g_{\Omega^-\Xi^-\overline{K}^0} = -1.06$

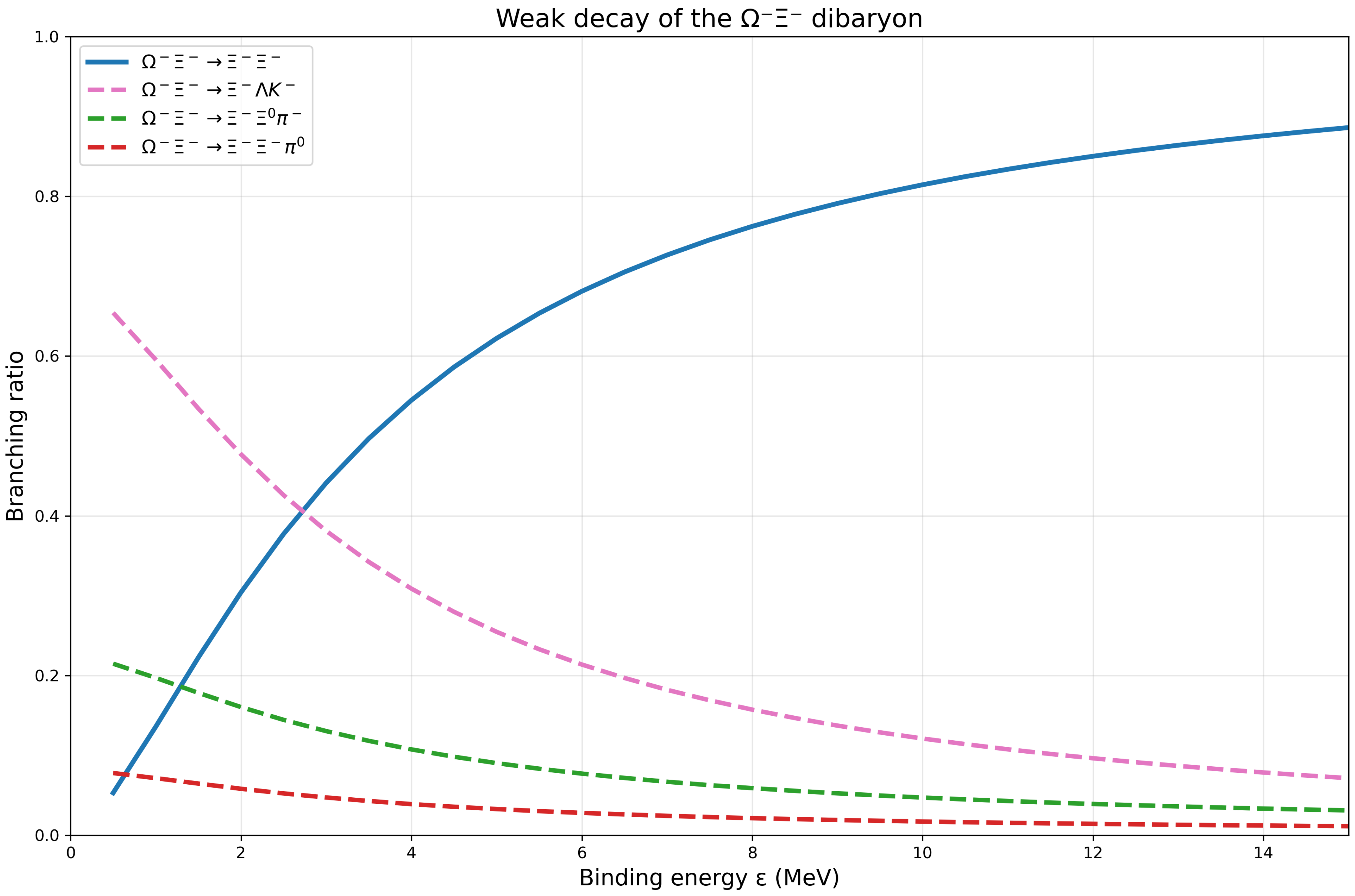
Assume $g_{\Omega^-\Omega^-\pi^0} = 0$, $A_{\Omega^-\Omega^-\pi} = 0$ and

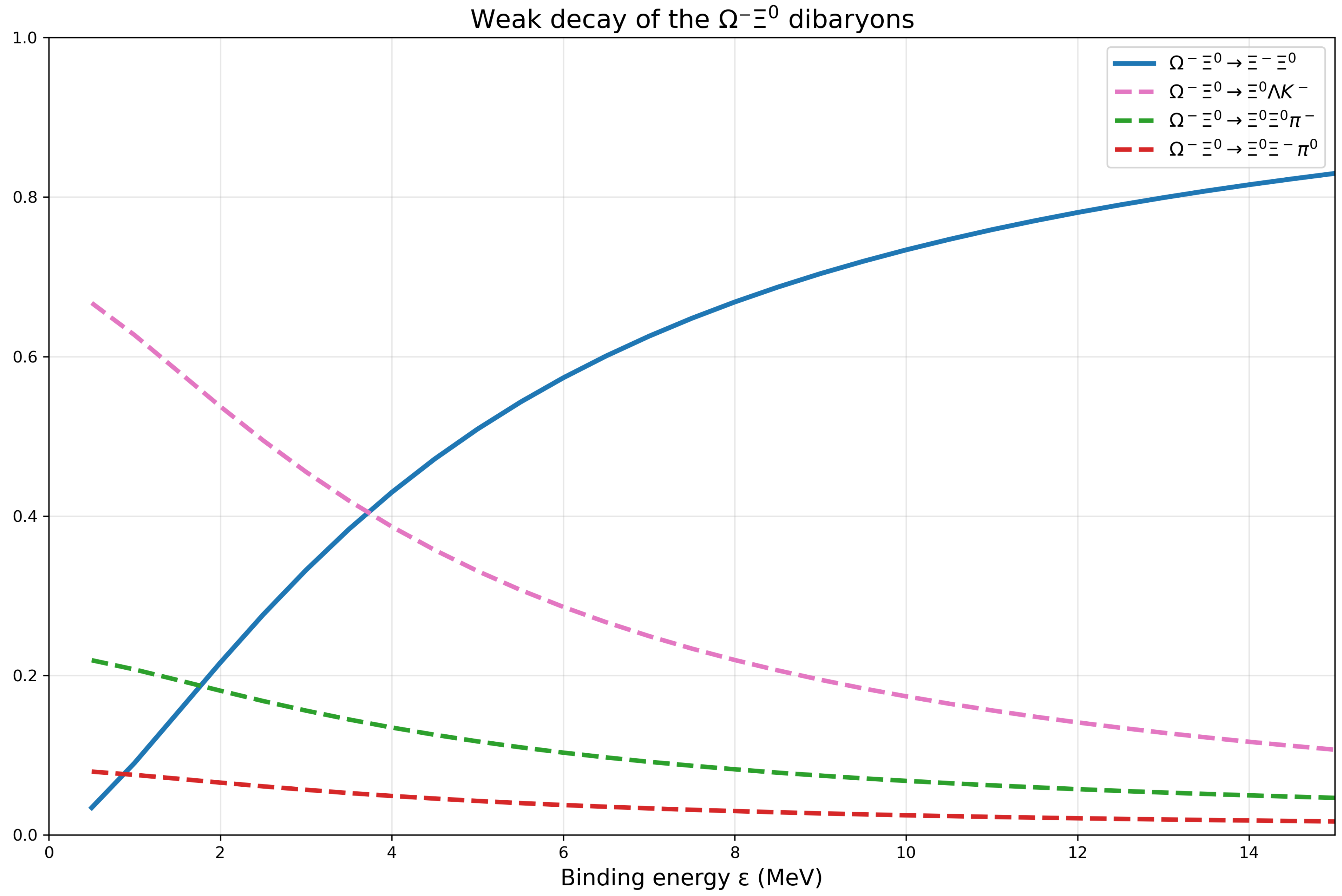
$g_{\Omega^-\Omega^-K} = 0$

-> decay channels 2) and 4) not relevant



Results





- For small ε, mesonic decays dominate $\rightarrow$ decays like free hyperons
- For large ε, non − mesonic decay dominates

$\rightarrow$ for $\Omega^-\Xi^-$ for $\varepsilon > 2.7$ MeV

$\rightarrow$ for $\Omega^-\Xi^0$ for $\varepsilon > 3.8$ MeV

Summary

- **Motivation:** Understanding hyperon-hyperon interaction and neutron star matter.
- **Decay Modes:**
  - **Mesonic:** similar to free hyperon decays (e.g. $\Omega^- \rightarrow \Lambda + K^-$).
  - **Non-Mesonic:** dominant for bound states -> ideal for experimental detection (e.g., $\Omega^-\Xi^- \rightarrow \Xi^- + \Xi^-$).
- **Theoretical Approach:** Usage of SU(3) model and Pole Model to calculate weak decay amplitudes
- **Key Result:** identifies promising non-mesonic decay channels for Ω^- dibaryons.
- **Outlook:** Modeling $\Omega^-\Omega^-$ decay modes by varying unkown coupling constant