How diquarks manifest themselves?

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Joint Workshop on Charmed Hadron Decays at BESIII, Belle, LHCb, Sept. 22-23, 2017, Nankai University

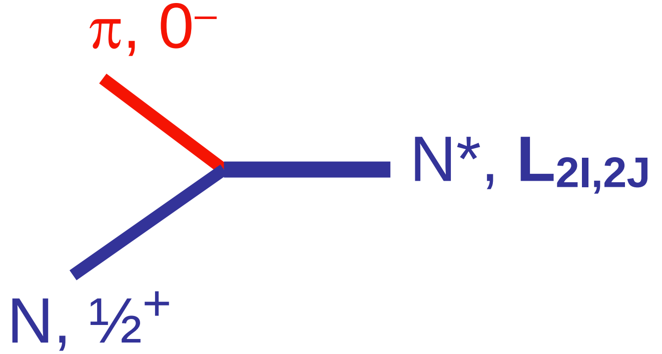
Outline

- The puzzle of diquark degrees of freedom?
- Hyperon weak decay and lifetime of free Λ and $\Sigma^{\pm}$
- Shortened lifetime of ${}^{3}_{\Lambda}\mathrm{H}$
- Heavy flavored baryon decays
- Brief summary

“Old question about “missing baryon resonances”

The non-relativistic constituent quark model (NRCQM) predicted a much richer baryon spectrum than observed in πN scatterings.

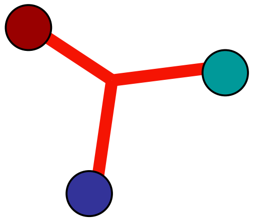
– “Missing Resonances”.

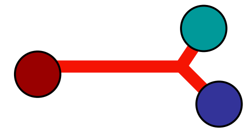


$P_{33}(1232)$ Δ
$P_{11}(1440)$
$S_{11}(1535)$
$D_{13}(1520)$
…

Dilemma:

a) The NRCQM is WRONG: quark-diquark configuration? …

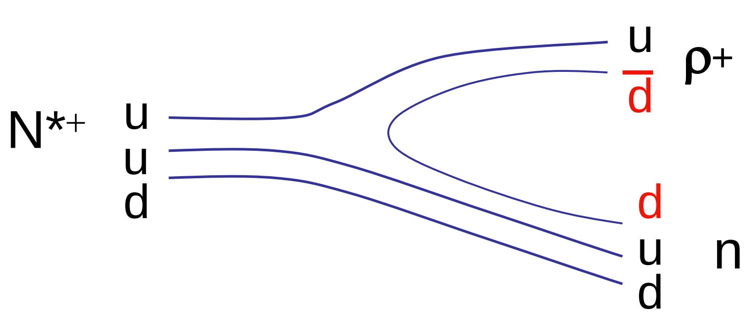




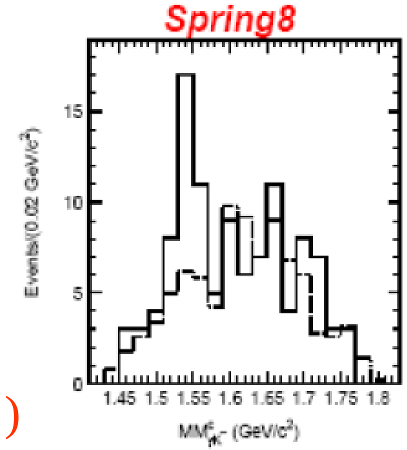
b) The NRCQM is CORRECT, but those missing states have only weak couplings to πN, i.e. small $g_{\pi N^*N}$. (Isgur, 1980)

Looking for "missing resonances" in $N^* \rightarrow$ ηN, KΣ, KΛ, ρN, ωN, ϕN, γN …

(Exotics …)



A baryon made of 5 quarks ?

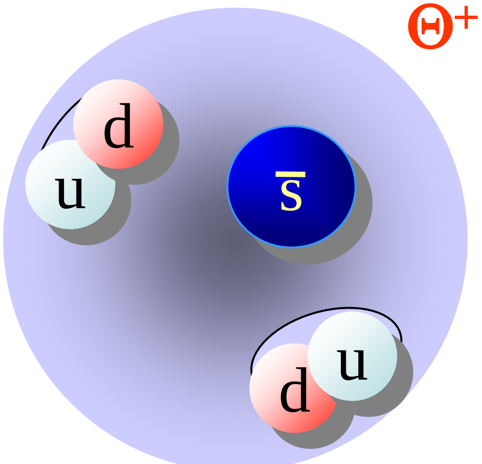


LEPS at SPring-8 (2003)

$\gamma\, n \rightarrow K^- \Theta^+$

$\hookrightarrow$ n (udd) $K^+ (u\bar{s})$

First evidence for a baryon with five constituent quarks !



$\Theta^+ (1/2^+)$

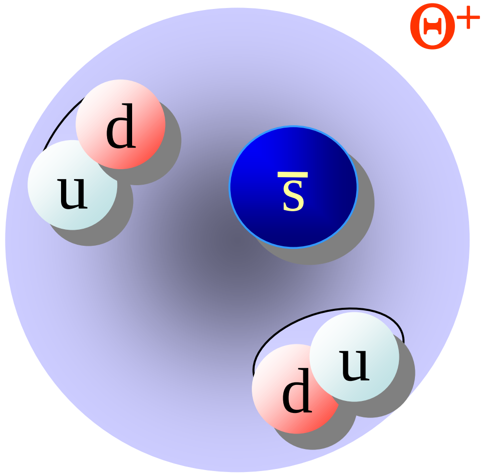
Conventional Baryon (qqq)	Pentaquark Baryon ($qqqq\bar{q}$)
Proton: (uud) Neutron: (udd) Λ: (uds) ⋮	Θ^+: ($uudd\bar{s}$) ⋮

LEPS Collaboration, Phys. Rev. Lett. 91 (2003) 012002, cited 987 times

Exotic $\Theta^+ \rightarrow n\, K^+ (u\bar{s})$

- First baryon with strangeness S=+1 from $\bar{s}$;
- mass of 1.54 GeV;
- narrow width < 15 MeV (~ 1 MeV).

Jaffe and Wilczek's scenario: diquark-diquark model



$\Theta^+(1/2^+)$

$\Theta^+ \quad (ud)(ud)\,\bar{s}$

	(ud)	(ud)	(ud)(ud)	$\bar{s}$
Spin	0	0	0	½
Color	$\bar{3}$	$\bar{3}$	3 ($\bar{6}$)	$\bar{3}$
Flavor	$\bar{3}$	$\bar{3}$	$\bar{6}$ (3)	$\bar{3}$
Ω^-(sss)	$\bar{3}$	$\bar{3}$	$\bar{6}$ (3)	$\bar{3}$

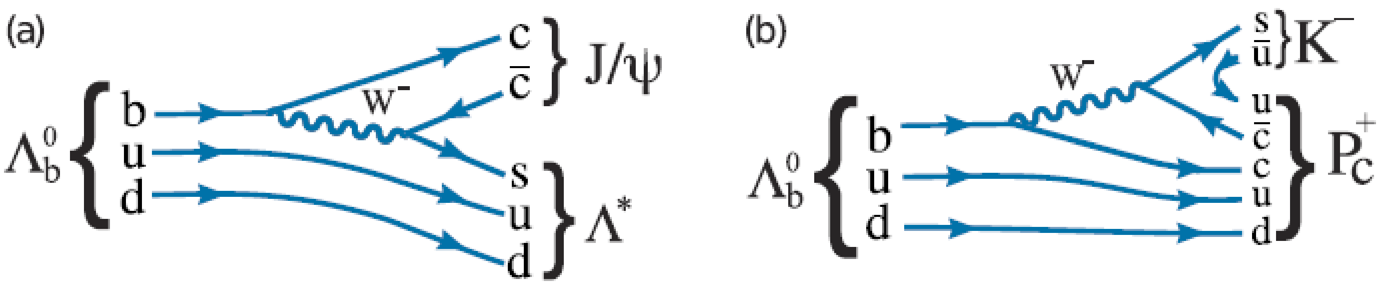
Θ^+ could have cluster structure due to the requirement of symmetry and strong QCD correlation.

Orbital angular momentum: 1

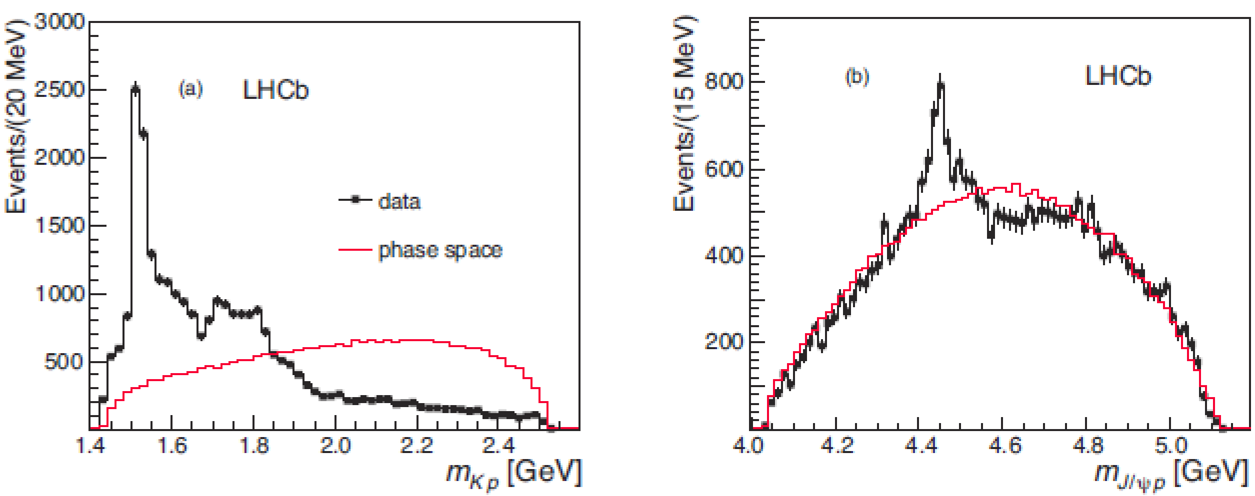
$$(ud)(ud)\bar{s} \rightarrow \bar{6} \otimes \bar{3} = \overline{10} \oplus 8$$

- Jaffe and Wilczek, Phys. Rev. Lett. 91, 232003 (2004); cited **804** times arXiv:1507.03414v2 [hep-ex], PRL(2015)

Observation of $J/\psi\, p$ resonances consistent with pentaquark states in $\Lambda_b^0 \to J/\psi K^- p$ decays



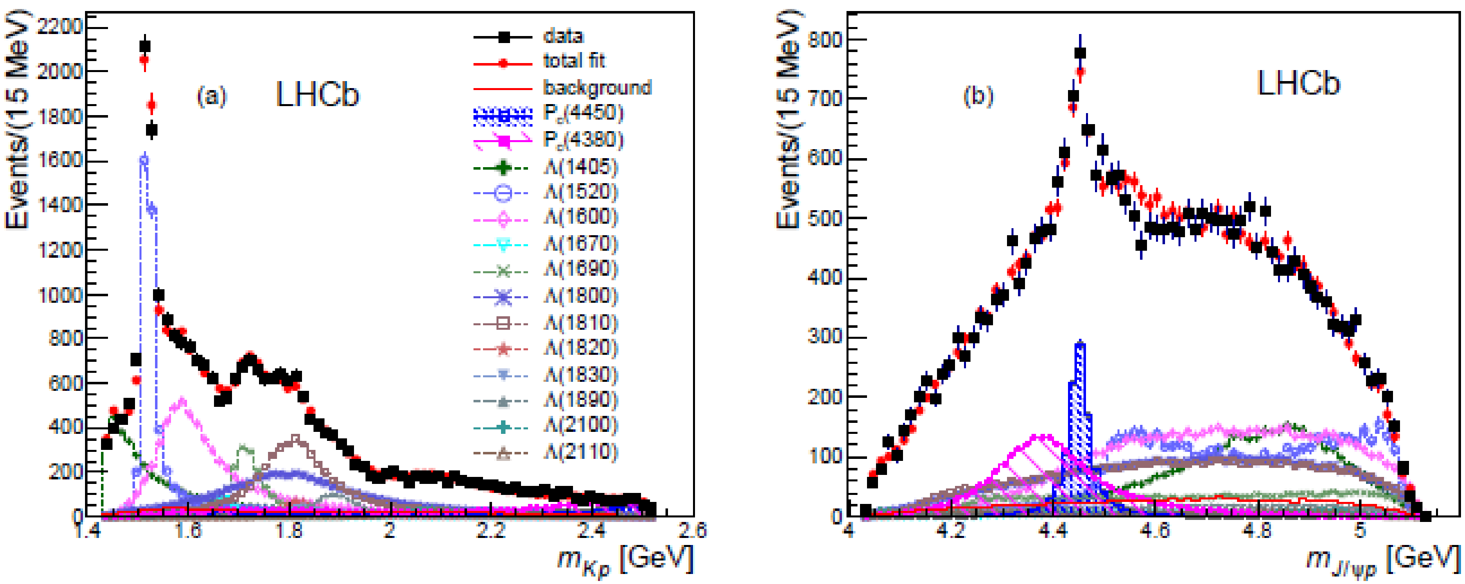
Diquark property keeps!



$Pc^+(4380)$

$Pc^+(4450)$

Data analysis including Λ* and pentaquark states



$M[P_c^+(4380)] = (4380 \pm 8 \pm 29)$ MeV, $\Gamma = (205 \pm 18 \pm 86)$ MeV

$M[P_c^+(4450)] = (4449.8 \pm 1.7 \pm 2.5)$ MeV, $\Gamma = (39 \pm 5 \pm 19)$ MeV

$J^P = (3/2^-, 5/2^+)$ or $(3/2^+, 5/2^-)$

Immediate theoretical studies:

1) Molecular states of e.g. $\Sigma_c^* \bar{D}^*$ favored by potential models:

R. Chen, X. Liu, X.-Q. Li, S.-L. Zhu, arXiv:1507.03704[hep-ph]

L. Roca, J. Nieves and E. Oset, arXiv:1507.04249 [hep-ph].

A. Feijoo, V. K. Magas, A. Ramos and E. Oset, arXiv:1507.04640 [hep-ph]

J. He, arXiv:1507.05200 [hep-ph]

U.-G. Meissner, J.A. Oller, arXiv:1507.07478v1 [hep-ph]

2) Multiquark state as an overall color singlet

L. Maiani, A.D. Polosa, and V. Riquer, arXiv:1507.04980 [hep-ph]

R.L. Lebed, arXiv:1507.05867 [hep-ph]

V.V. Anisovich et al., arXiv:1507.07652[hep-ph]

G.-N. Li, X.-G. He, M. He, arXiv:1507.08252 [hep-ph]

3) Soliton model

N.N. Scoccolaa, D.O. Riska, Mannque Rho, arXiv:1508.01172 [hep-ph]

4) Sum rules study

H. X. Chen, W. Chen, X. Liu, T.G. Steele and S. L. Zhu, arXiv:1507.03717

Z.-G. Wang, arXiv:1508.01468.

Some early studies:

J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. Lett. **105**, 232001 (2010) [arXiv:1007.0573 [nucl-th]].

J. J. Wu, R. Molina, E. Oset and B. S. Zou, Phys. Rev. C **84**, 015202 (2011) [arXiv:1011.2399 [nucl-th]].

J. J. Wu, T.-S. H. Lee and B. S. Zou, Phys. Rev. C **85**, 044002 (2012) [arXiv:1202.1036 [nucl-th]].

Z. C. Yang, Z. F. Sun, J. He, X. Liu and S. L. Zhu, Chin. Phys. C **36**, 6 (2012) [arXiv:1105.2901 [hep-ph]].

Alternative solutions?

Threshold enhancement produced by anomalous triangle singularity:

F.-K. Guo, U.-G. Meissner, W. Wang, and Z. Yang, arXiv:1507.04950 [hep-ph]

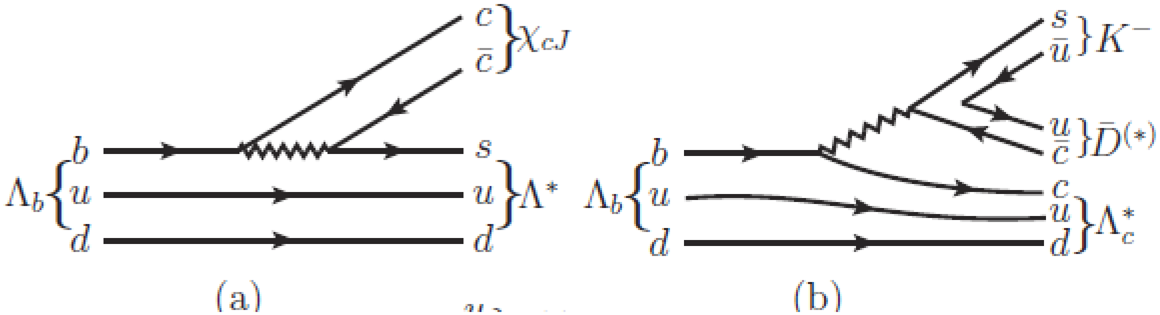
X.-H. Liu, Q. Wang, and Q. Zhao, arXiv:1507.05359 [hep-ph]

M. Mikhasenko, arXiv:1507.06552v1 [hep-ph]

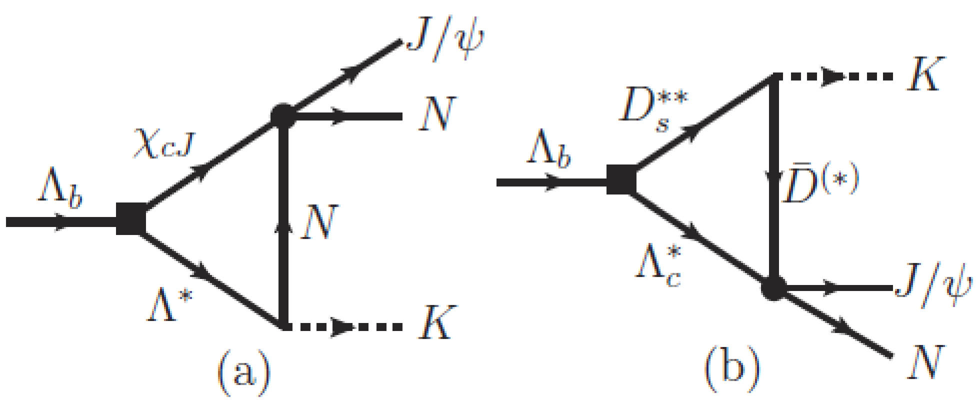
Or some other peculiar mechanisms?

Production mechanism in Λ_b decay if not a genuine state

Leading production of Λc^* $\bar{\text{D}}$(*) instead of Σc^* $\bar{\text{D}}$(*) !

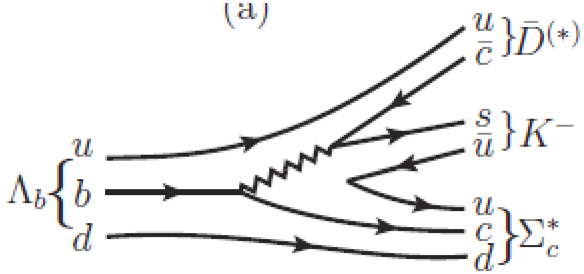


Rescattering via triangle diagrams

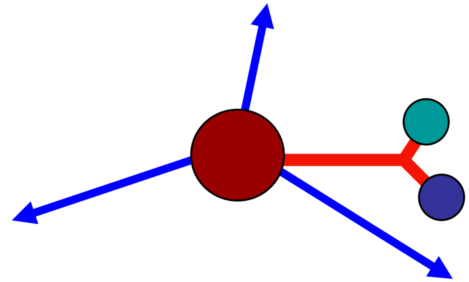


X.-H. Liu, Q. Wang, and Q. Zhao, arXiv:1507.05359 [hep-ph]

Should be a leading order mechanism if Pc is a genuine state!



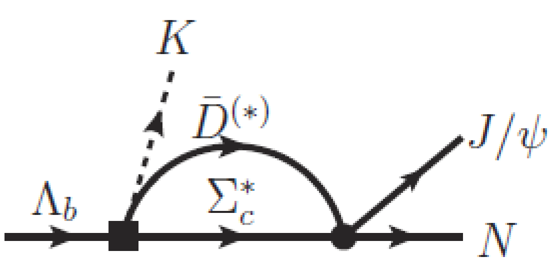
(c)



$1/m_Q << 1/m_q$

$$\langle Y_c\bar K\bar D|\hat H_w|\Lambda_b\rangle_{(c)} = \frac{1}{2\sqrt{2}}\left[-\Sigma_c^{++}K^-D^- + \frac{1}{2}\Sigma_c^+\bar K^0D^- - \frac{1}{2}\Sigma_c^+K^-\bar D^0 + \Sigma_c^0\bar K^0\bar D^0 + \frac{1}{2}\Lambda_c^+K^-\bar D^0 - \frac{1}{2}\Lambda_c^+\bar K^0D^-\right]$$

Rescattering to generate a pole?

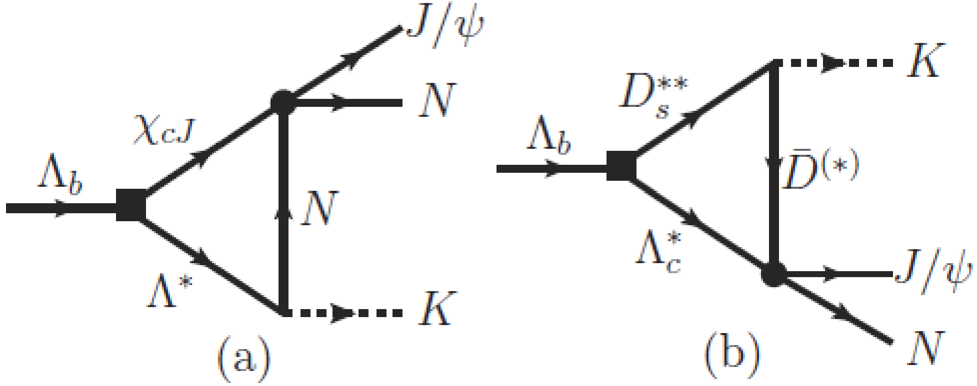


(c)

- **Favored by the molecular picture although color suppressed.**
- **However, compact diquark should be ruled out.**

X.-H. Liu, Q. Wang, and Q. Zhao, arXiv:1507.05359 [hep-ph]

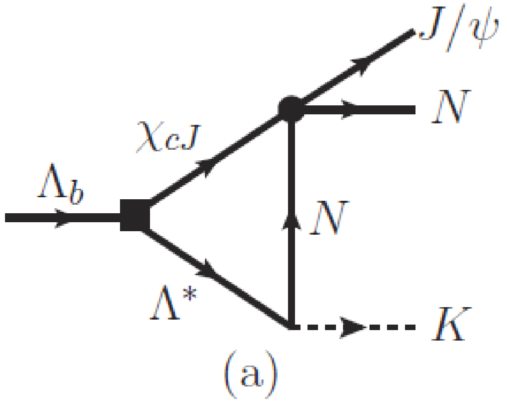
The anomalous triangle singularity can be recognized

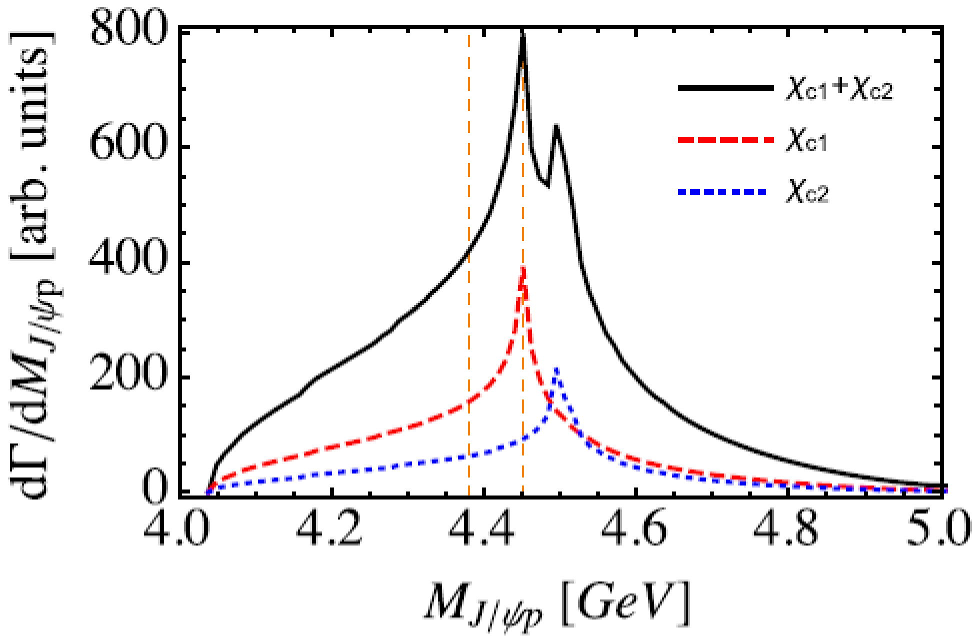


F.-K. Guo, U.-G. Meissner, W. Wang, and Z. Yang, arXiv:1507.04950 [hep-ph]
X.-H. Liu, Q. Wang, and Q. Zhao, arXiv:1507.05359 [hep-ph]
F.K. Guo, C. Hanhart, U.-G. Meissner, Q. Wang, Q. Zhao, B.S. Zou, arXiv:1705.00141, to appear in Rev. Mod. Phys.

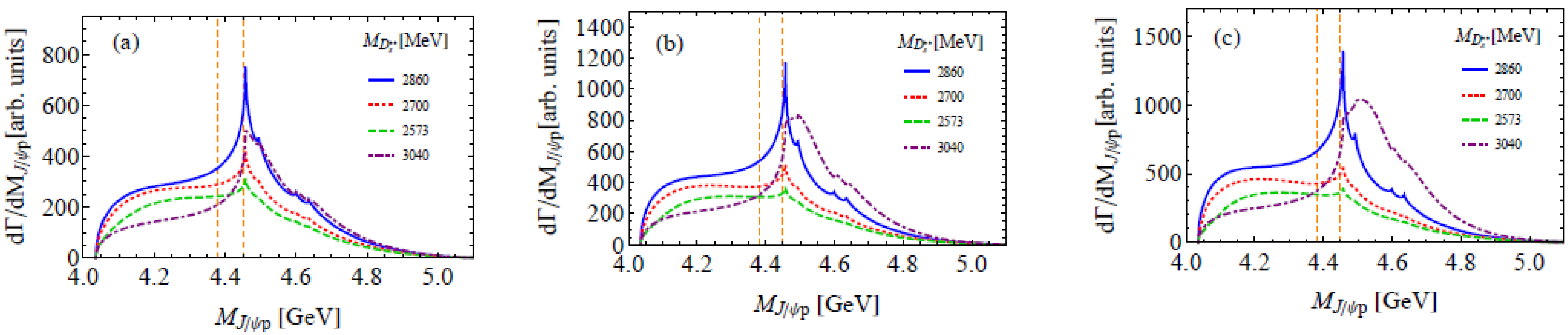
Thresholds for χ_{cJ} p

Threshold masses [MeV]	$\chi_{c0}(1P)\ 0^+$	$\chi_{c1}(1P)\ 1^+$	$\chi_{c2}(1P)\ 2^+$
$p\ 1/2^+$	4353	4449	4494

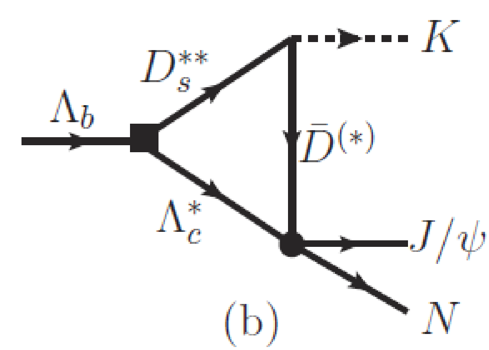




X.-H. Liu, Q. Wang, and Q. Zhao, arXiv:1507.05359 [hep-ph]



Threshold masses [MeV]	$\Lambda_c(2286)$ $1/2^+$	$\Lambda_c(2595)$ $1/2^-$	$\Lambda_c(2625)$ $3/2^-$	$\Lambda_c(2880)$ $5/2^+$
$\bar{D}_s(1968)$ 0^-	4254	4563	4593	4848
$\bar{D}_s^*(2112)$ 1^-	4398	4707	4737	4994
$\bar{D}_{s0}(2317)$ 0^+	4585	4912	4942	5197
$\bar{D}_{s1}(2460)$ 1^+	4728	5055	5085	5340
$\bar{D}_{s1}(2536)$ 1^+	4822	5131	5161	5416
$\bar{D}_{s2}(2573)$ 2^+	4859	5168	5198	5453
$\bar{D}_{s1}(2700)$ 1^-	4986	5295	5325	5580
$\bar{D}_{sJ}(2860)$ $?^?$	5146	5455	5485	[5740]
$\bar{D}_{sJ}(3040)$ $?^?$	5331	[5636]	[5672]	[5926]

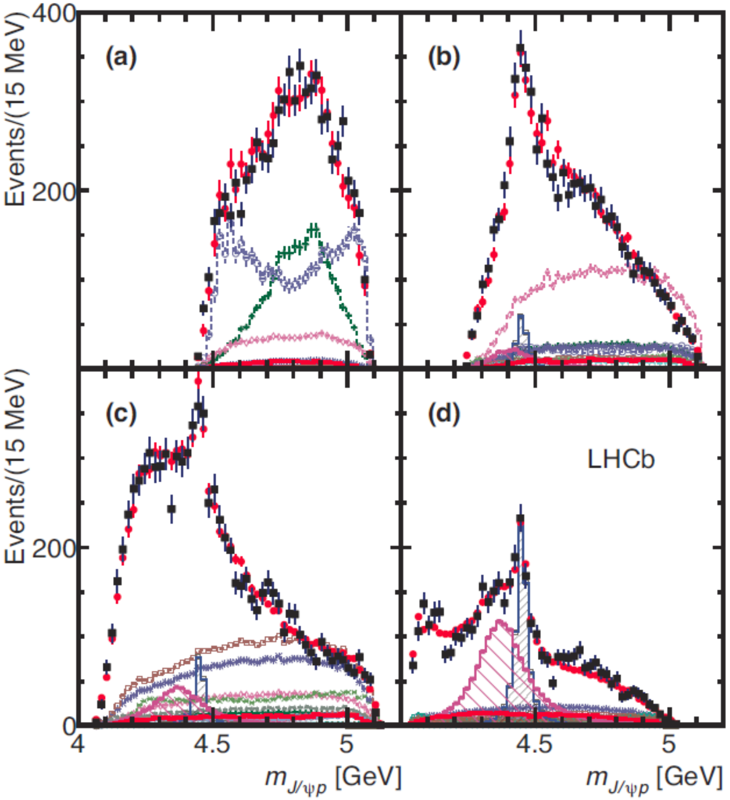


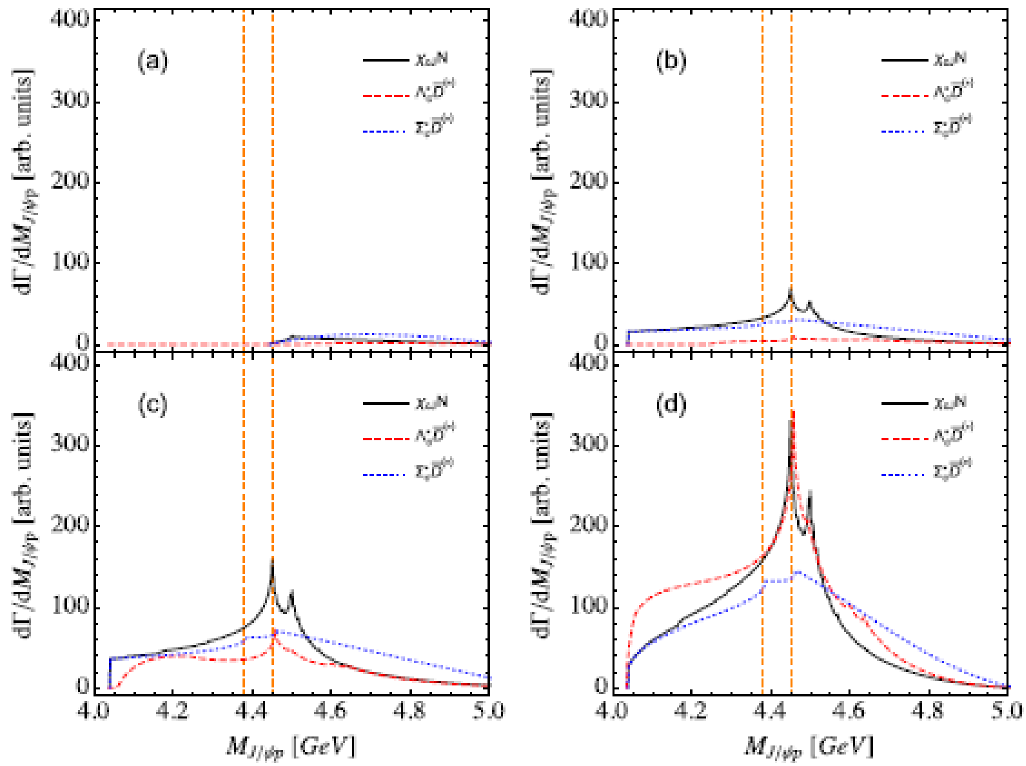
Threshold masses [GeV]	$\Sigma_c(2455)$ $1/2^+$	$\Sigma_c(2520)$ $3/2^+$	$\Sigma_c(2625)$ $?^?$
$\bar{D}(1865)$ 0^-	4.321	4.385	4.668
$\bar{D}^*(2007)$ 1^-	4.463	4.527	4.810
$\bar{D}_1(2420)$ 1^+	4.875	4.939	5.222
$\bar{D}_2(2460)$ 2^+	4.917	4.981	5.264

Invariant mass distribution of J/ψ p with different K⁻p momentum cuts

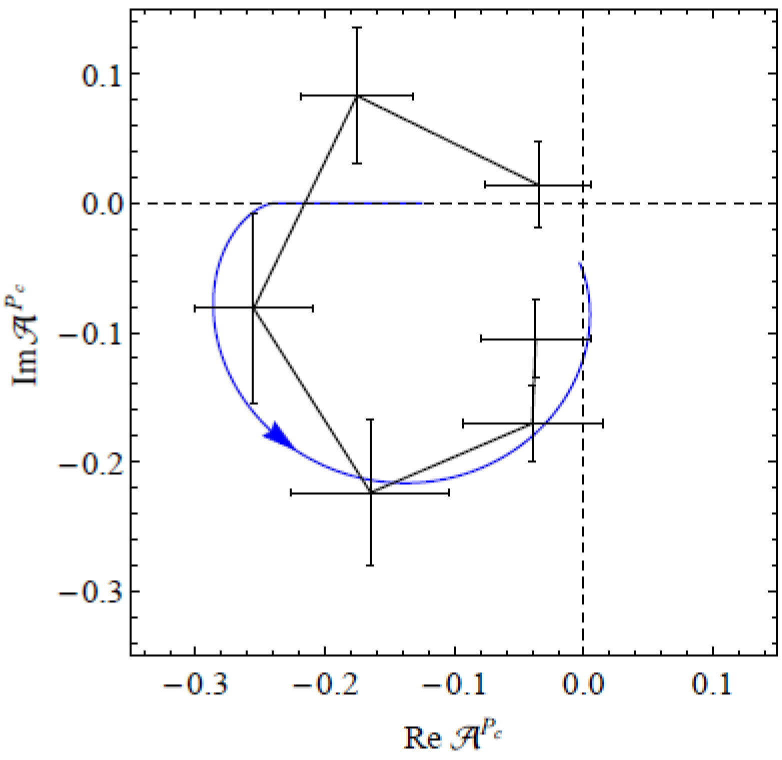
(a) $m_{Kp} < 1.55$ GeV,(b) 1.55 GeV $< m_{Kp} < 1.07$ GeV,

(c) 1.07 GeV $< m_{Kp} < 12.0$ GeV, (d) $m_{Kp} > 2.0$ GeV.



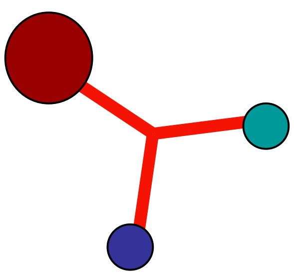


The ATS can mimic a resonance behavior in certain cases!

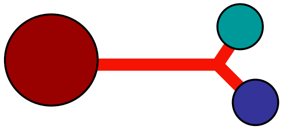


F.-K. Guo, U.-G. Meissner, W. Wang, and Z. Yang, arXiv:1507.04950 [hep-ph]

Hyperon weak decay and lifetime of free Λ[(ud)s]

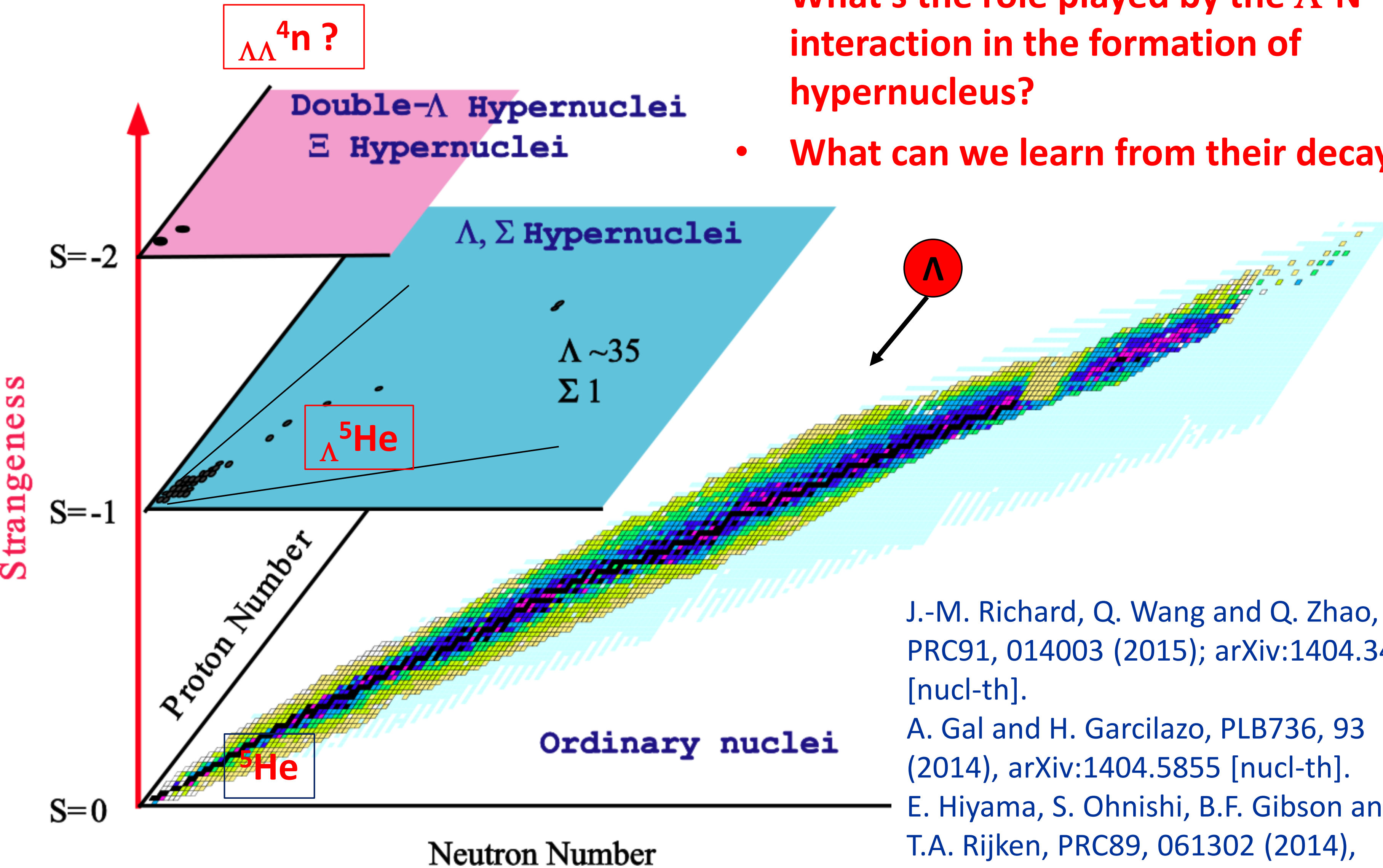


s



(ud)

Nuclear chart with strangeness



- **What's the role played by the Λ-N interaction in the formation of hypernucleus?**
- **What can we learn from their decays?**

J.-M. Richard, Q. Wang and Q. Zhao, PRC91, 014003 (2015); arXiv:1404.3473 [nucl-th].
A. Gal and H. Garcilazo, PLB736, 93 (2014), arXiv:1404.5855 [nucl-th].
E. Hiyama, S. Ohnishi, B.F. Gibson and T.A. Rijken, PRC89, 061302 (2014), arXiv:1405.2365 [nucl-th]

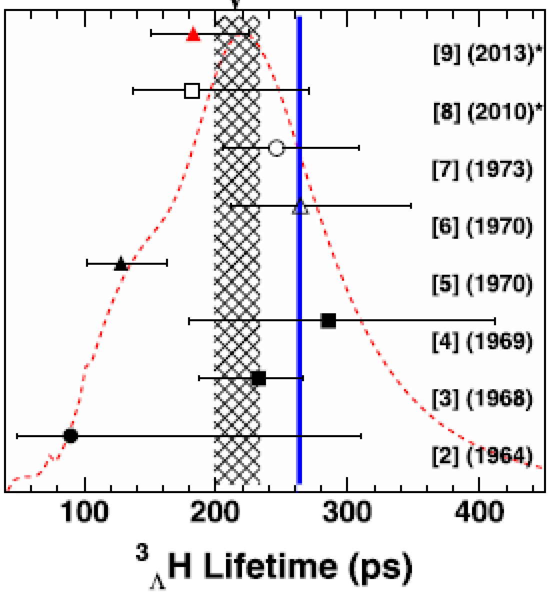
Nuclear chart from E. Hiyama

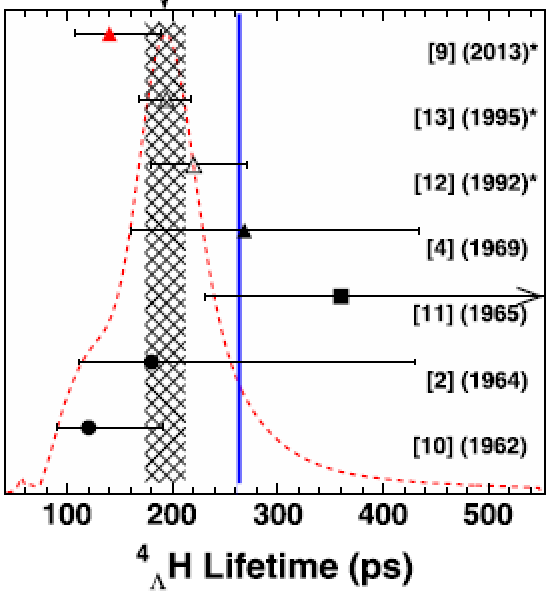
Lifetime measurement of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$

217^{+19}_{-16} ps

194^{+20}_{-18} ps

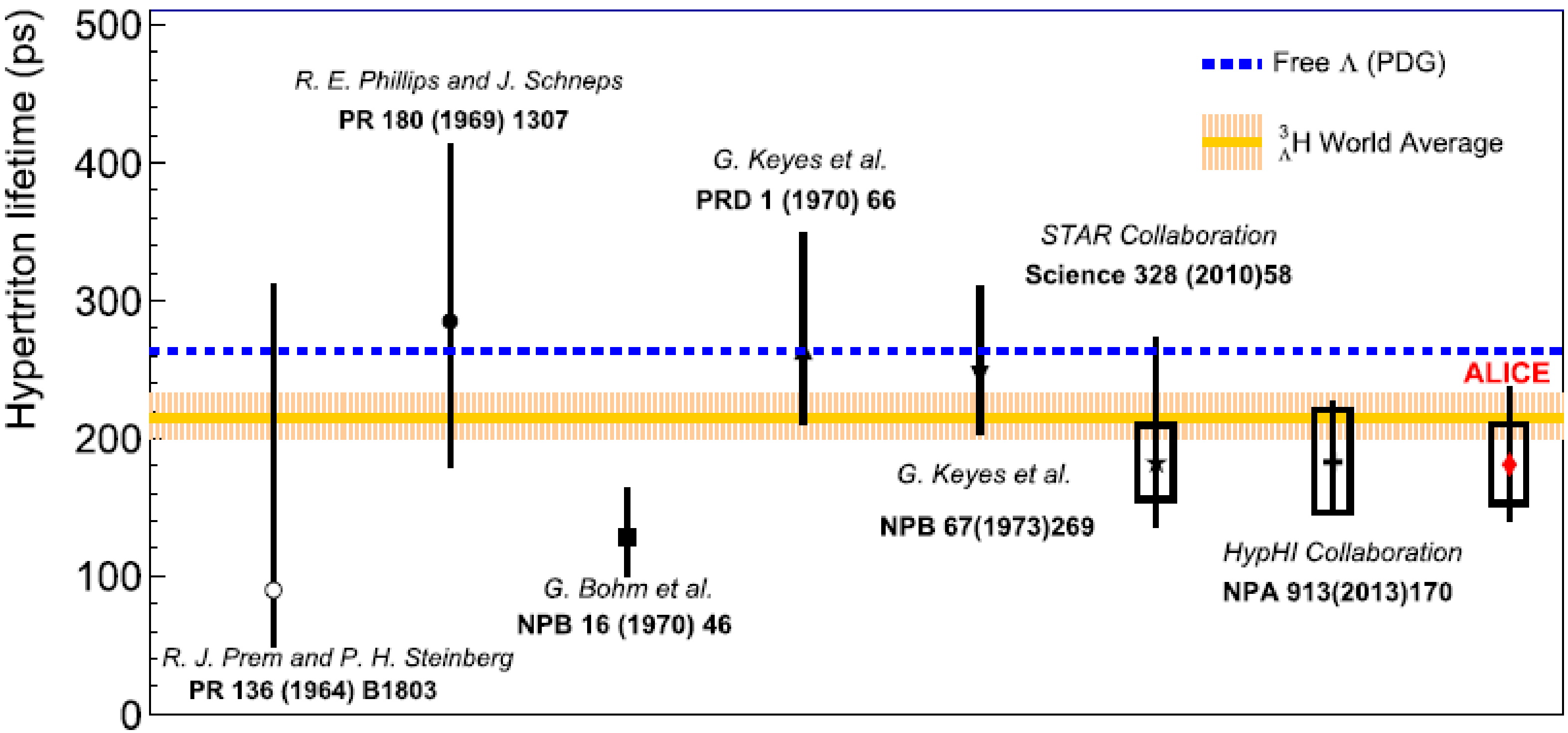
Free Λ: (263.2 ± 2.0) ps





- **The lifetimes of both ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ are shorter than that of the free Λ!**

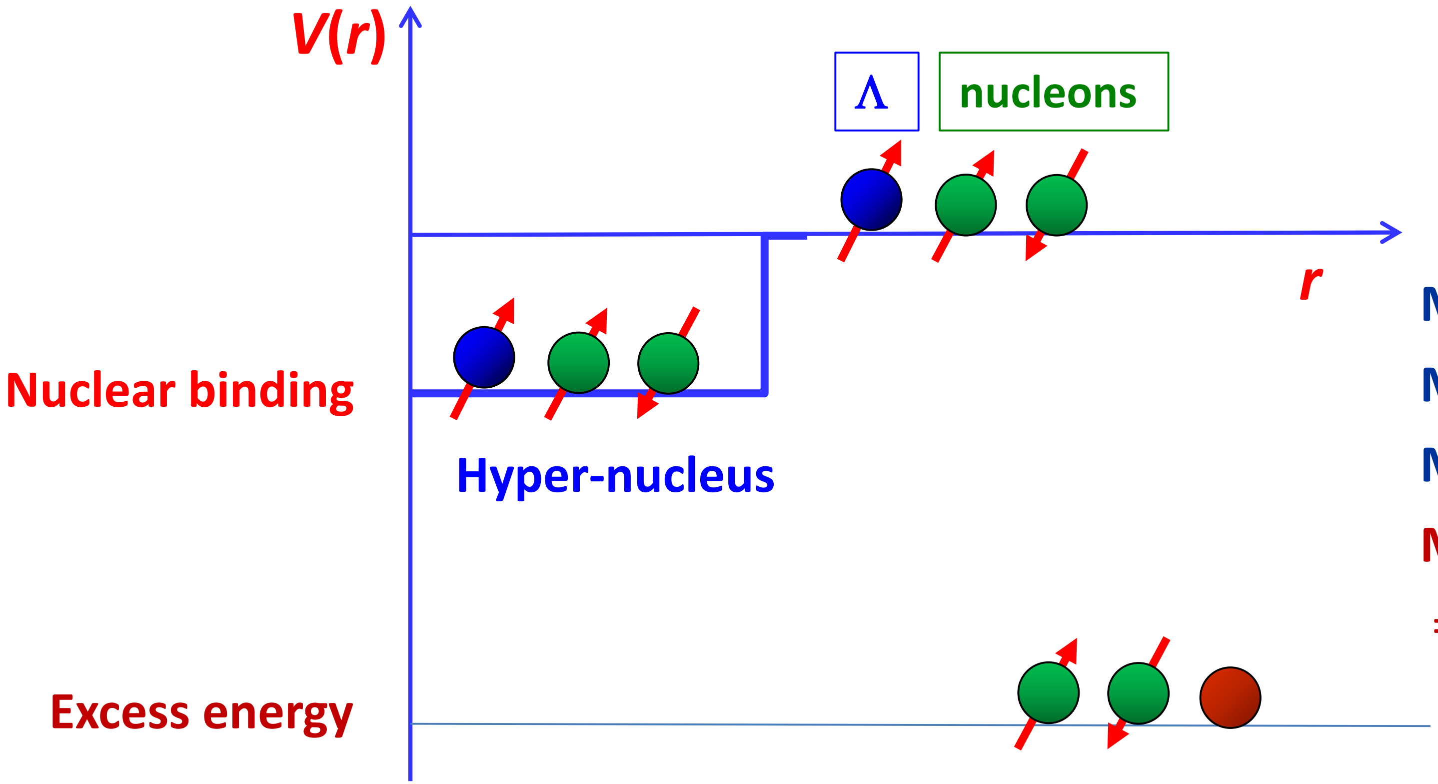
C. Rappold et al., Physics Letters B 728 (2014) 543–548



ALICE Collaboration, Physics Letters B 754 (2016) 360–372

Lifetime of Λ: (263.2 ± 2.0) ps = 2.63×10^{-10} s.

$\Lambda \rightarrow p + \pi^-, \; n + \pi^0$



Mp= 938 MeV

Mπ= 139 MeV

MΛ= 1115 MeV

MΛ −(**M**p+ **M**π)

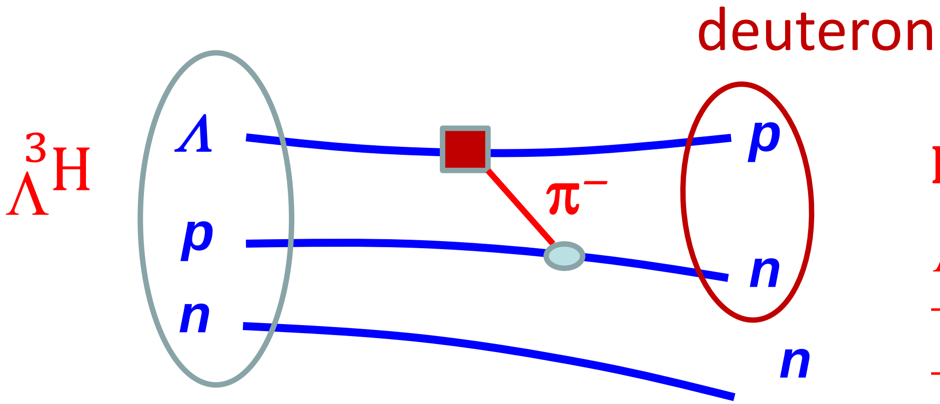
= 38 MeV

For a "weakly-bound" "light" hyper-nucleus, its lifetime should not be much different from that of a free Λ.

Why surprising?

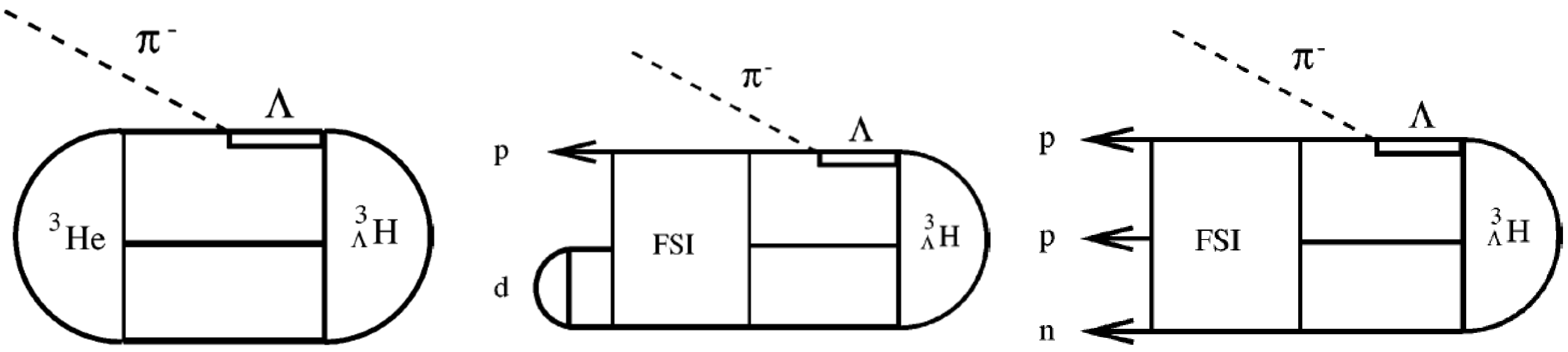
- For the weakly bound system, the non-mesonic weak decay will be suppressed by the pion propagator. Hence, one would expect that the lifetime of ${}^{3}_{\Lambda}\mathrm{H}$ is more or less the same as the free Λ.

Non-mesonic weak decay, e.g. ${}^{3}_{\Lambda}\mathrm{H} \rightarrow p + 2n,\ d + n$



Mesonic decay is dominant via
${}^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^- + {}^{3}\mathrm{He}\ ,\ \pi^- + {}^{3}\mathrm{H}\ ,\ \pi^- + d + p,\ \pi^- + 2p + n,\ \pi^0 + d + n,\ \pi^0 + p + 2n$

H. Kamada, J. Golak, K. Miyagawa, H. Witała, and W. Glockle, Phys. Rev. C 57, 1595 (1998)



Pionic weak transition operator has been parametrized out:

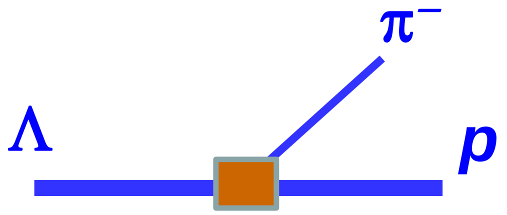
$$O = i\sqrt{2}\,G_F m_\pi^2 \overline{u_N}(\vec{k}_3)(A_\pi + B_\pi \gamma_5) u_\Lambda(\vec{k}_3)$$

$$O \rightarrow i\sqrt{2}\,G_F m_\pi^2 \left(A_\pi + \frac{B_\pi}{2M} \vec{\sigma} \cdot \vec{k}_\pi \right)$$

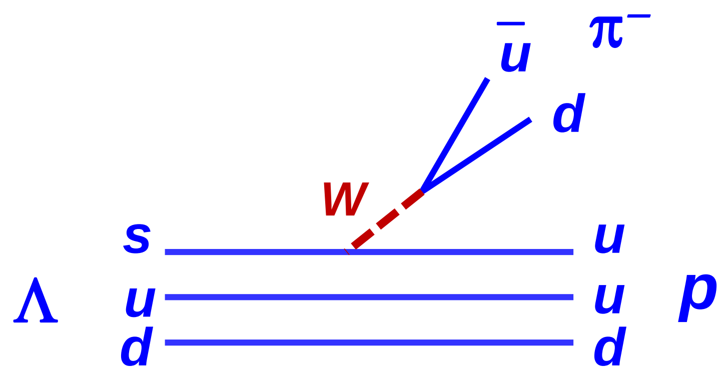
TABLE I. Partial and total mesonic and nonmesonic decay rates and corresponding lifetimes.

Channel	Γ [sec^{-1}]	Γ/Γ_Λ	$\tau=\Gamma^{-1}$ [sec]
^{3}He $+\pi^-$ and ^{3}H $+\pi^0$	0.146×10^{10}	0.384	0.684×10^{-9}
$d+p+\pi^-$ and $d+n+\pi^0$	0.235×10^{10}	0.619	0.425×10^{-9}
$p+p+n+\pi^-$ and $p+n+n+\pi^0$	0.368×10^{8}	0.0097	0.271×10^{-7}
All mesonic channels	0.385×10^{10}	1.01	0.260×10^{-9}
$d+n$	0.67×10^{7}	0.0018	0.15×10^{-6}
$p+n+n$	0.57×10^{8}	0.015	0.18×10^{-7}
All nonmesonic channels	0.64×10^{8}	0.017	0.16×10^{-7}
All channels	0.391×10^{10}	1.03	2.56×10^{-10}
Expt. [6]			$2.64\ +0.92\ -0.54\times10^{-10}$
Expt. (averaged) [11]			$2.44\ +0.26\ -0.22\times10^{-10}$

The Λ weak decay



I) Direct pion emission



- **Highly suppressed for $n\pi^0$!**

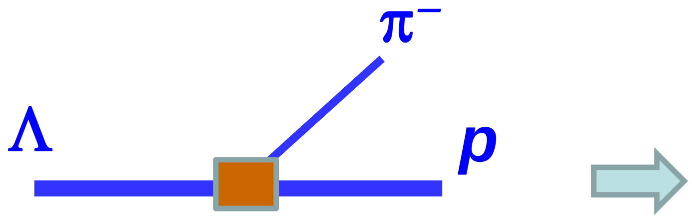
PDG:

BR($\Lambda \rightarrow p\pi^-$) = (63.9±0.5)%

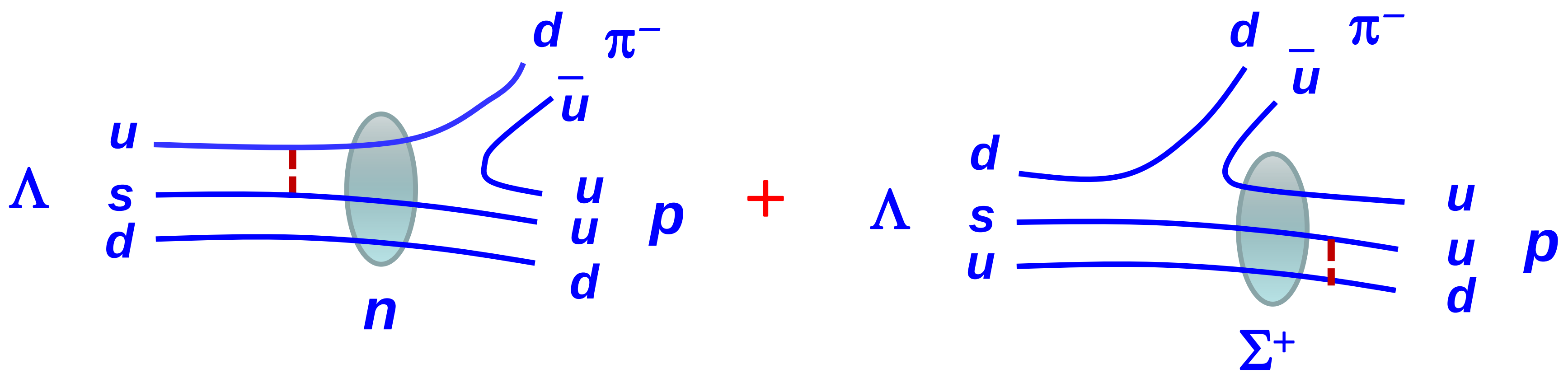
BR($\Lambda \rightarrow n\pi^0$) = (35.8±0.5)%

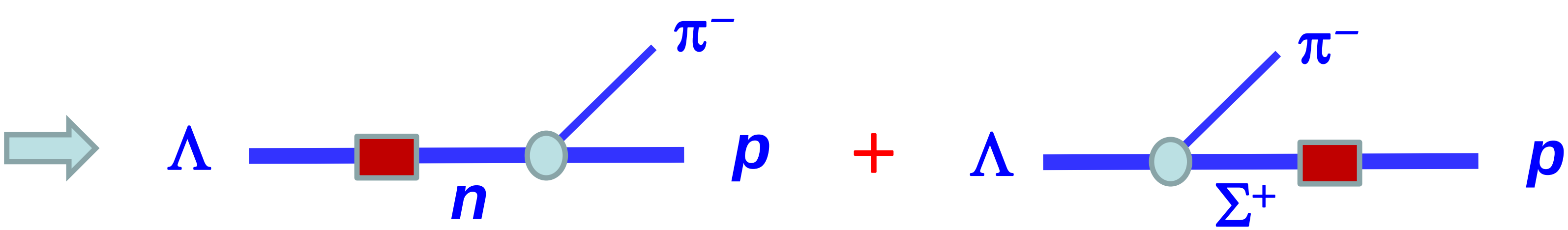
- **Direct pion emission CANNOT be dominant!**

The Λ weak decay

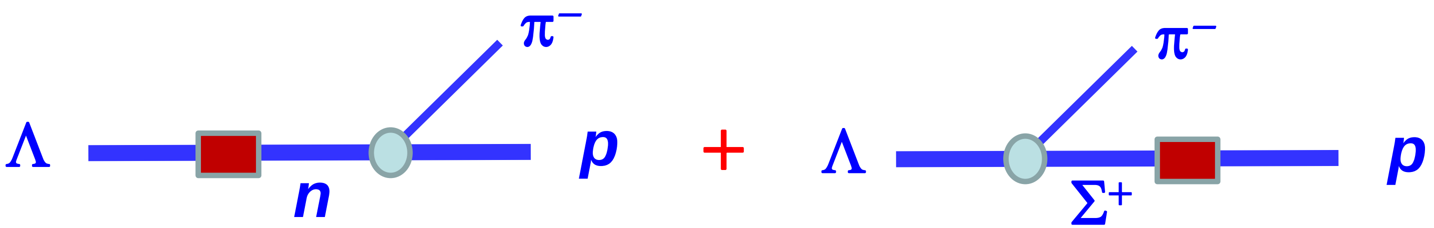


II) Pole contribution via baryon internal conversion





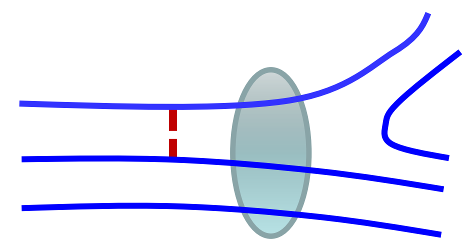
In the quark model the transition amplitude can be expressed as:



$$\mathcal{M} = \langle p|H_\pi|n\rangle \frac{i}{\not{p} - m_n} \langle n|H_w|\Lambda\rangle + \langle p|H_w|\Sigma^+\rangle \frac{i}{\not{p} - m_\Sigma} \langle \Sigma^+|H_\pi|\Lambda\rangle$$

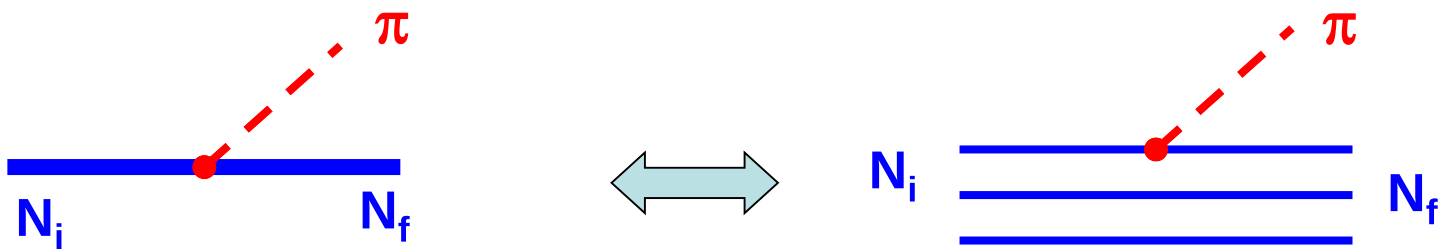
$$H_w = H_w^{PC} + H_w^{PV} \quad \left\{ \begin{array}{lcl} H_w^{PC} & = & \frac{G_F}{\sqrt{2}} \int d\boldsymbol{x} [j_\mu^{(-)}(\boldsymbol{x}) j^{(+)\mu}(\boldsymbol{x}) + j_{5\mu}^{(-)}(\boldsymbol{x}) j_5^{(+)\mu}(\boldsymbol{x})] \\ H_w^{PV} & = & \frac{G_F}{\sqrt{2}} \int d\boldsymbol{x} [j_\mu^{(-)}(\boldsymbol{x}) j_5^{(+)\mu}(\boldsymbol{x}) + j_{5\mu}^{(-)}(\boldsymbol{x}) j^{(+)\mu}(\boldsymbol{x})] \end{array} \right.$$

$$\langle B_f|H_w^{PC}|B_i\rangle = 6\langle B_f(1,2,3)|H_w^{PC}(1,2)|B_i(1,2,3)\rangle$$



$$\boxed{H_w^{PC}(1,2) = \delta(\boldsymbol{P}_f - \boldsymbol{P}_i) \frac{G_F}{\sqrt{2}} \cos\theta_C \sin\theta_C \langle \tilde{B}_f(1,2,3)|\tau_1^{(-)} v_2^{(+)} (1 - \sigma_1 \cdot \sigma_2) \delta(\boldsymbol{r}_1 - \boldsymbol{r}_2)|\tilde{B}_i(1,2,3)\rangle}$$

Explicit calculation of the strong and weak transition matrix elements in the quark model:



$$\boxed{H_\pi = \frac{1}{f_\pi}\sum_j \bar{\psi}_j \gamma_\mu \gamma_5 \partial^\mu \phi_\pi \hat{I}_j^\pi \psi_j}$$

The non-relativistic expansion gives

$$H_\pi = \frac{1}{f_\pi}\sum_j \left[\frac{q_0}{E_f+M_f}\sigma_j\cdot\boldsymbol{P}_f + \frac{q_0}{E_i+M_i}\sigma_j\cdot\boldsymbol{P}_i - \sigma_j\cdot\boldsymbol{q} + \frac{q_0}{2\mu_q}\sigma_j\cdot\boldsymbol{p}_j\right]\hat{I}_j^\pi e^{-i\boldsymbol{q}\cdot\boldsymbol{r}_j}$$

Goldberger-Treiman relation:

$$g_{B_iB_f\pi} \equiv \frac{C_{B_iB_f\pi}\, g_A(B_iB_f\pi)\,\bar{M}}{f_\pi} \qquad g_A(B_iB_f\pi) \equiv \frac{\langle B_f|\sum_j \hat{I}_j^\pi \sigma_{jz}|B_i\rangle}{\langle B_f|\sigma_z^{tot}|B_i\rangle}$$

The transition amplitude becomes:

$$\boxed{\mathcal{M} = \hat{\mathcal{V}}\,\mathcal{G}(\Lambda \to p\pi^-)}$$

$$\left\{ \begin{array}{l} \hat{\mathcal{V}} \equiv \sqrt{2M_i(M_f+E_f)}\left(1+\dfrac{q_0}{E_f+M_f}+\dfrac{q_0}{3\mu_q}\right) \times 12\,|\boldsymbol{q}|\exp\left[-\dfrac{\boldsymbol{q}^2}{6\,\alpha_h^2}\right]\left(\dfrac{\alpha_h}{\sqrt{\pi}}\right)^3 G_F\cos\theta_C\sin\theta_C \\ \mathcal{G}_{(\Lambda\to p\pi^-)} \equiv \left[\boxed{\dfrac{g_{np\pi^-}C^W_{(\Lambda\to n)}}{M_\Lambda^2-M_n^2}}+\boxed{\dfrac{g_{\Lambda\Sigma^+\pi^-}C^W_{(\Sigma^+\to p)}}{M_p^2-M_\Sigma^2}}\right] \end{array} \right.$$

$$\boxed{g_{B_iB_f\pi} \equiv \frac{C_{B_iB_f\pi}\, g_A(B_iB_f\pi)\,\bar{M}}{f_\pi}}$$

$C_{B_iB_f\pi}$ **indicates the SU(3) flavor symmetry breaking.**

Explicit cancellation between the pole terms.

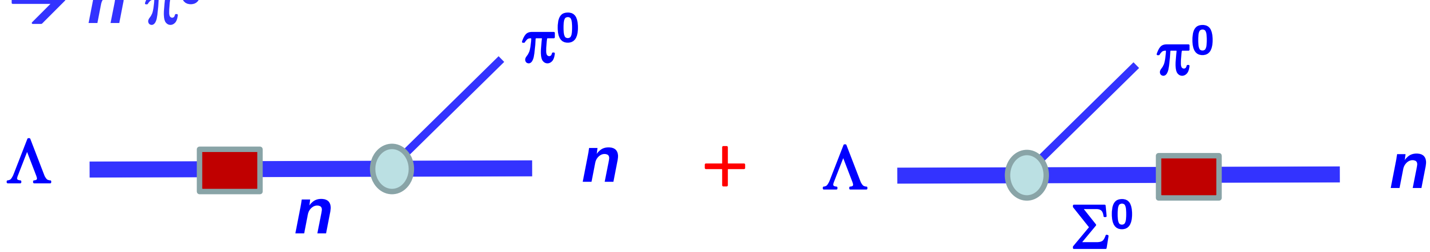
$C_{B_iB_f\pi}$ **is determined by the free Λ and Σ decays and will be fixed.**

$\langle n\|\hat{O}^W\|\Lambda\rangle$	$\langle p\|\hat{O}^W\|\Sigma^+\rangle$	$\langle n\|\hat{O}^W\|\Sigma^0\rangle$
$-1/\sqrt{6}$	$+1$	$1/\sqrt{2}$

Process	g_A	Process	g_A
$p \to n\pi^+$	$5/3$	$\Sigma^+ \to \Lambda\pi^+$	$-2/\sqrt{6}$
$n \to p\pi^-$	$5/3$	$\Sigma^- \to \Lambda\pi^-$	$-2/\sqrt{6}$
$n \to n\pi^0$	$5/(3\sqrt{2})$	$\Sigma^+ \to \Sigma^0\pi^+$	$4/(3\sqrt{2})$
$p \to p\pi^0$	$-5/(3\sqrt{2})$	$\Sigma^+ \to \Sigma^+\pi^0$	$-4/(3\sqrt{2})$
$\Lambda \to \Sigma^+\pi^-$	$-2/\sqrt{6}$	$\Sigma^- \to \Sigma^0\pi^-$	$-4/(3\sqrt{2})$
$\Lambda \to \Sigma^0\pi^0$	$-2/\sqrt{6}$		

All involve cancellations among the pole terms due to SU(3) flavor symm.

I) $\Lambda \to n\,\pi^0$



$$\mathcal{G}_{(\Lambda\to p\pi^-)} \equiv \left[\boxed{\frac{g_{np\pi^-}C^W_{(\Lambda\to n)}}{M_\Lambda^2-M_n^2}} + \boxed{\frac{g_{\Lambda\Sigma^+\pi^-}C^W_{(\Sigma^+\to p)}}{M_p^2-M_\Sigma^2}}\right]$$

$$R \equiv \frac{\Gamma(\Lambda\to p\pi^-)}{\Gamma(\Lambda\to n\pi^0)} \simeq 2$$

PDG:

BR($\Lambda \to p\pi^-$) = (63.9±0.5)%

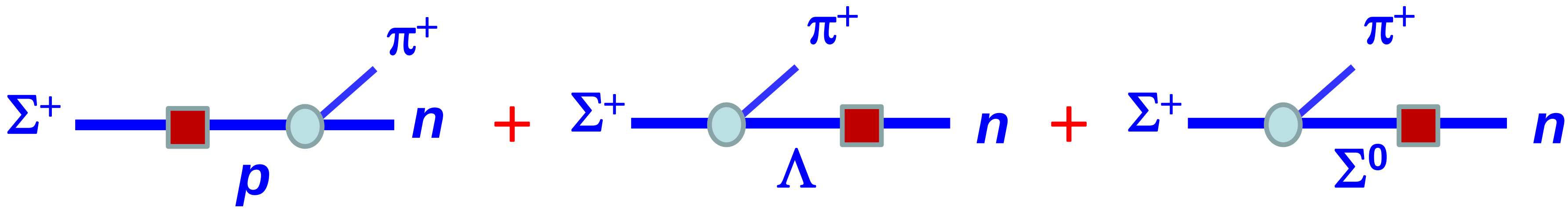
BR($\Lambda \to n\pi^0$) = (35.8±0.5)%

$\langle n\vert\hat{O}^W\vert\Lambda\rangle$	$\langle p\vert\hat{O}^W\vert\Sigma^+\rangle$	$\langle n\vert\hat{O}^W\vert\Sigma^0\rangle$
$-1/\sqrt{6}$	$+1$	$1/\sqrt{2}$

Process	g_A	Process	g_A
$p\to n\pi^+$	$5/3$	$\Sigma^+\to\Lambda\pi^+$	$-2/\sqrt{6}$
$n\to p\pi^-$	$5/3$	$\Sigma^-\to\Lambda\pi^-$	$-2/\sqrt{6}$
$n\to n\pi^0$	$5/(3\sqrt{2})$	$\Sigma^+\to\Sigma^0\pi^+$	$4/(3\sqrt{2})$
$p\to p\pi^0$	$-5/(3\sqrt{2})$	$\Sigma^+\to\Sigma^+\pi^0$	$-4/(3\sqrt{2})$
$\Lambda\to\Sigma^+\pi^-$	$-2/\sqrt{6}$	$\Sigma^-\to\Sigma^0\pi^-$	$-4/(3\sqrt{2})$
$\Lambda\to\Sigma^0\pi^0$	$-2/\sqrt{6}$		

All involve cancellations among the pole terms due to SU(3) flavor symm.

II) $\Sigma^+ \to n\, \pi^+$



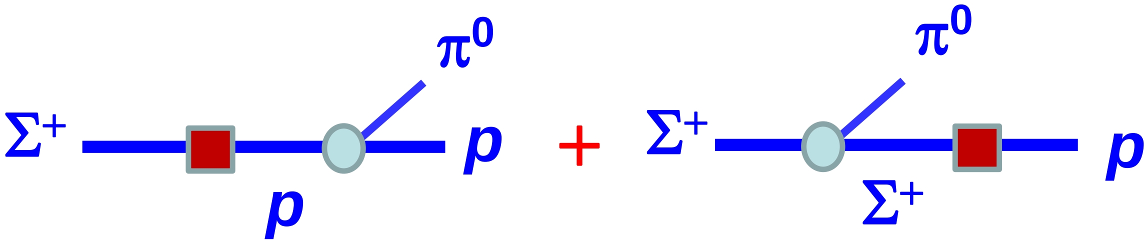
$$\mathcal{G}_{(\Sigma^+\to n\pi^+)} \equiv \left[\boxed{\frac{g_{pn\pi^+} C^W_{(\Sigma^+\to p)}}{M_\Sigma^2 - M_p^2}} + \boxed{\frac{g_{\Sigma^+\Lambda\pi^+} C^W_{(\Lambda\to n)}}{M_n^2 - M_\Lambda^2}} + \boxed{\frac{g_{\Sigma^+\Sigma^0\pi^+} C^W_{(\Sigma^0\to n)}}{M_n^2 - M_\Sigma^2}} \right],$$

Sign difference arising from signs of the propagators!

$\langle n\|\hat{O}^W\|\Lambda\rangle$	$\langle p\|\hat{O}^W\|\Sigma^+\rangle$	$\langle n\|\hat{O}^W\|\Sigma^0\rangle$
$-1/\sqrt{6}$	$+1$	$1/\sqrt{2}$

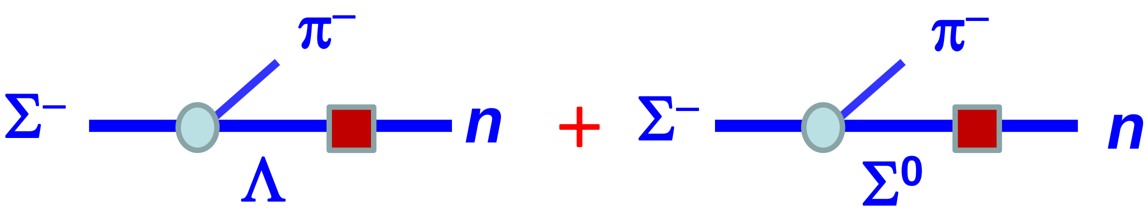
Process	g_A	Process	g_A
$p \to n\pi^+$	$5/3$	$\Sigma^+ \to \Lambda\pi^+$	$-2/\sqrt{6}$
$n \to p\pi^-$	$5/3$	$\Sigma^- \to \Lambda\pi^-$	$-2/\sqrt{6}$
$n \to n\pi^0$	$5/(3\sqrt{2})$	$\Sigma^+ \to \Sigma^0\pi^+$	$4/(3\sqrt{2})$
$p \to p\pi^0$	$-5/(3\sqrt{2})$	$\Sigma^+ \to \Sigma^+\pi^0$	$-4/(3\sqrt{2})$
$\Lambda \to \Sigma^+\pi^-$	$-2/\sqrt{6}$	$\Sigma^- \to \Sigma^0\pi^-$	$-4/(3\sqrt{2})$
$\Lambda \to \Sigma^0\pi^0$	$-2/\sqrt{6}$		

III) $\Sigma^+ \to p\,\pi^0$



$$\mathcal{G}_{(\Sigma^+ \to p\pi^0)} \equiv C^W_{(\Sigma^+ \to p)} \left[\frac{g_{pp\pi^0}}{M_\Sigma^2 - M_p^2} + \frac{g_{\Sigma^+\Sigma^+\pi^0}}{M_p^2 - M_\Sigma^2} \right]$$

IV) $\Sigma^- \to n\,\pi^-$



$$\mathcal{G}_{(\Sigma^- \to n\pi^-)} \equiv \left[\frac{g_{\Sigma^-\Lambda\pi^-} C^W_{(\Lambda \to n)}}{M_n^2 - M_\Lambda^2} + \frac{g_{\Sigma^-\Sigma^0\pi^-} C^W_{(\Sigma^0 \to n)}}{M_n^2 - M_\Sigma^2} \right]$$

TABLE I: Weak matrix element $C^W_{(A\to B)} \equiv \langle B|\hat{\mathcal{O}}^W|A\rangle$ for the baryon conversions, with $\hat{\mathcal{O}}^W \equiv \tau_1^{(-)} v_2^{(+)}(1-\sigma_1\cdot\sigma_2)$.

$\langle n\|\hat{\mathcal{O}}^W\|\Lambda\rangle$	$\langle p\|\hat{\mathcal{O}}^W\|\Sigma^+\rangle$	$\langle n\|\hat{\mathcal{O}}^W\|\Sigma^0\rangle$
$-1/\sqrt{6}$	$+1$	$1/\sqrt{2}$

TABLE II: Axial-vector couplings for the pion emission.

Process	g_A	Process	g_A
$p\to n\pi^+$	$5/3$	$\Sigma^+\to\Lambda\pi^+$	$-2/\sqrt{6}$
$n\to p\pi^-$	$5/3$	$\Sigma^-\to\Lambda\pi^-$	$-2/\sqrt{6}$
$n\to n\pi^0$	$5/(3\sqrt{2})$	$\Sigma^+\to\Sigma^0\pi^+$	$4/(3\sqrt{2})$
$p\to p\pi^0$	$-5/(3\sqrt{2})$	$\Sigma^+\to\Sigma^+\pi^0$	$-4/(3\sqrt{2})$
$\Lambda\to\Sigma^+\pi^-$	$-2/\sqrt{6}$	$\Sigma^-\to\Sigma^0\pi^-$	$-4/(3\sqrt{2})$
$\Lambda\to\Sigma^0\pi^0$	$-2/\sqrt{6}$		

$$\alpha_h = 305.12 \pm 0.75 \text{ MeV}$$

$$\left[\begin{aligned} C_{NN\pi} &= 0.843 \pm 0.001 \\ C_{\Lambda\Sigma\pi} &= 1.400 \pm 0.086 \\ C_{\Sigma\Sigma\pi} &= 1.128 \pm 0.002 \end{aligned} \right.$$

The SU(3) flavor symmetry parameters are strongly correlated indicating an intrinsic dynamic connection.

The partial decay widths for Λ and $\Sigma^{\pm}$ pionic weak decays in unit of 10^{-6} eV.

Channels	SU(3)	Fitting	Experimental data
$\Lambda \to p\pi^-$	0.65	$1.62^{+0.50}_{-0.43}$	1.60 ± 0.02
$\Lambda \to n\pi^0$	0.35	$0.91^{+0.28}_{-0.24}$	0.895 ± 0.014
$\Sigma^+ \to p\pi^0$	57.32	$5.64^{+0.17}_{-0.17}$	4.23 ± 0.03
$\Sigma^+ \to n\pi^+$	31.22	$2.34^{+1.05}_{-0.85}$	3.96 ± 0.03
$\Sigma^- \to n\pi^-$	3.87	$3.38^{+1.13}_{-0.97}$	4.44 ± 0.03

Some general features:

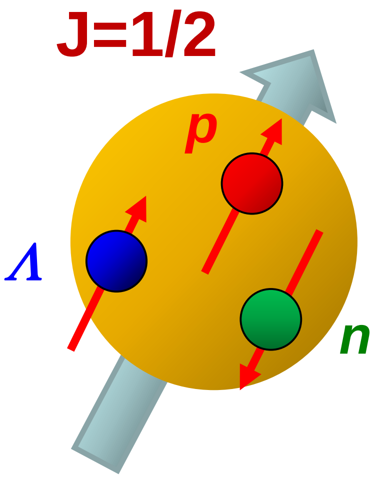
i) The Λ and Σ hadronic weak decays involve significant cancelations among the pole terms which is determined by the SU(3) flavor symmetry.

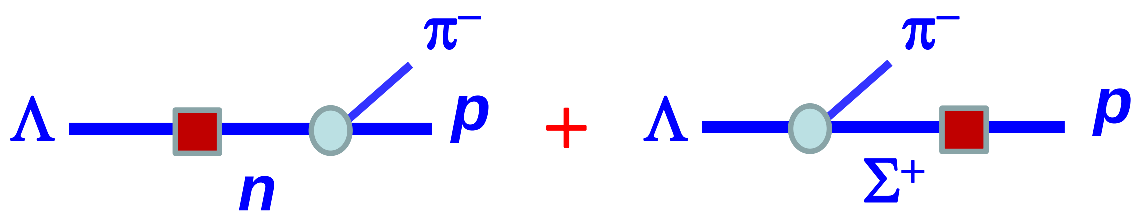
ii) However, the cancellations are sensitive to the SU(3) flavor symmetry breaking, which means a coherent study of the free Λ and Σ hadronic weak decay is necessary.

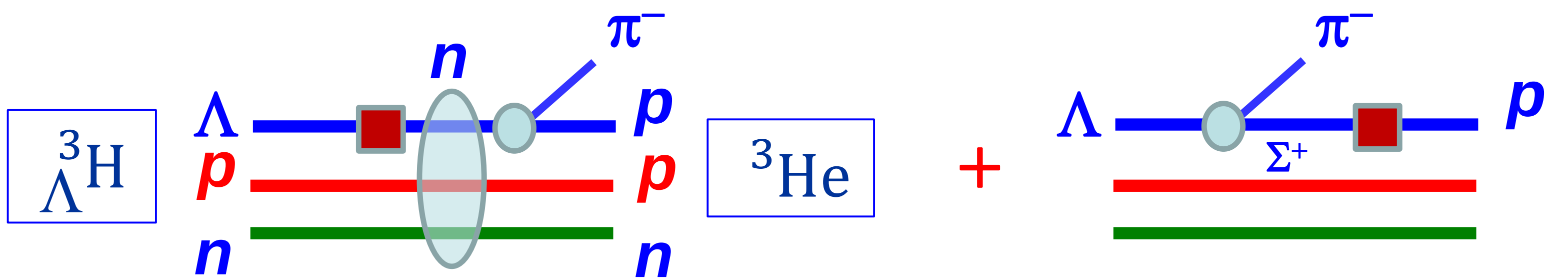
iii) Information about the short-distance behavior of the wavefunction is also crucial, but only contributes to the overall factor.

The dominance of pole contributions in the Λ and Σ hadronic weak decays has important consequence for the lifetime of light hyper-nuclei.

Hadronic weak decay of ${}^{3}_{\Lambda}\mathrm{H}$







- **Pauli principle will forbid the intermediate (*nn*) to stay in the same state, which will make these two pole terms different in hyper-nucleus decays.**

Wavefunctions for the light nuclei, -- anti-symmetrized in the isospin space

$$\begin{cases} |{}^3_\Lambda\mathrm{H}\rangle \equiv \phi^\rho_{{}^3_\Lambda\mathrm{H}}\chi^\lambda_{\frac{1}{2}}\psi^s(\boldsymbol{R},\rho,\lambda) \\ |{}^3\mathrm{H}\rangle \equiv \frac{1}{\sqrt{2}}[\phi^\rho_{{}^3\mathrm{H}}\chi^\lambda_{\frac{1}{2}} - \phi^\lambda_{{}^3\mathrm{H}}\chi^\rho_{\frac{1}{2}}]\psi^s(\boldsymbol{R},\rho,\lambda) \\ |{}^3\mathrm{He}\rangle \equiv \frac{1}{\sqrt{2}}[\phi^\rho_{{}^3\mathrm{He}}\chi^\lambda_{\frac{1}{2}} - \phi^\lambda_{{}^3\mathrm{He}}\chi^\rho_{\frac{1}{2}}]\psi^s(\boldsymbol{R},\rho,\lambda) \end{cases}$$

The spin and isospin wavefunctions are:

$$\begin{cases} \chi^s(S_z=\frac{3}{2}) = \uparrow\uparrow\uparrow \\ \chi^\rho(S_z=\frac{1}{2}) = \frac{1}{\sqrt{2}}(\uparrow\downarrow\uparrow - \downarrow\uparrow\uparrow) \\ \chi^\lambda(S_z=\frac{1}{2}) = \frac{1}{\sqrt{6}}(2\uparrow\uparrow\downarrow - \downarrow\uparrow\uparrow - \uparrow\downarrow\uparrow) \end{cases}$$

$$\begin{cases} \phi^\rho_{{}^3_\Lambda\mathrm{H}} = \frac{1}{\sqrt{2}}(pn-np)\Lambda\ , \\ \phi^\rho_{{}^3\mathrm{H}} = \frac{1}{\sqrt{2}}(pn-np)n\ , \\ \phi^\lambda_{{}^3\mathrm{H}} = \frac{1}{\sqrt{6}}(-2nnp+pnn+npn)\ , \\ \phi^\rho_{{}^3\mathrm{He}} = \frac{1}{\sqrt{2}}(pn-np)p\ , \\ \phi^\lambda_{{}^3\mathrm{He}} = \frac{1}{\sqrt{6}}(-2ppn+pnp+npp)\ . \end{cases}$$

Spacial wavefunction:

$$\tilde{\Psi}(\boldsymbol{r}_i) \;=\; N \exp[-\tfrac{1}{2}\textstyle\sum_i \beta_i r_i^2]$$

$$\left\{\begin{array}{lcl} \boldsymbol{R} & = & \sum_i m_i \boldsymbol{r}_i / \sum_i m_i \;=\; 0 \\ N^2 & \equiv & \pi^{-3}\Delta^{\frac{3}{2}}(m_1+m_2+m_3)^{-3} \\ \Delta & \equiv & m_3^2\beta_1\beta_2 + m_2^2\beta_1\beta_3 + m_1^2\beta_2\beta_3 \end{array}\right.$$

Wavefunction in momentum space:

$$\Psi(\boldsymbol{p}_i) = \int \tilde{\Psi}(\boldsymbol{r}_i)\delta^3(\boldsymbol{R})\Pi_i[\exp(-i\boldsymbol{p}_i\cdot\boldsymbol{r}_i)d^3\boldsymbol{r}_i] \qquad (12)$$

$$= \frac{(\sum_i m_i)^3 N}{\Delta^{\frac{3}{2}}} \exp - \left[\frac{\sum_{i\neq j\neq k}\beta_i(m_j\boldsymbol{p}_k - m_k\boldsymbol{p}_j)^2}{2\Delta}\right]$$

with the normalization $\int \Psi(\boldsymbol{p}_i)^2\delta^3(\boldsymbol{P})\prod_{i=1}^{3} d^3\boldsymbol{p}_i = 1$

Mean square radius:

$$\langle \boldsymbol{r}_i^2 \rangle = \frac{3}{2}\frac{m_j^2\beta_k + m_k^2\beta_j}{\Delta}$$

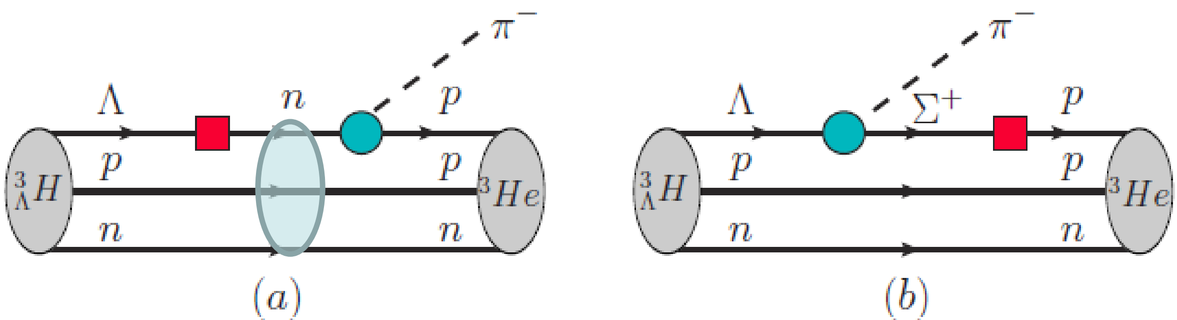
The r.m.s are from Juelich model and Nijmegen model, with which the HO parameters are fixed.

System	r_n(fm)	r_p(fm)	r_Λ(fm)
^{3}He	1.38	1.49	–
$^3_\Lambda$H (I)	1.60	1.60	1.65
$^3_\Lambda$H (II)	2.32	2.32	2.84

β_n(fm^{-2})	β_p(fm^{-2})	β_Λ(fm^{-2})
0.430	0.573	–
0.469	0.469	0.220
0.296	0.296	-0.023

- H. Polinder, J. Haidenbauer and U.-G. Meisner, Phys. Lett. B **653**, 29 (2007)
- J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meisner, A. Nogga and W. Weise, Nucl. Phys. A **915**, 24 (2013)
- T. A. Rijken, M. M. Nagels and Y. Yamamoto, Few Body Syst. 54, 801 (2013)

Transition matrix element for $^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$



$$\mathcal{M} = \frac{1}{(2\pi)^{12}} \int \Psi^*_{^3\mathrm{He}}(\mathbf{P}_f; \mathbf{p}'_1, \mathbf{p}'_2, \mathbf{p}'_3) \left\{ \langle {}^3\mathrm{He}|H^{(3)}_\pi|[p,n,n]^a\rangle \frac{i}{\not{p}_1 - M_1} \frac{i}{\not{p}_2 - M_2} \frac{i}{\not{p}_3 - M_n} \langle [p,n,n]^a|H^{(3)}_w|{}^3_\Lambda\mathrm{H}\rangle \right.$$
$$\left. + \ \langle {}^3\mathrm{He}|H^{(3)}_w|[p,n,\Sigma^+]\rangle \frac{i}{\not{p}'_1 - M_1} \frac{i}{\not{p}'_2 - M_2} \frac{i}{\not{p}'_3 - M_\Sigma} \langle [p,n,\Sigma^+]|H^{(3)}_\pi|{}^3_\Lambda\mathrm{H}\rangle \right\} \Psi_{^3_\Lambda\mathrm{H}}(\mathbf{P}_i; \mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)$$
$$\times \ \Delta(P_f; q; p'_1, p'_2, p'_3; P_i; p_1, p_2, p_3) dp'_1 \ dp'_2 \ dp'_3 \ dp_1 \ dp_2 \ dp_3 \ ,$$

$$\mathcal{M} = \int \Psi^*_{^3\mathrm{He}}(\mathbf{P}_f; \mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3 - \mathbf{q}) \frac{(2\pi i)^2 \langle {}^3\mathrm{He}|H^{(3)}_\pi|\boxed{p,n,n]^a\rangle\langle [p,n,n]^a}|H^{(3)}_w|{}^3_\Lambda\mathrm{H}\rangle}{M_{^3_\Lambda\mathrm{H}} - (M_1 + M_2 + M_n) - (\frac{\mathbf{p}_1^2}{2M_1} + \frac{\mathbf{p}_2^2}{2M_2} + \frac{\mathbf{p}_3^2}{2M_n})} \Psi_{^3_\Lambda\mathrm{H}}(\mathbf{P}_i = 0; \mathbf{p}_1, \mathbf{p}_2, \mathbf{p}_3)$$
$$\times \delta(\mathbf{p}_1 + \mathbf{p}_2 + \mathbf{p}_3) \frac{d\mathbf{p}_1}{(2\pi)^3} \frac{d\mathbf{p}_2}{(2\pi)^3} \frac{d\mathbf{p}_3}{(2\pi)^3}$$
$$+ \int \Psi^*_{^3\mathrm{He}}(\mathbf{P}_f; \mathbf{p}'_1, \mathbf{p}'_2, \mathbf{p}'_3) \frac{(2\pi i)^2 \langle {}^3\mathrm{He}|H^{(3)}_w|[p,n,\Sigma^+]\rangle\langle [p,n,\Sigma^+]|H^{(3)}_\pi|{}^3_\Lambda\mathrm{H}\rangle}{E_{^3\mathrm{He}} - (M_1 + M_2 + M_\Sigma) - (\frac{\mathbf{p}_1'^2}{2M_1} + \frac{\mathbf{p}_2'^2}{2M_2} + \frac{\mathbf{p}_3'^2}{2M_\Sigma})} \Psi_{^3_\Lambda\mathrm{H}}(\mathbf{P}_i = 0; \mathbf{p}'_1, \mathbf{p}'_2, \mathbf{p}'_3 + \mathbf{q})$$
$$\times \delta(\mathbf{p}'_1 + \mathbf{p}'_2 + \mathbf{p}'_3 - \mathbf{P}_f) \frac{d\mathbf{p}'_1}{(2\pi)^3} \frac{d\mathbf{p}'_2}{(2\pi)^3} \frac{d\mathbf{p}'_3}{(2\pi)^3} \ .$$

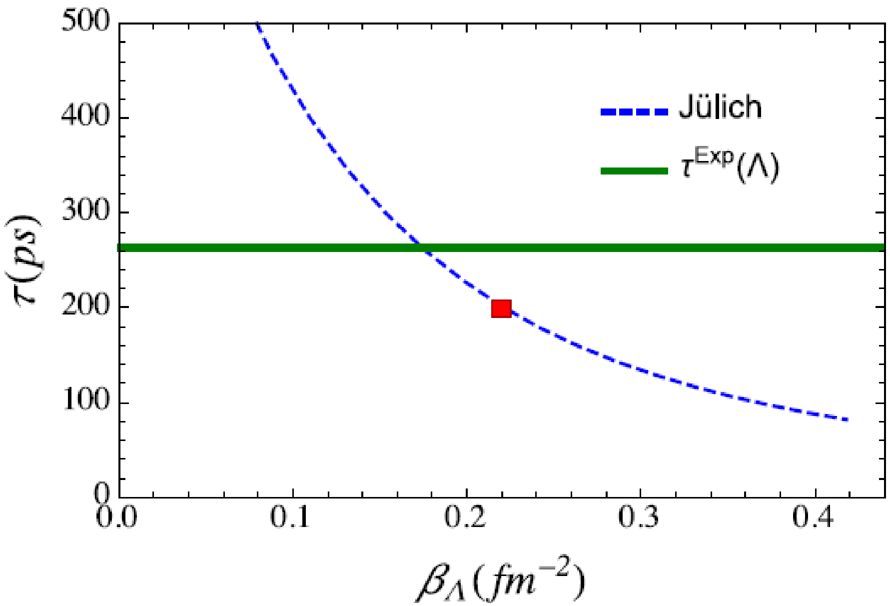
Partial width:

$\Gamma({}^3_\Lambda\mathrm{H} \to {}^3\mathrm{He} + \pi^-)(10^{-6}\mathrm{eV})$	(a)	(b)	Total
Jülich model	3.25	10.75	2.18

"Lifetime" in comparison with the exp. data:

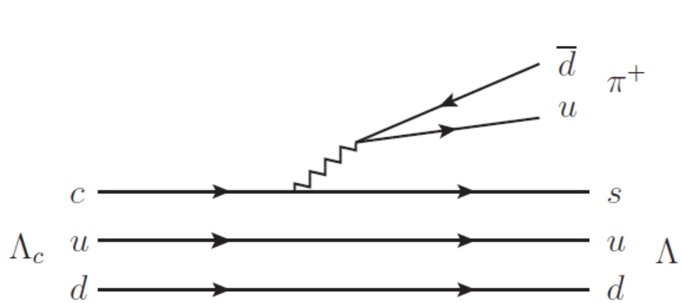
Ref. [3]	Ref. [2]	Ref. [4]	Ref. [5]	Theory
217^{+19}_{-16}	$183^{+42}_{-32} \pm 37$	$181^{+54}_{-39} \pm 33$	$155^{+25}_{-22} \pm 29$	200 ± 23

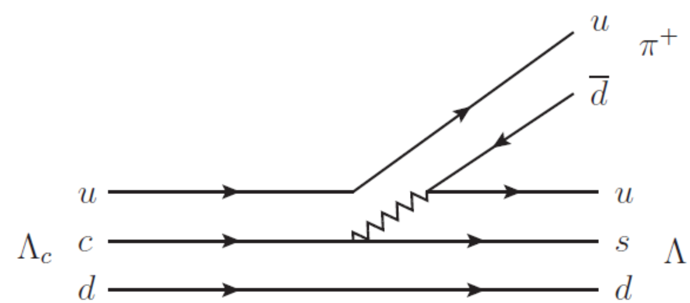
Sensitivity of the pole term cancellation mechanism to the nuclear model:

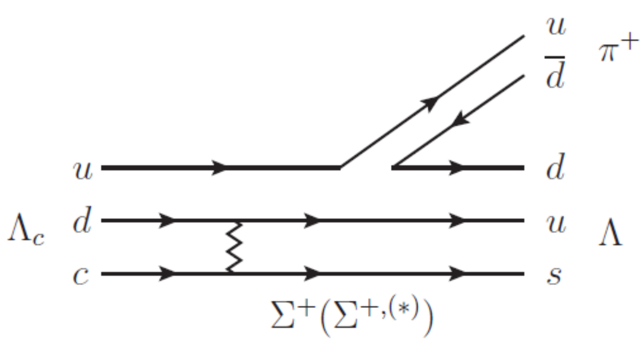


Other channels, e.g. ${}^3_\Lambda\mathrm{H} \rightarrow \pi^- + d + p$, $\pi^- + 2p + n$, $\pi^0 + d + n$, $\pi^0 + p + 2n$, will further contribute to the partial width and further shorten the lifetime.

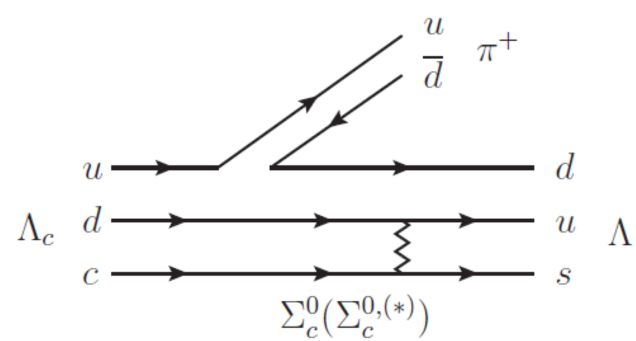
$$\boxed{\Lambda_c \to \Lambda\pi^+}$$





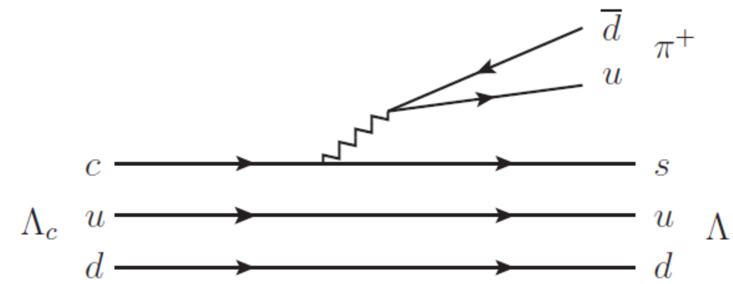


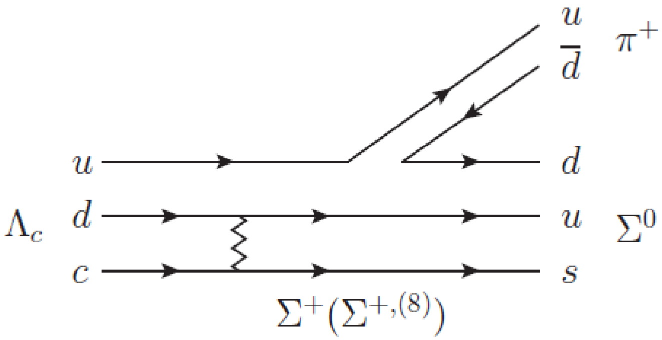
(a)



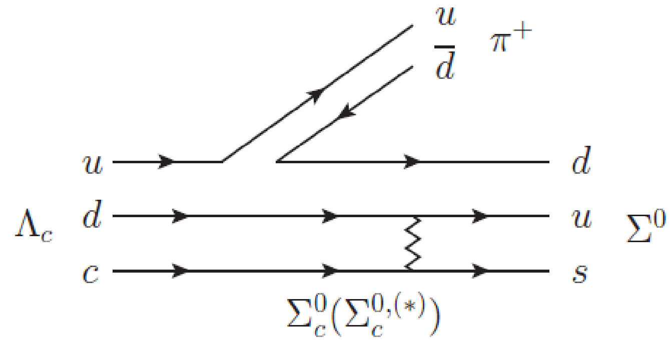
(b)

$\Lambda_c \to \Sigma^0 \pi^+$ and $\Lambda_c \to \Sigma^+ \pi^0$

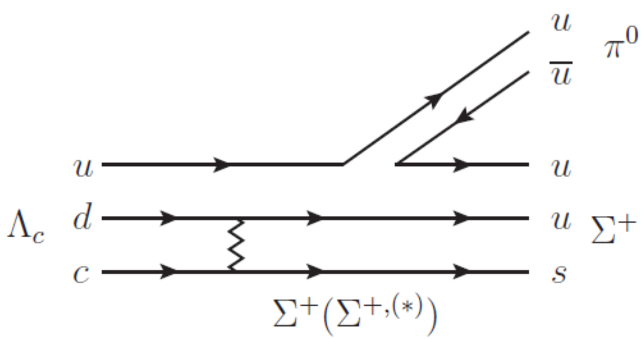




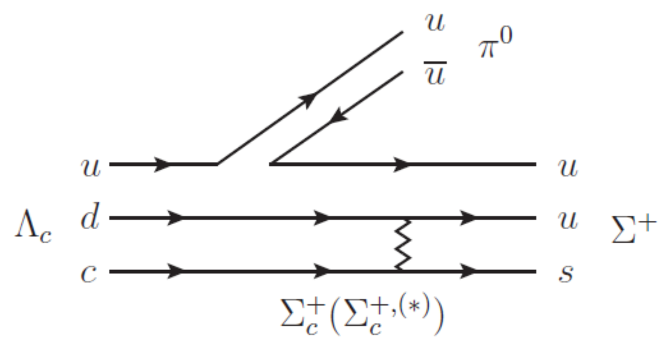
(a)



(b)



(a)



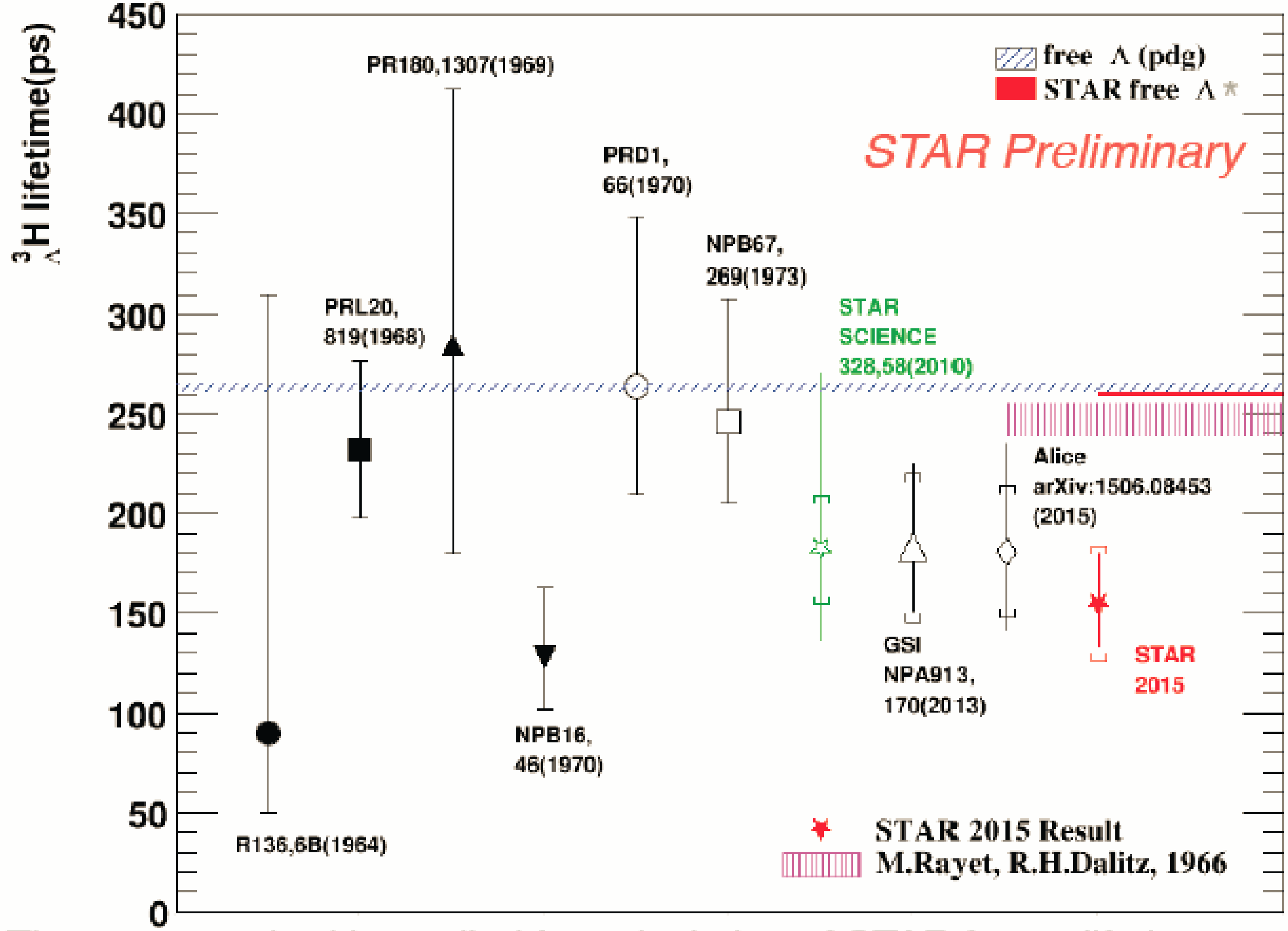
(b)

Brief summary

- **Diquark does not favor to be a compact object although spin-flavor correlations might exist.**
- **The Λ and $\Sigma^{\pm}$ hadronic weak decays are dominated by non-local interactions.**
- **The presence of Pauli blocking plays a unique role in light hypernucleus weak decays and can explain the fastened lifetime of ${}^{3}_{\Lambda}H$.**
- **Contributions from pole terms cannot be neglected in charmed baryon hadronic weak decays.**

Thanks for your attention!

World Data



* The same method is applied for calculation of STAR free Λ lifetime.

Lifetime of neutron: 880 sec.

$$n \rightarrow p + e^{-} + \bar{\nu}_e$$

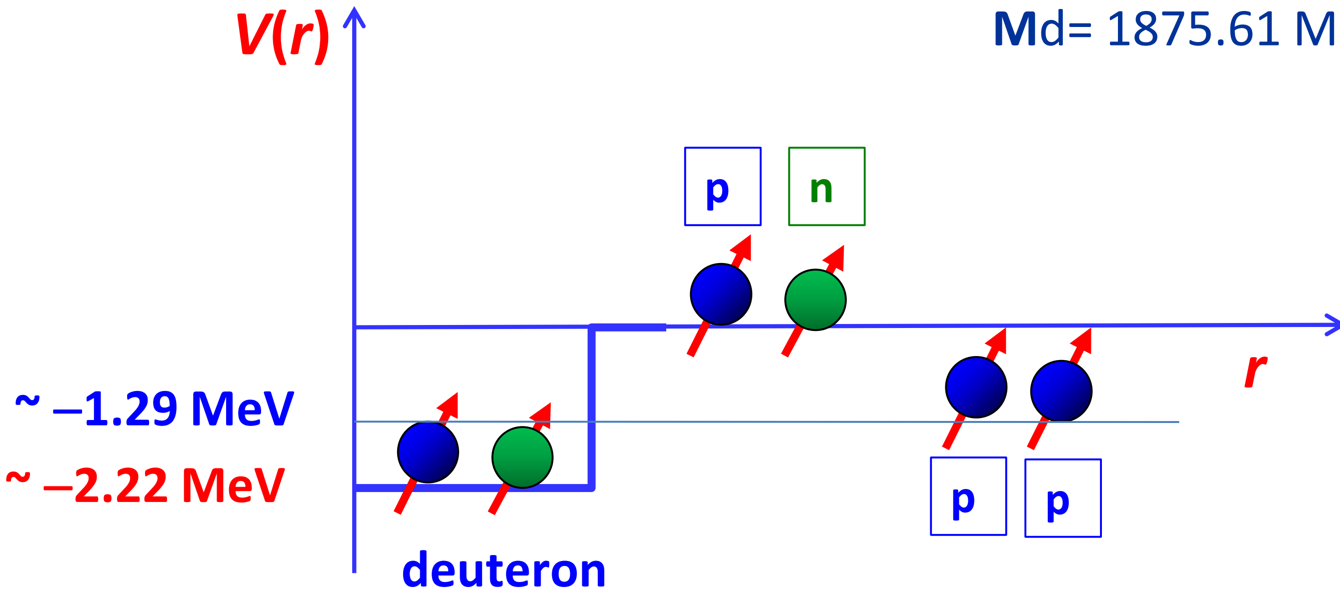
Mp= 938.27 MeV

Mn= 939.56 MeV

Mp+**M**n= 1877.83 MeV

Mp+**M**p= 1876.54 MeV

Md= 1875.61 MeV



Neutron becomes stable inside the deuteron since the binding energy is larger than the excess energy.