中国科学院高能物理研究所
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Weak decay of Λ in nuclear medium

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In collaboration with J.-M. Richard and Q. Wang, to be submitted

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Outline

1. Brief introduction to the "heavy hadron" Collaboration

2. Weak decay of Λ in nuclear medium

- Surprising data from experiment
- Lifetime of free Λ
- Lifetime of ${}^{3}_{\Lambda}\mathrm{H}$
- Brief summary

FCPPL Project report for 2014

TH-HEP-PKU-IPNL-LAL-LUPM: HEAVY HADRONS					
Members	French Group			Chinese Group	
	Name	Title	Affiliation (institute)	Name	Title
	Leader Jean-Marc RICHARD	Pr.	IPNL (Lyon)	***Leader*** *Qiang ZHAO*	Pr.
	Emi KOU	Dr.	LAL (Orsay)	Shi-Lin Zhu	Pr.
	Stephan NARISON	Pr.	LUPM (Montpellier)	Cai-Dian Lu	Pr.
				Han-Qing Zheng	Pr.
				Jian-Xiong Wang	Pr.
				Xue-Qian Li	Pr.
				Fu-Sheng Yu	Ass. Pr.
				Xuan-Gong Wang	Postdoc

Topics in the Heavy Hadron Collaboration

- **Activities in charmonium physics: "$\rho\pi$ puzzle", $\psi(3770)$ non-$D\bar{D}$ decay, etc**
- **Activities in exotic hadrons: XYZ states**
- **Activities in B physics: Time-dependent CP asymmetry, Left-right symmetric model in the light of LHC data**
- **Activities in hypernuclear physics: Neutral hypernuclei ($\Lambda\Lambda nn$), and lifetime of ${}^{3}_{\Lambda}\mathrm{H}$**
- **……**

Activities in B physics

F.-S. Yu (Lanzhou Univ.), E. Kou (LAL), C.-D. Lu (IHEP)

- The dilution factor for the TDCP asymmetry in $B^0 \to \rho^0 K_S \gamma$

LAL-15-75 (to be submitted soon to arXiv)

> The time-dependent CP asymmetry in $B \to \rho K_S \gamma \to K_S \pi^+ \pi^- \gamma$ has been measured by the Belle and Babar collaborations. The main difficulty to interpret these results comes from the fact that the final $K_S \pi^+ \pi^-$ state can originate not only from ρK_S intermediate state but also from others such as $K^* \pi, (K\pi)_0 \pi$ which may posses different CP properties. In this paper, we re-derive the so-called *dilution factor*, $\mathcal{D}$, which represent the difference between CP violations of the ρK_S intermediated channel and of the total $K_S \pi^+ \pi^-$ channel.

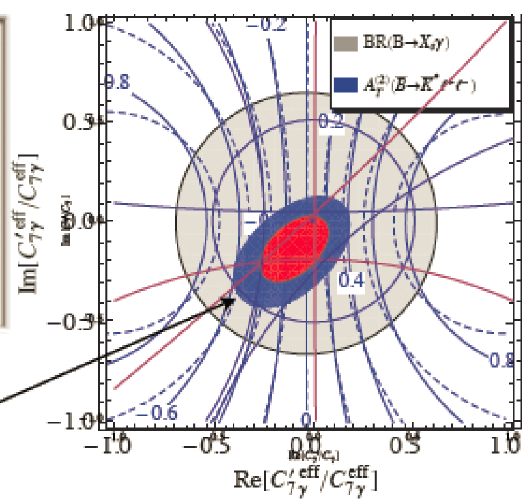
S. Akar, E. Ben-Haim, J. Hebinger, E. Kou and F.-S. Yu

- Update of the Left-Right symmetric model in the light of LHC data

> In the previous work (joint-PhD thesis of F.-S. Yu), we have investigated the Left-Right Symmetric Model (LRSM), especially the impact on the $b \to s\gamma$ processes. Since then, ATLAS/CMS have published new results on the right-handed W boson mass and also LHCb, the photon polarization measurement via angular distribution analysis of $B \to K^* e^+ e^-$. We are now updating our previous results including these new data.

E. Kou, C.-D. Lu and F.-S. Yu

Preliminary result on the new constraints from recent result by LHCb

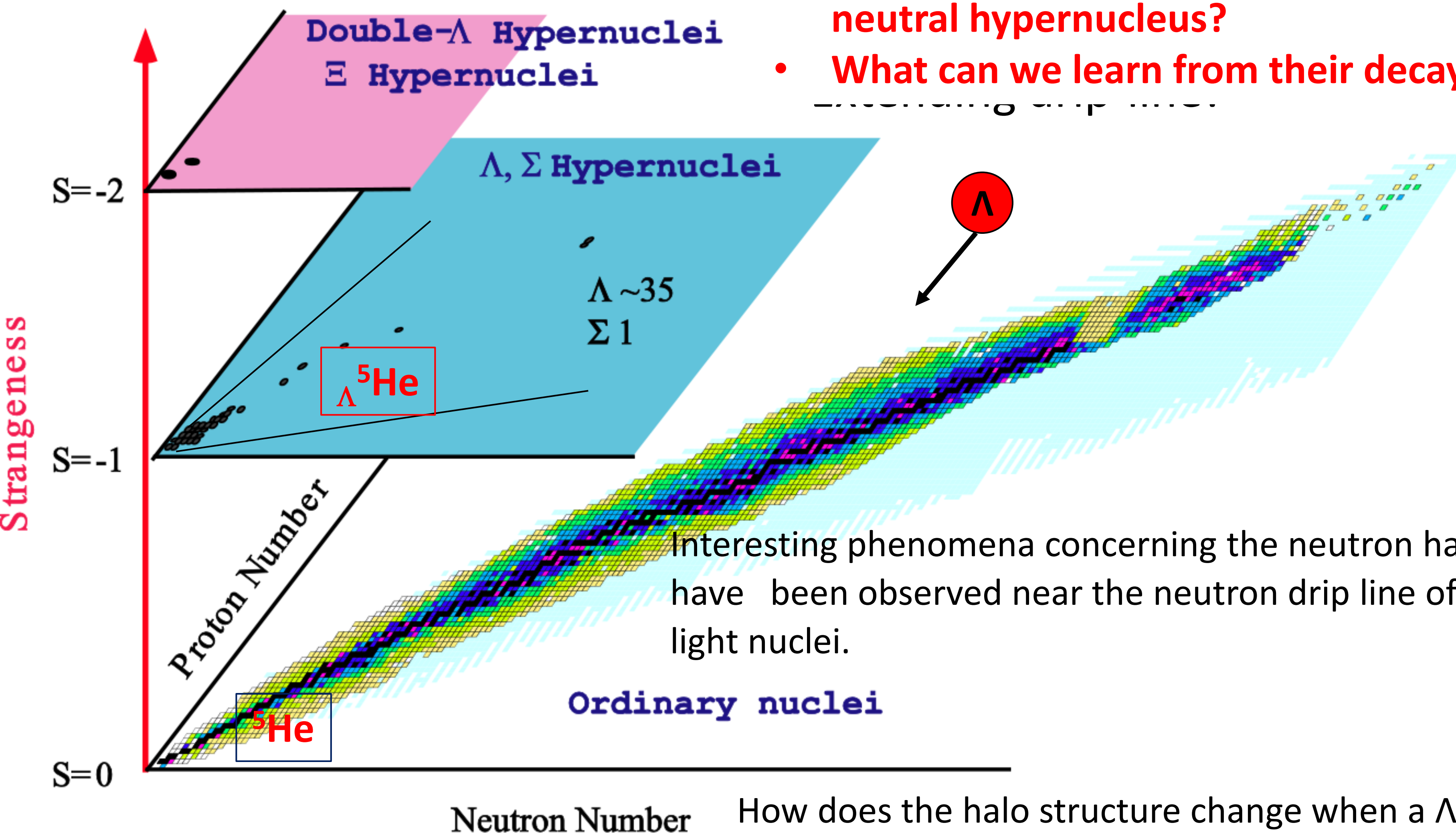


2. Weak decay of Λ in nuclear medium

Nuclear chart with strangeness

Multi-strangeness system such as Neutron star

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



Interesting phenomena concerning the neutron halo have been observed near the neutron drip line of light nuclei.

How does the halo structure change when a Λ particle is injected into an unstable nucleus?

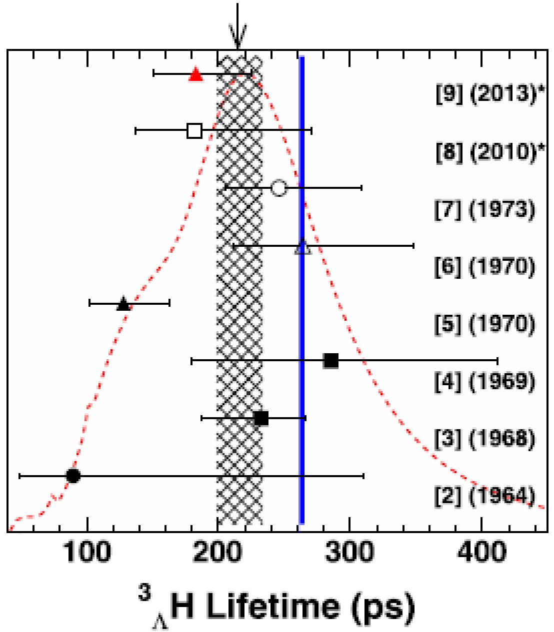
Slide from E. Hiyama

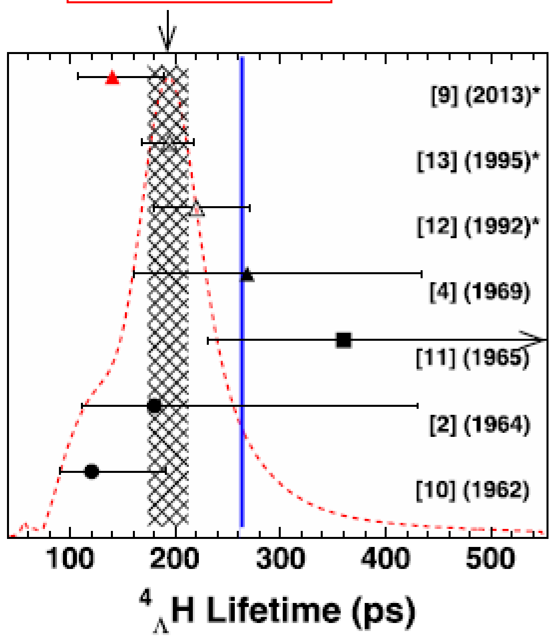
Lifetime measurement of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$

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

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

Free Λ: (263.2±2.0) ps





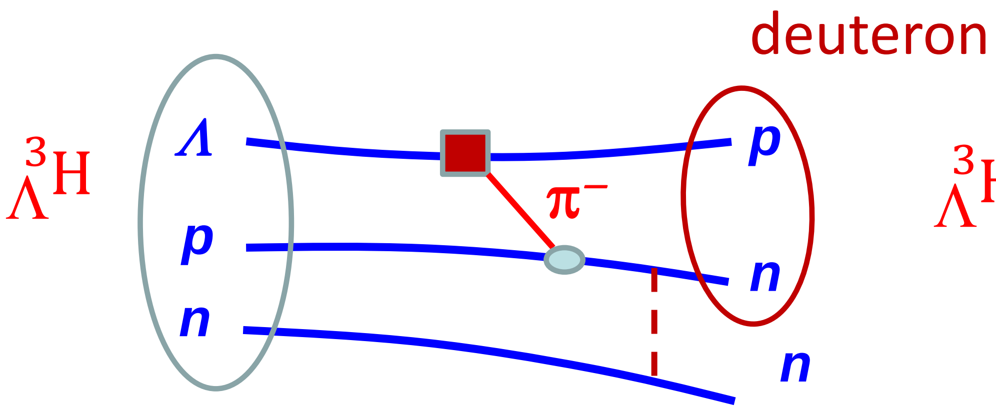
- The lifetimes of both ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ are shorter than that of the free Λ!

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

Why surprising?

- Since the $^{3}_{\Lambda}\mathrm{H}$ system is weakly bound its non-mesonic weak decay is expected to be small. Hence, one would expect that the lifetime of $^{3}_{\Lambda}\mathrm{H}$ is more or less the same as the free Λ.
- In comparison, the non-mesonic weak decay mode for $^{4}_{\Lambda}\mathrm{H}$ can enhance the decay width and make the lifetime of $^{4}_{\Lambda}\mathrm{H}$ much shorter than the free one.

Non-mesonic weak decay

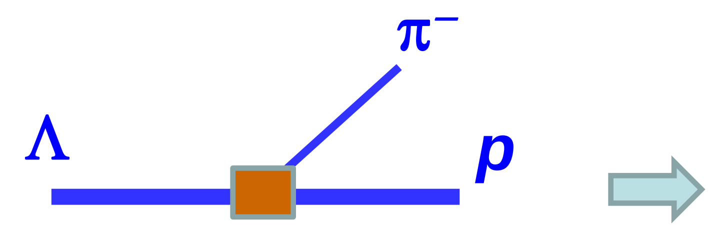


$$^{3}_{\Lambda}\mathrm{H} \rightarrow \pi^- + \text{all } (\,^{3}\mathrm{He}\ /\ \mathrm{d} + \mathrm{p}\ldots)$$

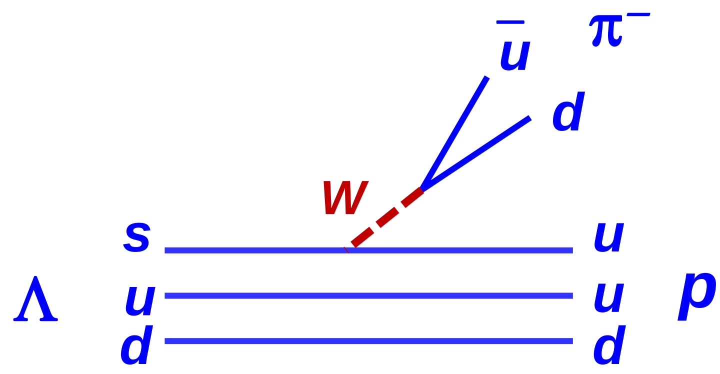
$$\mathrm{d} + \mathrm{n}$$

$$\mathrm{p} + 2\mathrm{n}$$

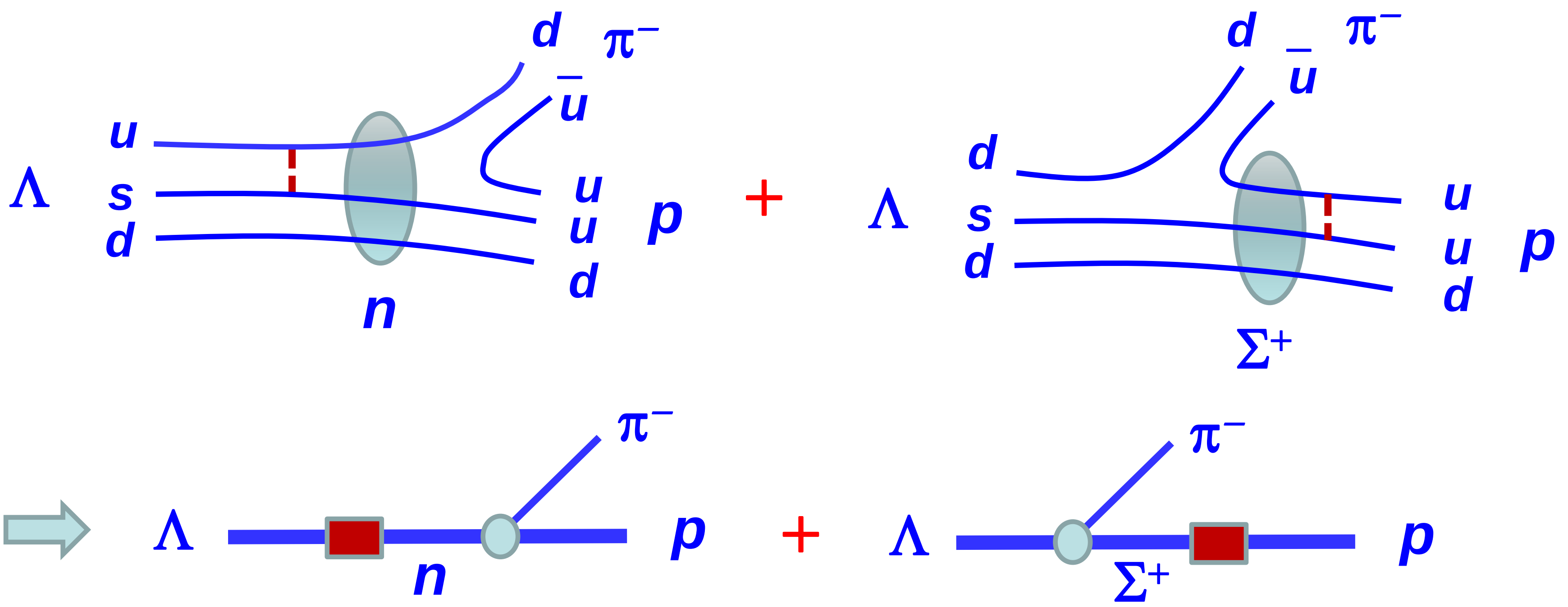
The Λ weak decay



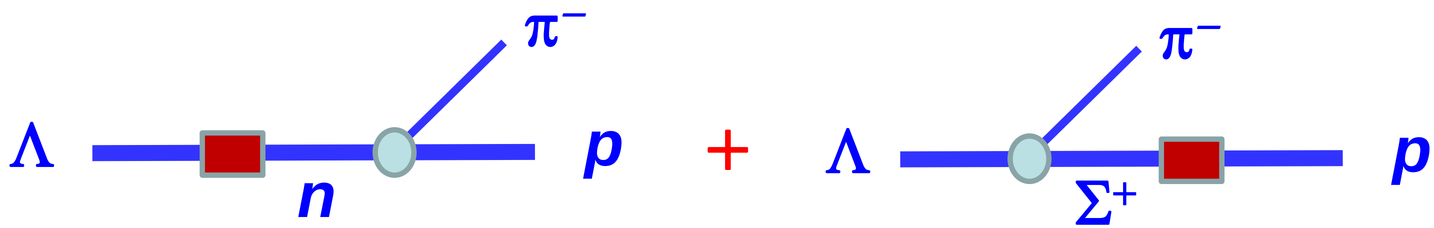
I) Direct pion emission



II) Pole contribution via baryon internal conversion



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



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

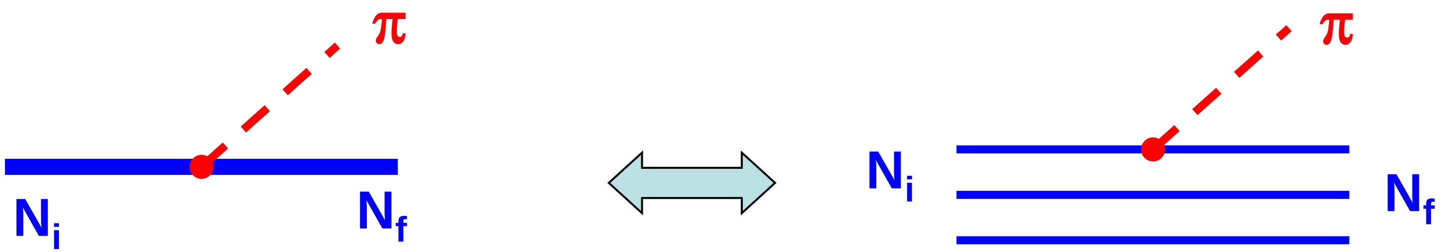
$$H_w = H_w^{PC} + H_w^{PV}$$

$$\begin{cases} H_w^{PC} = \dfrac{G_F}{\sqrt{2}} \int d\boldsymbol{x} [j_\mu^{(-)}(\boldsymbol{x}) j^{(+)\mu}(\boldsymbol{x}) + j_{5\mu}^{(-)}(\boldsymbol{x}) j_5^{(+)\mu}(\boldsymbol{x})] \\ H_w^{PV} = \dfrac{G_F}{\sqrt{2}} \int d\boldsymbol{x} [j_\mu^{(-)}(\boldsymbol{x}) j_5^{(+)\mu}(\boldsymbol{x}) + j_{5\mu}^{(-)}(\boldsymbol{x}) j^{(+)\mu}(\boldsymbol{x})] \end{cases}$$

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

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

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



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

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:

$$g_{\pi B_i B_f} = \frac{g_A \bar{M}}{f_\pi} \qquad g_A \equiv \frac{\langle B_f | \sum_j \hat{I}_j^\pi \sigma_j | B_i \rangle}{\langle B_f | \sigma_{tot} | B_i \rangle}$$

The transition amplitude becomes:

$$\mathcal{M} = \frac{1}{f_\pi} e^{-q^2/6\alpha_h^2} \sqrt{2M_i(M_f+E_f)} \left(1 + \frac{q_0}{E_f+M_f} + \frac{q_0}{3\mu_q}\right) |\boldsymbol{q}| \left(\frac{\alpha_h}{\sqrt{\pi}}\right)^3 6 G_F \cos\theta_C \sin\theta_C$$
$$\times \left[C_W(\Lambda \to n) \frac{2M_n}{M_\Lambda^2 - M_n^2} g_A(np\pi^-) + g_A(\Lambda\Sigma^+\pi^-) \frac{2M_\Sigma}{M_p^2 - M_\Sigma^2} C_W(\Sigma^+ \to p) \right] ,$$

$$\mathcal{M} = \frac{M_n}{f_\pi} e^{-q^2/6\alpha_h^2} \sqrt{2M_i(M_f+E_f)} \left(1 + \frac{q_0}{E_f+M_f} + \frac{q_0}{3\mu_q}\right) |\boldsymbol{q}| \left(\frac{\alpha_h}{\sqrt{\pi}}\right)^3 2\sqrt{6} G_F \cos\theta_C \sin\theta_C$$
$$\times \left[-\frac{5}{6} \frac{1}{M_\Lambda^2 - M_n^2} + \xi \frac{1}{M_\Sigma^2 - M_p^2} \right] ,$$

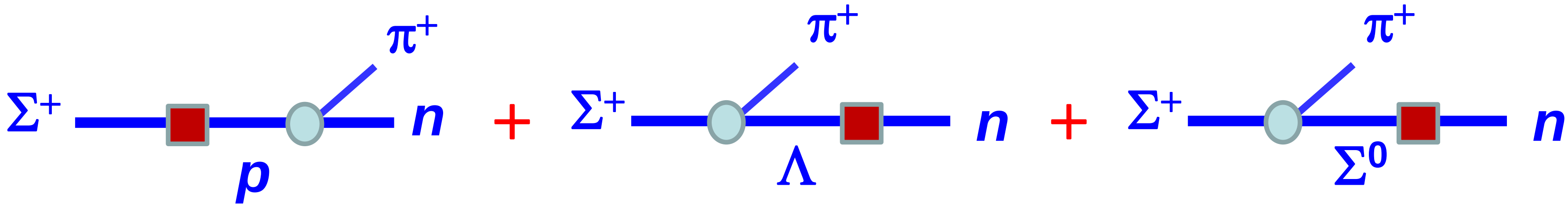
$\xi \simeq M_\Sigma / M_n$ indicates the SU(3) flavor symmetry breaking.

Explicit cancellation between the pole terms.

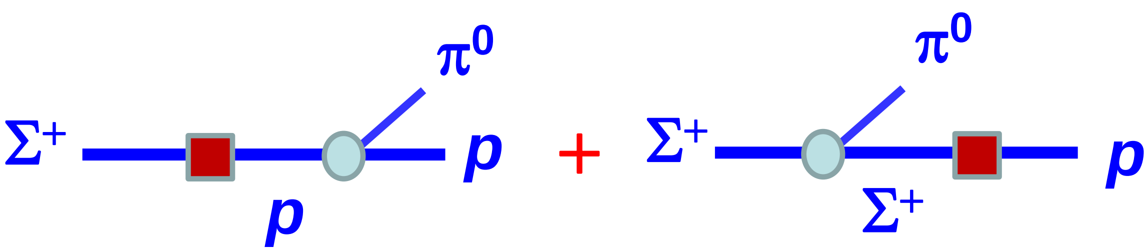
ξ is determined by the free Λ decay and will be fixed.

All involve cancellations among the pole terms

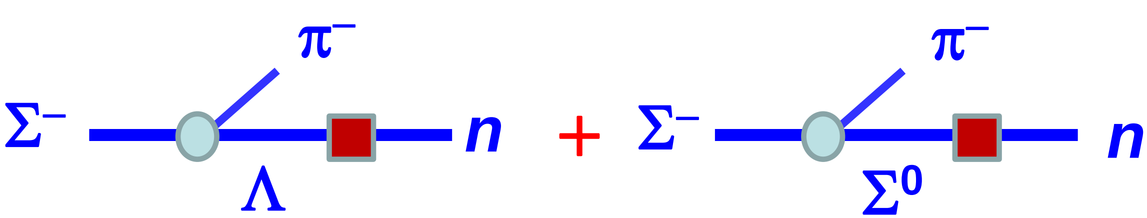
I) $\Sigma^+ \rightarrow n\,\pi^+$



II) $\Sigma^+ \rightarrow p\,\pi^0$



III) $\Sigma^- \rightarrow n\,\pi^-$



Process	g_A
$p \rightarrow n\pi^+$	$\frac{5}{3}$
$n \rightarrow p\pi^-$	$\frac{5}{3}$
$n \rightarrow n\pi^0$	$\frac{5}{3\sqrt{2}}$
$\Lambda \rightarrow \Sigma^+\pi^-$	$-\frac{2}{\sqrt{6}}$
$\Lambda \rightarrow \Sigma^0\pi^0$	$-\frac{2}{\sqrt{6}}$
$\Sigma^+ \rightarrow \Lambda\pi^+$	$-\frac{2}{\sqrt{6}}$
$\Sigma^- \rightarrow \Lambda\pi^-$	$-\frac{2}{\sqrt{6}}$
$\Sigma^+ \rightarrow \Sigma^0\pi^+$	$\frac{4}{3\sqrt{2}}$

$$C_W(A \rightarrow B) \equiv \langle B|\hat{O}_W|A\rangle$$

$$\hat{O}_W \equiv \tau_1^{(-)} v_2^{(+)} (1 - \sigma_1 \cdot \sigma_2)$$

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

Some general features:

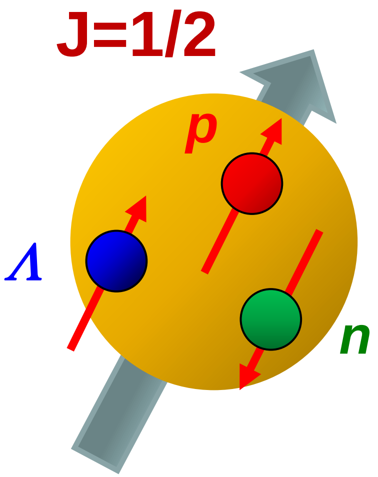
i) The Λ and Σ hadronic weak decays involve significant cancelations among the pole terms which is determined by the SU(3) flavor symmetry.

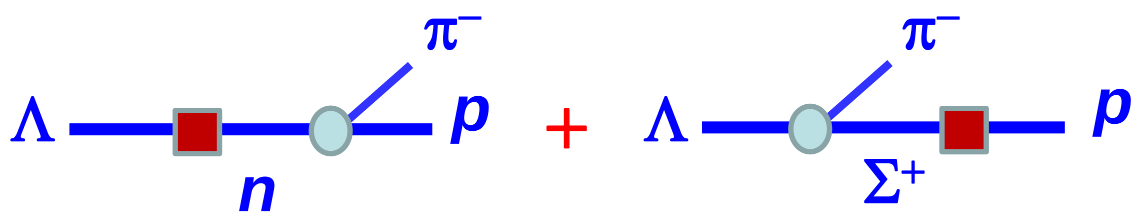
ii) However, the cancellations are sensitive to the SU(3) flavor symmetry breaking, which means a coherent study of the free Λ and Σ hadronic weak decay is necessary.

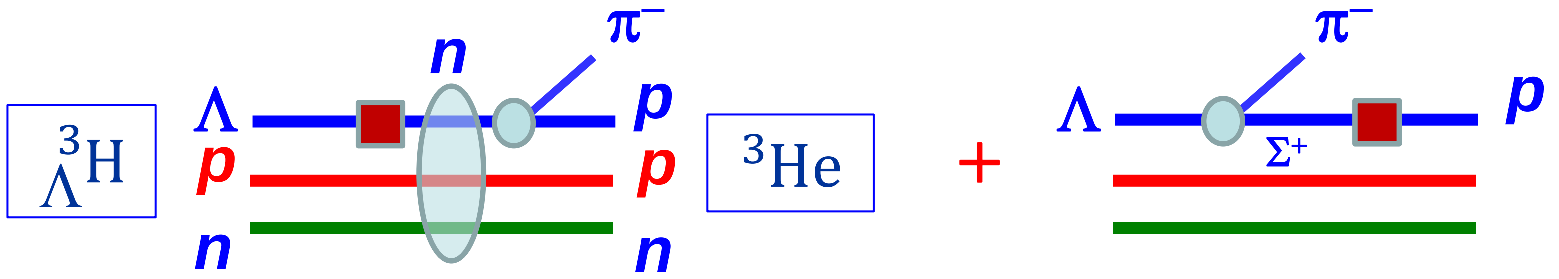
iii) Information about the short-distance behavior of the wavefunction is also crucial, but only contributes to the overall factor.

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.

The presence of Pauli principle will affect the relative strength between the pole terms.

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

$$\mathcal{M} = \frac{1}{f_\pi} e^{-q^2/6\alpha_h^2} \sqrt{2M_i(M_f + E_f)} \left(1 + \frac{q_0}{E_f + M_f} + \frac{q_0}{3\mu_q}\right) |\boldsymbol{q}| \left(\frac{\alpha_h}{\sqrt{\pi}}\right)^3 6G_F \cos\theta_C \sin\theta_C$$
$$\times \left[\beta C_W(\Lambda \to n) \frac{2M_n}{M_\Lambda^2 - M_n^2} g_A(np\pi^-) + g_A(\Lambda\Sigma^+\pi^-) \frac{2M_\Sigma}{M_p^2 - M_\Sigma^2} C_W(\Sigma^+ \to p)\right],$$

where $\beta = \begin{cases} 1.0 & \textbf{No Pauli blocking} \\ 0.5 & \textbf{Fully Pauli blocked} \end{cases}$

The Pauli blocking leads to significant change of the cancellation pattern and strongly increase the transition amplitude.

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:

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

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

The spatial integral is model dependent, while the spin-isospin wavefunctions are better defined.

$$\begin{aligned}\mathcal{M} &= \langle {}^3\mathrm{He}|H_\pi^{(3)}|{}^3\mathrm{H}\rangle\langle {}^3\mathrm{H}|\frac{i}{\not p_{{}^3_\Lambda\mathrm{H}} - M_{{}^3\mathrm{H}}} H_w^{(3)}|{}^3_\Lambda\mathrm{H}\rangle \\ &\quad + \langle {}^3\mathrm{He}|H_w^{(3)}\frac{i}{\not p - m_\Sigma}|p,n,\Sigma^+\rangle\langle p,n,\Sigma^+|H_\pi^{(3)}|{}^3_\Lambda\mathrm{H}\rangle \ , \\ &\simeq i\langle {}^3\mathrm{He}|H_\pi^{(3)}|{}^3\mathrm{H}\rangle\frac{2M_{{}^3\mathrm{H}}}{M^2_{{}^3_\Lambda\mathrm{H}} - M^2_{{}^3\mathrm{H}}}\langle {}^3\mathrm{H}|H_w^{(3)}|{}^3_\Lambda\mathrm{H}\rangle \\ &\quad + i\langle {}^3\mathrm{He}|H_w^{(3)}|p,n,\Sigma^+\rangle\frac{2m_\Sigma}{m_p^2 - m_\Sigma^2}\langle p,n,\Sigma^+|H_\pi^{(3)}|{}^3_\Lambda\mathrm{H}\rangle\end{aligned}$$

Intermediate ^{3}H saturation

Brief summary

- The presence of Pauli blocking plays a unique role in light hypernucleus weak decays and can explain the fastened lifetime of ${}^{3}_{\Lambda}H$.
- More analysis is needed to test this mechanism, e.g. in measurement of the lifetime of sigma hypernuclei.

Thanks for your attention!

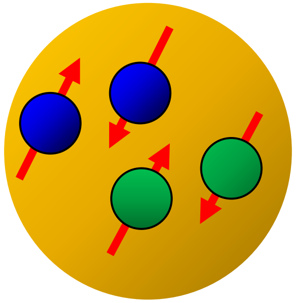
- How to organize the ($\Lambda\Lambda$nn) system?

T=${}_{\Lambda\Lambda}{}^{4}$n=($\Lambda\Lambda$nn)

S=0, I=1, L=0

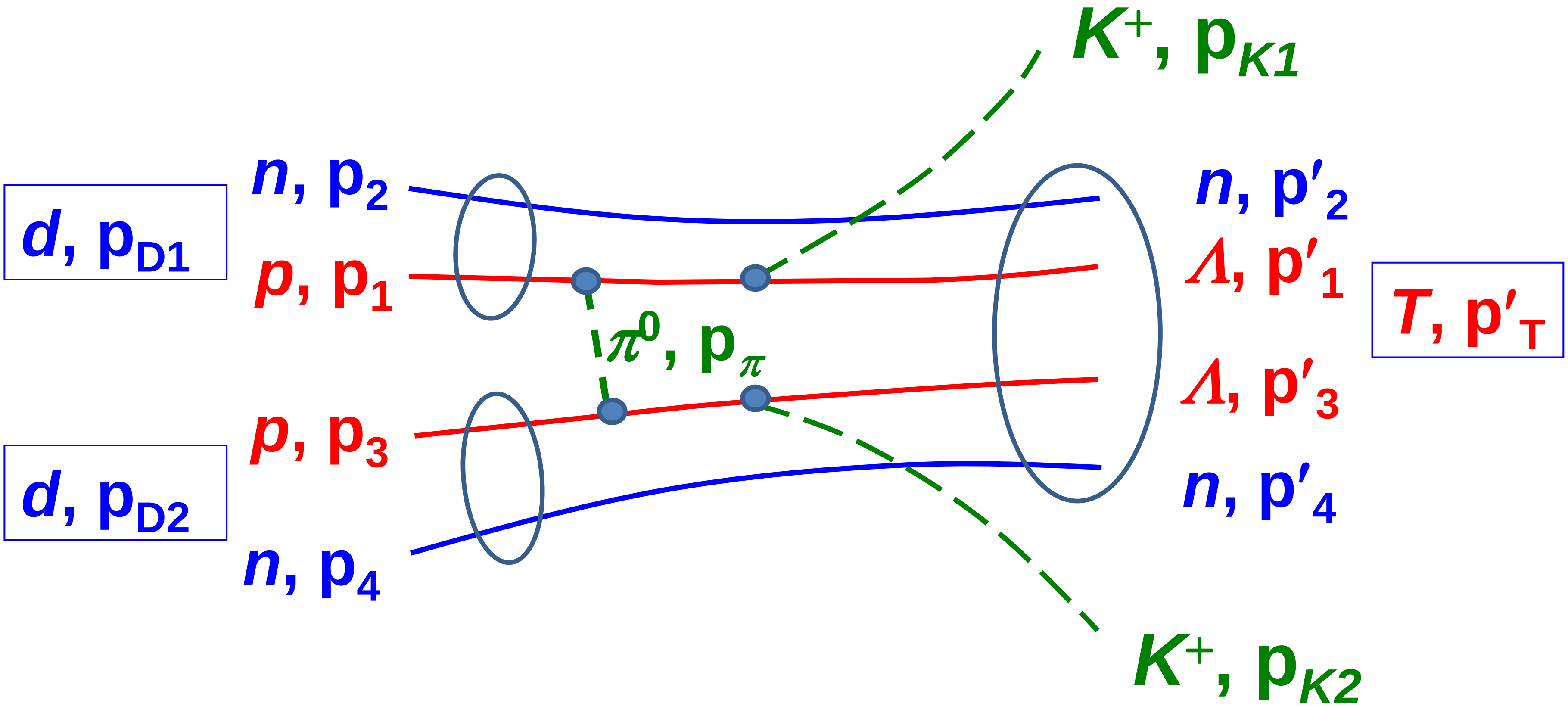
No Pauli blocking

Groundstate: $J^P=0^+$



Wang, Richard and Zhao, PRC91, 014003 (2015); 1404.3473[nucl-th]

Production mechanism for $(\Lambda\Lambda nn)$ in deuteron-deuteron collision

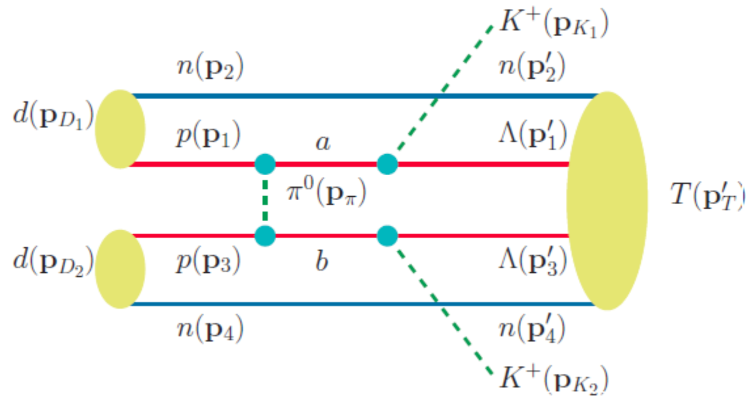


- The two K^+ production is via the elementary process, $pp \rightarrow \Lambda\Lambda K^+ K^+$.
- The intermediate $S_{11}(1535)$ excitations is sizeable near threshold.

Wang, Richard and Zhao, 1404.3473[nucl-th]

- Production mechanism for (ΛΛnn)

$$d + d \to K^+ + K^+ + T.$$



$$\int \psi^*_{(\Lambda\Lambda nn)}(\vec{p}_1{}', \vec{p}_2{}', \vec{p}_3{}', \vec{p}_4{}'; \vec{P}_C{}')\, \psi^*_{K_1}(\vec{p}_{K_1})\, \psi^*(\vec{p}_{K_2})\, \hat{O}_{tran}(\vec{p}_1{}', \vec{p}_3{}', \vec{p}_1, \vec{p}_3, \vec{p}_{K_1}, \vec{p}_{K_2})$$

$$\times\, \psi_{D_1}(\vec{p}_1, \vec{p}_2; \vec{P}_{D_1})\, \psi_{D_2}(\vec{p}_3, \vec{p}_4; \vec{P}_{D_2})\, \delta(\vec{P}_C{}' + \vec{p}_{K_1} + \vec{p}_{K_2} - \vec{P}_{D_1} - \vec{P}_{D_2})$$

$$\times\, \delta(\vec{p}_1 + \vec{p}_2 - \vec{P}_{D_1})\, \delta(\vec{p}_3 + \vec{p}_4 - \vec{P}_{D_2})\, \delta(\vec{p}_1{}' + \vec{p}_2{}' + \vec{p}_3{}' + \vec{p}_4{}' - \vec{P}_C{}')$$

$$\times\, \delta(\vec{p}_2 - \vec{p}_2{}')\, \delta(\vec{p}_4 - \vec{p}_4{}')\, d\vec{p}_1\, d\vec{p}_2\, d\vec{p}_3\, d\vec{p}_4\, d\vec{p}_1{}'\, d\vec{p}_2{}'\, d\vec{p}_3{}'\, d\vec{p}_4{}'$$

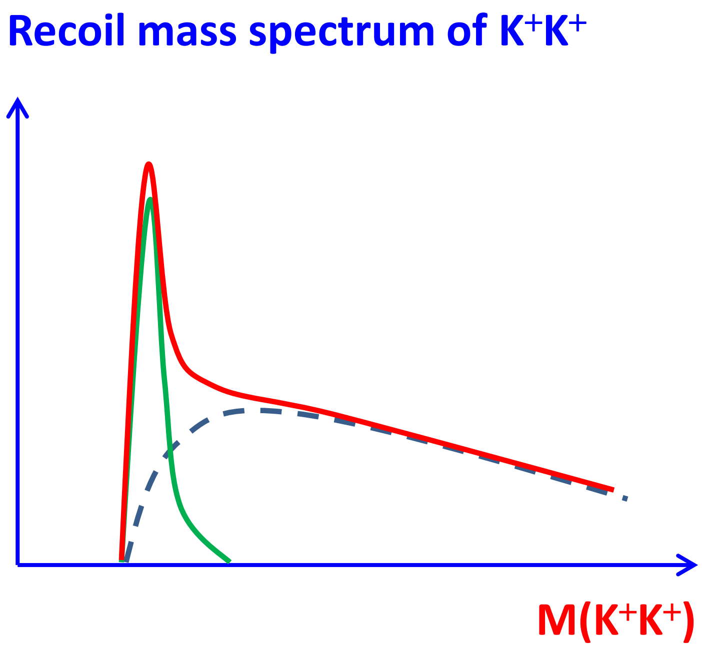
(Energy conservati is implied)

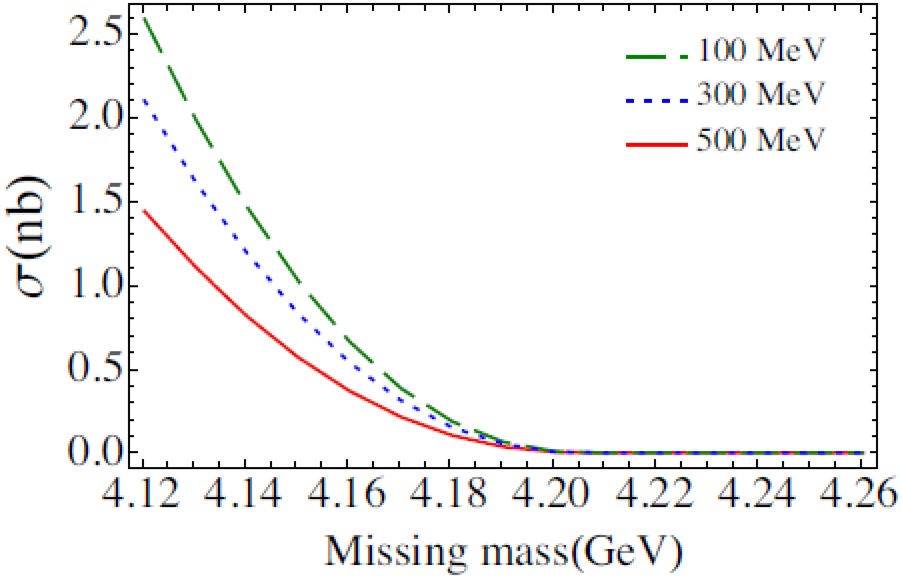
Assumption: The S-wave nuclear wavefunctions are dominant.

Wang, Richard and Zhao, 1404.3473[nucl-th]

- Missing mass spectrum for $(\Lambda\Lambda nn)$

$$d + d \to K^+ + K^+ + T.$$

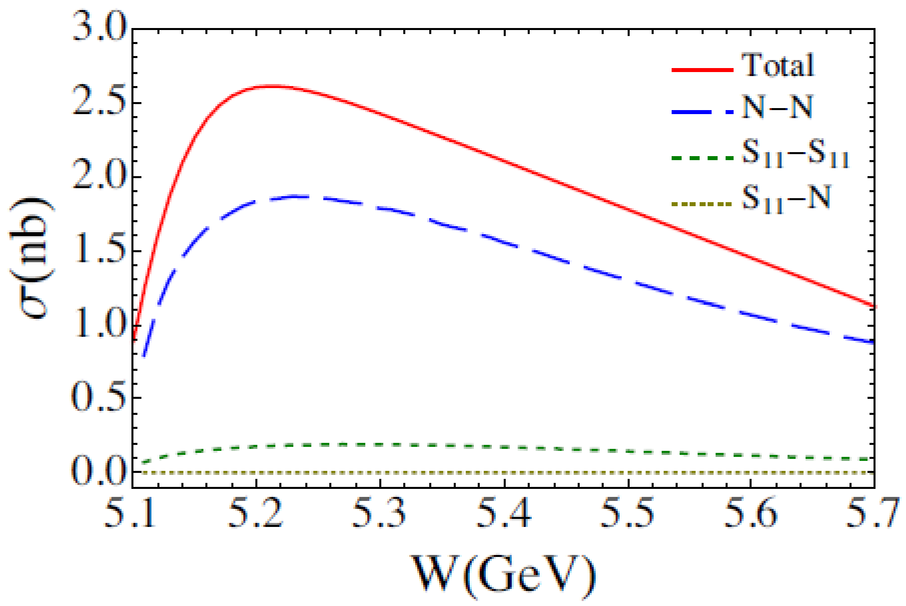




By tagging the two K+ in the final state, the production of the $(\Lambda\Lambda nn)$ will suffer nearly no background at all. The signal will peak at the mass of the $(\Lambda\Lambda nn)$.

Wang, Richard and Zhao, 1404.3473[nucl-th]

- Total cross section for (ΛΛnn)



The interference between the double nucleon Born term and double S_{11}(1535) excitation plays a significant role.