第五届强子与重味物理理论与实验联合研讨会

利用夸克模型的研究重子半轻衰变

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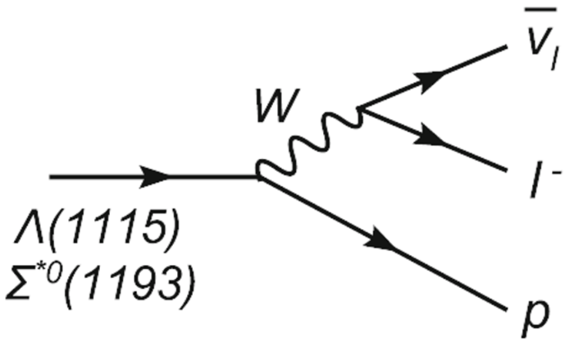
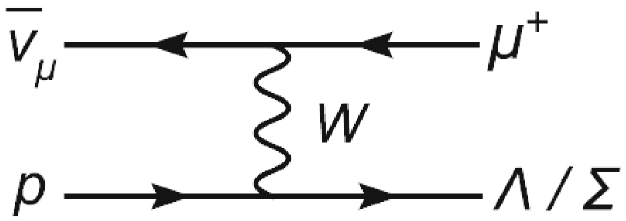
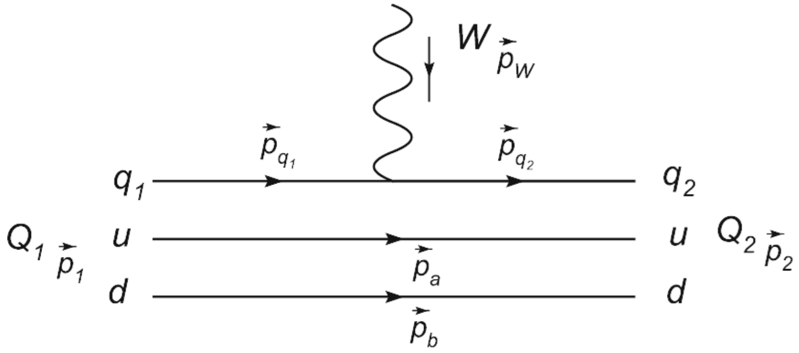
- 小结和展望

动机

- 弱作用过程的强作用相关顶点 => 强子物理







- 如何利用该顶点研究强子的性质？
- 如何利用该顶点寻找超出传统夸克模型的强子成分？

背景：研究超子物理的反应

$\gamma p \to KY^*, \pi p \to KY^*, e^+e^- \to Y\bar{Y}^*, ep \to eKY^*, pp \to KNY^*$

问题：多强子末态带来的困扰！

$K^- p \to Y^*$

问题：束流能量选择有限制！

背景：研究超子物理的反应

$\gamma p \to KY^*, \pi p \to KY^*, e^+e^- \to Y\bar{Y}^*, ep \to eKY^*, pp \to KNY^*$

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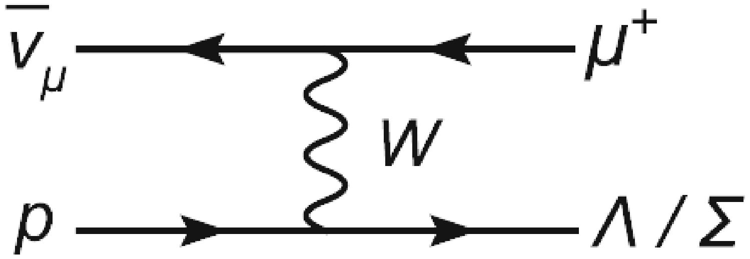
$K^-p \to Y^*$

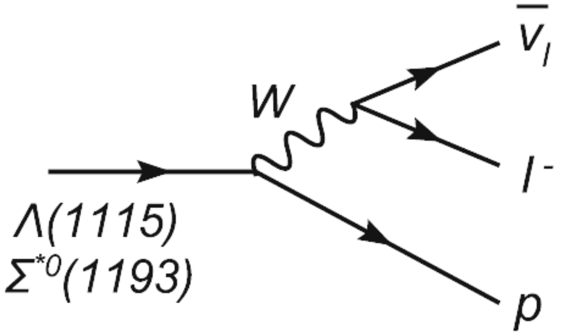
问题：束流能量选择有限制！

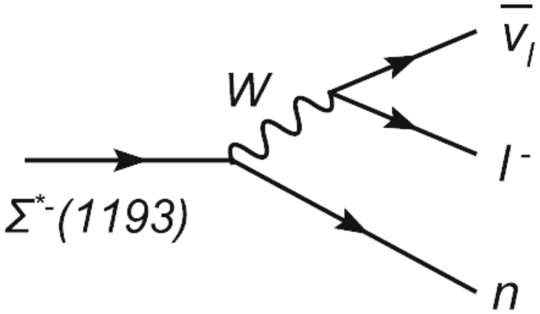
$\bar{\nu}p \to l^+Y^*, \quad \Lambda_c \to \bar{\nu}l^-Y^*$

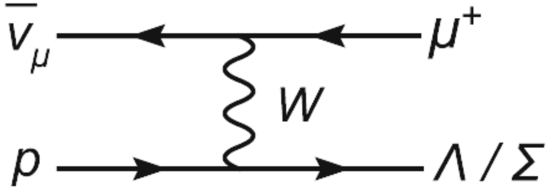


如何利用该顶点研究强子的性质？

超子反应振幅计算





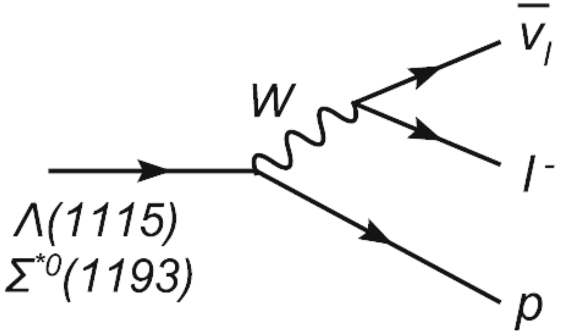


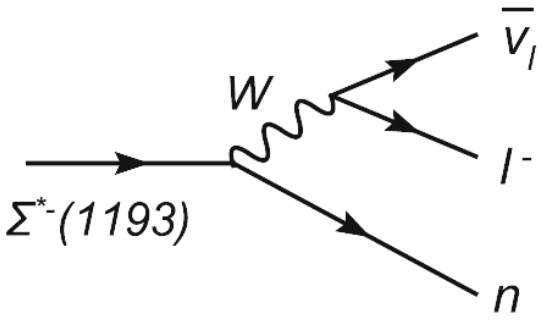
$$\mathcal{M} = T_1^{\mu} T_2^{\nu} G_{W\ \mu\nu} \qquad T_1^{\mu} = \sqrt{\frac{G_F m_W}{\sqrt{2}}}\left(\bar{l}\gamma^{\mu}(1-\gamma^5)\nu_l + h.c.\right) \qquad G_W^{\mu\nu} = \frac{-g^{\mu\nu} + p_W^{\mu} p_W^{\nu}/m_W^2}{p_W^2 - m_W^2}$$

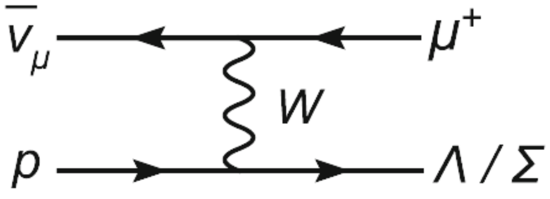
$$d\sigma = \frac{(2\pi)^4}{2E_\nu}\frac{1}{2}\sum_{s_z^\nu,\ s_z^{N1}}\sum_{s_z^l,\ s_z^{N2}}|\mathcal{M}|^2\delta^{(4)}_{(p_\nu+p_{N_1}-p_l-p_{N_2})}\frac{d^3\mathbf{p}_{N_1}m_{N_1}}{(2\pi)^3E_{N_1}}\frac{d^3\mathbf{p}_l m_l}{(2\pi)^3E_l}$$

$$d\Gamma = \frac{(2\pi)^4}{2M_\Lambda}\frac{1}{2}\sum_{s_z^\Lambda}\sum_{s_z^\nu, s_z^l,\ s_z^p}|\mathcal{M}|^2\delta^{(4)}_{(p_\nu+p_l+p_p)}\frac{d^3\mathbf{p}_p m_p}{(2\pi)^3E_p}\frac{d^3\mathbf{p}_\nu}{(2\pi)^3 2E_\nu}\frac{d^3\mathbf{p}_l m_l}{(2\pi)^3E_l}$$

W-强子对的顶点计算







基于强子层次的计算

$$T_{2\,BNW}^{\mu} = \sqrt{\frac{G_F m_W}{\sqrt{2}}}\,|v_{us}|(V^\mu + A^\mu)$$

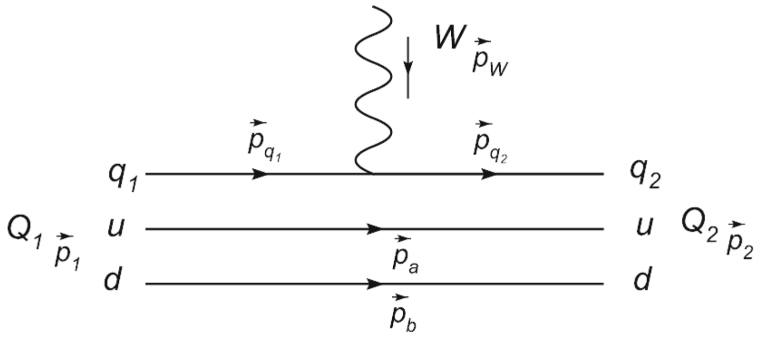
$$\text{with}\quad V^\mu = \bar{B}\left(f_1(q^2)\gamma^\mu - i\frac{f_2(q^2)\sigma^{\mu\nu}q_\nu}{m_B} + f_3(q^2)\frac{q_\mu}{m_B}\right)N + h.c.,$$

$$A^\mu = \bar{B}\left(g_1(q^2)\gamma^\mu - i\frac{g_2(q^2)\sigma^{\mu\nu}q_\nu}{m_B} + g_3(q^2)\frac{q_\mu}{m_B}\right)\gamma^5 N + h.c.$$

$$f_1(q^2) = \frac{f_1(0)}{(1-q^2/M_v^2)^2}$$

$$g_1(q^2) = \frac{g_1(0)}{(1-q^2/M_a^2)^2}$$

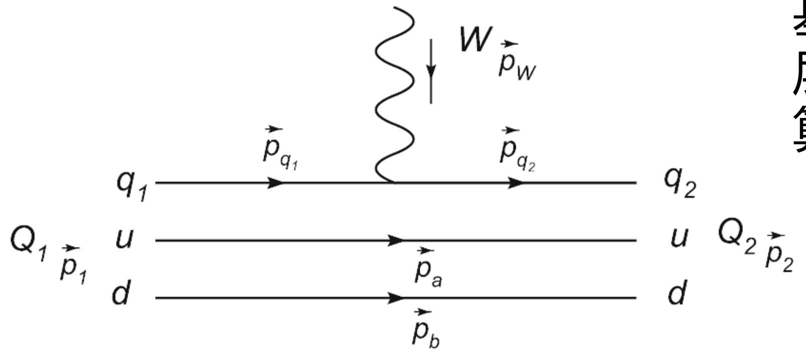
$$f_2(q^2) = f_2(0).$$?



基于夸克层次的计算

$$T_2^\nu(\mathbf{p}_w, s_z^{Q_1}, s_z^{Q_2}) = \int d\mathbf{p}_a d\mathbf{p}_b d\mathbf{p}_{q_1} d\mathbf{p}_{q_2}\,\delta(\mathbf{p}_a+\mathbf{p}_b+\mathbf{p}_{q_1})\,\delta(\mathbf{p}_{q_2}-\mathbf{p}_{q_1}-\mathbf{p}_w) \times \sqrt{\frac{G_F m_W}{\sqrt{2}}}\,|v_{q_1 q_2}|$$
$$\times \sum_{s_z^{q2},\, s_z^{q1}} \langle X^{Q_2},\, s_z^{Q_2},\, \Phi^{Q_2}|\chi^+_{q2,\, s_z^{q2}}\chi_{q1,\, s_z^{q1}}|X^{Q_1},\, s_z^{Q_1},\, \Phi^{Q_1}\rangle$$
$$\times\, \bar{u}_{q2}(\mathbf{p}_{q2},\, s_z^{q2})\gamma^\nu(1-\gamma^5)u_{q_1}(\mathbf{p}_{q_1},\, s_z^{q1}),$$

W-强子对的顶点计算



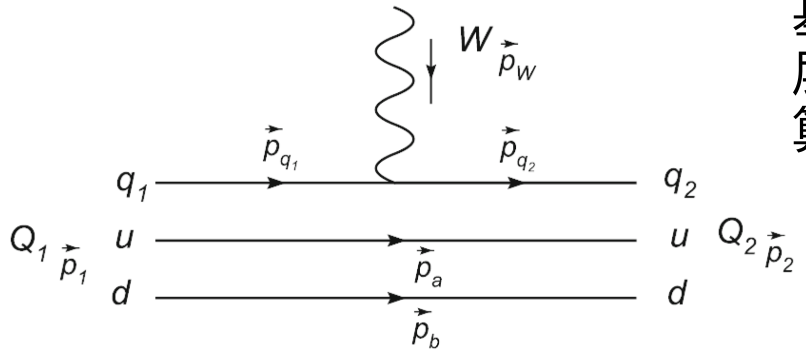
基于夸克层次的计算

$$T_2^{\nu}(\mathbf{p}_w, s_z^{Q_1}, s_z^{Q_2}) = \int d\mathbf{p}_a d\mathbf{p}_b d\mathbf{p}_{q_1} d\mathbf{p}_{q_2} \delta_{(\mathbf{p}_a+\mathbf{p}_b+\mathbf{p}_{q_1})} \delta_{(\mathbf{p}_{q_2}-\mathbf{p}_{q_1}-\mathbf{p}_w)} \times \sqrt{\frac{G_F m_W}{\sqrt{2}}} |v_{q_1 q_2}|$$
$$\times \sum_{s_z^{q_2}, s_z^{q_1}} \langle X^{Q_2}, s_z^{Q_2}, \Phi^{Q_2} | \chi^+_{q_2, s_z^{q_2}} \chi_{q_1, s_z^{q_1}} | X^{Q_1}, s_z^{Q_1}, \Phi^{Q_1} \rangle$$
$$\times \bar{u}_{q_2}(\mathbf{p}_{q_2}, s_z^{q_2}) \gamma^{\nu} (1-\gamma^5) u_{q_1}(\mathbf{p}_{q_1}, s_z^{q_1}),$$

$$|N(939)\rangle = 0.90|N_8^2 S_s\rangle + 0.34|N_8^2 S_s'\rangle - 0.27|N_8^2 S_M\rangle,$$
$$|\Lambda(1115)\rangle = 0.93|\Lambda_8^2 S_s\rangle + 0.30|\Lambda_8^2 S_s'\rangle - 0.20|\Lambda_8^2 S_M\rangle,$$

$$\left|B_8^2 S_s, \frac{1}{2}^+\right\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle_\lambda \left|\frac{1}{2}, s_z\right\rangle_\lambda + |B\rangle_\rho \left|\frac{1}{2}, s_z\right\rangle_\rho\right) \Phi_{000}(\mathbf{q}_\lambda, \mathbf{q}_\rho)$$

W-强子对的顶点计算



基于夸克层次的计算

$$T_2^{\nu}(\mathbf{p}_w, s_z^{Q_1}, s_z^{Q_2}) = \int d\mathbf{p}_a d\mathbf{p}_b d\mathbf{p}_{q_1} d\mathbf{p}_{q_2} \delta(\mathbf{p}_a+\mathbf{p}_b+\mathbf{p}_{q_1}) \delta(\mathbf{p}_{q_2}-\mathbf{p}_{q_1}-\mathbf{p}_w) \times \sqrt{\frac{G_F m_W}{\sqrt{2}}} |v_{q_1 q_2}|$$
$$\times \sum_{s_z^{q_2},\, s_z^{q_1}} \langle X^{Q_2},\ s_z^{Q_2},\ \Phi^{Q_2} | \chi^{+}_{q_2,\, s_z^{q_2}} \chi_{q_1,\, s_z^{q_1}} | X^{Q_1},\ s_z^{Q_1},\ \Phi^{Q_1} \rangle$$
$$\times \bar{u}_{q_2}(\mathbf{p}_{q_2},\ s_z^{q_2}) \gamma^{\nu} (1-\gamma^5) u_{q_1}(\mathbf{p}_{q_1},\ s_z^{q_1}),$$

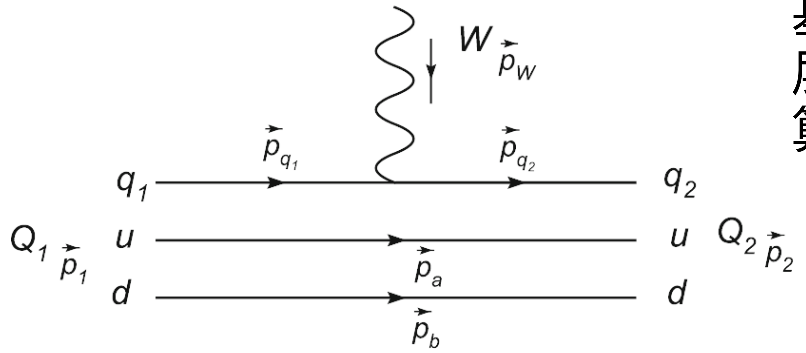
$$|N(939)\rangle = 0.90|N_8^2 S_s\rangle + 0.34|N_8^2 S_s'\rangle - 0.27|N_8^2 S_M\rangle,$$
$$|\Lambda(1115)\rangle = 0.93|\Lambda_8^2 S_s\rangle + 0.30|\Lambda_8^2 S_s'\rangle - 0.20|\Lambda_8^2 S_M\rangle,$$

$$\left|B_8^2 S_s, \frac{1}{2}^+\right\rangle = \frac{1}{\sqrt{2}} \left(|B\rangle_\lambda \left|\frac{1}{2}, s_z\right\rangle_\lambda + |B\rangle_\rho \left|\frac{1}{2}, s_z\right\rangle_\rho \right) \Phi_{000}(\mathbf{q}_\lambda, \mathbf{q}_\rho)$$

味道波函数部分

$${}_\lambda\langle \Lambda|\chi_s^+ \chi_u|p\rangle_\lambda = 0,$$
$${}_\lambda\langle \Lambda|\chi_s^+ \chi_u|p\rangle_\rho = 0,$$
$${}_\rho\langle \Lambda|\chi_s^+ \chi_u|p\rangle_\lambda = 0,$$
$${}_\rho\langle \Lambda|\chi_s^+ \chi_u|p\rangle_\rho = \frac{\sqrt{6}}{3}.$$

W-强子对的顶点计算



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$$T_2^{\nu}(\mathbf{p}_w, s_z^{Q_1}, s_z^{Q_2}) = \int d\mathbf{p}_a d\mathbf{p}_b d\mathbf{p}_{q_1} d\mathbf{p}_{q_2} \delta_{(\mathbf{p}_a+\mathbf{p}_b+\mathbf{p}_{q_1})} \delta_{(\mathbf{p}_{q_2}-\mathbf{p}_{q_1}-\mathbf{p}_w)} \times \sqrt{\frac{G_F m_W}{\sqrt{2}}} |v_{q_1 q_2}|$$
$$\times \sum_{s_z^{q_2},\, s_z^{q_1}} \langle X^{Q_2},\, s_z^{Q_2},\, \Phi^{Q_2} | \chi^+_{q_2,\, s_z^{q_2}} \chi_{q_1,\, s_z^{q_1}} | X^{Q_1},\, s_z^{Q_1},\, \Phi^{Q_1} \rangle$$
$$\times \bar{u}_{q_2}(\mathbf{p}_{q_2},\, s_z^{q_2}) \gamma^{\nu} (1-\gamma^5) u_{q_1}(\mathbf{p}_{q_1},\, s_z^{q_1}),$$

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味道波函数部分

$${}_\lambda\langle \Lambda | \chi_s^+ \chi_u | p \rangle_\lambda = 0,$$
$${}_\lambda\langle \Lambda | \chi_s^+ \chi_u | p \rangle_\rho = 0,$$
$${}_\rho\langle \Lambda | \chi_s^+ \chi_u | p \rangle_\lambda = 0,$$
$${}_\rho\langle \Lambda | \chi_s^+ \chi_u | p \rangle_\rho = \frac{\sqrt{6}}{3}.$$

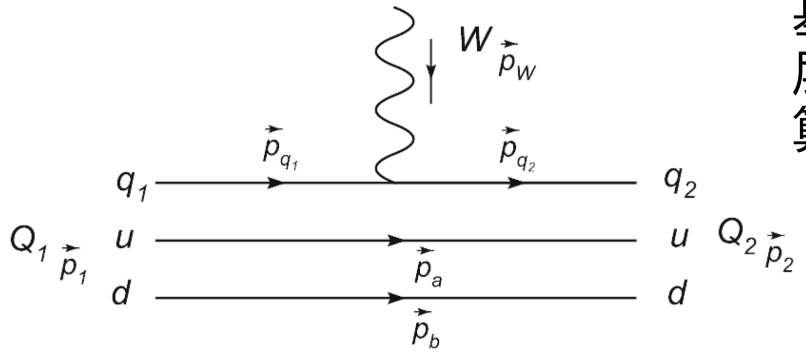
自旋波函数部分

$${}_\rho\left\langle \frac{1}{2}, s_z^\Lambda | \hat{O}^\mu | \frac{1}{2}, s_z^p \right\rangle_\rho = O^\mu(s_z^\Lambda, s_z^p),$$
$${}_\rho\left\langle \frac{1}{2}, s_z^\Lambda | \hat{O}^\mu | \frac{1}{2}, s_z^p \right\rangle_\lambda = 0,$$
$${}_\lambda\left\langle \frac{1}{2}, s_z^\Lambda | \hat{O}^\mu | \frac{1}{2}, s_z^p \right\rangle_\rho = 0,$$
$${}_\lambda\left\langle \frac{1}{2}, s_z^\Lambda = \frac{1}{2} | \hat{O}^\mu | \frac{1}{2}, s_z^p = \frac{1}{2} \right\rangle_\lambda = \frac{1}{3}\left(O^\mu\left(\frac{1}{2}, \frac{1}{2}\right) + 2 O^\mu\left(-\frac{1}{2}, -\frac{1}{2}\right)\right)$$
$${}_\lambda\left\langle \frac{1}{2}, s_z^\Lambda = -\frac{1}{2} | \hat{O}^\mu | \frac{1}{2}, s_z^p = \frac{1}{2} \right\rangle_\lambda = \frac{1}{3} O^\mu\left(-\frac{1}{2}, \frac{1}{2}\right),$$

$$O^\mu(s_z^s, s_z^u) = \bar{u}_s(\mathbf{q}_s,\, s_z^s)\, \gamma^\nu \left(1-\gamma^5\right) u_u(\mathbf{q}_u,\, s_z^u)$$

$$\mathbf{p}_{1\,\rho} = \frac{\mathbf{p}_a - \mathbf{p}_b}{\sqrt{2}},$$
$$\mathbf{p}_{1\,\lambda} = \frac{\mathbf{p}_a + \mathbf{p}_b - 2\mathbf{p}_{q_1}}{\sqrt{6}} = \frac{-3\mathbf{p}_{q_1}}{\sqrt{6}},$$
$$\mathbf{p}_{2\,\rho} = \frac{\mathbf{p}_a - \mathbf{p}_b}{\sqrt{2}},$$
$$\mathbf{p}_{2\,\lambda} = \frac{\mathbf{p}_a + \mathbf{p}_b - 2\mathbf{p}_{q_2}}{\sqrt{6}} = \frac{-3\mathbf{p}_{q_1} - 2\mathbf{p}_w}{\sqrt{6}}$$

W-强子对的顶点计算



基于夸克层次的计算

$$T_2^{\nu}(\mathbf{p}_w, s_z^{Q_1}, s_z^{Q_2}) = \int d\mathbf{p}_a d\mathbf{p}_b d\mathbf{p}_{q_1} d\mathbf{p}_{q_2} \delta_{(\mathbf{p}_a+\mathbf{p}_b+\mathbf{p}_{q_1})}\delta_{(\mathbf{p}_{q_2}-\mathbf{p}_{q_1}-\mathbf{p}_w)} \times \sqrt{\frac{G_F m_W}{\sqrt{2}}}|v_{q_1q_2}|$$
$$\times \sum_{s_z^{q_2},\, s_z^{q_1}} \langle X^{Q_2},\ s_z^{Q_2},\ \Phi^{Q_2}|\chi^+_{q_2,\ s_z^{q_2}}\chi_{q_1,\ s_z^{q_1}}|X^{Q_1},\ s_z^{Q_1},\ \Phi^{Q_1}\rangle$$
$$\times \bar{u}_{q_2}(\mathbf{p}_{q_2},\ s_z^{q_2})\gamma^{\nu}(1-\gamma^5)u_{q_1}(\mathbf{p}_{q_1},\ s_z^{q_1}),$$

$$|N(939)\rangle = 0.90|N_8^2 S_s\rangle + 0.34|N_8^2 S_s'\rangle - 0.27|N_8^2 S_M\rangle,$$
$$|\Lambda(1115)\rangle = 0.93|\Lambda_8^2 S_s\rangle + 0.30|\Lambda_8^2 S_s'\rangle - 0.20|\Lambda_8^2 S_M\rangle,$$

$$\left|B_8^2 S_s, \frac{1}{2}^+\right\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle_\lambda \left|\frac{1}{2}, s_z\right\rangle_\lambda + |B\rangle_\rho \left|\frac{1}{2}, s_z\right\rangle_\rho\right)\Phi_{000}(\mathbf{q}_\lambda, \mathbf{q}_\rho)$$

味道波函数部分

$$_\lambda\langle\Lambda|\chi_s^+\chi_u|p\rangle_\lambda = 0,$$
$$_\lambda\langle\Lambda|\chi_s^+\chi_u|p\rangle_\rho = 0,$$
$$_\rho\langle\Lambda|\chi_s^+\chi_u|p\rangle_\lambda = 0,$$
$$_\rho\langle\Lambda|\chi_s^+\chi_u|p\rangle_\rho = \frac{\sqrt{6}}{3}.$$

自旋波函数部分

$$_\rho\left\langle\frac{1}{2}, s_z^\Lambda|\hat{O}^\mu|\frac{1}{2}, s_z^p\right\rangle_\rho = O^\mu(s_z^\Lambda, s_z^p),$$
$$_\rho\left\langle\frac{1}{2}, s_z^\Lambda|\hat{O}^\mu|\frac{1}{2}, s_z^p\right\rangle_\lambda = 0,$$
$$_\lambda\left\langle\frac{1}{2}, s_z^\Lambda|\hat{O}^\mu|\frac{1}{2}, s_z^p\right\rangle_\rho = 0,$$
$$_\lambda\left\langle\frac{1}{2}, s_z^\Lambda = \frac{1}{2}|\hat{O}^\mu|\frac{1}{2}, s_z^p = \frac{1}{2}\right\rangle_\lambda = \frac{1}{3}\left(O^\mu\left(\frac{1}{2}, \frac{1}{2}\right) + 2O^\mu\left(-\frac{1}{2}, -\frac{1}{2}\right)\right)$$
$$_\lambda\left\langle\frac{1}{2}, s_z^\Lambda = -\frac{1}{2}|\hat{O}^\mu|\frac{1}{2}, s_z^p = \frac{1}{2}\right\rangle_\lambda = \frac{1}{3}O^\mu\left(-\frac{1}{2}, \frac{1}{2}\right),$$

$$O^\mu\left(s_z^s, s_z^u\right) = \bar{u}_s\left(\mathbf{q}_s,\ s_z^s\right)\gamma^\nu\left(1-\gamma^5\right)u_u\left(\mathbf{q}_u,\ s_z^u\right)$$

结合空间波函数部分

$$T^\mu_{2\ \Lambda-p-W}(s_z^\Lambda, s_z^p) = \int -\frac{9}{2}d\mathbf{q}_u d\mathbf{q}_\rho \sqrt{\left(\frac{G_F m_W^2}{\sqrt{2}}\right)}|v_{us}|$$
$$\times\left\{\left[\frac{0.90}{\sqrt{2}}\Phi_{000}(\mathbf{q}_\lambda^p, \mathbf{q}_\rho) + \frac{0.34}{\sqrt{2}}\Phi^s_{200}(\mathbf{q}_\lambda^p, \mathbf{q}_\rho) + \frac{0.27}{2}\Phi^\lambda_{200}(\mathbf{q}_\lambda^p, \mathbf{q}_\rho)\right]\right.$$
$$\times\left[\frac{0.93}{\sqrt{2}}\Phi_{000}(\mathbf{q}_\lambda^\Lambda, \mathbf{q}_\rho) + \frac{0.30}{\sqrt{2}}\Phi^s_{200}(\mathbf{q}_\lambda^\Lambda, \mathbf{q}_\rho) + \frac{0.20}{2}\Phi^\lambda_{200}(\mathbf{q}_\lambda^\Lambda, \mathbf{q}_\rho)\right]$$
$$\times\ _\rho\langle\frac{1}{2}, s_z^\Lambda|\hat{O}^\nu|\frac{1}{2}, s_z^p\rangle_\rho$$
$$\left.+\frac{0.27}{2}\frac{0.20}{2}\Phi^\lambda_{200}(\mathbf{q}_\lambda^p, \mathbf{q}_\rho)\Phi^\lambda_{200}(\mathbf{q}_\lambda^\Lambda, \mathbf{q}_\rho)_\lambda\langle\frac{1}{2}, s_z^\Lambda|\hat{O}^\nu|\frac{1}{2}, s_z^p\rangle_\lambda\right\}$$

$$\mathbf{q}_\lambda^p = -3\mathbf{q}_u/\sqrt{6}, \qquad \mathbf{q}_\lambda^\Lambda = -(3\mathbf{q}_u + 2\mathbf{q}_W)/\sqrt{6}.$$

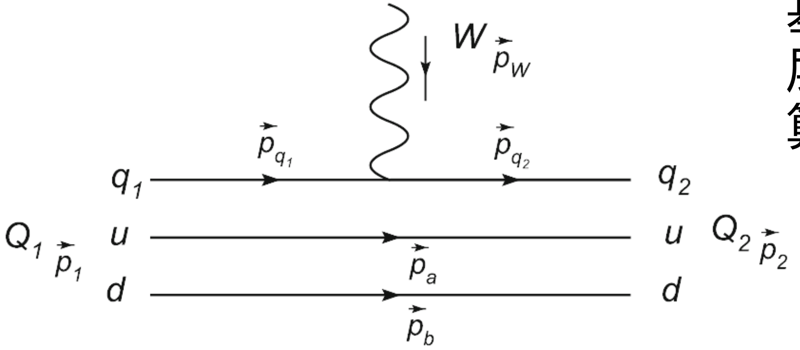
W-强子对的顶点计算

$$\mathbf{p}_{1\,\rho} = \frac{\mathbf{p}_a - \mathbf{p}_b}{\sqrt{2}},$$

$$\mathbf{p}_{1\,\lambda} = \frac{\mathbf{p}_a + \mathbf{p}_b - 2\mathbf{p}_{q_1}}{\sqrt{6}} = \frac{-3\mathbf{p}_{q_1}}{\sqrt{6}},$$

$$\mathbf{p}_{2\,\rho} = \frac{\mathbf{p}_a - \mathbf{p}_b}{\sqrt{2}},$$

$$\mathbf{p}_{2\,\lambda} = \frac{\mathbf{p}_a + \mathbf{p}_b - 2\mathbf{p}_{q_2}}{\sqrt{6}} = \frac{-3\mathbf{p}_{q_1} - 2\mathbf{p}_w}{\sqrt{6}}$$



基于夸克层次的计算

$$T_2^{\nu}(\mathbf{p}_w, s_z^{Q_1}, s_z^{Q_2}) = \int d\mathbf{p}_a d\mathbf{p}_b d\mathbf{p}_{q_1} d\mathbf{p}_{q_2} \delta_{(\mathbf{p}_a+\mathbf{p}_b+\mathbf{p}_{q_1})} \delta_{(\mathbf{p}_{q_2}-\mathbf{p}_{q_1}-\mathbf{p}_w)} \times \sqrt{\frac{G_F m_W}{\sqrt{2}}} |v_{q_1 q_2}|$$
$$\times \sum_{s_z^{q_2},\, s_z^{q_1}} \langle X^{Q_2},\, s_z^{Q_2},\, \Phi^{Q_2} | \chi^+_{q_2,\, s_z^{q_2}} \chi_{q_1,\, s_z^{q_1}} | X^{Q_1},\, s_z^{Q_1},\, \Phi^{Q_1} \rangle$$
$$\times \bar{u}_{q_2}(\mathbf{p}_{q_2},\, s_z^{q_2}) \gamma^{\nu} (1-\gamma^5) u_{q_1}(\mathbf{p}_{q_1},\, s_z^{q_1}),$$

$$|N(939)\rangle = 0.90|N_8^2 S_s\rangle + 0.34|N_8^2 S_s'\rangle - 0.27|N_8^2 S_M\rangle,$$
$$|\Lambda(1115)\rangle = 0.93|\Lambda_8^2 S_s\rangle + 0.30|\Lambda_8^2 S_s'\rangle - 0.20|\Lambda_8^2 S_M\rangle,$$

$$\left|B_8^2 S_s, \frac{1}{2}^+\right\rangle = \frac{1}{\sqrt{2}}\left(|B\rangle_\lambda \left|\frac{1}{2}, s_z\right\rangle_\lambda + |B\rangle_\rho \left|\frac{1}{2}, s_z\right\rangle_\rho\right)\Phi_{000}(\mathbf{q}_\lambda, \mathbf{q}_\rho)$$

味道波函数部分

$${}_\lambda\langle \Lambda | \chi_s^+ \chi_u | p \rangle_\lambda = 0,$$
$${}_\lambda\langle \Lambda | \chi_s^+ \chi_u | p \rangle_\rho = 0,$$
$${}_\rho\langle \Lambda | \chi_s^+ \chi_u | p \rangle_\lambda = 0,$$
$${}_\rho\langle \Lambda | \chi_s^+ \chi_u | p \rangle_\rho = \frac{\sqrt{6}}{3}.$$

自旋波函数部分

$$D(\boldsymbol{k}, \boldsymbol{P}) \equiv S^{-1}(\boldsymbol{p})\, S(\boldsymbol{P})\, S(\boldsymbol{k}). \quad \boldsymbol{p} = \boldsymbol{k} + \frac{\boldsymbol{P}}{M}\left(\epsilon + \frac{\boldsymbol{P}\cdot\boldsymbol{k}}{E+M}\right)$$

$$S_k = \frac{1}{2}\mathrm{Tr}\left[D^\dagger(\boldsymbol{k}_k', \boldsymbol{P}_f) D(\boldsymbol{k}_k, \boldsymbol{P}_i)\right]$$

$$D(\boldsymbol{k}, \boldsymbol{P}) = \mathcal{N}_W \left[(e+m)(\epsilon+m) + \boldsymbol{p}\cdot\boldsymbol{k} + i\boldsymbol{\sigma}\cdot(\boldsymbol{p}\times\boldsymbol{k})\right],$$

结合空间波函数部分

$$\Psi_f^{(\boldsymbol{P}_f)}(\{\boldsymbol{p}_i\}) = \sqrt{\mathcal{J}_f(\{\boldsymbol{p}_i\}; \boldsymbol{P}_f)}\, \Psi_f^{(\mathbf{0})}(\{\boldsymbol{k}_i\})$$

$$k_{i,z} = \gamma(p_{i,z} - v e_i), \quad \boldsymbol{k}_{i,\perp} = \boldsymbol{p}_{i,\perp},$$

$$\mathcal{J}_f = \frac{E_f}{M_f}\prod_{i=1}^{3}\frac{\epsilon_i}{e_i}, \qquad \epsilon_i = \sqrt{m_i^2 + \boldsymbol{k}_i^2}$$

$$O^{\mu}\left(s_z^s, s_z^u\right) = \bar{u}_s\left(\mathbf{q}_s,\, s_z^s\right)\gamma^{\nu}\left(1-\gamma^5\right)u_u\left(\mathbf{q}_u,\, s_z^u\right)$$

考虑了相对论运动系带来的效应

夸克模型：重子波函数的计算

$$H = \sum_{i=1}^{3} \sqrt{\boldsymbol{p}_i^2 + m_i^2} + \sum_{i<j} V(r_{ij}) + C_0,$$

$$V(r_{ij}) = V_{\text{corn}}(r_{ij}) + V_{\text{hyp}}(r_{ij})$$

$$V_{\text{corn}}(r_{ij}) = -\frac{2}{3}\frac{\alpha_s^{ij}}{r_{ij}} + \frac{b}{2} r_{ij}$$

$$V_{\text{hyp}}(r_{ij}) = \frac{16\pi\alpha_s^{ij}}{9\, m_i m_j} \frac{e^{-r_{ij}^2/r_0^2(ij)}}{\pi^{3/2} r_0^3(ij)} (\boldsymbol{S}_i \cdot \boldsymbol{S}_j)$$

$$\sum_{k'=1}^{\mathcal{N}} (H_{kk'} - E\, N_{kk'}) c_{k'} = 0,$$

$$\Psi_{JM_J} = \sum_{k=1}^{\mathcal{N}} c_k \left[\psi_{\text{space}}^{(k)} \otimes \chi_{\text{spin}} \otimes \phi_{\text{flavor}} \otimes \phi_{\text{color}}\right]_{JM_J}$$

轻味重子波函数

$$|B_{\mathbf{8}}(1/2^+)\rangle = \frac{1}{\sqrt{2}}\left(\phi_{\mathbf{8}}^{\rho}\chi_{\frac{1}{2}}^{\rho} + \phi_{\mathbf{8}}^{\lambda}\chi_{\frac{1}{2}}^{\lambda}\right)\psi_{\text{space}}^{S},$$

$$|B_{\mathbf{10}}(3/2^+)\rangle = \phi_{\mathbf{10}}^{S}\chi_{\frac{3}{2}}^{S}\psi_{\text{space}}^{S}.$$

单重味重子波函数

$$|B_{\mathbf{6}}(1/2^+)\rangle = \phi_{\mathbf{6}}^{\lambda}\chi_{\frac{1}{2}}^{\lambda}\psi_{\text{space}}^{S},$$

$$|B_{\mathbf{6}}(3/2^+)\rangle = \phi_{\mathbf{6}}^{\lambda}\chi_{\frac{3}{2}}^{S}\psi_{\text{space}}^{S},$$

$$|B_{\bar{\mathbf{3}}}(1/2^+)\rangle = \phi_{\bar{\mathbf{3}}}^{\rho}\chi_{\frac{1}{2}}^{\rho}\psi_{\text{space}}^{S}.$$

$m_{u/d}$ (MeV)	m_s (MeV)	m_c (MeV)	m_b (MeV)
300.0	489.4	1737.3	5111.8
$g_{u/d}$	g_s	g_c	g_b
0.7500	0.6539	0.5100	0.4400
A (GeV^{B-1})	B	b (GeV^2)	C_0 (MeV)
1.0538	0.5498	0.1621	−582.1

States	Ours	Exp.	Deviation
p	946.6	938.3	+8.3
Δ	1227.1	1234.9	−7.8
Λ	1113.0	1115.7	−2.7
Σ	1196.2	1192.6	+3.5
Σ^*	1366.2	1382.8	−16.6
Ξ	1326.6	1314.9	+11.7
Ξ^*	1506.7	1531.8	−25.1
Ω	1649.0	1672.4	−23.5
Λ_c	2246.9	2286.5	−39.6
Σ_c	2437.1	2453.7	−16.7
Σ_c^*	2490.7	2518.5	−27.8
Ξ_c	2476.4	2471.0	+5.4
Ξ_c'	2645.3	2578.7	+66.6
Ξ_c^*	2631.3	2646.2	−14.9
Ω_c	2736.4	2695.3	+41.1
Ω_c^*	2774.2	2766.0	+8.2
Λ_b	5574.3	5619.6	−45.3
Σ_b^*	5816.4	5830.3	−13.9
Σ_b	5797.2	5810.6	−13.4
Ξ_b	5802.6	5791.7	+10.9
Ξ_b'	5959.8	5934.9	+24.9
Ξ_b^*	5954.4	5952.3	+2.1
Ω_b	6080.8	6045.8	+35.0
Ω_b^*	6095.0	6085.0	+10.0
$N(1440)$	1492.5	1440.0	+52.5
$\Delta(1600)$	1722.8	1570.0	+152.8
$\Lambda(1600)$	1655.4	1600.0	+55.4
$\Sigma(1660)$	1712.0	1660.0	+52.0
$\Sigma(1780)$	1856.7	1780.0	+76.7

轻味重子半轻衰变计算

Table 5: Comparison of the semileptonic decay rates for Σ hyperons. The experimental data are taken from RPP [1] unless otherwise specified.

Decay Mode	Branching Fraction ($\mathcal{B}$)		Ratio ($R_{\mu e}$ or ...)	
($\ell = e, \mu$)	Exp. (RPP/BESIII)	Ours	Exp.	Ours
Electron channels ($\ell = e$)				
$\Sigma^- \to n e^- \bar{\nu}_e$	$(10.17 \pm 0.34) \times 10^{-4}$	6.99×10^{-4}	—	—
$\Sigma^- \to \Lambda e^- \bar{\nu}_e$	$(5.73 \pm 0.27) \times 10^{-5}$	4.48×10^{-5}	—	—
$\Sigma^+ \to \Lambda e^+ \nu_e$	$(2.3 \pm 0.4) \times 10^{-5}$	1.46×10^{-5}	$1.37 \pm 0.25^\dagger$	$1.66^\dagger$
$\Sigma^- \to \Sigma^0 e^- \bar{\nu}_e$	—	1.21×10^{-10}	—	—
$\Sigma^0 \to p e^- \bar{\nu}_e$	—	1.58×10^{-13}	—	—
Muon channels ($\ell = \mu$)				
$\Sigma^- \to n \mu^- \bar{\nu}_\mu$	$(4.5 \pm 0.4) \times 10^{-4}$	3.21×10^{-4}	$0.442 \pm 0.056^\ddagger$	$0.459^\ddagger$
$\Sigma^0 \to p \mu^- \bar{\nu}_\mu$	—	7.04×10^{-14}	—	$0.444^\ddagger$

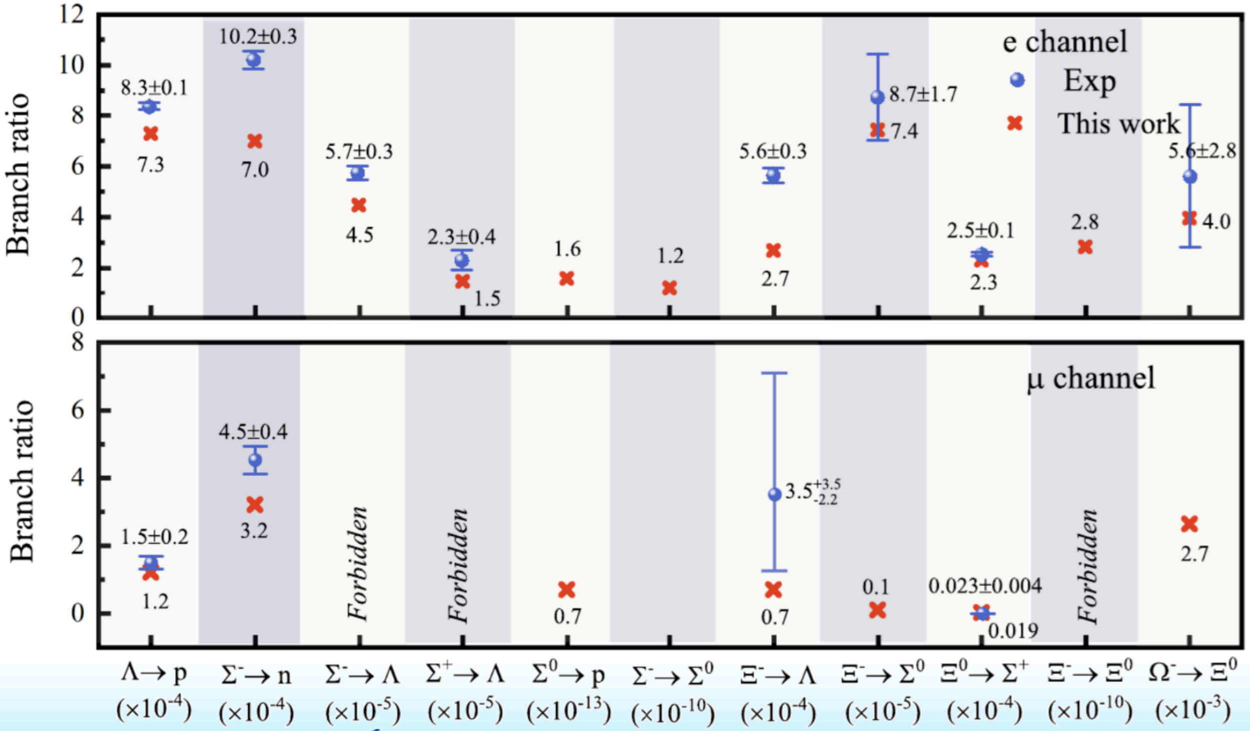
† Ratio defined as $\Gamma(\Sigma^- \to \Lambda e^- \bar{\nu}_e)/\Gamma(\Sigma^+ \to \Lambda e^+ \nu_e)$. ‡ Ratio defined as Γ_μ/Γ_e.

Table 6: Comparison of the semileptonic decay rates for Ξ and Ω hyperons. The BESIII result for $\Xi^- \to \Lambda$ is from Ref. [3].

Channel	Decay Mode	Exp. Value	Ours	Ratio ($R_{\mu e}$) [Ours]
$\Xi^- \to \Lambda \ell^- \bar{\nu}_\ell$	$\Xi^- \to \Lambda e^- \bar{\nu}_e$	$(3.60 \pm 0.50) \times 10^{-4}$ (BESIII)	2.68×10^{-4}	0.276
	$\Xi^- \to \Lambda \mu^- \bar{\nu}_\mu$	$(3.5^{+3.5}_{-2.2}) \times 10^{-4}$ (RPP)	0.74×10^{-4}	
$\Xi^- \to \Sigma^0 \ell^- \bar{\nu}_\ell$	$\Xi^- \to \Sigma^0 e^- \bar{\nu}_e$	$(8.7 \pm 1.7) \times 10^{-5}$	7.44×10^{-5}	0.0013
	$\Xi^- \to \Sigma^0 \mu^- \bar{\nu}_\mu$	$< 8 \times 10^{-4}$	1.0×10^{-6}	
$\Xi^0 \to \Sigma^+ \ell^- \bar{\nu}_\ell$	$\Xi^0 \to \Sigma^+ e^- \bar{\nu}_e$	$(2.52 \pm 0.08) \times 10^{-4}$	2.30×10^{-4}	0.0084
	$\Xi^0 \to \Sigma^+ \mu^- \bar{\nu}_\mu$	$(2.33 \pm 0.35) \times 10^{-6}$	1.93×10^{-6}	
$\Omega^- \to \Xi^0 \ell^- \bar{\nu}_\ell$	$\Omega^- \to \Xi^0 e^- \bar{\nu}_e$	$(5.6 \pm 2.8) \times 10^{-3}$	3.95×10^{-3}	0.6709
	$\Omega^- \to \Xi^0 \mu^- \bar{\nu}_\mu$	—	2.65×10^{-3}	
Rare Decay	$\Xi^- \to \Xi^0 e^- \bar{\nu}_e$	$< 2.59 \times 10^{-4}$	2.83×10^{-10}	—

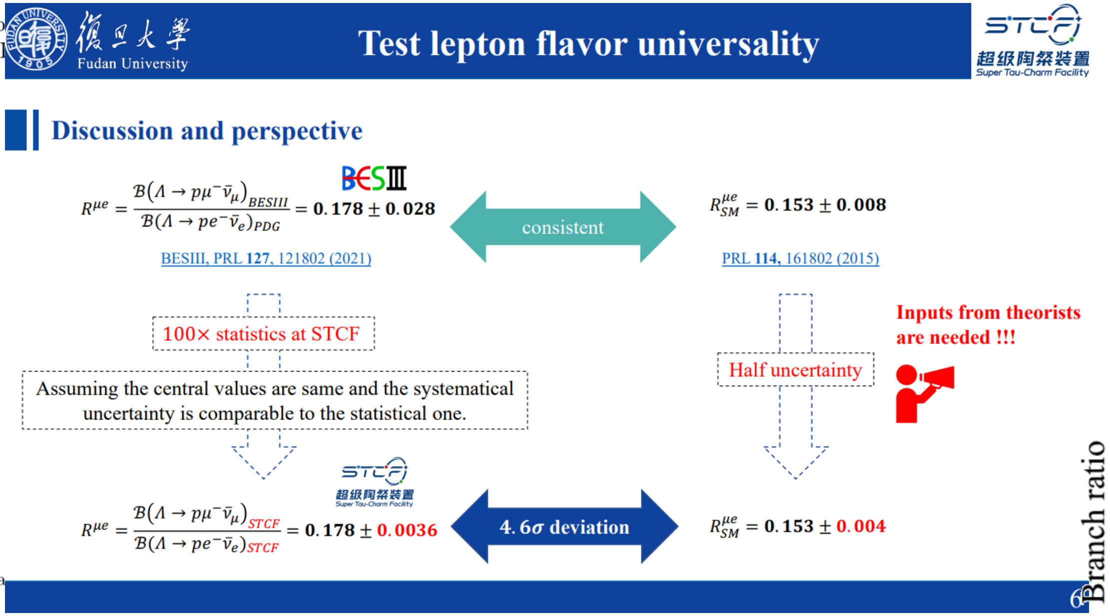
Table 4: Comparison of the $\Lambda \to p \ell^- \bar{\nu}_\ell$ semileptonic decay rates. The ratio is defined as $R_{\mu e} \equiv \Gamma_\mu / \Gamma_e$.

Reference	$\mathcal{B}(\Lambda \to p e^- \bar{\nu}_e)$	$\mathcal{B}(\Lambda \to p \mu^- \bar{\nu}_\mu)$	$R_{\mu e}$
LQCD [4]	$(7.68 \pm 0.48) \times 10^{-4}$	$(1.33 \pm 0.16) \times 10^{-4}$	0.1735 ± 0.098
LHCb [2]	—	$(1.462 \pm 0.127) \times 10^{-4}$	0.175 ± 0.012
RPP [1]	$(8.34 \pm 0.14) \times 10^{-4}$	$(1.51 \pm 0.19) \times 10^{-4}$	0.181 ± 0.026
Ours	$\mathbf{7.30 \times 10^{-4}}$	$\mathbf{1.21 \times 10^{-4}}$	**0.166**



轻味重子半轻衰变计算

Tab
RPI



† Ra

Table 4: Comparison of the $\Lambda \to p\ell^-\bar{\nu}_\ell$ semileptonic decay rates. The ratio is defined as $R_{\mu e} \equiv \Gamma_\mu/\Gamma_e$.

Reference	$\mathcal{B}(\Lambda \to pe^-\bar{\nu}_e)$	$\mathcal{B}(\Lambda \to p\mu^-\bar{\nu}_\mu)$	$R_{\mu e}$
LQCD [4]	$(7.68 \pm 0.48) \times 10^{-4}$	$(1.33 \pm 0.16) \times 10^{-4}$	0.1735 ± 0.098
LHCb [2]	—	$(1.462 \pm 0.127) \times 10^{-4}$	0.175 ± 0.012
RPP [1]	$(8.34 \pm 0.14) \times 10^{-4}$	$(1.51 \pm 0.19) \times 10^{-4}$	0.181 ± 0.026
Ours	$\mathbf{7.30 \times 10^{-4}}$	$\mathbf{1.21 \times 10^{-4}}$	**0.166**

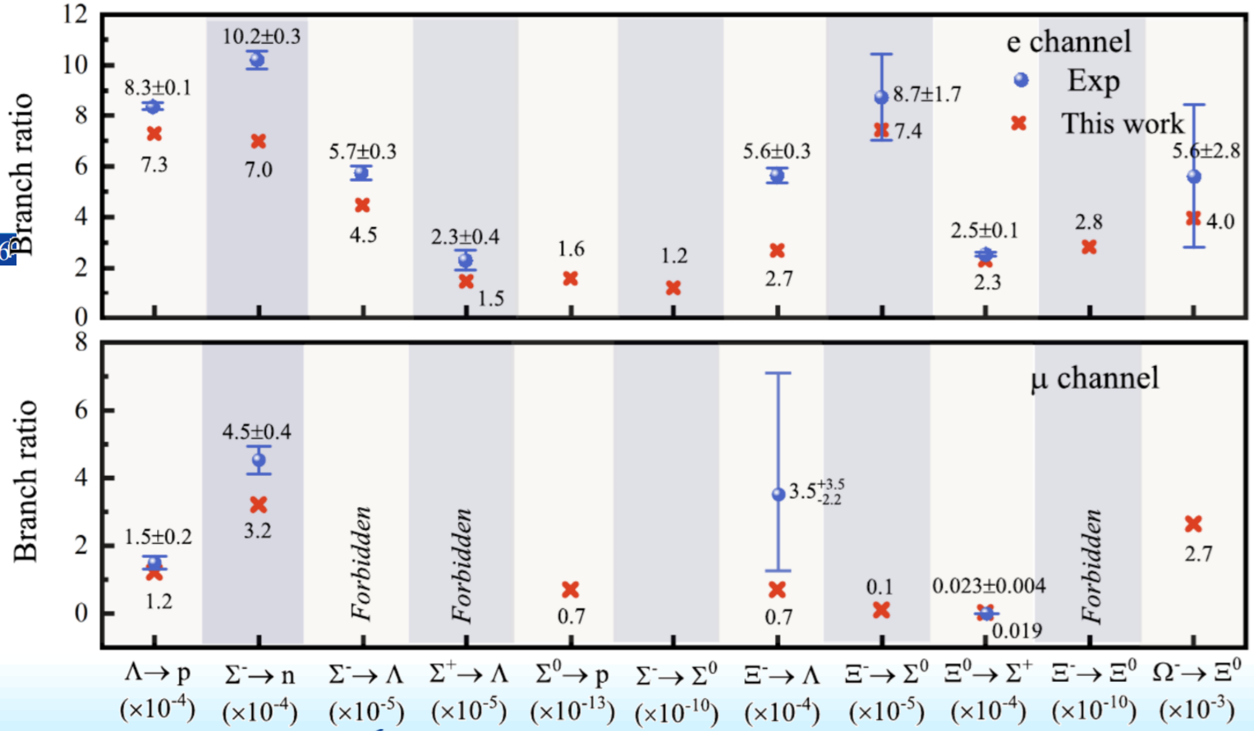


Table 6: Comparison of the semileptonic decay rates for Ξ and Ω hyperons. The BESIII result for $\Xi^- \to \Lambda$ is from Ref. [3].

Channel	Decay Mode	Exp. Value	Ours	Ratio ($R_{\mu e}$) [Ours]
$\Xi^- \to \Lambda\ell^-\bar{\nu}_\ell$	$\Xi^- \to \Lambda e^-\bar{\nu}_e$	$(3.60 \pm 0.50) \times 10^{-4}$ (BESIII)	2.68×10^{-4}	0.276
	$\Xi^- \to \Lambda\mu^-\bar{\nu}_\mu$	$(3.5^{+3.5}_{-2.2}) \times 10^{-4}$ (RPP)	0.74×10^{-4}	
$\Xi^- \to \Sigma^0\ell^-\bar{\nu}_\ell$	$\Xi^- \to \Sigma^0 e^-\bar{\nu}_e$	$(8.7 \pm 1.7) \times 10^{-5}$	7.44×10^{-5}	0.0013
	$\Xi^- \to \Sigma^0\mu^-\bar{\nu}_\mu$	$< 8 \times 10^{-4}$	1.0×10^{-6}	
$\Xi^0 \to \Sigma^+\ell^-\bar{\nu}_\ell$	$\Xi^0 \to \Sigma^+ e^-\bar{\nu}_e$	$(2.52 \pm 0.08) \times 10^{-4}$	2.30×10^{-4}	0.0084
	$\Xi^0 \to \Sigma^+\mu^-\bar{\nu}_\mu$	$(2.33 \pm 0.35) \times 10^{-6}$	1.93×10^{-6}	
$\Omega^- \to \Xi^0\ell^-\bar{\nu}_\ell$	$\Omega^- \to \Xi^0 e^-\bar{\nu}_e$	$(5.6 \pm 2.8) \times 10^{-3}$	3.95×10^{-3}	0.6709
	$\Omega^- \to \Xi^0\mu^-\bar{\nu}_\mu$	—	2.65×10^{-3}	
Rare Decay	$\Xi^- \to \Xi^0 e^-\bar{\nu}_e$	$< 2.59 \times 10^{-4}$	2.83×10^{-10}	—

形状因子计算

基于强子层次的计算

$$T^{\mu}_{2\,BNW} = \sqrt{\frac{G_F m_W}{\sqrt{2}}}|v_{us}|(V^{\mu} + A^{\mu})$$

$$with \quad V^{\mu} = \bar{B}\left(f_1(q^2)\gamma^{\mu} - i\frac{f_2(q^2)\sigma^{\mu\nu}q_\nu}{m_B} + f_3(q^2)\frac{q_\mu}{m_B}\right)N + h.c.,$$

$$A^{\mu} = \bar{B}\left(g_1(q^2)\gamma^{\mu} - i\frac{g_2(q^2)\sigma^{\mu\nu}q_\nu}{m_B} + g_3(q^2)\frac{q_\mu}{m_B}\right)\gamma^5 N + h.c.$$

$$f_1(q^2) = \frac{f_1(0)}{(1-q^2/M_v^2)^2}$$

$$g_1(q^2) = \frac{g_1(0)}{(1-q^2/M_a^2)^2}$$

$$f_2(q^2) = f_2(0).$$?

g_2 is zero at exact SU(3) limit

f_3, g_3 terms are suppressed by $(m_l/M_B)^2$

基于夸克层次的计算

$$T_2^{\nu}(\mathbf{p}_w, s_z^{Q_1}, s_z^{Q_2}) = \int d\mathbf{p}_a d\mathbf{p}_b d\mathbf{p}_{q_1} d\mathbf{p}_{q_2} \delta_{(\mathbf{p}_a+\mathbf{p}_b+\mathbf{p}_{q_1})}\delta_{(\mathbf{p}_{q_2}-\mathbf{p}_{q_1}-\mathbf{p}_w)} \times \sqrt{\frac{G_F m_W}{\sqrt{2}}}|v_{q_1 q_2}|$$
$$\times \sum_{s_z^{q_2},\, s_z^{q_1}} \langle X^{Q_2},\, s_z^{Q_2},\, \Phi^{Q_2}|\chi^{+}_{q_2,\, s_z^{q_2}}\chi_{q_1,\, s_z^{q_1}}|X^{Q_1},\, s_z^{Q_1},\, \Phi^{Q_1}\rangle$$
$$\times \bar{u}_{q_2}(\mathbf{p}_{q_2},\, s_z^{q_2})\gamma^{\nu}(1-\gamma^5)u_{q_1}(\mathbf{p}_{q_1},\, s_z^{q_1}),$$

矢量流 (Vector Current, H_V^{μ}, 弱磁项衰变取 $-i\sigma q$，散射取 $+i\sigma q$)

0 (时间)	↑↑	$\bar{u}_f\gamma^0 u_i$	$\mathcal{N}\left[f_1 - \frac{E_f - M_f}{M}f_2 + \frac{M_i - E_f}{M}f_3\right]$	$\mathcal{N}\left[f_1 - \frac{E_f - M_f}{M}f_2 + \frac{E_f - M_i}{M}f_3\right]$
1 (横向)	↑↓	$\bar{u}_f\gamma^1 u_i$	$-\mathcal{N}R\left[f_1 + \frac{M_i + M_f}{M}f_2\right]$	$-\mathcal{N}R\left[f_1 + \frac{M_i + M_f}{M}f_2\right]$
2 (横向)	↑↓	$\bar{u}_f\gamma^2 u_i$	$-i\mathcal{N}R\left[f_1 + \frac{M_i + M_f}{M}f_2\right]$	$-i\mathcal{N}R\left[f_1 + \frac{M_i + M_f}{M}f_2\right]$
3 (纵向)	↑↑	$\bar{u}_f\gamma^3 u_i$	$\mathcal{N}\left[Rf_1 + R\frac{M_i - E_f}{M}f_2 - \frac{|\mathbf{p}_f|}{M}f_3\right]$	$\mathcal{N}\left[Rf_1 + R\frac{M_i - E_f}{M}f_2 + \frac{|\mathbf{p}_f|}{M}f_3\right]$

轴矢量流 (Axial Current, H_A^{μ}, 感生张量项衰变取 $-i\sigma q\gamma^5$，散射取 $+i\sigma q\gamma^5$)

0 (时间)	↑↑	$\bar{u}_f\gamma^0\gamma^5 u_i$	$\mathcal{N}\left[Rg_1 + \frac{|\mathbf{p}_f|}{M}g_2 - R\frac{M_i - E_f}{M}g_3\right]$	$\mathcal{N}\left[Rg_1 + \frac{|\mathbf{p}_f|}{M}g_2 - R\frac{E_f - M_i}{M}g_3\right]$
1 (横向)	↑↓	$\bar{u}_f\gamma^1\gamma^5 u_i$	$\mathcal{N}\left[g_1 - \frac{M_i - M_f}{M}g_2\right]$	$\mathcal{N}\left[g_1 - \frac{M_i - M_f}{M}g_2\right]$
2 (横向)	↑↓	$\bar{u}_f\gamma^2\gamma^5 u_i$	$i\mathcal{N}\left[g_1 - \frac{M_i - M_f}{M}g_2\right]$	$i\mathcal{N}\left[g_1 - \frac{M_i - M_f}{M}g_2\right]$
3 (纵向)	↑↑	$\bar{u}_f\gamma^3\gamma^5 u_i$	$\mathcal{N}\left[g_1 - \frac{M_i - E_f}{M}g_2 + R\frac{|\mathbf{p}_f|}{M}g_3\right]$	$\mathcal{N}\left[g_1 - \frac{M_i - E_f}{M}g_2 - R\frac{|\mathbf{p}_f|}{M}g_3\right]$

By introducing helicity matrix elements, $H^0_{V/A}(\uparrow\uparrow)$, $H^3_{V/A}(\uparrow\uparrow)$ and $H^1_{V/A}(\uparrow\downarrow)$ to obtain $f_{1\text{-}3}$， $g_{1\text{-}3}$.

$$f_2(q^2) = -\frac{M}{2M_i\mathcal{N}}\left[H_V^0(\uparrow\uparrow) + \frac{M_i - E_f}{|\mathbf{p}_f|}H_V^3(\uparrow\uparrow) + \left(\frac{1}{R} + \frac{M_i - E_f}{|\mathbf{p}_f|}\right)H_V^1(\uparrow\downarrow)\right],$$

$$f_1(q^2) = -\frac{M_i + M_f}{M}f_2(q^2) - \frac{H_V^1(\uparrow\downarrow)}{\mathcal{N}R},$$

$$f_3(q^2) = \frac{M}{M_i - E_f}\left[\frac{H_V^0(\uparrow\uparrow)}{\mathcal{N}} - f_1(q^2) + \frac{E_f - M_f}{M}f_2(q^2)\right].$$

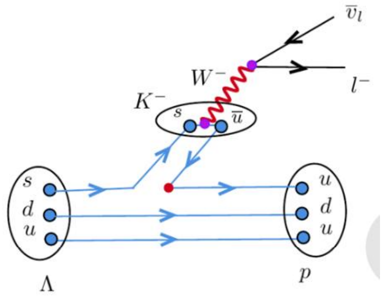
$$g_2(q^2) = \frac{M}{2M_i\mathcal{N}}\left[\frac{1}{R}H_A^0(\uparrow\uparrow) + \frac{M_i - E_f}{R|\mathbf{p}_f|}H_A^3(\uparrow\uparrow) - \left(1 + \frac{M_i - E_f}{R|\mathbf{p}_f|}\right)H_A^1(\uparrow\downarrow)\right],$$

$$g_1(q^2) = \frac{H_A^1(\uparrow\downarrow)}{\mathcal{N}} + \frac{M_i - M_f}{M}g_2(q^2),$$

$$g_3^{\text{bare}}(q^2) = \frac{M}{R|\mathbf{p}_f|}\left[\frac{H_A^3(\uparrow\uparrow)}{\mathcal{N}} - g_1(q^2) + \frac{M_i - E_f}{M}g_2(q^2)\right].$$

$$\mathcal{N} = \sqrt{2M_i(E_f + M_f)}$$
$$R = |\mathbf{p}_f|/(E_f + M_f).$$

形状因子计算



$\Lambda \xrightarrow{W^-} \bar{\nu}_l + l^- + p$

基于强子层次的计算

$$T^{\mu}_{2\,BNW} = \sqrt{\frac{G_F m_W}{\sqrt{2}}}|v_{us}|(V^\mu + A^\mu)$$

$$\text{with} \quad V^\mu = \bar{B}\left(f_1(q^2)\gamma^\mu - i\frac{f_2(q^2)\sigma^{\mu\nu}q_\nu}{m_B} + f_3(q^2)\frac{q_\mu}{m_B}\right)N + h.c.,$$

$$A^\mu = \bar{B}\left(g_1(q^2)\gamma^\mu - i\frac{g_2(q^2)\sigma^{\mu\nu}q_\nu}{m_B} + g_3(q^2)\frac{q_\mu}{m_B}\right)\gamma^5 N + h.c.$$

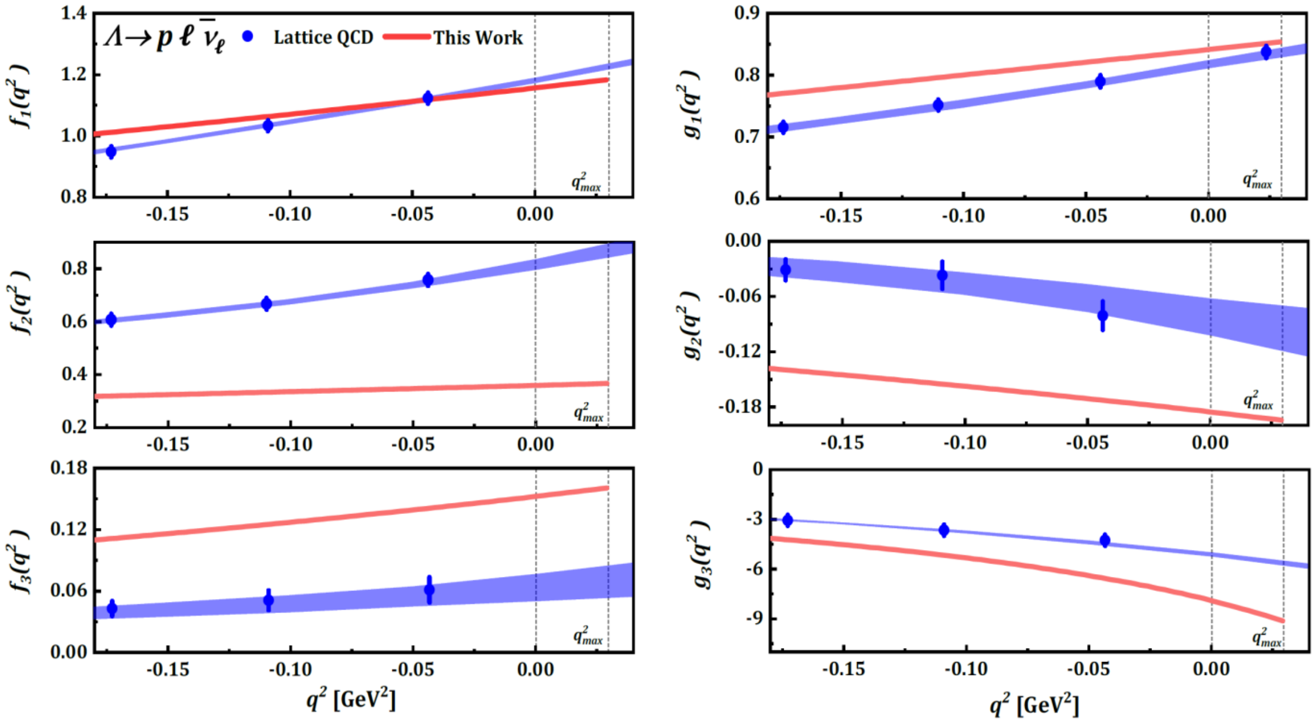
$$f_1(q^2) = \frac{f_1(0)}{(1-q^2/M_v^2)^2}$$

$$g_1(q^2) = \frac{g_1(0)}{(1-q^2/M_a^2)^2}$$

$$f_2(q^2) = f_2(0).?$$

g_2 is zero at exact SU(3) limit

f_3, g_3 terms are suppressed by $(m_l/M_B)^2$



$$f_2(q^2) = -\frac{M}{2M_i\mathcal{N}}\left[H_V^0(\uparrow\uparrow) + \frac{M_i - E_f}{|\mathbf{p}_f|}H_V^3(\uparrow\uparrow) + \left(\frac{1}{R} + \frac{M_i - E_f}{|\mathbf{p}_f|}\right)H_V^1(\uparrow\downarrow)\right],$$

$$f_1(q^2) = -\frac{M_i + M_f}{M}f_2(q^2) - \frac{H_V^1(\uparrow\downarrow)}{\mathcal{N}R},$$

$$f_3(q^2) = \frac{M}{M_i - E_f}\left[\frac{H_V^0(\uparrow\uparrow)}{\mathcal{N}} - f_1(q^2) + \frac{E_f - M_f}{M}f_2(q^2)\right].$$

$$g_2(q^2) = \frac{M}{2M_i\mathcal{N}}\left[\frac{1}{R}H_A^0(\uparrow\uparrow) + \frac{M_i - E_f}{R|\mathbf{p}_f|}H_A^3(\uparrow\uparrow) - \left(1 + \frac{M_i - E_f}{R|\mathbf{p}_f|}\right)H_A^1(\uparrow\downarrow)\right],$$

$$g_1(q^2) = \frac{H_A^1(\uparrow\downarrow)}{\mathcal{N}} + \frac{M_i - M_f}{M}g_2(q^2),$$

$$g_3^{\text{bare}}(q^2) = \frac{M}{R|\mathbf{p}_f|}\left[\frac{H_A^3(\uparrow\uparrow)}{\mathcal{N}} - g_1(q^2) + \frac{M_i - E_f}{M}g_2(q^2)\right].$$

$$\mathcal{N} = \sqrt{2M_i(E_f + M_f)}$$
$$R = |\mathbf{p}_f|/(E_f + M_f).$$

Simone Bacchio, Andreas Konstantinou Cyprus group PRL 135 231901

形状因子计算

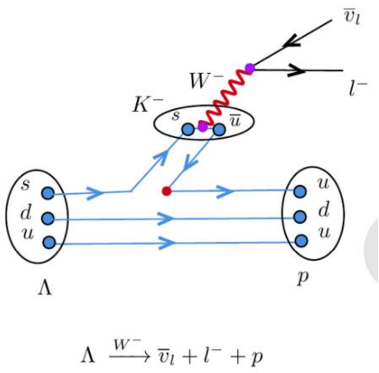
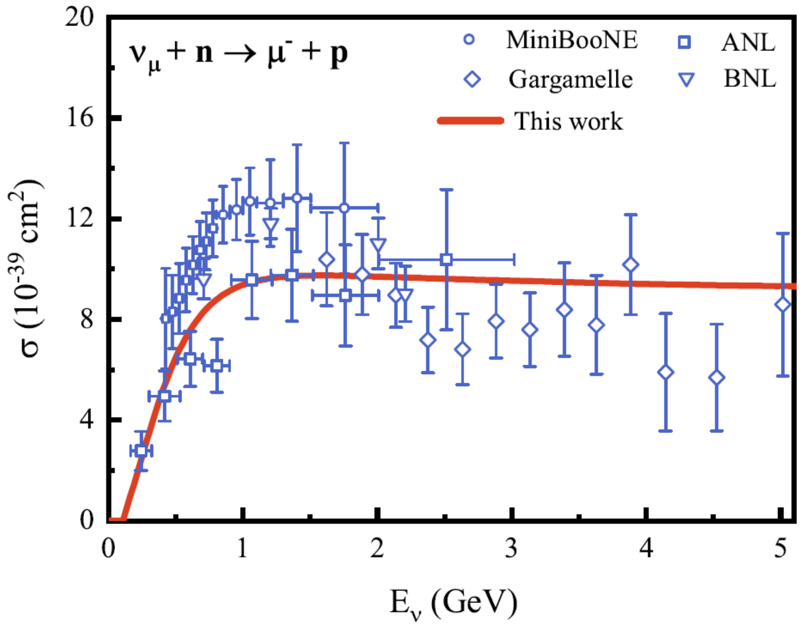
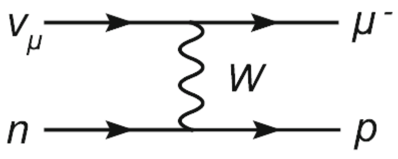


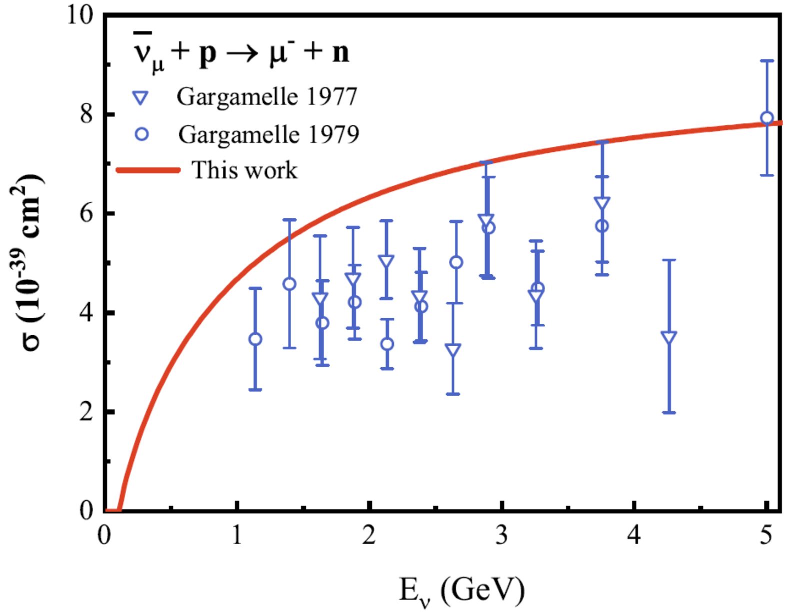
TABLE VI. Transition form factors at $q^2 = 0$ for $\Lambda \to p\ell^-\bar{\nu}_\ell$, adapted to the unified conventions described in Sec. II B 4. The last two columns show magnitudes normalized to the static SU(6) limit ($|f_1^{SU(3)}| = |g_1^{SU(3)}| = \sqrt{3/2}$). χQSM [33] and LQCD [39] natively adopt a phase convention consistent with ours; others are sign-flipped as described in the text.

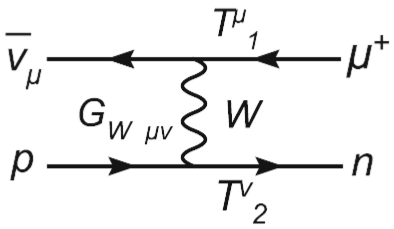
Approach	f_1	f_2	f_3	g_1	g_2	g_3	f_2/f_1	g_1/f_1	$\|f_1\|/\|f_1^{SU(3)}\|$	$\|g_1\|/\|g_1^{SU(3)}\|$
LFQM [32]	1.190	0.950	—	0.990	0.070	—	0.798	0.826	0.972	0.808
χQM [70]	1.220	0.913	−0.337	0.820	0.054	−11.407	0.748	0.672	0.996	0.670
CQM [35]	1.226	1.226	−0.067	0.888	0.072	−6.760	1.000	0.724	1.001	0.725
χQSM [33]	1.225	0.870	—	0.830	—	—	0.710	0.678	1.000	0.678
χCQM$_{\text{config}}$ [34]	1.225	0.563	−0.225	0.909	0.092	−11.244	0.460	0.742	1.000	0.742
QCDSR [40]	1.179(75)	0.888(74)	—	0.843(10)	—	—	0.752(74)	0.708(47)	0.963(61)	0.688(8)
LQCD [39]	1.185(6)	0.821(19)	0.062(13)	0.818(6)	−0.082(19)	−5.14(11)	0.693(17)	0.690(4)	0.968(5)	0.668(4)
This work	**1.157**	**0.359**	**0.153**	**0.842**	**−0.185**	**−7.912**	**0.310**	**0.727**	**0.945**	**0.687**

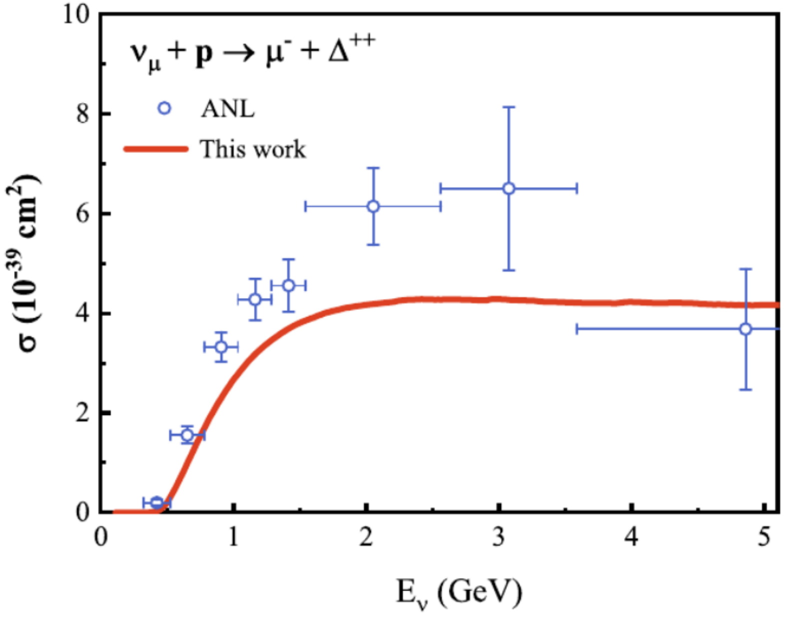
中微子核反应截面估计

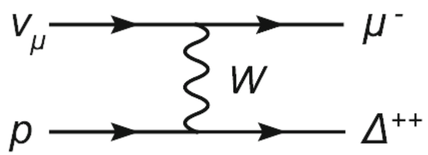

$\nu_\mu + n \to \mu^- + p$
MiniBooNE
ANL
Gargamelle
BNL
This work
$\sigma\ (10^{-39}\ cm^2)$
E_ν (GeV)


ν_μ
μ^-
W
n
p

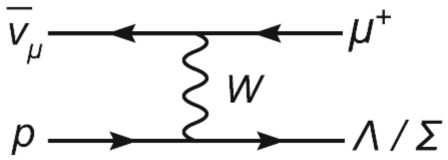

$\bar{\nu}_\mu + p \to \mu^- + n$
Gargamelle 1977
Gargamelle 1979
This work
$\sigma\ (10^{-39}\ cm^2)$
E_ν (GeV)


$\bar{\nu}_\mu$
$T^\mu{}_1$
μ^+
$G_{W\ \mu\nu}$
W
p
n
$T^\nu{}_2$

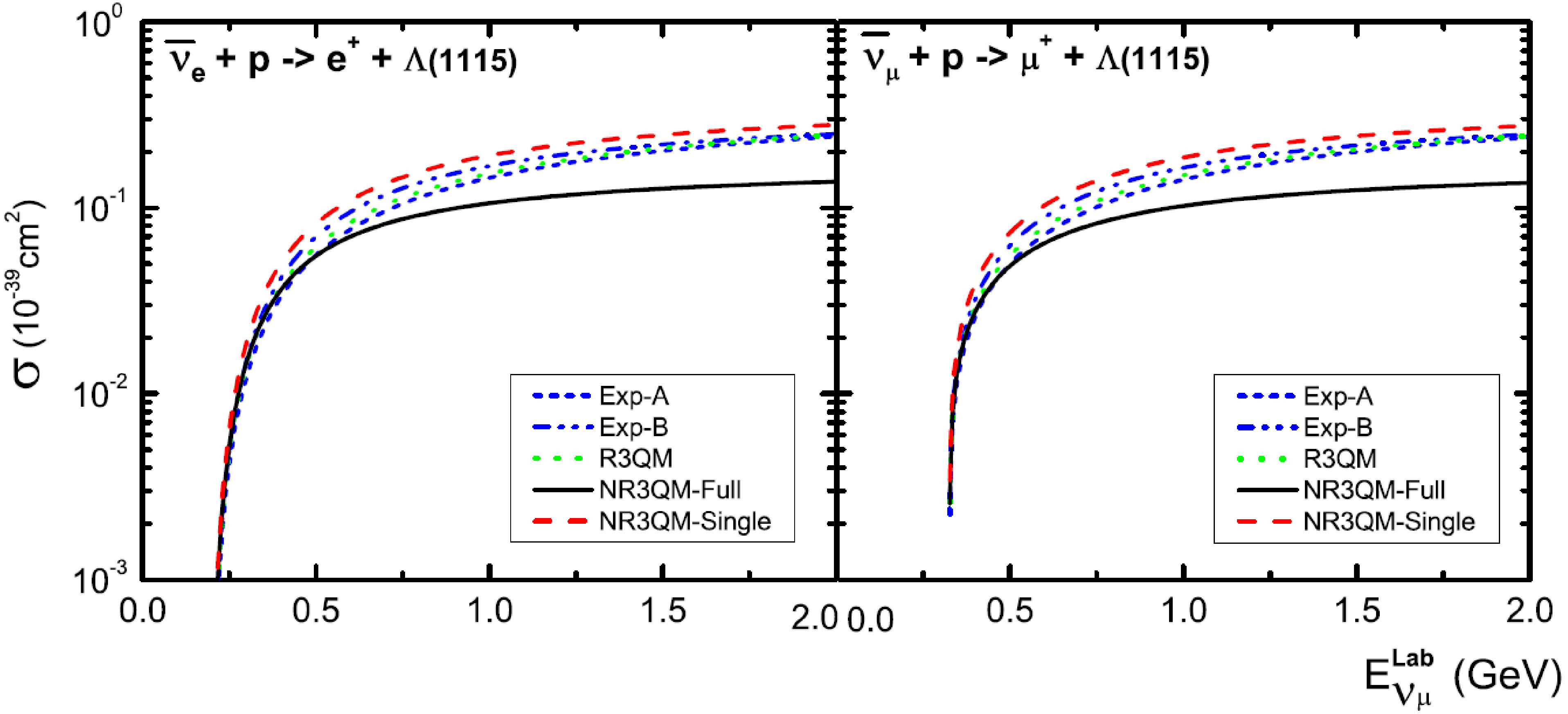

$\nu_\mu + p \to \mu^- + \Delta^{++}$
ANL
This work
$\sigma\ (10^{-39}\ cm^2)$
E_ν (GeV)


ν_μ
μ^-
W
p
Δ^{++}

中微子核反应截面估计

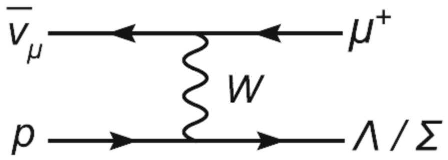


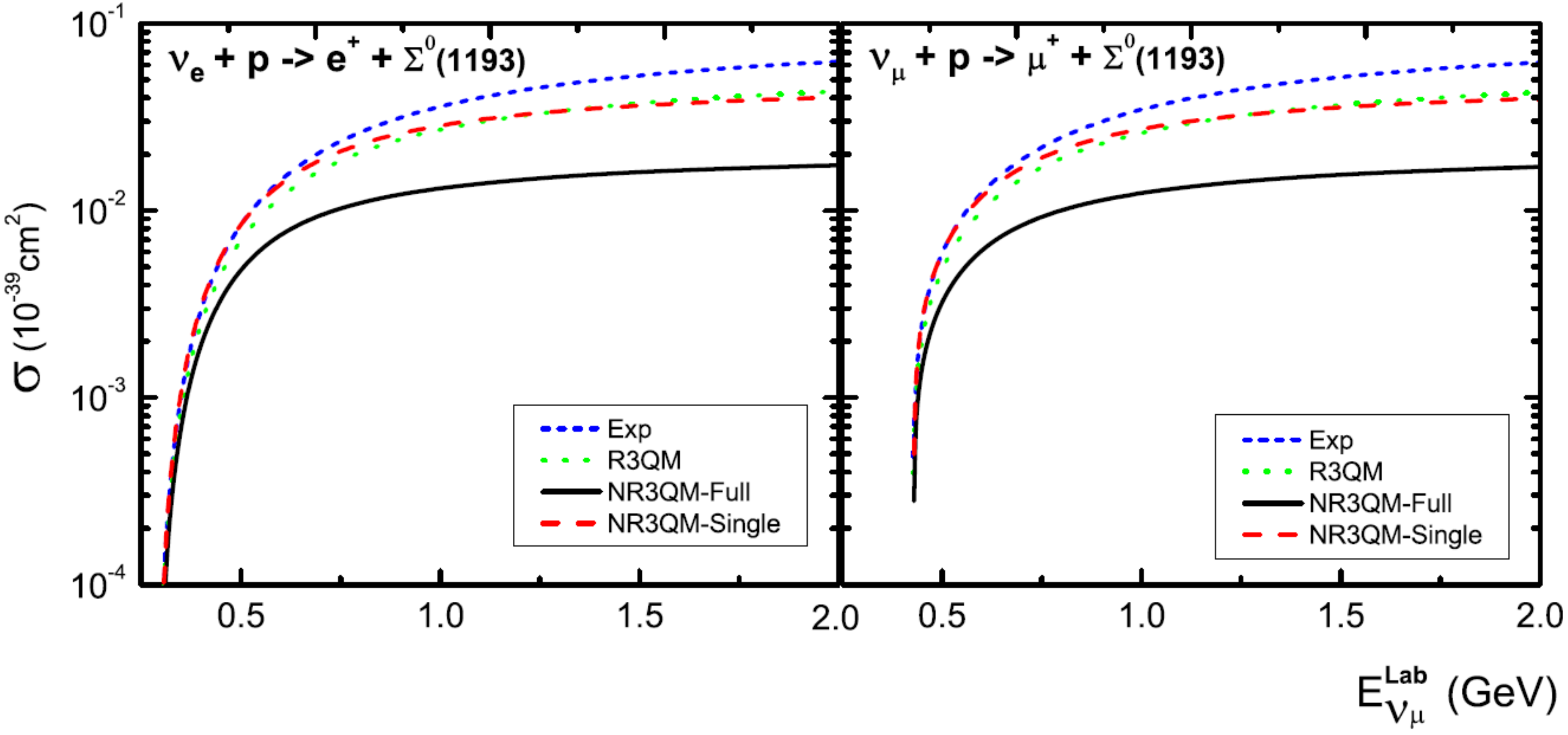
$\bar{\nu}_\mu$
μ^+
W
p
Λ / Σ



$\bar{\nu}_e$ + p -> e^+ + Λ(1115)
$\bar{\nu}_\mu$ + p -> μ^+ + Λ(1115)
σ (10^{-39}cm^2)
$E^{Lab}_{\nu_\mu}$ (GeV)
Exp-A
Exp-B
R3QM
NR3QM-Full
NR3QM-Single

中微子核反应截面估计


$\bar{\nu}_\mu$
μ^+
W
p
Λ / Σ


$\nu_e + p \rightarrow e^+ + \Sigma^0(1193)$
$\nu_\mu + p \rightarrow \mu^+ + \Sigma^0(1193)$
$\sigma\ (10^{-39}\mathrm{cm}^2)$
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0.5
1.0
1.5
2.0
Exp
R3QM
NR3QM-Full
NR3QM-Single
$E_{\nu_\mu}^{Lab}$ (GeV)

小结

利用夸克模型计算了一系列重子半轻衰变的分子比，大体上和实验符合，这给予了我们信心利用弱作用去更加细致的研究强子的性质。

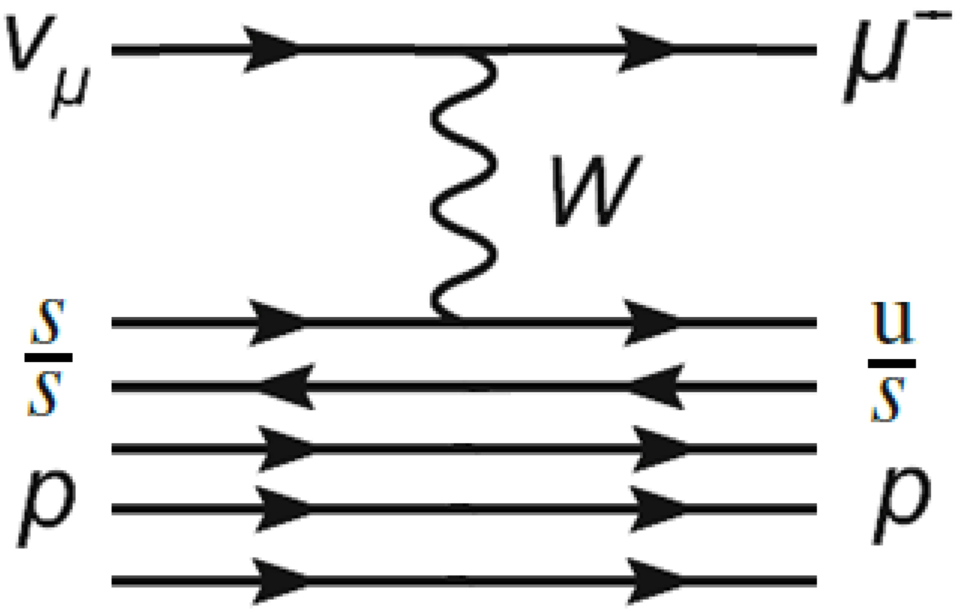
期待相关实验的检验，并且我们相信现在的理论估计是非常粗糙的，只是在量级上估计，亟待实验数据的输入能够鉴别参数和约束更多的模型参数

展望

利用中微子束流估计核子内部的$s\bar{s}/c\bar{c}$成分。

-----邹冰松老师 idea

举例而言



谢谢

背景：研究核子内部的五夸克成分

$$|p\rangle = c_1|uud\rangle + c_2|uud(u\bar{u})\rangle + c_3|uud(d\bar{d})\rangle + c_4|uud(s\bar{s})\rangle + c_5|uud(c\bar{c})\rangle.$$

考虑（反）中微子核子反应，其中可以交换（W^+）W^-玻色子【相对中微子入射】，其中W^+不和d和s夸克作用，而 W^-不和c和u夸克作用。

W^+ :

$c \to d$	$\bar{d} \to \bar{c}$
$c \to s$	$\bar{s} \to \bar{c}$
$u \to d$	$\bar{d} \to \bar{u}$
$u \to s$	$\bar{s} \to \bar{u}$

$c \to d \Rightarrow (c\bar{c})uud \to d\bar{c}uud$

$\bar{d} \to \bar{c} \Rightarrow (d\bar{d})uud \to d\bar{c}uud$

$c \to s \Rightarrow (c\bar{c})uud \to s\bar{c}uud$

$\bar{s} \to \bar{c} \Rightarrow (s\bar{s})uud \to s\bar{c}uud$

$u \to d \Rightarrow (u\bar{u})uud \to d\bar{u}uud$ ×

$uud \to dud$

$\bar{d} \to \bar{u} \Rightarrow (d\bar{d})uud \to d\bar{u}uud$ ×

$u \to s \Rightarrow (u\bar{u})uud \to s\bar{u}uud$ ×

$uud \to sud$

$\bar{s} \to \bar{u} \Rightarrow (s\bar{s})uud \to s\bar{u}uud$ ×

暂时不考虑末态相互作用

背景：研究核子内部的五夸克成分

$$|p\rangle = c_1|uud\rangle + c_2|uud(u\bar{u})\rangle + c_3|uud(d\bar{d})\rangle + c_4|uud(s\bar{s})\rangle + c_5|uud(c\bar{c})\rangle.$$

考虑（反）中微子核子反应，其中可以交换（W^+）W^-玻色子【相对中微子入射】，其中W^+不和d和s夸克作用，而 W^-不和c和u夸克作用。

W^- :

$d \rightarrow u$	$\bar{u} \rightarrow \bar{d}$
$d \rightarrow c$	$\bar{c} \rightarrow \bar{d}$
$s \rightarrow u$	$\bar{u} \rightarrow \bar{s}$
$s \rightarrow c$	$\bar{c} \rightarrow \bar{s}$

$d \rightarrow u \Rightarrow (d\bar{d})uud \rightarrow u\bar{d}uud$ ×

$uud \rightarrow uuu$

$\bar{u} \rightarrow \bar{d} \Rightarrow (u\bar{u})uud \rightarrow u\bar{d}uud$ ×

$d \rightarrow c \Rightarrow (d\bar{d})uud \rightarrow c\bar{d}uud$ ×

$uud \rightarrow uuc$

$\bar{c} \rightarrow \bar{d} \Rightarrow (c\bar{c})uud \rightarrow c\bar{d}uud$ ×

$s \rightarrow u \Rightarrow (s\bar{s})uud \rightarrow u\bar{s}uud$

$\bar{u} \rightarrow \bar{s} \Rightarrow (u\bar{u})uud \rightarrow u\bar{s}uud$

$s \rightarrow c \Rightarrow (s\bar{s})uud \rightarrow c\bar{s}uud$

$\bar{c} \rightarrow \bar{s} \Rightarrow (c\bar{c})uud \rightarrow c\bar{s}uud$

暂时不考虑末态相互作用

八个重要的过程：

W^+:

① $(d\bar{d})uud \rightarrow d\bar{c}uud$

② $(s\bar{s})uud \rightarrow s\bar{c}uud$

③ $uud \rightarrow dud$

④ $uud \rightarrow sud$

W^-:

⑤ $uud \rightarrow uuu$

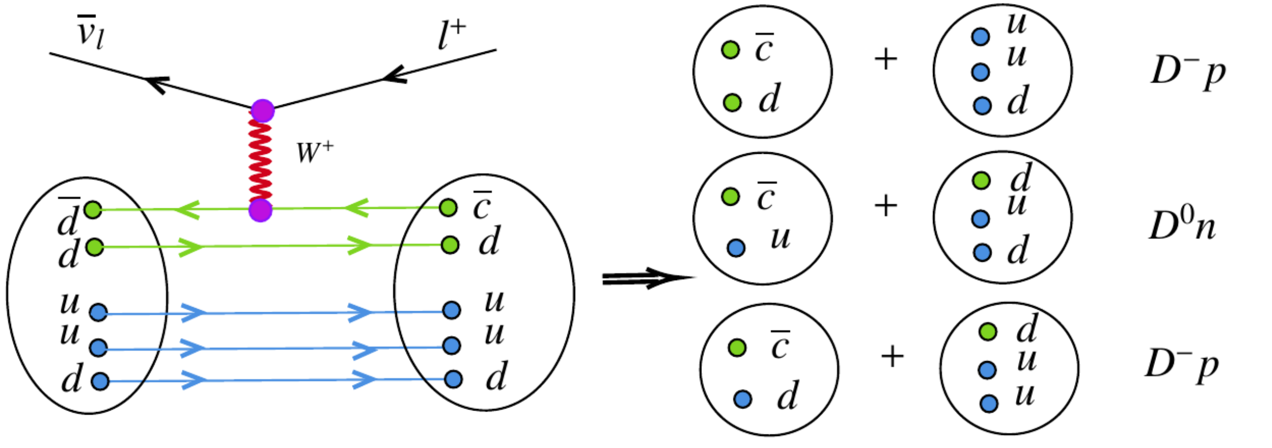
⑥ $uud \rightarrow uuc$

⑦ $(u\bar{u})uud \rightarrow u\bar{s}uud$

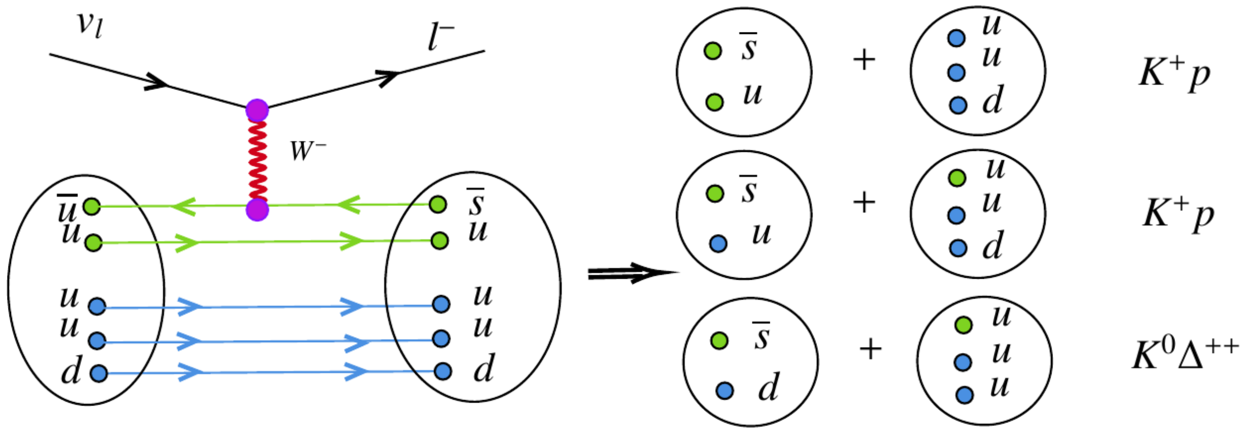
⑧ $(s\bar{s})uud \rightarrow c\bar{s}uud$

- ③, ④, ⑤ 我们已经研究过了，包括$\bar{\nu}_l/\nu_l + p \rightarrow l^{\pm} + n/\Lambda/\Sigma_0\ /\Delta^{++}$
- ⑥ 可以用来估计Σ_c^{++}的产生截面
- ①和⑦ 可以用来研究质子中的 $u\bar{u}$ 和 $d\bar{d}$ 的成分，则可以检查质子中的$\bar{d}$ 和 $\bar{u}$ 的不对称性， $P_{\bar{d}-\bar{u}} \simeq (11.8 \pm 1.2)\ \%$.
- ② **和**⑧可以用来研究质子中的$s\bar{s}$ 的成分.

检查 $\bar{d}$ 和 $\bar{u}$ 的不对称性：末态强子

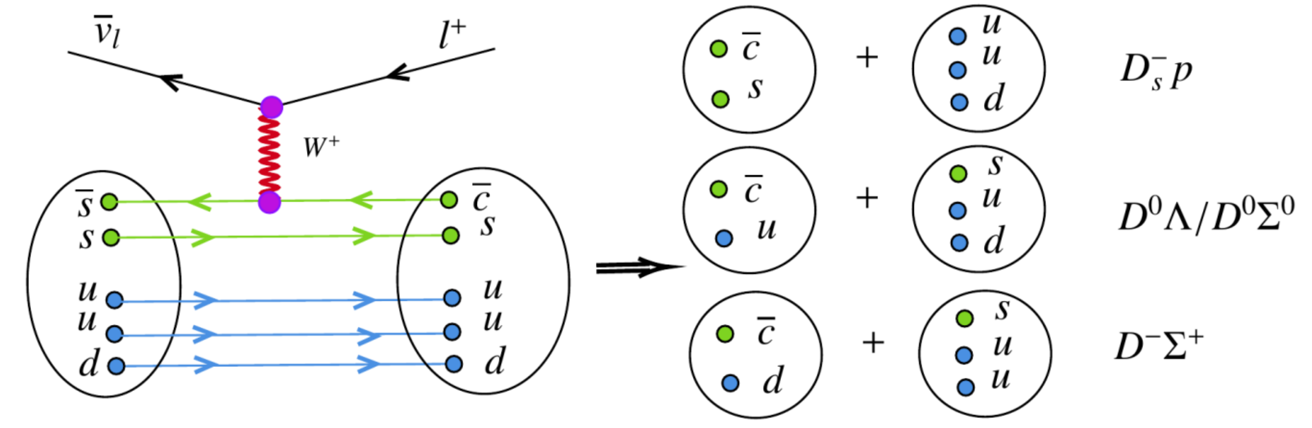


$$p\,[(d\bar{d})uud] + \bar{\nu}_l \xrightarrow{W^+} l^+ + \left(D^- p, D^0 n\right)$$

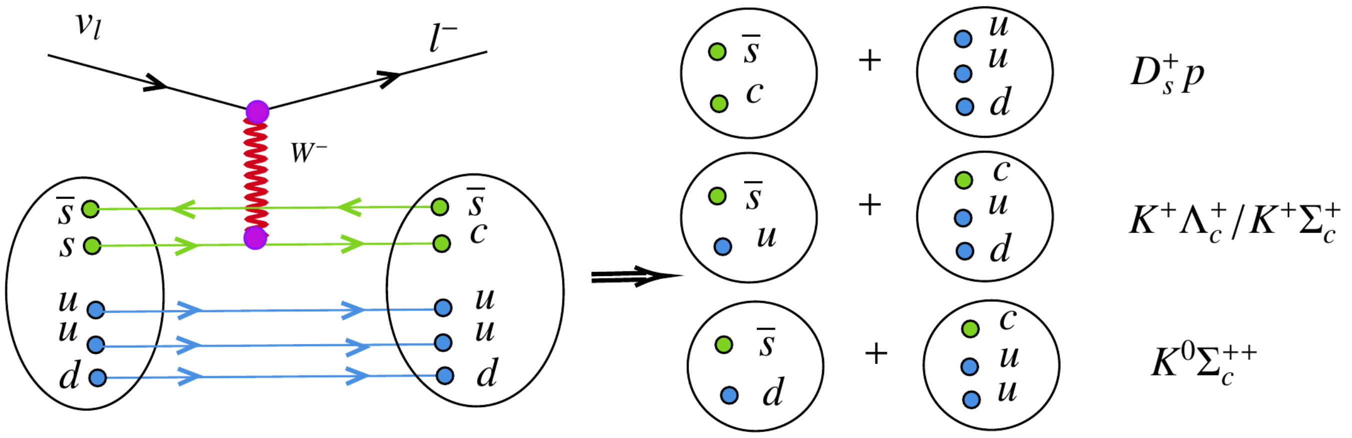


$$p\,[(u\bar{u})uud] + \nu_l \xrightarrow{W^-} l^- + \left(K^+ p, K^0 \Delta^{++}\right)$$

检查 $s\bar{s}$ 的成分：末态强子



$$p\,[(s\bar{s})uud] + \bar{\nu}_l \xrightarrow{W^+} l^+ + \left(D_s^- p, D^0\Lambda/D^0\Sigma^0, D^-\Sigma^+\right)$$

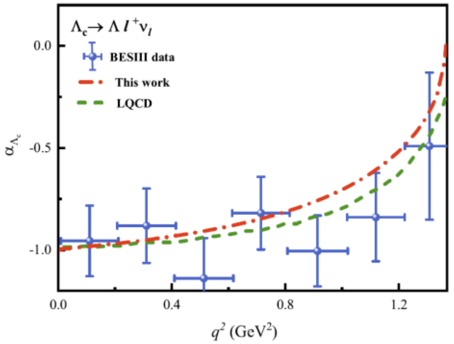


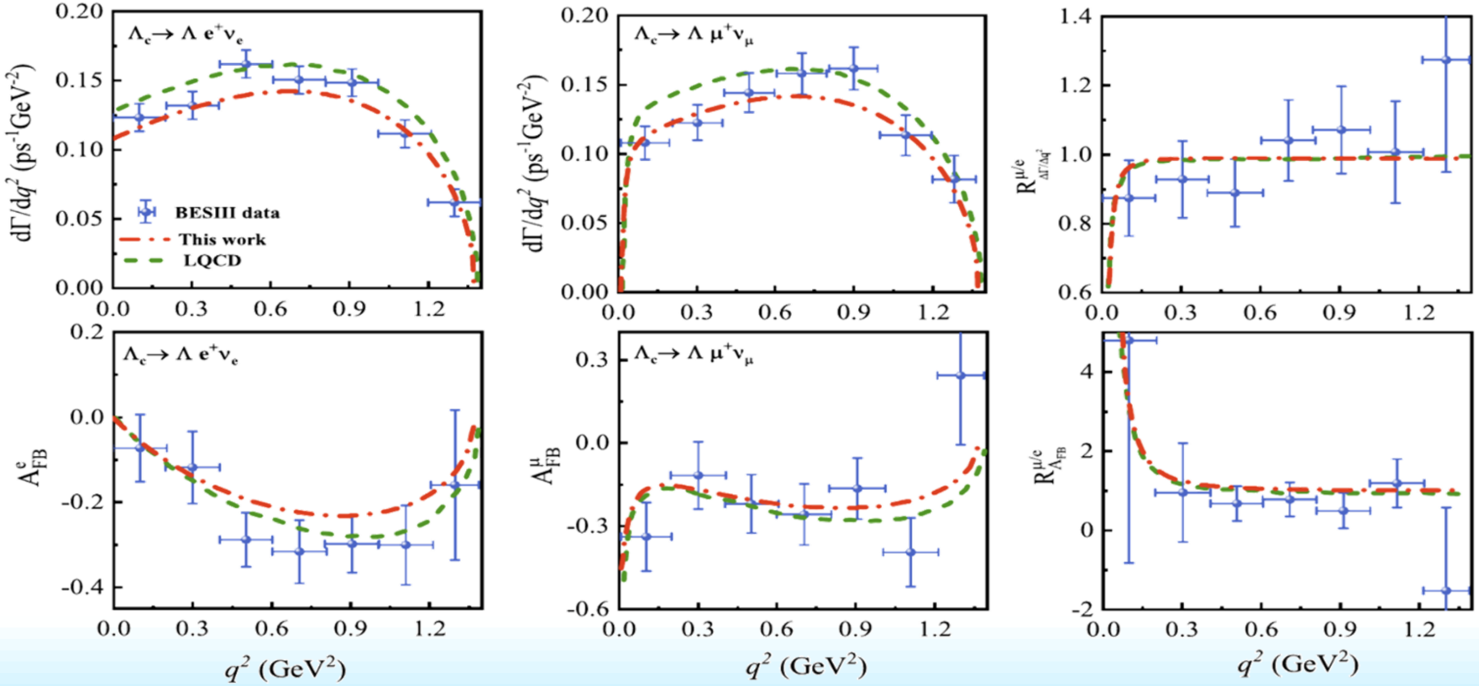
$$p\,[(s\bar{s})uud] + \nu_l \xrightarrow{W^-} l^- + \left(D_s^+ p, K^+\Lambda_c^+/K^+\Sigma_c^+, K^0\Sigma_c^{++}\right)$$

如何利用该顶点寻找超出传统夸克模型的强子成分？

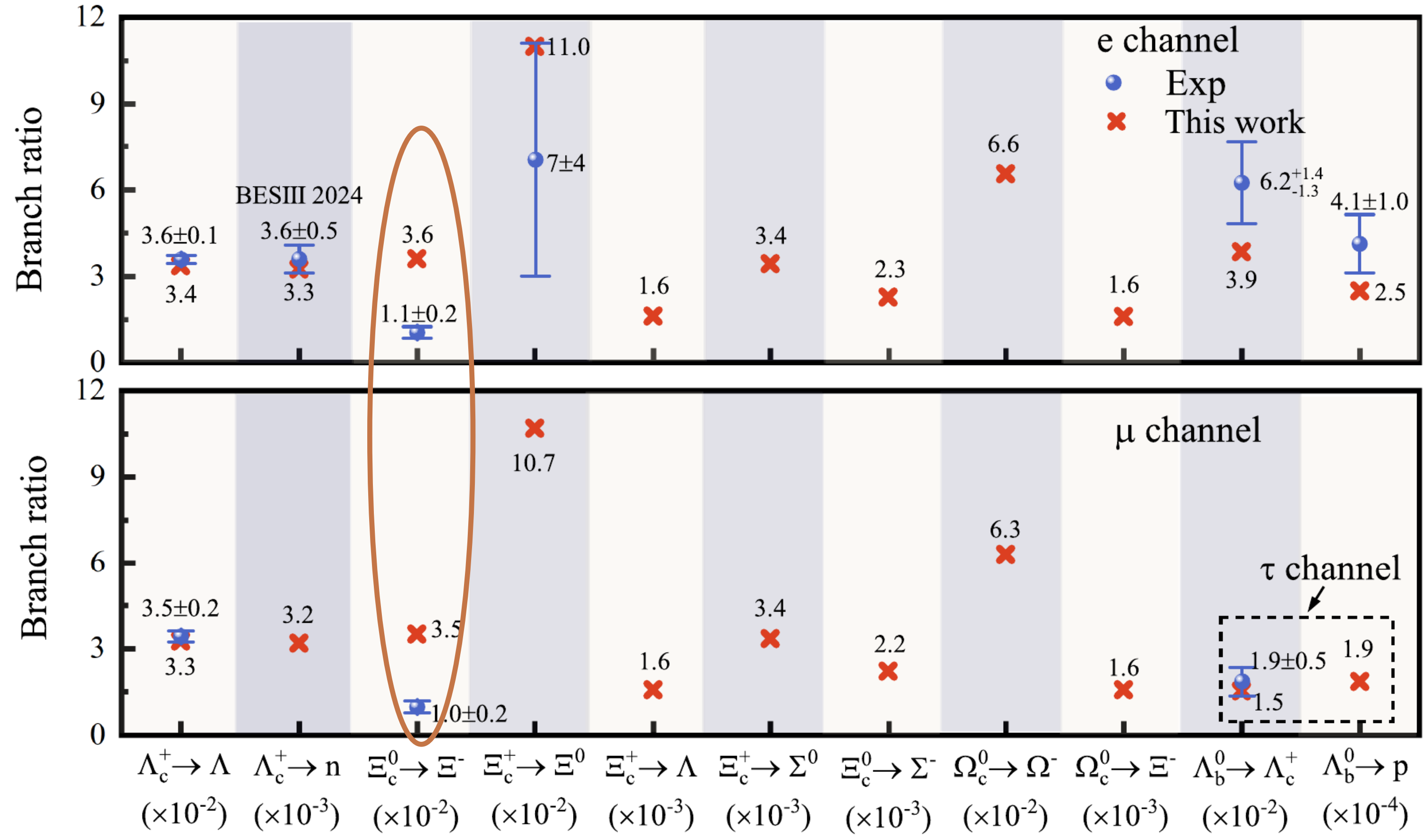
重味重子半轻衰变计算

Refs.	$\mathcal{B}(\ell = e)$	$\mathcal{B}(\ell = \mu)$	$R_{\mu e}$
$\Lambda_c^+ \to \Lambda \ell^+ \nu_\ell$			
RPP [?]	$(3.56 \pm 0.13) \times 10^{-2}$	$(3.48 \pm 0.17) \times 10^{-2}$	0.98 ± 0.06
Ours	$\mathbf{3.38 \times 10^{-2}}$	$\mathbf{3.27 \times 10^{-2}}$	**0.967**
$\Lambda_c^+ \to n \ell^+ \nu_\ell$ (Cabibbo-suppressed)			
BESIII [?]	$(3.57 \pm 0.48) \times 10^{-3}$	—	—
Ours	$\mathbf{3.26 \times 10^{-3}}$	$\mathbf{3.19 \times 10^{-3}}$	**0.979**





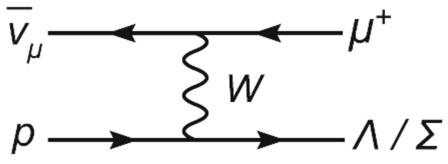
重味重子半轻衰变计算



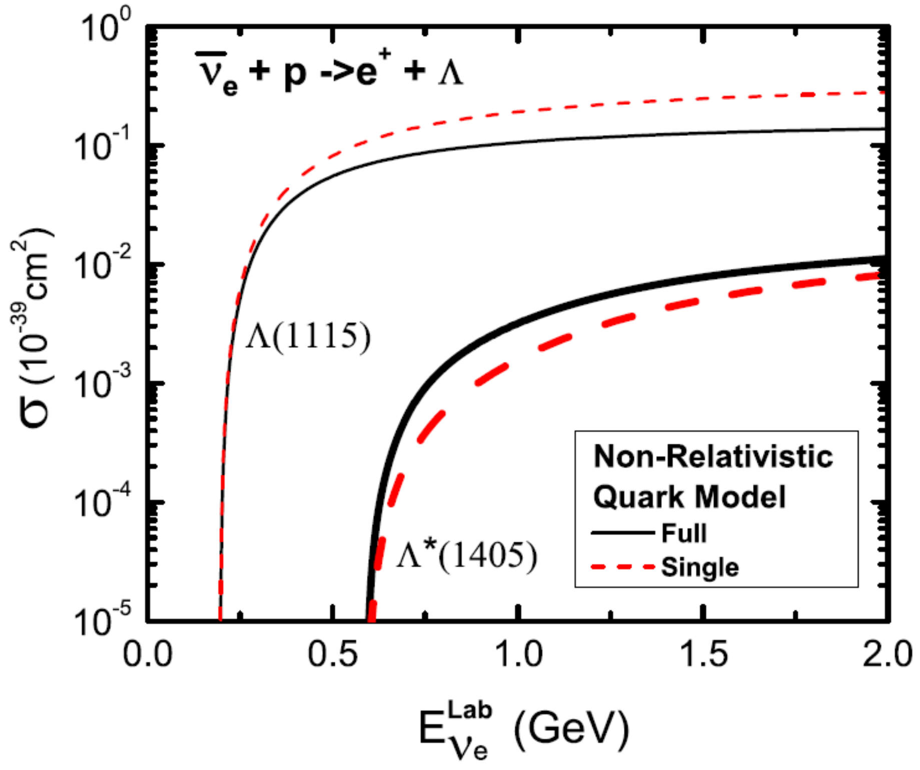
Refs.	$\mathcal{B}(\ell=e)$	$\mathcal{B}(\ell=\mu)$	$R_{\mu e}$
$\Xi_c^+ \to \Xi^0 \ell^+ \nu_\ell$			
RPP [?]	$(7\pm4)\times10^{-2}$	—	—
Ours	$\mathbf{11.0\times10^{-2}}$	$\mathbf{10.68\times10^{-2}}$	**0.971**
$\Xi_c^+ \to \Lambda \ell^+ \nu_\ell$ (Cabibbo-suppressed)			
RPP [?]	—	—	—
Ours	$\mathbf{1.62\times10^{-3}}$	$\mathbf{1.58\times10^{-3}}$	**0.975**
$\Xi_c^+ \to \Sigma^0 \ell^+ \nu_\ell$			
Ours	$\mathbf{3.44\times10^{-3}}$	$\mathbf{3.35\times10^{-3}}$	**0.974**
$\Xi_c^0 \to \Xi^- \ell^+ \nu_\ell$			
RPP [?]	$(1.05\pm0.20)\times10^{-2}$	$(1.01\pm0.21)\times10^{-2}$	0.96 ± 0.27
Ours	$\mathbf{3.62\times10^{-2}}$	$\mathbf{3.51\times10^{-2}}$	**0.970**
$\Xi_c^0 \to \Sigma^- \ell^+ \nu_\ell$			
Ours	$\mathbf{2.28\times10^{-3}}$	$\mathbf{2.22\times10^{-3}}$	**0.974**

Refs.	$\mathcal{B}(\ell=e)$	$\mathcal{B}(\ell=\mu)$	$R_{\mu e}$
$\Lambda_b^0 \to \Lambda_c^+ \ell^- \bar\nu_\ell$ (Light leptons)			
RPP [?]	$6.2^{+1.4}_{-1.3}\times10^{-2}$ (Average ℓ)		—
Ours	$\mathbf{3.88\times10^{-2}}$	$\mathbf{3.87\times10^{-2}}$	—
$\Lambda_b^0 \to \Lambda_c^+ \tau^- \bar\nu_\tau$ (Tau mode)			
RPP [?]	$(1.9\pm0.5)\times10^{-2}$		—
Ours	$\mathbf{1.53\times10^{-2}}$		$R_{\tau\ell}=\mathbf{0.394}$
$\Lambda_b^0 \to p \ell^- \bar\nu_\ell$ (Light leptons)			
RPP [?]	—	$(4.1\pm1.0)\times10^{-4}$	—
Ours	$\mathbf{2.55\times10^{-4}}$	$\mathbf{2.55\times10^{-4}}$	—
$\Lambda_b^0 \to p \tau^- \bar\nu_\tau$ (Tau mode)			
RPP [?]	–		—
Ours	$\mathbf{1.89\times10^{-4}}$		$R_{\tau\ell}=\mathbf{0.741}$

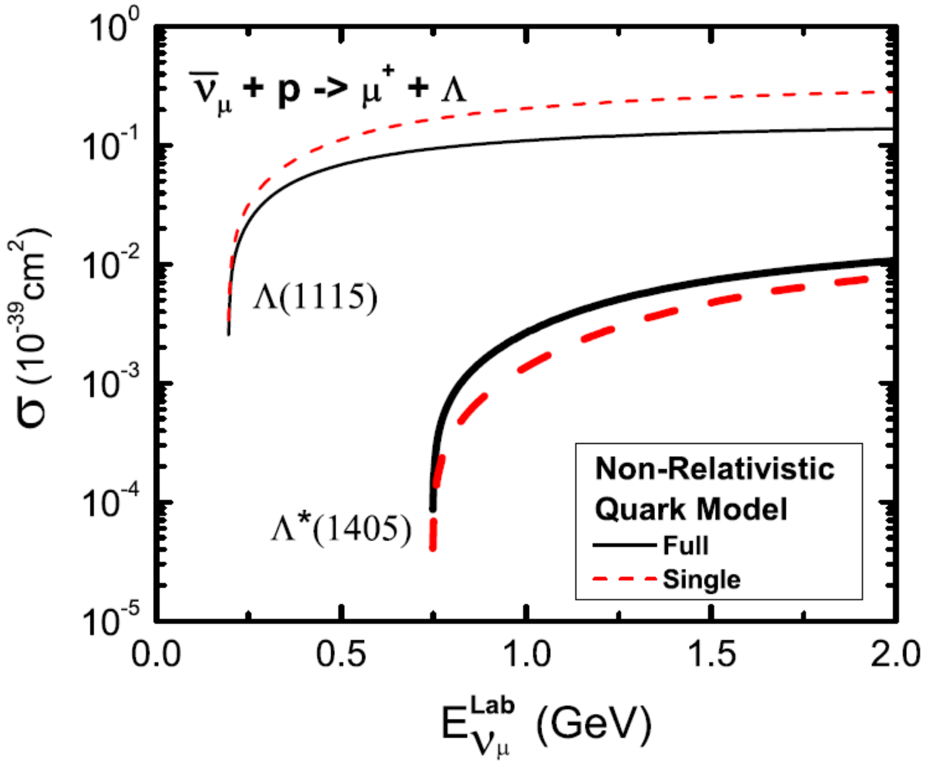
中微子核反应截面估计



$\bar{\nu}_\mu$
μ^+
W
p
Λ/Σ

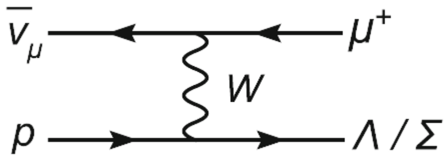


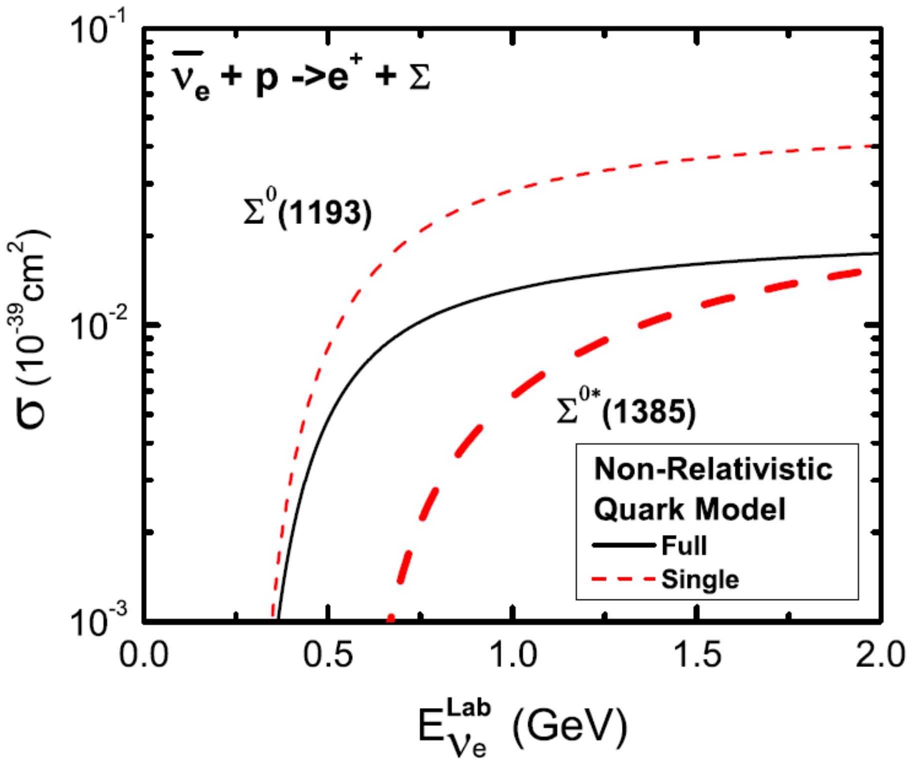
$\bar{\nu}_e$ + p ->e$^+$ + Λ
Λ(1115)
Λ*(1405)
Non-Relativistic
Quark Model
Full
Single
σ (10^{-39}cm^2)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.0
0.5
1.0
1.5
2.0
$E_{\nu_e}^{Lab}$ (GeV)

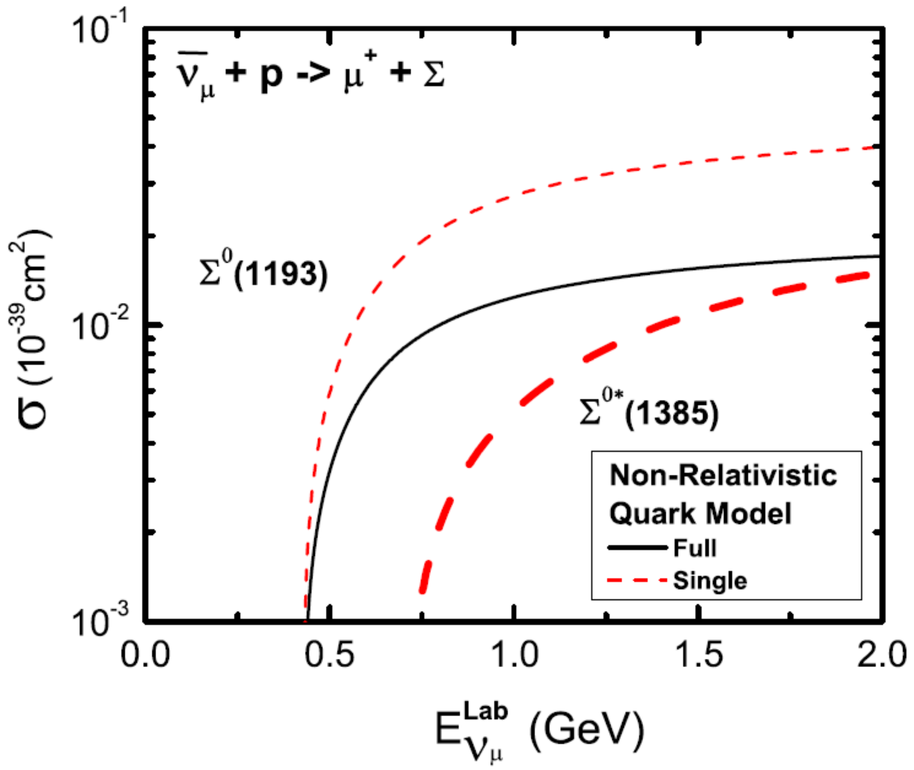


$\bar{\nu}_\mu$ + p -> μ$^+$ + Λ
Λ(1115)
Λ*(1405)
Non-Relativistic
Quark Model
Full
Single
σ (10^{-39}cm^2)
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
0.0
0.5
1.0
1.5
2.0
$E_{\nu_\mu}^{Lab}$ (GeV)

中微子核反应截面估计


$\bar{\nu}_\mu$
μ^+
W
p
Λ / Σ

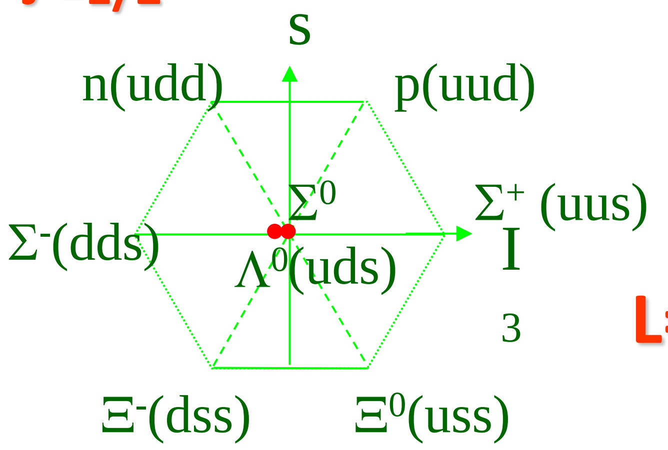

$\bar{\nu}_e$ + p ->e$^+$ + Σ
Σ^0(1193)
Σ^{0*}(1385)
Non-Relativistic
Quark Model
Full
Single
σ (10^{-39}cm^2)
10^{-1}
10^{-2}
10^{-3}
0.0
0.5
1.0
1.5
2.0
$E^{Lab}_{\nu_e}$ (GeV)


$\bar{\nu}_\mu$ + p -> μ^+ + Σ
Σ^0(1193)
Σ^{0*}(1385)
Non-Relativistic
Quark Model
Full
Single
σ (10^{-39}cm^2)
10^{-1}
10^{-2}
10^{-3}
0.0
0.5
1.0
1.5
2.0
$E^{Lab}_{\nu_\mu}$ (GeV)

强子物理的问题：传统夸克模型 vs 五夸克态

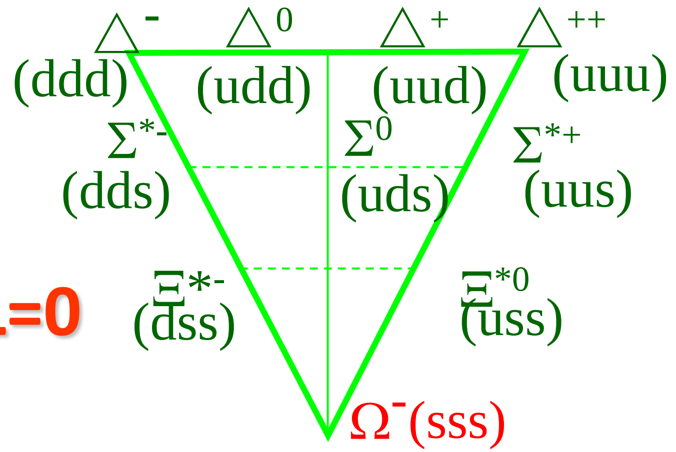
- **三夸克模型**

$J^P=1/2^+$



$J^P=3/2^+$

L=0



激发态 $L=1,\ J^P=1/2^-$

$N^*(1535), \Sigma^*(1620), \Lambda^*(1405), \Xi^*(1690?)$

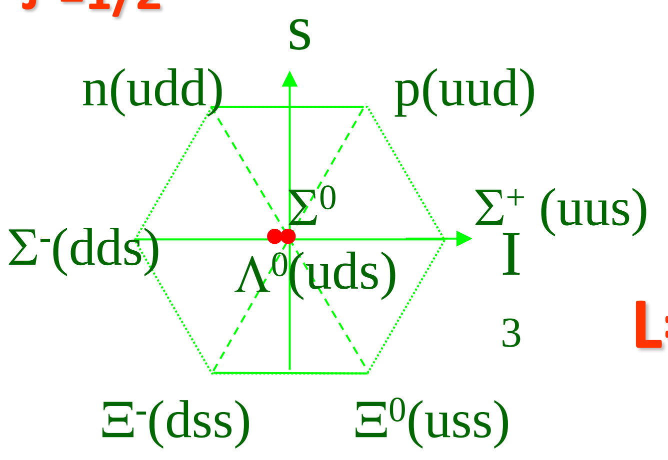
$N(940),\quad \Sigma(1189),\quad \Lambda(1115),\quad \Xi(1314)$

三夸克模型一定有问题

强子物理的问题：传统夸克模型 vs 五夸克态

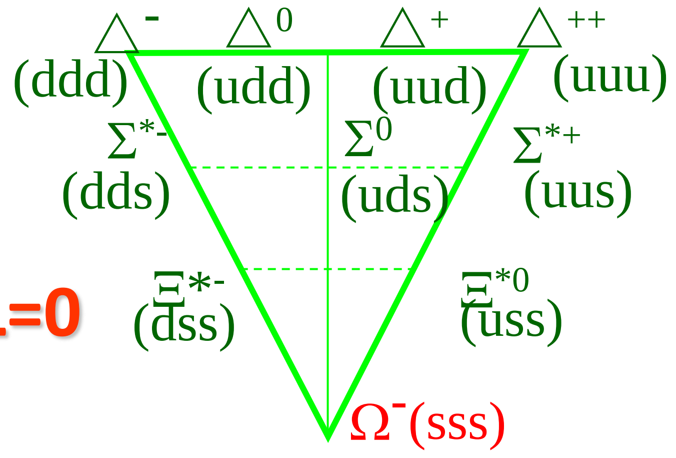
- **三夸克模型**

$J^P=1/2^+$

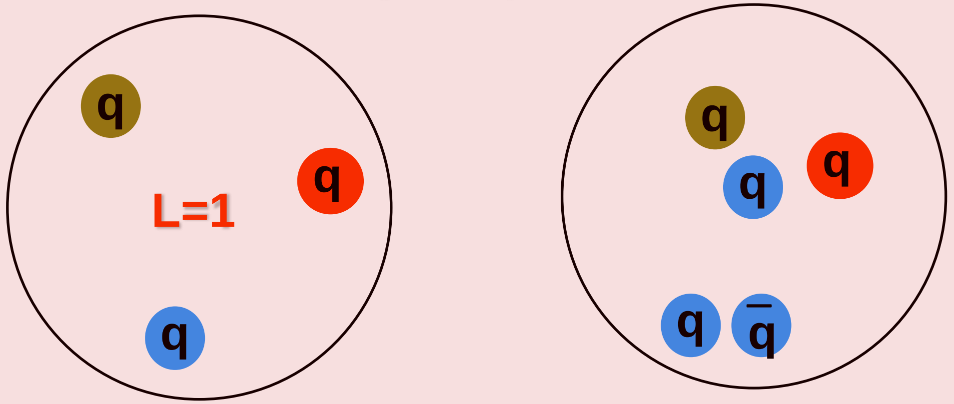


$J^P=3/2^+$

L=0



$J^P=1/2^-$



qqq with L=1 VS qqqqq in S-wave

Two possible patterns !

激发态L=1, $J^P=1/2^-$

$N^*(1535), \Sigma^*(1620), \Lambda^*(1405), \Xi^*(1690?)$

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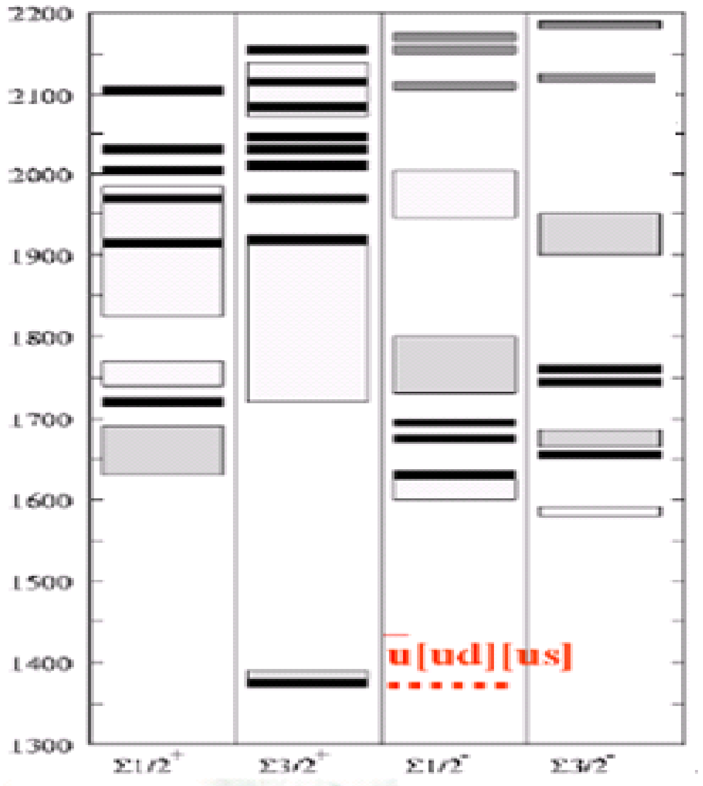
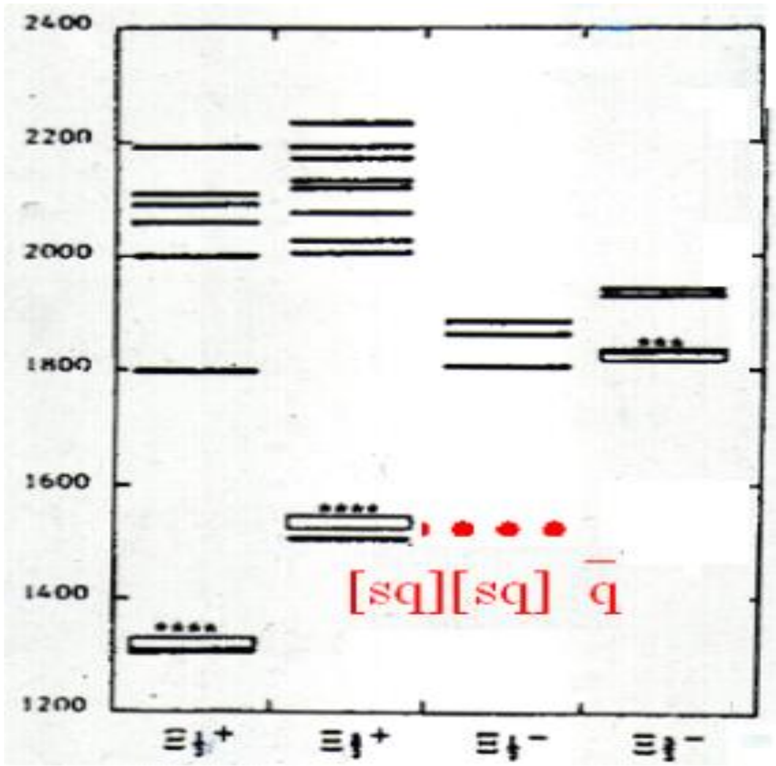
三夸克模型一定有问题

强子物理的问题：传统夸克模型 vs 五夸克态

Λ^*	[ud][sq] $\bar{q}$	~	1405 MeV
Σ^*	[us][du] $\bar{d}$	~	1360 MeV
Ξ^*	[us][ds] $\bar{u}$	~	1520 MeV

$J^P=1/2^-$

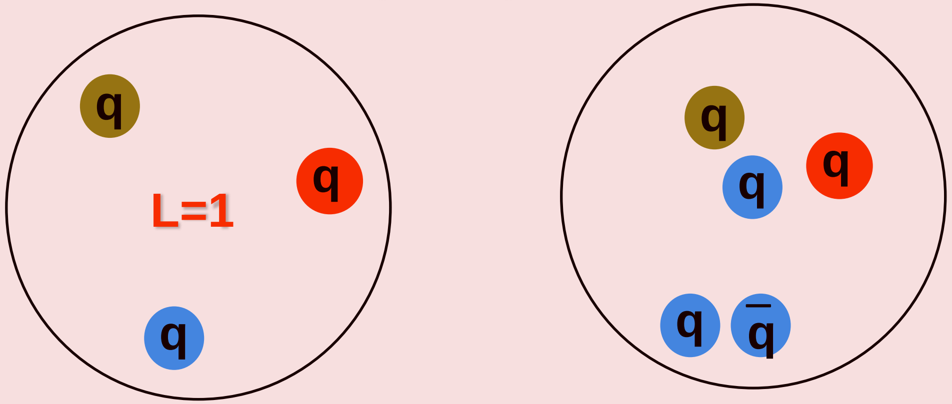




五夸克的基态往往比三夸克的第一轨道激发态要低

强子物理的问题：传统夸克模型 vs 五夸克态

$J^P=1/2^-$



qqq with L=1 VS qqqqq in S-wave

Two possible patterns !

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POSSIBLE RESONANT STATE IN PION-HYPERON SCATTERING*

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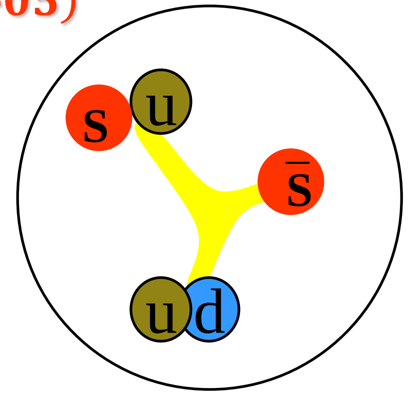
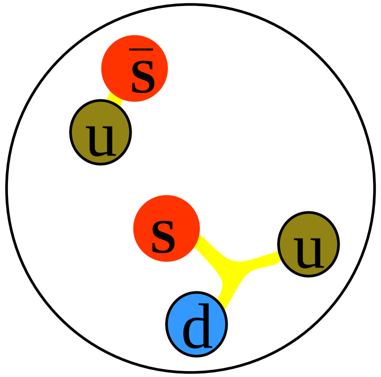
(Received April 27, 1959)

$\Lambda^*(1405)$



penta-quark

C. Helminen and D. O. Riska, NPA699, 624(2002).
S. L. Zhu, etc. High Energy Phys. Nucl. Phys. 29, 250(2005).
B. S. Zou, EPJA35, 325 (2008).



meson cloud/molecule

N. Kaiser, P. B. Siegel, and W. Weise, PLB 362,23 (1995).
D. Jido, J. A. Oller, E. Oset, A. Ramos, and U. G.Meissner, NPA725, 181 (2003).