Λ hyperon in covariant confined quark model

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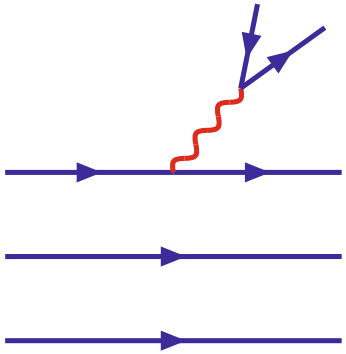
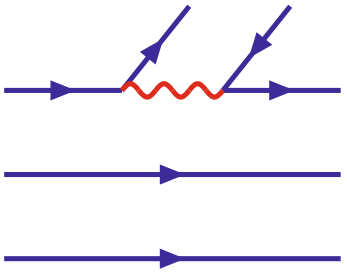
Nonleptonic two-body weak decays of baryons

- Ground states of baryons with $J^P = \frac{1}{2}^+$ can decay only weakly via the internal W-exchange.
- The nonleptonic two-body decays of baryons have five different color-flavor quark topologies.
- They can be divided into two groups:
  - reducible tree-diagrams
  - irreducible W–exchange diagrams
- The tree-diagrams are factorized into the lepton decay of the emitted meson and the baryon-baryon transition matrix elements of the weak currents.
- W–exchange diagrams are more difficult to evaluate from first principles.
- First attempts to estimate the W–exchange contributions have been made by using a pole model approach.
- It was shown that W–exchange contributions are sizeable and cannot be neglected.

Topology of nonleptonic weak decays

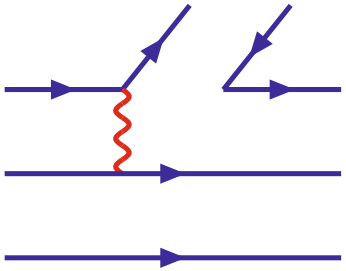


Ia

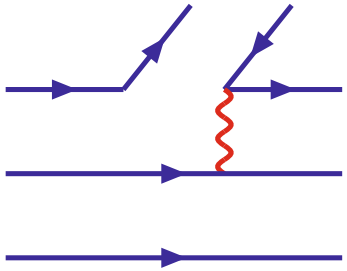


Ib

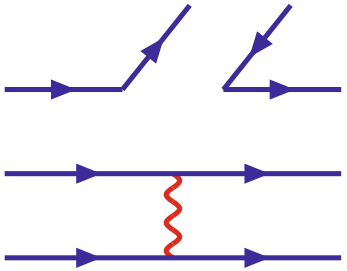
Tree diagrams



IIa



IIb



III

W-exchange diagrams

Nonleptonic double charmed baryon decays

	I_a	I_b	II_a	II_b	III
$\Xi_{cc}^{++} \to \Sigma_c^{(*)++} + \bar{K}^{(*)0}$	-	$\surd$	–	–	–
$\Xi_{cc}^{++} \to \Xi_c^{(\prime,*)+} + \pi^+(\rho^+)$	$\surd$	–	–	$\surd$	–
$\Xi_{cc}^{++} \to \Sigma^{(*)+} + D^{(*)+}$	–	–	–	$\surd$	–
$\Xi_{cc}^{+} \to \Xi_c^{(\prime,*)0} + \pi^+(\rho^+)$	$\surd$	–	$\surd$	–	–
$\Xi_{cc}^{+} \to \Lambda_c^+(\Sigma_c^{(*)+}) + \bar{K}^{(*)0}$	–	$\surd$	$\surd$	–	–
$\Xi_{cc}^{+} \to \Sigma_c^{(*)++} + K^{(*)-}$	–	–	$\surd$	–	–
$\Xi_{cc}^{+} \to \Xi_c^{(\prime,*)+} + \pi^0(\rho^0)$	–	–	$\surd$	$\surd$	–
$\Xi_{cc}^{+} \to \Xi_c^{(\prime,*)+} + \eta(\eta')$	–	–	$\surd$	$\surd$	–
$\Xi_{cc}^{+} \to \Omega_c^{(*)0} + K^{(*)+}$	–	–	$\surd$	–	–
$\Xi_{cc}^{+} \to \Lambda^0(\Sigma^{(*)0}) + D^{(*)+}$	–	–	–	$\surd$	$\surd$
$\Xi_{cc}^{+} \to \Sigma^{(*)+} + D^{(*)0}$	–	–	–	–	$\surd$
$\Xi_{cc}^{+} \to \Xi^{(*)0} + D_s^{(*)+}$	–	–	–	–	$\surd$
$\Omega_{cc}^{+} \to \Xi_c^{(\prime,*)+} + \bar{K}^{(*)0}$	–	$\surd$	–	$\surd$	–
$\Omega_{cc}^{+} \to \Xi^{(*)0} + D^{(*)+}$	–	–	–	$\surd$	–
$\Omega_{cc}^{+} \to \Omega_c^{(*)0} + \pi^+(\rho^+)$	$\surd$	–	–	–	–

Nonleptonic double charmed baryon decays

We will consider the decays that belong to the same topology class:

$$\Xi_{cc}^{++} \to \Xi_c^{+}\,(\Xi_c^{\prime +}) + \pi^{+}(\rho^{+}) \qquad \text{T-Ia and W-IIb}$$

$$\Omega_{cc}^{+} \to \Xi_c^{+}\,(\Xi_c^{\prime +}) + \bar{K}^{0}(K^{*\,0}) \qquad \text{T-Ib and W-IIb}$$

Quantum numbers and interpolating currents:

Baryon	J^P	Interpolating current	Mass (MeV)
Ξ_{cc}^{++}	$\frac{1}{2}^{+}$	$\varepsilon_{abc}\,\gamma^{\mu}\gamma_5\, u^a(c^b C\gamma_\mu c^c)$	3620.6
Ω_{cc}^{+}	$\frac{1}{2}^{+}$	$\varepsilon_{abc}\,\gamma^{\mu}\gamma_5\, s^a(c^b C\gamma_\mu c^c)$	3710.0
$\Xi_c^{\prime +}$	$\frac{1}{2}^{+}$	$\varepsilon_{abc}\,\gamma^{\mu}\gamma_5\, c^a(u^b C\gamma_\mu s^c)$	2577.4
Ξ_c^{+}	$\frac{1}{2}^{+}$	$\varepsilon_{abc}\, c^a(u^b C\gamma_5 s^c)$	2467.9

Körner-Pati-Woo (KPW) theorem

J.G. Körner, Nucl. Phys. B25, 282 (1971); J.C. Pati and C.H. Woo, Phys. Rev. D3, 2920 (1971)

The W–exchange contributions to the above decays fall into two classes:

- The decays with a $\Xi_c^{\prime +}$-baryon containing a symmetric $\{us\}$ diquark described by the interpolating current $\varepsilon_{abc}\,(u^b C\gamma_\mu s^c)$.
- The W–exchange contribution is strongly suppressed due to the KPW theorem which states that the contraction of the flavor antisymmetric current-current operator with a flavor symmetric final state configuration is zero in the $SU(3)$ limit.
- The decays with a Ξ_c^{+}-baryon containing an antisymmetric $[us]$ diquark described by the interpolating current $\varepsilon_{abc}\,(u^b C\gamma_5 s^c)$.
- In this case the W–exchange contribution is not a priori suppressed.

Effective Hamiltonian and nonlocal quark currents

The effective Hamiltonian describing the $\bar{q}_1 q_2 \to \bar{q}_1' q_2'$ transition is given by

$$\mathcal{H}_{\rm eff} = -\frac{G_F}{\sqrt{2}} V_{q_1 q_2} V^{\dagger}_{q_1' q_2'} \left(C_1 \mathcal{Q}_1 + C_2 \mathcal{Q}_2\right)$$

$$\mathcal{Q}_1 = (\bar{q}_{1\,a} O_L q_{2\,b})(\bar{q}_{1\,b}' O_L q_{2\,a}') \qquad \mathcal{Q}_2 = (\bar{q}_{1\,a} O_L q_{2\,a})(\bar{q}_{1\,b}' O_L q_{2\,b}')$$

The notation is $O^{\mu}_{L/R} = \gamma^{\mu}(1 \mp \gamma_5)$.

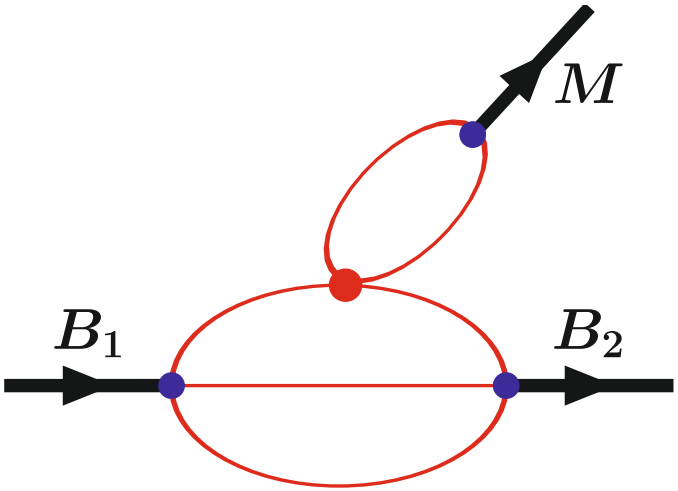
The nonlocal version of the interpolating currents:

$$J_B(x) = \int dx_1 \int dx_2 \int dx_3\, F_B(x; x_1, x_2, x_3)\, \varepsilon^{a_1 a_2 a_3} \Gamma_1 q_1^{a_1}(x_1) \left(q_2^{a_2}(x_2) C \Gamma_2 q_3^{a_3}(x_3)\right)$$

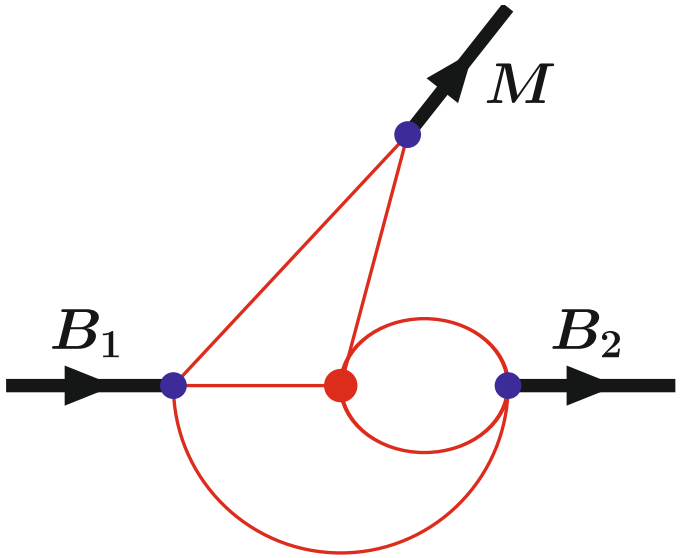
$$F_B = \delta^{(4)}\Big(x - \sum_{i=1}^{3} w_i x_i\Big) \Phi_B\Big(\sum_{i<j} (x_i - x_j)^2\Big)$$

where $w_i = m_i / (\sum_{j=1}^{3} m_j)$ and m_i is the quark mass. Γ_1, Γ_2 are the Dirac strings of the initial and final baryons.

Matrix elements



tree diagrams Ia, Ib



W-exchange diagram IIb

$$< B_2\, M|\mathcal{H}_{\rm eff}|B_1 >= \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^{\dagger}\, \bar{u}(p_2)\Big(12\, C_T\, M_T + 12\,(C_1 - C_2)\, M_W\Big) u(p_1).$$

$$C_T = \begin{cases} C_T = +(C_2 + \xi C_1) & \text{charged meson} \\ C_T = -(C_1 + \xi C_2) & \text{neutral meson} \end{cases}$$

The factor of $\xi = 1/N_c$ is set to zero in the numerical calculations.

Tree-diagram contribution: factorization

The contribution from the tree diagram factorizes into two pieces:

$$M_T = M_T^{(1)} \cdot M_T^{(2)}$$

$$M_T^{(1)} = N_c\, g_M \int \frac{d^4k}{(2\pi)^4 i} \widetilde{\Phi}_M(-k^2)\, \mathrm{tr}\left[O_L S_d(k - w_d q)\Gamma_M S_{s(u)}(k + w_{s(u)} q)\right]$$

$$\begin{aligned} M_T^{(2)} &= g_{B_1} g_{B_2} \int \frac{d^4k_1}{(2\pi)^4 i} \int \frac{d^4k_2}{(2\pi)^4 i} \widetilde{\Phi}_{B_1}\left(-\vec{\Omega}_1^2\right) \widetilde{\Phi}_{B_2}\left(-\vec{\Omega}_2^2\right) \\ &\times \Gamma_1 S_c(k_2)\gamma^\mu S_c(k_1 - p_1) O_R S_{u(s)}(k_1 - p_2) \widetilde{\Gamma}_2 S_{s(u)}(k_1 - k_2)\gamma_\mu\gamma_5 \end{aligned}$$

The $M_T^{(1)}$ is related to the leptonic decay constants:

$$M_T^{(1)} = \begin{cases} -f_P \cdot q & \text{pseudoscalar meson} \\ +f_V m_V \cdot \epsilon_V & \text{vector meson} \end{cases}$$

W-exchange diagram contribution: no factorization

$$
\begin{aligned}
M_W &= g_{B_1} g_{B_2} g_M \int \frac{d^4 k_1}{(2\pi)^4 i} \int \frac{d^4 k_2}{(2\pi)^4 i} \int \frac{d^4 k_3}{(2\pi)^4 i} \widetilde{\Phi}_{B_1}\Big(-\vec{\Omega}_1^2\Big) \widetilde{\Phi}_{B_2}\Big(-\vec{\Omega}_2^2\Big) \widetilde{\Phi}_M(-P^2) \\
&\times\ 2\Gamma_1 S_c(k_1)\gamma^\mu S_c(k_2)(1-\gamma_5) S_d(k_2-k_1+p_2)\Gamma_M S_{s(u)}(k_2-k_1+p_1)\gamma_\mu\gamma_5 \\
&\times\ \mathrm{tr}\Big[S_{u(s)}(k_3)\widetilde{\Gamma}_2 S_{s(u)}(k_3-k_1+p_2)(1+\gamma_5)\Big]
\end{aligned}
$$

Here $\Gamma_1 \otimes \widetilde{\Gamma}_2 = I \otimes \gamma_5$ for $B_2 = \Xi_c^+$ and $-\gamma_\nu\gamma_5 \otimes \gamma^\nu$ for $B_2 = \Xi_c'^+$.

To verify the KPW theorem in the case of $B_2 = \Xi_c'^+$ we use the identity

$$
\mathrm{tr}\Big[S_u(k_3)\gamma_\nu S_s(k_3-k_1+p_2)\Big] = -\,\mathrm{tr}\Big[S_s(-k_3+k_1-p_2)\gamma_\nu S_u(-k_3)\Big]
$$

Then by shifting $k_3 \to -k_3 + k_1 - p_2$ one gets the same expression with opposite sign and $u \leftrightarrow s$ interchange. Thus, if $m_u = m_s$ then $M_W \equiv 0$.

It directly confirms the KPW–theorem.

Evaluation of the diagrams

- Use the Schwinger representation of the propagator:

$$\frac{m + \not{k}}{m^2 - k^2} = (m + \not{k}) \int_0^\infty d\alpha \, \exp[-\alpha(m^2 - k^2)]$$

- Choose a simple Gaissian form for the vertex function

$$\Phi(-K^2) = \exp\left(K^2/\Lambda^2\right)$$

where the parameter Λ characterizes the hadron size.

- We imply that the loop integration k proceed over Euclidean space:

$$k^0 \to e^{i\frac{\pi}{2}} k_4 = ik_4 \,, \qquad k^2 = (k^0)^2 - \vec{k}^2 \to -k_E^2 \leq 0 \,.$$

- We also put all external momenta p to Euclidean space:

$$p^0 \to e^{i\frac{\pi}{2}} p_4 = ip_4 \,, \qquad p^2 = (p^0)^2 - \vec{p}^2 \to -p_E^2 \leq 0$$

so that the quadratic momentum form in the exponent becomes negative-definite and the loop integrals are absolutely convergent.

Evaluation of the diagrams

- Convert the loop momemta in the numerator into derivatives over external momenta:

$$k_i^\mu e^{2kr} = \frac{1}{2}\frac{\partial}{\partial r_{i\,\mu}} e^{2kr},$$

- Move the derivatives outside of the loop integrals.
- Calculate the scalar loop integral:

$$\prod_{i=1}^{n} \int \frac{d^4 k_i}{i\pi^2} e^{kAk+2kr} = \prod_{i=1}^{n} \int \frac{d^4 k_i^E}{\pi^2} e^{-k_E A k_E - 2k_E r_E} = \frac{1}{|A|^2} e^{-rA^{-1}r}$$

where a symmetric $n \times n$ real matrix A is positive-definite.

- Use the identity

$$P\left(\frac{1}{2}\frac{\partial}{\partial r}\right) e^{-rA^{-1}r} = e^{-rA^{-1}r} P\left(\frac{1}{2}\frac{\partial}{\partial r} - A^{-1}r\right)$$

to move the exponent to the left.

Evaluation of the diagrams

- Employ the commutator

$$[\frac{\partial}{\partial r_{i\,\mu}}, r_{j\,\nu}] = \delta_{ij}\, g_{\mu\nu}$$

to make differentiation in

$$P\left(\frac{1}{2}\frac{\partial}{\partial r} - A^{-1} r\right)$$

for any polynomial P. The necessary commutations of the differential operators are done by a FORM program.

- One obtains

$$\Pi = \int_0^\infty d^n\alpha\, F(\alpha_1, \ldots, \alpha_n)\,,$$

where F stands for the whole structure of a given diagram.

Evaluation of the diagrams

The set of Schwinger parameters α_i can be turned into a simplex by introducing an additional t–integration via the identity

$$1 = \int_0^\infty dt\, \delta(t - \sum_{i=1}^n \alpha_i)$$

leading to

$$\Pi = \int_0^\infty dt t^{n-1} \int_0^1 d^n\alpha\, \delta\Big(1 - \sum_{i=1}^n \alpha_i\Big)\, F(t\alpha_1, \ldots, t\alpha_n)\,.$$

Infrared confinement

- Cut off the upper integration at $1/\lambda^2$

$$\Pi^c = \int_0^{1/\lambda^2} dt t^{n-1} \int_0^1 d^n\alpha\, \delta\Big(1 - \sum_{i=1}^n \alpha_i\Big)\, F(t\alpha_1, \ldots, t\alpha_n)$$

- The infrared cut-off has removed all possible thresholds in the quark loop diagram.

- We take the cut-off parameter λ to be the same in all physical processes.

T. Branz, A. Faessler, T. Gutsche, M. A. Ivanov, J. G. Körner and V. E. Lyubovitskij, Phys. Rev. D81, 034010 (2010)

Invariant and helicity amplitudes

The transition amplitudes in terms of invariant amplitudes:

$$< B_2\, P|\mathcal{H}_{\rm eff}|B_1 > \;=\; \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^{\dagger}\, \bar{u}(p_2)\,(A + \gamma_5\, B)\, u(p_1)$$

$$< B_2\, V|\mathcal{H}_{\rm eff}|B_1 > \;=\; \frac{G_F}{\sqrt{2}} V_{cs} V_{ud}^{\dagger}$$

$$\times\; \bar{u}(p_2)\, \epsilon^{*}_{V\delta} \left(\gamma^{\delta} V_{\gamma} + p_1^{\delta} V_p + \gamma_5 \gamma^{\delta} V_{5\gamma} + \gamma_5 p_1^{\delta}\, V_{5p}\right) u(p_1)$$

The helicity amplitudes in terms of invariant amplitudes:

$$H^{V}_{\frac{1}{2}\,t} = \sqrt{Q_+}\, A \qquad H^{A}_{\frac{1}{2}\,t} = \sqrt{Q_-}\, B$$

$$H^{V}_{\frac{1}{2}\,0} = +\sqrt{Q_-/q^2}\left(m_+\, V_{\gamma} + \tfrac{1}{2} Q_+\, V_p\right) \qquad H^{V}_{\frac{1}{2}\,1} = -\sqrt{2Q_-}\, V_{\gamma}$$

$$H^{A}_{\frac{1}{2}\,0} = +\sqrt{Q_+/q^2}\left(m_-\, V_{5\gamma} + \tfrac{1}{2} Q_-\, V_{5p}\right) \qquad H^{A}_{\frac{1}{2}\,1} = -\sqrt{2Q_+}\, V_{5\gamma}$$

Here $m_{\pm} = m_1 \pm m_2$, $Q_{\pm} = m_{\pm}^2 - q^2$ **and** $|\mathrm{p}_2| = \lambda^{1/2}(m_1^2, m_2^2, q^2)/(2m_1)$.

The parity relations: $H^{V}_{-\lambda_2,-\lambda_M} = +H^{V}_{\lambda_2,\lambda_M}\,,\; H^{A}_{-\lambda_2,-\lambda_M} = -H^{A}_{\lambda_2,\lambda_M}$

Decay widths

The semileptonic decay widths read

$$\Gamma(B_1 \to B_2 + \ell^+ \nu_\ell) = \int_0^{(M_1-M_2)^2} dq^2 \, \frac{d\,\Gamma(B_1 \to B_2 + \ell^+ \nu_\ell)}{dq^2},$$

$$\frac{d\,\Gamma(B_1 \to B_2 + \ell^+ \nu_\ell)}{dq^2} = \frac{1}{192\pi} G_F^2 \, \frac{|\mathrm{p}_2| q^2}{M_1^2} \, |V_{ij}|^2 \, \mathcal{H}_V \, .$$

The two-body decay widths read

$$\Gamma\Big(B_1 \to B_2 + P(V)\Big) = \frac{G_F^2}{32\pi} \, |V_{cs} V_{ud}^\dagger|^2 \, \frac{|\mathrm{p}_2|}{m_1^2} \, \mathcal{H}_{P(V)}$$

$$\mathcal{H}_P = \left|H_{\frac{1}{2}\,t}\right|^2 + \left|H_{-\frac{1}{2}\,t}\right|^2,$$

$$\mathcal{H}_V = \left|H_{\frac{1}{2}\,0}\right|^2 + \left|H_{-\frac{1}{2}\,0}\right|^2 + \left|H_{\frac{1}{2}\,1}\right|^2 + \left|H_{-\frac{1}{2}\,-1}\right|^2,$$

where $H = H^V - H^A$.

Semileptonic decays

Cabibbo-favored semileptonic decays of double heavy charm baryons induced by the charm level $c \to s$ transition ($\ell = e^+, \mu^+$).

	Γ [10^{-13} ГэВ]	Γ [10^{-13} ГэВ]	B [%]
$1/2^+ \to 1/2^+$			
$\Xi_{cc}^{++} \to \Xi_c^+ + \ell^+\nu_\ell$	0.70	0.77 ± 0.37 [1]	2.72
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} + \ell^+\nu_\ell$	0.97	0.53 ± 0.35 [1]	3.76
$\Xi_{cc}^{+} \to \Xi_c^0 + \ell^+\nu_\ell$	0.69	0.77 ± 0.37 [1]	2.00
$\Xi_{cc}^{+} \to \Xi_c^{\prime 0} + \ell^+\nu_\ell$	0.97	0.53 ± 0.35 [1]	2.79
$\Omega_{cc}^{+} \to \Omega_c^0 + \ell^+\nu_\ell$	1.82	1.25 ± 0.80 [1]	7.07
$1/2^+ \to 3/2^+$			
$\Xi_{cc}^{++} \to \Xi_c^{*+} + \ell^+\nu_\ell$	0.22	—	0.86
$\Xi_{cc}^{+} \to \Xi_c^{*0} + \ell^+\nu_\ell$	0.22	—	0.64
$\Omega_{cc}^{+} \to \Omega_c^{*0} + \ell^+\nu_\ell$	0.40	0.32 [2]	1.27

[1] Y. J. Shi, W. Wang and Z. X. Zhao, Eur. Phys. J. C 80, no.6, 568 (2020).

[2] Z. X. Zhao, Eur. Phys. J. C 78, no.9, 756 (2018).

T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij and Z. Tyulemissov, Phys. Rev. D 100, no.11, 114037 (2019)

$\Omega_{cc}^{+} \to \Xi_c'^{+} + \bar{K}^0(\bar{K}^{*0})$

Helicity	Tree diagram	W diagram	total
$H^V_{\frac{1}{2}\,t}$	0.20	−0.01	0.19
$H^A_{\frac{1}{2}\,t}$	0.25	−0.01	0.24
$\Gamma(\Omega_{cc}^{+} \to \Xi_c'^{+} + \bar{K}^0) = 0.15 \cdot 10^{-13}$ GeV			
$H^V_{\frac{1}{2}\,0}$	−0.25	0.04×10^{-1}	−0.25
$H^A_{\frac{1}{2}\,0}$	−0.50	0.01	−0.49
$H^V_{\frac{1}{2}\,1}$	0.27	−0.01	0.26
$H^A_{\frac{1}{2}\,1}$	0.56	0.04×10^{-2}	0.56
$\Gamma(\Omega_{cc}^{+} \to \Xi_c'^{+} + \bar{K}^{*0}) = 0.74 \cdot 10^{-13}$ GeV			

T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij and Z. Tyulemissov, Phys. Rev. D 99, no.5, 056013 (2019)

$\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^0(\bar{K}^{*0})$

Helicity	Tree diagram	W diagram	total
$H^V_{\frac{1}{2}\,t}$	-0.35	1.06	0.71
$H^A_{\frac{1}{2}\,t}$	-0.10	0.31	0.21
$\Gamma(\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^0) = 0.95 \cdot 10^{-13}$ GeV			
$H^V_{\frac{1}{2}\,0}$	0.50	-0.69	-0.19
$H^A_{\frac{1}{2}\,0}$	0.18	-0.45	-0.27
$H^V_{\frac{1}{2}\,1}$	-0.11	-0.24	-0.35
$H^A_{\frac{1}{2}\,1}$	-0.18	0.66	0.48
$\Gamma(\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^{*0}) = 0.62 \cdot 10^{-13}$ GeV			

T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij and Z. Tyulemissov, Phys. Rev. D 99, no.5, 056013 (2019)

$\Xi_{cc}^{++} \to \Xi_c'^{+} + \pi^+(\rho^+)$

Helicity	Tree diagram	W diagram	total
$H^V_{\frac{1}{2}\,t}$	-0.38	-0.01	-0.39
$H^A_{\frac{1}{2}\,t}$	-0.55	-0.02	-0.57
$\Gamma(\Xi_{cc}^{++} \to \Xi_c'^{+} + \pi^+) = 0.82 \cdot 10^{-13}$ GeV			
$H^V_{\frac{1}{2}\,0}$	0.60	0.04×10^{-1}	0.61
$H^A_{\frac{1}{2}\,0}$	1.20	0.01	1.21
$H^V_{\frac{1}{2}\,1}$	-0.49	-0.01	-0.50
$H^A_{\frac{1}{2}\,1}$	-1.27	0.01×10^{-1}	-1.27
$\Gamma(\Xi_{cc}^{++} \to \Xi_c'^{+} + \rho^+) = 4.27 \cdot 10^{-13}$ GeV			

T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij and Z. Tyulemissov, Phys. Rev. D 99, no.5, 056013 (2019)

$\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+(\rho^+)$

Helicity	Tree diagram	W diagram	total
$H^V_{\frac{1}{2}\,t}$	-0.70	0.99	0.29
$H^A_{\frac{1}{2}\,t}$	-0.21	0.30	0.09
$\Gamma(\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+) = 0.18 \cdot 10^{-13}$ GeV			
$H^V_{\frac{1}{2}\,0}$	1.17	-0.70	0.47
$H^A_{\frac{1}{2}\,0}$	0.45	-0.44	0.003
$H^V_{\frac{1}{2}\,1}$	-0.20	-0.23	-0.43
$H^A_{\frac{1}{2}\,1}$	-0.41	0.62	0.21
$\Gamma(\Xi_{cc}^{++} \to \Xi_c^+ + \rho^+) = 0.63 \cdot 10^{-13}$ GeV			

T. Gutsche, M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij and Z. Tyulemissov, Phys. Rev. D 99, no.5, 056013 (2019)

Comparison with other approaches. Abbr.: M=NRQM, T=HQET

Mode	Width (in 10^{-13} GeV)					
	our	Dhir	Jiang	Wang	Yu	Likhoded
$\Omega_{cc}^{+} \to \Xi_c^{\prime +} + \bar{K}^0$	0.15	0.31 (M) 0.59 (T)				
$\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^0$	0.95	0.68 (M) 1.08 (T)				
$\Omega_{cc}^{+} \to \Xi_c^{\prime +} + \bar{K}^{*0}$	0.74		$2.64^{+2.72}_{-1.79}$			
$\Omega_{cc}^{+} \to \Xi_c^{+} + \bar{K}^{*0}$	0.62		$1.38^{+1.49}_{-0.95}$			
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} + \pi^+$	0.82	1.40 (M) 1.93 (T)		1.10		
$\Xi_{cc}^{++} \to \Xi_c^{+} + \pi^+$	0.18	1.71 (M) 2.39 (T)		1.57	1.58	2.25
$\Xi_{cc}^{++} \to \Xi_c^{\prime +} + \rho^+$	4.27		$4.25^{+0.32}_{-0.19}$	4.12	3.82	
$\Xi_{cc}^{++} \to \Xi_c^{+} + \rho^+$	0.63		$4.11^{+1.37}_{-0.86}$	3.03	2.76	6.70

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Estimating uncertainties in the decay widths

- The only free parameter in our approach is the size parameter Λ_{cc}.
- We have chosen $\Lambda_{cc} = \Lambda_c = 0.8675$ GeV.
- To estimate the uncertaintity caused by the choice of the size parameter we allow the size parameter to vary from 0.6 to 1.135 GeV.
- We evaluate the mean $\bar{\Gamma} = \sum \Gamma_i / N$ and the mean square deviation $\sigma^2 = \sum (\Gamma_i - \bar{\Gamma})^2 / N$.
- The rate errors amount to $6 - 15\%$.

Mode	Width (in 10^{-13} GeV)
$\Omega_{cc}^+ \to \Xi_c'^+ + \bar{K}^0$	0.14 ± 0.01
$\Omega_{cc}^+ \to \Xi_c'^+ + \bar{K}^{*0}$	0.72 ± 0.06
$\Omega_{cc}^+ \to \Xi_c^+ + \bar{K}^0$	0.87 ± 0.13
$\Omega_{cc}^+ \to \Xi_c^+ + \bar{K}^{*0}$	0.58 ± 0.07
$\Xi_{cc}^{++} \to \Xi_c'^+ + \pi^+$	0.77 ± 0.05
$\Xi_{cc}^{++} \to \Xi_c'^+ + \rho^+$	4.08 ± 0.29
$\Xi_{cc}^{++} \to \Xi_c^+ + \pi^+$	0.16 ± 0.02
$\Xi_{cc}^{++} \to \Xi_c^+ + \rho^+$	0.59 ± 0.04

Λ-hyperon

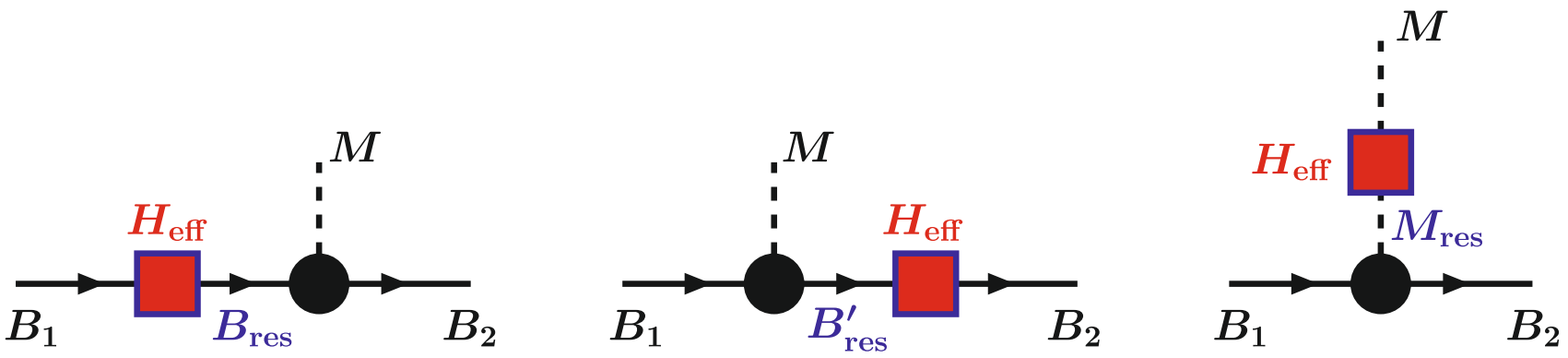
- **Mass of Λ-hyperon** $m_\Lambda = 1.115683 \pm 0.000006$ **GeV.**
- **Mean life of Λ-hyperon** $\tau_\Lambda = 2.632 \pm 0.020 \cdot 10^{-10}$ **s.**
- **Modes**

$$Br(\Lambda \to p\pi^-) = (63.9 \pm 0.5)\%,$$
$$Br(\Lambda \to n\pi^0) = (35.8 \pm 0.5)\%$$

M. A. Ivanov, J. G. Körner, V. E. Lyubovitskij and Z. Tyulemissov, Phys. Rev. D 104, no.7, 074004 (2021)

There are two classes of the Feynman diagrams generating matrix elements of these processes:

- short-distance (SD) diagrams,
- long-distance (LD) or pole diagrams.



Matrix element

Matrix element of $\frac{1}{2}^+ \to \frac{1}{2}^+ + 0^-$ decay reads

$$M(B_1 \to B_2 + M) = M_{\rm SD}(B_1 \to B_2 + M) + M_{\rm LD_1}(B_1 \to B_{\rm res} \to B_2 + M) + M_{\rm LD_2}(B_1 \to B'_{\rm res} + M \to B_2 + M)\,,$$

$$\begin{aligned} M_{\rm SD} &= i^4\,\bar{u}(p_2)\,\Gamma_{B_1 B_2 M}(p_1, p_2, q)\,u(p_1)\,, \\ M_{\rm LD_1} &= i^6 \int \frac{d^4k}{(2\pi)^4 i}\,\bar{u}(p_2)\,\Gamma_{B_{\rm res} M B_2}(k, p_2, q)\,S_{B_{\rm res}}(k)\,\Gamma_{B_1 B_{\rm res}}(p_1, k)\,u(p_1)\,, \\ M_{\rm LD_2} &= i^6 \int \frac{d^4k}{(2\pi)^4 i}\,\bar{u}(p_2)\,\Gamma_{B_{\rm res} B_2}(k, p_2)\,S_{B_{\rm res}}(k)\,\Gamma_{B_1 M B_{\rm res}}(p_1, k, q)\,u(p_1)\,, \end{aligned}$$

The propagator of the $\frac{1}{2}^+$ resonances is the ordinary Dirac propagator,

$$S(p) = \frac{1}{m_{\rm res} - \not{p}} = \frac{m_{\rm res} + \not{p}}{m_{\rm res}^2 - p^2}\,.$$

The invariant matrix elements for the pole diagrams with intermediate $\frac{1}{2}^+$ resonances

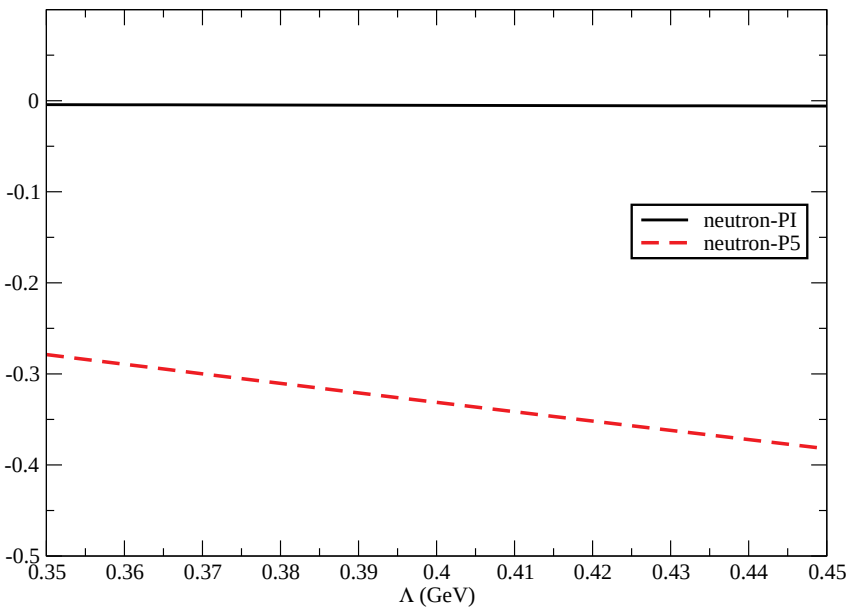
$$\widetilde{M}_{\mathrm{LD}_1} \equiv \widetilde{M}_n = \bar{u}(p_2)\left(A_n + \gamma_5 B_n\right)u(p_1)\,,$$

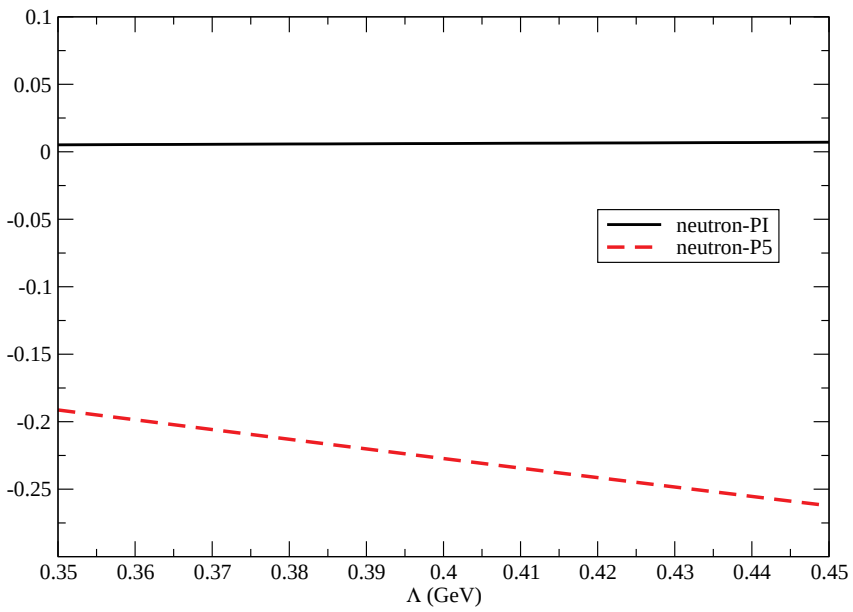
$$A_n = -\frac{B_{\Lambda n}(C_{n\pi p} - m_\Lambda D_{n\pi p})}{m_n + m_\Lambda}\,, \qquad B_n = -\frac{A_{\Lambda n}(C_{n\pi p} + m_\Lambda D_{n\pi p})}{m_n - m_\Lambda}\,,$$

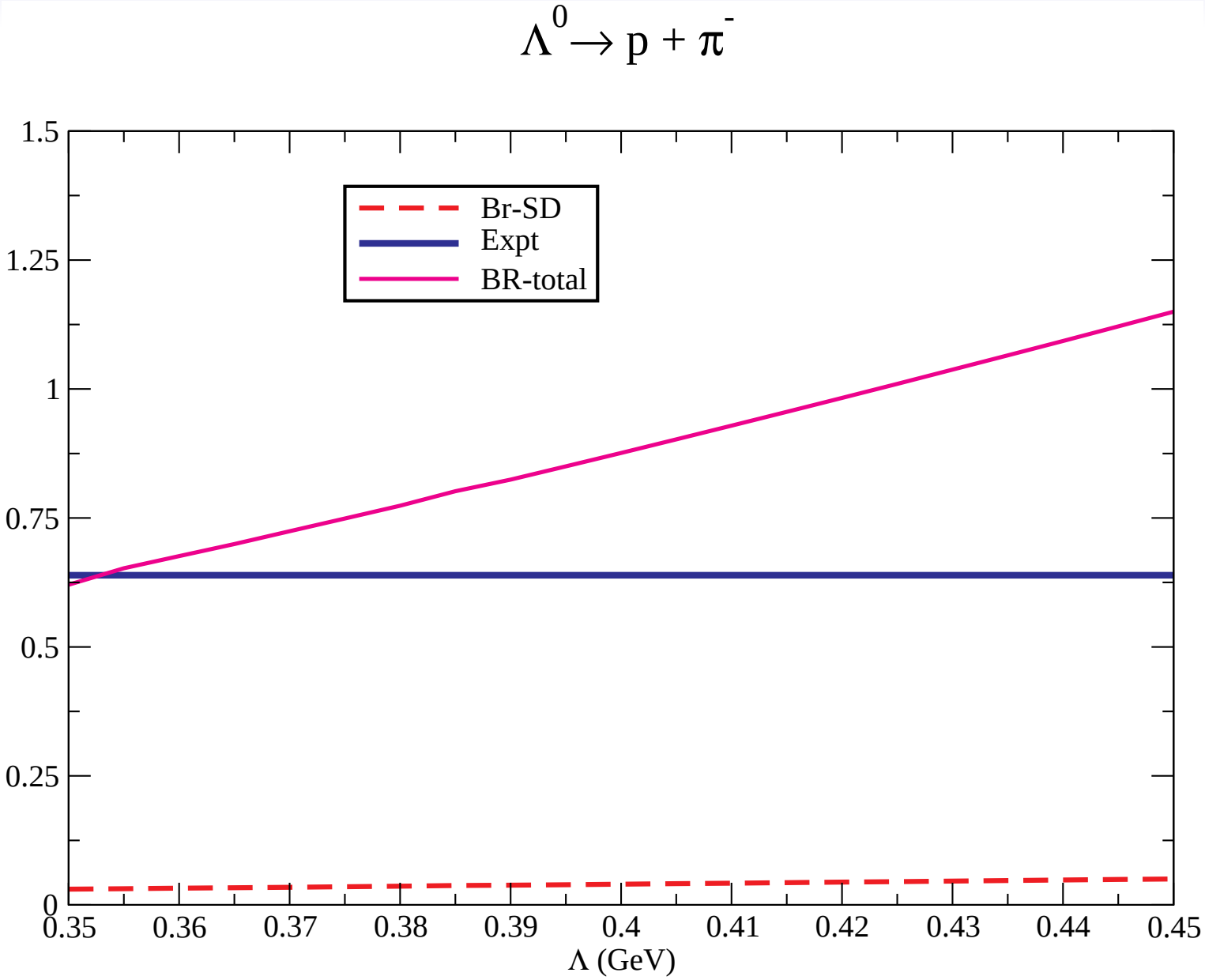
$$\widetilde{M}_{\mathrm{LD}_2} \equiv \widetilde{M}_\Sigma = \bar{u}(p_2)\left(A_\Sigma + \gamma_5 B_\Sigma\right)u(p_1)\,,$$

$$A_\Sigma = -\frac{B_{\Sigma^+ p}(C_{\Lambda\pi\Sigma^+} - m_p D_{\Lambda\pi\Sigma^+})}{m_\Sigma + m_p}\,, \qquad B_\Sigma = -\frac{A_{\Sigma^+ p}(C_{\Lambda\pi\Sigma^+} + m_p D_{\Lambda\pi\Sigma^+})}{m_\Sigma - m_p}\,,$$

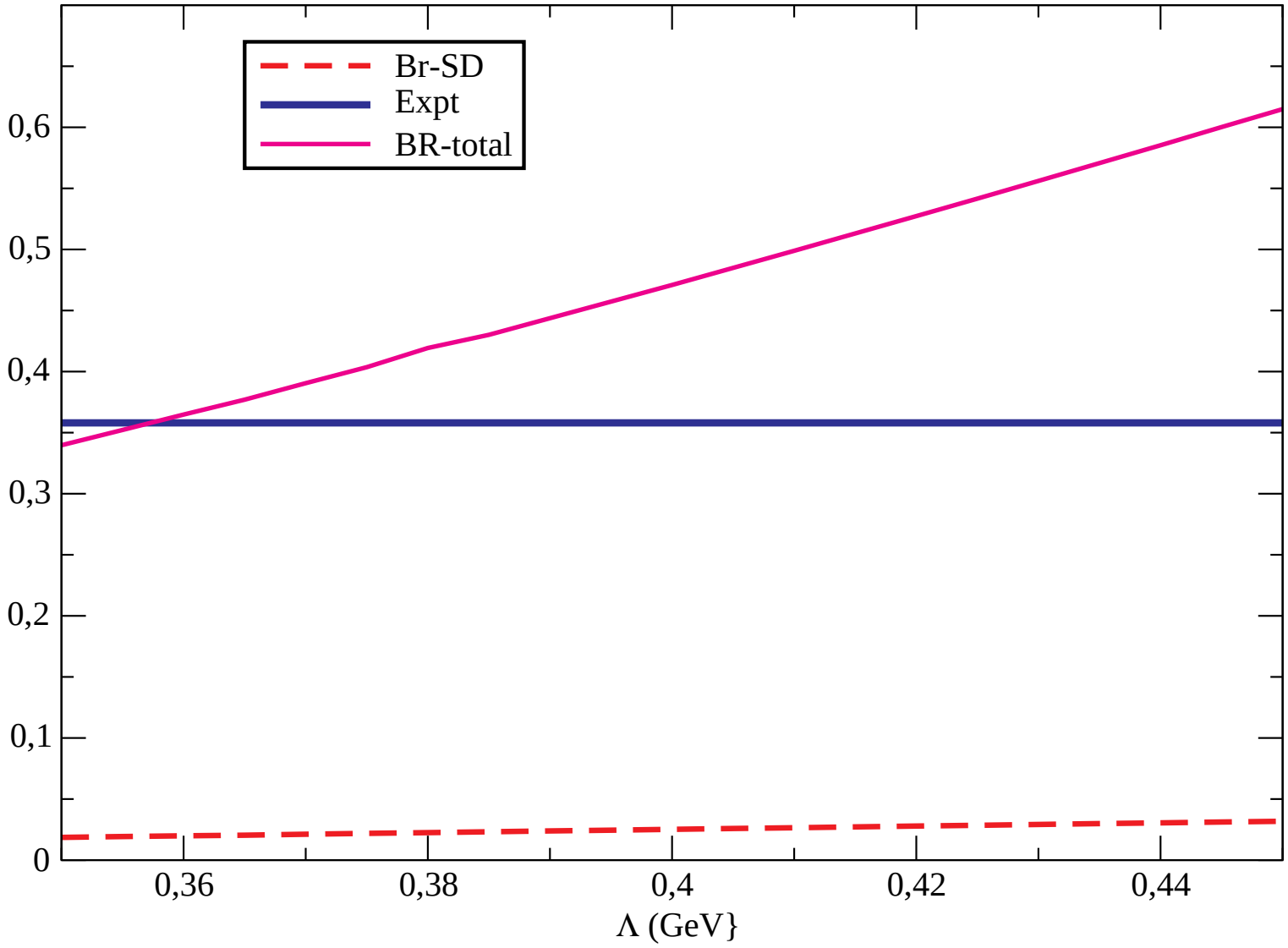
Dependence of the helicities $PI \equiv H^V_{1/2\,t}$ and $P5 \equiv H^A_{1/2\,t}$ on the size parameter in the case of the neutron resonance. Left panel: the decay $\Lambda \to p + \pi$; right panel: the decay $\Lambda \to n + \pi$.






$\Lambda^0 \rightarrow p + \pi^-$
Br-SD
Expt
BR-total
1.5
1.25
1
0.75
0.5
0.25
0
0.35
0.36
0.37
0.38
0.39
0.4
0.41
0.42
0.43
0.44
0.45
Λ (GeV)

$$\Lambda^0 \rightarrow n + \pi^0$$



$\Lambda \to p\pi^-$

SD contibutions to the amplitudes A and B of the decay $\Lambda \to p\pi^-$ in units of GeV^2.

	Ia	IIa	IIb	III	Sum(SD)
$A_{\rm SD}$	$-0.372 \cdot 10^{-1}$	$0.269 \cdot 10^{-3}$	$0.300 \cdot 10^{-1}$	$0.213 \cdot 10^{-1}$	$0.144 \cdot 10^{-1}$
$B_{\rm SD}$	-0.345	-0.116	0.167	-0.452	-0.746

LD contibutions to the amplitudes A and B of the decay $\Lambda \to p\pi^-$ in units of GeV^2.

	n	Σ^+	K	K^*	$\frac{1}{2}^-$	Sum(LD)
$A_{\rm LD}$	$-2.1 \cdot 10^{-3}$	$-9.5 \cdot 10^{-3}$	0	$2.6 \cdot 10^{-2}$	$0.9 \cdot 10^{-1}$	$1.1 \cdot 10^{-1}$
$B_{\rm LD}$	-2.55	$2.3 \cdot 10^{-1}$	$2.8 \cdot 10^{-2}$	0	0	-2.3

$\Lambda \to n\pi^0$

SD contibutions to the amplitudes A and B of the decay $\Lambda \to n\pi^0$ in units of GeV^2.

	Ib	IIa	IIb	III	Sum(SD)
$A_{\rm SD}$	$-0.120 \cdot 10^{-1}$	$0.190 \cdot 10^{-3}$	$0.211 \cdot 10^{-1}$	$0.150 \cdot 10^{-1}$	$0.243 \cdot 10^{-1}$
$B_{\rm SD}$	-0.112	$-0.82 \cdot 10^{-1}$	0.119	-0.319	-0.394

LD contibutions to the amplitudes A and B of the decay $\Lambda \to n\pi^0$ in units of GeV^2.

	n	Σ^0	K	K^*	$\frac{1}{2}^-$	Sum
$A_{\rm LD}$	$-1.5 \cdot 10^{-3}$	$-6.6 \cdot 10^{-3}$	0	$8.4 \cdot 10^{-3}$	$6.2 \cdot 10^{-2}$	$0.6 \cdot 10^{-1}$
$B_{\rm LD}$	-1.83	$1.6 \cdot 10^{-1}$	$0.9 \cdot 10^{-2}$	0	0	-1.67

Asymmetry in Λ decays

• $\alpha = 0.87 \pm 0.09$	**CCQM**
• $\alpha = 0.642 \pm 0.013$	**Particle Data Group 2016.**
• $\alpha = 0.750 \pm 0.009 \pm 0.004$	**BESIII Collab. 1808.08917.**
• $\alpha = 0.7542 \pm 0.0010 \pm 0.0020$	**BESIII Collab. 2204.11058.**

Thanks a lot for your attention