Light-cone distribution amplitudes of the baryon octet

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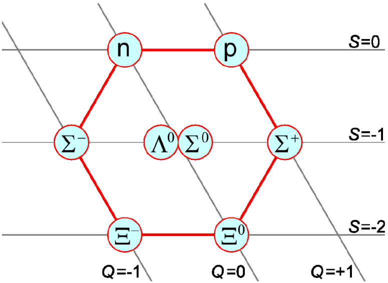
Outline

In a nutshell: The baryon octet

- 3 quark flavors: up, down, strange: $3 \otimes 3 \otimes 3 = 10 \oplus 8 \oplus 8 \oplus 1$
- $\psi = \phi_{\text{flavour}} \, \chi_{\text{spin}} \, \xi_{\text{colour}} \, \eta_{\text{space}}$



Motivation: Why are baryon DAs interesting?

- What are Distribution Amplitudes (DAs)?
- Full baryonic wave functions very complex ⇒ reduce complexity by introducing DAs

Bethe-Salpeter wave function

$$\Psi_{BS}(x, k_\perp) = \langle 0 | \epsilon^{ijk} f^i(x_1, k_{1\perp}) g^j(x_2, k_{2\perp}) h^k(x_3, k_{3\perp}) | B \rangle$$

$$\Phi(x, \mu) = Z(\mu) \int\limits_{|k_\perp| \leq \mu} [d^2 k_\perp] \; \Psi_{BS}(x, k_\perp)$$

- Three-quark DAs contain information about the momentum distribution of valence quarks at small transverse separations

Matrix element decomposition

- Leading twist decomposition of the nucleon-to-vacuum matrix element

$$
\begin{aligned}
&4\langle 0|u_\alpha(a_1 n)u_\beta(a_2 n)d_\gamma(a_3 n)|N(p,\lambda)\rangle \\
&= \int [dx] e^{-i\, n\cdot p \sum_i a_i x_i} \Big[V^N(x_i)(\tilde{\not{n}} C)_{\alpha\beta}(\gamma_5 u_N^+(p,\lambda))_\gamma + A^N(x_i)(\tilde{\not{n}}\gamma_5 C)_{\alpha\beta}(u_N^+(p,\lambda))_\gamma \\
&\qquad + T^N(x_i)(i\sigma_{\perp\tilde{n}} C)_{\alpha\beta}(\gamma^\perp\gamma_5 u_N^+(p,\lambda))_\gamma + \ldots \Big]
\end{aligned}
$$

- "..." contain 21 DAs of higher twist
- One independent leading twist distribution amplitude

$$\Phi^N(x_1,x_2,x_3) = V^N(x_1,x_2,x_3) - A^N(x_1,x_2,x_3)$$

- Due to isopsin symmetry

$$2\,T^N(x_1,x_3,x_2) = \Phi^N(x_1,x_2,x_3) + \Phi^N(x_3,x_2,x_1)$$

Nucleon wave function

- Consider the three-quark Fock state in the infinite momentum frame
- At leading twist with transverse momentum components integrated out the nucleon wave function can be written as

$$
\begin{aligned}
|N^{\uparrow}\rangle &= \int \frac{[dx]}{8\sqrt{6x_1x_2x_3}} |uud\rangle \otimes \Big\{ [V+A]^N(x_1,x_2,x_3)|{\downarrow}{\uparrow}{\uparrow}\rangle + [V-A]^N(x_1,x_2,x_3)|{\uparrow}{\downarrow}{\uparrow}\rangle \\
&\qquad -2\,T^N(x_1,x_2,x_3)|{\uparrow}{\uparrow}{\downarrow}\rangle \Big\} \\
&= \int \frac{[dx]}{8\sqrt{3x_1x_2x_3}} |{\uparrow}{\uparrow}{\downarrow}\rangle \otimes \Big\{ -\sqrt{3}\Phi_+^N(x_1,x_3,x_2)|\mathsf{MS}, N\rangle + \Phi_-^N(x_1,x_3,x_2)|\mathsf{MA}, N\rangle \Big\}
\end{aligned}
$$

Nucleon wave function

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- At leading twist with transverse momentum components integrated out the nucleon wave function can be written as

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- Mixed symmetric and mixed antisymmetric flavor wave function

$$|\mathsf{MS},N\rangle = (2|uud\rangle - |udu\rangle - |duu\rangle)/\sqrt{6} \qquad |\mathsf{MA},N\rangle = (|udu\rangle - |duu\rangle)/\sqrt{2}$$

- One can combine $\Phi^N = \Phi_+^N + \Phi_-^N$
- Wave function at the origin $f^N = \int [dx]\ \Phi^N(x_i)$

Definition of octet DAs (leading twist)

$$\Phi_{\pm}^{B\neq\Lambda}(x_1,x_2,x_3) = \tfrac{1}{2}\Big([V-A]^B(x_1,x_2,x_3) \pm [V-A]^B(x_3,x_2,x_1)\Big)$$
$$\Pi^{B\neq\Lambda}(x_1,x_2,x_3) = T^B(x_1,x_3,x_2)$$
$$\Phi_{+}^{\Lambda}(x_1,x_2,x_3) = +\sqrt{\tfrac{1}{6}}\Big([V-A]^\Lambda(x_1,x_2,x_3) + [V-A]^\Lambda(x_3,x_2,x_1)\Big)$$
$$\Phi_{-}^{\Lambda}(x_1,x_2,x_3) = -\sqrt{\tfrac{3}{2}}\Big([V-A]^\Lambda(x_1,x_2,x_3) - [V-A]^\Lambda(x_3,x_2,x_1)\Big)$$
$$\Pi^{\Lambda}(x_1,x_2,x_3) = \sqrt{6}\; T^\Lambda(x_1,x_3,x_2)$$

- **No mixing** under chiral extrapolation
- Good behaviour in the SU(3) symmetric limit

$$\Phi_+^\star \equiv \Phi_+^{N\star} = \Phi_+^{\Sigma\star} = \Phi_+^{\Xi\star} = \Phi_+^{\Lambda\star} = \Pi^{N\star} = \Pi^{\Sigma\star} = \Pi^{\Xi\star}$$
$$\Phi_-^\star \equiv \Phi_-^{N\star} = \Phi_-^{\Sigma\star} = \Phi_-^{\Xi\star} = \Phi_-^{\Lambda\star} = \Pi^{\Lambda\star}$$

- The Λ baryon fits in nicely

Moments $\longleftrightarrow$ matrix elements of local operators

Moments of DAs

$$V^B_{lmn} = \int [dx]\; x_1^l x_2^m x_3^n\, V^B(x_1, x_2, x_3)$$

- Unlike the full DAs the moments can be directly evaluated on the lattice
- For that purpose we define local operators such as

$$\mathcal{V}^{B,000}_{\rho} = \epsilon^{ijk}\Big(f^{Ti}(0)\, C\gamma_\rho g^j(0)\Big)\gamma_5 h^k(0)$$
$$\mathcal{V}^{B,001}_{\rho\nu} = \epsilon^{ijk}\Big(f^{Ti}(0)\, C\gamma_\rho g^j(0)\Big)\gamma_5 \Big[iD_\nu h(0)\Big]^k$$

- These operators clearly have the desired Dirac-matrix, flavor and color structure

Normalization and shape parameters

- Distribution amplitudes can be expanded in a set of orthogonal polynomials

$$\Phi_+^B = 120 x_1 x_2 x_3 \left(\varphi_{00}^B \mathcal{P}_{00} + \varphi_{11}^B \mathcal{P}_{11} + \dots \right)$$
$$\Phi_-^B = 120 x_1 x_2 x_3 \left(\varphi_{10}^B \mathcal{P}_{10} + \dots \right)$$
$$\Pi^{B\neq\Lambda} = 120 x_1 x_2 x_3 \left(\pi_{00}^B \mathcal{P}_{00} + \pi_{11}^B \mathcal{P}_{11} + \dots \right)$$
$$\Pi^{\Lambda} = 120 x_1 x_2 x_3 \left(\pi_{10}^\Lambda \mathcal{P}_{10} + \dots \right)$$

$$\mathcal{P}_{00} = 1 \qquad \mathcal{P}_{11} = 7(x_1 - 2x_2 + x_3) \qquad \mathcal{P}_{10} = 21(x_1 - x_3)$$

- Couplings and shape parameters can be reexpressed as moments of V^B, A^B and T^B

$$f^{B\neq\Lambda} = \varphi_{00}^B = V_{000}^B$$
$$f_T^{B\neq\Lambda} = \pi_{00}^B = T_{000}^B$$
$$f^{\Lambda} = \varphi_{00}^\Lambda = -\sqrt{\tfrac{2}{3}} A_{000}^\Lambda$$

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- Couplings and shape parameters can be reexpressed as moments of V^B, A^B and T^B

$$\varphi_{11}^{B\neq\Lambda} = \tfrac{1}{2}\left([V-A]_{100}^B - 2[V-A]_{010}^B + [V-A]_{001}^B\right)$$
$$\varphi_{10}^{B\neq\Lambda} = \tfrac{1}{2}\left([V-A]_{100}^B - [V-A]_{001}^B\right)$$
$$\pi_{11}^{B\neq\Lambda} = \tfrac{1}{2}\left(T_{100}^B + T_{010}^B - 2\,T_{001}^B\right)$$

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- Couplings and shape parameters can be reexpressed as moments of V^B, A^B and T^B

$$\varphi_{11}^\Lambda = \frac{1}{\sqrt{6}} \left([V-A]_{100}^\Lambda - 2[V-A]_{010}^\Lambda + [V-A]_{001}^\Lambda \right)$$
$$\varphi_{10}^\Lambda = -\sqrt{\frac{3}{2}} \left([V-A]_{100}^\Lambda - [V-A]_{001}^\Lambda \right)$$
$$\pi_{10}^\Lambda = \sqrt{\frac{3}{2}} \left(T_{100}^\Lambda - T_{010}^\Lambda \right)$$

Normalization and shape parameters

- Distribution amplitudes can be expanded in a set of orthogonal polynomials

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- The normalization can also be calculated from first moments

$$\varphi_{00,(1)}^{B\neq\Lambda} = [V-A]_{100}^B + [V-A]_{010}^B + [V-A]_{001}^B$$
$$\varphi_{00,(1)}^{\Lambda} = \sqrt{\tfrac{2}{3}}\left([V-A]_{100}^\Lambda + [V-A]_{010}^\Lambda + [V-A]_{001}^\Lambda\right)$$
$$\pi_{00,(1)}^{B\neq\Lambda} = T_{100}^B + T_{010}^B + T_{001}^B$$

Normalization and shape parameters

- Distribution amplitudes can be expanded in a set of orthogonal polynomials

$$\begin{aligned}
\Phi_+^B &= 120 x_1 x_2 x_3 \left(\varphi_{00}^B \mathcal{P}_{00} + \varphi_{11}^B \mathcal{P}_{11} + \dots\right) \\
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\Pi^{B \neq \Lambda} &= 120 x_1 x_2 x_3 \left(\pi_{00}^B \mathcal{P}_{00} + \pi_{11}^B \mathcal{P}_{11} + \dots\right) \\
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- The normalization can also be calculated from first moments

$$\begin{aligned}
\varphi_{00,(1)}^{B \neq \Lambda} &\xrightarrow{a \to 0} f^B \\
\varphi_{00,(1)}^{\Lambda} &\xrightarrow{a \to 0} f^\Lambda \\
\pi_{00,(1)}^{B \neq \Lambda} &\xrightarrow{a \to 0} f_T^B
\end{aligned}$$

Correlation functions: normalization constants

- $\gamma_+ = (\mathbb{1} + k\gamma_4)/2$ with $k = m_{B^*}/E_{B^*}$

$$
\begin{aligned}
C_{\mathcal{N}} &= \langle \mathcal{N}^B_\tau(t,\mathbf{p}) \bar{\mathcal{N}}^B_{\tau'}(0,\mathbf{p}) (\gamma_+)_{\tau'\tau} \rangle \\
&= Z_B \frac{m_B + kE_B}{E_B} e^{-E_B t} \\
C_{\mathcal{O}} &= \langle \mathcal{O}_\tau(t,\mathbf{p}) \bar{\mathcal{N}}^B_{\tau'}(0,\mathbf{p}) \rangle \\
&= \frac{\sqrt{Z_B}}{2E_B} \sum_\lambda \langle 0 | \mathcal{O}_\tau(0) | B(\mathbf{p},\lambda) \rangle \; \bar{u}^B_{\tau'}(\mathbf{p},\lambda) e^{-E_B t}
\end{aligned}
$$

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\text{e.g. } C^{B,000}_{\mathcal{V},\mathfrak{B}} &= \langle \left(\gamma_4 \mathcal{O}^{B,000}_{\mathcal{V},\mathfrak{B}}(t,\mathbf{p}) \right)_\tau \bar{\mathcal{N}}^B_{\tau'}(0,\mathbf{p}) (\gamma_+)_{\tau'\tau} \rangle \\
&= V^B_{000} \sqrt{Z_B} \frac{E_B(m_B + kE_B) + kp_3^2}{E_B} e^{-E_B t}
\end{aligned}
$$

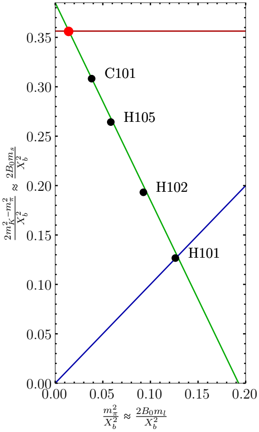
- $T^{B\neq\Lambda}_{000} \sim f^B_T$ and $V^B_{000} - A^B_{000} \sim f^B$

Correlation functions: first moments

$$
\begin{aligned}
C^{B,lmn}_{\mathcal{X},\mathfrak{A},1} &= \langle \left(\gamma_4\gamma_1\mathcal{O}^{B,lmn}_{\mathcal{X},\mathfrak{A}}(t,\mathbf{p})\right)_\tau \bar{\mathcal{N}}^{B}_{\tau'}(0,\mathbf{p})(\gamma_+)_{\tau'\tau}\rangle \\
&= -c_X X^B_{lmn}\sqrt{Z_B}p_1\frac{E_B(m_B+kE_B)+k(2p_2^2-p_3^2)}{E_B}e^{-E_Bt} \\
C^{B,lmn}_{\mathcal{X},\mathfrak{B},2} &= \langle \left(\gamma_4\gamma_2\mathcal{O}^{B,lmn}_{\mathcal{X},\mathfrak{B}}(t,\mathbf{p})\right)_\tau \bar{\mathcal{N}}^{B}_{\tau'}(0,\mathbf{p})(\gamma_+)_{\tau'\tau}\rangle \\
&= +c_X X^B_{lmn}\sqrt{Z_B}p_2\frac{E_B(m_B+kE_B)+kp_3^2}{E_B}e^{-E_Bt} \\
C^{B,lmn}_{\mathcal{X},\mathfrak{C},3} &= \langle \left(\gamma_4\gamma_3\mathcal{O}^{B,lmn}_{\mathcal{X},\mathfrak{C}}(t,\mathbf{p})\right)_\tau \bar{\mathcal{N}}^{B}_{\tau'}(0,\mathbf{p})(\gamma_+)_{\tau'\tau}\rangle \\
&= +c_X X^B_{lmn}\sqrt{Z_B}p_3\frac{k(p_1^2-p_2^2)}{E_B}e^{-E_Bt}
\end{aligned}
$$

- $l+m+n=1$
- $\mathcal{X}$ can be $\mathcal{V}$, $\mathcal{A}$ or $\mathcal{T}$ with $c_V=c_A=1$ and $c_T=-2$

Simulation details



id	β	N_s	N_t	κ_u	κ_s	m_π [MeV]	m_K [MeV]	$m_\pi L$	#conf.
H101	3.40	32	96	0.13675962	0.13675962	421	421	5.8	2000
H102	3.40	32	96	0.136865	0.136549339	355	442	4.9	1997
H105	3.40	32	96	0.136970	0.136340790	281	466	3.9	2833
C101	3.40	48	96	0.137030	0.136222041	223	476	4.6	1552

- CLS $N_f = 2 + 1$
- Open boundary conditions in time direction
- Twisted-mass determinant reweighting
- Consistency check at the flavor symmetric point
- Source positions $t_\mathsf{src} = 30$, 47 and 65

Extrapolation formulas and SU(3) breaking

$$\Phi_\pm^B = g_{\Phi\pm}^B(\delta m)\left(\Phi_\pm^\star + \delta m \; \Delta\Phi_\pm^B\right)$$

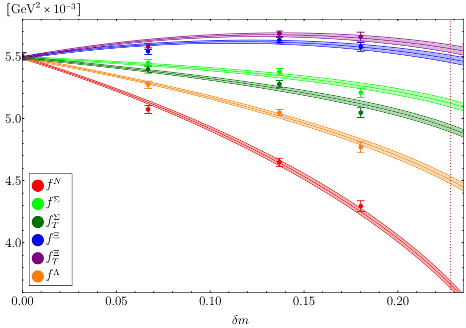
$$\Pi^B = g_\Pi^B(\delta m) \times \begin{cases} \Phi_+^\star + \delta m \; \Delta\Pi^B & \text{, if } B \neq \Lambda \\ \Phi_-^\star + \delta m \; \Delta\Pi^B & \text{, if } B = \Lambda \end{cases}$$

$$\delta m = \frac{4(m_K^2 - m_\pi^2)}{3X_b^2} \propto m_s - m_l$$

$\rightarrow$ all results: **JHEP 1505 (2015) 073**

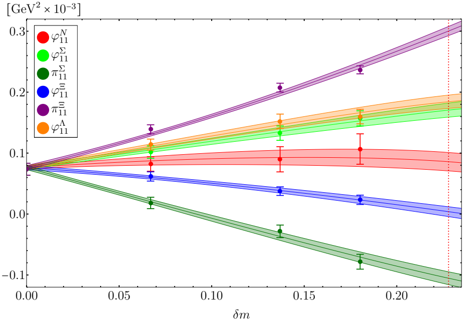
- Formulas for appropriately defined higher twist DAs have similar form
- Complete non-analytic structure is contained in prefactors
- The prefactors are defined such that $g_{\text{DA}}^B(0) = 1$

Chiral extrapolation: f^B and f_T^Σ, f_T^Ξ



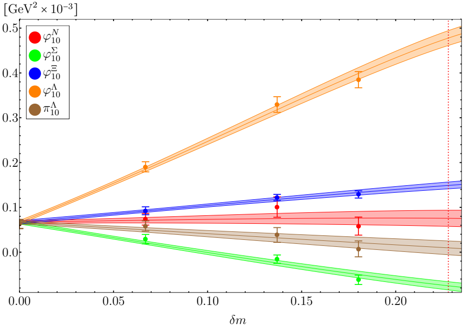
- 7 parameter ChPT-fit
- $f^\star = f^{N\star} = f^{\Sigma\star} = f^{\Xi\star} = f^{\Lambda\star} = f_T^{\Sigma\star} = f_T^{\Xi\star}$ is fulfilled exactly
- SU(3) breaking $\sim 50\%$: $f_T^\Xi \approx 1.5 f^N$

Chiral extrapolation: first moments φ_{11}^{B} and π_{11}^{Σ}, π_{11}^{Ξ}



- 7 parameter ChPT-fit
- $\varphi_{11}^{\star} = \varphi_{11}^{N\star} = \varphi_{11}^{\Sigma\star} = \varphi_{11}^{\Xi\star} = \varphi_{11}^{\Lambda\star} = \pi_{11}^{\Sigma\star} = \pi_{11}^{\Xi\star}$ is fulfilled exactly
- Very large SU(3) breaking $\sim 200\%$: $\pi_{11}^{\Xi} \approx 3\varphi_{11}^{N}$
- The moment π_{11}^{Σ} changes its sign!

Chiral extrapolation: first moments φ_{10}^{B} and π_{10}^{Λ}



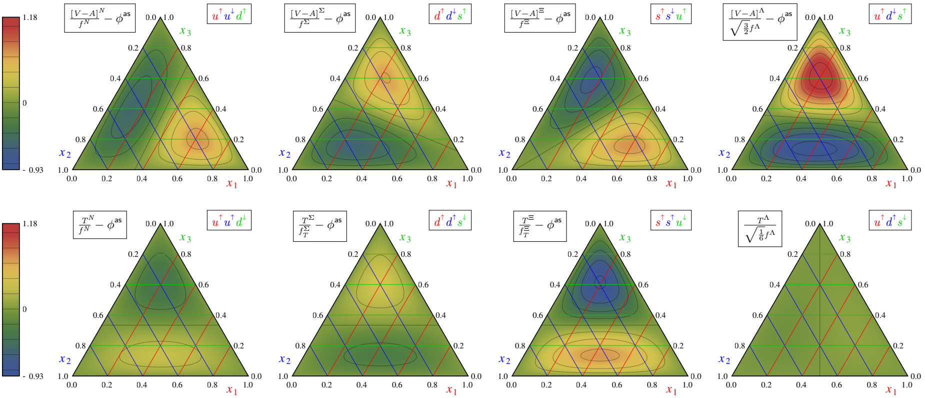
- 6 parameter ChPT-fit
- $\varphi_{10}^{\star} = \varphi_{10}^{N\star} = \varphi_{10}^{\Sigma\star} = \varphi_{10}^{\Xi\star} = \varphi_{10}^{\Lambda\star} = \pi_{10}^{\Lambda\star}$ is fulfilled exactly
- Very large SU(3) breaking $\sim 500\%$: $\varphi_{10}^{\Lambda} \approx 6\varphi_{10}^{N}$
- The moment φ_{10}^{Σ} changes its sign!

Comparison

B	method	$f^B \times 10^3$	$f_T^B \times 10^3$	$\varphi_{11}^B \times 10^3$	$\pi_{11}^B \times 10^3$	$\varphi_{10}^B \times 10^3$	$\pi_{10}^B \times 10^3$
N	$N_f = 2+1$	3.66	3.66	0.09	0.09	0.076	—
	$N_f = 2$	2.84	2.84	0.085	0.085	0.082	—
	COZ	4.60	4.60	0.886	0.886	0.748	—
Σ	$N_f = 2+1$	5.12	4.92	0.17	−0.11	−0.075	—
	COZ	4.70	4.51	1.11	0.511	0.523	—
Ξ	$N_f = 2+1$	5.48	5.56	0.004	0.30	0.15	—
	COZ	4.88	4.97	0.685	1.10	0.883	—
Λ	$N_f = 2+1$	4.51	—	0.18	—	0.48	0.01
	COZ	4.74	—	1.05	—	1.39	1.32

- Results for the nucleon are consistent with our previous $N_f = 2$ analysis (Schiel et al.)
- Note that f^N of the $N_f = 2$ analysis is continuum extrapolated
- Shape parameters are an order of magnitude smaller than predicted by QCDSR (COZ)
- However: the relative SU(3) breaking is even larger than in COZ

Barycentric plots



- Deviations of $[V-A]^B$ (top) and T^B (bottom) from asymptotic shape
- From left to right the plots show the baryons N, Σ, Ξ, Λ
- $B \neq \Lambda$: shift towards strange quarks and towards the leading quark
- T^Λ: asymptotic limit vanishes by construction; also deviations are very small

Summary and outlook

- First ab initio lattice QCD calculation of normalization constants and first moments of the leading twist distribution amplitudes of the full baryon octet
- (All Higher twist normalization constants have been evaluated as well)
- Extrapolation to the physical point using three-flavor BChPT formulas
- We find significant SU(3) flavor breaking effects
- Future studies have to include much smaller lattice spacings to control the systematic uncertainties

Octet baryon wave functions

- Since $\mathrm{SU}(3)$ symmetry is broken Π^B is now an independent DA
- Totally symmetric (decuplet-like) and antisymmetric (singlet-like) flavor functions appear in the helicity ordered octet baryon wave functions

$$
\begin{aligned}
|(B \neq \Lambda)^{\uparrow}\rangle = \int \frac{[dx]}{8\sqrt{3x_1x_2x_3}} |{\uparrow\uparrow\downarrow}\rangle \otimes \Big\{ & -\sqrt{3}\Phi_+^B(x_1,x_3,x_2)\big(|\mathsf{MS}, B\rangle - \sqrt{2}|\mathsf{S}, B\rangle\big)/3 \\
& -\sqrt{3}\Pi^B(x_1,x_3,x_2)\big(2|\mathsf{MS}, B\rangle + \sqrt{2}|\mathsf{S}, B\rangle\big)/3 \\
& + \Phi_-^B(x_1,x_3,x_2)|\mathsf{MA}, B\rangle \Big\} \\
|\Lambda^{\uparrow}\rangle = \int \frac{[dx]}{8\sqrt{3x_1x_2x_3}} |{\uparrow\uparrow\downarrow}\rangle \otimes \Big\{ & -\sqrt{3}\Phi_+^\Lambda(x_1,x_3,x_2)|\mathsf{MS}, \Lambda\rangle \\
& + \Pi^\Lambda(x_1,x_3,x_2)\big(2|\mathsf{MA}, \Lambda\rangle - \sqrt{2}|\mathsf{A}, \Lambda\rangle\big)/3 \\
& + \Phi_-^\Lambda(x_1,x_3,x_2)\big(|\mathsf{MA}, \Lambda\rangle + \sqrt{2}|\mathsf{A}, \Lambda\rangle\big)/3 \Big\}
\end{aligned}
$$