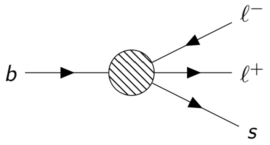
Study of $\Lambda_b \to \Lambda^*(\to KN)\ell^+\ell^-$ decay

Martín Novoa Brunet, Sébastien Descotes-Genon

Laboratoire de Physique Théorique (UMR8627), CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

November 6, 2018

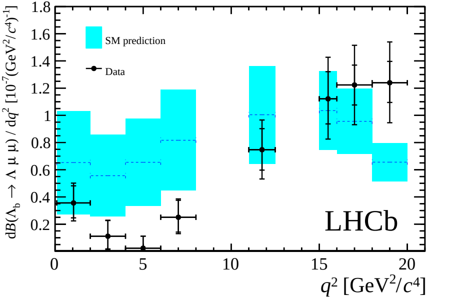
$b \to s\ell^+\ell^-$ transition



- Studies have shown a consistent pattern of deviations from the SM
- Several studies have been done for this transition on the meson side.

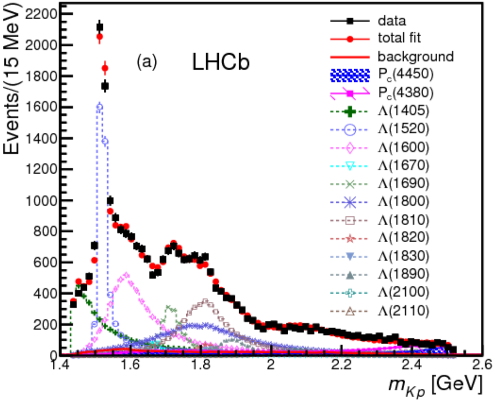
LHCb also able to test Λ_b decays, in particular $\Lambda_b \to \Lambda\mu\mu$

- $\Lambda(1115)$ is the simplest baryonic decay to include $b \to s\ell^+\ell^-$ transition
- $J^P = 1/2^+$
- Decays mainly into $N\pi$ through weak interaction



[1503.07138]

Why not try to test for other baryonic decays ?



[1507.03414]

- $\Lambda^*(1520)$ is dominant at $q^2_{\ell\ell} = m^2_{J/\Psi}$ according to LHCb study on $\Lambda_b \to J/\Psi(\to \mu\mu)Kp$
- $J^P = 3/2^-$
- We will consider the decay into $\bar{K}N$ through strong interaction (which is the most accessible experimentally)

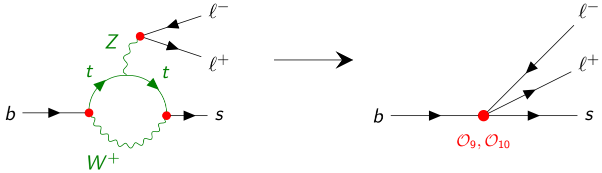
$b \to s\ell^+\ell^-$: Effective Hamiltonian

Local operator effective theory for $b \to s$ transitions. Non-local high energy processes are reduce to local operators as in Fermi Theory.

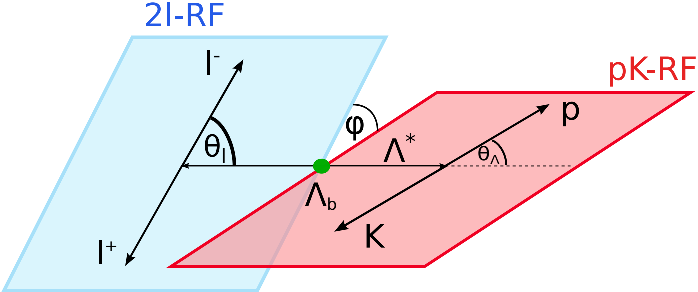
$$\mathcal{H}_{\text{eff}}(b \to s\ell^+\ell^-) = -\frac{4G_F}{\sqrt{2}} V_{tb} V_{ts}^* \sum_i \mathcal{C}_i \mathcal{O}_i$$

$$\mathcal{O}_7 = \frac{e}{g^2} m_b (\bar{s}\sigma_{\mu\nu} P_R b) F^{\mu\nu} \quad \mathcal{O}_9 = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \ell) \quad \mathcal{O}_{10} = \frac{e^2}{g^2} (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

- Wilson coefficients ($\mathcal{C}_i$) contain short distance dynamics.
- They are accurately computed in SM and would deviate in presence of NP.
- For our analysis we will allow NP in $\mathcal{O}_7, \mathcal{O}_9, \mathcal{O}_{10}$ and chirally flipped operators



Kinematics of $\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-$

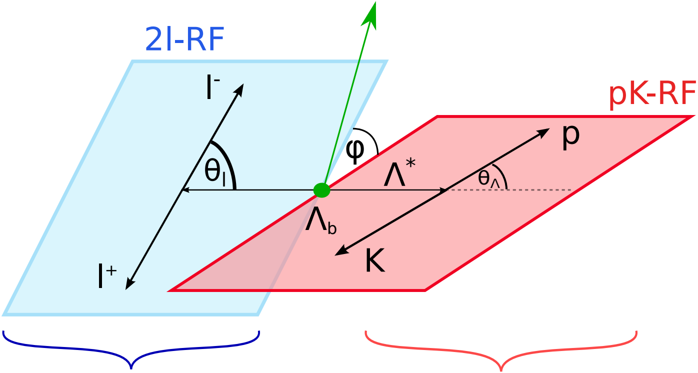


$$\Lambda_b(p, s_\Lambda) \to \Lambda^*(k, s_{\Lambda^*})[\to K(k_1)p(k_2, s_p)]\ell^+(q_1)\ell^-(q_2)$$

$$q \equiv q_1 + q_2 = p - k$$

Kinematics of $\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-$

Effective Hamiltonian Formalism
Helicity Amplitudes
Hadronic Amplitudes and Form Factors



Explicit spin 1/2 solutions
Helicity Amplitudes

Propagation of Spin 3/2 Particle
Breitt Wigner + Narrow Width
Interaction of Spin 3/2 with Kp

Outline of the calculations

We separate the decay into differents steps

$$\mathcal{M}(\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-) = \langle \Lambda^*(\to Kp)\ell^+\ell^- | \mathcal{H}_{int} | \Lambda_b \rangle$$
$$= \sum_{s_{\Lambda^*}} \frac{\langle Kp | \mathcal{H}_{int}^{3/2} | \Lambda^*(s_{\Lambda^*}) \rangle \langle \Lambda^*(s_{\Lambda^*}) \ell^+\ell^- | \mathcal{H}_{eff} | \Lambda_b \rangle}{k^2 - m_{\Lambda^*}^2 + i m_{\Lambda^*} \Gamma_{\Lambda^*}}$$

- Step 1: Separation of hadronic and leptonic parts using the helicity amplitude approach
- Step 2: Expression of $\Lambda_b \to \Lambda^*$ transition in terms of form factors
- Step 3: Propagation of the Λ^* and Breitt Wigner + Narrow Width Approximation

$$\frac{1}{\left| k^2 - m_{\Lambda^*}^2 + i m_{\Lambda^*} \Gamma_{\Lambda^*} \right|^2} \to \frac{\pi}{m_{\Lambda^*} \Gamma_{\Lambda^*}} \delta(k^2 - m_{\Lambda^*}^2)$$

- Step 4: $\Lambda^* \to Kp$ decay (Effective Lagrangian and explicit solutions U_α for Λ^*)

Helicity Amplitudes

Separate the hadronic and leptonic parts

$$\langle \Lambda^* \ell^+ \ell^- | \mathcal{H}_{eff} | \Lambda_b \rangle = \sum_{X=V,A,T,T5} \mathcal{C}_X H^X [\bar{u}_{\ell^-} J^X v_{\ell^+}]$$

The helicity amplitude approach is particularly convenient in this case (Lorentz invariance, physical interpretation in chain decays)

$$\begin{aligned}
&H_m^V(s_{\Lambda_b}, s_{\Lambda^*}) \equiv \varepsilon_\mu^*(m) \langle \Lambda^*(k, s_{\Lambda^*}) | \bar{s}\gamma^\mu b | \Lambda_b(p, s_{\Lambda_b}) \rangle \\
&L_m^V(s_{\ell^+}, s_{\ell^-}) \equiv \varepsilon_\mu(m) \bar{v}_{\ell^-} \gamma^\mu u_{\ell^+} \qquad\qquad m \in \{0, +, -, t\} \\
&\langle \Lambda^* \ell^- \ell^+ | \bar{\ell}\gamma_\mu \ell \bar{s}\gamma^\mu b | \Lambda_b \rangle = \sum_m L_m^V(s_{\ell^+}, s_{\ell^-}) H_m^V(s_{\Lambda_b}, s_{\Lambda^*})
\end{aligned}$$

They are frame independent, thus we can obtain the hadronic and leptonic amplitudes each on the simplest frame.

Hadronic Amplitudes

- Written as a function of form factors and all the tensors available.

$$\langle \Lambda^* | \bar{s}\gamma^\mu b | \Lambda_b \rangle = \bar{U}_\alpha(k, s_{\Lambda^*}) \Big\{ p^\alpha \Big[F_1 p^\mu + F_2 k^\mu + F_3 \gamma^\mu \Big] + F_4 g^{\alpha\mu} \Big\} u(p, s_{\Lambda_b})$$

$$\begin{aligned}\langle \Lambda^* | \bar{s}\gamma^\mu b | \Lambda_b \rangle =& \bar{U}_\alpha(k, s_{\Lambda^*}) \Big\{ p^\alpha \Big[f_t^V(q^2)(M_{\Lambda_b} - m_{\Lambda^*}) \frac{q^\mu}{q^2} \\ &+ f_0^V(q^2) \frac{M_{\Lambda_b} + m_{\Lambda^*}}{s_+} (p^\mu + k^\mu - \frac{q^\mu}{q^2}(M_{\Lambda_b}^2 - m_{\Lambda^*}^2)) \\ &+ f_\perp^V(q^2)(\gamma^\mu - 2\frac{m_{\Lambda^*}}{s_+} p^\mu - 2\frac{M_{\Lambda_b}}{s_+} k^\mu) \Big] \\ &+ f_g^V(q^2) \Big[g^{\alpha\mu} - p^\alpha \frac{q^\mu}{q^2} - C p^\alpha (p^\mu + k^\mu - \frac{q^\mu}{q^2}(M_{\Lambda_b}^2 - m_{\Lambda^*}^2)) \Big] \Big\} u(p, s_{\Lambda_b})\end{aligned}$$

- Form factors are generally determined via non perturbative QCD (Lattice QCD, Sum Rules)

- Only preliminary results on the form factors for $\Lambda_b \to \Lambda^* \ell^+ \ell^-$ are available from lattice simulations [1608.08110] so we use a quark model from [1108.6129] to test our results

Transversity Amplitudes

Combining all the elements together, the primary decay $\Lambda_b \to \Lambda^* \ell^+ \ell^-$ is described by 12 transversity amplitudes

$$TA = \left\{ B^{L(R)}_{\perp 1}, B^{L(R)}_{\| 1}, A^{L(R)}_{\perp 1}, A^{L(R)}_{\| 1}, A^{L(R)}_{\perp 0}\ A^{L(R)}_{\| 0} \right\}$$

$$B^{L(R)}_{\perp 1} \propto \left(\mathcal{C}^{L(R)}_{9,10,+} H^V_+(-1/2,-3/2) - \frac{2m_b(\mathcal{C}_7 + \mathcal{C}_{7'})}{q^2} H^T_+(-1/2,-3/2) \right)$$

$$A^{L(R)}_{\| 0} \propto \left(\mathcal{C}^{L(R)}_{9,10,-} H^A_0(+1/2,+1/2) + \frac{2m_b(\mathcal{C}_7 - \mathcal{C}_{7'})}{q^2} H^{T5}_0(+1/2,+1/2) \right)$$

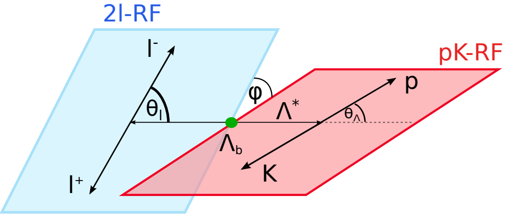
$$\vdots$$

$$\mathcal{C}^{L(R)}_{9,10,+} = (\mathcal{C}_9 \mp \mathcal{C}_{10}) + (\mathcal{C}_{9'} \mp \mathcal{C}_{10'}) \qquad \mathcal{C}^{L(R)}_{9,10,-} = (\mathcal{C}_9 \mp \mathcal{C}_{10}) - (\mathcal{C}_{9'} \mp \mathcal{C}_{10'})$$

And their normalization is such that

$$\frac{d\Gamma(\Lambda_b \to \Lambda^* \ell^+ \ell^-)}{dq^2} = \sum_{X \in TA} |X|^2$$

Angular Observables



$$\frac{d^4\Gamma(\Lambda_b \to \Lambda^*(\to Kp)\ell^+\ell^-)}{dq^2 d\cos\theta_\ell d\cos\theta_\Lambda d\phi} = \frac{3}{8\pi} K(q^2, \theta_\ell, \theta_\Lambda, \phi)$$

$$\begin{aligned} K(q^2, \theta_\ell, \theta_\Lambda, \phi) = & \cos^2\theta_\Lambda \left(K_{1c}\cos\theta_\ell + K_{1cc}\cos^2\theta_\ell + K_{1ss}\sin^2\theta_\ell\right) \\ & + \sin^2\theta_\Lambda \left(K_{2c}\cos\theta_\ell + K_{2cc}\cos^2\theta_\ell + K_{2ss}\sin^2\theta_\ell\right) \\ & + \sin^2\theta_\Lambda \left(K_{3ss}\sin^2\theta_\ell\cos^2\phi + K_{4ss}\sin^2\theta_\ell\sin\phi\cos\phi\right) \\ & + \sin\theta_\Lambda\cos\theta_\Lambda\cos\phi(K_{5s}\sin\theta_\ell + K_{5sc}\sin\theta_\ell\cos\theta_\ell) \\ & + \sin\theta_\Lambda\cos\theta_\Lambda\sin\phi(K_{6s}\sin\theta_\ell + K_{6sc}\sin\theta_\ell\cos\theta_\ell) \end{aligned}$$

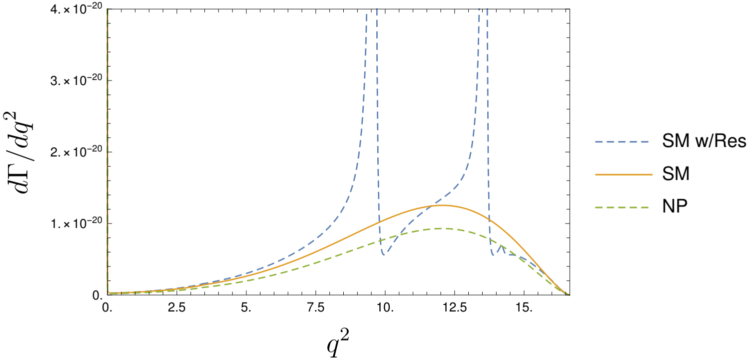
Where the K_{xx} are interferences of the transversity amplitudes.

Simple Observables

- We compare SM observables with the following NP scenario for illustration.

$$\mathcal{C}_9 = \mathcal{C}_{9SM} + \mathcal{C}_{9NP} \quad \mathcal{C}_{10} = \mathcal{C}_{10SM} + \mathcal{C}_{10NP} \quad \mathcal{C}_{9NP} = -\mathcal{C}_{10NP} = -0.62 \qquad [1704.05340]$$

- Differential decay width

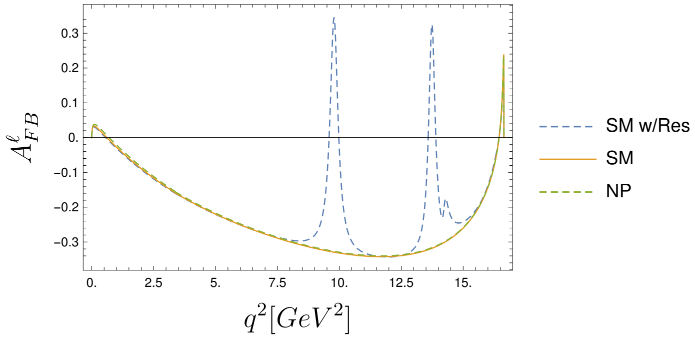


$$\frac{d\Gamma}{dq^2} = \frac{1}{3}(K_{1cc} + 2(K_{1ss} + K_{2cc} + 2K_{2ss} + K_{3ss}))$$

Simple Observables

- Forward-Backward asymmetry for the leptonic scattering angle

$$A_{FB}^{\ell} = \frac{3(K_{1c} + 2K_{2c})}{2(K_{1cc} + 2(K_{1ss} + K_{2cc} + 2K_{2ss} + K_{3ss}))}$$

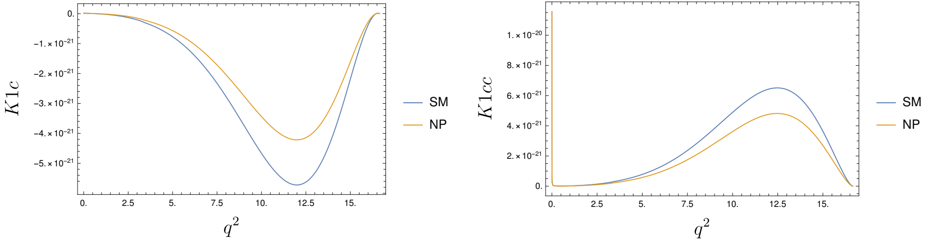


- Baryonic and combined Forward-backward asymmetry

$$A_{FB}^{\Lambda} = 0 \qquad A_{FB}^{\ell\Lambda} = 0$$

Simple Observables

- K_i observables

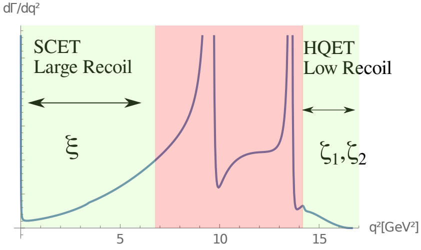


- CP-averages and CP-assymetry

$$S_i = \frac{K_i + \bar{K}_i}{d(\Gamma + \bar{\Gamma})/dq^2} \quad A_i = \frac{K_i - \bar{K}_i}{d(\Gamma + \bar{\Gamma})/dq^2}$$

Low- and large- recoil limits (HQET and SCET)

- SCET and HQET approximations reduce the number of form factors on leading order $\left(\mathcal{O}\left(\alpha_s, \frac{\Lambda_{QCD}}{m_b}\right)\right)$:



- SCET $\rightarrow$ 1 Form factor (ξ)
- HQET $\rightarrow$ 2 Form factor (ζ_1, ζ_2)

- Corrections on $\mathcal{O}(\alpha_s)$ are computable and they don't affect the amount of form factors.
- Corrections on $\mathcal{O}\left(\frac{\Lambda_{QCD}}{m_b}\right)$ will add new form factors to consider.
- These limits can be used to identify combinations of angular observables with smaller hadronic uncertanties

Conclusions

- $\Lambda_b \to \Lambda^* \ell^+ \ell^-$ is an other way to test $b \to s\ell^+\ell^-$ and exploit LHCb data
- We're still studying which observables could be of interest and trying to build more complex observables with enhanced sensitivity to NP
- We hope to stimulate the study of $\Lambda_b \to \Lambda^* \ell^+ \ell^-$ on LHCb and by Lattice QCD people
- Hoping to publish soon

Study of $\Lambda_b \to \Lambda^*(\to KN)\ell^+\ell^-$ decay

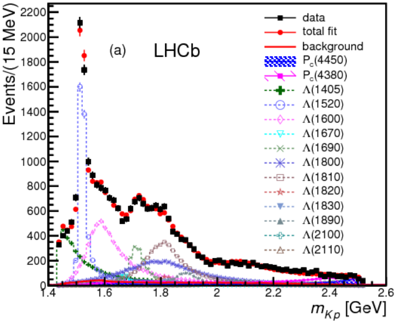
Martín Novoa Brunet, Sébastien Descotes-Genon

Laboratoire de Physique Théorique (UMR8627), CNRS, Univ. Paris-Sud, Université Paris-Saclay, 91405 Orsay, France

November 6, 2018

Back up

Separating the different $\Lambda_b \to pK\ell^+\ell^-$ signals



[1507.03414]

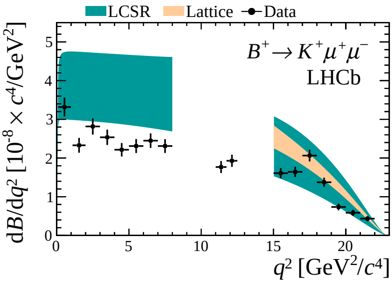
- Not trivial to compute all different contributions, we would need to compute FF for each of them (and knowing how they interfere).
- Possibility to separate the signals because of their different nature (spin).
- We can build observables that would differ strongly for spin 1/2 and 3/2 (this can be used to check the selection is correctly done)

$\Lambda(1115) \longrightarrow 1/2^+$	$\Lambda(1520) \longrightarrow 3/2^-$	$\Lambda(1670) \longrightarrow 1/2^-$
$\Lambda(1405) \longrightarrow 1/2^-$	$\Lambda(1600) \longrightarrow 1/2^+$	$\Lambda(1690) \longrightarrow 3/2^-$

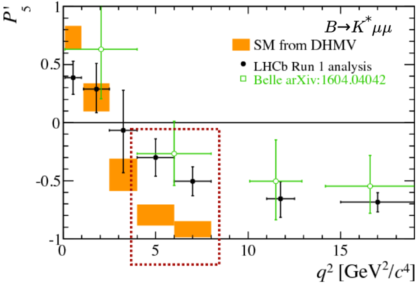
B-physics anomalies

Deviations from the SM expectations in $b \to s\ell^+\ell^-$:

- Branching ratios and angular observables in $b \to s\mu\mu$ $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$



[1403.8044]

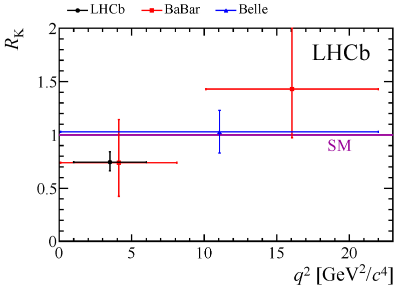


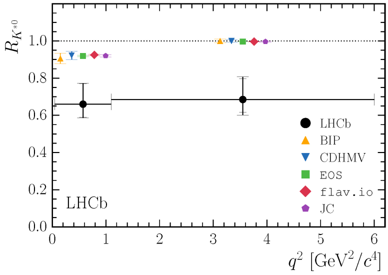
[1612.03528]

B-physics anomalies

Deviations from the SM expectations in $b \to s\ell^+\ell^-$:

- Branching ratios and angular observables in $b \to s\mu\mu$ $B \to K\mu\mu$, $B \to K^*\mu\mu$, $B_s \to \phi\mu\mu$
- Lepton-flavour universality ratio comparing $b \to s\mu\mu$ and $b \to see$ $B \to K\ell^+\ell^-$, $B \to K^*\ell^+\ell^-$





[1406.6482]

[1705.05802]

Spin 3/2 Field treatement

Rarita-Schwinger Equations

Equation for a 3/2 spin field obtained combining $1 \otimes \frac{1}{2} = \frac{3}{2} \oplus \frac{1}{2}$

$$(\Box - m^2)\Psi^\nu(x) = 0 \qquad \partial_\nu \Psi^\nu(x) = 0 \qquad (\not\partial + m)\Psi^\nu(x) = 0$$

$\gamma_\nu \Psi^\nu(x) = 0 \rightarrow$ Preserve only the 3/2 spin part

$$U^\nu_{3/2,m}(\vec{p}) = \sum_{\lambda=-1}^{1} \sum_{r=-1/2}^{1/2} \epsilon^\nu_\lambda(\vec{p}) u_r(\vec{p}) \langle 1, \lambda; \frac{1}{2}, r | \frac{3}{2}, m \rangle$$

[10.1140/epjc/s2002-01026-1]

Λ^* propagation and decay

3/2 spin Propagator

$$P_{RS}^{\alpha\beta} = \frac{\not{k} + M}{k^2 - M^2}\left(g^{\alpha\beta} - \frac{1}{3}\gamma^\alpha\gamma^\beta - \frac{2k^\alpha k^\beta}{3M^2} + \frac{\gamma^\beta k^\alpha - \gamma^\alpha k^\beta}{3M}\right)$$

[nucl-th/9812043]

$\Lambda K p$ interaction

$$\mathcal{L}_{int}^{3/2} = g\varepsilon^{\mu\nu\alpha\beta}(\partial_\mu \Psi_\nu)\gamma_\alpha \psi \partial_\beta \phi + h.c.$$

[10.1103/PhysRevD.58.096002]

- Lowest order lorentz invariant coupling for a 3/2 spin field.
- Preserves only the 3/2 spin component.
- Done in analogy with $\Delta \to \pi N$