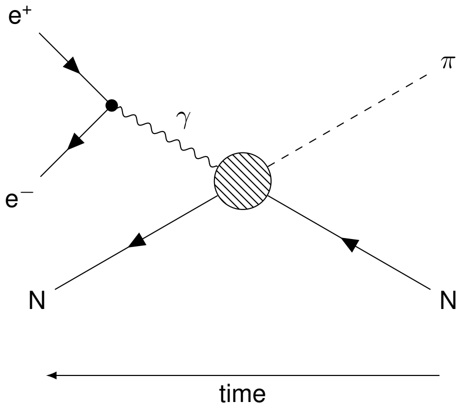
t-channel dilepton production and anisotropy in πN collisions

Hirschegg 2019



In collaboration with
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NHQ

Introduction

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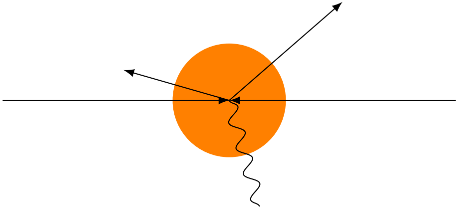
- Spin studies reveal interaction mechanisms of hadronic matter
- HADES experiment conducted studies at 1.49 GeV
- Polarisation information in dileptons
- Electromagnetic probes can escape collision volume



Introduction

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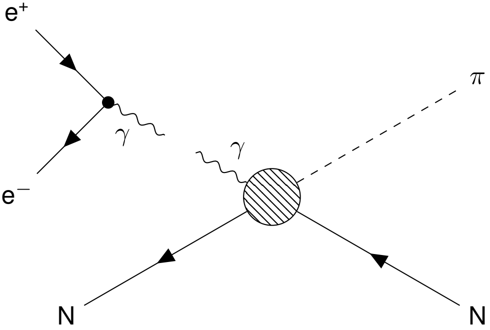
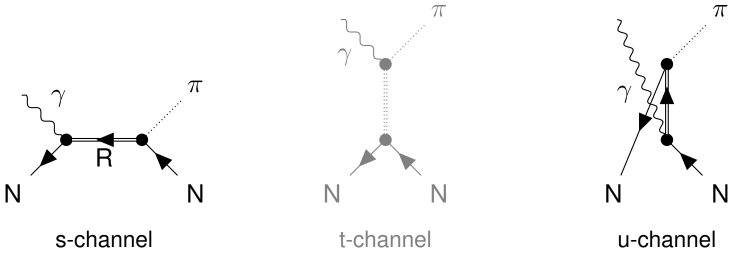
- Split the diagram into production and decay part



Introduction

- E. Speranza et al. investigated $\pi N \rightarrow Ne^+e^-$ E. Speranza, M. Zétényi, B. Friman Phys.Lett. B764 (2017)
- Introduced anisotropy coefficients
- s- and u-channel diagrams for different nucleon resonances



Introduction

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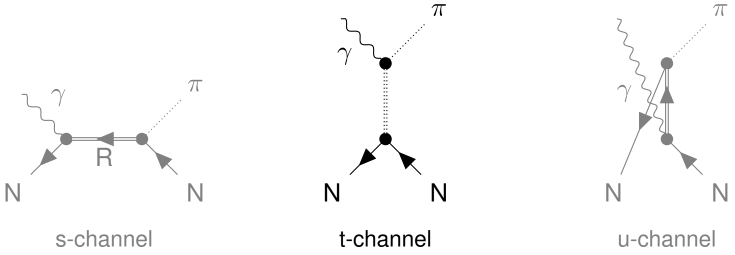
- Introduced anisotropy coefficients
- s- and u-channel diagrams for different nucleon resonances
- Goal: include t-channel



Theory - Decay Matrix

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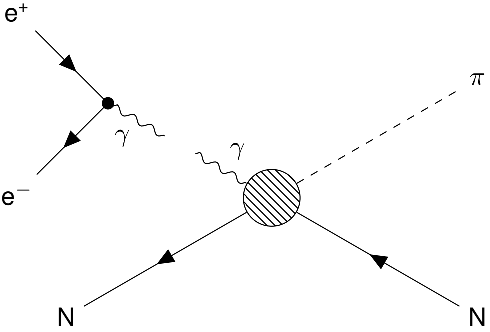
- $\mathcal{M} = \sum_{\lambda} \mathcal{M}^{\text{decay}}(\lambda)\mathcal{M}^{\text{prod}}(\lambda)$



Theory - Decay Matrix

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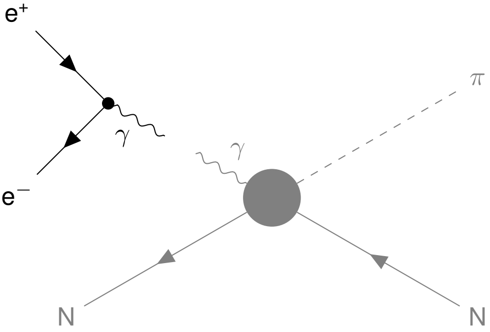
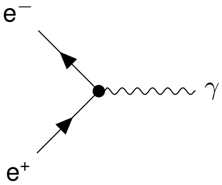
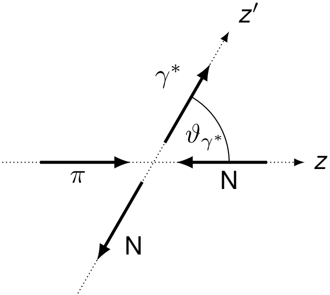


Theory - Decay Matrix



- $-i\sum_{\lambda}\mathcal{M}(\lambda) = \sum_{\lambda} -e\bar{u}\gamma^{\mu}v\epsilon_{\mu}(\lambda) = -e\mathcal{L}^{\mu}\epsilon_{\mu}(\lambda)$
- $\left|\mathcal{M}\right|^2 = \sum_{\text{pol}}\sum_{\lambda,\lambda'} e^2\mathcal{L}^{\mu}\epsilon_{\mu}(\lambda)\epsilon^{*}_{\nu}(\lambda')\mathcal{L}^{*\nu}$
- $\mathcal{L}^{\mu\nu} = \sum_{\text{pol}}\mathcal{L}^{\mu}\mathcal{L}^{*\nu}$
- $\rho^{\text{decay}}_{\lambda\lambda'} = \epsilon^{*}_{\mu}(\lambda)\mathcal{L}^{\mu\nu}\epsilon_{\nu}(\lambda')$

Theory - Kinematics



- πN CM-system

Theory - Anisotropy Coefficients

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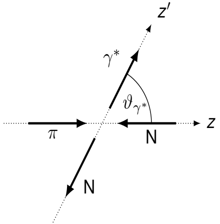
- Align z'-axis along virtual photon momentum
- Boost to γ^*-rest frame:
- $\epsilon^{\mu}(p,-1) = \frac{1}{\sqrt{2}}(0,1,-i,0)^{\mu}$
- $\epsilon^{\mu}(p,+1) = \frac{-1}{\sqrt{2}}(0,1,i,0)^{\mu}$
- $\epsilon^{\mu}(p,0) = (0,0,0,1)^{\mu}$
- Choose canonical spherical coordinates for dilepton momenta in γ^*-RF
- $p^{\pm} = q(1, \pm\sin\vartheta\cos\varphi, \pm\sin\vartheta\sin\varphi, \pm\cos\vartheta)$



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Theory - Anisotropy Coefficients

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- $\rho^{\text{decay}}_{\lambda'\lambda} = \epsilon^*_\mu(\lambda')\mathcal{L}^{\mu\nu}\epsilon_\nu(\lambda)$
- $\rho^{\text{decay}}_{\lambda'\lambda} = 4q^2 \begin{pmatrix} 1+\cos^2\vartheta & -\frac{\sqrt{2}}{2}e^{i\varphi}\sin 2\vartheta & e^{2i\varphi}\sin^2\vartheta \\ -\frac{\sqrt{2}}{2}e^{-i\varphi}\sin 2\vartheta & 2(1-\cos^2\vartheta) & \frac{\sqrt{2}}{2}e^{i\varphi}\sin 2\vartheta \\ e^{-2i\varphi}\sin^2\vartheta & \frac{\sqrt{2}}{2}e^{-i\varphi}\sin 2\vartheta & 1+cos^2\vartheta \end{pmatrix}_{\lambda'\lambda}$
- Total invariant amplitude: $|\mathcal{M}|^2 = \sum_{\lambda,\lambda'} \rho^{\text{decay}}_{\lambda',\lambda}\rho^{\text{prod}}_{\lambda,\lambda'}$
- Hadron Tensor $\mathcal{M}^{\text{prod}} = \epsilon^*_\mu\mathcal{H}^\mu$
- $\mathcal{H}^{\mu\nu} = \sum_{\text{pol}} \mathcal{H}^\mu\mathcal{H}^{*\nu}$
- $\rho^{\text{prod}}_{\lambda\lambda'} = \epsilon^*_\mu(\lambda)\mathcal{H}^{\mu\nu}\epsilon_\nu(\lambda')$

Theory - Anisotropy Coefficients

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- $|\mathcal{M}|^2 \propto \mathcal{N}\left(1 + \lambda_\vartheta \cos^2\vartheta + \lambda_\varphi \sin^2\vartheta \cos 2\varphi + \lambda_{\vartheta\varphi} \sin 2\vartheta \cos\varphi + \lambda_\varphi^\perp \sin^2\vartheta \sin 2\varphi + \lambda_{\vartheta\varphi}^\perp \sin 2\vartheta \sin\varphi\right)$
- $\lambda_\vartheta = \frac{1}{\mathcal{N}}\left(\rho^{\text{prod}}_{-1,-1} + \rho^{\text{prod}}_{+1,+1} - 2\rho^{\text{prod}}_{0,0}\right)$
- $\lambda_\varphi = 2\frac{1}{\mathcal{N}}\mathcal{Re}\left(\rho^{\text{prod}}_{-1,+1}\right)$
- $\lambda_{\vartheta\varphi} = \frac{\sqrt{2}}{\mathcal{N}}\mathcal{Re}\left(\rho^{\text{prod}}_{0,+1} - \rho^{\text{prod}}_{-1,0}\right)$
- $\lambda_\varphi^\perp = \frac{2}{\mathcal{N}}\mathcal{Im}\left(\rho^{\text{prod}}_{-1,+1}\right)$
- $\lambda_{\vartheta\varphi}^\perp = \frac{\sqrt{2}}{\mathcal{N}}\mathcal{Im}\left(\rho^{\text{prod}}_{0,+1} - \rho^{\text{prod}}_{-1,0}\right)$
- $\mathcal{N} = \rho^{\text{prod}}_{-1,-1} + \rho^{\text{prod}}_{+1,+1} + 2\rho^{\text{prod}}_{0,0}$

Theory - Anisotropy Coefficients

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Theory - Anisotropy Coefficients

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- $\lambda_\vartheta = \frac{1}{\mathcal{N}}\left(\rho^{\text{prod}}_{-1,-1} + \rho^{\text{prod}}_{+1,+1} - 2\rho^{\text{prod}}_{0,0}\right)$
- $\Sigma_\perp = \rho^{\text{prod}}_{-1,-1} + \rho^{\text{prod}}_{+1,1} \quad \Sigma_\parallel = 2\rho^{\text{prod}}_{0,0}$
- $\lambda_\vartheta = \frac{\Sigma_\perp - \Sigma_\parallel}{\Sigma_\perp + \Sigma_\parallel}$
- Interpretation of λ_ϑ:
- $\lambda_\vartheta = +1 \rightarrow$ completely transversely polarised photon
- $\lambda_\vartheta = -1 \rightarrow$ completely longitudinally polarised photon

Theory - Production Matrix

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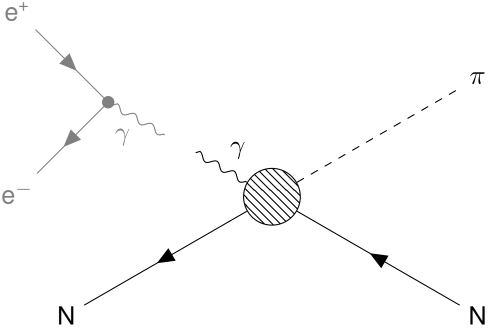
- $\mathcal{M} = \mathcal{M}^{\text{decay}} \mathcal{M}^{\text{prod}}$



Theory - Vector Meson Dominance

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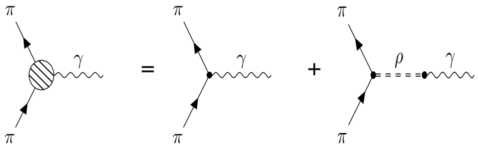
- J. J. Sakurai proposed intermediate vector mesons Ann. Phys., 11 (1960)
- $\mathcal{L}^1_{\rho\gamma\pi} = -\frac{em_\rho^2}{g_\rho}\rho^0_\mu A^\mu - g_{\rho\pi\pi}\rho^0_\mu J^\mu$

- Refined by N. M. Kroll, T. D. Lee, and B. Zumino Phys. Rev., 157 (1967)
- $\mathcal{L}^2_{\rho\gamma\pi} = -\frac{e}{2g_\rho}F^{\mu\nu}\rho^0_{\mu\nu} - g_{\rho\pi\pi}\rho^0_\mu J^\mu - eJ_\mu A^\mu$
- because in p-space $\mathcal{L}^2_{\rho\gamma} = -\frac{e}{g_\rho}p^2 A^\mu \rho_\mu$

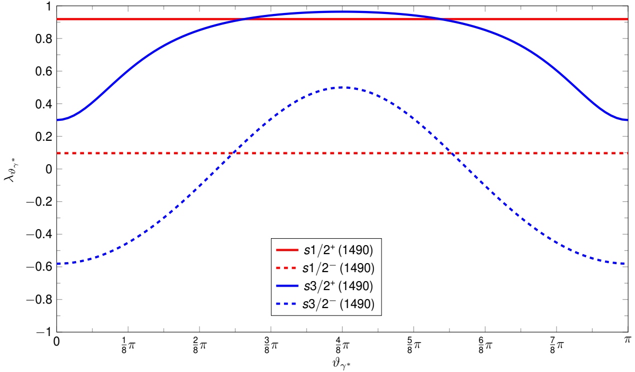


Results

- Nuclear Resonances $N^*(1440)$ and $N^*(1520)$
- t-channel: π, ρ and a_1
- $\sqrt{s} = 1.49\,\text{GeV}$
- $m_{\text{inv}} = 100...500$ MeV
- Interactions taken from M. Zétényi and G. Wolf Phys. Rev. C 86 (2012)

Results - Validation

- Reproduction of *s*- and *u*-channel resonant diagrams
- Hypothetical on-shell resonances with $m = \sqrt{s} = 1.49\,\text{GeV}$



Results - Validation

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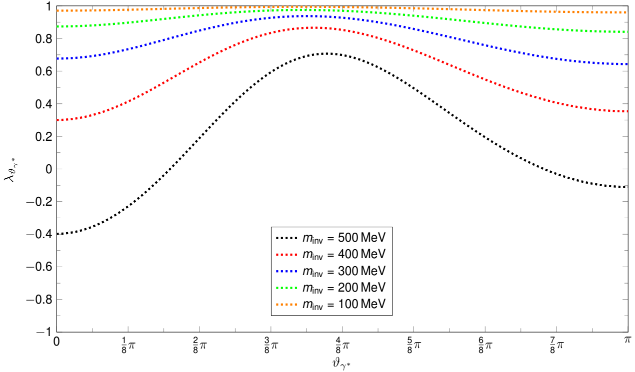
- Reproduction of *s*- and *u*-channel resonant diagrams
- Interference between dominant *N*(1440) and *N*(1520)



Results - t-Channel $m_{\text{inv}} = 500\,\text{MeV}$

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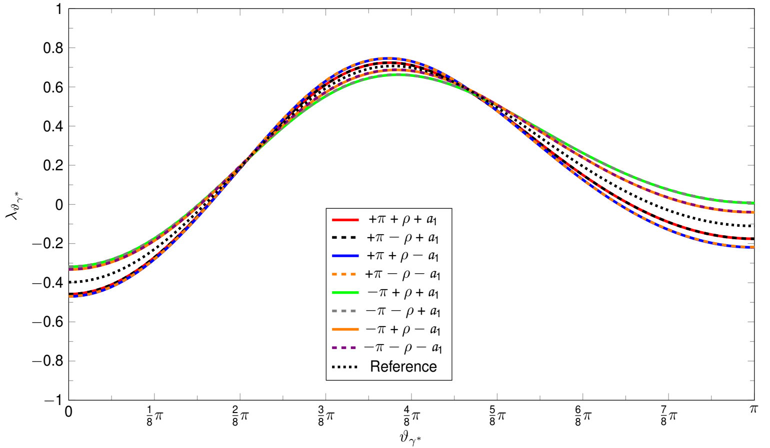

Results - t-Channel $m_{\text{inv}} = 400\,\text{MeV}$

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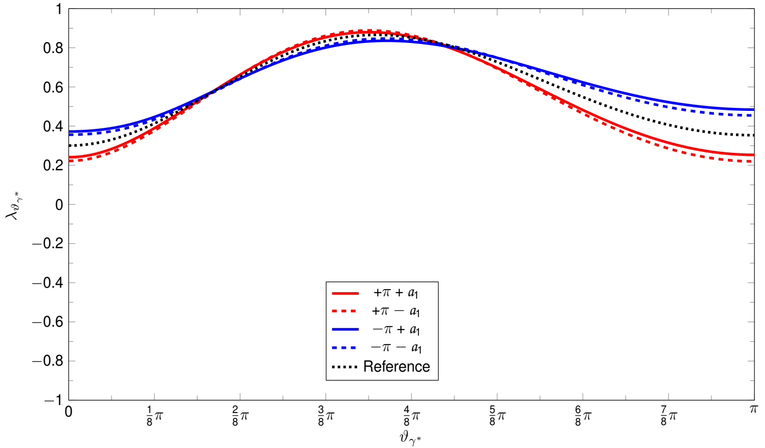
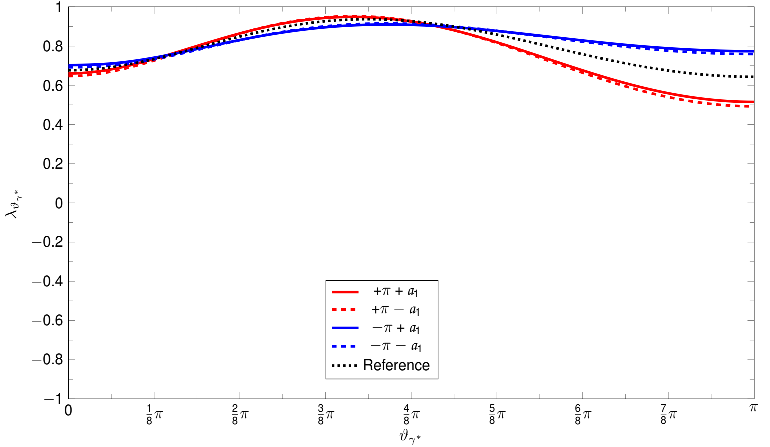


Results - t-Channel m_{inv} = 300 MeV



Results - t-Channel $m_{\text{inv}} = 200\,\text{MeV}$

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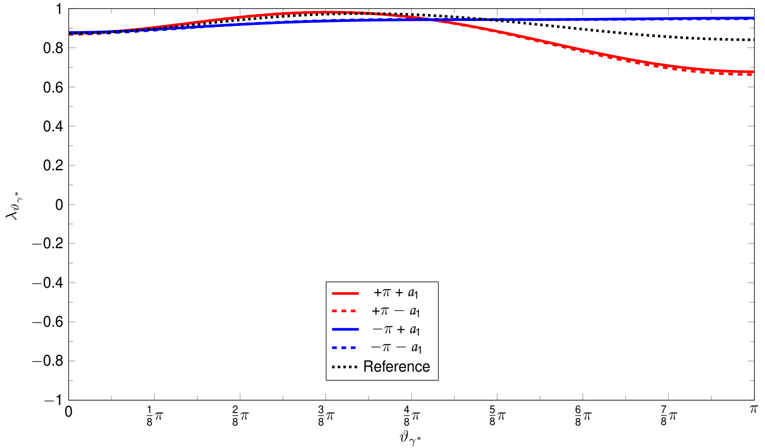

Results - t-Channel $m_{\text{inv}} = 100\,\text{MeV}$

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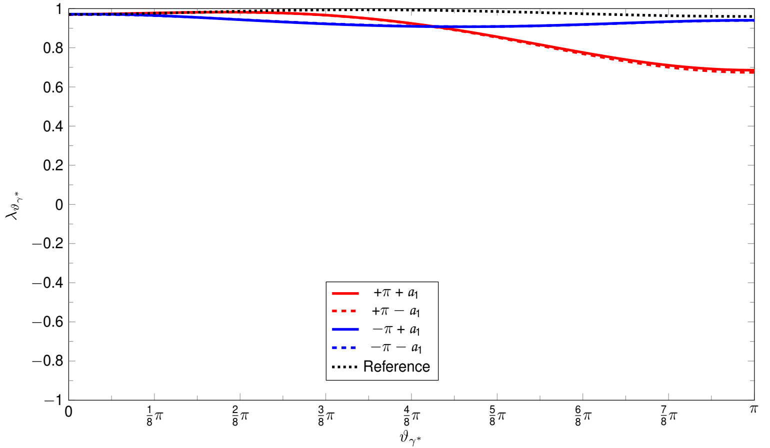

Summary / Outlook

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- Implemented the t-channel in πN $\rightarrow$ Ne^{+}e^{-}
- Main contribution in t-channel due to pions
- t-channel ρ-meson has no visible impact
- Impact of a_1-resonance diminishes with lower invariant dilepton mass

- Include non-resonant terms
- Different $\sqrt{s}$
- Heavy-ion collisions
- ω in VMD

Interactions

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- $\mathcal{L}_{\rho\mathrm{NR}_{1/2}} = \frac{g_{\rho\mathrm{NR}}}{2m_\rho}\overline{\psi}_\mathrm{R}\vec{\tau}\sigma^{\mu\nu}\tilde{\Gamma}\psi_\mathrm{N}\cdot\vec{\rho}_{\mu\nu} + \text{h.c.}$
- $\mathcal{L}_{\gamma\mathrm{NR}_{1/2}} = \frac{g_{\rho\mathrm{NR}}}{2m_\rho}\overline{\psi}_\mathrm{R}\sigma^{\mu\nu}\tilde{\Gamma}\psi_\mathrm{N}\mathcal{F}_{\mu\nu} + \text{h.c.}$
- $\mathcal{L}_{\pi\mathrm{NR}_{1/2}} = -\frac{g_{\pi\mathrm{NR}}}{m_\pi}\overline{\psi}_\mathrm{R}\Gamma\gamma^{\mu}\vec{\tau}\psi_\mathrm{N}\cdot\partial_\mu\vec{\pi} + \text{h.c.}$
- $\mathcal{L}_{\rho\mathrm{NR}_{3/2}} = -\mathrm{i}\frac{g_{\rho\mathrm{NR}}}{m_\rho}\overline{\psi}^{\mu}_\mathrm{R}\vec{\mathcal{T}}\gamma^{\nu}\tilde{\Gamma}\psi_\mathrm{N}\cdot\vec{\rho}_{\mu\nu} + \text{h.c.}$
- $\mathcal{L}_{\gamma\mathrm{NR}_{3/2}} = -\mathrm{i}\frac{g_{\rho\mathrm{NR}}}{m_\rho}\overline{\psi}^{\mu}_\mathrm{R}\gamma^{\nu}\tilde{\Gamma}\psi_\mathrm{N}\mathcal{F}_{\mu\nu} + \text{h.c.}$
- $\mathcal{L}_{\pi\mathrm{NR}_{3/2}} = \frac{g_{\pi\mathrm{NR}}}{m_\pi}\overline{\psi}^{\mu}_\mathrm{R}\Gamma\vec{\mathcal{T}}\psi_\mathrm{N}\cdot\partial_\mu\vec{\pi} + \text{h.c.}$
- $\Gamma = \gamma^5$ for resonances with $J^P \in \{1/2^+, 3/2^-\}$ and $\Gamma = 1$ otherwise, and $\tilde{\Gamma} = \gamma^5\Gamma$

Interactions

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- $\mathcal{L}_{\pi \mathrm{NN}} = -\frac{g_{\pi \mathrm{NN}}}{m_\pi} \overline{\psi}_\mathrm{N} \gamma^5 \gamma^\mu \vec{\tau} \psi_\mathrm{N} \cdot \partial_\mu \vec{\pi}$
- $\mathcal{L}_{\rho \mathrm{NN}} = \frac{g_\rho}{2} \overline{\psi}_\mathrm{N} \left(\vec{\not\rho} - \kappa_\rho \frac{\sigma_{\mu\nu}}{4 m_\mathrm{N} \vec{\rho}^{\mu\nu}} \right) \cdot \vec{\tau} \psi_\mathrm{N}$
- $\mathcal{L}_{a_1 \mathrm{NN}} = g_{a_1 \mathrm{NN}} \overline{\psi}_\mathrm{N} \gamma^\mu \gamma^5 \vec{\tau} \psi_\mathrm{N} \vec{a_1}_\mu$
- $\mathcal{L}_{\pi\pi\rho} = -g_{\pi\pi\rho} [(\partial^\mu \vec{\pi}) \times \vec{\pi}] \vec{\rho}_\mu$
- $\mathcal{L}_{\pi\pi\gamma} = -e A_\mu J^\mu_\pi$
- $\mathcal{L}_{\rho\pi\gamma} = e \frac{g_{\pi\rho\gamma}}{4 m_\pi} \varepsilon_{\mu\nu\alpha\beta} \mathfrak{F}^{\mu\nu} \vec{\rho}^{\alpha\beta} \cdot \vec{\pi}$
- $\mathcal{L}_{a_1 \pi\gamma} = -\mathrm{i} e \frac{g_{a_1 \pi\gamma}}{m_\pi} \vec{a_1}_\mu \mathfrak{F}^{\mu\nu} \cdot \partial_\nu \vec{\pi}$