Theory and Phenomenology of Axion-Meson Interactions

Noé Duarte González

Theory Group @ IFAE
Universitat Autònoma de Barcelona

IMPRS Recruitment Workshop. July 2025

Contents

Contents

Academic background

- BSc in Physics and BSc in Mathematics @ University of Seville (2018-2023)
    - BSc Thesis: *Shape of atomic nuclei and dynamical symmetries*

Academic background

- BSc in Physics and BSc in Mathematics @ University of Seville (2018-2023)
  - BSc Thesis: *Shape of atomic nuclei and dynamical symmetries*
- MSc in Particle Physics and Astrophysics @ University of Granada (2023-2024)
  - MSc Thesis: *Neutrino-nucleus interactions in scaling models*

Academic background

- BSc in Physics and BSc in Mathematics @ University of Seville (2018-2023)
  - BSc Thesis: *Shape of atomic nuclei and dynamical symmetries*
- MSc in Particle Physics and Astrophysics @ University of Granada (2023-2024)
  - MSc Thesis: *Neutrino-nucleus interactions in scaling models*
- Doctoral Student @ IFAE/UAB (January 2025-). FPU Fellowship
  - PhD Thesis: *Theory and Phenomenology of Axion-Meson Interactions*

Contents

Introduction

- QCD Axion: Solution to the **strong $\mathbf{CP}$ problem**:

- QCD Axion: Solution to the **strong CP problem**:

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{8\pi} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu}, \quad \overline{\theta} = \theta - \arg(\det(Y_u Y_d)) < 10^{-10}$$

Introduction

- QCD Axion: Solution to the **strong CP problem**:

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{8\pi} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu}, \quad \overline{\theta} = \theta - \arg(\det(Y_u Y_d)) < 10^{-10}$$

Peccei-Quinn mechanism

$$\mathcal{L} \supset \left(\theta - \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu}$$

Introduction

- QCD Axion: Solution to the **strong CP problem**:

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{8\pi} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu}, \quad \overline{\theta} = \theta - \arg(\det(Y_u Y_d)) < 10^{-10}$$

Peccei-Quinn mechanism

$$\mathcal{L} \supset \left(\theta - \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu}$$

- Axion-Like-Particles (ALPs): do not solve strong CP, more general pseudoscalars

Introduction

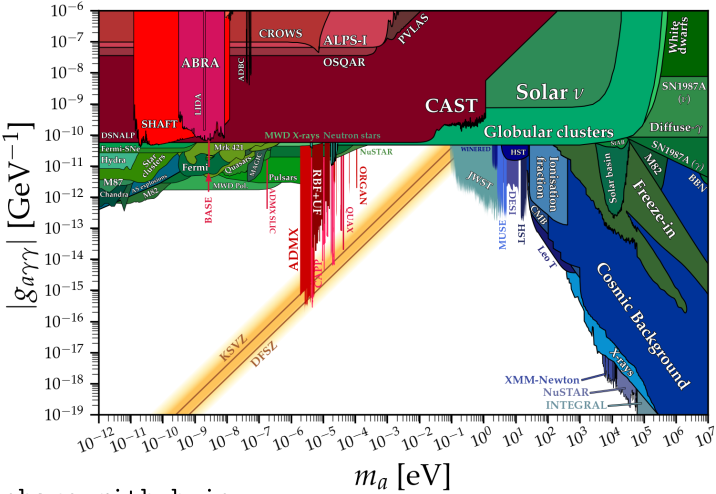
- QCD Axion: Solution to the **strong CP problem**:

$$\mathcal{L}_{QCD} \supset \theta \frac{\alpha_s}{8\pi} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu}, \quad \overline{\theta} = \theta - \arg(\det(Y_u Y_d)) < 10^{-10}$$

Peccei-Quinn mechanism

$$\mathcal{L} \supset \left(\theta - \frac{a}{f_a}\right) \frac{\alpha_s}{8\pi} G^{a,\mu\nu} \tilde{G}^a_{\mu\nu}$$

- Axion-Like-Particles (ALPs): do not solve strong CP, more general pseudoscalars
- Dark matter candidates!



cajohare.github.io

Introduction

- **Motivation**
  - Effects of ALPs in low energy QCD
  - Formalism of axion-meson interaction

- **Objectives**
  - Axio-hadronic decays: $\eta/\eta' \to \pi\pi a$
  - Study of axion-meson interactions in the early universe
    - $\pi\pi \leftrightarrow \pi a$
    - $K\pi \leftrightarrow Ka$

Contents

ALP-QCD Lagrangian

N-quark QCD Lagrangian:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^{a,\mu\nu}G^{a}_{\mu\nu} + \overline{q}(i\not{D} - \mathcal{M})q + \theta\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

$$q = (u, d, s)^T$$
$$\mathcal{M} = \text{diag}(m_q)$$

ALP-QCD Lagrangian

N-quark QCD Lagrangian:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^{a,\mu\nu}G^{a}_{\mu\nu} + \overline{q}(i\not{D} - \mathcal{M})q + \theta\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

Axion-Like-Particle (ALP) Lagrangian:

$$\mathcal{L} \supset \mathcal{L}_{QCD} - \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

ALP-QCD Lagrangian

N-quark QCD Lagrangian:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^{a,\mu\nu}G^{a}_{\mu\nu} + \overline{q}(i\not{D} - \mathcal{M})q + \theta\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

Axion-Like-Particle (ALP) Lagrangian:

$$\mathcal{L} \supset \mathcal{L}_{QCD} - \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_0^2 a^2$$

ALP-QCD Lagrangian

N-quark QCD Lagrangian:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^{a,\mu\nu}G^{a}_{\mu\nu} + \overline{q}(i\not{D} - \mathcal{M})q + \theta\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

Axion-Like-Particle (ALP) Lagrangian:

$$\mathcal{L} \supset \mathcal{L}_{QCD} - \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_0^2 a^2 - \frac{\partial^\mu a}{2f_a}\overline{q}c\gamma_\mu\gamma_5 q$$

ALP-QCD Lagrangian

N-quark QCD Lagrangian:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^{a,\mu\nu}G^{a}_{\mu\nu} + \overline{q}(i\not{D} - \mathcal{M})q + \theta\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

Axion-Like-Particle (ALP) Lagrangian:

$$\mathcal{L} \supset \mathcal{L}_{QCD} - \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_0^2 a^2 - \frac{\partial^\mu a}{2f_a}\overline{q}c\gamma_\mu\gamma_5 q$$

$$q \mapsto \exp\left(i\frac{a}{2f_a}\kappa\gamma_5\right)q$$

ALP-QCD Lagrangian

N-quark QCD Lagrangian:

$$\mathcal{L}_{QCD} = -\frac{1}{4}G^{a,\mu\nu}G^{a}_{\mu\nu} + \overline{q}(i\not{D} - \mathcal{M})q + \theta\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu}$$

Axion-Like-Particle (ALP) Lagrangian:

$$\mathcal{L} \supset \mathcal{L}_{QCD} - \frac{a}{f_a}\frac{\alpha_s}{8\pi}G^{a,\mu\nu}\tilde{G}^{a}_{\mu\nu} + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_0^2 a^2 - \frac{\partial^\mu a}{2f_a}\overline{q}c\gamma_\mu\gamma_5 q$$

Equivalent ALP Lagrangian:

$$\mathcal{L} \supset -\frac{1}{4}G^{a,\mu\nu}G^{a}_{\mu\nu} + \overline{q}(i\not{D} - \tilde{\mathcal{M}}(a))q + \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_0^2 a^2 - \frac{\partial^\mu a}{2f_a}\overline{q}\gamma_\mu\gamma_5\overline{c}q$$

Chiral Perturbation Theory

Leading order Large-N_c χPT Lagrangian:

$$\mathcal{L} \supset \frac{F^2}{4}\langle (D_\mu \mathcal{U})(D^\mu \mathcal{U})^\dagger \rangle + \frac{F^2}{4}\langle \chi \mathcal{U}^\dagger + \chi^\dagger \mathcal{U} \rangle - \frac{1}{2} M_0^2 \phi_0^2$$

Chiral Perturbation Theory

Leading order Large-N_c χPT Lagrangian:

$$\mathcal{L} \supset \frac{F^2}{4}\langle (D_\mu \mathcal{U})(D^\mu \mathcal{U})^\dagger \rangle + \frac{F^2}{4}\langle \chi \mathcal{U}^\dagger + \chi^\dagger \mathcal{U} \rangle - \frac{1}{2} M_0^2 \phi_0^2$$

$$D_\mu \mathcal{U} = \partial_\mu \mathcal{U} - i \frac{\partial_\mu a}{2 f_a} \{\bar{c}, \mathcal{U}\}$$

$$\chi = 2B_0 \exp\left(-i \frac{a}{2f_a} \kappa\right) \mathcal{M} \exp\left(-i \frac{a}{2f_a}\kappa\right) = 2B_0 \hat{\mathcal{M}}(a)$$

Leading order Large-N_c χPT Lagrangian:

$$\mathcal{L} \supset \frac{F^2}{4}\langle (D_\mu \mathcal{U})(D^\mu \mathcal{U})^\dagger \rangle + \frac{F^2}{4}\langle \chi \mathcal{U}^\dagger + \chi^\dagger \mathcal{U} \rangle - \frac{1}{2} M_0^2 \phi_0^2$$

Leading order χPT-ALP Lagrangian:

$$\begin{aligned}\mathcal{L} \supset\ & \frac{F^2}{4}\langle (\partial_\mu \mathcal{U})(\partial^\mu \mathcal{U}^\dagger) \rangle + \frac{B_0 F^2}{2}\langle \hat{\mathcal{M}}(a) \mathcal{U}^\dagger + \hat{\mathcal{M}}(a)^\dagger \mathcal{U} \rangle - \frac{1}{2} M_0^2 \phi_0^2 + \\ & + \frac{1}{2}(\partial_\mu a)(\partial^\mu a) - \frac{1}{2} m_0^2 a^2 - \\ & - i \frac{F^2}{4 f_a}(\partial_\mu a)\langle \overline{c}(\mathcal{U}^\dagger \partial^\mu \mathcal{U} - \mathcal{U} \partial^\mu \mathcal{U}^\dagger) \rangle + \frac{F^2}{8 f_a^2}(\partial_\mu a)(\partial^\mu a)\langle \overline{c}^2 + \overline{c}\mathcal{U}\overline{c}\mathcal{U}^\dagger \rangle\end{aligned}$$

Contents

Axion-meson mixing

For the neutral fields, $\varphi = (a_0, \phi_3, \phi_8, \phi_0)^T$:

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \varphi)^T K (\partial^\mu \varphi) - \frac{1}{2}\varphi^T M^2_{\text{mix}} \varphi \neq \sum_i \frac{1}{2}(\partial_\mu \varphi_i)(\partial^\mu \varphi_i) - \frac{1}{2} m_i^2 \varphi_i^2$$

Axion-meson mixing

For the neutral fields, $\varphi = (a_0, \phi_3, \phi_8, \phi_0)^T$:

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \varphi)^T K (\partial^\mu \varphi) - \frac{1}{2}\varphi^T M^2_{\text{mix}} \varphi \neq \sum_i \frac{1}{2}(\partial_\mu \varphi_i)(\partial^\mu \varphi_i) - \frac{1}{2} m_i^2 \varphi_i^2$$

Mixing: Field redefinition $\varphi \mapsto \varphi_{\text{phys}} = (a, \pi^0, \eta, \eta')$

Axion-meson mixing

For the neutral fields, $\varphi = (a_0, \phi_3, \phi_8, \phi_0)^T$:

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \varphi)^T K (\partial^\mu \varphi) - \frac{1}{2}\varphi^T M^2_{\text{mix}} \varphi \neq \sum_i \frac{1}{2}(\partial_\mu \varphi_i)(\partial^\mu \varphi_i) - \frac{1}{2} m_i^2 \varphi_i^2$$

Mixing: Field redefinition $\varphi \mapsto \varphi_{\text{phys}} = (a, \pi^0, \eta, \eta')$

6-angle parameterization of $R \in \mathbb{R}^4$:

$$R \equiv R_6(\theta_{a\eta'}) R_5(\theta_{a\eta}) R_4(\theta_{a\pi}) R_3(\theta_{\pi\eta'}) R_2(\theta_{\pi\eta}) R_1(\theta_{\eta\eta'})$$

Axion-meson mixing

For the neutral fields, $\varphi = (a_0, \phi_3, \phi_8, \phi_0)^T$:

$$\mathcal{L} \supset \frac{1}{2}(\partial_\mu \varphi)^T K (\partial^\mu \varphi) - \frac{1}{2}\varphi^T M^2_{\text{mix}} \varphi \neq \sum_i \frac{1}{2}(\partial_\mu \varphi_i)(\partial^\mu \varphi_i) - \frac{1}{2} m_i^2 \varphi_i^2$$

Mixing: Field redefinition $\varphi \mapsto \varphi_{\text{phys}} = (a, \pi^0, \eta, \eta')$

6-angle parameterization of $R \in \mathbb{R}^4$:

$$R \equiv R_6(\theta_{a\eta'}) R_5(\theta_{a\eta}) R_4(\theta_{a\pi}) R_3(\theta_{\pi\eta'}) R_2(\theta_{\pi\eta}) R_1(\theta_{\eta\eta'})$$

Small angle dependence:

$$\theta_{\pi\eta^{(\prime)}} \propto \varepsilon(m_u - m_d) \sim 0.01, \quad \theta_{aP} \propto \frac{F}{f_a} \ll 1$$

Axion-meson mixing

Axion mass:

$$m_a^2 = m_0^2 + \frac{F^2}{f_a^2} \frac{B_0 m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s}$$

Axion-meson mixing

Axion mass:

$$m_a^2 = m_0^2 + \frac{F^2}{f_a^2} \frac{B_0 m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s}$$

Field mixing:

$$\phi_8 = \cos(\theta_{\eta\eta'})\eta + \sin(\theta_{\eta\eta'})\eta' + [\cos(\theta_{\eta\eta'})\theta_{\pi\eta} + \sin(\theta_{\eta\eta'})\theta_{\pi\eta'}]\pi^0 + \gamma_{a\eta} a$$

$$\phi_0 = -\sin(\theta_{\eta\eta'})\eta + \cos(\theta_{\eta\eta'})\eta' - [\sin(\theta_{\eta\eta'})\theta_{\pi\eta} - \cos(\theta_{\eta\eta'})\theta_{\pi\eta'}]\pi^0 + \gamma_{a\eta'} a$$

$$\phi_3 = \pi^0 - \theta_{\pi\eta}\eta - \theta_{\pi\eta'}\eta' + \gamma_{a\pi} a$$

$$a_0 = a + h_\pi \pi^0 + h_{\eta'}\eta' + h_\eta \eta$$

Axion-meson mixing

Axion mass:

$$m_a^2 = m_0^2 + \frac{F^2}{f_a^2} \frac{B_0 m_u m_d m_s}{m_u m_d + m_u m_s + m_d m_s}$$

Field mixing:

$$\phi_8 = \cos(\theta_{\eta\eta'})\eta + \sin(\theta_{\eta\eta'})\eta' + [\cos(\theta_{\eta\eta'})\theta_{\pi\eta} + \sin(\theta_{\eta\eta'})\theta_{\pi\eta'}]\pi^0 + \gamma_{a\eta} a$$

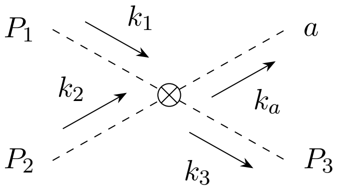
$$\phi_0 = -\sin(\theta_{\eta\eta'})\eta + \cos(\theta_{\eta\eta'})\eta' - [\sin(\theta_{\eta\eta'})\theta_{\pi\eta} - \cos(\theta_{\eta\eta'})\theta_{\pi\eta'}]\pi^0 + \gamma_{a\eta'} a$$

$$\phi_3 = \pi^0 - \theta_{\pi\eta}\eta - \theta_{\pi\eta'}\eta' + \gamma_{a\pi} a$$

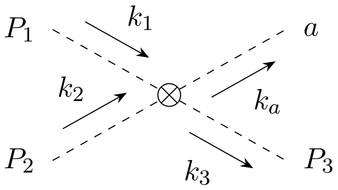
$$a_0 = a + h_\pi \pi^0 + h_{\eta'}\eta' + h_\eta \eta$$

Contents

One axion amplitudes

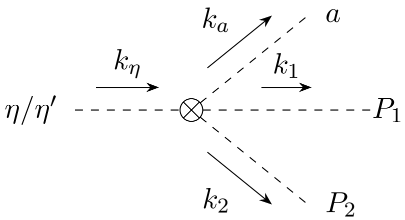


One axion amplitudes

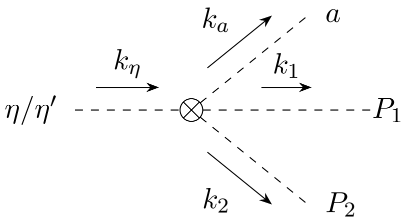


$$\mathcal{A} = c_{s_4}^{P}\gamma_{aP} + \frac{c_{s_3}}{f_a} + \left(\frac{c_{ax}^{aP_1}}{f_a} + c_D^{aP_1;P}\gamma_{aP}\right)(k_a \cdot k_1) + \\ + \left(\frac{c_{ax}^{aP_2}}{f_a} + c_D^{aP_2;P}\gamma_{aP}\right)(k_a \cdot k_2) - \left(\frac{c_{ax}^{aP_3}}{f_a} + c_D^{aP_3;P}\gamma_{aP}\right)(k_a \cdot k_3) - \\ - c_D^{P_1P_2;P}\gamma_{aP}(k_1 \cdot k_2) + c_D^{P_1P_3;P}\gamma_{aP}(k_1 \cdot k_3) + c_D^{P_2P_3;P}\gamma_{aP}(k_2 \cdot k_3)$$

Application: neutral η/η' decays



Application: neutral η/η' decays



$$\mathcal{A} = c_{s_4}^{\pi}\gamma_{a\pi} + c_{s_4}^{\eta}\gamma_{a\eta} + c_{s_4}^{\eta'}\gamma_{a\eta'} + \frac{c_{s_3}}{f_a}$$

Contents

Conclusions and outlook

- **Conclusions**
  - Theoretical study of insertion of ALPs in χPT at LO
  - Formal calculation of axion-meson mixing, including isospin breaking corrections
  - Complete parameterizations of 4-body amplitudes with 1 to 4 axions

Conclusions and outlook

- **Conclusions**
  - Theoretical study of insertion of ALPs in χPT at LO
  - Formal calculation of axion-meson mixing, including isospin breaking corrections
  - Complete parameterizations of 4-body amplitudes with 1 to 4 axions
- **Outlook**
  - Beyond LO (χPT@NLO, resonances, FSI...)
  - Application of this framework to cosmological problems
  - Axion search with phenomenological η/η' decay analysis ($\eta \to \pi\pi l^+ l^-, \dots$)

Back-up slides

BACK UP SLIDES

Kinetic mixing

There is only kinetic mixing with the axion at LO:

$$K(\phi_\alpha, \phi_\beta) = \delta_{\alpha\beta}, \quad \alpha, \beta = 0, 3, 8$$

$$K(a, \phi_\beta) = \frac{F}{2f_a}\langle \overline{c}\lambda_\beta \rangle$$

$$K(a, a) = 1 + \frac{F^2}{2f_a^2}\langle \overline{c}^2 \rangle$$

Kinetic mixing

There is only kinetic mixing with the axion at LO:

$$K(\phi_\alpha, \phi_\beta) = \delta_{\alpha\beta}, \quad \alpha, \beta = 0, 3, 8$$

$$K(a, \phi_\beta) = \frac{F}{2f_a}\langle \bar{c}\lambda_\beta \rangle$$

$$K(a, a) = 1 + \frac{F^2}{2f_a^2}\langle \bar{c}^2 \rangle$$

At a LO in $1/f_a$, we take $\Lambda = K^{1/2}$:

$$\Lambda(\phi_\alpha, \phi_\beta) = \delta_{\alpha\beta}, \quad \alpha, \beta = 0, 3, 8$$

$$\Lambda(a, \phi_\beta) = \frac{F}{4f_a}\langle \bar{c}\lambda_\beta \rangle$$

$$\Lambda(a, a) = 1$$

Decays of interest for axion searches

ALP-lepton and ALP-photon terms:

$$\mathcal{L}_{ALP} \supset -\frac{\partial^\mu a}{2f_a}\bar{l}c_l\gamma_\mu\gamma_5 l - \frac{a}{f_a}\frac{\alpha_{\rm em}}{8\pi}\tilde{c}_\gamma F_{\mu\nu}\tilde{F}^{\mu\nu}$$

η/η' decays of interest:

$$\eta/\eta' \to \pi\pi a^* \to \pi\pi\gamma\gamma$$
$$\eta/\eta' \to \pi\pi a^* \to \pi\pi l^+ l^-$$
$$\eta' \to \pi^+\pi^- a^* \to 2(\pi^+\pi^-)\pi^0$$

Four-field Lagrangian

$$\mathcal{L}_{LO}^{(4)} = -\frac{1}{48F^2}\langle[\Phi,\partial_\mu\Phi][\Phi,\partial^\mu\Phi]\rangle + \frac{B_0}{24F^2}\langle\mathcal{M}\Phi^4\rangle -$$
$$-\frac{B_0}{6Ff_a}\frac{a}{\langle\mathcal{M}^{-1}\rangle}\langle\Phi^3\rangle - \frac{1}{12Ff_a}(\partial_\mu a)\langle\overline{c}[\Phi,[\Phi,\partial^\mu\Phi]]\rangle +$$
$$+\frac{B_0}{4f_a^2}\frac{a^2}{\langle\mathcal{M}^{-1}\rangle^2}\langle\mathcal{M}^{-1}\Phi^2\rangle + \frac{1}{16f_a^2}(\partial_\mu a)(\partial^\mu a)\langle[\overline{c},\Phi][\overline{c},\Phi]\rangle +$$
$$+\frac{B_0F}{6f_a^3}\frac{a^3}{\langle\mathcal{M}^{-1}\rangle^3}\langle(\mathcal{M}^{-1})^2\Phi\rangle + \frac{B_0F^2}{24f_a^4}\frac{a^4}{\langle\mathcal{M}^{-1}\rangle^4}\langle(\mathcal{M}^{-1})^3\rangle$$

Commutator structure of kinetic terms!

Back-up slides - Master's Thesis

Índice

Introducción

$$\text{Modelo Estándar Física de Partículas} \supset \begin{cases} \text{Neutrinos} \\ \text{Interacciones débiles} \end{cases}$$

Introducción

$$\text{Modelo Estándar Física de Partículas} \supset \begin{cases} \text{Neutrinos} \\ \text{Interacciones débiles} \end{cases}$$

- Oscilaciones de neutrinos

Introducción

$$\text{Modelo Estándar Física de Partículas} \supset \begin{cases} \text{Neutrinos} \\ \text{Interacciones débiles} \end{cases}$$

- Oscilaciones de neutrinos
- Asimetría materia-antimateria y violación de CP

Introducción

Modelo Estándar Física de Partículas $\supset \begin{cases} \text{Neutrinos} \\ \text{Interacciones débiles} \end{cases}$

- Oscilaciones de neutrinos
- Asimetría materia-antimateria y violación de CP
- Fermiones de Dirac/Majorana

Introducción

$$\text{Modelo Estándar Física de Partículas} \supset \begin{cases} \text{Neutrinos} \\ \text{Interacciones débiles} \end{cases}$$

- Oscilaciones de neutrinos
- Asimetría materia-antimateria y violación de CP
- Fermiones de Dirac/Majorana
- Caracterización de fenómenos astrofísicos y cosmológicos

Introducción

Modelo Estándar Física de Partículas $\supset \begin{cases} \text{Neutrinos} \\ \text{Interacciones débiles} \end{cases}$

- Oscilaciones de neutrinos
- Asimetría materia-antimateria y violación de CP
- Fermiones de Dirac/Majorana
- Caracterización de fenómenos astrofísicos y cosmológicos

Fuentes de neutrinos

- Naturales: rayos cósmicos, neutrinos cosmológicos, decaimiento β...

Introducción

Modelo Estándar Física de Partículas $\supset \begin{cases} \text{Neutrinos} \\ \text{Interacciones débiles} \end{cases}$

- Oscilaciones de neutrinos
- Asimetría materia-antimateria y violación de CP
- Fermiones de Dirac/Majorana
- Caracterización de fenómenos astrofísicos y cosmológicos

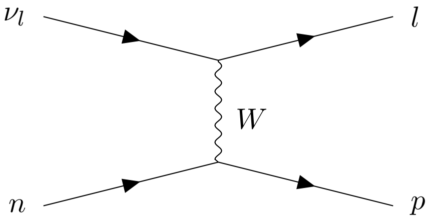
Fuentes de neutrinos

- Naturales: rayos cósmicos, neutrinos cosmológicos, decaimiento β...
- Artificiales: centrales nucleares, aceleradores (decaimiento π)...

Índice

Interacción elástica neutrino-nucleón

$$\nu_l + n \longrightarrow l + p$$



Límite elástico: $|Q^2| \ll M_W^2$

Interacción elástica neutrino-nucleón

Sección eficaz

$$d\sigma = \frac{|S|^2}{T\Phi_{inc}} dN_f, \quad S = -i\int d^4X\, H_w(X)$$

Interacción elástica neutrino-nucleón

Sección eficaz

$$d\sigma = \frac{|S|^2}{T\Phi_{inc}} dN_f, \quad S = -i \int d^4X \, H_w(X)$$

Hamiltoniano electrodébil

$$H_w(X) = \left(\frac{g}{2\sqrt{2}}\right)^2 J_\mu^{(l)\dagger} A^\mu_{(N)}(X)$$

Interacción elástica neutrino-nucleón

Sección eficaz

$$d\sigma = \frac{|S|^2}{T\Phi_{inc}} dN_f, \quad S = -i \int d^4X \, H_w(X)$$

Hamiltoniano electrodébil

$$H_w(X) = \left(\frac{g}{2\sqrt{2}}\right)^2 J_\mu^{(l)\dagger} A^\mu_{(N)}(X)$$

Corriente leptónica

$$J_\mu^{(l)\dagger} = \overline{\psi}_l \gamma_\mu (1 - \gamma_5) \psi_{\nu_l}$$

Sección eficaz

$$d\sigma = \frac{|S|^2}{T\Phi_{inc}} dN_f, \quad S = -i \int d^4X \, H_w(X)$$

Hamiltoniano electrodébil

$$H_w(X) = \left(\frac{g}{2\sqrt{2}} \right)^2 J_\mu^{(l)\dagger} A^\mu_{(N)}(X)$$

Corriente leptónica

$$J_\mu^{(l)\dagger} = \overline{\psi}_l \gamma_\mu (1 - \gamma_5) \psi_{\nu_l}$$

4-potencial hadrónico

$$A^\mu_{(N)}(X) = \int dY \int dQ \, D_W^{\mu\nu}(Q) J_\nu^{(N)}(Y) \frac{e^{iQ(X-Y)}}{(2\pi)^4}.$$

Propagador bosón W

$$D^W_{\mu\nu}(Q) = \frac{1}{Q^2 - M_W^2 + i\varepsilon}\left(-g_{\mu\nu} + \frac{Q_\mu Q_\nu}{M_W^2}\right) \sim \frac{g_{\mu\nu}}{M_W^2}$$

Interacción elástica neutrino-nucleón

Propagador bosón W

$$D^{W}_{\mu\nu}(Q) = \frac{1}{Q^2 - M_W^2 + i\varepsilon}\left(-g_{\mu\nu} + \frac{Q_\mu Q_\nu}{M_W^2}\right) \sim \frac{g_{\mu\nu}}{M_W^2}$$

Corriente hadrónica

$$J^{(N)}_{\mu} = \sqrt{\frac{M^2}{E_p E_n}}\,\overline{u}_p \Gamma_\mu u_n, \quad \Gamma_\mu \in \langle \mathbb{1}, \gamma_\mu, \gamma_5, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\rangle$$

Interacción elástica neutrino-nucleón

Propagador bosón W

$$D^W_{\mu\nu}(Q) = \frac{1}{Q^2 - M_W^2 + i\varepsilon}\left(-g_{\mu\nu} + \frac{Q_\mu Q_\nu}{M_W^2}\right) \sim \frac{g_{\mu\nu}}{M_W^2}$$

Corriente hadrónica

$$J^{(N)}_\mu = \sqrt{\frac{M^2}{E_p E_n}}\overline{u}_p \Gamma_\mu u_n, \quad \Gamma_\mu \in \langle \mathbb{1}, \gamma_\mu, \gamma_5, \gamma_\mu\gamma_5, \sigma_{\mu\nu}\rangle$$

$$\Gamma^\mu = \Gamma^\mu_V + \Gamma^\mu_A = \left(F_1\gamma^\mu + \frac{i}{2M}F_2\sigma^{\mu\nu}Q_\nu\right) + \left(G_P\gamma^5 Q^\mu + G_A\gamma^\mu\gamma^5\right)$$

Interacción elástica neutrino-nucleón

Sección eficaz

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W^{\mu\nu}$$

Sección eficaz

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1} \tilde{\eta}_{\mu\nu} W^{\mu\nu}$$

Tensor leptónico

$$\tilde{\eta}_{\mu\nu} = m_{\nu_l} m_l \overline{\sum_{s_{\nu_l}, s_l}} J_\mu^{(l)\dagger} J_\nu^{(l)}$$

Interacción elástica neutrino-nucleón

Sección eficaz

$$\frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W^{\mu\nu}$$

Tensor leptónico

$$\tilde{\eta}_{\mu\nu} = m_{\nu_l}m_l \overline{\sum_{s_{\nu_l},s_l}} J_\mu^{(l)\dagger}J_\nu^{(l)}$$

Tensor hadrónico

$$W_{\mu\nu} = \overline{\sum_{s_p,s_n}} J_\mu^{(N)\dagger}J_\nu^{(N)}$$

Índice

Factores de forma hadrónicos

$$\Gamma_V^\mu = \left(F_1 \gamma^\mu + \frac{i}{2M} F_2 \sigma^{\mu\nu} Q_\nu \right)$$

Factores de forma hadrónicos

$$\Gamma_V^\mu = \left(F_1 \gamma^\mu + \frac{i}{2M} F_2 \sigma^{\mu\nu} Q_\nu \right)$$

Conservación corriente vectorial $\rightarrow$ Relación con los factores EM

Factores de forma hadrónicos

$$\Gamma^\mu_V = \left(F_1 \gamma^\mu + \frac{i}{2M} F_2 \sigma^{\mu\nu} Q_\nu \right)$$

Conservación corriente vectorial $\rightarrow$ Relación con los factores EM

Factores EM de Sachs: $G_E^{n,p}$, $G_M^{n,p}$

Factores de forma hadrónicos

$$\Gamma^{\mu}_{V} = \left(F_1 \gamma^{\mu} + \frac{i}{2M} F_2 \sigma^{\mu\nu} Q_{\nu} \right)$$

Conservación corriente vectorial $\rightarrow$ Relación con los factores EM

Factores EM de Sachs: $G_E^{n,p}$, $G_M^{n,p}$

Factores débiles

$$F_1 = \frac{(G_E^p - G_E^n) + \tau (G_M^p - G_M^n)}{2(1+\tau)}, \quad F_2 = \frac{(G_M^p - G_M^n) - (G_E^p - G_E^n)}{2(1+\tau)}$$

Parametrización dipolar de Galster

$$G_E^p = G_D(Q^2), \qquad G_E^n = 0$$
$$G_M^p = \mu_p G_D(Q^2), \quad G_M^n = \mu_n G_D(Q^2)$$

Factores de forma hadrónicos

Parametrización dipolar de Galster

$$G_E^p = G_D(Q^2), \qquad G_E^n = 0$$
$$G_M^p = \mu_p G_D(Q^2), \quad G_M^n = \mu_n G_D(Q^2)$$

Factor dipolar

$$G_D(Q^2) = \left(1 + \frac{|Q^2|}{M_V^2}\right)^{-2}, \quad M_V = 0.843 \text{ GeV}$$

Factores de forma hadrónicos

Parametrización dipolar de Galster

$$G_E^p = G_D(Q^2), \qquad G_E^n = 0$$
$$G_M^p = \mu_p G_D(Q^2), \quad G_M^n = \mu_n G_D(Q^2)$$

Factor dipolar

$$G_D(Q^2) = \left(1 + \frac{|Q^2|}{M_V^2}\right)^{-2}, \quad M_V = 0.843 \text{ GeV}$$

Parametrizaciones de Gary-Krümpelmann y GKeX
Se extienden hasta $|Q^2| \sim 10$ GeV incluyendo pQCD y mesones vectoriales

Factores de forma hadrónicos

$$\Gamma^{\mu}_{A} = \left(G_P \gamma^5 Q^{\mu} + G_A \gamma^{\mu} \gamma^5\right)$$

Factores de forma hadrónicos

$$\Gamma^\mu_A = (G_P \gamma^5 Q^\mu + G_A \gamma^\mu \gamma^5) \longrightarrow \begin{cases} G_A\text{: Estructura axial} \\ G_P\text{: Estructura pseudoescalar} \end{cases}$$

Factores de forma hadrónicos

$$\Gamma_A^\mu = \left(G_P \gamma^5 Q^\mu + G_A \gamma^\mu \gamma^5\right) \quad \longrightarrow \quad \begin{cases} G_A\text{: Estructura axial} \\ G_P\text{: Estructura pseudoescalar} \end{cases}$$

Estructura axial

$$G_A(Q^2) = g_A \left(1 + \frac{|Q^2|}{M_A^2}\right)^{-2}, \quad \begin{cases} g_A = -1.267 \\ M_A = 1.03 \text{ GeV} \end{cases}$$

Factores de forma hadrónicos

$$\Gamma_A^\mu = \left(G_P \gamma^5 Q^\mu + G_A \gamma^\mu \gamma^5\right) \longrightarrow \begin{cases} G_A\text{: Estructura axial} \\ G_P\text{: Estructura pseudoescalar} \end{cases}$$

Estructura axial

$$G_A(Q^2) = g_A \left(1 + \frac{|Q^2|}{M_A^2}\right)^{-2}, \quad \begin{cases} g_A = -1.267 \\ M_A = 1.03 \text{ GeV} \end{cases}$$

Estructura pseudoescalar

$$G_P(Q^2) = \frac{2M}{Q^2 + m_\pi^2} G_A(Q^2)$$

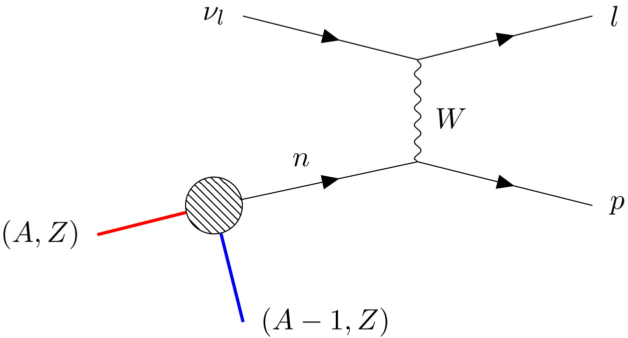
Índice

Interacción QE neutrino-núcleo

$$\nu_\mu + (A, Z) \;\longrightarrow\; \mu^- + p + (A-1, Z)$$

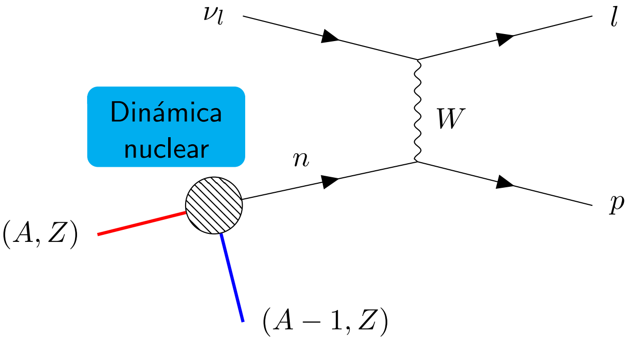
Interacción QE neutrino-núcleo

$$\nu_\mu + (A, Z) \longrightarrow \mu^- + p + (A-1, Z)$$



Interacción QE neutrino-núcleo

$$\nu_\mu + (A, Z) \longrightarrow \mu^- + p + (A-1, Z)$$



Interacción QE neutrino-núcleo

Dinámica nuclear

Interacción QE neutrino-núcleo

Dinámica nuclear

$$\left[\frac{d\sigma}{d\Omega}\right]_{sn} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W_{sn}^{\mu\nu}$$

Interacción QE neutrino-núcleo

Dinámica nuclear

$$\left[\frac{d\sigma}{d\Omega}\right]_{sn} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W_{sn}^{\mu\nu} \longmapsto \frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W^{\mu\nu}$$

Interacción QE neutrino-núcleo

Dinámica nuclear

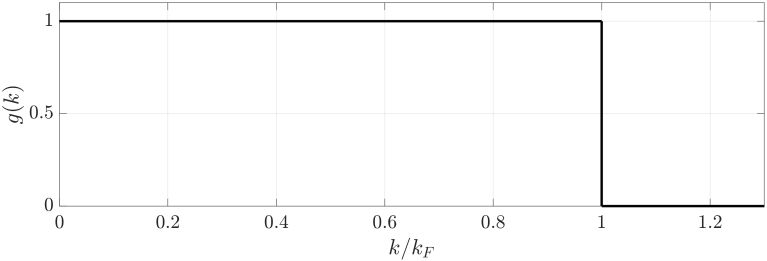
$$\left[\frac{d\sigma}{d\Omega}\right]_{sn} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W_{sn}^{\mu\nu} \longmapsto \frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W^{\mu\nu}$$

Gas de Fermi relativista (RFG)

Dinámica nuclear

$$\left[\frac{d\sigma}{d\Omega}\right]_{sn} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W_{sn}^{\mu\nu} \longmapsto \frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W^{\mu\nu}$$

Gas de Fermi relativista (RFG)



Interacción QE neutrino-núcleo

Dinámica nuclear

$$\left[\frac{d\sigma}{d\Omega}\right]_{sn} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W_{sn}^{\mu\nu} \longmapsto \frac{d\sigma}{d\Omega} = \frac{G_F^2}{4\pi^2}\frac{|\vec{p}_l|}{E_{\nu_l}} f_{rec}^{-1}\tilde{\eta}_{\mu\nu}W^{\mu\nu}$$

Gas de Fermi relativista (RFG)

Relación de scaling

$$W^{\mu\nu} = \frac{1}{k_F} f_{RFG}(\psi)\frac{\mathcal{N}}{2\kappa}W_{sn}^{\mu\nu}$$

Función de scaling

$$f_{RFG}(\psi) = \frac{3}{4}(1-\psi^2)\Theta(1-\psi^2)$$

Interacción QE neutrino-núcleo

Función de scaling

$$f_{RFG}(\psi) = \frac{3}{4}(1-\psi^2)\Theta(1-\psi^2)$$

Clases de scaling

Interacción QE neutrino-núcleo

Función de scaling

$$f_{RFG}(\psi) = \frac{3}{4}(1-\psi^2)\Theta(1-\psi^2)$$

Clases de scaling

- Primera clase: f sólo depende de q mediante ψ

Interacción QE neutrino-núcleo

Función de scaling

$$f_{RFG}(\psi) = \frac{3}{4}(1-\psi^2)\Theta(1-\psi^2)$$

Clases de scaling

- Primera clase: f sólo depende de q mediante ψ
- Segunda clase: f es independiente de la especie nuclear

Interacción QE neutrino-núcleo

Función de scaling

$$f_{RFG}(\psi) = \frac{3}{4}(1-\psi^2)\Theta(1-\psi^2)$$

Clases de scaling

- Primera clase: f sólo depende de q mediante ψ
- Segunda clase: f es independiente de la especie nuclear
- Clase cero: $f_L = f_T = f$

Interacción QE neutrino-núcleo

Función de scaling

$$f_{RFG}(\psi) = \frac{3}{4}(1-\psi^2)\Theta(1-\psi^2)$$

Clases de scaling

- Primera clase: f sólo depende de q mediante ψ
- Segunda clase: f es independiente de la especie nuclear
- Clase cero: $f_L = f_T = f$
- **Superscaling**: todas las condiciones previas

Interacción QE neutrino-núcleo: scaling

Superscaling approach (SuSA)

Interacción QE neutrino-núcleo: scaling

Superscaling approach (SuSA): Función scaling fenomenológica

$$f_{SuSA}(\psi) = \frac{p_1}{[1 + p_2^2(\psi - p_3)^2](1 + e^{p_4\psi})}$$

Interacción QE neutrino-núcleo: scaling

Superscaling approach (SuSA): Función scaling fenomenológica

$$f_{SuSA}(\psi) = \frac{p_1}{[1 + p_2^2(\psi - p_3)^2](1 + e^{p_4 \psi})}$$

Observaciones experimentales

- Ruptura scaling (clase 0)

$$f_T(\psi) > f_L(\psi)$$

Interacción QE neutrino-núcleo: scaling

Superscaling approach (SuSA): Función scaling fenomenológica

$$f_{SuSA}(\psi) = \frac{p_1}{[1 + p_2^2(\psi - p_3)^2](1 + e^{p_4 \psi})}$$

Observaciones experimentales

- Ruptura scaling (clase 0)

$$f_T(\psi) > f_L(\psi)$$

- Mejor ajuste incluyendo RMF

Interacción QE neutrino-núcleo: scaling

Superscaling approach (SuSA): Función scaling fenomenológica

$$f_{SuSA}(\psi) = \frac{p_1}{[1 + p_2^2(\psi - p_3)^2](1 + e^{p_4 \psi})}$$

Observaciones experimentales

- Ruptura scaling (clase 0)

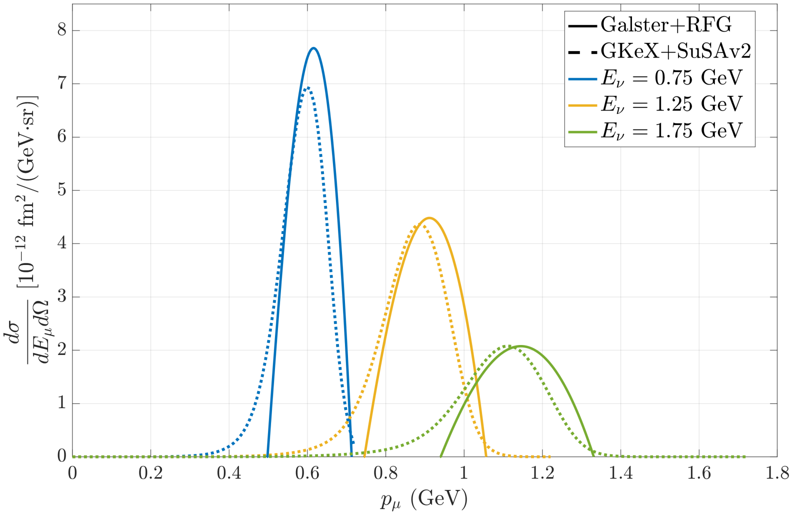
$$f_T(\psi) > f_L(\psi)$$

- Mejor ajuste incluyendo RMF

SuSAv2: mejora de SuSA con efectos teóricos de RMF

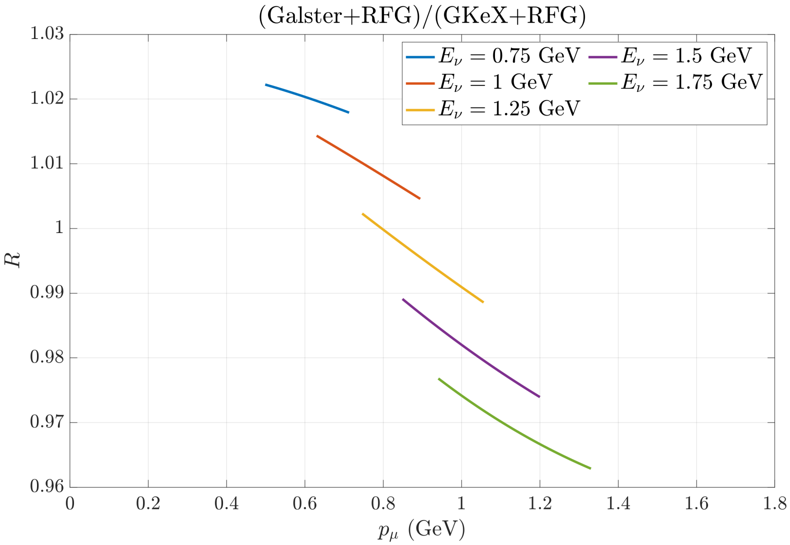
Índice

Resultados

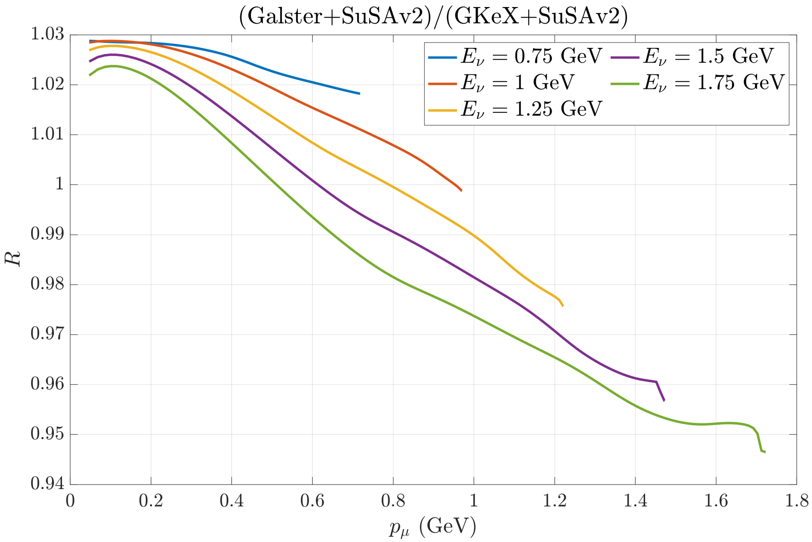


Galster+RFG
GKeX+SuSAv2
$E_\nu = 0.75$ GeV
$E_\nu = 1.25$ GeV
$E_\nu = 1.75$ GeV
$\frac{d\sigma}{dE_\mu d\Omega}$ [10^{-12} fm^2/(GeV·sr)]
p_μ (GeV)
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
0
1
2
3
4
5
6
7
8

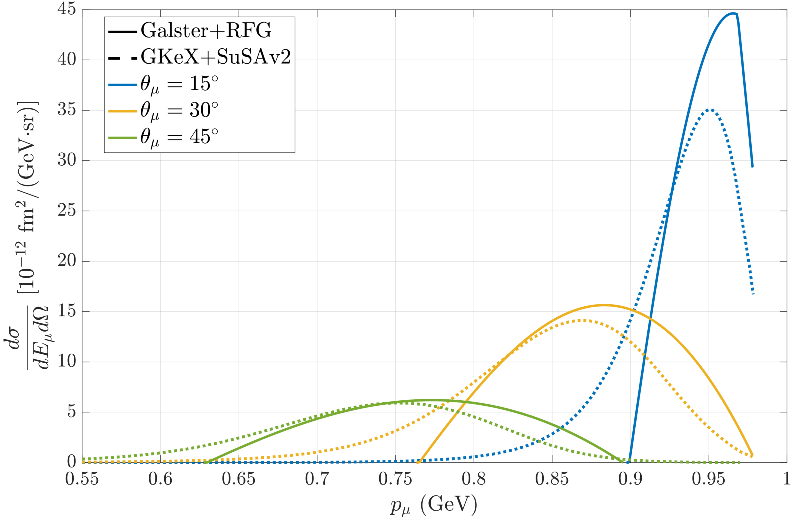
Resultados


(Galster+RFG)/(GKeX+RFG)
$E_\nu = 0.75$ GeV
$E_\nu = 1$ GeV
$E_\nu = 1.25$ GeV
$E_\nu = 1.5$ GeV
$E_\nu = 1.75$ GeV
R
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
p_μ (GeV)

Resultados


(Galster+SuSAv2)/(GKeX+SuSAv2)
$E_\nu = 0.75$ GeV
$E_\nu = 1$ GeV
$E_\nu = 1.25$ GeV
$E_\nu = 1.5$ GeV
$E_\nu = 1.75$ GeV
R
p_μ (GeV)
1.03
1.02
1.01
1
0.99
0.98
0.97
0.96
0.95
0.94
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8

Resultados



Galster+RFG
GKeX+SuSAv2
$\theta_\mu = 15^\circ$
$\theta_\mu = 30^\circ$
$\theta_\mu = 45^\circ$
$\frac{d\sigma}{dE_\mu d\Omega}$ $[10^{-12}\ \mathrm{fm}^2/(\mathrm{GeV}\cdot\mathrm{sr})]$
p_μ (GeV)
0.55 0.6 0.65 0.7 0.75 0.8 0.85 0.9 0.95 1
0 5 10 15 20 25 30 35 40 45

Índice

Conclusiones

- Estudio de la interacción elástica neutrino-nucleón y la dependencia con los factores de forma hadrónicos
- Análisis de la interacción cuasielástica neutrino-núcleo y su relación con la interacción neutrino-núcleo en modelos de scaling
- Comparación de predicciones teóricas que caracterizan los factores de forma y el modelo nuclear