Axion like particle production in $\eta \to \pi\pi a$ decay

arXiv: 2403.16064 [hep-ph]

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OUTLINE

- Introduction and motivation
- Axion SU(3) chiral perturbation theory
- Axion like particle (ALP) production in η decay
- Summary

- PQ mechanism is an elegant solution of the strong CP problem [Peccei and Quinn 1977]
- $U(1)_{PQ}$ spontaneously symmetry breaking (SSB) → Axion [Weinberg, 1978][Wilczek, 1978]

$$\mathcal{L}_a = \frac{1}{2}\left(\partial_\mu a\right)^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2}G_{\mu\nu}^c\tilde{G}_c^{\mu\nu} + \mathcal{L}\left(\partial_\mu a, \psi\right).$$

- Axion couples to gauge bosons, quarks, leptons fields, has abundant phenomenology. [Luzio, et.al, Phys.Rept., 2020]

- Standard QCD axion mass relation

$$m_a = \sqrt{\frac{m_u m_d}{(m_u + m_d)^2}}\frac{F_\pi}{f_a} m_\pi \simeq 5.7\left(\frac{10^6\ \text{GeV}}{f_a}\right)\text{eV}.$$

- ➢ Visible axion model: $f_a \lesssim 10^4$ GeV (ruled out by astrophysical experiments) [Dicus, et.al, Phys. Rev. D, 1978][Dicus, et.al, Phys. Rev. D, 1980]

- ➢ Invisible axion model: 10^9 GeV $\lesssim f_a \lesssim 10^{12}$ GeV, [Kim and Carosi, Rev. Mod. Phys., 2010]

  KSVZ axion model [Kim, Jihn E, 1979, Shifman, et al., Valentin I, 1980]
  DFSZ axion model [Dine, et al., 1981, Zhitnitsky, 1980]

- Heavy axions/Axion like particles (ALPs)

Holdom and Peskin, “Raising the Axion Mass”, NPB 208 (1982) 397-412.

Agrawal and Howe, “Factoring the Strong CP problem”, JHEP 12 (2018) 029.

Giorgi, et.al., “GeV ALP from TeV Vector-like Leptons”, arXiv:2402.14059 [hep-ph].

- ALPs phenomenology

Jaeckel and Spannowsky, “Probing MeV to 90 GeV axion-like particles with LEP and LHC”, PLB (2016) 482-487.

Bauer and Neubert and Thamm, “Collider Probes of Axion-Like Particles”, JHEP 12 (2017) 044.

Aloni and Soreq and Williams, “Coupling QCD-Scale Axionlike Particles to Gluons”, PRL 123 (2019) 3, 031803.

Di Luzio and Piazza, $a \to \pi\pi\pi$ decay at next-to-leading order in chiral perturbation theory”, JHEP 12 (2022) 041.

We focus on ALP production in $\eta \to \pi\pi$a decay

- Rare $\eta^{(\prime)}$ decays provide ideal probes to detect sub-GeV new light particles.
[Precision frontier experiments in JLab, BESIII, STCF]

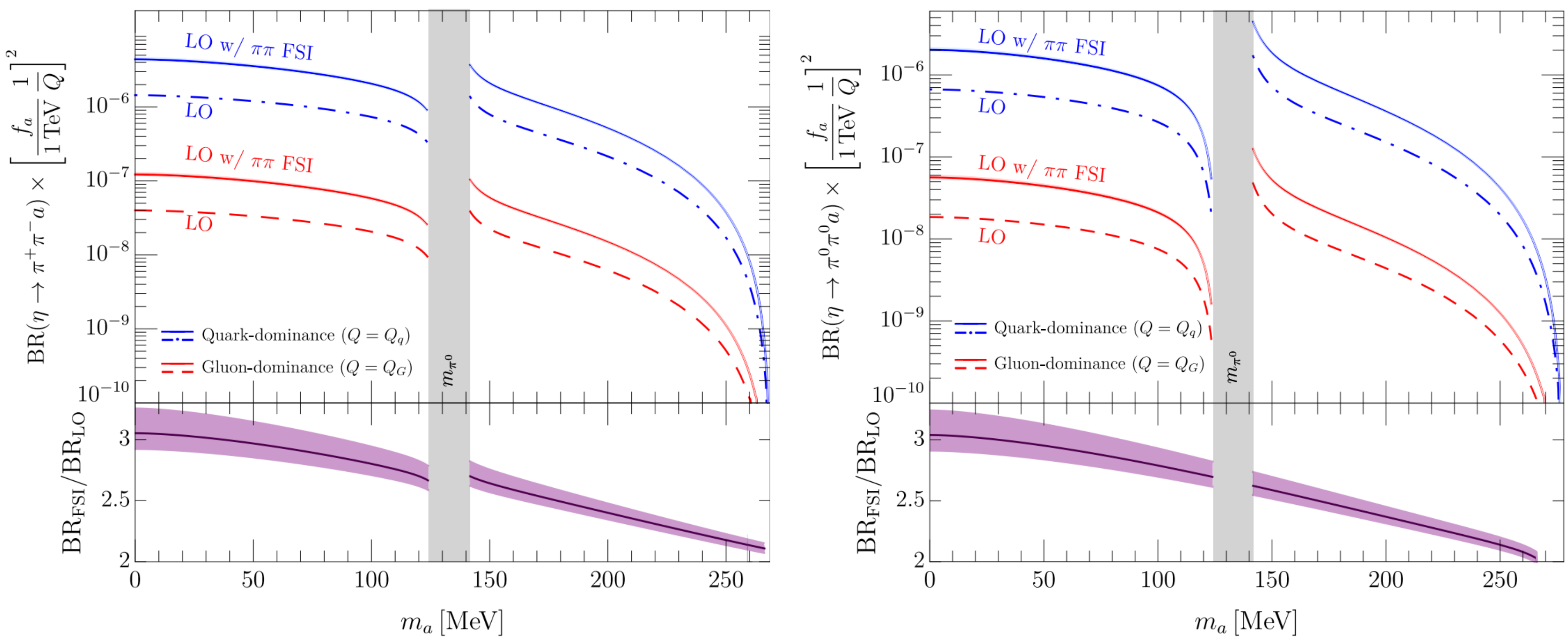
- ALPs in $\eta^{(\prime)}$ decay

Landini and Meggiolaro, “Study of the interactions of the axion with mesons and photons using a chiral effective Lagrangian model”, EPJC 80 (2020) 4, 302.

Gan, et.al., “Precision tests of fundamental physics with η and η' mesons”, Phys. Rept. 945 (2022) 1-105.

Alves and Sergi, “Final state rescattering effects in axio-hadronic η and η' decays”, arXiv:2402.02993 [hep-ph].

Alves and Sergi, arXiv:2402.02993 [hep-ph].



- **In this talk**, we discuss $\eta \to \pi\pi a$ decay in SU(3) ChPT up to NLO.
- NLO perturbative decay amplitude include s- and $t(u)$-channel interactions perturbatively.
- The unitarized decay amplitude will also constructed to account for the s-channel $\pi\pi$ final state interaction (FSI) effect.

- We stick on the minimal axion coulping

$$\mathcal{L}_{\rm ALP} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_{a,0}^2 a^2 + \frac{a}{f_a}\frac{g_s^2}{32\pi^2} G^c_{\mu\nu}\widetilde{G}_c^{\mu\nu}\,,$$

$m_{a,0}$ the bare PQ breaking axion mass.

- Axial transformation $q \to e^{i\frac{a}{2f_a}Q_a\gamma_5} q\,, \quad Q_a = \frac{M^{-1}}{\langle M^{-1}\rangle}\,,$

$$\mathcal{L}_{\rm ALP+QCD} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2} m_{a,0}^2 a^2 + \mathcal{L}^0_{\rm QCD} - \frac{\partial_\mu a}{2f_a}\bar{q}\gamma^\mu\gamma_5 Q_a q - (\bar{q}_R M(a) q_L + {\rm H.c.})\,,$$

$M(a) \equiv M e^{-i\frac{a}{f_a}Q_a}\,,$ work in isospin limit $M = {\rm diag}(\hat{m}, \hat{m}, m_s)\,, \quad \hat{m} = \frac{m_u + m_d}{2}\,.$

Study $\eta \to \pi\pi a$ decay in SU(3) chiral perturbation theory (ChPT)

[Gasser and Leutwyler, NPB, 1985]

- Effective d.o.f: eight pNGBs corresponding to SSB $SU(3)_L \times SU(3)_R \to SU(3)_V$

$$U = \exp\left(\frac{i\Phi}{F}\right), \quad \Phi = \begin{pmatrix} \pi^0 + \frac{1}{\sqrt{3}}\eta_8 & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & -\pi^0 + \frac{1}{\sqrt{3}}\eta_8 & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & -\frac{2}{\sqrt{3}}\eta_8 \end{pmatrix}$$

- Effective Lagrangians can be constructed order by order

Chiral expansion by soft momentum and light quarks masses
$p^2, m_q \sim O(p^2)$

$$\mathcal{L}_{\text{eff}} = \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_{a,0}^2 a^2 + \mathcal{L}_2 + \mathcal{L}_4 + \cdots,$$

axion couplings can be introduced as external fields.

- LO Lagrangian

$$\mathcal{L}_2 = \frac{F^2}{4}\langle \partial_\mu U \partial^\mu U^\dagger + \chi U^\dagger + U\chi^\dagger \rangle + \frac{\partial_\mu a}{2f_a} J_A^\mu|_{\text{LO}},$$

$$\chi = 2B_0 M(a), \quad J_A^\mu|_{\text{LO}} = -i\frac{F^2}{2}\langle \bar{Q}_a \{\partial^\mu U, U^\dagger\}\rangle.$$

- NLO Lagrangian

$$\mathcal{L}_4 = L_1 \langle \partial_\mu U \partial^\mu U^\dagger \rangle \langle \partial_\nu U \partial^\nu U^\dagger \rangle + \cdots + \frac{\partial_\mu a}{2f_a} J_A^\mu|_{\text{NLO}},$$

$$J_A^\mu|_{\text{NLO}} = -4iL_1 \langle \bar{Q}_a \{U^\dagger, \partial^\mu U\}\rangle \langle \partial_\nu U \partial^\nu U^\dagger \rangle + \cdots.$$

- LECs: $F, B_0, L_{1\sim 8}$.
- $\bar{Q}_a$ denotes octet component of Q_a.
- We ignore the singlet component of $\bar{q}\gamma^\mu\gamma_5 Q_a q$.

There is mixing between ALP and η_8 fields

- LO mixing

$$\mathcal{L}_{\rm mix}^{\rm LO} = \frac{1}{2}\partial_\mu a\partial^\mu a + \frac{1}{2}\partial_\mu\eta_8\partial^\mu\eta_8 + \frac{F}{f_a}C_k^{a\eta}\partial_\mu a\partial^\mu\eta_8 - \frac{1}{2}\left(m_{a,0}^2 + \frac{F^2}{f_a^2}C_m^a\right)a^2 - \frac{1}{2}\bar{m}_{\eta_8}^2\eta_8^2\,,$$

$$C_k^{a\eta} = \frac{1}{2}\langle\bar{Q}_a\lambda_8\rangle = \frac{\bar{m}_{\eta_8}^2 - \bar{m}_\pi^2}{2\sqrt{3}\bar{m}_{\eta_8}^2}\,,\quad C_m^a = \frac{B_0}{\langle M^{-1}\rangle} = \frac{\bar{m}_\pi^2(3\bar{m}_{\eta_8}^2 - \bar{m}_\pi^2)}{12\bar{m}_{\eta_8}^2}\,,$$

LO contribution of pNGBs masses from light quarks masses $\bar{m}_\pi^2 = 2B_0\hat{m}\,,\quad \bar{m}_{\eta_8}^2 = \frac{2B_0}{3}(\hat{m} + 2m_s)$

- Fields redefinitions up to $O(1/f_a^3)$

$$a = \left[1 + \frac{1}{2}(C_k^{a\eta})^2\frac{m_{a,0}^2(m_{a,0}^2 - 2\bar{m}_{\eta_8}^2)}{(m_{a,0}^2 - \bar{m}_{\eta_8}^2)^2}\frac{F^2}{f_a^2}\right]\widetilde{a} - \frac{F}{f_a}C_k^{a\eta}\frac{\bar{m}_{\eta_8}^2}{\bar{m}_{\eta_8}^2 - m_{a,0}^2}\widetilde{\eta}\,,$$

$$\eta_8 = \left[1 + \frac{1}{2}(C_k^{a\eta})^2\frac{\bar{m}_{\eta_8}^2(\bar{m}_{\eta_8}^2 - 2m_{a,0}^2)}{(m_{a,0}^2 - \bar{m}_{\eta_8}^2)^2}\frac{F^2}{f_a^2}\right]\widetilde{\eta} - \frac{F}{f_a}C_k^{a\eta}\frac{m_{a,0}^2}{m_{a,0}^2 - \bar{m}_{\eta_8}^2}\widetilde{a}\,.$$

$$\mathcal{L}_{\rm mix}^{\rm LO} = \frac{1}{2}\partial_\mu\widetilde{a}\partial^\mu\widetilde{a} - \frac{1}{2}\bar{m}_a^2\widetilde{a}^2 + \frac{1}{2}\partial_\mu\widetilde{\eta}\partial^\mu\widetilde{\eta} - \frac{1}{2}\bar{m}_\eta^2\widetilde{\eta}^2 + \mathcal{O}\left(\frac{F^3}{f_a^3}\right)\,,$$

$$\bar{m}_a^2 = m_{a,0}^2 + \frac{F^2}{f_a^2}\left(C_m^a + \frac{(C_k^{a\eta})^2 m_{a,0}^4}{m_{a,0}^2 - \bar{m}_{\eta_8}^2}\right)\,,\quad \bar{m}_\eta^2 = \bar{m}_{\eta_8}^2 + \frac{F^2}{f_a^2}\frac{(C_k^{a\eta})^2\bar{m}_{\eta_8}^4}{\bar{m}_{\eta_8}^2 - m_{a,0}^2}\,.$$

- NLO mixing and fields redefinitions for ALP and η fields

$$\mathcal{L}_{\rm mix}^{\rm NLO} = \frac{1}{2}(1-\Sigma_{aa}^{(4)\prime})\partial_\mu\tilde{a}\partial^\mu\tilde{a} + \frac{1}{2}(1-\Sigma_{\eta\eta}^{(4)\prime})\partial_\mu\tilde{\eta}\partial^\mu\tilde{\eta} - \Sigma_{a\eta}^{(4)\prime}\partial_\mu\tilde{a}\partial^\mu\tilde{\eta} - \frac{1}{2}\left[\bar{m}_a^2+\Sigma_{aa}^{(4)}(0)\right]\tilde{a}^2 - \frac{1}{2}\left[\bar{m}_\eta^2+\Sigma_{\eta\eta}^{(4)}(0)\right]\tilde{\eta}^2 - \Sigma_{a\eta}^{(4)}(0)\tilde{a}\tilde{\eta}\,.$$

$\Sigma_{ij}^{(4)}(p^2)$ is the $O(p^4)$ two-point 1PI amplitude

$$\Sigma_{aa}^{(4)} = O(p^4/f_a^2)\,, \qquad \Sigma_{a\eta}^{(4)} = O(p^4/f_a)\,, \qquad \Sigma_{\eta\eta}^{(4)} = O(p^4)\,.$$

$\Sigma_{ij}^{(4)\prime}$ denotes $d\Sigma_{ij}^{(4)}(p^2)/dp^2$, which is momentum independent up to NLO.

- Fields redefinitions at NLO

$$\tilde{a} = \left(1+\frac{1}{2}\Sigma_{aa}^{(4)\prime}\right)a_{\rm phy} + \frac{\Sigma_{a\eta}^{(4)}(m_\eta^2)}{m_\eta^2-m_a^2}\eta_{\rm phy}\,, \quad \tilde{\eta} = \left(1+\frac{1}{2}\Sigma_{\eta\eta}^{(4)\prime}\right)\eta_{\rm phy} + \frac{\Sigma_{a\eta}^{(4)\prime}(m_a^2)}{m_a^2-m_\eta^2}a_{\rm phy}\,.$$

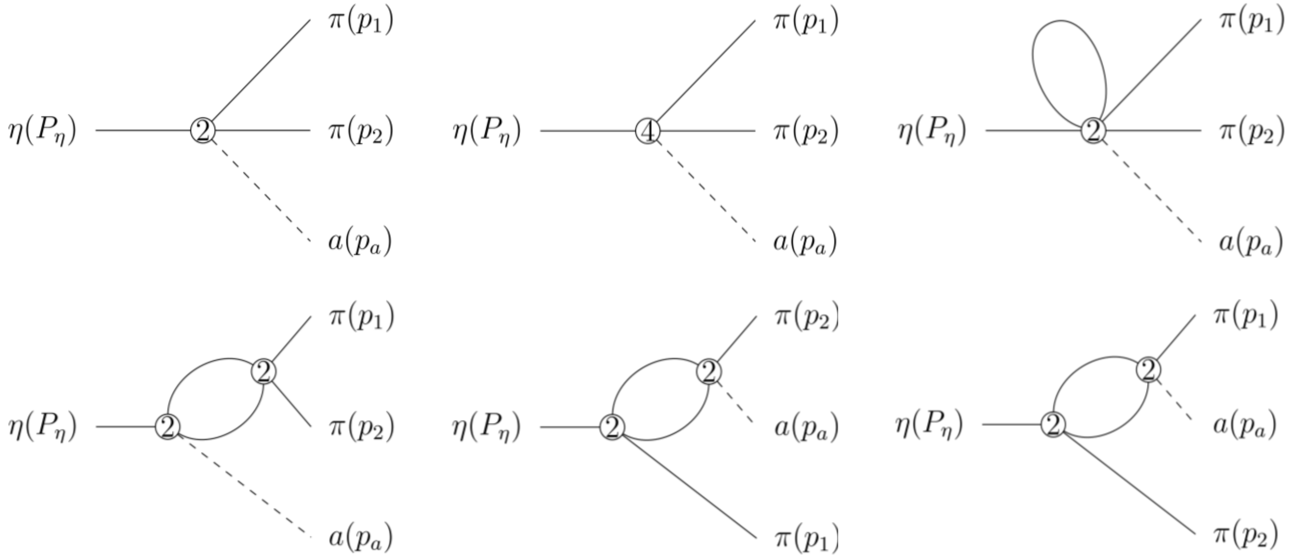
$$\mathcal{L}_{\rm mix}^{\rm NLO} = \frac{1}{2}\partial_\mu a_{\rm phy}\partial^\mu a_{\rm phy} - \frac{1}{2}m_a^2 a_{\rm phy}^2 + \frac{1}{2}\partial_\mu\eta_{\rm phy}\partial^\mu\eta_{\rm phy} - \frac{1}{2}m_\eta^2\eta_{\rm phy}^2$$

Perturbative calculation of the amplitude is performed by using fields variables $a_{\rm phy}$ and $\eta_{\rm phy}$.

$$\langle a(p_a)\pi^i(p_1)\pi^j(p_2)|\hat{T}|\eta(P_\eta)\rangle = (2\pi)^4\delta^4(P_\eta - p_1 - p_2 - p_a)\mathcal{M}_{\eta;\pi^i\pi^j a}(s,t,u)\,,$$

$$s = (p_1 + p_2)^2 = m_{\pi\pi}^2, \qquad t = (p_a + p_2)^2 = m_{a\pi}^2, \qquad u = (p_a + p_1)^2$$

- Feynman diagrams up to NLO



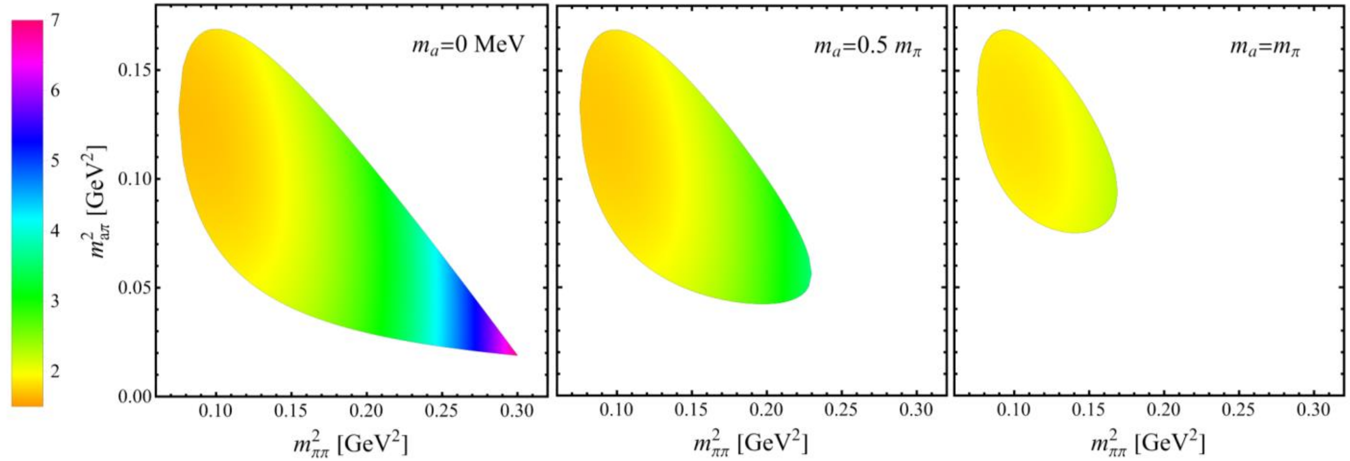
- Parameters

Masses and F_π [MeV]				LECs $L_i^r(\mu)$ at $\mu = 770$ MeV (in unit of 10^{-3})							
m_π	m_K	m_η	F_π	L_1^r	L_2^r	L_3^r	L_4^r	L_5^r	L_6^r	L_7^r	L_8^r
137	496	548	92.1	1.0(1)	1.6(2)	−3.8(3)	0.0(3)	1.2(1)	0.0(4)	−0.3(2)	0.5(2)

[J. Bijnens and G. Ecker, Ann. Rev. Nucl. Part. Sci. 64, 149 (2014)]

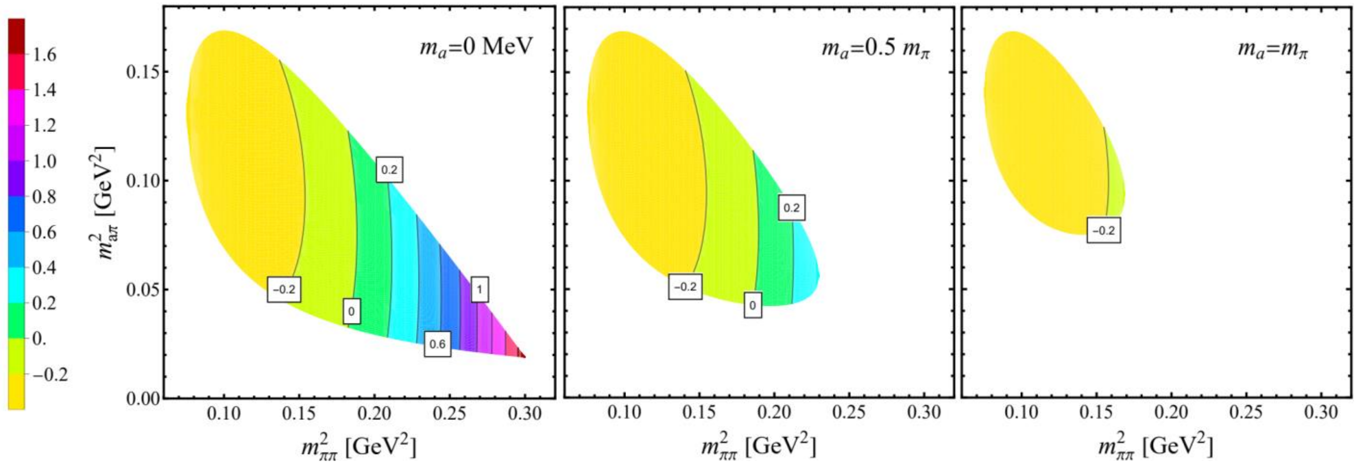
In isospin limit, the decay amplitudes for $\pi^+\pi^-$ channel and $\pi^0\pi^0$ channel turn out to be the same up to NLO.

$$10^6 f_a^2 \frac{d^2\Gamma_{\eta\to\pi^+\pi^- a}}{ds\,dt} = \frac{10^6 f_a^2}{32(2\pi)^3 m_\eta^3}\left(\left|\mathcal{M}^{(2)}_{\eta;\pi\pi a}\right|^2 + 2\mathcal{M}^{(2)}_{\eta;\pi\pi a}\mathrm{Re}\left(\mathcal{M}^{(4)}_{\eta;\pi\pi a}\right) + \left|\mathcal{M}^{(4)}_{\eta;\pi\pi a}\right|^2\right) \quad \text{in unit of GeV}^{-1}$$



$$\left(2\mathcal{M}^{(2)}_{\eta;\pi\pi a}\mathrm{Re}\left(\mathcal{M}^{(4)}_{\eta;\pi\pi a}\right) + \left|\mathcal{M}^{(4)}_{\eta;\pi\pi a}\right|^2\right) / \left|\mathcal{M}^{(2)}_{\eta;\pi\pi a}\right|^2$$

We focus on s-channel $\pi\pi$ two-body FSI in unitarization.



- Isospin amplitude

$$\mathcal{M}^{I=0}_{\eta;\pi\pi a} = -\frac{1}{\sqrt{3}}\mathcal{M}_{\eta;\pi^+\pi^- a} - \frac{1}{\sqrt{3}}\mathcal{M}_{\eta;\pi^-\pi^+ a} - \frac{1}{\sqrt{3}}\mathcal{M}_{\eta;\pi^0\pi^0 a} = -\sqrt{3}\mathcal{M}_{\eta;\pi\pi a}\,,$$
$$\mathcal{M}^{I=1}_{\eta;\pi\pi a} = -\frac{1}{\sqrt{2}}\mathcal{M}_{\eta;\pi^+\pi^- a} + \frac{1}{\sqrt{2}}\mathcal{M}_{\eta;\pi^-\pi^+ a} = 0\,,$$

- Partial waves (PWs) in $\pi\pi$ c.o.m frame

$$\mathcal{M}^{0J}_{\eta;\pi\pi a}(s) = \frac{1}{2(\sqrt{2})}\int_{-1}^{+1} \mathrm{d}\cos\theta P_J(\cos\theta)\mathcal{M}^{0}_{\eta;\pi\pi a}(s,t,u)\,, \quad J = 0, 2, 4, \cdots\,,$$

- Unitary relation consider s-channel $\pi\pi$ contribution

$$\mathrm{Im}\mathcal{M}^{0J}_{\eta;\pi\pi a}(s+i0^+) = \rho_{\pi\pi}(s)\mathcal{M}^{0J}_{\eta;\pi\pi a}(s)T^{0J*}_{\pi\pi\to\pi\pi}(s)\,, \qquad (2m_\pi < \sqrt{s} < 2m_K)\,,$$
$$\mathrm{Im}\mathcal{M}^{00,(4)}_{\eta;\pi\pi a}(s+i0^+) = \rho_{\pi\pi}(s)\mathcal{M}^{00,(2)}_{\eta;\pi\pi a}(s)\,T^{00,(2)}_{\pi\pi\to\pi\pi}(s)\,, \qquad (2m_\pi < \sqrt{s} < 2m_K)\,.$$

$$\rho_{\pi\pi}(s) = \frac{1}{16\pi}\sqrt{1-\frac{4m_\pi^2}{s}}\,, \quad T^{00,(2)}_{\pi\pi\to\pi\pi}(s) = \frac{2s-m_\pi^2}{2F_\pi^2}\,.$$

- Unitarized PW amplitude

$$\mathcal{M}^{00,\mathrm{Uni}}_{\eta;\pi\pi a}(s) = \frac{\mathcal{M}^{00,\mathrm{L}}_{\eta;\pi\pi a}(s)}{1 - G_{\pi\pi}(s) T^{00,(2)}_{\pi\pi\to\pi\pi}(s)} ,$$

$$G_{\pi\pi}(s) = -\frac{1}{(4\pi)^2}\left(\log\frac{m_\pi^2}{\mu^2} - \sigma_\pi(s)\log\frac{\sigma_\pi(s)-1}{\sigma_\pi(s)+1} - 1\right) ,$$

$$\mathcal{M}^{00,\mathrm{L}}_{\eta;\pi\pi a}(s) = \mathcal{M}^{00,(2)}_{\eta;\pi\pi a}(s) + \mathcal{M}^{00,(4)}_{\eta;\pi\pi a}(s) - G_{\pi\pi}(s)\,\mathcal{M}^{00,(2)}_{\eta;\pi\pi a}(s)\,T^{00,(2)}_{\pi\pi\to\pi\pi}(s) .$$

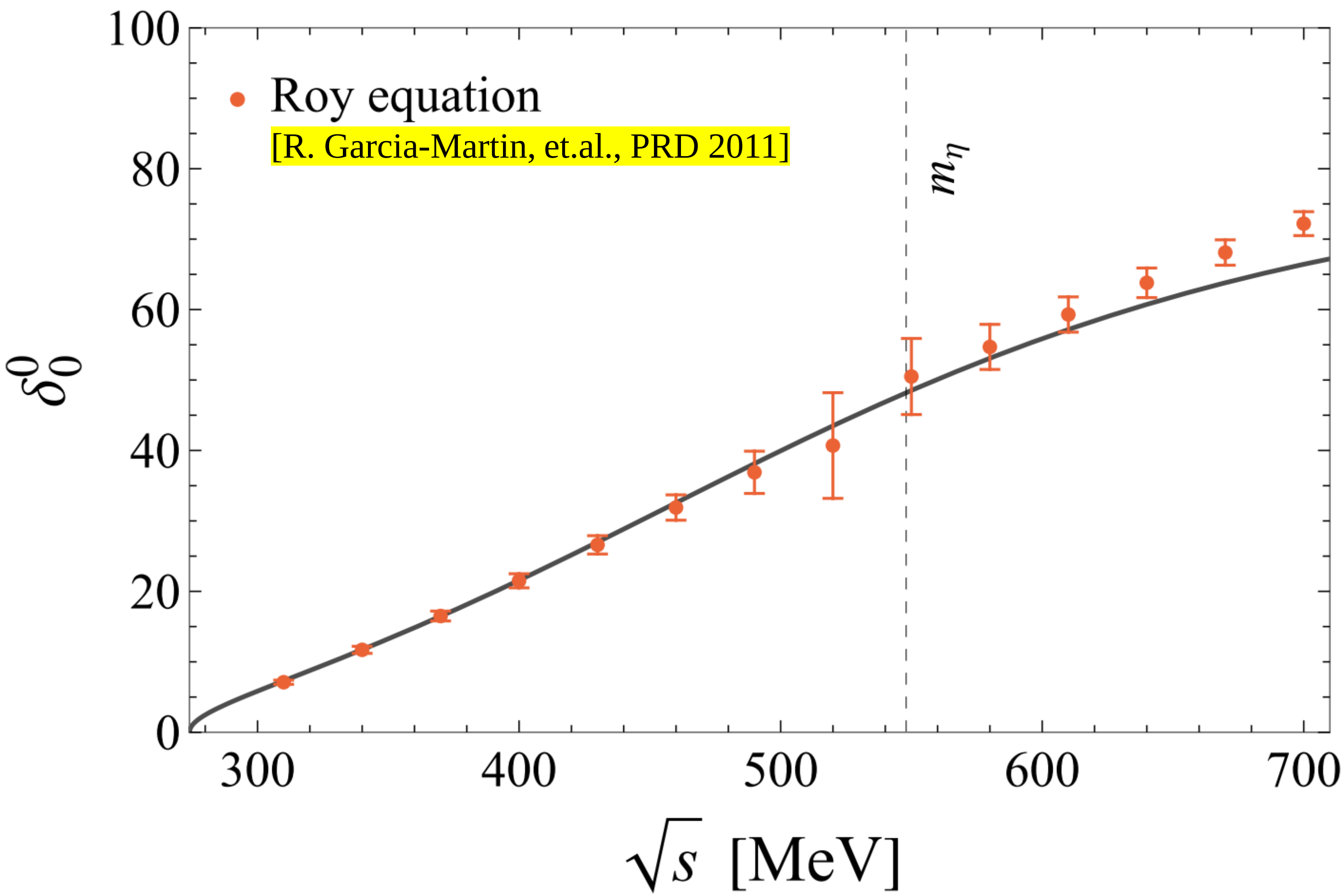
The unitarized amplitude satisfies the relation

$$\mathrm{Im}\mathcal{M}^{00,\mathrm{Uni}}_{\eta;\pi\pi a}(s) = \rho_{\pi\pi}(s)\mathcal{M}^{00,\mathrm{Uni}}_{\eta;\pi\pi a}(s)\left(T^{00,\mathrm{Uni}}_{\pi\pi\to\pi\pi}(s)\right)^* , \qquad (2m_\pi < \sqrt{s} < 2m_K)$$

if we define the unitarized $\pi\pi$ PW $\quad T^{00,\mathrm{Uni}}_{\pi\pi\to\pi\pi}(s) = \frac{T^{00,(2)}_{\pi\pi\to\pi\pi}(s)}{1 - G_{\pi\pi}(s)T^{00,(2)}_{\pi\pi\to\pi\pi}(s)}$

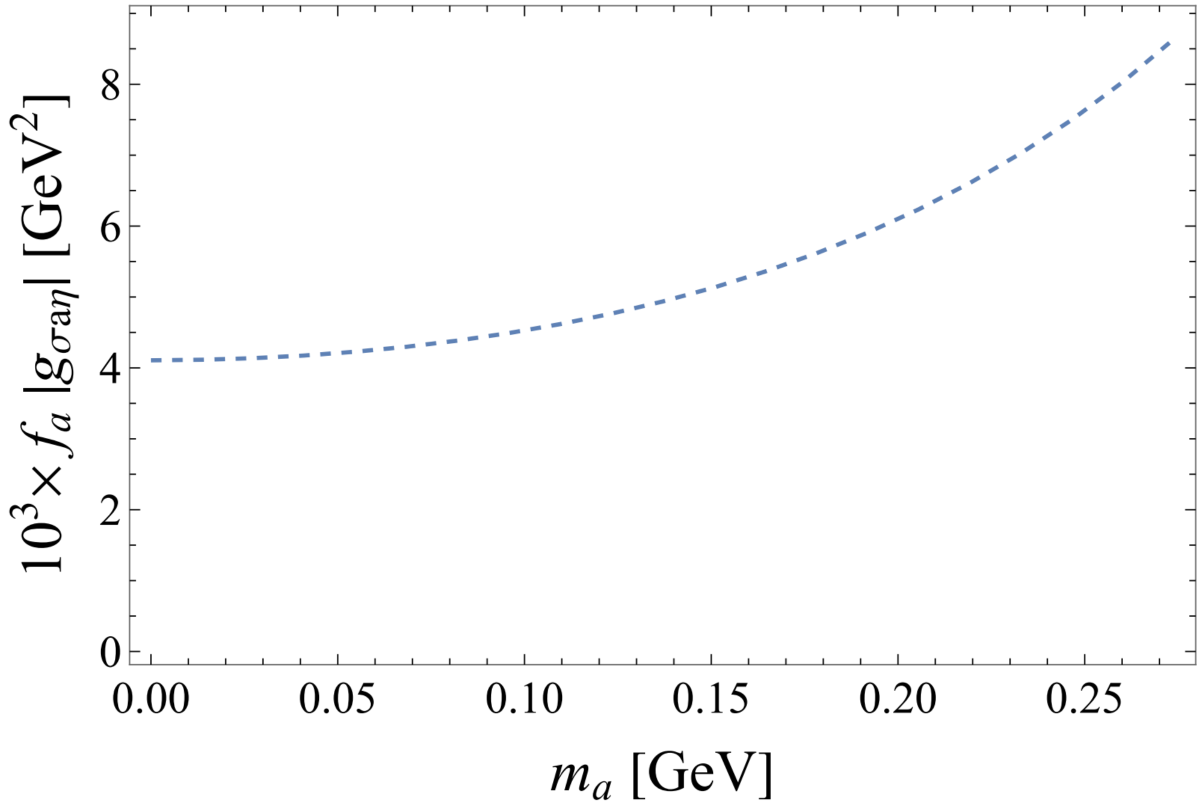
- Unitarized PW amplitude based on LO amplitude

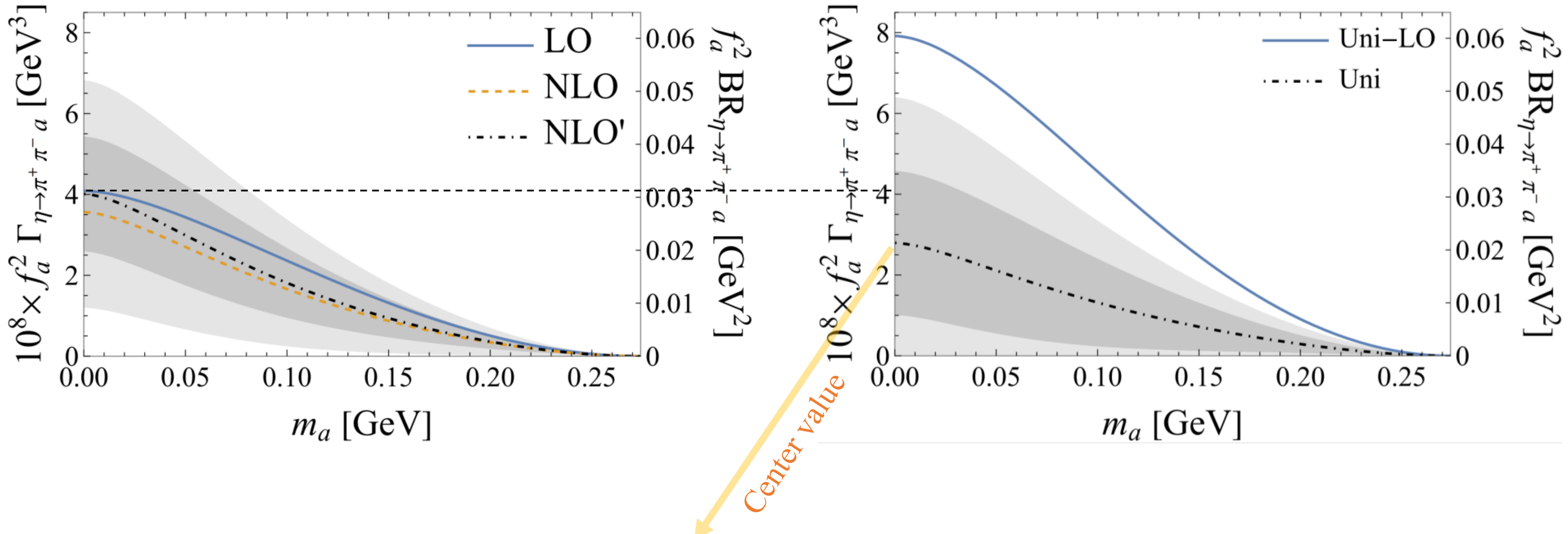
$$\mathcal{M}^{00,\mathrm{Uni-LO}}_{\eta;\pi\pi a}(s) = \frac{\mathcal{M}^{00,(2)}_{\eta;\pi\pi a}(s)}{1 - G_{\pi\pi}(s)T^{00,(2)}_{\pi\pi\to\pi\pi}(s)} .$$


Roy equation
[R. Garcia-Martin, et.al., PRD 2011]
m_η
100
80
60
40
20
0
δ_0^0
300
400
500
600
700
$\sqrt{s}$ [MeV]

- Pole position of $f_0(500)/\sigma$ on the second Riemann sheet $\sqrt{s_\sigma} = 457 \pm i251$ MeV
- σ-$a\eta$ coupling varying with m_a

$$\mathcal{M}^{00,\mathrm{Uni,II}}_{\eta;\pi\pi a}(s)\Big|_{s\to s_\sigma} \sim -\frac{g_{\sigma\pi\pi}g_{\sigma a\eta}}{s-s_\sigma}$$



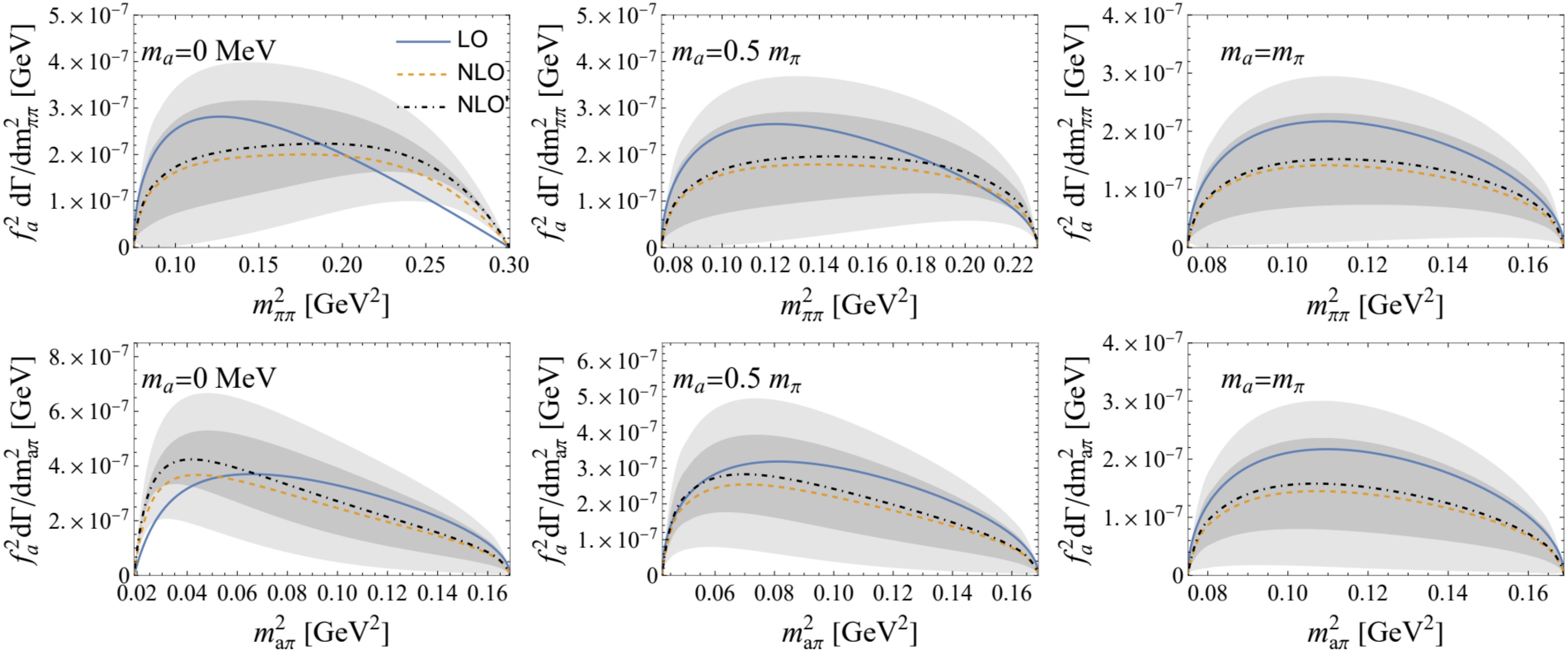


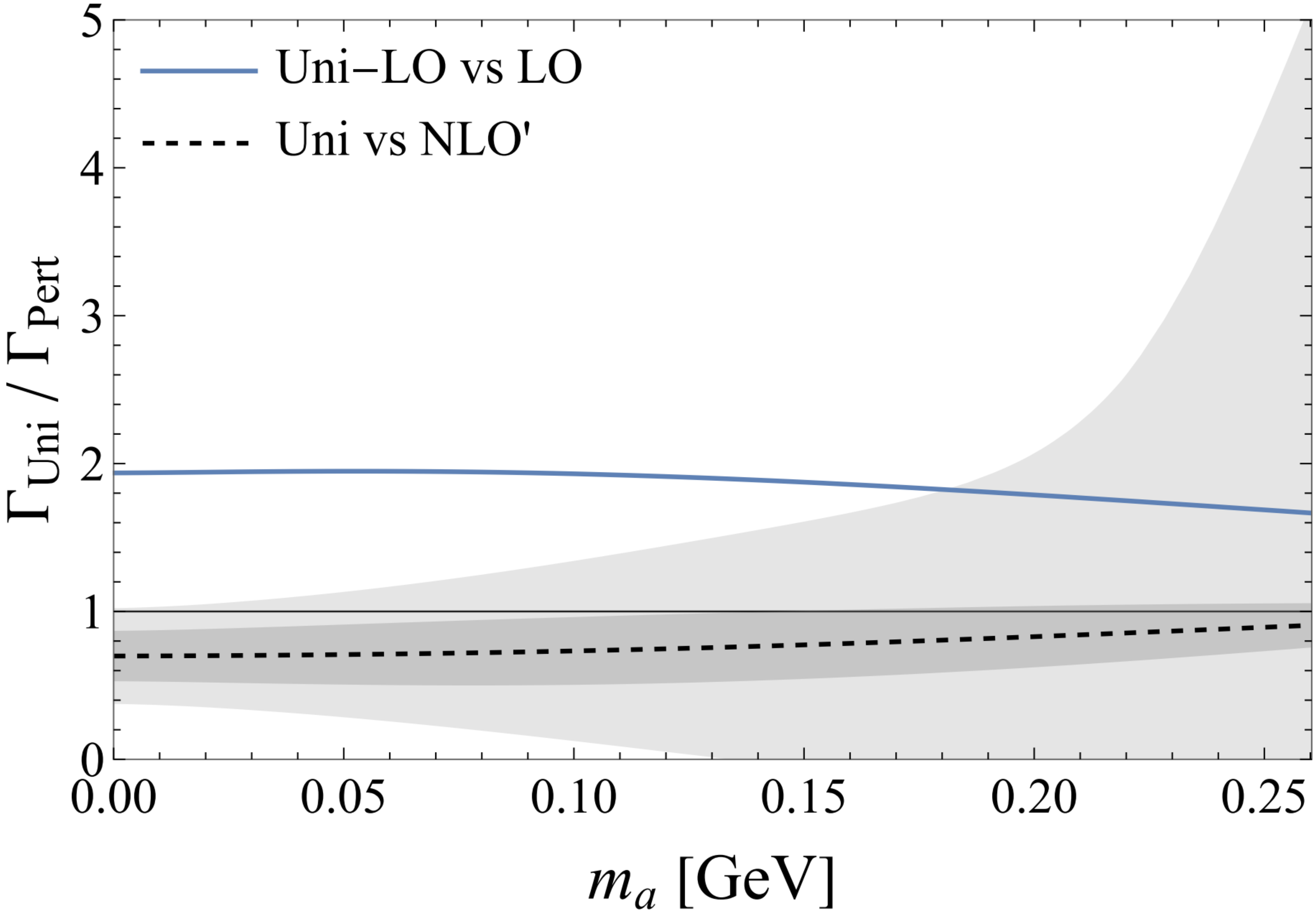
$$\mathrm{BR}_{\eta\to\pi^+\pi^- a}\Big|_{m_a\to 0} = 2.1\times 10^{-2}\left(\frac{\mathrm{GeV}^2}{f_a^2}\right)$$

SUMMARY

- We study $\eta \to \pi\pi a$ decay up to NLO in SU(3) ChPT.
- The unitarized decay amplitudes were further constructed to consider the s-channel $\pi\pi$ final state interaction effect, which can cause 30% correction in the estimation of partial decay width.
- We predict the branch ratio for $\eta \to \pi\pi a$ decay by varying m_a from 0 to $m_\eta - 2m_\pi$, but the result has a large uncertainty due to the error of LECs. To further pin down the error bars of LECs will be helpful to give more precise predictions to $\eta \to \pi\pi a$ decay process.

Thank you for listening


m_a=0 MeV
LO
NLO
NLO'
m_a=0.5 m_π
m_a=m_π
$f_a^2\, d\Gamma/dm_{\pi\pi}^2$ [GeV]
$m_{\pi\pi}^2$ [GeV^2]
$f_a^2 d\Gamma/dm_{a\pi}^2$ [GeV]
$m_{a\pi}^2$ [GeV^2]


Uni−LO vs LO
Uni vs NLO'
Γ_Uni / Γ_Pert
m_a [GeV]
0
1
2
3
4
5
0.00
0.05
0.10
0.15
0.20
0.25