Exploring new physics in η/η' factory

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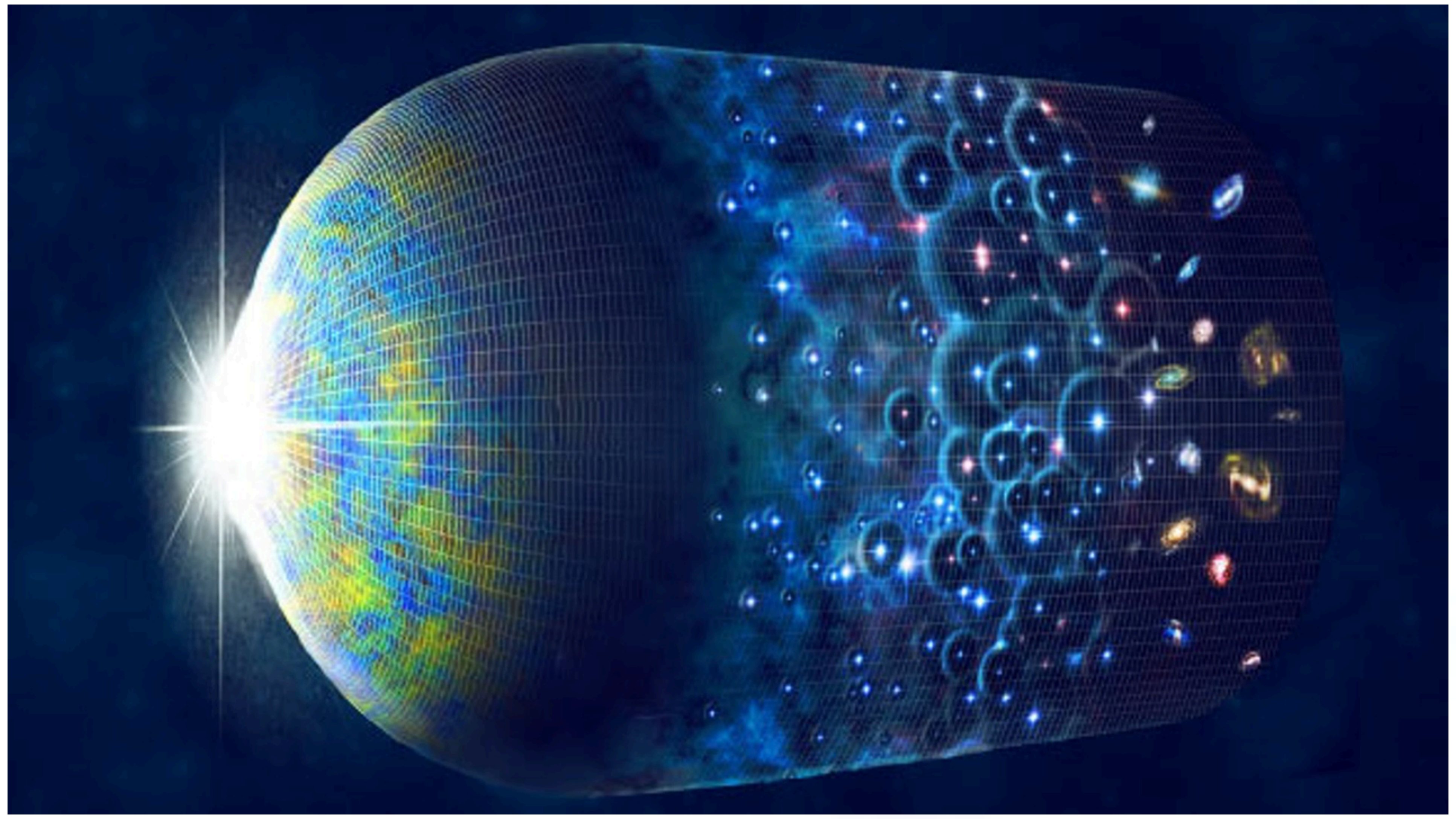
Motivation



Baryon asymmetry in universe (BAU):

$$\eta_B = \frac{n_B - n_{\bar{B}}}{n_\gamma} = \frac{n_B}{n_\gamma} : \quad 5.8 \times 10^{-10} \leq \eta_B \leq 6.5 \times 10^{-10} \text{ (95 \% CL)}$$

Fields, Molaro & Sarkar, review in PDG (2019)

Sakharov conditions:
i) baryon number violation
ii) C and CP violation
iii) deviation from thermal equilibrium

Sakharov, Pisma Zh. Eksp. Teor. Fiz. 5 (1967)

Standard Model cannot explain the size of BAU

CPV in SM: $|\eta_B| < 10^{-26}$

Farrar and Shaposhnikov, PRL 70 (1993)
Gavela et al., Mod. Phys. Lett.A9 (1994)
Huet and Sather, PRD51 (1995)

Motivation

Absence of conclusive evidence of new physics at high energies and dark matter studies suggest to probe new physics at low energies

e.g. Batell, Pospelov and Ritz, PRD80 (2009) 095024

Special Properties of η/η':

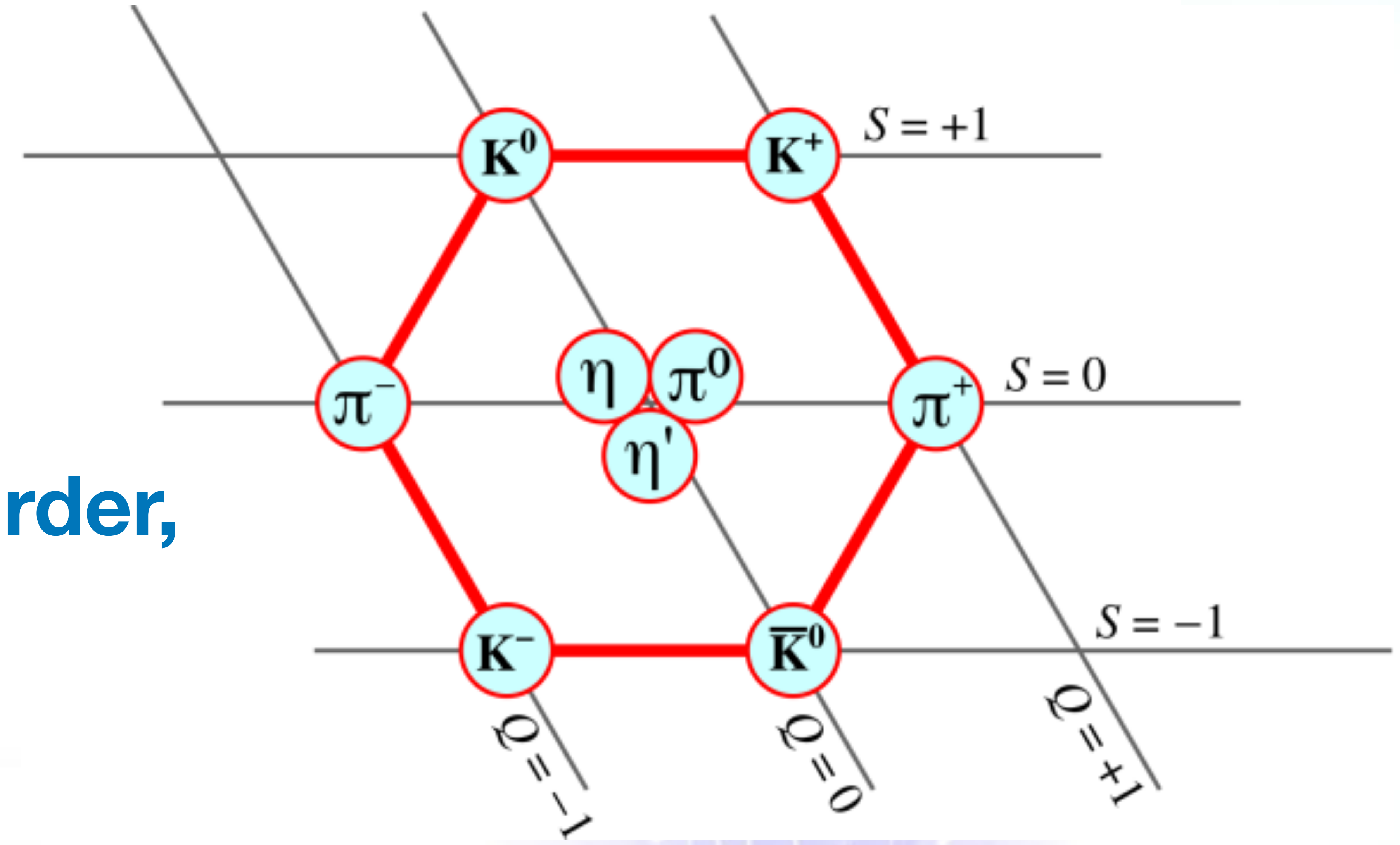
- **Eigenstate of C, P, CP, I and G:** $I^G J^{PC} = 0^+ 0^{-+}$
- **The same quantum numbers (except parity) as Higgs**

  "low-energy Higgs factory"

- **All decays are flavor-conserving (c.f. K and B decays)**
- **Most strong and EM decays are forbidden at the lowest order,**

  $\Gamma_\eta = 1.31 \pm 0.05$ **keV**, $\Gamma'_\eta = 188 \pm 6$ **keV**

  $M_\eta = 547.862 \pm 0.017$ **MeV**, $M_{\eta'} = 957.78 \pm 0.06$ **MeV**



η/η' decays provide a unique playground for precision test of the SM & to probe new physics

Physics in η/η' decays

Standard Model precision tests:

- **Chiral anomalies**

  $\eta/\eta' \to \gamma\gamma$ $\eta/\eta' \to \pi^+\pi^-\gamma\gamma$

- **Extract light-quark mass ratio** $Q = \sqrt{(m_s^2 - \hat{m}^2)/(m_u^2 - m_d^2)}$

  $\eta/\eta' \to 3\pi^0$ $\eta/\eta' \to \pi^+\pi^-\pi^0$

- **Theoretical inputs to** $(g-2)_\mu$

  $\eta/\eta' \to \pi^+\pi^-\gamma$ $\eta/\eta' \to e^+e^-\gamma$ $\eta/\eta' \to \mu^+\mu^-\gamma$

  $\eta/\eta' \to e^+e^-$ $\eta/\eta' \to \mu^+\mu^-$ $\eta/\eta' \to l^+l^-l^+l^-$

  $\eta' \to 2(\pi^+\pi^-)$ $\eta' \to \omega\gamma$ $\eta' \to \omega e^+e^-$

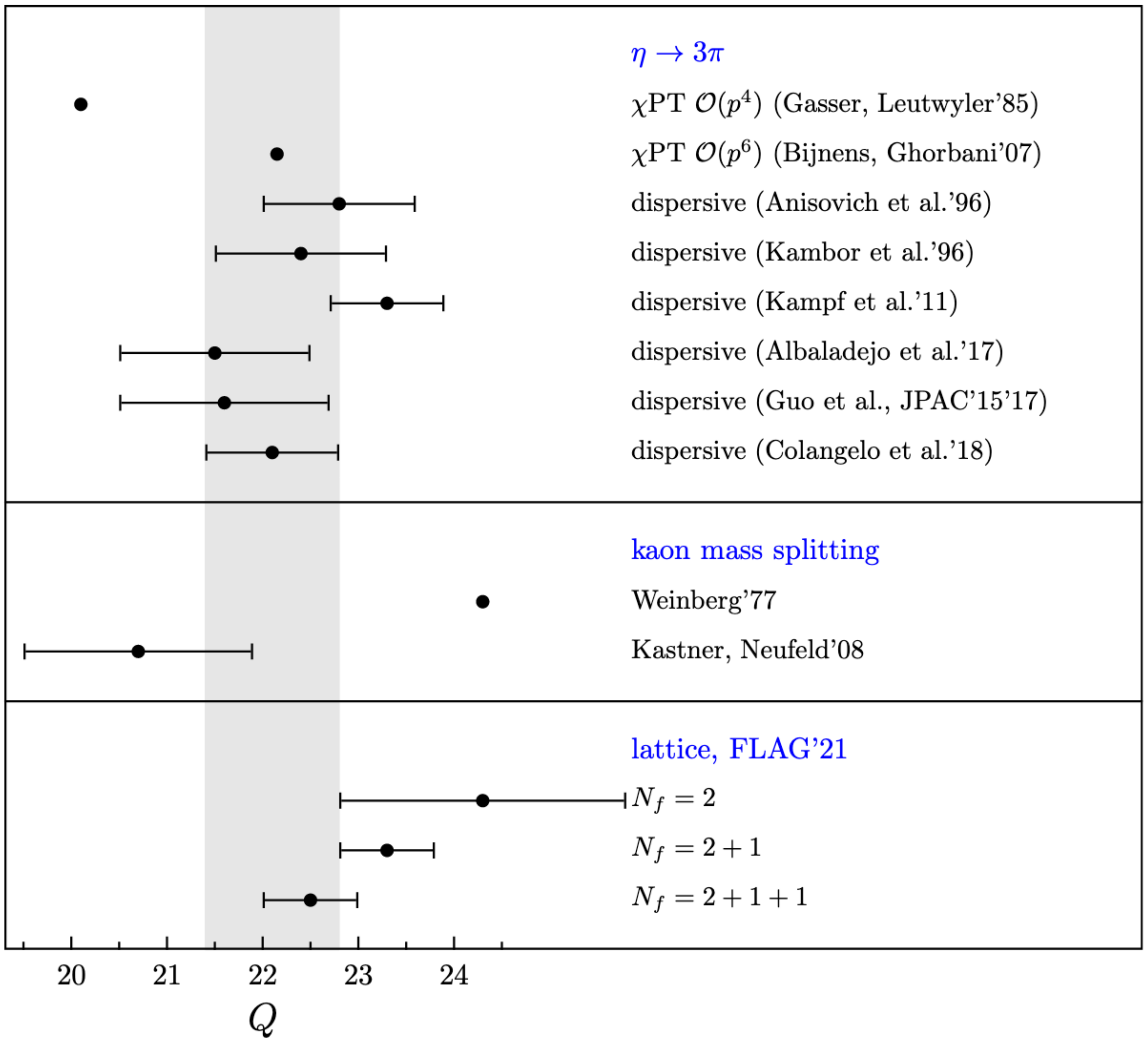
- ...

REDTOP arXiv: 2203.07651(2022)

L. Gan et al., Phys.Rept.945(2022)

Physics in η/η' decays

Status of Q



REDTOP arXiv: 2203.07651(2022)

Physics in η/η' decays

"Light dark matter (LDM) must be neutral under SM charges"

Search for four portals connecting dark sector and the SM:

- Vector portal

  dark photon: $\eta/\eta' \to \gamma A \to \gamma l^+l^-$

  leptophobic B boson: $\eta/\eta' \to \gamma B' \to \pi^0\gamma\gamma$ $\quad$ $\eta' \to B\gamma \to \pi^+\pi^-\pi^0\gamma$

  protophobic X boson: $\eta/\eta' \to \gamma X \to e^+e^-\gamma$ $\quad$ $\eta/\eta' \to \gamma X \to \mu^+\mu^-\gamma$

  $\eta/\eta' \to \pi^+\pi^- X \to \pi^+\pi^- l^+l^-$

- Scalar portal

  $\eta/\eta' \to \pi^0 S \to \pi^0 e^+e^-$ $\quad$ $\eta/\eta' \to \pi^0 S \to \pi^0\mu^+\mu^-$ $\quad$ $\eta' \to \eta S \to \eta\pi^+\pi^-$

- Pseudoscalar portal or axion-like particles (ALPs)

  $\eta/\eta' \to \pi\pi a \to \pi\pi\gamma\gamma,\ l^+l^-$ $\quad$ $\eta' \to \pi\pi a \to \pi\pi\pi^+\pi^-\gamma,\ 5pi$ $\quad$ $\eta' \to \eta\pi^0 a \to \eta\pi^0\gamma\gamma,\ \eta\pi^0 l^+l^-$

- Heavy Neutral Lepton portal

  $\eta/\eta' \to \pi^0 H, \quad H \to \nu N_2, \quad N_2 \to h' N_1, \quad h' \to e^+e^-$

Physics in η/η' decays

Fundamental symmetries tests:

- **Lepton flavor violation**

$\eta/\eta' \to e^-\mu^+ + e^+\mu^-$ $\eta/\eta' \to \gamma e^-\mu^+ + \gamma e^+\mu^-$ $\eta' \to \eta\mu^+\mu^-$

- **P and CP violation (EDM)**

$\eta/\eta' \to 2\pi$ $\eta/\eta' \to 4\pi^0$ $\eta/\eta' \to \pi^+\pi^-\gamma$

$\eta/\eta' \to \pi^+\pi^-e^+e^-,$ $\eta/\eta' \to \pi^+\pi^-\mu^+\mu^-$ $\eta/\eta' \to \mu^+\mu^-$

- **C and CP violation**

$\eta/\eta' \to \pi^+\pi^-\pi^0$ $\eta' \to \eta\pi^+\pi^-$

$\eta/\eta' \to \pi^+\pi^-\gamma$ $\eta/\eta' \to 3\gamma$

$\eta/\eta' \to \pi^0 l^+ l^-$ $\eta' \to \eta l^+ l^-$ $\eta \to 4\pi^0 l^+ l^-$

Physics in η/η' decays

η **decay channels**

Channel	Expt. branching ratio	Discussion
$\eta \to 2\gamma$	39.41(20)%	Chiral anomaly, η–η' mixing
$\eta \to 3\pi^0$	32.68(23)%	$m_u - m_d$
$\eta \to \pi^0\gamma\gamma$	$2.56(22) \times 10^{-4}$	χPT at $\mathcal{O}(p^6)$, leptophobic B boson, light Higgs scalars
$\eta \to \pi^0\pi^0\gamma\gamma$	$<1.2 \times 10^{-3}$	χPT, axion-like particles (ALPs)
$\eta \to 4\gamma$	$<2.8 \times 10^{-4}$	$<10^{-11}$[55]
$\eta \to \pi^+\pi^-\pi^0$	22.92(28)%	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta \to \pi^+\pi^-\gamma$	4.22(8)%	Chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta \to \pi^+\pi^-\gamma\gamma$	$<2.1 \times 10^{-3}$	χPT, ALPs
$\eta \to e^+e^-\gamma$	$6.9(4) \times 10^{-3}$	Theory input for $(g-2)_\mu$, dark photon, protophobic X boson
$\eta \to \mu^+\mu^-\gamma$	$3.1(4) \times 10^{-4}$	Theory input for $(g-2)_\mu$, dark photon
$\eta \to e^+e^-$	$<7 \times 10^{-7}$	Theory input for $(g-2)_\mu$, BSM weak decays
$\eta \to \mu^+\mu^-$	$5.8(8) \times 10^{-6}$	Theory input for $(g-2)_\mu$, BSM weak decays, P/CP violation
$\eta \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta \to \pi^+\pi^-e^+e^-$	$2.68(11) \times 10^{-4}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to \pi^+\pi^-\mu^+\mu^-$	$<3.6 \times 10^{-4}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, ALPs
$\eta \to e^+e^-e^+e^-$	$2.40(22) \times 10^{-5}$	Theory input for $(g-2)_\mu$
$\eta \to e^+e^-\mu^+\mu^-$	$<1.6 \times 10^{-4}$	Theory input for $(g-2)_\mu$
$\eta \to \mu^+\mu^-\mu^+\mu^-$	$<3.6 \times 10^{-4}$	Theory input for $(g-2)_\mu$
$\eta \to \pi^+\pi^-\pi^0\gamma$	$<5 \times 10^{-4}$	Direct emission only
$\eta \to \pi^\pm e^\mp \nu_e$	$<1.7 \times 10^{-4}$	Second-class current
$\eta \to \pi^+\pi^-$	$<4.4 \times 10^{-6}$ [56]	P/CP violation
$\eta \to 2\pi^0$	$<3.5 \times 10^{-4}$	P/CP violation
$\eta \to 4\pi^0$	$<6.9 \times 10^{-7}$	P/CP violation

L. Gan et al., Phys.Rept.945(2022)

Physics in η/η' decays

η' **decay channels**

L. Gan et al., Phys.Rept.945(2022)

Channel	Expt. branching ratio	Discussion
$\eta' \to \eta\pi^+\pi^-$	42.6(7)%	Large-N_c χPT, light Higgs scalars
$\eta' \to \pi^+\pi^-\gamma$	28.9(5)%	Chiral anomaly, theory input for singly-virtual TFF and $(g-2)_\mu$, P/CP violation
$\eta' \to \eta\pi^0\pi^0$	22.8(8)%	Large-N_c χPT
$\eta' \to \omega\gamma$	2.489(76)% [58]	Theory input for singly-virtual TFF and $(g-2)_\mu$
$\eta' \to \omega e^+e^-$	$2.0(4) \times 10^{-4}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$
$\eta' \to 2\gamma$	2.331(37)% [58]	Chiral anomaly, η–η' mixing
$\eta' \to 3\pi^0$	2.54(18)% $^{(\star)}$	$m_u - m_d$
$\eta' \to \mu^+\mu^-\gamma$	$1.09(27) \times 10^{-4}$	Theory input for $(g-2)_\mu$, dark photon
$\eta' \to e^+e^-\gamma$	$4.73(30) \times 10^{-4}$	Theory input for $(g-2)_\mu$, dark photon
$\eta' \to \pi^+\pi^-\mu^+\mu^-$	$<2.9 \times 10^{-5}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, dark photon, ALPs
$\eta' \to \pi^+\pi^-e^+e^-$	$2.4(^{+1.3}_{-1.0}) \times 10^{-3}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$, P/CP violation, dark photon, ALPs
$\eta' \to \pi^0\pi^0\ell^+\ell^-$		C/CP violation, ALPs
$\eta' \to \pi^+\pi^-\pi^0$	$3.61(17) \times 10^{-3}$	$m_u - m_d$, C/CP violation, light Higgs scalars
$\eta' \to 2(\pi^+\pi^-)$	$8.4(9) \times 10^{-5}$	Theory input for doubly-virtual TFF and $(g-2)_\mu$
$\eta' \to \pi^+\pi^-2\pi^0$	$1.8(4) \times 10^{-4}$	
$\eta' \to 2(\pi^+\pi^-)\pi^0$	$<1.8 \times 10^{-3}$	ALPs
$\eta' \to K^\pm\pi^\mp$	$<4 \times 10^{-5}$	Weak interactions
$\eta' \to \pi^\pm e^\mp\nu_e$	$<2.1 \times 10^{-4}$	Second-class current
$\eta' \to \pi^0\gamma\gamma$	$3.20(24) \times 10^{-3}$	Vector and scalar dynamics, B boson, light Higgs scalars
$\eta' \to \eta\gamma\gamma$	$8.3(3.5) \times 10^{-5}$ [59]	Vector and scalar dynamics, B boson, light Higgs scalars
$\eta' \to 4\pi^0$	$<4.94 \times 10^{-5}$ [60]	(S-wave) P/CP violation
$\eta' \to e^+e^-$	$<5.6 \times 10^{-9}$	Theory input for $(g-2)_\mu$, BSM weak decays
$\eta' \to \mu^+\mu^-$		Theory input for $(g-2)_\mu$, BSM weak decays
$\eta' \to \ell^+\ell^-\ell^+\ell^-$		Theory input for $(g-2)_\mu$
$\eta' \to \pi^+\pi^-\pi^0\gamma$		B boson
$\eta' \to \pi^+\pi^-$	$<1.8 \times 10^{-5}$	P/CP violation
$\eta' \to 2\pi^0$	$<4 \times 10^{-4}$	P/CP violation

Physics in η/η' decays

High priority η/η' decay channels suggested in L. Gan et al., Phys. Rept. 945 (2022)

Decay channel	Standard Model	Discrete symmetries	Light BSM particles
$\eta \to \pi^+\pi^-\pi^0$	light quark masses	C/CP violation	scalar bosons (also η')
$\eta^{(\prime)} \to \gamma\gamma$	η–η' mixing, precision partial widths		
$\eta^{(\prime)} \to \ell^+\ell^-\gamma$	$(g-2)_\mu$		Z' bosons, dark photon
$\eta \to \pi^0\gamma\gamma$	higher-order χPT, scalar dynamics		$U(1)_B$ boson, scalar bosons
$\eta^{(\prime)} \to \mu^+\mu^-$	$(g-2)_\mu$, precision tests	CP violation	
$\eta \to \pi^0\ell^+\ell^-$		C violation	scalar bosons
$\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$	$(g-2)_\mu$		ALPs, dark photon
$\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$		C violation	ALPs

Features of $\eta \to \pi^+\pi^-\pi^0$

$\eta: \quad I^G J^{PC} = 0^+0^{-+}$

$\pi^0: \quad I^G J^{PC} = 1^-0^{-+}$

$\pi^\pm: \quad I^G J^P = 1^-0^-$

$\pi^+\pi^-\pi^0: \quad C = -(-1)^I$

$\underline{\text{final states}}$	$\underline{\text{decay amplitude}}$
$I=1,\ C=+1$	$C \quad \lvert\Delta I\rvert = 1$
$I=0,\ C=-1$	$\cancel{C} \quad \lvert\Delta I\rvert = 0$
$I=2,\ C=-1$	$\cancel{C} \quad \lvert\Delta I\rvert = 2$
$\cdots$	$\cdots$

Lee, PR(1965)

$I=1$ **dominant,** $\propto (m_u - m_d)$

$$P\,\lvert[\pi_1(\mathbf{p})\pi_2(-\mathbf{p})]_l\pi_3(\mathbf{p}')_l\rangle = -\,\lvert[\pi_1(\mathbf{p})\pi_2(-\mathbf{p})]_l\pi_3(\mathbf{p}')_l\rangle$$

P is conserved $\Rightarrow$ C and CP violation

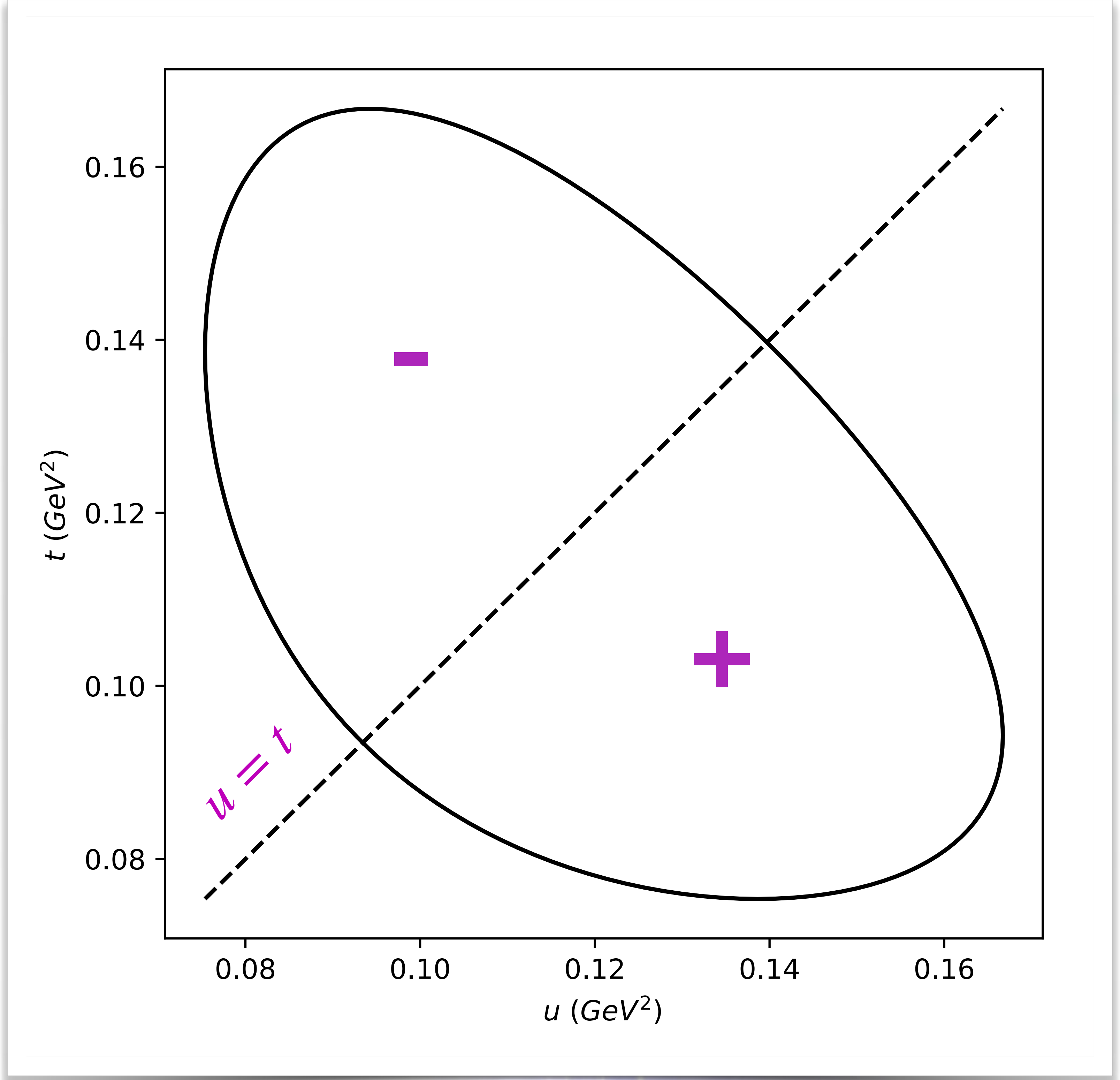
- **flavor-conserving C & CP violation**
- **no more theoretical considerations of CPV in $\eta \to \pi^+\pi^-\pi^0$ from 1966 to 2020**

Experimental Observables of CPV in $\eta \to \pi^+\pi^-\pi^0$

$$s = (p_{\pi^+} + p_{\pi^-})^2, \quad t = (p_{\pi^-} + p_{\pi^0})^2, \quad u = (p_{\pi^+} + p_{\pi^0})^2$$

C transformation $\Leftrightarrow \pi^+ \leftrightarrow \pi^- \Leftrightarrow t \leftrightarrow u$

Distribution asymmetry across the mirror line t=u of the Dalitz plot will show evidence of C & CP violation



left-right asymmetry: $A_{LR} = \dfrac{N_+ - N_-}{N_+ + N_-}$ $\quad (N_+ : \ u > t, N_- : \ u < t)$

$A_{LR} = (-5.0 \pm 4.5^{+5.0}_{-11}) \cdot 10^{-4}$ KLOE2 2016

$A_{LR} = (1.14 \pm 1.31) \times 10^{-3}$ BESIII 2023

Future experiments with higher statistics: Jlab eta factory, REDTOP, HIAF...

PoS CD2021(2024)029 arXiv: 2203.07651 arXiv: 2407.00874

Phenomenological Study of CPV in $\eta \to \pi^+\pi^-\pi^0$

C conserving: total isospin I=1

$$M_1^C(s,t,u) = f\left[M_0(s) + (s-u)M_1(t) + (s-t)M_1(u) + M_2(t) + M_2(u) - \frac{2}{3}M_2(s)\right]$$

dominant, $f \propto (m_u - m_d)$

C violating: total isospin I=0 and I=2

$$M_0^{\not C}(s,t,u) = \alpha[(s-t)M_1'(u) + (u-s)M_1'(t) - (u-t)M_1'(s)]$$

$$M_2^{\not C}(s,t,u) = \beta\left\{(s-t)M_1''(u) + (u-s)M_1''(t) + 2(u-t)M_1''(s) + \sqrt{5}[M_2''(u) - M_2''(t)]\right\}$$

$M_I(z)$: 2π scattering amplitude in z channel with I

total amplitude: $A(s,t,u) = M_1^C(s,t,u) + M_0^{\not C}(s,t,u) + M_2^{\not C}(s,t,u)$

$$|A(s,t,u)|^2 = |M_1^C(s,t,u) + M_0^{\not C}(s,t,u) + M_2^{\not C}(s,t,u)|^2 \sim |M_1^C|^2 + [M_1^C \cdot (M_0^{\not C} + M_2^{\not C})^* + h.c.] + \mathcal{O}(\alpha^2, \beta^2)$$

α and β can be determined by experiments

Different phenomenological studies found

Gardner and Shi, PRD101 (2020) 115038; Akdag, Isken and Kubis, JHEP 02(2022)137

$$|\beta|/|\alpha| \sim 10^{-3}$$

CP odd operators from SMEFT

$$SU(3)_C \times SU(2)_L \times U(1)_Y$$

$$\mathscr{L}_{\rm eff} = \mathscr{L}^{(4)}_{SM} + \mathscr{L}^{(4)}_{\theta} + \frac{1}{\Lambda}\mathscr{L}^{(5)} + \boxed{\frac{1}{\Lambda^2}\mathscr{L}^{(6)}} + \cdots \qquad \frac{1}{\Lambda^2}\sum_k C^{(6)}_k \mathscr{O}^{(6)}_k + \cdots$$

Grzadkowski et al., JHEP(2010)

- **CP survey: all dim-6 $\Delta B = 0,\ \Delta L = 0$ P & CP-odd + C & CP-odd operators from SMEFT**
- **flavor-conserving C & CP-odd operators at $E < M_W$**

$$(\bar{q}_L \sigma^{\mu\nu} \Gamma^d_W d_R)\tau^i \varphi W^i_{\mu\nu} + \mathrm{h.c.} \rightarrow v i\mathrm{Im}(\Gamma^d_W)\Big[(\bar{u}_L \sigma^{\mu\nu} d_R)\partial_\mu W^+_\nu - (\bar{d}_R \sigma^{\mu\nu} u_L)\partial_\mu W^-_\nu + \dots\Big] \rightarrow i\mathrm{Im}(\Gamma^d_W)\frac{gv}{2m_W^2}[(\bar{u}_L \sigma^{\mu\nu} d_R)\partial_\mu(\bar{d}'_L \gamma_\nu u_L) - (\bar{d}_R \sigma^{\mu\nu} u_L)\partial_\mu(\bar{u}_L \gamma_\nu d'_L)] + \cdots$$

$$\cdots v[(\bar{u}\sigma^{\mu\nu}\gamma_5 d)\partial_\mu(\bar{d}'\gamma_\nu u) + (\bar{d}\sigma^{\mu\nu}\gamma_5 u)\partial_\mu(\bar{u}\gamma_\nu d')]\cdots \qquad \cdots v[(\bar{u}\sigma^{\mu\nu} d)\partial_\mu(\bar{d}'\gamma_\nu u) - (\bar{d}\sigma^{\mu\nu} u)\partial_\mu(\bar{u}\gamma_\nu d')]\cdots$$

P odd C even

C odd P even

C and CP odd Operators pertinent to $\eta \to \pi^+\pi^-\pi^0$

$$\Omega^{\not{C}P} \sim \frac{i\sqrt{2}v}{\Lambda^2}\left\{\frac{g_Z}{4M_z^2}(\mathbf{Im}(C_{quZ\varphi}^{pp})\bar{u}_p\sigma^{\mu\nu}\gamma_5 u_p + \mathbf{Im}(C_{qdZ\varphi}^{pp})\bar{d}_p\sigma^{\mu\nu}\gamma_5 d_p)\partial_\mu\left(\bar{d}_r\gamma_\nu\gamma_5 d_r - \bar{u}_r\gamma_\nu\gamma_5 u_r\right)\right.$$

$$+\frac{g}{4M_W^2}\mathbf{Im}(C_{quW\varphi}^{pr} - C_{qdW\varphi}^{rp})\left[\bar{d}_p\sigma^{\mu\nu}u_r\partial_\mu(\bar{u}_r\gamma_\mu V_{rp}d_p) - \bar{u}_r\sigma^{\mu\nu}d_p\partial_\mu(\bar{d}_p\gamma_\mu V_{rp}^* u_r)\right]$$

$$\left.-\frac{g}{4M_W^2}\mathbf{Im}(C_{quW\varphi}^{pr} + C_{qdW\varphi}^{rp})\left[\bar{d}_p\sigma^{\mu\nu}\gamma_5 u_r\partial_\mu(\bar{u}_r\gamma_\mu\gamma_5 V_{rp}d_p) + \bar{u}_r\sigma^{\mu\nu}\gamma_5 d_p\partial_\mu(\bar{d}_p\gamma_\mu\gamma_5 V_{rp}^* u_r)\right]\right\}$$

$$\rightarrow \quad \begin{aligned} & i\bar{\psi}_i\sigma^{\mu\nu}\gamma_5\psi_i\partial_\mu(\bar{\psi}_j\gamma_\nu\gamma_5\psi_j), \\ & i\bar{\psi}_i\sigma^{\mu\nu}\gamma_5\psi_j\partial_\mu(\bar{\psi}_j\gamma_\nu\gamma_5\psi_i) + i\bar{\psi}_j\sigma^{\mu\nu}\gamma_5\psi_i\partial_\mu(\bar{\psi}_i\gamma_\nu\gamma_5\psi_j), \quad (i \neq j) \\ & i\bar{\psi}_i\sigma^{\mu\nu}\psi_j\partial_\mu(\bar{\psi}_j\gamma_\nu\psi_i) - i\bar{\psi}_j\sigma^{\mu\nu}\psi_i\partial_\mu(\bar{\psi}_i\gamma_\nu\psi_j), \quad (i \neq j) \end{aligned}$$

Using equations of motion, Fierz identities and integration by parts, they are equivalent with

$$\Omega^{\not{C}P} \sim \frac{vg}{M_W^2}\frac{1}{\Lambda^2}c_{ij}\bar{\psi}_i\overleftrightarrow{\partial}_\mu\gamma_5\psi_i\psi_j\gamma^\mu\gamma_5\psi_j$$

Matching to ChPT

$$\Omega^{\not{C}P} \sim \frac{vg}{M_W^2}\frac{1}{\Lambda^2} c_{ij}\bar{\psi}_i \overleftrightarrow{D}_\mu \gamma_5 \psi_i \psi_j \gamma^\mu \gamma_5 \psi_j$$

$$\sim \frac{vg}{M_W^2}\frac{1}{\Lambda^2} c_{ij}\Big[(\bar{q}_L \overleftrightarrow{D}_\mu \lambda_i^\dagger q_R)(\bar{q}_R \gamma^\mu \lambda_{R,j} q_R) - (\bar{q}_R \overleftrightarrow{D}_\mu \lambda_i q_L)(\bar{q}_R \gamma^\mu \lambda_{R,j} q_R)$$

$$+(\bar{q}_R \overleftrightarrow{D}_\mu \lambda_i q_L)(\bar{q}_L \gamma^\mu \lambda_{L,j} q_L) - (\bar{q}_L \overleftrightarrow{D}_\mu \lambda_i^\dagger q_R)(\bar{q}_L \gamma^\mu \lambda_{L,j} q_L)\Big]$$

chiral transformation property of spurions:

$$\mathcal{O}(p^0):\ \lambda \to R\lambda L^\dagger, \quad \lambda^\dagger \to L\lambda^\dagger R; \qquad \lambda_R \to R\lambda_R R^\dagger, \quad \lambda_L \to L\lambda_L L^\dagger$$

Matching to meson-level operators:

replacing the quark fields with chiral building blocks coupled to the spurions

Graesser JHEP2017(2017)99; Liao, Ma and Wang, JHEP01(2020)127; Akdag, Kubis and Wirzba, JHEP06(2023)154

$$\bar{U} = \exp\left(\bar{\Phi}/\mathrm{F}_0\right) \qquad \bar{\Phi} = \begin{pmatrix} \frac{1}{\sqrt{3}}\eta' + \sqrt{\frac{2}{3}}\eta + \pi^0 & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & \frac{1}{\sqrt{3}}\eta' + \sqrt{\frac{2}{3}}\eta - \pi^0 & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & \frac{2}{\sqrt{3}}\eta' - \sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

C and CP odd ChPT operators

order p^2: $$\mathscr{L}^{\not{C}P}_{p^2} = \frac{ivg}{M_W^2}\frac{1}{\Lambda^2}c_{ij}\Big[g_1\langle(\lambda_i D^2\bar{U}^\dagger\bar{U}\lambda_{L,j}\bar{U}^\dagger + \lambda_i^\dagger D^2\bar{U}\bar{U}^\dagger\lambda_{R,j}\bar{U}) - \mathrm{H.c.}\rangle$$
$$+g_2\langle(\lambda_i D_\mu\bar{U}^\dagger D^\mu\bar{U}\lambda_{L,j}\bar{U}^\dagger + \lambda_i^\dagger D_\mu\bar{U}D^\mu\bar{U}^\dagger\lambda_{R,j}\bar{U}) - \mathrm{H.c.}\rangle$$
$$+g_3\langle(\lambda_i\bar{U}^\dagger D^2\bar{U}\lambda_{L,j}\bar{U}^\dagger + \lambda_i^\dagger\bar{U}D^2\bar{U}^\dagger\lambda_{R,j}\bar{U}) - \mathrm{H.c.}\rangle\Big]$$

$g_i \sim [M]^5$

expanding $\bar{U}$ to $\bar{\Phi}^4$:

$$\frac{ivg}{M_W^2}\frac{1}{\Lambda^2F_0^4}2\mathcal{N}_{p^2}\partial^\mu\pi^0(\pi^+\partial_\mu\pi^- - \pi^-\partial_\mu\pi^+)\eta$$

$$\mathcal{N}_{p^2} = 4\sqrt{\frac{2}{3}}(c_{uu} - c_{ud} - c_{du} + c_{dd})(-g_1 + g_2 - g_3)$$

$$\mathscr{M}^{\not{C}}_{p^2}(s,t,u) = i\frac{vg}{M_W^2}\frac{1}{\Lambda^2F_0^4}\mathcal{N}_{p^2}(t-u) \equiv i\beta(t-u)$$

$\beta \sim [M]^{-2}$

decompose to $I=0$ and $I=2$:

$$\mathscr{M}^{\not{C}}_{I=0} = \frac{1}{\sqrt{6}}\left[-\mathscr{M}^{\not{C}}(t,s,u) + \mathscr{M}^{\not{C}}(s,t,u) - \mathscr{M}^{\not{C}}(u,t,s)\right],$$

$$\mathscr{M}^{\not{C}}_{I=2} = -\frac{1}{2\sqrt{3}}\left[\mathscr{M}^{\not{C}}(t,s,u) + 2\mathscr{M}^{\not{C}}(s,t,u) + \mathscr{M}^{\not{C}}(u,t,s)\right]$$

$$\mathscr{M}^{\not{C}}_{I=0,p^2} = 0$$

$$\mathscr{M}^{\not{C}}_{I=2,p^2} = -\sqrt{3/2}\mathscr{M}^{\not{C}}_{p^2}$$

Determine coefficient of p^2 C-violating amplitude

$$A(s,t,u) = M_1^C(s,t,u) + M^{\not C}(s,t,u)$$

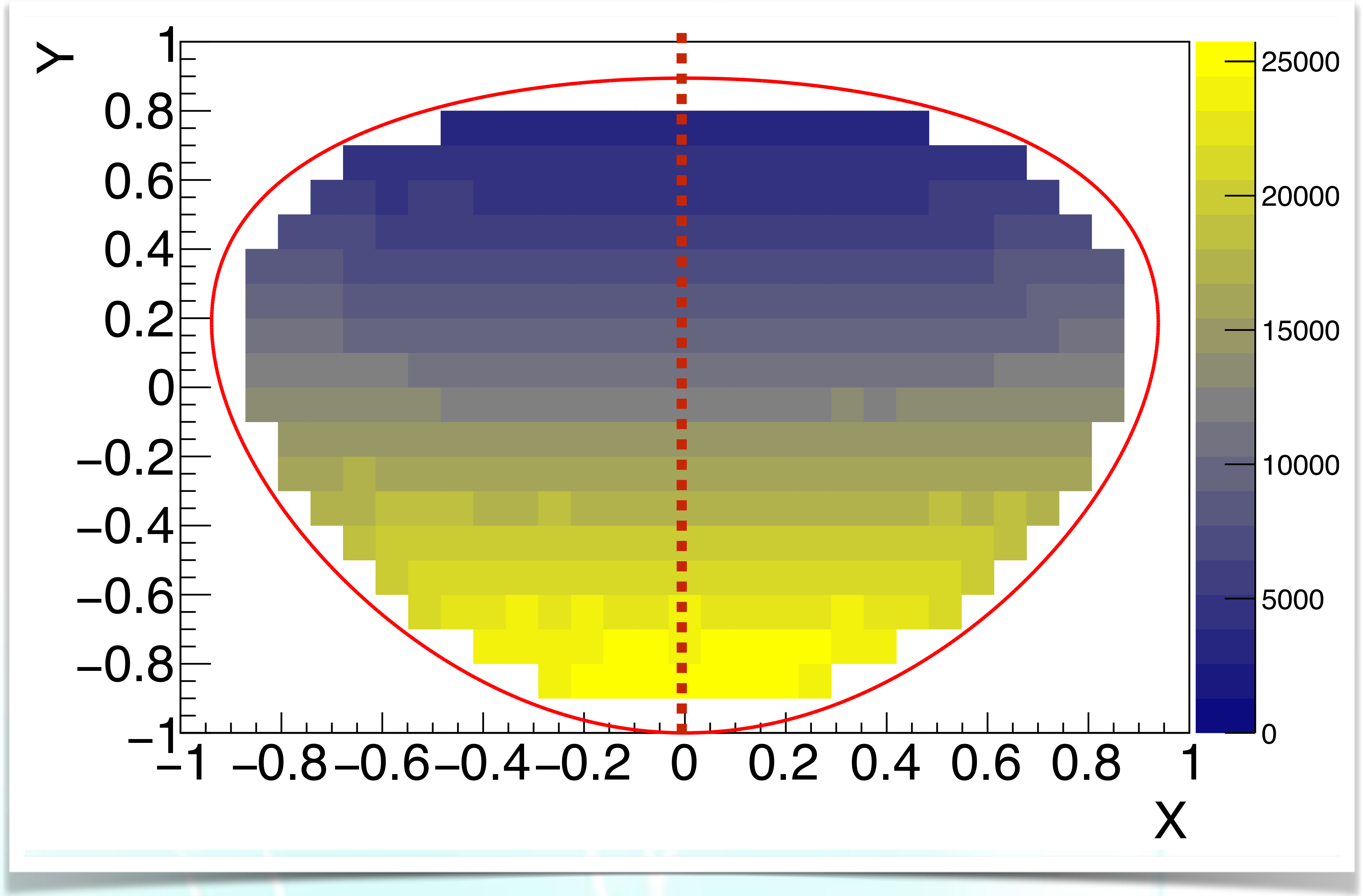
$$|A(s,t,u)|^2 = |M^C(s,t,u)|^2 + 2\mathrm{Re}[M^C(s,t,u)M^{\not C *}(s,t,u)] + \mathcal{O}(\beta^2)$$

$$X = \sqrt{3}\frac{T_{\pi^+} - T_{\pi^-}}{Q_\eta} = \frac{\sqrt{3}}{2m_\eta Q_\eta}(u-t),$$

$$Y = \frac{3T_{\pi^0}}{Q_\eta} - 1 = \frac{3}{2m_\eta Q_\eta}[(m_\eta - m_{\pi^0})^2 - s] - 1,$$

$$M^{\not C}(s,t,u) = \mathcal{M}^{\not C}_{p^2} = i\frac{vg}{M_W^2}\frac{1}{\Lambda^2 F_0^4}\mathcal{N}_{p^2}(t-u) \equiv i\beta(t-u),$$ $M^C(s,t,u)$ **from NLO ChPT**

Gasser and Leutwyler, NPB250(1985)539



KLOE2(2016)

$$N_i^{\not C}(X_i, Y_i) = \frac{1}{2}[N_i(X_i, Y_i) - N_i(-X_i, Y_i)], \quad (X_i > 0)$$

$$\frac{N_i^{\not C}}{N_{\mathrm{tot}}} = \frac{\int_i 2\mathrm{Re}\left[\mathcal{M}^C(X,Y)\cdot\mathcal{M}^{\not C}(X,Y)^*\right] dXdY}{\int |\mathcal{M}^C(X,Y)|^2 dXdY}$$

By a combined fit of KLOE2(2016) and BESIII(2023):

KLOE2, JHEP2016(2016)19; BESIII, PRD107(2023)092007

$$\beta = -0.026(13)\ \mathrm{GeV}^{-2}$$

New Physics Scale from Naive Dimensional Analysis

$$\mathcal{M}^{\mathbb{C}}_{p^2} = i\frac{vg}{M_W^2}\frac{1}{\Lambda^2 F_0^4}\mathcal{N}_{p^2}(t-u) \equiv i\beta(t-u)$$, **where** $\mathcal{N}_{p^2} = 4\sqrt{\frac{2}{3}}(c_{uu} - c_{ud} - c_{du} + c_{dd})(-g_1 + g_2 - g_3)$

From Naive Dimensional Analysis, e.g. B. M. Gavela et. al, Eur.Phys.J.C 76(2016)485; Manohar, arxiv:hep-ph/9606222

$g_i \sim F_0^4/\Lambda_\chi^3$ **with** $\Lambda_\chi = 4\pi F_0$.

Assuming no fine tuning in the UV completion of SMEFT, $c_{ij} \sim \mathcal{O}(1)$**.**

$\rightarrow$ $\mathcal{N}_{p^2} \sim F_0^4/\Lambda_\chi^3$

$$\Lambda \sim \left(\frac{vg\Lambda_\chi}{M_W^2}\frac{1}{|\beta|}\right)^{1/2}$$

Shi, Liang, and Gardner, PRD110(2024)

Using $|\beta| \lesssim 0.05\mathrm{GeV}^{-2}$ **at 90% C.L.,** $\Lambda \gtrsim 0.8\mathrm{GeV}^{-2}$

also note the LEFT study, $\Lambda \sim |\beta|^{-1/4}$

Akdag, Kubis and Wirzba, JHEP06(2023)154

- $\eta \to \pi^+\pi^-\pi^0$ **:** $\Lambda > 13$ GeV
- $\eta' \to \eta\pi^+\pi^-$ **:** $\Lambda > 4$ GeV
- $\eta(\eta') \to \pi^+\pi^-\gamma$**:** $\Lambda > 0.5$ GeV
- $\eta \to 3\pi^0\gamma$**:** $\Lambda > 140$ MeV
- $\eta(\eta') \to 3\gamma$**:** $\Lambda > 120$ MeV

Impact Study of Future Experiments

$$\Lambda \sim \left(\frac{vg\Lambda_\chi}{M_W^2} \frac{1}{|\beta|} \right)^{1/2}$$

Uncertainty reflect experiment's precision

Using $|\beta| \lesssim 0.01\mathrm{GeV}^{-2}$, $\Lambda \gtrsim 1.7\mathrm{GeV}^{-2}$

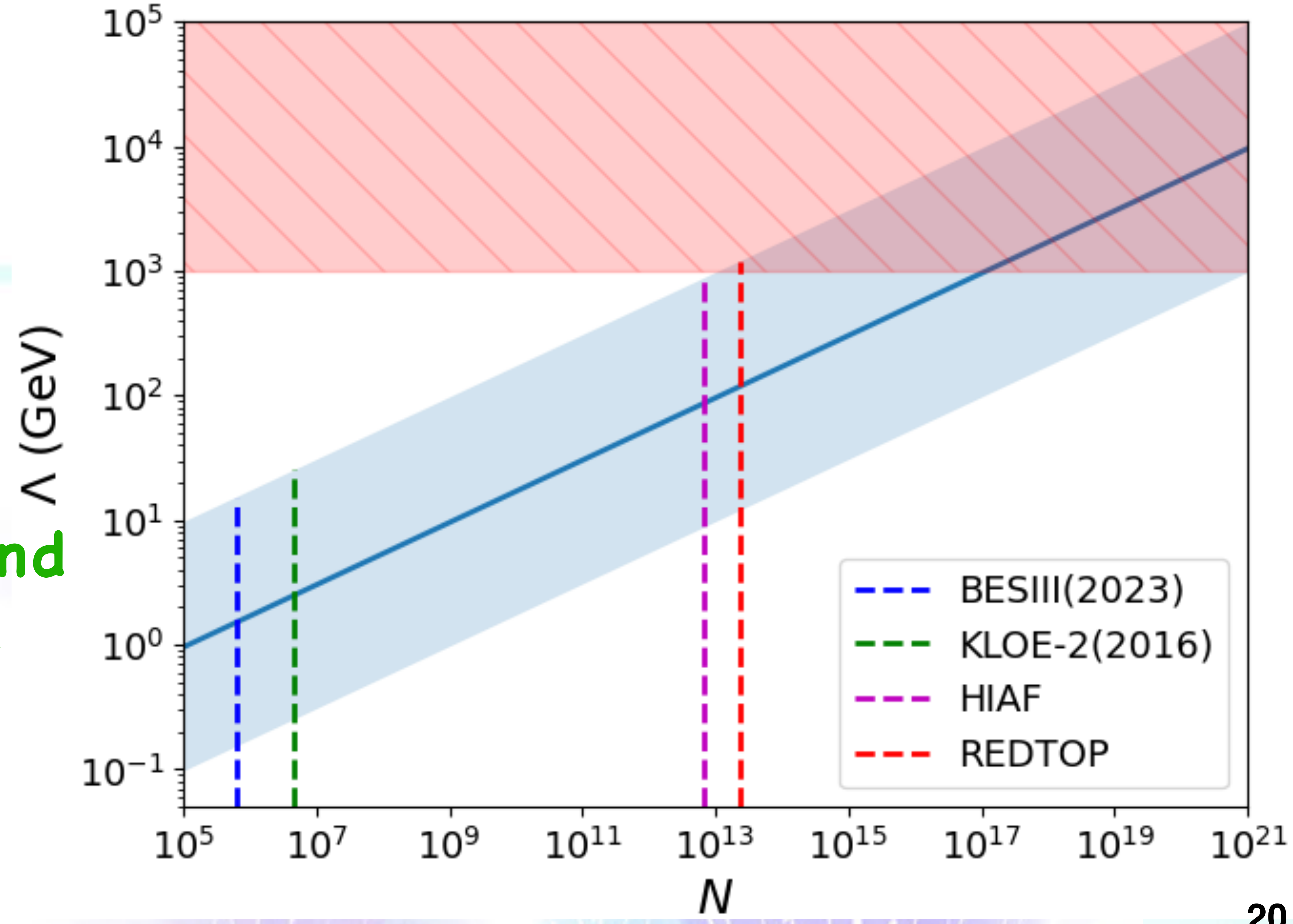
Assuming order of Λ has ± 1 uncertainty, $0.1\ \mathrm{GeV} \lesssim \Lambda \lesssim 10\ \mathrm{GeV}$

If Λ increase 10^n times, uncertainty of β should decrease 10^{2n} times, exp. statistics should increase 10^{4n} times

Shi, Liang, and Gardner, PRD110(2024)055039

KLOE2(2016): 4.7×10^6, **BESIII** 6.3×10^5

REDTOP: 2.3×10^{13}**/3yr, HIAF** 6.9×10^{12}**/3yr**



Channels with CPV from the interference of SM and BSM are less suppressed by the new physics scale comparing with pure C and CP violating channels

$$\eta \to \pi^+\pi^-\pi^0,\ \eta' \to \eta\pi^+\pi^-,\ \eta/\eta' \to \pi^+\pi^-\gamma$$

Summary and Outlook

- η/η' factory is a perfect laboratory for SM precision test and probing new physics beyond the SM.

- For flavor conserving C and CP violation study, preferred channels include $\eta \to \pi^+\pi^-\pi^0$, $\eta' \to \eta\pi^+\pi^-$, $\eta/\eta' \to \pi^+\pi^-\gamma$.

- Priority decay channels:

Decay channel	Standard Model	Discrete symmetries	Light BSM particles
$\eta \to \pi^+\pi^-\pi^0$	light quark masses	C/CP violation	scalar bosons (also η')
$\eta^{(\prime)} \to \gamma\gamma$	η–η' mixing, precision partial widths		
$\eta^{(\prime)} \to \ell^+\ell^-\gamma$	$(g-2)_\mu$		Z' bosons, dark photon
$\eta \to \pi^0\gamma\gamma$	higher-order χPT, scalar dynamics		$U(1)_B$ boson, scalar bosons
$\eta^{(\prime)} \to \mu^+\mu^-$	$(g-2)_\mu$, precision tests	CP violation	
$\eta \to \pi^0\ell^+\ell^-$		C violation	scalar bosons
$\eta^{(\prime)} \to \pi^+\pi^-\ell^+\ell^-$	$(g-2)_\mu$		ALPs, dark photon
$\eta^{(\prime)} \to \pi^0\pi^0\ell^+\ell^-$		C violation	ALPs

Looking forward to new experimental data!

Thank you!

Physics from η/η' decays

- **Search for axion-like particles**

$\eta/\eta' \to \pi^0\pi^0\gamma\gamma$ $\eta/\eta' \to \pi^+\pi^-\gamma\gamma$ $\eta/\eta' \to \pi^0\pi^0 e^+e^-$

$\eta/\eta' \to \pi^0\pi^0\mu^+\mu^-$

- **Weak decays beyond SM**

$\eta/\eta' \to e^+e^-$ $\eta/\eta' \to \mu^+\mu^-$

$\eta/\eta' \to \pi^+\pi^-\mu^+\mu^-$

- **Input of the precision calculation of the QCD axion $a \to \gamma\gamma$**

$\eta/\eta' \to \gamma\gamma$

C and CP odd ChPT operators

lowest order that yield non-vanishing $I=0$ amplitude:

$$\frac{ivg}{M_W^2}\frac{1}{\Lambda^2}c_{ij}\Big[f_1\langle\lambda\partial_\mu\partial_\nu\partial_\rho\bar U^\dagger U\lambda_L\partial^\mu\partial^\nu\bar U^\dagger U\partial^\rho\bar U^\dagger+\lambda^\dagger\partial_\mu\partial_\nu\partial_\rho\bar U U^\dagger\lambda_R\partial^\mu\partial^\nu\bar U U^\dagger\partial^\rho\bar U-\mathrm{H.c.}\rangle$$

$$+f_2\langle\lambda\partial_\mu\partial_\nu\partial_\rho\bar U^\dagger U\partial^\mu\partial^\nu\bar U^\dagger\lambda_R U\partial^\rho\bar U^\dagger+\lambda^\dagger\partial_\mu\partial_\nu\partial_\rho\bar U U^\dagger\partial^\mu\partial^\nu\bar U\lambda_L U^\dagger\partial^\rho\bar U-\mathrm{H.c.}\rangle$$

$$+f_3\langle\lambda\partial_\mu\partial_\nu\partial_\rho\bar U^\dagger\partial^\mu\partial^\nu U\bar U^\dagger\partial^\rho U\lambda_L\bar U^\dagger+\lambda^\dagger\partial_\mu\partial_\nu\partial_\rho\bar U\partial^\mu\partial^\nu U^\dagger\bar U\partial^\rho U^\dagger\lambda_R\bar U-\mathrm{H.c.}\rangle$$

$$+f_4\langle\lambda\partial_\mu\partial_\nu\partial_\rho\bar U^\dagger\partial^\mu\partial^\nu U\bar U^\dagger\lambda_R\partial^\rho U\bar U^\dagger+\lambda^\dagger\partial_\mu\partial_\nu\partial_\rho\bar U\partial^\mu\partial^\nu U^\dagger\bar U\lambda_L\partial^\rho U^\dagger\bar U-\mathrm{H.c.}\rangle$$

$$+f_5\langle\lambda\partial_\mu\partial_\nu\partial_\rho\bar U^\dagger U\lambda_L\partial^\mu\partial^\nu\bar U^\dagger\partial^\rho U\bar U^\dagger+\lambda^\dagger\partial_\mu\partial_\nu\partial_\rho\bar U U^\dagger\lambda_R\partial^\mu\partial^\nu\bar U\partial^\rho U^\dagger\bar U-\mathrm{H.c.}\rangle$$

$$+f_6\langle\lambda\partial_\mu\partial_\nu\partial_\rho\bar U^\dagger U\partial^\mu\partial^\nu\bar U^\dagger\lambda_R\partial^\rho U\bar U^\dagger+\lambda^\dagger\partial_\mu\partial_\nu\partial_\rho\bar U U^\dagger\partial^\mu\partial^\nu\bar U\lambda_L\partial^\rho U^\dagger\bar U-\mathrm{H.c.}\rangle$$

$$+f_7\langle\lambda\partial_\mu\partial_\nu\partial_\rho\bar U^\dagger U\partial^\mu\partial^\nu\bar U^\dagger\partial^\rho U\lambda_L\bar U^\dagger+\lambda^\dagger\partial_\mu\partial_\nu\partial_\rho\bar U U^\dagger\partial^\mu\partial^\nu\bar U\partial^\rho U^\dagger\lambda_R\bar U-\mathrm{H.c.}\rangle\Big]\qquad f_i\sim[M]$$

expanding $\bar U$ to $\bar\Phi^4$: $\dfrac{ivg}{M_W^2}\dfrac{1}{\Lambda^2F_0^4}8\mathcal{N}_{p^6}\epsilon_{IJK}(\partial_\mu\partial_\nu\partial_\rho\pi^I)(\partial^\mu\partial^\nu\pi^J)(\partial^\rho\pi^K)\eta$

$$\mathcal{N}_{p^6}=\sqrt{\frac{2}{3}}(c_{uu}-c_{ud}-c_{du}+c_{dd})(f_1+f_2+f_3-f_4-f_5-f_6+f_7)$$

$$\mathcal{M}_{p^6}^{\not{C}P}=i\frac{vg}{M_W^2}\frac{1}{\Lambda^2F_0^4}\mathcal{N}_{p^6}(s-t)(u-s)(t-u)\equiv i\alpha(s-t)(u-s)(t-u)\qquad\alpha\sim[M]^{-6}$$