New Physics from η/η' Rare Decays

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第二届惠州大科学装置高精度物理研讨会

Aug. 25, 2024

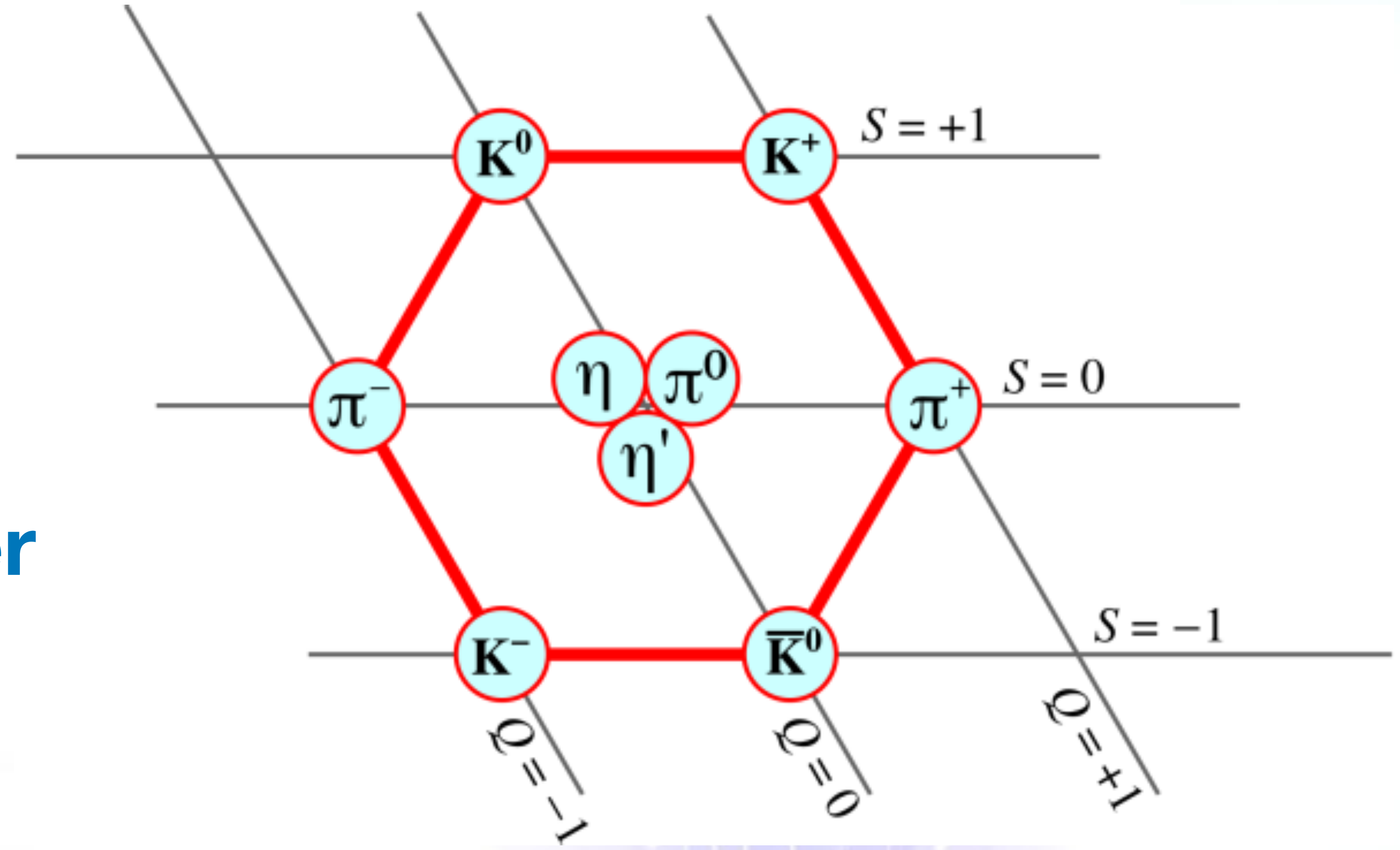
Motivation

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
- All decays are flavor-conserving (c.f. K and B decays)
- Most strong and EM decays are forbidden at leading order within SM



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

Physics from η/η' decays

Standard Model tests:

- **Chiral symmetry and anomalies**

  $\eta \to 2\gamma$, $\eta \to \pi^0\gamma\gamma$, $\eta \to \pi^0\pi^0\gamma\gamma$, $\eta \to \pi^+\pi^-\gamma\gamma$

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

  $\eta \to 3\pi^0$, $\eta \to \pi^+\pi^-\pi^0$

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

  $\eta \to \pi^+\pi^-\gamma$, $\eta \to e^+e^-\gamma$, $\eta \to \mu^+\mu^-\gamma$, $\eta \to e^+e^-$, $\eta \to \mu^+\mu^-$,
  $\eta \to e^+e^-\mu^+\mu^-$, $\eta \to \mu^+\mu^-\mu^+\mu^-$

- **…**

REDTOP arXiv: 2203.07651(2022); LiPing Gan et. al, Phys.Rept.945(2021) 2191

Physics from η/η' decays

Search for four portals connecting dark sector and the SM:

- **Vector portal**

  $\eta/\eta' \to \gamma l^+ l^-$ **(dark photon);** $\eta/\eta' \to \pi^0\gamma\gamma$ **(B boson);** $\eta/\eta' \to e^+e^-\gamma$ **(X boson)**

- **Scalar or Higgs portal**

  $\eta \to \pi^0 e^+ e^-$, $\eta \to \pi^0 \mu^+ \mu^-$

- **Pseudoscalar or Axion portal**

  $\eta \to \pi^+\pi^- l^+ l^-$, $\eta \to \pi^0\pi^0 l^+ l^-$, $\eta \to \pi^+\pi^-\gamma\gamma$

- **Heavy Neutral Lepton portal**

  $\eta \to \pi^0 e^+ e^-$

Physics from η/η' decays

Fundamental symmetries tests:

- **Lepton flavor violation**

  $\eta \to e^-\mu^+ + c.c., \eta \to \gamma e^-\mu^+ + c.c., \eta' \to \eta\mu^+\mu^-$

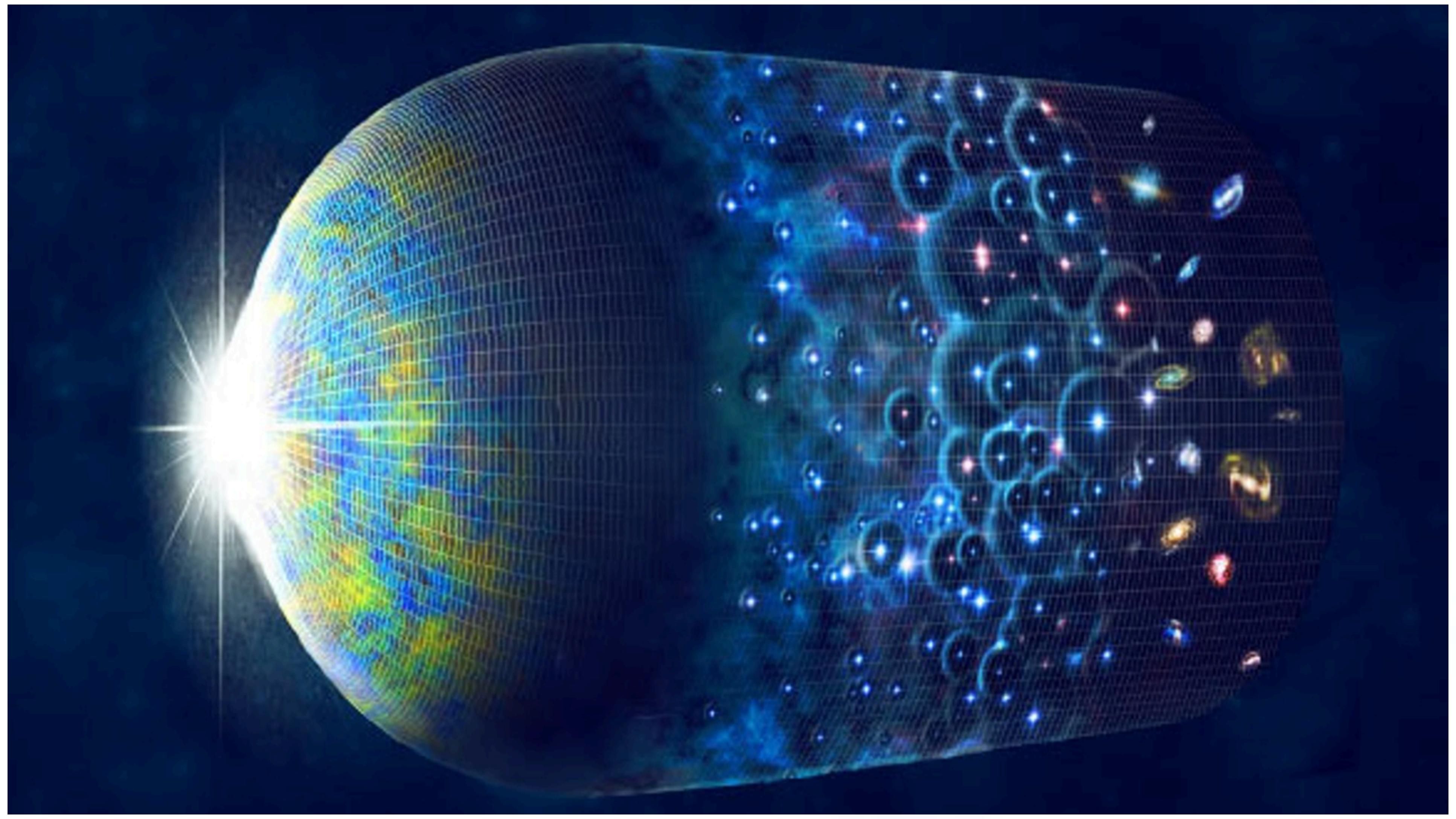
- **P and CP violation**

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

- **C and CP violation**

  $\eta \to \pi^+\pi^-\pi^0, \eta' \to \pi^+\pi^-\pi^0, \eta' \to \eta\pi^+\pi^-, \eta \to \pi^0 l^+l^-, \eta' \to \eta l^+l^-,$
  $\eta/\eta' \to \pi^+\pi^-\gamma, \eta \to 3\gamma, \eta \to 4\pi^0 l^+l^-$

Background of CP violation



Baryon asymmetry in universe (BAU):

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

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)

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

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

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

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

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

Lee, PR(1965)

final states	decay amplitude
$I = 1,\ C = +1$	$C \ \lvert\Delta I\rvert = 1$
$I = 0,\ C = -1$	$\not{C} \ \lvert\Delta I\rvert = 0$
$I = 2,\ C = -1$	$\not{C} \ \lvert\Delta I\rvert = 2$
$\cdots$	$\cdots$

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

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

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**

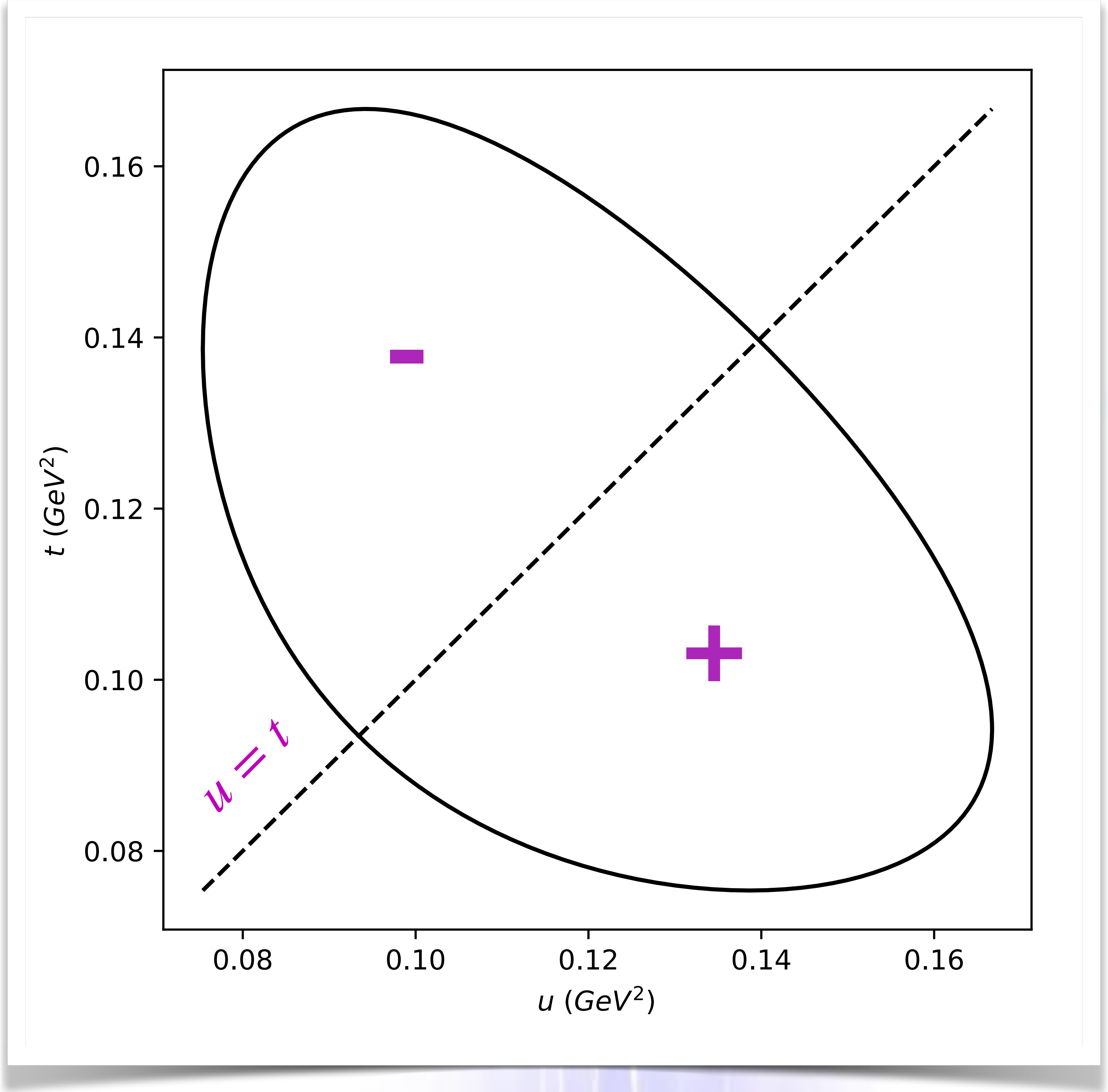
Experimental Observables of CPV in $\eta \to \pi^+\pi^-\pi^0$

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

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

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

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

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 $E < M_W$**

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

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

P odd C even

C odd P even

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

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

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

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

→

$$i\bar{\psi}_i\sigma^{\mu\nu}\gamma_5\psi_i\partial_\mu(\bar{\psi}_j\gamma_\nu\gamma_5\psi_j),$$

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

$$i\bar{\psi}_i\sigma^{\mu\nu}\psi_j\partial_\mu(\bar{\psi}_j\gamma_\nu\psi_i) - i\bar{\psi}_j\sigma^{\mu\nu}\psi_i\partial_\mu(\bar{\psi}_i\gamma_\nu\psi_j), \quad (i \neq j)$$

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

$$\bar{U} = \exp\left(\bar{\Phi}/F_0\right)$$

$$\bar{\Phi} = \begin{pmatrix} \frac{1}{\sqrt{3}}\eta' + \sqrt{\frac{2}{3}}\eta + \pi^0 & \sqrt{2}\pi^+ & \sqrt{2}K^+ \\ \sqrt{2}\pi^- & \frac{1}{\sqrt{3}}\eta' + \sqrt{\frac{2}{3}}\eta - \pi^0 & \sqrt{2}K^0 \\ \sqrt{2}K^- & \sqrt{2}\bar{K}^0 & \frac{2}{\sqrt{3}}\eta' - \sqrt{\frac{2}{3}}\eta \end{pmatrix}$$

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** $\bar{\Phi}^4$**:**

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

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

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

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

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

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

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

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

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

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

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

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

Determine coefficient of p^2 C-violating amplitude

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

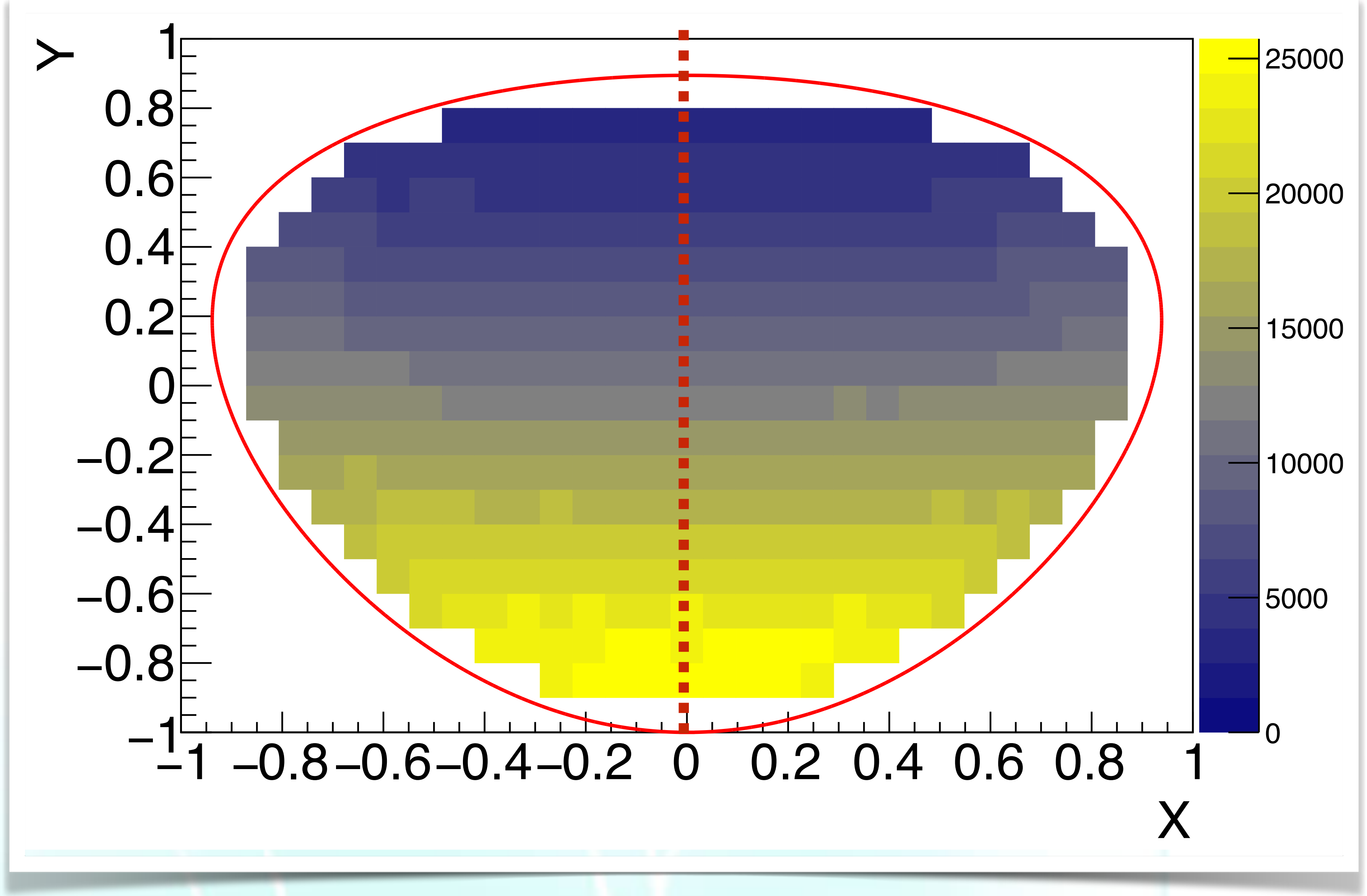
$$|A(s,t,u)|^2 = |M^C(s,t,u)|^2 + 2\mathrm{Re}[M^C(s,t,u)M^{\not C *}(s,t,u)] + \mathcal{O}(\beta^2)$$

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

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

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

Gasser and Leutwyler, NPB250(1985)539



KLOE2(2016)

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

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

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

$$\mathcal{M}^{\mathcal{C}}_{p^2} = i\frac{vg}{M_W^2}\frac{1}{\Lambda^2 F_0^4}\mathcal{N}_{p^2}(t-u) \equiv i\beta(t-u)$$, **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, $c_{ij} \sim \mathcal{O}(1)$**.**

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

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

Shi, Liang, and Gardner, arXiv: 2407.08766

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

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

- $\eta \to \pi^+\pi^-\pi^0$ **:** $\Lambda > 13$ 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

Akdag, Kubis and Wirzba, JHEP06(2023)154

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

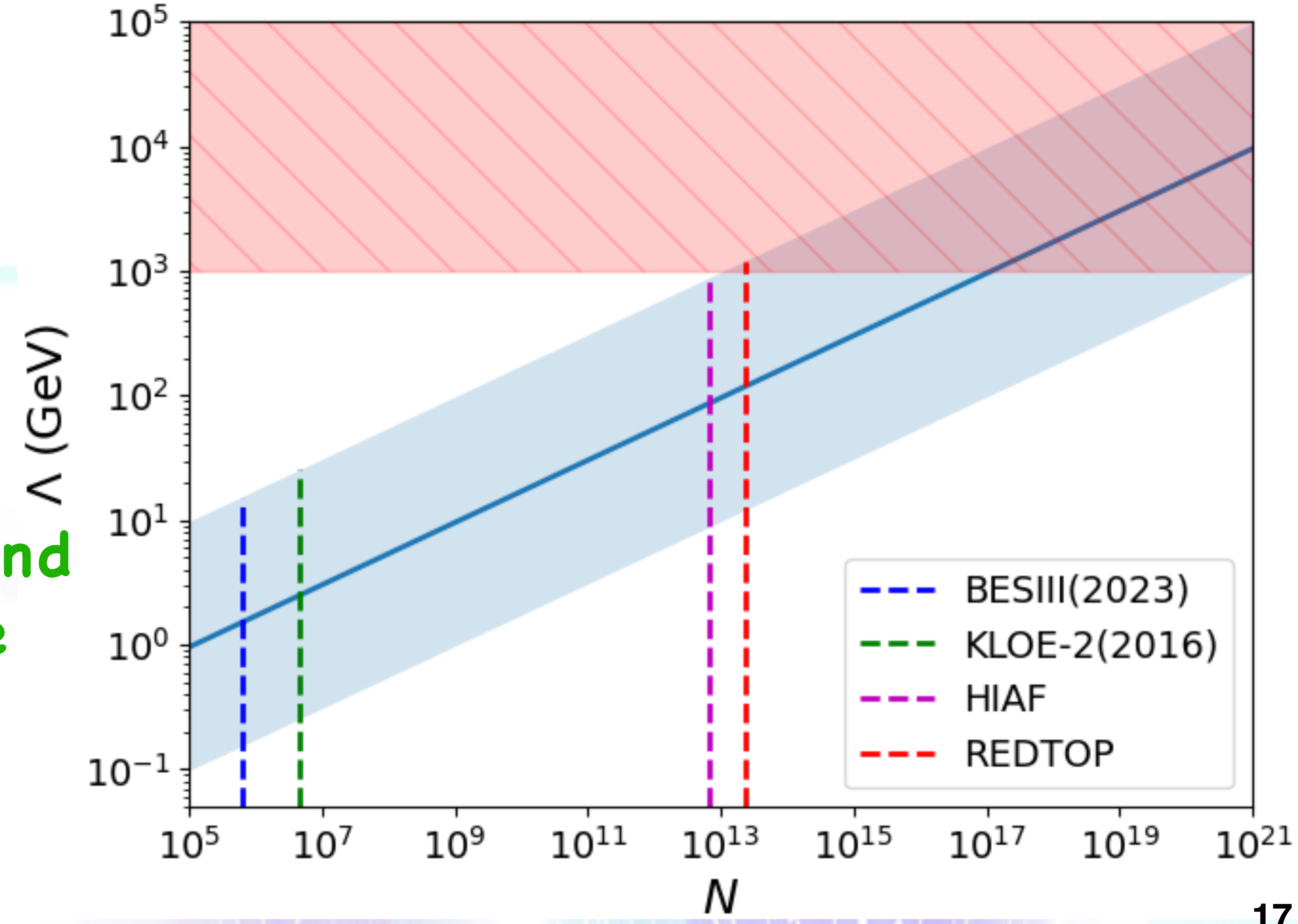
Assuming order of Λ **has** ± 1 **uncertainty,** $0.1\ \text{GeV} \lesssim \Lambda \lesssim 10\ \text{GeV}$

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, arXiv: 2407.08766

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, channels with CPV from the interference of SM and BSM are more suitable for probing new physics. $\eta \to \pi^+\pi^-\pi^0$, $\eta' \to \eta\pi^+\pi^-$, $\eta/\eta' \to \pi^+\pi^-\gamma$.

- We have established a complete theoretical framework to study η/η' decays and explore new physics. Looking forward to new experimental data!

Thank you!