MONASH University

Constraining new physics with hyperon decays

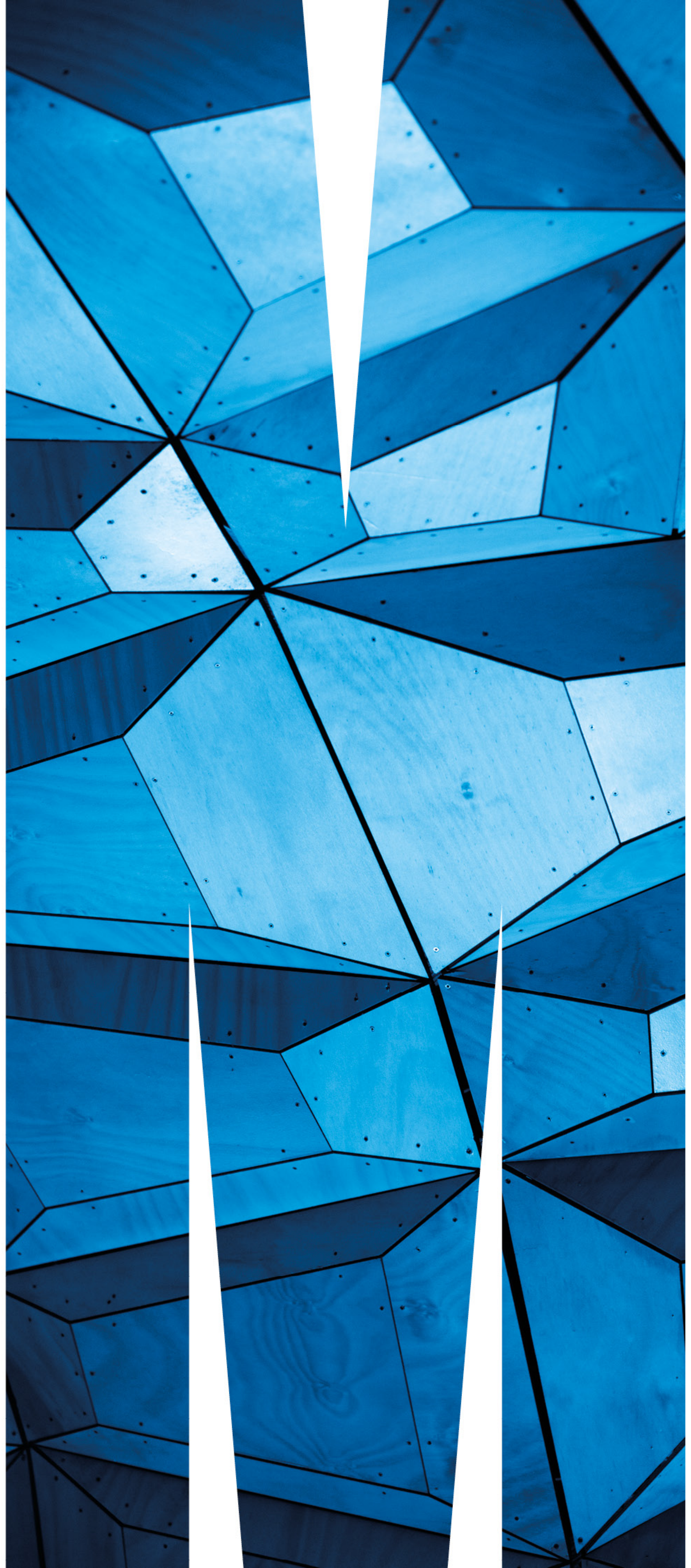
Corfu Summer Institute:
Workshop on the Standard Model and Beyond, 2023

German Valencia

based on work with Jusak Tandean and Xiao-Gang He

2304.02559 (to appear in PRD), Sci.Bull. 67 (2022) 1840-1843 (2209.04377), and JHEP 10 (2018) 040 (1806.08350), JHEP 07 (2019) 022 (1903.01242)

GROUP OF EIGHT AUSTRALIA



Present and future of hyperon physics

- LHCb A. Alves et. al. Prospects for Measurements with Strange Hadrons at LHCb *JHEP* 05 (2019) 048
  - $\Sigma^+ \to p\mu^+\mu^-$ already measured, $BR \simeq 2.4 \times 10^{-8}$, for run II expects $\gtrsim 150$ events
  - $\Xi^0 \to p\pi^-$ ($\Delta S = 2$) BR of $10^{-9} - 10^{-10}$ possible with LHCb upgrade
  - semileptonic modes, Ω decays, and others, improving current limits by orders of magnitude

- BESIII M.Ablikim et. al. for BESIII, Future Physics Programme of BESIII *Chin.Phys.C* 44 (2020) 4, 040001, Hai-Bo Li Prospects for rare and forbidden hyperon decays at BESIII
  - Can collect 10^6-10^8 Λ, Σ, Ξ, Ω and test BR in $10^{-5} - 10^{-8}$ range
  - Expect $\sim 10^6$ fully reconstructed $J/\psi \to \Lambda\bar{\Lambda} \to p\pi^-\bar{p}\pi^+$ and other two body chains

- Super tau-charm factory M. Achasov et. al. STCF Conceptual Design Report: Volume I - Physics & Detector e-Print: 2303.15790
  - Whereas BESIII could get $\sim 10^{10}$ J/ψ, the super tau-charm factory $\sim 3.4 \times 10^{12}$ J/ψ

Outline of the talk

- Physics: $\Delta S = 1$ and $\Delta S = 2$ decays
  - Rare decays
    - $\Sigma^+ \to p\mu^+\mu^-$ - anomalies?
      - complementary to $K^+ \to \pi^+\mu^+\mu^-, \quad K_L \to \mu^+\mu^-$
      - long distance dominated, very difficult to calculate precisely
    - $\Sigma^+ \to pe^\pm\mu^\mp$ - charged lepton flavour violation
      - complementary to $K_L \to \mu^\pm e^\mp, \quad K^+ \to \pi^+\mu^\pm e^\mp$
  - $\Delta S = 2$ beyond kaon mixing
  - CP violation beyond ϵ and ϵ'

χPT at leading order

- Strong interactions:

$$\mathscr{L}_s = \frac{f_\pi^2}{4}\mathrm{Tr}\left(\partial_\mu U \partial^\mu U^\dagger\right) + \mathrm{Tr}\overline{B}(i\not\partial - M)B + i\mathrm{Tr}\overline{B}\gamma^\mu\left[V_\mu, B\right]$$
$$+\mathrm{Tr}\left(D\overline{B}\gamma^\alpha\gamma_5\{\mathscr{A}_\alpha, B\} + F\overline{B}\gamma^\alpha\gamma_5[\mathscr{A}_\alpha, B]\right)$$
$$+\epsilon_{kln}\mathscr{C}\left[\left(\overline{T}_{nvw}\right)^\alpha(\mathscr{A}_{wl})_\alpha B_{vk} + \overline{B}_{kv}(\mathscr{A}_{lw})_\alpha(T_{nvw})^\alpha\right],$$

$$\pi = \frac{1}{\sqrt{2}}\begin{pmatrix} \frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & \pi^+ & K^+ \\ \pi^- & -\frac{1}{\sqrt{2}}\pi^0 + \frac{1}{\sqrt{6}}\eta_8 & K^0 \\ K^- & \overline{K}^0 & -\frac{2}{\sqrt{6}}\eta_8 \end{pmatrix} \qquad B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

$$T_{111} = \Delta^{++}, \quad T_{112} = \frac{1}{\sqrt{3}}\Delta^+, \quad T_{122} = \frac{1}{\sqrt{3}}\Delta^0, \quad T_{222} = \Delta^-,$$
$$T_{113} = \frac{1}{\sqrt{3}}\Sigma^{*+}, \quad T_{123} = \frac{1}{\sqrt{6}}\Sigma^{*0}, \quad T_{223} = \frac{1}{\sqrt{3}}\Sigma^{*-},$$
$$T_{133} = \frac{1}{\sqrt{3}}\Xi^{*0}, \quad T_{233} = \frac{1}{\sqrt{3}}\Xi^{*-}, \quad T_{333} = \Omega^- .$$

- D, F from semileptonic decay and $\mathscr{C}$ from strong $TB\phi$ decay
  - corrections $\sim 30\,\%$ if decuplet is included

$$\xi = e^{i\pi/f},\ U = \xi^2$$
$$A_\mu = i(\xi\partial_\mu\xi^\dagger - \xi^\dagger\partial_\mu\xi)$$
$$\hat{\kappa} = (\lambda_6 + i\lambda_7)/2$$

- Weak interactions

$$\mathscr{L}^{sm}_{\Delta S=1} \supset \mathrm{Tr}\left(h_D\overline{B}\{\xi^\dagger\hat{\kappa}\xi, B\} + h_F\overline{B}\left[\xi^\dagger\hat{\kappa}\xi, B\right]\right) + h_C\left(\overline{T}_{kln}\right)^\eta\left(\xi^\dagger\hat{\kappa}\xi\right)_{no}(T_{klo})_\eta$$

- h_D, h_F, h_C from fits to weak non-leptonic hyperon decay (S or P wave usual problem) and P waves of $\Omega \to B\phi$ decay
  - order of magnitude estimate

$$\Sigma^+ \rightarrow p\mu^+\mu^-$$

$\Sigma^+ \to p\mu^+\mu^-$ - experiment

- HyperCP (2005) $B(\Sigma^+ \to p\mu^+\mu^-) = (8.6^{+6.6}_{-5.4} \pm 5.5) \times 10^{-8}$
- LHCb (2018) $B(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$ with no structure

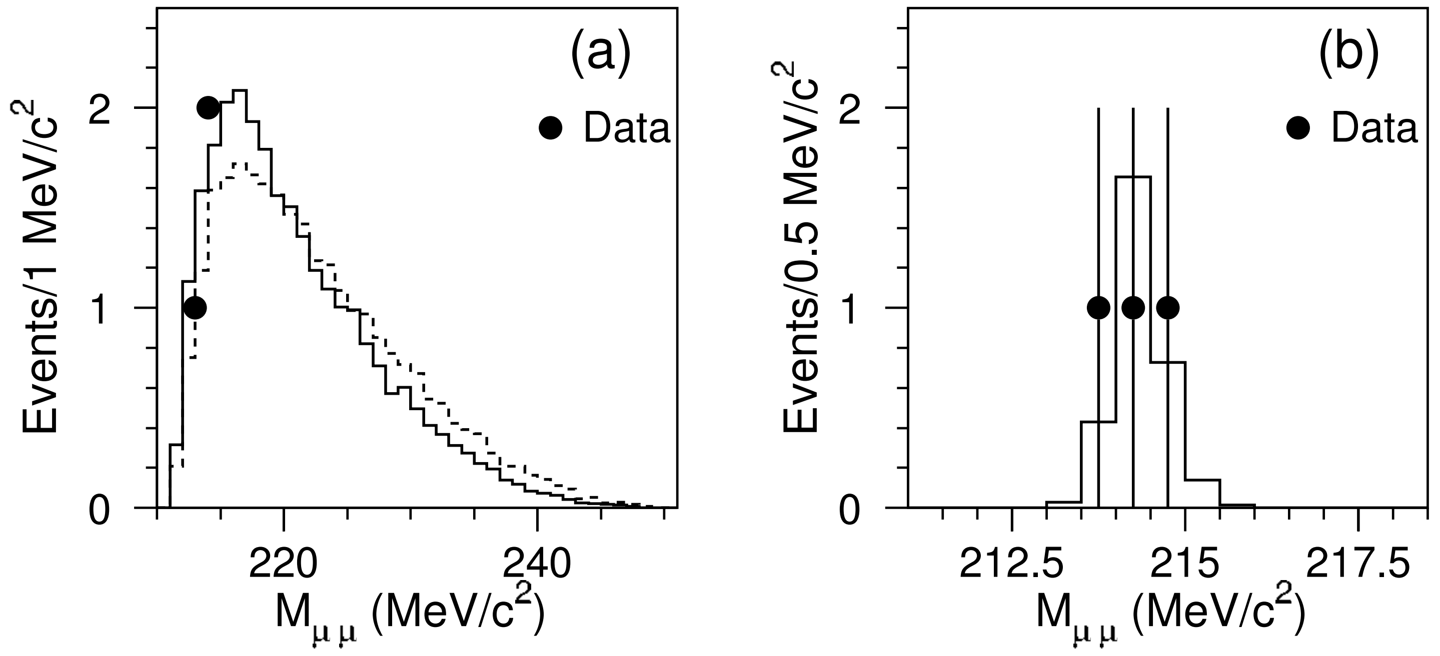
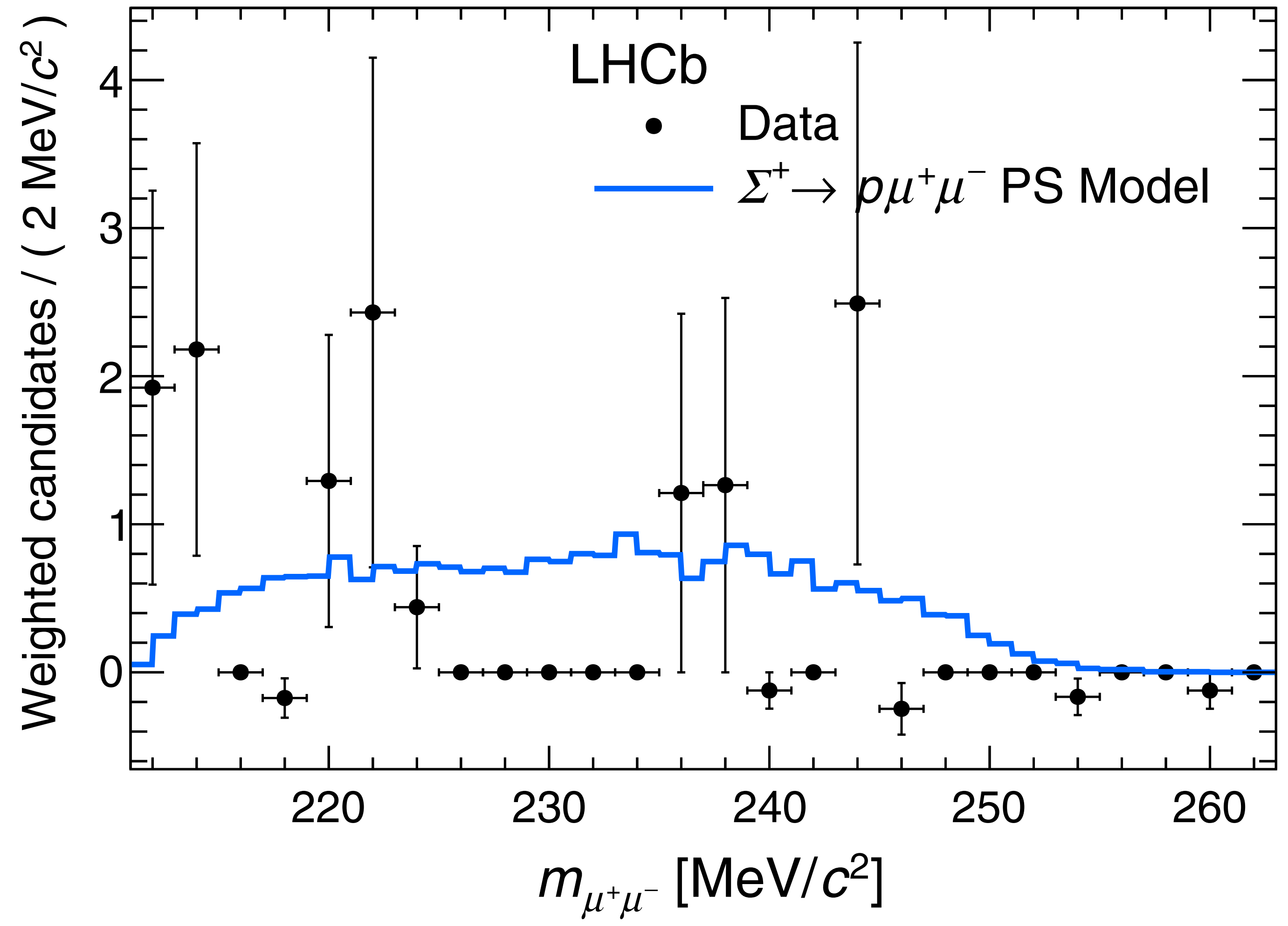


FIG. 4. Real (points) and MC (histogram) dimuon mass distributions for (a) $\Sigma^+_{p\mu\mu}$ MC events (arbitrary normalization) with a form-factor decay (solid histogram) and uniform phase-space decay (dashed histogram) model, and (b) $\Sigma^+_{pP\mu\mu}$ MC events normalized to match the data.



$$M_{P^0} = 214.3 \pm 0.5 \text{ MeV}$$

$$B(\Sigma^+ \to pP^0 \to p\mu^+\mu^-) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$$

$$B(\Sigma^+ \to pP^0 \to p\mu^+\mu^-) < 1.4 \times 10^{-8} \text{ at } 90\,\%$$

HyperCP Collaboration: HyangKyu Park et al. PRL 94 (2005) 021801
Evidence for the decay $\Sigma^+ \to p\mu^+\mu^-$

LHCb Collaboration: R. Aaij et al.
PRL 120 (2018) 221803
Evidence for the rare decay $\Sigma^+ \to p\mu^+\mu^-$

sm calculation

- short distance: (Flavio wet basis at 1GeV)

$$\mathscr{L}_{\text{eff}} = \sum_i C_i \mathcal{O}_i + \text{H.c.}$$

$$\mathcal{O}_9^\mu = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{e^2}{16\pi^2} (\bar{d}_L \gamma^\mu s_L)\ (\bar{\mu}\gamma_\mu \mu), \quad \mathcal{O}_{10}^\mu = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{e^2}{16\pi^2} (\bar{d}_L \gamma^\mu s_L)\ (\bar{\mu}\gamma_\mu \gamma_5 \mu)$$

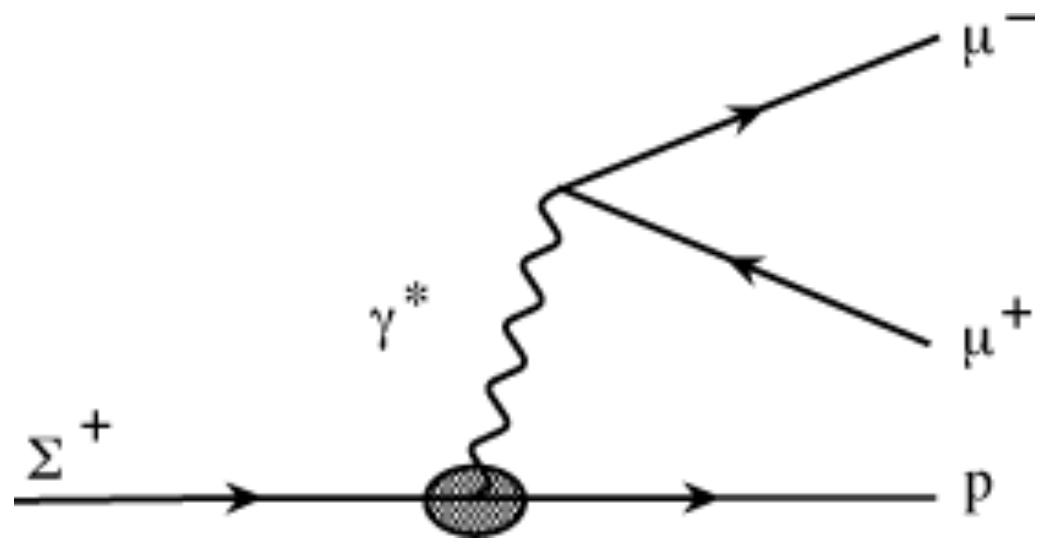
$$\langle p | \bar{d}\gamma^\kappa s | \Sigma^+ \rangle = -\, \bar{u}_p \gamma^\kappa u_\Sigma \,,$$

$$\langle p | \bar{d}\gamma^\nu \gamma_5 s | \Sigma^+ \rangle = (D-F)\left(\bar{u}_p \gamma^\nu \gamma_5 u_\Sigma + \frac{m_\Sigma + m_p}{q^2 - m_K^2} \bar{u}_p \gamma_5 u_\Sigma \, q^\nu \right)$$

$$\Longrightarrow \; B_{SD}(\Sigma^+ \to p\mu^+\mu^-) \sim \mathcal{O}(10^{-12})$$

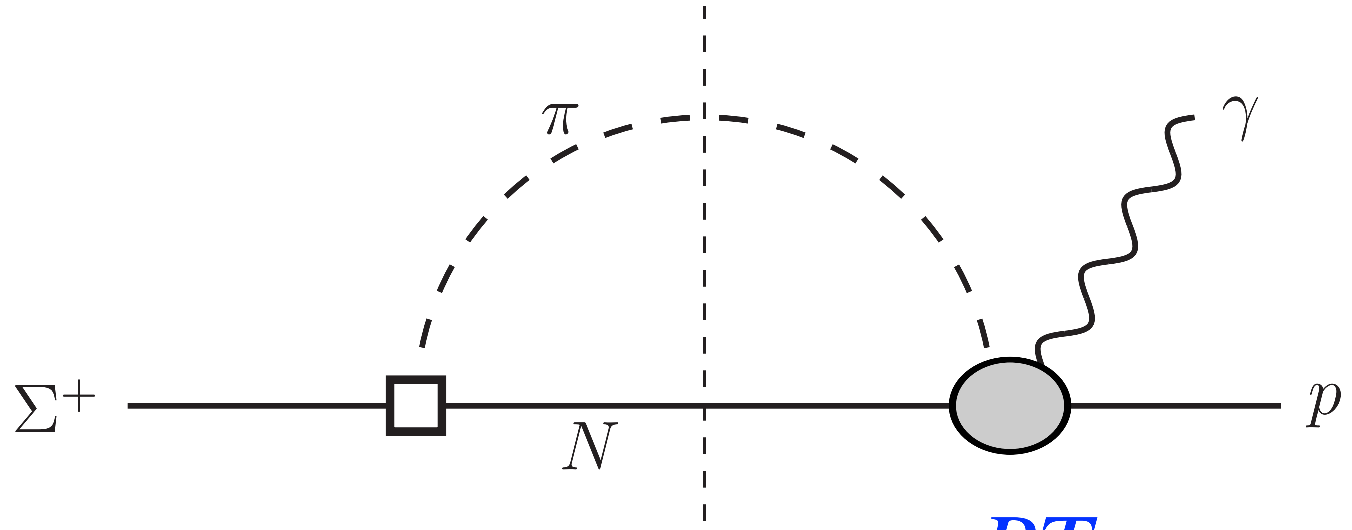
- Long distance:

$$\mathscr{M}_{\text{SM}}^{\text{LD}} = \frac{-ie^2 G_{\text{F}}}{q^2} \bar{u}_p (a + b\gamma_5) \sigma_{\kappa\nu} q^\kappa u_\Sigma \, \bar{u}_\mu \gamma^\nu v_{\bar{\mu}} - e^2 G_{\text{F}} \, \bar{u}_p \gamma_\kappa (c + d\gamma_5) u_\Sigma \, \bar{u}_\mu \gamma^\kappa v_{\bar{\mu}}$$



- $a(q^2), c(q^2)$ are parity conserving
- $b(q^2), d(q^2)$ are parity violating
- $a(0), b(0)$ contribute to $\Sigma^+ \to p\gamma$
- All four are complex

imaginary part

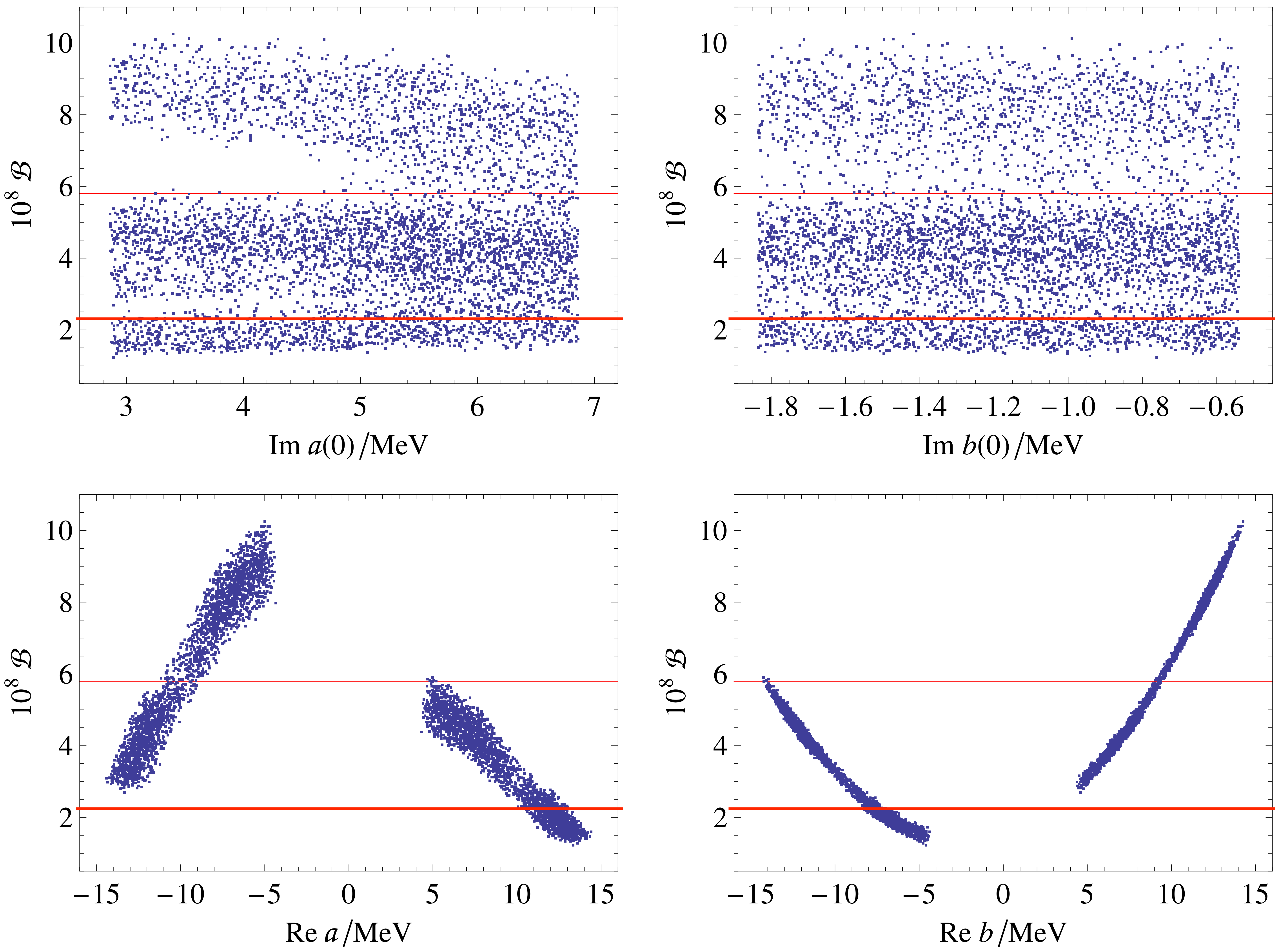


exp χPT

there is a new BESIII measurement
Phys.Rev.Lett. 130 (2023) 21, 211901

Long distance BR $\sim \mathcal{O}(10^{-8})$

He, Tandean, G.V JHEP10(2018)040



- imaginary parts from cut incorporating theory uncertainty
- using $\mathrm{Im}a(0), \mathrm{Im}b(0)$ extract the real part from $\Sigma^+ \to p\gamma$, use 2σ range (four-fold ambiguity)
- Real parts of $c(q^2), d(q^2)$from a vector meson dominance model

$$1.2 \lesssim \mathcal{B} \times 10^8 \lesssim 10.2$$

- red lines LHCb central value and 2σ upper limit
- another recent estimate $1.6 \lesssim \mathcal{B} \times 10^8 \lesssim 8.9$

Geng, Camalich, Shi, *JHEP* 02 (2022) 178

new physics at high scale

- constrain the $\bar{d}s\ell^+\ell^-$ sector

$$\mathscr{L}_{\rm eff} = \sum_i C_i \mathcal{O}_i + \mathrm{H.c.}$$

also $\mathcal{O}_{S,S',P,P'}$

$$\mathcal{O}_9^\mu = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{e^2}{16\pi^2} (\bar{d}_L \gamma^\mu s_L)\ (\bar{\mu}\gamma_\mu \mu) \qquad \mathcal{O}_{10}^\mu = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{e^2}{16\pi^2} (\bar{d}_L \gamma^\mu s_L)\ (\bar{\mu}\gamma_\mu \gamma_5 \mu) \qquad \mathcal{O}_7 = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{e^2}{16\pi^2} m_s (\bar{d}_L \sigma^{\mu\nu} s_R)\ F_{\mu\nu}$$

$$\mathcal{O}_{9'}^\mu = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{e^2}{16\pi^2} (\bar{d}_R \gamma^\mu s_R)\ (\bar{\mu}\gamma_\mu \mu) \qquad \mathcal{O}_{10'}^\mu = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{e^2}{16\pi^2} (\bar{d}_R \gamma^\mu s_R)\ (\bar{\mu}\gamma_\mu \gamma_5 \mu) \qquad \mathcal{O}_{7'} = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{e^2}{16\pi^2} m_s (\bar{d}_R \sigma^{\mu\nu} s_L)\ F_{\mu\nu}$$

- Relevant modes are long-distance dominated
  - $B(K_L \to \mu^+\mu^-)_{SD} \simeq (2 \pm 1.5) \times 10^{-10}$ (exp – abs) - below SD in SM
  - $B(K^+ \to \pi^+\mu^+\mu^-)_{exp} \simeq (9.15 \pm 0.08) \times 10^{-8}$ NA62 - fits a new parameter in χPT
  - $B(K_L \to \pi^0\pi^0\mu^+\mu^-) < 9.2 \times 10^{-11}$ KTeV at 90 % - very small phase space volume available
  - there is room for NP but calculations are not precise
- hyperon decays can provide additional observables (polarization)
- complementary coverage of parameter space, some directions are well tested, some can still be very large

additional observables: forward-backward asymmetry

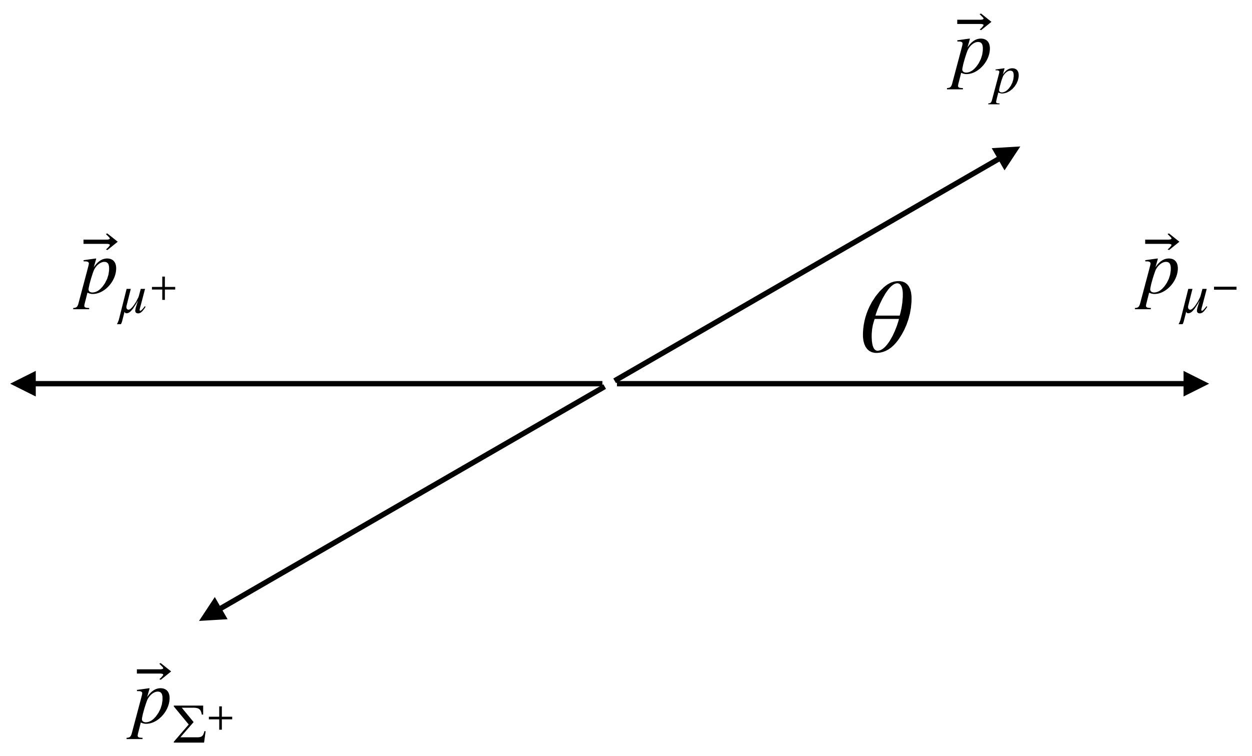
- forward-backward asymmetry (binned by q^2 or integrated)
- based on the angle in the dimuon rest frame

Geng, Camalich, Shi, *JHEP* 02 (2022) 178

- very small in SM

$$-1.4 \lesssim A_{FB} \times 10^5 \lesssim 0.6$$

- LD-SD interference so sensitive to NP

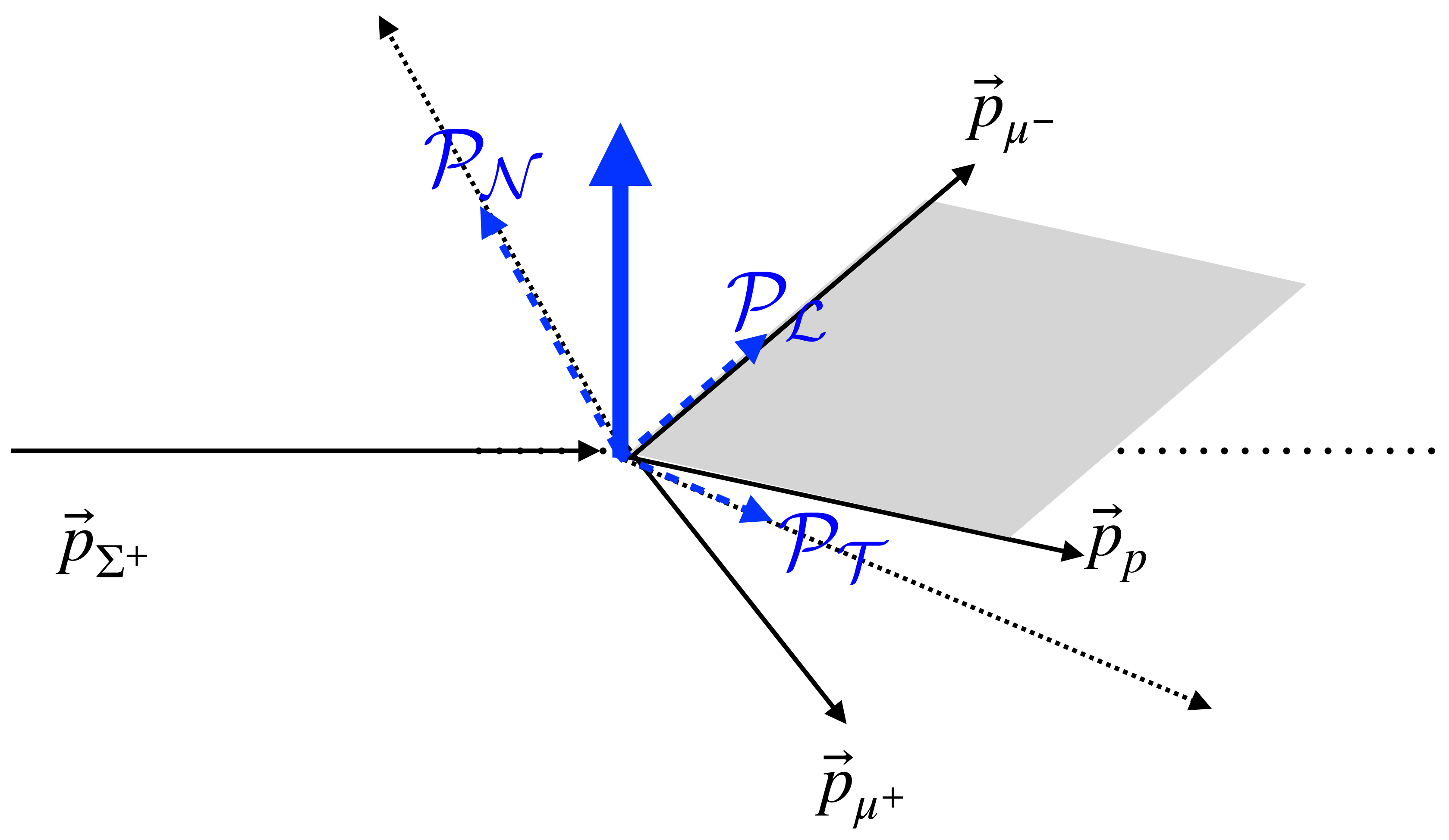


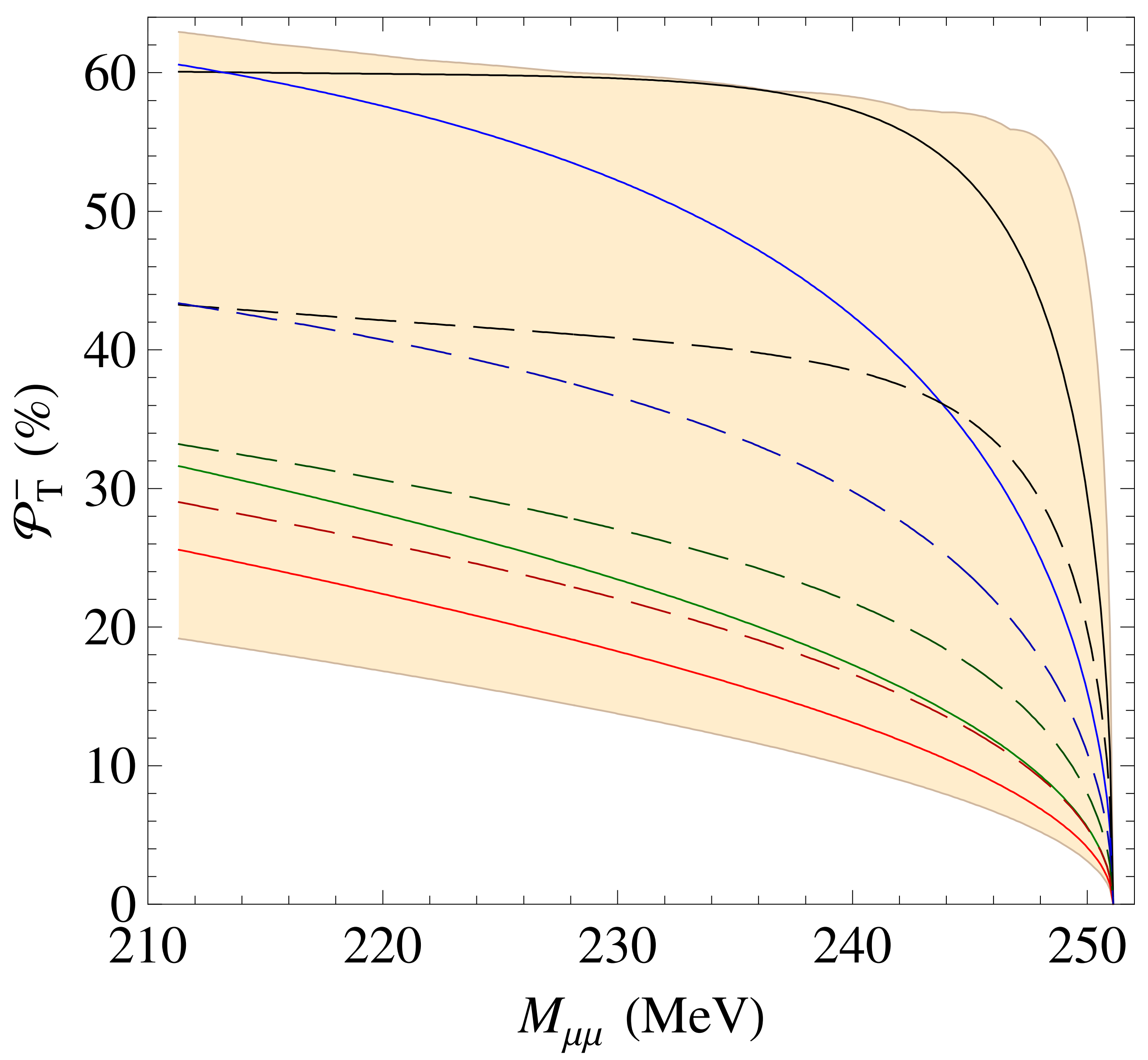
$$\mathcal{A}_{\rm FB} = \frac{\int_{-1}^{1} dc_\theta \; \mathrm{sgn}(c_\theta) \; \Gamma''}{\int_{-1}^{1} dc_\theta \; \Gamma''}, \qquad \Gamma'' \equiv \frac{d^2\Gamma(\Sigma^+ \to p\mu^+\mu^-)}{dq^2 \, dc_\theta}$$

– Similar $A_{FB} = (0.0 \pm 0.7) \times 10^{-2}$ in $K^+ \to \pi^+\mu^+\mu^-$ has been recently measured (NA62 JHEP 11, 011 (2022))

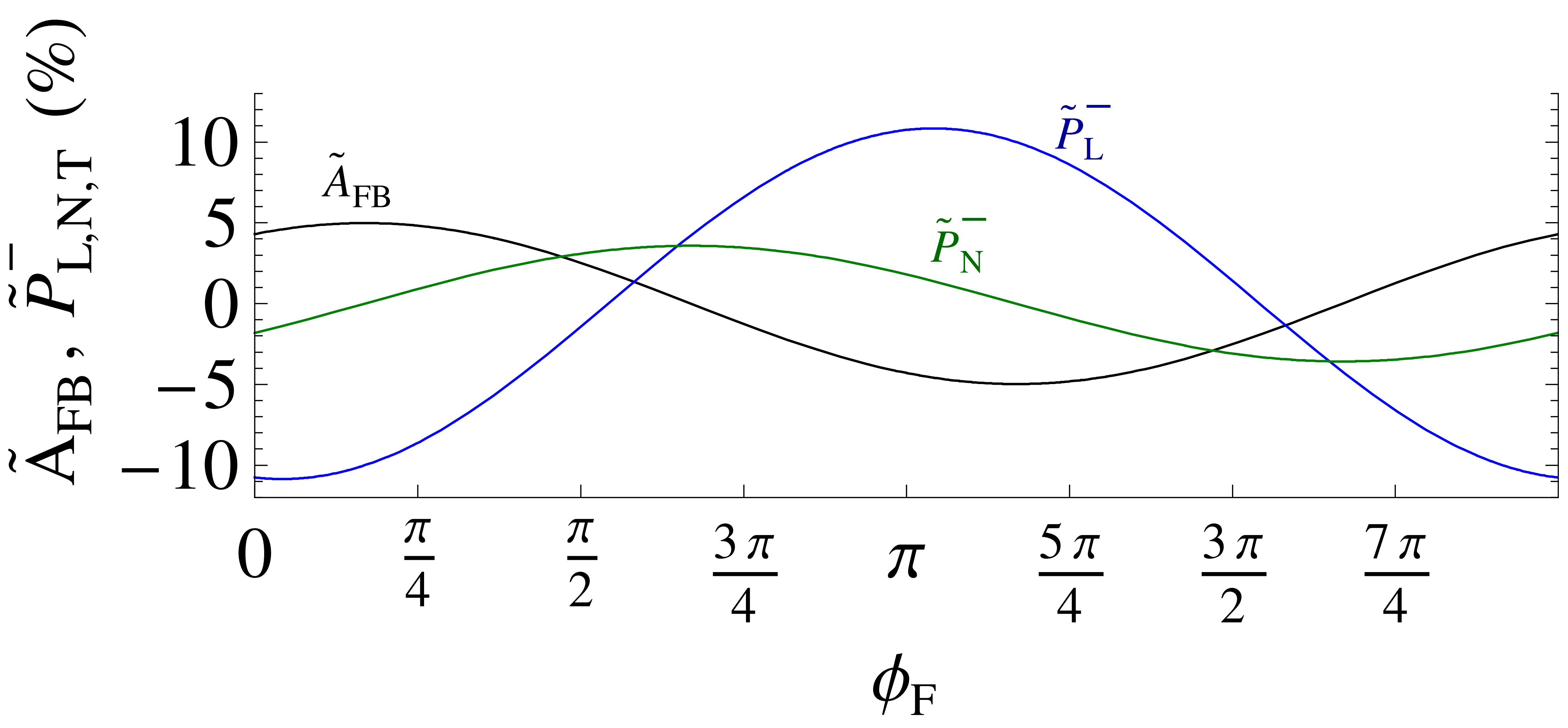
additional observables: muon polarisation

- if the muon polarisation can be measured
  - $\mathcal{P}_L$ sensitive to P-violation in leptonic current (BSM)
  - $\mathcal{P}_N$ is naive T odd (BSM)
  - $\mathcal{P}_T$ sensitive to P-violation. (large in SM)

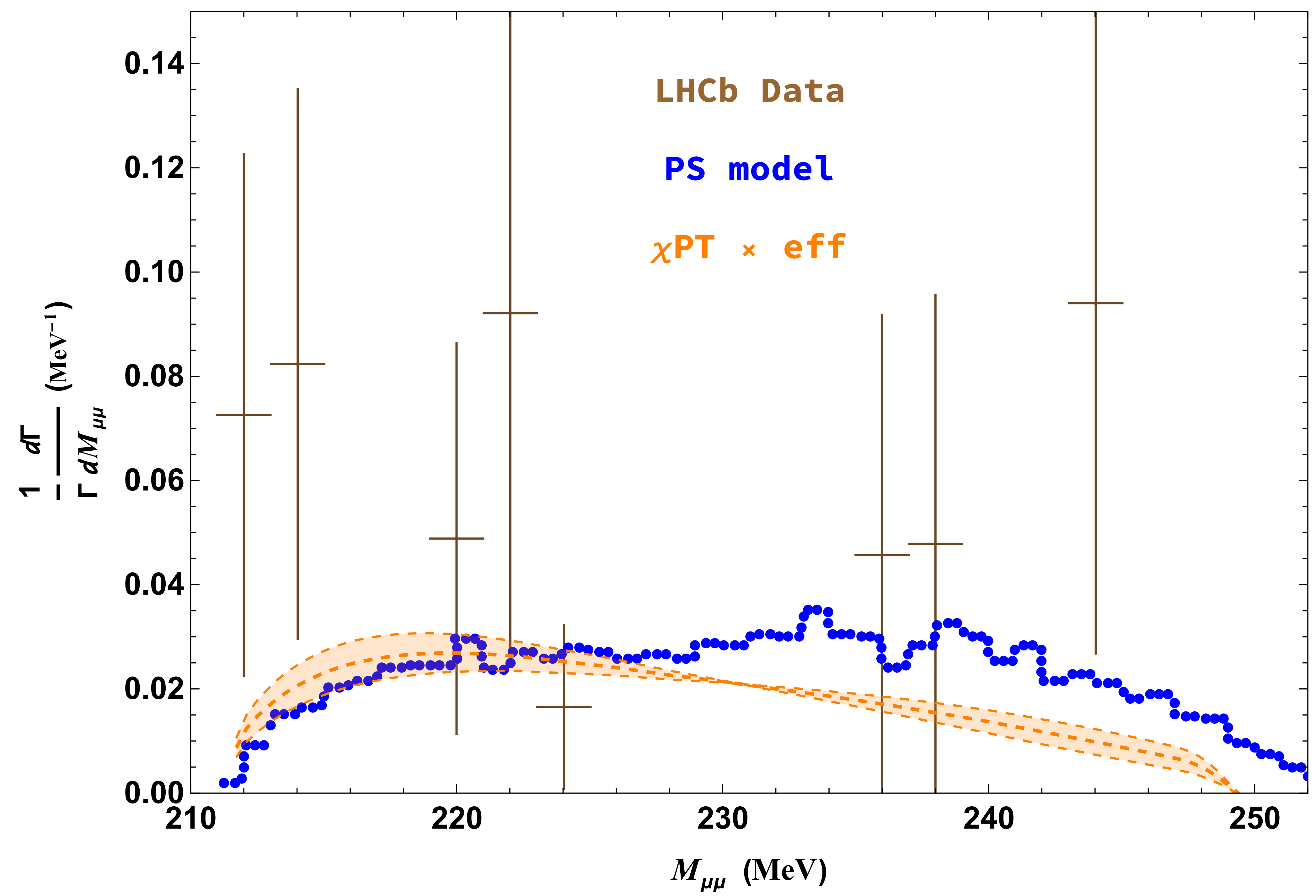




observables beyond the decay rate



He, Tandean, G.V JHEP10(2018)040



- BSM
  - keep rate unchanged: NP such that $B(\Sigma^+ \to p\mu^+\mu^-) \simeq 2 \times 10^{-8}$
  - modify only SD (combination of C_{10} and $C_{10'}$ can be very large, effectively removing λ_t suppression)
  - also affect kaon modes but complementary Geng, Camalich, Shi, *JHEP* 02 (2022) 178

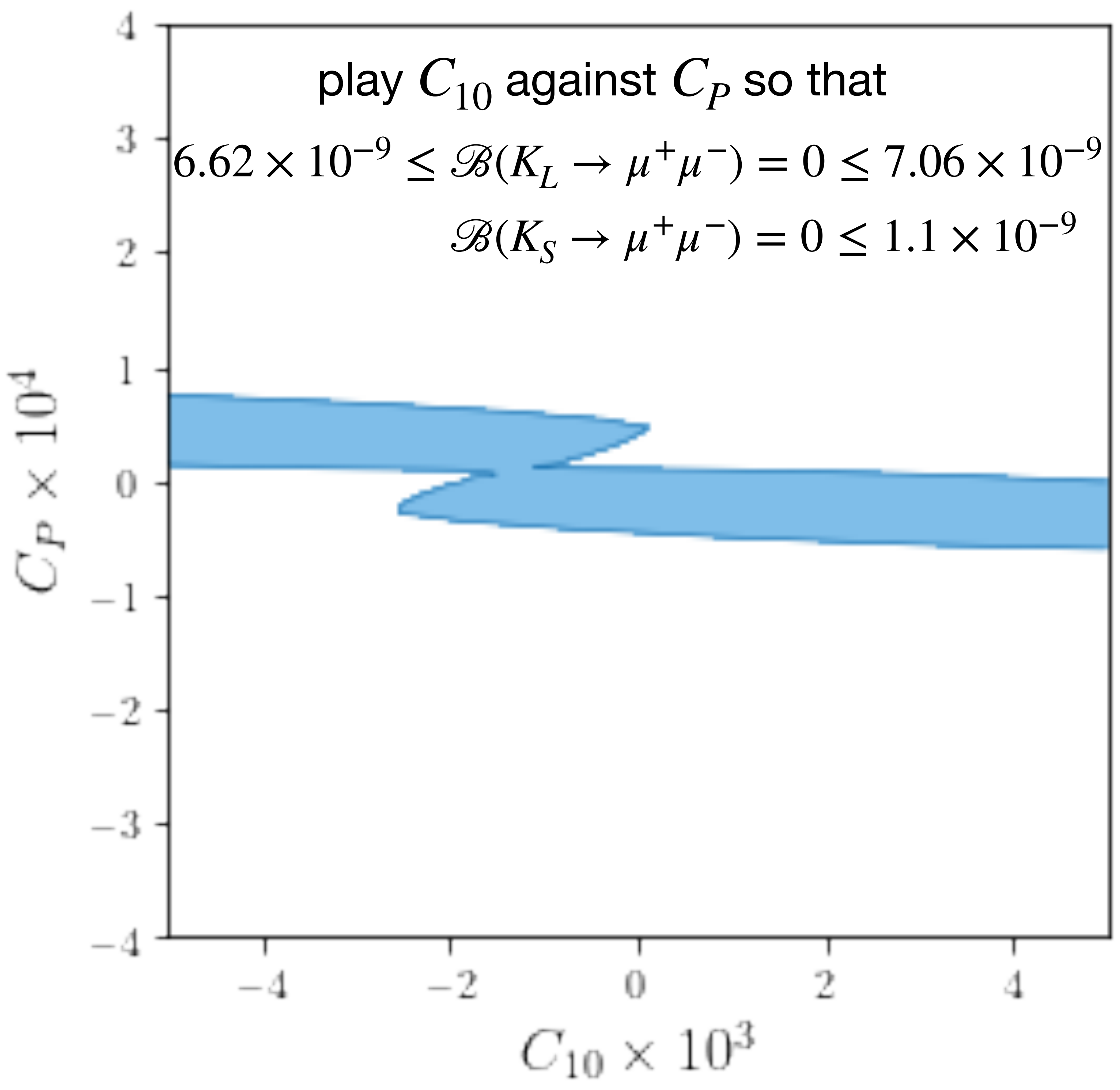
complementarity in parameter space

$$\mathcal{O}^\mu_{10} = \frac{4G_F}{\sqrt{2}} V_{ts}V^*_{td}\frac{e^2}{16\pi^2}(\bar{d}_L\gamma^\mu s_L)\,(\bar{\mu}\gamma_\mu\gamma_5\mu), \quad \mathcal{O}^\mu_{10'} = \frac{4G_F}{\sqrt{2}} V_{ts}V^*_{td}\frac{e^2}{16\pi^2}(\bar{d}_R\gamma^\mu s_R)\,(\bar{\mu}\gamma_\mu\gamma_5\mu)$$

$$\mathcal{O}^\mu_{P} = \frac{4G_F}{\sqrt{2}} V_{ts}V^*_{td}\frac{e^2}{16\pi^2}(\bar{d}_L s_R)\,(\bar{\mu}\gamma_5\mu), \quad \mathcal{O}^\mu_{P'} = \frac{4G_F}{\sqrt{2}} V_{ts}V^*_{td}\frac{e^2}{16\pi^2}(\bar{d}_R s_L)\,(\bar{\mu}\gamma_5\mu)$$

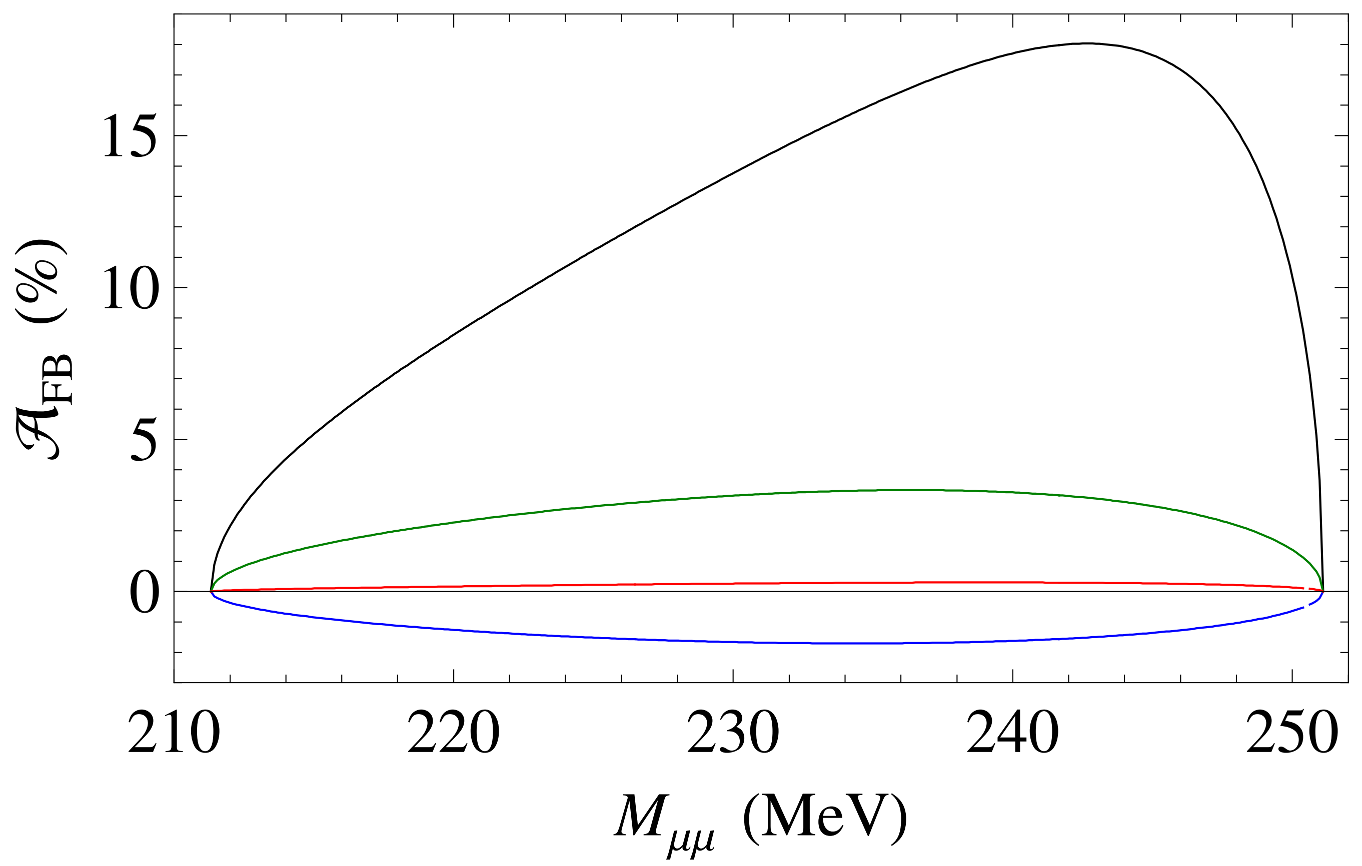
$$C_{10} = -C_{10'} \implies \bar{d}\gamma^\mu\gamma^5 s \implies \quad \mathcal{M}_{NP}(K \to \pi\mu^+\mu^-) = 0$$

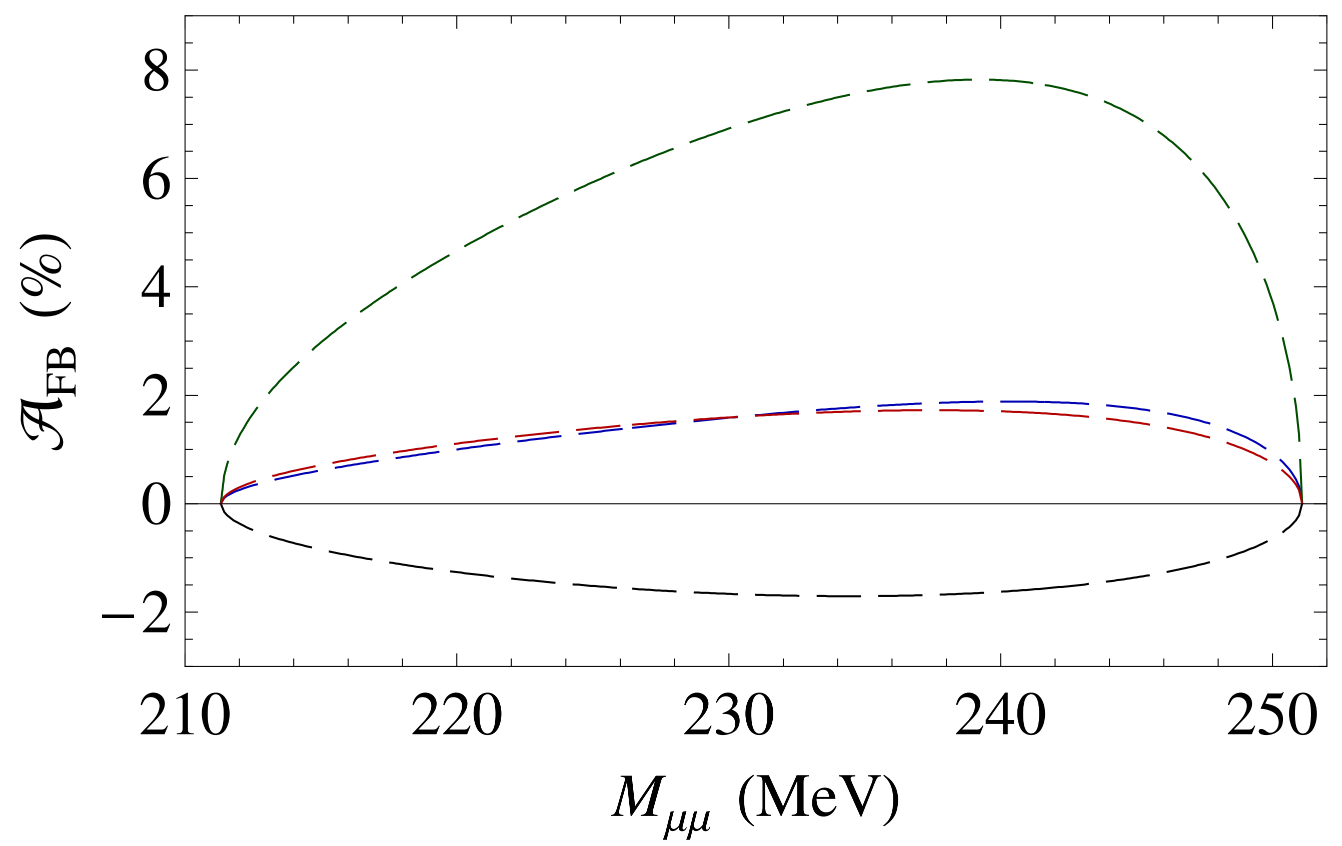
$$C_P = -C_{P'} \implies \bar{d}\gamma^5 s \implies \quad \mathcal{M}_{NP}(K \to \pi\mu^+\mu^-) = 0$$



$$\text{LHCb}: B(\Sigma^+ \to p\mu^+\mu^-) = (2.2^{+1.8}_{-1.3}) \times 10^{-8}$$

$\frac{\text{Re}\,a}{\text{MeV}}$	$\frac{\text{Re}\,b}{\text{MeV}}$	$10^8\,\mathcal{B}$	$\tilde{A}_{\text{FB}}$ (%)
13.3	−6.0	1.8	12
−13.3	6.0	3.7	−1
6.0	−13.3	5.3	3
−6.0	13.3	9.3	0.2
11.1	−7.3	2.5	12
−11.1	7.3	4.8	1
7.3	−11.1	4.2	6
−7.3	11.1	7.6	1





What about the light new particle? - probably ruled out

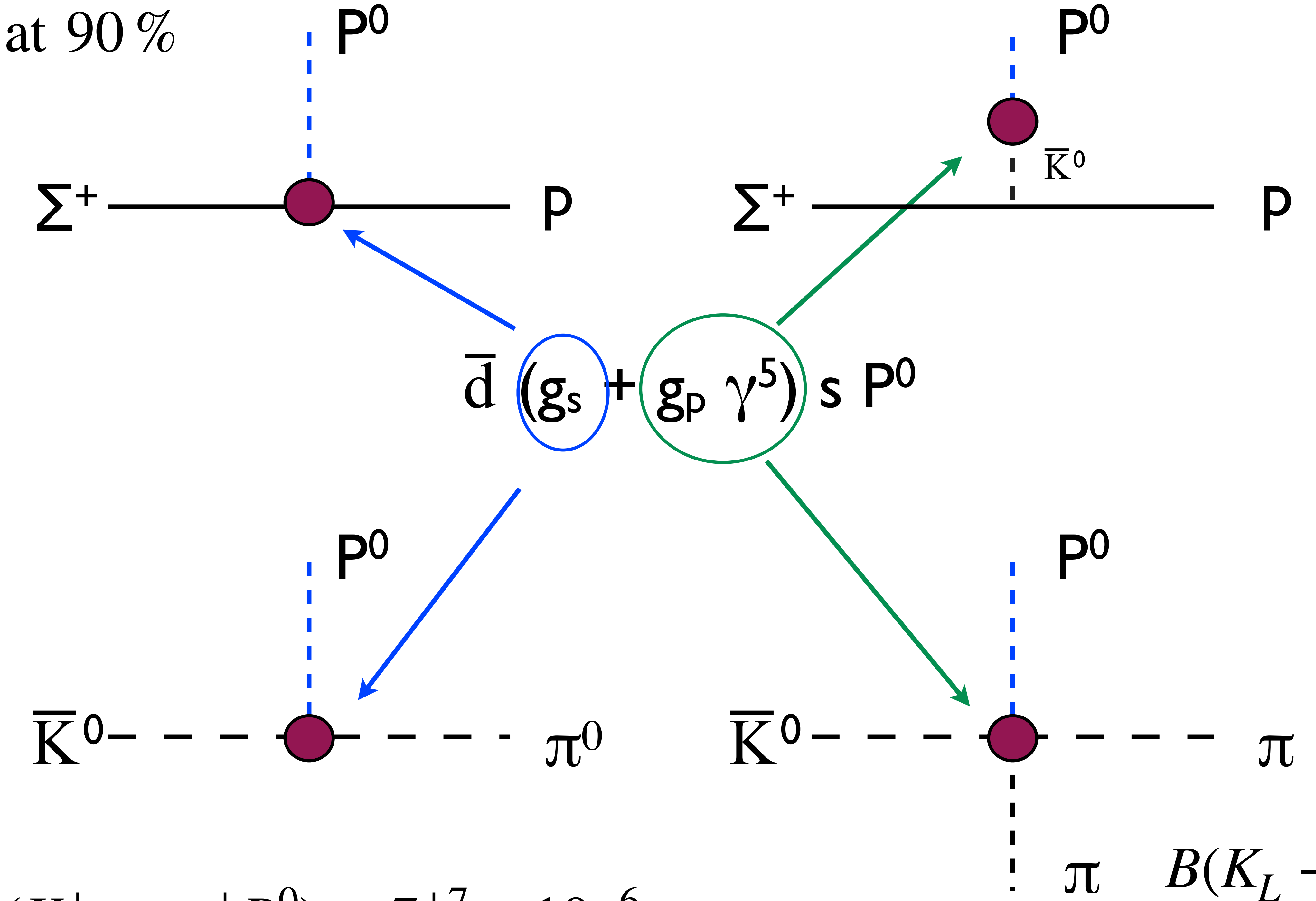
$M_{P^0} = 214.3 \pm 0.5$ MeV

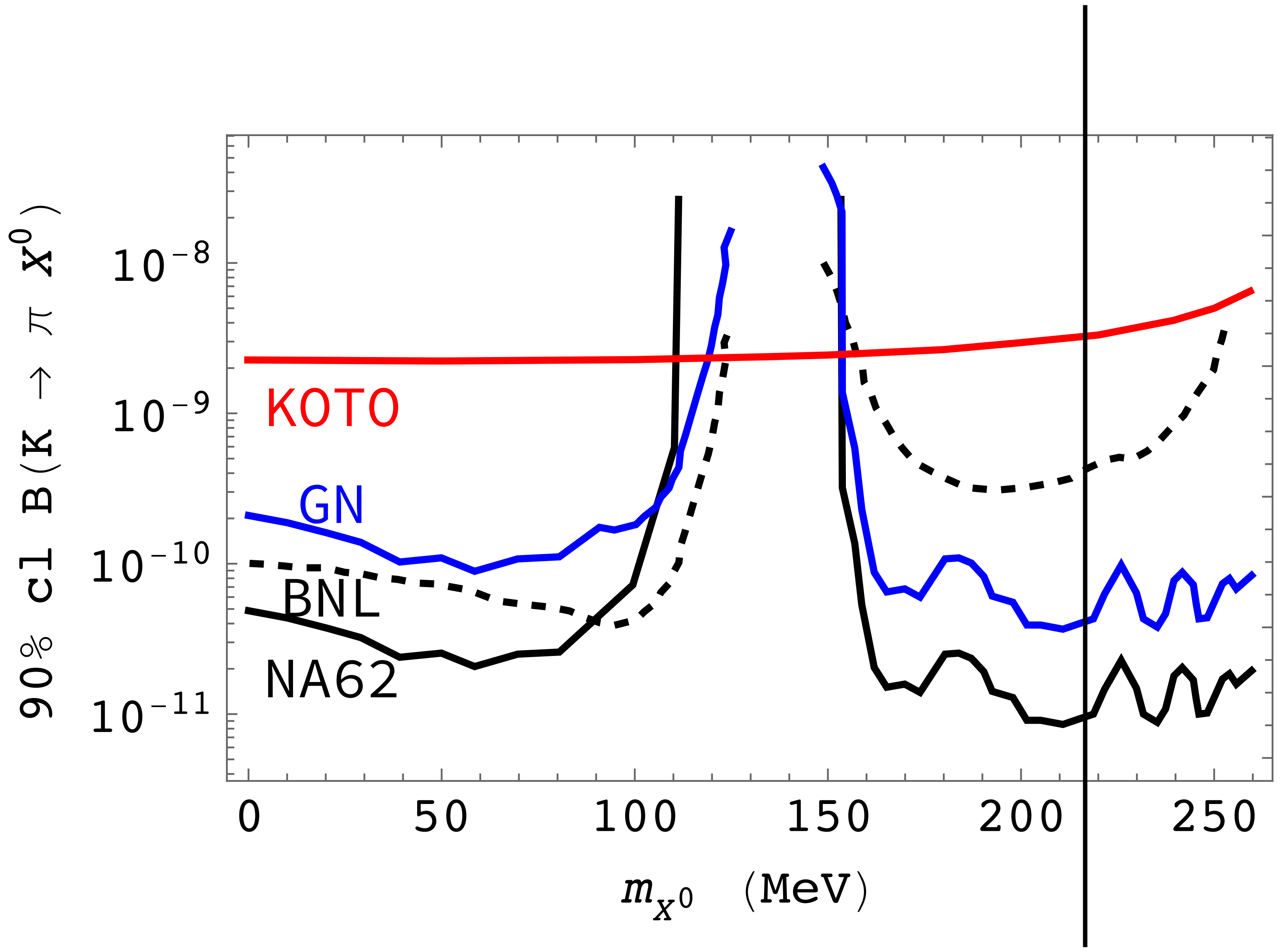
$B(\Sigma^+ \to pP^0 \to p\mu^+\mu^-) = (3.1^{+2.4}_{-1.9} \pm 1.5) \times 10^{-8}$ HyperCP

$B(\Sigma^+ \to pP^0 \to p\mu^+\mu^-) < 1.4 \times 10^{-8}$ LHCb at 90 %

$B(\Omega^- \to \Xi^- P^0) \simeq (2.0^{+1.6}_{-1.2}) \times 10^{-6}$

$B(\Omega^- \to \Xi^- P^0) < 6.1 \times 10^{-6}$ HyperCP





$B(K^+ \to \pi^+ P^0) \sim 7^{+7}_{-6} \times 10^{-6}$

$B(K_L \to \pi^+\pi^- P^0) \simeq (1.8^{+1.6}_{-1.4}) \times 10^{-9}$

$B(K_L \to \pi^0\pi^0 P^0) \simeq (8.3^{+7.5}_{-6.6}) \times 10^{-9}$.

$B(K_L \to \pi^0\pi^0 X^0 \to \pi^0\pi^0\mu^+\mu^-) < 1 \times 10^{-10}$ KTeV at 90 %

CLFV: $B \to B' e^{\pm} \mu^{\mp}$

CLFV

- At dimension six, NP operators with CLFV take the form (SMEFT)

$$\mathscr{L}_{\rm NP} = \frac{1}{\Lambda^2_{\rm NP}}\left(\sum_{k=1}^{5} c_k^{ijxy}\mathscr{Q}_k^{ijxy} + (c_6^{ijxy}\mathscr{Q}_6^{ijxy} + {\rm H.c.})\right)$$

$$\mathscr{Q}_1^{ijxy} = \overline{q}_i\gamma^\eta q_j\overline{l}_x\gamma_\eta l_y \qquad \mathscr{Q}_2^{ijxy} = \overline{q}_i\gamma^\eta\tau_I q_j\overline{l}_x\gamma_\eta\tau_I l_y \qquad \mathscr{Q}_3^{ijxy} = \overline{d}_i\gamma^\eta d_j\overline{e}_x\gamma_\eta e_y$$

$$\mathscr{Q}_4^{ijxy} = \overline{d}_i\gamma^\eta d_j\overline{l}_x\gamma_\eta l_y \qquad \mathscr{Q}_5^{ijxy} = \overline{q}_i\gamma^\eta q_j\overline{e}_x\gamma_\eta e_y \qquad \mathscr{Q}_6^{ijxy} = \overline{l}_i e_j\overline{d}_x q_y$$

- Matching at low scales to forms such as

$$\mathscr{O}^{ij}_{9(9')} = (\bar{s}_{L(R)}\gamma_\mu d^k_{L(R)})(\bar{\ell}_i\gamma^\mu\ell_j),\ \mathscr{O}^{ij}_{10(10')} = (\bar{s}_{L(R)}\gamma_\mu d^k_{L(R)})(\bar{\ell}_i\gamma^\mu\gamma_5\ell_j)\cdots$$

- Leading order χPT including octet and decuplet baryons coupled to external sources:

$$\bar{d}\gamma_\eta s \Leftrightarrow -\sqrt{\frac{3}{2}}\,\bar{n}\gamma_\eta\Lambda - \bar{p}\gamma_\eta\Sigma^+ + \sqrt{\frac{3}{2}}\,\overline{\Lambda}\gamma_\eta\Xi^0 - \frac{1}{\sqrt{2}}\overline{\Sigma}^0\gamma_\eta\Xi^0 + \overline{\Sigma}^0\gamma_\eta\Xi^-$$

$$\bar{d}s \Leftrightarrow \sqrt{\frac{3}{2}}\,\frac{m_\Lambda - m_N}{\hat{m} - m_s}\bar{n}\Lambda + \frac{m_\Sigma - m_N}{\hat{m} - m_s}\bar{p}\Sigma^+ + \sqrt{\frac{3}{2}}\,\frac{m_\Xi - m_\Lambda}{m_s - \hat{m}}\overline{\Lambda}\Xi^0 + \frac{m_\Xi - m_\Sigma}{\hat{m} - m_s}\left(\frac{\overline{\Sigma}^0\Xi^0}{\sqrt{2}} - \overline{\Sigma}^0\Xi^-\right)$$

$$\bar{d}\gamma_\eta\gamma_5 s \Leftrightarrow \frac{-D-3F}{\sqrt{6}}\,\bar{n}\gamma_\eta\gamma_5\Lambda + (D-F)\bar{p}\gamma_\eta\gamma_5\Sigma^+ - \frac{D-3F}{\sqrt{6}}\,\overline{\Lambda}\gamma_\eta\gamma_5\Xi^0\frac{D+F}{\sqrt{2}}\,\overline{\Sigma}^0\gamma_\eta\gamma_5\Xi^0 + (D+F)\overline{\Sigma}^0\gamma_\eta\gamma_5\Xi^- + C\overline{\Xi}^0\Omega^-_\eta$$

measurements with hyperons complement those with kaons

$$\mathscr{L}_{NP} \supset \frac{-1}{\Lambda_{NP}^2} \sum_{\ell,\ell'} \left[\bar{d}\gamma^\kappa s\, \bar{\ell}\gamma_\kappa (V_{\ell\ell'} + \gamma_5 A_{\ell\ell'})\ell' + \bar{d}\gamma^\kappa\gamma_5 s\, \bar{\ell}\gamma_\kappa (\tilde{V}_{\ell\ell'} + \gamma_5 \tilde{A}_{\ell\ell'})\ell' + \bar{d}s\, \bar{\ell}(S_{\ell\ell'} + \gamma_5 P_{\ell\ell'})\ell' + \bar{d}\gamma_5 s\, \bar{\ell}(\tilde{S}_{\ell\ell'} + \gamma_5 \tilde{P}_{\ell\ell'})\ell' \right]$$

$$\mathscr{B}\left(\Xi^0 \to \Lambda e^-\mu^+\right)\Big[2.4\left(|V_{e\mu}|^2 + |A_{e\mu}|^2\right) + 7.5\left(|S_{e\mu}|^2 + |P_{e\mu}|^2\right) + 6.5\,\mathrm{Re}\left(A^*_{e\mu}P_{e\mu} - V^*_{e\mu}S_{e\mu}\right)$$

$$+\ 0.25\left(|\tilde{V}_{e\mu}|^2 + |\tilde{A}_{e\mu}|^2\right) + 0.07\left(|\tilde{S}_{e\mu}|^2 + |\tilde{P}_{e\mu}|^2\right) - 0.08\,\mathrm{Re}\left(\tilde{A}^*_{e\mu}\tilde{P}_{e\mu} - \tilde{V}^*_{e\mu}\tilde{S}_{e\mu}\right)\Big] \times 10^{-5}\left(\frac{1\ \mathrm{TeV}^4}{\Lambda_{NP}}\right)^4$$

$$\mathscr{B}\left(K_L \to e^\pm\mu^\mp\right) = 3.8\left[|\tilde{V}_{e\mu} + \tilde{V}^*_{\mu e} + 19\left(\tilde{S}_{e\mu} - \tilde{S}^*_{\mu e}\right)|^2 + |\tilde{A}_{e\mu} + \tilde{A}^*_{\mu e} - 19\left(\tilde{P}_{e\mu} + \tilde{P}^*_{\mu e}\right)|^2\right] \times 10^{-1}\left(\frac{1\ \mathrm{TeV}^4}{\Lambda_{NP}}\right)^4 < 4.7 \times 10^{-12}$$

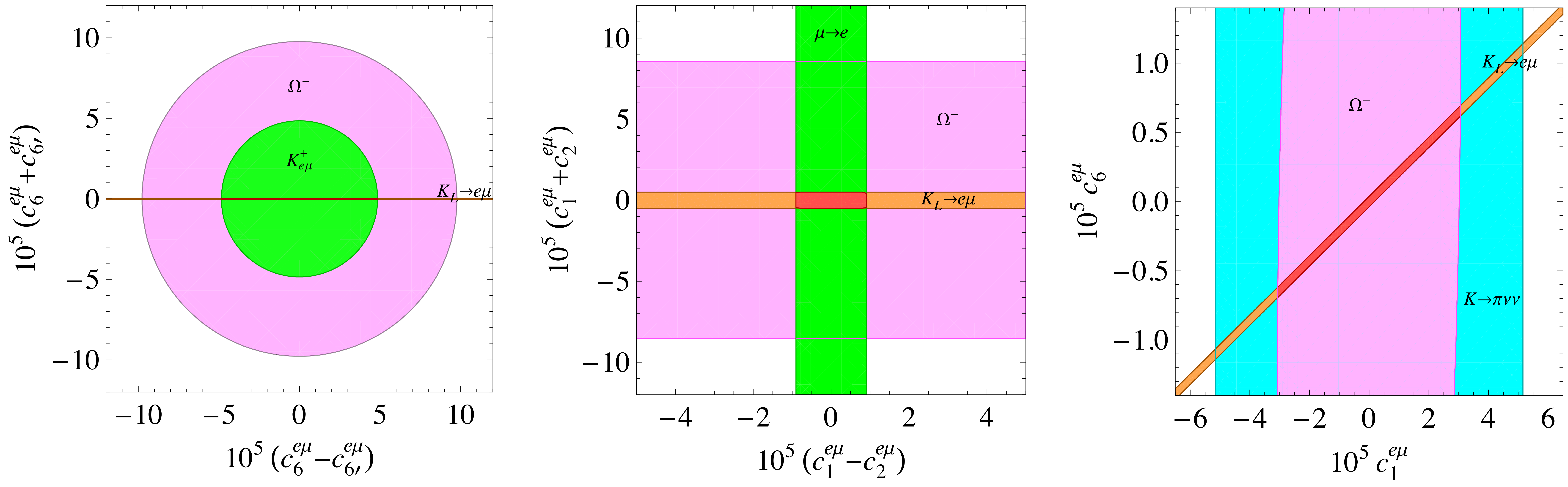
$$\mathscr{B}\left(K^+ \to \pi^+e^-\mu^+\right) = 8.7\left[|V_{\mu e}|^2 + |A_{\mu e}|^2 + 10\left(|S_{\mu e}|^2 + |P_{\mu e}|^2\right) + 3.6\,\mathrm{Re}\left(A^*_{\mu e}P_{\mu e} + V^*_{\mu e}S_{\mu e}\right)\right] \times 10^{-2}\left(\frac{1\ \mathrm{TeV}^4}{\Lambda_{NP}}\right)^4 < 1.3 \times 10^{-11}$$

- kaon constraints on $\bar{d}(\gamma_\mu)\gamma_5 s$ are more sensitive than those on $\bar{d}(\gamma_\mu)s$
- hyperons are complementary, and sensitive to all the couplings but need to reach very low BR to be fully competitive with kaon modes

comparison of hyperon modes

- Possible constraints for different hyperon modes
  - $\Lambda \to n e^- \mu^+$, $\Sigma^+ \to p e^- \mu^+$, $\Xi^0 \to \Lambda e^- \mu^+$, $\Omega^- \to \Xi^- e^- \mu^+$
  - taking $\Lambda_{NP} = 1$ TeV and assuming branching rations are probed at order 10^{-10}.
- Ω decays are the most sensitive when the branching ratios are probed at the same level but only to some couplings

current kaon constraints vs $\mathscr{B}_\Omega \sim \mathcal{O}(10^{-12})$

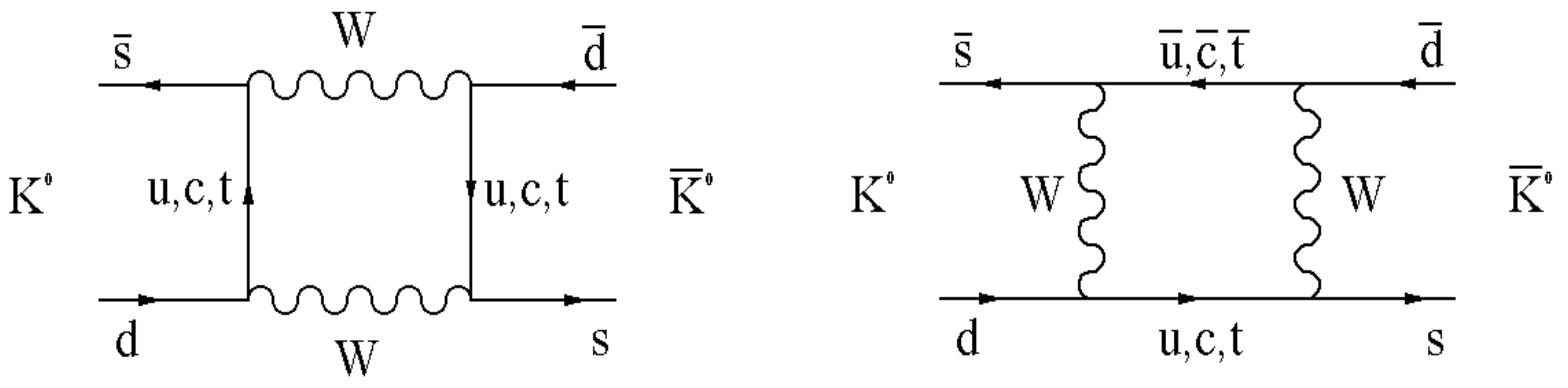


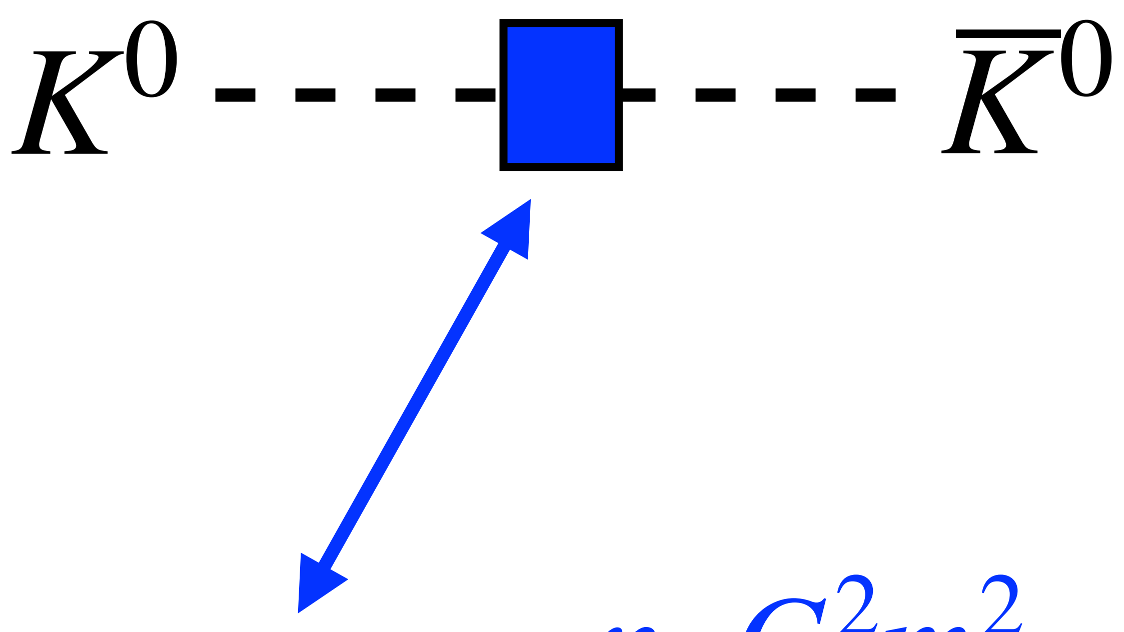
- current constraints placed by $K_L \to e^\pm\mu^\mp$, $K^+ \to \pi^+ e^- \mu^+$ and $\mu^- \to e^-$ conversion compared to what can be achieved if sensitivity at the level of $\mathscr{B}(\Omega^- \to \Xi^- e^- \mu^+) \lesssim 10^{-12}$ is reached
    - $\mathcal{Q}_1^{e\mu} = \overline{q}_1\gamma^\eta q_2\,\overline{\ell}_1\gamma_\eta\ell_2, \quad \mathcal{Q}_2^{e\mu} = \overline{q}_1\gamma^\eta\tau_I q_2\,\overline{\ell}_1\gamma_\eta\tau_I\ell_2,, \quad \mathcal{Q}_6^{e\mu} = \overline{\ell}_1\mu\bar{d}q_2, \cdots$

$|\Delta S| = 2$ hyperon decays

$|\Delta S| = 2$ decays within SM

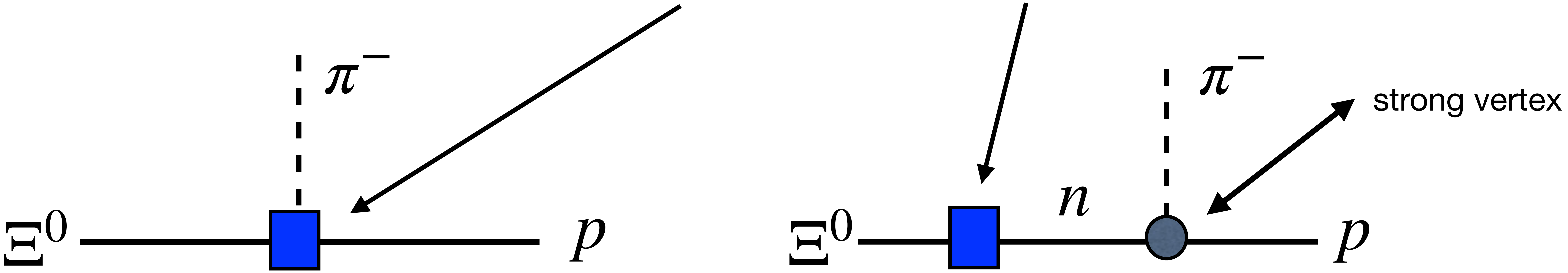
- Within the SM look at kaon mixing





$$\mathscr{H}^{SM}_{\Delta S=2} = \frac{\eta_{cc} G_F^2 m_c^2}{4\pi^2} \left(V^*_{cd} V_{cs}\right)^2 \bar{d}\gamma^\alpha P_L s \;\; \bar{d}\gamma_\alpha P_L s$$

- But the matrix element is only sensitive to parity even part of the operators
- Hyperon decay is sensitive to both P odd and P even operators



χPT matching

- the SM operator is part of the $(27_L, 1_R)$ so its coefficient can be related to $\Delta I = 3/2$ non-leptonic hyperon decay amplitudes
- Difficult due to $\Delta I = 1/2$ dominance but slightly better for S-wave $\Sigma^+ \to n\pi^+$ (octet matrix element vanishes at leading order in χPT)

$$\mathcal{Q}_{LL} = \bar{d}\gamma^\alpha P_L s\, \bar{d}\gamma_\alpha P_L s \;=\; \mathrm{t}_{kl,no}\overline{\psi}_k\gamma^\alpha P_L\psi_n\overline{\psi}_l\gamma_\alpha P_L\psi_o$$

$$\to\; \Lambda_\chi f_\pi^2\, \mathrm{t}_{kl,no}\Big[\hat{\beta}_{27}\left(\xi\overline{B}\xi^\dagger\right)_{nk}\left(\xi B\xi^\dagger\right)_{ol} + \hat{\delta}_{27}\,\xi_{nx}\xi_{oz}\xi^\dagger_{vk}\xi^\dagger_{wl}\left(\overline{T}_{rvw}\right)^\alpha(T_{rxz})_\alpha\Big],$$

$$\mathcal{H}^{sm}_{\Delta I=3/2,\Delta S=1} = \sqrt{8}(\hat{c}_1+\hat{c}_2)G_{\mathrm{F}}V^*_{ud}V_{us}\mathcal{Q}^{\Delta I=3/2}_{\Delta S=1}, \qquad \mathcal{Q}^{\Delta I=3/2}_{\Delta S=1} = \tilde{t}_{kl,no}\overline{\psi}_k\gamma^\alpha P_L\psi_n\overline{\psi}_l\gamma_\alpha P_L\psi_o$$

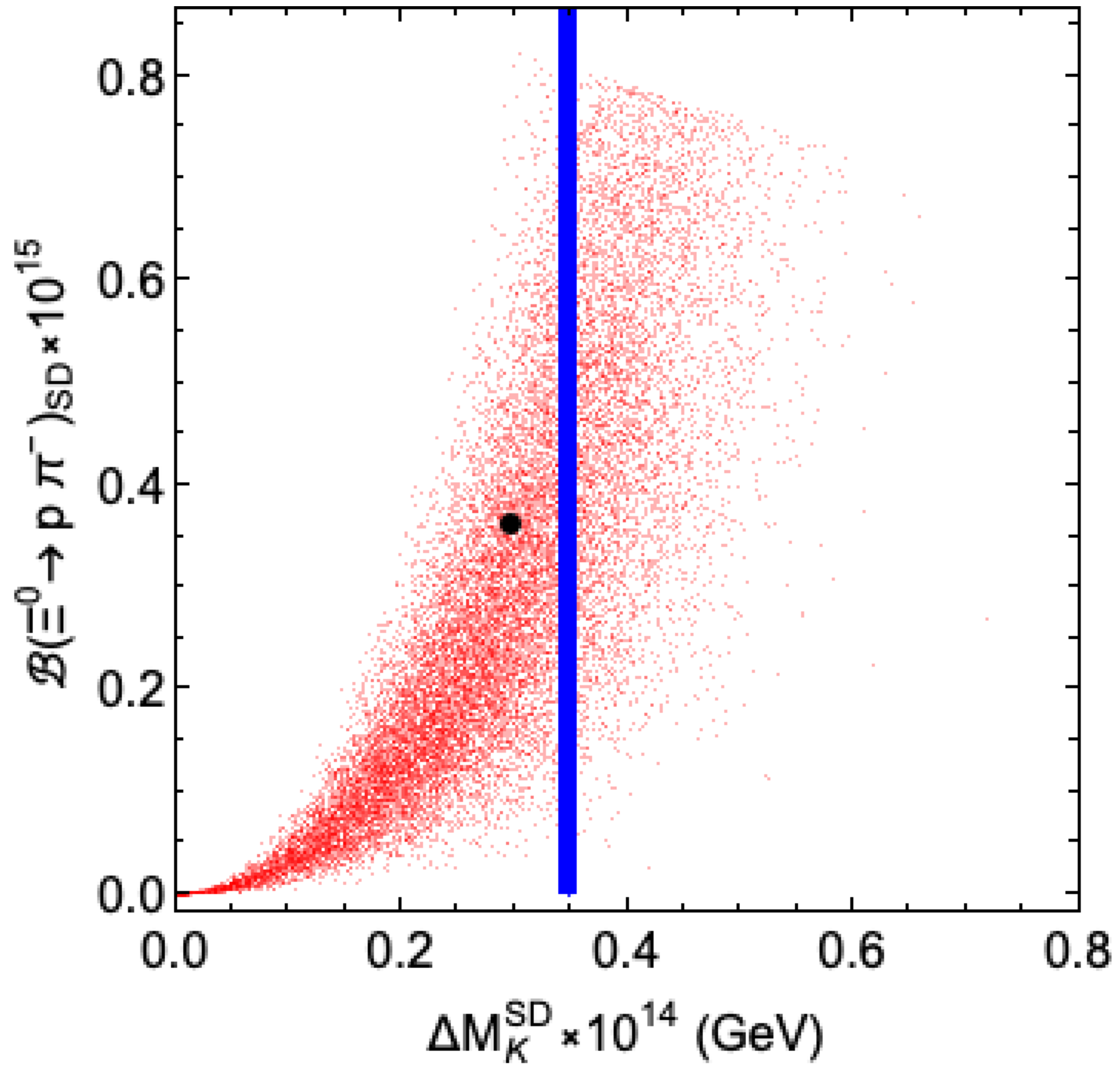
$$\mathcal{Q}^{\Delta I=3/2}_{\Delta S=1} \to \Lambda_\chi f_\pi^2\tilde{t}_{kl,no}\left[\hat{\beta}_{27}\left(\xi\overline{B}\xi^\dagger\right)_{nk}\left(\xi B\xi^\dagger\right)_{ol} + \hat{\delta}_{27}\xi_{nx}\xi_{oz}\xi^\dagger_{vk}\xi^\dagger_{wl}\left(\overline{T}_{rvw}\right)^\eta(T_{rxz})_\eta\right]$$

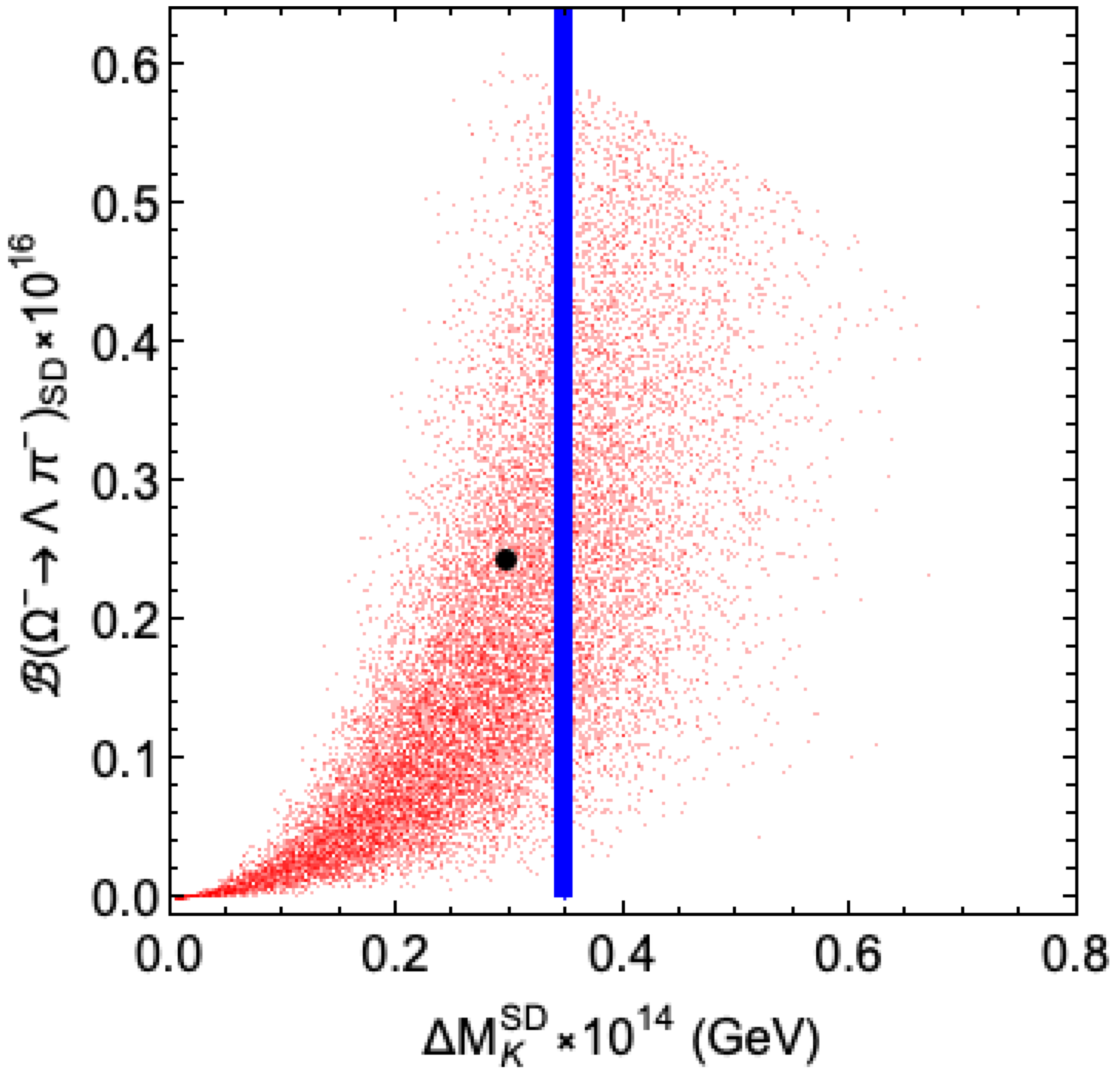
- $\hat{\beta}_{27} = 0.076 \pm 0.015$ but $\hat{\delta}_{27}$ not known yet - assume similar size for estimate

Short distance SM results

- $\Delta S = 2$ hyperon decay rates from short-distance SM are very small
- Even though ΔM_K only constrains the P-even part of the operator, the P-odd part is not independent in the SM
- There are also long-distance contributions which turn out to be much larger

$-\eta_{cc} = 1.87 \pm 0.76$ Brod and Gorbahn PRL 108 (2012) 121801



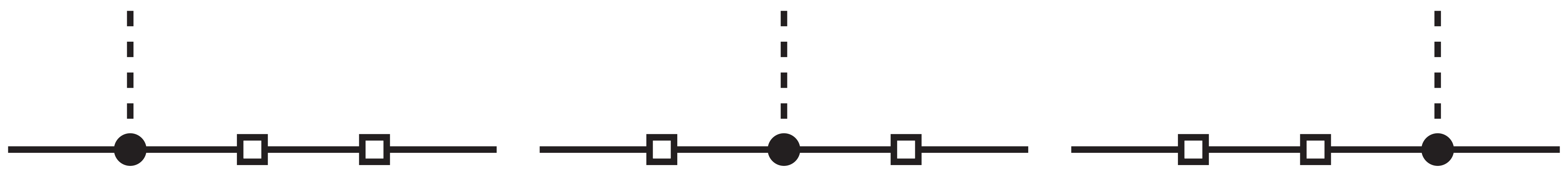


ΔM_K measured value

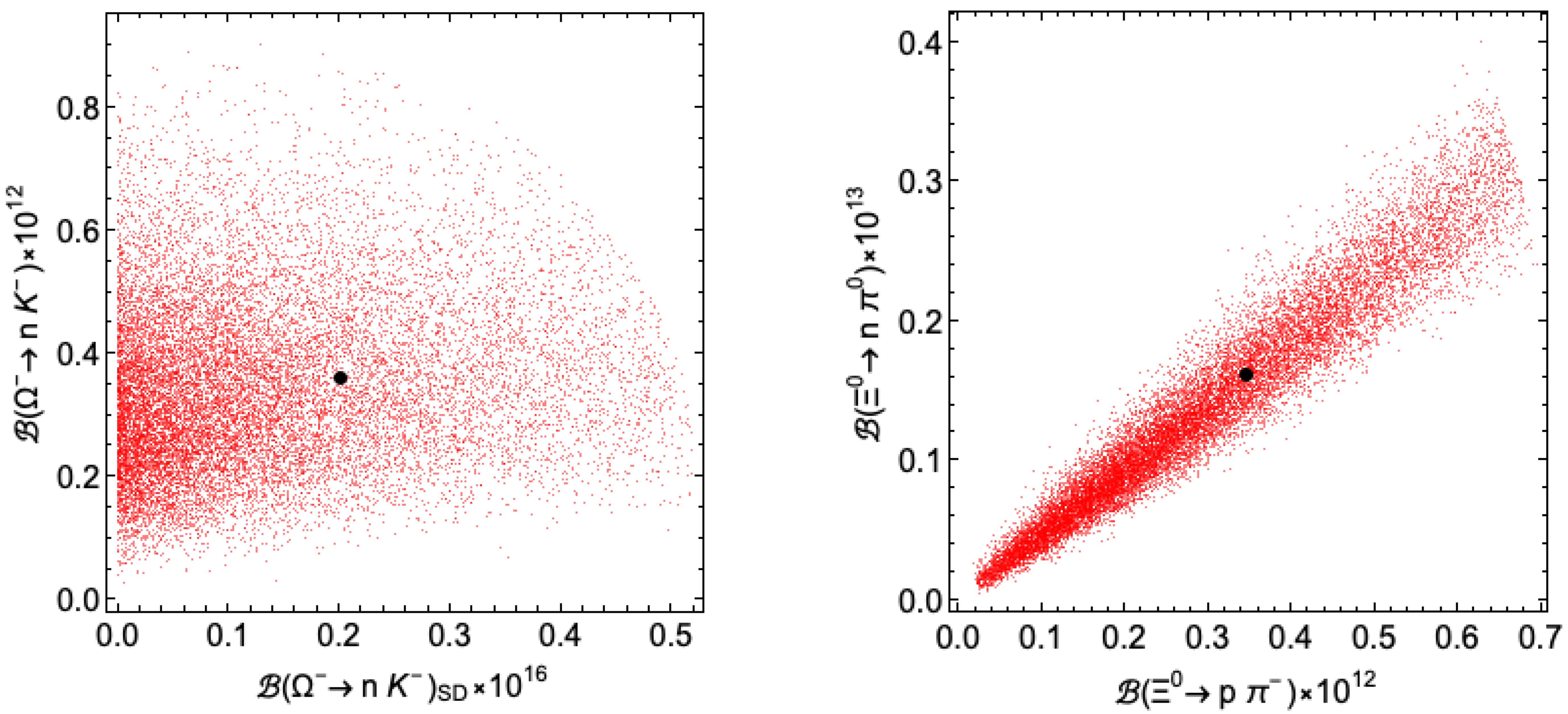
Long distance SM results

Pole diagrams with
two weak interactions

S-waves



P-waves



- $\Delta S = 2$ hyperon decay rates from long distance SM can be much larger, but still too small for observation. Uncertainty is large, order of magnitude estimate

Sample decays

- SM estimates

Mode	Branching fractions			
	SD	SD + LD ($\tilde{\mathrm{S}}$)	SD + LD ($\tilde{\mathrm{P}}$)	HyperCP 90% c.l
$\Xi^0 \to p\pi^-$	$(0.03, 1) \times 10^{-15}$	$(0.01, 2.6) \times 10^{-14}$	$(0.7, 8.2) \times 10^{-13}$	8×10^{-6}
$\Xi^0 \to n\pi^0$	$(0.03, 1) \times 10^{-15}$	$(0., 0.9) \times 10^{-15}$	$(0.03, 0.4) \times 10^{-13}$	
$\Xi^- \to n\pi^-$	$(0.07, 2.6) \times 10^{-16}$	$(0.01, 1.3) \times 10^{-14}$	$(0.03, 0.3) \times 10^{-12}$	1.9×10^{-5}
$\Omega^- \to nK^-$	$(0.1, 6.5) \times 10^{-17}$	$(0.2, 0.6) \times 10^{-12}$	$(0.2, 2.1) \times 10^{-12}$	
$\Omega^- \to \Lambda\pi^-$	$(0.2, 7.1) \times 10^{-17}$	$(0.4, 1.5) \times 10^{-13}$	$(0.2, 4.2) \times 10^{-13}$	2.9×10^{-6}
$\Omega^- \to \Sigma^0\pi^-$	$(0.04, 1.7) \times 10^{-17}$	$(0.5, 3.1) \times 10^{-14}$	$(0.05, 2.2) \times 10^{-14}$	

- $\Xi^0 \to p\pi^-$ BR of $10^{-9} - 10^{-10}$ possible with LHCb upgrade
- Window to new physics constrained by kaon mixing

$|\Delta S| = 2$ decays beyond SM

- effective Hamiltonian at dimension six: (example)

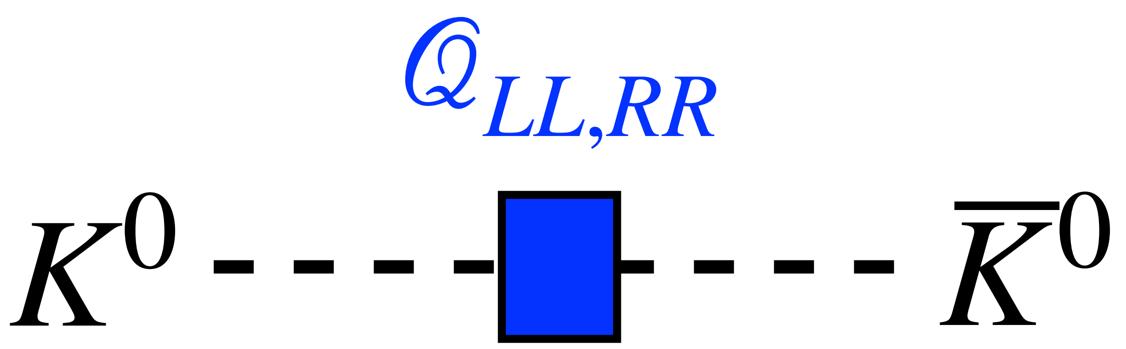
SM LRM QCD

$$\mathcal{H} = C_{LL}\mathcal{Q}_{LL} + C_{RR}\mathcal{Q}_{RR} + C_{LR}\mathcal{Q}_{LR} + C'_{LR}\mathcal{Q}'_{LR}$$

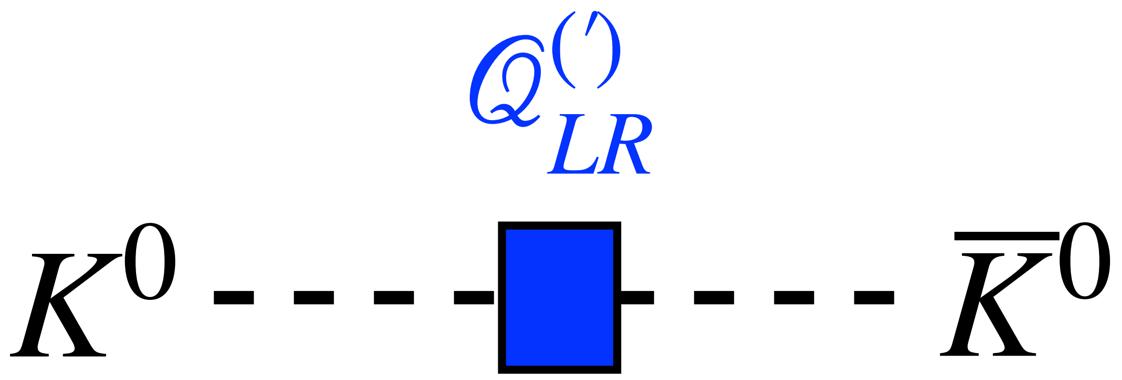
$$\mathcal{Q}_{LL} = \bar{d}\gamma^\alpha P_L s\, \bar{d}\gamma_\alpha P_L s, \qquad \mathcal{Q}_{RR} = \bar{d}\gamma^\alpha P_R s\, \bar{d}\gamma_\alpha P_R s$$

$$\mathcal{Q}_{LR} = \bar{d}\gamma^\alpha P_L s\, \bar{d}\gamma_\alpha P_R s, \qquad \mathcal{Q}'_{LR} = \bar{d}P_L s\, \bar{d}P_R s$$

a) fine-tuned using



$\neq$



b) or $(\mathcal{Q}_{LL} - \mathcal{Q}_{RR}) \sim \bar{d}\gamma^\alpha s\, \bar{d}\gamma_\alpha\gamma_5 s$ which is parity odd (difficult to construct a model (see Tandean, He, GV *2304.02559*)

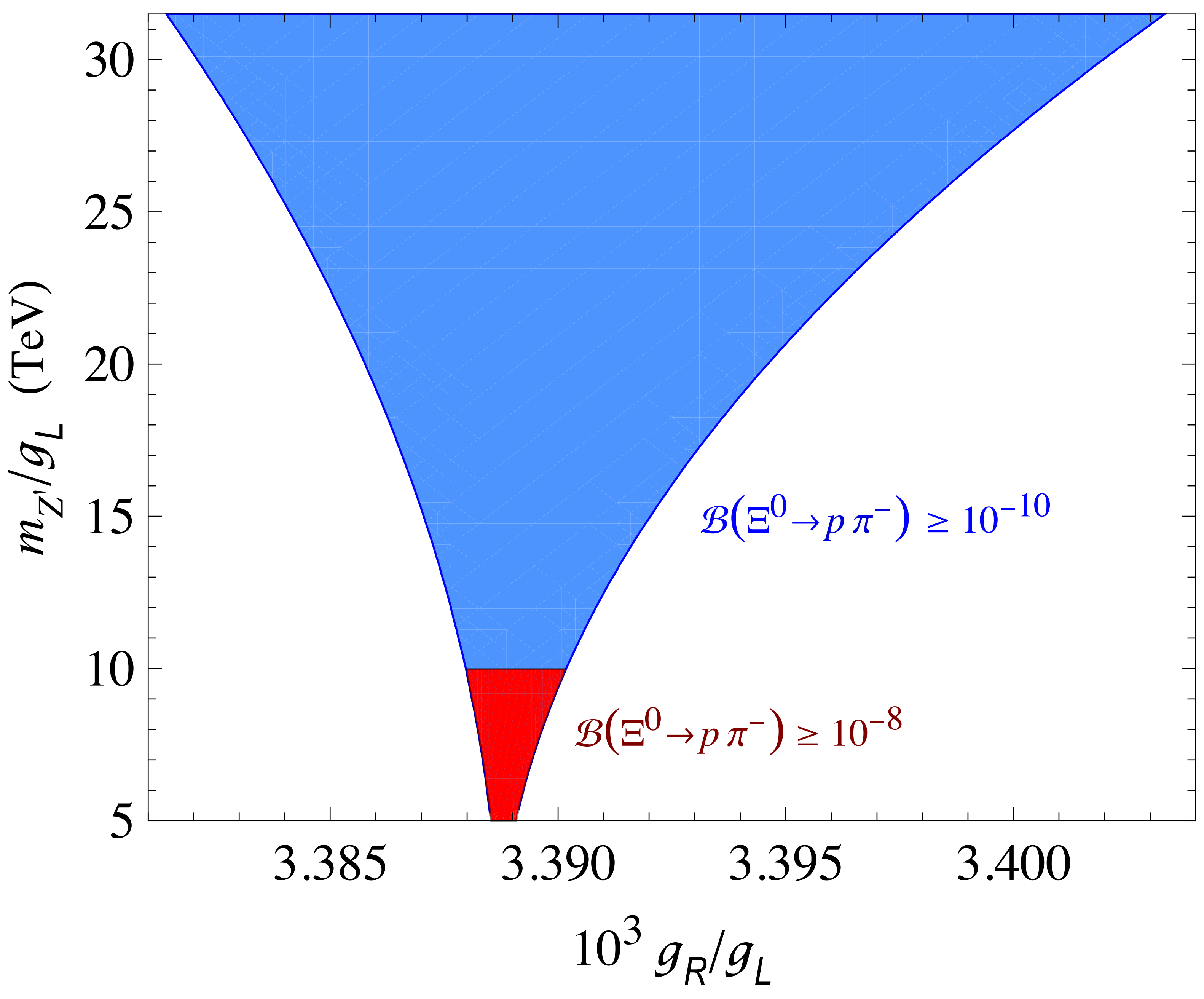
small contribution to ΔM_K by fine-tuning

- consider Z' FCNC couplings $\mathscr{L}_{dsZ'} = -\bar{d}\gamma^\beta(g_L P_L + g_R P_R)s\, Z'_\beta$
- then after QCD corrections

$$\Delta M_K^{Z'} = \frac{2}{4 m_{K^0} m_{Z'}^2} \Re\left(\eta_{LL}\,(g_L^2 + g_R^2)\langle \mathcal{Q}_{LL}\rangle + 2 g_L g_R\,(\eta_{LR}\langle \mathcal{Q}_{LR}\rangle + \eta'_{LR}\langle \mathcal{Q}'_{LR}\rangle)\right)$$

- using lattice input[1] and values from[2] the last 2 terms are negative, the first two positive
- allowing $-1 < \Delta M_K^{Z'}/\Delta M_K^{\rm exp} < 0.5$ which is the 2σ range of $\Delta M_K^{EXP} - \Delta M_K^{SM}$
- assuming $g_L,\ g_R$ real there are regions of parameters with large $|\Delta S| = 2$ hyperon rates.

(see Tandean, He, GV *2304.02559*)

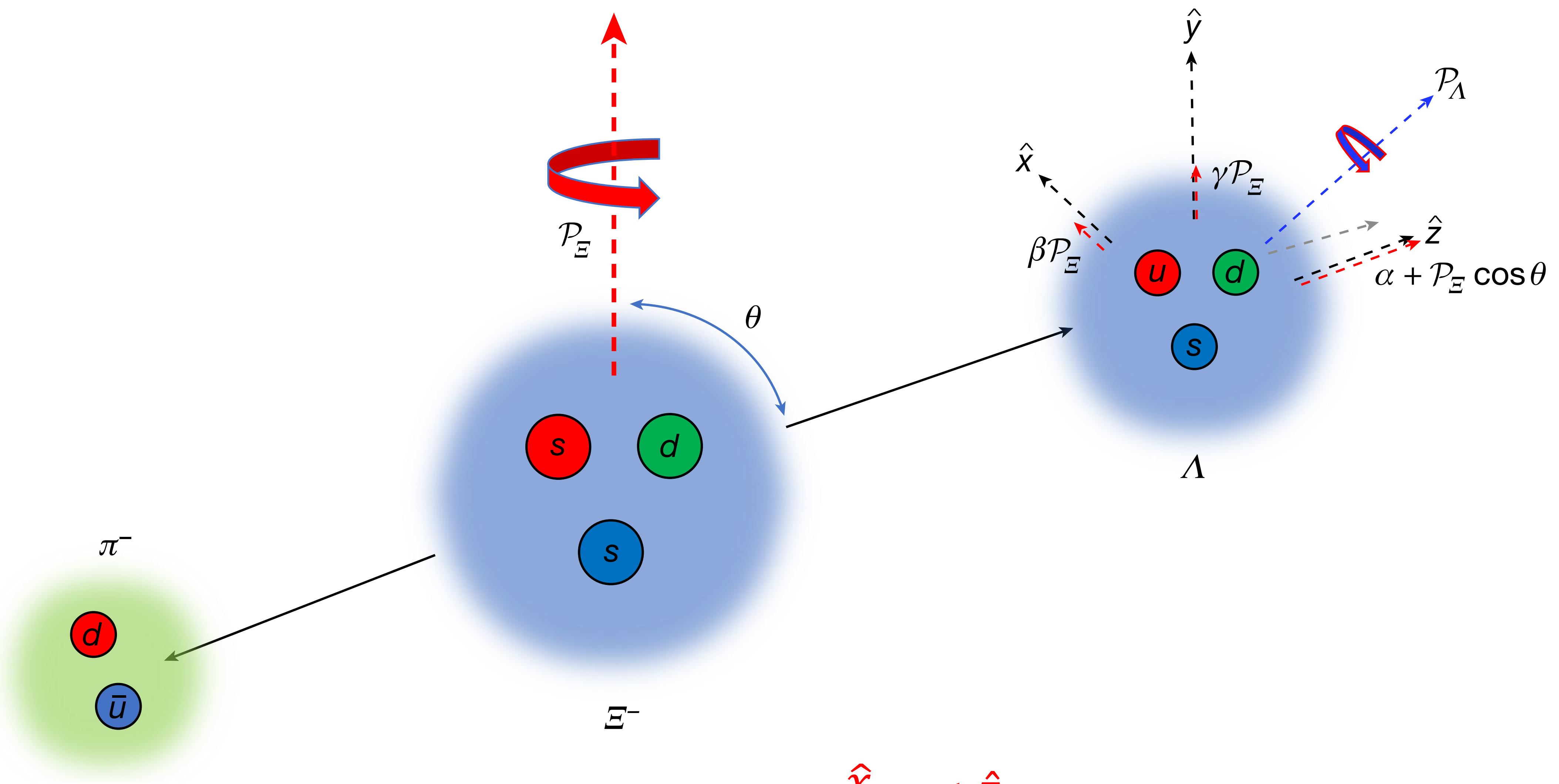


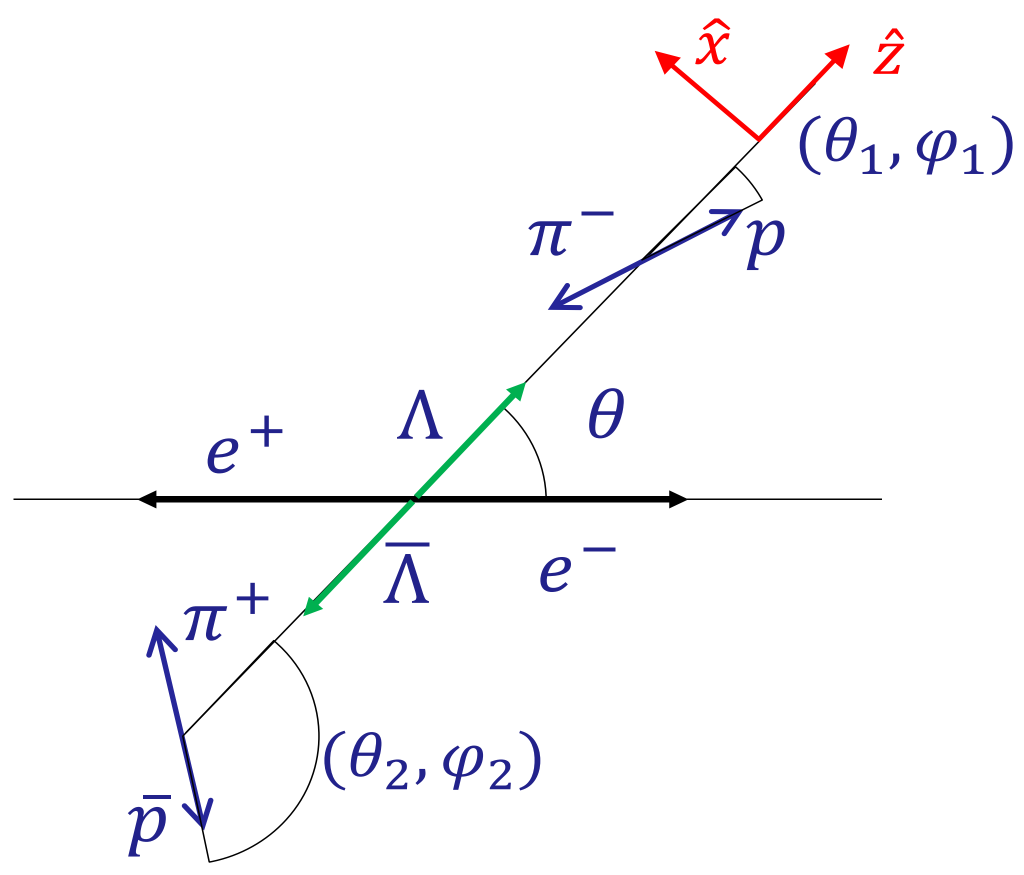
1 FLAG *Eur.Phys.J.C* 80 (2020) 2, 113

2. J. Aebischer et. al *JHEP* 12 (2020) 187

CP violation in Hyperon non-leptonic decay

Hyperon non-leptonic decay - observables





$$\frac{d\Gamma_{\mathcal{B}_i \to \mathcal{B}_f \pi}}{d\Omega_f} = \frac{\Gamma_{\mathcal{B}_i \to \mathcal{B}_f \pi}}{4\pi} \left(1 + \alpha\, \mathbf{P}_i \cdot \hat{\mathbf{p}}_f\right)$$

$$\mathbf{P_f} = \frac{\left(\alpha + \mathbf{P_i} \cdot \hat{\mathbf{p}}_\mathbf{f}\right) \hat{\mathbf{p}}_\mathbf{f} + \beta \mathbf{P_i} \times \hat{\mathbf{p}}_\mathbf{f} + \gamma\, \hat{\mathbf{p}}_\mathbf{f} \times \left(\mathbf{P_i} \times \hat{\mathbf{p}}_\mathbf{f}\right)}{1 + \alpha\, \mathbf{P_i} \cdot \hat{\mathbf{p}}_\mathbf{f}}$$

- CP tests: $\Delta = \dfrac{\Gamma - \overline{\Gamma}}{\Gamma + \overline{\Gamma}}$
- $A_{CP} = \dfrac{\alpha + \overline{\alpha}}{\alpha - \overline{\alpha}}, \quad B_{CP} = \dfrac{\beta + \overline{\beta}}{\alpha - \overline{\alpha}}$

Figures from BESIII collaboration:

Ablikim, M., Achasov, M. N., Adlarson, P., Cetin, H. O., Kolcu, O. B. (2022). Probing CP symmetry and weak phases with entangled double-strange baryons. Nature, 606(7912), 64.
And fron https://doi.org/10.1007/s00601-022-01762-0

Not all are the same size

- The matrix element receives contributions from different isospin and different parity amplitudes
- $$\mathscr{M} = G_F m_\pi^2 \overline{u}_f \left(A - B\gamma_5\right) u_i \quad \begin{cases} S = A \to S_1 e^{i\delta_1^S} + S_3 e^{i\delta_3^S} \\ P = B\dfrac{|\vec{p}_f|}{E_f + m_f} \to P_1 e^{i\delta_1^P} + P_3 e^{i\delta_3^P} \end{cases}$$

One finds

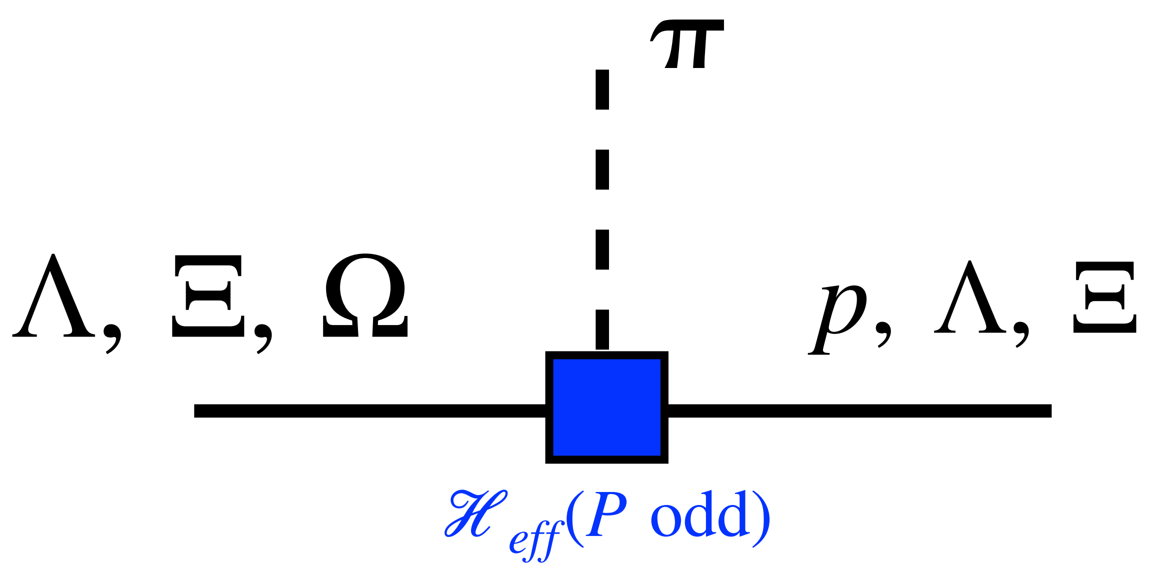
$$\Delta_{CP} \simeq \sqrt{2} \underbrace{\frac{S_3}{S_1}}_{\Delta I = 1/2 \text{ rule}} \underbrace{\sin(\delta_3^S - \delta_1^S)}_{\text{strong phases}} \underbrace{\sin(\xi_3^S - \xi_1^S)}_{\text{weak phases}}$$

$$A_{CP} \simeq -\tan(\delta_P - \delta_S)\, \tan(\xi_P - \xi_S)$$

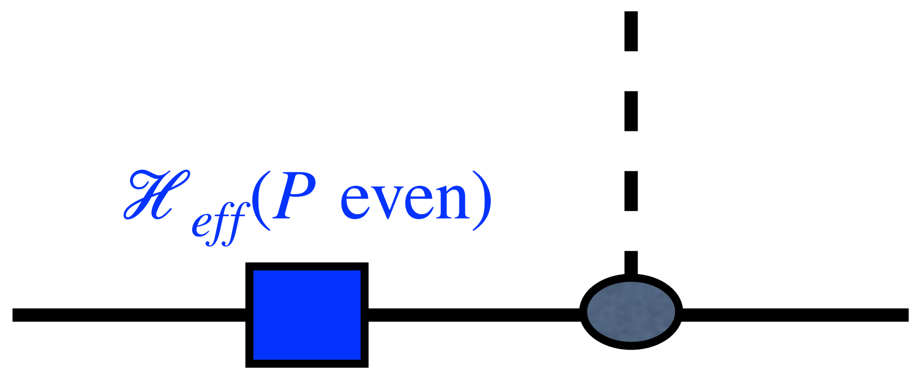
$$B_{CP} \simeq \tan(\xi_P - \xi_S)$$

CP violation beyond SM - illustrative example

S (or D) waves

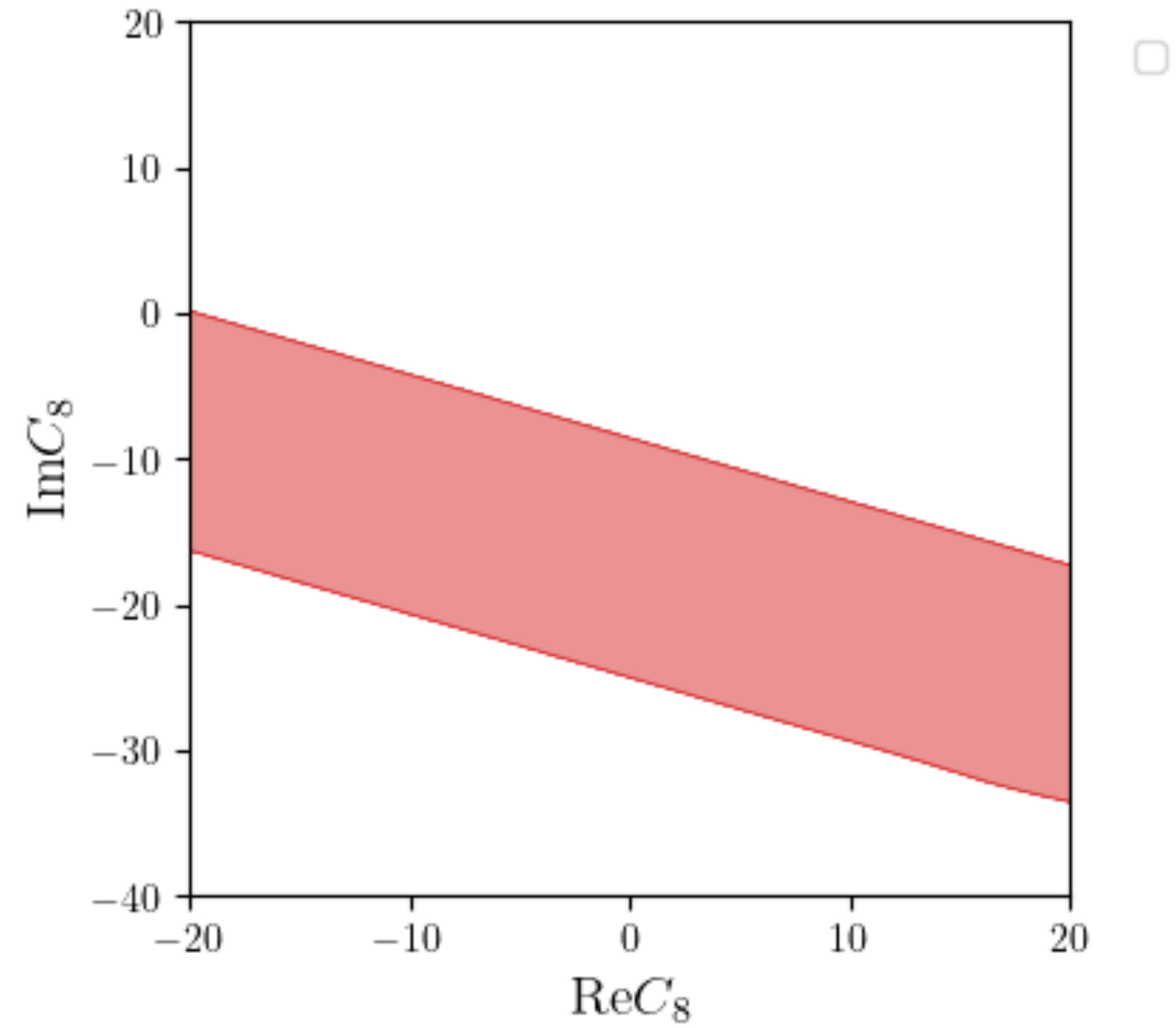


P waves

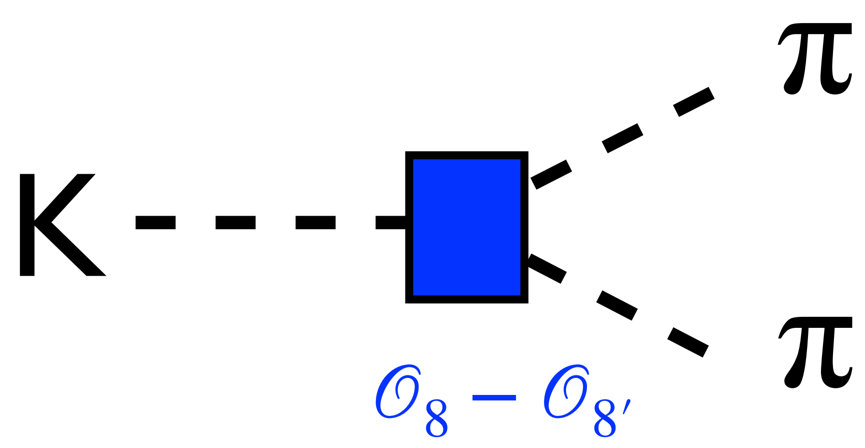


$$\mathscr{L}_{NP} \supset C_8 \mathcal{O}_8 + C_{8'} \mathcal{O}_{8'},$$

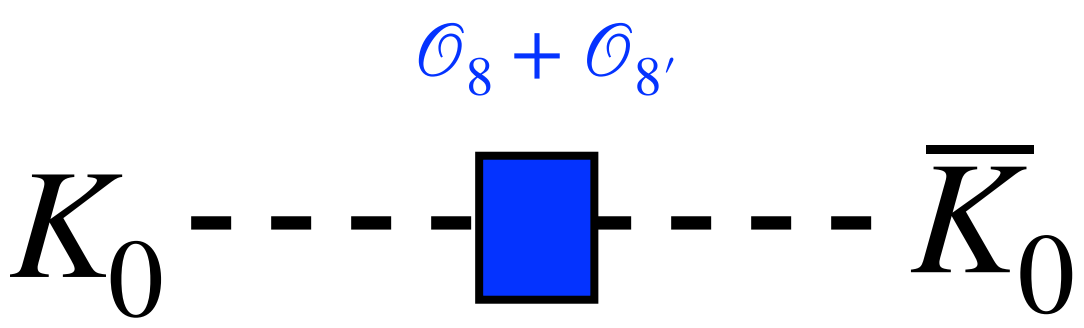
$$\mathcal{O}_{8(8')} = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{g_s}{16\pi^2} m_s \bar{d}_{L(R)} \sigma^{\mu\nu} T^a s_{R(L)} G^a_{\mu\nu}$$



constraint from ε′



constraint from ε



$$|\epsilon| = (2.228 \pm 0.011) \times 10^{-3}, \qquad \mathrm{Re}\left(\frac{\epsilon'}{\epsilon}\right) = (1.66 \pm 0.23) \times 10^{-3}$$

Theory error at this level

BSM possible range

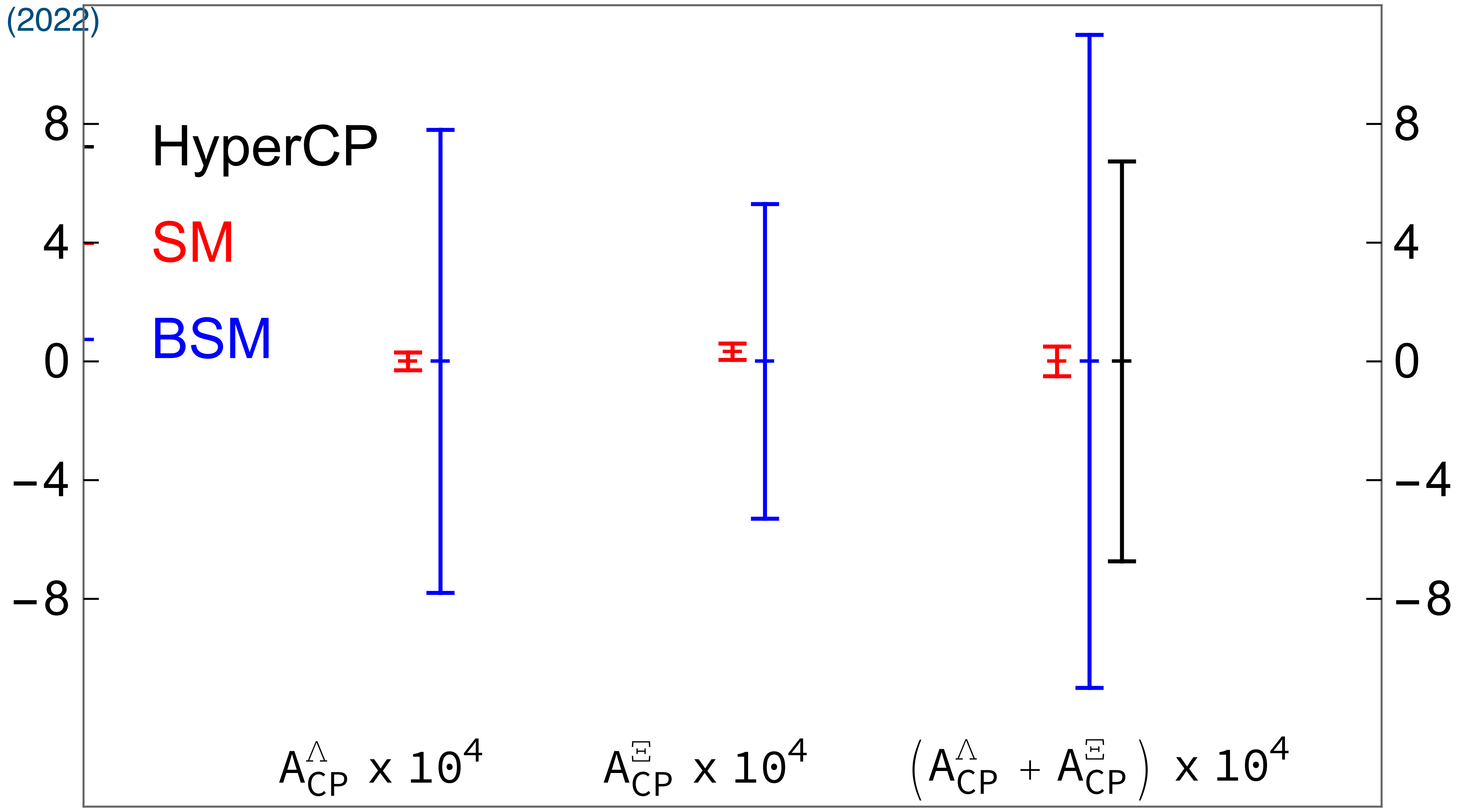
- use as an example $\mathscr{L}_{NP} \supset C_8 \mathcal{O}_8 + C_{8'} \mathcal{O}_{8'}$, $\mathcal{O}_{8(8')} = \frac{4G_F}{\sqrt{2}} V_{ts} V_{td}^* \frac{g_s}{16\pi^2} m_s \bar{d}_{L(R)} \sigma^{\mu\nu} T^a s_{R(L)} G^a_{\mu\nu}$

then $(\xi_P - \xi_S) \sim \left(C' \left(\frac{\epsilon'}{\epsilon} \right)_{BSM} + C\, \epsilon_{BSM} \right)$

J. Tandean PHYSICAL REVIEW D **69**, 076008 ?2004?, N Salone et.al. PHYSICAL REVIEW D 105, 116022 (2022)

- using $\left| \frac{\epsilon'}{\epsilon} \right|_{BSM} \lesssim 1 \times 10^{-3}$, $|\epsilon|_{BSM} \lesssim 2 \times 10^{-4}$
- (theoretical uncertainty in SM)

J. Aebischer, A. J. Buras, and J. Kumar, J. High Energy Phys. 12 (2020) 097.



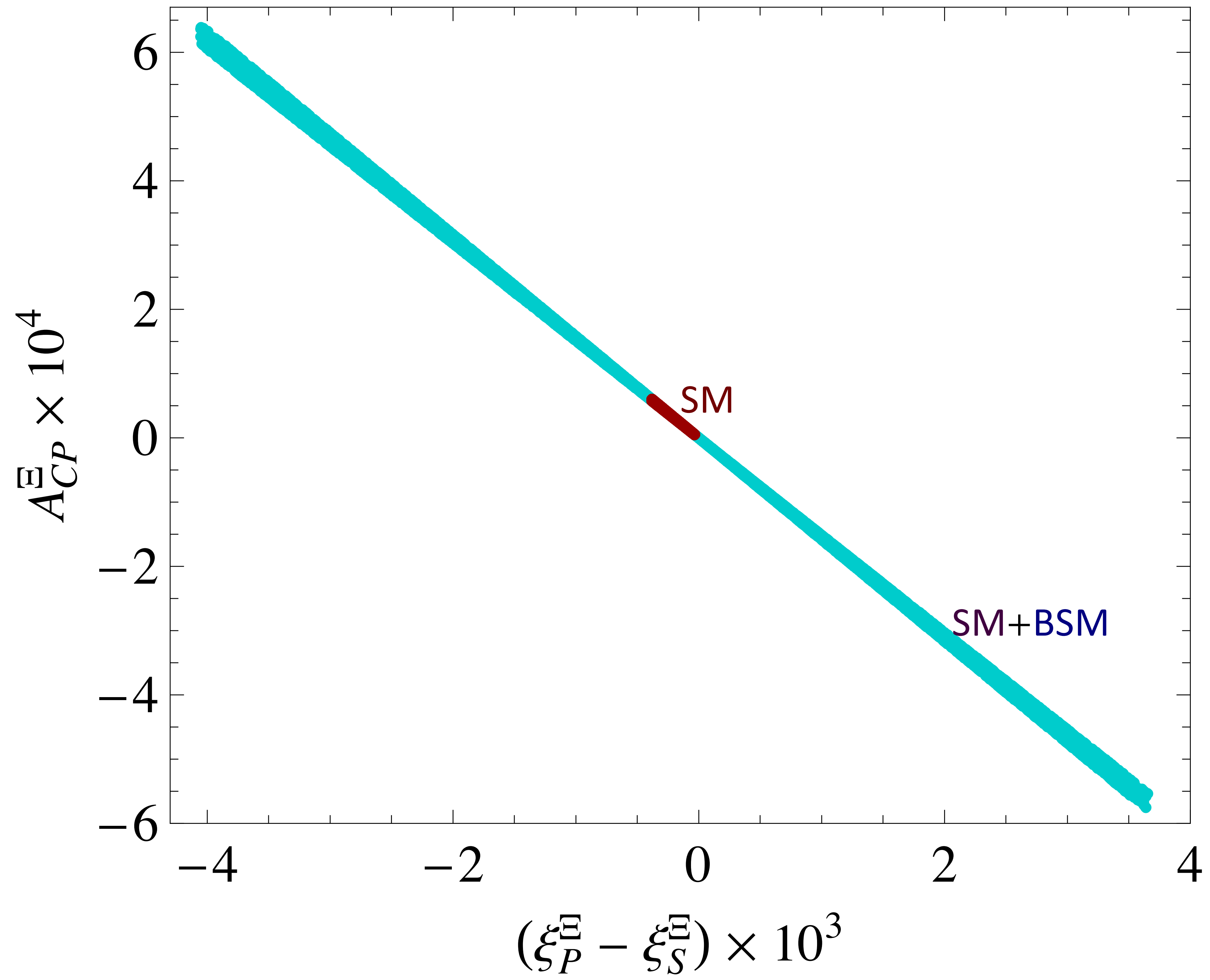
HyperCP result

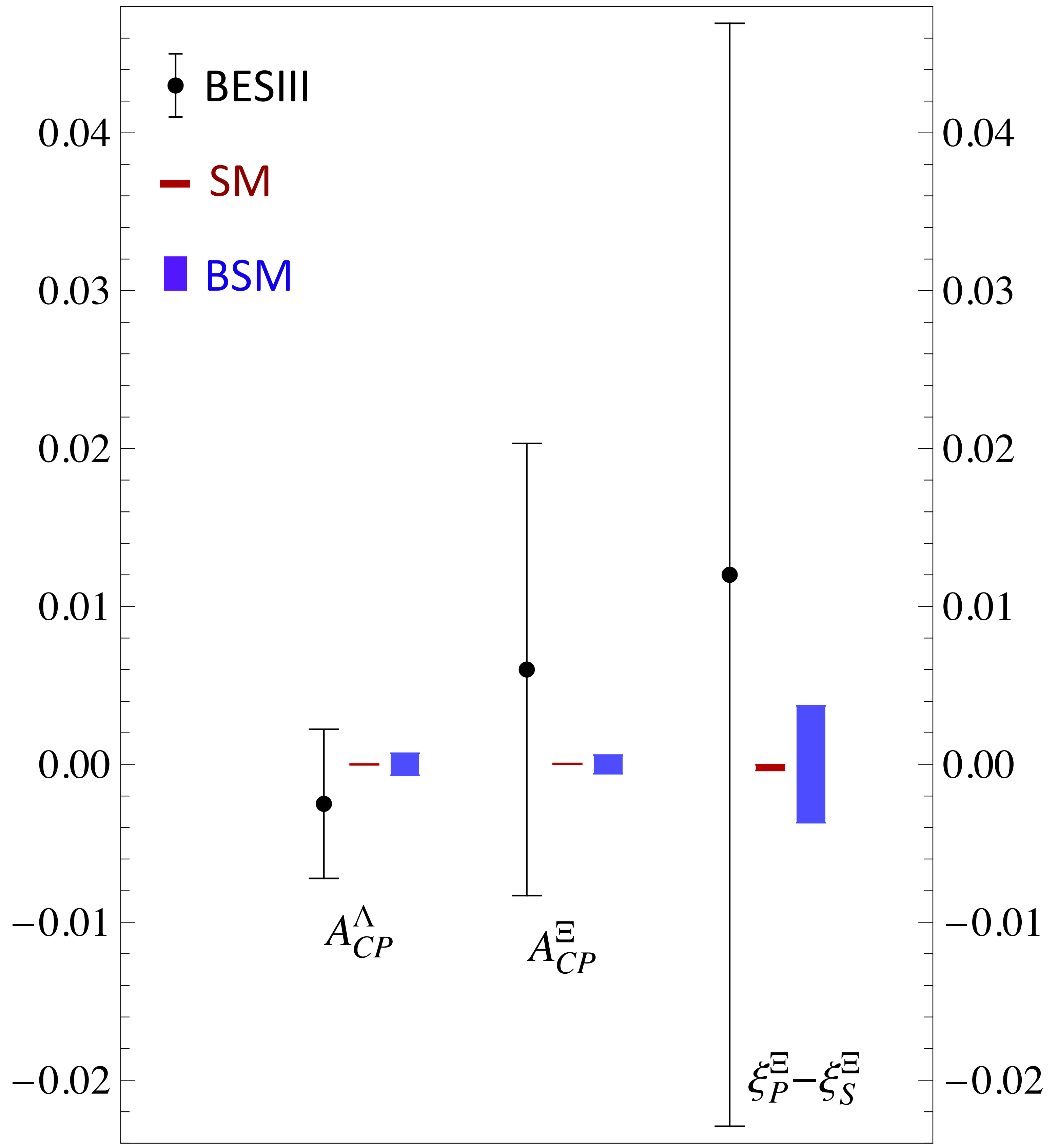
Phys.Rev.Lett.93:262001,2004.

$$A_{\Xi\Lambda} = [0.0 \pm 5.1(\mathrm{stat}) \pm 4.4(\mathrm{syst})] \times 10^{-4}$$

BES III results vs BSM scenarios

Tandean, He, G.V. Sci.Bull. 67 (2022) 1840





- BESIII also has a new result from 448×10^6 $e^+e^- \to \psi(3686) \to \Xi^0\overline{\Xi}^0 \to \pi^0\pi^0\Lambda\overline{\Lambda}$ events
- measure

$$A_{CP}^{\Xi^0} = -0.007 \pm 0.082 \pm 0.025$$

BESIII, *Phys.Rev.D* 108 (2023) 1, L011101

projections

	Number of J/ψ	sensitivity to A_{CP}^{Ξ}
BESIII (current)	1.3×10^9	1.3×10^{-2}
BESIII (future)	1×10^{10}	4.8×10^{-3}
tau-charm factory	3.4×10^{12}	2.6×10^{-4}

Salone et. al., PHYSICAL REVIEW D 105, 116022 (2022)

Summary and conclusions

- Hyperon decays can play a role in probing BSM physics in the $s \to d$ sector, complementing kaon decays, but need much higher sensitivity
- Decay modes allowed in the SM receive large long distance contributions that are difficult to estimate reliably, the lattice community has started to look at some of these modes
- Near future LHCb $\Sigma^+ \to p\mu^+\mu^-$ can definitively rule out the “hyperCP” particle. It will also accurately measure the rate and spectrum.
  – form factors
  – new exotic particle searches
- expected sensitivity to $\Delta S = 2$ modes at LHCb can begin to probe exotic BSM scenarios
- Upcoming BESIII measurements will add to our picture of CP violation in hyperons