

KAON THEORY

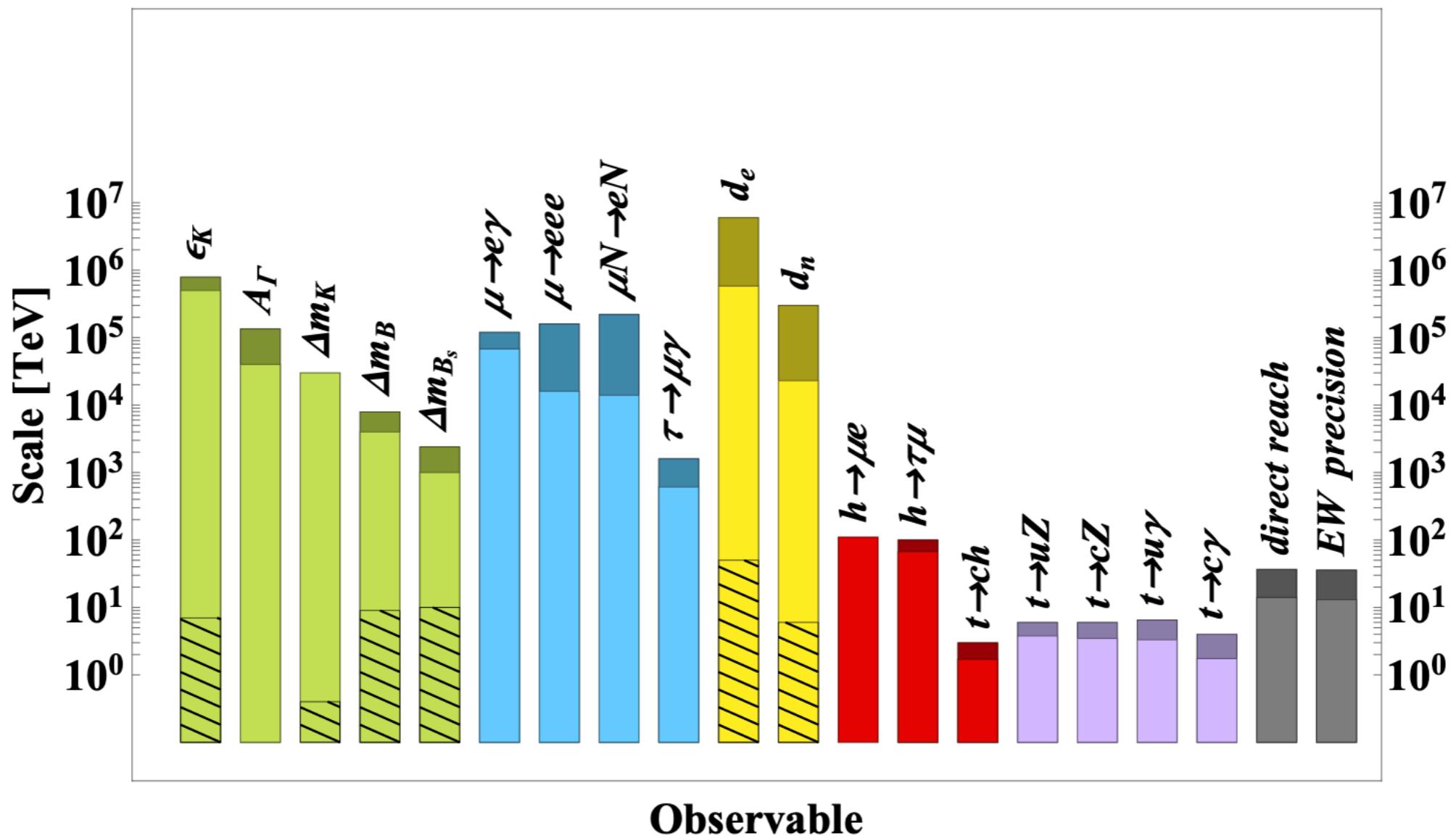
JURE ZUPAN
U. OF CINCINNATI

Prospecting for New Physics through Flavor, Dark Matter, and Machine Learning, Aspen, Mar 30, 2023

WHY KAONS?

- an extremely sensitive probe of NP
 - e.g. assuming dim 6 NP ops: $\sim (\bar{s}\gamma^\mu d_L)^2/\Lambda^2$

[Physics Briefing Book, 1910.11775](#)

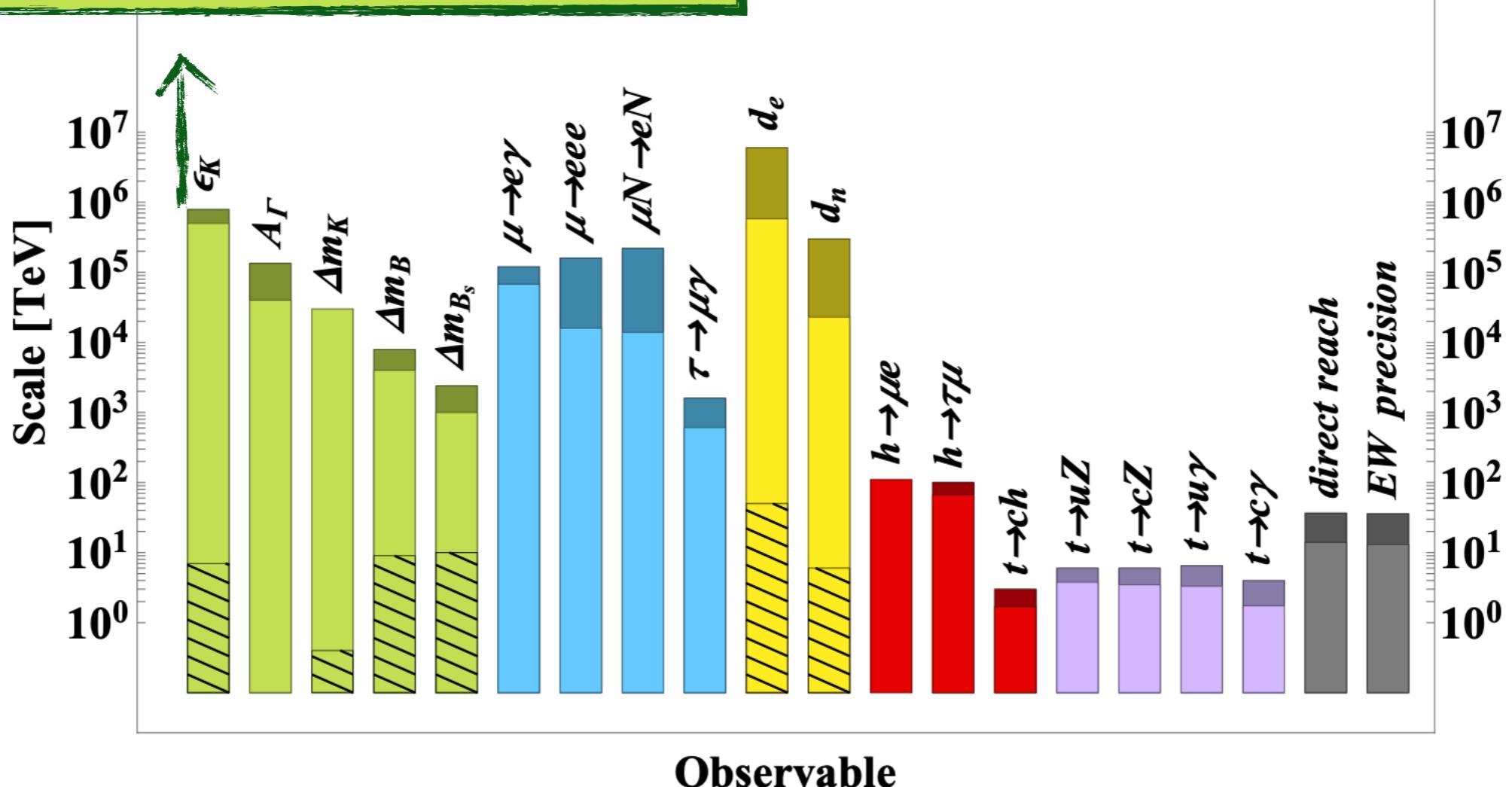


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The future: how far can we reach?



OUTLINE

- searching for heavy new physics
 - SM predictions crucial
- searching for light new physics
 - increased sensitivity to UV

HEAVY NEW PHYSICS

SM THEORY - ϵ_K

- in the last few years a qualitative jump in precision of theory prediction for ϵ_K

Brod, Gorbahn, Stamou

(+Kvedaraite, Polonsky, Youssef)
1911.06822, 2108.00017, 2207.07669

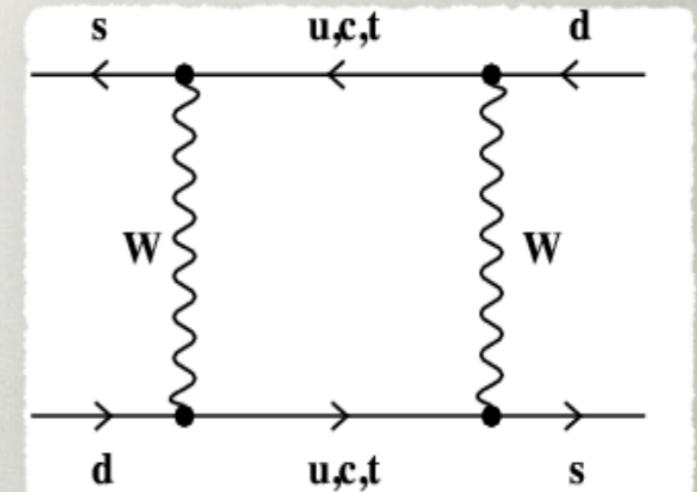
- the CKM unitarity $\lambda_u + \lambda_c + \lambda_t = 0$ ($\lambda_i = V_{is}^* V_{id}$) can be used to organize perturbative series in two ways

- old: $\lambda_u = -\lambda_c - \lambda_t$

$$\mathcal{L}_{f=3}^{\Delta S=2} = -\frac{G_F^2 M_W^2}{4\pi^2} [\lambda_c^2 C_{S2}^{cc}(\mu) + \lambda_t^2 C_{S2}^{tt}(\mu) + \lambda_c \lambda_t C_{S2}^{ct}(\mu)] Q_{S2} + \text{h.c.} + \dots$$

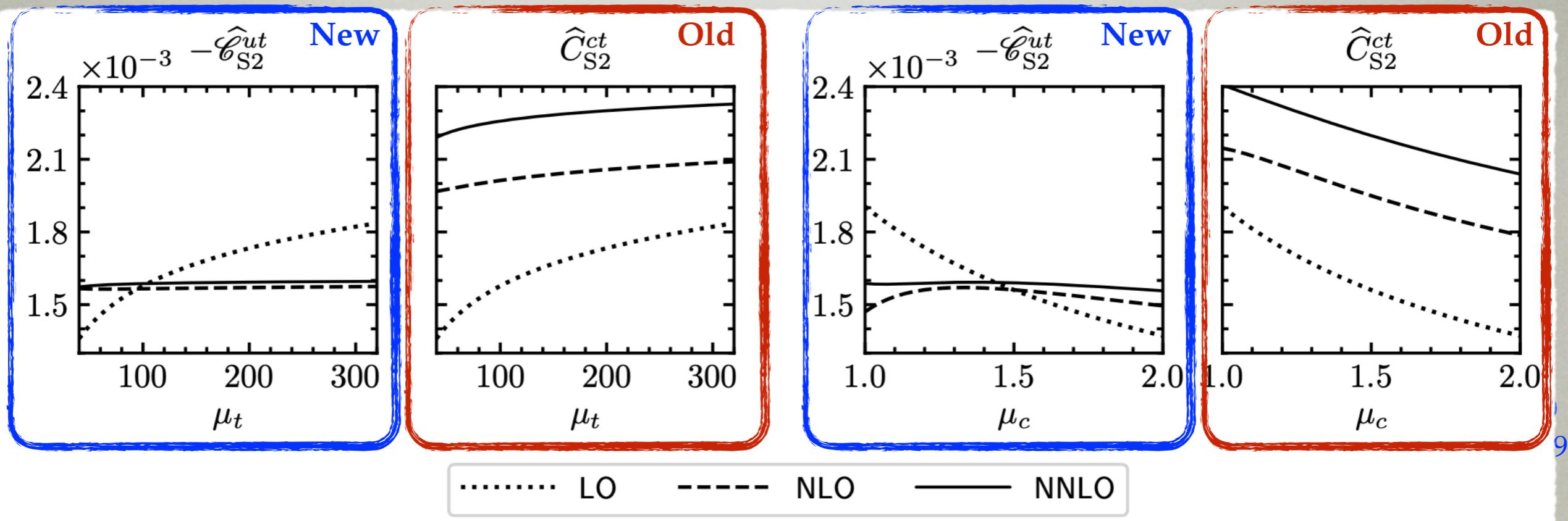
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$$Q_{S2} = (\bar{s}_L \gamma_\mu d_L) \otimes (\bar{s}_L \gamma^\mu d_L)$$

- dramatically improves calculation of ϵ_K by removing spurious long distance charm contrib.

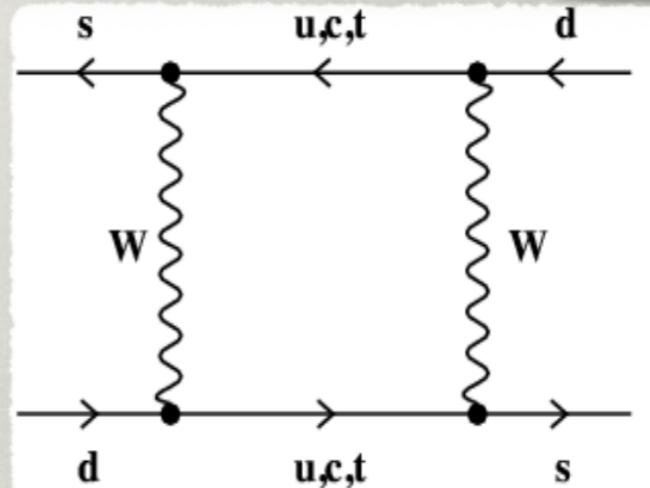


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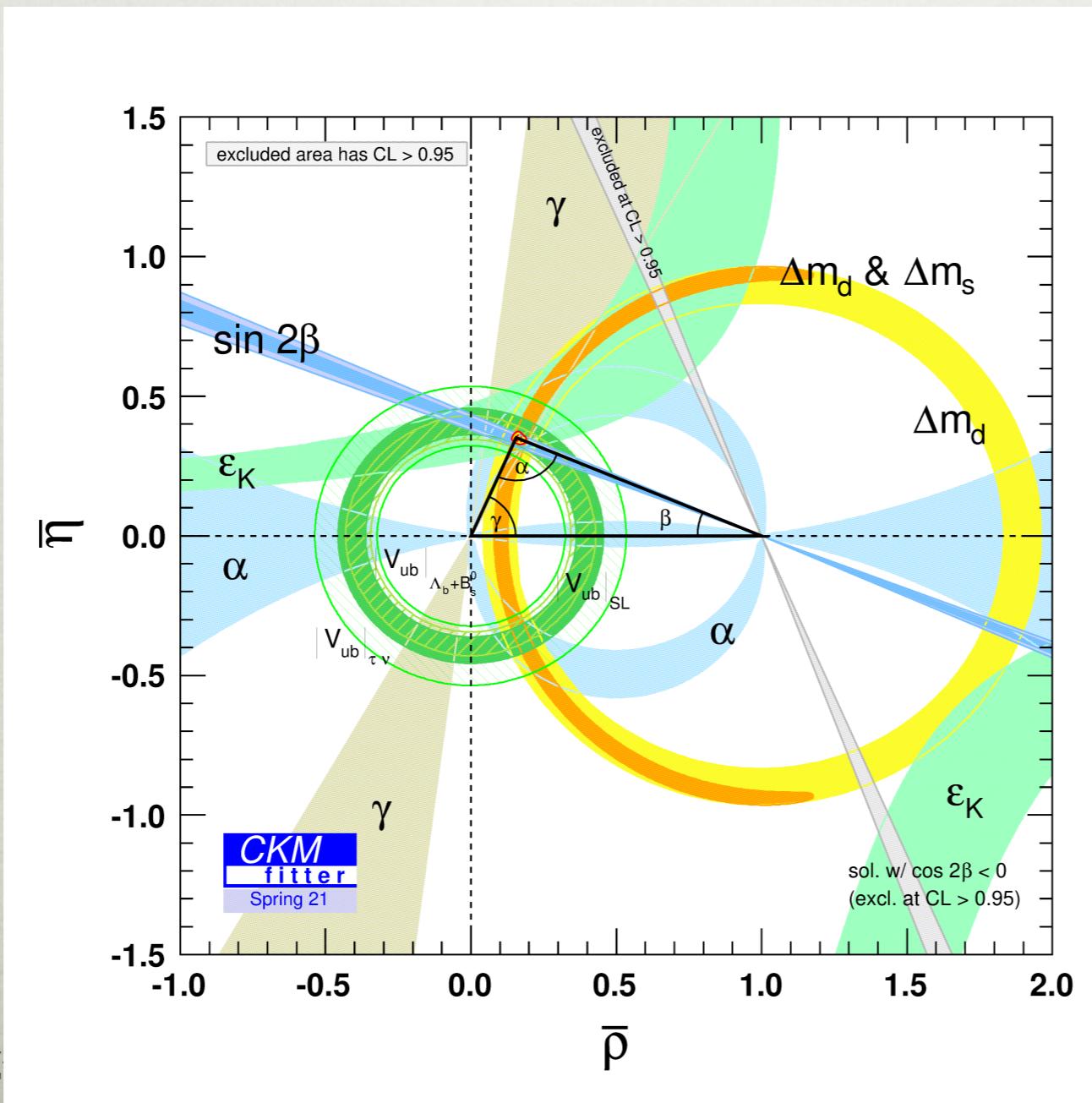


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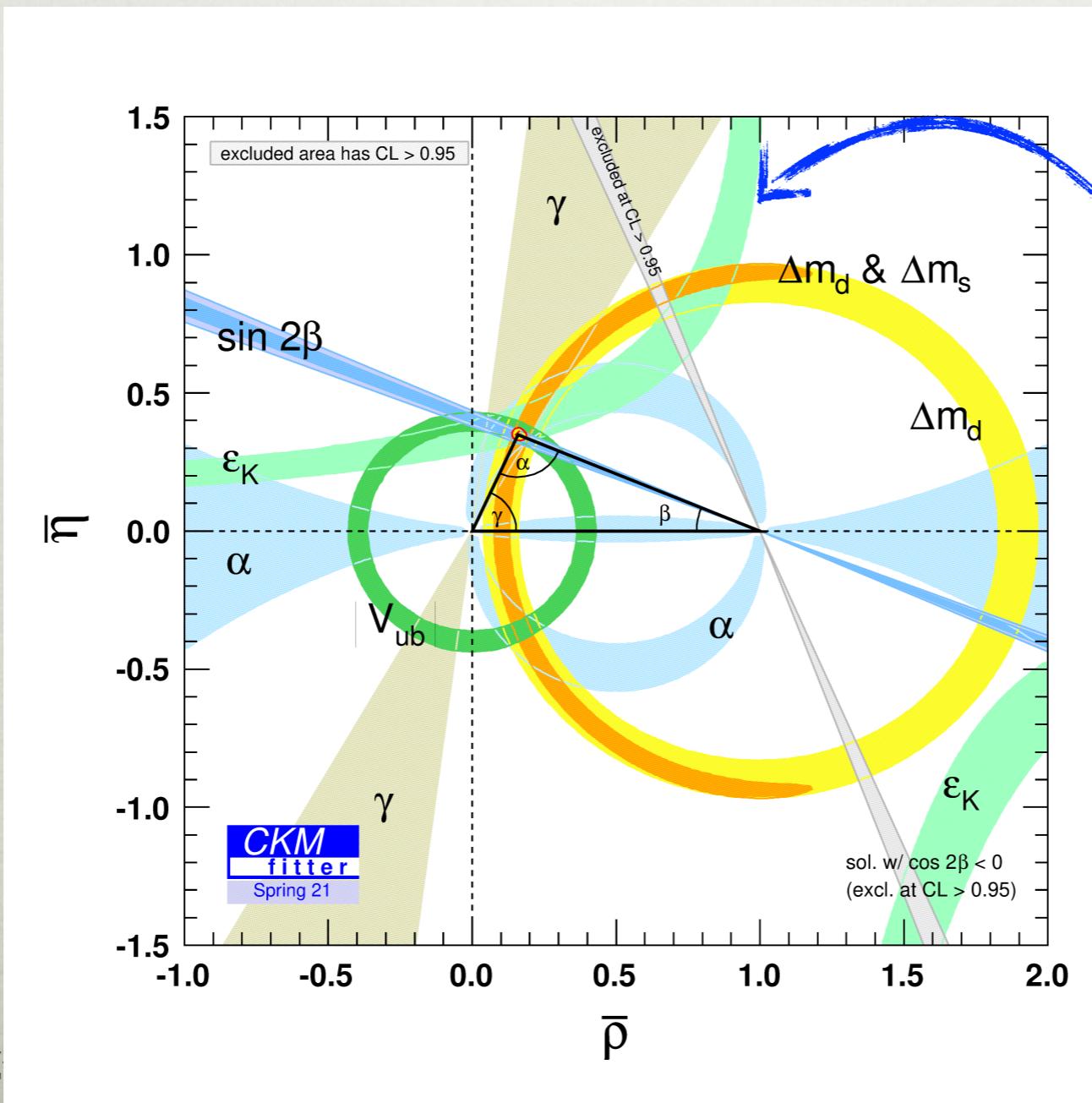
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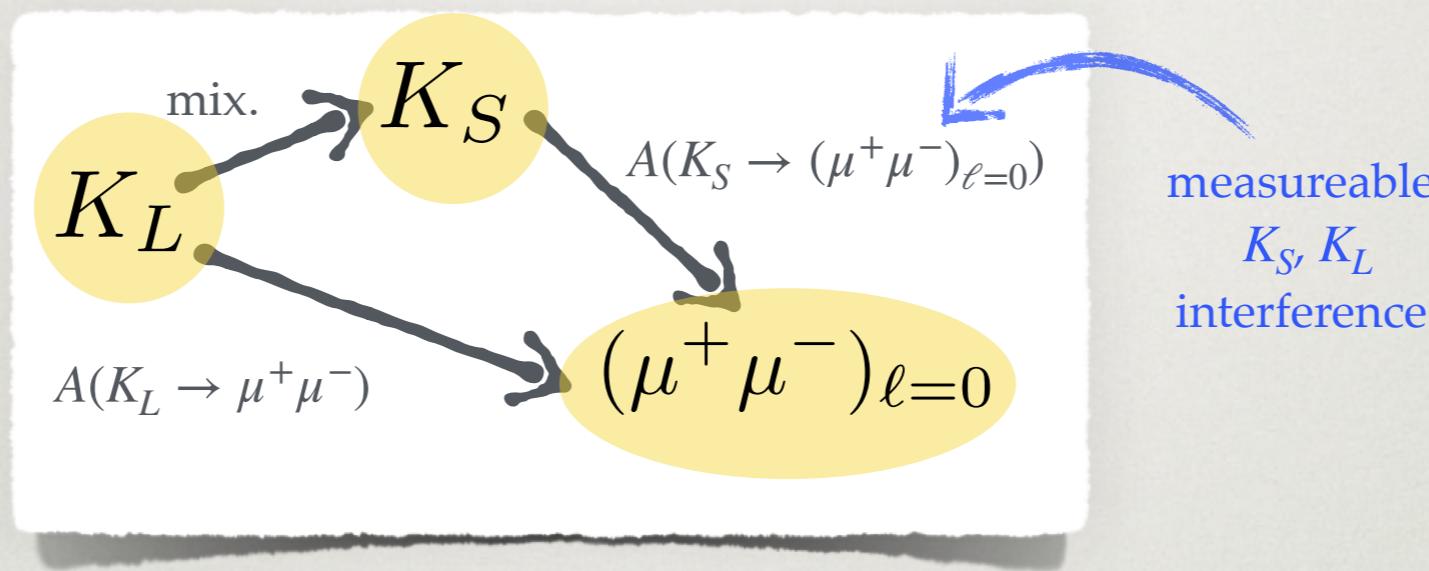
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could be improved by:
- three-loop QCD corrections to top quark contribs.
- NLO scheme conversion from RI/SMOM to \overline{MS}

NEW SHORT DISTANCE PROBES

- precision probe of UV physics from $K_S \rightarrow \mu^+ \mu^-$

D'Ambrosio, Kitahara, 1707.06999
 Dery et al, 2104.06427
 see also Dery, 2211.06446



- from $\Gamma(K \rightarrow \mu^+ \mu^-)(t)$ can measure $\text{BR}(K_S \rightarrow (\mu^+ \mu^-)_{\ell=0})$ from interf.
 - is CP violating, short distance, precisely calculable
 - very small remaining intrinsic uncertainty

Brod, Stamou, 2209.07445

$$\text{Br}(K_S \rightarrow \mu^+ \mu^-)_{\ell=0} = 1.70(02)_{\text{QCD/QED}}(01)_{f_K}(06)_{\text{ICPV}}(19)_{\text{param.}} \times 10^{-13},$$

- can be used to search for new physics
 - e.g., leptoquarks or charged Higgs with nontrivial flavor structure can saturate the present bounds from $\text{BR}(K_S \rightarrow \mu^+ \mu^-)$

Dery, Ghosh, 2112.05801

KAONIC NULL TESTS

- golden kaonic quartet
 - $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu}), \text{Br}(K^0 \rightarrow \pi^0 \nu \bar{\nu}), \text{BR}(K_S \rightarrow (\mu^+ \mu^-)_{\ell=0}), \epsilon_K$
 - for first two active experimental program at NA62, KOTO
 - all precisely calculable, parametric uncertainty dominated by CKM (V_{cb})
- factoring out V_{cb} dependence \Rightarrow SM sum rules involving (almost) just kaon sector observables
 - null test of the SM, require only kaons+ β
 - two ratios with very small theory errors $\approx 4\%$ and $\approx 1.6\%$

Buras, Venturini, 2109.11032

$$R_{11} = \frac{\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})}{|\epsilon_K|^{0.82}} = (1.31 \pm 0.05) \times 10^{-8} \left(\frac{\sin \gamma}{\sin 67^\circ} \right)^{0.015} \left(\frac{\sin 22.2^\circ}{\sin \beta} \right)^{0.71},$$

$$R_{12} = \frac{\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})}{|\epsilon_K|^{1.18}} = (3.87 \pm 0.06) \times 10^{-8} \left(\frac{\sin \gamma}{\sin 67^\circ} \right)^{0.03} \left(\frac{\sin \beta}{\sin 22.2^\circ} \right)^{0.98}$$

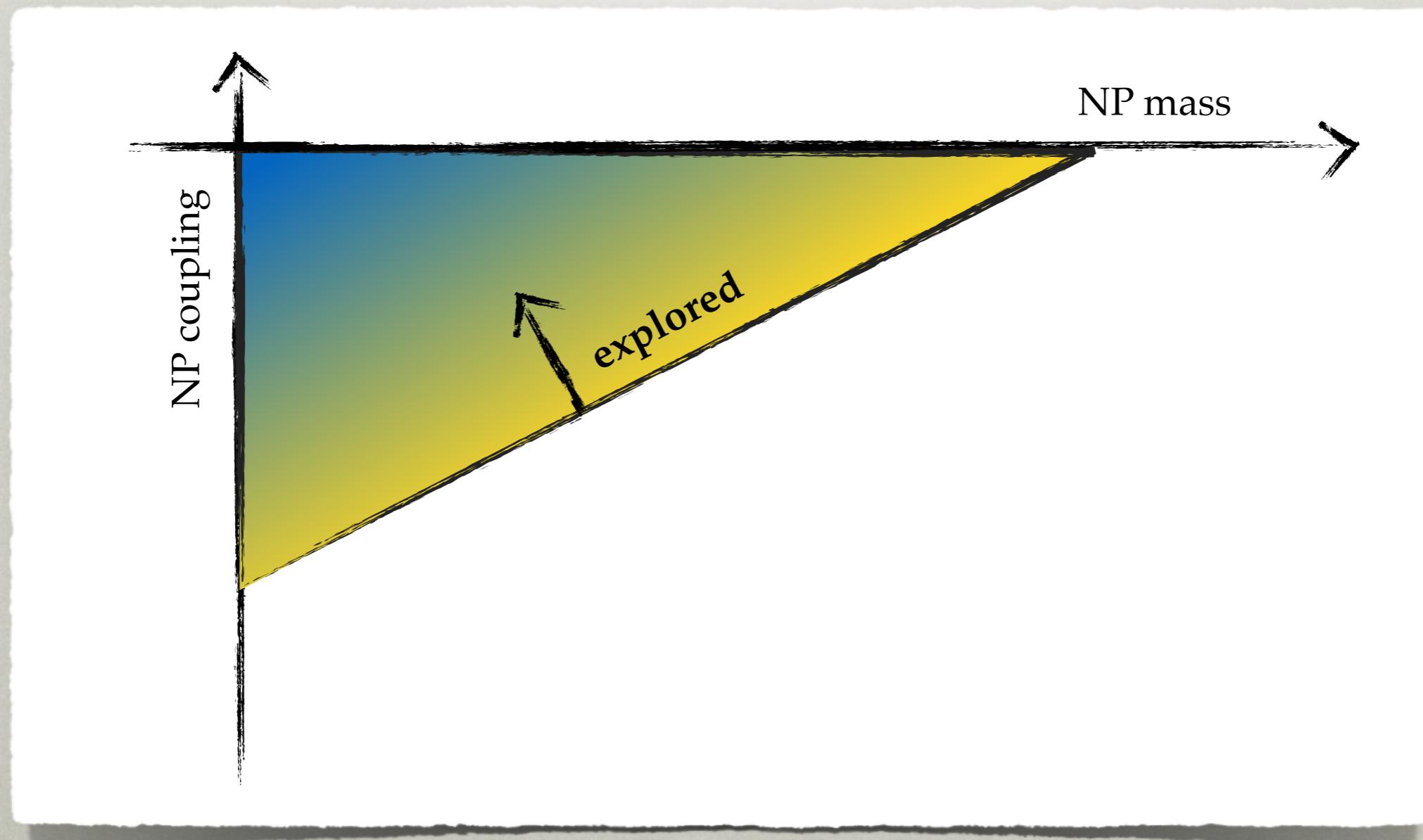
- one ratio that only depends on well known λ, m_t

$$R_{\text{SL}} = \frac{\mathcal{B}(K_S \rightarrow \mu^+ \mu^-)_{\text{SD}}}{\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})} = 1.55 \times 10^{-2} \left[\frac{\lambda}{0.225} \right]^2 \left[\frac{Y(x_t)}{X(x_t)} \right]^2$$

LIGHT NEW PHYSICS

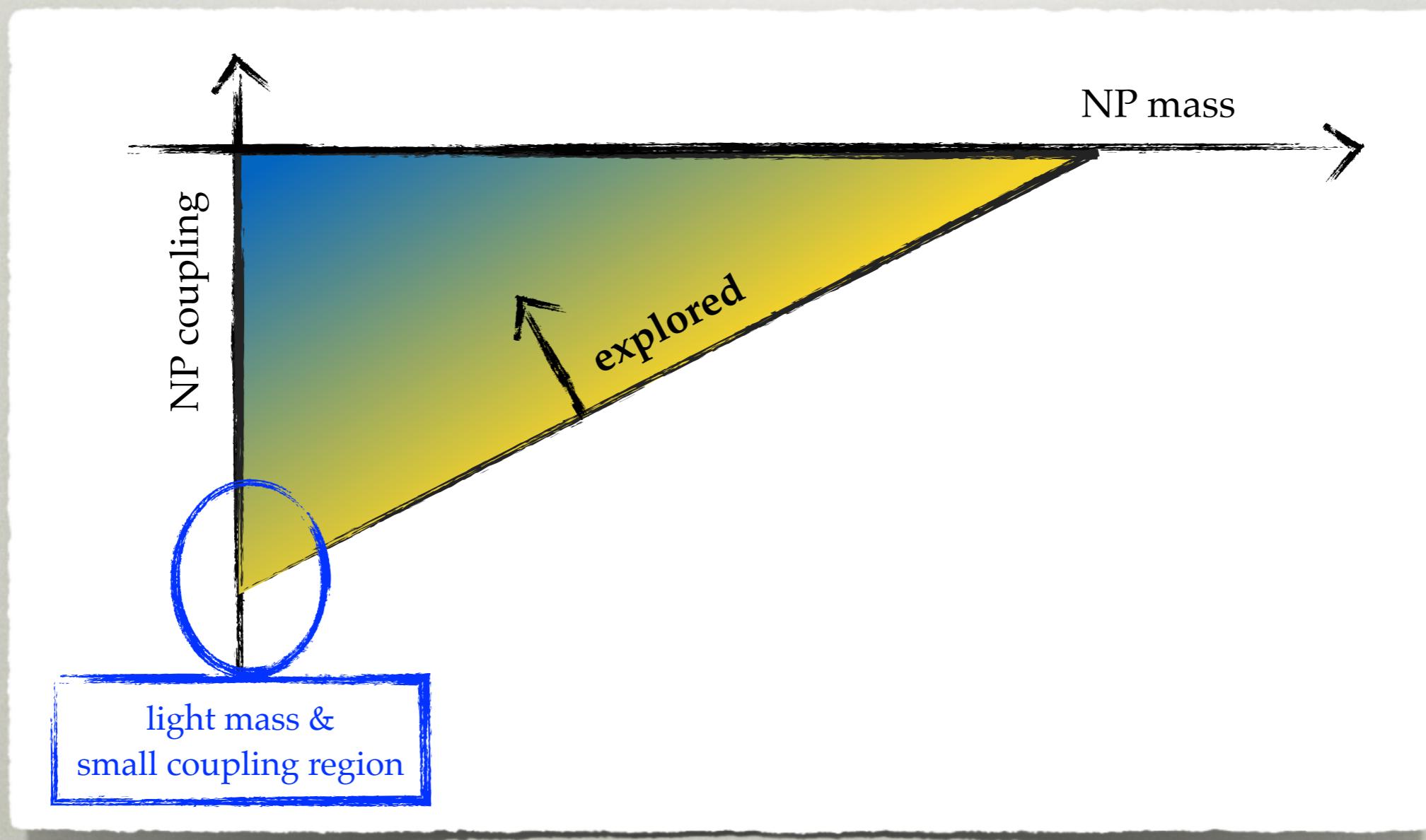
THE CASE FOR LIGHT NEW PHYSICS SEARCHES

- explored only part of the NP parameter space
- light particles: a window to high UV dynamics



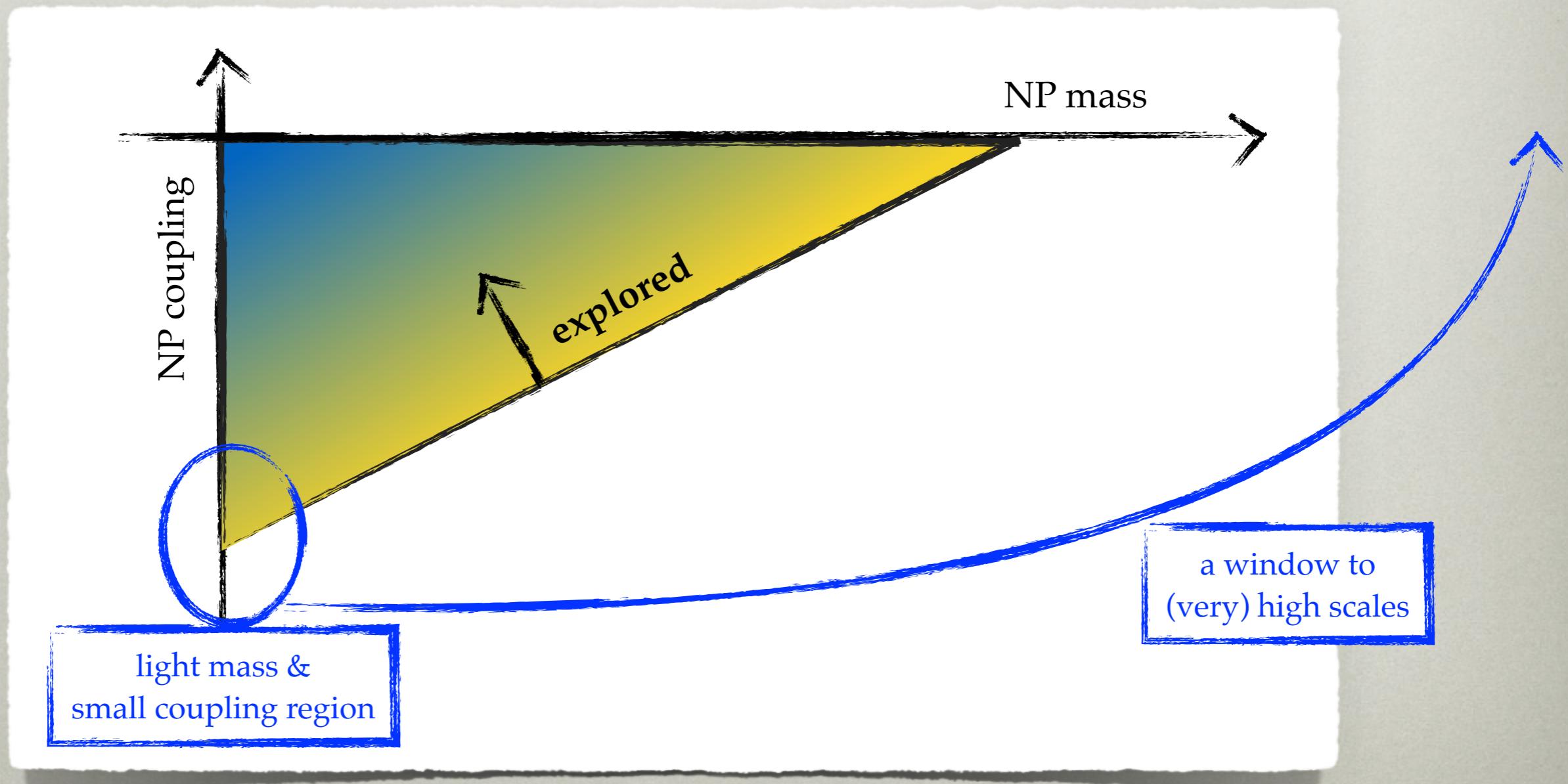
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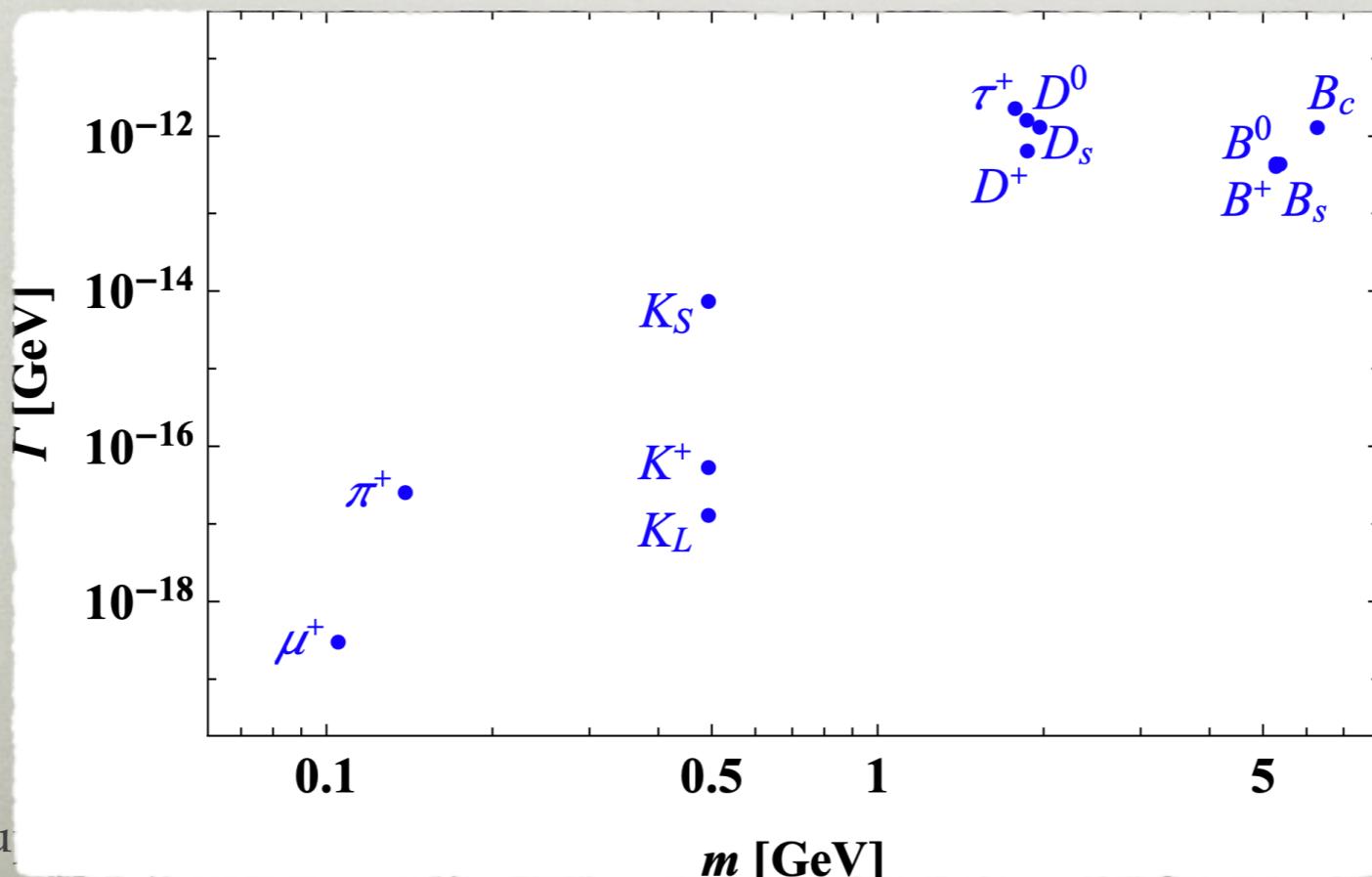
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LIGHT NEW PHYSICS

FCNC PROBES

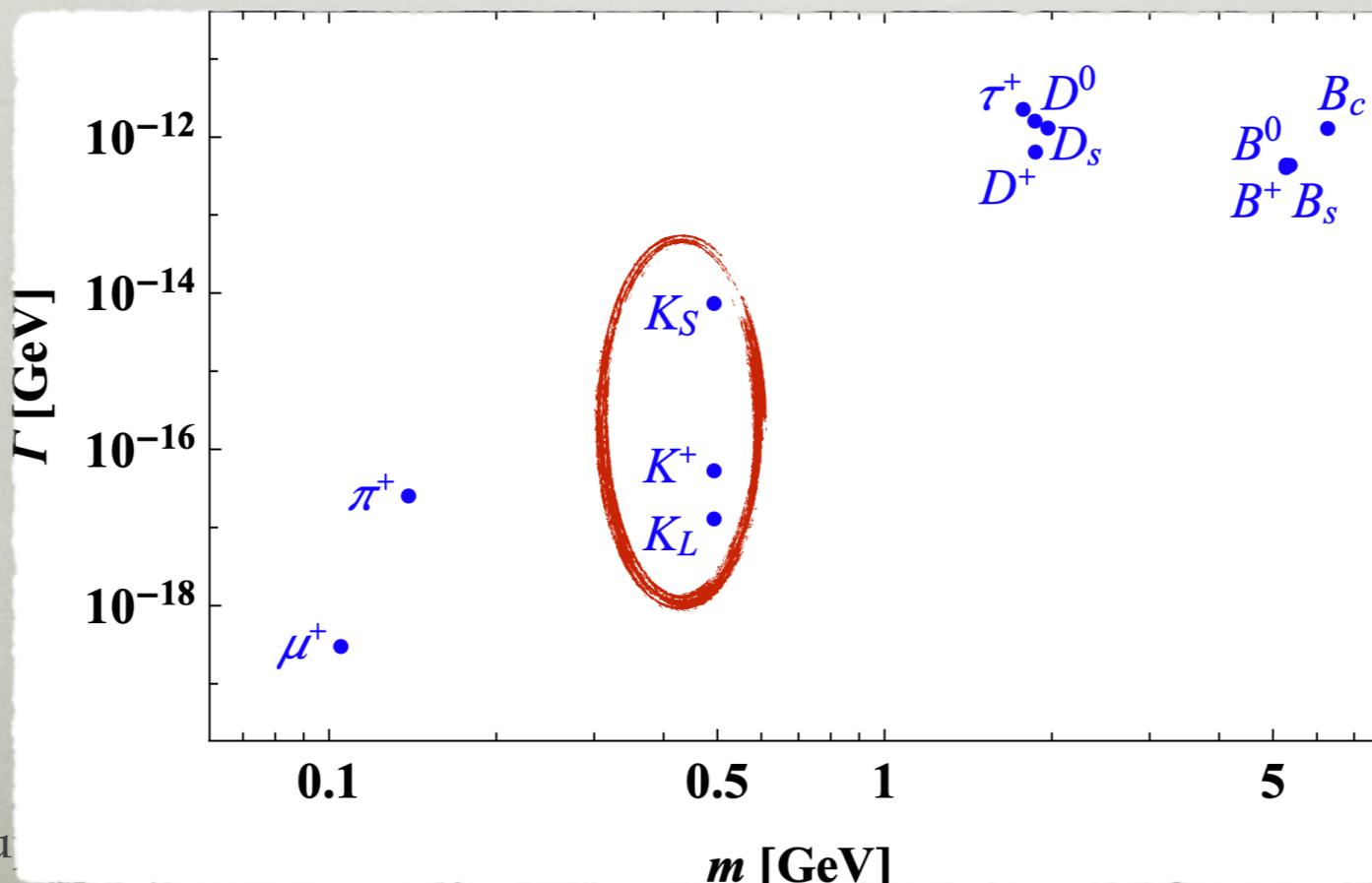
- parametric gain in sensitivity to UV scale
 - SM decay widths small for weak decays $\Gamma \propto m^5/m_W^4$
- if light NP couples through dim 5 ops. supp. by $1/f_a$
 - $\Rightarrow Br(K \rightarrow \pi\varphi) \propto (m_W^2/f_a m_K)^2$
 - similar for other mesons, leptons \Rightarrow which wins depends on flavor structure of NP



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MANY MODES

[Goudzovski et al, 2201.07805](#)

- many modes / possible NP searches
possible at kaon&hyperon factories

MANY MODES

Goudzovski et al, 2201.07805

- many modes / possible NP searches

| Decay \ Model | 2.1 Higgs portal | 2.2 ALP | 2.3 Heavy Neutral Lepton | 2.4 Dark Photon | 2.5 Leptonic Force (X) | 2.6 Strongly Int. Neutrino | 2.7 GN Violation | 2.8 Two dark sector particles | 2.9 Dark Baryons | 2.10 More exotic | 2.11 Heavy New Physics |
|---|--|--|--|---|---|----------------------------|------------------|--|------------------|--|--------------------------|
| 4.1 $K \rightarrow \pi + \text{inv}$ | ✓ | ✓ | — | ✓ even massless | — | ✓ | ✓ | ✓ | — | — | ✓ |
| 4.2 $K \rightarrow \pi\pi + \text{inv}$ | CP viol. | axial coupl. | — | ✓ even massless | — | — | — | — | — | — | — |
| 4.3 $K \rightarrow \pi\gamma + \text{inv}$ | possible in extensions | possible in extensions | — | ✓ even massless | — | — | — | — | — | — | — |
| 4.4 $K \rightarrow 2\pi\gamma + \text{inv}$ | — | — | — | $\pi^0 \rightarrow \gamma A'$ | — | — | — | — | — | possible | — |
| 4.5 $K \rightarrow \pi\gamma\gamma$ | negligible (✓ dilaton) | ✓ prompt | — | — | — | — | — | lifetime loophole | — | — | — |
| 4.6 $K \rightarrow \pi\ell_\alpha\ell_\alpha$ | ✓ prompt | ✓ prompt | — | ✓ | — | — | — | lifetime loophole | — | — | — |
| 4.7 $K \rightarrow \pi\pi\ell_\alpha\ell_\alpha$ | CP viol. | axial coupl. & prompt | — | ✓ | — | — | — | — | — | — | — |
| 4.8 $K \rightarrow \pi\ell_\alpha\ell_\alpha\ell_\beta\ell_\beta$ | — | — | — | — | — | — | — | A' , MeV axion, also $K \rightarrow \pi 2\ell_\alpha 2\ell_\beta \text{inv}$ | — | — | — |
| 4.9 $K_L \rightarrow \gamma + \text{inv}$ | — | — | — | ✓ | — | — | — | — | — | — | — |
| 4.10 $K \rightarrow \pi\gamma, 3\gamma$ | — | — | — | — | — | — | — | — | — | Lorentz viol. | — |
| 4.11 $K_L \rightarrow \gamma\gamma + \text{inv}$ | — | — | — | — | — | — | ✓ (Table 2) | — | — | — | — |
| 4.12 $K_{S,L} \rightarrow \ell^+\ell^- + \text{inv}$ | — | — | — | — | — | — | possible | possible | — | — | $K_S \rightarrow \mu\mu$ |
| 4.12 $K_{S,L} \rightarrow 2\ell 2\gamma$ | — | — | — | — | — | — | possible | possible | — | — | — |
| 4.13 $K^0 \rightarrow 4\ell$ | — | — | — | — | — | — | possible | possible | — | — | — |
| 4.14 $K^+ \rightarrow \ell^+ + \text{inv}$ | — | — | ✓ | — | ✓ ($X \rightarrow \text{inv}$) | ✓ | — | — | — | — | — |
| 4.15 $K^+ \rightarrow 3\ell + \text{inv}$ | — | — | possible | — | ✓ ($X \rightarrow \ell\ell$) | — | — | $U(1) + \text{HNL}$ | — | — | — |
| 4.16 $K^+ \rightarrow \ell\gamma\gamma + \text{inv}$ | — | — | $K^+ \rightarrow \pi^0\ell^+ N$ ($m_N \lesssim 20 \text{ MeV}$) | — | possible ($X \rightarrow 2\gamma$) | possible | — | possible | — | — | — |
| 4.17 LFV | — | — | — | — | — | — | — | — | — | FV ALP, Z' | FV ALP |
| 4.18 LNV | — | — | $K^+ \rightarrow \ell^+ N$, $N \rightarrow \pi^- \ell^+$ | — | — | — | — | — | — | — | ✓ (Maj. HNL) |
| 4.19 Rare K_S decays | $K_S \rightarrow \pi(\pi)2\ell$ $\rightarrow \pi(\pi)2\gamma$ | $K_S \rightarrow \pi(\pi)2\ell$ $\rightarrow A'\gamma\pi$ | — | $K_S \rightarrow A'\gamma$ $\rightarrow A'\gamma\pi$ | — | — | — | $K_S \rightarrow 4\ell$ | — | $K_S \rightarrow 2\gamma + \text{inv}$ | $K_S \rightarrow \mu\mu$ |
| 4.20 Dark Shower | — | — | — | — | — | — | — | — | — | ✓ | — |
| 5 Hyperon | $B_1 \rightarrow B_2\varphi$ | Table 8 | — | $B_1 \rightarrow B_2 A'$ | — | — | — | — | Table 4 | — | — |
| | | | | | | | | $B \rightarrow \gamma/M + \text{inv}$ | | | |

-
- in the rest of the talk will focus on ALPs/light scalars
 - a selection of other examples in backup slides

ALPs

- generic in NP scenarios : whenever global U(1) spontaneously broken \Rightarrow pNGB
 - celebrated example: QCD axion
- in general flavor violating couplings
- from low energy perspective the EFT starts at dim 5

$$\mathcal{L}_{\text{ALP-gauge}} = \frac{N_3 \alpha_s}{8\pi f_a} a G_{\mu\nu}^a \tilde{G}^{a\mu\nu} + \frac{N_2 \alpha_2}{8\pi f_a} a W_{\mu\nu}^i \tilde{W}^{i\mu\nu} + \frac{N_1 \alpha_1}{8\pi f_a} a B_{\mu\nu} \tilde{B}^{\mu\nu}.$$

$$\mathcal{L}_{\text{ALP-f}} = \frac{\partial_\mu a}{2f_a} \bar{f}_i \gamma^\mu (C_{f_i f_j}^V + C_{f_i f_j}^A \gamma_5) f_j,$$

FLAVOR STRUCTURE

- two phenomenologically very different regimes
- if FV in the UV: $C_{ds}^{A,V}(\Lambda_{\text{UV}}) \neq 0$
 - very stringent constraints on $f_a \Rightarrow a$ does not decay in the detector
 - $K^+ \rightarrow \pi^+ a$ decay results in $K^+ \rightarrow \pi^+ + \text{inv}$ signature
- if FV only from the SM: $C_{ds}^{A,V}(\Lambda_{\text{UV}}) = 0$
 - $s \rightarrow da$ coupling from RG \Rightarrow much weaker constraints

$$C_{ds}^{A,V}(M_Z) = \frac{y_t^2}{16\pi^2} V_{td}^* V_{ts} C_{tt}^A \log \frac{\Lambda_{\text{UV}}}{M_Z} \simeq 2 \times 10^{-6} C_{tt}^A \log \frac{\Lambda_{\text{UV}}}{M_Z}$$

- a decaying inside detector possible

Flavor Anarchy

- two constraints
- if $C_{sd}(\Lambda_{UV}) = 1$
- $f_a \gg m_K - m_\pi$
- if FV only from the SM: $C_{ds}^{A,V}(\Lambda_{UV}) = 0$
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- a decaying inside detector possible

- two constraints
 - if $|f_a| \lesssim 10^4$
 - $m_a \gtrsim 100$ MeV
 - if $|f_a| \gtrsim 10^4$
 - $\tau_a > 1\text{s}$
- Minimal Flavor Violation**
-

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PROMPT ALPS

- searches for prompt ALPs in $K \rightarrow \pi a$
 - either $a \rightarrow \gamma\gamma$ or $a \rightarrow e^+e^-$
- the bounds depend on what exactly the couplings are
- several examples for $C_{ij}^{V,A}$ at $\mu = \Lambda_{\text{UV}} = 4\pi f_a$
 - coupling to only gluons: $N_3 \neq 0$
 - coupling to W, Z only: $N_2 \neq 0$
 - only $C_{uu}^A \neq 0$
 - only $C_{dd}^A \neq 0$

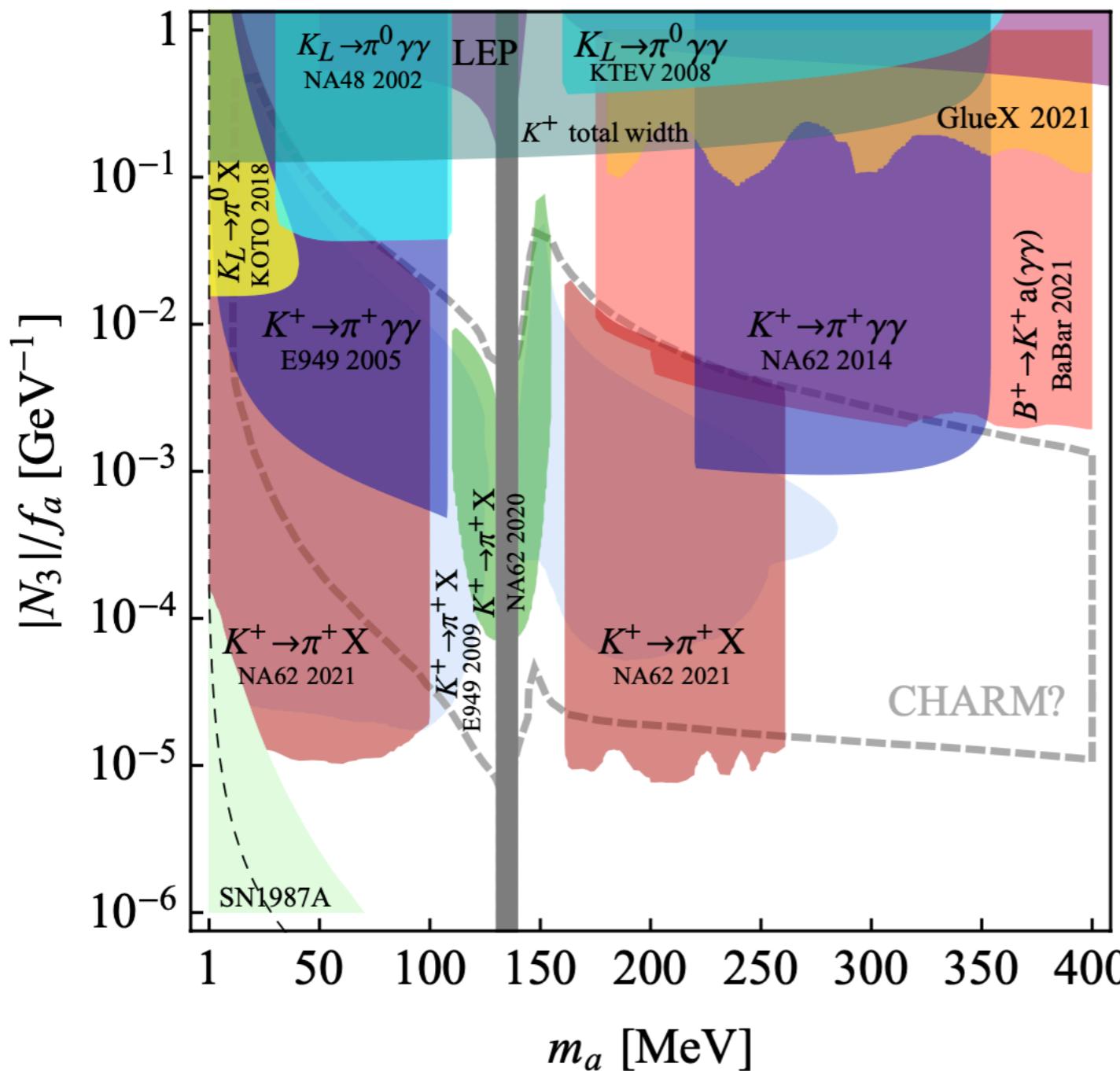
LPS

 $\rightarrow \pi a$

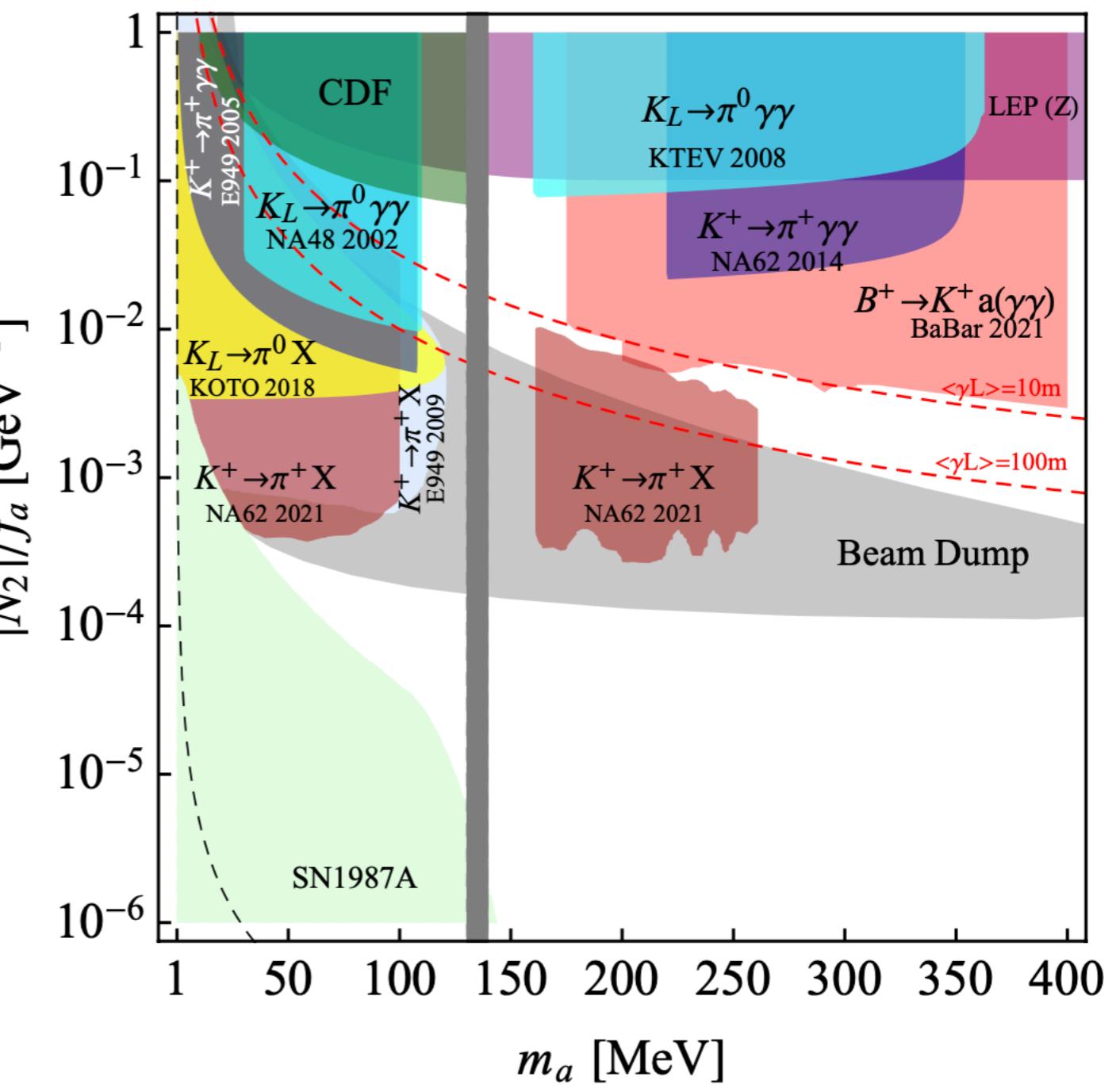
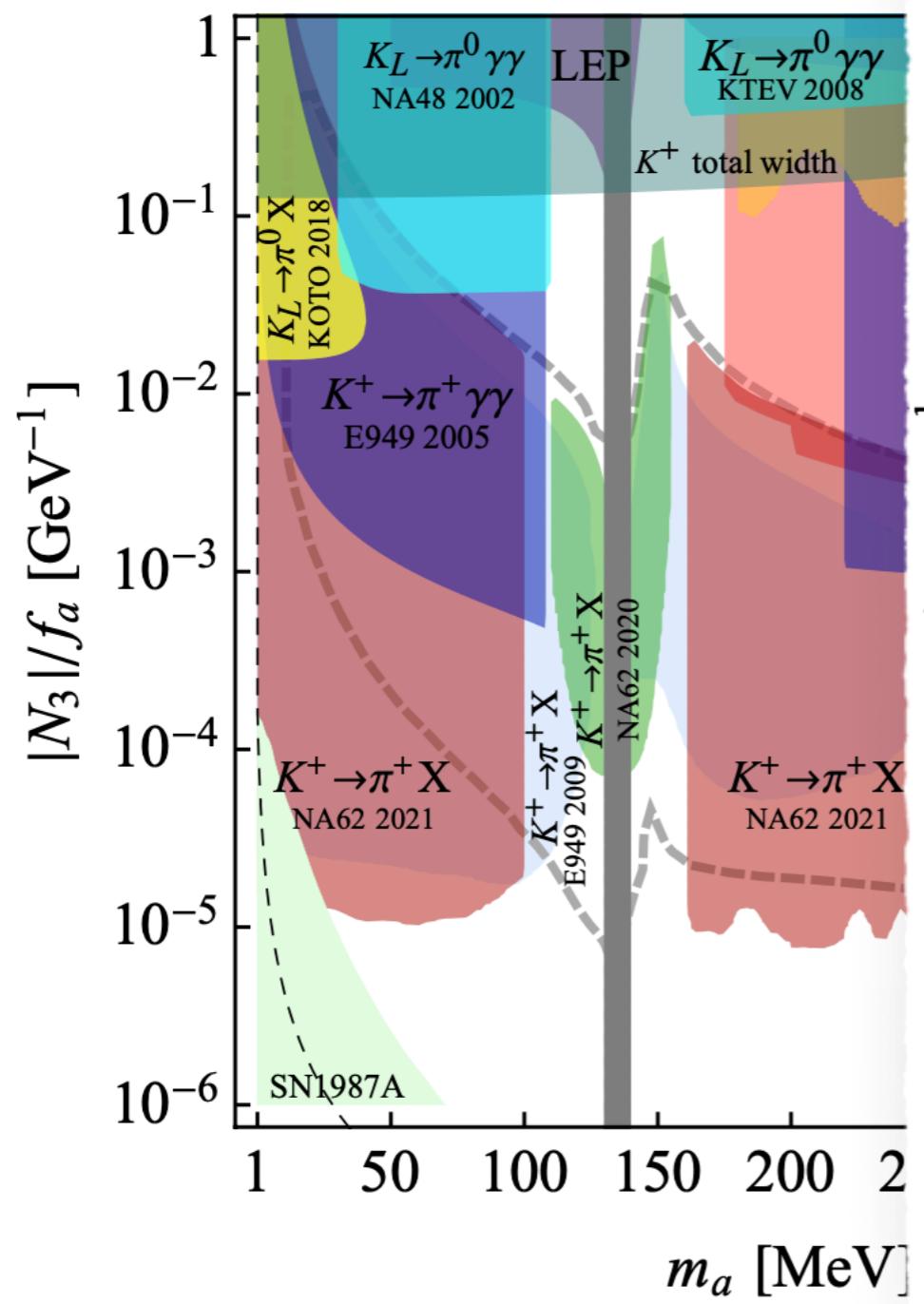
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$$\Lambda_{\text{UV}} = 4\pi f_a$$

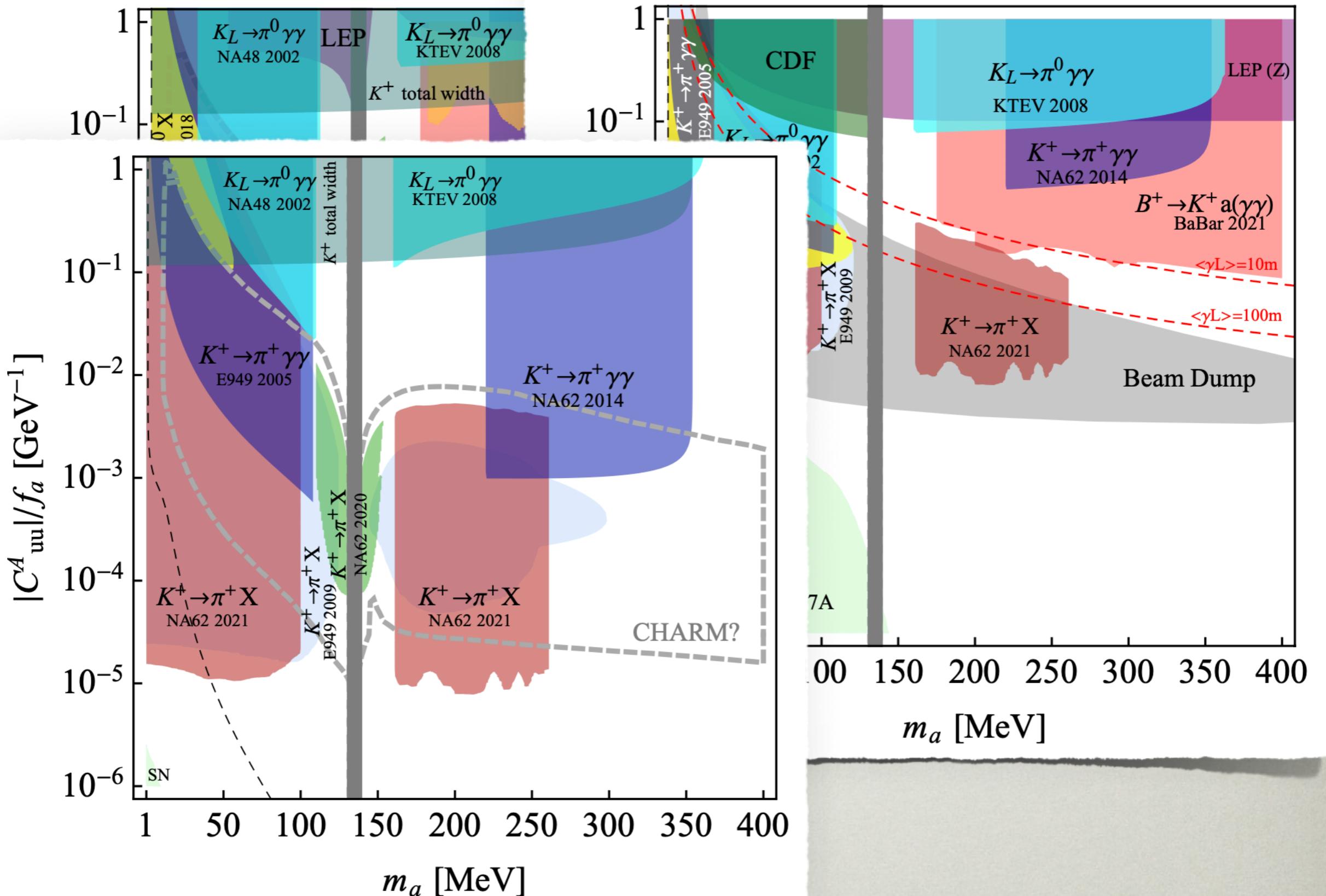
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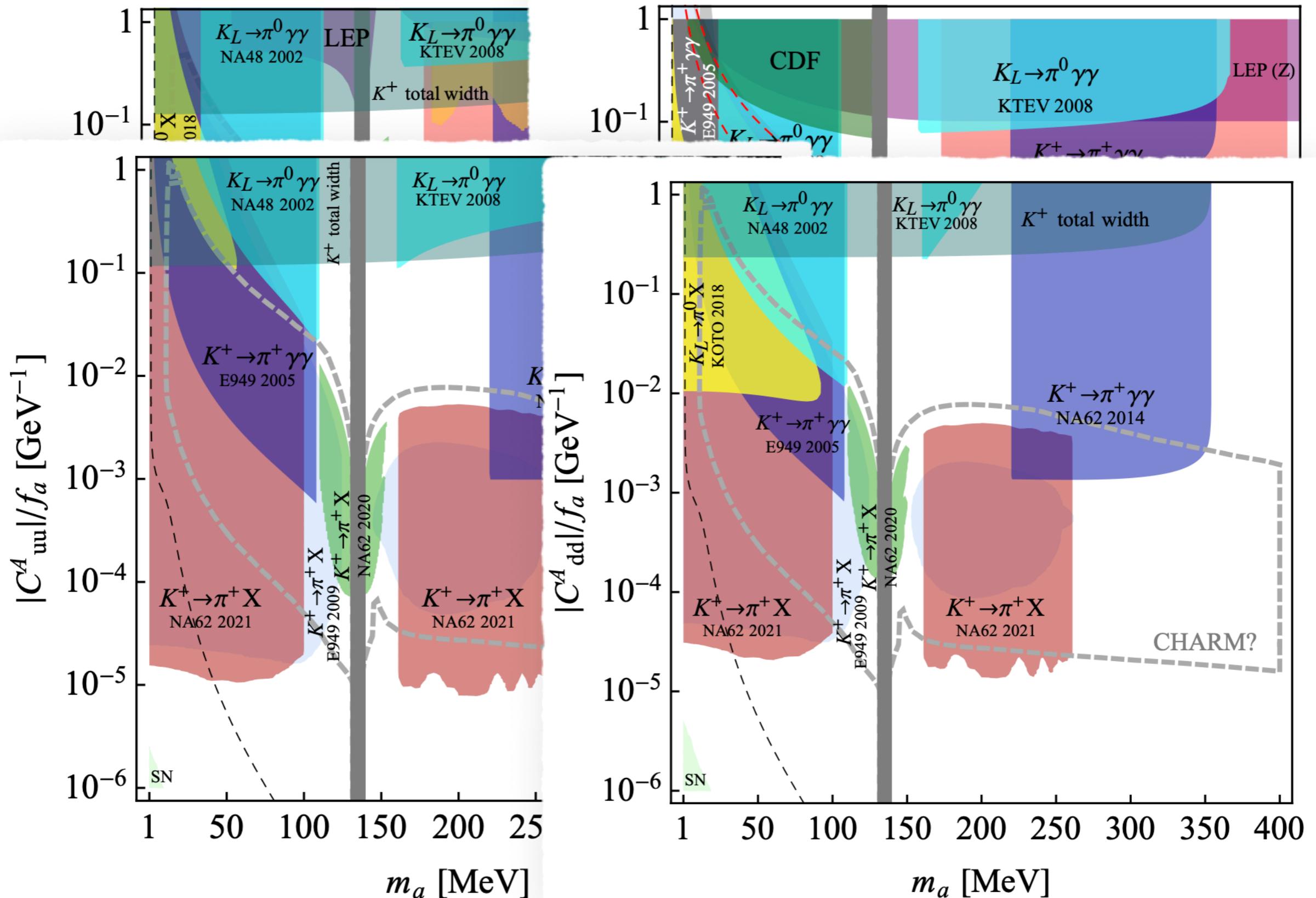
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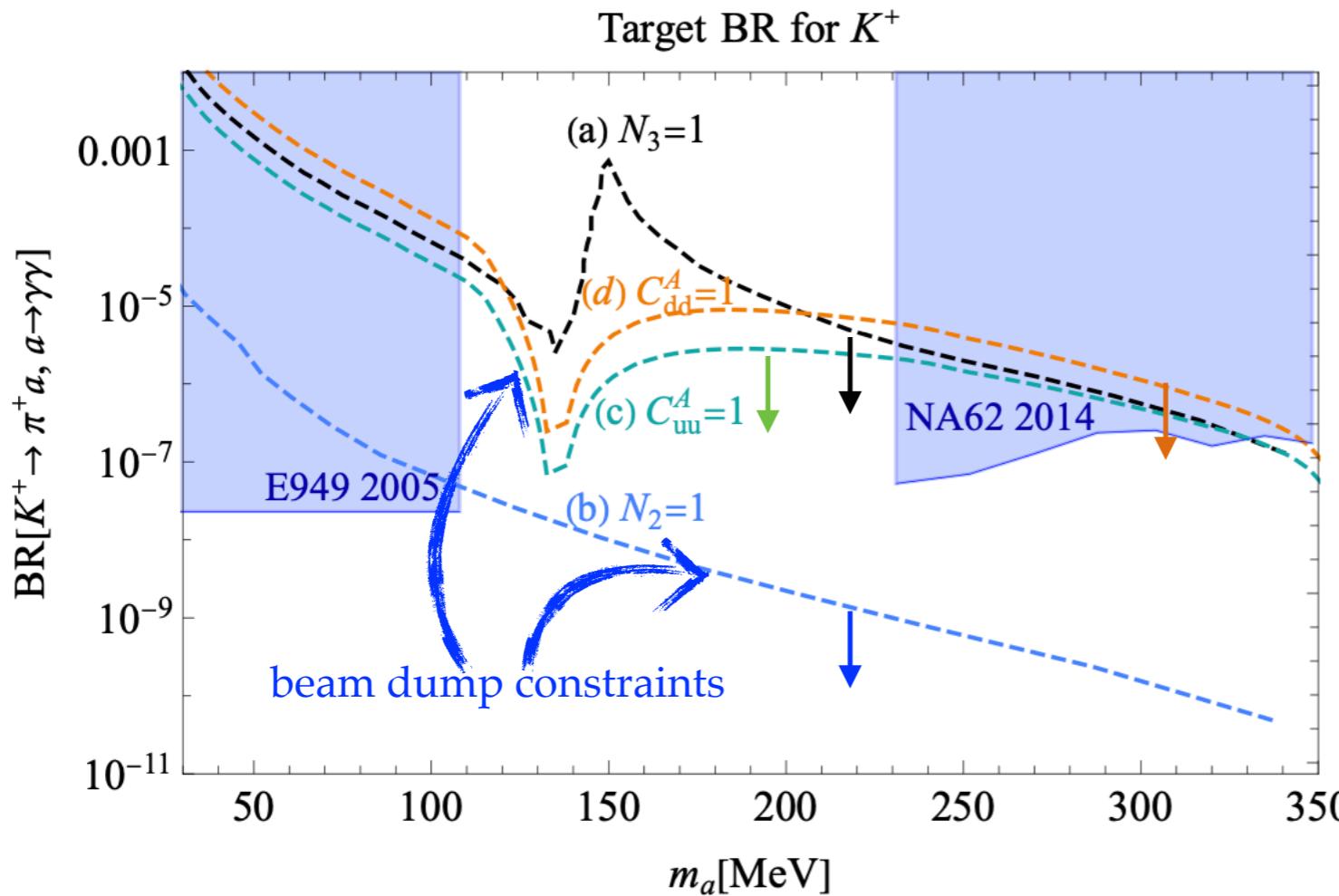


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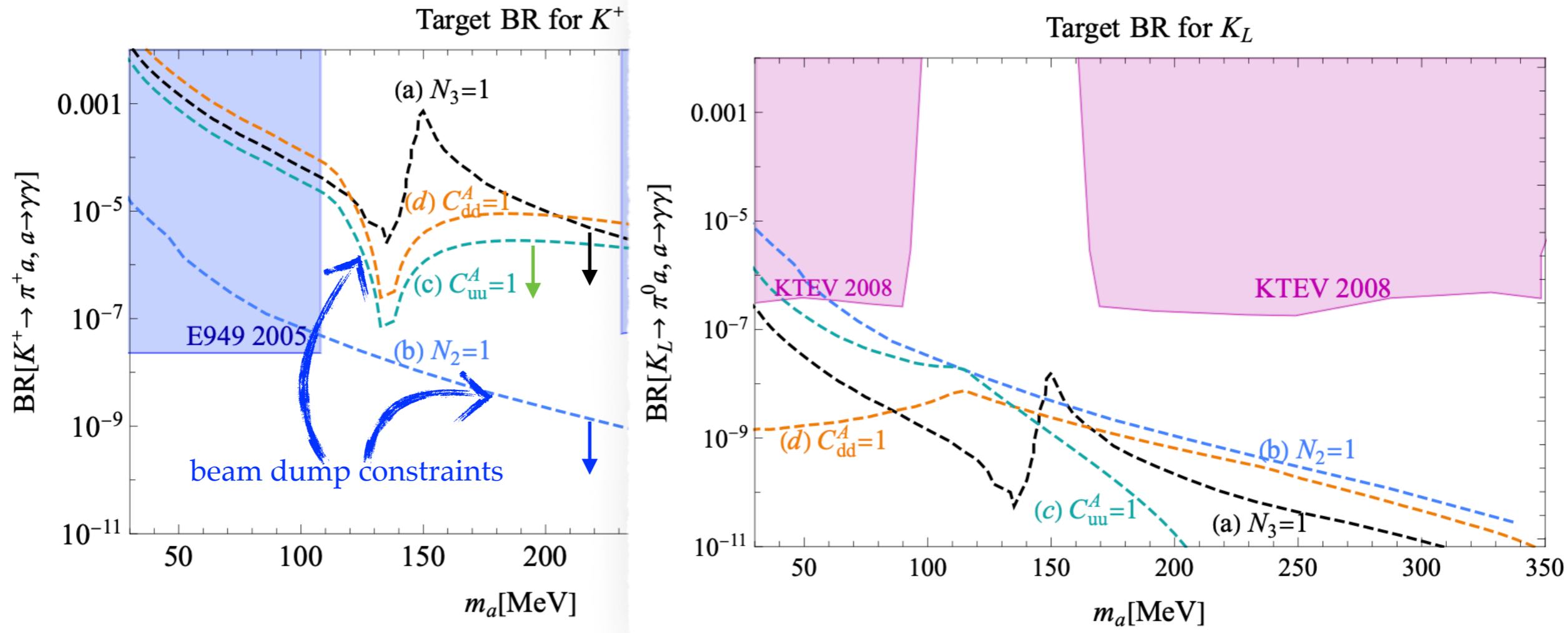
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 - close the gap to constraints from beam dump searches
- \Rightarrow either discovery or only $K \rightarrow \pi a_{\text{inv}}$ signature remains

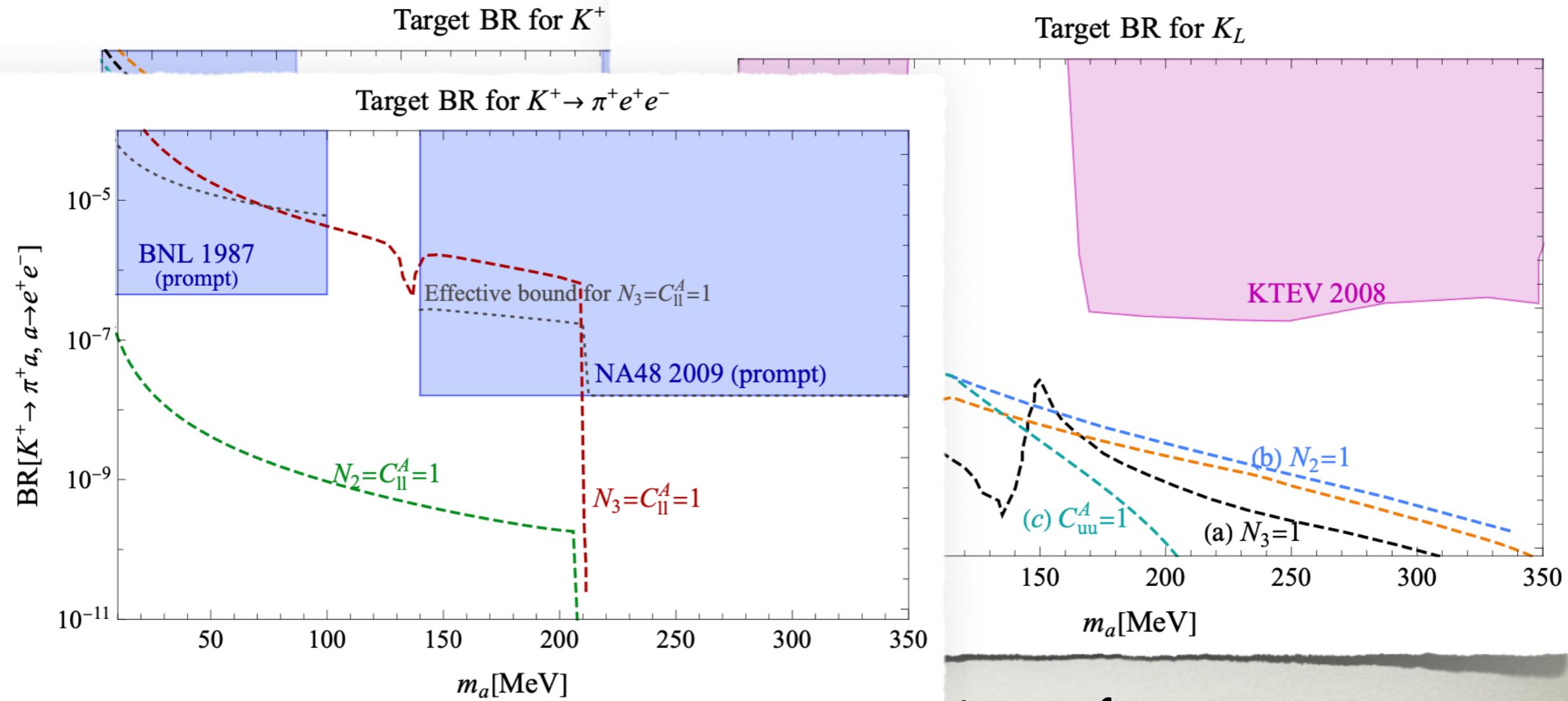
PS

 $s \text{ in } K \rightarrow \pi a$
 $+ e^-$


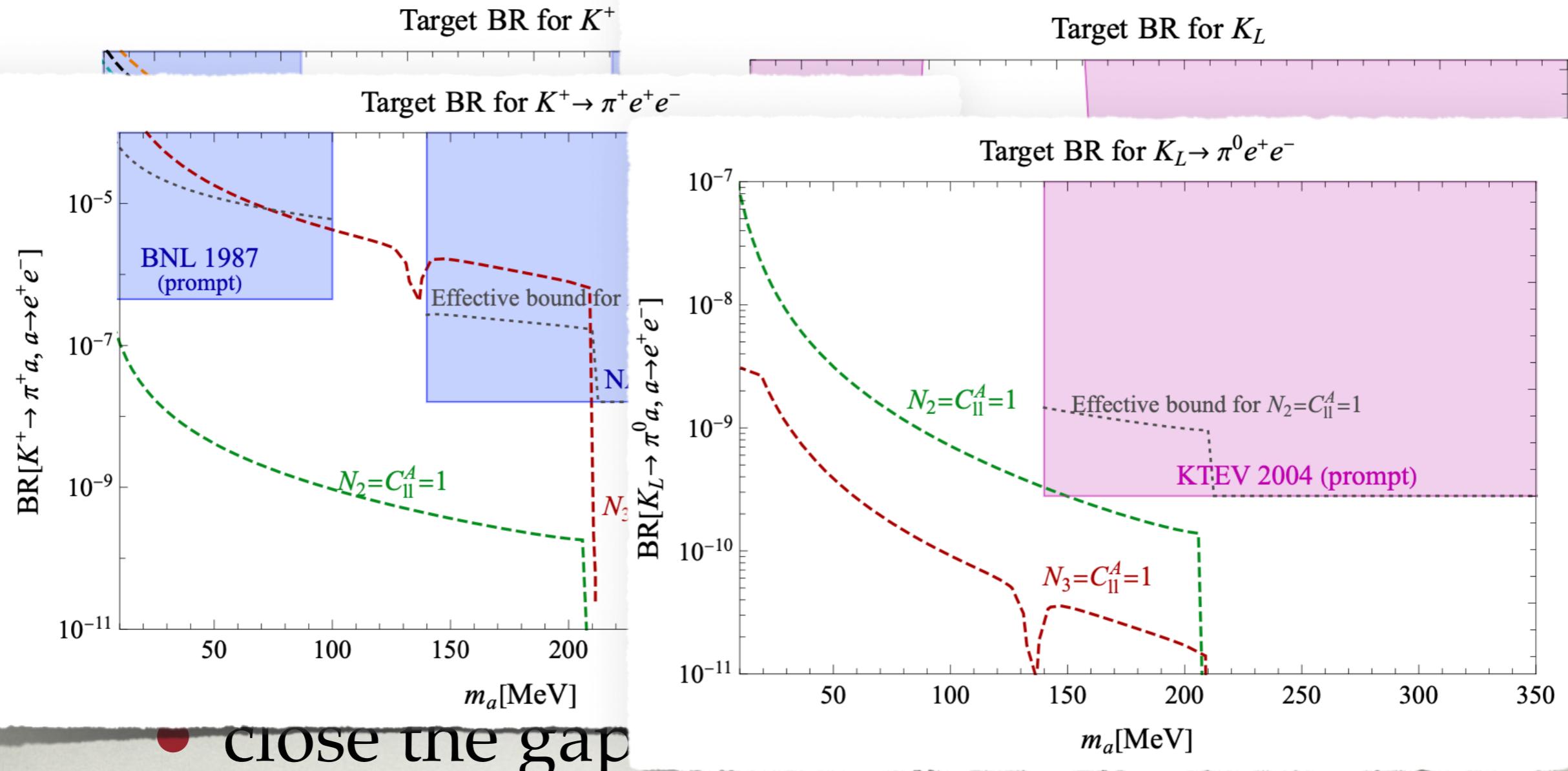
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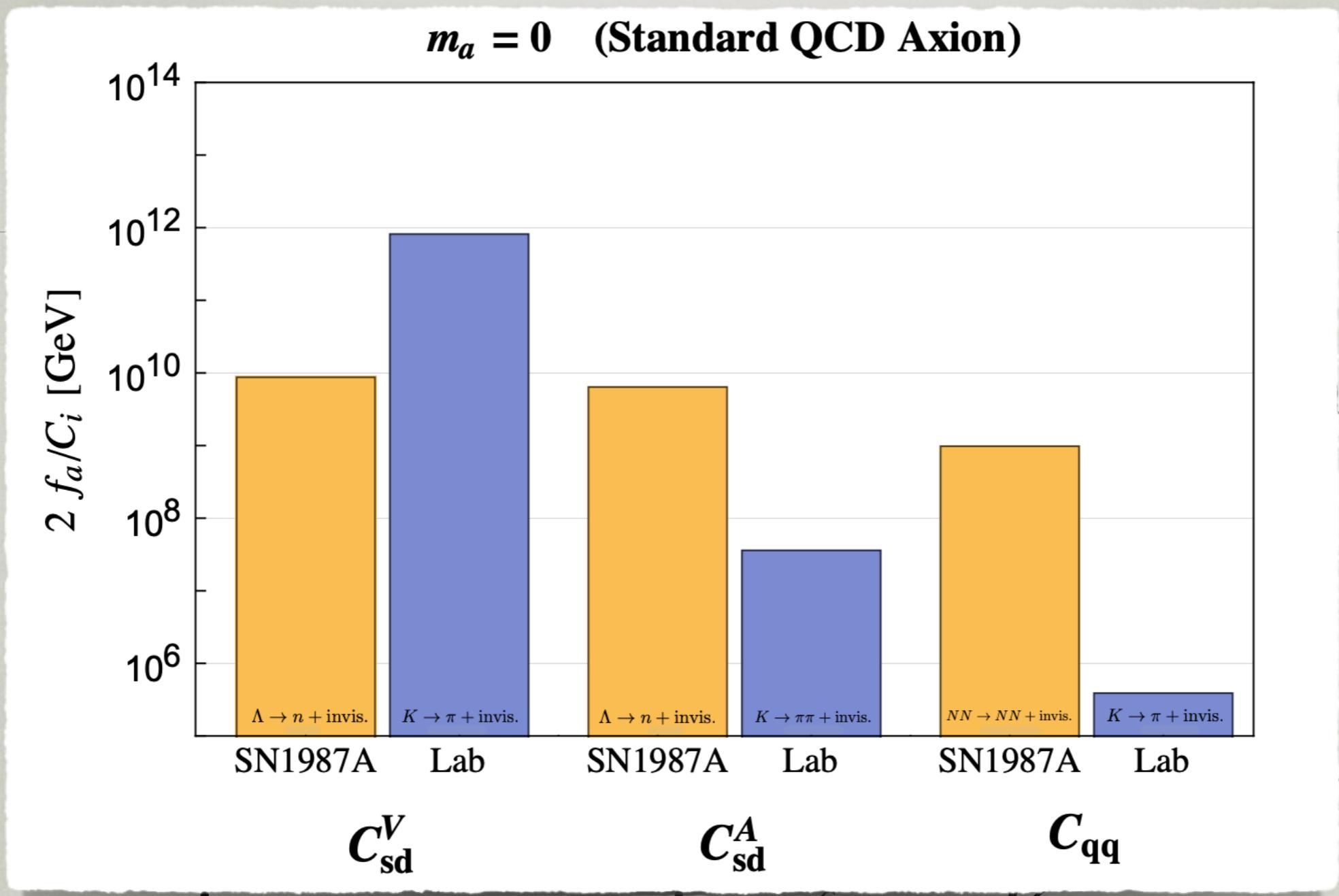
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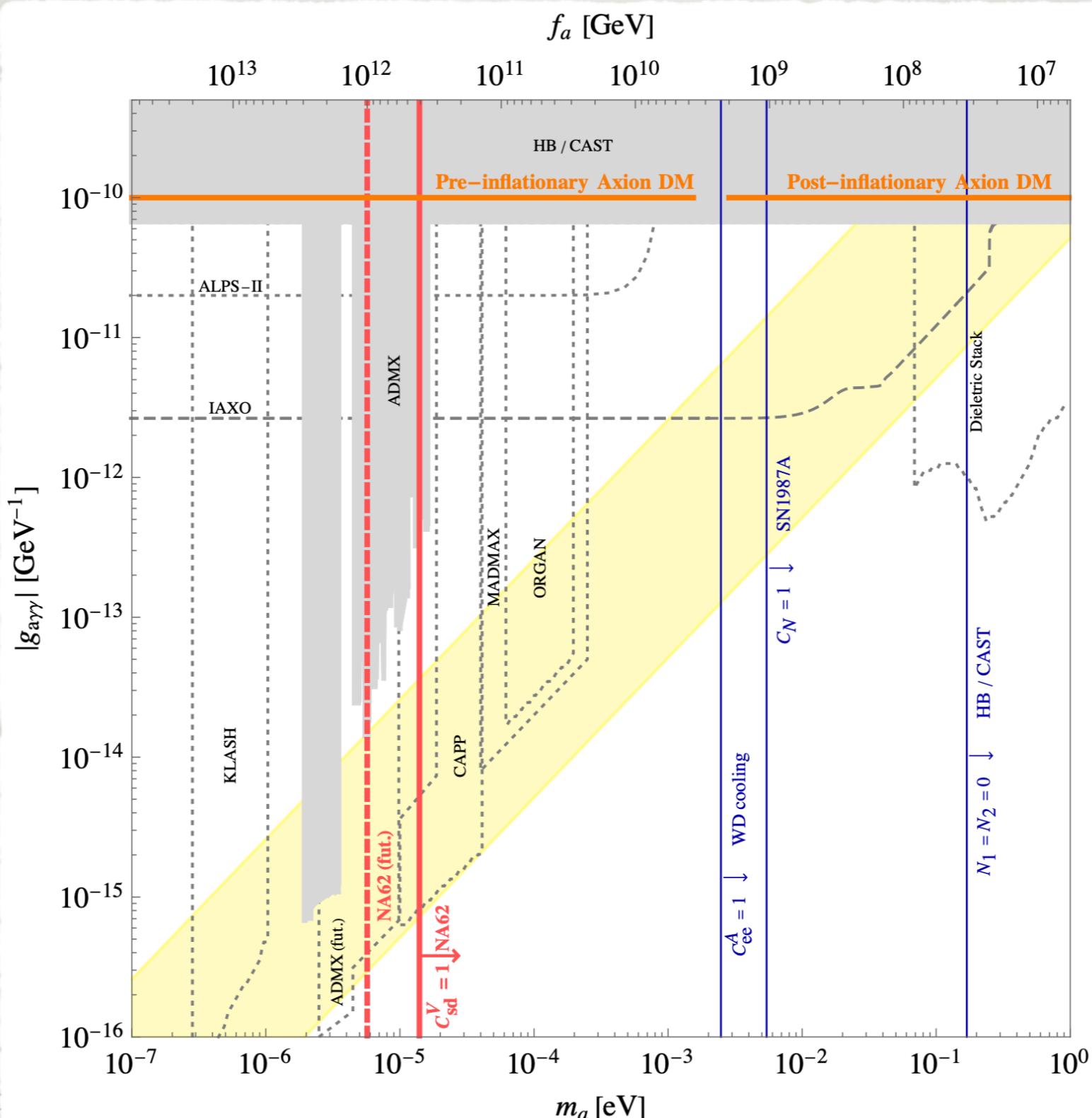
FLAVOR VIOLATING QCD AXION

- QCD axion with FV couplings to quarks
 - solves the strong CP problem
 - can be a cold DM candidate
 - effectively massless in FV transitions
- stringent constraints from $K \rightarrow \pi a$,
 $K \rightarrow \pi\pi a$ where a invisible
 - can be a discovery mode



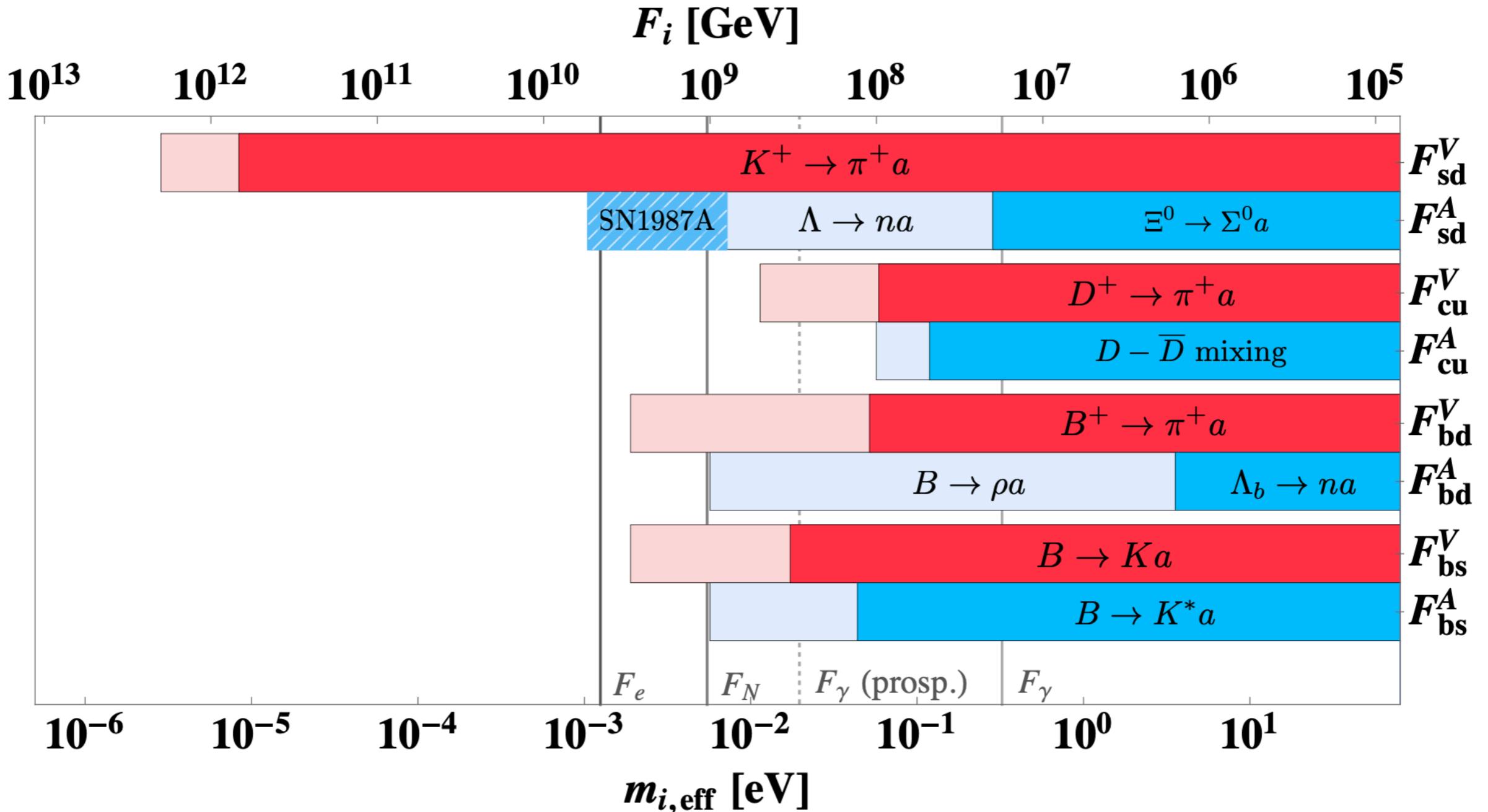
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FLAVOR VIOLATING QCD AXION



MANY OTHER FV SEARCHES FOR QCD AXION

Martin Camalich, Pospelov, Vuong, Ziegler, JZ, 2002.04623

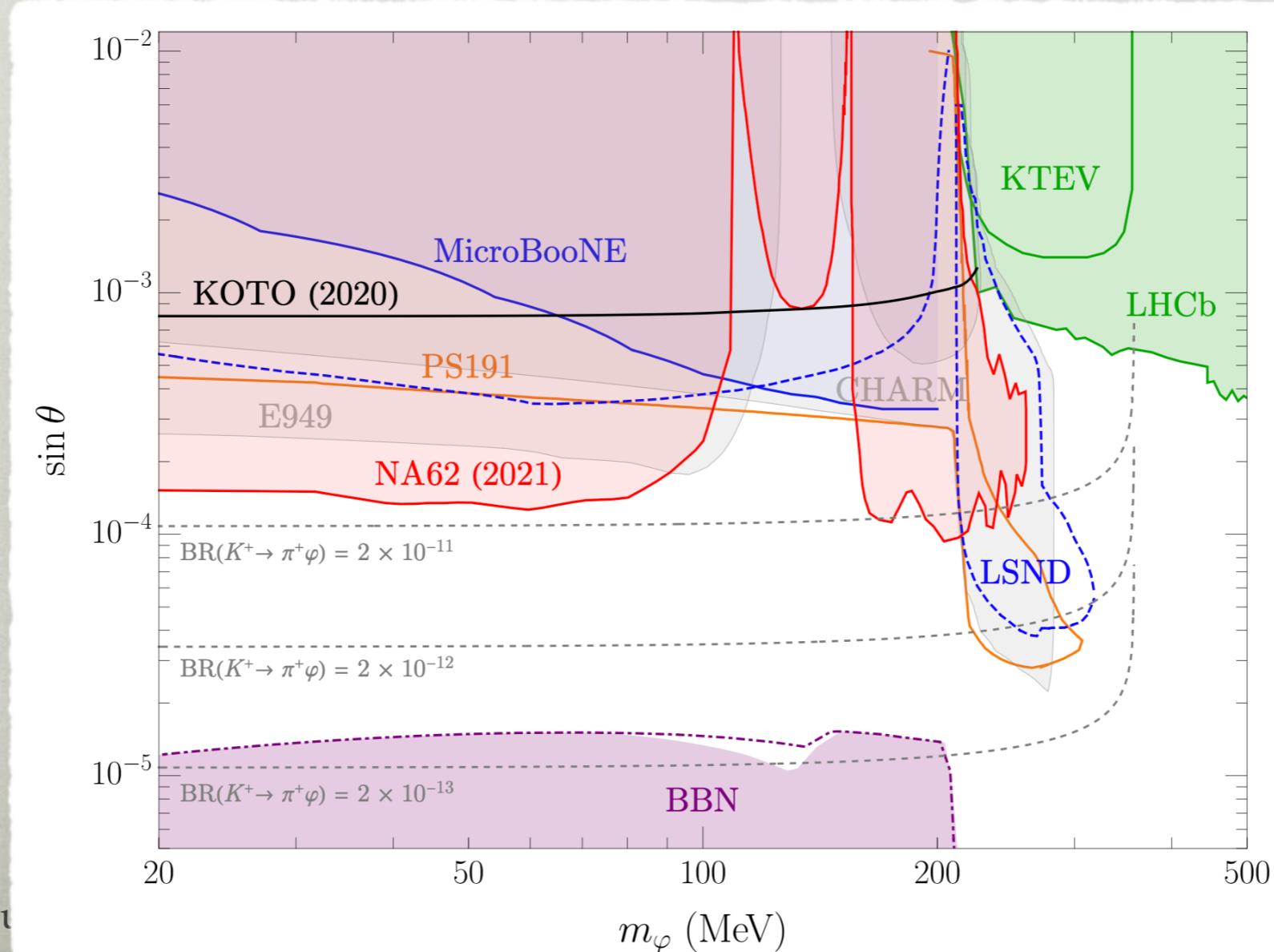


LIGHT SCALARS

- above general analysis valid for pNGBs with pseudoscalar and scalar couplings
- what changes for scalars with dim-4 couplings?
- usual benchmark light Higgs mixed scalar
 - parameter space reduced to $\sin \theta, m_\phi$
 - note: not the most general possibility
 - especially for couplings to light quarks since Higgs yukawas very suppressed

HIGGS MIXED SCALAR

- for two to three orders of magnitude larger datasets
 - ⇒ could close the gap for Higgs-mixed scalar all the way to the BBN floor



PROTON CHARGE RADIUS PUZZLE+

Delaunay, Karr, Kitahara, Koelemeij, Soreq, JZ, 2210.10056

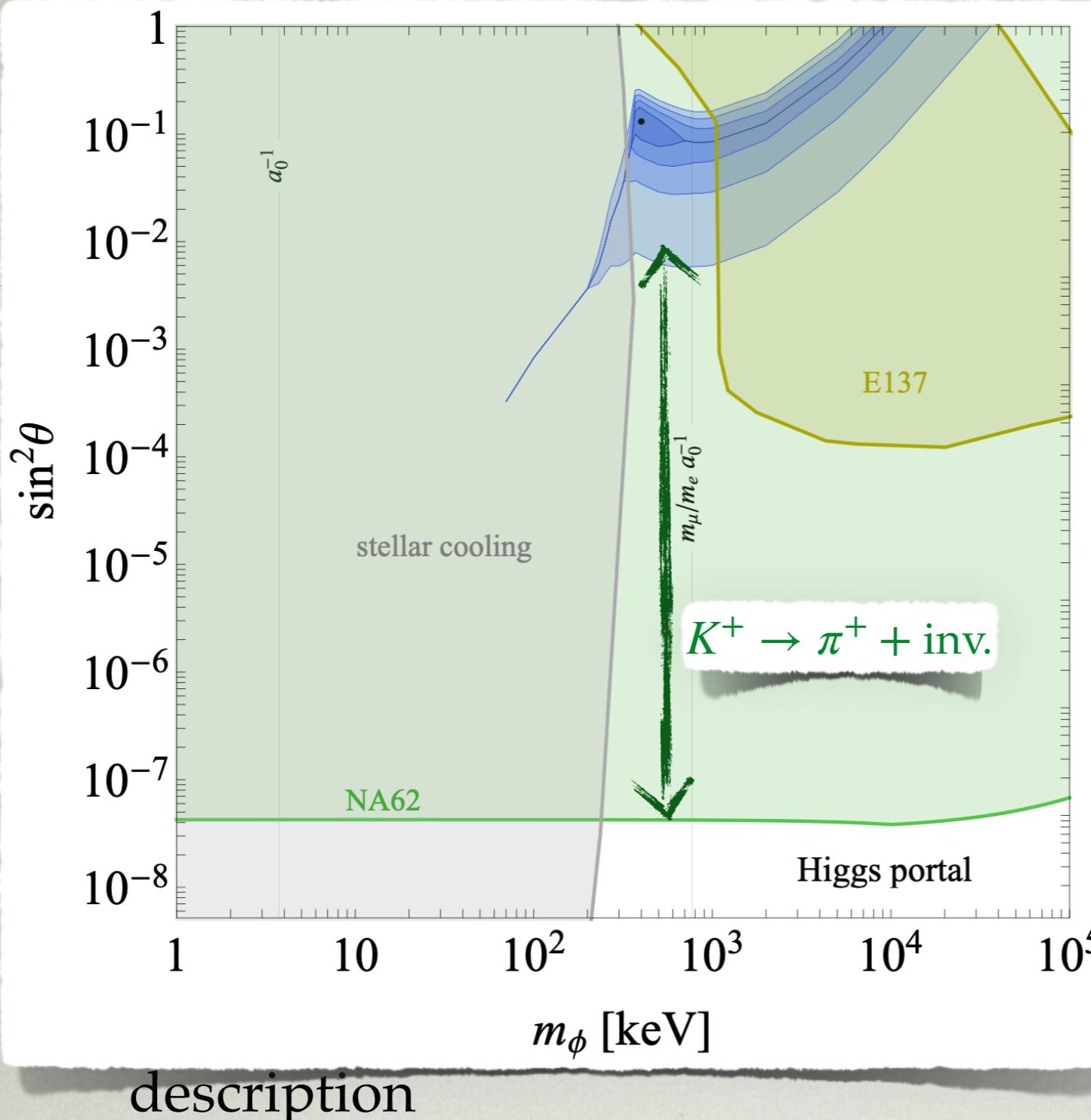
- important to stress how sensitive are rare kaon decays
- compare with sensitivity of spectroscopic probes
 - hydrogen/deuterium+muonic hydrogen/deuterium data
- several $\sim 3\sigma$ anomalies in obs. related to proton charge radius and mass
 - exp+th errors under-appreciated? \Rightarrow CODATA 2018
 - NP? : global analysis of SM + light scalar \Rightarrow consistent description
 - light Higgs mixed scalar excluded by NA62 $K^+ \rightarrow \pi^+ + \text{inv}$ search

RGE

LE+

Kitahara, Koelemeij, Soreq, JZ, 2210.10056

kaon decays
probes
en / deuterium data
proton charge radius and
ODATA 2018
ar \Rightarrow consistent

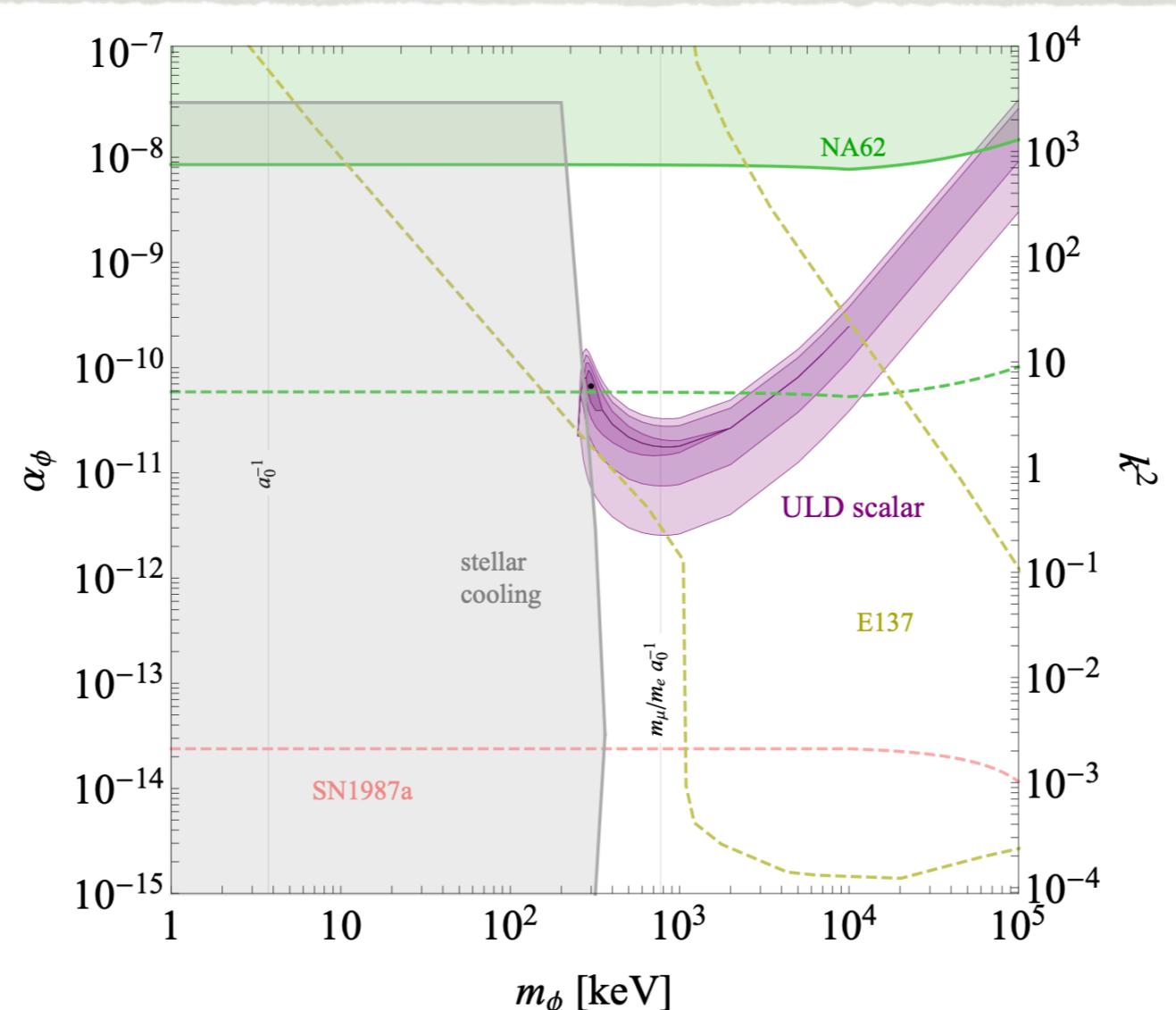


description

- light Higgs mixed scalar excluded by NA62 $K^+ \rightarrow \pi^+ + \text{inv.}$ search

PROTON CHARGE RADIUS PUZZLE+

- possible to (almost) evade NA62 $K^+ \rightarrow \pi^+ + \text{inv.}$ bound
 - scalar that couples only to u, e, μ + dark sector
 - note: only flavor diagonal couplings, still very strong constraint from $K \rightarrow \pi + \text{inv}$ [Delaunay, Karr, Kitahara, Koelemeij, Soreq, JZ, 2210.10056](#)



CONCLUSIONS

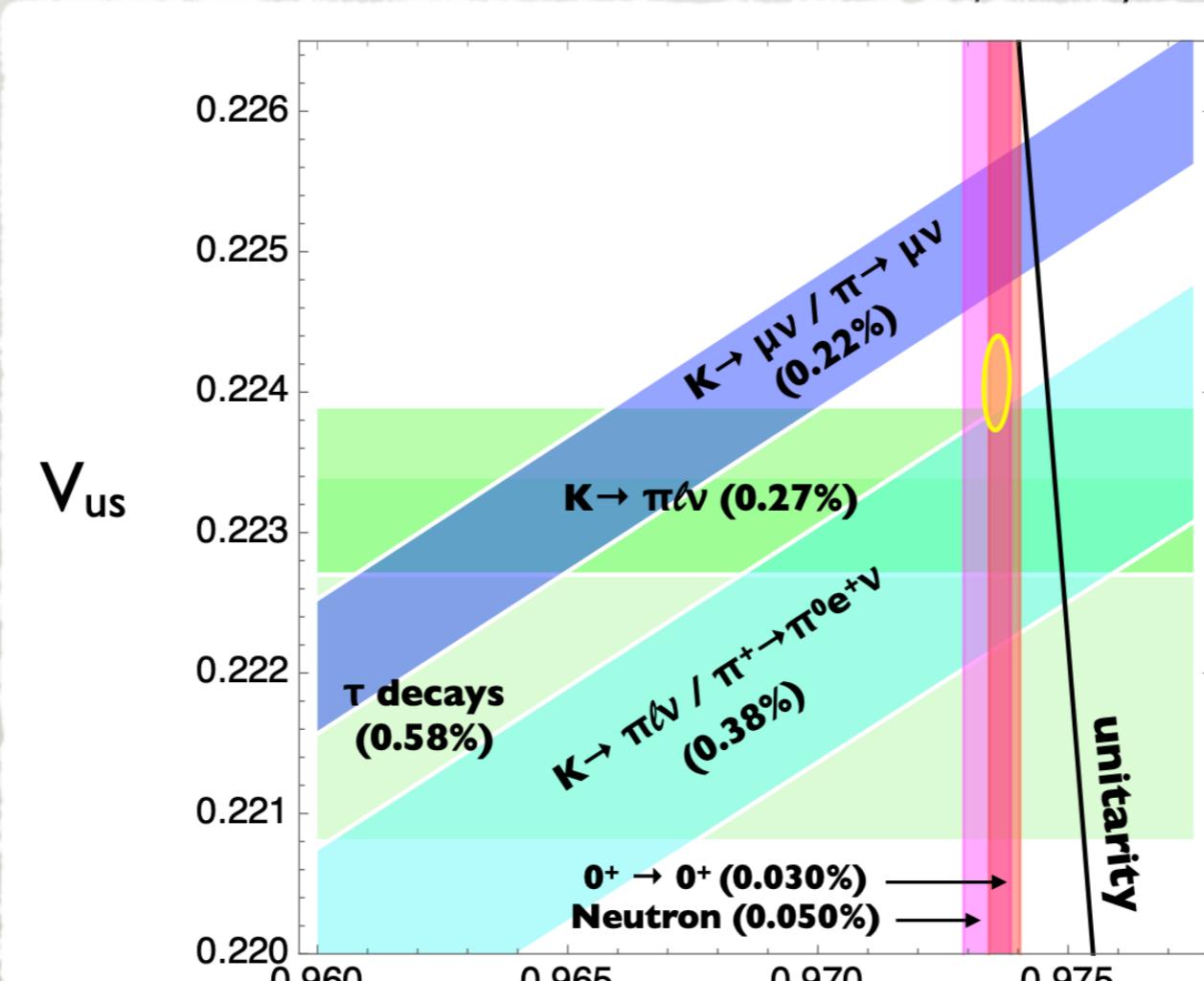
- golden kaonic quartet
 - $\text{Br}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$
 - $\text{Br}(K^0 \rightarrow \pi^0 \nu \bar{\nu})$
 - $\text{BR}(K_S \rightarrow (\mu^+ \mu^-)_{\ell=0})$
 - ϵ_K
- searches for rare kaon decays to light new physics \Rightarrow enhanced sensitivity to UV

BACKUP SLIDES

FIRST ROW UNITARITY

- persistent anomaly at $\sim 3\sigma$ level
 - a hint of right handed currents?
 - useful additional measurement: $K_{\mu 3}/K_{\mu 2}$

Cirigliano et al, 2208.11707



RELATION TO GOLDEN MODES- KAONIC NULL TESTS

- sum rule involving (almost) just kaon sector observables
 - null test of the SM, require only kaons+ β
 - very small theory errors $\approx 4\%$ and $\approx 1.6\%$

Buras, Venturini, 2109.11032

$$R_{11} = \frac{\mathcal{B}(K^+ \rightarrow \pi^+ \nu \bar{\nu})}{|\varepsilon_K|^{0.82}} = (1.31 \pm 0.05) \times 10^{-8} \left(\frac{\sin \gamma}{\sin 67^\circ} \right)^{0.015} \left(\frac{\sin 22.2^\circ}{\sin \beta} \right)^{0.71},$$

$$R_{12} = \frac{\mathcal{B}(K_L \rightarrow \pi^0 \nu \bar{\nu})}{|\varepsilon_K|^{1.18}} = (3.87 \pm 0.06) \times 10^{-8} \left(\frac{\sin \gamma}{\sin 67^\circ} \right)^{0.03} \left(\frac{\sin \beta}{\sin 22.2^\circ} \right)^{0.98}$$

approximate numerical versions \Rightarrow better to use analytic expressions

- theory predictions for $Br(K_L \rightarrow \pi^0 \nu \bar{\nu})$, $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$, ε_K essential
 - improved theory pred. \Rightarrow exponents will change (within errors)
- can turn around and use them to predict Br's
 - probably not what most would call the SM prediction for $Br(K^+ \rightarrow \pi^+ \nu \bar{\nu})$, $Br(K_L \rightarrow \pi^0 \nu \bar{\nu})$
 - SM prediction = use V_{cb} that gives best global description assuming SM (i.e. from global CKM fits)

NEW SHORT DISTANCE PROBES

D'Ambrosio, Kitahara, 1707.06999

- precision probe of UV physics from $K_S \rightarrow \mu^+ \mu^-$

Dery et al, 2104.06427

$$\text{Br}(K_S \rightarrow \mu^+ \mu^-)_{\ell=0} = \text{Br}(K_L \rightarrow \mu^+ \mu^-) \times \frac{\tau_S}{\tau_L} \times \left(\frac{C_{\text{int}}}{C_L} \right)^2,$$

measureable
 K_S, K_L
interference

Brod, Stamou, 2209.07445

- relation valid to all orders in ϵ_K
- CP violating $\text{Br}(K_S \rightarrow \mu^+ \mu^-)_{\ell=0}$ does get LD contrib. at $\mathcal{O}(\epsilon_K)$

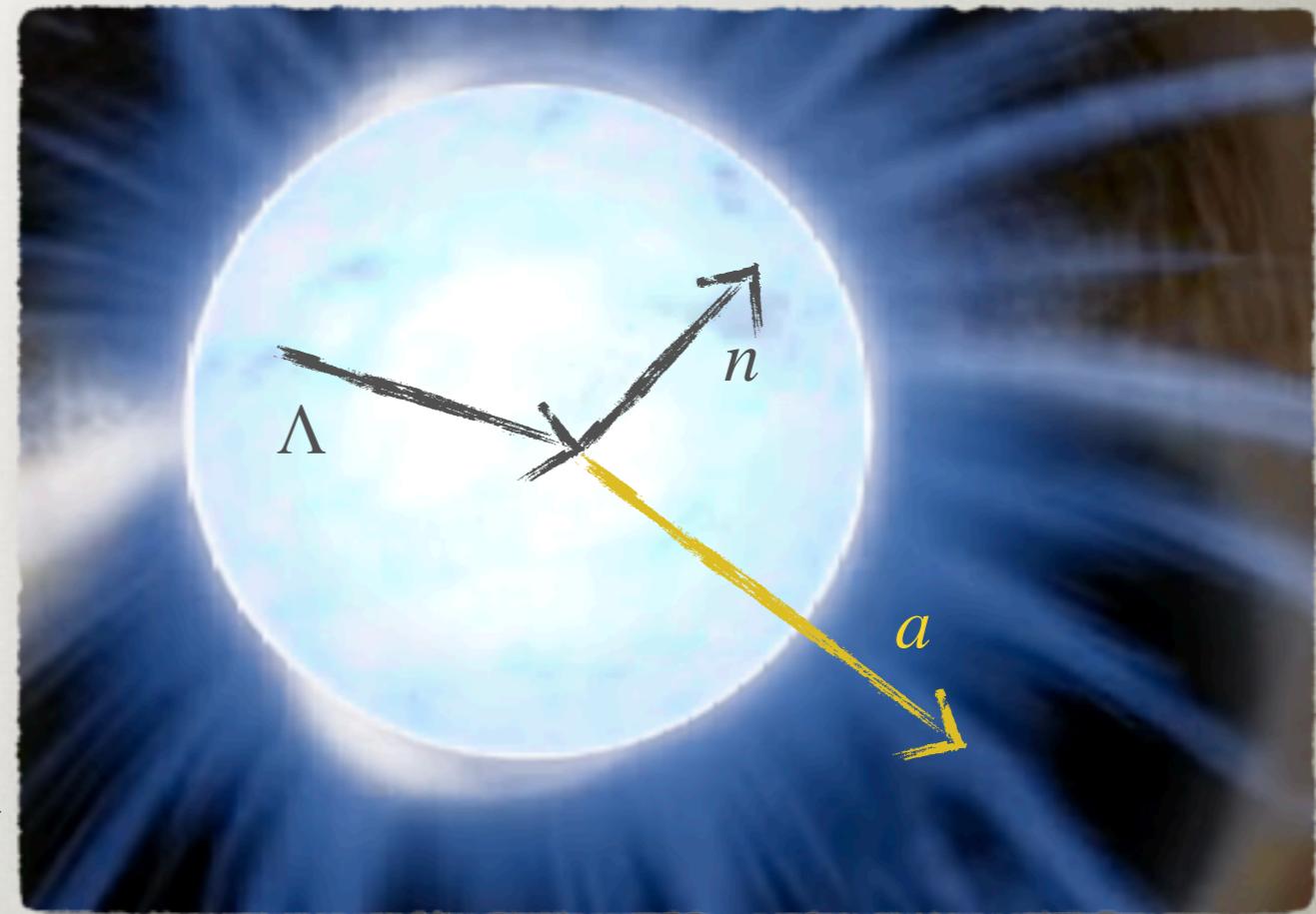
$$\text{Br}(K_S \rightarrow \mu^+ \mu^-)_{\ell=0} = \text{Br}(K_S \rightarrow \mu^+ \mu^-)_{\ell=0}^{\text{pert.}} \times \left(1 + \sqrt{2} |\epsilon_K| \frac{|A_0^L|}{|A_0^S|} (\cos \phi_0 - \sin \phi_0) \right),$$

- correction in principle measurable
 - very small remaining intrinsic uncertainty
- measureable
 K_S, K_L
interference

$$\text{Br}(K_S \rightarrow \mu^+ \mu^-)_{\ell=0} = 1.70(02)_{\text{QCD/QED}}(01)_{f_K}(06)_{\text{ICPV}}(19)_{\text{param.}} \times 10^{-13},$$

SUPERNOVA BOUNDS

- in neutron star Λ, n, p, e are in equilibrium
- $\Lambda \rightarrow na$ decays can cool the proto-neutron star
- Λ, n have the same Fermi energy
 \Rightarrow at $T=0$ Pauli blocking forbids $\Lambda \rightarrow na$ decays
- at finite temperature volume emission rate (in NR limit)



$$Q \simeq n_n (m_\Lambda - m_n) \Gamma(\Lambda \rightarrow na) e^{-\frac{m_\Lambda - m_n}{T}},$$

see also Camalich et al, 2012.11632

- assuming this is below neutrino emission rate 1sec after the collapse of SN1987A
 - bounds on $|F_{sd}^A|$ and $|F_{sd}^V|$ in the range $10^9 - 10^{10}$ GeV

FV FROM RUNNING

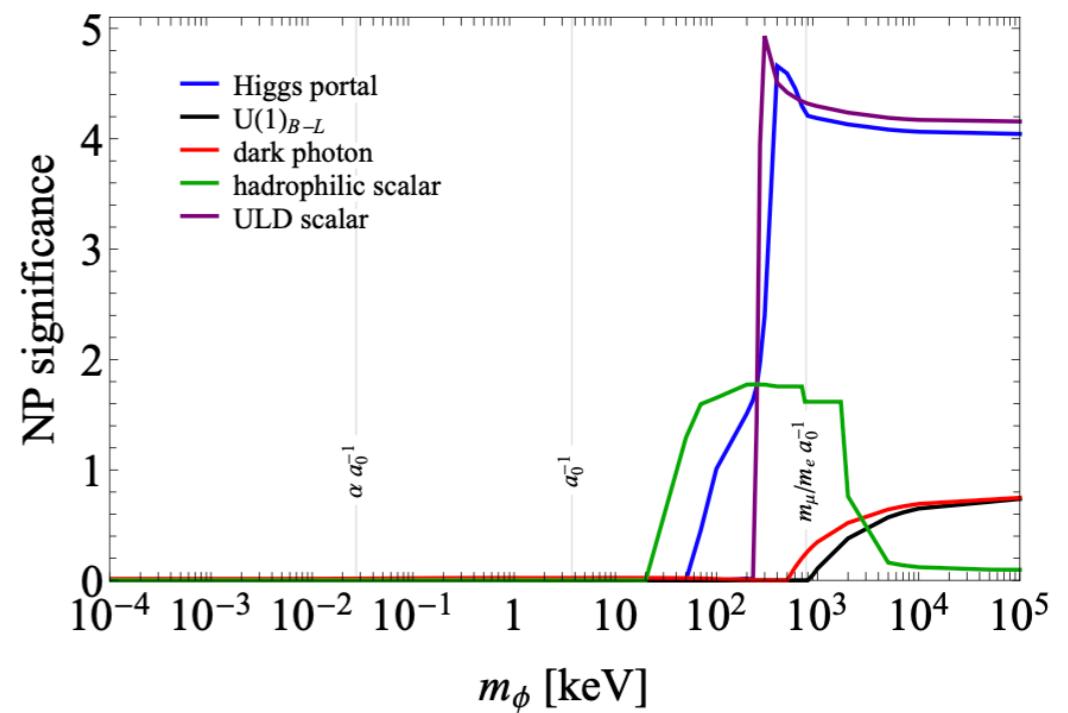
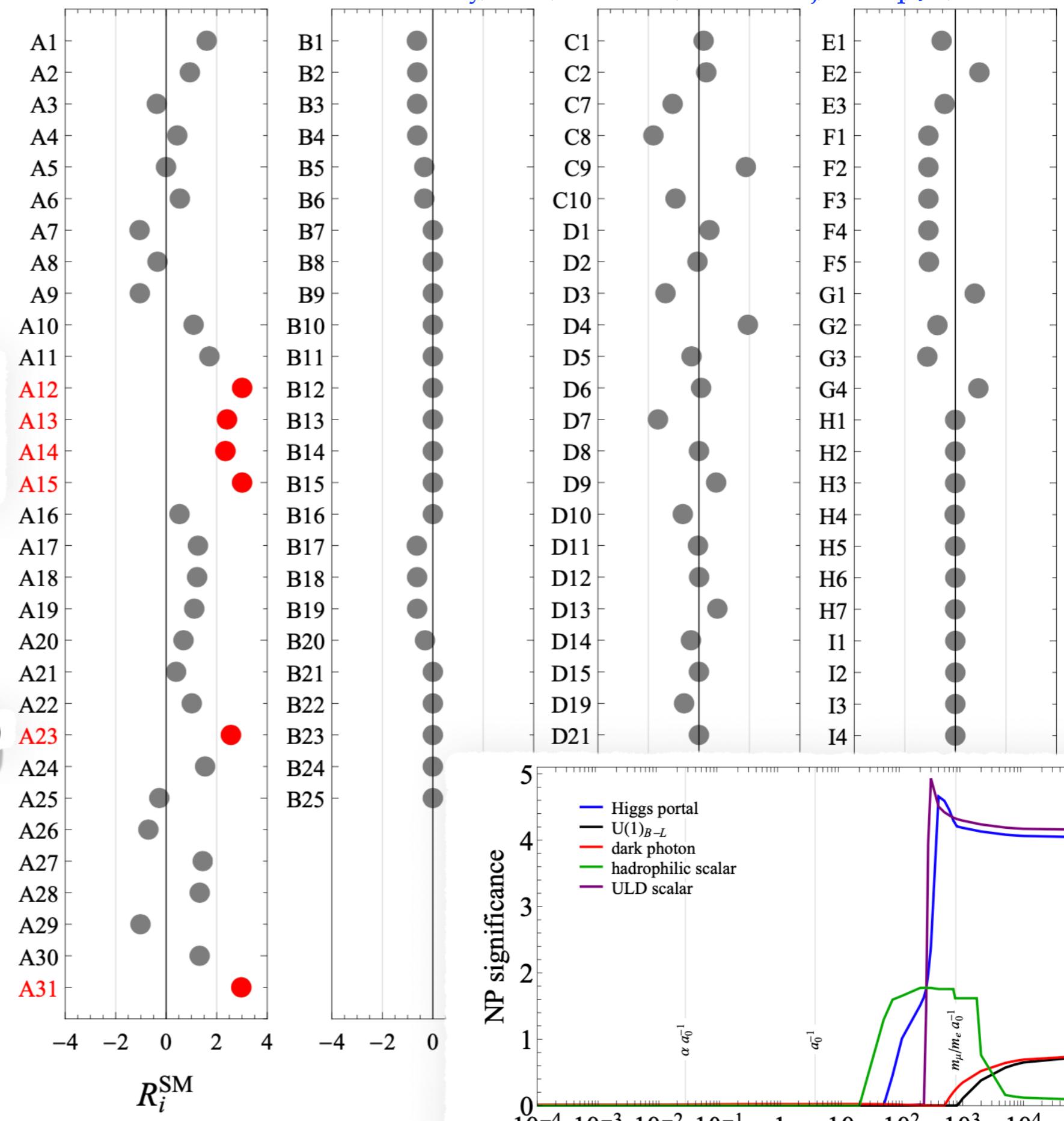
- numerical solution to RG runnin

$$C_{ds}^V \supset -10^{-6} \left[(2+i) C_{tt}^A \left(\log \frac{\Lambda_{\text{UV}}}{\mu_t} + 0.02 \right) + 0.08 C_{cc}^A \left(\log \frac{\Lambda_{\text{UV}}}{\mu_c} + 11 \right) - (4+2i) 10^{-3} N_2 \right].$$

A12 $\nu_H(2S_{1/2} - 8D_{5/2})$
 A13 $\nu_D(2S_{1/2} - 8S_{1/2})$
 A14 $\nu_D(2S_{1/2} - 8D_{3/2})$
 A15 $\nu_D(2S_{1/2} - 8D_{5/2})$

 A23 $\nu_H(1S_{1/2} - 3S_{1/2})$

 A24 $\nu_H(2S_{1/2} - 8D_{5/2})$
 A25
 A26
 A27
 A28
 A29
 A30
 A31 $\nu_H(2S_{1/2} - 8D_{5/2})$

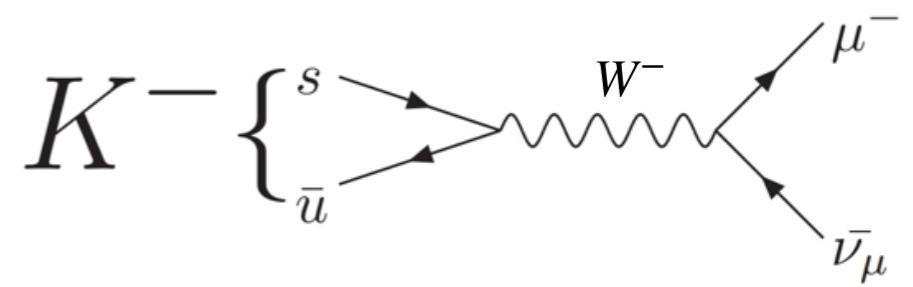


PORtALS

| Portal | Interactions |
|-------------------------------|--|
| Dark Photon, A'_μ | $-\epsilon F'_{\mu\nu} B^{\mu\nu}$ |
| Dark Higgs, S | $(\mu S + \lambda S^2) H^\dagger H$ |
| Heavy Neutral Lepton, N | $y_N L H N$ |
| Axion-like pseudo scalar, a | $a F \tilde{F} / f_a, a G \tilde{G} / f_a, (\bar{\psi} \gamma^\mu \gamma_5 \psi) \partial_\mu a / f_a$ |

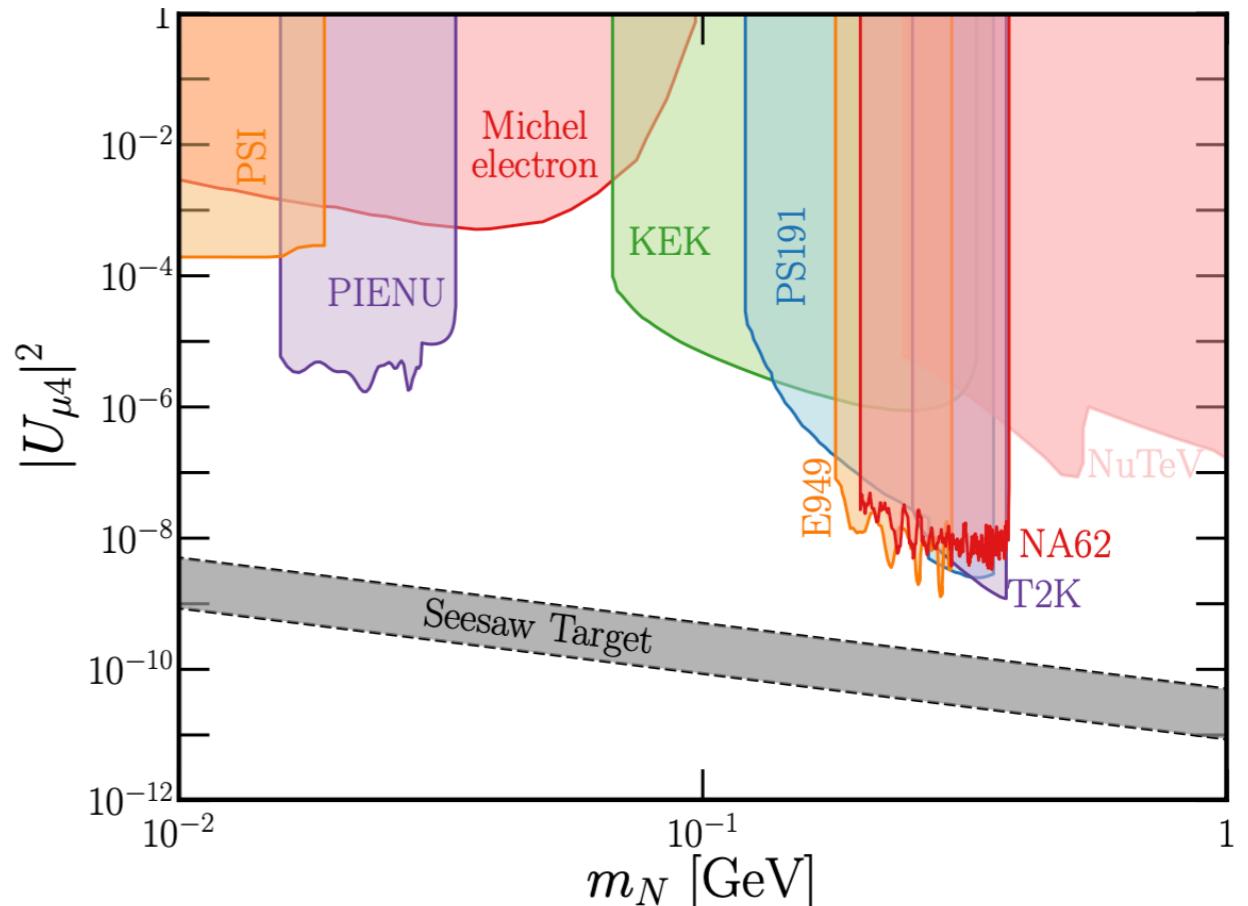
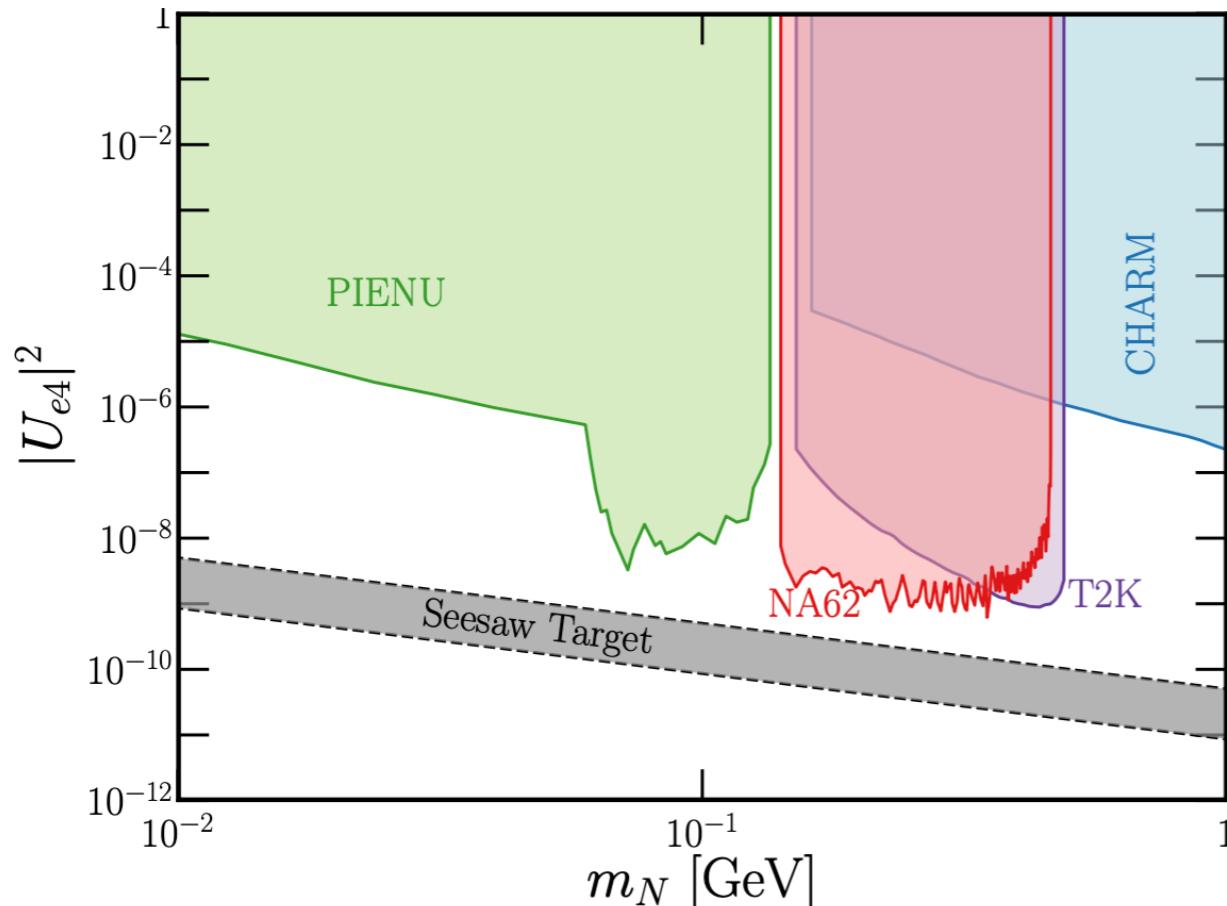
LIGHT NEW PHYSICS \Rightarrow PROBE OF HIGH SCALES

- rare decays into a light state, X , e.g.,
 $K \rightarrow \pi X$,
 - exquisite probes of UV physics
- parametric gains compared to probing NP through dim-6 ops.
 - SM decay width power suppressed: $\Gamma_K \propto m_K^5/m_W^4$
- if through dim 5 op. suppressed by $1/f_a$
 - $\Rightarrow Br(K \rightarrow \pi\varphi) \propto (m_W^2/f_a m_K)^2$
 - similar for dim 4
- no such $1/m_K$ enhancement for dim. 6 couplings
 - $Br(K \rightarrow \pi e^- \mu^+) \propto (m_W/\Lambda)^4$



HEAVY NEUTRINOS

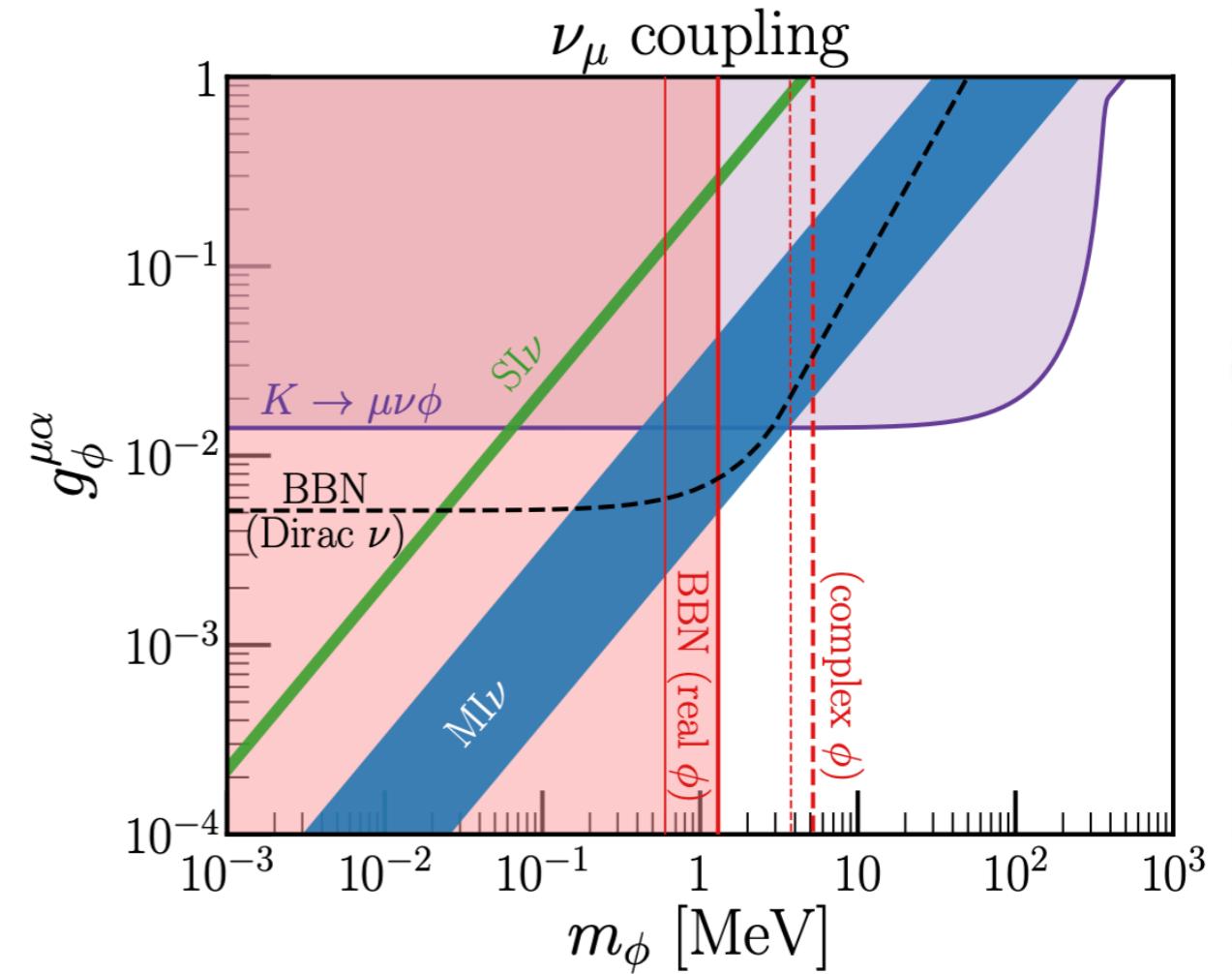
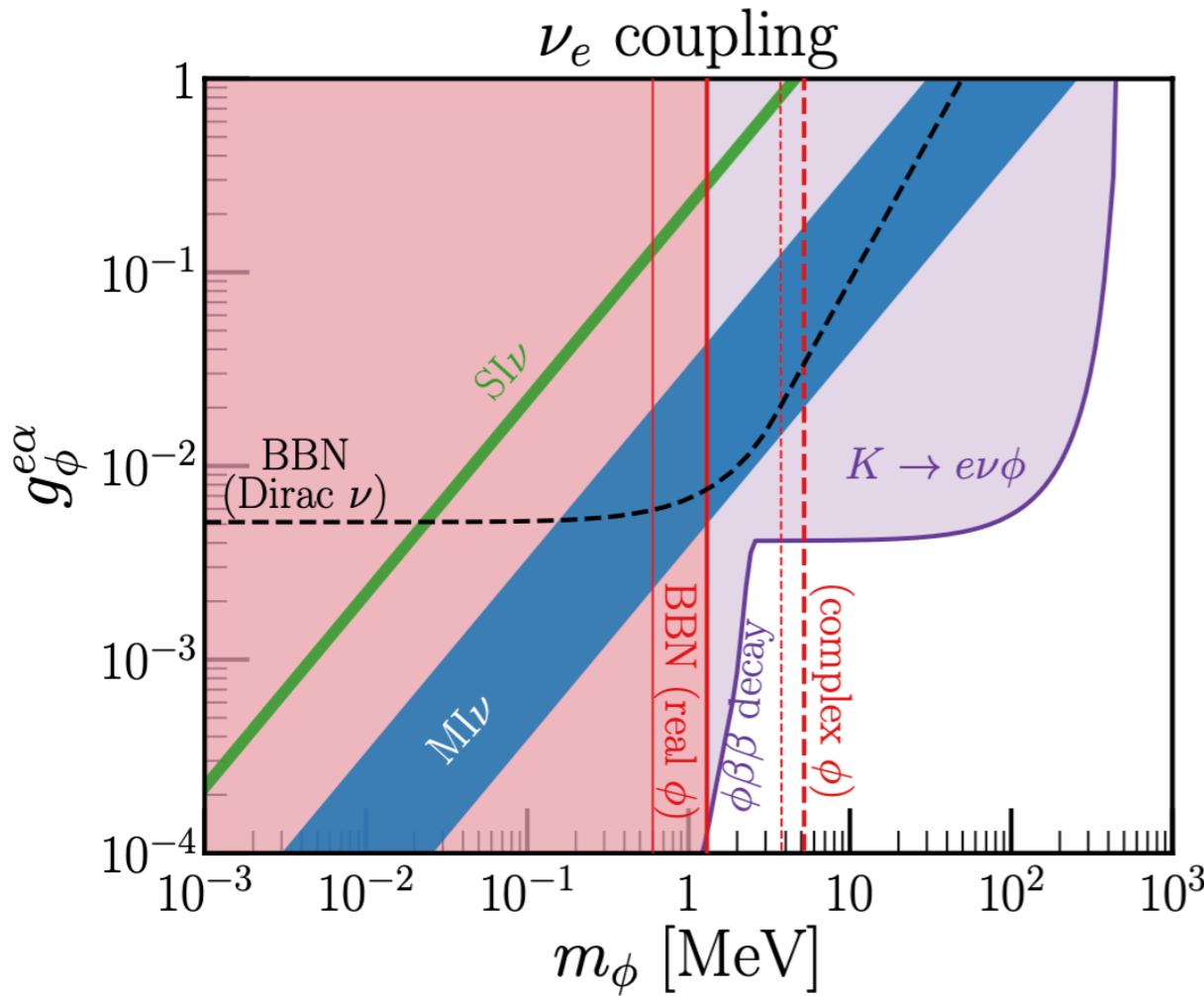
- two orders improvement in $Br(K^+ \rightarrow \ell^+ N)$
 - start probing minimal see-saw neutrino mass models
 - for O(100 MeV) sterile neutrino masses



- start probing minimal see-saw neutrino mass models
- for O(100 MeV) sterile neutrino masses

SELF INTERACTING ν 'S

- order of magnitude improvement on $Br(K^+ \rightarrow \mu^+ \nu X_{\text{inv}})$
- probe fully self-interacting $\nu_{e,\mu}$ explanation of Hubble tension



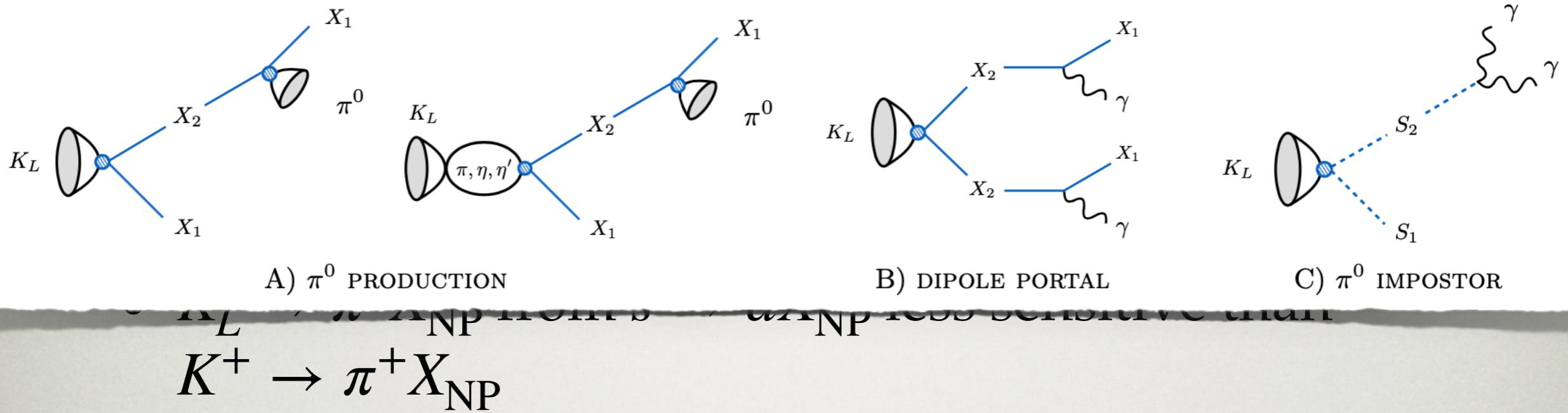
K_L DECAYS

- $K_L \rightarrow \pi^0 X_{\text{NP}}$ from $s \rightarrow dX_{\text{NP}}$ less sensitive than
 $K^+ \rightarrow \pi^+ X_{\text{NP}}$
- still, many K_L decays with leading sensitivity to NP
 - $K_L \rightarrow \pi^0 \nu \bar{\nu}$ theoretically the cleanest SM prediction
 - will provide higher sensitivity to heavy NP than
 $K^+ \rightarrow \pi^+ \nu \bar{\nu}$
 - K_L decays can probe Grossman-Nir violating models
- subleading constr. from K^+ decays
 - Egana-Ugrinovic, Homiller, Meade, 1911.10203; Kitahara, Okui, Perez, Soreq, Tobioka, 1909.11111;
 - Liu, McGinnis, Wagner, Wang, 2001.06522; Liao, Wang, Yao, Zhang, 2005.00753

[Hostert, Kaneta, Pospelov, 2005.07102](#)

[Gori, Perez, Tobioka, 2005.05170](#)

[Ziegler, Zupan, Zwicky, 2005.00451](#)



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HIGH SENSITIVITY KAONS VS. ATOMIC

- important to stress how sensitive are rare kaon decays
- another example from atomic physics
 - precision quickly improving

