LEPTON FLAVOUR VIOLATION
(LECTURES 3 & 4)

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Future flavours: prospects for beauty, charm, and tau physics, ICTS, May 3 2022

OUTLINE

- lecture 1: lepton flavor in the SM
- lecture 2: LFV observables - muons
- lecture 3: LFV in taus, Higgs and flavor
- lecture 4: LFV searches and light new physics

SHORT REVIEW OF LECTURES 1 AND 2

- in the SM leptonic flavor violation is essentially zero
  - if signal in any of the FCNC transitions $\mu \to e\gamma, \mu \to 3e, \mu \to e, \tau \to \mu\gamma, \ldots$
  - $\Rightarrow$ discovery of New Physics
- significant experimental progress expected in searches with muons
  - MEG-II, Mu3e, DeeMee, Mu2e, COMET

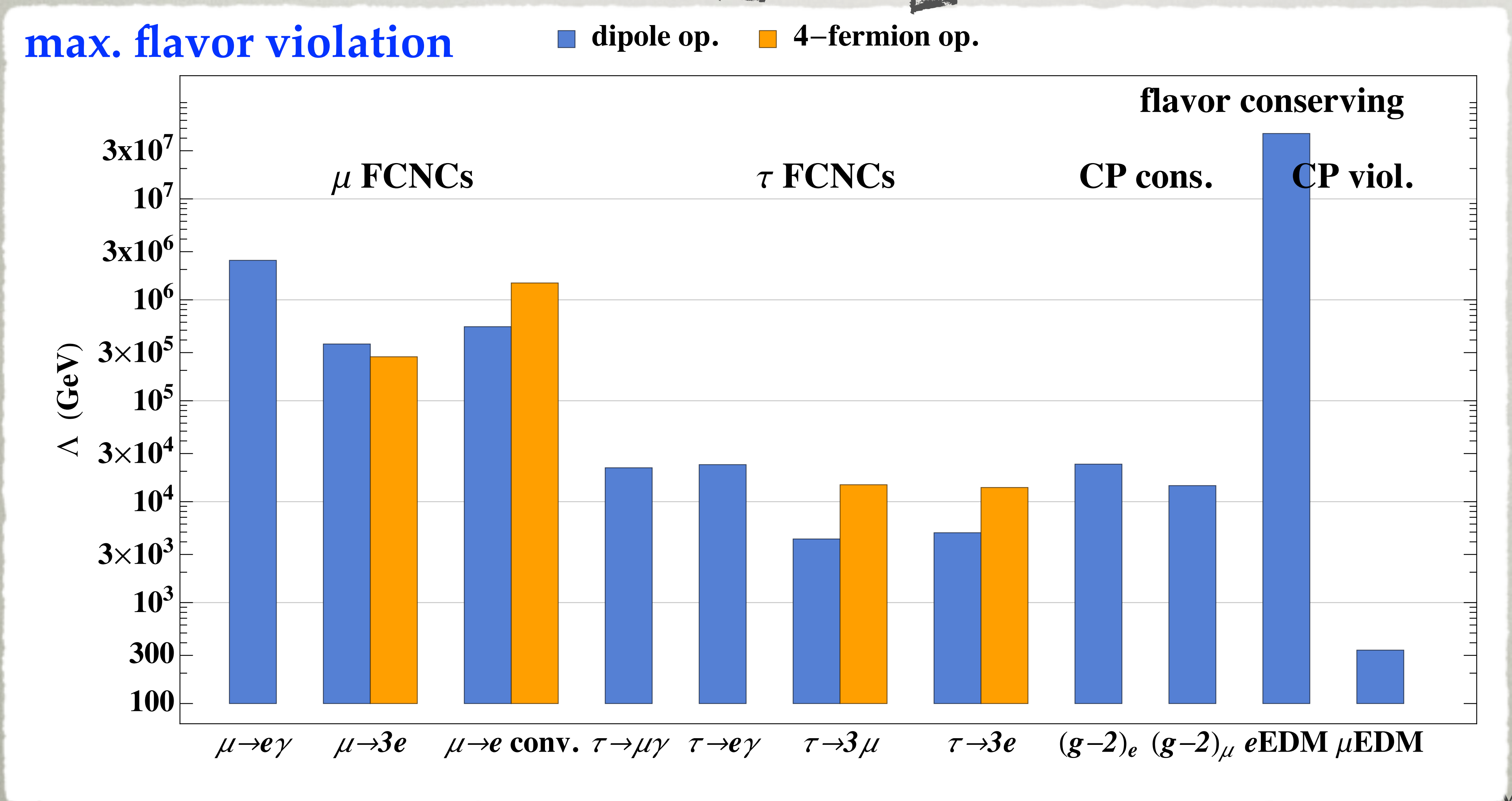
SUMMARY OF CLFV

- many different charged lepton transitions
- in principle probe very high scales
- in the example switched on only two sets of ops.*

$$\mathcal{L} = \sum_a \frac{C_a}{\Lambda^2} Q_a$$

$$Q_\gamma^{ij} = \frac{e}{8\pi^2} H (\bar{\ell}^i \sigma^{\mu\nu} P_L \ell^j) F_{\mu\nu}$$

$$Q_{4\ \text{ferm.}}^{ijk} = (\bar{\ell}^i \gamma^\mu \ell^j)(\bar{f}^k \gamma_\mu f^k)$$



*in bounds either $C_a=1$ or $C_a=i$

**$(g\text{-}2)_\mu$ and $(g\text{-}2)_e$ interpreted as bounds

OUTLINE LECTURES 3 & 4

- in lectures 3 & 4:
  - LFV in tau decays
  - LFV using *B*, *D*, *K* decays
  - searching for light NP using LFV decays
  - Higgs as a probe of flavor
  - flavor diagonal observables: eEDM and $(g-2)_\mu$

LFV in τ decays

LFV τ DECAYS

- several important differences relative to muons
- experimental:
  - τ lifetime is short $\Rightarrow$ no "tau beams"
    - need to be produced in $e^+e^- \to \tau^+\tau^-$ (Belle II) or in pp collisions (LHC)
    - smaller experimental samples compared to muons
  - τ is heavier, $m_\tau = 1.777\,\text{GeV}$, many decay modes possible
- theoretical:
  - the models that lead to CLFV in muons tend to give CLFV tau decays
  - often couplings to 3rd generation are larger (motivated by flavor structure in the SM)

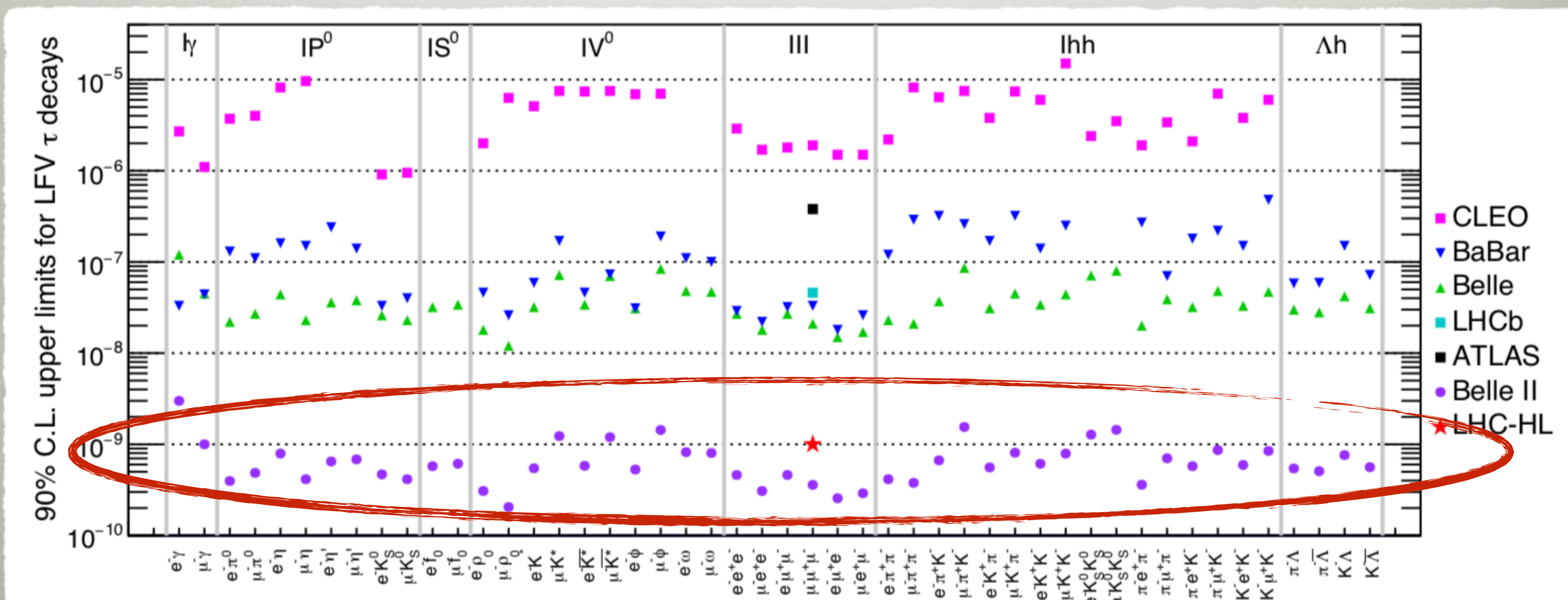
$\tau_\tau \sim 3 \times 10^{-13} s$
$\tau_\mu \sim 2 \times 10^{-6} s$

FUTURE REACH

- significant improvements in the experimental reach expected

Akar et al., 1812.07638

- example for tau: Belle 2 and HL-LHC reach



Experiment	Number of τ pairs
LEP	~3.3 x 10^5
CLEO	~1 x 10^7
BaBar	~5 x 10^8
Belle	~9 x 10^8
Belle II	~4.6 x 10^{10}
SτcF	~2.1 x 10^{10}

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E REACH

ements in the

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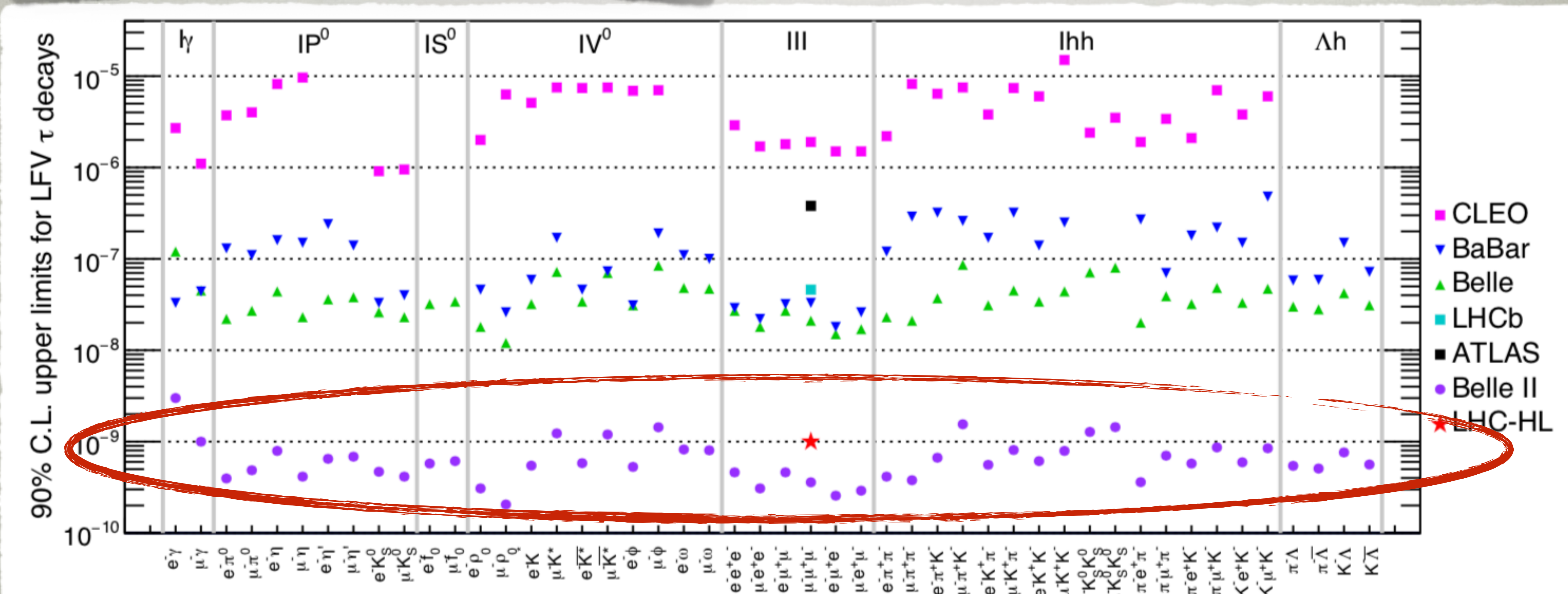
Akar et al., 1812.07638

elle 2 and HL-LHC reach



NEW PHYSICS IN TAU DECAYS

- two categories of LFV tau decays
  - purely leptonic: $\tau \to \mu\gamma, \tau \to 3e, \tau \to 3\mu, \ldots$
    - NP can be purely leptophilic
  - also involving hadrons: $\tau \to \mu\rho, \tau \to e\rho, \tau \to \mu K_S$, ...
    - NP needs to couple to both leptons and quarks
    - the quark couplings may or may not be flavor violating
- comparison with FCNC muon decays
  - need concrete models to compare muon and tau decays

TWO EXAMPLES

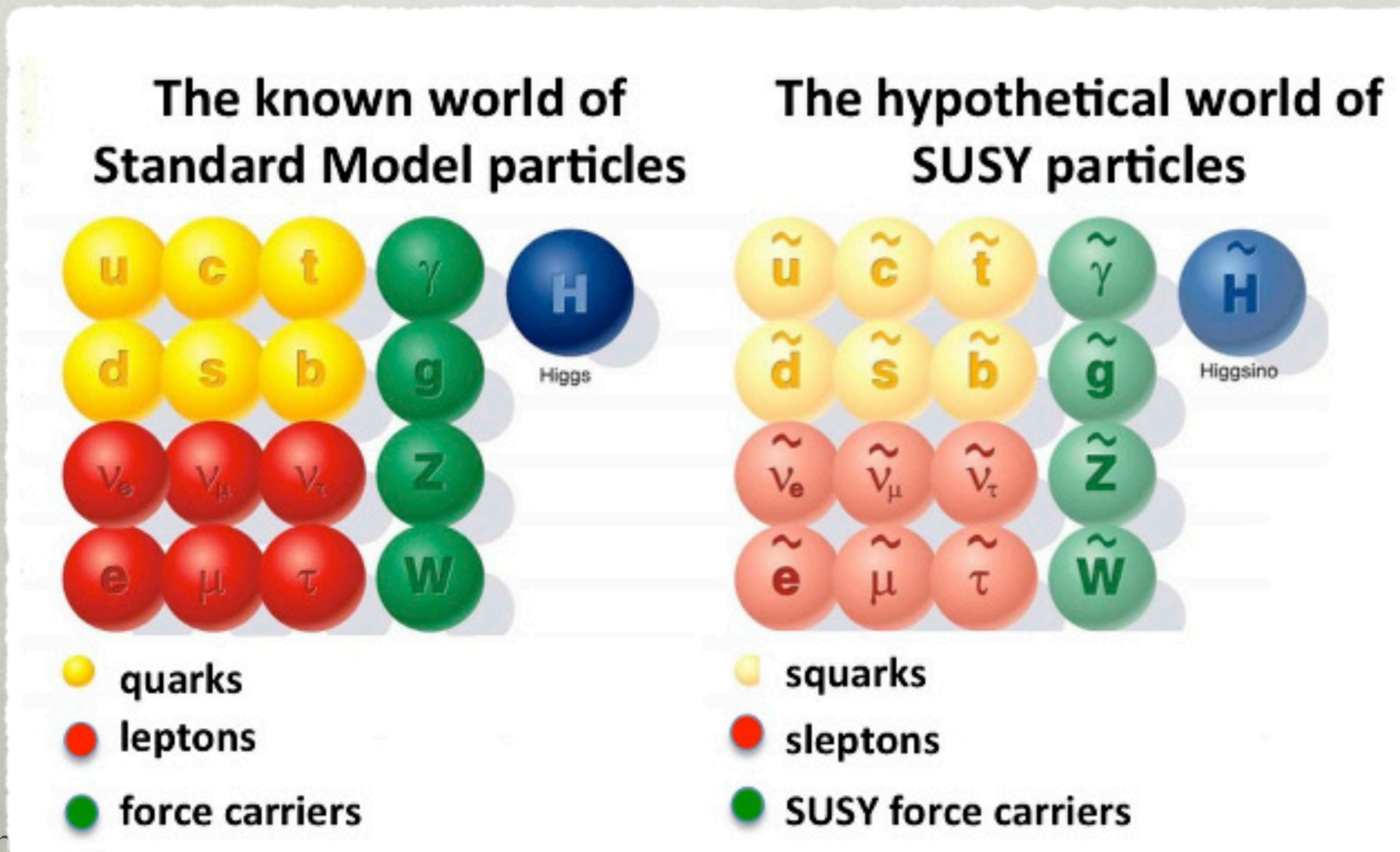
- the examples of NP with nontrivial flavor structure
  - a model of neutrino masses
    - supersymmetric see-saw
  - a model of flavor
    - gauged U(1)' Froggatt-Nielsen model

SUSY SEE-SAW EXAMPLE

SUPERSYMMETRIC SEE-SAW

Antusch et al., hep-ph/0607263

- SM is enlarged by 3 generations of RH neutrinos
- to stabilize the electroweak scale the model is assumed to be supersymmetric



SUPERSYMMETRIC SEE-SAW

- in general there are many flavor violating parameters even in the minimal SUSY see saw model
  - 124 from minimal SUSY SM (MSSM)
  - another 18 in the neutrino sector
- most of these related to SUSY breaking
  - the form of slepton and squark mass matrices
- focus on a very restricted case: constrained MSSM

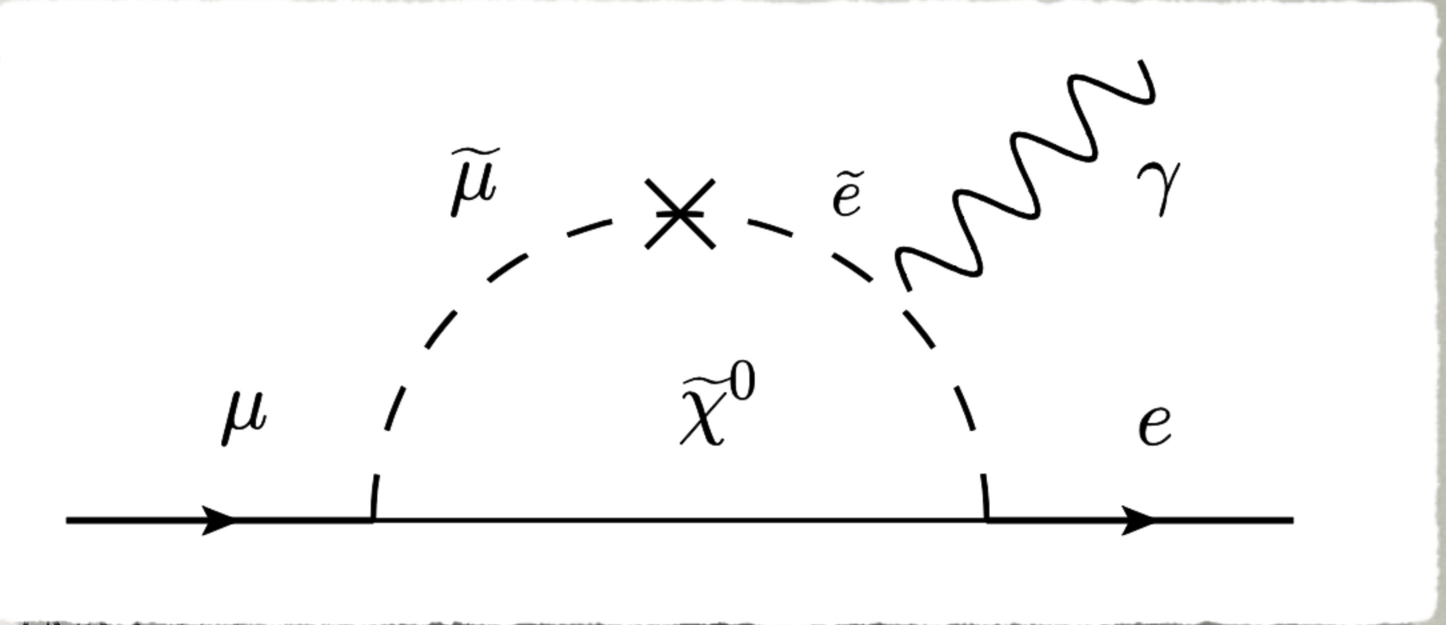
Antusch et al., hep-ph/0607263

  - SUSY breaking parameters are assumed to be flavor universal at the UV scale (=GUT scale)
- all LFV originates solely from the neutrino sector
  - some of the parameters are fixed by requiring to reproduce neutrino masses and PMNS, scanned over the rest

$$m_\nu = -\frac{v^2}{2} Y_\nu^T M_R^{-1} Y_\nu$$

  - FV in slepton mass matrices from RGEs

SUPERS... SE...



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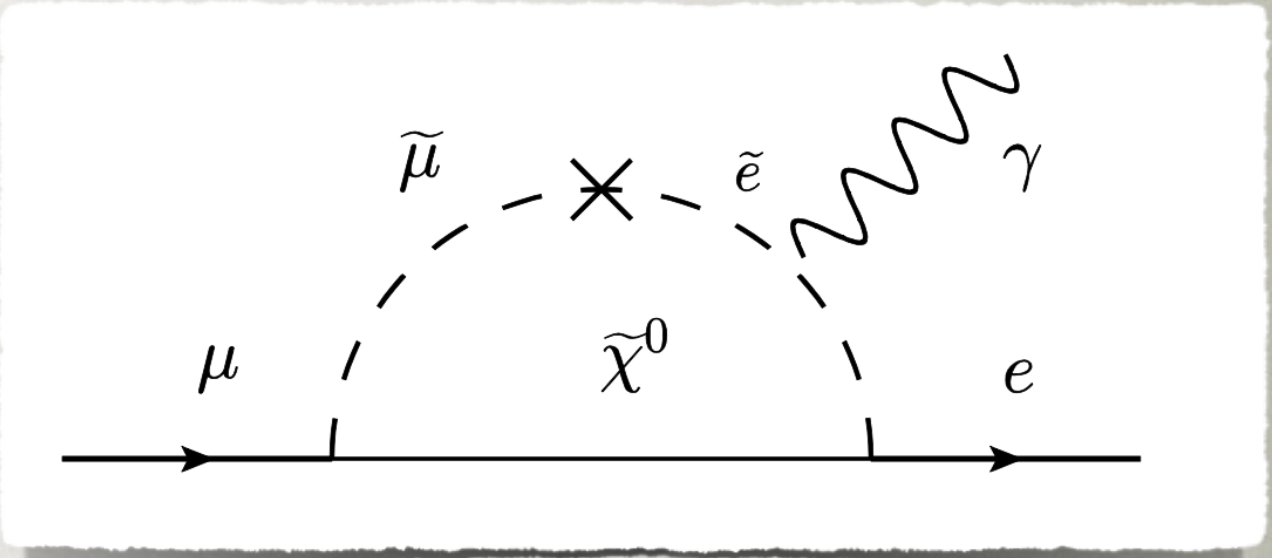
SUPERSYMMETRIC SEE-SAW

- the dominant LFV contribution comes from dipole operators ("photon penguin")



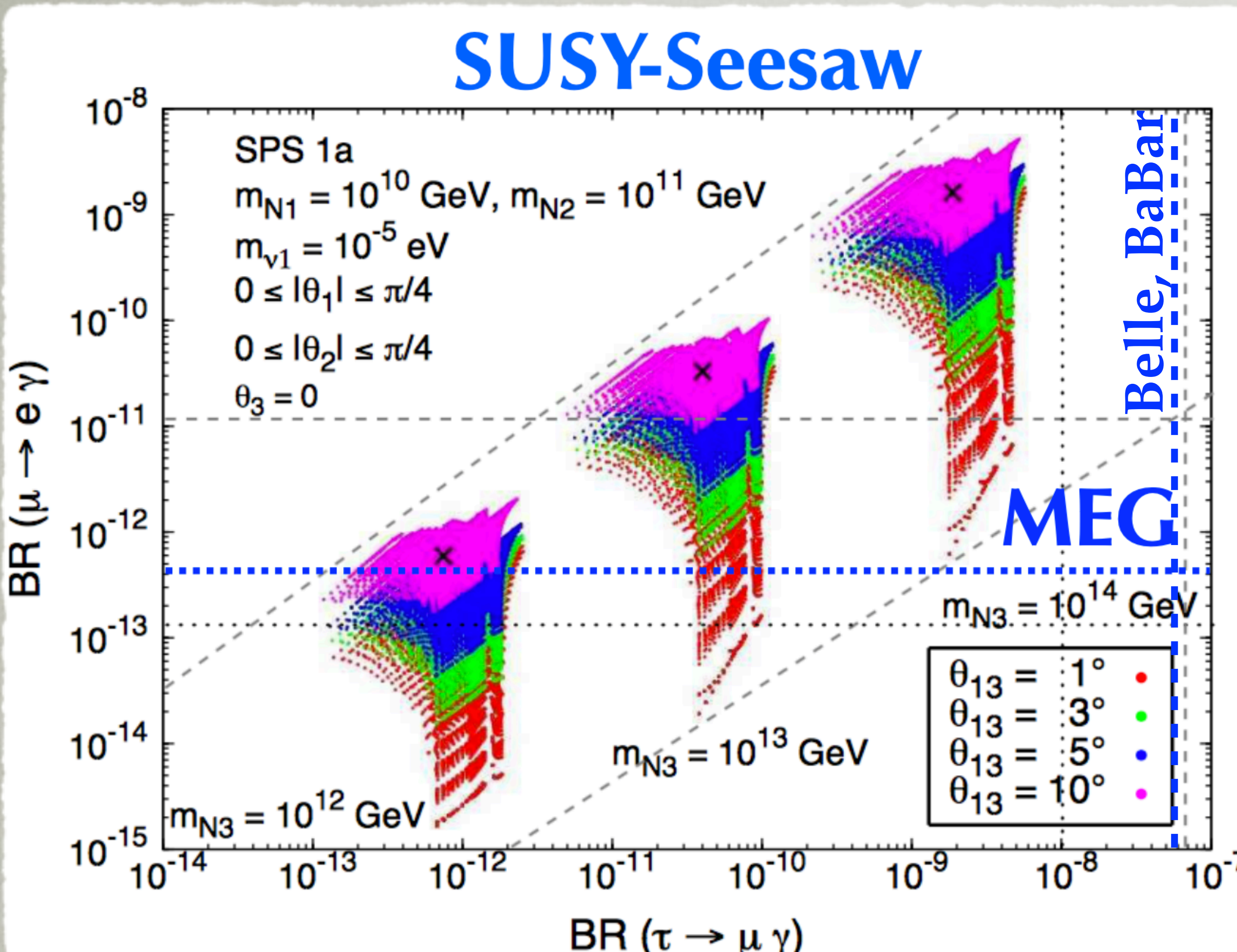
- the $\ell_j \to 3\ell_i$ are thus given by

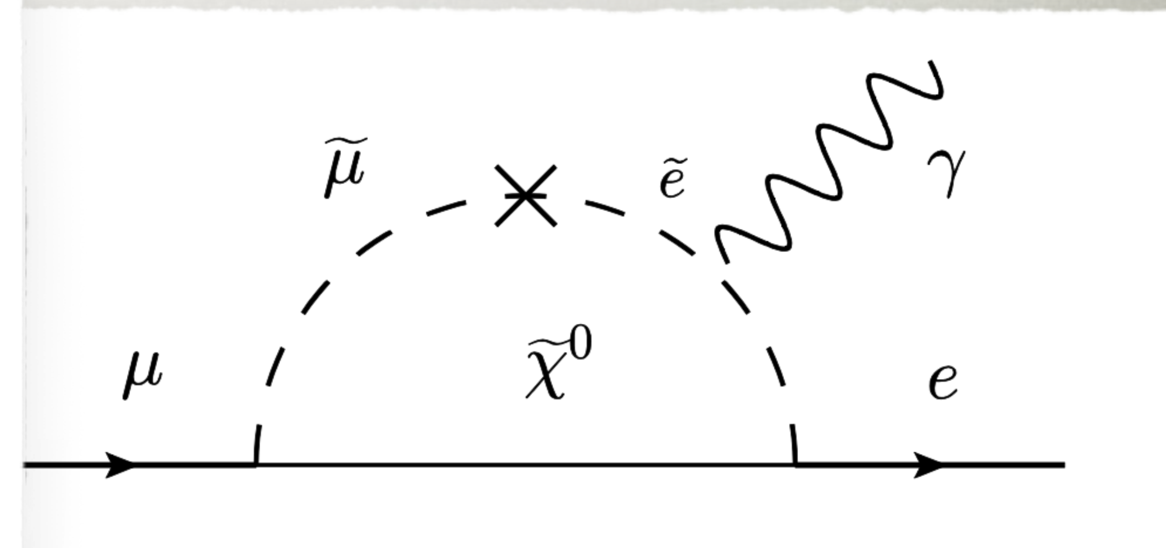
Antusch et al., hep-ph/0607263

$$\mathrm{BR}(l_j \to 3l_i) = \frac{\alpha}{3\pi}\left(\log\frac{m_{l_j}^2}{m_{l_i}^2} - \frac{11}{4}\right) \times \mathrm{BR}(l_j \to l_i\,\gamma)\,,$$

- because of restricted flavor structure there is also a relation between $\mu \to e\gamma$ and $\tau \to \mu\gamma$

...METRIC ...AW





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Antusch et al., hep-ph/0607263

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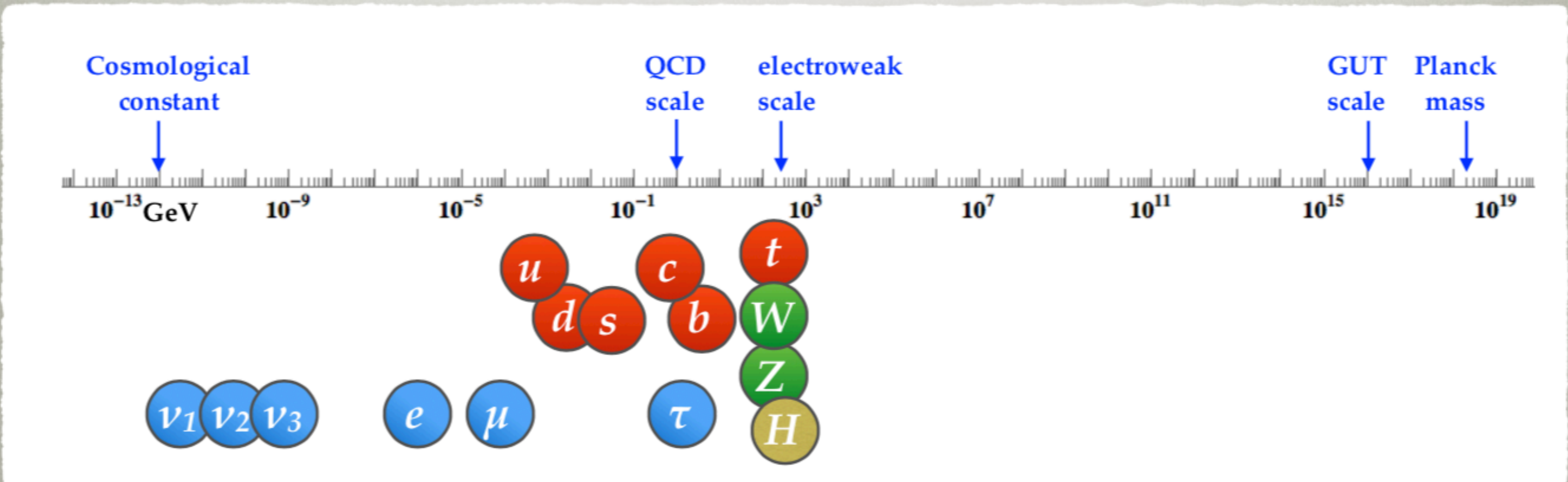
- because of restricted flavor structure there is also a relation between $\mu \to e\gamma$ and $\tau \to \mu\gamma$

GAUGED FN MODEL EXAMPLE

STANDARD MODEL FLAVOR PUZZLE

- in this example the flavor structure is not ad-hoc
- the model solves the SM flavor puzzle
  - why are fermion masses so hierarchical?
  - an explanation of mixing patterns?



FN solution to the flavor puzzle

Froggatt, Nielsen, NPB 147, 277 (1979),...

- Large hierarchies in quark + lepton masses and in CKM matrix
  - can be addressed via horizontal $U(1)_{\rm FN}$ symmetry
  - SM LH and RH fermions have different $U(1)_{\rm FN}$ charges
  - hierarhical Higgs Yukawas after $U(1)_{\rm FN}$ broken via vev of scalar field, the flavon Φ
  - if $U(1)_{\rm FN}$ gauged there is an associated Z'

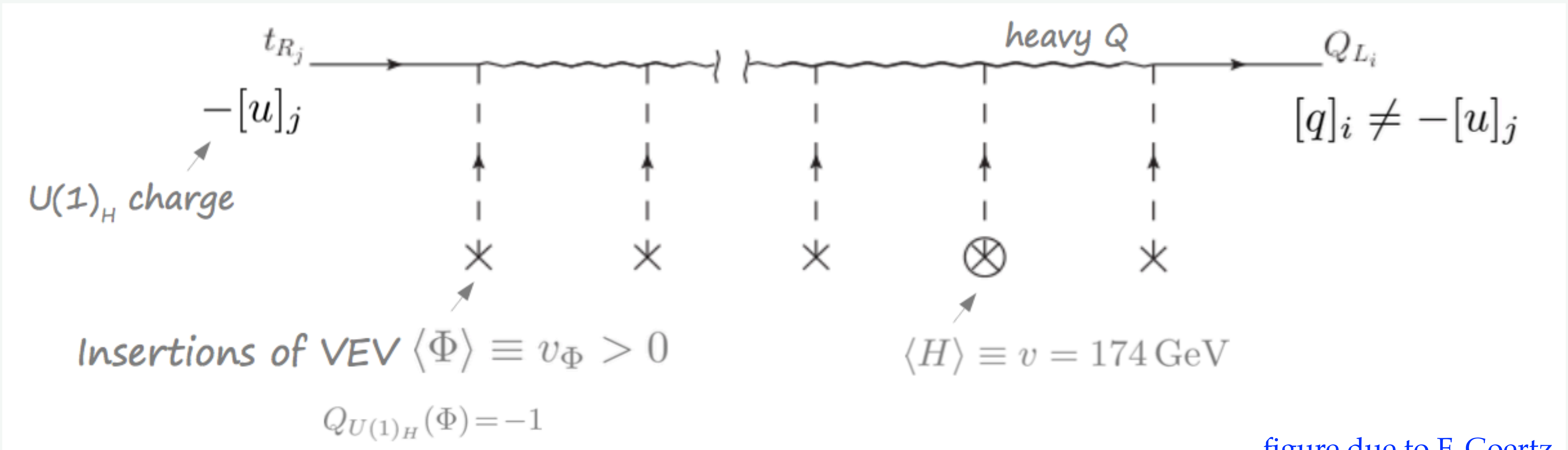
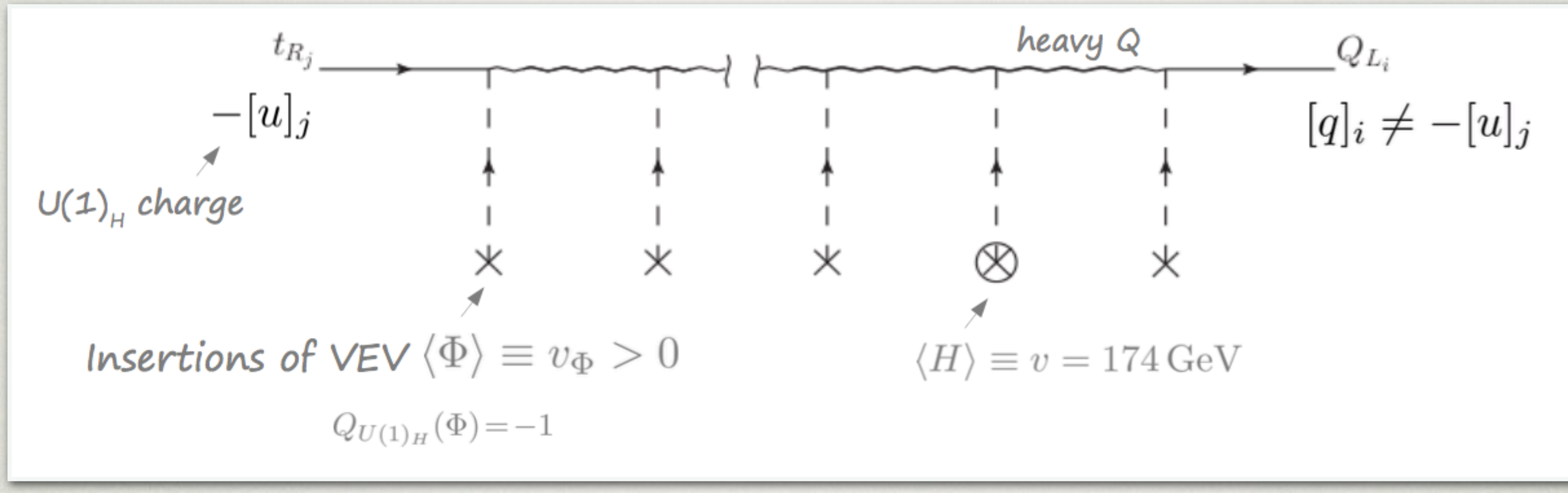


figure due to F. Goertz

SPURION ANALYSIS



- effective Yukawas governed by flavon insertions (so that invariant under flavor symm.)

$$\mathcal{L}_{eff} \sim \left(\frac{\phi}{\Lambda_F}\right)^{x_{ij}} h\,\bar{q}_i u_j \qquad \epsilon \equiv \frac{\phi}{\Lambda_F}$$

  - hierarchy from powers of small parameter ε
- FN mechanism involves
  - vector-like fermions + scalar flavon fields (no anomaly)
  - chiral fields at the end of the chains: in general anomalous $U(1)_{\mathrm{FN}}$
    - we show the results for an anomaly free $U(1)_{\mathrm{FN}}$ (inverted FN) that is gauged

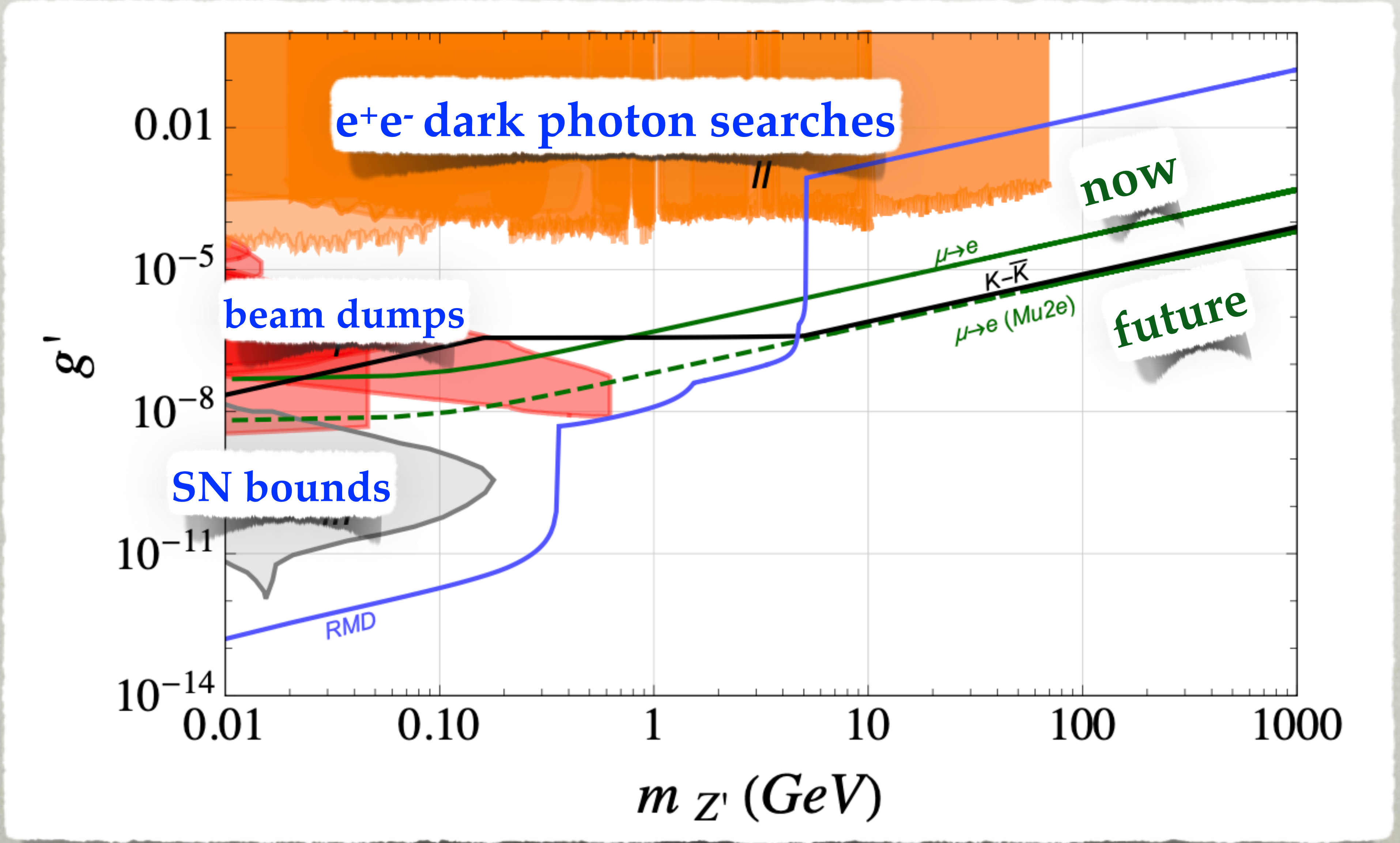
Smolkovic, Tammaro, JZ, 1907.10063

EXPERIMENTAL SEARCHES

- how to observe experimentally?
- search in FCNCs
  - $K-\bar{K}$, $B-\bar{B}$ mixing, etc.
  - exchanges of flavons, heavy vector-like fermions, flavorful Z' s
  - for $\mathcal{O}(1)$ couplings masses $\gtrsim 10^7$ GeV
- for small $U(1)_{FN}$ gauge couplings Z' can be light
  - can also search for it directly: beam dumps, e^+e^- colliders, astrophysics

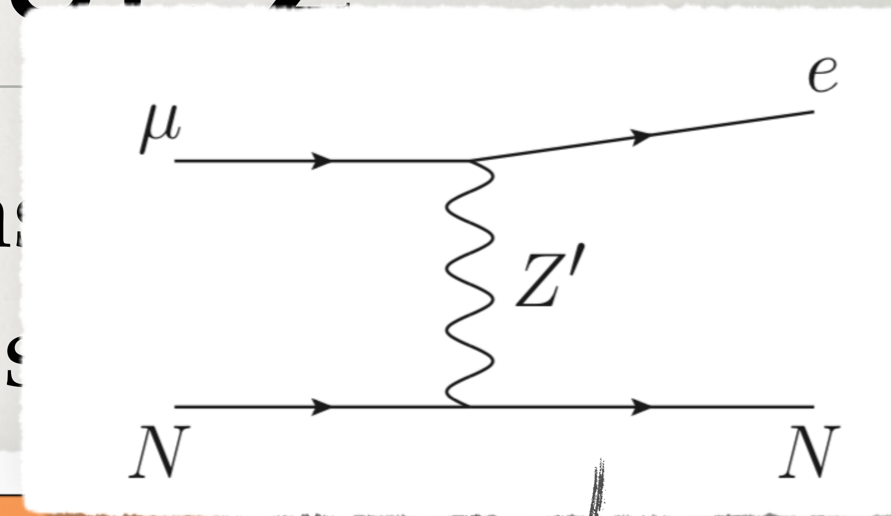
FLAVORFUL Z'

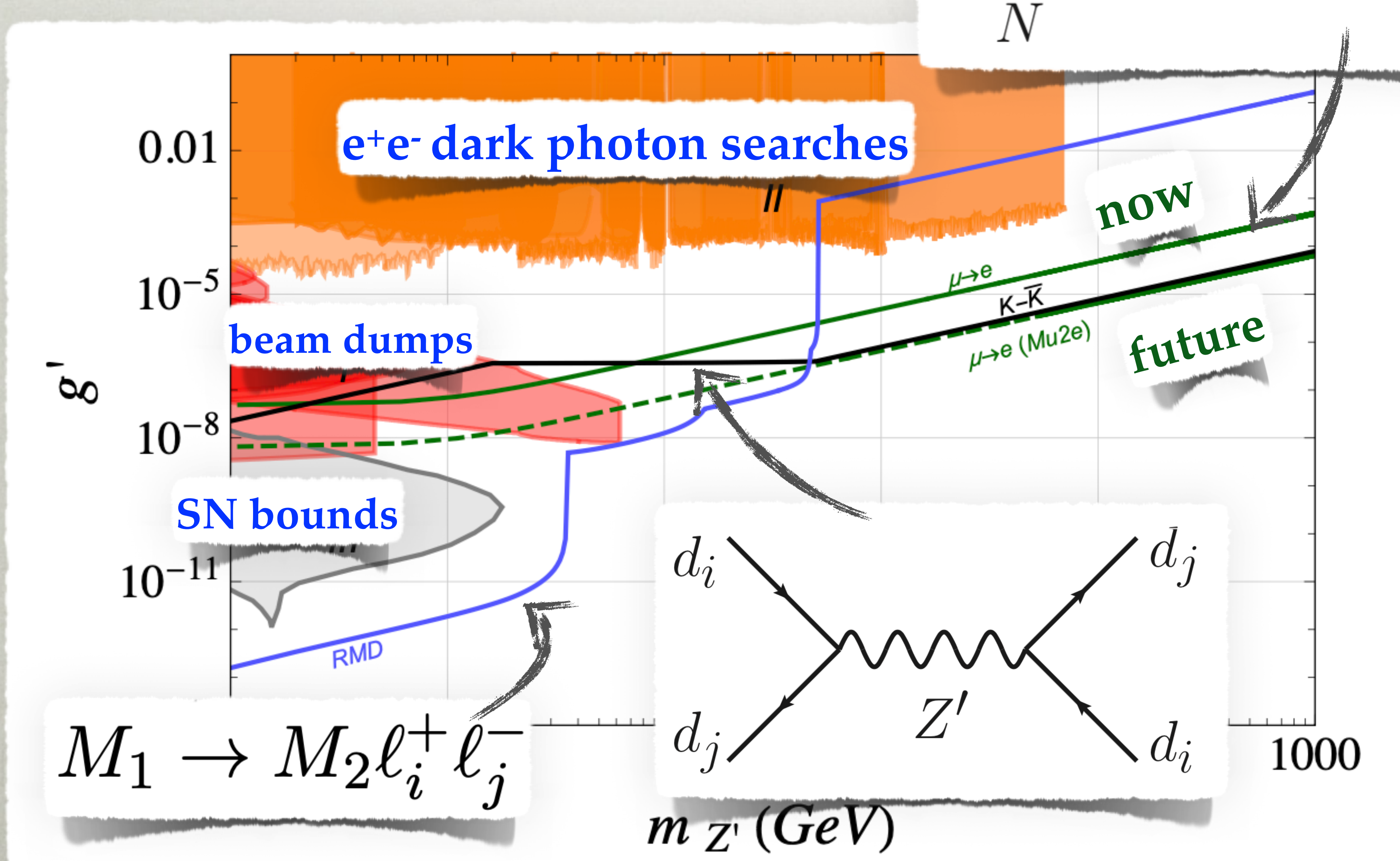
- for $U(1)_{FN}$ benchmark, assuming anarching neutrino mass from Weinber op.



FLAVORFUL Z'

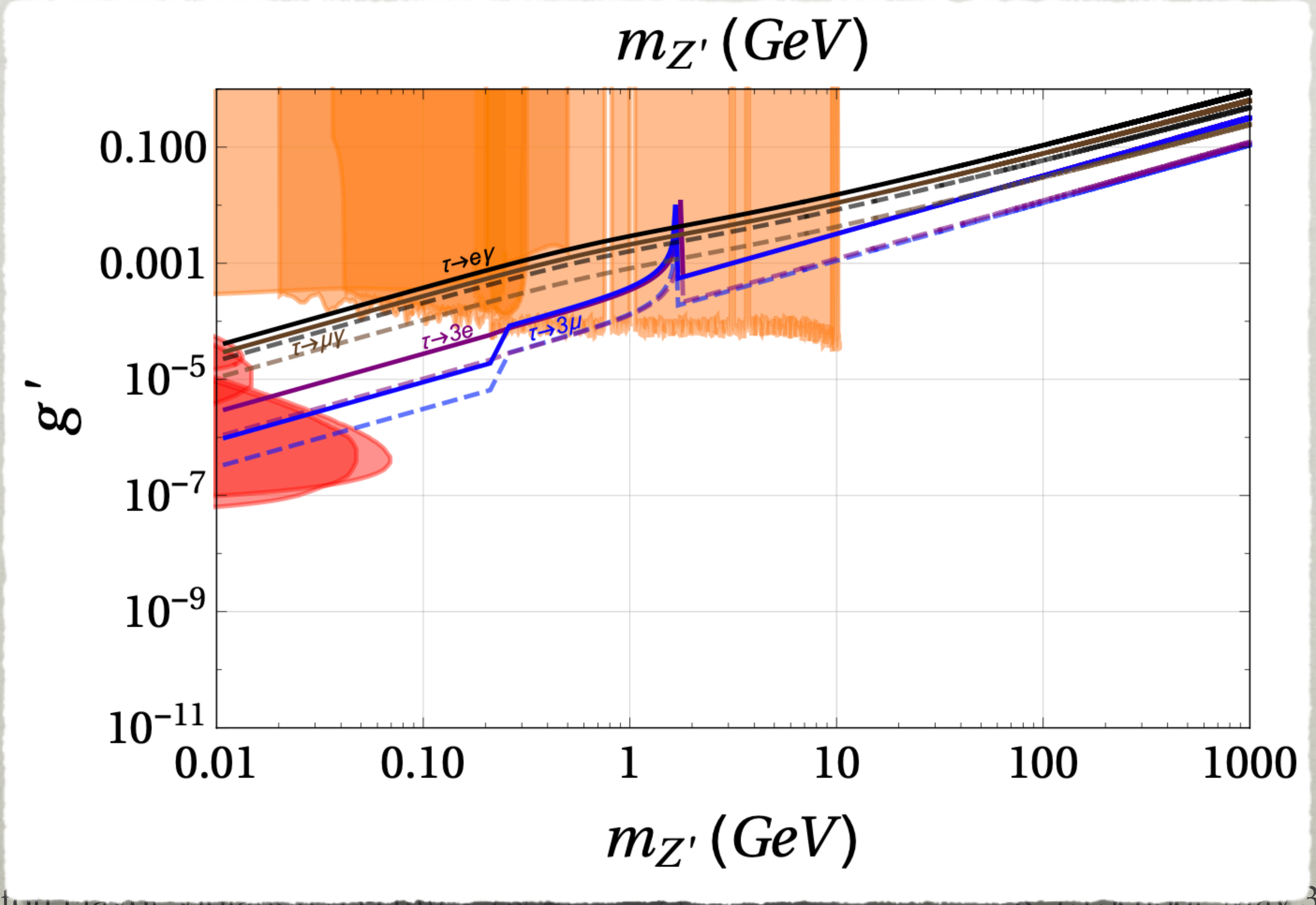
- for $U(1)_{FN}$ benchmark, a
  anarching neutrino mass





TAU DECAYS

- in this model tau decays less sensitive as discovery tool
- but essential to be measured in order to confirm the model

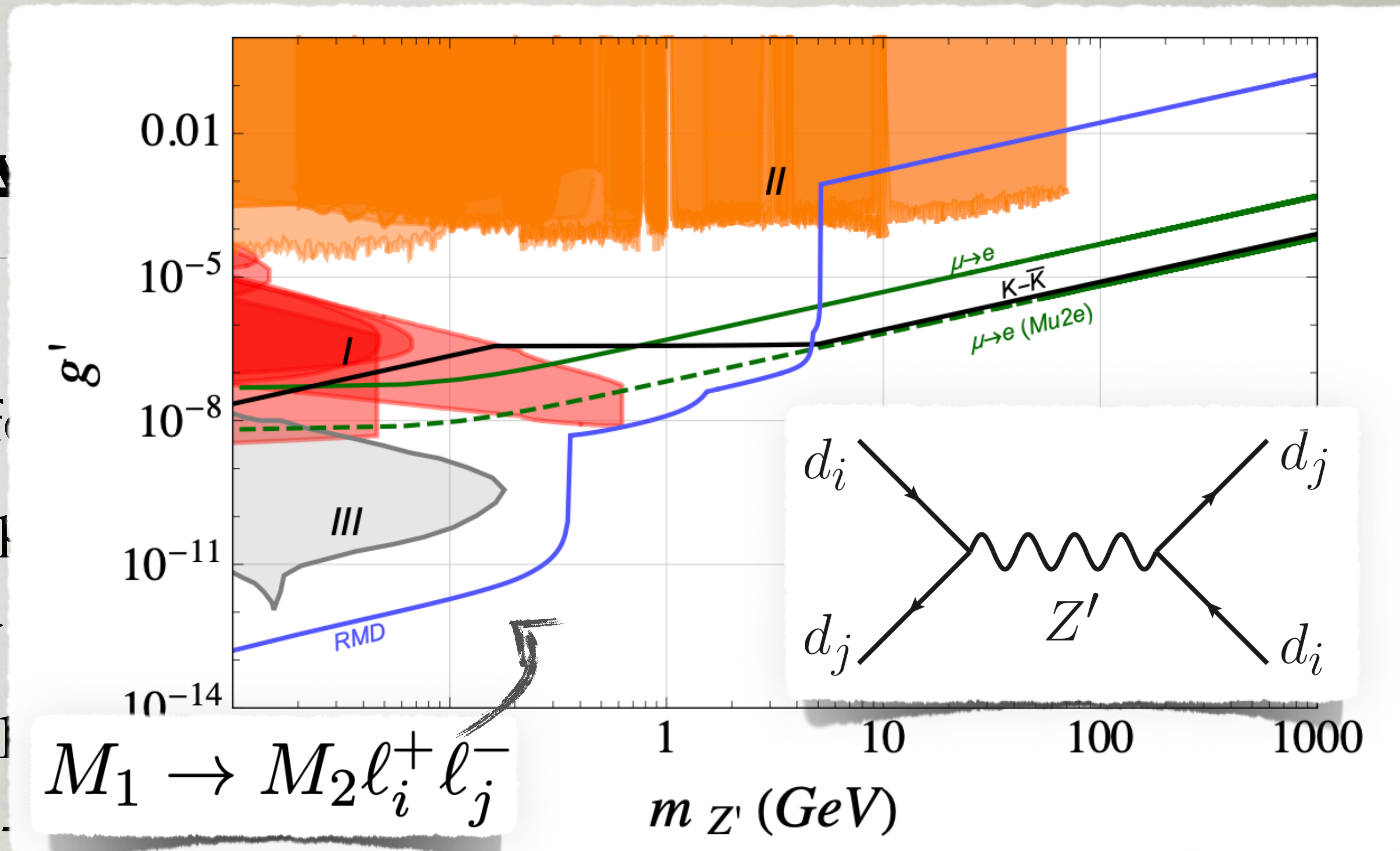


LFV in
B, D, K decaus

RARE MESON DECAYS

- so far a focus on LFV transitions with μ, τ in the initial state
- another possibility, use meson decays
    - $K^+ \to \pi^+ \mu^+ e^-,\ B^+ \to K^+ \mu^+ e^-, ...$
- an example already shown is Z' in $U(1)_{\rm FN}$
    - if tree-level mediator off-shell⇒ meson mixing or LFV FCNCs more constrained
    - for on-shell Z' on the other hand $M_i \to M_j Z'$ gives the leading constraints
    - note: Z' may decay through flavor conserving mode, so searches such as $B \to K \mu^+ \mu^-$ also relevant

RA



- so far a f
- another
  - $K^+ \to$
- an examp
  - if tree-
    FCNCs more constrained
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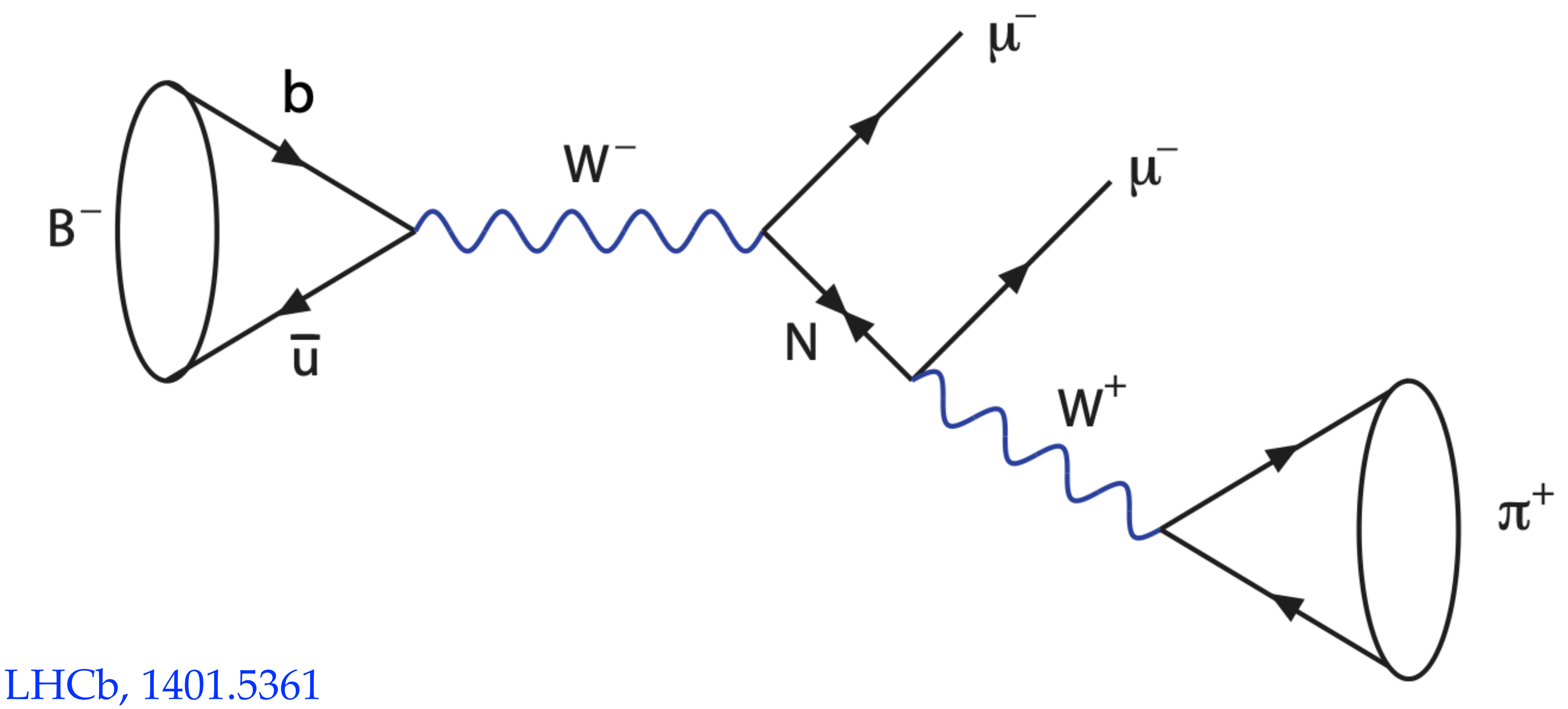
  - note: Z' may decay through flavor conserving mode, so searches such as $B \to K\mu^+\mu^-$ also relevant

MAJORANA NEUTRINOS

- if neutrinos Majorana fermions then lepton number violating decays possible
- leptons can be of same flavor, $B^- \to \pi^+\mu^-\mu^-$, or different flavor, $B^- \to \pi^+\mu^-e^-$,$B^- \to \pi^+\mu^-\tau^-$, ...



LHCb, 1401.5361

SEARCHING FOR LIGHT NEW PHYSICS

LIGHT NEW PHYSICS ⇒ PROBE OF HIGH SCALES

- rare decays into a light state, X, e.g., K → πX or μ → eX,
  - exquisite probes of UV physics
- parametric gains compared to probing NP through dim-6 ops
  - the reason is that the SM decay widths are power suppressed $\Gamma_\ell \propto m_\ell^5/m_W^4$
- if light NP couples through dim 4 op with mixing angle $\theta \Rightarrow$ $\Gamma(K \to \pi\varphi) \propto \theta^2 m_K \Rightarrow Br(K \to \pi\varphi) \propto \theta^2 (m_W/m_K)^4$
- if through dim 5 op. suppressed by $1/f_a \Rightarrow$ $Br(\mu \to e\varphi) \propto (m_W^2/f_a m_\mu)^2$
- no such $1/m_\mu$ or $1/m_K$ enhancement for dimension 6 couplings $Br(\mu \to 3e) \propto (m_W/\Lambda)^4$

UPSHOT

- searching for $\mu \to eX$, $\tau \to \mu X$ decays expect to reach very high UV scales
- are such light NP particles common?
  - any spontaneously broken global symmetry results in massless Nambu-Goldstone bosons
- often (but not always) the mass of PNGBs is taken as a free parameter
  - proportional to explicit breaking of global symmetry

QCD axion

- a celebrated example: QCD axion

STRONG CP PROBLEM

- Lorentz and gauge invariance allow a CP violating term in QCD

$$\mathcal{L} = \theta \frac{\alpha_s}{8\pi} G_a^{\mu\nu} \tilde{G}_{a,\mu\nu} = \theta \frac{\alpha_s}{16\pi} \epsilon_{\mu\nu\rho\sigma} G_a^{\mu\nu} G_a^{\rho\sigma}$$

  - physically observable is the combination

$$\bar{\theta} \equiv \theta + \arg\det(\mathcal{M}_u \mathcal{M}_d)$$

- experimentally :

$$d_n \approx 4 \times 10^{-16} \bar{\theta}\, e\,\text{cm} \quad \longleftrightarrow \quad |d_n|_{\text{exp}} < 3 \times 10^{-26}\, e\,\text{cm}$$

- why $\bar{\theta}$ so small?

$$\bar{\theta} < 10^{-10}$$

  - very puzzling given large CPV phase in the CKM

Peccei, Quinn, PRL 38, 1440 (1977)
Weinberg, PRL 40, 223, (1978)
Wilczek, PRL 46, 279 (1978)
Vafa, Witten, PRL 53, 535 (1984)

AXION

- if $\bar{\theta}(x)$ a dynamical field and couples only to $\bar{\theta}G\tilde{G}$
  $\Rightarrow$ potential min. at $\bar{\theta}(x) = 0$

$$F^{V,A}_{f_i f_j} \equiv \frac{2f_a}{c^{V,A}_{f_i f_j}}$$

  - new ultra-light particle - axion

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a}G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a}F\tilde{F} + \frac{\partial_\mu a}{2f_a}\,\bar{f}_i\gamma^\mu(C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5)f_j$$

  - obtains mass from QCD anomaly

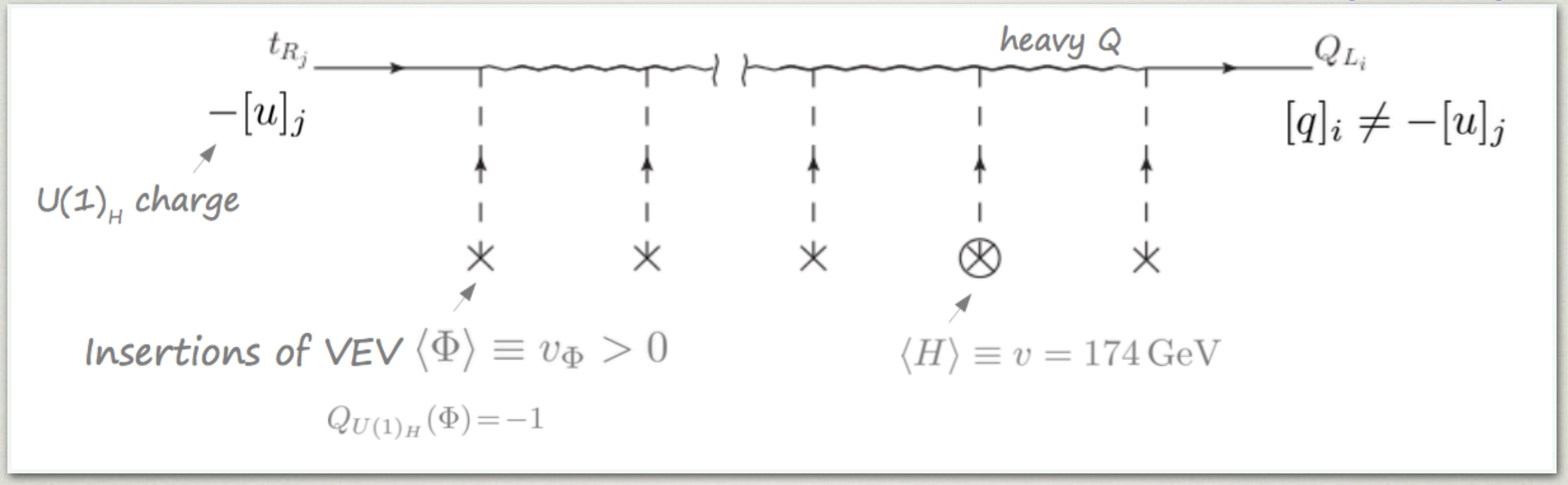
$$m_a = 5.70(7)\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

  - viable cold dark matter candidate for

$$10^{-8}\,\text{eV} \lesssim m_a \lesssim 10^{-3}\,\text{eV}$$

EXPLICIT MODEL - AXIFLAVON

Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040



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  - vector-like fermions (no QCD anomaly)
  - scalar flavon fields
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$$\mathcal{L}_{eff} \sim \left(\frac{\phi}{\Lambda_F}\right)^{x_{ij}} h\,\bar{q}_i u_j$$

$$\epsilon \equiv \frac{\phi}{\Lambda_F}$$

  - hierarchy from powers of small parameter ε

AXIFLAVON

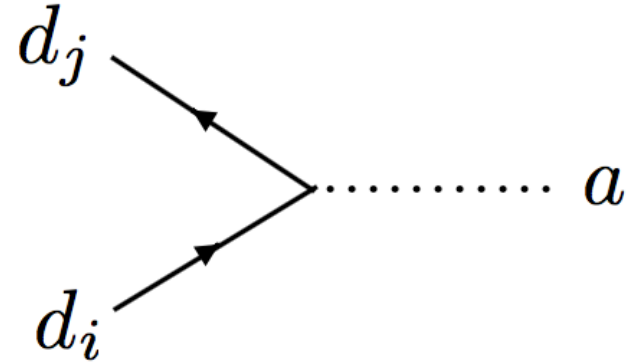
- ingredients for axion mechanism
  - need a global PQ symmetry that is spontaneously broken $\Rightarrow$ Goldstone boson is the axion
  - global symmetry needs to be anomalous under QCD
- flavor symmetries that explain Yukawa hierarchies have a QCD anomaly
- axiflavon mechanism: identify PQ symmetry with FN $U(1)_H$
  - the phase of the flavon is the QCD axion = axiflavon

$$\Phi = \frac{f + \phi(x)}{\sqrt{2}} e^{ia(x)/f}$$

Wilczek, PRL 49, 1549 (1982)
Calibbi, Goertz, Redigolo, Ziegler, JZ, 1612.08040
Ema, Hamaguchi, Moroi, Nakayama, 1612.05492

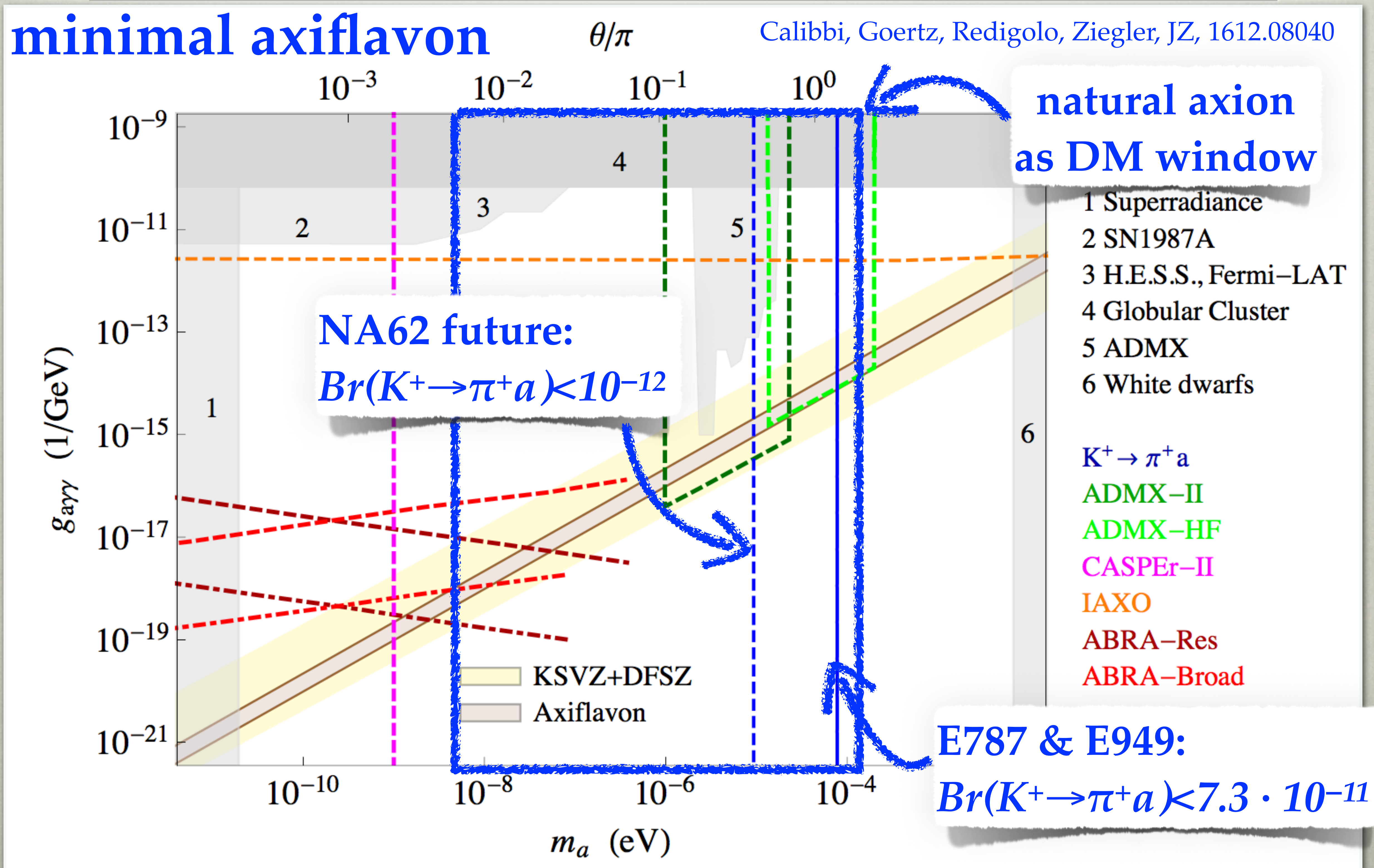
SEARCHING FOR AXIONS/ AXIFLAVONS

- axiflavon
    - flavor violating couplings to fermions
    - in addition to flavor diagonal couplings to electrons, nucleons, couplings to photons, gluons
    - in the minimal FN axiflavon model



$$\sim \frac{\sqrt{m_i m_j}}{f_a} \sim \frac{m_a}{\mu\text{eV}} \frac{\sqrt{m_i m_j}}{10^{12}\text{GeV}}$$

SEARCHING FOR AXIONS/ AXIFLAVONS



LEPTOPHILIC ALPs

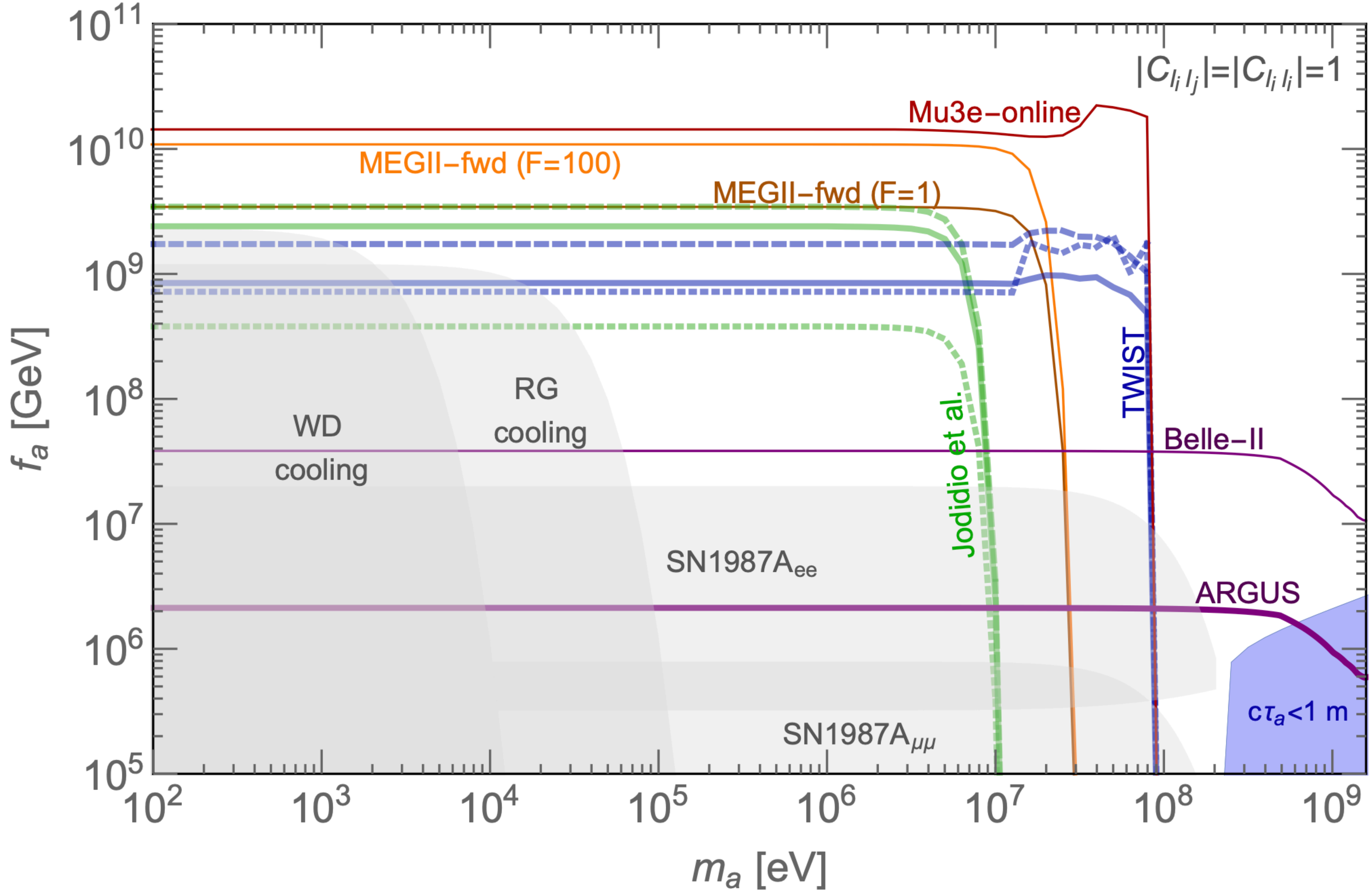
- in the minimal model
  - $K \to \pi a$ the most sensitive
  - mass of a is fixed from QCD dynamics
- both of these results are model dependent
  - focus on examples where LFV is the most important
- here bottom up approach
  - allow for any a mass (Axion-Like Particle =ALP)
  - use the effective Lagrangian

$$\mathcal{L}_{\rm eff} = \frac{\alpha_s}{8\pi}\frac{a}{f_a} G\tilde{G} + \frac{E}{N}\frac{\alpha_{\rm em}}{8\pi}\frac{a}{f_a} F\tilde{F} + \frac{\partial_\mu a}{2 f_a}\,\bar{f}_i \gamma^\mu (C^V_{f_i f_j} + C^A_{f_i f_j}\gamma_5) f_j$$

  - switch on all ALP couplings to leptons

Calibbi, Redigolo, Ziegler, JZ, 2006.04795

BOUNDS ON LEPTOPHILIC ALP

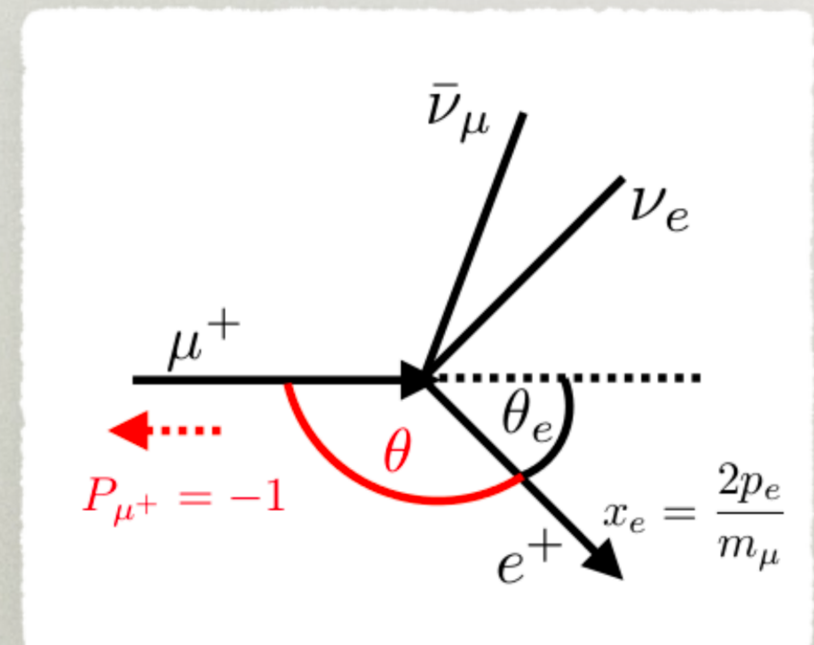


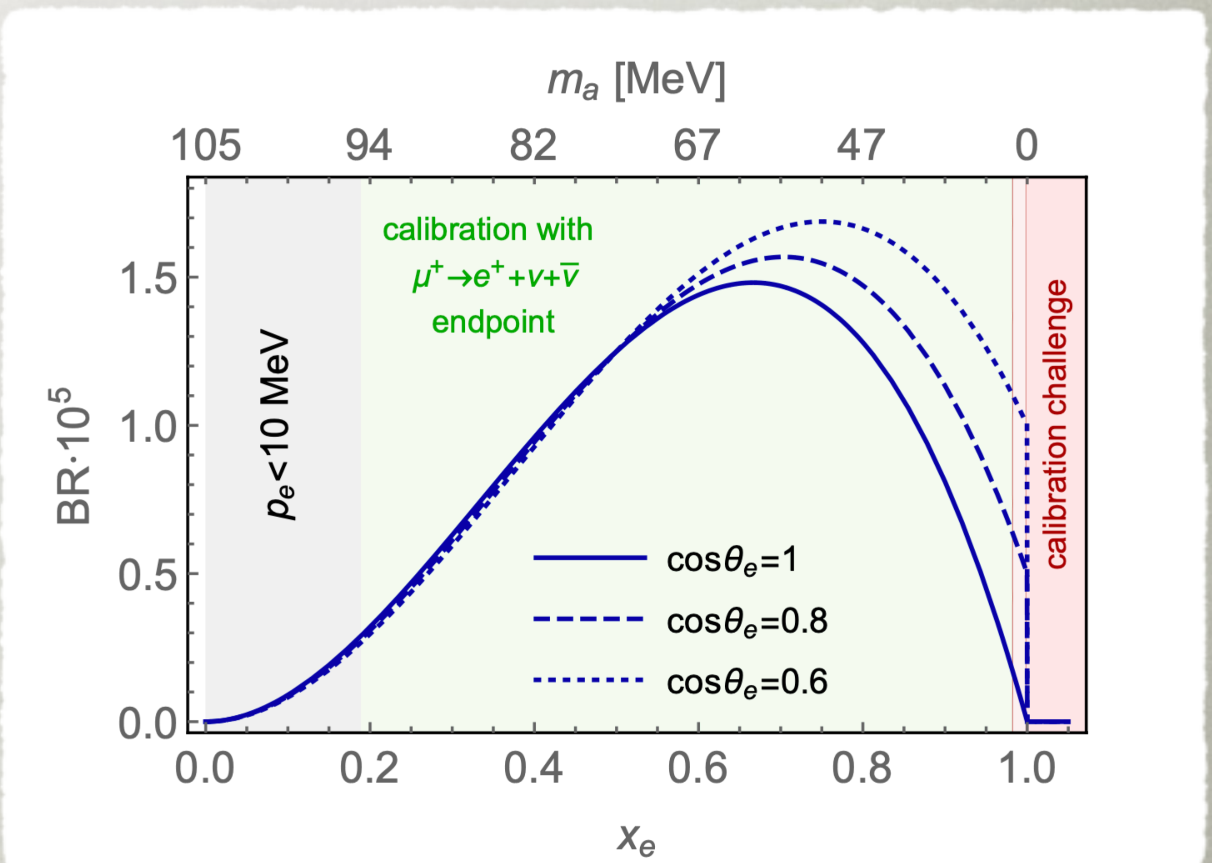
$\mu^+ \to e^+ a$ SEARCHES

- two types of searches for $\mu^+ \to e^+ a$ positron line
- suppress the SM bckg., $\mu \to e\nu\bar{\nu}$

Jodidio et al. 1986

  - use polarized muons $\langle P_\mu \rangle \simeq -1$, in the forward region SM suppressed
  - sensitive only to RH ALP





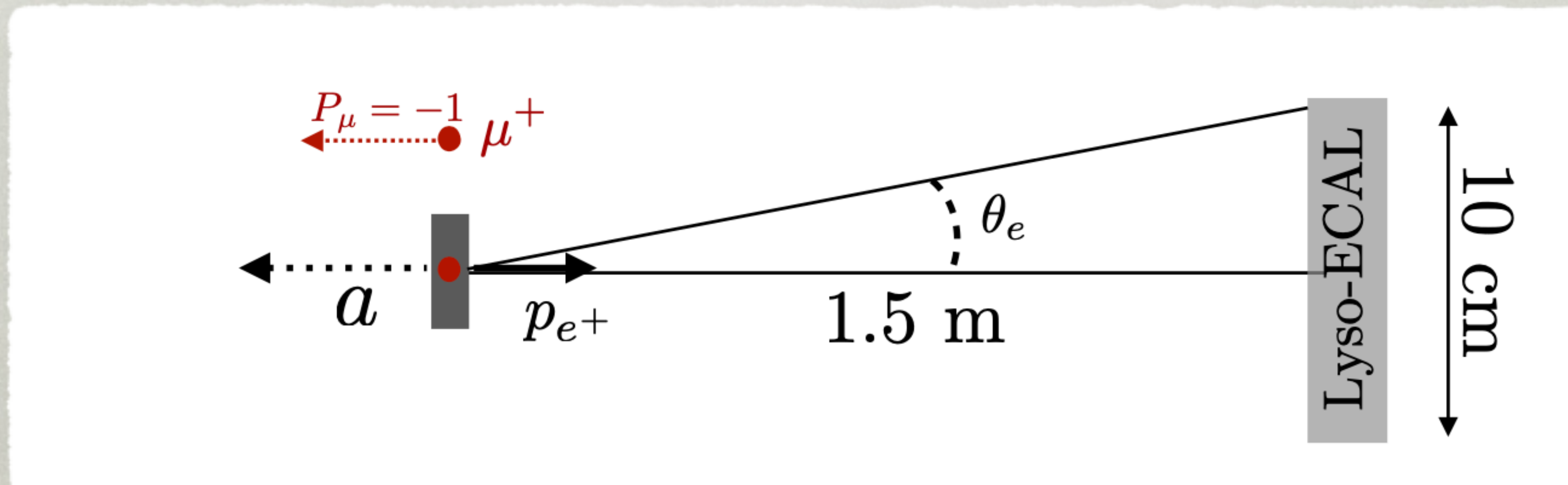
- do not suppress the SM, also sensitive to LH ALP, TWIST

TWIST, 2015

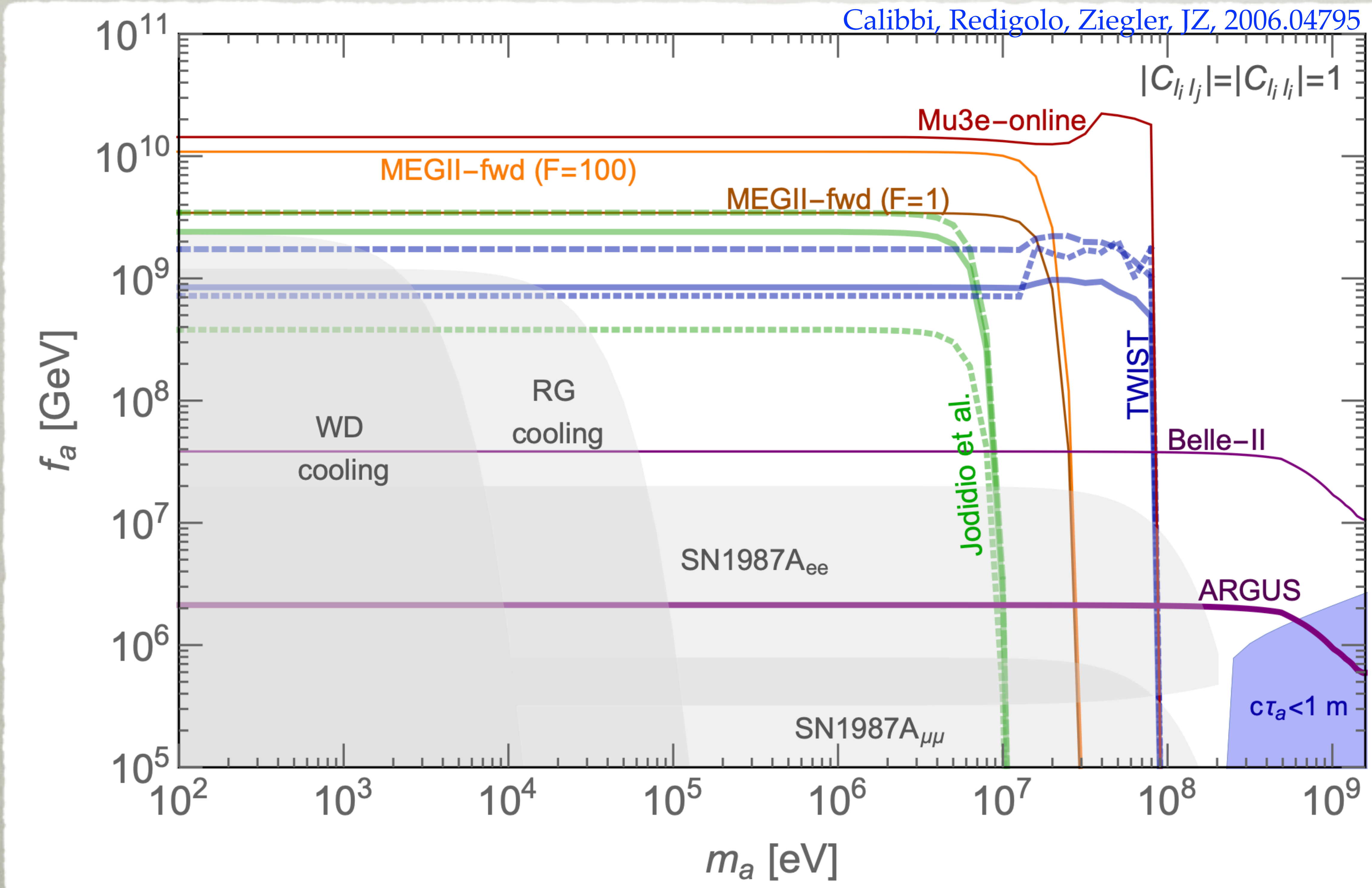
Calibbi, Redigolo, Ziegler, JZ, 2006.04795

MEGII-fwd

- MEGII could be repurposed for $\mu^+ \to e^+ a$ search $\Rightarrow$ MEGII-fwd
  - already has polarized muons
  - place a Lyso ECAL downstream



- two projections were shown for 2 weeks of running
  - no focusing, F=1, or gain from focusing, F=100

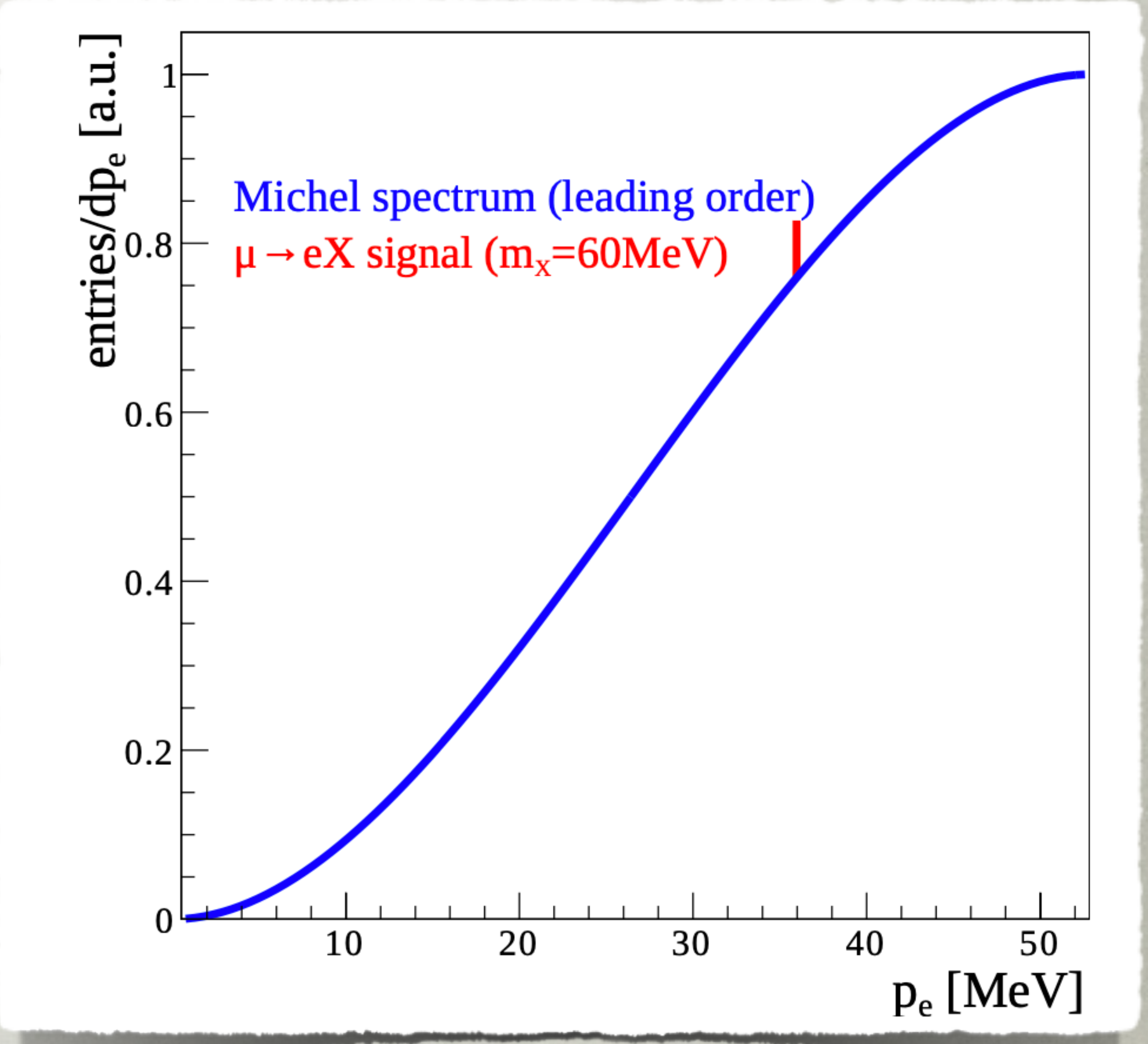


Calibbi, Redigolo, Ziegler, JZ, 2006.04795
$|C_{l_i l_j}|=|C_{l_i l_i}|=1$
Mu3e−online
MEGII−fwd (F=100)
MEGII−fwd (F=1)
Jodidio et al.
TWIST
Belle−II
ARGUS
WD cooling
RG cooling
$SN1987A_{ee}$
$SN1987A_{\mu\mu}$
$c\tau_a$<1 m
f_a [GeV]
m_a [eV]

Mu3e-online

A.-K. Perrevoort , PhD thesis

- Mu3e-online: a dedicated search strategy at Mu3e
- online event reconstruction with "short tracks"
- bump hunt on Michel spectrum
  - sensitive to both LH and RH ALPs



ALPs in tau decays

- for $\tau \to \ell a$ the challenge is the extra missing energy
  - $e^+e^- \to \tau^+(\to \ell^+ a)\tau^-(\to \rho^- \nu_\tau)$
- can only boost to pseudo-rest frame of tau
- current bound from ARGUS 1995

$$\mathrm{BR}(\tau \to \mu\, a) < 4.5 \times 10^{-3} \quad (95\%\ \text{C.L.}) \quad \Rightarrow \quad F_{\tau\mu} \gtrsim 3.3 \times 10^{6}\ \text{GeV}\,.$$

ARGUS, 1995

$$\text{Belle (1/ab) prospect:} \quad \mathrm{BR}(\tau \to \mu\, a) < 1.1 \times 10^{-4} \quad \Rightarrow \quad F_{\tau\mu} \gtrsim 2.1 \times 10^{7}\ \text{GeV}\,.$$

Belle, 2017

$$\text{Belle-II (50/ab) prospect:} \quad \mathrm{BR}(\tau \to \mu\, a) < 1.4 \times 10^{-5} \quad \Rightarrow \quad F_{\tau\mu} \gtrsim 5.6 \times 10^{7}\ \text{GeV}.$$

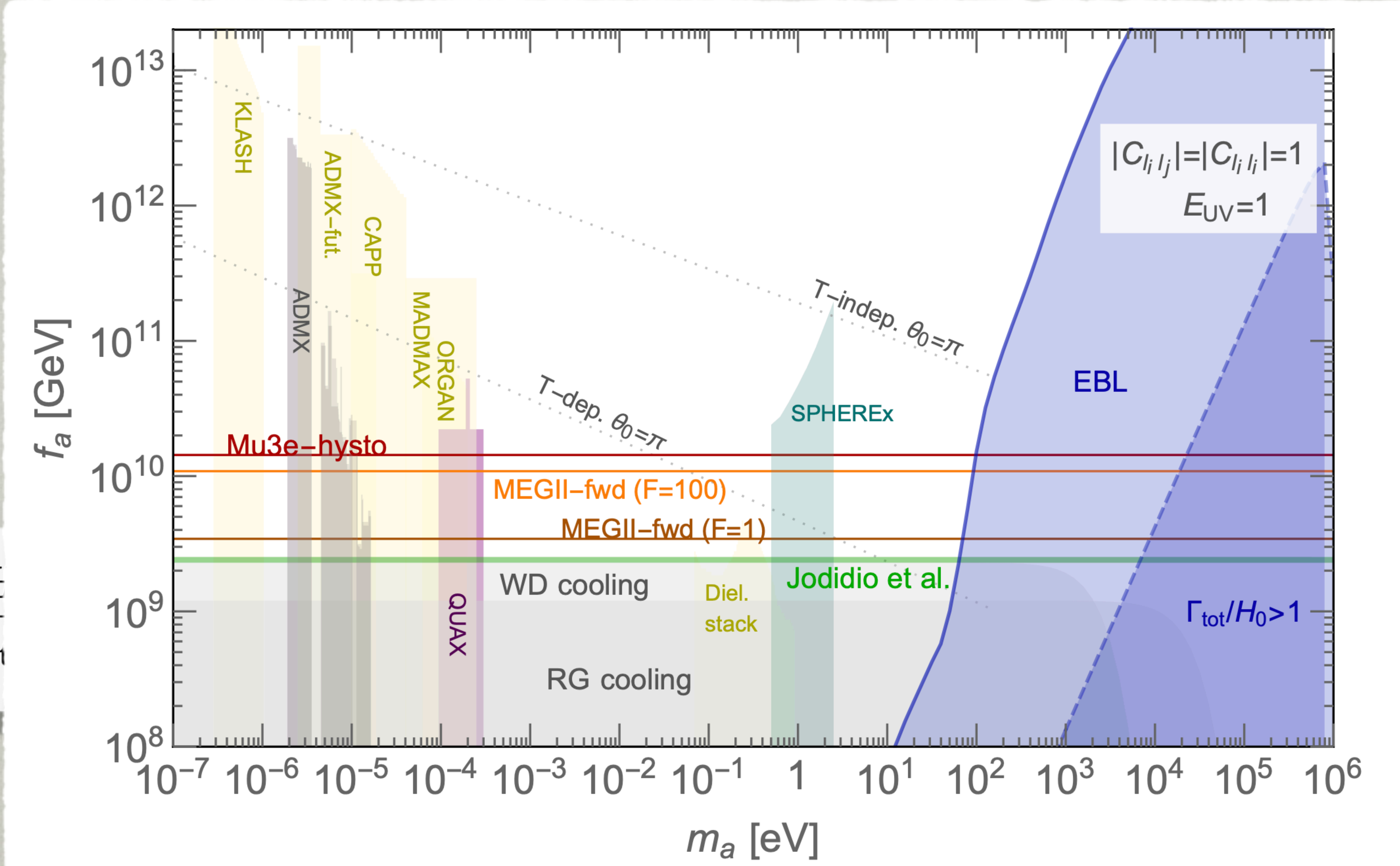
naive rescaling

LFV ALP dark matter

- 0-th order condition for ALP to be a DM: be stable on Hubble time
- assume $a \to \gamma\gamma$ dominates

$$\frac{H_0}{\Gamma_{\rm tot}} = H_0\tau_a > 1, \quad \text{where} \quad H_0\tau_a \simeq 5.4 \left(\frac{1}{E^2_{\rm eff}}\right)^2 \left(\frac{10~\text{keV}}{m_a}\right)^3 \left(\frac{f_a}{10^{10}~\text{GeV}}\right)^2 .$$

- if ALP is observed in a LFV process $\Rightarrow m_a \lesssim 10$ keV
  - LFV experiments most sensitive for some m_a
  - need other experiments to confirm it is DM



- LFV experiments most sensitive for some m_a
- need other experiments to confirm it is DM

LFV axiflavon

Calibbi, Redigolo, Ziegler, JZ, 2006.04795
see also, Linster, Ziegler, 1805.07341

- the PQ symmetry is part of $SU(2)_F \times U(1)_F$ flavor group
  - all FV couplings need to go through 3rd generation
  - for leptons 1-2 and 1-3 mixings are larger (in LH sector to reproduce PMNS matrix)
- $\Rightarrow$ unlike minimal axiflavon, $K \to \pi a$ suppr.
  - the observation mode is $\mu \to e a$

06.04795
)5.07341

- the PQ
  flavor
  - all F
    gen
  - for I
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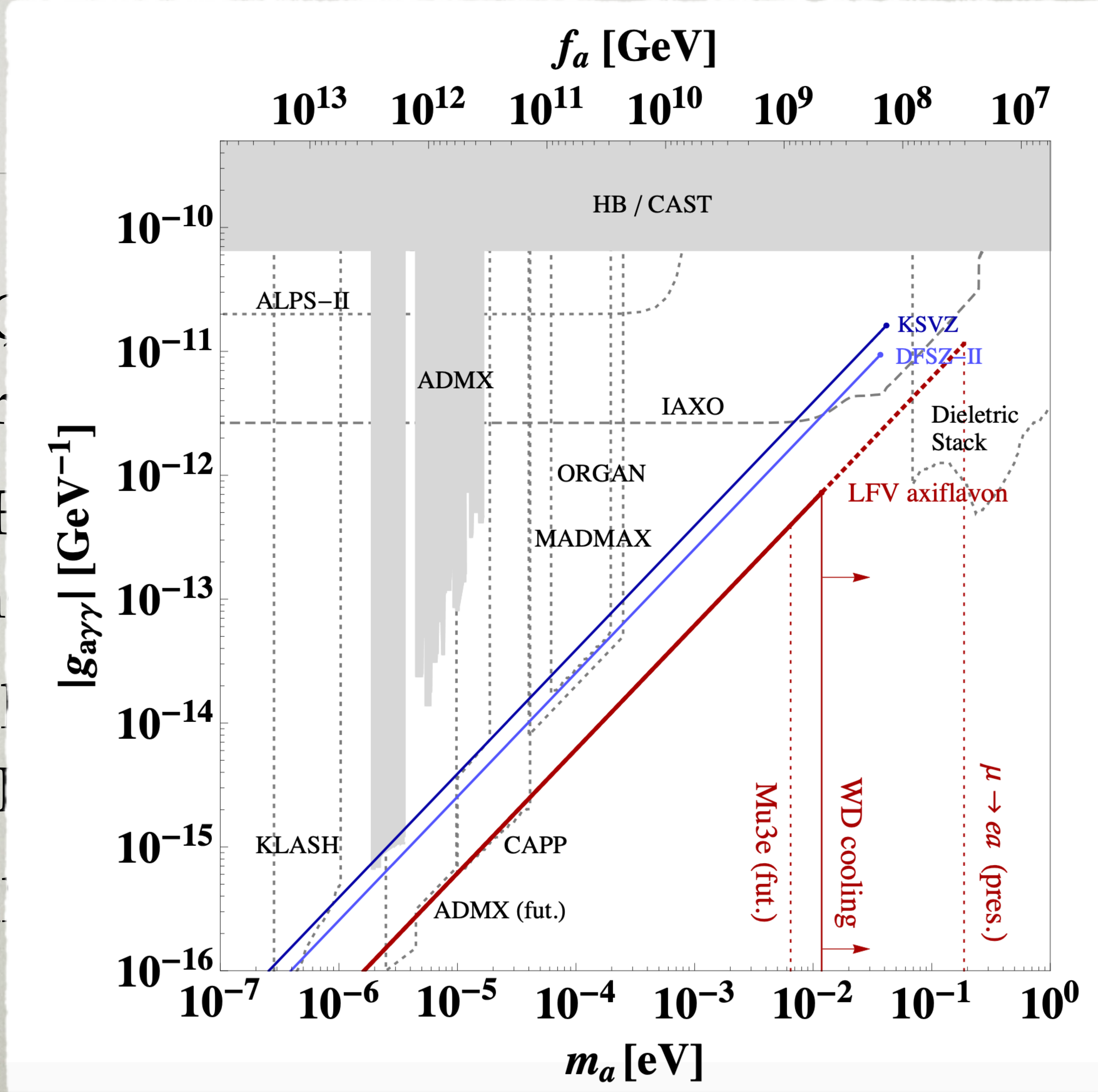
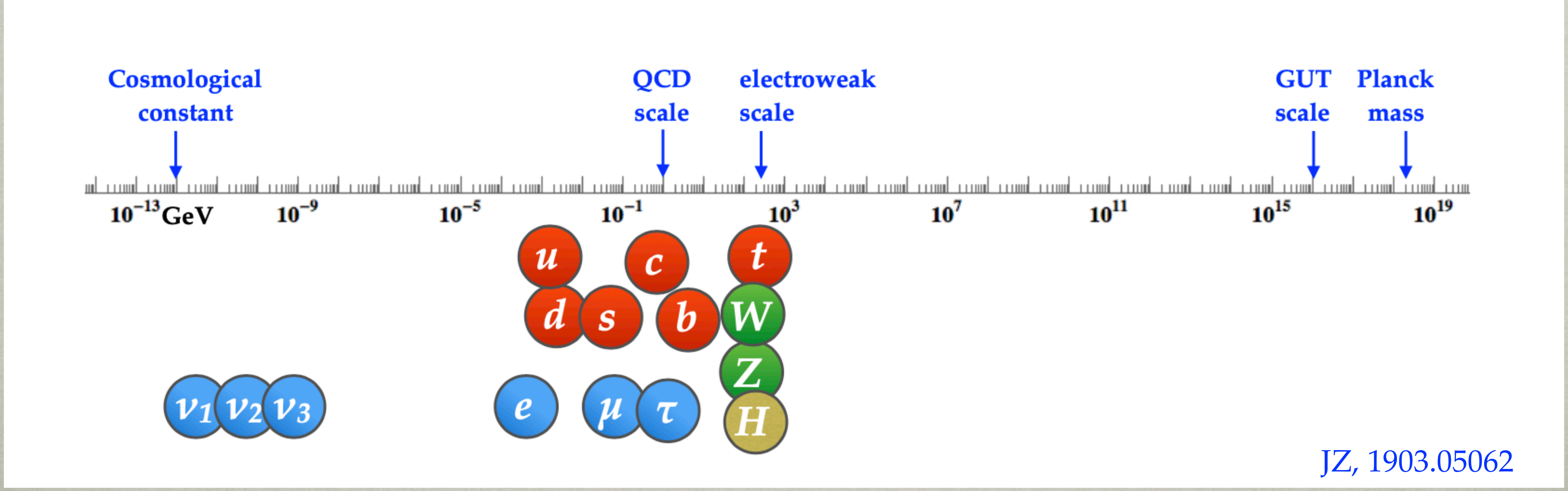
- ⇒ unl
  - the



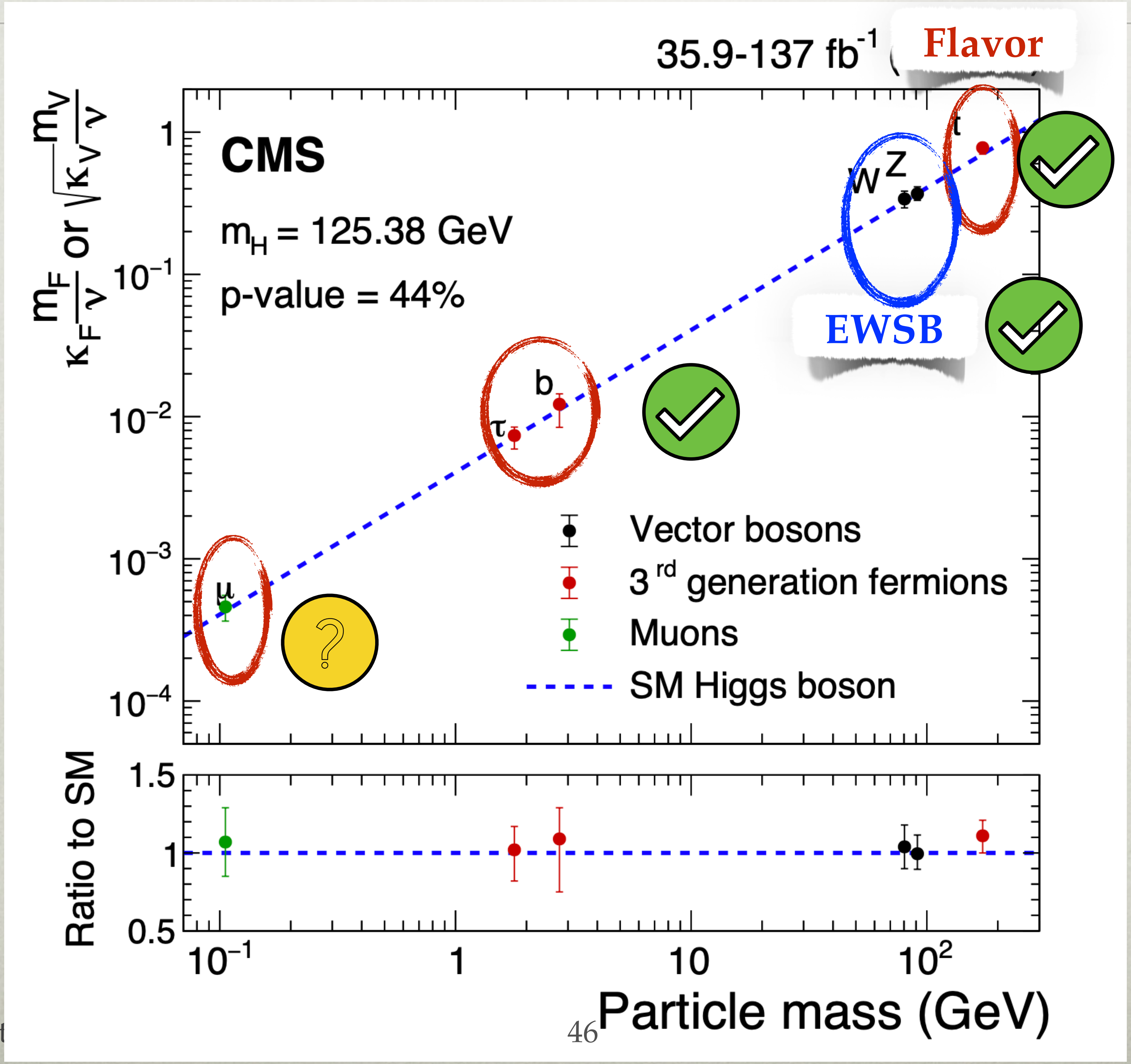
HIGGS AS A PROBE OF FLAVOR

DUAL ROLE

- in the SM Higgs has a dual role
  - breaks electroweak symmetry and gives the masses to W, Z gauge bosons
  - same EWSB source gives the masses to the SM fermions
- how well have we tested this?



DUAL ROLE OF THE HIGGS



see, e.g., Cohen, Craig, Lu, Sutherland, 2008.08597

SMEFT AND HEFT

- no sign of new physics at the LHC
  - assume it is heavy ⇒ integrate out, obtain EFTs
- SMEFT - uses EW symmetric phase, Higgs assumed to be EW doublet

$$\mathcal{L} \supset \lambda_{ij}(\bar{f}^i_L f^j_R)H - \frac{\lambda'_{ij}}{\Lambda^2}(\bar{f}^i_L f^j_R)H(H^\dagger H) + \cdots$$

- HEFT - uses EW broken phase
  - κ framework: dim4 HEFT in unitary gauge

$$\mathcal{L} \supset -m_i \bar{f}^i_L f^i_R - Y_{ij}(\bar{f}^i_L f^j_R)h + \cdots$$

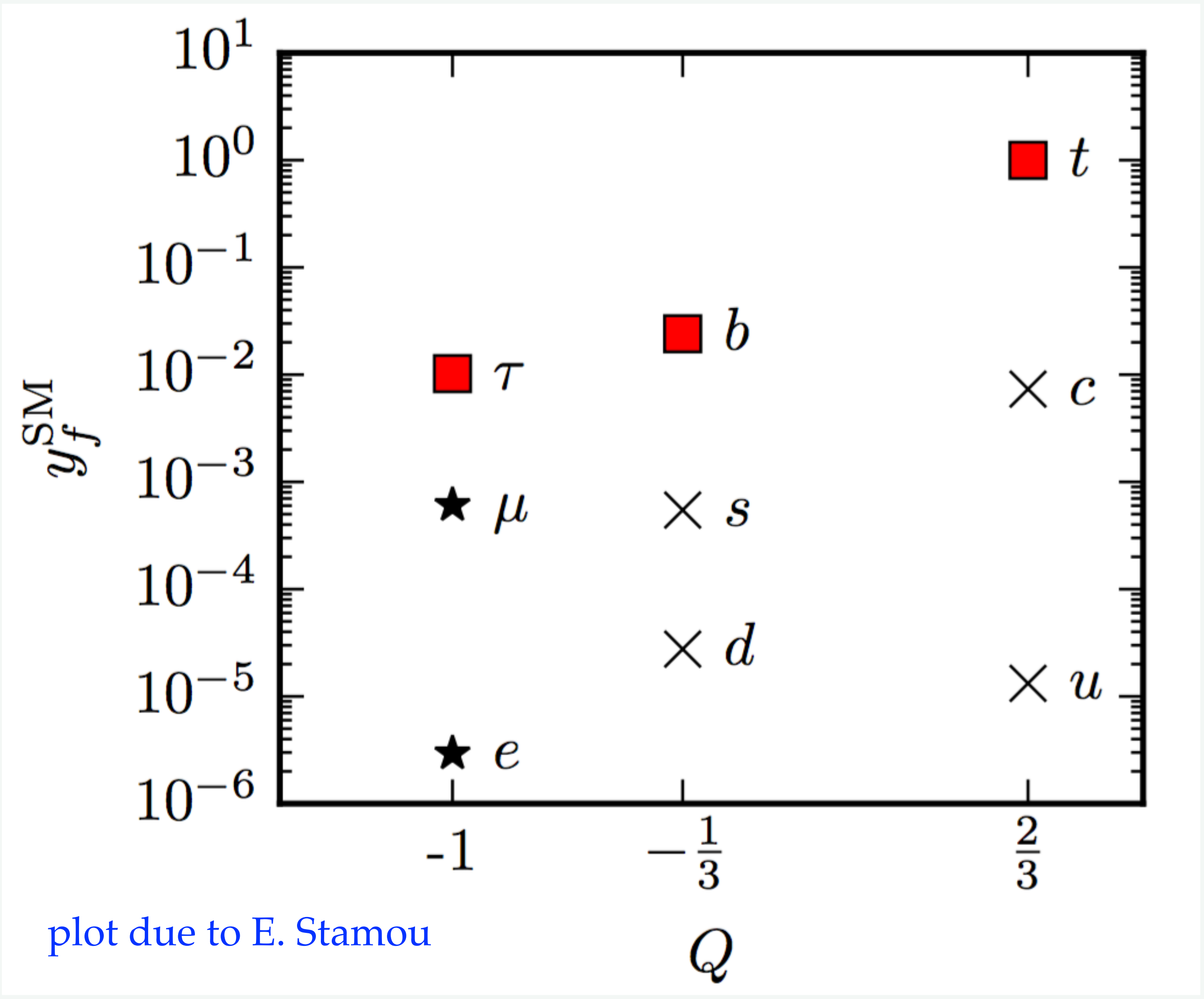
$$\mathcal{L}_{\text{eff,q}} = -\kappa_q \frac{m_q}{v_W}\bar{q}qh - i\tilde{\kappa}_q \frac{m_q}{v_W}\bar{q}\gamma_5 qh - \Big[\big(\kappa_{qq'} + i\tilde{\kappa}_{qq'}\big)\bar{q}_L q'_R h + \text{h.c.}\Big],$$

HIGGS - A PROBE OF FLAVOR

- in the SM all flavor structure due to the Higgs Yukawa couplings

$$y_f = \sqrt{2} m_f / v$$

- implies Higgs has very hierarchical couplings to fermions
- clear experimental prediction

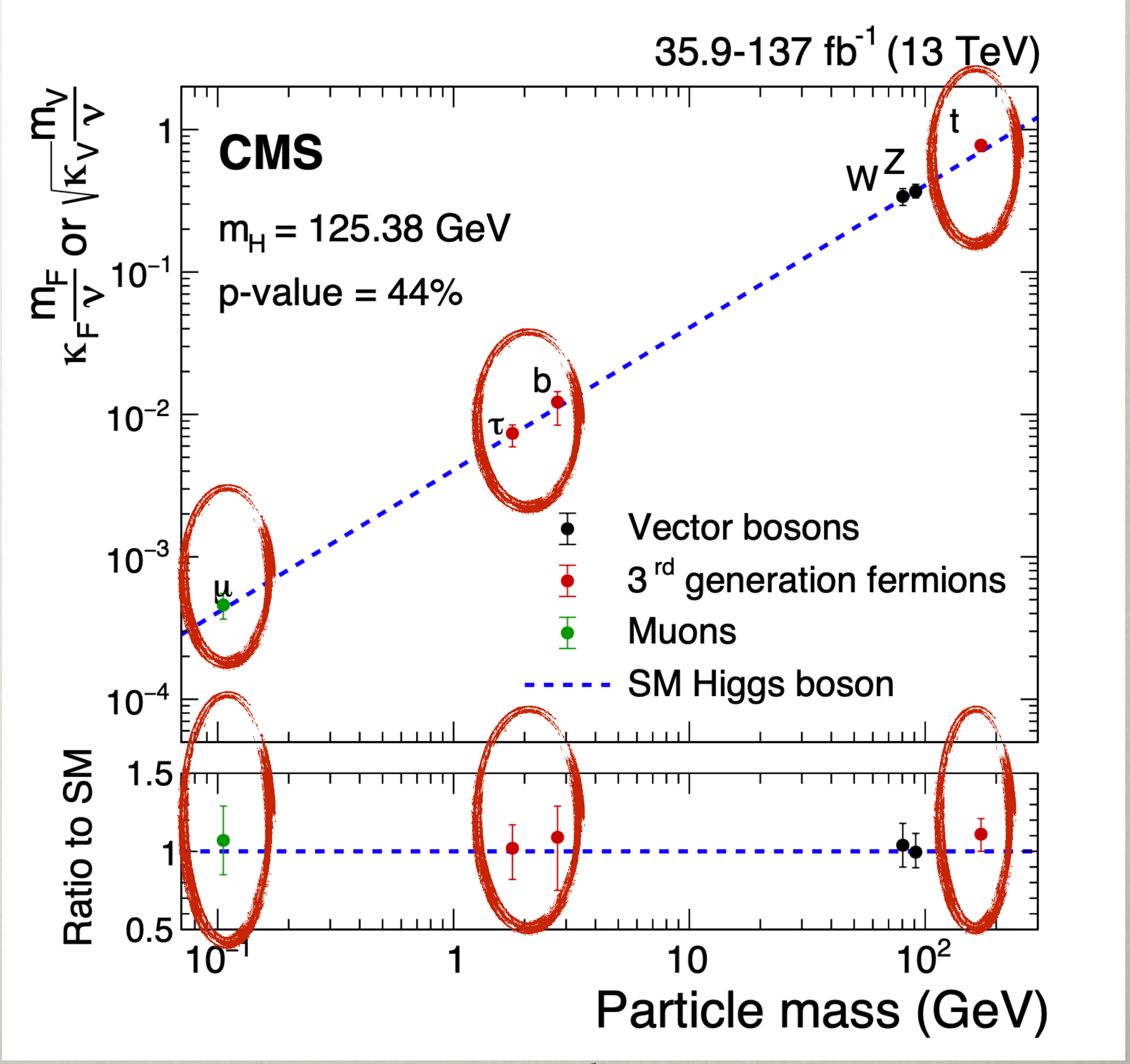


TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433; JZ, 1903.05062

- several questions
  - proportionality
    $$y_{ii} \propto m_i$$
  - factor of proportionality
    $$y_{ii}/m_i = \sqrt{2}/v$$
  - diagonality (flavor violation)
    $$y_{ij} = 0, \quad i \neq j$$
  - reality (CP violation)
    $$\mathrm{Im}(y_{ij}) = 0$$

$$y_f^{\mathrm{SM}} = \sqrt{2} m_f / v$$

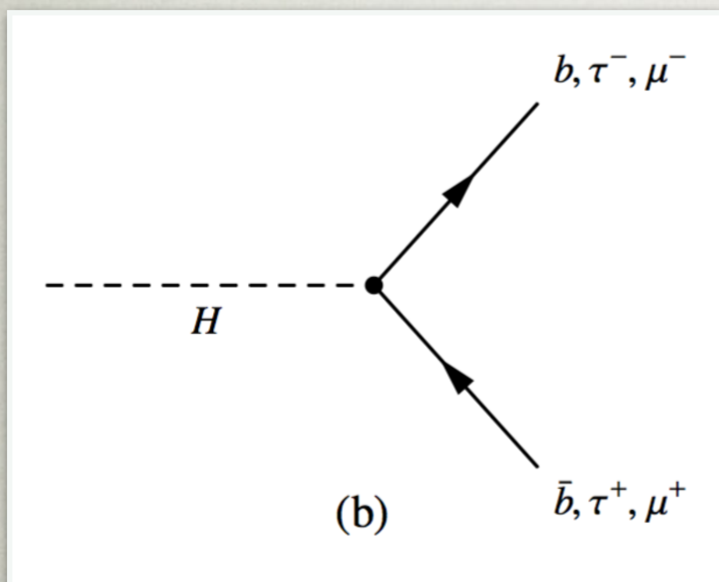


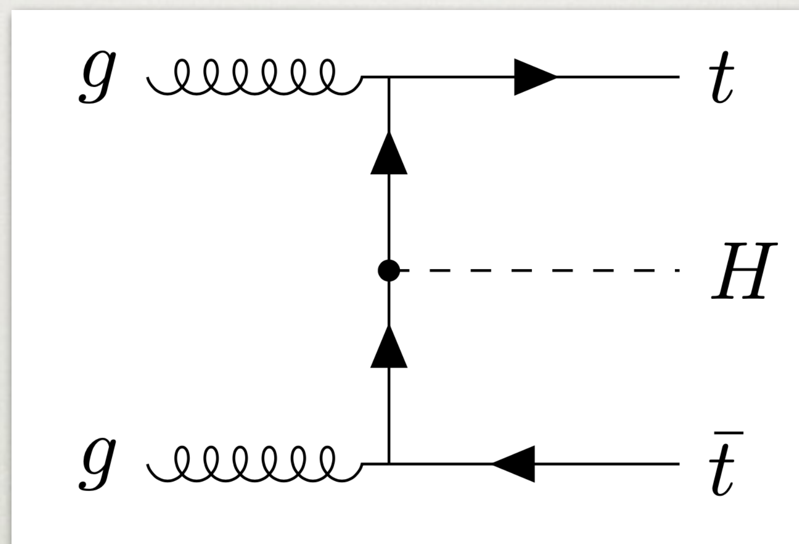
PROPORTIONALITY

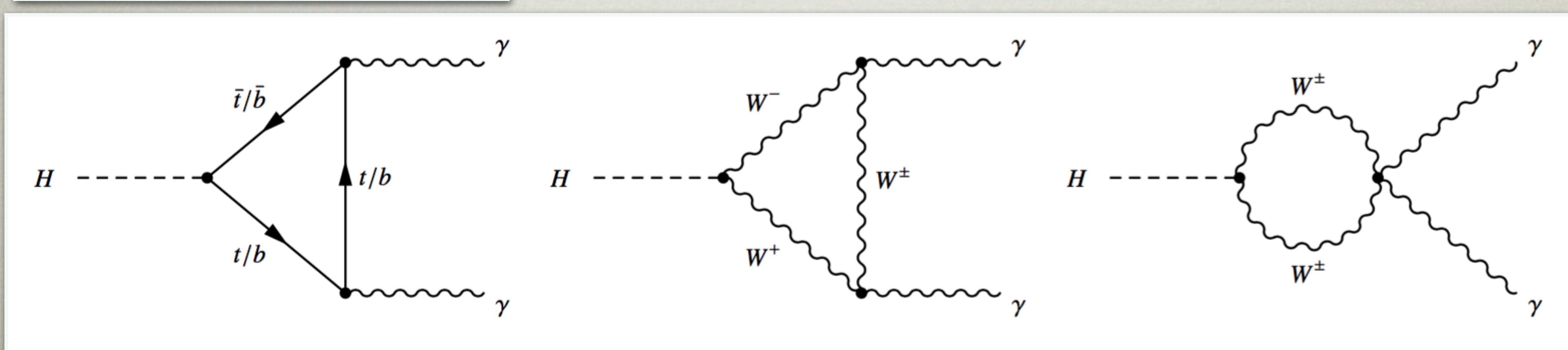
- "proportionality" and "factor of proportionality"

$$y_{ii} \propto m_i \qquad\qquad y_{ii}/m_i = \sqrt{2}/v$$

- reasonably well tested for 3rd generation fermions





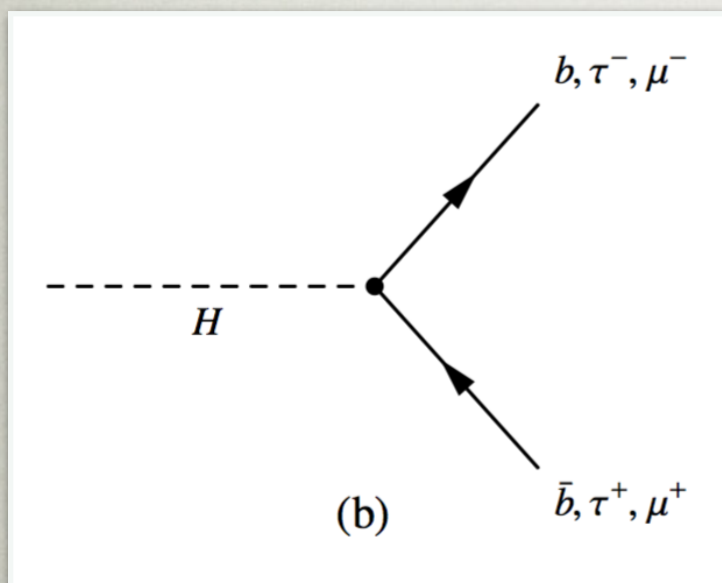


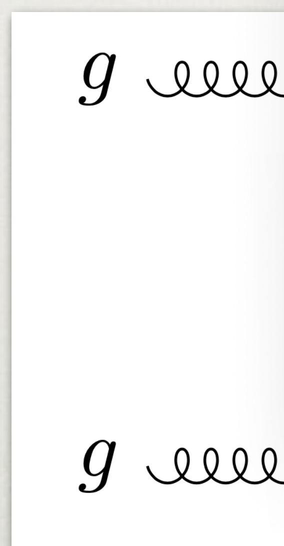
PROPOR

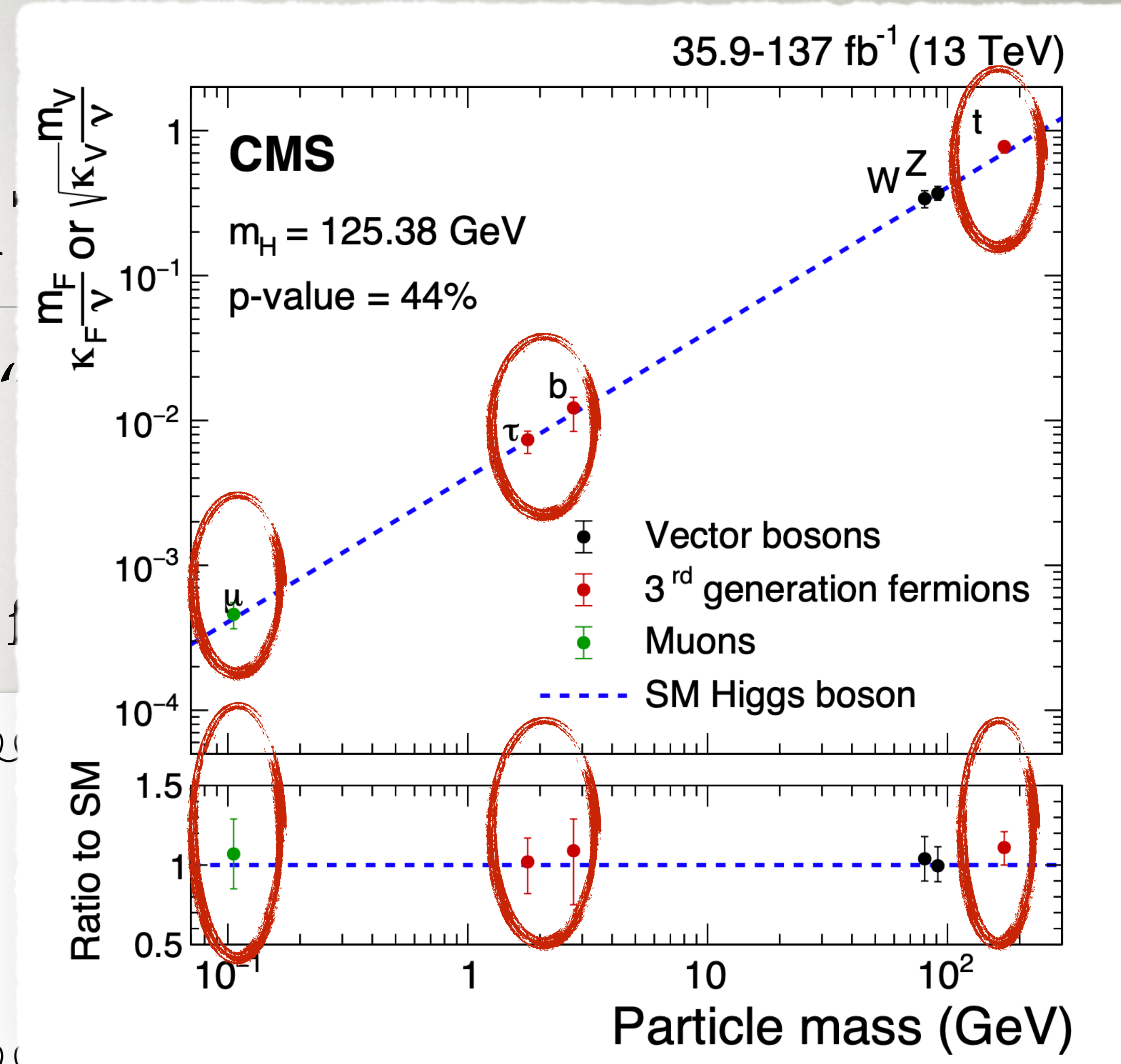
- “proportionality” and “

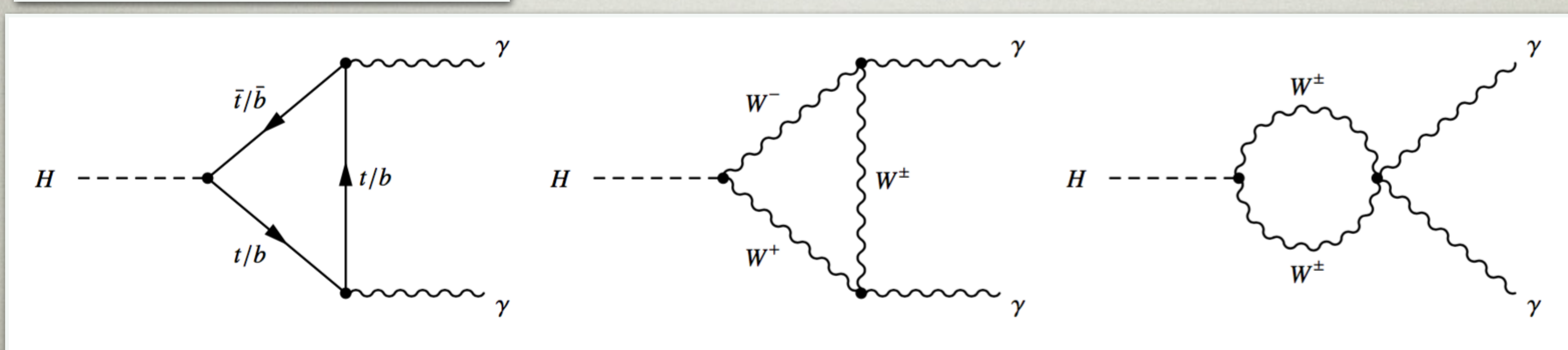
$$y_{ii} \propto m_i$$

- reasonably well tested f

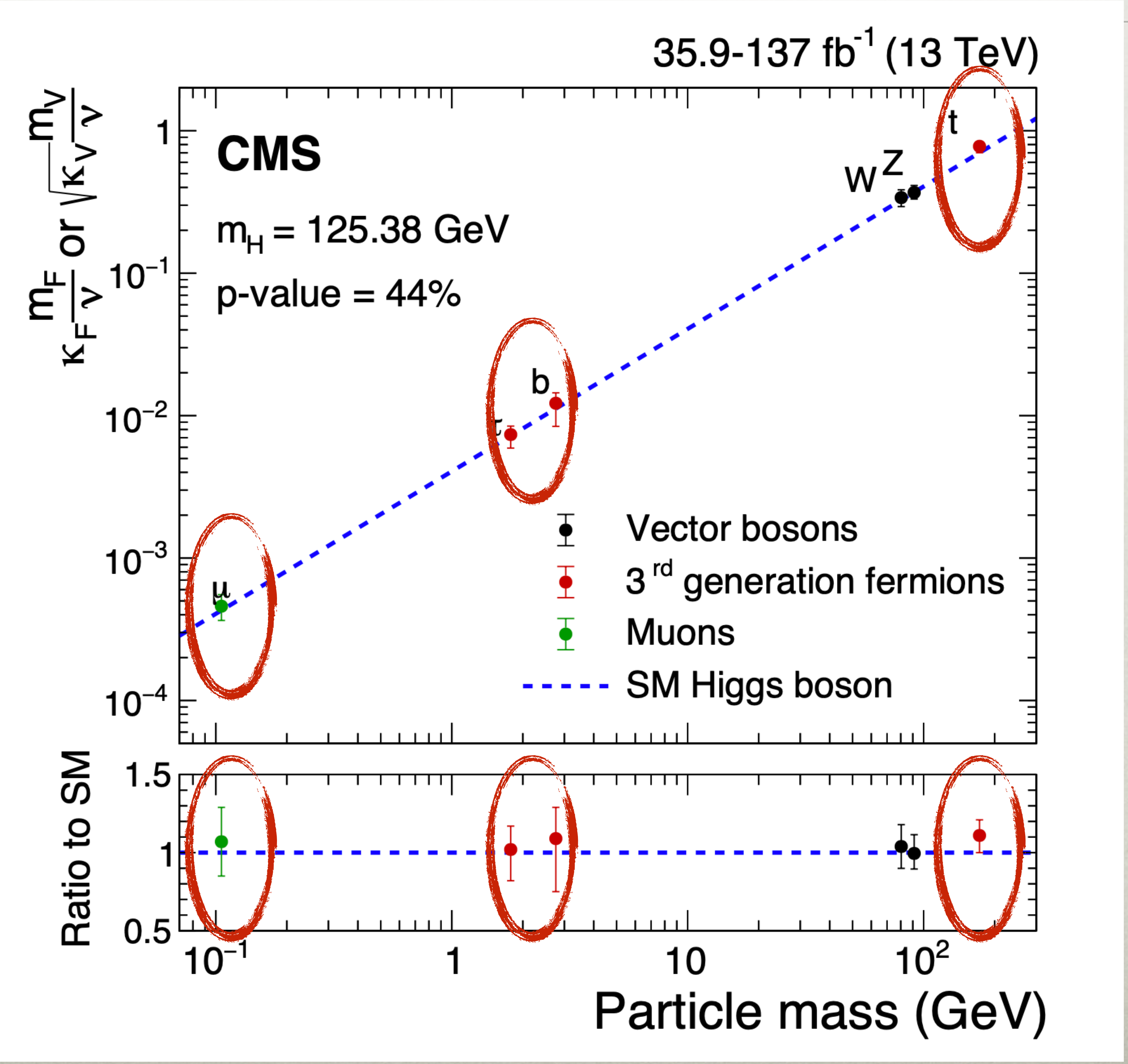








TESTING FLAVOR OF THE HIGGS



HIERARCHICAL COUPLINGS?

- does Higgs couple to the first two generations?
  - tough: couplings are small
- more modest question: can we show that the couplings are hierarchical?
  - yes, but for quarks with some assumptions

$$\frac{Y_{e(\mu)}^{\rm exp}}{Y_\tau^{\rm exp}} < 0.22(0.10), \qquad \frac{Y_{u(c)}^{\rm exp}}{Y_t^{\rm exp}} \lesssim 0.04, \qquad \frac{Y_{d(s)}^{\rm exp}}{Y_t^{\rm exp}} < 0.7(6)$$

direct measurements

global fit

p_T distrib.

MUON YUKAWA

CMS, 2009.04363; ATLAS, 2007.07830

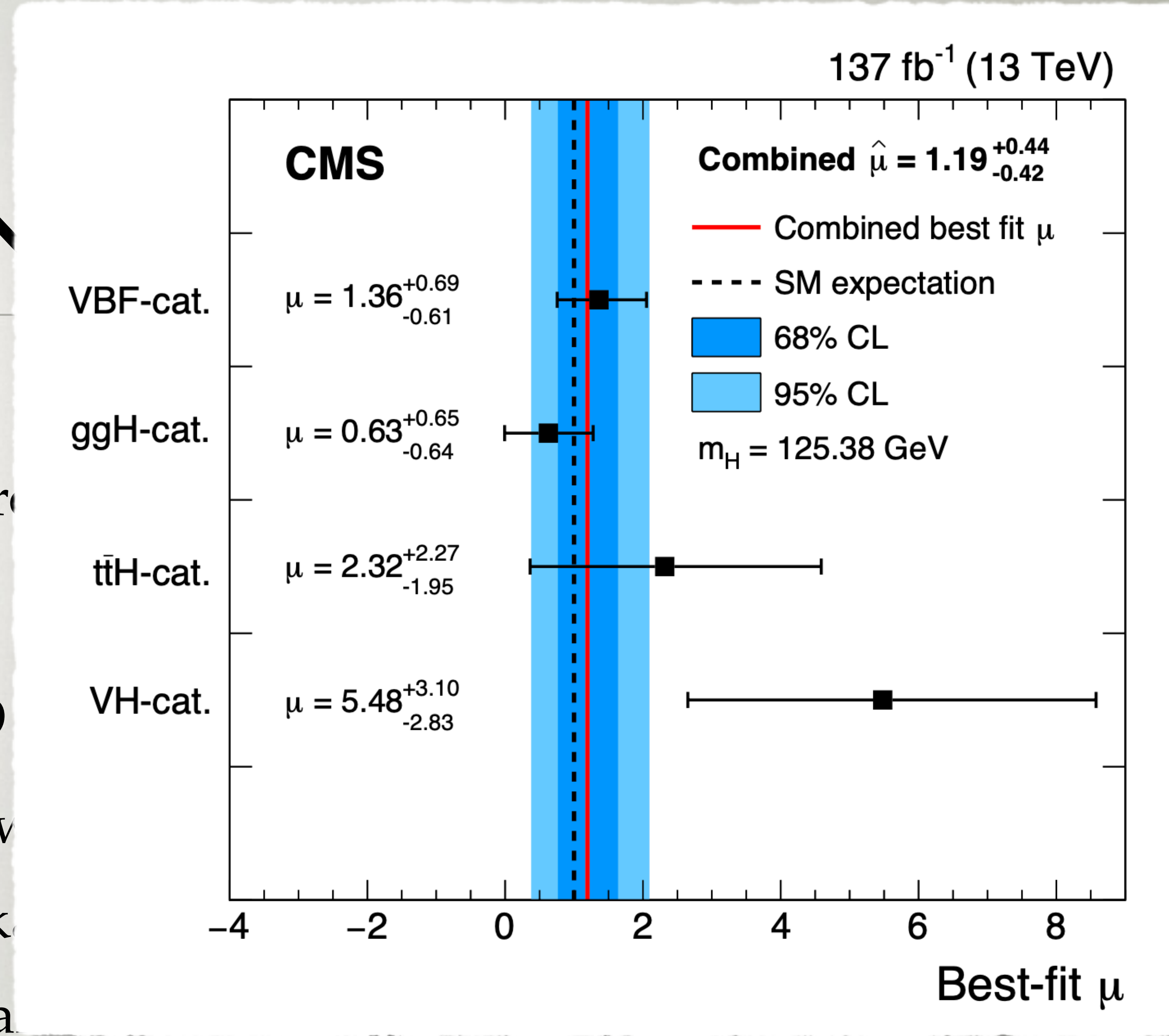
- CMS: evidence for nonzero SM muon Yukawa

$$\hat{\mu}_\mu|_{\text{CMS}} = 1.19 \pm 0.43, \quad \hat{\mu}_\mu|_{\text{ATLAS}} = 1.2 \pm 0.6$$

$$\Rightarrow \kappa_\mu = 1.09 \pm 0.16$$

- a qualitative change following from this measurement:
  - implies that Higgs Yukawas span many orders of magnitudes
  - before: 2HDM would allow for $\mathcal{O}(1)$ 3rd generation Yukawas
    - 2nd generation could be from a completely new sector EWSB with O(1) Yukawa
    - note: EWSB vev required for m_μ is only ~100MeV
    - caveat: still possible this is the case within present exp. errors

MUON



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FLAVOR VIOLATING HIGGS COUPLINGS

FLAVOR VIOLATING COUPLINGS

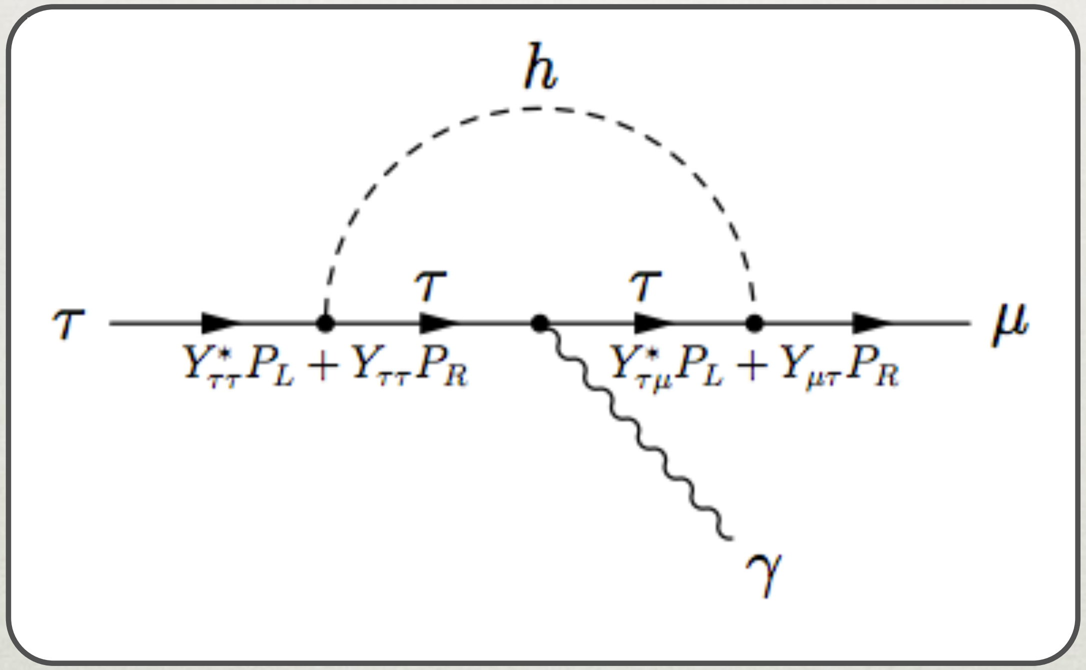
- in the SM Higgs couplings flavor diagonal
  - discovering flavor violating couplings mean New Physics
- for charged lepton final states accessible directly
  - from $h\to\tau\mu$, $h\to\tau e$

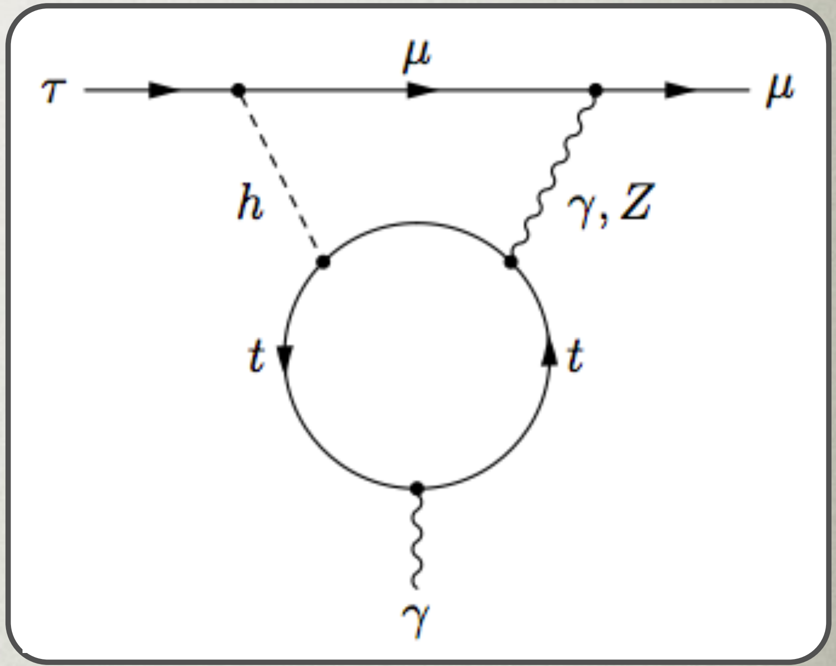
INDIRECT BOUNDS ON $h \to \tau\mu$

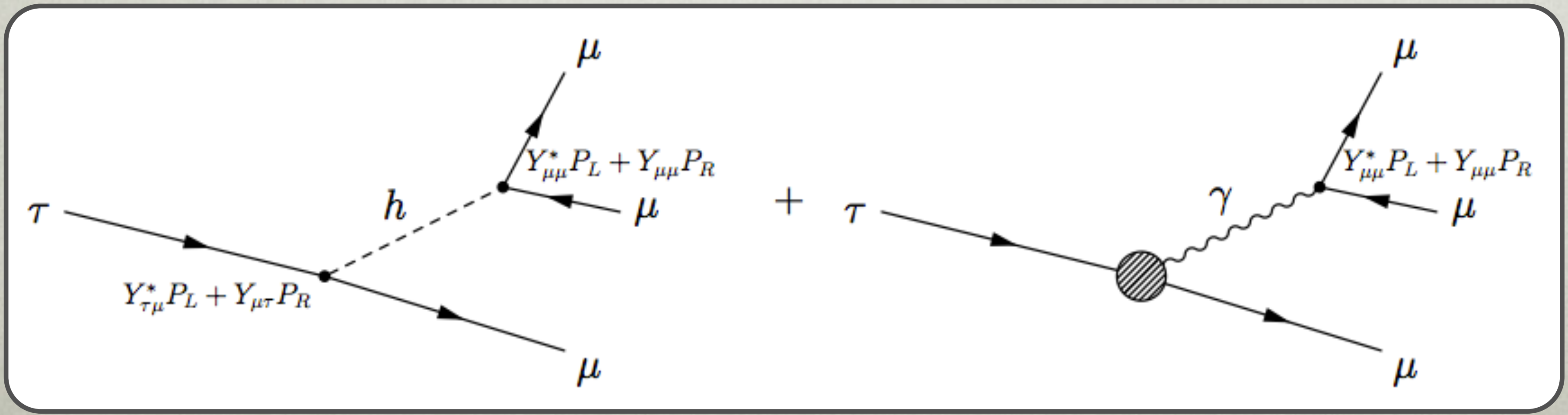
Harnik, Kopp, JZ, 1209.1397

see also Blankenburg, Ellis, Isidori, 1202.5704

- indirect bounds from charged lepton FCNC transitions
  - $\tau \to \mu\gamma$
  - $\tau \to 3\mu$







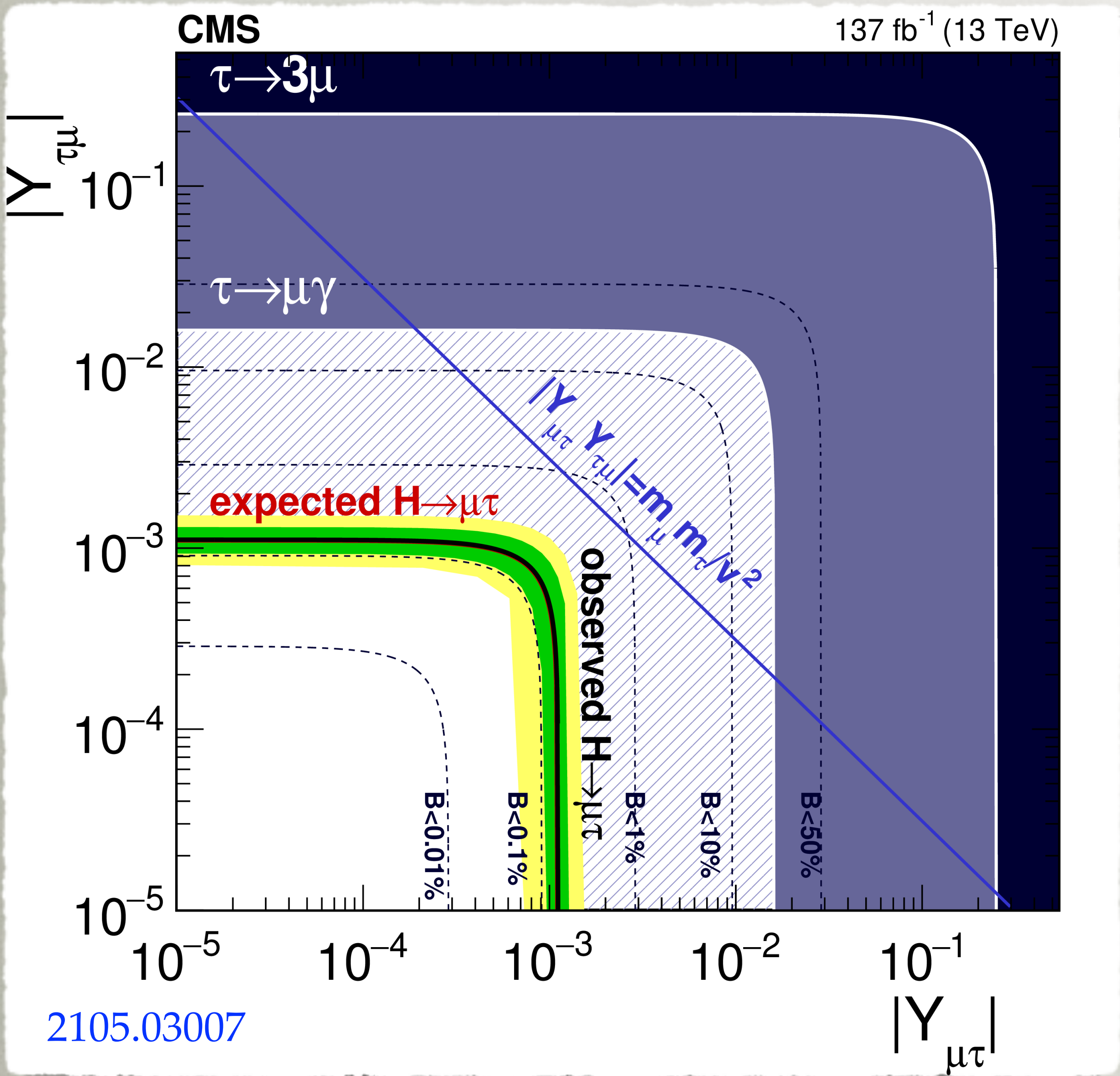
see also ATLAS 1907.06131

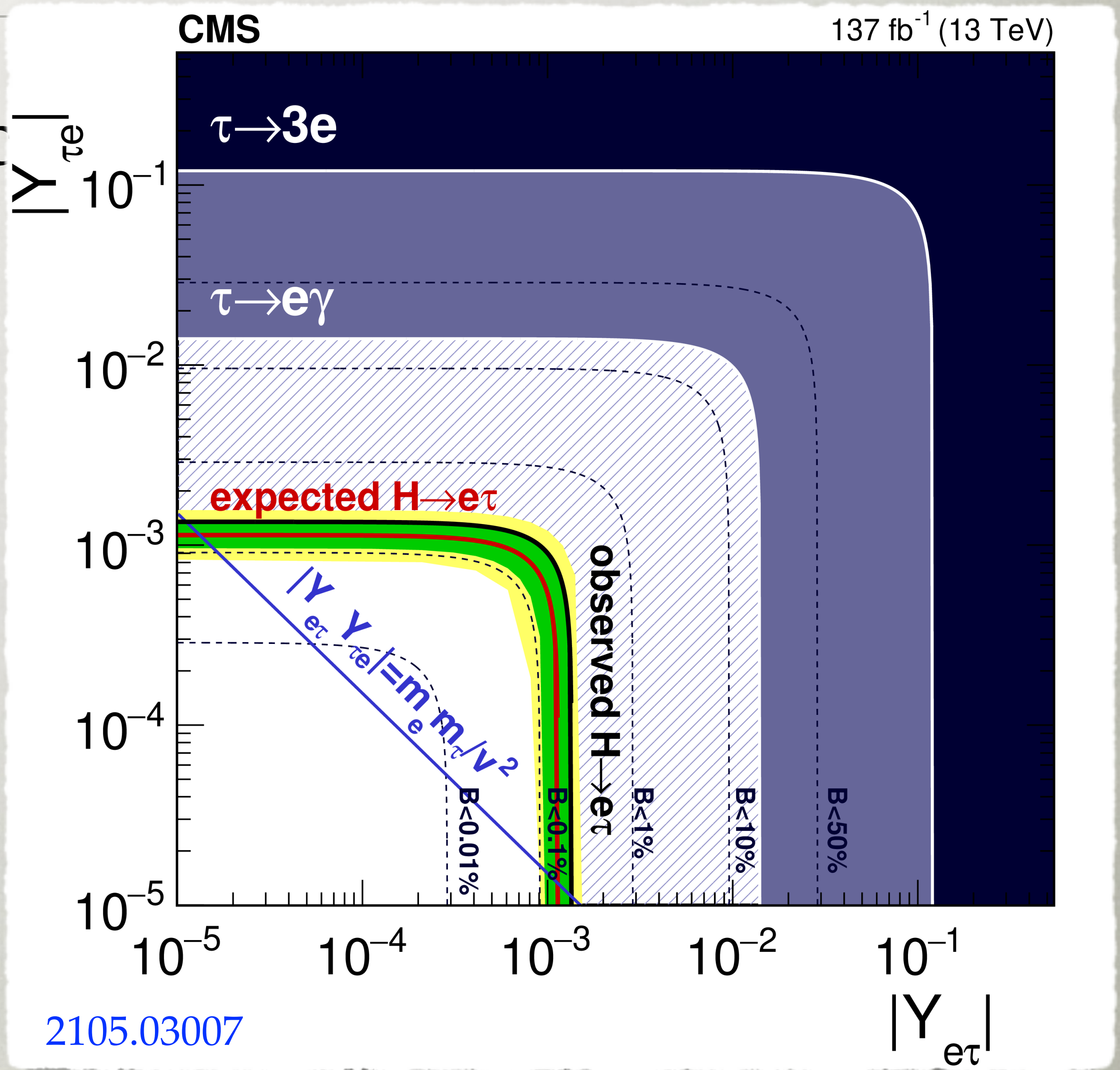
FLAVOR VIOLATING COUPLINGS

- accessible directly for charged lepton final states
  - from $h \to \tau\mu$, $h \to \tau e$

see also ATLAS 1907.06131

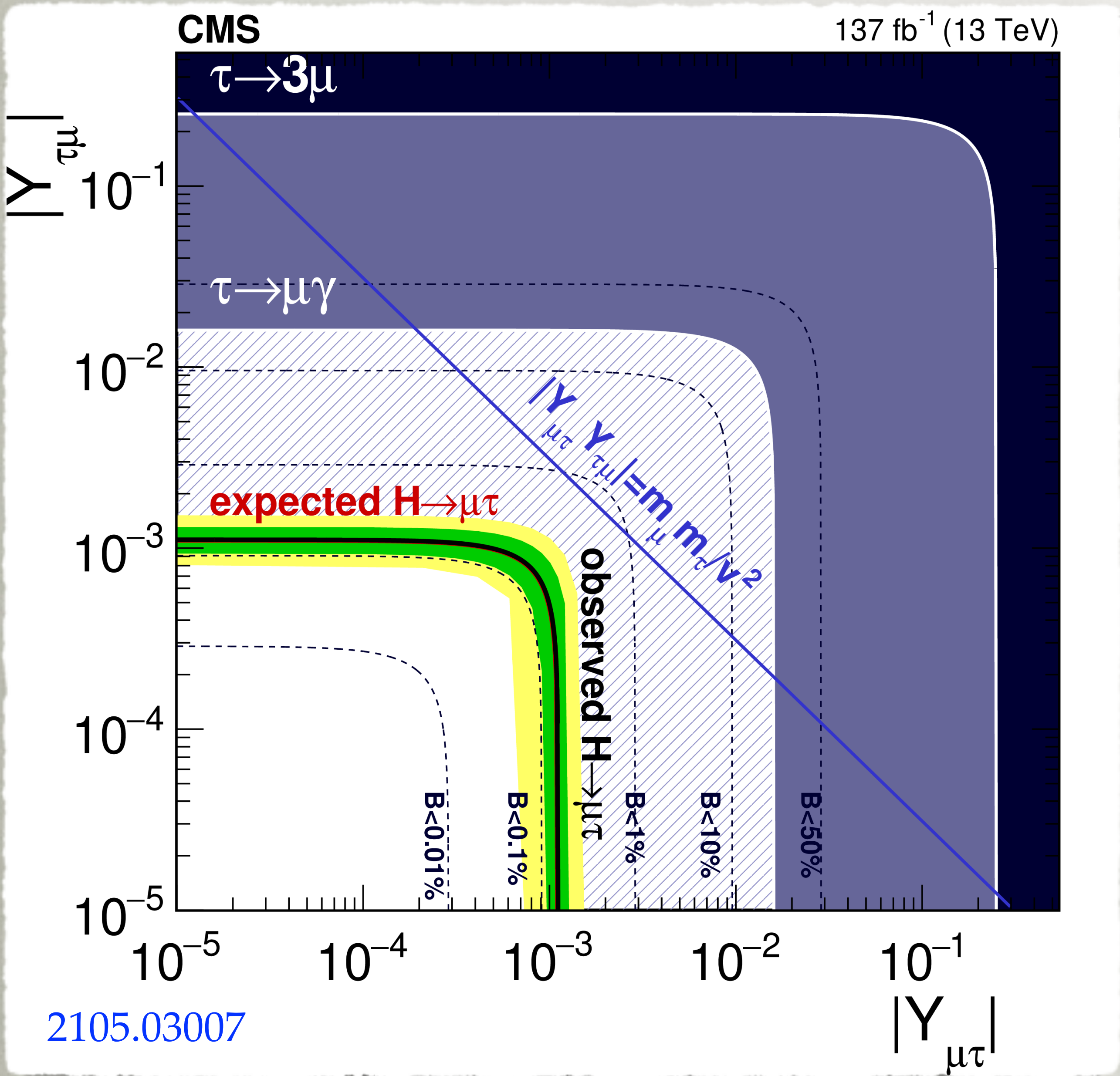
FLAVOR VIOLATING COUPLINGS

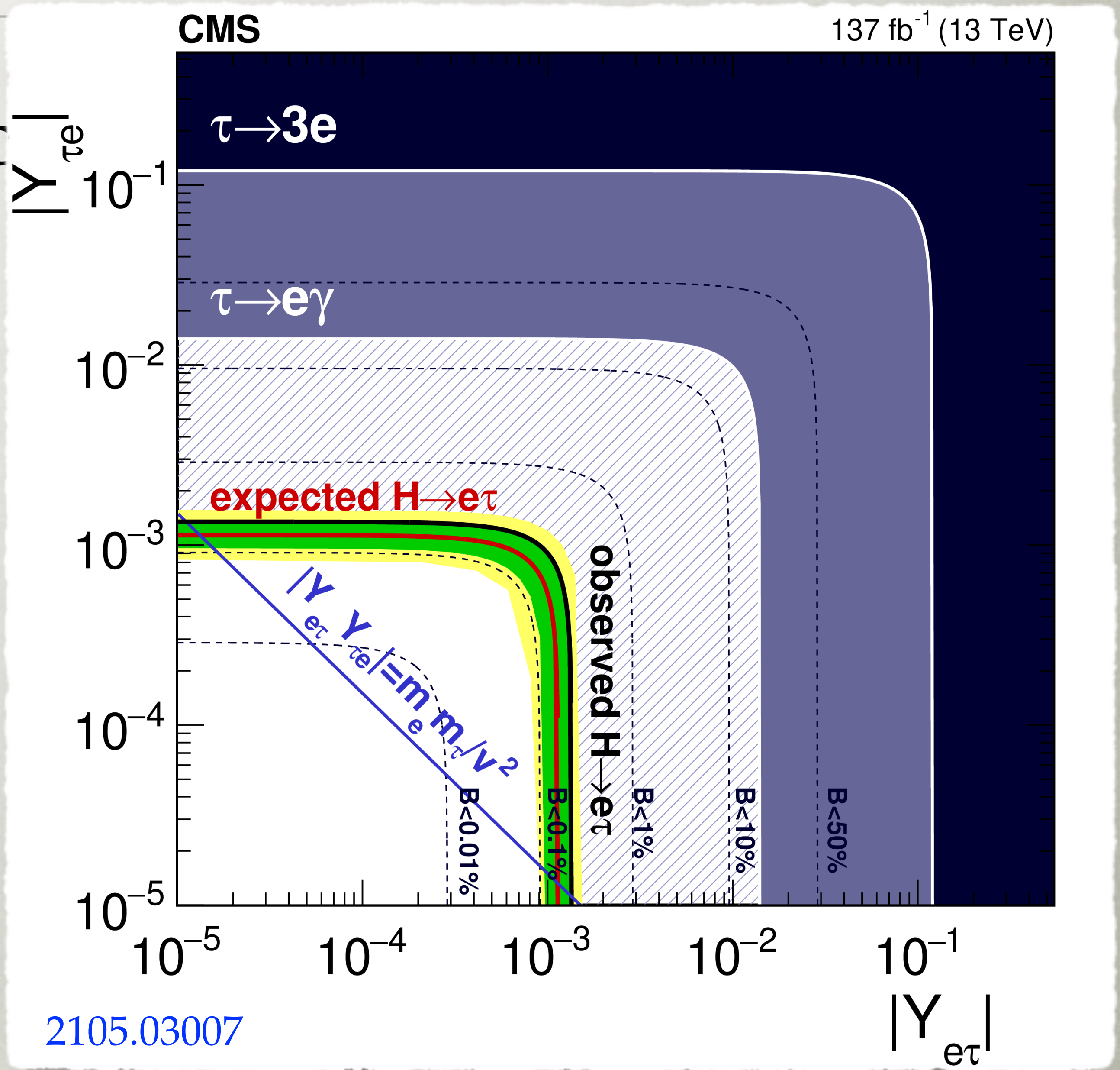




see also ATLAS 1907.06131

FLAVOR VIOLATING COUPLINGS





$$Y_{ij} = \frac{m_i}{v}\delta_{ij} + \frac{v^2}{\sqrt{2}\Lambda^2}\hat{\lambda}_{ij}$$

$$\Lambda_{\mu\tau} > 5.5 \text{ TeV}$$

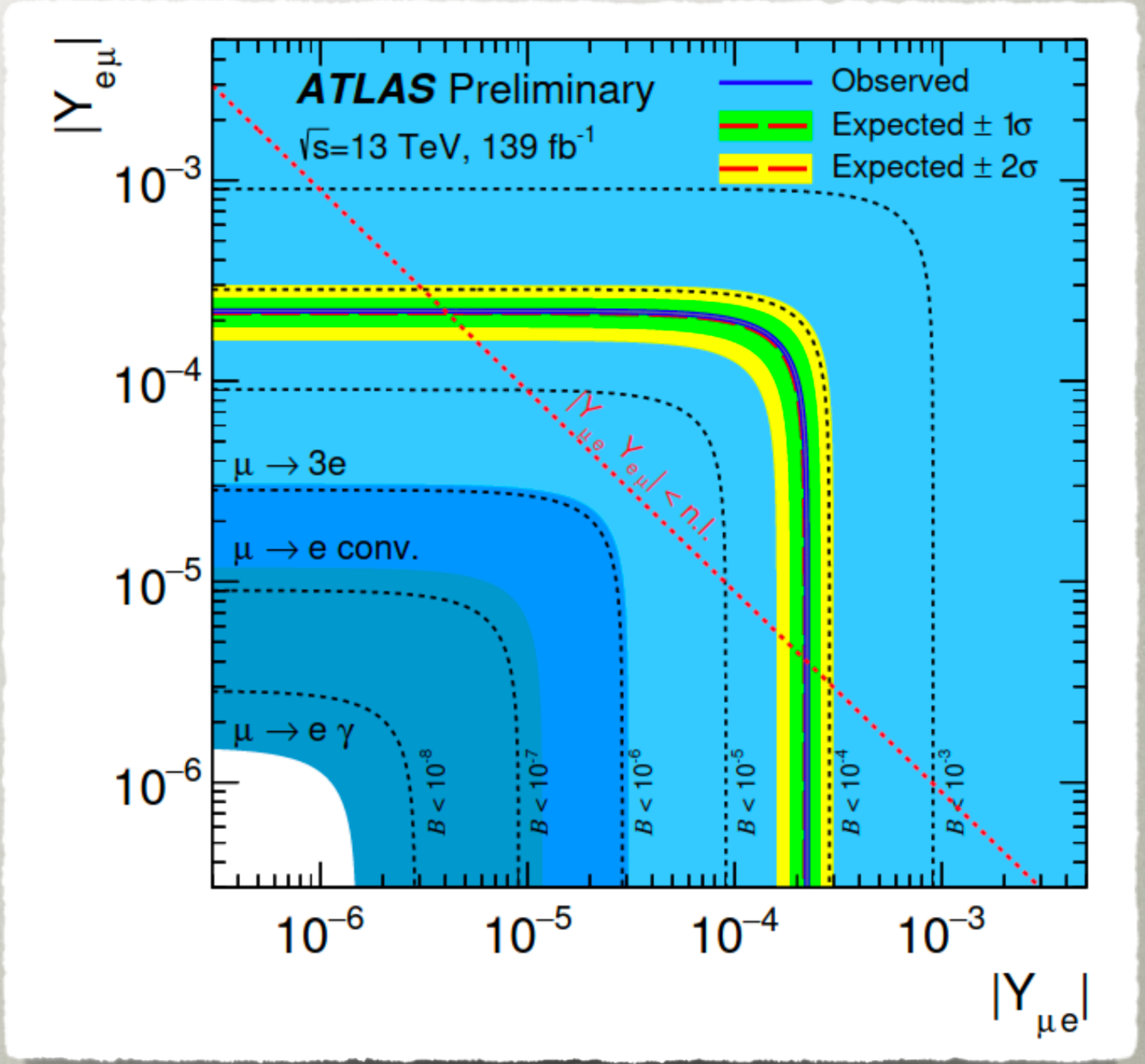
$$\Lambda_{e\tau} > 4.4 \text{ TeV}$$

for $\hat{\lambda}_{ij} = 1$

INDIRECT BOUNDS ON $h \to e\mu$

Harnik, Kopp, JZ, 1209.1397

- indirect bounds especially severe for $h \to e\mu$
- $Br(h \to e\mu) < 10^{-8}$ required to surpass the bound from $Br(\mu \to e\gamma)$
- caveat: could be cancellations in the loop



CP VIOLATING COUPLINGS

CLV HIGGS AND EDMS

- the notation

$$\mathcal{L} \supset -\frac{y_f}{\sqrt{2}} \left(\kappa_f \bar{f} f + i\tilde{\kappa}_f \bar{f}\gamma_5 f\right) h$$

  - strong constraints from eEDM
  - also from nEDM once all hadronic matrix elements available from Lattice QCD
  - linear scaling with improvement on EDMs
  - connections with baryogenesis

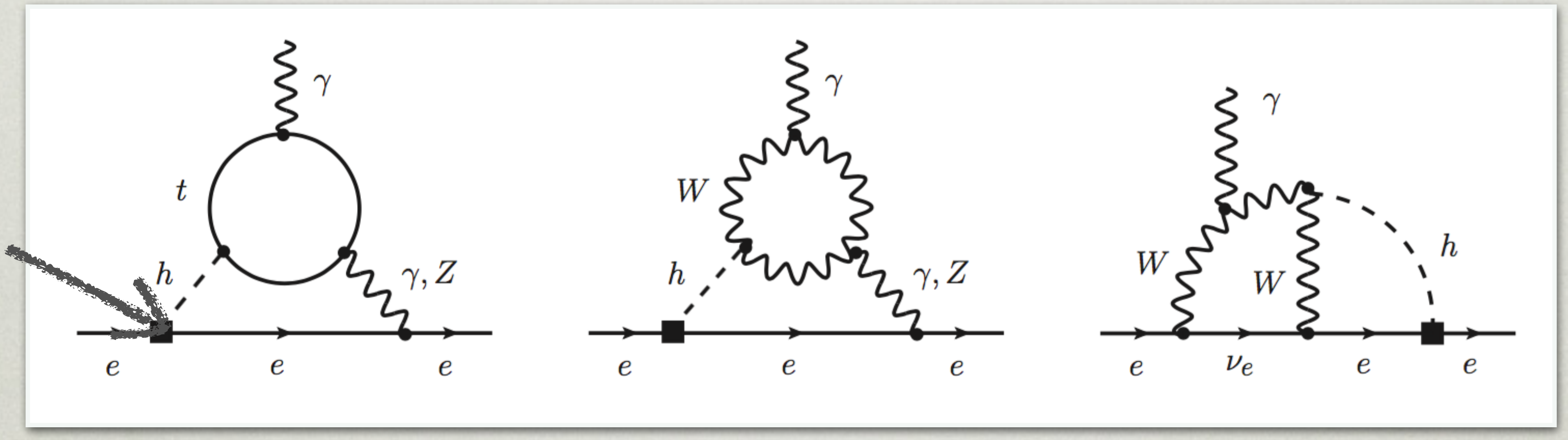
ELECTRON YUKAWA

- $\tilde{\kappa}_e \neq 0$ induces electron EDM

Altmannshofer, Brod, Schmaltz, 1503.04830

- dominant contributions at 2-loop

CPV



- experimental bound ACME coll., 2018

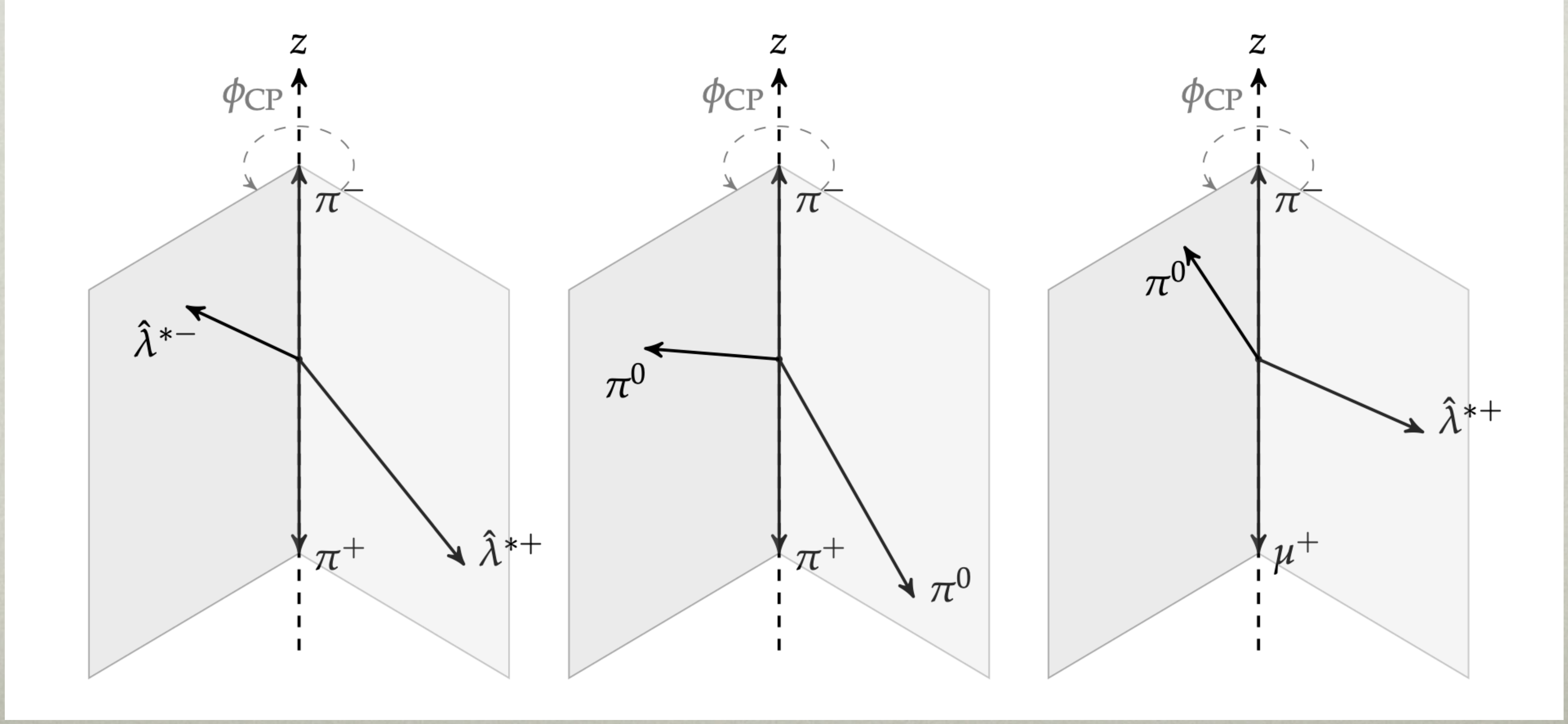
$$\left|\frac{d_e}{e}\right|_{\rm exp} < 1.1 \times 10^{-29}\ \text{cm} \quad @90\,\%\,\text{C.L.}$$

$$|\tilde{\kappa}_e| < 0.6 \cdot 10^{-2}$$

HL-LHC implications

- at HL-LHC potential to measure CPV $h \to \tau\tau$ coupling
- for different tau decay modes define appropriate decay planes
    - such that the angle $\phi_{\tau\tau}$ between them is CP violating

Mode	$\mu^\pm$	$\pi^\pm$	$\rho^\pm \to \pi^\pm\pi^0$	$a_1{}^\pm \to \pi^\pm\pi^0\pi^0$	$a_1{}^\pm \to \pi^\pm\pi^\mp\pi^\pm$
$\mathcal{B}(\%)$	17.4	11.5	25.9	9.5	9.8



Harnik, Martin, Okui, Primulando, Yu, 1308.1094
CMS Coll., CMS-PAS-HIG-20-006

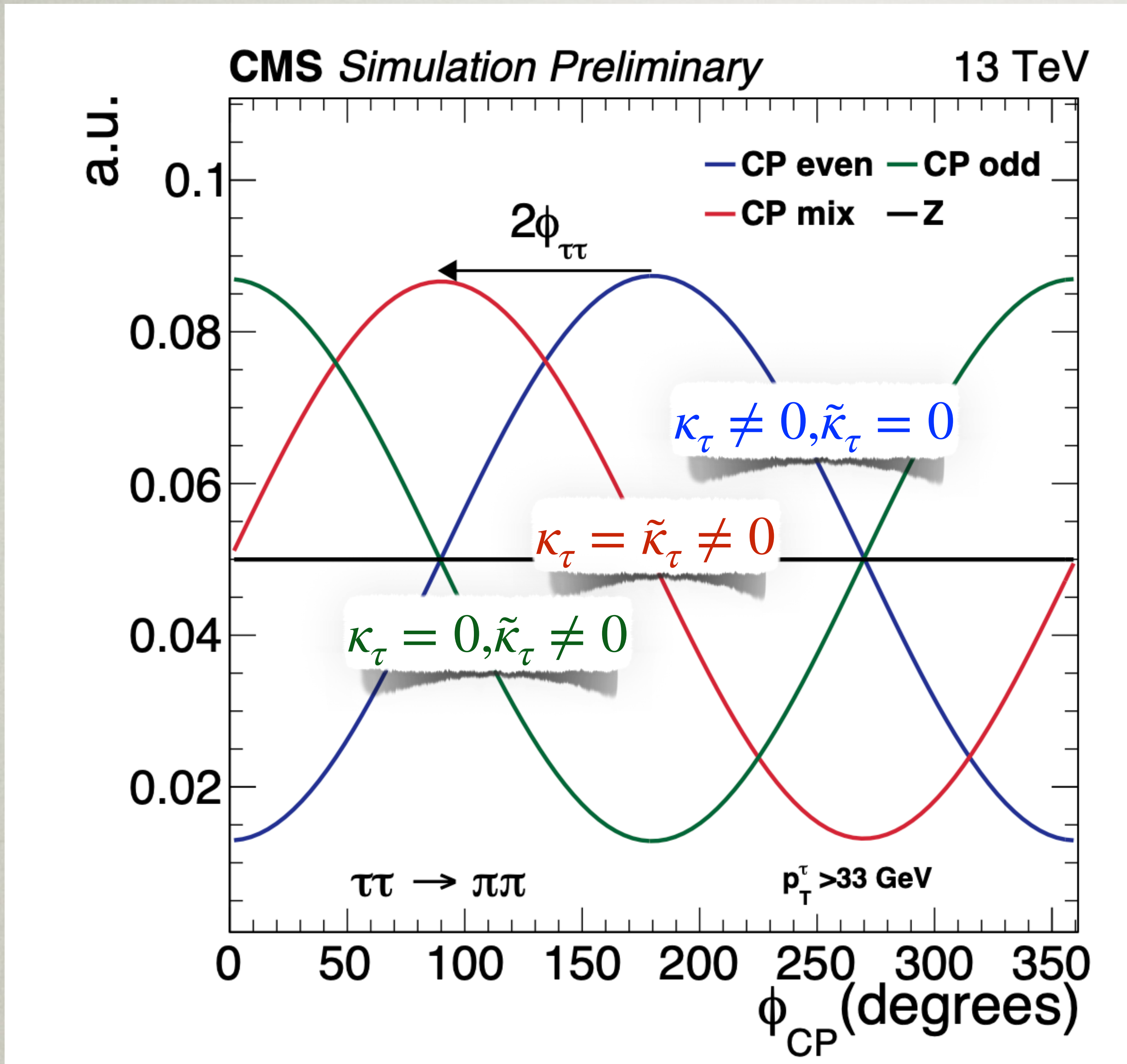
...TIONS

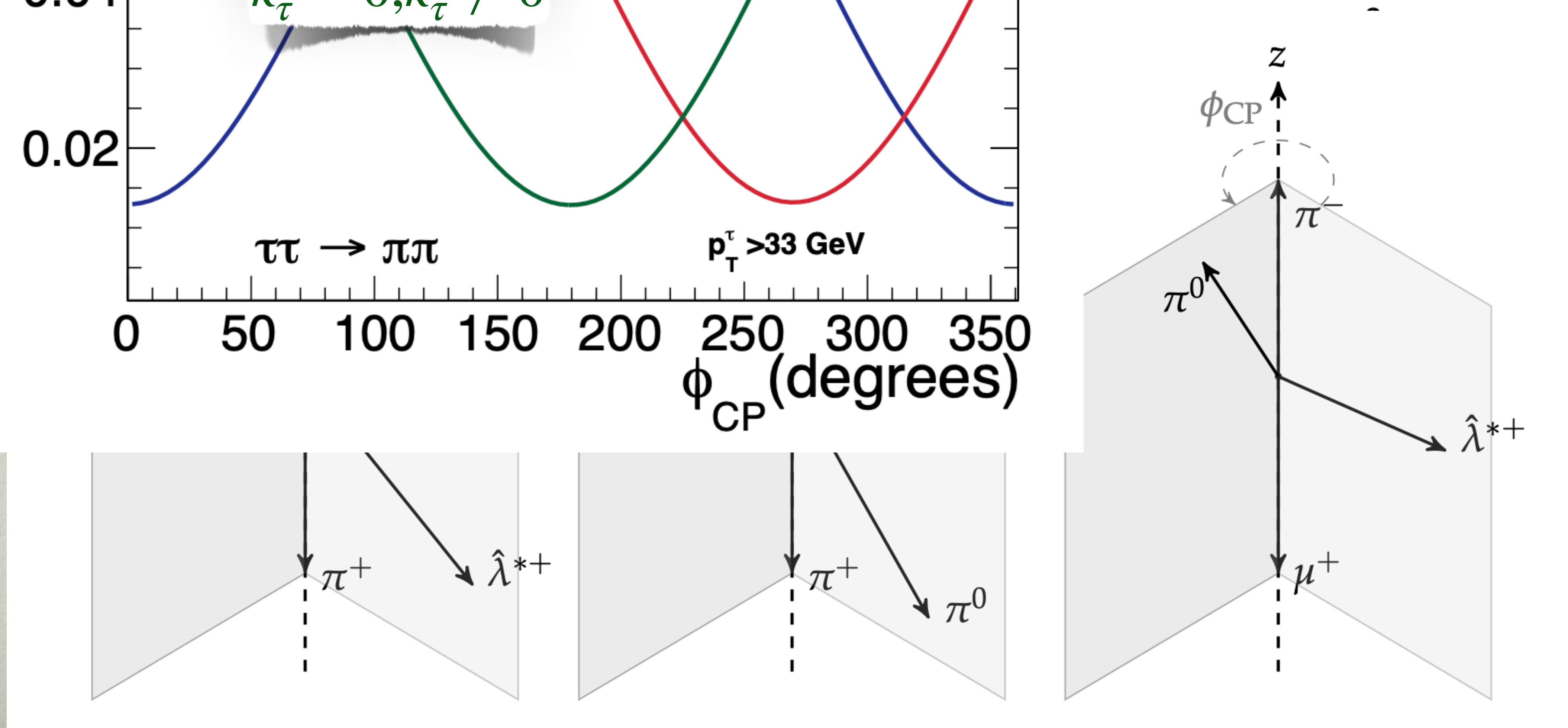
... $\to \tau\tau$ coupling

...propriate decay planes

... is CP violating

...π^0	$a_1^\pm \to \pi^\pm\pi^\mp\pi^\pm$
	9.8

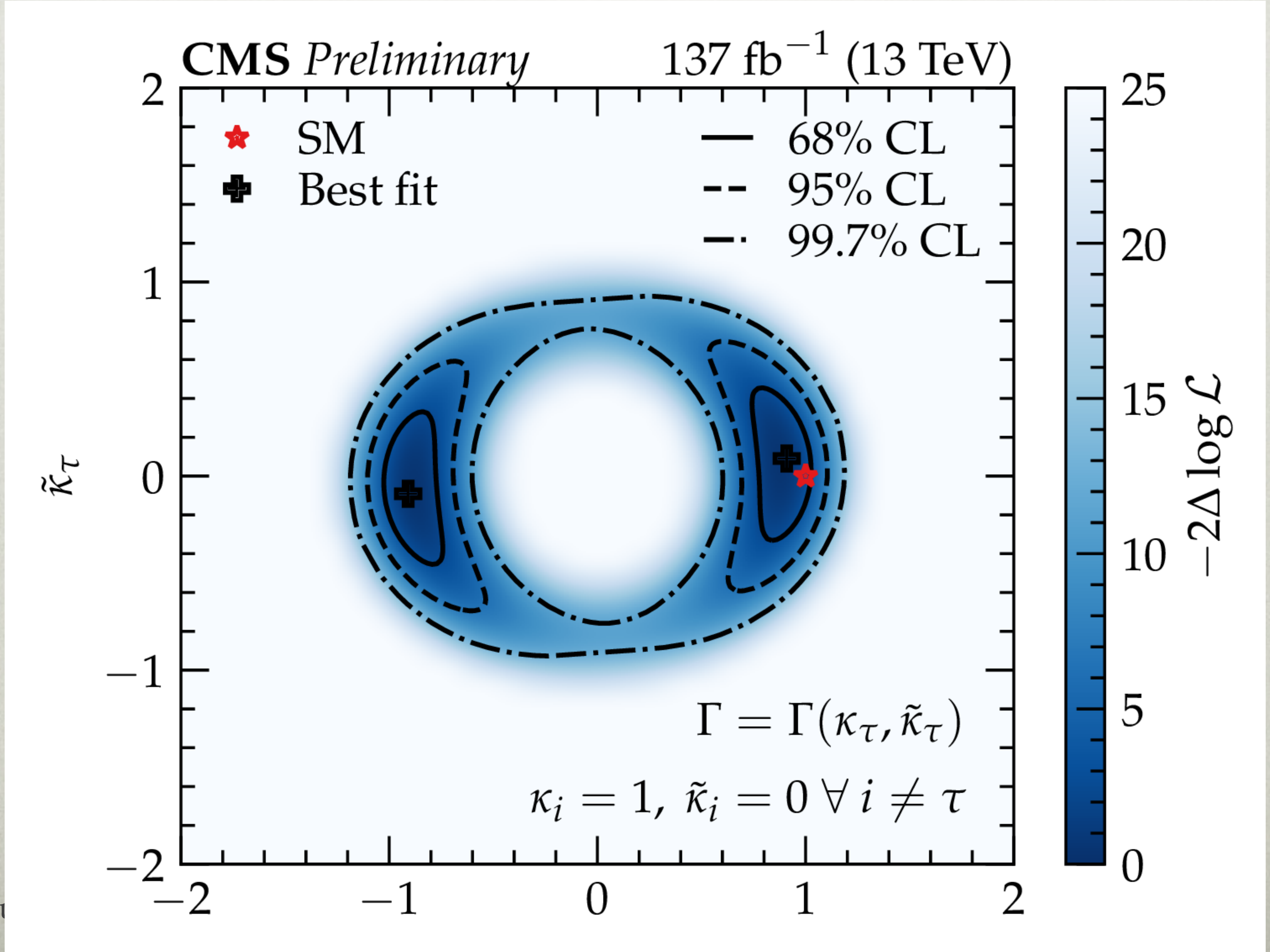




CMS Coll., CMS-PAS-HIG-20-006

PRESENT CONSTRAINT

- CMS with 137 fb^{-1}



FLAVOR DIAGONAL PROBES: MAGNETIC MOMENTS

MAGNETIC AND ELECTRIC DIPOLE MOMENTS

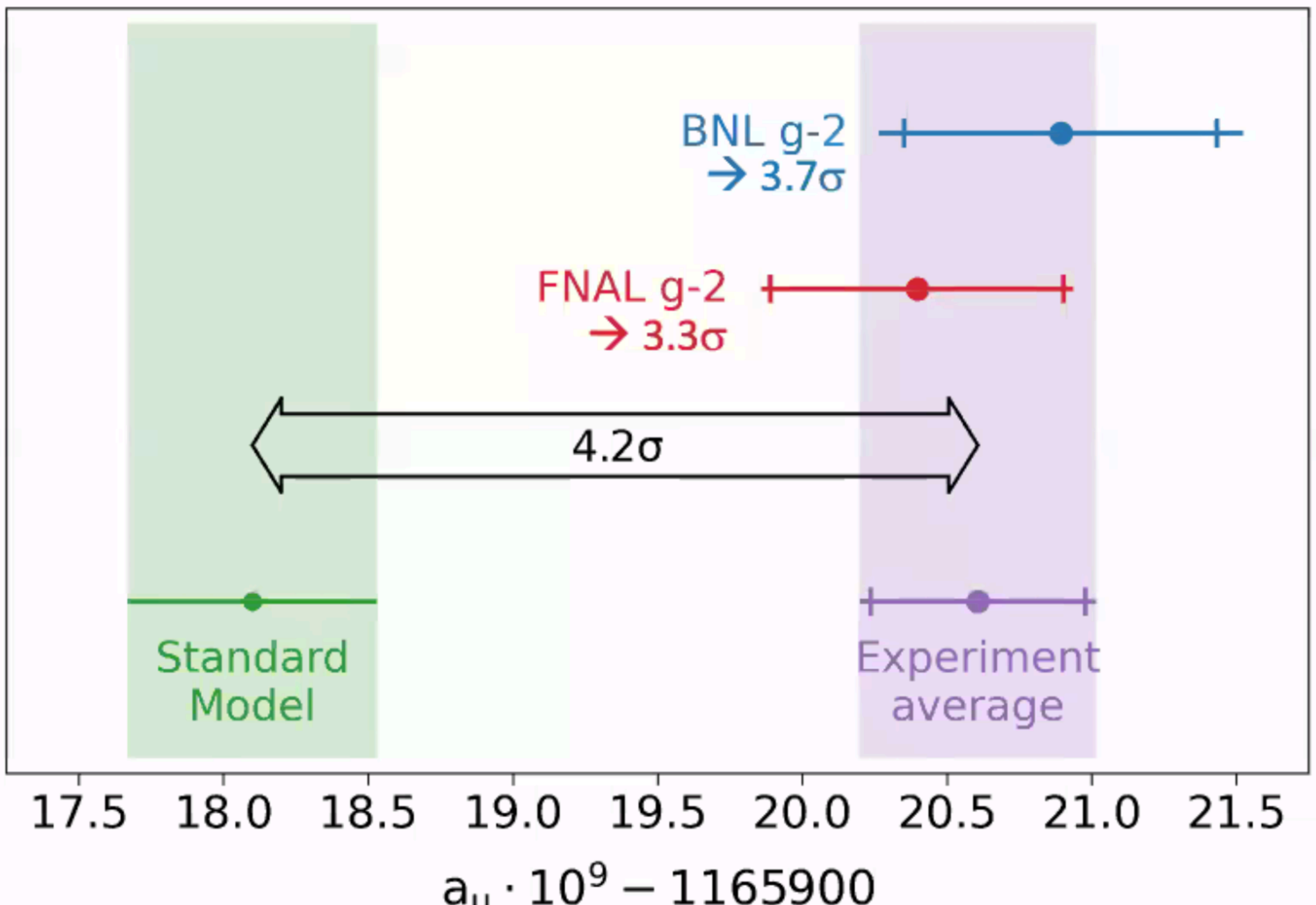
- two flavor diagonal dimension 5 operators

$$\mathcal{L}_{\rm eff} \supset -\frac{e a_\ell}{4 m_\ell}\big(\bar\ell \sigma^{\mu\nu}\ell\big) F_{\mu\nu} - \frac{d_\ell}{2}\big(\bar\ell\sigma^{\mu\nu} i\gamma_5 \ell\big) F_{\mu\nu}$$

- anomalous magnetic moment $(g-2)_\ell = 2a_\ell$
  - CP conserving
  - SM value nonzero
- electric dipole moment d_ℓ
  - CP violating
  - SM value highly suppressed

NEW PHYSICS IN $(g-2)_\mu$?!

$a_\mu(SM) = 0.00116591810(43) \rightarrow 368$ ppb



- Individual tension with SM
  - BNL: 3.7σ
  - FNAL: 3.3σ

$a_\mu(Exp) - a_\mu(SM) = 0.00000000251(59) \rightarrow 4.2\sigma$

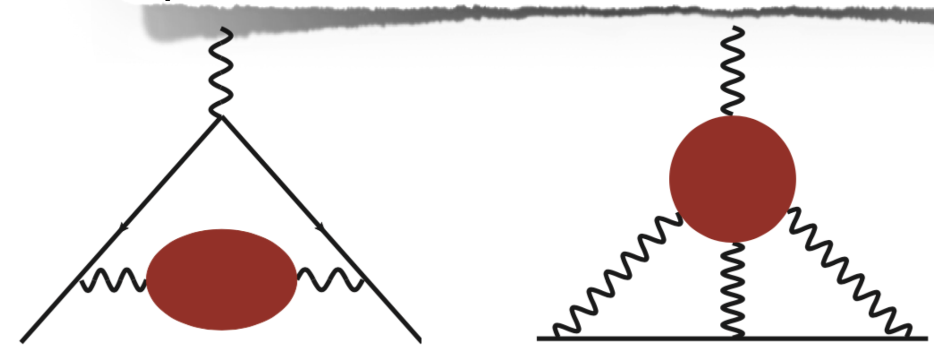
POSSIBLE DEVIATION IN $(g-2)_\mu$

- the value of $(g-2)_\mu$ from g-2 coll.

$$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-10}$$

- the SM theory error dominated by hadronic uncert.

$$a_\mu^{\rm SM} = 116591810(43) \times 10^{-10}$$



QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)

The muon g-2 theory initiative, 2006.04822

IF NEW PHYSICS...

- $(g-2)_\mu$ showing 4.2σ deviation from the SM
  - in SMEFT from dim6 operator

$$\mathcal{L} \supset -\frac{\sqrt{2} e\, v}{(4\pi\Lambda_{ij})^2}\, \bar{\ell}^i_{\rm L} \sigma^{\mu\nu} \ell^j_{\rm R} F_{\mu\nu} + {\rm h.c.}\ ,$$

$$(g-2)_\mu \Rightarrow \Lambda_{22} \sim 15\,\text{TeV}$$

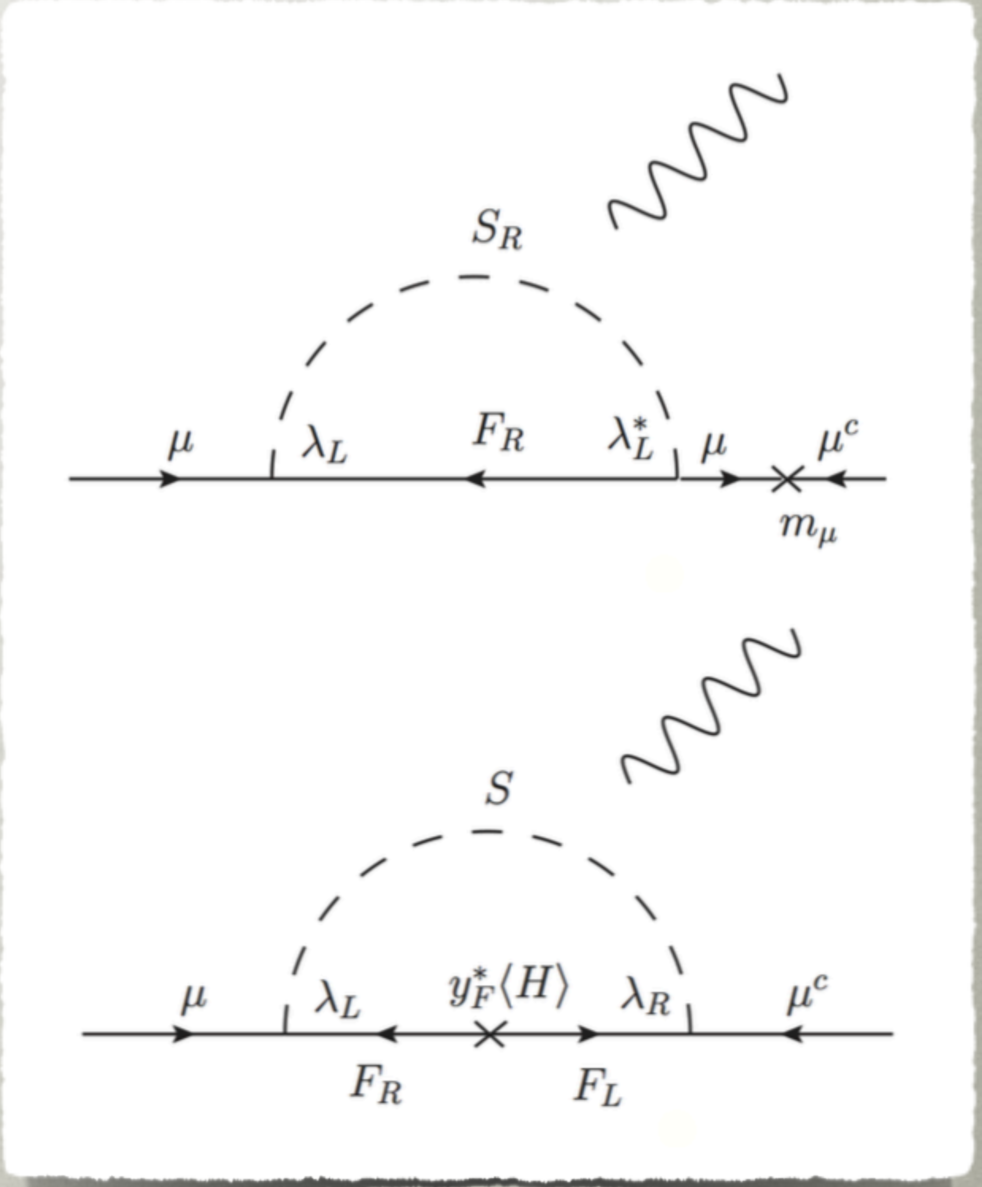
- note: any flavor violation needs to be highly suppressed $\mu \to e\gamma \Rightarrow \Lambda_{21} \gtrsim 3500\,\text{TeV}$ Greljo, Stangl, Thomsen, 2103.13991
- a possible (natural) solution - a symmetry
  - a phenomenologically viable example: $L_\mu - L_\tau$

$(g-2)_\mu$ NEW PHYSICS MODELS

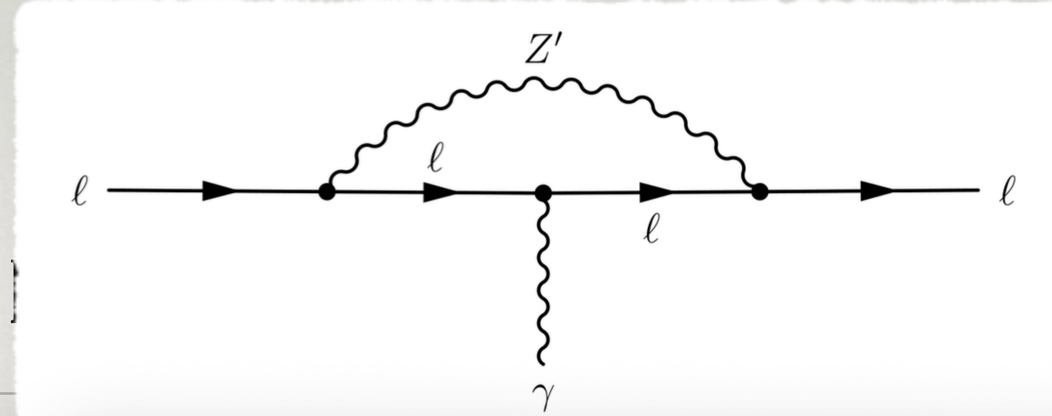
$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251(59) \times 10^{-10}$

$$\frac{e}{8\pi^2}(\bar{\mu}\sigma^{\mu\nu}\mu)F_{\mu\nu}$$

- NP models of two types
- chirality flip on SM fermion leg
  - NP need to be light, example: Z' from $L_\mu - L_\tau$
- chirality flip can be on the NP fermion leg
  - NP can be much heavier
  - example: minimal models with DM

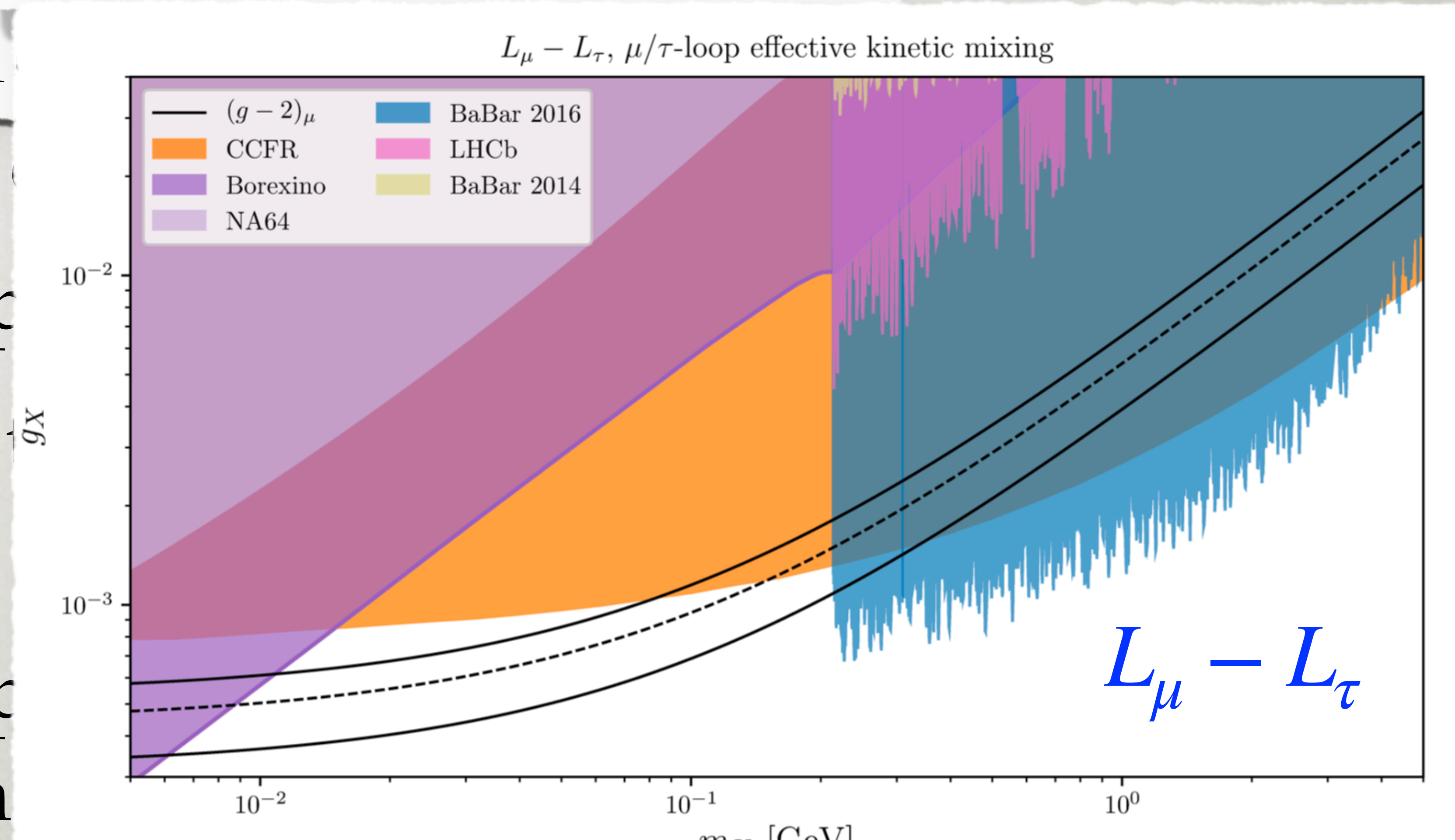


$(g-2)_\mu$ ... ODELS

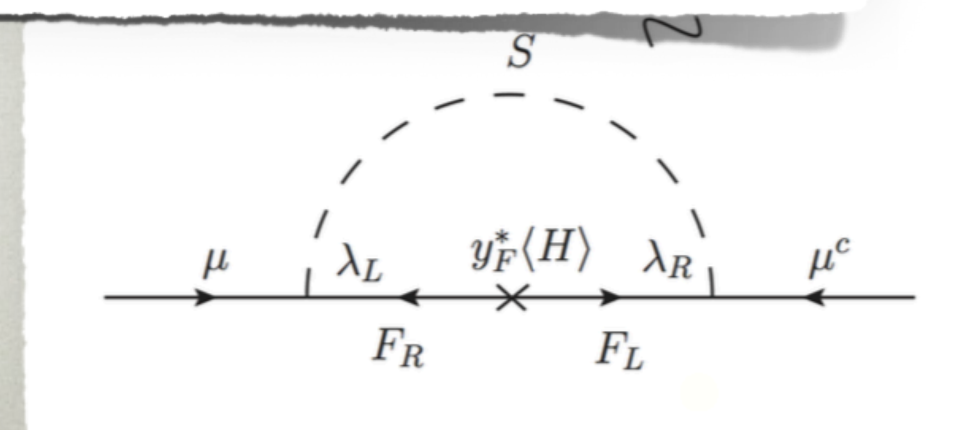


$a_\mu^{\rm exp} - a_\mu^{\rm SM} = 251$ ...

- NP models ...
- chirality flip ...
  - NP need ...
    example: ...
- chirality flip ...
  NP fermion ...
  - NP can be much heavier
  - example: minimal models with DM



Greljo et al, 2203.13731



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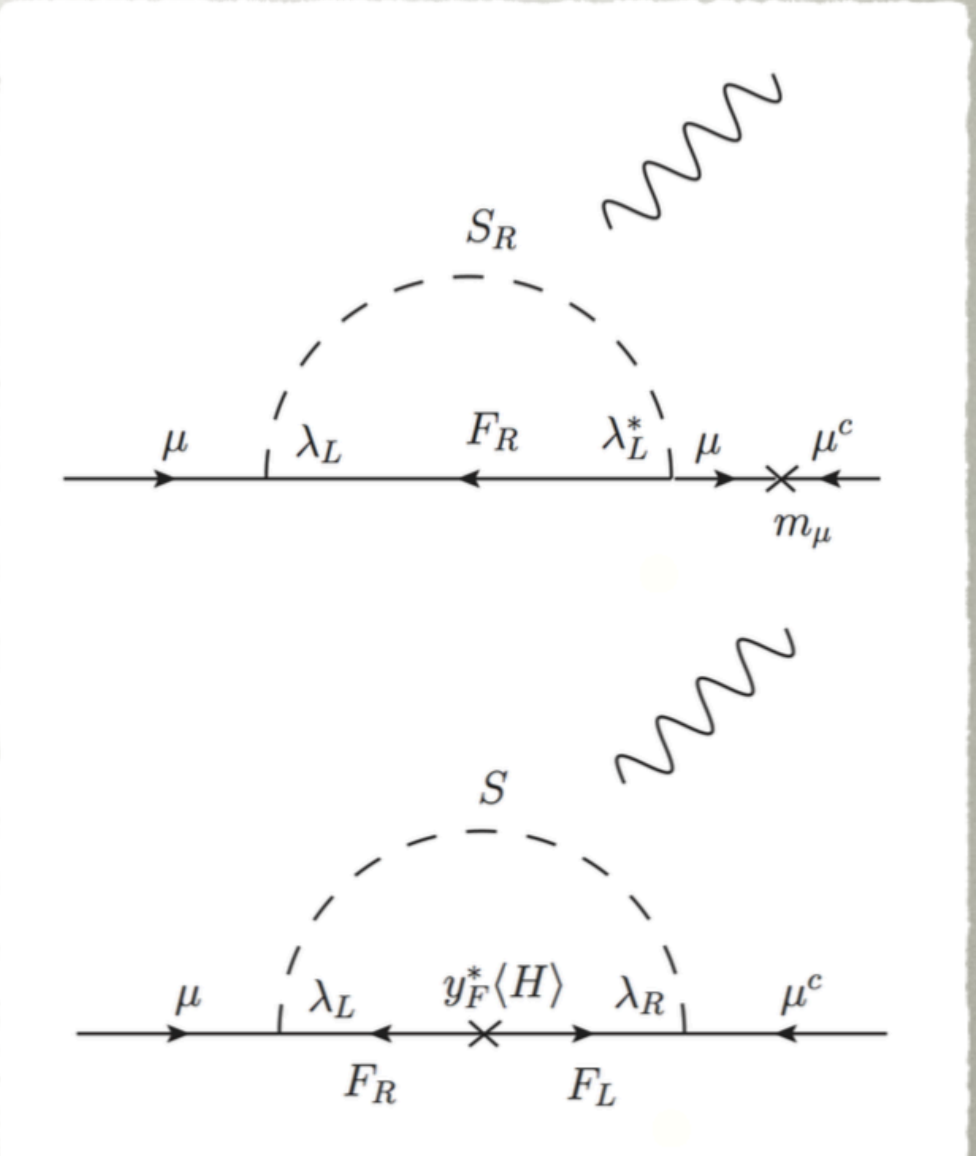


$(g-2)_\mu$ NEW PHYSICS MODELS

exp SM 251(59) $\times 10^{-10}$

$$\frac{e}{8\pi^2}(\bar{\mu}\sigma^{\mu\nu}\mu)F_{\mu\nu}$$

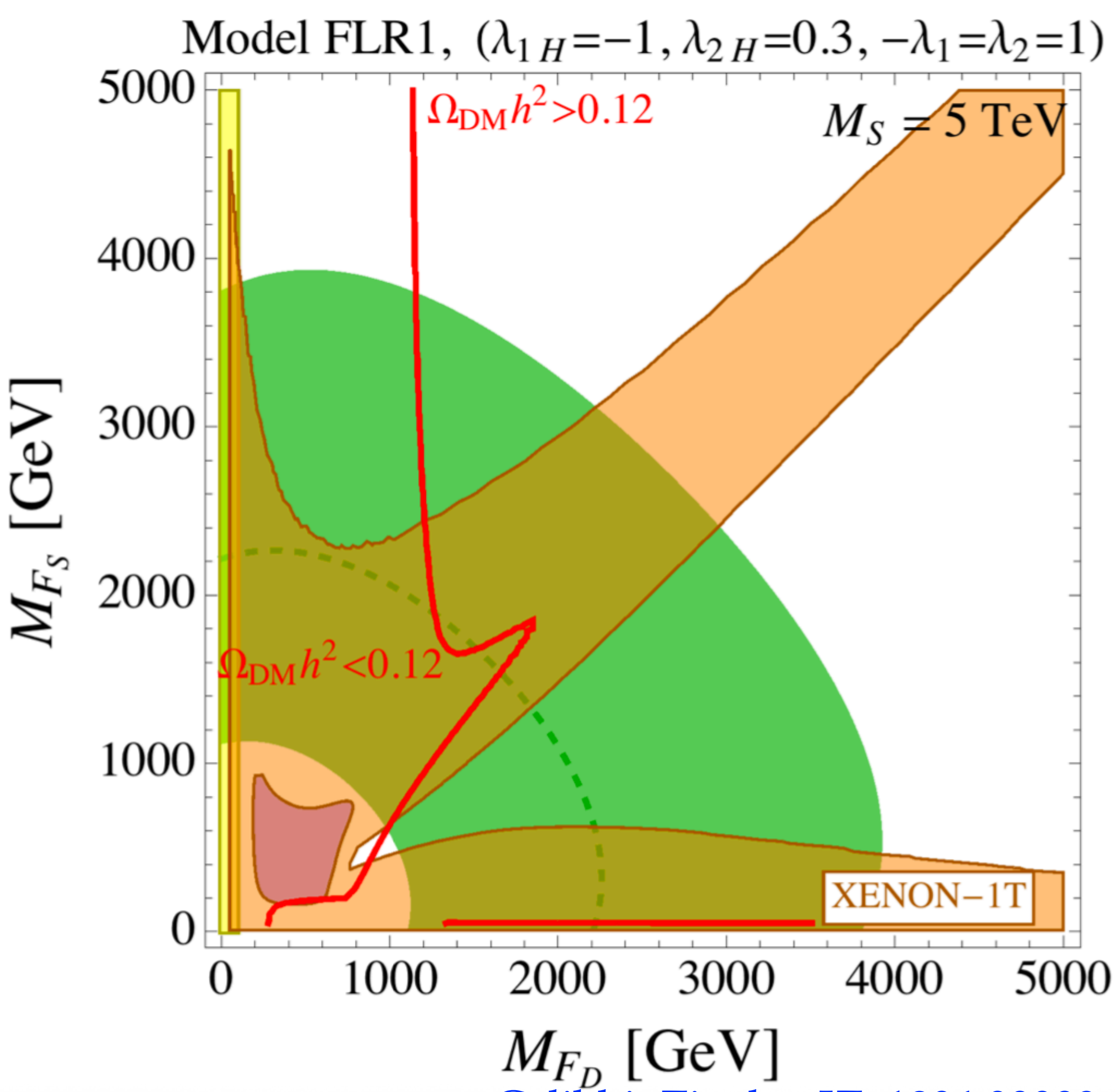
ion leg

L_τ

e

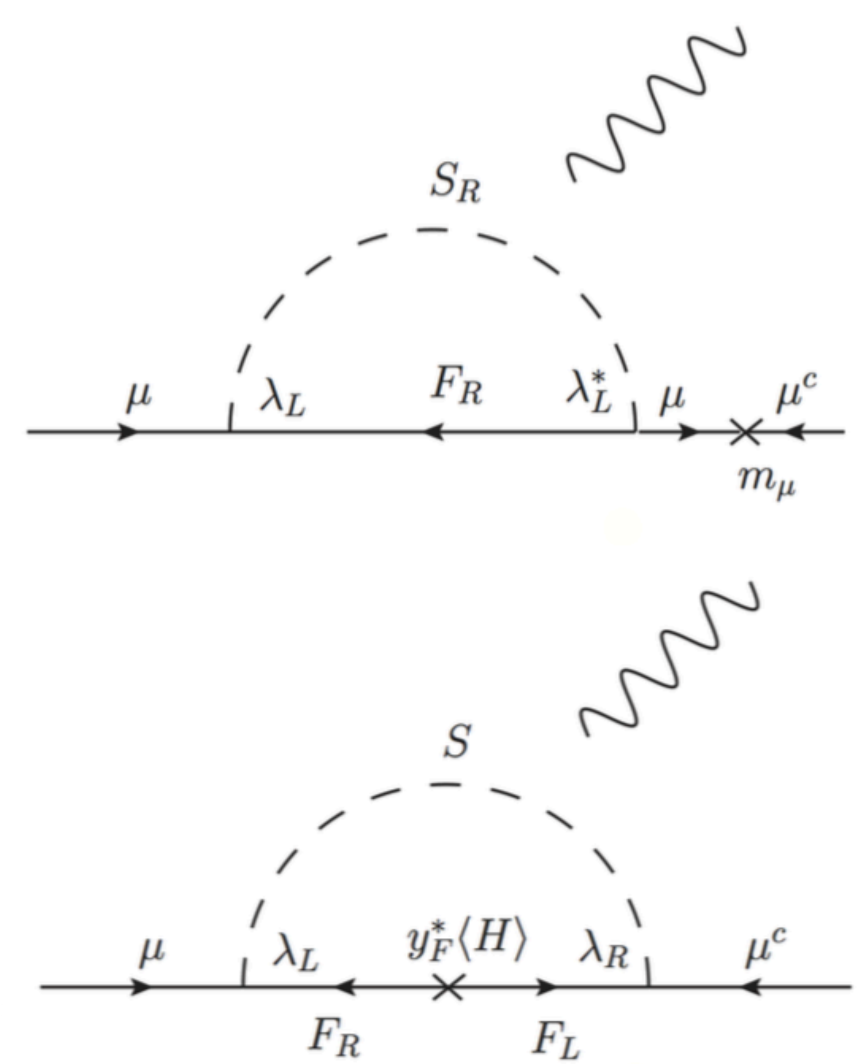
er

dels



Calibbi, Ziegler, JZ, 1804.00009

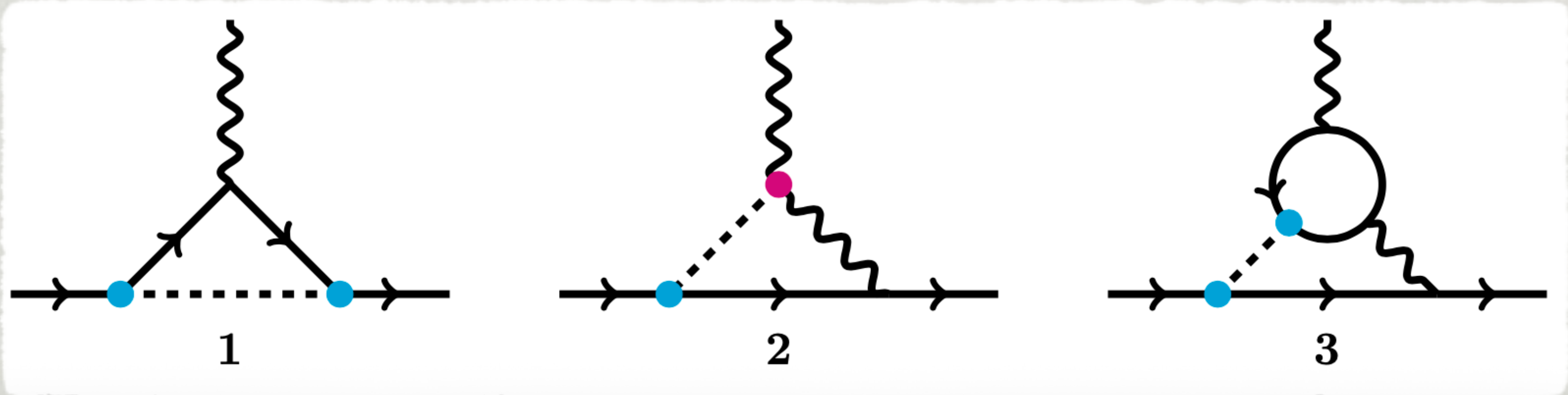
$F_S \equiv F_R \sim 1_0, \quad F_D \equiv F_L \sim 2_{-1/2}, \quad F_D^c \equiv F_L^c \sim 2^*_{1/2}, \quad S \equiv S_R \sim 2_{1/2},$



Buen-Abad, Fan, Reece, Sun, 2104.03267

FLAVOR DIAGONAL ALP?

- ALP coupling to muons gives wrong sign contrib. to Δa_μ

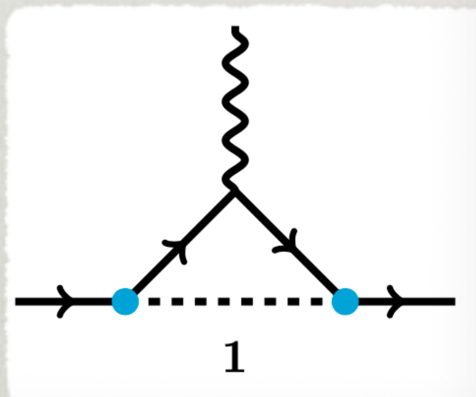


$$\Delta a_\mu^{(1)} \propto -\frac{c_{\mu\mu}^2}{16\pi^2}, \quad \Delta a_\mu^{(2)} \propto -\frac{c_{\mu\mu} c_{\gamma\gamma}\alpha}{16\pi^3}, \quad \Delta a_\mu^{(3)} \propto -\frac{c_{\mu\mu} c_{ii}\alpha}{16\pi^3},$$

  - need to compensate with $aF\tilde{F}$ coupling at 1-loop, and with 2-loop contribs
  - the scale required to explain Δa_μ anomaly low, $f_a \sim 100\,\mathrm{GeV}$
  - difficult model building
- note: at the same order, $1/f_a^2$, expect other contribs. to a_μ from UV

FLAVOR

- ALP coupling to muo



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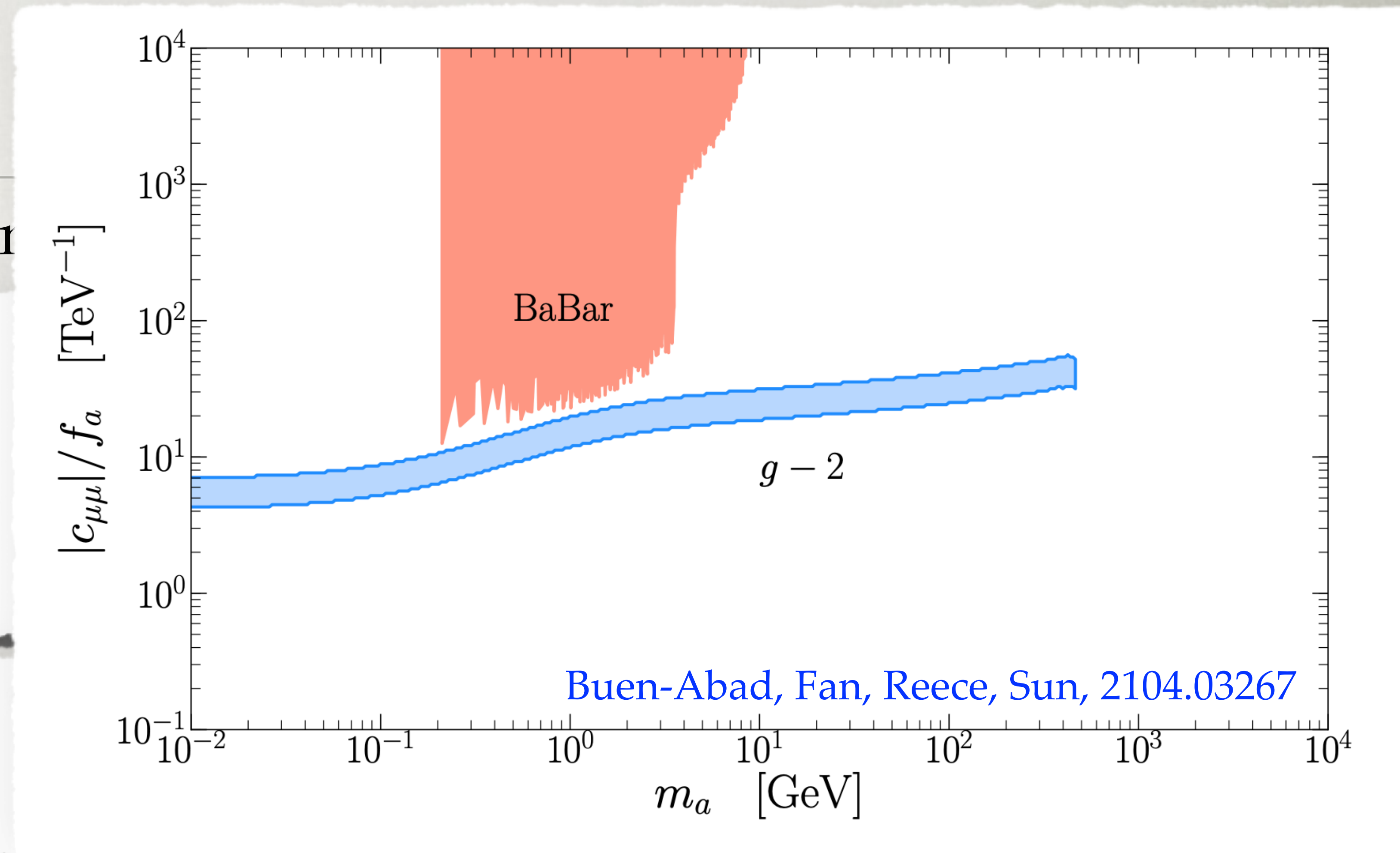

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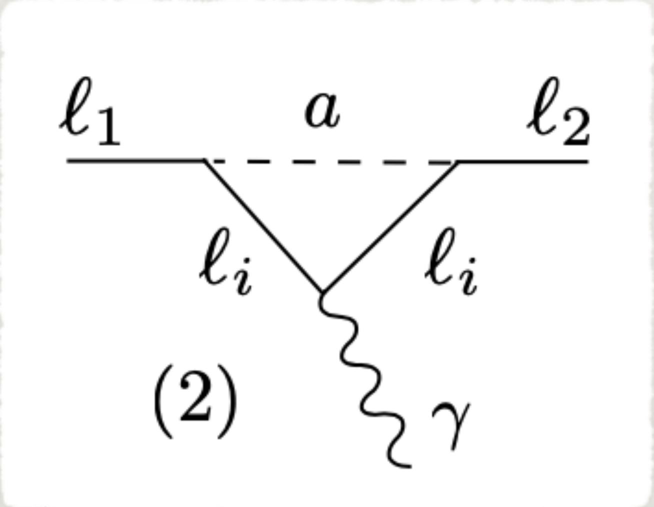
Bauer, Neubert, Renner, Schnubel, Thamm, 1908.00008

FLAVOR VIOLATING ALP FOR $(g-2)_\mu$

- FV coupling $c^A_{e\mu}$ gives the right sign of Δa_μ for $m_a > m_\mu$

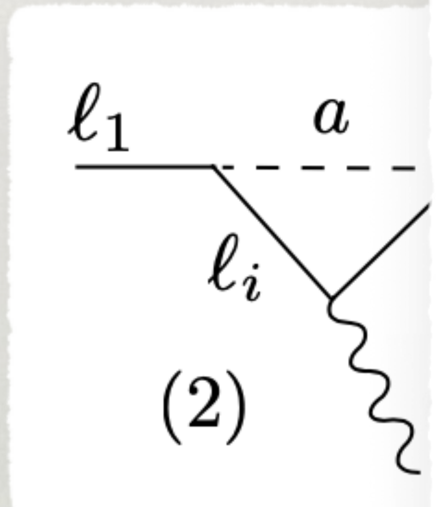


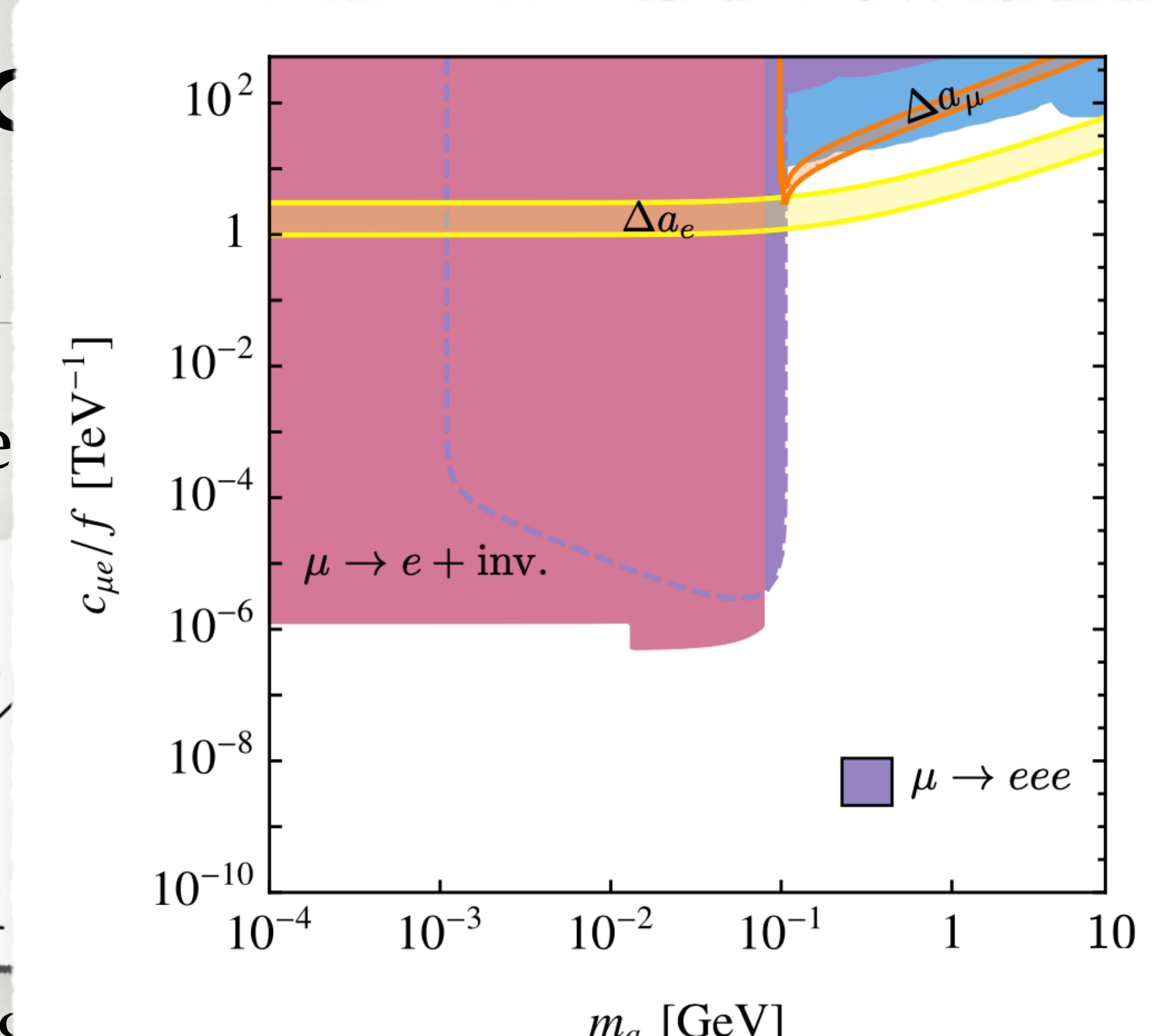
- same model building challenge: low f_a
- a possible way out: couple μ off-diagonally to heavy vector-like fermions E_i, L_i
  - chirality flip from internal E_i, L_i line $\Rightarrow$ higher $f_a \gtrsim 1$ TeV

Brdar, Jana, Kubo, Lindner, 2104.03282

FLAVOR VI
FOR

- FV coupling $c^A_{e\mu}$ give
  $m_a > m_\mu$





Bauer, Neubert, Renner, Schnubel, Thamm, 1908.00008

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FLAVOR VIO
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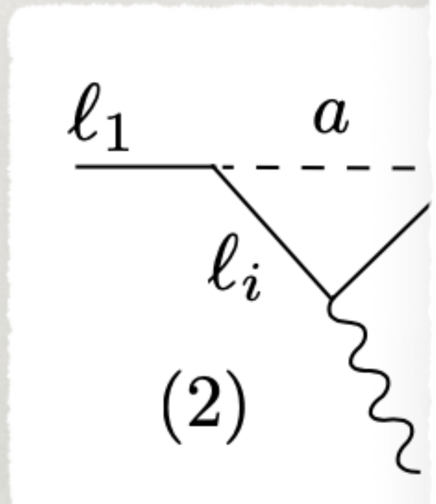

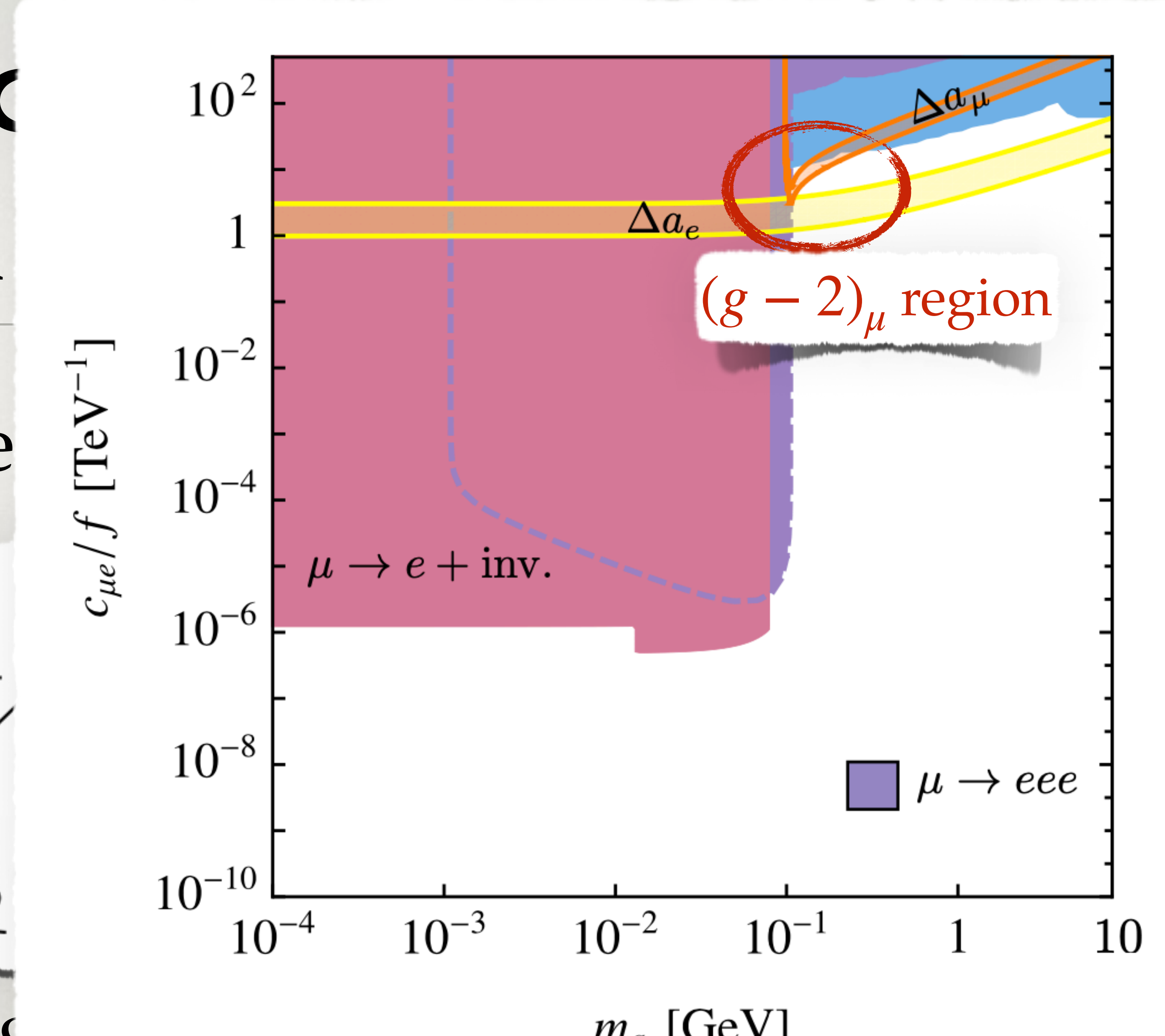

Bauer, Neubert, Renner, Schnubel, Thamm, 1908.00008

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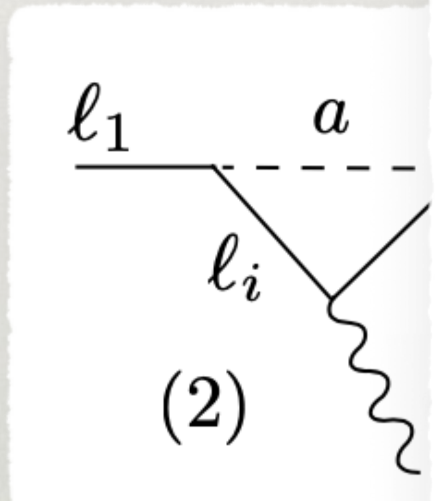
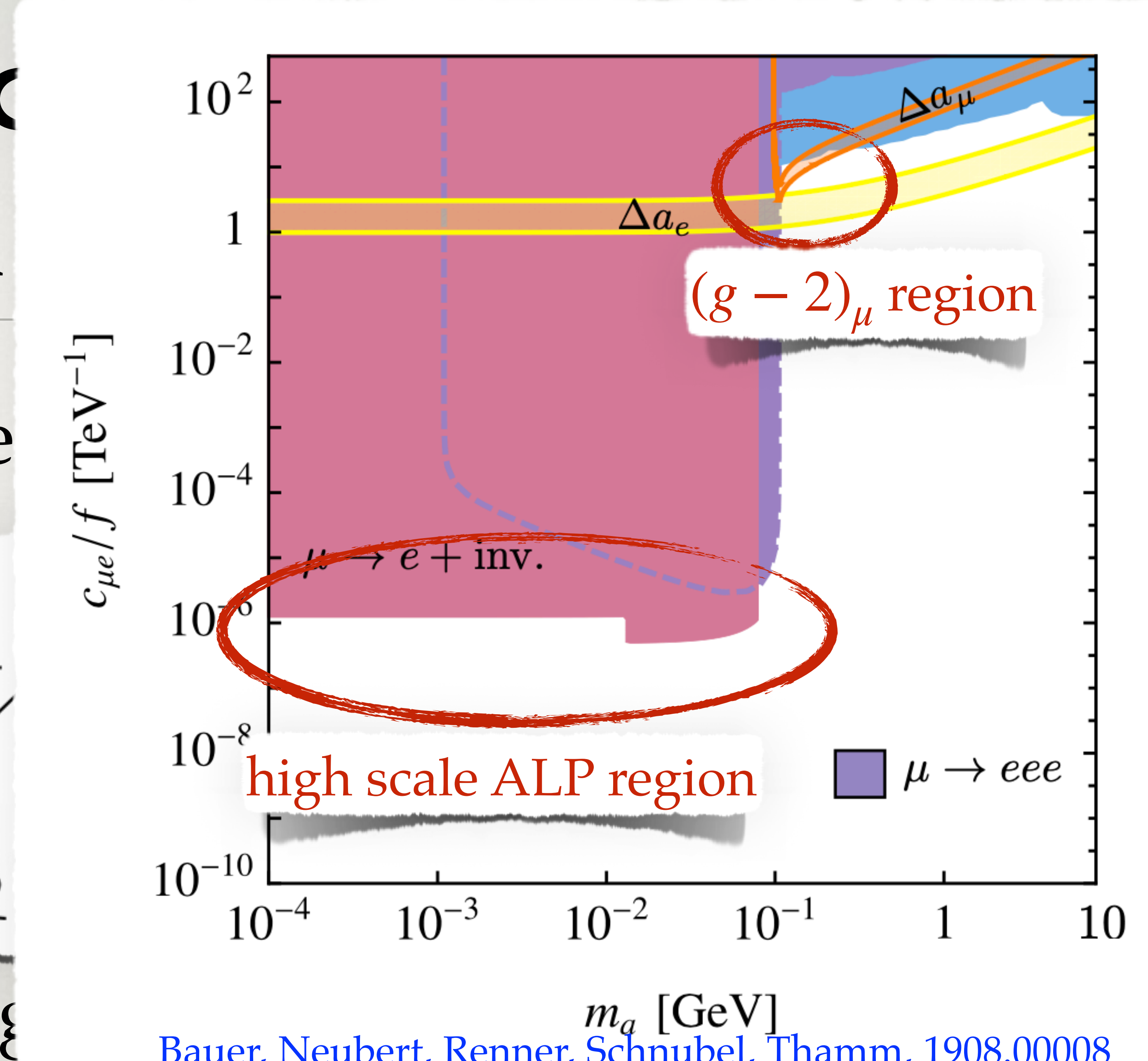
Brdar, Jana, Kubo, Lindner, 2104.03282

FLAVOR VIO... FOR...

- FV coupling $c^A_{e\mu}$ give...
  $m_a > m_\mu$





Bauer, Neubert, Renner, Schnubel, Thamm, 1908.00008

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Brdar, Jana, Kubo, Lindner, 2104.03282

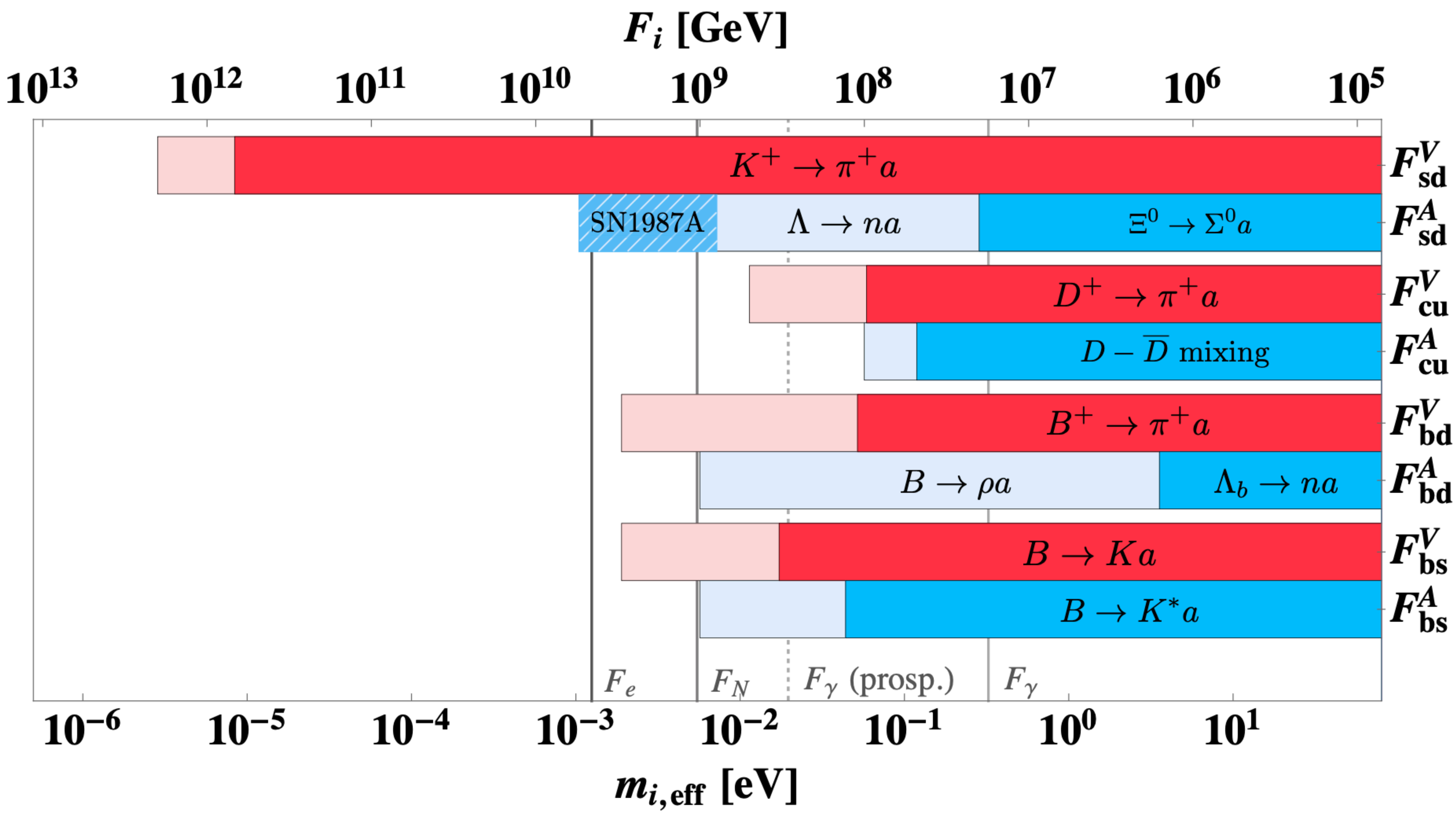
CONCLUDING REMARKS

- charged lepton flavor violating probes give us access to physics at very high scales
- both light and heavy NP of interest
- especially interesting in view of experimental anomalies involving muons

BACKUP SLIDES

THE STRONGEST FV CONSTRAINTS

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



- show several examples of LFV ALP
    - LFV QCD axion
    - LFV axiflavon
    - leptonic familon
    - majoron

LFV QCD axion

- DFSZ-like model: 2HDM+S: $X_S = 1, X_{H_2} = 2 + X_{H_1}$
- flavor universal $U(1)_{\rm PQ}$ charges in quark sector, non-universal in leptonic

Yukawa coupl. to H_1 — Yukawa coupl. to H_2

$$y_e = \begin{pmatrix} 0 & x & x \\ x & 0 & 0 \\ x & 0 & 0 \end{pmatrix}, \quad y_e' = \begin{pmatrix} 0 & 0 & 0 \\ 0 & x & x \\ 0 & x & x \end{pmatrix}$$

⇒ gives lepton FV coupl.s of axion

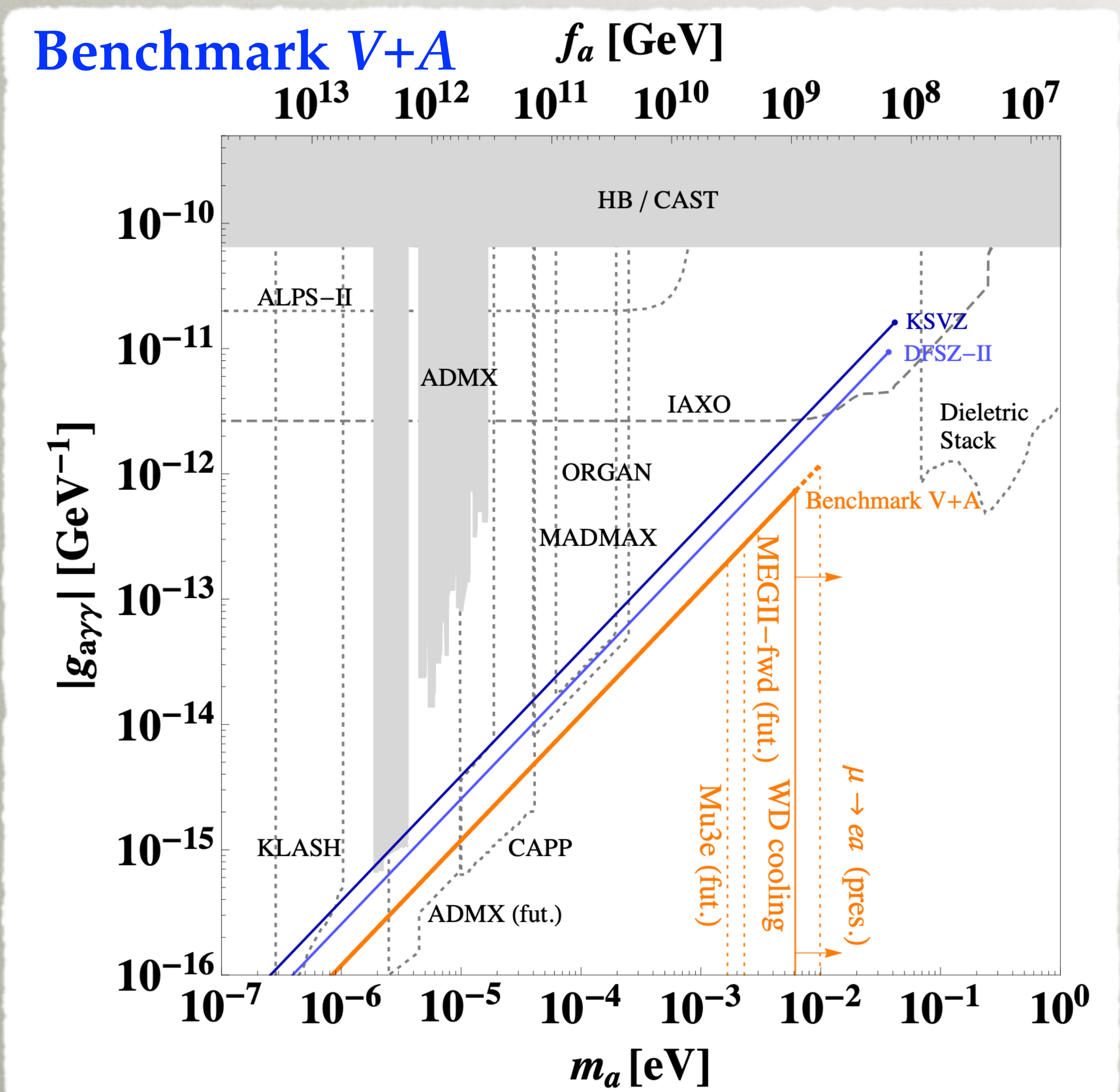
$$y_u = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}, \quad y_d = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

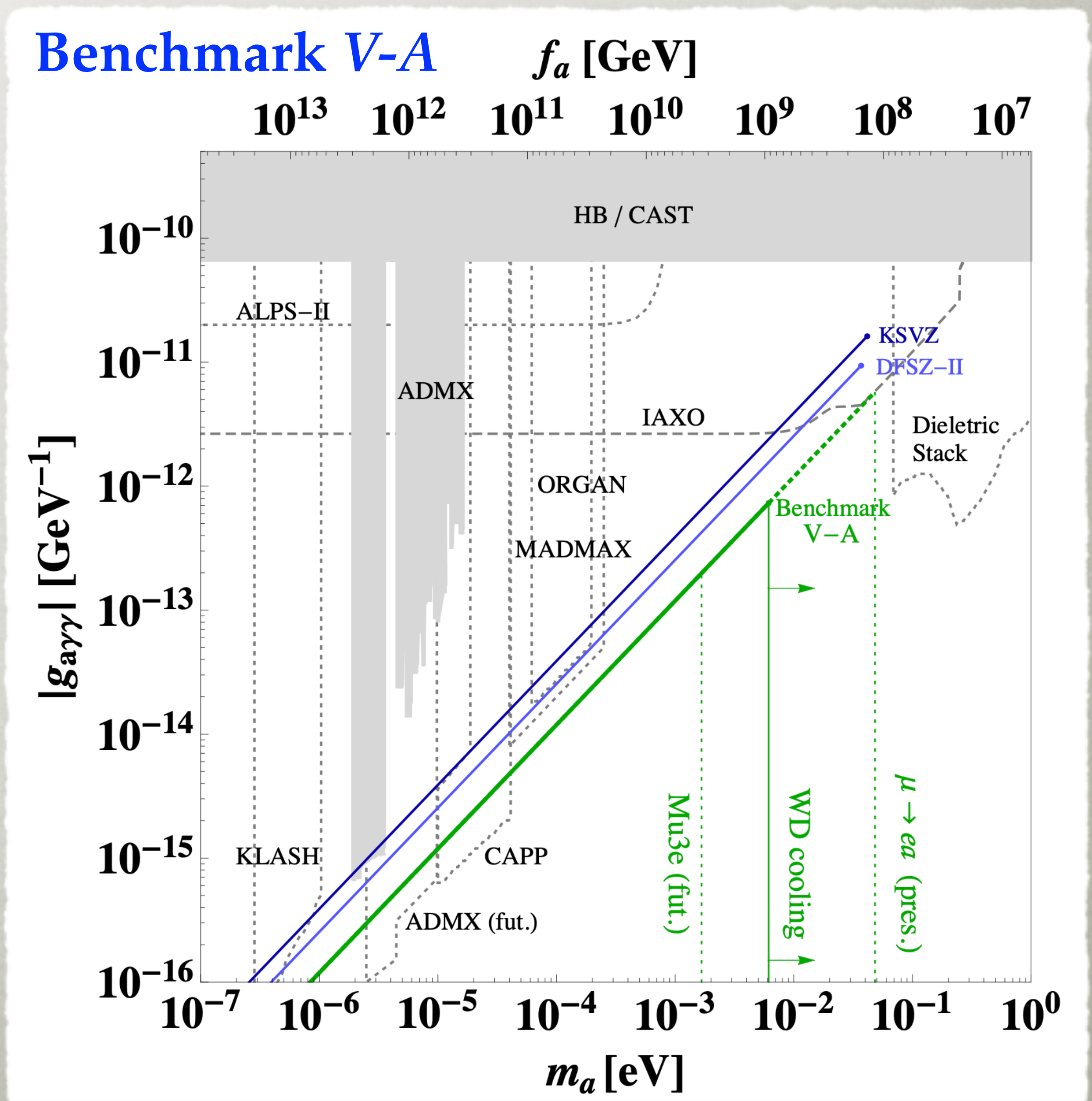
⇒ axion-quark couplings flavor diagonal

- hierarchy of entries external input

LFV QCD axion

- two benchmarks, assume just 1-2 mixing





LEPTONIC FAMILON

- separate Froggatt-Nielsen U(1) for quarks and leptons
  - leptonic f_a scale assumed lighter ⇒ these couplings dominate
- two benchmark charge assignments

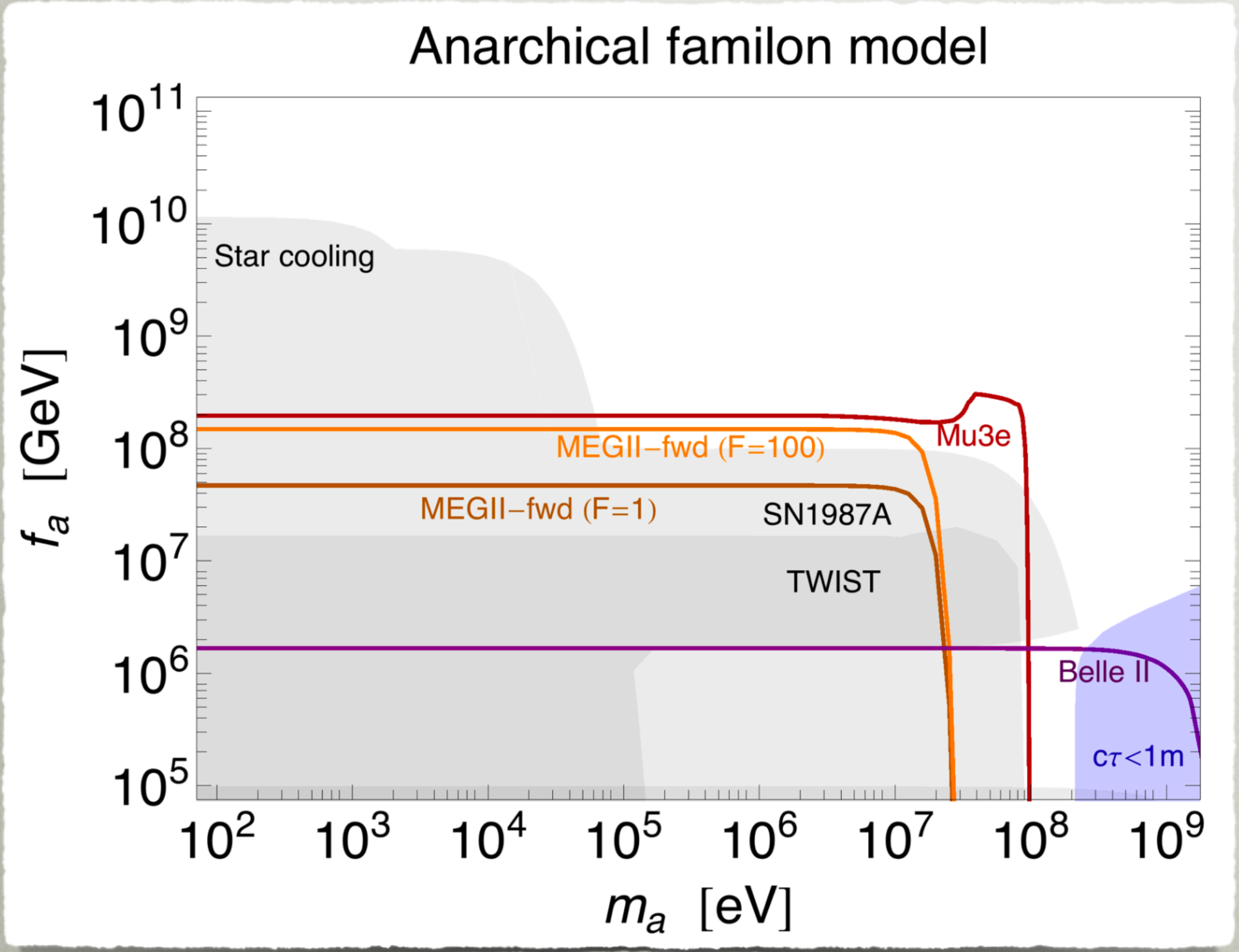
$$([L]_1, [L]_2, [L]_3) = (L, L, L), \qquad [\texttt{Pure Anarchy}].$$

⇒ RH ALP

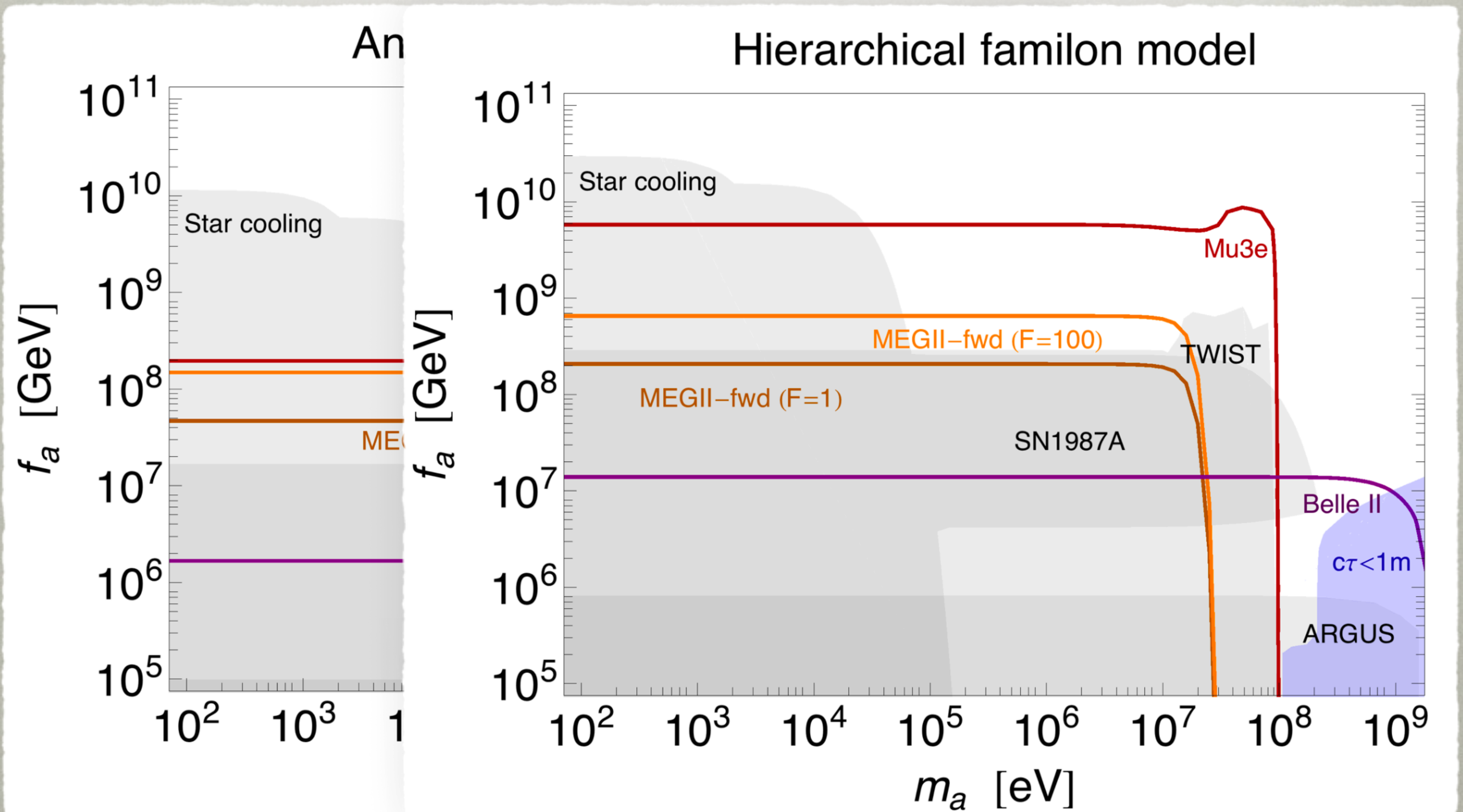
$$([L]_1, [L]_2, [L]_3) = (L+2, L+1, L), \qquad [\texttt{Hierarchy}].$$

⇒ LH and RH couplings

LEPTONIC FAMILON

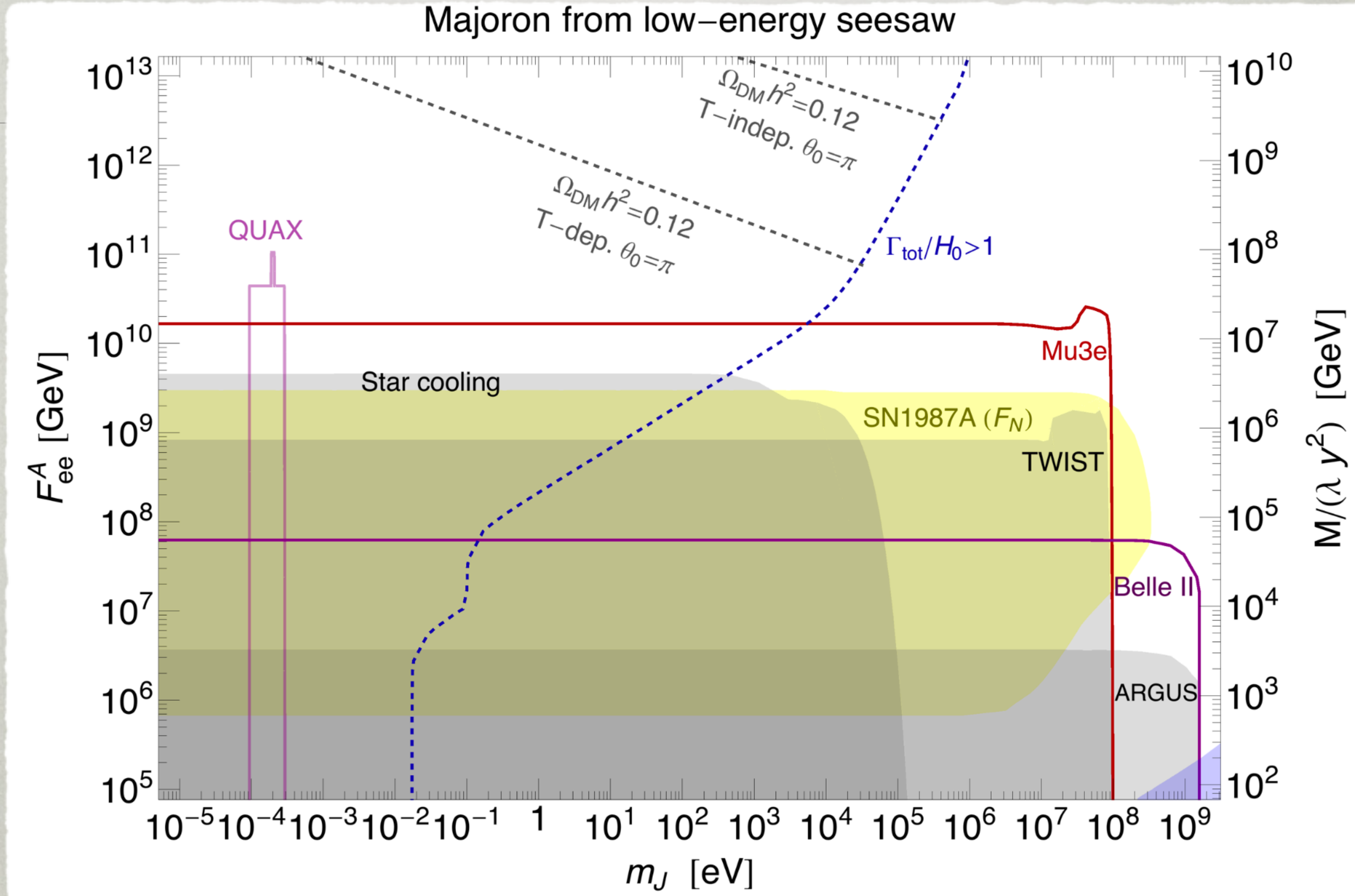


LEPTONIC FAMILON



MAJORON

- majoron- PNGB due to spontaneous breaking of the lepton number
- neutrino masses $m_\nu \propto y_\nu y_\nu^T v^2/m_N$
- majoron couplings, $C_{ij} \propto y_\nu y_\nu^\dagger$
- if m_ν suppressed by global U(1)
  - ⇒ majoron observable
  - "low energy see-saw"

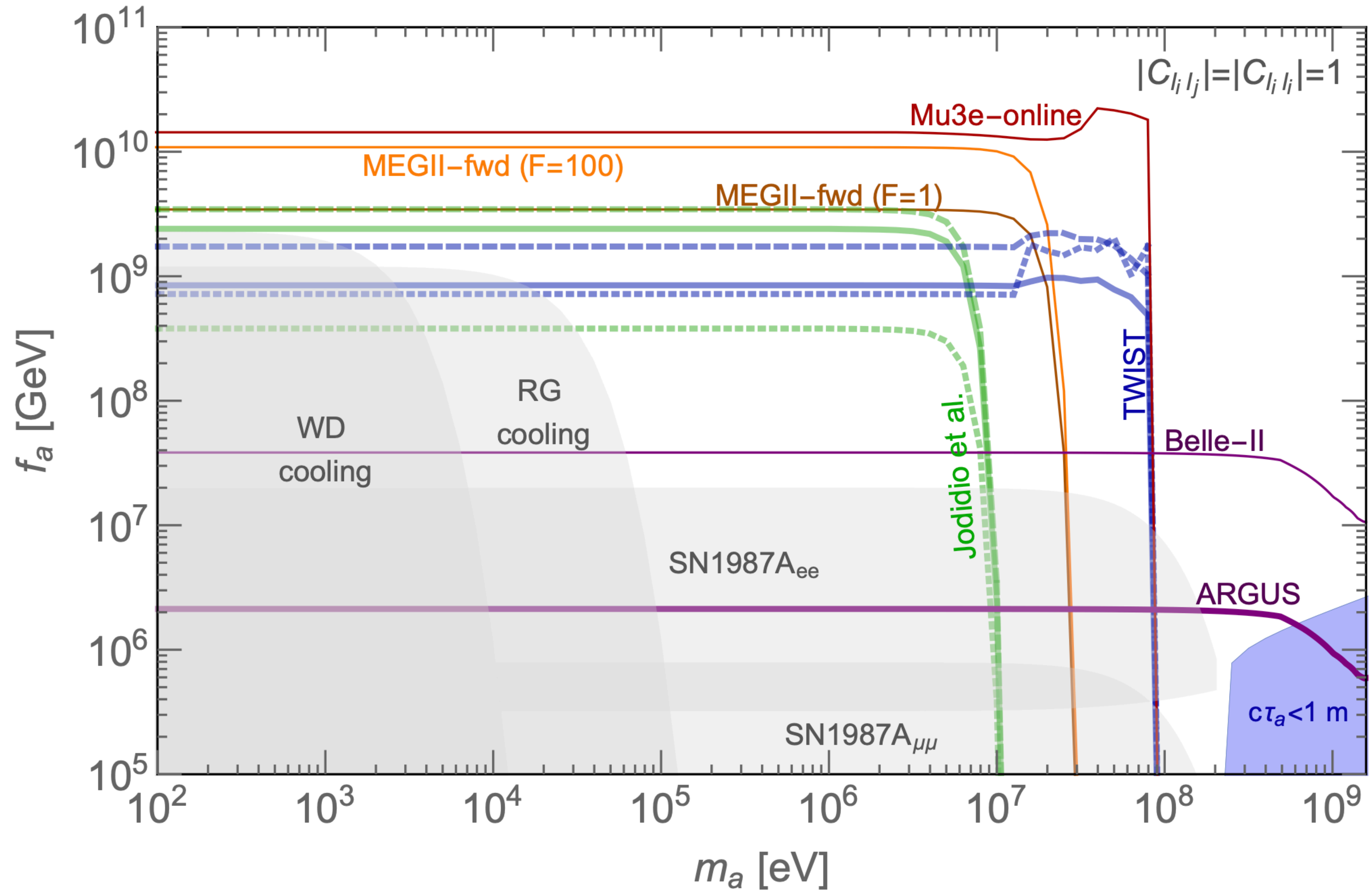


- "low energy see-saw"

ASTROPHYSICS BOUNDS

Raffelt, Weiss , hep-ph/9410205

- bounds on massless ALP-electron from red giants and white-dwarf cooling well known
  - due to $e^- + N \to e^- + N + a$
  - rescaled to nonzero ALP masses
- above $m_a \gtrsim 0.1$ MeV SN bounds become important
- also bounds on couplings to muons, but less severe



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- also bounds on couplings to muons, but less severe

CONNECTION TO BARYOGENESIS

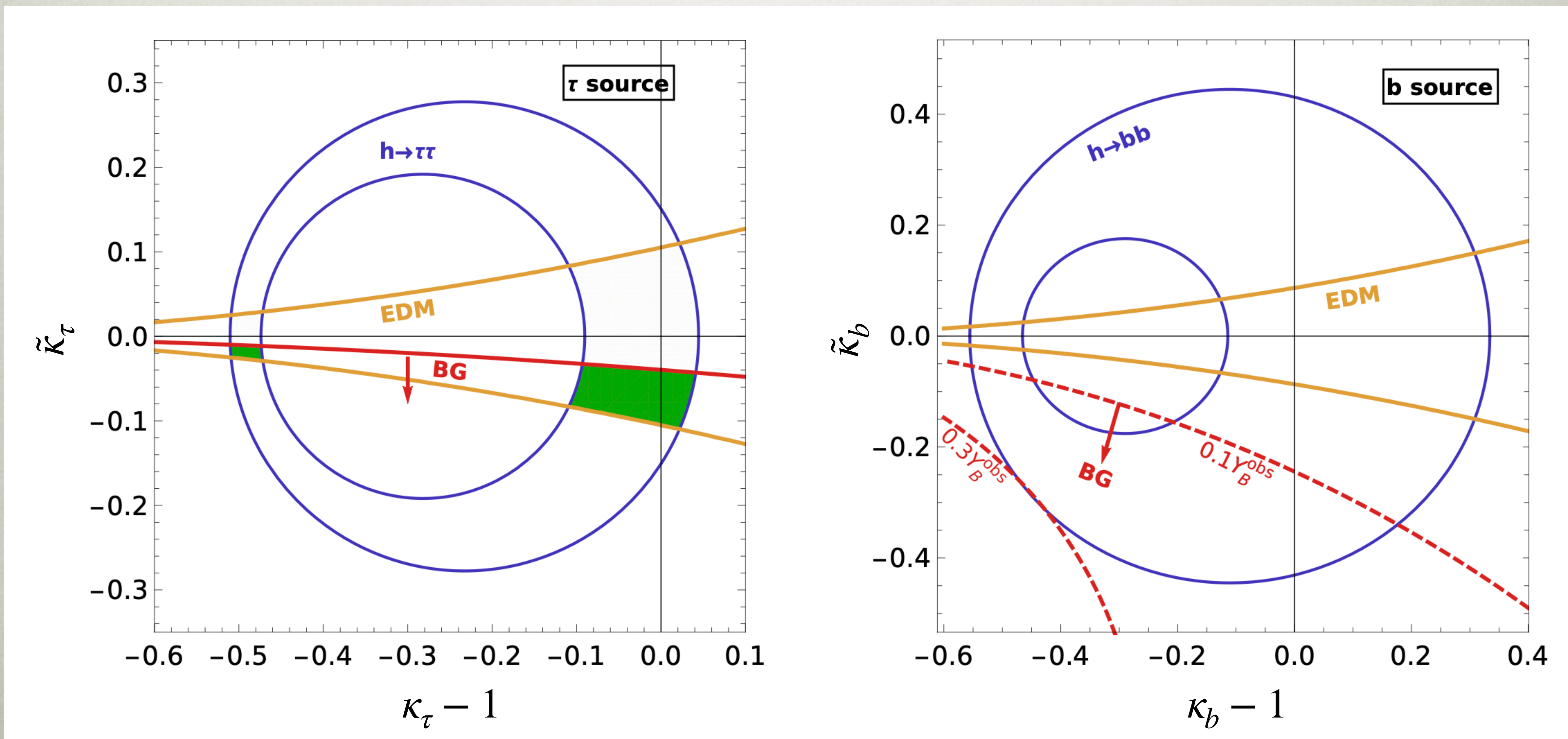
Fuchs, Losada, Nir, Viernik, 1911.08495, 2003.00099

- if EW baryogenesis assumed to be dominated by dim 6 Yukawas
  - $\Rightarrow$ lower limit on CPV Yukawas, κ_f
- additional assumptions:
  - there are additional d.o.f.s that give strongly first-order EWPT
  - these do not change SM fermion interact. in the bubble wall
  - no other (relevant) sources of CPV
- tau $\tilde{\kappa}_\tau \neq 0$ can explain EWBG, but not top or bottom
  - reduced wash-out since no strong sphalerons for tau lepton
  - large lepton diffusion coeffs. lead to efficient diffusion of baryon assmymetry intto the broke phase
  - overcompensate the smaller τ-Yukawa coupling

CONNECTION TO BARYOGENESIS

Fuchs, Losada, Nir, Viernik, 2003.00099

- $\tilde{\kappa}_\tau \sim 0.01 - 0.1$ required for successful EWBG
- corresponds to $\Lambda/\sqrt{\lambda'_{\tau\tau}} \lesssim 18\ \text{TeV}\sqrt{0.01/\tilde{\kappa}_\tau}$

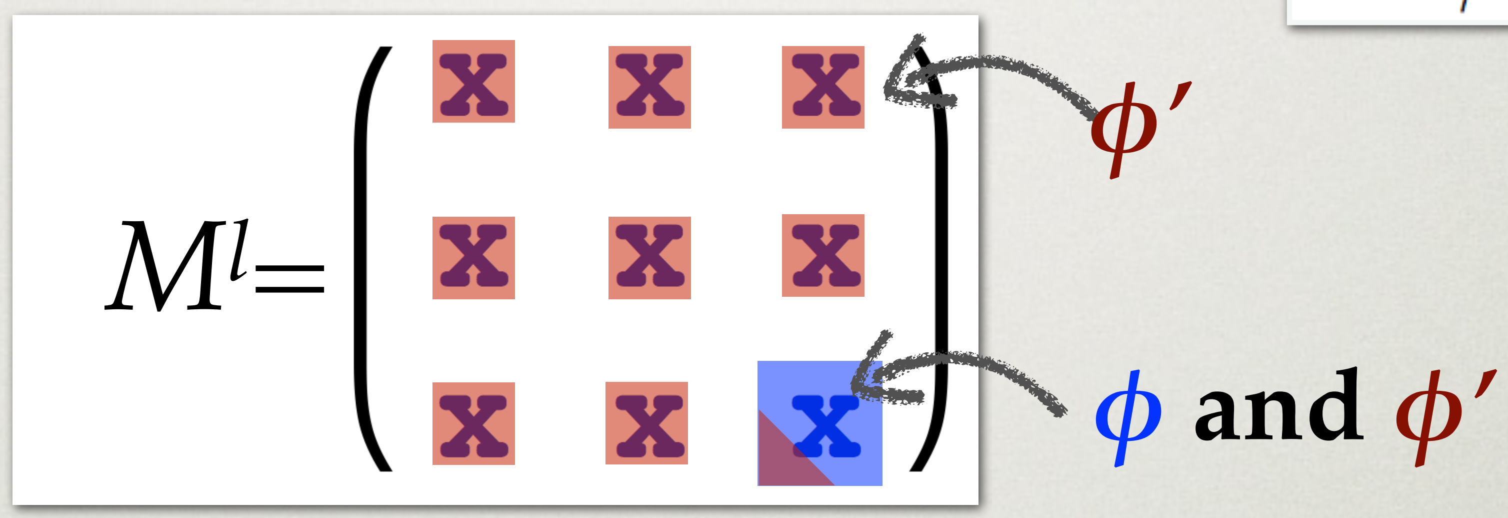


Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

2HDM EXAMPLE: SEQUESTERED MASS GENERATION

- two Higgs doublets, neutral compts: ϕ, ϕ',vevs v, v'
  - ϕ couples to 3rd family, ϕ' to all three

$\tan\beta = v/v'$



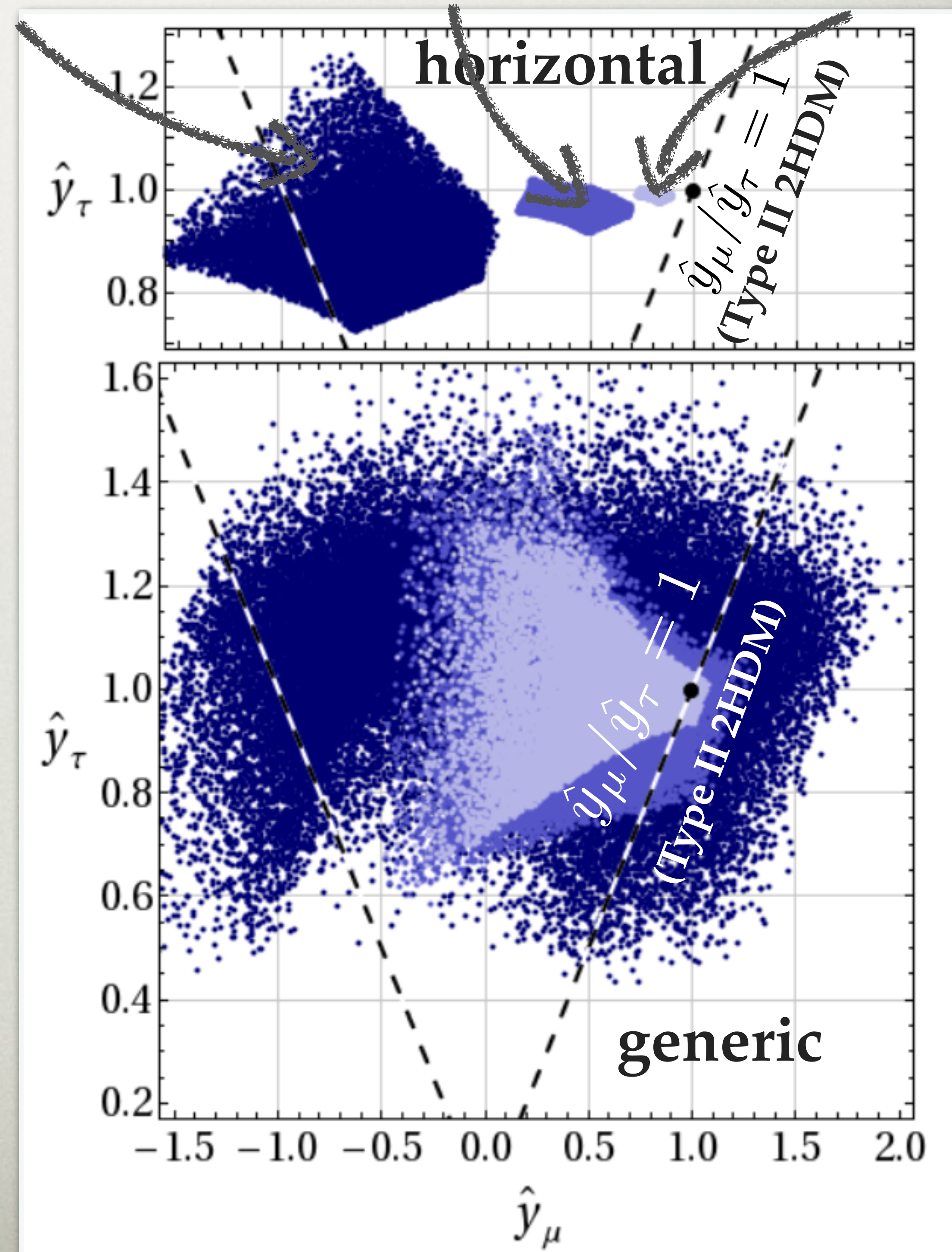
  - a hierarchy of vevs $v \gg v'$ can explain $m_\tau \gg m_\mu$
- consider two flavor structures for ϕ' contribs. to M^l
  - *"horizontal"*: only off-diagonal entries nonzero
  - *"generic"*: all m_{ij}' nonzero

Altmannshofer, Gori, Kagan, Silvestrini, JZ, 1507.07927

DIAGONAL YUKAWAS

- scanning over mass matrix entries and imposing:
  - that m_μ, m_τ are eigenvalues
  - the heavy Higgs xsec bounds
- ratios $\kappa_\mu < 1$ and $\kappa_\mu/\kappa_\tau < 1$ favored
- sizeable flavor violating $Br(h \to \tau\mu)$

CMS: $Br(h \to \tau\mu) < 0.15\,\%$



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