BASICS OF LEPTON FLAVOR VIOLATION

Jure Zupan
U. of Cincinnati

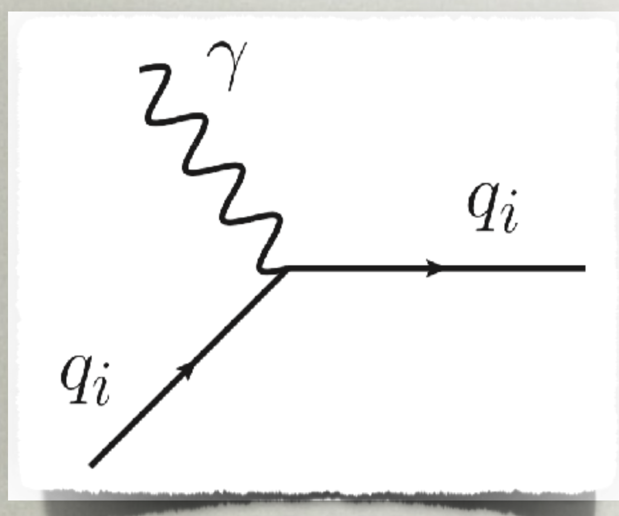
2024 Belle II Physics Week, KEK, Oct 17 2024

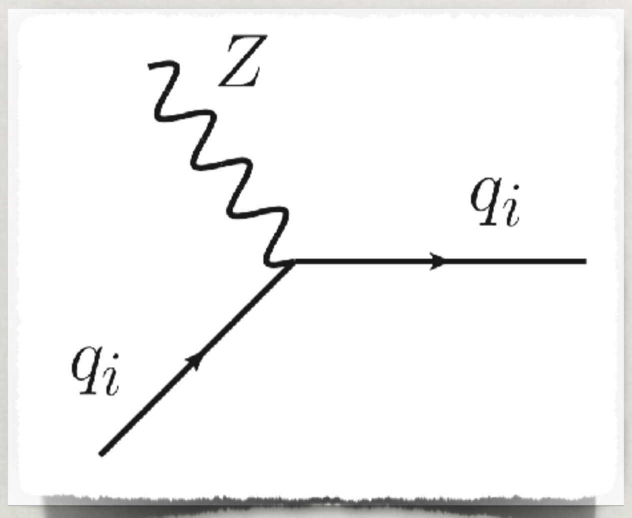
USEFUL REFERENCES

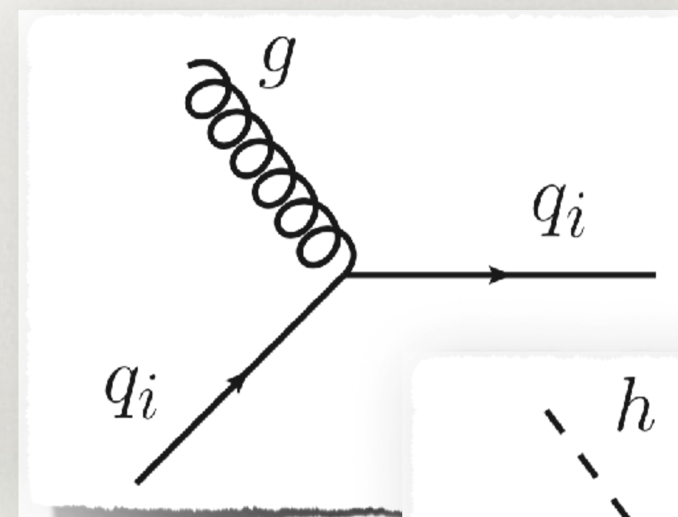
- some general introductions to flavor physics
  - Nir, 0708.1872, 1605.00433
  - Grossman, Tanedo, 1711.03624
  - JZ, 1903.05062
  - ...
- on lepton flavor violation
  - Calibbi, Sirognelli, 1709.00294
  - Ardu, Pezzullo, 2204.08220

FLAVOR IN THE SM QUARK SECTOR

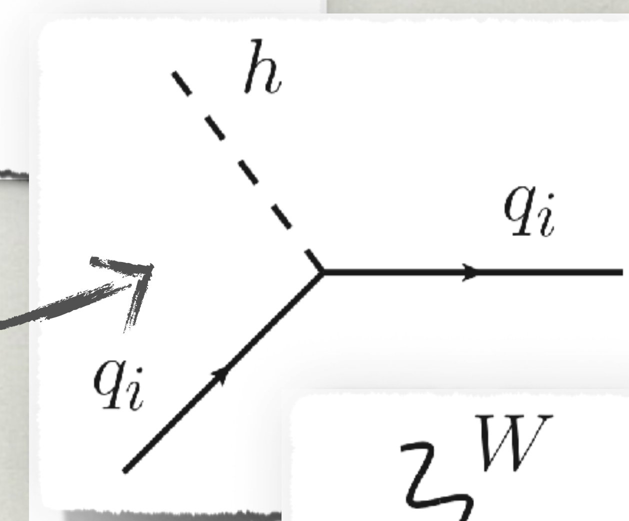
- neutral currents are flavor conserving (at tree level)
  - photon, gluon, *Z:* have *flavor (generation) universal* interactions



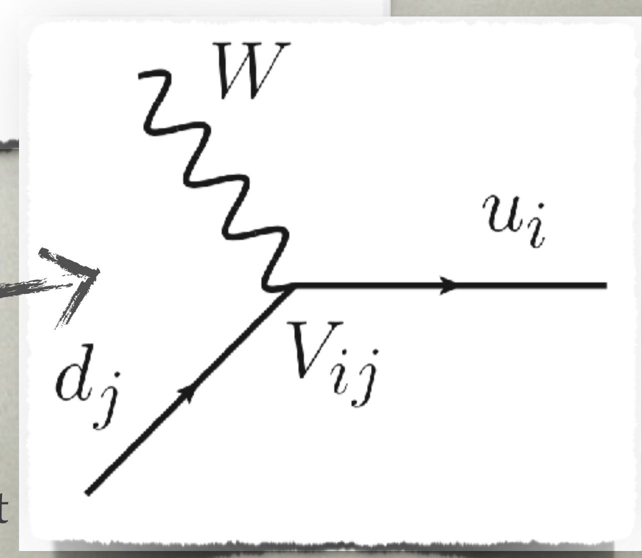




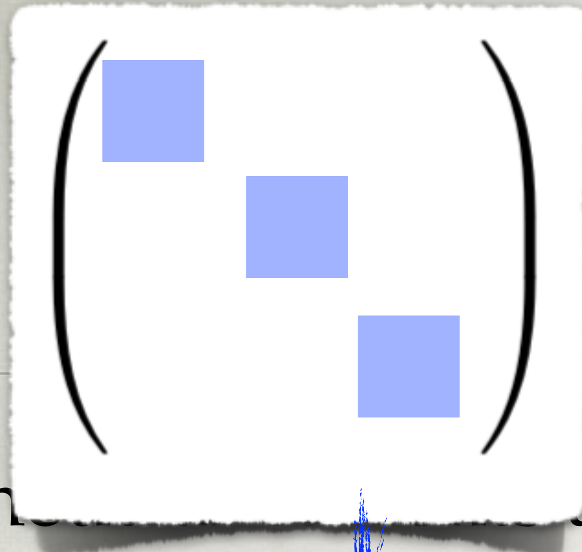
  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass



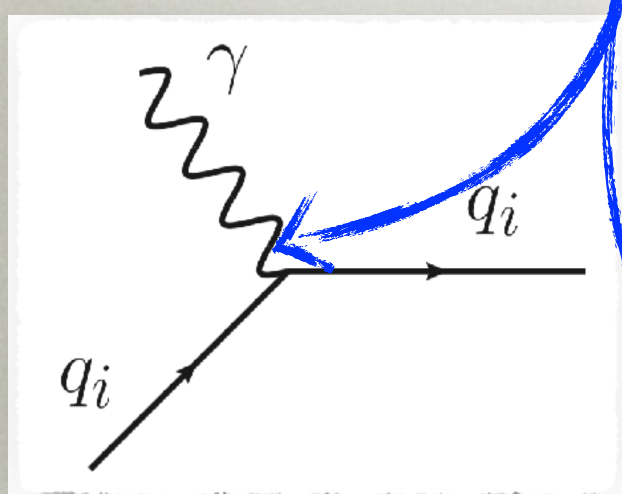
- charged currents are *flavor changing*
  - *W* couplings are flavor changing

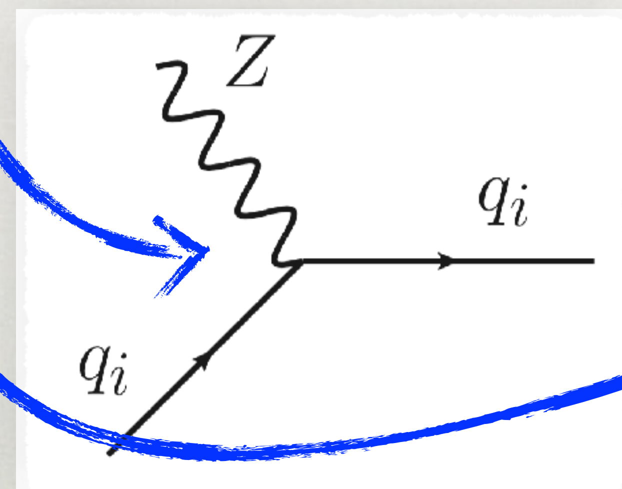


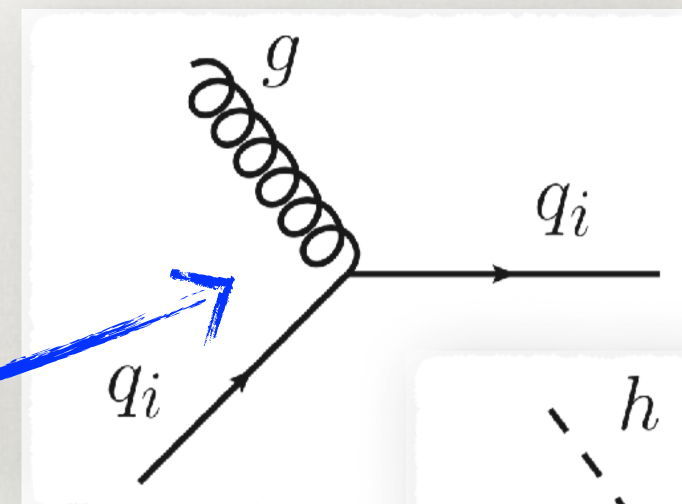
…vor in the SM …uark sector



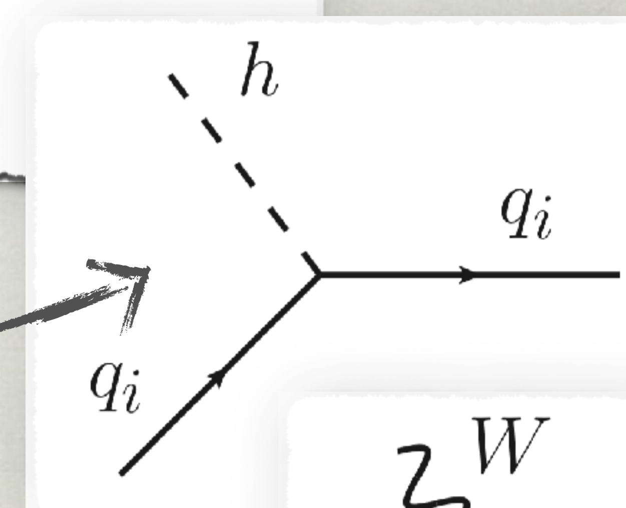
- n… are flavor conserving (at tree level)
  - photon, gluon, *Z*: have *flavor (generation) universal* interactions



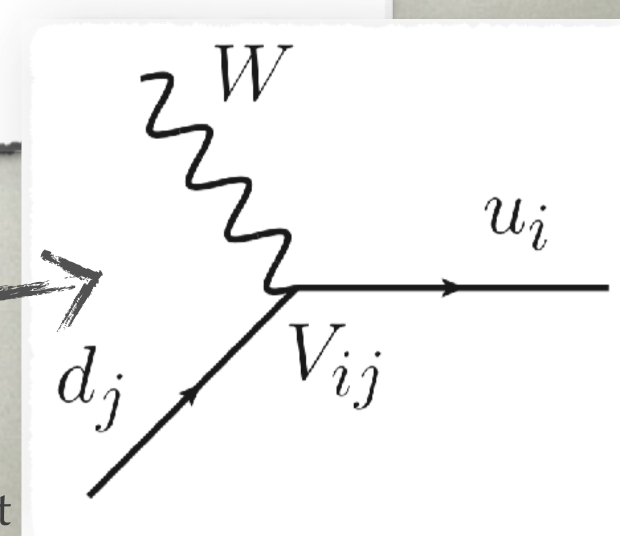




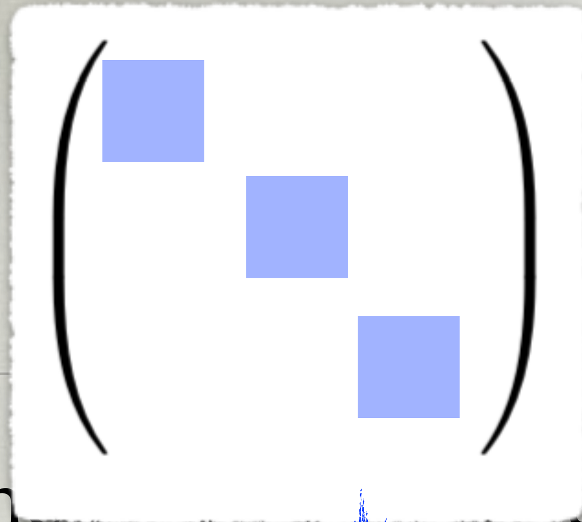
  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass

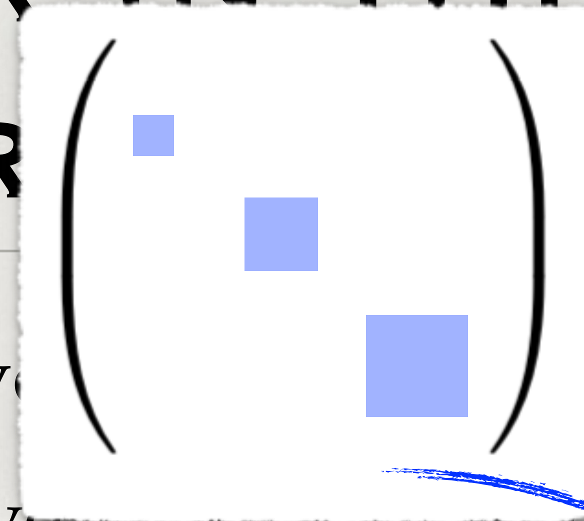


- charged currents are *flavor changing*
  - *W* couplings are flavor changing

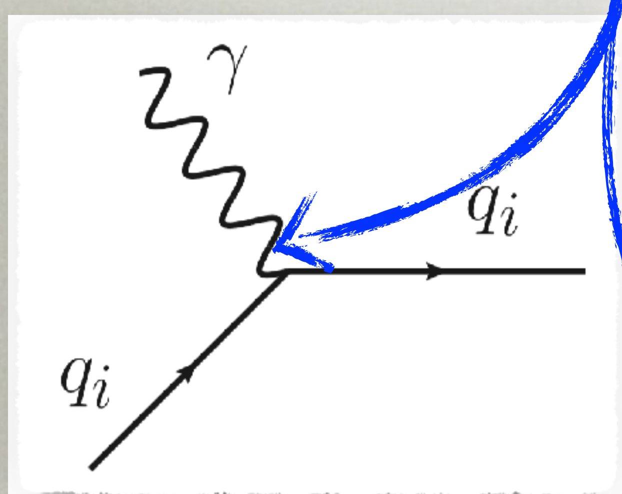


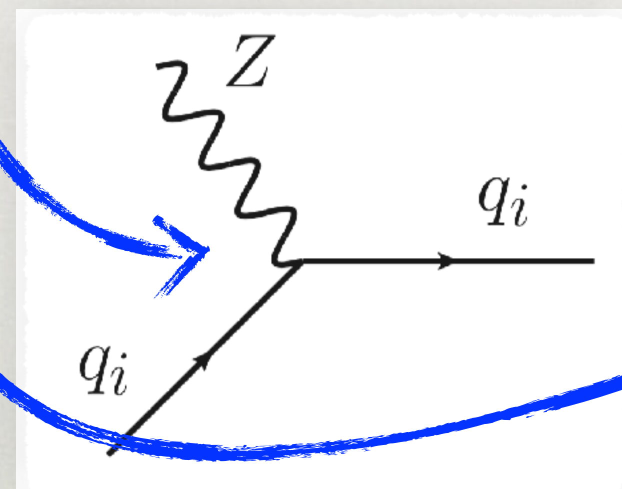
VOR IN THE SM
JAR OR

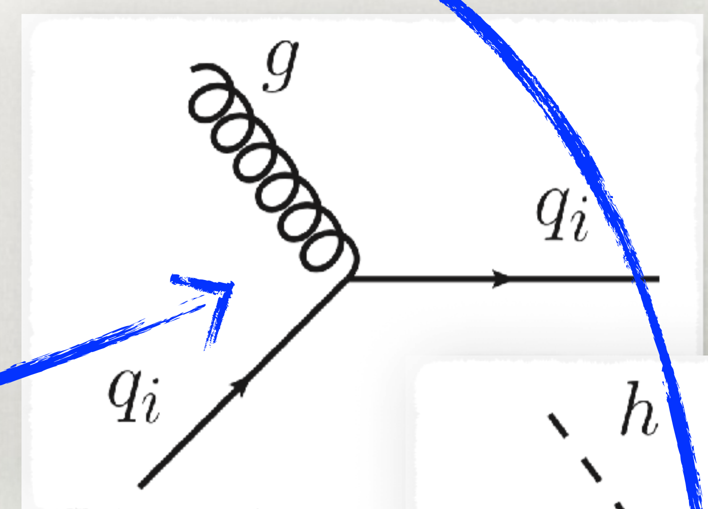




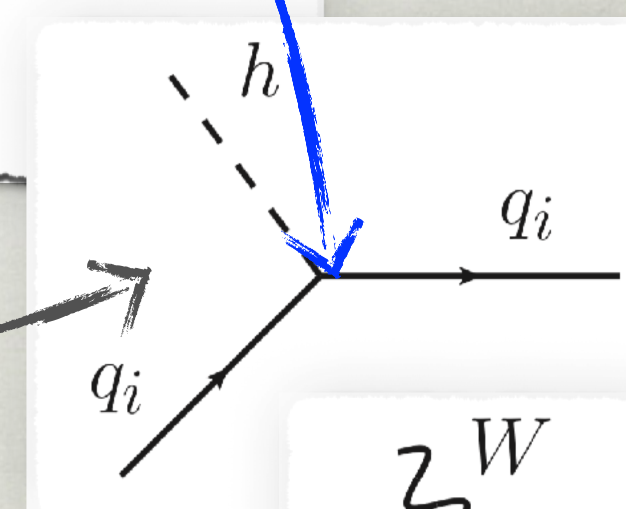
- n… are flav… t tree level)
  - photon, gluon, *Z*: have *flavor (generation)* *universal* interactions



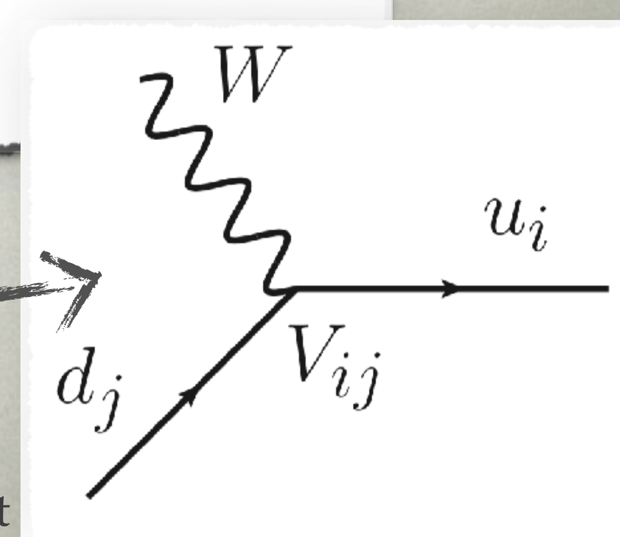




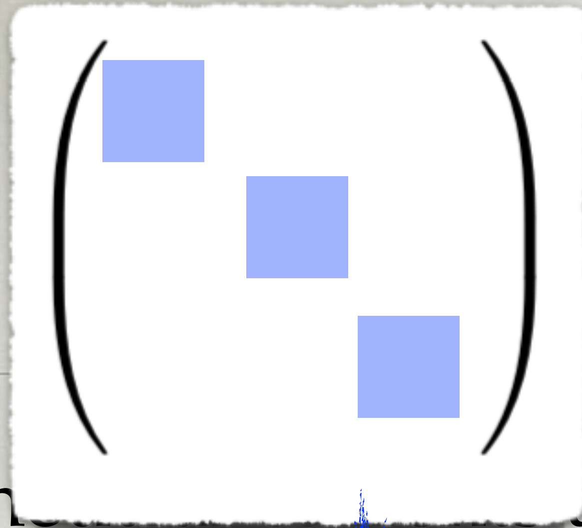
  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass

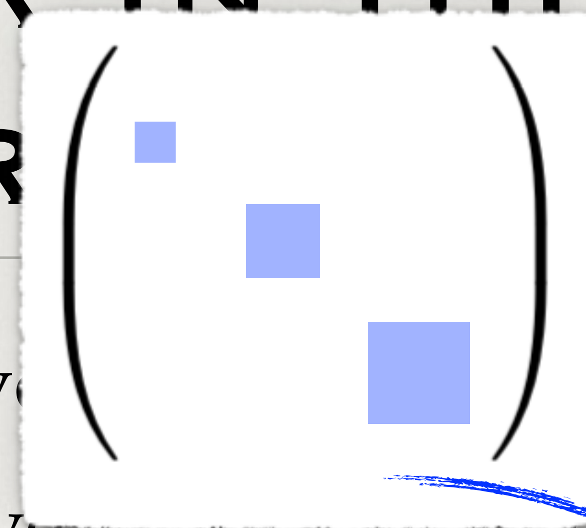


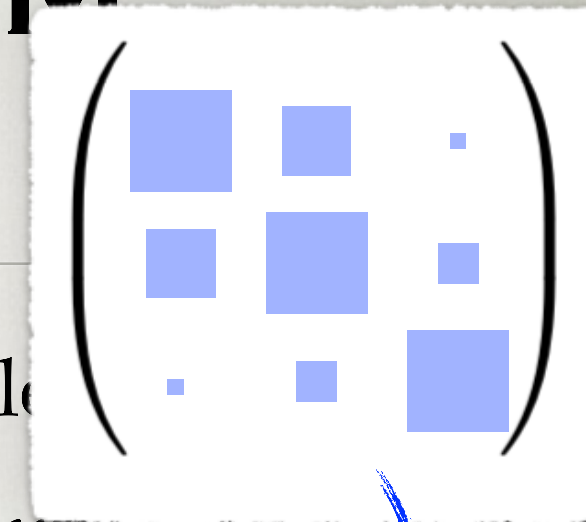
- charged currents are *flavor changing*
  - *W* couplings are flavor changing



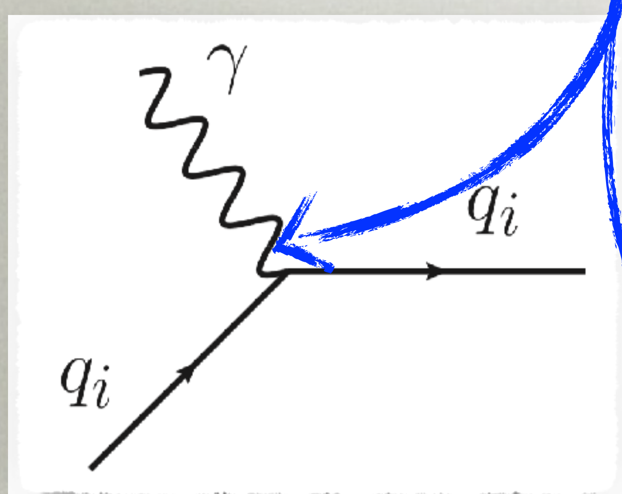
...VOR IN THE SM
...UAR ... OR

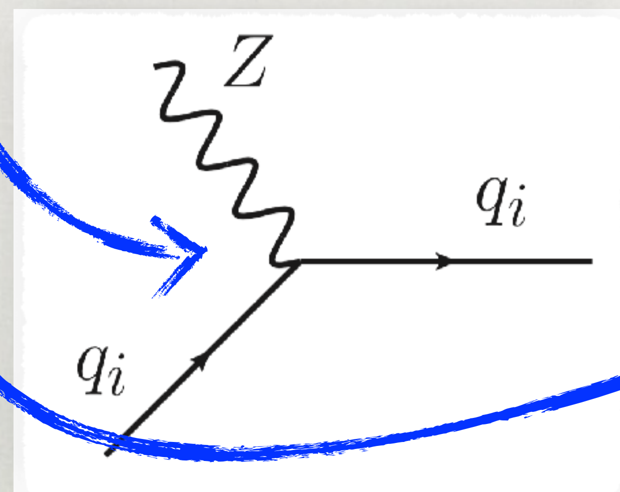


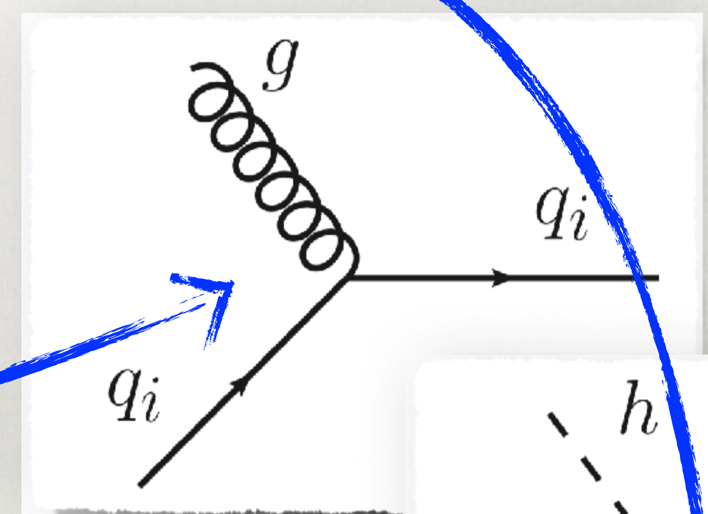




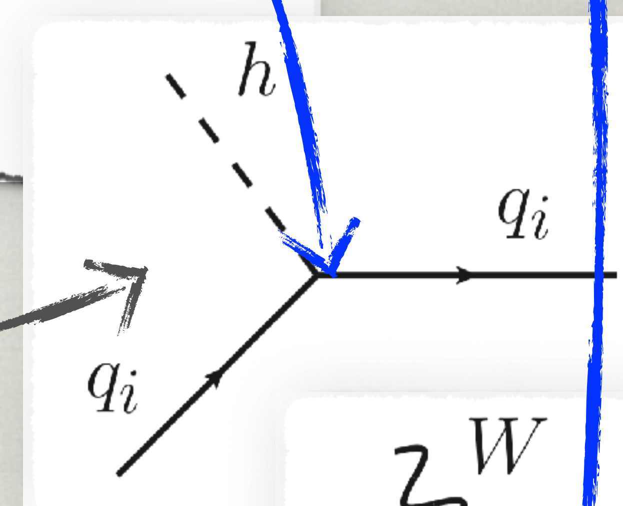
- n... are flav... t tree le...
  - photon, gluon, *Z*: have ... *universal* interactions



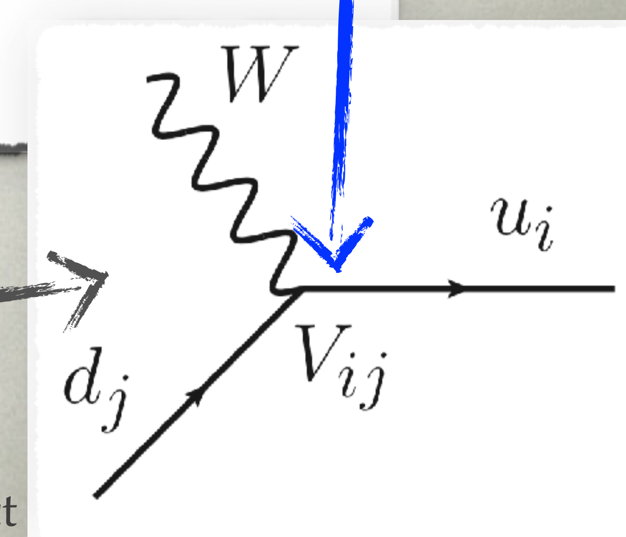




  - Higgs has *flavor diagonal* interactions
    - proportional to quark mass



- charged currents are *flavor changing*
  - *W* couplings are flavor changing

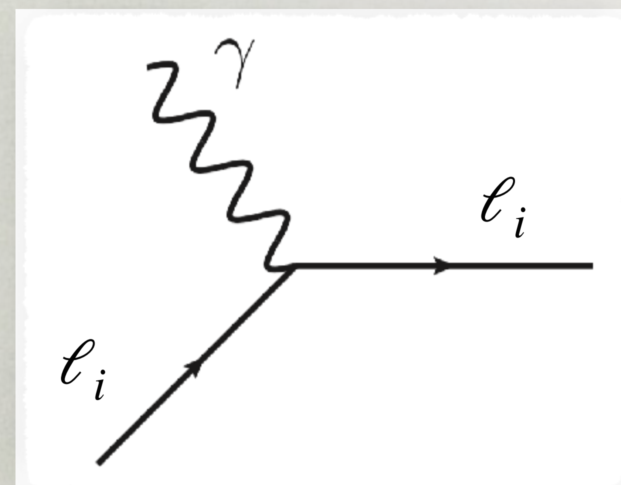


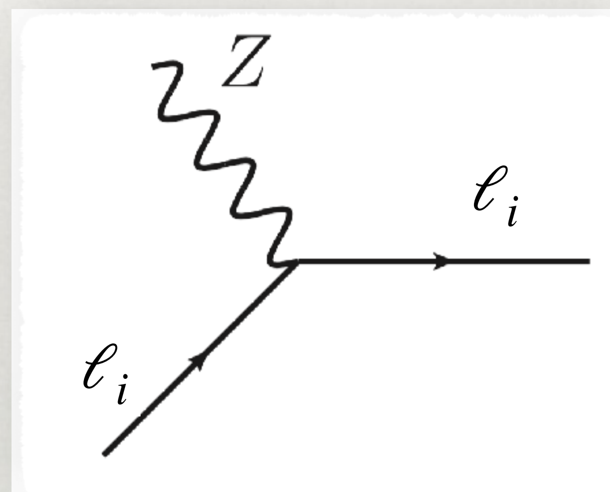
LEPTONS

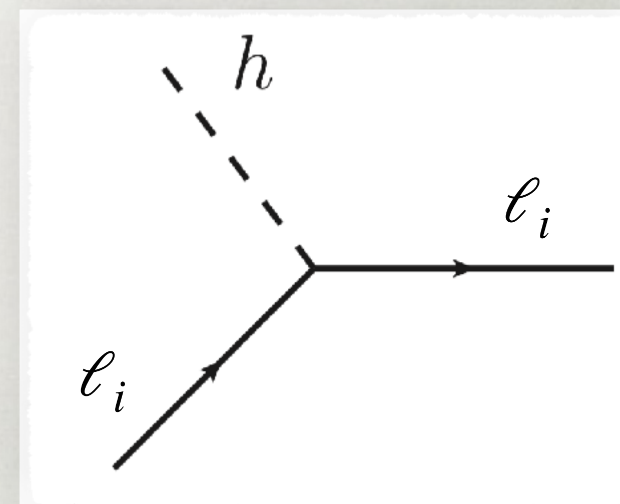
- first assume that neutrino masses are zero
- extremelly good approximation in
  - collider experiments, meson decays, charged lepton decays,...
  - in each of these: $E \gg m_\nu$

LEPTONS

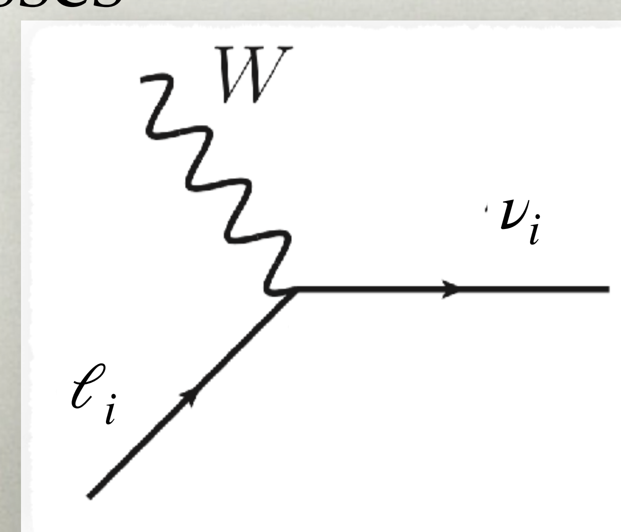
- ⇒ in SM with massless ν no leptonic FCNCs
  - photon, *Z: flavor (generation) universal* interactions

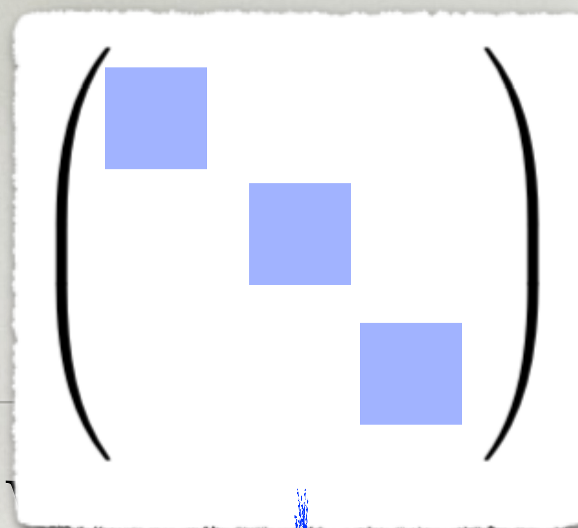






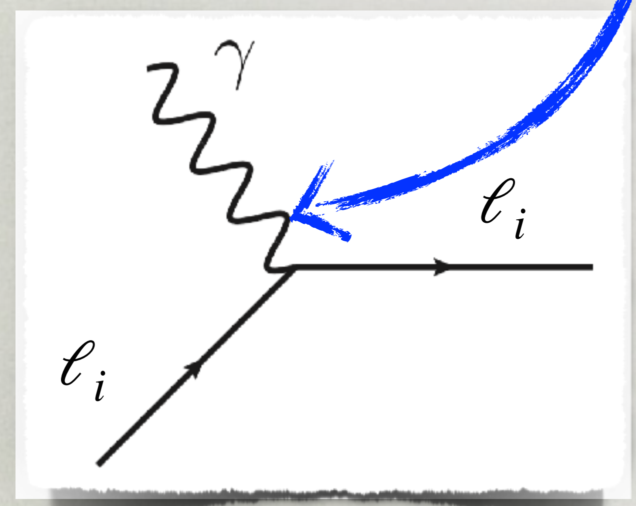
  - Higgs has *flavor diagonal* interactions
    - proportional to lepton masses
- charged currents (*W* couplings) are *flavor universal*

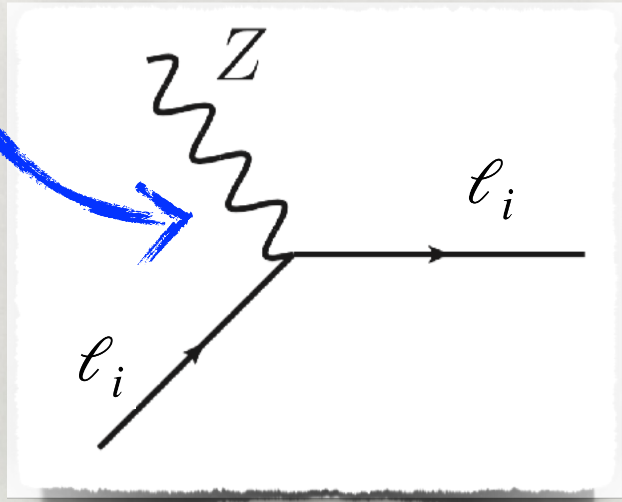


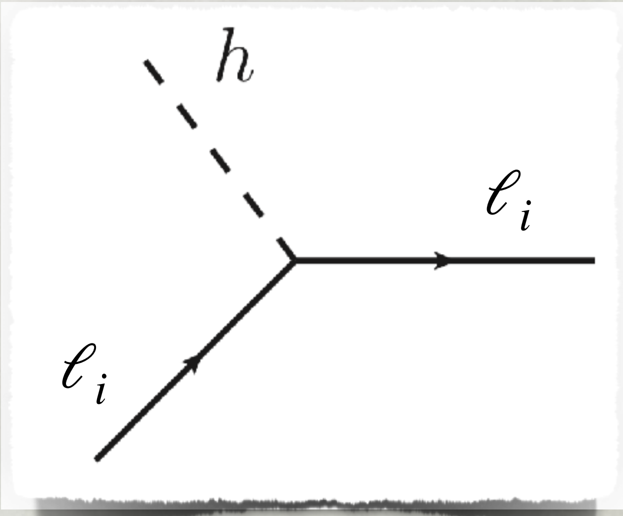


PTONS

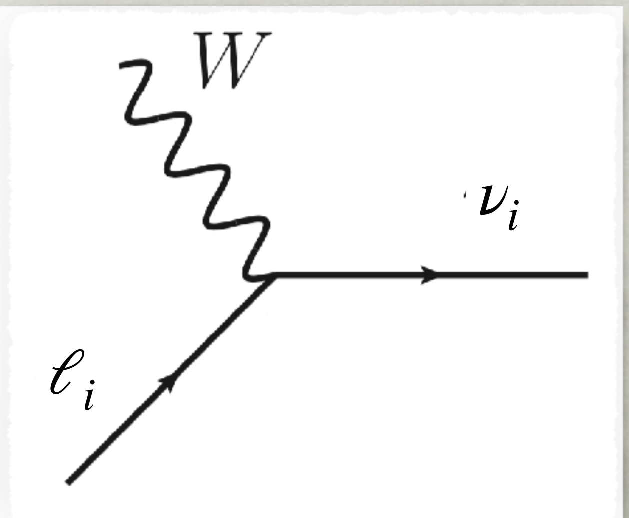
- ⇒ in SM no leptonic FCNCs
  - photon, *Z: flavor (generation) universal* interactions

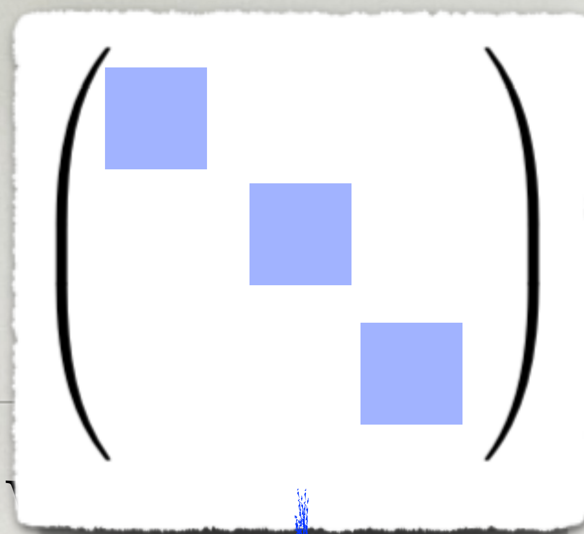




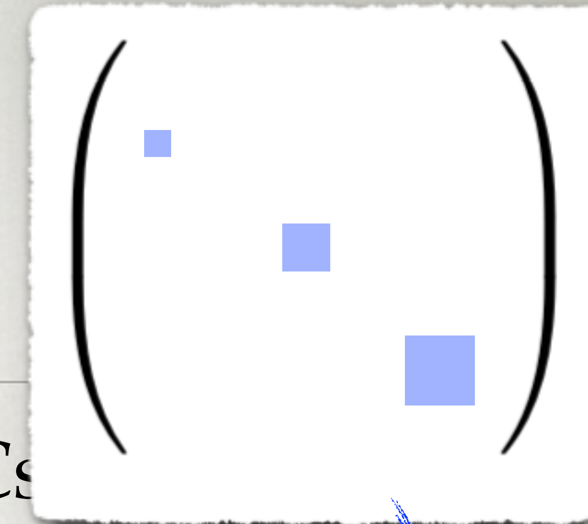


  - Higgs has *flavor diagonal* interactions
    - proportional to lepton masses
- charged currents (*W* couplings) are *flavor universal*

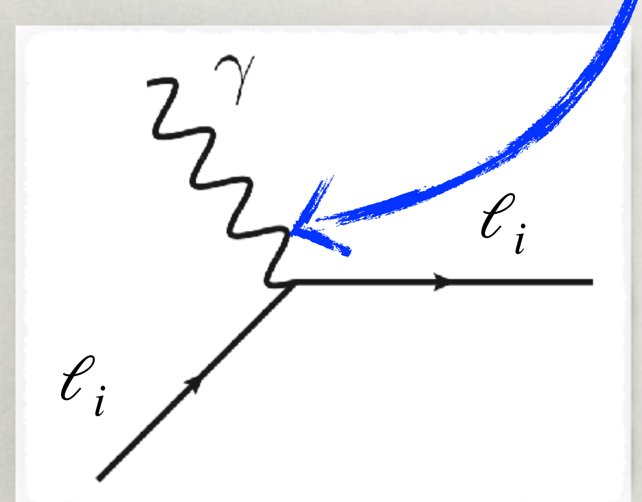


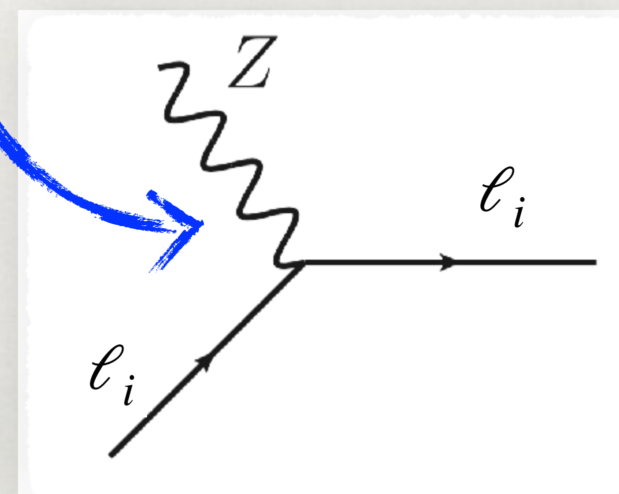


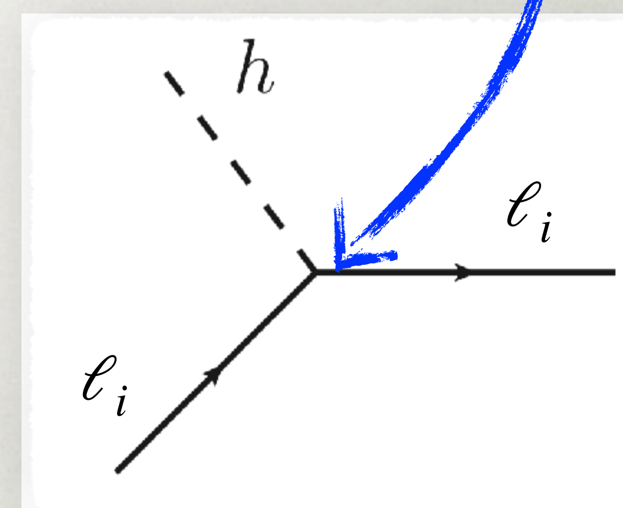
PTONS



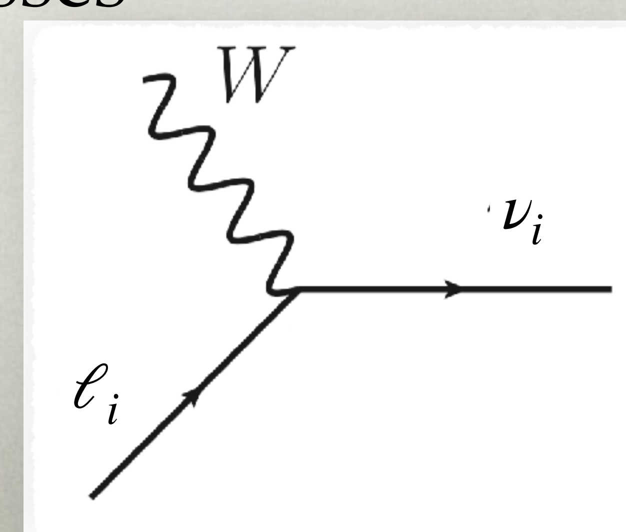
- ⇒ in SM no leptonic FCNCs
  - photon, *Z: flavor (generation) universal* interactions



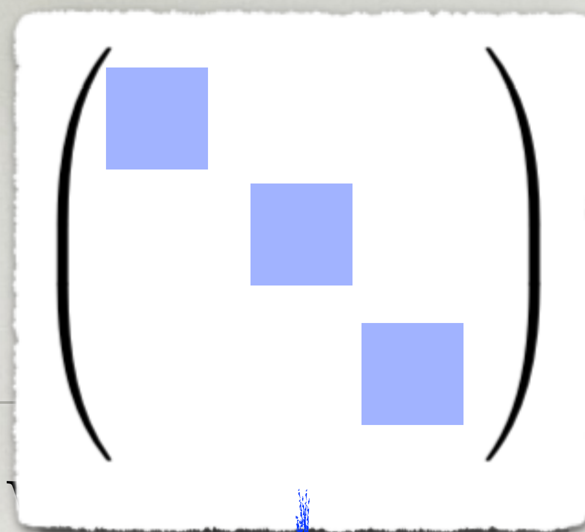


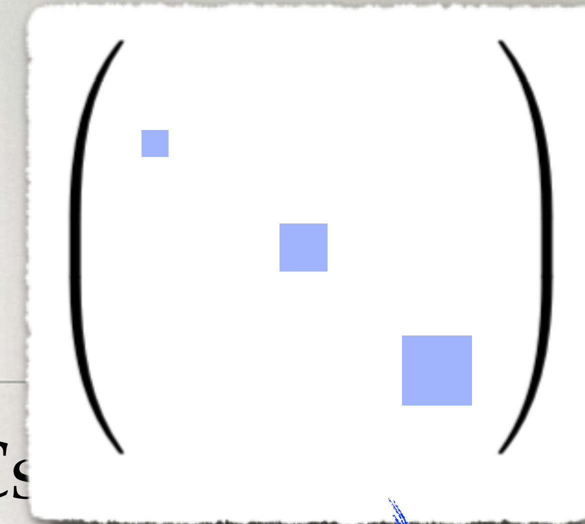


  - Higgs has *flavor diagonal* interactions
    - proportional to lepton masses
- charged currents (*W* couplings) are *flavor universal*

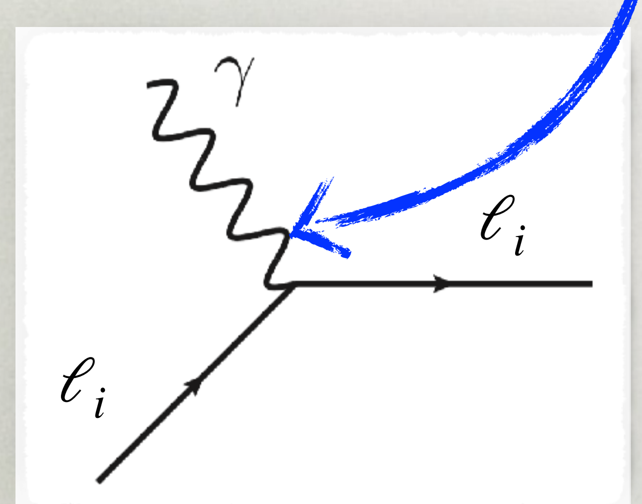


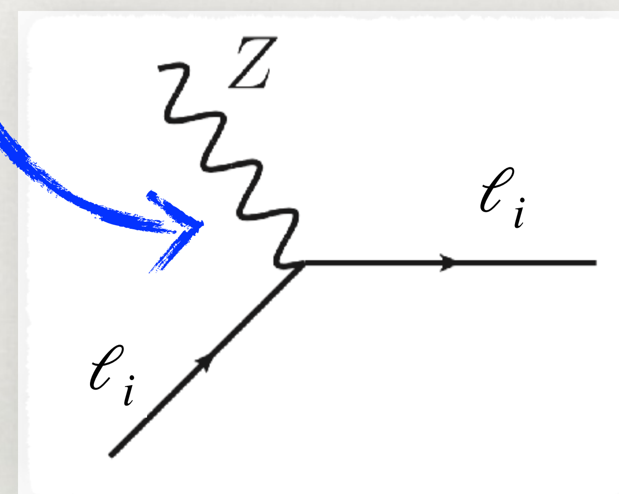
…PTONS

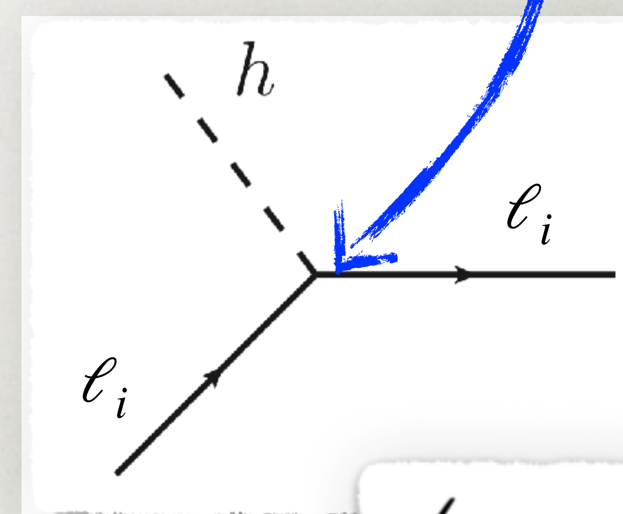


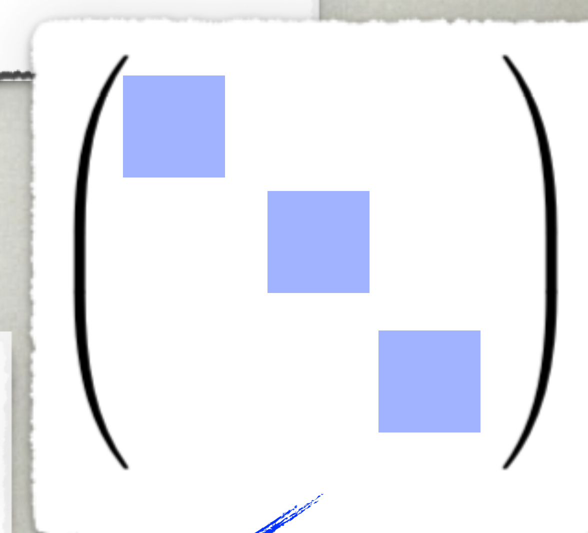


- ⇒ in SM … no leptonic FCNCs
  - photon, *Z: flavor (generation) universal* interactions

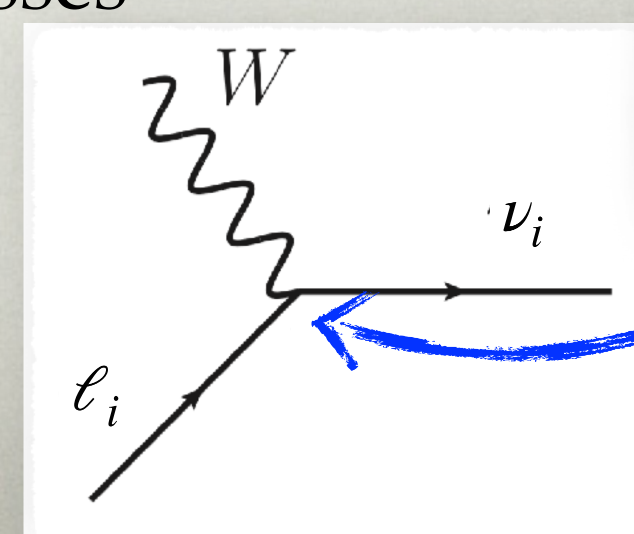








  - Higgs has *flavor diagonal* interactions
    - proportional to lepton masses
- charged currents (*W* couplings) are *flavor universal*



LEPTONS

- this means that for $m_\nu = 0$ in the SM
  - $Br(\mu^+ \to e^+e^-e^+) = 0$
  - $Br(\mu^+ \to e^+\gamma) = 0$
  - $Br(\tau^+ \to \mu^+\mu^-\mu^+) = 0$
  - $Br(\tau^+ \to \mu^+\rho^0) = 0$
  - ...

LEPTONS

- agrees well with stringent experimental bounds in PDG
  - $Br(\mu^+ \to e^+ e^- e^+) < 1.0 \times 10^{-12}$
  - $Br(\mu^+ \to e^+ \gamma) < 4.2 \times 10^{-13}$
  - $Br(\tau^+ \to \mu^+ \mu^- \mu^+) < 2.1 \times 10^{-8}$
  - $Br(\tau^+ \to \mu^+ \rho^0) < 1.2 \times 10^{-8}$
  - ...

NEUTRINO MASSES

- however, neutrinos are not completely massless
  - at some level leptonic FCNCs will arise in the SM
- how much does $m_\nu \neq 0$ matter?
- in experiments we are interested in: not too much
  - corrections suppressed by $(m_\nu/E)^n \ll 1$
  - for instance for muon decays: $E \sim m_\mu \Rightarrow m_\nu/m_\mu < 10^{-9}$

NEUTRINO MASSES

- with *QUDL* field content m_ν forbidden in the SM
- two ways of introducing ν masses
  - *Dirac neutrinos:* add RH neutrino fields ν_R, singlets under SM + conserv. L

$$\mathcal{L}_{\rm Yukawa} \supset -Y_\nu^{ij}\bar L_L^i H^c \nu_R^j + {\rm h.c.}$$

3×3 complex

  - *Majorana neutrinos*: m_ν from dimension 5 Weinberg operator, is $\Delta L = 2$

$$\mathcal{L}_{\rm dim.\,5} \supset -\frac{1}{2}\frac{Y_\nu^{\prime ij}}{\Lambda}\big(\bar L_L^{ci} H^c\big)\big(H^{c*} L_L^j\big) + {\rm h.c.}$$

3×3 symm., complex

- counting of physical parameters slightly differs in the two cases
  - in both cases weak (flavor) eigenstates are linear superpositions of mass eigenstates

$$\nu_{aL} = \sum_{i=1}^{3} U_{ai}\nu_{iL}, \qquad a = e,\mu,\tau$$

PMNS matrix

PMNS matrix

- canonical form of the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix

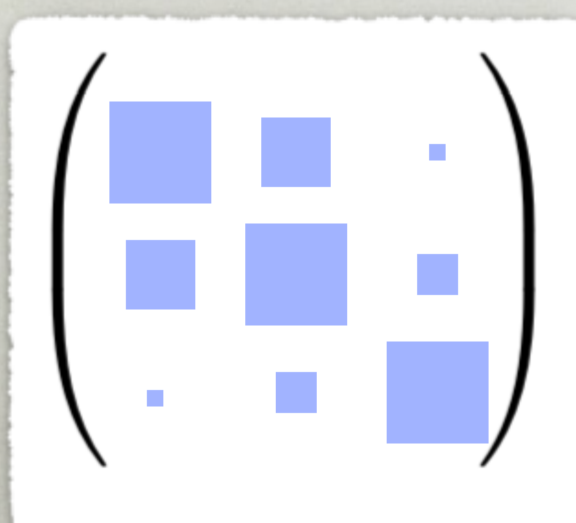
$$U = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix} \times P$$

- P matrix takes the form:
  - $P = 1$ for Dirac neutrinos
  - $P = \text{diag}\,(1, e^{i\alpha_{21}}, e^{i\alpha_{31}})$ for Majorana ν's

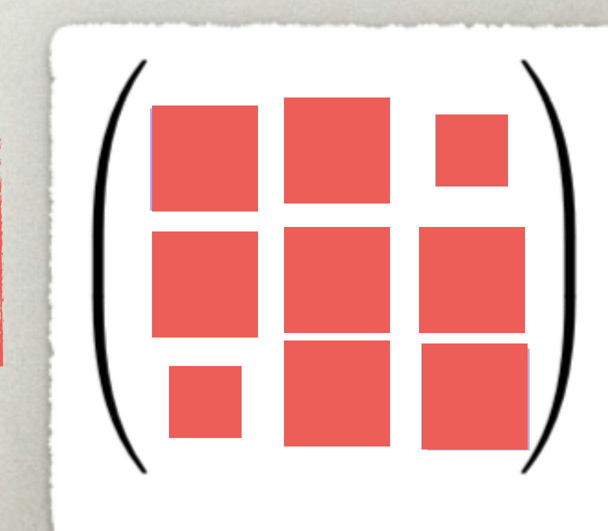
PMNS matrix

- assuming "normal ordering": $m_3 > m_2 > m_1$
  $m_2^2 - m_1^2 \sim (10^{-3}\,\mathrm{eV})^2$
  $m_3^2 - m_1^2 \sim (0.05\,\mathrm{eV})^2$
  $\sin\theta_{12} \sim \sin\theta_{23} \sim 0.5, \sin\theta_{13} \sim 0.15$
  $\delta, \alpha_{12}, \alpha_{13} = ?$

CKM matrix



PMNS matrix



$\mu \to e\gamma$ IN THE SM

- we already know that $\mu \to e\gamma$ vanishes for massless neutrinos
  - GIM mechanism very effective in LFV transitions
  - amplitude proportional to $A(\mu \to e\gamma) \propto m_\nu^2$

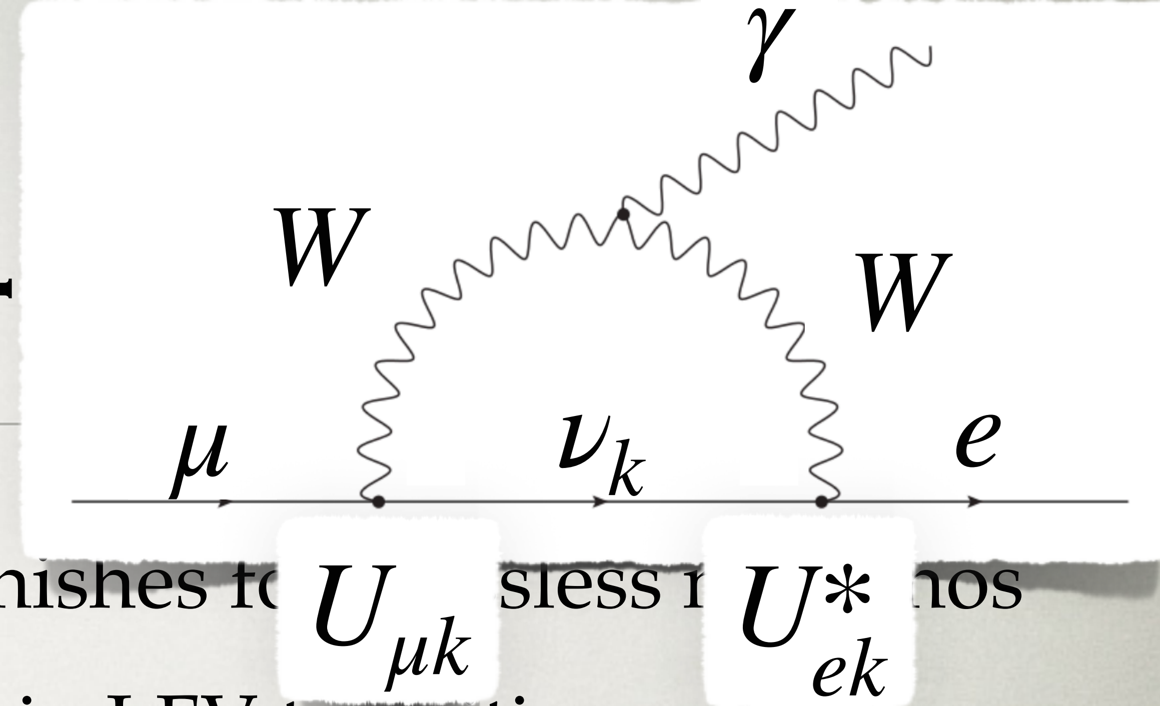
Very small !!!

$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi}\left|\sum_{k=1,3}\frac{U_{\mu k}U^*_{ek}m^2_{\nu_k}}{M_W^2}\right|^2 .$$

$$\mathrm{BR}(\mu \to e\gamma) = 10^{-55} \div 10^{-54}$$

  - similar suppressions for $\mu \to 3e, \tau \to 3\mu, \mu \to e, \ldots$
- for charged LFV transitions SM is well below experimental reach
  - if found, a clear signal of new physics

$\mu \to e\gamma$ IN T[...]



- we already know that $\mu \to e\gamma$ vanishes fo[...] sless n[...] nos
  - GIM mechanism very effective in LFV transitions
  - amplitude proportional to $A(\mu \to e\gamma) \propto m_\nu^2$

Very small !!!

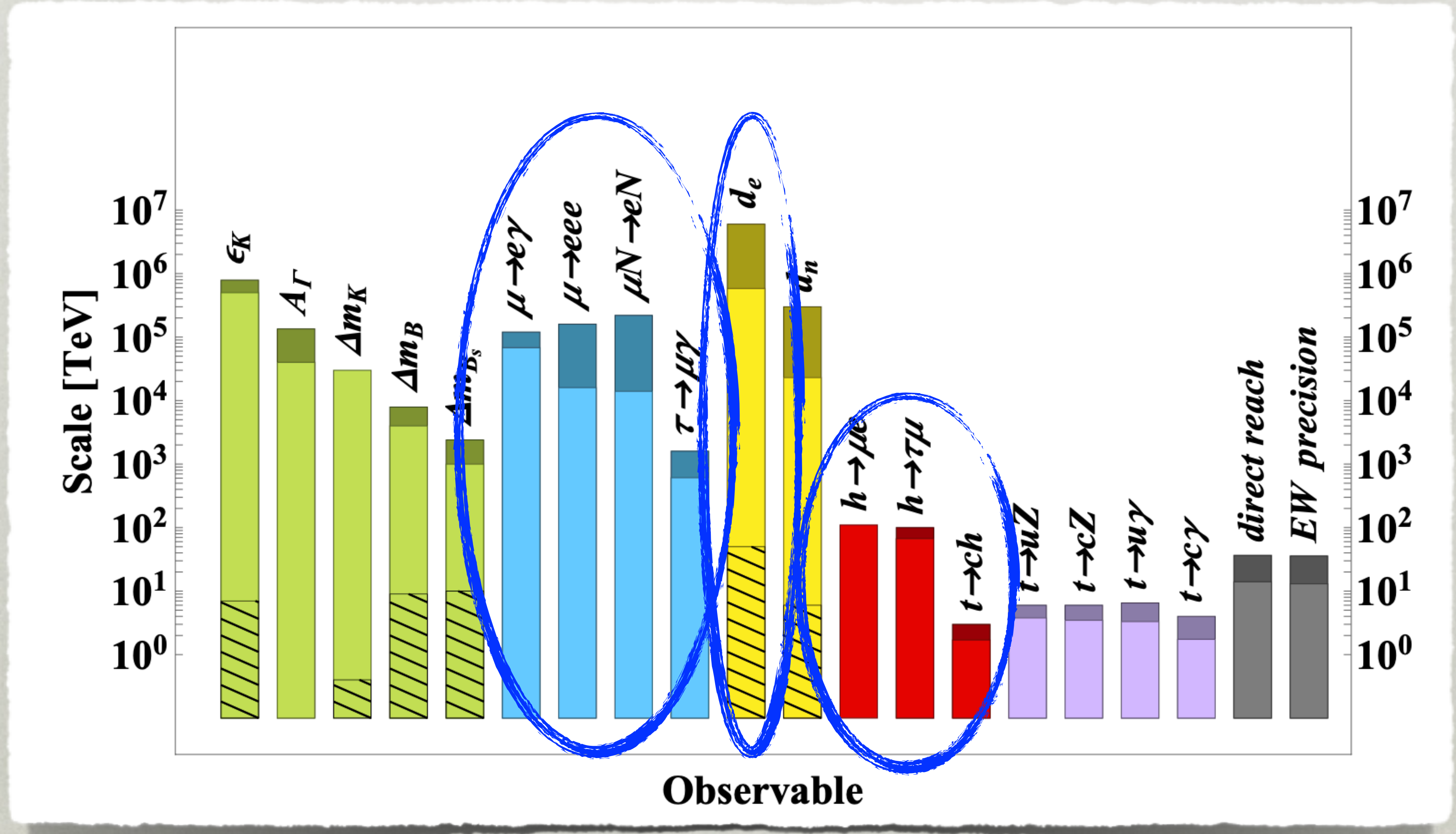
$$\mathrm{BR}(\mu \to e\gamma) \simeq \frac{\Gamma(\mu \to e\gamma)}{\Gamma(\mu \to e\nu\bar{\nu})} = \frac{3\alpha}{32\pi} \left| \sum_{k=1,3} \frac{U_{\mu k} U^*_{ek} m^2_{\nu_k}}{M_W^2} \right|^2 .$$

$$\mathrm{BR}(\mu \to e\gamma) = 10^{-55} \div 10^{-54}$$

  - similar suppressions for $\mu \to 3e, \tau \to 3\mu, \mu \to e, \ldots$
- for charged LFV transitions SM is well below experimental reach
  - if found, a clear signal of new physics

SEARCHING FOR NEW PHYSICS

- LFV observables probe very high scales



- the rest of these lectures: focusing on the above observables

OBSERVABLES

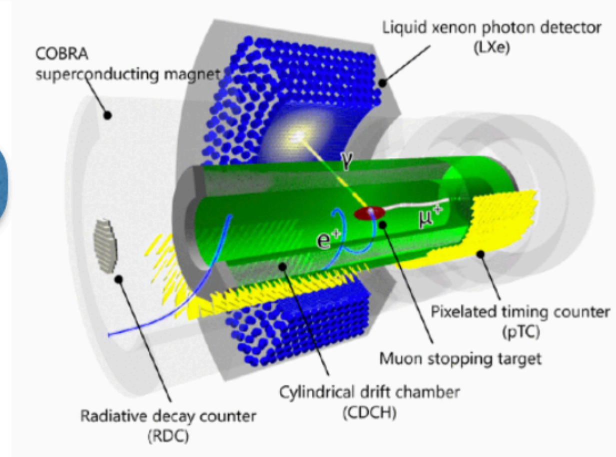
- CLFV transitions
  - $\mu \to e\gamma, \tau \to \mu\gamma, \mu \to 3e, \mu \to e$ conv., ...
- searching for light new physics
- Higgs decays
  - $h \to \tau\tau, h \to \mu\mu, h \to \tau\mu$, ...

talk by Toshiyuki Iwamoto @ FPCP2020

cLFV experiments in the world

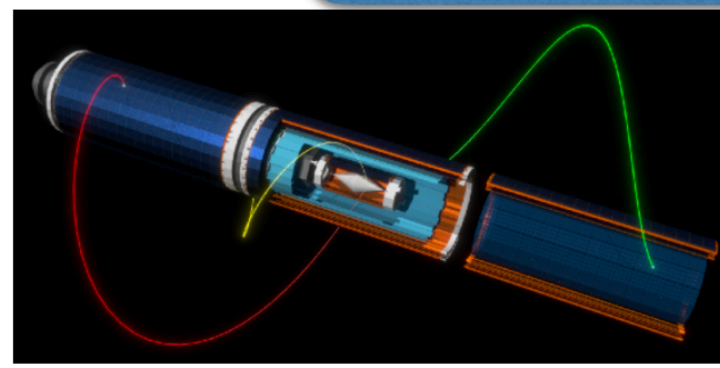
MEG II

$\mu^+ \to e^+\gamma$



Mu3e

$\mu^+ \to e^+e^+e^-$



Coincidence measurement: DC beam needed to minimize backgrounds from accidental coincidences

BKG $\propto$ (Rate)^2

PSI

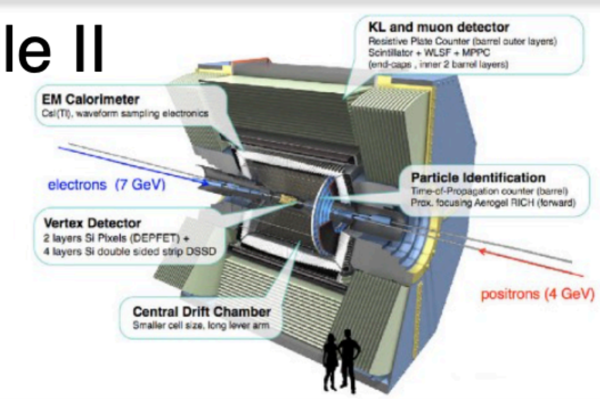
CERN

LHCb/ATLAS/CMS

$\tau \to 3\mu$, $\tau \to \mu\gamma$

KEK

Belle II

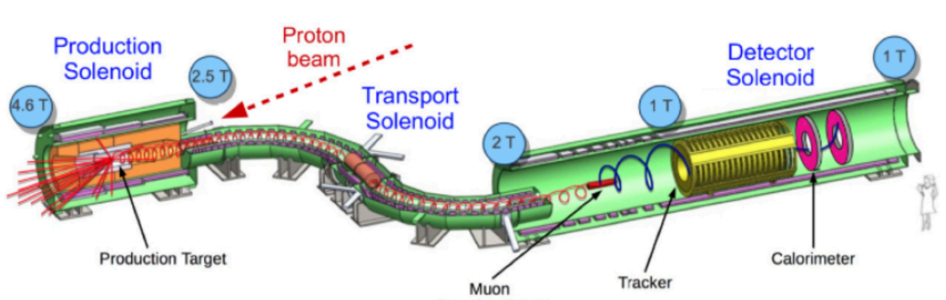


Fermilab

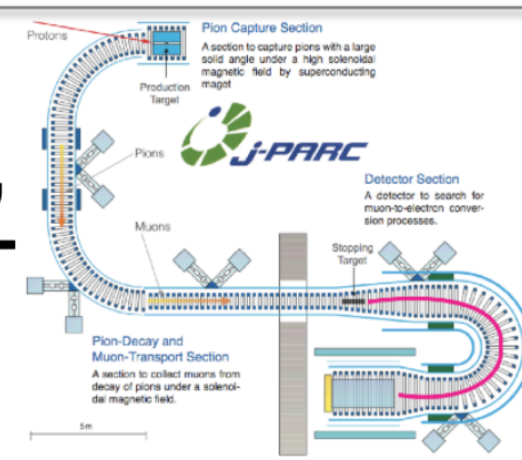
$\mu^- N \to e^- N$

J-PARC

Mu2e



DeeMe, COMET



Single e$^-$ measurement: pulsed beam needed

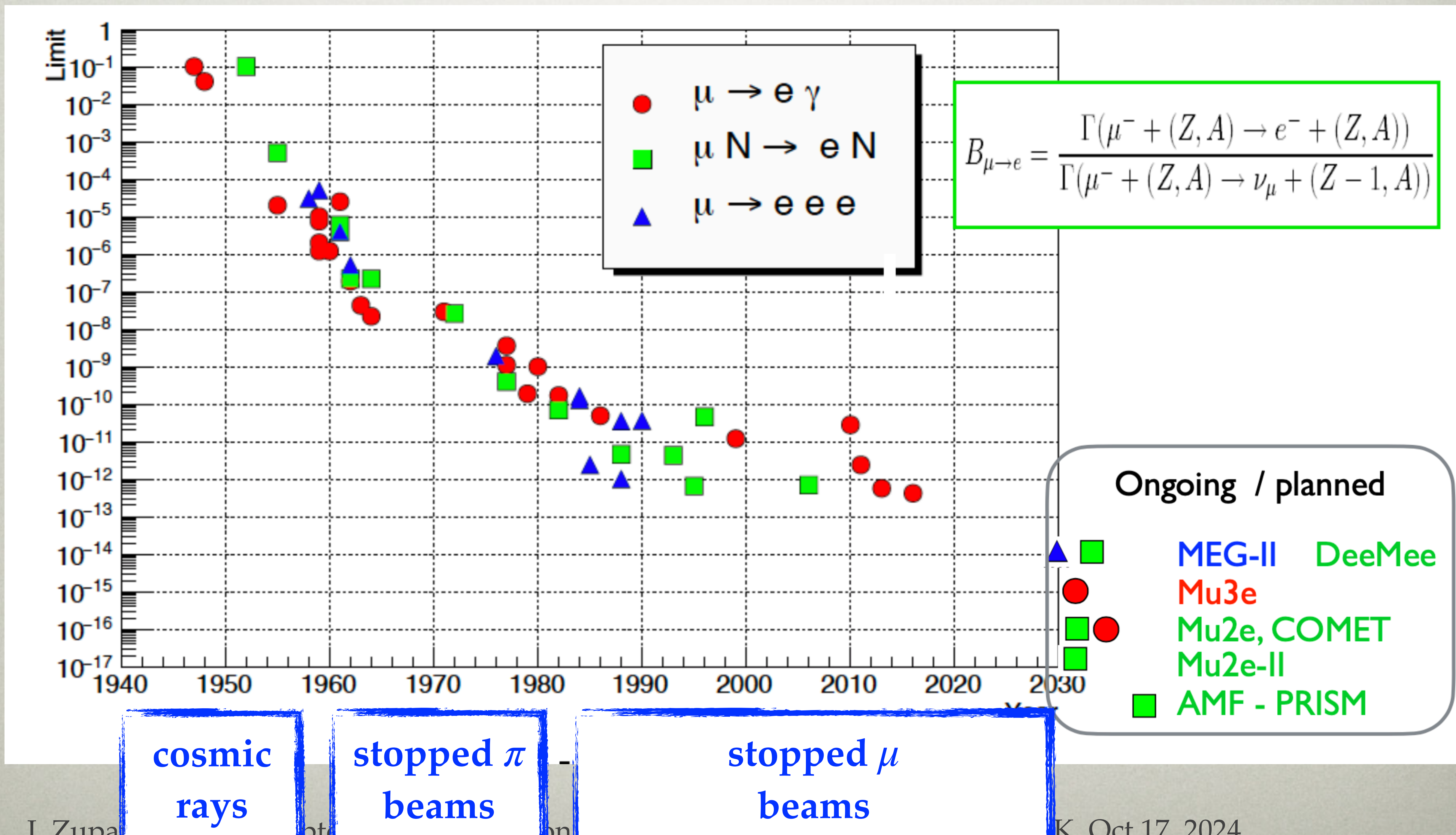
Many pion-induced backgrounds after proton pulse

wait it out with 26 ns lifetime

MUONS

EXPERIMENTAL PROGRESS

- steady experimental progress since 1940s



COMPLEMENTARY PROBES

- complete list of dim 6 CLFV operators

4-leptons operators		Dipole operators	
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$		
2-lepton 2-quark operators			
$Q^{(1)}_{\ell q}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q^{(3)}_{\ell q}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(1)}_{\ell equ}$	$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$
Lepton-Higgs operators			
$Q^{(1)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q^{(3)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

probed by
$\mu \to e\gamma$
$\mu \to 3e$
$\mu \to e$

J. Z

$$\mu \to e\gamma$$

$\mu \to e\gamma$ EXPERIMENTAL RESULTS

- present best bound
  - MEG (2016): $Br(\mu^+ \to e^+\gamma) < 4.2 \times 10^{-13}$

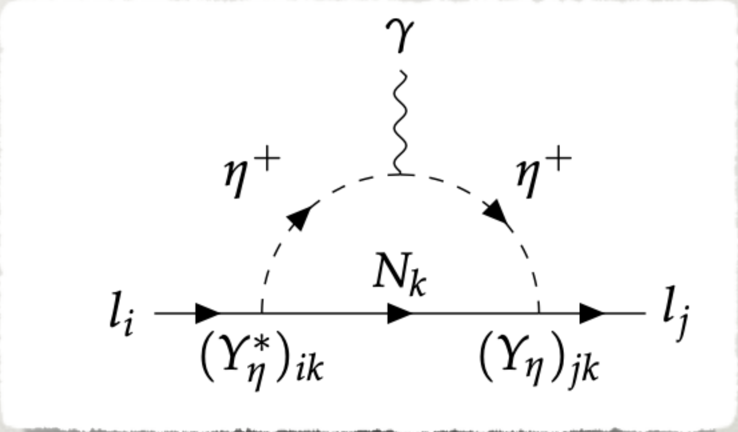
MEG coll., hep-ex/1605.05081

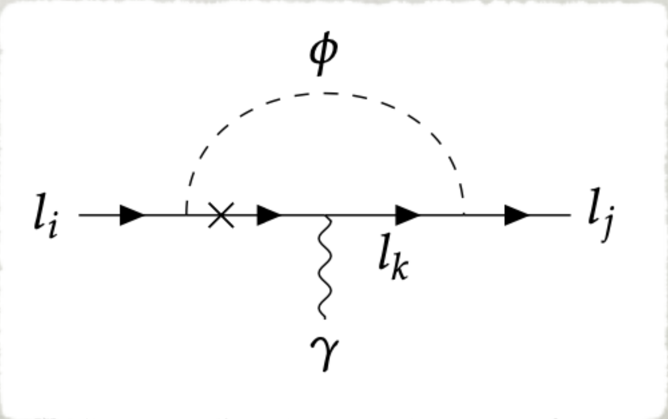
- future experiment (just started physics data taking)
  - MEG-II (~2025): $Br(\mu^+ \to e^+\gamma) < 6 \times 10^{-14}$

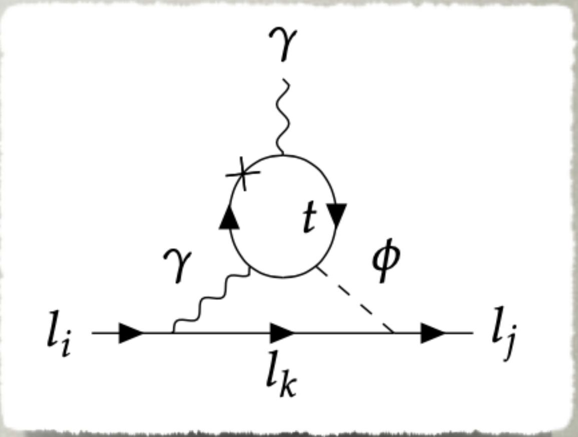
present status in Meucci, 2201.08200

NEW PHYSICS EXAMPLES FOR $\mu \to e\gamma$

- any new states with FV couplings to SM leptons will contribute to $\mu \to e\gamma$
- a selection of examples
  - neutrino mass models
    - see-saw
    - loop generated neutrino masses
  - 2 Higgs Doublet Model
  - low energy supersymmetry
  - extra dimensional models



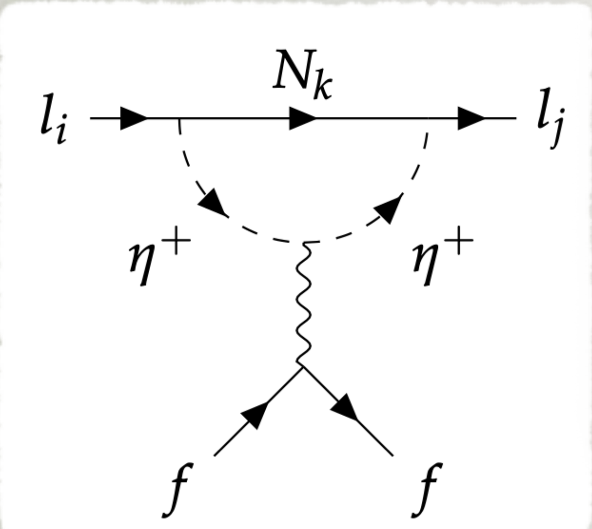


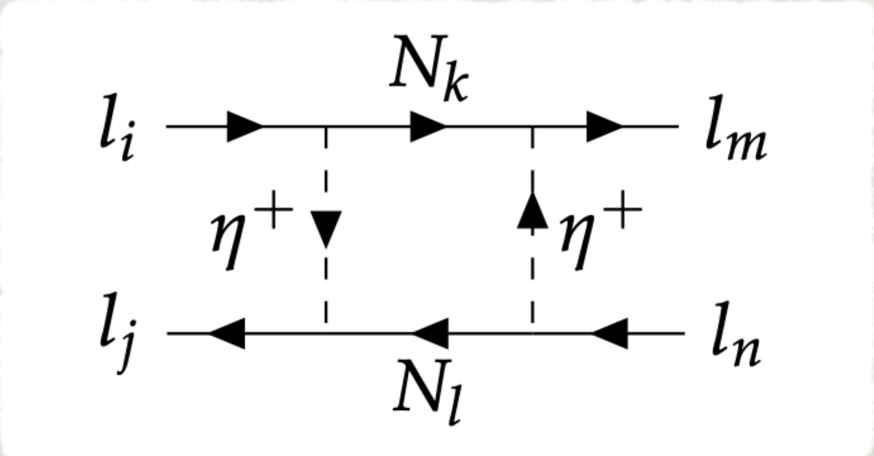


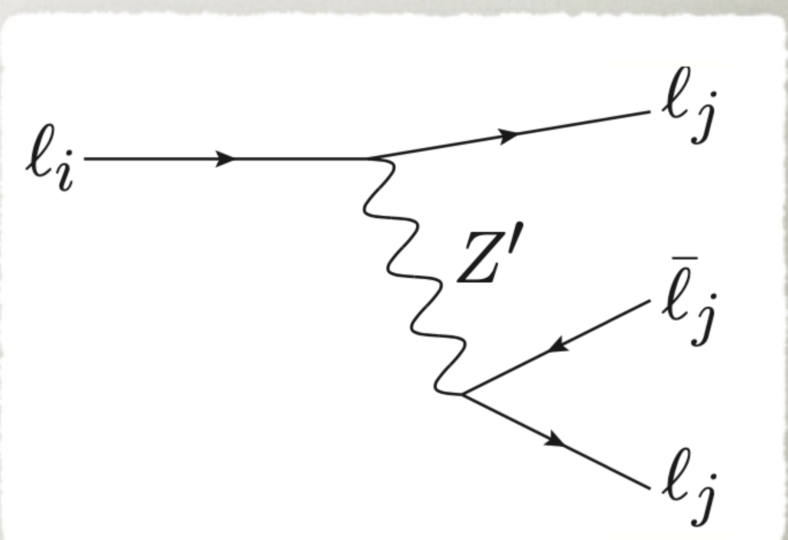
$$\mu \to 3e$$

$\mu \to 3e$

- $\mu^+ \to e^+ e^- e^+$: tree level or one loop NP contribs. possible





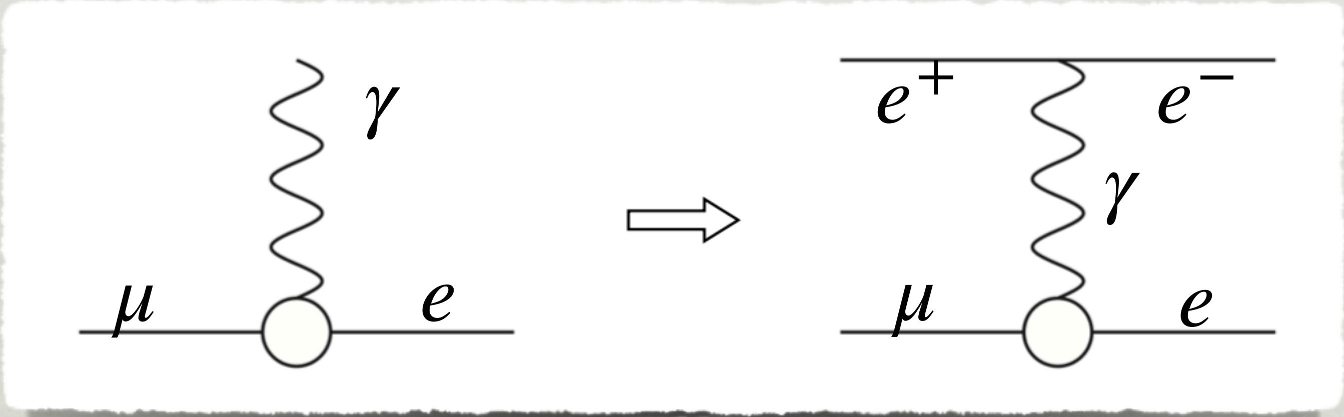


- if NP heavy, can be integrated out
  - then the $\mu \to 3e$ transition described by an EFT with
    - dipole operators $\bar{\ell}^i_{\rm L} \sigma^{\mu\nu} \ell^j_{\rm R} F_{\mu\nu}$
    - four fermion operators

$$(\bar{L}_L \gamma_\mu L_L)(\bar{L}_L \gamma^\mu L_L)$$
$$(\bar{e}_R \gamma_\mu e_R)(\bar{e}_R \gamma^\mu e_R)$$
$$(\bar{L}_L \gamma_\mu L_L)(\bar{e}_R \gamma^\mu e_R)$$

DIPOLE LIMIT

- if NP such that the dipole contribution dominates
- then $\mu \to 3e$ and $\mu \to e\gamma$ rates are related



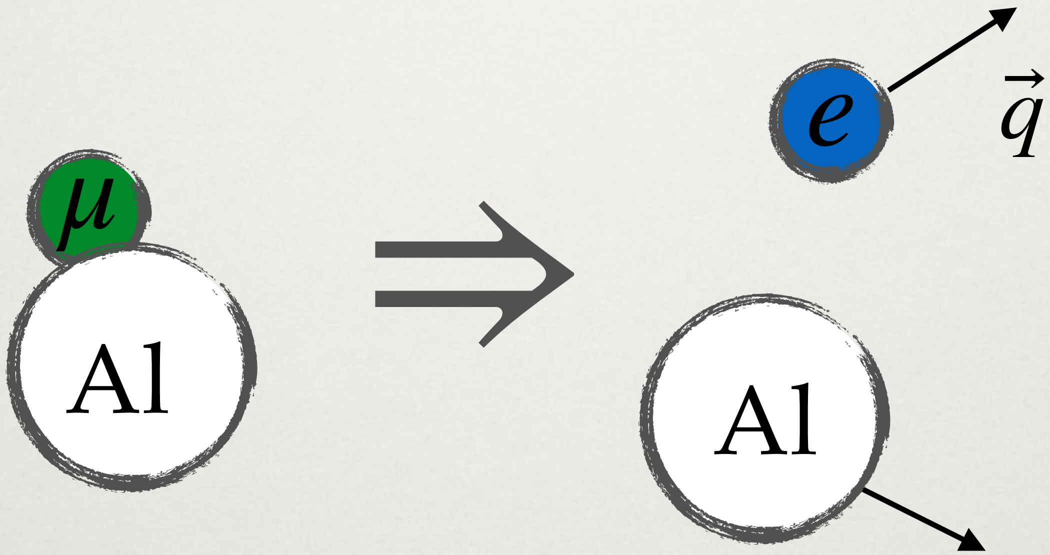
$$\mathrm{BR}(\mu \to eee) \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2} - 3\right) \times \mathrm{BR}(\mu \to e\gamma)$$

- in general all operators are present
  - the above operators mix under the RG

$\mu \to e$ CONVERSION

$\mu \to e$ CONVERSION

- initial state: μ^- in 1s orbital



- a theory challenge: predictions require nuclear physics
- there is a small parameter $|\vec{q}| \sim \mathcal{O}(100\,\text{MeV}) \ll m_N$
  - can use EFT techniques (non-relativistic EFT / chiral EFT)
  - **MuonBridge** code

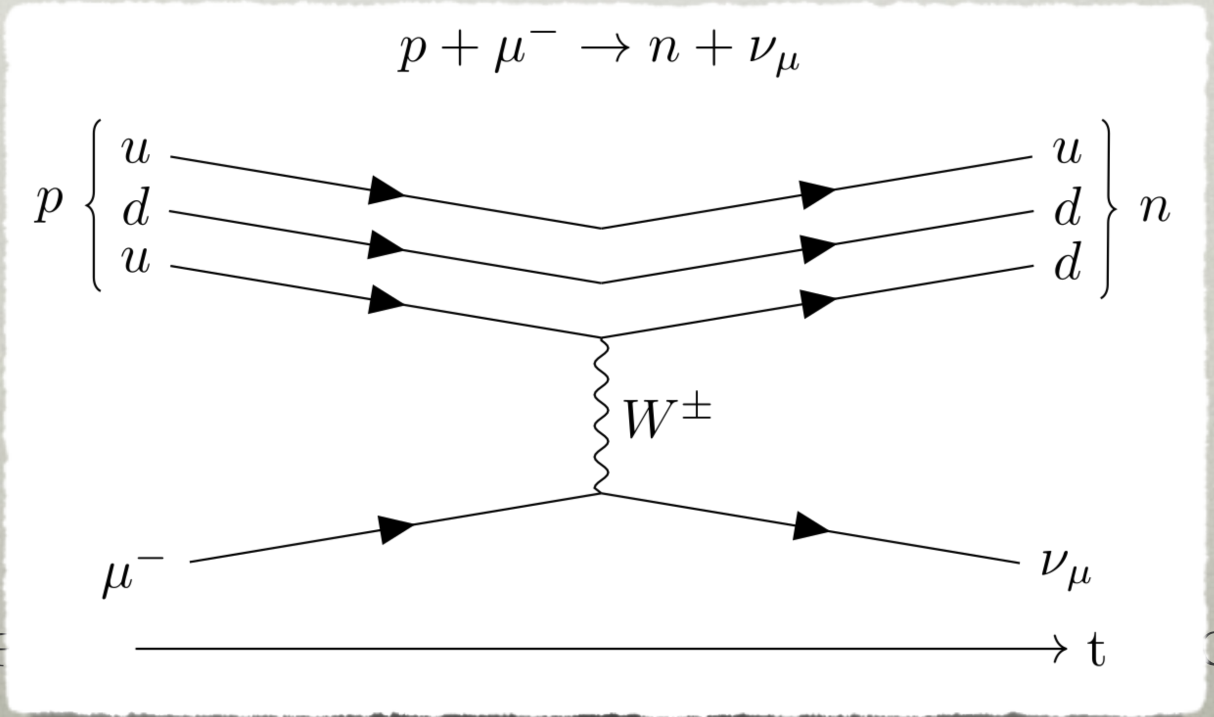
Haxton, McElvain, Menzo, Rule, JZ, 2406.13818

$\mu^- N \to e^- N$ conversion

- results are quoted in terms of normalized conversion rate

$$R_{\mu e} = \mathrm{CR}(\mu N \to e N) \equiv \frac{\Gamma(\mu - e \text{ conversion})}{\Gamma(\text{nuclear capture})}$$

- normalization to nuclear capture rate reduces theoretical uncertainties



COMPLEMENTARY PROBES

- complete list of dim 6 CLFV operators

	4-leptons operators		Dipole operators
$Q_{\ell\ell}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{L}_L\gamma^\mu L_L)$	Q_{eW}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\tau_I\Phi W^I_{\mu\nu}$
Q_{ee}	$(\bar{e}_R\gamma_\mu e_R)(\bar{e}_R\gamma^\mu e_R)$	Q_{eB}	$(\bar{L}_L\sigma^{\mu\nu}e_R)\Phi B_{\mu\nu}$
$Q_{\ell e}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{e}_R\gamma^\mu e_R)$		
	2-lepton 2-quark operators		
$Q^{(1)}_{\ell q}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{Q}_L\gamma^\mu Q_L)$	$Q_{\ell u}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{u}_R\gamma^\mu u_R)$
$Q^{(3)}_{\ell q}$	$(\bar{L}_L\gamma_\mu\tau_I L_L)(\bar{Q}_L\gamma^\mu\tau_I Q_L)$	Q_{eu}	$(\bar{e}_R\gamma_\mu e_R)(\bar{u}_R\gamma^\mu u_R)$
Q_{eq}	$(\bar{e}_R\gamma^\mu e_R)(\bar{Q}_L\gamma_\mu Q_L)$	$Q_{\ell edq}$	$(\bar{L}^a_L e_R)(\bar{d}_R Q^a_L)$
$Q_{\ell d}$	$(\bar{L}_L\gamma_\mu L_L)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(1)}_{\ell equ}$	$(\bar{L}^a_L e_R)\epsilon_{ab}(\bar{Q}^b_L u_R)$
Q_{ed}	$(\bar{e}_R\gamma_\mu e_R)(\bar{d}_R\gamma^\mu d_R)$	$Q^{(3)}_{\ell equ}$	$(\bar{L}^a_i\sigma_{\mu\nu}e_R)\epsilon_{ab}(\bar{Q}^b_L\sigma^{\mu\nu}u_R)$
	Lepton-Higgs operators		
$Q^{(1)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{L}_L\gamma^\mu L_L)$	$Q^{(3)}_{\Phi\ell}$	$(\Phi^\dagger i\overleftrightarrow{D}^I_\mu\Phi)(\bar{L}_L\tau_I\gamma^\mu L_L)$
$Q_{\Phi e}$	$(\Phi^\dagger i\overleftrightarrow{D}_\mu\Phi)(\bar{e}_R\gamma^\mu e_R)$	$Q_{e\Phi 3}$	$(\bar{L}_L e_R\Phi)(\Phi^\dagger\Phi)$

probed by
$\mu\to e\gamma$
$\mu\to 3e$
$\mu\to e$

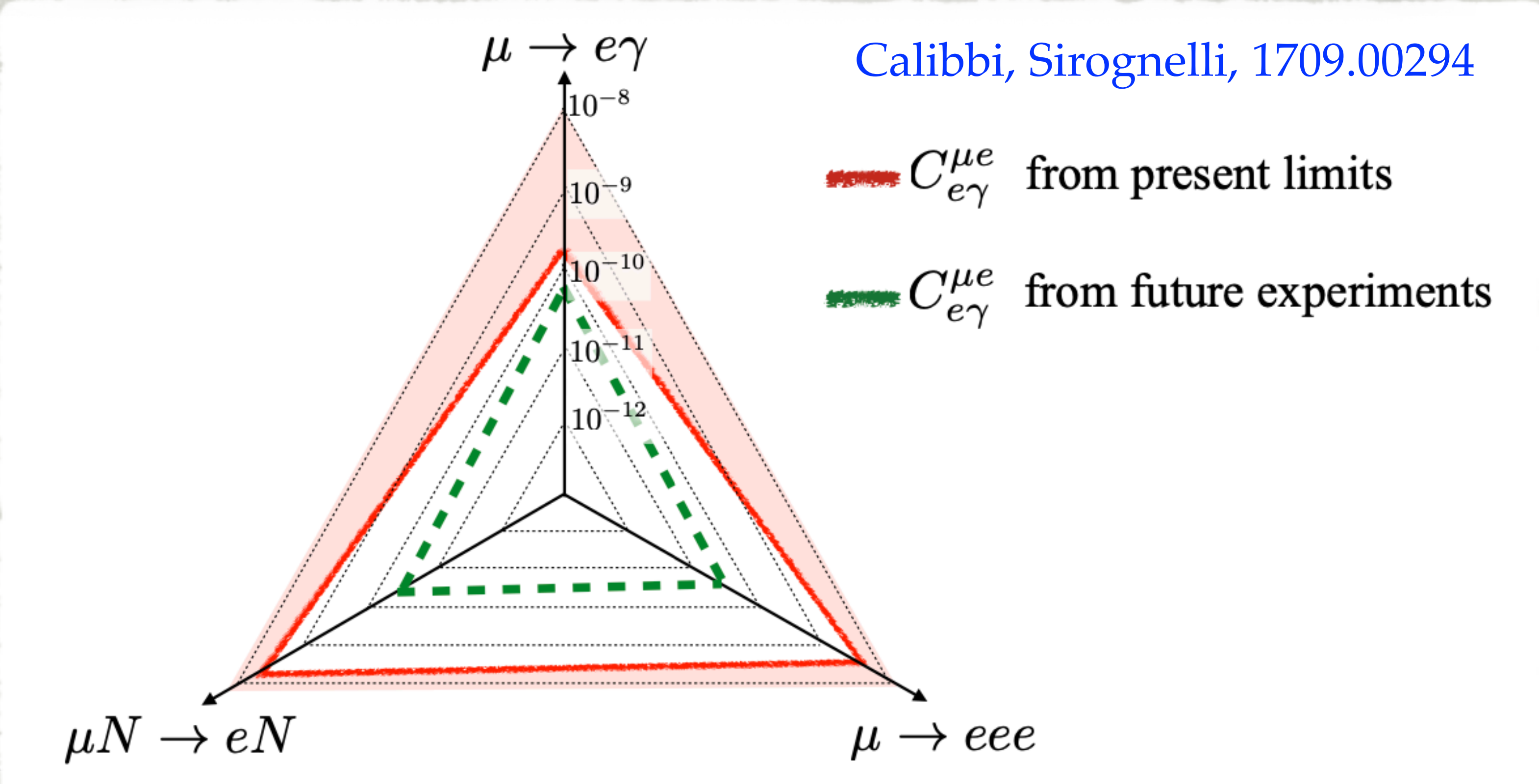
J. …

DIPOLE OPERATOR DOMINANCE

- simplified scenario - assume the dipole operator dominates
- interesting to compare the reach of different experiments

$$\mathrm{BR}(\mu \to eee) \simeq \frac{\alpha}{3\pi}\left(\log\frac{m_\mu^2}{m_e^2} - 3\right) \times \mathrm{BR}(\mu \to e\gamma)\,,$$

$$\mathrm{CR}(\mu\ \mathrm{N} \to e\ \mathrm{N}) \simeq \alpha \times \mathrm{BR}(\mu \to e\gamma)\,.$$



UPSHOT

- several different probes in rare muon decays
  - can probe different types of new physics
  - also disentangle different contributions
- significant improvements projected

LFV in τ decays

LFV τ DECAYS

- several important differences relative to muons
- experimental:

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

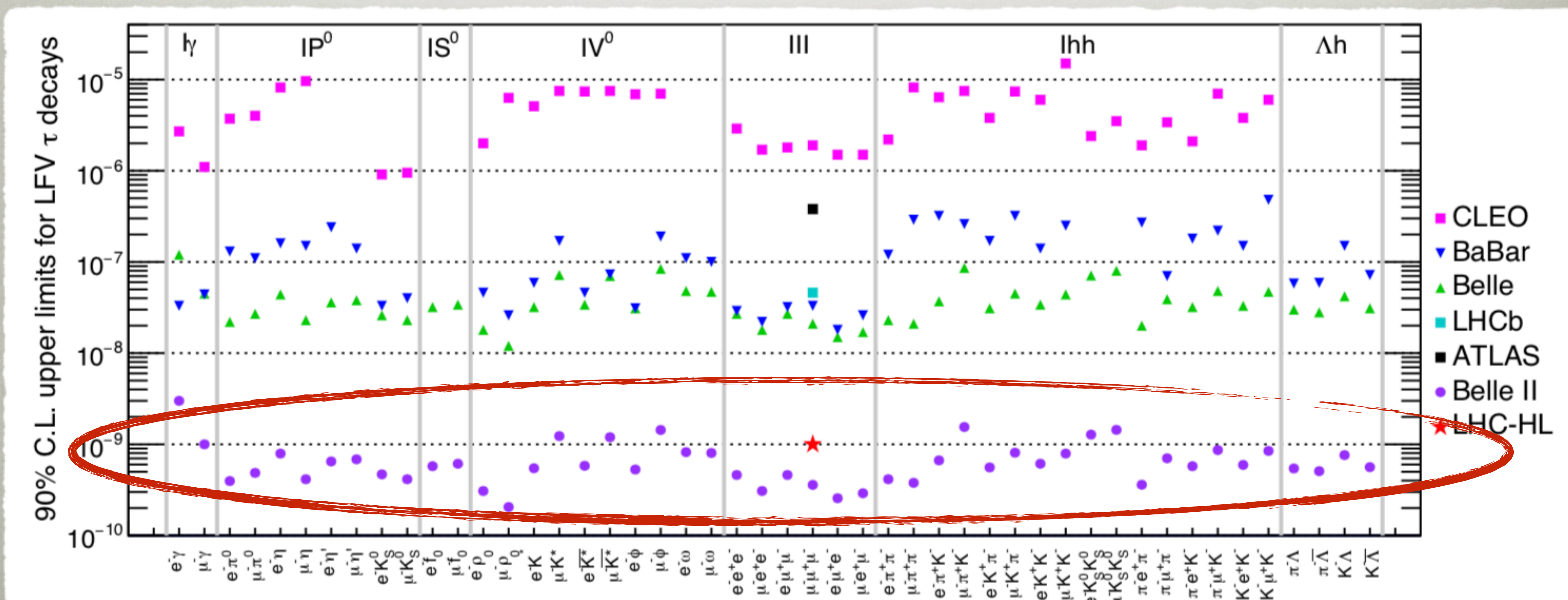
  - τ lifetime is short $\Rightarrow$ no "tau beams"
    - need to be produced in $e^+e^- \to \tau^+\tau^-$ (Belle II) or in pp collisions (LHC)
    - smaller experimental samples compared to muons
  - τ is heavier, $m_\tau = 1.777\,\text{GeV}$, many decay modes possible
- theoretical:
  - the models that 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)

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}

E. Passemar

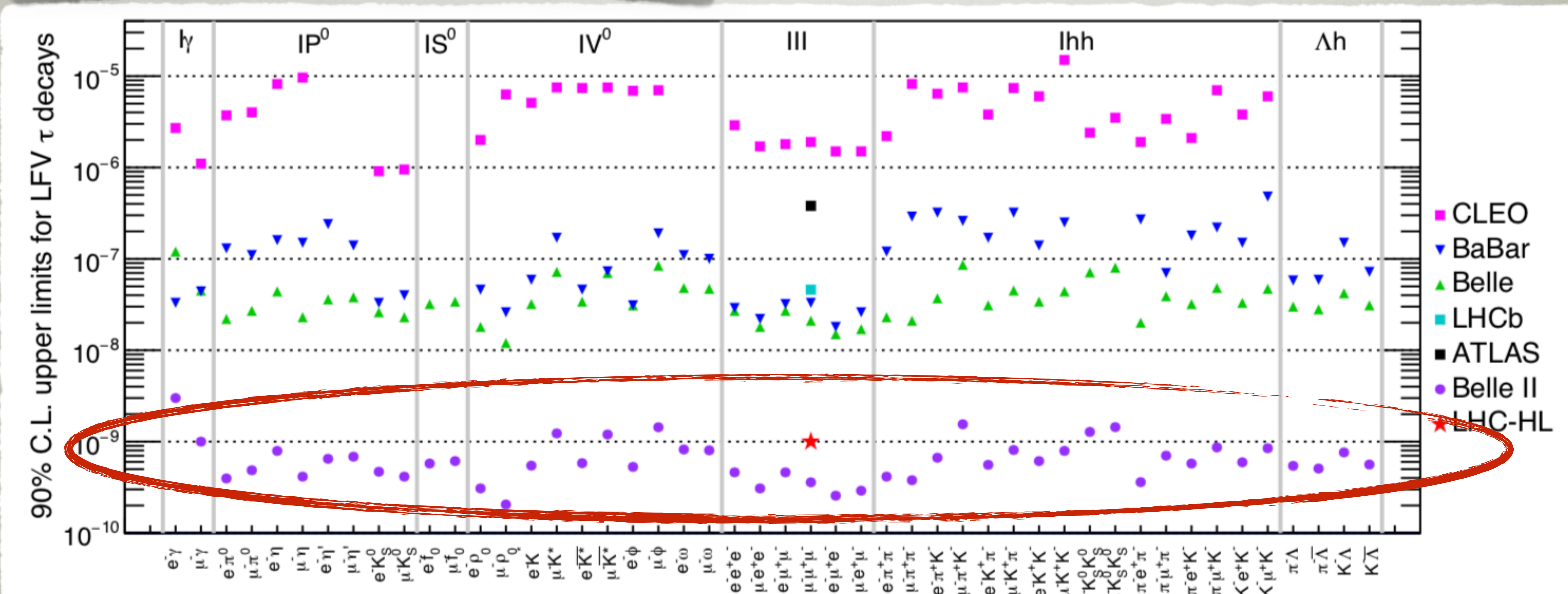
E REACH

ements in the

n expected

Akar et al., 1812.07638

elle 2 and HL-LHC reach



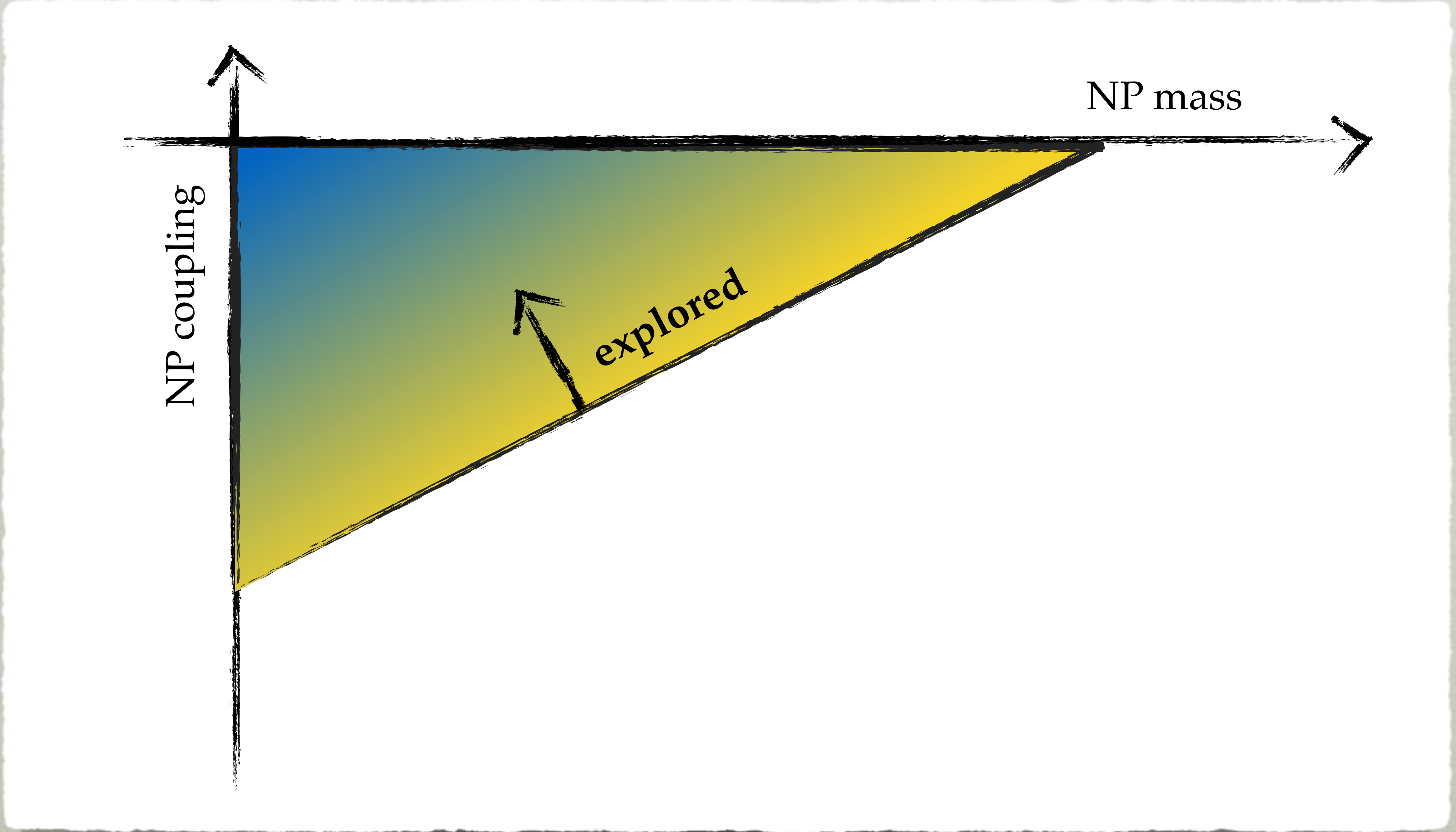
NEW PHYSICS IN TAU DECAYS

- 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:
    $\tau \to \mu\rho, \tau \to e\rho, \tau \to \mu K_S, \ldots$
    - 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

SEARCHING FOR LIGHT NEW PHYSICS

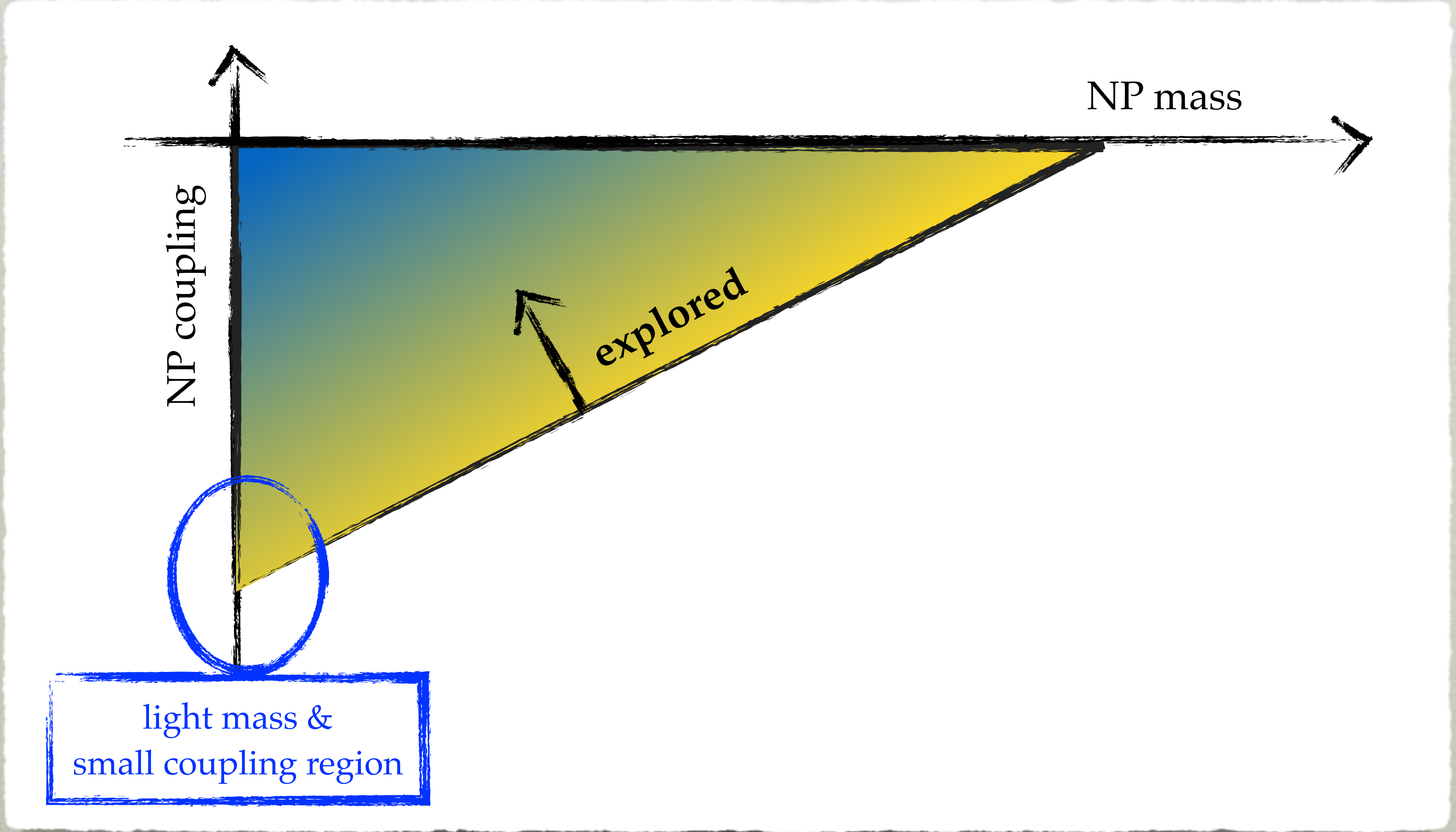
SEARCHING FOR LIGHT NEW PHYSICS

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



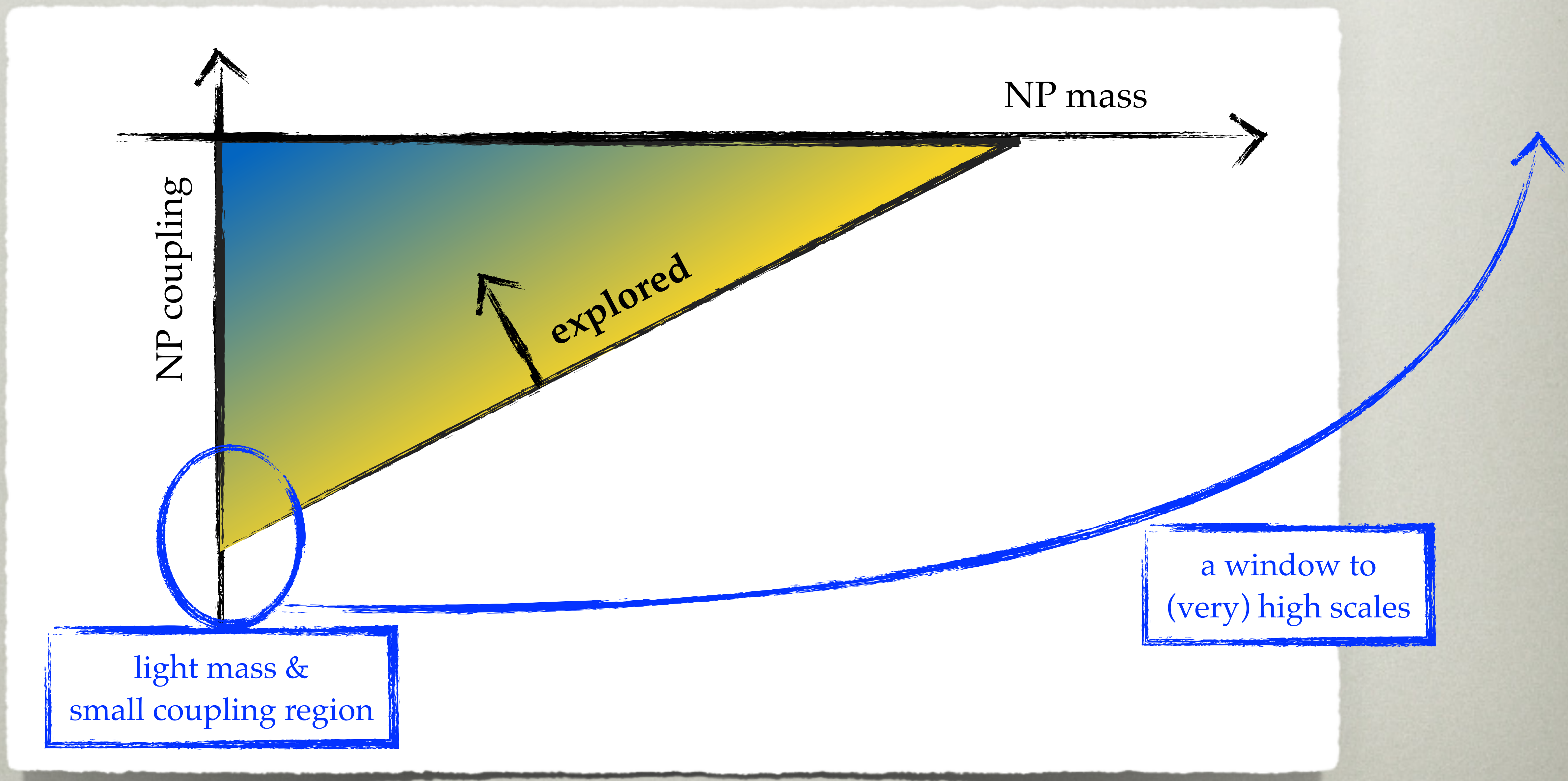
SEARCHING FOR LIGHT NEW PHYSICS

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



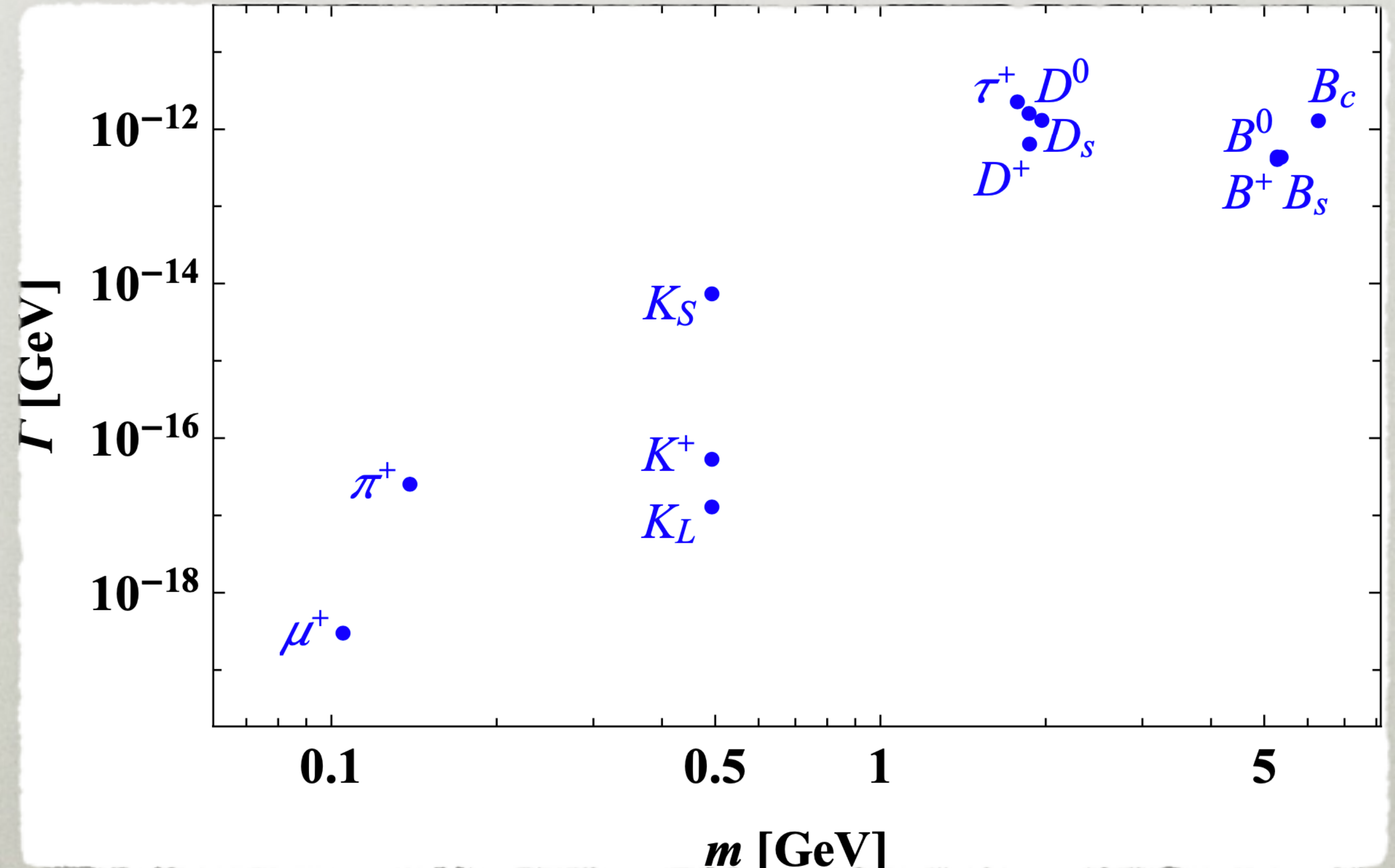
SEARCHING FOR LIGHT NEW PHYSICS

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



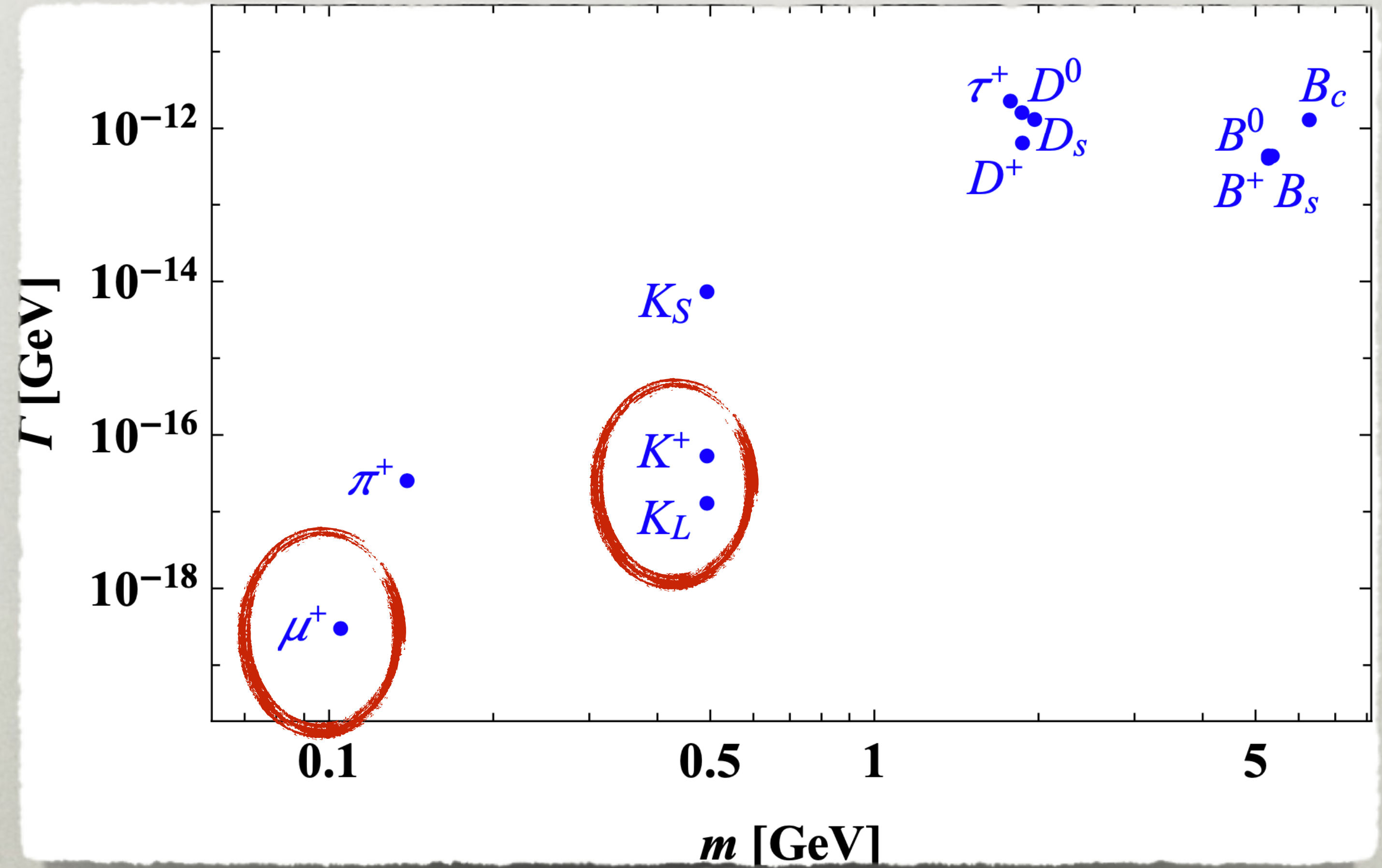
FLAVOR PORTAL

- example of a flavor portal: dim 5 op. $\partial_\alpha \varphi(\bar{e}\gamma^\alpha\gamma_5\mu)/f_a \Rightarrow$ $Br(\mu \to e\varphi) \propto (m_W^2/f_a m_\mu)^2$
- searching for $K \to \pi X$, $\mu \to eX$, $\pi \to X$ decays expect to reach very high UV scales

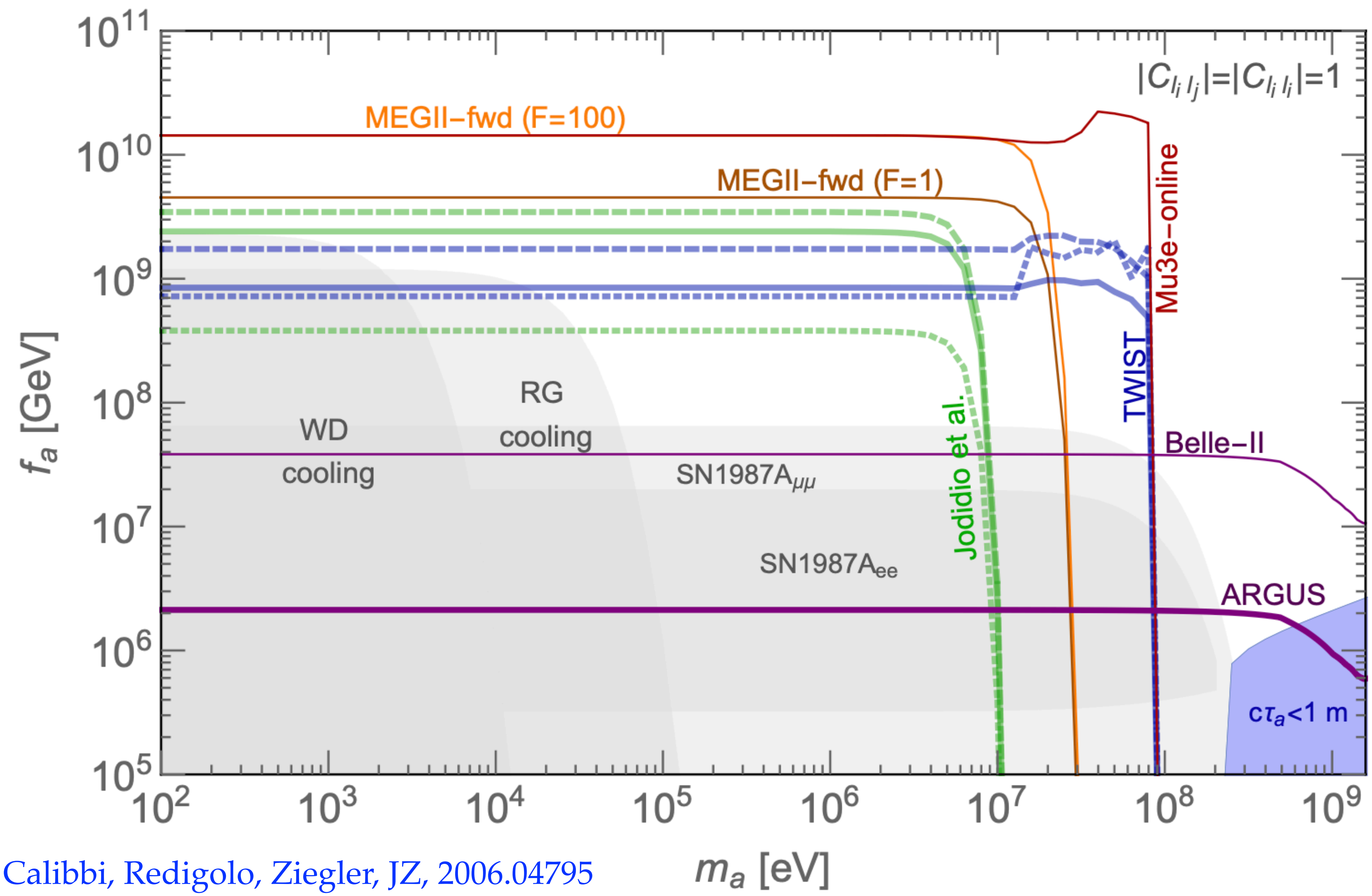


FLAVOR PORTAL

- example of a flavor portal: dim 5 op. $\partial_\alpha \varphi (\bar{e} \gamma^\alpha \gamma_5 \mu)/f_a \Rightarrow$ $Br(\mu \to e\varphi) \propto (m_W^2/f_a m_\mu)^2$
- searching for $K \to \pi X$, $\mu \to eX$, $\pi \to X$ decays expect to reach very high UV scales



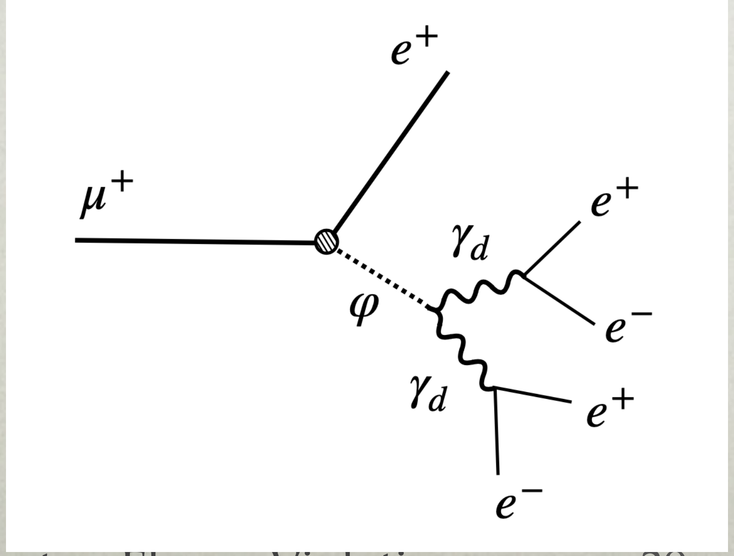
ALPs



Calibbi, Redigolo, Ziegler, JZ, 2006.04795

$\mu \to 5e$

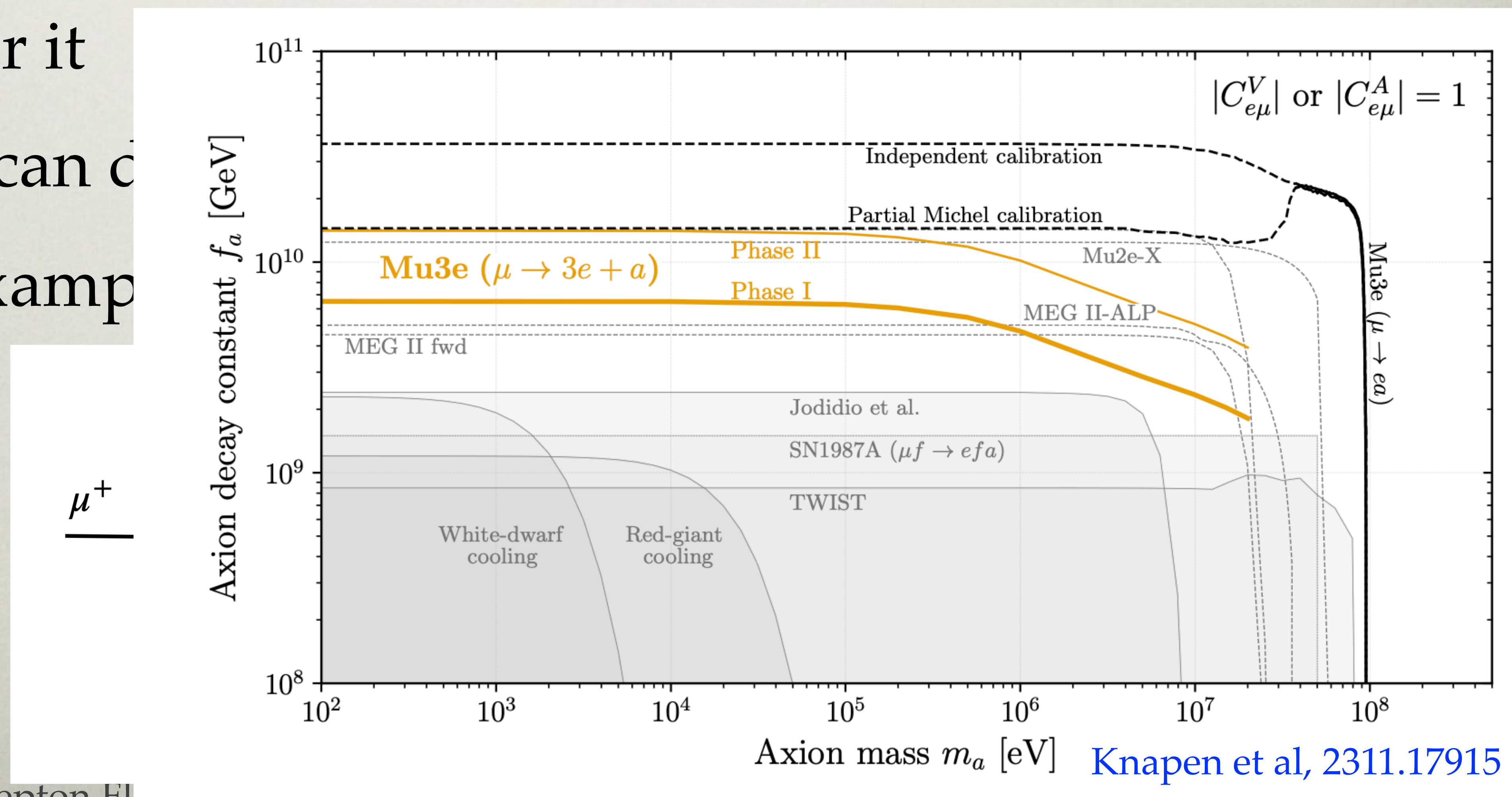
- if $\frac{m_\mu}{\Lambda}\phi(\bar{e}\mu)$ coupling ⇒ mediates $\mu \to e\varphi$
  - if φ QCD axion ⇒ escapes the detector $\mu \to e + \text{inv}$
    - MEG-II, Mu3e, Mu2e-X, COMET-X can search for it
  - if φ can decay ⇒ sensitivity to even higher scales
    - example: $\mu \to 5e$ can probe $f_a \gtrsim 10^{13}$GeV



Hostert, Menzo, Pospelov, JZ, 2306.15631

$\mu \to 5e$

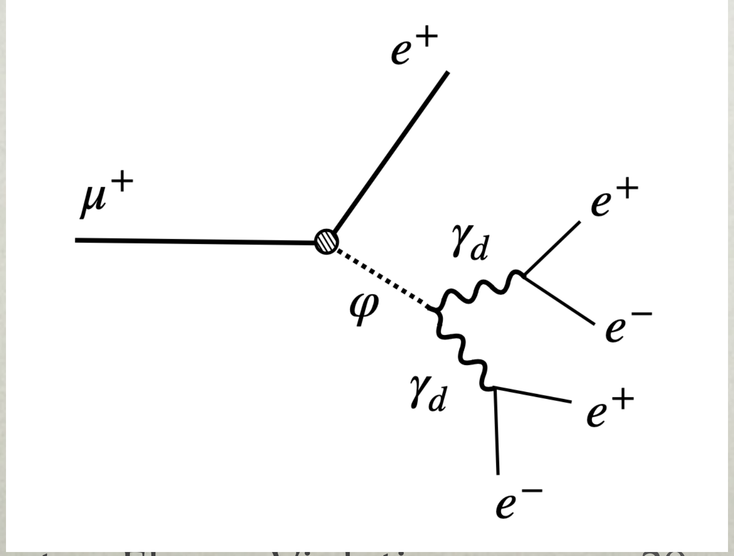
- if $\frac{m_\mu}{\Lambda}\phi(\bar{e}\mu)$ coupling $\Rightarrow$ mediates $\mu \to e\varphi$
  - if φ QCD axion $\Rightarrow$ escapes the detector $\mu \to e + \text{inv}$
    - MEG-II, Mu3e, Mu2e-X, COMET-X can search for it
  - if φ can d
    - examp



Knapen et al, 2311.17915

$\mu \to 5e$

- if $\frac{m_\mu}{\Lambda}\phi(\bar{e}\mu)$ coupling ⇒ mediates $\mu \to e\varphi$
  - if φ QCD axion ⇒ escapes the detector $\mu \to e + \text{inv}$
    - MEG-II, Mu3e, Mu2e-X, COMET-X can search for it
  - if φ can decay ⇒ sensitivity to even higher scales
    - example: $\mu \to 5e$ can probe $f_a \gtrsim 10^{13}$GeV

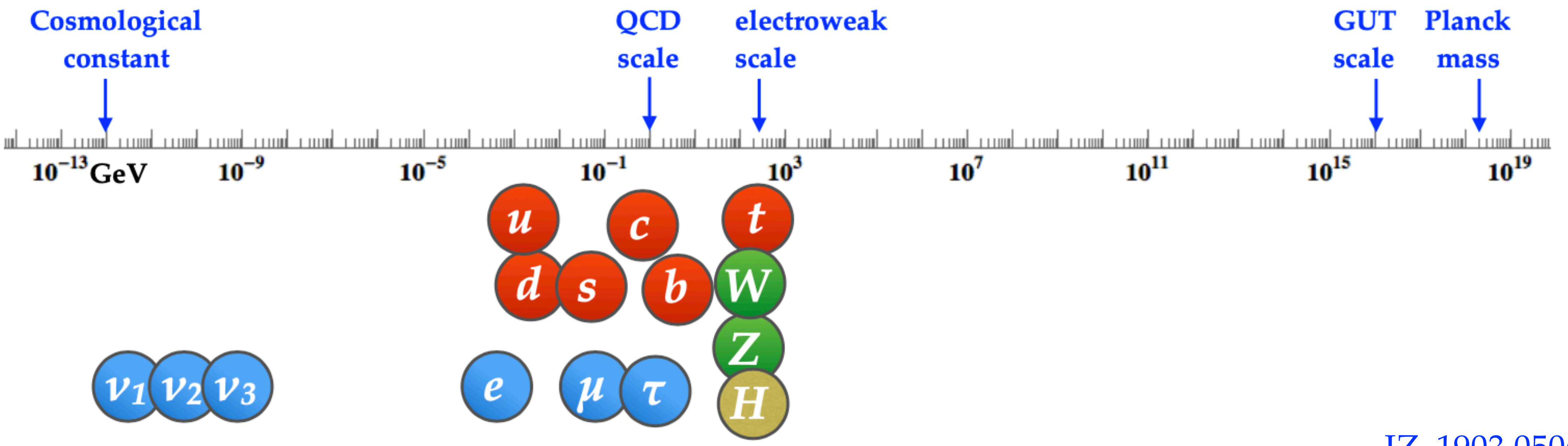


Hostert, Menzo, Pospelov, JZ, 2306.15631

HIGGS AS A PROBE OF FLAVOR

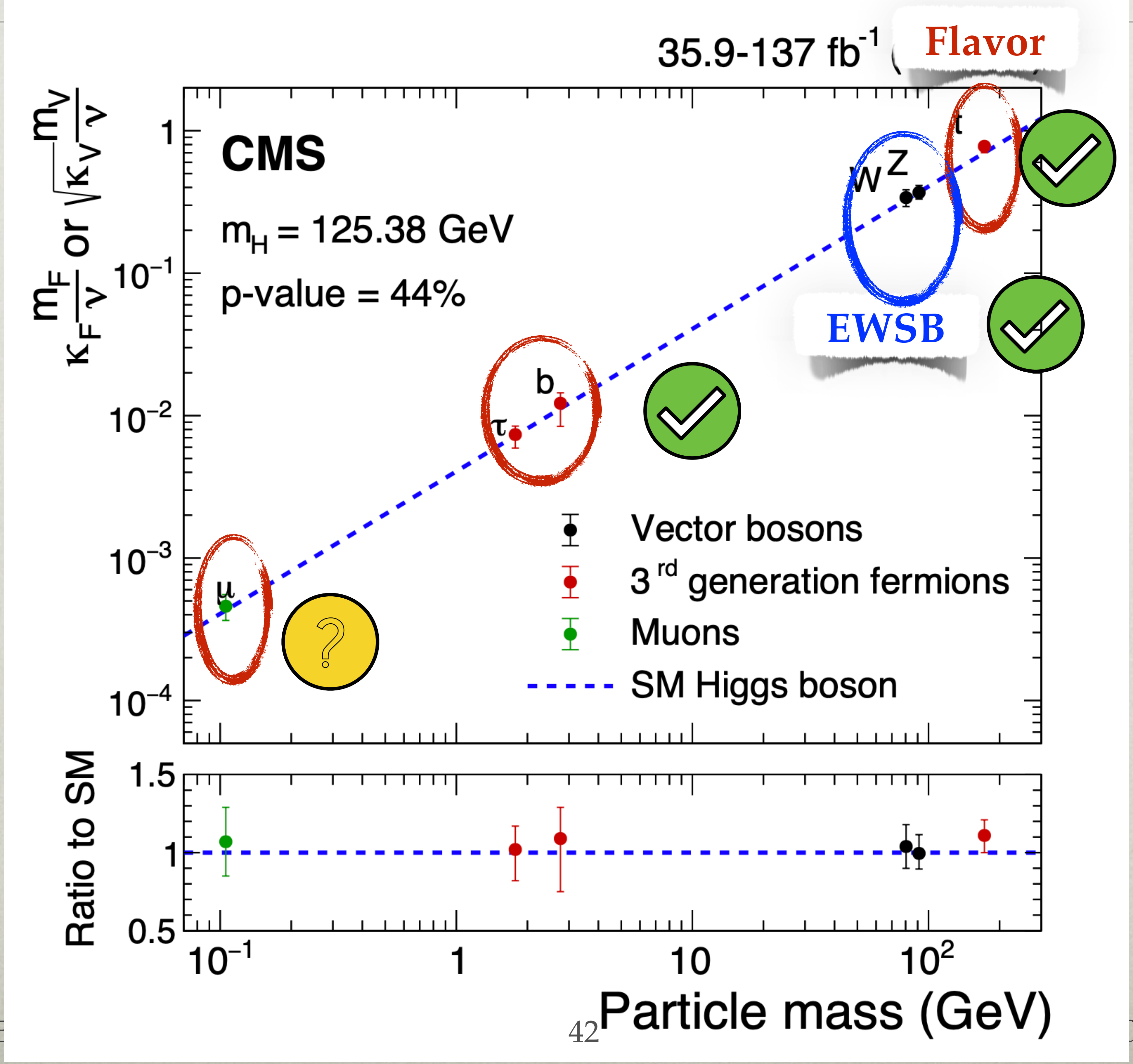
DUAL ROLE

- 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?



JZ, 1903.05062

DUAL ROLE OF THE HIGGS



TESTING THE FLAVOR OF THE HIGGS

Nir, 1605.00433; JZ, 1903.05062

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

- several questions
  - proportionality

    $$y_{ii} \propto m_i$$

  - factor of proportionality

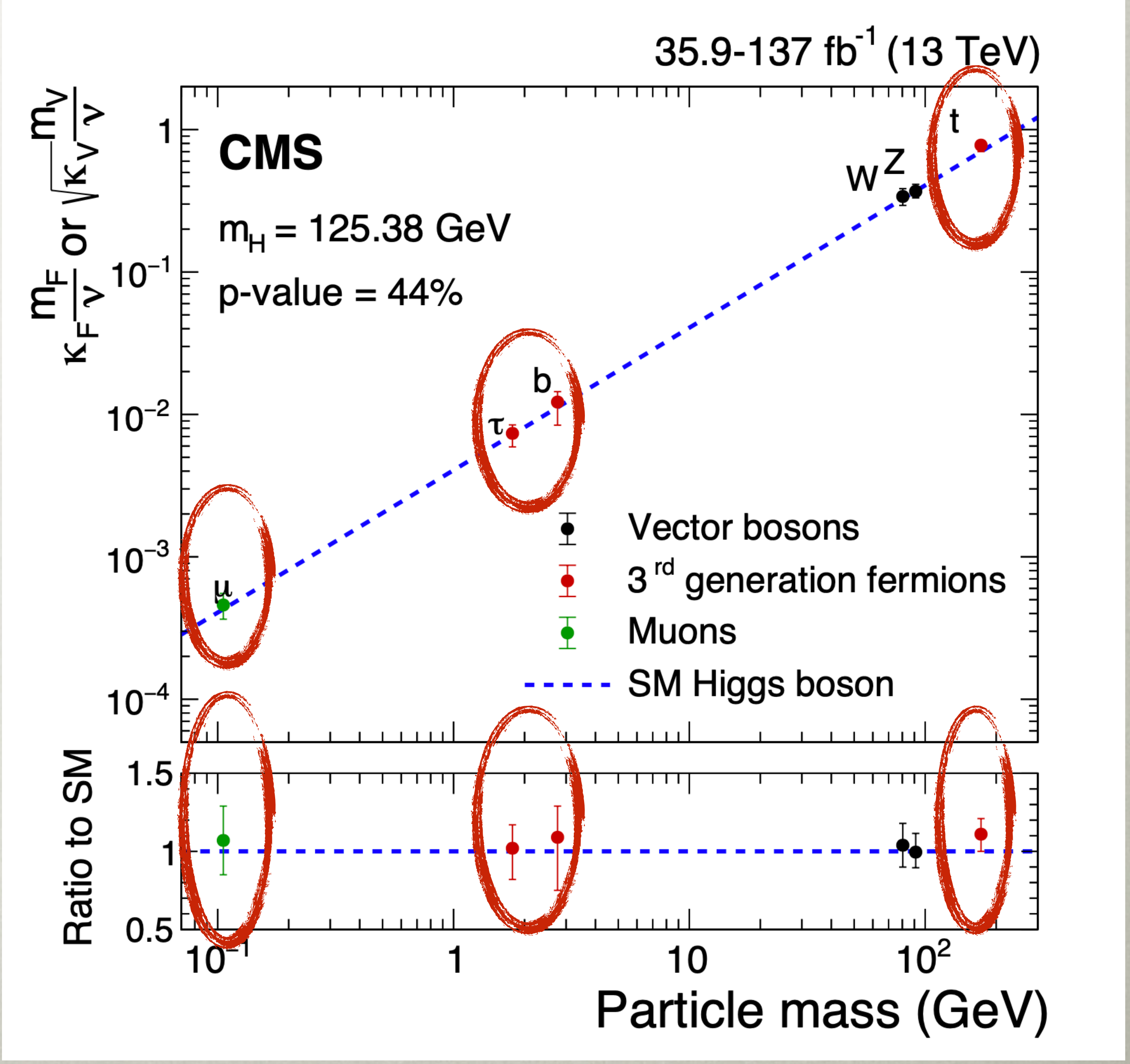
    $$y_{ii}/m_i = \sqrt{2}/v$$

  - diagonality (flavor violation)

    $$y_{ij} = 0, \quad i \neq j$$

  - reality (CP violation)

    $$\mathrm{Im}(y_{ij}) = 0$$



FLAVOR VIOLATING COUPLINGS

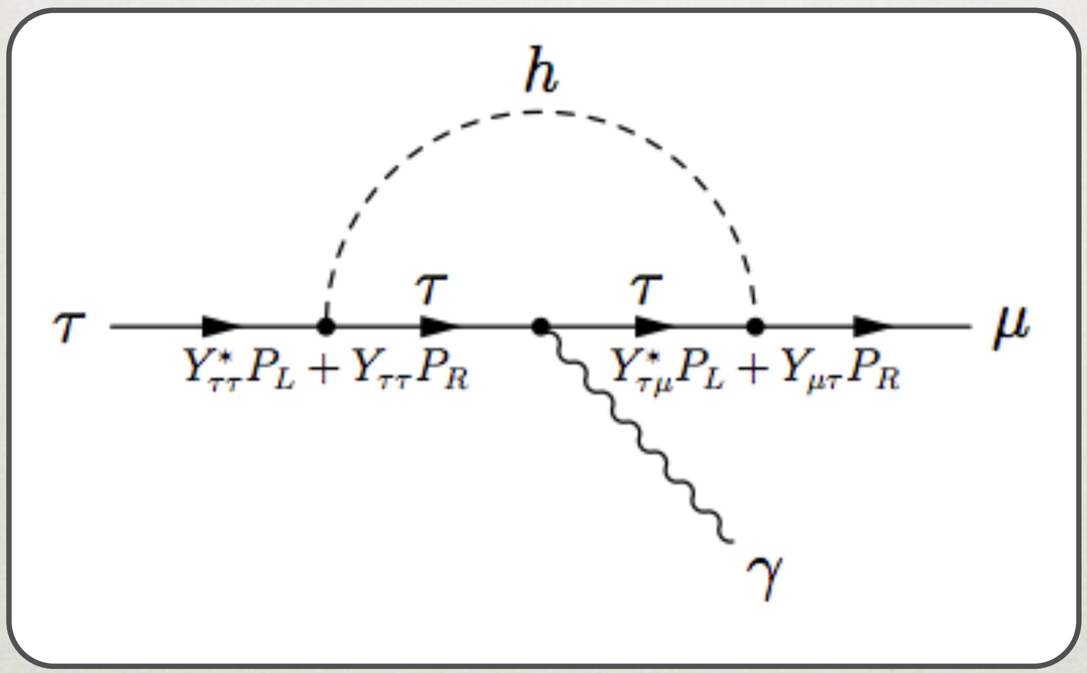
- in the SM Higgs couplings flavor diagonal
  - discovering flavor violating couplings mean New Physics
- for charged lepton final states accessible directly
  - from $h \to \tau\mu$, $h \to \tau e$

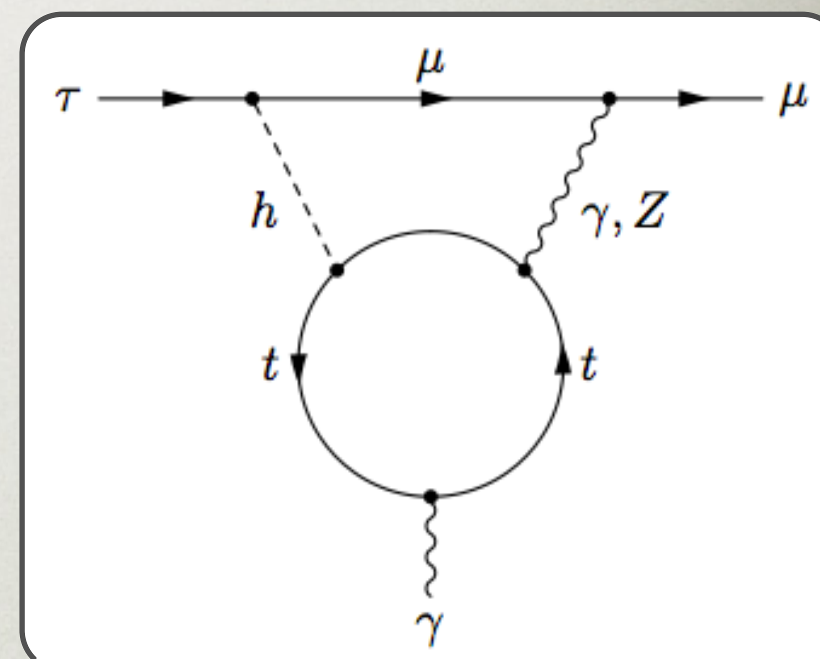
INDIRECT BOUNDS ON $h\to\tau\mu$

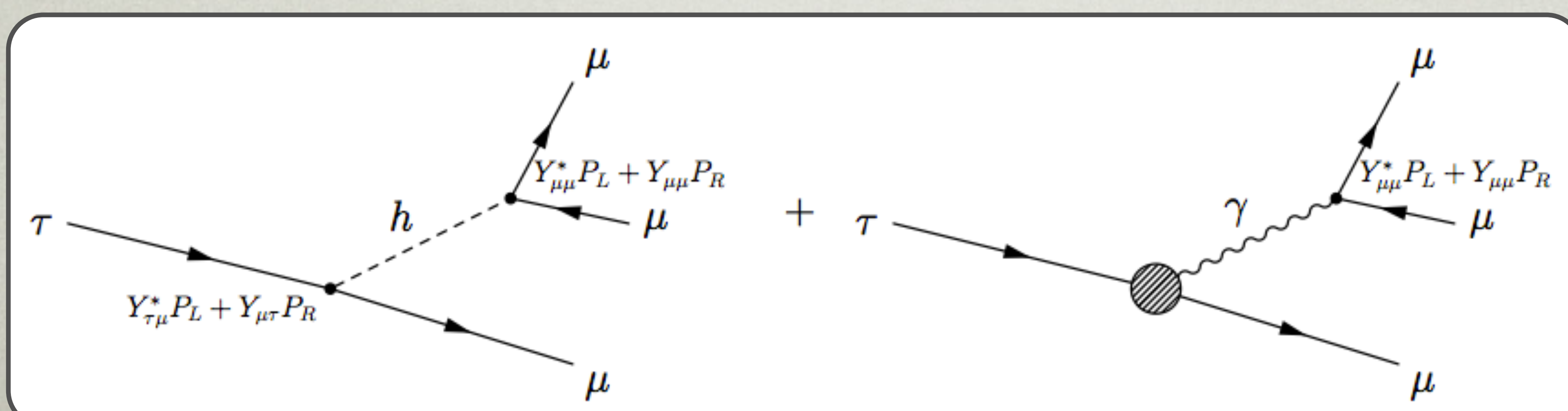
Harnik, Kopp, JZ, 1209.1397

see also Blankenburg, Ellis, Isidori, 1202.5704

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







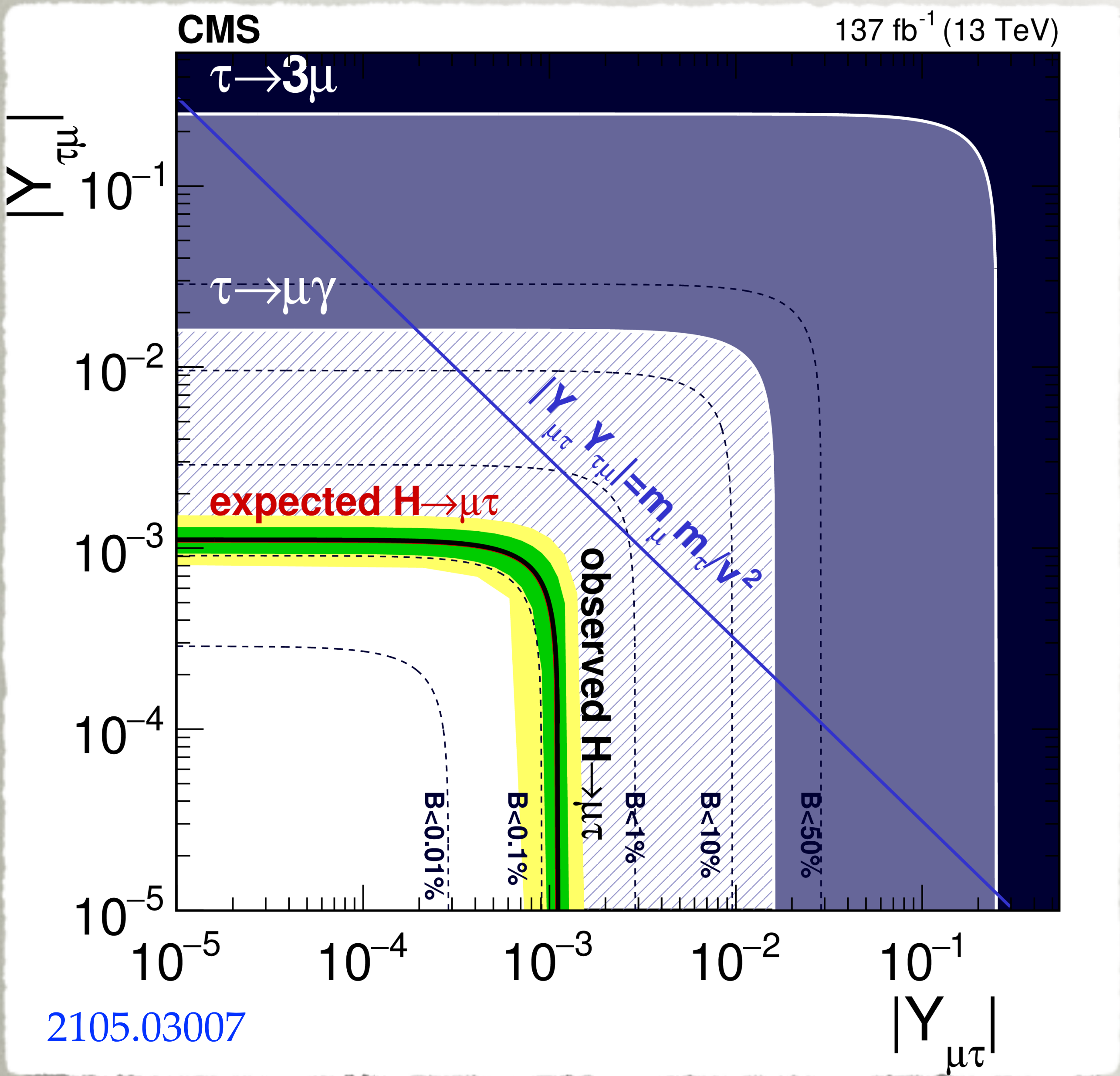
see also ATLAS 1907.06131

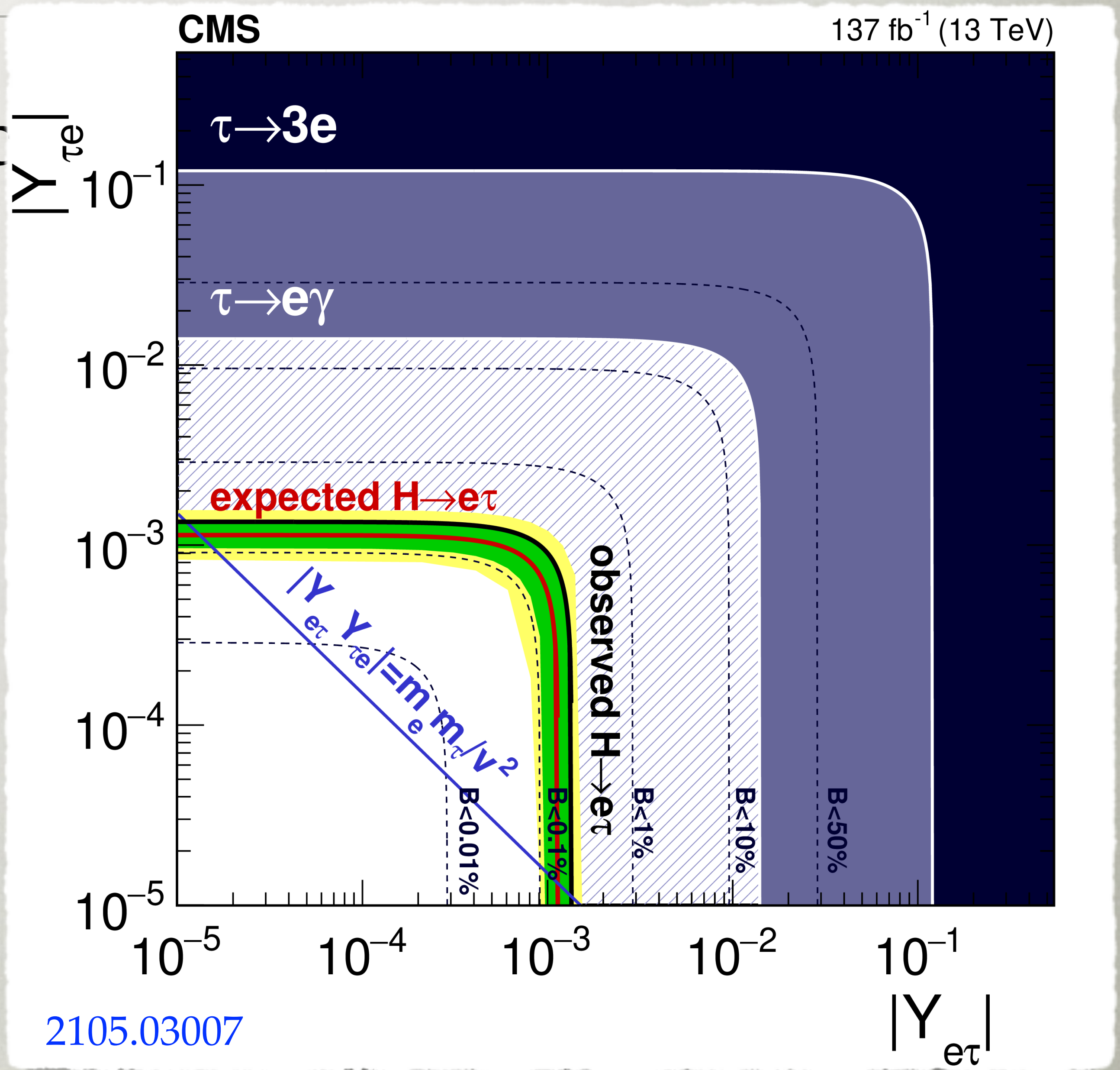
FLAVOR VIOLATING COUPLINGS

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

see also ATLAS 1907.06131

FLAVOR VIOLATING COUPLINGS





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

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

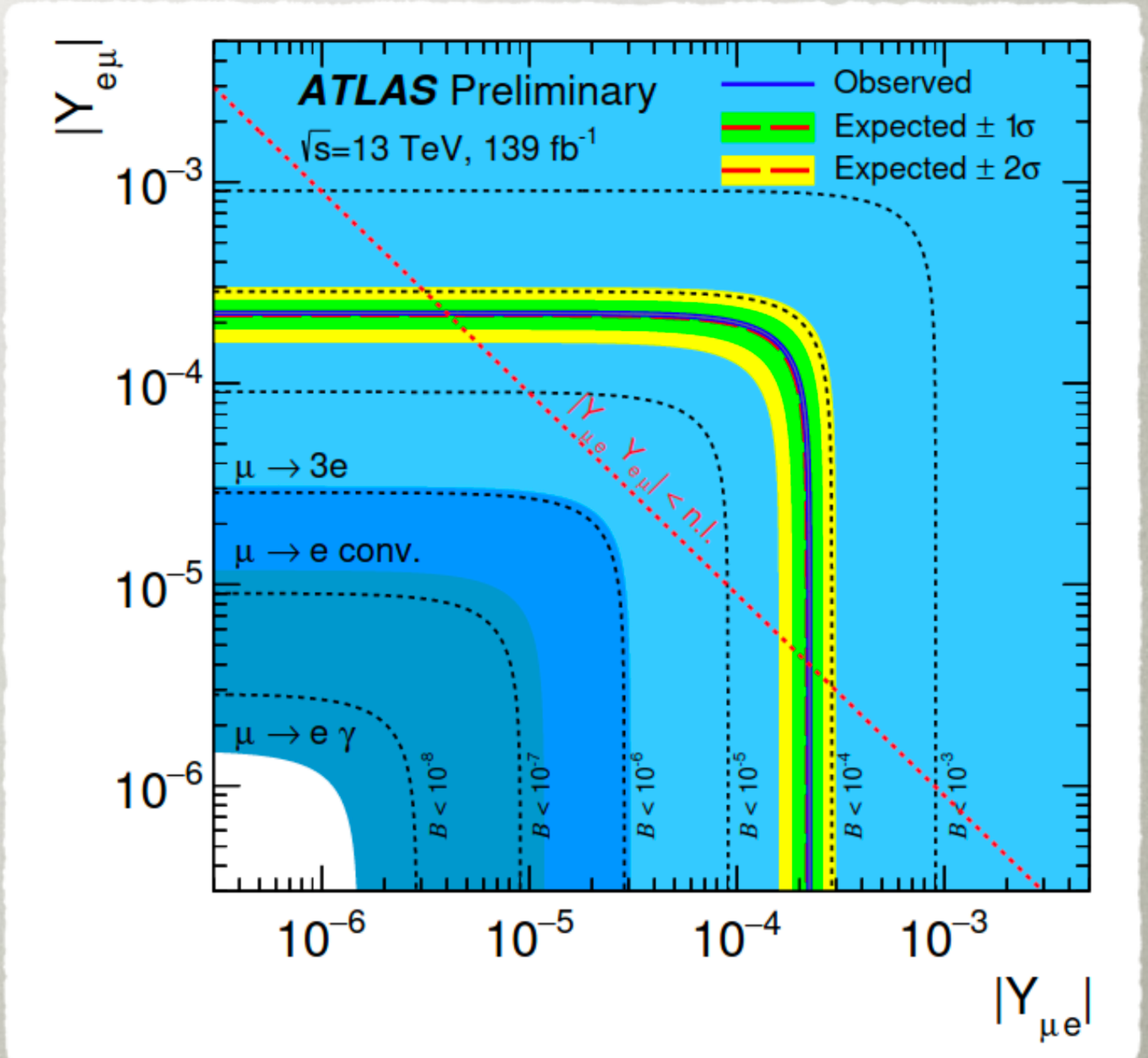
$$\Lambda_{e\tau} > 4.4 \text{ TeV}$$

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



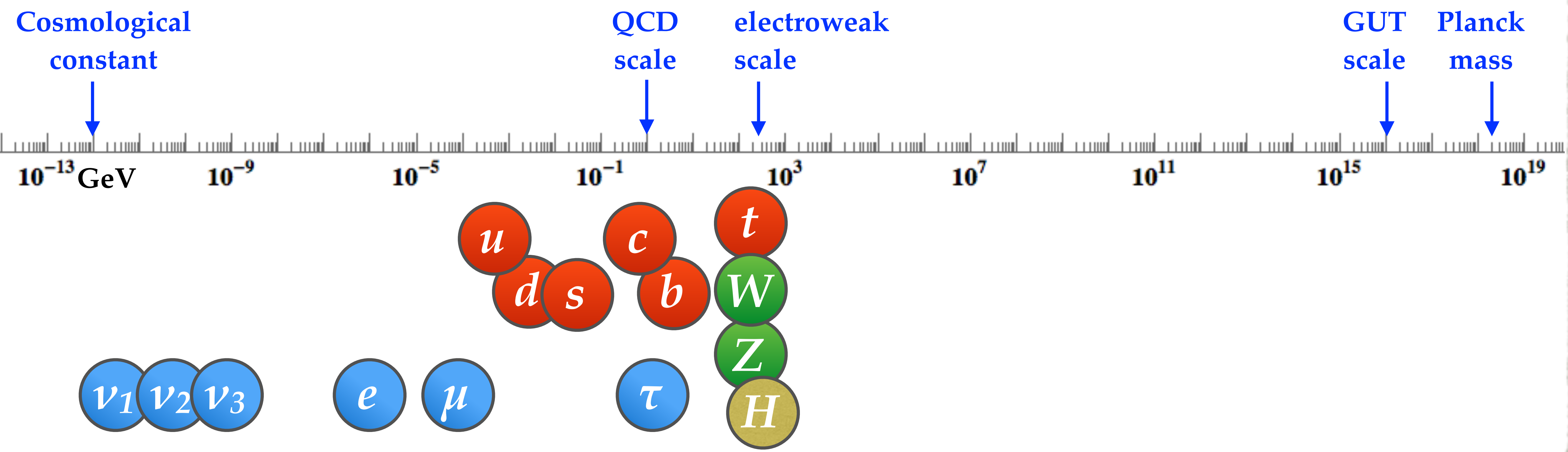
CONCLUDING REMARKS

- 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

QUARKS VS. LEPTONS

- when comparing quark and lepton sector of the Standard Model we observe:
- leptons of the same generation are lighter than quarks
  - smaller number of kinematically allowed decay modes for τ, μ than for t,b,c
  - *e.g.*, $B^- \to \tau^- \bar{\nu}_\tau$ allowed, while $\tau^- \to B^- \nu_\tau$ is not
- quarks carry color ⇒ bound inside hadrons
  - lepton decays are simpler to predict
- "up" leptons' (=ν's) mass ≪ "down" leptons' (=ℓ') mass
  - absolute neutrino masses not yet known
  - in many processes neutrino masses can be neglected



- leptons of the same generation are lighter than quarks
  - smaller number of kinematically allowed decay modes for τ, μ than for t,b,c
  - *e.g.*, $B^- \to \tau^- \bar{\nu}_\tau$ allowed, while $\tau^- \to B^- \nu_\tau$ is not
- quarks carry color ⇒ bound inside hadrons
  - lepton decays are simpler to predict
- "up" leptons' (=ν's) mass ≪ "down" leptons' (=ℓ') mass
  - absolute neutrino masses not yet known
  - in many processes neutrino masses can be neglected

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**

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

$\Rightarrow$ gives lepton FV coupl.s of axion

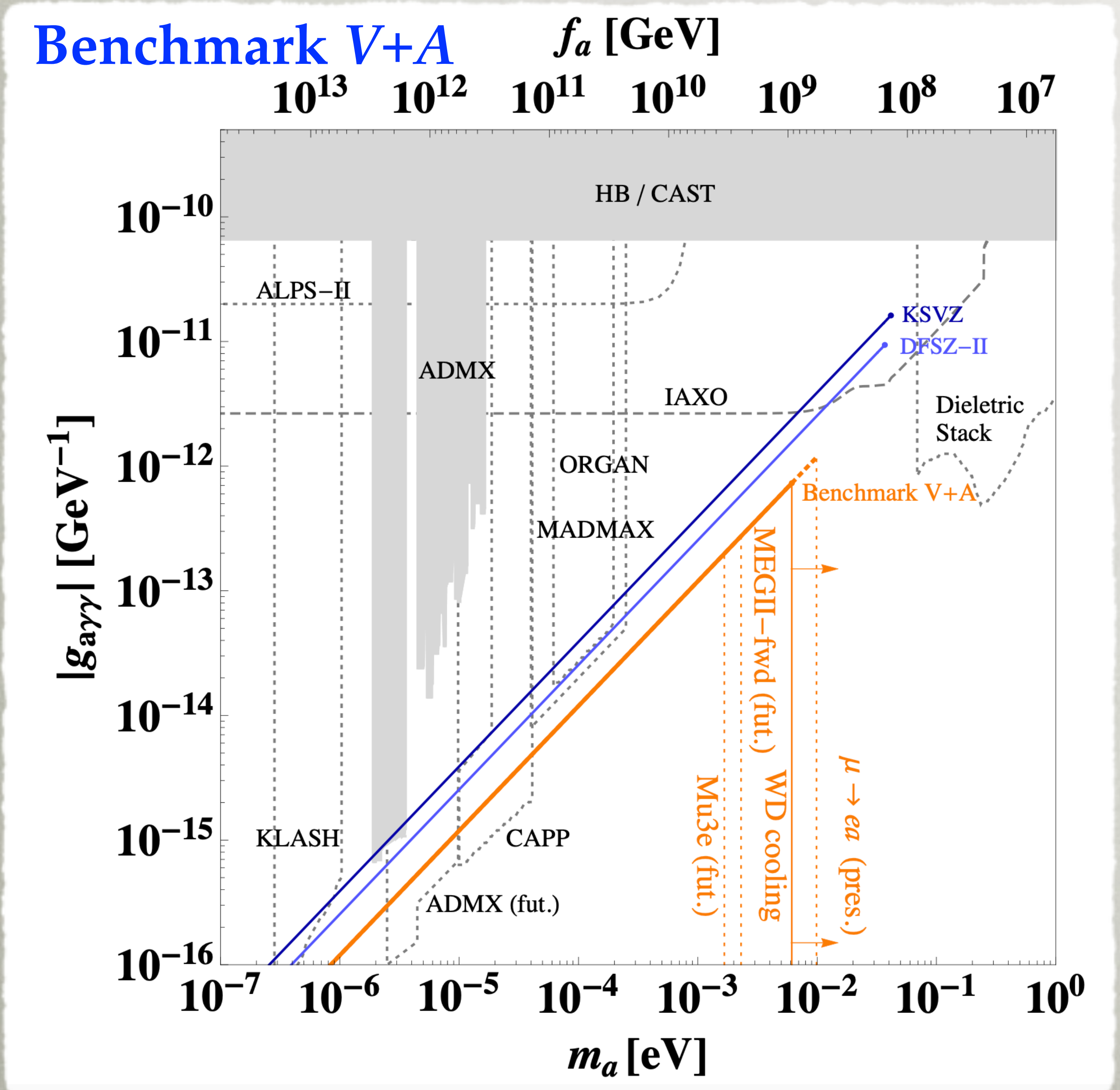
$$y_u = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}, \quad y_d = \begin{pmatrix} x & x & x \\ x & x & x \\ x & x & x \end{pmatrix}$$

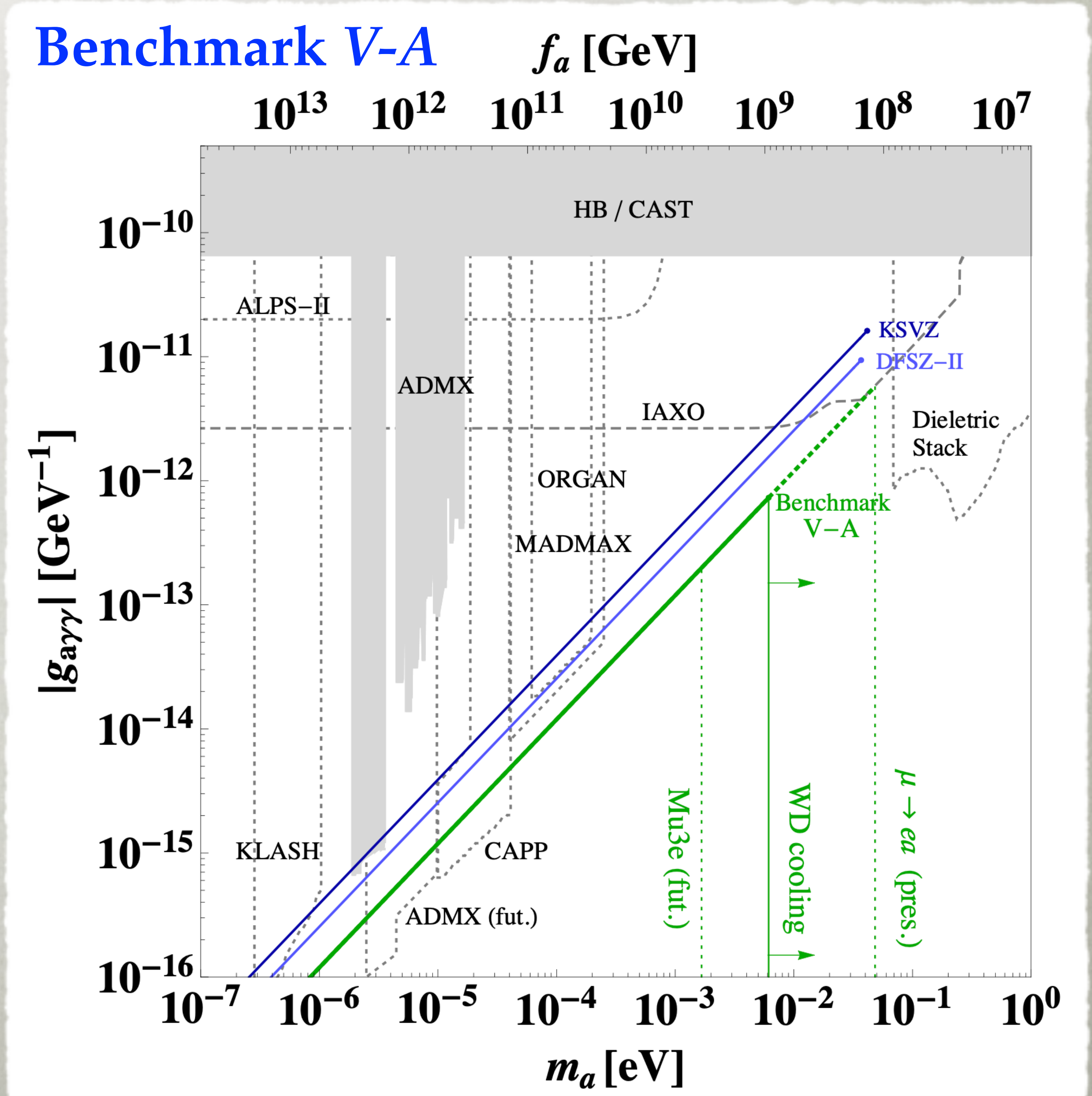
$\Rightarrow$ axion-quark couplings flavor diagonal

- 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

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

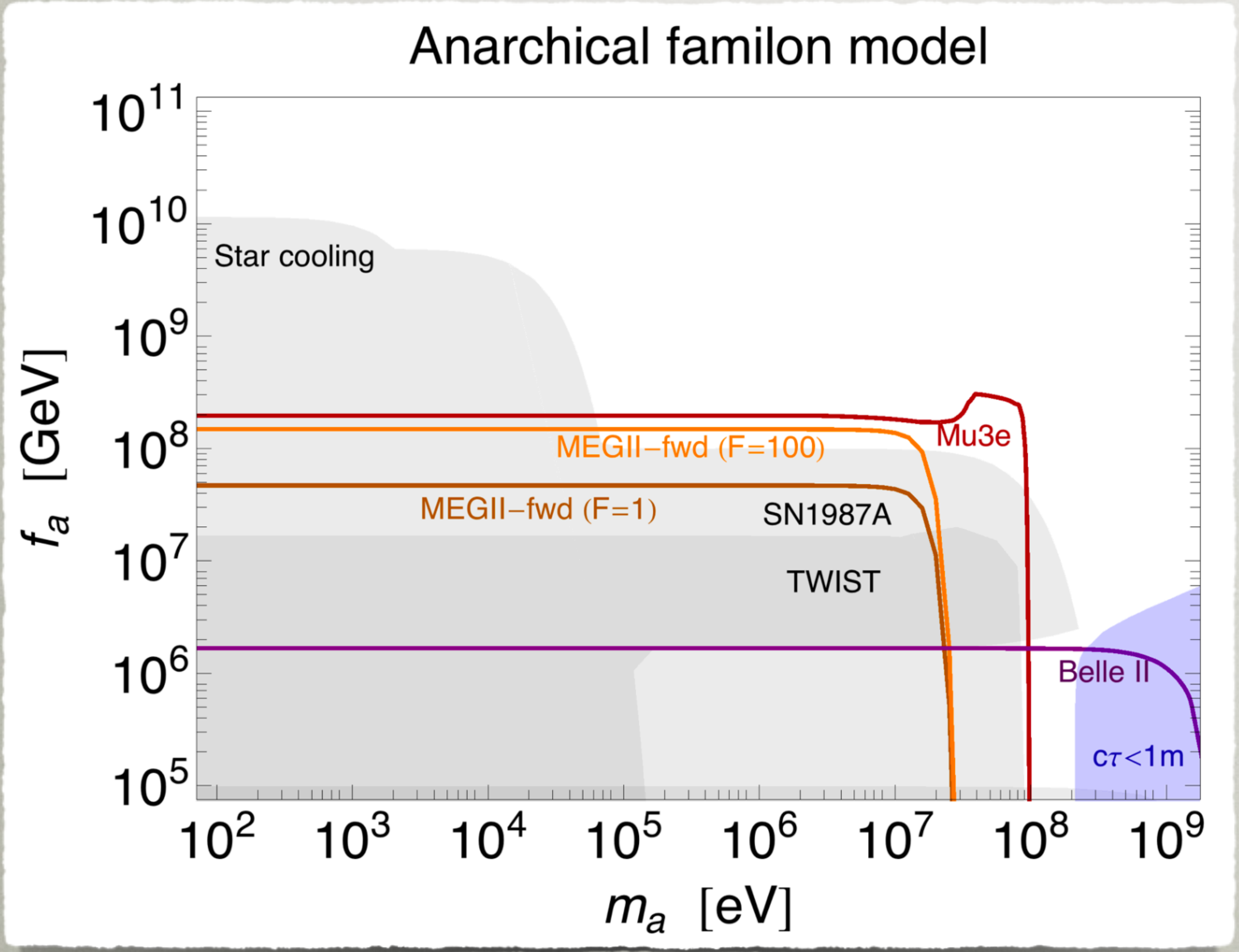
⇒ RH ALP

- two benchmark charge assignments

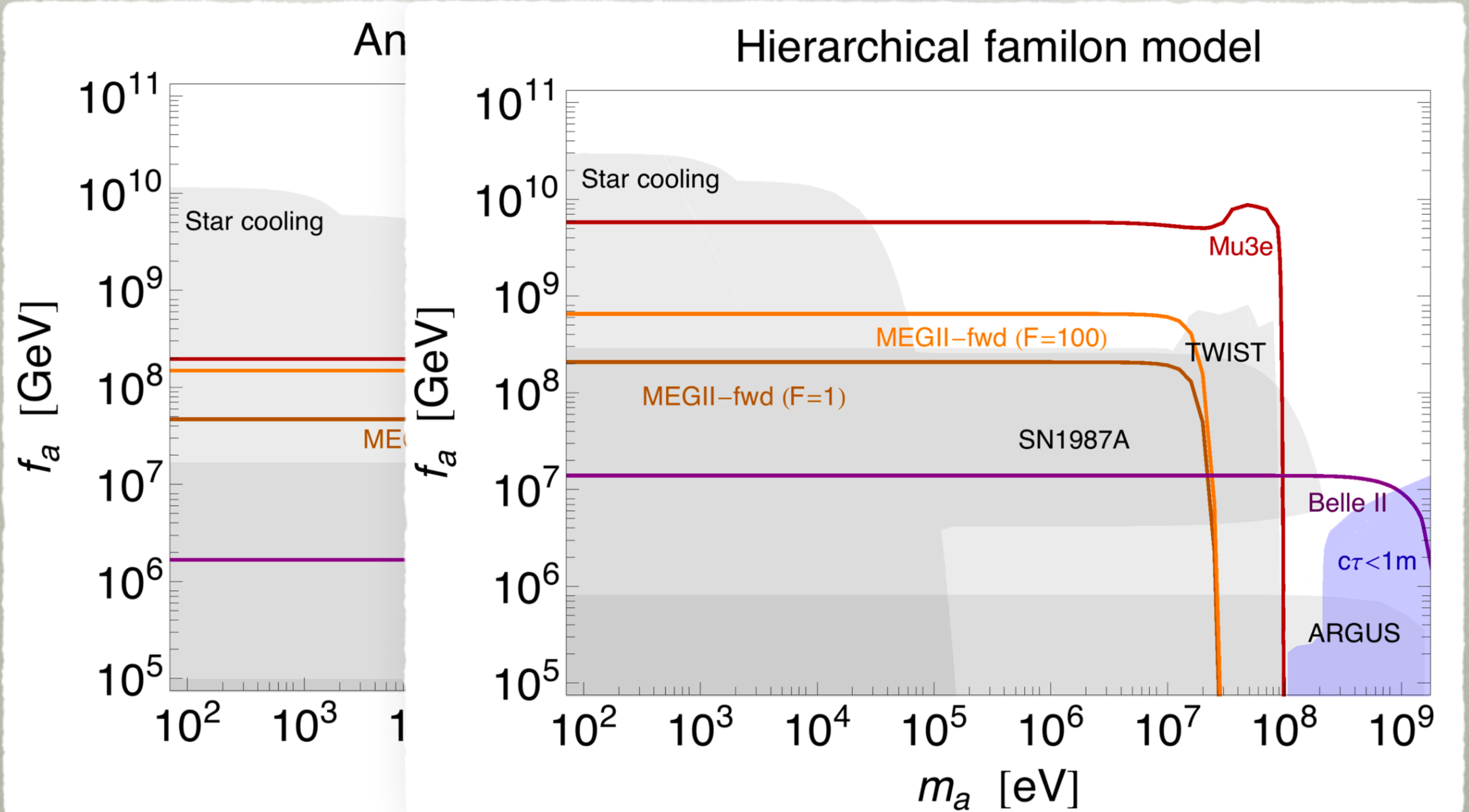
$$([L]_1,\,[L]_2,\,[L]_3) \;=\; (L+2,\,L+1,\,L), \qquad [\texttt{Hierarchy}]\,.$$

⇒ LH and RH couplings

LEPTONIC FAMILON

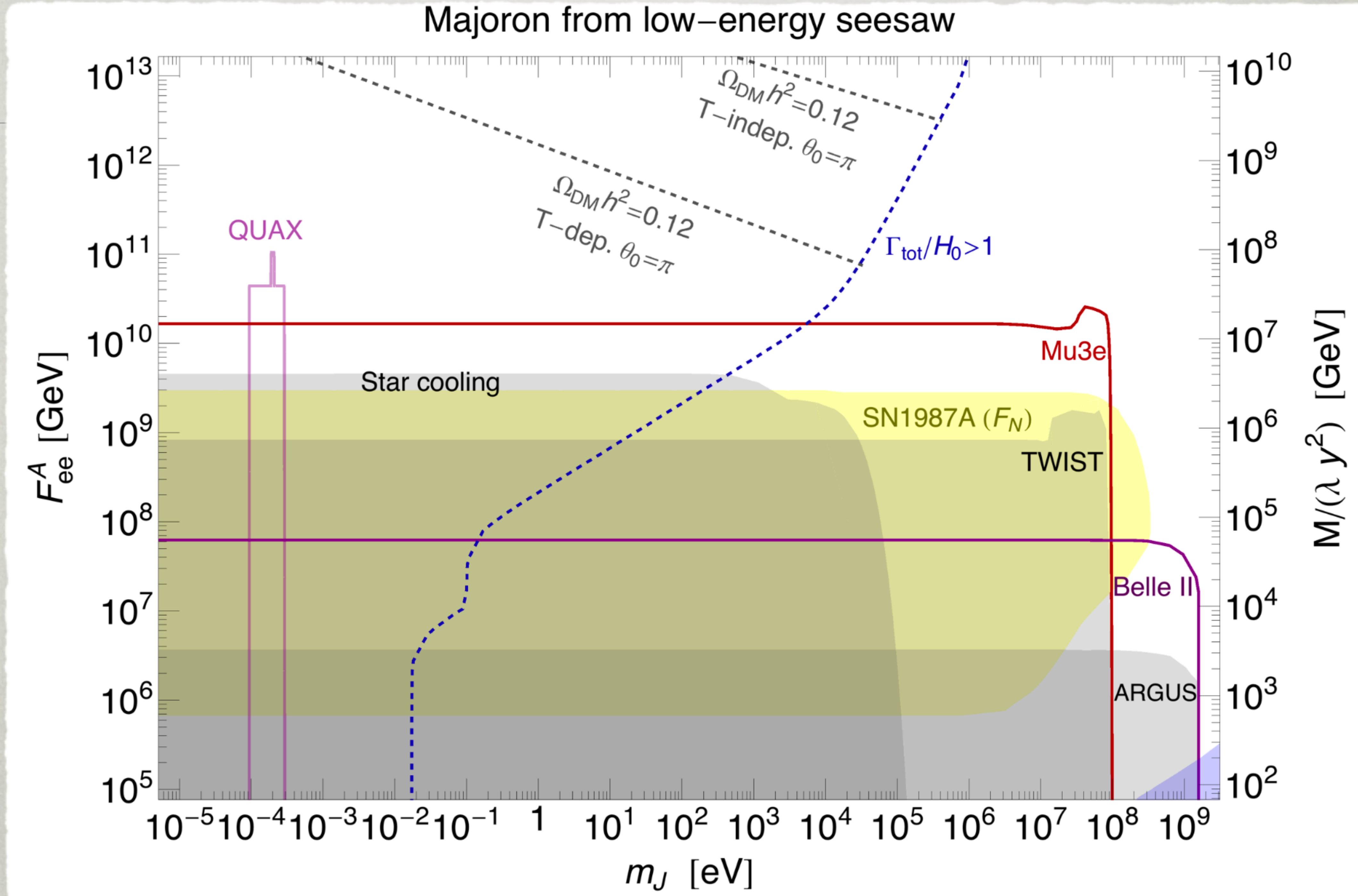


LEPTONIC FAMILON



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)
  - $\Rightarrow$ majoron observable
  - "low energy see-saw"



- "low energy see-saw"

NEW PHYSICS: SEE SAW EXAMPLE

- a simple example of new physics probed by $\mu \to e\gamma$
- a see-saw model for neutrino masses
  - allow for Majorana mass term for ν_R

$$\mathcal{L} = \mathcal{L}_{\rm SM} + i\bar{\nu}_R \partial\!\!\!/ \nu_R - \left(Y_\nu \bar{\nu}_R \widetilde{\Phi}^\dagger L_L + \frac{1}{2} M_R \bar{\nu}_R \nu_R^c + \text{h.c.} \right).$$

Dirac mass term ⇒ mixing of ν_L and ν_R

- mass spectrum consists of Majorana neutrinos
  - 3 heavy states, mostly ν_R with masses $\sim M_R$
  - 3 light neutrinos, mostly ν_L, mass matrix

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

SEE SAW AND $\mu \to e\gamma$

- due to ν_L and ν_R mixing
  - PMNS matr. does not diagonalize the full $\nu_{L,R}$ mass matrix
  - the mixing matrix $\mathcal{U}$ entering the $W - \ell - \nu$ vertex is not unitary

$$\mathcal{U} = \left(1 - \frac{v^2}{2} Y_\nu^\dagger M_R^{-2} Y_\nu\right) U \,.$$

note: in m_ν we have Y_ν^T not $Y_\nu^\dagger$

- modified prediction for $\mu \to e\gamma$

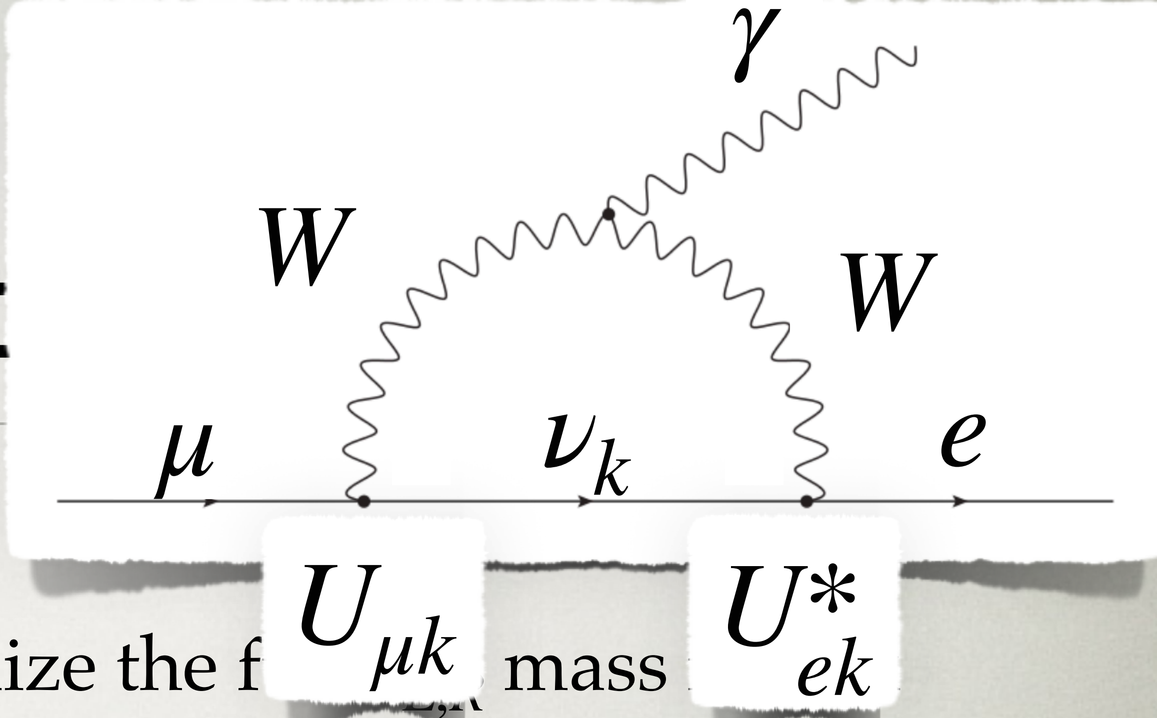
$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \frac{\left|\sum_k \mathcal{U}_{\mu k} \mathcal{U}_{ek}^* F(x_k)\right|^2}{(\mathcal{U}\mathcal{U}^\dagger)_{\mu\mu} (\mathcal{U}\mathcal{U}^\dagger)_{ee}},$$

$$F(x_k) = \tfrac{10}{3} - x_k + \mathcal{O}\left(x_k^2\right).$$

$$x_k = m_{\nu_k}^2 / M_W^2$$

  - GIM mechanism no longer fully operational
  - $Br(\mu \to e\gamma)$ not suppressed by light ν masses, can be larger

SEE SAW AND



- due to ν_L and ν_R mixing
  - PMNS matr. does not diagonalize the f mass
  - the mixing matrix $\mathcal{U}$ entering the $W - \ell - \nu$ vertex is not unitary

$$\mathcal{U} = \left(1 - \frac{v^2}{2} Y_\nu^\dagger M_R^{-2} Y_\nu\right) U \,.$$

note: in m_ν we have Y_ν^T not $Y_\nu^\dagger$

- modified prediction for $\mu \to e\gamma$

$$\mathrm{BR}(\mu \to e\gamma) = \frac{3\alpha}{32\pi} \frac{\left|\sum_k \mathcal{U}_{\mu k} \mathcal{U}^*_{ek} F(x_k)\right|^2}{(\mathcal{U}\mathcal{U}^\dagger)_{\mu\mu} (\mathcal{U}\mathcal{U}^\dagger)_{ee}},$$

$$F(x_k) = \frac{10}{3} - x_k + \mathcal{O}\left(x_k^2\right).$$

$$x_k = m^2_{\nu_k} / M_W^2$$

  - GIM mechanism no longer fully operational
  - $Br(\mu \to e\gamma)$ not suppressed by light ν masses, can be larger

HEAVY NEW PHYSICS

- if there is heavy NP, can be integrated out
  - results in SM Effective Field Theory (SMEFT)
  - renormalizable SM supplemented by higher dimensional operators

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda}\sum_a C_a^{(5)} Q_a^{(5)} + \frac{1}{\Lambda^2}\sum_a C_a^{(6)} Q_a^{(6)} + \dots$$

- $\mu \to e\gamma$ results in a dimension 6 operator

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

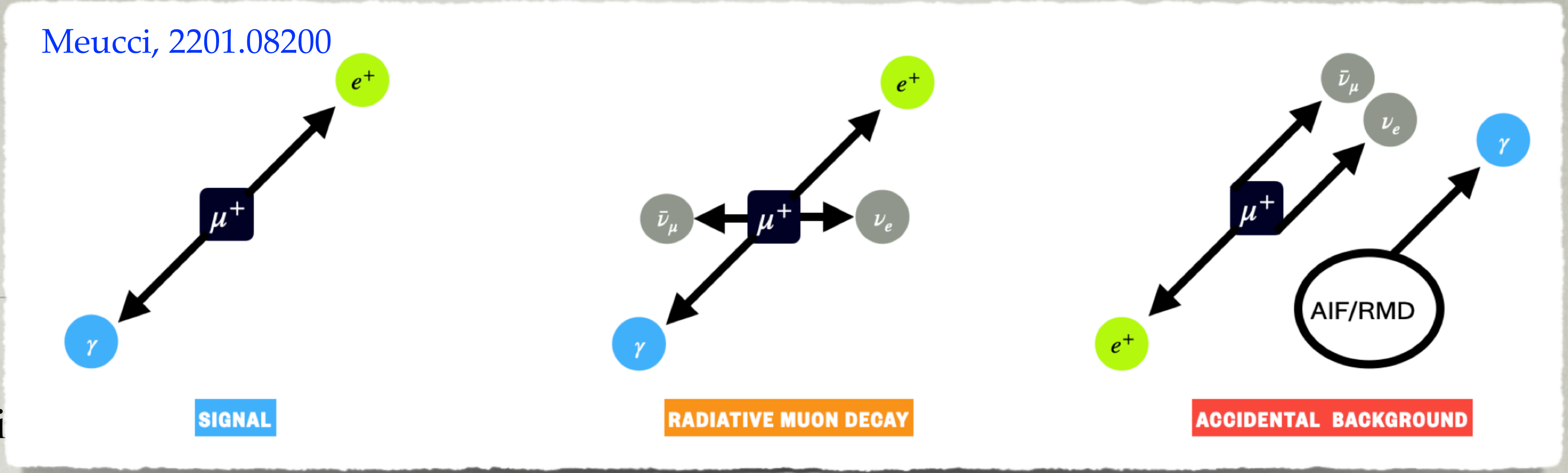
  - exp. bounds imply that it is highly suppressed

$$\mu \to e\gamma \Rightarrow \Lambda_{21} \gtrsim 3500\,\text{TeV}$$

Greljo, Stangl, Thomsen, 2103.13991

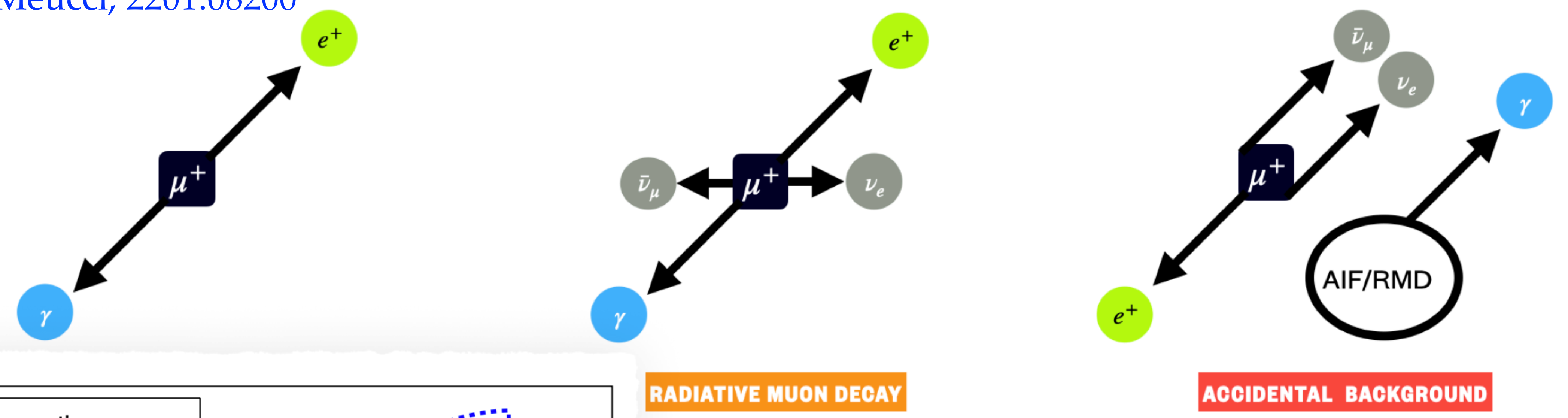
$\mu \to e\gamma$ EXPERIMENTS

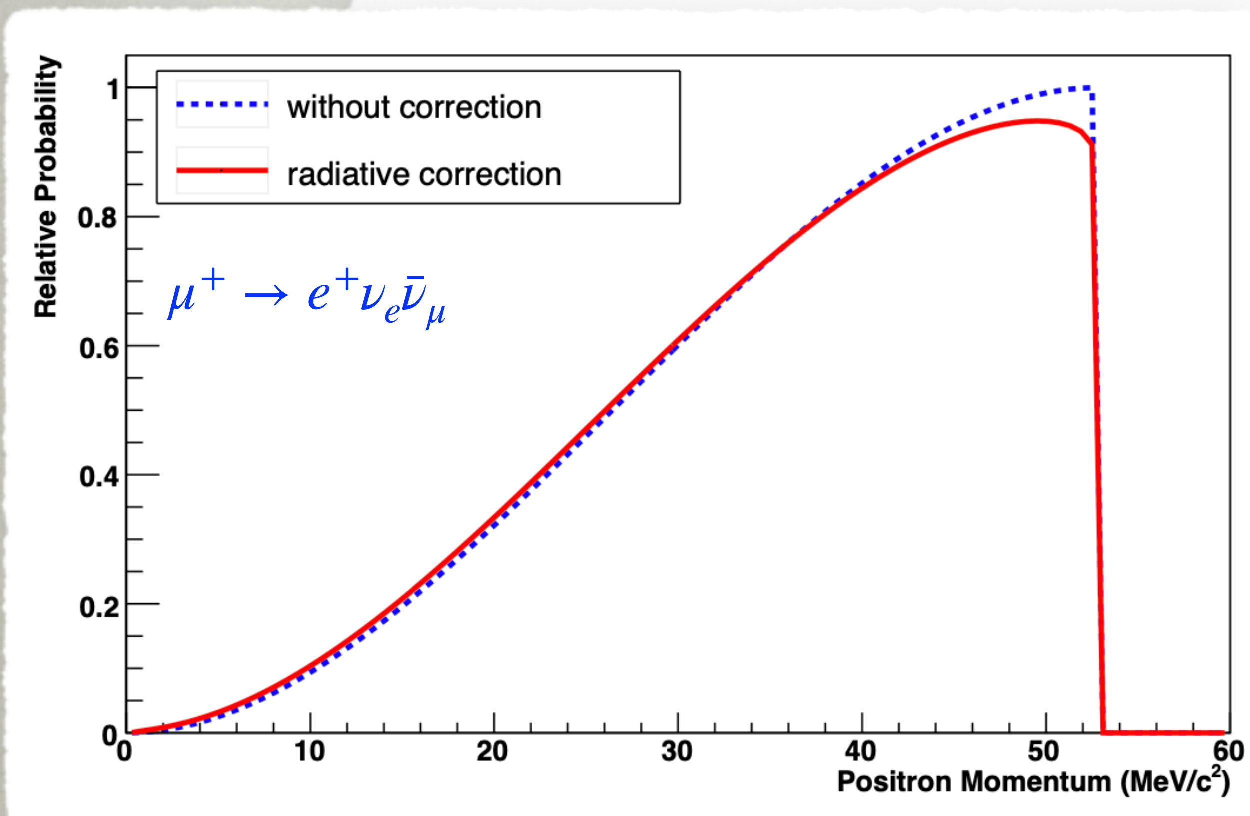
- in muon rest frame e and γ are monochromatic
  - $E_e = E_\gamma \simeq m_\mu/2 \simeq 52.8\,\mathrm{MeV}$
- convenient to perform experiments with stopped muons
  - use μ^+ so that it does not get bound to nucleus, i.e., avoid the spread of line from decay in orbit
  - the measured process is thus $\mu^+ \to e^+\gamma$
- muons are stopped in the thinnest possible targets
  - so that the e^+ do not loose energy when escaping
  - search for monochromatic e^+ line at the kinematical edge of SM $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay (the "Michele edge")
  - require coincidence with a photon of the same energy
  - energy resolution very important to reduce SM background
    - irreducible background is the SM decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$



- i
    - $E_e = E_\gamma \simeq m_\mu/2 \simeq 52.8\,\mathrm{MeV}$
- convenient to perform experiments with stopped muons
    - use μ^+ so that it does not get bound to nucleus, i.e., avoid the spread of line from decay in orbit
    - the measured process is thus $\mu^+ \to e^+\gamma$
- muons are stopped in the thinnest possible targets
    - so that the e^+ do not loose energy when escaping
    - search for monochromatic e^+ line at the kinematical edge of SM $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay (the "Michele edge")
    - require coincidence with a photon of the same energy
    - energy resolution very important to reduce SM background
        - irreducible background is the SM decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$

Meucci, 2201.08200





with stopped muons

und to nucleus, i.e., avoid the spread of

$\to e^+\gamma$

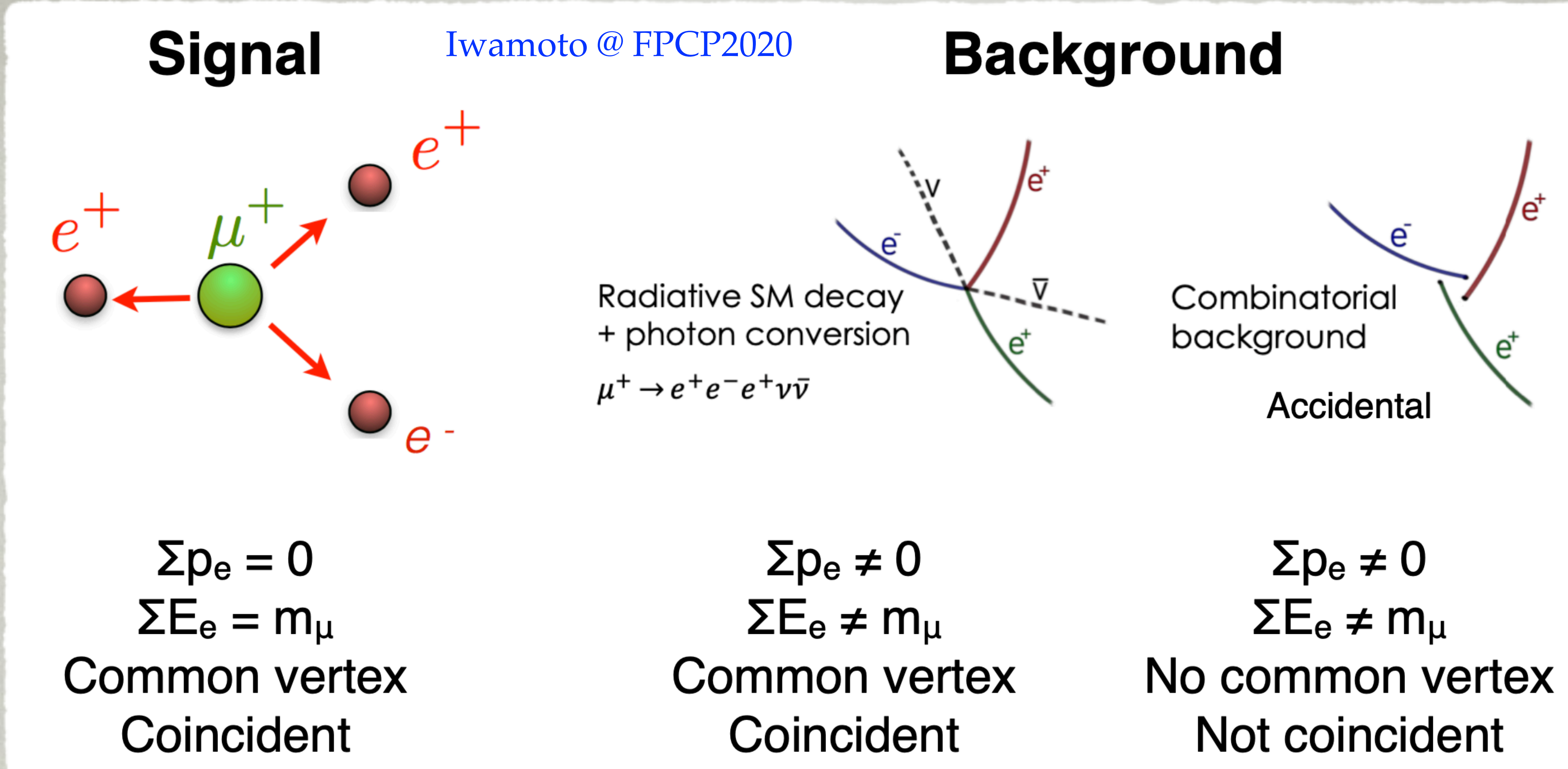
ossible targets

gy when escaping

- search for monochromatic e^+ line at the kinematical edge of SM $\mu^+ \to e^+\nu_e\bar{\nu}_\mu$ decay (the "Michele edge")
- require coincidence with a photon of the same energy
- energy resolution very important to reduce SM background
  - irreducible background is the SM decay $\mu^+ \to e^+\nu_e\bar{\nu}_\mu\gamma$

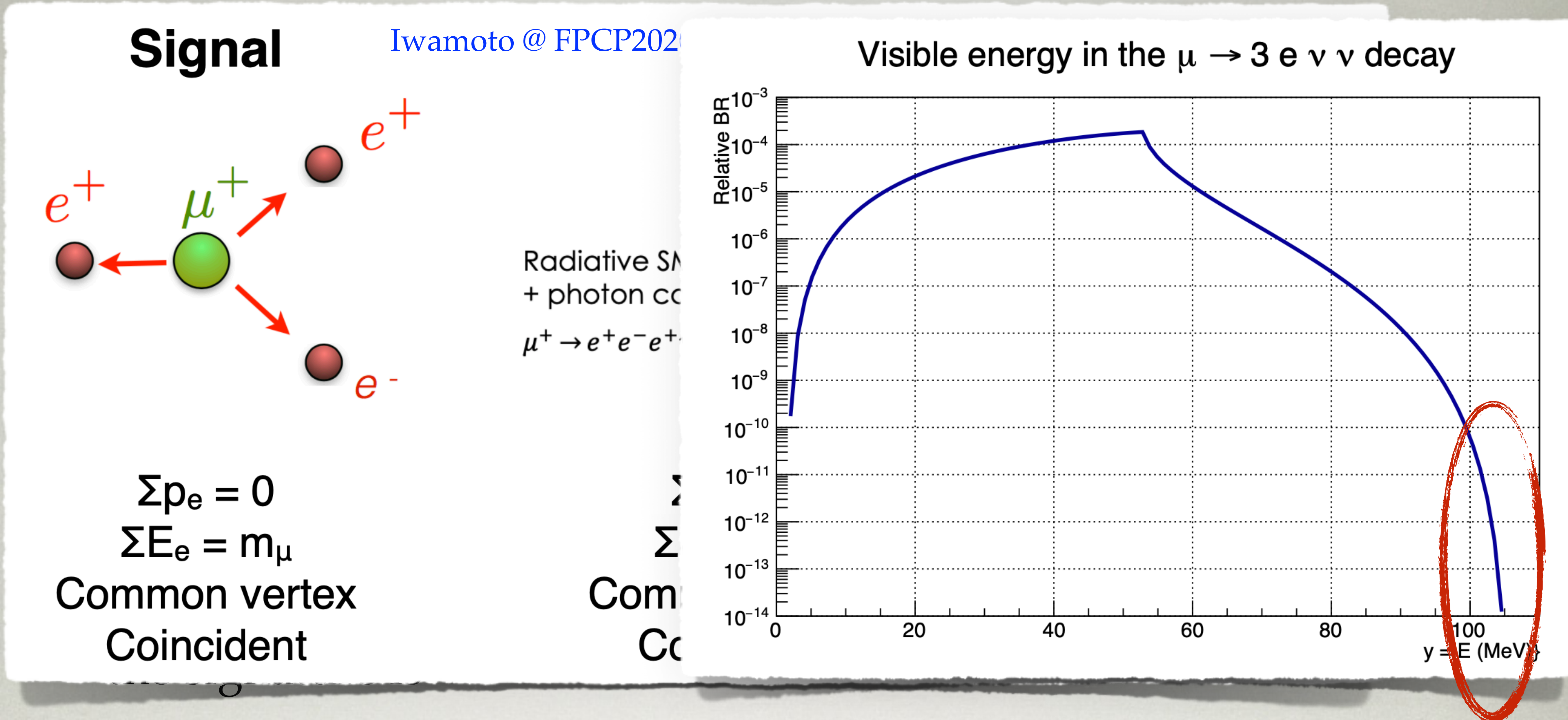
EXPERIMENTS

- also use stopped μ^+ so the lab frame is the muon rest frame
- $\mu^+ \to e^+ e^- e^+$ is a 3-body decay, so no mono-energetic particle
  - maximal energy for each e is $E_{\text{max}} \simeq m_\mu / 2$
- the signature is
  - $2e^+$ and $1e^-$ coming from common vertex (and nothing else)
  - their energy adds up to m_μ
- the main "irreducible" SM background $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$ decay
  - two neutrinos appear as missing energy E_{inv}
  - need very precise energy measurement to make sure $E_{e^+} + E_{e^-} + E_{e^+} = m_\mu$



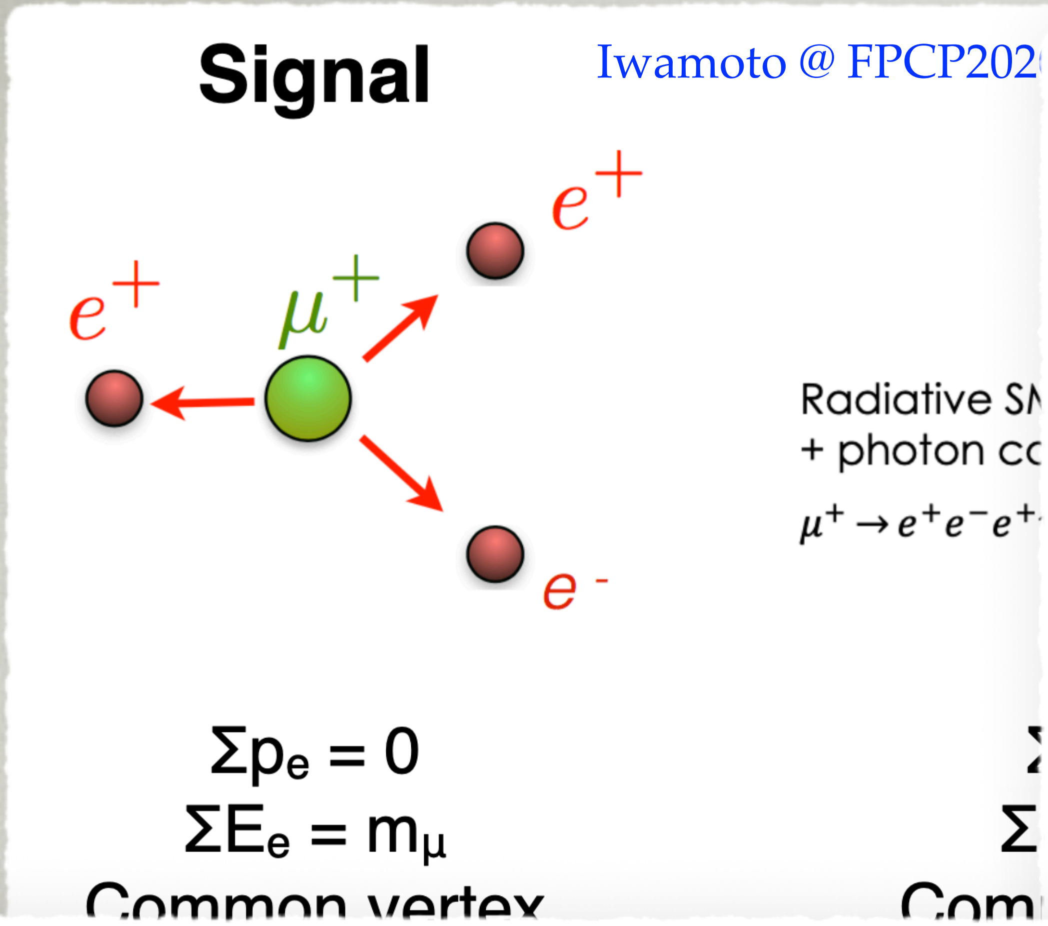
- $2e^+$ and $1e^-$ coming from common vertex (and nothing else)
- their energy adds up to m_μ

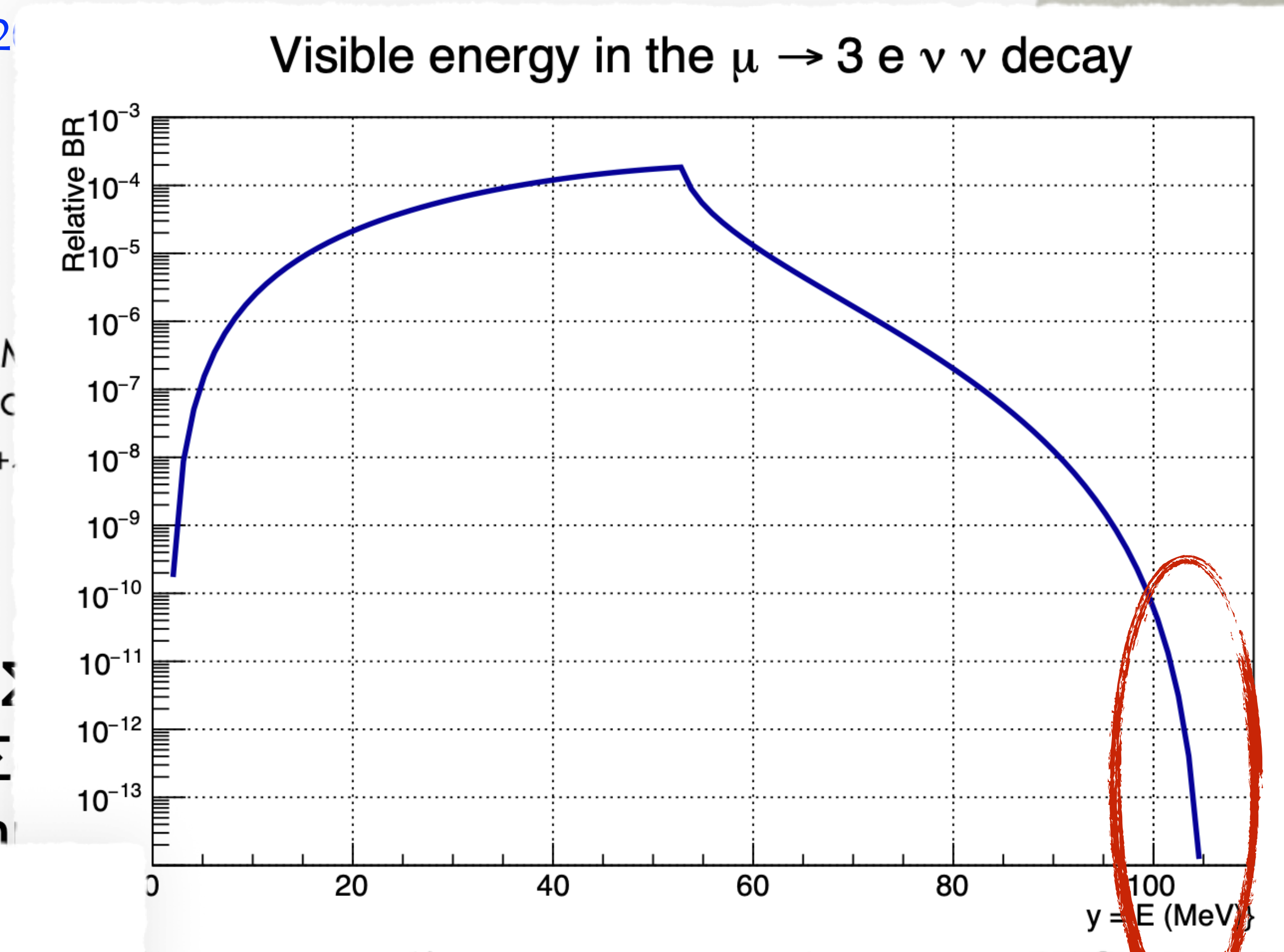
- the main "irreducible" SM background $\mu^+ \to e^+ e^- e^+ \bar{\nu}_\mu \nu_e$ decay
  - two neutrinos appear as missing energy $E_{\rm inv}$
  - need very precise energy measurement to make sure $E_{e^+} + E_{e^-} + E_{e^+} = m_\mu$

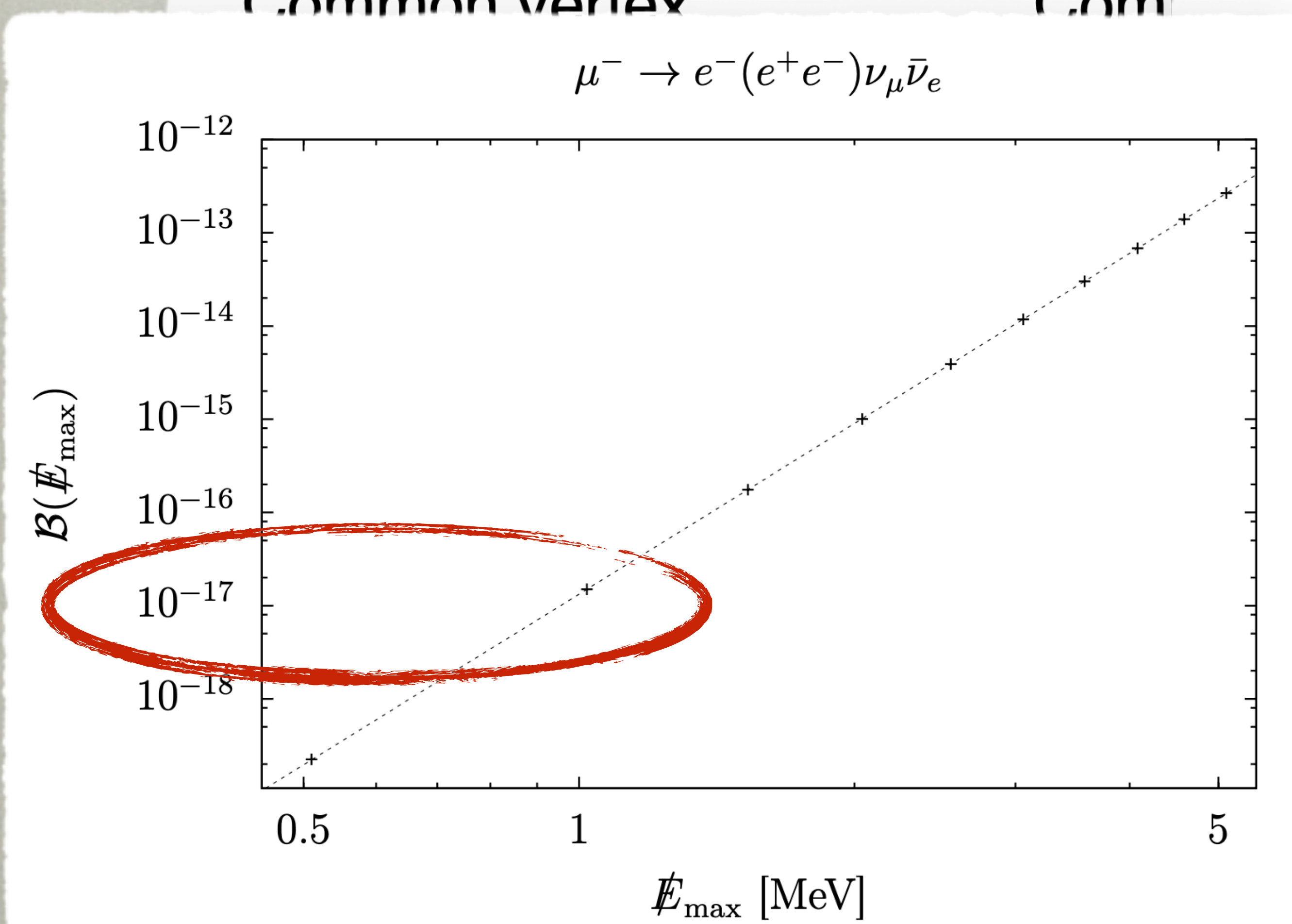


- $2e^+$ and $1e^-$ coming from common vertex (and nothing else)
- their energy adds up to m_μ

- the main "irreducible" SM background $\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$ decay
  - two neutrinos appear as missing energy $E_{\rm inv}$
  - need very precise energy measurement to make sure $E_{e^+} + E_{e^-} + E_{e^+} = m_\mu$







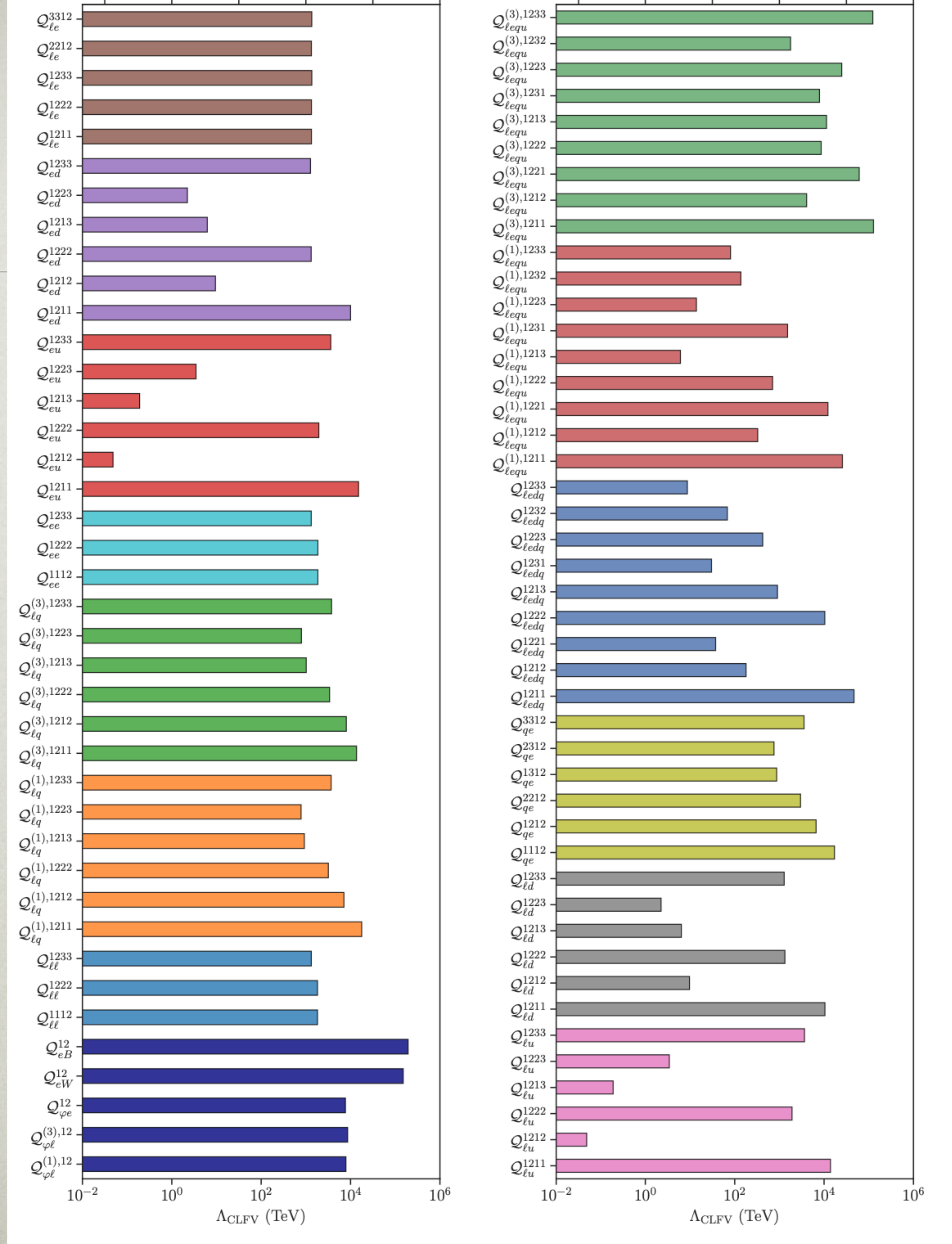
nmon vertex (and nothing else)

round $\mu^+ \to e^+e^-e^+\bar{\nu}_\mu\nu_e$ decay

ing energy $E_{\rm inv}$

asurement to make sure

- present best bound
  - SINDRUM (1988): Nuclear Physics B 1988, 299
    $Br(\mu^+ \to e^+ e^- e^+) < 1.0 \times 10^{-12}$
- future
  - Mu3e: 2009.11690
    Phase 1 (~2025): $Br(\mu \to 3e) < 2 \times 10^{-15}$
    Phase 2 (2030s): $Br(\mu \to 3e) \lesssim 10^{-16}$



-

Nuclear Physics B 1988, 299

-12

-

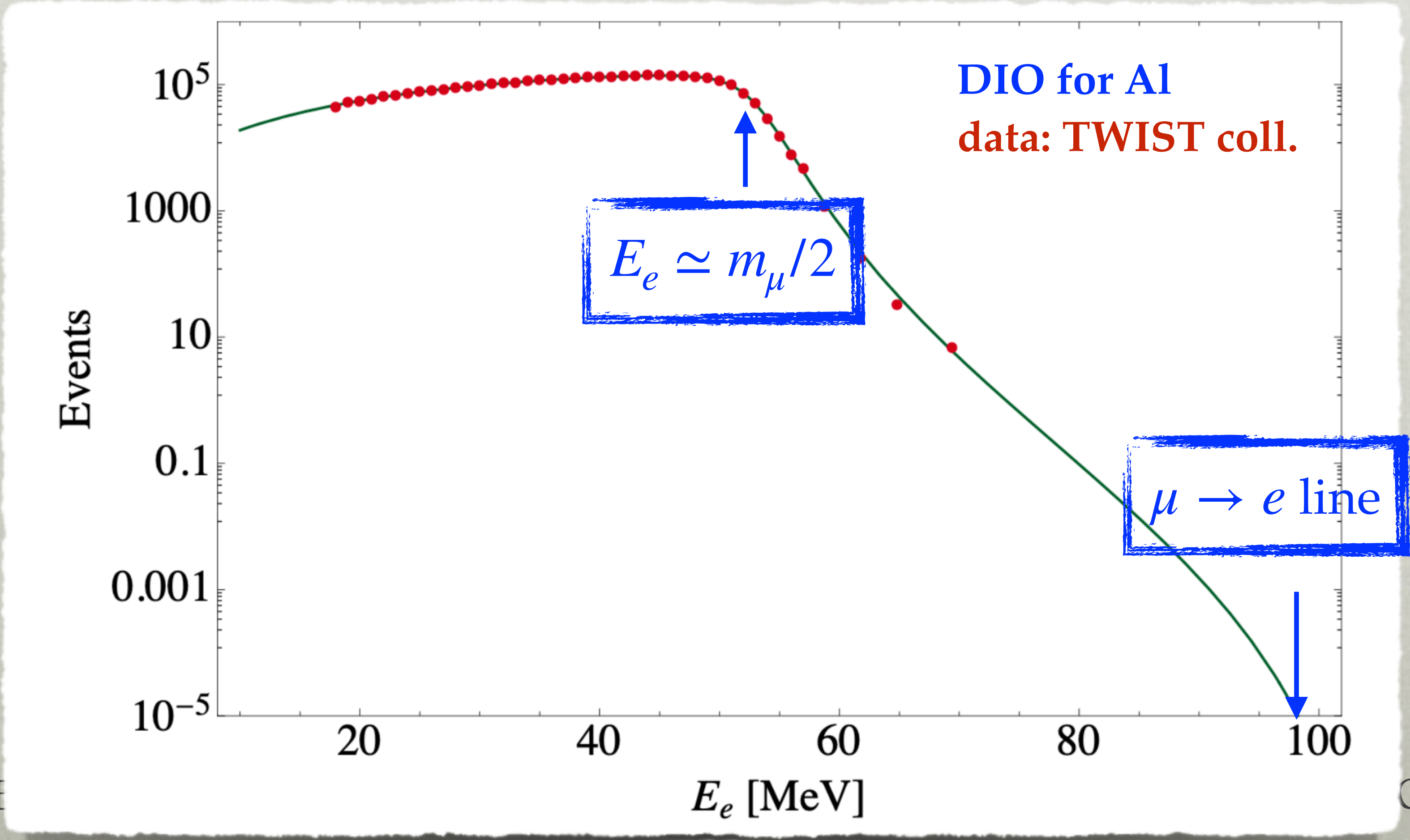
2009.11690

$< 2 \times 10^{-15}$

$\lesssim 10^{-16}$

$\mu^- N \to e^- N$ conversion

- experimentally $\mu \to e$ conversion offers many advantages over, e.g., $\mu \to e\gamma$
  - the only intrinsic bckgd is $\mu^- \to e^- \nu_\mu \bar{\nu}_e$ decay in orbit
  - in $\mu^- N \to e^- N$ the e^- is at the kinematical edge of DIO



$\mu^- N \to e^- N$ CONVERSION

- present bound
  - SINDRUM-II (1993, 2006):
    $R_{\mu e} < 6.1(7.1) \times 10^{-13}$ on Ti (Au)

Physics Letters B 1993, 317, 631
Eur. Phys. J. C 2006, 47

- future (on C)
  - DeeMee: $R_{\mu e} \lesssim 1(0.2) \times 10^{-13}$ on C (SiC)
- future (on Al)
  - COMET Phase 1: $R_{\mu e} \lesssim 10^{-15}$
  - Mu2e & COMET Phase-II: $R_{\mu e} \lesssim 10^{-17}$
  - Mu2e-II: $R_{\mu e} \lesssim 10^{-18}$

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

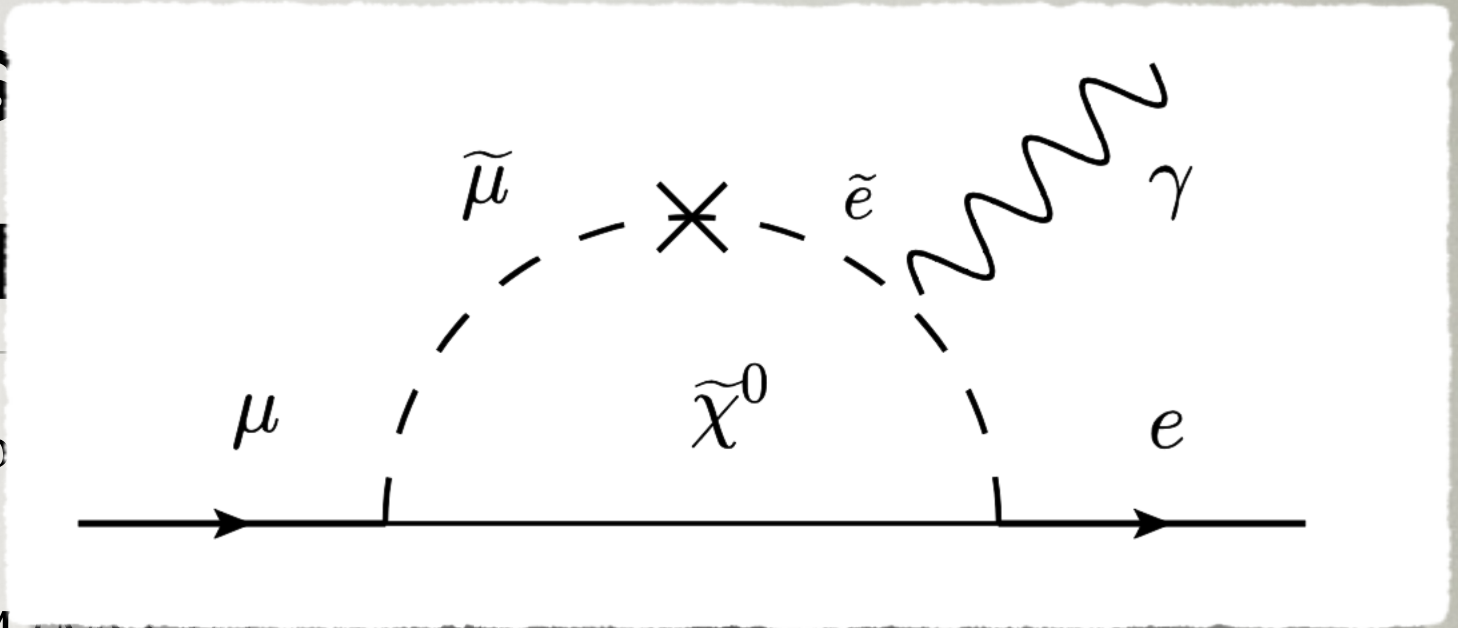
Antusch et al., hep-ph/0607263

  - 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



- in general there are many flavo
  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

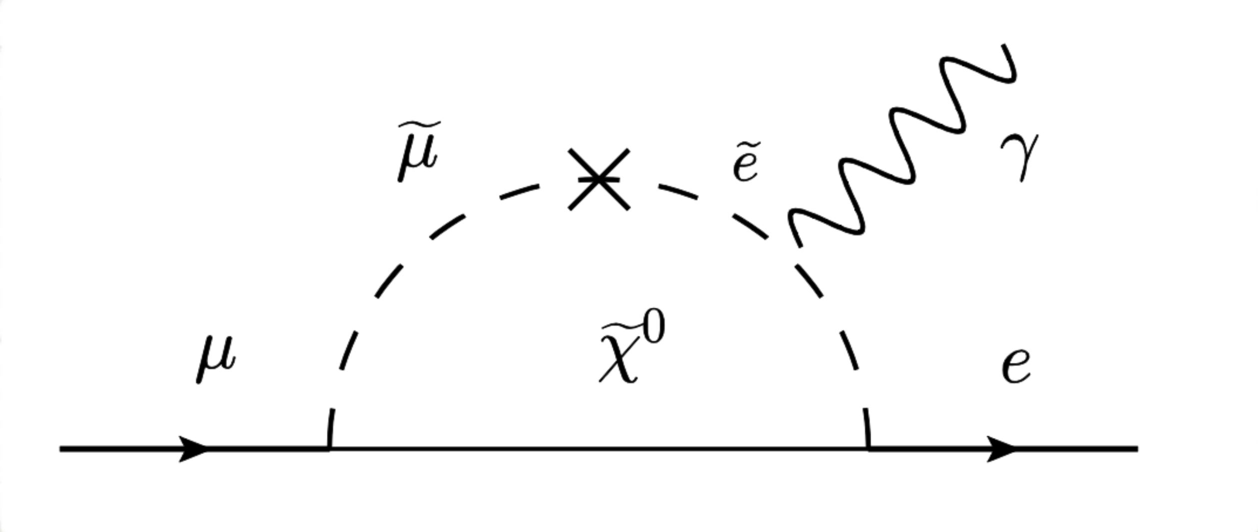
  - SUSY breaking parameters are assumed to be flavor universal at the UV scale (=GUT scale)
- all LFV originates solely from the neutrino sector
  - some of the parameters are fixed by requiring to reproduce neutrino masses and PMNS, scanned over the rest

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

  - FV in slepton mass matrices from RGEs

SUPERSYMMETRIC SEE-SAW

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



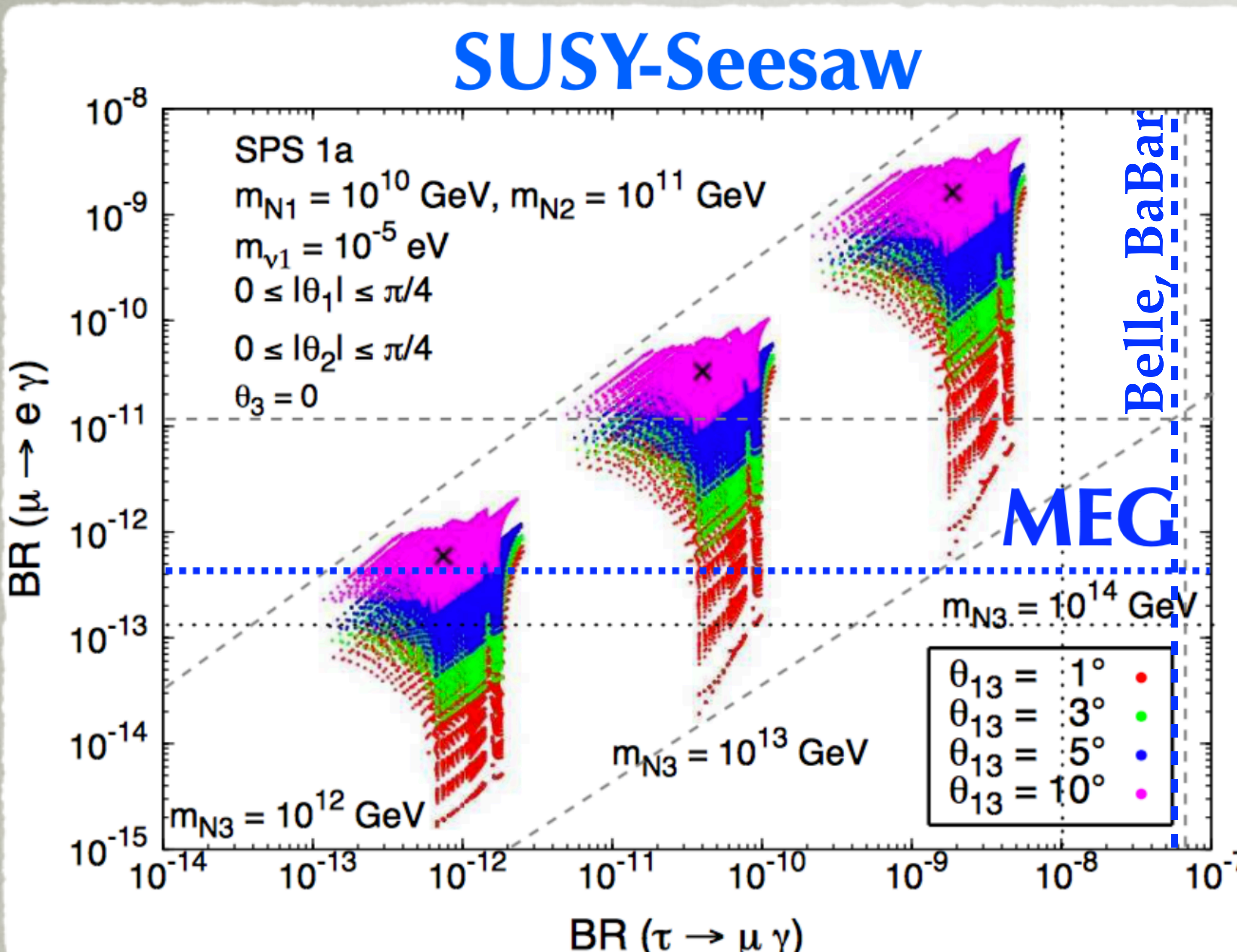
- the $\ell_j \to 3\ell_i$ are thus given by

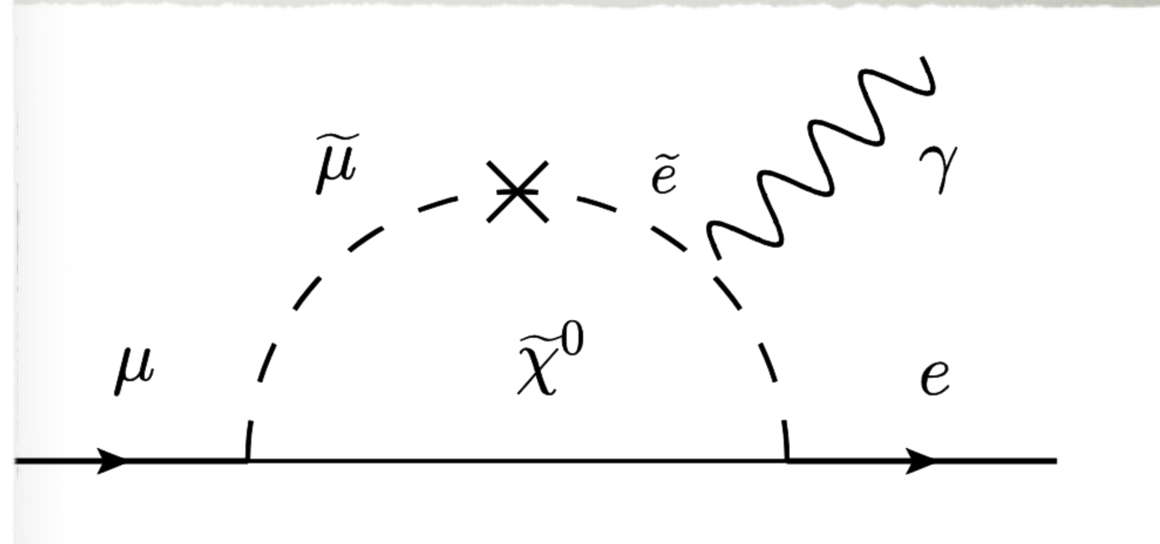
Antusch et al., hep-ph/0607263

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

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

METRIC
AW





n by

Antusch et al., hep-ph/0607263

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

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

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'

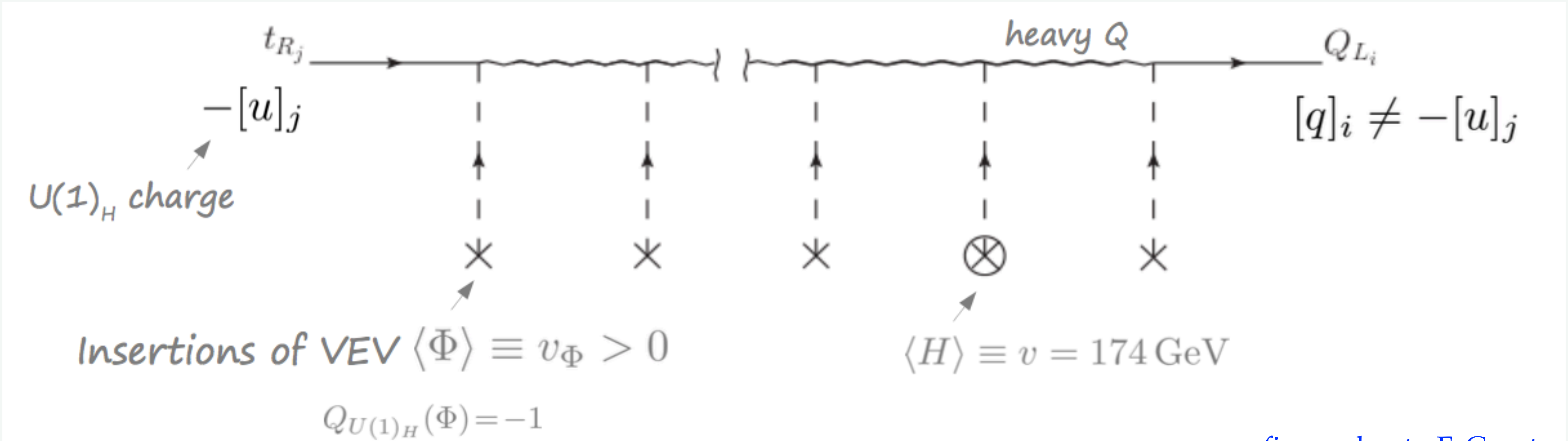
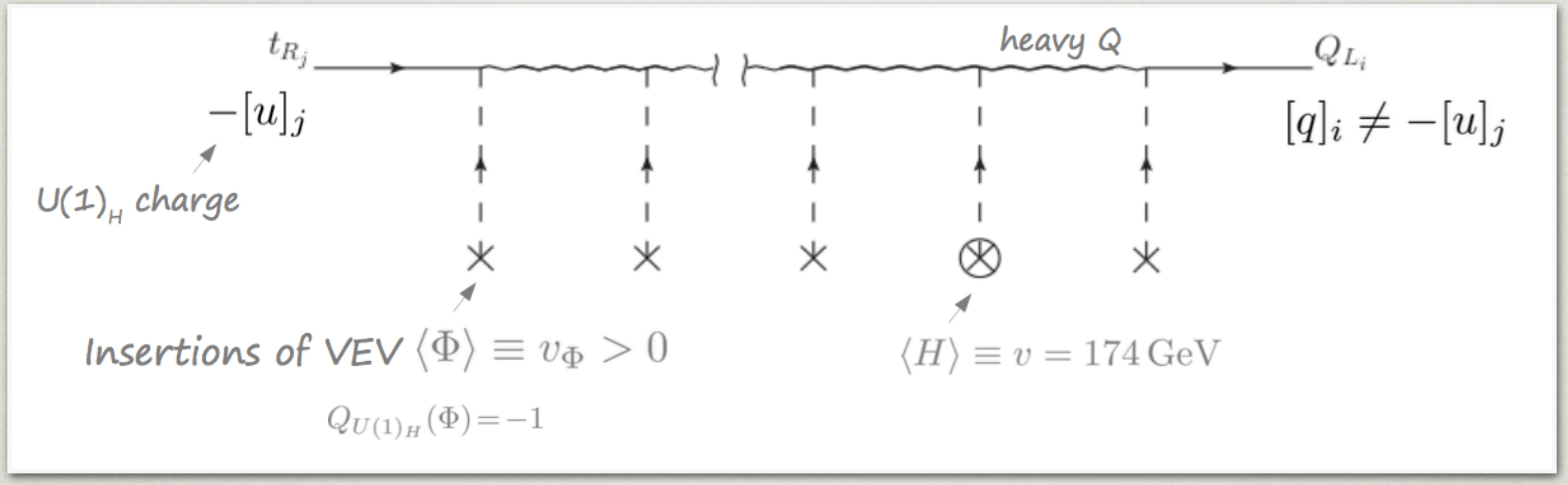


figure due to F. Goertz

Smolkovic, Tammaro, JZ, 1907.10063

SPURION ANALYSIS



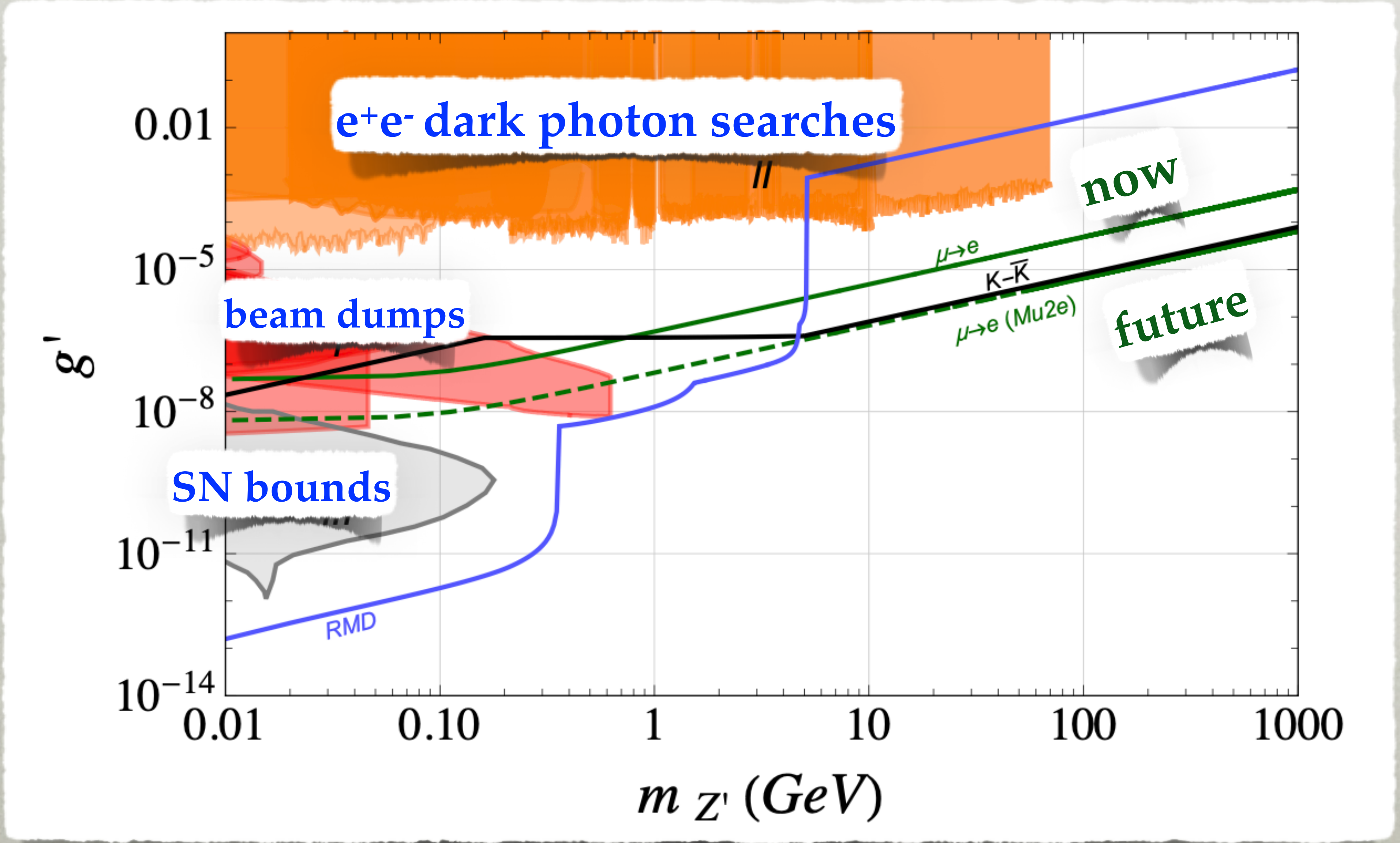
- effective Yukawas governed by flavon insertions (so that invariant under flavor symm.)

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

  - 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 $U(1)_{\rm FN}$
    - we show the results for an anomaly free $U(1)_{\rm FN}$ (inverted FN) that is gauged

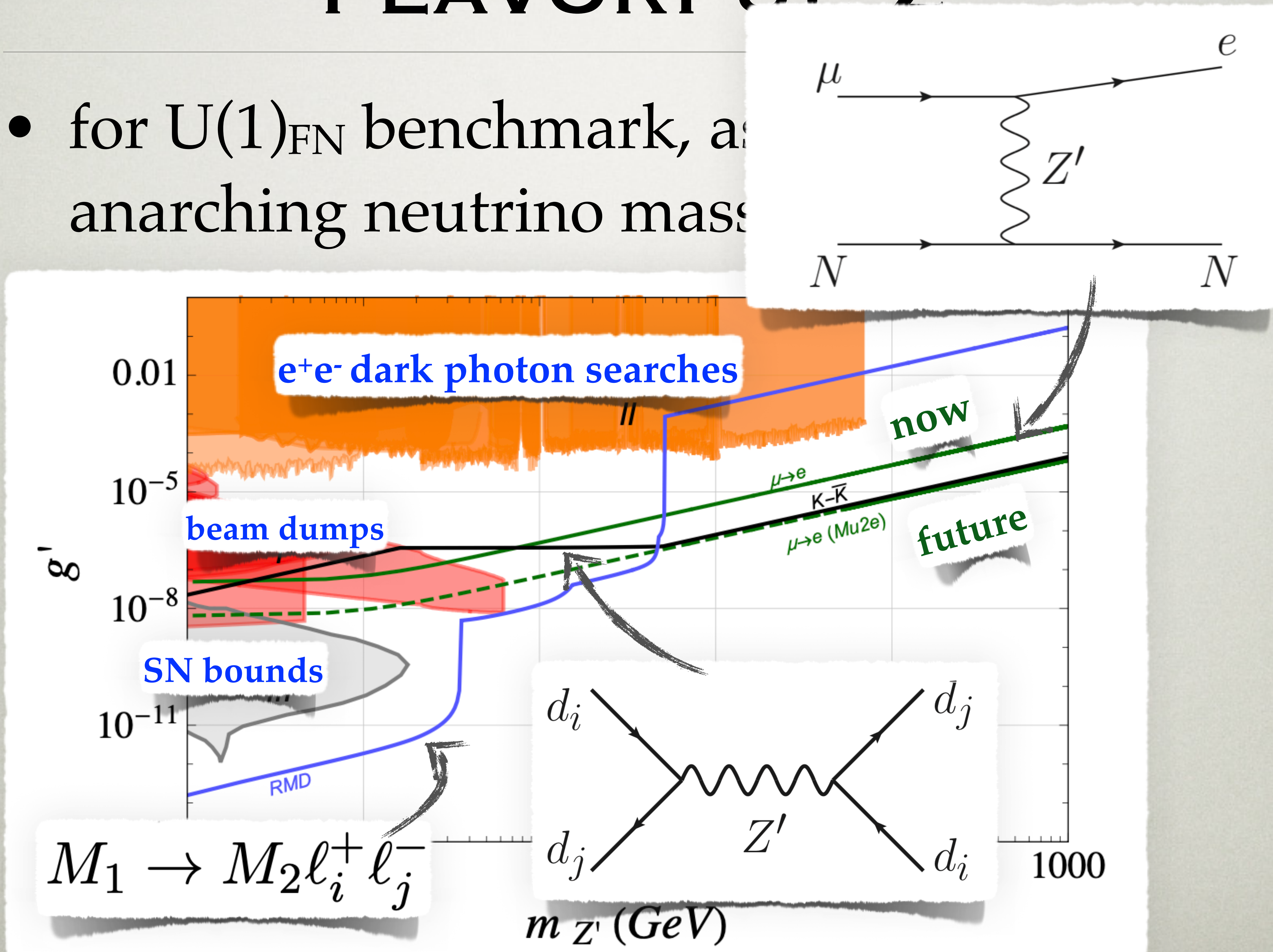
FLAVORFUL Z'

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



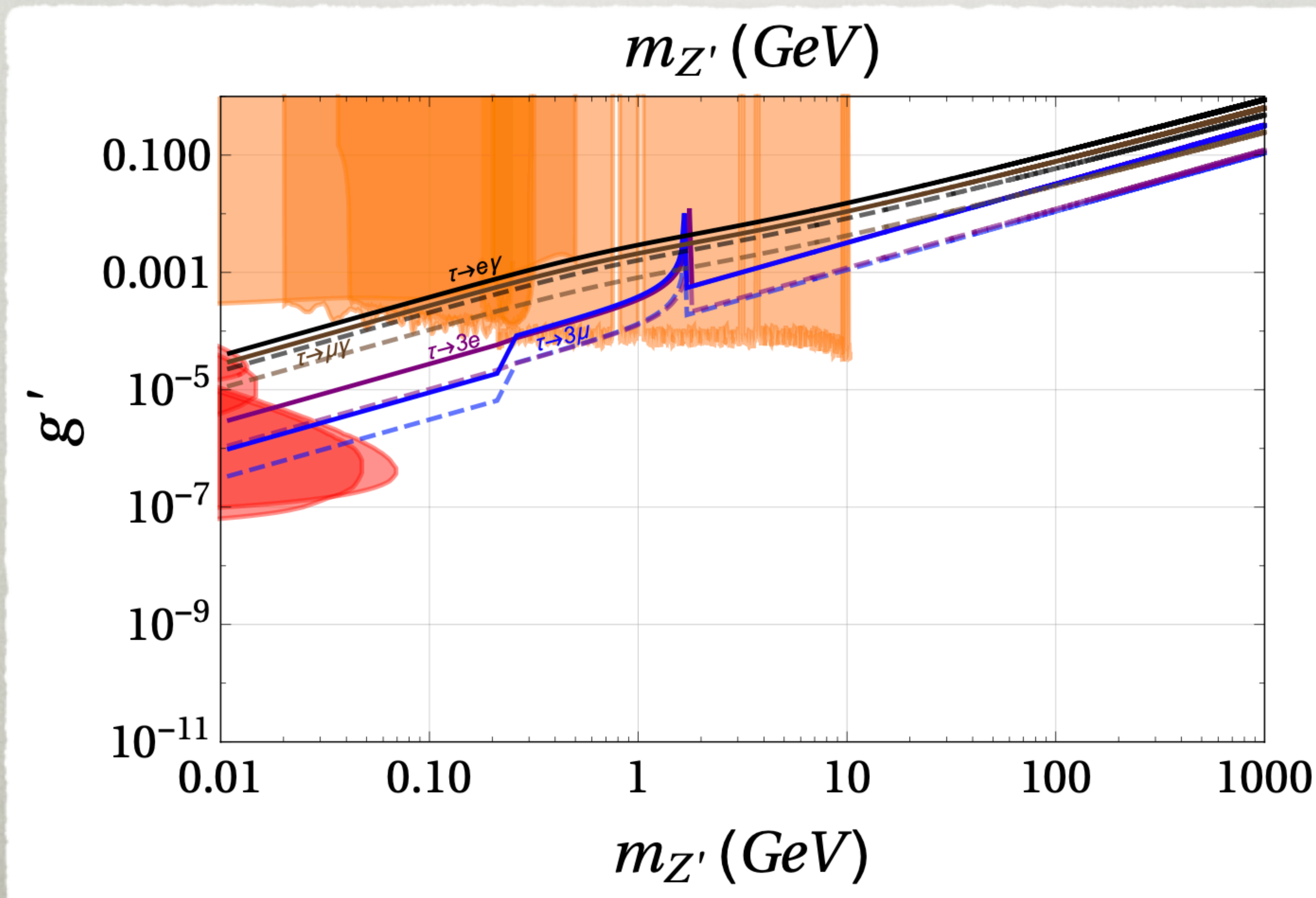
FLAVORFUL Z'

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



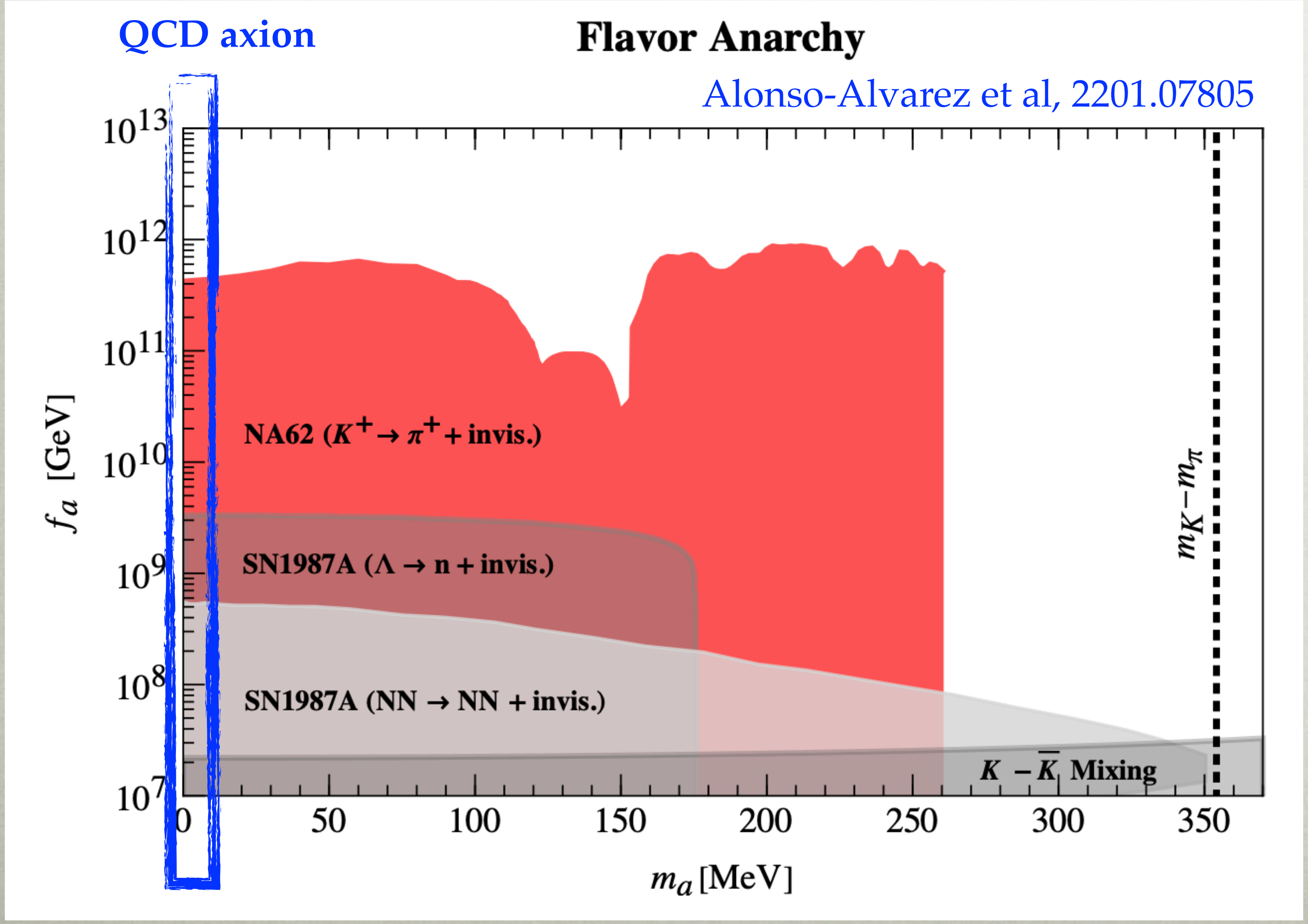
TAU DECAYS

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



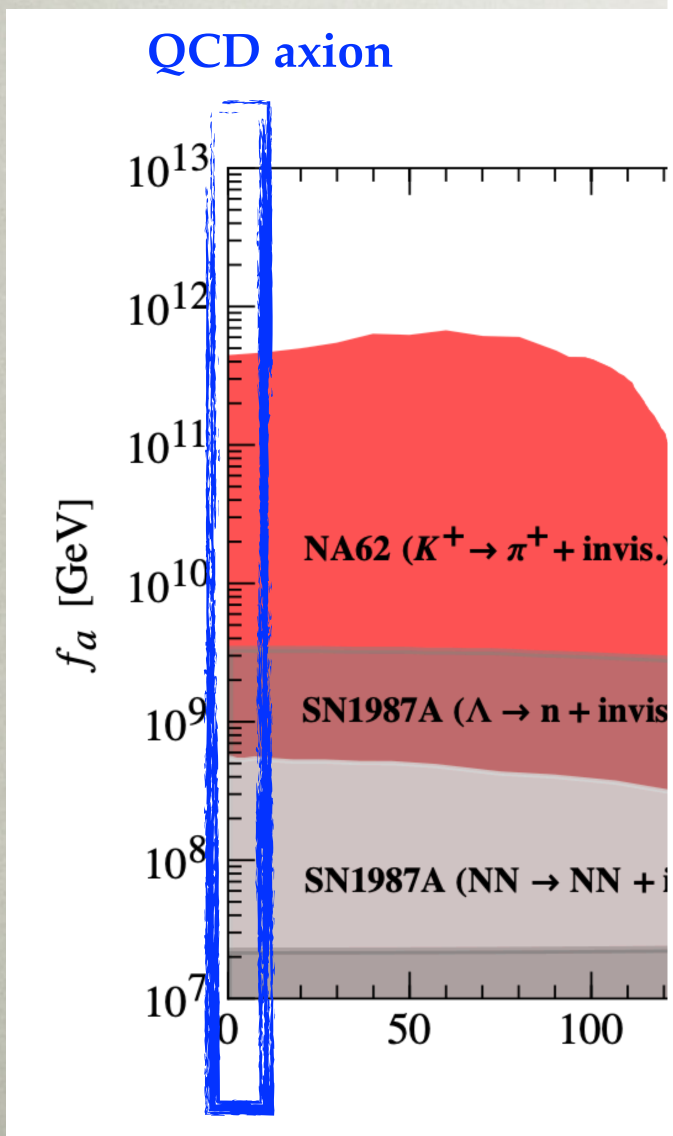
FLAVORFUL QCD AXION

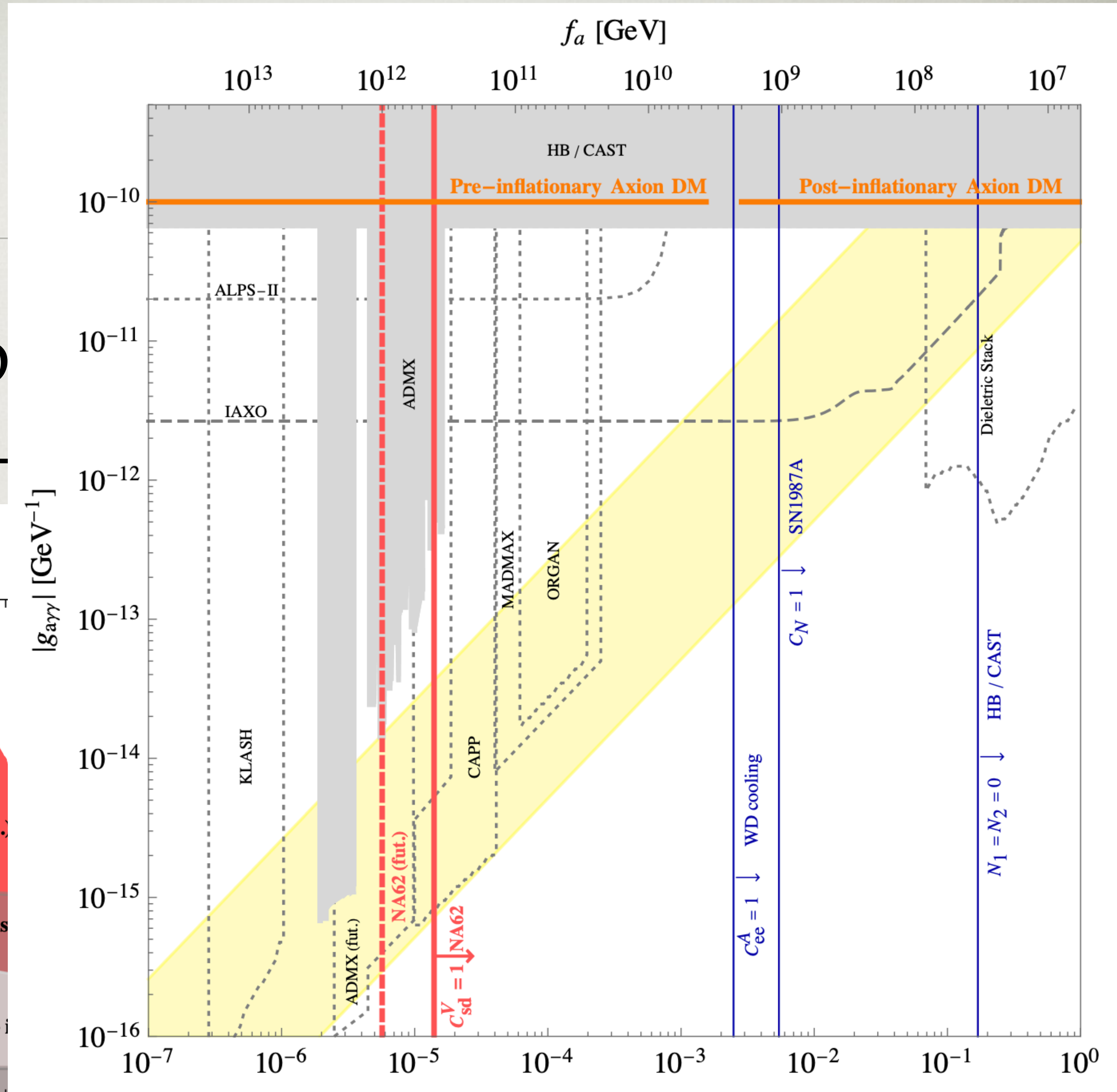
- if QCD axion has $\partial_\mu a(\bar{d}\gamma^\mu\gamma_5 s)/f_a$ coupling $\Rightarrow K^+ \to \pi^+ a$ decay a very sensitive probe



- if QCD

$\Rightarrow K^+$ -





Alonso-Alvarez et al, 2201.07805