Fermilab ACE (Accelerator Complex Evolution) Science Workshop
June 14-15 2023

Lepton Flavor Violation — theory

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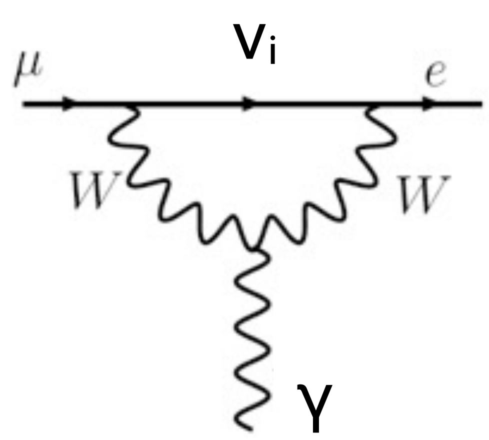
Outline

- Introduction: Lepton Flavor Violation & BSM physics
- LFV probes across energy scales
    - Reach in mass scale
    - Model-diagnosing power
- Conclusion and outlook — key opportunities in muon physics

Vast literature — apologies in advance for incomplete referencing.
Snowmass white papers are a great resource.

LFV and new physics (I)

- ν oscillations ⇒ $L_{e,\mu,\tau}$ not conserved
- In SM + massive ν, Charged-LFV decays suppressed to unobservable level



$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}}$$

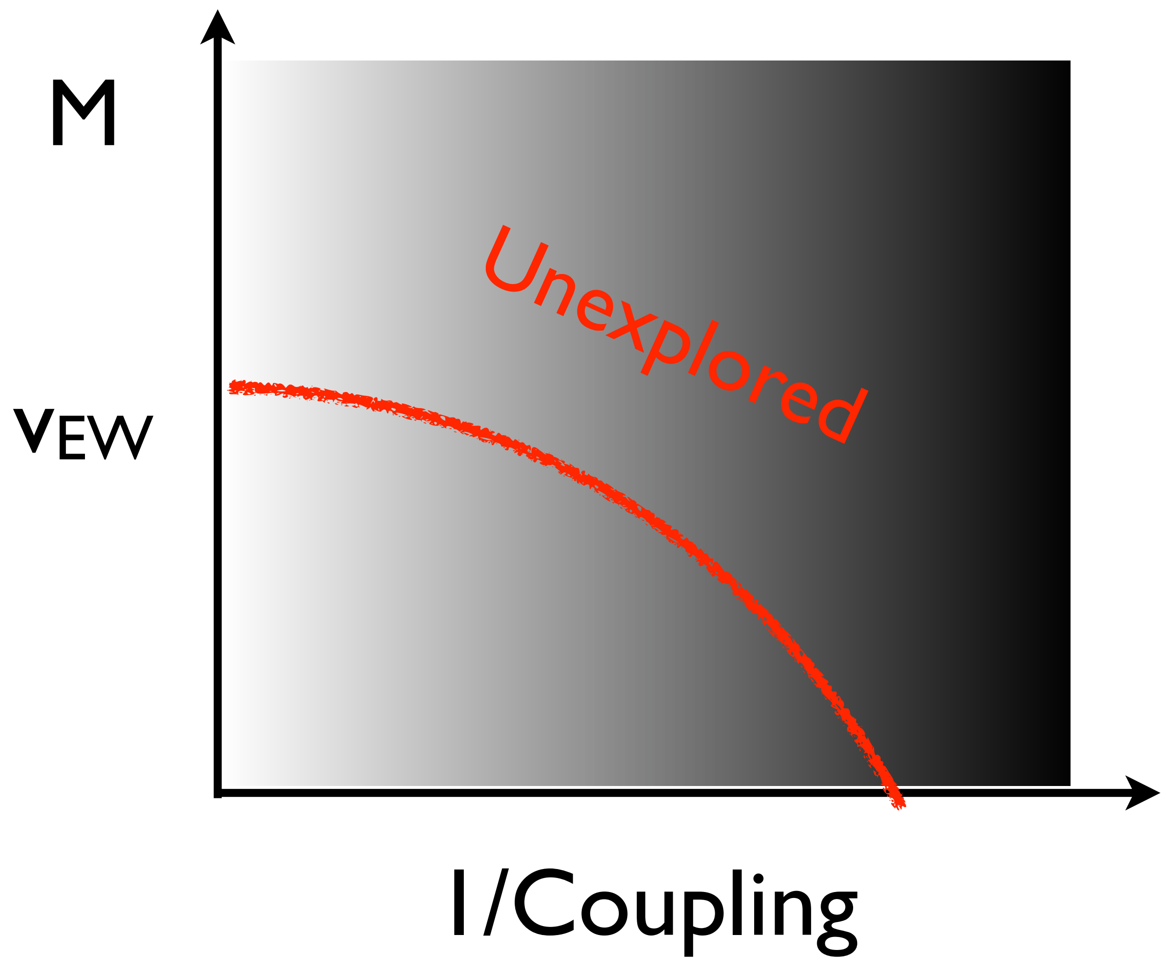
$$Br(\mu \to e\gamma) = \frac{3\alpha}{32\pi}\left|\sum_{i=2,3} U^*_{\mu i} U_{ei} \frac{\Delta m^2_{1i}}{M^2_W}\right|^2 < 10^{-54}$$

Petcov '77, Marciano-Sanda '77, Shrock '77…

- Observation of CLFV processes would unambiguously indicate BSM physics, related to the origin of leptonic 'flavor' & possibly neutrino mass

LFV and new physics (2)

- Sensitivity to broad spectrum of new physics: both heavy and light + weakly coupled



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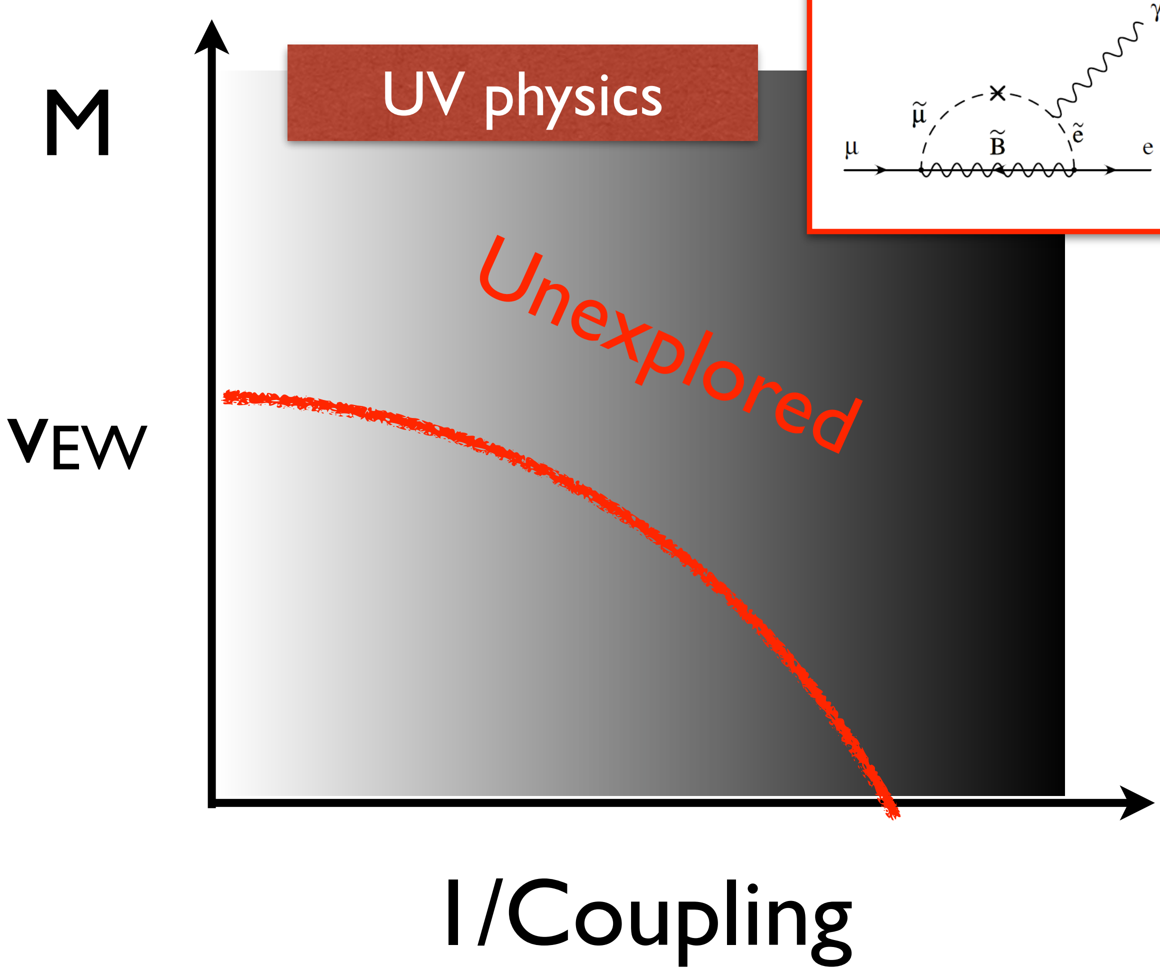

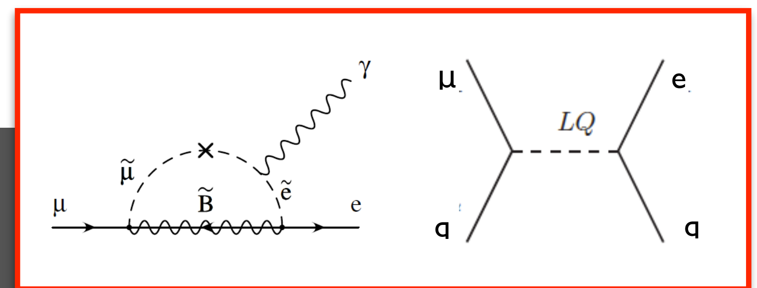

→

$$\mathcal{L}_{\rm SMEFT} \supset \sum_n \frac{C_n}{\Lambda^2} O_n^{\rm LFV} + \ldots$$

$\Lambda/\sqrt{C}$ up to ~ $10^{4\text{-}5}$ TeV

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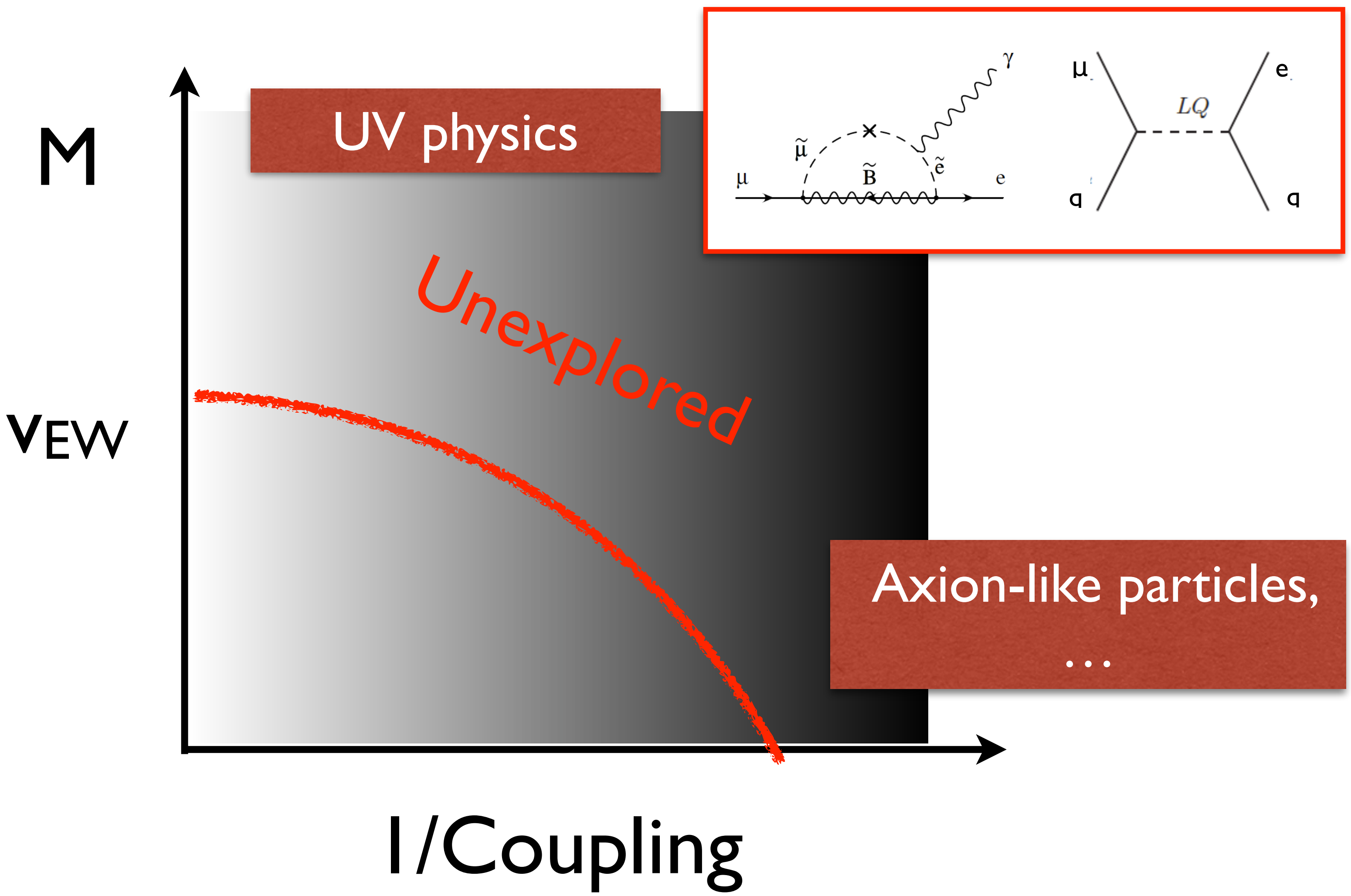

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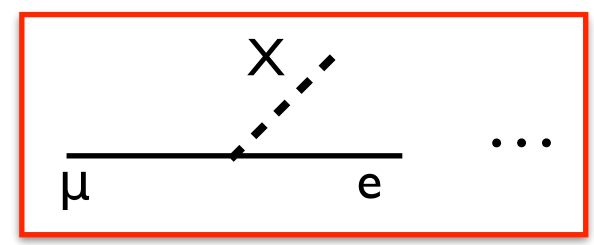

$$\mathcal{L}_{\rm portals} \supset \frac{1}{F^{\Gamma}_{\alpha\beta}} \partial_\mu a \; \bar{\ell}_\alpha \Gamma^\mu \ell_\beta + \ldots$$

$F_{\alpha\beta}$ up to ~ $10^{6\text{-}7}$ TeV

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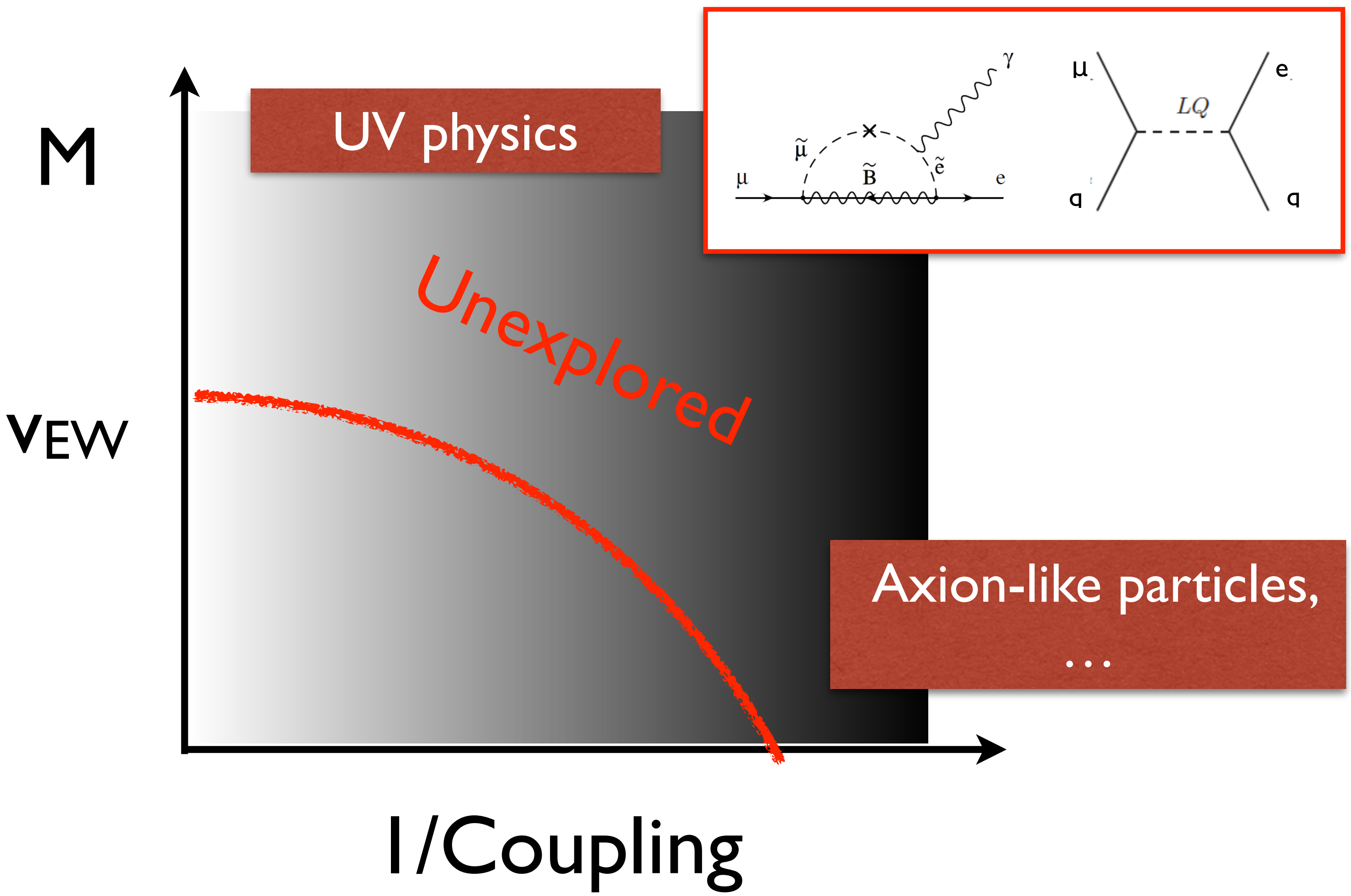

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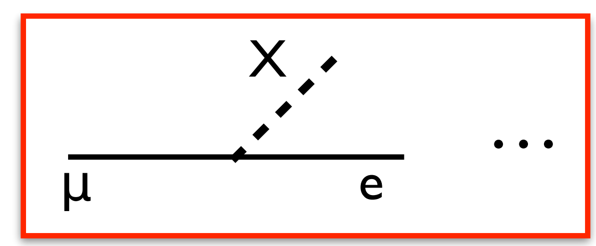

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$F_{\alpha\beta}$ up to ~ $10^{6\text{-}7}$ TeV

We can probe LFV dynamics through a combination of low-energy and collider searches

LFV probes across energy scales

- Decays of μ, τ (and mesons)

(K →πμe; B → Kμτ, Kμe; B_s → μτ, μe, quarkonia , … not discussed in detail in this talk)

$$\mu \to e\gamma, \quad \mu \to e\bar{e}e, \quad \mu\,(A,Z) \to e\,(A,Z) \qquad M_\mu - \overline{M}_\mu \qquad \mu \to ea$$

$$\tau \to \ell\gamma, \quad \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta, \;\; \tau \to \ell\,Y \qquad Y = P, S, V, P\bar{P}, \ldots$$

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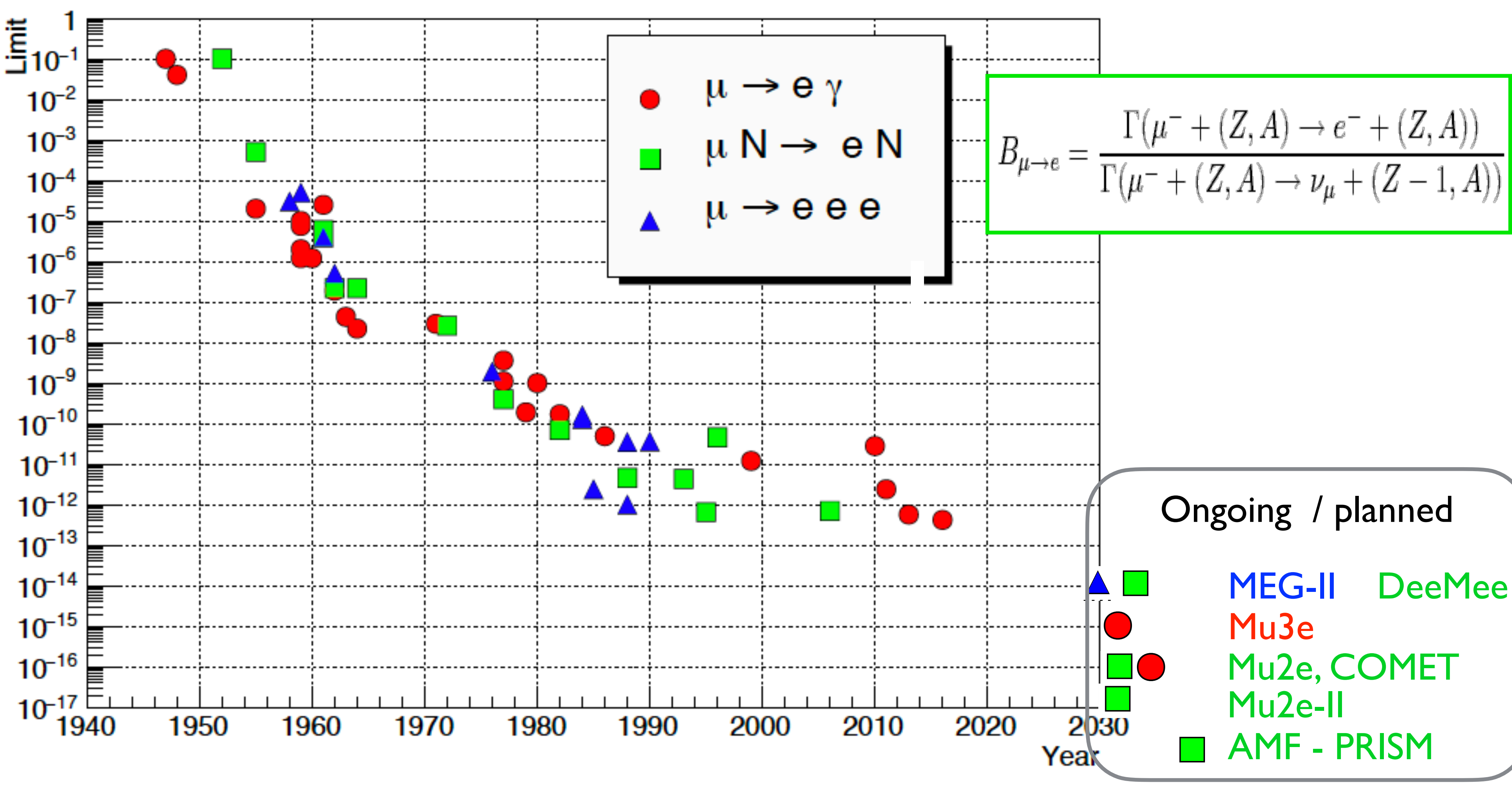

$$B_{\mu\to e} = \frac{\Gamma(\mu^- + (Z,A) \to e^- + (Z,A))}{\Gamma(\mu^- + (Z,A) \to \nu_\mu + (Z-1,A))}$$

Modified from Calibbi-Signorelli 1709.00294

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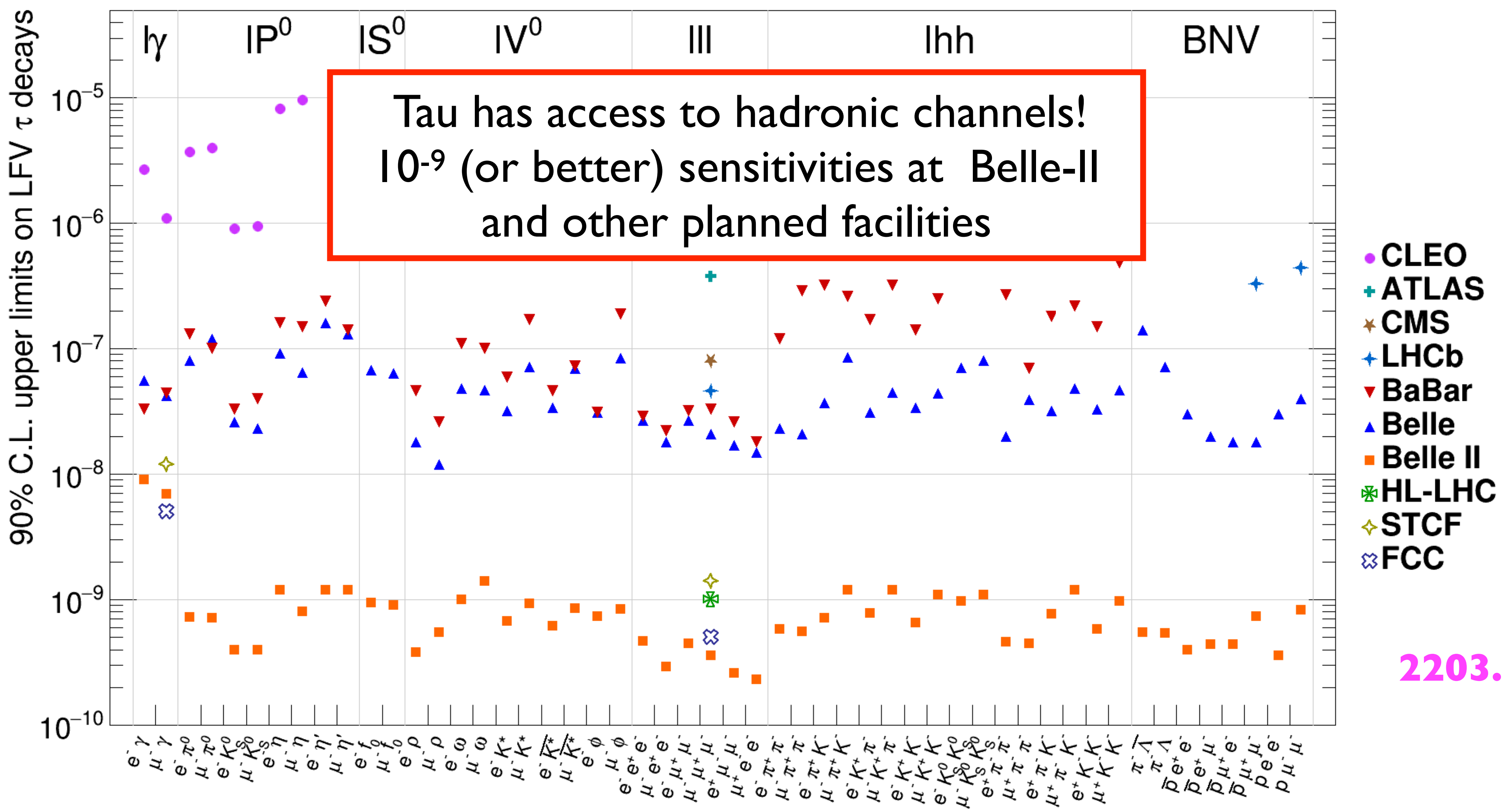

Tau has access to hadronic channels!
10^{-9} (or better) sensitivities at Belle-II
and other planned facilities

2203.14919

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- Collider processes:

LHC

$$p\,p \;\to\; R \to \; \ell_\alpha \bar{\ell}_\beta \,+\, X \qquad R = Z, h, \tilde{\nu}, \ldots.$$

$$p\,p \;\to\; \ell_\alpha \bar{\ell}_\beta \,+\, X$$

HERA, EIC

$$e\,p \;\to\; \ell \,+\, X$$

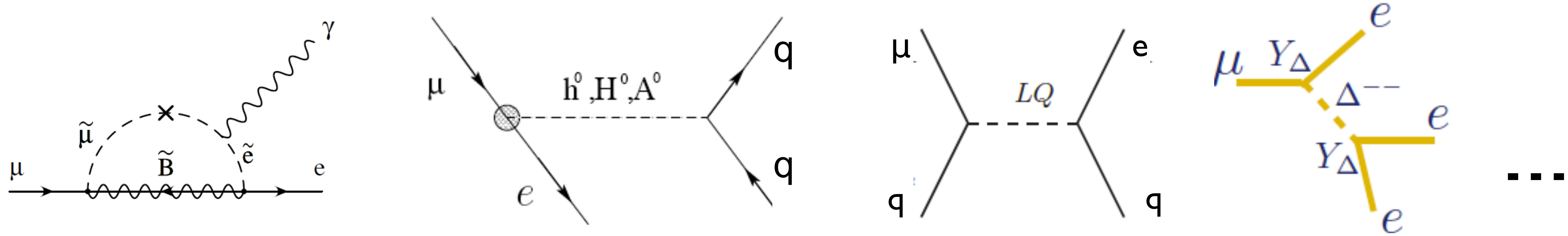
Connecting scales with EFT

M

Λ

v_{ew}

Λ_{QCD}



Dipole: SUSY-GUT and SUSY see-saw scenarios, …

Scalar: RPV SUSY and RPC SUSY for large tan(β) and low m_A, leptoquarks, …

Vector Type III seesaw, LRSM, leptoquarks, …

4-lepton: Type II seesaw, RPV SUSY, LRSM, …

$$\mathcal{L}_{d=6} \supset \frac{v C_D^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha \sigma_{\mu\nu}\ell^\beta F^{\mu\nu} + \sum_{\Gamma} \frac{C_\Gamma^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha \Gamma \ell^\beta \, \bar{q}\Gamma q + \sum_{\tilde{\Gamma}} \frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2}\bar{\ell}^\alpha \tilde{\Gamma}\ell^\beta \, \bar{\ell}\tilde{\Gamma}\ell$$

Connecting scales with EFT

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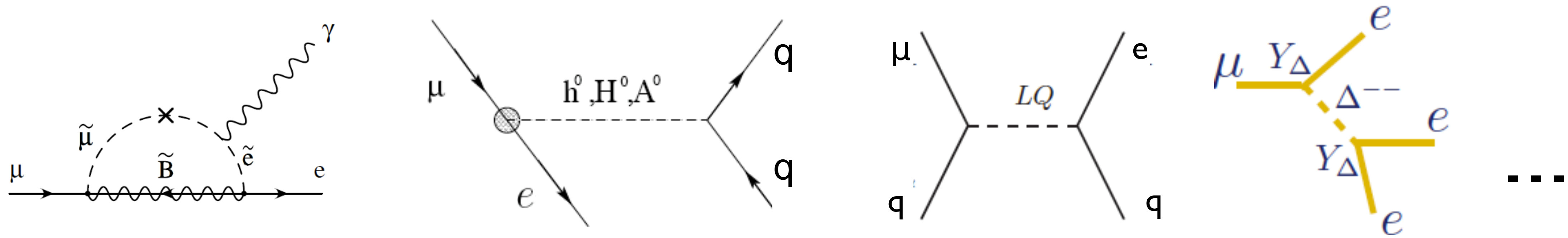

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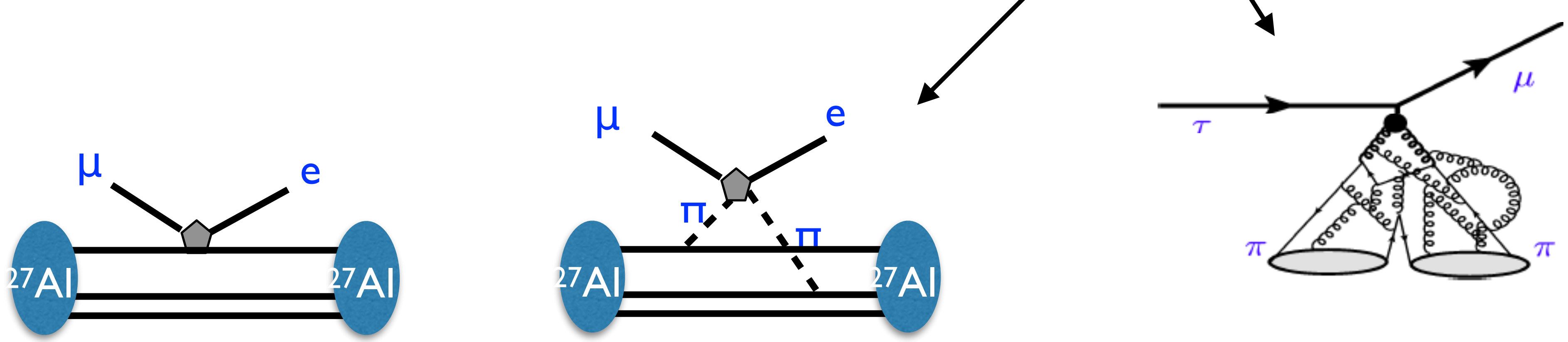

CLFV phenomenology

$$\mathcal{L}_{\rm LFV} \supset \frac{v C_D^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \sigma_{\mu\nu} \ell^\beta + \sum_{\tilde{\Gamma}} \frac{C_{\tilde{\Gamma}}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \tilde{\Gamma} \ell^\beta \bar{\ell} \tilde{\Gamma} \ell + \sum_{\Gamma} \frac{C_{\Gamma}^{\alpha\beta}}{\Lambda^2} \bar{\ell}^\alpha \Gamma \ell^\beta \bar{q} \Gamma q + \frac{1}{F_{\alpha\beta}^{\Gamma}} \partial_\mu a \, \bar{\ell}^\alpha \Gamma^\mu \ell^\beta$$

Each model generates a specific pattern of operators

→ multiple CLFV measurements needed to extract the underlying physics

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Each model generates a specific pattern of operators
→ multiple CLFV measurements needed to extract the underlying physics

- New physics mass scale through any process

$$BR_{\alpha\to\beta} \sim (v_{ew}/\Lambda)^4 * |(C_n)^{\alpha\beta}|^2$$

μ-e sector:	$\Lambda/\sqrt{C} \sim 10^{4\text{-}5}$ TeV	(Muon decays)
τ-μ(e) sector:	$\Lambda/\sqrt{C} \sim 10^{2}$ TeV	(Tau decays)

CLFV phenomenology

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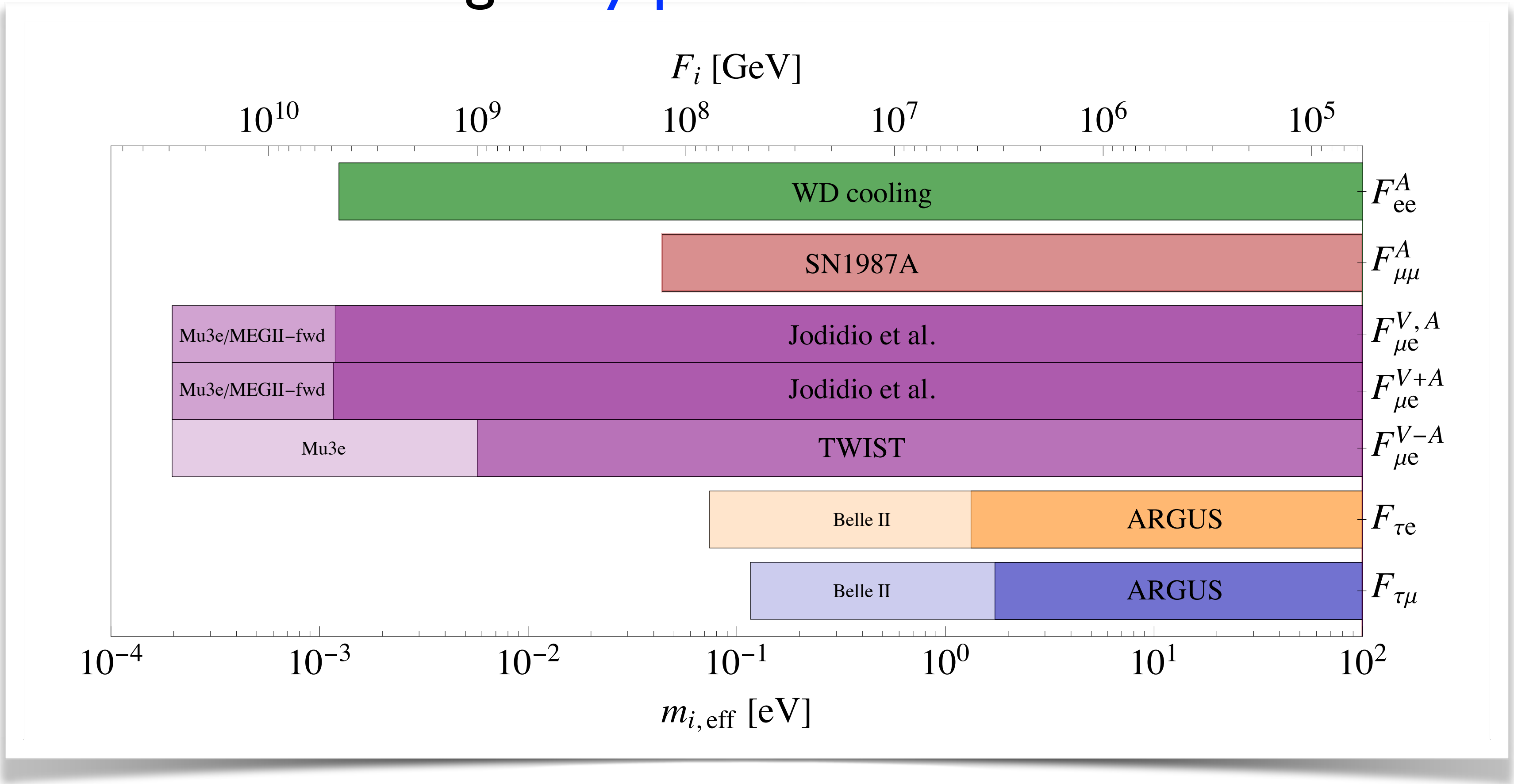
$BR(l_\alpha \to l_\beta\, a) \sim ((v_{ew})^2/(m_\alpha F_{\alpha\beta}))^2$



Calibbi-Redigolo-Ziegler-Zupan 2006.04795

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- Relative strength of operators ($[C_D]^{e\mu}$ vs $[C_S]^{e\mu}$…) through μ →3e versus μ →eγ versus μ →e conversion ⇒ Mediators, mechanism

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- New physics mass scale through any process

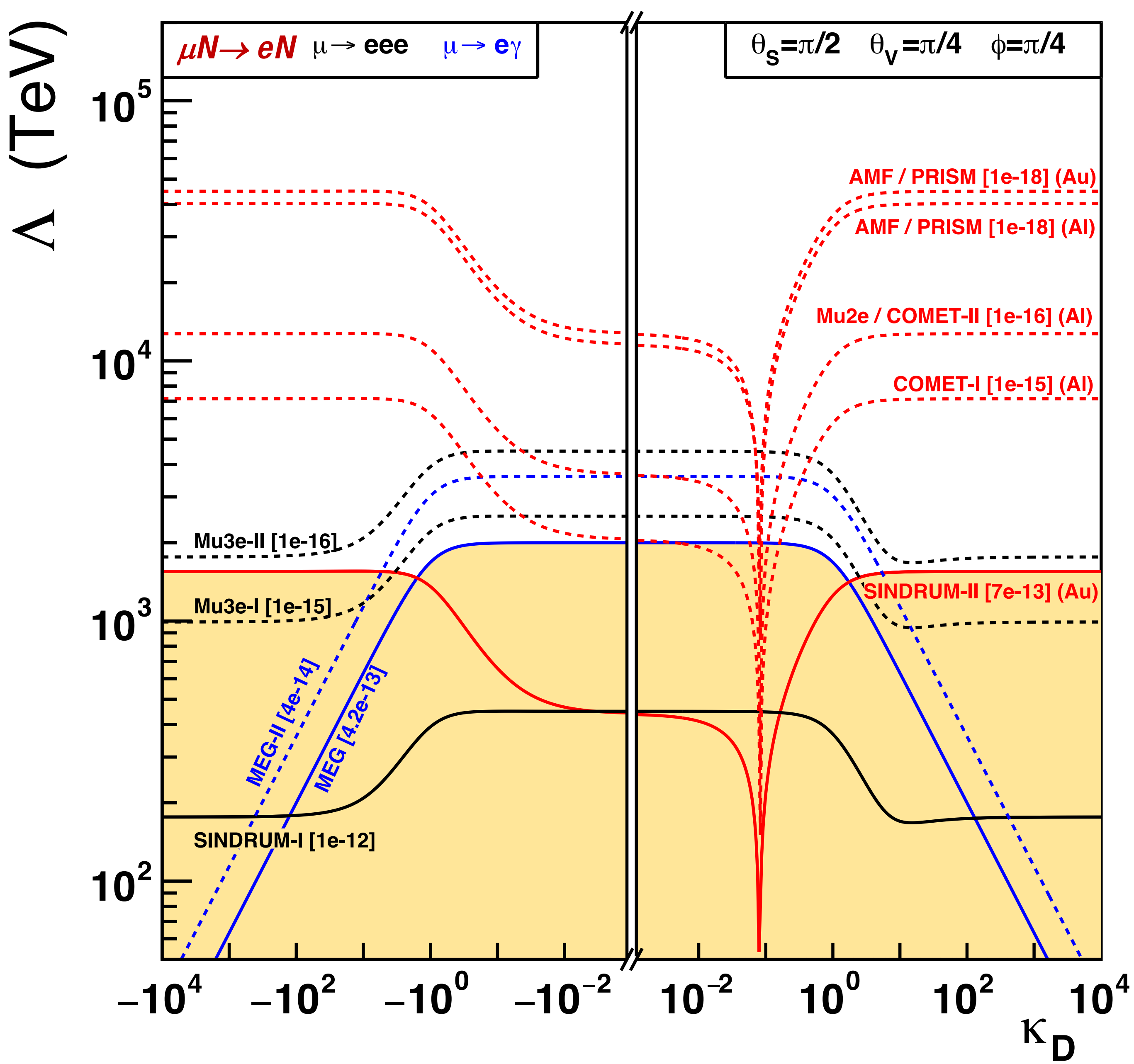
- Relative strength of operators ($[C_D]^{e\mu}$ vs $[C_S]^{e\mu}$…) through $\mu \to 3e$ versus $\mu \to e\gamma$ versus $\mu \to e$ conversion ⇒ Mediators, mechanism

- Flavor structure of couplings ($[C_D]^{e\mu}$ vs $[C_D]^{\tau\mu}$…) through $\mu \to e$ versus $\tau \to \mu$ versus $\tau \to e$ ⇒ Sources of flavor breaking

μ-e sector: mass reach

- Sensitivity is dominated by low-energy muon decay / conversion

Davidson-Echenard 2204.00564



$\kappa_D = cotan(\theta_D - \pi/2)$

κ_D: relative strength of dipole vs four-fermion operators (inspired from the "κ parameterization" in 1303.0497)

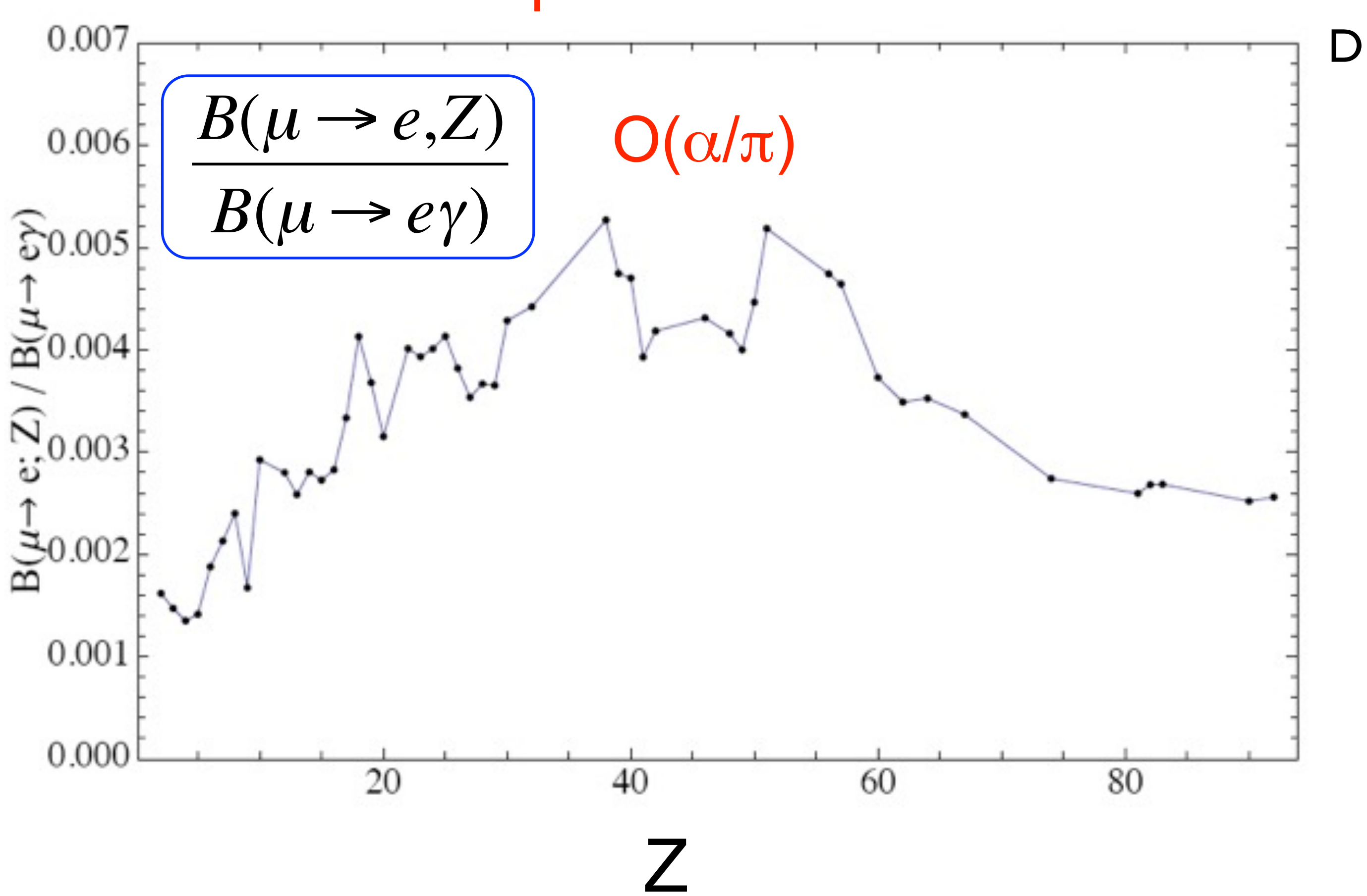
$|\kappa_D| \ll 1$ dipole dominant
$|\kappa_D| \gg 1$ four-fermion dominant

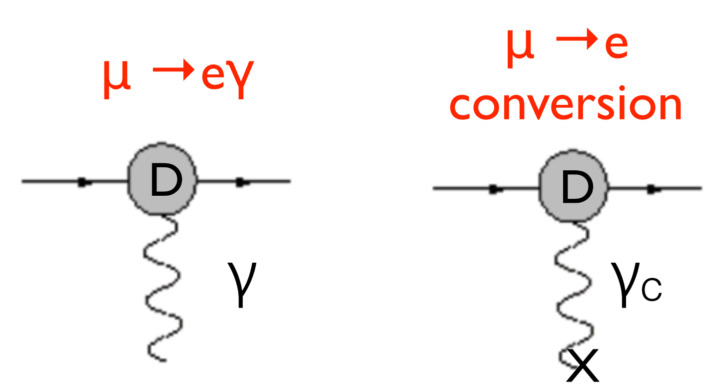
- Very high scale probed! Discovery opportunities in current and planned searches
- Notion of 'best probe' is model-dependent

μ-e sector: diagnosing tools (1)

- Extract info on effective couplings from pattern of BRs:
  μ → e vs μ → eγ

Dipole dominance



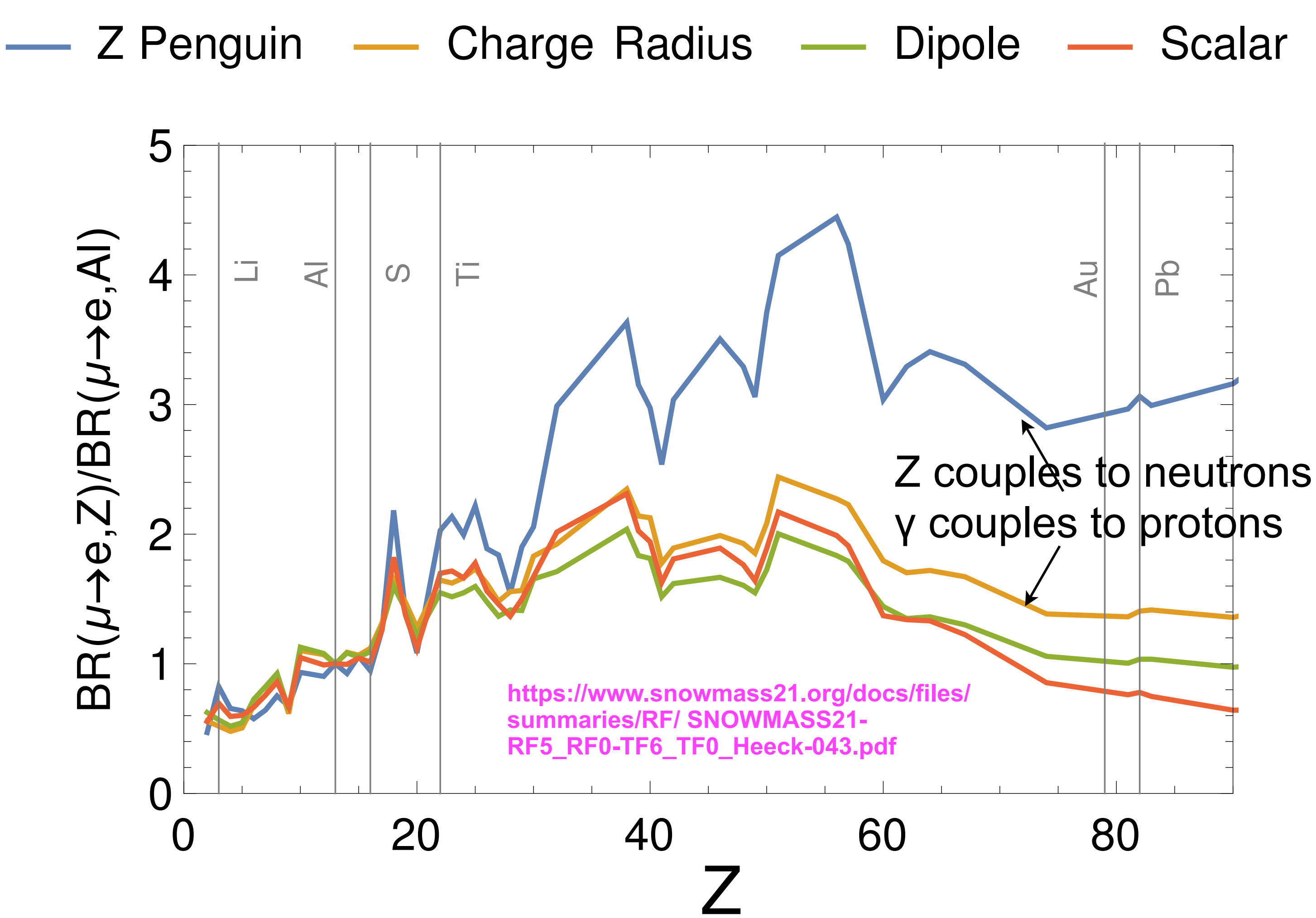


- Pattern controlled by
  - Behavior of overlap integrals
  - Total capture rate

Kitano-Koike-Okada hep-ph/0203110, VC-Kitano-Okada-Tuzon 0904.0957, ...

μ-e sector: diagnosing tools (2)

- Extract info on effective couplings from pattern of BRs:
  target-dependence of μ →e conversion



- Model diagnosing requires:

~5% measurement of Ti/Al
~20% measurement of Au/Al

- Ideal world: use Al and a large-Z target

Kitano-Koike-Okada hep-ph/0203110, VC-Kitano-Okada-Tuzon 0904.0957, ...

μ-e sector: diagnosing tools (2)

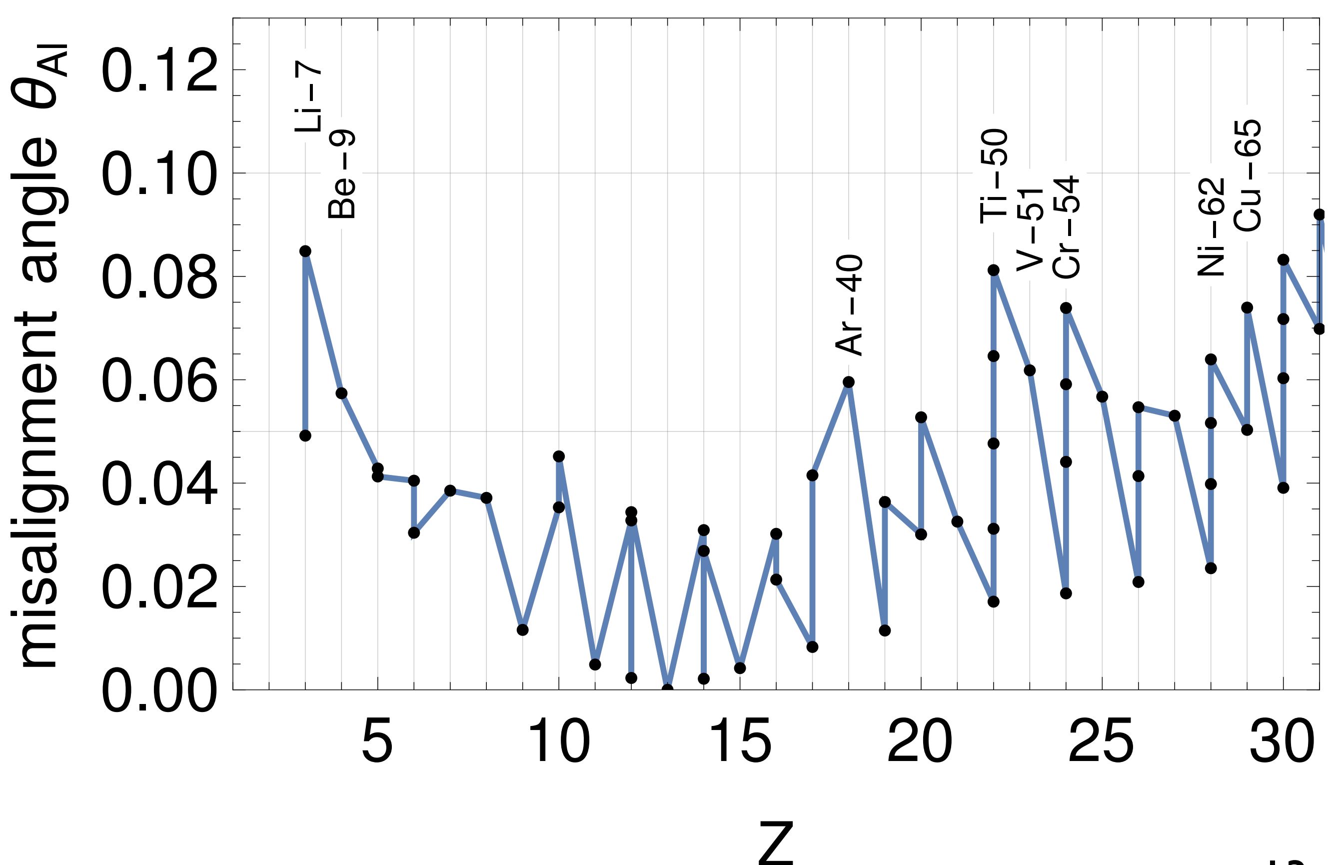
- Extract info on effective couplings from pattern of BRs:
  target-dependence of μ →e conversion

- Conversion rate characterized by a target-dependent 'vector' of amplitudes

$$R_{\mu e} = \frac{32 G_F^2}{\Gamma_{\rm capture}} \left[|\vec{v} \cdot \vec{C}_L|^2 + |\vec{v} \cdot \vec{C}_R|^2 \right]$$

$$\vec{v} \equiv \left(\frac{D}{4}, V^{(p)}, S^{(p)}, V^{(n)}, S^{(n)} \right)$$

Heek-Szafron-Uesaka 2203.00702, ...



- Misalignment angle among targets quantifies the 'complementarity"

$$\theta_{\rm Al} = \arccos \left(\frac{\vec{v} \cdot \vec{v}_{\rm Al}}{|\vec{v}||\vec{v}_{\rm Al}|} \right)$$

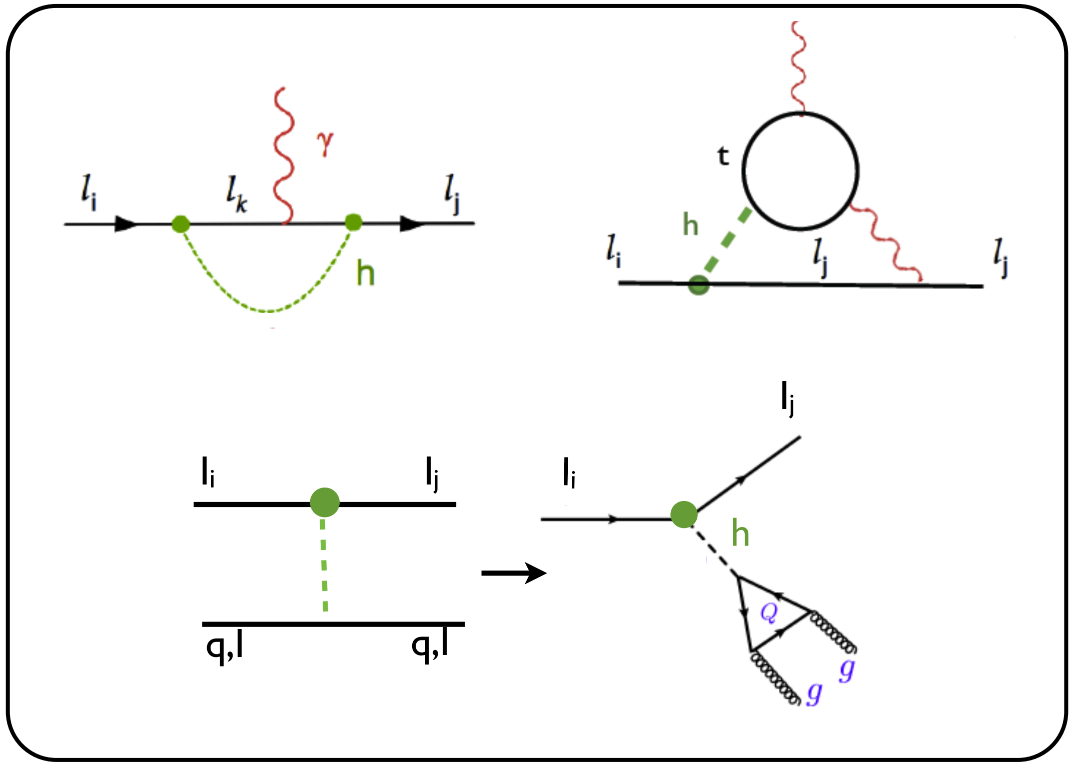
- Among low-Z target, ^{7}Li and ^{51}V stand out (large nat. abundance)

μ-e sector: diagnosing tools (3)

- Illustration: Higgs-mediated LFV, e.g. from dim-6 operator

  Harnik-Kopp-Zupan 1209.1397, ...

$$\Delta\mathcal{L} \supset Y_{ij}\, \bar{e}_L^i\, e_R^j\, h \;+\; \mathrm{H.c.}$$



- $\mu \to e\gamma$ is currently probing $|Y_{\mu e}| \sim 10^{-6}$ ($BR(h \to \mu e) < 10^{-9}$)

- Correlated signals in $\mu \to e$ transitions**

  $BR(\mu \to e, Al) / BR(\mu \to e\gamma) = 8.7(3)\ 10^{-3}$

  $BR(\mu \to e, Ti) / BR(\mu \to e, Al) = 1.5(1)$

  VC, Fuyuto, Ramsey-Musolf, Rule 2203.09547

  (See also Crivellin et al. 1404.7134)

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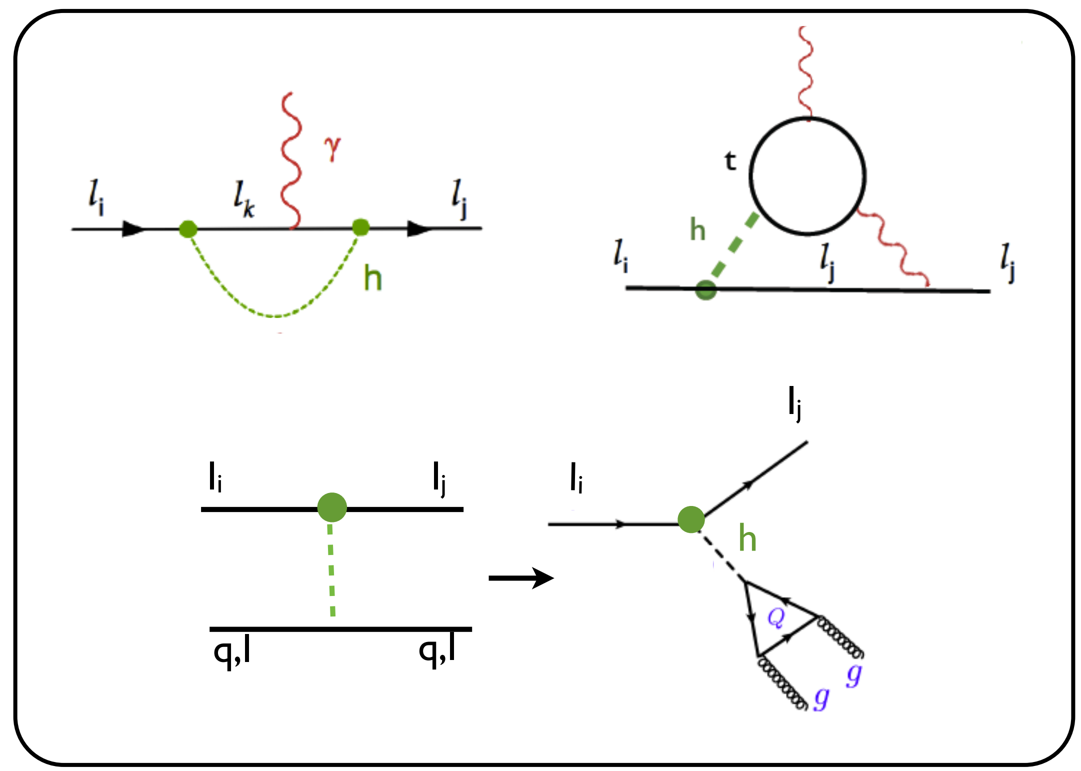

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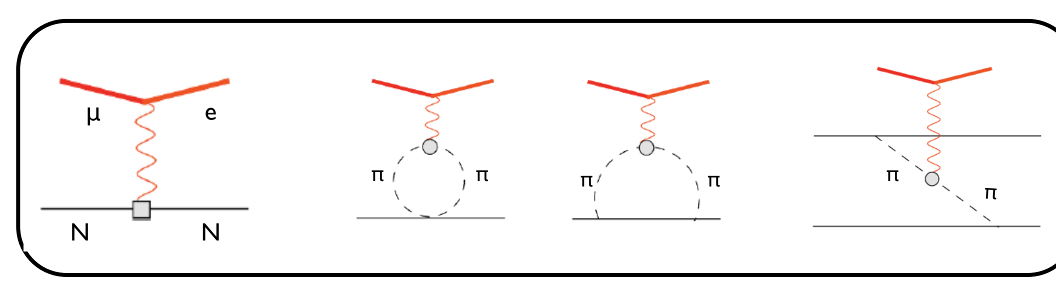
** Included NLO chiral EFT corrections in computation of conversion rate.

For NR nuclear EFT approach see Rule et al, 2109.13503



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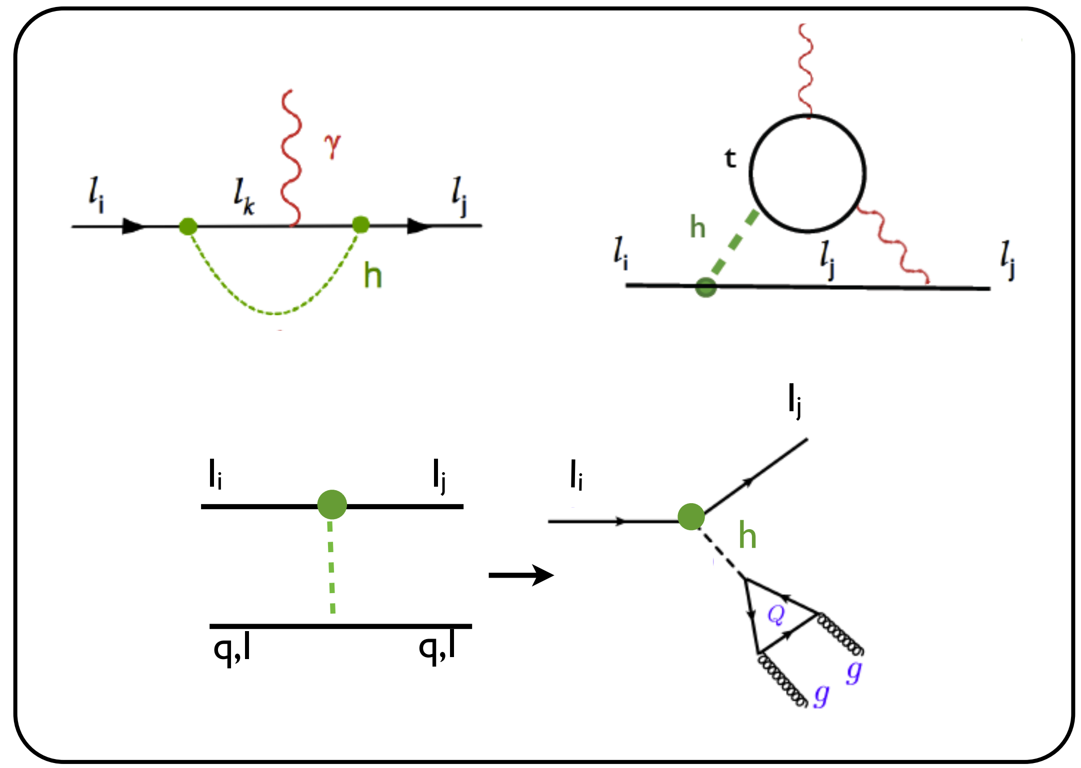

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- Correlated signals in μ→e transitions**

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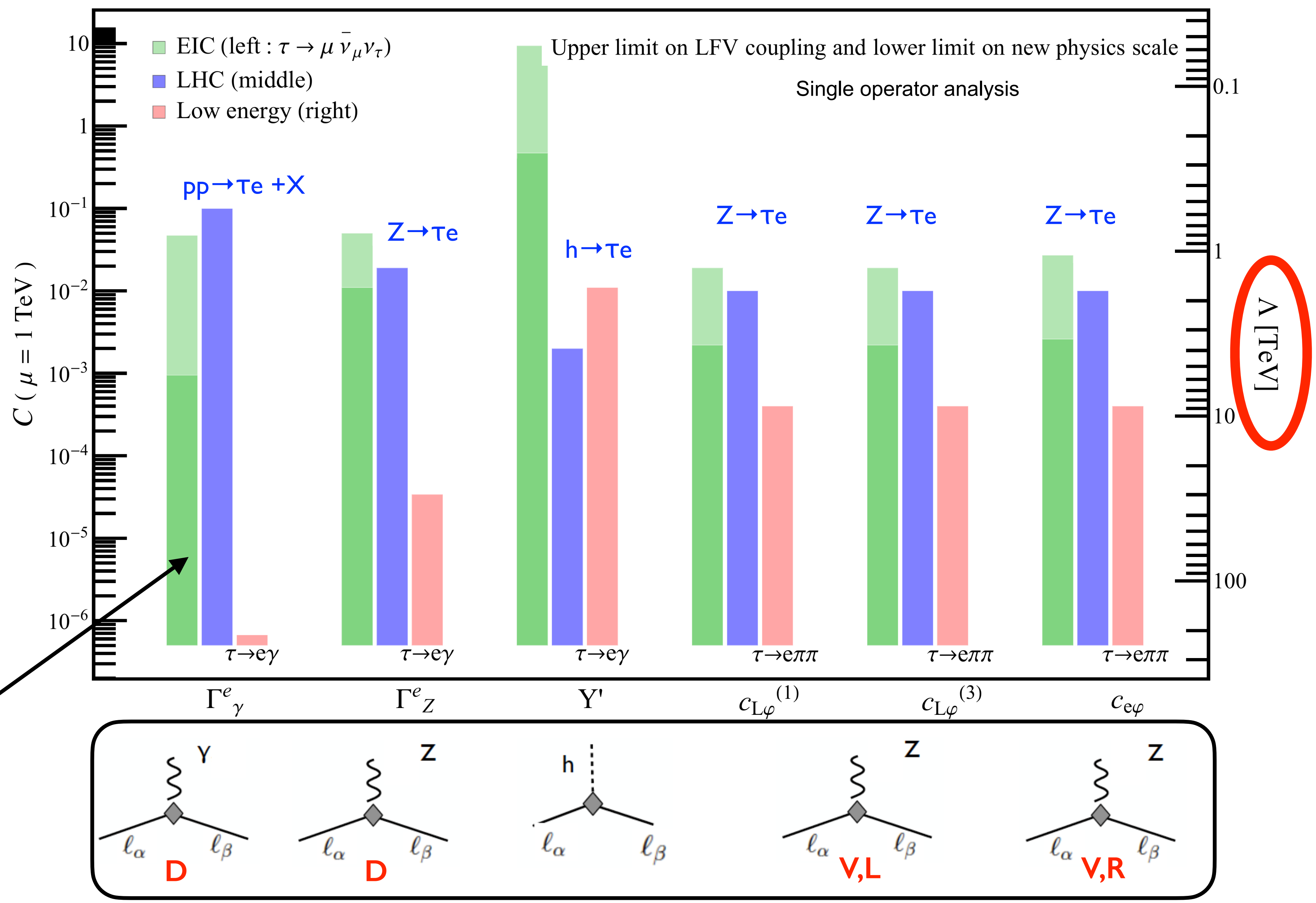
  (See also Crivellin et al. 1404.7134)

- Muon decays provide clean probe of LFV Higgs couplings

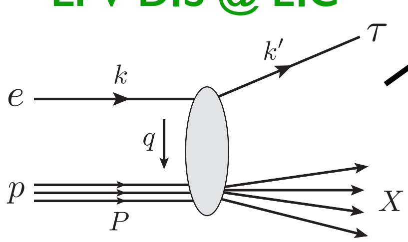
τ-e(μ) sector: mass reach (I)

- Bounds dominated by τ decays, with few exceptions from Higgs decay, LFV Drell-Yan, and B decays

VC-Fuyuto-Lee-Mereghetti-Yan 2102.06176



LFV DIS @ EIC

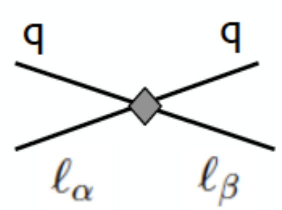


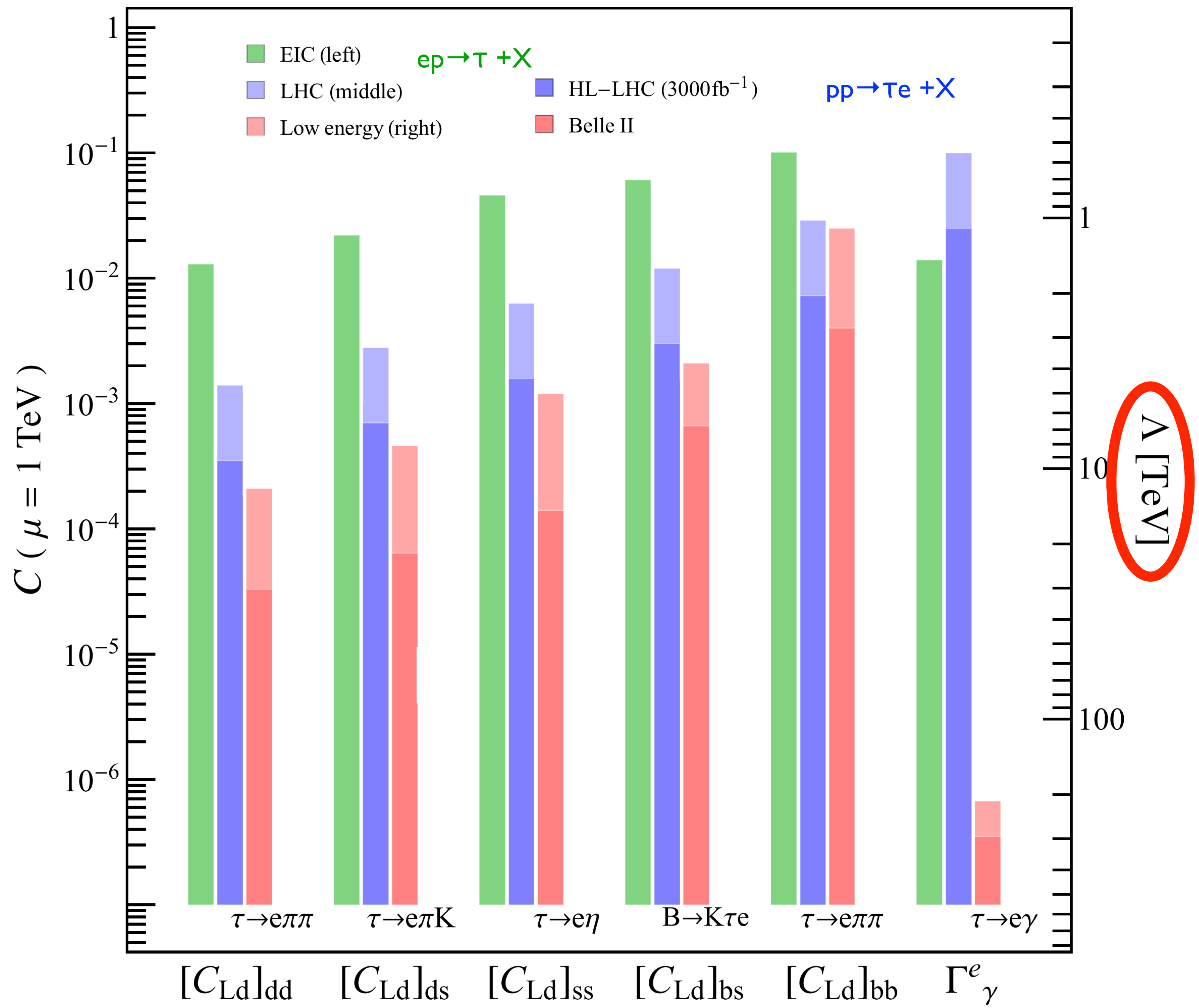
(Similar pattern for τ-μ, without EIC)

τ-e(μ) sector: mass reach (2)

- Bounds dominated by τ decays, with few exceptions from Higgs decay, LFV Drell-Yan, and B decays

$$\bar{\ell}_\tau \gamma^\mu \ell_e \bar{d}_i \gamma_\mu d_j$$





White paper 2203.14919

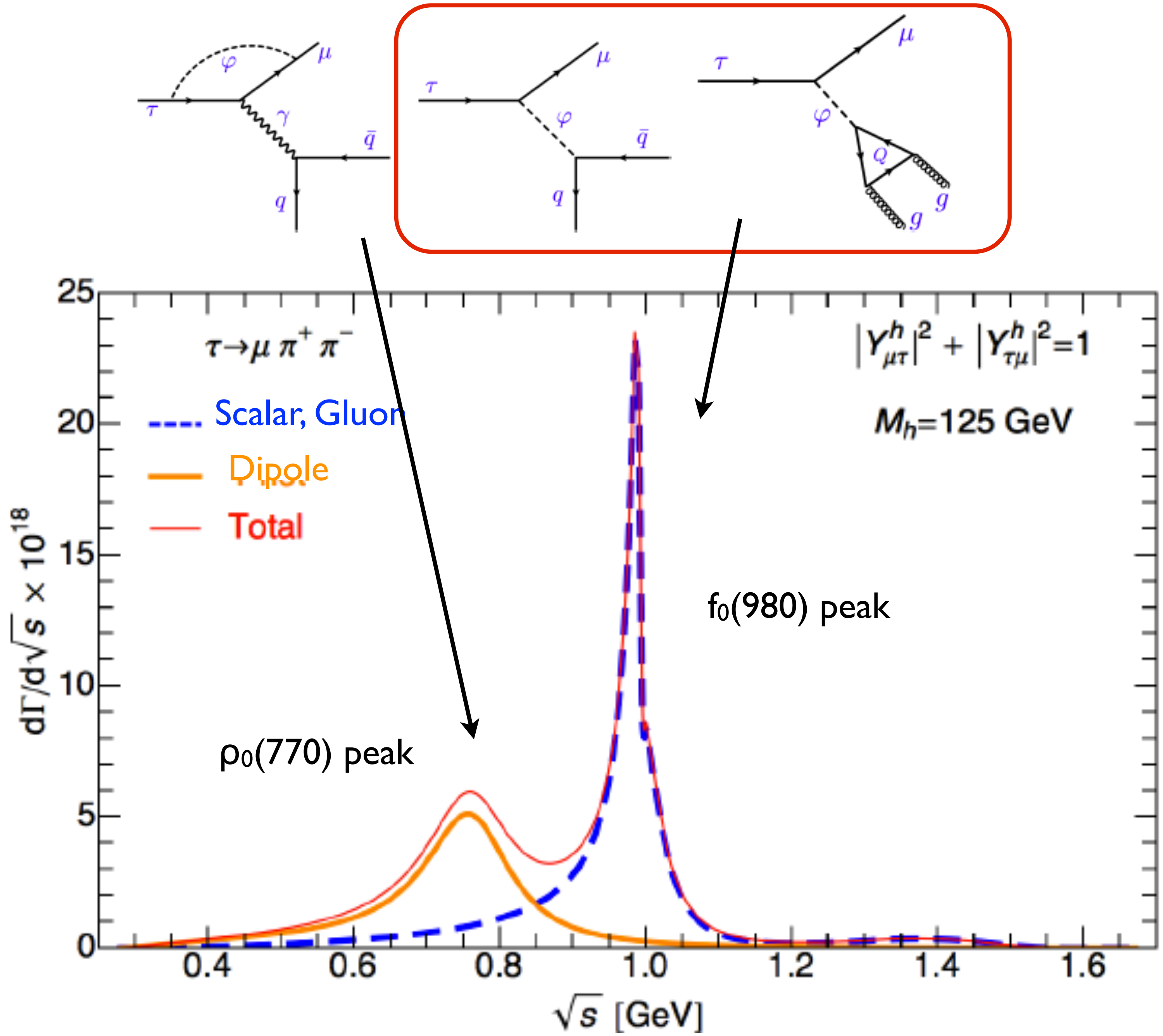
(Similar pattern for τ-μ, without EIC)

τ-μ(e) sector: diagnosing tools

- Pattern of BRs and differential distributions. Illustration via Higgs-mediated LFV

- Given BR(h→μτ) < 0.15%, τ→μππ is observable at Belle-II if $Y_{u,d,s} \sim Y_b$

- Higgs-specific combination of D, S, G → unique signature in ππ spectrum



Celis-VC-Passemar 1309.3564

Probing the flavor-breaking pattern: μ vs τ

- Smaller samples of taus compared to muons ⇒ $BR_\tau \sim 10^{-8}$ while $BR_\mu \sim 10^{-13}$
- Well motivated flavor-breaking patterns (leptonic MFV, GUTs, U(2) symmetries, …) suppress μ → e compared to τ → μ:

Leptonic MFV**:	$BR(\mu \to e\gamma) / BR(\tau \to \mu\gamma) \sim s_{13}^2 \sim 10^{-2}$
GUT models:	$BR(\mu \to e\gamma) / BR(\tau \to \mu\gamma) \sim \lvert V_{us}\rvert^6 \sim 10^{-4}$

VC-Grinstein-Isidori-Wise, hep-ph/0507001, hep-ph/0608123, ...

Barbieri-Hall-Strumia, hep-ph/9501334

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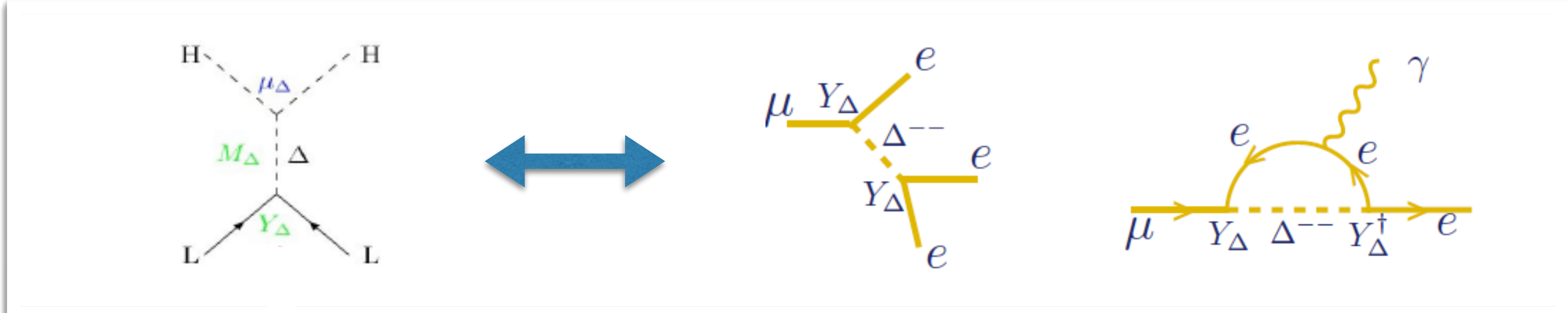
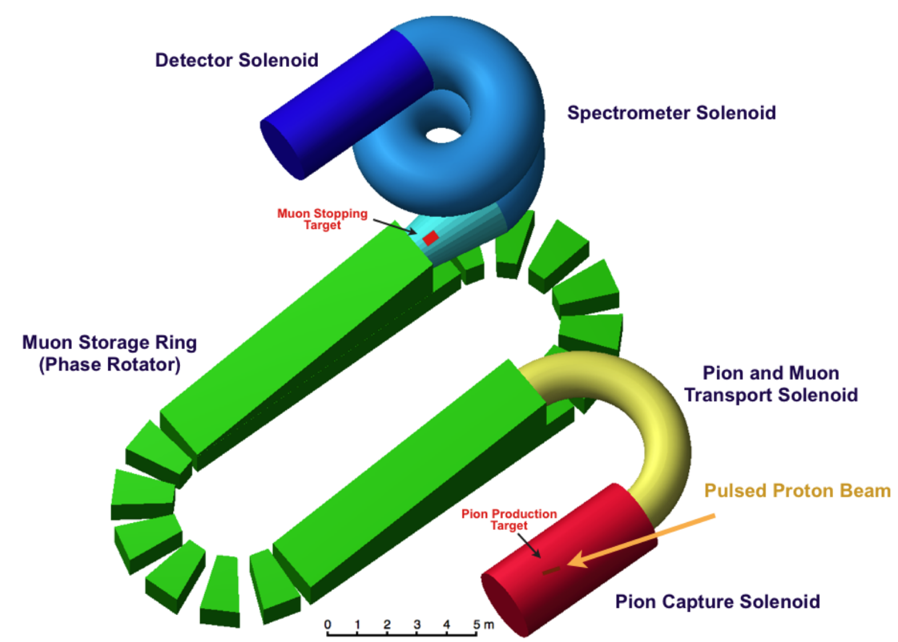
** Explicitly realized in Type-II seesaw (scalar triplet) CLFV controlled by $Y_\Delta \propto m_\nu$



Experimental prospects

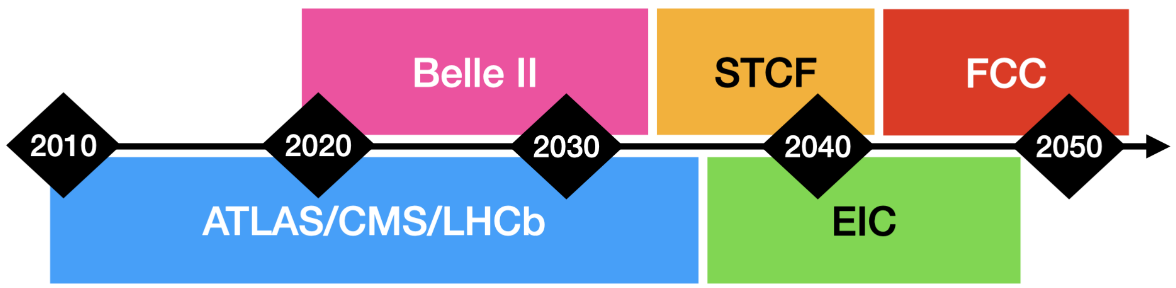
- Key facilities for muons: FNAL, J-PARC, PSI

PRISM concept
(Phase Rotated Intense Slow Muon beam)
[Kuno, Mori]



- Next generation muon experiments at FNAL:
  - Mu2e-II, 10x better sensitivity
  - Advanced Muon Facility:
    - PRISM concept: 100x improvement μ-to-e conversion and high-Z target
    - Muonium-antimuonium, muon EDM,…

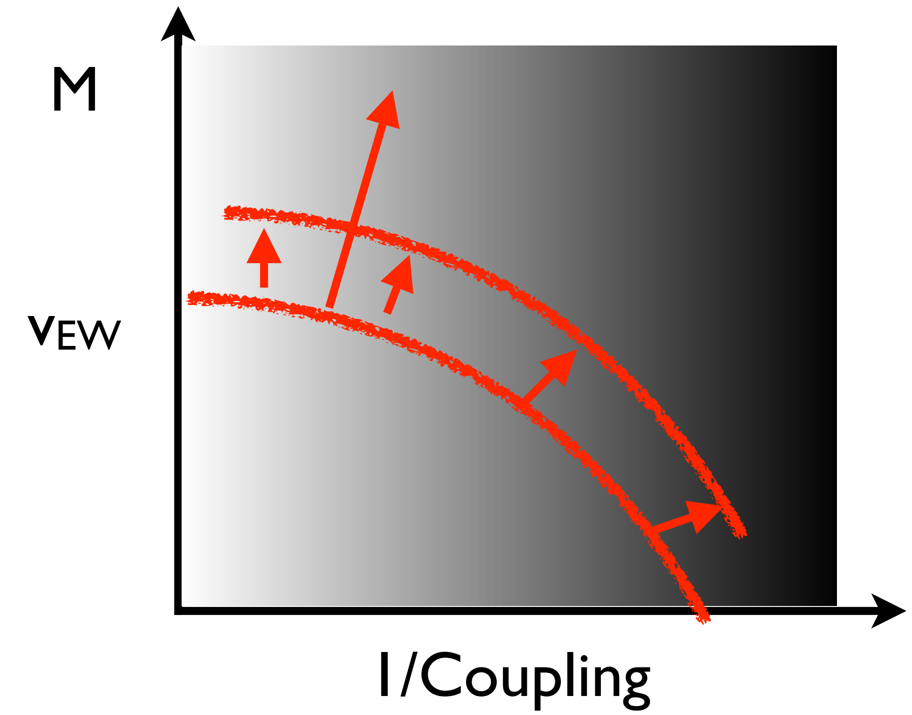
- Current / next gen. experiments relevant for CLFV in tau (and mesons)



Conclusions & Outlook

- Charged LFV processes probe a broad spectrum of new physics
  - *Discovery* tools: clean, very high scale reach
  - *Model-diagnosing* tools: mediators, sources of flavor breaking

- 'Win-win' situation
  - Should new physics appear (at the LHC or elsewhere) LFV will provide unique input on its symmetry structure
  - Should new physics NOT appear (at the LHC or elsewhere), LFV will be for a while one of the strongest tools to probe the mass scale of new physics



Conclusions & Outlook

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Exciting experimental prospects

★ 4-6 (1-2) orders of magnitude improvement in μ (τ) decays

★ LHC & EIC will be competitive in τ-μ and τ-e transitions ($h \to \tau\mu$, $e \to \tau$)

★ Muon processes have unmatched sensitivity in μ-e transitions.
Great opportunity for the Fermilab muon program