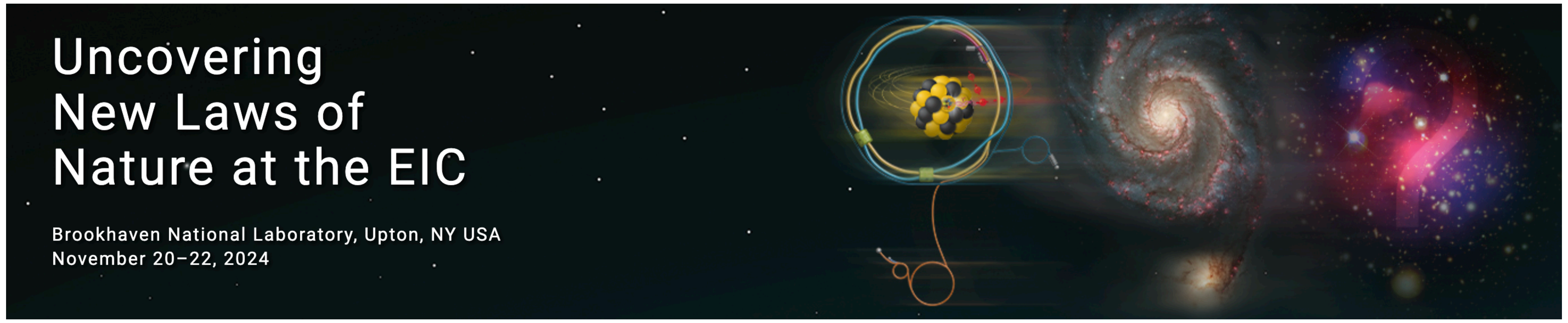

Low energy probes of physics beyond the Standard Model

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UNIVERSITY of WASHINGTON

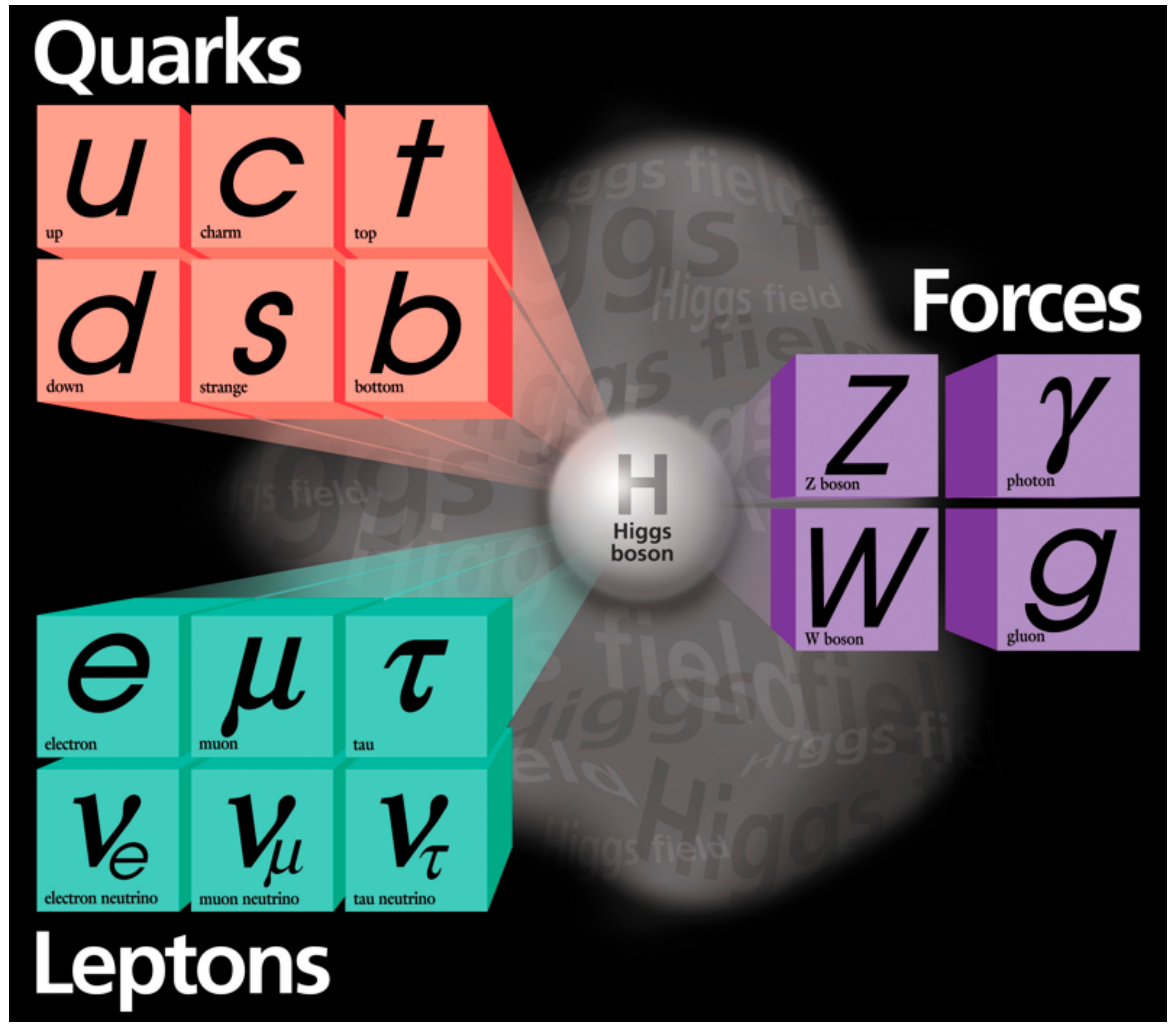
Outline

- The quest for new physics at the low-energy precision / intensity frontier — landscape
- Shedding light on the origin and nature of neutrino mass (with an eye towards the EIC)
    - Lepton flavor violation
    - Lepton number violation

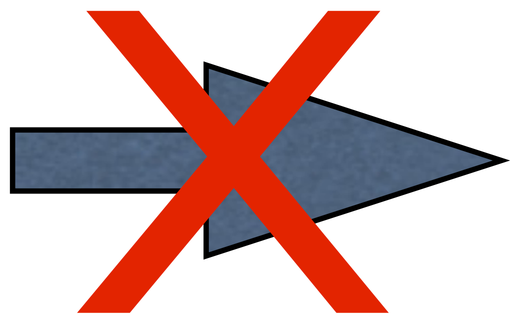
The quest for new physics at the precision / intensity frontier

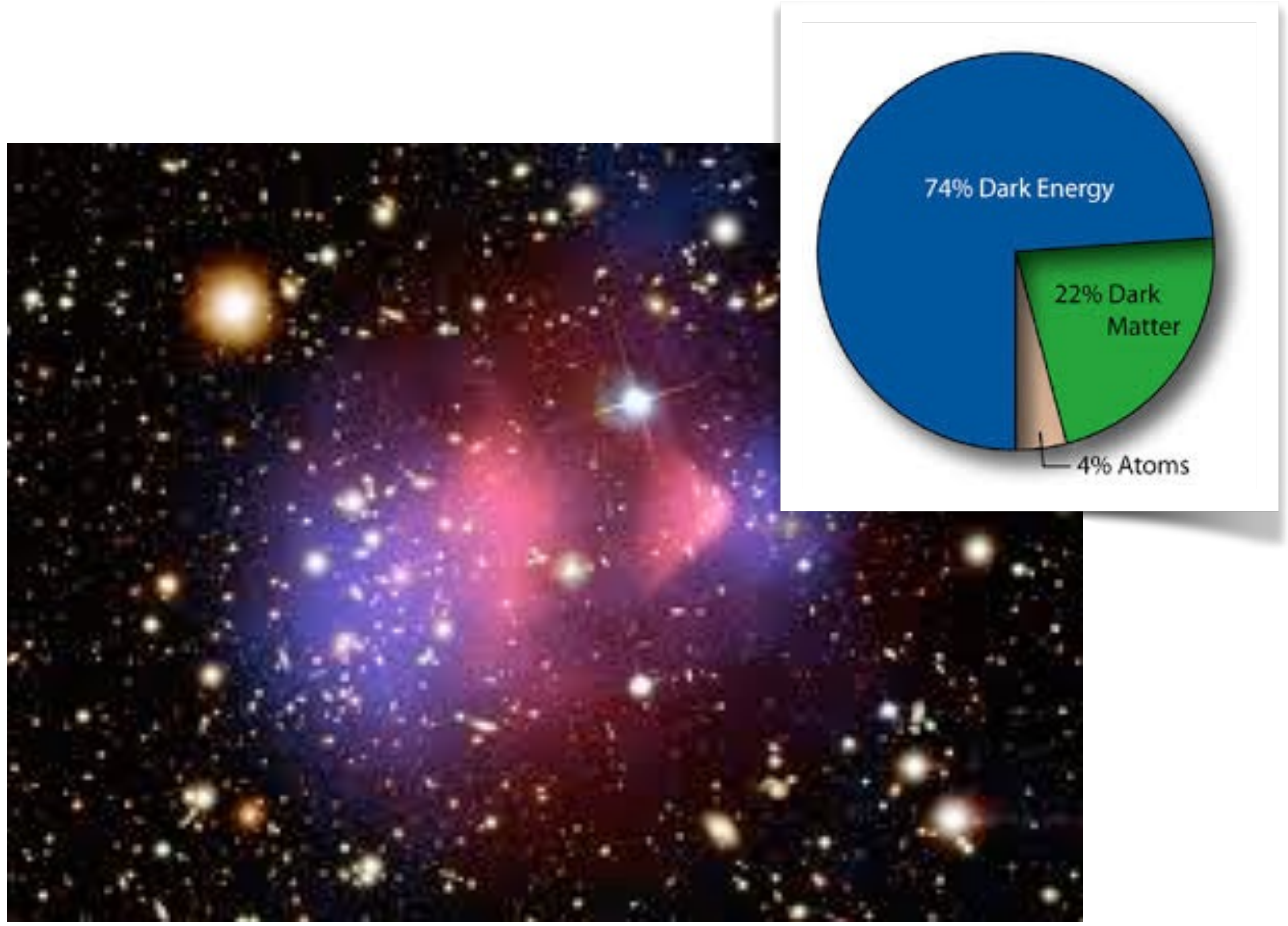
New physics: why?

- The SM is remarkably successful but it’s likely incomplete



Credit: Fermilab





Credit: X-ray: NASA/CXC/CfA/M.Markevitch et al.; Optical: NASA/STScI; Magellan/U.Arizona/ D.Clowe et al.; Lensing Map: NASA/STScI; ESO WFI; Magellan/U.Arizona/D.Clowe et al.

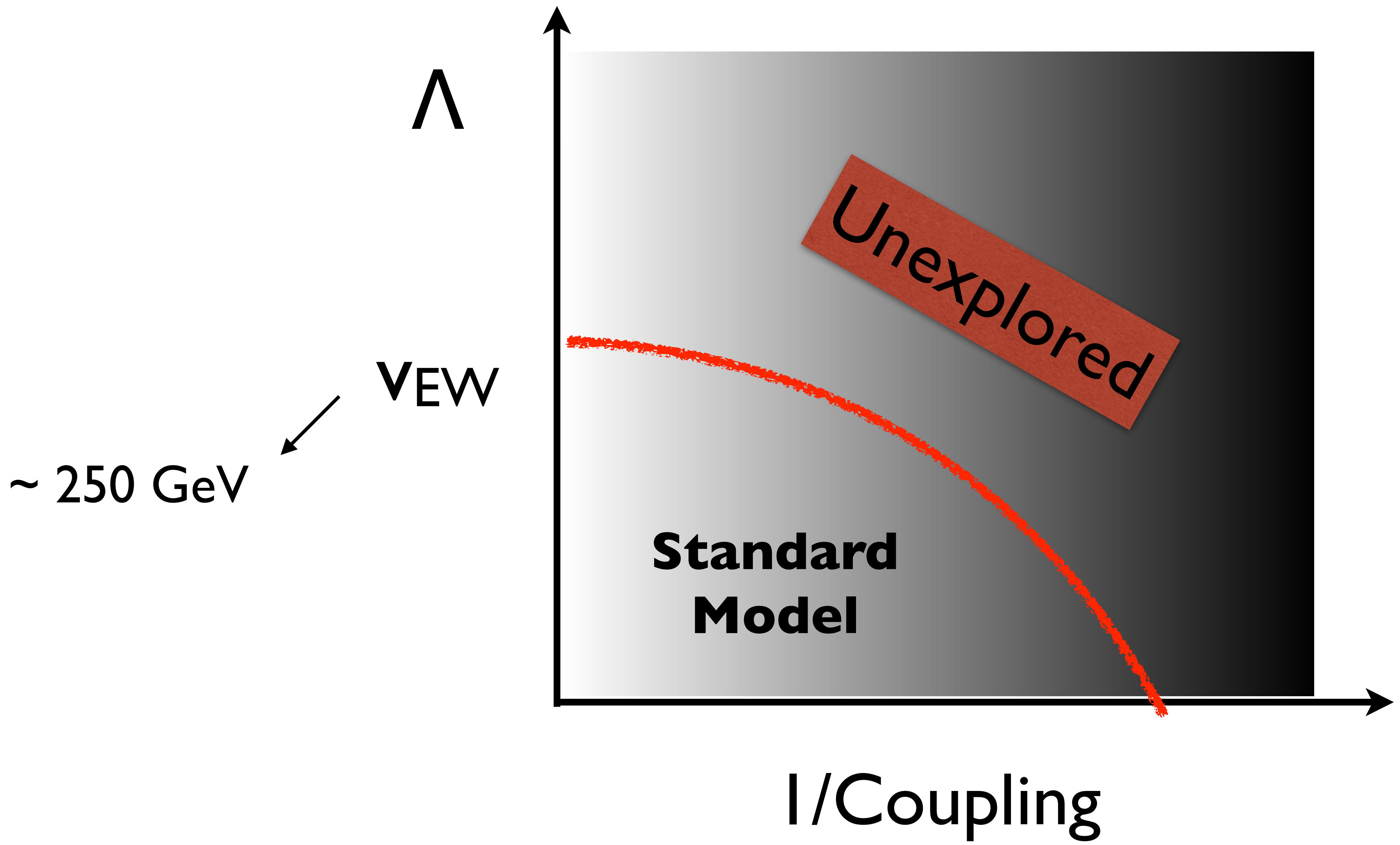
No Neutrino Mass, no Baryon Asymmetry, no Dark Matter, no Dark Energy

Origin of flavor, Strong CP problem, Unification,…

Addressing these shortcomings & puzzles requires new physics

New physics: where?

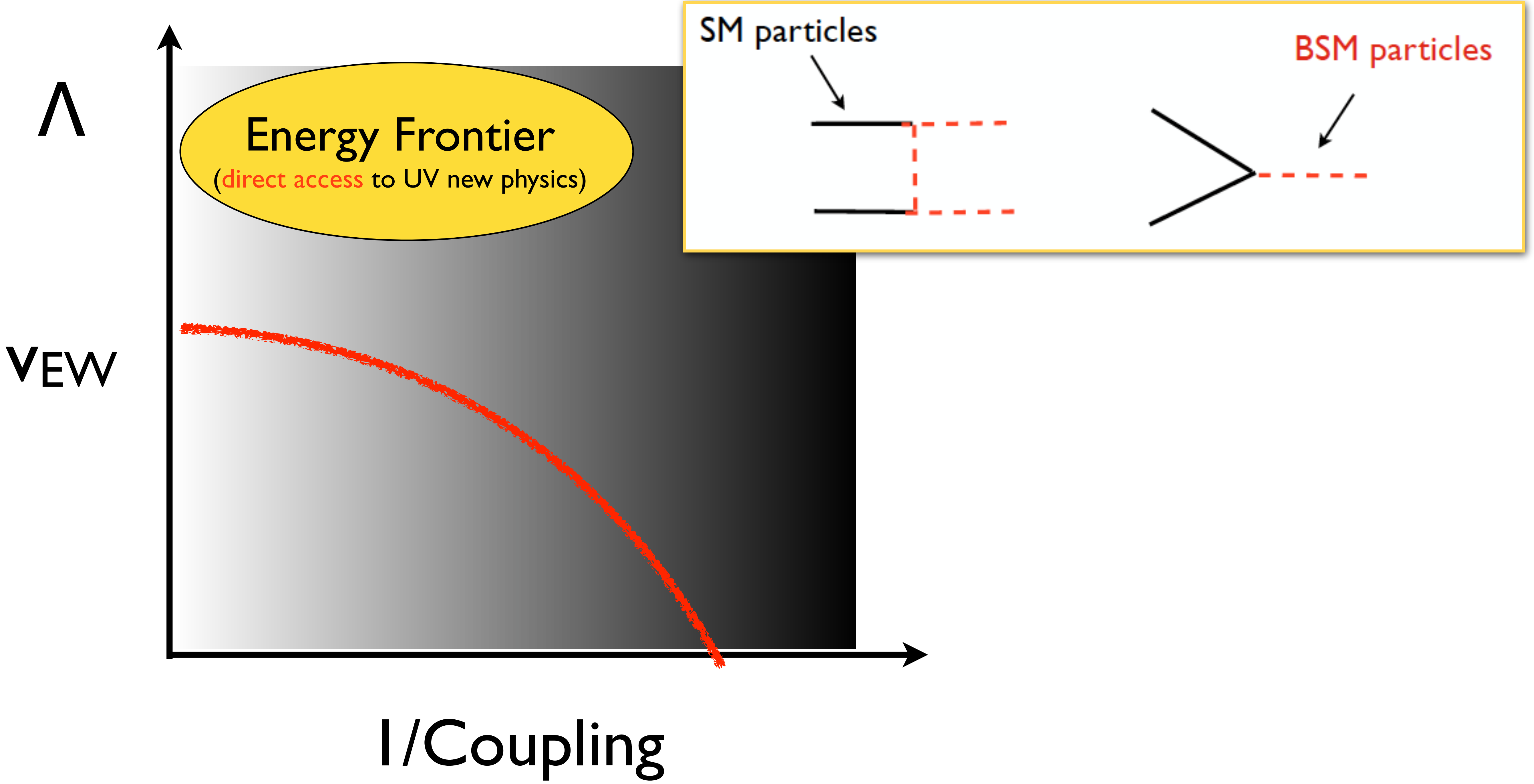
- Where is the new physics? Is it Heavy? Is it Light & weakly coupled?



New physics: how?

- Two complementary paths to search for new physics

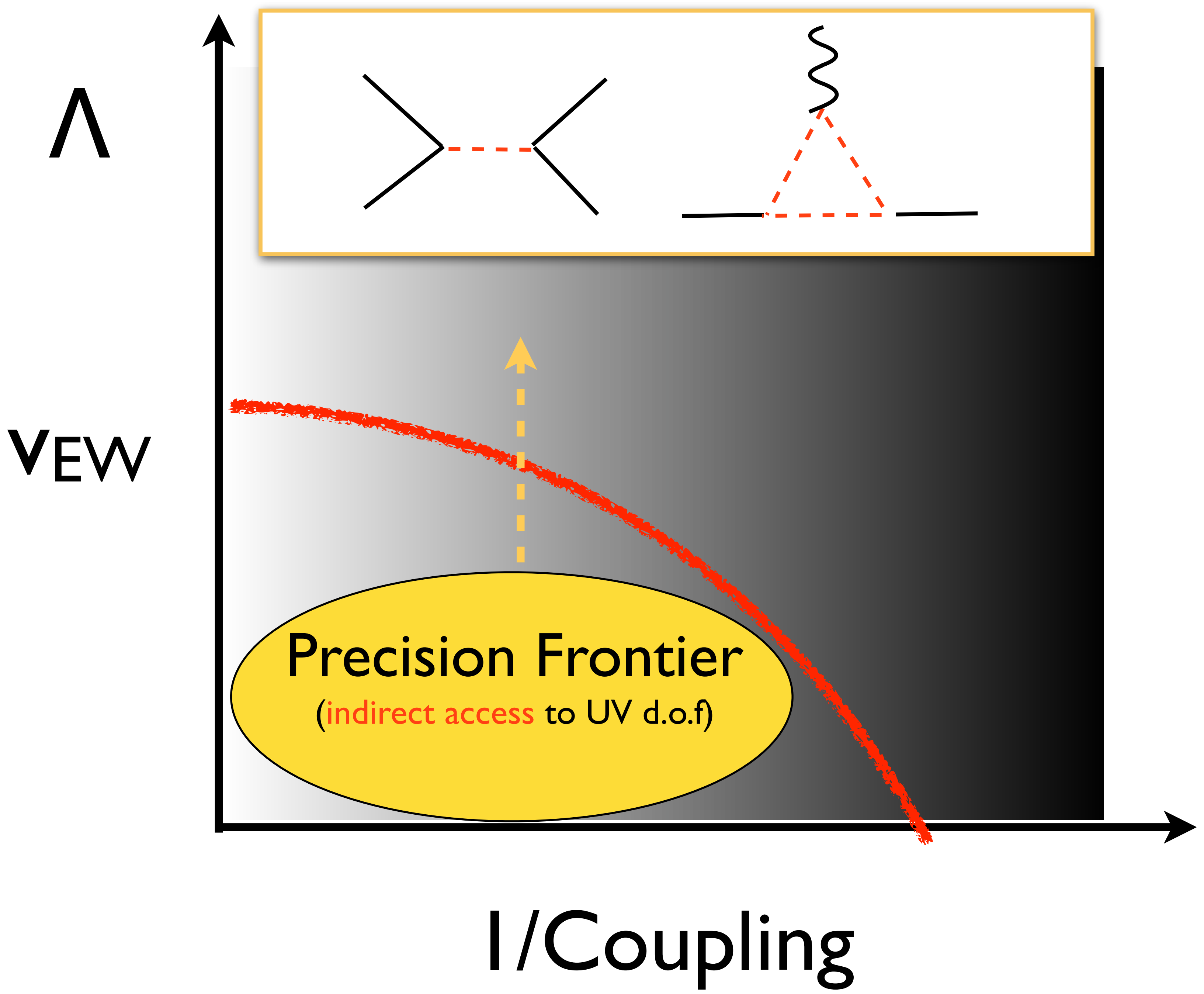
$$E = mc^2$$

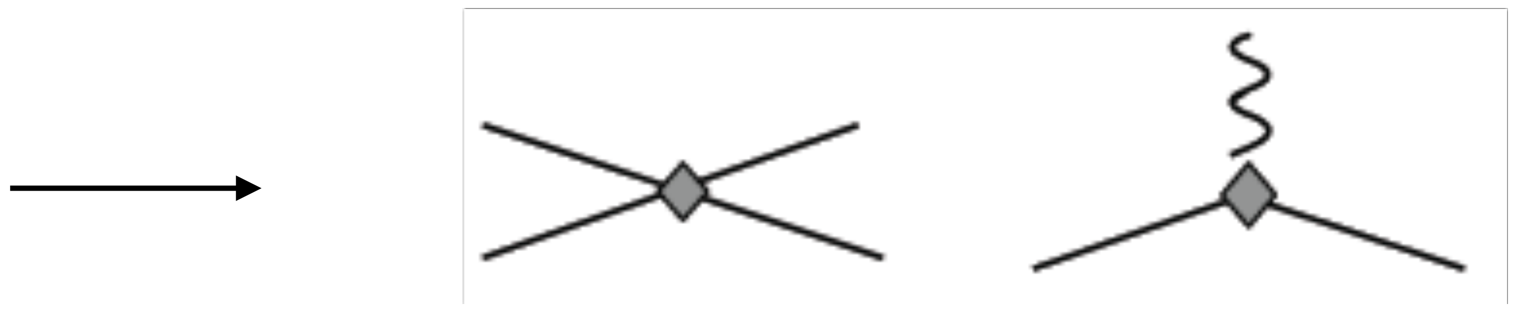


New physics: how?

- Two complementary paths to search for new physics

$$\Delta E\,\Delta t \sim h$$



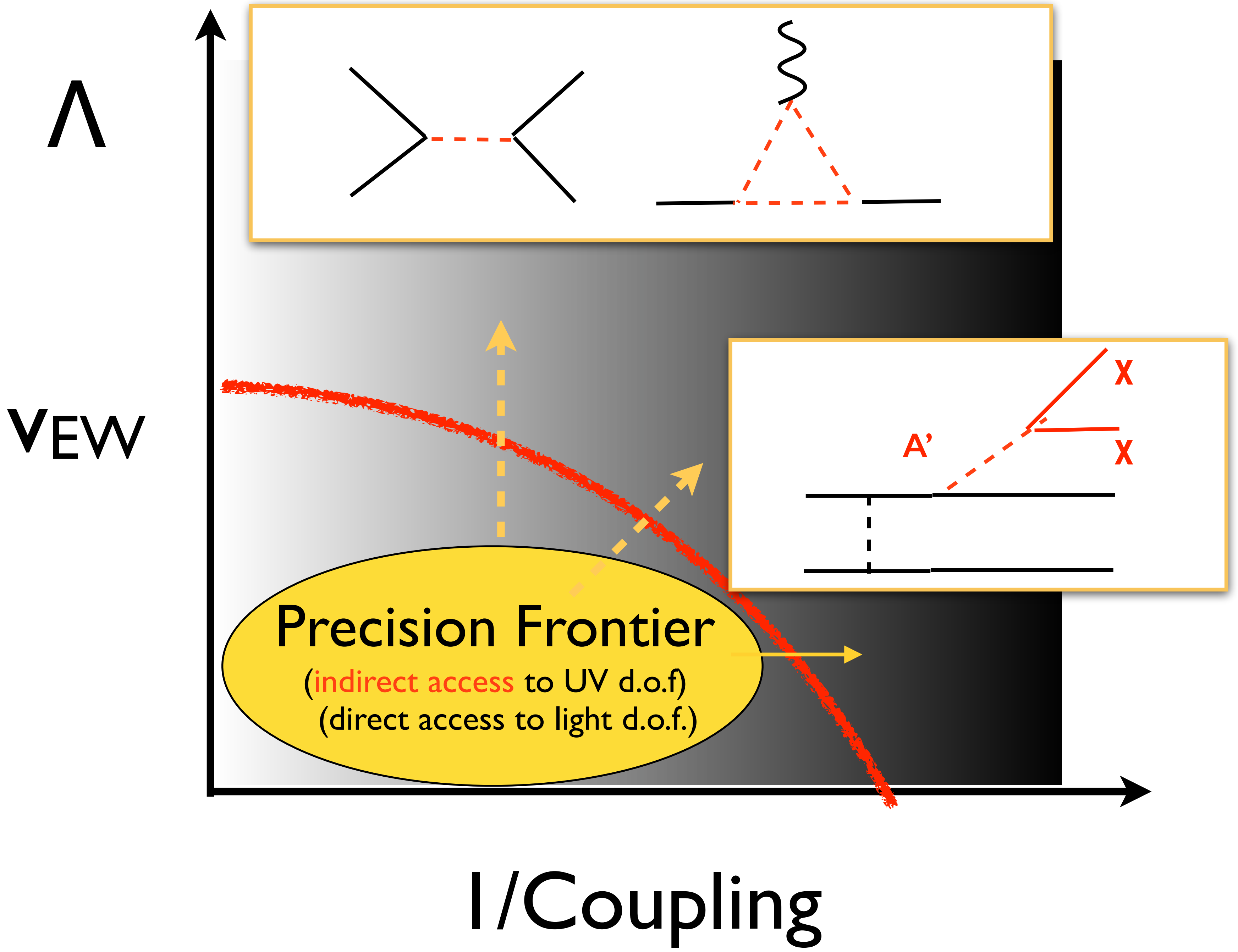


$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d\geq 5,n} \frac{C_n^{(d)}\, O_n^{(d)}}{\Lambda^{d-4}}$$

Imprints of heavy BSM physics: new local interactions suppressed by inverse powers of mass

New physics: how?

- Two complementary paths to search for new physics

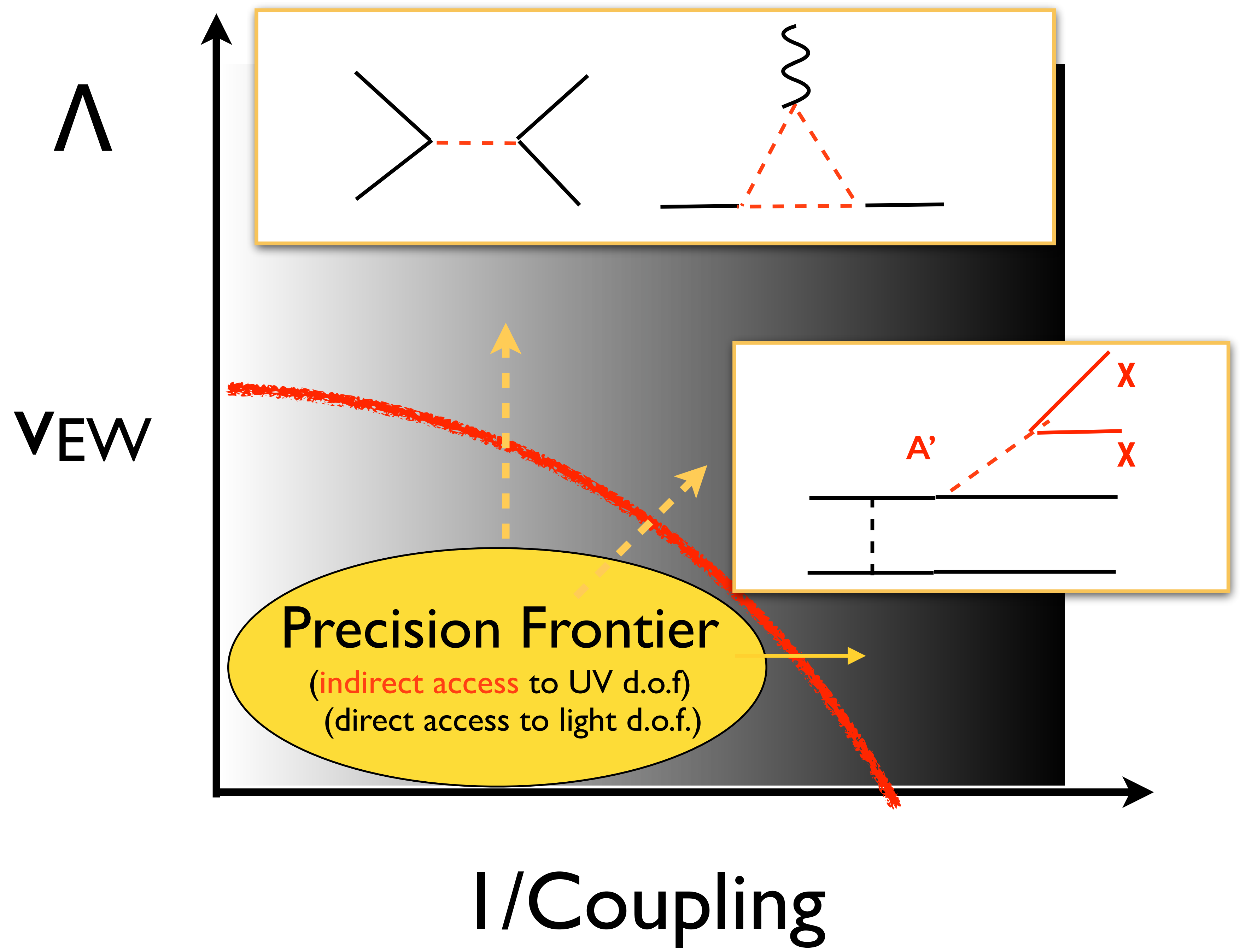


"Portals": leading SM interactions with the dark sector (though lowest dimensional SM singlet operators)

$$\mathcal{L} \sim O_{\text{portals}} + O\left(\frac{1}{\Lambda}\right)$$

New physics: how?

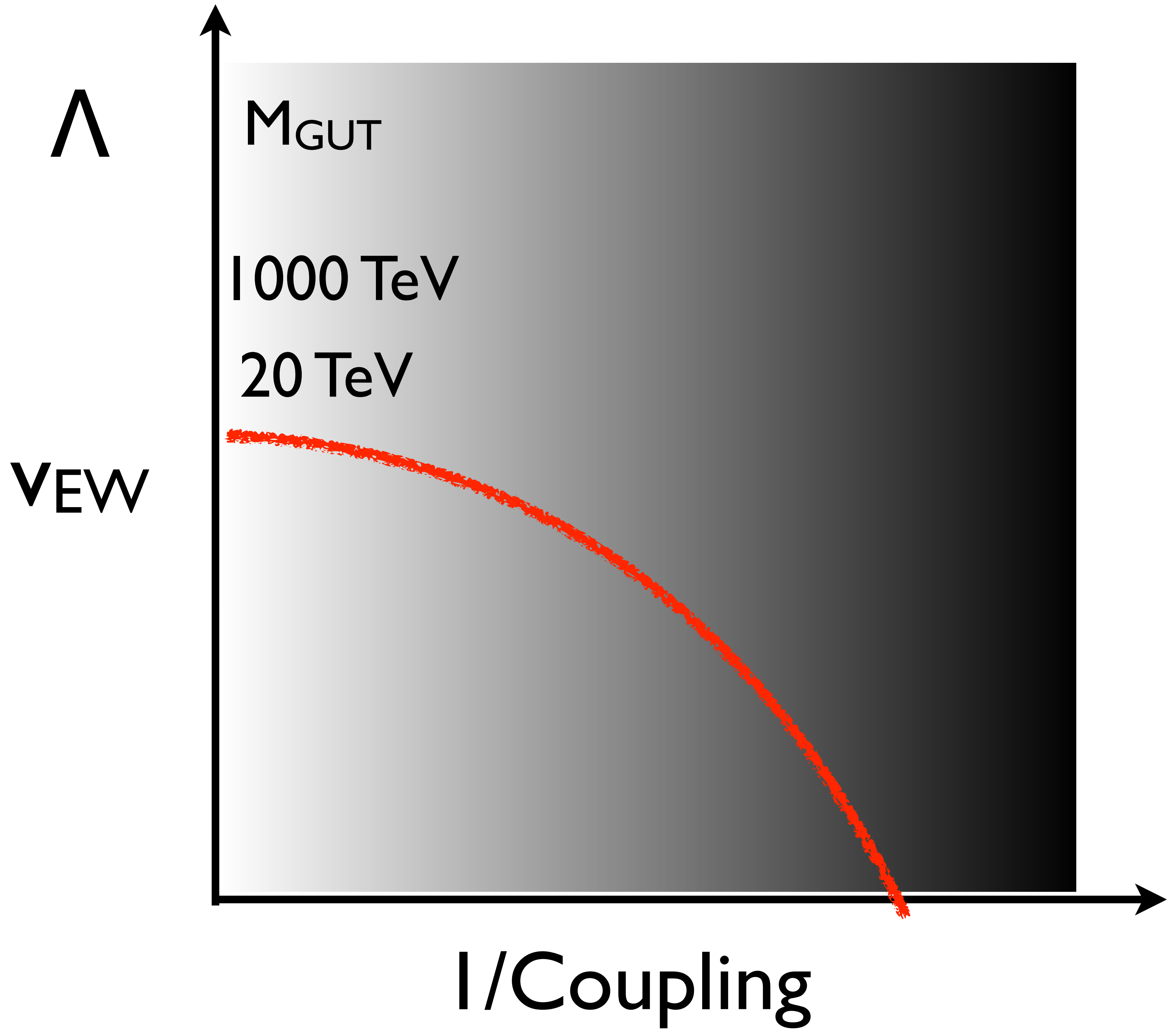
- Two complementary paths to search for new physics



- Both frontiers needed to probe the particle content & symmetries of $\mathcal{L}_{BSM}$ and address the open questions

BSM probes @ the Precision / Intensity Frontier

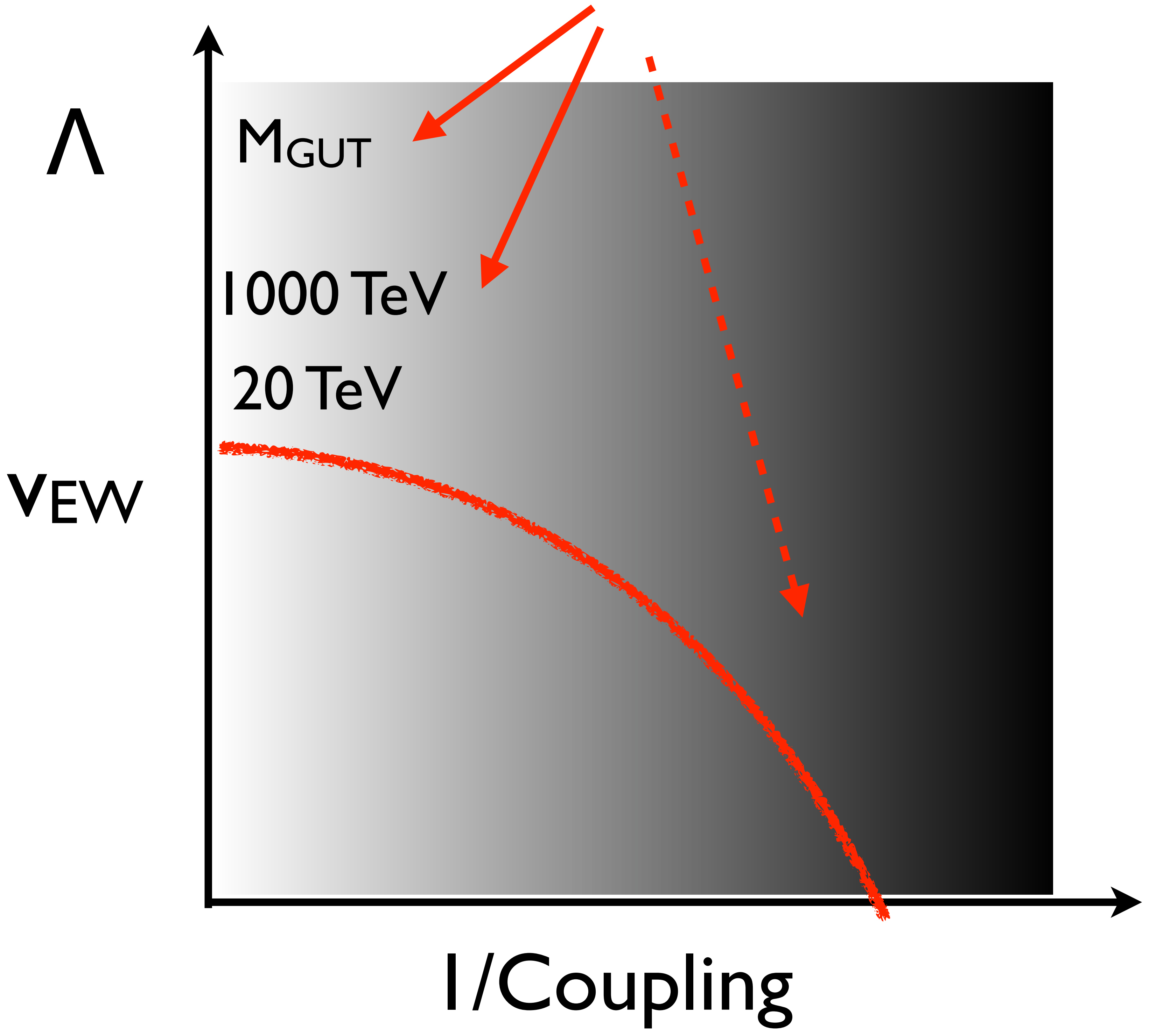
- Three classes, pushing the boundary in qualitatively different ways and at different mass scales



BSM probes @ the Precision / Intensity Frontier

- Three classes, pushing the boundary in qualitatively different ways and at different mass scales

1. Searches for rare or SM-forbidden processes that probe approximate or exact symmetries of the SM (L, B, CP, L_α): $0\nu\beta\beta$ decay, proton decay, EDMs, LFV ($\mu \to e$ conversion, $ep \to \tau X$, …), …



Sensitive to very high mass scale.

Connection to Sakharov conditions for baryogenesis (LNV, BNV, CPV) & origin and nature of neutrino masses (LNV, LFV)

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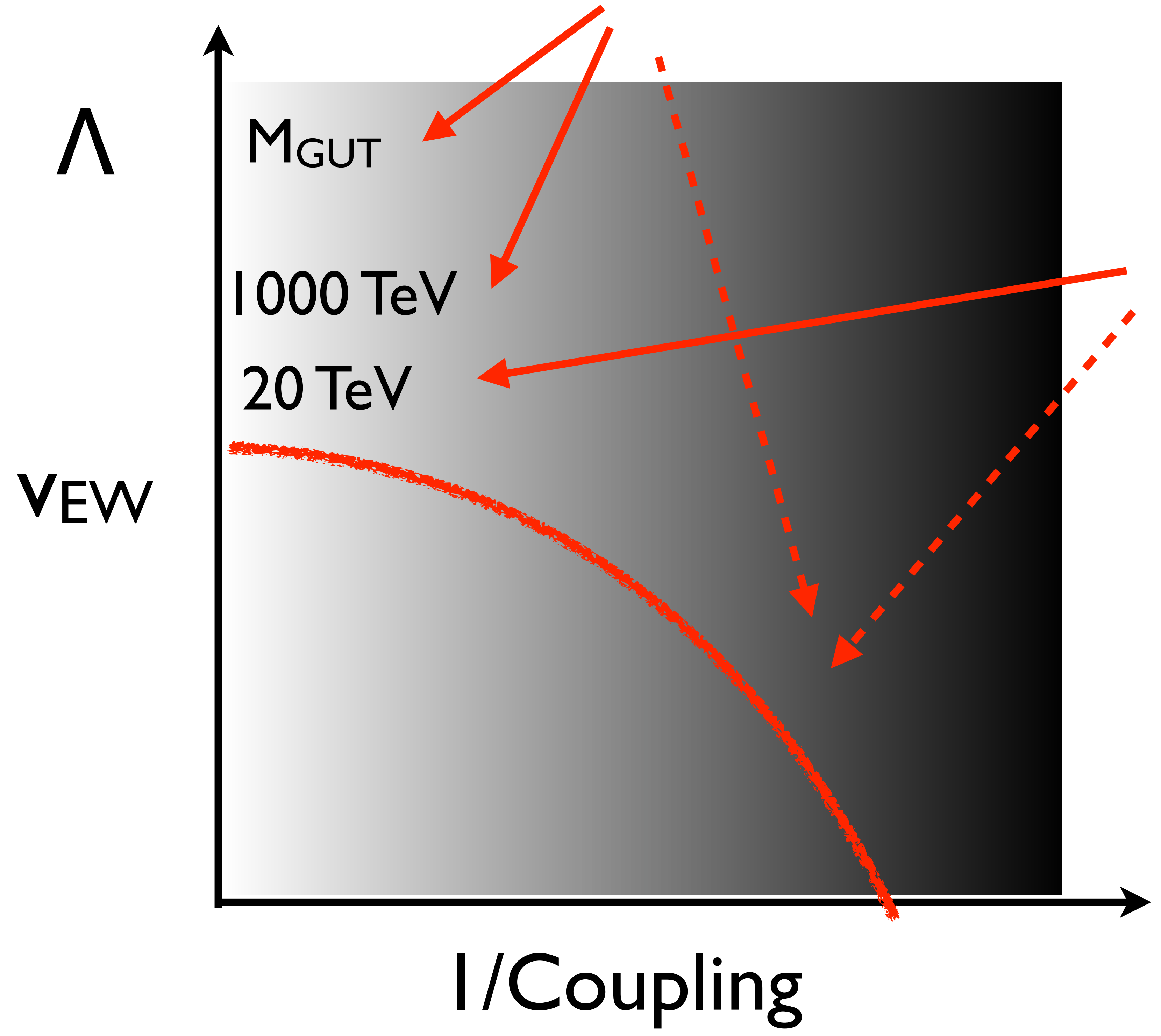

2. Precision tests of SM-allowed processes: β-decays (mesons, neutron, nuclei), PV electron scattering, muon g-2, …

Can detect the footprints of mutli-TeV force mediators as well as light mediators

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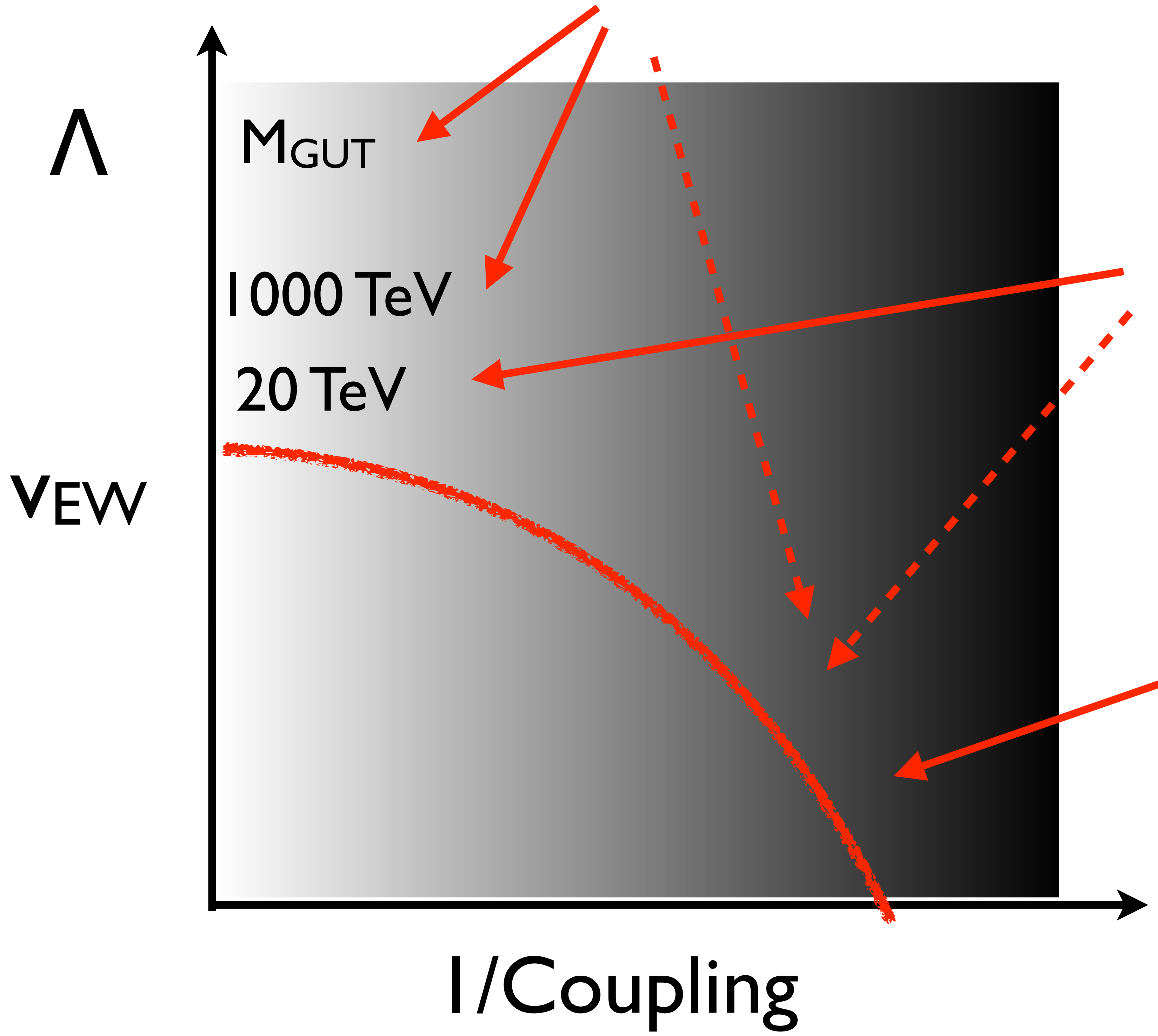

2. Precision tests of SM-allowed processes: β-decays (mesons, neutron, nuclei), PV electron scattering, muon g-2, …

3. Searches / characterization of light and weakly coupled particles: active ν's, sterile ν's, dark sector particles and mediators, axions, …

Probe neutrino properties, dark matter & dark sectors

BSM probes @ the Precision / Intensity Frontier

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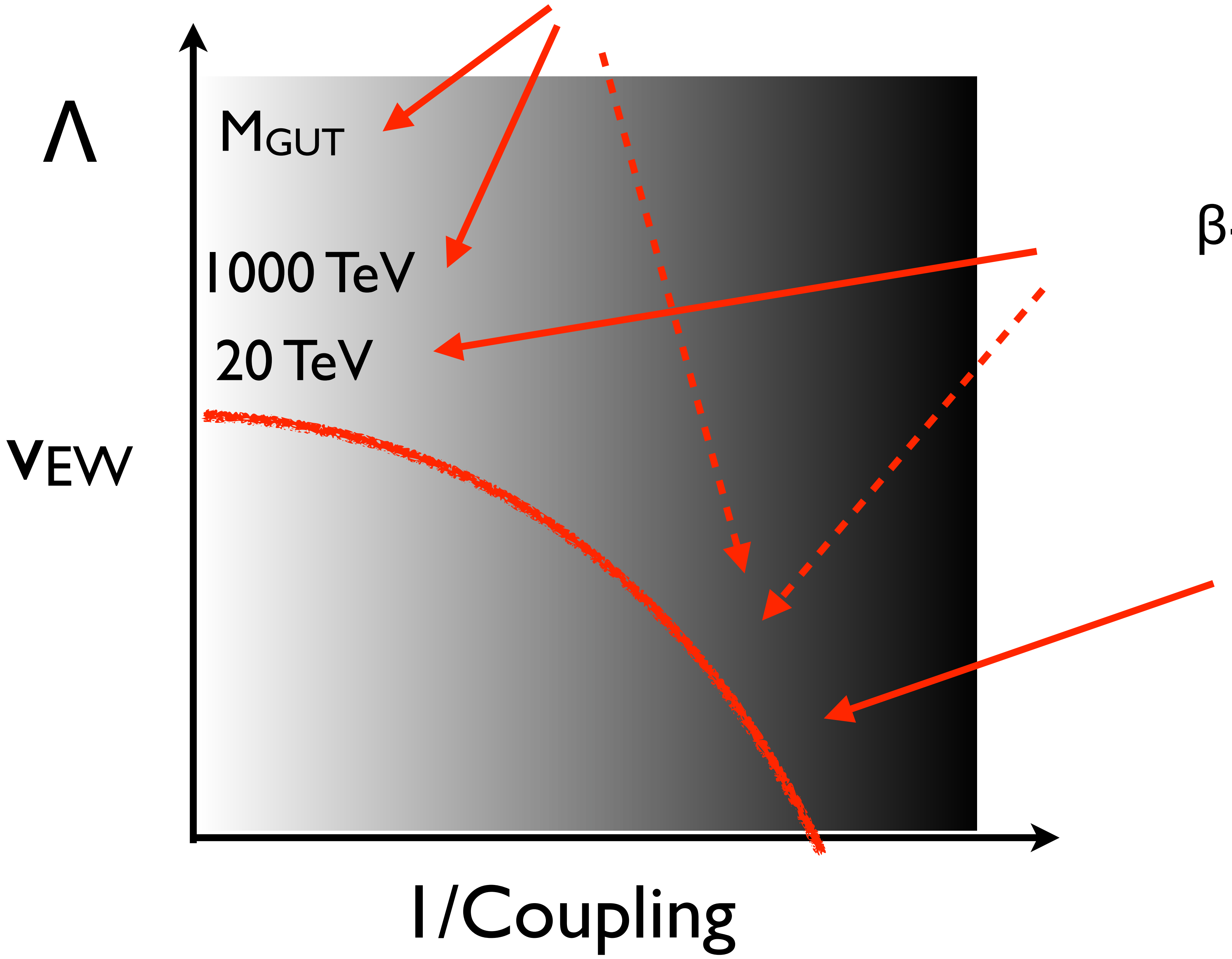

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The EIC is an intensity frontier machine and can play a role in all three classes

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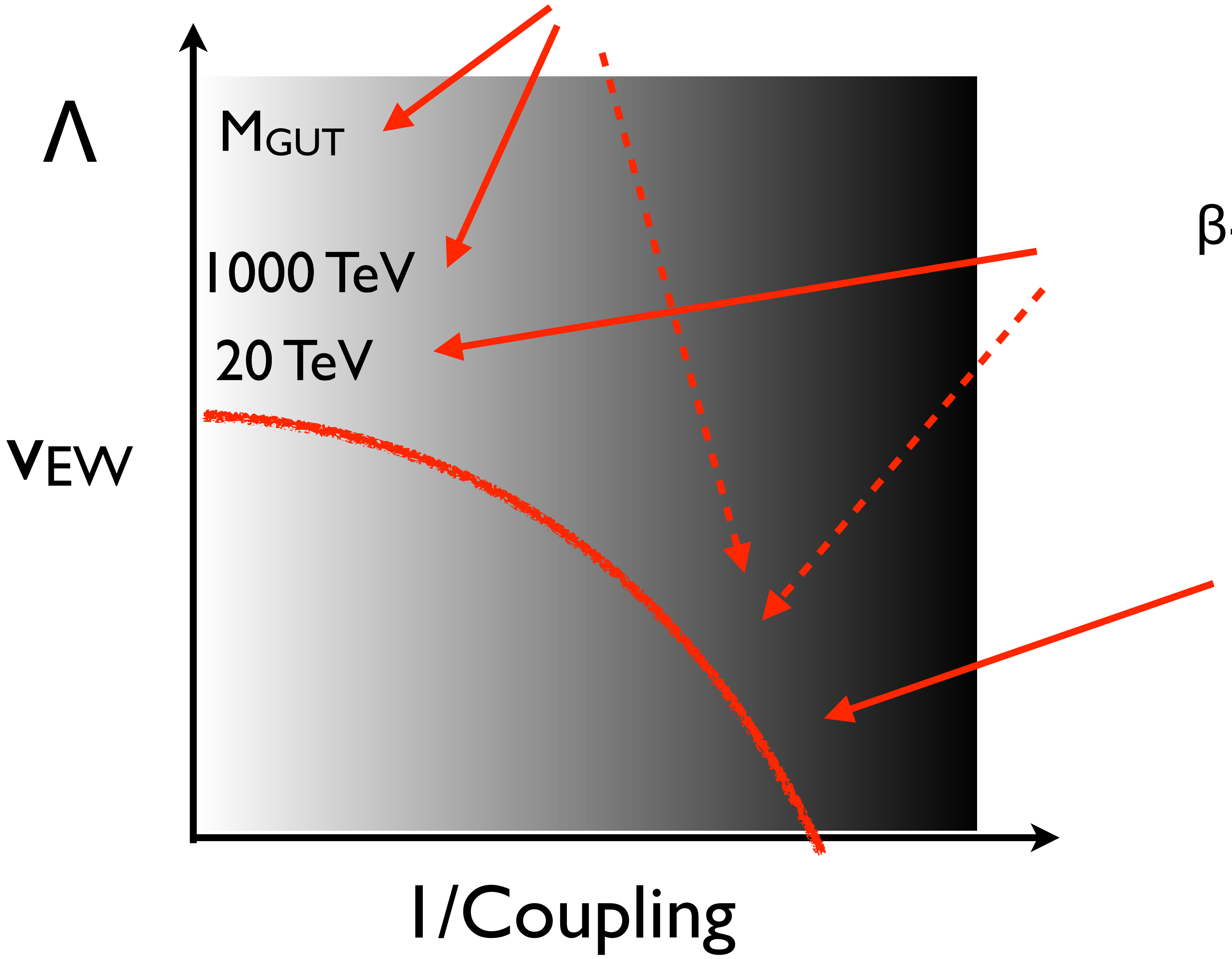

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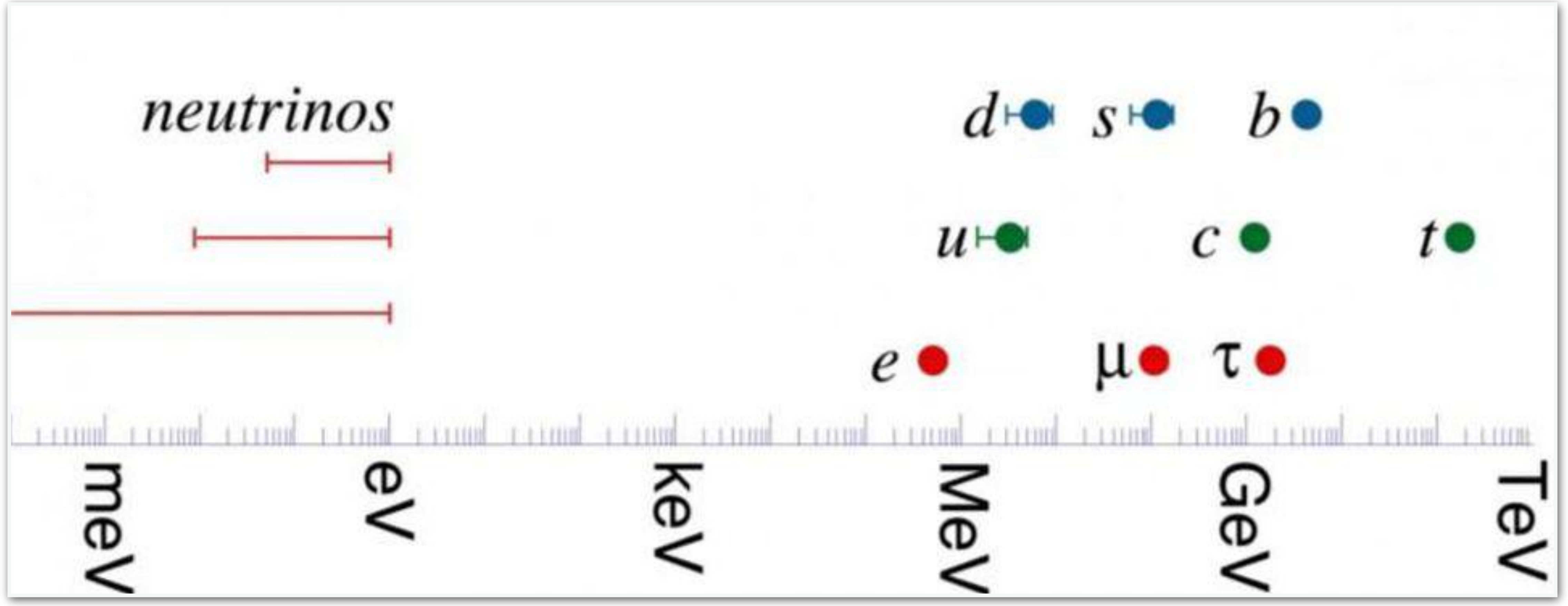
Will discuss LFV & LNV
with an eye towards the EIC

Probing the origin of neutrino mass

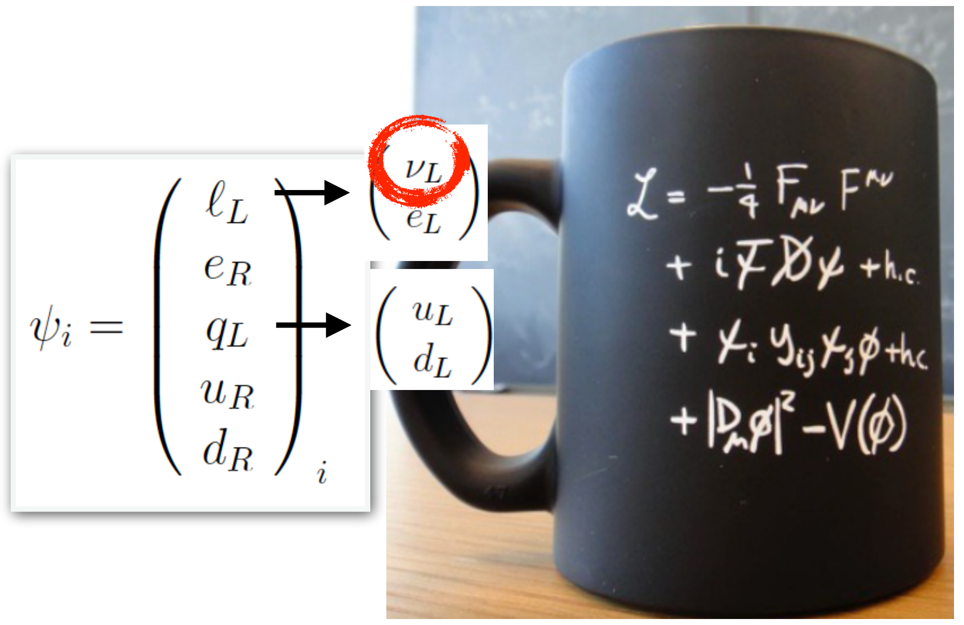


H. Murayama

Neutrino mass & new physics

- Massive neutrinos provide the only laboratory-based evidence of physics beyond the Standard Model
- Lorentz invariance ⇒ two options for massive neutrinos: Dirac or Majorana

The Standard Model



?

No neutrino mass

ΔL= 0

ΔL=2

$$\mathcal{L}_D \sim \bar{\nu}_R \, M_D \, \nu_L$$

Conserves L=L_e+L_μ+L_τ

$$\mathcal{L}_M \sim \nu_L^T \, C M_M \, \nu_L$$

Violates L (ΔL=2)

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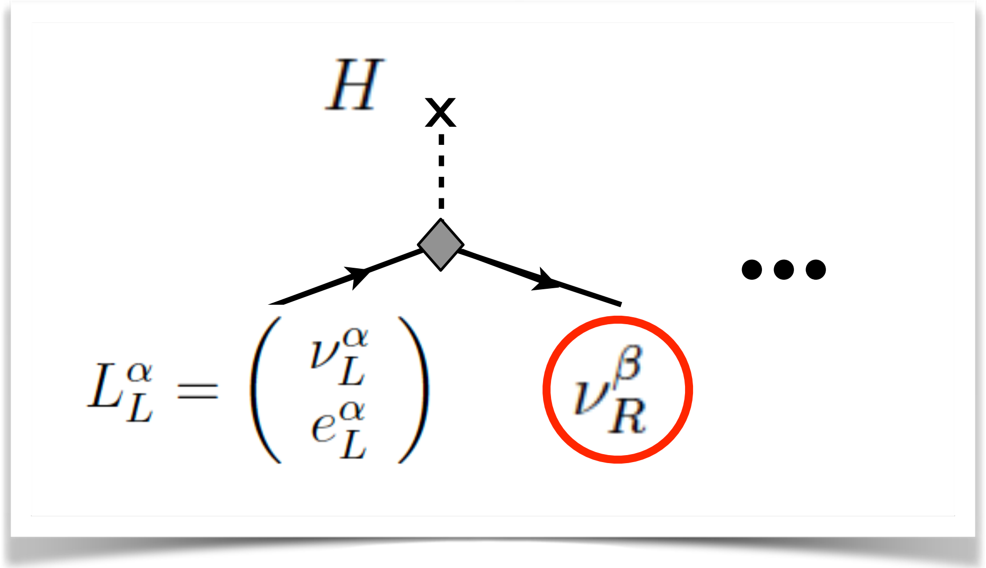
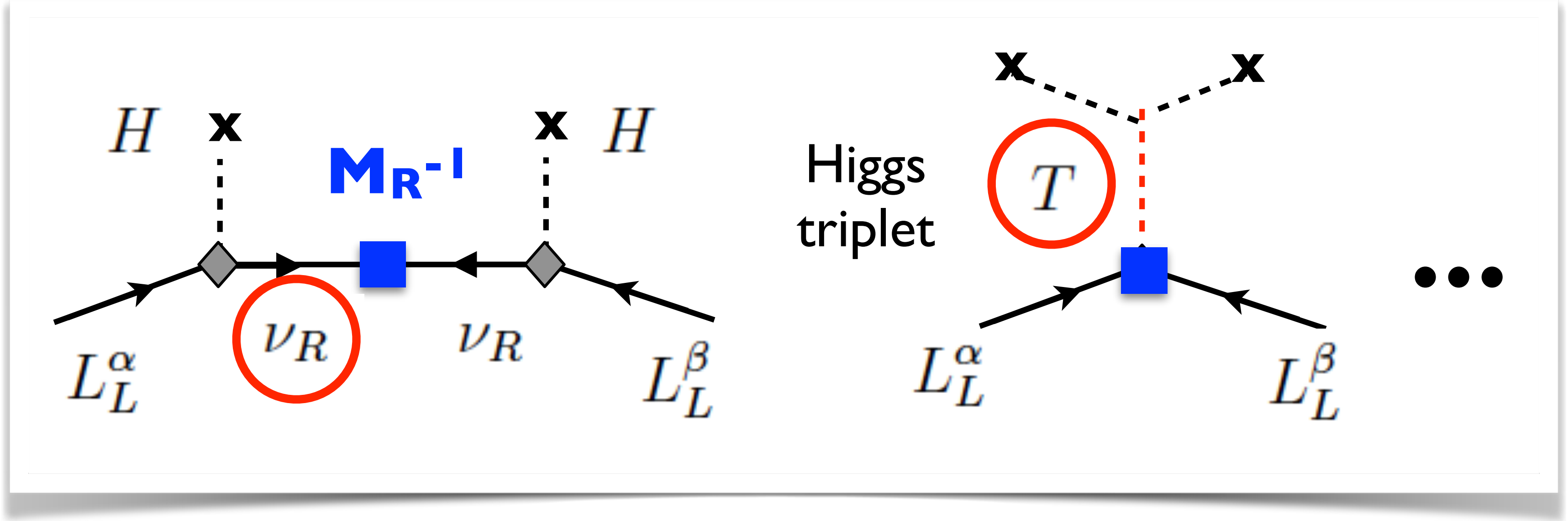
- Models of ν mass typically introduce new degrees of freedom & interactions

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

Dirac?

Majorana?





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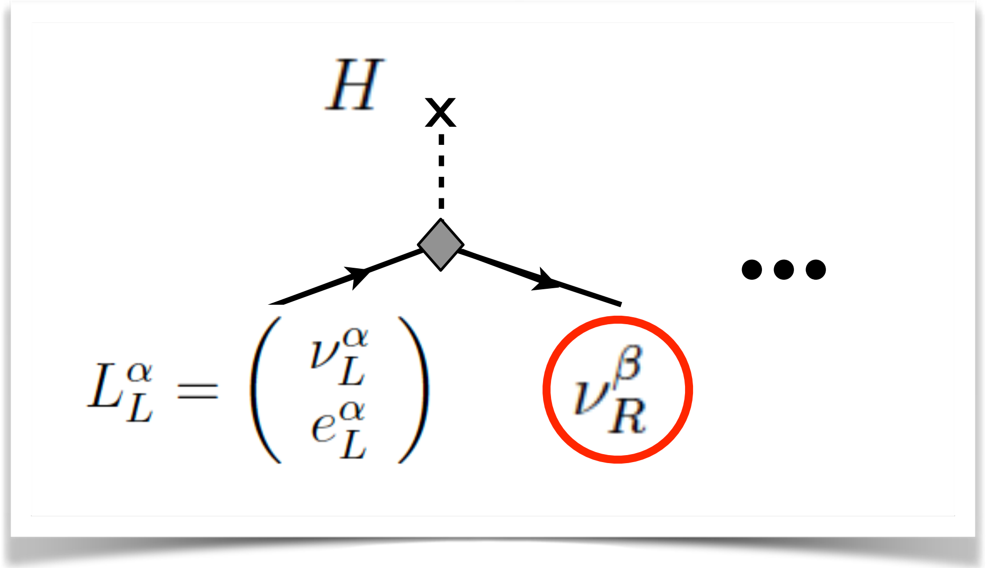
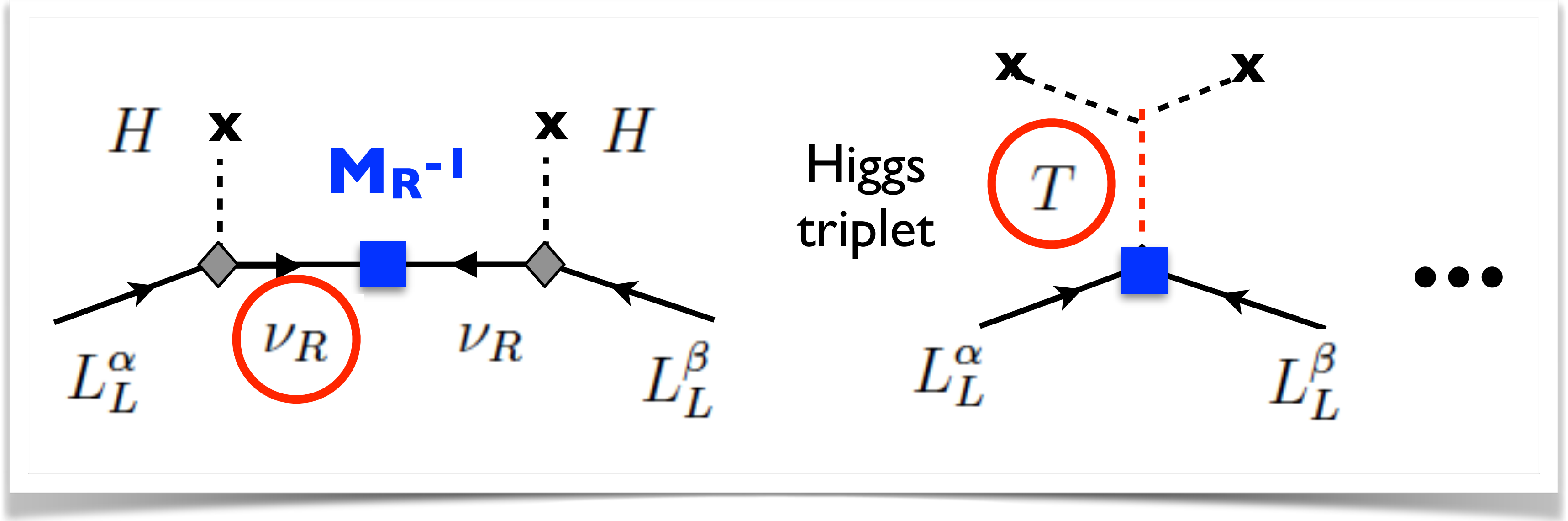


Majorana?



Are neutrinos Dirac or Majorana fermions?

Lepton Number Violation

(0νββ, meson and lepton decays, collider processes, …)

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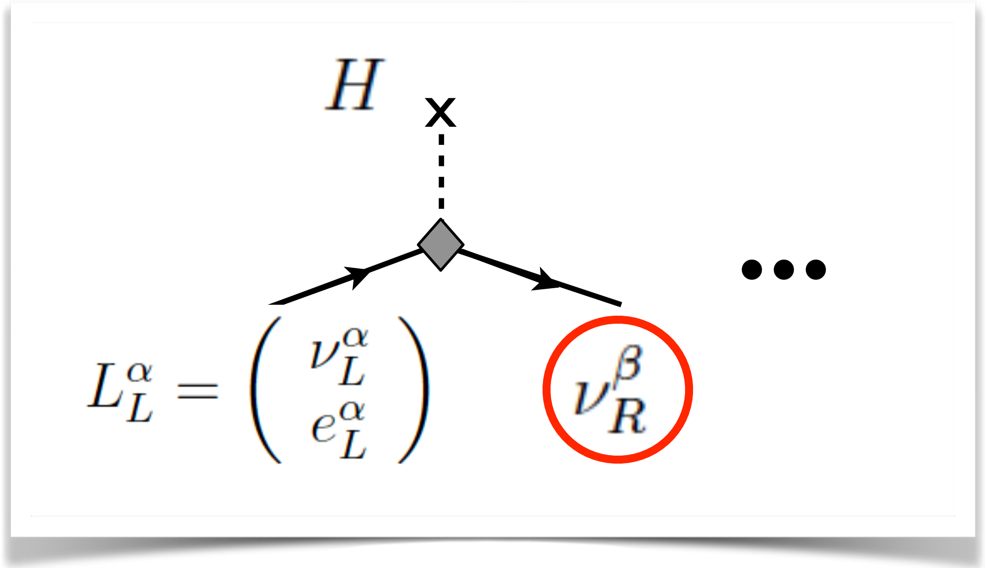
$$\mathcal{L}_{\nu\mathrm{SM}} = \mathcal{L}_{\mathrm{SM}} + \mathcal{L}_{\nu-\mathrm{mass}} + \ldots$$

What are the sources and mediators of lepton family violation?

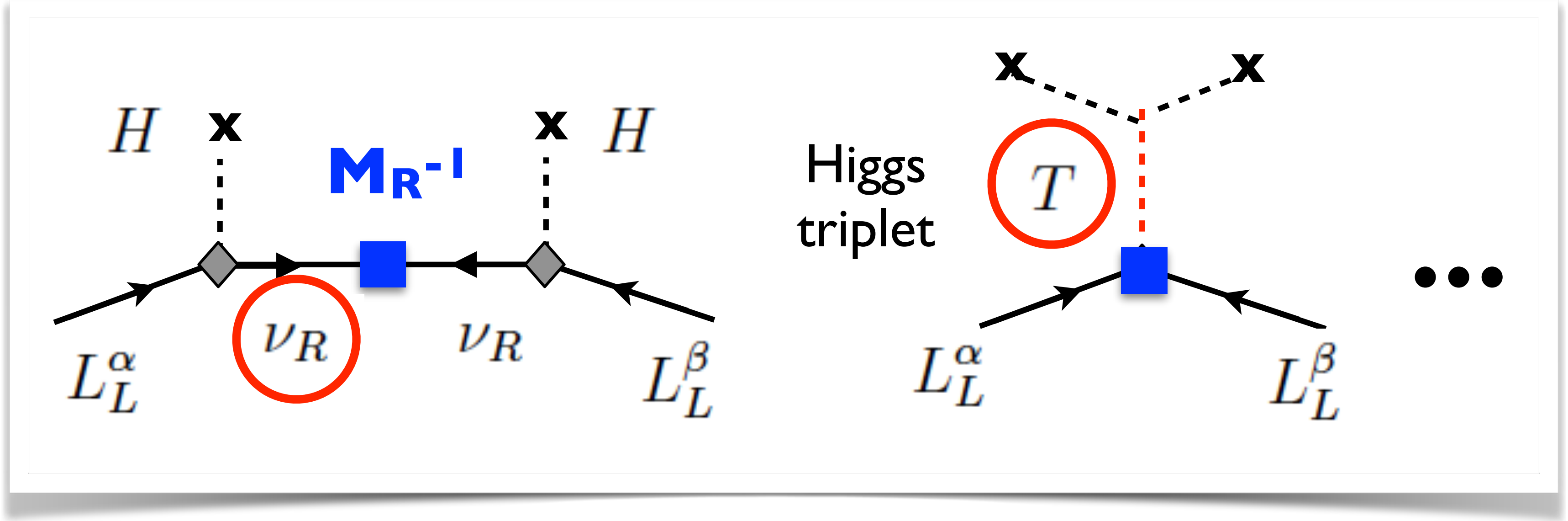
“Charged” Lepton Flavor Violation

(μ ↔ e, , τ ↔ μ , τ ↔ e processes)

Dirac?



Majorana?



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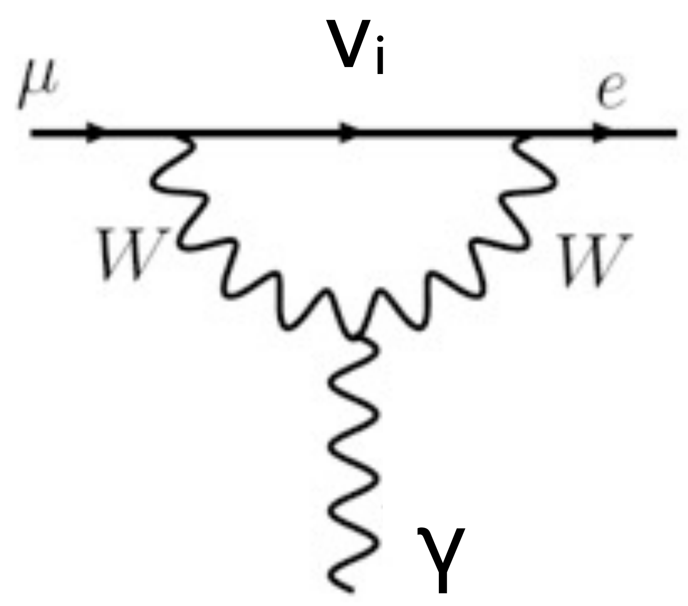
Charged Lepton Flavor Violation

LFV with charged leptons

- ν oscillations ⇒ $L_{e,\mu,\tau}$ not conserved. However, in SM + massive ν, Charged-LFV decays are 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…

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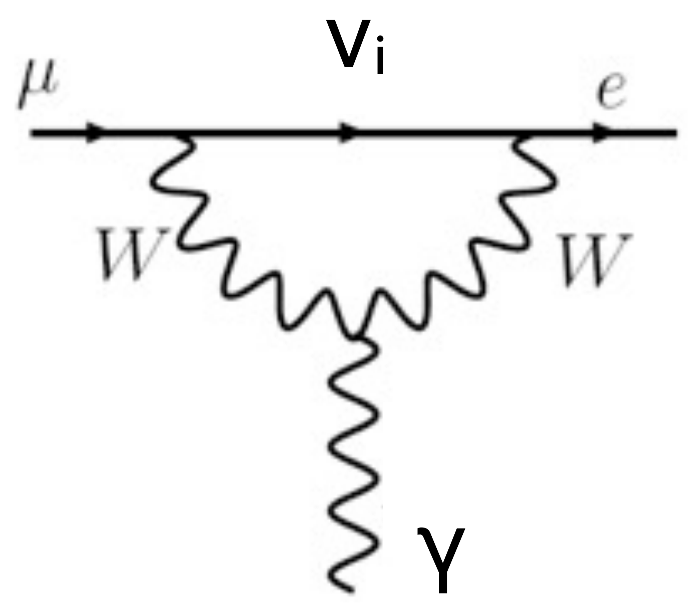

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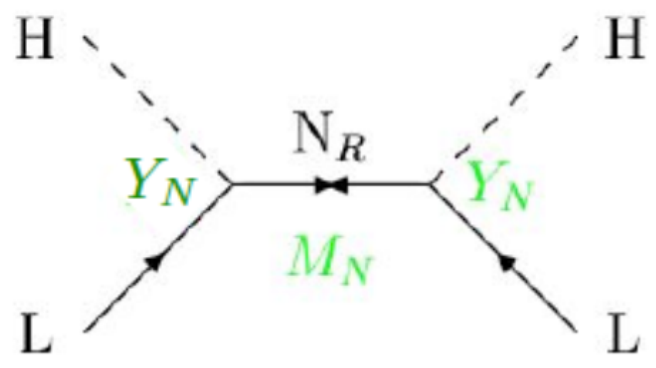
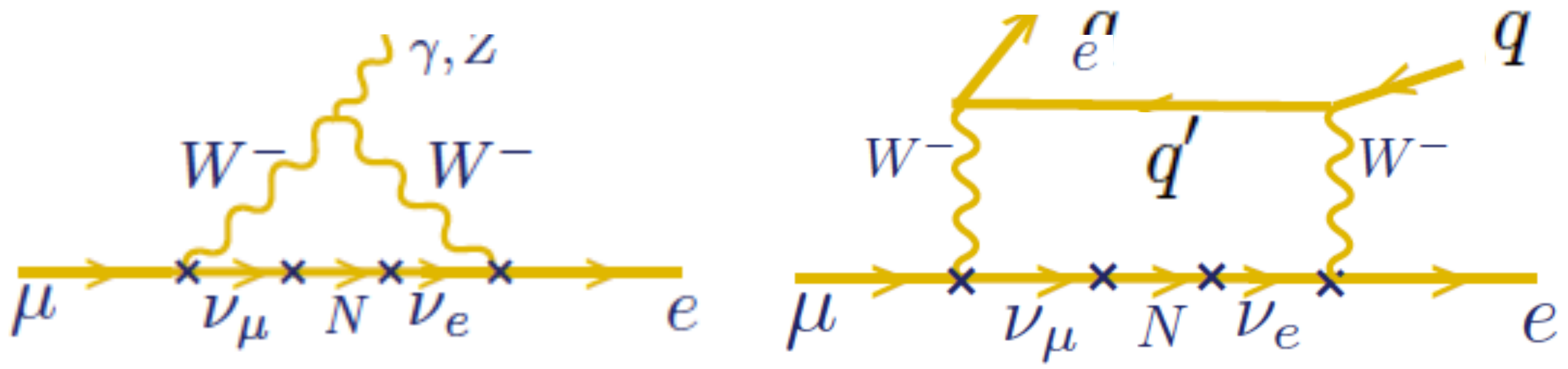
Petcov '77, Marciano-Sanda '77, Shrock '77…

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

Ex: Type-I seesaw





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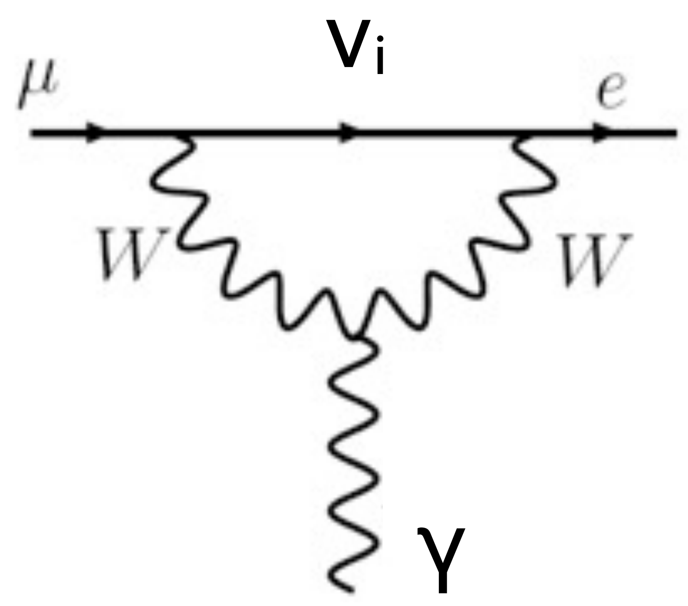

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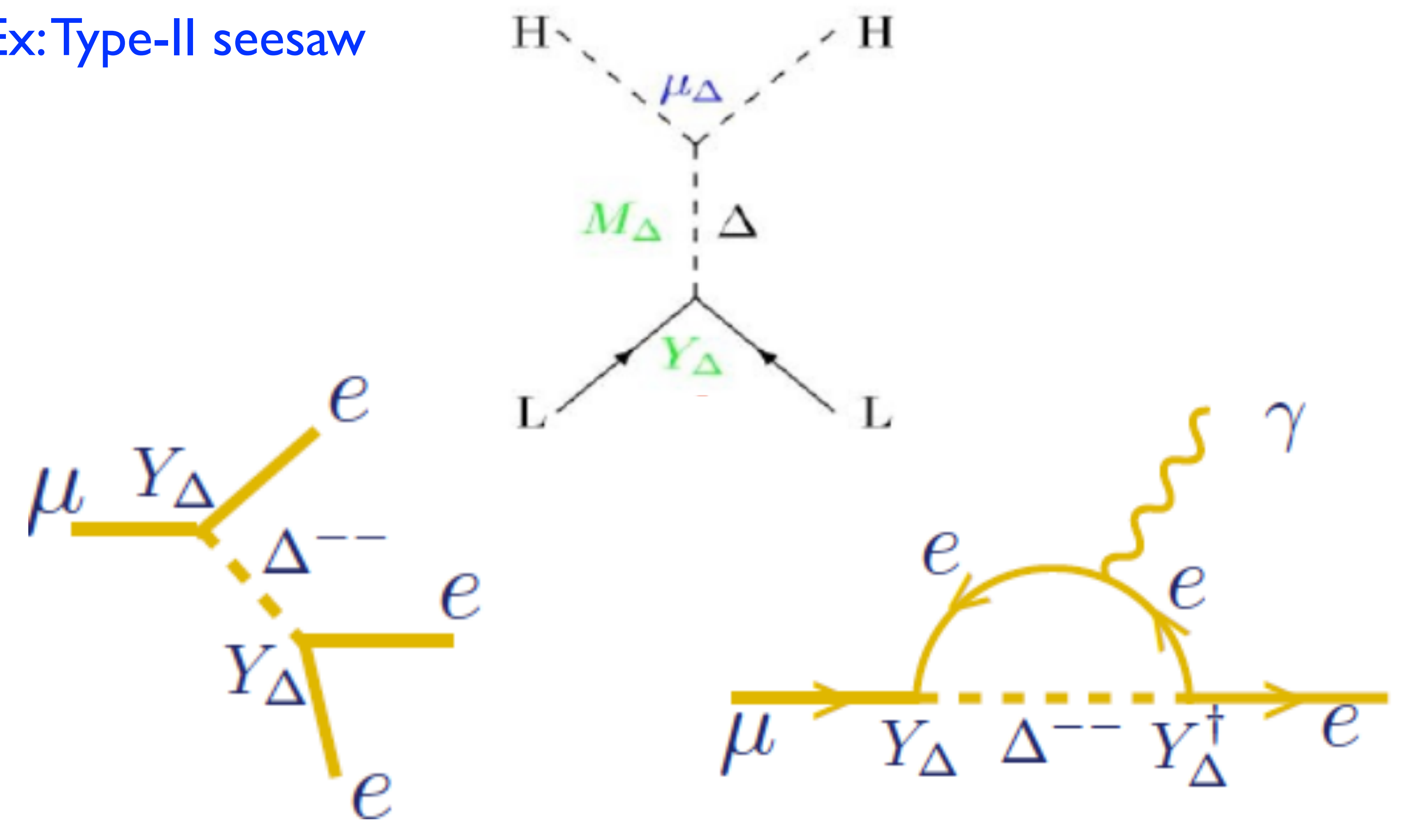
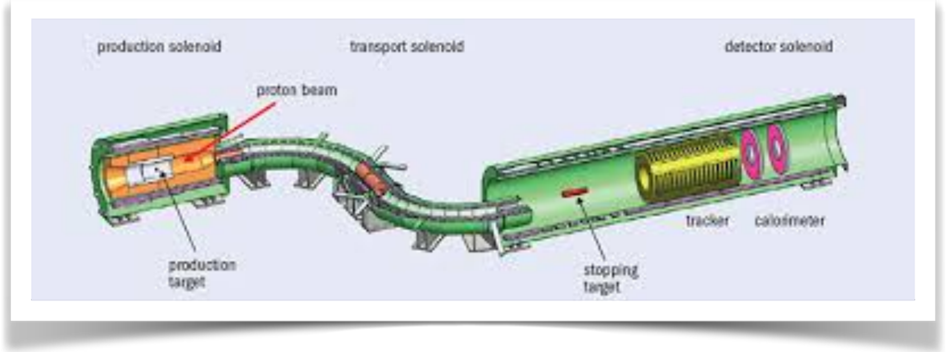
Ex: Type-II seesaw



LFV probes across energy scales

- Decays of μ, τ (and mesons)

Mu2e, Comet, MEG2, Mu3e, ...

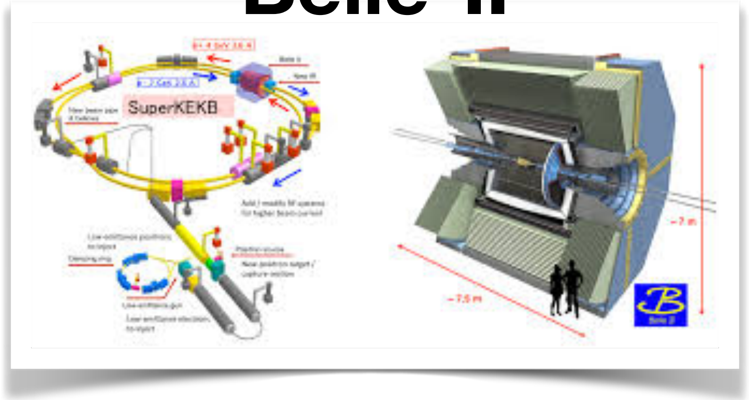


($K \to \pi\mu e$; $B \to K\mu\tau, K\mu e$; $B_s \to \mu\tau, \mu e$, quarkonia , …)

BR~ 10^{-13} (BR~ 10^{-6}) $\mu \to e\gamma, \quad \mu \to e\bar{e}e, \quad \mu\,(A,Z) \to e\,(A,Z)$ $\mu \to e\,a$

BR~ 10^{-8} $\tau \to \ell\gamma, \quad \tau \to \ell_\alpha \bar{\ell}_\beta \ell_\beta, \quad \tau \to \ell\, Y \qquad Y = P, S, V, P\bar{P}, \ldots$

Belle-II

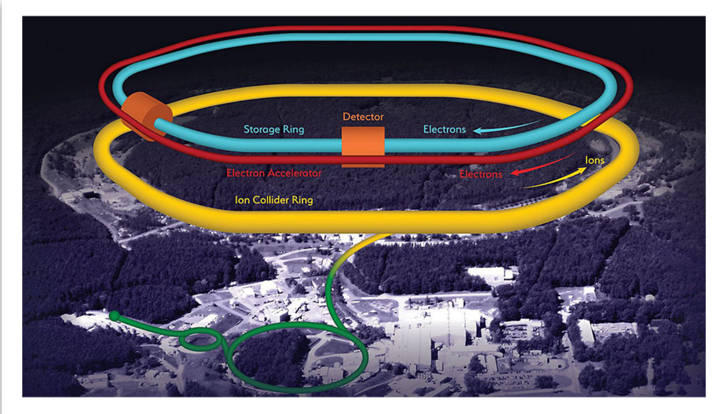


- Collider processes:

HERA,
EIC

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

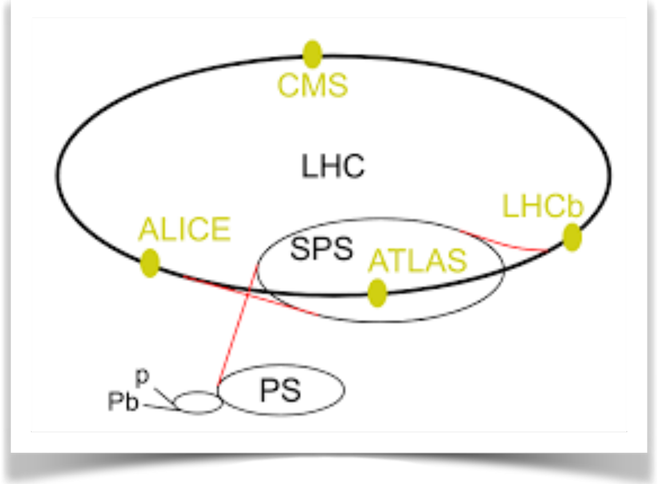
EIC



LHC

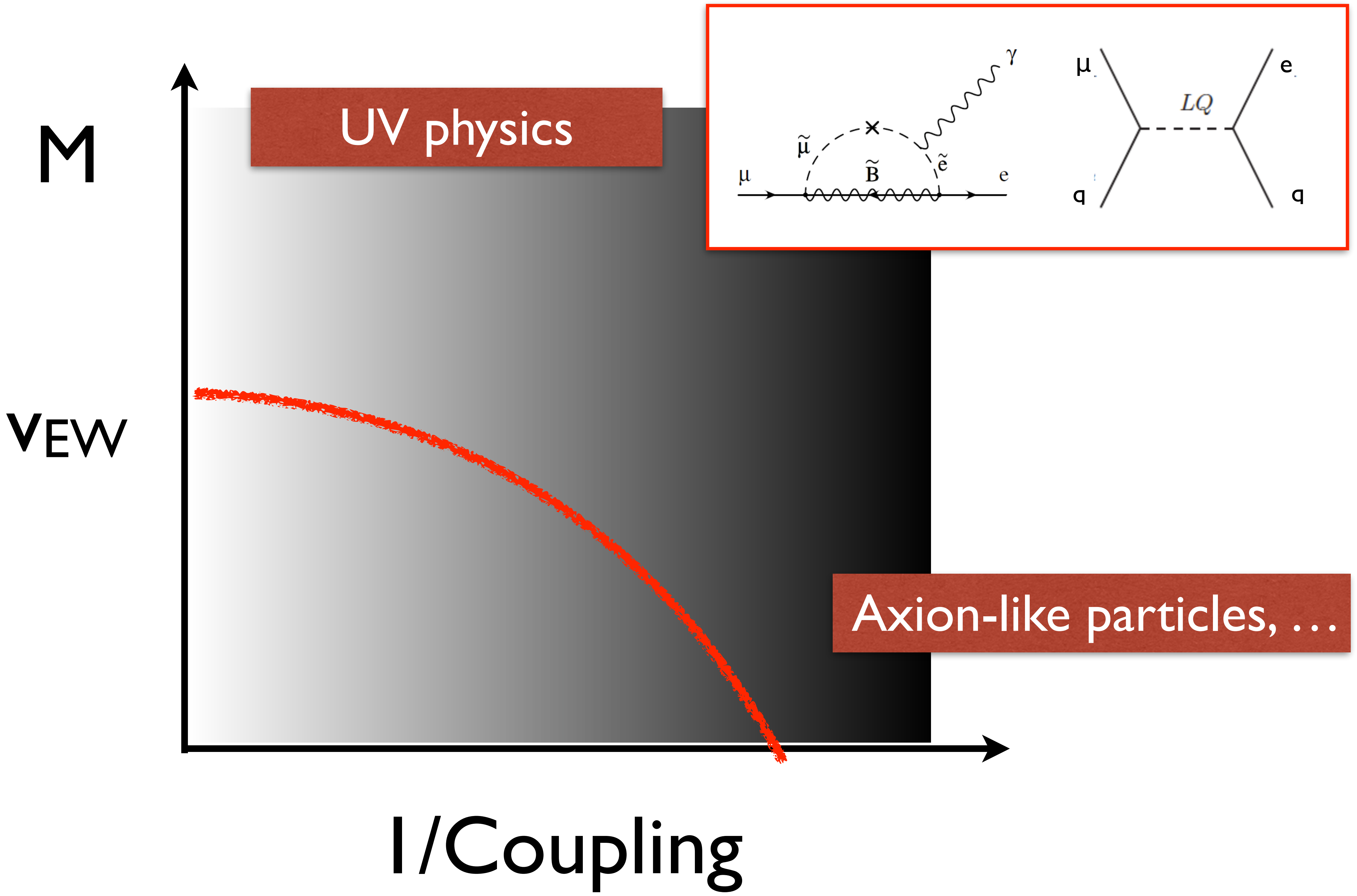
$$pp \;\to\; R \to \ell_\alpha \bar{\ell}_\beta + X \qquad R = Z', h, \tilde{\nu}, \ldots.$$
$$pp \;\to\; \ell_\alpha \bar{\ell}_\beta + X$$

LHC



CLFV physics reach

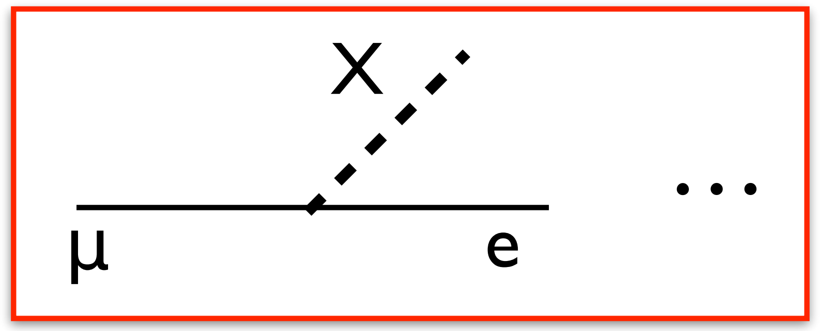
- LFV processes are sensitive to both heavy and light + weakly coupled new physics



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

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

See Kaori Fuyuto's talk



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

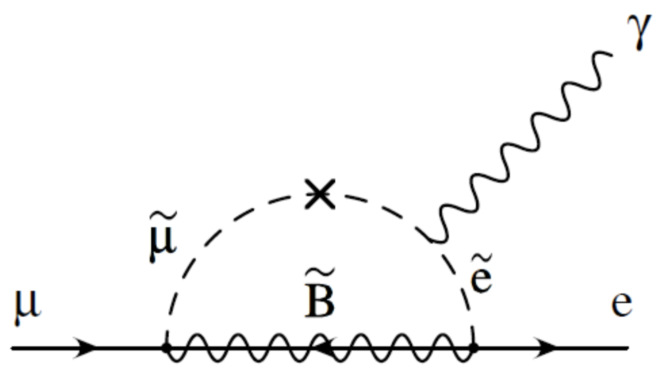
$F_{\alpha\beta}$ up to ~ 10^9 TeV

Calibbi-Redigolo-Ziegler-Zupan 2006.04795

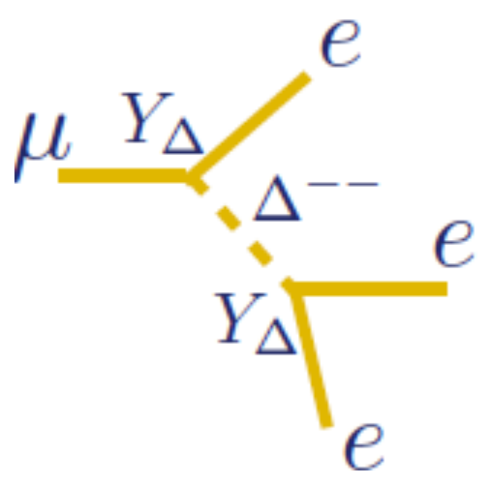
See Ethan Neil's talk

CLFV phenomenology

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

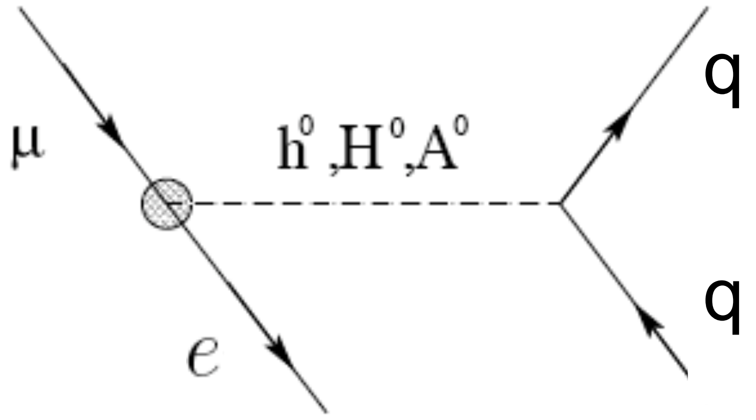


Dipole: SUSY-GUT and SUSY see-saw scenarios, …

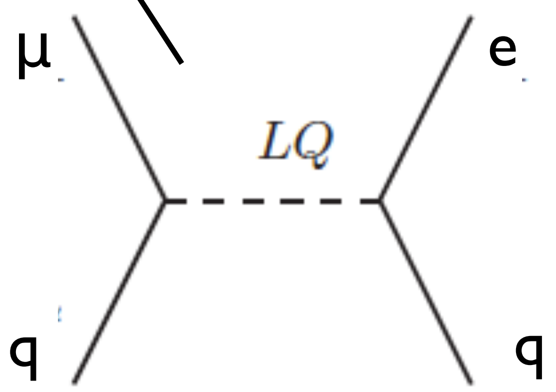


4-lepton: Type II seesaw, RPV SUSY, LRSM, …

...



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



Vector Type III seesaw, LRSM, leptoquarks, …

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

CLFV phenomenology

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

Key features of the underlying physics that we'd like to uncover:

CLFV phenomenology

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

Key features of the underlying physics that we'd like to uncover:

- 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

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

Key features of the underlying physics that we'd like to uncover:

- 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 (and similarly for $\tau \to e,\mu$) ⇒ Mediators, mechanism

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- 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

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- 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

Multiplicity of searches is essential. The EIC can play an important role

LFV @ the EIC?

Experience at HERA → Gonderinger & Ramsey-Musolf, 1006.5063 EIC Yellow Report, 2103.05419 Zhang et al. 2207.10261 …

VC, Kaori Fuyuto, Chris Lee, Emanuele Mereghetti, Bin Yan, 2102.06176

Given the relatively low c.m.s. energy, the discovery potential and diagnosing power of the EIC can be studied in the context of the SMEFT & portals**

** See talks by Kaori Fuyuto and Ethan Neil

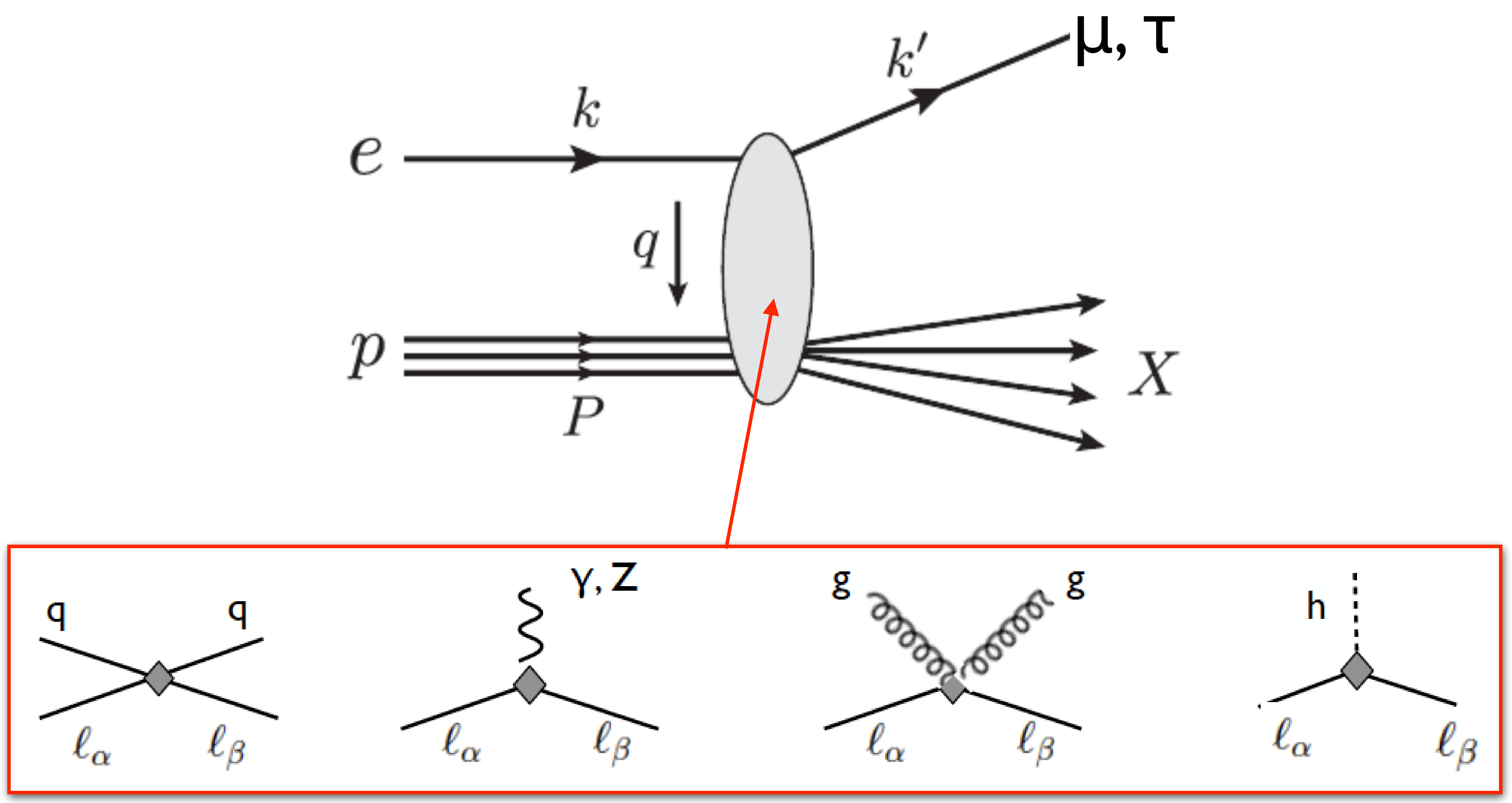
The EIC is an intensity frontier machine!

LFV @ the EIC?

Experience at HERA → Gonderinger & Ramsey-Musolf, 1006.5063 EIC Yellow Report, 2103.05419 Zhang et al. 2207.10261 ...

VC, Kaori Fuyuto, Chris Lee, Emanuele Mereghetti, Bin Yan, 2102.06176

- Here focus on UV physics in the *model-independent* EFT framework ($\sqrt{S} < v_{ew}$)



Leading terms induced by dim-6 operators ~ $1/\Lambda^2$

- Need to compare sensitivity of the EIC and other probes (μ, τ decays,…)

EIC vs decays: 'back of the envelope'

VC, Kaori Fuyuto, Chris Lee, Emanuele Mereghetti, Bin Yan, 2102.06176

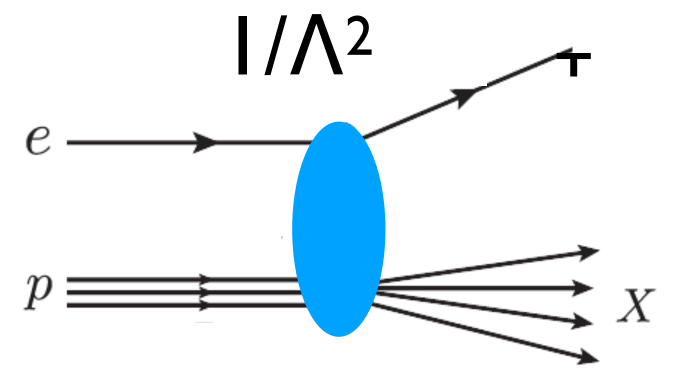
- Number of LFV DIS signal events: $$N_S^{scatt} = \epsilon_s \; \mathcal{L} \; \sigma_{ep \to \ell X}$$

Total signal efficiency: selection cut, reconstruction, detection

Integrated luminosity

- Observing one event requires $$\epsilon_s \mathcal{L} = \frac{\Lambda^4}{\bar{\sigma}(S)}$$

$$\sigma_{ep \to \ell X} = \frac{\bar{\sigma}(S)}{\Lambda^4}$$



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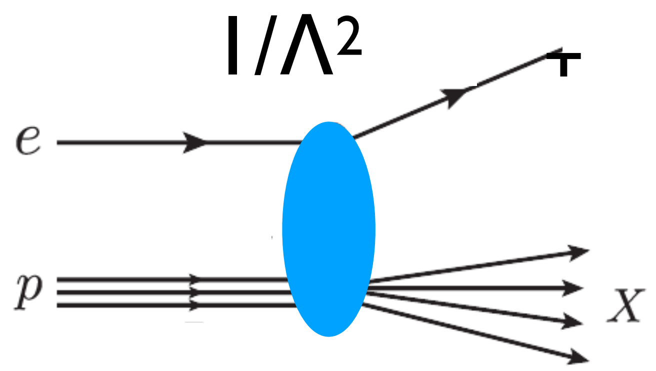
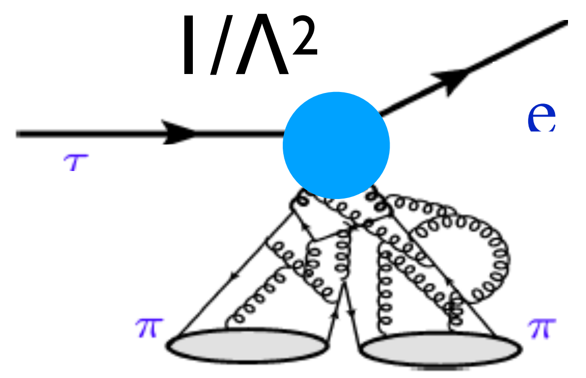


- But scale is constrained by upper limit on BR:

$$\Lambda^4 \geq \frac{\tau_\ell \bar{\Gamma}_\ell}{\mathrm{BR}^{\mathrm{UL}}_{\ell \to eY}}$$

$$\tau_\ell \, \Gamma_{\ell \to eY} \leq \mathrm{BR}^{\mathrm{UL}}_{\ell \to eY}$$

$$\Gamma_{\ell \to eY} = \frac{\bar{\Gamma}_\ell(m_\ell)}{\Lambda^4}$$



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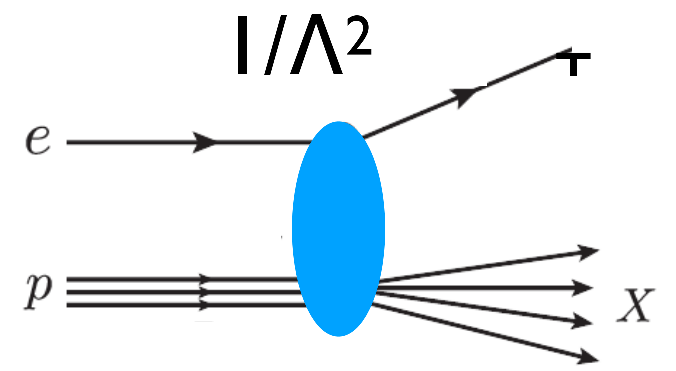

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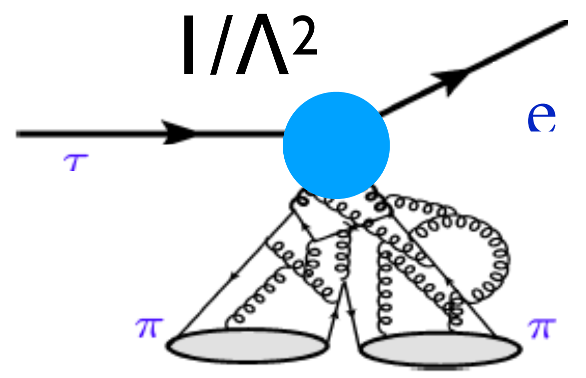


- Requirement on integrated luminosity × efficiency

$$\epsilon_s \, \mathcal{L} \geq \frac{\bar{\Gamma}_\ell}{\bar{\sigma}} \frac{\tau_\ell}{\mathrm{BR}^{\mathrm{UL}}_{\ell\to eY}} = \frac{\Gamma_{\ell\to eY}}{\sigma_{ep\to\ell X}} \frac{\tau_\ell}{\mathrm{BR}^{\mathrm{UL}}_{\ell\to eY}}$$

RHS does not depend on Λ. Uniquely determined if a single BSM operator dominates

EIC vs lepton decays

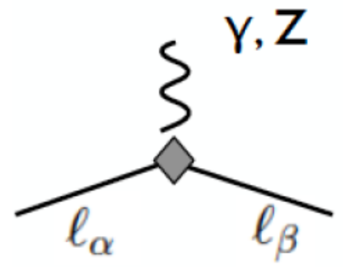
VC, Kaori Fuyuto, Chris Lee, Emanuele Mereghetti, Bin Yan, 2102.06176

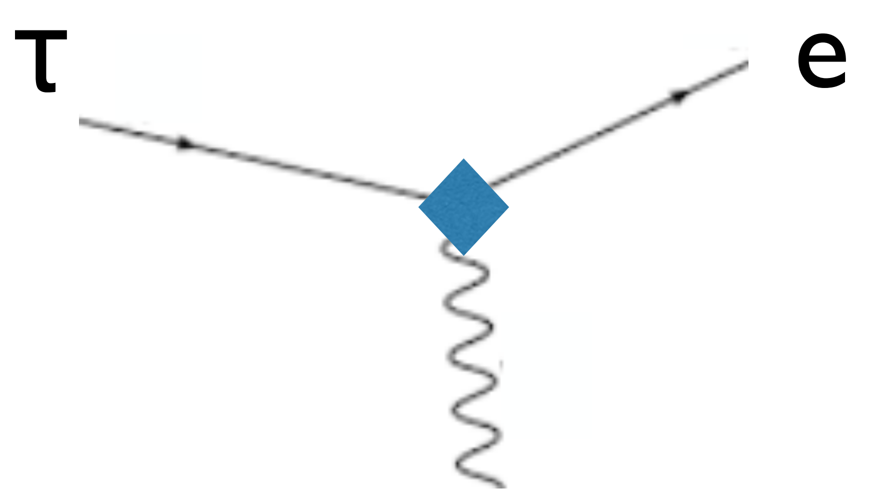
- ‘Back of the envelope’ requirement on integrated luminosity $\times$ efficiency

$$\epsilon_s \, \mathcal{L} \;\geq\; \frac{\Gamma_{\ell \to eY}}{\sigma_{ep \to \ell X}} \times \frac{\tau_\ell}{\mathrm{BR}^{\mathrm{UL}}_{\ell \to eY}}$$

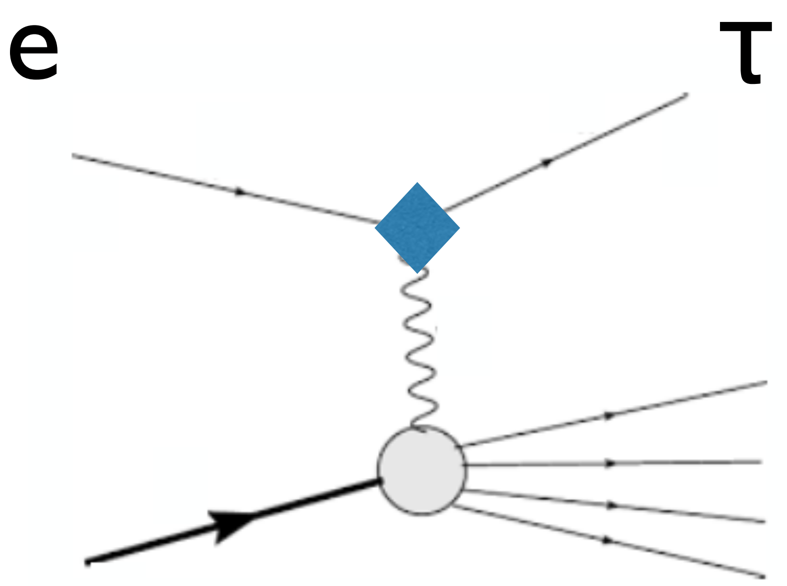
- Selected examples

(assume ~5-10 fb^{-1} / year at EIC)

Dipole		$\frac{\Gamma_{\tau \to e\gamma}}{\sigma_{ep \to \tau X}} = \kappa_D m_\tau^3$	$\epsilon_s \mathcal{L} = 10^8 \, \mathrm{fb}^{-1}$	Prohibitive



$$\Gamma_{\tau \to e\gamma} \sim \frac{v^2 m_\tau^3}{(2\pi)\Lambda^4}$$



$$\sigma_{ep \to \tau X} \sim \frac{v^2}{(2\pi)\Lambda^4}$$

EIC vs lepton decays

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- ‘Back of the envelope’ requirement on integrated luminosity × efficiency

$$\epsilon_s \mathcal{L} \geq \frac{\Gamma_{\ell \to eY}}{\sigma_{ep \to \ell X}} \times \frac{\tau_\ell}{\mathrm{BR}^{\mathrm{UL}}_{\ell \to eY}}$$

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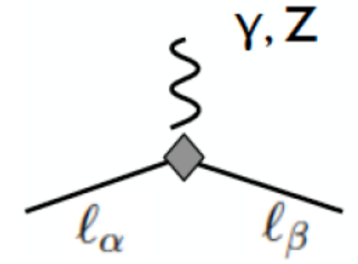
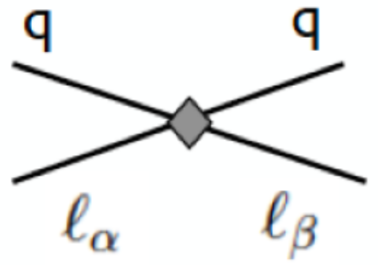
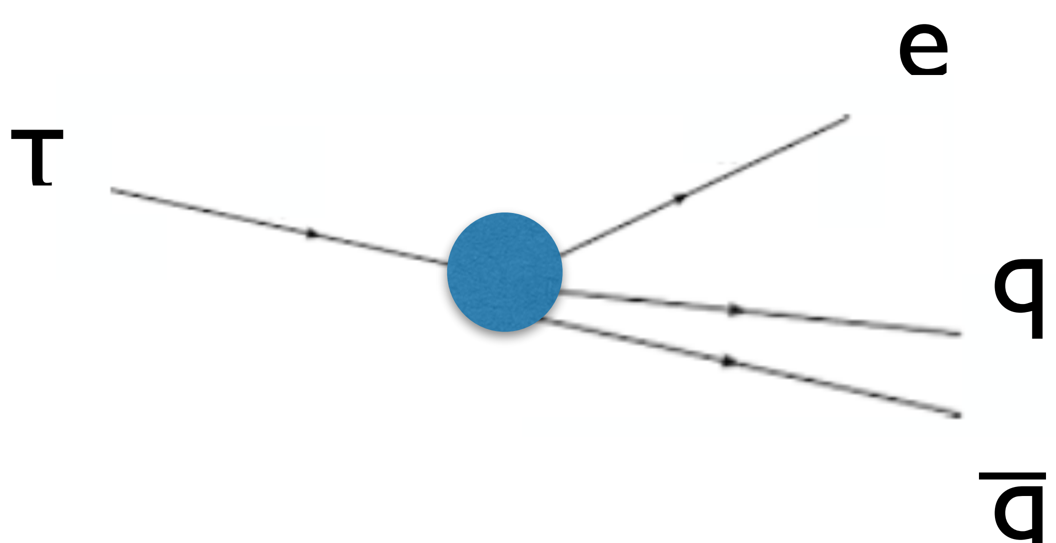
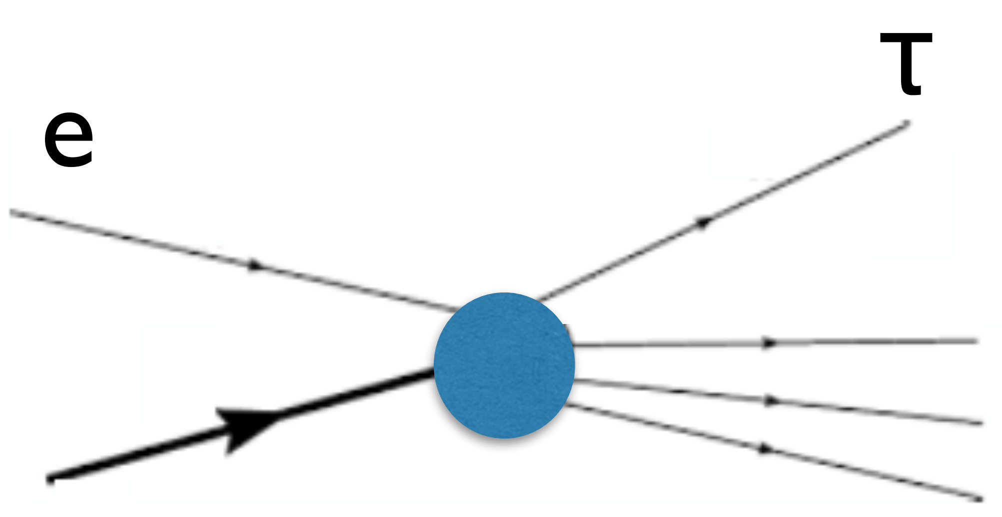
Dipole		$\frac{\Gamma_{\tau \to e\gamma}}{\sigma_{ep \to \tau X}} = \kappa_D m_\tau^3$	$\epsilon_s \mathcal{L} = 10^8 \, \mathrm{fb}^{-1}$	Prohibitive
Light quarks		$\frac{\Gamma_{\tau \to e\pi\pi}}{\sigma_{ep \to \tau X}} = \kappa_{S,V} \frac{m_\tau^5}{(2\pi)^2 S}$	$\epsilon_s \mathcal{L} = 10^3 \, \mathrm{fb}^{-1}$	Borderline



$$\Gamma_{\tau \to e\pi\pi} \sim \frac{m_\tau^5}{(2\pi)^3 \Lambda^4}$$



$$\sigma_{ep \to \tau X} \sim \frac{S}{(2\pi)\Lambda^4}$$

EIC vs lepton decays

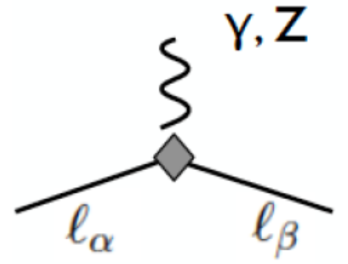
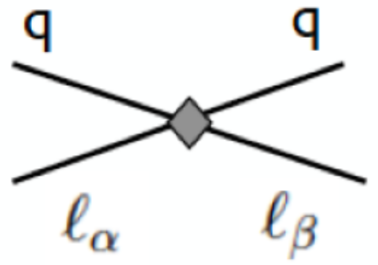
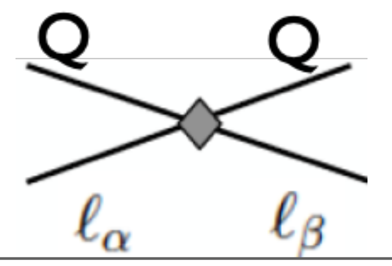
VC, Kaori Fuyuto, Chris Lee, Emanuele Mereghetti, Bin Yan, 2102.06176

- 'Back of the envelope' requirement on integrated luminosity × efficiency

$$\epsilon_s \, \mathcal{L} \; \geq \; \frac{\Gamma_{\ell \to e Y}}{\sigma_{ep \to \ell X}} \times \frac{\tau_\ell}{\mathrm{BR}^{\mathrm{UL}}_{\ell \to e Y}}$$

- Selected examples

(assume ~5-10 fb^{-1} / year at EIC)

Dipole		$\frac{\Gamma_{\tau\to e\gamma}}{\sigma_{ep\to\tau X}} = \kappa_D m_\tau^3$	$\epsilon_s \mathcal{L} = 10^8 \, \mathrm{fb}^{-1}$	Prohibitive
Light quarks		$\frac{\Gamma_{\tau\to e\pi\pi}}{\sigma_{ep\to\tau X}} = \kappa_{S,V} \frac{m_\tau^5}{(2\pi)^2 S}$	$\epsilon_s \mathcal{L} = 10^3 \, \mathrm{fb}^{-1}$	Borderline
Heavy quarks		$\frac{\Gamma_{\tau\to e\pi\pi}}{\sigma_{ep\to\tau X_Q}} \sim 10^{-4} \frac{m_\tau^5}{(2\pi)^2 S}$	$\epsilon_s \mathcal{L} = 0.1 \, \mathrm{fb}^{-1}$	Very competitive!

Suppression factors in the cross section (due to PDF) and decay rate (due to loop) differ by orders of magnitude

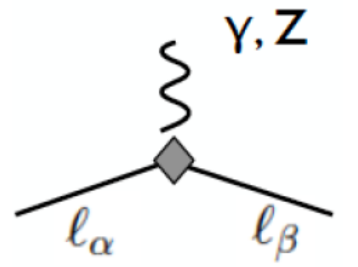
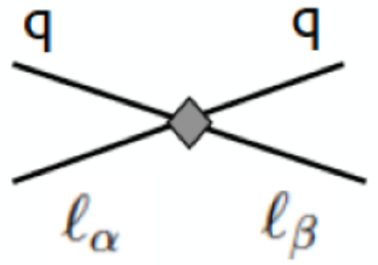
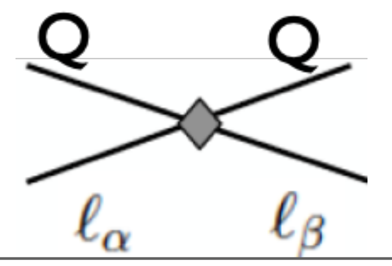
EIC vs lepton decays

VC, Kaori Fuyuto, Chris Lee, Emanuele Mereghetti, Bin Yan, 2102.06176

- 'Back of the envelope' requirement on integrated luminosity × efficiency

$$\epsilon_s \mathcal{L} \geq \frac{\Gamma_{\ell \to eY}}{\sigma_{ep \to \ell X}} \times \frac{\tau_\ell}{\mathrm{BR}^{\mathrm{UL}}_{\ell \to eY}}$$

- Selected examples

Dipole		$\frac{\Gamma_{\tau \to e\gamma}}{\sigma_{ep \to \tau X}} = \kappa_D m_\tau^3$	$\epsilon_s \mathcal{L} = 10^8\,\mathrm{fb}^{-1}$	Prohibitive
Light quarks		$\frac{\Gamma_{\tau \to e\pi\pi}}{\sigma_{ep \to \tau X}} = \kappa_{S,V} \frac{m_\tau^5}{(2\pi)^2 S}$	$\epsilon_s \mathcal{L} = 10^3\,\mathrm{fb}^{-1}$	Borderline
Heavy quarks		$\frac{\Gamma_{\tau \to e\pi\pi}}{\sigma_{ep \to \tau X_Q}} \sim 10^{-4} \frac{m_\tau^5}{(2\pi)^2 S}$	$\epsilon_s \mathcal{L} = 0.1\,\mathrm{fb}^{-1}$	Very competitive!

(For e → μ transitions $\varepsilon\mathcal{L}$ gets larger…)

EIC vs lepton decays

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- If one ‘turns on’ multiple SMEFT effective couplings, then the requirements for the EIC luminosity and efficiency become less stringent due to possible cancellations in the numerator of this ratio

$$\frac{\Gamma_{\ell \to eY}}{\sigma_{ep \to \ell X}}$$

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$$\frac{\Gamma_{\ell\to eY}}{\sigma_{ep\to \ell X}}$$

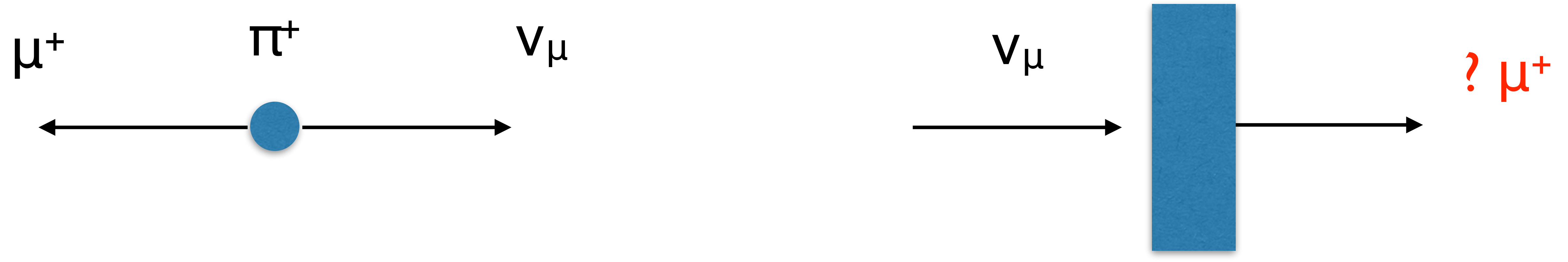
These rough dimensional analysis estimates are confirmed by explicit calculation.
Highest discovery potential in heavy quark operators.
In presence of multiple operators the EIC plays a key role in constraining ‘flat directions’.

See talk by K. Fuyuto

Lepton Number Violation

Are neutrinos Dirac or Majorana?

- Simple test (B. Kayser): generate ν beam from $\pi^+ \to \mu^+ \nu_\mu$ and check whether it produces μ^+ on a target downstream



A Dirac neutrino won't do that.
A Majorana neutrino with helicity=+1 ($\nu(R)=\nu_+$) will produce μ^+.
But fraction of $\nu(R)=\nu_+$ produced in $\pi^+ \to \mu^+ \nu_\mu$ is $\sim(m_\nu/E_\nu)^2 < 10^{-16}$!!

Smallness of ν mass and V-A nature of the weak interactions imply that

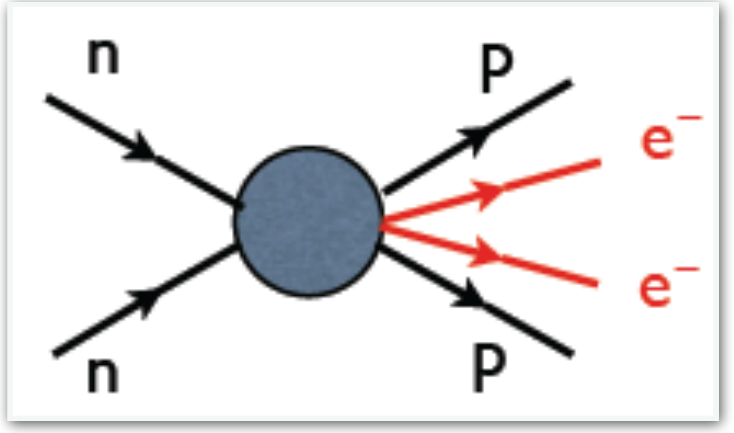
Neutrinoless probes of $\Delta L=2$ dynamics are our best bet!

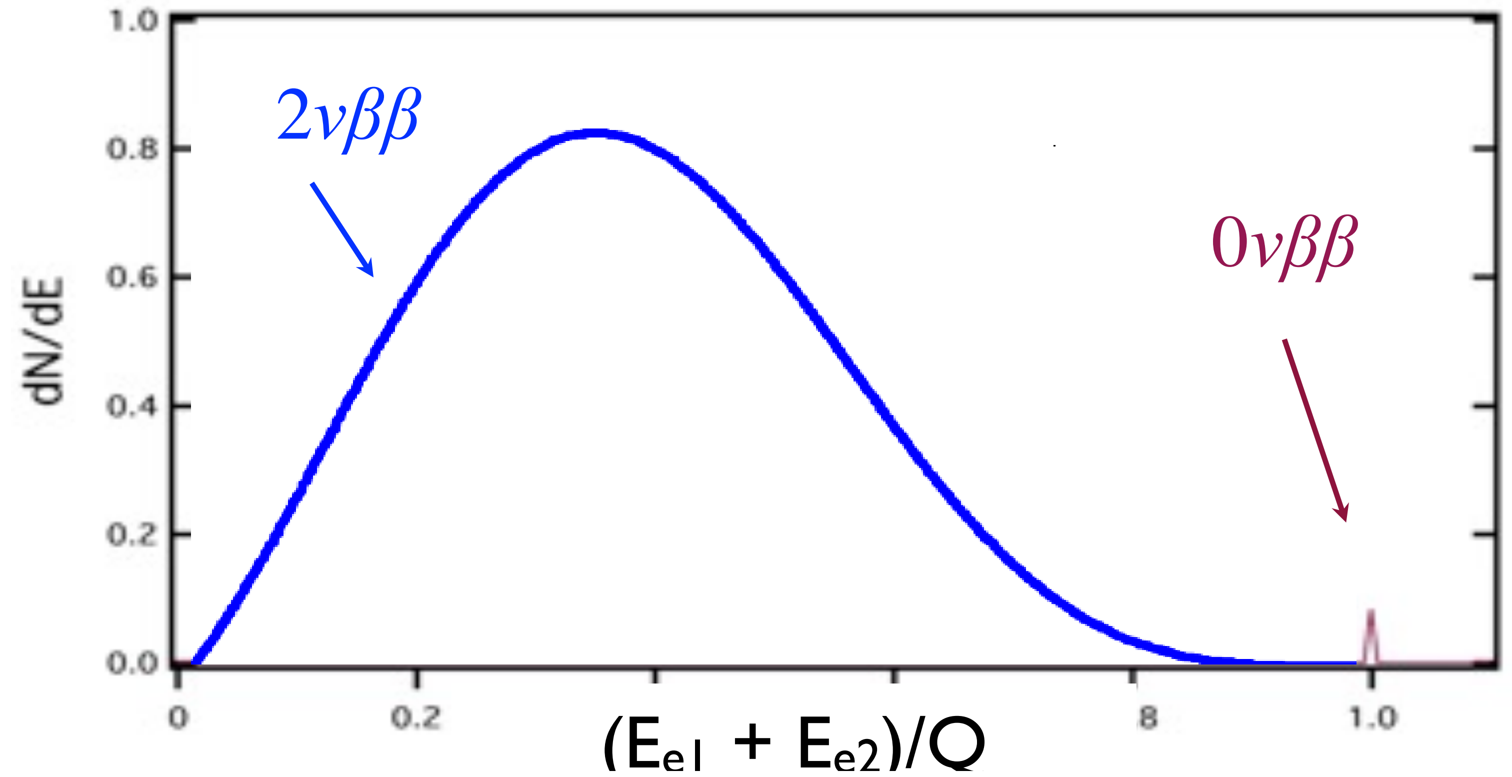
ΔL=2 neutrinoless processes

- Neutrinoless double beta decay

$$(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$$

$$T_{1/2} > \# 10^{25}\text{yr}$$





Potentially observable only in certain even-even nuclei (^{76}Ge, ^{100}Mo, ^{136}Xe, …) for which single beta decay is energetically forbidden

Observation ⇒ BSM physics with far reaching implications

Demonstrate Majorana nature of massive neutrinos (neutrino=antineutrino)

Demonstrate that an excess of matter over antimatter can be created in an elementary process, pointing to an explanation of the baryon asymmetry in the universe

ΔL=2 neutrinoless processes

- Neutrinoless double beta decay $(N,Z) \to (N-2, Z+2) + e^- + e^-$ $T_{1/2} > \# 10^{25}\text{yr}$

- Meson and charged lepton decays & collider processes

$K^+ \to \pi^- \ell_1^+ \ell_2^+$ $\ell_{1,2} = e, \mu$

$B^+ \to h^- \ell_1^+ \ell_2^+$ $h = \pi, K$ $\ell_{1,2} = e, \mu$

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

$\tau^- \to \ell^+ h_1^- h_2^-$

$\ell = e, \mu$ $h_{1,2} = \pi, K$

Same sign di-leptons @ the LHC

$pp \to \ell\ell + 2 \text{ jets}$

$\ell = e, \mu, \tau$

Flavorful LNV DIS @ the EIC ?

$e^- p \to \ell^+ + X$

$\ell = e, \mu, \tau$

BR (K) ~ 10^{-10} BR (B) ~ 10^{-8} BR (μ) ~ 10^{-13} BR (τ) ~ 10^{-8}

ΔL=2 neutrionless processes

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Flavorful LNV DIS @ the EIC ?

$e^- p \to \ell^+ + X$

$\ell = e, \mu, \tau$

BR (K) ~ 10^{-10} BR (B) ~ 10^{-8} BR (μ) ~ 10^{-13} BR (τ) ~ 10^{-8}

Among (e^-e^-) ΔL=2 *neutrinoless* processes 0νββ decay is generically the strongest probe — "Avogadro's number wins"(P. Vogel)

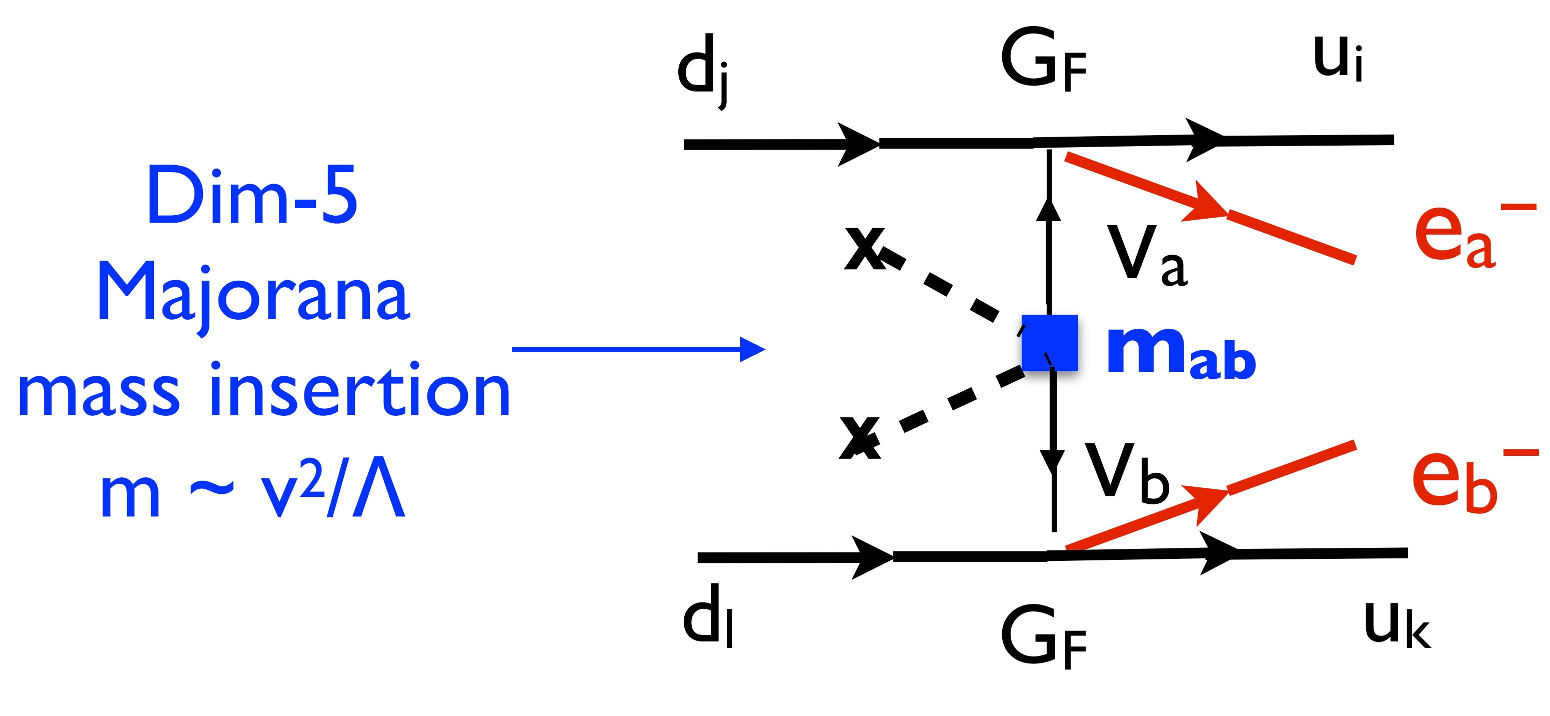
But in certain scenarios other probes can compete and give access to flavorful LNV

LNV @ the EIC?

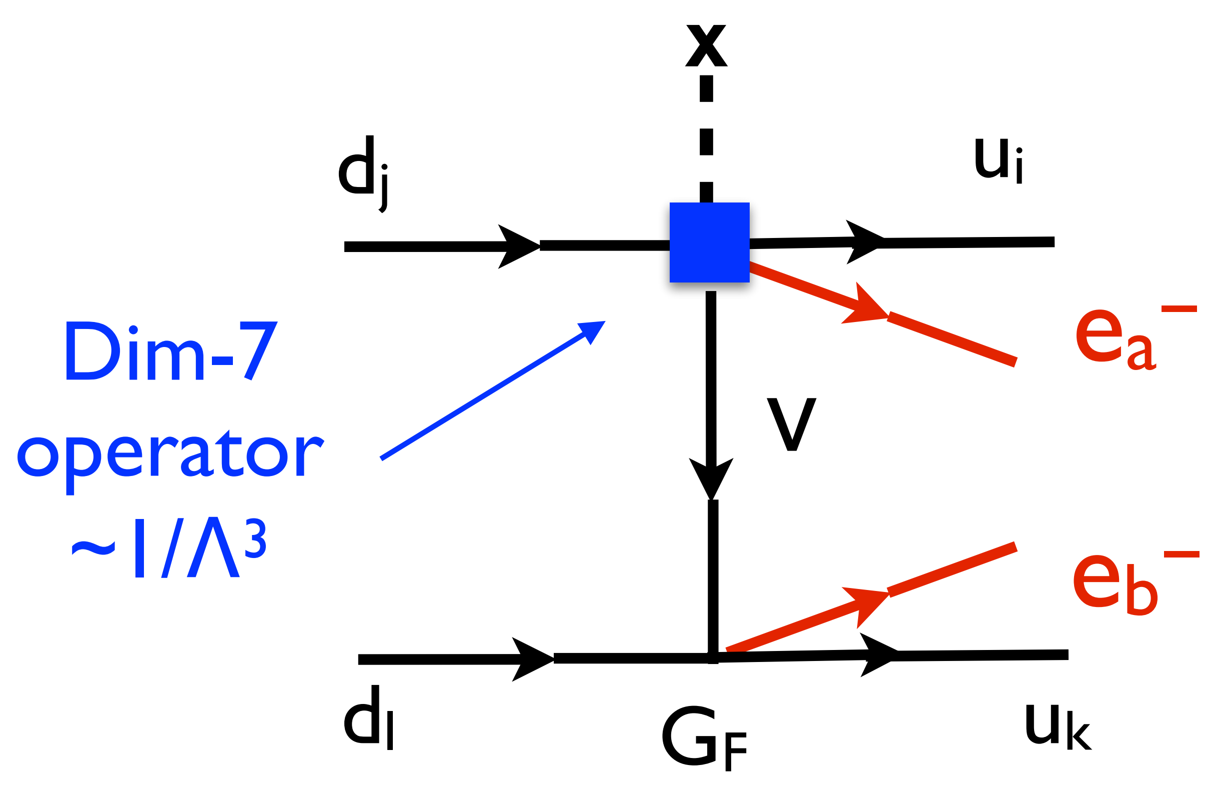
Unpublished work done in collaboration with Kaori Fuyuto and Emanuele Mereghetti

- Use general frameworks: SMEFT and 'neutrino portal' (SM $+\nu_R$) **See talk by Tao Han**

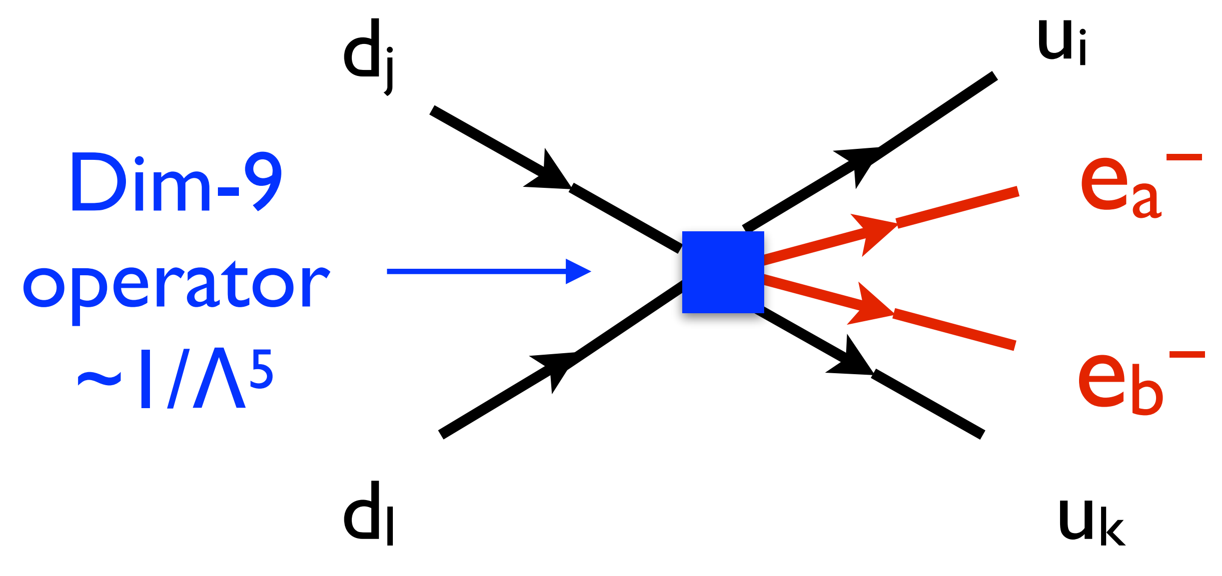
- ΔL=2 operators appear in SMEFT at d=5, 7, 9 , … ⇒ Generate effective vertices $\bar{u}_i \Gamma d_j \, \bar{u}_k \Gamma d_l \bar{e}_a e_b^c$



$(LH)(LH)$



$LHQ\bar{d}H$



$\bar{Q}Q\bar{u}d\bar{L}L^c$

LNV @ the EIC?

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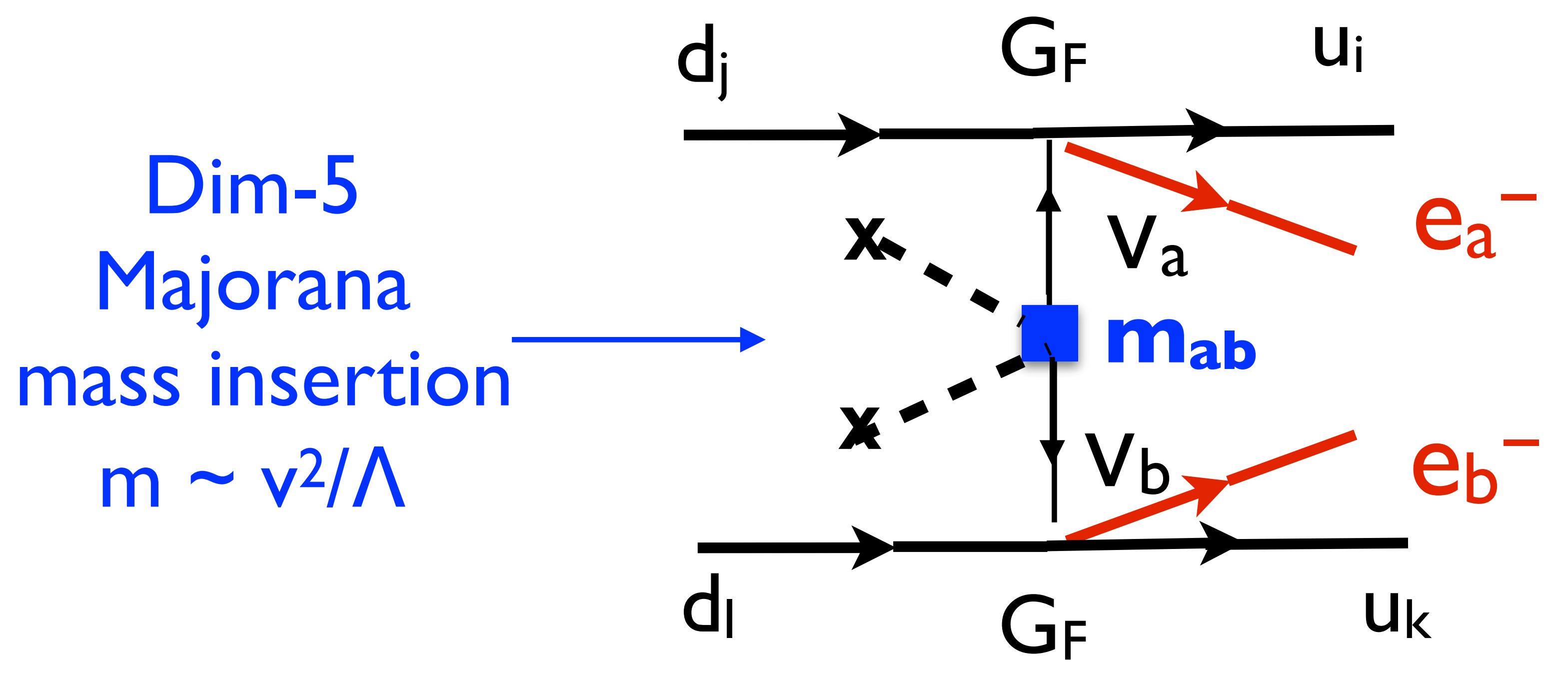
- $\Delta L=2$ operators appear in SMEFT at d=5, 7, 9 , … $\Rightarrow$ Generate effective vertices $\bar{u}_i \Gamma d_j \, \bar{u}_k \Gamma d_l \bar{e}_a e^c_b$



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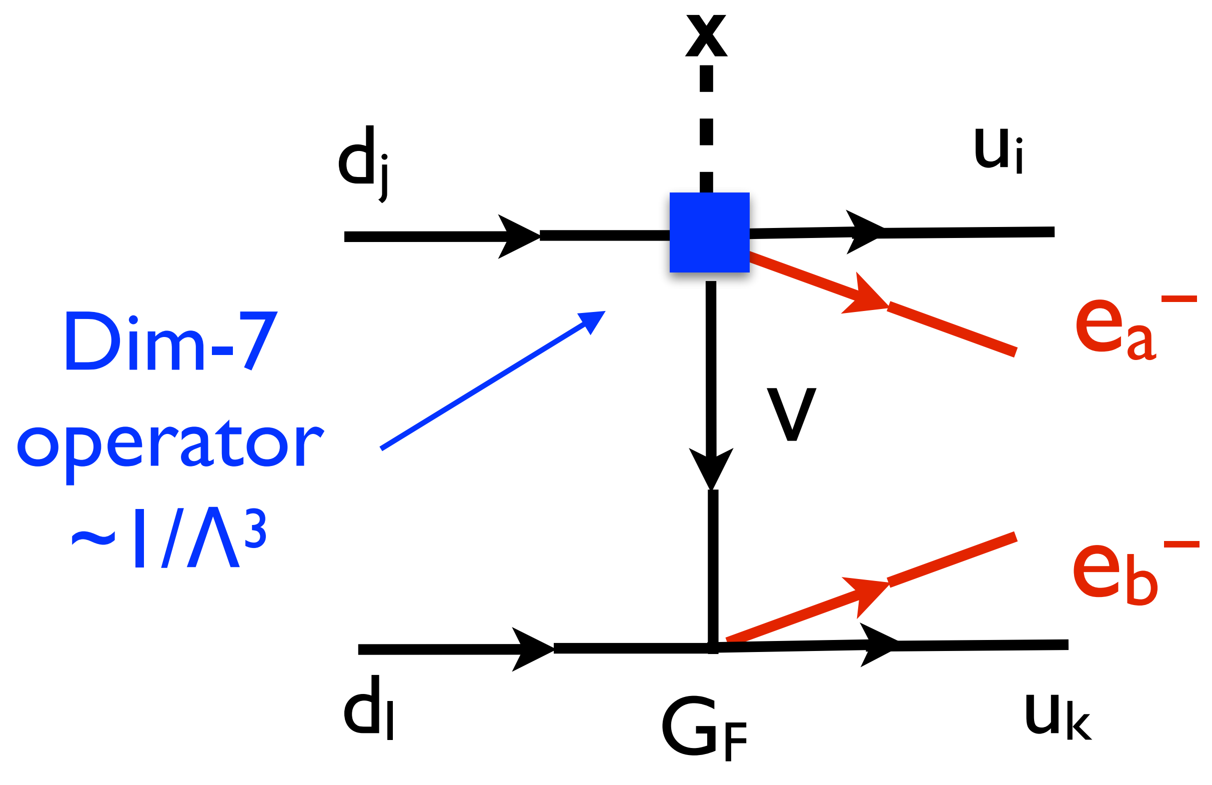
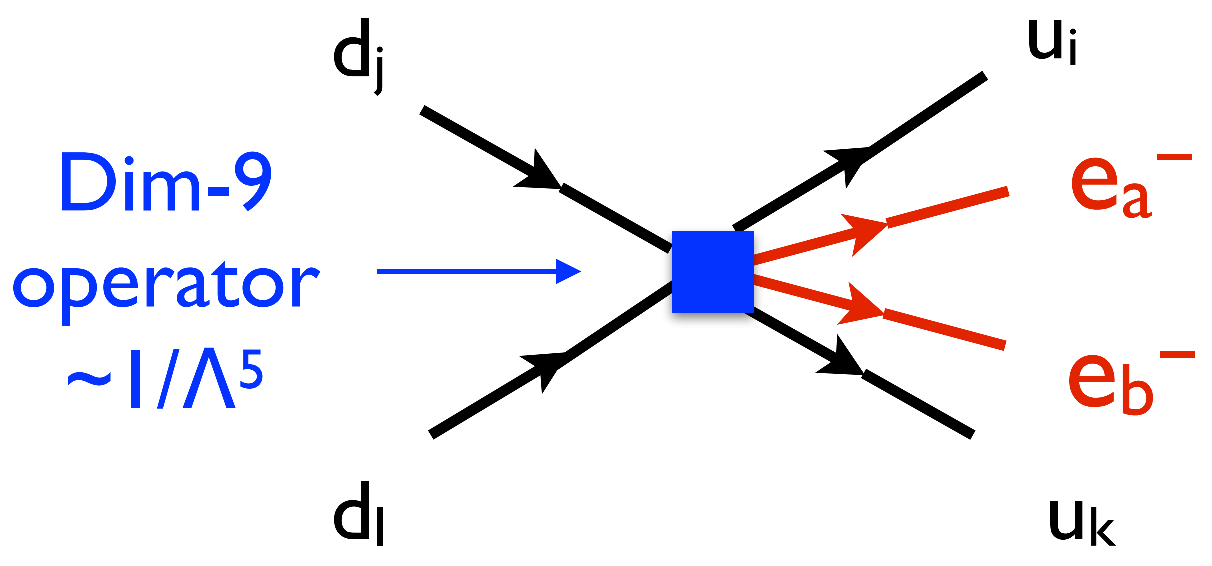


$LHQ\bar{d}H$

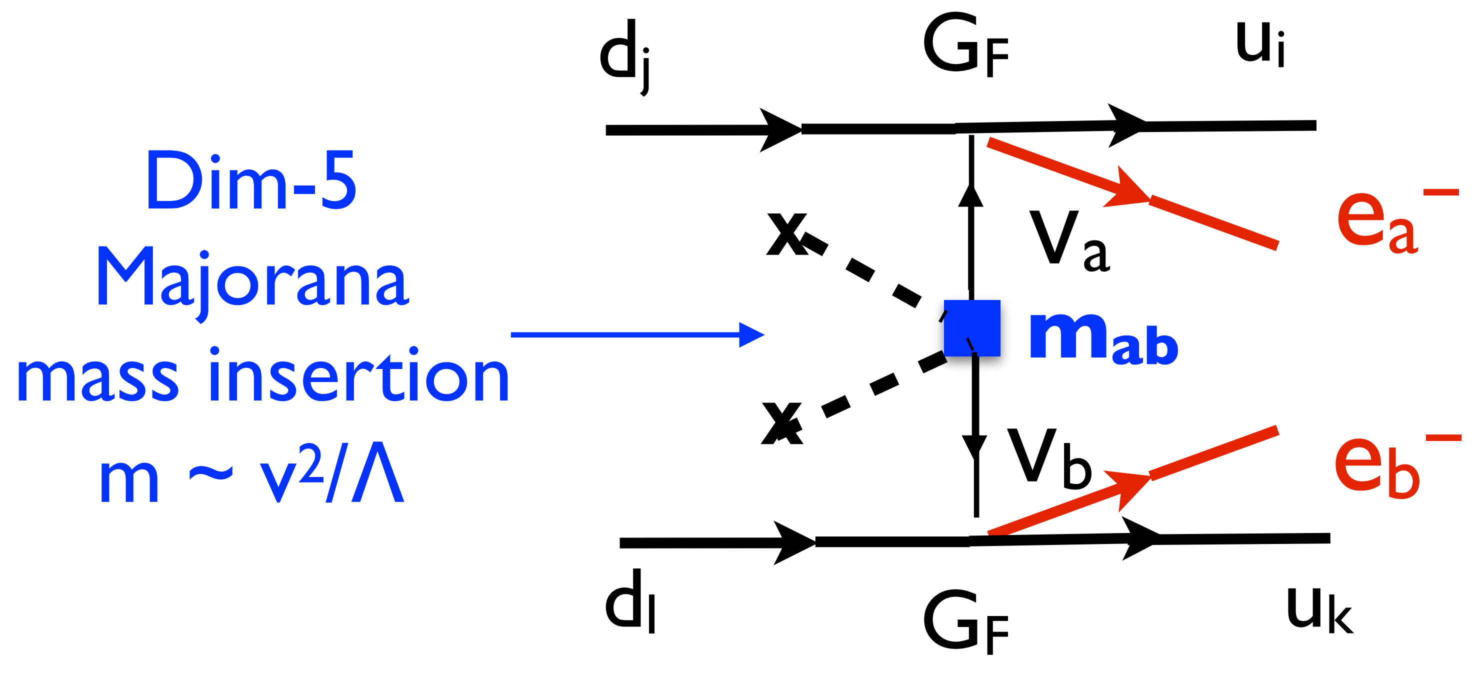


$\bar{Q}Q\bar{u}d\bar{L}L^c$

- To assess sensitivity, consider the following processes: $e^- p \to \ell^+ + 3 \text{ jets}$ vs $\mu^- A \to e^+ A'$, $\tau^- \to \ell^+ \pi^- \pi^-$

EIC vs other probes: dim-5

- ‘Back of the envelope’ estimate (with $\Lambda^4 \rightarrow \Lambda^{2(d-4)}$)



$(LH)(LH)$

$$e^- p \to \ell^+ + 3 \text{ jets}$$

$$\sigma \sim \frac{1}{(2\pi)^5} \frac{m_{e\ell}^2 S^2}{v^8}$$

Berryman, deGouvea, Kelly, Kobach 1611.00032

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

$$\Gamma_\mu \sim \frac{1}{(2\pi)} \frac{m_{e\mu}^2 Q^7}{v^8} (\alpha Z)^3$$

$$Q \sim m_\mu$$

Atre, Barger, Han hep-ph/0502163

Liao, Ma, Wang 2102.03491

$$\tau^- \to \ell^+ \pi^- \pi^-$$

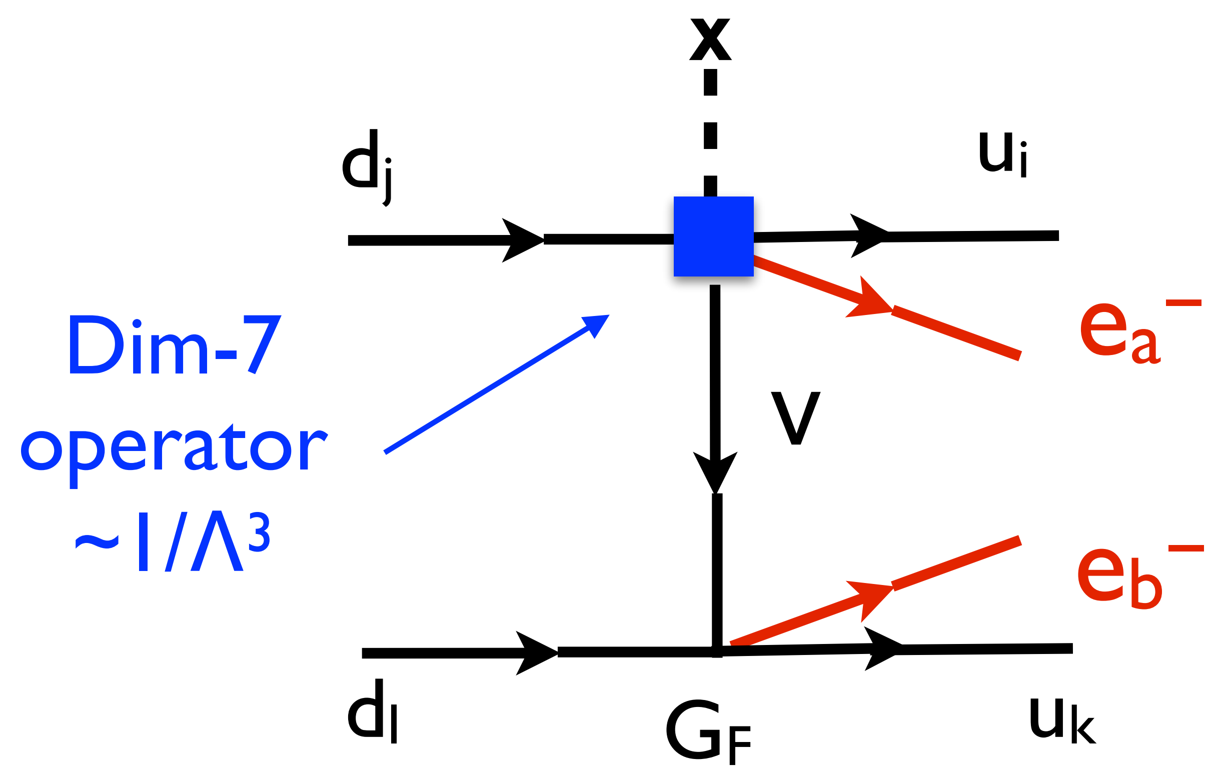
$$\Gamma_\tau \sim \frac{1}{(2\pi)^3} \frac{m_{e\tau}^2 Q^4 m_\tau^3}{v^8}$$

$$Q \sim \Lambda_{\rm QCD}$$

- Both EIC and rare decays probe ‘uninteresting’ regime
- For example $\sigma \sim 1 \text{fb}^{-1}$ for $m_{e\mu} \sim m_{e\tau} \sim 10$ GeV (but we know that $m_{e\mu} \sim m_{e\tau} \sim m_{ee}$ < eV)

EIC vs other probes: dim-7

- ‘Back of the envelope’ estimate (with $\Lambda^4 \rightarrow \Lambda^{2(d-4)}$)



$LHQ\bar{d}H$

$$e^- p \rightarrow \ell^+ + 3 \text{ jets}$$

$$\sigma \sim \frac{1}{(2\pi)^5} \frac{v^2 S}{\Lambda^6}$$

Berryman, deGouvea, Kelly, Kobach 1611.00032

$$\mu^- A \rightarrow e^+ A'$$

$$\Gamma_\mu \sim \frac{1}{(2\pi)} \frac{Q^9}{v^2 \Lambda^6} (\alpha Z)^3$$

$$Q \sim m_\mu$$

$$\epsilon_{\rm coll} \mathcal{L}^{D=7}_{e\mu} \sim 10^{-2}\ \text{fb}^{-1}$$

Atre, Barger, Han hep-ph/0502163

Liao, Ma, Wang 2102.03491

$$\tau^- \rightarrow \ell^+ \pi^- \pi^-$$

$$\Gamma_\tau \sim \frac{1}{(2\pi)^3} \frac{m_\tau^3 Q^6}{v^2 \Lambda^6}$$

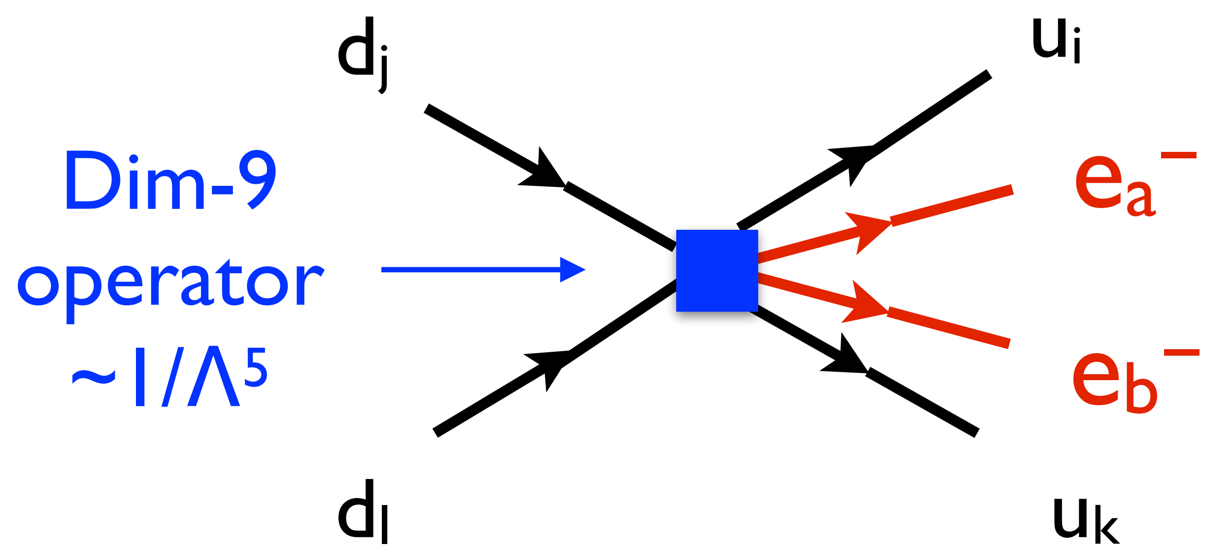
$$Q \sim \Lambda_{\rm QCD}$$

$$\epsilon_{\rm coll} \mathcal{L}^{D=7}_{e\tau} \sim 10^{-3}\ \text{fb}^{-1}$$

- EIC competitive!
- It probes relatively low scale LNV: $\sigma \sim 1\text{fb}^{-1}$ for $\Lambda \sim 500$ GeV

EIC vs other probes: dim-9

- 'Back of the envelope' estimate (with $\Lambda^4 \rightarrow \Lambda^{2(d-4)}$)



$$\bar{Q}Q\bar{u}d\bar{L}L^c$$

$$e^- p \rightarrow \ell^+ + 3 \text{ jets}$$

$$\sigma \sim \frac{1}{(2\pi)^5} \frac{S^4}{\Lambda^{10}}$$

Berryman, deGouvea, Kelly, Kobach 1611.00032

$$\mu^- A \rightarrow e^+ A'$$

$$\Gamma_\mu \sim \frac{1}{(2\pi)} \frac{Q^{11}}{\Lambda^{10}} (\alpha Z)^3$$

$$Q \sim m_\mu$$

$$\epsilon_{\rm coll} \mathcal{L}_{e\mu}^{D=9} \sim 2 \times 10^{-7}\, \text{fb}^{-1}$$

Atre, Barger, Han hep-ph/0502163

Liao, Ma, Wang 2102.03491

$$\tau^- \rightarrow \ell^+ \pi^- \pi^-$$

$$\Gamma_\tau \sim \frac{1}{(2\pi)^3} \frac{m_\tau^3 Q^8}{\Lambda^{10}}$$

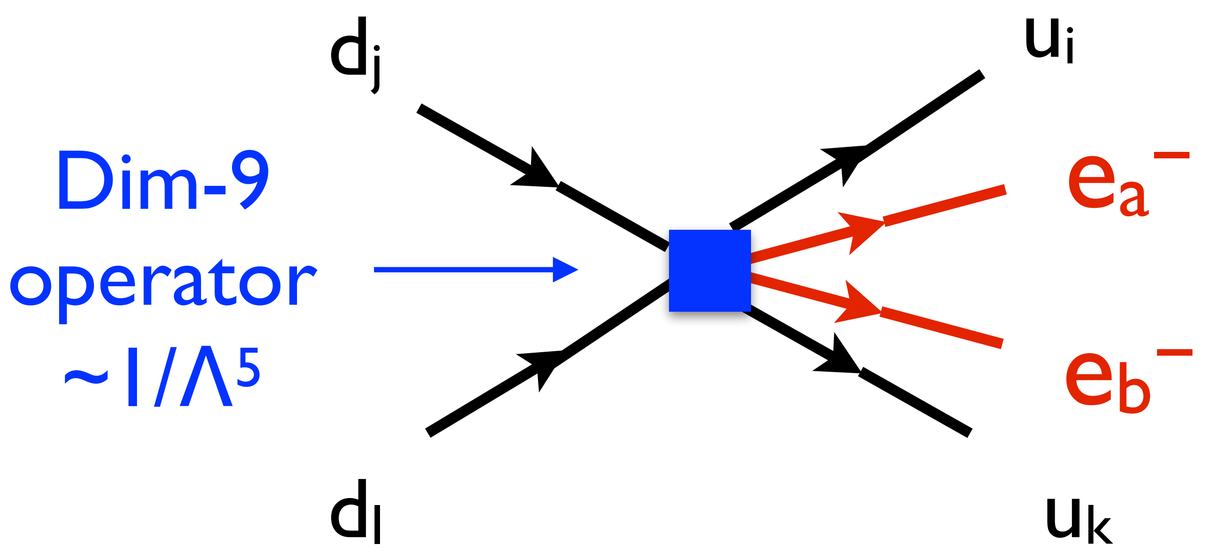
$$Q \sim \Lambda_{\rm QCD}$$

$$\epsilon_{\rm coll} \mathcal{L}_{e\tau}^{D=9} \sim 2 \times 10^{-6}\, \text{fb}^{-1}$$

- EIC competitive!
- It probes low scale LNV: $\sigma \sim 1\,\text{fb}^{-1}$ for $\Lambda \sim$ 100-200 GeV

EIC vs other probes: dim-9

- 'Back of the envelope' estimate (with $\Lambda^4 \rightarrow \Lambda^{2(d-4)}$)



$\bar{Q}Q\bar{u}d\bar{L}L^c$

$$e^- p \rightarrow \ell^+ + 3 \text{ jets}$$

$$\sigma \sim \frac{1}{(2\pi)^5} \frac{S^4}{\Lambda^{10}}$$

Berryman, deGouvea, Kelly, Kobach 1611.00032

$$\mu^- A \rightarrow e^+ A'$$

$$\Gamma_\mu \sim \frac{1}{(2\pi)} \frac{Q^{11}}{\Lambda^{10}} (\alpha Z)^3$$

$$Q \sim m_\mu$$

$$\epsilon_{\rm coll} \mathcal{L}_{e\mu}^{D=9} \sim 2 \times 10^{-7} \, {\rm fb}^{-1}$$

Atre, Barger, Han hep-ph/0502163

Liao, Ma, Wang 2102.03491

$$\tau^- \rightarrow \ell^+ \pi^- \pi^-$$

$$\Gamma_\tau \sim \frac{1}{(2\pi)^3} \frac{m_\tau^3 Q^8}{\Lambda^{10}}$$

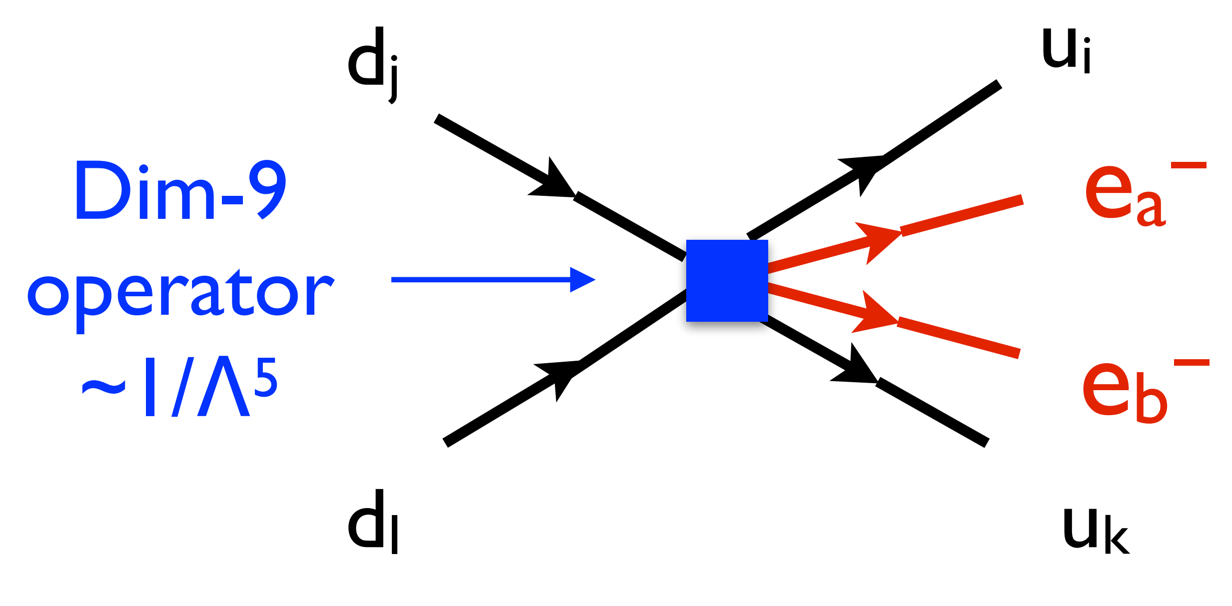
$$Q \sim \Lambda_{\rm QCD}$$

$$\epsilon_{\rm coll} \mathcal{L}_{e\tau}^{D=9} \sim 2 \times 10^{-6} \, {\rm fb}^{-1}$$

- Caveats:
  - Large uncertainty due to high power of scale Q associated with non-perturbative QCD effects
  - Given low scale Λ, EFT analysis should be taken with a grain of salt

EIC vs other probes: dim-9

- 'Back of the envelope' estimate (with $\Lambda^4 \to \Lambda^{2(d-4)}$)



$\bar{Q}Q\bar{u}d\bar{L}L^c$

$$e^- p \to \ell^+ + 3 \text{ jets}$$

$$\sigma \sim \frac{1}{(2\pi)^5} \frac{S^4}{\Lambda^{10}}$$

Berryman, deGouvea, Kelly, Kobach 1611.00032

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

$$\Gamma_\mu \sim \frac{1}{(2\pi)} \frac{Q^{11}}{\Lambda^{10}} (\alpha Z)^3$$

$$Q \sim m_\mu$$

$$\epsilon_{\rm coll} \mathcal{L}^{D=9}_{e\mu} \sim 2 \times 10^{-7} \text{ fb}^{-1}$$

Atre, Barger, Han hep-ph/0502163

Liao, Ma, Wang 2102.03491

$$\tau^- \to \ell^+ \pi^- \pi^-$$

$$\Gamma_\tau \sim \frac{1}{(2\pi)^3} \frac{m_\tau^3 Q^8}{\Lambda^{10}}$$

$$Q \sim \Lambda_{\rm QCD}$$

$$\epsilon_{\rm coll} \mathcal{L}^{D=9}_{e\tau} \sim 2 \times 10^{-6} \text{ fb}^{-1}$$

- These rough estimates suggest that the EIC can be very competitive in probing 'flavorful' LNV

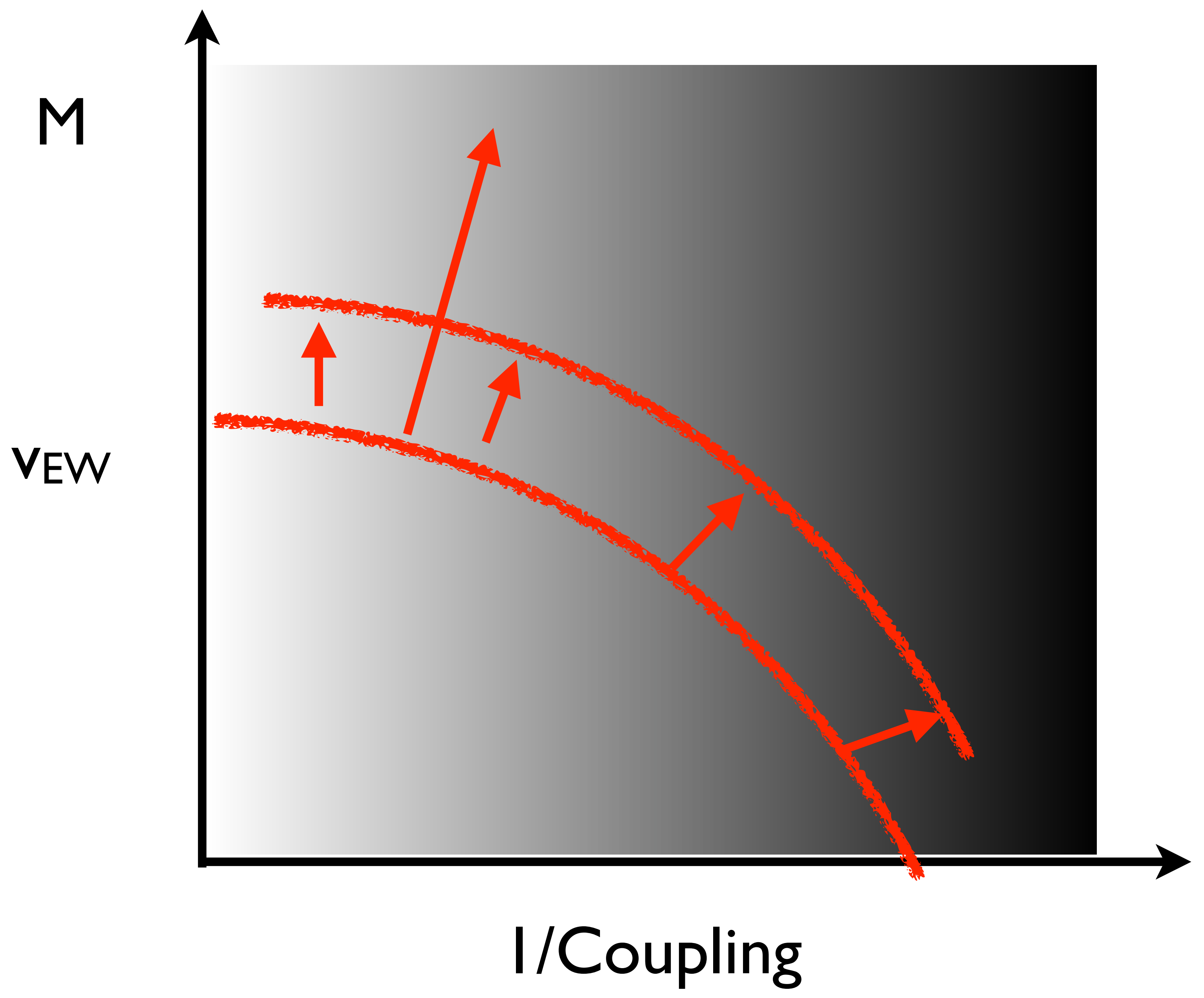
  Motivates a real study (beyond dimensional analysis) both for low-energy probes and EIC signatures

Conclusions and outlook

- Vibrant experimental & theoretical activity exploring BSM physics at the precision / intensity frontier

- Shed light on open questions, complementary to high-E searches. Illustrated impact through two examples:

    - Charged lepton flavor violation
    - Lepton number violation



- The EIC will play a role in this exciting endeavor

    - Model independent dimensional analysis considerations suggest that the EIC can probe uncharted territory in LFV and flavorful LNV
    - More work needed on theory / simulation / detector development