Snowmass Community Summer Study Workshop
July 21 2022, Seattle

Searching for New Physics with Rare Processes and Precision Measurements

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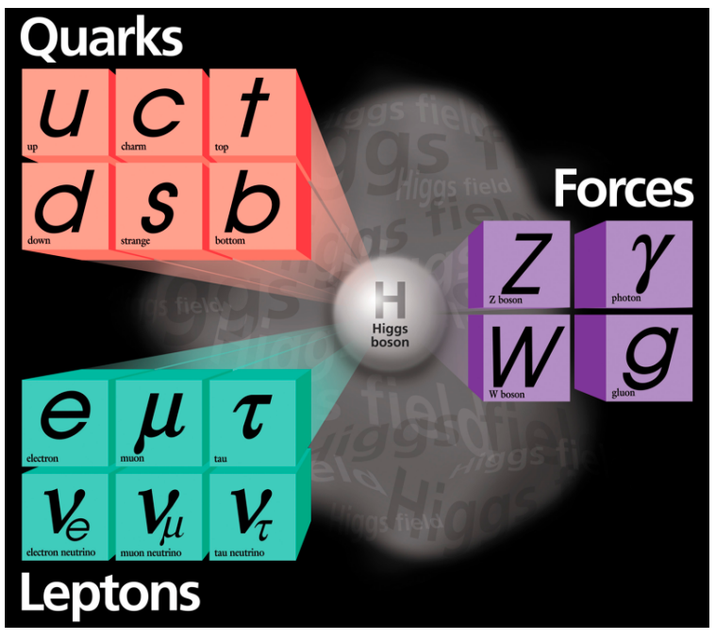
University of Washington

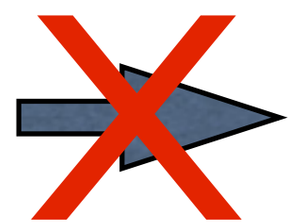
Outline

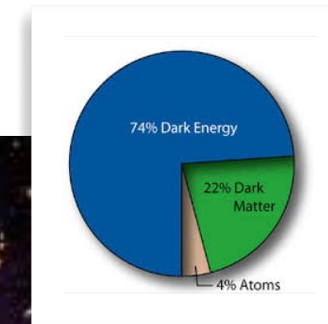
- Theory overview of Rare Processes & Precision Measurements
- Three "short tales"
  - $0\nu\beta\beta$ and the nature of neutrino mass
  - Probing Lepton Flavor Violation with charged leptons
  - Probing Cabibbo & lepton universality with light quarks

New physics: why?

- The SM is remarkably successful, but it's not the whole story





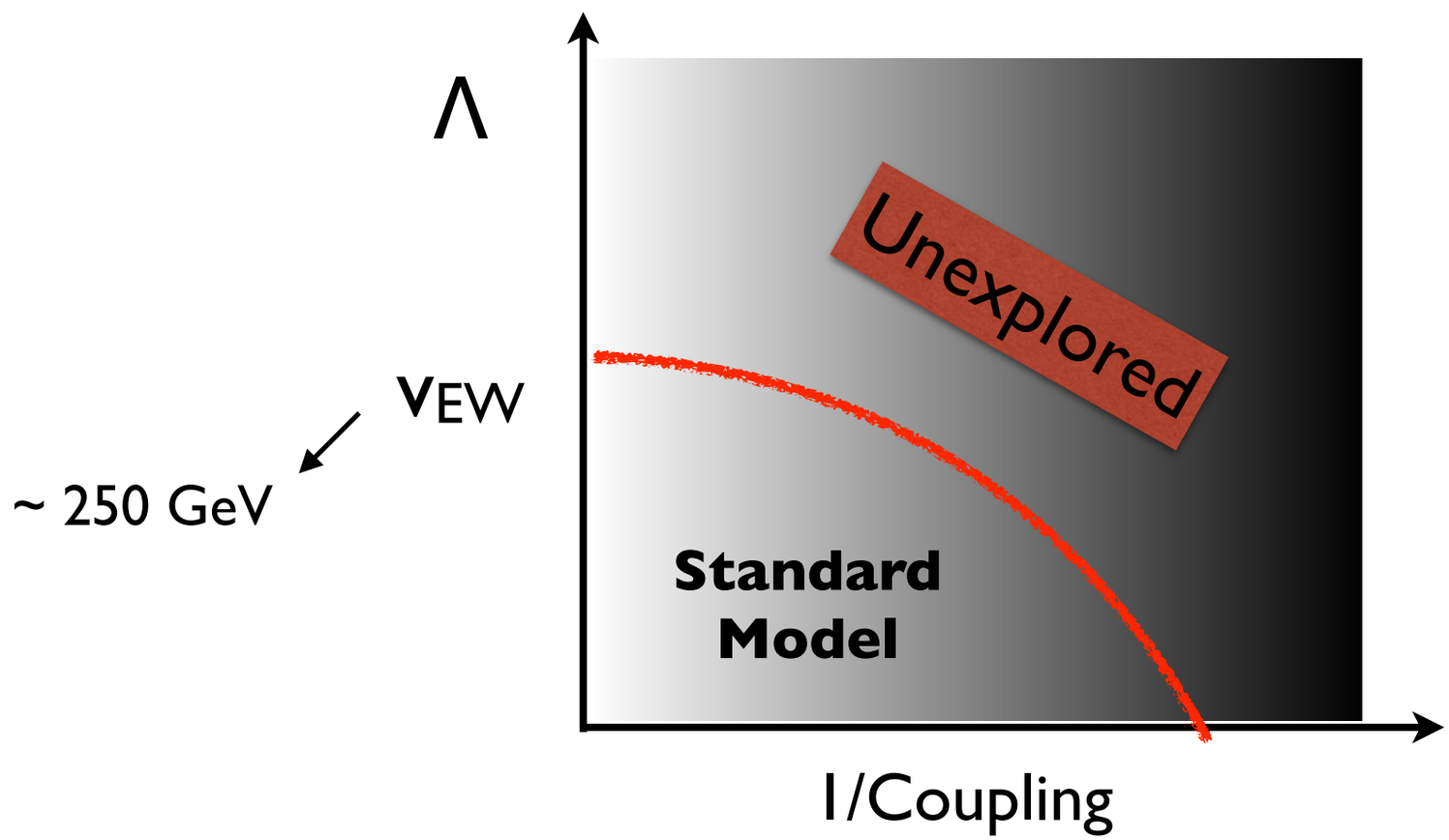


No Baryon Asymmetry, no Dark Matter, no Dark Energy, no Neutrino Mass
Origin of flavor, Strong CP problem, Higgs naturalness, Unification,…

Addressing these puzzles requires new physics

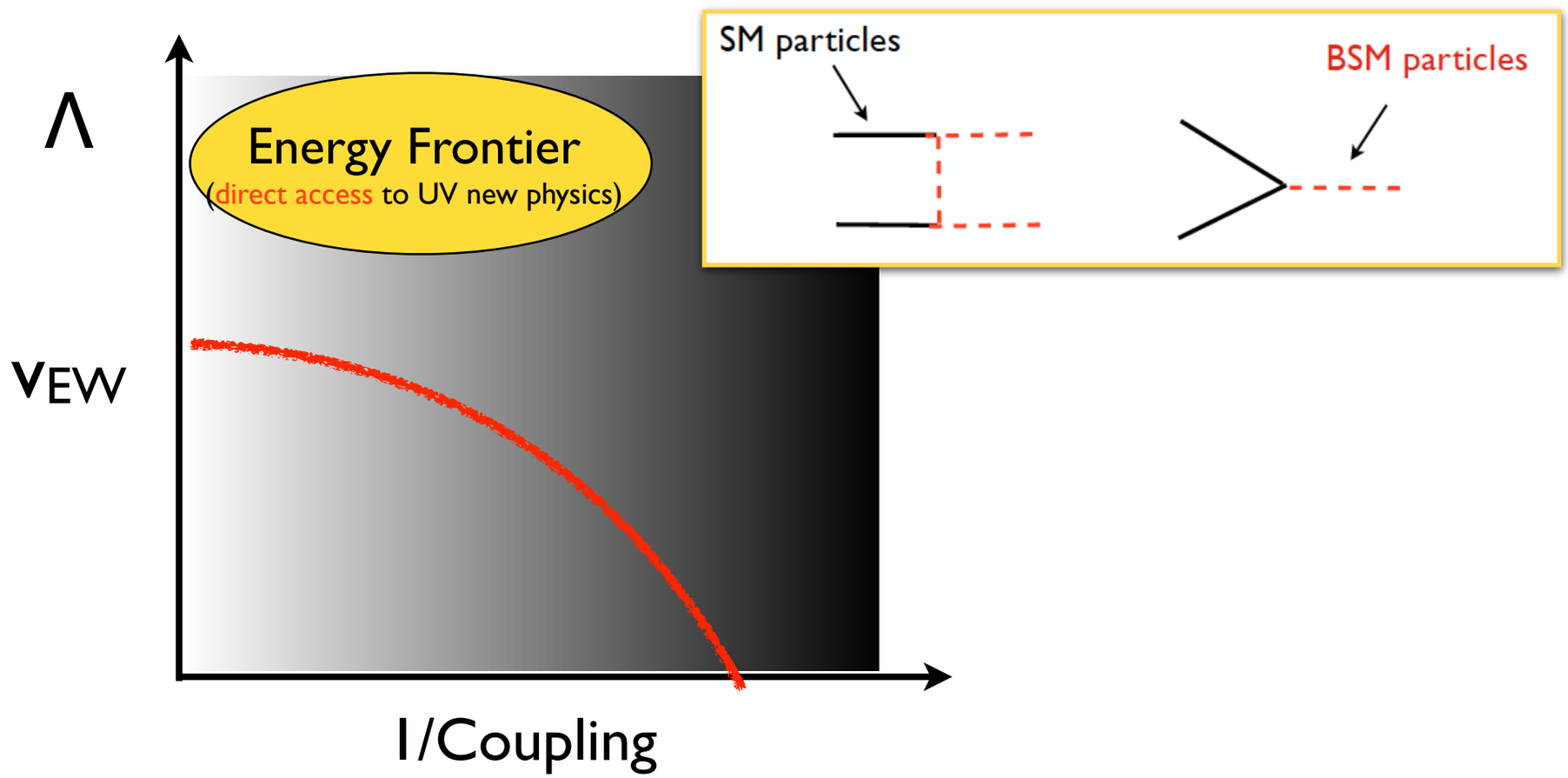
New physics: where?

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



New physics: how?

- Complementary paths to discovery



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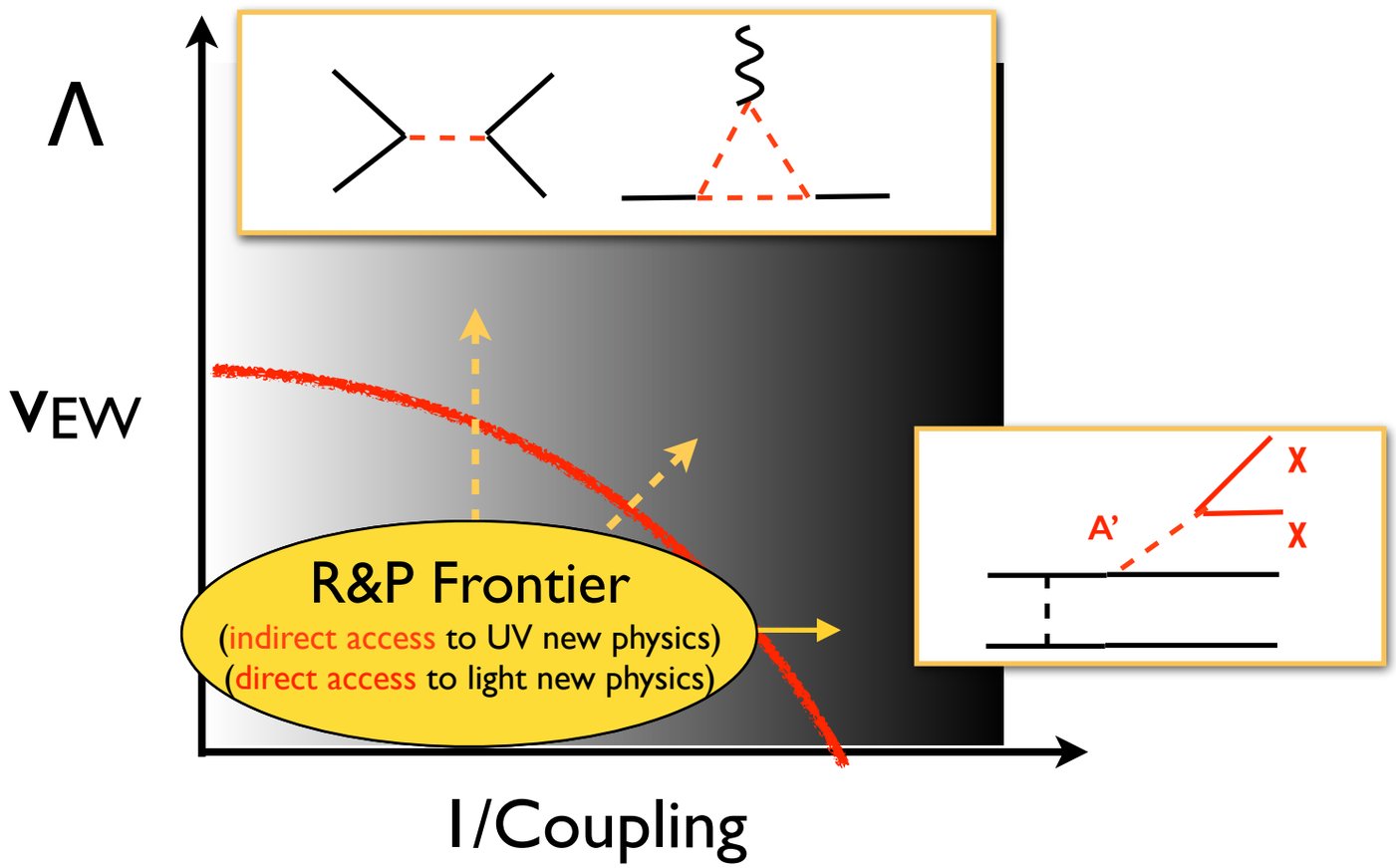

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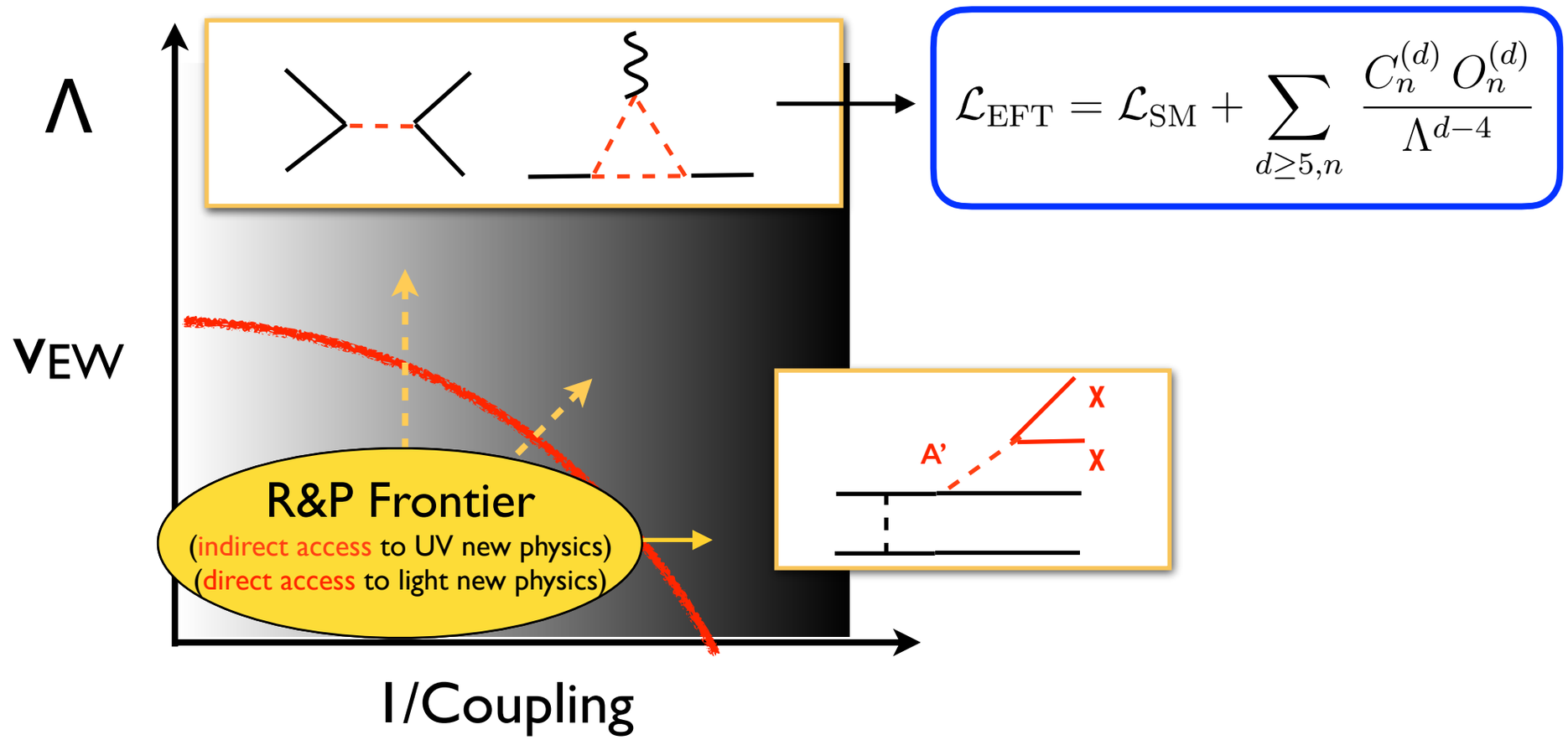

Full theory ← Simplified model ← SM-EFT → LEFT → hadronic EFT, LQCD, …

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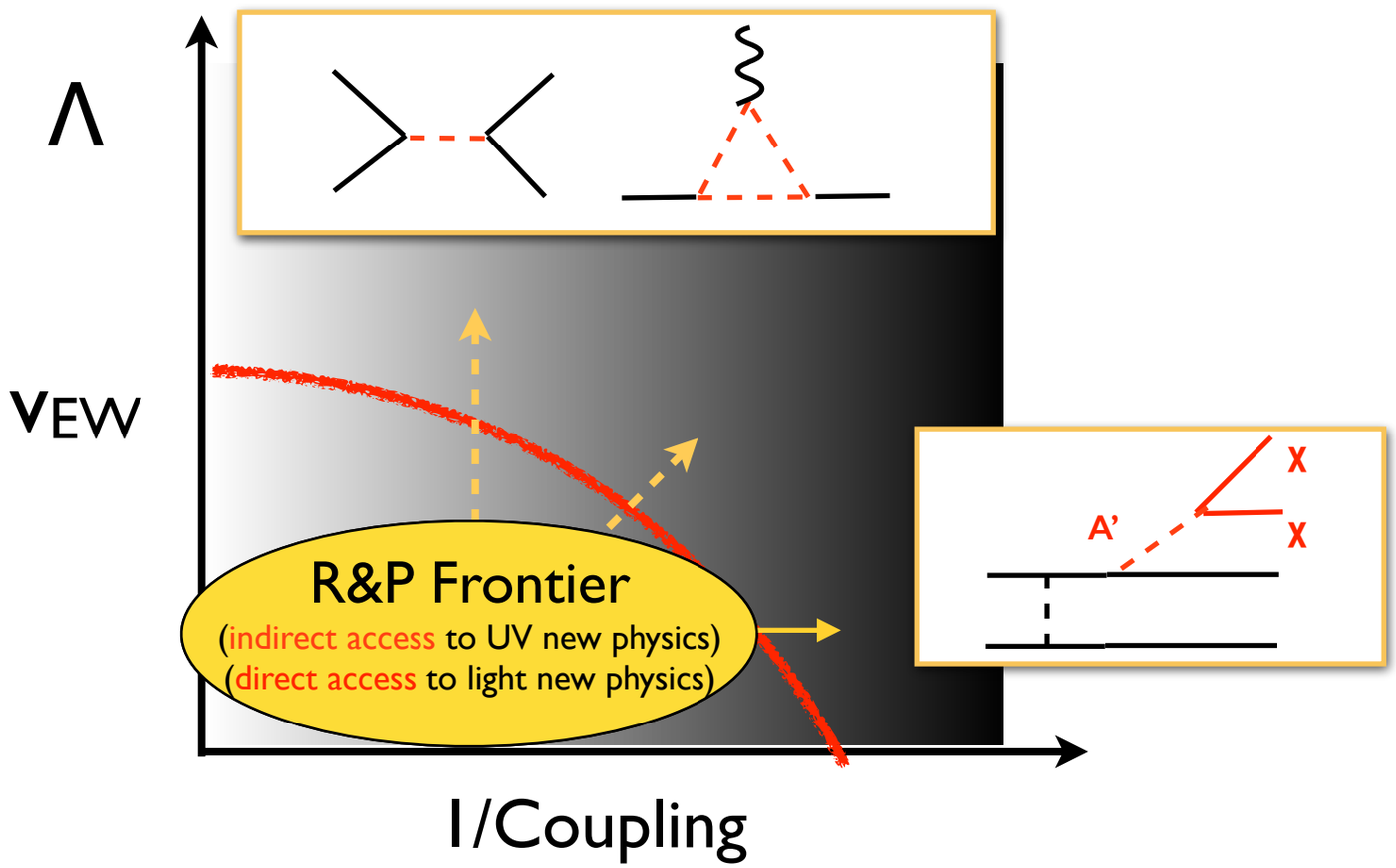
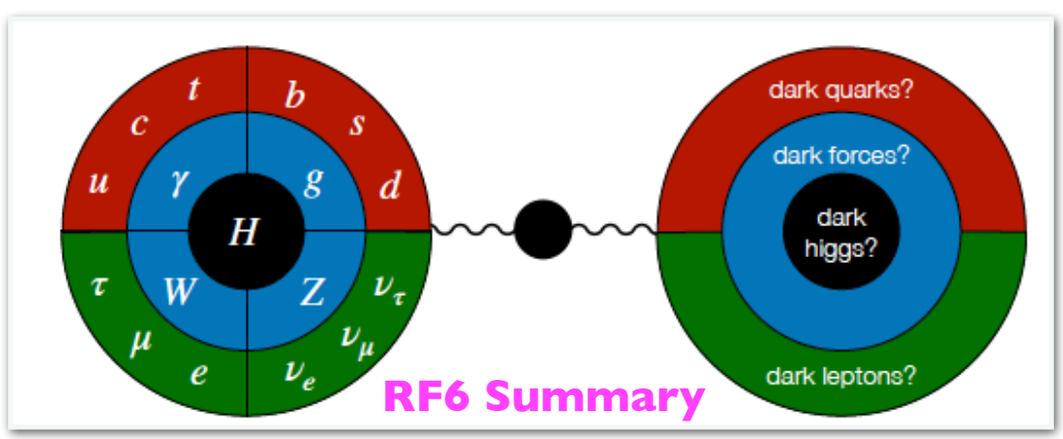


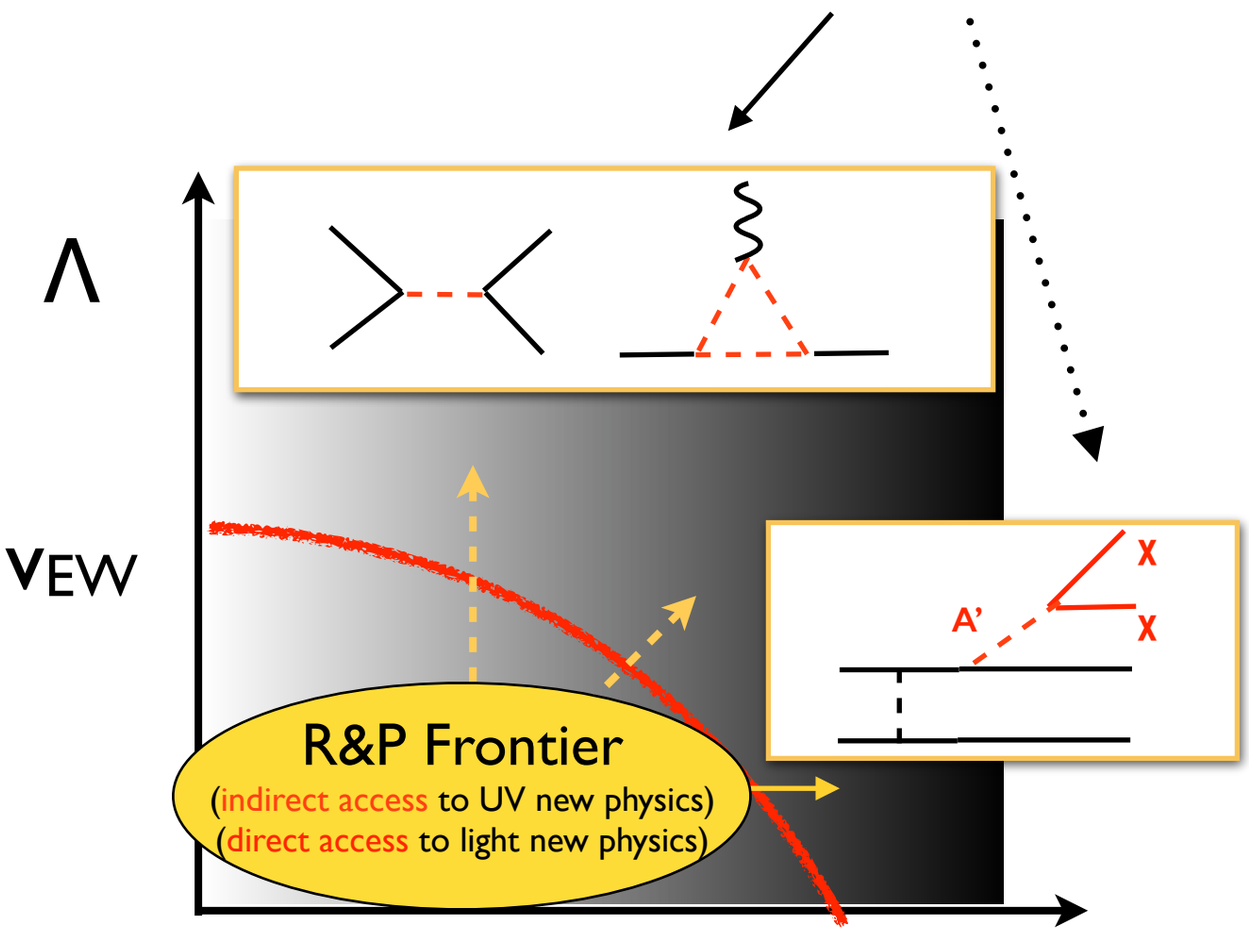


Portal interactions: Vector, Neutrino, Higgs, Axion, …

The "Rare & Precision" frontier

- Three classes of new physics probes

1. Searches for rare or SM-forbidden processes that probe (accidental) symmetries of the SM ($B-L$, $L_{e,\mu,\tau}$) or specific symmetry-violation patterns of the SM (CP, quark flavor)



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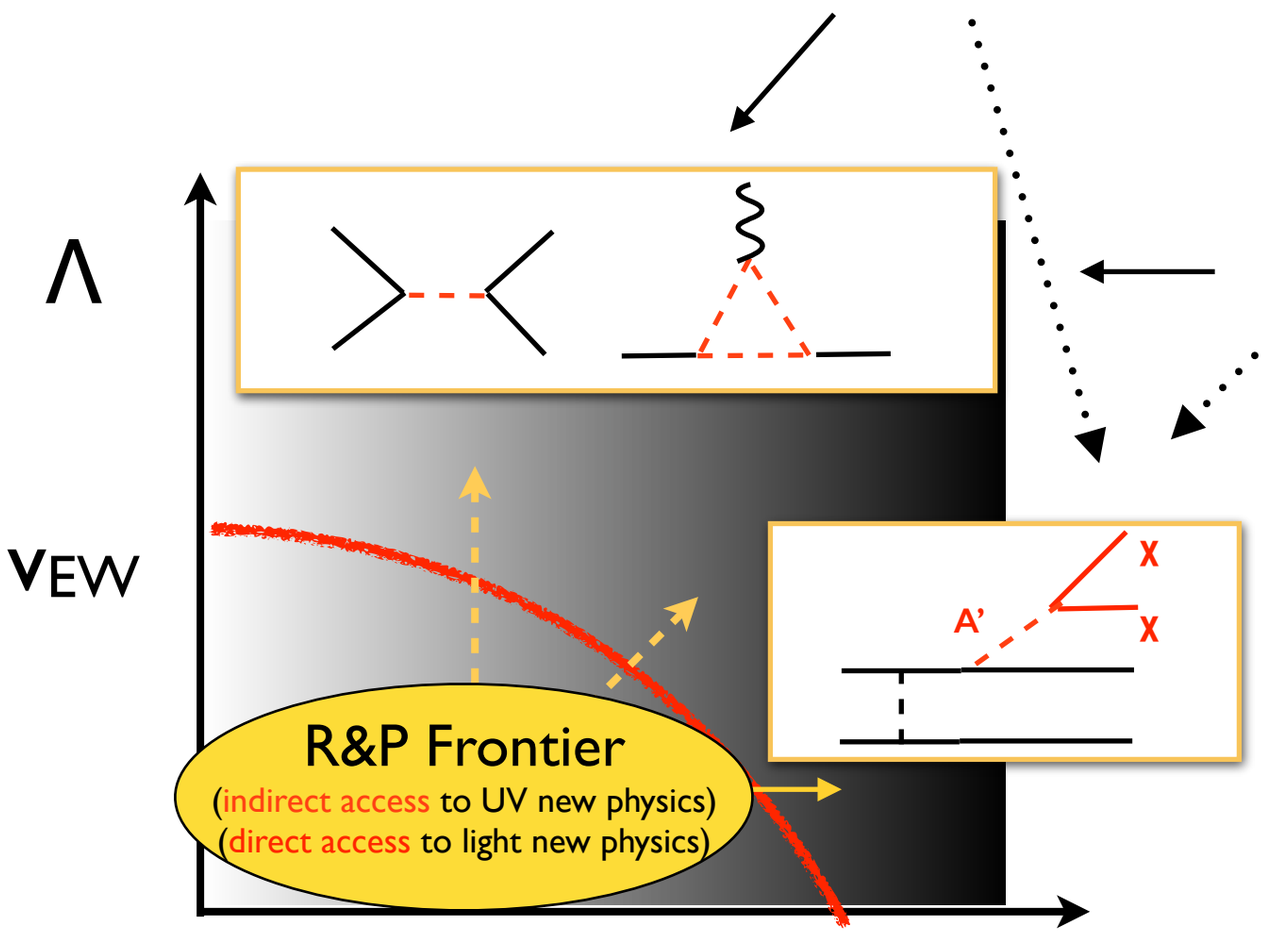

2. Precision measurements of SM-allowed processes (theory input is crucial to claim discovery): lepton g-2, CC weak decays, …

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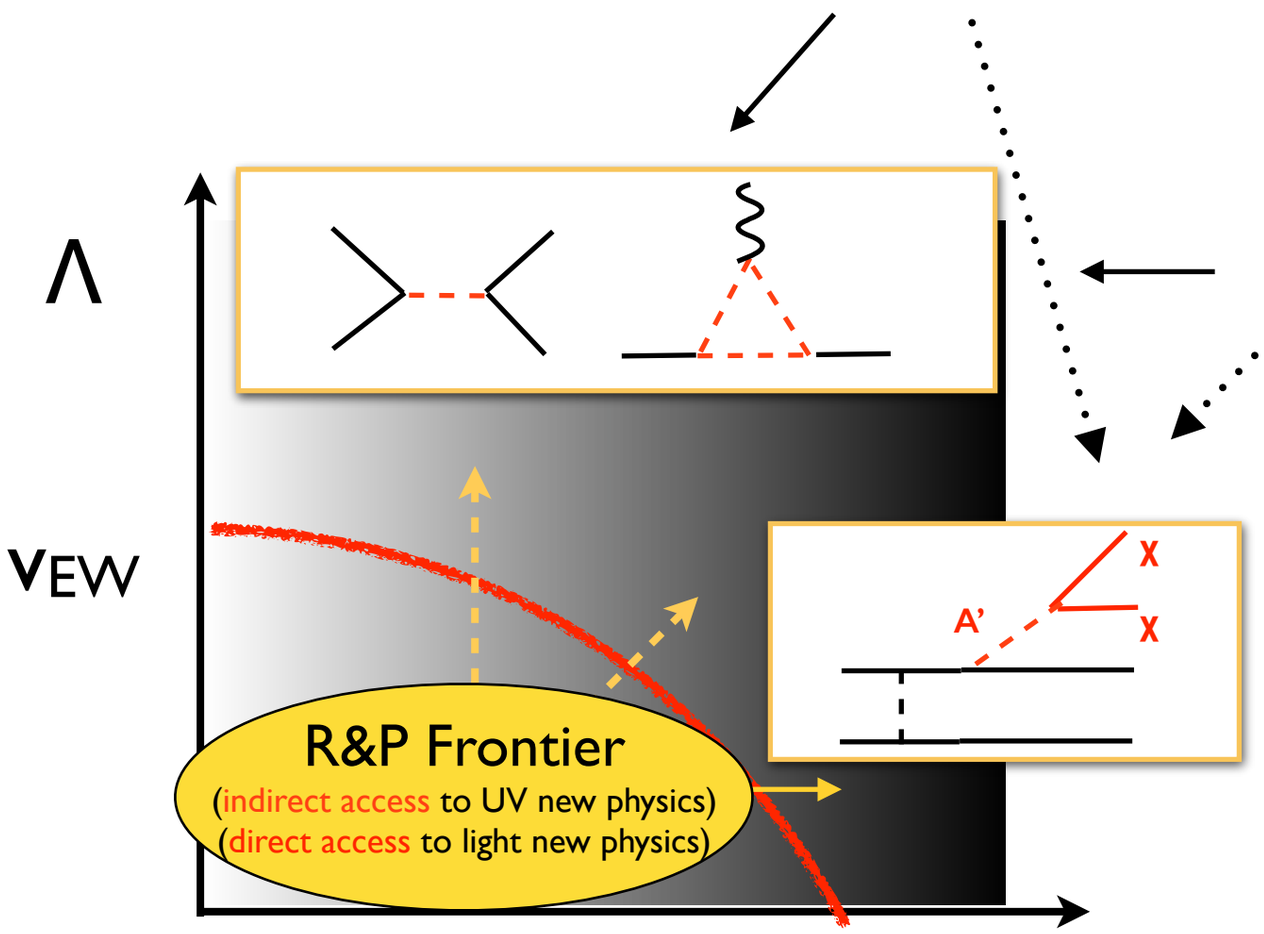

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See Stefania Gori's Colloquium on 7/20

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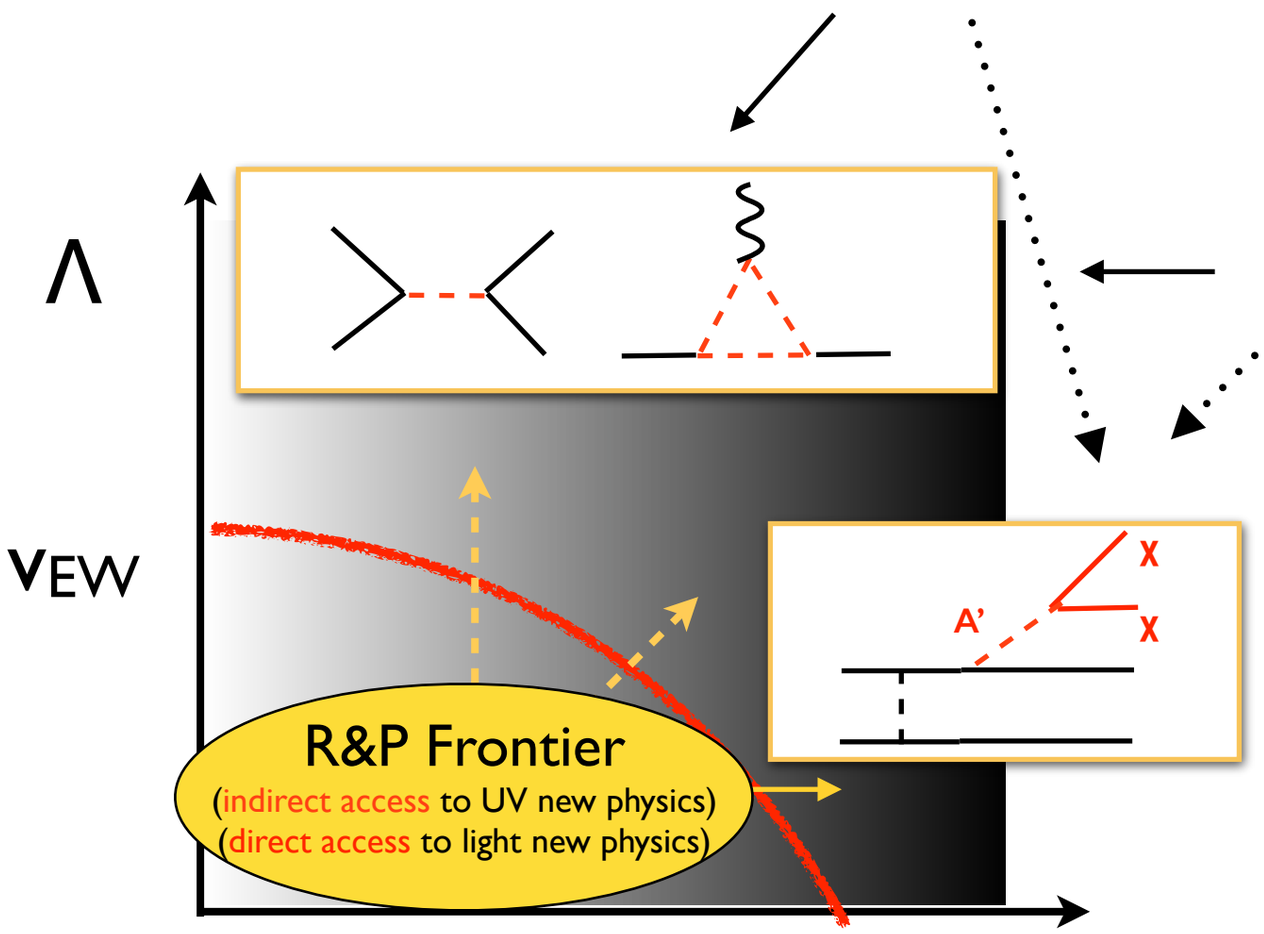

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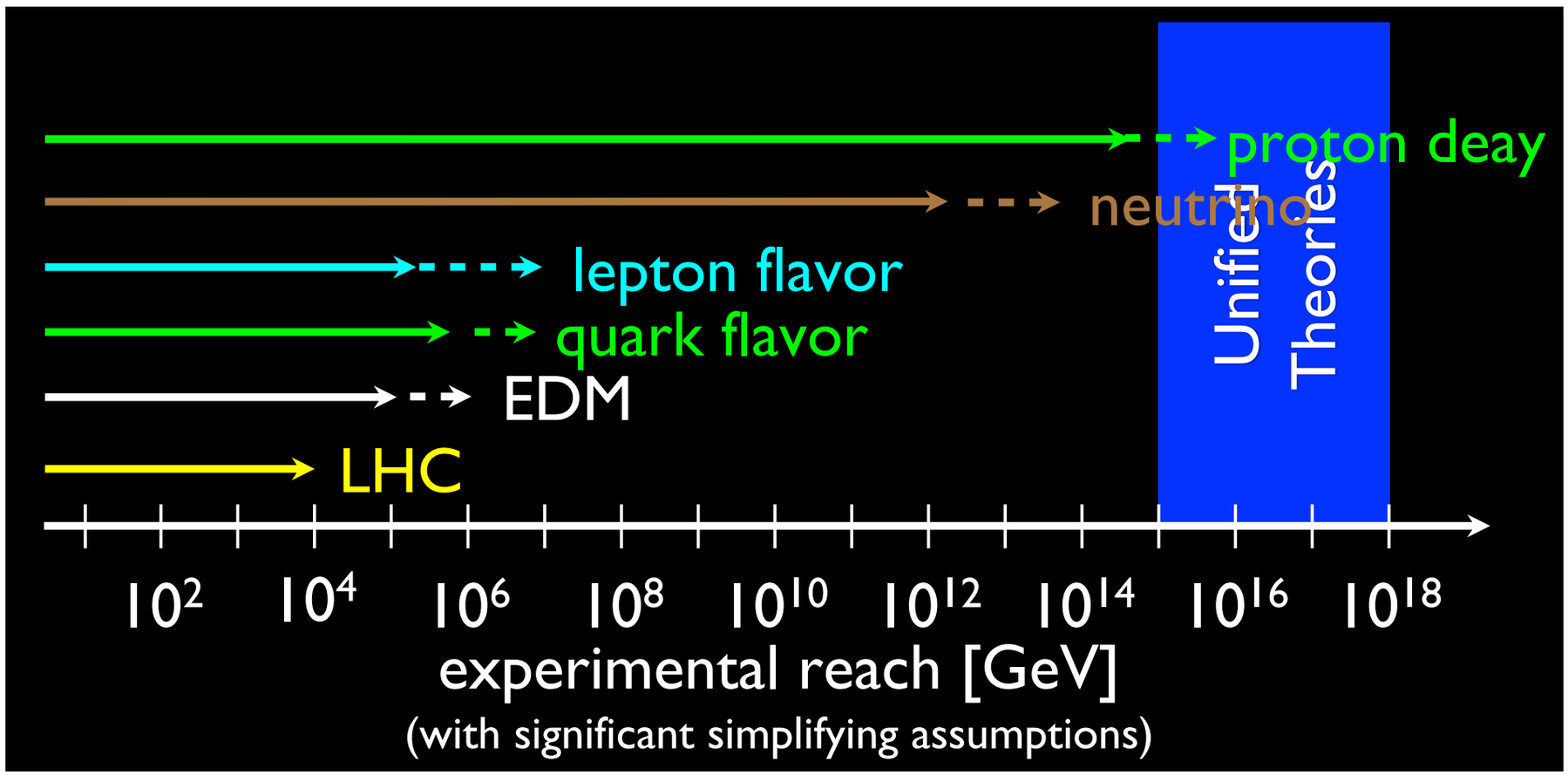
Strong overlap and synergy of HEP, NP, AMO

Impact of R&P searches

- Discovery potential
  - Look for cracks in the SM in many promising channels: a single deviation from SM expectation → new physics!



From Hitoshi Murayama's talk

Impact of R&P searches

- Discovery potential
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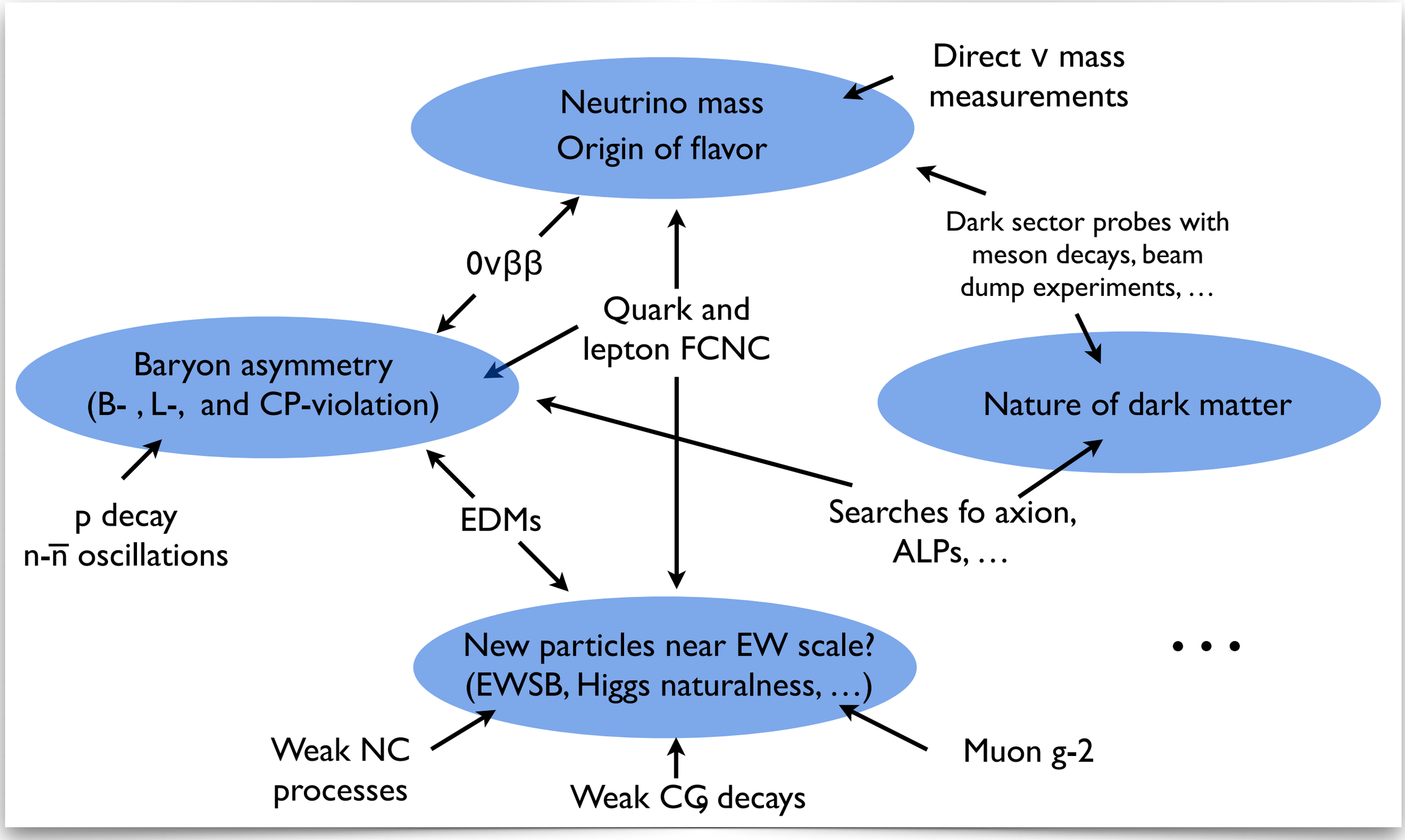
- Diagnosing power
  - Multiple probes → narrow down BSM scenarios

- Shed light on big questions
  - Sensitivity to (1) symmetry breaking required by Sakharov's conditions for baryogengesis (B,L,CP); (2) origin of neutrino mass; (3) TeV-scale physics (EWSB, naturalness); (4) dark sectors; …

Connection to big questions

R&P probes of new physics cluster around open questions



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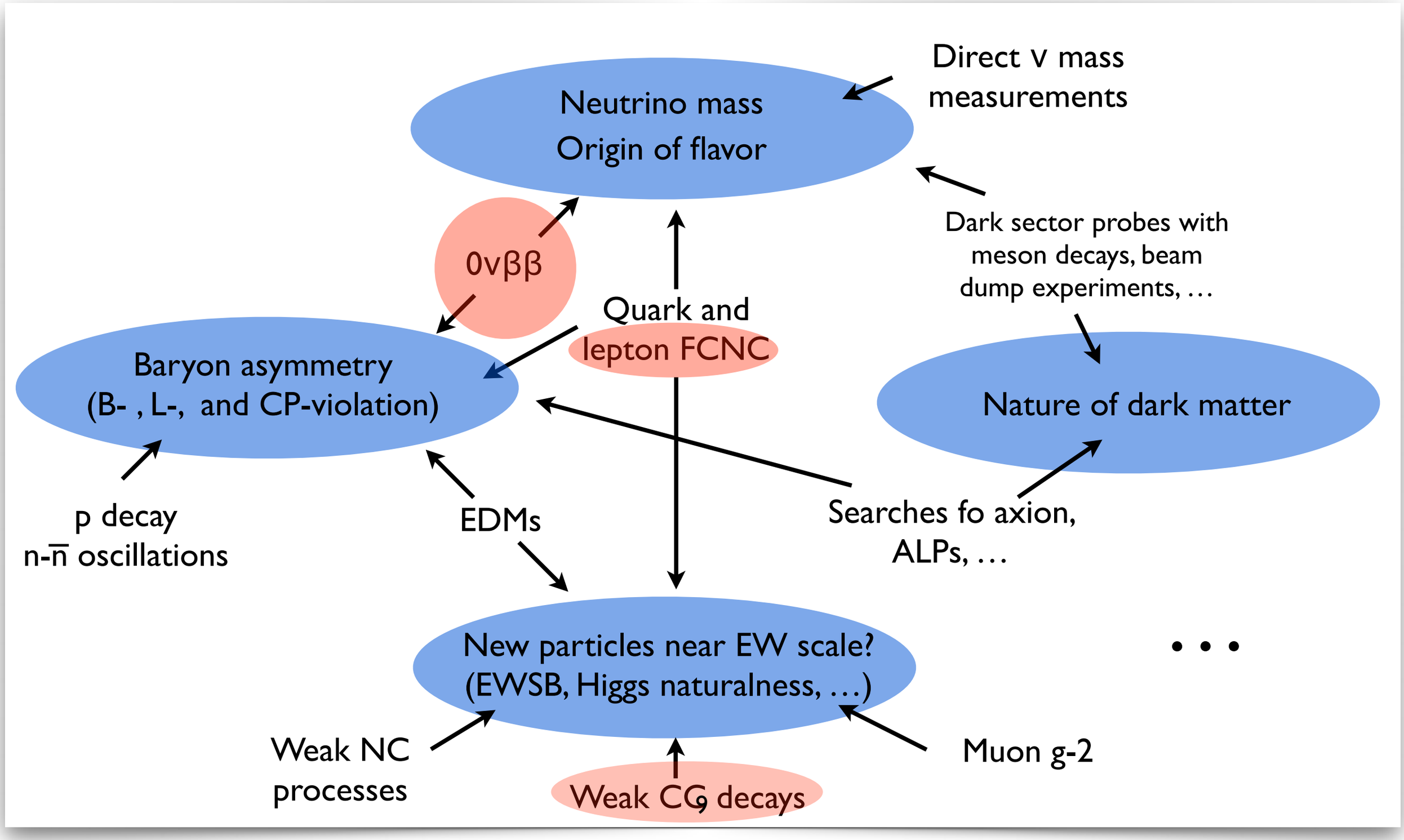

0νββ and the nature of neutrino mass

Neutrino mass

- Massive neutrinos = BSM physics. Yet, what's the nature of neutrino mass?

Dirac mass

$$m_D \, \overline{\psi_L} \, \psi_R \; + \; \text{h.c.}$$

Violates $L_{e,\mu,\tau}$, conserves $L=L_e+L_\mu+L_\tau$

Majorana mass

$$m_M \, \psi_L^T \, C\psi_L \; + \; \text{h.c.}$$

Violates $L_{e,\mu,\tau}$ *and* L ($\Delta L=2$)

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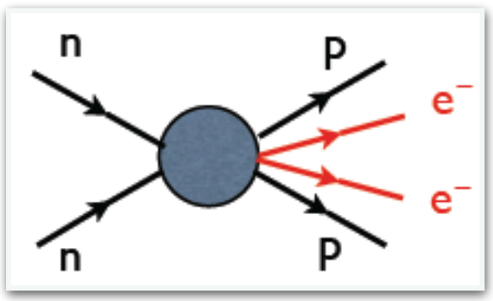
- To learn more, need $\Delta L=2$ processes: $0\nu\beta\beta$ is the most promising**

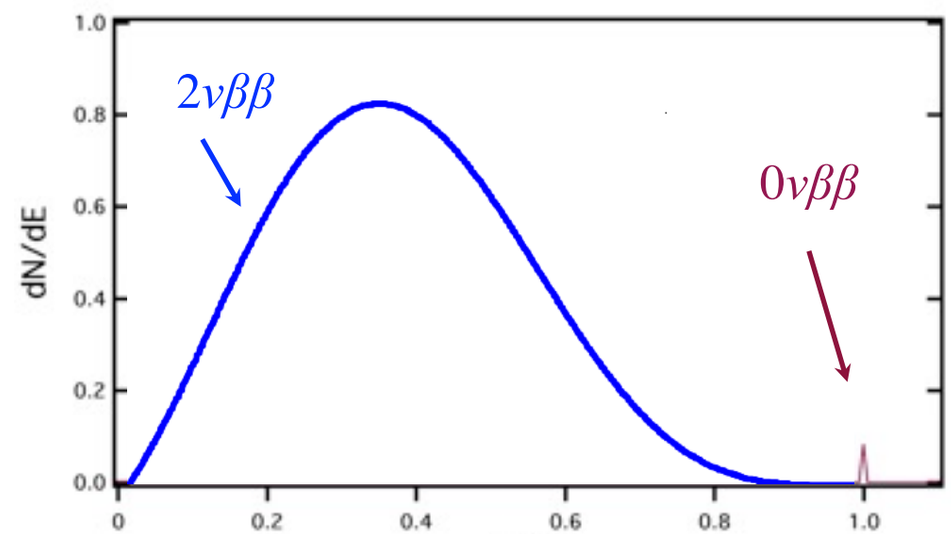
Neutrinoless double beta decay

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

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

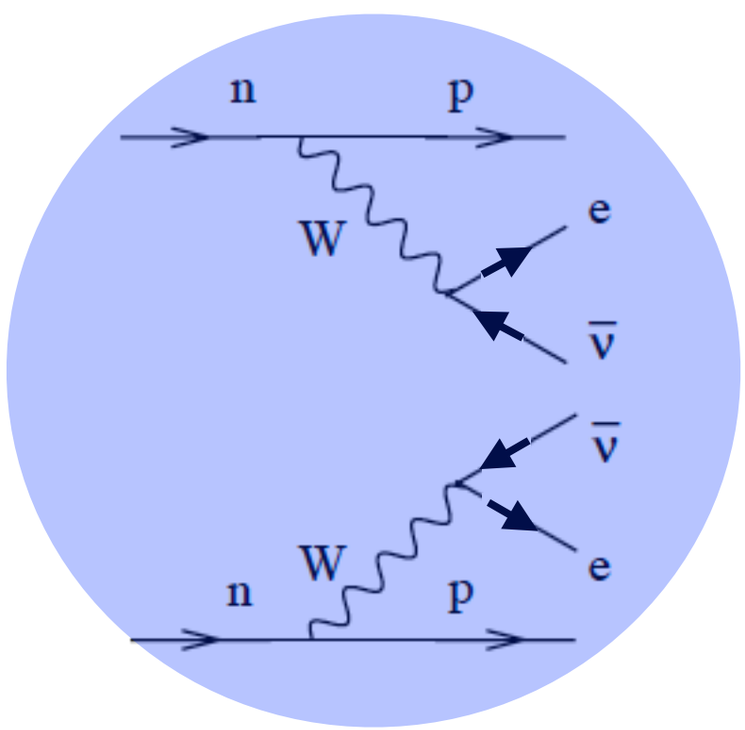


ΔL=2



$(E_{e1} + E_{e2})/Q$

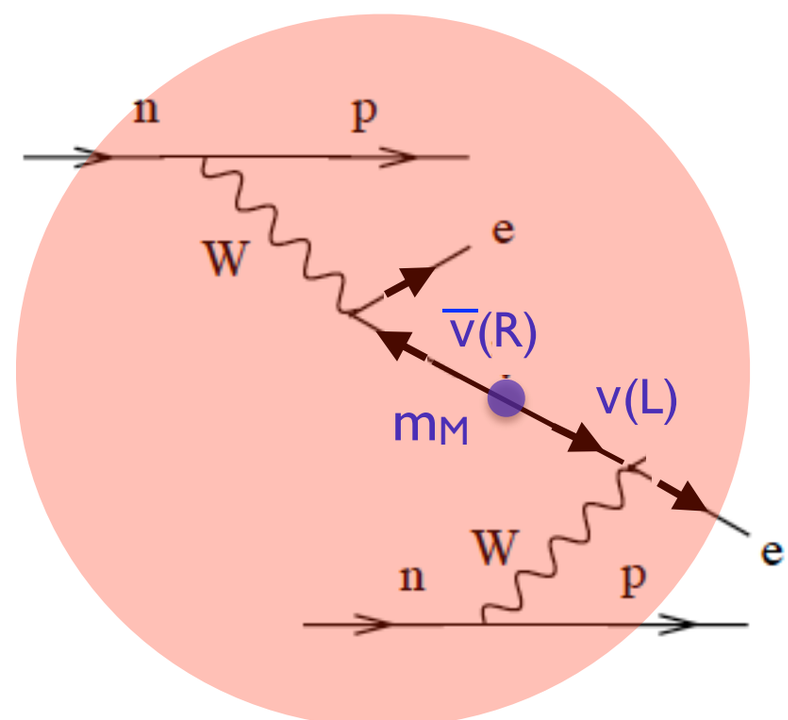
Potentially observable in certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …) for which single beta decay is energetically forbidden



Simplest mechanism:
Majorana mass term

But not the only one!

Furry 1939



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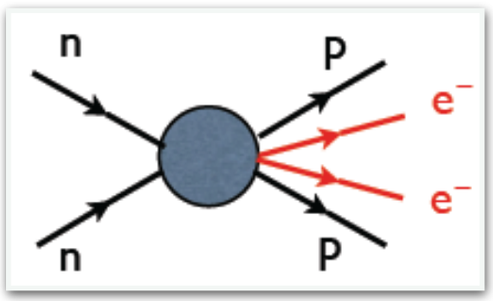

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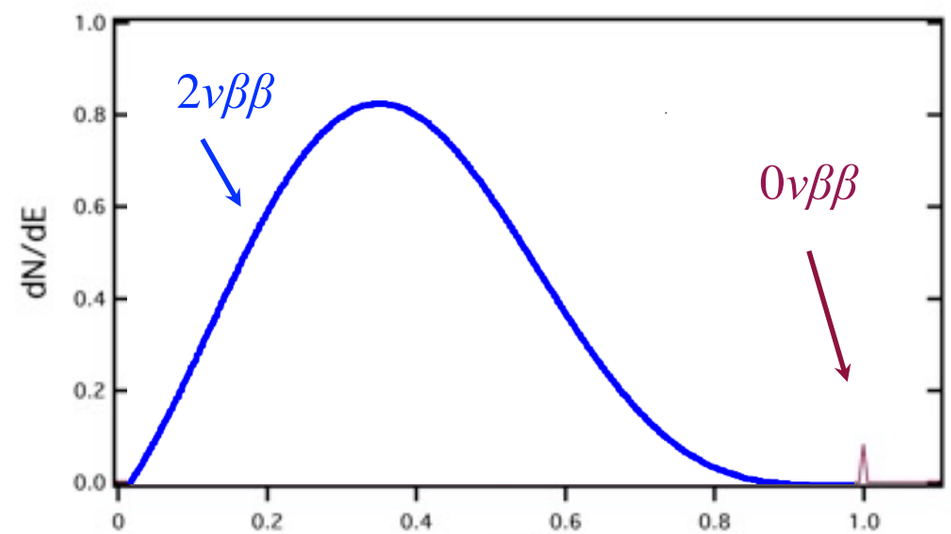

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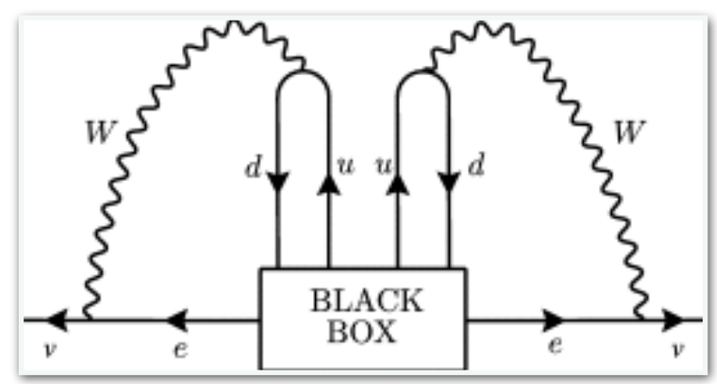
Potentially observable in certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …) for which single beta decay is energetically forbidden

- Observation would have far-reaching implications
  - Demonstrate that neutrinos are Majorana fermions
  - Establish LNV, key ingredient to generate baryon asymmetry via leptogenesis

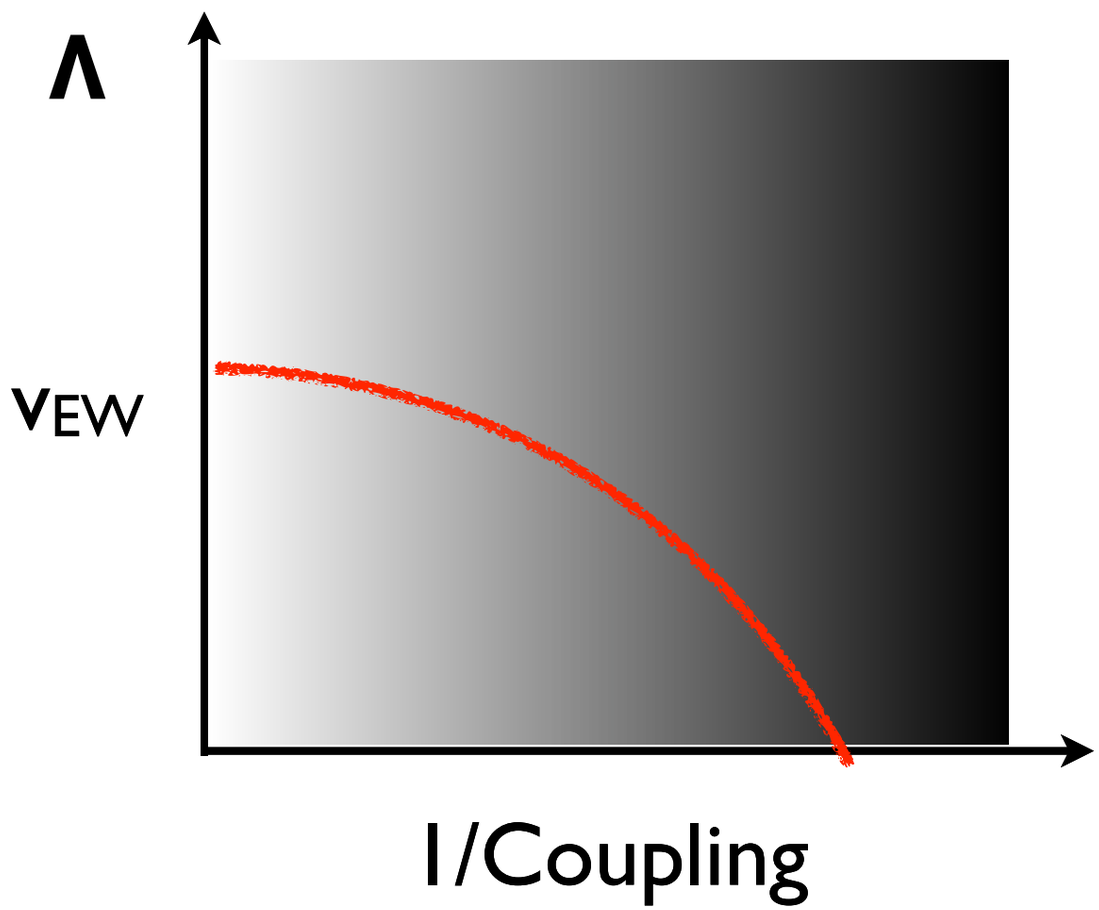
Fukugita-Yanagida 1987

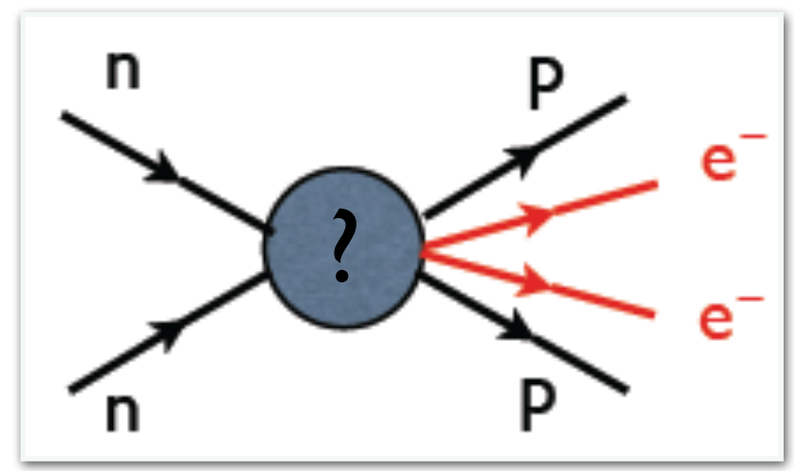


Shechter-Valle 1982

0νββ physics reach

- 0νββ searches @ $T_{1/2}$ >$10^{27\text{-}28}$ yr will have broad sensitivity to LNV mechanisms





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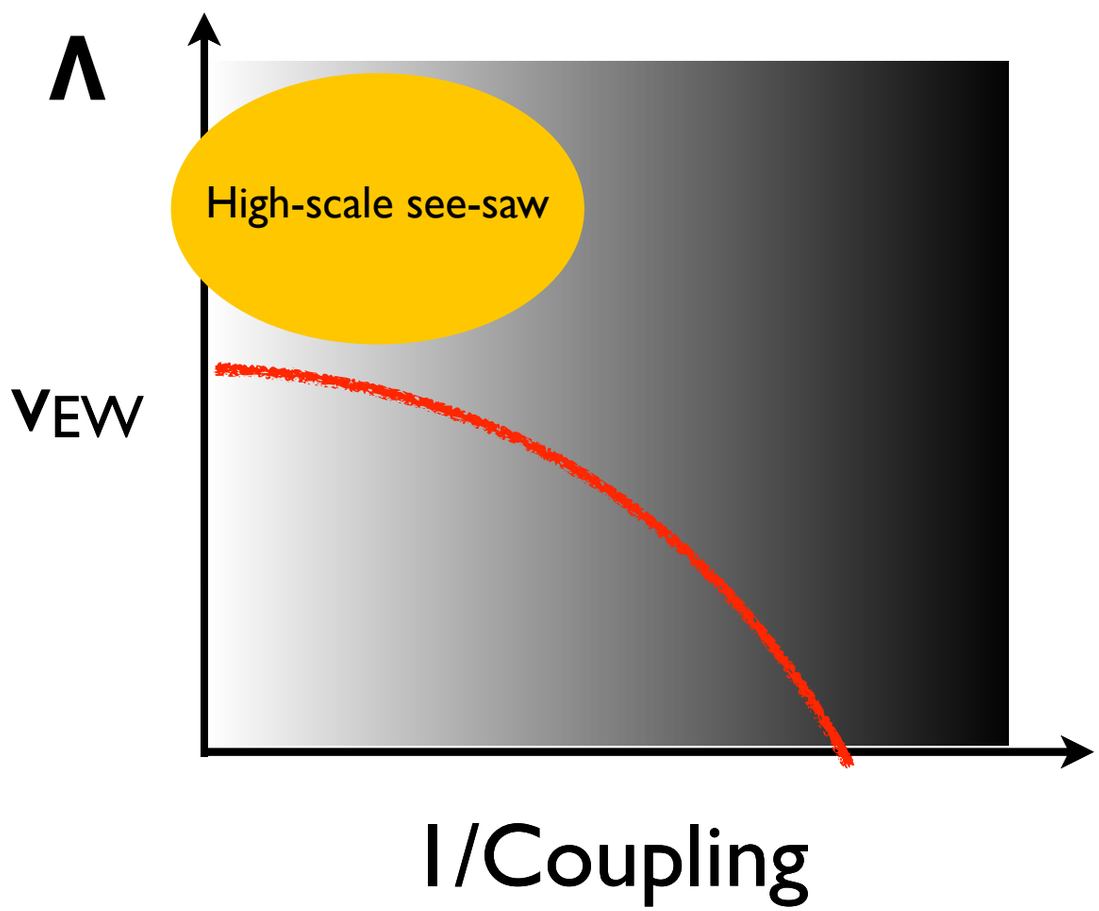
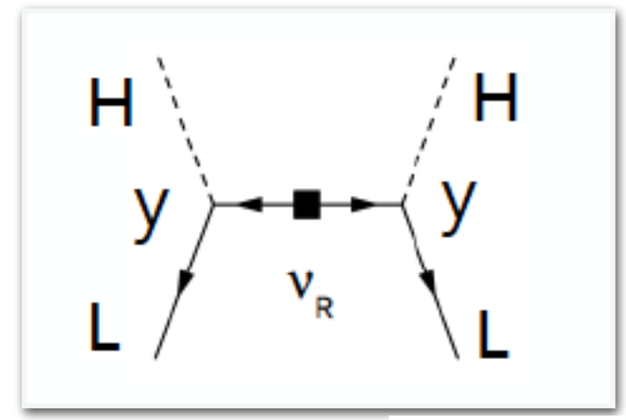
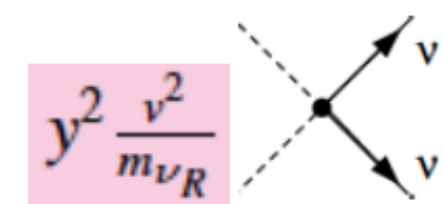
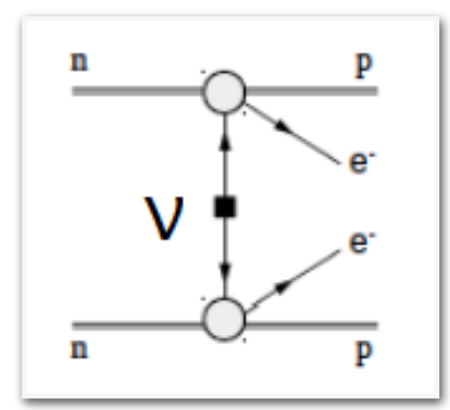




dim5
Majorana
Mass for light
ν's





Only low-E remnant of LNV
is the neutrino mass

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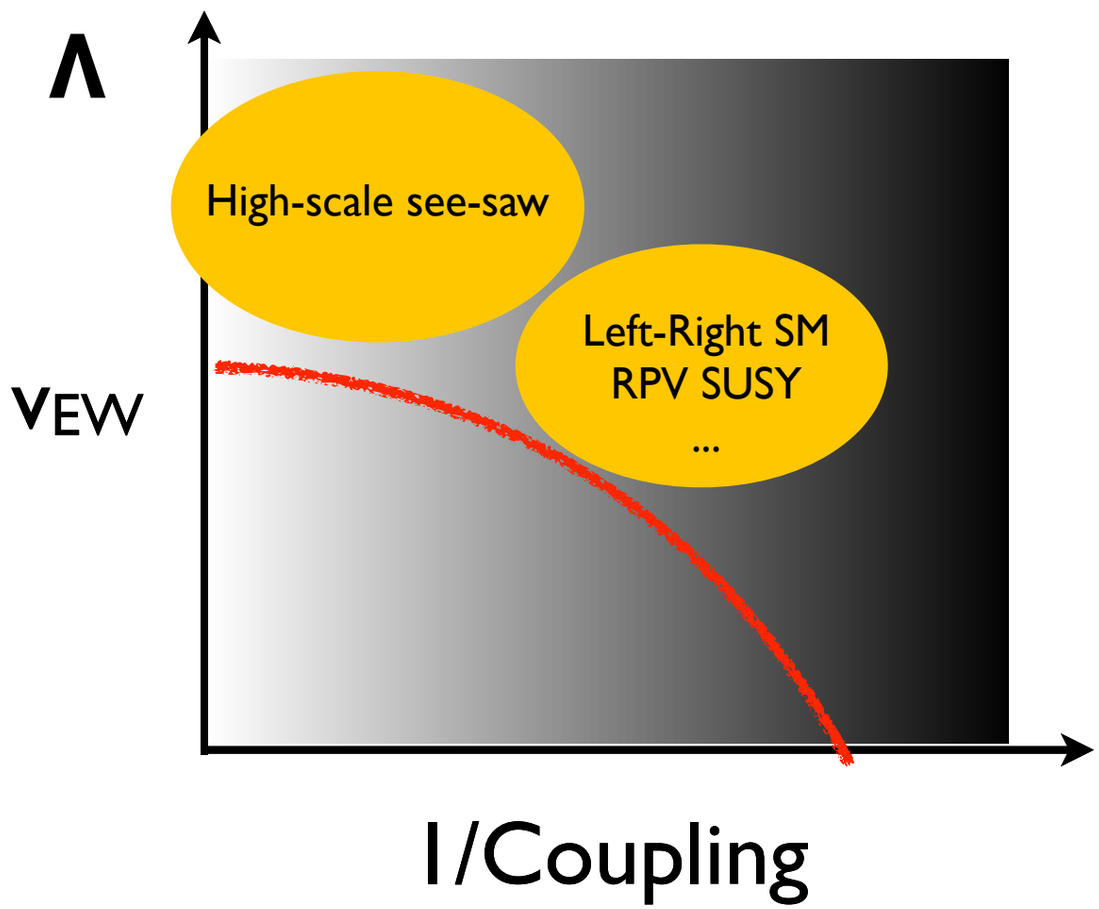
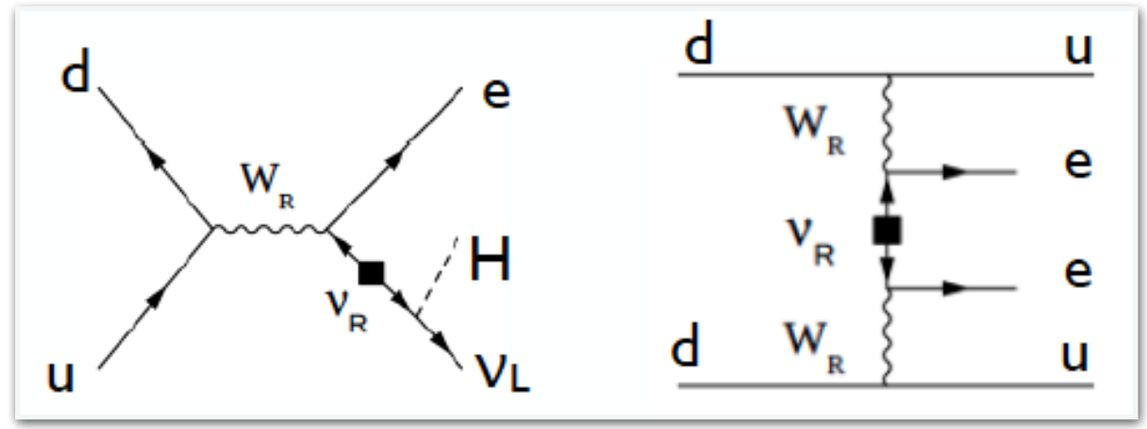
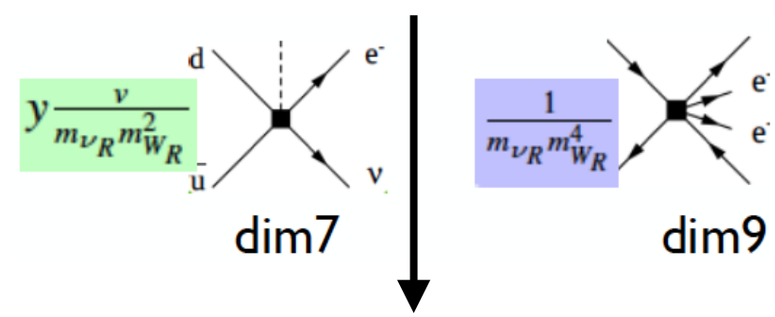
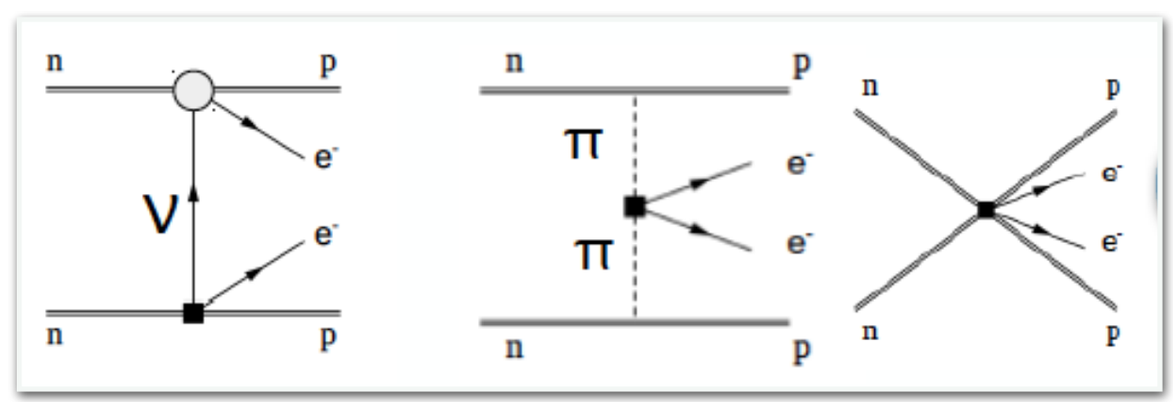


These contributions can compete if scale is not too high (10-100 TeV) and lead to new mechanisms at the nuclear scale







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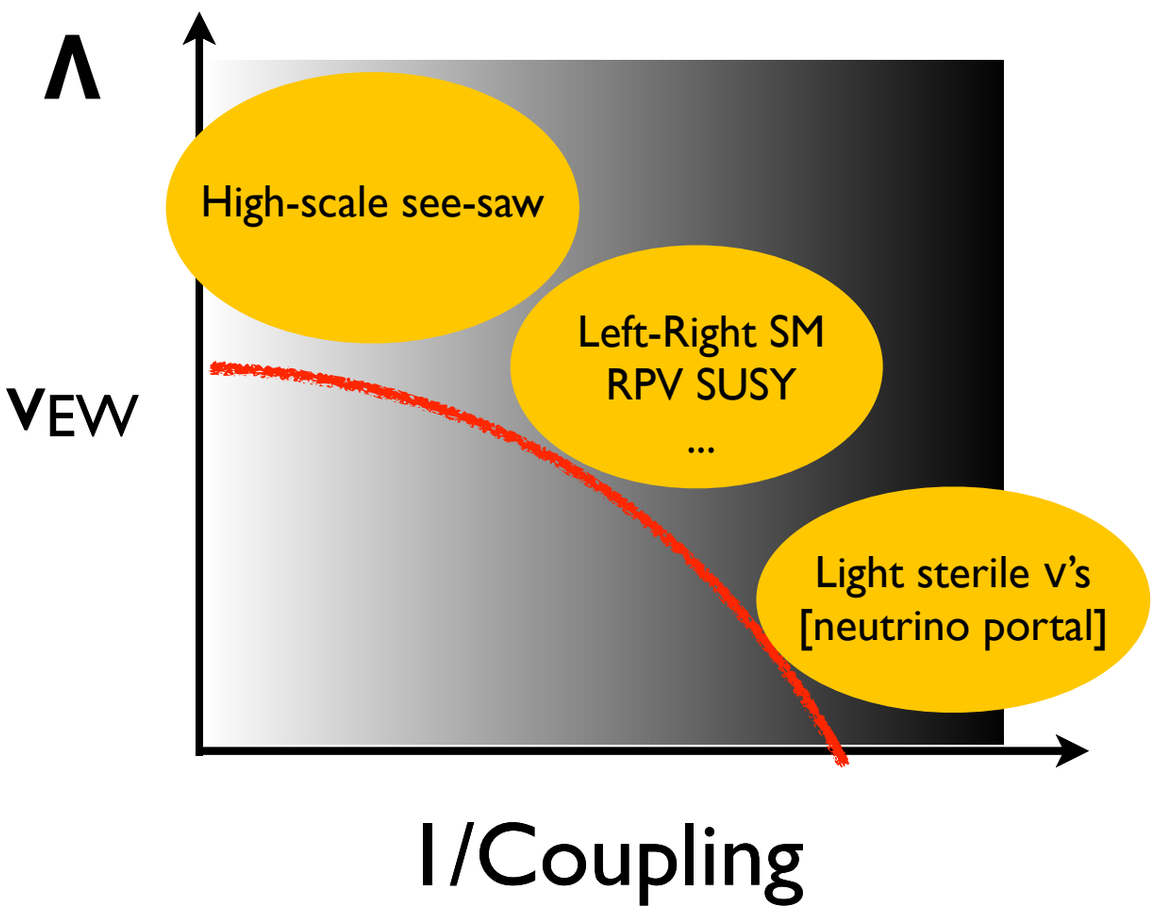
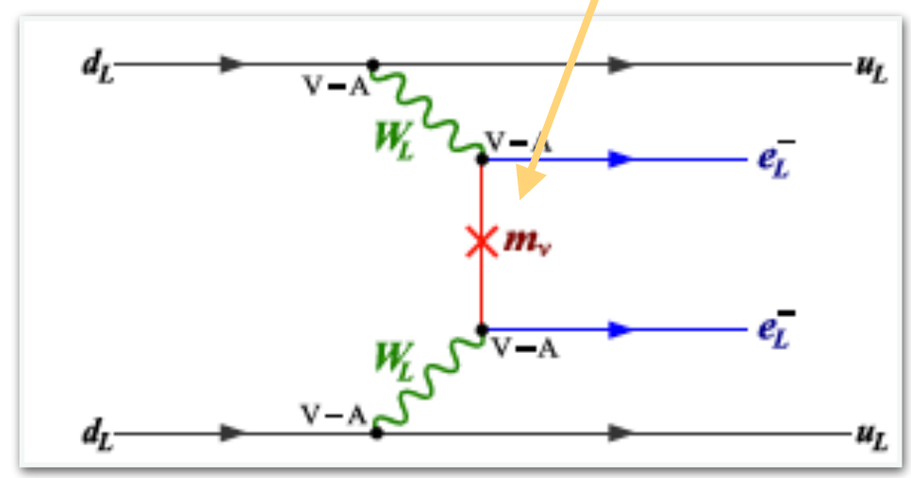


Light (nearly sterile) Majorana neutrinos



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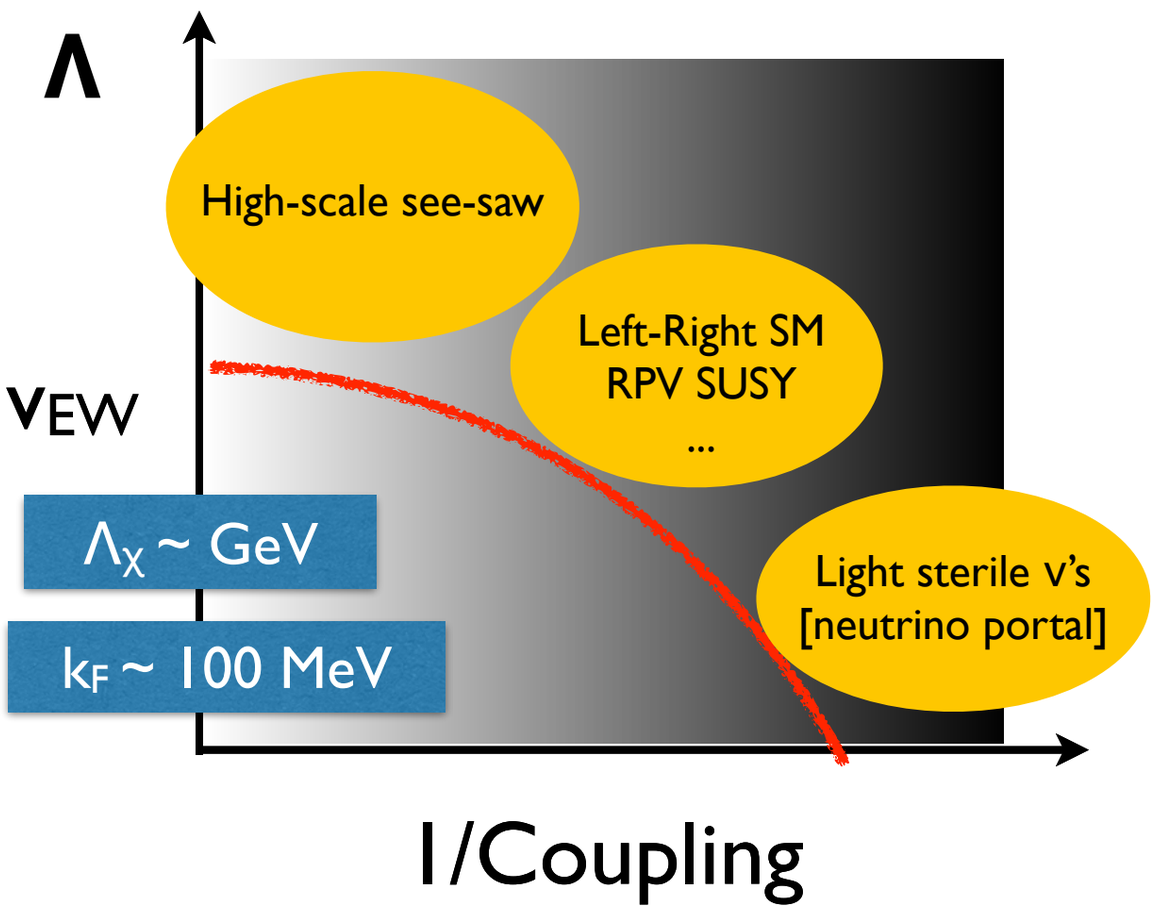


- Multi-scale problem best tackled through 'end-to-end' EFT: only chance to achieve controllable uncertainty
- Importance of GeV threshold!
- Synergy of EFT, Lattice QCD, and first-principles nuclear structure

SMEFT	LEFT	Chiral EFT

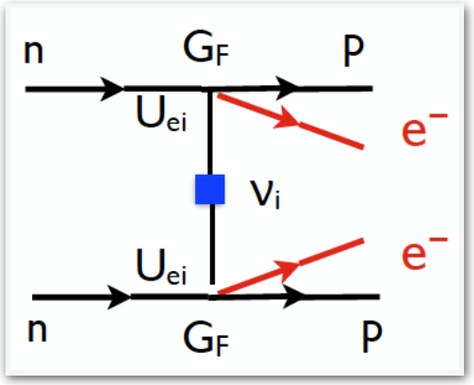
$$T_{1/2} \propto (m_W/\Lambda)^A \, (\Lambda_\chi/m_W)^B \, (k_F/\Lambda_\chi)^C$$

White paper 2203. 21169 and refs therein

High-scale seesaw (1)

- $0\nu\beta\beta$ can be predicted in terms of ν mass parameters: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

$$\langle m_{\beta\beta} \rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$



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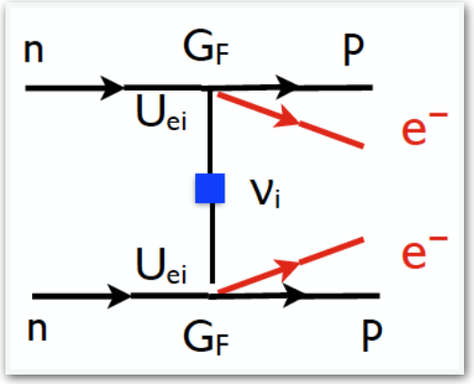
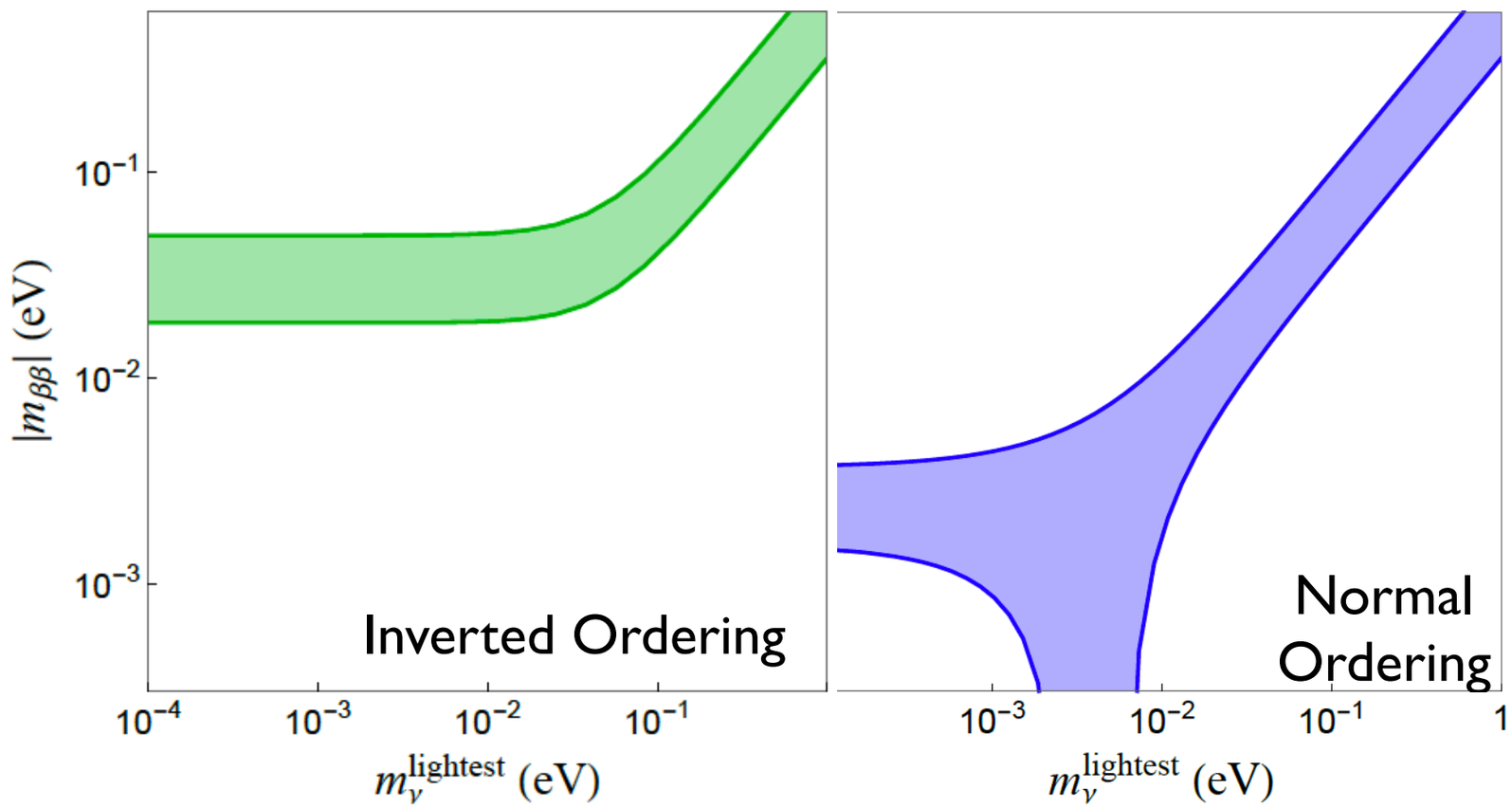


Bands: unknown Majorana phases



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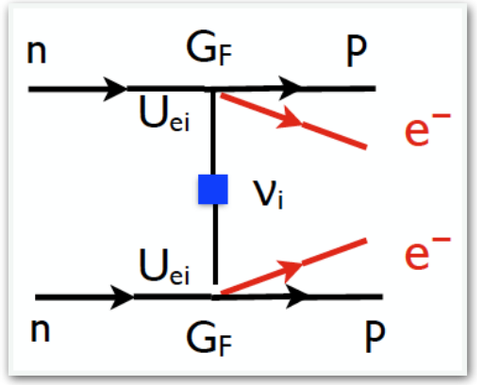
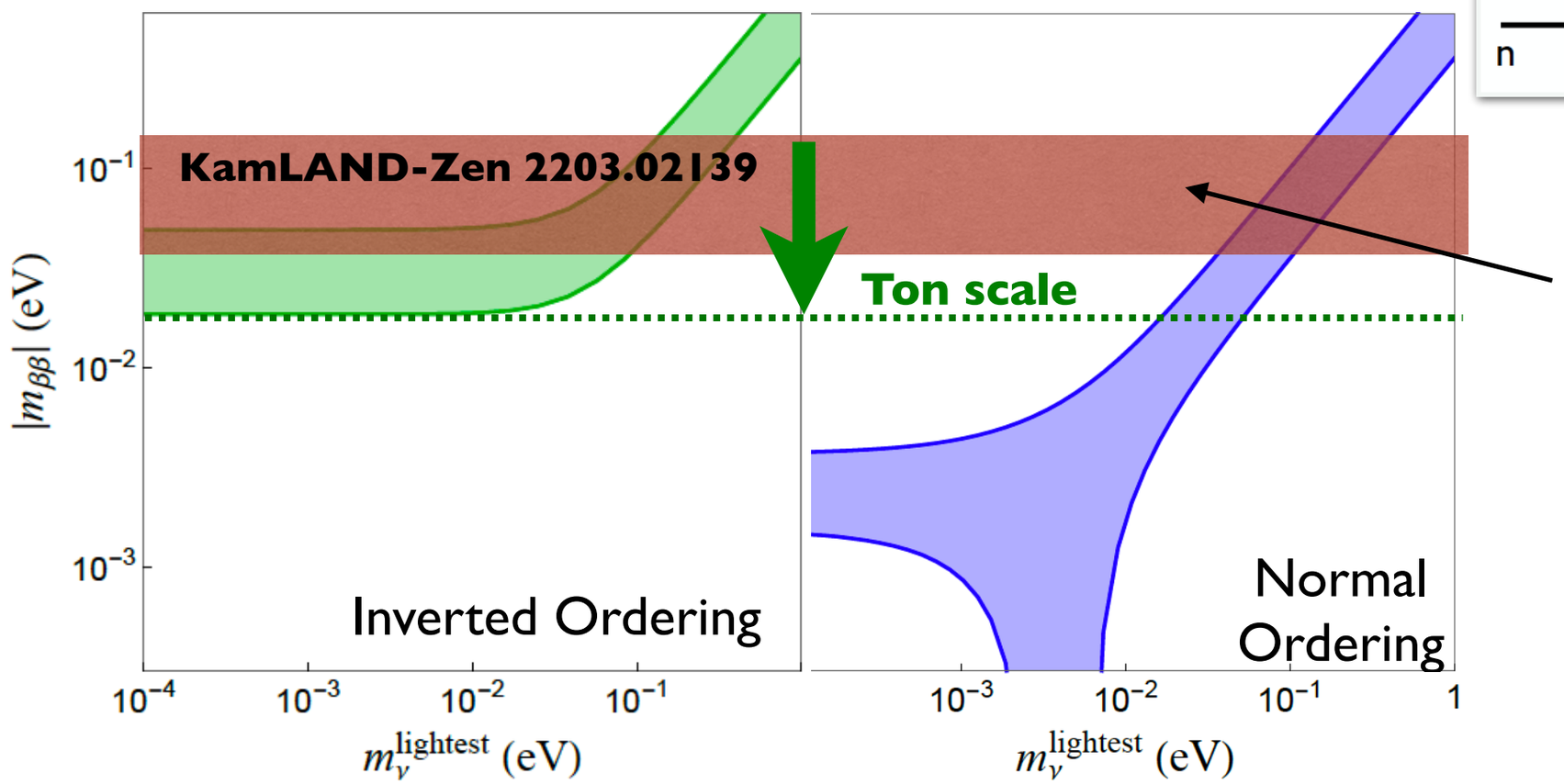




Bands: unknown Majorana phases

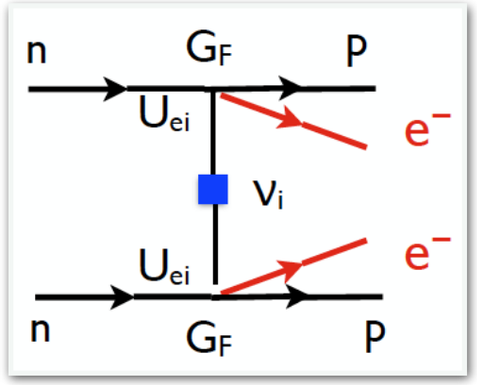
Assume range for nuclear matrix elements from different nuclear calculations

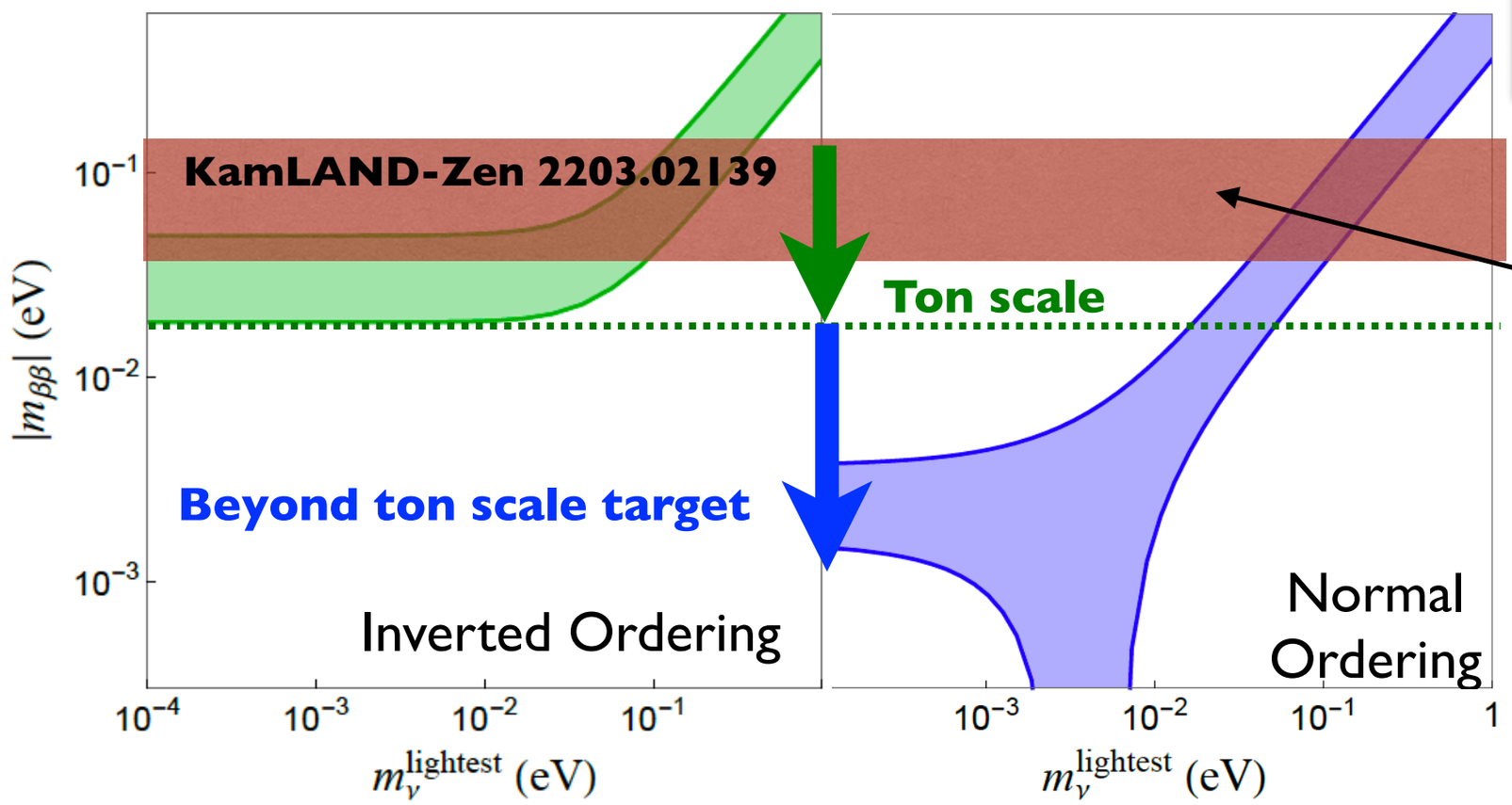
Assuming current range for matrix elements, discovery @ ton-scale *possible* for inverted spectrum or $m_{\rm lightest}$ > 50 meV

High-scale seesaw (1)

- $0\nu\beta\beta$ can be predicted in terms of ν mass parameters: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$





Bands: unknown Majorana phases

Assume range for nuclear matrix elements from different nuclear calculations

Natural (but challenging!) beyond ton-scale target is $m_{\beta\beta} \sim$ meV

High-scale seesaw (2)

- High scale seesaw implies falsifiable correlations with other ν mass probes

$$m_{\beta\beta} = \left| \sum_i U_{ei}^2 \, m_i \right|$$

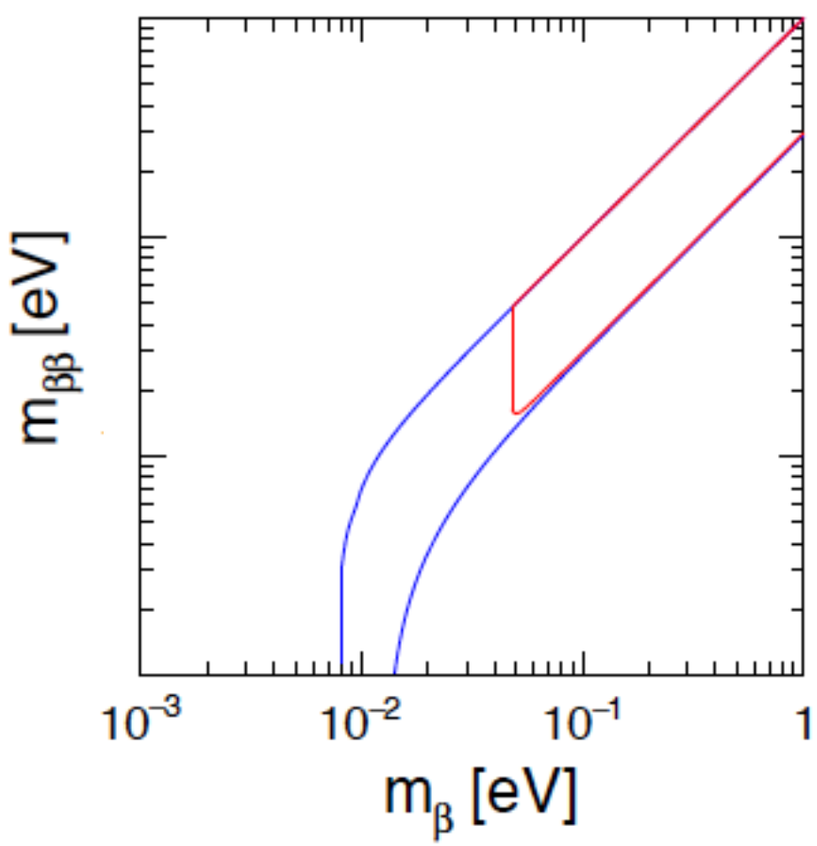
0νββ decay

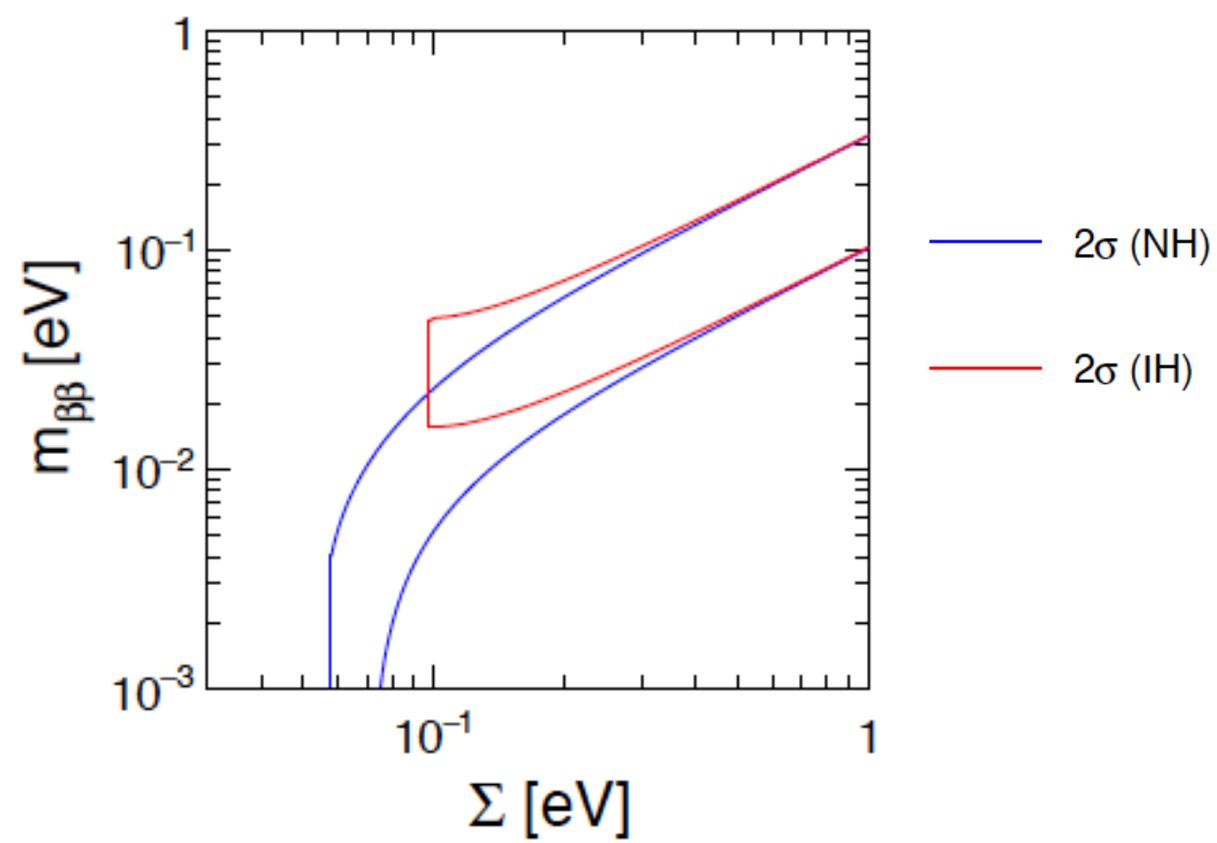
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





High-scale seesaw (2)

- High scale seesaw implies falsifiable correlations with other ν mass probes

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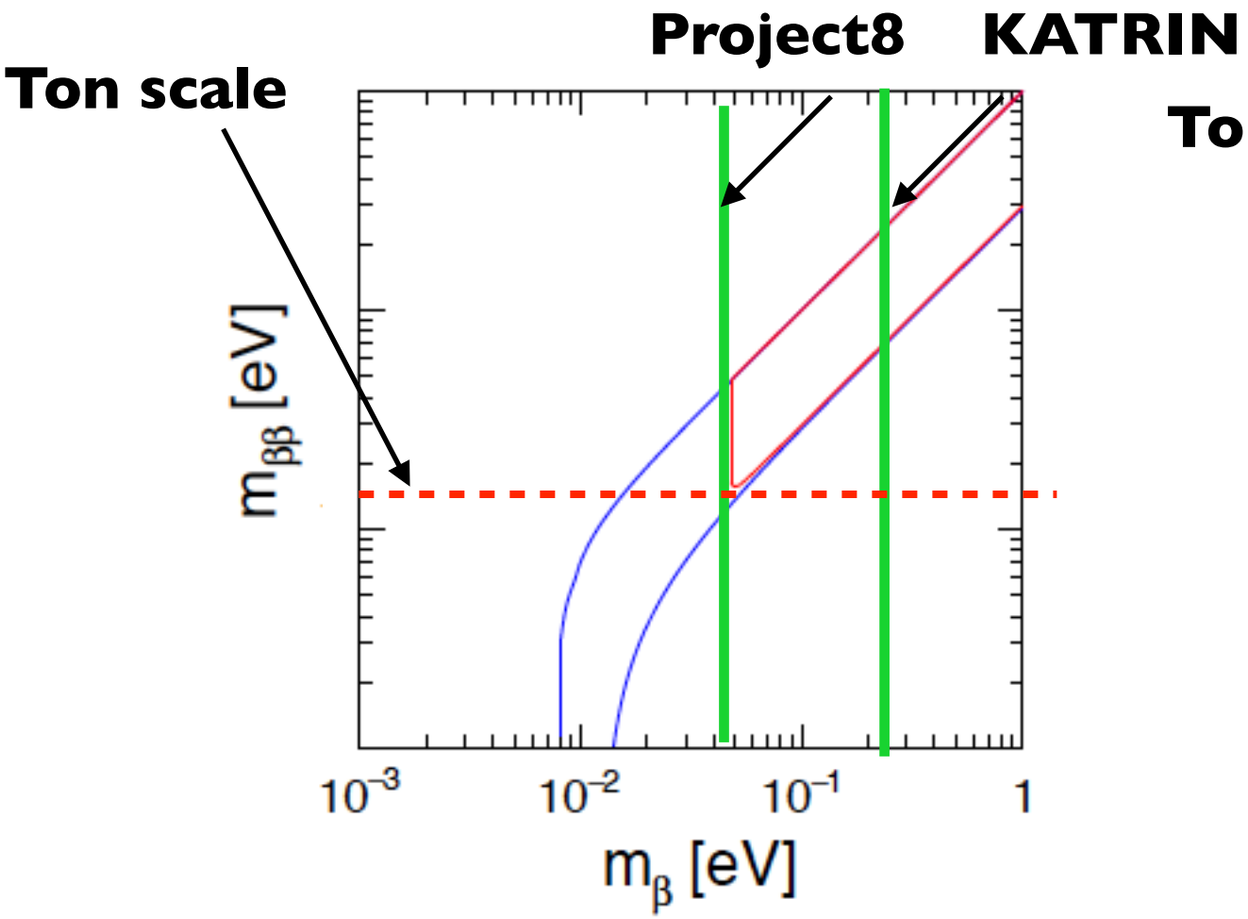

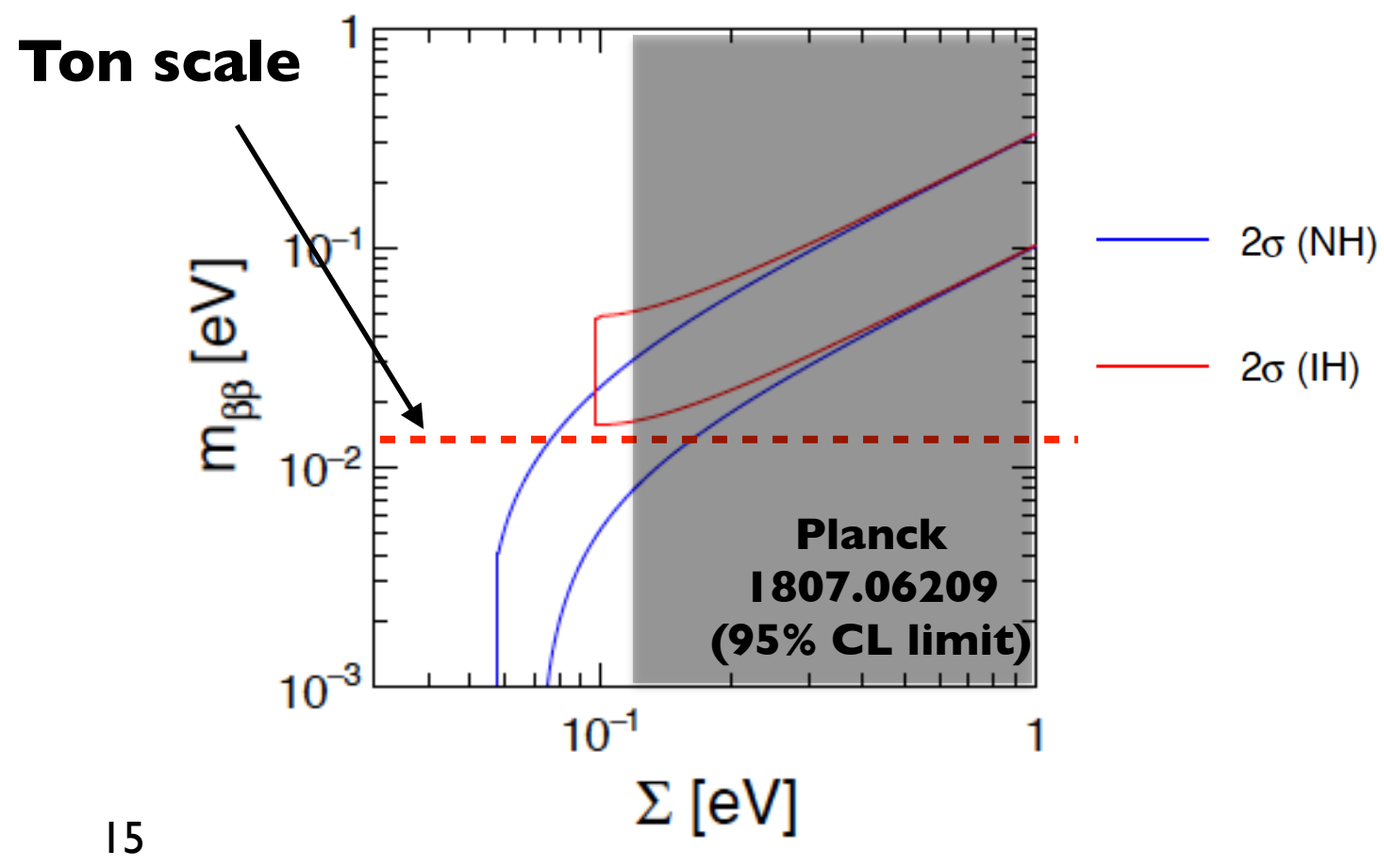

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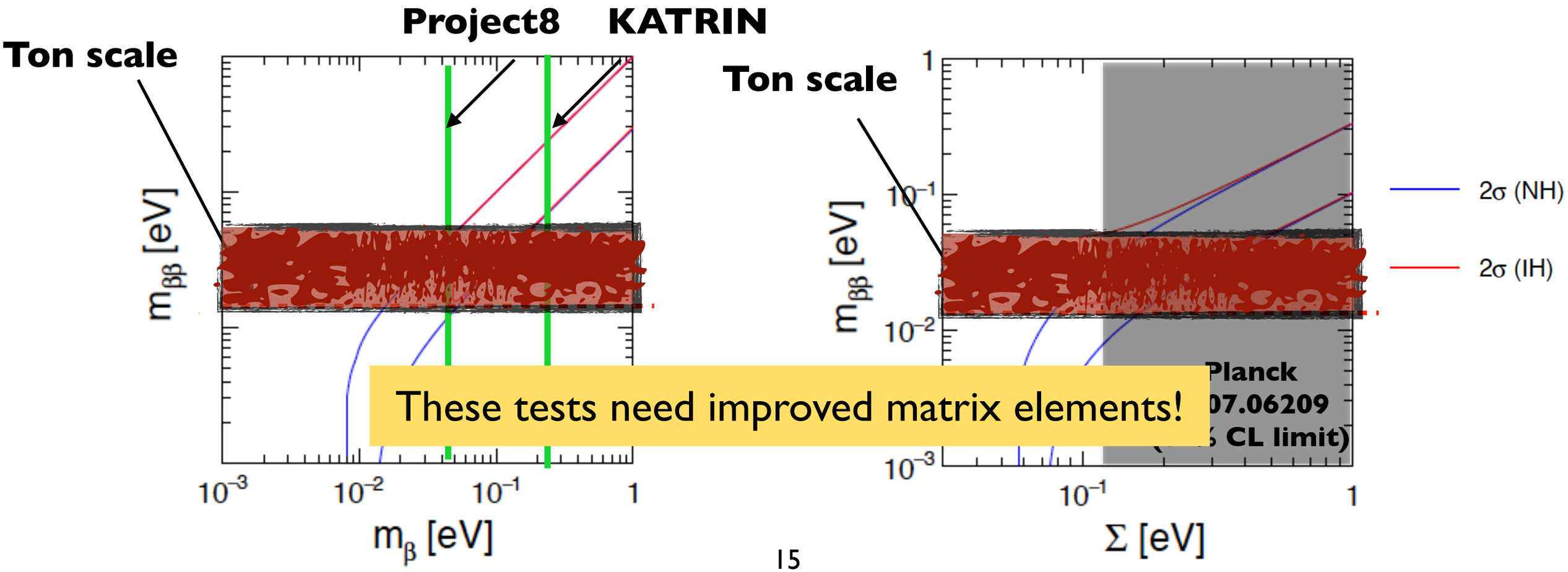
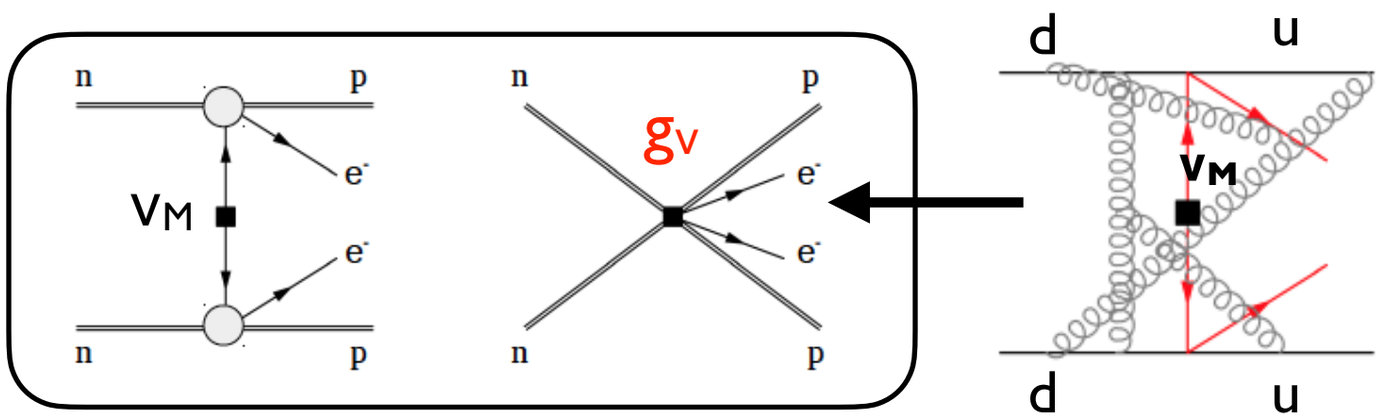


These tests need improved matrix elements!

(Recent theoretical developments)

- Insight from EFT: new NN contact interaction to leading order in Q/Λ_χ

$Q \sim k_F \sim m_\pi$
$\Lambda_\chi \sim$ GeV



VC, W. Dekens, J. de Vries, M. Graesser,
E. Mereghetti, S. Pastore, U. van Kolck 1802.10097

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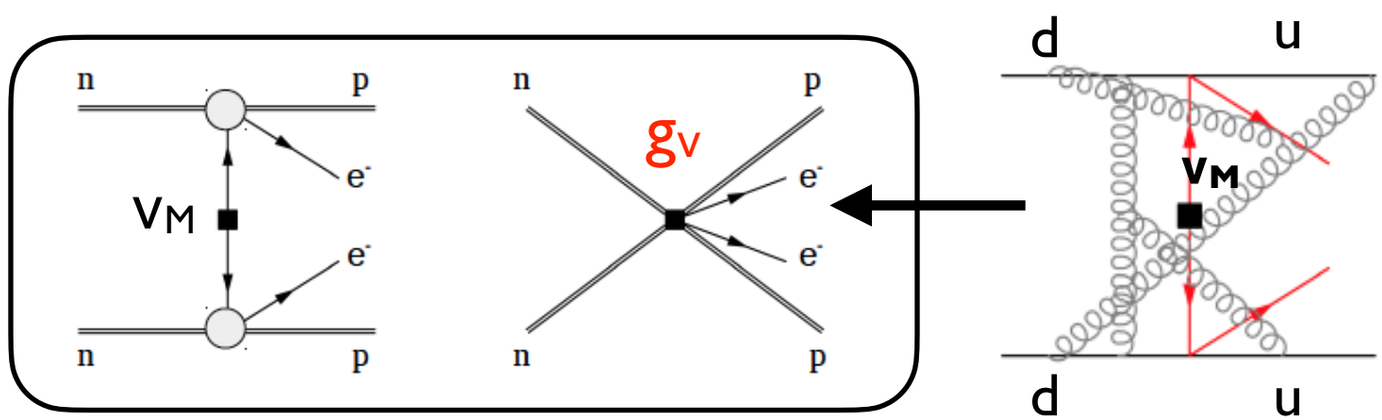

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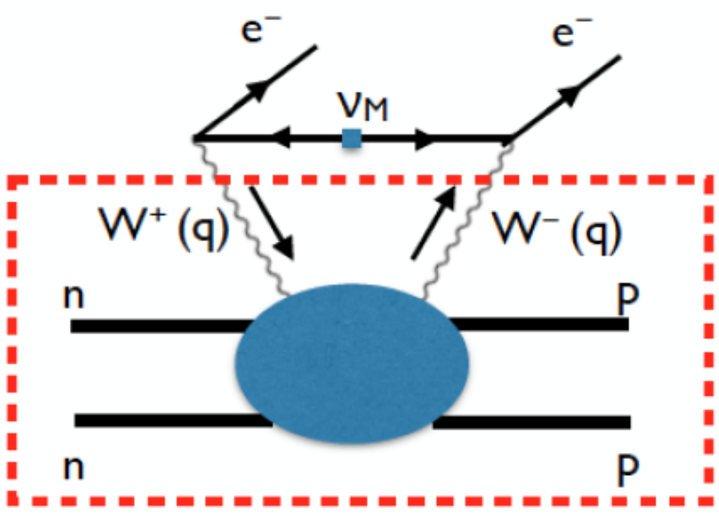
- g_V estimated through dispersive analysis [1] and used in first-principles calculation [2] of $^{48}Ca \rightarrow {}^{48}Ti$: contact term enhances n.m.e. by ~50%



[1] VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371
[2] Wirth, Yao, Hergert, 2105.05415

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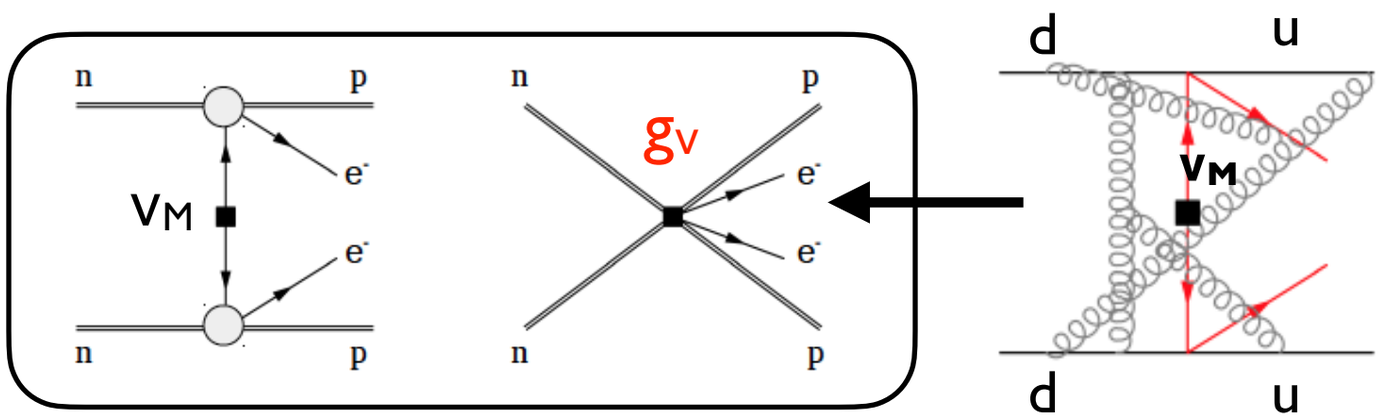

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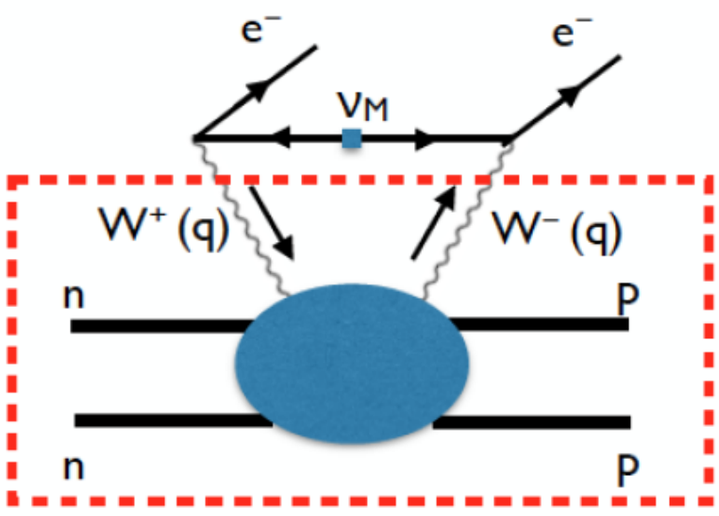

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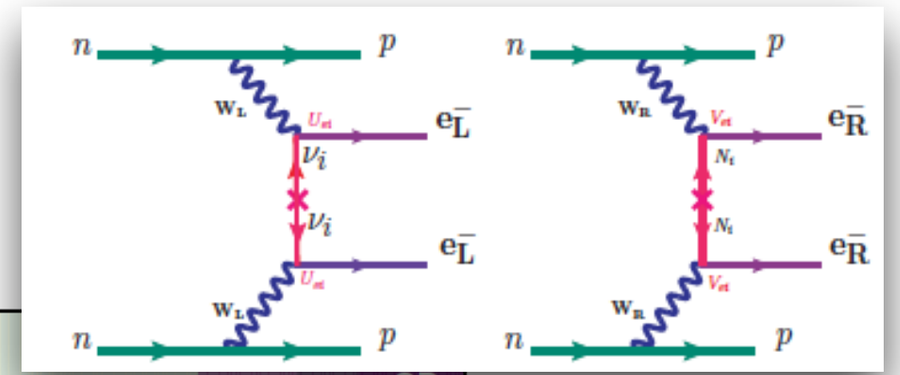
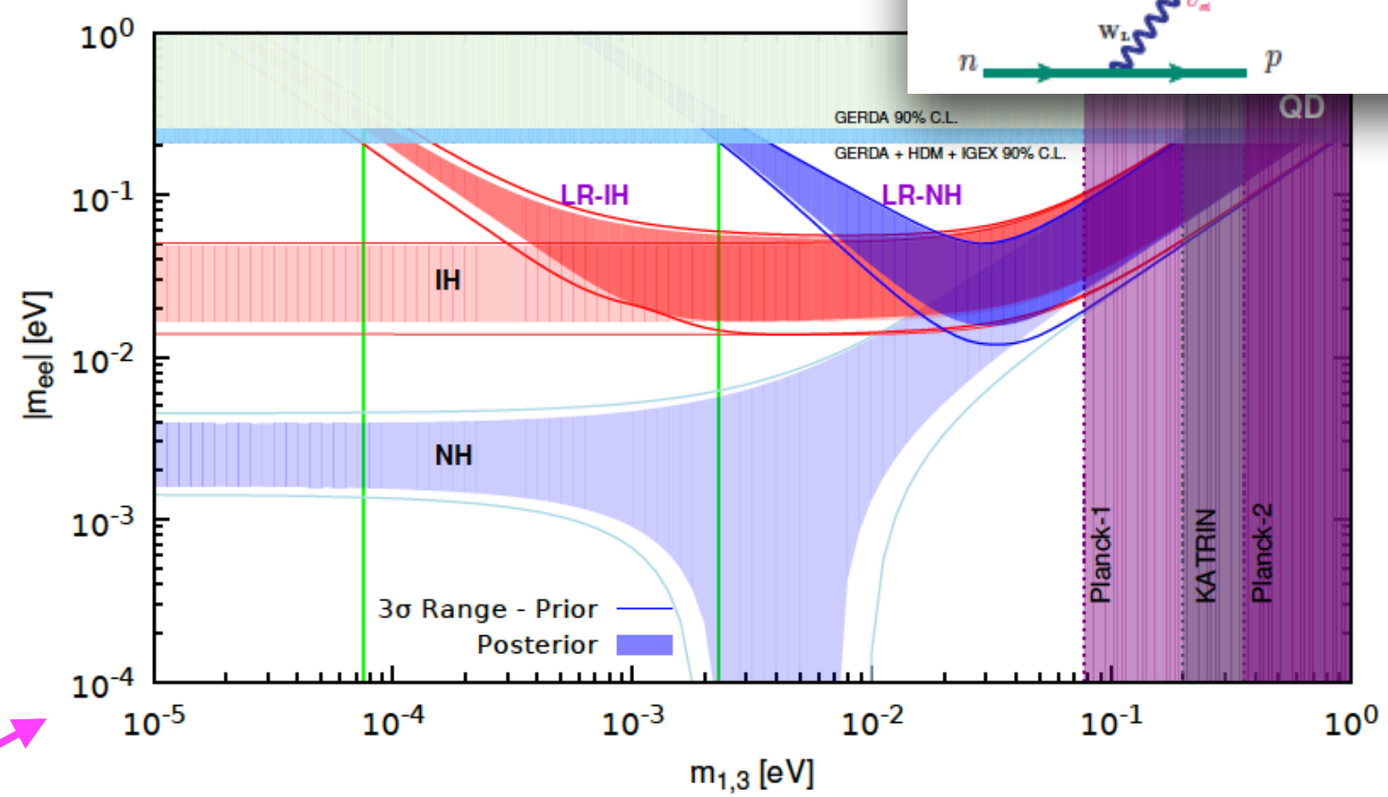
Future progress requires theoretical activity at the interface of EFT, lattice QCD, and nuclear structure

TeV-scale LNV (1)

- TeV-scale LNV induces contributions to 0νββ *not directly related to the exchange of light neutrinos,* within reach of planned experiments

Example: left-right symmetric model with type-II seesaw





$$M_i \propto m_i$$

$$V_R^{PMNS} = V_L^{PMNS}$$

$$M_i = \frac{m_1}{m_3} M_3, \text{ for NH}$$
$$M_i = \frac{m_1}{m_2} M_2, \text{ for IH.}$$

$M_{2,3}$ = 1 TeV

Tello-Nemevesek-Nesti-Senjanovic-Vissani 1011.3522

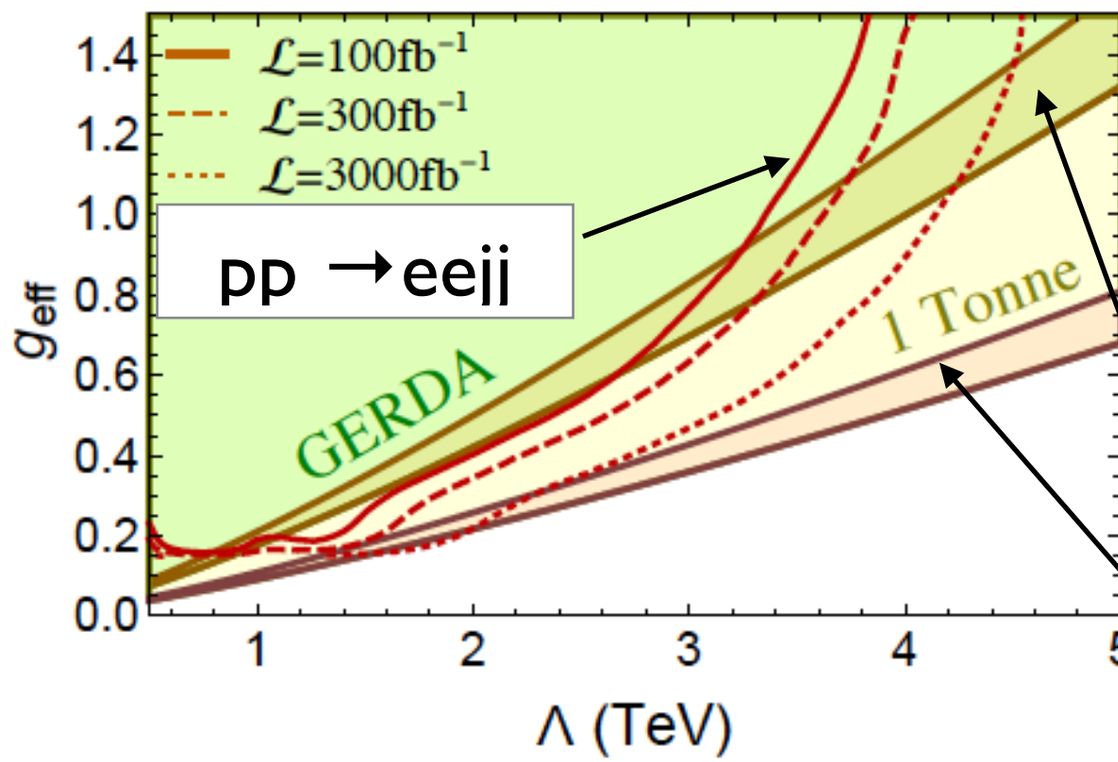
Ge-Lindner-Patra 1508.07286

...

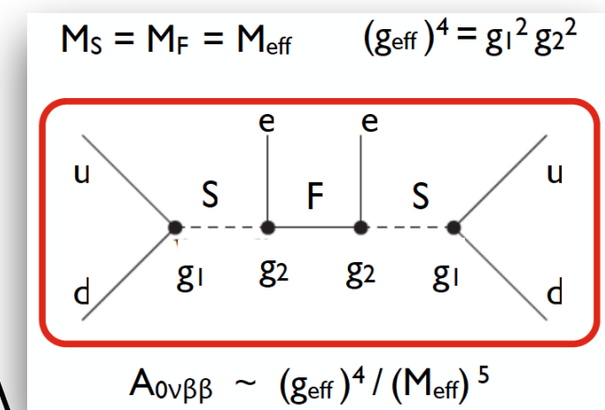
TeV-scale LNV (2)

- May lead to correlated (and possibly precursor!) signal at LHC: pp →ee jj

Keung-Senjanovic '83
...
Peng, Ramsey-Musolf, Winslow, 1508.0444
...
Cai, Han, Li, Ruiz 1711.02180
...



Simplified model



Hadronic / nuclear uncertainty

- LHC searches important to unravel origin of LNV and implications for letpogenesis

Deppisch-Harz-Hirsch 1312.4447, Deppisch-Graf-Harz-Huang 1711.10432, ...

Experimental landscape

- Ton-scale experiments with different isotopes and technologies under way, with sensitivity up to $T_{1/2} \sim 10^{28}$ yr

- Extending the reach is motivated for either outcome of ton-scale program:
  - Post-discovery → 'diagnosing phase': isotope dependence [*], single electron spectra and angular distribution. [*] Need improved matrix elements!
  - Continue the 'search phase': $T_{1/2} \sim 10^{30}$ yr well motivated target

Experimental landscape

- Ton-scale experiments with different isotopes and technologies under way, with sensitivity up to $T_{1/2} \sim 10^{28}$ yr

-

0νββ experiments offer significant discovery opportunity:
we simply don't know the origin of m_ν and the scale Λ associated with LNV

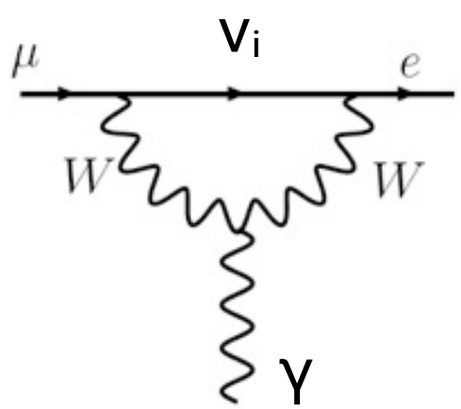
Broader output of these experiments:
new physics in 2νββ (Majorons, …), dark matter searches, …

on

Probing Lepton Flavor Violation with charged leptons

LFV and new physics

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



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

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

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

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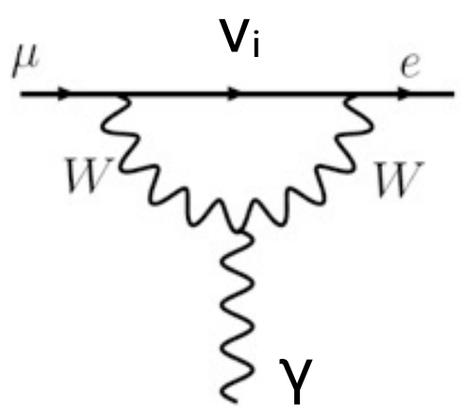

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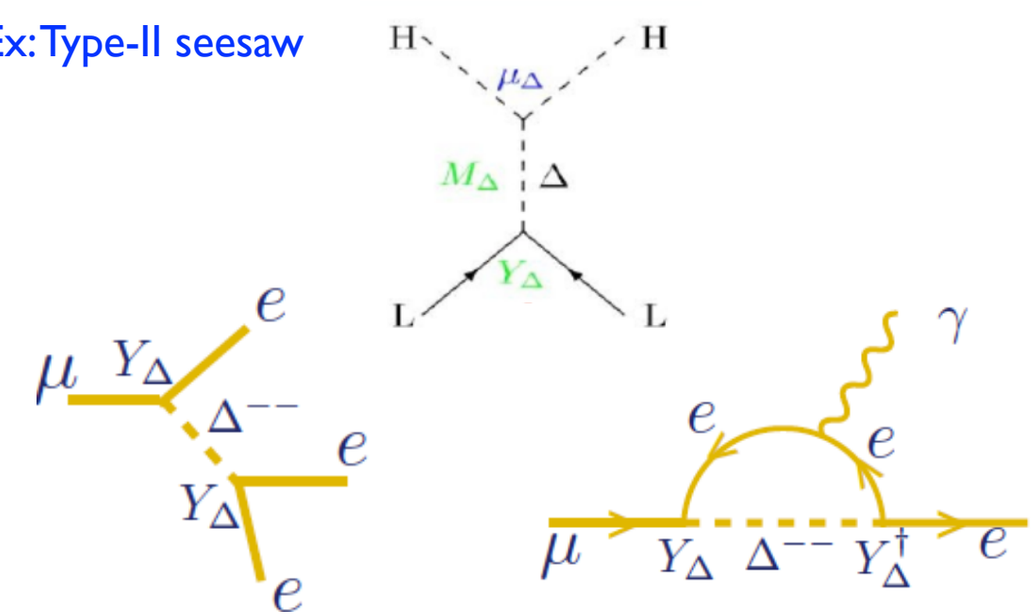
Petcov '77, Marciano-Sanda '77, Shrock '77…

- Clean probe of BSM physics
- Related to origin of neutrino mass

Ex: Type-II seesaw



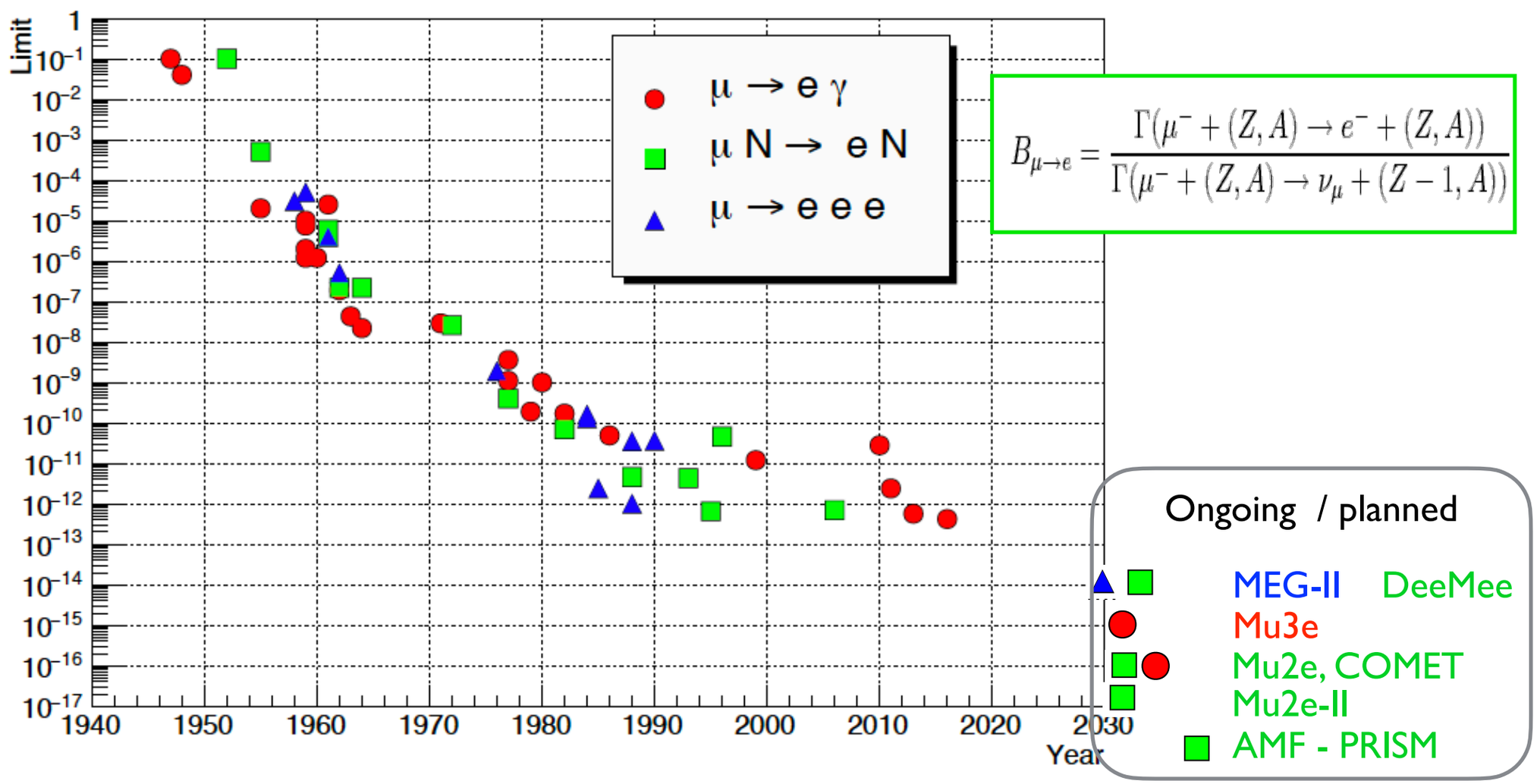
LFV probes across energy scales

- Decays of μ, τ (and mesons)

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

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

Modified from Calibbi-Signorelli 1709.00294



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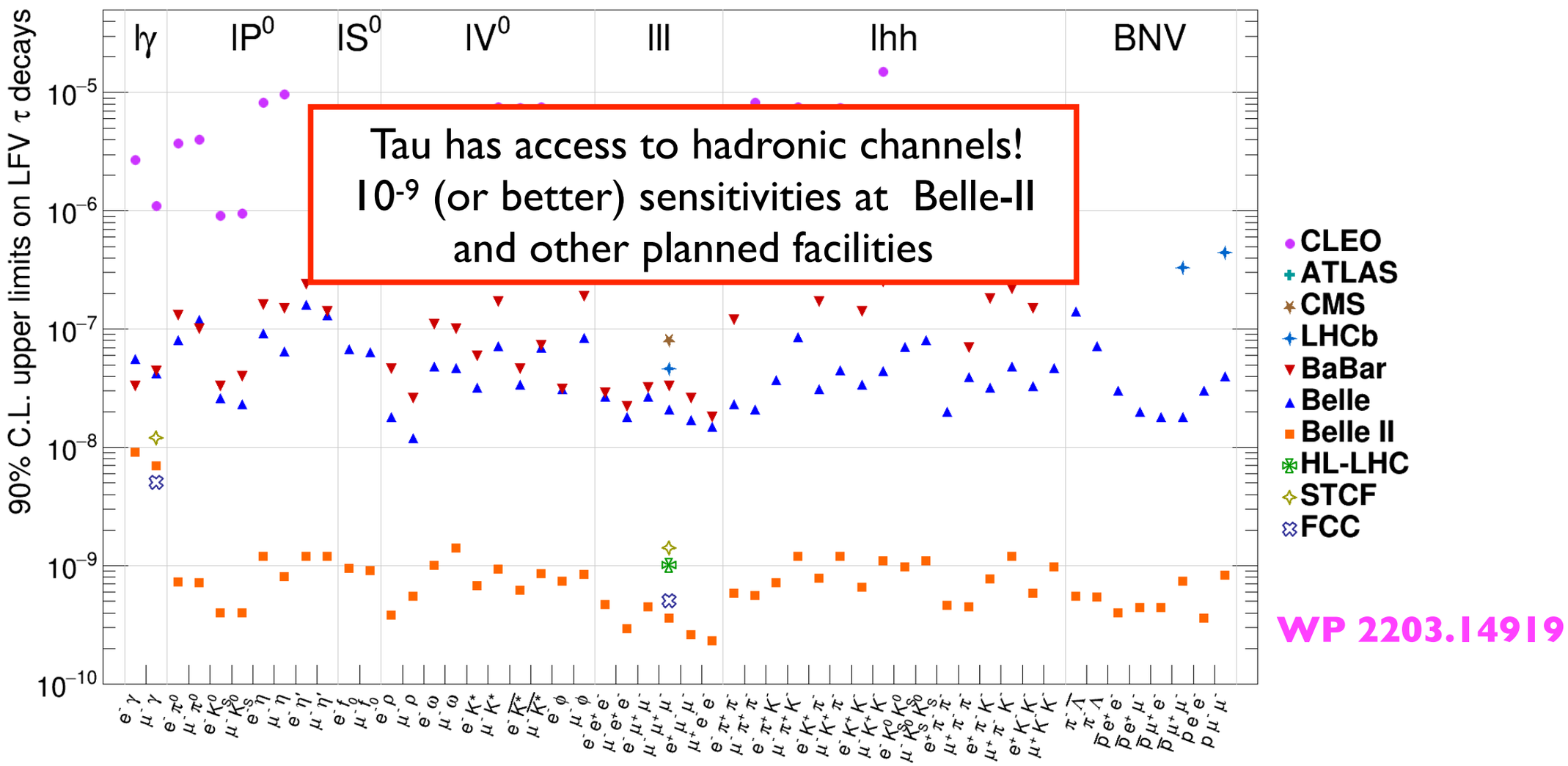

Tau has access to hadronic channels!
10^{-9} (or better) sensitivities at Belle-II
and other planned facilities

WP 2203.14919

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- Collider processes:

LHC

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

$$pp \to \ell_\alpha \bar{\ell}_\beta + X$$

HERA, EIC

$$ep \to \ell + X$$

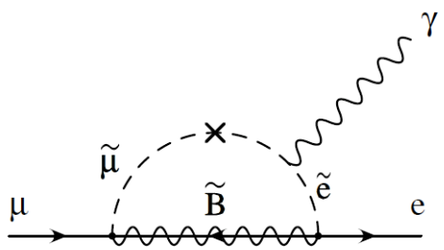
Connecting scales

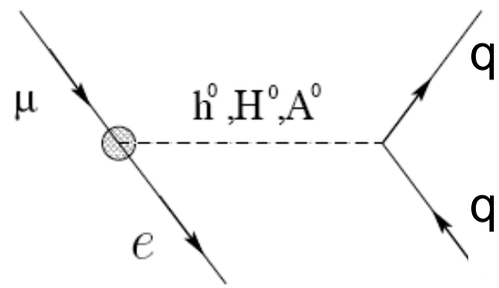
M

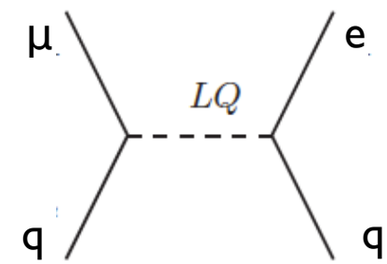
Λ

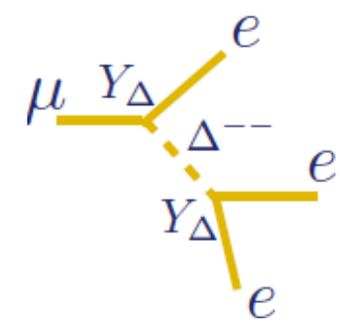
v_{ew}

Λ_X









...

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, …

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(Will not discuss the interesting case of ALPs with LFV couplings, see Calibbi et al. 2006.04795)

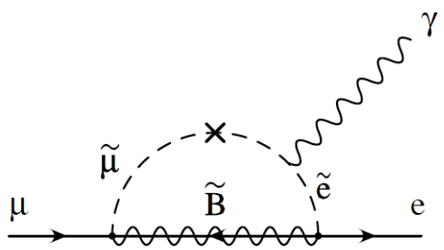
Connecting scales

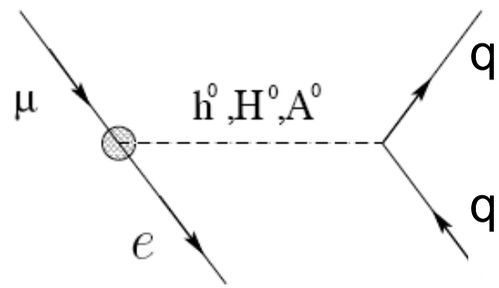
M

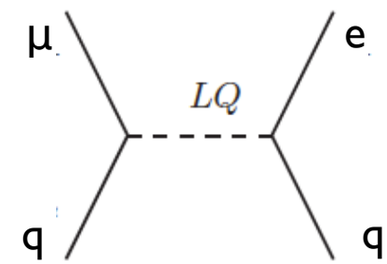
Λ

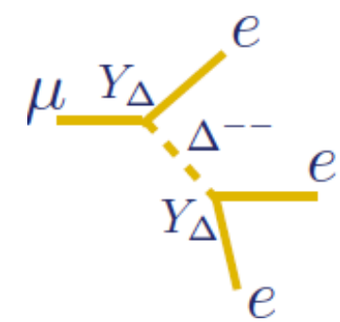
v_{ew}

Λ_χ









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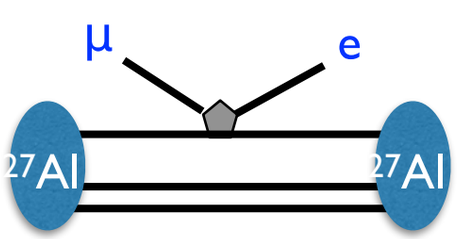
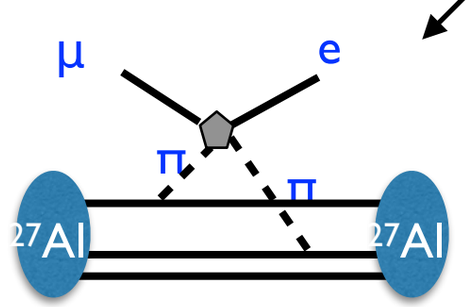
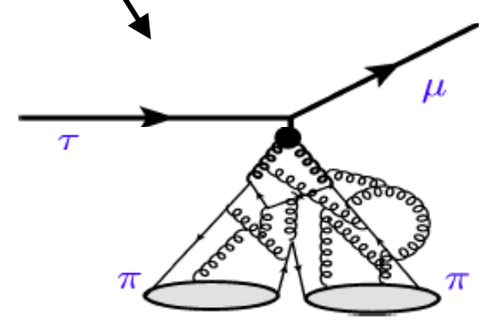






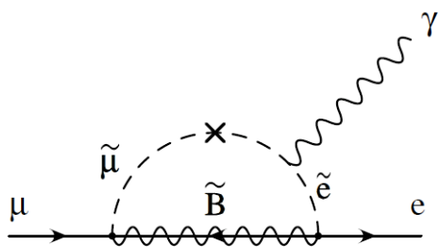
Connecting scales

M

Λ

v_{ew}

Λ_X



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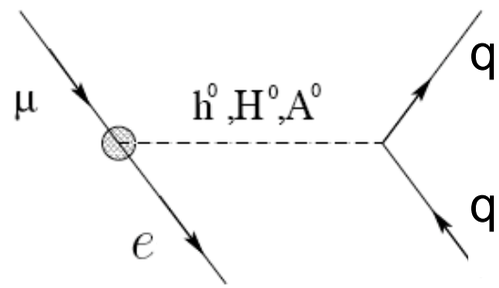

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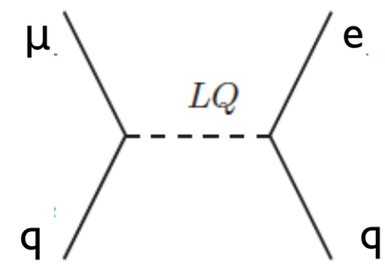
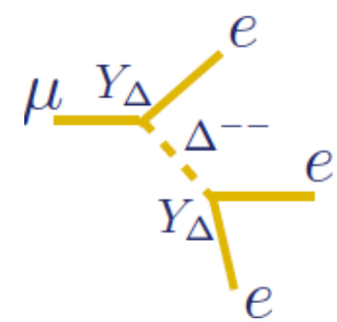


Vector Type III seesaw, LRSM, leptoquarks, …



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

…

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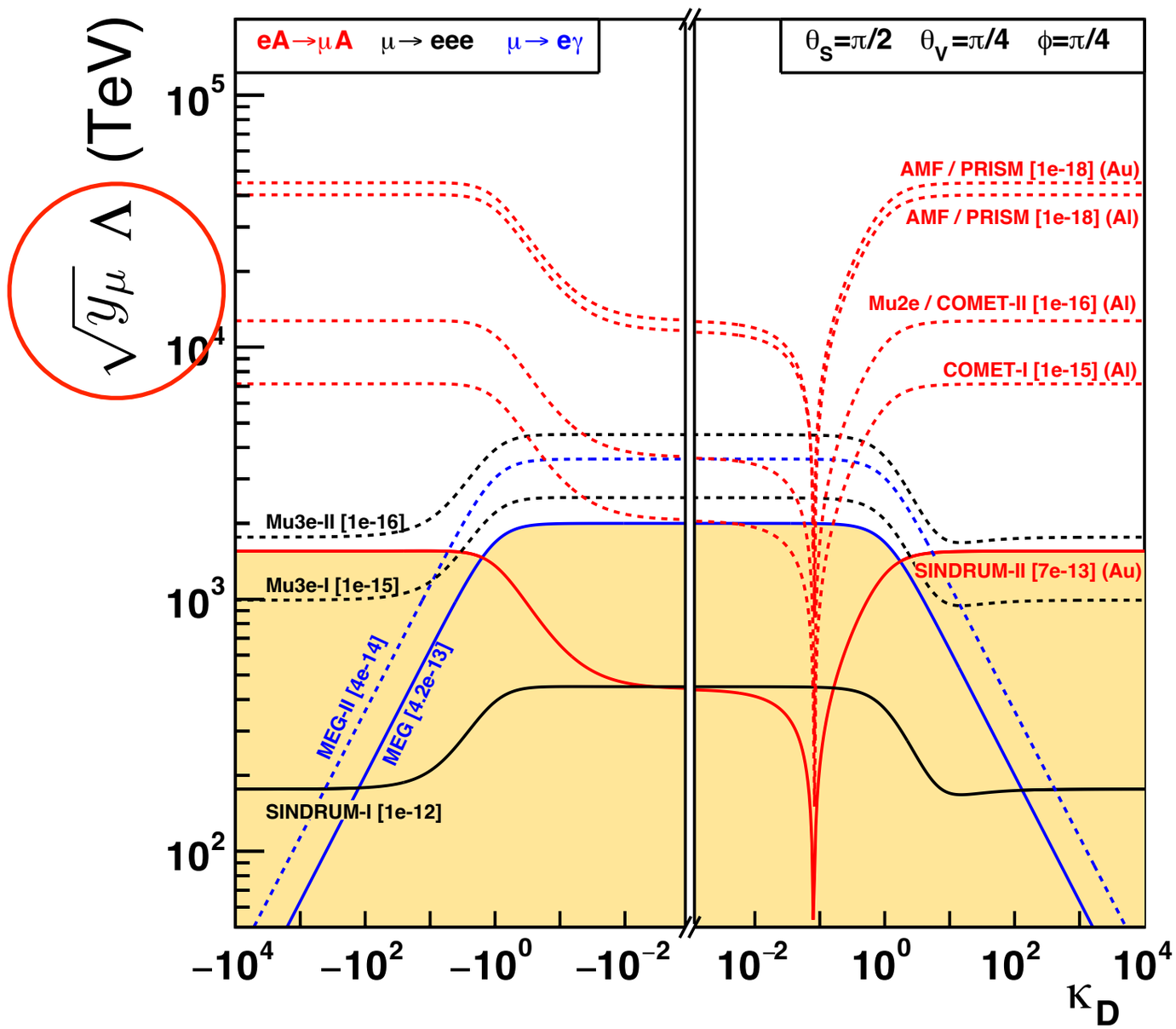
$$BR_{\alpha\to\beta} \sim (v_{ew}/\Lambda)^4 * |(C_n)^{\alpha\beta}|^2$$

What scales are we probing?

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)

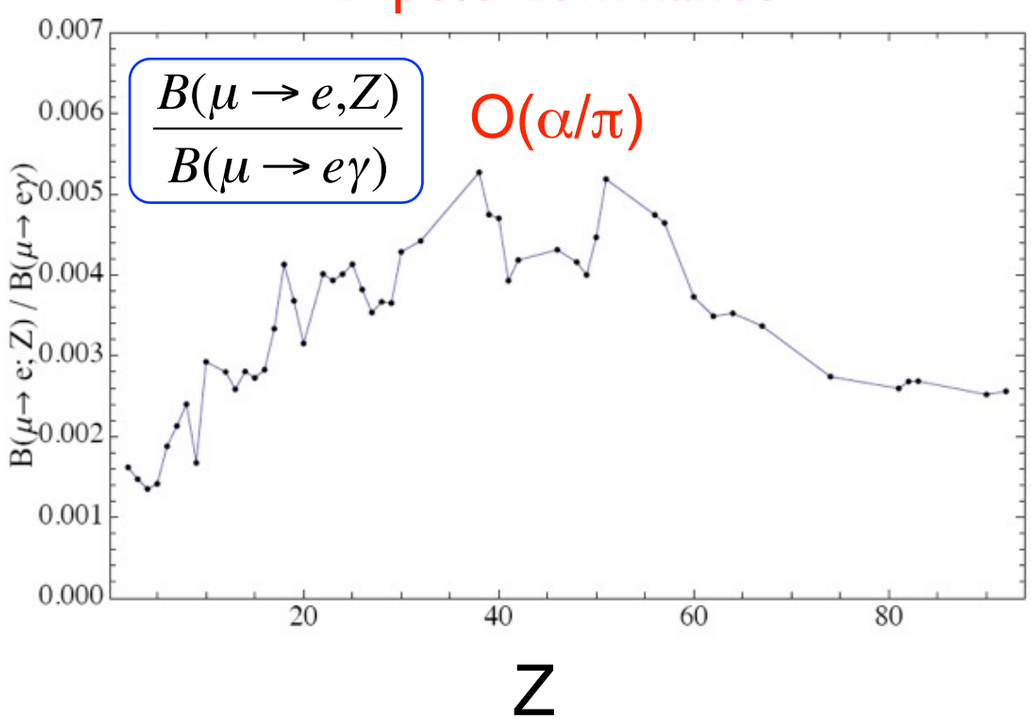
$|\kappa_D| << 1$ dipole dominant
$|\kappa_D| >> 1$ four-fermion dominant

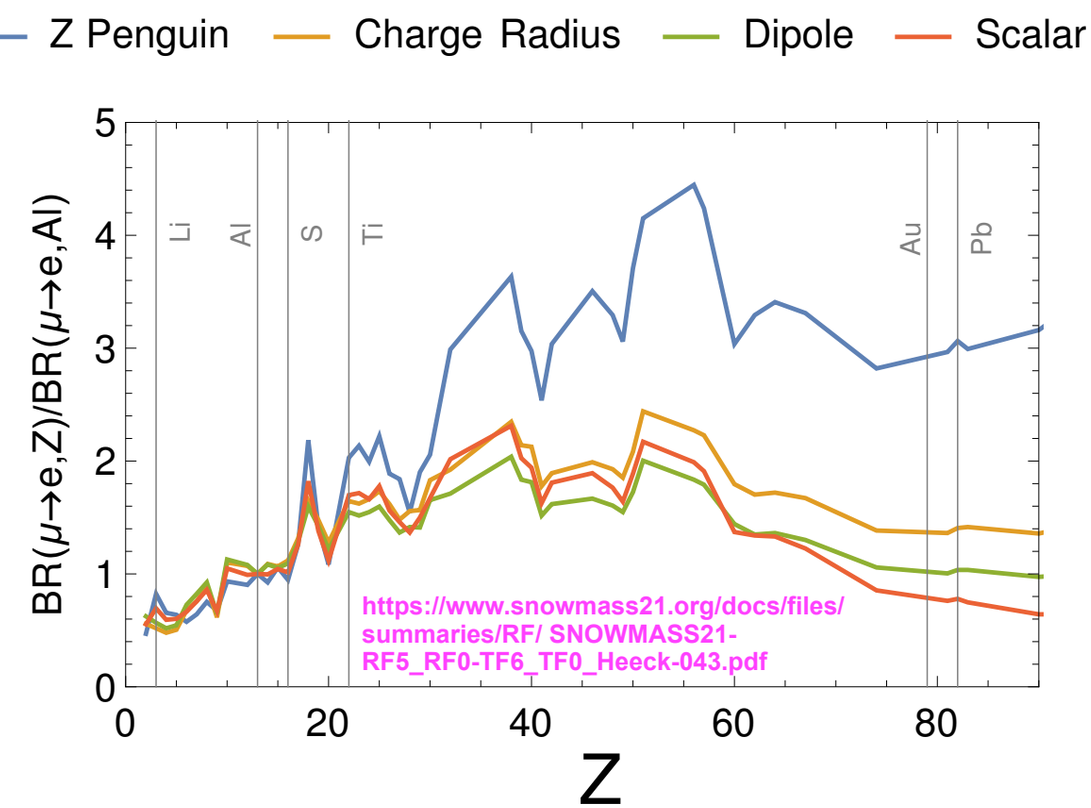
- Very high scale probed!
- Notion of 'best probe' is model-dependent
- Discovery opportunities in current and planned searches

μ-e sector: diagnosing tools

- Extract info on effective couplings by comparing μ →e to μ →eγ and through target-dependence of μ →e conversion

Dipole dominance





Kitano-Koike-Okada hep-ph/0203110, VC-Kitano-Okada-Tuzon 0904.0957, Heek-Szafron-Uesaka 2203.00702, ...

μ-e sector: diagnosing tools

- Extract info on effective couplings by comparing $\mu \to e$ to $\mu \to e\gamma$ and through target-dependence of $\mu \to e$ conversion

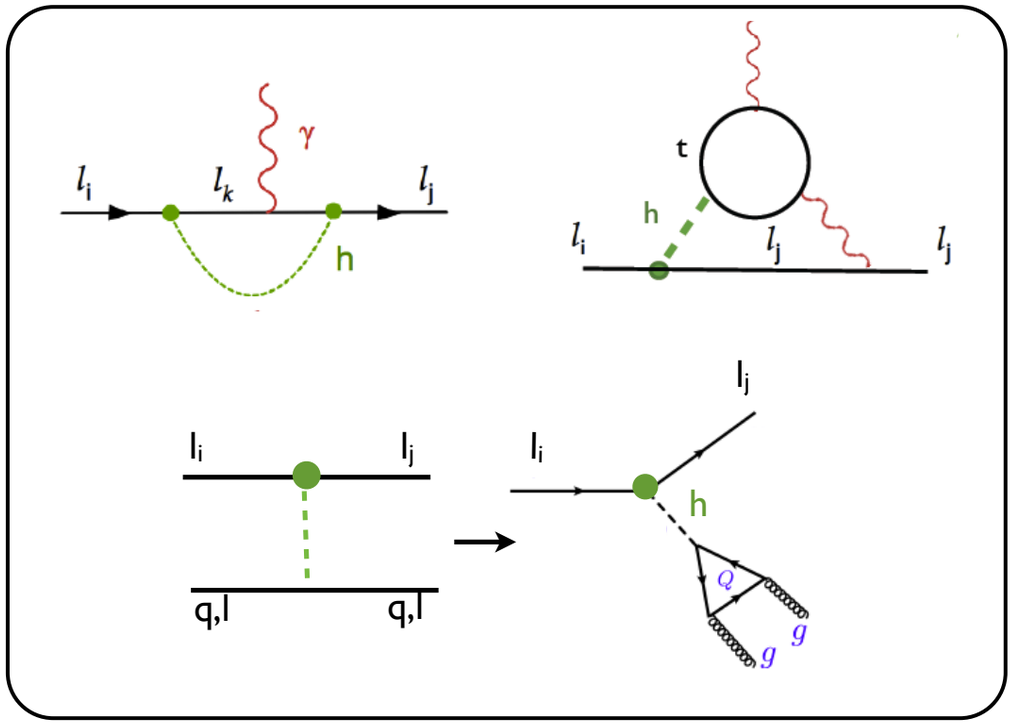
- Example: Higgs-mediated LFV
- $\mu \to e\gamma$ is currently probing $|Y_{\mu e}| \sim 10^{-6}$ ($BR(h \to \mu e) < 10^{-9}$)
- Correlated signals in $\mu \to e$ transitions

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

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

VC, Fuyuto, Ramsey-Musolf, Rule 2203.09547

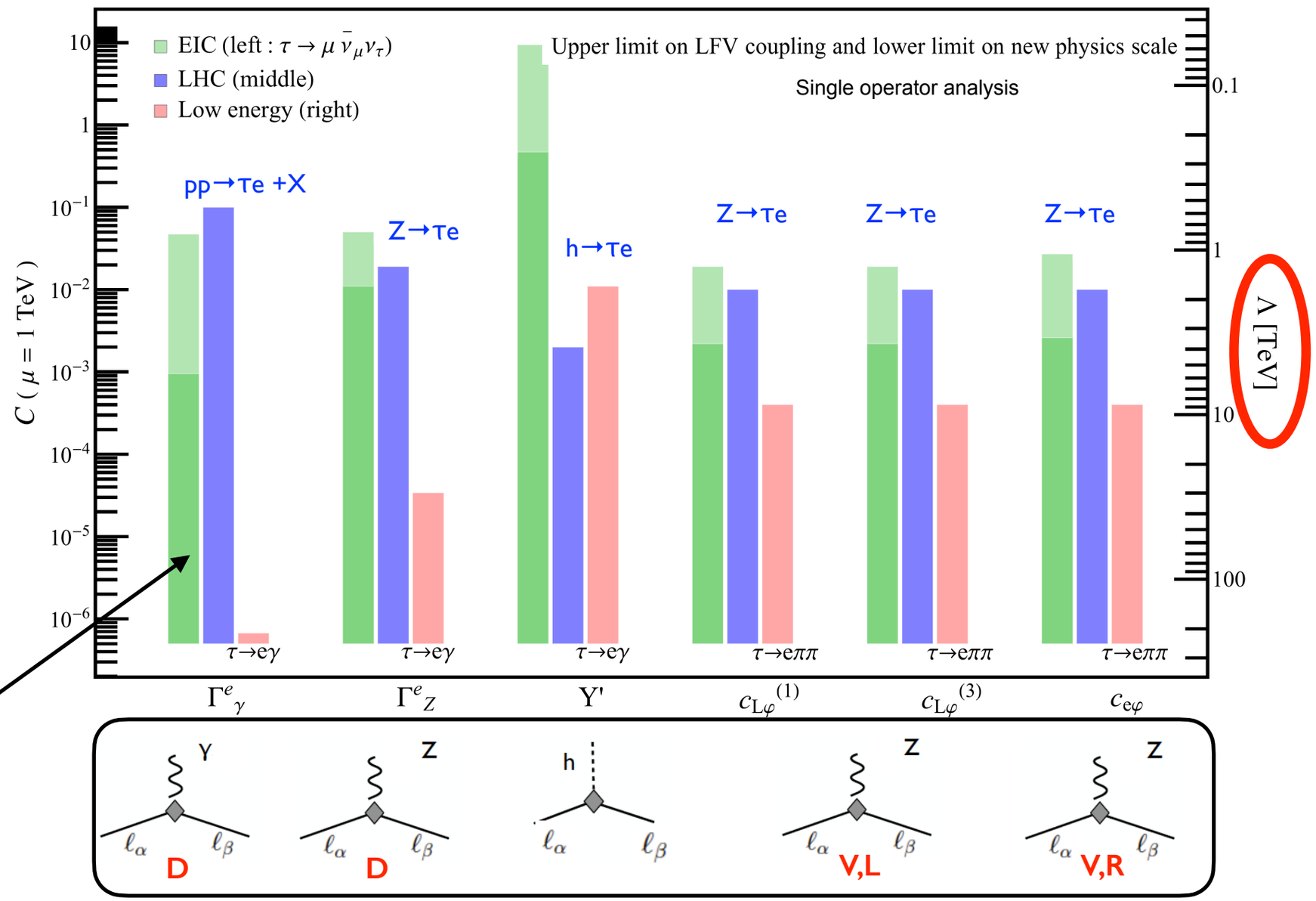
Harnik-Kopp-Zupan 1209.1397, ...



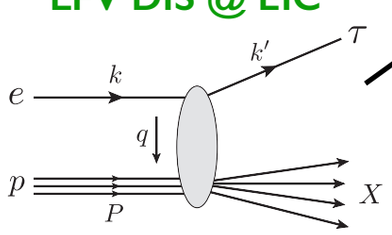
τ-e(μ) sector: mass reach (1)

- For certain operators, Higgs decay and LFV Drell-Yan compete

VC-Fuyuto-Lee-Mereghetti-Yan 2102.06176



LFV DIS @ EIC

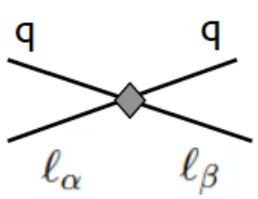


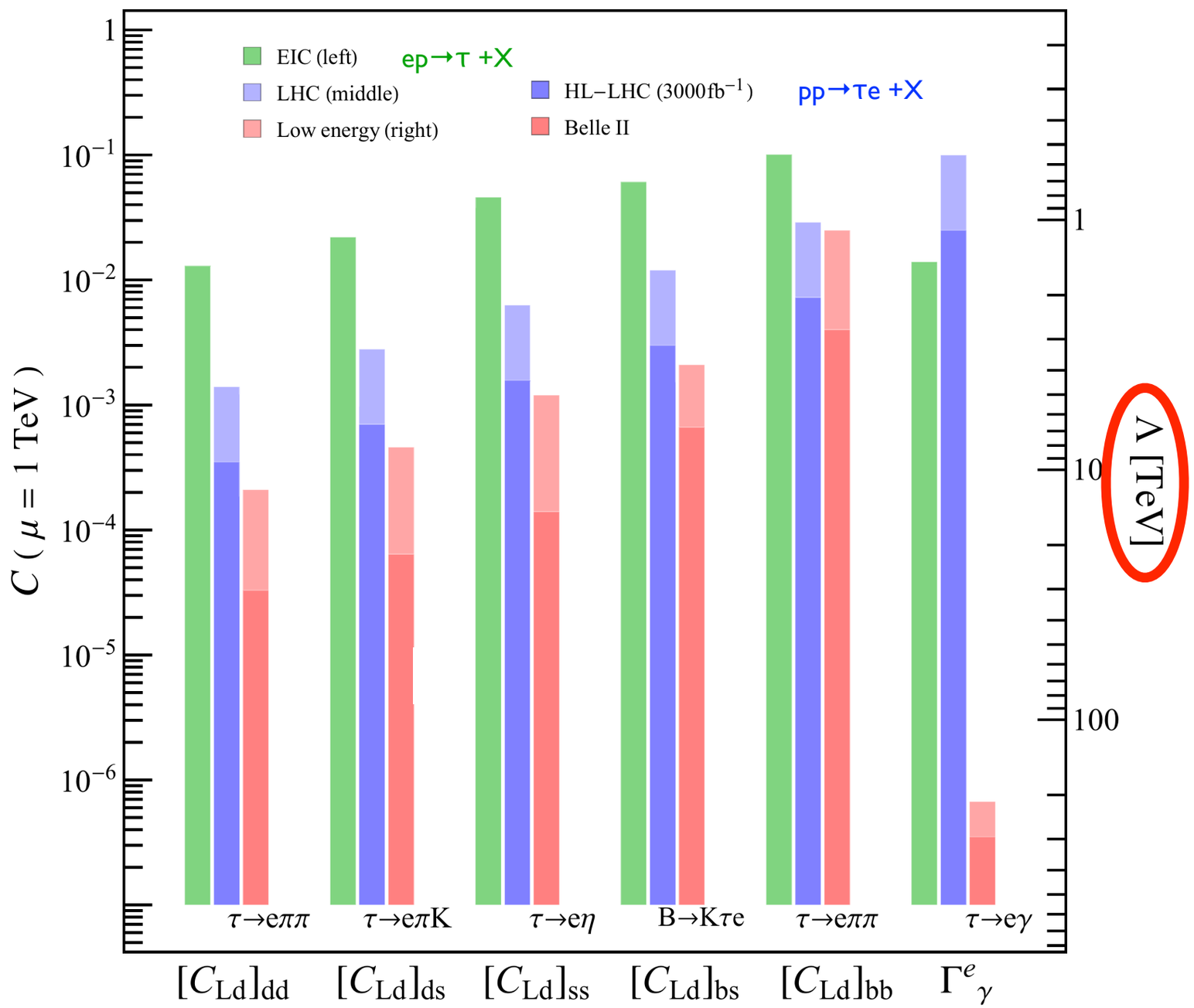
(Similar pattern for τ-μ, without EIC)

τ-e(μ) sector: mass reach (2)

- For many other operators, bounds dominated by τ (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)

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 $\mu \to e$ compared to $\tau \to \mu$:

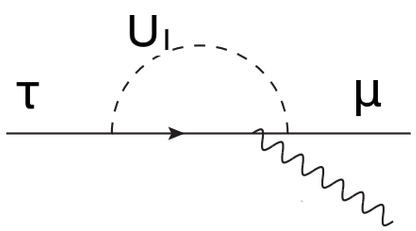
Leptonic MFV:	$BR(\mu \to e\gamma) / BR(\tau \to \mu\gamma) \sim s_{13}^2 \sim 10^{-2}$
GUT models:	$BR(\mu \to e\gamma) / BR(\tau \to \mu\gamma) \sim \lvert V_{us}\rvert^6 \sim 10^{-4}$

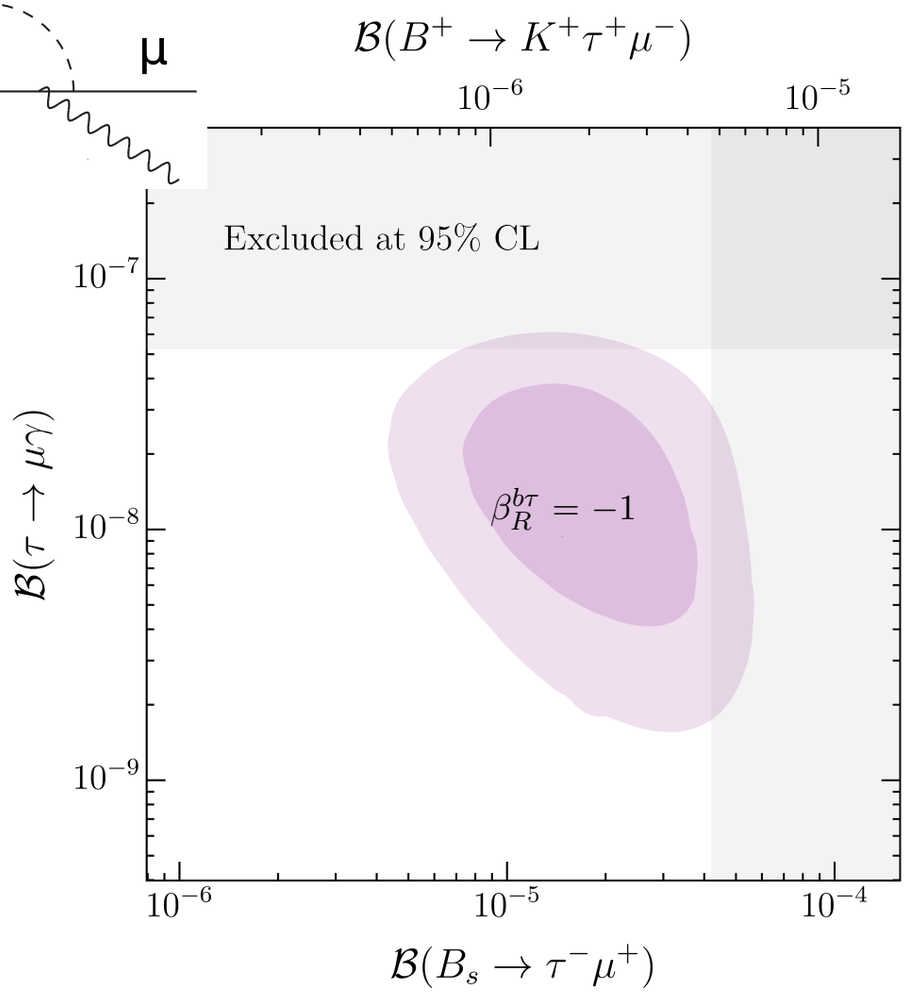
VC-Grinstein-Isidori-Wise, hep-ph/0507001, hep-ph/0608123

Barbieri-Hall-Strumia, hep-ph/9501334

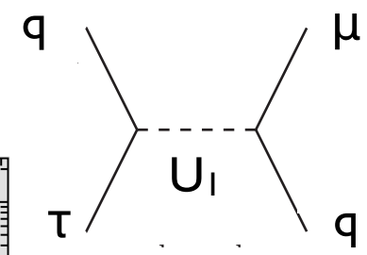
Connection with LFU in B decays

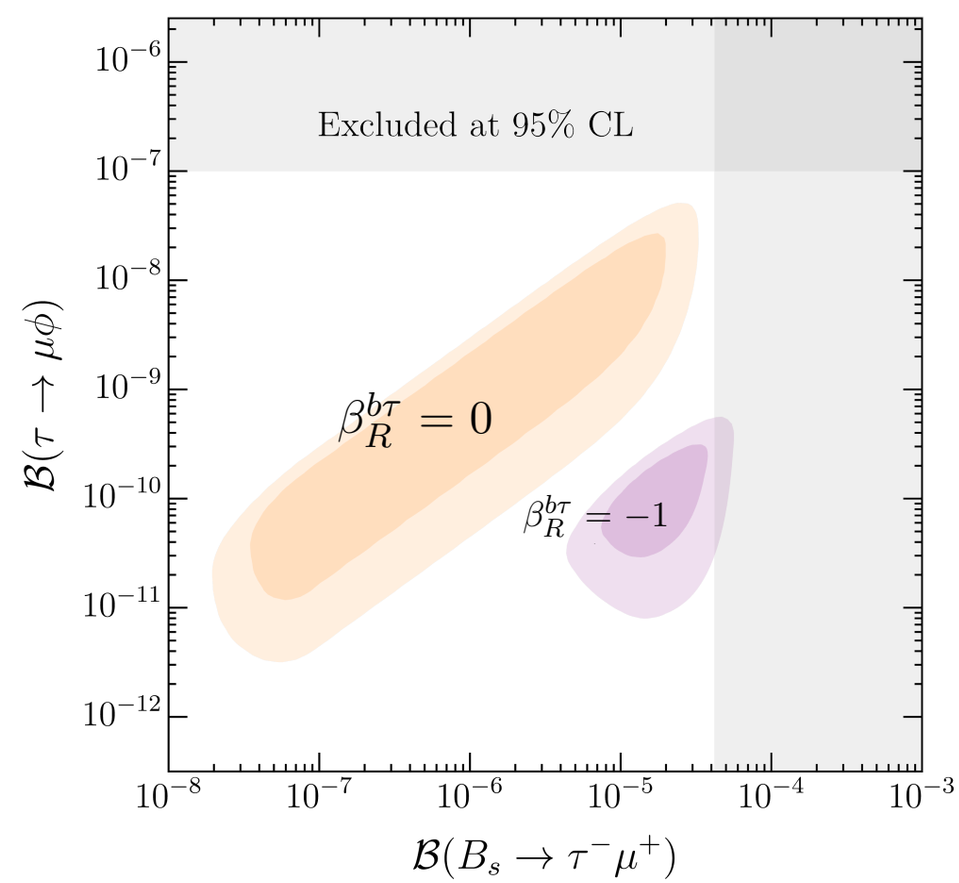
- *Interesting case*: U_1 (3,1,2/3) vector leptoquark accounts for B 'anomalies'
- Fitting low-energy data sets the scale ⇒ preferred ranges for LFV tau (and B) decays not far from current limits
- Also testable at the LHC through U_1 pair production and pp → ττ + X





$$J_\mu^U = \beta_L^{i\alpha}\,(\bar{q}_L^i \gamma_\mu \ell_L^\alpha) + \beta_R^{i\alpha}\,(\bar{d}_R^i \gamma_\mu e_R^\alpha)$$



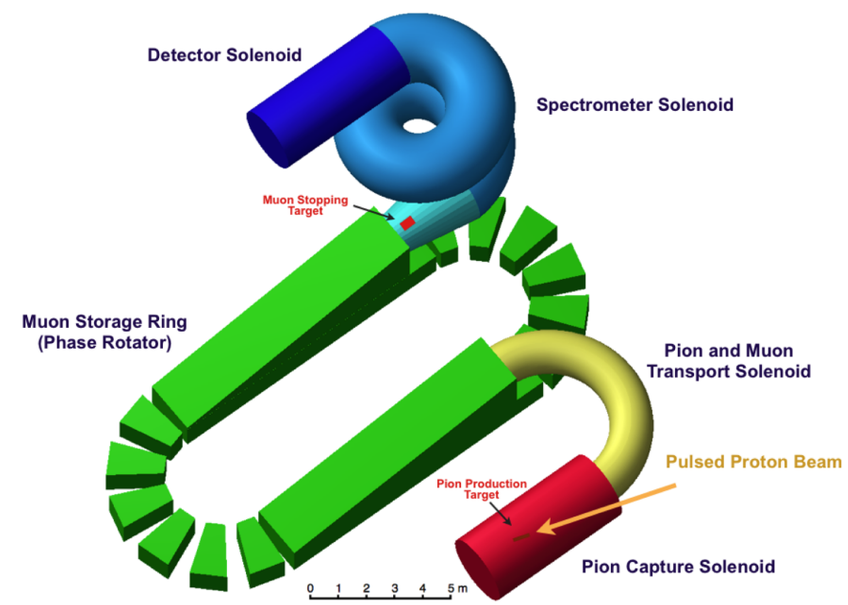


Cornella et al., 2103.16558

Experimental landscape

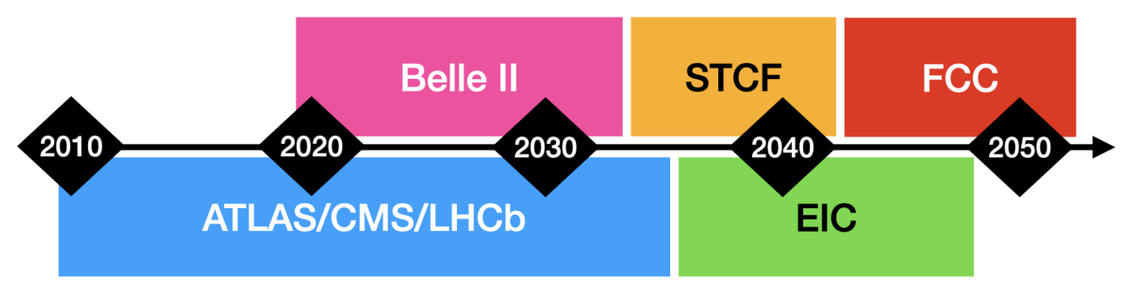
- Key facilities for muons: FNAL, J-PARC, PSI

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,…

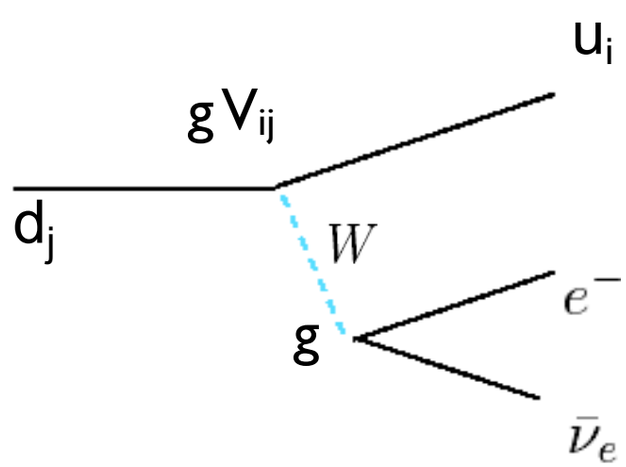
- Current / next gen. experiments relevant for CLFV in tau (and mesons)



Probing Cabibbo and lepton universality with light quark decays

Semileptonic decays in the SM and beyond

- In the SM, W exchange $\Rightarrow$ universality relations



$G_F^{(\beta)} \sim g^2 V_{ij}/M_w^2 \sim G_F^{(\mu)} V_{ij} \sim 1/v^2 V_{ij}$

Cabibbo universality

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

Lepton Flavor Universality (LFU)

$$[G_F]_e / [G_F]_\mu = 1$$

Semileptonic decays in the SM and beyond

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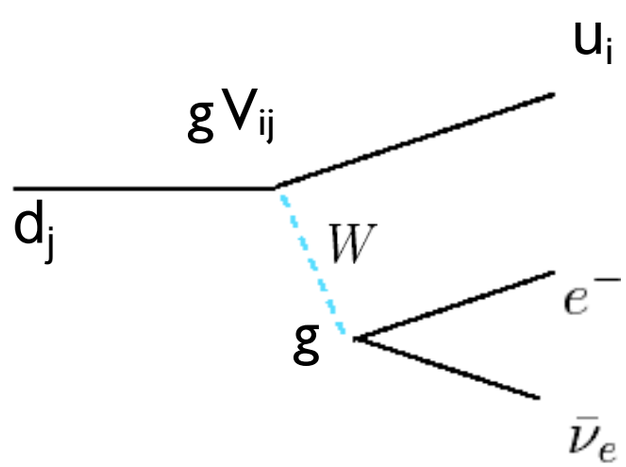

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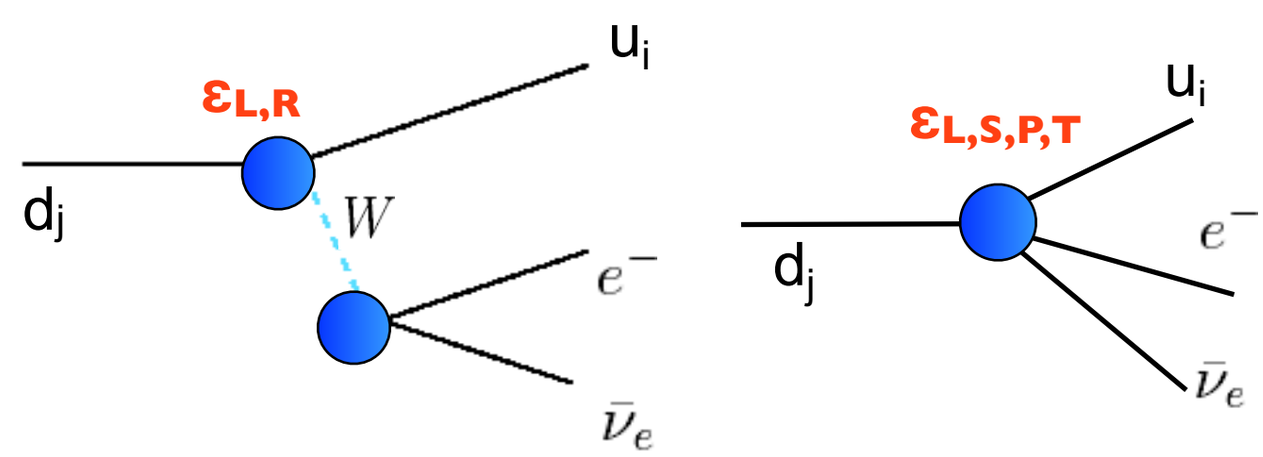
Cabibbo universality

$$|V_{ud}|^2 + |V_{us}|^2 + \cancel{|V_{ub}|^2} = 1$$

$$[G_F]_e/[G_F]_\mu = 1$$

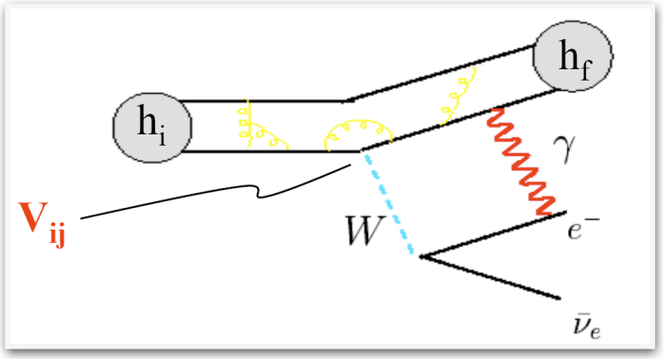
Lepton Flavor Universality (LFU)

- BSM effects $\varepsilon \sim (v/\Lambda)^2$, can spoil universality. Precision of 0.1-0.01% probes $\Lambda > 10$ TeV



Probing Cabibbo universality

Extract $V_{ud}=\cos\theta_C$ and $V_{us}=\sin\theta_C$ from various channels

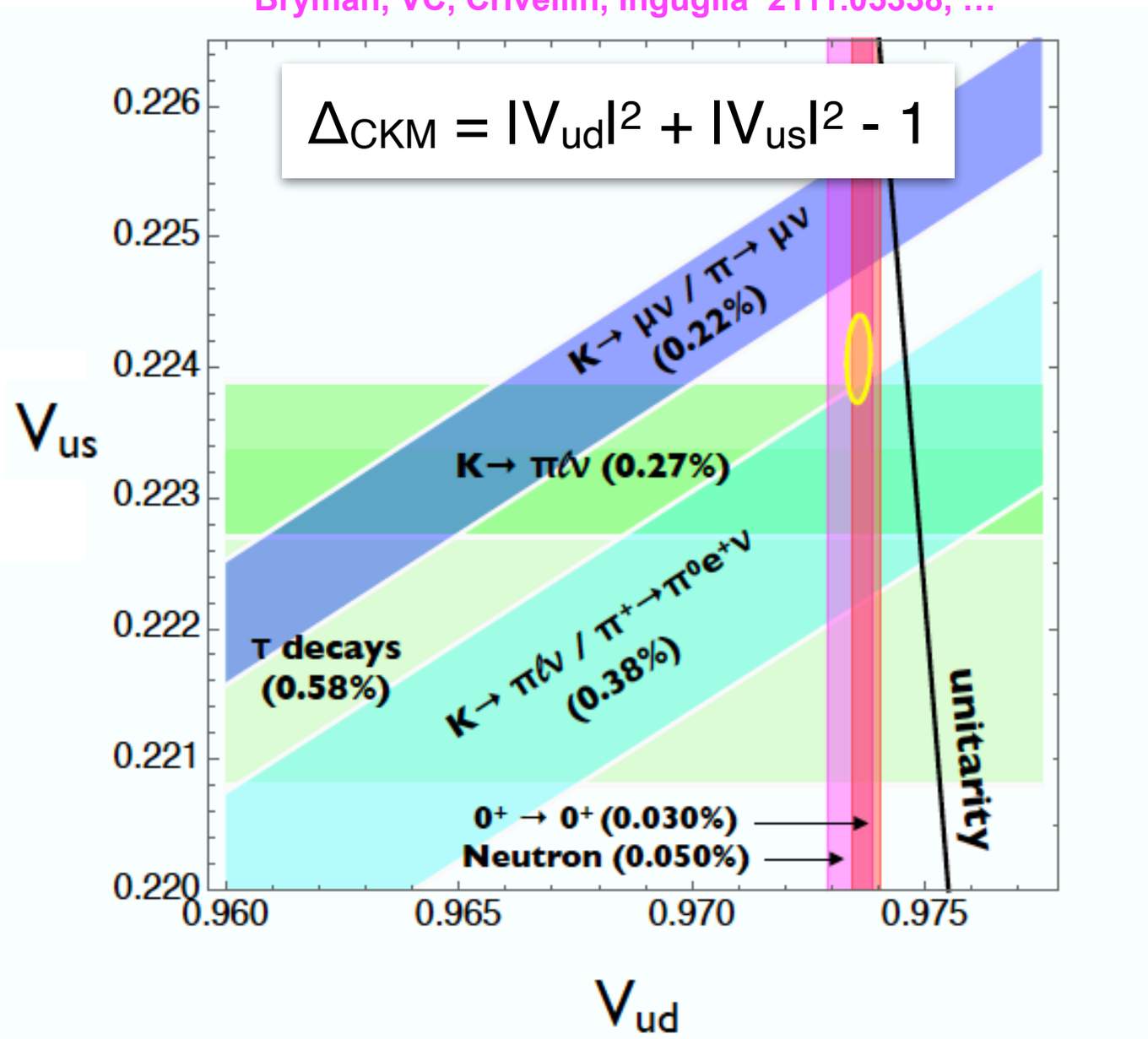


$$\Gamma_k = (G_F^{(\mu)})^2 \times |V_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\delta_{RC}) \times F_{\rm kin}$$

Input from *many* experiments and theory papers

Probing Cabibbo universality

Bryman, VC, Crivellin, Inguglia 2111.05338, …



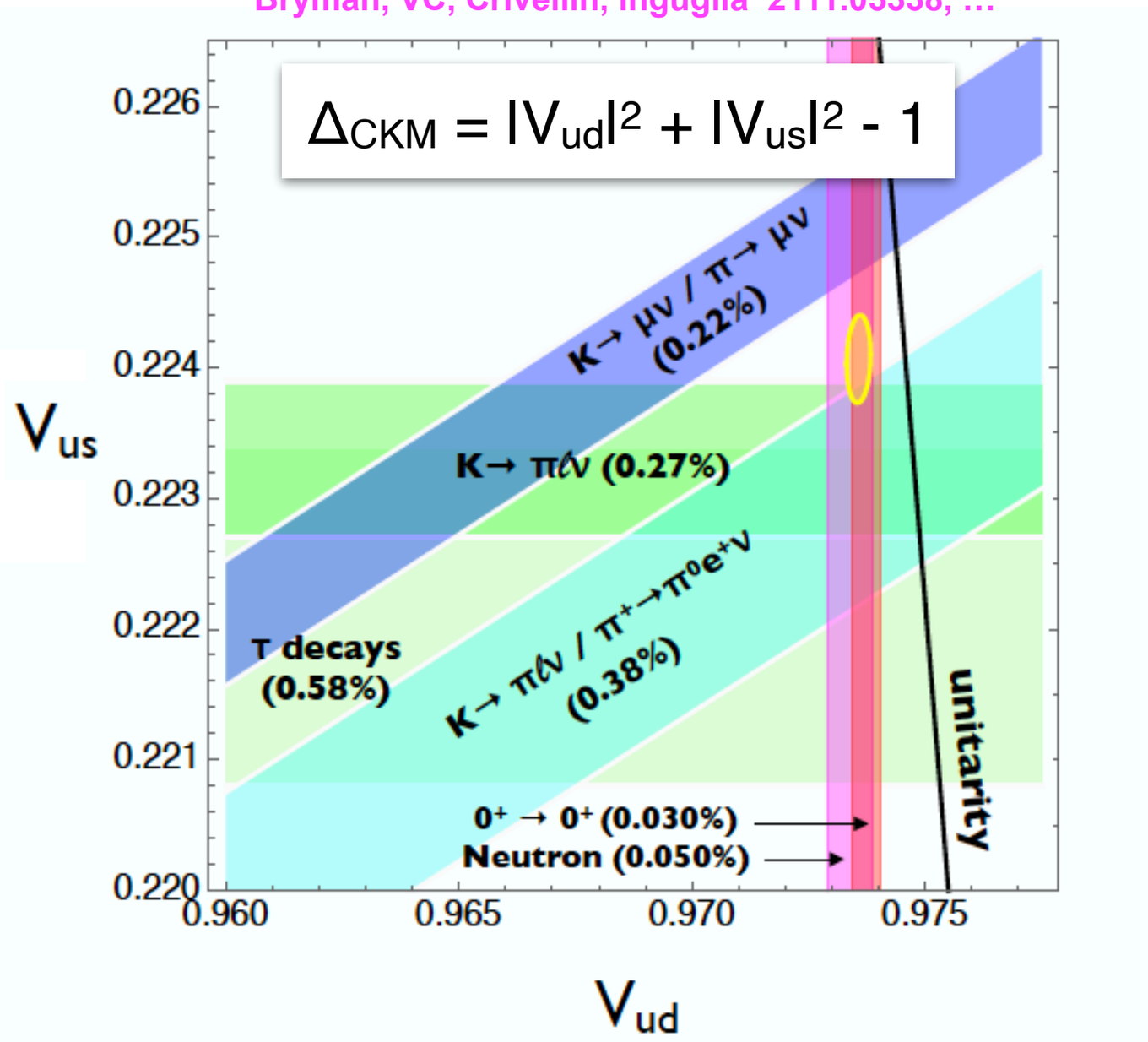
$$\Delta_{CKM} = (-19.5 \pm 5.3) \times 10^{-4}$$

χ^2/dof = 2.8, S=1.67

- Neutron and nuclear decays compatible
- ~3 sigma problem in meson sector (Kl2 vs Kl3)
- ~4 sigma effect in global fit
- ~3 sigma effect persists if one removes nuclear decays from the fit

Probing Cabibbo universality

Bryman, VC, Crivellin, Inguglia 2111.05338, …



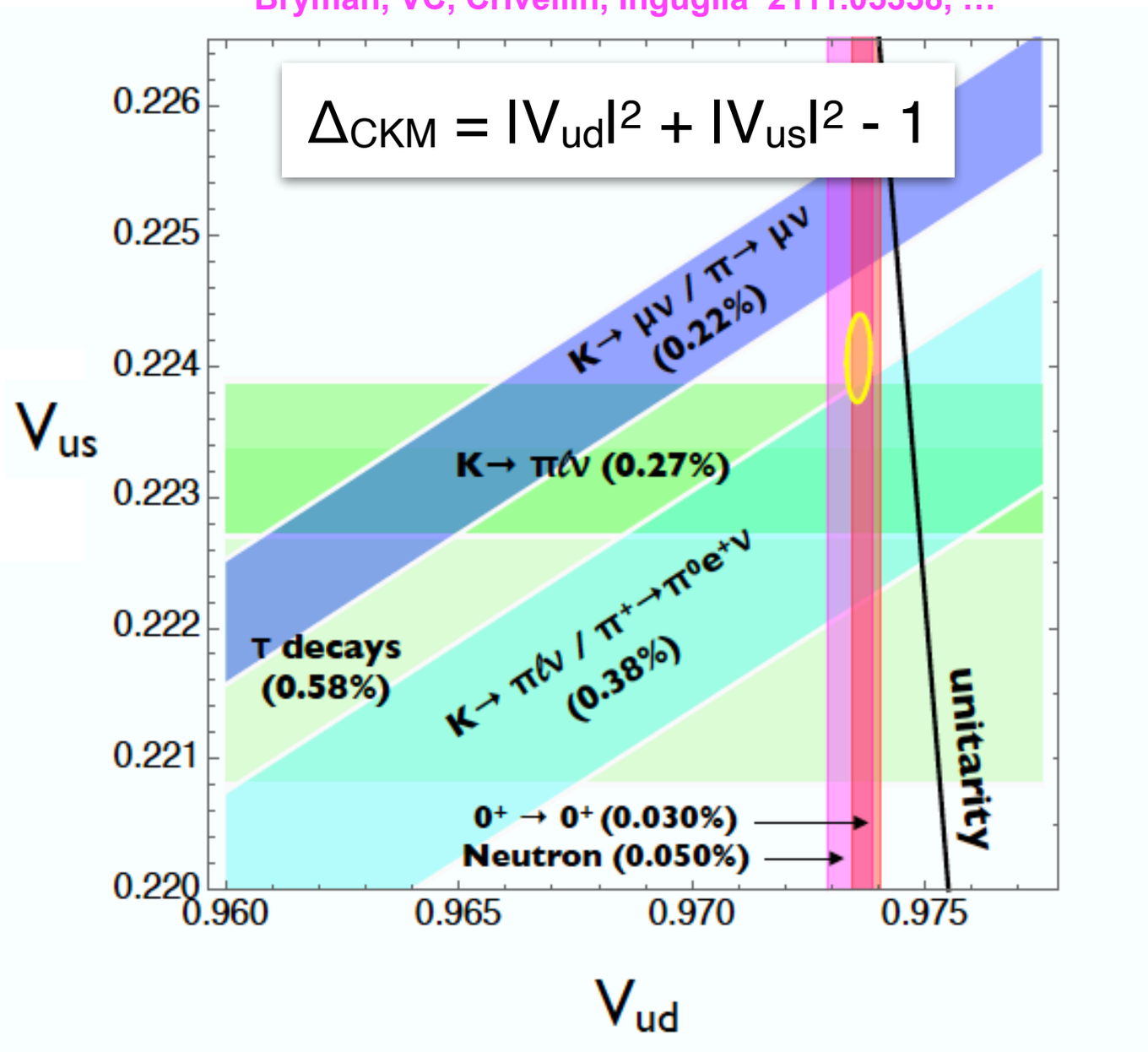
$$\Delta_{CKM} = (-19.5 \pm 5.3) \times 10^{-4}$$

χ^2/dof = 2.8, S=1.67

- Expected experimental improvements:
  - neutron decay (will match nominal nuclear uncertainty)
  - pion decay (3x to 10x at PIONEER phases II, III)
  - possibly new K BR measurements at NA62
- Expected theoretical improvements: radiative corrections in QCD+QED on the lattice for Kl3 and neutron decay (currently only for $K_{\mu 2}$)

Probing Cabibbo universality

Bryman, VC, Crivellin, Inguglia 2111.05338, …



$$\Delta_{CKM} = (-19.5 \pm 5.3) \times 10^{-4}$$

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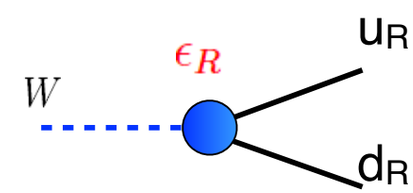
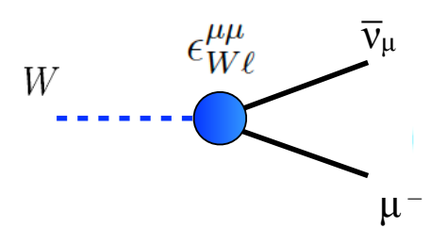
- Possible BSM explanations:
  - R-handed currents

    Grossman-Passemar-Schacht 1911.07821
    Alioli et al 1703.04751
    VC, Diaz-Calderon, et al, 2112.02087
    Belfatto-Berezhiani 2103.05549



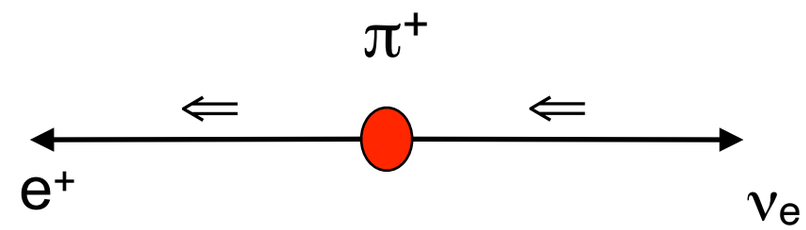
  - Leptonic vertex corrections: connection to LFU tests

    Crivellin-Hoferichter 2002.07184
    Capdevila et al., 2005.13542



Probing LFU with rare pion decays

- $R_{e/\mu} = \Gamma(\pi \to e\nu)/\Gamma(\pi \to \mu\nu)$
  helicity suppressed the SM (V-A),
  zero if $m_e \to 0$.



- $\sigma_{exp} \sim 15\ \sigma_{th} \Rightarrow$

  pristine test of LFU possible!

VC-Rosell 0707.3439

$$R_{e/\mu}(\mathrm{SM}) = 1.23524(015) \times 10^{-4}$$

$$R_{e/\mu}(\mathrm{Exp}) = 1.23270(230) \times 10^{-4}$$

PIENU Coll.

- Current reach: $g_e/g_\mu = 0.9990(9) \Rightarrow \Lambda_A > 10\ \mathrm{TeV}$ or $\Lambda_P > 350\ \mathrm{TeV}$ (helicity!)

"This just demands to be tested better!
A clean generic way to look for new physics.
Theory vs Experiment in high precision test."

David Hertzog

Probing LFU with rare pion decays

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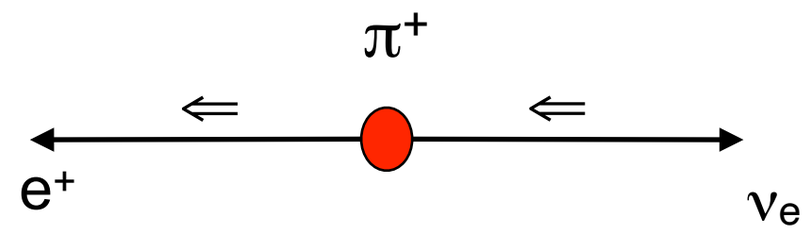

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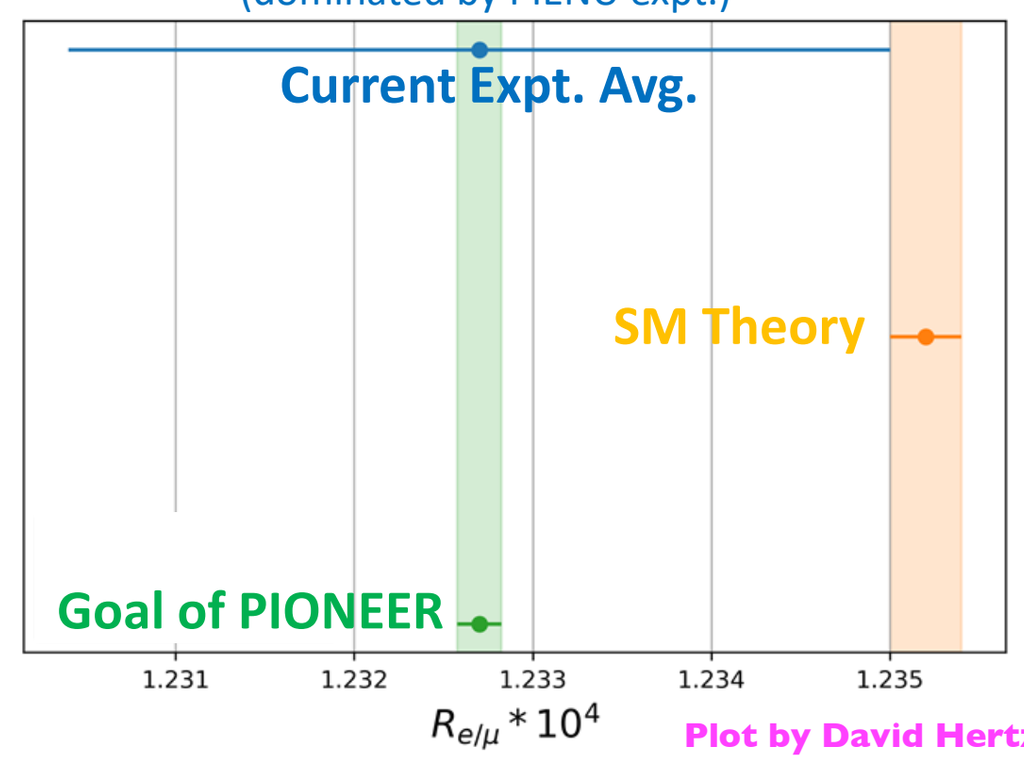
PIENU Coll.

PIONEER

- The future: new experiment @ PSI
  - Phase I: match th. uncertainty in $R_{e/\mu}$
  - Phase II, III: Pion beta decay (V_{ud})
  - Along the way, probe dark sectors!

(dominated by PIENU expt.)



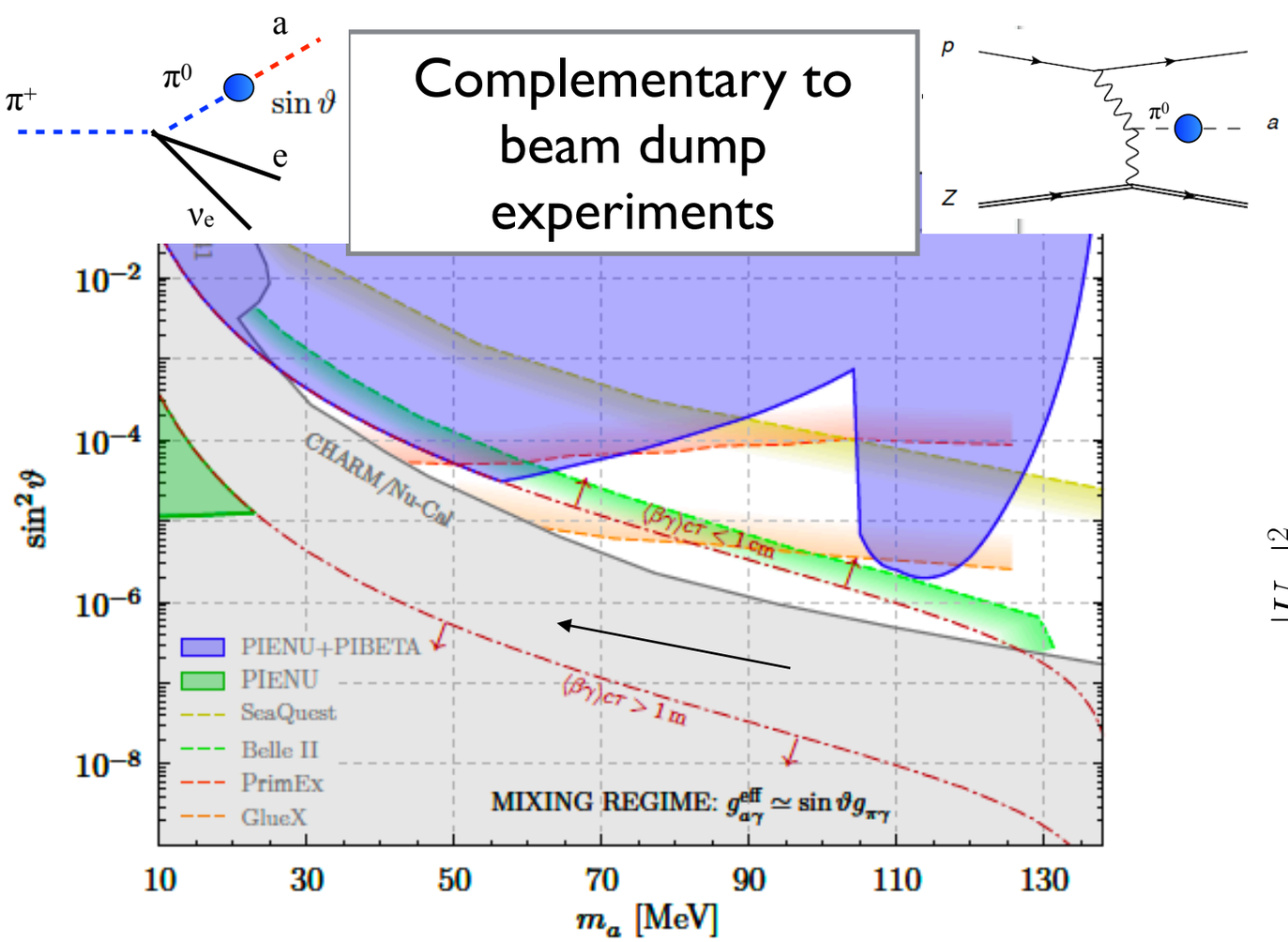
2203.01981

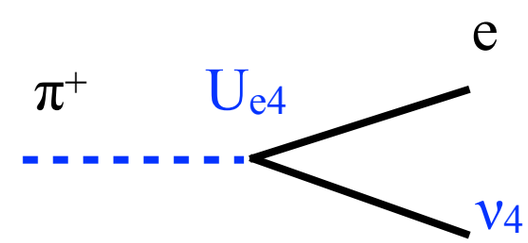
Plot by David Hertzog

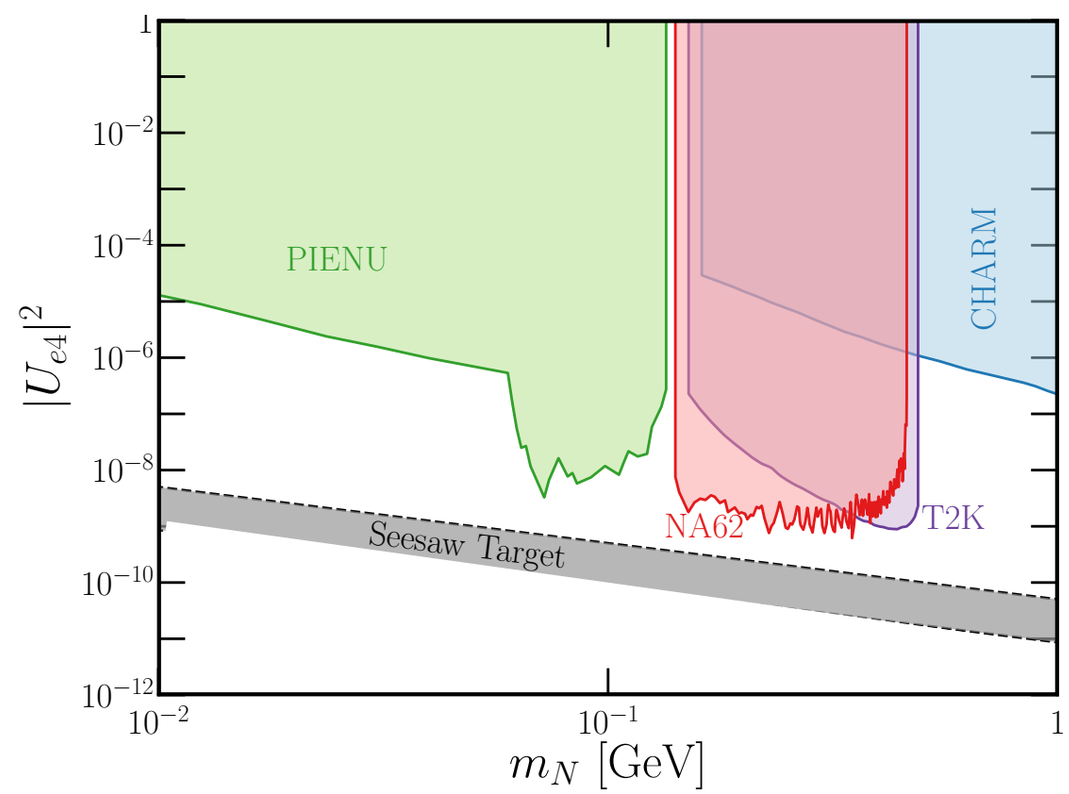
Probing dark sectors with rare pion decays

- ALPs: a-π^0 mixing induces the decay $\pi^+ \to a e \nu$. Affects E_{cal} distribution in PIENU and the $\gamma\gamma$ opening angle distribution in PIBETA

- Sterile neutrinos: $\pi \to e \nu_4$ provides strongest bounds for $m_{\nu 4} \sim 1$-140 MeV





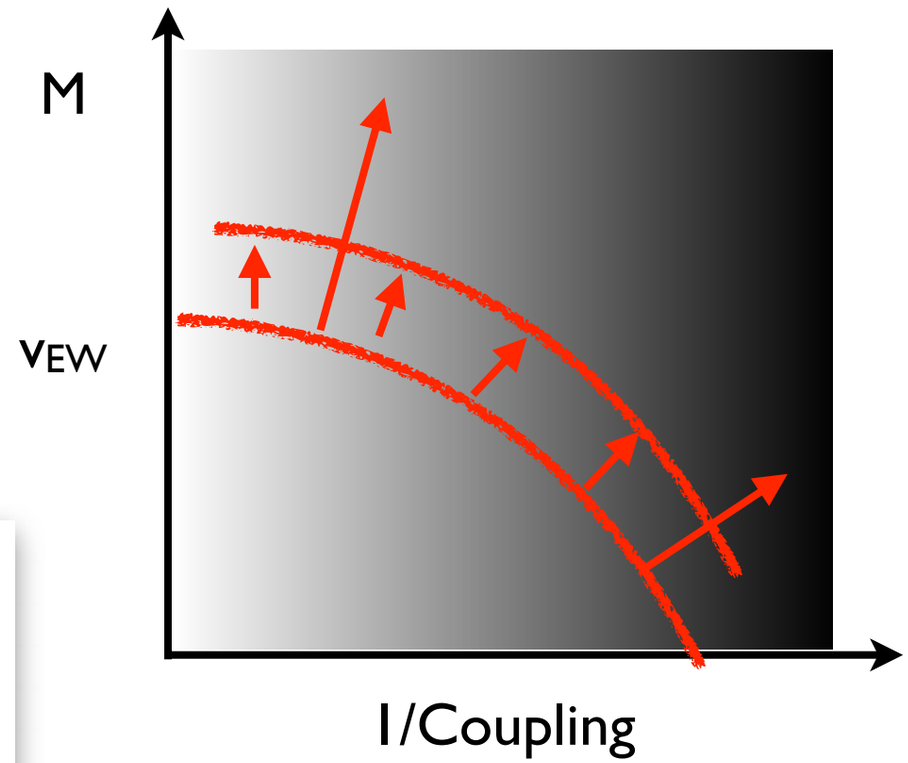


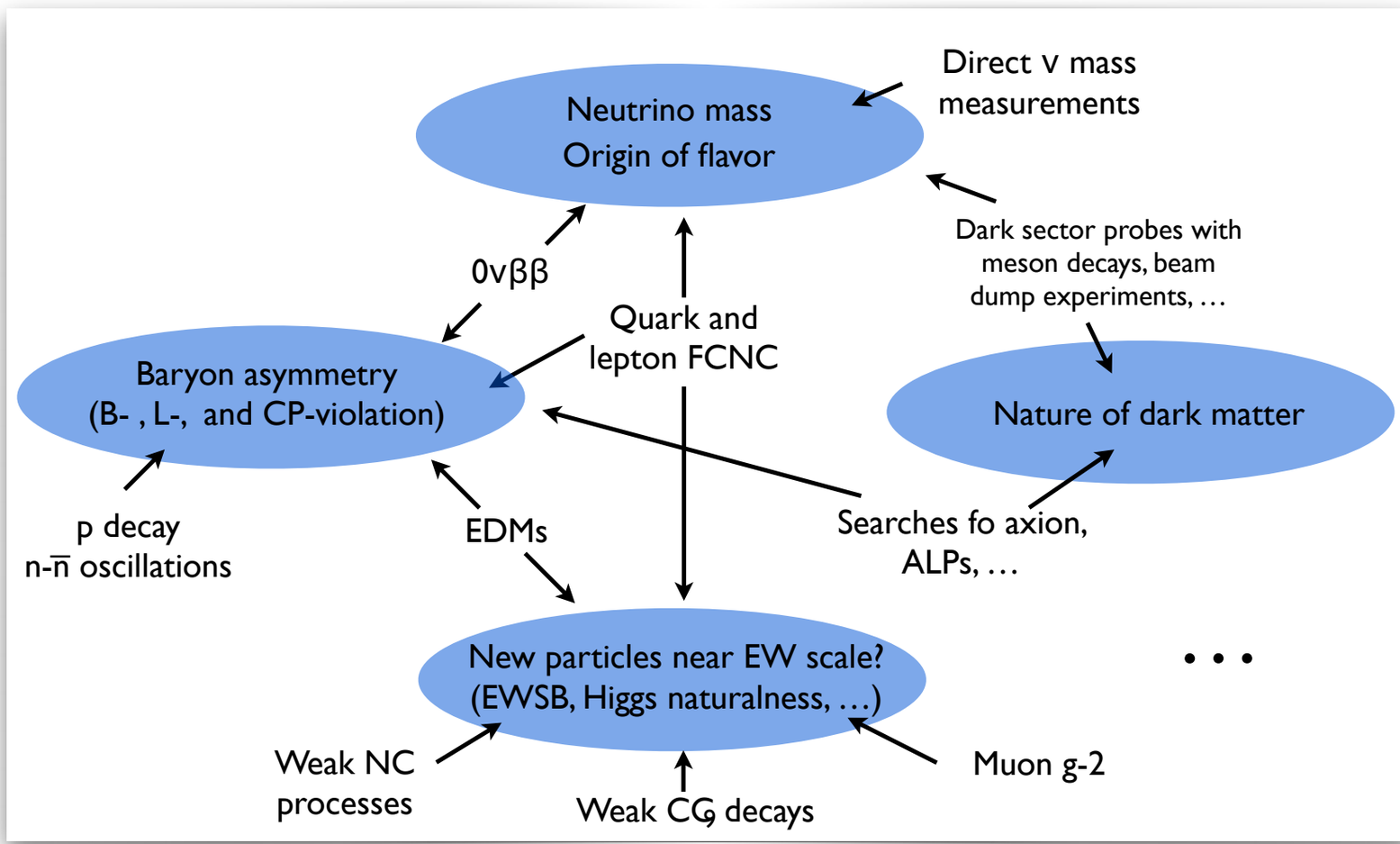
Altmanshofer-Gori-Robinson 1909.00005

Goudzovski et al., 2201.07805

Concluding comments

- Rare Processes & Precision Measurements are exploring uncharted territory in the search for new physics, in a complementary way to other frontiers





- Vibrant experimental program probes BSM physics related to "big questions"

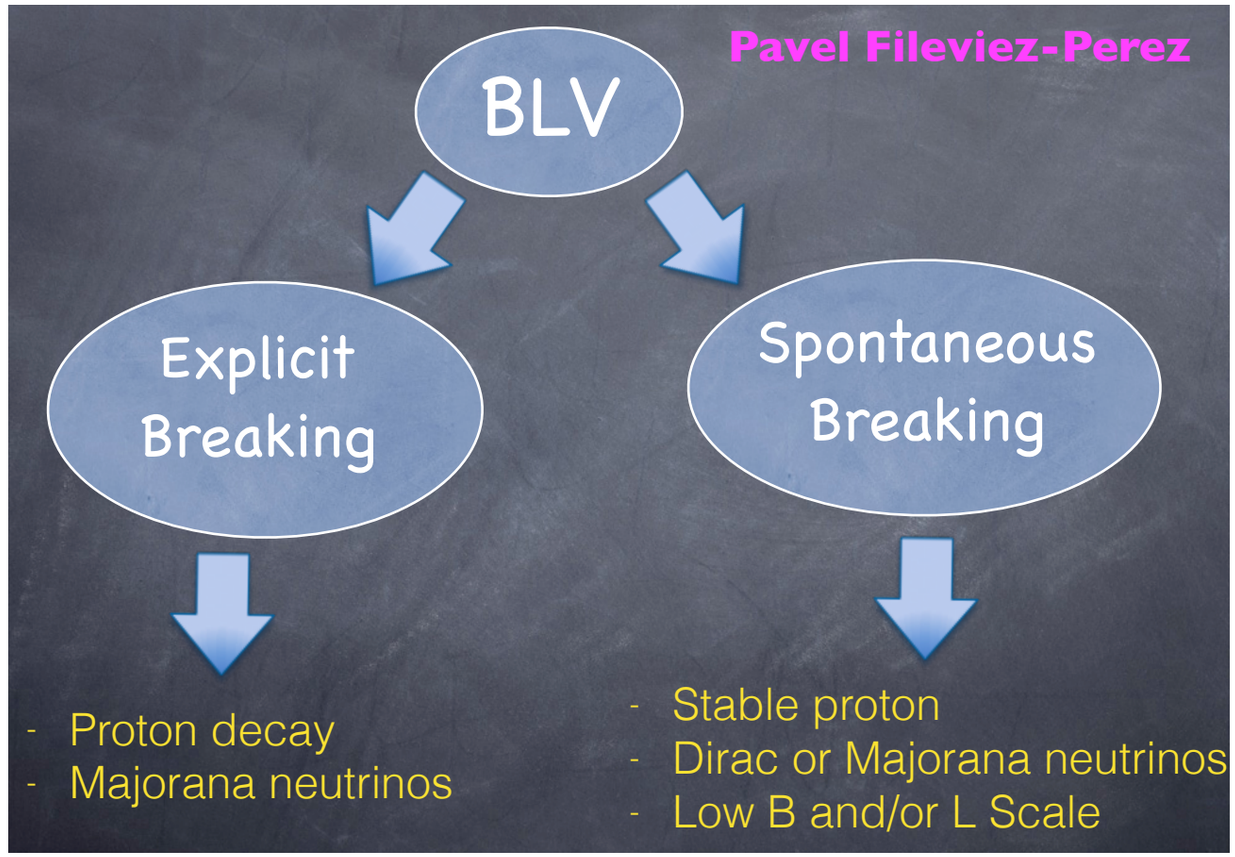
Backup

Baryon and Lepton Number

- B&L violation tied to the origin of baryon asymmetry and neutrino mass

- In explicit models, BLV realized through different mechanisms and at different scales:

- SU(5), SO(10) GUTs, (RPV) SUSY.
- Typically high scale



- B and/or L as gauge symmetries. Simplest Models have $\Delta B=3$ & dark matter candidate

- Pati-Salam models: $\Delta B=2$, $\Delta L=2$.

- Low-scale: new particles can be probed at colliders

- Experimental probes include: proton decay [SK,HK,JUNO, DUNE]; n-$\bar{n}$ oscillations [ORNL, ESS]; neutrinoless double beta decay ($0\nu\beta\beta$); BLV at colliders