IUPAP Nuclear Science Symposium
University of Notre Dame, London Global Gateway
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Searching for New Physics: the Fundamental Symmetry Experiments

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Los Alamos National Laboratory

Outline

- The quest for new physics: Energy and Precision / Intensity frontiers

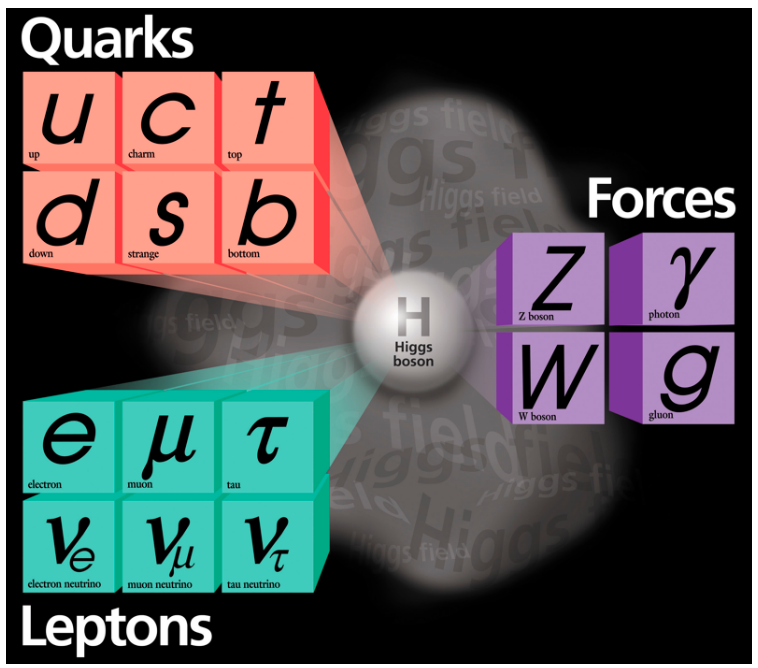
- The role of nuclear science experiments at the Precision / Intensity frontier — a theory overview

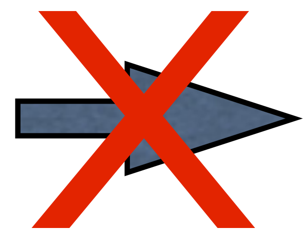
- Selected topics:
  - rare / forbidden processes: $0\nu\beta\beta$ decay, EDMs
  - precision measurements: β decays

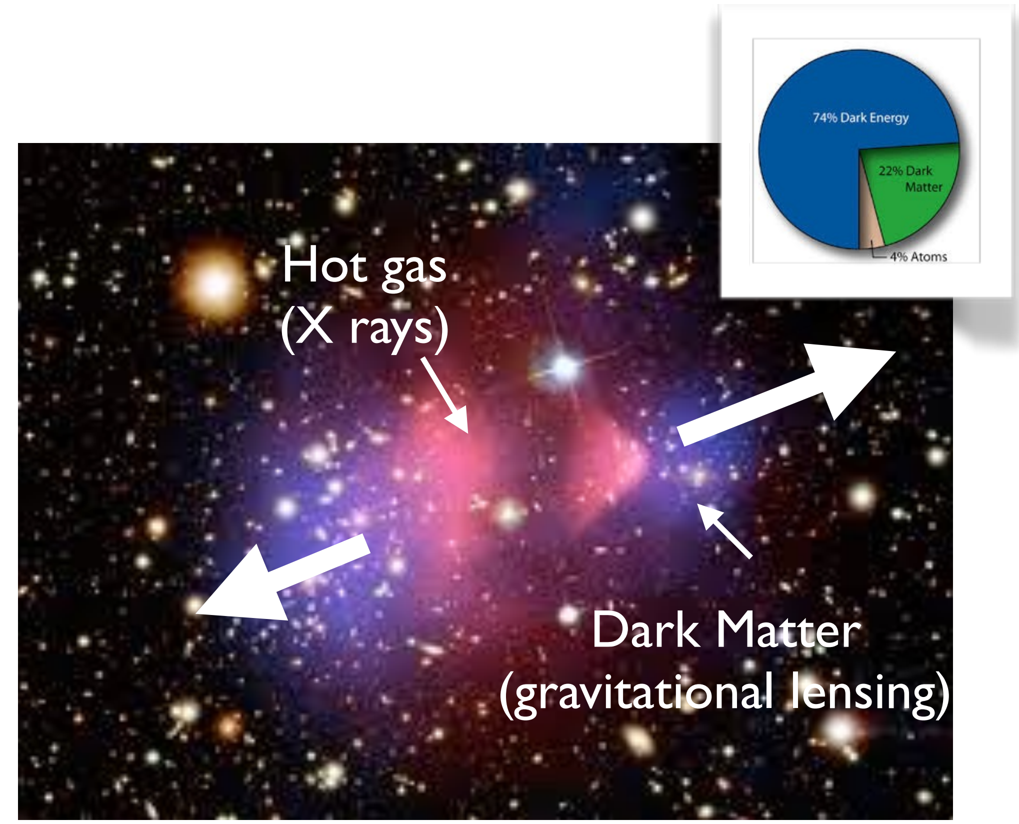
The quest for new physics

New physics: why?

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







No Baryonic Matter, no Dark Matter, no Dark Energy, no Neutrino Mass

What stabilizes G_{Fermi}/G_{Newton} against radiative corrections?

Do forces unify at high E? What is the origin of families?

…

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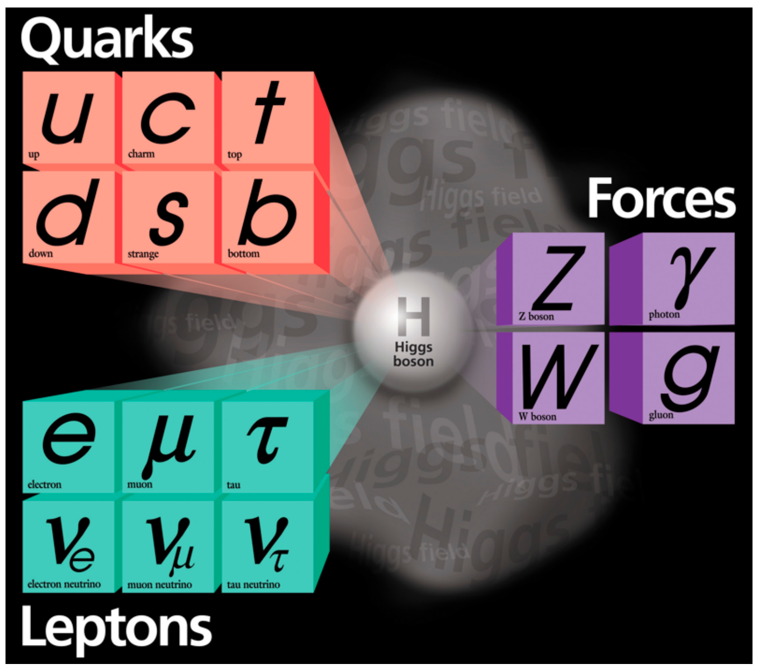

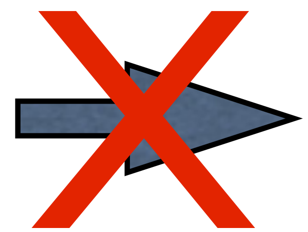

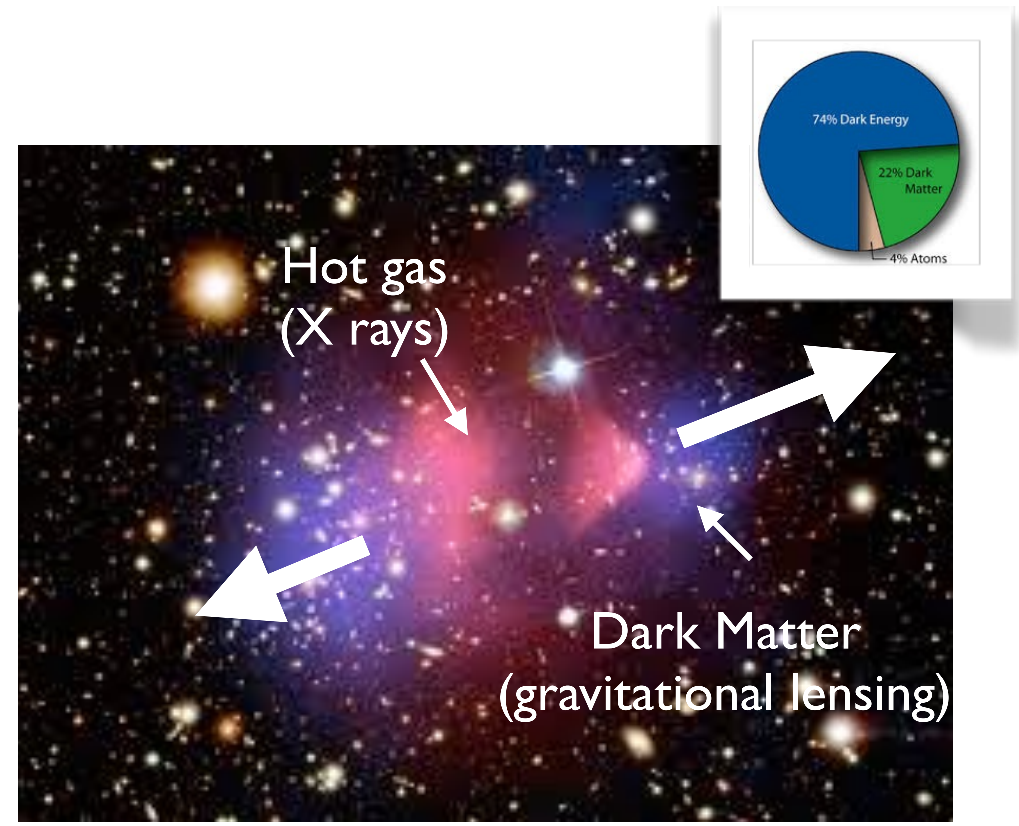

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What stabilizes G_{Fermi}/G_{Newton} against radiative corrections?

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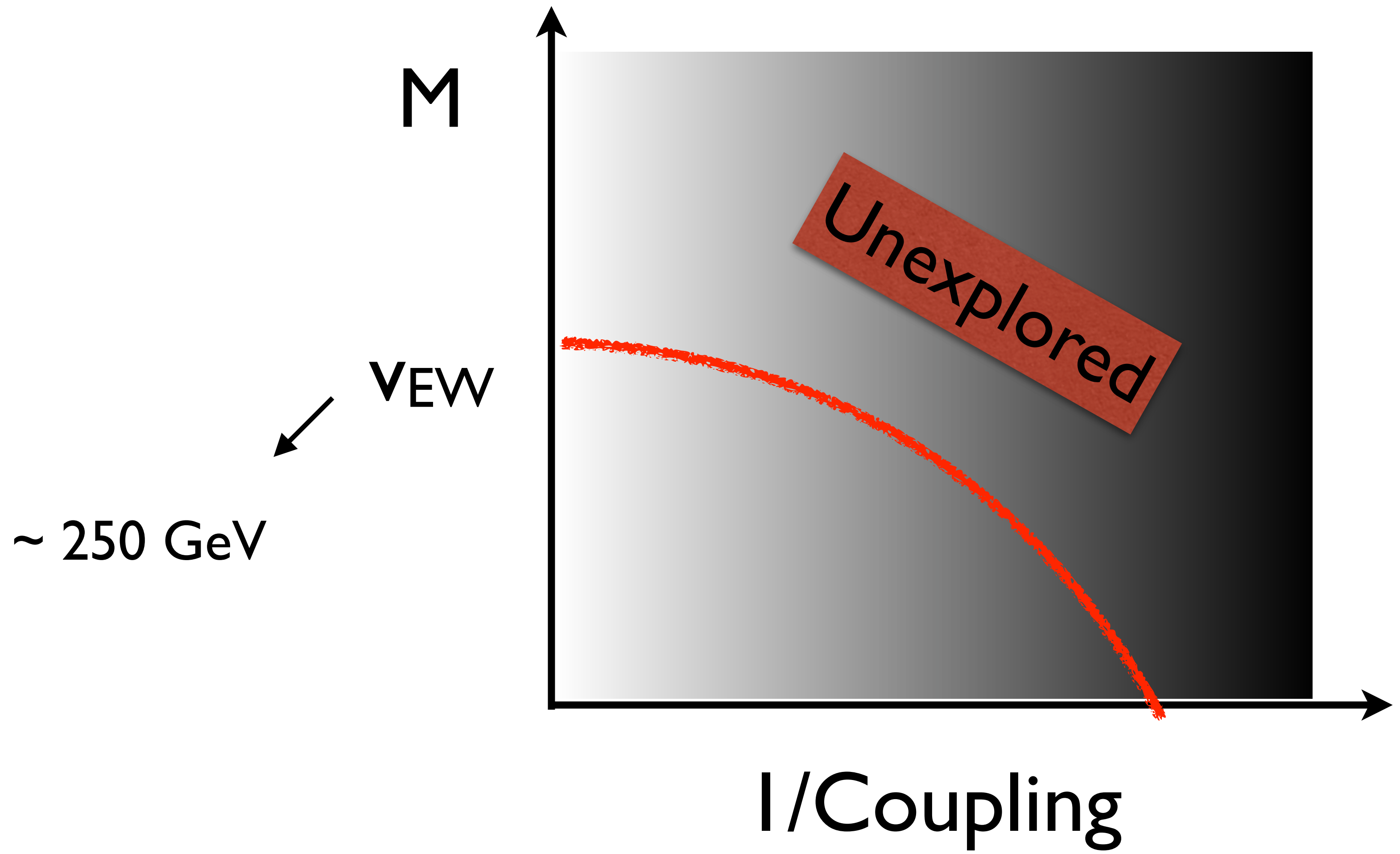
. . .

Addressing these puzzles likely requires new degrees of freedom

New physics: where?

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



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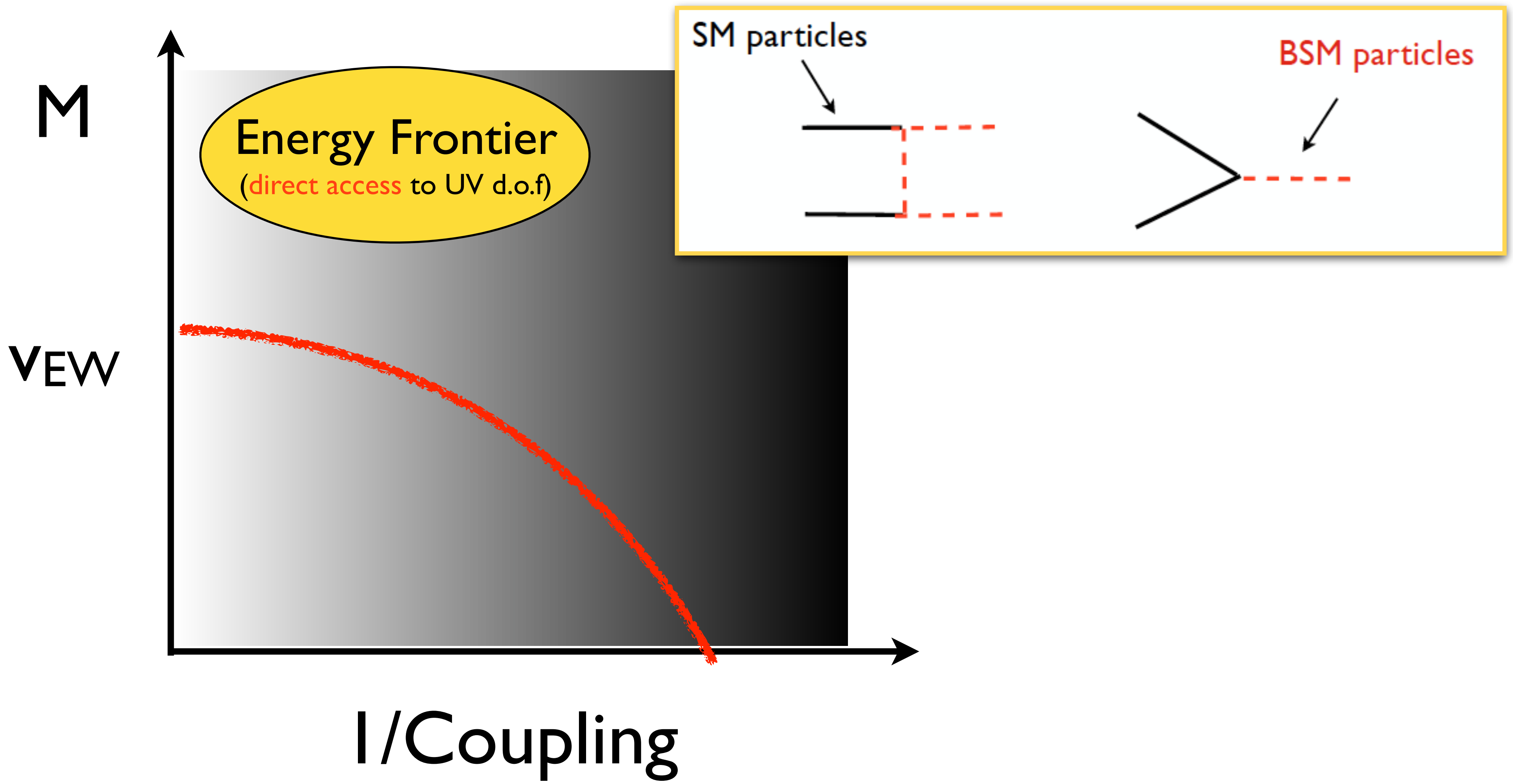

- Two approaches

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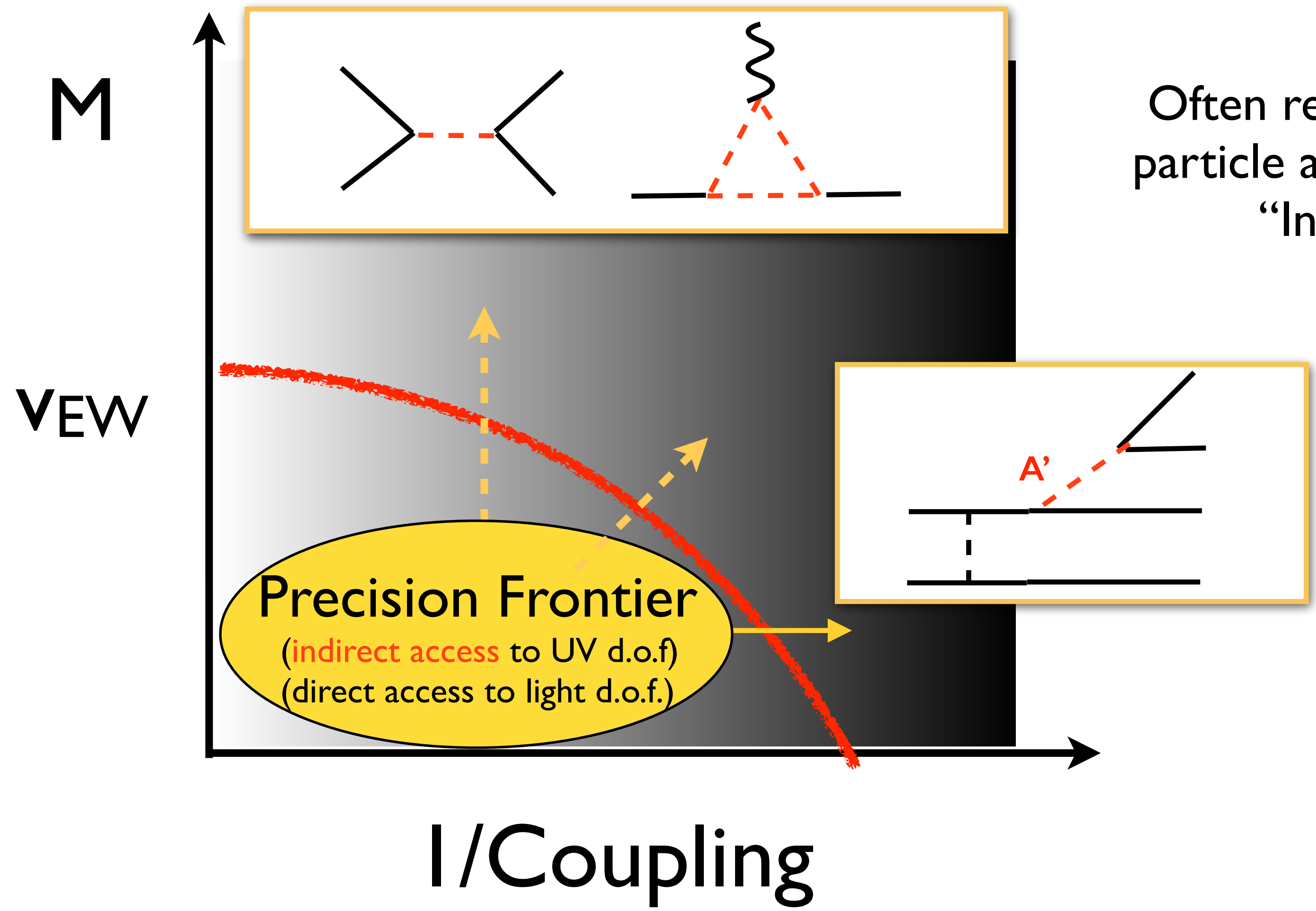

Often requires use of powerful particle accelerators (hence also “Intensity Frontier”)

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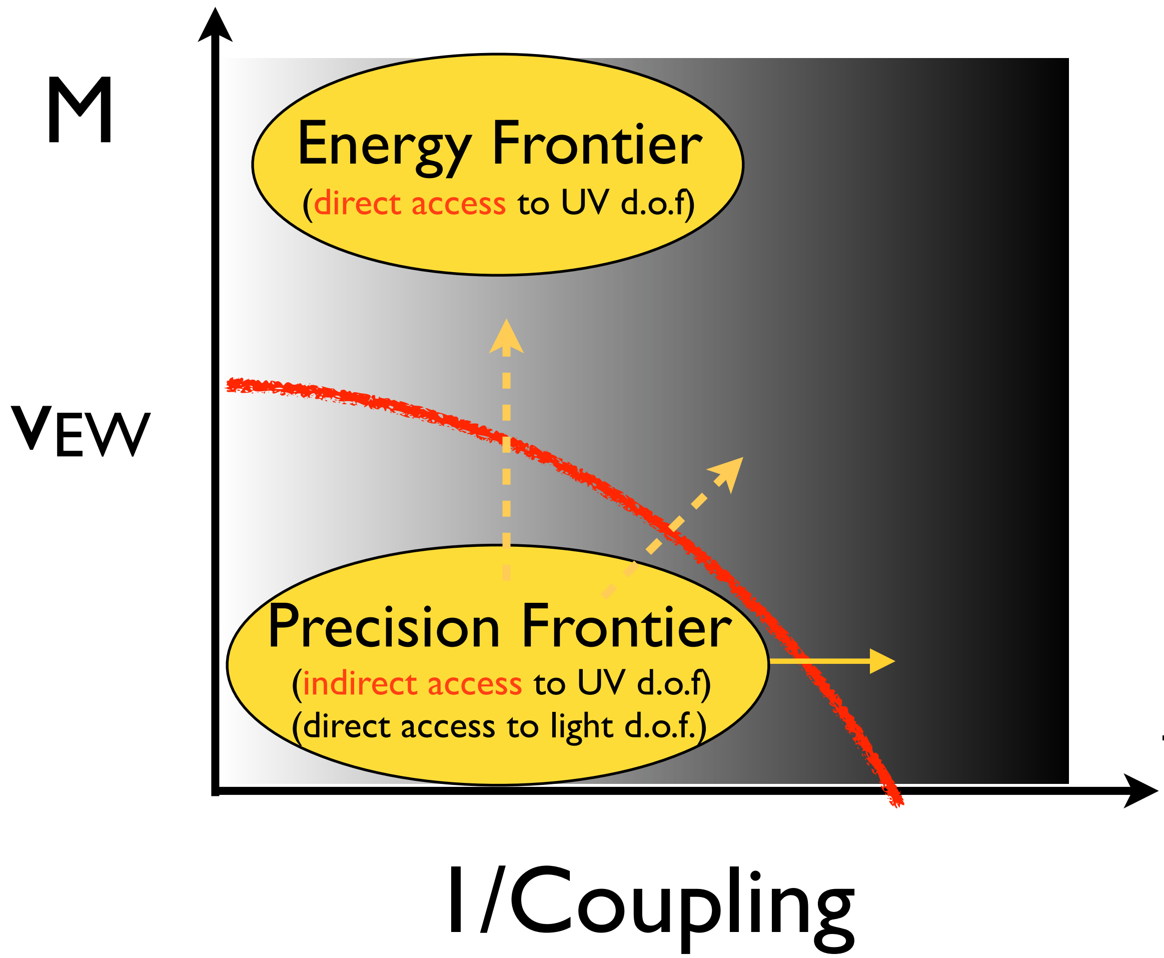

- EWSB mechanism
- Direct access to heavy particles
- ...

- L and B violation
- CP violation (w/o flavor)
- Flavor violation: quarks, leptons
- Heavy mediators: precision tests
- Neutrino properties
- Dark sectors
- ...

- Two approaches, both needed to reconstruct BSM dynamics: structure, symmetries, and parameters of $\mathcal{L}_{BSM}$

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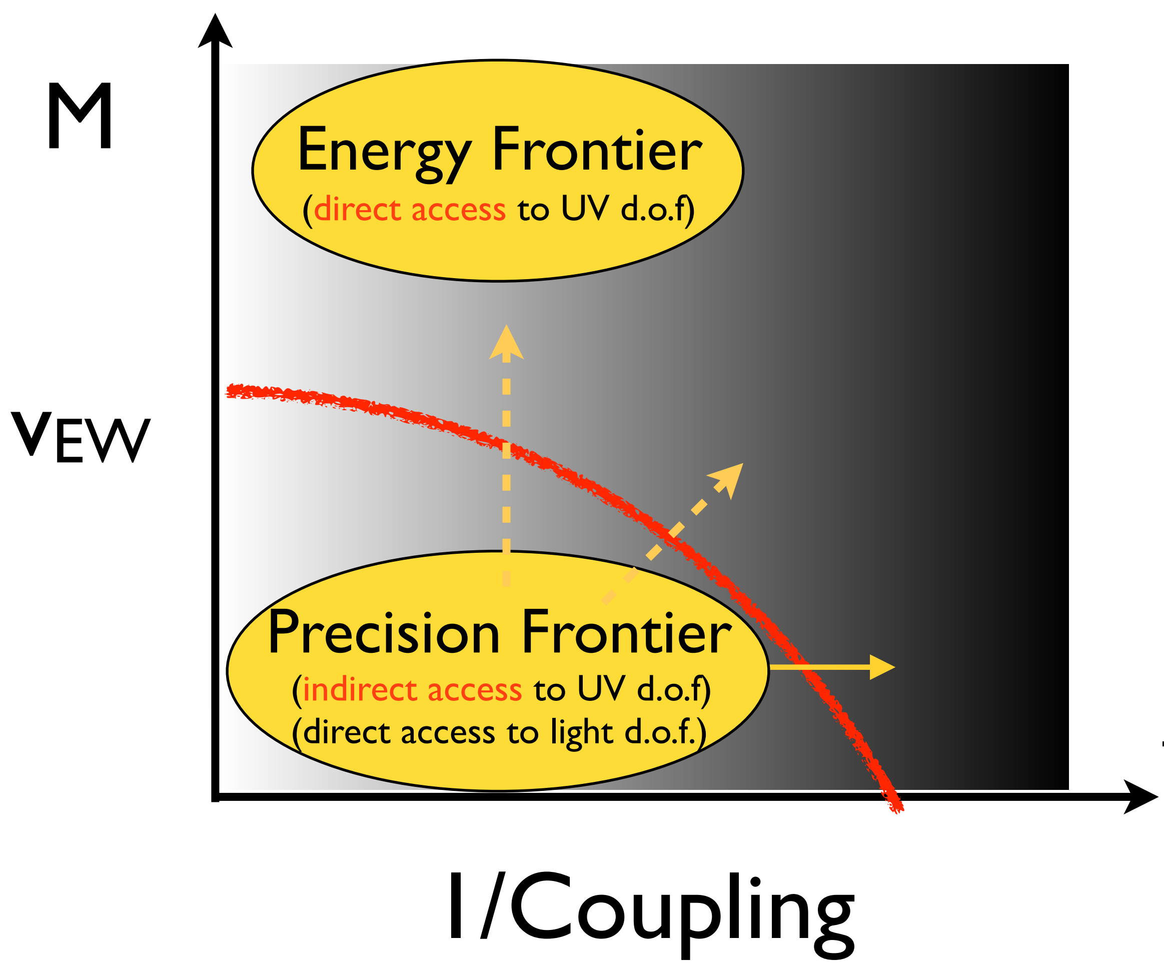

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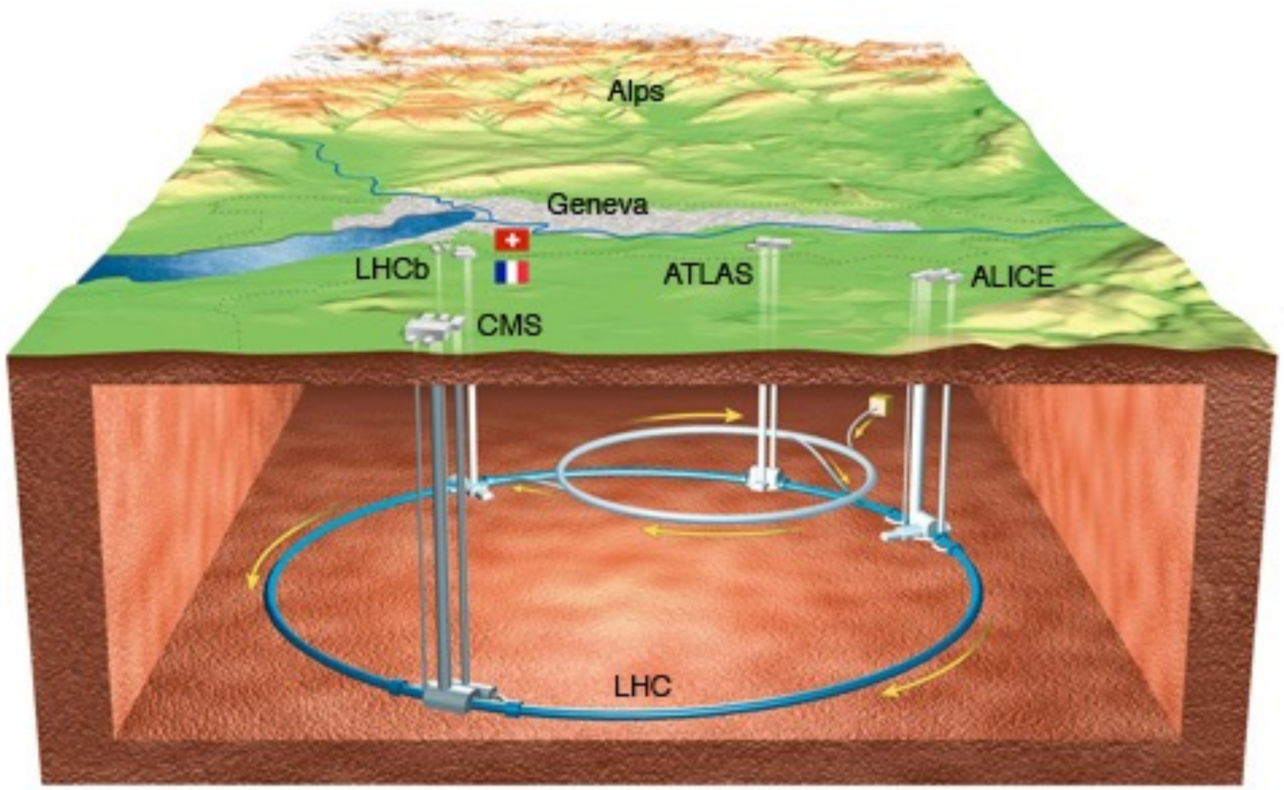
Nuclear Science Fundamental Symmetry experiments
play a prominent role at the Precision Frontier

News from the energy frontier

The Large Hadron Collider



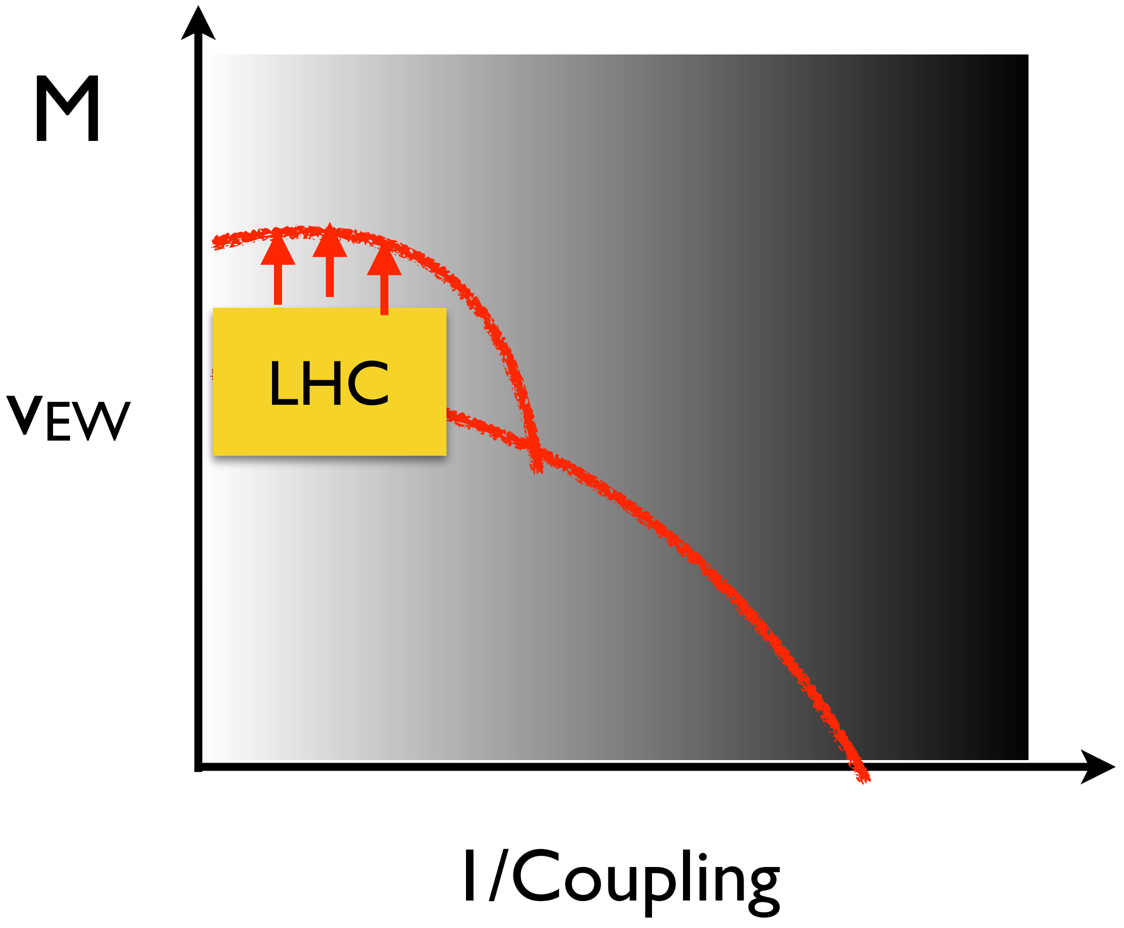
- Run 1: pp @ $\sqrt{s}$ = 7-8 TeV
- Run 2: pp @ $\sqrt{s}$ = 13 TeV
  Integrated luminosity ~ 150 fb^{-1}

- Major discovery: Higgs boson with m_h=125 GeV
- So far negative results from *direct* searches for TeV-scale new dynamics
- Few-σ "anomalies" in semi-leptonic B-meson decays (LHCb) [this is really intensity frontier!]

News from the energy frontier

- Simplest scenarios of new physics pushed to TeV scale and beyond

- High hopes for the High Luminosity / High Energy LHC upgrade (3000 fb^{-1} over next two decades)

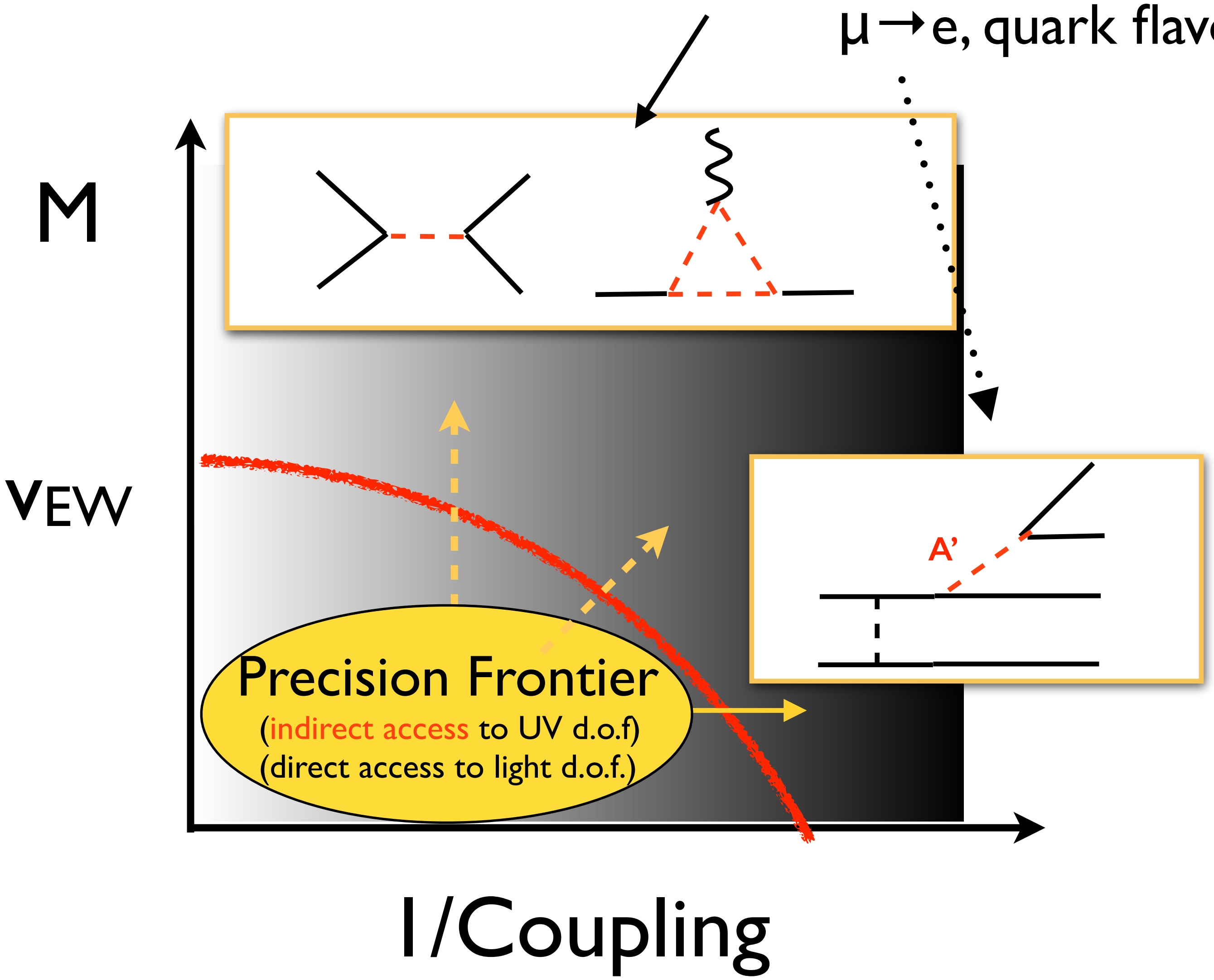


Precision frontier searches — a theory overview

The precision frontier

- Three classes of new physics probes

1. Searches for rare or forbidden processes that probe approximate or exact symmetries of the SM: proton decay, n-nbar oscillations, $0\nu\beta\beta$, EDMs, $\mu \to e$, quark flavor violation, …



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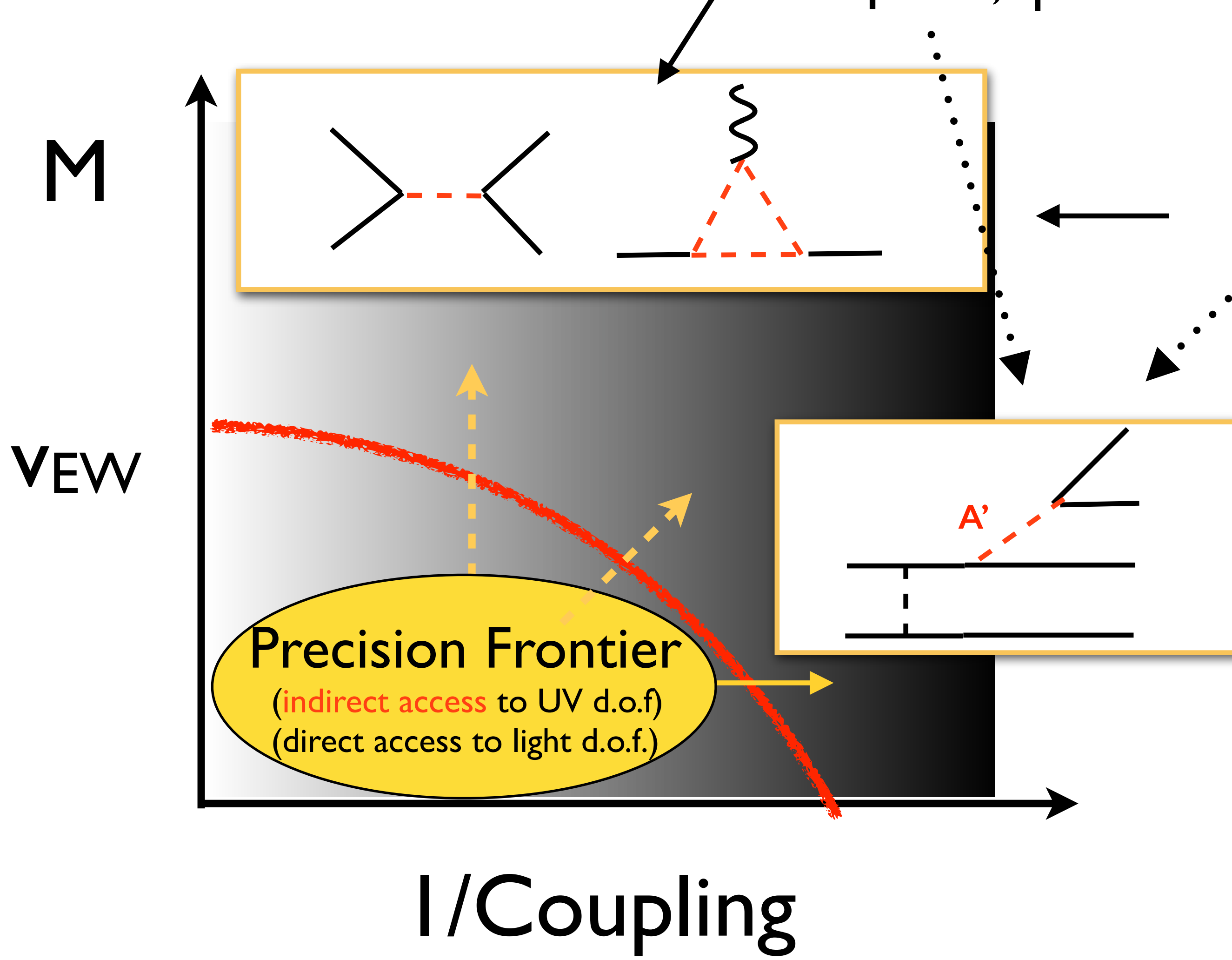

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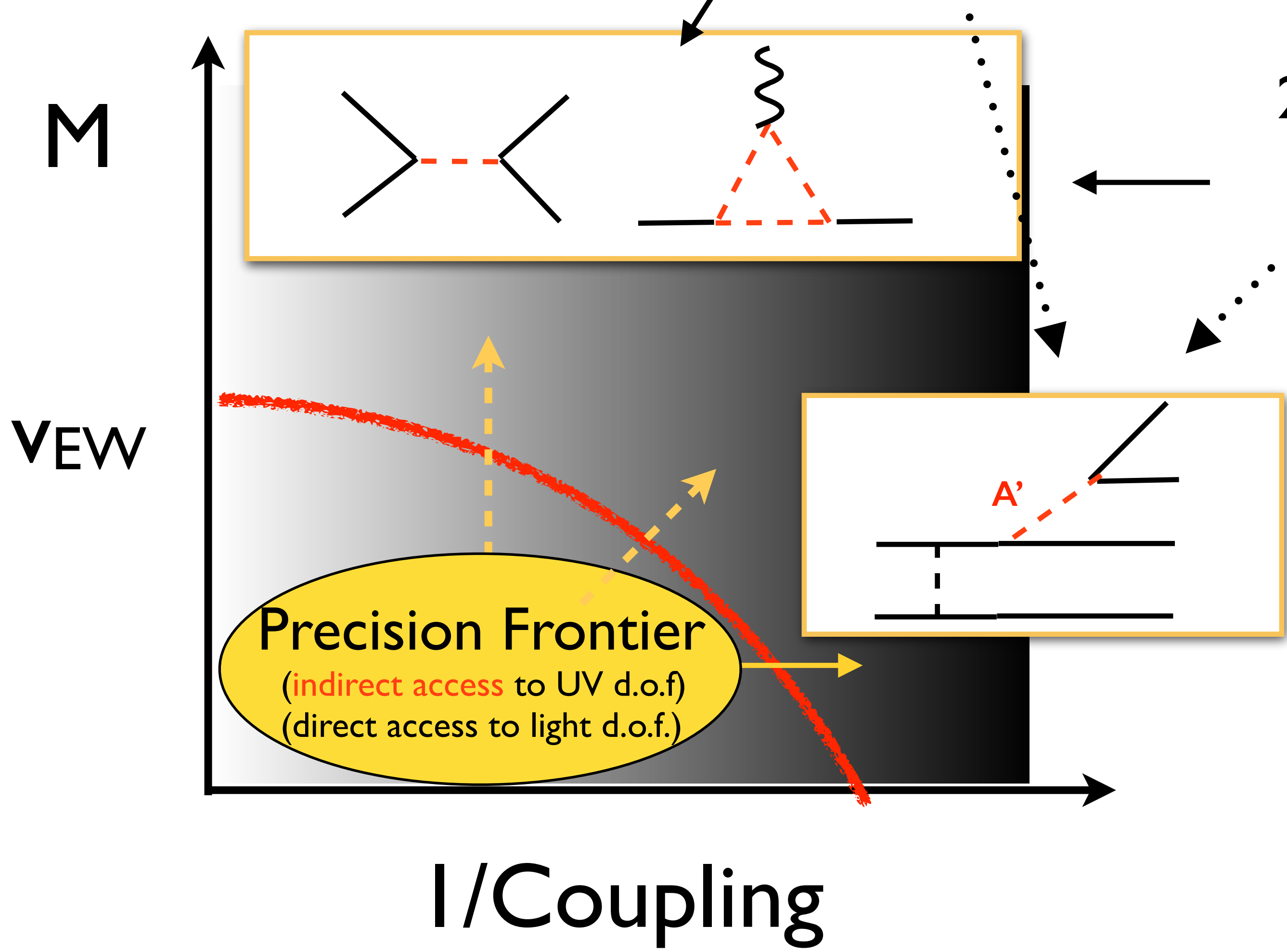
3. Searches / characterization of light and weakly coupled particles: active νs, sterile νs, dark photon, dark Higgs, axion, …



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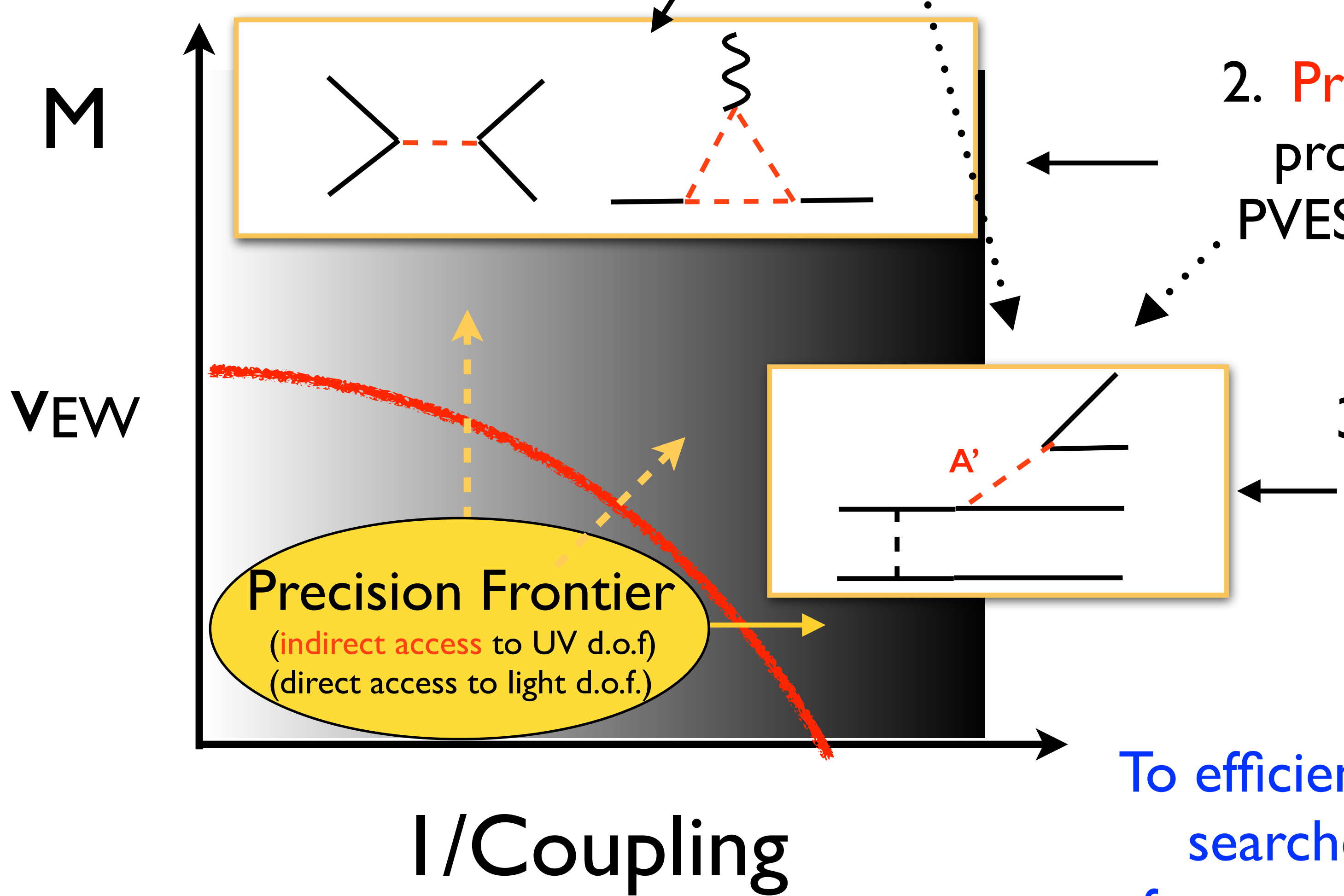

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To efficiently analyze the impact of precision frontier searches, one would like a fairly general theory framework, encompassing many underlying models

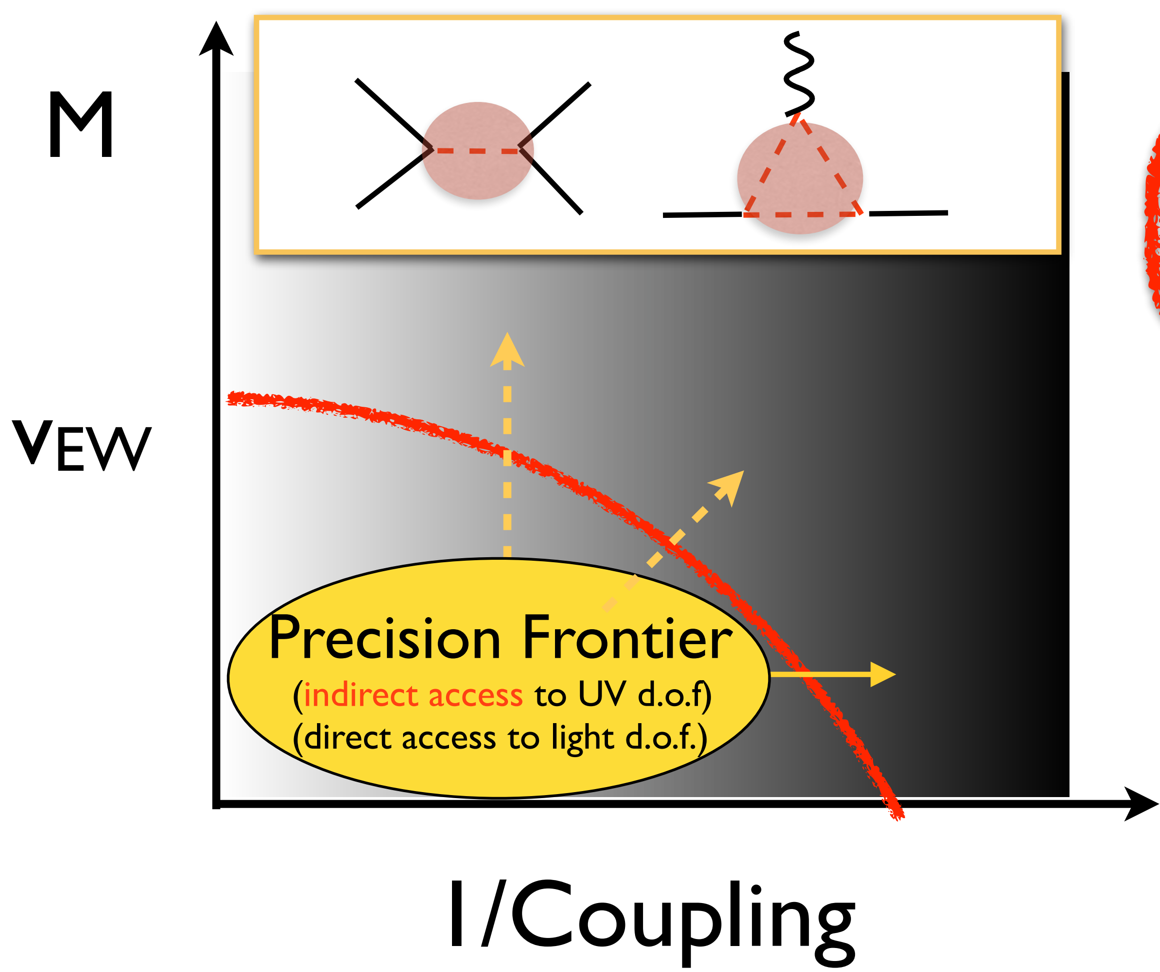
Theory framework

- IR new physics: "portals" (vector, neutrino, Higgs, axion)

See talk by S. Reddy

- UV new physics: EFT

Heavy new particles affect low-energy physics through local operators suppressed by inverse powers of heavy scale



Weinberg 1979, Wilczek-Zee1979 , Buchmuller-Wyler 1986, ...

$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

[$\Lambda \leftrightarrow M_{\rm Heavy}$] $C_i\ [g_{\rm BSM},\ M_a/M_b]$

For any observable *O*,
$\delta O_{\rm BSM} / O_{\rm SM} \sim (v_{EW}/\Lambda)^n$ $n=2,4,..$

Can make "apples-to-apples" model-independent sensitivity comparisons with collider probes

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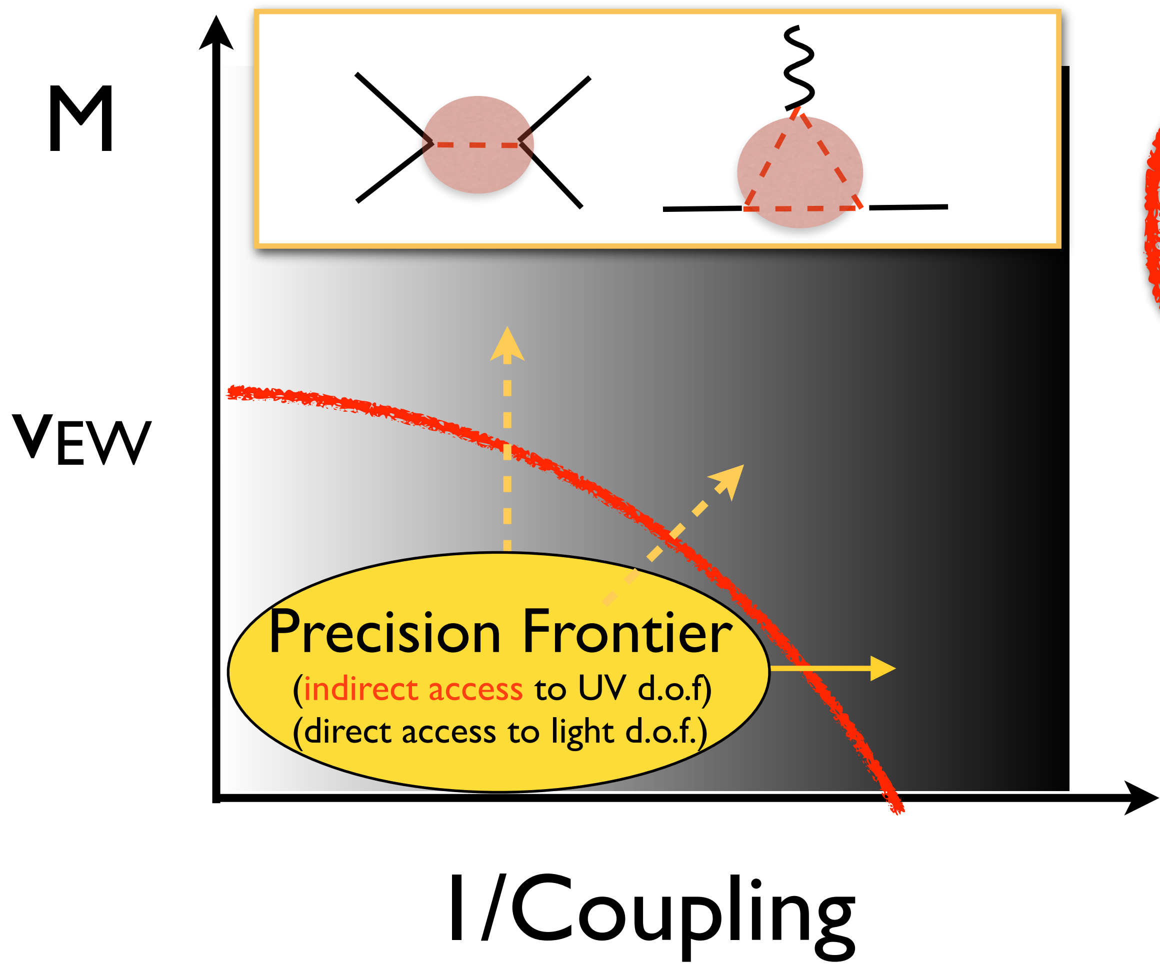

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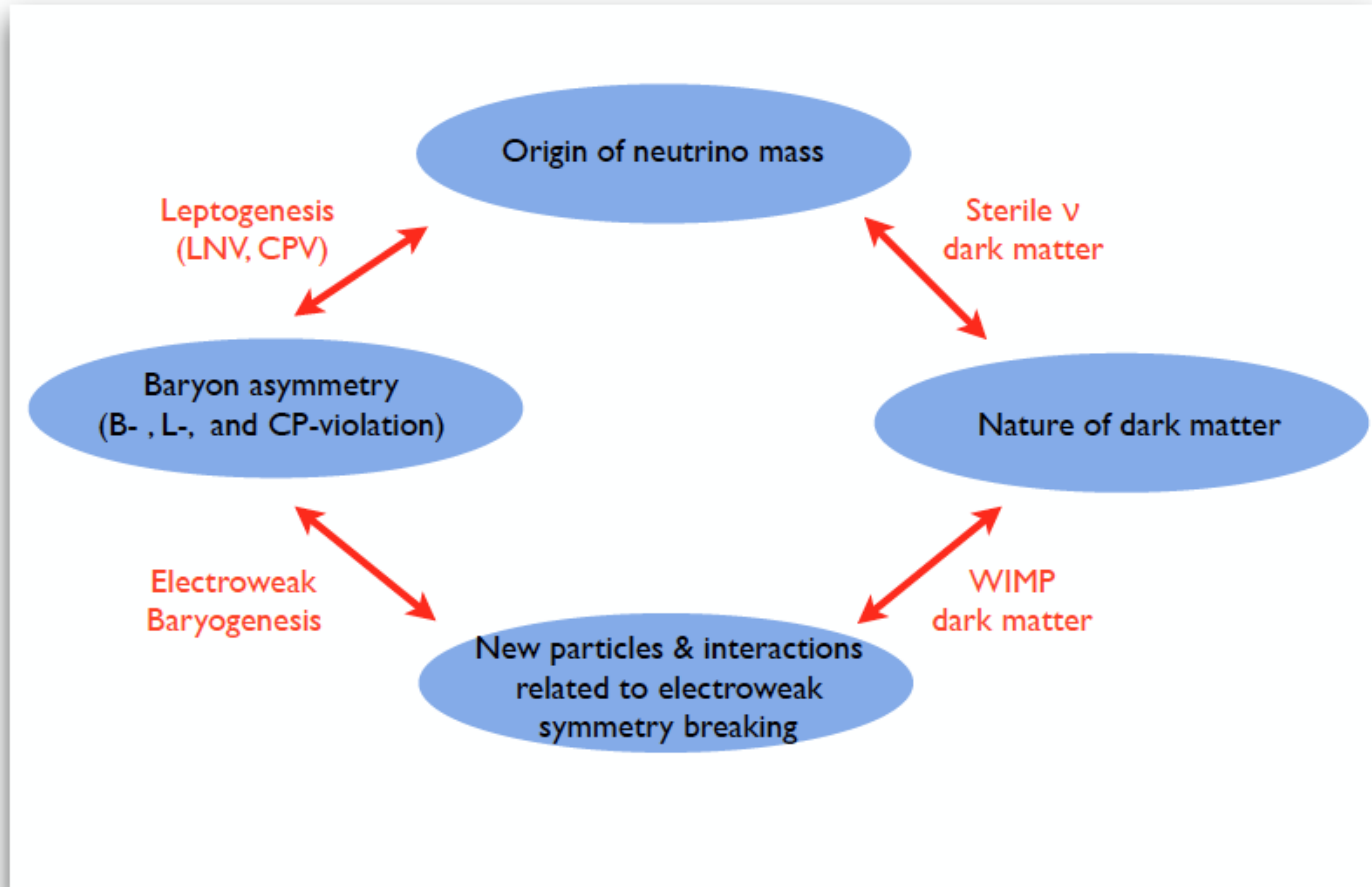
At lower energy, to connect to hadronic / nuclear observables, use tools such as chiral EFT, lattice QCD, dispersion relations, quantum many body methods

Impact of precision frontier searches

- Discovery potential
  - new ways to look for cracks in the SM
- Diagnosing power
  - Multiple EDM searches → underlying sources of CPV
  - $0\nu\beta\beta$, mass scale, oscillations, LFV ($\mu \to e$, …) → neutrino mass model
  - …
- Connection to big open questions
  - e.g. unique sensitivity to symmetry breaking required by Sakharov conditions for baryogenesis (B, L, CP);
  - …

Connection to big questions

- Nuclear Science Fundamental Symmetries experiments cluster around open questions — often probing dynamics otherwise inaccessible



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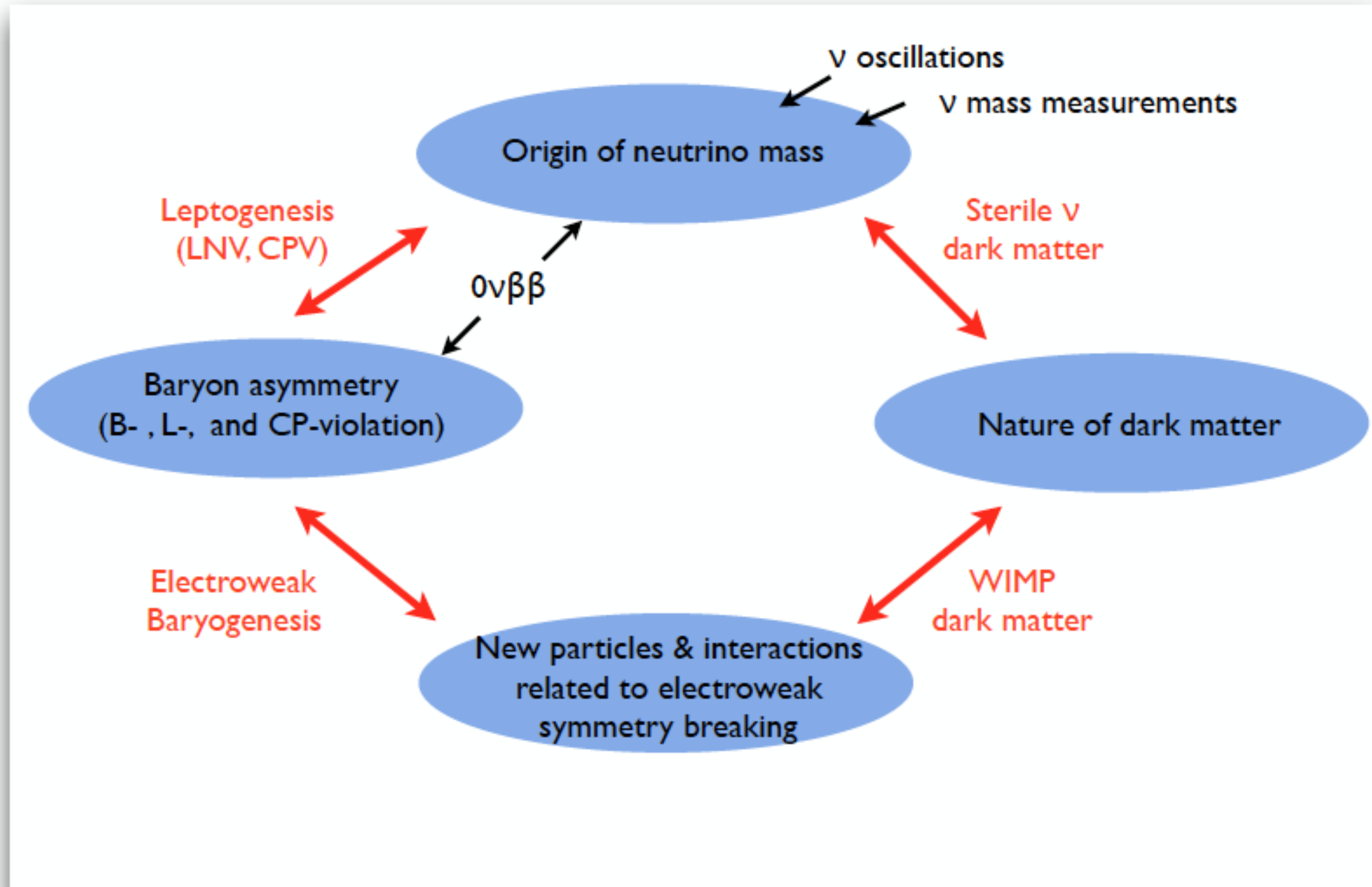

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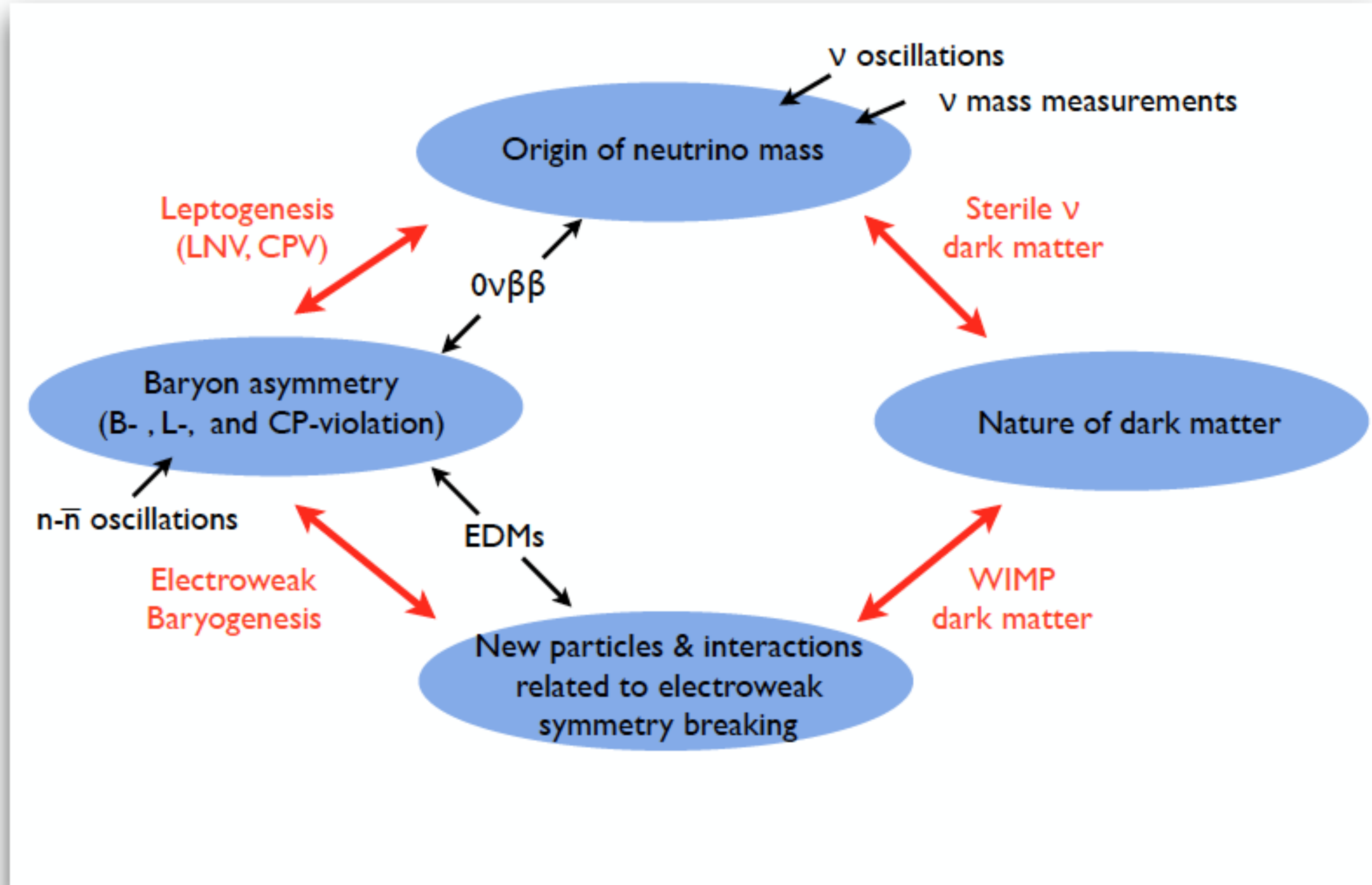

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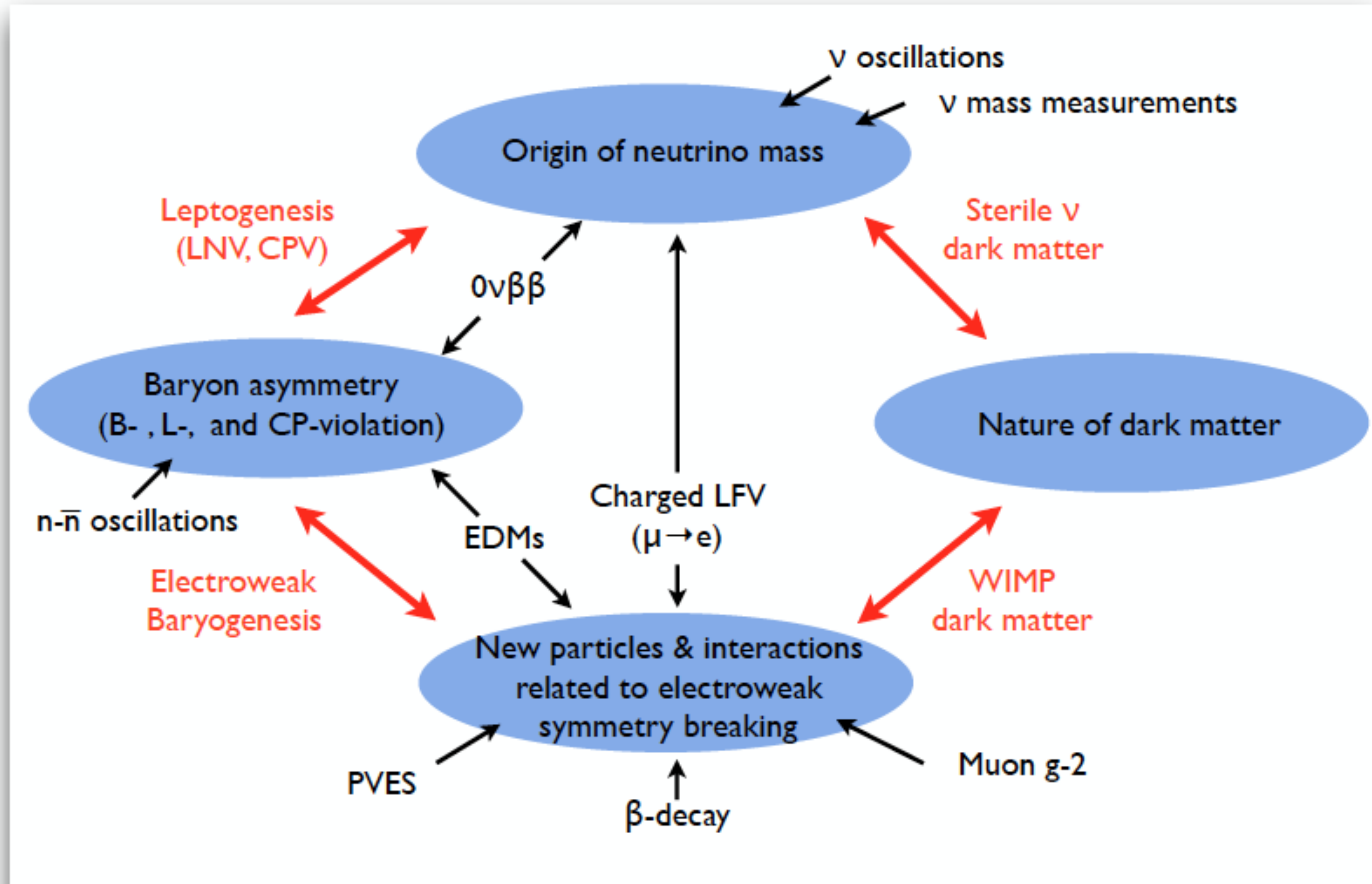

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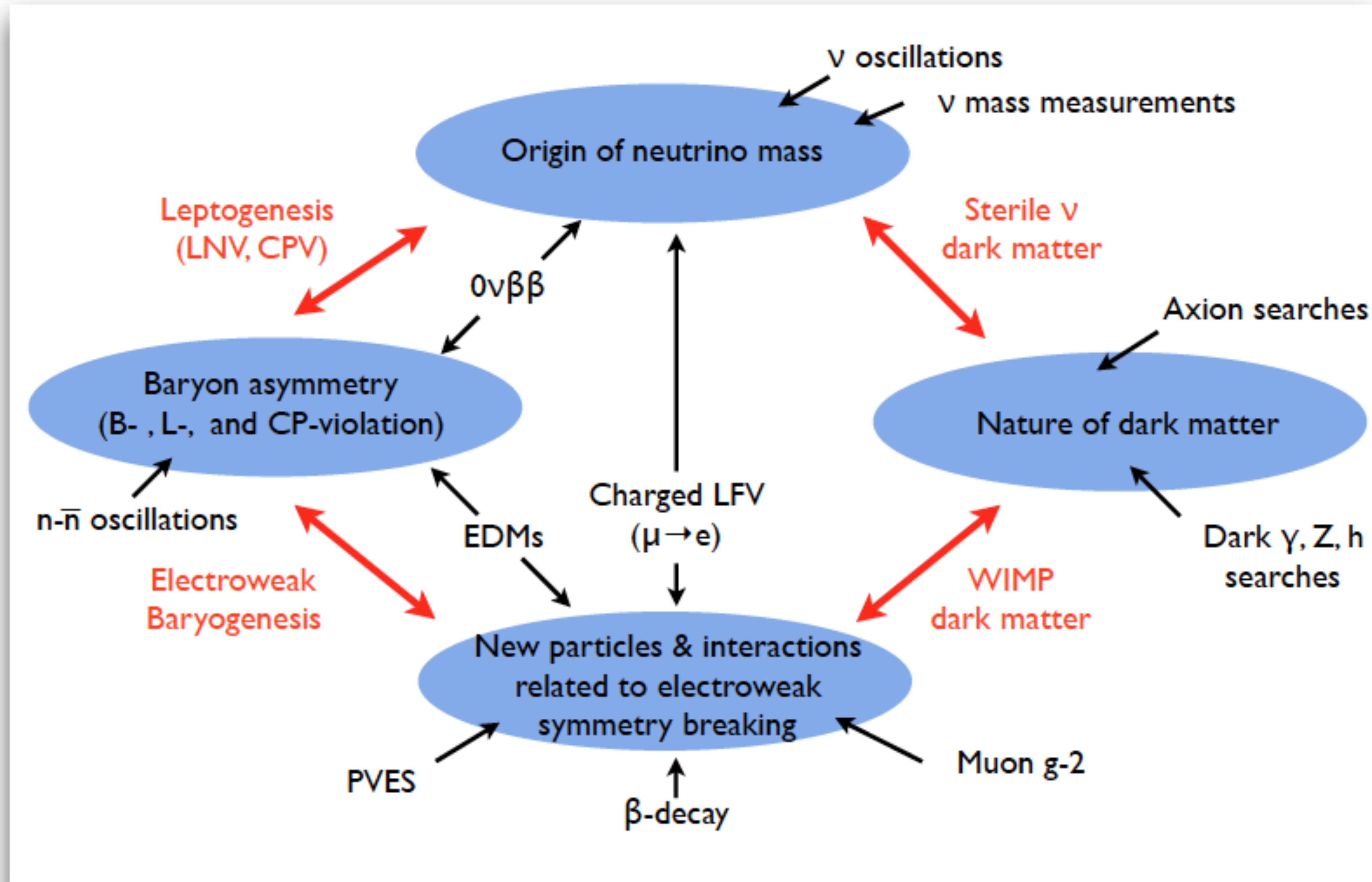

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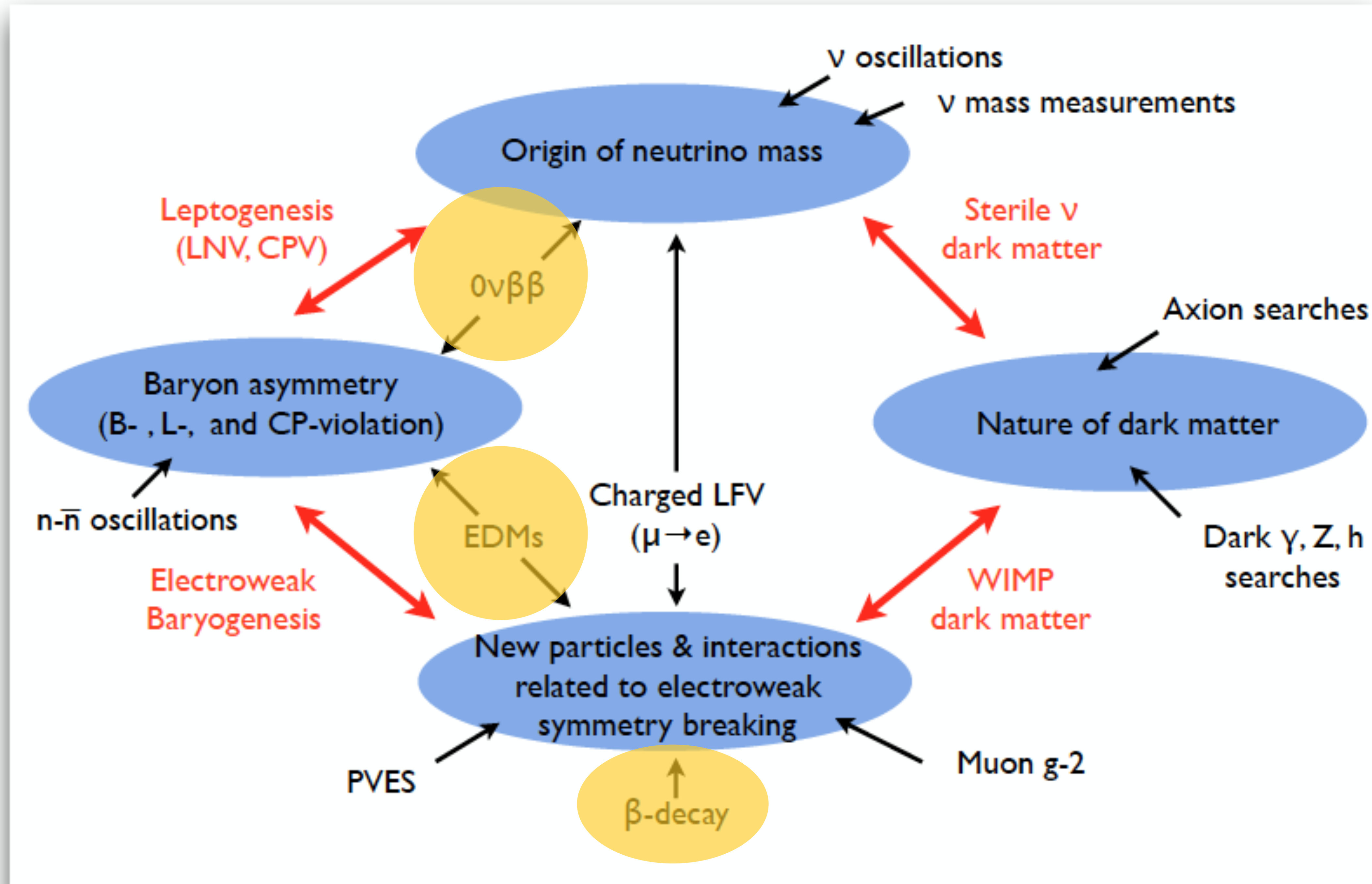
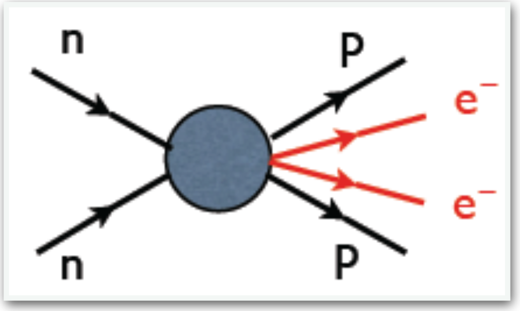


Neutrinoless double beta decay
and
Lepton Number Violation

See talk by J. Klein

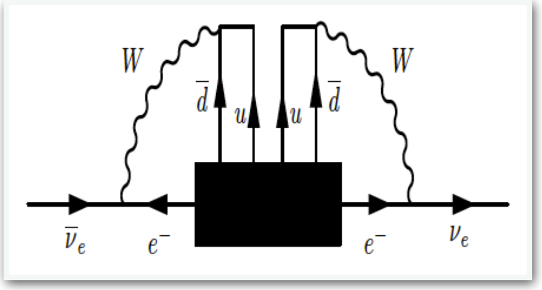
Neutrinoless double beta decay (0νββ)

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

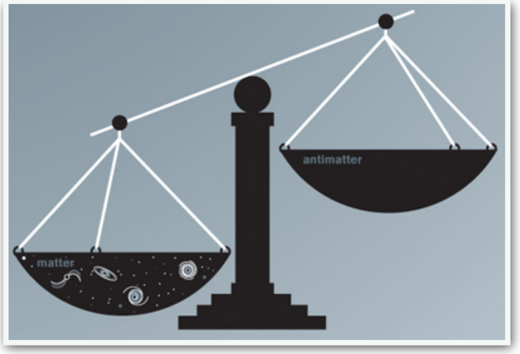


Lepton number changes by two units: ΔL=2

- B-L conserved in SM → new physics, with far-reaching implications
  - Demonstrate that neutrinos are their own antiparticles
  - Establish a key ingredient to generate the baryon asymmetry via leptogenesis



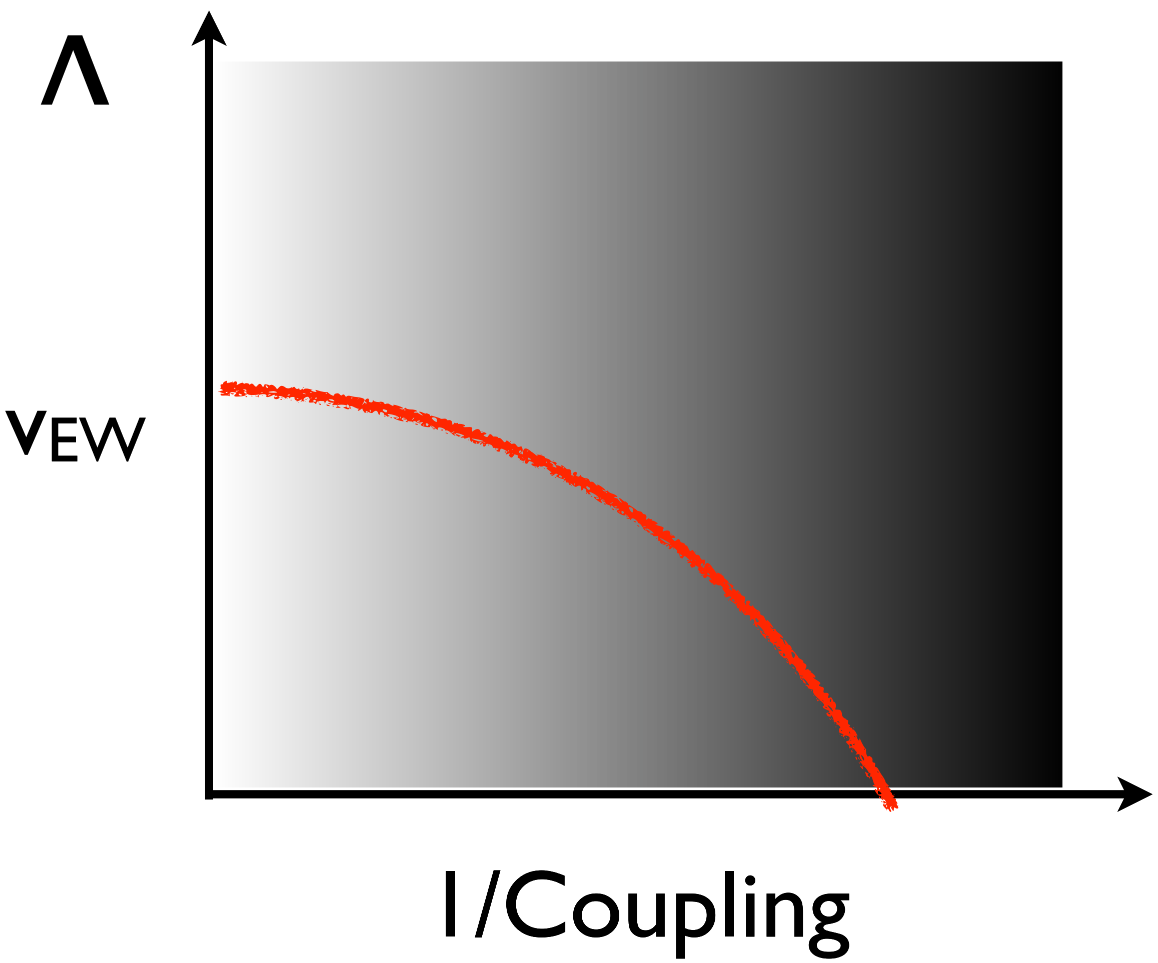
Shechter-Valle 1982

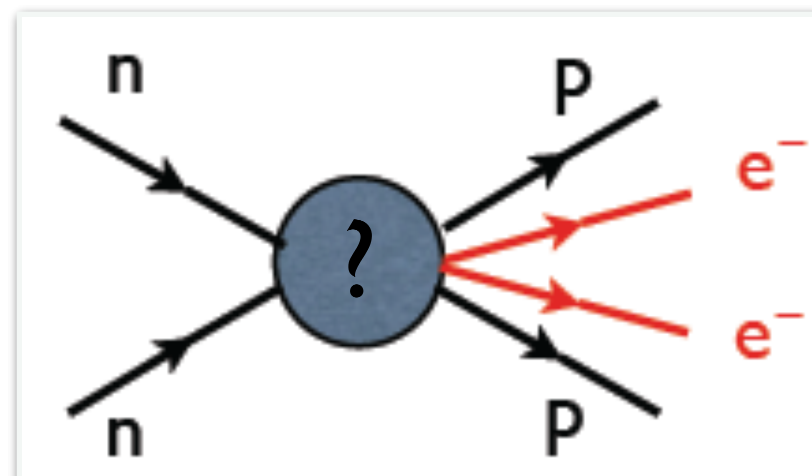


Fukujgita-Yanagida 1987

$0\nu\beta\beta$ physics reach

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) will probe at unprecedented levels LNV from a variety of mechanisms





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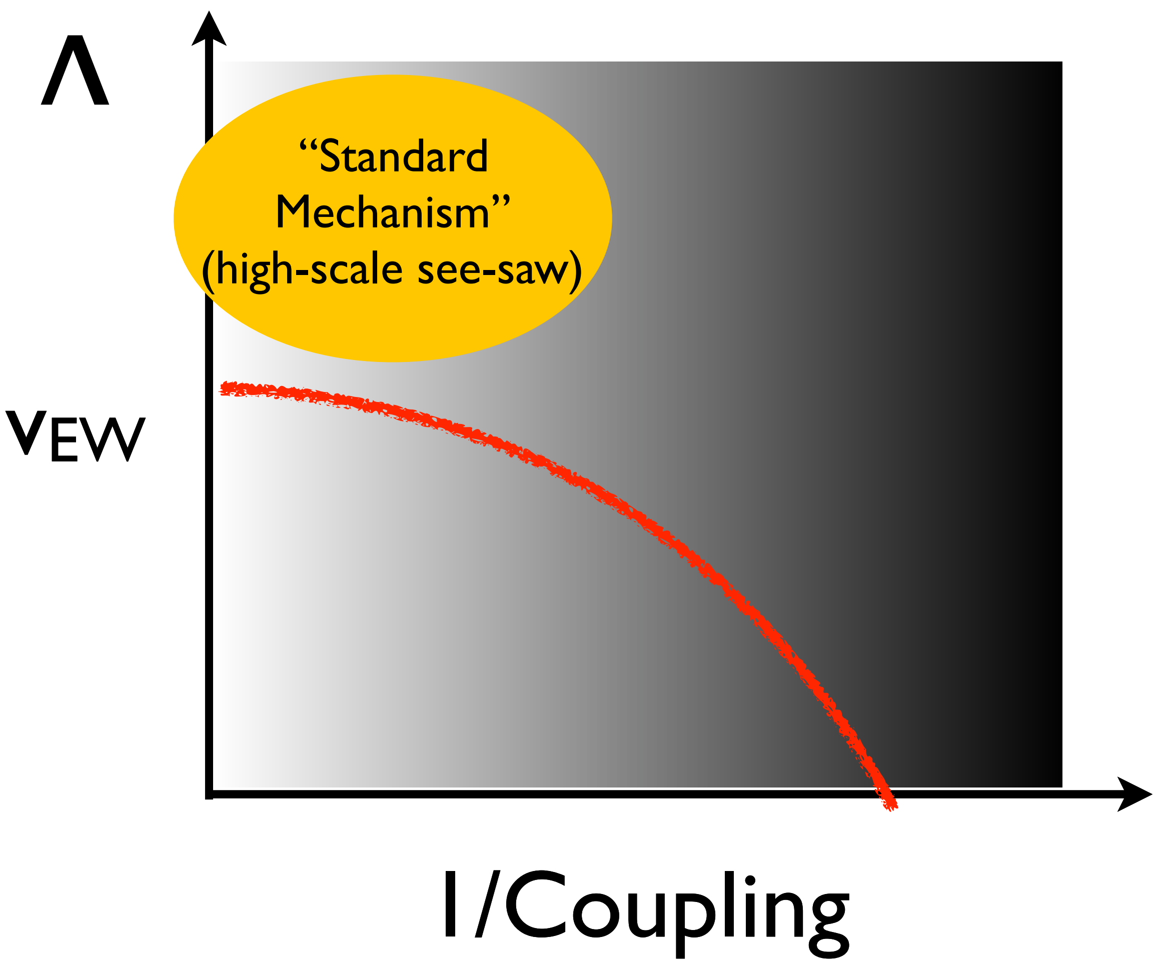

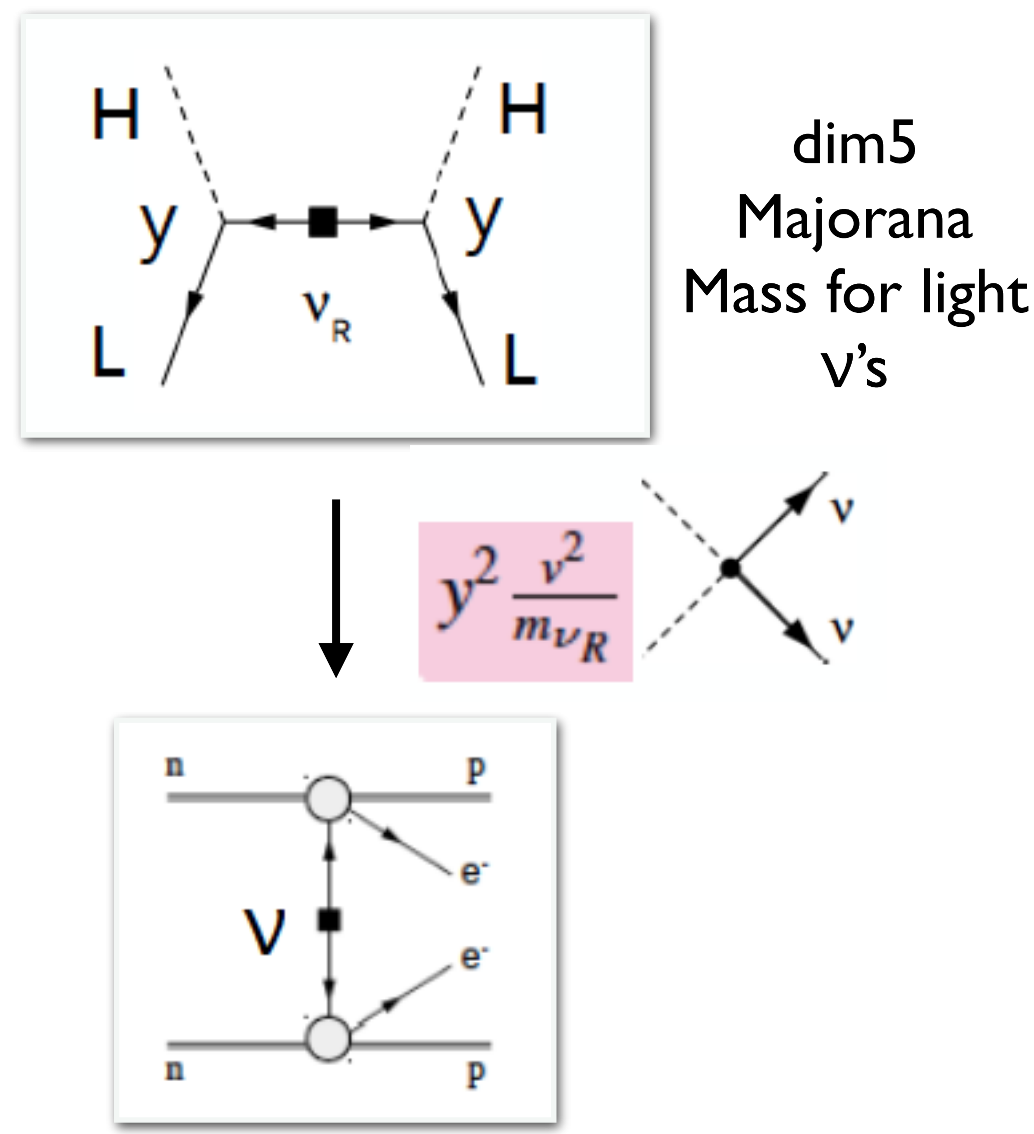

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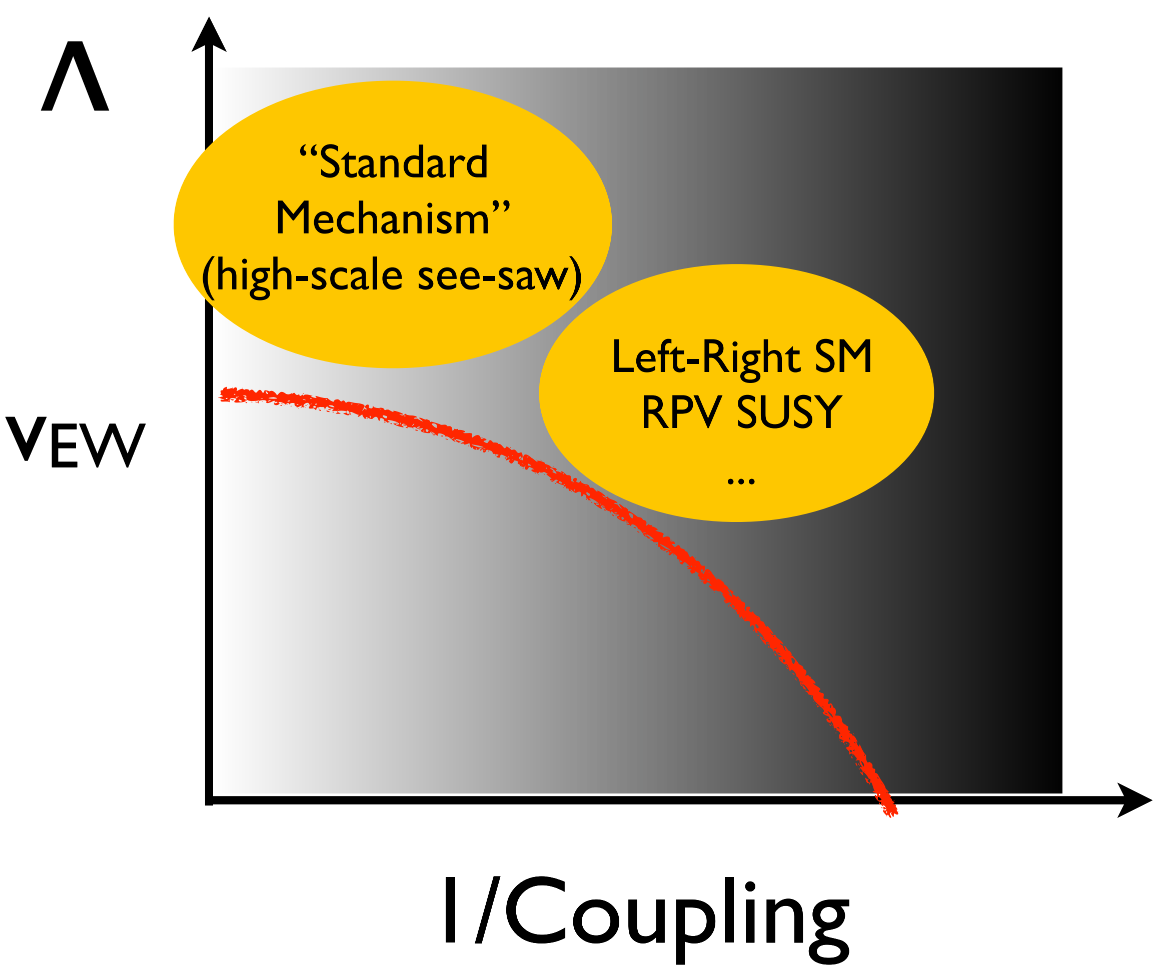

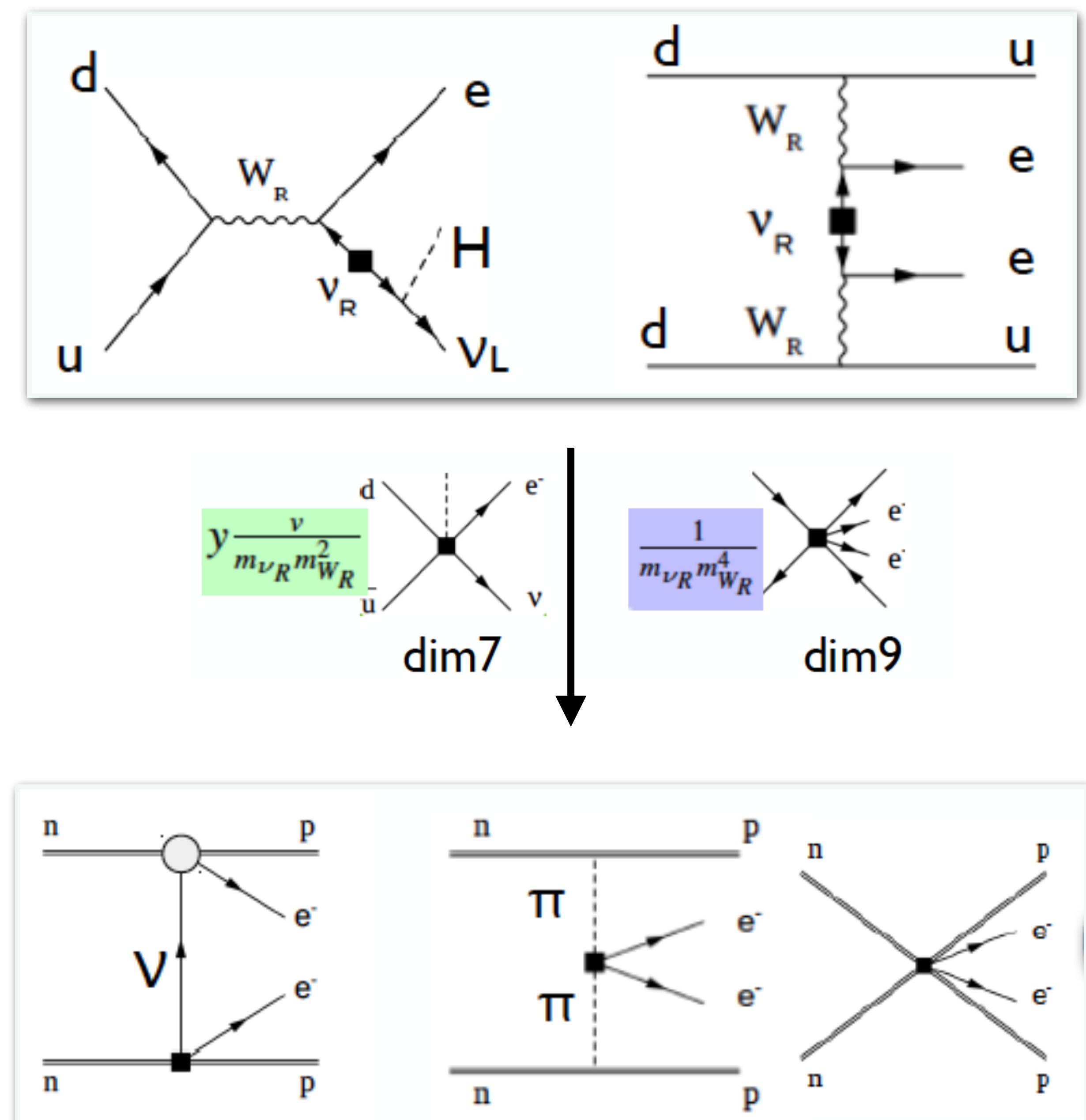

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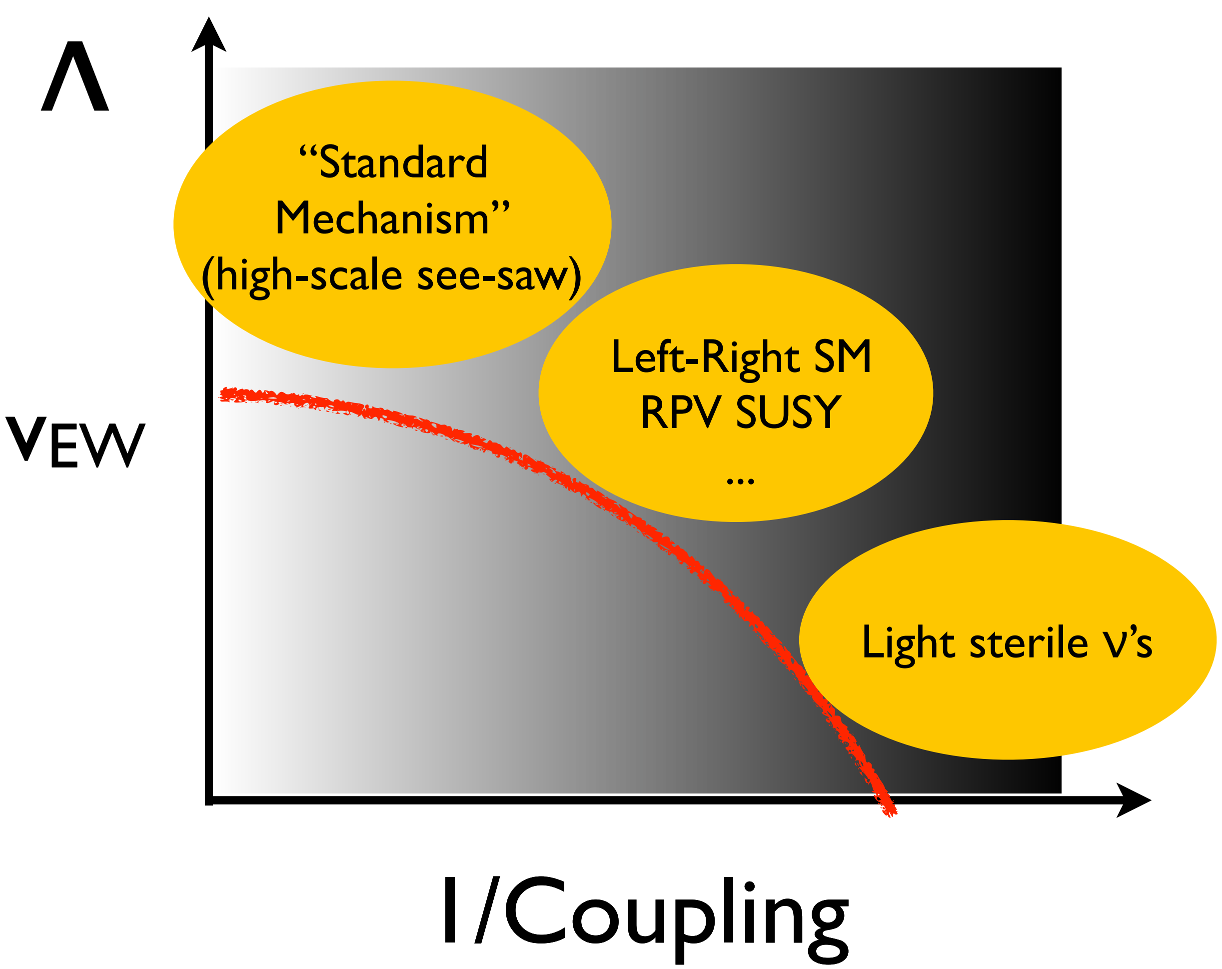
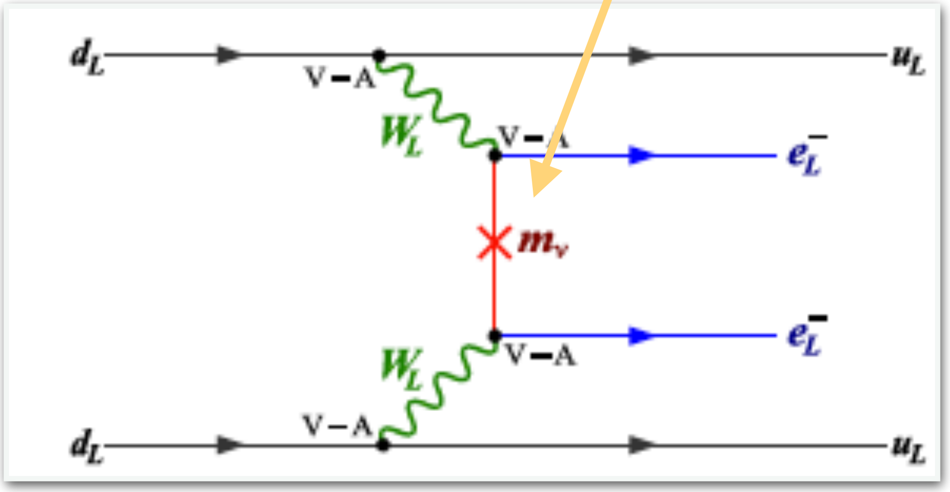


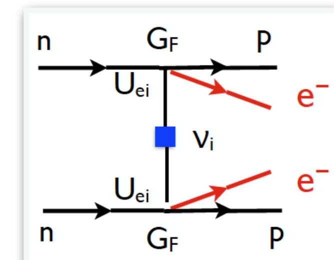
Light (nearly sterile) Majorana neutrinos:
$M_R \sim$ eV → GeV:



High-scale seesaw: discovery potential

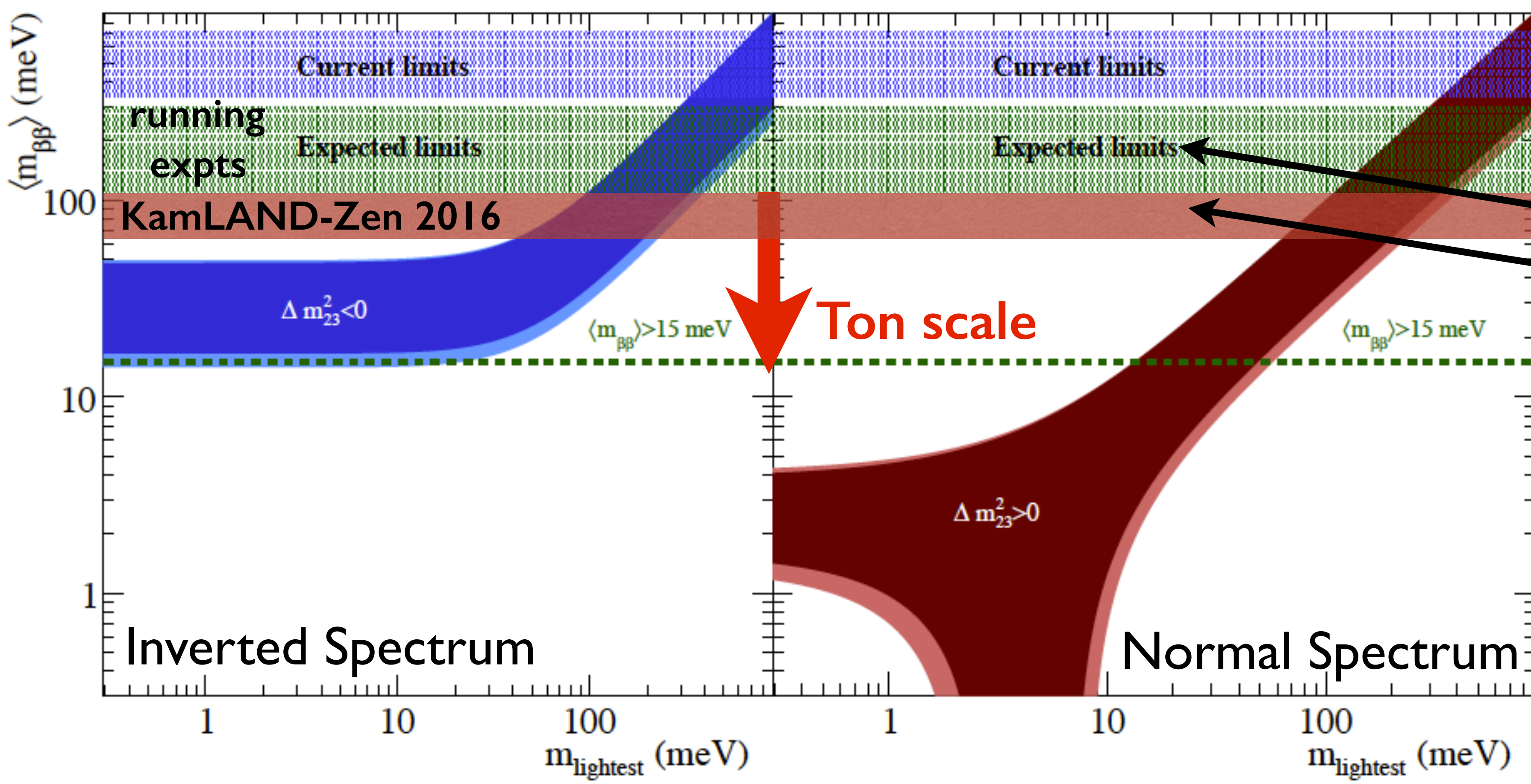
- In this case $0\nu\beta\beta$ is a direct probe of ν mass matrix: $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

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



Dark bands: unknown phases

Light bands: uncertainty from oscillation parameters(90% CL)



Assume range for nuclear matrix elements from different many-body methods

Plot by K. Heeger

Discovery *possible* for inverted spectrum or $m_{lightest}$ > 50 meV

High-scale seesaw: diagnosing power

- Interplay with other ν mass probes can test high-scale seesaw and possibly unravel new sources of LNV or physics beyond "ΛCDM + m_ν"

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

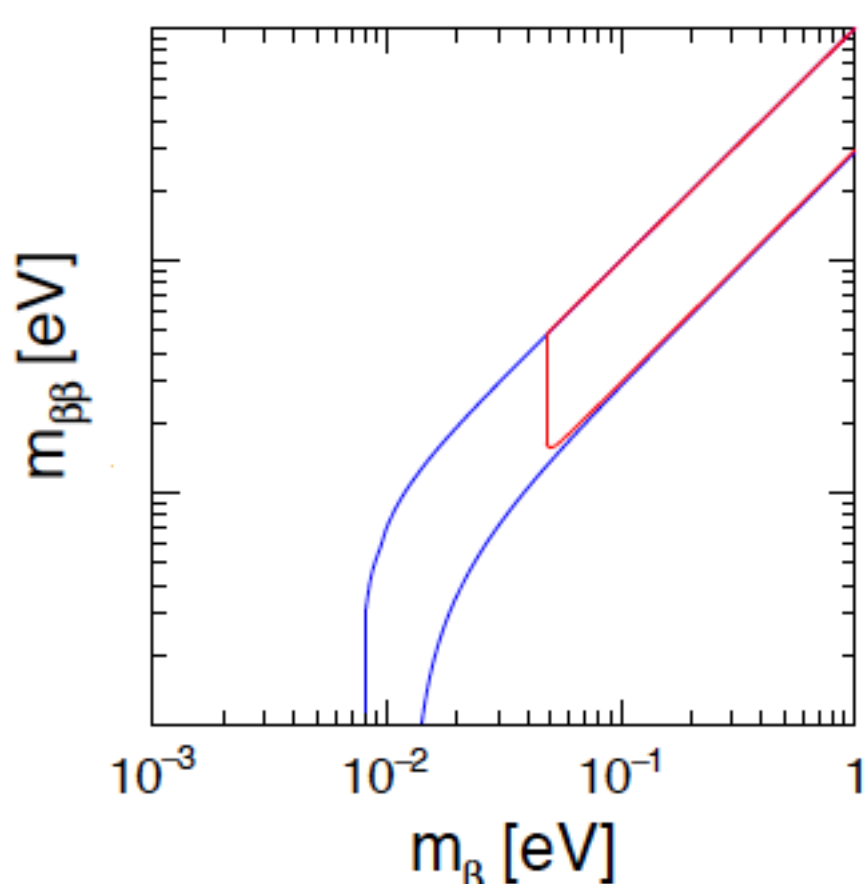
0νββ decay

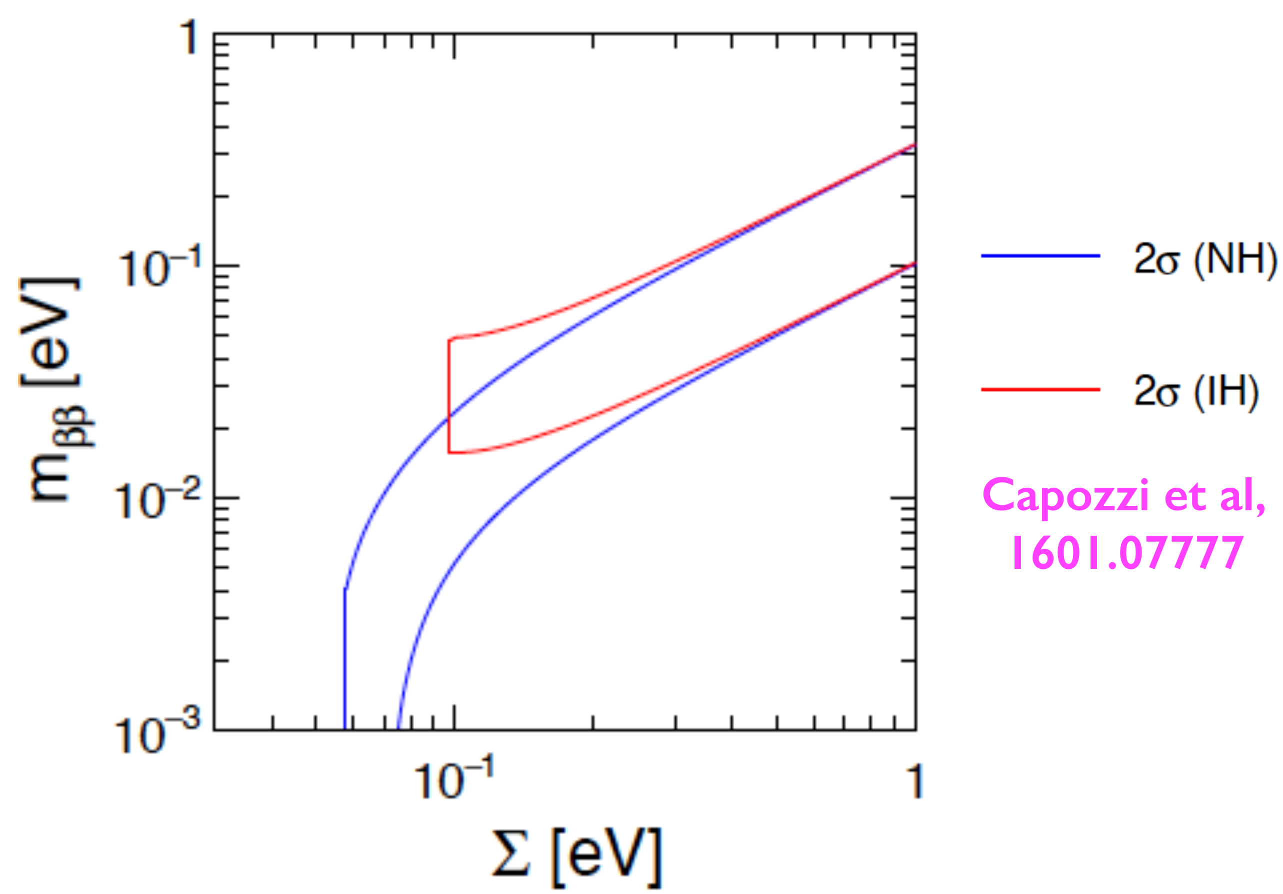
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





Capozzi et al, 1601.07777

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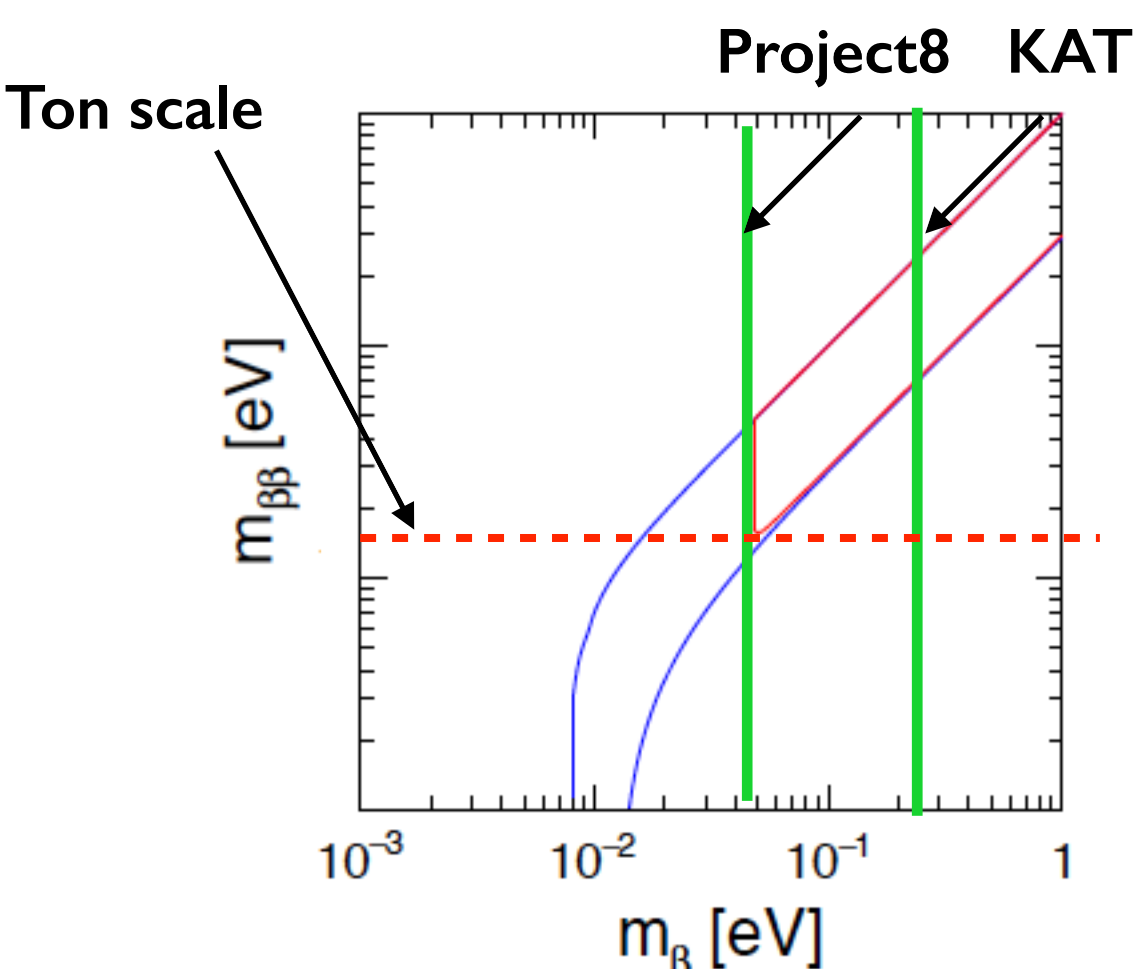
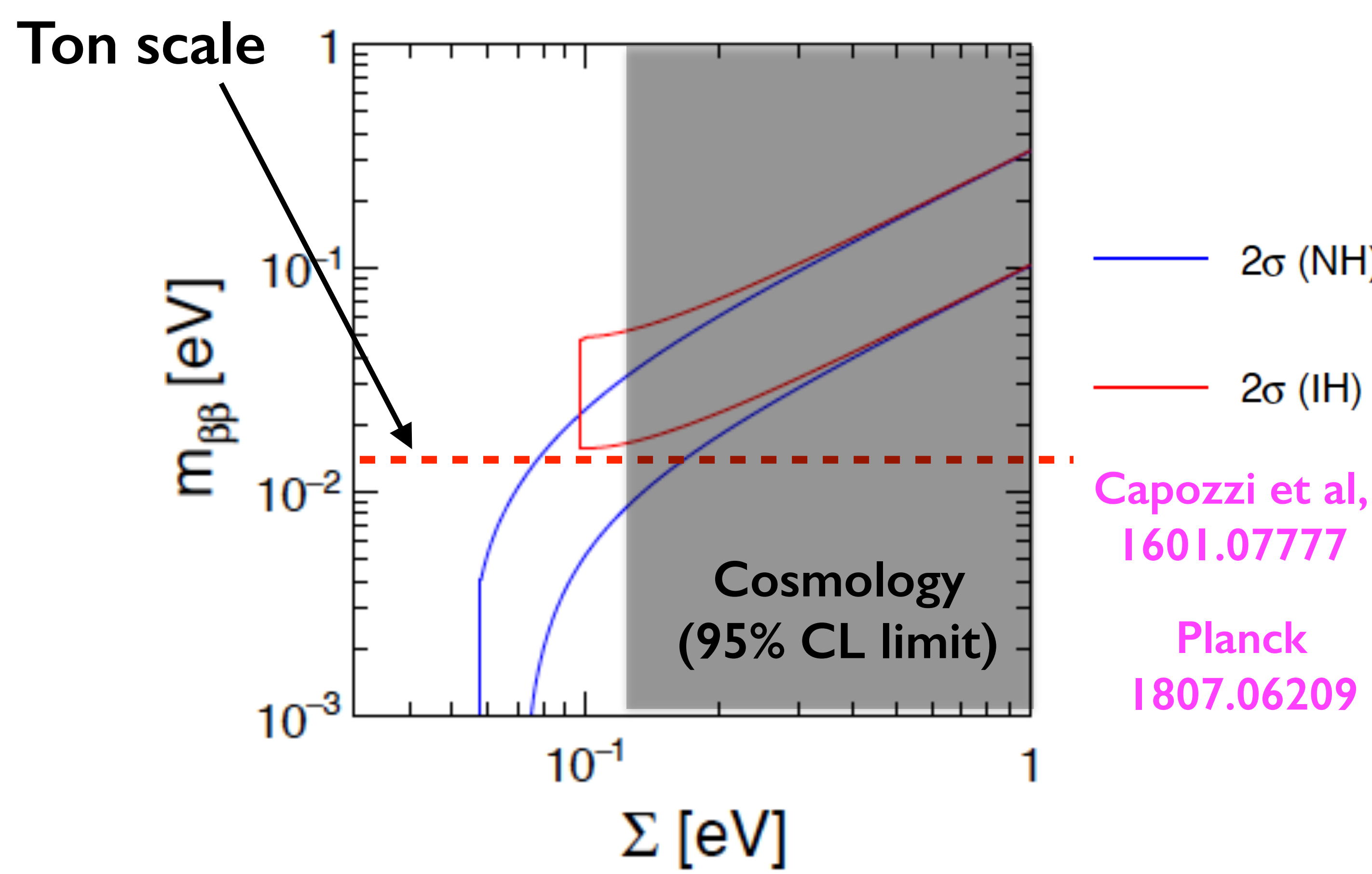
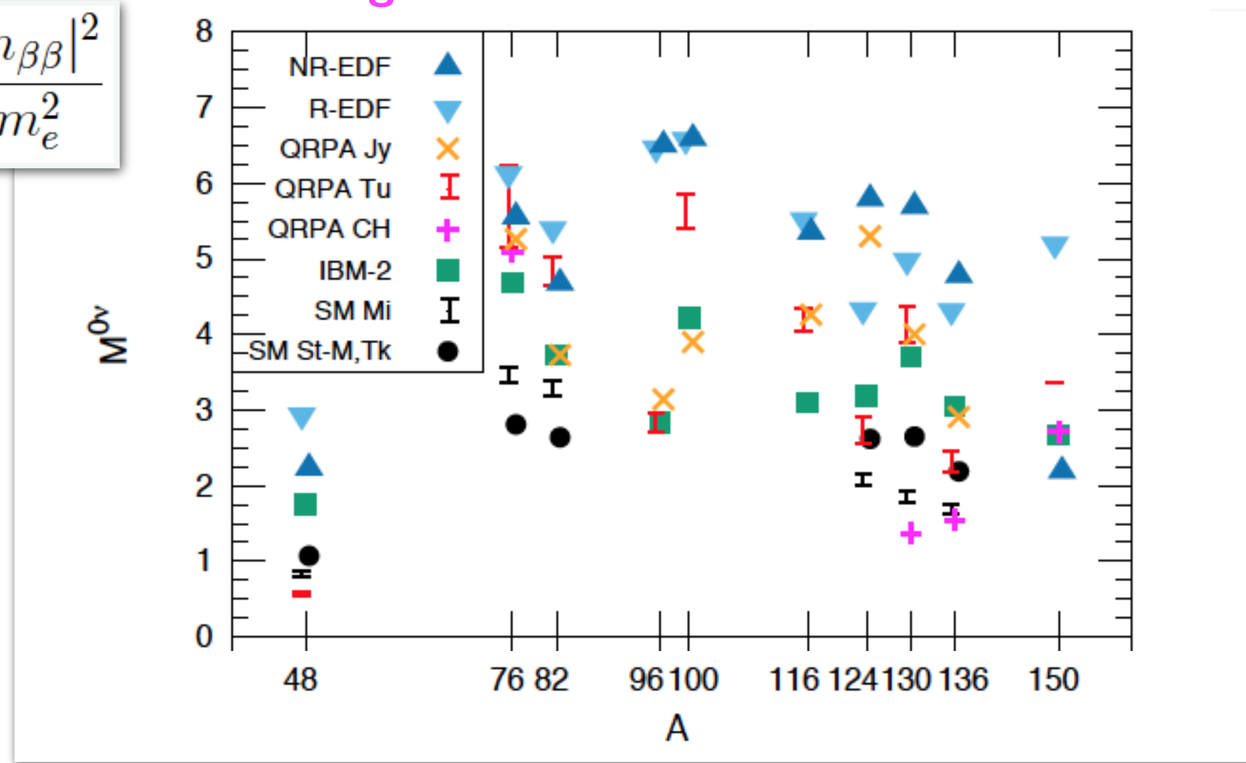




High-scale seesaw: theory developments

$$\left(T^{0\nu}_{1/2}\right)^{-1} = g_A^4\, G_{01}\, |M_{0\nu}|^2 \frac{|m_{\beta\beta}|^2}{m_e^2}$$

Engel-Menendez 1610.06548

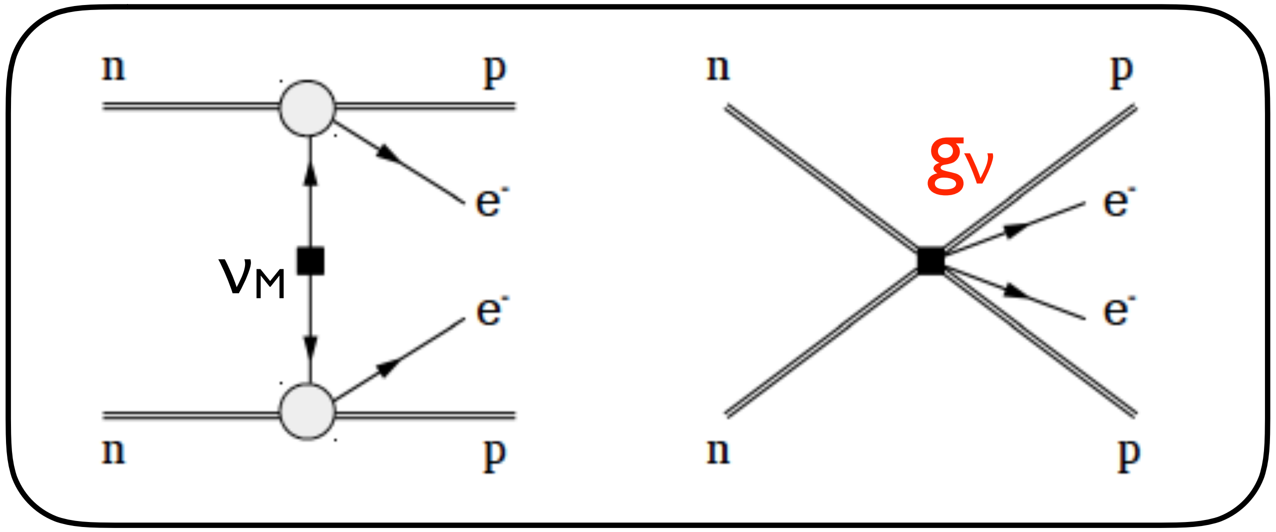


- Steps towards controllable uncertainties in matrix elements:
  - Use chiral EFT as guiding principle
  - Use first-principles results in light nuclei as a benchmark
  - “Ab initio” nuclear structure calculations with QCD-rooted potentials for ^{48}Ca and ^{76}Ge

Coordinated effort through DOE-funded DBD Nuclear Theory Topical Collaboration (PI Jon Engel)
http://c51.lbl.gov/~0nubb/webhome/

New insights from EFT

Leading order nn→pp transition operator
for nuclear structure calculations should be

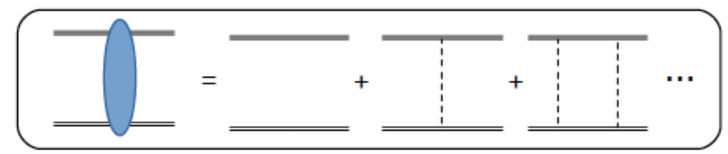


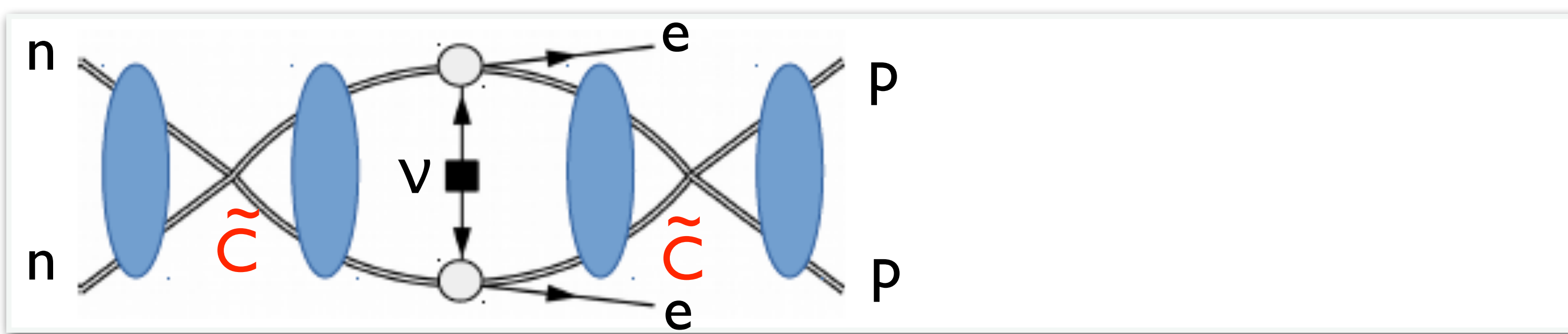
V.C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck
1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001

New insights from EFT

- Renormalization of nn→ppee amplitude (in $^1S_0$ channel) requires a new leading order $\Delta L=2$ contact term

Strong short-range interaction → $\tilde{C} \sim 4\pi/(m_N Q)$ Q is soft scale ~ k_F





UV divergence ~ $1/(Q^2)\log(\mu)$

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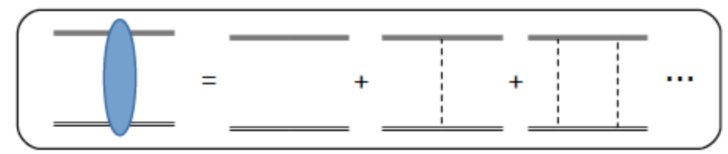
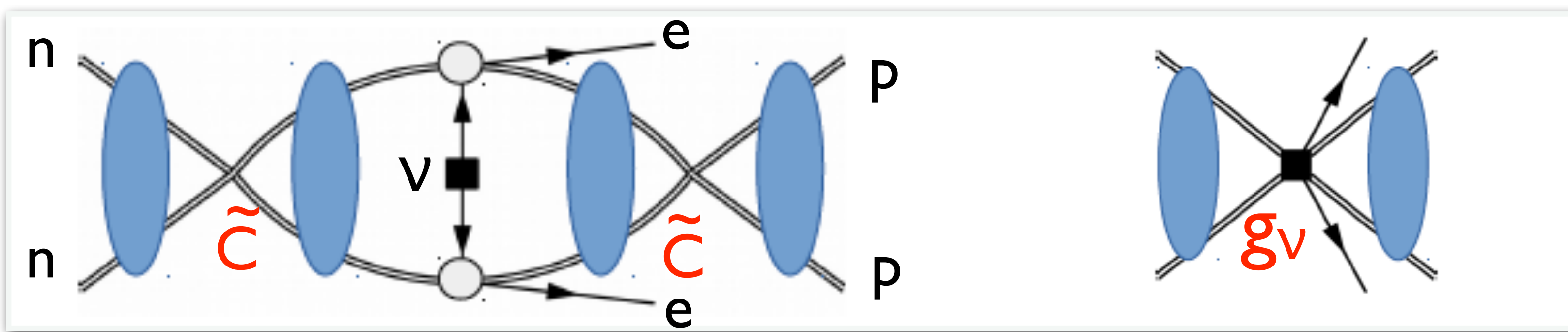




UV divergence ~ $1/(Q^2)\log(\mu)$ reabsorbed by g_ν

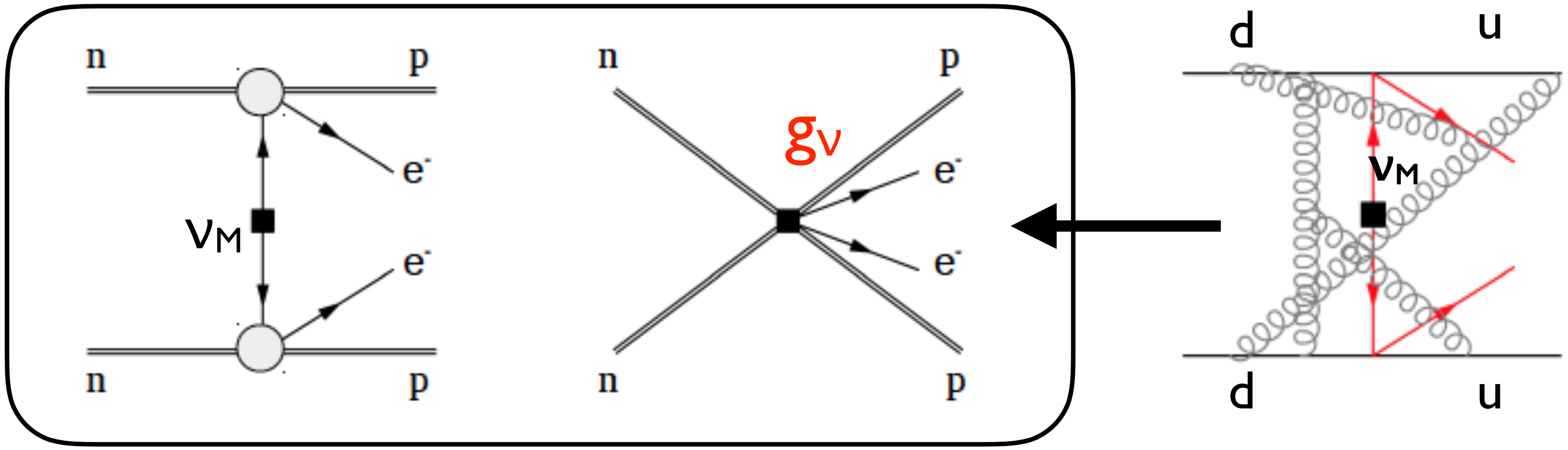
- Coupling flows to $g_\nu \sim 1/Q^2 \sim 1/k_F^2$, same order as tree-level ν exchange

V.C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck
1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001

New insights from EFT

- Renormalization of nn→ppee amplitude (in $^1S_0$ channel) requires a new leading order $\Delta L=2$ contact term

Leading order nn→pp transition operator
for nuclear structure calculations should be



Previously missed short-range coupling g_ν encodes the physics of "high momentum" ν_M exchange ($q >> k_F$)

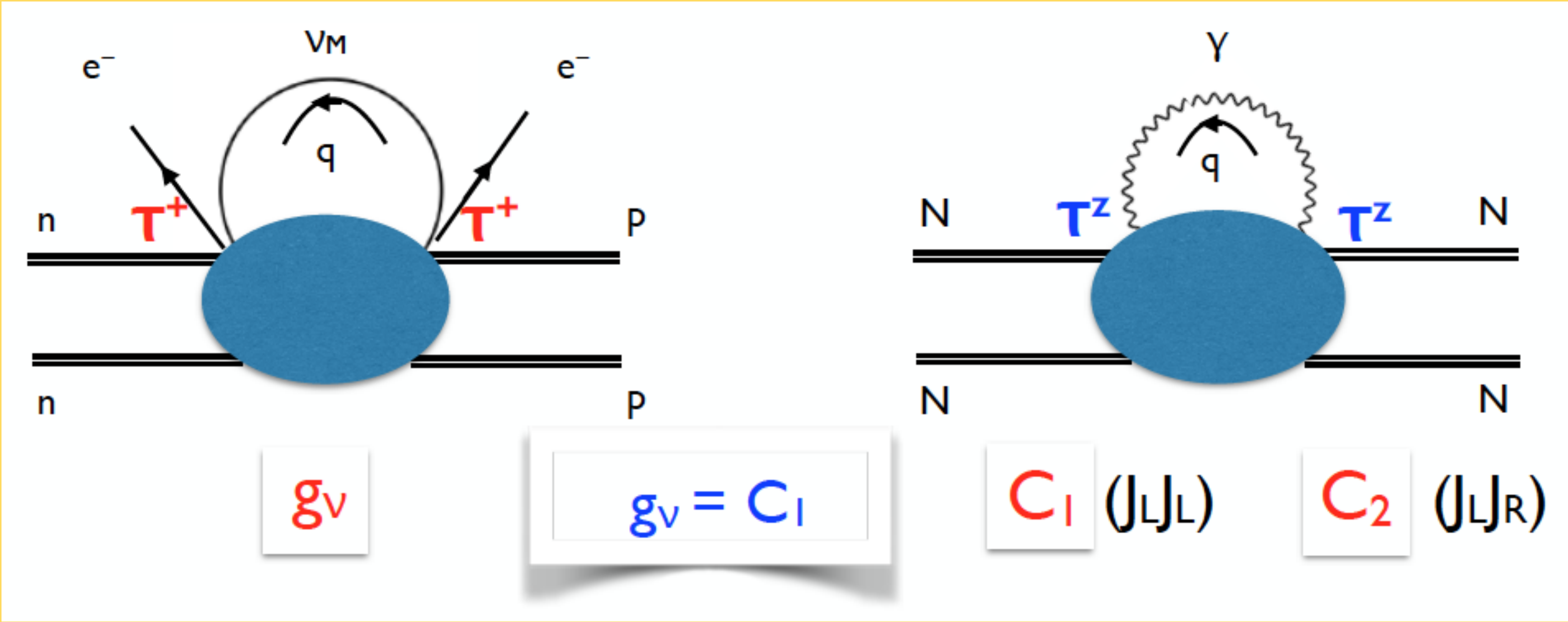
V.C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck
1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001

New insights from EFT

- Renormalization of nn→ppee amplitude (in $^1S_0$ channel) requires a new leading order ΔL=2 contact term

Expect significant impact of (unknown) g_ν on $m_{\beta\beta}$ phenomenology

Several approaches to estimate g_ν
(symmetry relation to I=2 EM couplings**, dispersive, lattice QCD)



Work is underway on various fronts

V.C., W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck
1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001

LNV from multi-TeV scale dynamics

- TeV sources of LNV may lead to sizable contributions to NLDBD *not directly related to the exchange of light neutrinos*

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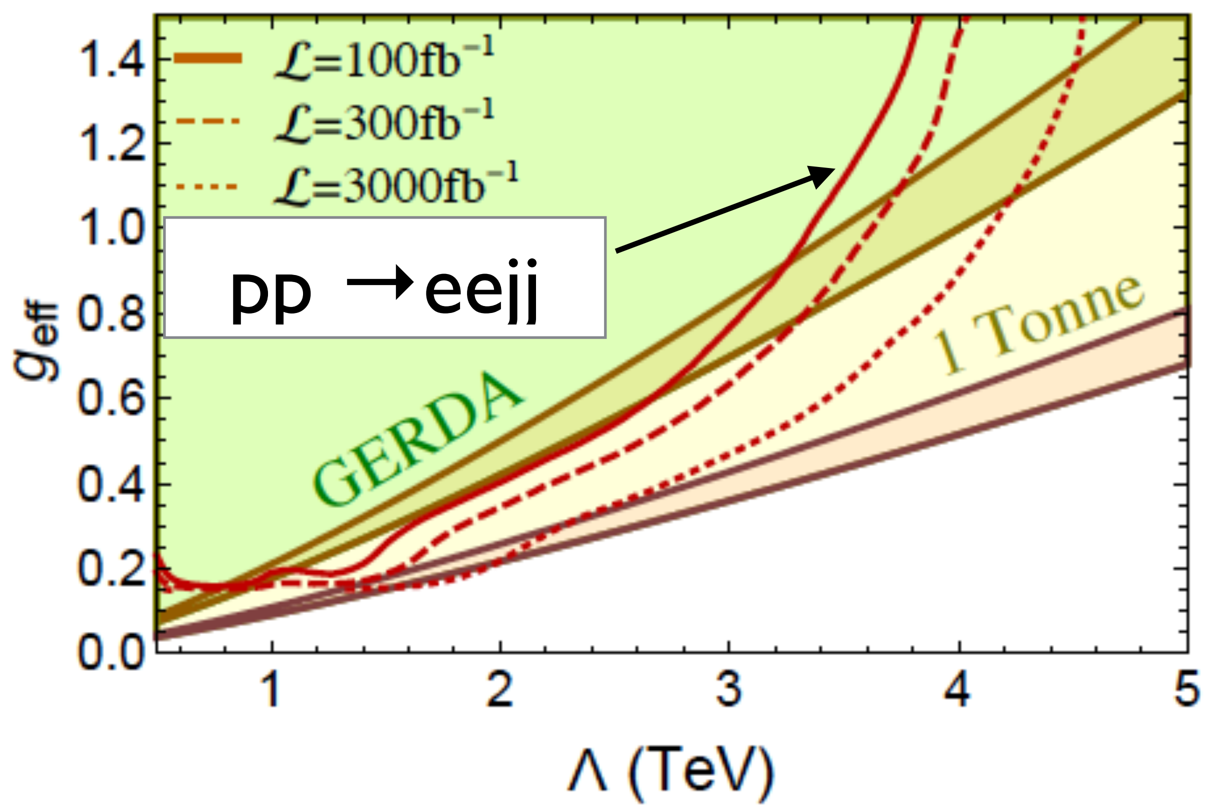
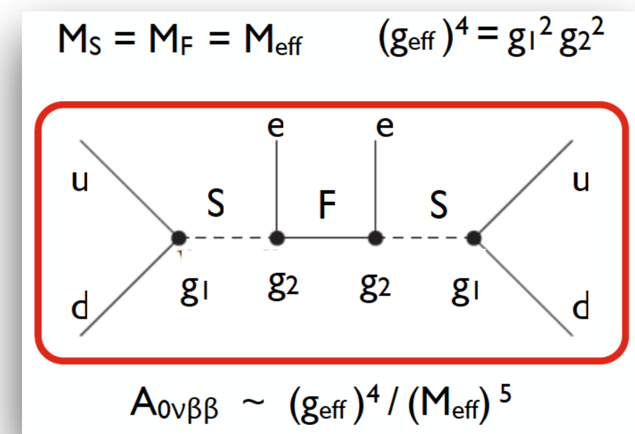
- LHC can compete with $0\nu\beta\beta$ in certain (limited) parameter space

Peng, Ramsey-Musolf, Winslow, 1508.0444



Simplified model ~ RPV-SUSY



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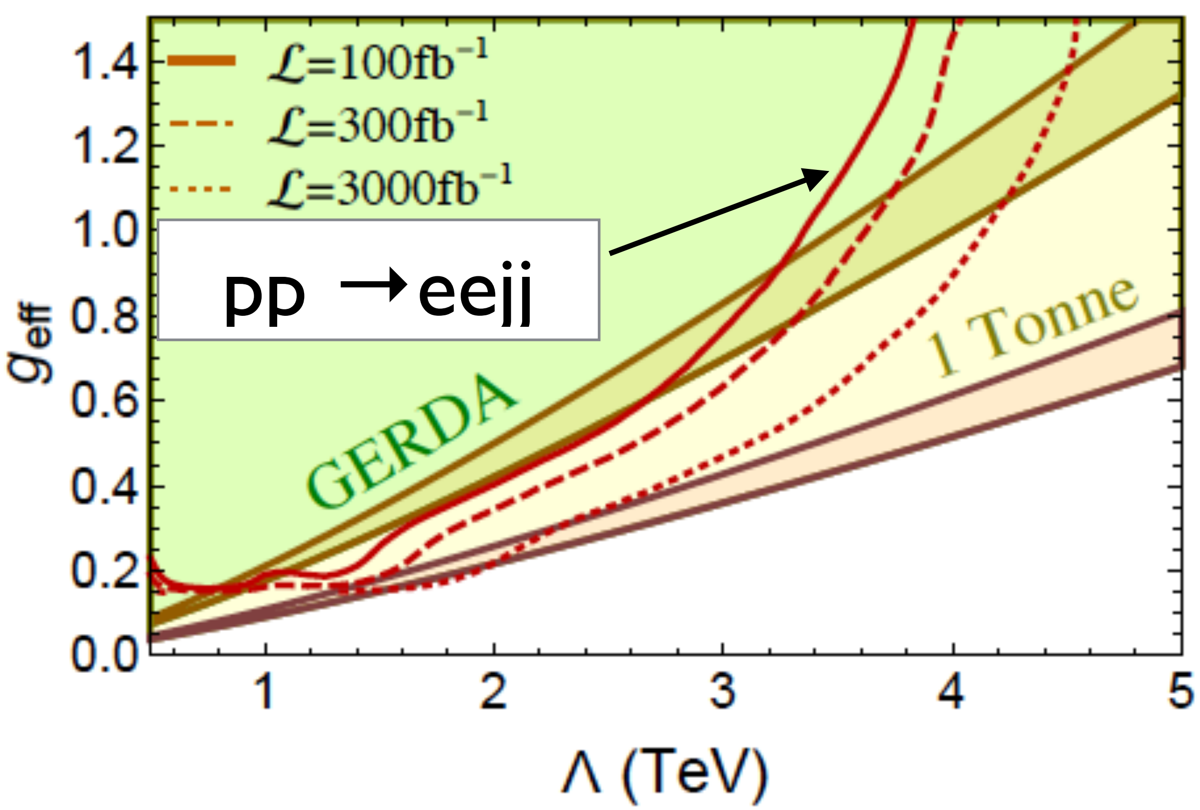
Peng, Ramsey-Musolf, Winslow, 1508.0444



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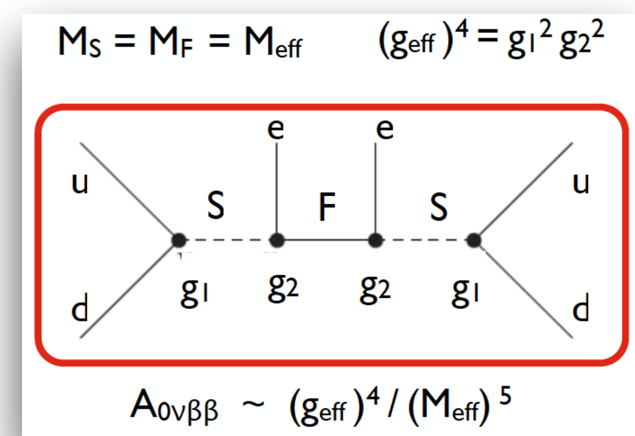
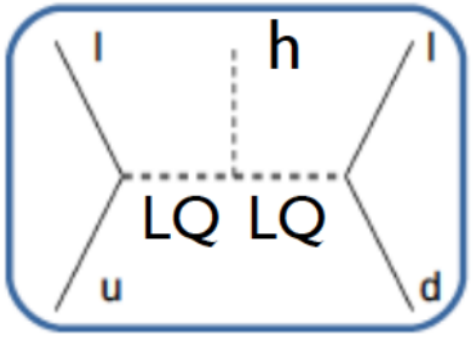
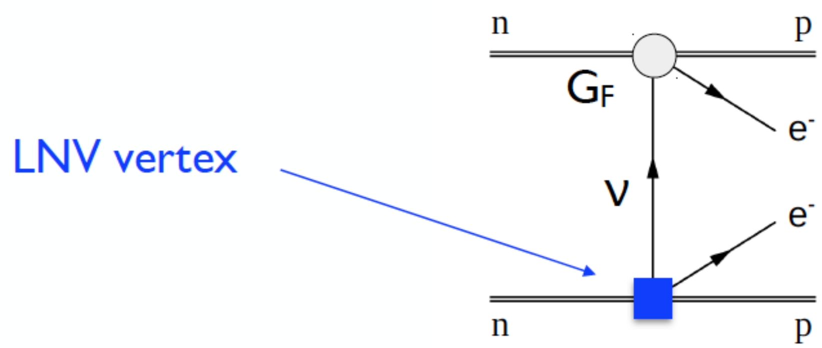


- New contributions can interfere with $m_{\beta\beta}$ or add incoherently, significantly affecting the interpretation of experimental results

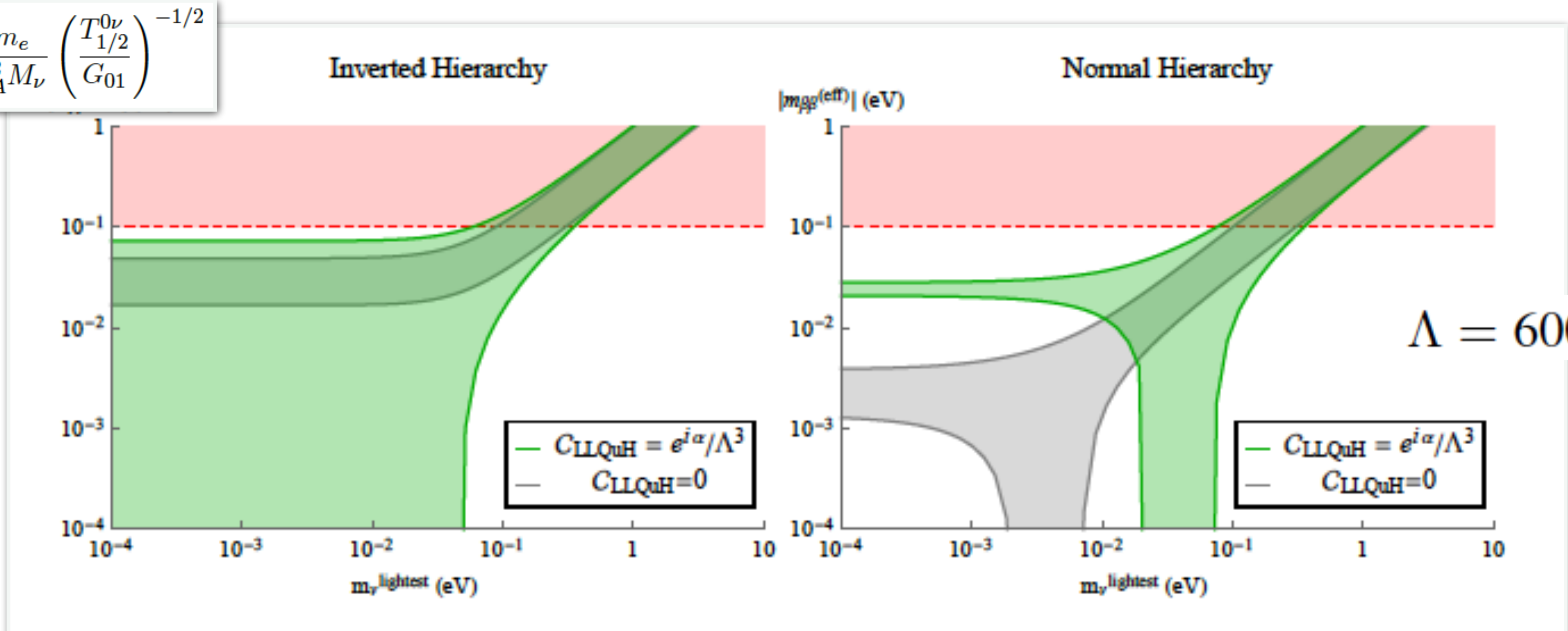
LNV from multi-TeV scale dynamics

- Leptoquark example: dim-7 operator can interfere with dim-5 ($m_{\beta\beta}$)





$$m_{\beta\beta}^{(\mathrm{eff})} = \frac{m_e}{g_A^2 M_\nu}\left(\frac{T_{1/2}^{0\nu}}{G_{01}}\right)^{-1/2}$$

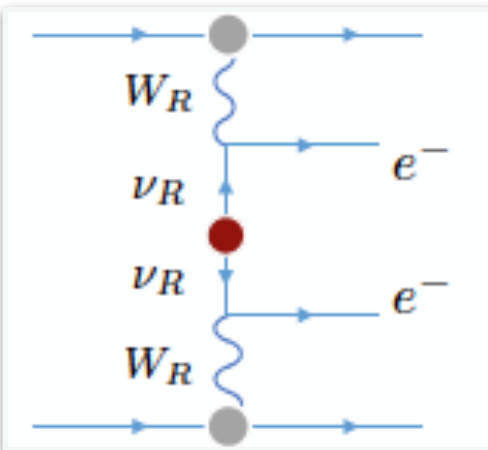


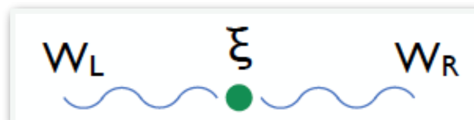
$\Lambda = 600$ TeV

VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1708.09390

LNV from multi-TeV scale dynamics

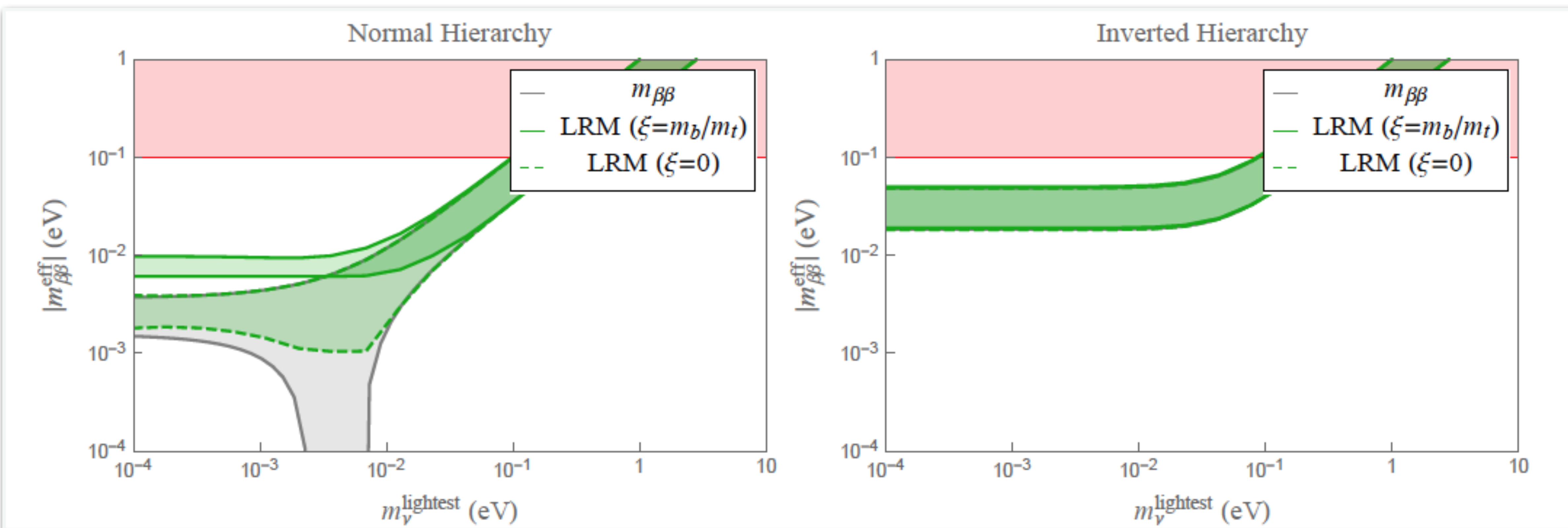
- Left-right symmetric model: dim-9 contribution can be dominant in NH





Illustrative LHC-safe (pp →ee jj) parameters

$$\boxed{\begin{aligned} m_{W_R} &= 4.5\ \text{TeV} \\ m_{\nu_R} &= O(10\ \text{TeV}) \\ U_R &= U_{\text{PMNS}} \end{aligned}}$$



VC, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, 1806.02789

$0\nu\beta\beta$ physics reach — summary

- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) have significant discovery potential — and yes, even "if it's normal hierarchy" ! (This is because we don't know the scale Λ associated with LNV)

- Model diagnosing: in combination with osc., direct mass meas., cosmology & LHC, can probe source of LNV

- Exciting prospects to improve theory uncertainties thanks to synergy of EFT, lattice QCD, and nuclear structure

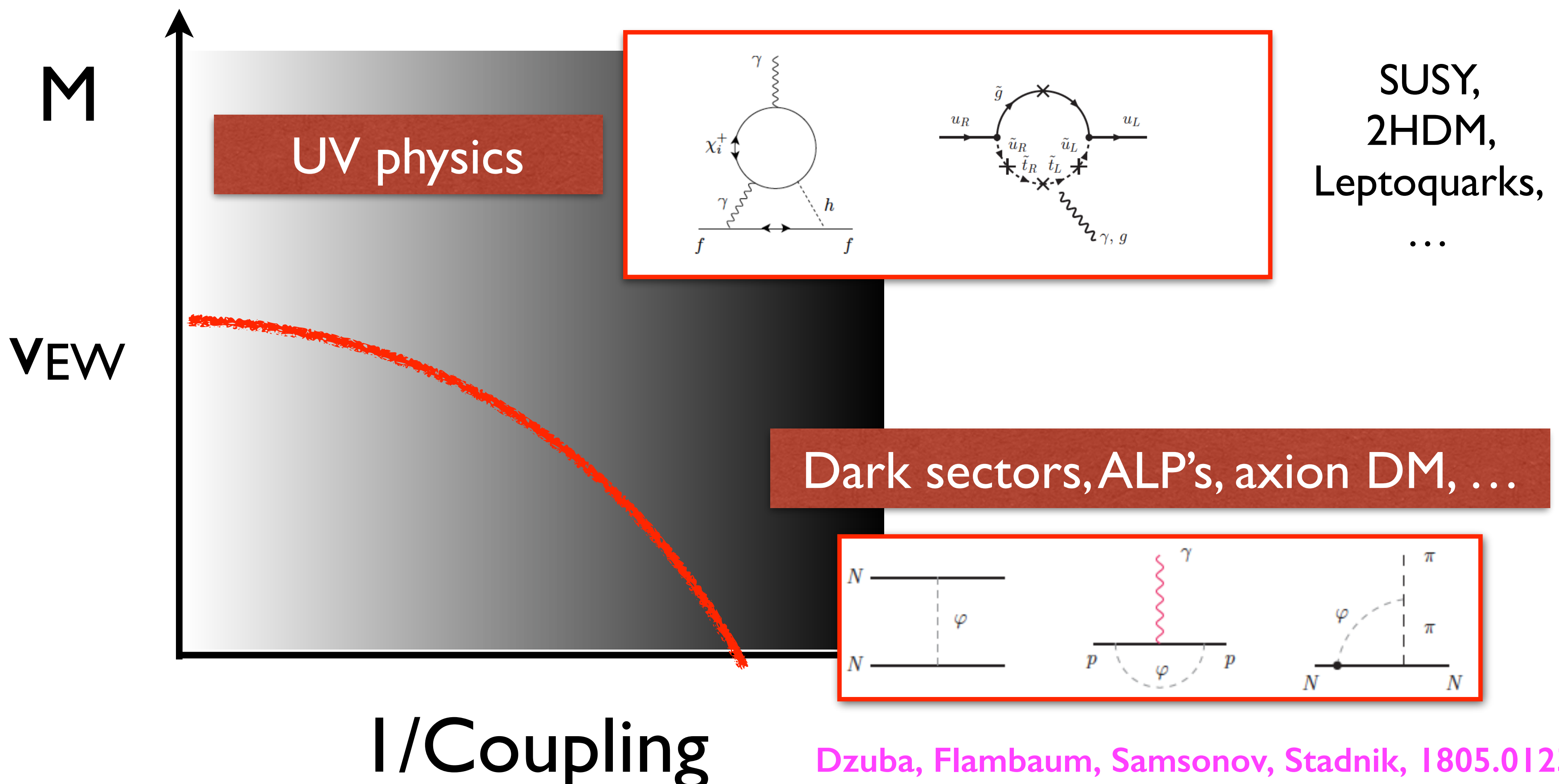
Electric Dipole Moments

- Essentially free of SM background (from CKM CP-violation)
- Probe new sources of CPV for baryogenesis (SM CPV is insufficient)

See talk by G. Pignol

Broad sensitivity to new physics

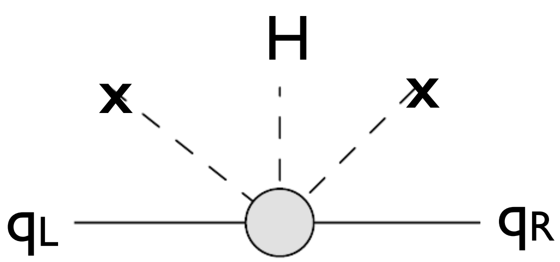
- Strongest constraints of CPV Higgs couplings
- One of few observables probing PeV scale SUSY
- Strong constraints on baryogenesis models



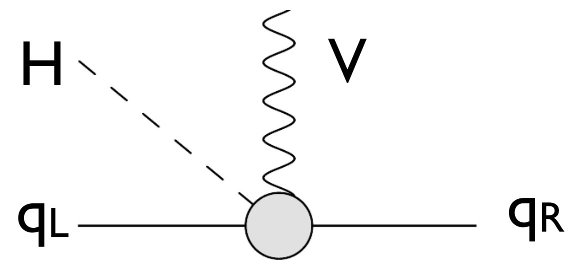
Dzuba, Flambaum, Samsonov, Stadnik, 1805.01234
Abel et al., 1708.06367
LeDall, Pospelov, Ritz 1505.01865
Mantry, Pitschmann, Ramsey-Musolf 1401.7339
…

EDMs and CPV Higgs couplings

- Leading ($1/\Lambda^2$) CP-violating BSM interactions involving the Higgs:

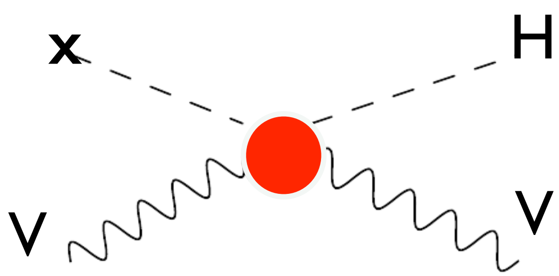


H-q_L-q_R: pseudo-scalar Yukawa couplings



H-q_L-q_R-V: dipole

V = g, W^a, B



H-H-V-$\tilde{V}$

$F_{\mu\nu}\tilde{F}^{\mu\nu} \sim \mathbf{E}\cdot\mathbf{B}$

Brod Haisch Zupan 1310.1385

Chien-VC-Dekens-de Vries-Mereghetti, 1510.00725

Brod-Stamou, 1812.12303

...

VC-Dekens-de Vries-Mereghetti, 1603.03049

Fuyuto & Ramsey-Musolf 1706.08548

...

McKeen-Pospelov-Ritz 1208.4597

...

VC, Crivellin,, Dekens, de Vries, Hoferichter, Mereghetti, 1903.03625, Phys. Rev. Lett. 123, 051801 (2019)

...

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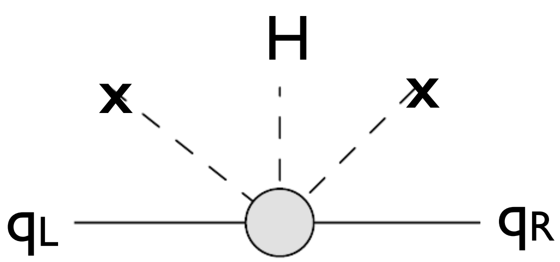

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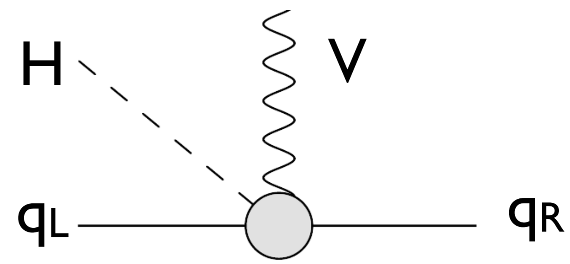

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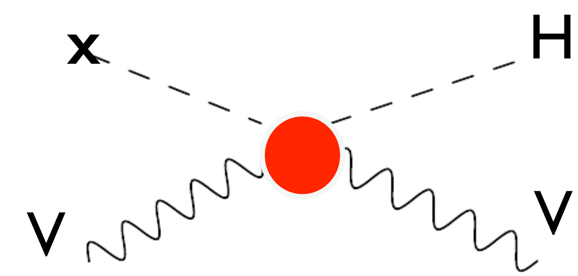
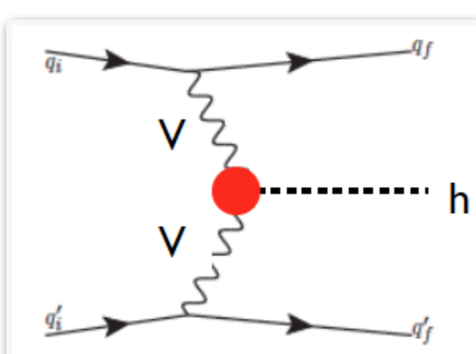
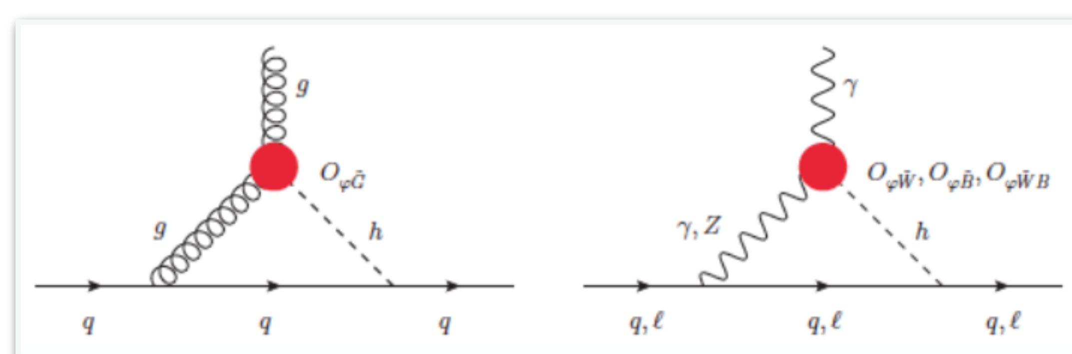


H-H-V-$\tilde{V}$

$F_{\mu\nu}\tilde{F}^{\mu\nu} \sim$ **E · B**

- Affect Higgs production / decay at the LHC and EDMs, e.g.:





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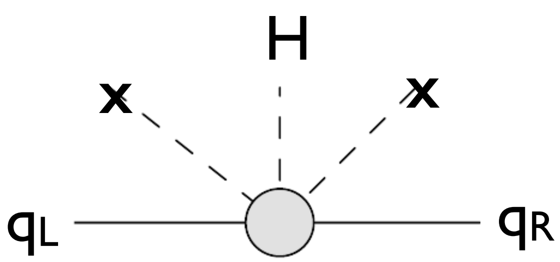

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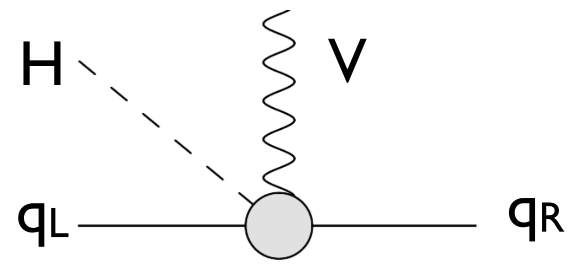
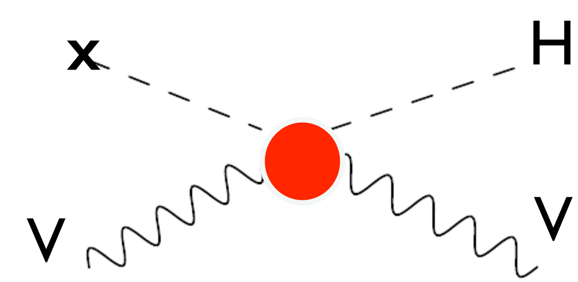


H-q_L-q_R-V: dipole

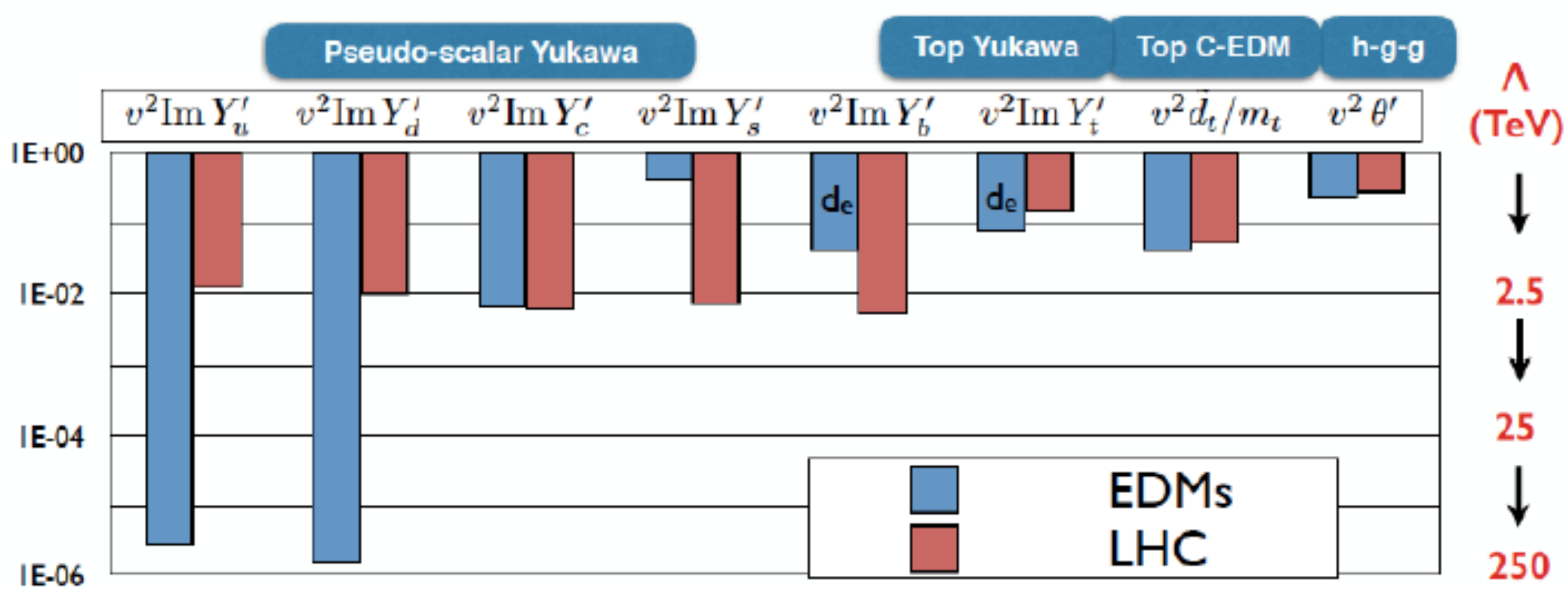
$V = g, W^a, B$



H-H-V-$\tilde{V}$

$F_{\mu\nu} \tilde{F}^{\mu\nu} \sim \mathbf{E} \cdot \mathbf{B}$

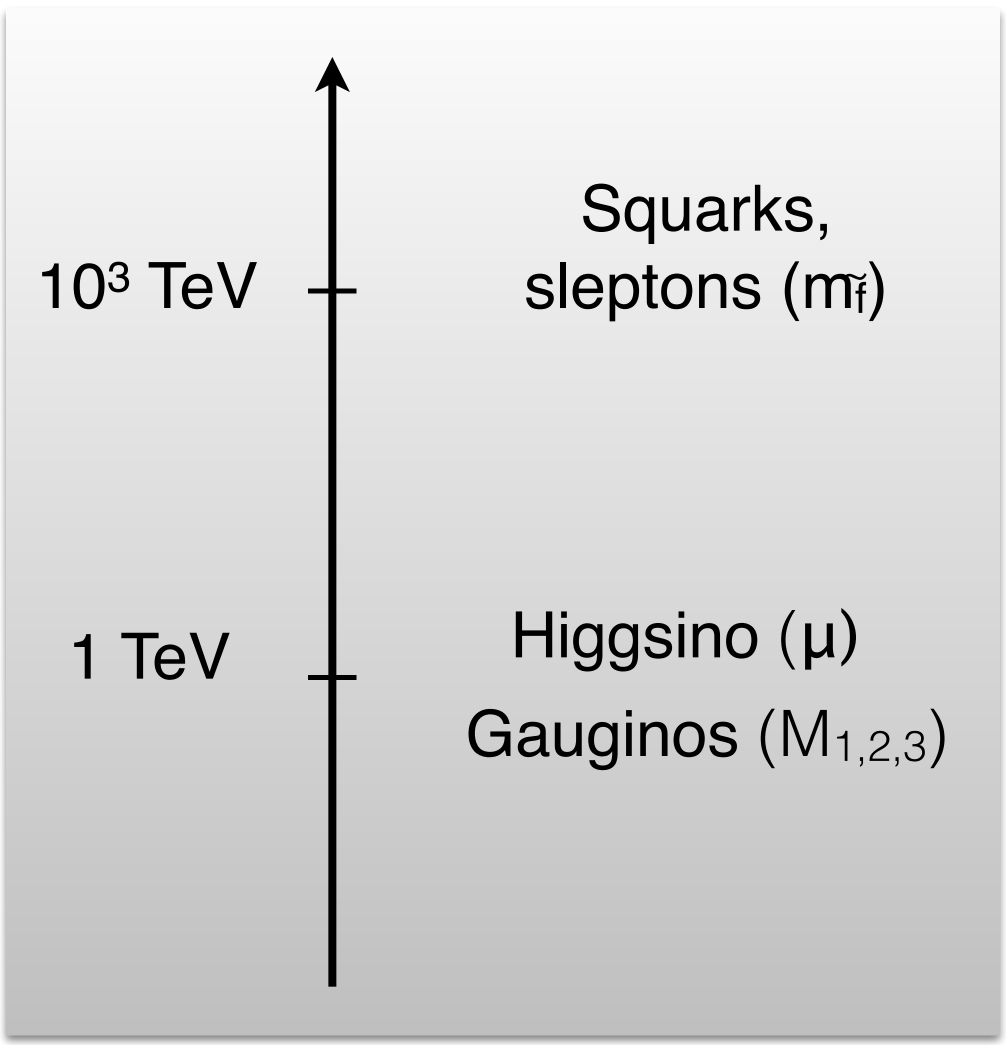
- EDMs provides the strongest constraints in most cases
- Sensitivity @ 5×10^{-27} e cm with mildly improved matrix elements will make nEDM the strongest probe for all couplings involving quarks and gluons



EDMs in high-scale SUSY models

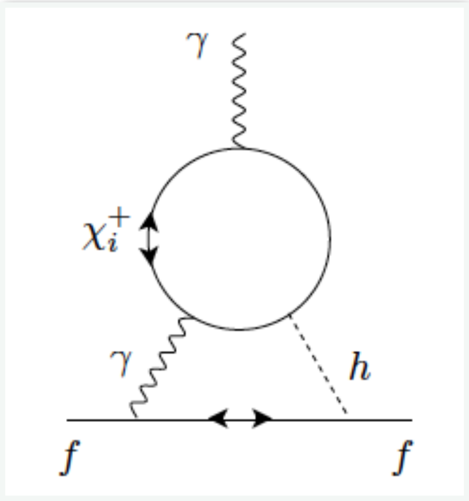
- "Split-SUSY": retain gauge coupling unification and DM candidate

Arkani-Hamed, Dimopoulos 2004, Giudice, Romanino 2004, Arkani-Hamed et al 2012, Altmannshofer-Harnik-Zupan 1308.3653, …



EDMs among a handful of observables capable of probing such high scales

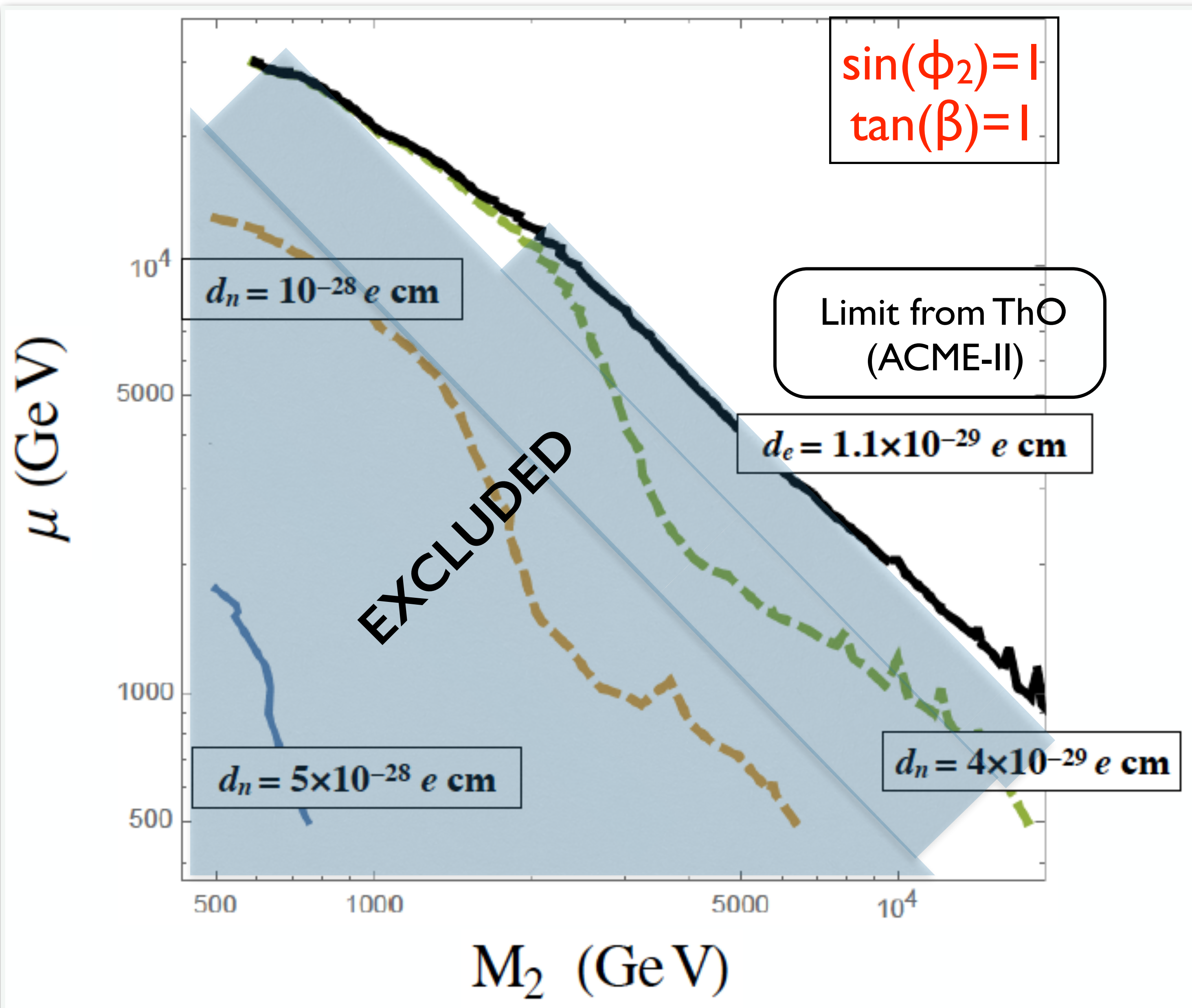
Same CPV phase controls d_e, d_n [d_q]



Barr-Zee diagram

EDMs in high-scale SUSY models

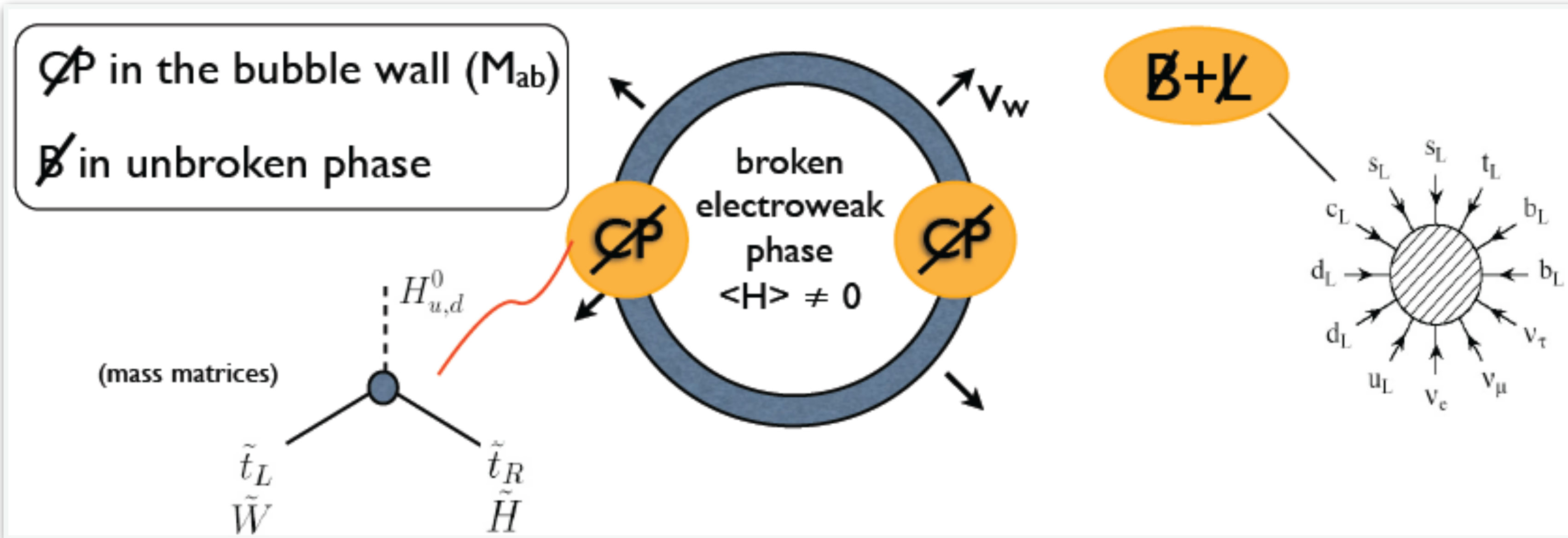
Bhattacharya, VC, Gupta, Lin, Yoon 1506.04196 , 1808.07597



- Studying the ratio d_n / d_e *with precise matrix elements (LQCD)* → stringent upper bound $d_n < 4.1 \times 10^{-29}$ e cm
- Split-SUSY can be falsified by current EDM searches

Example of model diagnosing enabled by multiple measurements (e,n) and controlled theoretical uncertainty

EDMs and weak scale baryogenesis

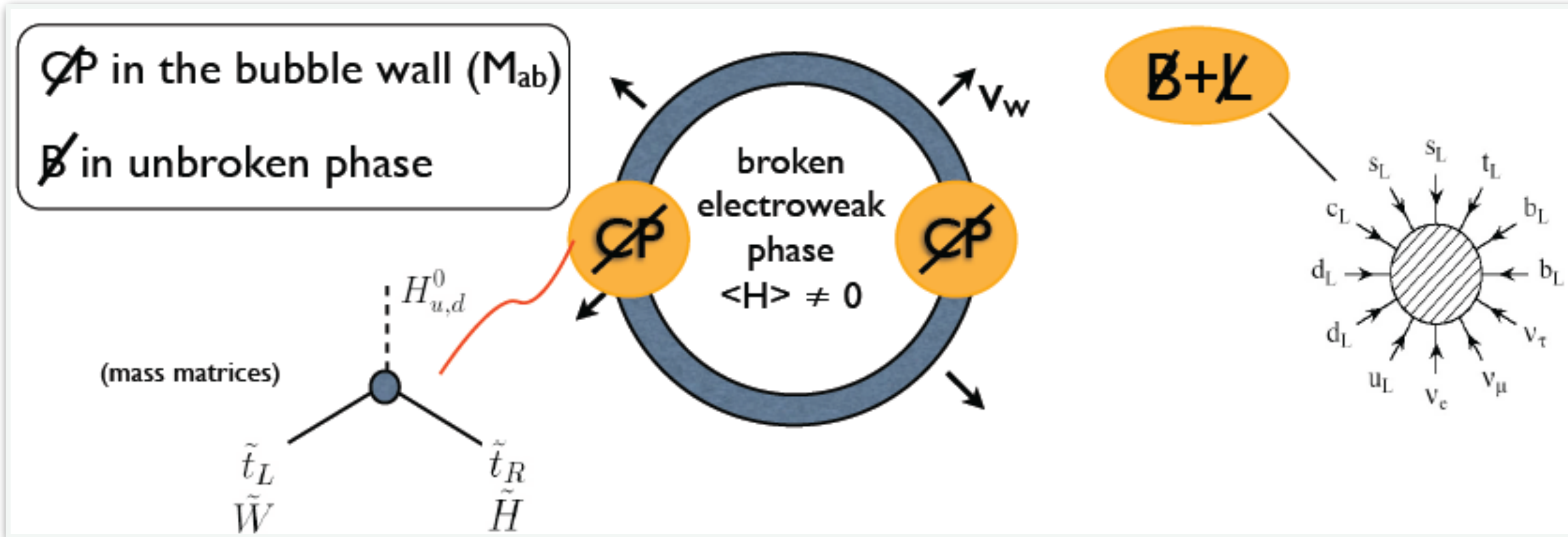


- B violation
- C & CP violation
- Departure from thermal equilibrium

Sakharov 1967

For a review see: Morrissey & Ramsey-Musolf 1206.2942

EDMs and weak scale baryogenesis



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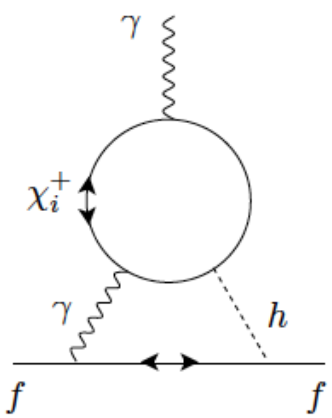
- B violation
- C & CP violation
- Departure from thermal equilibrium

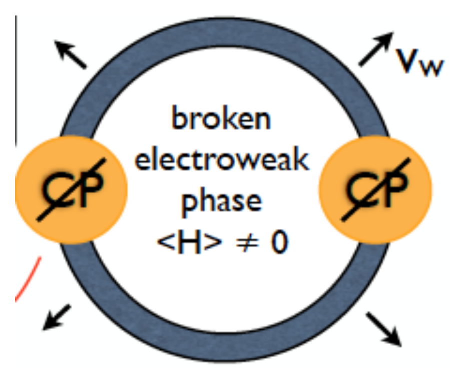
Sakharov 1967

- Requirements on BSM scenarios:
  - 1st order phase transition (testable at LHC & future colliders)
  - New CPV (EDMs often provide strongest constraint)
- Rich literature: (N)MSSM, Higgs portal (scalar extensions), flavored baryogenesis,…

EDMs and weak scale baryogenesis

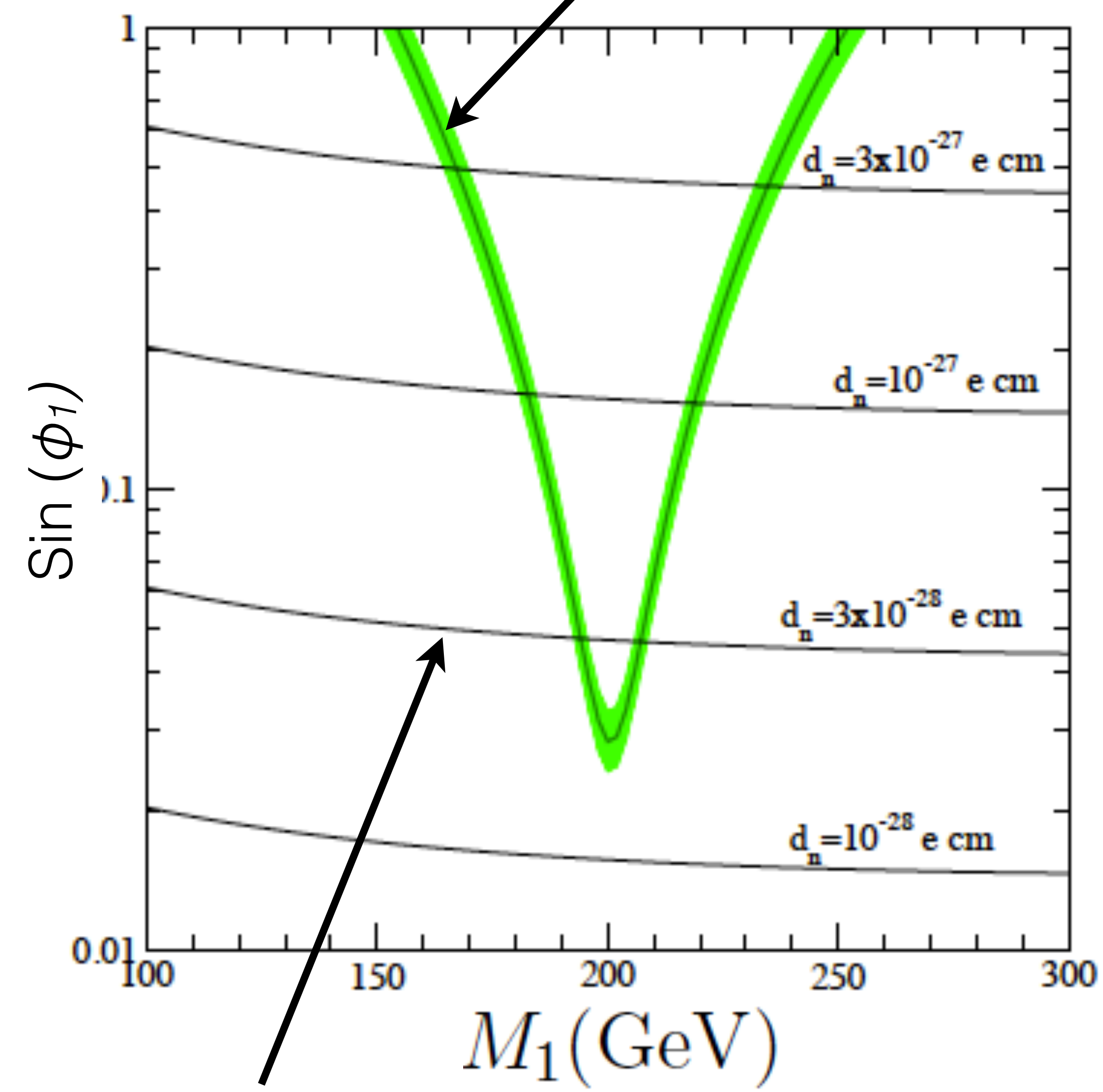
- NMSSM: CPV couplings appearing in the gaugino-higgsino mixing contribute to both BAU and EDM





- In *simplest case (with only one CP-violating coupling)*, successful baryogenesis implies a “guaranteed signal” for next generation EDMs searches

Compatible with baryon asymmetry



Next generation neutron EDM

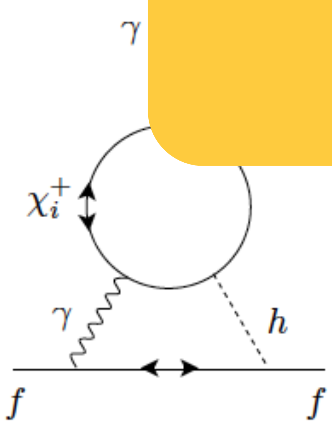
Li, Profumo, Ramsey-Musolf
0811.1987

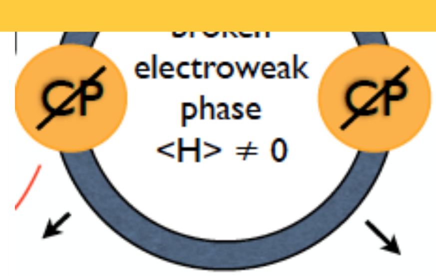
EDMs and weak scale baryogenesis

- NMS
in the
contr

CAVEAT: current uncertainties in
1) hadronic matrix elements;
2) early universe calculations;
may shift these lines and alter the conclusions

VC, C. Lee, S. Tulin, 1106/0747





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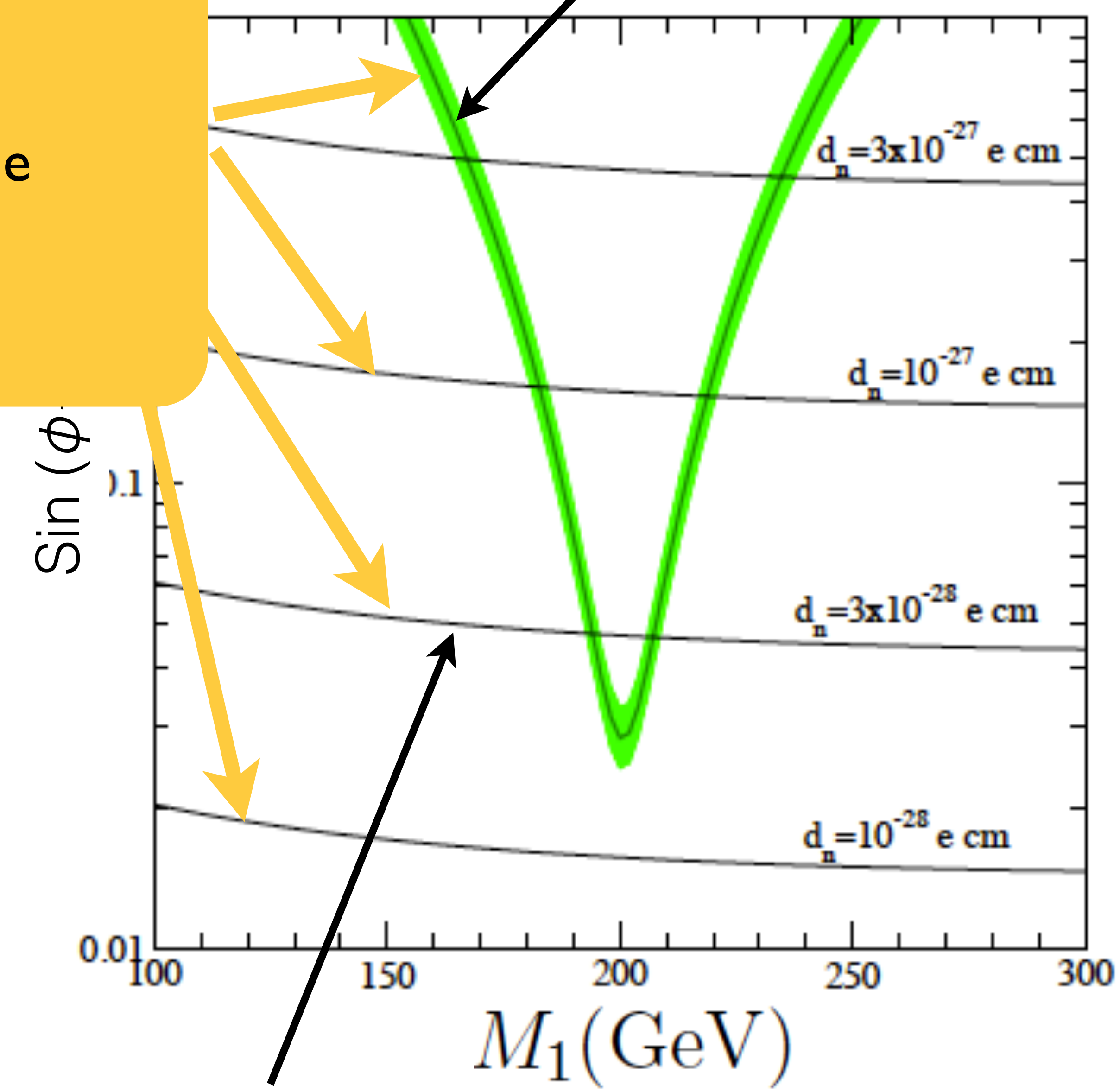

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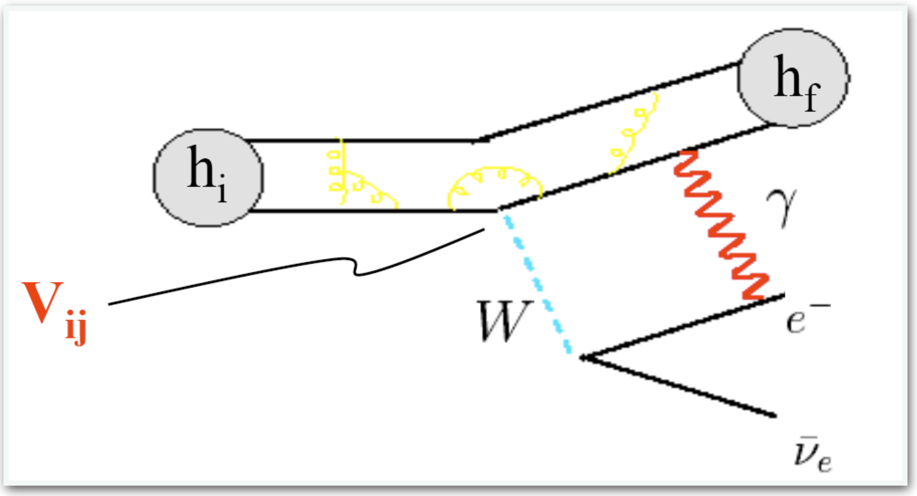
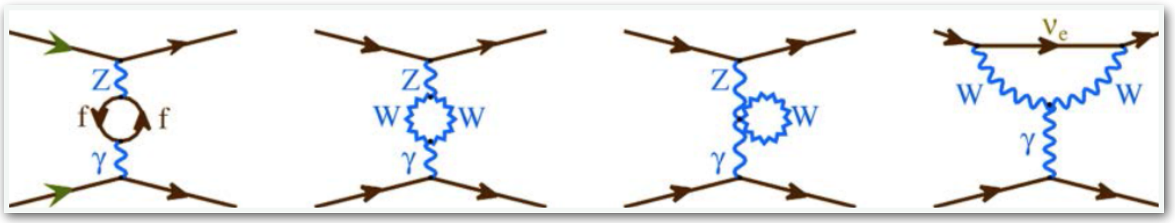
Precision measurements

Precision measurements

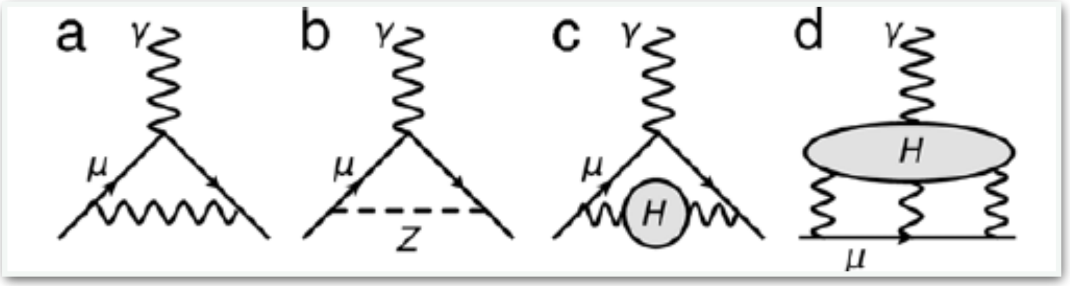
- Beta decays and parity-violating electron scattering have played a central role in establishing the Standard Model
- Today, with precision approaching the 0.1% level (together with the muon g-2 at the <ppm level!) they probe quantum effects in the Standard Model at unprecedented levels
- "Broad band" sensitivity to new physics, both heavy and light



β decay



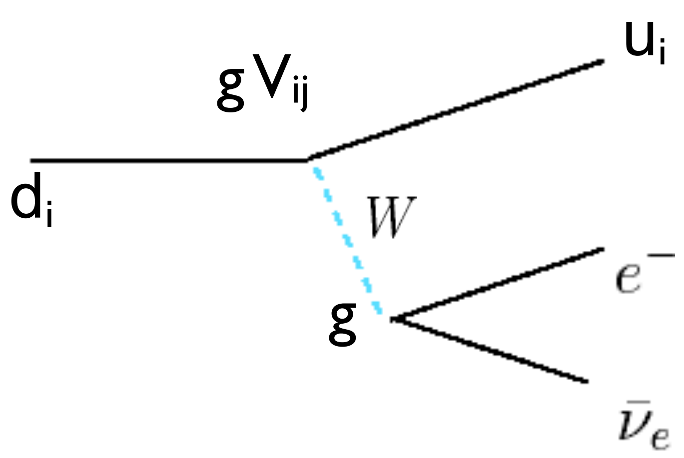
Radiative corrections to electron scattering



Representative diagrams for muon g-2

Beta decays: SM and beyond

- In the SM, W exchange $\Rightarrow$ V-A currents, universality



$G_F \sim g^2 V_{ij}/M_W^2 \sim V_{ij}/v^2$

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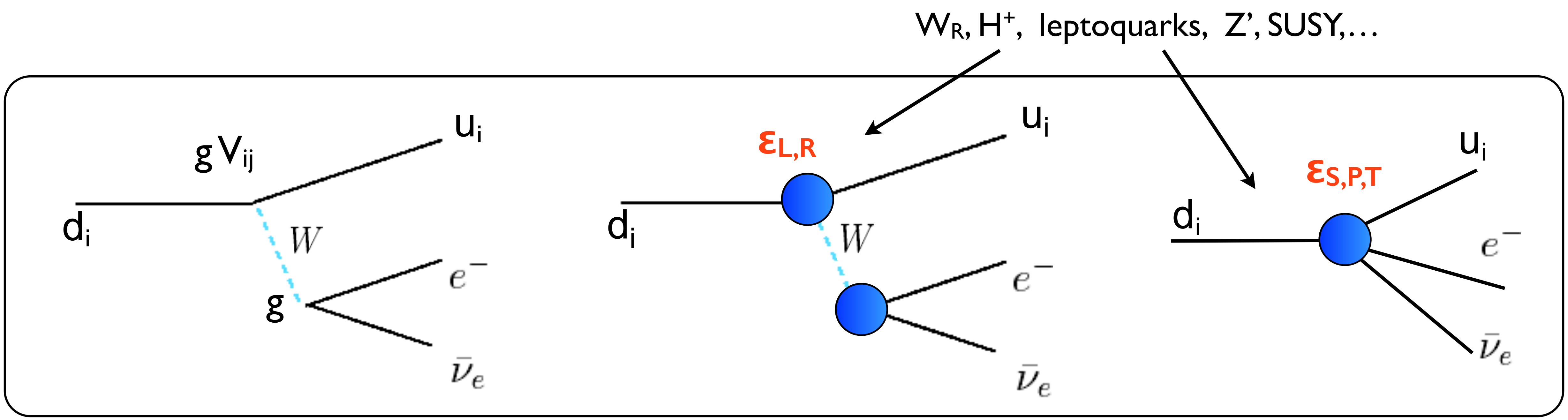


$G_F \sim g^2 V_{ij}/M_W^2 \sim V_{ij}/v^2$ $1/\Lambda^2$ $1/\Lambda^2$

$E \ll \Lambda$ $\downarrow$ $\epsilon_\Gamma \sim \tilde{\epsilon}_\Gamma \sim (v/\Lambda)^2$

$$\mathcal{L}_{\rm SM} - \frac{G_F V_{ud}}{\sqrt{2}} \sum_\Gamma \left[\epsilon_\Gamma \; \bar{\ell}\Gamma \nu_L \cdot \bar{u}\Gamma d \; + \; \tilde{\epsilon}_\Gamma \; \bar{\ell}\Gamma \nu_R \cdot \bar{u}\Gamma d \right]$$

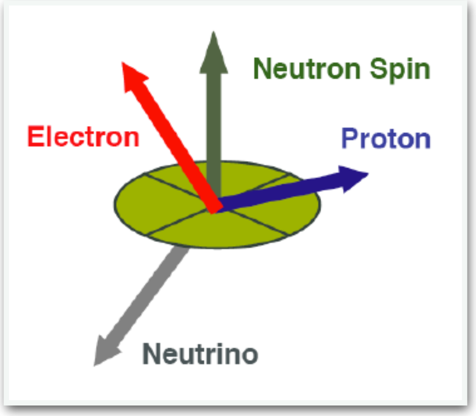
Ten effective couplings $\Gamma = L, R, S, P, T$

How do we probe the ε_α?

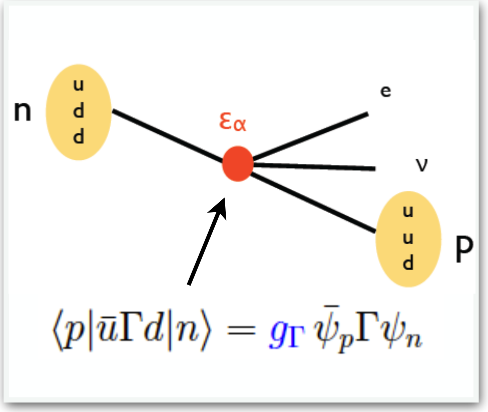
For comprehensive review, see Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

1. Differential decay distribution

$$d\Gamma \propto F(E_e)\left\{1 + b\,\frac{m_e}{E_e} + a\,\frac{\vec{p}_e\cdot\vec{p}_\nu}{E_e E_\nu} + \langle\vec{J}\rangle\cdot\left[\,A\,\frac{\vec{p}_e}{E_e} + B\,\frac{\vec{p}_\nu}{E_\nu} + \cdots\right]\right\}$$



$a(g_A)$, $A(g_A)$, $B(g_A, g_\alpha\varepsilon_\alpha)$, …
isolated via suitable experimental asymmetries



Nucleon charges from LQCD

CalLat 1805.12030
Bhattacharya et al 1806.09006

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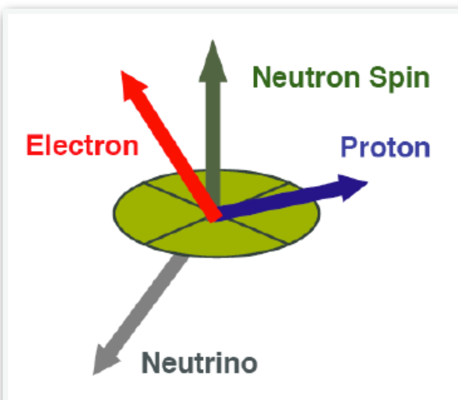
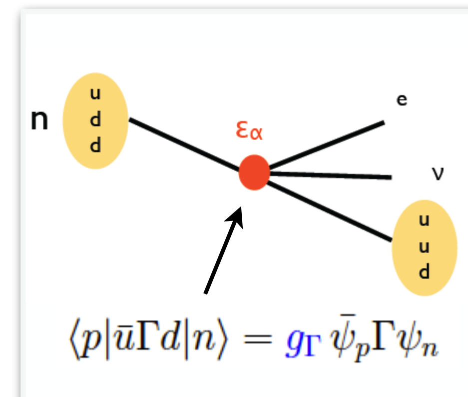


$a(g_A)$, $A(g_A)$, $B(g_A, g_\alpha\varepsilon_\alpha)$, …
isolated via suitable experimental asymmetries



Nucleon charges from LQCD

CalLat 1805.12030
Bhattacharya et al 1806.09006

2. Total decay rates

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

CKM Unitarity Test $\quad |\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\rm CKM}(\epsilon_i)$

CKM unitarity test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$

Extraction dominated by $0^+ \to 0^+$ nuclear transitions

Hardy-Towner 1411.5987
CKM 2016

Extraction dominated by K decays:

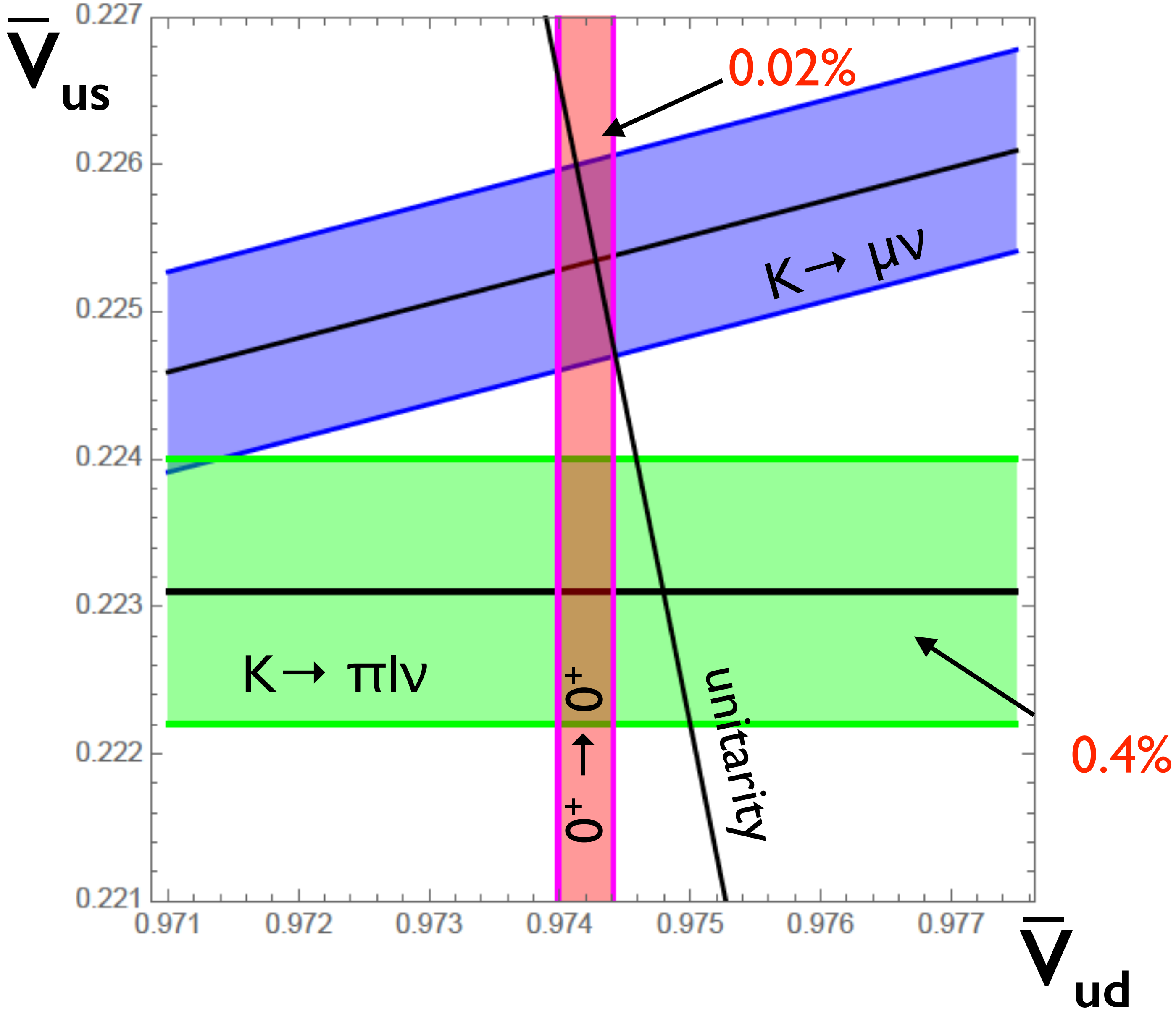
$K \to \pi e \nu$ & $K \to \mu\nu$ vs $\pi \to \mu\nu$ (V_{us}/V_{ud})

FLAVIANET report 1005.2323 and refs therein

Lattice QCD input from FLAG 1607.00299 and refs therein
+ MILC 2018 1809.02827

CKM unitarity test

$$\boxed{|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)}$$



V_{us} from K→ μν

$\Delta_{\rm CKM}$ = - (4 ± 5) ∗ 10^{-4} ~ 1σ

$\Delta_{\rm CKM}$ = - (12 ± 6) ∗ 10^{-4} ~ 2σ

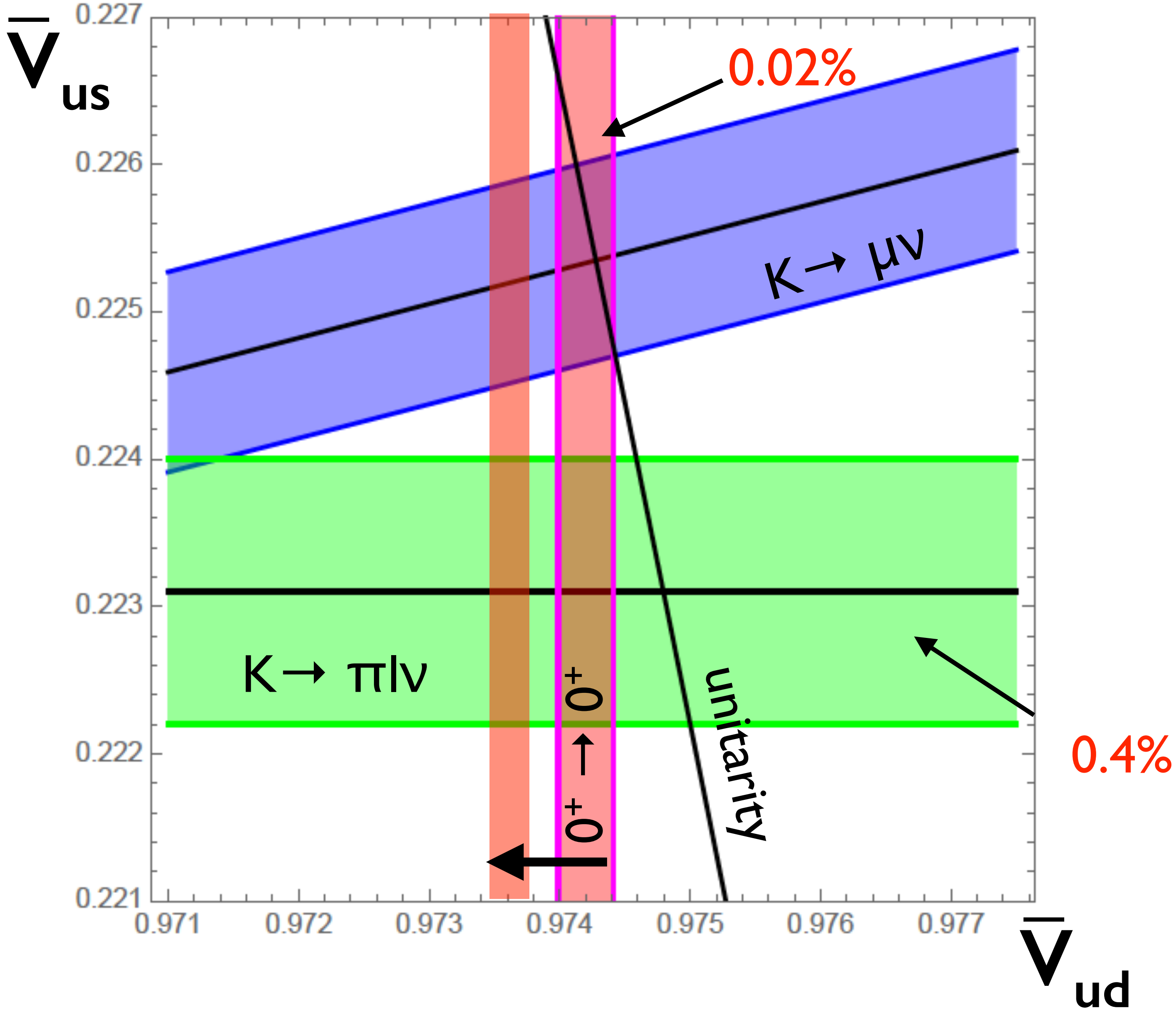
V_{us} from K→ πlν

Hint of $\varepsilon_L + \varepsilon_R \neq 0$
or SM theory input?

Worth a closer look:
at the level of the best EW precision tests,
probing scale Λ~10 TeV

CKM unitarity test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



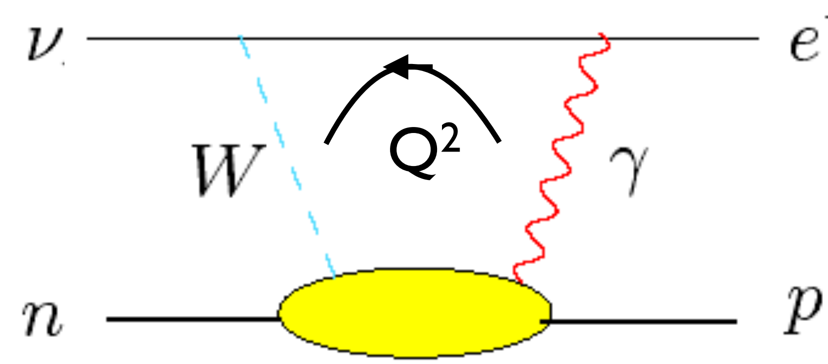
V_{us} from K→ μν

$\Delta_{\rm CKM}$ = - (14 ± 4) * 10^{-4} ~3.5σ

$\Delta_{\rm CKM}$ = - (22 ± 5) * 10^{-4} ~4.5σ

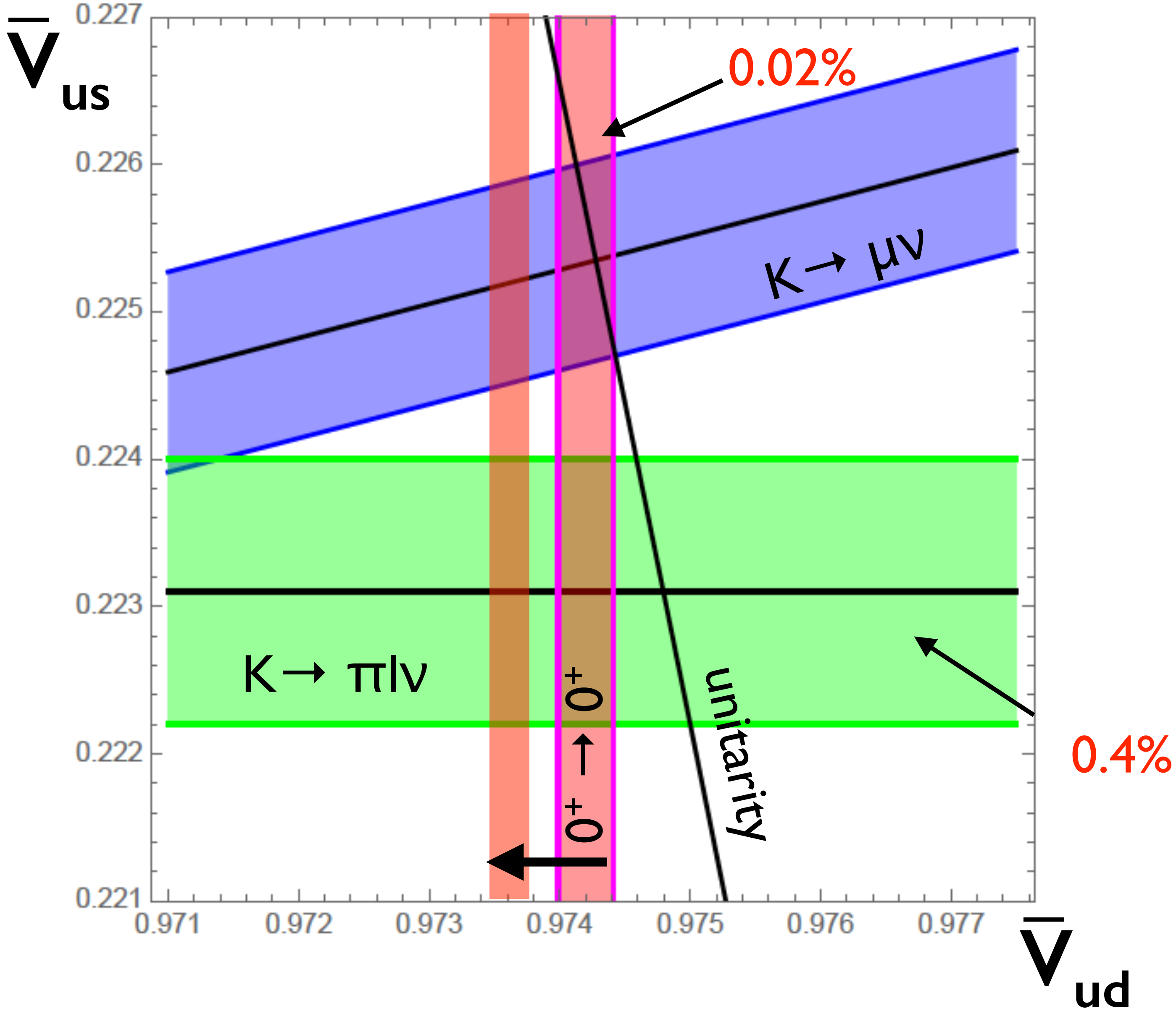
V_{us} from K→ πlν

With new radiative correction from Seng-Gorchtein-Patel-RamseyMusolf [1807.10197]



CKM unitarity test

$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



V_{us} from K→ μν

$\Delta_{\rm CKM}$ = - (14 ± 4) $*$ 10^{-4} ~3.5σ

$\Delta_{\rm CKM}$ = - (22 ± 5) $*$ 10^{-4} ~4.5σ

V_{us} from K→ πlν

With new radiative correction from Seng-Gorchtein-Patel-RamseyMusolf [1807.10197]

With radiative correction from Czarnecki-Marciano-Sirlin [1907.06737] one gets 2(3) σ

Something to watch closely in the future. Neutron decay can be the arbiter!

Impact of neutron mesurements

- Independent extraction of V_{ud} @ 0.02% requires:

$$\bar{g}_A = g_A\,(1 - 2\epsilon_R)$$

$$\bar{V}_{ud} = \left[\frac{4908.6(1.9)\ s}{\tau_n\ (1 + 3\bar{g}_A^2)}\right]^{1/2}$$

Czarnecki, Marciano, Sirlin
1802.01804

$\delta\tau_n \sim 0.35$ s
$\delta\tau_n/\tau_n \sim 0.04$ %

$\delta g_A/g_A \sim 0.15\% \rightarrow 0.03\%$
($\delta a/a$, $\delta A/A \sim 0.14\%$)

UCNτ @ LANL [$\tau_n \sim 877.7(7)(3)$s]
is almost there, will reach $\delta\tau_n \sim 0.2$ s
1707.01817

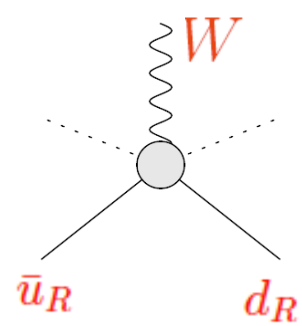
$\delta A/A < 0.2\%$ can be reached
by PERC, UCNA+
$\delta a/a \sim 0.1\%$ at Nab

Sensitivity to ε_L and ε_R: β vs collider

- Due to SU(2) gauge invariance:
  - Vertex corrections inducing $\varepsilon_{L,R}$ involve the Higgs field!
  - ε_L also corrects Zqq vertex

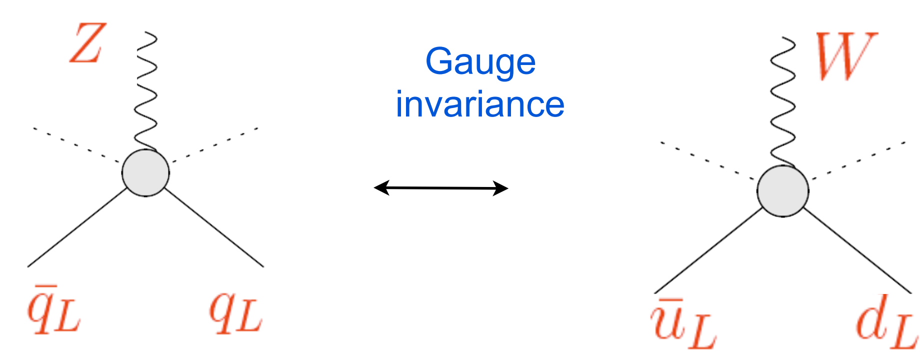
ε_R

$$O_{\varphi\varphi} = i(\varphi^T \epsilon D_\mu \varphi)(\overline{u}\gamma^\mu d)$$



ε_L

$$O_{\varphi q}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi)(\overline{q}\gamma_\mu \sigma^a q)$$

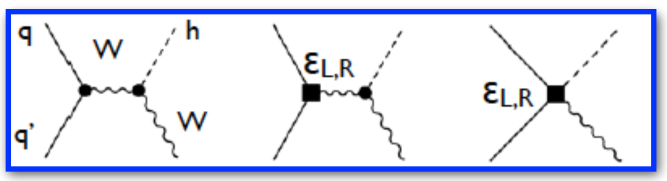


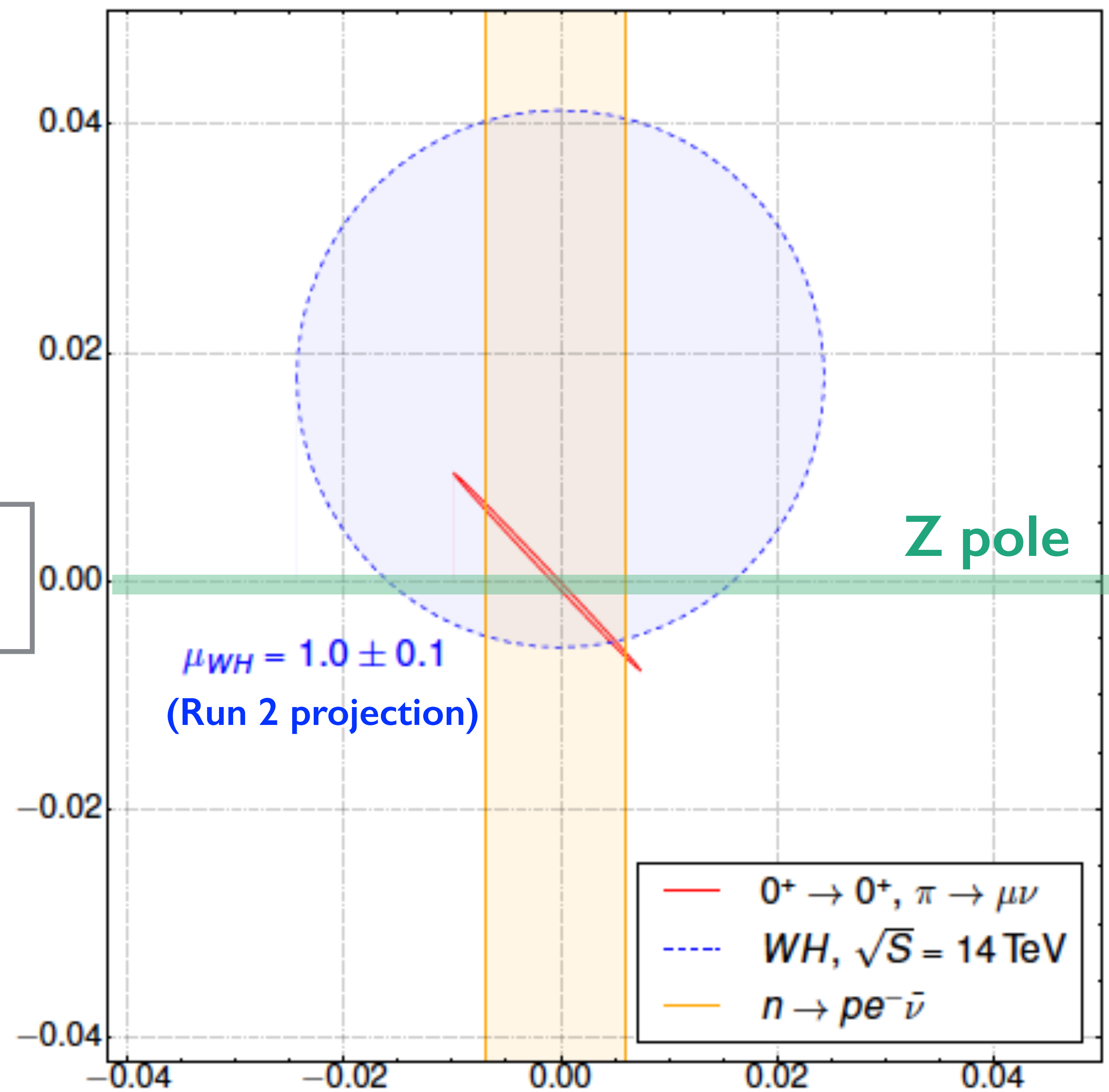
Sensitivity to ε_L and ε_R: β vs collider

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

90%CL, assumes only two operators at high scale

Associated Higgs production at LHC





ε_L

ε_R

LEP, SLC

Z-pole:
Falkowski et al
1706.03783

Neutron decay:
$\lambda = g_A\,(1 - 2\,\varepsilon_R)$

Constraint on ε_R uses
$g_A = 1.271(13)$
(CalLat 1805.12030)

$\Delta_{CKM} \propto \varepsilon_L + \varepsilon_R$

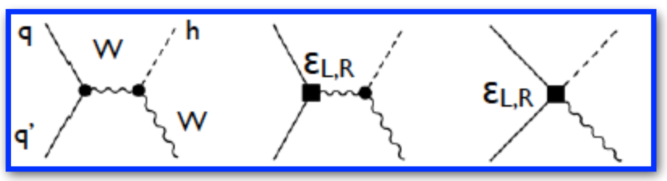
$\delta\Gamma_{(\pi\to\mu\nu)} \propto \varepsilon_L - \varepsilon_R$
[f_π from LQCD]

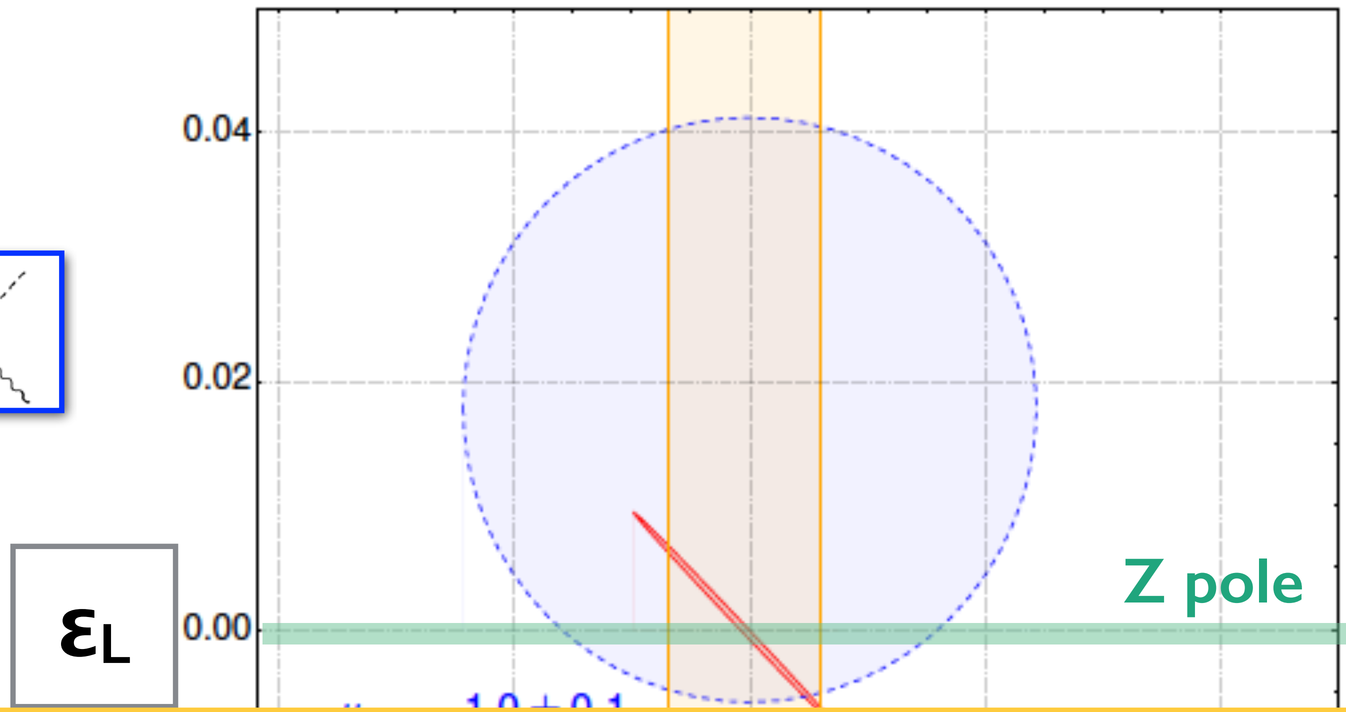
Sensitivity to ε_L and ε_R: β vs collider

S. Alioli, VC, W. Dekens, J. de Vries, E. Mereghetti 1703.04751

90%CL, assumes only two operators at high scale

Associated Higgs production at LHC





Neutron decay:
$\lambda = g_A\,(1 - 2\,\varepsilon_R)$

Constraint on ε_R uses g_A =1.271(13) (CalLat 1805.12030)

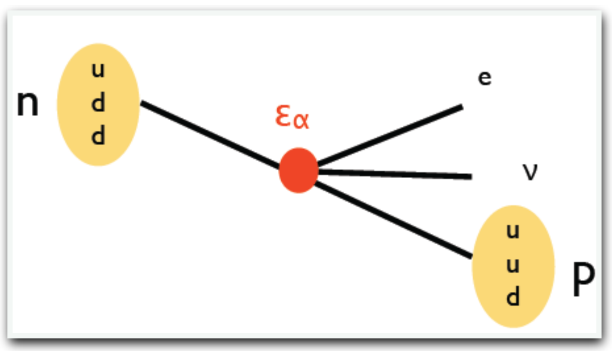
- β decays quite competitive with collider (probing $\Lambda_{L,,R}$ >10 TeV)
- Caveat: going beyond a 2-coupling analysis relaxes some of these constraints (but not the one on ε_R from λ!)
- β decays provide *independent competitive constraints* in a global analysis

Sensitivity to ε_S and ε_T: β vs collider

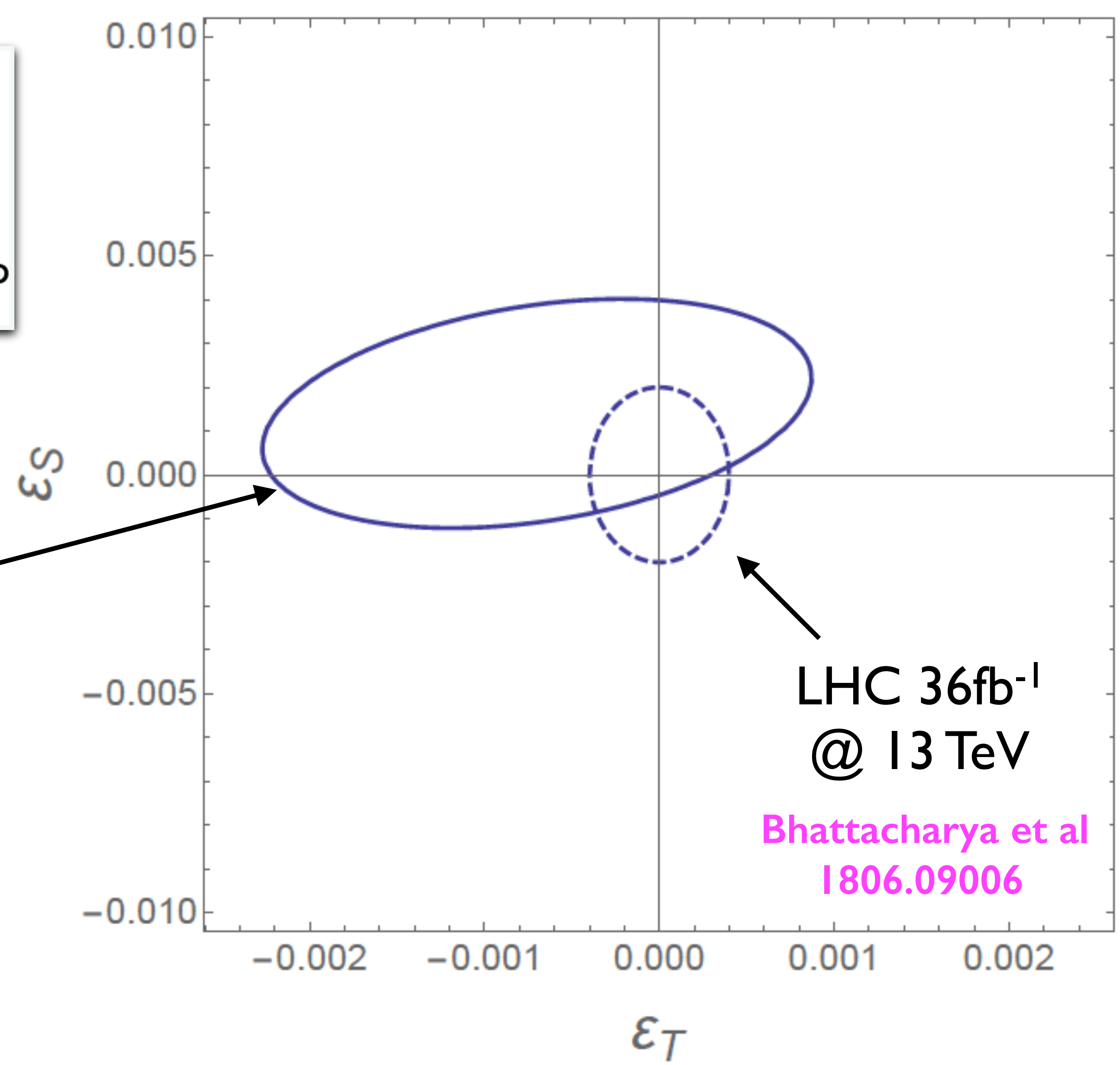
CURRENT

$\varepsilon_{S,T}$ @ μ= 2 GeV (MS-bar)

n → p e ν



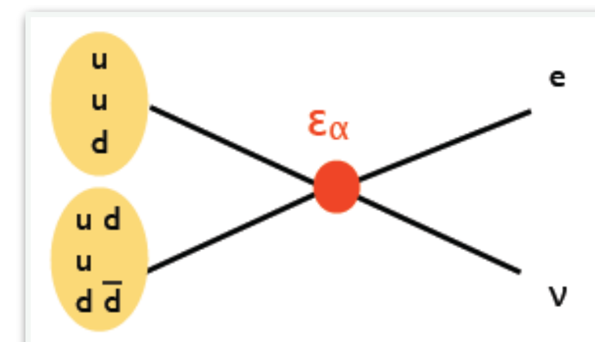
Current low-E data:
dominated by
$0^+ \rightarrow 0^+$, $\tau(n)$, $A(n)$

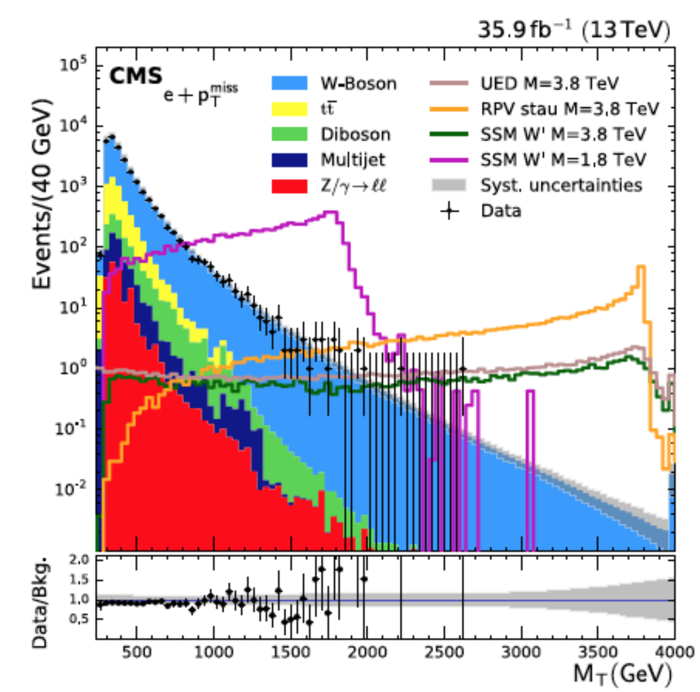


Gonzalez-Alonso,
Naviliat-Cuncic,
Severijns, 1803.08732

Bhattacharya et al
1806.09006

LHC: pp → e ν + X

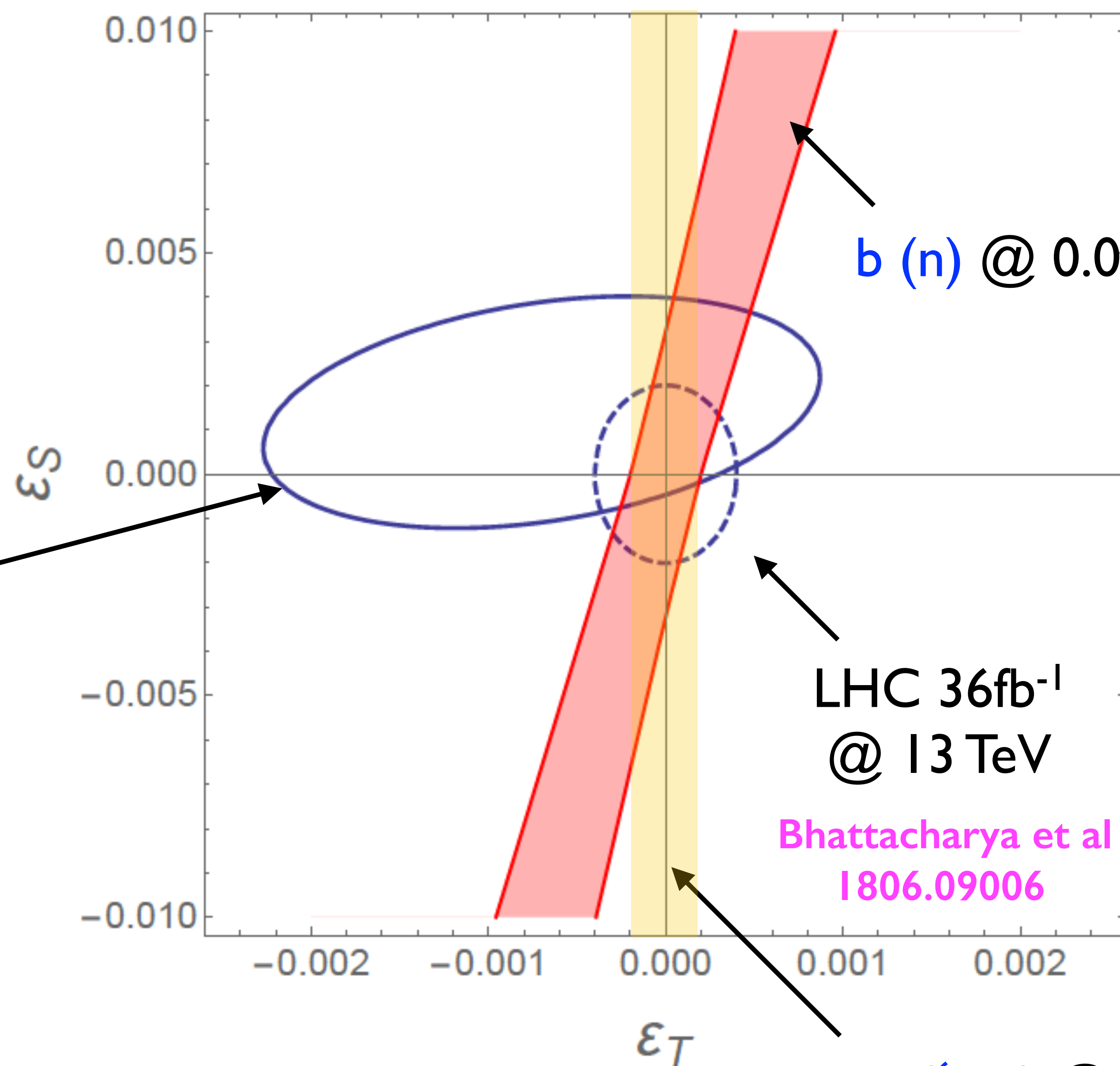




Sensitivity to ε_S and ε_T: β vs collider

FUTURE

$\varepsilon_{S,T}$ @ μ= 2 GeV (MS-bar)



$d\Gamma \sim \Gamma_0 \, (1 + b \, m_e / E_e)$

b (n) @ 0.001

Prospective beta decay measurements competitive with strong LHC constraints, probing $\Lambda_{S,T} \sim$ 5-10 TeV

Current low-E data: dominated by $0^+ \rightarrow 0^+$, $\tau(n)$, $A(n)$

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

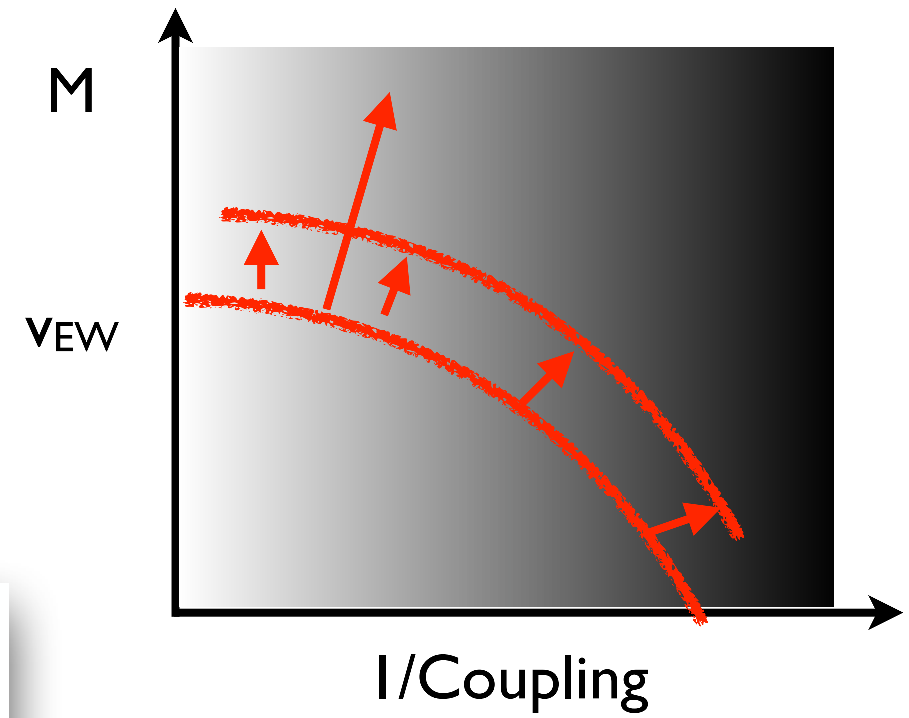
LHC 36fb^{-1} @ 13 TeV

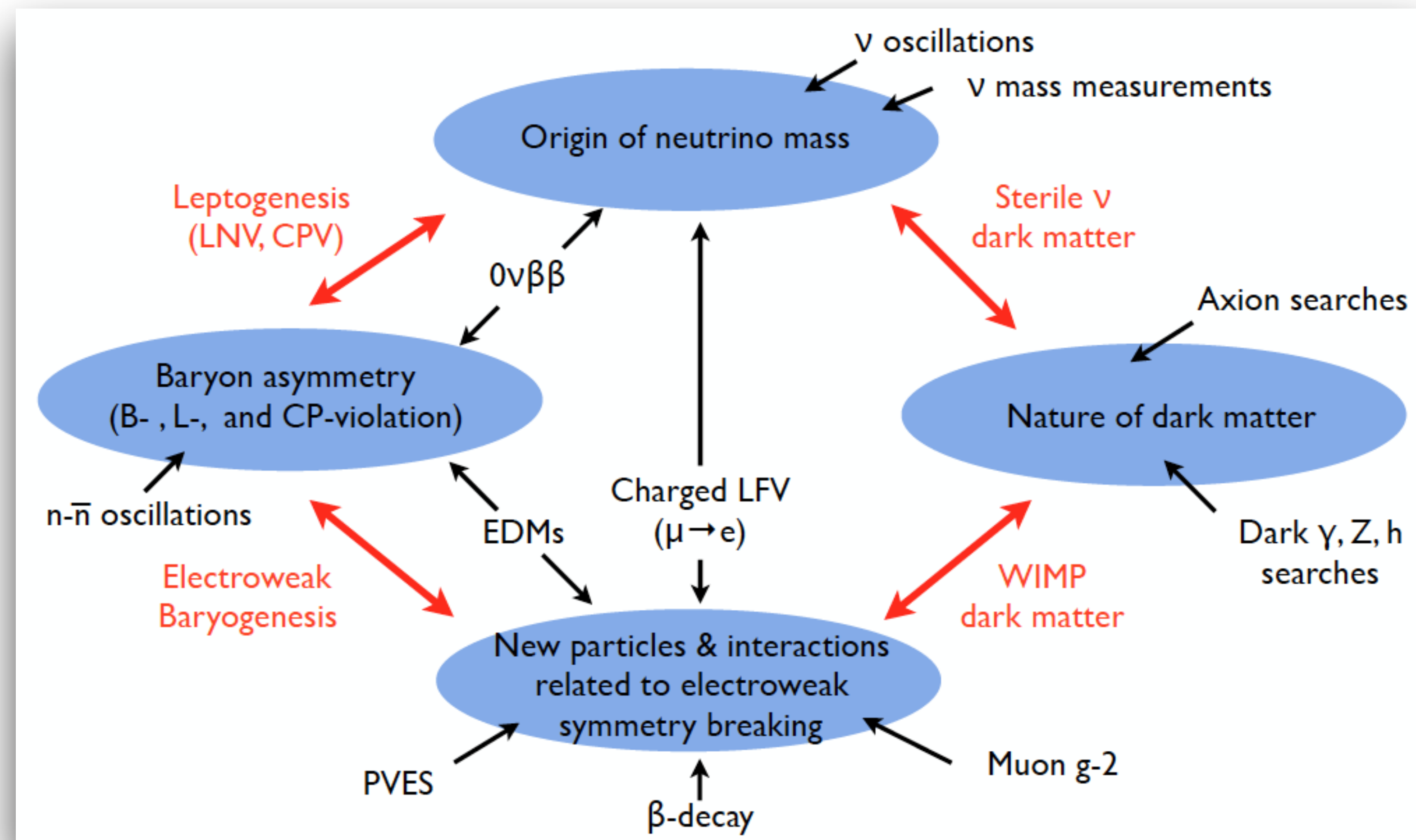
Bhattacharya et al 1806.09006

b (^{6}He) @ 0.001

Concluding comments

- Energy and Precision frontiers are exploring uncharted territory in our search for BSM physics



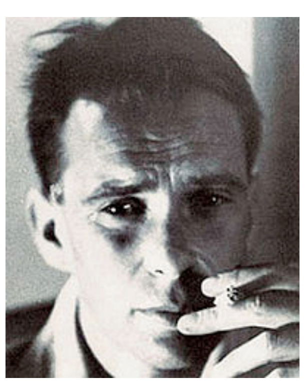


- Vibrant Nuclear Science portfolio probes BSM dynamics related to open questions about our universe

Concluding comments

- Current / planned nuclear science experiments provide competitive probes of dark sectors and new physics up to $\Lambda >> \text{TeV}$
- Win-win situation:
    - Should new physics appear at the LHC, Nuclear Science probes will play a key role in understanding the symmetries of BSM dynamics and disentangle models
    - Should new physics NOT appear at the LHC, the precision frontier will be for a while the only laboratory tool to explore new physics

Thank you!



A drawing by
Bruno Touschek