ASU Theoretical Physics Colloquium
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Probing physics beyond the Standard Model at low energies

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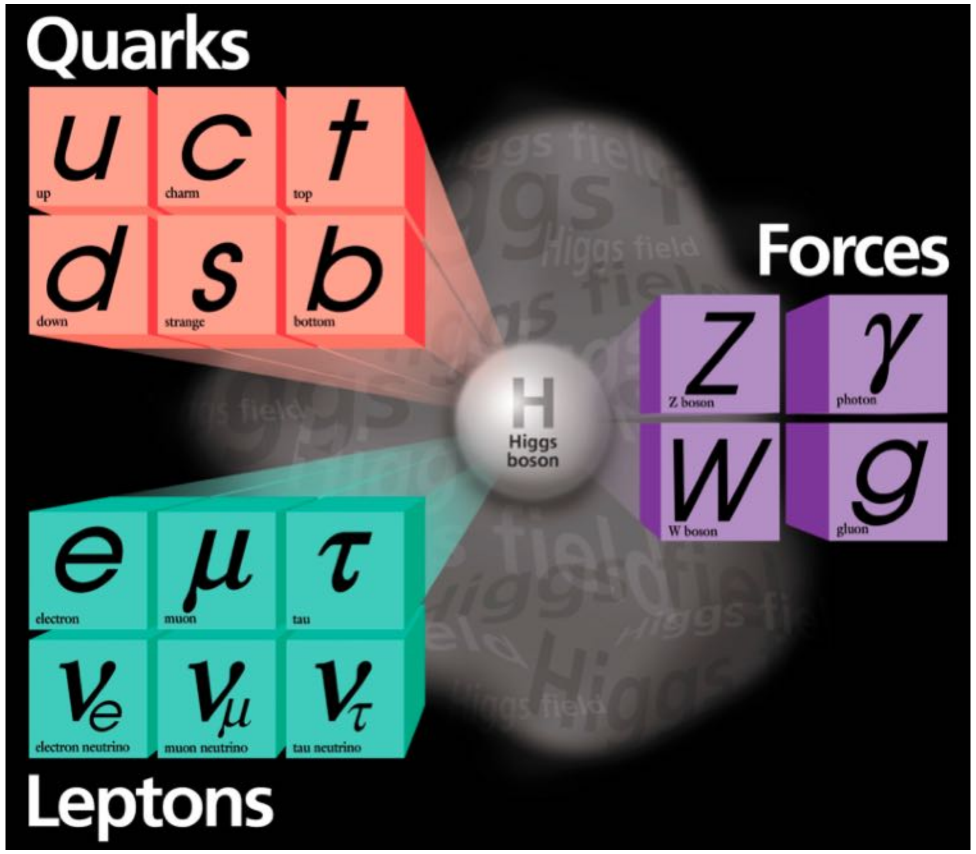
Outline

- The quest for new physics: Energy and Precision Frontiers
- Two exciting Precision Frontier probes
    - β decays as a probe of new physics at the multi-TeV scale
    - Neutrinoless ββ decay and Lepton Number Violation

The quest for
new physics

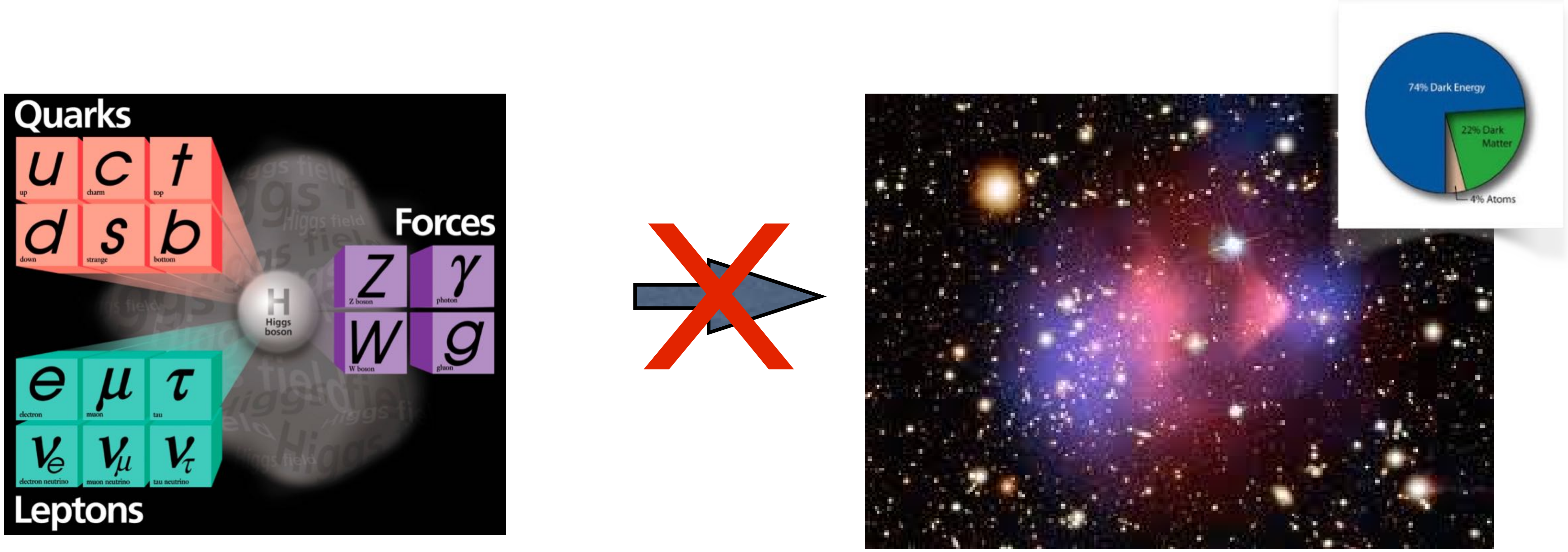
The (known) building blocks of nature



The "Standard Model" is a remarkably successful theory, tested over a wide range of energies (atomic to ~TeV)

However, the SM is probably not the whole story…

New physics: why?

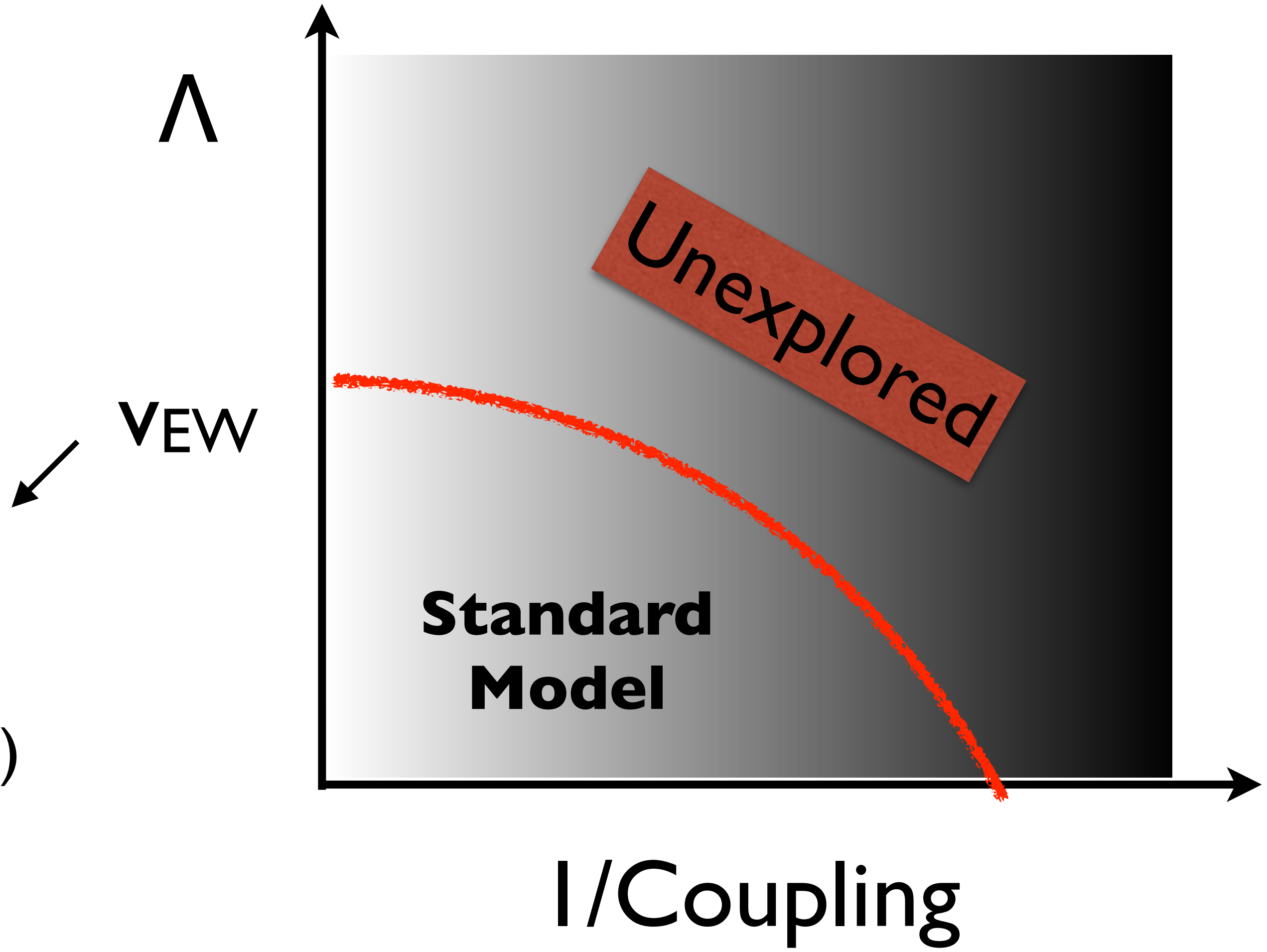


No Baryon Asymmetry, no Dark Matter, no Dark Energy, no Neutrino Mass
Origin of families, Strong CP problem, Higgs naturalness, Unification,…

Addressing these puzzles requires new physics

New physics: where?

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



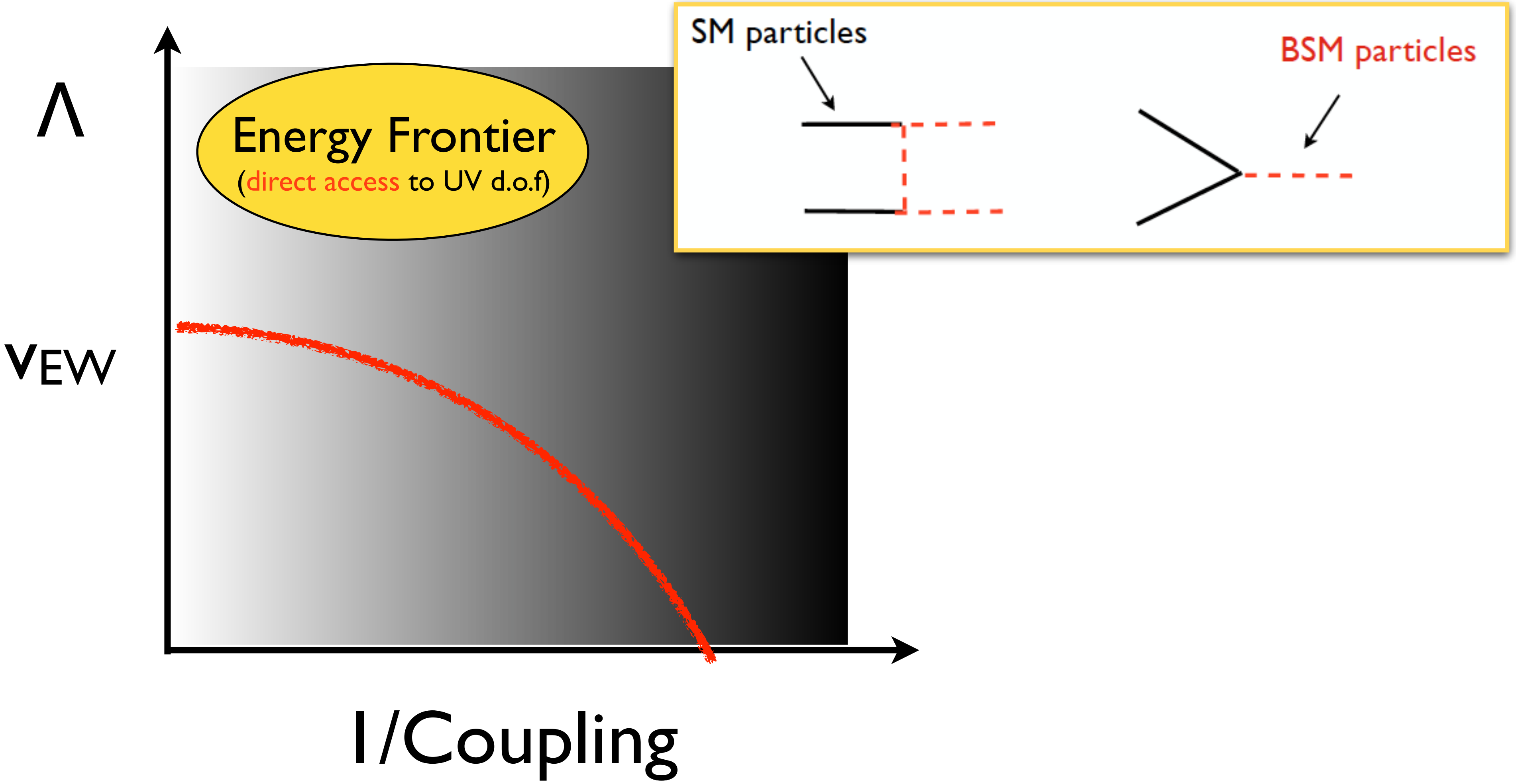
~ 250 GeV

(m_{proton} ~ 1 GeV)

New physics: how?

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

$$E = mc^2$$

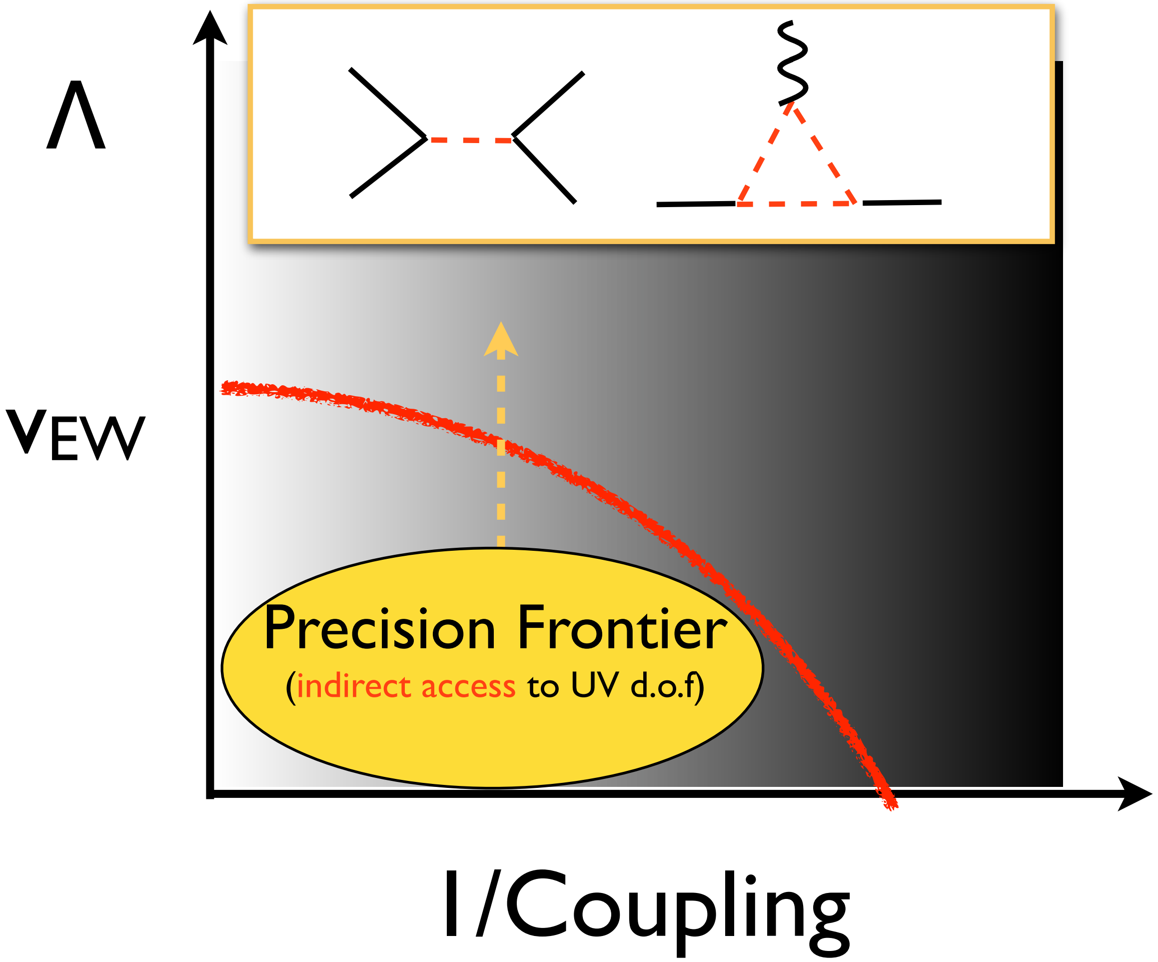


- Two approaches

New physics: how?

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

$$\Delta E\,\Delta t > h$$



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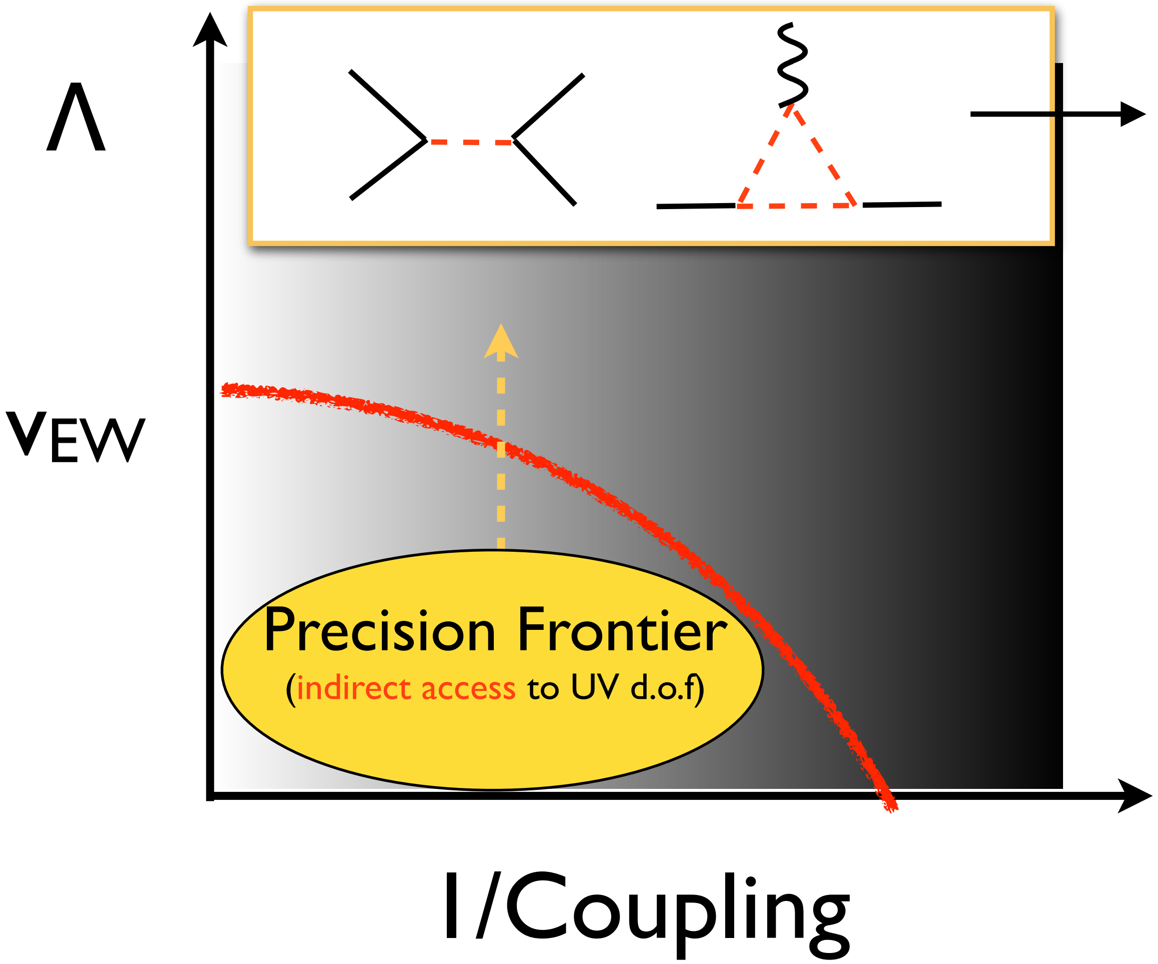

$$\mathcal{L}_{\rm EFT} = \mathcal{L}_{\rm SM} + \sum_{d \geq 5, n} \frac{C_n^{(d)} \, O_n^{(d)}}{\Lambda^{d-4}}$$

- Two approaches

New physics: how?

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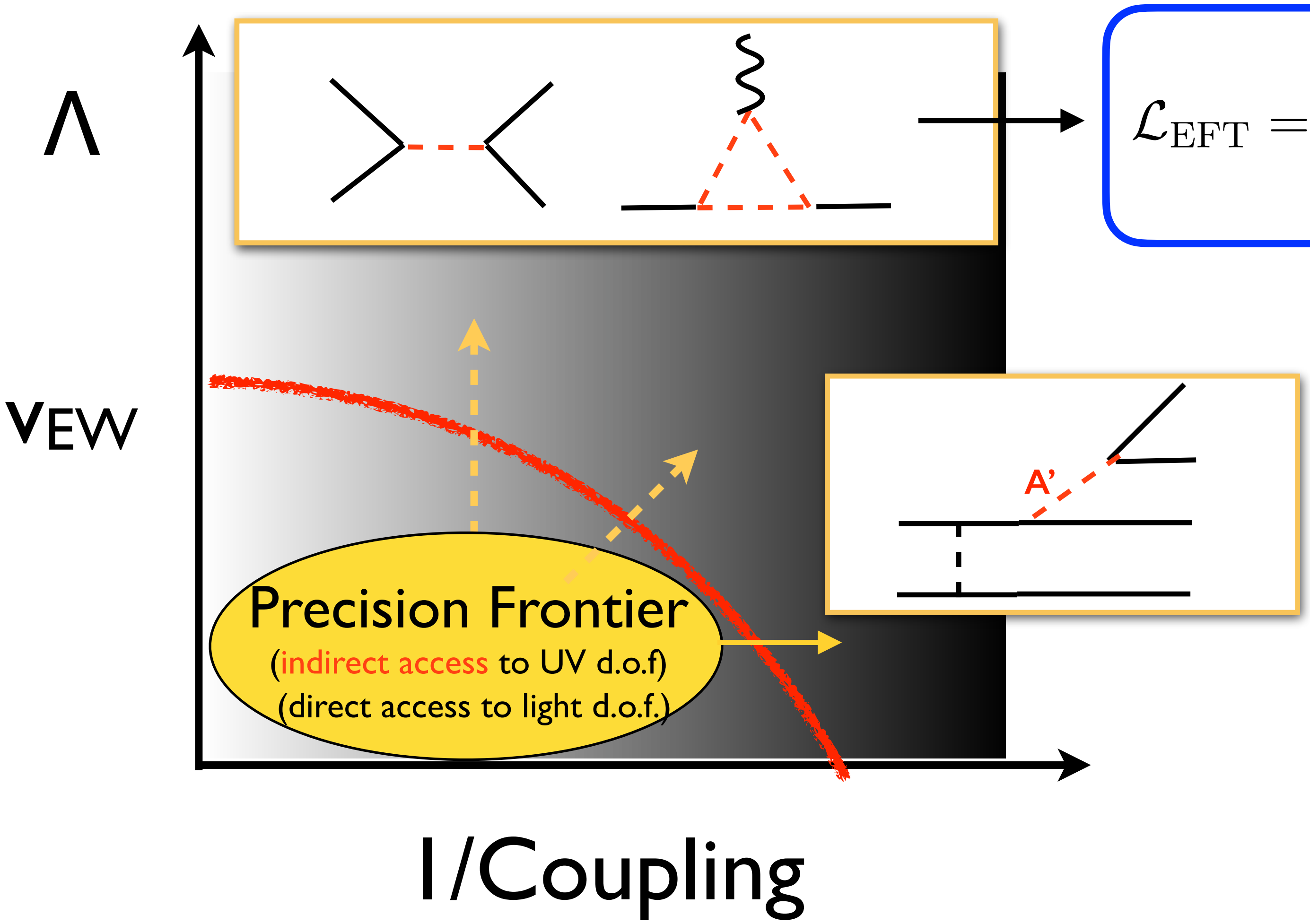

Precision Frontier
(indirect access to UV d.o.f)
(direct access to light d.o.f.)

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

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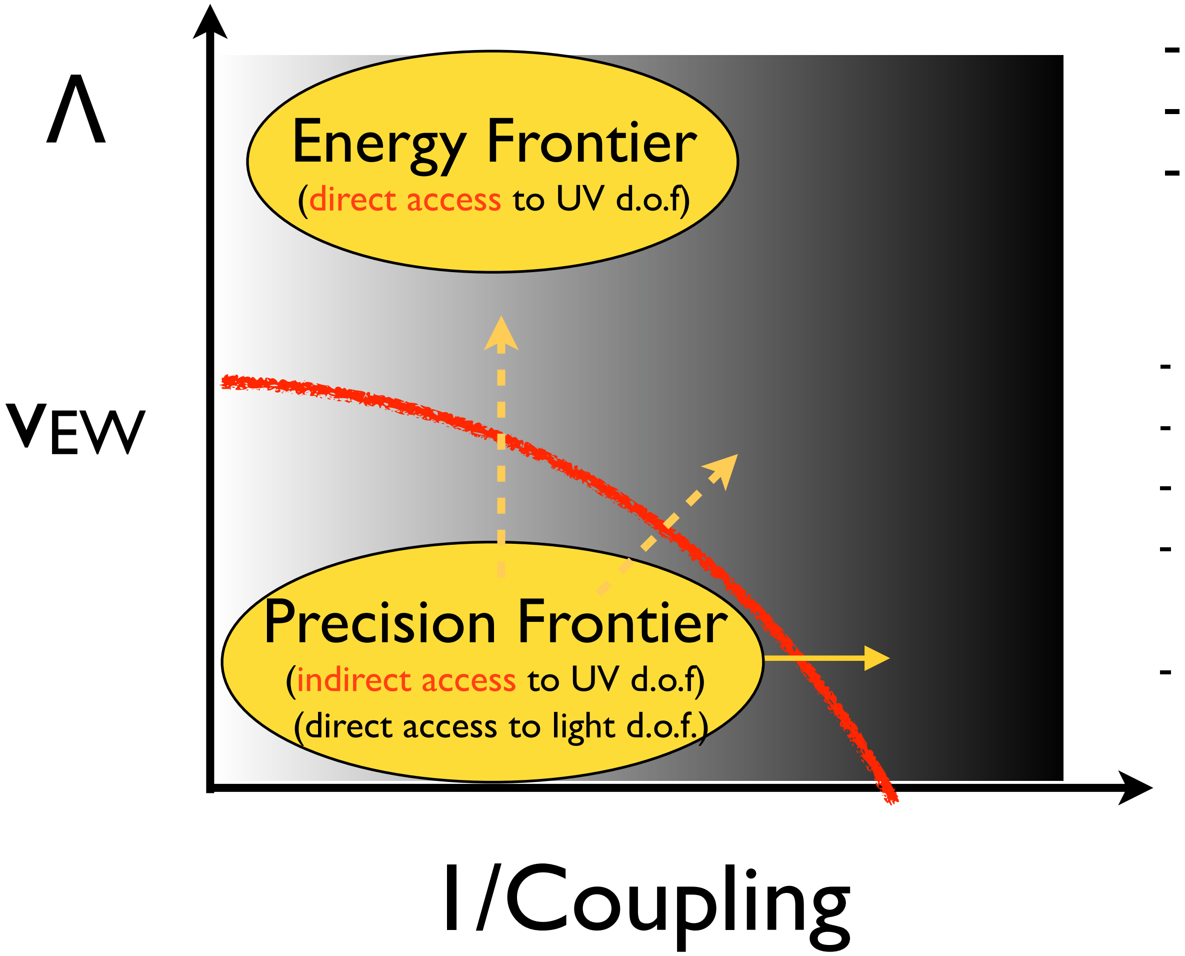


Energy Frontier
(direct access to UV d.o.f)

Precision Frontier
(indirect access to UV d.o.f)
(direct access to light d.o.f.)

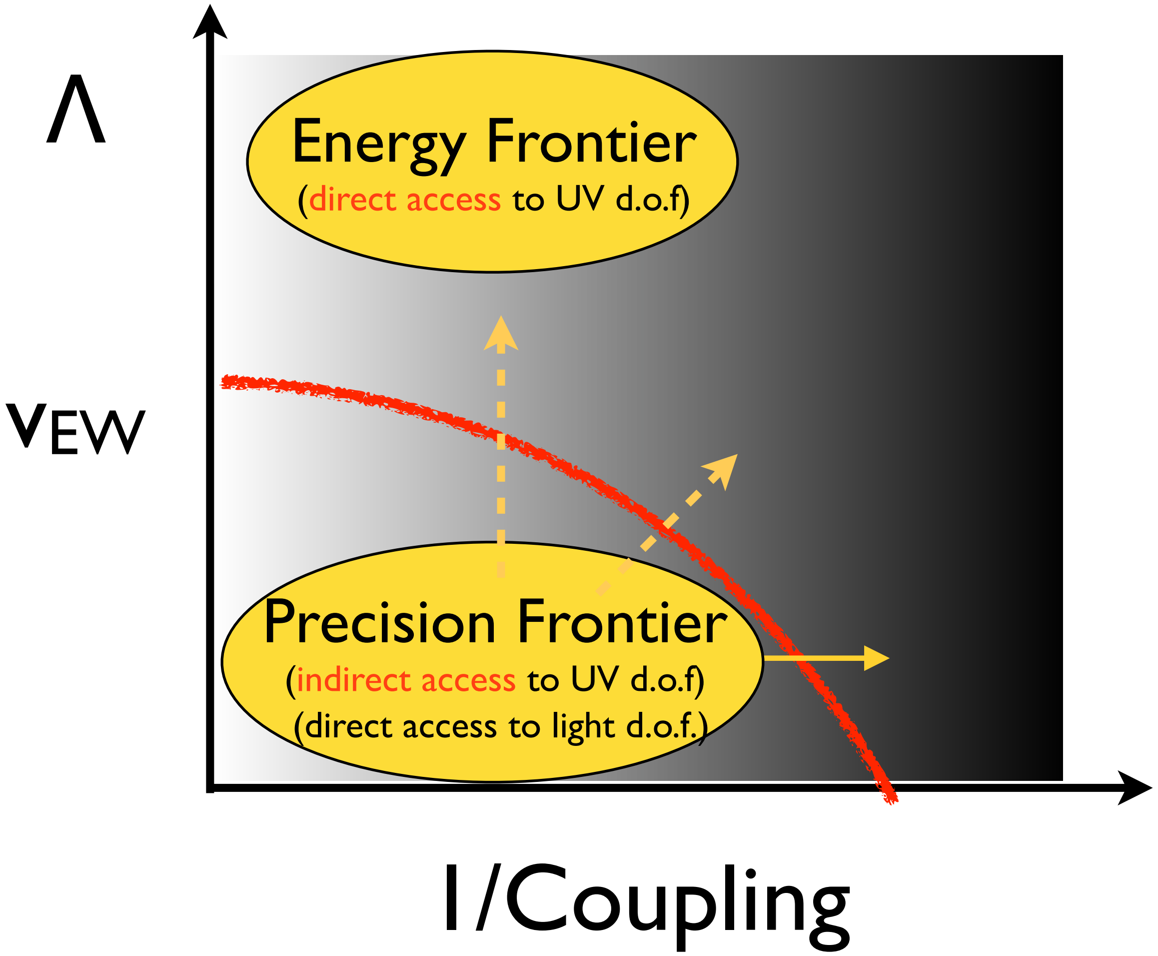
- EWSB mechanism
- Direct access to heavy particles
- ...

- L and B non conservation
- CP violation (w/o flavor)
- Flavor violation: quarks, leptons
- Precision tests sensitive to multi-TeV scale force mediators
- Light and weakly coupled particles: neutrino properties, dark sectors, …

- Two approaches, both needed to pin down BSM dynamics (content and symmetries of $\mathcal{L}_{BSM}$) and answer open questions

New physics: how?

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



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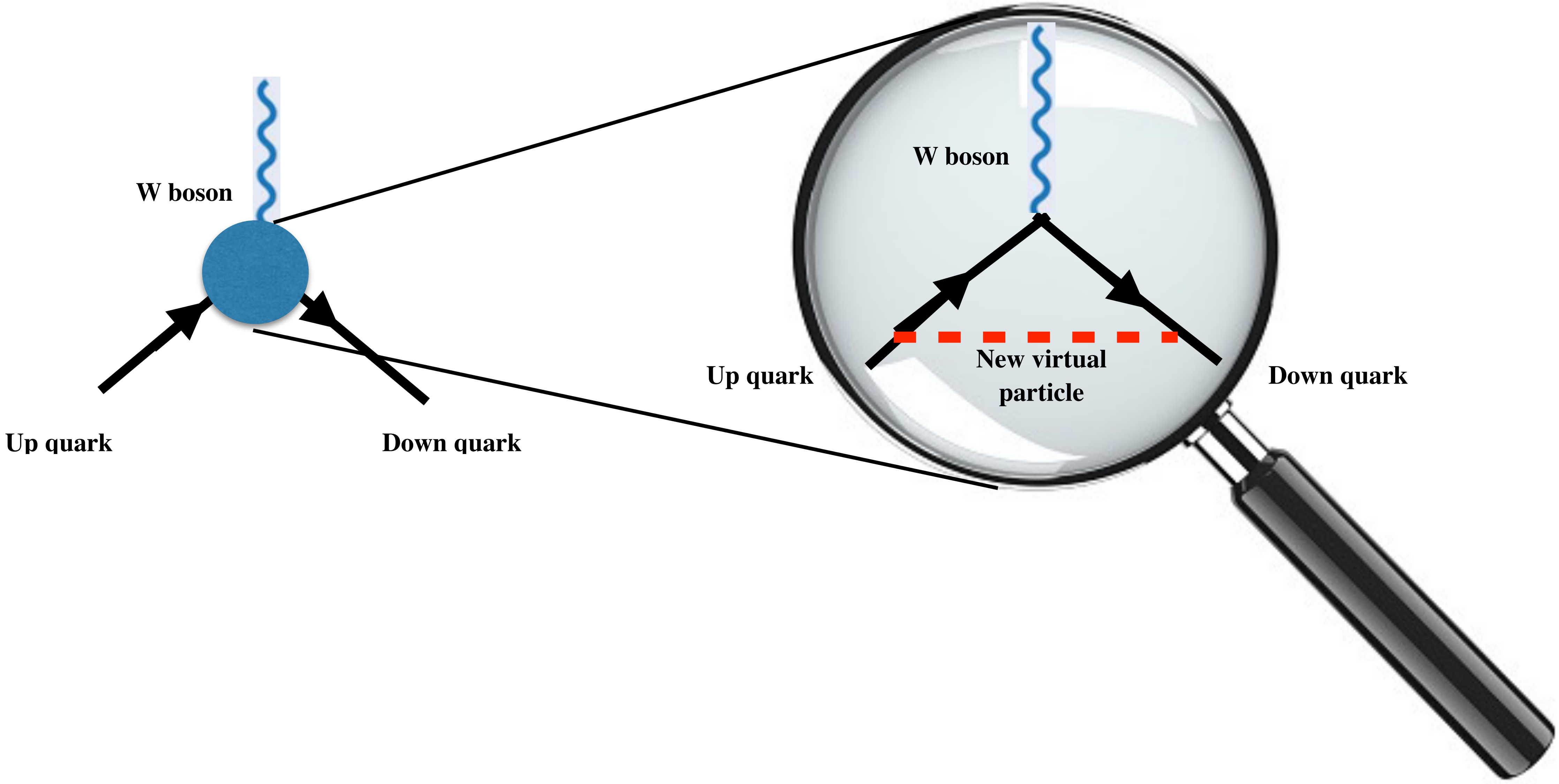
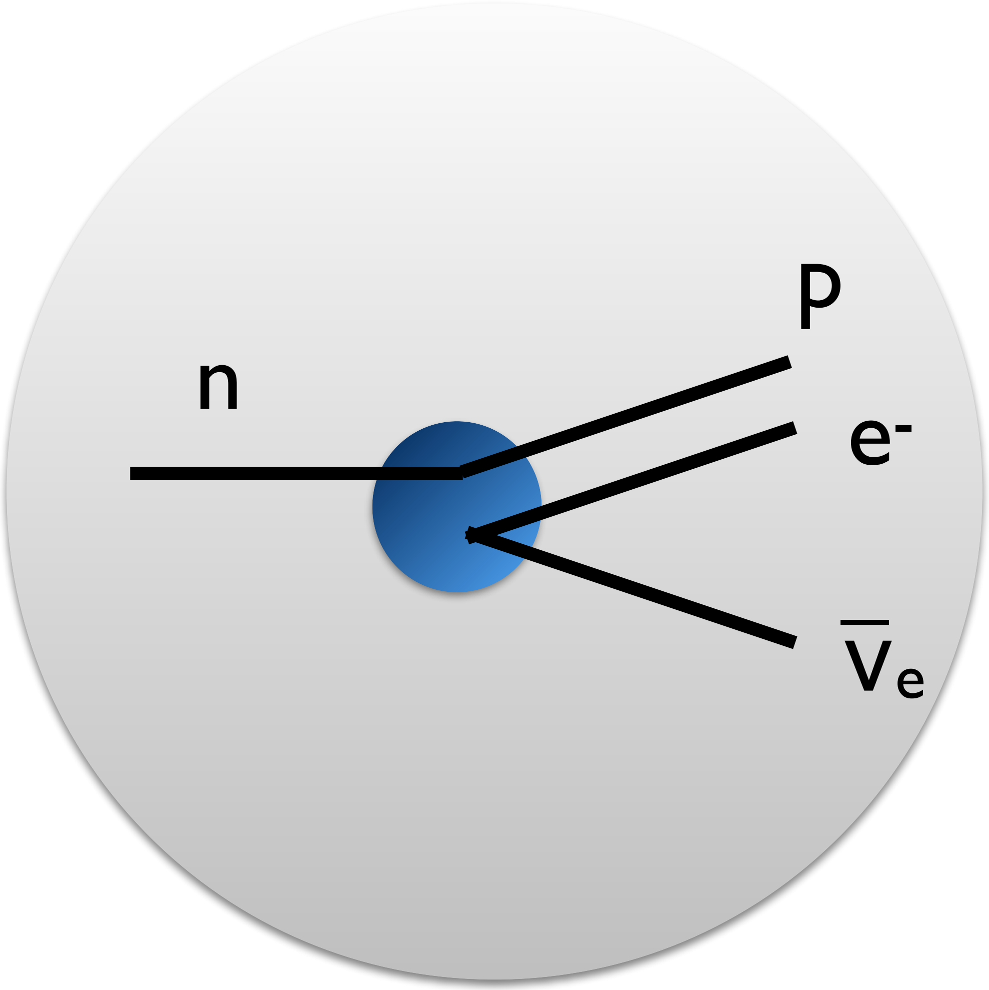
I will discuss β and ββ decays as probes of BSM weak interactions and L# non-conservation, respectively

Beta decays as a probe of new physics



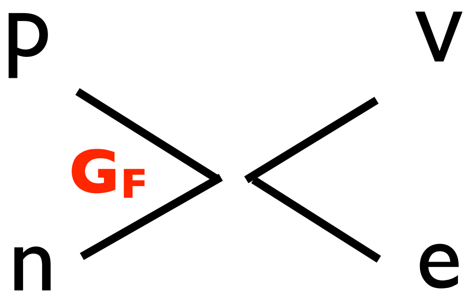
β-decays in the SM and beyond



- Beta decays have played a central role in the development of the SM
- Nowadays: tool to challenge the SM & probe possible new physics

β-decays: historic perspective

Fermi, 1934



Current-current,
parity conserving

Fermi scale:
$\Lambda = G_F^{-1/2} \sim 250$ GeV

Fermi's theory of beta decays ($n \to p\, e\, \bar{\nu}_e$):

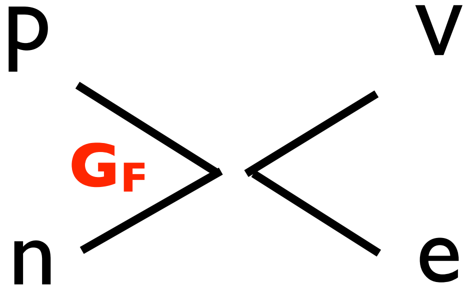
Postulate new local interaction in terms of "light" degrees of freedom (n,p,e,ν_e): $H \sim G_F\, \bar{p}\Gamma n\, \bar{e}\Gamma \nu_e$

Coupling constant $G_F \equiv 1/\Lambda^2$ determined by fitting the "slow" beta decay rates ⇒

point to mass scale $\Lambda >> m_n \sim$ GeV

β-decays: historic perspective

Fermi, 1934



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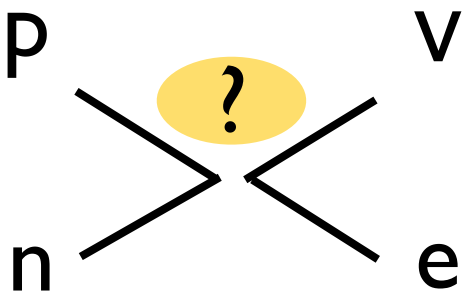
Lee and Yang, 1956



Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Lee and Yang:
use most general Lorentz-invariant interaction

β-decays: historic perspective

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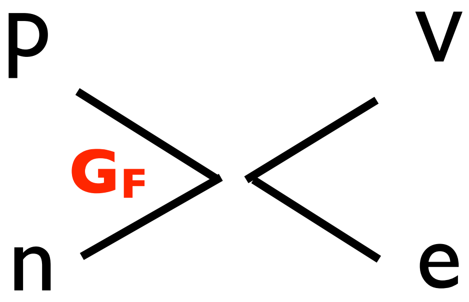

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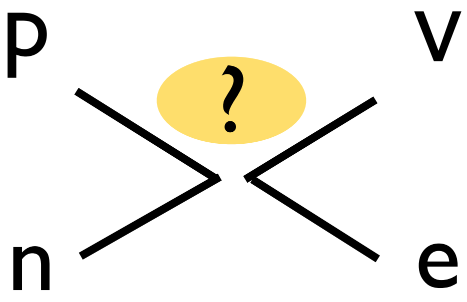

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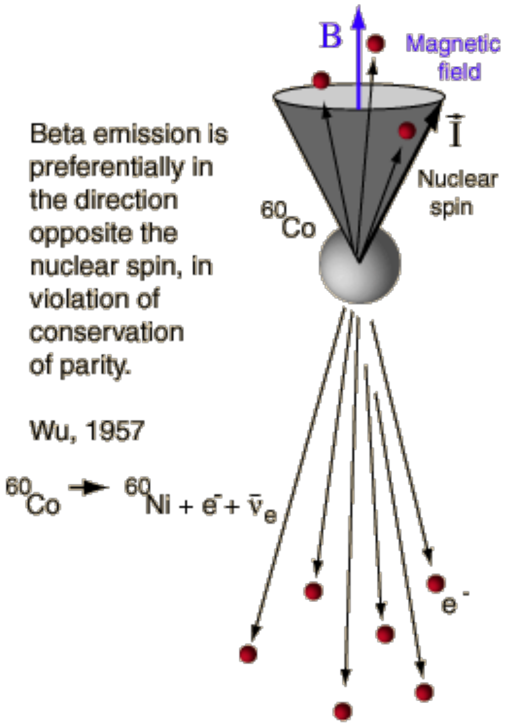


Beta emission is preferentially in the direction opposite the nuclear spin, in violation of conservation of parity.

Wu, 1957

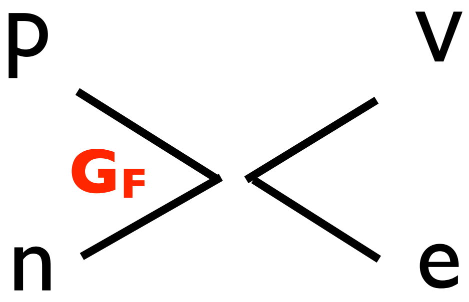
$^{60}\text{Co} \rightarrow {}^{60}\text{Ni} + e^- + \bar{\nu}_e$

C-S Wu

Experiment: parity is violated!
(but could be VA, SP, …)

β-decays: historic perspective

Fermi, 1934



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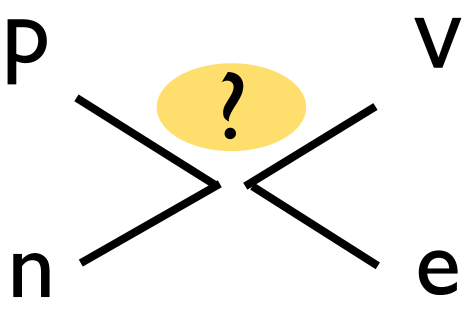
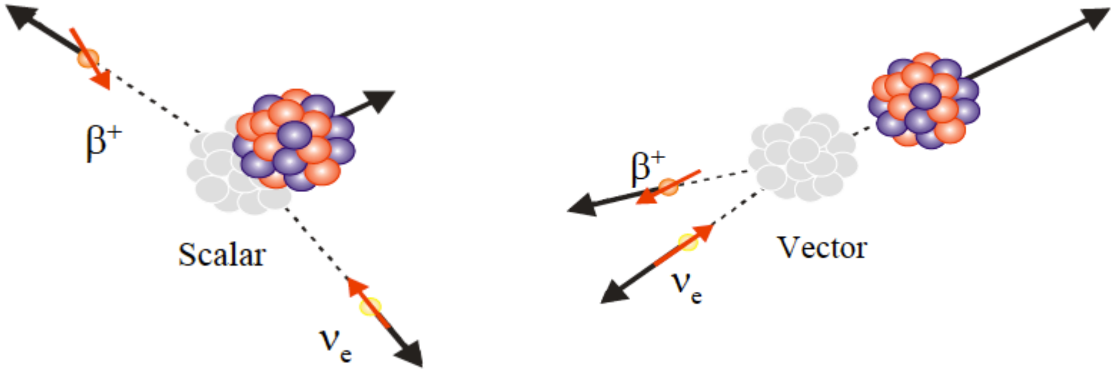


Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

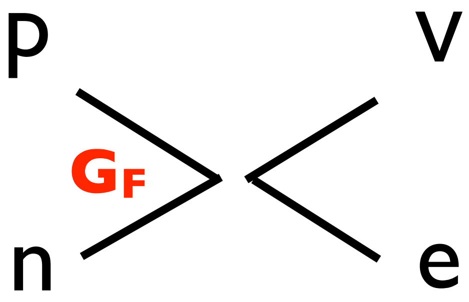
Differential decay distributions
depend on structure of currents



Model diagnosing!

β-decays: historic perspective

Fermi, 1934



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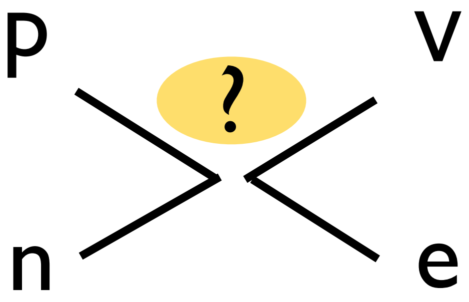


Parity conserving:
VV, AA, SS, TT ...
Parity violating: VA, SP, ...

Marshak & Sudarshan,
Feynman & Gell-Mann 1958

It's (V-A)*(V-A) !!

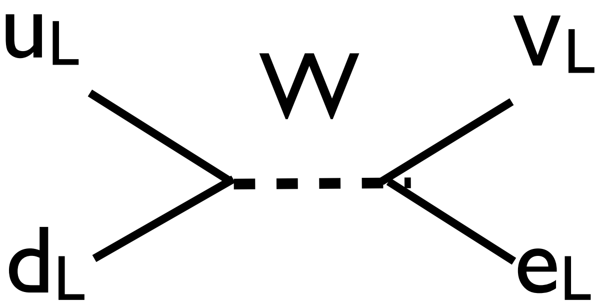
"V-A was the key"
S. Weinberg

Glashow,
Salam,
Weinberg


Sheldon Lee Glashow


Abdus Salam


Steven Weinberg



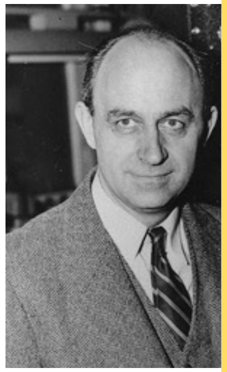
Embed in non-abelian chiral gauge theory, predict neutral currents

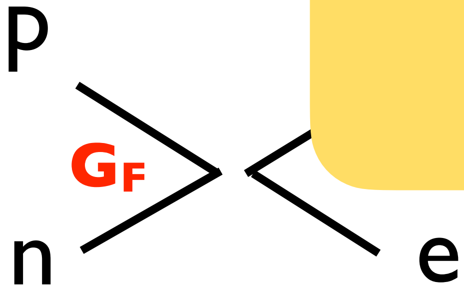
β-decays: historic perspective

Lessons: nuclear beta decays were able to

- “Detect” physics originating at $\Lambda = G_F^{-1/2} \sim 250$ GeV
- Point to key features of the underlying interactions, that led to the formulation of the Standard Model

Fermi, 193





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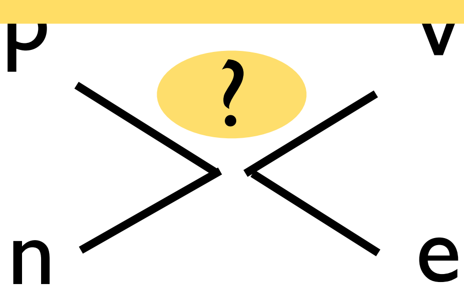

Parity conserving: VV, AA, SS, TT ...
Parity violating: VA, SP, ...

It’s (V-A)*(V-A) !!

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ashow,
alam,
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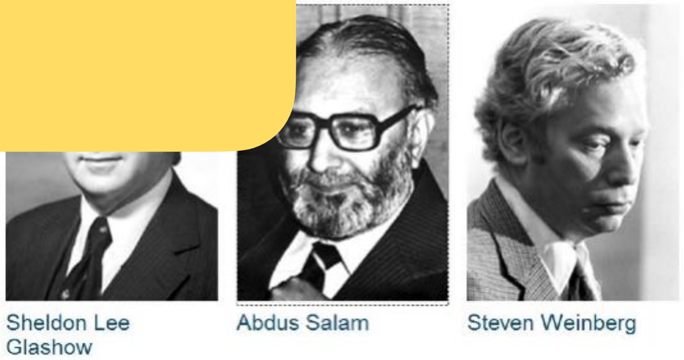
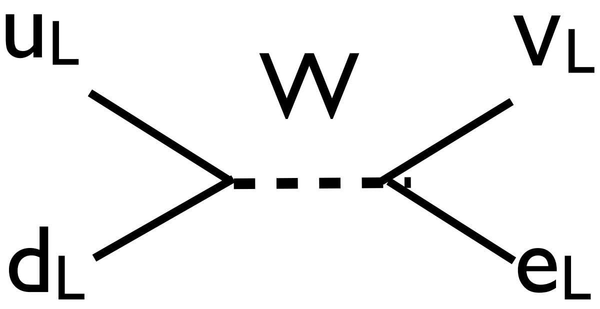
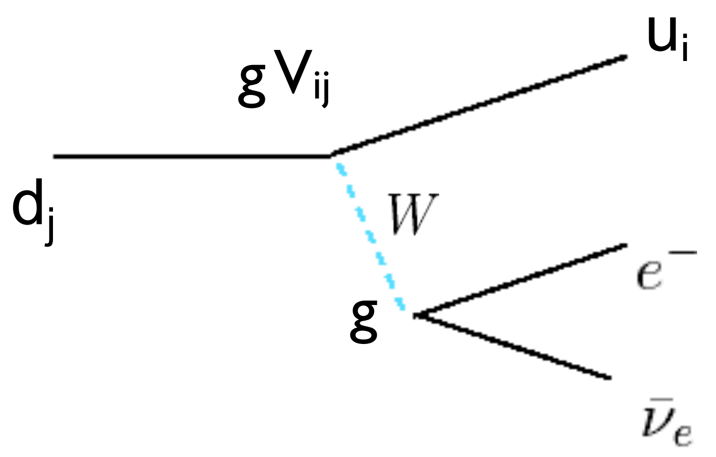




Embed in non-abelian chiral gauge theory, predict neutral currents

β-decays: current perspective

- In the SM, W exchange ⇒ universality relations



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

$$\begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Cabibbo-Kobayashi-Maskawa

Cabibbo Universality

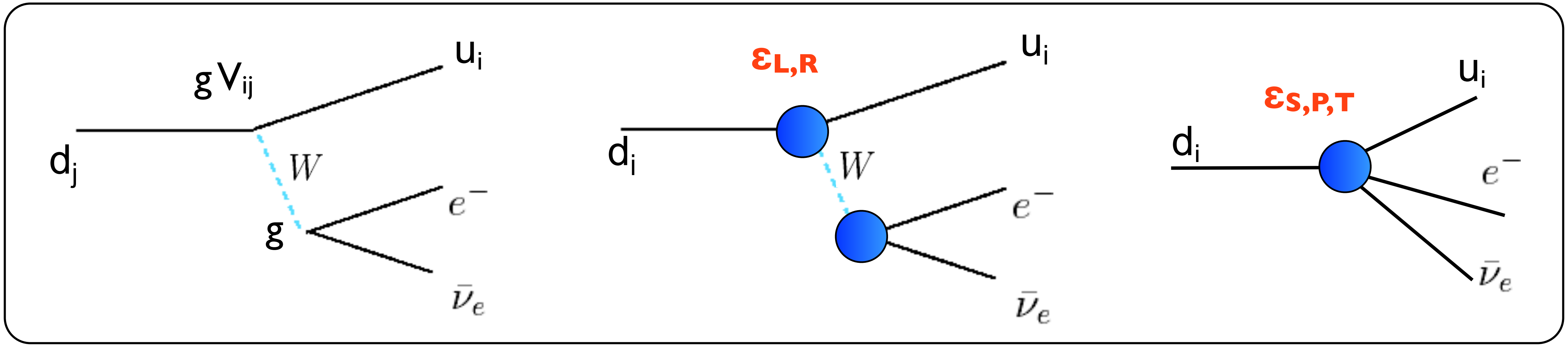
$$|V_{ud}|^2 + |V_{us}|^2 + |\cancel{V_{ub}}|^2 = 1$$

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

Lepton Flavor Universality (LFU)

β-decays: current perspective

- In the SM, W exchange ⇒ universality relations



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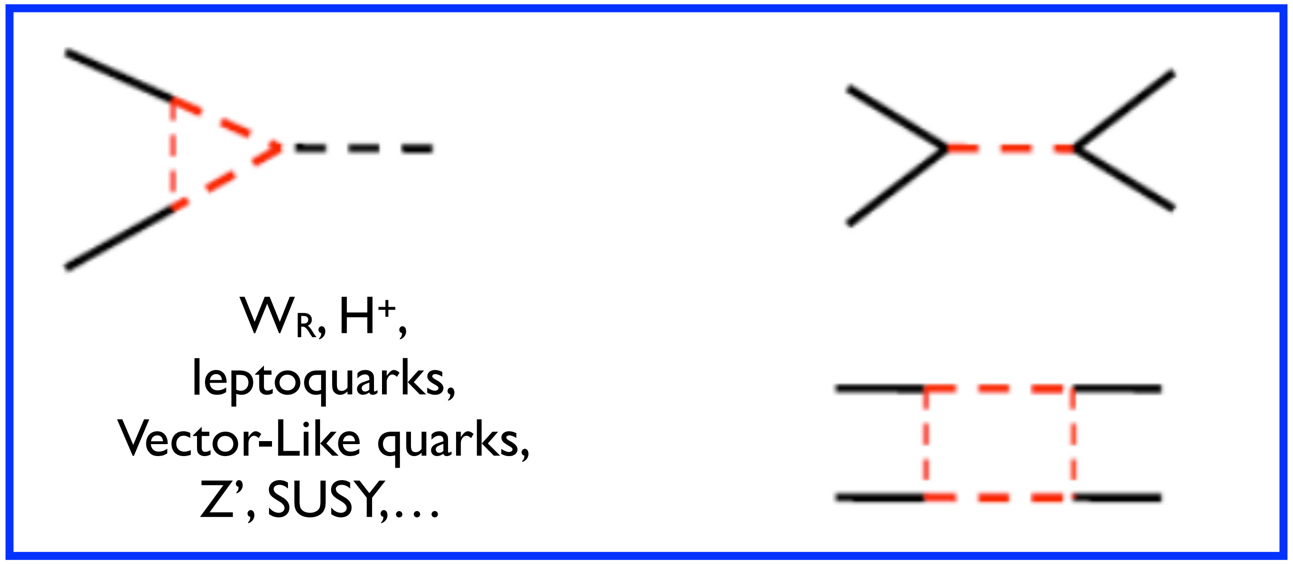
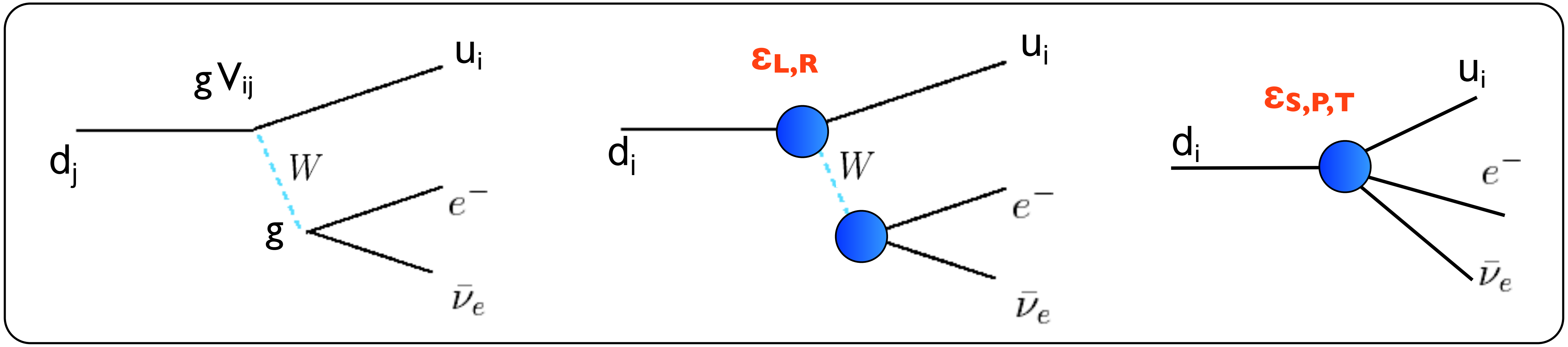


W_R, H^+,
leptoquarks,
Vector-Like quarks,
Z', SUSY,...

β-decays: current perspective

- In the SM, W exchange ⇒ universality relations



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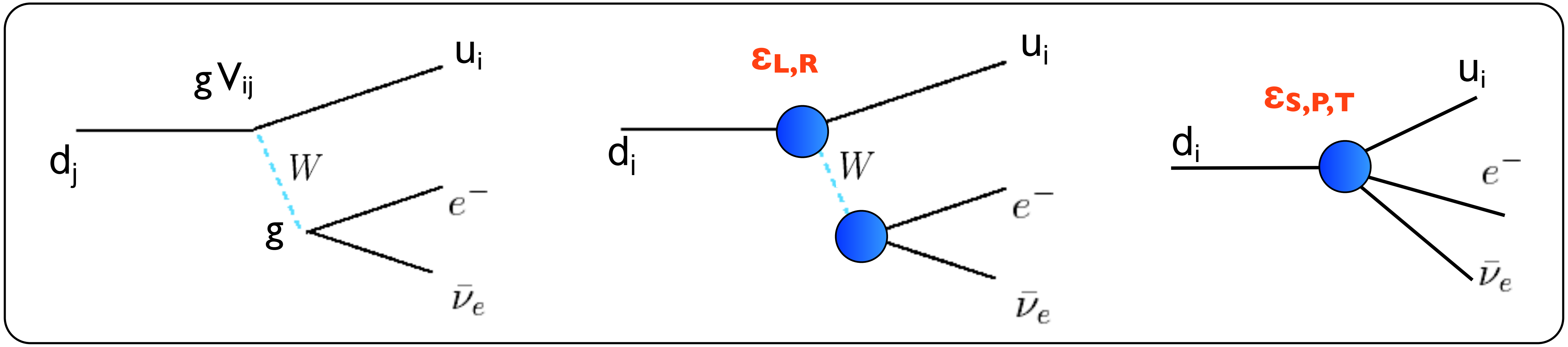
$E \ll \Lambda$ $\downarrow$ $\varepsilon_\Gamma \sim \tilde{\varepsilon}_\Gamma \sim (v/\Lambda)^2$

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

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

β-decays: current perspective

- In the SM, W exchange ⇒ universality relations



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

- BSM effects can spoil universality. Precision of 0.1-0.01% probes Λ > 10 TeV

Cabibbo universality tests

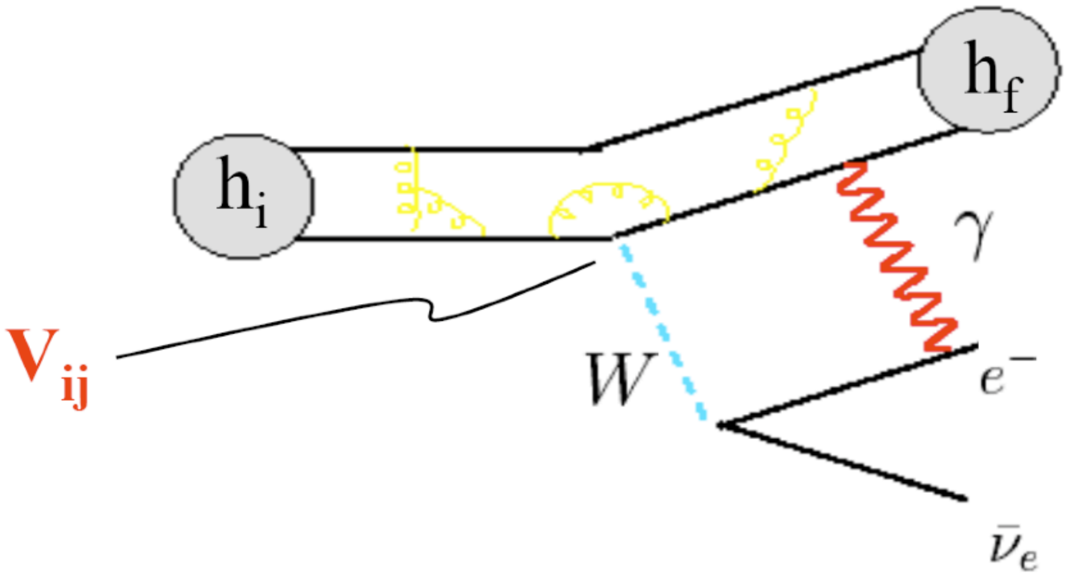
Extract $V_{ud}=\mathrm{Cos}\theta_C$ and $V_{us}=\mathrm{Sin}\theta_C$ from various decays

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

Channel-dependent
effective CKM element

Hadronic matrix
element

Radiative corrections:
$(\alpha/\pi) \sim 2.\times 10^{-3}$



Cabibbo universality tests

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

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

Channel-dependent effective CKM element

Hadronic matrix element

Radiative corrections: $(\alpha/\pi) \sim 2.\times 10^{-3}$

$$|\bar{V}_{ij}|^2 = |V_{ij}|^2 \times \left(1 + \sum_\alpha c_k^\alpha \, \epsilon_\alpha\right)$$

Calculable coefficients

BSM effective couplings

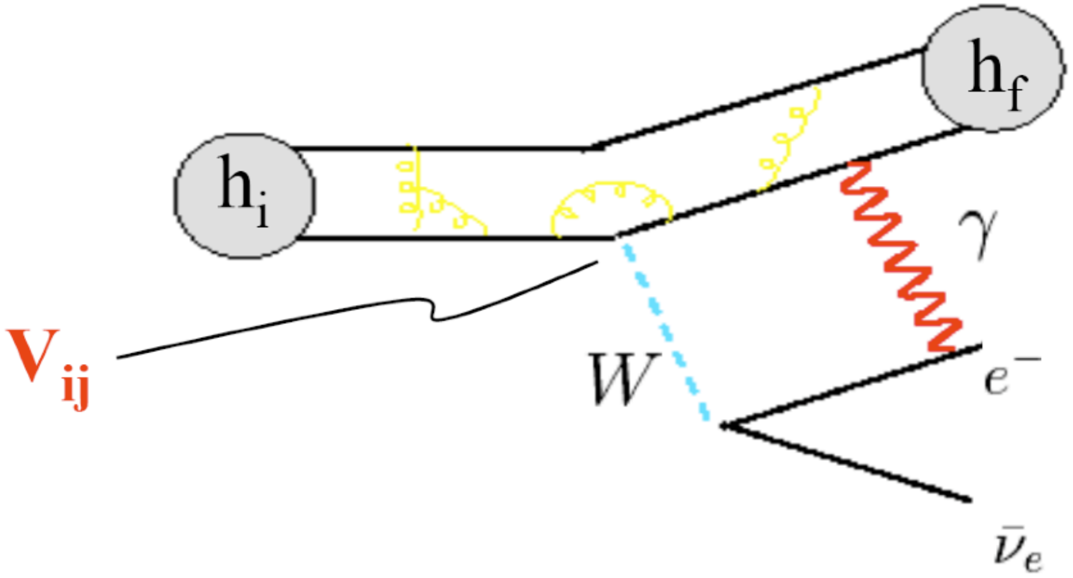
$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + |\bar{V}_{ub}|^2 = 1 + \Delta_{\text{CKM}}(\epsilon_i)$$

Paths to V_{ud} and V_{us}

V_{ud}	$0^+ \to 0^+$ $(\pi^\pm \to \pi^0 e \nu)$	$n \to p e \bar{\nu}$	$\pi \to \mu \nu$
V_{us}	$K \to \pi l \nu$	$(\Lambda \to p e \bar{\nu}, \dots)$	$K \to \mu \nu$

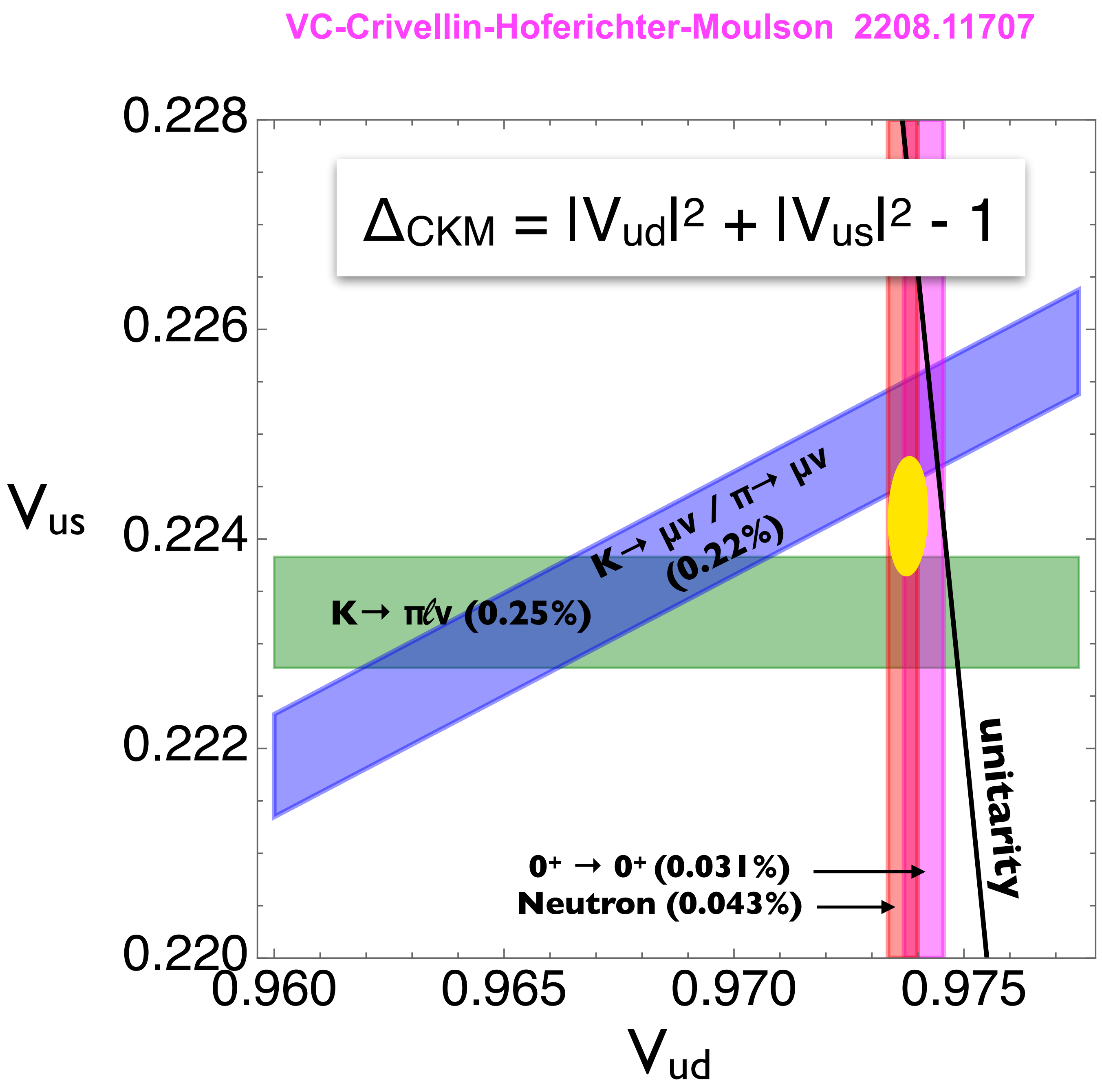
(Hadronic τ decays)

Quark current mediating the decay → V V, A A



Input from *many* experiments and theory papers

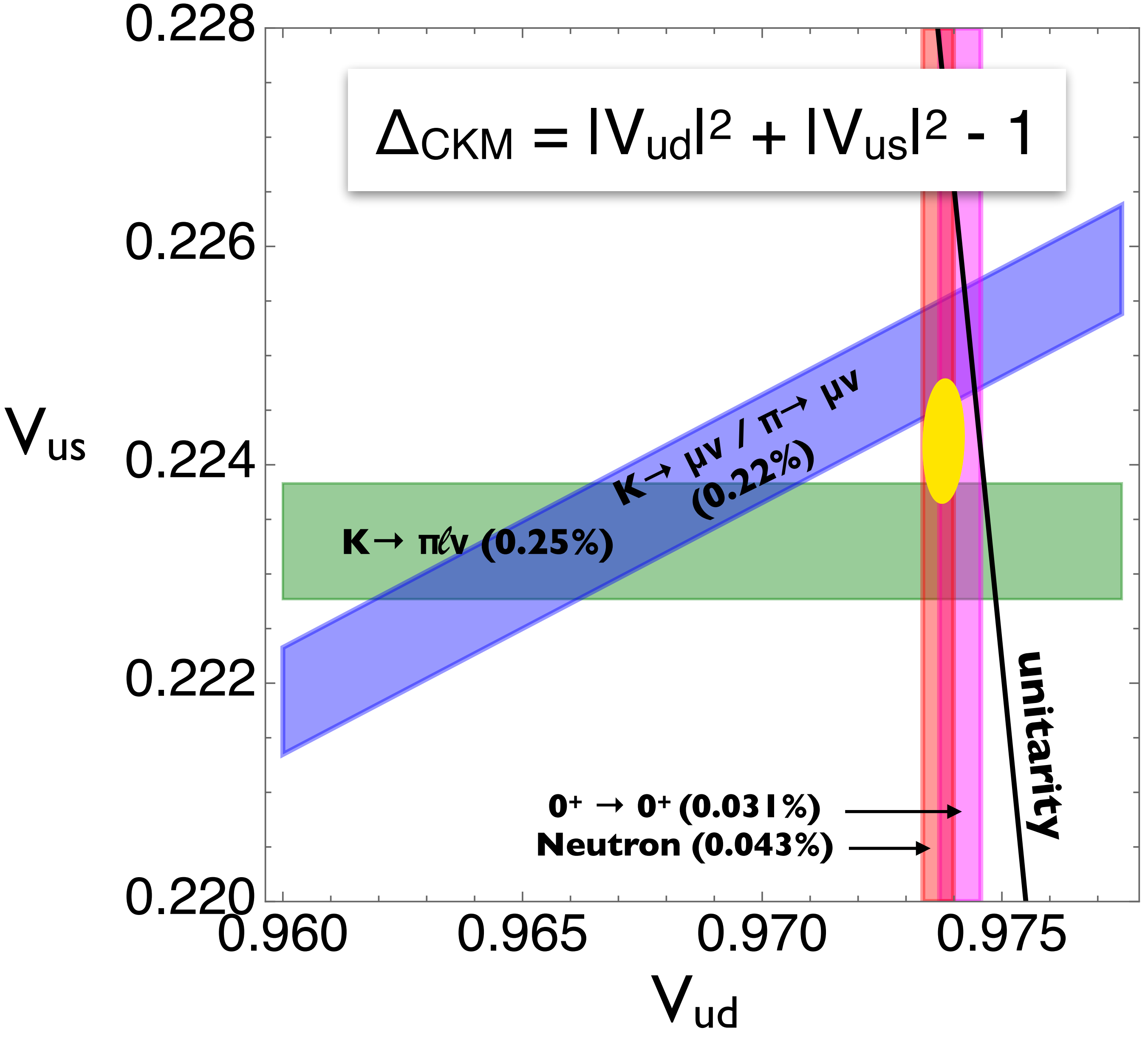
The Cabibbo angle “anomaly”



- Two ‘anomalies’:
  - ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)
  - ~3σ problem in meson sector (Kl2 vs Kl3)

The Cabibbo angle “anomaly”

VC-Crivellin-Hoferichter-Moulson 2208.11707

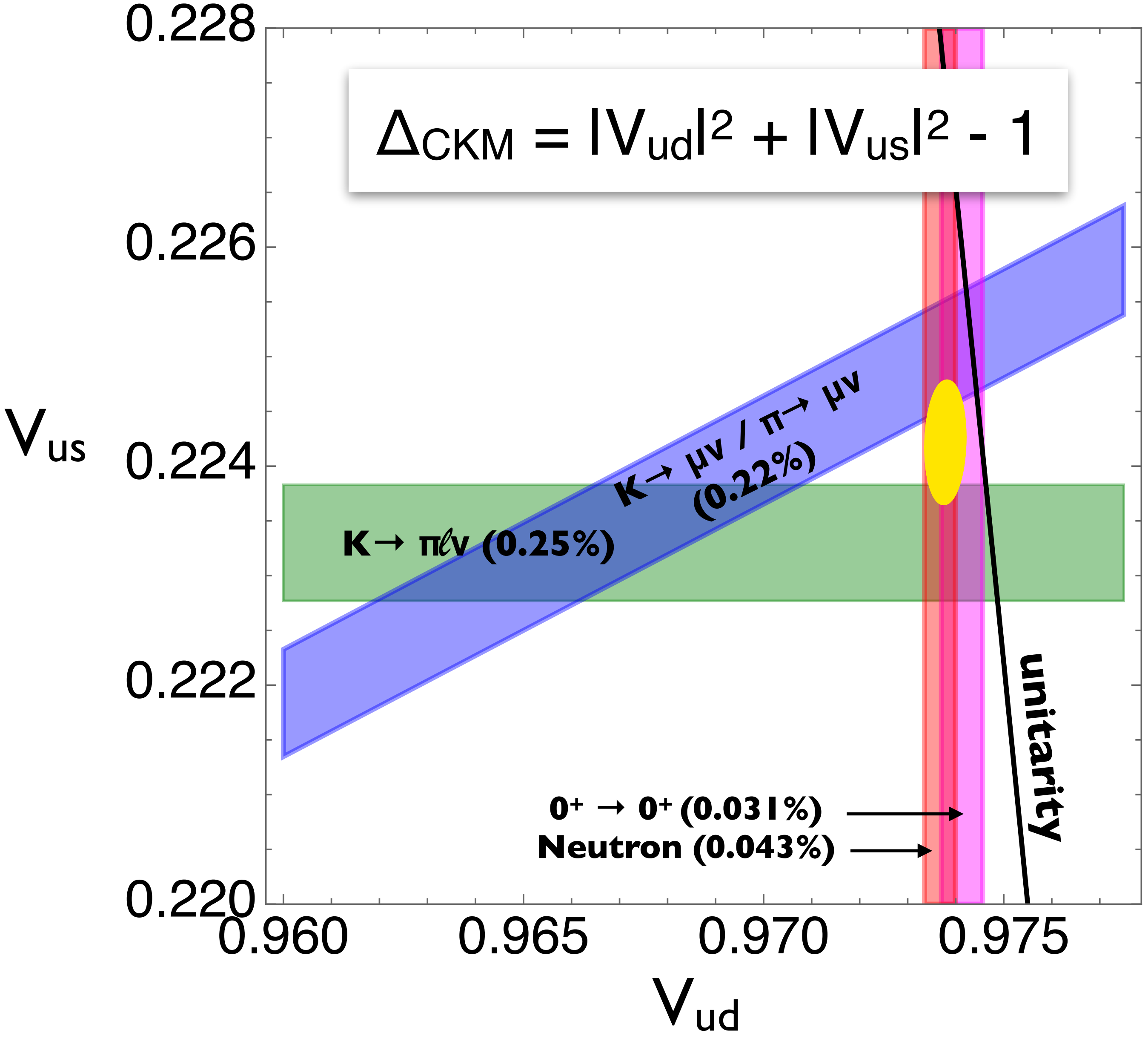


- Two ‘anomalies’:
    - ~3σ effect in global fit ($\Delta_{CKM} = -1.48(53) \times 10^{-3}$)
    - ~3σ problem in meson sector (Kl2 vs Kl3)
- Three versions of Δ_{CKM}:

$$\begin{aligned}
\Delta^{(1)}_{CKM} &= |V^{\beta}_{ud}|^2 + |V^{K_{\ell 3}}_{us}|^2 - 1 \\
&= -1.76(56) \times 10^{-3} \\
\Delta^{(2)}_{CKM} &= |V^{\beta}_{ud}|^2 + |V^{K_{\ell 2}/\pi_{\ell 2},\,\beta}_{us}|^2 - 1 \\
&= -0.98(58) \times 10^{-3} \\
\Delta^{(3)}_{CKM} &= |V^{K_{\ell 2}/\pi_{\ell 2},\,K_{\ell 3}}_{ud}|^2 + |V^{K_{\ell 3}}_{us}|^2 - 1 \\
&= -1.64(63) \times 10^{-2}
\end{aligned}$$

The Cabibbo angle “anomaly”

VC-Crivellin-Hoferichter-Moulson 2208.11707



- 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 with lattice gauge theory for Kl3 and neutron;
  - EFT-based first-principles nuclear structure corrections

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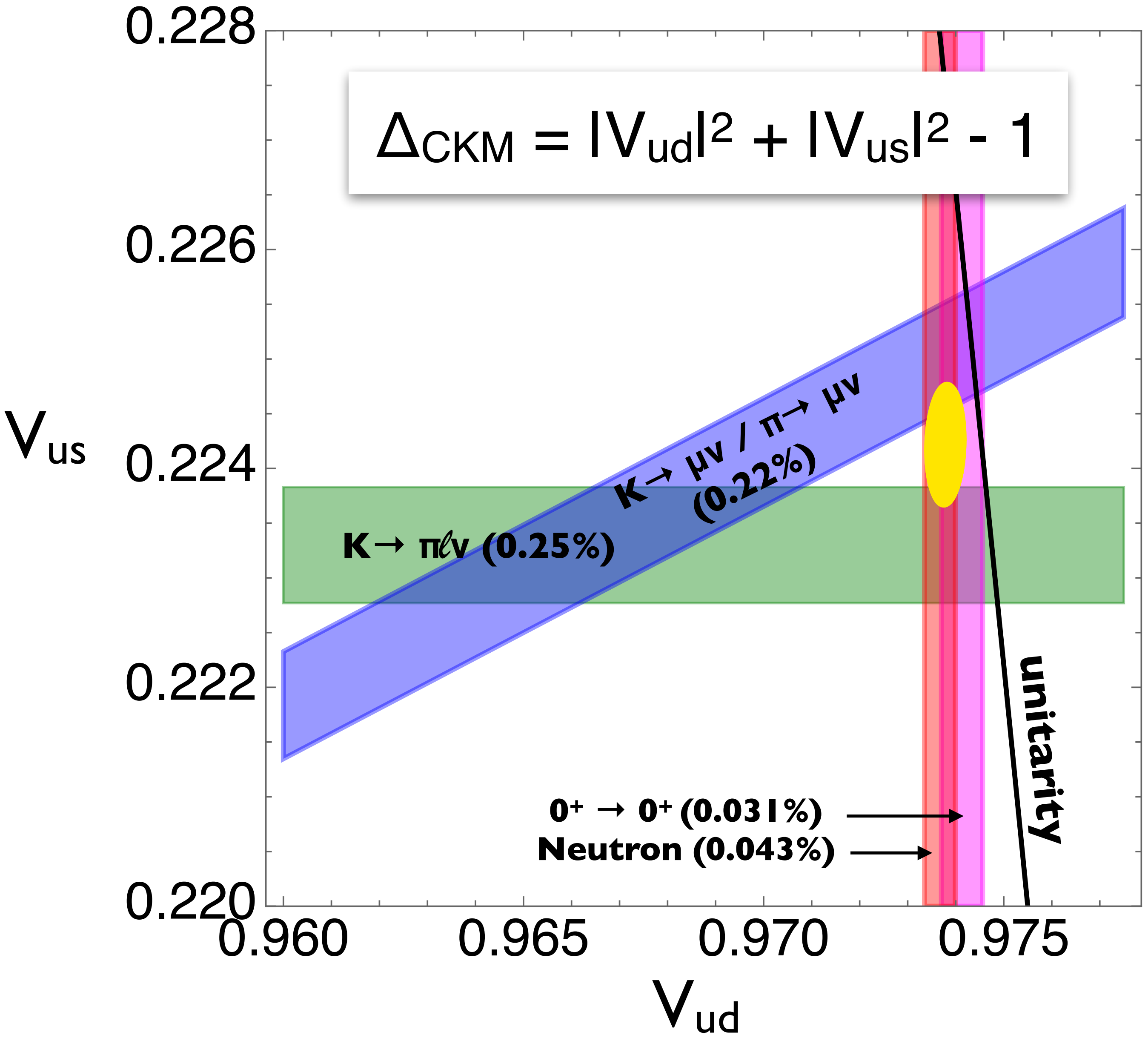
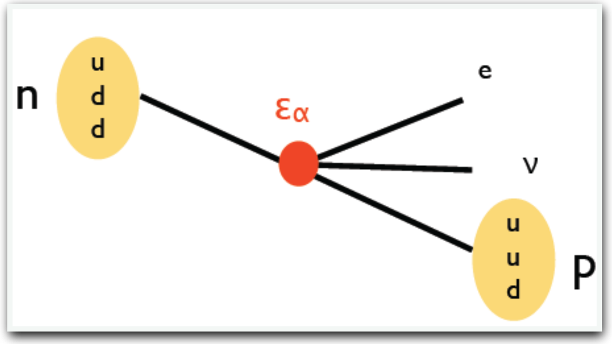


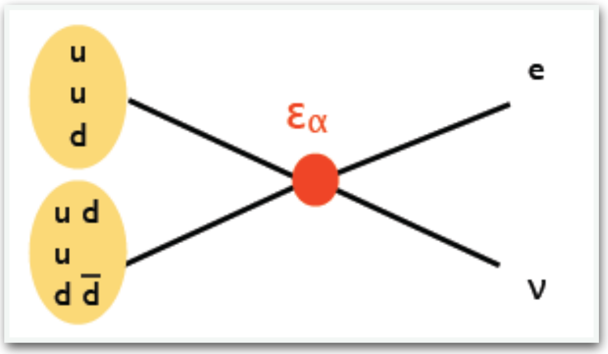
- Possible BSM explanations:

    - 4-fermion operators strongly constrained by LHC measurements

n → p e ν



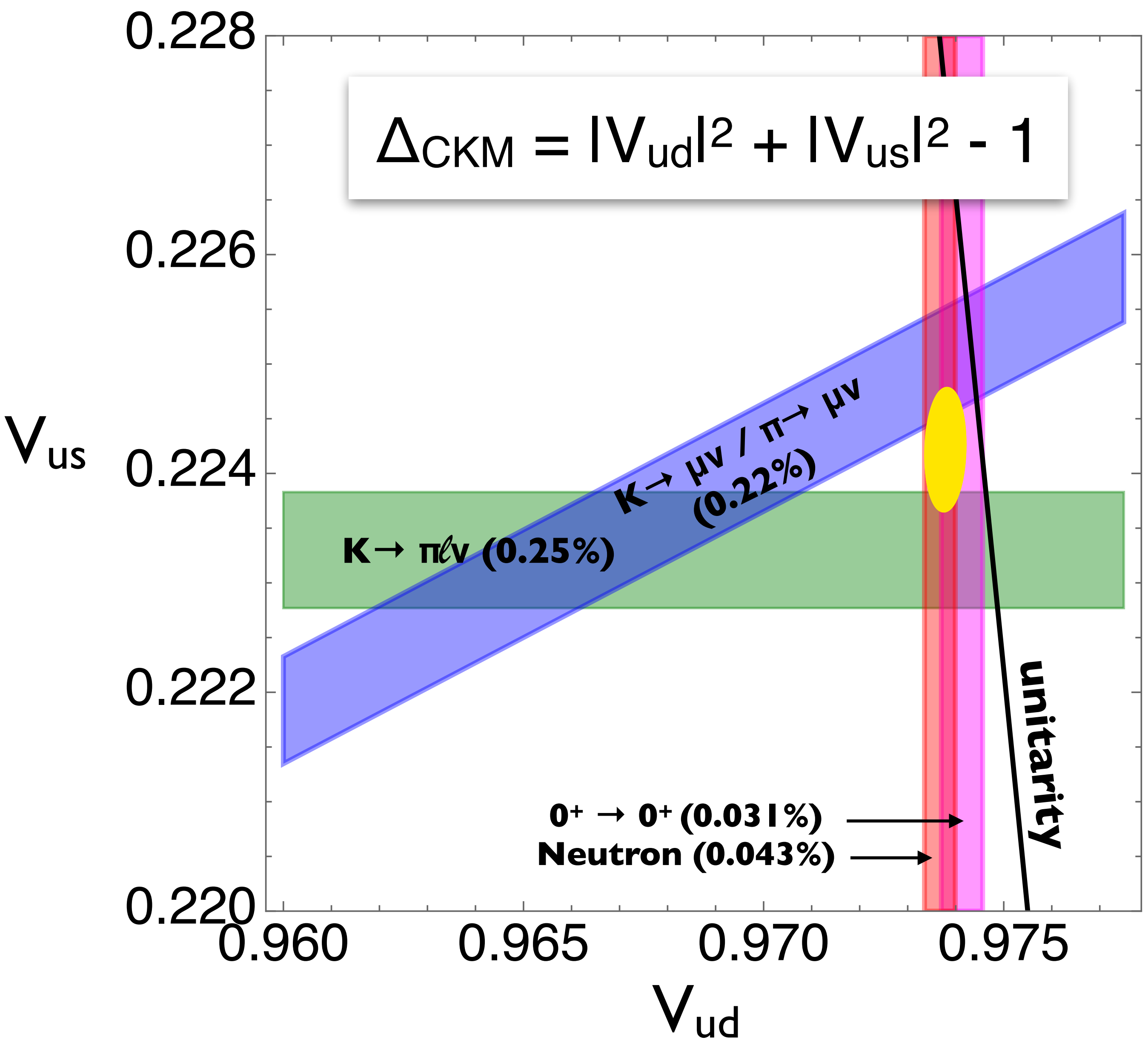
LHC: pp → eν + X



VC, Gonzalez-Alonso, Graesser 1210.4553

The Cabibbo angle “anomaly”

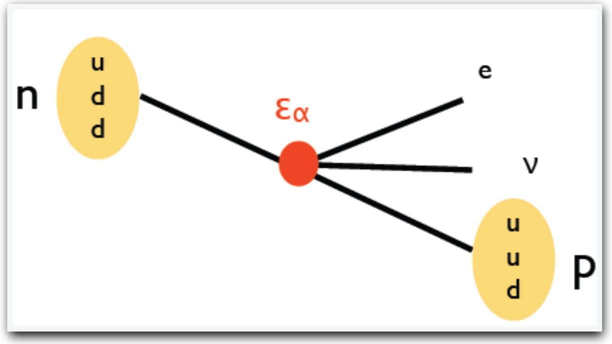
VC-Crivellin-Hoferichter-Moulson 2208.11707



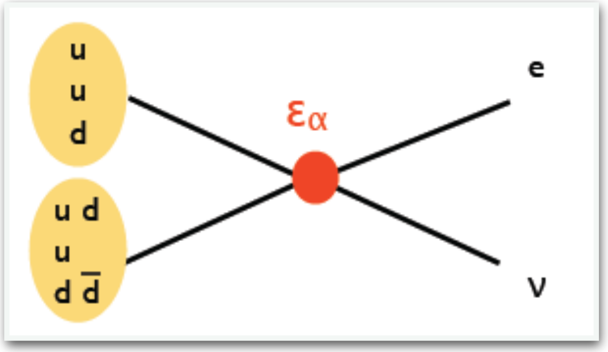
- Possible BSM explanations:

  - 4-fermion operators strongly constrained by LHC measurements

$n \to p\, e\, \nu$

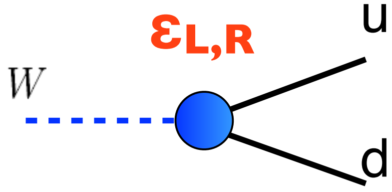


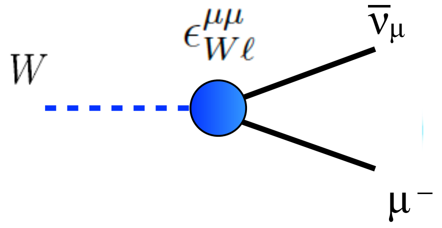
LHC: $pp \to e\nu + X$



VC, Gonzalez-Alonso, Graesser 1210.4553

  - Vertex corrections (quark and leptons) remain viable candidates





For mini-review see A. Crivellin 2207.02507

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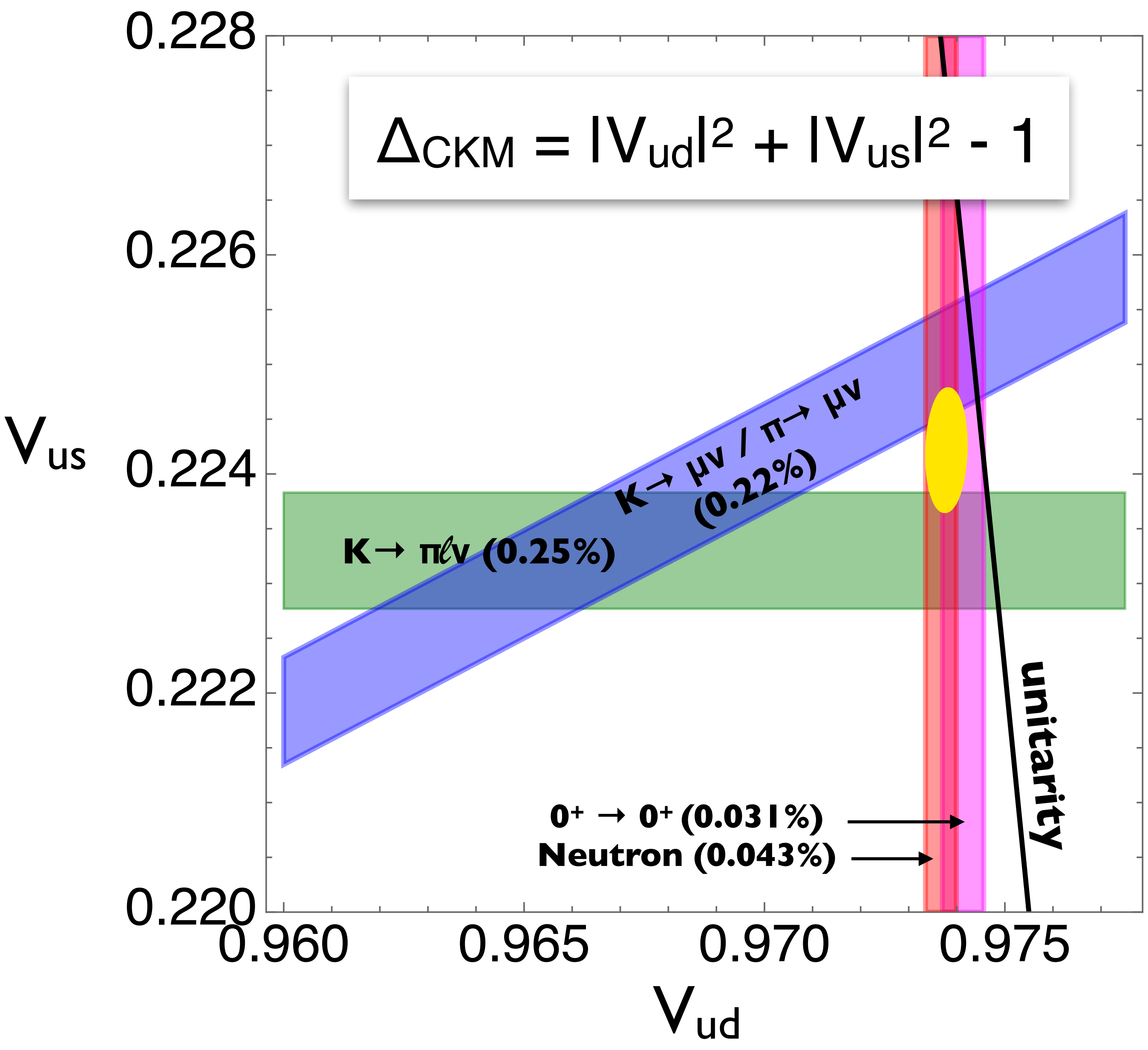
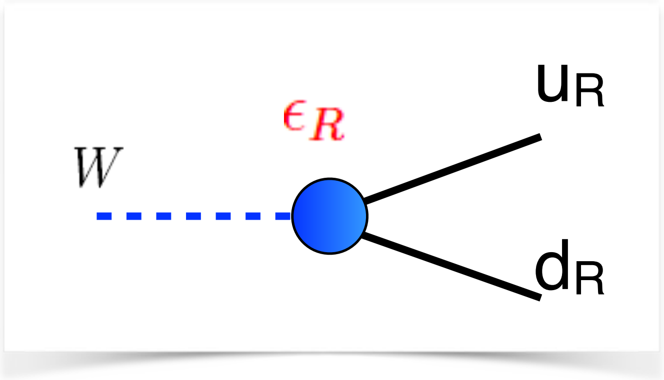


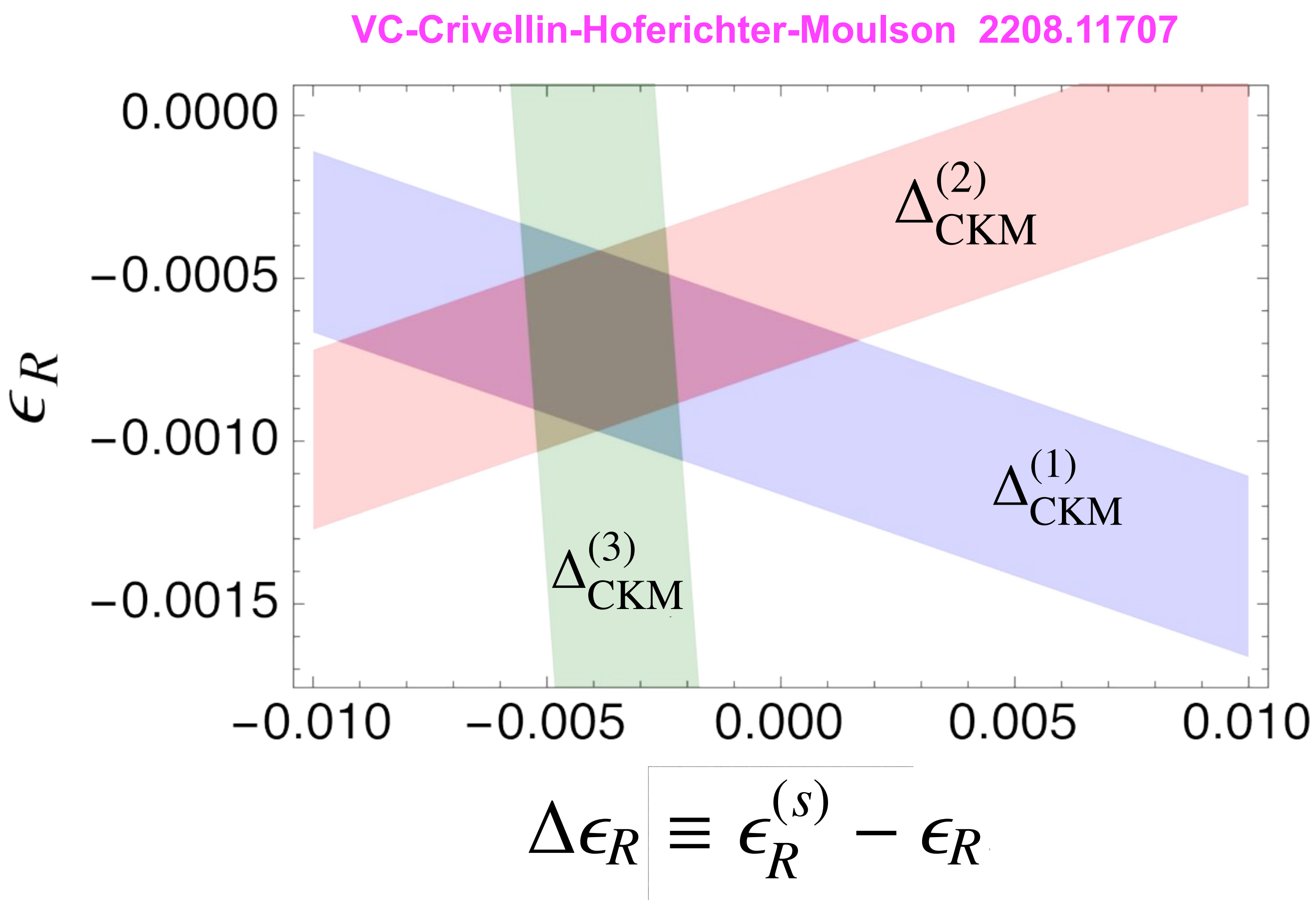
- All discrepancies can be solved by R-handed quark currents (both 'ud' and 'us'): ε_R , $\varepsilon_R^{(s)}$



- CKM elements extracted from vector (axial) channels are shifted by $1+\varepsilon_R$ ($1-\varepsilon_R$)

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

Unveiling R-handed quark currents?



$$\Delta^{(1)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R V_{us}^2,$$

$$\Delta^{(2)}_{\rm CKM} = 2\epsilon_R - 2\Delta\epsilon_R V_{us}^2,$$

$$\Delta^{(3)}_{\rm CKM} = 2\epsilon_R + 2\Delta\epsilon_R(2 - V_{us}^2)$$

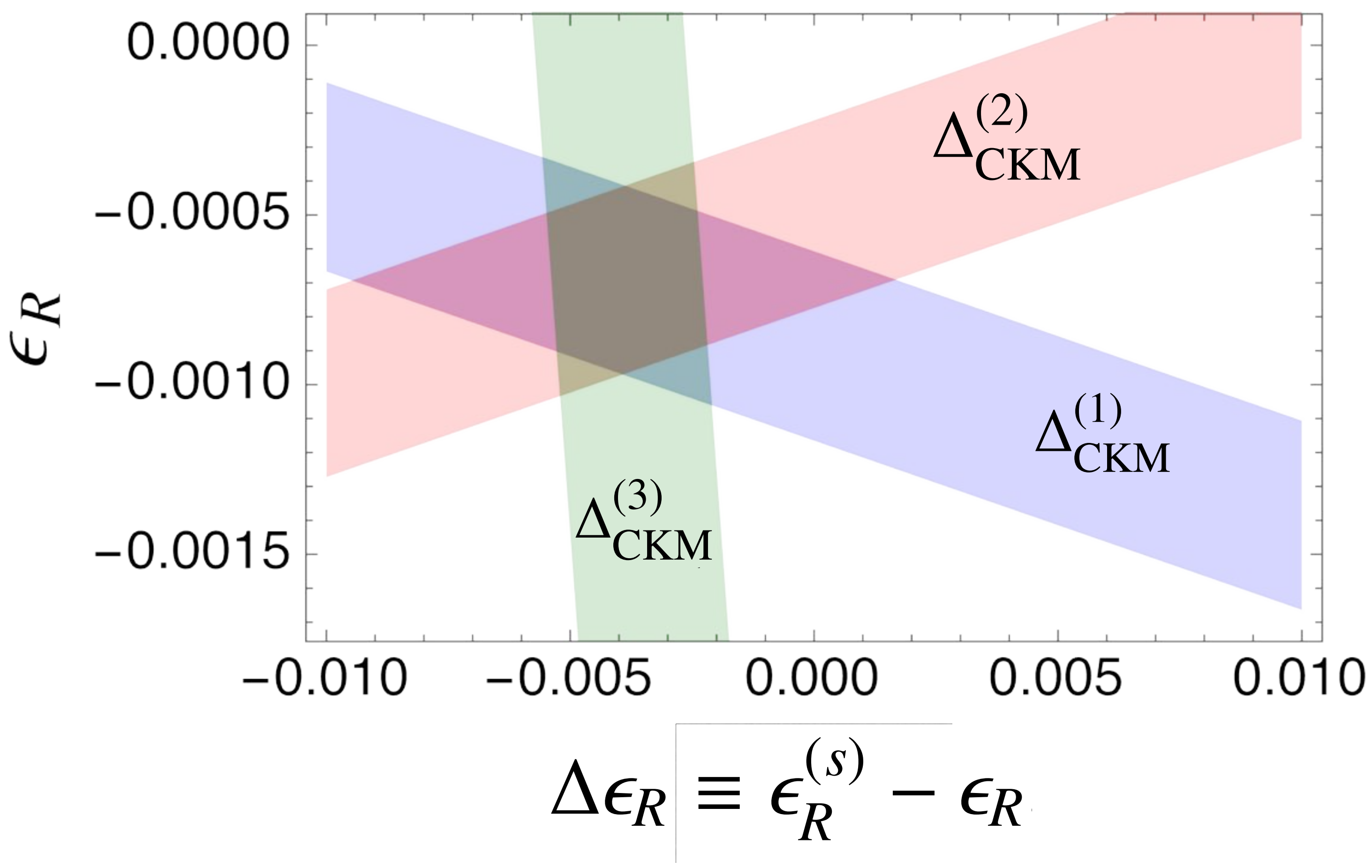
$$\downarrow$$

$$\boxed{\begin{aligned}\epsilon_R &= -0.69(27)\times 10^{-3}\\ \Delta\epsilon_R &= -3.9(1.6)\times 10^{-3}\end{aligned}}$$

Λ_R ~ 5-10 TeV   2.5σ effect

Unveiling R-handed quark currents?

VC-Crivellin-Hoferichter-Moulson 2208.11707



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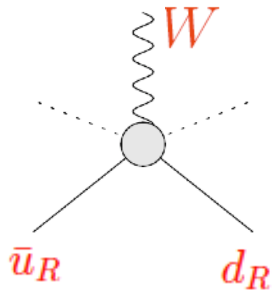
Λ_R ~ 5-10 TeV   2.5σ effect

- Preferred ranges are not in conflict with other data from βdecays or the LHC, such as pp→ eν+X and pp→ Wh+X (projected constraints at few % level)

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



Unveiling R-handed quark currents?

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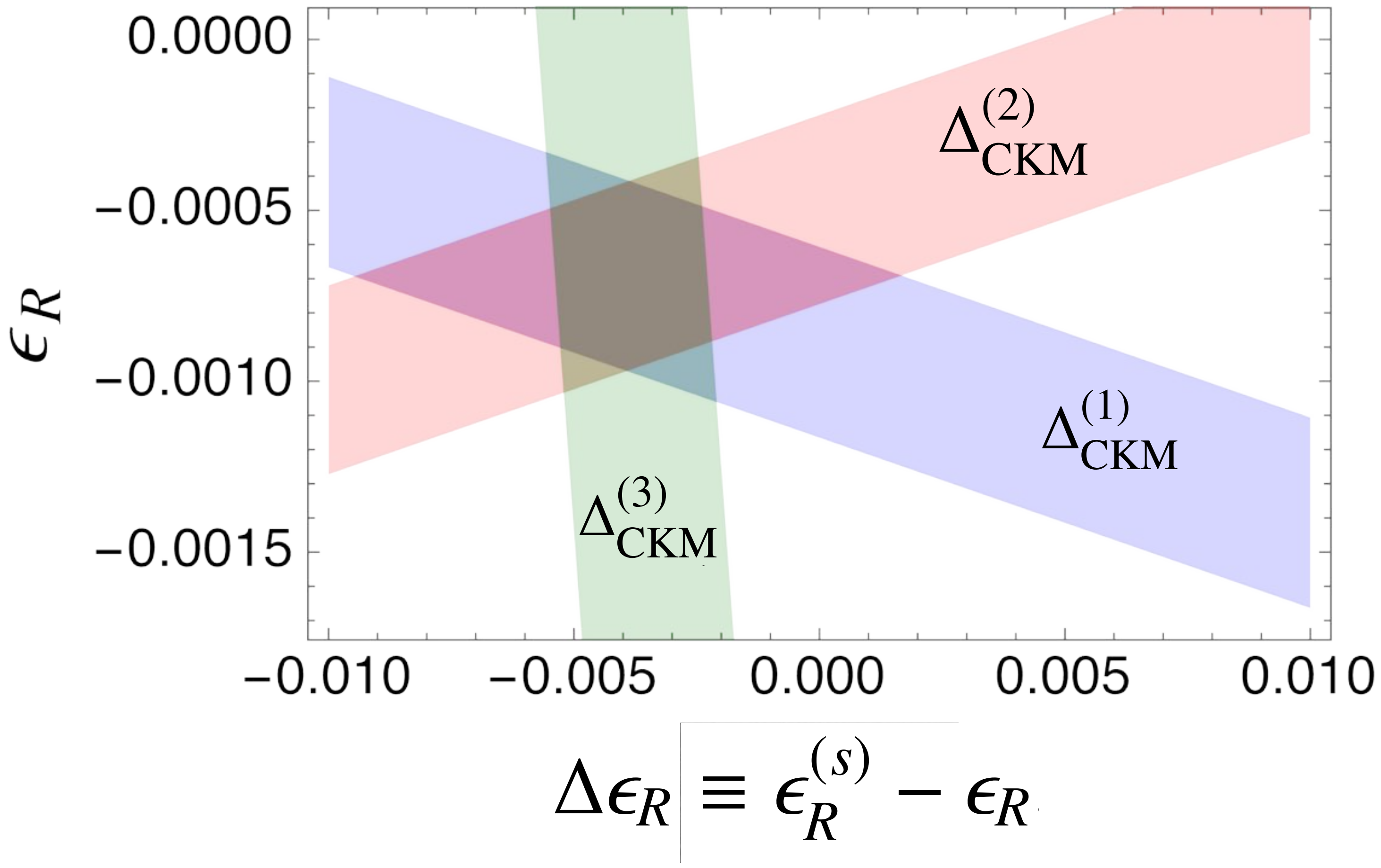

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Λ_R ~ 5-10 TeV   2.5σ effect

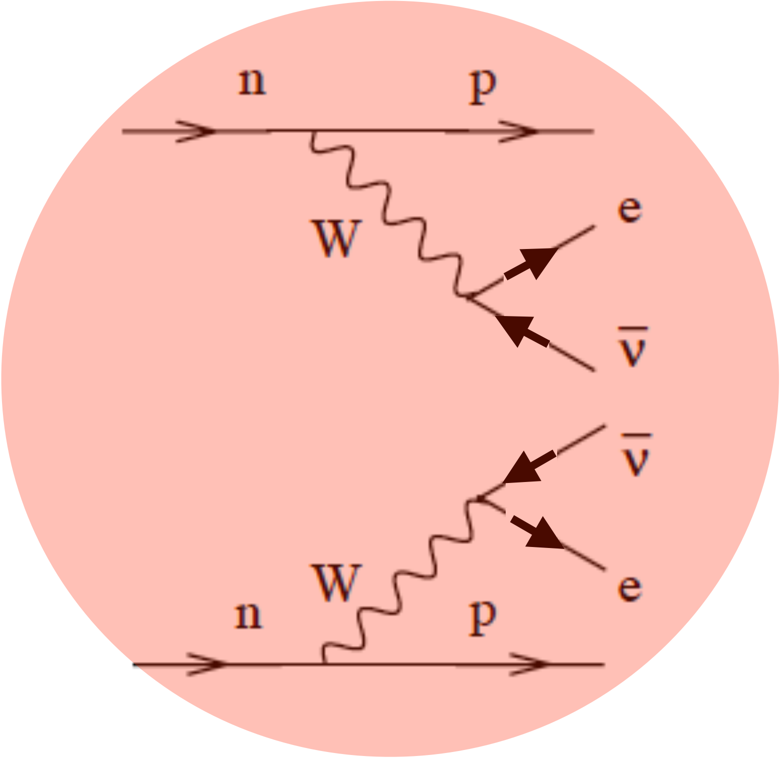
- A measurement of BR(K→πμν)/BR(K→μν) at 0.2% level (possible at NA62, CERN) will corroborate or rule out the presence of R-handed effects
- CKM unitarity test is a very competitive and compelling probe of multi-TeV scale physics well in the LHC era!

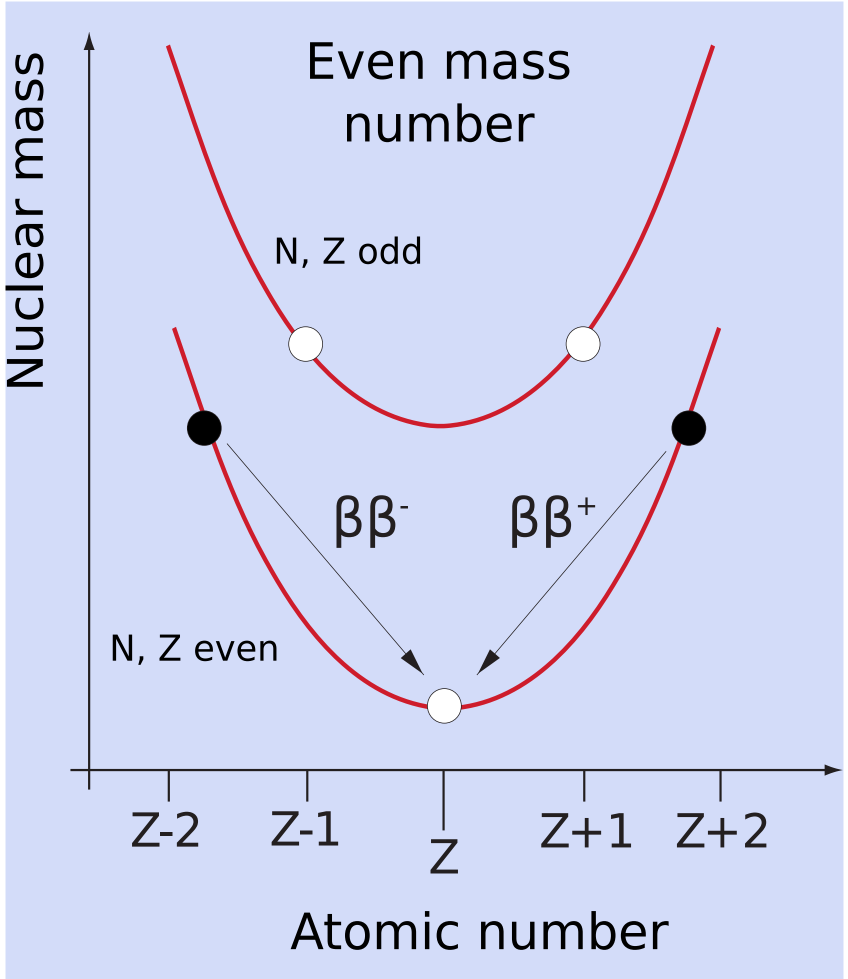
Neutrinoless double beta decay

Double beta decay

- For certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …), single β decay is energetically forbidden → ββ decay!

M. Goppert Mayer, 1935



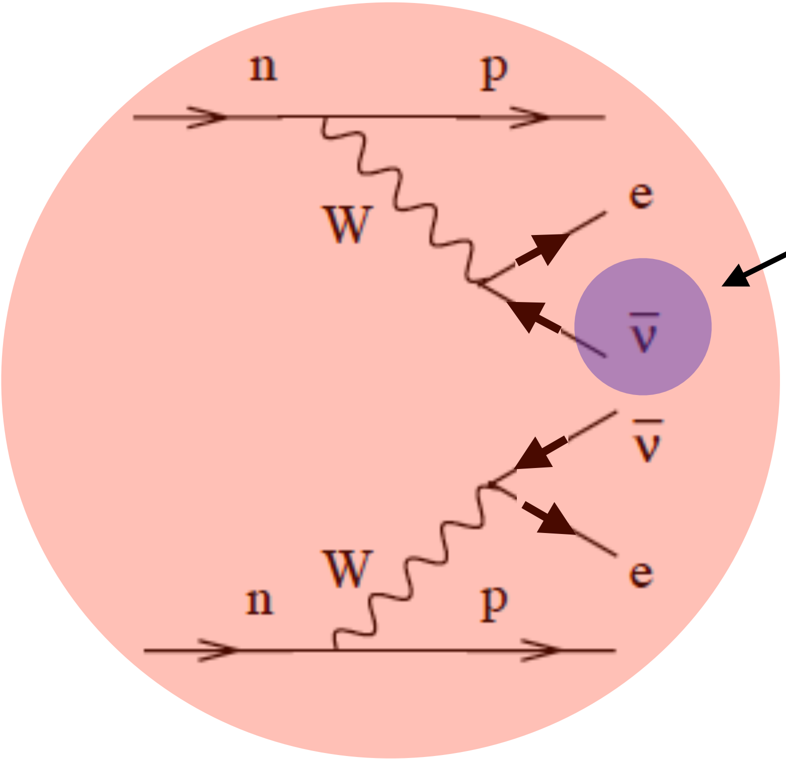


- 2νββ is the rarest process ever observed, with $T_{1/2} \sim 10^{21}$ years (first observation in 1987)

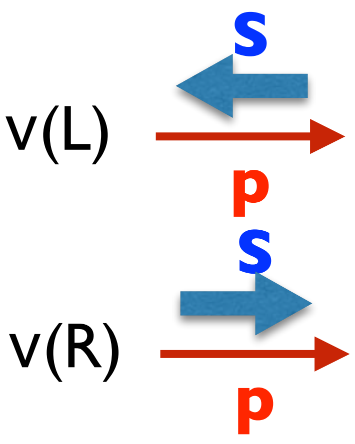
Neutrinoless double beta decay?

- Yes, if neutrinos are massive Majorana particles (i.e. their own antiparticles)

W. H. Furry, 1939



This is just ν(R), which mixes with ν(L) via mass insertion



E. Majorana, 1937

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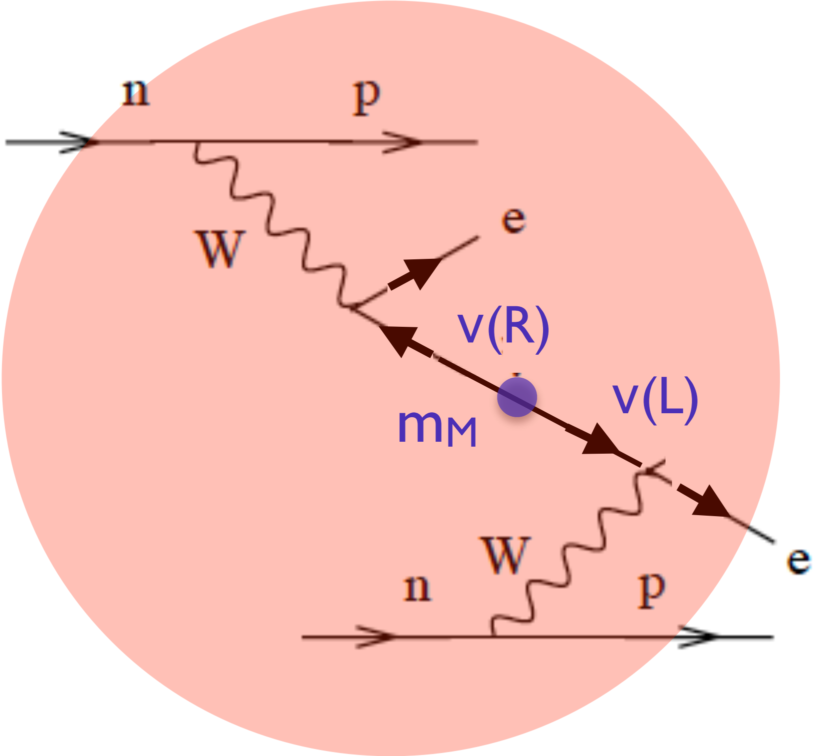

"Subject to the usual limitations on the meaning of such language, one can say that a (virtual) neutrino is emitted together with one of the electrons and reabsorbed when the other electron is emitted."

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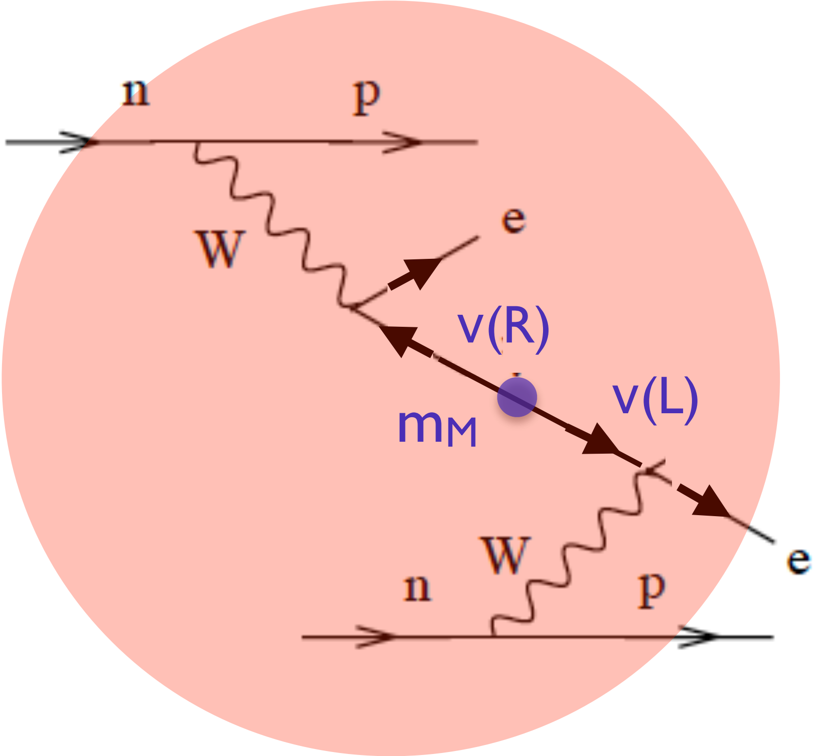

"Subject to the usual limitations on the meaning of such language, one can say that a (virtual) neutrino is emitted together with one of the electrons and reabsorbed when the other electron is emitted."

- Key point: in 0νββ Lepton Number changes by two units.
  Majorana ν exchange is just one possible mechanism. Furry understood this:

"The Majorana form of the theory is not the only one that permits this new form of disintegration […]. The Majorana theory provides, so to speak, a canonical form."

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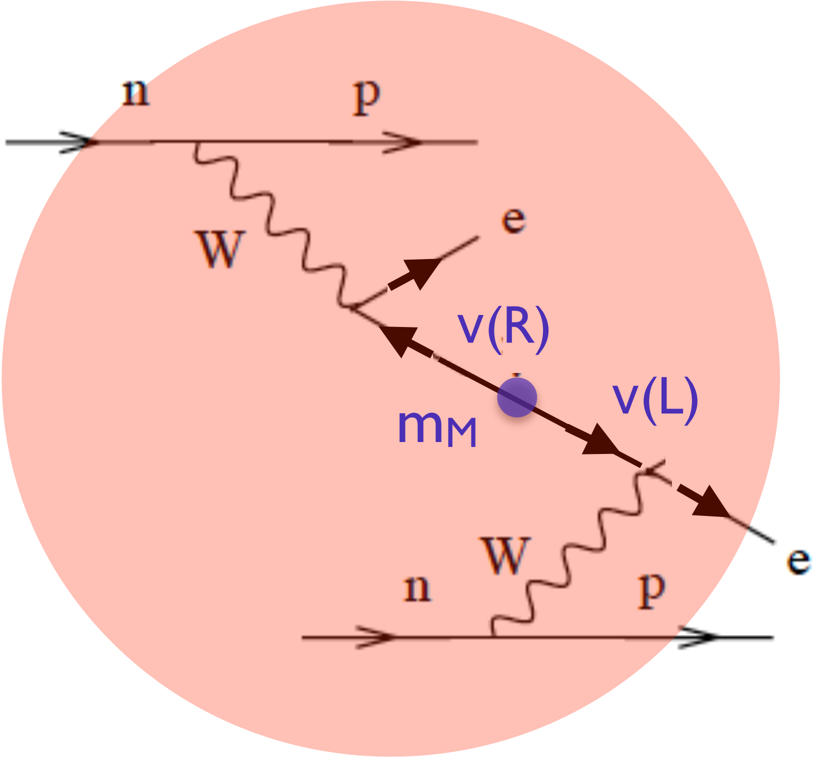
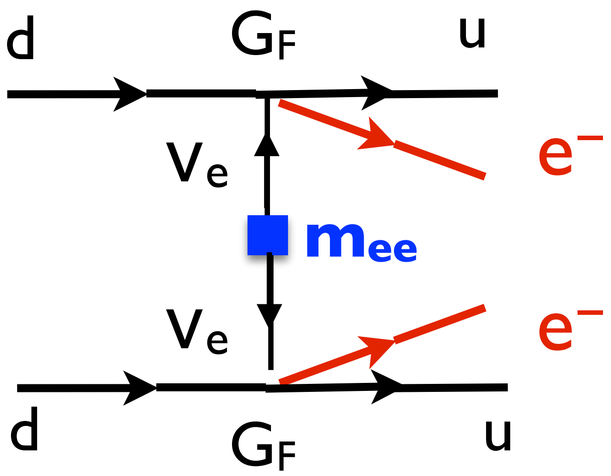
W. H. Furry, 1939

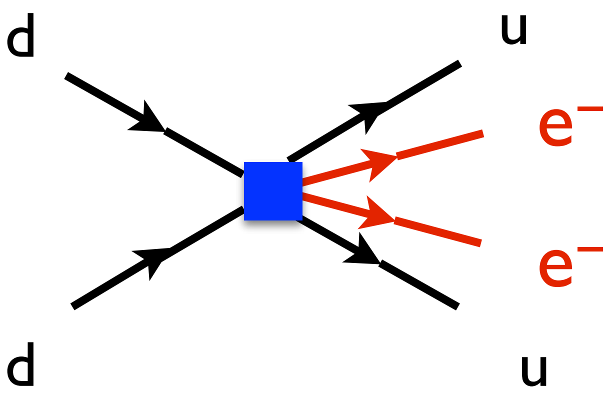


"Subject to the usual limitations on the meaning of such language, one can say that a (virtual) neutrino is emitted together with one of the electrons and reabsorbed when the other electron is emitted."

- Modern viewpoint on Lepton Number Violation:



but also

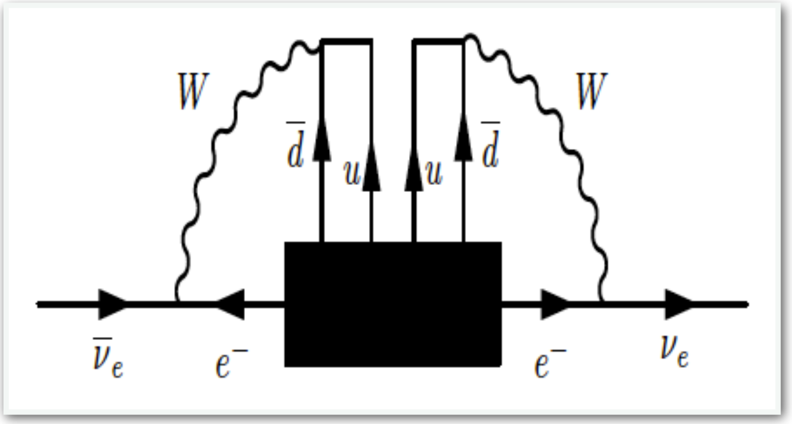


Exchange of heavier neutrinos or other Majorana particles. At low-energy induce six-fermion operator $\sim 1/\Lambda^5$

Significance of 0νββ

- B-L conserved in SM → 0νββ = new physics, with far-reaching implications

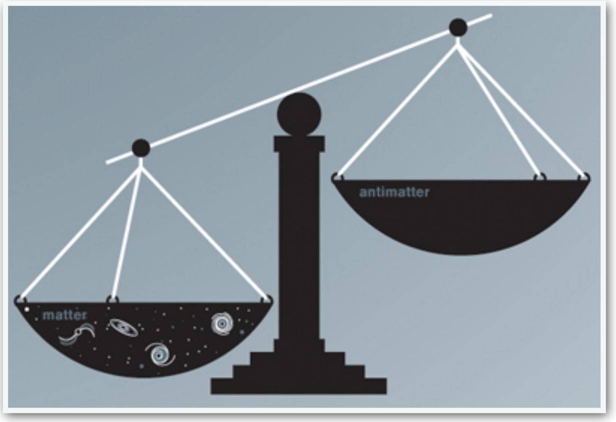
- Demonstrate that neutrinos are their own antiparticles (Majorana fermions)



Shechter-Valle 1982

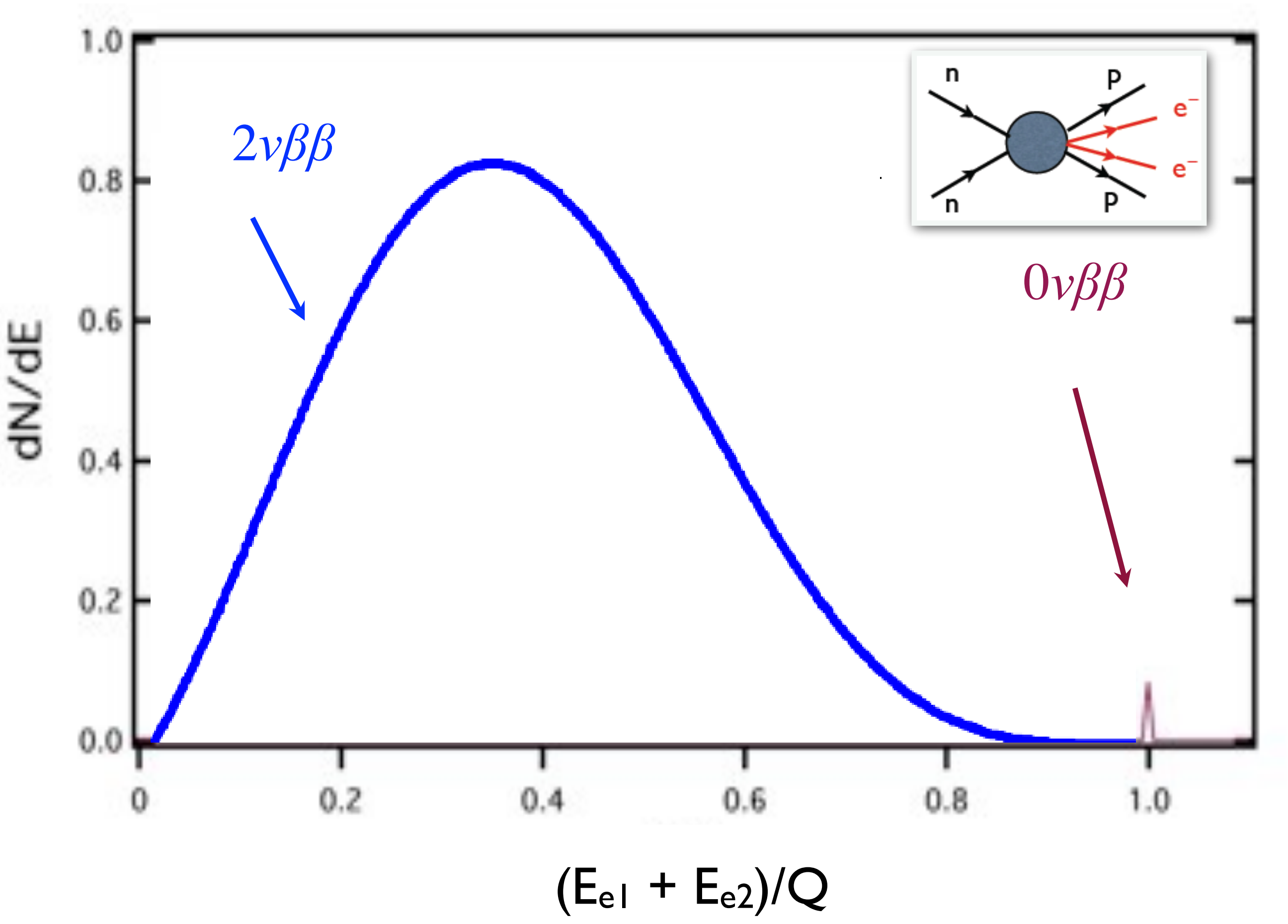
- Establish L non-conservation, key ingredient to generate the baryon asymmetry via leptogenesis

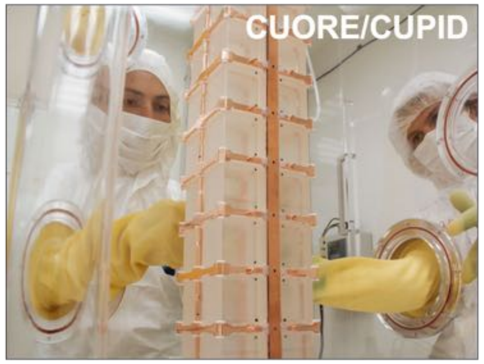
Fukujita-Yanagida 1987

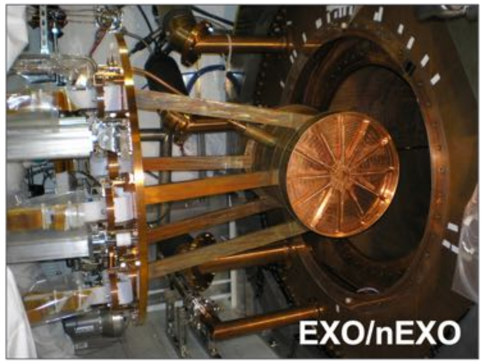


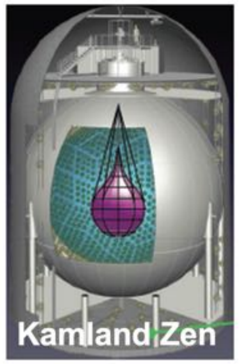
The quest is on…

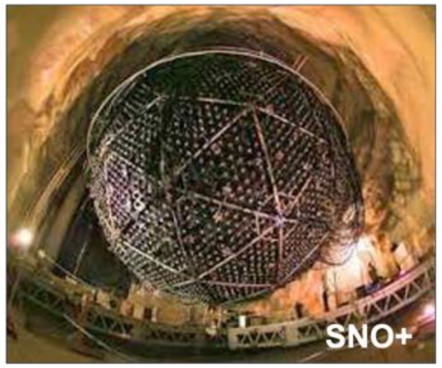
- Several international “ton-scale” experiments with different isotopes and technologies under way, with sensitivity up to $T_{1/2} \sim 10^{28}$ yr





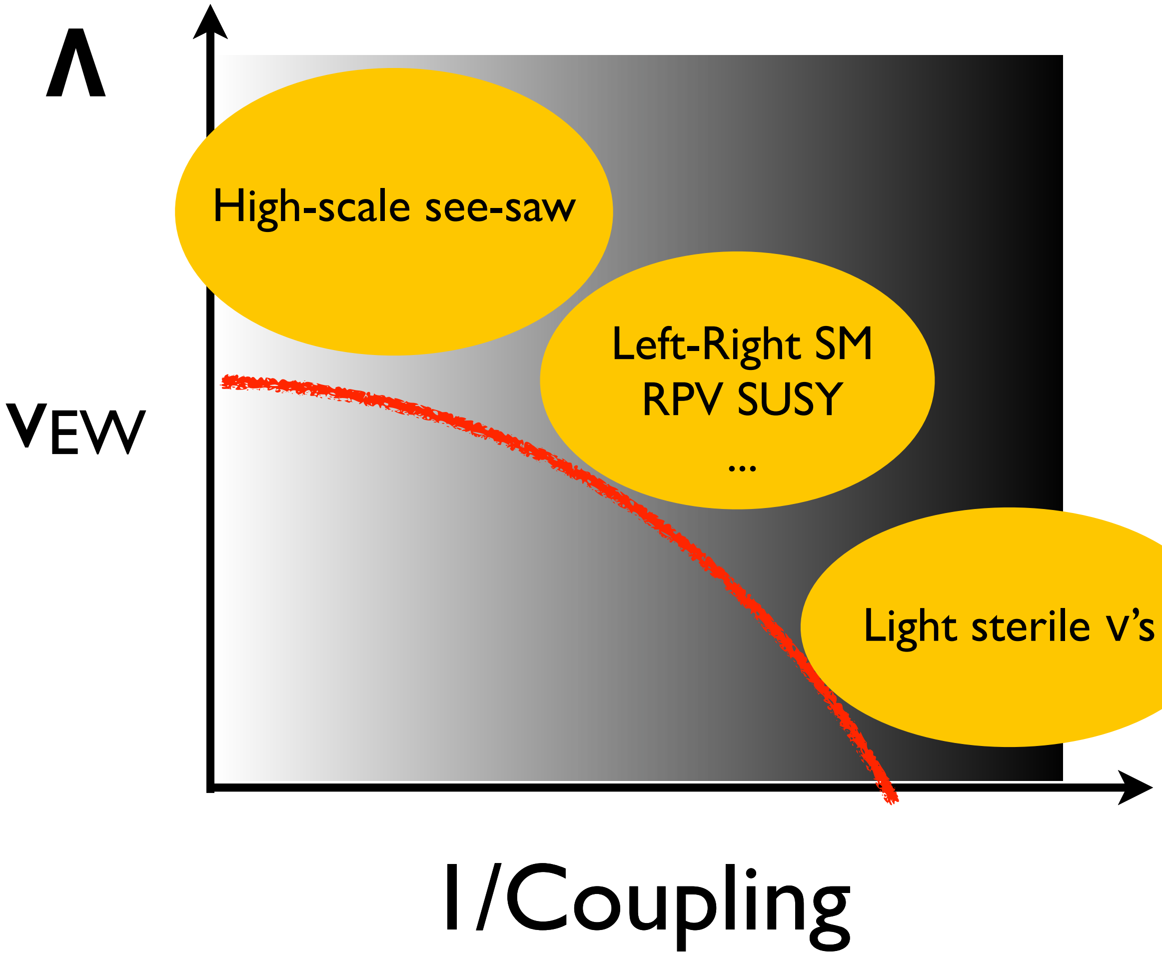


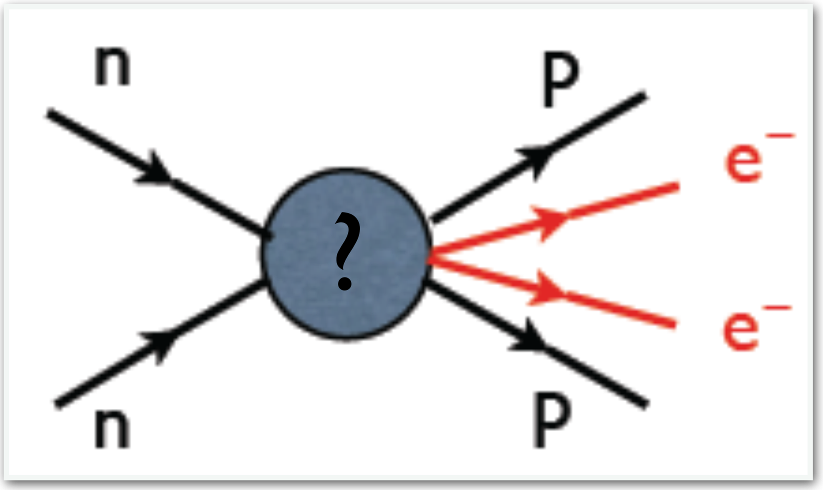




0νββ physics reach

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





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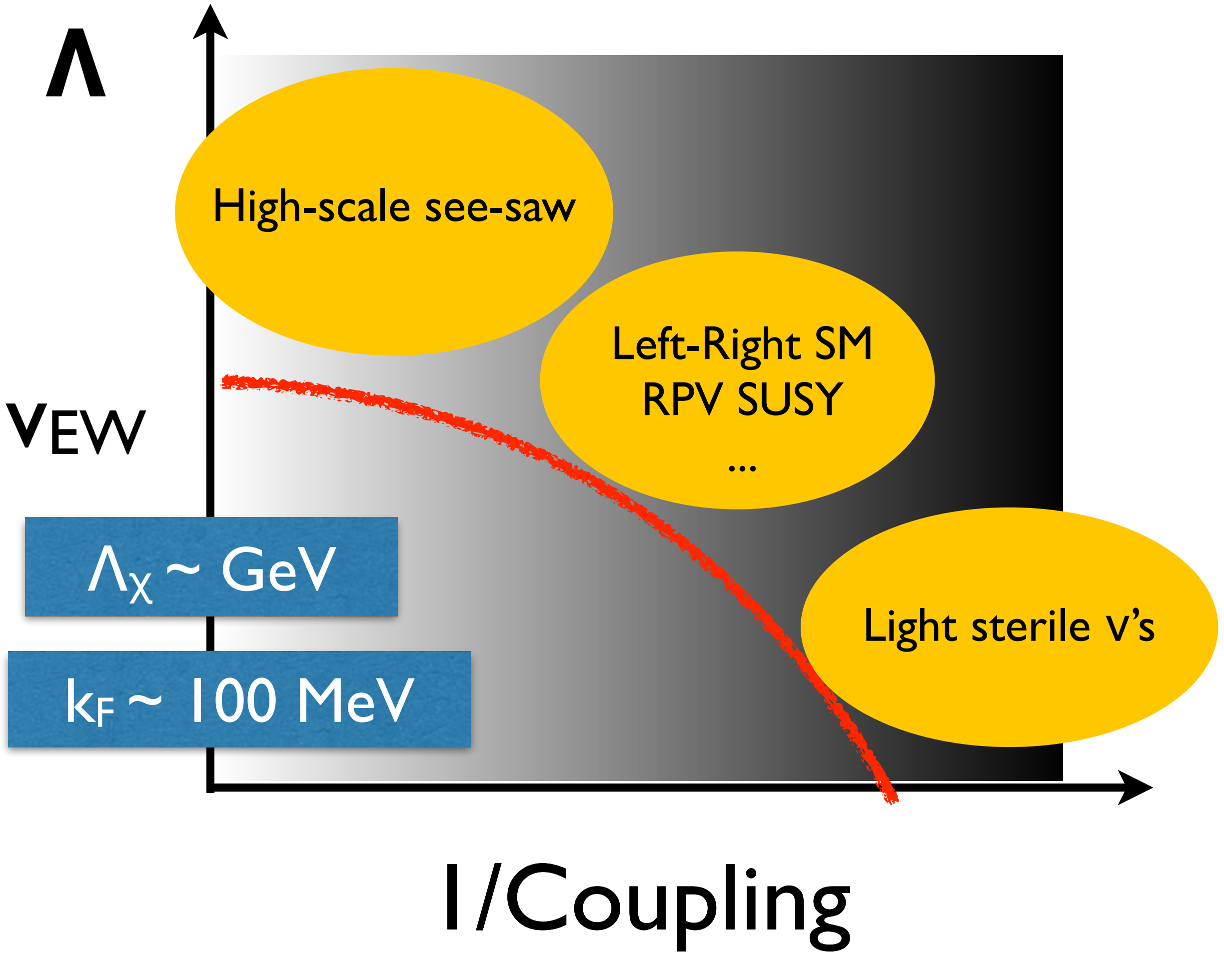


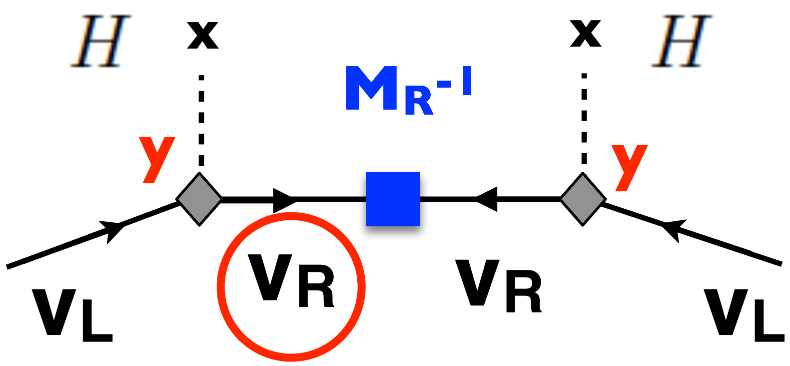
- Multi-scale problem best tackled through 'end-to-end' EFT: only chance to achieve controllable uncertainty
- Synergy of EFT, Lattice QCD, and first-principles nuclear structure

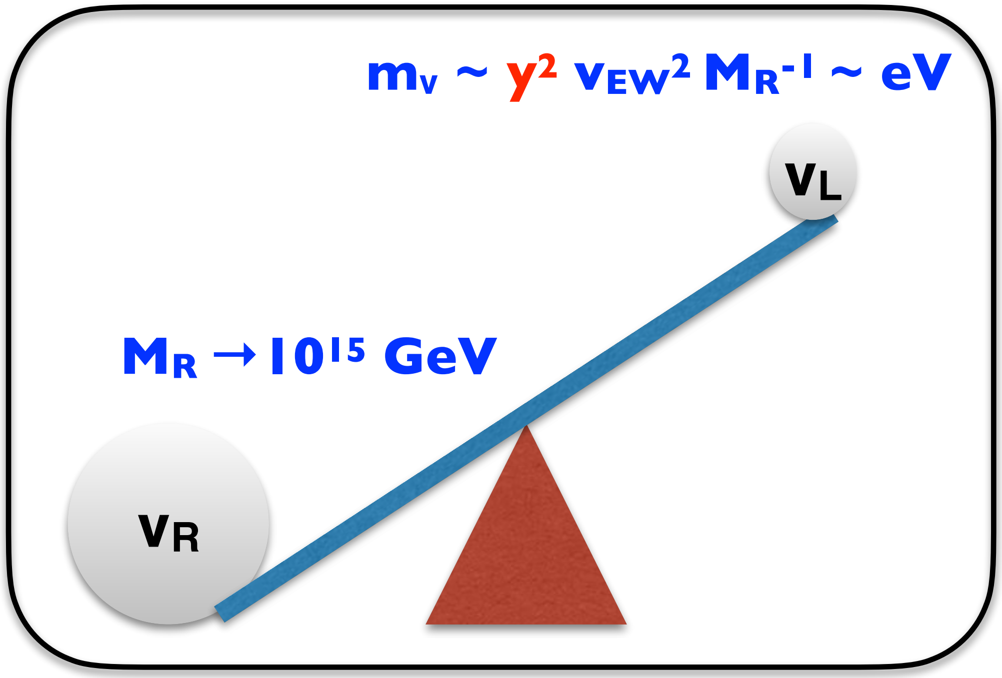
$$T_{1/2} \propto \overset{\text{SMEFT}}{(m_W/\Lambda)^A}\ \overset{\text{LEFT}}{(\Lambda_\chi/m_W)^B}\ \overset{\text{Chiral EFT}}{(k_F/\Lambda_\chi)^C}$$

Snowmass white paper 2203. 21169 and refs therein

High-scale seesaw

- Majorana mass generated by exchange of heavy particles, such as heavy neutrinos that are neutral under all SM charges (=sterile)





Naturally small ν mass

High-scale seesaw

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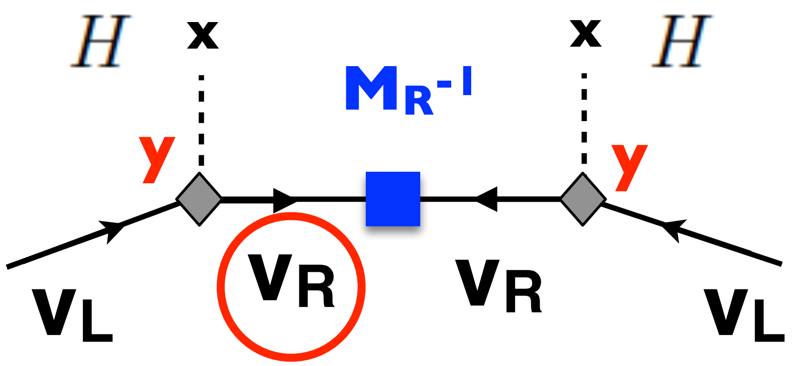
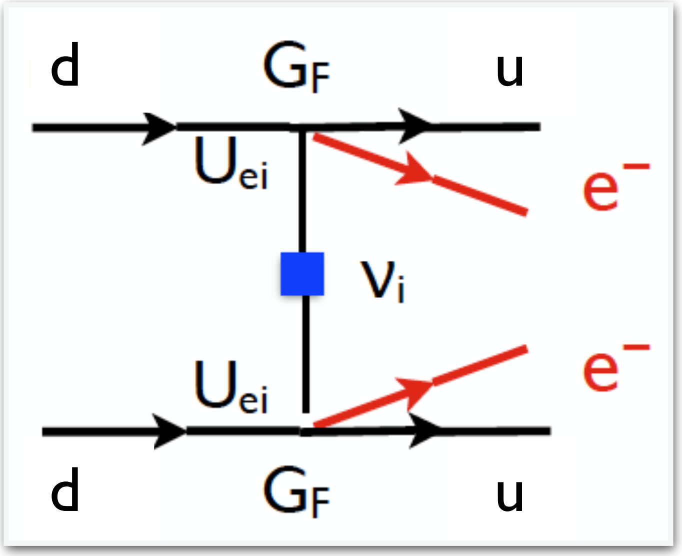


$M_R >> v_{EW}$

$m_\nu \sim y^2 v_{EW}^2 M_R^{-1}$



0νββ mediated by light neutrinos

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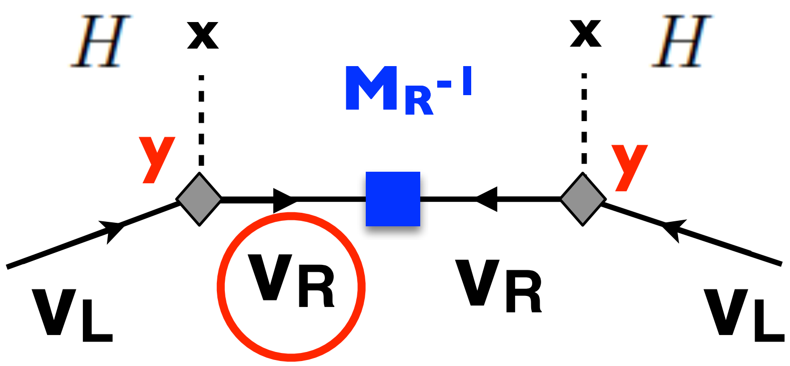

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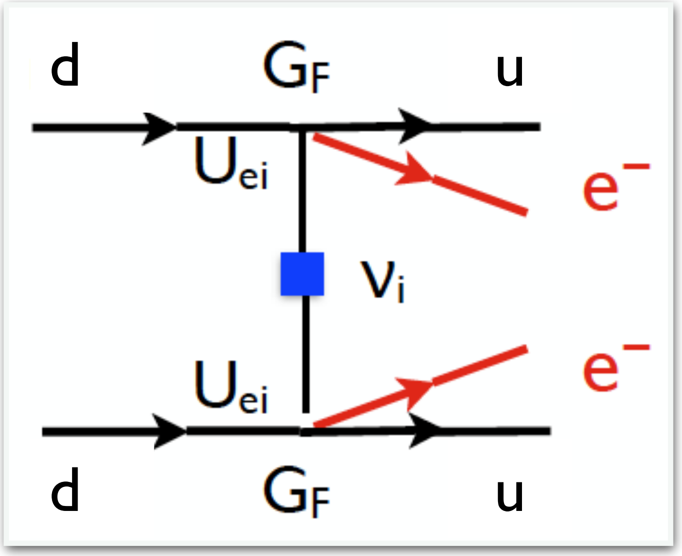


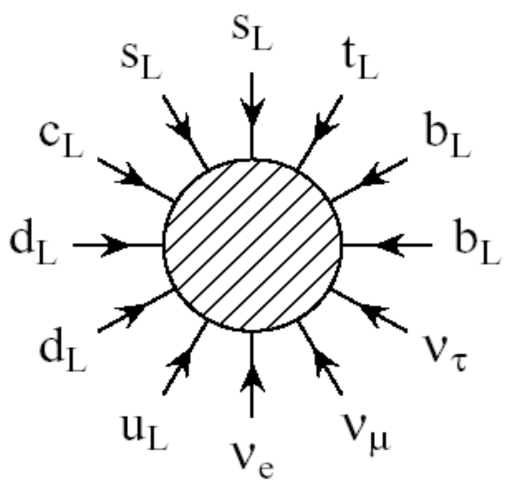
0νββ mediated by light neutrinos

Baryogengesis via Leptogenesis

1) CP- and L- violating
out-of-equilibrium
decays of heavy ν_{Ri} ⇒ n_L

$$\boxed{\Gamma(\nu_R \to H^*\ell) \neq \Gamma(\nu_R \to H\bar{\ell})}$$

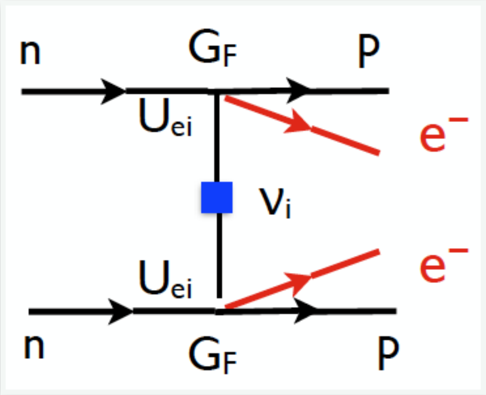
2) EW sphalerons ⇒ $n_B = \# \, n_L$



Discovery potential / target

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

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



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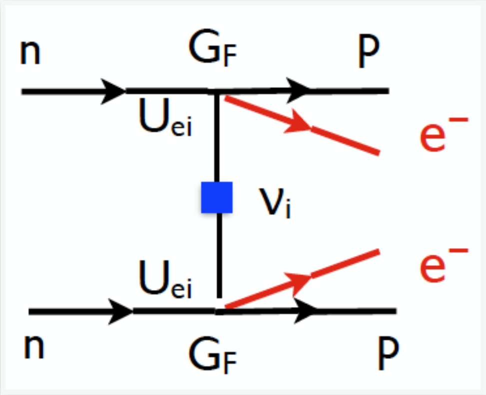

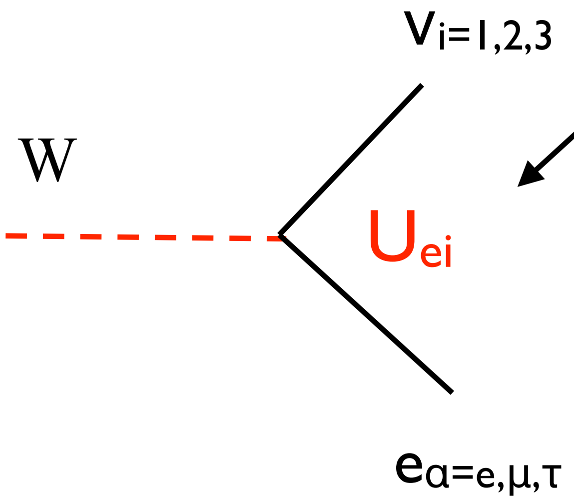

$$\frac{g}{\sqrt{2}} W_\mu^- \bar{e}_L^\alpha \gamma^\mu U^{\alpha i} \nu_L^i$$

Unitary mixing in CC vertex
(Pontecorvo-Maki-Nakagawa-Sakata):
3 angles (known), 1+2 phases (unknown)

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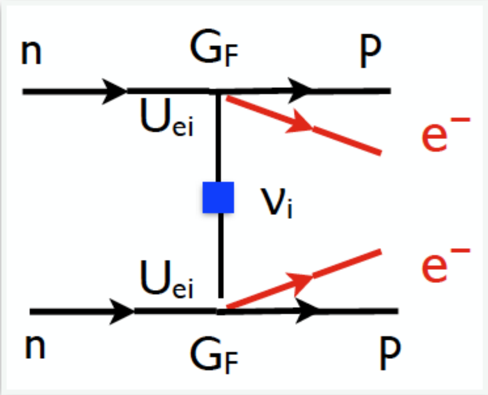

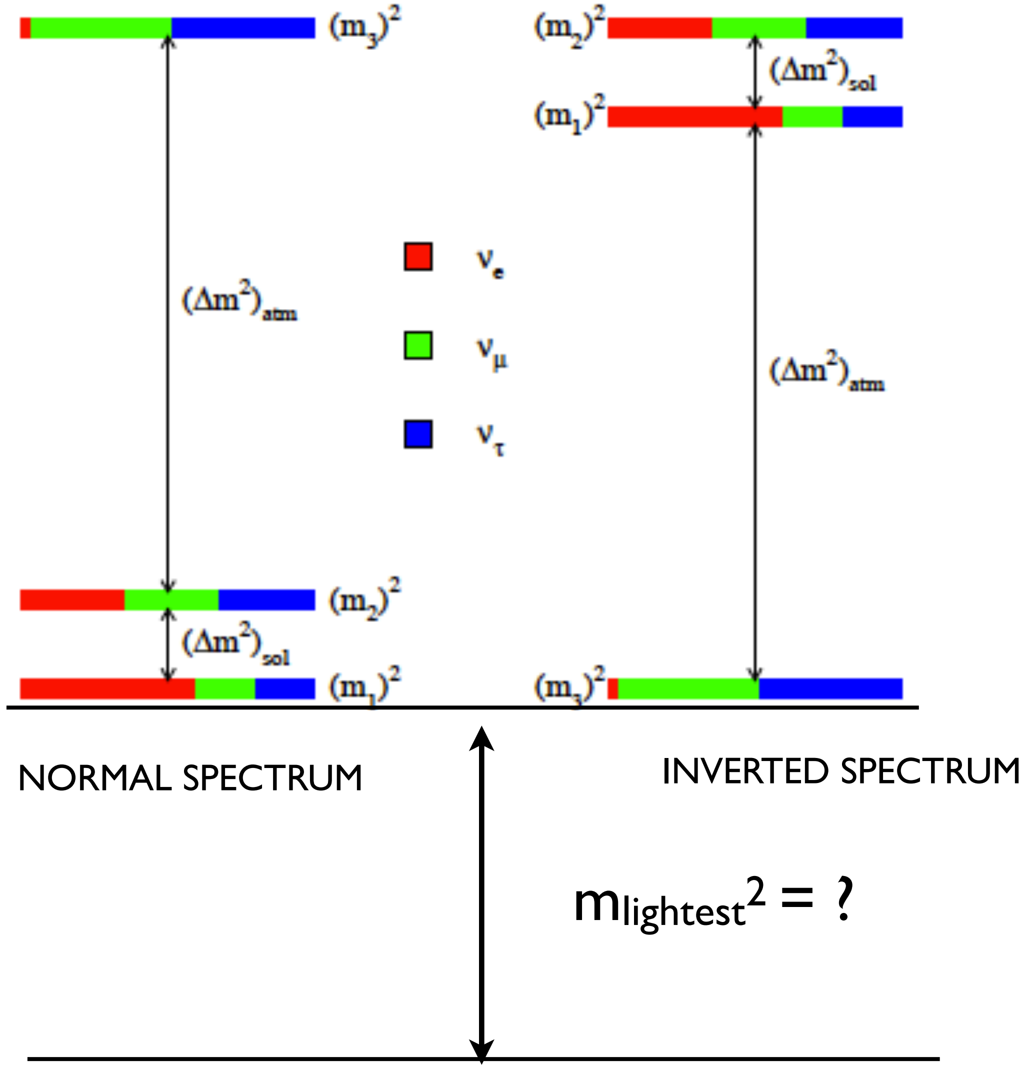

Mass ordering still not fixed by oscillation data

Discovery potential / target

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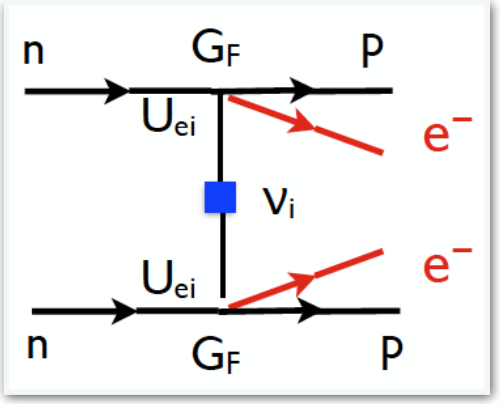
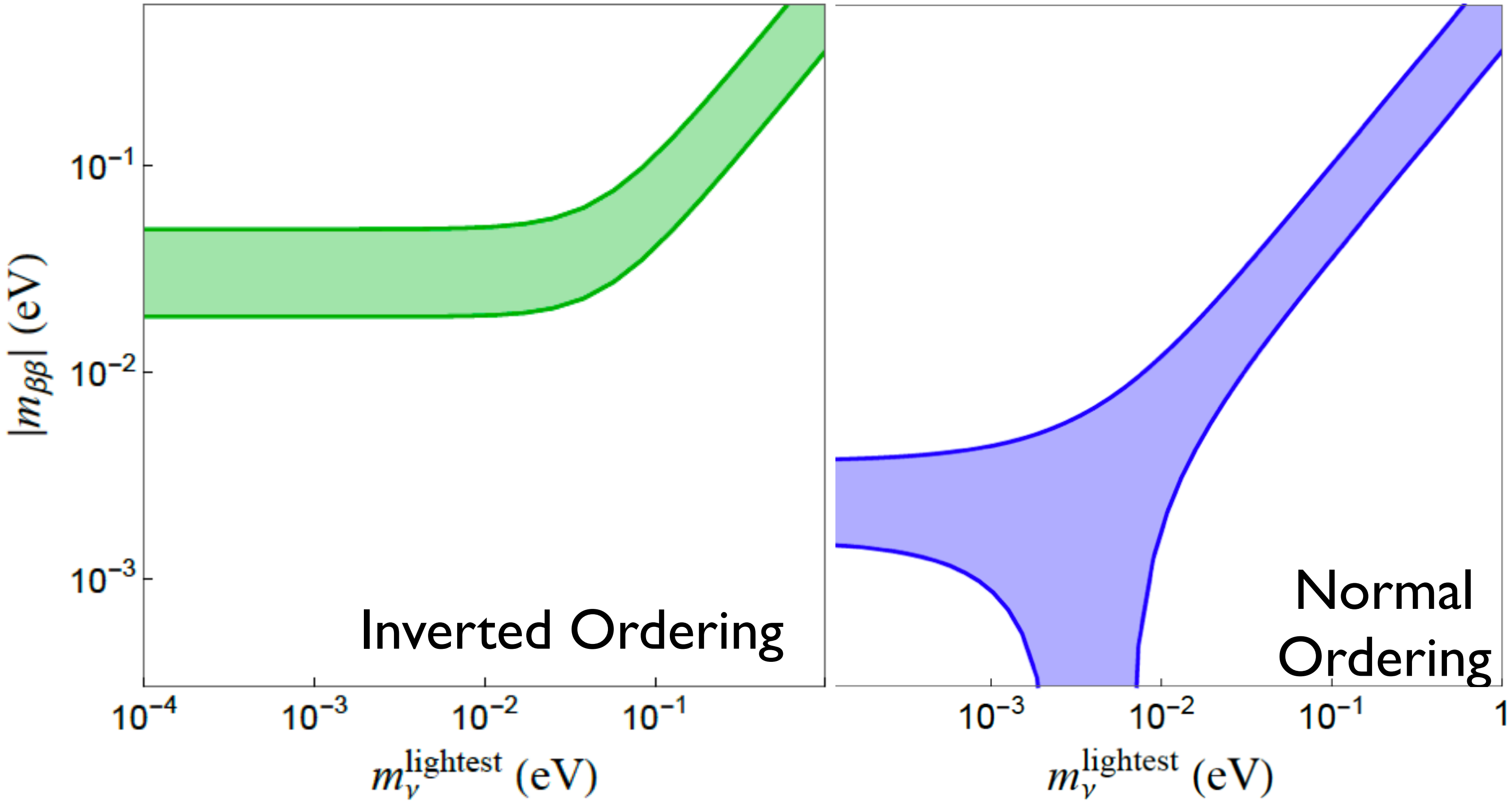


Bands: unknown Majorana phases



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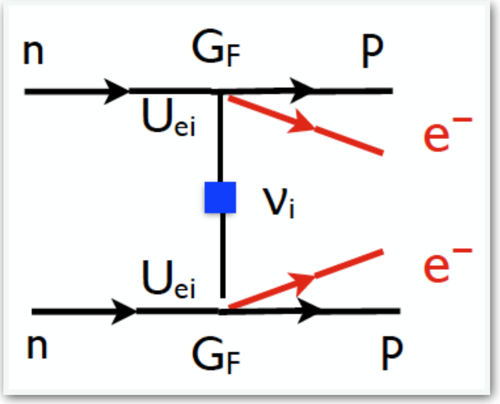

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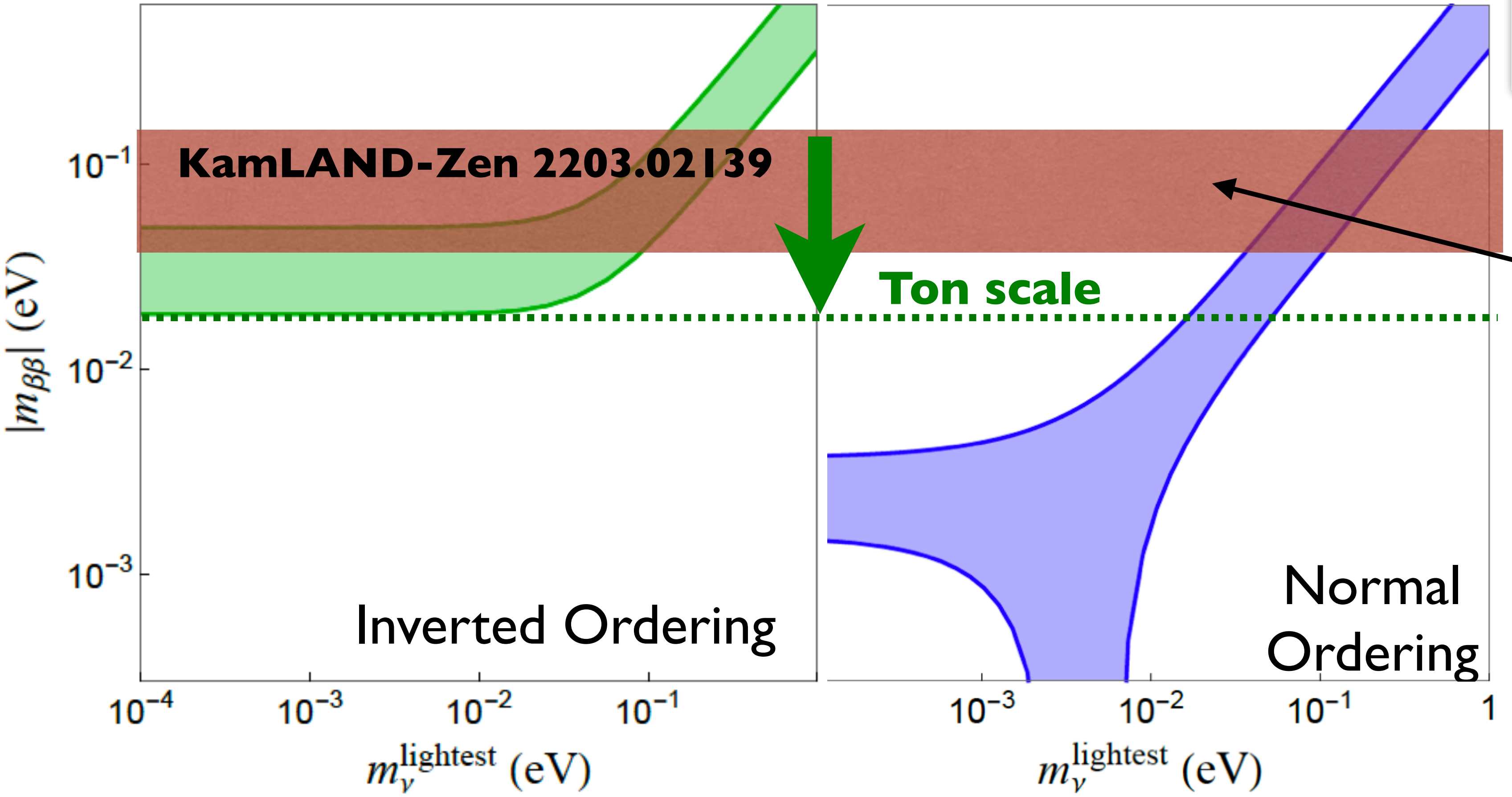

Assume range for nuclear matrix elements from different nuclear calculations

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

Discovery potential / target

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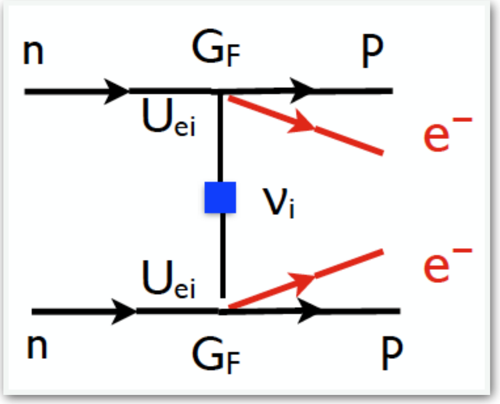

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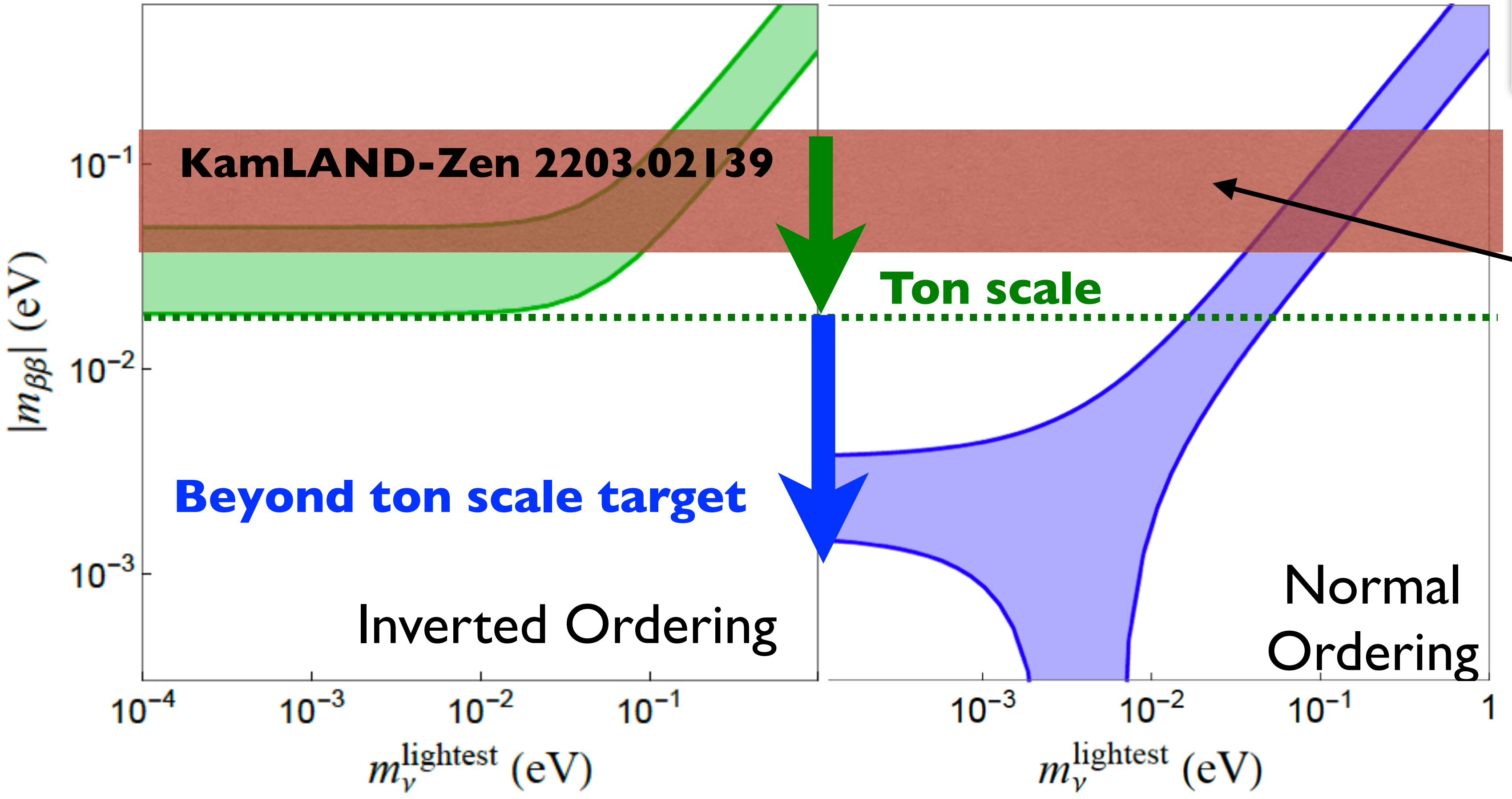


Assume range for nuclear matrix elements from different nuclear calculations

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

Diagnosing power

- High scale seesaw implies falsifiable correlations with other ν mass probes. Future data can unravel new LNV sources or physics beyond "ΛCDM + m_ν"

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

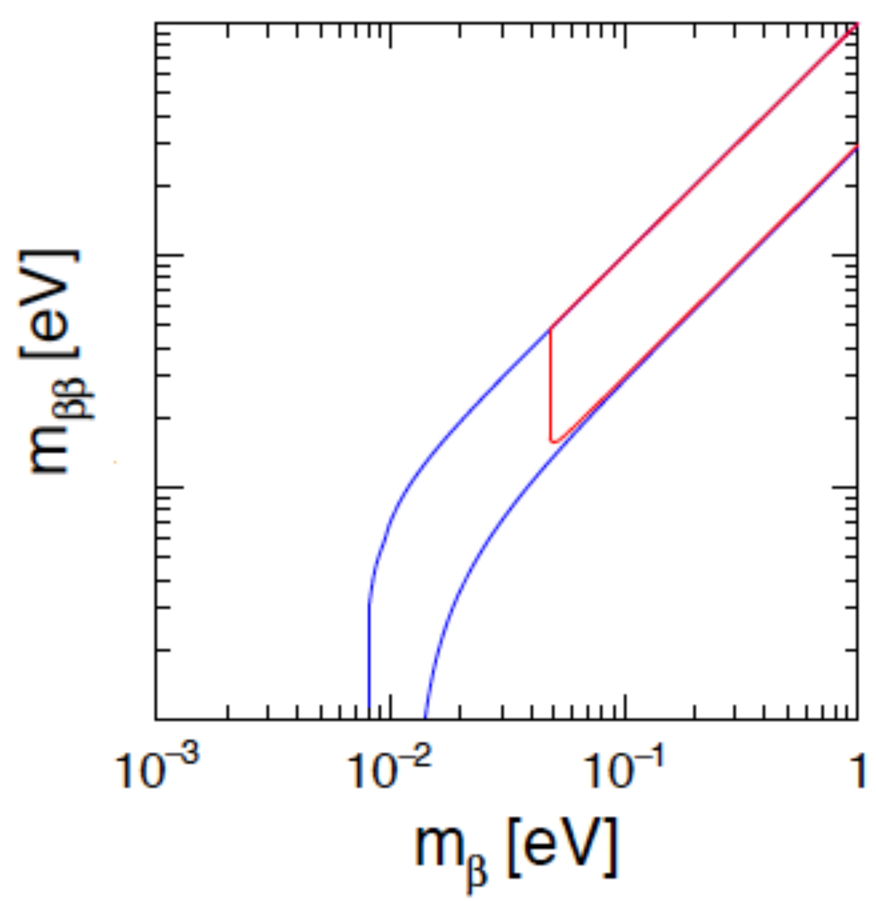
0νββ decay

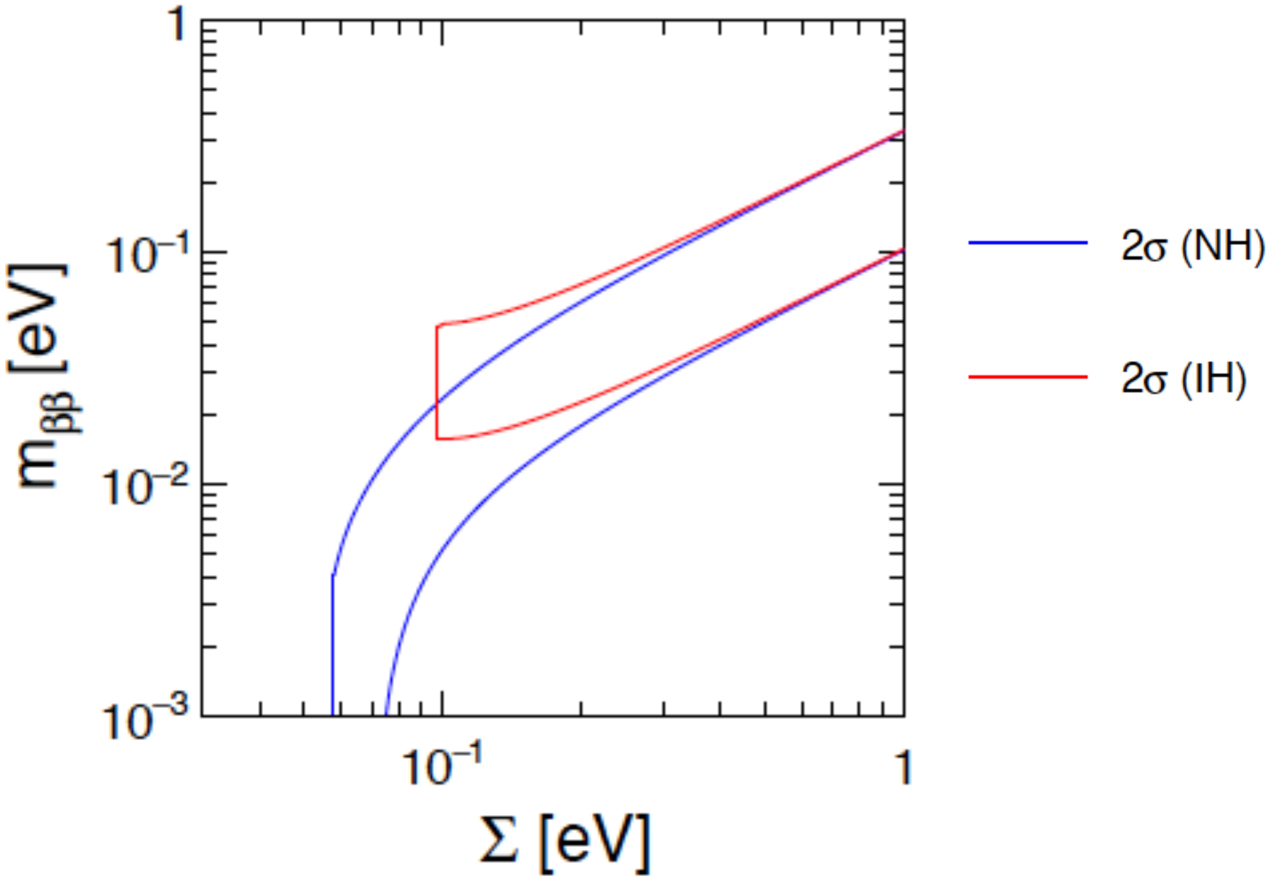
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





Diagnosing power

- High scale seesaw implies falsifiable correlations with other ν mass probes. Future data can unravel new LNV sources or physics beyond “ΛCDM + m_ν”

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

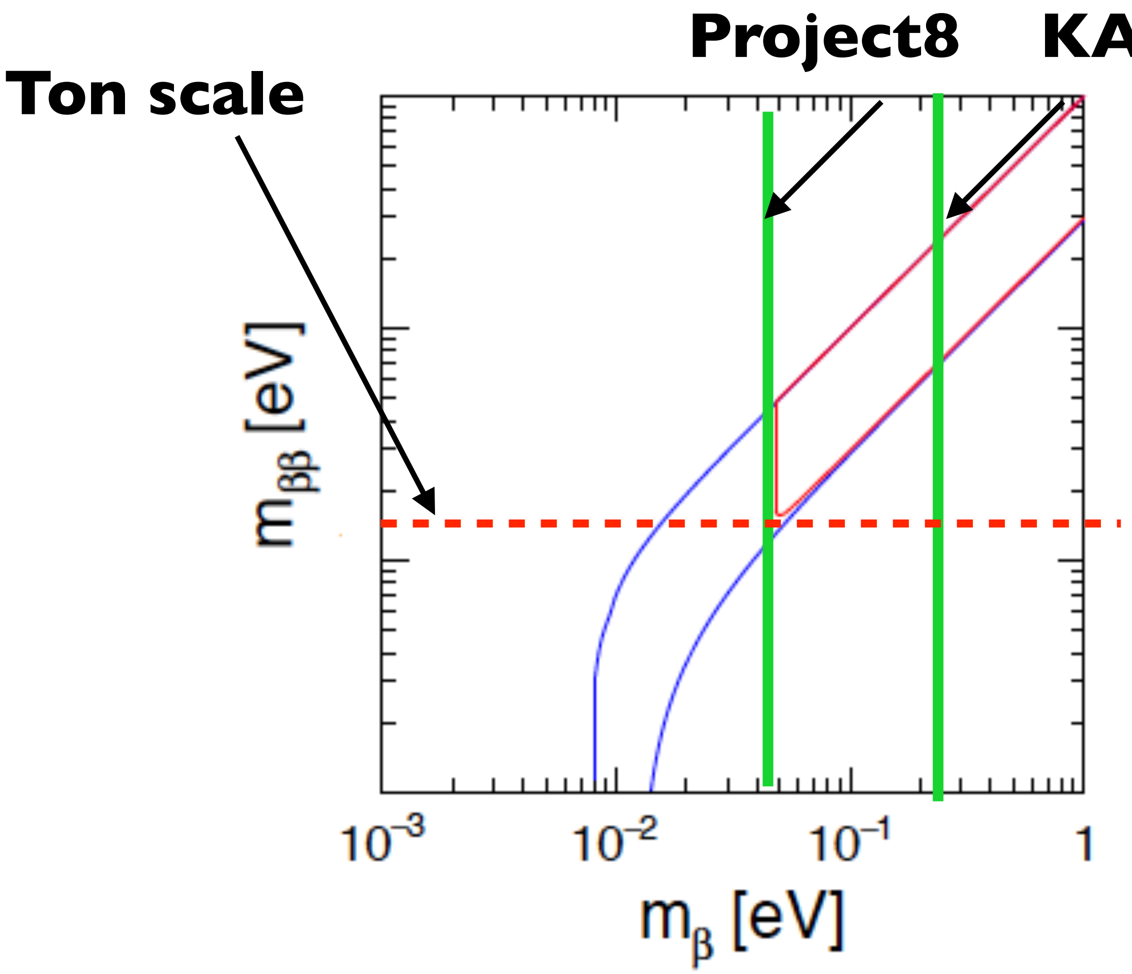
0νββ decay

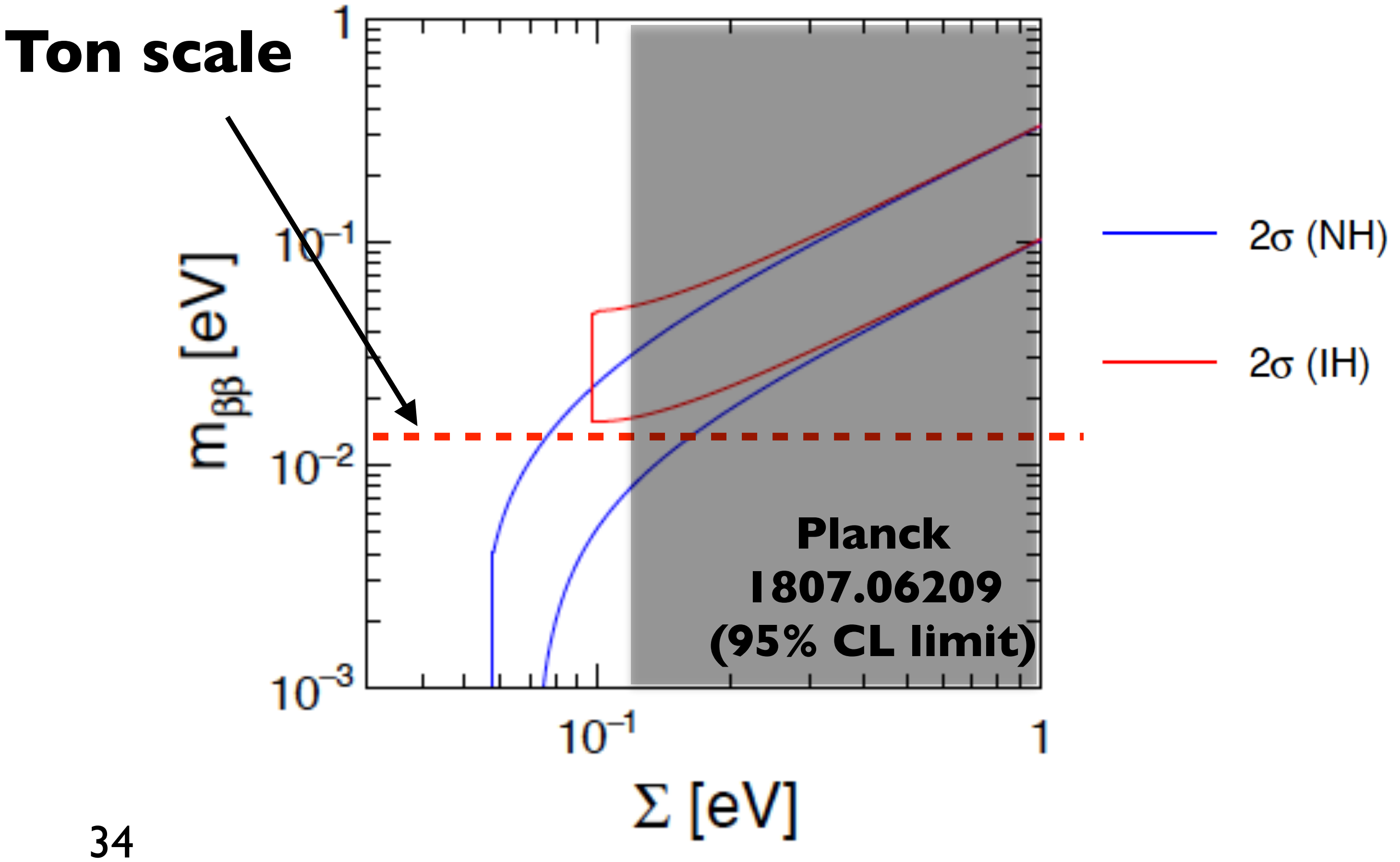
$$m_\beta = \sqrt{\sum_i |U_{ei}|^2 m_i^2}$$

Tritium β decay

$$\Sigma = \sum_i m_i$$

Cosmology





Diagnosing power

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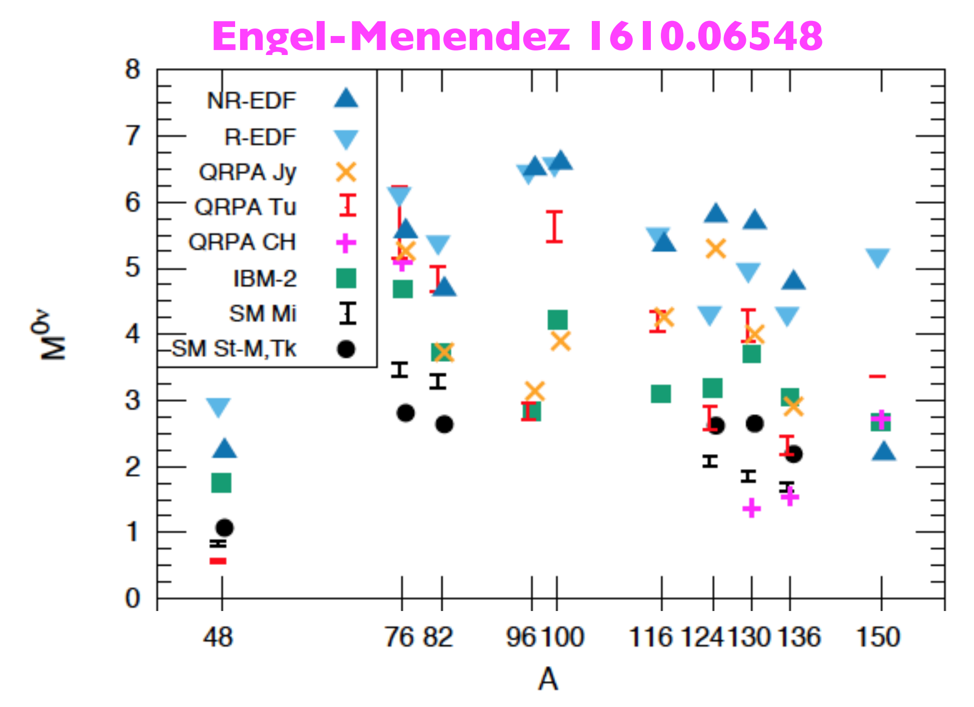

$\Gamma \propto |M_{0\nu}|^2 \, (m_{\beta\beta})^2$

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

0νββ decay

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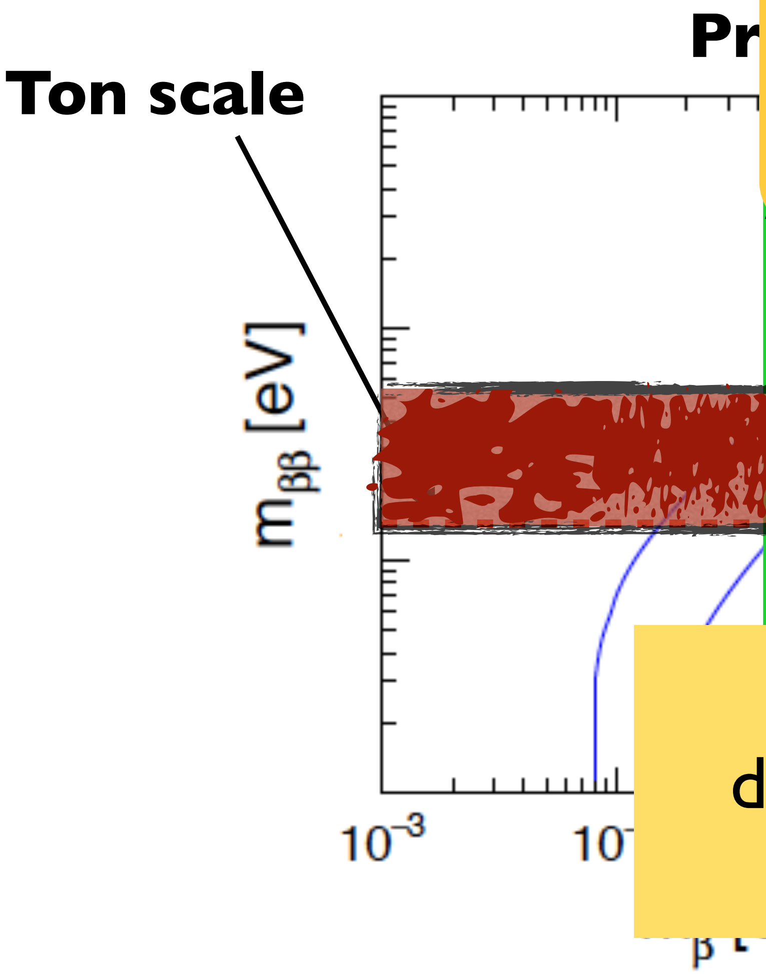
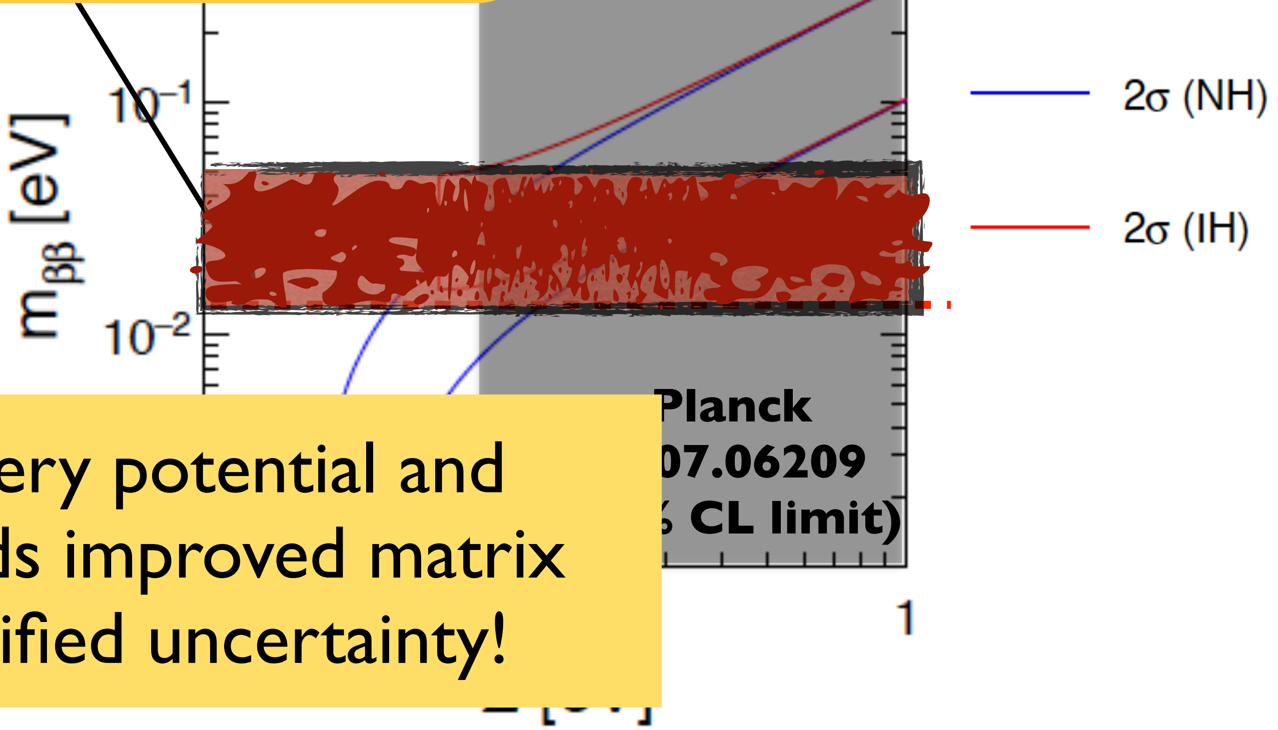
Cosmology





Assessing the discovery potential and diagnosing power needs improved matrix elements, with quantified uncertainty!

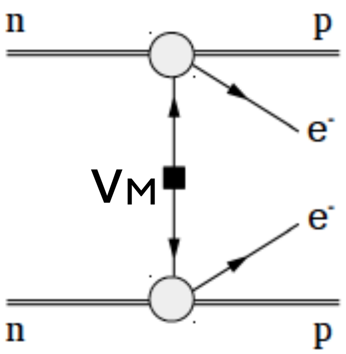
New insights from EFT

VC, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

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

- Transition operator to leading order in Q/Λ_χ ($Q \sim k_F \sim m_\pi$, $\Lambda_\chi \sim$ GeV)

'Usual' V_M exchange
$\sim 1/k_F^2 \sim 1/Q^2$
Coulomb-like potential



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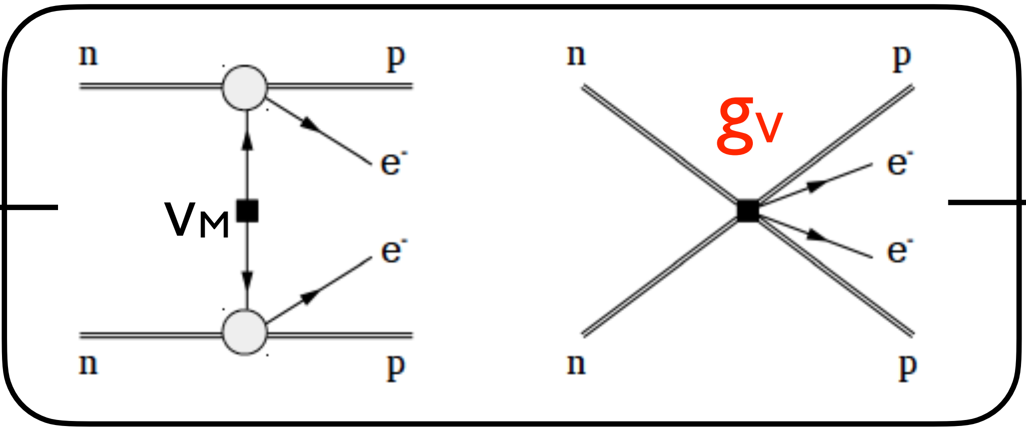
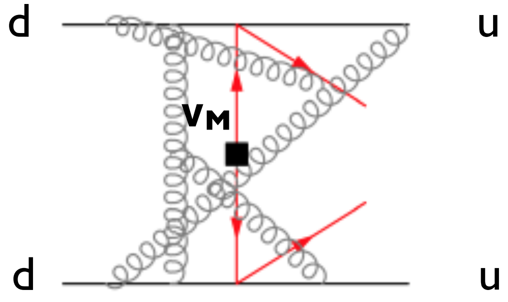


'New': short-range
coupling $g_\nu \sim 1/Q^2$



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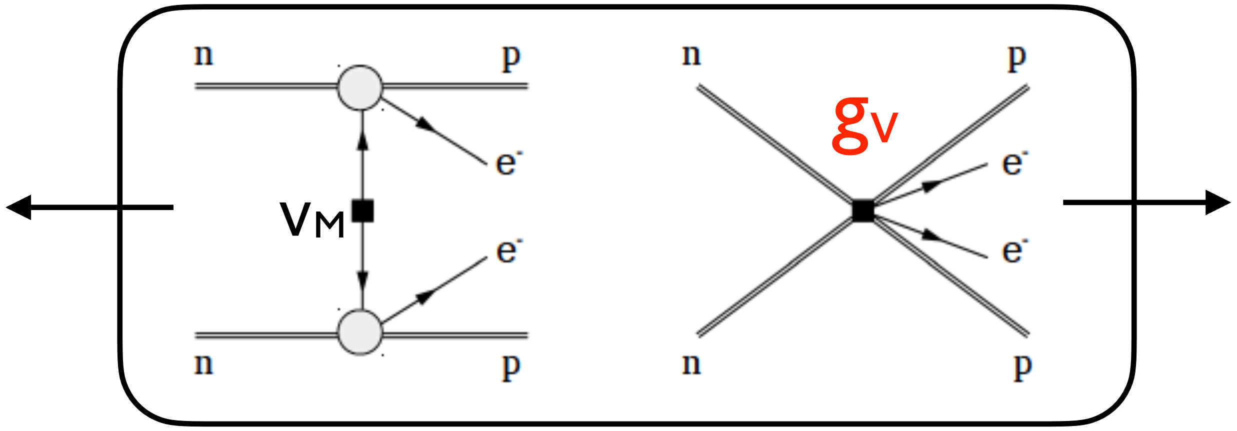

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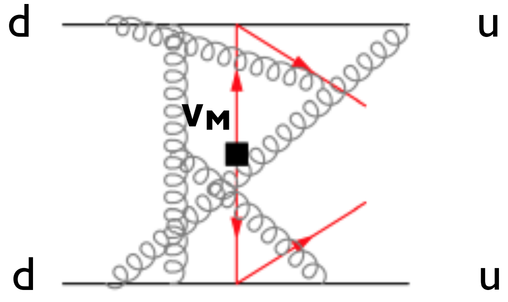
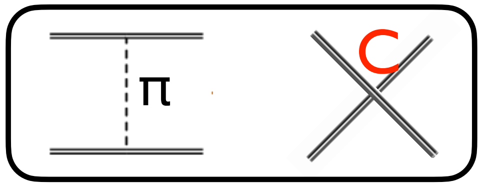


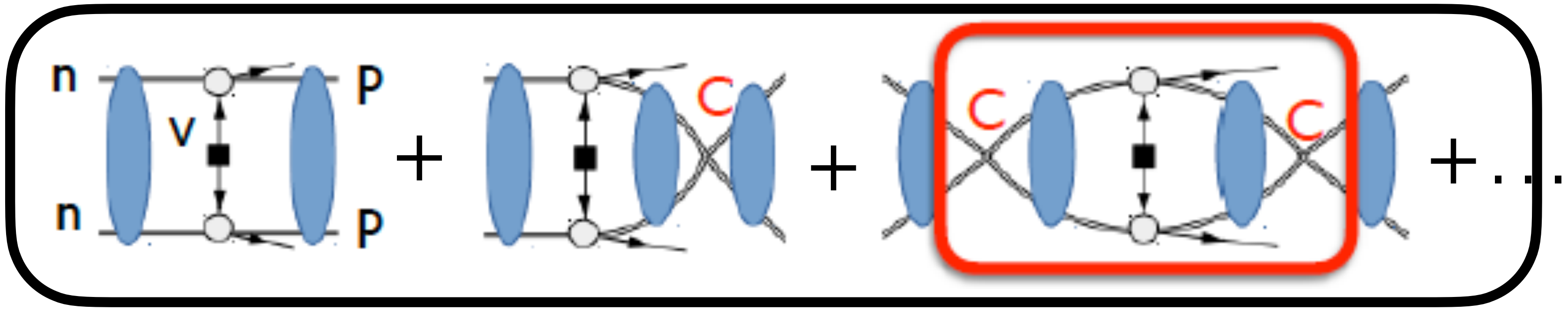
- Required by renormalization of nn → pp amplitude in presence of strong interactions

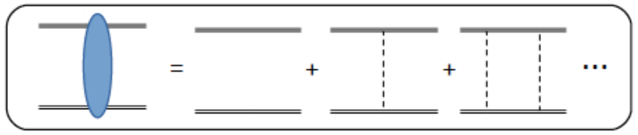
UV divergence $\propto$ $(m_N C/4\pi)^2 \sim 1/Q^2$

LO strong potential



$C \sim 4\pi/(m_N Q)$

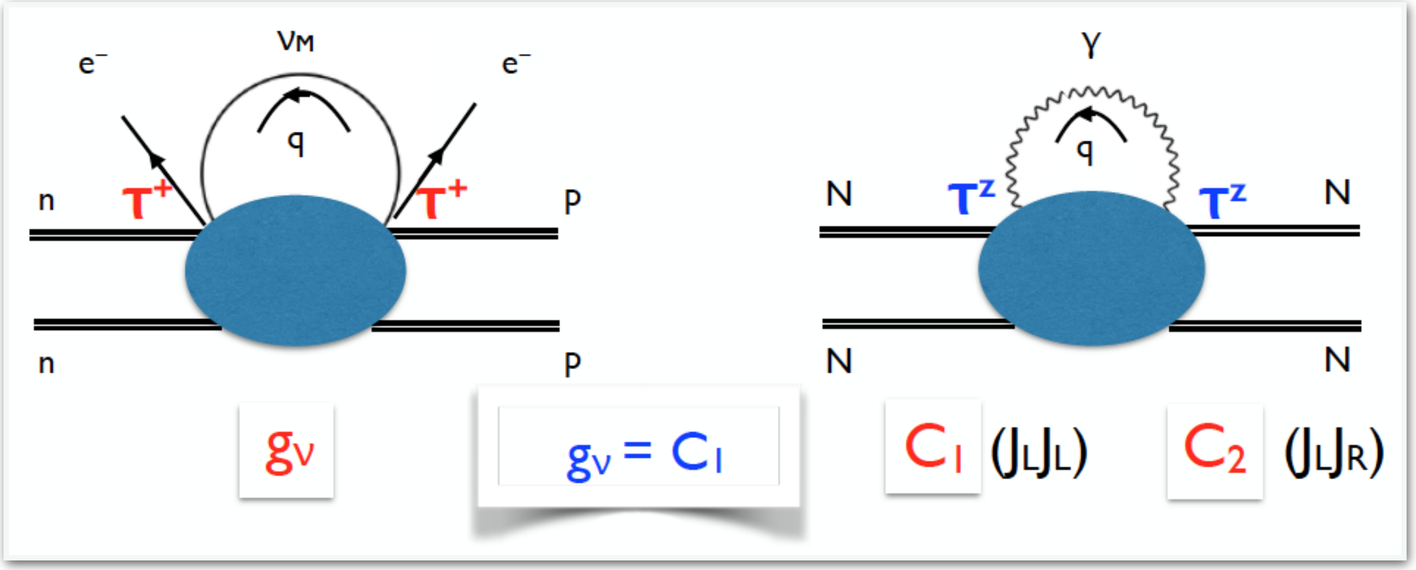




Impact on nuclear matrix elements

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

- Chiral+isospin symmetry relate g_ν to one of two I=2 e.m. couplings (hard γ's & ν's)
- NN data ($a_{nn}+a_{pp}-2a_{np}$) determine C_1+C_2, confirming LO scaling



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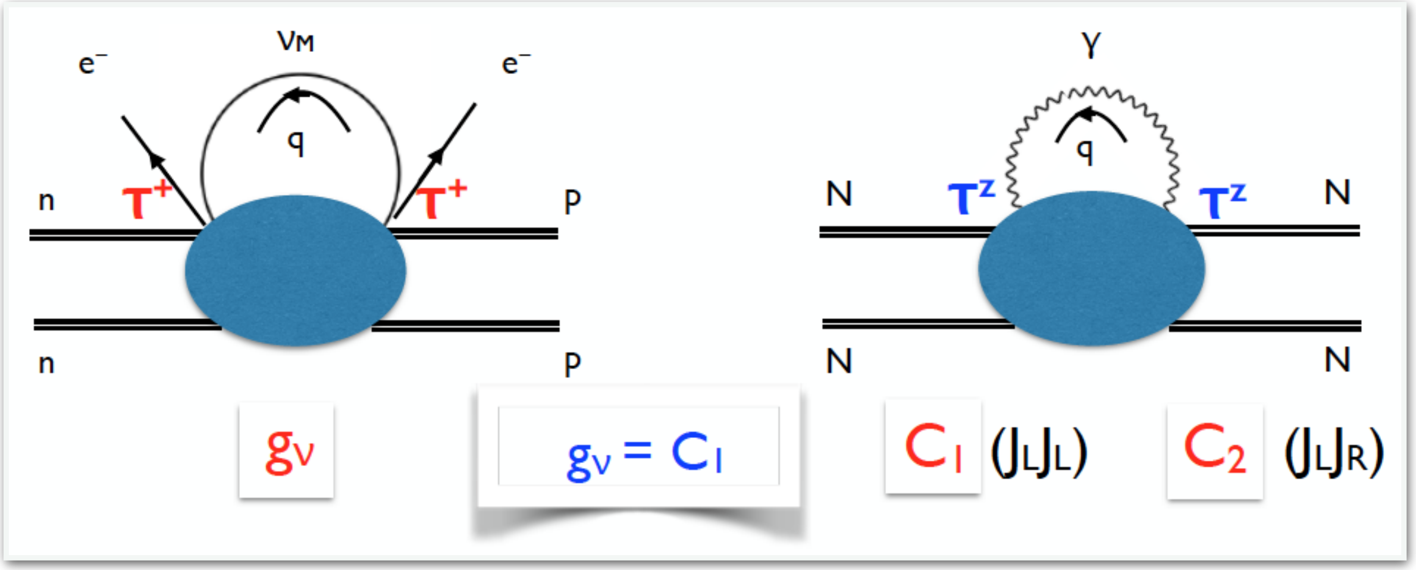
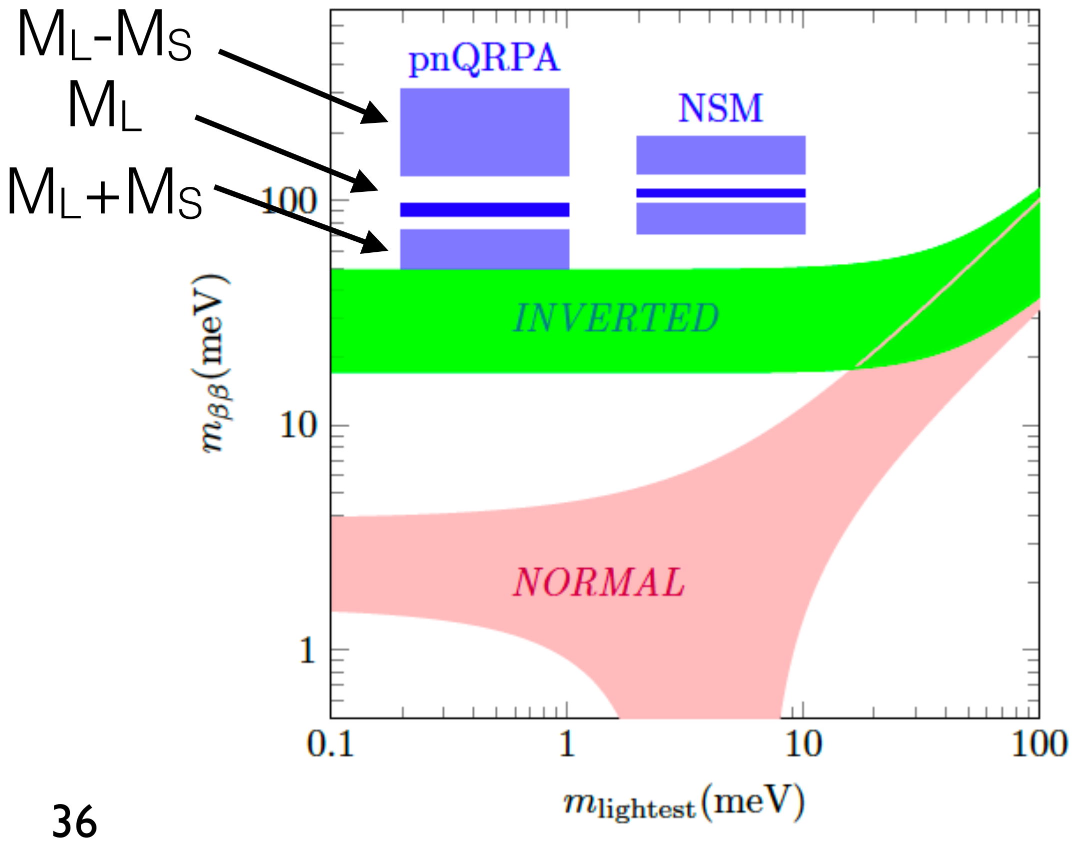


- *Assuming* $g_V \sim (C_1+C_2)/2$ → O(1) impact on m.e. and $m_{\beta\beta}$ extraction

Jokiniemi-Soriano-Menendez, 2107.13354



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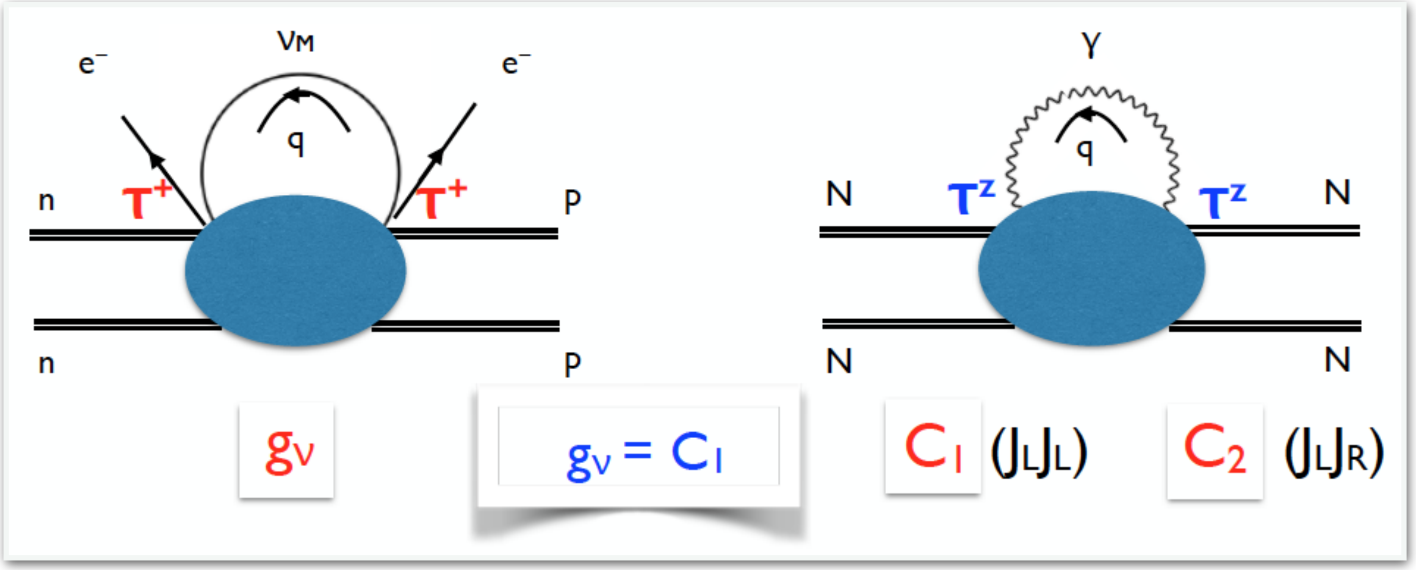

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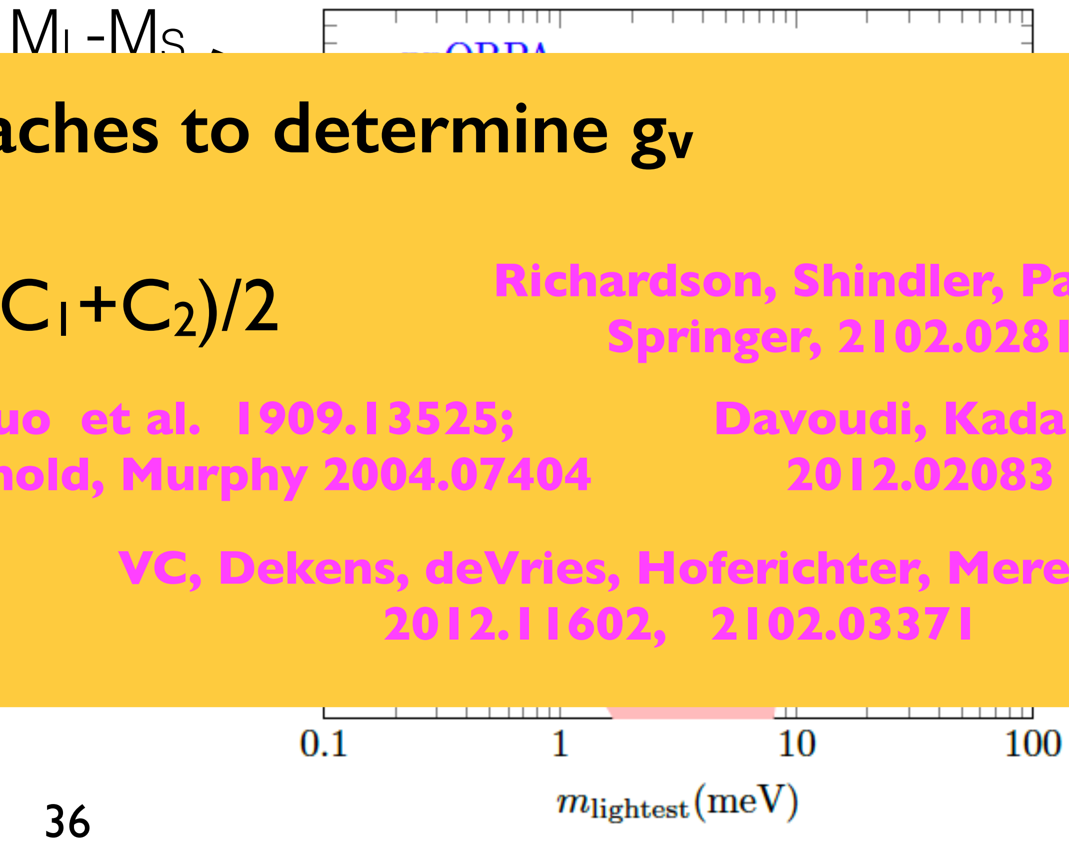


Several approaches to determine g_ν

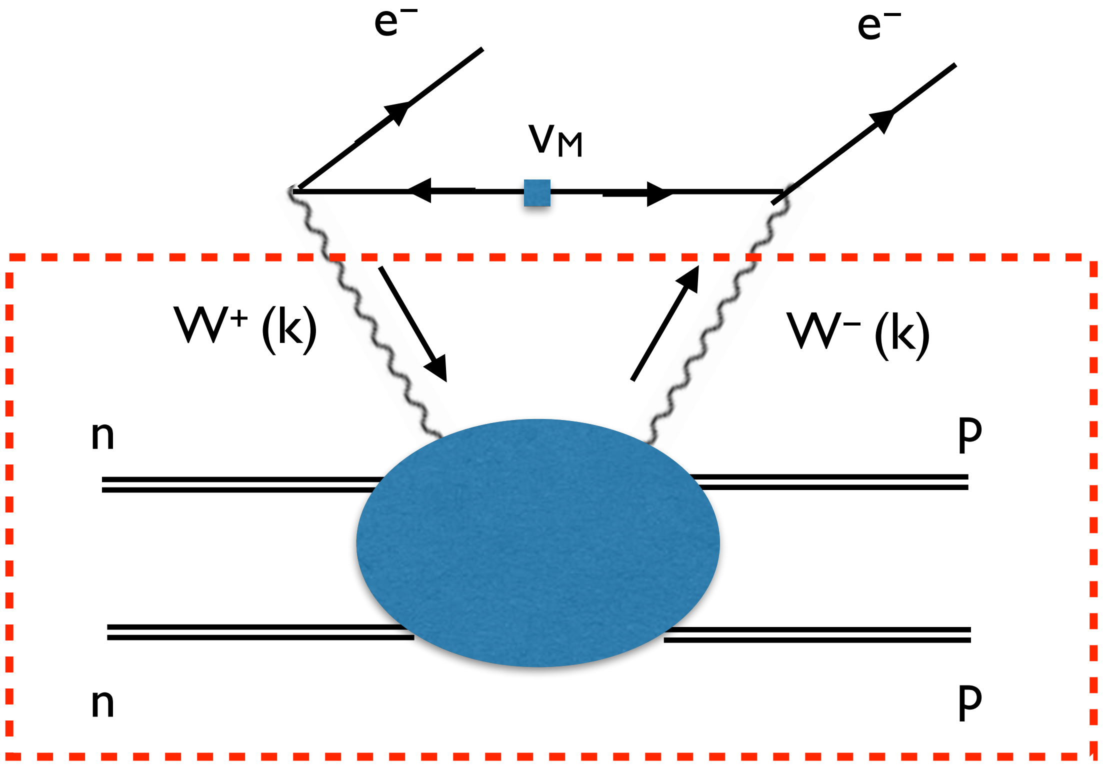
- Large-N_C arguments point to $g_\nu \sim (C_1+C_2)/2$ **Richardson, Shindler, Pastore, Springer, 2102.02814**
- Lattice QCD — gearing up **Tuo et al. 1909.13525; Detmold, Murphy 2004.07404** **Davoudi, Kadam, 2012.02083**
- Dispersive approach **VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371**

Estimating the contact term (1)

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Useful representation of the amplitude

$$\mathcal{A}_\nu \propto \int \frac{d^4k}{(2\pi)^4} \frac{g_{\alpha\beta}}{k^2 + i\epsilon} \boxed{\int d^4x \, e^{ik\cdot x} \langle pp | T\{ j_{\rm w}^{\alpha}(x) j_{\rm w}^{\beta}(0)\} | nn \rangle}$$



Forward "Compton" amplitude

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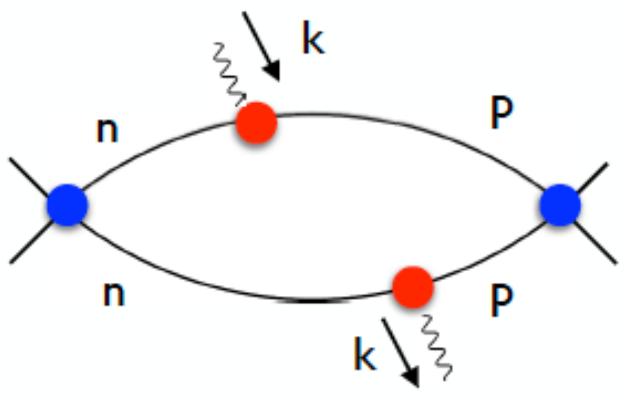
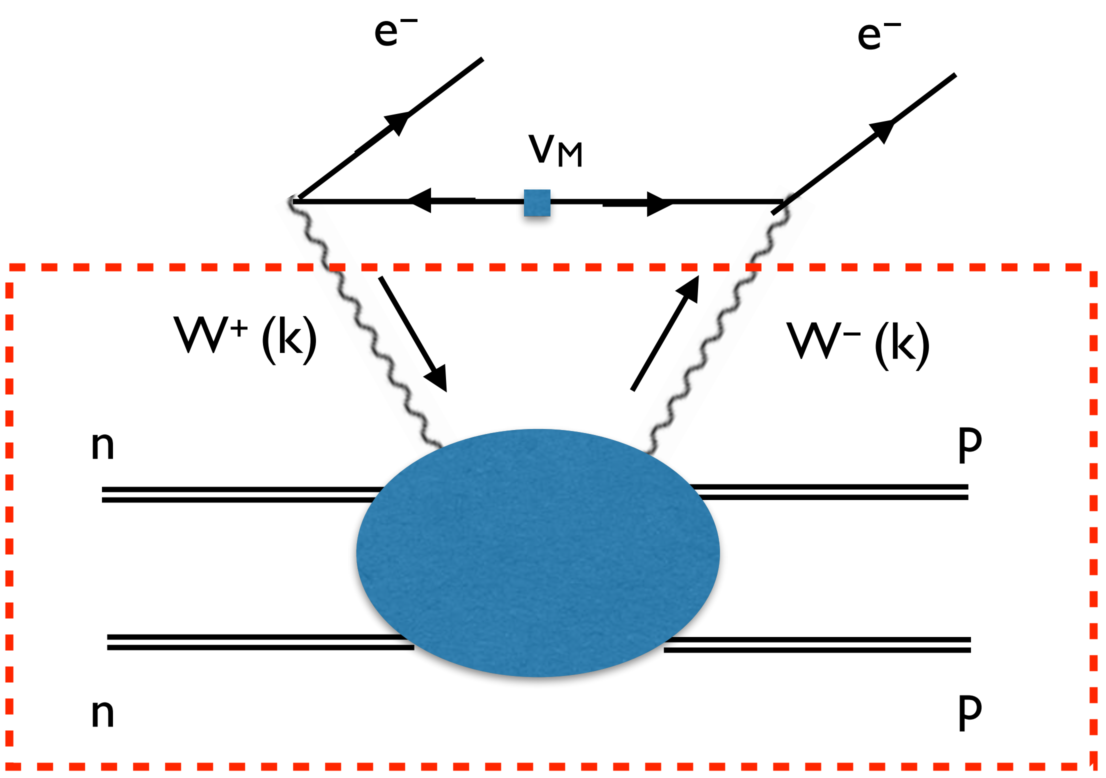
Low k: chiral EFT to NLO

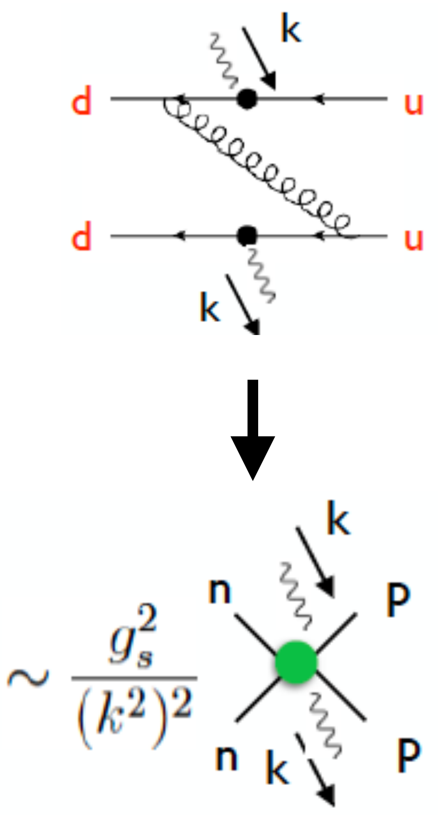


Intermediate k: resonance contributions in 🔵 and 🔴, πNN intermediate state, …



Forward "Compton" amplitude

High k: QCD OPE



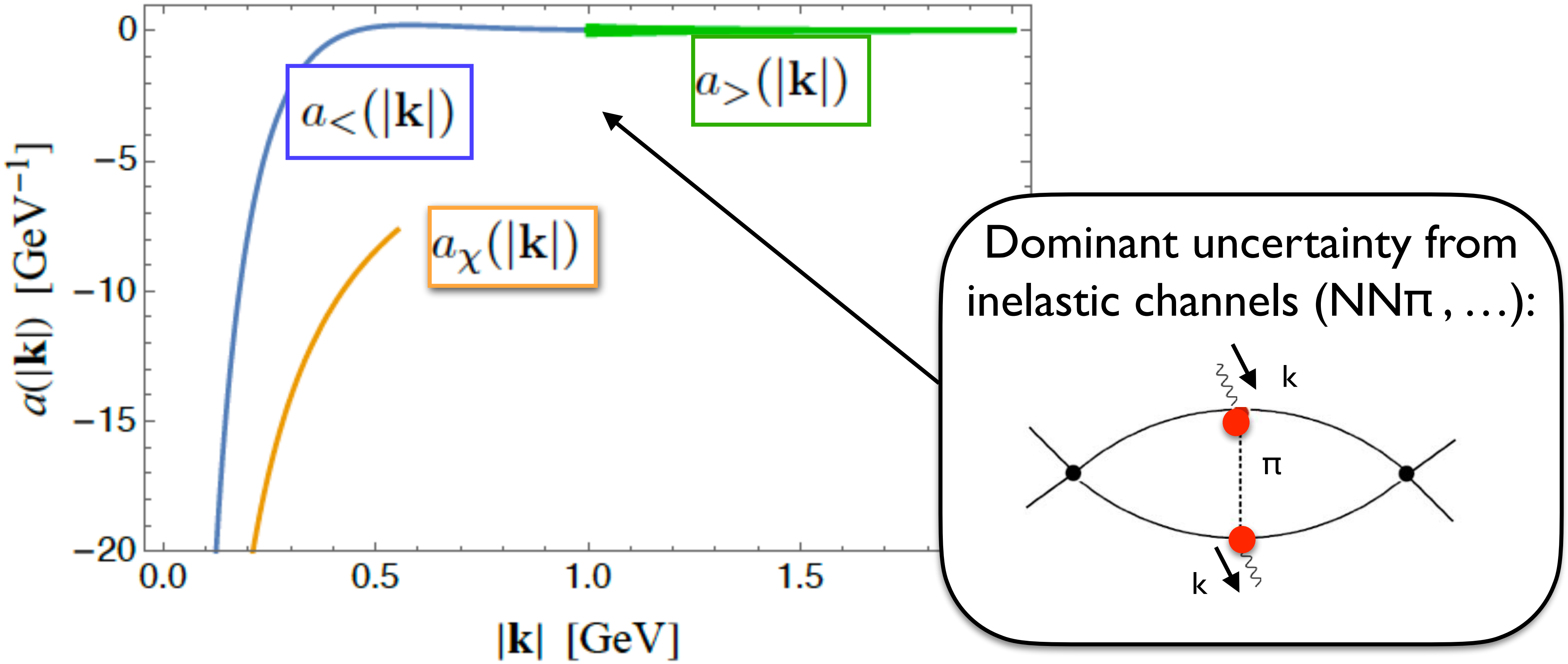
$$\sim \frac{g_s^2}{(k^2)^2}$$

Estimating the contact term (2)

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Determine $C_{1,2}$ with ~ 30% uncertainty (dominated by intermediate k)

$$\mathcal{A}_\nu \propto \int_0^\Lambda d|\mathbf{k}|\; a_<(|\mathbf{k}|) + \int_\Lambda^\infty d|\mathbf{k}|\; a_>(|\mathbf{k}|)$$



Dominant uncertainty from inelastic channels (NNπ , …):

Estimating the contact term (2)

VC, Dekens, deVries, Hoferichter, Mereghetti, 2012.11602, 2102.03371

- Determine $C_{1,2}$ with ~ 30% uncertainty (dominated by intermediate k)
- Validation: $C_1+C_2 \Rightarrow (a_{nn}+a_{pp})/2 - a_{np}$ = 15.5(4.5) fm versus 10.4(2) fm (exp)
- Provided 'synthetic data' for the nn→pp amplitude at threshold
- First calculation of ^{48}Ca →^{48}Ti with contact fitted to synthetic data ⇒ contact term enhances nuclear matrix element by (43±7)%

Wirth, Yao, Hergert, 2105.05415

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Good news, while we wait for lattice results and first-principles calculations in heavier nuclei

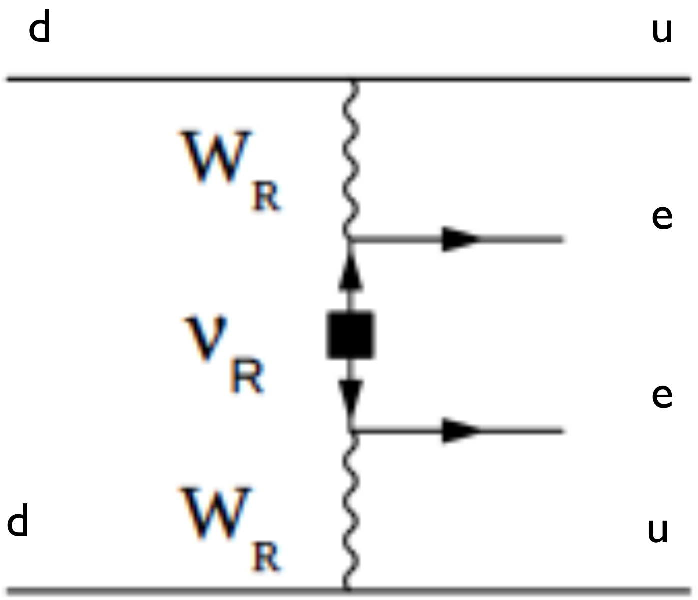
LNV from multi-TeV scale physics

- Observable contributions to $0\nu\beta\beta$ *not directly related to the exchange of light neutrinos:*

$$m_{\beta\beta} G_F^2/Q^2 \sim 1/\Lambda^5$$

(if $m_{\beta\beta} \sim 0.1$ eV and $\Lambda \sim$ TeV)

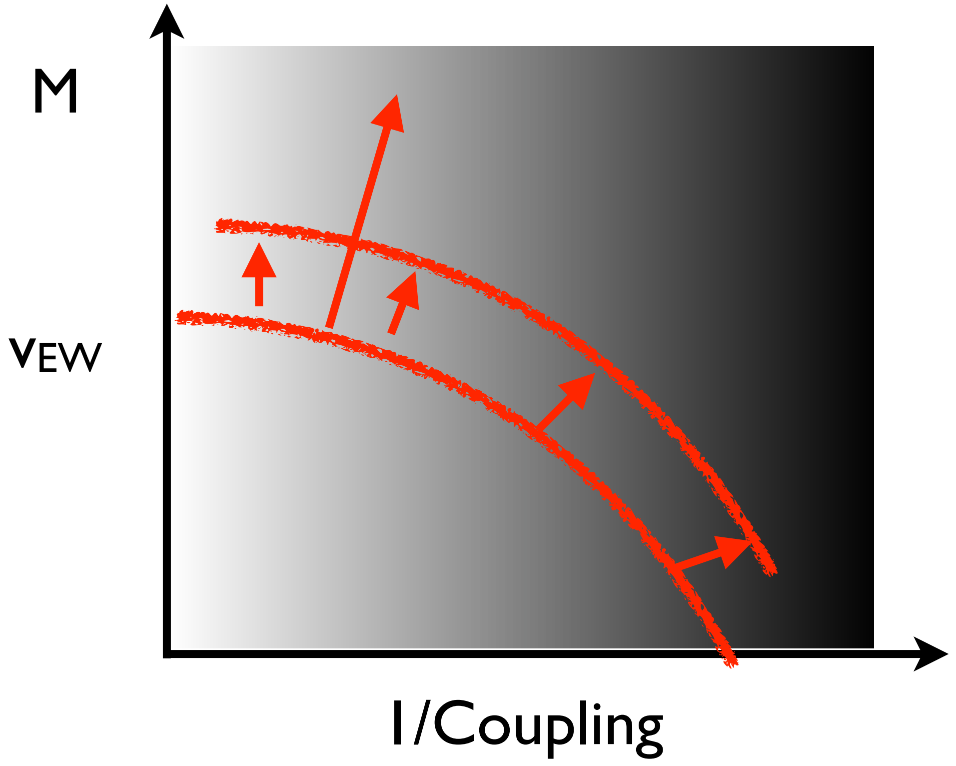
($\Lambda \sim M_{\nu R} \sim M_{WR}$)



- New contributions *can interfere with $m_{\beta\beta}$* or add incoherently, thus changing the interpretation of experimental results in terms of m_ν

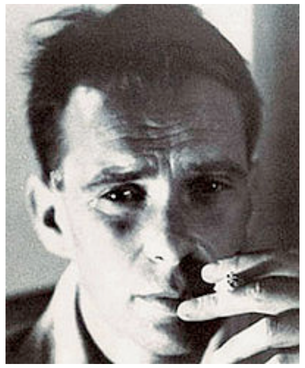
- Correlated (or precursor!) signal at LHC: pp → ee jj

Concluding comments



- Precision frontier experiments offer powerful ways to search for new physics
- Illustrated impact through two examples:
- β decays as a precision electroweak test
  - CKM unitarity test sensitive to new physics in multi-TeV range. Discovery window exists well into the LHC era
- 0νββ decay and lepton number violation
  - Ton-scale searches have great discovery potential — we simply don't know origin of neutrino mass and scale Λ associated with LNV
  - Theory progress through synergy of EFT, lattice QCD, and nuclear structure

Thank you!



A drawing by
Bruno Touschek