SLAC Summer Institute 2018
Standard Model at 50: Successes and Challenges
July 30 - Aug 10 2018

Challenging the Standard Model with nuclei, atoms, and molecules - I

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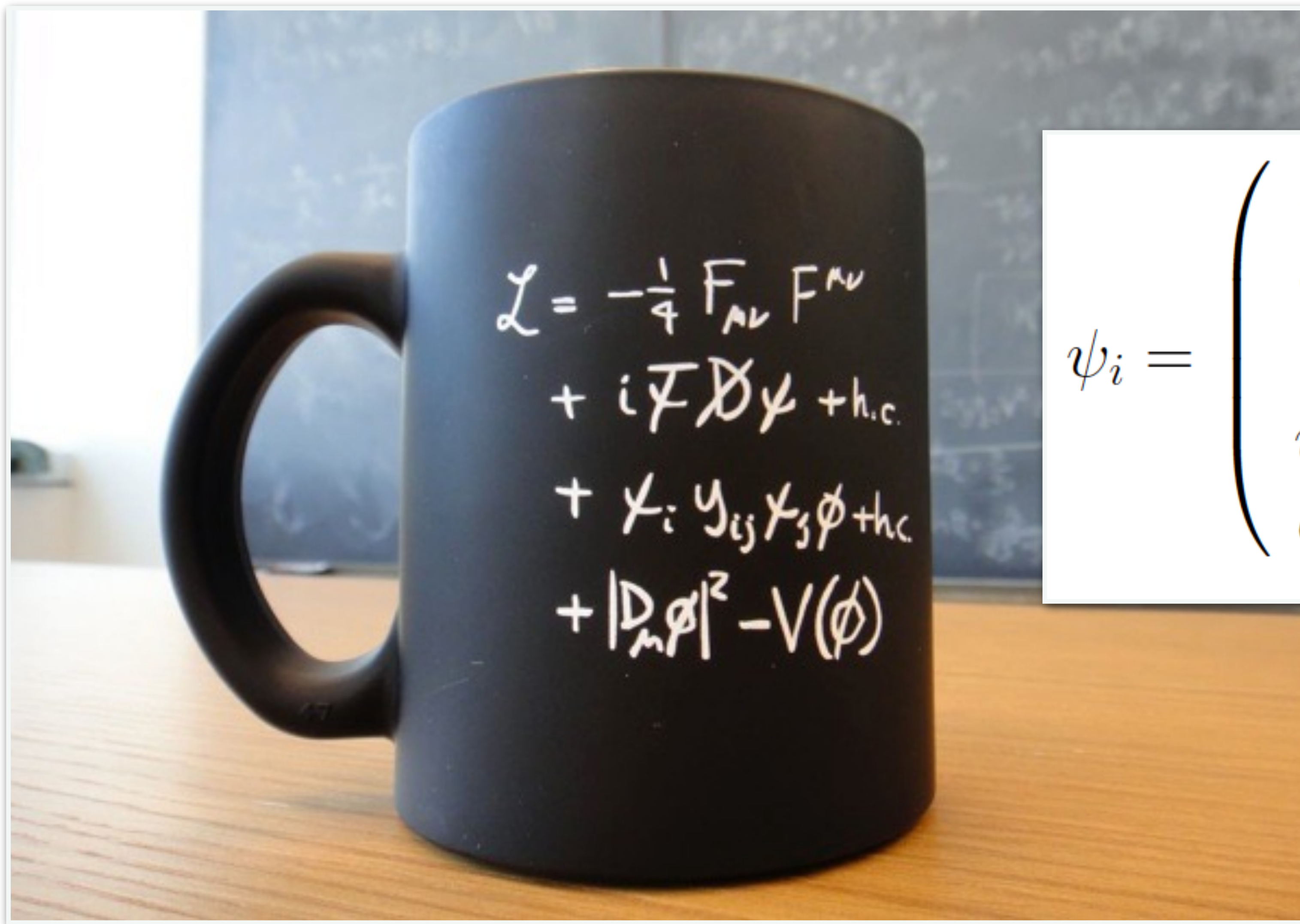
Plan of the lectures

- Introduction:
  - Nuclei / atoms / molecules as probes of the Standard Model (exact or approximate) symmetries and what may lie beyond
- Selected topics:
  - Nuclear beta decays: gauge coupling universality
  - Neutrinoless double beta decay: B-L violation and nature of ν's
  - Permanent Electric Dipole Moments: CP violation

Introduction

The fate of symmetries in the SM



$$\psi_i = \begin{pmatrix} \ell_L \\ e_R \\ q_L \\ u_R \\ d_R \end{pmatrix}_i \qquad \ell_L \rightarrow \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \qquad q_L \rightarrow \begin{pmatrix} u_L \\ d_L \end{pmatrix}$$

The fate of symmetries in the SM

- Gauge symmetry: $SU(3)_c \times SU(2)_W \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{EM}$
- Global symmetries:
  - Quark flavor violation controlled by Yukawa couplings: V_{CKM} and eigenvalues of $Y_{u,d}$
  - Lepton flavor ($L_{\alpha=e,\mu,\tau}$) and B-L are conserved ("accidental")
  - ($L_{\alpha=e,\mu,\tau}$ broken by ν mass. L broken iff ν is Majorana)
- Discrete symmetries:
  - P, C maximally violated by weak interactions
  - CP (and T) violated by V_{CKM} ($\leftarrow$Yukawas) and QCD θ-term: specific pattern of CPV in flavor sector and EDMs

The fate of symmetries in the SM

- Gauge symmetry: $SU(3)_c \times SU(2)_W \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{EM}$

Through precision measurements and the search for rare or SM-forbidden processes, Nuclei / Atoms / Molecules allow us to probe and challenge this pattern of (approximate) symmetries

Address physics often inaccessible at high-energy colliders

- Discrete symmetries:
  - P, C maximally violated by weak interactions
  - CP (and T) violated by V_{CKM} ($\leftarrow$Yukawas) and QCD θ-term: specific pattern of CPV in flavor sector and EDMs

Impact of nuclei / atoms / molecules

Gauge symmetry	Global symmetries	Discrete symmetries
$SU(3)_c \times SU(2)_W \times U(1)_Y$ $\to SU(3)_c \times U(1)_{EM}$	B-L and $L_{\alpha=e,\mu,\tau}$	P, C maximally violated CP: V_{CKM} and θ_{QCD}
Precision beta decay: charged current universality, R-handed currents (extended gauge group?), … Atomic parity violation: neutral current …		

Probes of
SM gauge interaction
at loop-level

Impact of nuclei / atoms / molecules

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Precision beta decay: charged current universality, R-handed currents (extended gauge group?), … Atomic parity violation: neutral current …	Neutrinoless double beta decay: B-L and nature of ν's $\mu \rightarrow e$ conversion in nuclei: lepton flavor violation …	

Unique probes of the "νSM" & connection to baryogenesis via leptogenesis

Impact of nuclei / atoms / molecules

Gauge symmetry	Global symmetries	Discrete symmetries
$SU(3)_c \times SU(2)_W \times U(1)_Y$ $\rightarrow SU(3)_c \times U(1)_{EM}$	B-L and $L_{\alpha=e,\mu,\tau}$	P, C maximally violated CP: V_{CKM} and θ_{QCD}
Precision beta decay: charged current universality, R-handed currents (extended gauge group?) Atomic parity violation neutral current ...	Neutrinoless double beta decay: B-L and nature of ν's ...	Permanent EDMs: (B)SM CP violation T-odd correlations in beta decays ...

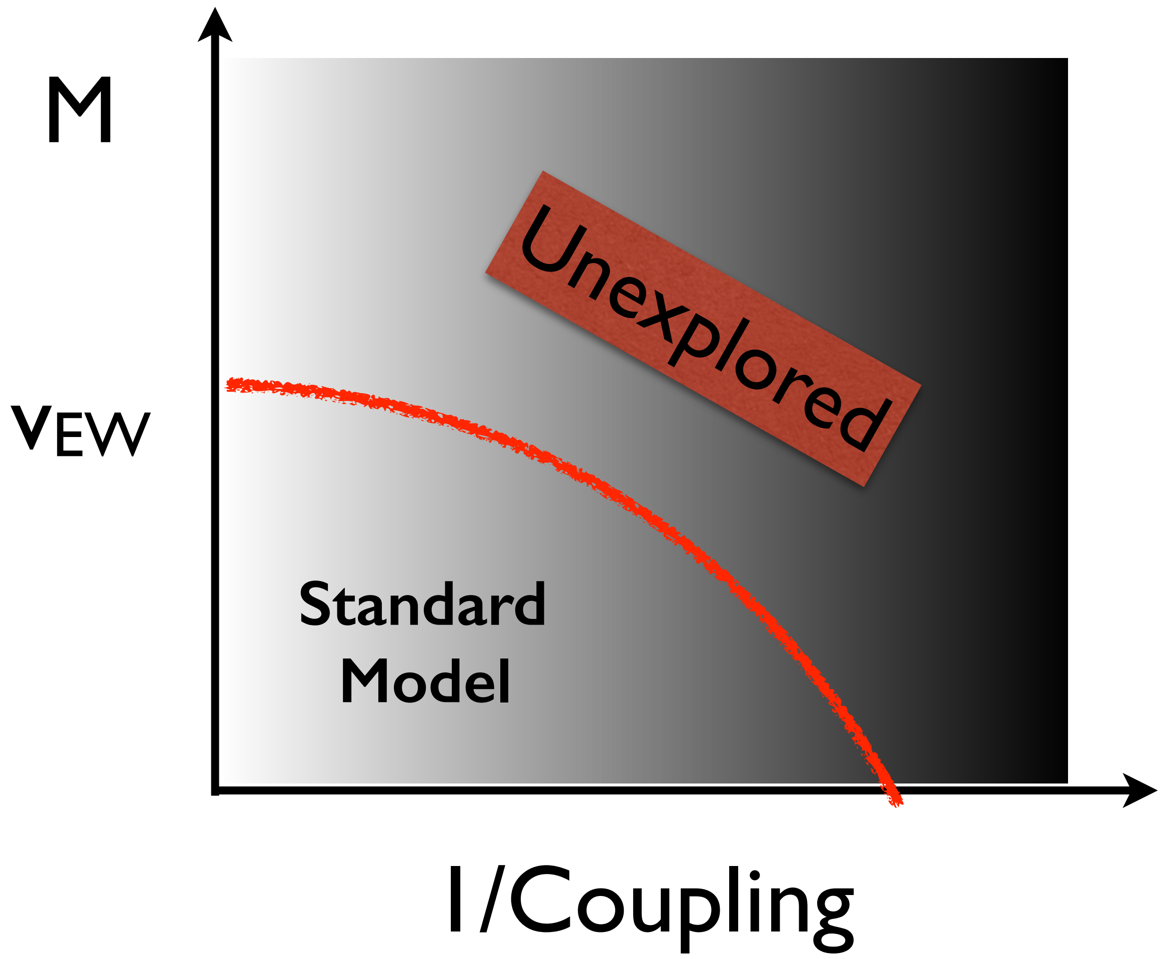
Unique probes of BSM CP violation required in low-scale baryogenesis models

Impact of nuclei / atoms / molecules

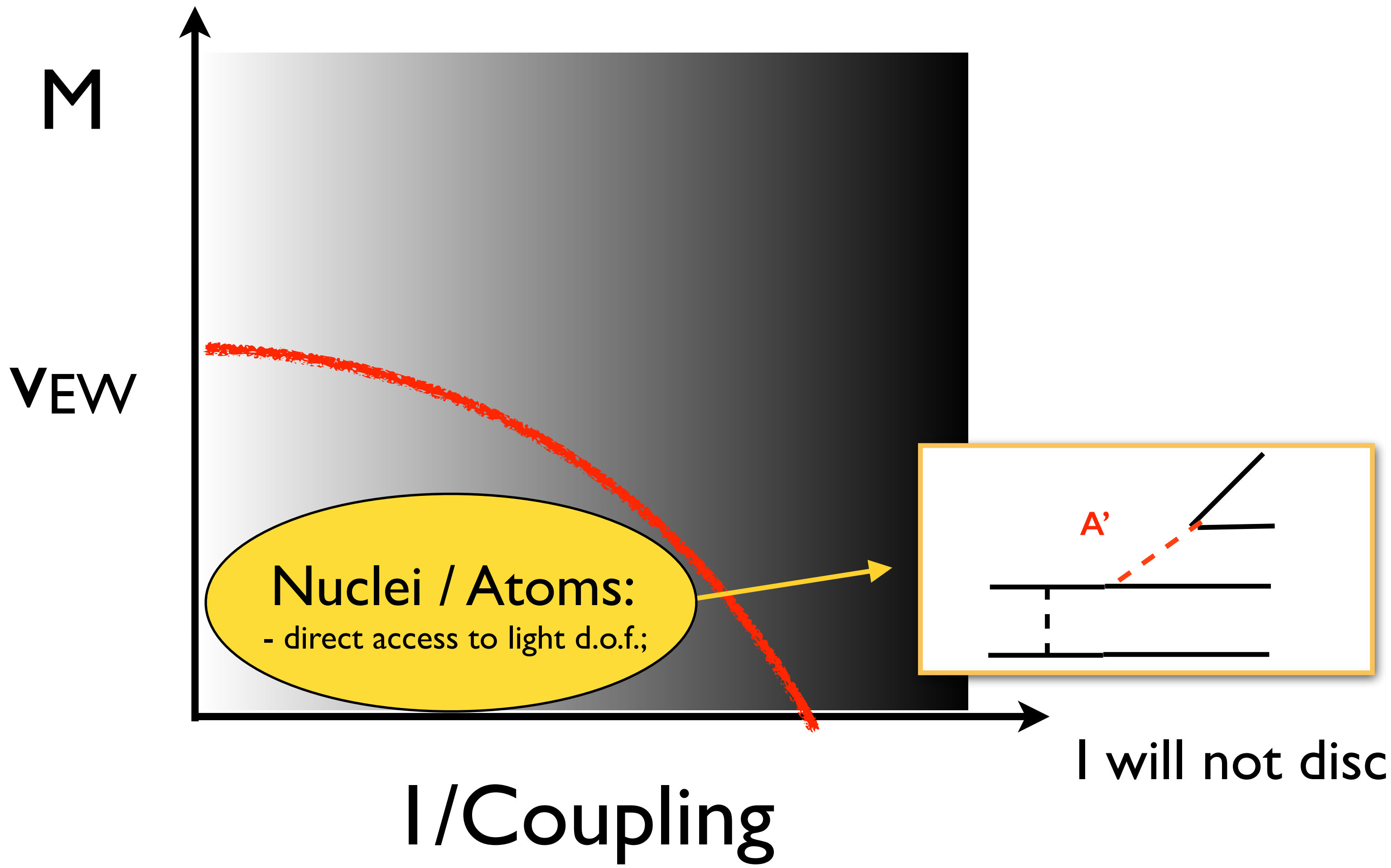
Gauge symmetry	Global symmetries	Discrete symmetries
$SU(3)_c \times SU(2)_W \times U(1)_Y \rightarrow SU(3)_c \times U(1)_{EM}$	B-L and $L_{\alpha=e,\mu,\tau}$	P, C maximally violated CP: V_{CKM} and θ_{QCD}
Precision beta decay: charged current universality, R-handed currents (extended gauge group?), … Atomic parity violation: neutral current (see W. Marciano's lecture) …	Neutrinoless double beta decay: B-L and nature of ν's $\mu \rightarrow e$ conversion in nuclei: lepton flavor violation …	Permanent EDMs: (B)SM CP violation T-odd correlations in beta decays …

I will focus on selected topics that probe the boundaries of the SM

Probing the boundaries



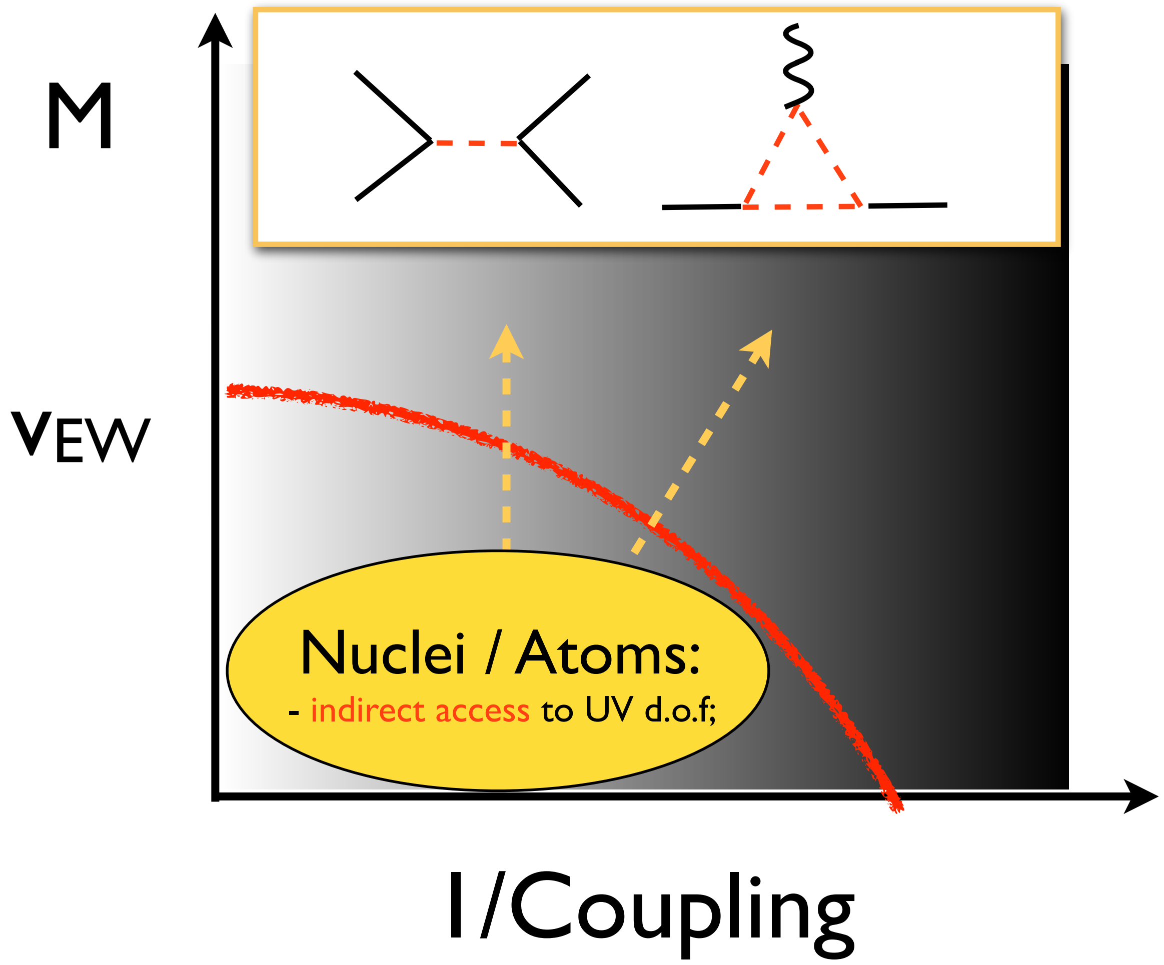
Probing the boundaries



Dark gauge bosons, axion-like particles, light sterile ν's…

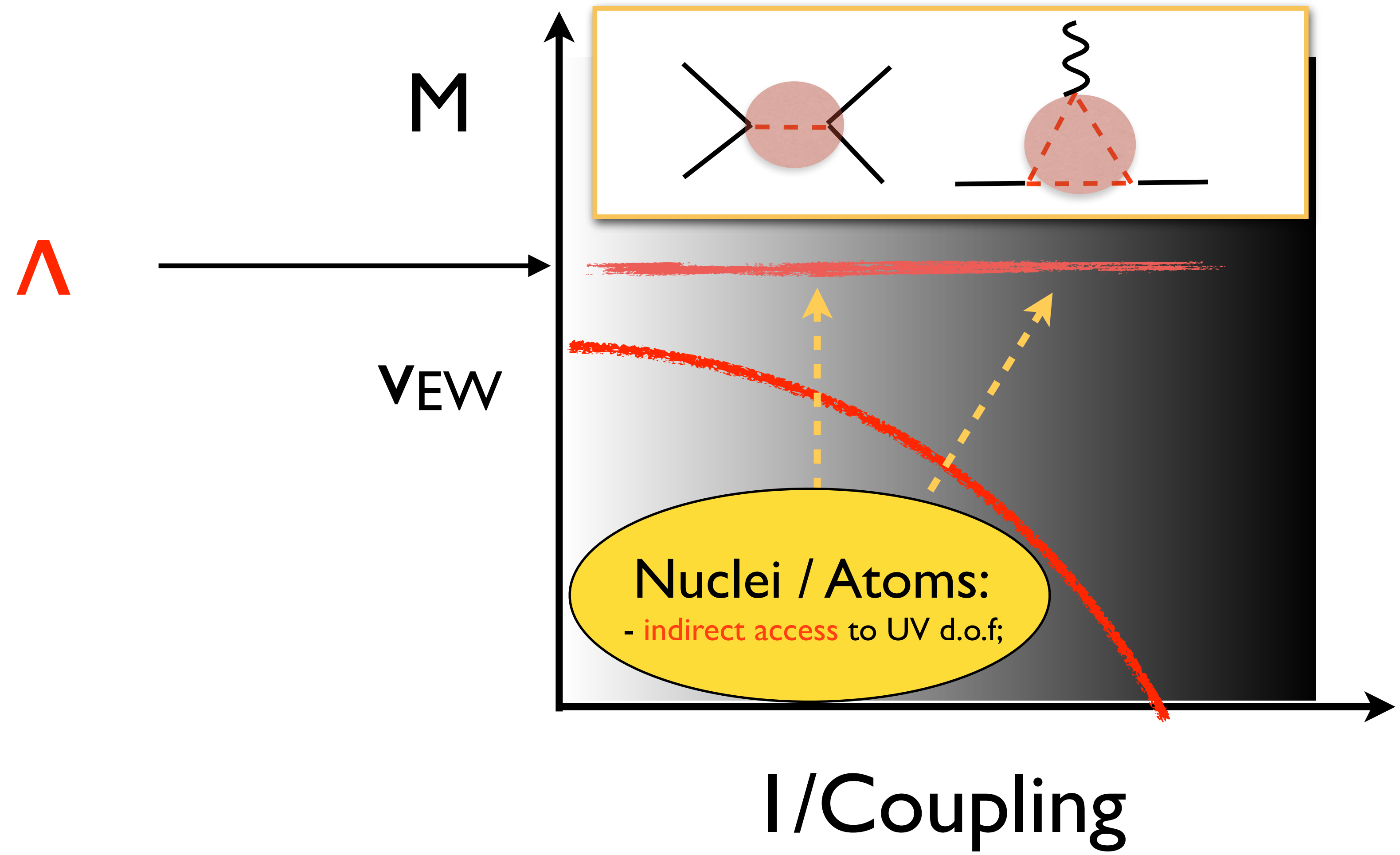
I will not discuss much these

Probing the boundaries



Probing the boundaries

- Given the separation of scales (nuclear, atomic vs electroweak & beyond), effective field theory is the theoretical tool of choice



The "Standard Model EFT"

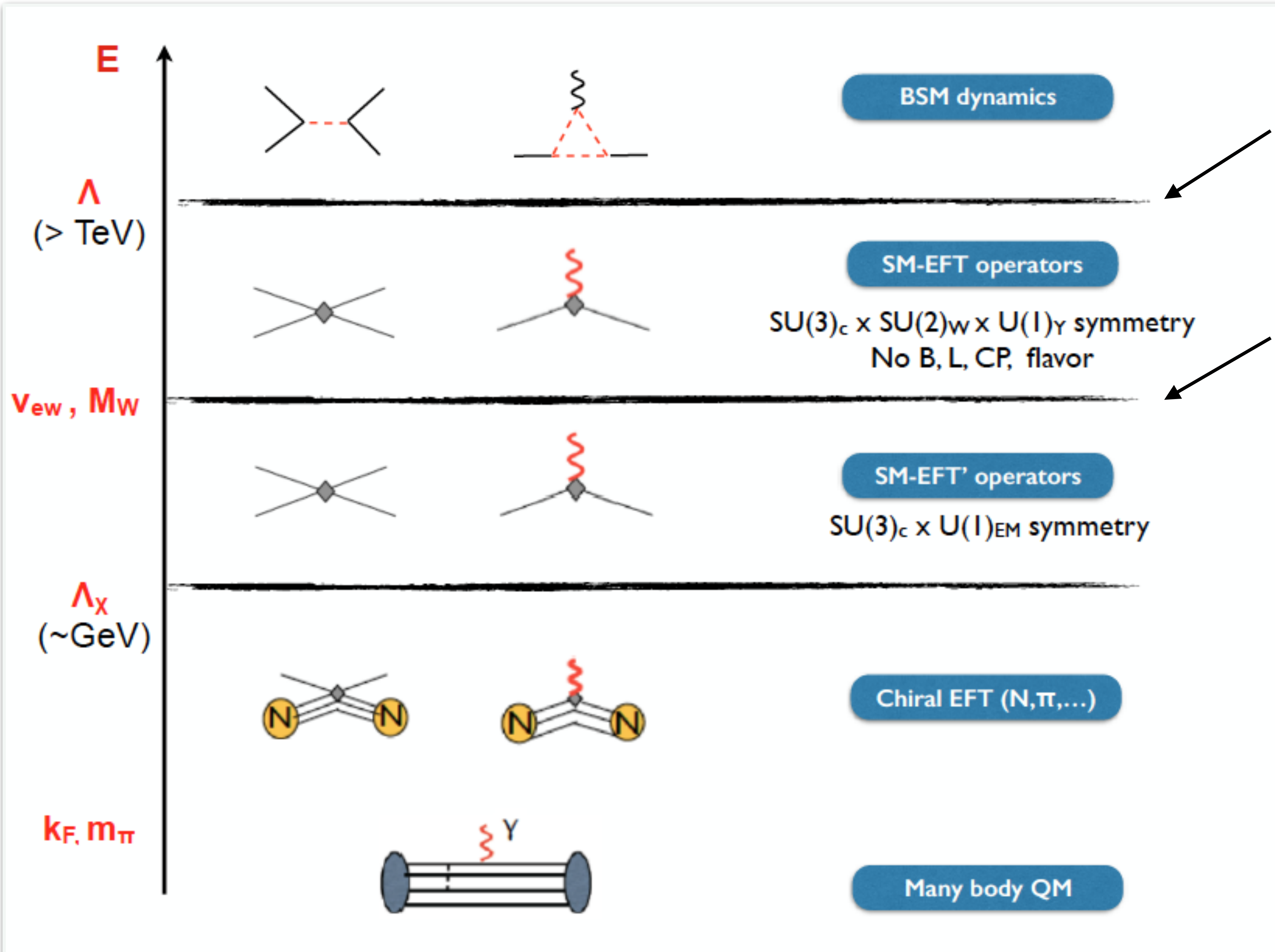
$$\mathcal{L}_{\rm eff} = \mathcal{L}_{SM} + \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} O_i^{(6)} + \ldots$$

Weinberg 1979
Wilczek-Zee1979
Buchmuller-Wyler 1986, ...
Grzadkowski-Iskrzynksi-Misiak-Rosiek (2010)

$C_i^{(d)}$ encode information about underlying model

Connecting scales

To connect UV physics to nuclei & atoms, use multiple EFTs

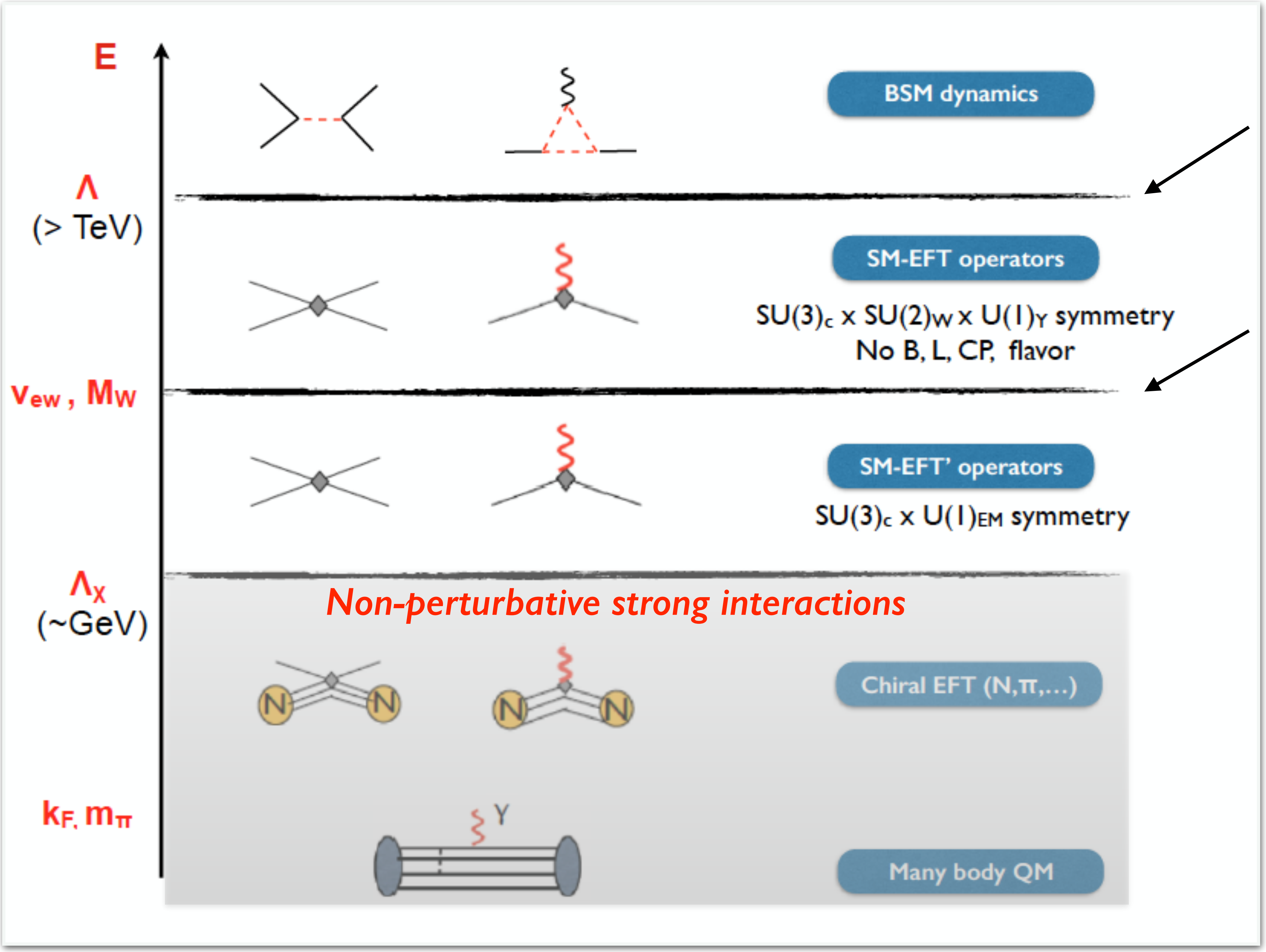


Matching to BSM scenarios

Perturbative matching within SM

Connecting scales

To connect UV physics to nuclei & atoms, use multiple EFTs



Matching to BSM scenarios

Perturbative matching within SM

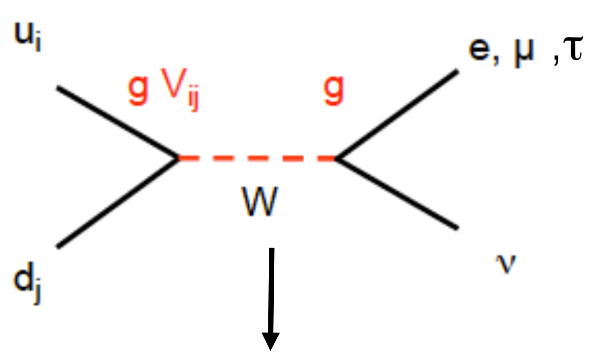
Hadronic matrix elements

Nuclear & atomic matrix elements

Precision beta decays

Semileptonic processes: SM and beyond

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



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

Semileptonic processes: SM and beyond

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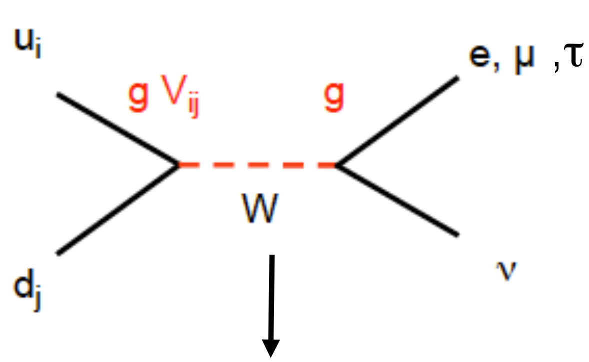


$G_F \sim g^2 V_{ij}/M_W^2 \sim 1/v^2$

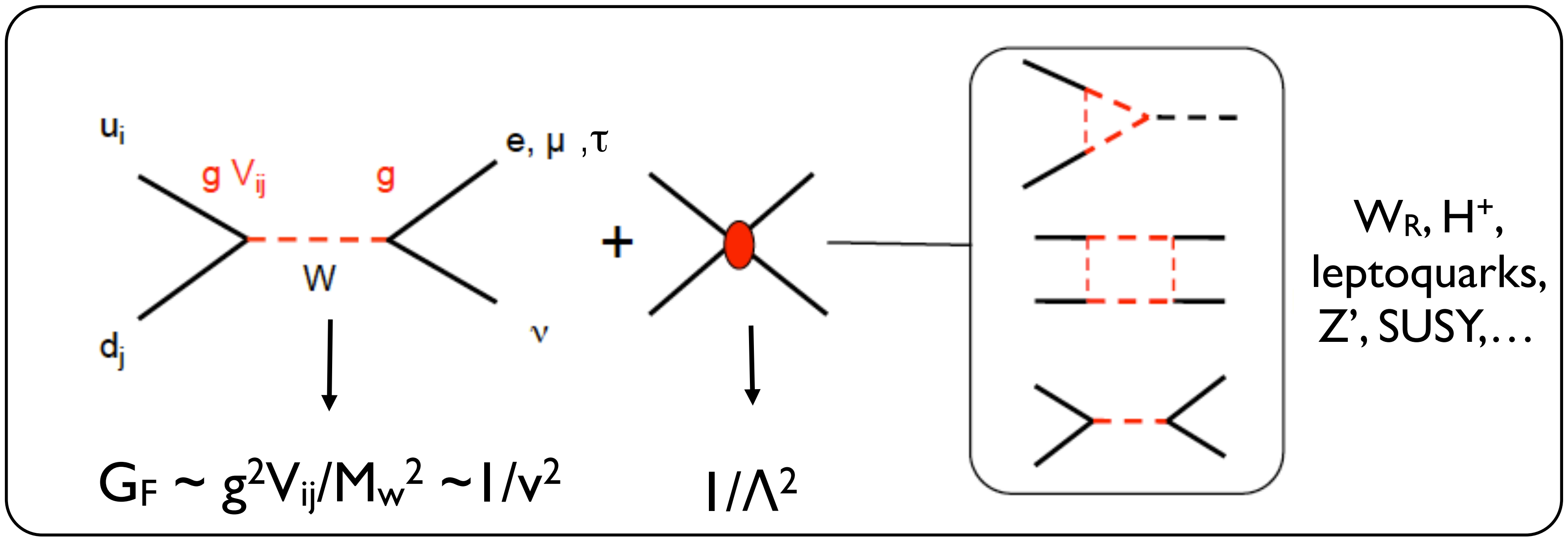
$$\frac{g}{\sqrt{2}} W_\mu^+ \, \bar{u}_L \, \gamma^\mu \, d_L \longrightarrow \frac{g}{\sqrt{2}} W_\mu^+ \, \bar{u}_L \, V_{\rm CKM} \, \gamma^\mu \, d_L$$

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

Cabibbo-Kobayashi-Maskawa (unitary) matrix:
Mismatch in the transformation
of u_L and d_L needed to diagonalize quark masses

Semileptonic processes: SM and beyond

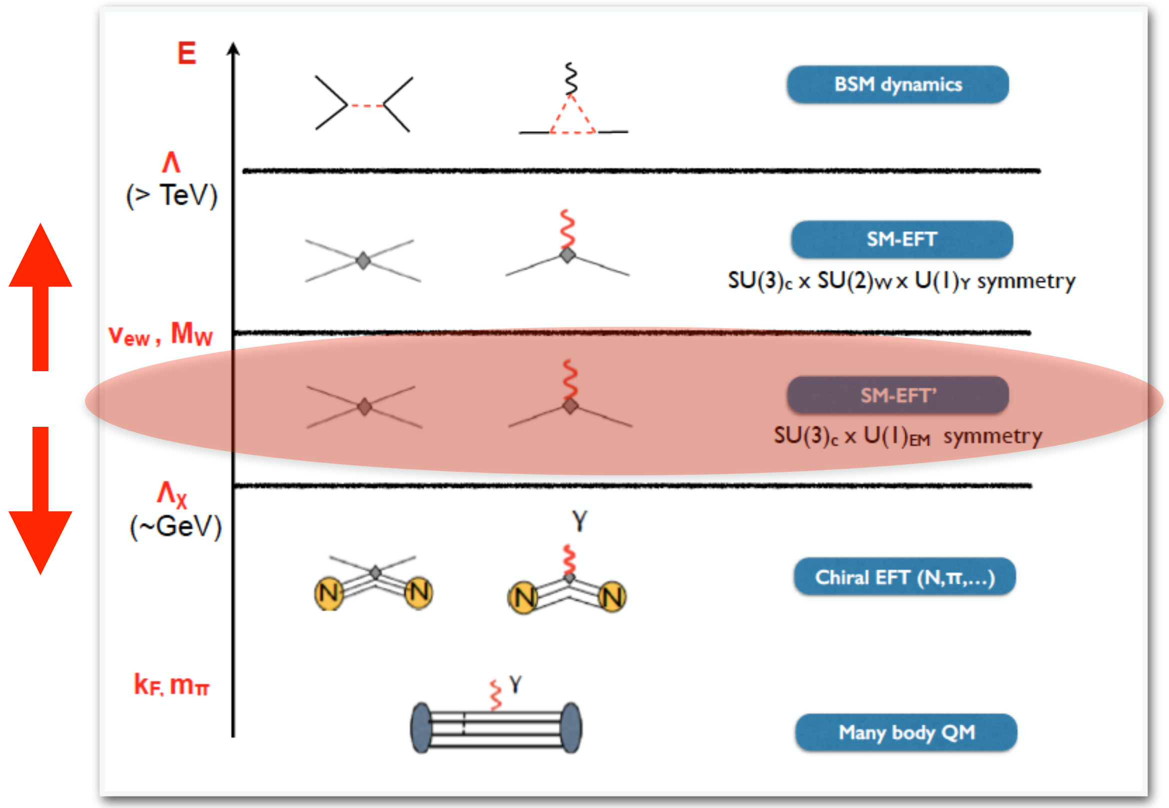
- In the SM, W exchange ⇒ V-A currents, universality



- Broad sensitivity to BSM scenarios
- Experimental and theoretical precision at or approaching 0.1% level
  Probe effective scale Λ in the 5-10 TeV range

Effective Lagrangian at E~GeV

- New physics effects are encoded in ten quark-level couplings



- Quark-level version of Lee-Yang effective Lagrangian, allows us to connect nuclear & high energy probes

Effective Lagrangian at E~GeV

- New physics effects are encoded in ten quark-level couplings

$$
\begin{aligned}
\mathcal{L}_{CC} &= -\frac{G_F^{(\beta)}}{\sqrt{2}} V_{ud} \\
&\times \Big[\Big(1+\epsilon_L\Big) \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \; \bar{u}\gamma^\mu(1-\gamma_5)d \\
&+ \epsilon_R \; \bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \; \bar{u}\gamma^\mu(1+\gamma_5)d \\
&+ \epsilon_S \; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}d \\
&- \epsilon_P \; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}\gamma_5 d \\
&+ \epsilon_T \; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \; \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}
\end{aligned}
$$

$\epsilon_i \; , \tilde{\epsilon}_i \sim (M_W/\Lambda)^2$

← Can interfere with SM: linear sensitivity to ε_i

Effective Lagrangian at E~GeV

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& - \; \epsilon_P \; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}\gamma_5 d \\
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\end{aligned}
$$

$$\epsilon_i \; , \tilde{\epsilon}_i \sim (M_W/\Lambda)^2$$

← Can interfere with SM: linear sensitivity to ϵ_i

$$+ \quad \epsilon_i \longrightarrow \tilde{\epsilon}_i \qquad (1-\gamma_5)\nu_\ell \longrightarrow (1+\gamma_5)\nu_\ell$$

← Interference with SM suppressed by m_ν/E: quadratic sensitivity to $\tilde{\epsilon}_i$

Effective Lagrangian at E~GeV

- Work to first order in rad. corr. and new physics

$$\mathcal{L}_{\rm CC} = -\frac{G_F^{(\mu)}}{\sqrt{2}} V_{ud} \left(1+\delta_{\rm RC}\right)\left(1-\frac{\delta G_F^{(\mu)}}{G_F^{(\mu)}}\right)\left(1+\epsilon_L+\epsilon_R\right)$$
$$\times \Big[\bar{\ell}\gamma_\mu(1-\gamma_5)\nu_\ell \; \bar{u}\gamma^\mu\left(1-\left(1-2\,\epsilon_R\right)\gamma_5\right)d$$
$$+ \;\epsilon_S \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}d$$
$$- \;\epsilon_P \;\; \bar{\ell}(1-\gamma_5)\nu_\ell \; \bar{u}\gamma_5 d$$
$$+ \;\epsilon_T \;\; \bar{\ell}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \; \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d \Big] + \text{h.c.}$$

$G_F^{(\mu)}$

Fermi constant *extracted* fro muon lifetime, possibly "contaminated" by new physics

$\delta_{\rm RC}$

SM rad. corr. ⊃ "large log" $(\alpha/\pi)\times\text{Log}(M_Z/\mu)$

Marciano-Sirlin 1981
Sirlin 1982

Note: besides the pre-factor, ϵ_R appears in nuclear decays in the combination $\bar{g}_A \equiv g_A \times (1-2\epsilon_R)$

How do we probe the ε_α? (I)

1. Differential decay distribution

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

Lee-Yang, 1956 Jackson-Treiman-Wyld 1957

How do we probe the ε_α? (1)

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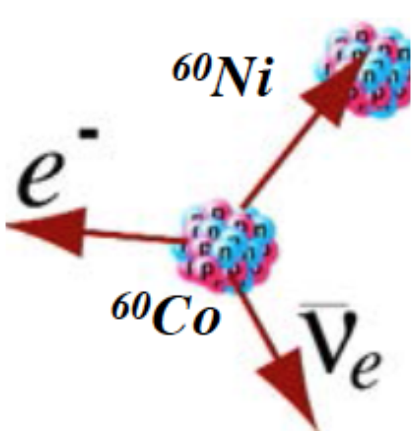

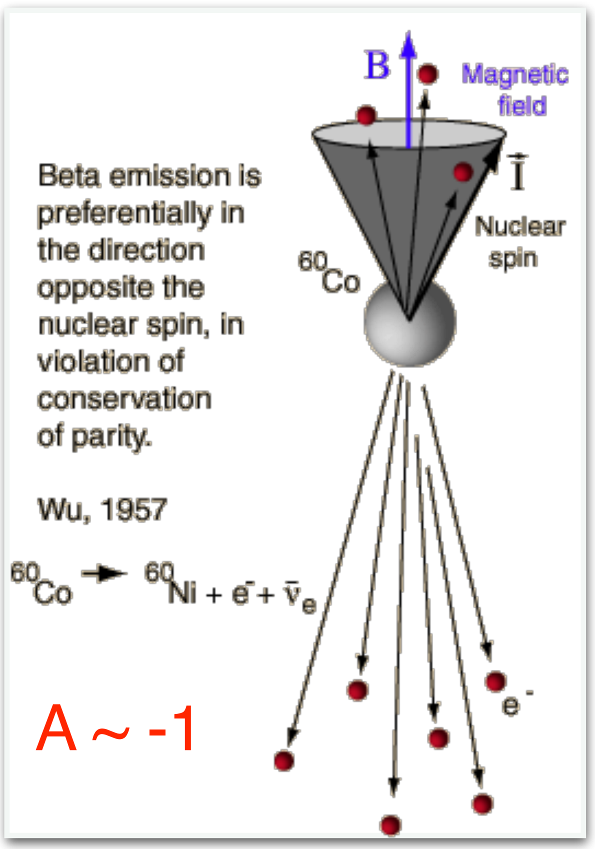

C-S Wu

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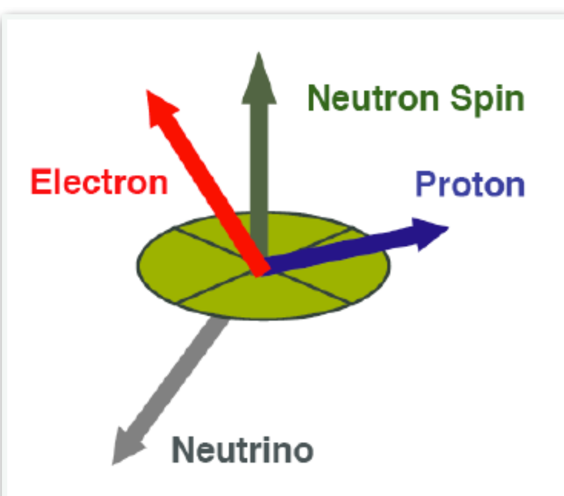

$a(g_A)$, $A(g_A)$, $B(g_A, g_\alpha \varepsilon_\alpha)$, …
isolated via suitable experimental asymmetries

How do we probe the ϵ_α? (I)

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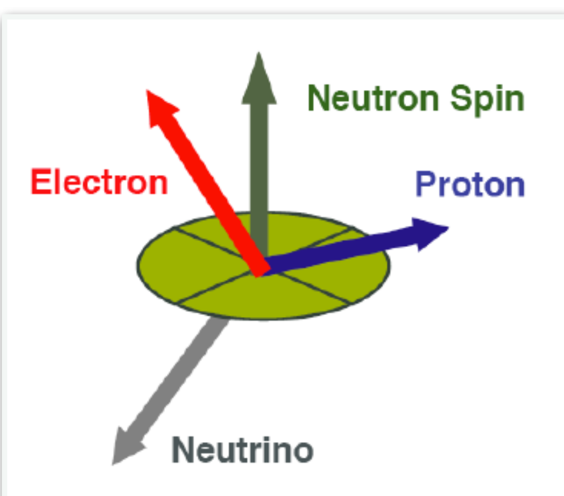

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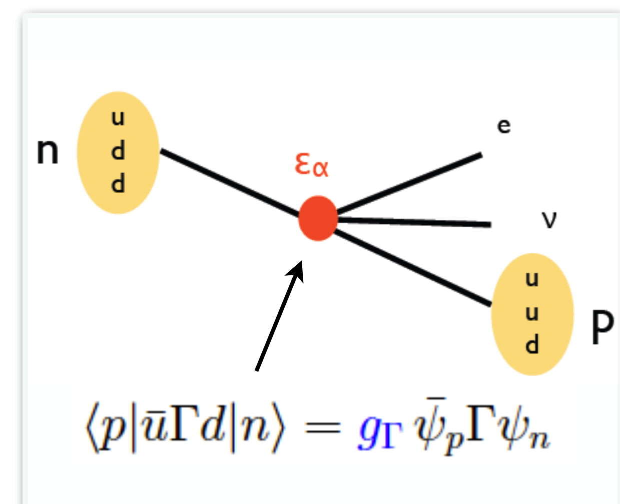
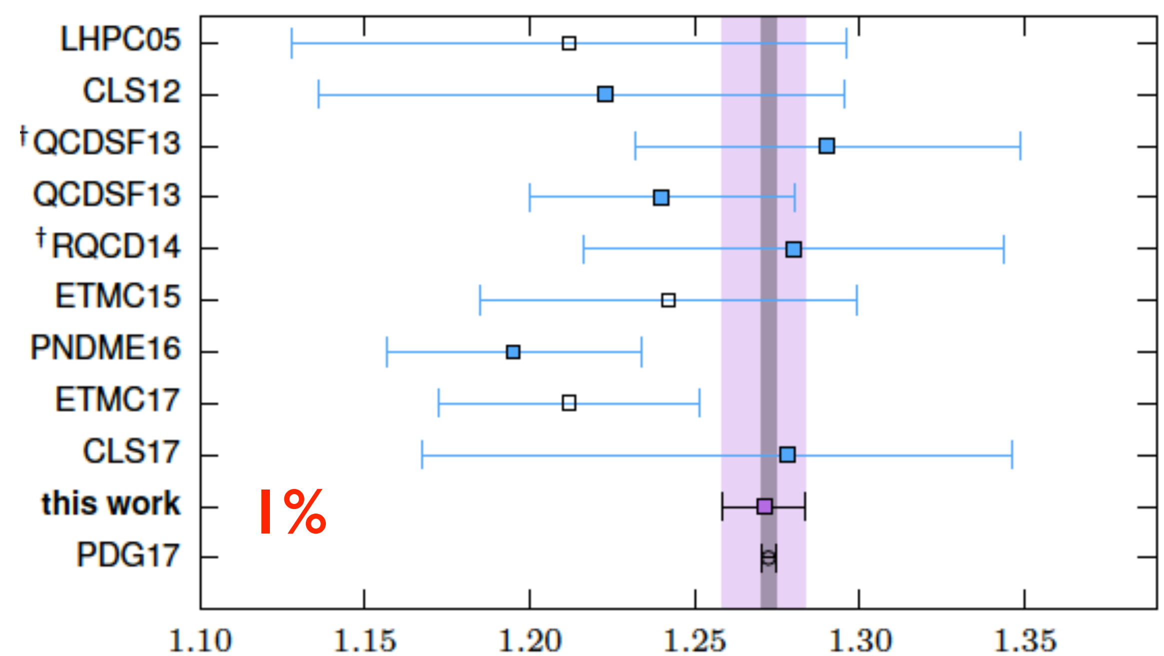


Theory input: $g_{V,A,S,T}$ (from lattice QCD) + rad. corr.

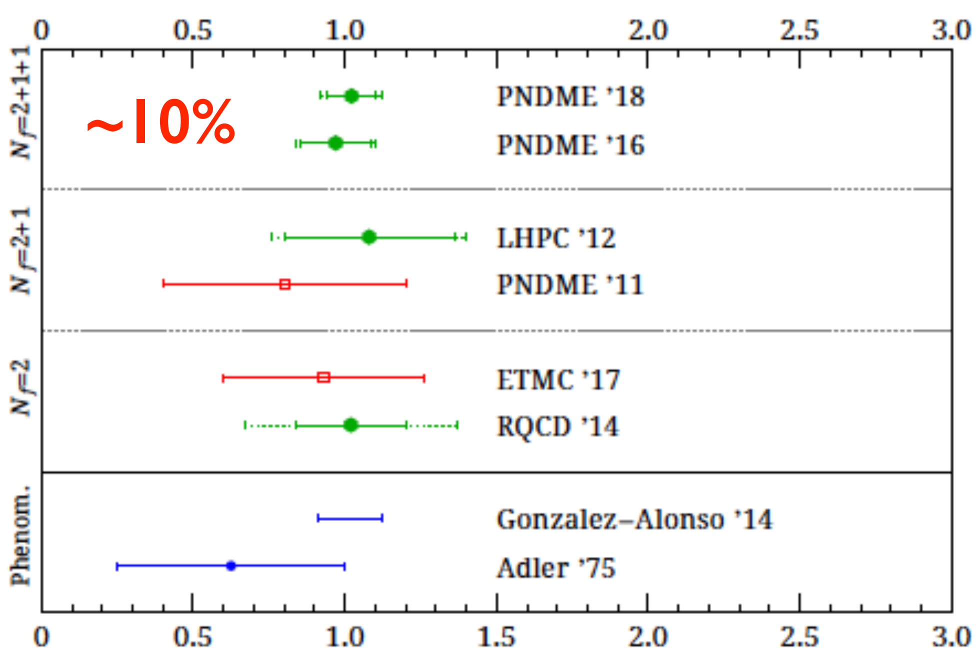
Nucleon charges from lattice QCD

With estimates of all systematic errors (m_q, a, V, excited states)

Chang et al. (CalLat) 1805.12030



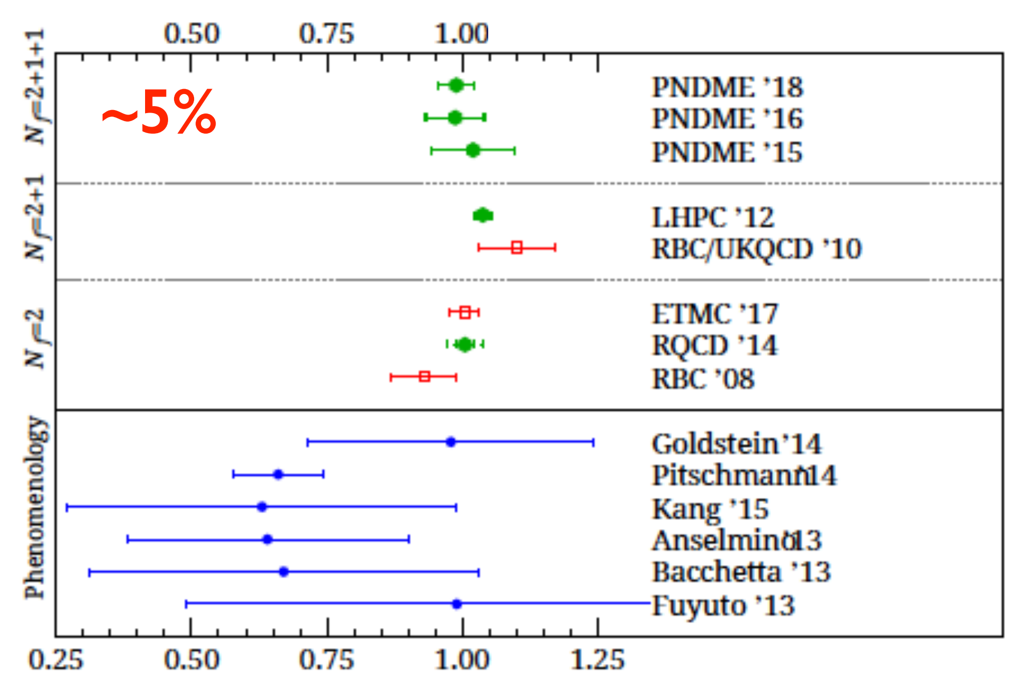
g_S



g_A

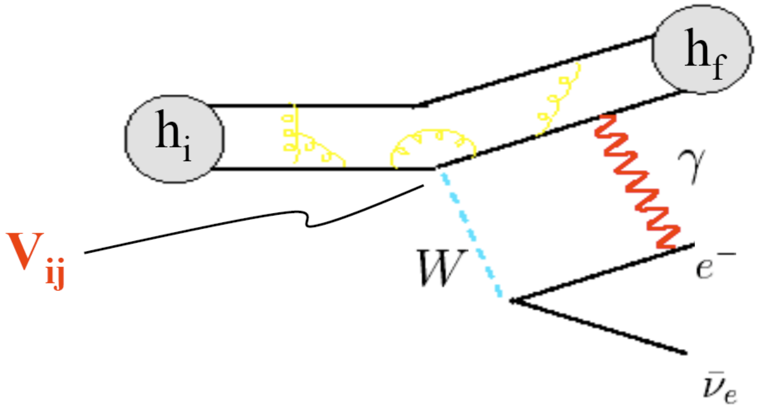
Bhattacharya et al. 1806.09006

g_T



How do we probe the ε_α? (2)

2. Total decay rates



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

How do we probe the ε_α? (2)

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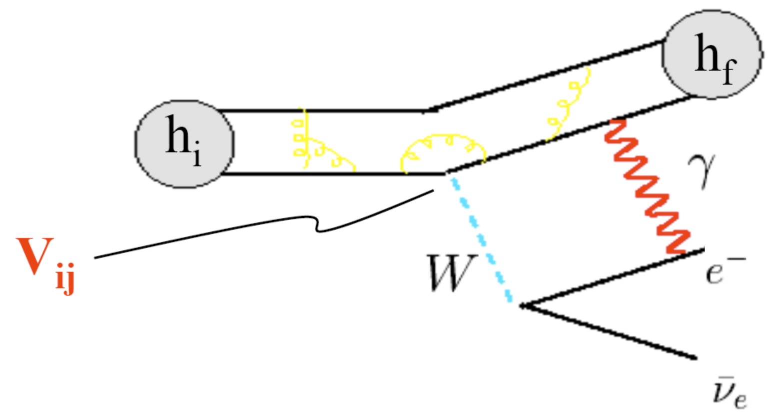

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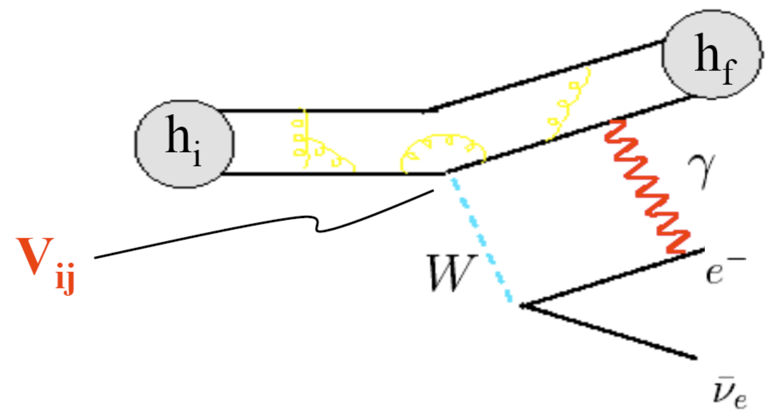
Lifetimes, BRs

Experimental input

Q-values → phase space

How do we probe the ε_α? (2)

2. Total decay rates



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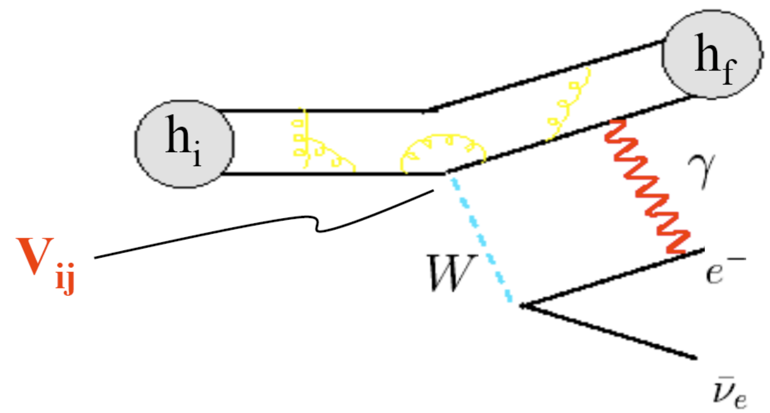
Theory input

Hadronic / nuclear matrix elements and radiative corrections

LQCD, chiral EFT, dispersion relations, …

How do we probe the ε_α? (2)

2. Total decay rates



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

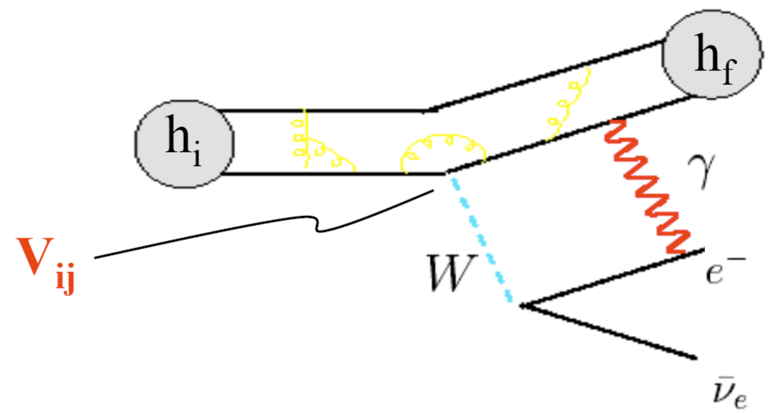
Channel-dependent effective CKM element

$$\bar{V}_{ud} = V_{ud}\left[1 + \epsilon_L + \epsilon_R + b(\epsilon_S, \epsilon_T)\, \widetilde{F}_{\rm kin}\right]$$

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

How do we probe the ε_α? (2)

2. Total decay rates



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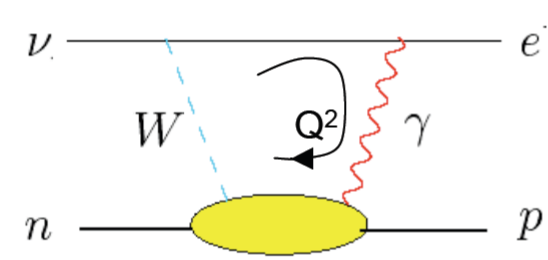
For nuclei, rate traditionally written in terms of "corrected FT values"

$$\mathcal{F}t \equiv ft(1 + \delta_R')(1 + \delta_{NS} - \delta_C) = \frac{K}{2G_F^2 V_{ud}^2 (1 + \Delta_R^V)}$$

$$K = \frac{2\pi^3 \log 2}{m_e^5}$$

Nucleus-dependent radiative & Isospin Breaking correction

"Inner" radiative correction
Δ_R^V= (2.36 ± 0.04)%
[Marciano-Sirlin 2006]



Snapshot of the field

- Experimental precision between ~0.01% and few %

Ft (0+→0+) values

Parent	$\mathcal{F}t$ (s)
^{10}C	3078.0 ± 4.5
^{14}O	3071.4 ± 3.2
^{22}Mg	3077.9 ± 7.3
^{26m}Al	3072.9 ± 1.0
^{34}Cl	3070.7 ± 1.8
^{34}Ar	3065.6 ± 8.4
^{38m}K	3071.6 ± 2.0
^{38}Ca	3076.4 ± 7.2
^{42}Sc	3072.4 ± 2.3
^{46}V	3074.1 ± 2.0
^{50}Mn	3071.2 ± 2.1
^{54}Co	3069.8 ± 2.6
^{62}Ga	3071.5 ± 6.7
^{74}Rb	3076.0 ± 11.0

Correlation coefficients

Parent	Type	Parameter	Value
^{6}He	GT/β^-	a	$-0.3308(30)$[a]
^{32}Ar	F/β^+	$\tilde{a}$	0.9989(65)
^{38m}K	F/β^+	$\tilde{a}$	0.9981(48)
^{60}Co	GT/β^-	$\tilde{A}$	$-1.014(20)$
^{67}Cu	GT/β^-	$\tilde{A}$	0.587(14)
^{114}In	GT/β^-	$\tilde{A}$	$-0.994(14)$
^{14}O/^{10}C	F-GT/β^+	P_F/P_{GT}	0.9996(37)
^{26}Al/^{30}P	F-GT/β^+	P_F/P_{GT}	1.0030 (40)
^{8}Li	GT/β^-	R	0.0009(22)

Neutron data

Parameter	Value	
τ_n (s)	879.75(76)	* (S = 1.9!!)
a_n	$-0.1034(37)$	*
$\tilde{a}_n$	$-0.1090(41)$	
$\tilde{A}_n$	$-0.11869(99)$	* (S = 2.6!!)
$\tilde{B}_n$	0.9805(30)	*
λ_{AB}	$-1.2686(47)$	
D_n	$-0.00012(20)$	*
R_n	0.004(13)	

* Average

$S = (\chi^2_{min}/dof)^{1/2}$

Nuclei

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732 & M. Gonzalez-Alonso talk at CIPANP 2018

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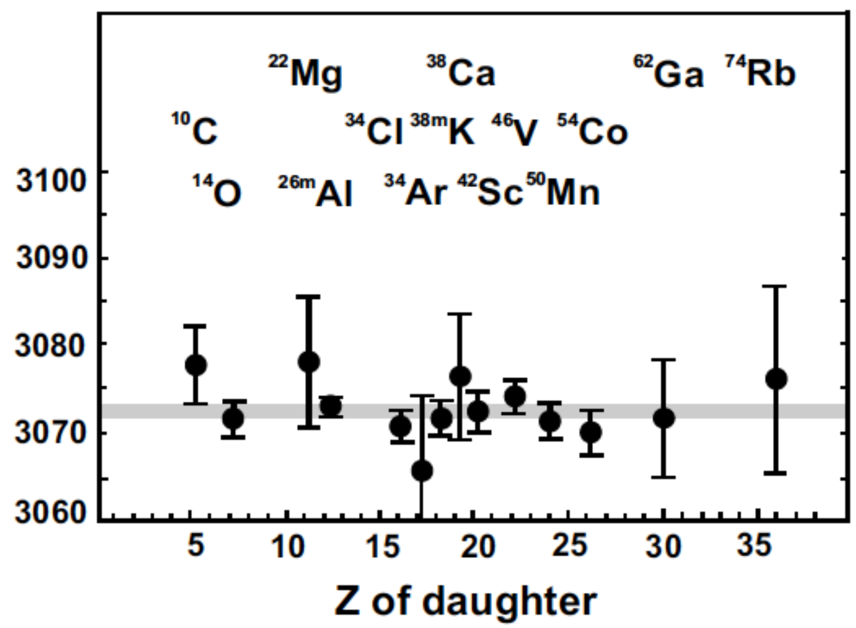
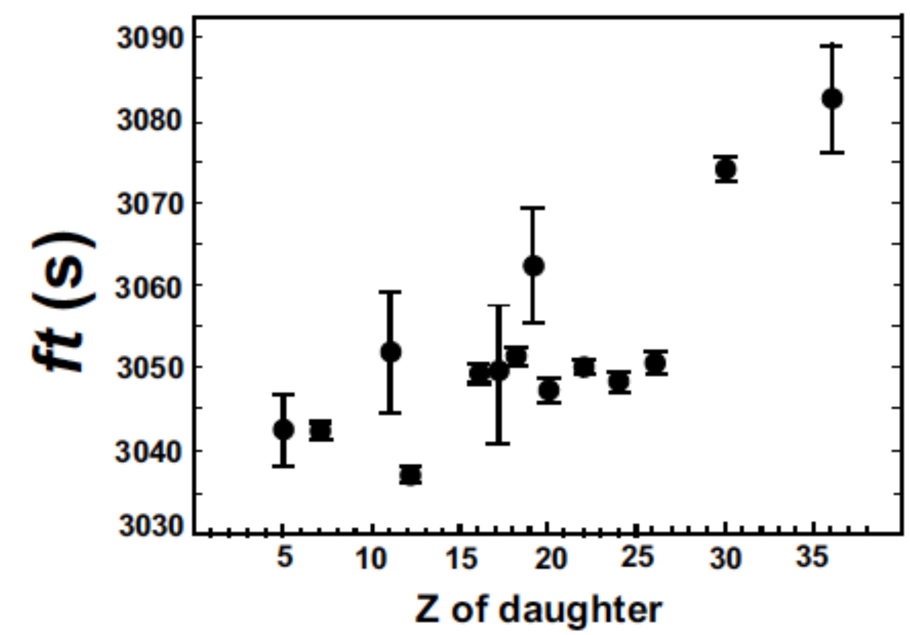
^{38m}K	3071.6 ± 2.0
^{38}Ca	3076.4 ± 7.2
^{42}Sc	3072.4 ± 2.3
^{46}V	3074.1 ± 2.0
^{50}Mn	3071.2 ± 2.1
^{54}Co	3069.8 ± 2.6
^{62}Ga	3071.5 ± 6.7
^{74}Rb	3076.0 ± 11.0

"Corrected" FT values



FT values before including nucleus-dependent radiative correction

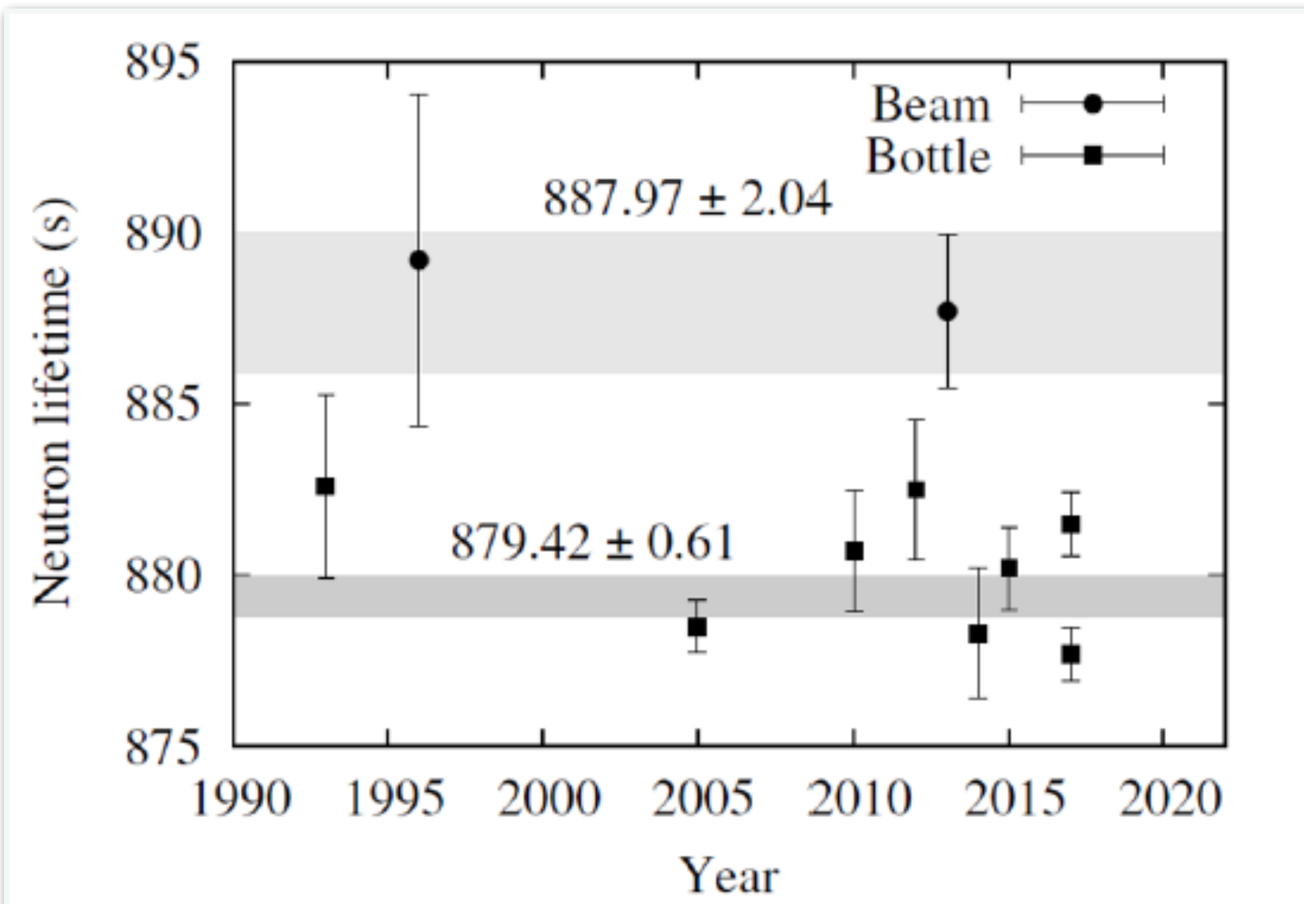


Hardy-Towner 1411.5987

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732 & M. Gonzalez-Alonso talk at CIPANP 2018

Snapshot of the field

- Experimental precision between ~0.01% and few %



Neutron data

Parameter	Value
τ_n (s)	879.75(76) * (S = 1.9!!)
a_n	−0.1034(37) *
$\tilde{a}_n$	−0.1090(41)
$\tilde{A}_n$	−0.11869(99) * (S = 2.6!!)
$\tilde{B}_n$	0.9805(30) *
λ_{AB}	−1.2686(47)
D_n	−0.00012(20) *
R_n	0.004(13)

* Average

$S = (\chi^2_{min}/dof)^{1/2}$

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732 & M. Gonzalez-Alonso talk at CIPANP 2018

Results of global fit to low-E data

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

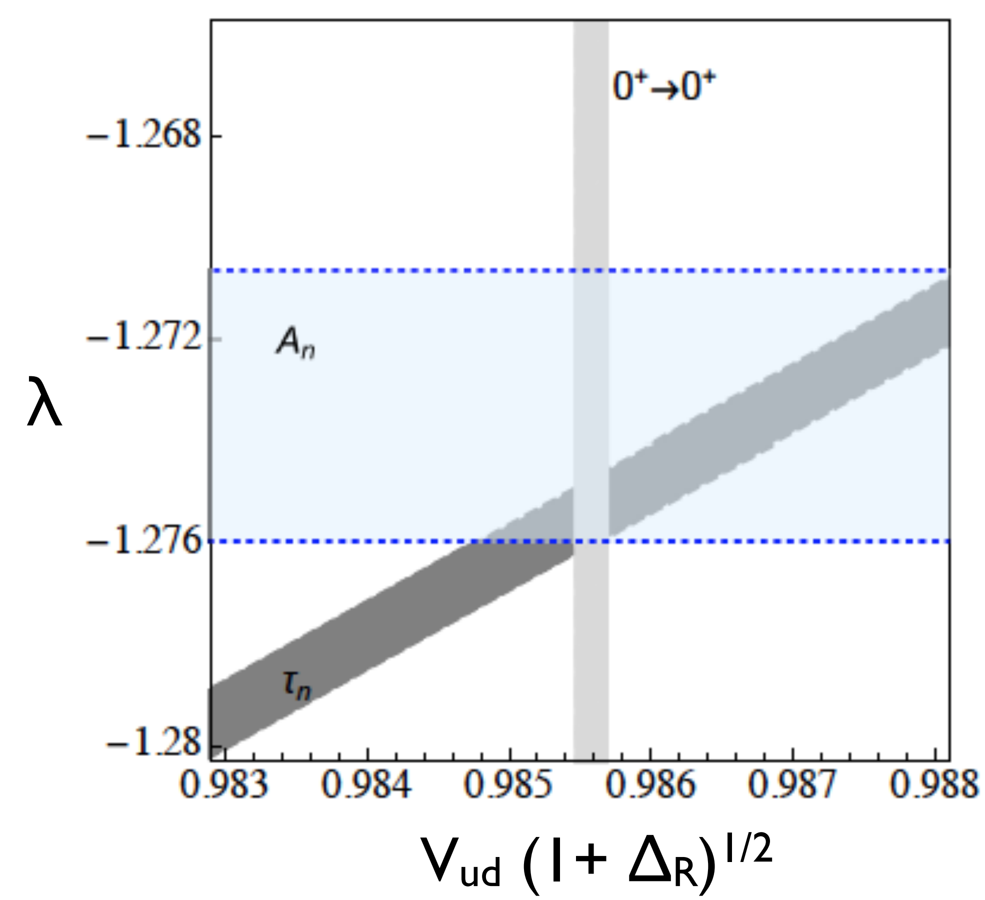
- Standard Model fit ($\lambda = g_A/g_V$)

Experimental ↓ (11)   Radiative corrections (Δ_R) ↓ (19)

$$|V_{ud}| = 0.97416(11)(19) = 0.97416(21)$$
$$\lambda = 1.27510(66)$$

$$\rho = -0.13$$
$$\chi^2_{\rm min}/\nu = 0.57.$$

- Fit driven by $\mathcal{F}t$'s ($0^+ \to 0^+$) and τ_n (not A_n)



Results of global fit to low-E data

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

- Fit including BSM couplings (driven by $\mathcal{F}t$'s ($0^+ \rightarrow 0^+$), τ_n, and A_n)

$$\tilde{V}_{ud} \equiv V_{ud}\,(1+\epsilon_L+\epsilon_R)\left(1-\frac{\delta G_F}{G_F}\right)$$

1st error: experimental

2nd error: Δ_R, g_A, g_S, and g_T

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

$$\begin{pmatrix} |\tilde{V}_{ud}| \\ \epsilon_R \\ \epsilon_S \\ \epsilon_T \end{pmatrix} = \begin{pmatrix} 0.97452(34)(19) & \\ 0.002(1)(21) & (90\%\ \mathrm{CL}) \\ 0.0014(20)(3) & (90\%\ \mathrm{CL}) \\ -0.0007(12)(1) & (90\%\ \mathrm{CL}) \end{pmatrix}$$

$\chi^2_{\rm min}/\nu = 0.46$.

~2 % → ~ 0.5% **

~0.2 %

~0.1 %

$$\rho = \begin{pmatrix} 1.00 & & & \\ 0.00 & 1.00 & & \\ 0.83 & 0.00 & 1.00 & \\ 0.28 & -0.04 & 0.31 & 1.00 \end{pmatrix}$$

Cabibbo universality test

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

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

Extraction dominated by K decays:

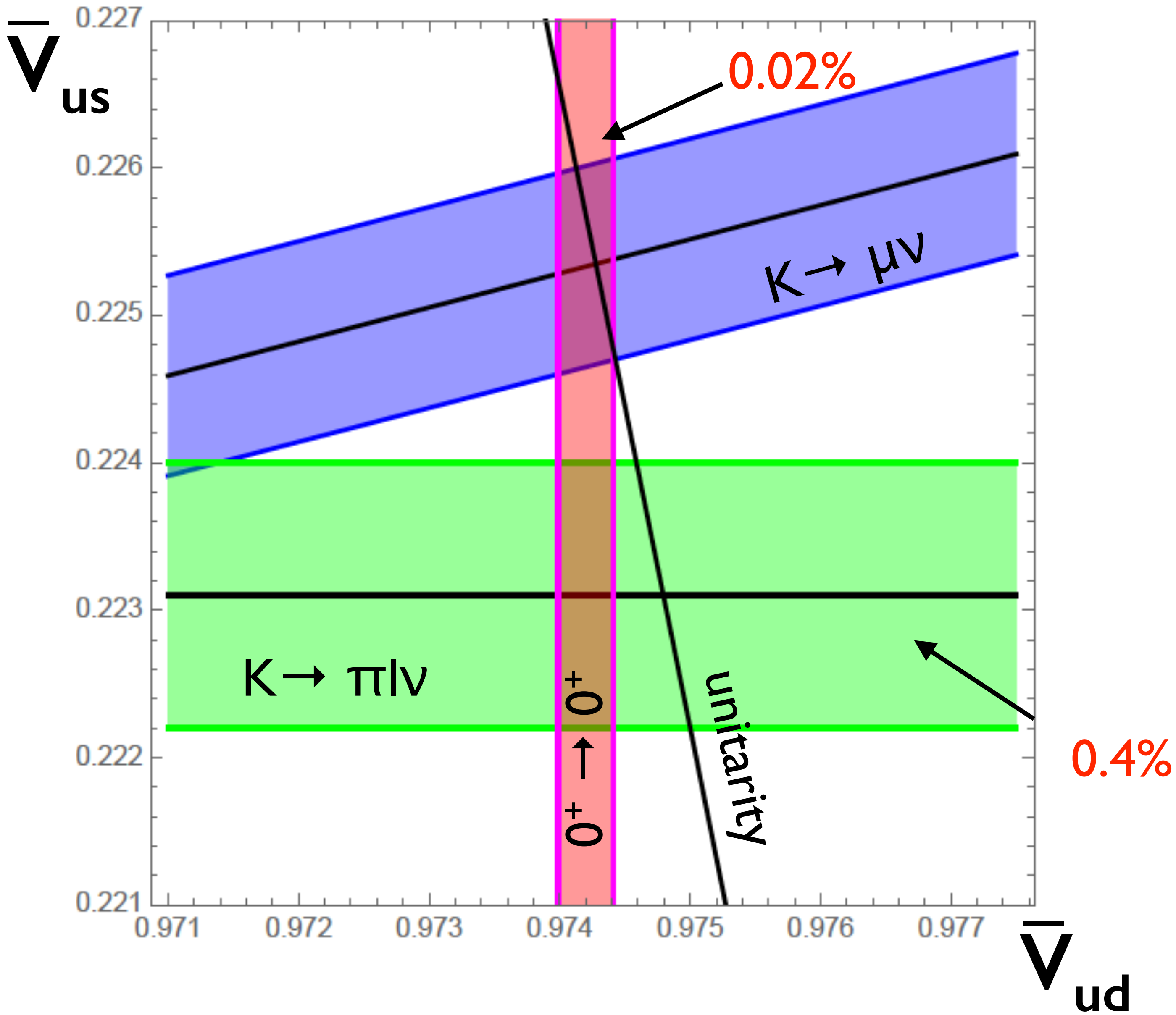
$K \to \pi e \nu$ & $K \to \mu\nu$ vs $\pi \to \mu\nu$ (V_{us}/V_{ud})

Hardy-Towner 1411.5987
CKM 2016

FLAVIANET report 1005.2323 and refs therein
Lattice QCD input from FLAG 1607.00299 and refs therein

Cabibbo universality test

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



V_{us} from $K\to\mu\nu$

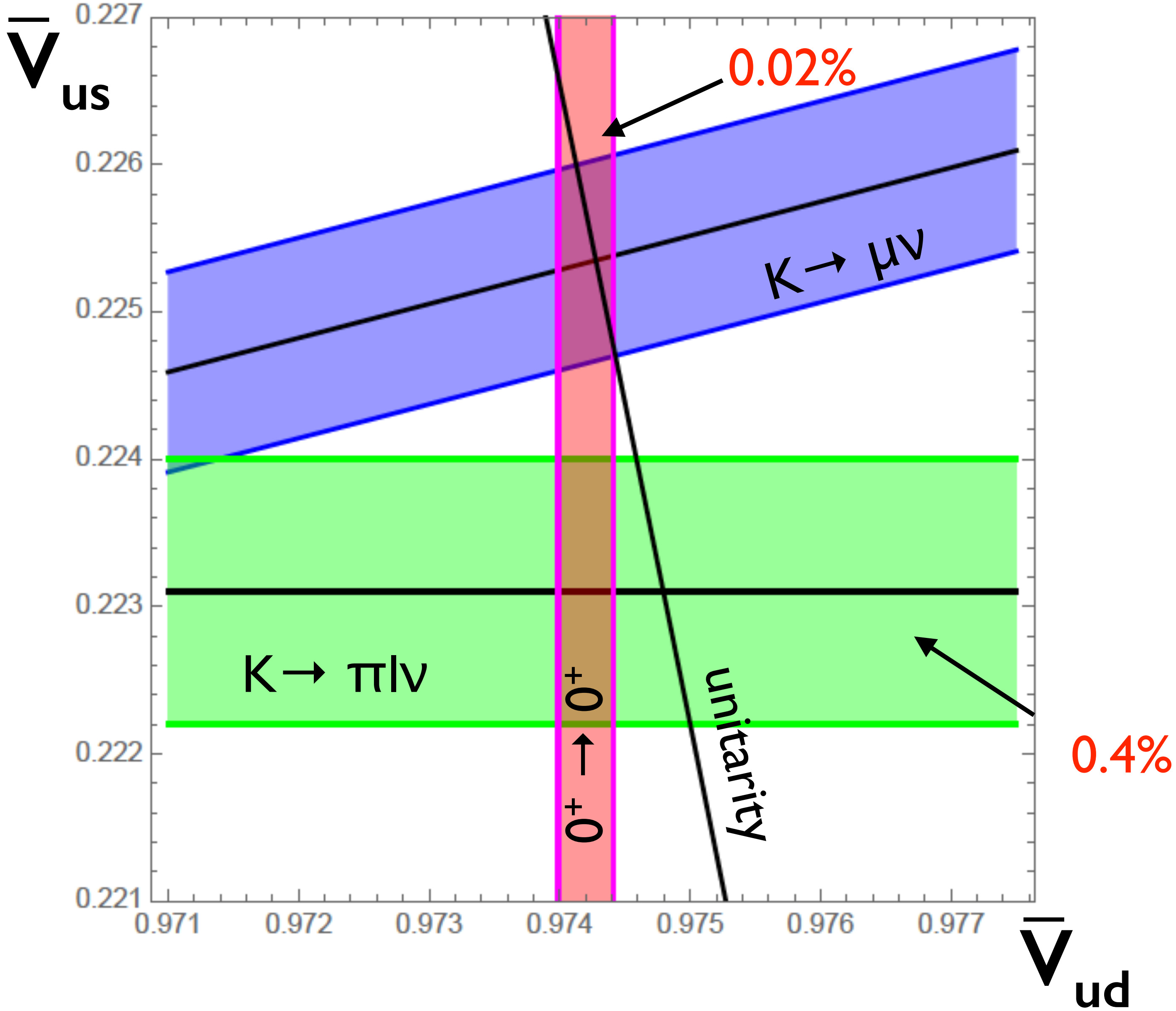
$\Delta_{\rm CKM} = -(4 \pm 5) * 10^{-4}$ ~ 1σ

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

V_{us} from $K\to\pi l\nu$

Cabibbo universality 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

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

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

V_{us} from K→ πlν

Hint of something
[ε's ≠0] or SM theory input?

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

Impact of neutrons

- 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

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

$\delta g_A/g_A \sim 0.15\% \rightarrow 0.03\%$

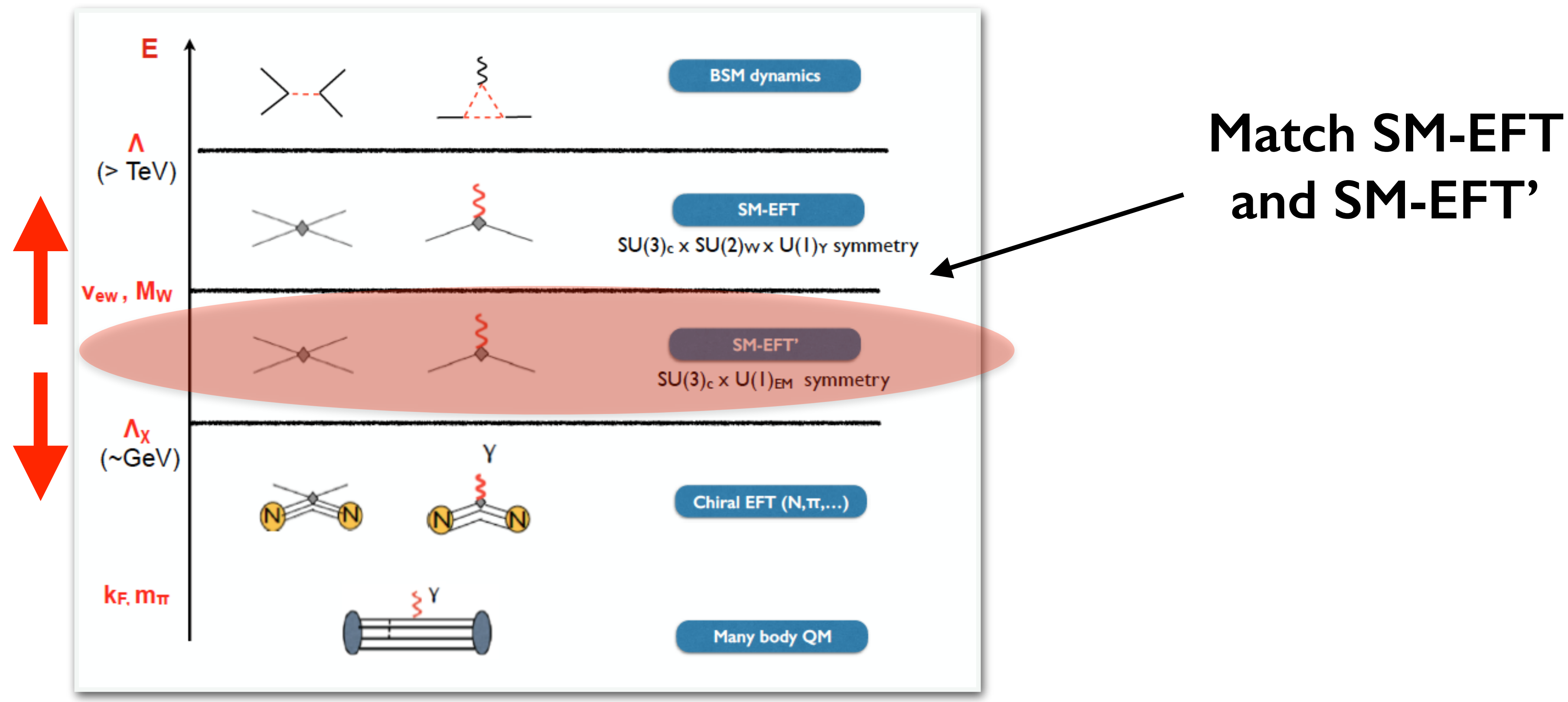
($\delta a/a$, $\delta A/A \sim 0.14\%$)

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+

Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α



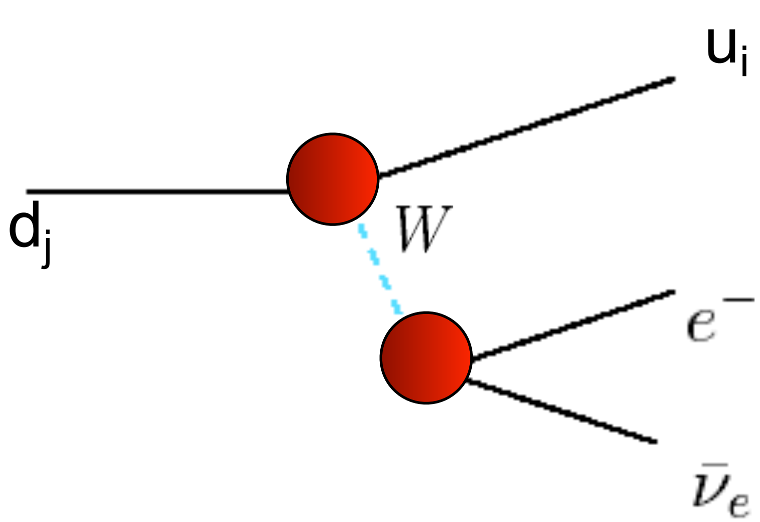
- Model-independent statements possible in <u>"heavy BSM" scenarios</u>: M_{BSM} > TeV → new physics looks point-like at collider

VC, Gonzalez-Alonso, Jenkins 0908.1754

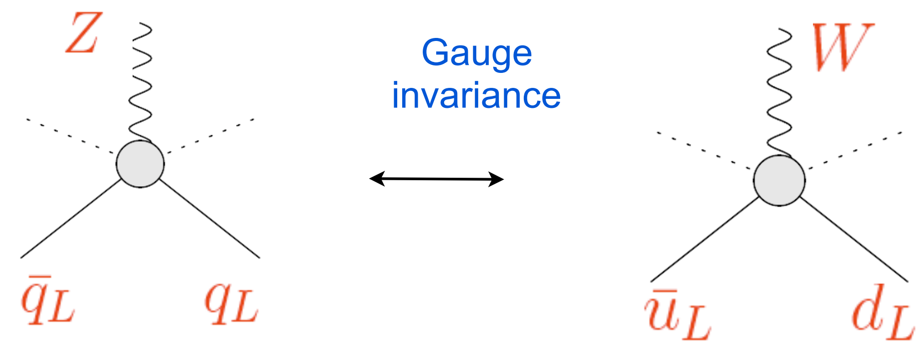
Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

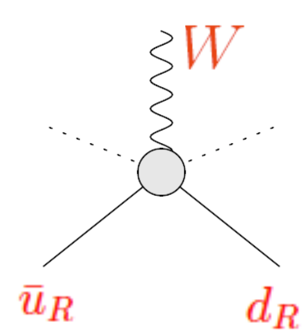
$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



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



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



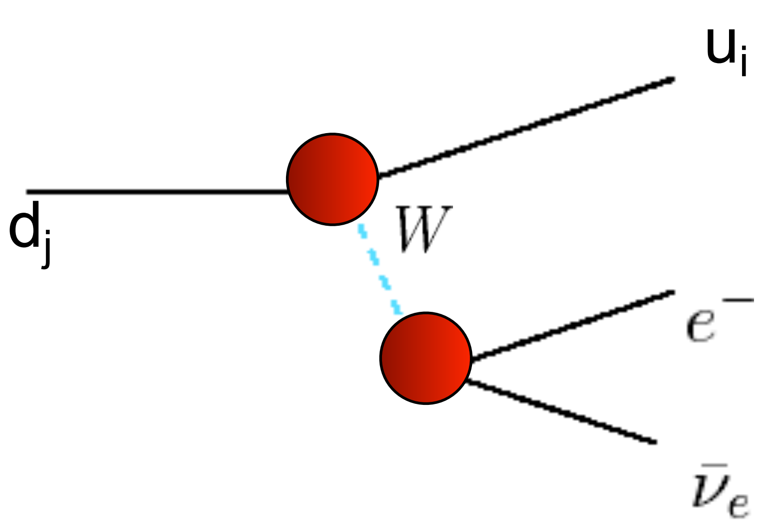
E.g. from W_L-W_R mixing in Left-Right symmetric models

VC, Gonzalez-Alonso, Jenkins 0908.1754

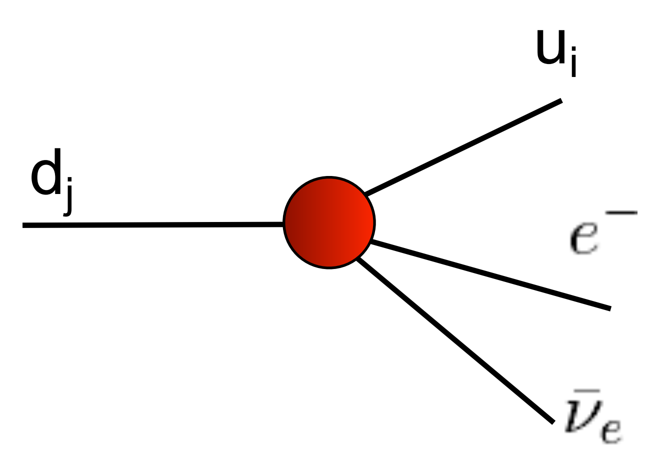
Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



$\varepsilon_{S,P,T}$ and one contribution to ε_L arise from SU(2)xU(1) invariant 4-fermion operators



$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q)$$

$$O_{qde} = (\bar{\ell}e)(\bar{d}q) + \text{h.c.}$$

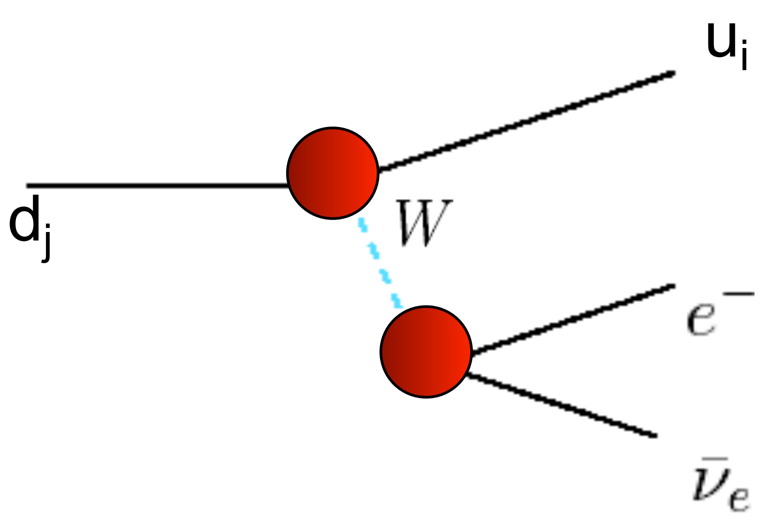
. . .

VC, Gonzalez-Alonso, Jenkins 0908.1754

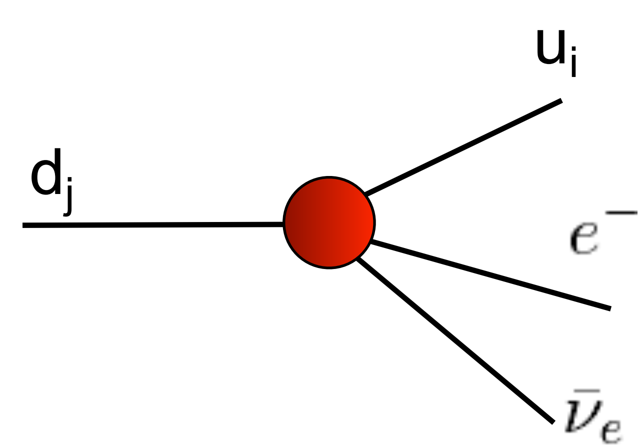
Interplay with High Energy physics

- Need to know high-scale origin of the various ε_α

$\varepsilon_{L,R}$ originate from SU(2)xU(1) invariant vertex corrections



$\varepsilon_{S,P,T}$ and one contribution to ε_L arise from SU(2)xU(1) invariant 4-fermion operators



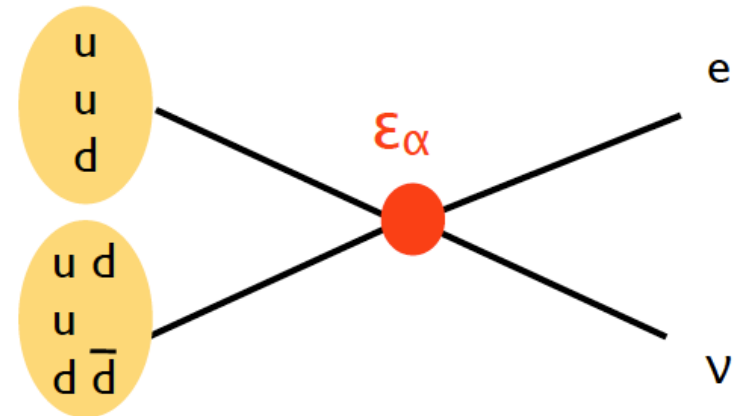
- LEP:
    - Strong constraints (<0.1%) on L-handed vertex corrections (Z-pole)
    - Weaker constraints on 4-fermion interactions (σ_{had})

- What about LHC?

LHC sensitivity: 4-fermions

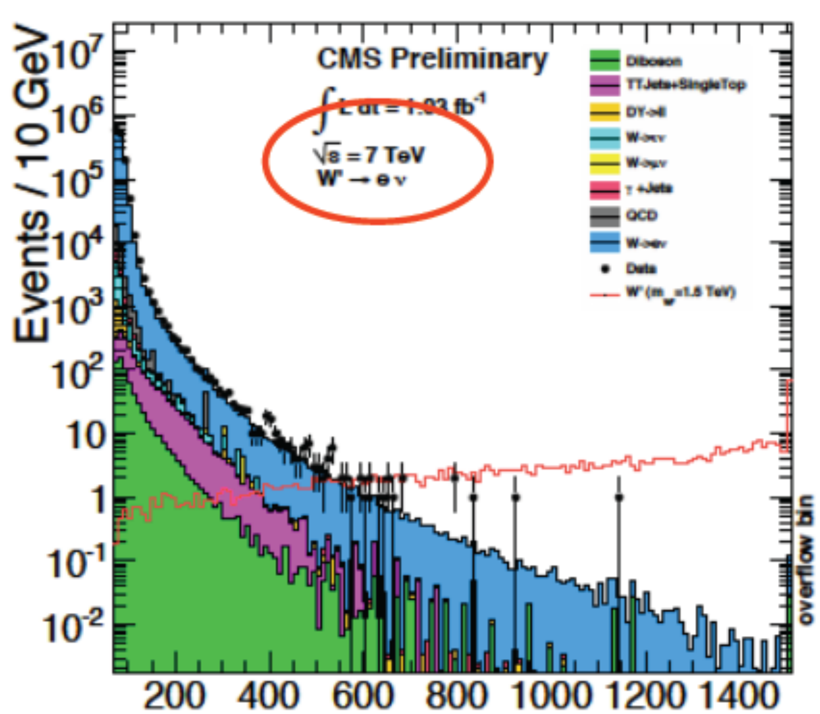
Bhattacharya et al., 1110.6448

- The effective couplings ε_α contribute to the process $pp \rightarrow e\nu + X$



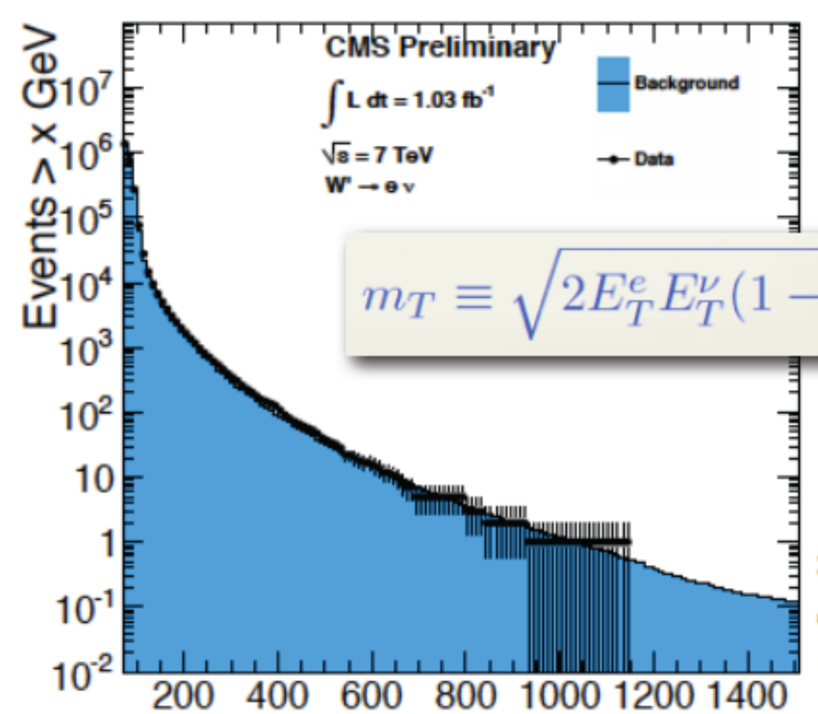
- No excess events in transverse mass distribution: bounds on ε_α

differential



m_T(GeV)

cumulative



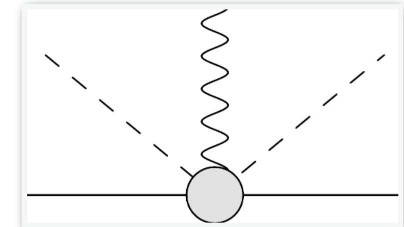
$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1 - \cos\Delta\phi_{e\nu})}$$

m_T(GeV)

LHC sensitivity: vertex corrections

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

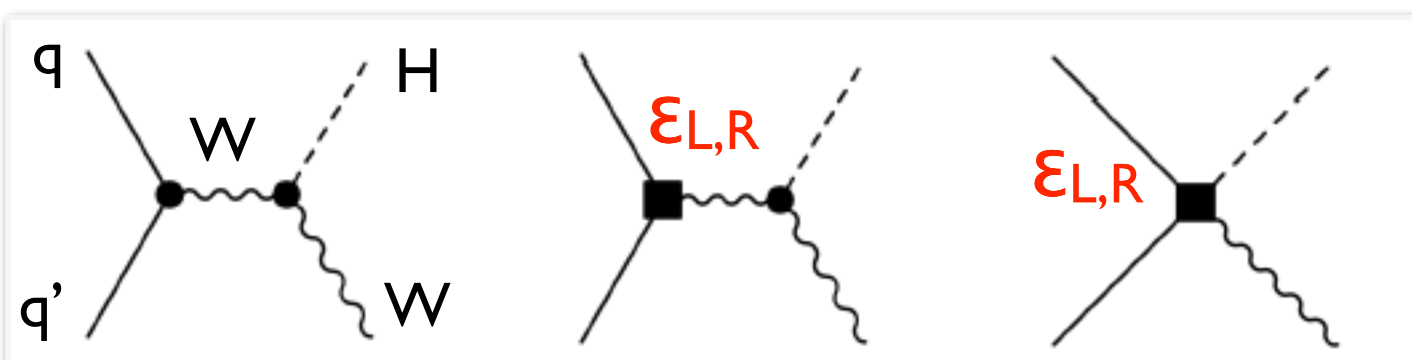
- Vertex corrections inducing $\varepsilon_{L,R}$ in the SM-EFT involve the Higgs field (due to SU(2) gauge invariance)



ε_L $$\varphi^\dagger \tau^a D_\mu \varphi \;\; \bar{q}_L \tau^a \gamma^\mu q_L$$

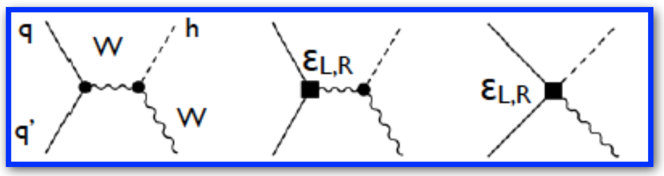
ε_R $$\varphi^T \epsilon D_\mu \varphi \;\; \bar{u}_R \gamma^\mu d_R$$

- Can be probed at the LHC by associated Higgs + W production



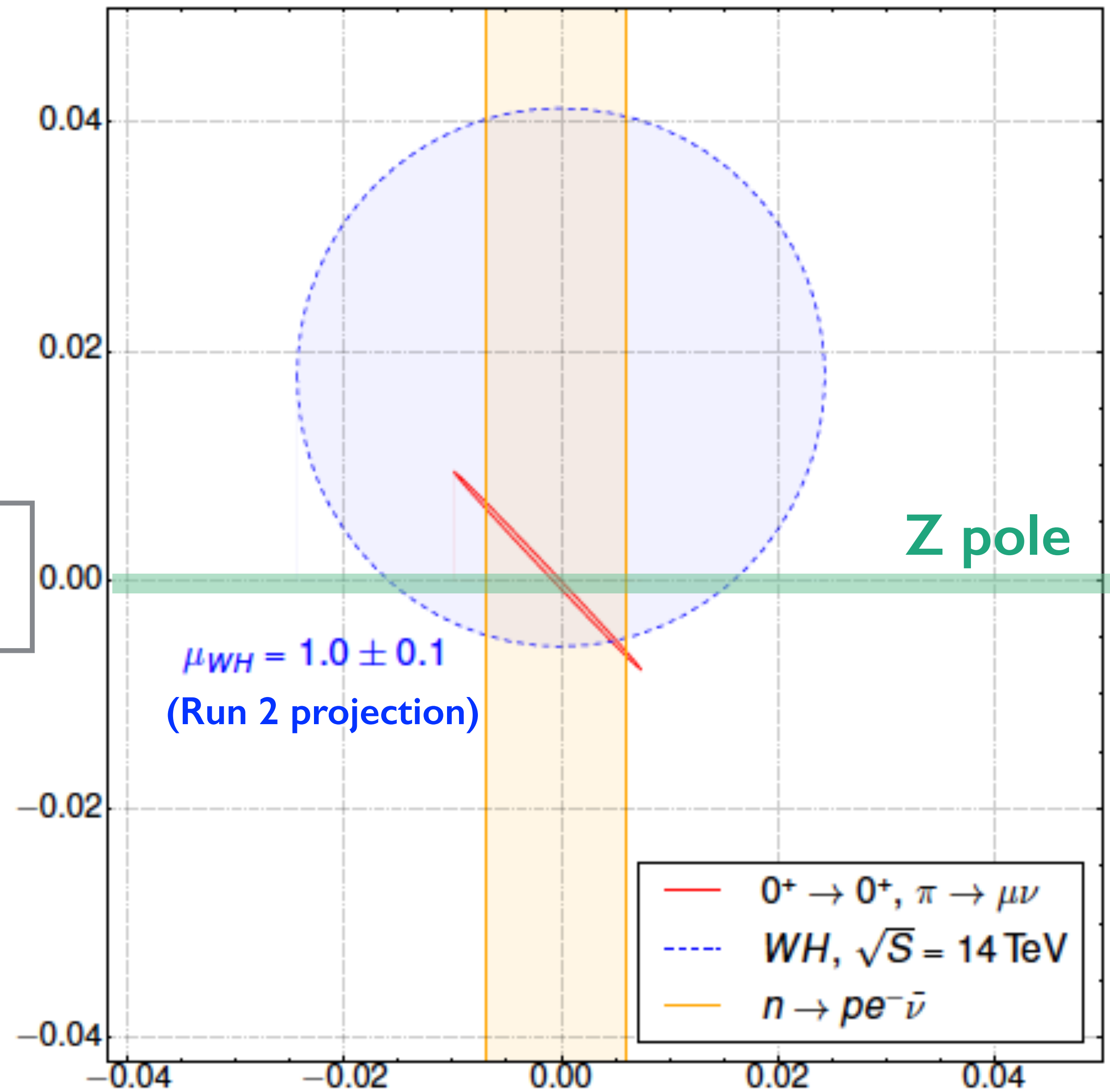
Example 1: ε_L and ε_R couplings

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



Z-pole → $\varepsilon_L^{(\nu)}$
Falkowski et al
1706.03783

90%CL, assumes only two operators at high scale



ε_L

ε_R

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]

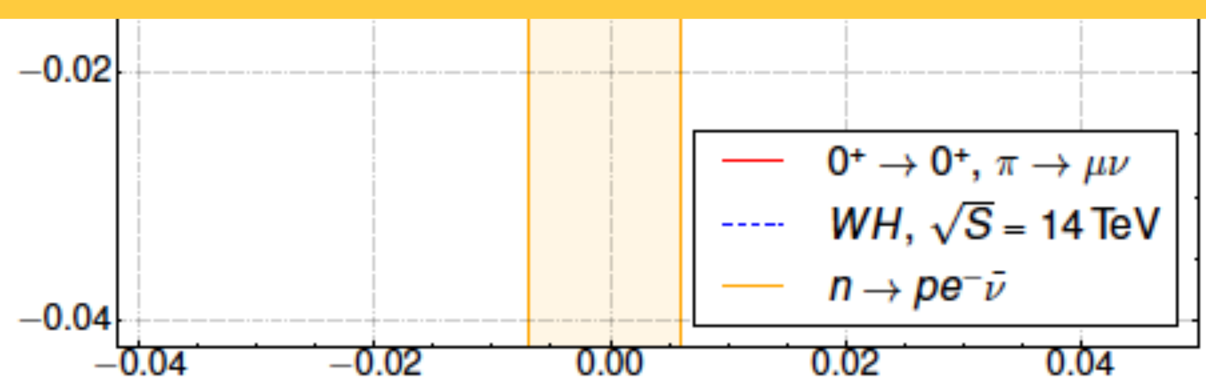
Example 1: ε_L and ε_R couplings

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

Several lessons:

- Beta decays can be quite competitive with collider
- Connection between CC and NC (gauge invariance!)
- Caveat: going beyond a 2-operator analysis relaxes some of these constraints (but not the one on ε_R from λ)
- All in all, beta decays provide *independent competitive constraints* in a global analysis

Z-pole → $\varepsilon_L^{(v)}$
Falkowski et al
1706.03783



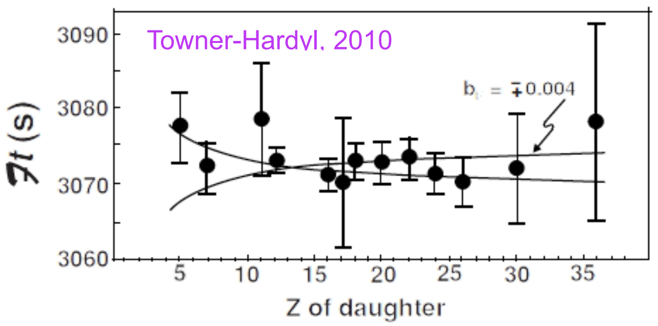
ε_R

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

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

Example 2: ε_S and ε_T couplings

$0^+ \rightarrow 0^+$ (b_F)



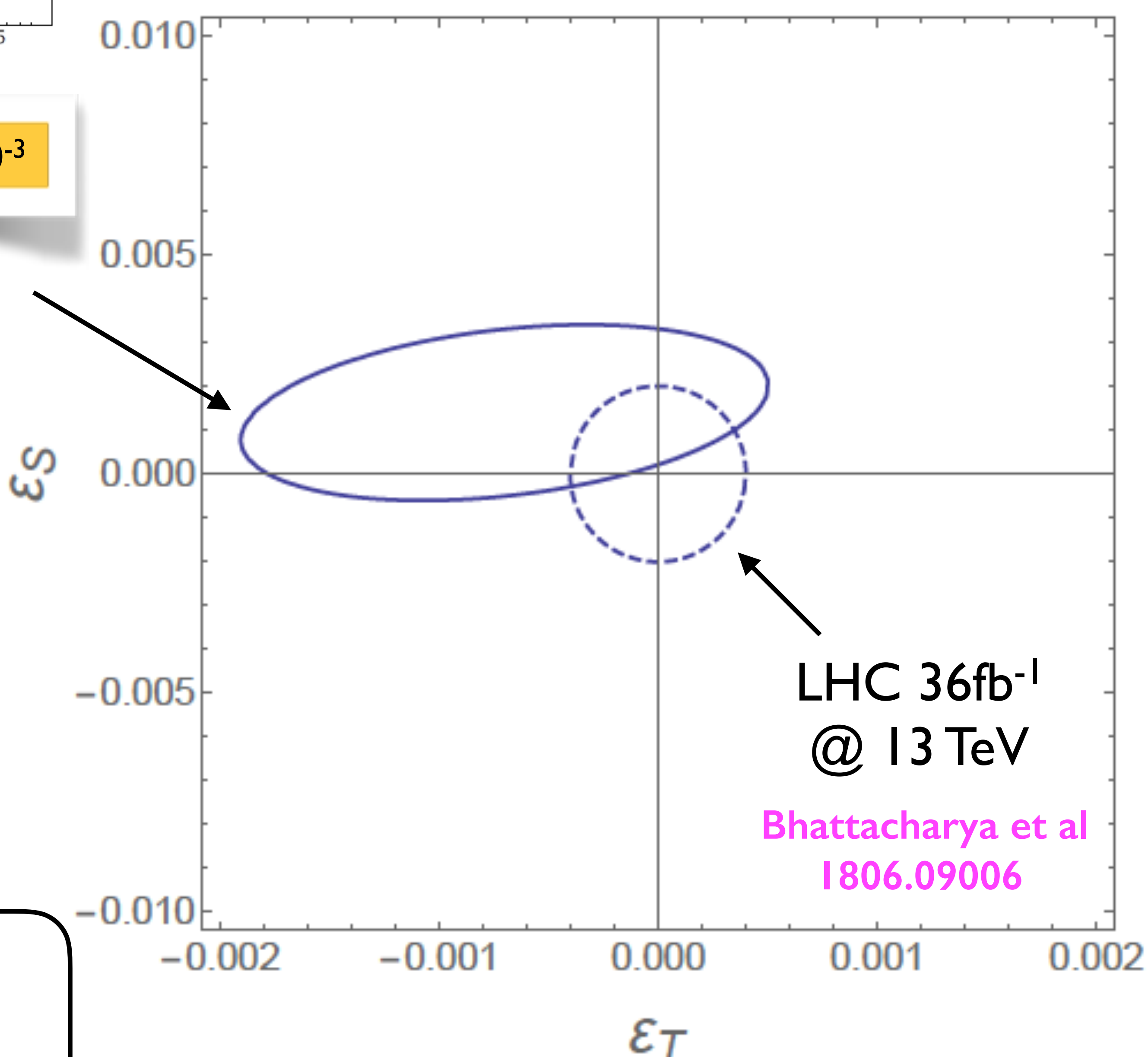
$-1.0\times10^{-3} < g_S\ \varepsilon_S < 3.2\times10^{-3}$

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

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

CURRENT

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



g_S =1.01(10)
g_T =0.99(4)
Bhattacharya et al (PNDME) 1806.09006

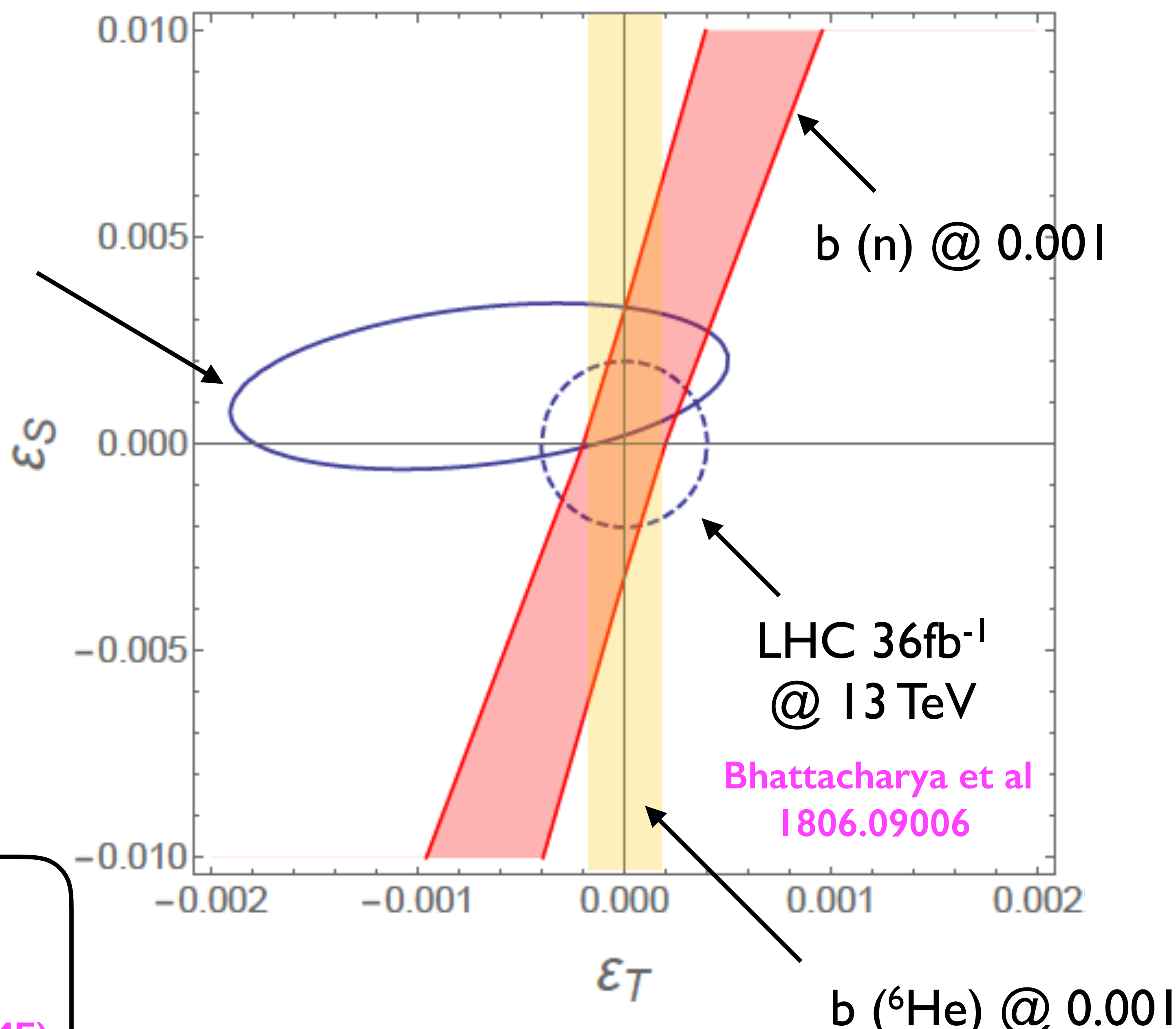
Example 2: ε_S and ε_T couplings

FUTURE

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

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

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732



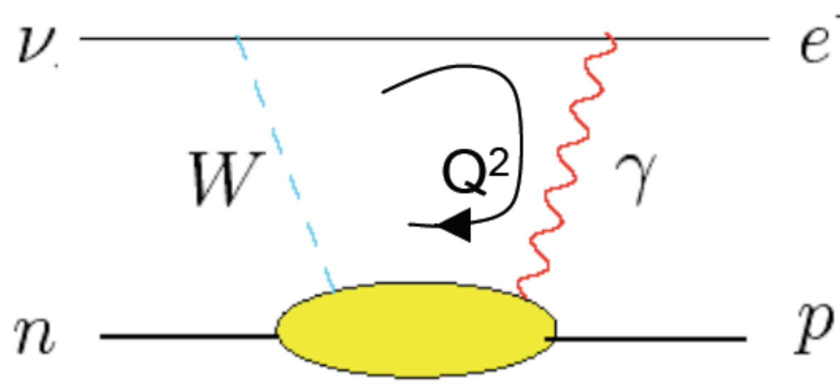
LHC puts very strong constraints on 4-fermion interactions

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

g_S =1.01(10)
g_T =0.99(4)
Bhattacharya et al (PNDME) 1806.09006

Looking ahead

- The next frontier in beta decays will likely include
  - Experiment: $\delta\tau_n \sim 0.1$s, <0.1% precision in neutron and nuclear correlation coefficients
  - Theory: g_A at sub-percent level from LQCD (?); improved radiative corrections: dispersive methods** and lattice QCD



This is currently the dominant contribution to V_{ud} error from $0^+ \to 0^+$: $\Delta_R = (2.36 \pm 0.04)\%$ [Marciano-Sirlin 2006]

** Recent preprint by Seng, Gorchtein, Patel, Ramsey-Musolf [1007.10197] finds $\Delta_R = (2.467 \pm 0.022)\%$
$\Delta_{CKM} = -(17 \pm 4) \times 10^{-4}$

Neutrinoless double beta decay: B-L violation and nature of ν's

Experimental aspects discussed in Krishna Kumar's lecture

Probing the νSM

- Neutrino mass requires introducing new degrees of freedom in the SM

Dirac mass:

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

- Requires introducing ν_R and using Higgs to make it SU(2) invariant at dim=4 (as for other fermions)
- Violates $L_{e,\mu,\tau}$, conserves L

Probing the νSM

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- Violates $L_{e,\mu,\tau}$, conserves L

Majorana mass:

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

- Can be made SU(2) invariant at dim-4 via Higgs triplet; or more generally at dim-5

$$\mathcal{L}_5 = \frac{g_{\alpha\beta}}{\Lambda} \, \ell_\alpha^T C \epsilon \phi \, \phi^T \epsilon \ell_\beta$$

Weinberg 1979

- Violates $L_{e,\mu,\tau}$, breaks total lepton number $\Delta L=2$

Dirac vs Majorana: simple test?

- Thought experiment (B. Kayser): generate ν beam from $\pi^+ \rightarrow \mu^+ \nu$ and check whether it produces μ^+ on a target downstream:
    - A Dirac neutrino in either helicity state won't do that
    - A Majorana neutrino with R-helicity will do that

Dirac vs Majorana: simple test?

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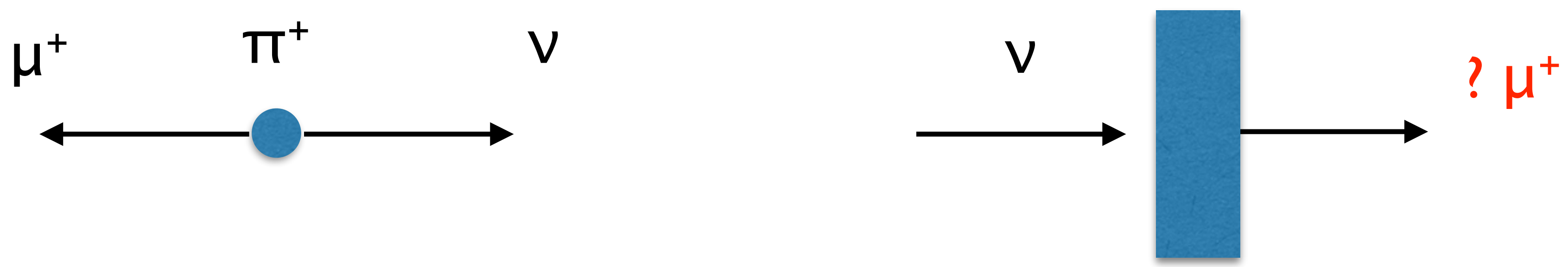
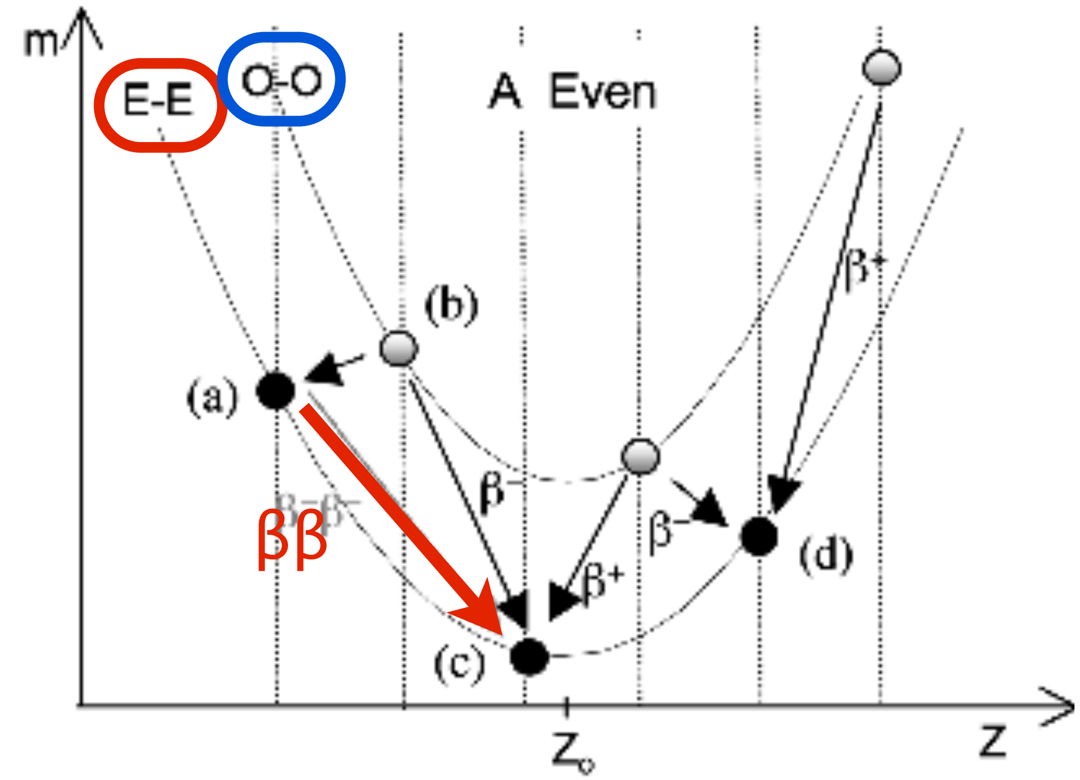


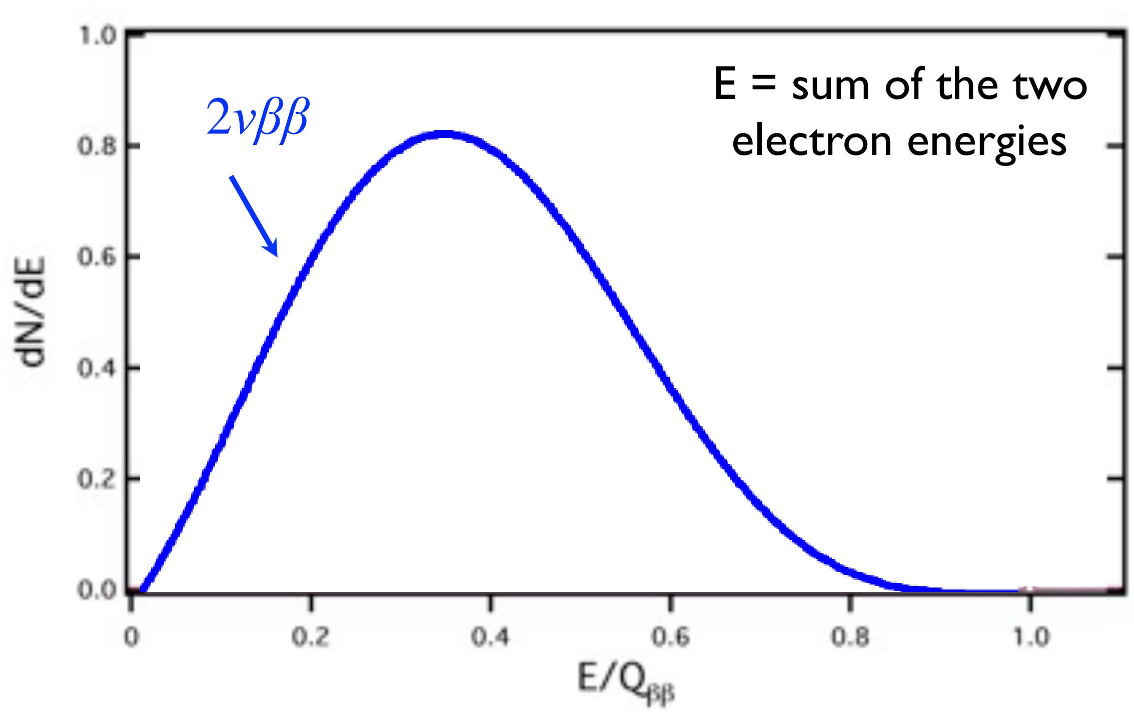
- But fraction of R-helicity ν's produced in $\pi^+ \to \mu^+ \nu$ is $\sim (m_\nu/E_\nu)^2 < 10^{-16}$!!

Observing lots of nuclei for a long time is our best bet: neutrinoless double beta decay

Double beta decay

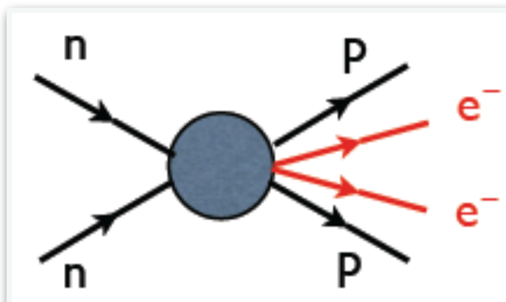
- For certain even-even nuclei (^{48}Ca, ^{76}Ge, ^{136}Xe, …), single beta decay is energetically forbidden
- 2νββ is a (very rare) 2nd order weak process, expected in the Standard Model and observed
- 0νββ is quite special



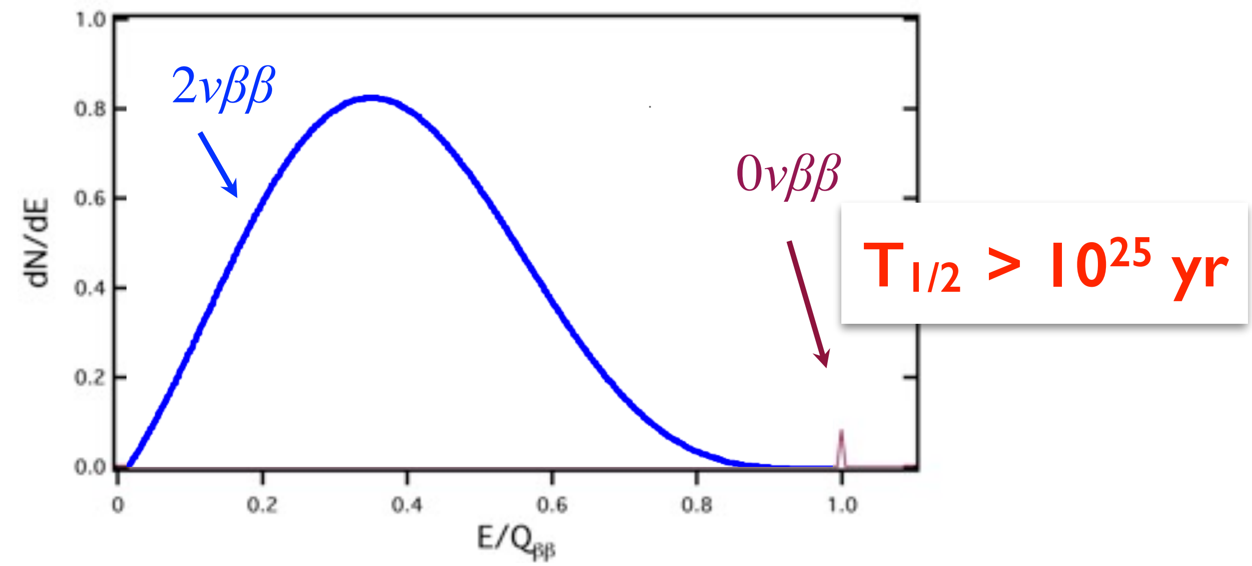


0νββ and Lepton Number Violation

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



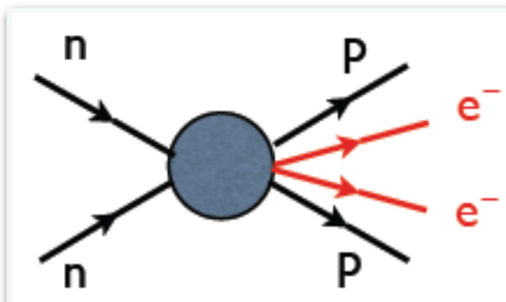
Lepton number changes by two units: ΔL=2



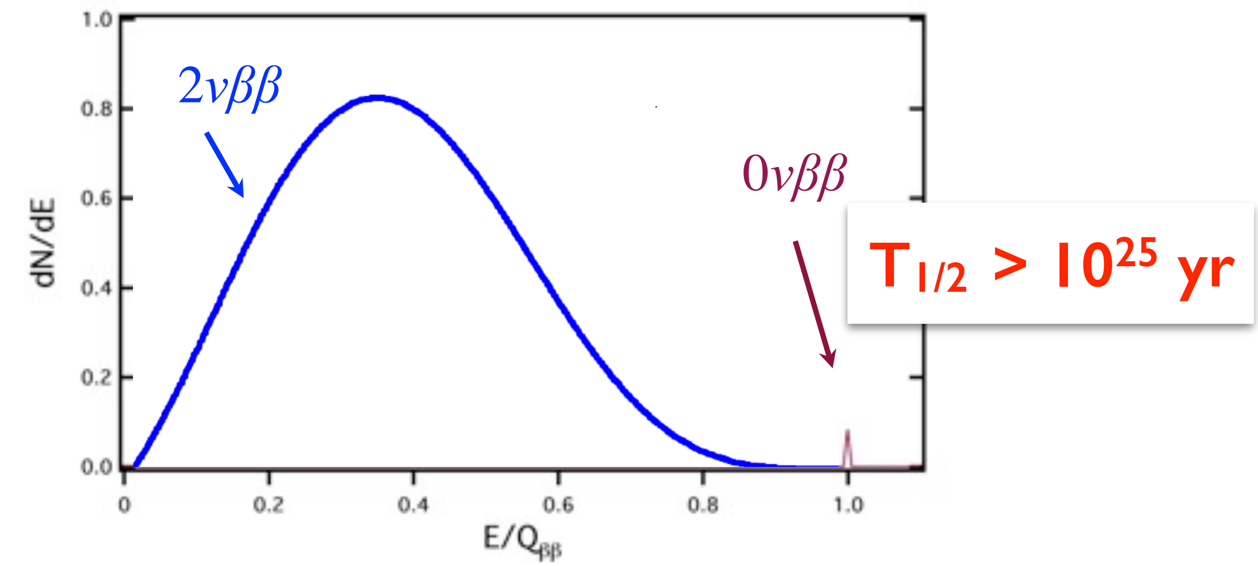
- B-L conserved in SM → 0νββ observation would signal new physics

0νββ and Lepton Number Violation

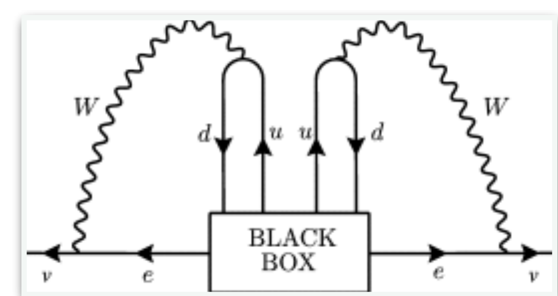
$$(N,Z) \rightarrow (N-2, Z+2) + e^- + e^-$$



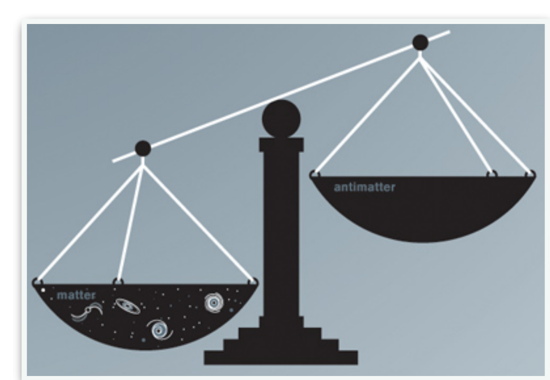
Lepton number changes by two units: $\Delta L=2$



- B-L conserved in SM → 0νββ observation would signal new physics
  - Demonstrate that neutrinos are Majorana fermions
  - Establish a key ingredient to generate the baryon asymmetry via leptogenesis



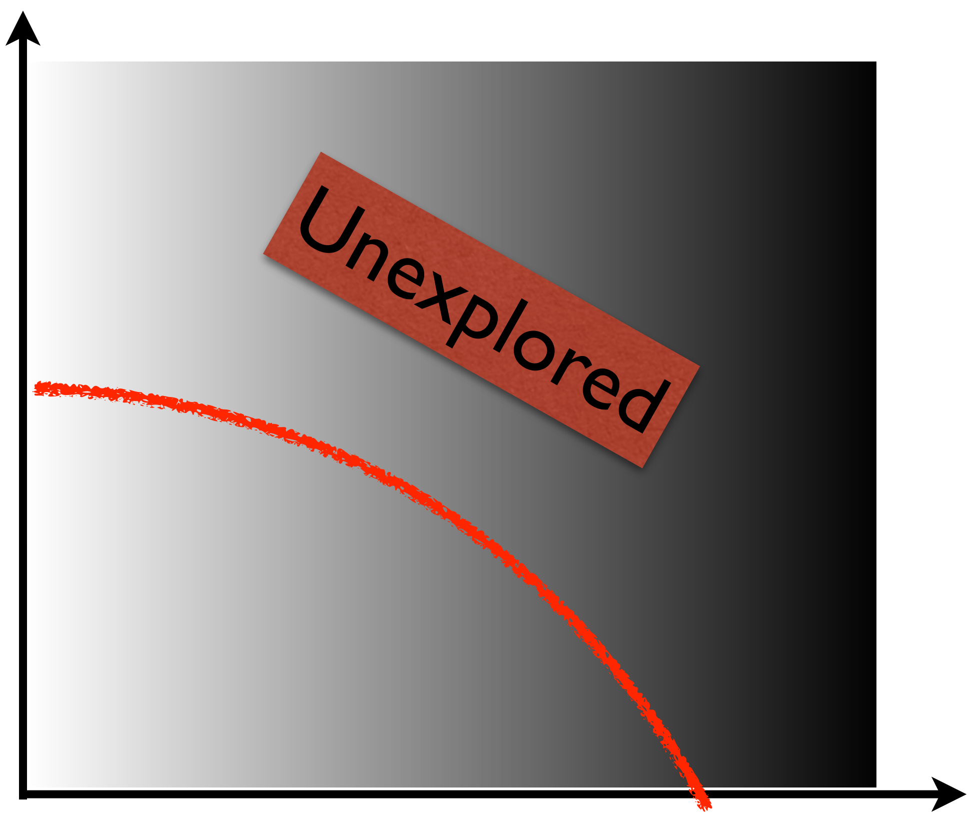
Shechter-Valle 1982

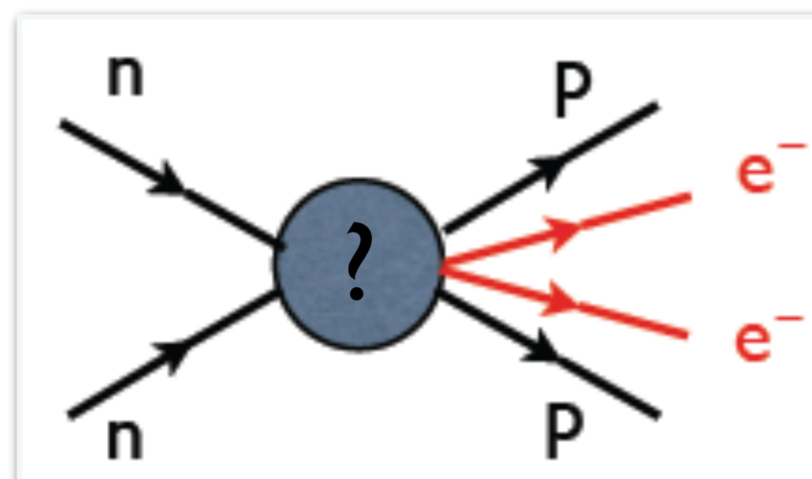


Fukujgita-Yanagida 1987

$0\nu\beta\beta$ and Lepton Number Violation

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





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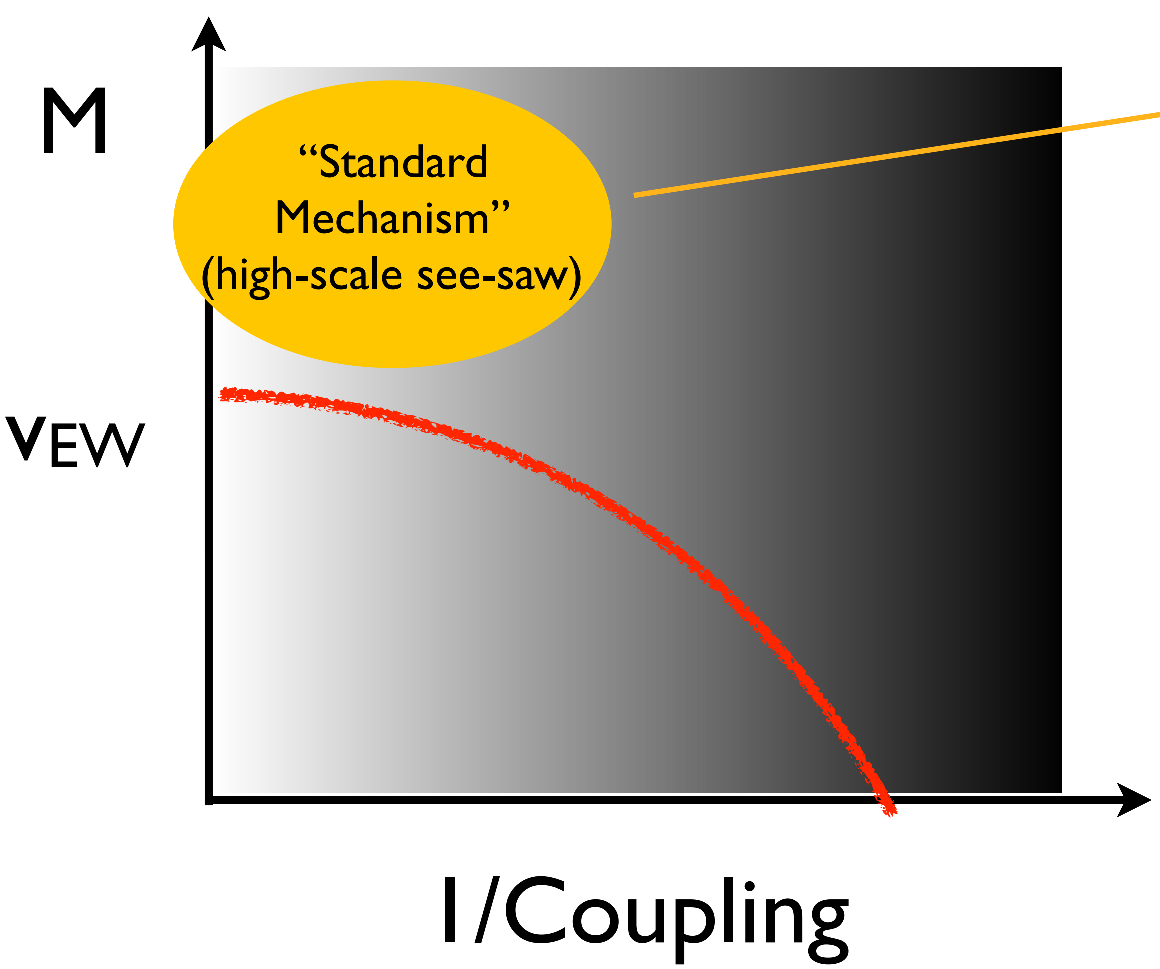
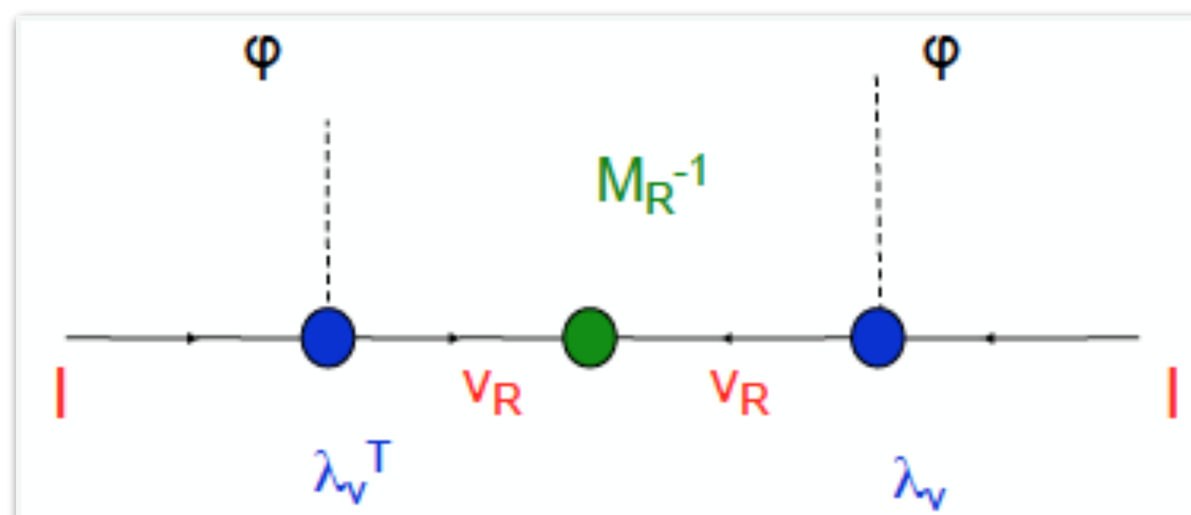


LNV dynamics at M >> TeV:
it leaves as *only* low-energy footprint
3 light Majorana neutrinos

Example: 3 heavy R-handed neutrinos



$$m_\nu \sim (v_{EW})^2 \, \lambda_\nu^T \, M_R^{-1} \, \lambda_\nu$$

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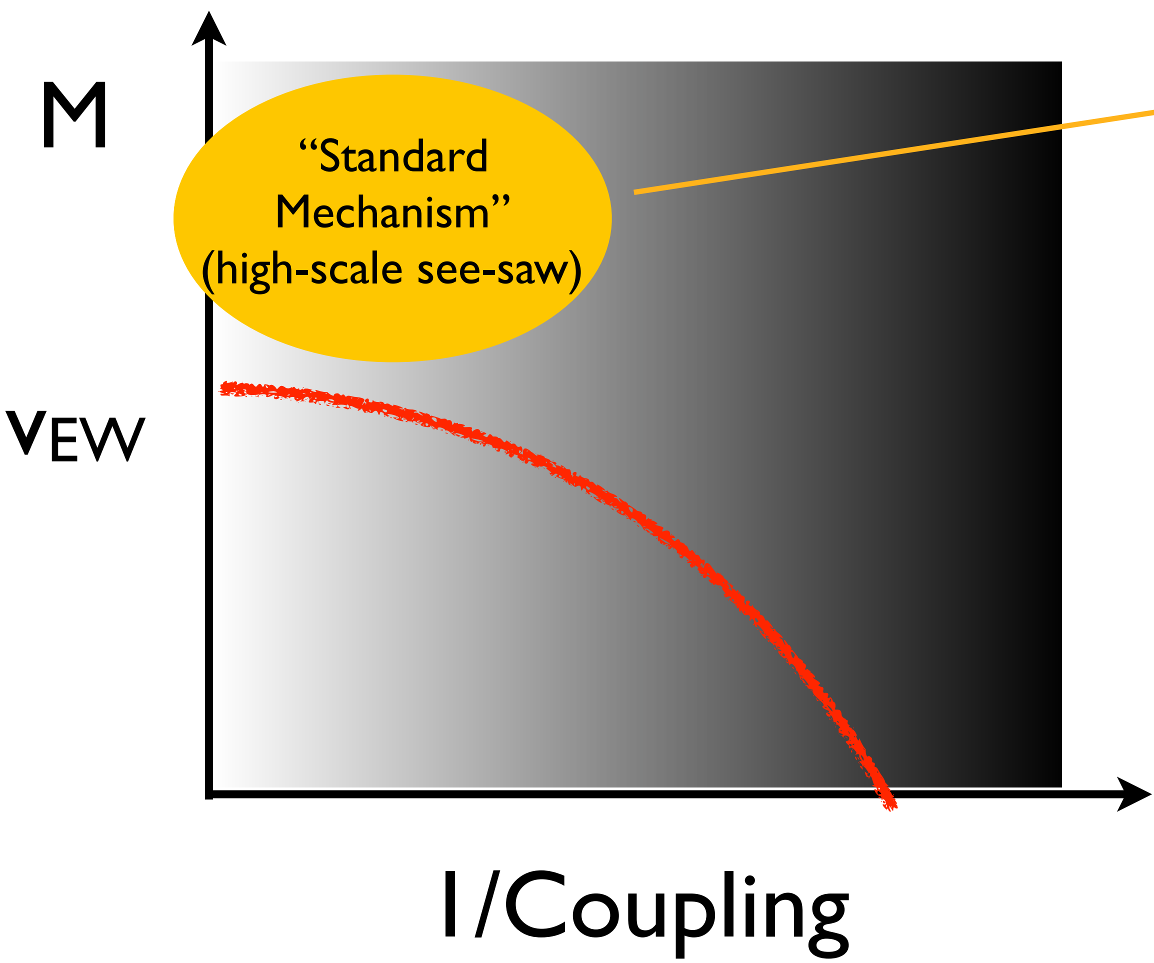

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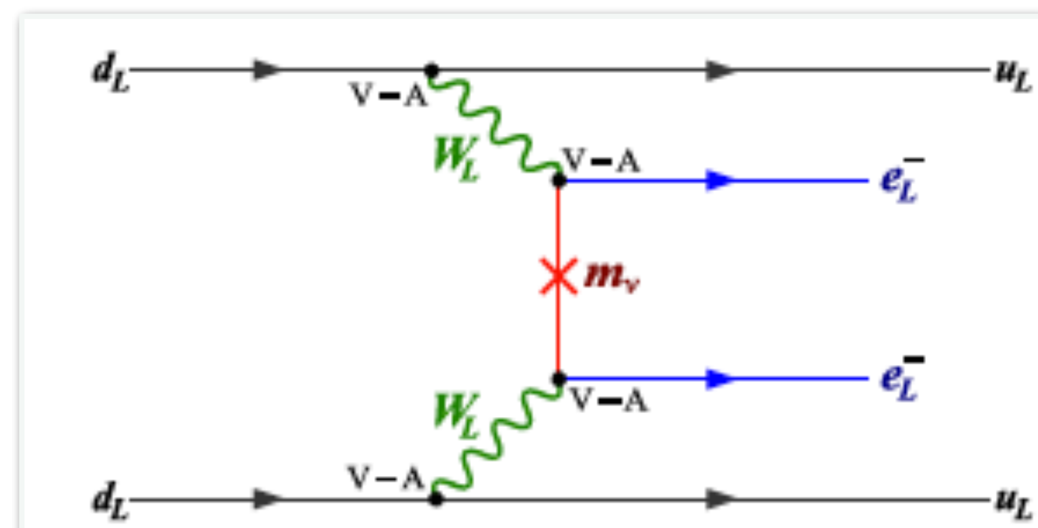

Amplitude proportional to

$$m_{\beta\beta} = \sum U_{ei}^2 m_i$$

0νββ and Lepton Number Violation

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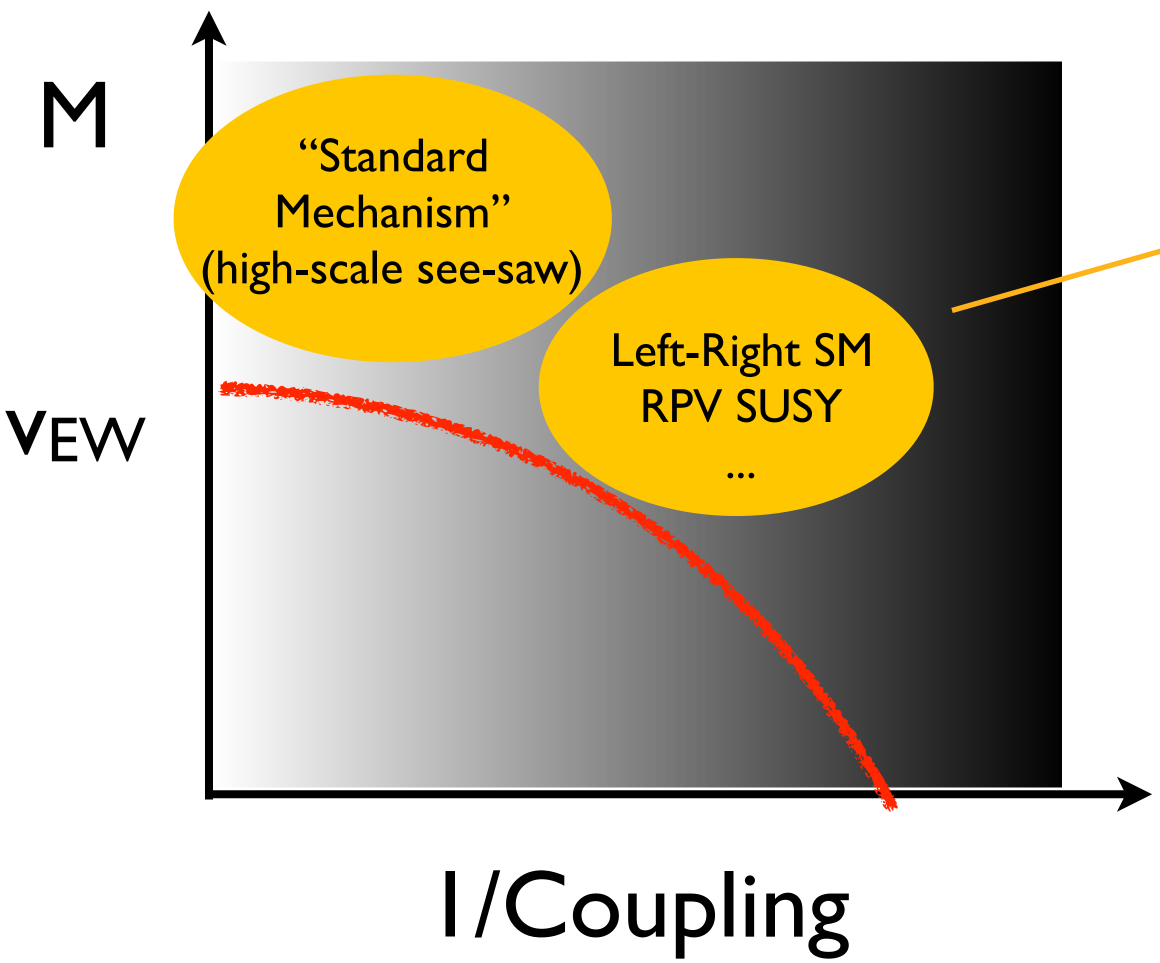
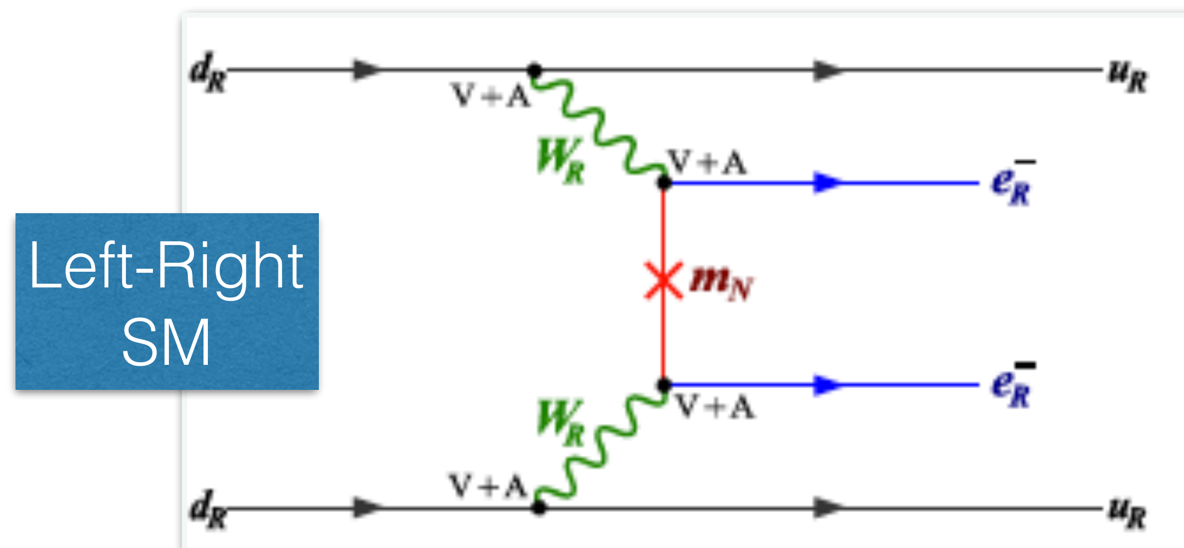


LNV dynamics at M ~ TeV:
1) new contribution to 0νββ not related to light neutrino mass;
2) pp → eejj at the LHC



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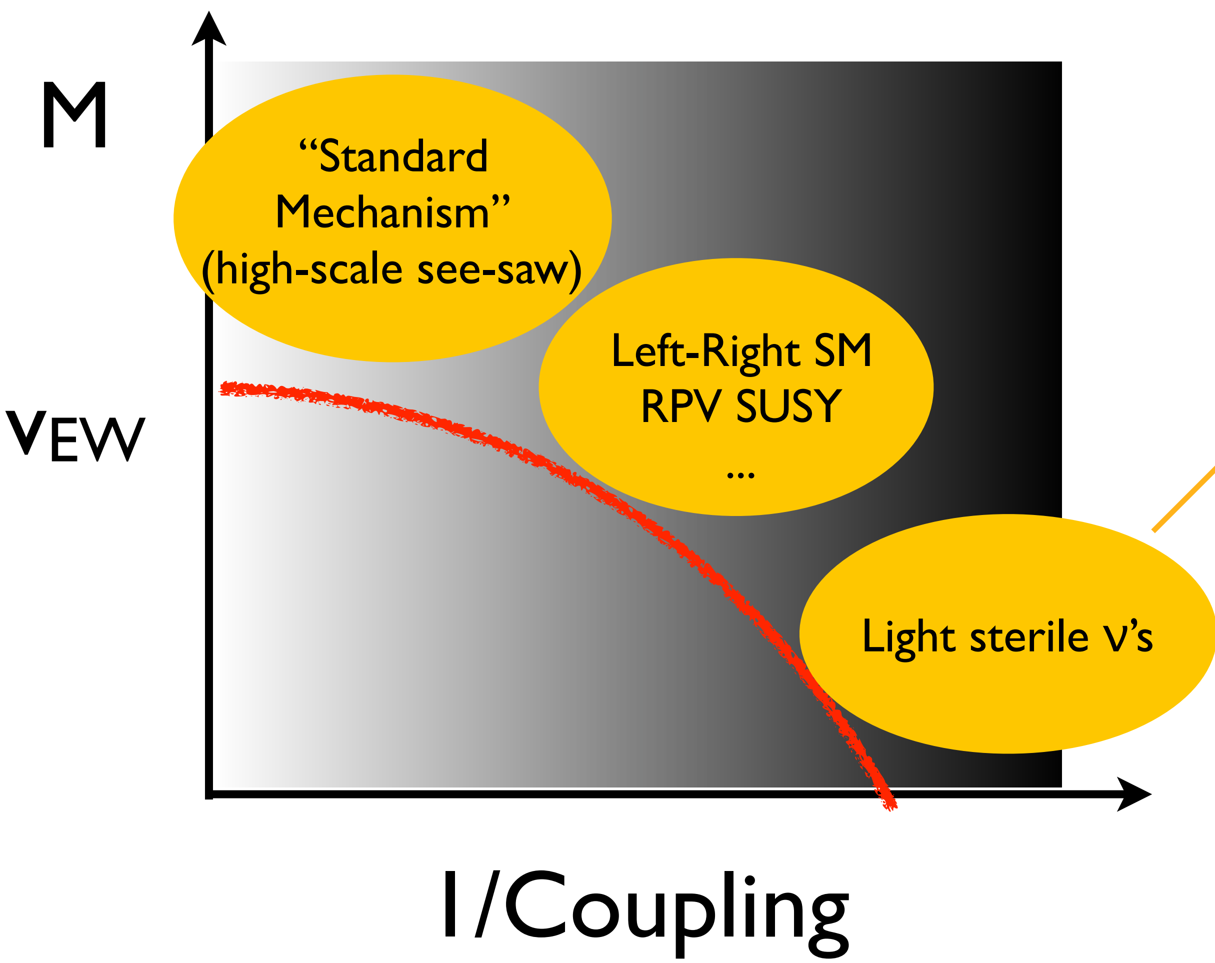
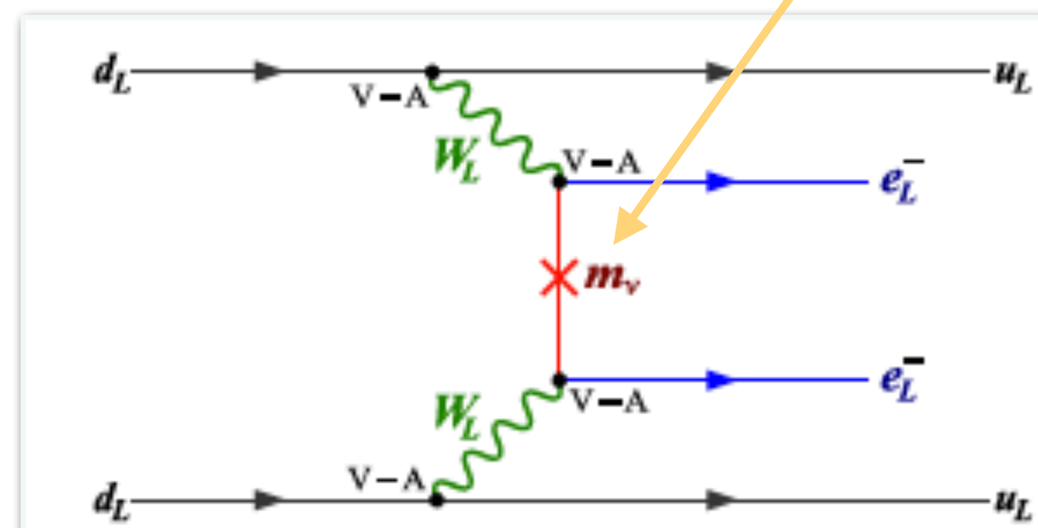


Additional light Majorana states (e.g. induced by singlet ν_R's with M_R: eV → GeV)



0νββ and Lepton Number Violation

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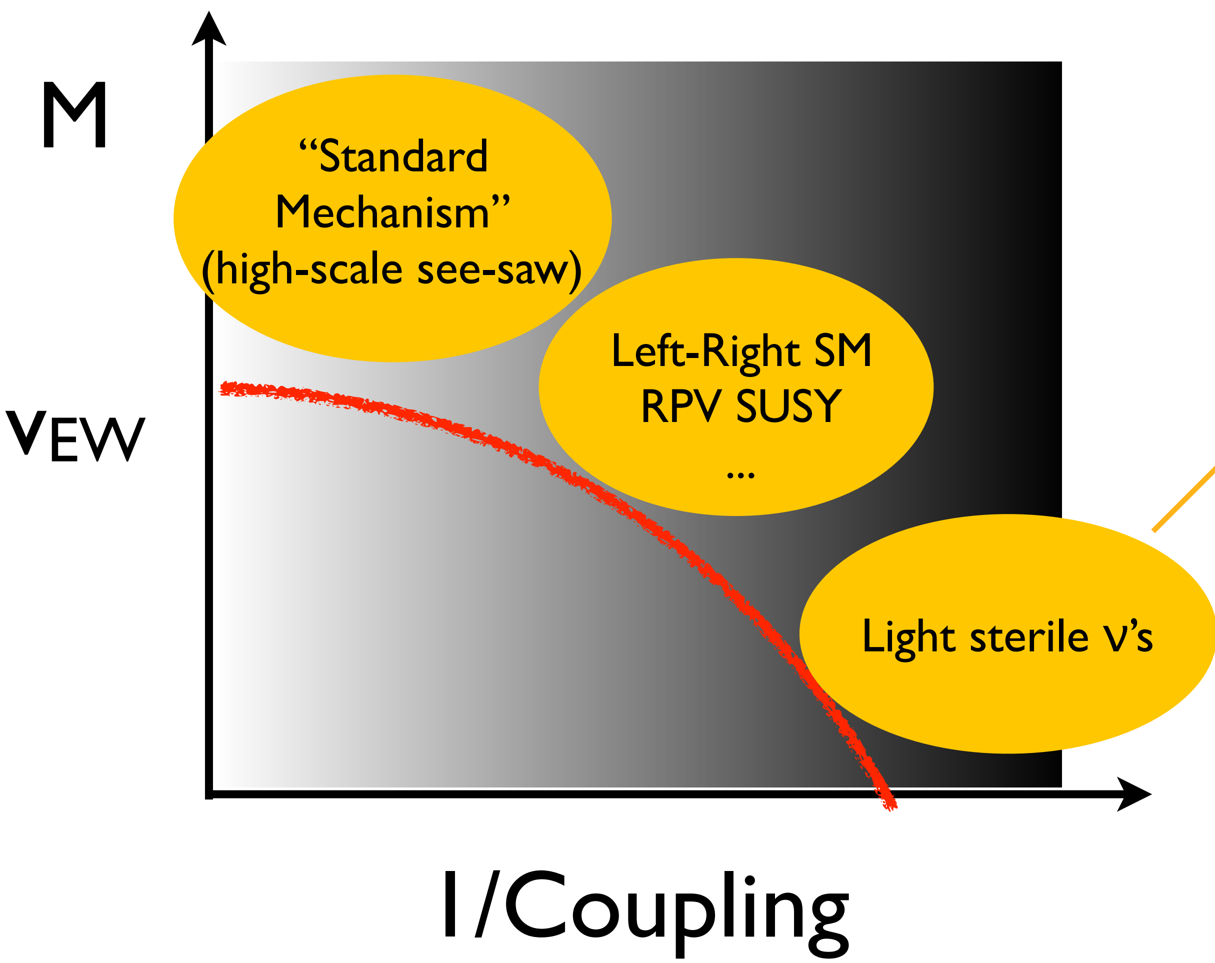

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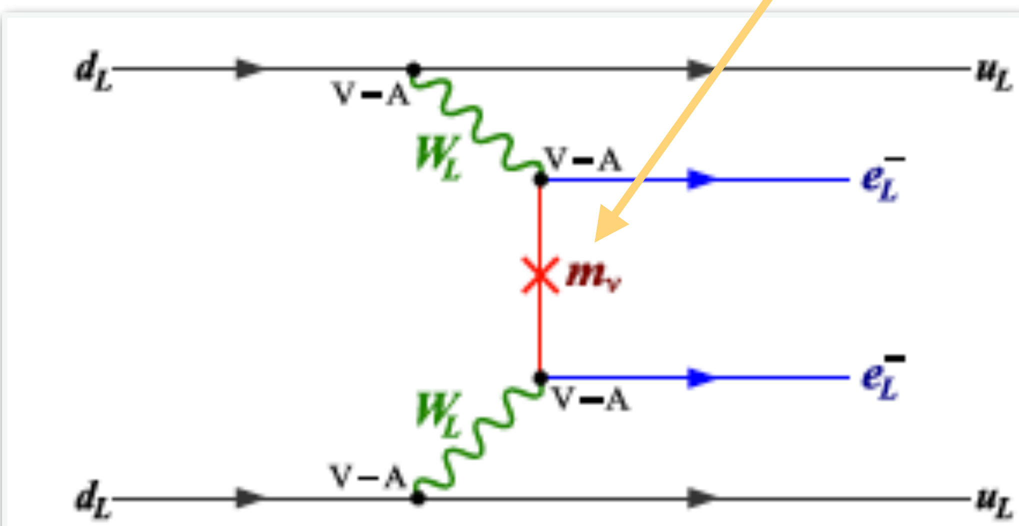
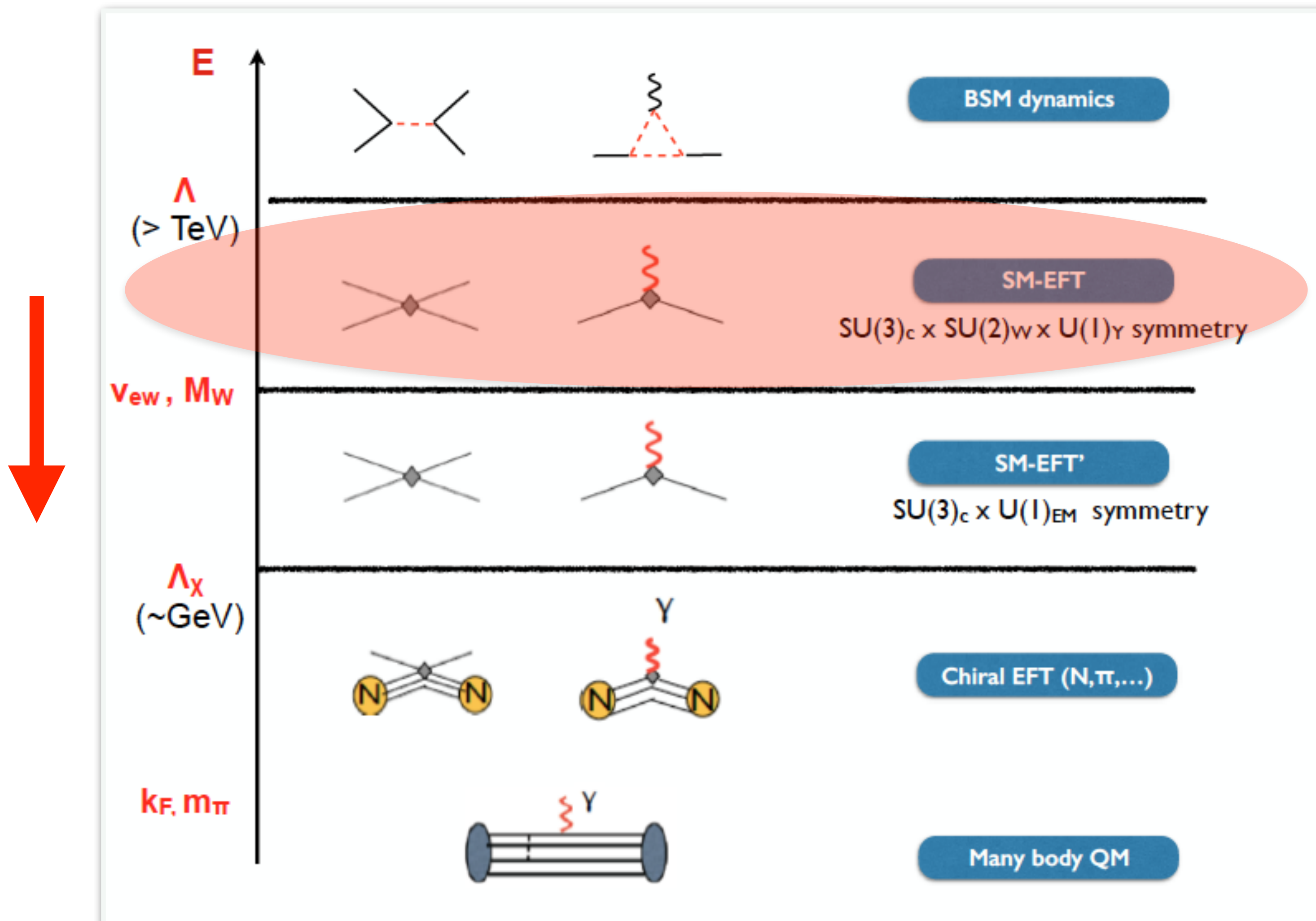


Impact of 0νββ searches most efficiently analyzed in EFT framework

High-scale effective Lagrangian



High-scale effective Lagrangian

- ΔL=2 operators appear at dim = 5, 7, 9, …

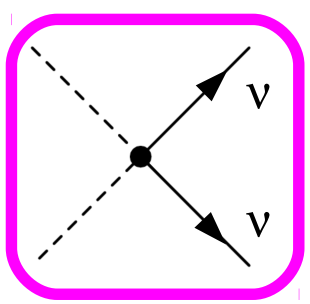
$$\mathcal{L}_{\text{eff}}^{\Delta L=2} = \frac{C^{(5)}}{\Lambda} O^{(5)} + \sum_i \frac{C_i^{(7)}}{\Lambda^3} O_i^{(7)} + \sum_i \frac{C_i^{(9)}}{\Lambda^5} O_i^{(9)} + \ldots$$

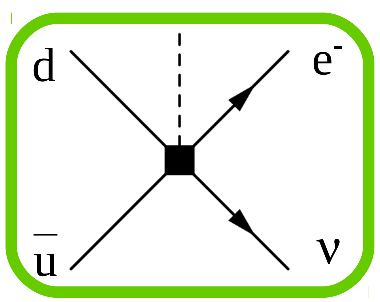
- One operator
- Twelve operators
- Eleven 6-fermion operators

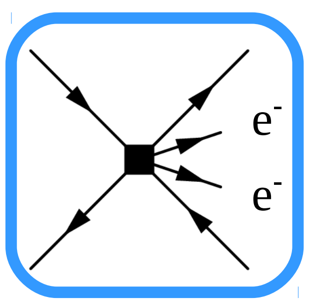
Weinberg 1979

Lehman 1410.4193

Graesser 1606.04549







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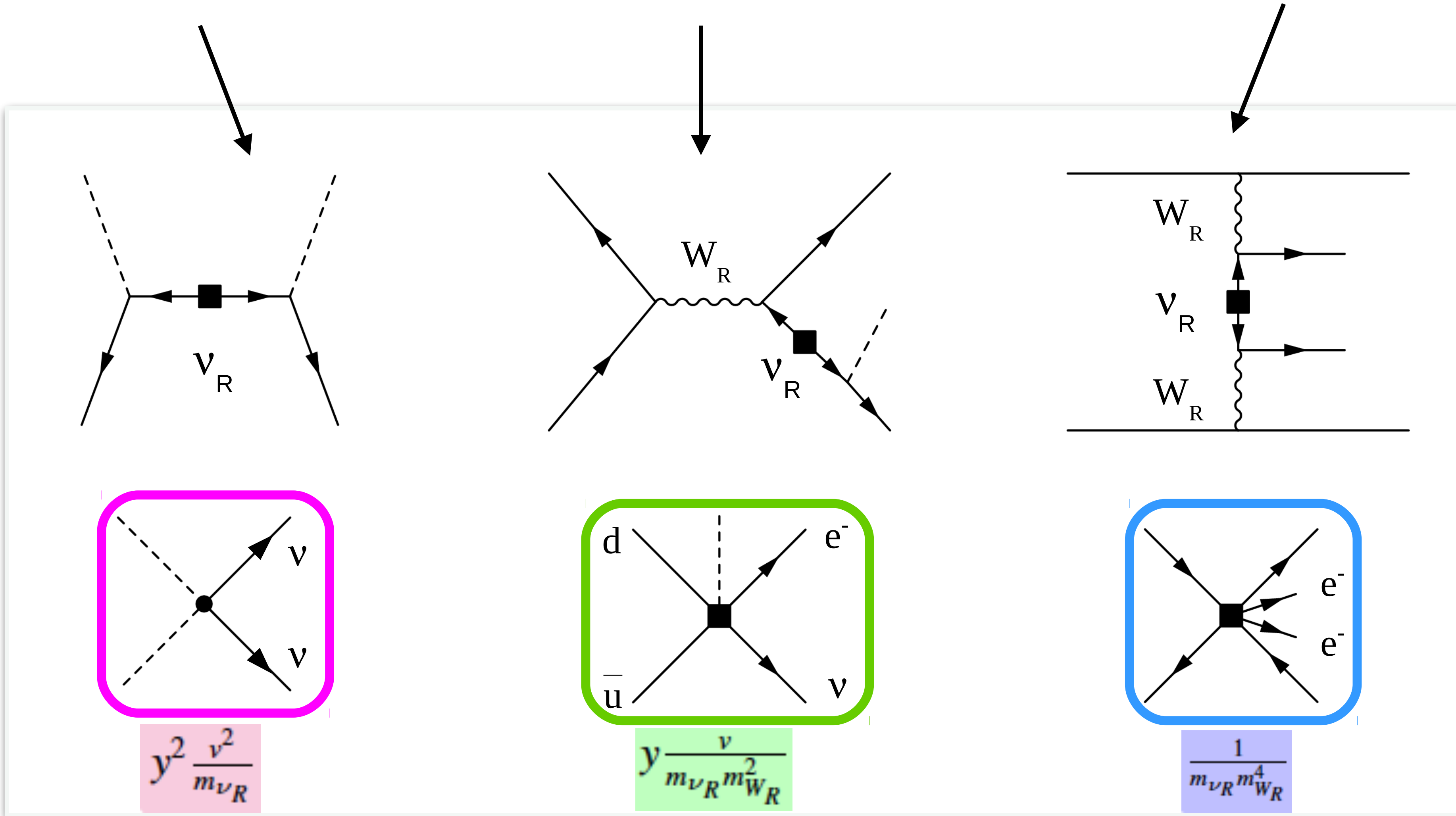
Model realization: Left-Right SM

For Λ~ TeVs, higher dim. ops. compete due to smallness of Yukawa couplings

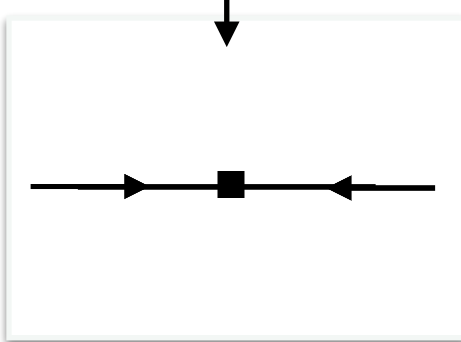


GeV-scale effective Lagrangian

- When the dust settles, get three classes of ΔL=2 operators

$v = \left(\sqrt{2}G_F\right)^{-1/2}$ $\quad \dfrac{v^2}{\Lambda}$ (dim-3)

$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2} m_{\beta\beta}\, \nu_{eL}^T C \nu_{eL}$$



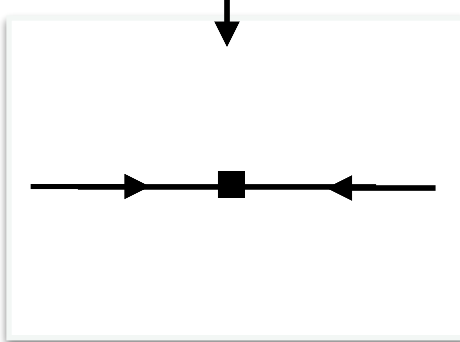
$m_{\beta\beta} = \sum U_{ei}^2 m_i$

GeV-scale effective Lagrangian

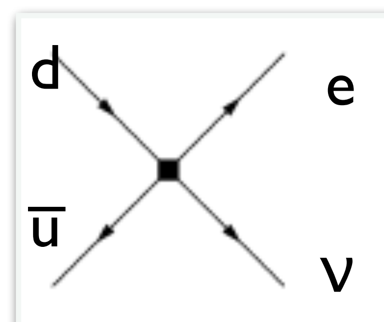
- When the dust settles, get three classes of ΔL=2 operators

$v = \left(\sqrt{2} G_F\right)^{-1/2}$ $\qquad \frac{v^2}{\Lambda}$ (dim-3) $\qquad \frac{v}{\Lambda^3}$ (dim-6)

$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2} m_{\beta\beta}\, \nu_{eL}^T C \nu_{eL} \; + \; C_\Gamma \; \bar{e} \Gamma C \bar{\nu}^T \; O_{2q}^{\Gamma} \;\; .$$



quark bilinears



$m_{\beta\beta} = \sum U_{ei}^2\, m_i$

Pas, Hirsch, Klapdor-Kleingrothaus, Kovalenko 1999

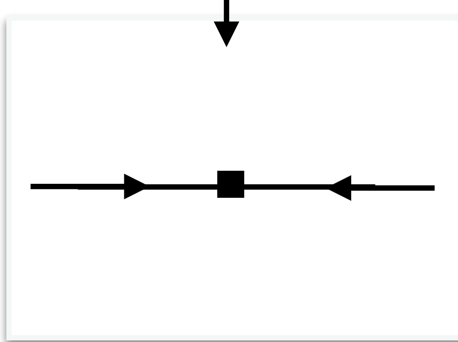
GeV-scale effective Lagrangian

- When the dust settles, get three classes of ΔL=2 operators

$v = \left(\sqrt{2} G_F\right)^{-1/2}$

$\frac{v^2}{\Lambda}$ (dim-3) $\frac{v}{\Lambda^3}$ (dim-6) $\frac{1}{v^2 \Lambda^3}, \frac{1}{\Lambda^5}$ (dim-9)

$$\mathcal{L}_{\Delta L=2} = -\frac{1}{2} m_{\beta\beta}\, \nu_{eL}^T C \nu_{eL} \; + \; C_\Gamma \; \bar{e} \Gamma C \bar{\nu}^T \; O_{2q}^\Gamma \; + \; C_{\Gamma'} \; \bar{e} \Gamma' e^c \; O_{4q}^{\Gamma'}$$



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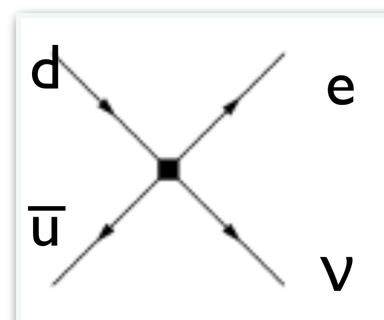
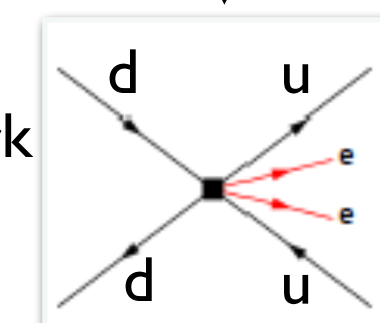


Pas, Hirsch, Klapdor-Kleingrothaus, Kovalenko 1999

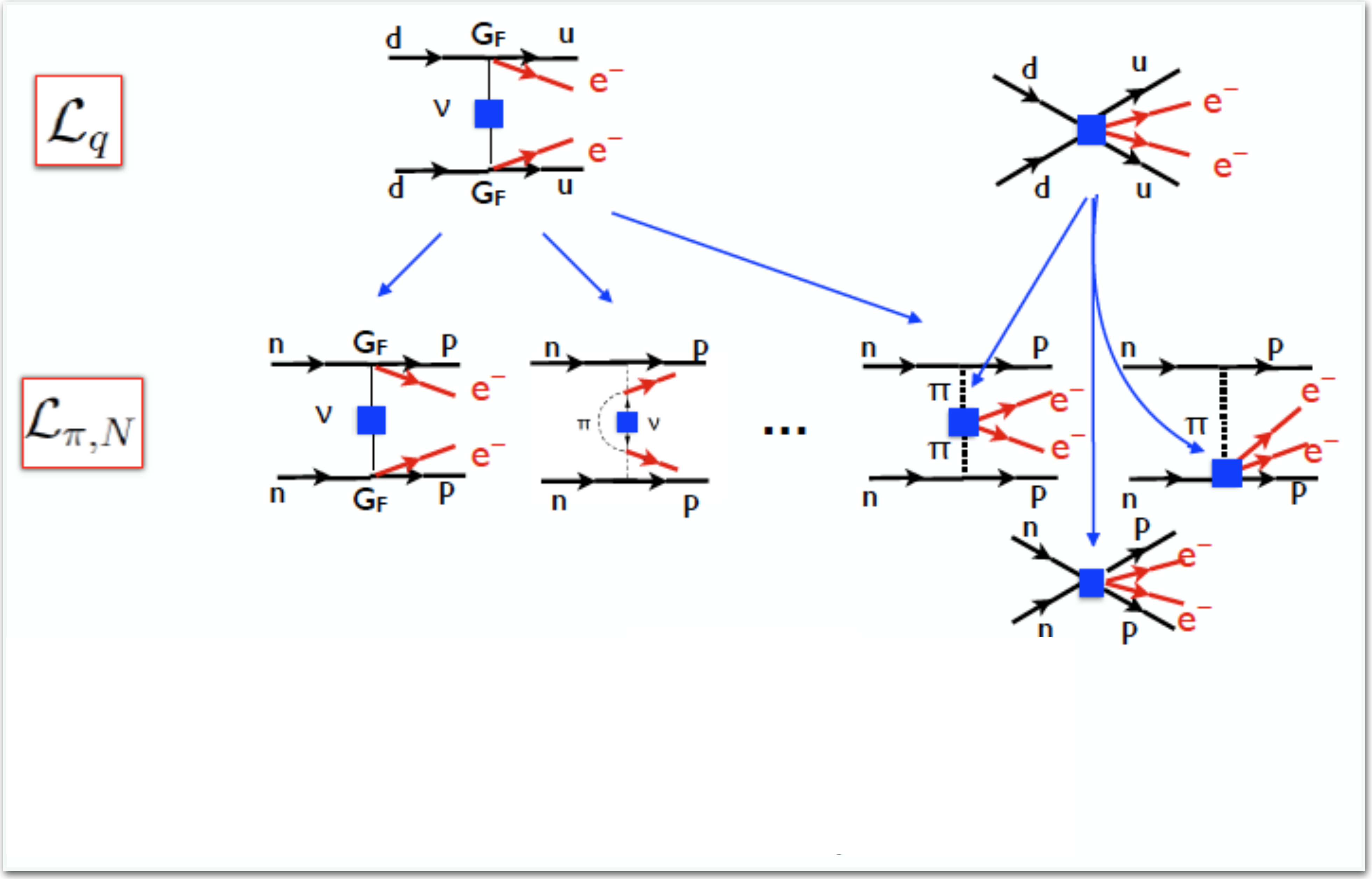
4-quark ops.



Prezeau, Ramsey-Musolf, Vogel hep-ph/0303205

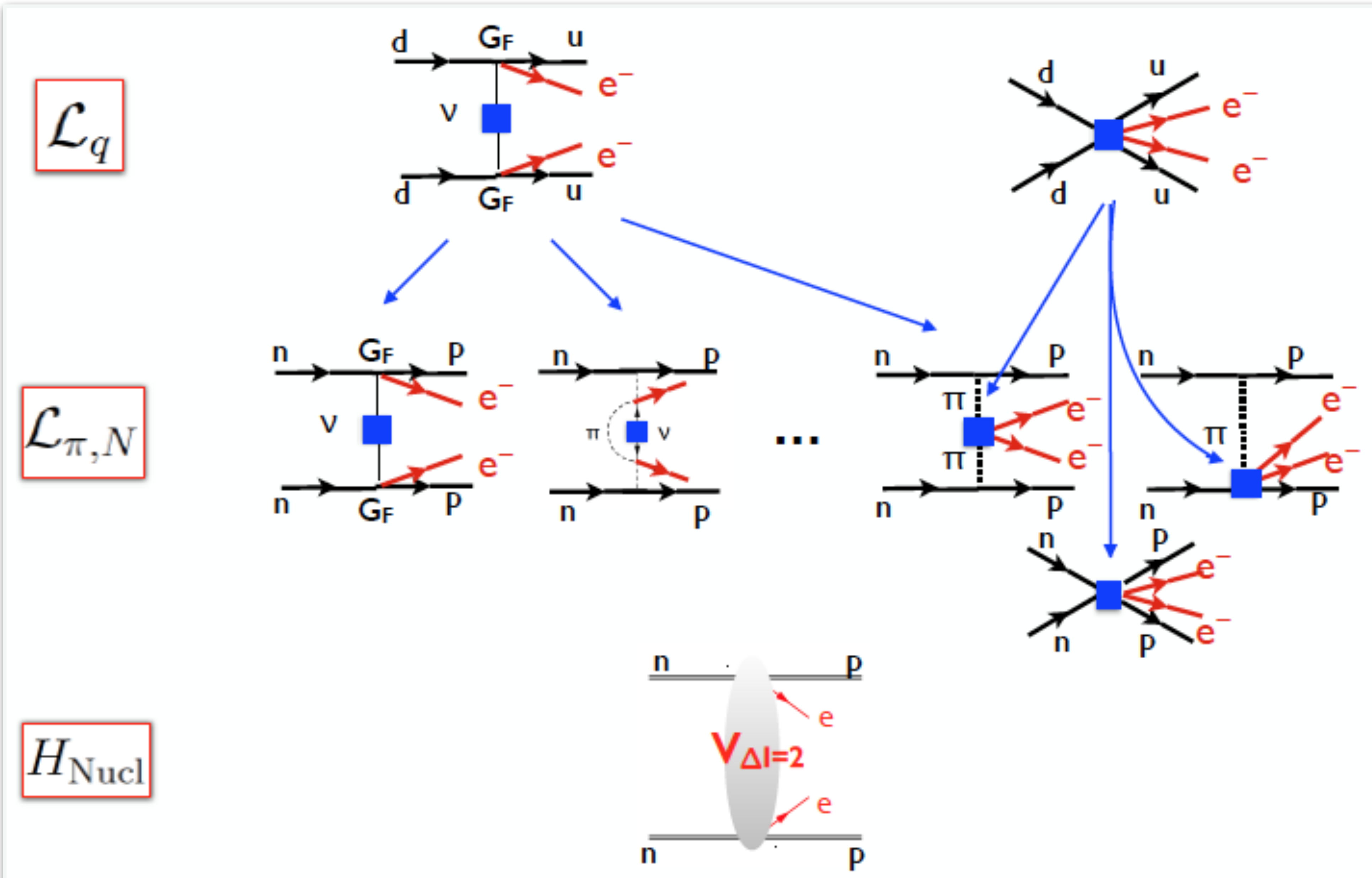
M. Graesser, 1606.04549

From quarks to nuclei



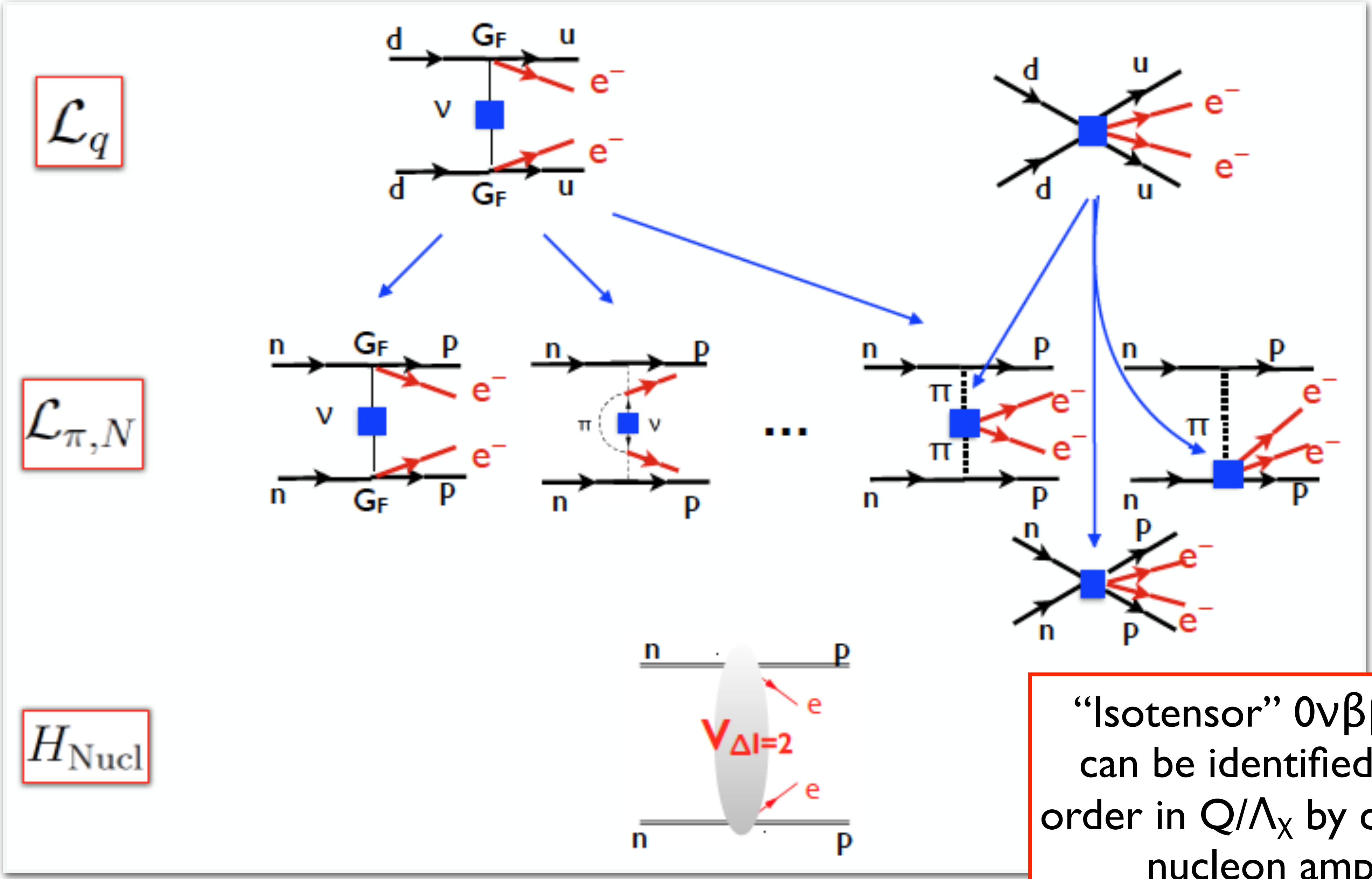
- At E ~ Λ_χ ~ m_N ~ GeV, map ΔL=2 Lagrangian onto π, N operators with same chiral properties
- Organize expansion according to power counting in Q/Λ_χ ($Q \sim k_F \sim m_\pi$)
- Effective couplings encode effects of "hard" ν's and gluons (E, |**p**|>Λ_χ)

From quarks to nuclei



- Integrate out "soft" and "potential" ν's and π's with (E,|**p**|)~Q and (E,|**p**|)~(Q^2/m_N, Q) → obtain nuclear "potentials"

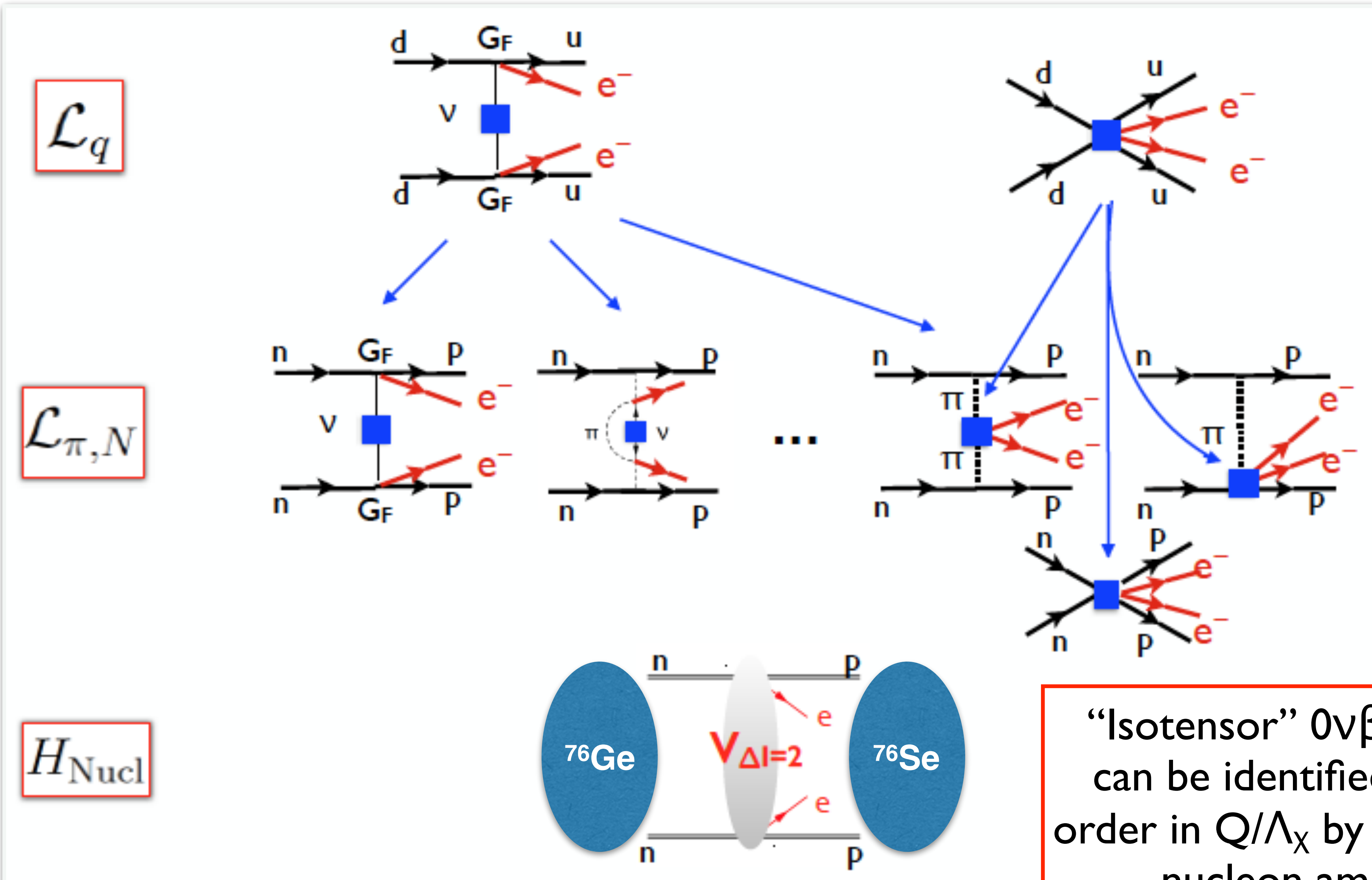
From quarks to nuclei



"Isotensor" 0νββ potential can be identified to a given order in Q/Λ_χ by computing 2-nucleon amplitudes

$$V_{I=2} = m_{\beta\beta} V_\nu + \frac{m_\pi^2}{v}\left(c_{\pi\pi} V_{\pi\pi} + c_{\pi N} V_{\pi N} + c_{NN} V_{NN}\right) + \ldots$$

From quarks to nuclei



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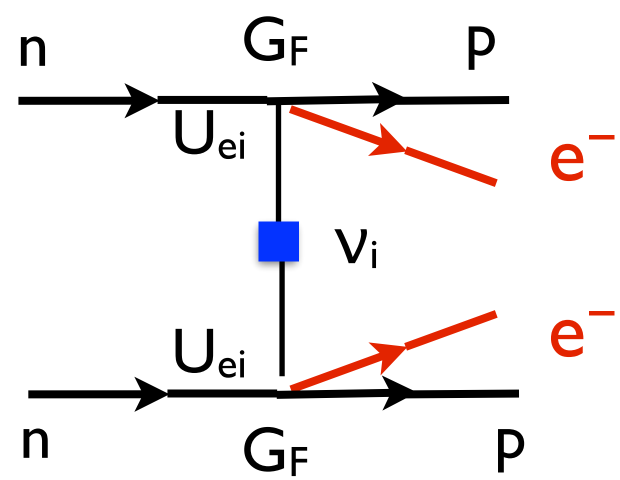
$0\nu\beta\beta$ from light ν_M exchange



Decay amplitude

$$A \propto m_{\beta\beta} \langle f | \sum_{a,b} V_\nu^{(a,b)} | i \rangle$$

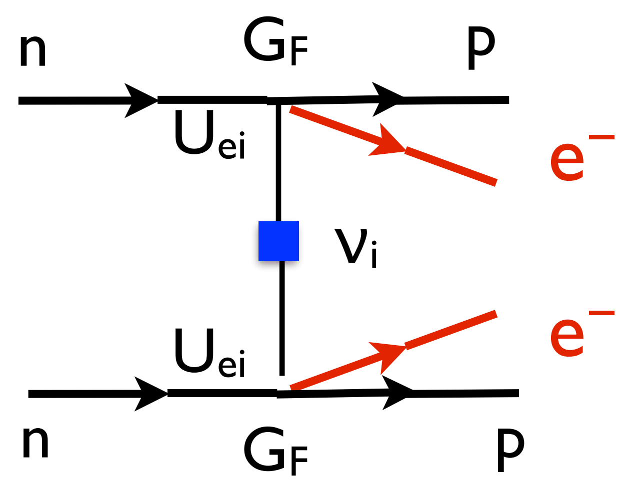
$m_{\beta\beta} = \sum U_{ei}^2 \, m_i$

Transition operator (traditional non-EFT-based analyses)

$$V_\nu^{(a,b)} = \tau^{+,a}\tau^{+,b} \frac{1}{\mathbf{q}^2} \left(J_V^{(a)}(\mathbf{q}) J_V^{(b)}(-\mathbf{q}) + J_A^{(a)}(\mathbf{q}) J_A^{(b)}(-\mathbf{q}) \right)$$

$$J_V \sim 1$$
$$J_A \sim g_A \, \sigma$$

0νββ from light ν_M exchange



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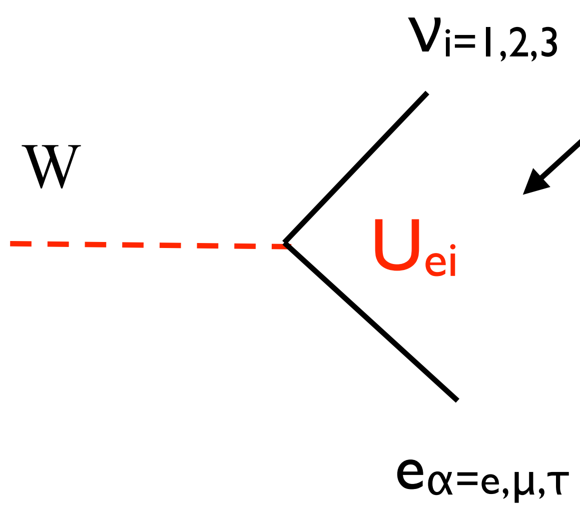
$$J_V \sim 1$$
$$J_A \sim g_A \, \sigma$$

In this case 0νββ is a *direct* probe of ν mass and mixing: $\Gamma \propto |A|^2 \, (m_{\beta\beta})^2$

$m_{\beta\beta}$ phenomenology

- Strong correlation of $0\nu\beta\beta$ with oscillation parameters: $\Gamma \propto (m_{\beta\beta})^2$

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



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

Unitary mixing in CC vertex:
3 angles (known), 1+2 phases (unknown)

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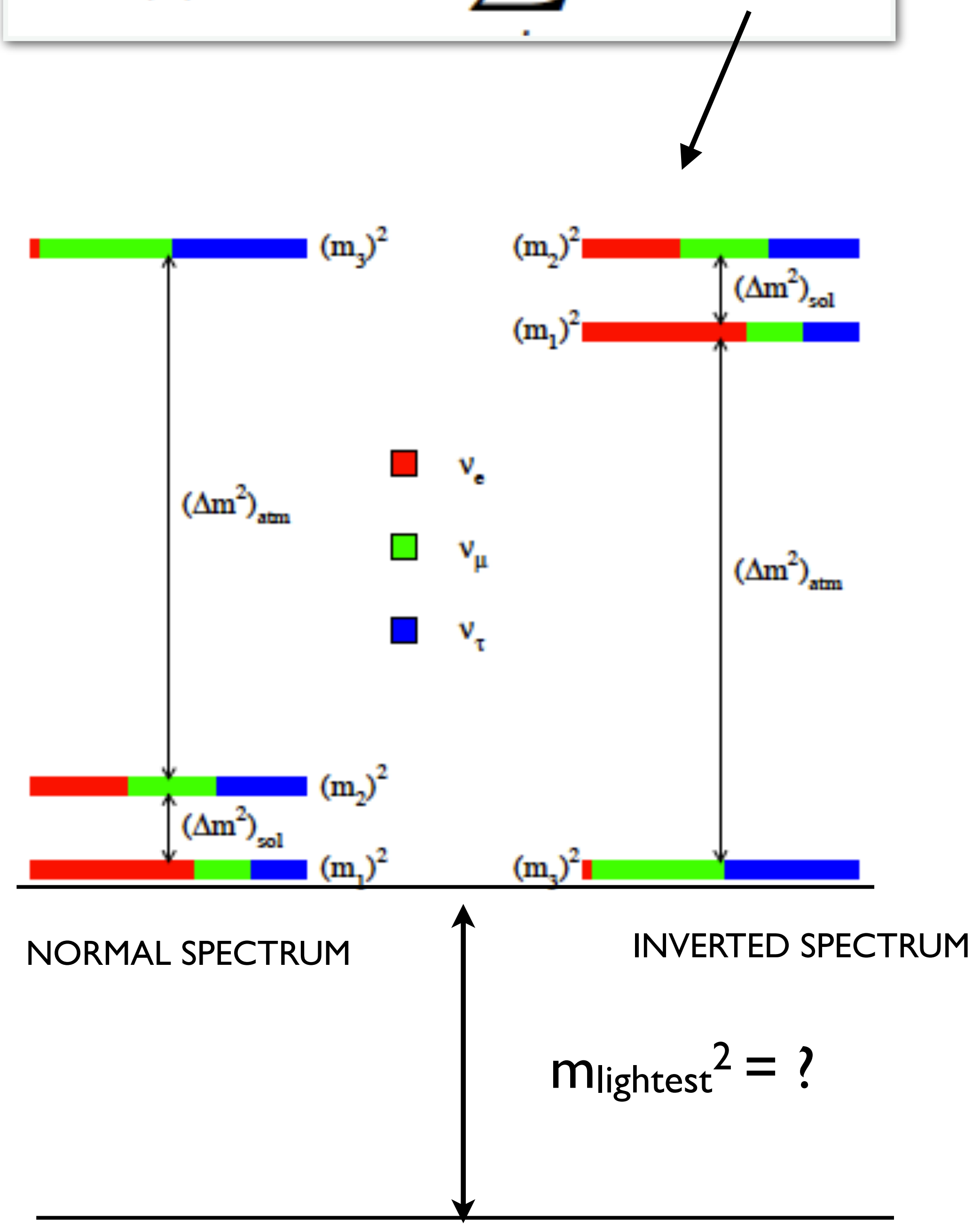
$$\langle m_{\beta\beta} \rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$



Mass ordering still not fixed by oscillation data

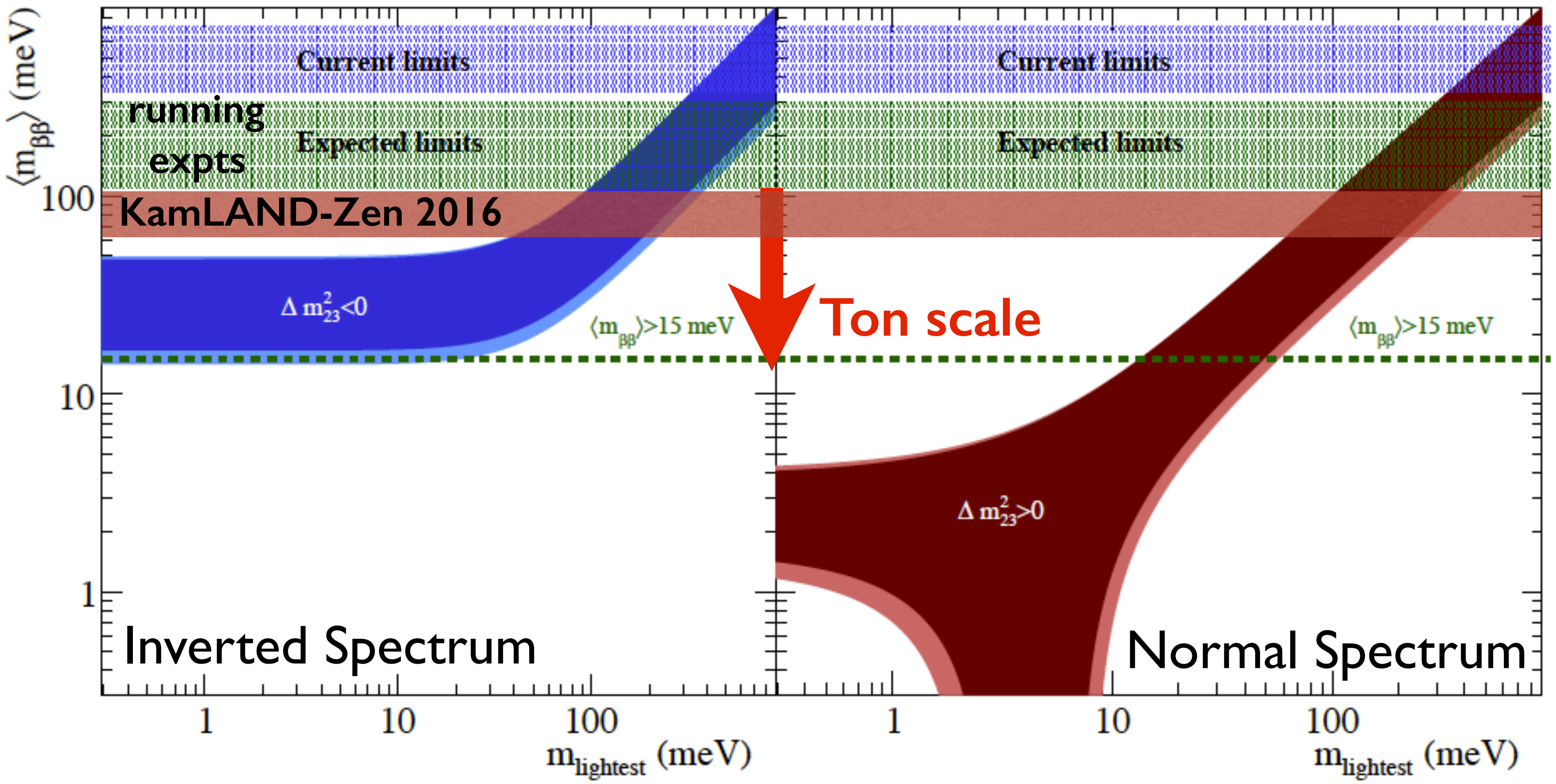
mββ phenomenology

- Strong correlation of 0νββ with oscillation parameters: $\Gamma \propto (m_{\beta\beta})^2$

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

Dark bands: unknown phases

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



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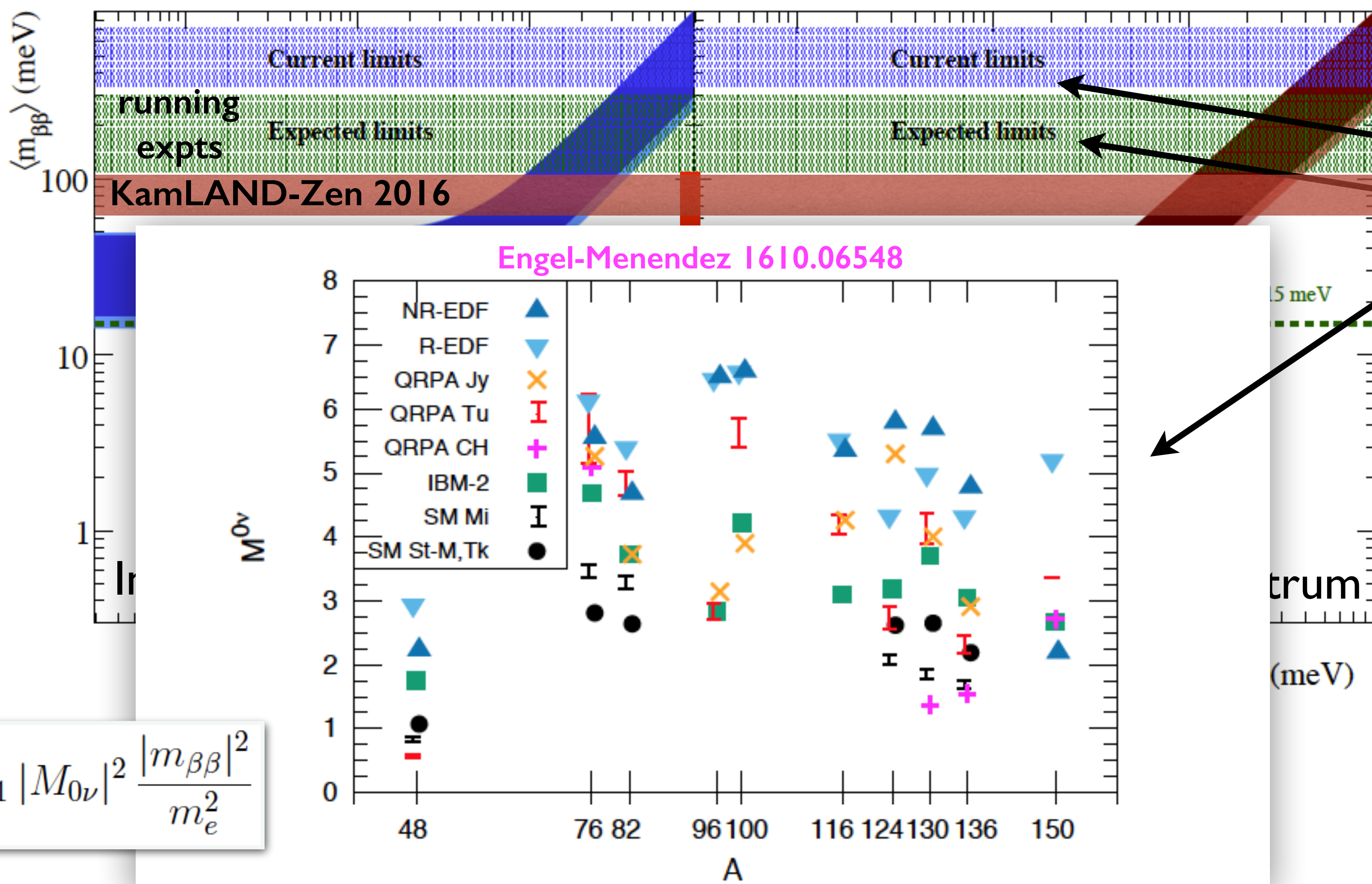

Assume range for nuclear matrix elements from different many-body methods

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

mββ phenomenology

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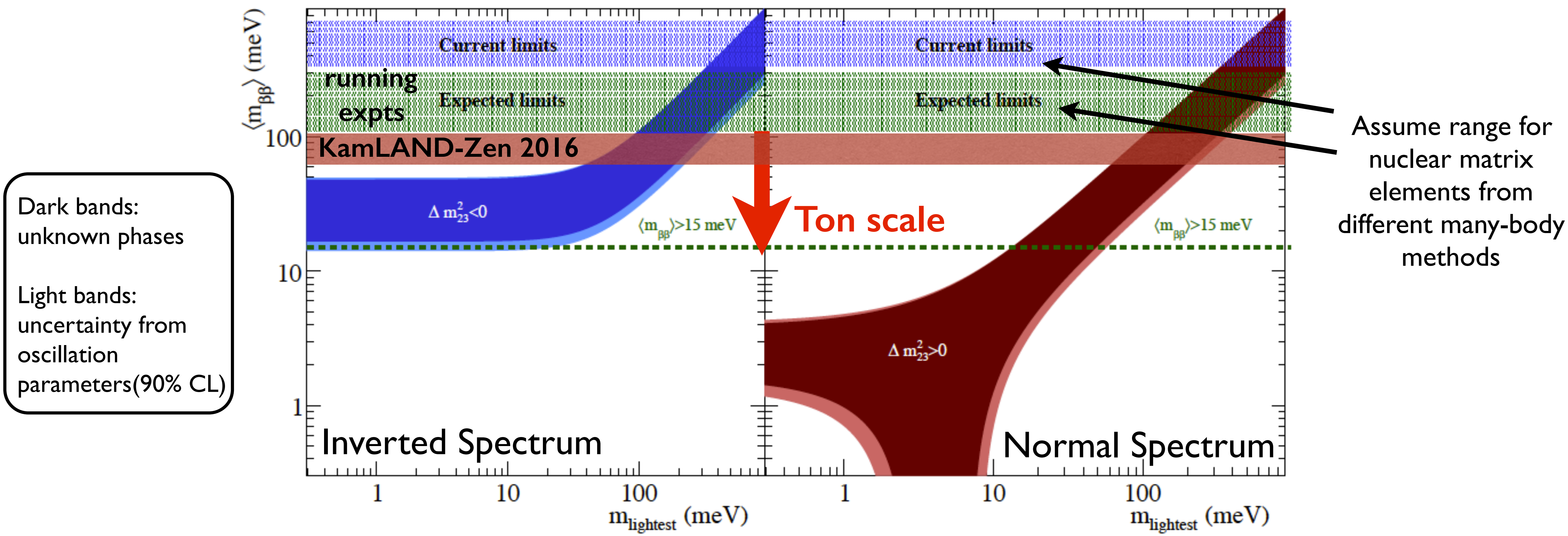
$$\langle m_{\beta\beta}\rangle^2 = |\sum U_{ei}^2 m_{\nu i}|^2$$

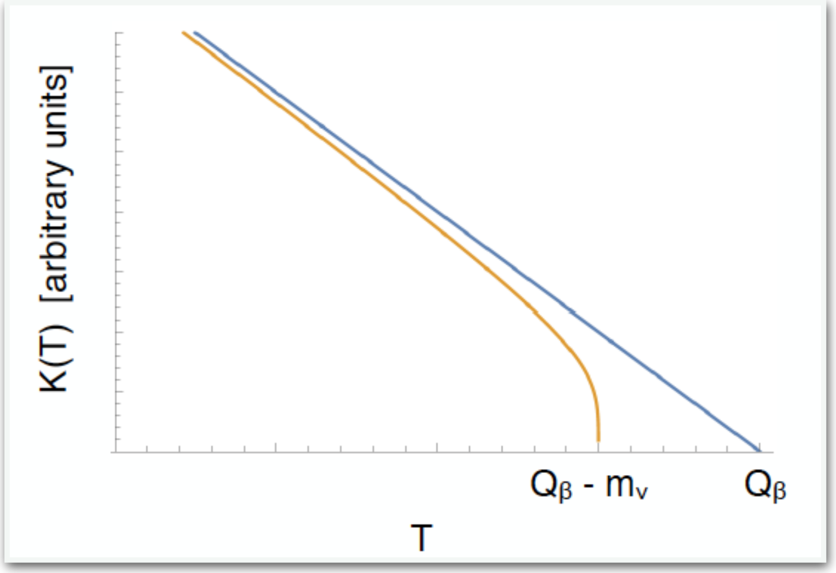


- Assuming current range for matrix elements, discovery *possible* for inverted spectrum or $m_{lightest}$ > 50 meV

$m_{\beta\beta}$ vs other mass probes

- Correlation with other mass probes will contribute to the interpretation of positive or null result

Electron spectrum endpoint



Tritium beta decay →

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

Cosmology →

$$\Sigma = \sum_i m_i$$

mββ vs other mass probes

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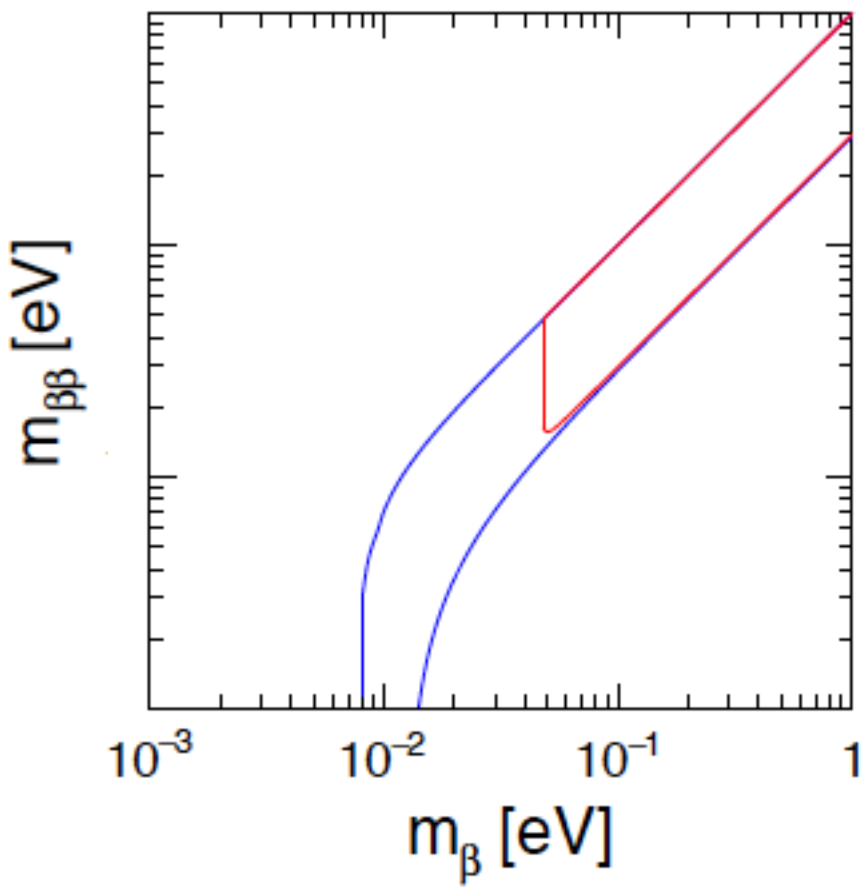

Capozzi et al, 1601.07777

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

mββ vs other mass probes

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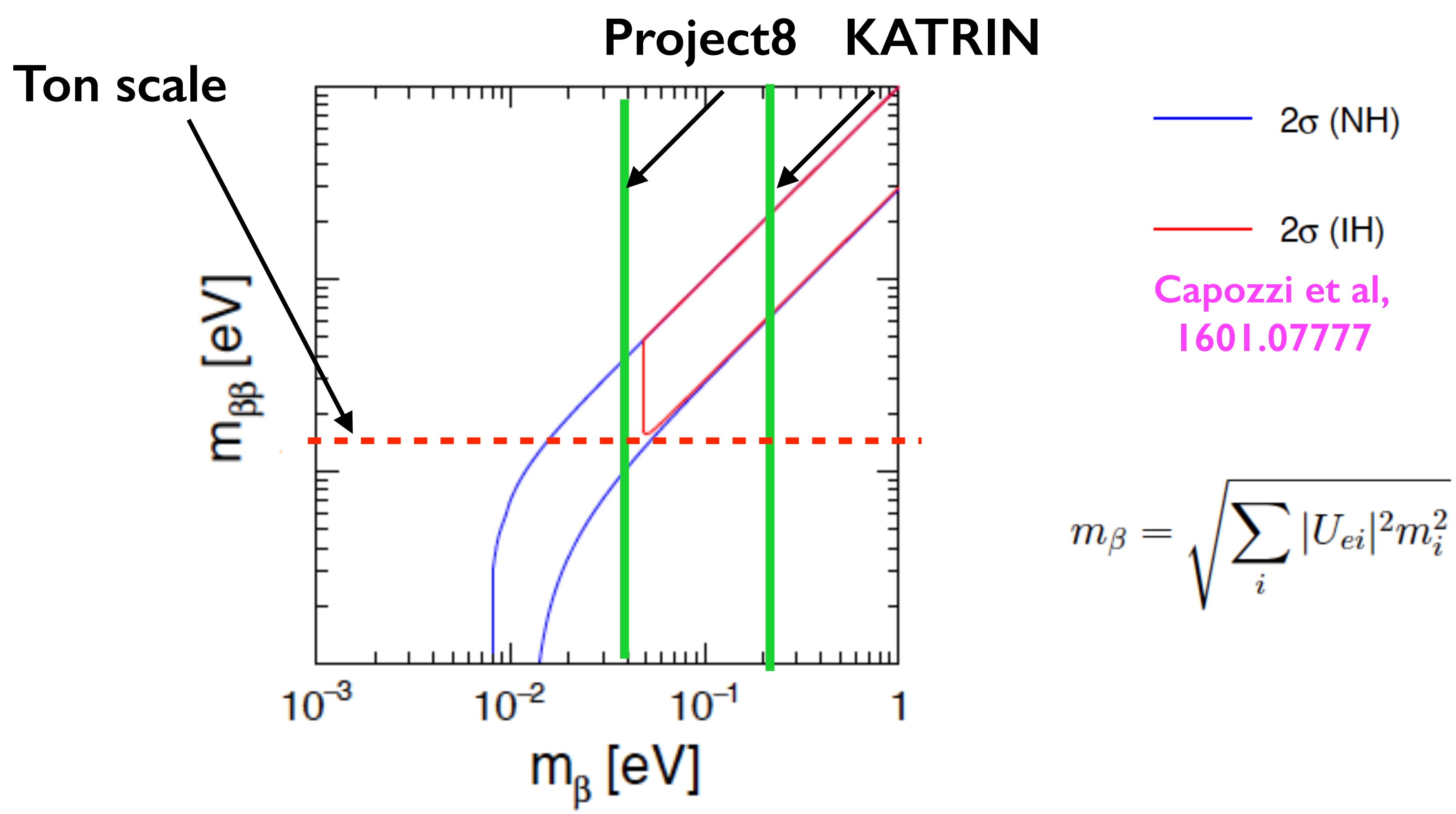

- Positive result in KATRIN, Project8 would imply $0\nu\beta\beta$ within reach

mββ vs other mass probes

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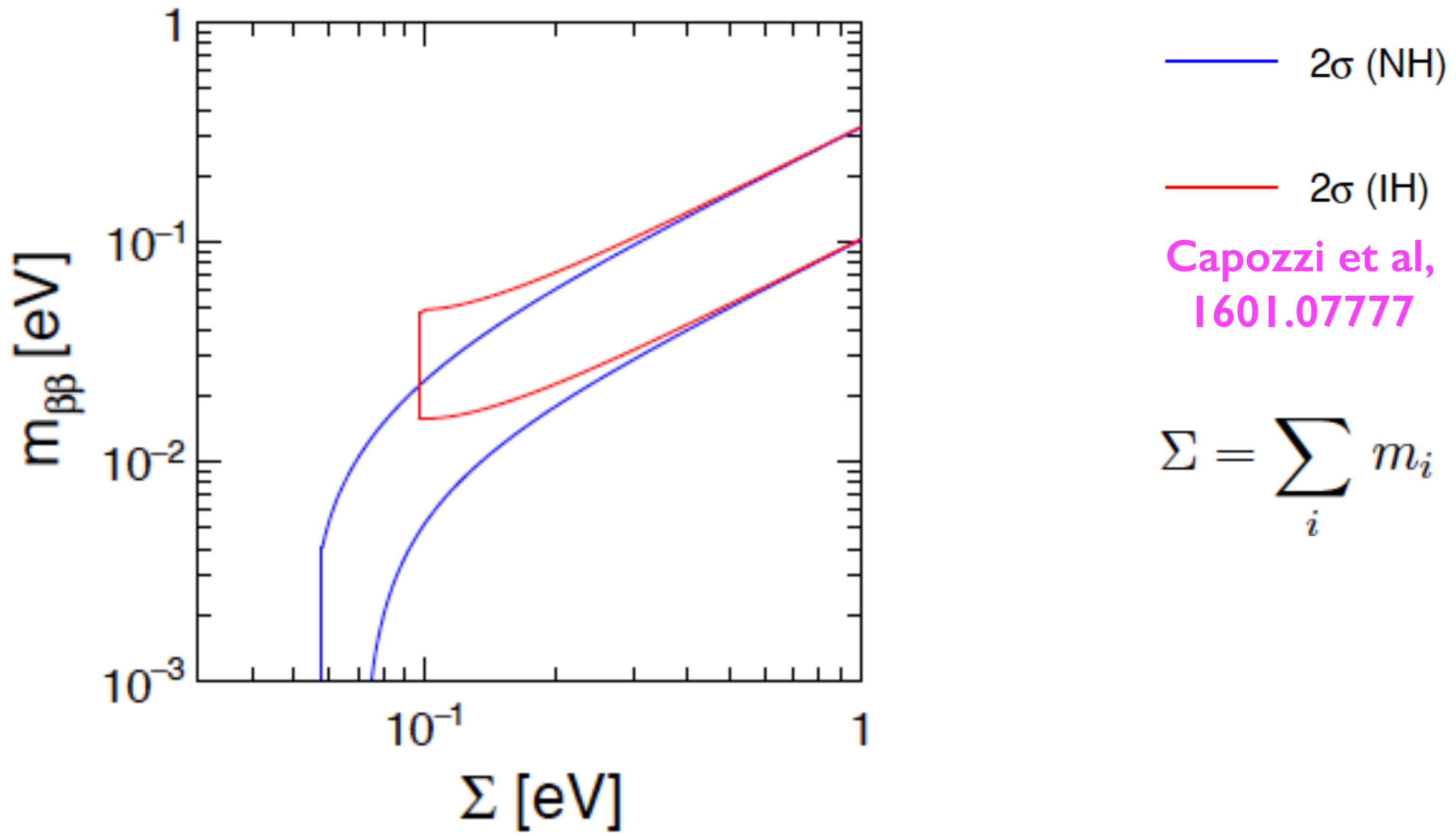

Capozzi et al, 1601.07777

$$\Sigma = \sum_i m_i$$

mββ vs other mass probes

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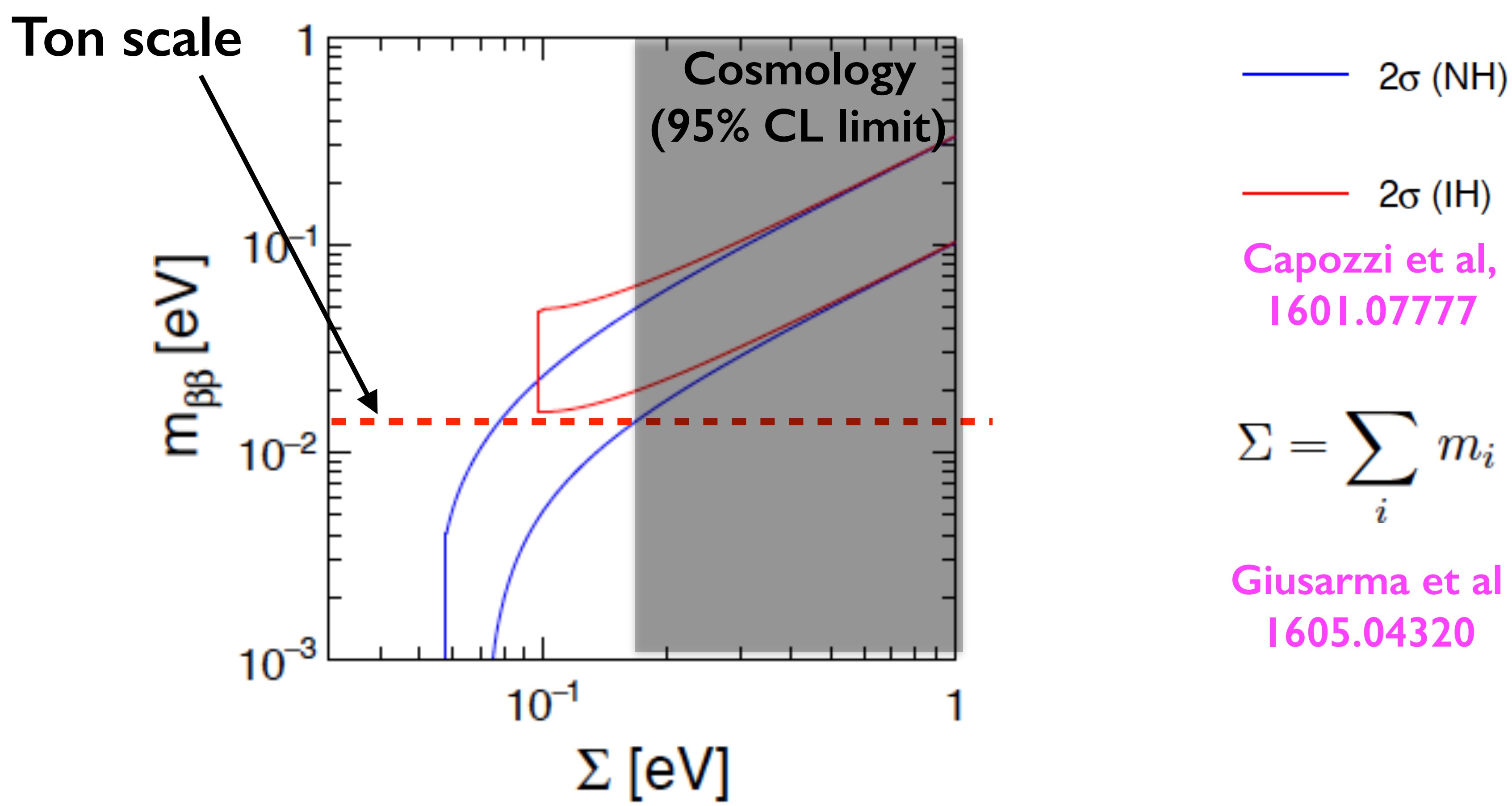

Capozzi et al, 1601.07777

$$\Sigma = \sum_i m_i$$

Giusarma et al 1605.04320

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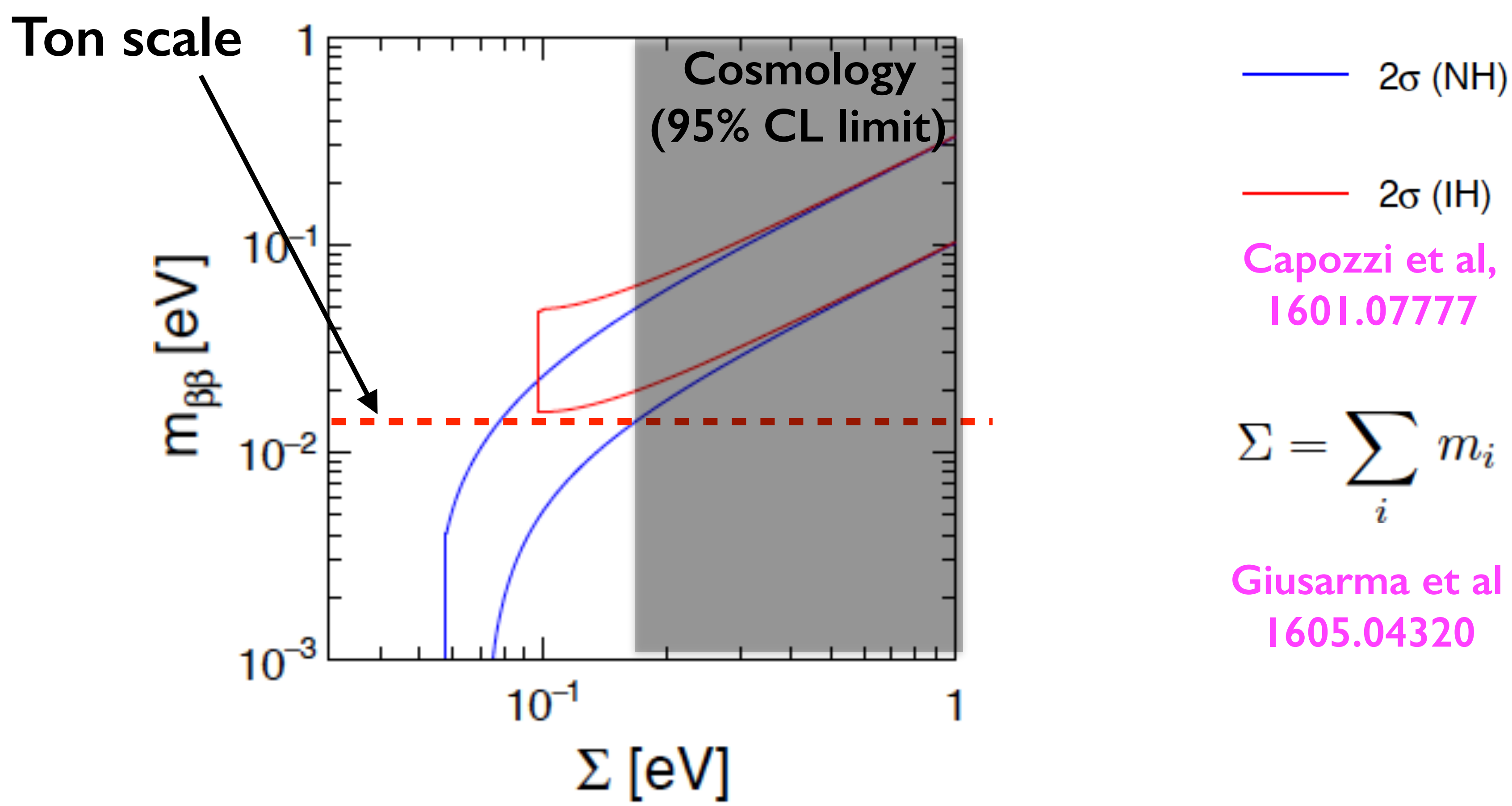


Capozzi et al, 1601.07777

$$\Sigma = \sum_i m_i$$

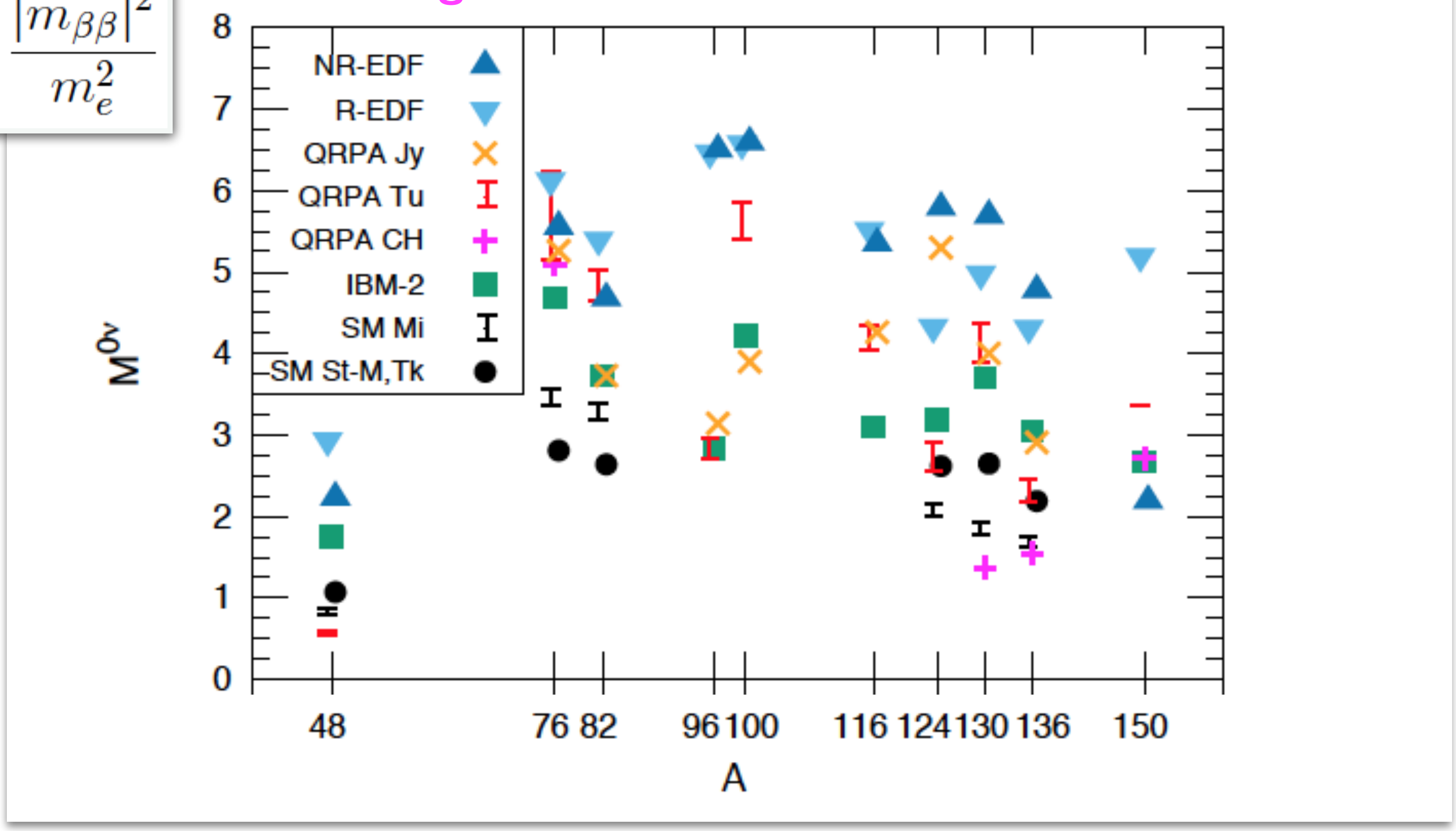
Giusarma et al 1605.04320

- Interplay with cosmic frontier: expose new physics in cosmology (is "ΛCDM + m_ν" the full story?) or in 0νββ (new sources of LNV?)
- Assuming we know correct range for nuclear matrix elements

Room for improvement?

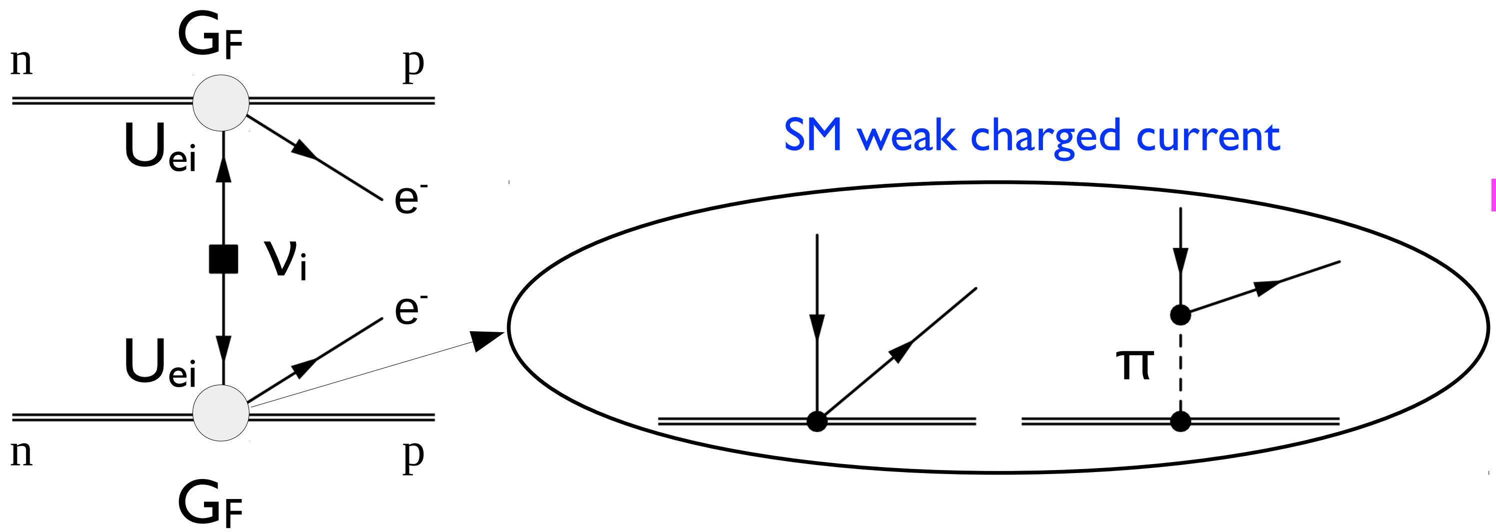
$$\left(T_{1/2}^{0\nu}\right)^{-1} = g_A^4\, G_{01}\, |M_{0\nu}|^2 \, \frac{|m_{\beta\beta}|^2}{m_e^2}$$

Engel-Menendez 1610.06548



- Steps towards controllable uncertainties in matrix elements:
  - Use EFT as guiding principle (both strong and ΔL=2 potentials)
  - Use exact results in light nuclei as a benchmark
  - “Ab initio” nuclear structure in sight for ^{48}Ca, with QCD-rooted chiral potentials

Light ν_M exchange in chiral EFT



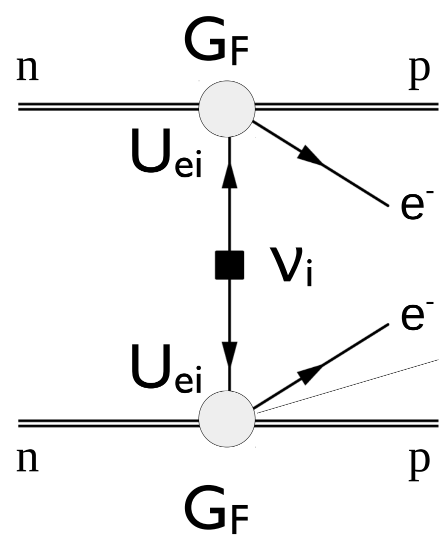
VC, W. Dekens, M. Graesser, E. Mereghetti, S. Pastore, J. de Vries, U. van Kolck 1802.10097

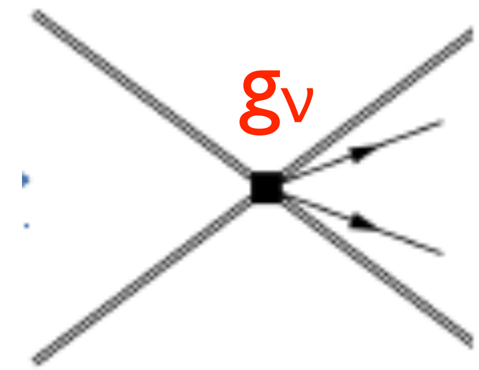
- Leading order contribution in Q/Λ_χ ($Q \sim k_F \sim m_\pi$): tree-level ν_M exchange

$$V_{\nu,0}^{(a,b)} = \tau^{(a)+}\tau^{(b)+} \frac{1}{\mathbf{q}^2} \left\{ 1 - g_A^2 \left[\boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} - \boldsymbol{\sigma}^{(a)} \cdot \mathbf{q}\, \boldsymbol{\sigma}^{(b)} \cdot \mathbf{q}\, \frac{2m_\pi^2 + \mathbf{q}^2}{(\mathbf{q}^2 + m_\pi^2)^2} \right] \right\}$$

Hadronic input: g_A

Light ν_M exchange in chiral EFT





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

- Leading order contribution in Q/Λ_χ ($Q \sim k_F \sim m_\pi$): tree-level ν_M exchange

$$V_{\nu,0}^{(a,b)} = \tau^{(a)+}\tau^{(b)+} \frac{1}{\mathbf{q}^2} \left\{ 1 - g_A^2 \left[\boldsymbol{\sigma}^{(a)} \cdot \boldsymbol{\sigma}^{(b)} - \boldsymbol{\sigma}^{(a)} \cdot \mathbf{q}\, \boldsymbol{\sigma}^{(b)} \cdot \mathbf{q}\, \frac{2m_\pi^2 + \mathbf{q}^2}{(\mathbf{q}^2 + m_\pi^2)^2} \right] \right\}$$

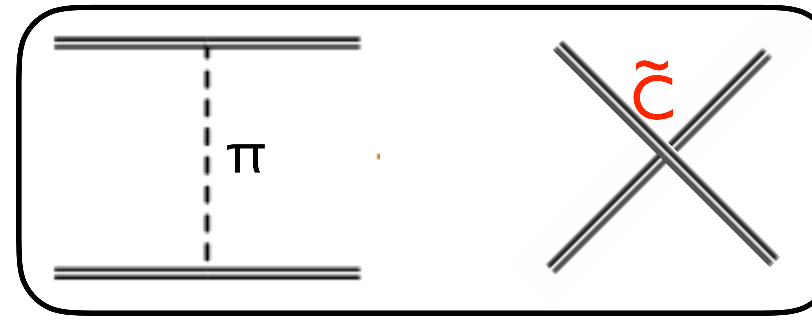
Hadronic input: g_A

- Renormalization of $nn \to ppee$ amplitude in presence of LO strong potential requires a leading order counterterm $g_\nu \sim 1/F_\pi^2 \sim 1/k_F^2$

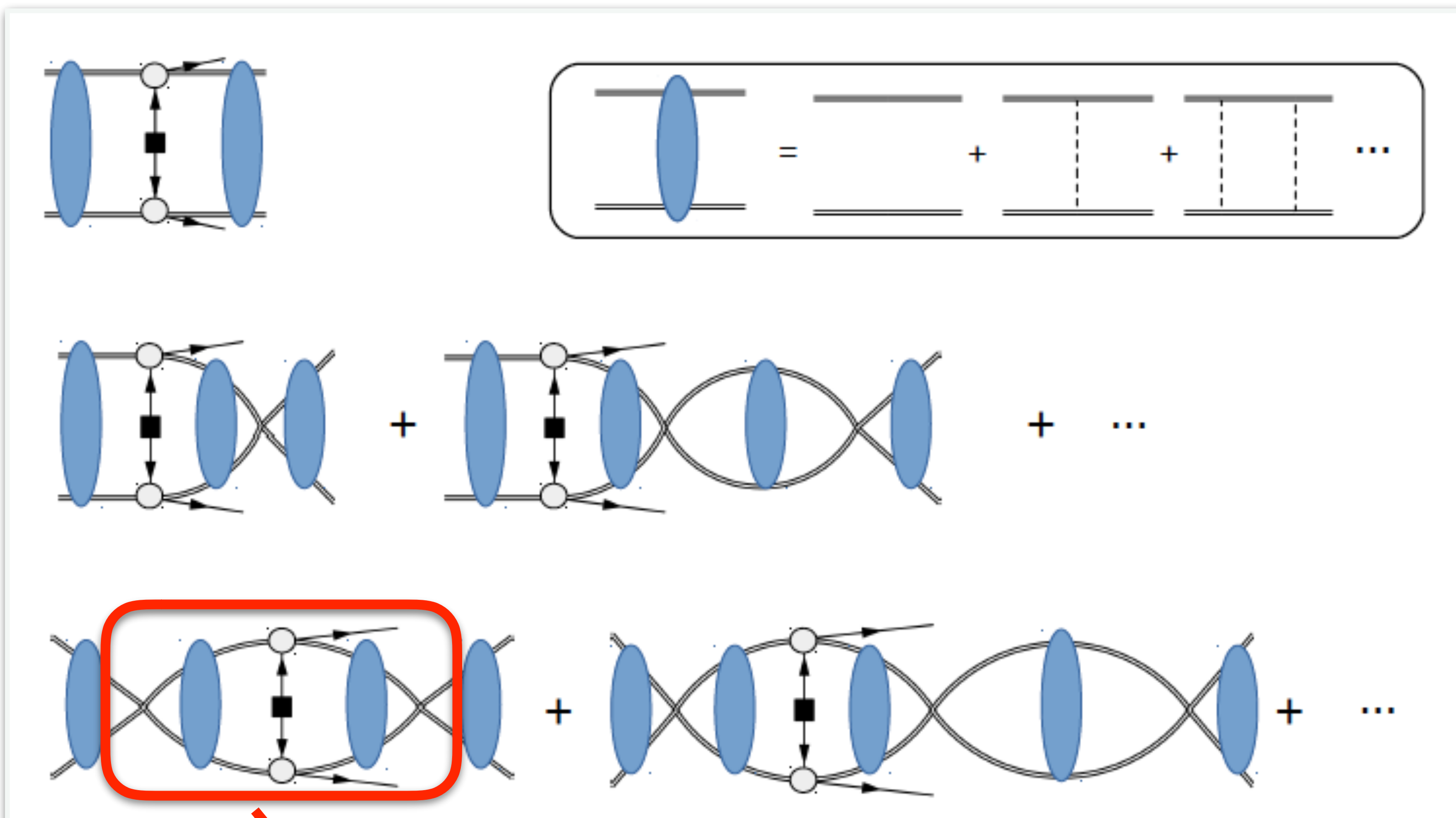
$$V_{\nu,CT}^{(a,b)} = -2\, g_\nu\, \tau^{(a)+}\tau^{(b)+}$$

Scaling of contact term in 0νββ

- nn→ppee amplitude with LO strong potential



$\tilde{C} \sim 1/F_\pi^2$ from fit to a_{NN}



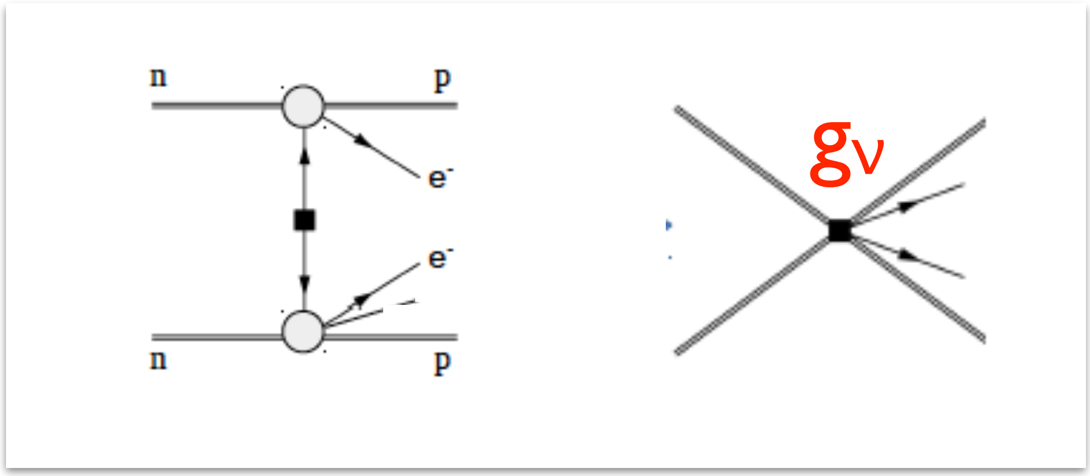
UV divergence

$$\sim \frac{1}{2}(1+2g_A^2)\left(\frac{m_N \tilde{C}}{4\pi}\right)^2 \left(\frac{1}{4-d} + \log\mu^2\right)$$

$\sim 1/F_\pi^2$

Anatomy of 0νββ amplitude

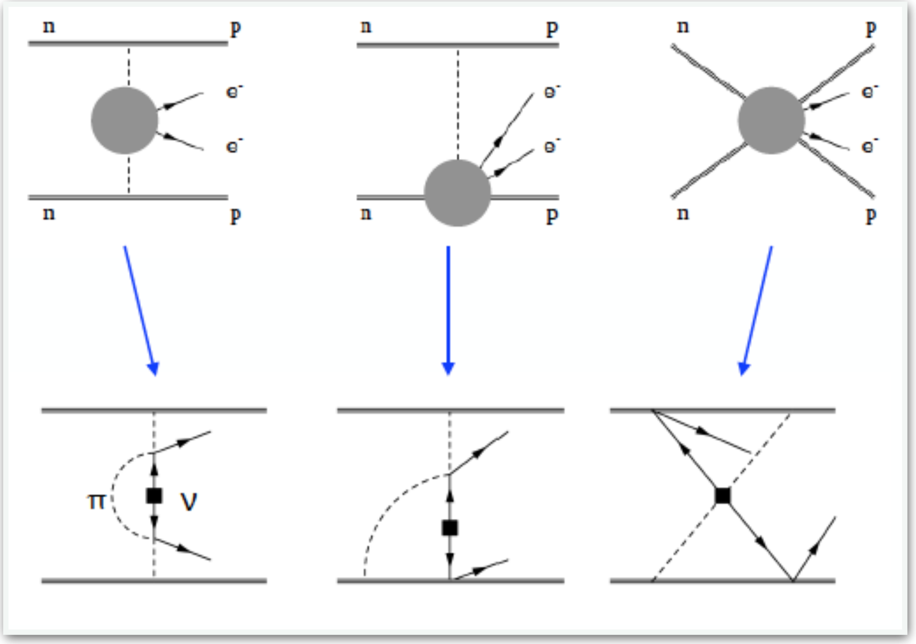
Leading order



$V_{I=2}$

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

N2LO



V. Cirigliano, W. Dekens, E. Mereghetti, A. Walker-Loud, 1710.01729

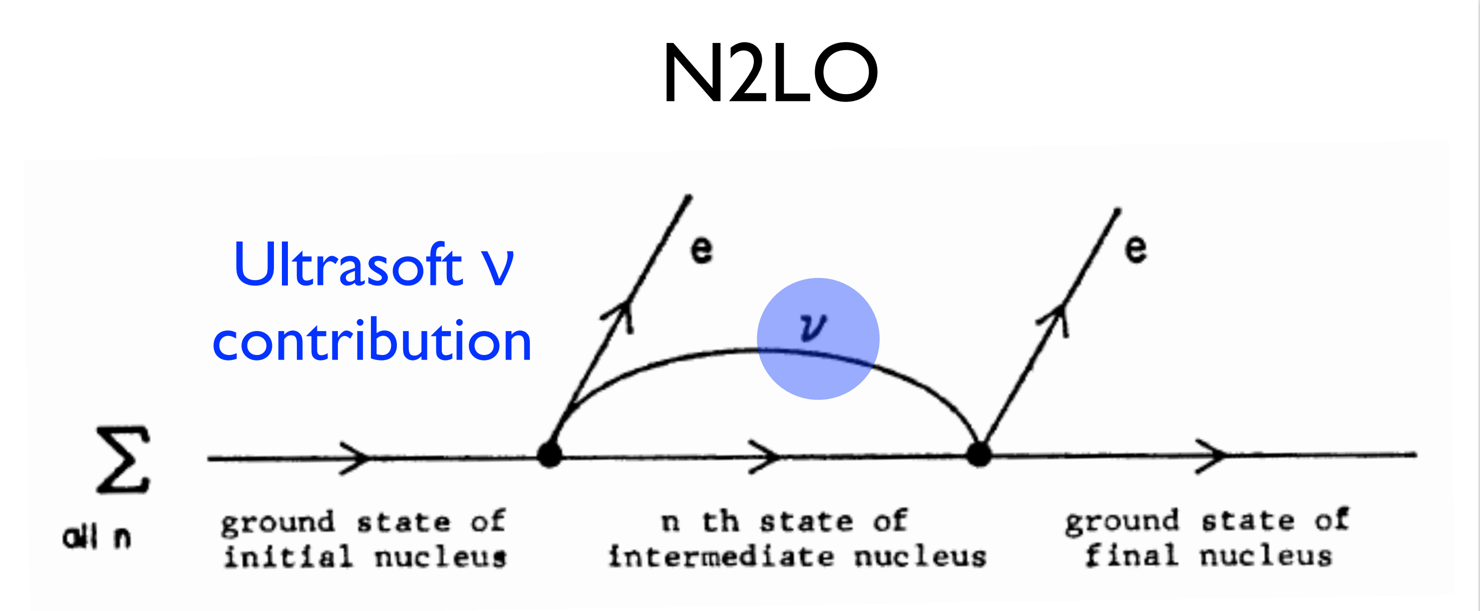


Figure adapted from Primakoff-Rosen 1969

Estimating finite part of g_ν

1) Match χEFT & lattice QCD calculation of hadronic amplitude nn→pp

$$S_{\rm eff}^{\Delta L=2} = \frac{i8G_F^2 V_{ud}^2 m_{\beta\beta}}{2!} \int d^4x\, \bar{e}_L(x) e_L^c(x) \int d^4y\, S(x-y)\, T\Big(\bar{u}_L \gamma_\mu d_L(x)\, \bar{u}_L \gamma_\mu d_L(y)\Big) g^{\mu\nu}$$

Scalar massless propagator
(remnant of ν propagator)

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$(J_+ \times J_+)$ vs $(J_{EM} \times J_{EM})_{I=2}$

2) Chiral symmetry relates g_ν to one of two I=2 EM LECs ($C_{1,2}$)

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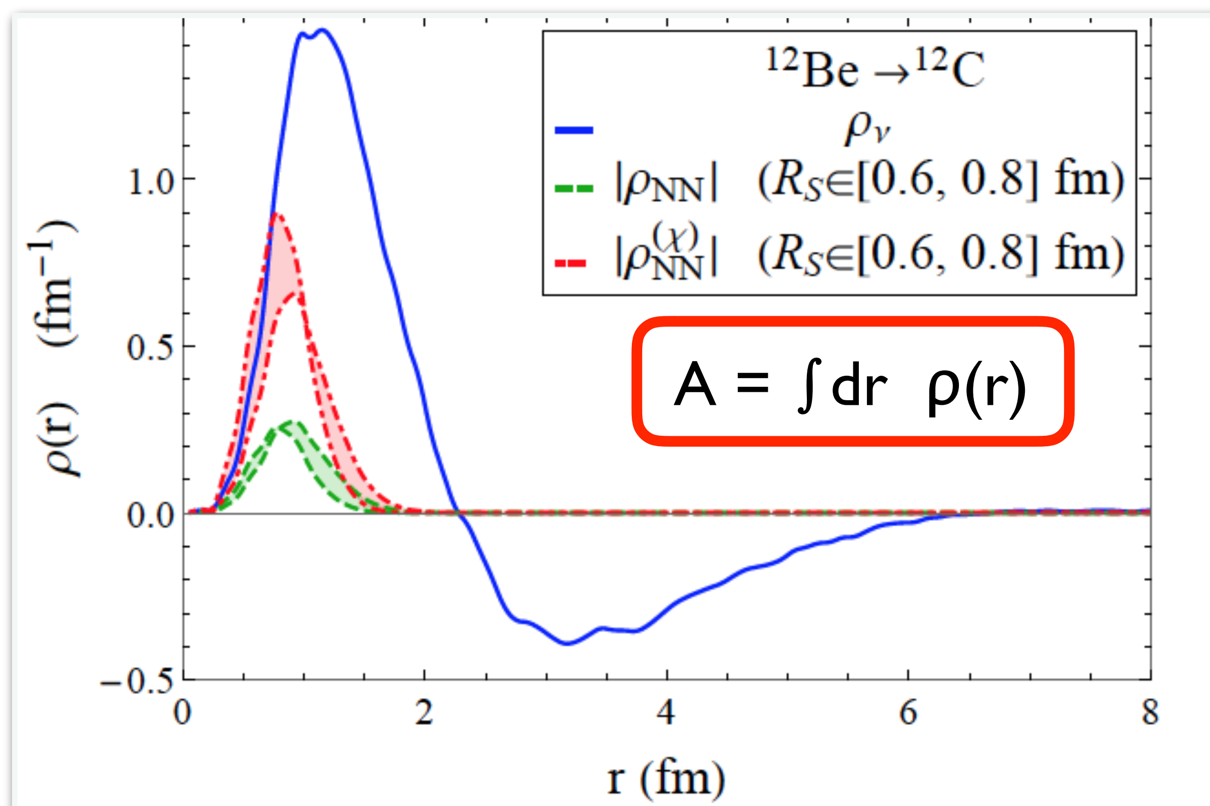
2) Chiral symmetry relates g_ν to one of two I=2 EM LECs ($C_{1,2}$)

Rough estimate of g_ν by fitting (C_1+C_2) to NN data

Effect on light nuclei matrix elements can be O(1): A_{NN}/A_ν = 25%-55%

Strong motivation to pursue lattice QCD calculation



Backup material

The Standard Model

- Gauge group: $SU(3)_c \times SU(2)_W \times U(1)_Y$
- Building blocks:

	$SU(3)_c \times SU(2)_W \times U(1)_Y$ representation: (dim[$SU(3)_c$], dim[$SU(2)_W$], Y)	$SU(2)_W$ transformation
$l = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	(1,2,-1/2)	$l \to V_{SU(2)}\, l$
$e = e_R$	(1,1,-1)	
$q^i = \begin{pmatrix} u^i_L \\ d^i_L \end{pmatrix}$	(3,2,1/6)	$q \to V_{SU(2)}\, q$
$u^i = u^i_R$	(3,1,2/3)	
$d^i = d^i_R$	(3,1,-1/3)	
$\varphi = \begin{pmatrix} \varphi^+ \\ \varphi^0 \end{pmatrix}$	(1,2,1/2)	$\varphi \to V_{SU(2)}\, \varphi$

$Q = T_3 + Y$

- SM Lagrangian = all operators of dimension ≤ 4 that respect gauge and Lorentz invariance

The Standard Model

$$\mathcal{L}_{SM} = \mathcal{L}_{\text{Gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}$$

$$D_\mu = I\,\partial_\mu - ig_s \frac{\lambda^A}{2} G^A_\mu - ig\frac{\sigma^a}{2} W^a_\mu - ig' Y B_\mu$$

$$\mathcal{L}_{\text{Gauge}} = -\frac{1}{4} G^A_{\mu\nu} G^{A\mu\nu} - \frac{1}{4} W^I_{\mu\nu} W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}$$

$$+ \sum_{i=1,2,3} \left(i\bar{\ell}_i \not{D} \ell_i + i\bar{e}_i \not{D} e_i + i\bar{q}_i \not{D} q_i + i\bar{u}_i \not{D} u_i + i\bar{d}_i \not{D} d_i \right)$$

$$\mathcal{L}_{\text{Higgs}} = (D_\mu \varphi)^\dagger (D^\mu \varphi) - \lambda(\varphi^\dagger \varphi - v^2)^2$$

EWSB →

$$\langle \varphi \rangle = \begin{pmatrix} 0 \\ v \end{pmatrix}$$

$$\langle \tilde{\varphi} \rangle = \begin{pmatrix} v \\ 0 \end{pmatrix}$$

$$\tilde{\varphi} = \epsilon\, \varphi^*$$

$$\mathcal{L}_{\text{Yukawa}} = \bar{\ell}\, Y_e\, e\varphi + \bar{q}\, Y_d\, d\varphi + \bar{q}\, Y_u\, u\tilde{\varphi} + \text{h.c.}$$

- CP & $U(3)^5$ symmetry ($\mathcal{L}_{\text{Gauge}}$) broken by complex Yukawa matrices $Y_{e,u,d}$

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Scalar massless propagator

$(J_+ \times J_+)$ vs $(J_{EM} \times J_{EM})_{I=2}$

2) Chiral symmetry relates g_ν to I=2 electromagnetic LECs (hard ν vs γ)

$$\mathcal{Q}_L = \frac{\tau^z}{2},\ \mathcal{Q}_R = \frac{\tau^z}{2}$$

$$e^2 C_1\left(\bar{N}\mathcal{Q}_L N\bar{N}\mathcal{Q}_L N - \frac{\mathrm{Tr}[\mathcal{Q}_L^2]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L\to R\right)$$

$$e^2 C_2\left(\bar{N}\mathcal{Q}_L N\bar{N}\mathcal{Q}_R N - \frac{\mathrm{Tr}[\mathcal{Q}_L\mathcal{Q}_R]}{6}\bar{N}\boldsymbol{\tau}N\cdot\bar{N}\boldsymbol{\tau}N + L\to R\right)$$

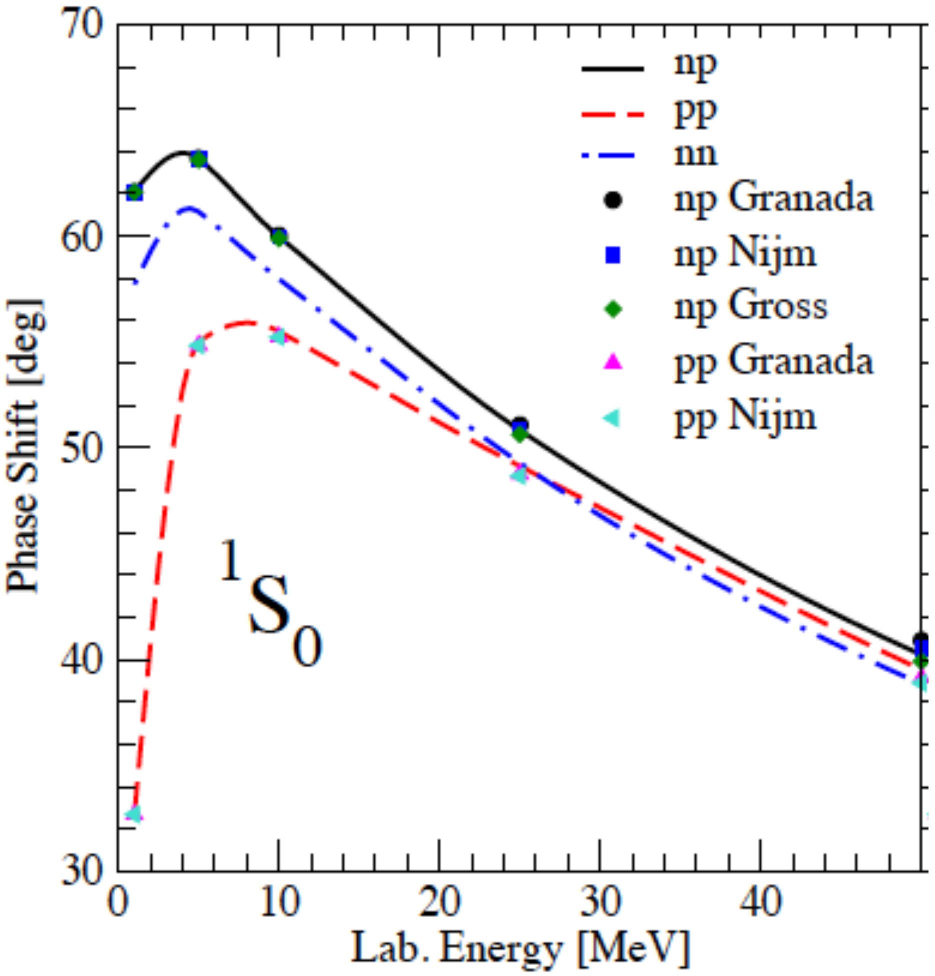
$$\mathcal{Q}_L = u^\dagger Q_L u$$
$$\mathcal{Q}_R = u Q_R u^\dagger$$
$$u = 1 + \frac{i\boldsymbol{\pi}\cdot\boldsymbol{\tau}}{2F_\pi} + \dots$$

Two I=2 NN non-derivative operators: chiral symmetry ⇒ $g_\nu = C_1$

0νββ vs EM isospin breaking

- NN observables cannot disentangle C_1 from C_2 (need pions), but provide data-based estimate of C_1+C_2

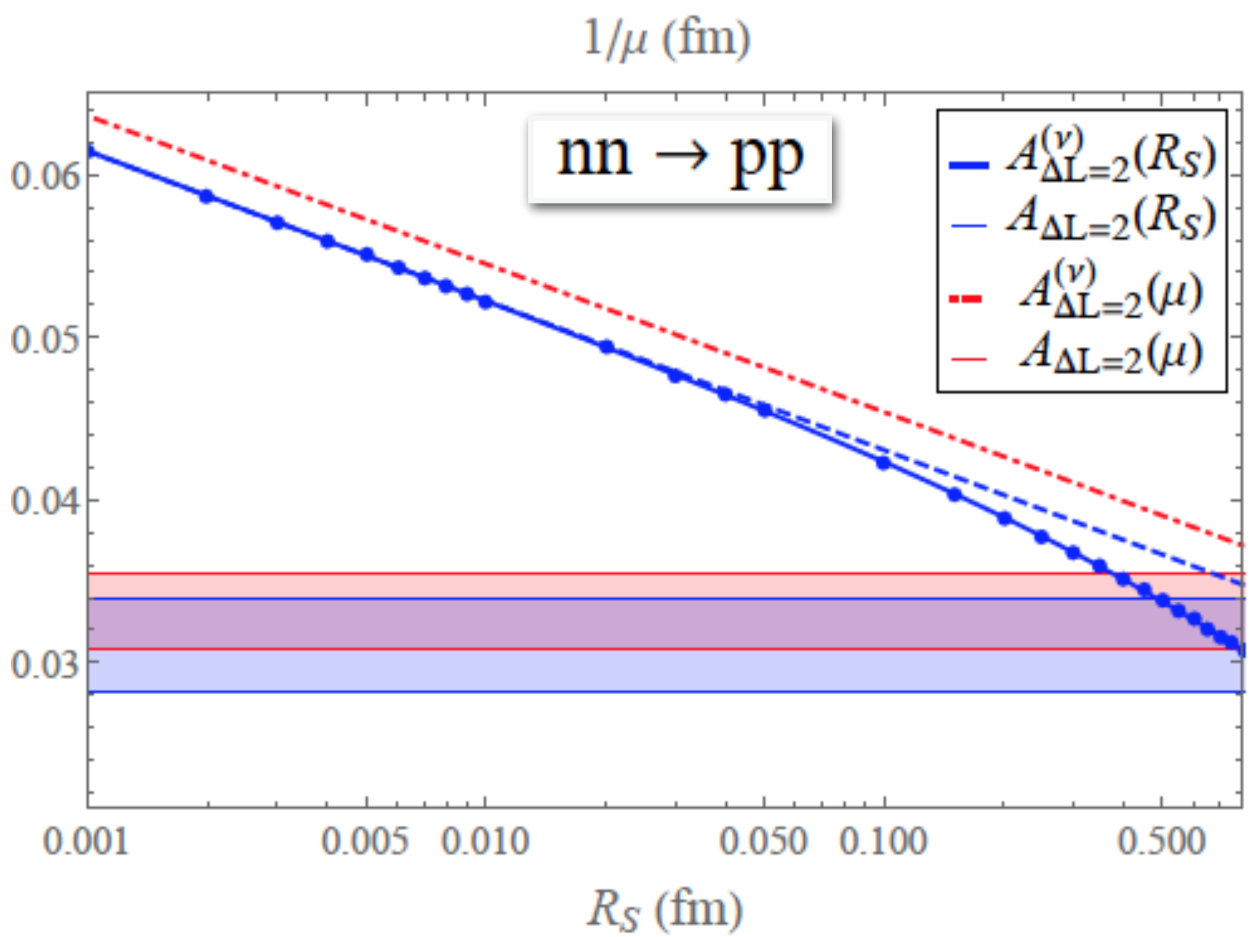
Piarulli et al, 1412.6446



- $C_1 + C_2$ controls IB combination of $^1S_0$ scattering lengths $a_{nn} + a_{pp} - 2\, a_{np}$

- Fit to data, including Coulomb potential, pion EM mass splitting, and contact terms confirms that $C_1 + C_2 \sim 1/F_\pi^2 \gg 1/(4\pi F_\pi)^2$

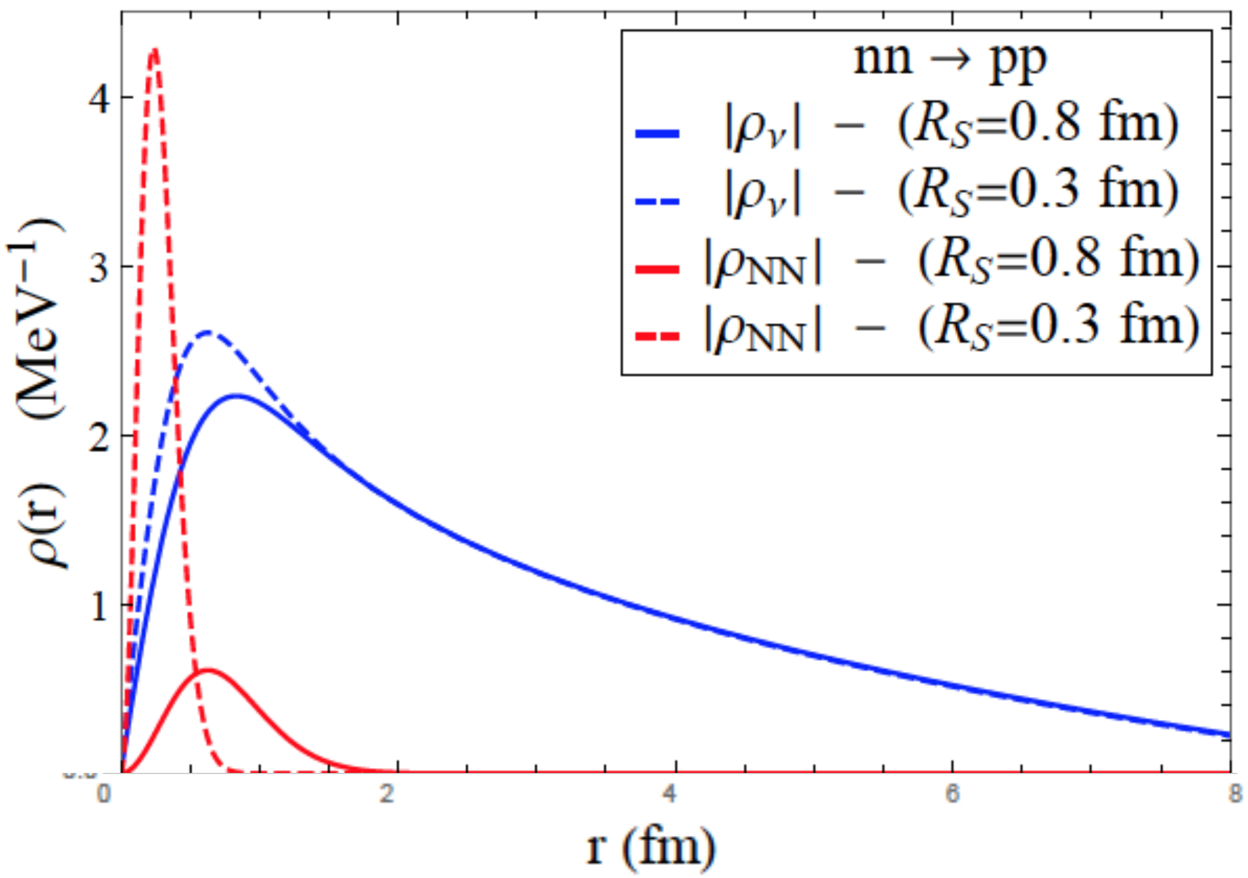
Estimating numerical impact (1)



- Assume $C_1=C_2$ and hence $g_\nu=(C_1+C_2)/2$ at some scale R_S
- $A_{NN}+A_\nu$ is R_S (or μ) independent and A_{NN}/A_ν ~ 10% (30%) at R_S~0.8 fm (0.3 fm) **
- ** Actual correction will be different because in general $C_1 \neq C_2$

Estimating numerical impact (1)

nn → pp $\Delta I=0$



$$A = \int dr \;\; \rho(r)$$

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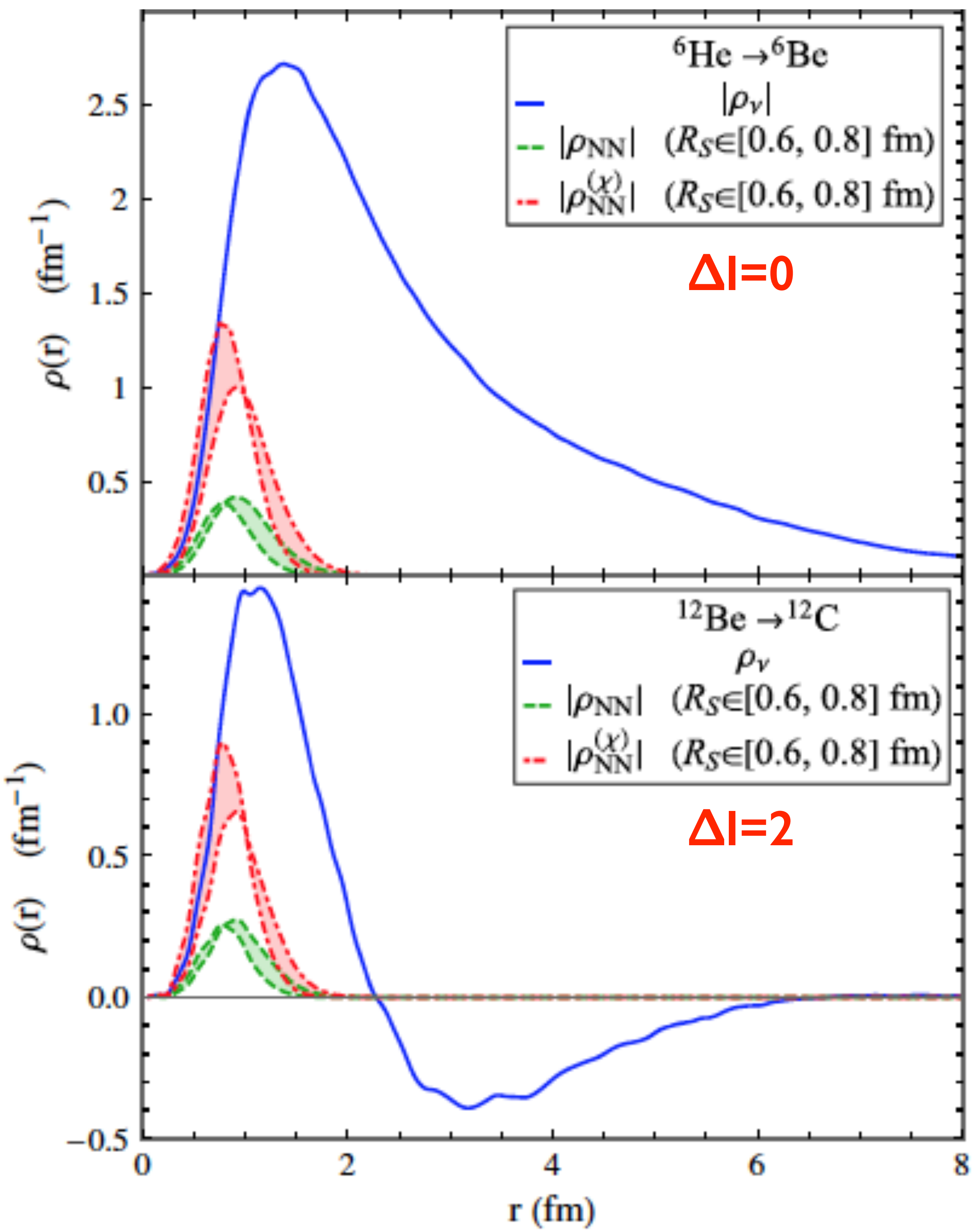
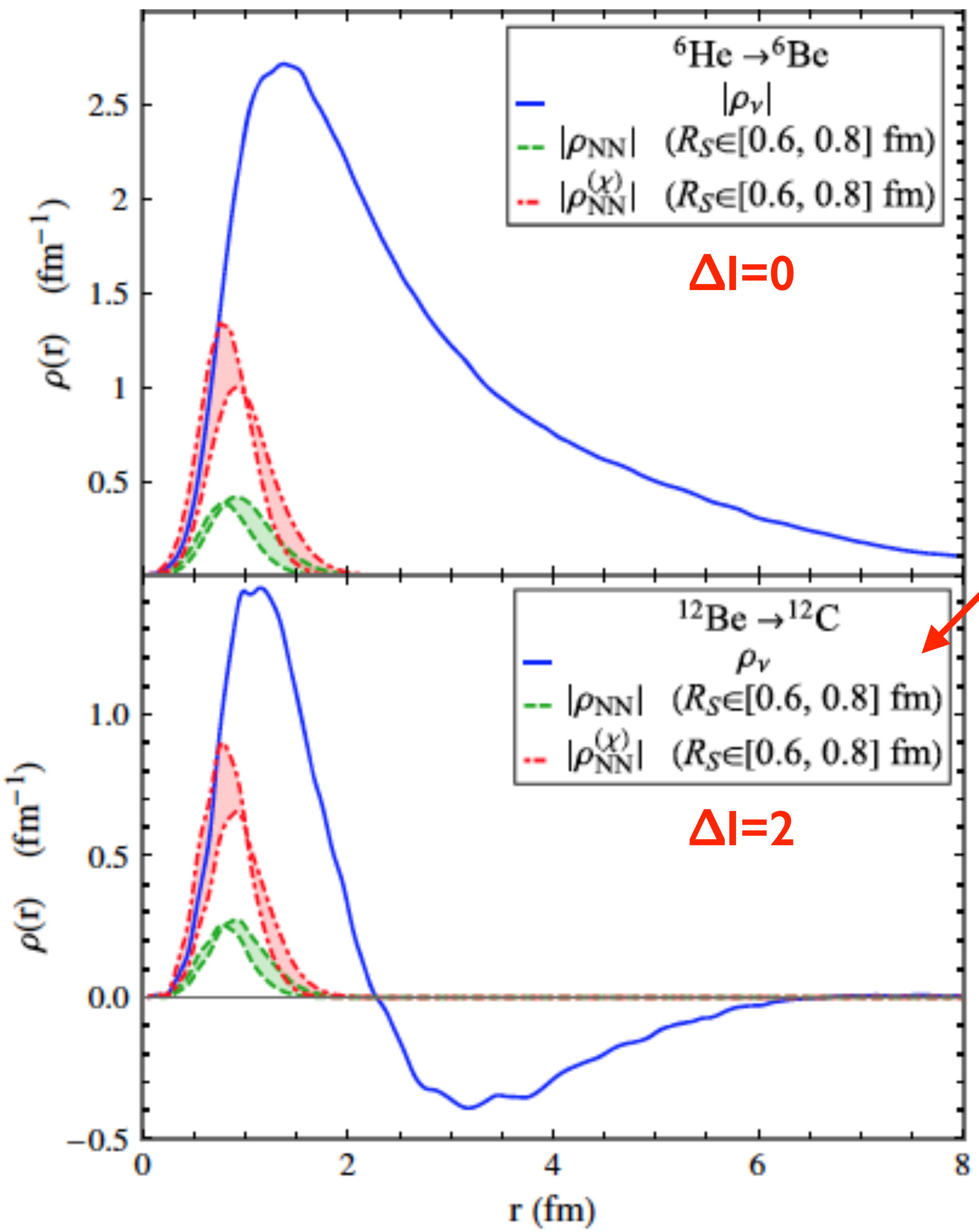
- $A_{NN}+A_\nu$ is R_S (or μ) independent and $A_{NN}/A_\nu \sim 10\%$ (30%) at $R_S\sim0.8$ fm (0.3 fm) **
- ** Actual correction will be different because in general $C_1 \neq C_2$
- To gain Insight on this result, look at "matrix-element density" as function of inter-nucleon distance

Estimating numerical impact (2)



- What about nuclei?
- For light nuclei: used wavefunctions obtained via Variational Monte Carlo from AV18 (NN) + U9 (NNN) potentials
- Hybrid calculation at this stage: can't expect R_S-independence
- $g_\nu \sim (C_1+C_2)/2$ taken from fit to NN data (ours vs Piarulli et al. 1606.06335)

Estimating numerical impact (2)



g_ν contribution sizable in ΔI=2 transition (*due to node*): for A=12, A_{NN}/A_ν = 25%-55%

Transitions of interest (^{76}Ge→ ^{76}Se, …) have ΔI=2 and node ⇒

$m_{\beta\beta}$ phenomenology can be significantly affected!