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Title: Searching for new physics with single and double beta decay

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Searching for new physics with single and double beta decay

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Outline

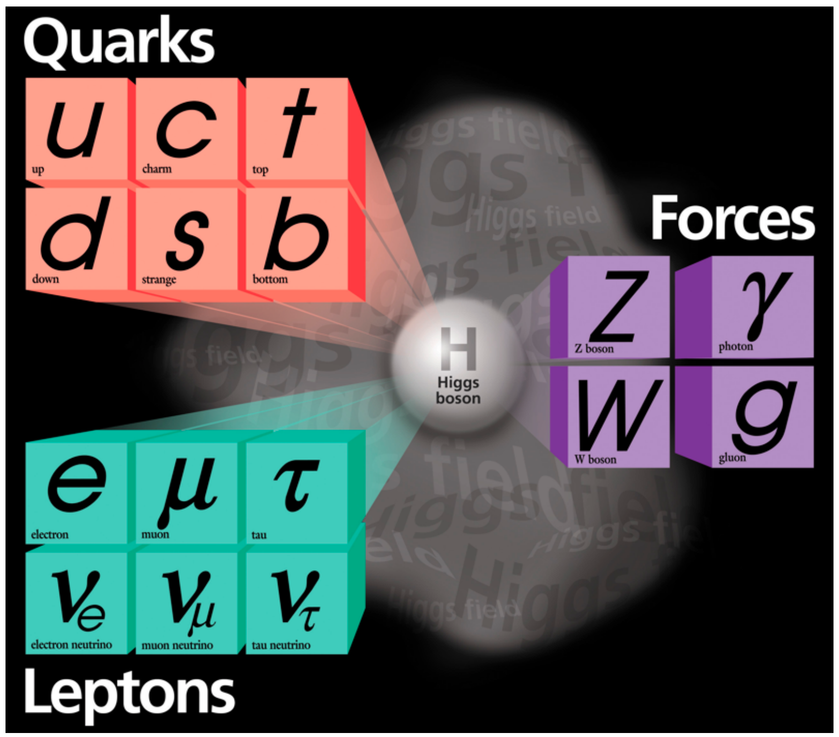
- The quest for new physics: Energy and Precision Frontiers

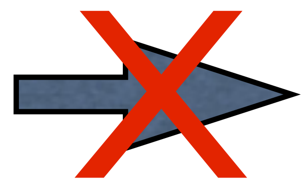
- Two Precision Frontier probes with strong LANL involvement:
  - Precision β decay measurements
  - Neutrinoless ββ decay

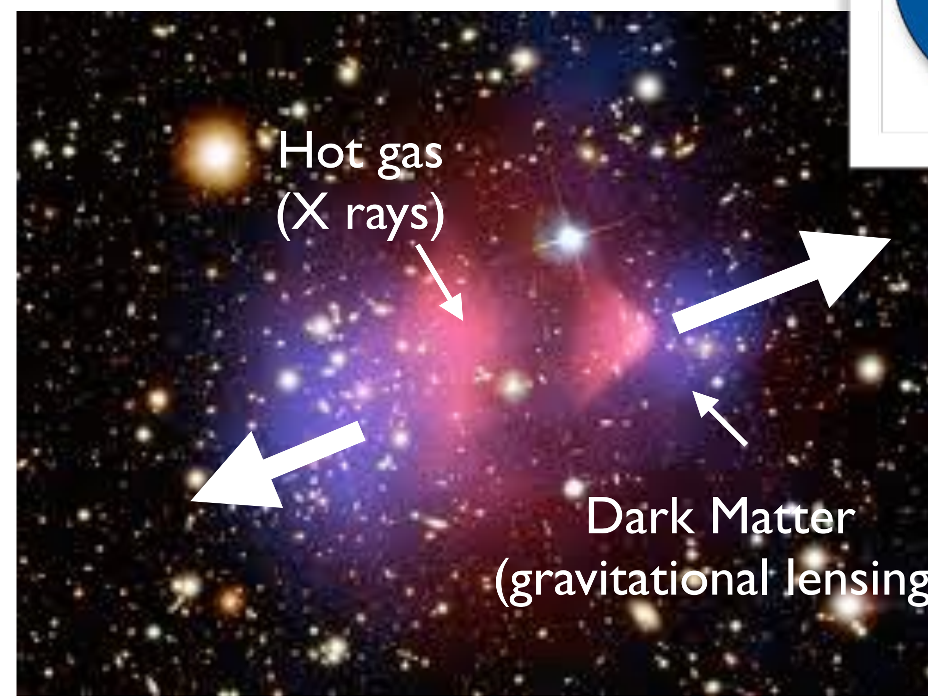
Acknowledgements:
T-2 / CCS-7 collaborators: T. Bhattacharya, K. Fuyuto, M. Graesser, R. Gupta, E. Mereghetti, B. Yoon
External collaborators: W. Dekens, J. de Vries, S. Pastore, M. Piarulli, R. Wiringa, U. Van Kolck
P-23 Weak Interactions Team
P-25 Neutron Physics Team

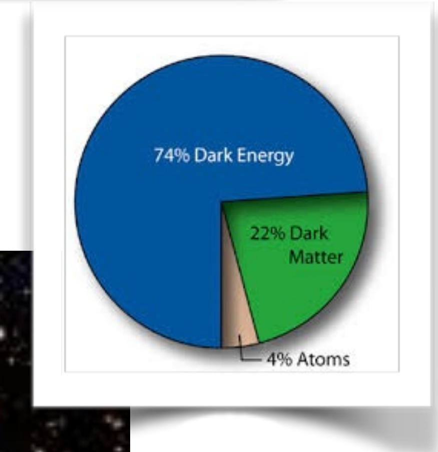
The quest for new physics

New physics: why?









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

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

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

. . .

Addressing these puzzles likely requires new degrees of freedom

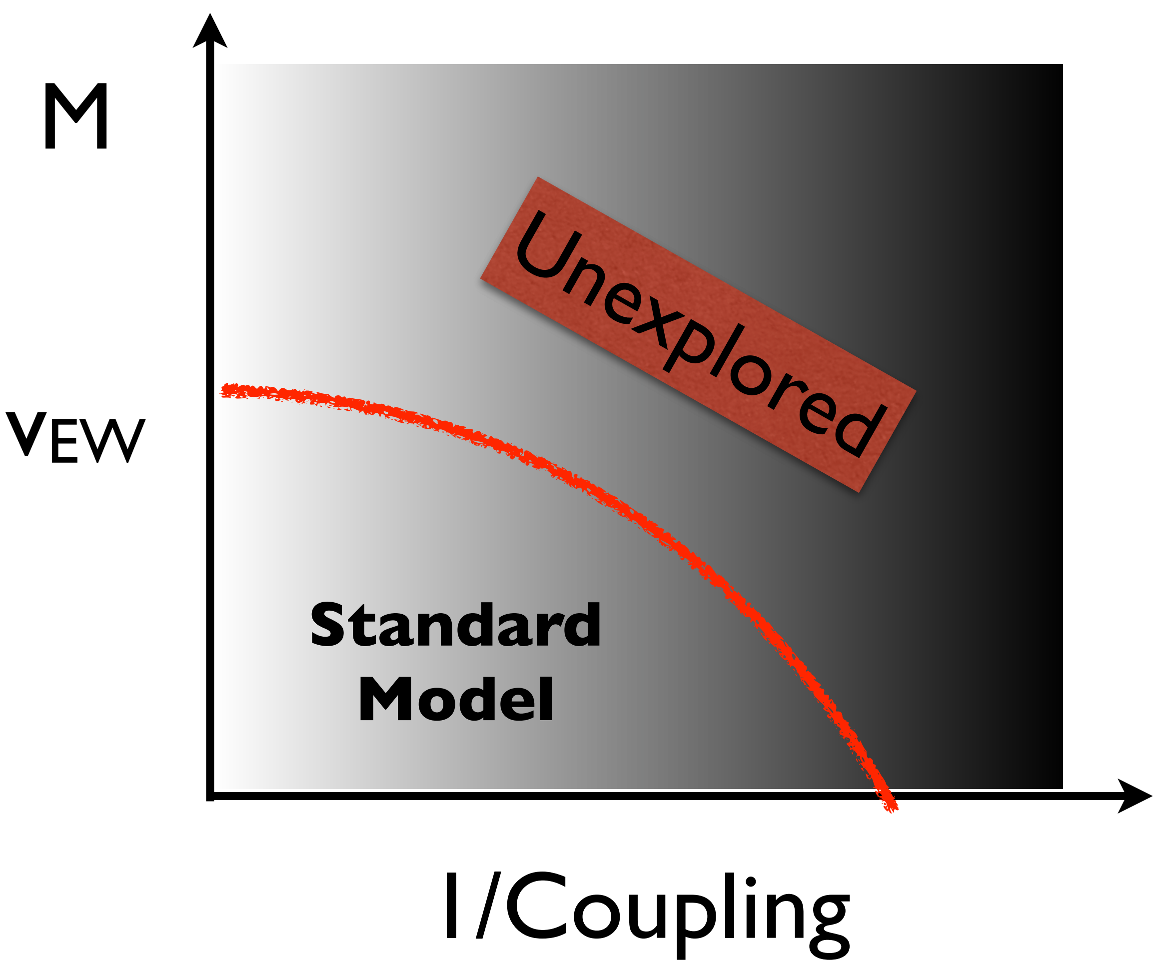
New physics: where?

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

v_{EW}

~ 250 GeV

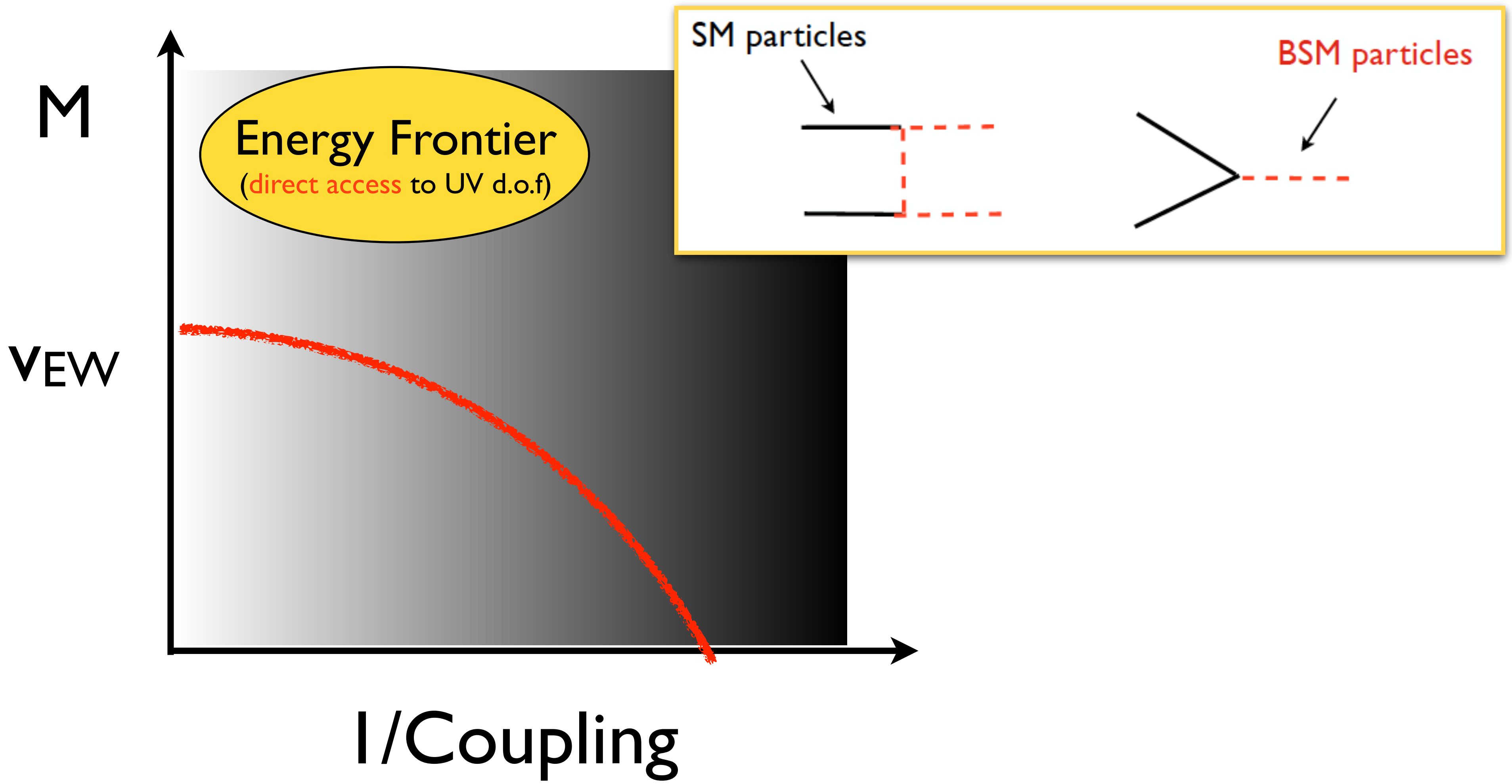
(m_{proton} ~ 1 GeV)



New physics: how?

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

$$E = mc^2$$

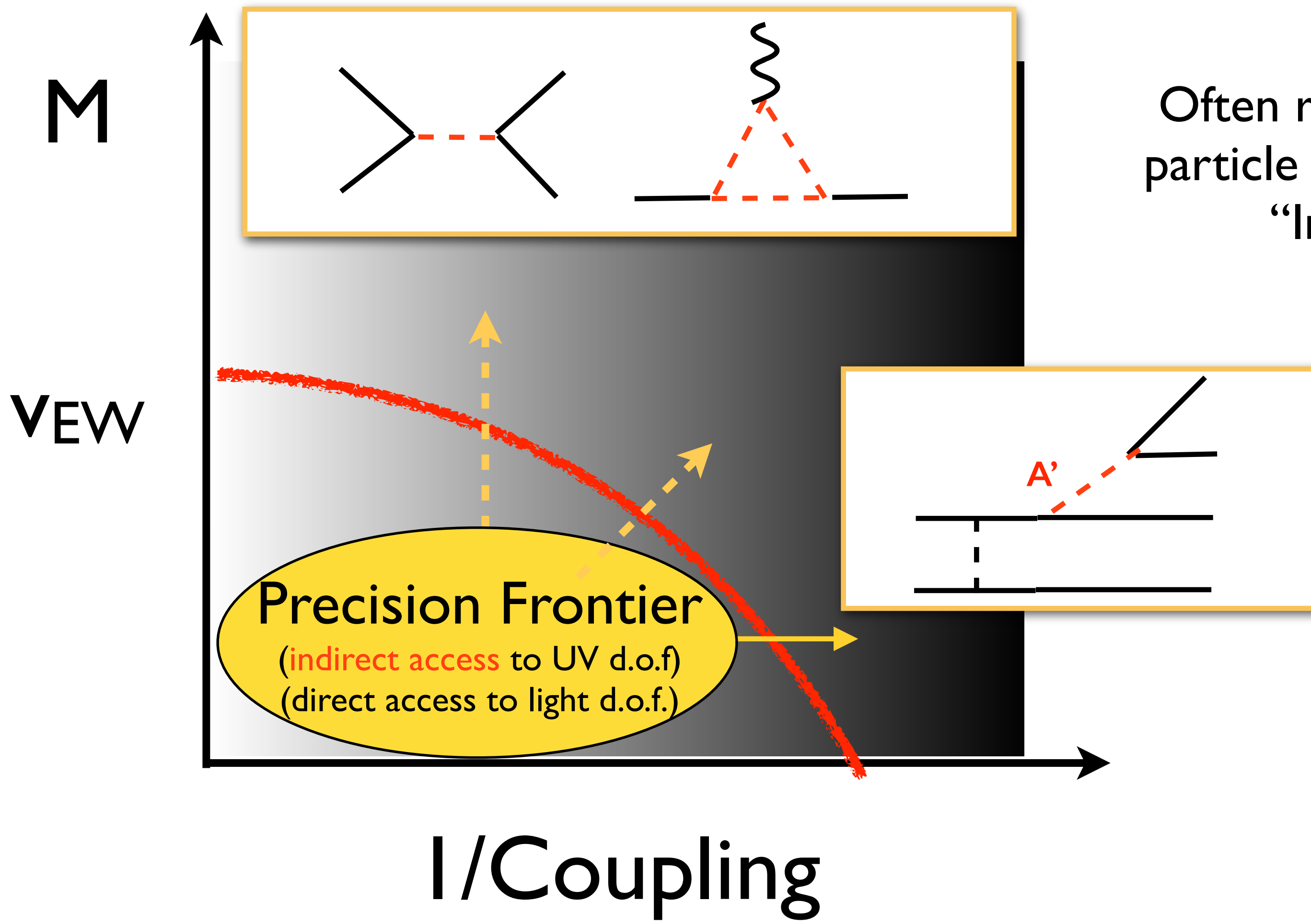


- Two approaches

New physics: how?

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

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

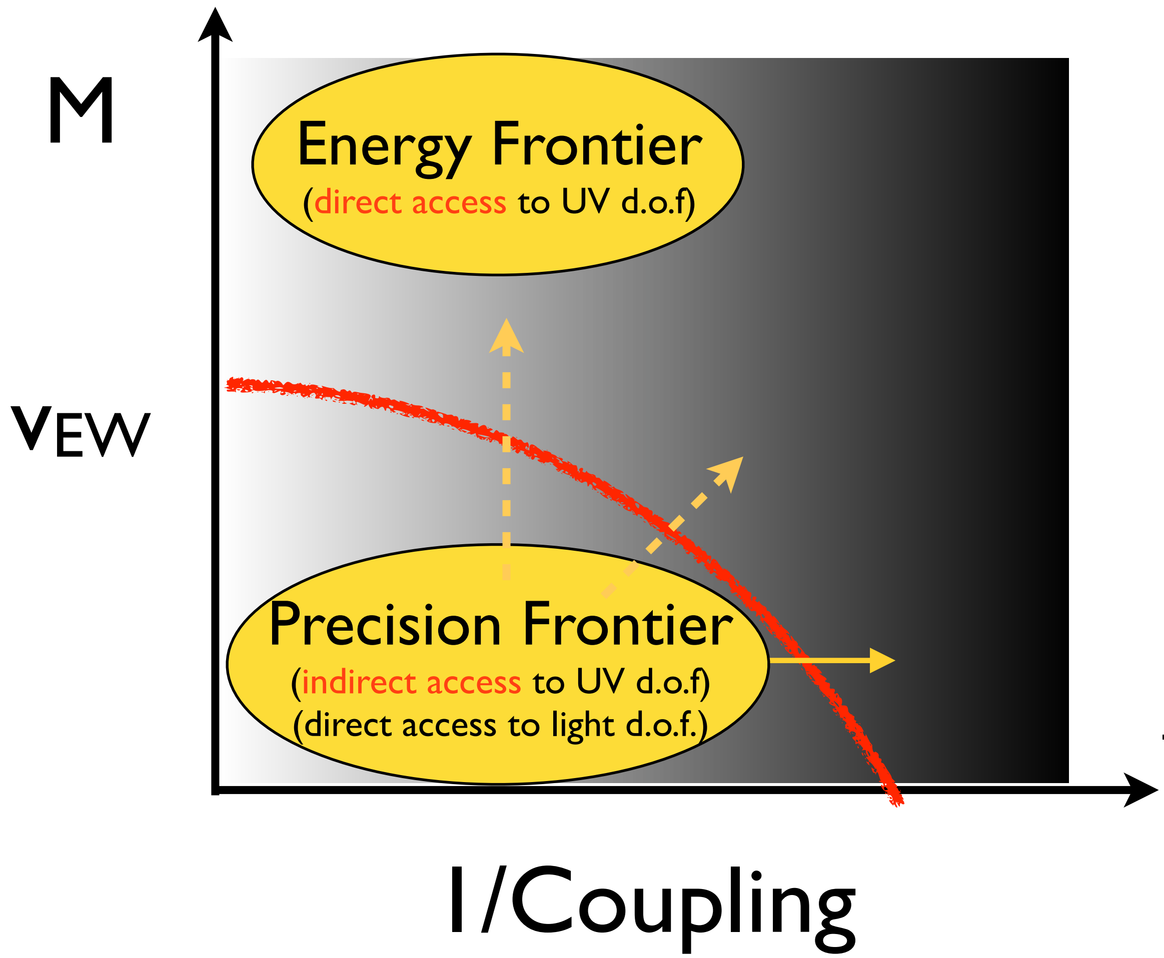


Often requires use of powerful particle accelerators (hence also "Intensity Frontier")

- Two approaches

New physics: how?

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



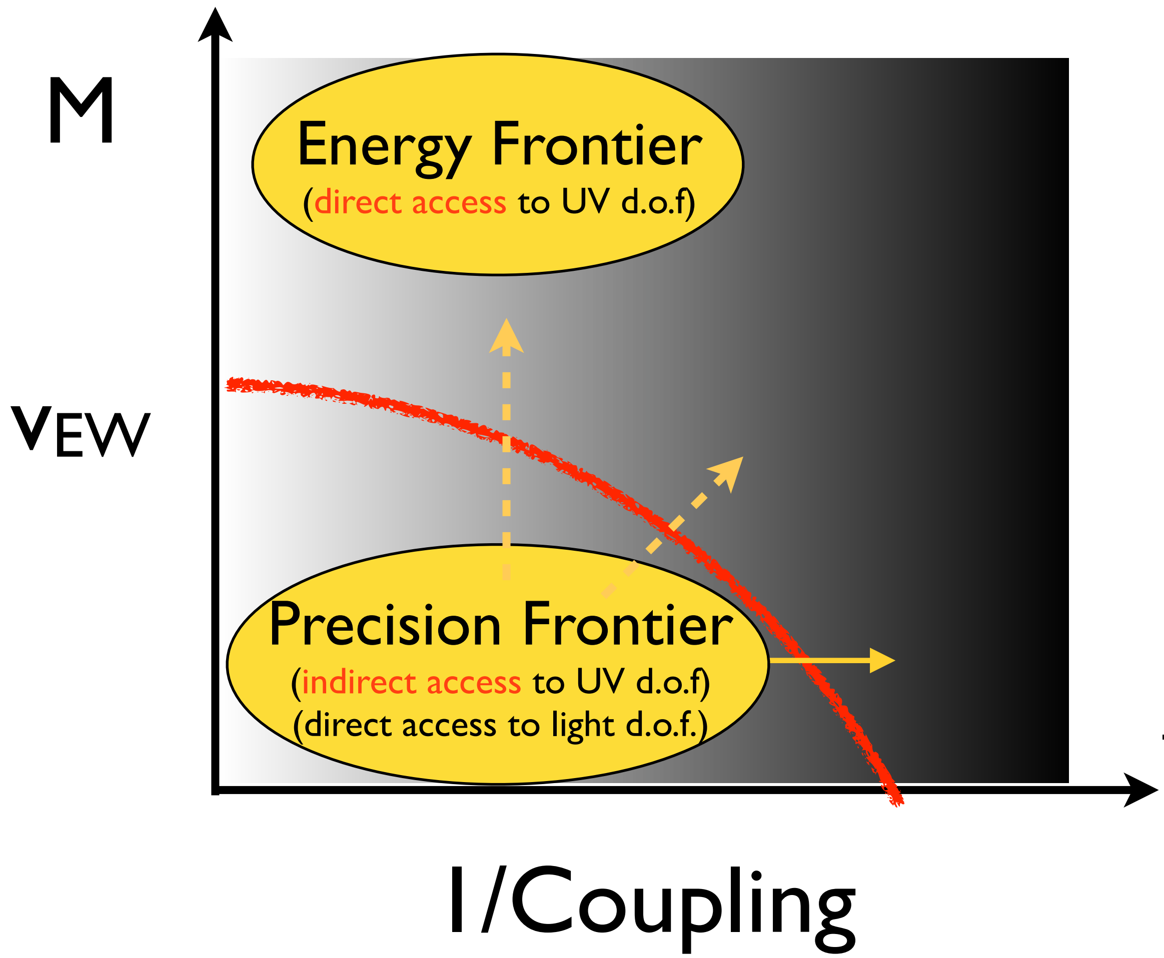
- EWSB mechanism
- Direct access to heavy particles
- ...

- L and B non conservation
- CP violation (w/o flavor)
- Flavor violation: quarks, leptons
- Multi-TeV scale interactions
- Neutrino properties
- Dark sectors
- …

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

New physics: how?

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



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LANL NP & HEP programs
play a prominent role at the Precision Frontier

New physics: how?

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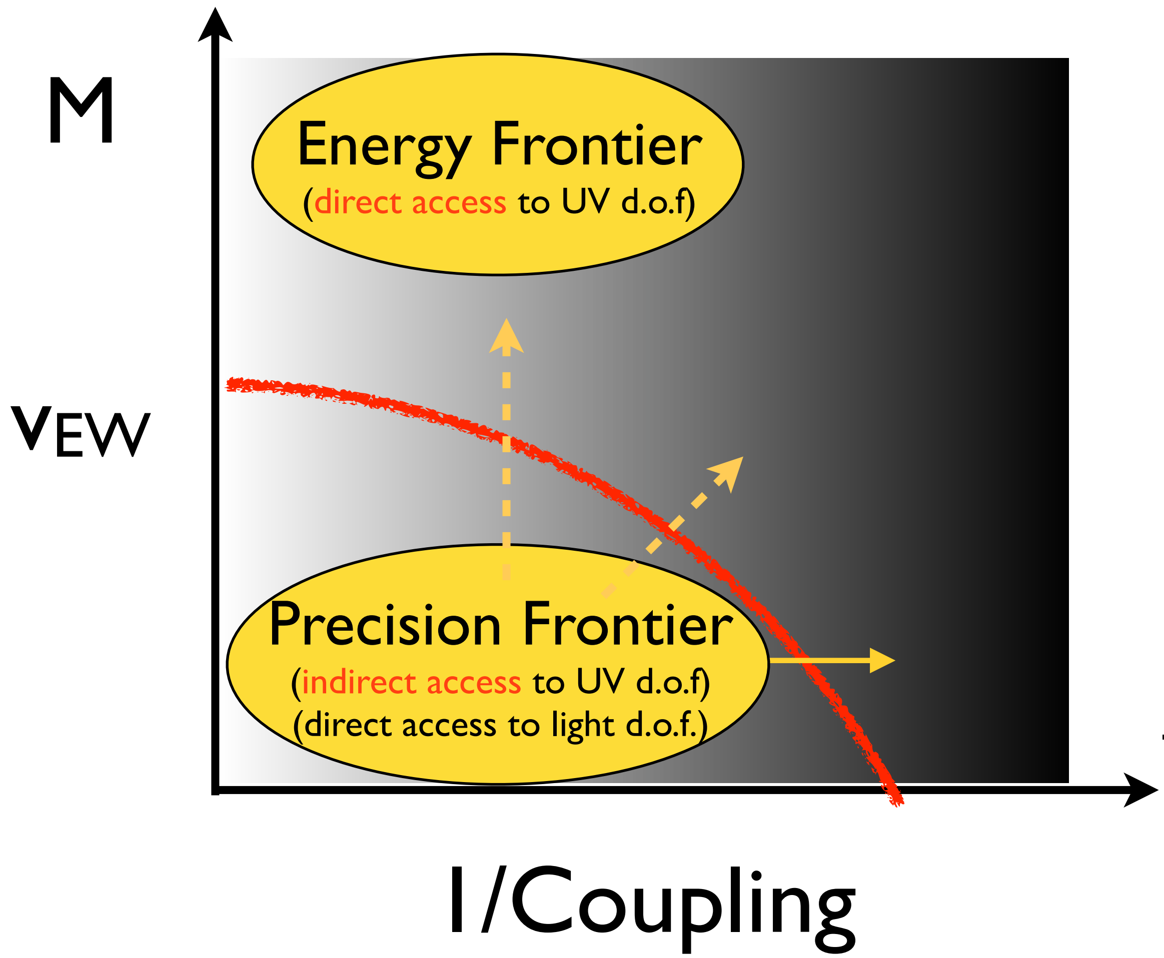

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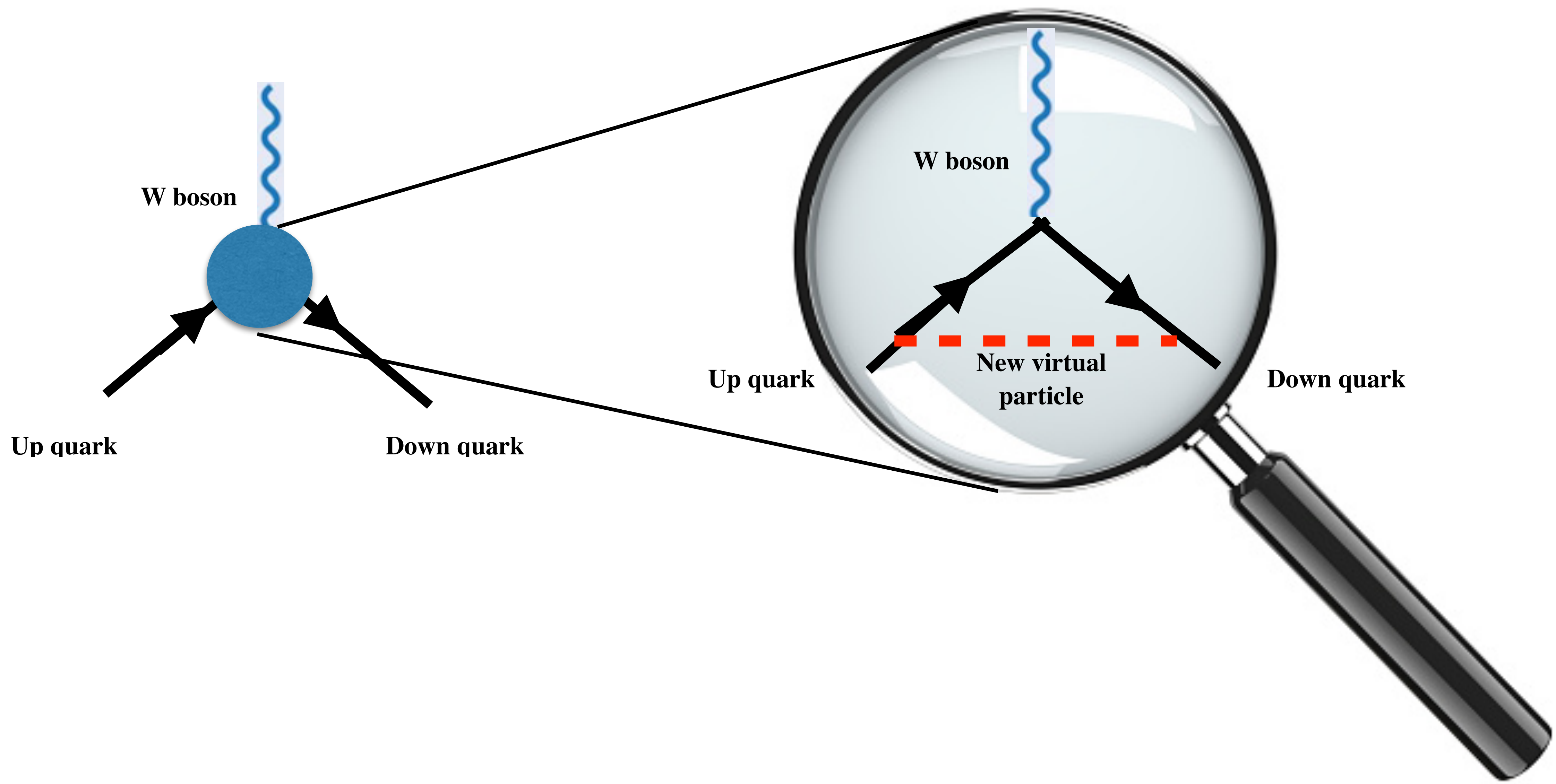
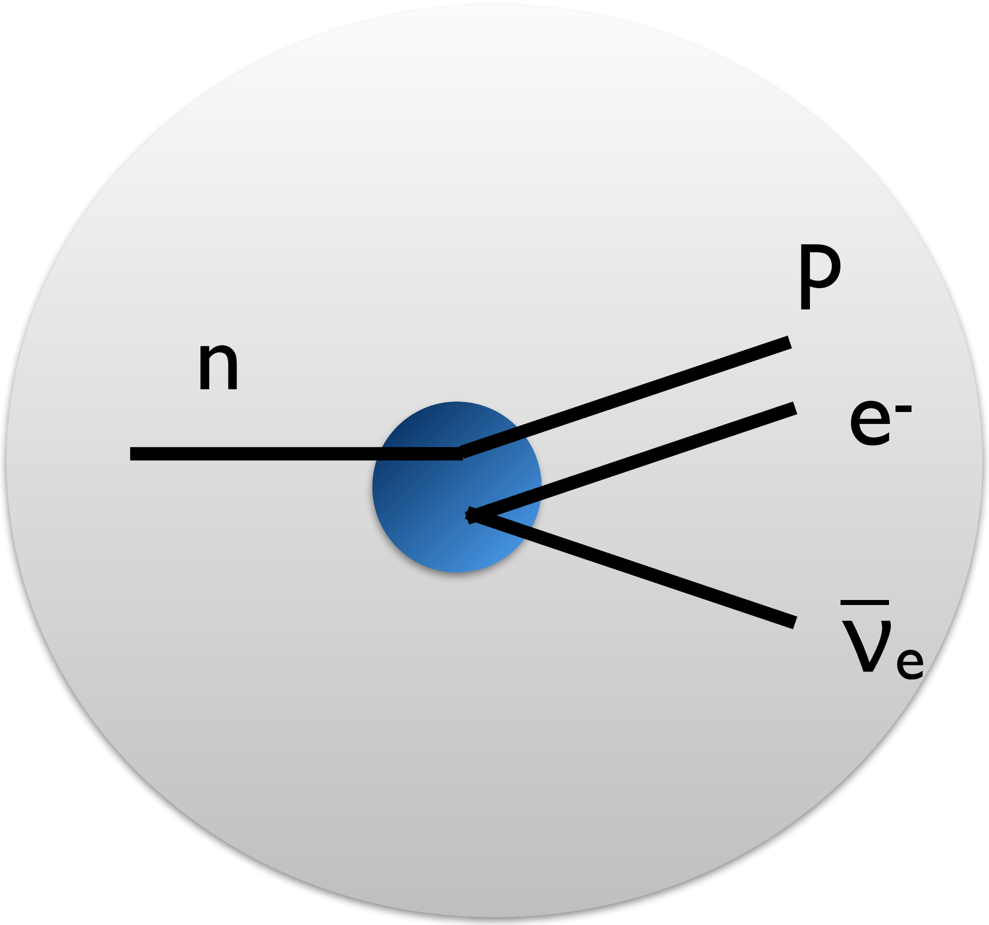
I will discuss β and ββ decays as probes of
BSM weak interactions and L# non-conservation, respectively

Beta decays as a probe of new physics



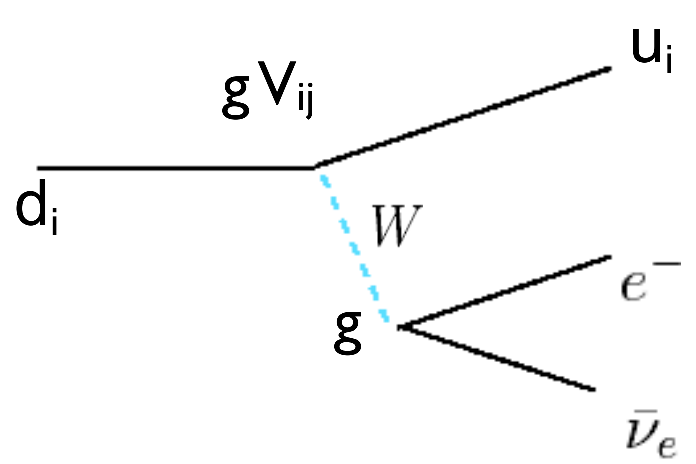
Beta decays in the SM and beyond



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

Beta decays in the SM and beyond

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



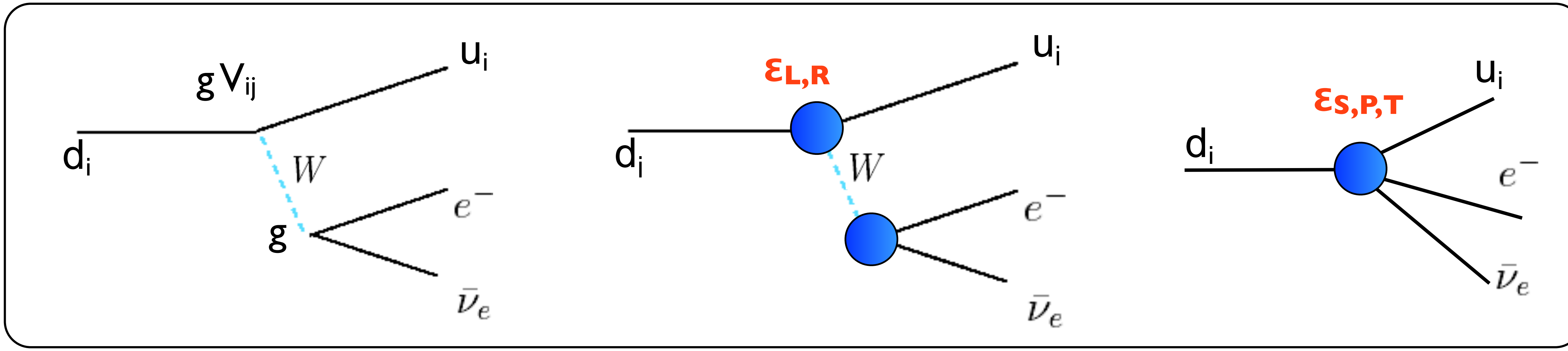
$G_F^{(\beta)} \sim g^2 V_{ij}/M_W^2 \sim G_F^{(\mu)} V_{ij} \sim 1/v^2\, V_{ij}$

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

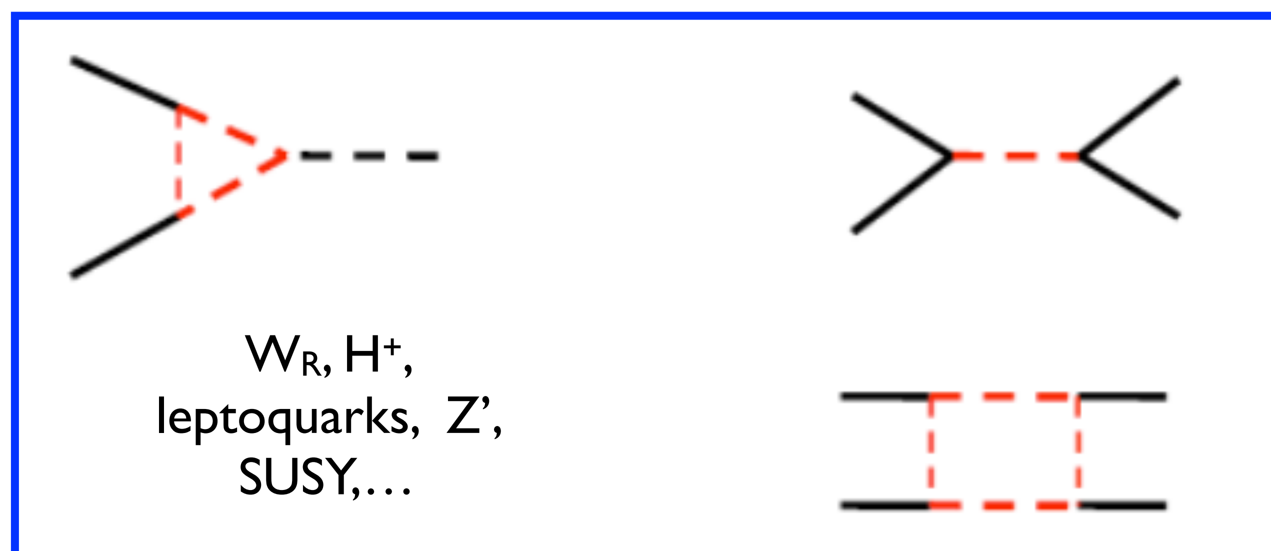
Cabibbo-Kobayashi-Maskawa

Beta decays in the SM and beyond

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



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



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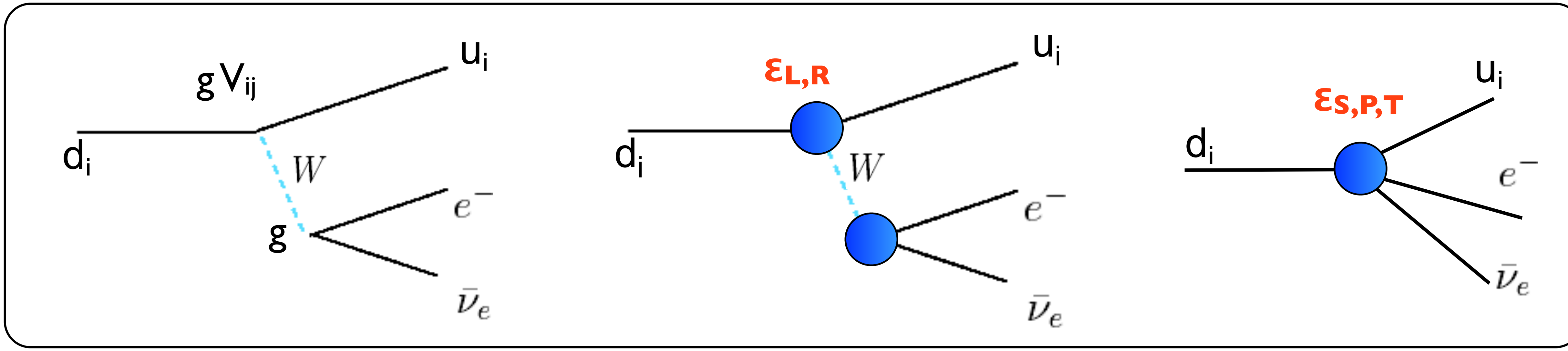

$G_F^{(\beta)} \sim g^2 V_{ij}/M_W^2 \sim G_F^{(\mu)} V_{ij} \sim 1/v^2\, V_{ij}$ $\quad 1/\Lambda^2 \quad 1/\Lambda^2$

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

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

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

How do we probe the ε_α? (1)

1. Differential decay distribution (mostly sensitive to $\varepsilon_{S,T}$)

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

Lee-Yang, 1956 **Jackson-Treiman-Wyld 1957**

How do we probe the ε_α? (I)

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b ($g_S \varepsilon_S$, $g_T \varepsilon_T$):
distortion of beta spectrum

How do we probe the ε_α? (I)

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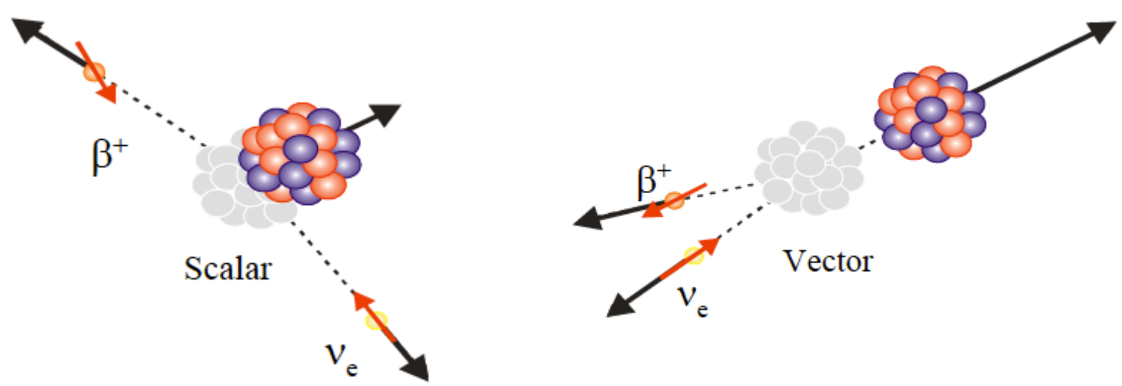

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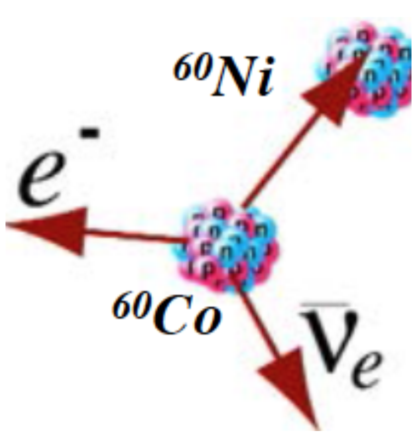

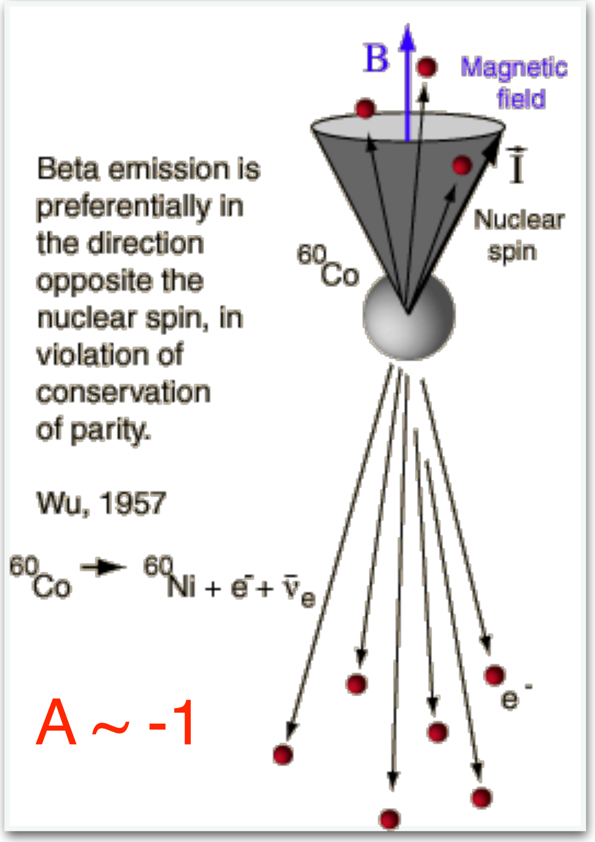

C-S Wu

How do we probe the ϵ_α? (I)

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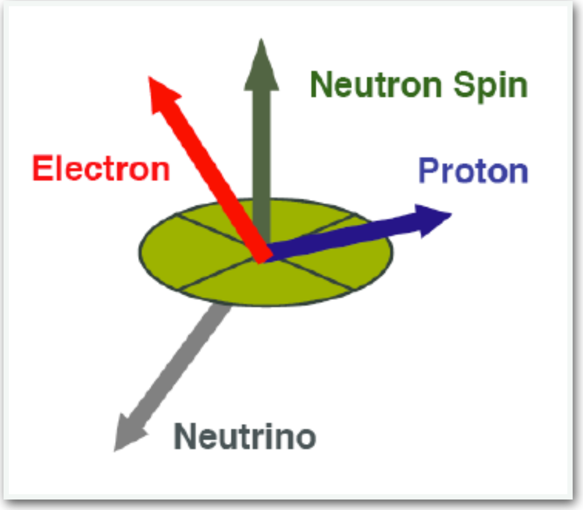

$a(g_A)$, $A(g_A)$, $B(g_A, g_\alpha \epsilon_\alpha)$, ...
isolated via suitable experimental asymmetries

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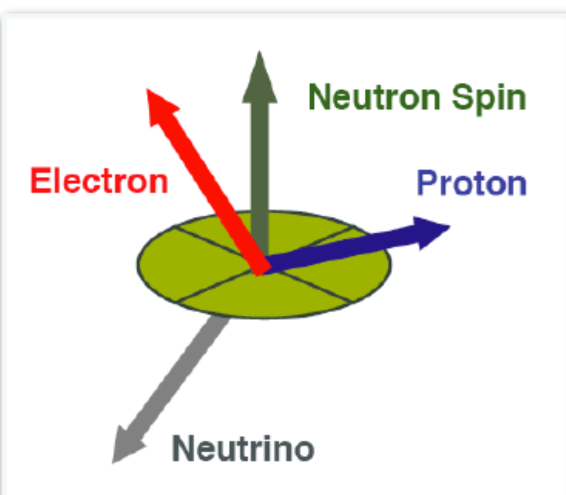

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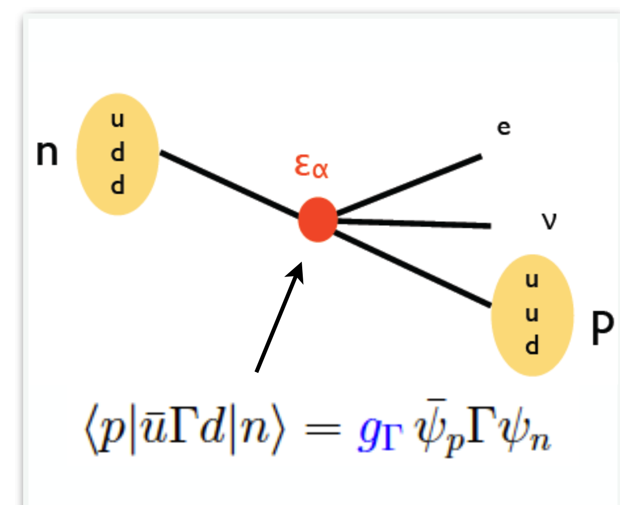
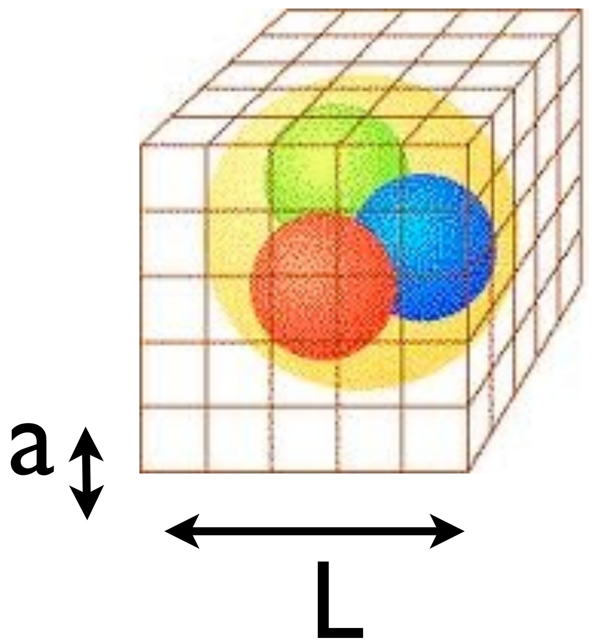
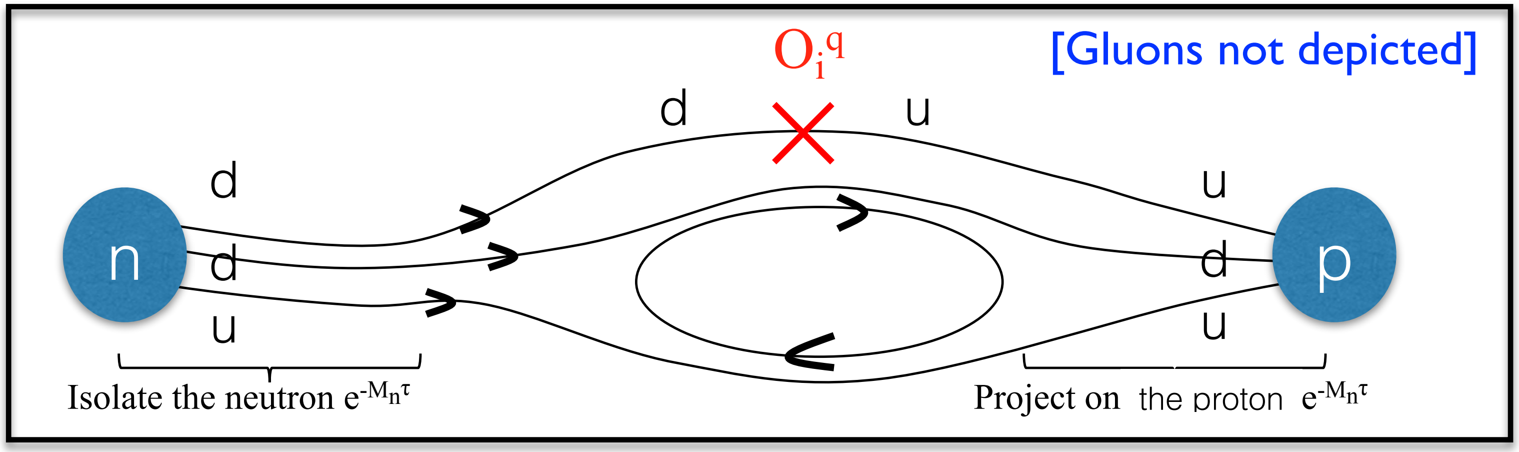


Theory input: nucleon charges $g_{A,S,T}$
Great progress in lattice QCD, spearheaded by LANL theory group

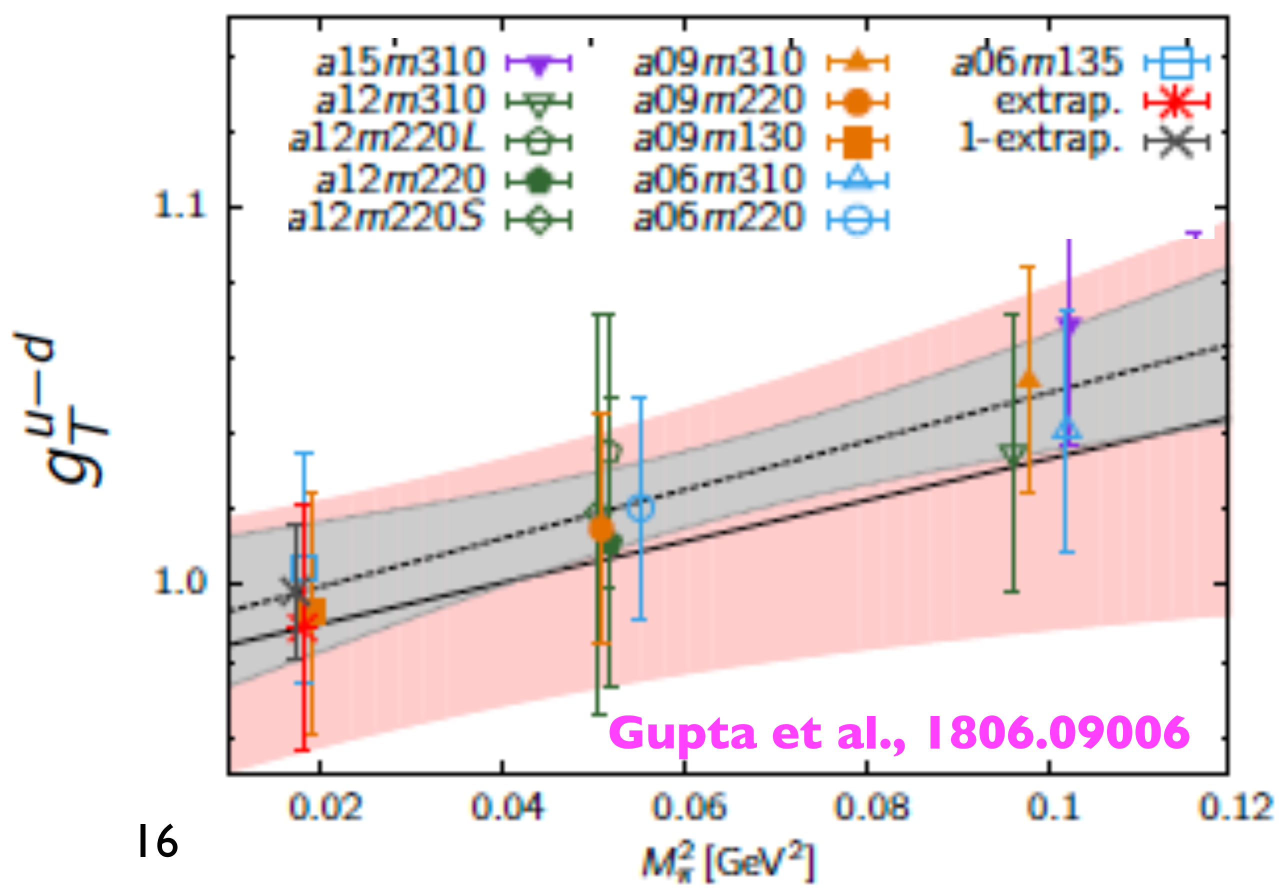
Nucleon charges from lattice QCD

- Discretize space-time into a finite Euclidean lattice (a,V) → perform Monte Carlo integration of the path integral



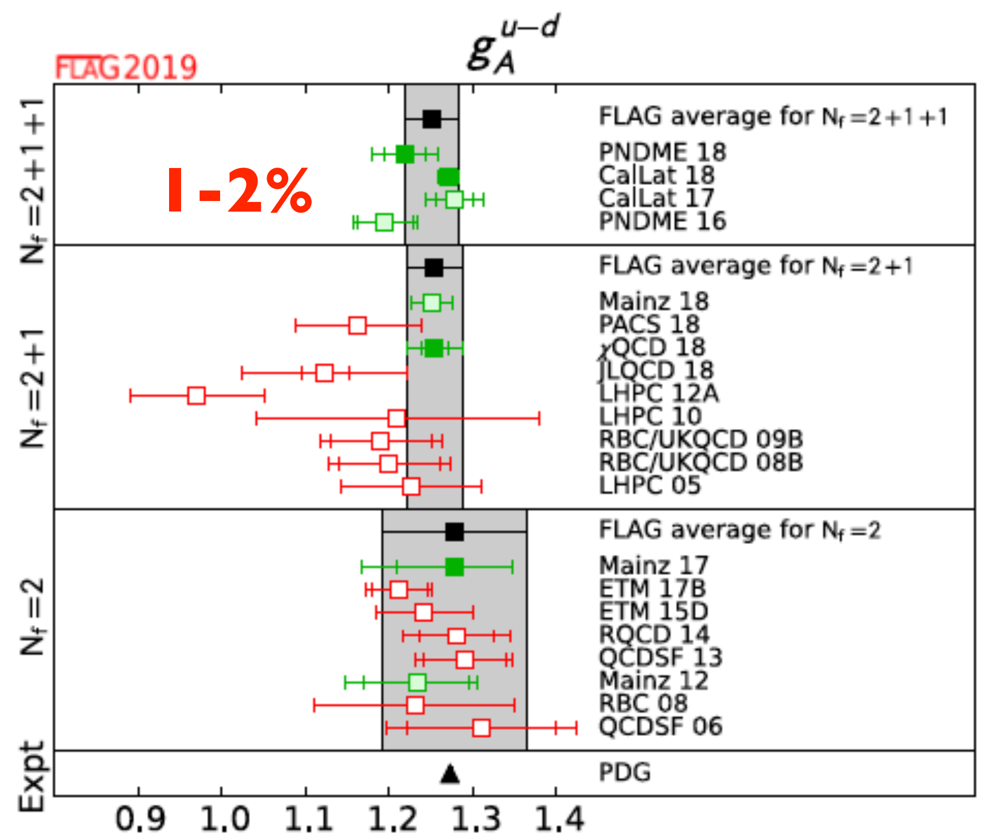


- Remove all systematics by performing calculation on many little universes with different m_q, a, L

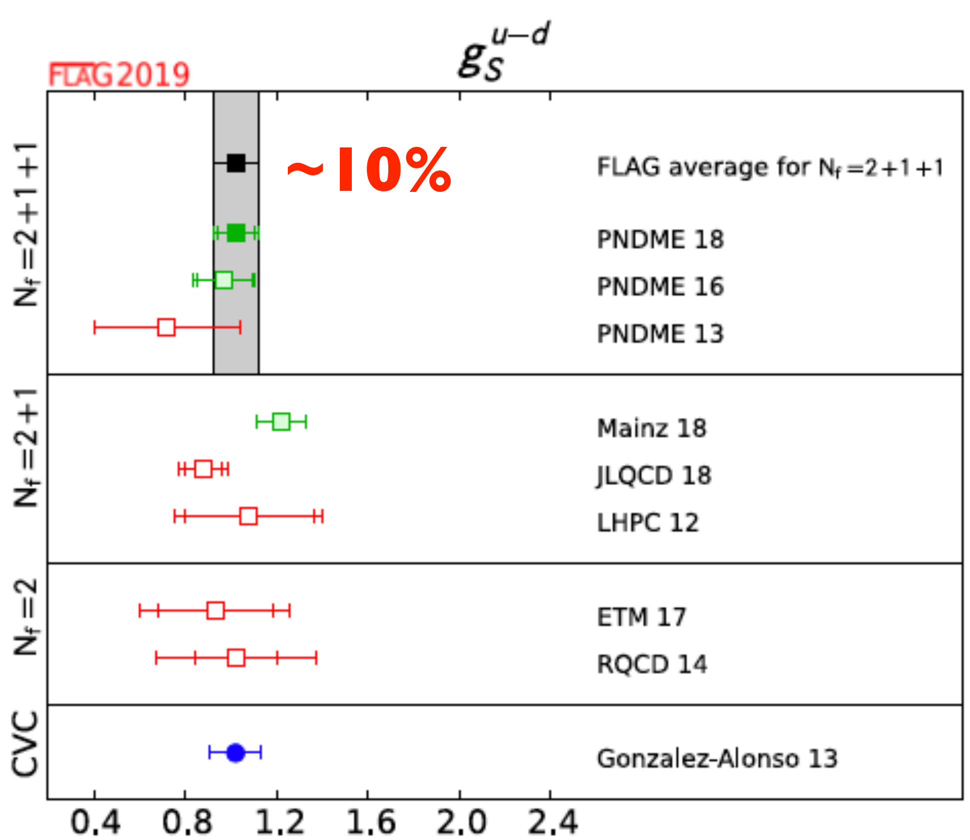


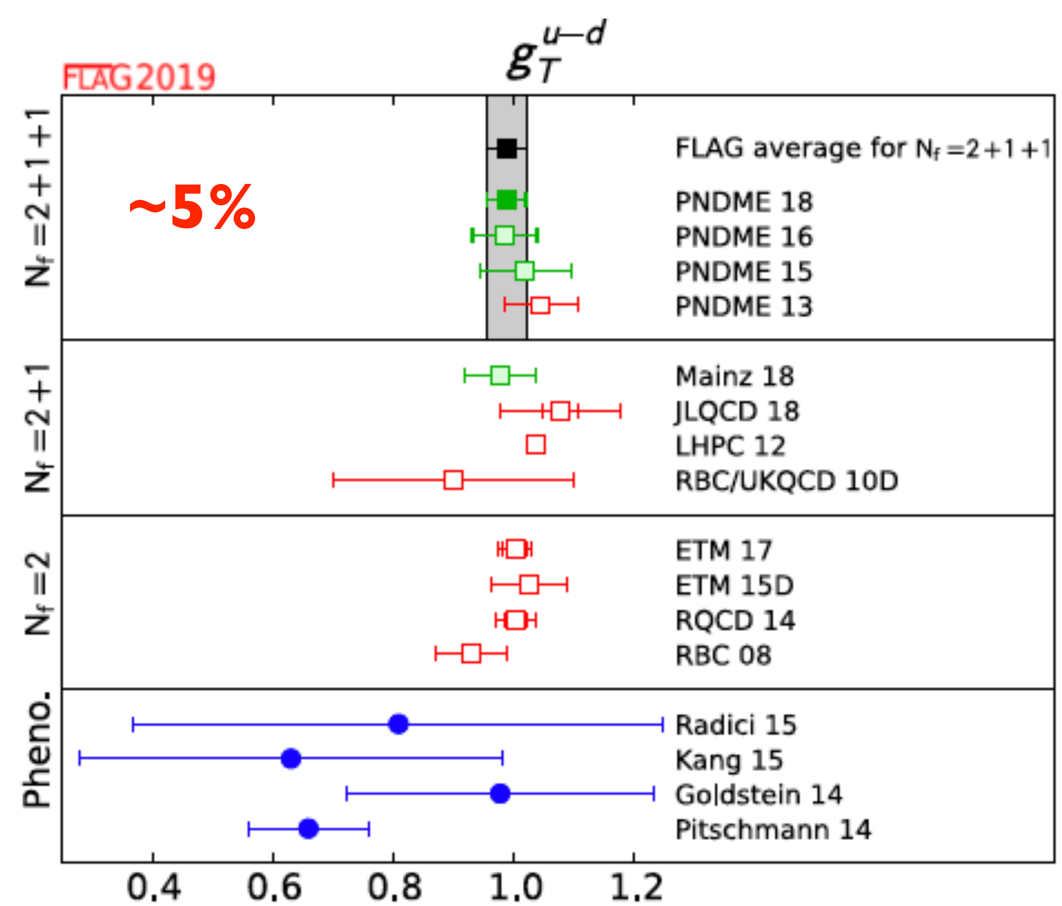
Nucleon charges from lattice QCD

World averages dominated by LANL results



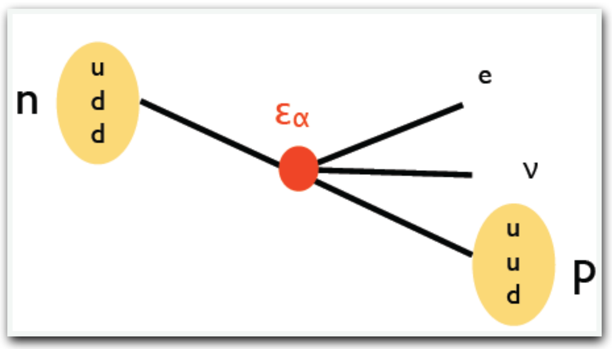
FLAG review 1902.08191





Sensitivity to ε_S and ε_T

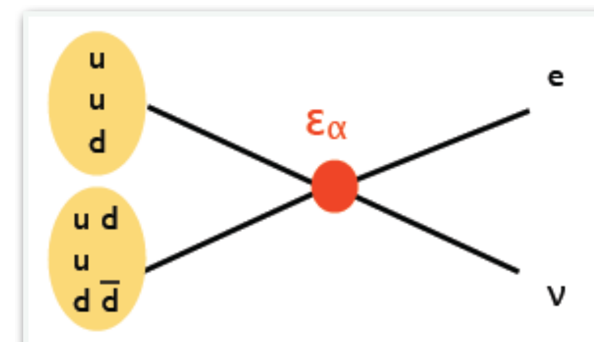
$n \to p\, e\, \nu$

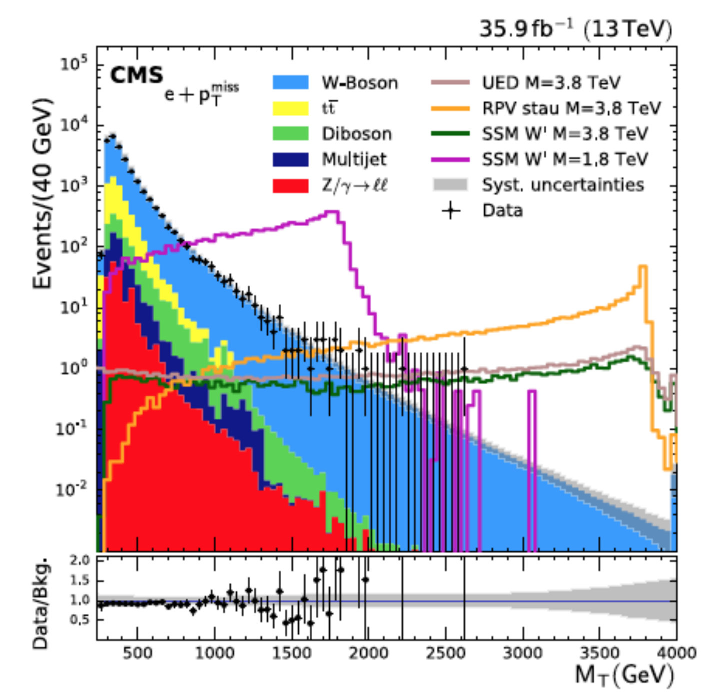


Current low-E data:
dominated by
$b(0^+ \to 0^+)$, $A(n)$

Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

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



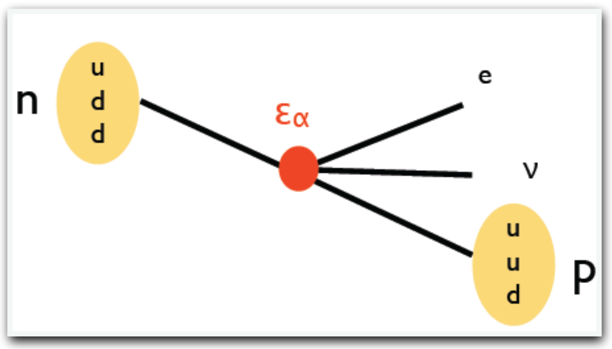


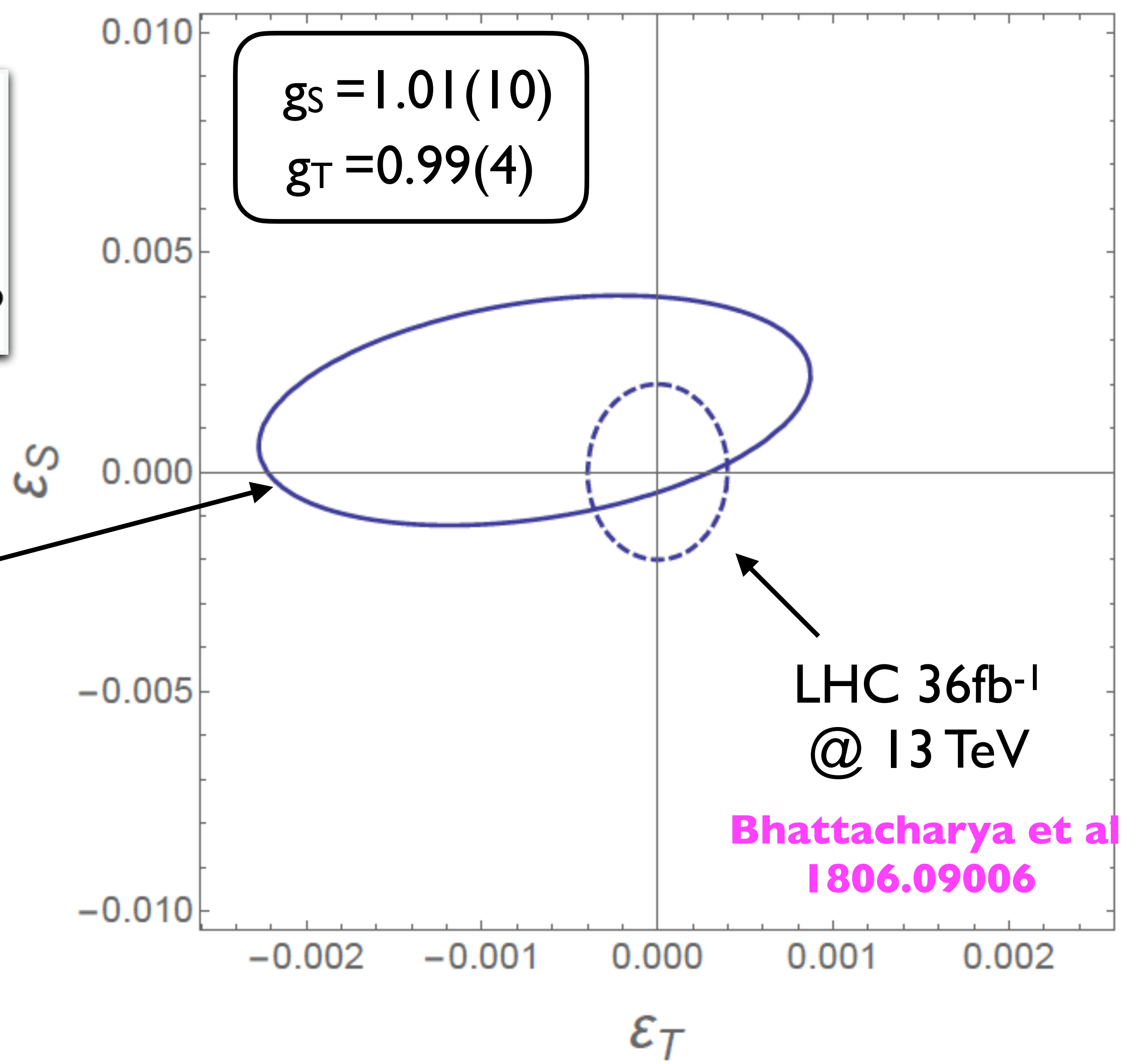
Sensitivity to ε_S and ε_T

CURRENT

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

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





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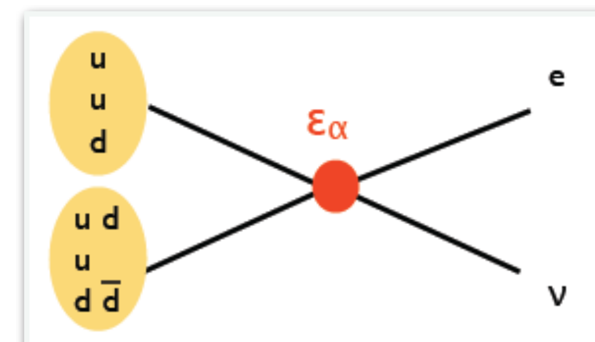
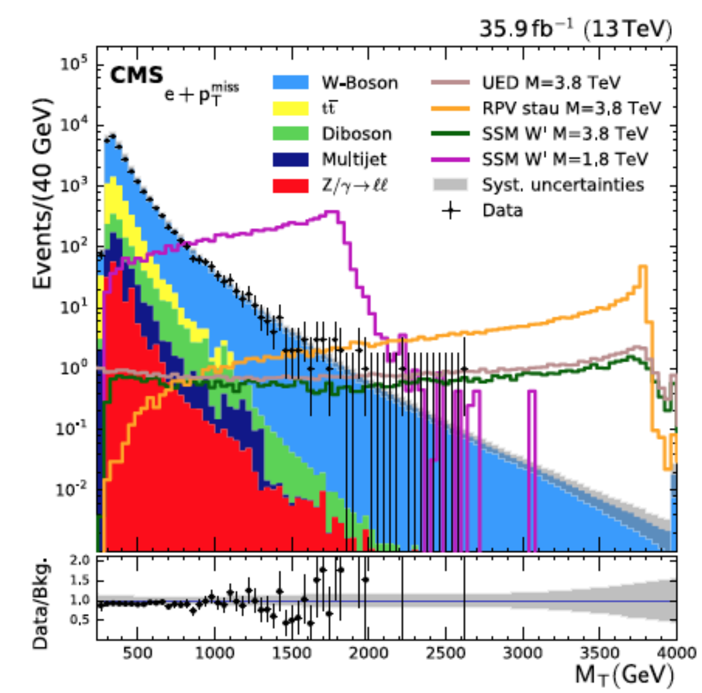
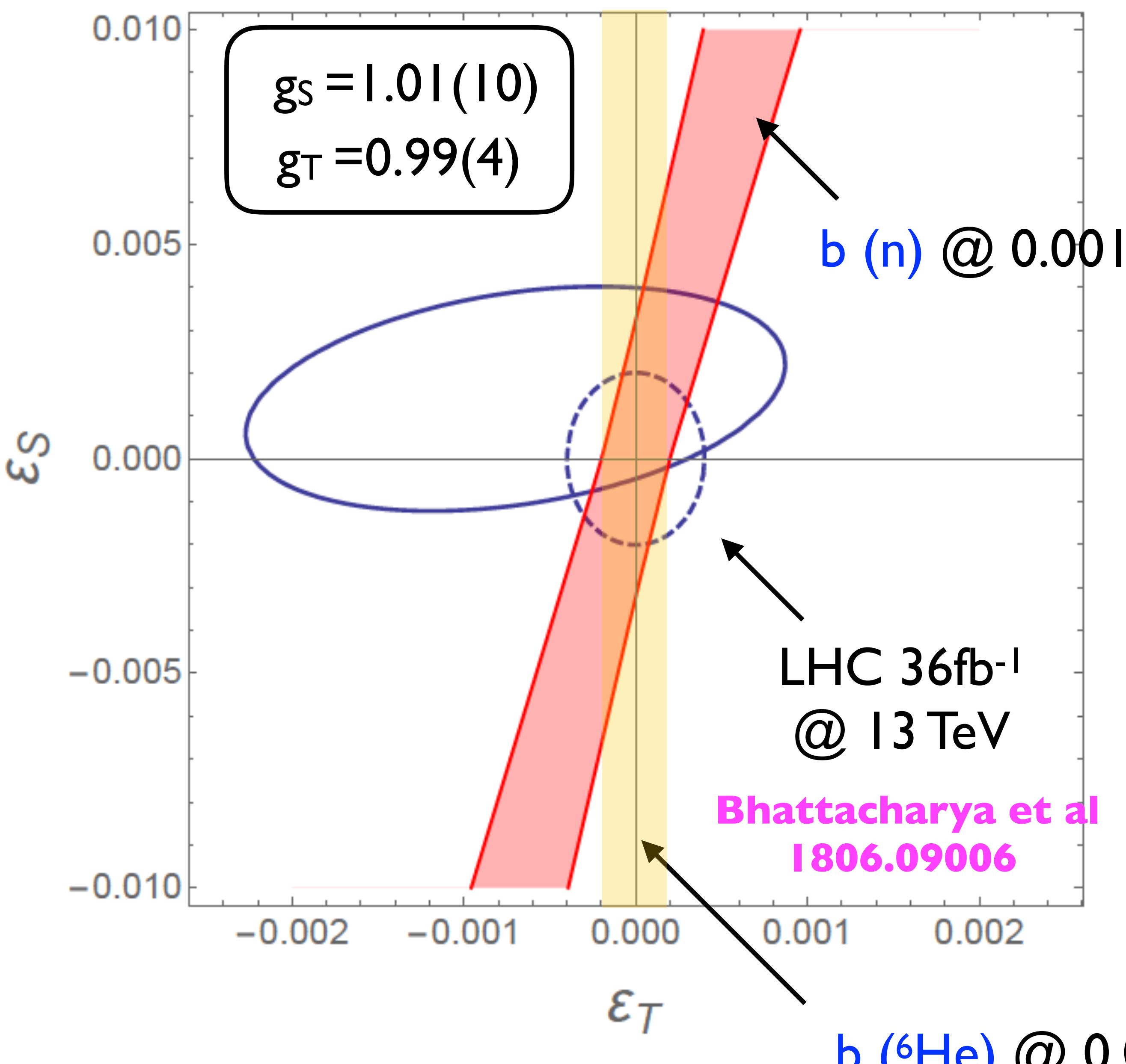




Sensitivity to ε_S and ε_T

FUTURE

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



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

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

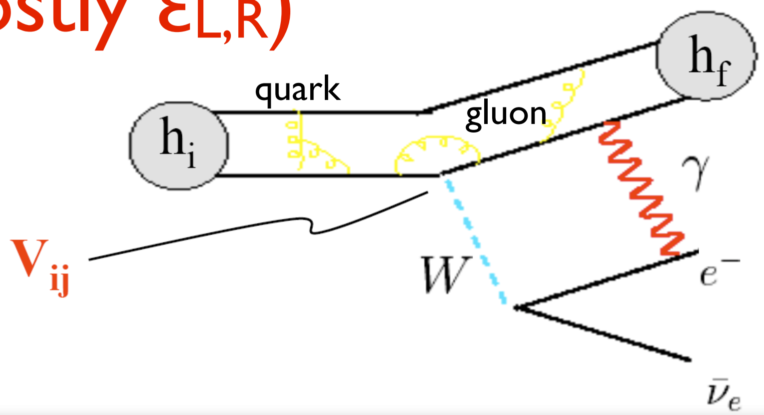
Gonzalez-Alonso, Naviliat-Cuncic, Severijns, 1803.08732

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

Note: $\lesssim 10\%$ uncertainty on $g_{S,T}$ is essential to achieve competitiveness

How do we probe the εα? (2)

2. Total decay rates (mostly $\varepsilon_{L,R}$)



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

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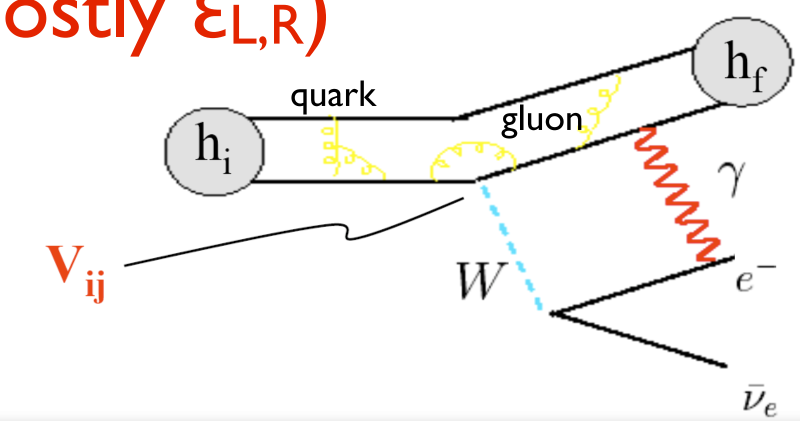

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Lifetimes, BRs

Experimental input

Q-values → phase space

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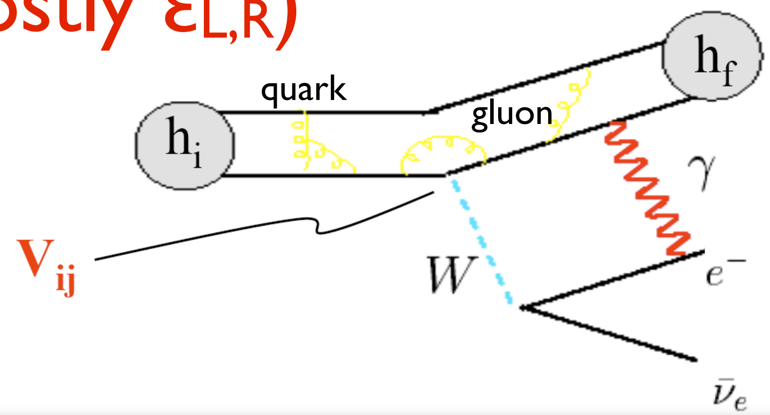


$$\Gamma_k = (G_F^{(\mu)})^2 \times |\bar{V}_{ij}|^2 \times |M_{\rm had}|^2 \times (1+\delta_{RC}) \times F_{\rm kin}$$

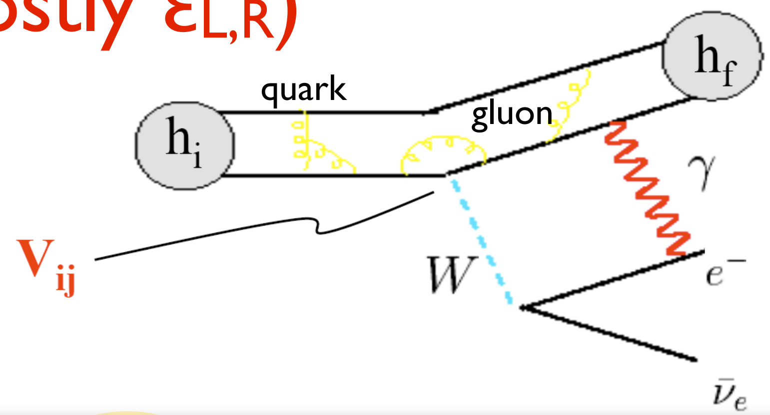
Theory input

Hadronic / nuclear
matrix elements
and radiative corrections

LQCD, chiral EFT,
dispersion relations
+ expt. input (g_A)

How do we probe the ε_α? (2)

2. Total decay rates (mostly $\varepsilon_{L,R}$)



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

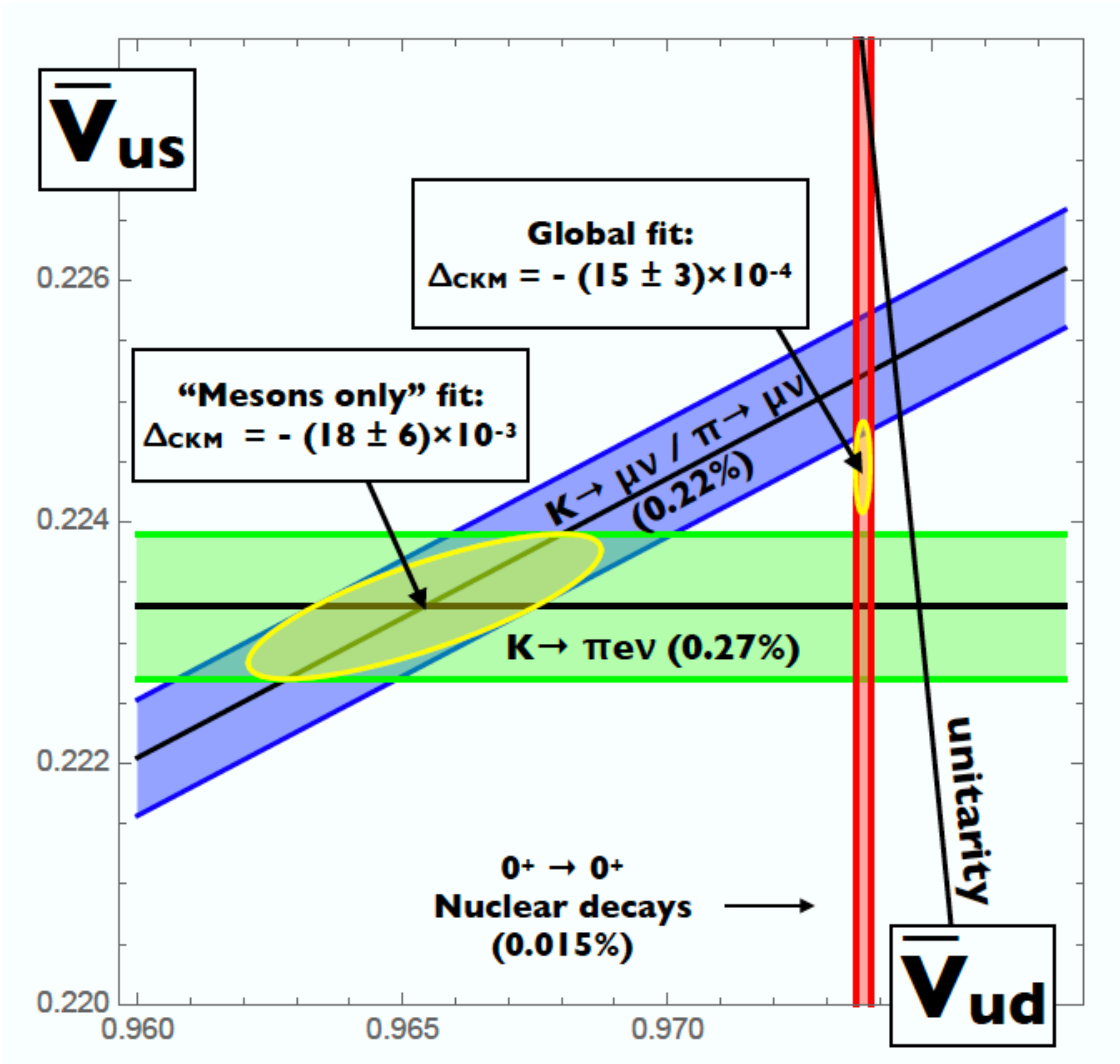
Channel-dependent effective CKM element

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

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

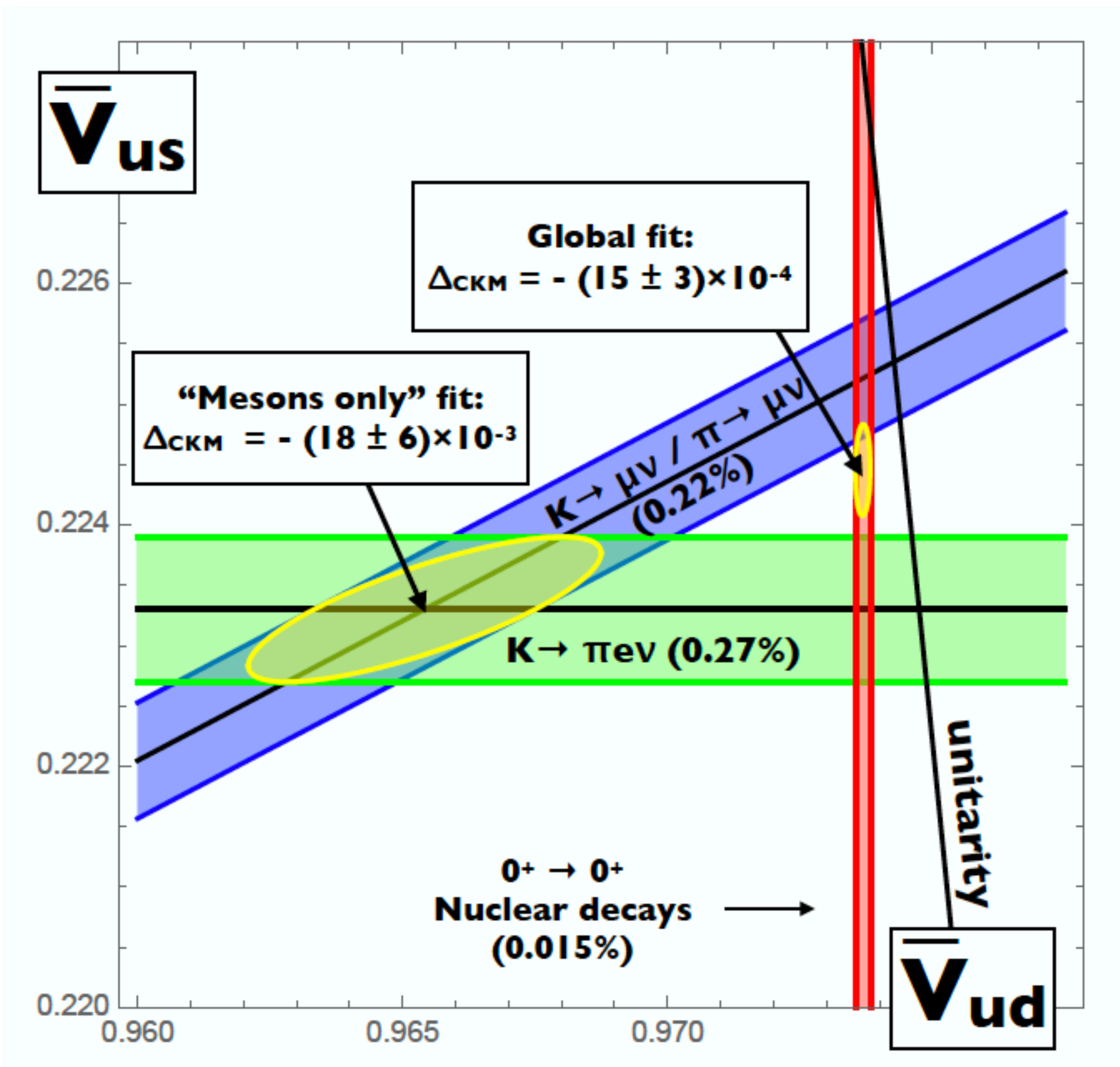
CKM unitarity test

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



CKM unitarity test

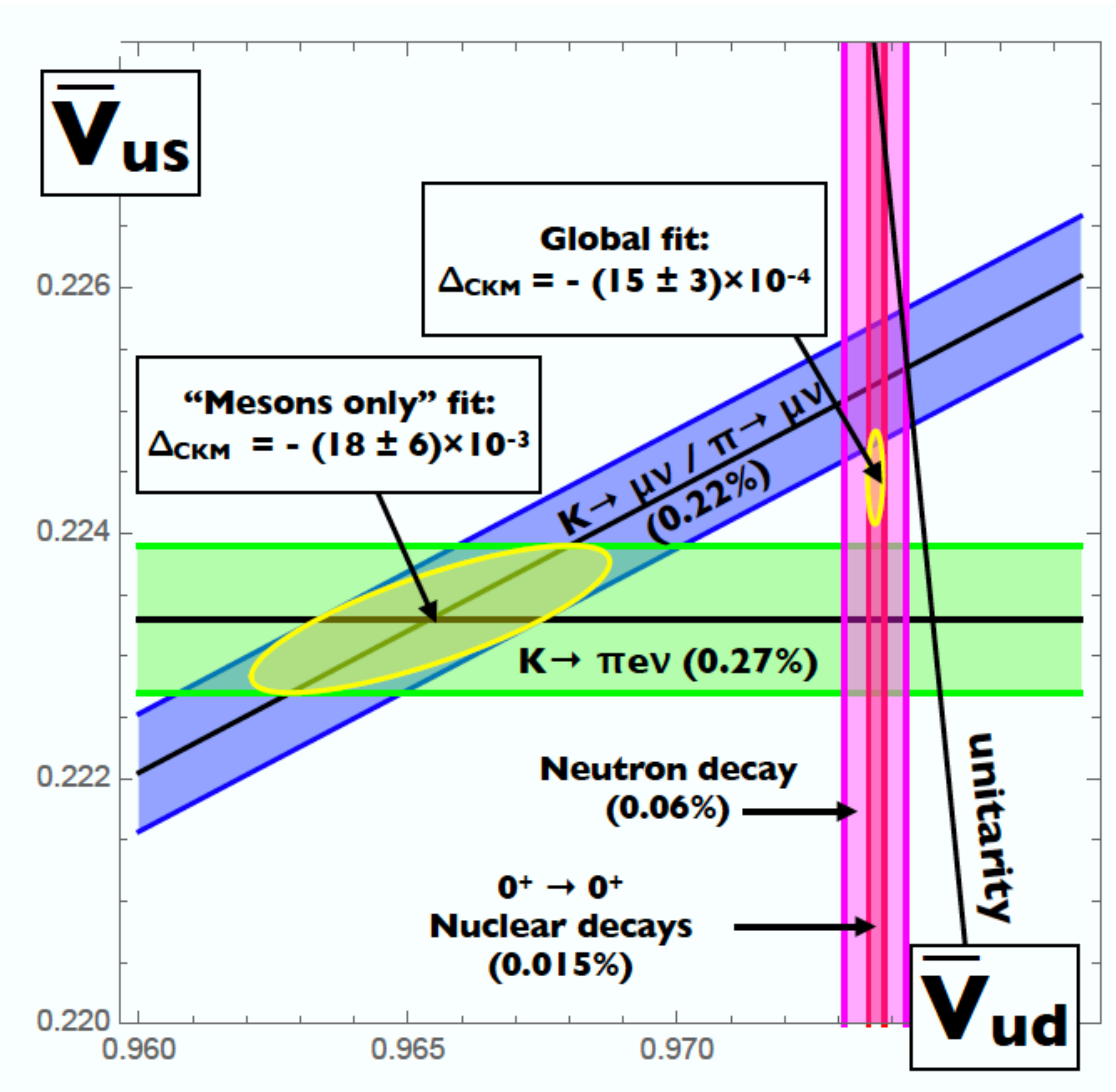
$$|\bar{V}_{ud}|^2 + |\bar{V}_{us}|^2 + \cancel{|\bar{V}_{ub}|^2} = 1 + \Delta_{\rm CKM}(\epsilon_i)$$



- Discrepancy could be explained in terms of $\varepsilon_R^{(s)}$ (~0.4%), and ε_R (~0.1%)
- Used radiative corrections from Seng et al, 1807.10197. Discrepancy goes from 5σ → 3σ if use Czarnecki et al, 1907.06737 → Importance of model-independent treatments of radiative corrections, in all decay channels (requires EFT + lattice QCD).
- Theory analysis of nuclear decays at 0.015% level currently suffers from nuclear structure uncertainties: neutron will be the arbiter

Impact of neutron measurements

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



- V_{ud} from neutron decay currently at 0.06%
- Independent extraction of V_{ud} @ 0.015%, via neutron decay requires:

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

$\delta\tau_n$ ~ 0.7s → 0.3s → 0.1s

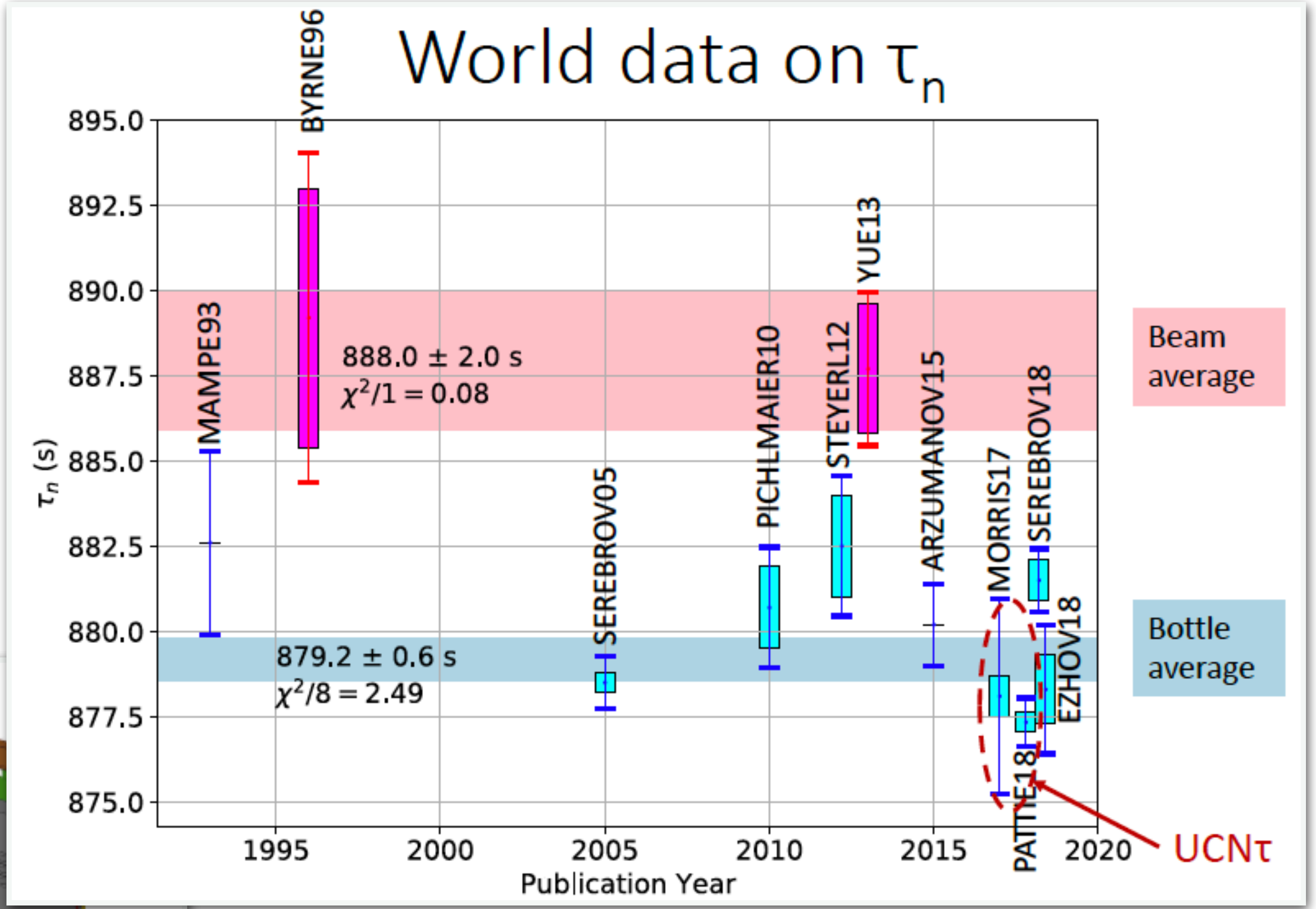
@ LANL UCNτ → UCNτ+

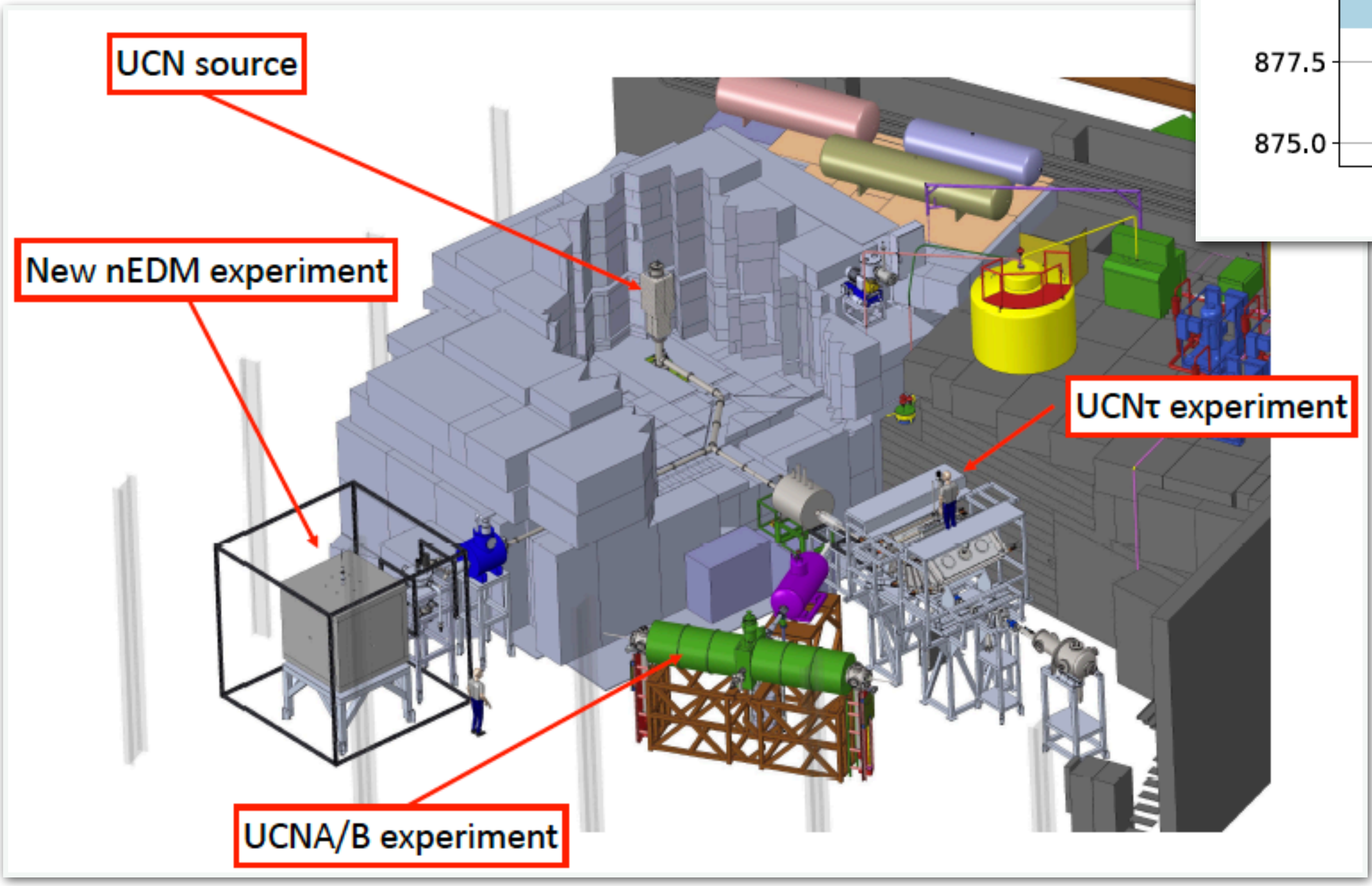
$\delta g_A/g_A$ ~0.044%→ 0.02 %

@ LANL UCNA+ → PERC

Impact of LANL

- UCNτ result is the world's most precise (Science, 2018)



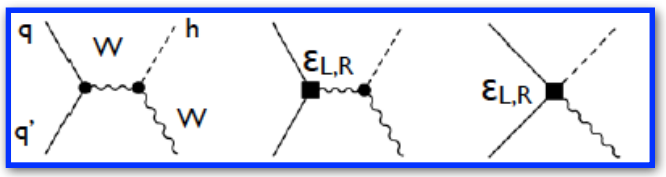


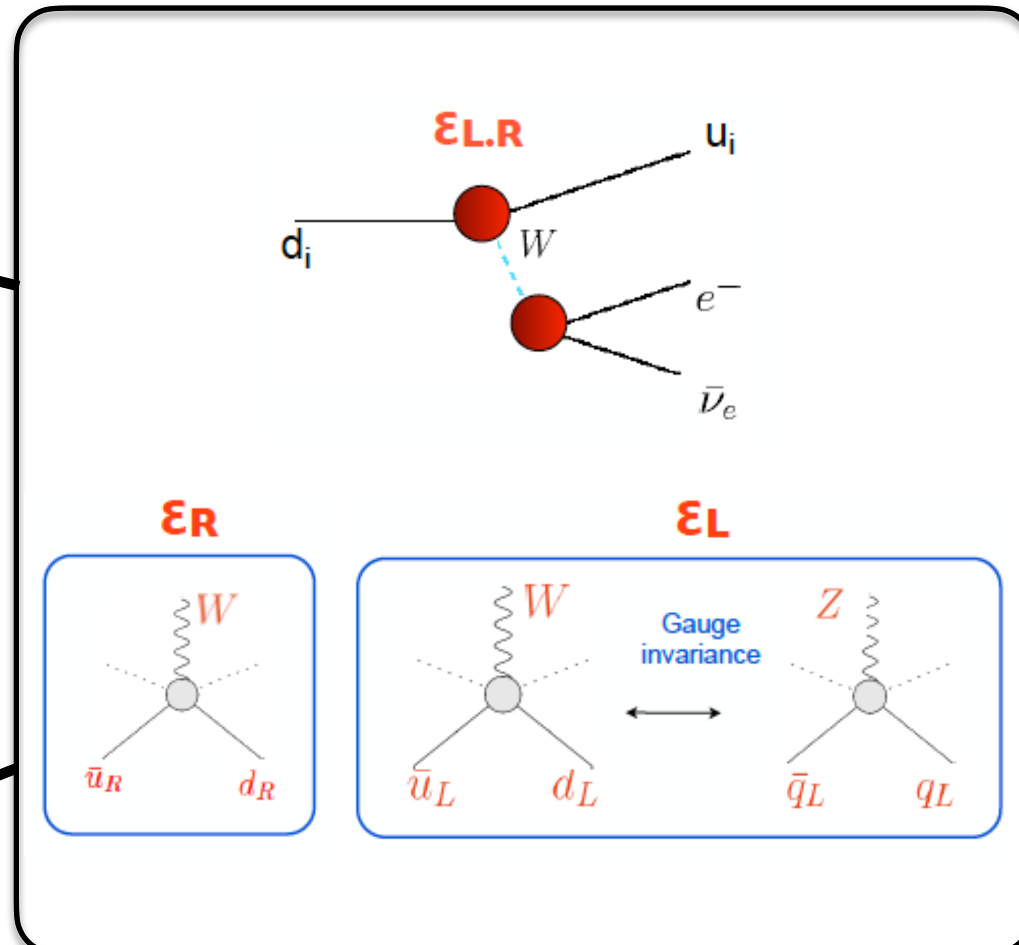
- New LDRD investment:
  - $\delta\tau_n \rightarrow 0.1$s
  - $\delta g_A/g_A \rightarrow 0.03\%$
  - Rad. Corr.: LQCD + EFT

Sensitivity to ε_L and ε_R

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

Associated Higgs production at LHC





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

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

LEP, SLC

Z-pole:
Falkowski et al
1706.03783

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

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

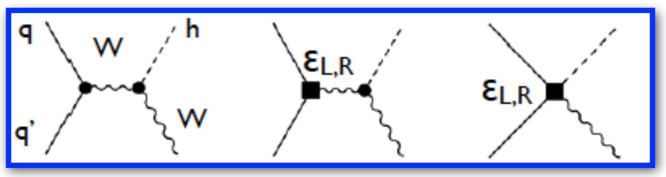
Due to weak
isospin symmetry, vertex corrections
involve the Higgs & Z bosons

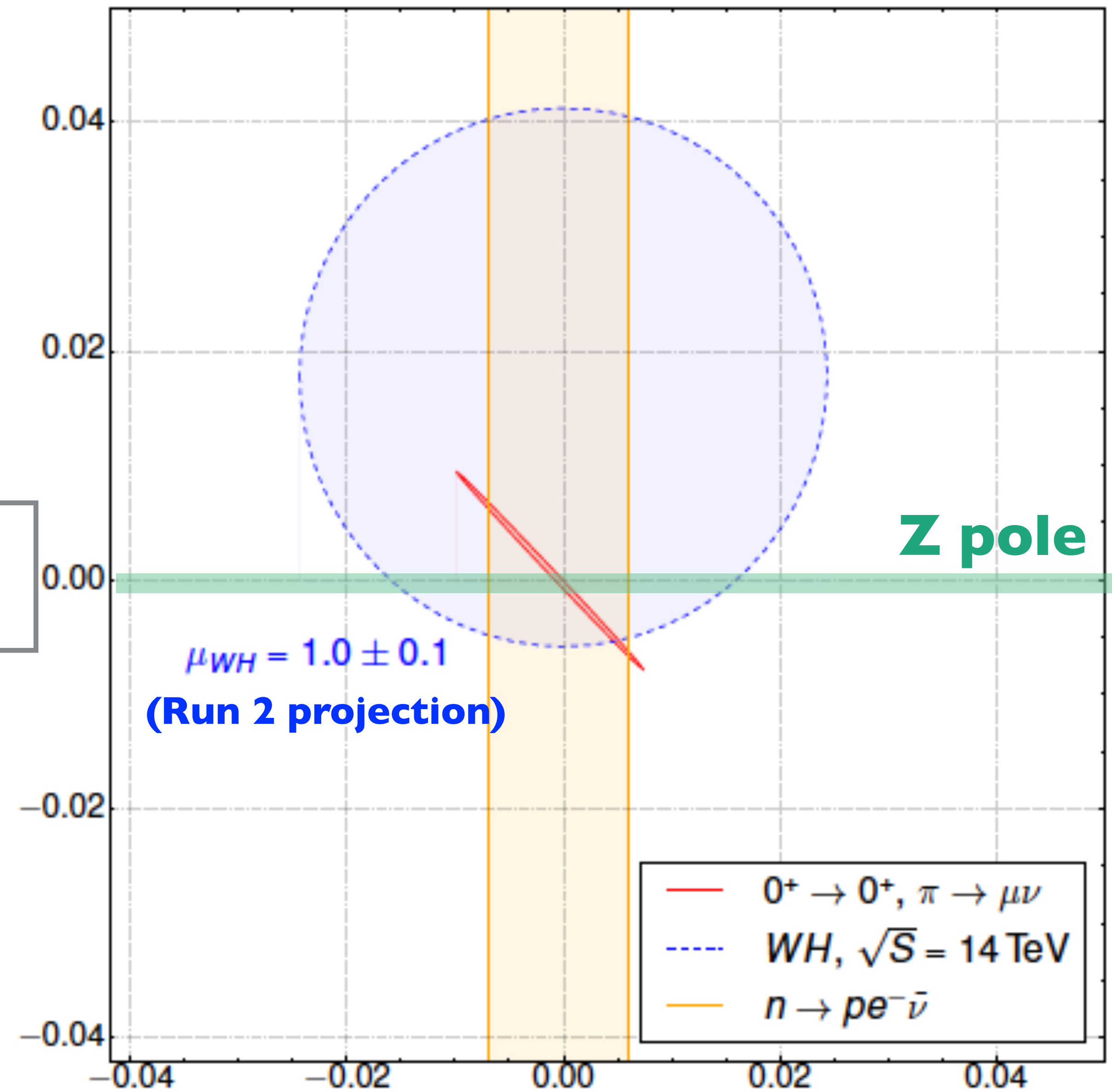
Sensitivity to ε_L and ε_R

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

90%CL allowed regions, assumes only two operators at high scale

Associated Higgs production at LHC





ε_L

ε_R

LEP, SLC

Z-pole: Falkowski et al 1706.03783

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

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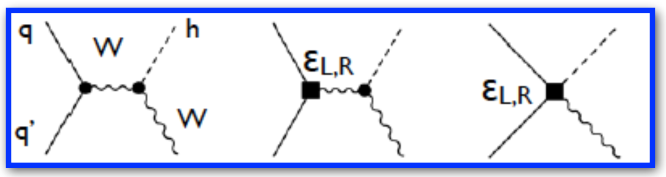

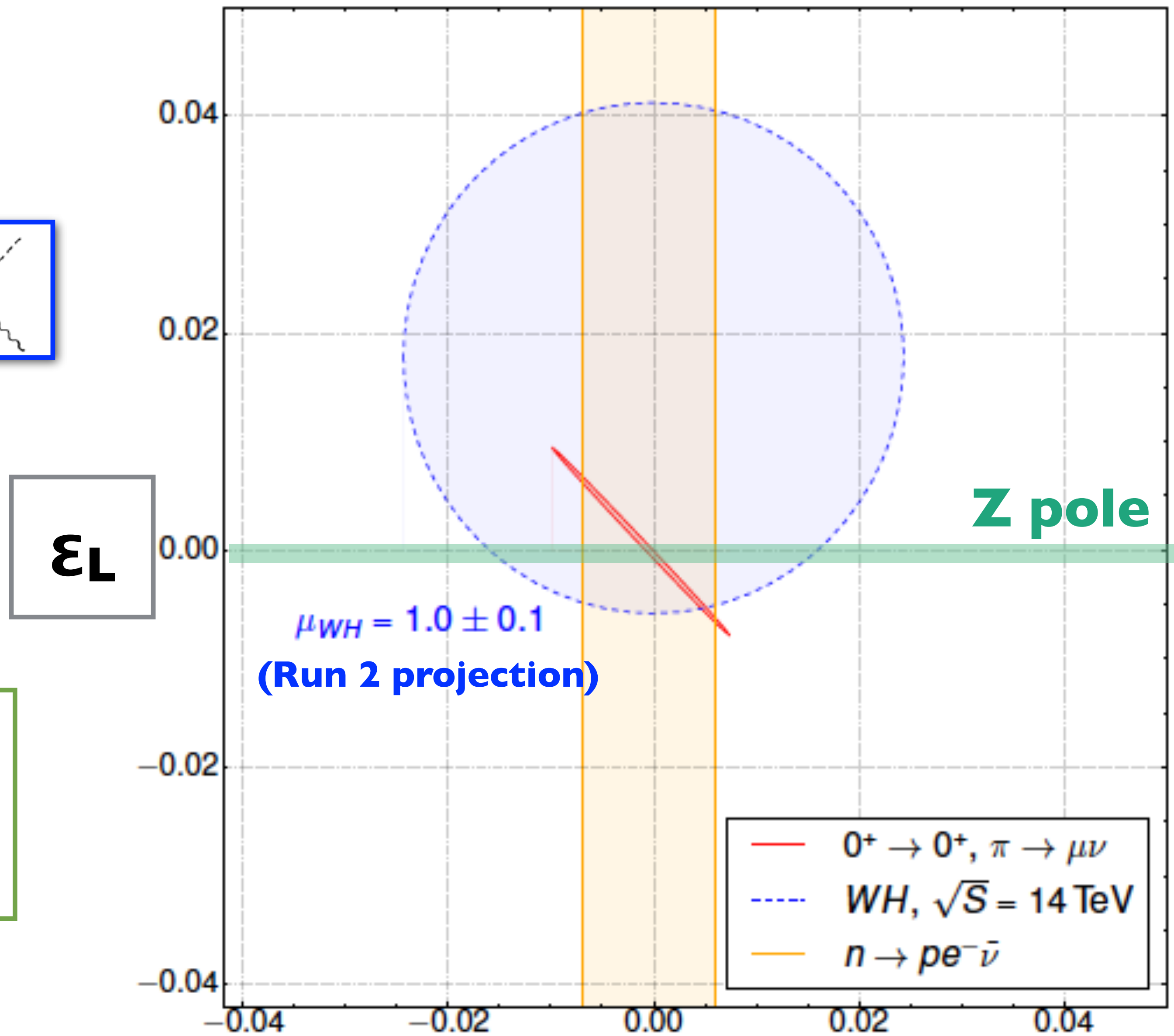

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$\delta\Gamma_{(\pi\to\mu\nu)} \propto \varepsilon_L - \varepsilon_R$
[f_π from LQCD]

β decays more constraining than collider: probing $\Lambda_{L,,R}$ ~20 TeV

β decays summary

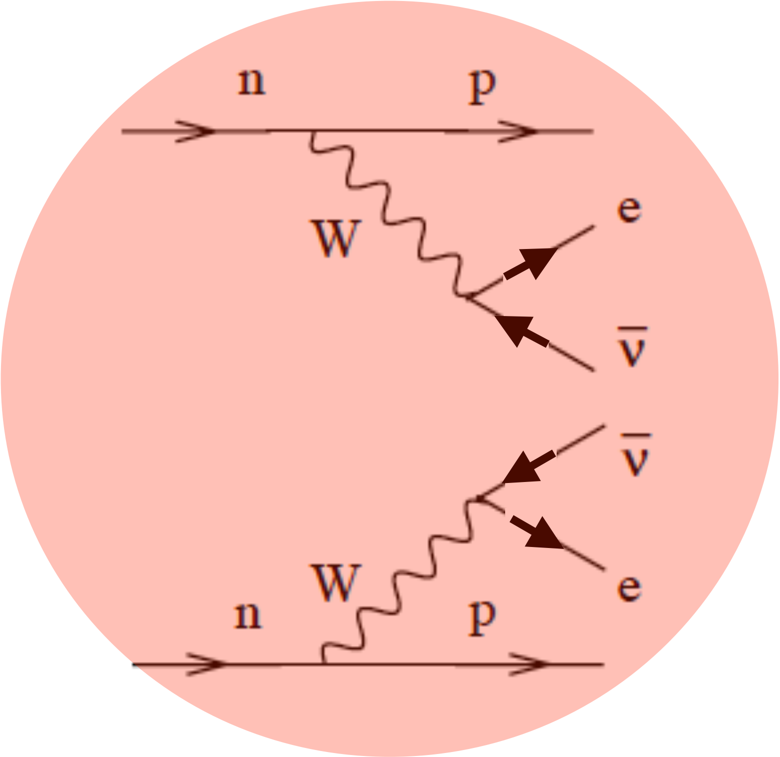
- EFT shows that a discovery window exists well into the LHC era
  - Beta decays play unique role in probing vertex corrections ε_L-ε_R (unmatched sensitivity compared to LHC)
  - Beta decays can be competitive in probing scalar and tensor interactions if precision reaches < 0.1% (ε_S-ε_T plots)
- LANL key player in the international neutron physics scene

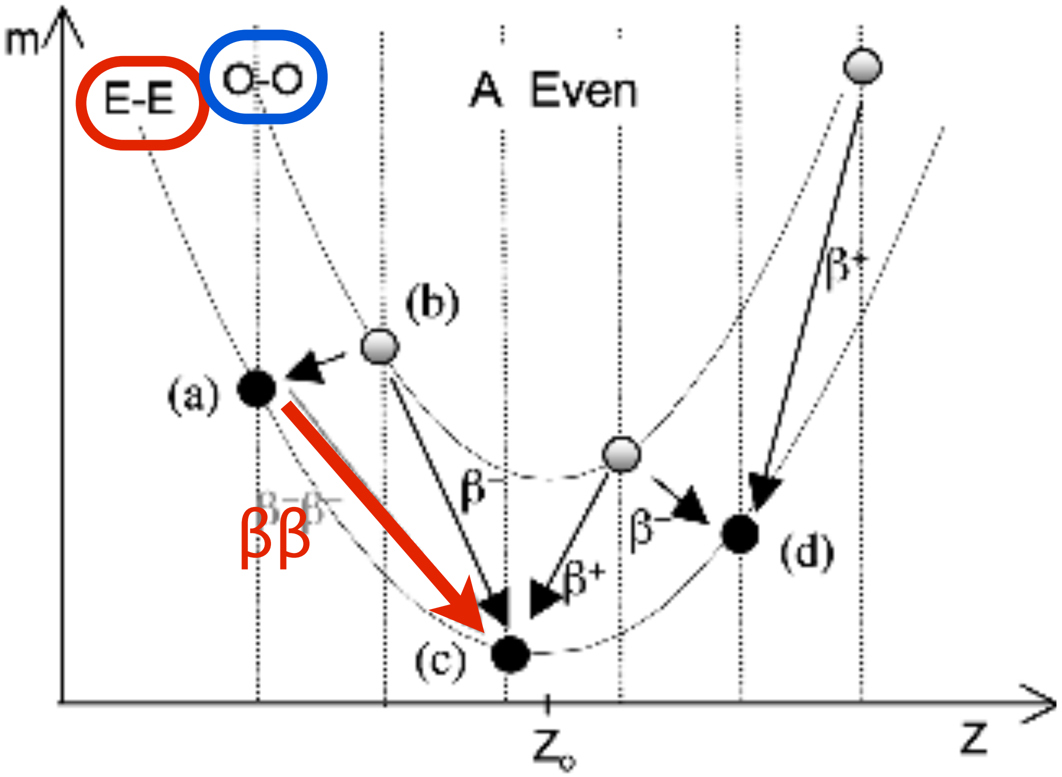
Neutrinoless double beta decay

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



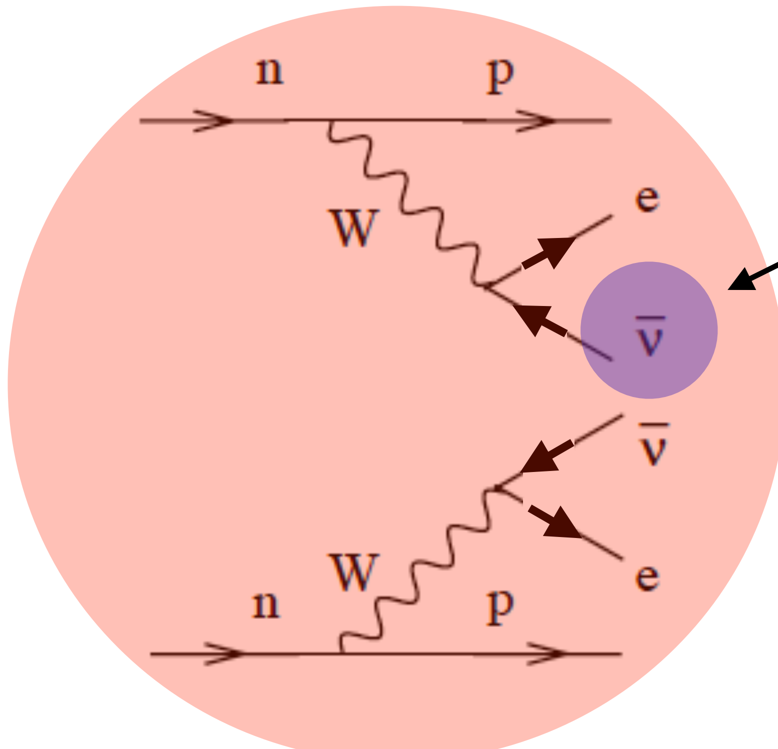


- 2νββ is the rarest process ever observed, with $T_{1/2} \sim 10^{21}$ years (first observation in 1987)

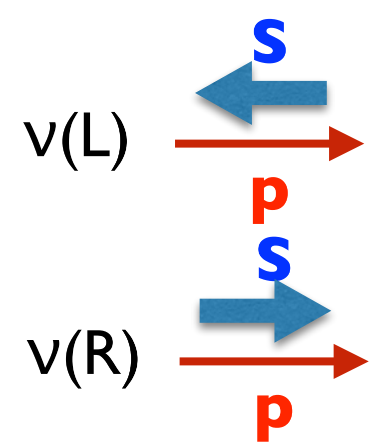
Neutrinoless double beta decay?

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

W. H. Furry, 1939



This is just $\nu(R)$, which mixes with $\nu(L)$ via mass insertion



E. Majorana, 1937

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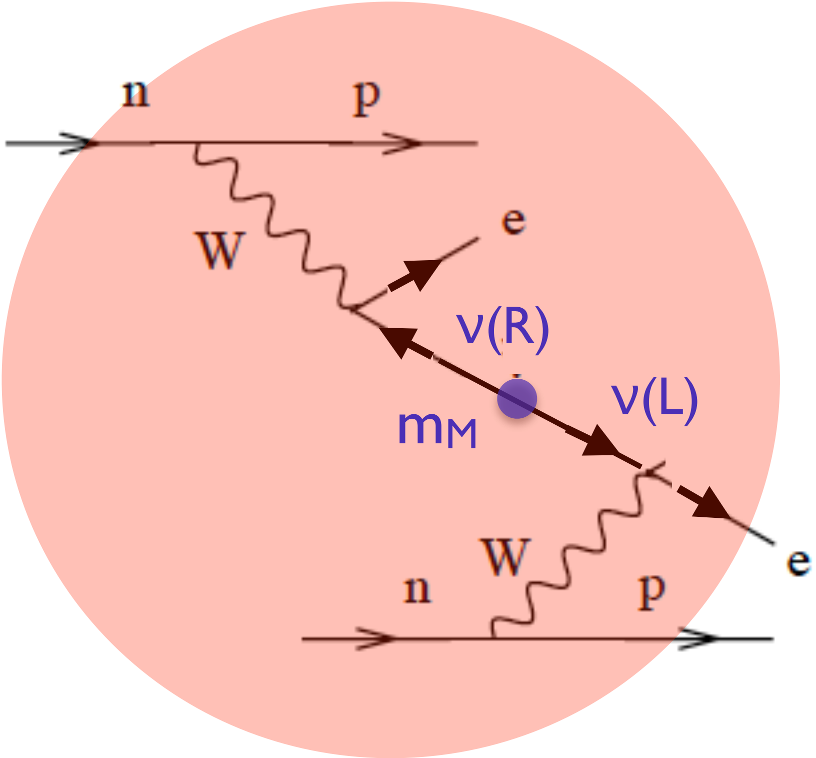

"Subject to the usual limitations on the meaning of such language, one can say that a (virtual) neutrino is emitted together with one of the electrons and reabsorbed when the other electron is emitted."

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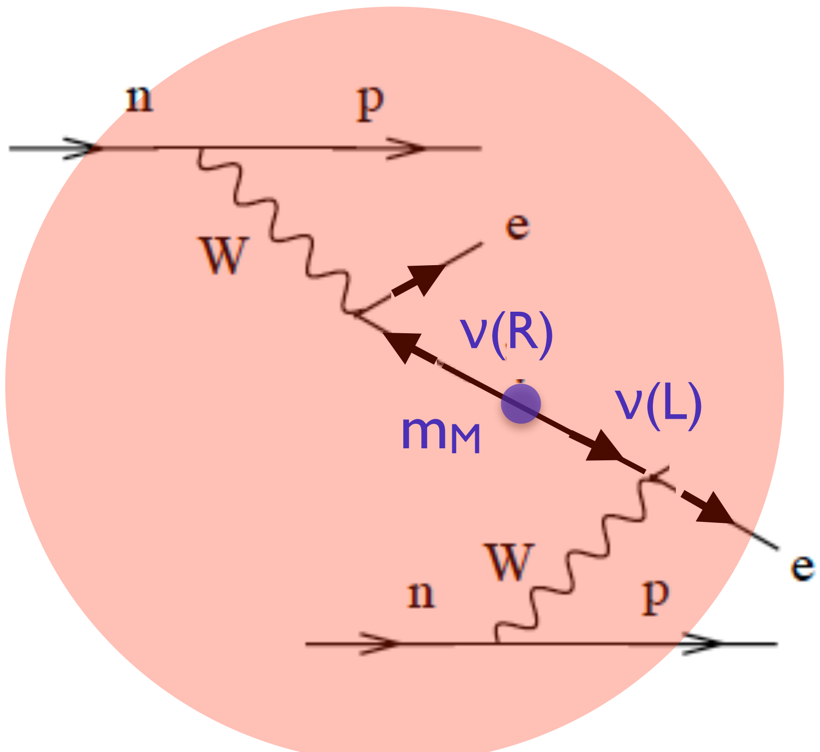

"Subject to the usual limitations on the meaning of such language, one can say that a (virtual) neutrino is emitted together with one of the electrons and reabsorbed when the other electron is emitted."

- Key point: in $0\nu\beta\beta$ Lepton Number changes by two units. ν_M 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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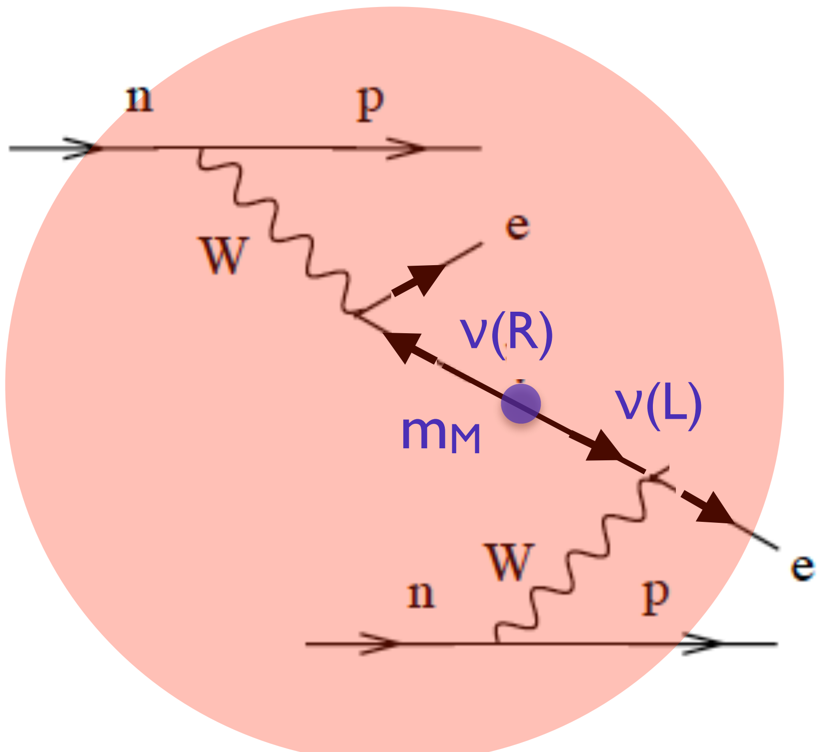
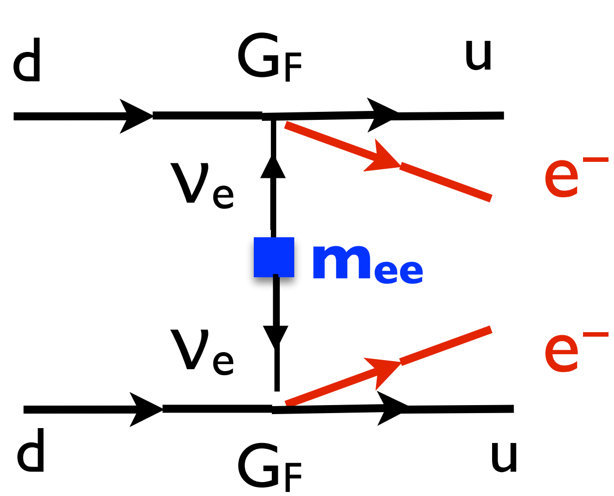
W. H. Furry, 1939

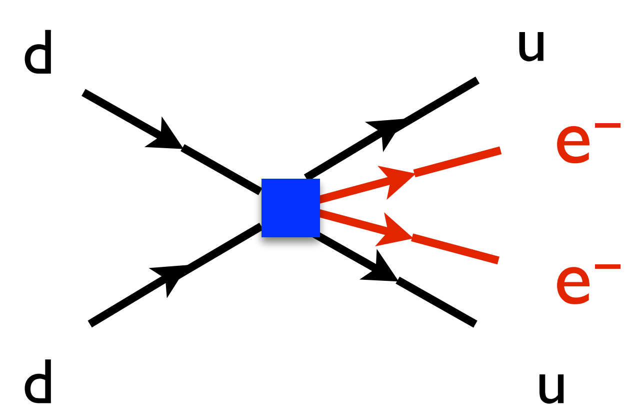


"Subject to the usual limitations on the meaning of such language, one can say that a (virtual) neutrino is emitted together with one of the electrons and reabsorbed when the other electron is emitted."

- Modern viewpoint on LNV:



but also

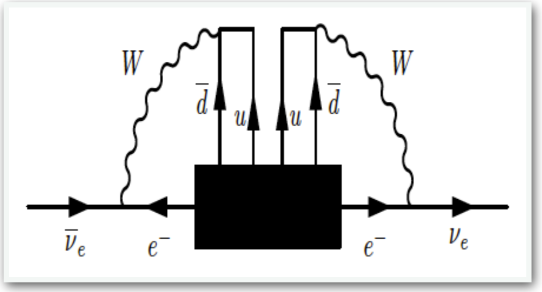


Exchange of heavier neutrinos or other Majorana particles. At low-energy induce six-fermion operator $\sim 1/\Lambda^5$

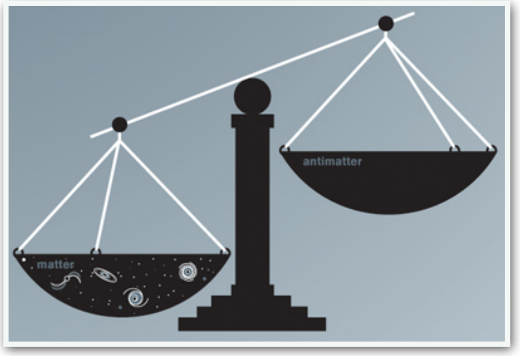
Significance of 0νββ

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

  - Demonstrate that neutrinos are their own antiparticles
  - Probe origin of neutrino mass
  - Establish L non-conservation, a key ingredient to generate the baryon asymmetry via leptogenesis



Shechter-Valle 1982



Fukujgita-Yanagida 1987

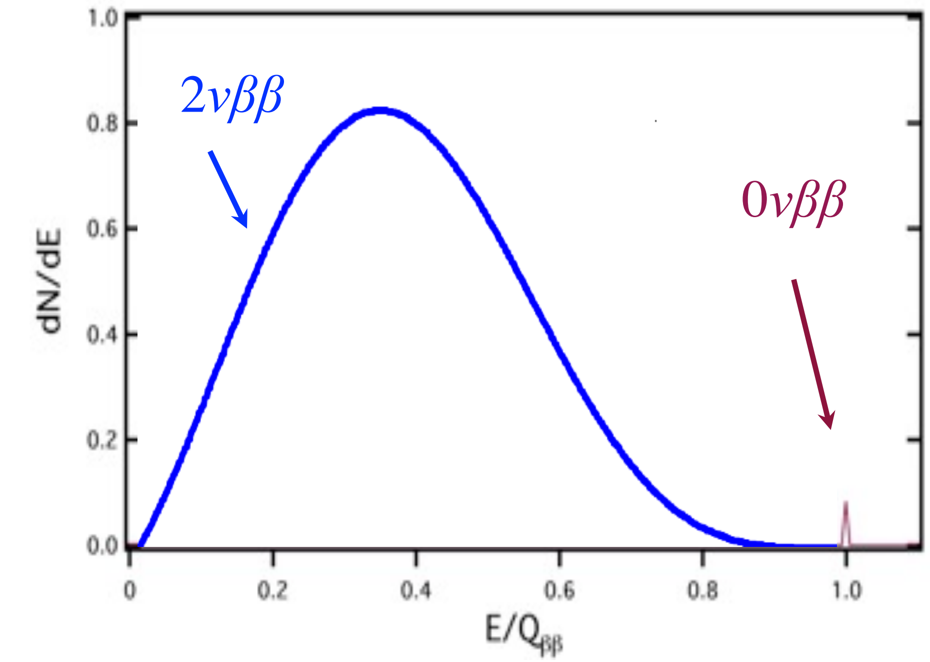
Construction of ton-scale 0νββ experiment ($T_{1/2} > 10^{27\text{-}28}$ yr) is the top priority for new project starts in the 2015 NSAC Long Range Plan

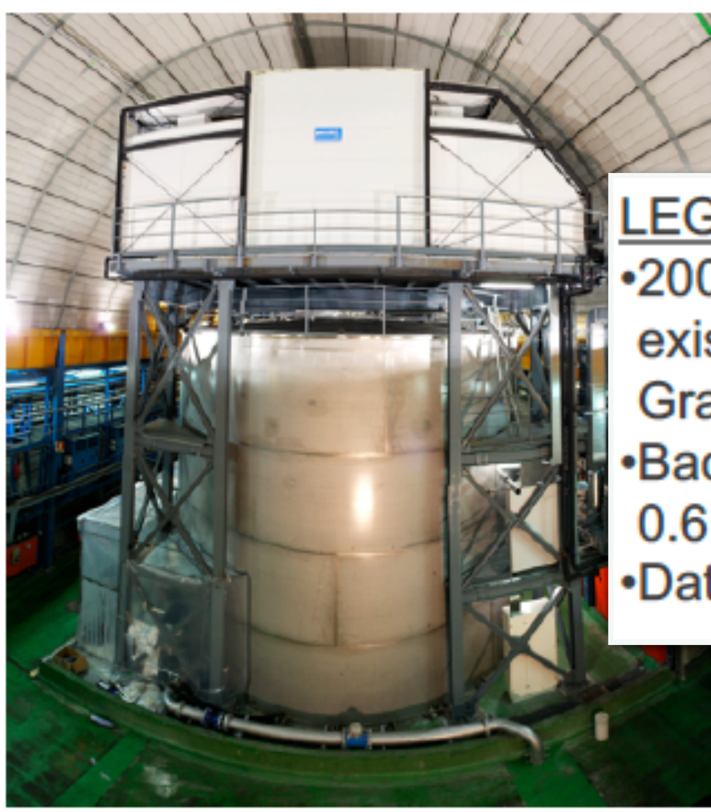
The quest is on…

- Several experiments worldwide

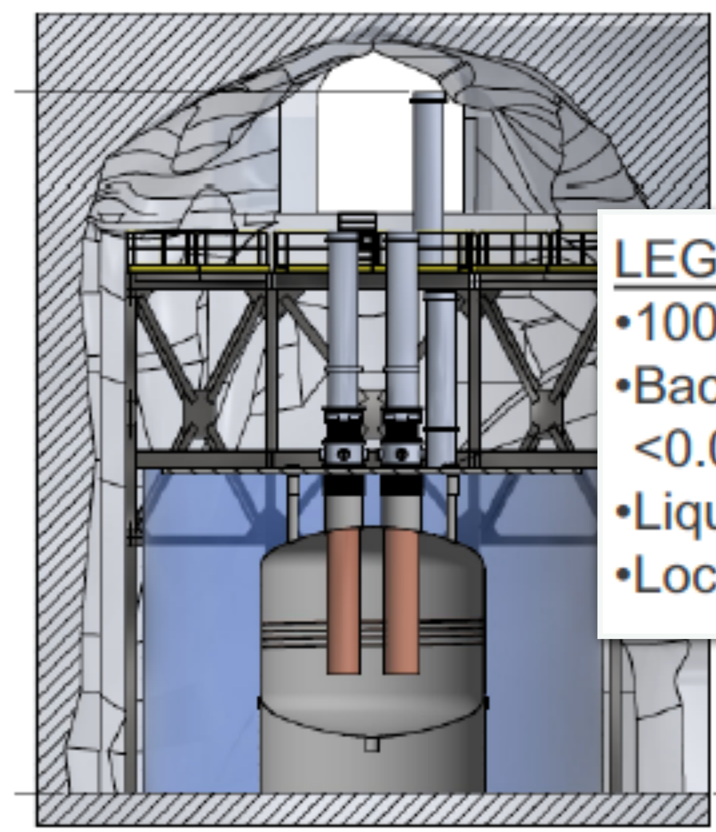
- LANL co-leads ^{76}Ge-based search.
  Majorana Demonstrator → LEGEND

~50 institutions, ~250 scientists, S. Elliott co-spokesperson





LEGEND-200:
- 200 kg in upgrade of existing infrastructure at Gran Sasso
- Background goal 0.6 cts/(FWHM t yr)
- Data start ~2021



$T_{1/2} \sim 10^{28}$ yr

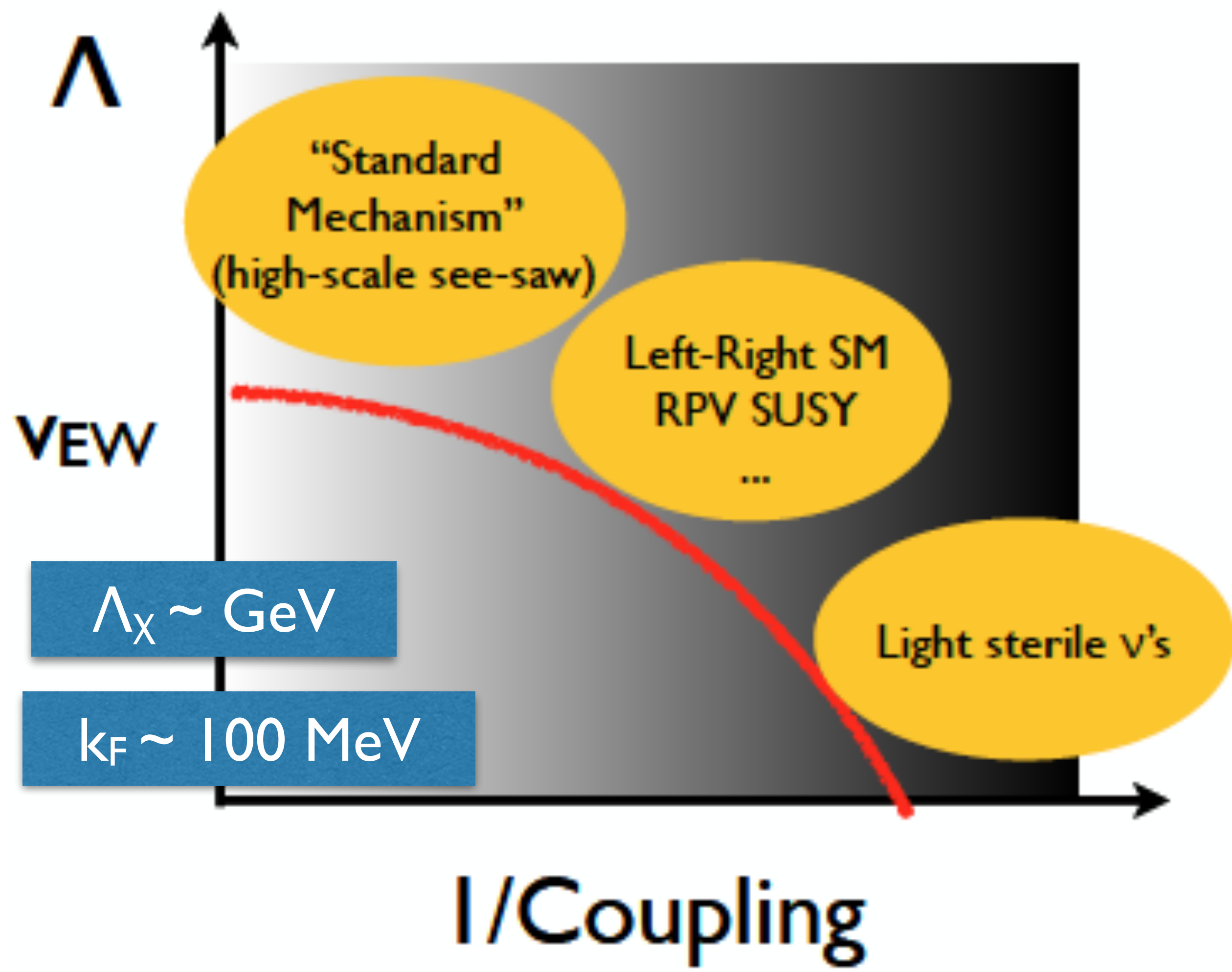
LEGEND-1000:
- 1000 kg, staged via 4 payloads
- Background goal <0.03 cts/(FWHM t yr)
- Liquid Ar cryostat shield
- Location to be selected

The quest is on…

- Challenging experiments and challenging theory!

- Connect *any* source of LNV to nuclei: multi-scale problem!

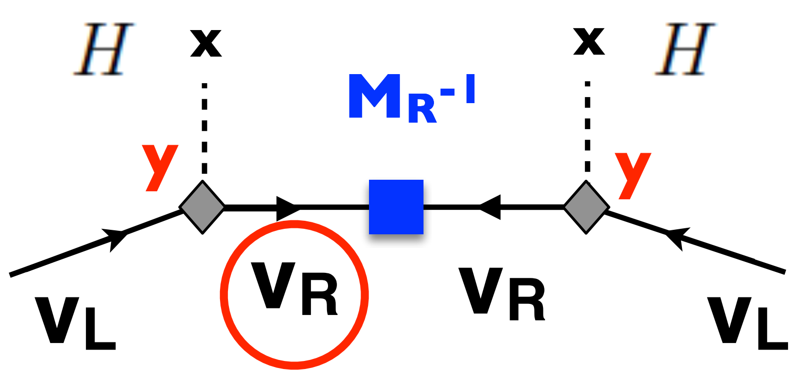
- Our approach: use effective field theory techniques to bridge scales, combined with LQCD and nuclear structure

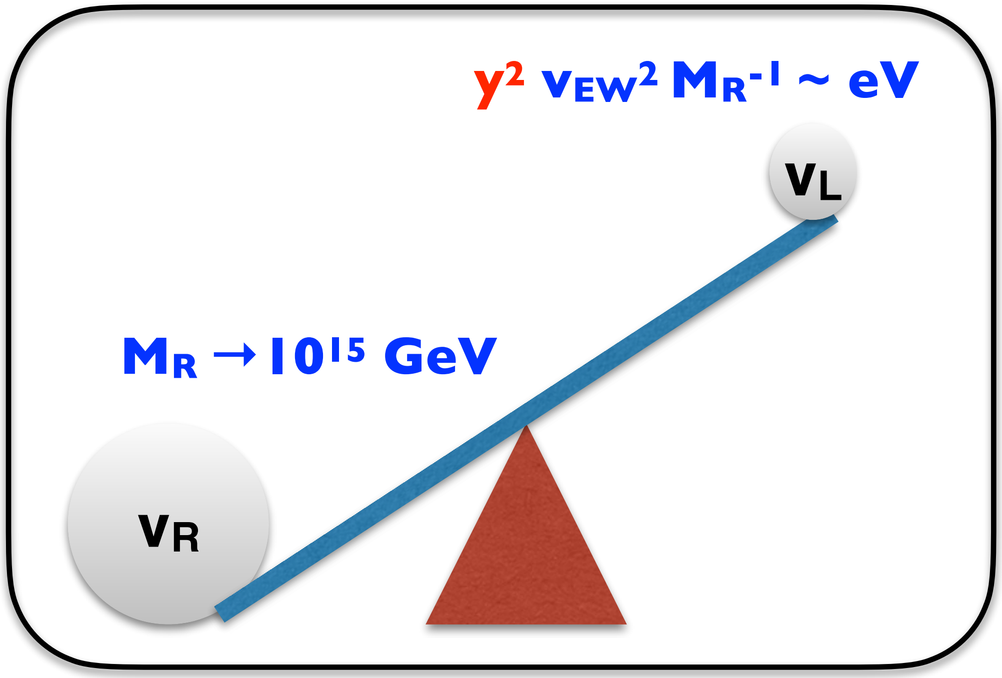


$$T_{1/2} \sim (m_W/\Lambda)^A \; (\Lambda_X/m_W)^B \; (k_F/\Lambda_X)^C$$

High-scale seesaw

- Majorana mass generated by exchange of heavy neutrinos, neutral under all SM charges (=sterile)





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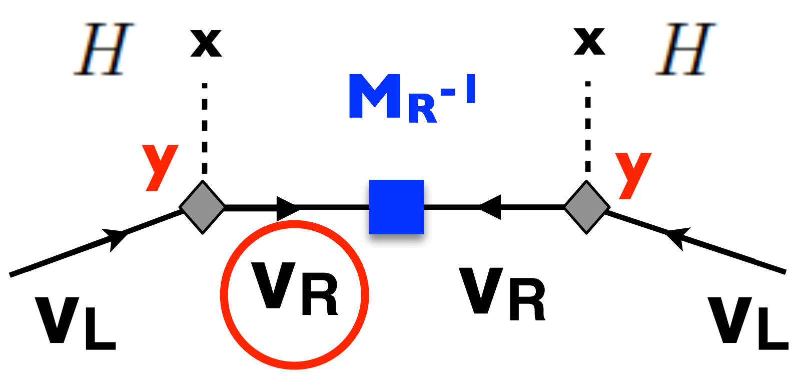
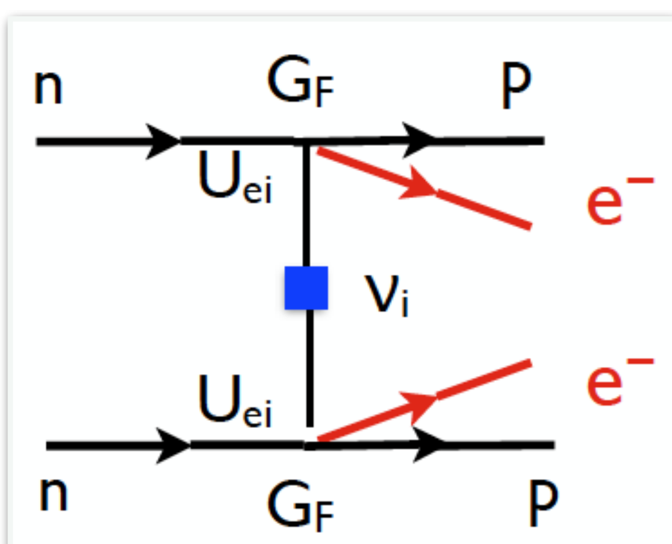


$M_R >> v_{EW}$

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



$0\nu\beta\beta$ mediated by light neutrinos

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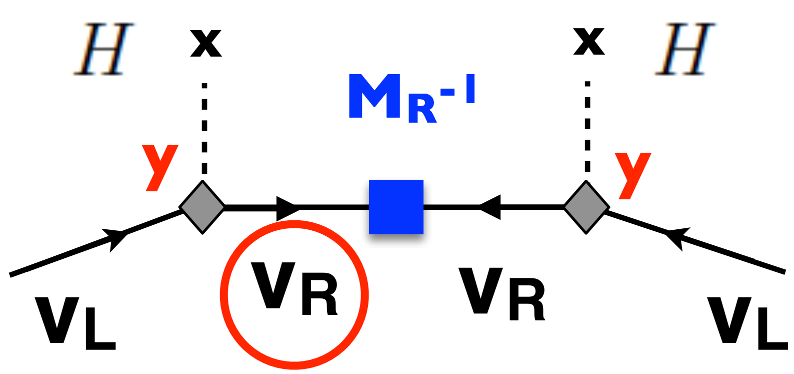

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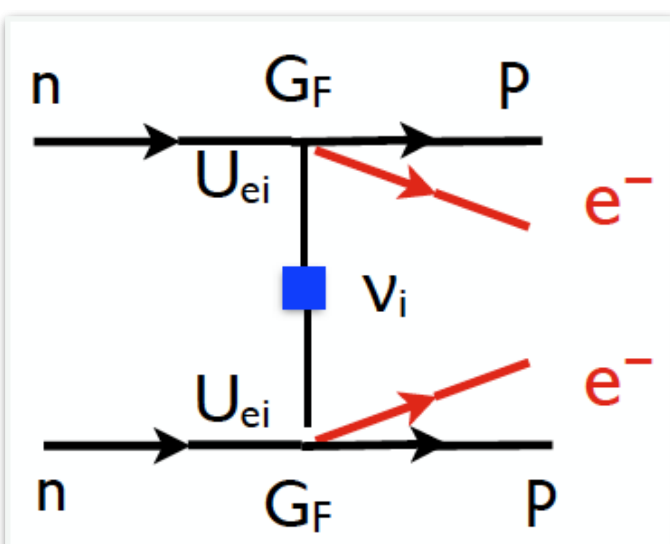


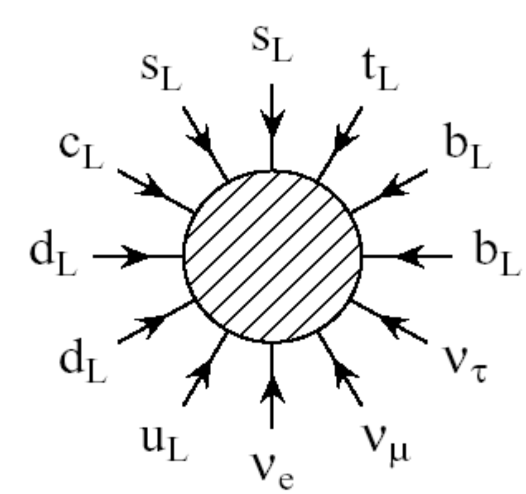
0νββ mediated by light neutrinos

Baryogengesis via Leptogenesis

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

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

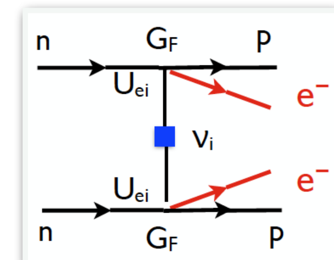
2) EW sphalerons ⇒ $n_B = \#\, n_L$



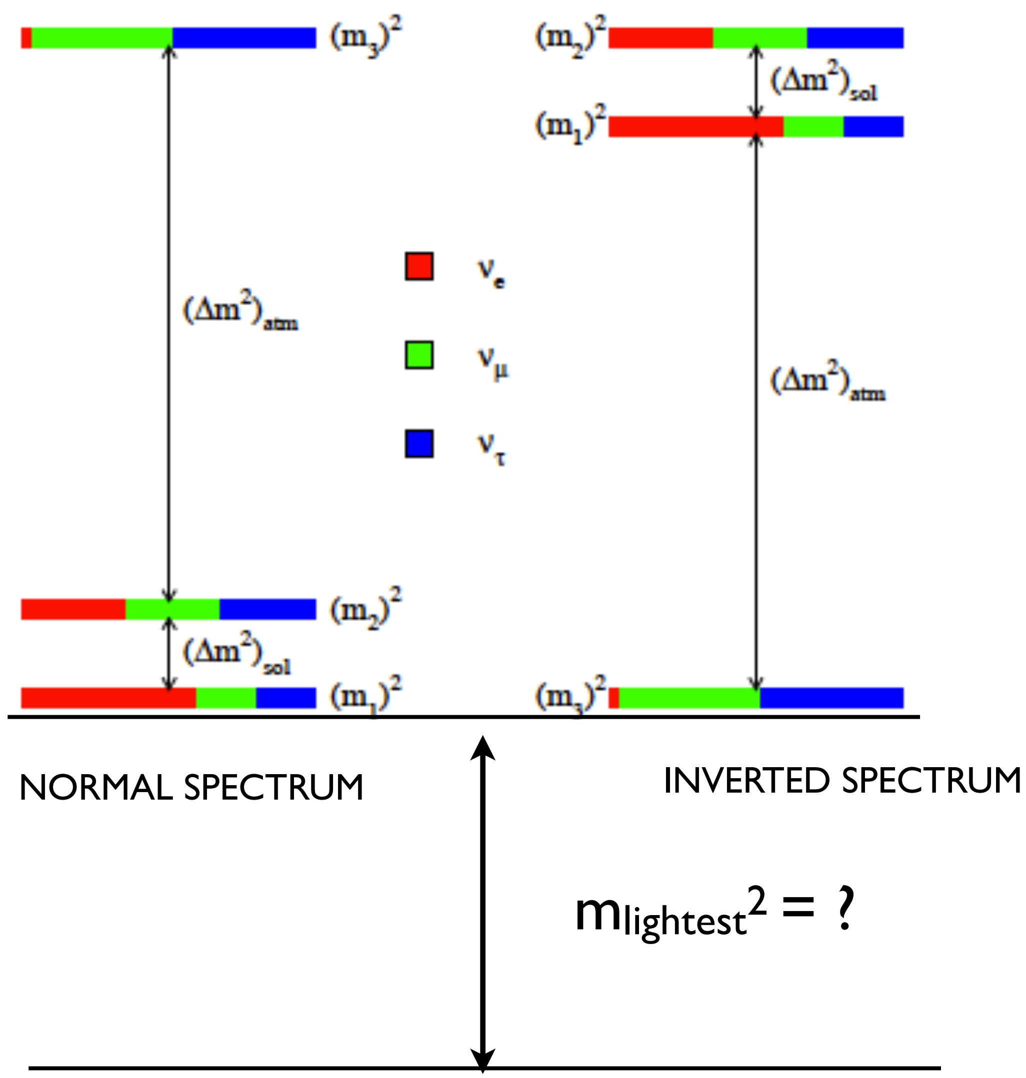
High-scale seesaw: discovery potential

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

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



Strong correlation with oscillation parameters



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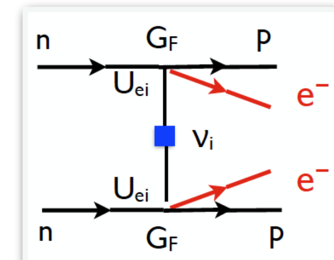
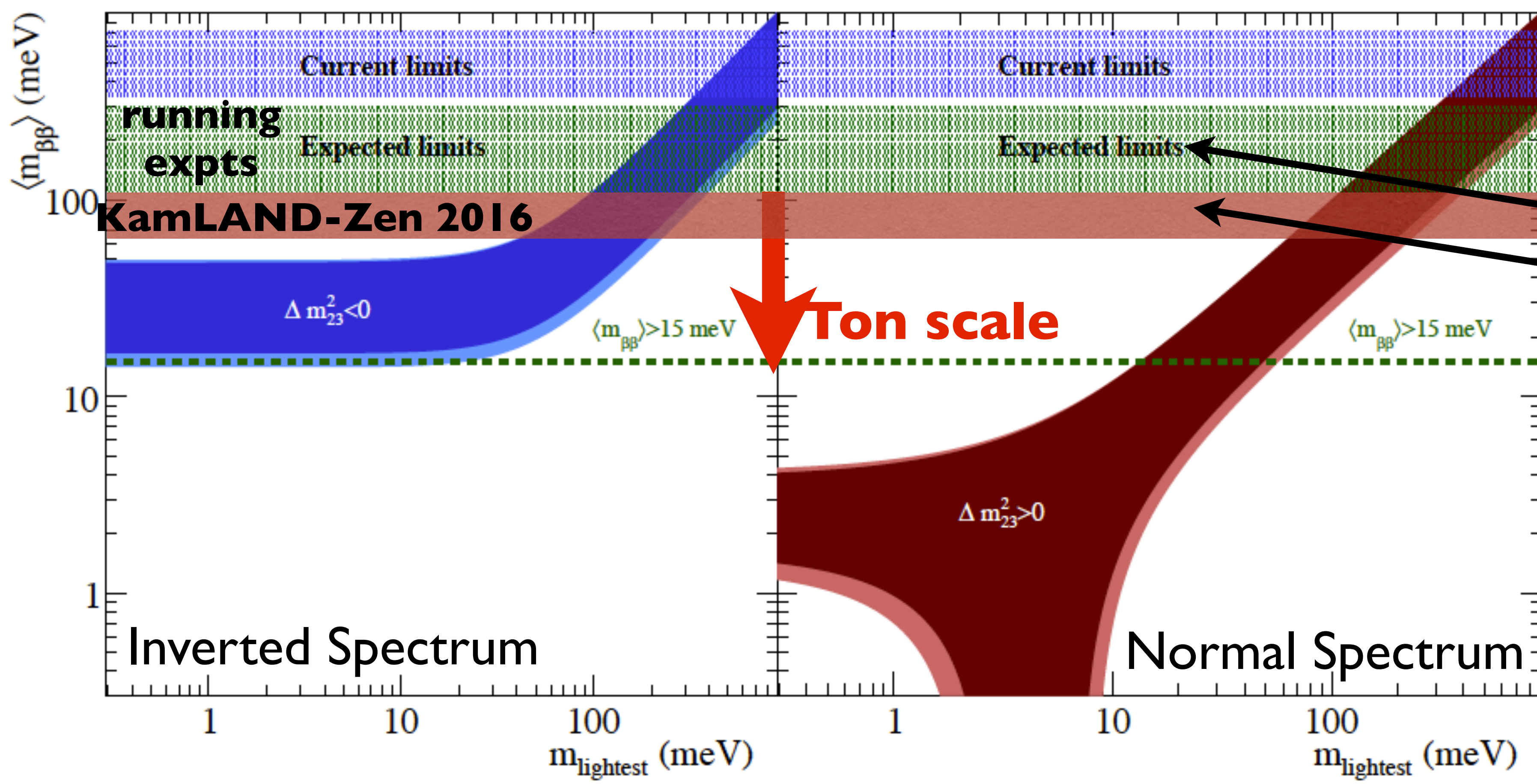


Dark bands: unknown phases

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



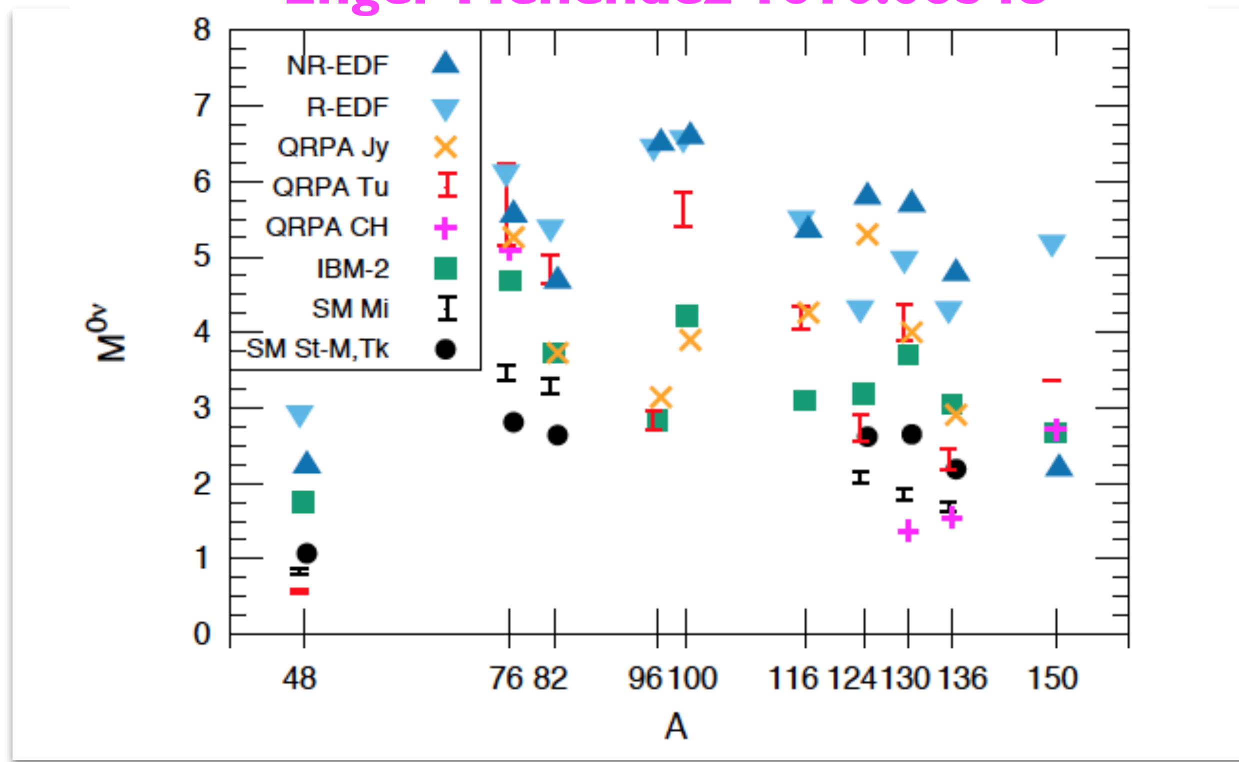
Assume range for nuclear matrix elements from different many-body methods

Plot by K. Heeger

Discovery @ ton-scale *possible* for inverted spectrum or $m_{lightest}$ > 50 meV

High-scale seesaw: theory developments

Engel-Menendez 1610.06548



- Sensitivity to $m_{\beta\beta}$ affected by large uncertainty in "nuclear matrix elements": $\Gamma \propto |M_{0\nu}|^2 (m_{\beta\beta})^2$

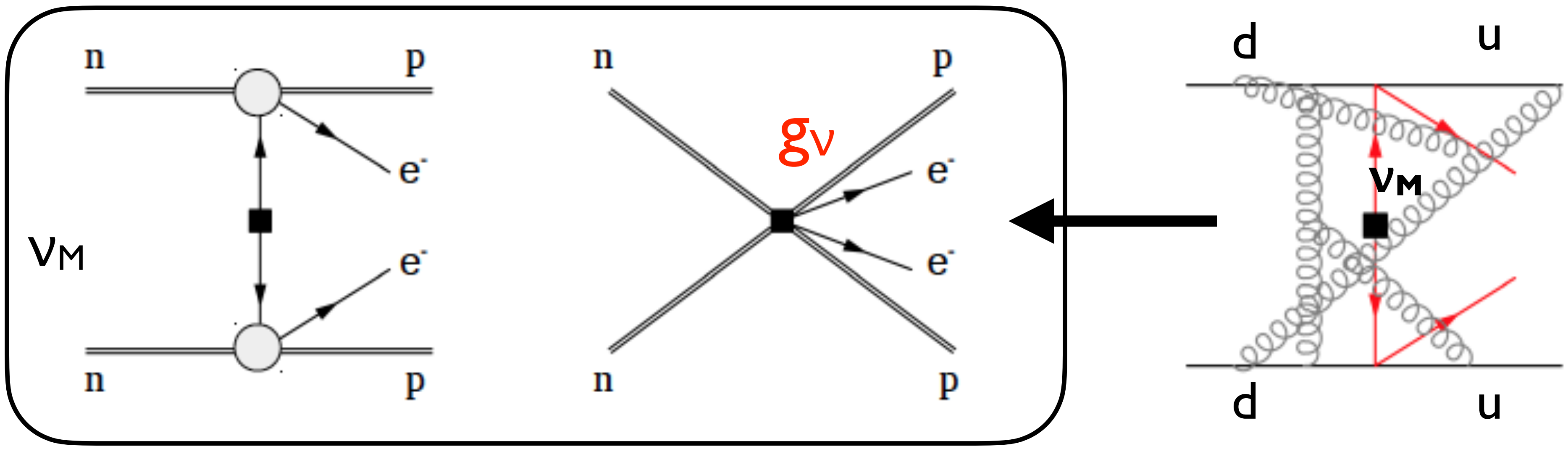
- Steps towards controllable uncertainties in matrix elements:
  - Use chiral EFT as guiding principle
  - Lattice QCD for *hadronic* matrix elements (e.g. $nn \to pp$)
  - "Ab initio" nuclear structure calculations: from light nuclei (benchmark) to ^{48}Ca and ^{76}Ge

DOE Nuclear Theory Topical Collaboration (PI Jon Engel): http://c51.lbl.gov/~0nubb/webhome/

New insights from EFT

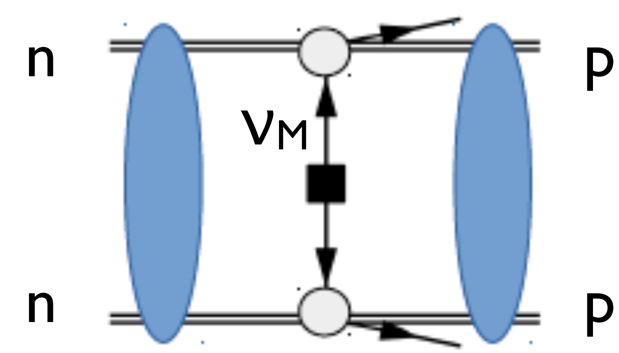
V. Cirigliano, W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, U. van Kolck
1802.10097, Phys.Rev.Lett. 120 (2018) no.20, 202001

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



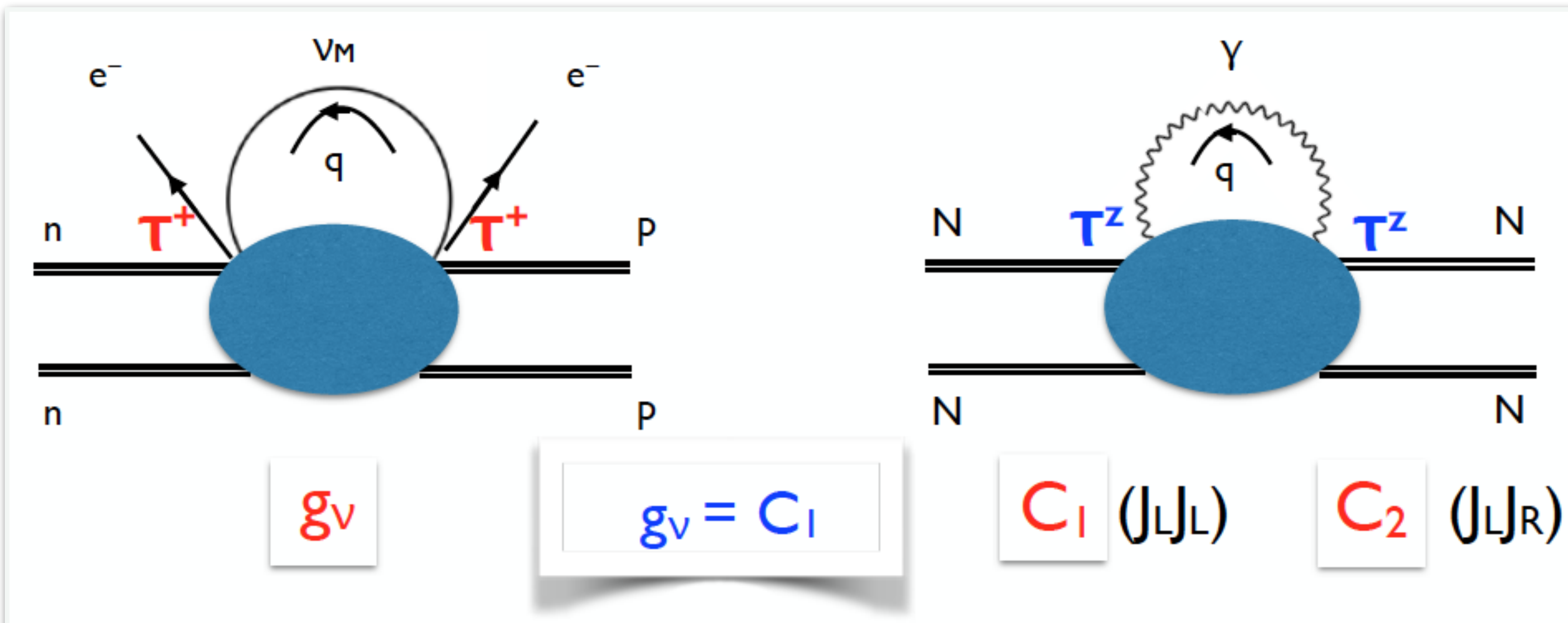
'Usual' ν_M exchange $\sim 1/Q^2$
Coulomb-like potential

'New': short-range coupling $g_\nu \sim 1/Q^2$.
Required by renormalization of $nn \to ppee$ amplitude in presence of strong interactions



Connection with data?

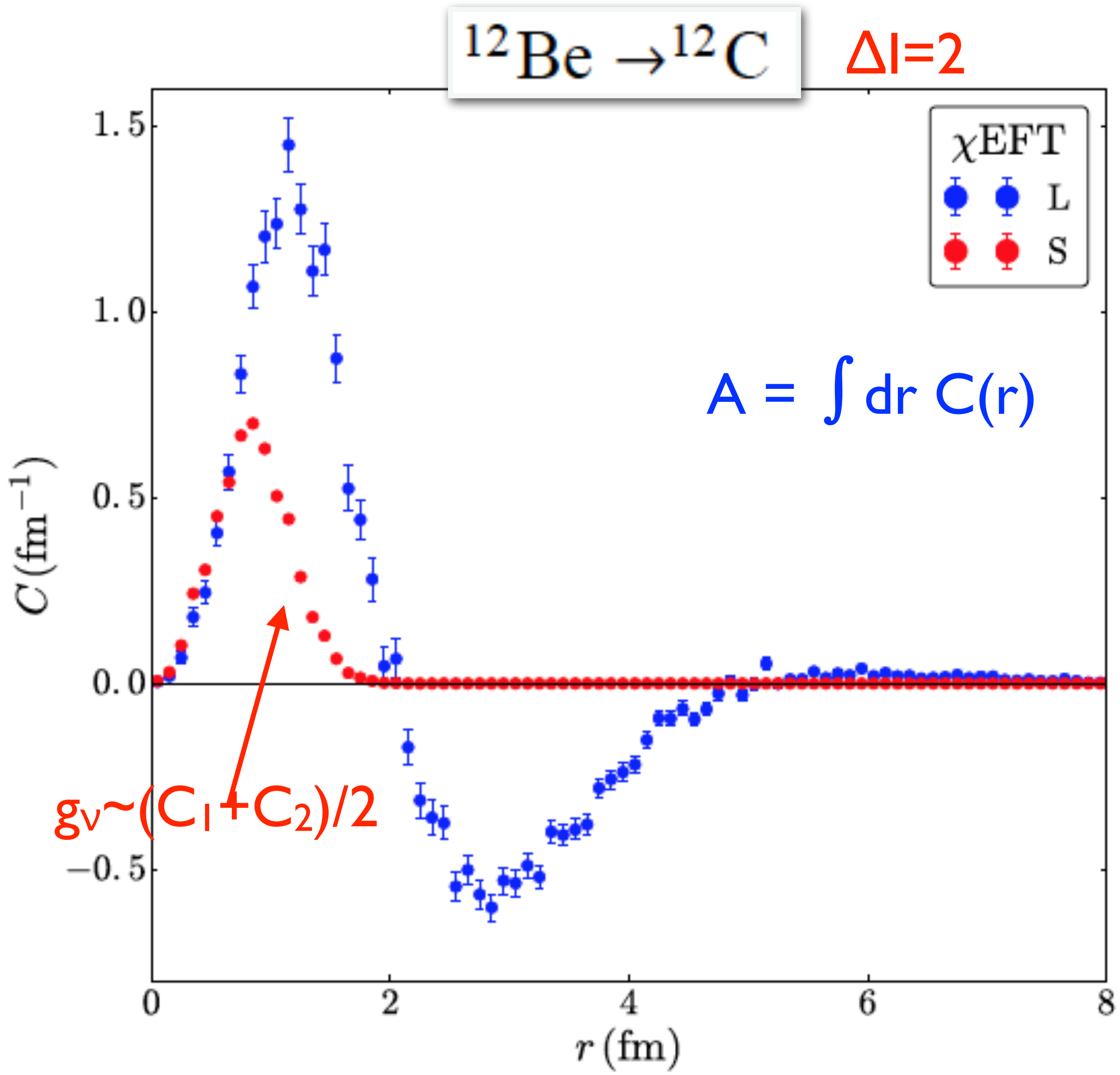
- Chiral symmetry relates g_ν to one of two I=2 EM LECs (hard γ's & ν's)



- NN scattering data determine (C_1+C_2), but not $g_\nu=C_1$
- Assuming $g_\nu \sim (C_1 + C_2)/2$, what is the impact on $m_{\beta\beta}$ extraction?

Impact on nuclear matrix elements

V.C , W. Dekens, J. de Vries, M. Graesser, E. Mereghetti, S. Pastore, M. Piarulli, U. van Kolck, R. Wiringa,
1907.11254



Evaluate impact in light nuclei using VMC wavefunctions from Norfolk chiral potential [1606.06335]

g_ν contribution sizable in ΔI=2 transition (due to node): for A=12, A_S/A_L = 0.75

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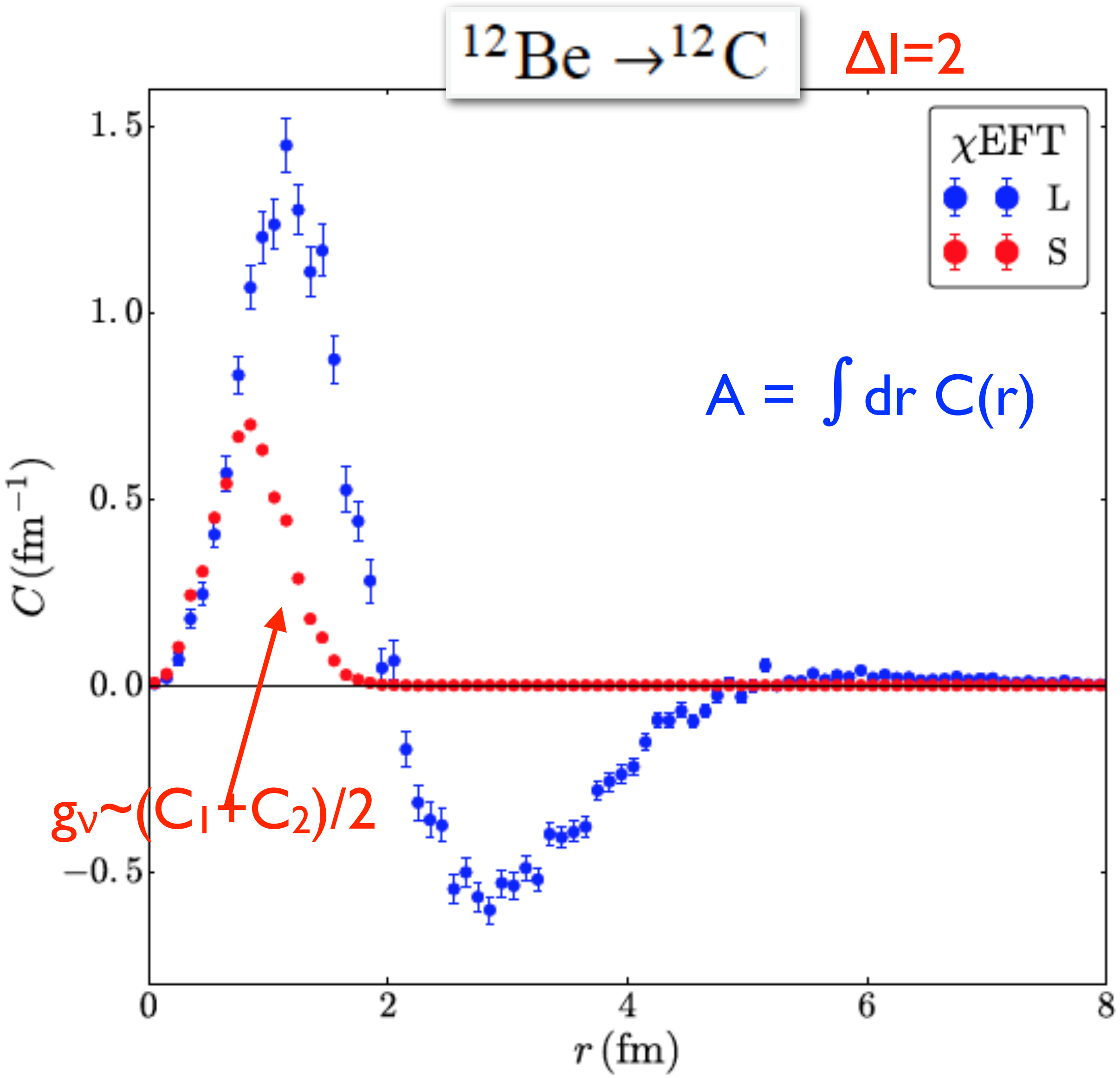


Evaluate impact in light nuclei using VMC wavefunctions from Norfolk chiral potential [1606.06335]

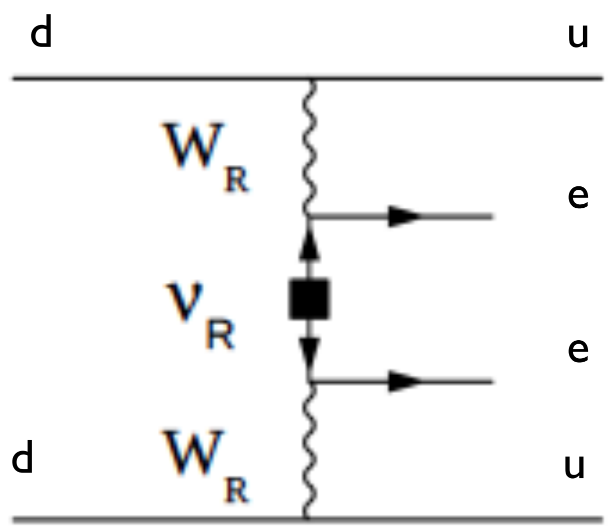
g_V contribution sizable in ΔI=2 transition (due to node): for A=12, $A_S/A_L = 0.75$

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

Determination of g_V is a `decadal' challenge: analytic methods & lattice QCD

TeV-scale LNV

- TeV sources of LNV may lead to observable contributions to $0\nu\beta\beta$ *not directly related to the exchange of light neutrinos*



- May lead to correlated (or precursor!) signal at LHC: $pp \rightarrow ee\, jj$

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

$0\nu\beta\beta$ summary

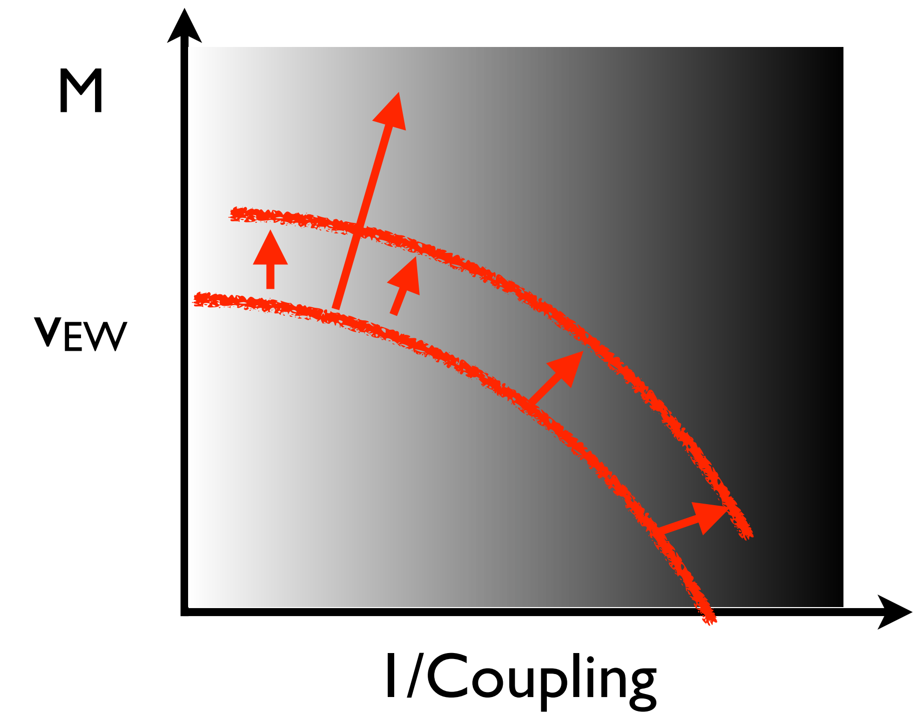
- Ton-scale $0\nu\beta\beta$ searches ($T_{1/2} > 10^{27\text{-}28}$ yr) have great discovery potential — we simply don't know the origin of neutrino mass and the scale Λ associated with LNV

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

- LANL co-leads a world wide ^{76}Ge-based experimental search

Concluding comments

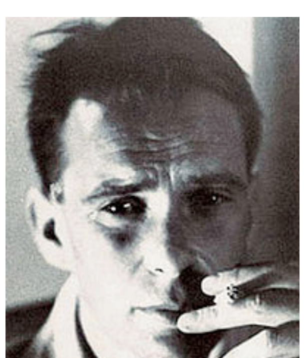
- Precision frontier experiments are exploring uncharted territory in our search for new physics. Important component of DOE mission (HEP, NP)



- LANL at the forefront of the precision frontier through experiment, theory, high performance computing

- Illustrated challenges and impact through β and ββ decays

Thank you!



A drawing by
Bruno Touschek