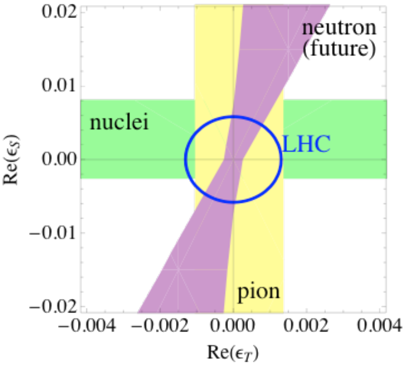
Precision measurements in nuclear β decays in the LHC era

ISOLDE seminar, CERN

November 2016



Martín González-Alonso

Institut de Physique Nucléaire de Lyon

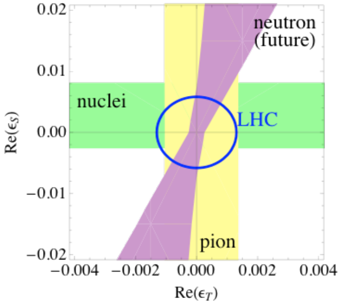
UCBL & CNRS/IN2P3

Labex LIO Institut des Origines de Lyon

Université de Lyon

Outline

- Introduction;
- Bounds from beta decays;
- Comparison with colliders;
- Summary;



[*Cirigliano, MGA & Jenkins*, NPB830 (2010)

Bhattacharya et al., PRD85 (2012)

Cirigliano, MGA & Graesser, JHEP1302 (2013)

MGA & Naviliat-Cuncic, Ann. Phys. 525 (2013)

MGA & Martin Camalich, PRL112 (2014)

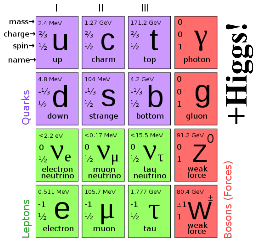
Chang, MGA & Martin Camalich, PRL114 (2015)

Courtoy, Baessler, MGA & Liuti, PRL115 (2015)

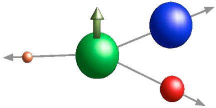
MGA & Naviliat-Cuncic, PRC 94 (2016)]

The search for ‘New Physics’

Standard Model

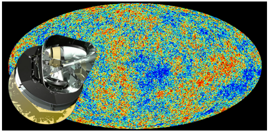


NEW PHYSICS : a new theory that completes the SM and solves (at least some of) the current puzzles.

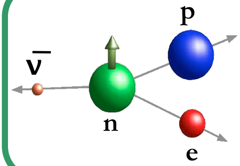


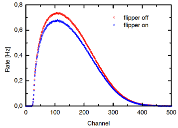
New Physics experimental searches...

- **Energy frontier ➔ Tevatron, LHC, ...**
- **Intensity frontier ➔ Nuclear physics, muon, ...**
- **Cosmic frontier ➔ Planck, ...**



Motivation





Precise data

+

Precise SM predictions

[Remember… $V_{ud} = 0.97425(22)$]

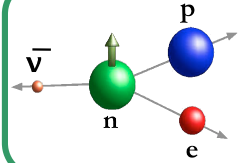
Neutron

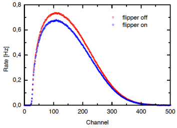
LANSCE (Los Alamos), ILL (Grenoble), J-PARC (Tokai), PNPI (Gatchina), FRM-II (Munich), SNS (Oak Ridge), NIST (Gaithersburg), PSI (Villigen), …

Nuclei

TRIUMF (^{38m}K, ^{37}K), ISOLDE (^{35}Ar), GANIL (^{35}Ar, ^{6}He), PSI (^{8}Li), Louvain-la-Neuve (^{14}O/ ^{10}C, ^{114}In, ^{60}Co), Groningen (^{26m}Al/^{30}K), Oak Ridge (^{6}He), Seattle (^{6}He), NSCL (^{6}He, ^{20}F), …

Motivation





Precise data

+

Precise SM predictions

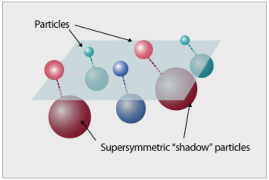
[Remember… $V_{ud} = 0.97425(22)$]

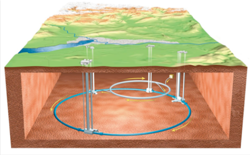
Implications for New Physics?

Competition with other searches?

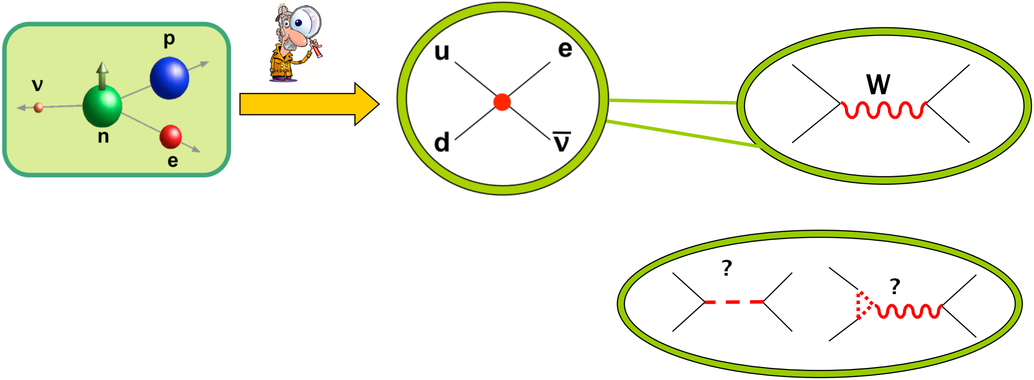
- **Specific model;**
  Barbieri et al. (1985), Marciano & Sirlin (1987), Hagiwara et al. (1995), Kurylov & Ramsey-Musolf (2002), Marciano (2007), Bauman et al. (2012), …

- **Something more general?**
  Effective Field Theory (EFT)!
  Not assumption-indep!

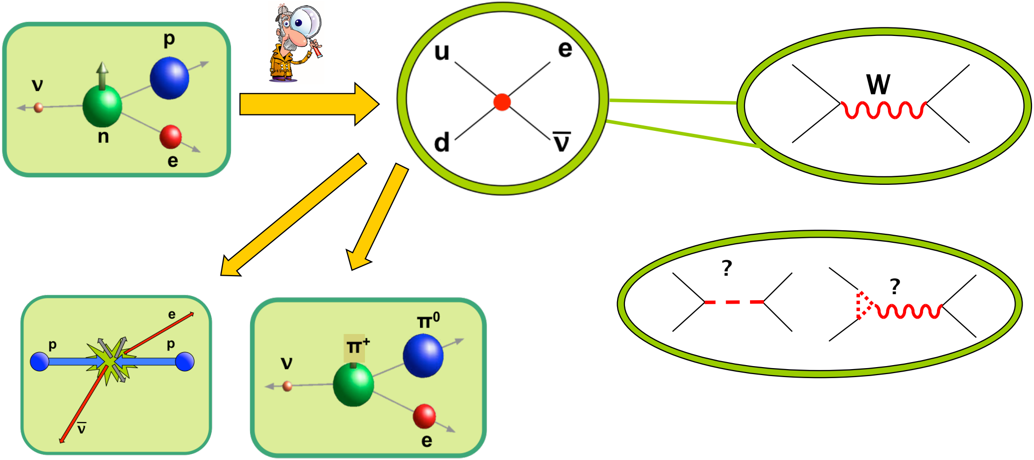




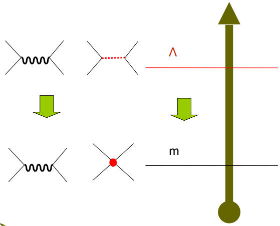
Motivation



Motivation



What's an EFT?



$$\mathcal{L} = \mathcal{L}(\phi, \phi_\Lambda)$$

$$\mathcal{L}_{eff} = \mathcal{L}_4(\phi) + \frac{1}{\Lambda}\mathcal{L}_5(\phi) + \frac{1}{\Lambda^2}\mathcal{L}_6(\phi) + \dots \rightarrow \sum \alpha_i \mathcal{O}_i$$

α_i : Wilson coefficients. They encode the Λ-scale (known?) physics.

Effective Field Theory = Fields + Symmetries

Fields:

- nuclei, e, v
- hadrons, e, v
- q, u, d, l, e
- W, Z, γ, g
- …

Symmetries:

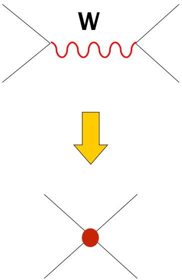
- Lorentz
- QED
- SU(2) x U(1)
- Flavour sym?
- B, L;

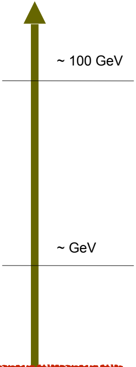
- Observables:

$$\mathcal{R} = \mathcal{R}_0 \left(1 + \frac{\mathcal{O}(m, E)}{\Lambda} + \frac{\mathcal{O}(m^2, E^2, mE)}{\Lambda^2} + \dots\right)$$

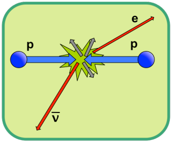
Validity of the EFT:
E << Λ

What's an EFT? Example: μ decay





$\mathcal{L}_{SM}$ (EW theory)



$$\mathcal{L}_{\mu \to e \bar{\nu}_e \nu_\mu} = -\frac{4 G_F}{\sqrt{2}} \bar{e} \gamma_\mu (1 - \gamma_5) \nu_e \cdot \bar{\nu}_\mu \gamma^\mu (1 - \gamma_5) \mu$$

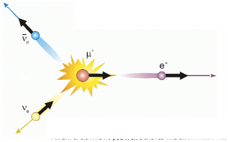
+ higher-dim terms

In real life, the process is the other way around!

"V-A was the key" S. Weinberg

$$G_F = \frac{g^2}{4\sqrt{2} m_W^2}$$

Wilson coefficient



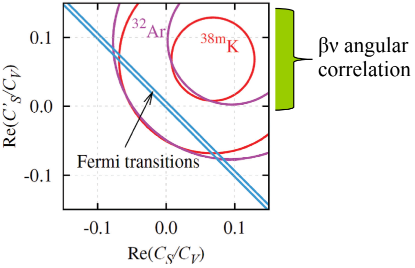
What's an EFT?

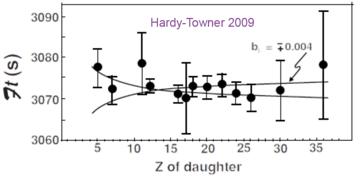
- How to compare different nuclear beta decays?
  - ➔ Effective Lagrangian at the **hadron** level!

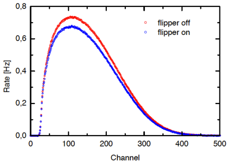
$$
\begin{aligned}
H_{V,A}^{(N)} &= \bar{e}\gamma_\mu(C_V + C_V'\gamma_5)\nu\bar{p}\gamma_\mu n \\
&\quad -\bar{e}\gamma_\mu\gamma_5(C_A + C_A'\gamma_5)\nu\bar{p}\gamma_\mu\gamma_5 n + \text{H.c.} \\
H_{S,P}^{(N)} &= \bar{e}(C_S + C_S'\gamma_5)\nu\bar{p}n + \text{H.c.} \\
H_T^{(N)} &= \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T + C_T'\gamma_5)\nu\bar{p}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}n + \text{H.c.}
\end{aligned}
$$

[Jackson, Treiman & Wyld'1957]

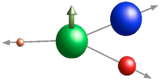
[MGA & Naviliat-Cuncic, 2013]







What's an EFT?



- How to compare different nuclear beta decays?
  - ➔ Effective Lagrangian at the **hadron** level!

$$\begin{aligned} H_{V,A}^{(N)} &= \bar{e}\gamma_\mu(C_V + C_V'\gamma_5)\nu\bar{p}\gamma_\mu n \\ &\quad -\bar{e}\gamma_\mu\gamma_5(C_A + C_A'\gamma_5)\nu\bar{p}\gamma_\mu\gamma_5 n + \text{H.c.} \\ H_{S,P}^{(N)} &= \bar{e}(C_S + C_S'\gamma_5)\nu\bar{p}n + \text{H.c.} \\ H_T^{(N)} &= \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T + C_T'\gamma_5)\nu\bar{p}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}n + \text{H.c.} \end{aligned}$$

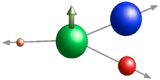
- How to compare with e.g. pion decays?
  - ➔ Effective Lagrangian at the **quark** level!

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon_{\rho\delta}^{\Gamma}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

$$G_F \sim \frac{1}{\mathrm{M}_\mathrm{W}^2}$$

$$G_F\varepsilon_i \sim \frac{1}{\mathrm{M}_\mathrm{NP}^2}$$

What’s an EFT?



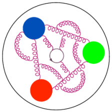
- How to compare different nuclear beta decays?
  - ➔ Effective Lagrangian at the **hadron** level!

$$
\begin{aligned}
H_{V,A}^{(N)} &= \bar{e}\gamma_\mu(C_V + C_V'\gamma_5)\nu\bar{p}\gamma_\mu n \\
&\quad -\bar{e}\gamma_\mu\gamma_5(C_A + C_A'\gamma_5)\nu\bar{p}\gamma_\mu\gamma_5 n + \text{H.c.} \\
H_{S,P}^{(N)} &= \bar{e}(C_S + C_S'\gamma_5)\nu\bar{p}n + \text{H.c.} \\
H_T^{(N)} &= \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T + C_T'\gamma_5)\nu\bar{p}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}n + \text{H.c.}
\end{aligned}
$$

- How to compare with e.g. pion decays?
  - ➔ Effective Lagrangian at the **quark** level!

$$
\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon^{\Gamma}_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]
$$

$$
G_F \sim \frac{1}{M_W^2} \qquad G_F\varepsilon_i \sim \frac{1}{M_{NP}^2}
$$



$$
C_i \approx (\text{Form factor}) \times \varepsilon_i
$$

Hadronic-level parameter (from experiment/th)

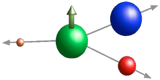
Hadronization (from lattice/th)

Quark-level parameter

Question: ?

How well do we know them?
Is that OK?

What's an EFT?



- How to compare different nuclear beta decays?
  - ➔ Effective Lagrangian at the **hadron** level!

$$
\begin{aligned}
H_{V,A}^{(N)} &= \bar{e}\gamma_\mu(C_V + C_V'\gamma_5)\nu\bar{p}\gamma_\mu n \\
&\quad -\bar{e}\gamma_\mu\gamma_5(C_A + C_A'\gamma_5)\nu\bar{p}\gamma_\mu\gamma_5 n + \text{H.c.} \\
H_{S,P}^{(N)} &= \bar{e}(C_S + C_S'\gamma_5)\nu\bar{p}n + \text{H.c.} \\
H_T^{(N)} &= \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T + C_T'\gamma_5)\nu\bar{p}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}n + \text{H.c.}
\end{aligned}
$$

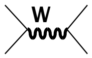
- How to compare with e.g. pion decays?
  - ➔ Effective Lagrangian at the **quark** level!

$$
\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon_{\rho\delta}^{\Gamma}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]
$$

$$
G_F \sim \frac{1}{M_W^2} \qquad G_F\varepsilon_i \sim \frac{1}{M_{NP}^2}
$$

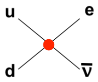
- How to compare with LHC experiments?
  - ➔ Effective Lagrangian at the **quark** level at the EW scale!

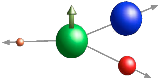
$$
\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i\,\mathcal{O}_i
$$



It's not only about comparing, but also about connecting with HEP (models!).

β decay Eff. Lagrangian





After hadronization and at order ε …

$$\mathcal{L}_{n\to pe^-\bar{\nu}_e} = -\sqrt{2}G_F V_{ud}\Big(1+\mathrm{Re}\,(\epsilon_L+\epsilon_R)\Big)\Big[\bar{e}_L\gamma_\mu\nu_L\cdot\bar{p}\big(\gamma^\mu - \tilde{g}_A\gamma^\mu\gamma_5\big)n + g_S\,\epsilon_S\,\bar{e}_R\nu_L\cdot\bar{p}n + 2g_T\,\epsilon_T\,\bar{e}_R\sigma_{\mu\nu}\nu_L\cdot\bar{p}\sigma^{\mu\nu}n_L\Big]$$

$$N \to N' e^{\pm}\nu$$

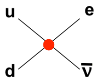
$$g_V \to M_F g_V$$
$$g_S \to M_F g_S$$
$$g_A \to M_{GT} g_A$$
$$g_T \to M_{GT} g_T$$

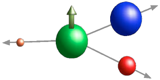
$$g_A = \langle p(p_p)|\,\bar{u}\gamma_\mu\gamma_5 d\,|\,n(p_n)\rangle$$
$$\tilde{g}_A \approx \bar{g}_A(1-2\epsilon_R)$$

Dictionary ("matching"):

$$1+\mathrm{Re}(\varepsilon_L+\varepsilon_R) \Leftrightarrow C_V + C_V'$$
$$g_S\varepsilon_S \Leftrightarrow C_S + C_S'$$
$$g_T\varepsilon_T \Leftrightarrow C_T + C_T'$$

β decay Eff. Lagrangian





After hadronization and at order ε …

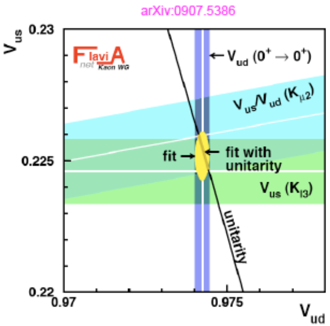
$$\mathcal{L}_{n\to pe^-\bar{\nu}_e} = -\sqrt{2}G_F V_{ud}\left(1+\mathrm{Re}\,(\epsilon_L+\epsilon_R)\right)\Big[\bar{e}_L\gamma_\mu\nu_L\cdot\bar{p}\left(\gamma^\mu - \tilde{g}_A\gamma^\mu\gamma_5\right)n + g_S\,\epsilon_S\,\bar{e}_R\nu_L\cdot\bar{p}n + 2g_T\,\epsilon_T\,\bar{e}_R\sigma_{\mu\nu}\nu_L\cdot\bar{p}\sigma^{\mu\nu}n_L\Big]$$

Lifetime shift ➔
CKM unitarity

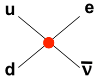
$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2-1=(0.1\pm0.6)\cdot 10^{-3}$$

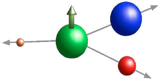
$$\varepsilon_L+\varepsilon_R\leq 5\cdot 10^{-4}$$

Cirigliano, MGA & Jenkins,
NPB830 (2010)



β decay Eff. Lagrangian





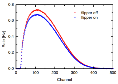
After hadronization and at order ε …

$$\mathcal{L}_{n\to pe^-\bar{\nu}_e} = -\sqrt{2}G_F V_{ud}\left(1+\mathrm{Re}\left(\epsilon_L+\epsilon_R\right)\right)\Big[\bar{e}_L\gamma_\mu\nu_L\cdot\bar{p}\left(\gamma^\mu - \tilde{g}_A\gamma^\mu\gamma_5\right)n + g_S\,\epsilon_S\,\bar{e}_R\nu_L\cdot\bar{p}n + 2g_T\,\epsilon_T\,\bar{e}_R\sigma_{\mu\nu}\nu_L\cdot\bar{p}\sigma^{\mu\nu}n_L\Big]$$

S and T affect the angular distributions and the spectrum!!

$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E)\left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + \left(B + b_B\frac{m_e}{E_e}\right)\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$

✓ Direct effect in the spectrum:



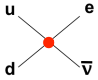
$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_e}$$

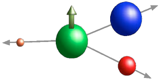
✓ Indirect effect in the asymmetries: $\tilde{X} = \dfrac{X}{1+b\langle m/E_e\rangle}$ *[e.g. beta asymmetry A]*

✓ Indirect effect in the lifetime;

[Hardy & Towner, 2009]

β decay Eff. Lagrangian





After hadronization and at order ε …

$$\mathcal{L}_{n\to pe^-\bar\nu_e} = -\sqrt{2}G_F V_{ud}\Big(1+\mathrm{Re}\left(\epsilon_L+\epsilon_R\right)\Big)\Big[\bar e_L\gamma_\mu\nu_L\cdot\bar p\Big(\gamma^\mu - \tilde g_A\gamma^\mu\gamma_5\Big)n + g_S\,\epsilon_S\,\bar e_R\nu_L\cdot\bar p n + 2g_T\,\epsilon_T\,\bar e_R\sigma_{\mu\nu}\nu_L\cdot\bar p\sigma^{\mu\nu}n_L\Big]$$

S and T affect the angular distributions and the spectrum!!

$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E)\left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + (B + b_B\frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$

Exp. give us ***b*** (i.e. $C_{S,T}$)

b = # g_S ε_S + # g_T ε_T

$\langle p|\bar u d|n\rangle$ $\langle p|\bar u\sigma_{\mu\nu}d|n\rangle$

QCD errors here can ruin the exp. effort!

Low-energy EFT: β decays

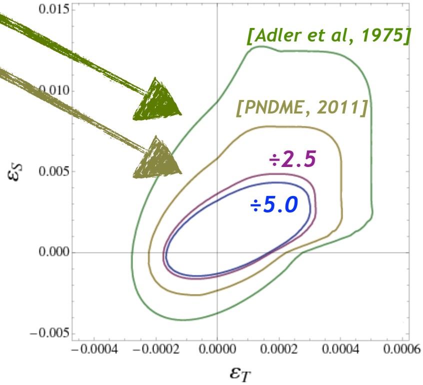
$b = \#\, g_S\, \varepsilon_S + \#\, g_T\, \varepsilon_T$

How well do we know g_S and g_T?

Is this precision OK?
How well do we need to know them?
(assuming $b_n < 0.001$)

	g_S	g_T
Adler et al.'1975 (quark model)	0.60(40)	1.45(85)
PNDME 2011	0.80(40)	1.05(35) *[average]*

$\delta g_{S,T}/g_{S,T} \sim$ 15-20%



[Bhattacharya, Cirigliano, Cohen, Filipuzzi, MGA, Graesser, Gupta, Lin, PRD85 (2012)*]*

Low-energy EFT: β decays

$b = \# \, g_S \, \varepsilon_S + \# \, g_T \, \varepsilon_T$

How well do we know g_S and g_T?

	g_S	g_T
Adler et al. '1975 (quark model)	0.60(40)	1.45(85)
PNDME 2011	0.80(40)	1.05(35)
LHPC 2012	1.08(32)	1.04(02)
RQCD 2014	1.02(35)	1.01(02)
PNDME 2013/15	0.72(32)	1.02(08)
ETMC 2015	1.21(42)	1.03(06)
CVC	1.02(11)	
PNDME 2016	0.97(13)	0.99(06)

Is this precision OK?
How well do we need to know them?
(assuming $b_n < 0.001$)

$\delta g_{S,T}/g_{S,T} \sim$ **15-20%** ✔

Not trivial!
Not the case in rad. pion decays, SL hyperon decays, …

"We quantify all syst. errors, including for the 1st time a simultaneous extrapolation in a, V & m_q"
[Bhattacharya et al., Phys. Rev. Lett. 115 (2015)]

$$\partial_\mu \left(\bar{u}\gamma^\mu d\right) = -i(m_d - m_u)\bar{u}d$$

$$g_S = \frac{\left(M_n - M_p\right)_{QCD}}{m_d - m_u} g_V$$

Useful connection between two different Lattice efforts!

[MGA & Martin Camalich, Phys. Rev. Lett. 112 (2014)]

Resuscitating the pseudoscalar interaction

Likewise...

[MGA & Martin Camalich, Phys. Rev. Lett. 112 (2014)]

$$\partial_\mu \left(\bar{u}\gamma^\mu\gamma_5 d\right) = i(m_d + m_u)\bar{u}\gamma_5 d \quad \Rightarrow \quad g_P = \frac{M_n + M_p}{m_d + m_u} g_A = 348(11)$$

Implications? It almost compensates the bilinear suppression!

- ***P bilinear ~ q/M ~10^{-3};***

$$\langle p(p_p)|\bar{u}\gamma_5 d|n(p_n)\rangle = g_P(q^2)\bar{u}_p(p_p)\gamma_5 u_n(p_n)$$

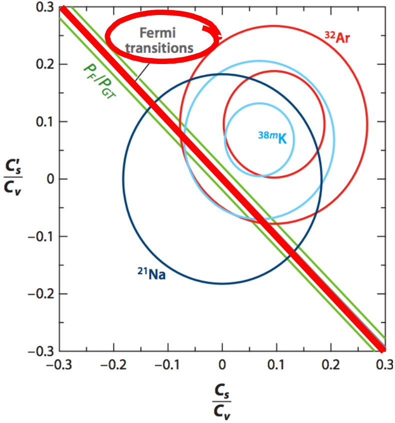
"since the nucleons are treated nonrelativistically, the pseudoscalar couplings are omitted"

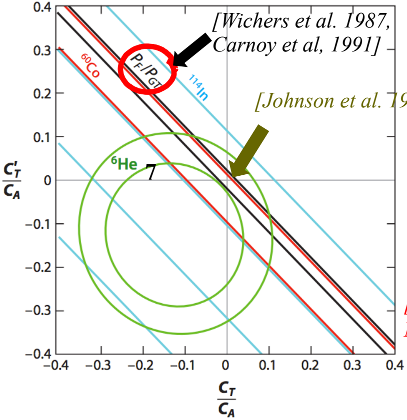
[Jackson, Treiman & Wyld, 1957]

Message:

the same β decay experiments that set bounds on S & T, are almost as sensitive to P!

β decay Eff. Lagrangian





[Wichers et al. 1987, Carnoy et al, 1991]

[Johnson et al. 1963]

[Severijns & Naviliat-Cuncic, 2011]

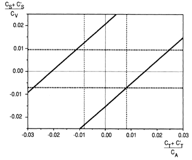
+ Neutron data $= f(C_S, C_T)$ → **Global fit** → $C_S, C_T, \ldots$ → **Form factors** → $\varepsilon_S, \varepsilon_T, \ldots$

[+ Mixed transitions]

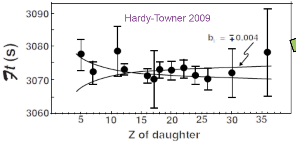
[Severijns et al.'2006, Wauters, Garcia & Hong, 2013]

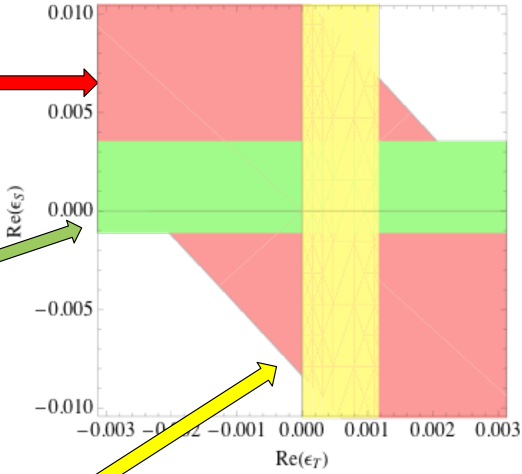
Current limits on S & T from low-E:

$\mathbf{P_F(^{14}O)/P_{GT}(^{10}C)}$ (Carnoy et al.'1991)



Superallowed nuclear β decays $(\mathbf{b_{0+}})$

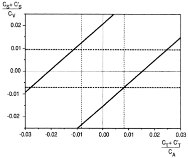


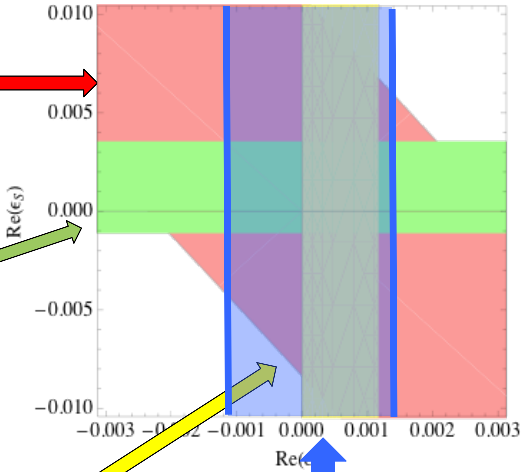


A global fit of nuclear & neutron β decay data.
[Wauters, Garcia & Hong, 2013]
[Pattie, Hickerson & Young, 2013]

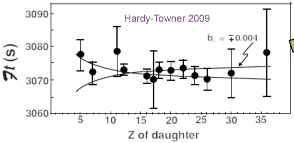
Current limits on S & T from low-E:

$P_F(^{14}O)/P_{GT}(^{10}C)$ (Carnoy et al.'1991)



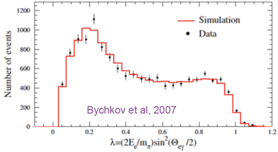


Superallowed nuclear β decays (b_{0+})



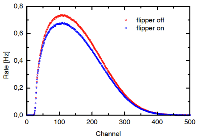
A global fit of nuclear & neutron β decay data.
[Wauters, Garcia & Hong, 2013]
[Pattie, Hickerson & Young, 2013]

$\pi \rightarrow e\nu\gamma$
(PIBETA´2009)



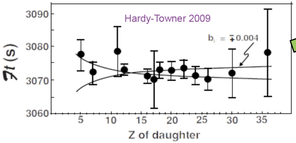
~~Current~~ Future limits on S & T from low-E:

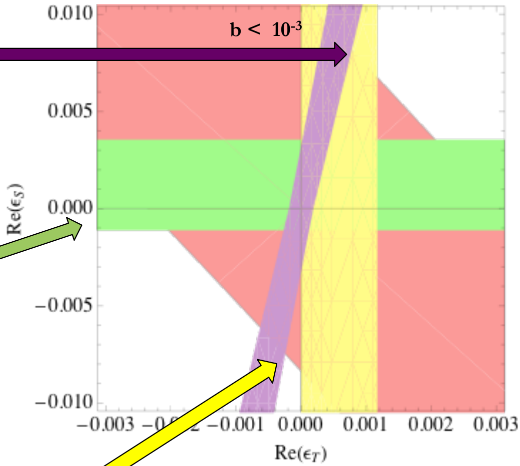
Future neutron decay exp.



$b \approx 0.3\, g_S\, \varepsilon_S - 5.0\, g_T\, \varepsilon_T$

Superallowed nuclear β decays (b_{0+})





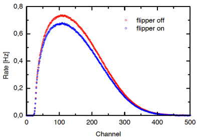
A global fit of nuclear & neutron β decay data.

[Wauters, Garcia & Hong, 2013]

[Pattie, Hickerson & Young, 2013]

Future ~~Current~~ limits on S & T from low-E:

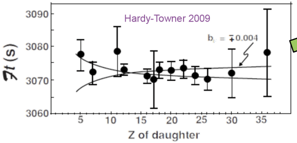
Future neutron decay exp.

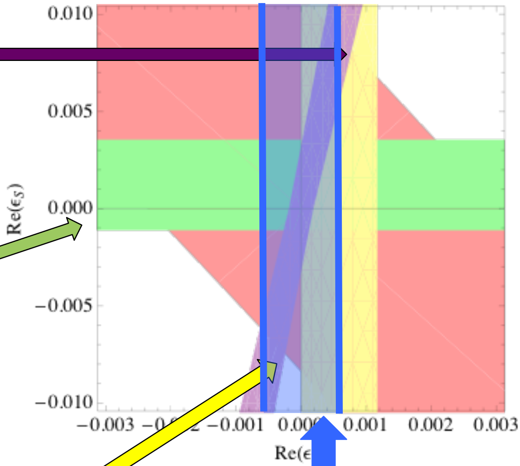


$b \approx 0.3\, g_S\, \varepsilon_S - 5.0\, g_T\, \varepsilon_T$

Mirror decays

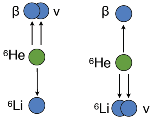
Superallowed nuclear β decays (b_{0+})



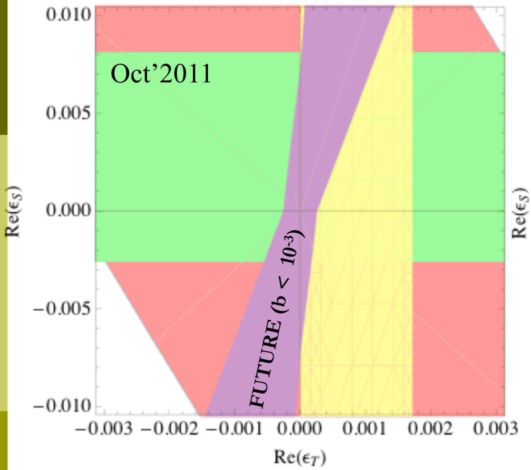


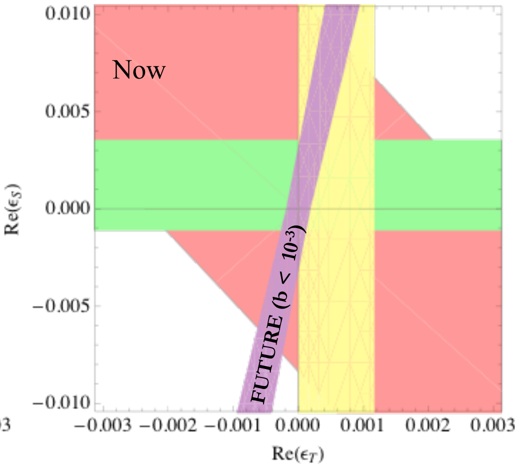
A global fit of nuclear & neutron β decay data.
[Wauters, Garcia & Hong, 2013]
[Pattie, Hickerson & Young, 2013]

b_{GT} from $\delta a(^6He) \sim 10^{-4}$



Future ~~Current~~ limits on S & T from low-E:

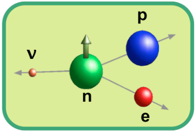


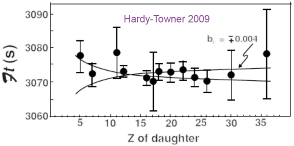


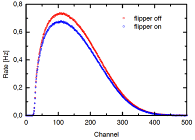
- We are benefiting here from the advance in the FF determinations!
- Conclusion: S,T are at least ~1000x weaker than the V-A Fermi interaction.

$$\varepsilon_i \sim \frac{M_W^2}{M_{NP}^2} \rightarrow M_{NP} \sim 2\ \text{TeV}$$

From (CP-cons) beta decay experiments…







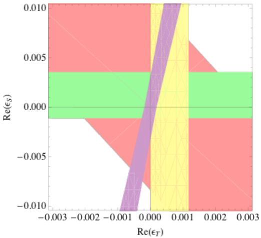
$$\mathcal{L}_{n\to pe^-\bar{\nu}_e} = -\sqrt{2}G_F V_{ud}\left(1+\mathrm{Re}\,(\epsilon_L+\epsilon_R)\right)\Big[\bar{e}_L\gamma_\mu\nu_L\cdot\bar{p}\left(\gamma^\mu - \tilde{g}_A\gamma^\mu\gamma_5\right)n + g_S\,\epsilon_S\,\bar{e}_R\nu_L\cdot\bar{p}n + 2g_T\,\epsilon_T\,\bar{e}_R\sigma_{\mu\nu}\nu_L\cdot\bar{p}\sigma^{\mu\nu}n_L\Big]$$

Lifetime shift → CKM unitarity

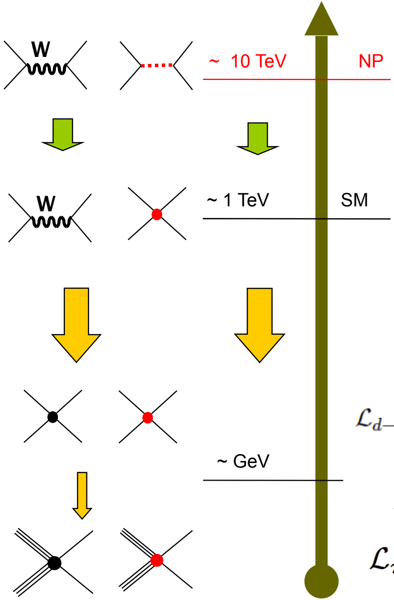
$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (0.1 \pm 0.6)\cdot 10^{-3}$$

$$\varepsilon_L + \varepsilon_R \leq 5\cdot 10^{-4}$$

Comparison with colliders?



High-E effective Lagrangian



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields, bSM fields})$$

[Buchmüller-Wyler'1986, Leung et al.'1986, Grzadkowski et al'2010]

$$\mathcal{L}_{eff.} = \mathcal{L}_{SM} + \frac{1}{\Lambda^2}\sum \alpha_i\, \mathcal{O}_i$$

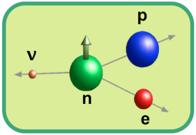
[Cirigliano, MGA, Jenkins'2010, Cirigliano, MGA, Graesser'2012]

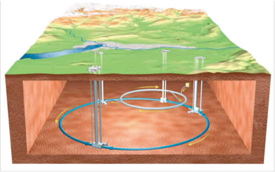
$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon^{\Gamma}_{\rho\delta}\;\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

$$\mathcal{L}_{\pi,N,\ldots} = \ldots$$

$$\varepsilon_i = f(\alpha_j)$$

Vector interactions:
CKM unitarity test vs LEP





CKM tests vs. HEP

[Cirigliano, MGA & Jenkins, Nucl. Phys B830 (2010)]

$$\Delta_{CKM} = 4\left(-\hat{\alpha}_{\varphi l}^{(3)} + \hat{\alpha}_{\varphi q}^{(3)} - \hat{\alpha}_{lq}^{(3)} + \hat{\alpha}_{ll}^{(3)}\right) = -(1 \pm 6)\cdot 10^{-4}$$

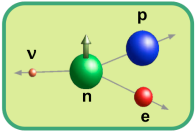
$$O_{ll}^{(3)} = \frac{1}{2}(\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{l}\gamma_{\mu}\sigma^{a}l)$$

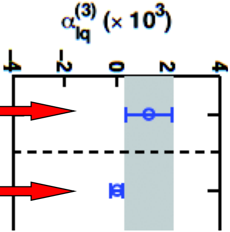
$$O_{lq}^{(3)} = (\bar{l}\gamma^{\mu}\sigma^{a}l)(\bar{q}\gamma_{\mu}\sigma^{a}q)$$

$$O_{\varphi l}^{(3)} = i(h^{\dagger}D^{\mu}\sigma^{a}\varphi)(\bar{l}\gamma_{\mu}\sigma^{a}l) + \text{h.c.},$$

$$O_{\varphi q}^{(3)} = i(\varphi^{\dagger}D^{\mu}\sigma^{a}\varphi)(\bar{q}\gamma_{\mu}\sigma^{a}q) + \text{h.c.}$$

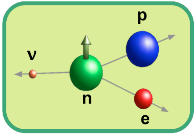
LEPII: $e^{+}e^{-} \rightarrow q\bar{q}$

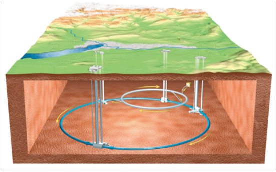




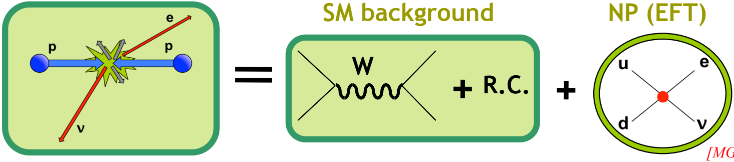
$$\Lambda_{NP}^{eff} = \frac{\Lambda_{NP}}{\sqrt{\hat{\alpha}}} > 11\,\text{TeV (90\% CL)}$$

Scalar & tensor interactions: b_{Fierz} vs LHC





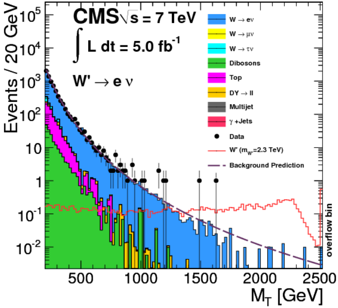
LHC limits on $\varepsilon_{S,T}$

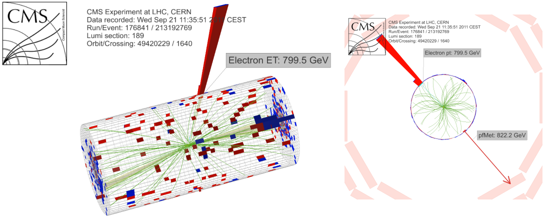


[MGA & Naviliat-Cuncic, Ann. Phys. 525 (2013)*]*
[Cirigliano, MGA & Graesser, JHEP1302 (2013)*]*
[Bhattacharya et al, PRD85 (2012)*]*

$$N_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times \mathrm{L} \times \sigma_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times \mathrm{L} \times \left(\sigma_W + \sigma_S\, \varepsilon_S^2 + \sigma_T\, \varepsilon_T^2\right)$$

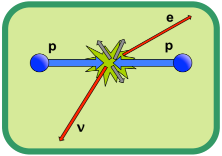
(Interference w/ SM ~ m/E)





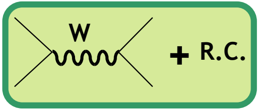
$$m_T \equiv \sqrt{2E_T^e E_T^\nu (1-\cos\Delta\phi_{e\nu})}$$

LHC limits on $\varepsilon_{S,T}$



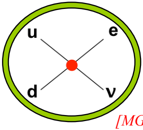
=

SM background



+

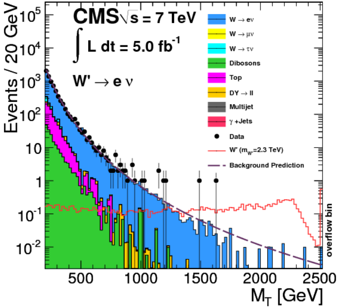
NP (EFT)

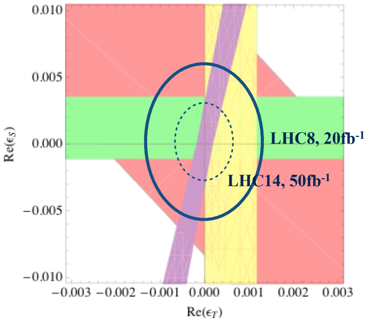


[MGA & Naviliat-Cuncic, Ann. Phys. 525 (2013)*]*
[Cirigliano, MGA & Graesser, JHEP1302 (2013)*]*
[Bhattacharya et al, PRD85 (2012)*]*

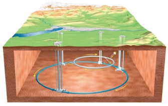
$$N_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times \mathrm{L} \times \sigma_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times \mathrm{L} \times \left(\sigma_W + \sigma_S\, \varepsilon_S^2 + \sigma_T\, \varepsilon_T^2\right)$$

(Interference w/ SM ~ m/E)



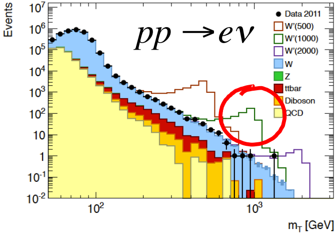


If we see a bump...



- EFT breaks down…
  Toy model: scalar resonance:

$$\mathcal{L} = \lambda_S V_{ud} \phi^+ \overline{u} d + \lambda_l \phi^- \overline{e} P_L \nu_e$$



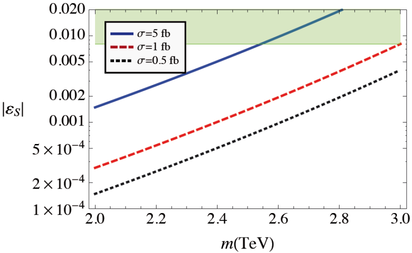
- Then we have a lower-limit value for ε_S:

$$\sigma \cdot \mathrm{BR} \leq \frac{|V_{ud}|}{12 v^2} \frac{\pi}{\sqrt{2 N_c}} |\epsilon_S| \tau L(\tau)$$

$$L(\tau) = \int_\tau^1 dx f_q(x) f'_q(\tau/x)/x$$

$$\tau = m^2/s$$

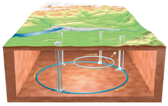
$$\epsilon_S = 2 \lambda_S \lambda_l \frac{v^2}{m^2}$$

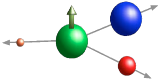


Nice interplay of two experiments separated for so many orders of magnitudes!!!!

[T. Battacharya et al., 2012]

Conclusions

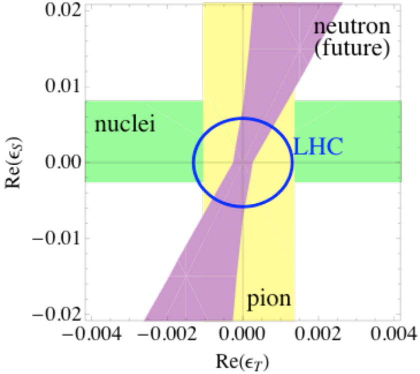




- β decays are sensitive to TeV physics!
  - Intense theoretical activity (FFs, NP, …);
  - Intense experimental activity;

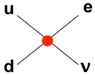
$$g_S = \frac{(M_n - M_p)_{QCD}}{m_d - m_u} = 1.02(11)$$

- EFT approach connects high- and low-E probes;
- This interplay becomes much more interesting if we see a NP signal!
- Beta decay searches are a very rich (and cross-disciplinary) field.



Backup slides

Low-energy EFT: $d_j \rightarrow u_i \, l \, \nu$



$$\mathcal{L} \sim (1+\epsilon_L)(V-A)(V-A) + \epsilon_R(V-A)(V+A) + \cancel{\tilde{\epsilon}_L(V+A)(V-A)} + \cancel{\tilde{\epsilon}_R(V+A)(V+A)}$$
$$+\epsilon_S\,(S-P)\,S - \epsilon_P(S-P)\,P + \cancel{\tilde{\epsilon}_S(S+P)\,S} - \cancel{\tilde{\epsilon}_P(S+P)\,P}$$
$$+\epsilon_T(T-T\gamma_5)(T+T\gamma_5) + \cancel{\tilde{\epsilon}_T(T+T\gamma_5)(T-T\gamma_5)}$$

Linear approximation: SM + small perturbation

$$\mathcal{L}_{d\to ue^-\bar{\nu}_e} = -\sqrt{2}G_F V_{ud}\Big(1+\mathrm{Re}\,(\epsilon_L+\epsilon_R)\Big)\Big[\bar{e}_L\gamma_\mu\nu_L \cdot \bar{u}\Big(\gamma^\mu - (1-2\epsilon_R)\gamma^\mu\gamma_5\Big)d$$
$$+ \epsilon_S\ \bar{e}_R\nu_L \cdot \bar{u}d - \epsilon_P\ \bar{e}_R\nu_L \cdot \bar{u}\gamma_5 d + 2\ \epsilon_T\ \bar{e}_R\sigma_{\mu\nu}\nu_L \cdot \bar{u}\sigma^{\mu\nu}d_L\Big]$$

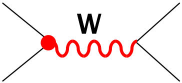
Underlying…

- ➔ nuclear & neutron beta decay;
- ➔ (semi)lepton pion decays;
- ➔ …

Process-dependent details:

- ➔ Hadronization (FFs) is different;
- ➔ Exp. is very different;

Form factors in β decay (SM)



Weinberg'58:

Related to μ_p-μ_n (up to isospin breaking corr.)

$$\langle p(p_p)|\,\bar{u}\gamma_\mu d\,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_V(q^2)\gamma_\mu + \frac{\tilde{g}_{T(V)}(q^2)}{2M_N}\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_S(q^2)}{2M_N}q_\mu\right]u_n(p_n)$$

$g_V(0)=1$ (Ademollo-Gatto'64)

$$\langle p(p_p)|\,\bar{u}\gamma_\mu\gamma_5 d\,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_A(q^2)\gamma_\mu + \frac{\tilde{g}_{T(A)}(q^2)}{2M_N}\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_P(q^2)}{2M_N}q_\mu\right]\gamma_5 u_n(p_n)$$

$g_A(0)$???

Key feature: $\frac{q}{M} \sim \frac{\Delta M}{M} \sim 10^{-3}$ ⇒ One can safely neglect $O(q^2/M^2)$ & quadratic corrections to the isospin limit

+ R.C. $\frac{\alpha}{2\pi} \sim 10^{-3}$

[Marciano & Sirlin, 1986]
[Czarnecki et al., 2004]
[Ando et al., 2004]
[Marciano & Sirlin, 2006]
[...]

$$O_{th} = O_{th}(G_F V_{ud}, g_A)$$

$$\delta O_{th} \sim 10^{-4} - 10^{-5}!!!!$$

Form factors in β decay (bSM)

Once we go beyond the SM…

$$\langle p(p_p)|\,\bar{u}\,d\,|n(p_n)\rangle = g_S(q^2)\,\bar{u}_p(p_p)\,u_n(p_n)$$

$$\langle p(p_p)|\,\bar{u}\,\gamma_5\,d\,|n(p_n)\rangle = g_P(q^2)\,\bar{u}_p(p_p)\,\gamma_5\,u_n(p_n)$$

$$\langle p(p_p)|\,\bar{u}\,\sigma_{\mu\nu}\,d\,|n(p_n)\rangle = \bar{u}_p(p_p)\left[g_T(q^2)\,\sigma_{\mu\nu} + g_T^{(1)}(q^2)\,(q_\mu\gamma_\nu - q_\nu\gamma_\mu) + g_T^{(2)}(q^2)\,(q_\mu P_\nu - q_\nu P_\mu) + g_T^{(3)}(q^2)\,(\gamma_\mu \not{q}\gamma_\nu - \gamma_\nu \not{q}\gamma_\mu)\right] u_n(p_n)$$

[Weinberg'58]

Now we don't keep corrections…

$$\varepsilon_i \sim \frac{M_W^2}{M_{NP}^2} \sim 10^{-3} \;\rightarrow\; \frac{q}{M} \times \varepsilon_i \sim 10^{-6}$$

In summary, we have 2 new form factors:

$$g_S \equiv g_S(q^2 = 0)$$

$$g_T \equiv g_T(q^2 = 0)$$

How well do we know them?

g_S & the nucleon splitting

[MGA & Martin Camalich, Phys. Rev. Lett. 112 (2014)]

$$\partial_\mu (\bar{u}\gamma^\mu d) = -i(m_d - m_u)\bar{u}d$$

$$g_S = \frac{(M_n - M_p)_{QCD}}{m_d - m_u} g_V$$

1

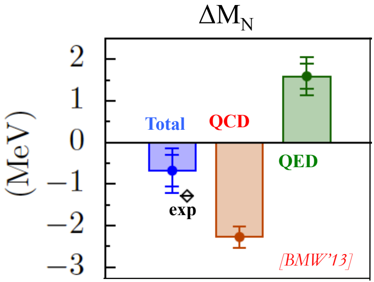
Isospin splitting in the nucleon

$$(M_n - M_p)_{exp} = 1.2933322(4)\ \text{MeV}$$

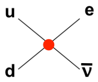
$$M_n - M_p = (M_n - M_p)_{QCD} + (M_n - M_p)_{QED}$$

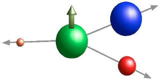
It turns out lattice-QCD is being calculating this recently!!!!

Useful connection between two different Lattice efforts!



β decay Eff. Lagrangian





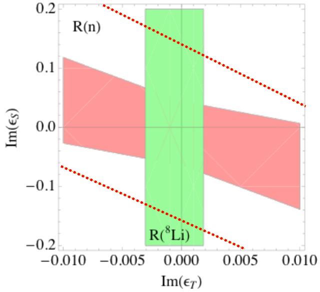
After hadronization and at order ε …

$$\mathcal{L}_{n\to pe^-\bar\nu_e} = -\sqrt{2}G_F V_{ud}\left(1+\mathrm{Re}\left(\epsilon_L+\epsilon_R\right)\right)\Big[\bar e_L\gamma_\mu\nu_L\cdot\bar p\left(\gamma^\mu - \tilde g_A\gamma^\mu\gamma_5\right)n + g_S\,\epsilon_S\,\bar e_R\nu_L\cdot\bar p n + 2g_T\,\epsilon_T\,\bar e_R\sigma_{\mu\nu}\nu_L\cdot\bar p\sigma^{\mu\nu}n_L\Big]$$

$$\tilde g_A \approx g_A(1-2\epsilon_R)$$
$$g_A = \langle p|\bar u\gamma_\mu\gamma_5 d|n\rangle$$

CP violating effects?

R, L, … coefficients: $\mathrm{Im}(\varepsilon_{S,T})$



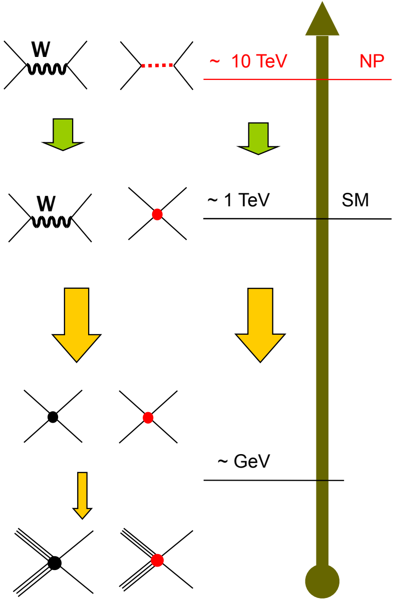
[MGA & Naviliat-Cuncic, 2013]

D coefficient: $\mathrm{Im}(\varepsilon_R)$

$$D = (1\pm 6)\times 10^{-4} \quad [^{19}\mathrm{Ne}]$$
$$D = (1\pm 2)\times 10^{-4} \quad [\mathrm{n}]$$

$$g_S\varepsilon_S \quad \Leftrightarrow \quad C_S + C_S'$$
$$g_T\varepsilon_T \quad \Leftrightarrow \quad C_T + C_T'$$
$$\mathrm{Im}(\varepsilon_R) \quad \Leftrightarrow \quad \mathrm{Im}\left(C_V C_A^* + C_V' C_A'^*\right)$$

Effective Lagrangians



$$\mathcal{L}(x) = \mathcal{L}\,(\text{SM fields},\ \text{bSM fields})$$

$$\alpha^t_{lq}\,(\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u)$$

$$\epsilon_T\ \bar{e}_R \sigma_{\mu\nu} \nu_L \cdot \bar{p} \sigma^{\mu\nu} n_L$$

$$V_{ud}\varepsilon_T = -\left[\alpha^t_{lq}\right]^*$$

$$\bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T + C'_T\gamma_5)\nu\bar{p}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}n$$

$$C_T^{(')} = 4 g_T \varepsilon_T$$

Connection with HEP

- Running + Matching with HEP Model/EFT:

$$\frac{\delta G_F}{G_F} = 2\,[\hat{\alpha}^{(3)}_{\varphi l}]_{11+22} - [\hat{\alpha}^{(1)}_{ll}]_{1221} - 2[\hat{\alpha}^{(3)}_{ll}]_{1122-\frac{1}{2}(1221)}\,,$$

$$V_{1j}\cdot\epsilon_L^{j\ell} = 2\,V_{1j}\left[\hat{\alpha}^{(3)}_{\varphi l}\right]_{\ell\ell} + 2\left[V\hat{\alpha}^{(3)}_{\varphi q}\right]_{1j} - 2\left[V\hat{\alpha}^{(3)}_{lq}\right]_{\ell\ell 1j}\,,$$

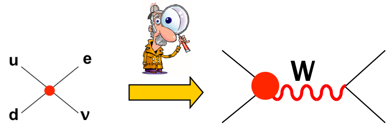
$$V_{1j}\cdot\epsilon_R^{j} = -\,[\hat{\alpha}_{\varphi\varphi}]_{1j}\,,$$

$$V_{1j}\cdot\epsilon_{sL}^{j\ell} = -\,[\hat{\alpha}_{lq}]^*_{\ell\ell j1}\,,$$

$$V_{1j}\cdot\epsilon_{sR}^{j\ell} = -\left[V\hat{\alpha}^{\dagger}_{qde}\right]_{\ell\ell 1j}\,,$$

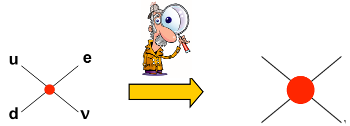
$$V_{1j}\cdot\epsilon_T^{j\ell} = -\,[\hat{\alpha}^{t}_{lq}]^*_{\ell\ell j1}\,,$$

$$\hat{\alpha} = \alpha\frac{v^2}{\Lambda^2}$$



(V-A) x (V+A)

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



S, P, T

$$(\bar{l}e)(\bar{d}q)$$

Their interference with the SM goes like m/E…

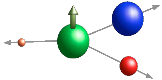
$$\sigma \;\sim\; \sigma_{SM}\left(1 + \frac{m}{\sqrt{s}}\hat{\alpha}_6\frac{\{v^2, s\}}{v^2} + \hat{\alpha}_6^2\frac{\{v^4, s^2\}}{v^4}\right)$$

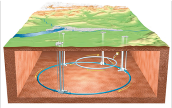
O(1) for LEP, but large for the LHC.

EFT analyses of LHC data requires 2 extra assumptions:
- (D=8) << (D=6)^2
- NP scale is larger than LHC scales;

$$\mathcal{L}_{eff.}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) + \frac{1}{\Lambda^4}\mathcal{L}_8(x) + \ldots$$

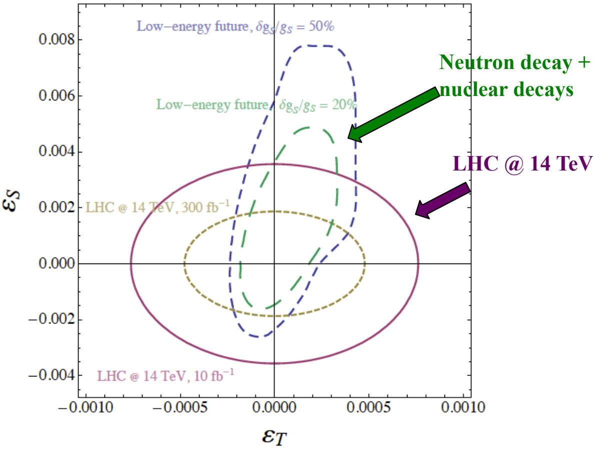
β decays vs. the LHC



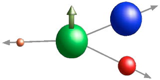


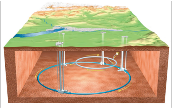
- The competition will continue:
  - New lattice data for the non-standard form factors;
  - New experimental data from beta decays;
  - LHC @ 14 TeV, with higher luminosity;

Bhattacharya et al.'2012



Beyond $\varepsilon_{S,T}$





Interesting competition*

ν_L

	Re ϵ_L	Re ϵ_R	Re ϵ_P	Re ϵ_S	Re ϵ_T	
Low-E	0.05	0.05	0.06	0.2	0.1	x 10^{-2}
LHC $(e\nu)$	-	-	0.6	0.6	0.1	x 10^{-2}

	Im ϵ_L	Im ϵ_R	Im ϵ_P	Im ϵ_S	Im ϵ_T	
Low-E	-	0.04	0.03	3	0.3	x 10^{-2}
LHC $(e\nu)$	-	-	0.6	0.6	0.1	x 10^{-2}

Low energy dominates!

ν_R

	$\lvert\tilde{\epsilon}_L\rvert$	$\lvert\tilde{\epsilon}_R\rvert$	$\lvert\tilde{\epsilon}_P\rvert$	$\lvert\tilde{\epsilon}_S\rvert$	$\lvert\tilde{\epsilon}_T\rvert$	
Low-E	6	6	0.03	14	3.0	x 10^{-2}
LHC $(e\nu)$	-	0.2	0.6	0.6	0.1	x 10^{-2}

LHC dominates!

$$\varepsilon \sim \alpha \frac{v^2}{\Lambda^2} \equiv \frac{v^2}{\Lambda_{eff}^2} \Rightarrow \Lambda_{eff} \sim 0.7 - 20.0 \text{ TeV}$$

[Cirigliano, MGA & Graesser, 2013
MGA & Naviliat-Cuncic, 2013]