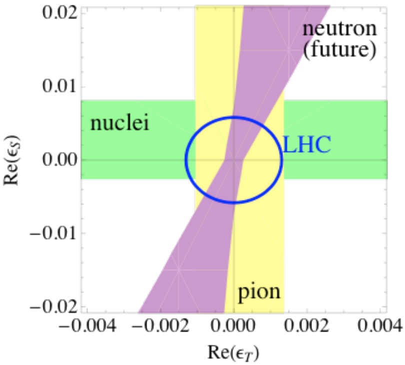
BSM effects in beta decays

... in the LHC era

INT Workshop | Oct 2nd, 2015



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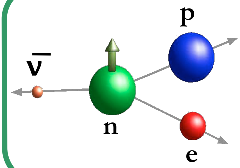
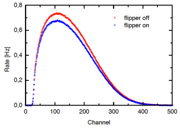
Outline

- Introduction and motivation;
- Low-energy searches of BSM effects in $d \rightarrow u\ e\ \nu$
  - Form factors!
- LHC searches;
- What about SL hyperon decays?
  ($s \rightarrow u\ e\ \nu$)

Motivation





Precise data

+

Precise SM predictions

[Remember… $V_{ud} = 0.97425(22)$]

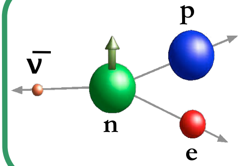
Neutron

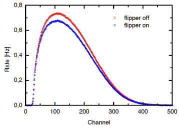
LANSCE (Los Alamos), ILL (Grenoble), J-PARC (Tokai), PNPI (Gatchina), FRM-II (Munich), SNS (Oak Ridge), NIST (Gaithersburg), PSI (Villigen), …

Nuclei

TRIUMF (^{38m}K, ^{37}K), CERN (^{32}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), Princeton (^{19}Ne), …

Motivation





Precise data

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Precise SM predictions

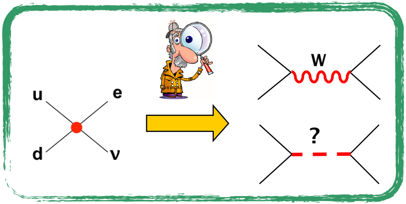
[Remember… $V_{ud} = 0.97425(22)$]

Implications for New Physics?

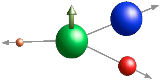
- **Specific model;** *Barbieri et al. (1985), Marciano & Sirlin (1987), Hagiwara et al. (1995), Kurylov & Ramsey-Musolf (2002), Marciano (2007), Bauman et al. (2012), …*
- **Something more general? EFTs!**
  Not assumption-indep! (Heavy NP + Field content + Symmetries)

Competitive probes?

- **Other low-E searches (e.g. Pion decays)**
- **High-E (LHC!!)**



Comparing experiments



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

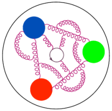
$$
\begin{aligned}
H^{(N)}_{V,A} &= \bar{e}\gamma_\mu(C_V + C'_V\gamma_5)\nu\bar{p}\gamma_\mu n \\
&\quad -\bar{e}\gamma_\mu\gamma_5(C_A + C'_A\gamma_5)\nu\bar{p}\gamma_\mu\gamma_5 n + \text{H.c.} \\
H^{(N)}_{S,P} &= \bar{e}(C_S + C'_S\gamma_5)\nu\bar{p}n + \text{H.c.} \\
H^{(N)}_{T} &= \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T + C'_T\gamma_5)\nu\bar{p}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}n + \text{H.c.}
\end{aligned}
$$

[Jackson, Treiman & Wyld'1957]

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

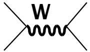
$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L \;+\; \sum_{\rho\delta\Gamma}\epsilon^\Gamma_{\rho\delta}\,\bar{\ell}_\rho\Gamma\nu\cdot\bar{u}\Gamma d_\delta\right]$$

$C_i \sim$ FF x ε_i



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

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



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  - Form factors!

- LHC searches;

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Low-E searches of NP in d → u e ν

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

Underlying…

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

Process-dependent details:

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

Low-E searches of NP in d → u e ν

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

Underlying…

- ➔ nuclear & neutron beta decay;
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Process-dependent details:

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- ➔ Exp. is very different;

Common features:

- ➔ V & A gets "hidden" inside V_{ud} & the axial-vector FF (precise LQCD needed).

$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2-1=(0.1\pm0.6)\cdot10^{-3}$$

$$\varepsilon_L+\varepsilon_R\lesssim 5\cdot10^{-4}$$

$\Big($ Form factors needed for β decay

Form factors in β decay (SM)

Weinberg'58:

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

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

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

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)

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$g_A(0)$???

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]

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

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

Form factors in β decay (bSM)

Once we go beyond the SM…

$$
\begin{aligned}
\langle p(p_p)|\,\bar{u}\,d\,|\,n(p_n)\rangle &= g_S(q^2)\;\bar{u}_p(p_p)\,u_n(p_n) \\
\langle p(p_p)|\,\bar{u}\,\gamma_5\,d\,|\,n(p_n)\rangle &= g_P(q^2)\;\bar{u}_p(p_p)\,\gamma_5\,u_n(p_n) \\
\langle p(p_p)|\,\bar{u}\,\sigma_{\mu\nu}\,d\,|\,n(p_n)\rangle &= \bar{u}_p(p_p)\left[g_T(q^2)\,\sigma_{\mu\nu} + g_T^{(1)}(q^2)\,(q_\mu\gamma_\nu - q_\nu\gamma_\mu)\right. \\
&+ \left. g_T^{(2)}(q^2)\,(q_\mu P_\nu - q_\nu P_\mu) + g_T^{(3)}(q^2)\,(\gamma_\mu \not{q} \gamma_\nu - \gamma_\nu \not{q} \gamma_\mu)\right] u_n(p_n)
\end{aligned}
$$

[Weinberg'58]

Now we don't keep corrections…

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

Form factors in β decay (bSM)

Once we go beyond the SM…

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

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

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

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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?

Form factors in β decay

$C_i \sim g_i \times \varepsilon_i$

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) *[average]*

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

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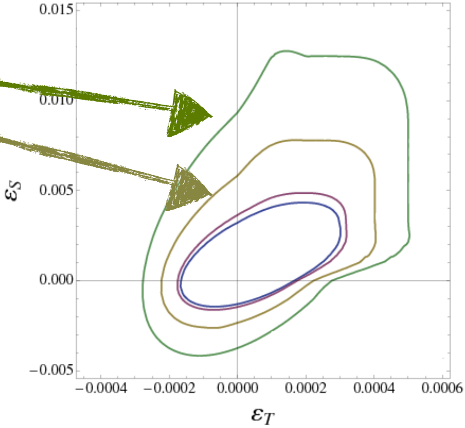
÷2.5	**20%**	**13%**
÷5.0	**10%**	**7%**



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

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$\delta g_S/g_S \sim 20\%$

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χQCD *2015*	$0.66(03)_{stat}$	-

"We quantify all syst. errors, including for the 1st time a simultaneous extrapolation in a, V & m_q"

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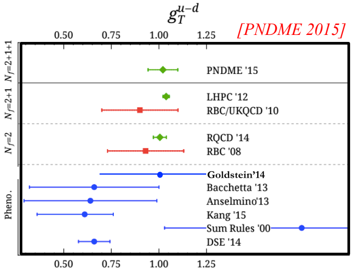
Pheno determinations

$$\langle p \mid \bar{u}\sigma_{\mu\nu} d \mid n\rangle = \langle p \mid \bar{u}\sigma_{\mu\nu} u - \bar{d}\sigma_{\mu\nu} d \mid p\rangle$$

Nucleon structure!

$$g_T = \int \left(h_1^u(x) - h_1^d(x)\right) dx$$

Transversity PDF



[PNDME 2015]

Very active field, with more data in the near future, which will improve these g_T determinations.

[Gao et al., 2011]
[Goldstein et al, 2014]
[Courtoy et al, 2015]

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

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

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

Well known, used in many other processes, e.g. EDMs or K→πeν…

$$f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_\pi^2} f_-(t)$$

[e.g. Anselm et al'1985, Ellis et al'2008, Engel et al'2013, …]

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Isospin splitting in the nucleon

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

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

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

[A. Walker-Loud's talk]

Useful connection between two different Lattice efforts!

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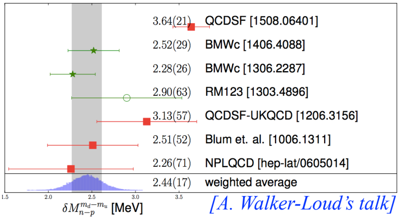
CVC	0.97(10)	

Much more precise!
Why don't we calculate the ratio directly in the lattice?

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

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

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



[A. Walker-Loud's talk]

$m_d - m_u = 2.52(19)$ MeV *[FLAG'2015]*

Form factors in β decay

$C_i \sim g_i \times \epsilon_i$

How well do we know g_S and g_T?

Is this precision OK?
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CVC	0.97(10)	-

$\delta g_S/g_S \sim 20\%$ ✔

$\delta g_T/g_T \sim 10\%$ ✔

Resuscitating the pseudoscalar interaction

Likewise...

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

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

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!

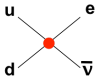
But… the bounds on ε_P from pion decays are much stronger!!!

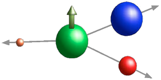
$$R_\pi \equiv \frac{\Gamma(\pi\to e\nu)}{\Gamma(\pi\to\mu\nu)} \approx R_\pi^{SM}\left(1 - \frac{B_0}{m_e}\varepsilon_P\right)$$

Form factors needed for β decay)

New physics searches in β decay

Neutron β decay bSM





$$\tilde{g}_A \approx g_A(1 - 2\epsilon_R)$$

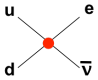
$$g_A = \langle p|\bar{u}\gamma_\mu\gamma_5 d|n\rangle$$

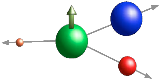
After hadronization and at order ε …

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

$$+ g_S\ \epsilon_S\ \bar{e}_R\nu_L\cdot\bar{p}n + 2g_T\ \epsilon_T\ \bar{e}_R\sigma_{\mu\nu}\nu_L\cdot\bar{p}\sigma^{\mu\nu}n_L\Big]$$

Neutron β decay bSM





Lifetime shift ➔ CKM unitarity

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

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

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

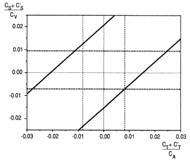
S and T affect the angular distributions and the spectrum!!

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

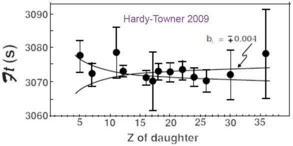
$$b \approx 0.3\, g_S\, \epsilon_S - 5.0\, g_T\, \epsilon_T$$
$$b_\nu - b \approx 0.1\, g_S\, \epsilon_S - 0.3\, g_T\, \epsilon_T$$

Current limits on S & T from low-E:

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



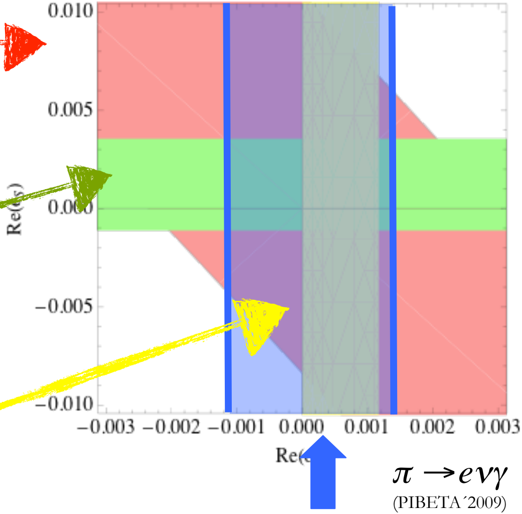
Superallowed nuclear β decays (b_{0+})



Global fit of nuclear & neutron β decay data.

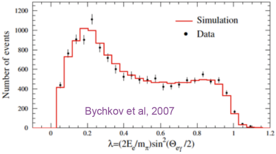
[Wauters, Garcia & Hong, 2013]

[Pattie, Hickerson & Young, 2013]



$\pi \to e \nu \gamma$

(PIBETA´2009)



$$\langle \gamma(\epsilon, p) | \bar{u} \sigma_{\mu\nu} \gamma_5 d | \pi^+ \rangle = -\frac{e}{2} f_T (p_\mu \epsilon_\nu - p_\nu \epsilon_\mu),$$

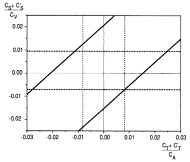
$f_T = 0.24(4)$ *[Mateu & Portolés, 2007]*

[large-N inspired resonance saturation model]

No LQCD calculation!

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

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



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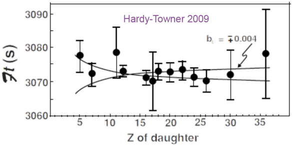

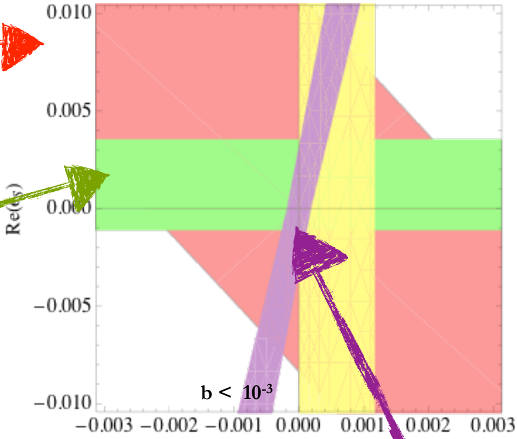

Global fit of nuclear & neutron β decay data.

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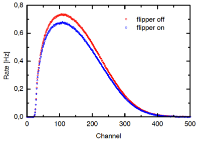
[Pattie, Hickerson & Young, 2013]

Future neutron decay exp.



$b \approx 0.3\, g_S\, \epsilon_S - 5.0\, g_T\, \epsilon_T$

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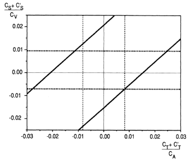
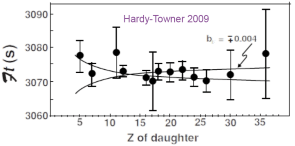
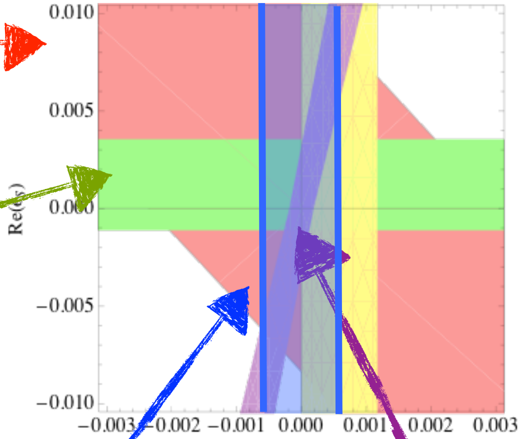


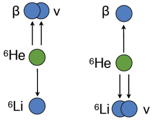
Superallowed nuclear β decays (b_{0+})



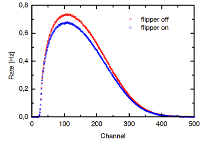


Global fit of nuclear & neutron β decay data.
[Wauters, Garcia & Hong, 2013]
[Pattie, Hickerson & Young, 2013]

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



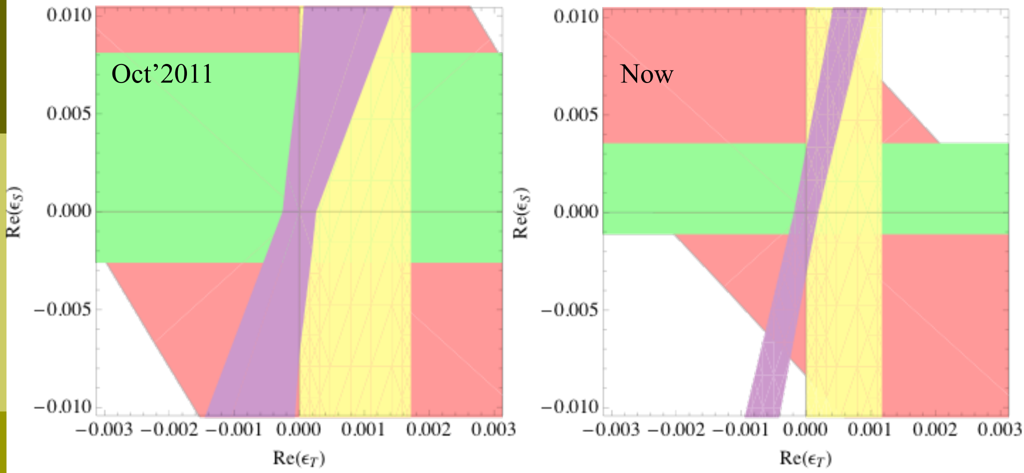
Future neutron decay exp.



$b \approx 0.3\ g_S\ \epsilon_S - 5.0\ g_T\ \epsilon_T$

PS: Rfit method used
[Bhattacharya et al, 2011]
[Gardner & Plaster, 2013]

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



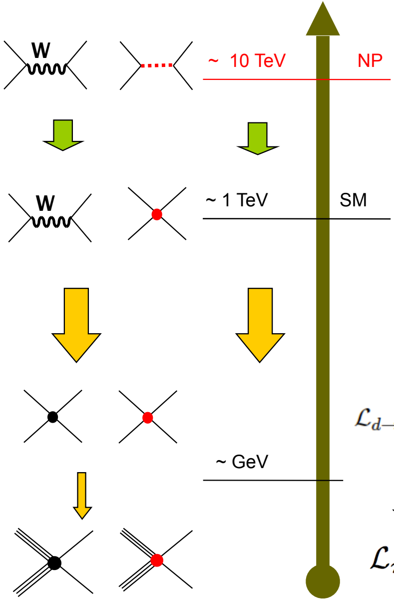
- We are benefiting here from the advance in the FF determinations!
- Conclusion: S,T are at least ~1000x weaker than the V-A Fermi interaction.

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

Outline

- Introduction and motivation; ✓
- New Physics searches in beta decays: ✓
  - New form factors;
  - Phenomenology;
- LHC searches;

The high-energy Effective Lagrangian



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

59 op. [Buchmüller-Wyler'1986, Leung et al.'1986]

535 @ D=8 [Lehman & Martin, 1510.00372]

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

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

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

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

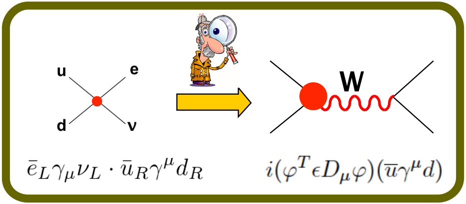
$$\mathcal{L}_{\pi, N, \ldots} = \ldots$$

The high-energy Effective Lagrangian

What are the consequences of assuming the (d → u e ν) low-E Lagrangian comes from the EW Effective Lagrangian (SMEFT)?

- ϵ_R is lepton independent:

  → Irrelevant for β decays, but not for e.g. π/K/hyperon decays, μ capture…



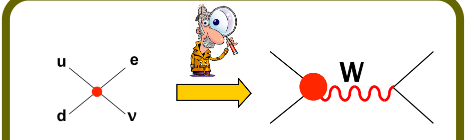
  → Very different in b → s e^+e^-, where some structures are forbidden! *[Martin Camalich's talk, Alonso, Grinstein & Martin Camalich'2014]*

  → Not true in the non-linear EFT! *[Cata & Jung'2015]*

The high-energy Effective Lagrangian

What are the consequences of assuming the (d → u e ν) low-E Lagrangian comes from the EW Effective Lagrangian (SMEFT)?

- ε_R is lepton independent;



$\bar{e}_L \gamma_\mu \nu_L \cdot \bar{u}_R \gamma^\mu d_R$ $\qquad$ $i(\varphi^T \epsilon D_\mu \varphi)(\bar{u}\gamma^\mu d)$

- If $U(3)^5$ is an approx. flavor sym (MFV), only ε_L is non-zero;

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 - 1 = (0.1 \pm 0.6)\cdot 10^{-3} \;=\; \mathbf{2\,\varepsilon_L} \;=\; 4\left(-\bar{\alpha}^{(3)}_{\varphi l} + \bar{\alpha}^{(3)}_{\varphi q} - \bar{\alpha}^{(3)}_{lq} + \bar{\alpha}^{(3)}_{ll}\right)$$

$\Lambda_{NP} > 11$ TeV

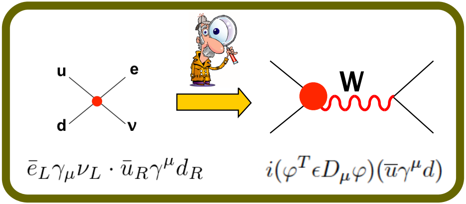
Better than LEP & LHC bounds!

[Cirigliano, MGA, Jenkins'2010]

[Cirigliano, MGA, Graesser'2012]

The high-energy Effective Lagrangian

What are the consequences of assuming the (d → u e ν) low-E Lagrangian comes from the EW Effective Lagrangian (SMEFT)?



- ε_R is lepton independent;
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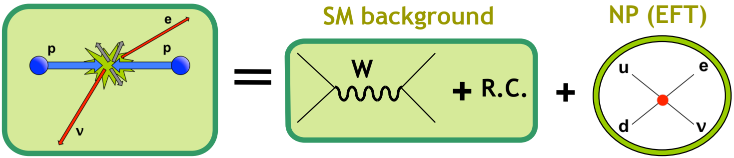
$\Lambda_{NP} > 11$ TeV

Better than LEP & LHC bounds!
[Cirigliano, MGA, Jenkins'2010]
[Cirigliano, MGA, Graesser'2012]

- It relates beta decays with a plethora of other experiments:
  - LEP physics;
  - LHC physics;
    - p p → e MET (+X)
    - p p → e⁺ e⁻ (+X)
    - Higgs decays
    - …

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



★ To suppress the bkg, we look for ***(e+ν)***-events with high m_T:

[Bhattacharya et al'2012, Cirigliano, MGA, Graesser'2012]

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

(Interference w/ SM ~ m/E)

Reminder: EFT counting…

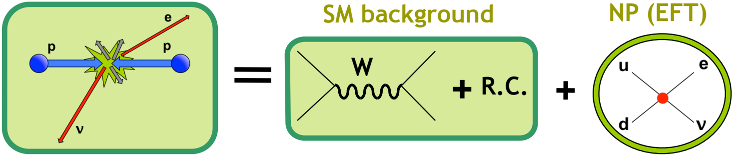
$$A \sim A_{SM}\left(1 + \alpha_6 \frac{v^2}{\Lambda^2} + \alpha_8 \frac{v^4}{\Lambda^4} + \ldots\right)$$
$$O \sim O_{SM}\left(1 + \alpha_6 \frac{v^2}{\Lambda^2} + \left(\alpha_6^2 + \alpha_8\right)\frac{v^4}{\Lambda^4} + \ldots\right)$$

Comments:

- **Same story for CPV contributions to CPC ops;**
- **Not same for EDMs!**

[V. Cirigliano's talk]

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



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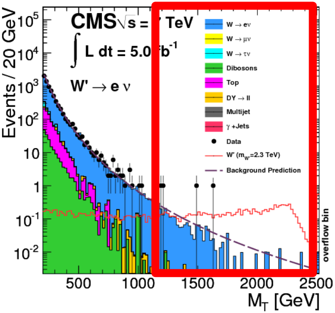

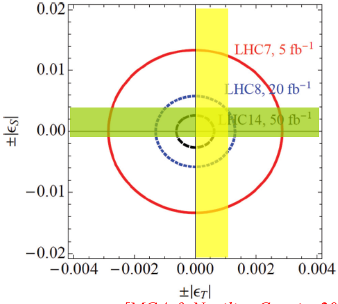

[MGA & Naviliat-Cuncic, 2013]

What about SL hyperon decays? $(s \to u\, e\, \nu)$

[Chang, MGA & Martin Camalich, Phys. Rev. Lett. 114 (2015)]

What about SL hyperon decays? ($s \to u\, e\, \nu$)

Differences with neutron decay

- Completely different exp. facility;
- BR are tiny (hadronic modes open);
- (Mainly) data from 70s-80s;
- $SU(2) \to SU(3)$
  $\delta = \Delta M/M \sim 0.001 \to$ 10-20%
- Muon channel open!
- 12 different channels (with diff. NP dependencies)
- New FFs (even in the SU(3) limit);
- S,P,T term $\sim m_\ell / q \;\to$ Tiny effects in the e-modes (useful for SM)

Theory at NLO is also OK here!
Error ~ NNLO ~ δ^2 ~ 1-5%

$\delta BR/BR$

	e	μ
$\Lambda \to p\, \ell\, \nu$	2 %	20 %
$\Sigma^- \to n\, \ell\, \nu$	3 %	10 %
$\Xi^0 \to \Sigma^+\, \ell\, \nu$	4 %	15 %
$\Xi^- \to \Lambda\, \ell\, \nu$	6 %	100 %
…		

NOTE:
Let's forget for now about kaons...

What about SL hyperon decays? (s → u e ν)

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2\, \mu^- \,\bar{\nu}_\mu)}{\Gamma(B_1 \to B_2\, e^- \,\bar{\nu}_e)}$$

Illustrative & very simple observable:

$$R^{\mu e}_{\rm SM} = \sqrt{1-\frac{m_\mu^2}{\Delta^2}}\left(1-\frac{9}{2}\frac{m_\mu^2}{\Delta^2}-4\frac{m_\mu^4}{\Delta^4}\right)+\frac{15}{2}\frac{m_\mu^4}{\Delta^4}\,{\rm arctanh}\left(\sqrt{1-\frac{m_\mu^2}{\Delta^2}}\right)$$

No FFs! (at NLO)

$$R^{\mu e}_{\rm NP} \simeq \frac{\left(\epsilon_S \frac{f_S(0)}{f_1(0)} + 12\,\epsilon_T\, \frac{g_1(0)}{f_1(0)}\frac{f_T(0)}{f_1(0)}\right)}{\left(1-\frac{3}{2}\delta\right)\left(1+3\frac{g_1(0)^2}{f_1(0)^2}\right)}\,\Pi(\Delta, m_\mu)$$

Scalar charges: CVC!

Tensor charges?

In the SU(3) limit you only need two:

- g_T ($n \to p$)
- One more! Only model calculations available (Ledwig et al'2010), LQCD desirable!

[Chang, MGA & Martin Camalich, PRL114 (2015)]

What about SL hyperon decays? ($s \to u\, e\, \nu$)

$$R^{\mu e} = \frac{\Gamma(B_1 \to B_2\, \mu^-\, \bar{\nu}_\mu)}{\Gamma(B_1 \to B_2\, e^-\, \bar{\nu}_e)}$$

Illustrative & very simple observable:

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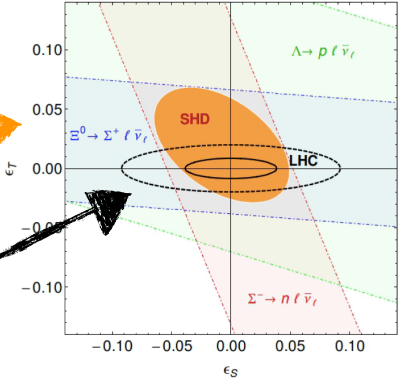
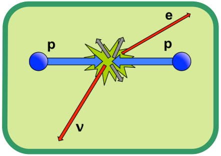
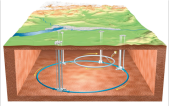
Old data sensitive to TeV physics!

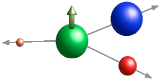




[Chang, MGA & Martin Camalich, PRL114 (2015)]

Conclusions





- β decay are sensitive to TeV physics!

  Intense activity exp/th;

- Complementary to collider searches;

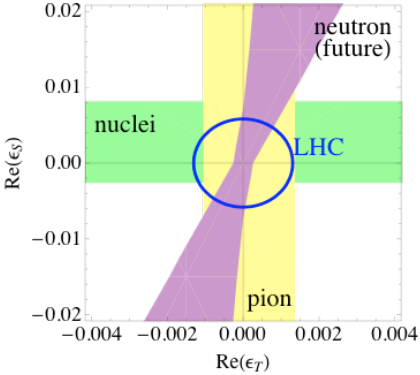
  This interplay becomes much more interesting if we see a NP signal!

- My wish-list for LQCD:

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

$$\langle B_2(p_2)|\bar{u}\sigma_{\mu\nu}s|B_1(p_1)\rangle \simeq \mathbf{g_T(0)}\ \bar{u}_2(p_2)\sigma_{\mu\nu}u_1(p_1).$$

$$\langle\gamma(\epsilon,p)|\bar{u}\sigma_{\mu\nu}\gamma_5 d|\pi^+\rangle = -\frac{e}{2}f_T(p_\mu\epsilon_\nu - p_\nu\epsilon_\mu),$$



Backup slides

Eff. Lagrangians

$$
\begin{aligned}
\mathcal{L}_{\rm CC} = -\frac{G_F^{(0)} V_{ud}}{\sqrt{2}} \Big[\Big(\delta_{e\ell} + \epsilon_L\Big) \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+\tilde{\epsilon}_L \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d \\
+\epsilon_R \bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d + \tilde{\epsilon}_R \bar{e}\gamma_\mu(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d \\
+\epsilon_S \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}d + \tilde{\epsilon}_S \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}d \\
-\epsilon_P \bar{e}(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d - \tilde{\epsilon}_P \bar{e}(1+\gamma_5)\nu_\ell \cdot \bar{u}\gamma_5 d \\
+\epsilon_T \bar{e}\sigma_{\mu\nu}(1-\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1-\gamma_5)d + \tilde{\epsilon}_T \bar{e}\sigma_{\mu\nu}(1+\gamma_5)\nu_\ell \cdot \bar{u}\sigma^{\mu\nu}(1+\gamma_5)d \Big]
\end{aligned}
$$

Low-E searches of NP in d → u e ν

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

$$\epsilon_L = \epsilon_L^{(v)} + \epsilon_L^{(c)} \qquad \tilde{\epsilon}_L = -\hat{\alpha}'^{*}_{\varphi\varphi}$$

$$\epsilon_L^{(v)} = 2\hat{\alpha}^{(3)}_{\varphi l} + 2\frac{[V\,(\hat{\alpha}^{(3)}_{\varphi q})^{\dagger}]_{11}}{V_{ud}} + 4\hat{\alpha}^{(3)}_{\varphi l}\,\delta_{el}\,\frac{[V\,(\hat{\alpha}^{(3)}_{\varphi q})^{\dagger}]_{11}}{V_{ud}}$$

$$\epsilon_L^{(c)} = -2\frac{[V\,\hat{\alpha}^{(3)}_{lq}]_{11}}{V_{ud}}$$

$$\epsilon_R = -\delta_{el}\frac{[\hat{\alpha}_{\varphi\varphi}]_{11}}{V_{ud}} \qquad \tilde{\epsilon}_R = -\frac{[\hat{\alpha}_{e\nu ud}]_{11}}{V_{ud}}$$

$$\epsilon_S - \epsilon_P = -2\frac{[V\,\hat{\alpha}^{\dagger}_{qde}]_{11}}{V_{ud}} \qquad \tilde{\epsilon}_S - \tilde{\epsilon}_P = 2\frac{[V\,\hat{\alpha}'_{lq}]_{11}}{V_{ud}}$$

$$\epsilon_S + \epsilon_P = -2\frac{[\hat{\alpha}^{\dagger}_{lq}]_{11}}{V_{ud}} \qquad \tilde{\epsilon}_S + \tilde{\epsilon}_P = -2\frac{[\hat{\alpha}_{qu\nu}]_{11}}{V_{ud}}$$

$$\epsilon_T = -\frac{[\hat{\alpha}^{t\,\dagger}_{lq}]_{11}}{V_{ud}} \qquad \tilde{\epsilon}_T = \frac{[V\,\hat{\alpha}^{t\,\prime}_{lq}]_{11}}{V_{ud}}\,.$$

Vertex corrections:

$$O_{\varphi\varphi} = i(\varphi^T \epsilon D_\mu \varphi)(\overline{u}\gamma^\mu d) + \text{h.c.}$$
$$O^{(3)}_{\varphi q} = i(\varphi^\dagger D^\mu \sigma^a \varphi)(\overline{q}\gamma_\mu \sigma^a q) + \text{h.c.}$$
$$O^{(3)}_{\varphi l} = i(\varphi^\dagger D^\mu \sigma^a \varphi)(\overline{l}\gamma_\mu \sigma^a l) + \text{h.c.}$$
$$O'_{\varphi\varphi} = i(\varphi^T \epsilon D_\mu \varphi)(\overline{\nu}\gamma^\mu e) + \text{h.c.}$$

Four-fermion operators:

$$O^{(3)}_{lq} = (\bar{l}\gamma^\mu \sigma^a l)(\bar{q}\gamma_\mu \sigma^a q) \qquad O_{e\nu ud} = (\overline{e}\gamma^\mu \nu)(\overline{u}\gamma_\mu d) + \text{h.c.}$$
$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.} \qquad O_{qu\nu} = (\bar{l}\nu)(\overline{u}q) + \text{h.c.}$$
$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.} \qquad O'_{lq} = (\bar{l}_a \nu)\epsilon^{ab}(\bar{q}_b d) + \text{h.c.}$$
$$O^t_{lq} = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.} \qquad O^{t\prime}_{lq} = (\bar{l}_a \sigma^{\mu\nu} \nu)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} d) + \text{h.c.}$$

Illustrative example:

RM123 Coll.

PHYSICAL REVIEW D 87, 114505 (2013)

Leading isospin breaking effects on the lattice

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(RM123 Collaboration)

$$g_S = \frac{\left(M_n - M_p\right)_{QCD}}{m_d - m_u} = 1.21(17)$$

The main results of the paper are

$$M^2_{\pi^+} - M^2_{\pi^0} = 1.44(13)(16) \times 10^3\ \text{MeV}^2,$$

$$[M^2_{K^+} - M^2_{K^0}]^{\text{QED}} = 2.26(23)(23) \times 10^3\ \text{MeV}^2,$$

$$[M^2_{K^+} - M^2_{K^0}]^{\text{QCD}} = -6.16(23)(23) \times 10^3\ \text{MeV}^2,$$

$$\varepsilon_\gamma = \frac{[M^2_{K^+} - M^2_{K^0}]^{\text{QED}} - [M^2_{\pi^+} - M^2_{\pi^0}]^{\text{QED}}}{M^2_{\pi^+} - M^2_{\pi^0}} = 0.79(18)(18),$$

$$[\hat{m}_d - \hat{m}_u](\overline{\text{MS}}, 2\ \text{GeV}) = 2.39(8)(17)\ \text{MeV},$$

$$\frac{\hat{m}_u}{\hat{m}_d}(\overline{\text{MS}}, 2\ \text{GeV}) = 0.50(2)(3),$$

$$\hat{m}_u(\overline{\text{MS}}, 2\ \text{GeV}) = 2.40(15)(17)\ \text{MeV},$$

$$\hat{m}_d(\overline{\text{MS}}, 2\ \text{GeV}) = 4.80(15)(17)\ \text{MeV},$$

$$R(\overline{\text{MS}}, 2\ \text{GeV}) = \left[\frac{\hat{m}_s - \hat{m}_{ud}}{\hat{m}_d - \hat{m}_u}\right](\overline{\text{MS}}, 2\ \text{GeV}) = 38(2)(3),$$

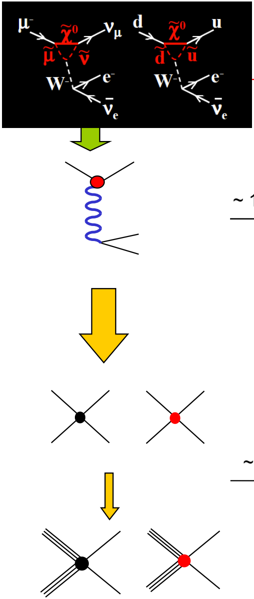
$$Q(\overline{\text{MS}}, 2\ \text{GeV}) = \left[\sqrt{\frac{\hat{m}_s^2 - \hat{m}_{ud}^2}{\hat{m}_d^2 - \hat{m}_u^2}}\right](\overline{\text{MS}}, 2\ \text{GeV}) = 23(1)(1),$$

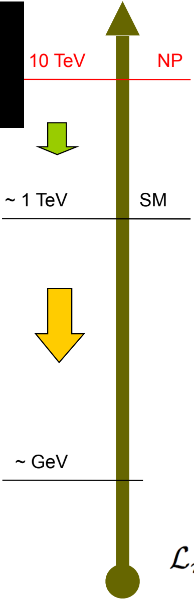
$$\left[\frac{F_{K^+}/F_{\pi^+}}{F_K/F_\pi} - 1\right]^{\text{QCD}} = -0.0040(3)(2),$$

$$[M_n - M_p]^{\text{QCD}} = 2.9(6)(2)\ \text{MeV},$$

This should be done by the collaboration (correlations!)

The high-energy Effective Lagrangian





MSSM

$$\alpha_i = f\,(g_i, m_i)$$

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

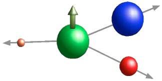
$$O_{\varphi q}^{(3)} = i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{q}\gamma_\mu \sigma^a q) + \text{h.c.}$$

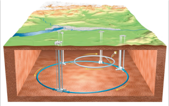
$$\epsilon_L \;\; \bar{e}_L \gamma_\mu \nu_L \cdot \bar{u}_L \gamma_\mu d_L$$

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

(Kurylov & Ramsey-Musolf, PRL88, 2002)

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

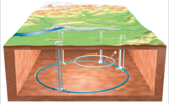
	$\lvert\tilde{\epsilon}_L\rvert$	$\lvert\tilde{\epsilon}_R\rvert$	$\lvert\tilde{\epsilon}_P\rvert$	$\lvert\tilde{\epsilon}_S\rvert$	$\lvert\tilde{\epsilon}_T\rvert$	
Low-E	6	6	0.03	14	3.0	x 10^{-2}
LHC $(e\nu)$	-	0.2	0.6	0.6	0.1	x 10^{-2}

LHC dominates!

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

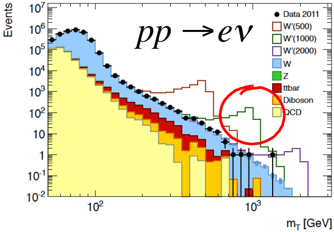
[Cirigliano, MGA & Graesser, 2013
MGA & Naviliat-Cuncic, 2013]

Scalar resonance



- What if we see a bump? EFT breaks down…
  TOY model: scalar resonance:

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



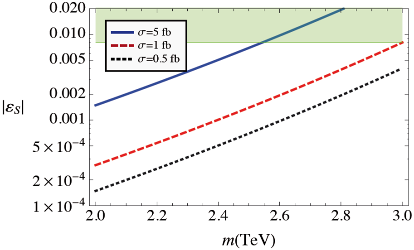
- Then we have a lower-limit value for ε_S:

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

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

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

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



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

[T. Battacharya et al., 2012]