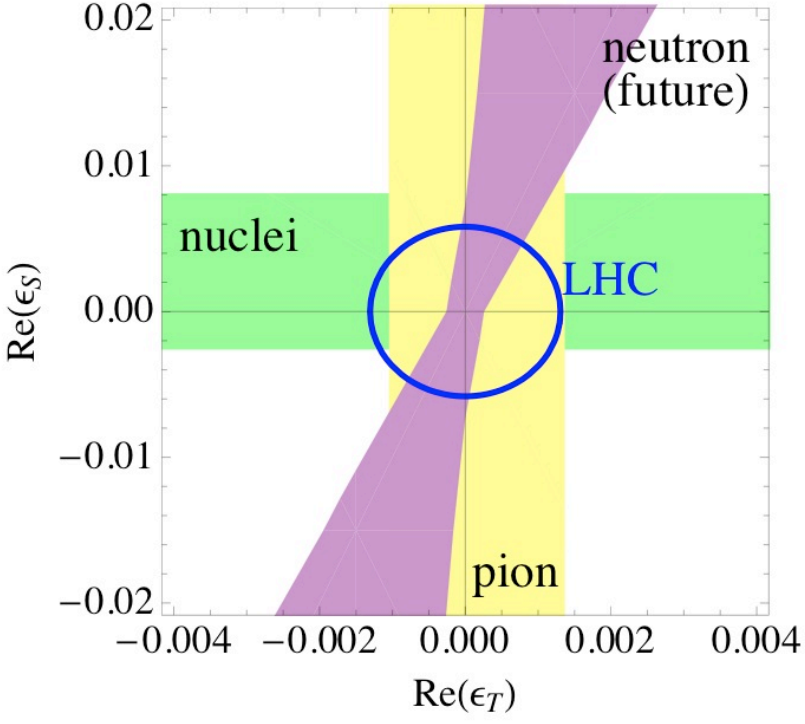
Looking for New Physics in semileptonic decays of light quarks

IFIC seminar **Sept. 5th, 2013**



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THE UNIVERSITY of WISCONSIN MADISON

INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Outline

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

[Cirigliano, MGA & Jenkins'2010]

[Bhattacharya, Cirigliano, Cohen, Filipuzzi, MGA, Graesser, Gupta, Lin'2012]

[Cirigliano, MGA & Graesser'2012]

[MGA & Naviliat-Cuncic'2013]

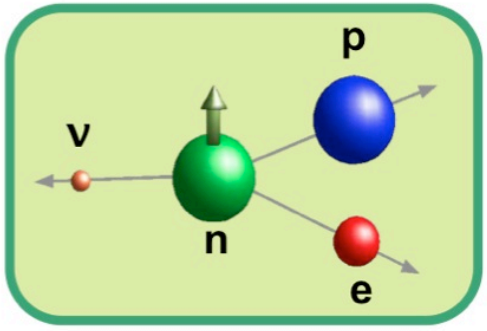
[MGA & Martin Camalich (in preparation)]

Motivation

- Very precise measurements available in nuclear/neutron beta decay (errors ~ 0.1%);
  A new generation will improve them substantially!

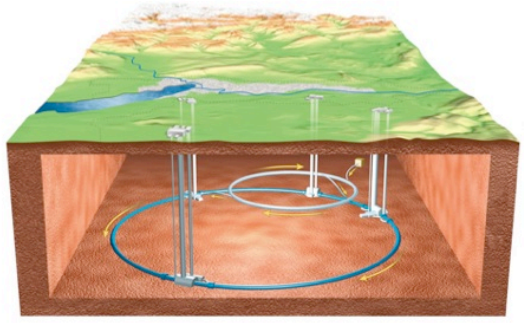
- Very precise theoretical SM-calculations (errors < 0.1%);

➔ Goal of these experiments:
extract SM parameters (V_{ij}), and/or search for New Physics!



Questions:

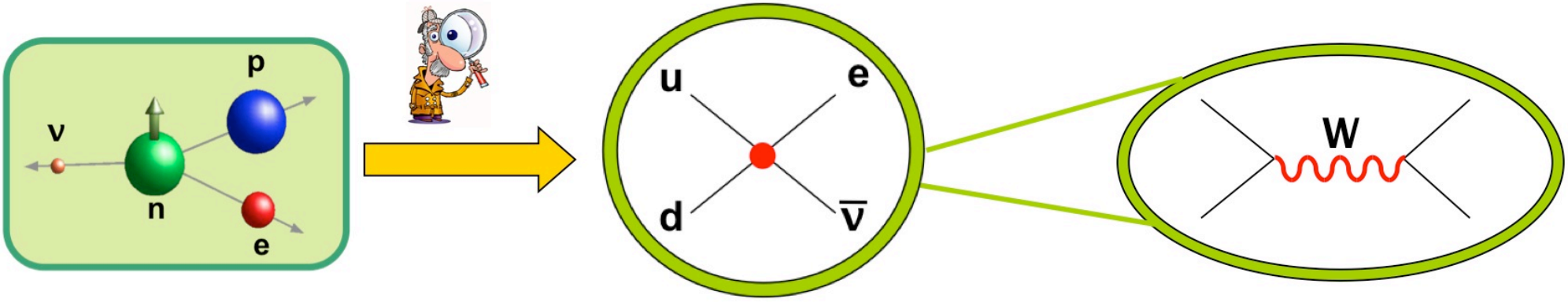
- Competitive with NP searches in pion decays?
- The LHC is here!
- General analysis beyond specific NP models:
  EFT approach!



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Motivation

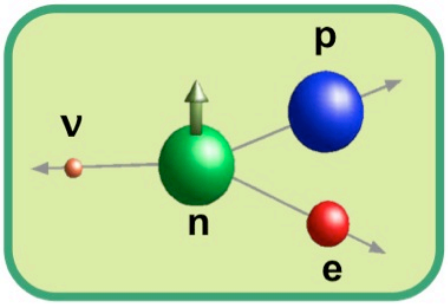
$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\ \bar{e}\gamma_\mu(1-\gamma_5)\nu\cdot\ \bar{u}\gamma_\mu(1-\gamma_5)d\ \right]$$



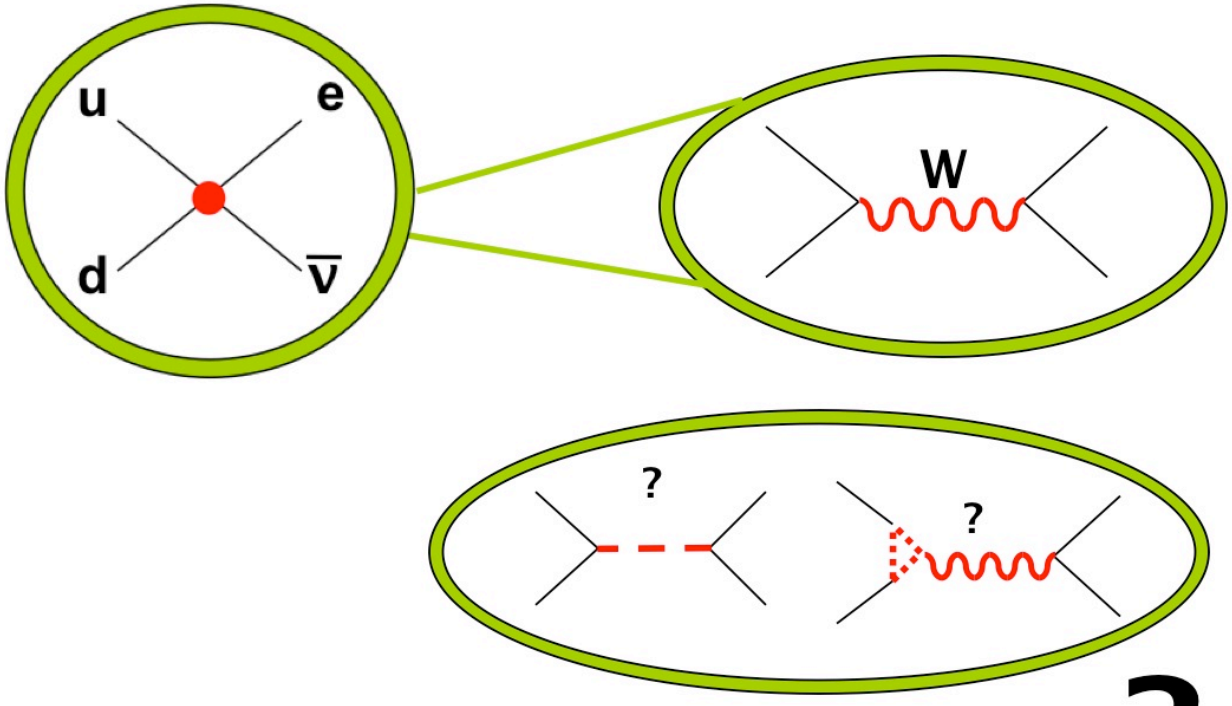
Motivation

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{e}\gamma_\mu(1-\gamma_5)\nu\cdot\ \bar{u}\gamma_\mu(1-\gamma_5)d\ +\ \sum_i \varepsilon_i\ \bar{e}\,\Gamma\nu\cdot\bar{u}\Gamma d\right]$$

Model-independent analysis





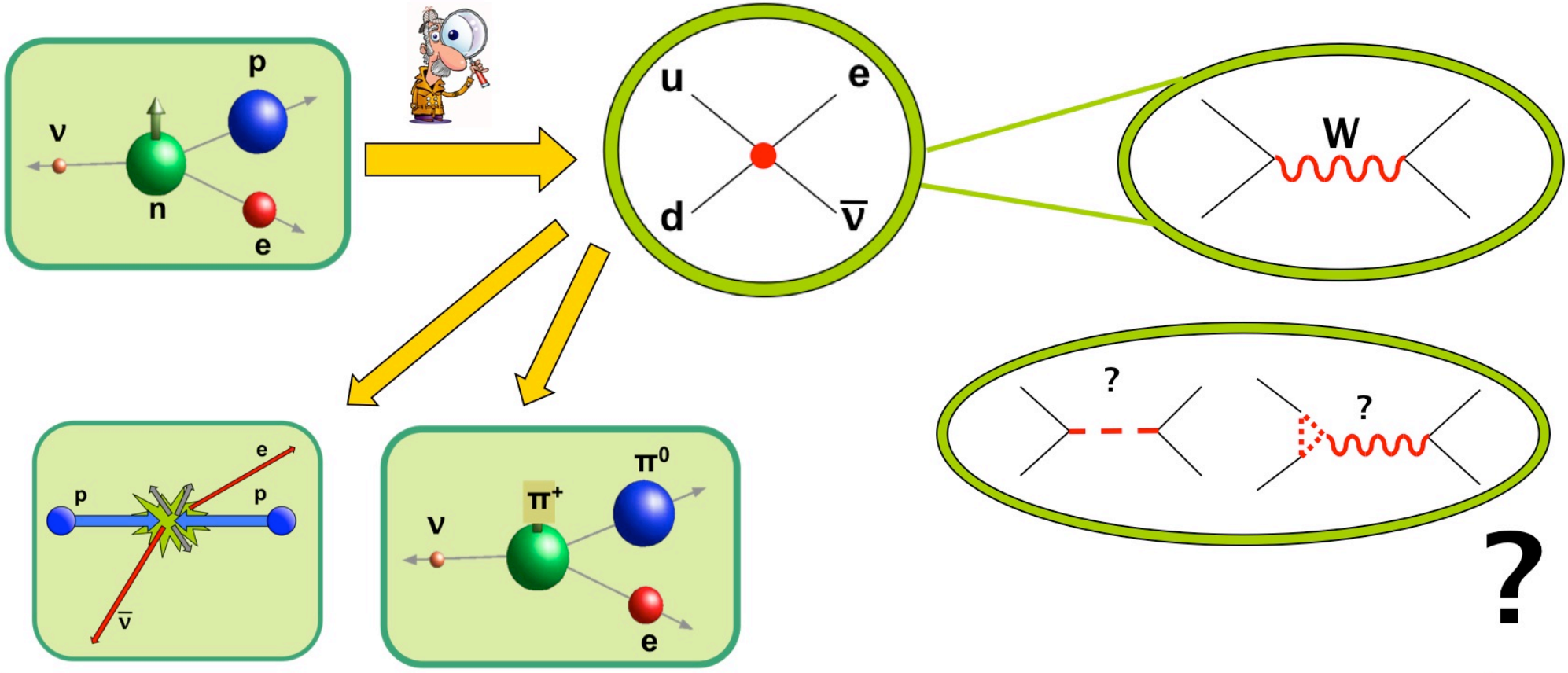


?

Motivation

$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{e}\gamma_\mu(1-\gamma_5)\nu\cdot\bar{u}\gamma_\mu(1-\gamma_5)d + \sum_i \varepsilon_i\,\bar{e}\,\Gamma\nu\cdot\bar{u}\Gamma d\right]$$

Model-independent analysis



Outline

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

[Cirigliano, MGA & Jenkins'2010]

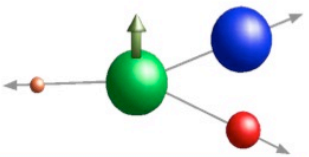
[Bhattacharya, Cirigliano, Cohen, Filipuzzi, MGA, Graesser, Gupta, Lin'2012]

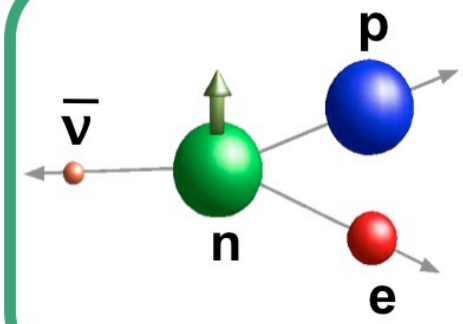
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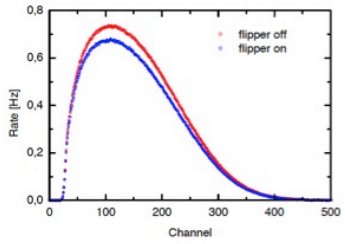
[MGA & Naviliat-Cuncic'2013]

[MGA & Martin Camalich (in preparation)]

NP searches in beta decays



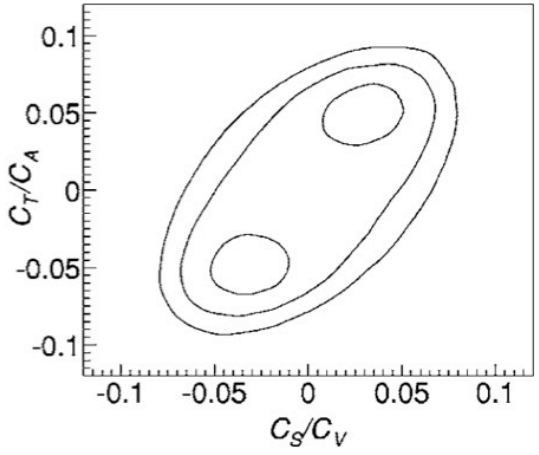




Lifetime;
Angular distributions;
Spectrum;
…

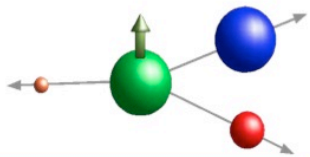
$$
\begin{aligned}
H_{V,A}^{(N)} &= \bar{e}\gamma_\mu(C_V + C'_V\gamma_5)\nu\bar{p}\gamma_\mu n \\
&\quad -\bar{e}\gamma_\mu\gamma_5(C_A + C'_A\gamma_5)\nu\bar{p}\gamma_\mu\gamma_5 n + \text{H.c.} \\
H_{S,P}^{(N)} &= \bar{e}(C_S + C'_S\gamma_5)\nu\bar{p}n + \text{H.c.} \\
H_T^{(N)} &= \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T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

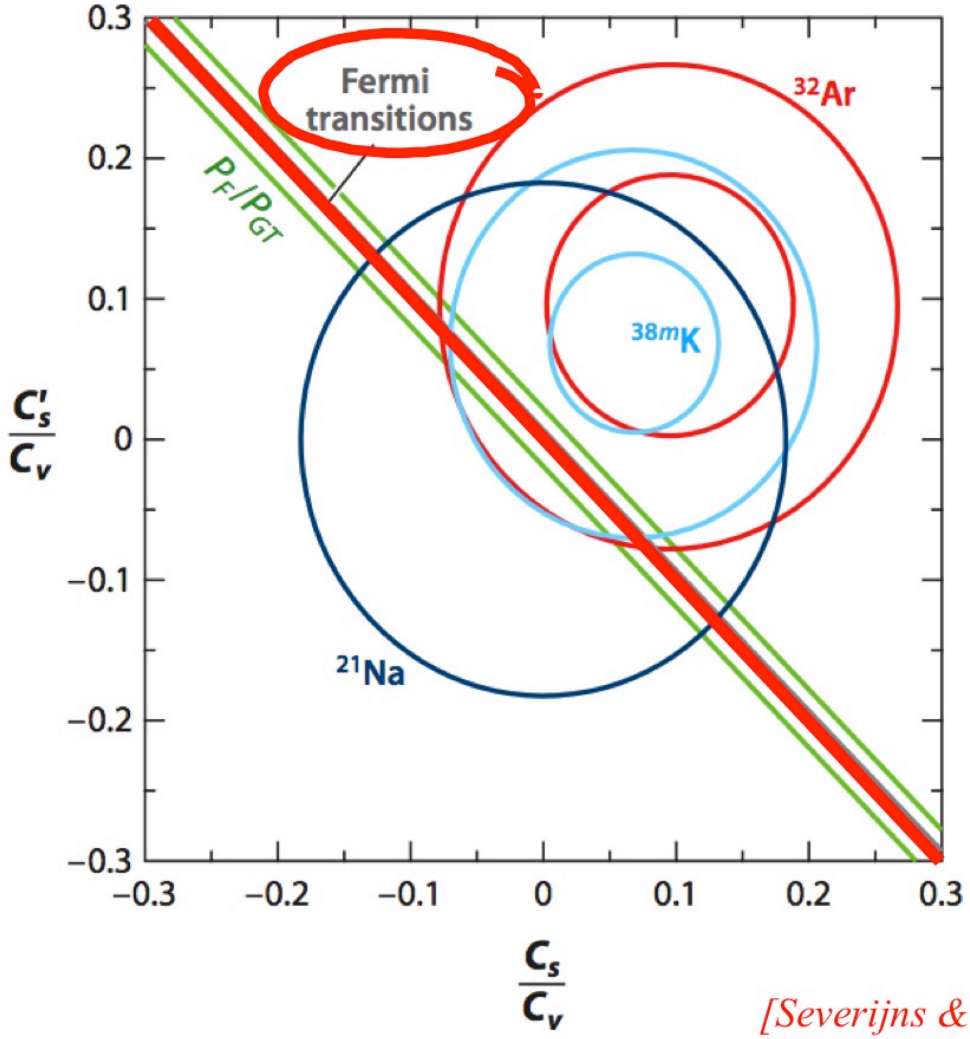
[Jackson, Treiman & Wyld'1957]

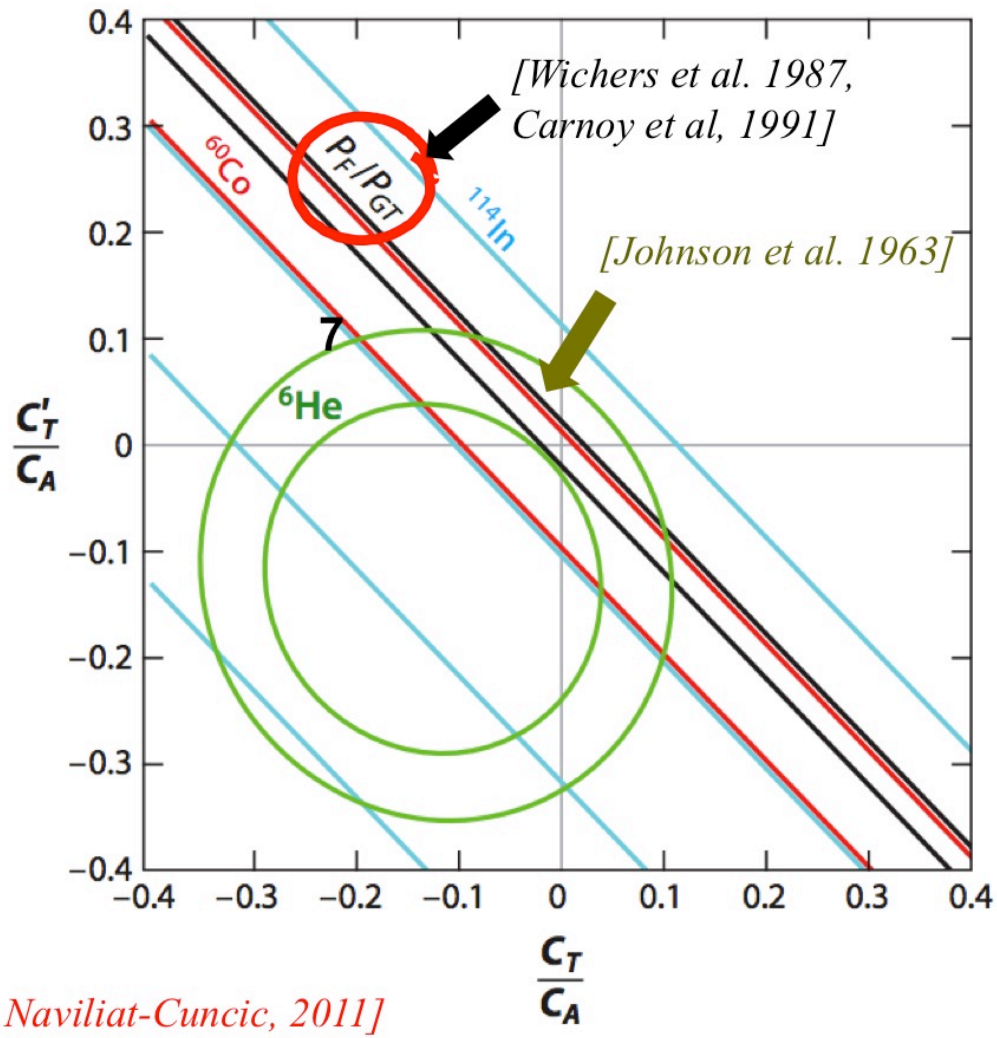


[Severijns, Beck & Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006), 991]

NP searches in beta decays

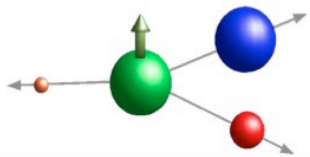






[Severijns & Naviliat-Cuncic, 2011]

NP searches in beta decays



- To allow comparison with e.g. pion decays: eff. Lagrangian at the quark level!

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

- CRUCIAL DETAIL: We need the form factors!!!!

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

Hadronic-level parameter (from experiment/th)

Hadronization (from lattice/th)

Quark-level parameter

$$G_F \sim \frac{1}{M_W^2}$$

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

Form factors needed for β decay

Form factors in β decay (SM)

Weinberg'58:

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

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

Linear expansion in the small quantities: $\frac{\alpha}{\pi}, \frac{\Delta M}{M}, \frac{q}{M} \sim 10^{-3}$

Form factors in β decay (SM)

Weinberg'58:

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

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

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

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

$g_A(0)$???

Linear expansion in the small quantities: $\frac{\alpha}{\pi}, \frac{\Delta M}{M}, \frac{q}{M} \sim 10^{-3}$

Therefore:

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

$$\delta O_{th} \sim 10^{-5} - 10^{-6}\,!!!!$$

Form factors in β decay (bSM)

Once we go beyond the SM…

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

[Weinberg'58]

Linear expansion in the small quantities: $\frac{\alpha}{\pi}, \frac{\Delta M}{M}, \frac{q}{M}, \varepsilon_i \sim 10^{-3}$

Form factors in β decay (bSM)

Once we go beyond the SM…

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

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

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

[Weinberg'58]

Linear expansion in the small quantities: $\frac{\alpha}{\pi}, \frac{\Delta M}{M}, \frac{q}{M}, \varepsilon_i \sim 10^{-3}$

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?

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Form factors in β decay

How well do we know g_S and g_T?

$$C_i \sim g_i \times \varepsilon_i$$

- Before 2011, we knew very little… **$0.25 < g_S < 1.00$** *[Adler et al.'1975]*
  $0.60 < g_T < 2.30$ *(quark model)*

- Recently, much more activity:
  - PNDME Coll. (October 2011) *(Bhattacharya, Cohen, Gupta, Joseph, Lin)* **g_S=1.05(35)** **g_T=0.80(40)** *(average)*
  - LHPC Coll. (June 2012) *(Green, Negele, Pochinsky, Syritsyn, Engelhardt, Krieg)* **g_S=1.08(32)** **g_T=1.04(02)**
  - PNDME Coll. (July 2013) **g_S=0.66(24)** **g_T=1.09(05)**

- MGA & Martin Camalich (Sept 2013): **g_S=1.04(13)** *[preliminary]*

Form factors in β decay

[MGA & Martin Camalich, Sept 2013]

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

$$g_S(q^2) = \frac{\left(\mathrm{M_n} - \mathrm{M_p}\right)_{QCD}}{m_d - m_u} g_V(q^2) + \frac{q^2/2\overline{M}}{m_d - m_u}\tilde{g}_S(q^2)$$

$$g_S = \frac{\left(\mathrm{M_n} - \mathrm{M_p}\right)_{QCD}}{m_d - m_u} g_V \to 1$$

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Form factors in β decay

[MGA & Martin Camalich, Sept 2013]

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

1

Isospin splitting in the nucleon

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

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

$$m_d \neq m_u$$

Form factors in β decay

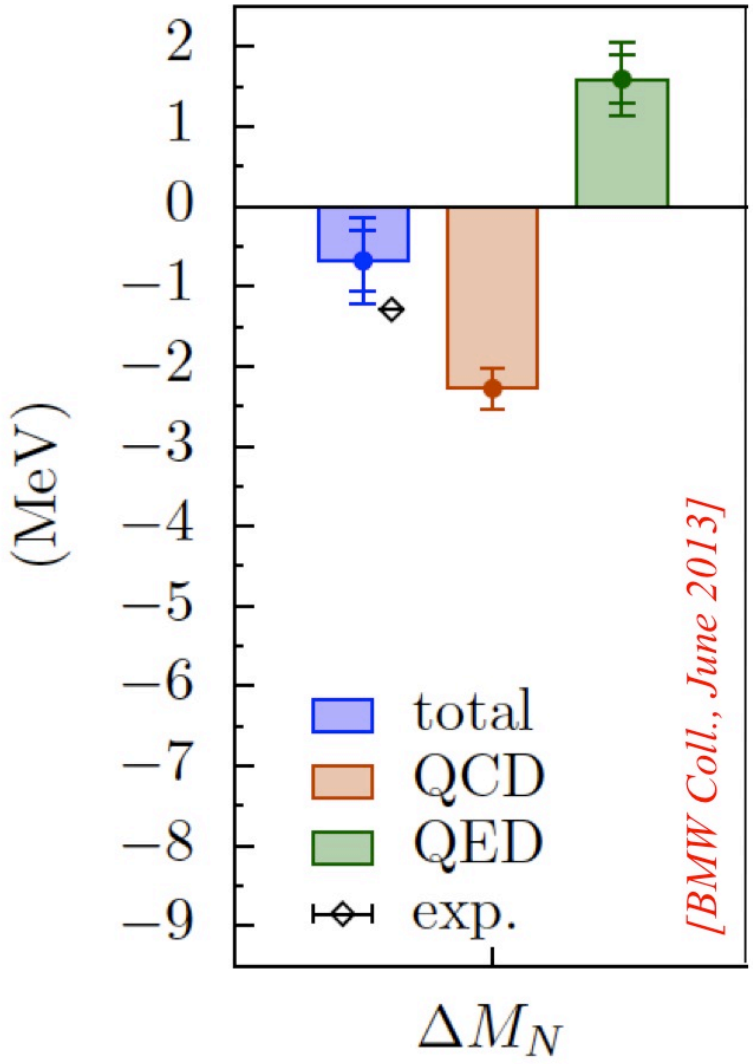
[MGA & Martin Camalich, Sept 2013]

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

Isospin splitting in the nucleon

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

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Form factors in β decay

[MGA & Martin Camalich, Sept 2013]

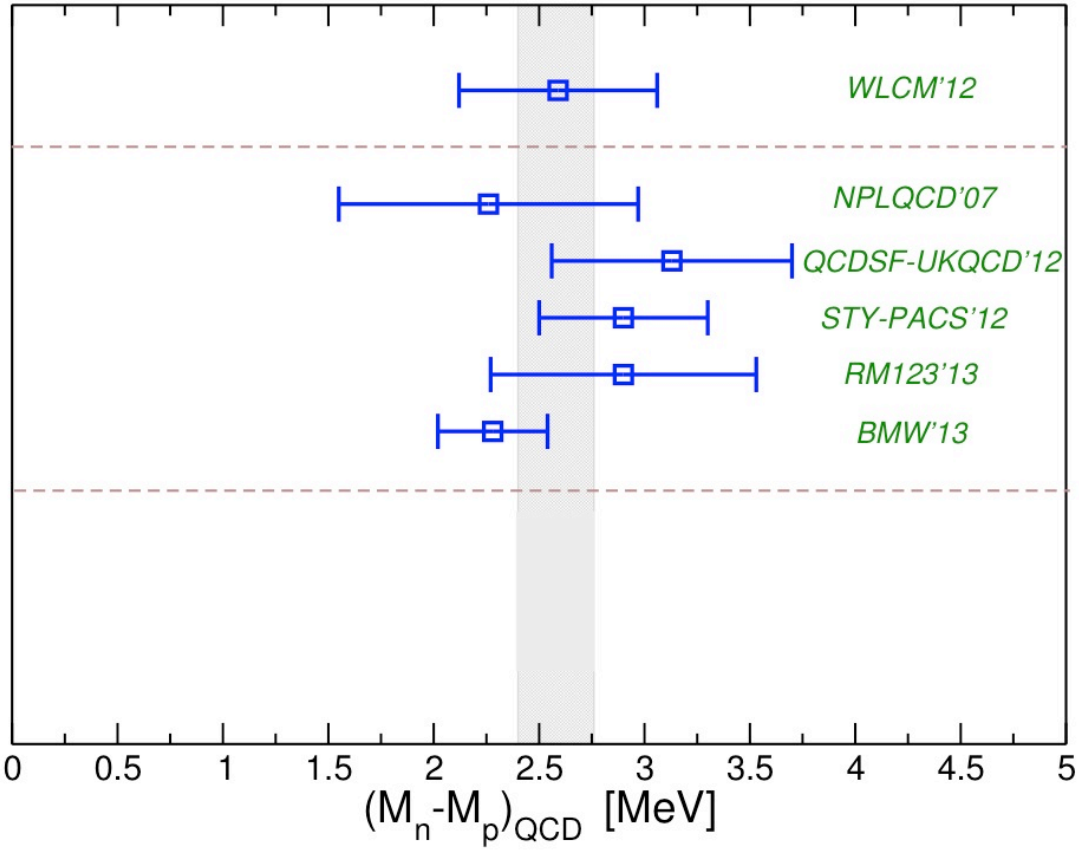
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Recent calculations!!!



Form factors in β decay

[MGA & Martin Camalich, Sept 2013]

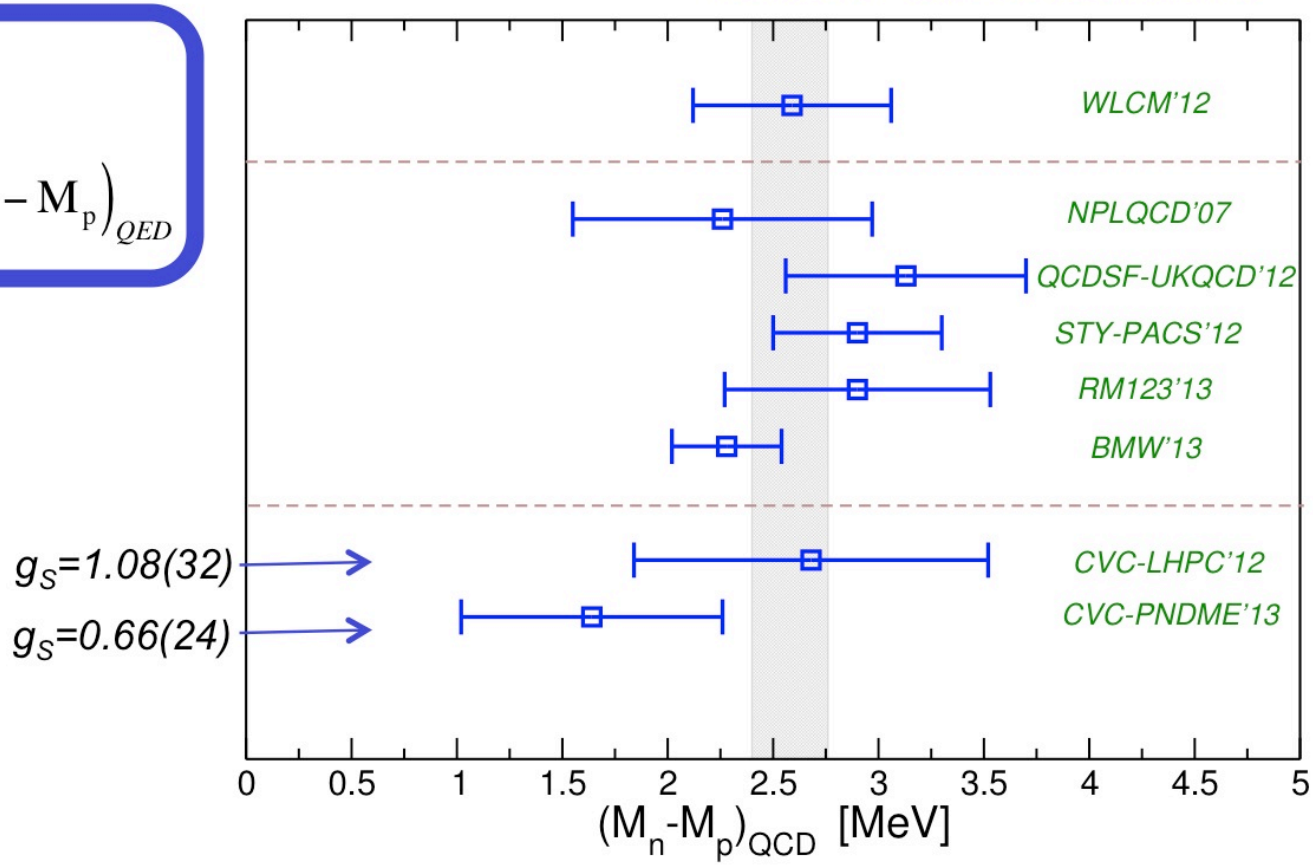
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Isospin splitting in the nucleon

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Recent calculations!!!



$$m_d - m_u = 2.48(25)\ \text{MeV}$$

[FLAG working group of FLAVIANET]

Form factors in β decay

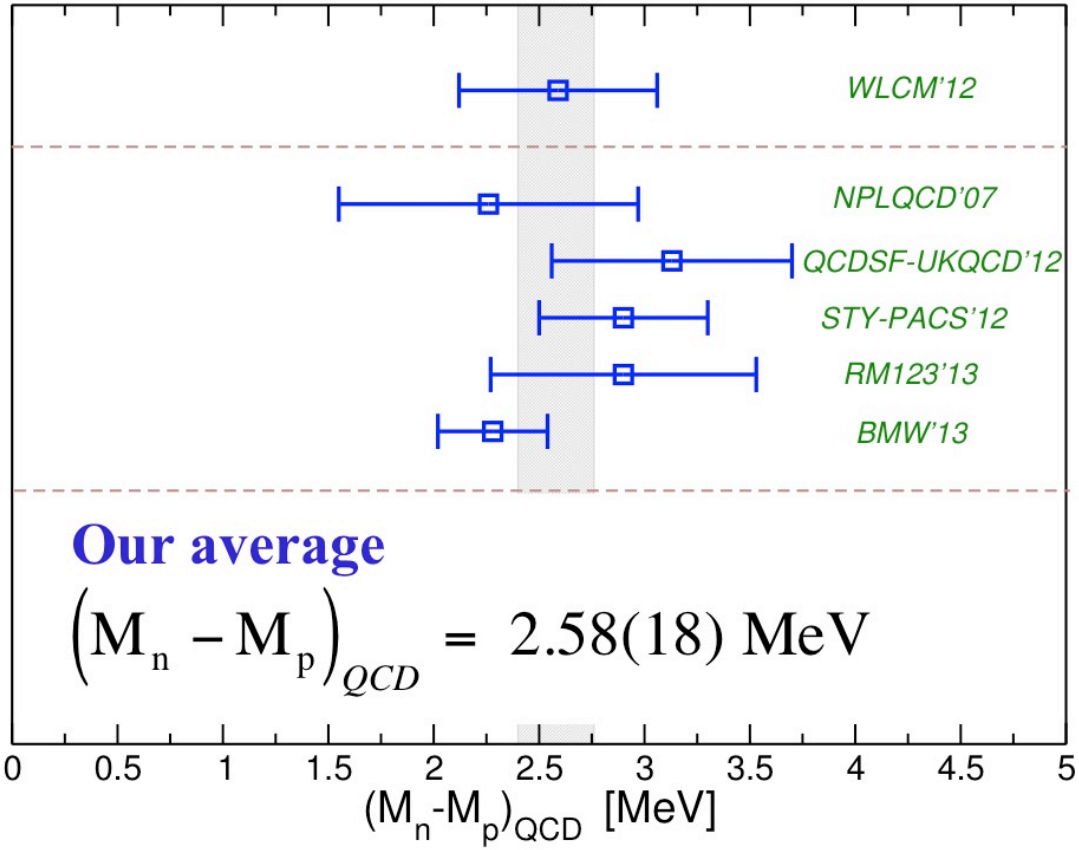
[MGA & Martin Camalich, Sept 2013]

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

Isospin splitting in the nucleon

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$$m_d - m_u = 2.48(25)\ \text{MeV}$$

[FLAG working group of FLAVIANET]

Form factors in β decay

[MGA & Martin Camalich, Sept 2013]

$$g_S = \frac{\left(M_n - M_p\right)_{QCD}}{m_d - m_u} = 1.04(10)_{\delta m_q}(7)_{\delta M_N} = 1.04(13)$$

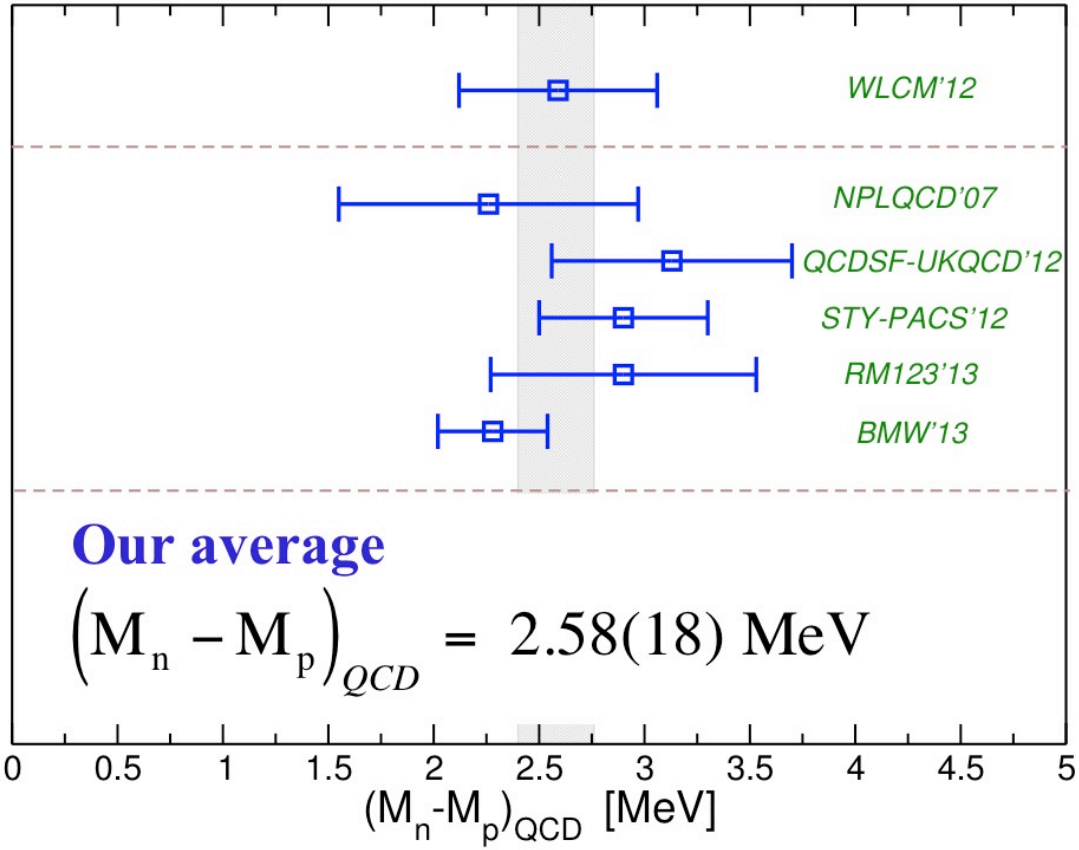
g_S=1.08(32) LHPC Coll.

g_S=0.66(24) PNDME Coll.

Isospin splitting in the nucleon

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$m_d - m_u$ = 2.48(25) MeV

[FLAG working group of FLAVIANET]

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Form factors in β decay

[MGA & Martin Camalich, Sept 2013]

$$\partial_\mu\,(\bar{u}\gamma^\mu d) = -i(m_d - m_u)\bar{u}d \quad \Rightarrow \quad g_S = \frac{\left(\mathrm{M_n} - \mathrm{M_p}\right)_{QCD}}{m_d - m_u} g_V = 1.04(13)$$

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

Form factors in β decay

[MGA & Martin Camalich, Sept 2013]

$$\partial_\mu\,(\bar{u}\gamma^\mu d) = -i(m_d - m_u)\bar{u}d \quad \Rightarrow \quad g_S = \frac{\left(\mathrm{M_n} - \mathrm{M_p}\right)_{QCD}}{m_d - m_u} g_V = 1.04(13)$$

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

- The effect of a pseudo-scalar interaction on β decays is not so negligible as traditionally thought:
  - ***NP:*** $\varepsilon_P \sim \mathrm{M_W^2}/\mathrm{M_{NP}^2} \sim 10^{-3}$
  - ***P bilinear ~ q^2/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]

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Form factors in β decay

[MGA & Martin Camalich, Sept 2013]

$$\partial_\mu\,(\bar{u}\gamma^\mu d) = -i(m_d - m_u)\bar{u}d \quad \Rightarrow \quad g_S = \frac{\left(\mathrm{M_n} - \mathrm{M_p}\right)_{QCD}}{m_d - m_u} g_V = 1.04(13)$$

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

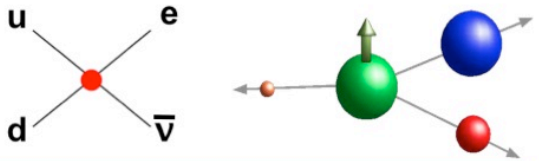
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  - ***P bilinear ~ q^2/M ~10^{-3};*** $\langle p(p_p)|\bar{u}\gamma_5 d|n(p_n)\rangle = g_P(q^2)\bar{u}_p(p_p)\gamma_5 u_n(p_n)$

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

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

New physics in β decay

Low-energy searches



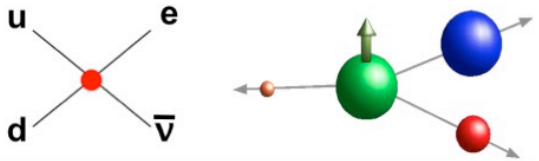
Eff. Lagrangian at the quark level

$$\mathcal{L} \sim (1+\epsilon_L)\,\underbrace{[V-A]}_{\text{Lepton current}}\,\underbrace{[V-A]}_{\text{Quark current}} + \epsilon_R(V-A)(V+A) + \tilde{\epsilon}_L(V+A)(V-A) + \tilde{\epsilon}_R(V+A)(V+A)$$
$$+ \epsilon_S - \epsilon_P(S-P)\,P + \tilde{\epsilon}_S(S+P)\,S - \tilde{\epsilon}_P(S+P)\,P$$
$$+ \epsilon_T \gamma_5) + \tilde{\epsilon}_T(T+T\gamma_5)(T-T\gamma_5)$$

- Hadronization ➔ Form factors!
- Option 1: keep all terms and do a global fit.
- Option 2: identify main sensitivities.

[Severijns, Beck & Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006), 991]
[Cirigliano, MGA & Graesser, JHEP 02 (2013), 046]

Low-energy searches



Eff. Lagrangian at the quark level

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

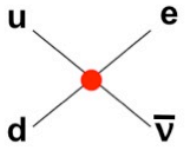
$O = O_{SM} + \varepsilon^2$

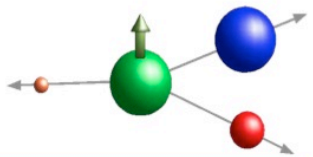
[Small effect ➔ weaker bounds]

- Hadronization ➔ Form factors!
- Option 1: keep all terms and do a global fit.
- Option 2: identify main sensitivities.

[Severijns, Beck & Naviliat-Cuncic, Rev. Mod. Phys. 78 (2006), 991]
[Cirigliano, MGA & Graesser, JHEP 02 (2013), 046]

Neutron β decay bSM



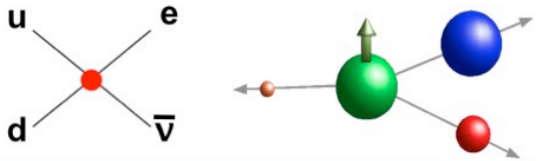


After hadronization and at order ε^2…

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

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

Neutron β decay bSM



After hadronization and at order ε^2…

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

Lifetime shift ➔
CKM unitarity

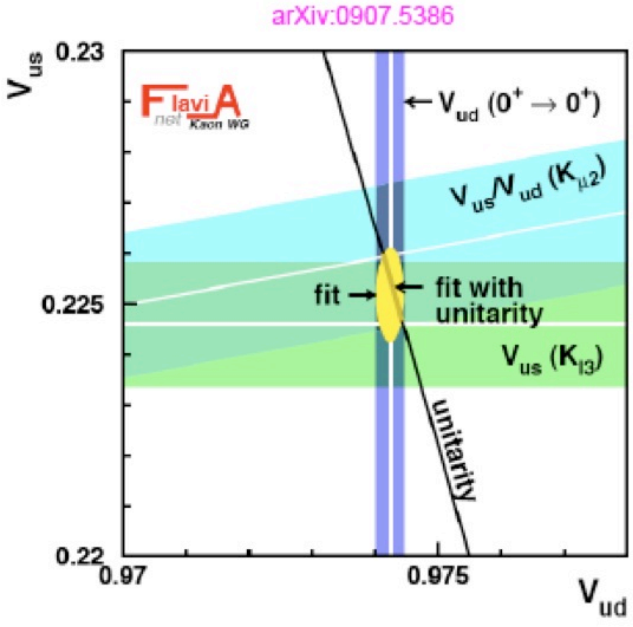
$$|V_{ud}|^2+|V_{us}|^2+|V_{ub}|^2-1=(0.1\pm0.6)\cdot10^{-3}$$

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

$$\Lambda_{NP}>11\ \text{TeV}\ (90\%\text{CL})$$

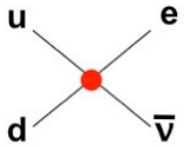
Cirigliano, MGA & Jenkins'2010:

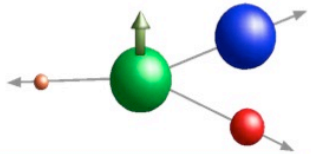
Better than colliders!



IFIC seminar

Neutron β decay bSM





After hadronization and at order ε^2…

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

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

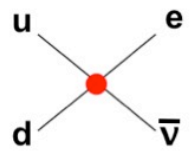
S and T affect the angular distributions and the spectrum!!

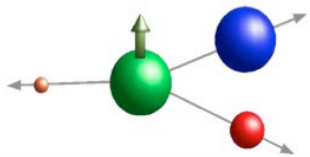
$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E)\left\{1 + a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_e E_\nu} + b\frac{m_e}{E_e} + A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J} + (B + b_B\frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$

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

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

Nuclear ~~Neutron~~ β decay bSM





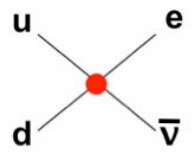
$N \to N' e^{\pm} \nu$

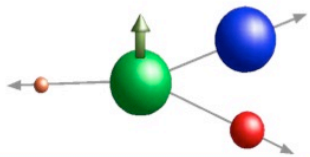
M_F M_{GT}

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

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

Nuclear ~~Neutron~~ β decay bSM





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

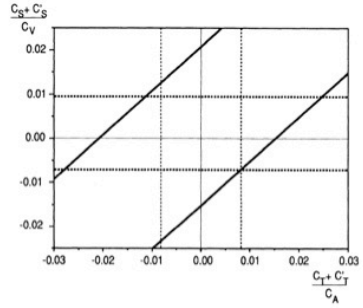
M_F M_{GT}

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

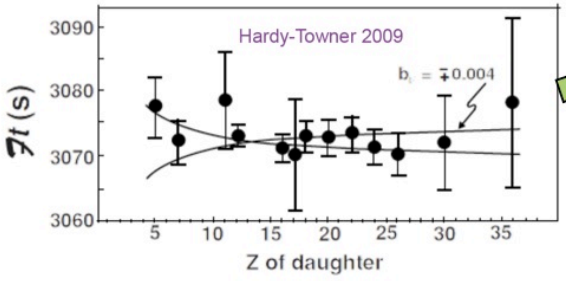
Let's see some numbers!

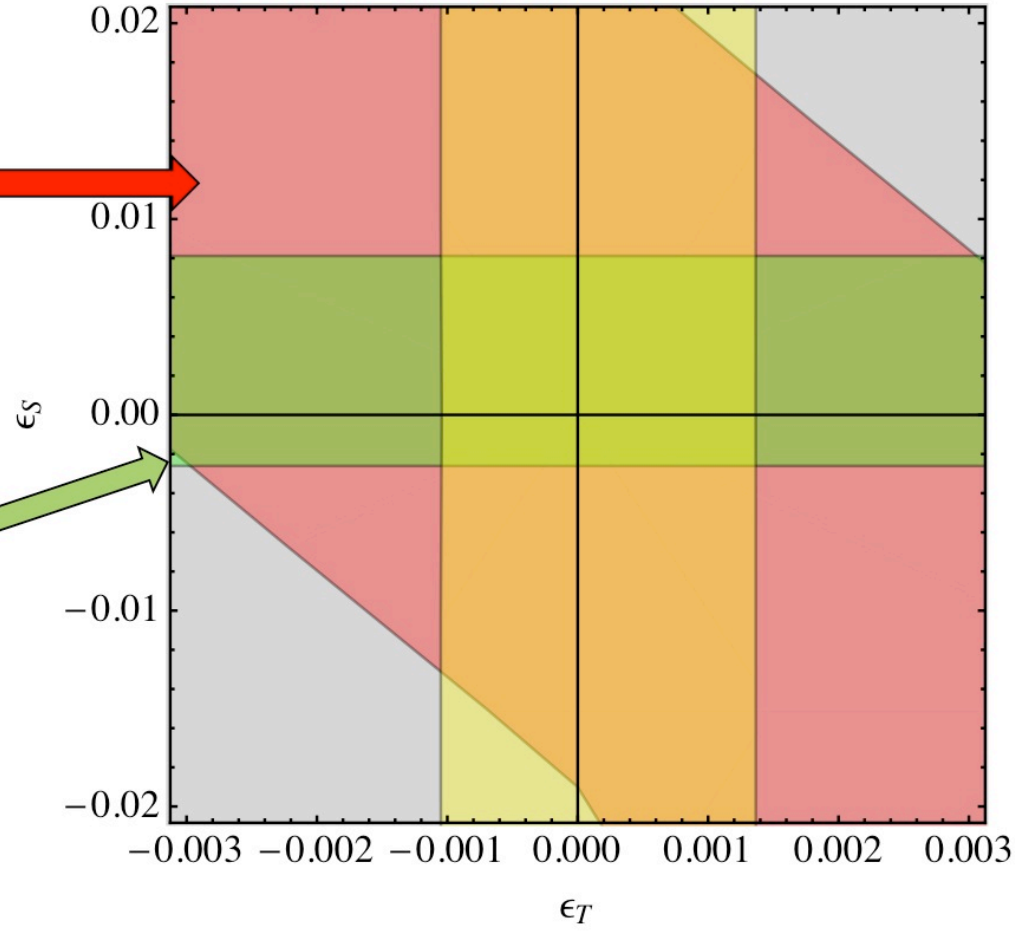
Current limits on S & T from low-E:

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



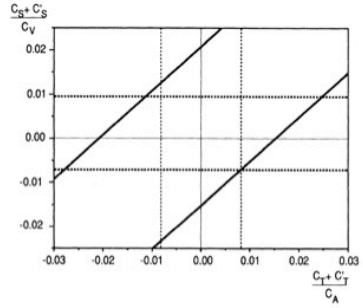
Superallowed nuclear β decays **(b_{0+})**



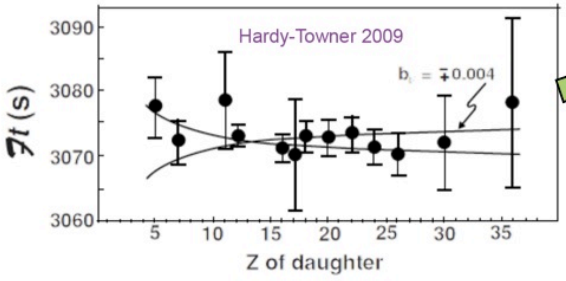


Current limits on S & T from low-E:

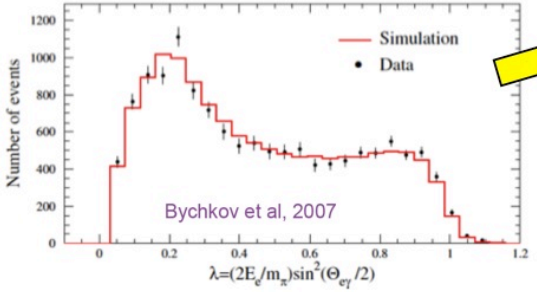
$P_F(^{14}O)/P_{GT}(^{10}C)$ (Carnoy et al.'1991)



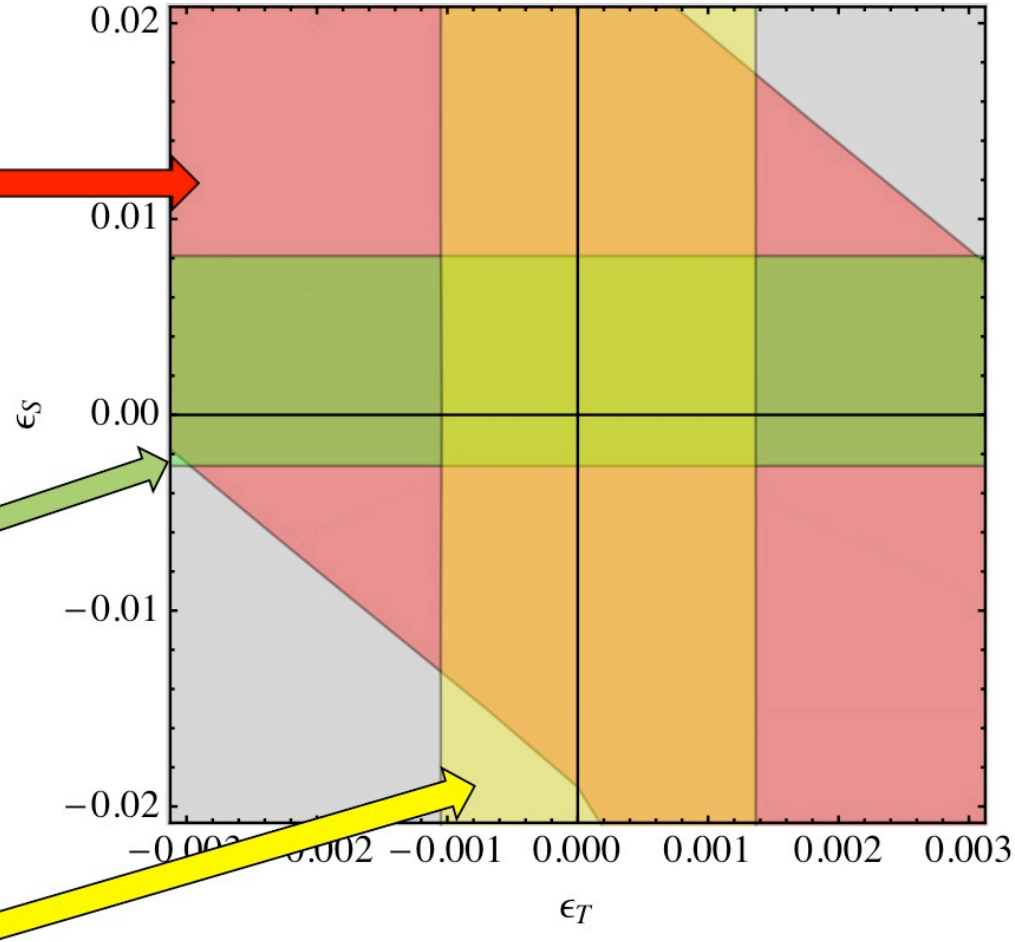
Superallowed nuclear β decays **(b_{0+})**



Radiative pion decay (PIBETA´2009)



$\pi \rightarrow e\nu\gamma$



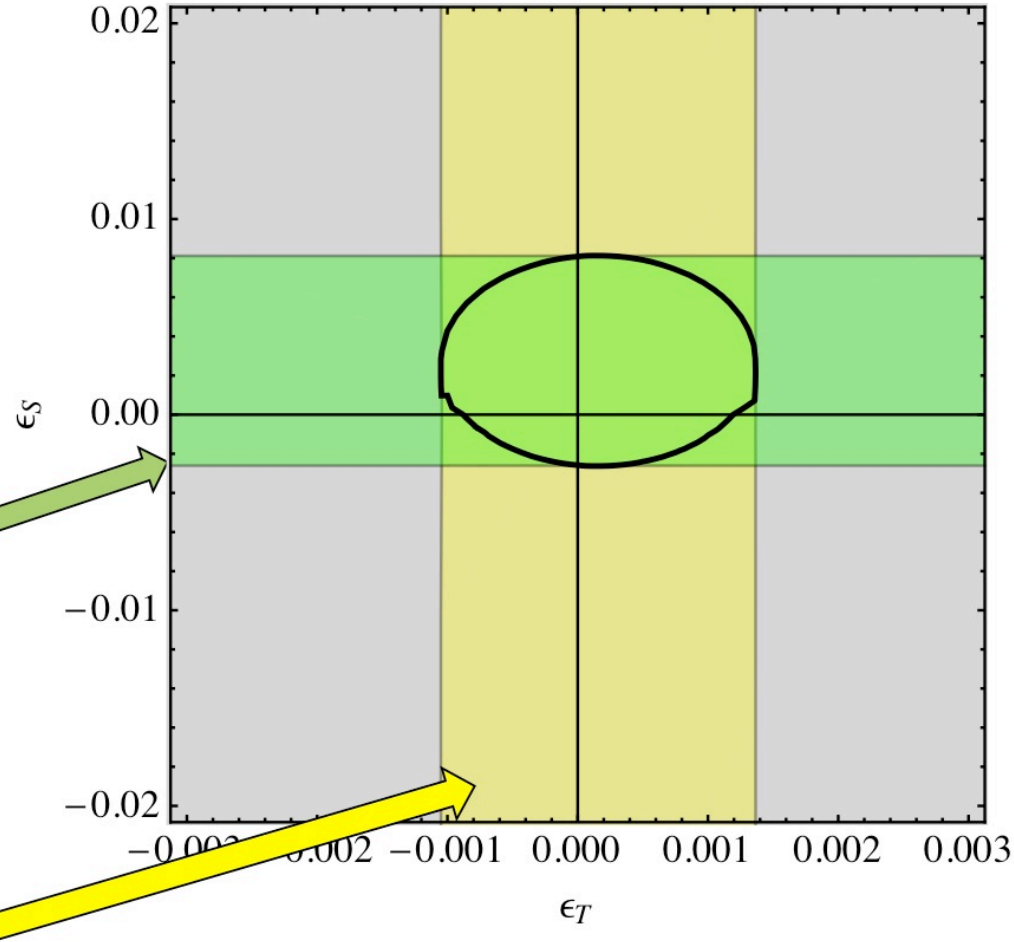
f_T=0.24(4)
(Mateu & Portolés, 2007)

June'2013:

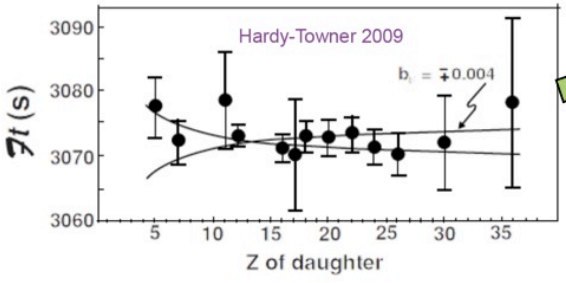
A global fit of nuclear and neutron beta decay data improves the bound on ε_T.

[Wauters, Garcia & Hong, 2013]

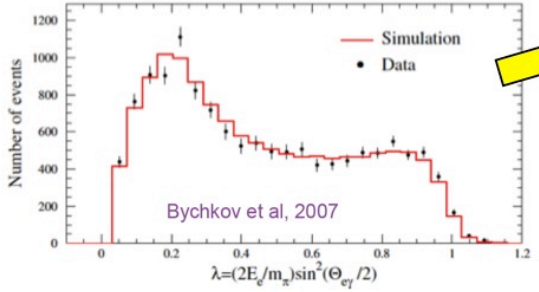
Current limits on S & T from low-E:



Superallowed nuclear β decays **(b_{0+})**



Radiative pion decay (PIBETA´2009)



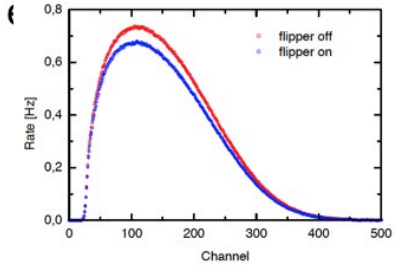
$\pi \to e\nu\gamma$

f_T=0.24(4)
(Mateu & Portolés, 2007)

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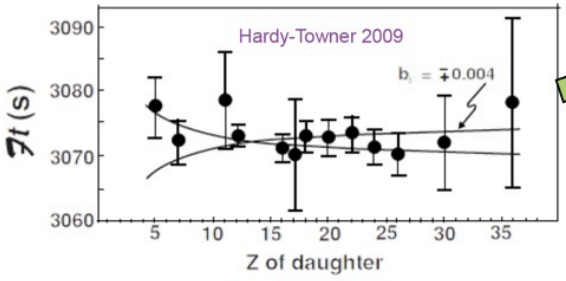
Future
~~Current~~ limits on S & T from low-E:

Future neutron decay

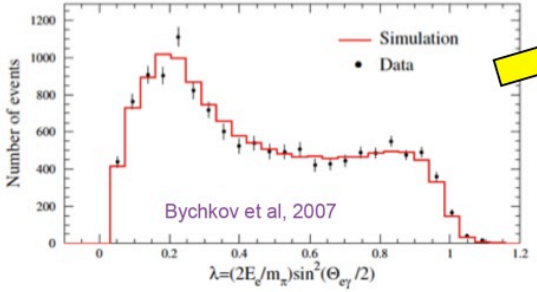


$b \approx 0.3\, g_S\, \varepsilon_S - 5.0\, g_T\, \varepsilon_T$

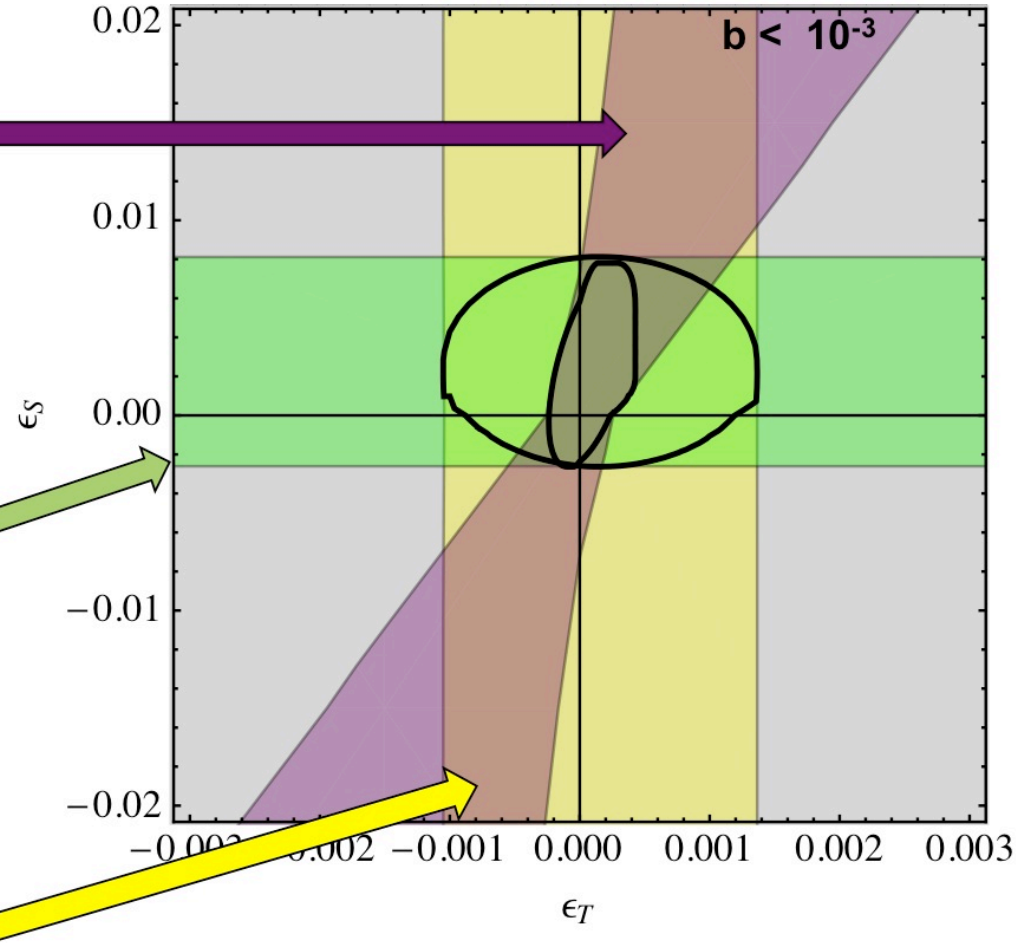
Superallowed nuclear β decays **(b_{0+})**



Radiative pion decay (PIBETA´2009)



$\pi \to e\nu\gamma$

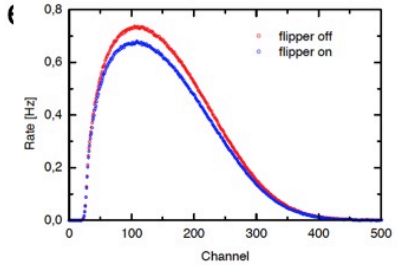


f_T=0.24(4)
(Mateu & Portolés, 2007)

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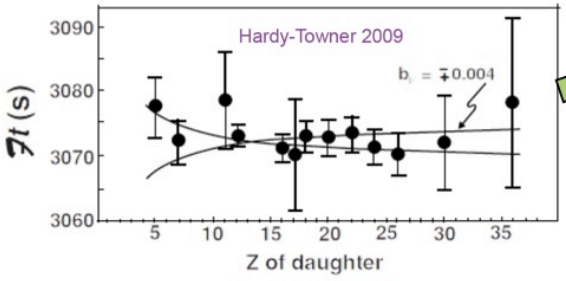
Future
~~Current~~ limits on S & T from low-E:

Future neutron decay

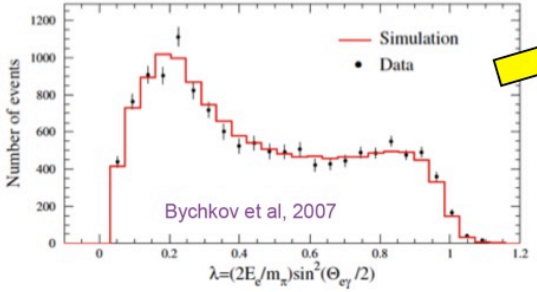


$b \approx 0.3\, g_S\, \varepsilon_S - 5.0\, g_T\, \varepsilon_T$

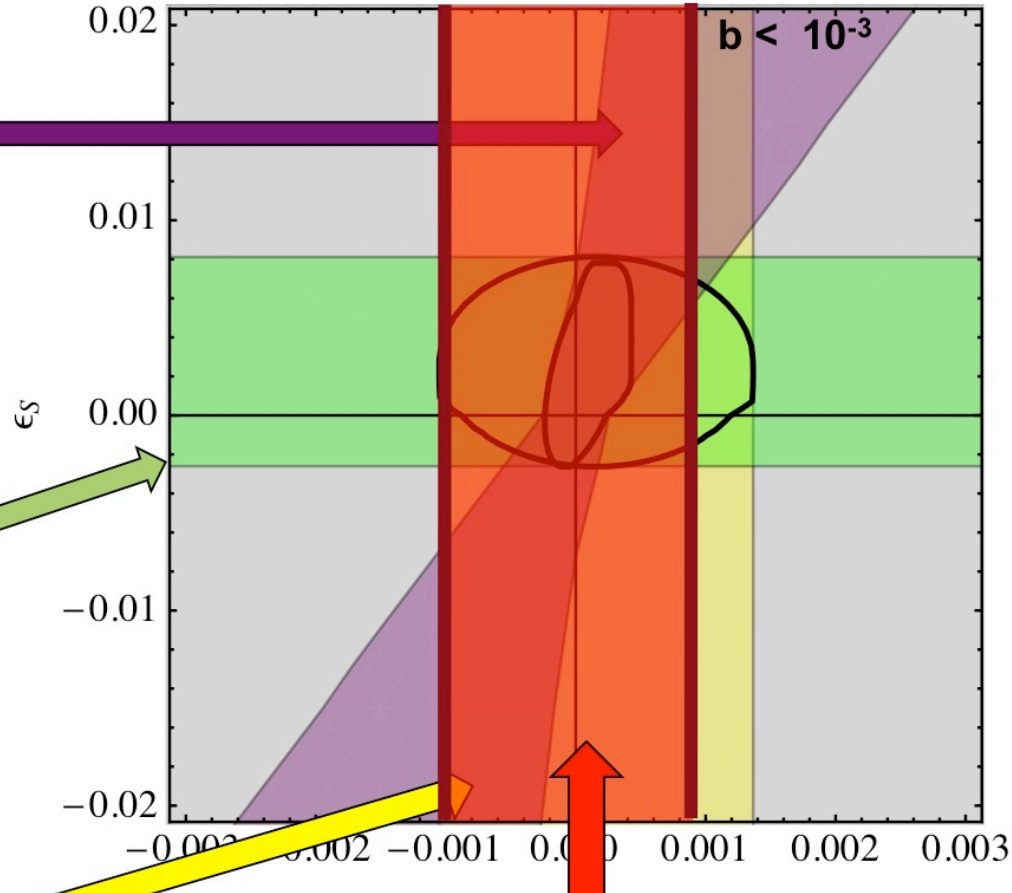
Superallowed nuclear β decays **(b_{0+})**



Radiative pion decay (PIBETA´2009)

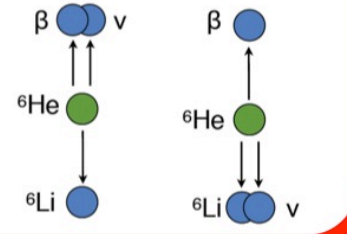


$\pi \rightarrow e\nu\gamma$



f_T=0.24(4)
(Mateu & Portolés, 2007)

b_{GT} from δa(^{6}He)~10^{-4}



Current NP bounds from low-energy searches: Summary

CKM unitarity tests

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

ν_L

	$\lvert\epsilon_L\rvert$	$\lvert\epsilon_R\rvert$	$\lvert\epsilon_P\rvert$	$\lvert\epsilon_S\rvert$	$\lvert\epsilon_T\rvert$
Low energy	0.05	0.05	0.06	0.8	0.1

$0^+ \to 0^+$ nuclear β decays

Rad. pion decay

x 10^{-2}

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 energy	6	6	0.03	14	3.0

x 10^{-2}

** Pion decay (R_π) also very powerful!*

$$R_\pi \equiv \frac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)}$$

Current NP bounds from low-energy searches: Summary

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

CKM unitarity tests

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

$0^+ \to 0^+$ nuclear β decays

Rad. pion decay

ν_L

	$\lvert\epsilon_L\rvert$	$\lvert\epsilon_R\rvert$	$\lvert\epsilon_P\rvert$	$\lvert\epsilon_S\rvert$	$\lvert\epsilon_T\rvert$	
Low energy	0.05	0.05	0.06	0.8	0.1	x 10^{-2}

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 energy	6	6	0.03	14	3.0	x 10^{-2}

Neutron/nuclear beta decays (angular distributions, spectra, …)

[Severijns, Beck & Naviliat-Cuncic'2006]

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

Outline

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

[Cirigliano, MGA & Jenkins'2010]

[Bhattacharya, Cirigliano, Cohen, Filipuzzi, MGA, Graesser, Gupta, Lin'2012]

[Cirigliano, MGA & Graesser'2012]

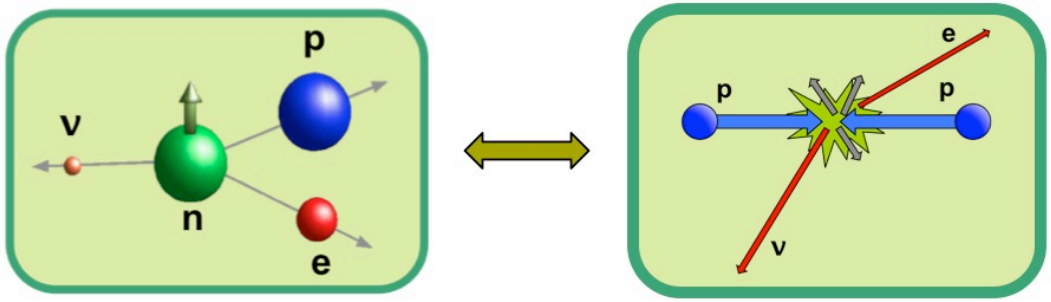
[MGA & Naviliat-Cuncic'2013]

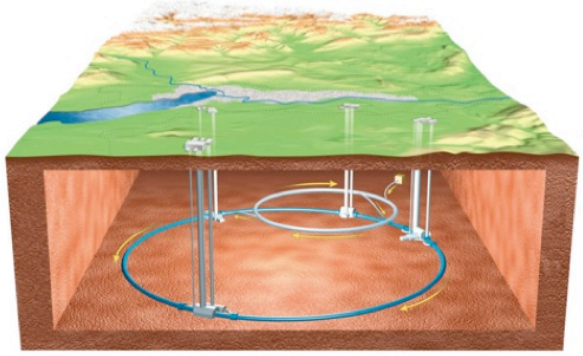
[MGA & Martin Camalich (in preparation)]

What about the LHC?



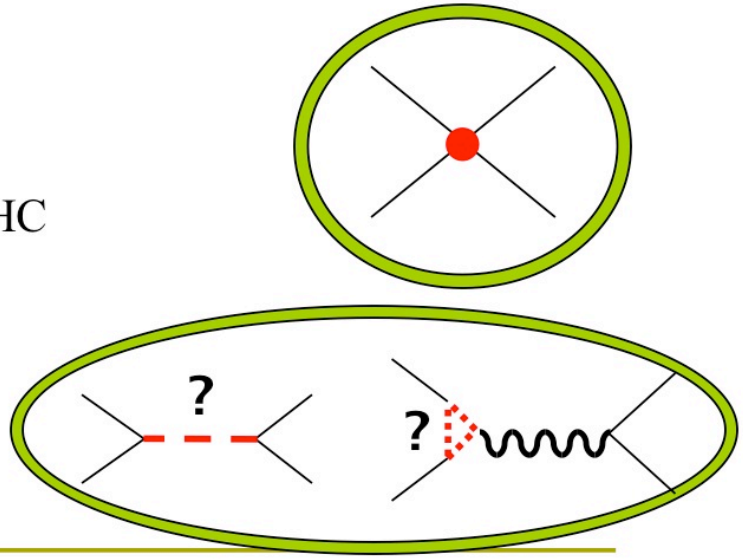
- These new particles would affect the pp collisions!



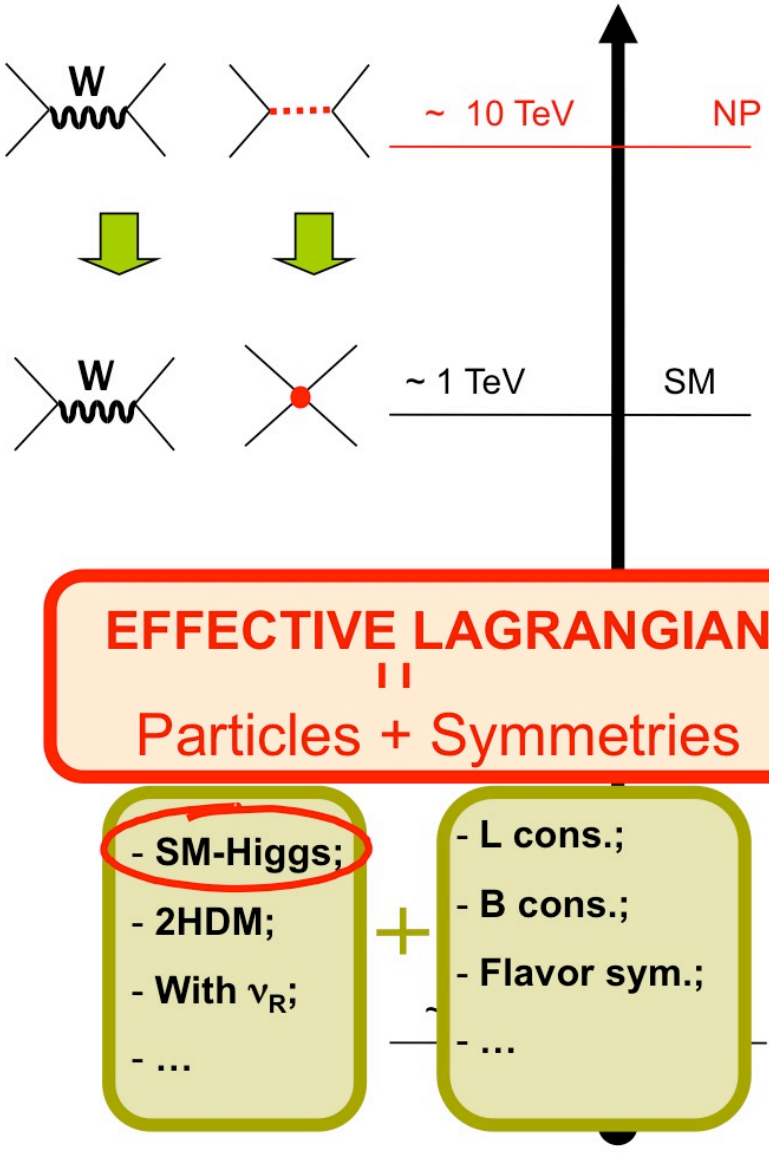


- S,T: In principle low-E experiments are favored (interference ~ m/E), but the LHC is powerful…

- There are 2 possible scenarios here:
  - The new particles are too heavy to be produced at the LHC
    ➔ EFT approach still OK!
  - The new particles can be produced at the LHC
    ➔ Model dependent!



The high-energy Effective Lagrangian



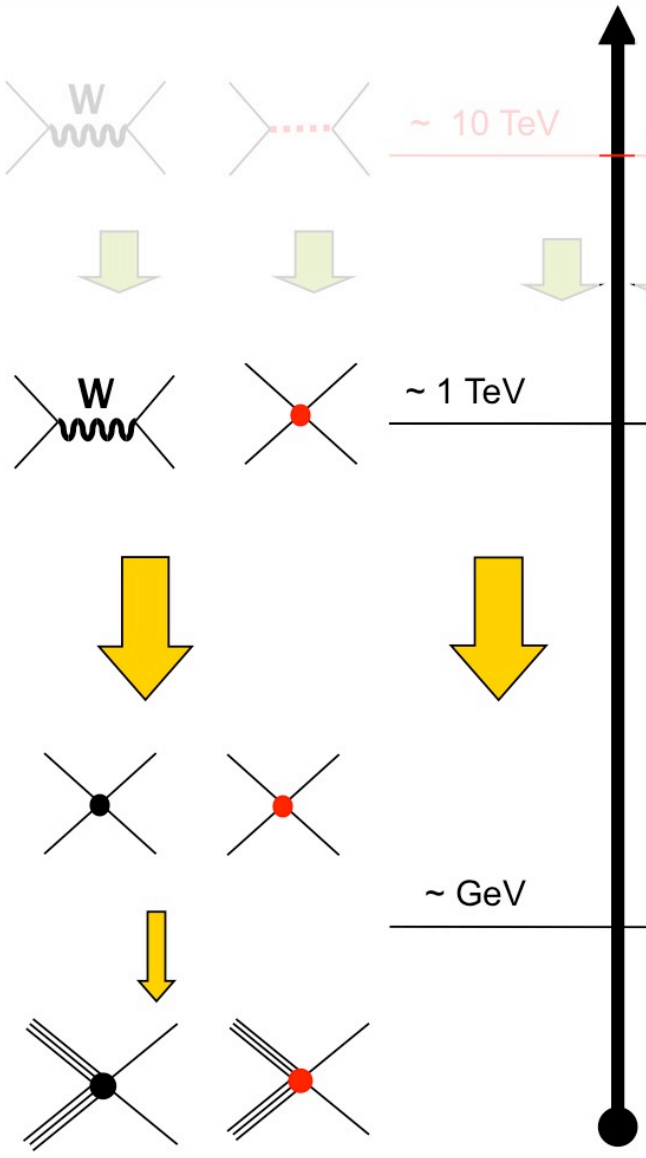
$$\mathbf{L}^{TeV}(x) = \mathbf{L}(\text{SM-fields, bSM-fields})$$

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

$$\mathbf{L}^{\text{eff.}}(x) = \mathbf{L}_{SM}(x) + \frac{1}{\Lambda}\mathbf{L}_5(x) + \frac{1}{\Lambda^2}\mathbf{L}_6(x) + \dots$$

$$\left(\mathbf{L}_n(x) = \sum_i \alpha_i^{(n)} \mathbf{O}_i^{(n)}(x)\right)$$

The high-energy Effective Lagrangian



$$\mathbf{L}^{TeV}(x) = \mathbf{L}(\text{SM-fields, bSM-fields})$$

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

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

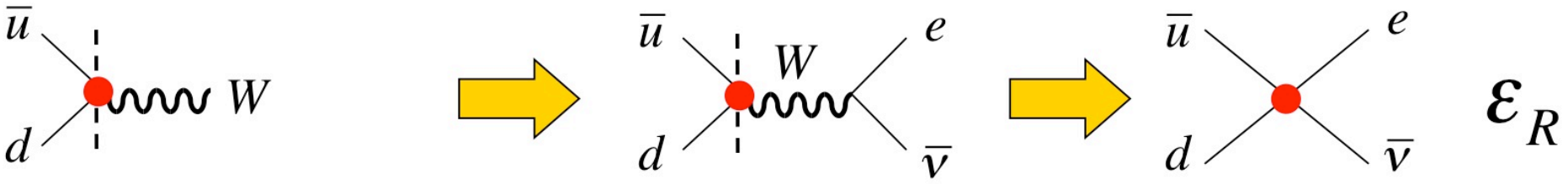
[Cirigliano, MGA, Jenkins'2010, Cirigliano, MGA, Graesser'2012]

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

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

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

Effective Lagrangians



$$O_{\varphi\varphi} = i(\varphi^T \epsilon D_\mu \varphi)(\bar{u}\gamma^\mu d) + \text{h.c.}$$

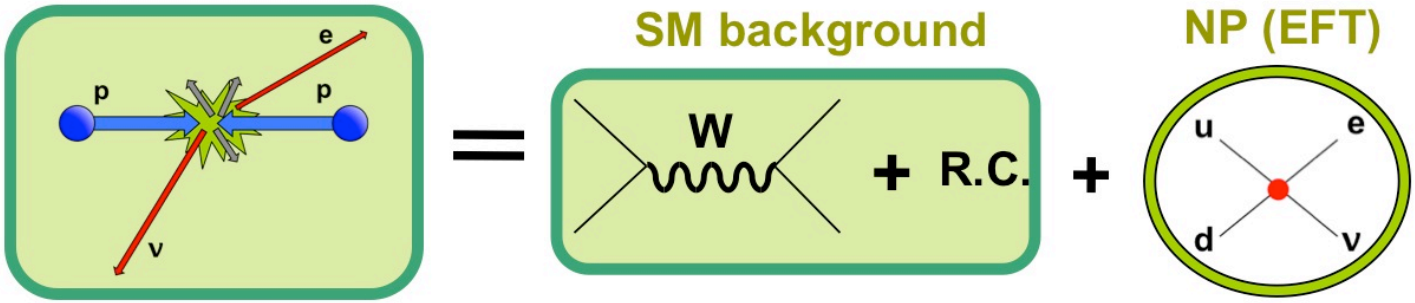
$$\bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$$

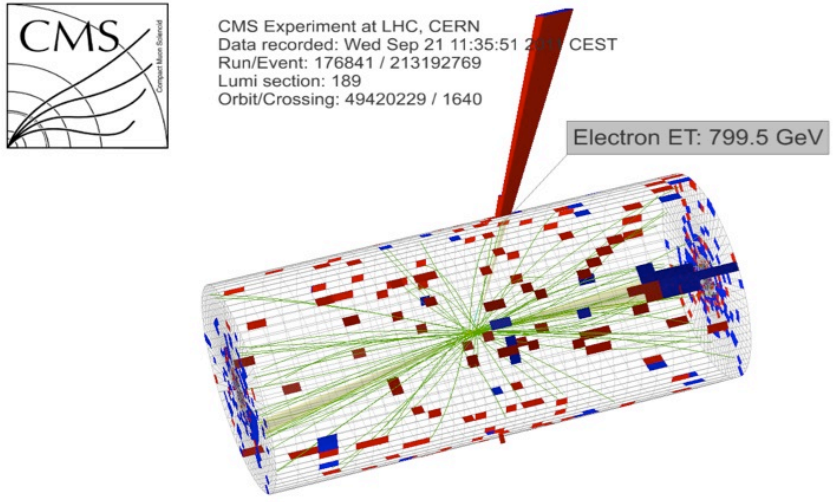
$$\epsilon_R = -\delta_{e\ell}\frac{[\hat{\alpha}_{\varphi\varphi}]_{11}}{V_{ud}}$$

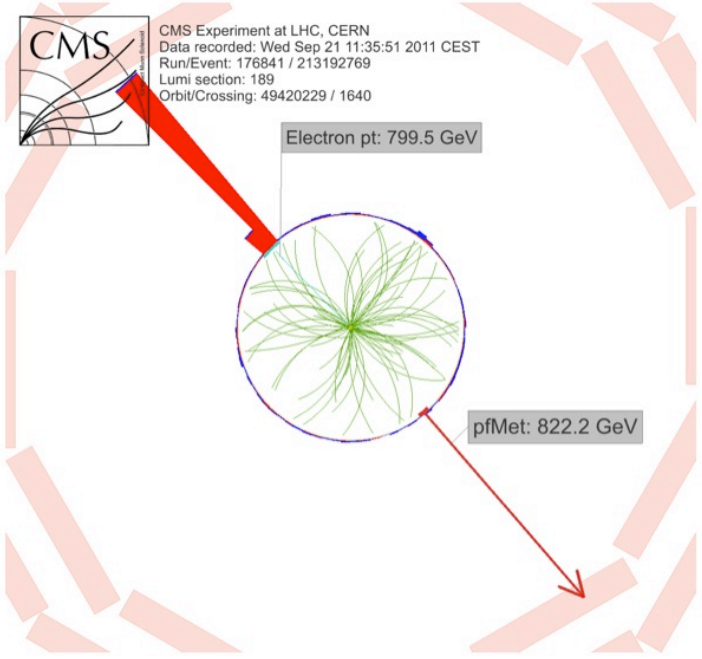
- LHC searches ⇒ $|\alpha| \leq \ldots$ ⇒ $|\varepsilon| \leq \ldots$

Let's do it!

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





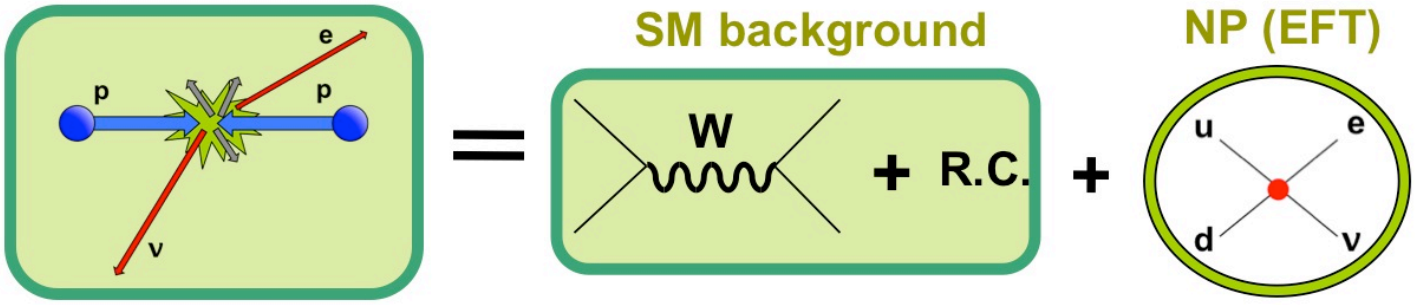


Each event can be characterized by the "transverse mass"

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

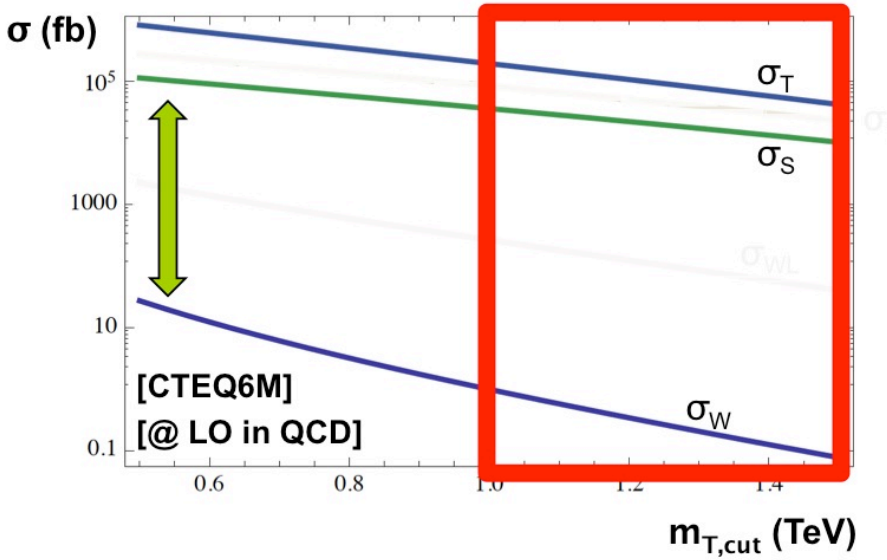
IFIC seminar

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

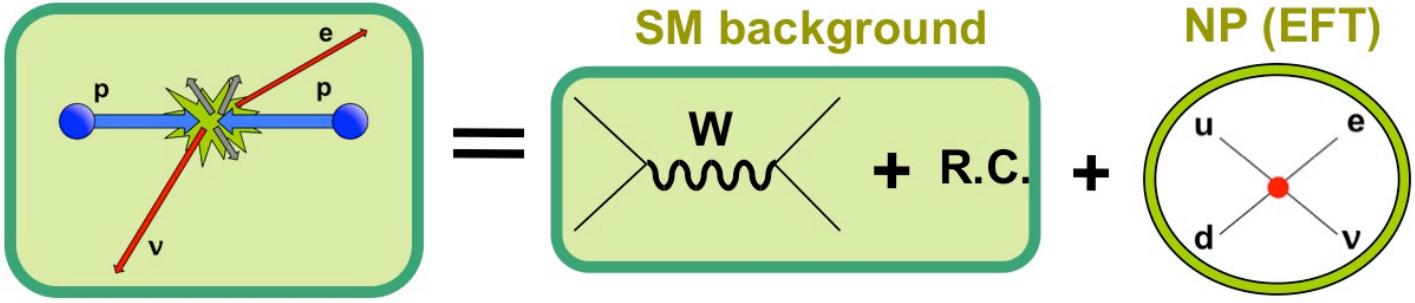


- To suppress the bkg, we look for ***(e+ν)***-events with high m_T:

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

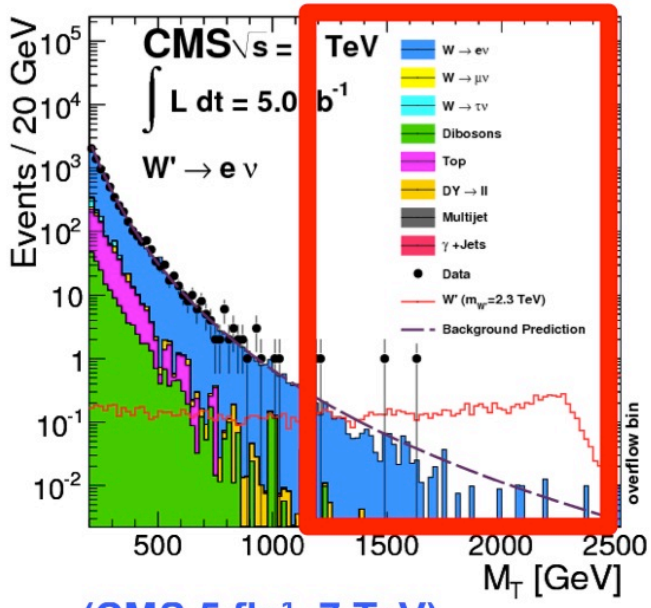


LHC limits on $\varepsilon_{S,T}$

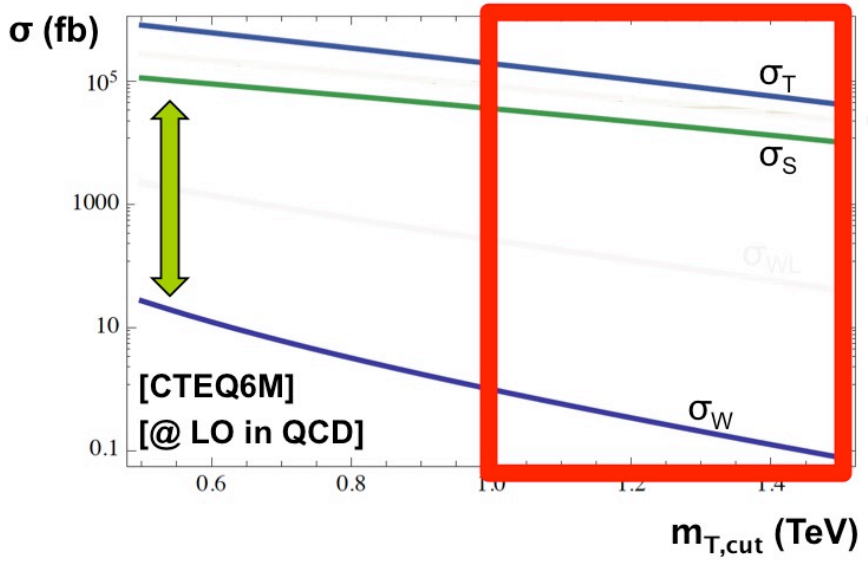


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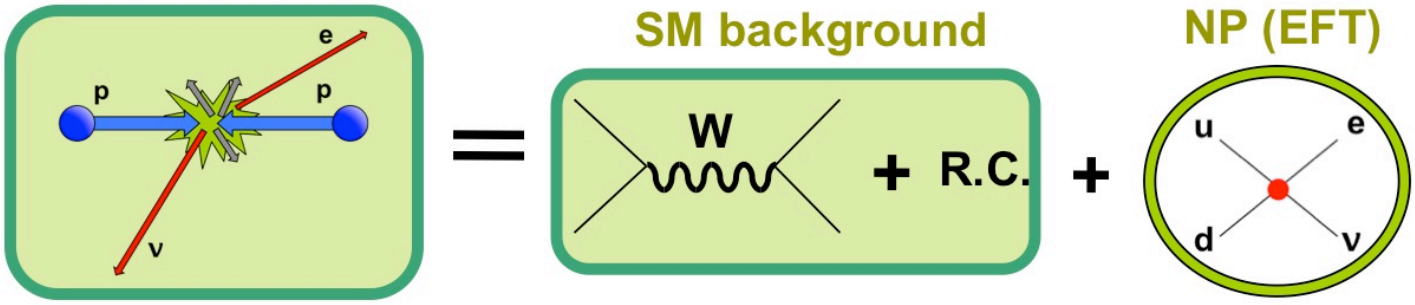


(CMS 5 fb^{-1}, 7 TeV)



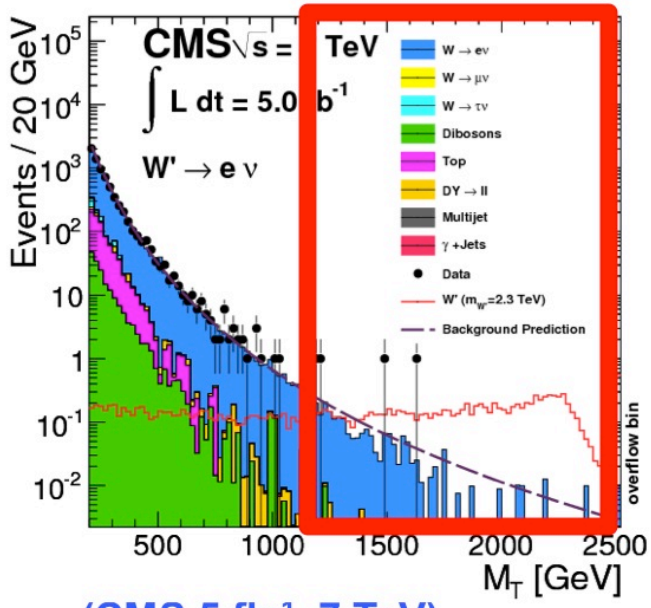
IFIC seminar

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

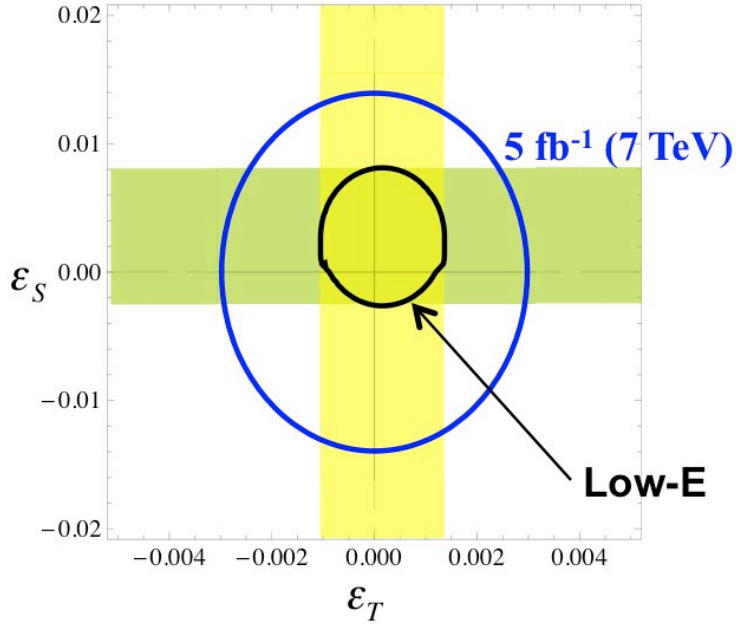


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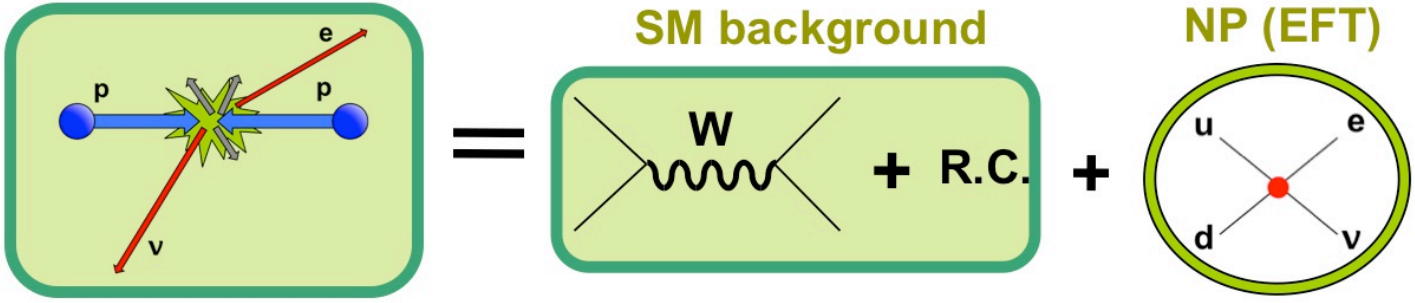
$$N_{pp\to evX}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times L \times \sigma_{pp\to evX}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times L \times \left(\sigma_W + \sigma_S\,\varepsilon_S^2 + \sigma_T\,\varepsilon_T^2\right)$$



(CMS 5 fb^{-1}, 7 TeV)

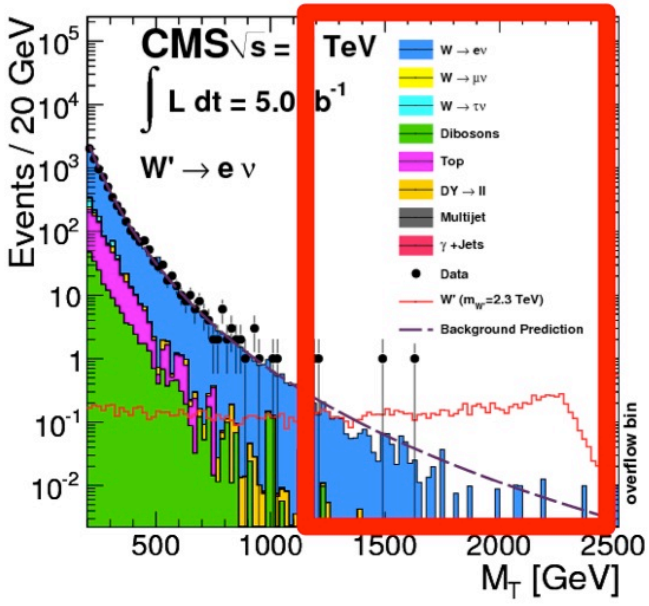


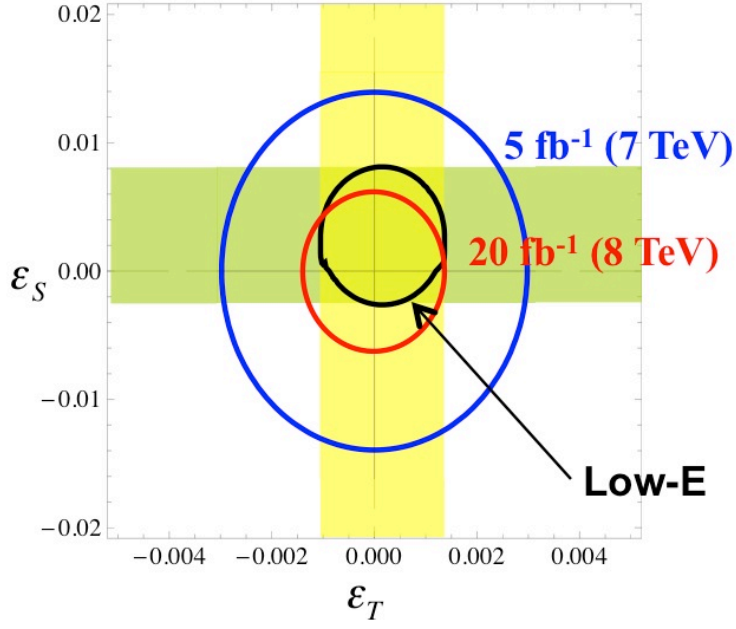
LHC limits on $\varepsilon_{S,T}$



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

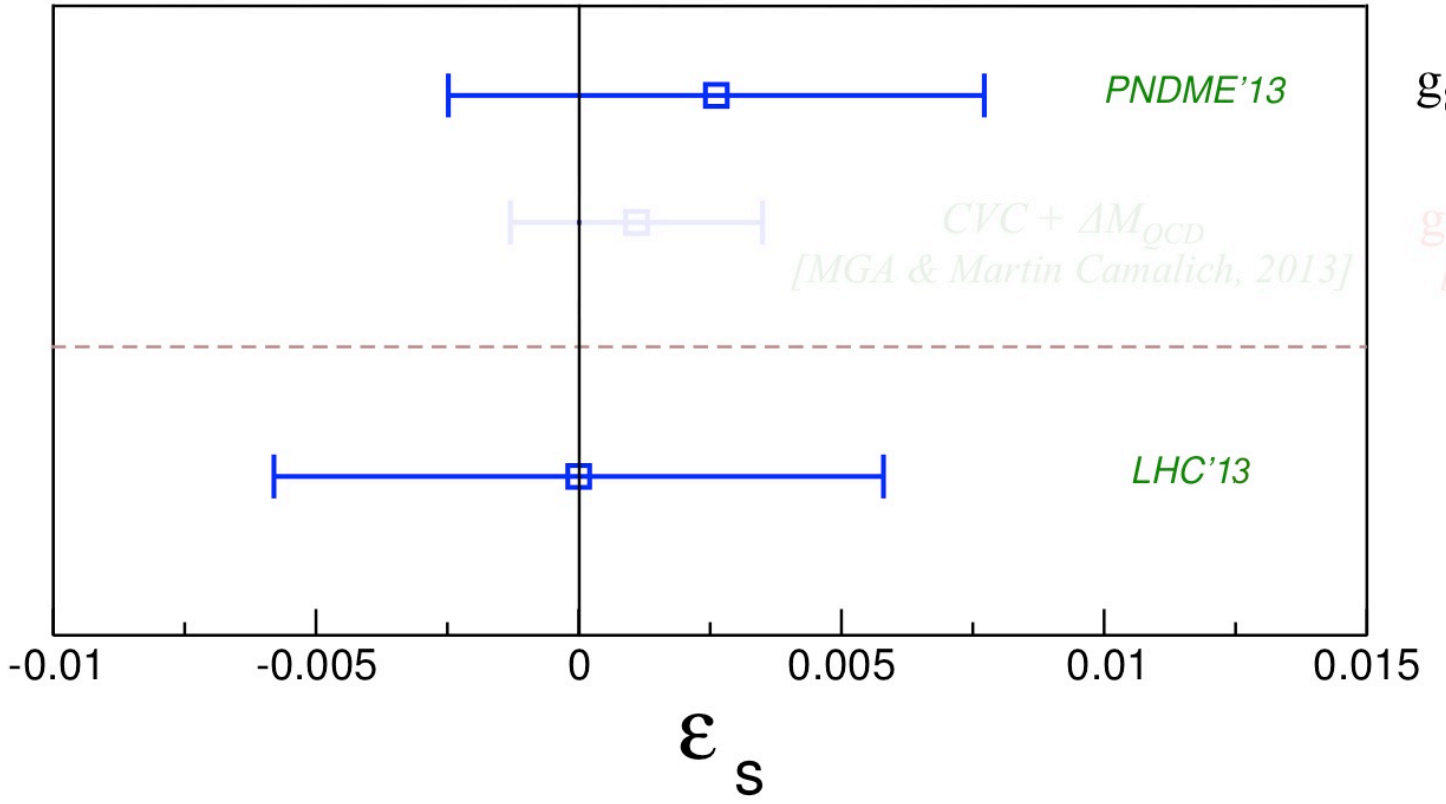
$$N_{pp\to evX}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times L \times \sigma_{pp\to evX}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times L \times \left(\sigma_W + \sigma_S\,\varepsilon_S^2 + \sigma_T\,\varepsilon_T^2\right)$$





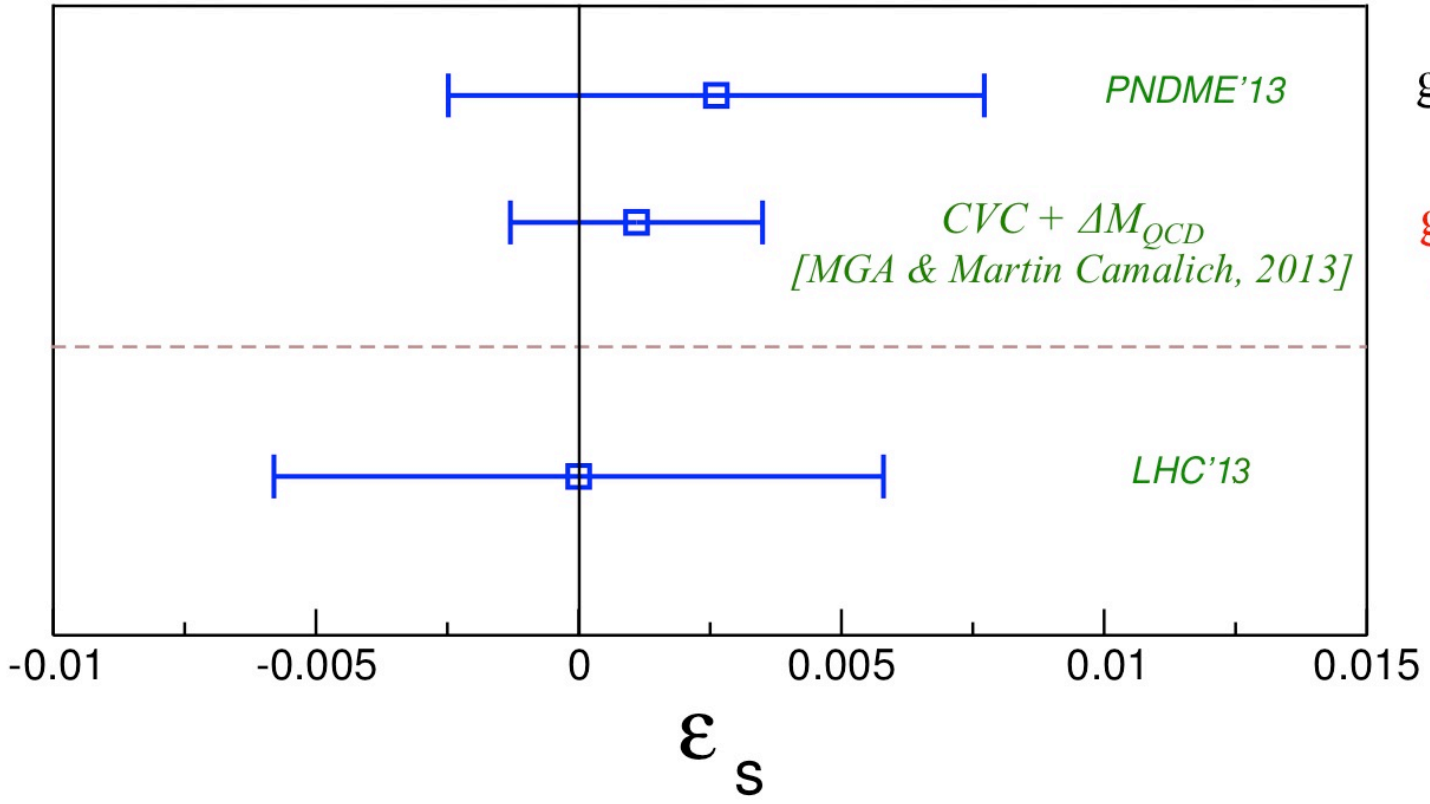
LHC limits on $\varepsilon_{S,T}$

Impact of the new determination of the scalar FF using CVC and ΔM_{QCD}?



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

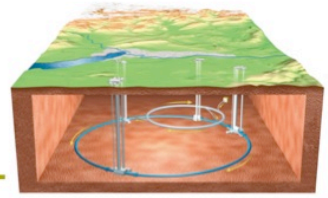
Impact of the new determination of the scalar FF using CVC and ΔM_{QCD}?



g_S=0.66(24)

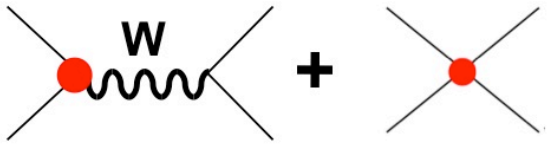
g_S=1.04(13)
[preliminary]

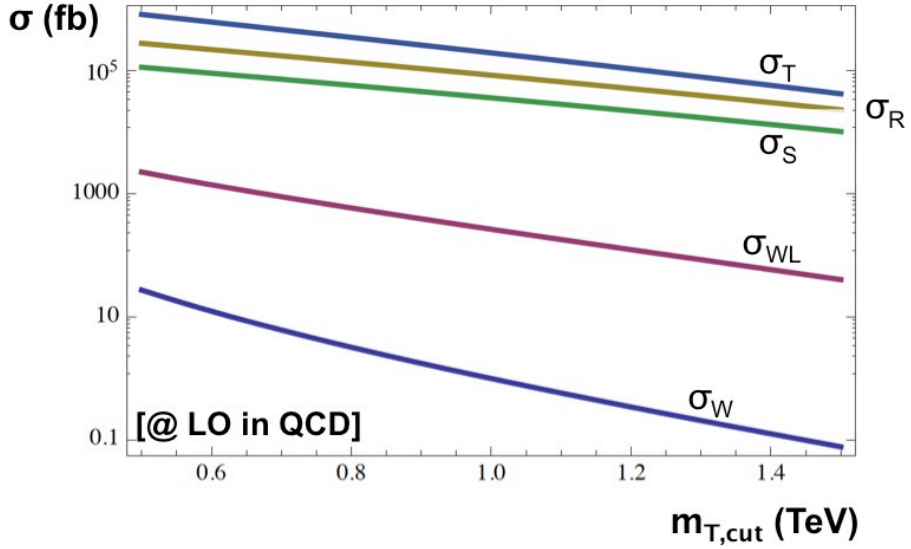
What about the other ε_x?



$$\sigma(m_T > \overline{m}_T) = \sigma_W \left[(1+\epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2 \right] - 2\,\sigma_{WL}\,\epsilon_L^{(c)} \left(1+\epsilon_L^{(v)}\right)$$
$$+ \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2 \right] + \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2 \right]$$
$$+ \sigma_T \left[|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2 \right] ,$$

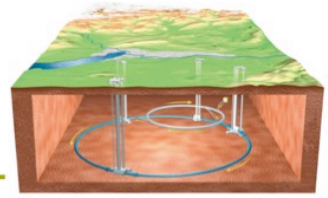
$$\epsilon_L = \epsilon_L^{(v)} + \epsilon_L^{(c)}$$





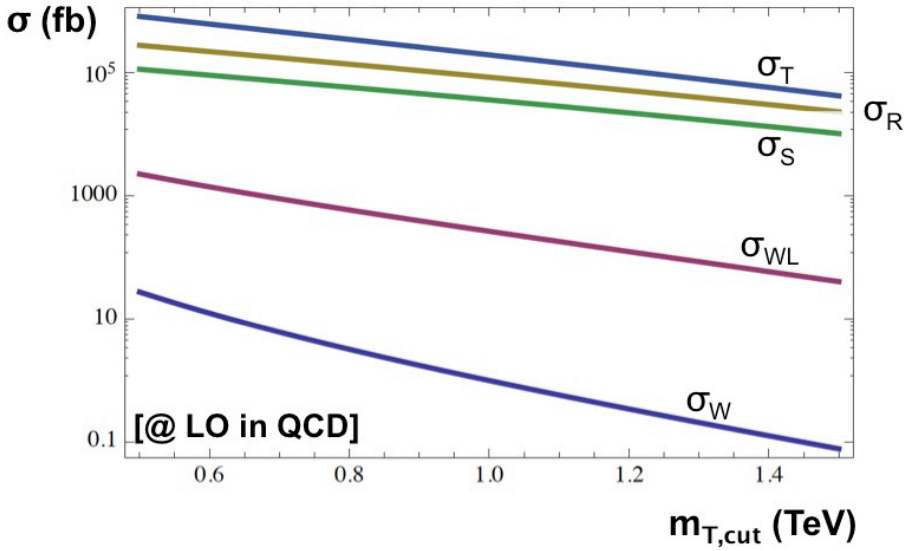
[Cirigliano, MGA & Graesser, 2012]

What about the other ε_x?



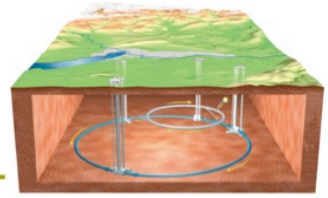
$$\sigma(m_T > \overline{m}_T) = \sigma_W \left[(1+\epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2 \right] - 2\,\sigma_{WL}\,\epsilon_L^{(c)} \left(1+\epsilon_L^{(v)}\right)$$
$$+ \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2 \right] + \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2 \right]$$
$$+ \sigma_T \left[|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2 \right],$$

- Strong bounds on S, T, P with LH neutrinos.
- Strong bounds on S, P, T, V+A with RH neutrinos;
- LHC not sensitive to the rest of couplings.



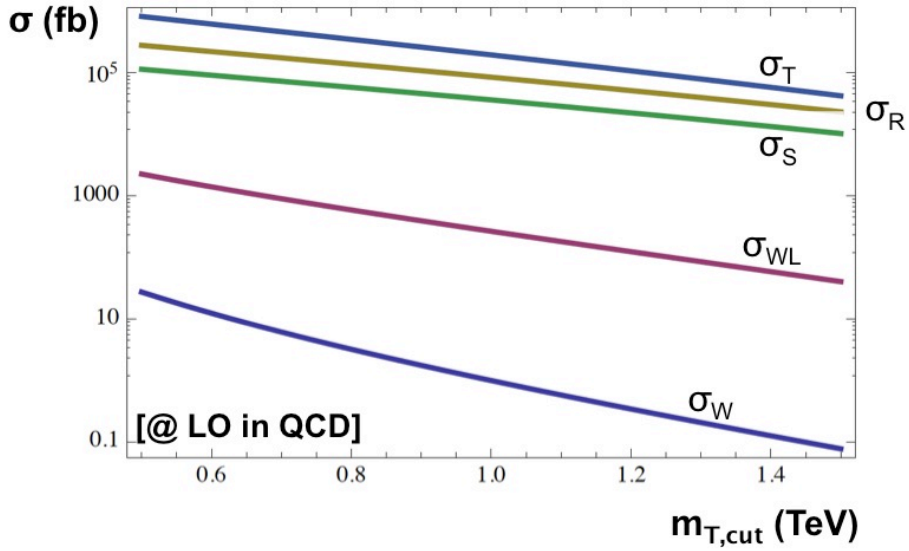
[Cirigliano, MGA & Graesser, 2012]

What about the other ε_x?



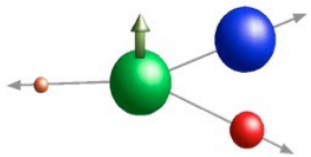
$$\sigma(m_T > \overline{m}_T) = \sigma_W \left[(1+\epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2 \right] - 2\sigma_{WL} \epsilon_L^{(c)} \left(1+\epsilon_L^{(v)}\right)$$
$$+ \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2 \right] + \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2 \right]$$
$$+ \sigma_T \left[|\epsilon_T|^2 + |\tilde{\epsilon}_T|^2 \right] ,$$

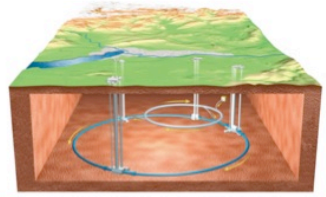
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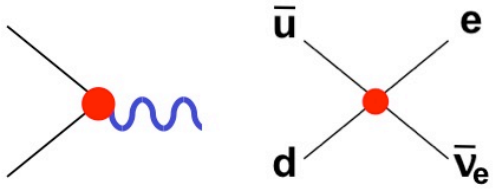


[Cirigliano, MGA & Graesser, 2012]

β decays vs. the LHC







ν_L

	$\lvert\epsilon_L^{(v)}\rvert$	$\epsilon_L^{(c)}$	$\lvert\epsilon_R\rvert$	$\lvert\epsilon_P\rvert$	$\lvert\epsilon_S\rvert$	$\lvert\epsilon_T\rvert$	
Low energy	0.05	0.05	0.05	0.06	0.8	0.1	x 10^{-2}
LHC $(e\nu)$	-	$(-0.3,+0.8)$	-	1.3	1.3	0.3	x 10^{-2}

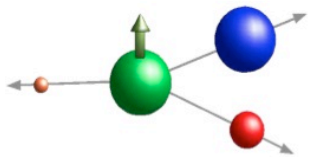
Interesting competition*

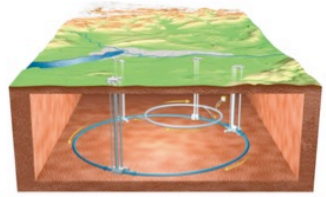
ν_R

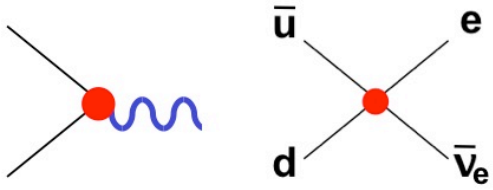
	$\lvert\tilde{\epsilon}_L\rvert$	$\lvert\tilde{\epsilon}_R\rvert$	$\lvert\tilde{\epsilon}_P\rvert$	$\lvert\tilde{\epsilon}_S\rvert$	$\lvert\tilde{\epsilon}_T\rvert$	
Low energy	6	6	0.03	14	3.0	x 10^{-2}
LHC $(e\nu)$	-	0.5	1.3	1.3	0.3	x 10^{-2}

*If the neutrino is an electron neutrino…

β decays vs. the LHC







ν_L

	$\lvert\epsilon_L^{(u)}\rvert$	$\epsilon_L^{(e)}$	$\lvert\epsilon_R\rvert$	$\lvert\epsilon_P\rvert$	$\lvert\epsilon_S\rvert$	$\lvert\epsilon_T\rvert$	
Low energy	0.05	0.05	0.05	0.06	0.8	0.1	x 10^{-2}
LHC ($e\nu$)	-	(-0.3,+0.8)	-	1.3	1.3	0.3	x 10^{-2}

Low energy dominates!

Interesting competition*

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 energy	6	6	0.03	14	3.0	x 10^{-2}
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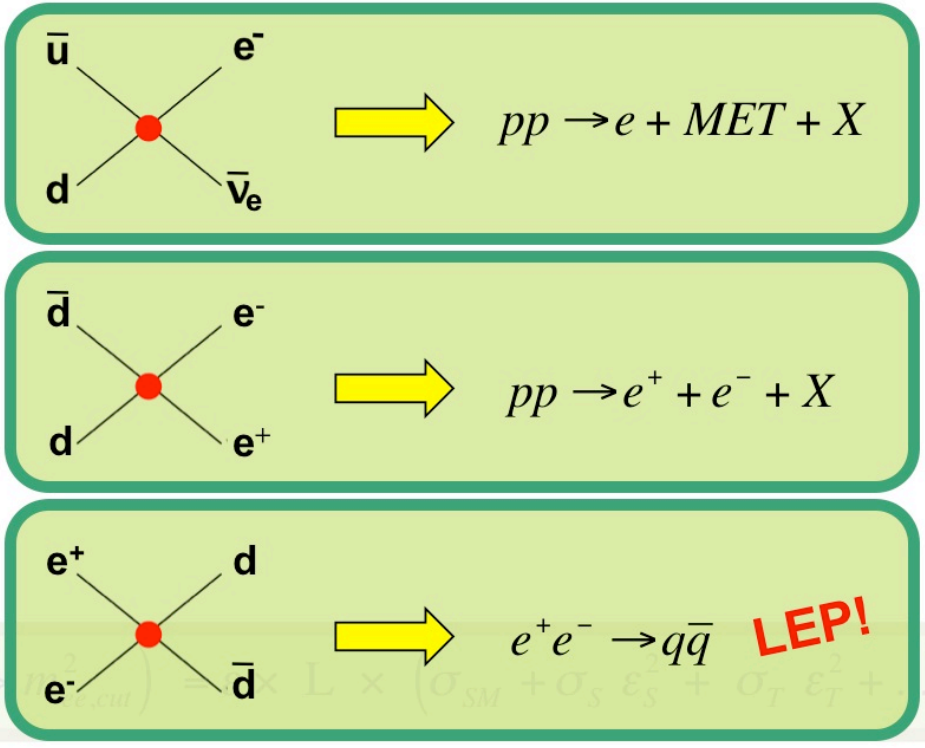
LHC dominates!

*If the neutrino is an electron neutrino…

Beyond the $pp \to e\nu X$ channel

- Using SU(2) gauge invariance…

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



- We can play the same game…

$$N_{pp\to eeX}\left(m^2_{ee} > m^2_{ee,cut}\right) = \varepsilon \times \mathrm{L} \times \sigma_{pp\to eeX}\left(m^2_{ee} > m^2_{ee,cut}\right) = \varepsilon \times \mathrm{L} \times \left(\sigma_{SM} + \sigma_S\,\varepsilon_S + \sigma_T\,\varepsilon_T^2 + \ldots\right)$$

…

Better than the LHC probing V/A interactions, but not better than CKM unitarity!

[Cirigliano, MGA & Jenkins'2010]

No events with m_{ee}>1.35 TeV

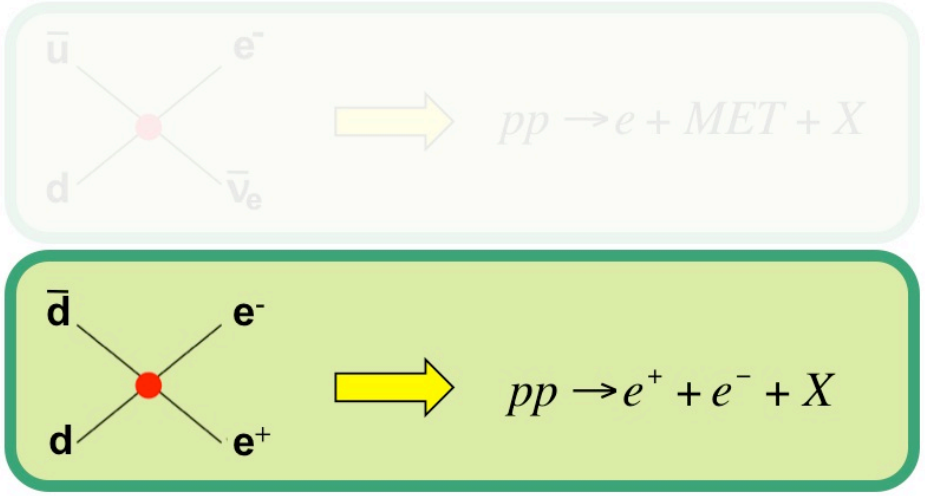


[Cirigliano, MGA & Graesser'2012]

Beyond the $pp \to e\nu X$ channel

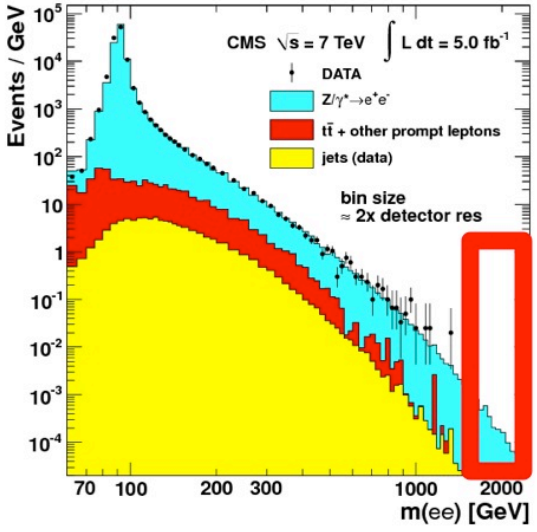
- Using SU(2) gauge invariance…

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

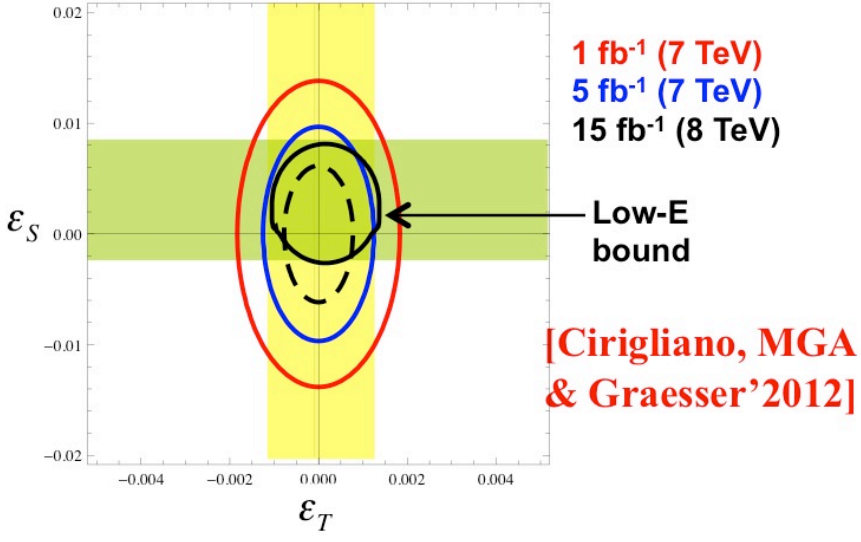


- We can play the same game…

$$N_{pp\to eeX}\left(m_{ee}^2 > m_{ee,cut}^2\right) = \varepsilon \times \mathrm{L} \times \sigma_{pp\to eeX}\left(m_{ee}^2 > m_{ee,cut}^2\right) = \varepsilon \times \mathrm{L} \times \left(\sigma_{SM} + \sigma_S\, \varepsilon_S^2 + \sigma_T\, \varepsilon_T^2 + \ldots\right)$$



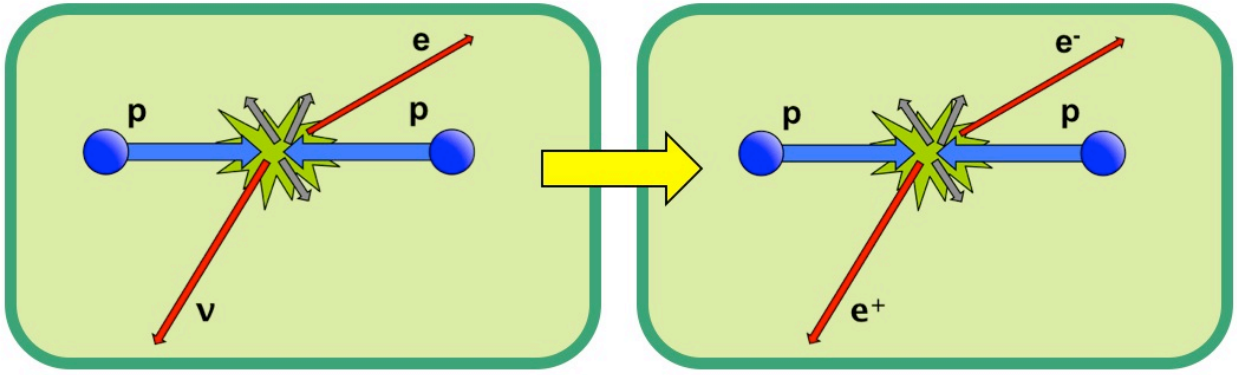
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[Cirigliano, MGA & Graesser'2012]

Beyond the $pp \to e\nu X$ channel

- Using SU(2) gauge invariance…

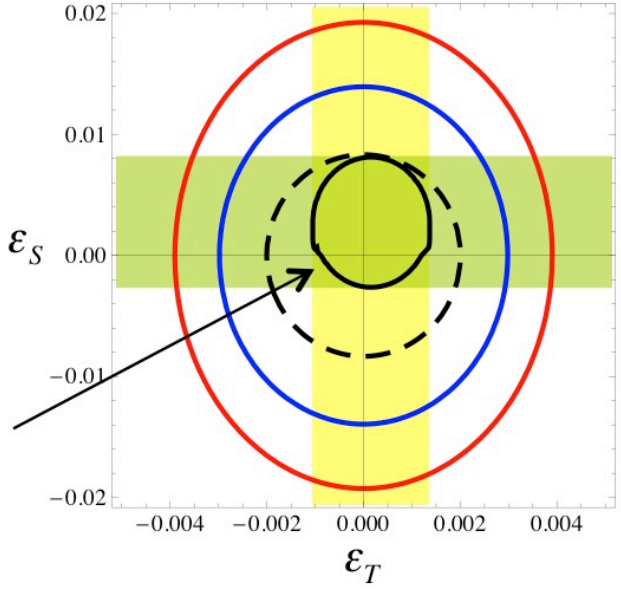


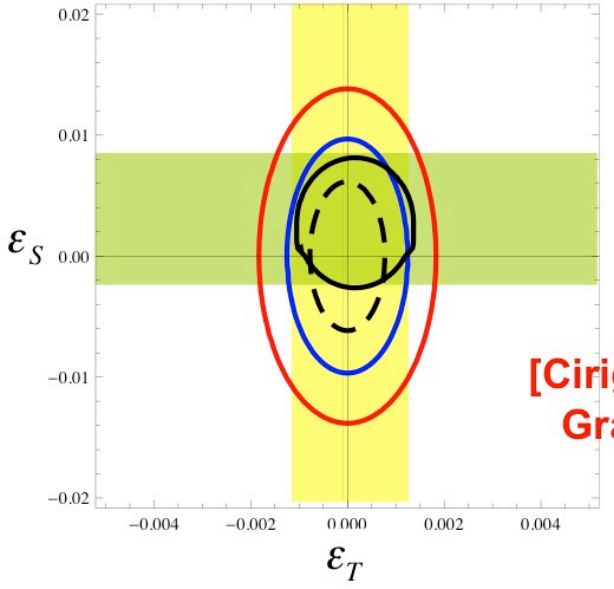
1 fb^{-1} (7 TeV)

5 fb^{-1} (7 TeV)

15 fb^{-1} (8 TeV)

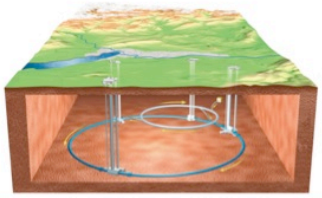
Low-E

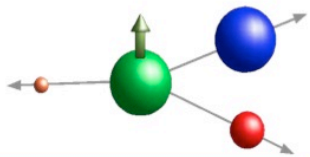




[Cirigliano, MGA & Graesser'2012]

Conclusions



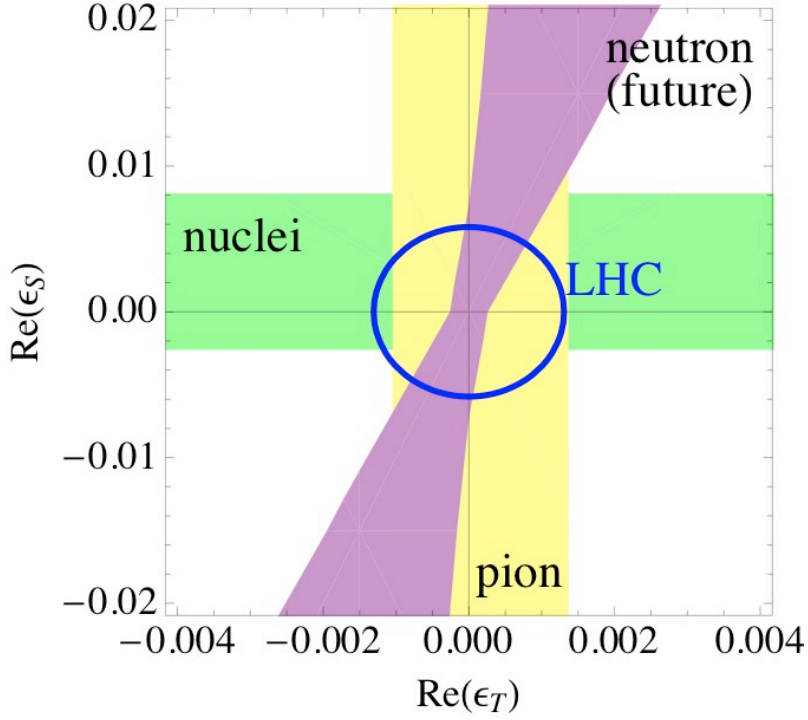


- β decay are sensitive to TeV physics!
  - Intense experimental activity worldwide;
  - Intense theoretical activity (form factors);

- Connecting high- and low-E probes: EFT approach (heavy mediators).
  - S,T: The LHC is catching up fast!! Interesting competition in the future.
  - Best probe for interactions involving RH neutrinos.

- Both LHC & low-energy searches needed to get a complete picture.

- Needless to say, this interplay becomes much more interesting if we see a NP signal!



Backup slides

Effective Lagrangians at the weak scale

$$\mathbf{L}^{\text{eff.}}(x) = \mathbf{L}_{\mathbf{SM}}(x) + \frac{1}{\Lambda^2}\mathbf{L}_6(x) \qquad \left(\mathbf{L}_6(x) = \sum_i^{25} \alpha_i \mathbf{O}_i(x)\right)$$

4-fermion op.

$$O_{lq}^{(3)} = (\bar{l}\gamma^\mu\sigma^a l)(\bar{q}\gamma_\mu\sigma^a q) \qquad O_{e\nu ud} = (\bar{e}\gamma^\mu\nu)(\bar{u}\gamma_\mu d) + \text{h.c.}$$

$$O_{qde} = (\bar{l}e)(\bar{d}q) + \text{h.c.} \qquad O_{qu\nu} = (\bar{l}\nu)(\bar{u}q) + \text{h.c.}$$

$$O_{lq} = (\bar{l}_a e)\epsilon^{ab}(\bar{q}_b u) + \text{h.c.} \qquad O'_{lq} = (\bar{l}_a \nu)\epsilon^{ab}(\bar{q}_b d) + \text{h.c.}$$

$$O_{lq}^{t} = (\bar{l}_a\sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu} u) + \text{h.c.} \qquad O_{lq}^{t'} = (\bar{l}_a\sigma^{\mu\nu} \nu)\epsilon^{ab}(\bar{q}_b\sigma_{\mu\nu} d) + \text{h.c.}$$

Vertex corr.

$$O_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\bar{u}\gamma^\mu d) + \text{h.c.} \qquad O'_{\varphi\varphi} = i(\varphi^T\epsilon D_\mu\varphi)(\bar{\nu}\gamma^\mu e) + \text{h.c.}$$

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

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

CKM tests vs. HEP

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

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

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

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

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

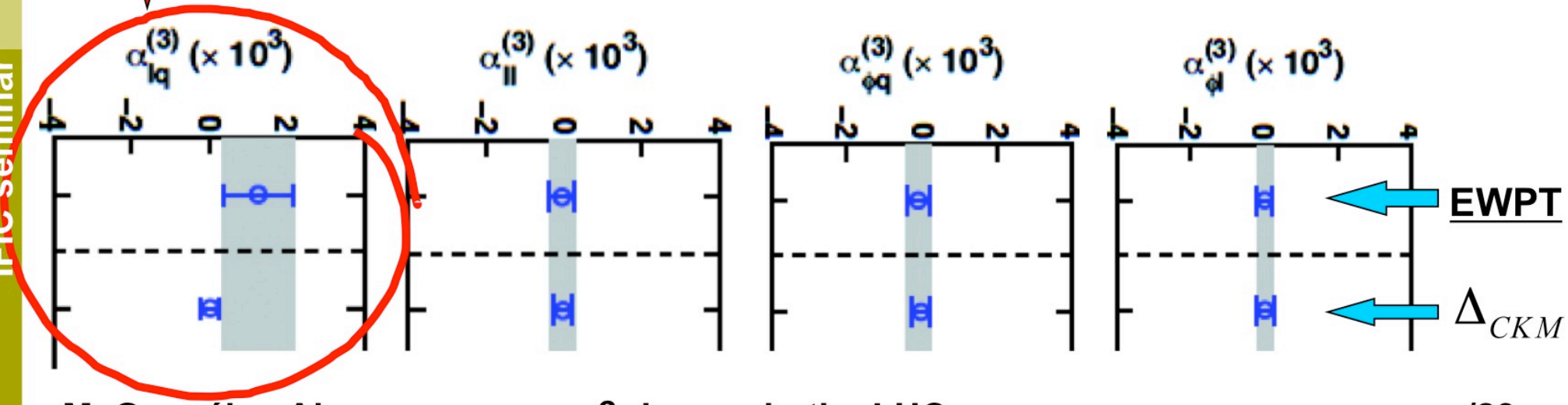
$$O^{(3)}_{\varphi} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\bar{q}\gamma_\mu\sigma^a q) + \text{h.c.}$$

What did we know about them from colliders and other EWPT?

Han & Skiba, PRD71, 2005:

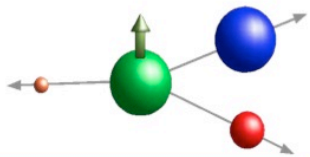
$$4\left(-\bar{\alpha}^{(3)}_{\varphi l} + \bar{\alpha}^{(3)}_{\varphi q} - \bar{\alpha}^{(3)}_{lq} + \bar{\alpha}^{(3)}_{ll}\right) = -(4.7\pm 2.9)\cdot 10^{-3}$$

5 times less precise!



IFIC seminar

Angular/Energy distribution



$$\mathcal{L}_{n\to pe^-\bar{\nu}_e} \sim \bar{e}_L\gamma_\mu\nu_L\cdot\bar{p}\left(\gamma^\mu - \tilde{\lambda}_A\gamma^\mu\gamma_5\right)n + \lambda_S\,\epsilon_S\,\bar{e}_R\nu_L\cdot\bar{p}n + 2\lambda_T\,\epsilon_T\,\bar{e}_R\sigma_{\mu\nu}\nu_L\cdot\bar{p}\sigma^{\mu\nu}n_L$$

(spectrum)

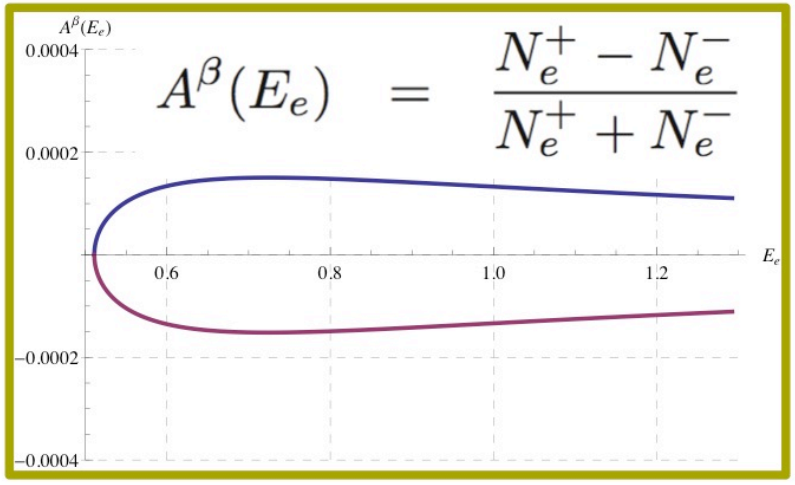
Angular distribution altered... and E-dependent!

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

$$b \approx 0.3\,\lambda_S\,\epsilon_S - 5.0\,\lambda_T\,\epsilon_T$$

$$b_B - b \approx 0.1\,\lambda_S\,\epsilon_S - 0.3\,\lambda_T\,\epsilon_T$$

Neutron β decay experimentalists language



IFIC seminar

Limits from leptonic pion decays

- Pion decay $R_\pi \equiv \dfrac{\Gamma(\pi \to e\nu)}{\Gamma(\pi \to \mu\nu)}$

$$|\varepsilon_T| \leq 10^{-5} - 10^{-3}$$
$$|\varepsilon_S| \leq 10^{-3} - 10^{-1}$$

  - Strong limits on the flavor structure of ε_P:

$$\frac{R_\pi}{R_\pi^{\rm SM}} = \frac{\left[\left(1-\frac{B_0}{m_e}\epsilon_P^{ee}\right)^2 + \left(\frac{B_0}{m_e}\epsilon_P^{e\mu}\right)^2 + \left(\frac{B_0}{m_e}\epsilon_P^{e\tau}\right)^2\right]}{\left[\left(1-\frac{B_0}{m_\mu}\epsilon_P^{\mu\mu}\right)^2 + \left(\frac{B_0}{m_\mu}\epsilon_P^{\mu e}\right)^2 + \left(\frac{B_0}{m_\mu}\epsilon_P^{\mu\tau}\right)^2\right]}$$

$$-1.4\times10^{-7} < \epsilon_P^{ee} < 5.5\times10^{-4}$$

Where…

$$\mathcal{L}_{\rm eff} \supset \frac{G_F}{\sqrt{2}} V_{ud}\, \epsilon_P^{\alpha\beta}\ \ \bar{e}_\alpha(1-\gamma_5)\nu_\beta \cdot \bar{u}\gamma_5 d$$

$$B_0(\mu) \equiv \frac{M_\pi^2}{m_u(\mu)+m_d(\mu)}$$

  - S, T generate P through loops: (Voloshin'92, Campbell-Maybury'05)

$$\frac{-1.4\times10^{-7}}{\log(\Lambda/\mu)} < \gamma_{SP}\,\epsilon_S + \gamma_{TP}\,\epsilon_T < \frac{5.5\times10^{-4}}{\log(\Lambda/\mu)}$$

$$\gamma_{SP} = \frac{15}{72}\frac{\alpha_1}{\pi} \approx 6.7\times10^{-4}$$
$$\gamma_{TP} = -\frac{9}{2}\frac{\alpha_2}{\pi} - \frac{15}{2}\frac{\alpha_1}{\pi} \approx -7.3\times10^{-2}$$

***RH neutrinos can also make the job (Herczeg'94)**

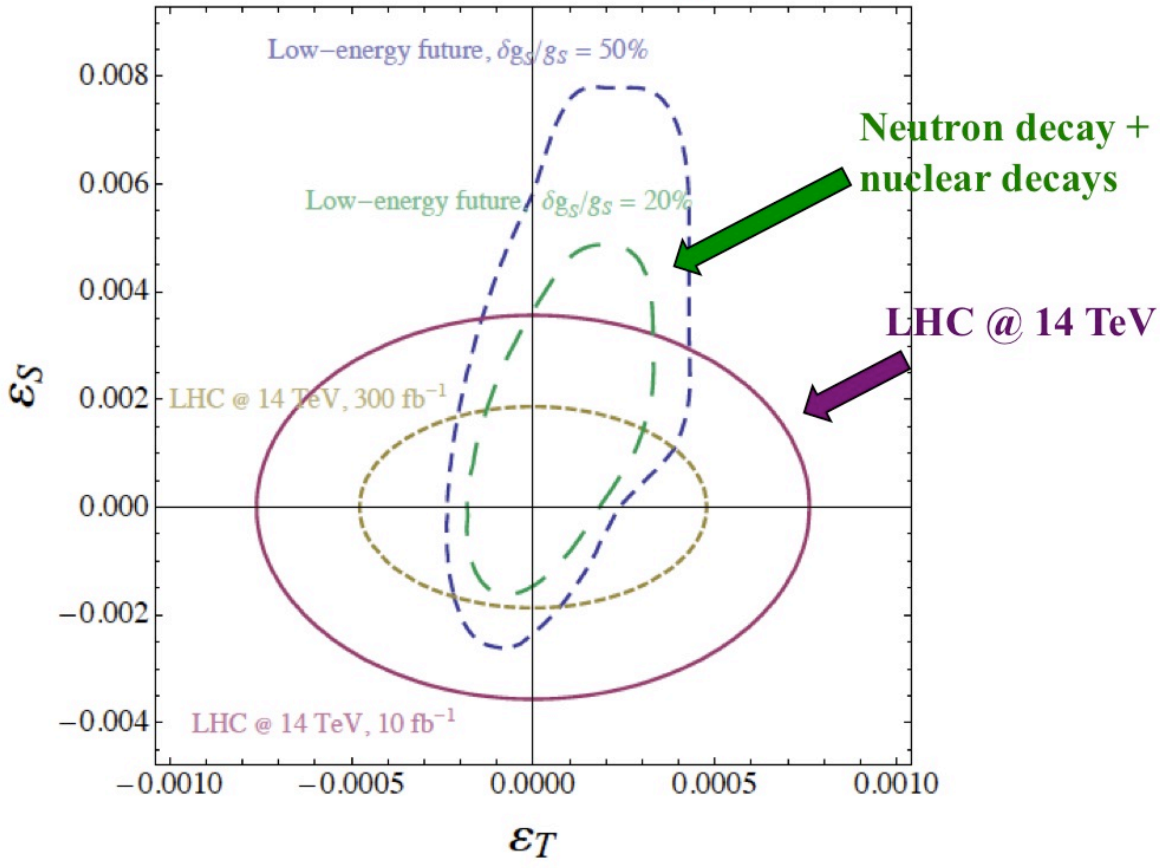
LHC limits on $\varepsilon_{S,T}$

- EFT approach:

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

- Estimate of future bounds:
  assuming n=0 with $m_T > 2.5(4.0)$ TeV
  - 14 TeV, 10 fb^{-1};
  - 14 TeV, 300 fb^{-1};

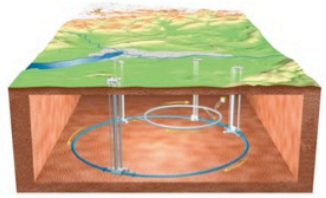
Bhattacharya et al.'2012



Comment:
Sizable QCD running of $\varepsilon_{S,T}$:

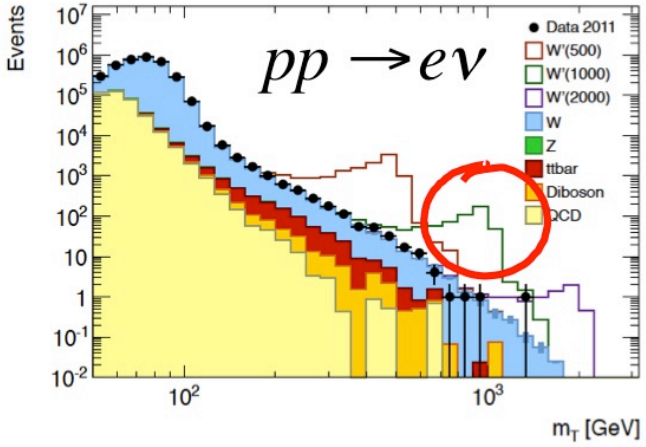
$$\varepsilon_S(\mu = 2\ \mathrm{GeV}) = 1.79\ \varepsilon_S(\mu = 1\ \mathrm{TeV})$$
$$\varepsilon_T(\mu = 2\ \mathrm{GeV}) = 0.83\ \varepsilon_T(\mu = 1\ \mathrm{TeV})$$

Scalar resonance



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

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



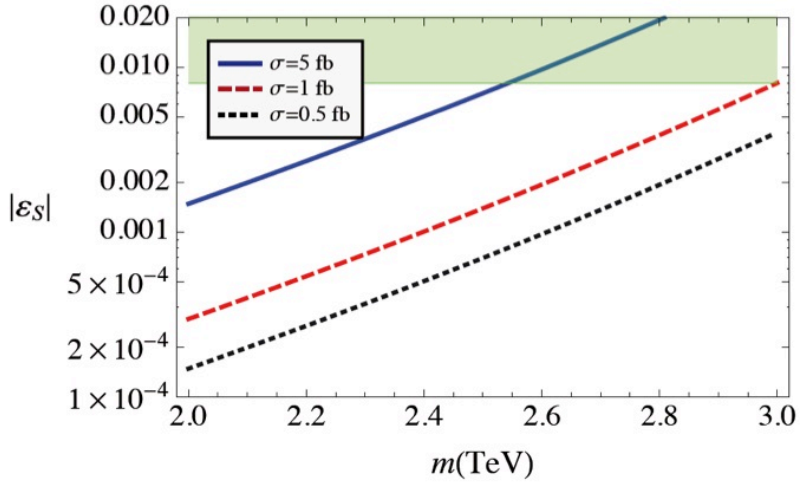
- Then we have a lower-limit value for ε_S:

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

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

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

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



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

[T. Battacharya et al., 2012]