Beta decays in the LHC era:

from ultracold neutrons to colliders

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Motivation & goals

$$d^j \to u^i l \bar{\nu}_l$$

- Very precise measurements in some low-energy experiments (errors ~ 0.1%);
- Very precise theoretical (th+lat) SM-calculations for these processes (errors < 0.1%);

➔ The agreement between data and SM-predictions puts strong constraints on the physics that lie beyond the SM;

$\pi^+ \to \pi^0 e^+ \nu_e$

$\pi^+ \to l^+ \nu_l$

$K \to \pi l \nu_l$

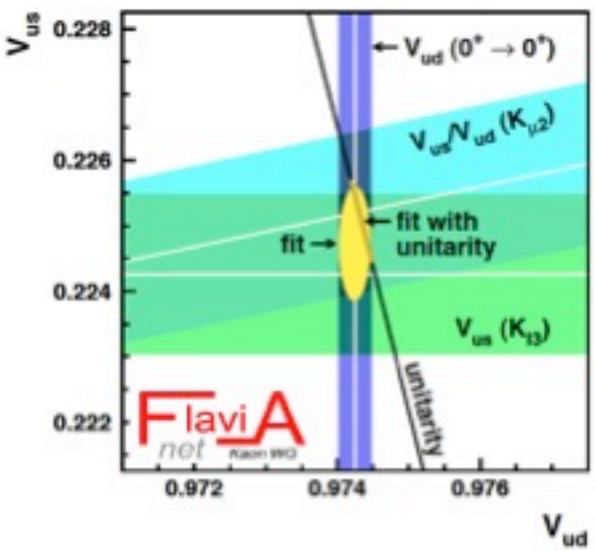
$K^+ \to l^+ \nu_l$

n decay

$0^+ \to 0^+$

...

$(\mu \to e \bar{\nu}_e \nu_\mu)$



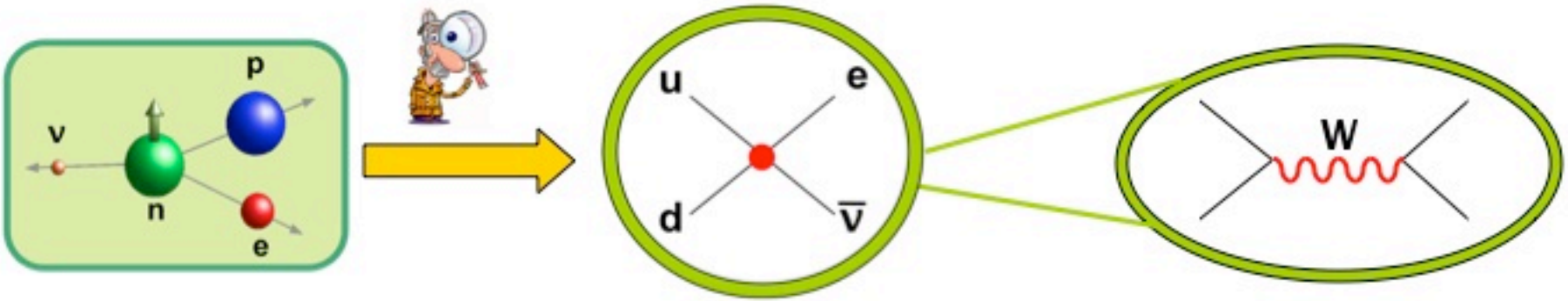
Questions:

What kind of NP can we probe with SL beta decays?

Which is the best process?

Motivation & goals

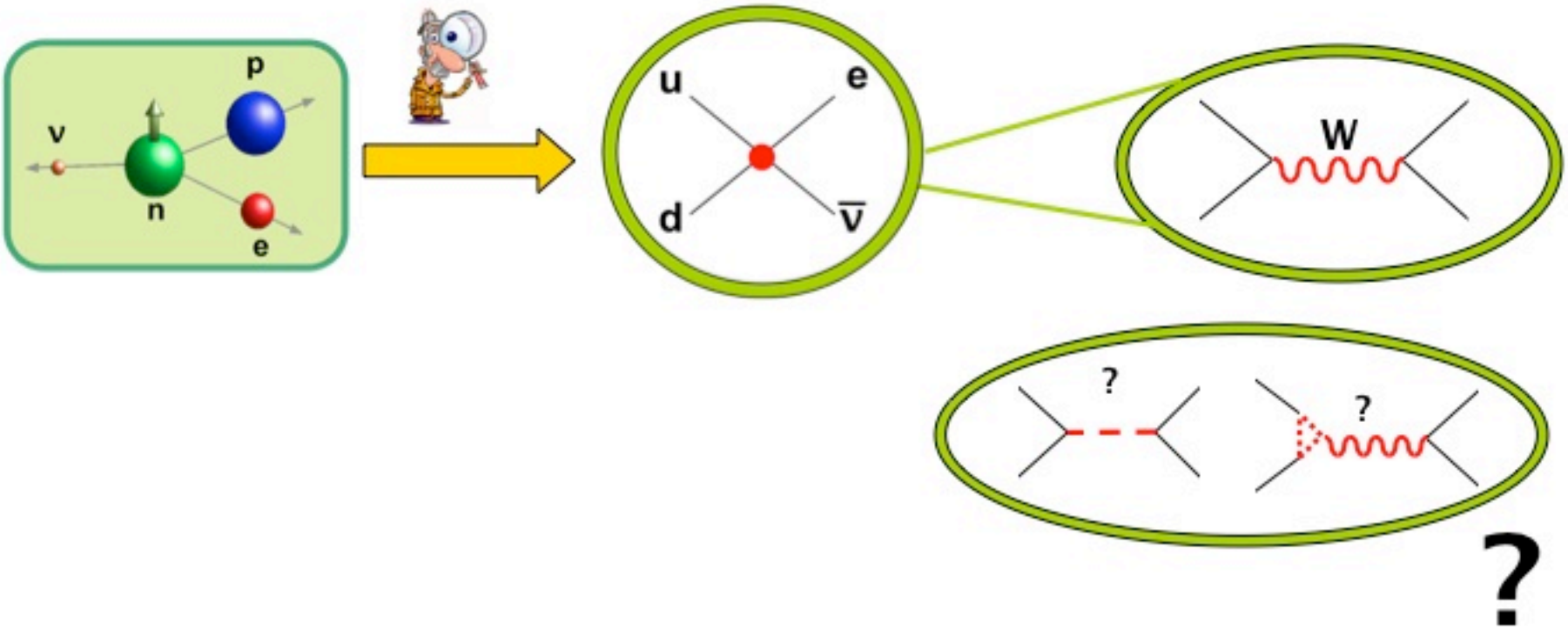
$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L\right]$$



Motivation & goals

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

Model-independent analysis



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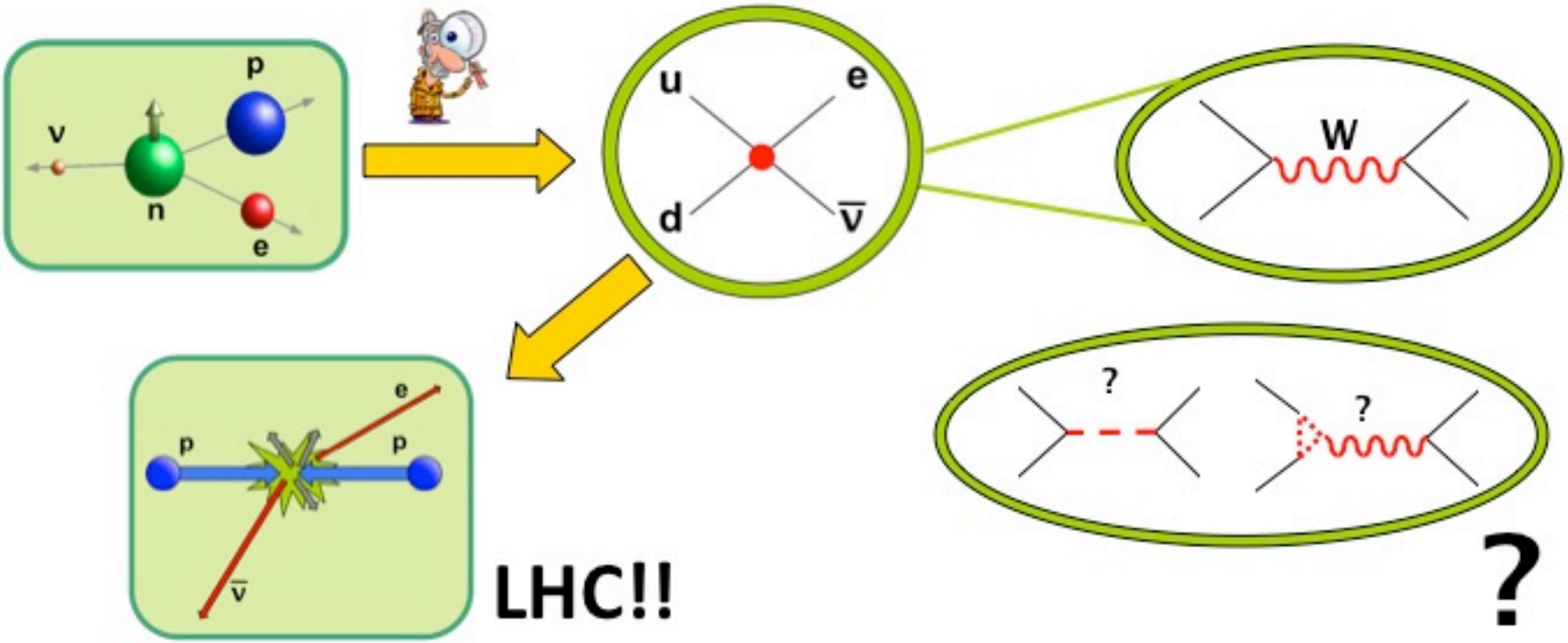


Outline

- Introduction and motivation; ✓
- EFT approach;
- LOW-ENERGY:
  Neutron beta decay measurements and other low-energy probes;
- HIGH ENERGY:
  NP bounds on these couplings from LHC measurements;

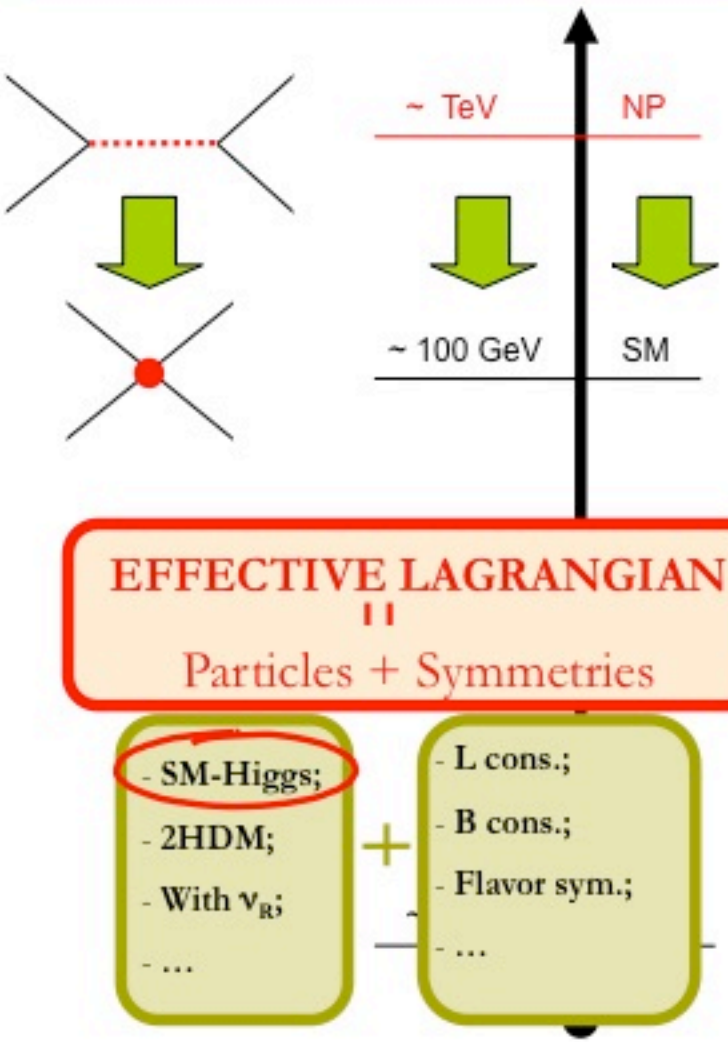
Cirigliano, MGA & Jenkins'2010

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

Cirigliano, MGA & Graesser (in preparation)

Abele, MGA, Pitschmann, Ramsey-Musolf (in preparation)

The eff. Lagrangian for E~100 GeV



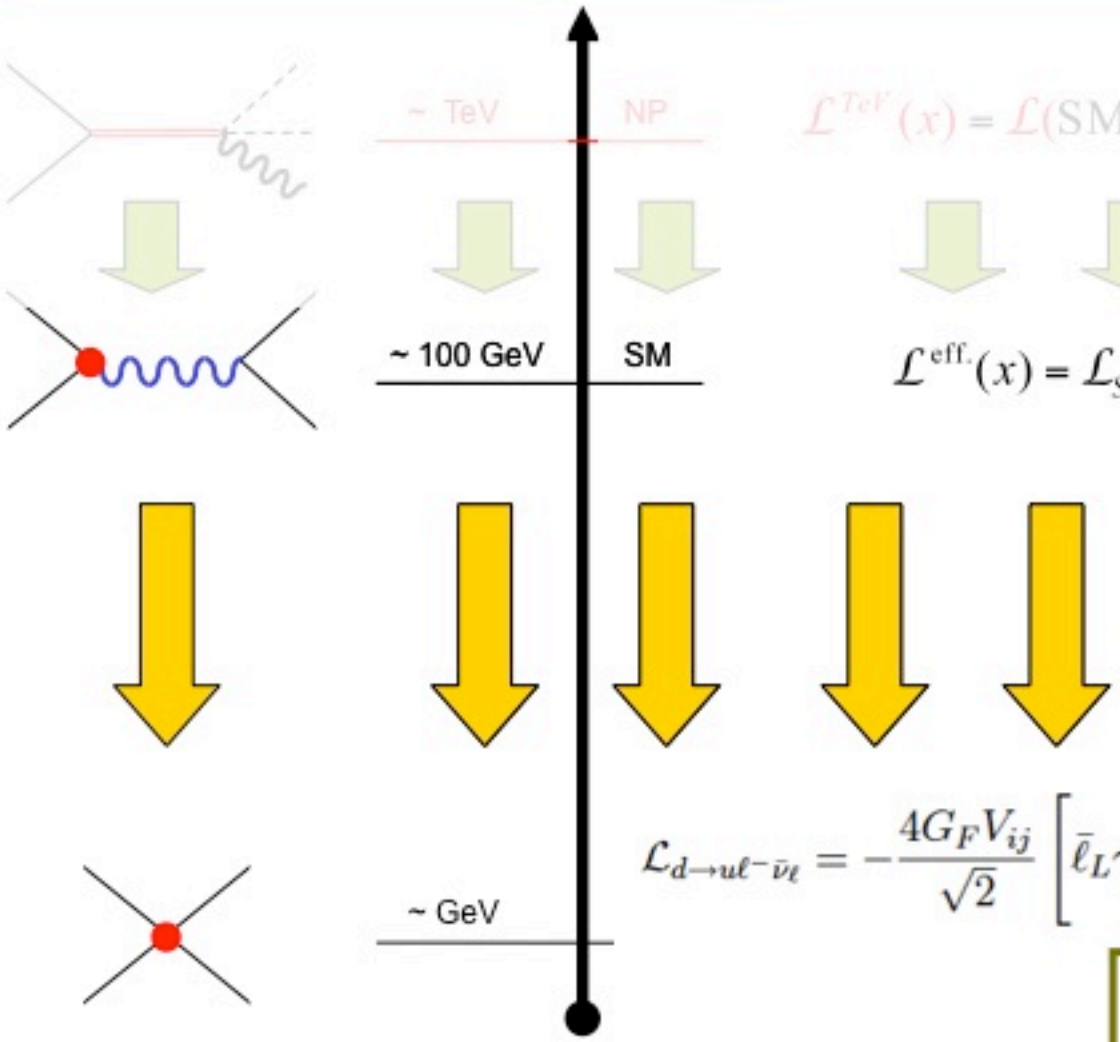
$$\mathcal{L}^{TeV}(x) = \mathcal{L}(\text{SM-fields, bSM-fields})$$

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

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

$$\left(\mathcal{L}_n(x) = \sum_i \alpha_i^{(n)} O_i^{(n)}(x)\right)$$

The eff. Lagrangian for E~1 GeV



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

$$\left(\mathcal{L}_6(x) = \sum_i^{25} \alpha_i O_i(x)\right)$$

[Cirigliano, MGA, Jenkins'2010
Cirigliano, MGA, Graesser, in preparation]

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

$$\boxed{\varepsilon = \sum c_i\alpha_i\frac{v^2}{\Lambda^2}}$$ *(v ≈ 174 GeV)*

The eff. Lagrangian for E~1 GeV

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

- Beta decay: $d^j \to u^i l \bar{\nu}_l$

$$\mathcal{L}^{eff}_{d^j \to u^i l \bar{\nu}_l}(x) = \frac{-g^2}{2m_W^2} V_{ij} \left[\begin{array}{l} \overset{\text{(V-A)}\bullet\text{(V-A)}}{(1+\varepsilon_L)(\bar{u}^i_L \gamma^\mu d^j_R)(\bar{l}_L \gamma_\mu \nu_{lL})} + \overset{\text{(V+A)}\bullet\text{(V-A)}}{\varepsilon_R (\bar{u}^i_R \gamma^\mu d^j_R)(\bar{l}_L \gamma_\mu \nu_{lL})} \\ \\ + \overset{\text{(S-P)}\bullet\text{(S+P)}}{\varepsilon^S_L (\bar{u}^i_R d^j_L)(\bar{l}_R \nu_{lL})} + \overset{\text{(S+P)}\bullet\text{(S+P)}}{\varepsilon^S_R (\bar{u}^i_L d^j_R)(\bar{l}_R \nu_{lL})} \\ \\ + \overset{\text{(T-T')}\bullet\text{(T-T')}}{\varepsilon_T (\bar{u}^i_R \sigma^{\mu\nu} d^j_L)(\bar{l}_R \sigma_{\mu\nu} \nu_{lL})} \end{array} \right] + h.c.$$

where…

$$\begin{aligned} V_{ij} \cdot [\varepsilon_L]_{\ell\ell ij} &= 2 V_{ij} \left[\hat{\alpha}^{(3)}_{\varphi l}\right]_{\ell\ell} + 2 V_{im} \left[\hat{\alpha}^{(3)}_{\varphi q}\right]^*_{jm} - 2 V_{im} \left[\hat{\alpha}^{(3)}_{lq}\right]_{\ell\ell mj} \\ V_{ij} \cdot [\varepsilon_R]_{\ell\ell ij} &= -[\hat{\alpha}_{\varphi\varphi}]_{ij} \\ V_{ij} \cdot [\varepsilon^S_L]_{\ell\ell ij} &= -[\hat{\alpha}_{lq}]^*_{\ell\ell ji} \\ V_{ij} \cdot [\varepsilon^S_R]_{\ell\ell ij} &= -V_{im} [\hat{\alpha}_{qde}]^*_{\ell\ell jm} \\ V_{ij} \cdot [\varepsilon_T]_{\ell\ell ij} &= -\left[\hat{\alpha}^t_{lq}\right]^*_{\ell\ell ji} \ . \end{aligned}$$

The effective Lagrangians

- Beta decay:

$$\mathcal{L}^{eff}_{d^j \to u^i l \bar{\nu}_l}(x) = \ldots \quad \Rightarrow \quad \Gamma(K_{l3}),\ \frac{\Gamma(K_{l2})}{\Gamma(\pi_{l2})},\ \ldots \quad \Rightarrow \quad |\varepsilon| \leq \ldots$$

- Colliders:

$$\mathcal{L}^{\text{eff.}}(x) = \mathcal{L}_{SM}(x) + \frac{1}{\Lambda^2}\mathcal{L}_6(x) \quad \Rightarrow \quad \text{Cross sections, } \ldots \quad \Rightarrow \quad |\alpha| \leq \ldots$$

$$\left(\mathcal{L}_6(x) = \sum_i^{25} \alpha_i O_i(x)\right)$$

- With our matching conditions we can compare!

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- HIGH ENERGY:
  NP bounds on these couplings from LHC measurements;
  - Detail analysis for S and T;
  - I'll talk about the other NP terms at the end.

Neutron β decay bSM

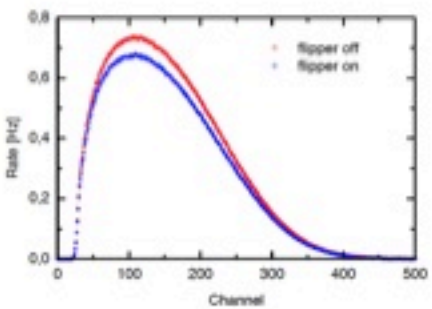
EXPERIMENT

Experimental activity worlwide:

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

Observables:

- *Lifetime;*
- *Spectrum;*
- *Angular distr.;*



THEORY: SM

SM prediction in very good shape!
Known up to quadratic effects in:

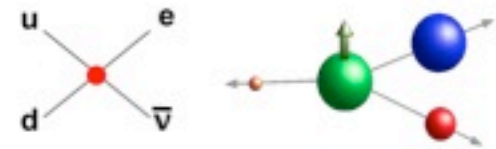
α/π , $\Delta M/M$, $q/M \sim 0.001$

$$O_{th} = O_{th}(G_F V_{ud}, g_A) \qquad \delta O_{th} \sim 10^{-5} - 10^{-6}$$

THEORY bSM

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

Neutron β decay bSM



$$\tilde{\lambda}_A \approx \lambda_A(1-2\epsilon_R)$$

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

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

Lifetime shift ➔ CKM unitarity

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

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

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

Marciano'2008

Cirigliano, MGA & Jenkins'2010

Neutron β decay bSM

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

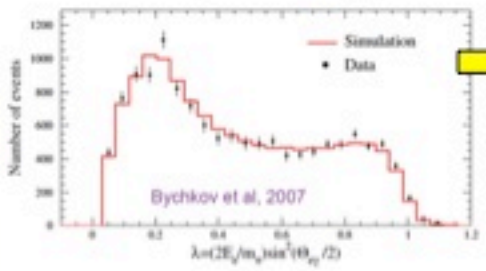
$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu}\sim\xi(E)\left\{1+a\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+b\frac{m_e}{E_e}+A\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J}+(B+b_B\frac{m_e}{E_e})\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$

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

Form factors needed!

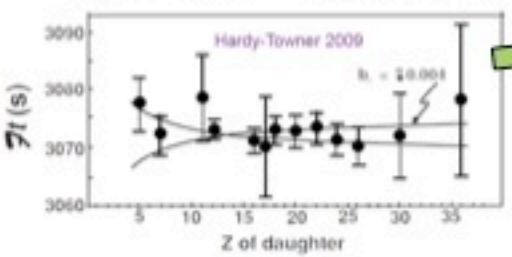
What do we know about S/T from other low-E exp.?

Radiative pion decay (PIBETA´2009)



f_T=0.24(4)
(Mateu & Portolés, 2007)

Superallowed nuclear β decays



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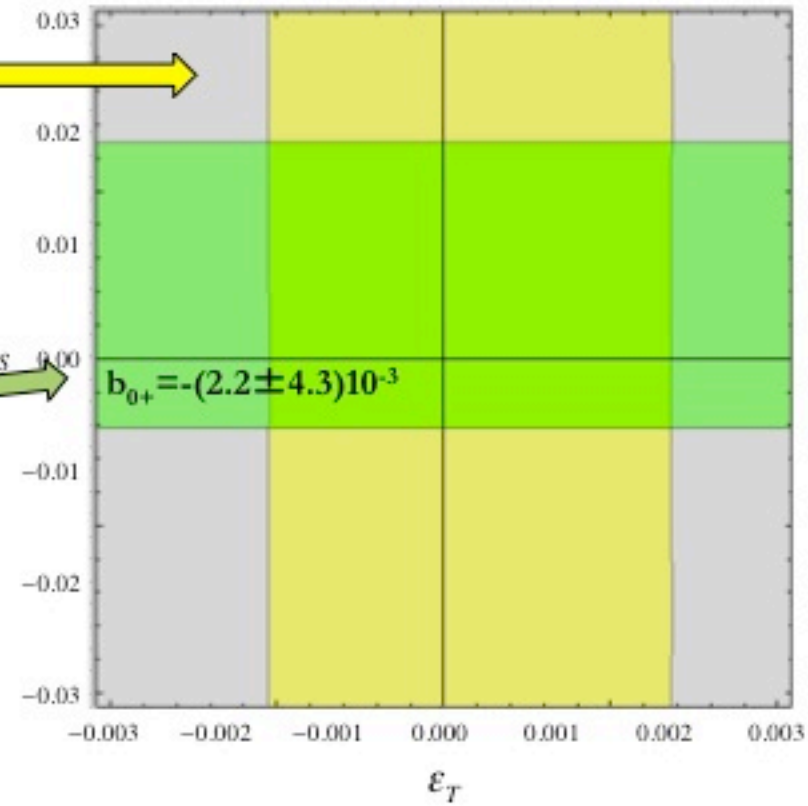

** Pion decay (R_π) also very powerful!*

***Other nuclear decays getting close…*

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

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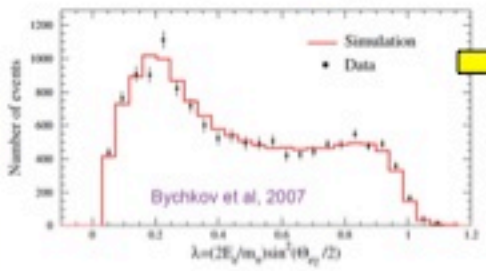

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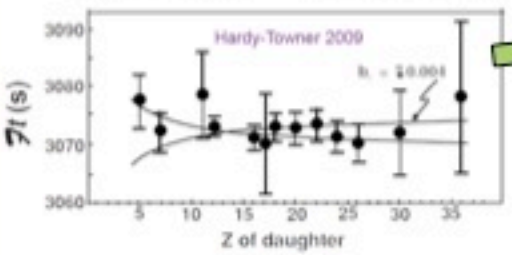

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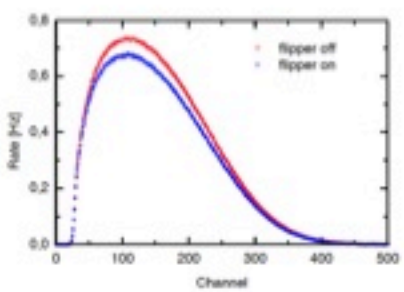
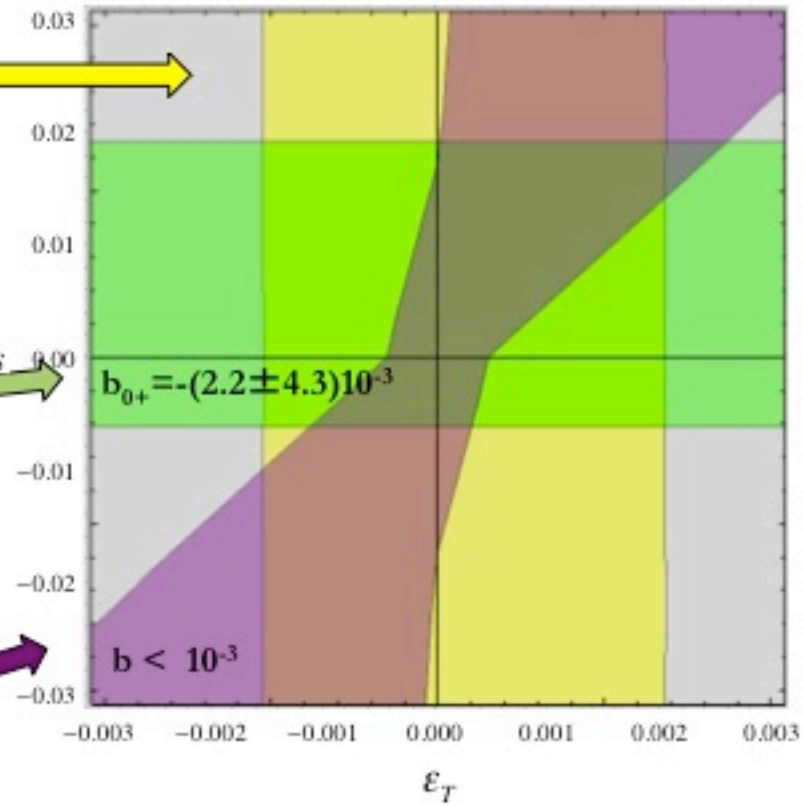
Future neutron decay exp.





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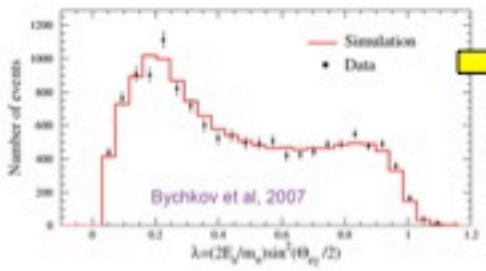

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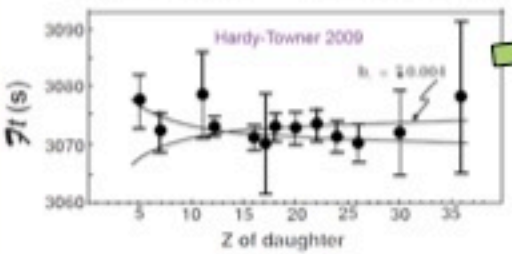

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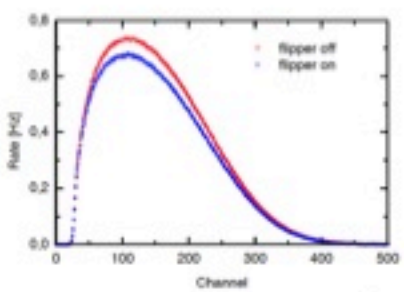

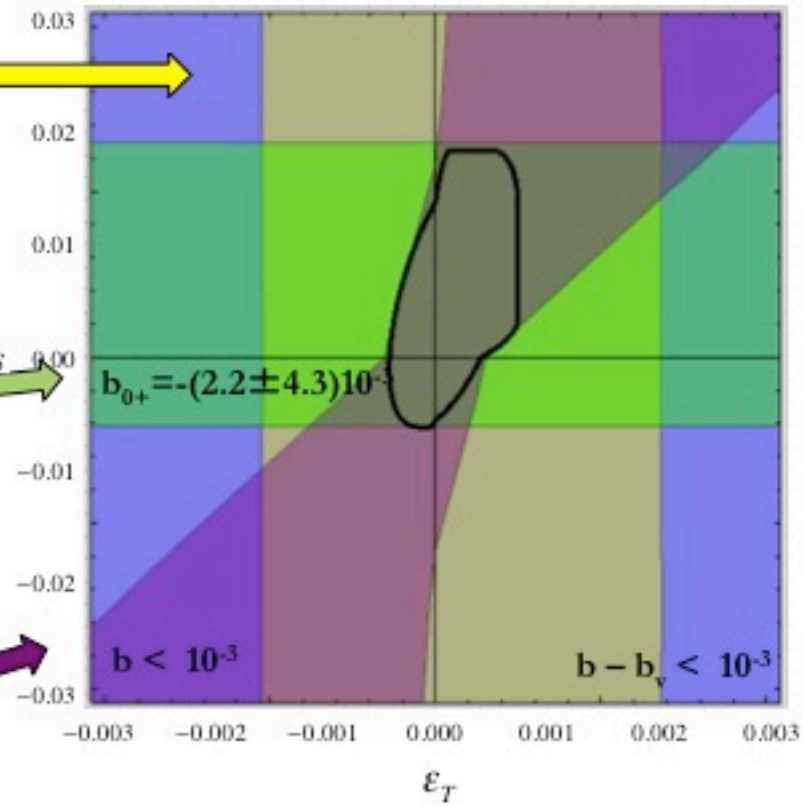

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What do we know about S/T from other low-E exp.?

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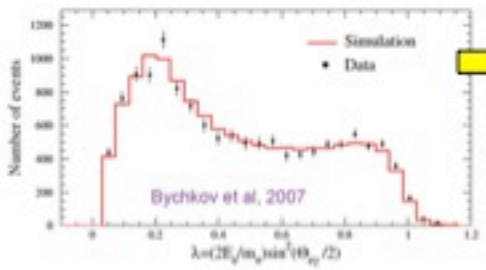

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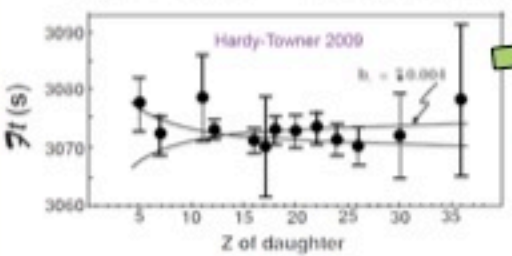

ε_S

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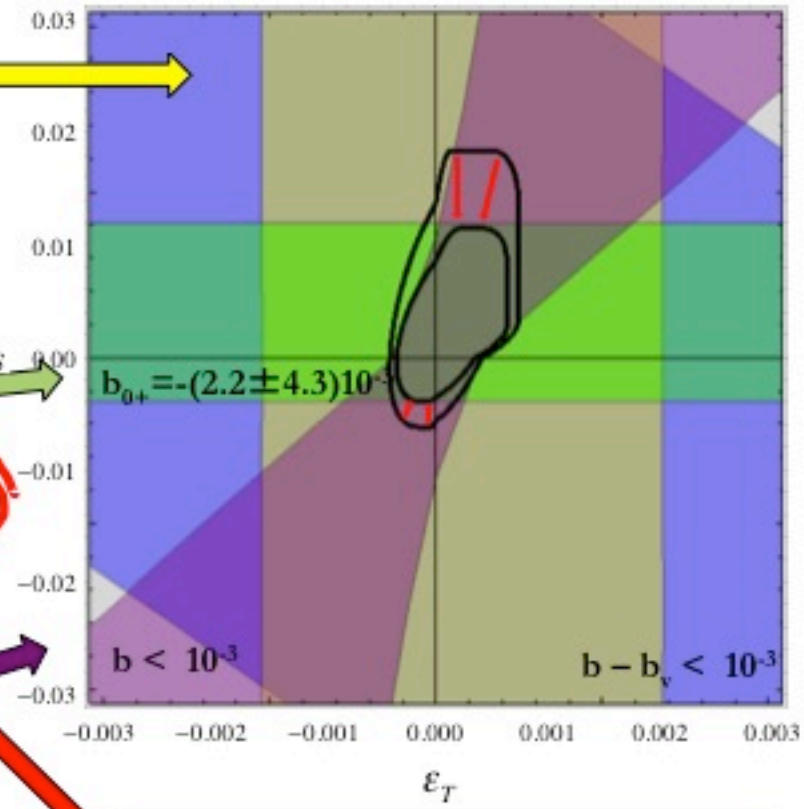

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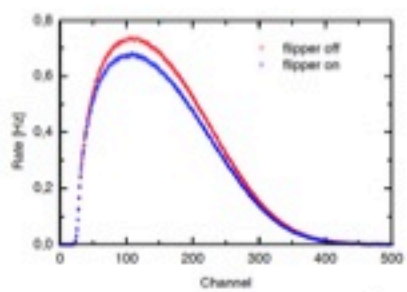

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$b_\nu - b \approx 0.1\, g_S\, \varepsilon_S - 0.3\, g_T\, \varepsilon_T$

LATTICE QCD!!

PNDME Coll.:

T. Bhattacharya, S. Cohen, R. Gupta, A. Joseph, H.W. Lin

g_S=1.05(35) g_T=0.8(4)
(Bhattacharya et al.'2012)

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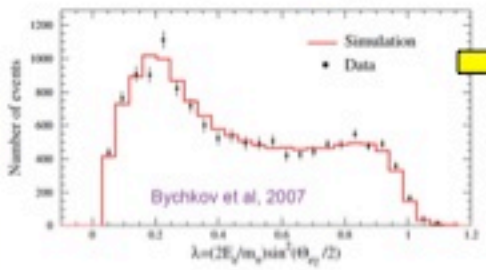

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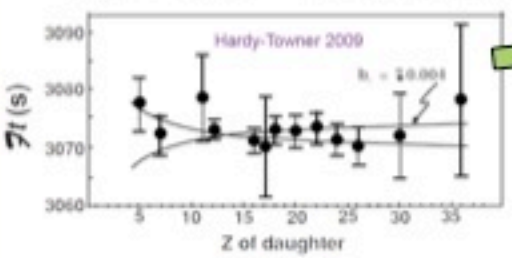

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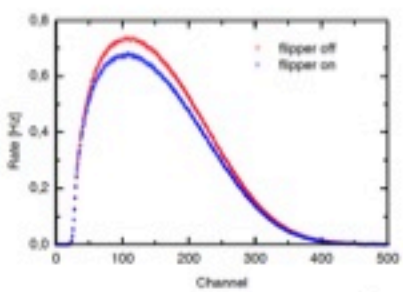

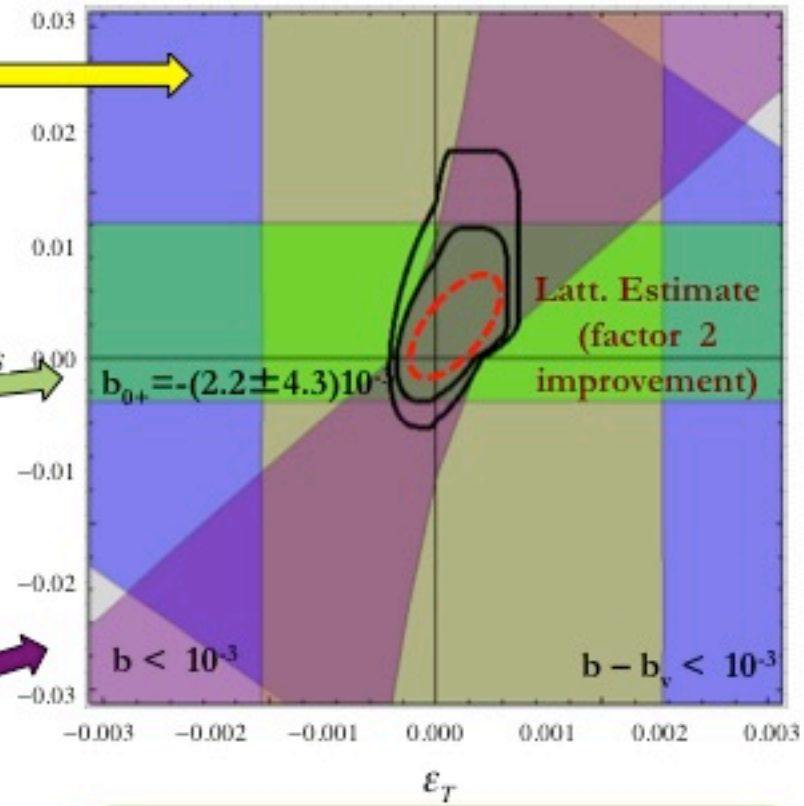

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PNDME Coll.

g_S=1.05(35) g_T=0.8(4)
(Bhattacharya et al.'2012)

g_S=1.08(28) g_T=1.038(11)
(Green et al.'2012)

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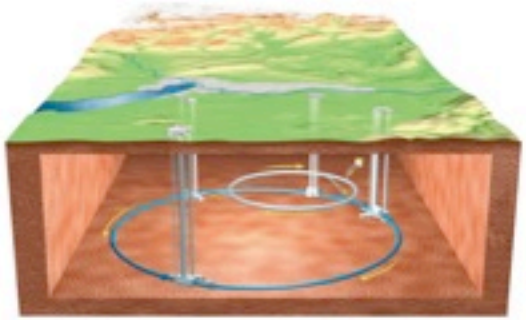
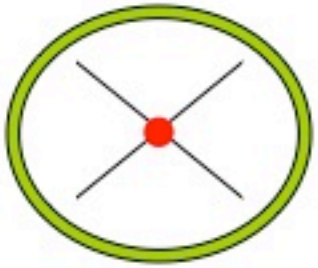
What about the LHC?

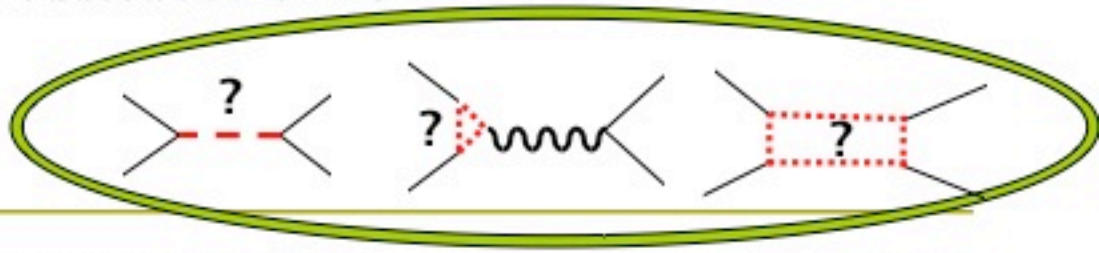


- S and T would affect the pp collisions!
- In principle low-E experiments are favored (interference ~ m/E), but the LHC is powerful…
- There are 2 possible scenarios here:
  - The new particles are too heavy to be produced at the LHC
    ➔ EFT approach still OK!



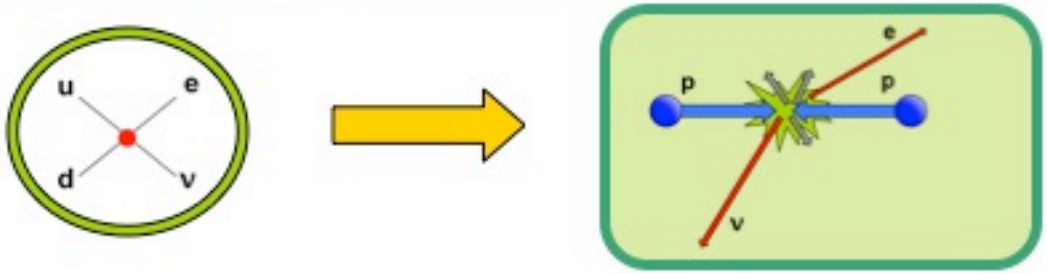
$$O^t_{lq} = (\bar{l}_a \sigma^{\mu\nu} e)\epsilon^{ab}(\bar{q}_b \sigma_{\mu\nu} u) + \text{h.c.} \Rightarrow \bar{e}_R \sigma_{\mu\nu} \nu_L \cdot \bar{p} \sigma^{\mu\nu} n_L$$

  - The new particles can be produced at the LHC
    ➔ Model dependent!



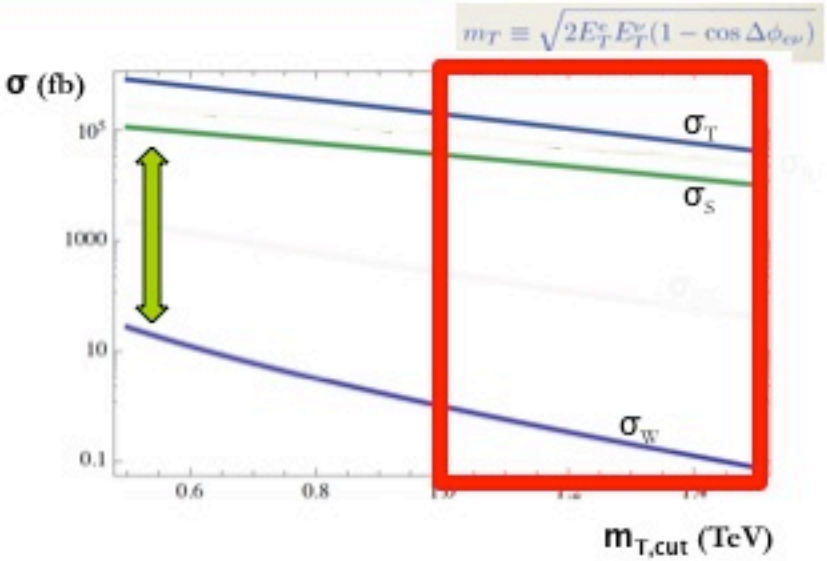
LHC limits on $\varepsilon_{S,T}$

- EFT approach:



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

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



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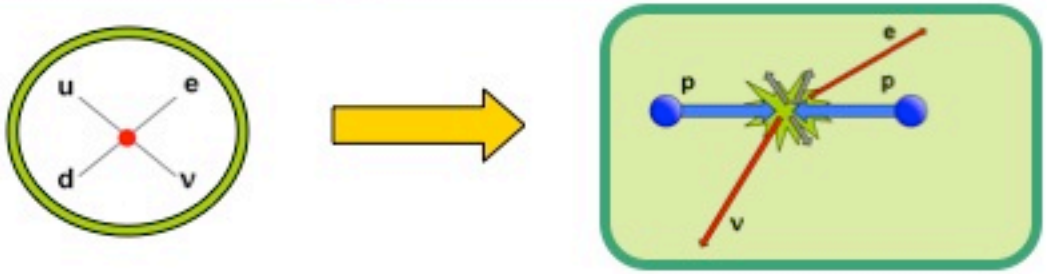

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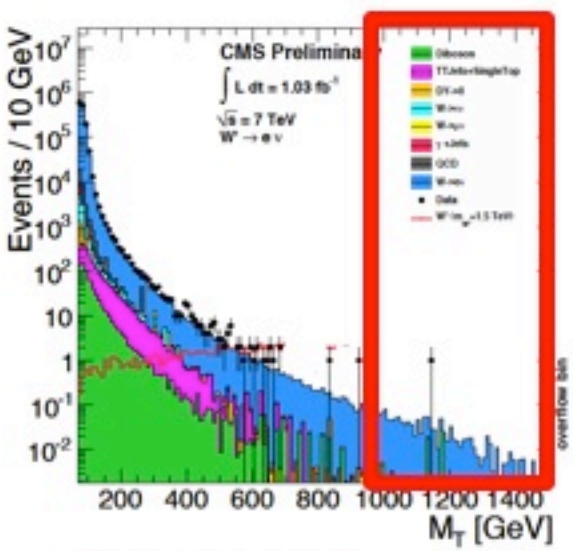
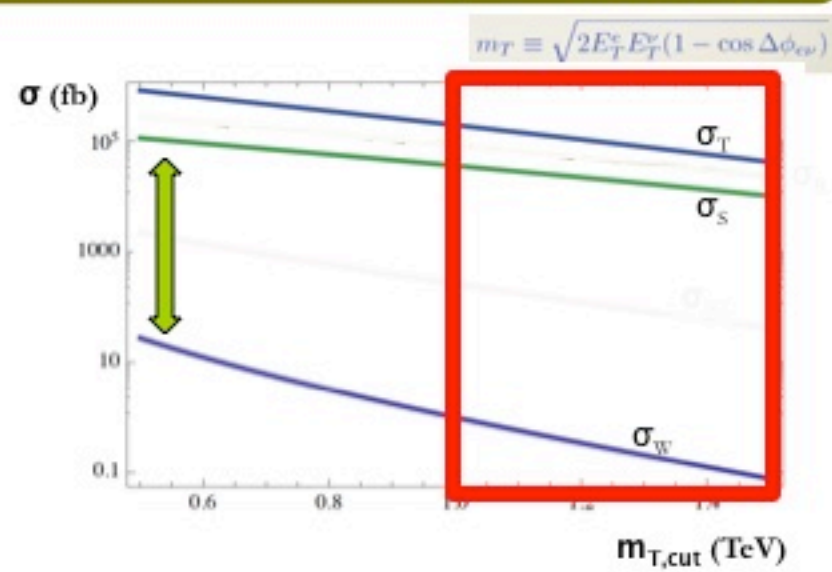


(CMS 1 fb^{-1}, 7 TeV)



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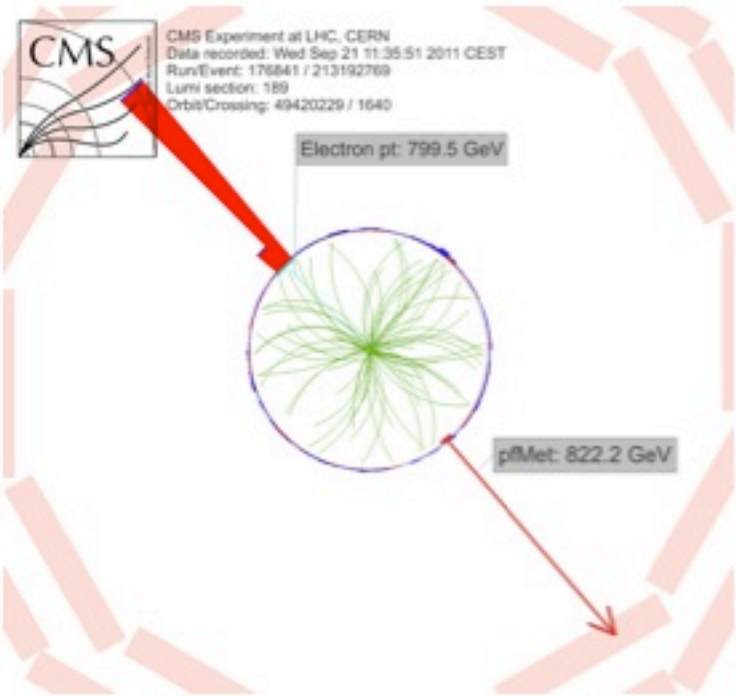

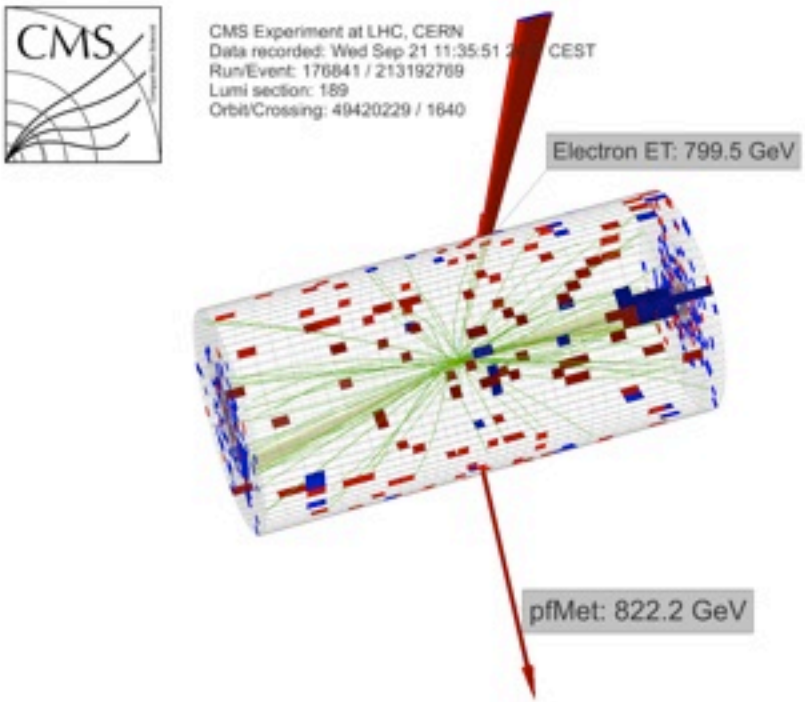

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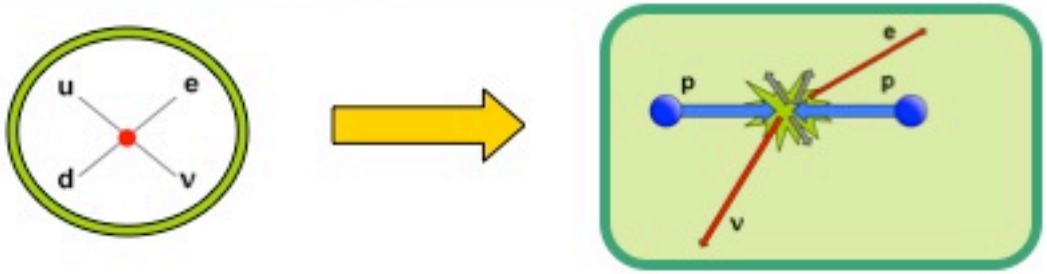

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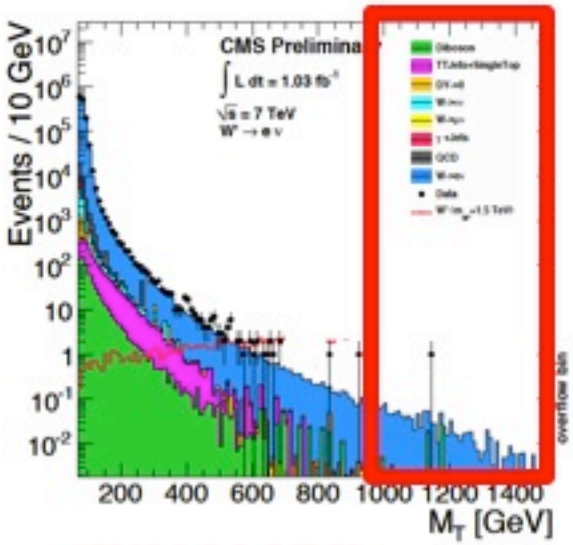

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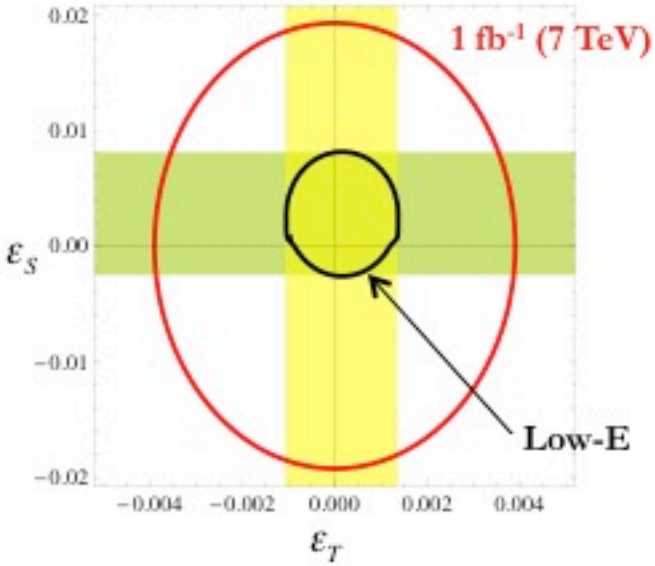

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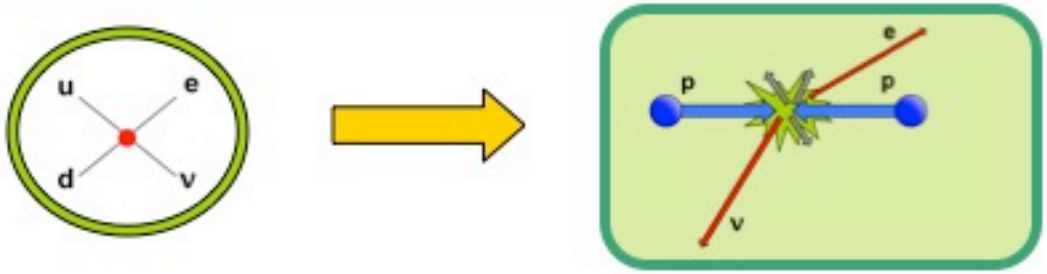

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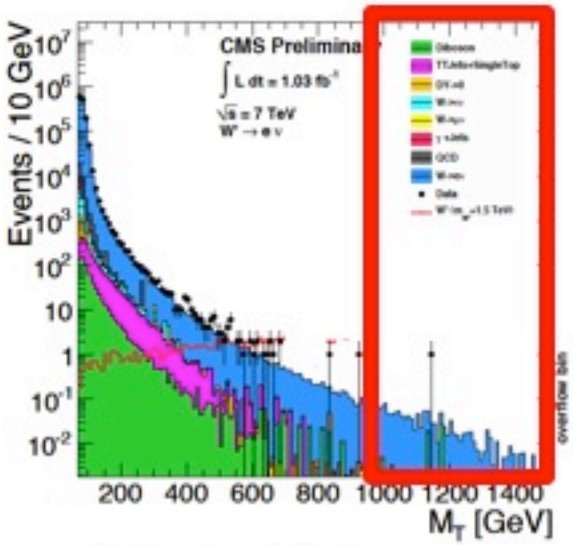

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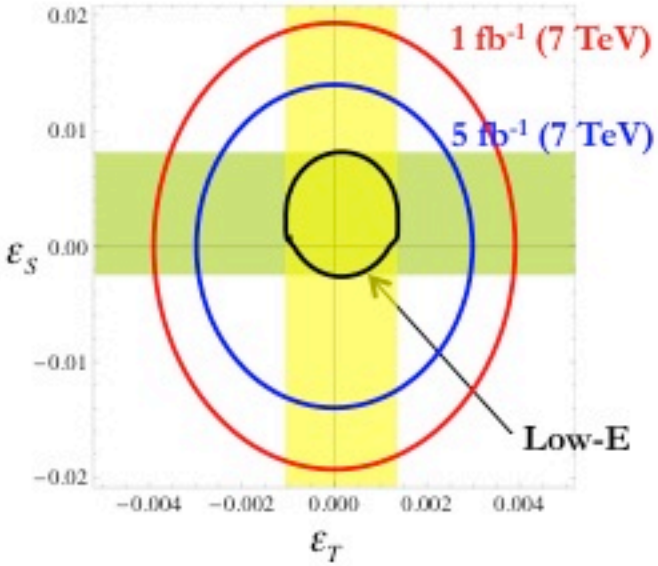

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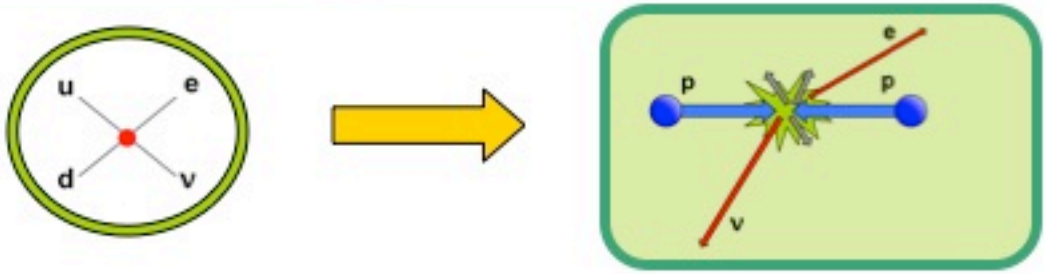

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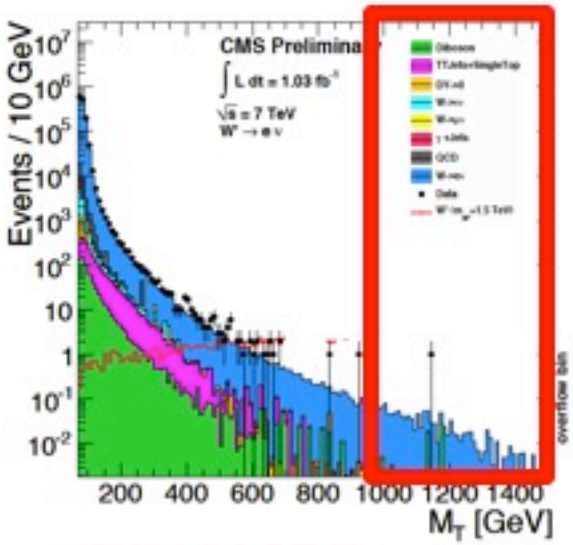

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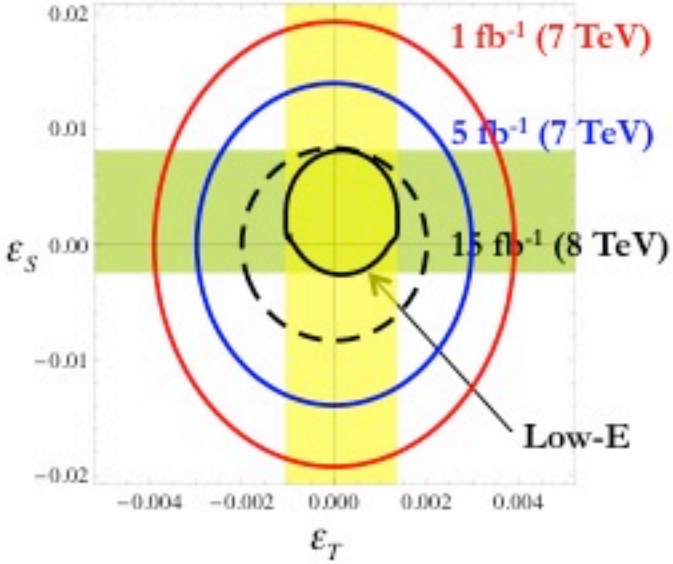

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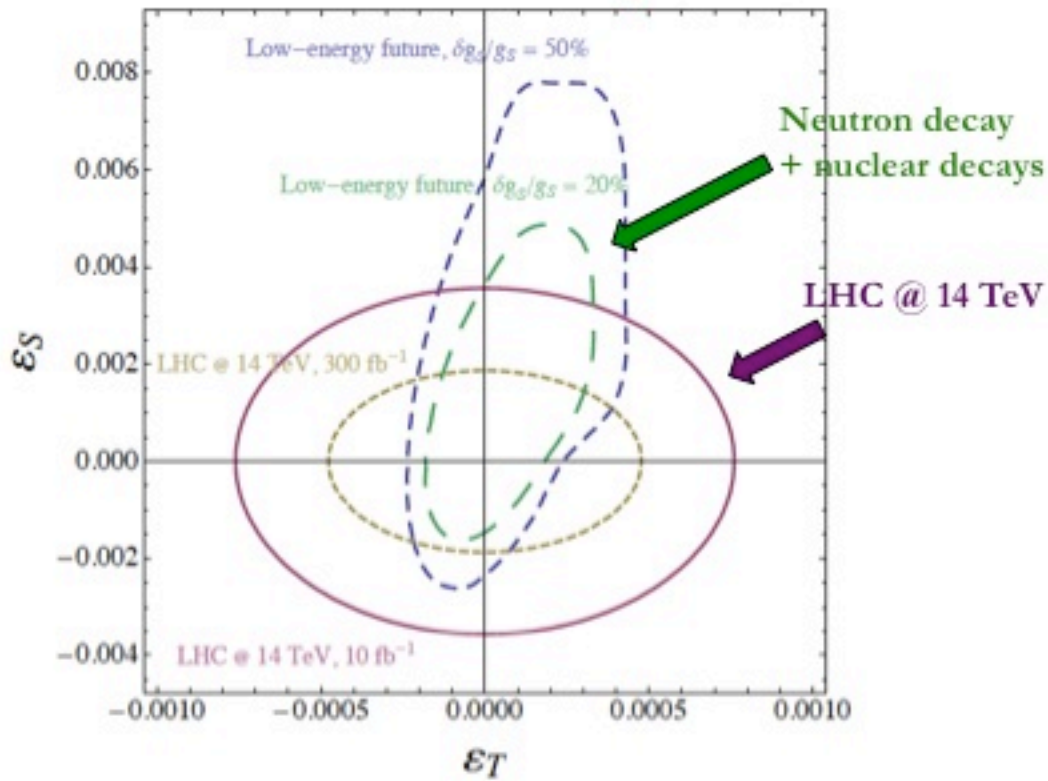
- Estimate of future bounds:
  assuming n=0 with m_T> 2.5(4.0) TeV
  - 14 TeV, 10 fb^{-1};
  - 14 TeV, 300 fb^{-1};

Bhattacharya et al.'2012



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

$$\varepsilon_S(\mu = 2\text{ GeV}) = 1.79\ \varepsilon_S(\mu = 1\text{ TeV})$$

$$\varepsilon_T(\mu = 2\text{ GeV}) = 0.83\ \varepsilon_T(\mu = 1\text{ TeV})$$

What about the other ε_x?

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

- Operators with LH neutrinos: linear effect.
  - S, T: spectrum and angular distributions;
  - L, R: CKM unitarity tests;

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

$\varepsilon \sim 10^{-2} - 10^{-4}$

$\Lambda \sim 2 - 20$ TeV

  - P: Linear sensitivity in pion decay (enhance by $1/m_e$);

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

$\varepsilon \sim 10^{-4} - 10^{-7}$

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    $\varepsilon \sim 10^{-4} - 10^{-7}$, $\Lambda \sim 20 - 600$ TeV
- Operators with RH neutrino: quadratic effect.
  - S, T, L, R: same observables… → $\varepsilon \sim 10^{-1} - 10^{-2}$, $\Lambda \sim 1$ TeV
  - P: The limit is still very strong, due to the mass enhancement. → $\varepsilon \sim 10^{-4} - 10^{-5}$, $\Lambda \sim 40$ TeV

What about the other ε_x?

$$\sigma(m_T > \overline{m}_T) = \sigma_W \left[(1+\epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2\right] - 2\,\sigma_{WL}\,\epsilon_L^{(c)}\left(1+\epsilon_L^{(v)}\right)$$
$$+ \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2\right] + \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2 + |\epsilon_P|^2 + |\tilde{\epsilon}_P|^2\right]$$
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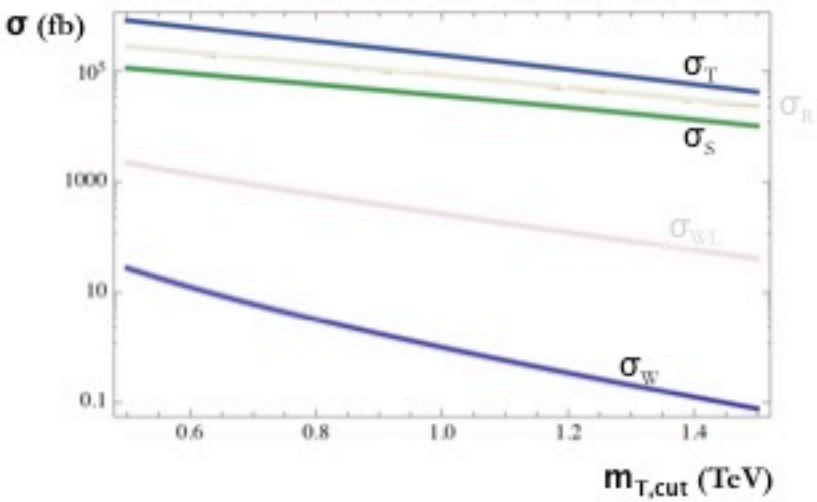
- S,T ➔ LHC almost there… interesting interplay in the future;



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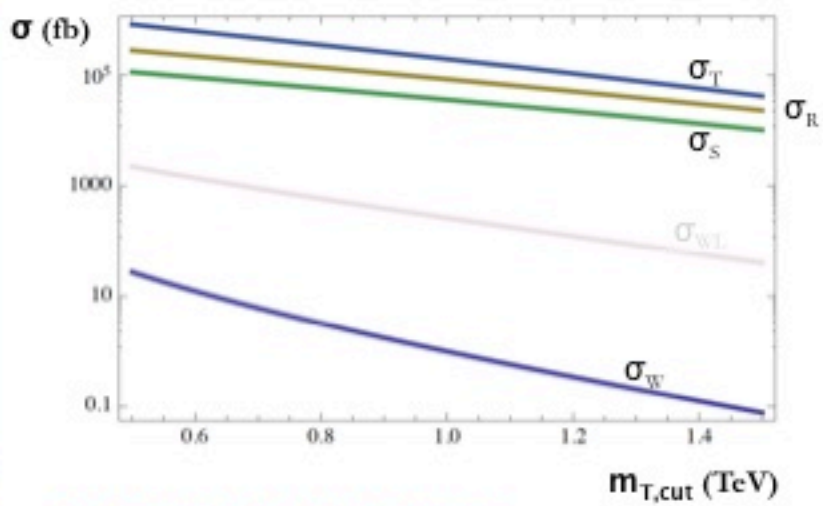
- S,T ➔ LHC almost there… interesting interplay in the future;
- Also strong bounds on S,T,R with RH neutrinos ➔ Difficult for low-E;



Cirigliano, MGA & Graesser, in preparation

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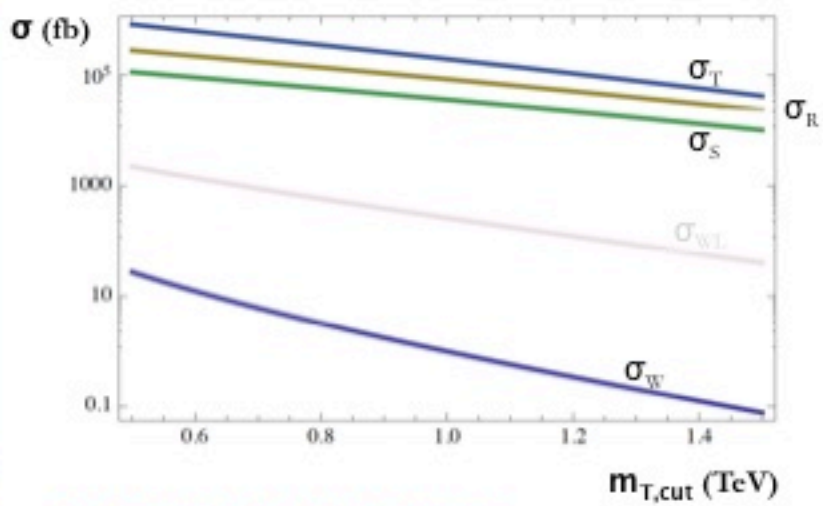

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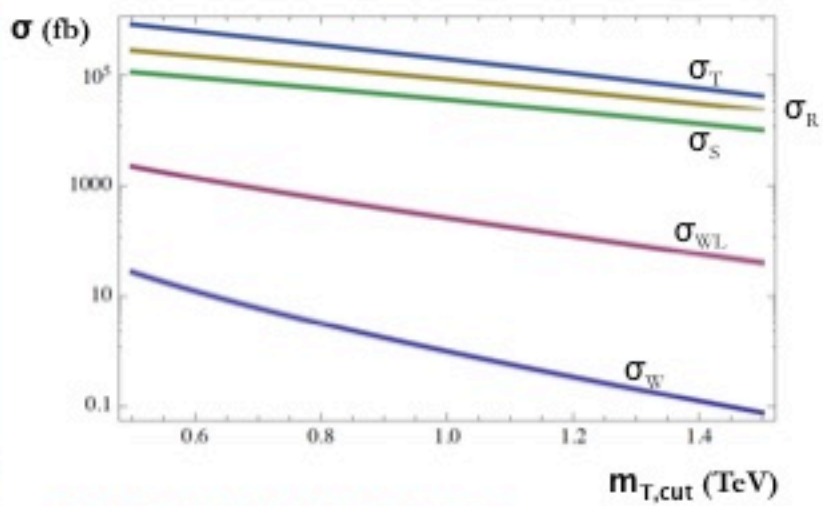
- S,T ➔ LHC almost there… interesting interplay in the future;
- Also strong bounds on S,T,R with RH neutrinos ➔ Difficult for low-E;
- Strong bounds on P, but R_π still ahead;
- LHC not sensitive to L, R ➔ CKM unitarity dominates;

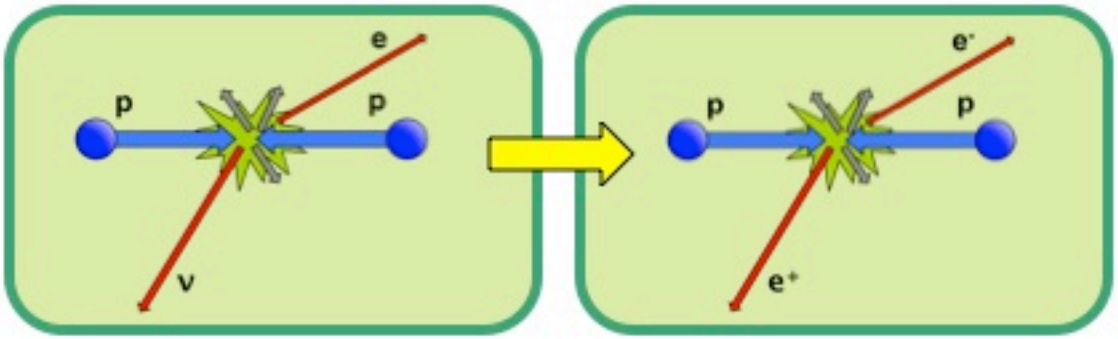


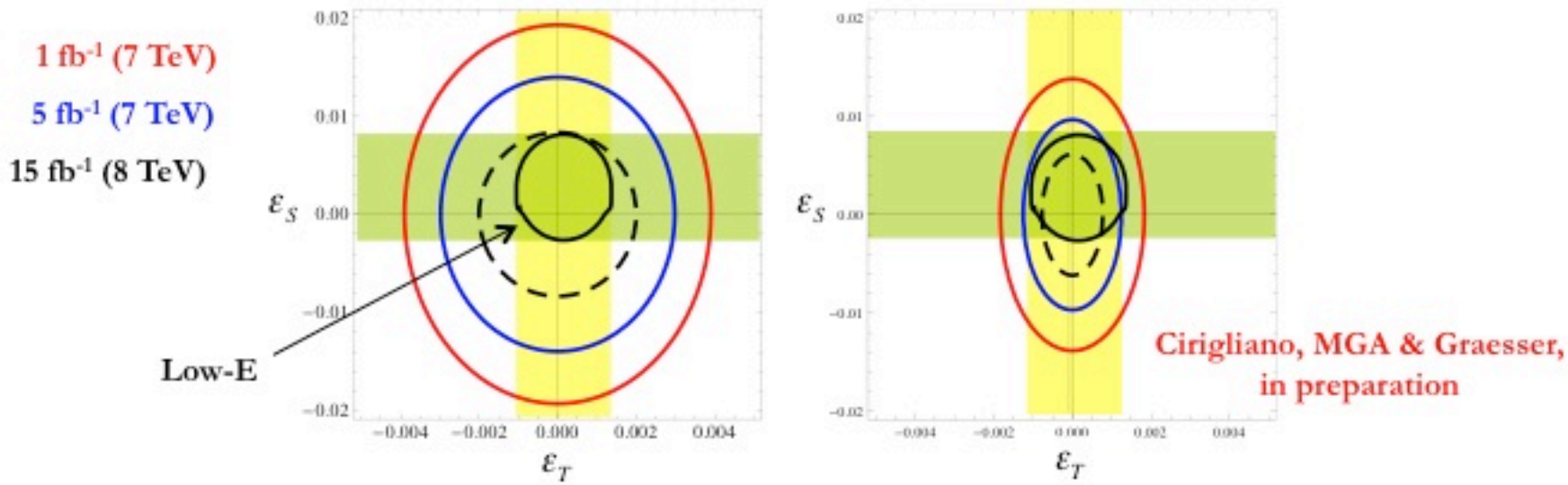
Cirigliano, MGA & Graesser, in preparation

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

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

- Using SU(2) gauge invariance, we can also extract bounds from…

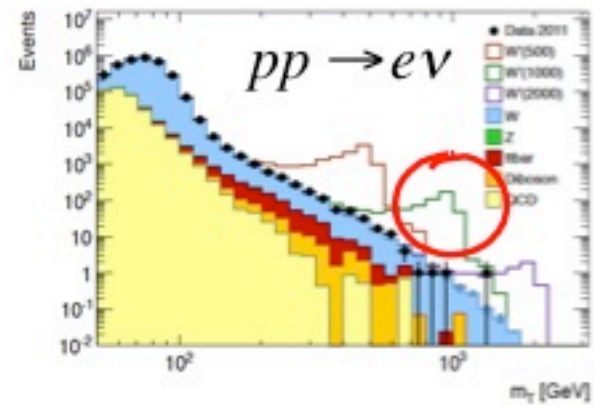




Scalar resonance

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

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



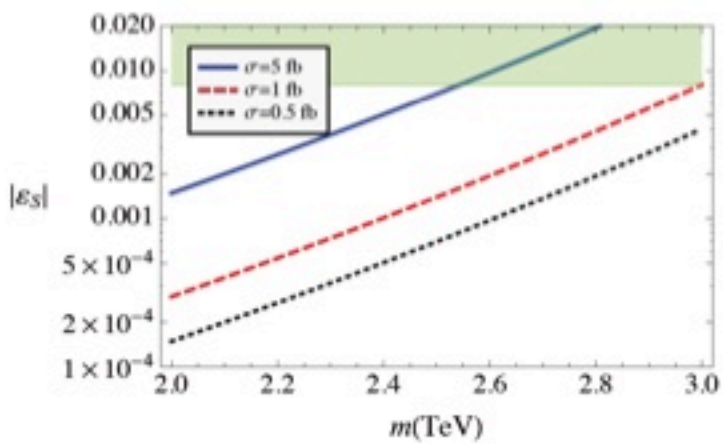
- Then we have a lower-limit value for ε_S:

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

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

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

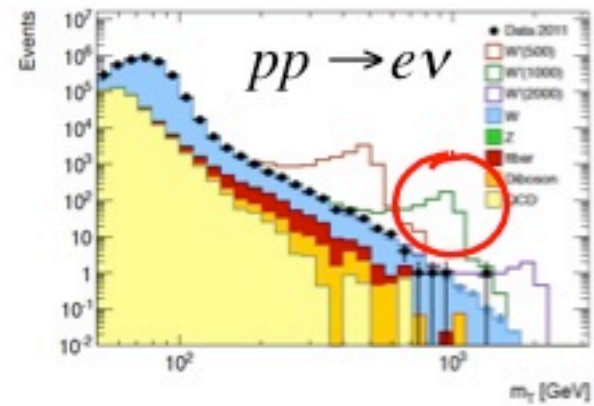
$$\epsilon_S \;=\; 2\lambda_S\lambda_l\frac{v^2}{m^2}$$



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

(T. Battacharya et al., 2012)

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



- 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:

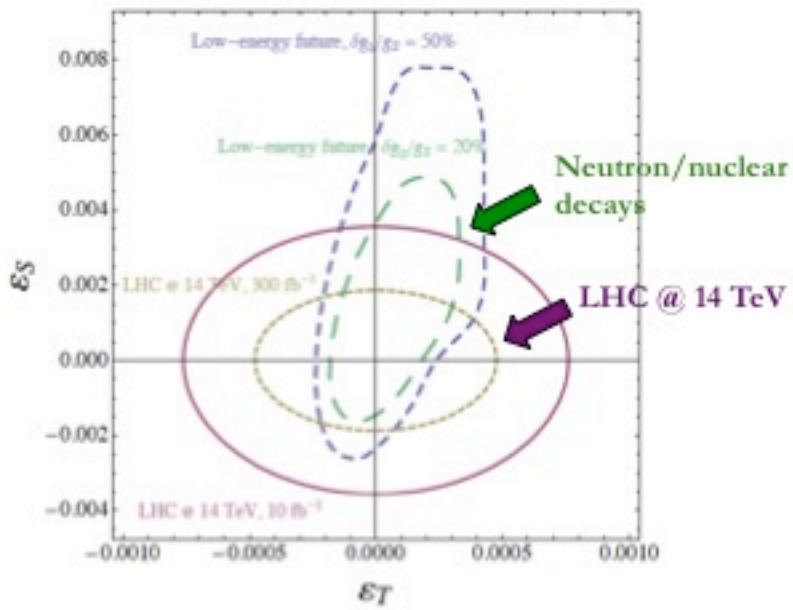
$$\sigma \cdot \mathrm{BR} \leq \frac{|V_{ud}|}{12 v^2} \frac{\pi}{\sqrt{2 N_c}} |\epsilon_S| \tau L(\tau)$$

- If the implied lower bound on eS is smaller than the low-E value of eS…
  - It's not a scalar resonance;
  - It couples to the muon/tau neutrino;
  - There is some cancellation with other scalar resonance or contact interaction…

(T. Battacharya et al., 2012)

Conclusions

- Connecting HEP and β decays: EFT approach (heavy mediators);
- β decays are exploring the TeV scale!
- Interesting interplay between LHC and β decays (+lattice) in the present/future;
- Needless to say, this interplay becomes way more interesting if we see a NP signal!



Backup slides

NP flavor structure

$$i(\varphi^\dagger D^\mu \sigma^a \varphi)\left(\begin{pmatrix}\bar{l}_e\\ \bar{l}_\mu\\ \bar{l}_\tau\end{pmatrix}\gamma_\mu \sigma^a \begin{pmatrix}\alpha_{11} & \alpha_{12} & \alpha_{13}\\ \alpha_{21} & \alpha_{22} & \alpha_{23}\\ \alpha_{31} & \alpha_{32} & \alpha_{33}\end{pmatrix}\begin{pmatrix} l_e & l_\mu & l_\tau\end{pmatrix}\right)$$

- Flavor blind…

(More precisely, $U(3)^5$ invariant)

$$\alpha^{(3)}_{\varphi l} = \begin{pmatrix}\alpha_{11} & \alpha_{12} & \alpha_{13}\\ \alpha_{21} & \alpha_{22} & \alpha_{23}\\ \alpha_{31} & \alpha_{32} & \alpha_{33}\end{pmatrix} = \bar{\alpha}^{(3)}_{\varphi l}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix}$$

$U(3)^5$ inv.

$$\begin{pmatrix} l_e\\ l_\mu\\ l_\tau\end{pmatrix}, \begin{pmatrix} e\\ \mu\\ \tau\end{pmatrix}, \begin{pmatrix} q_u\\ q_c\\ q_t\end{pmatrix}, \begin{pmatrix} u\\ c\\ t\end{pmatrix}, \begin{pmatrix} d\\ s\\ b\end{pmatrix}$$

$U(3)_q \times U(3)_u \times U(3)_d \times U(3)_l \times U(3)_\nu$

≈ MFV…

$$\alpha^{(3)}_{\varphi l} = \begin{pmatrix}\alpha_{11} & \alpha_{12} & \alpha_{13}\\ \alpha_{21} & \alpha_{22} & \alpha_{23}\\ \alpha_{31} & \alpha_{32} & \alpha_{33}\end{pmatrix} = \bar{\alpha}^{(3)}_{\varphi l}\, \mathbf{I}_{3\times 3} + \bar{\beta}^{(3)}_{\varphi l}\, \Delta^{(l)}_{LL} + \ldots$$

$$\Delta^{(q)}_{LL} = V^\dagger \bar{\lambda}_u^2 V$$
$$\Delta^{(\ell)}_{LL} = \frac{\Lambda^2_{\rm LN}}{v^4} U \bar{m}_\nu^2 U^\dagger$$

$$= \bar{\alpha}^{(3)}_{\varphi l}\begin{pmatrix}1 & 0 & 0\\ 0 & 1 & 0\\ 0 & 0 & 1\end{pmatrix} + \bar{\beta}^{(3)}_{\varphi l}\, 10^{-4}\begin{pmatrix}\sim 0.1 & \sim 0.1 & \sim 0.1\\ \sim 0.1 & \sim 1 & \sim 1\\ \sim 0.1 & \sim 1 & \sim 1\end{pmatrix} + \ldots$$

- More generic structure…

$$\alpha^{(3)}_{\varphi l} = \begin{pmatrix}\alpha_{11} & \alpha_{12} & \alpha_{13}\\ \alpha_{21} & \alpha_{22} & \alpha_{23}\\ \alpha_{31} & \alpha_{32} & \alpha_{33}\end{pmatrix}$$

$U(3)^5$ inv. case: Phenomenology

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

$\mu^- \to e^- \nu_\mu \bar{\nu}_e$

$$\mathcal{L}^{eff}_{\mu\to e\nu\bar{\nu}}(x) = \frac{-g^2}{2m_W^2}\left[(1+\tilde{v}_L)(\bar{e}_L\gamma_\mu\nu_{eL})(\bar{\nu}_{\mu L}\gamma_\mu\mu_L) + \cancel{\tilde{s}_L(\bar{e}_R\nu_{eL})(\bar{\nu}_{\mu L}\mu_R)}\right] + h.c.$$

where… $\tilde{v}_L = 4\bar{\alpha}^{(3)}_{\varphi l} - 2\bar{\alpha}^{(3)}_{ll}$

$$G_F^{pheno(\mu)} = G_F^{(0)}(1+\tilde{v}_L)$$

$d^j \to u^i l \bar{\nu}_l$

$$\mathcal{L}^{eff}_{d^j\to u^i l\bar{\nu}_l}(x) = \frac{-g^2}{2m_W^2}V_{ij}\left[\begin{array}{l}(1+v_L)(\bar{u}^i_L\gamma^\mu d^j_R)(\bar{l}_L\gamma_\mu\nu_{lL}) + \cancel{v_R(\bar{u}^i_R\gamma^\mu d^j_R)(\bar{l}_L\gamma_\mu\nu_{lL})} \\ \cancel{+s_L(\bar{u}^i_R d^j_L)(\bar{l}_R\nu_{lL}) + s_R(\bar{u}^i_L d^j_R)(\bar{l}_R\nu_{lL})} \\ \cancel{+t_L(\bar{u}^i_R\sigma^{\mu\nu}d^j_L)(\bar{l}_R\sigma_{\mu\nu}\nu_{lL})}\end{array}\right] + h.c.$$

where… $[v_L]_{llij} = 2\bar{\alpha}^{(3)}_{\varphi l} + 2\bar{\alpha}^{(3)}_{\varphi q} - 2\bar{\alpha}^{(3)}_{lq}$

$$G_F^{pheno(SL)} = G_F^{(0)}(1+v_L)$$

$U(3)^5$ inv. case: Phenomenology

- Thus, all the NP are:

$$G_F^{pheno(\mu)} = G_F^{(0)}(1+\tilde{v}_L)$$
$$G_F^{pheno(SL)} = G_F^{(0)}(1+v_L)$$

where…

$$\tilde{v}_L = 4\bar{\alpha}_{\varphi l}^{(3)} - 2\bar{\alpha}_{ll}^{(3)}$$
$$v_L = 2\bar{\alpha}_{\varphi l}^{(3)} + 2\bar{\alpha}_{\varphi q}^{(3)} - 2\bar{\alpha}_{lq}^{(3)}$$

- Just shifts of G_F and V_{ij}!!! (no channel-dependence, no new FFs)

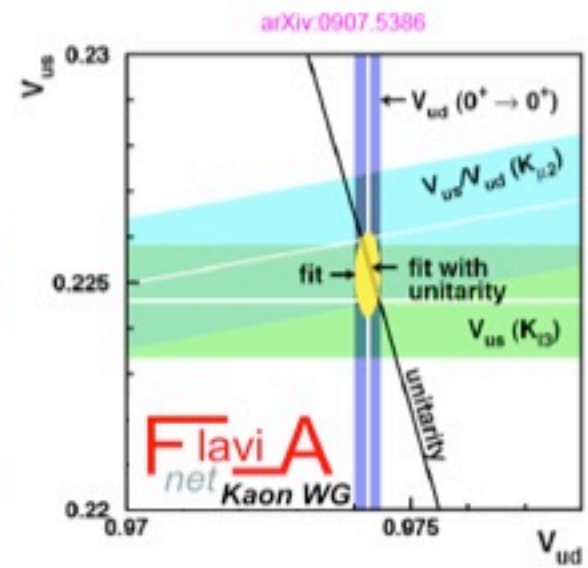
➔ Only one place where we are sensitive to this…

$$\Delta_{CKM} \equiv |V_{ud}^{pheno}|^2 + |V_{us}^{pheno}|^2 + |V_{ub}^{pheno}|^2 - 1 \Rightarrow \Delta_{CKM} = 4\left(-\bar{\alpha}_{\varphi l}^{(3)} + \bar{\alpha}_{\varphi q}^{(3)} - \bar{\alpha}_{lq}^{(3)} + \bar{\alpha}_{ll}^{(3)}\right)$$

- How well known is Δ_{CKM}?

$$V_{ud} = 0.97425(22)$$
$$V_{us} = 0.2252(9)$$
$$V_{ub} \sim 10^{-3}$$

$$\Rightarrow \Delta_{CKM} = -(0.1 \pm 0.6)\cdot 10^{-3}$$



CKM tests vs. HEP

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

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

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

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

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

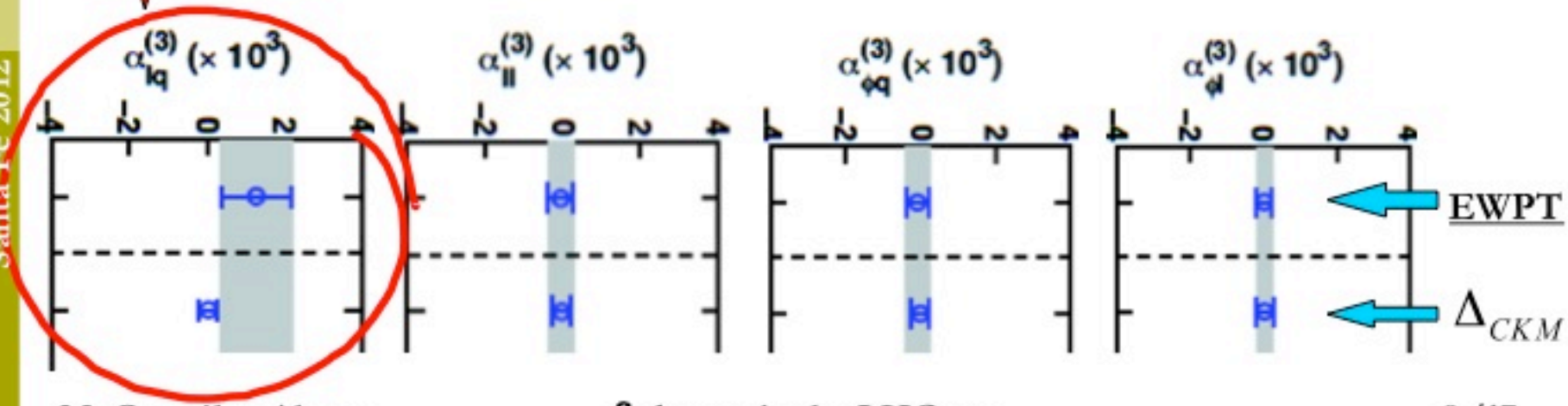
$$O^{(3)}_{\varphi q} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\bar{q}\gamma_\mu\sigma^a q) + \text{h.c.}$$

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!



Neutron β decay

THEORY: SM

SM prediction Known up to…

- Axial-vector FF;
- Quadratic effects in the following small parameters: α/π , $\Delta M/M$, $q/M \sim 0.001$

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

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

Weinberg'58:

$$\langle p(p_p)|\, \bar{u}\gamma_\mu d\,|\, n(p_n)\rangle = \bar{u}_p(p_p)\left[g_V(q^2)\,\gamma_\mu + \frac{\tilde{g}_{T(V)}(q^2)}{2M_N}\,\sigma_{\mu\nu}q^\nu + \frac{\tilde{g}_S(q^2)}{2M_N}\,q_\mu\right]u_n(p_n) \quad (5a$$

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

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

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$g_V(0)=1$, (Ademollo-Gatto'64) Related to μ_p-μ_n (up to isospin breaking corr.)

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

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

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

$$\langle p(p_p)|\, \bar{u}\,\sigma_{\mu\nu}\, d\,|\, n(p_n)\rangle = \bar{u}_p(p_p)\left[g_T(q^2)\,\sigma_{\mu\nu} + \cancel{g_T^{(1)}(q^2)(q_\mu\gamma_\nu - q_\nu\gamma_\mu)}\right.$$

$$\left. + \cancel{g_T^{(2)}(q^2)(q_\mu P_\nu - q_\nu P_\mu)} + \cancel{g_T^{(3)}(q^2)(\gamma_\mu \not{q}\gamma_\nu - \gamma_\nu \not{q}\gamma_\mu)}\right]u_n(p_n)$$

Angular/Energy distribution

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

(Jackson, Treiman & Wyld, 1957)

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

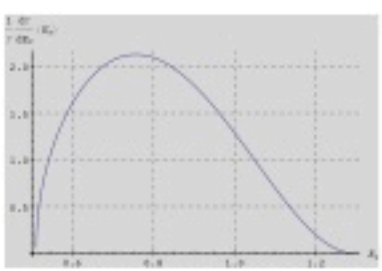
$$b \approx 0.3\,\lambda_S\,\epsilon_S - 5.0\,\lambda_T\,\epsilon_T$$

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

Neutron β decay experimentalists language

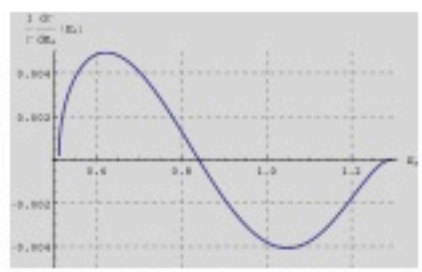
Normalized spectrum:

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



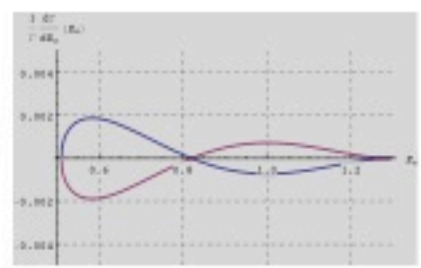
SM (LO)

+



SM (NLO)
x400 zoom

+



NP
x400 zoom

Angular/Energy distribution

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

(spectrum)

Angular distribution altered... and E-dependent!

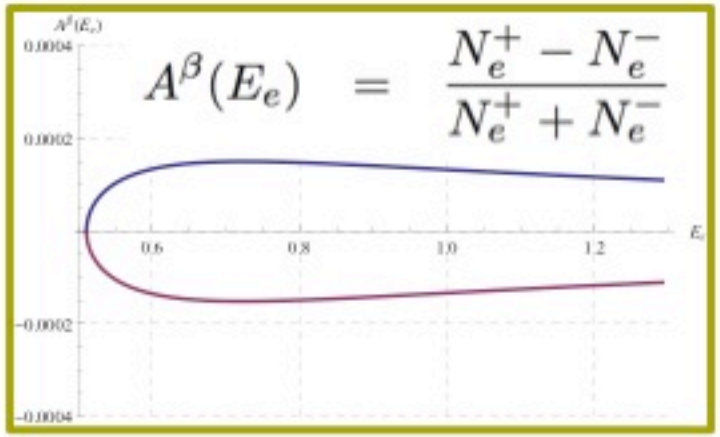
$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E)\left(1+b\frac{m_e}{E_e}\right)\left\{1+a\left(1-b\frac{m_e}{E_e}\right)\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+A\left(1-b\frac{m_e}{E_e}\right)\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J}+\left(B+(b_B-b)\frac{m_e}{E_e}\right)\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$

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

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

Neutron β decay experimentalists language

$$A^\beta(E_e) = \frac{N_e^+ - N_e^-}{N_e^+ + N_e^-}$$



What do we know about S/T from other low-E exp.?

- **Superallowed nuclear β decays:** $-1{,}0\cdot 10^{-3} \le g_S\varepsilon_S \le +3{,}2\cdot 10^{-3}$ **(90% C.L.)** *(Hardy & Towner, 2009)*
- **Radiative pion decay:** $-0{,}8\cdot 10^{-3} \le \varepsilon_T \le +1{,}1\cdot 10^{-3}$ **(90% C.L.)** *(PIBETA Coll., 2009)* *(Mateu & Portolés, 2007)*

- **Pion decay**
  - Strong limits on $\varepsilon_P^{\alpha\beta}$: $R_\pi \equiv \Gamma(\pi\to e\nu)/\Gamma(\pi\to\mu\nu)$
  - S, T generate P through loops (Voloshin'92, Campbell-Maybury'05)
  - Depending on the assumptions about the flavor structure of ε_P and the cancellations one is willing to accept we get: $|\varepsilon_T| \le 10^{-5} - 10^{-3}$, $|\varepsilon_S| \le 10^{-3} - 10^{-1}$
- **Other nuclear decays** are getting close…
  - β asymmetry in ^{60}Co: $|g_T\varepsilon_T| \le 1{,}5\cdot 10^{-2}$
  - β-ν asymmetry in diff. nuclei: $|g_T\varepsilon_T| \le 0{,}5\cdot 10^{-2}$
  - …

What do we know about S/T from other low-E exp.?

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

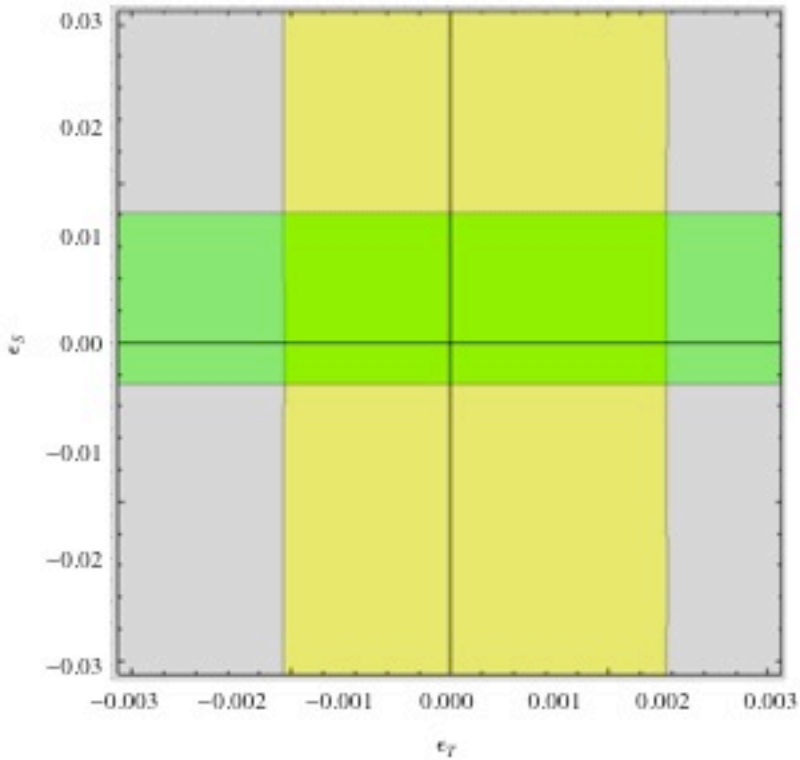
$$\frac{-1.4\times10^{-7}}{\log(\Lambda/\mu)} < \gamma_{SP}\,\epsilon_S + \gamma_{TP}\,\epsilon_T < \frac{5.5\times10^{-4}}{\log(\Lambda/\mu)}$$

$$\gamma_{SP} = \frac{15}{72}\frac{\alpha_1}{\pi} \approx 6.7\times10^{-4}$$

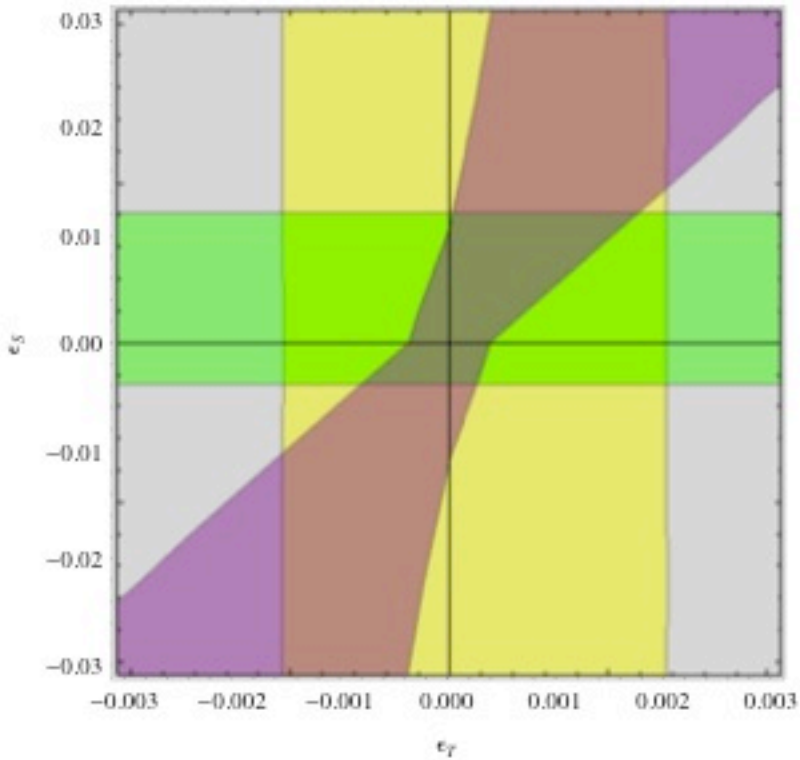
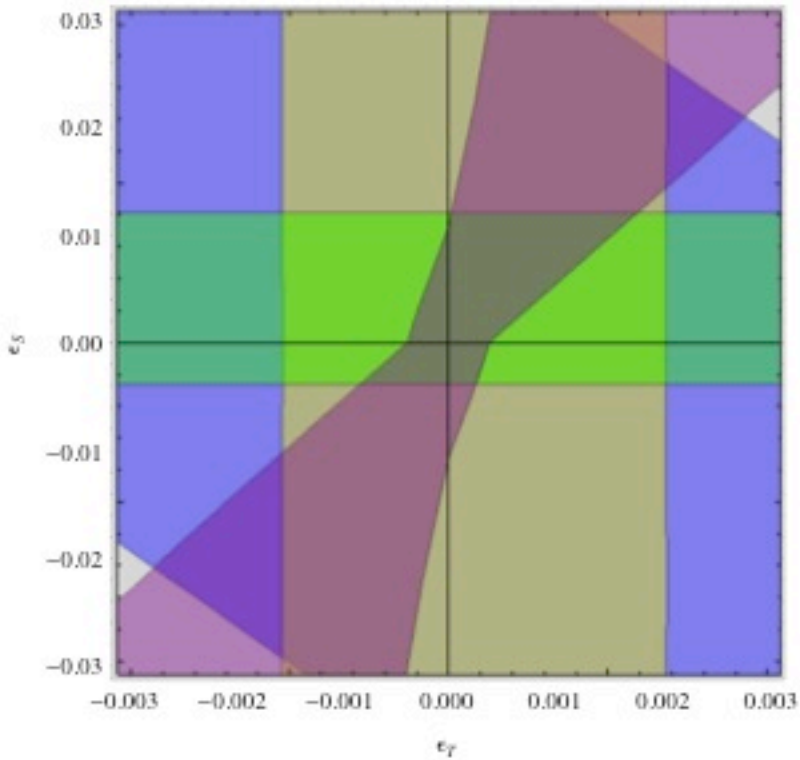
$$\gamma_{TP} = -\frac{9}{2}\frac{\alpha_2}{\pi} - \frac{15}{2}\frac{\alpha_1}{\pi} \approx -7.3\times10^{-2}$$

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

What do we know about S/T from other low-E exp.?



What do we know about S/T from other low-E exp.?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