Probing non-standard CC interactions:
from cold neutrons to the LHC

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NPAC Theory Group
University of Wisconsin – Madison

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Motivation & goals

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

➔ Not only useful to extract SM parameters (V_{ij}) but also to search for New Physics!

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

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

$K \to \pi l \nu_l$

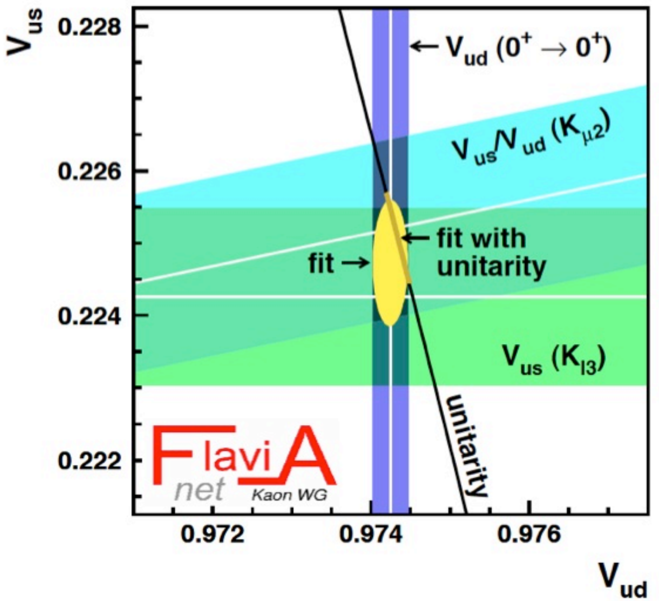
$K^+ \to l^+ \nu_l$

n decay

$0^+ \to 0^+$

. . .

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



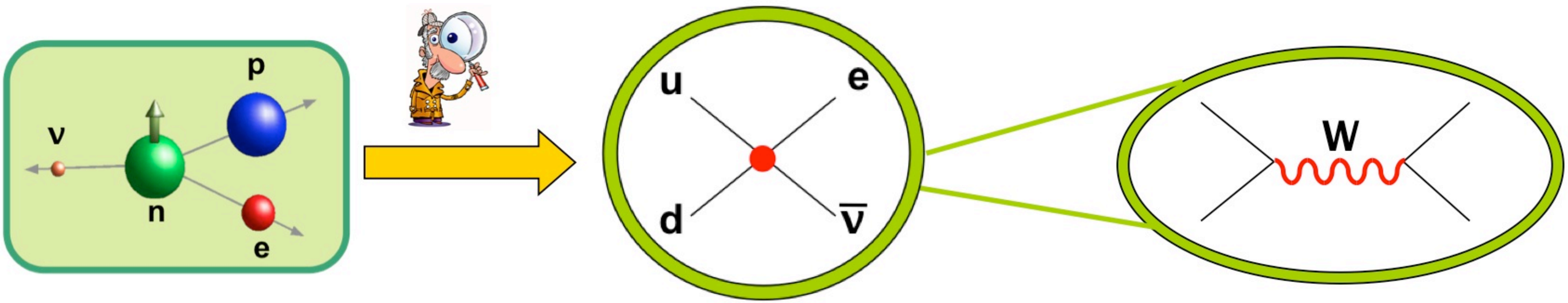
Questions:

- What kind of NP can we probe with SL beta decays? Which is the best process?

- LHC?

Motivation & goals

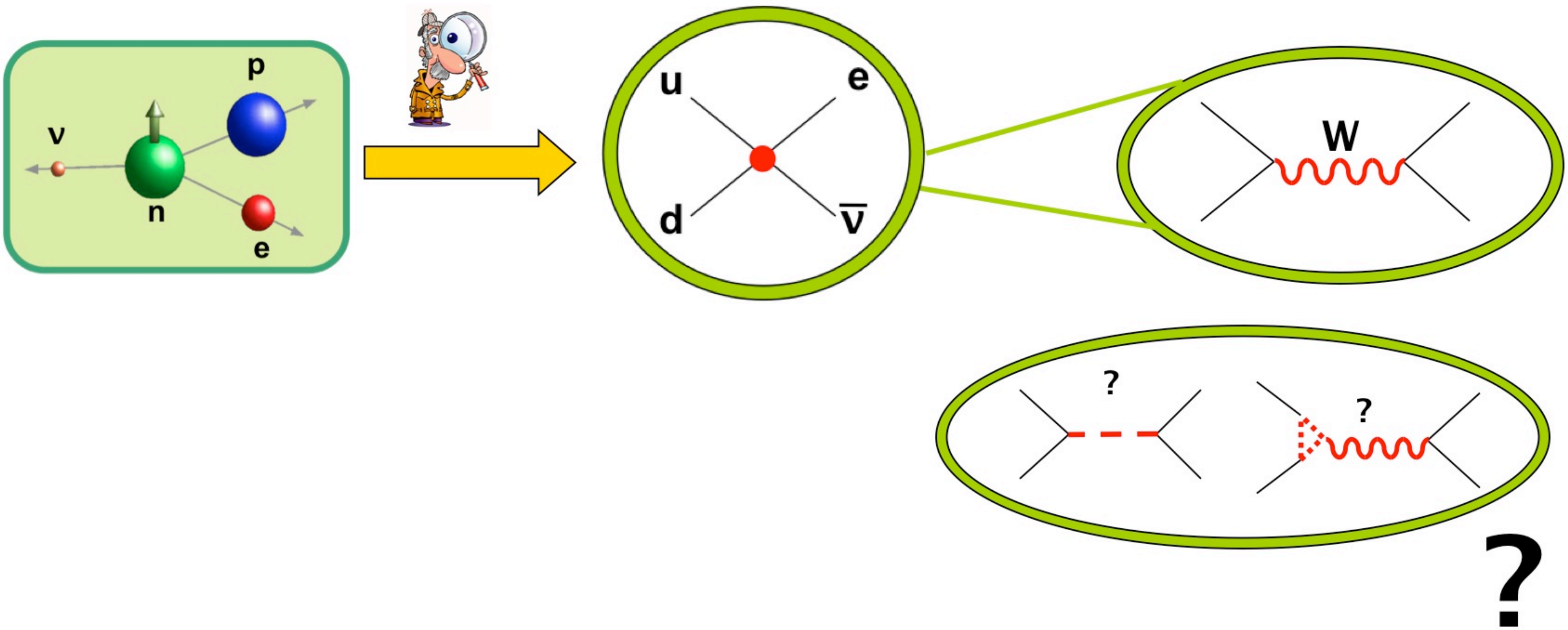
$$\mathcal{L}_{d\to u\ell^-\bar{\nu}_\ell} = -\frac{4G_F V_{ij}}{\sqrt{2}}\left[\bar{\ell}_L\gamma_\mu\nu\cdot\bar{u}\gamma^\mu d_L\right]$$



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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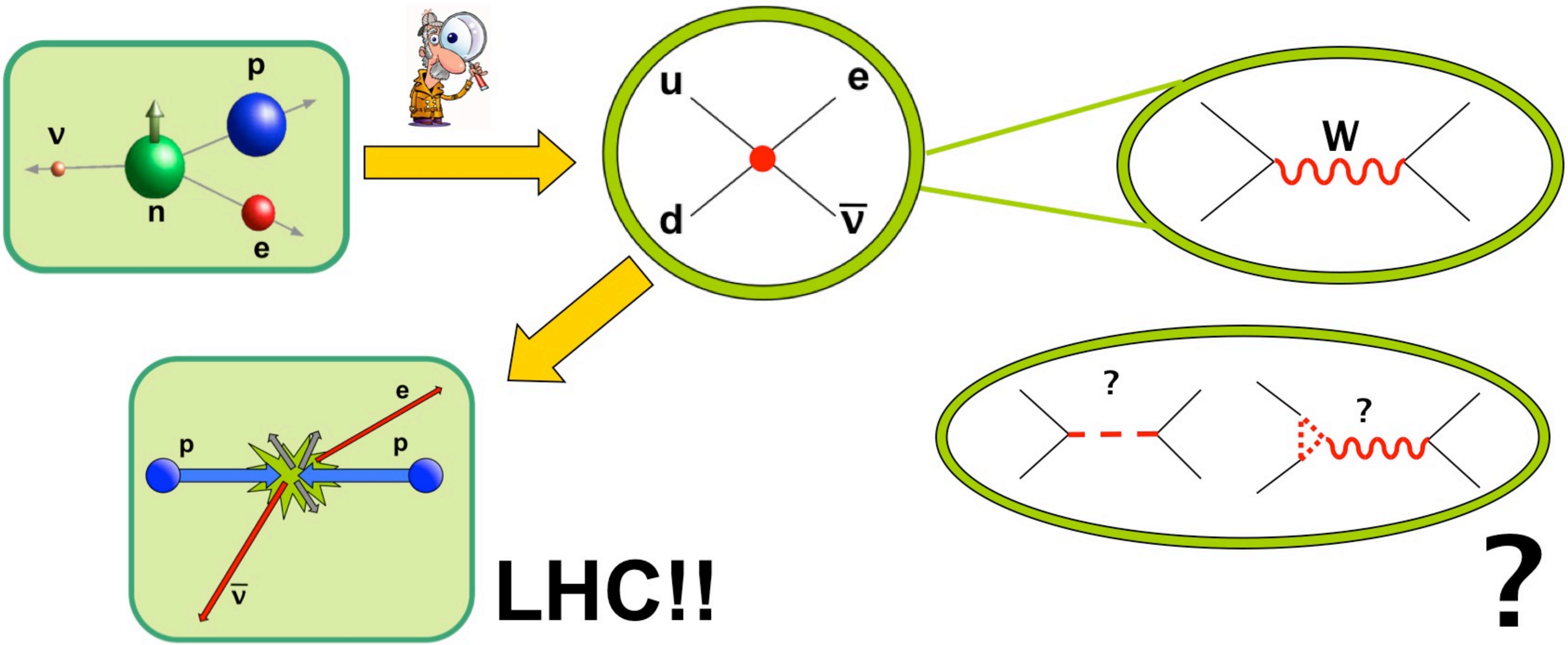


Outline

- Introduction and motivation; ✓
- EFT approach;
- Low-energy bounds:
- LHC bounds.

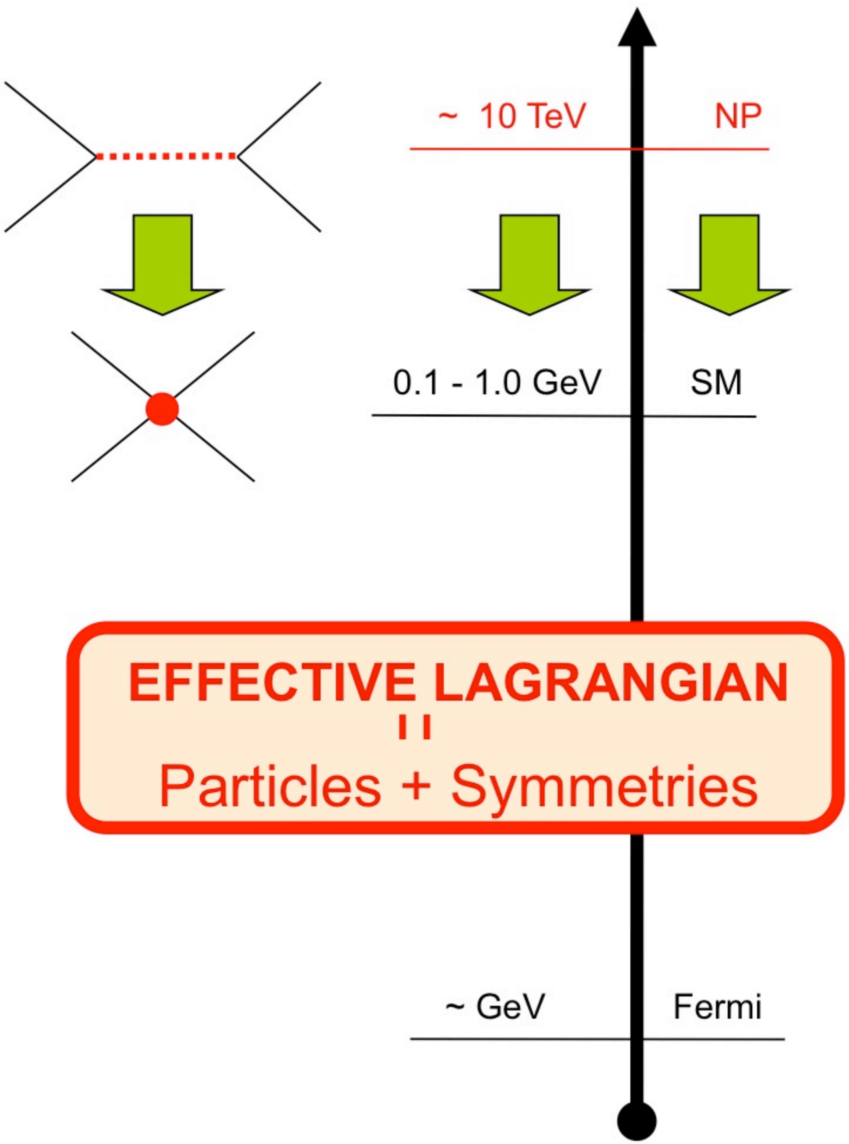
Cirigliano, MGA & Jenkins'2010

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

Cirigliano, MGA & Graesser'2012

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

The eff. Lagrangian for E~100 GeV



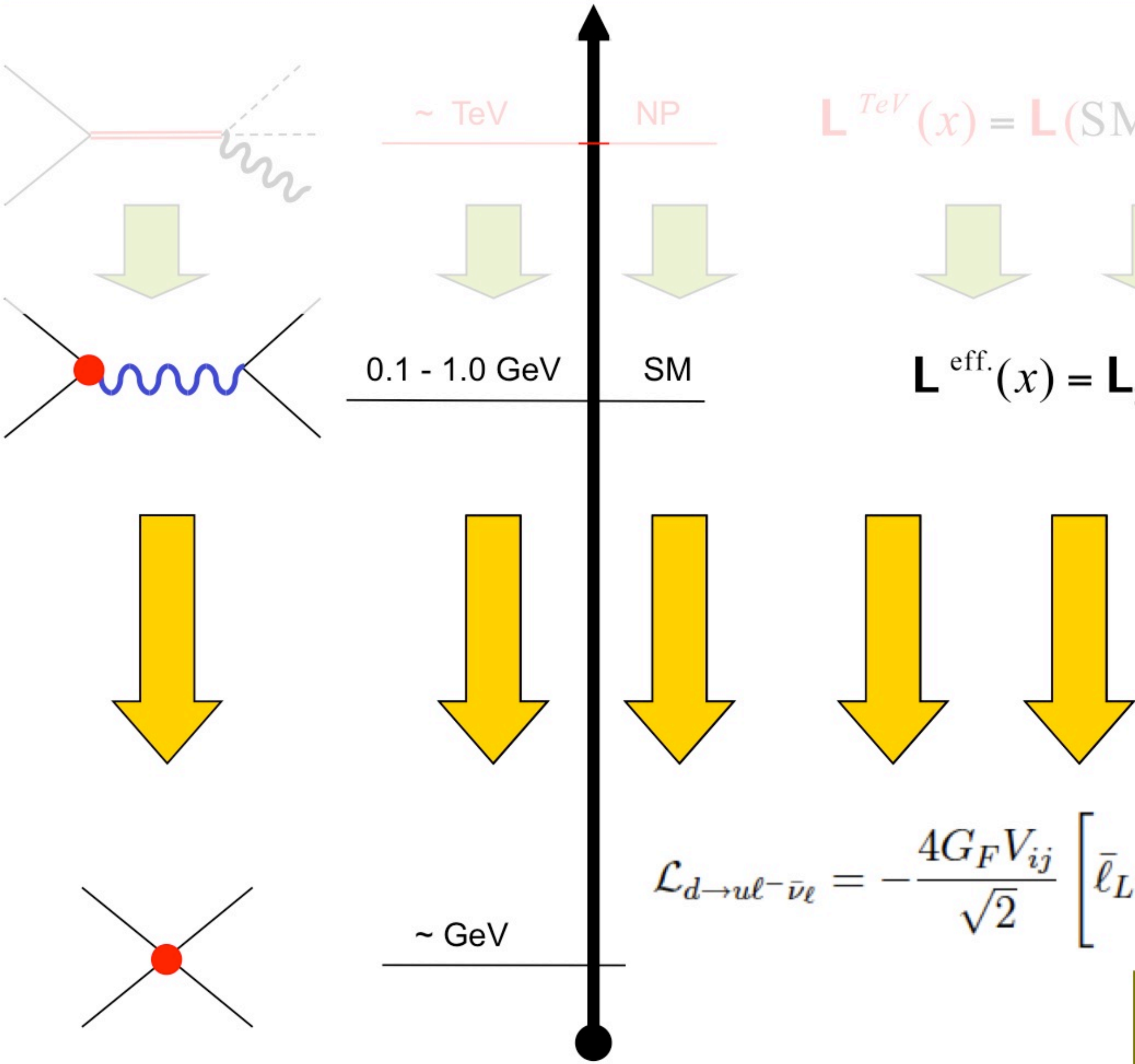
$$\mathbf{L}^{TeV}(x) = \mathbf{L}(\text{SM-fields, bSM-fields})$$

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

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

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

The eff. Lagrangian for E~1 GeV



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

$$\mathbf{L}^{\text{eff.}}(x) = \mathbf{L}_{\mathbf{SM}}(x) + \frac{1}{\Lambda^2}\mathbf{L}_{\mathbf{6}}(x)$$

$$\left(\mathbf{L}_{\mathbf{6}}(x) = \sum_{i}^{25} \alpha_i \mathbf{O}_{\mathbf{i}}(x)\right)$$

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

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

$$\varepsilon = \sum c_i\alpha_i \frac{v^2}{\Lambda^2}$$

(v ≈ 174 GeV)

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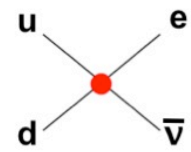
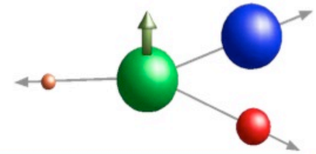
Low-energy searches

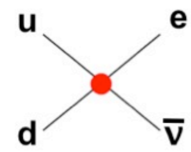


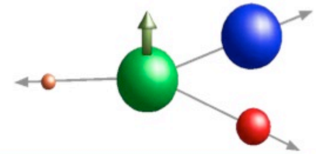


Eff. Lagrangian at the quark level

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

Low-energy searches





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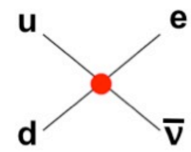
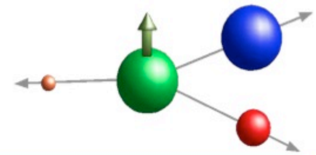
\end{aligned}
$$

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

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

Low-energy searches





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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)
$$

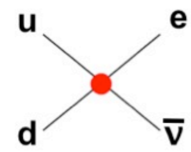
$$
\mathbf{O = O_{SM} + \varepsilon^2}
$$

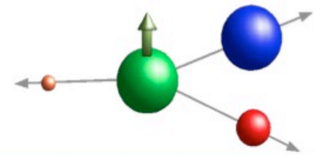
Eff. Lagrangian at the hadron level *(for n→pev, up to ε^2 terms)*

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

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

Low-energy searches





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

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

Lifetime shift ➔
CKM unitarity

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

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

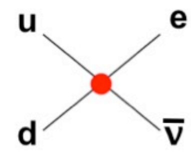
$$\Lambda_{NP} > 11 \text{ TeV } (90\%\text{CL})$$

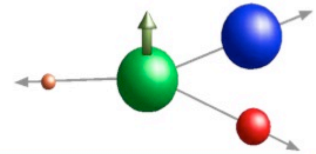
Marciano'2008

Cirigliano, MGA & Jenkins'2010

Bauman, Erler & Ramsey-Musolf'2012

Low-energy searches





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

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

Lifetime shift ➔ CKM unitarity

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

Marciano'2008

Cirigliano, MGA & Jenkins'2010

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

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

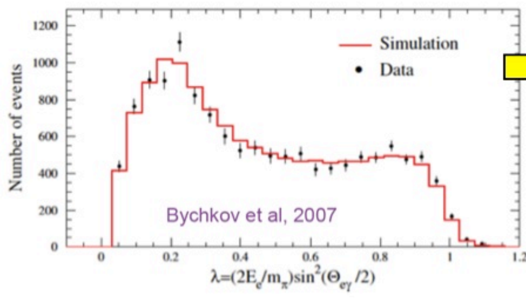
$$b \approx 0.3\ g_S\ \epsilon_S - 5.0\ g_T\ \epsilon_T$$

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

Form factors needed!

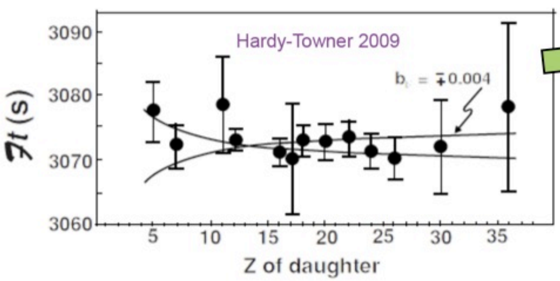
Low-energy searches: S & T

Radiative pion decay (PIBETA´2009)

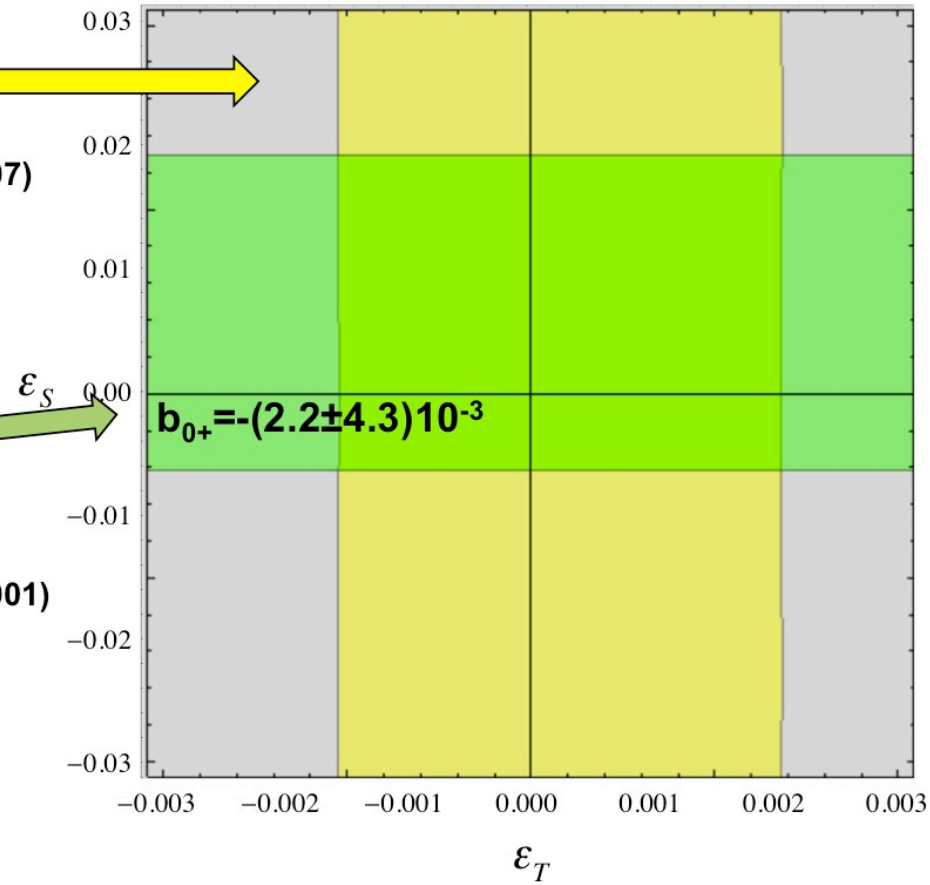


f_T=0.24(4)
(Mateu & Portolés, 2007)

Superallowed nuclear β decays



0.25<g_S<1.00
0.60<g_T<2.30
(Adler'1975, Herczeg'2001)



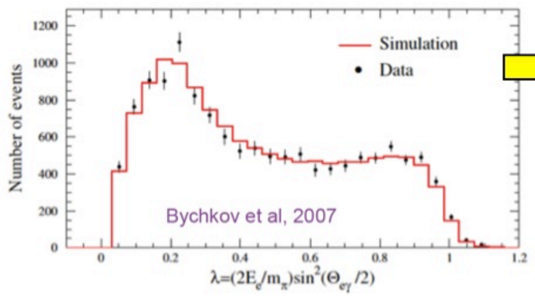
** Pion decay (R_π) also very powerful!*

***Other nuclear decays getting close…*

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

Low-energy searches: S & T

Radiative pion decay (PIBETA´2009)



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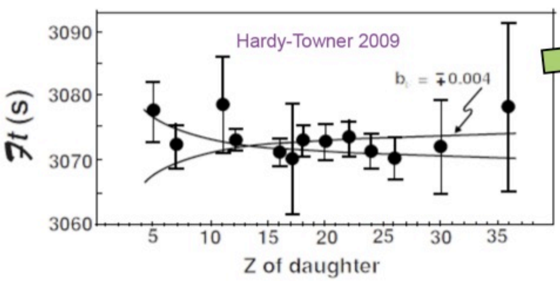

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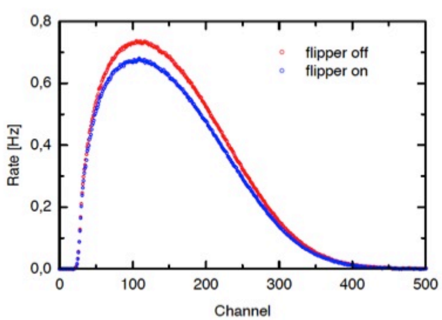
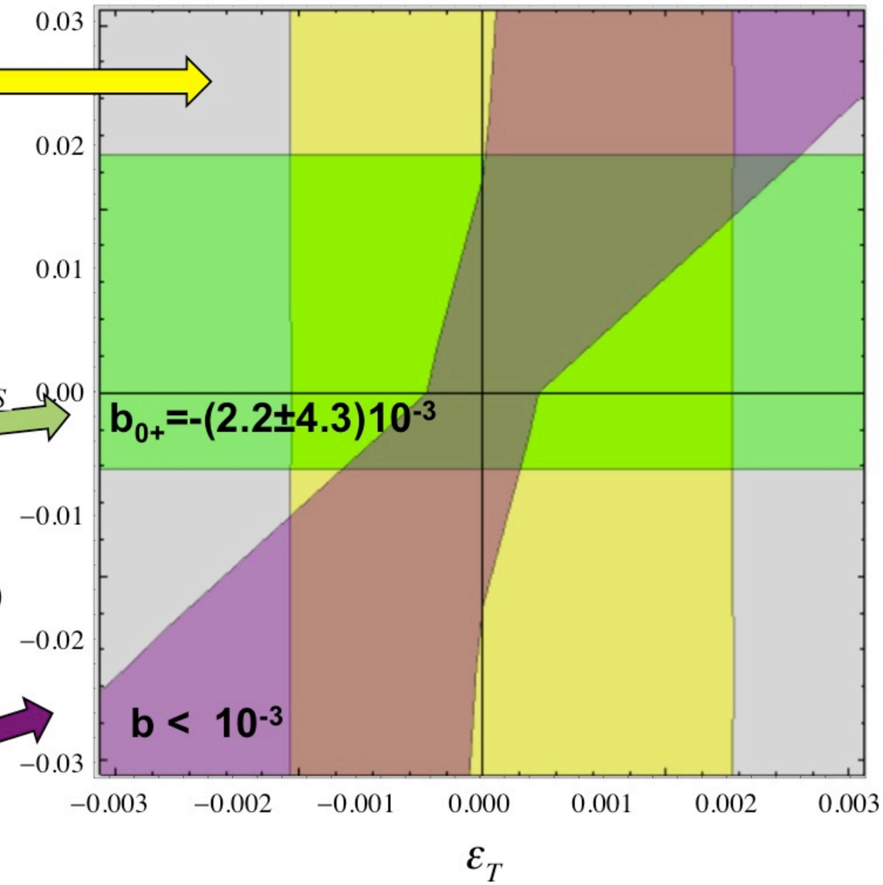
Future neutron decay exp.

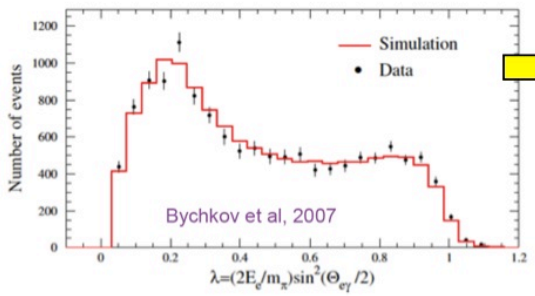




$b \approx 0.3\, g_S\, \varepsilon_S - 5.0\, g_T\, \varepsilon_T$

Low-energy searches: S & T

Radiative pion decay (PIBETA´2009)



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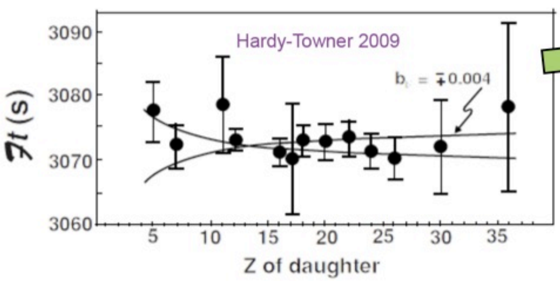

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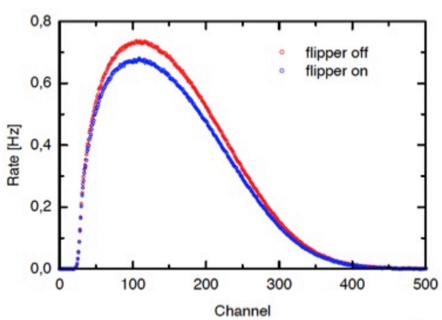

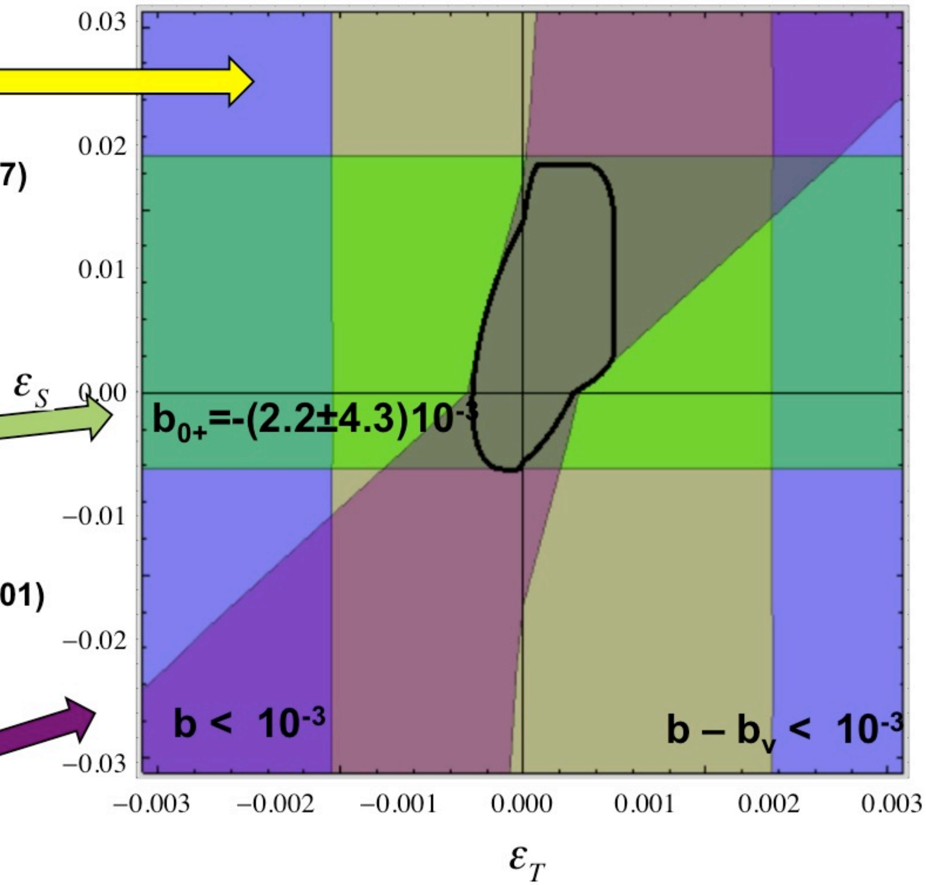

$$b \approx 0.3\, g_S\, \varepsilon_S - 5.0\, g_T\, \varepsilon_T$$
$$b_\nu - b \approx 0.1\, g_S\, \varepsilon_S - 0.3\, g_T\, \varepsilon_T$$

Low-energy searches: S & T

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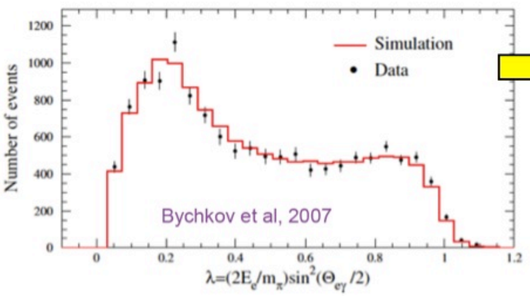

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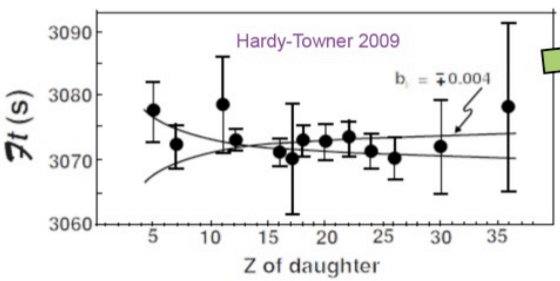

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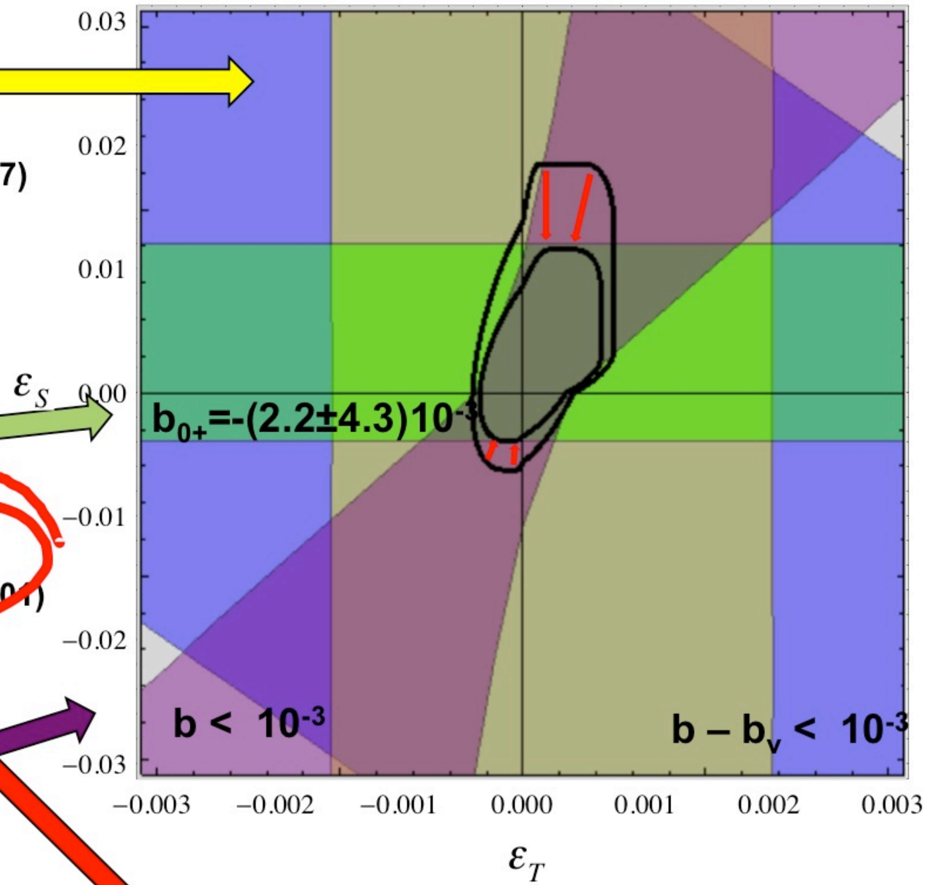

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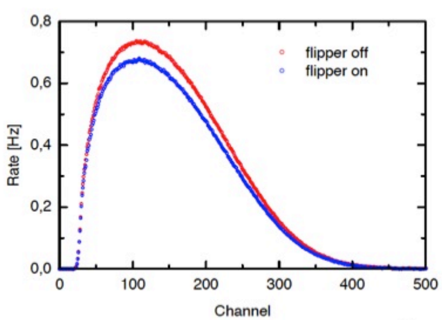

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LATTICE QCD!!

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)

NP bounds from low-energy searches

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

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

x 10^{-2}

	$\|\tilde{\epsilon}_L\|$	$\|\tilde{\epsilon}_R\|$	$\|\tilde{\epsilon}_P\|$	$\|\tilde{\epsilon}_S\|$	$\|\tilde{\epsilon}_T\|$
Low energy	6	6	0.03	14	3.0

x 10^{-2}

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x 10^{-2}

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x 10^{-2}

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

[Severijns, Beck & Naviliat-Cuncic'2006]

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- EFT approach; ✓
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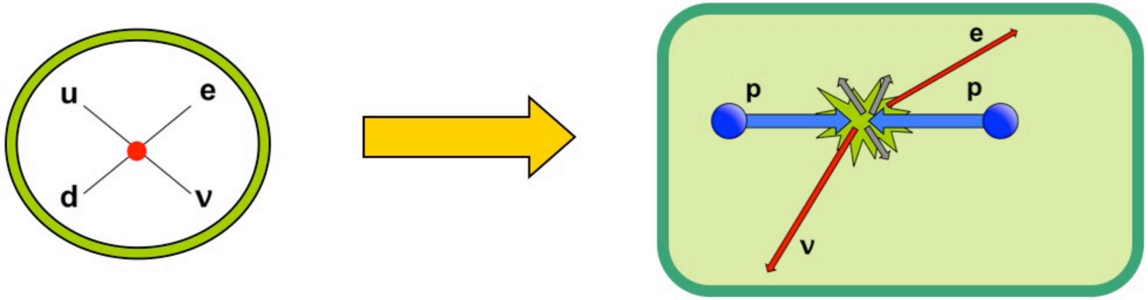
LHC limits on $\varepsilon_{S,T}$

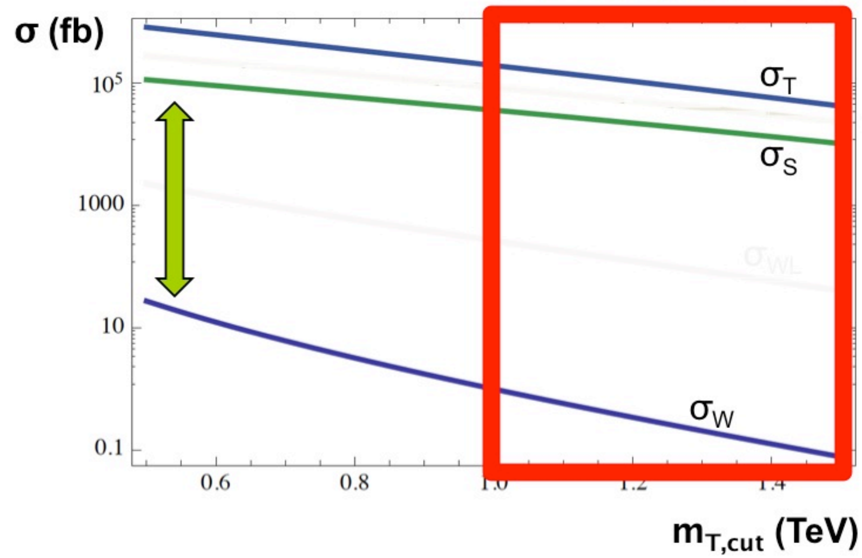
- EFT approach:



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

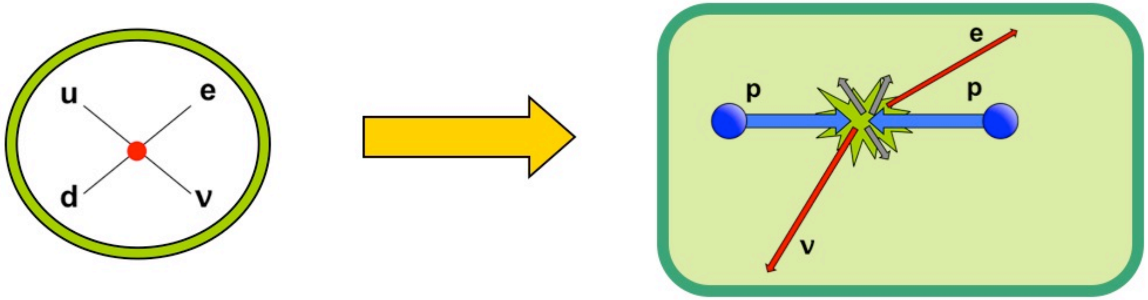
$$N_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times L \times \sigma_{pp\to e\nu X}\left(m_T^2 > m_{T,cut}^2\right) = \varepsilon \times L \times \left(\sigma_W + \sigma_S\, \varepsilon_S^2 + \sigma_T\, \varepsilon_T^2\right)$$

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



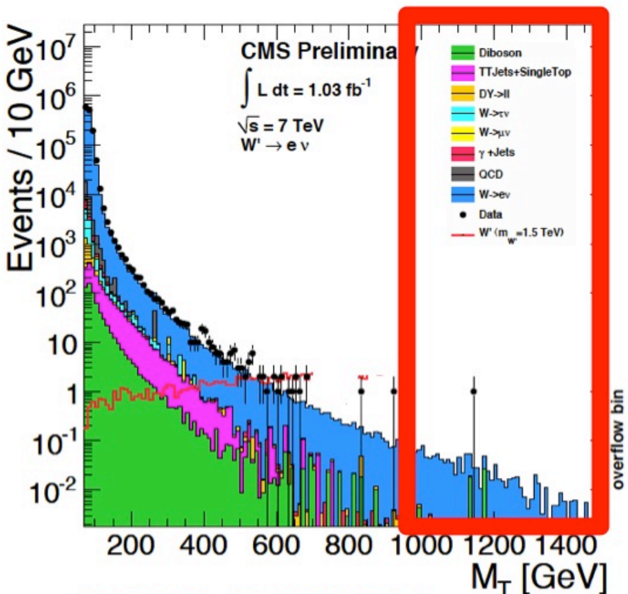
LHC limits on $\varepsilon_{S,T}$

- EFT approach:



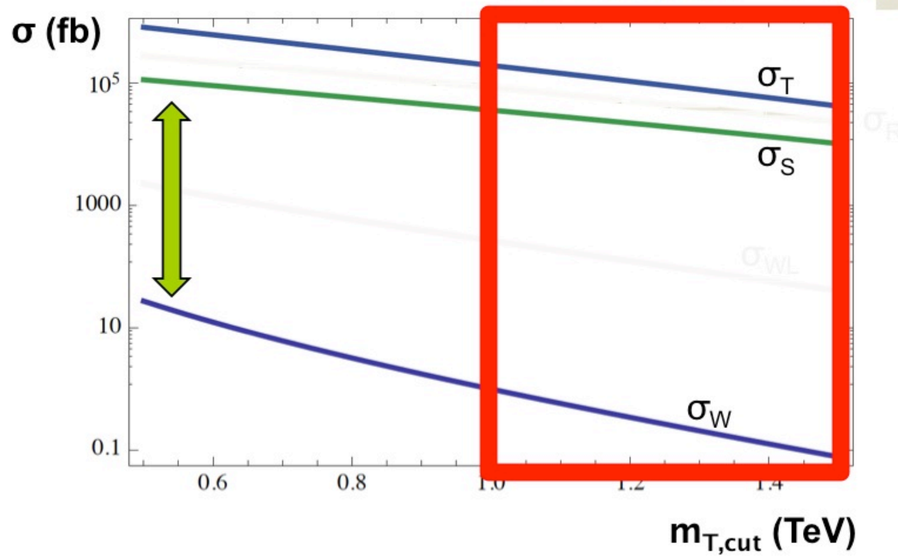
- To suppress the bkg, we look for ***(e+ν)***-events with high m_T:

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

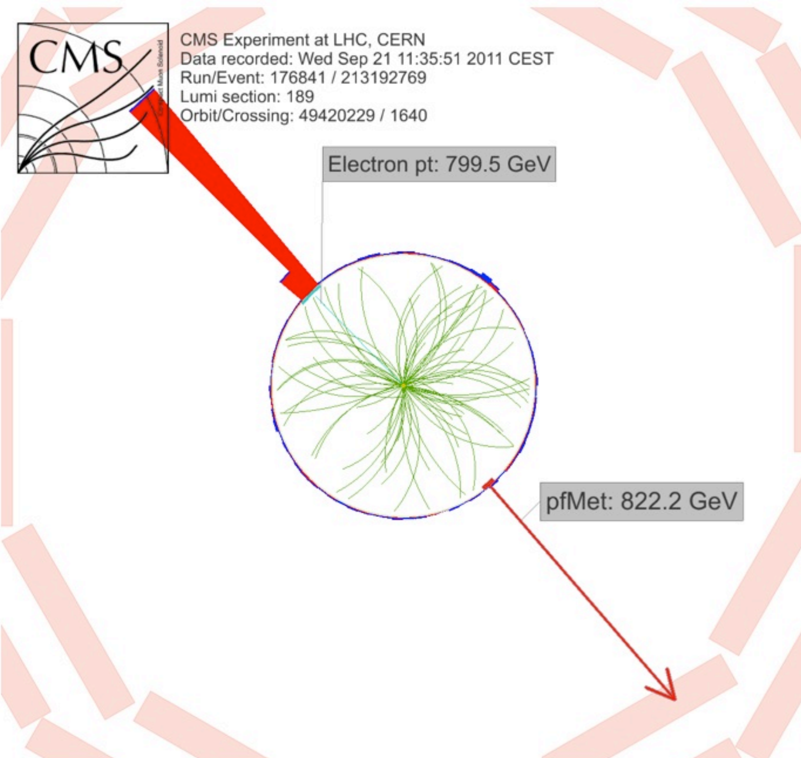


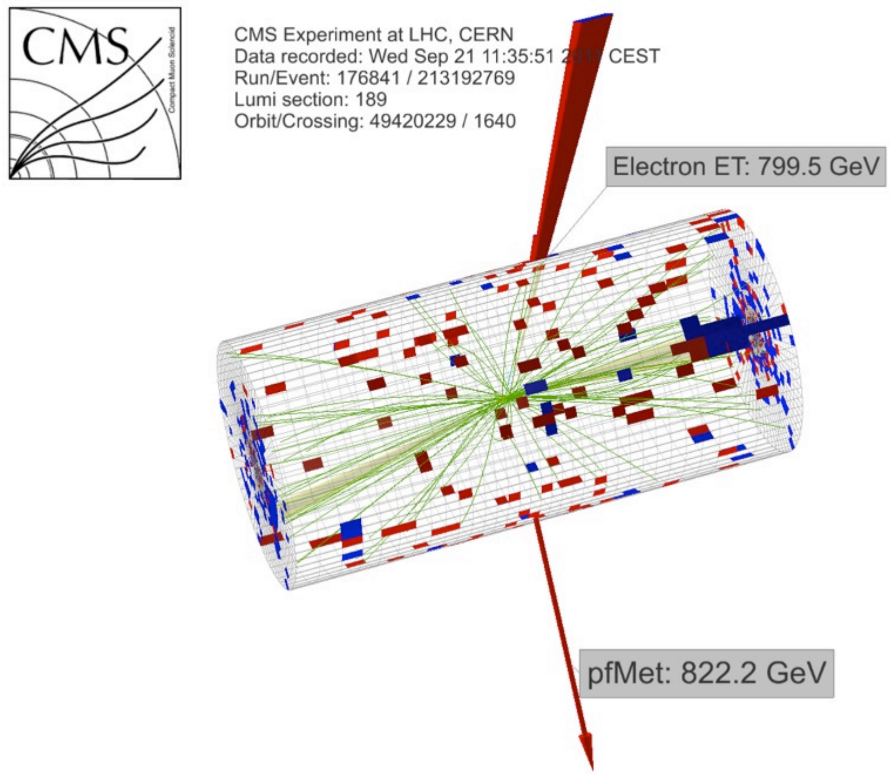
(CMS 1 fb^{-1}, 7 TeV)

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



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





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

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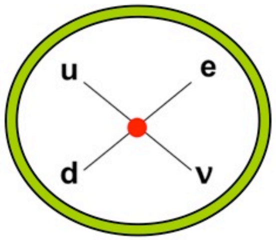

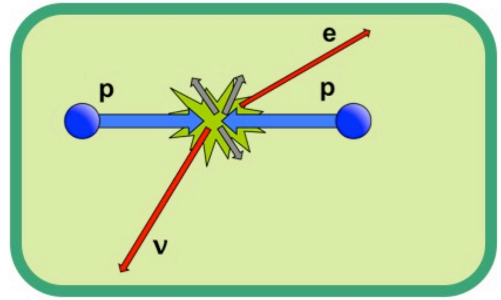

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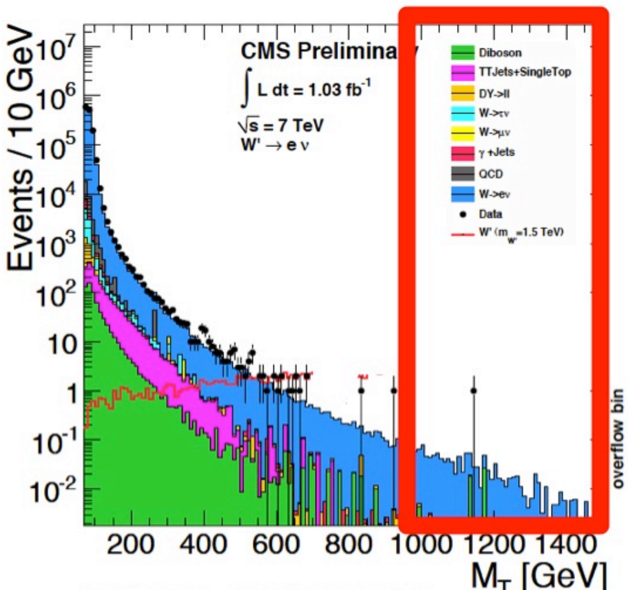
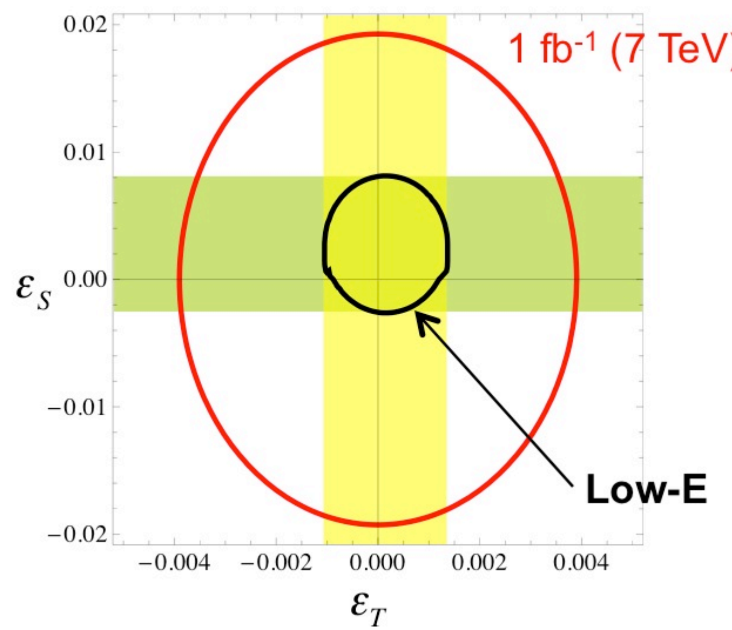


(CMS 1 fb^{-1}, 7 TeV)



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

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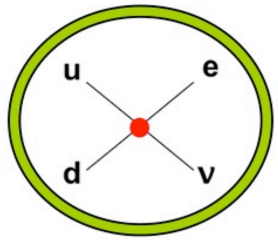

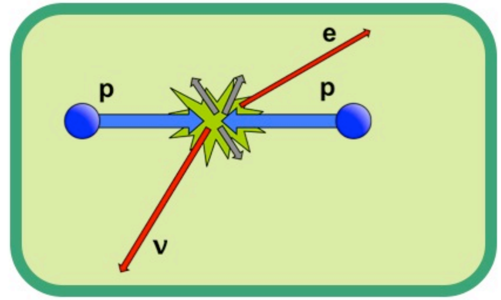

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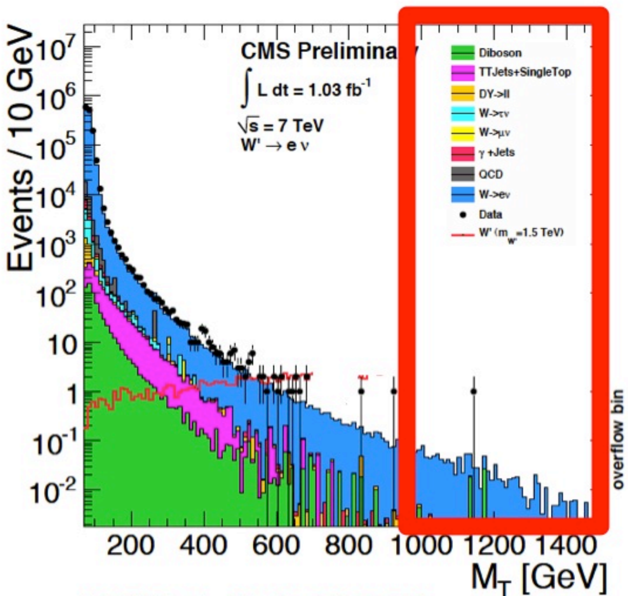
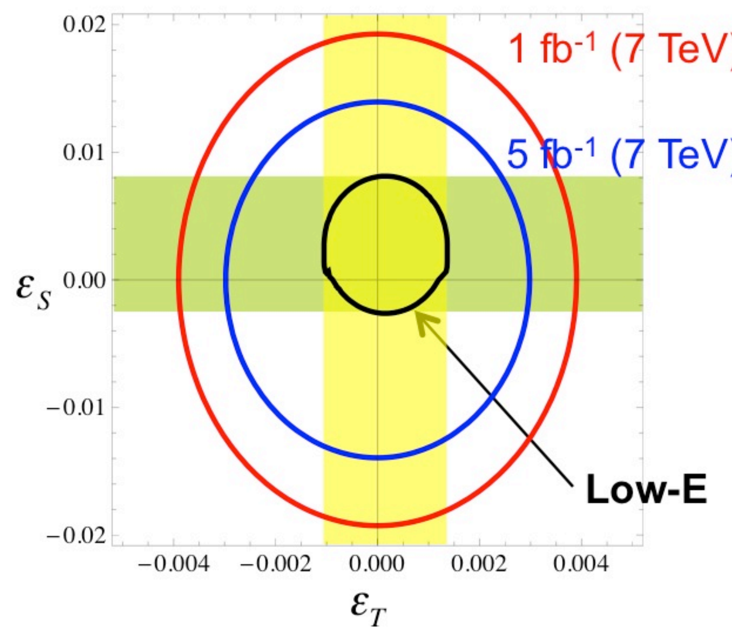
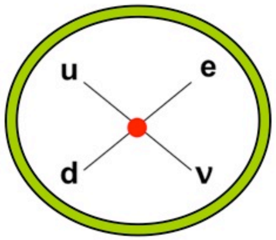


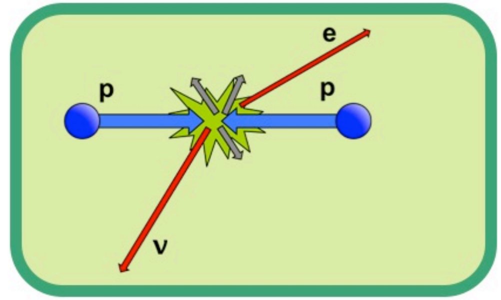
(CMS 1 fb-1, 7 TeV)



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

- EFT approach:





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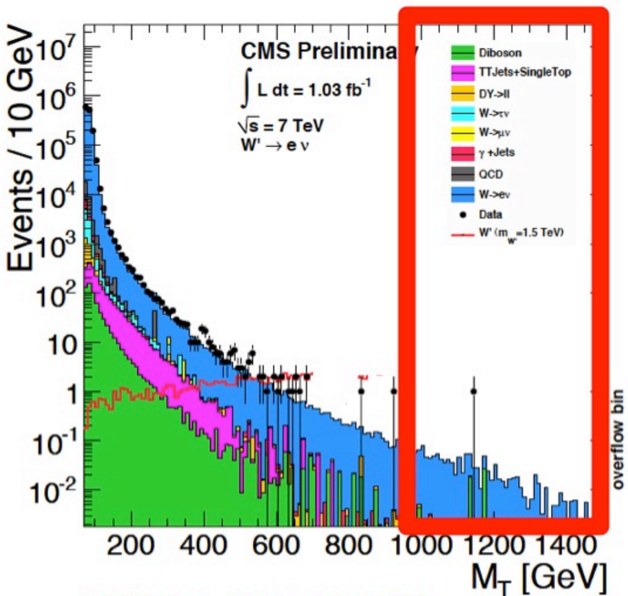
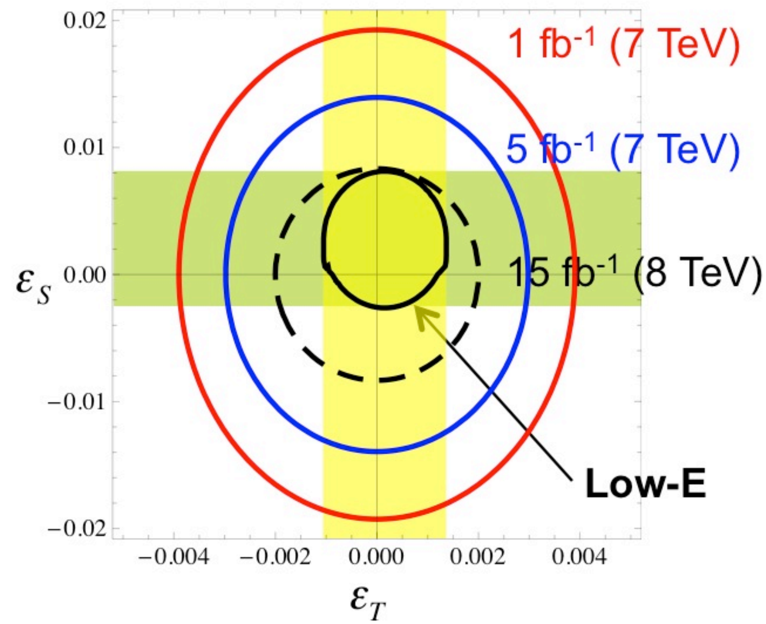


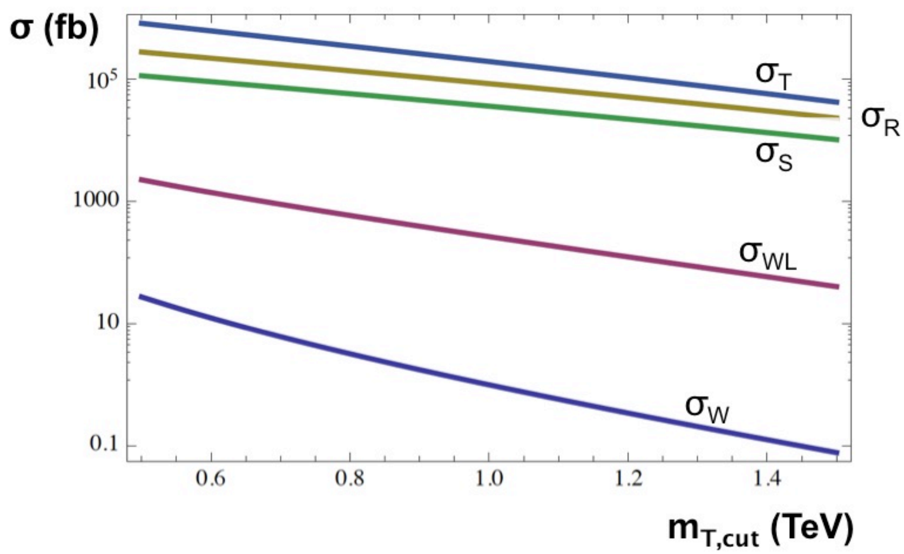
(CMS 1 fb⁻¹, 7 TeV)



What about the other ε_x?

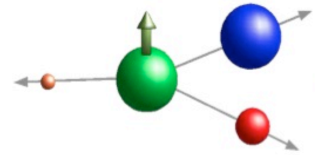
$$
\begin{aligned}
\sigma(m_T > \overline{m}_T) \;\; &= \sigma_W \left[(1+\epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2 \right] - 2\sigma_{WL}\, \epsilon_L^{(c)} \left(1 + \epsilon_L^{(v)} \right) \\
&+ \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2 \right] + \sigma_S \left[|\epsilon_S|^2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

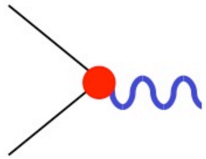
- Strong bounds on S, T, P with LH neutrinos.
- Strong bounds on S, P, T, V+A with RH neutrinos;
- LHC not sensitive to the rest of couplings.



[Cirigliano, MGA & Graesser, 2012]

β decays vs. the LHC



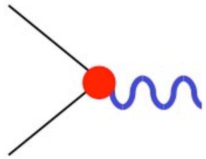


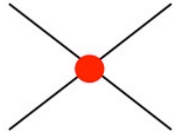
	$\lvert\epsilon_L^{(v)}\rvert$	$\epsilon_L^{(c)}$	$\lvert\epsilon_R\rvert$	$\lvert\epsilon_P\rvert$	$\lvert\epsilon_S\rvert$	$\lvert\epsilon_T\rvert$	
Low energy	0.05	0.05	0.05	0.06	0.8	0.1	x 10^{-2}
LHC $(e\nu)$	-	(-0.3,+0.8)	-	1.3	1.3	0.3	x 10^{-2}

Interesting competition

	$\lvert\tilde{\epsilon}_L\rvert$	$\lvert\tilde{\epsilon}_R\rvert$	$\lvert\tilde{\epsilon}_P\rvert$	$\lvert\tilde{\epsilon}_S\rvert$	$\lvert\tilde{\epsilon}_T\rvert$	
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}

β decays vs. the LHC





	$\|\epsilon_L^{(v)}\|$	$\epsilon_L^{(c)}$	$\|\epsilon_R\|$	$\|\epsilon_P\|$	$\|\epsilon_S\|$	$\|\epsilon_T\|$	
Low energy	0.05	0.05	0.05	0.06	0.8	0.1	x 10^{-2}
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Low energy dominates!

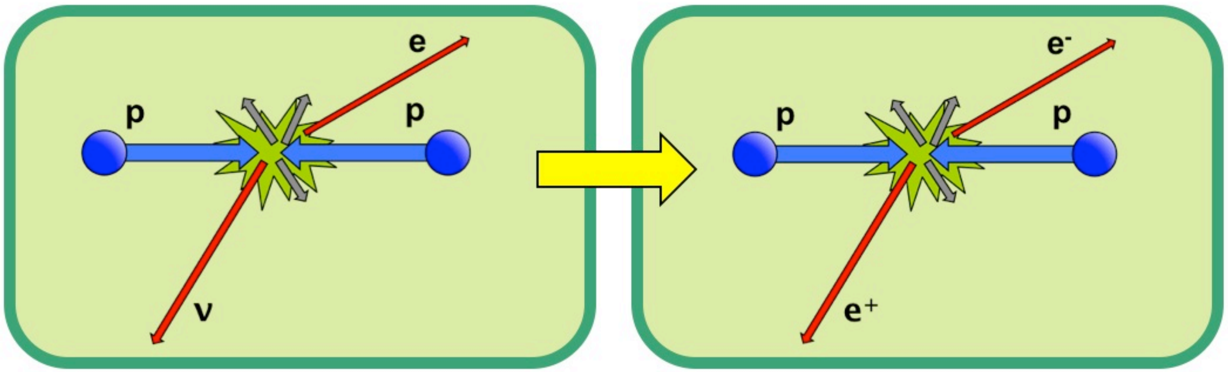
Interesting competition

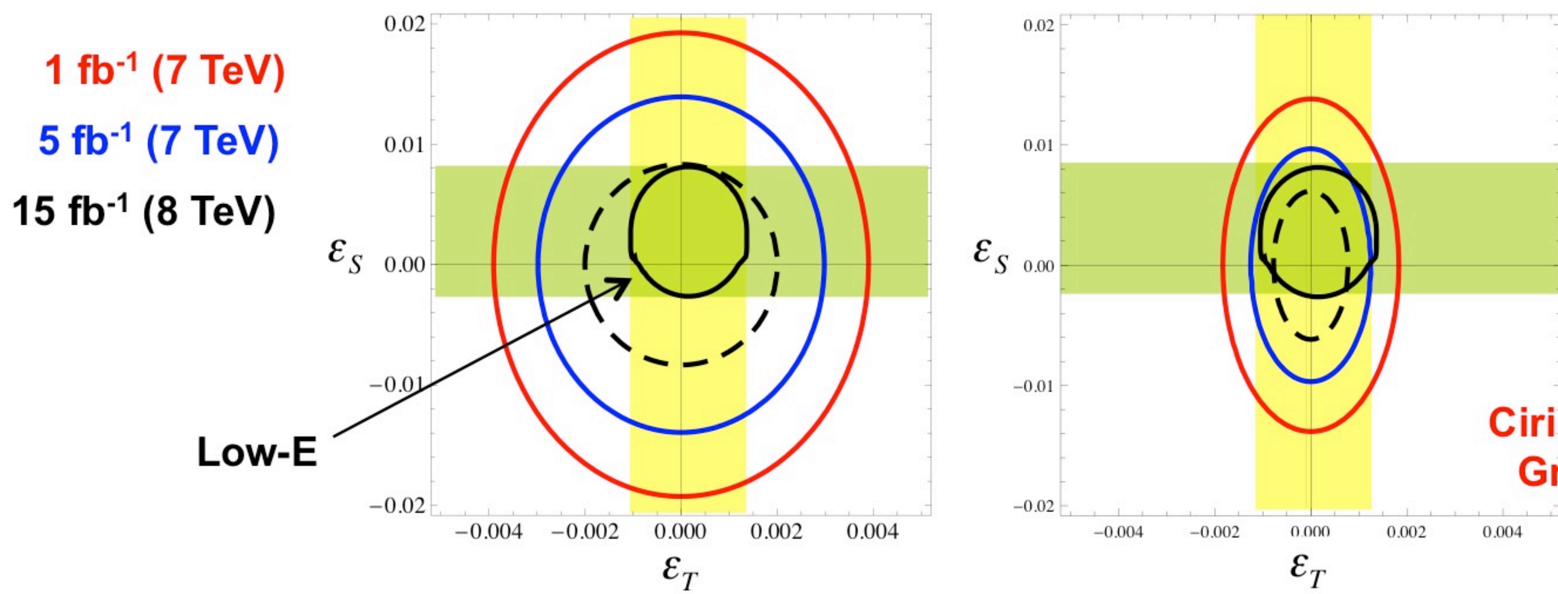
	$\|\tilde{\epsilon}_L\|$	$\|\tilde{\epsilon}_R\|$	$\|\tilde{\epsilon}_P\|$	$\|\tilde{\epsilon}_S\|$	$\|\tilde{\epsilon}_T\|$	
Low energy	6	6	0.03	14	3.0	x 10^{-2}
LHC ($e\nu$)	-	0.5	1.3	1.3	0.3	x 10^{-2}

LHC dominates!

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

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



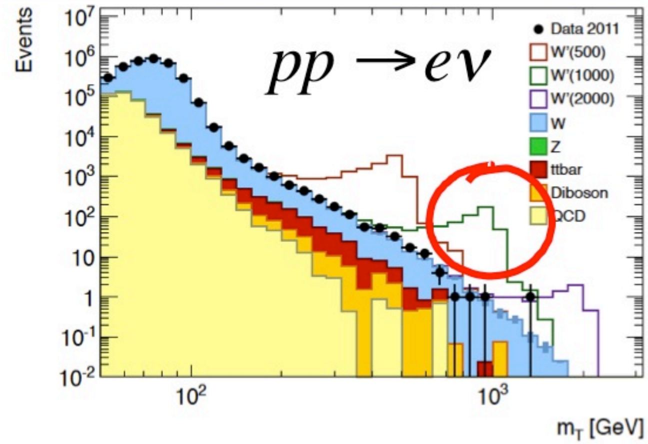


Cirigliano, MGA & Graesser, 2012

What if we see sth?

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

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



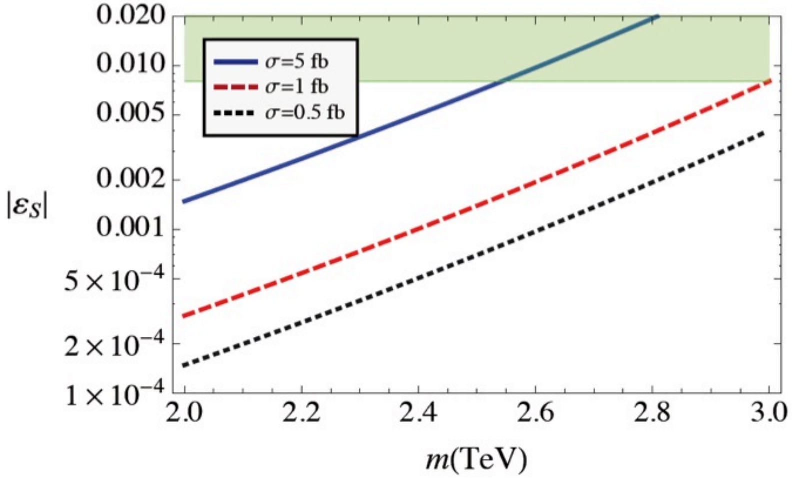
- Then we have a lower-limit value for ε_S:

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

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

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

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

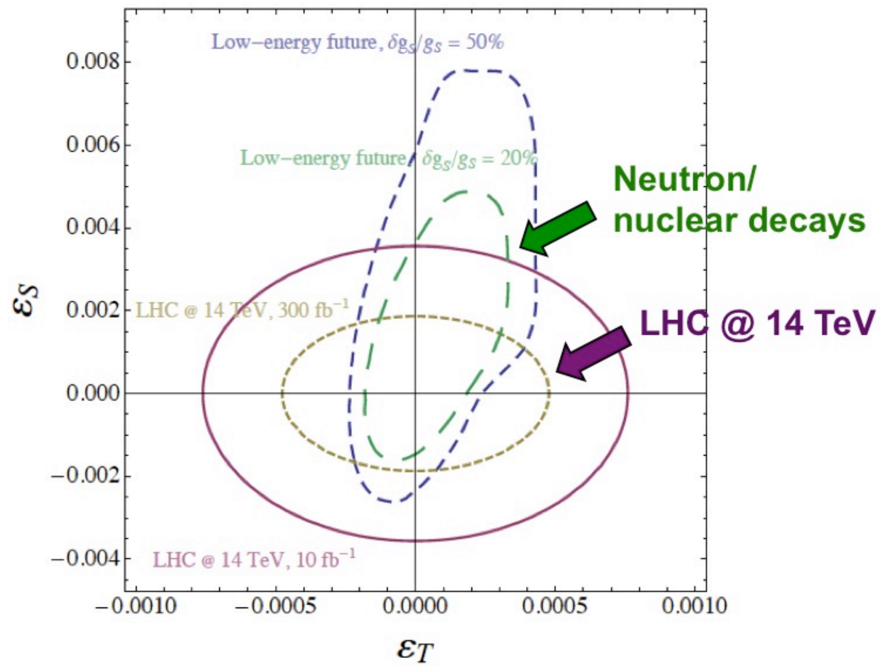


Nice interplay of two experiments separated for so many orders of magnitudes!!!!

(T. Battacharya et al., 2012)

Conclusions

- Connecting HEP and β decays: EFT approach (heavy mediators);
- β decays are exploring the TeV scale!
- Both LHC & low-energy searches needed to get a complete picture.
- Needless to say, this interplay becomes way more interesting if we see a NP signal!



Backup slides

The eff. Lagrangian for E~1 GeV

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

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

(V-A) • (V-A) (V+A) • (V-A)

(S-P) • (S+P) (S+P) • (S+P)

(T-T') • (T-T')

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

where…

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

CKM tests vs. HEP

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

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

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

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

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

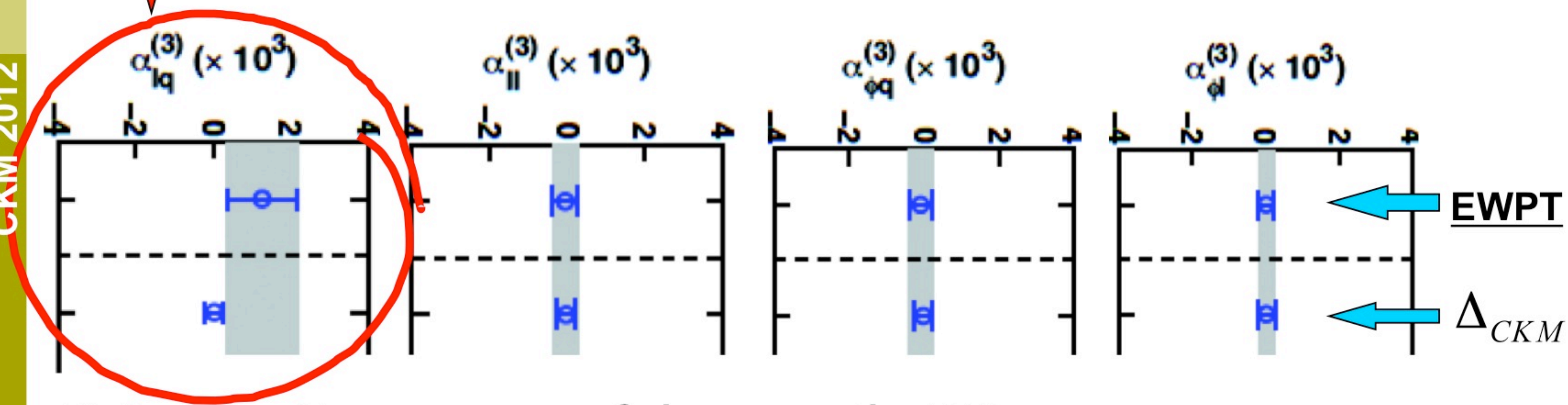
$$O_{\varphi q}^{(3)} = i(\varphi^{\dagger}D^{\mu}\sigma^{a}\varphi)(\bar{q}\gamma_{\mu}\sigma^{a}q) + \text{h.c.}$$

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

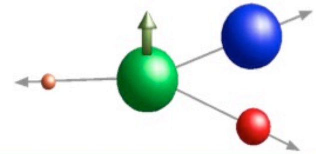
Han & Skiba, PRD71, 2005:

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

5 times less precise!



Angular/Energy distribution



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

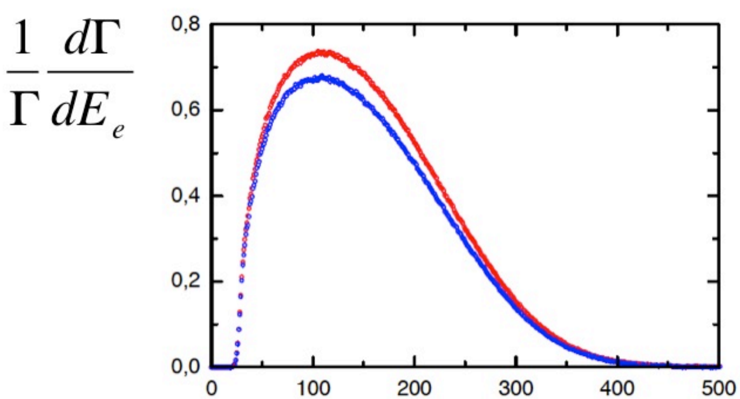
(spectrum) Angular distribution altered... and E-dependent!

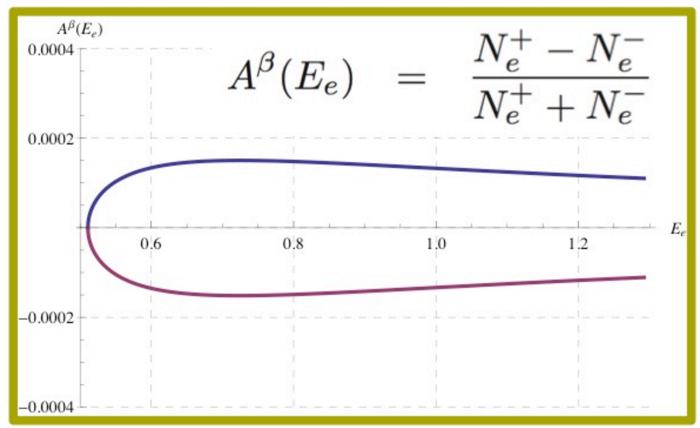
$$\frac{d\Gamma(\mathbf{J})}{dE_e d\Omega_e d\Omega_\nu} \sim \xi(E)\left(1+b\frac{m_e}{E_e}\right)\left\{1+a\left(1-b\frac{m_e}{E_e}\right)\frac{\mathbf{p}_e\cdot\mathbf{p}_\nu}{E_eE_\nu}+A\left(1-b\frac{m_e}{E_e}\right)\frac{\mathbf{p}_e}{E_e}\frac{\mathbf{J}}{J}+\left(B+(b_B-b)\frac{m_e}{E_e}\right)\frac{\mathbf{p}_\nu}{E_\nu}\frac{\mathbf{J}}{J}\right\}$$

(Jackson, Treiman & Wyld, 1957)

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

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





S & T bounds from low-E searches

- 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:

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

$$-1.4 \times 10^{-7} < \epsilon_P^{ee} < 5.5 \times 10^{-4}$$

Where…

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

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

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

$$|\varepsilon_T| \le 10^{-5} - 10^{-3}$$

$$|\varepsilon_S| \le 10^{-3} - 10^{-1}$$

$$\frac{-1.4 \times 10^{-7}}{\log(\Lambda/\mu)} < \gamma_{SP}\, \epsilon_S + \gamma_{TP}\, \epsilon_T < \frac{5.5 \times 10^{-4}}{\log(\Lambda/\mu)}$$

$$\gamma_{SP} = \frac{15}{72}\frac{\alpha_1}{\pi} \approx 6.7 \times 10^{-4}$$

$$\gamma_{TP} = -\frac{9}{2}\frac{\alpha_2}{\pi} - \frac{15}{2}\frac{\alpha_1}{\pi} \approx -7.3 \times 10^{-2}$$

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

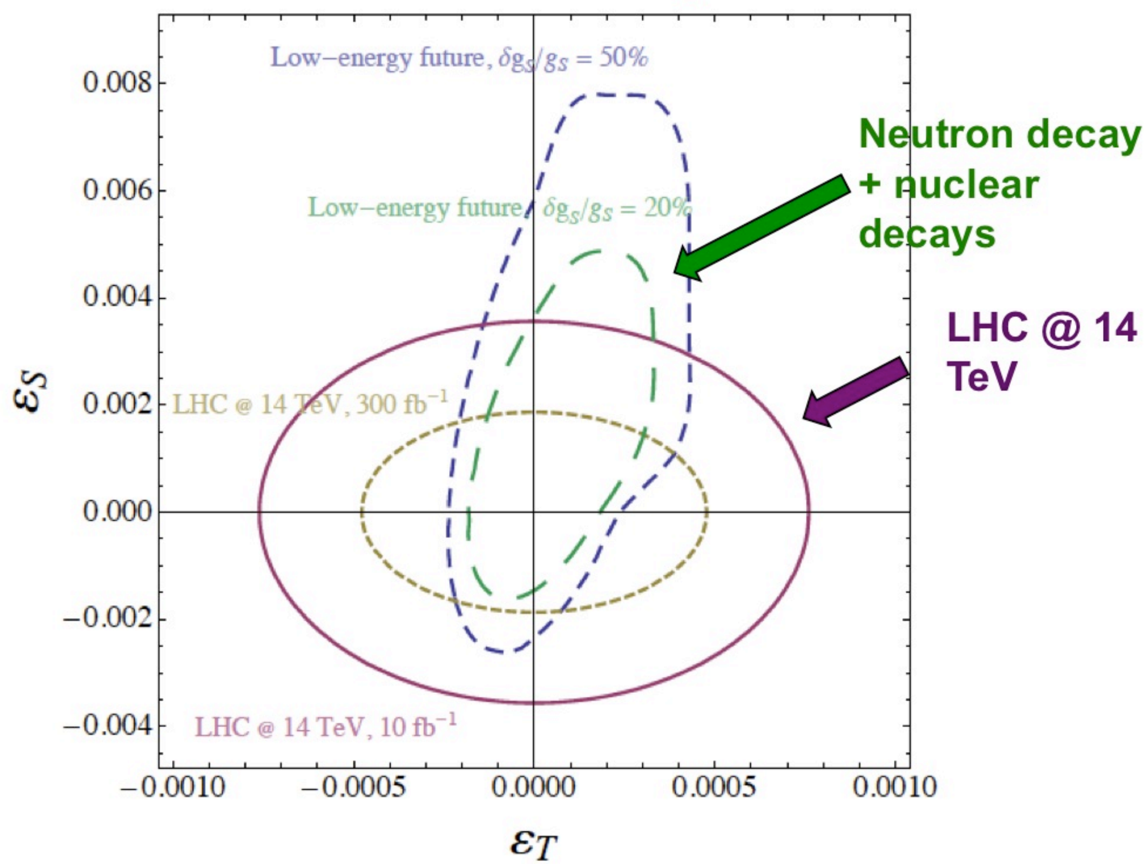
LHC limits on $\varepsilon_{S,T}$

- EFT approach:

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

- 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 $\varepsilon_{S,T}$:

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

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