Nuclear β decays and LHC:
an Effective Field Theory approach

Solvay Workshop — **September 2014**

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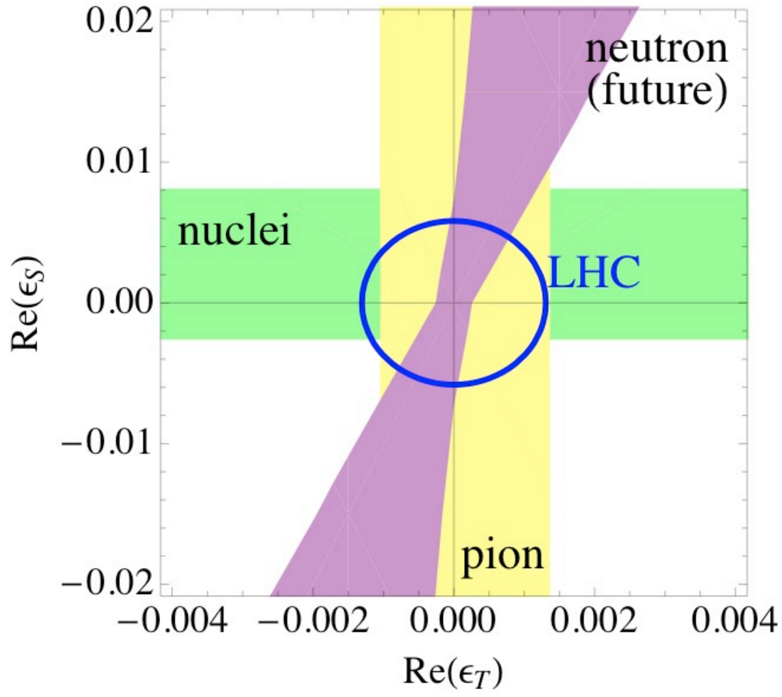

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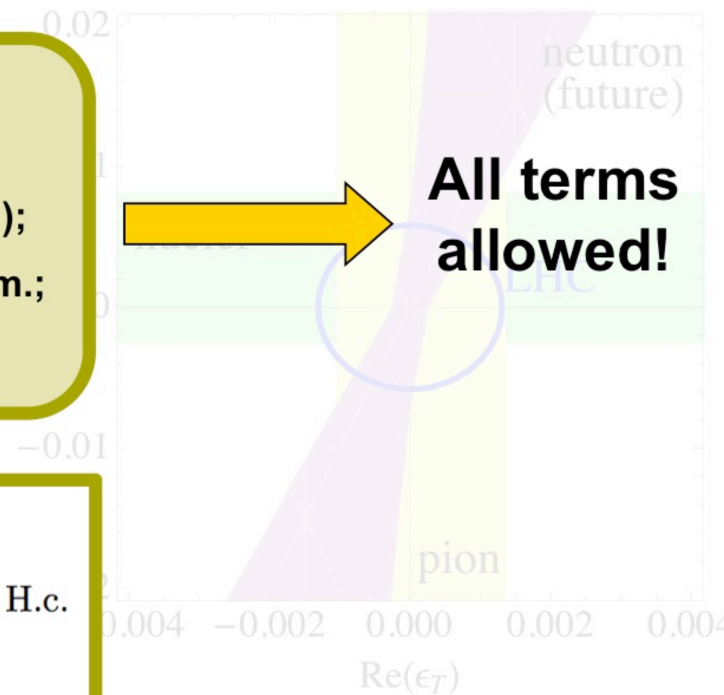
Fields + Symmetries

- nuclei, e, ν;
- n, p, e, ν;
- u, d, e, ν;
- W, Z, …
- bSM?

\+

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

→ **All terms allowed!**



Example:

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

Outline

- Introduction and motivation;
- New Physics searches in beta decays:
  - New form factors;
  - NP bounds.
- LHC searches;

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

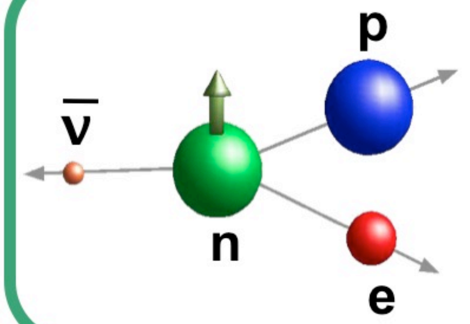
[Bhattacharya, Cirigliano, Cohen, Filipuzzi, MGA, Graesser, Gupta, Lin, PRD85 (2012)*]*

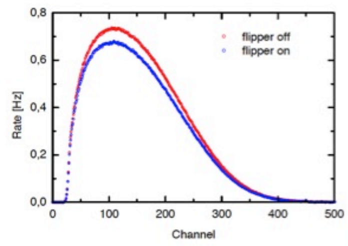
[Cirigliano, MGA & Graesser, JHEP1302 (2013)*]*

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

[MGA & Martin Camalich, PRL112 (2014)*]*

Motivation





Precise data

+

Precise SM predictions

[Remember… $V_{ud} = 0.97425(22)$]

Effective Lagrangian at the hadron level:

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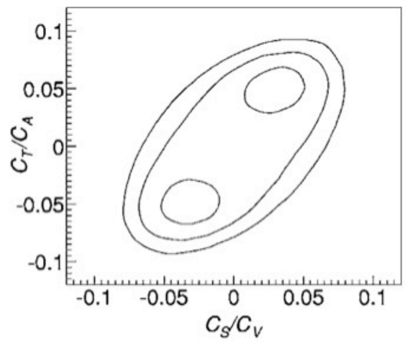
\end{aligned}
$$

[Jackson, Treiman & Wyld'1957]



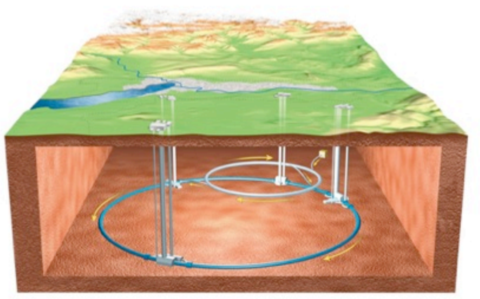
[Severijns, Beck & Naviliat-Cuncic'2006]

Question:

Pion decays? LHC?

Competitive?

?



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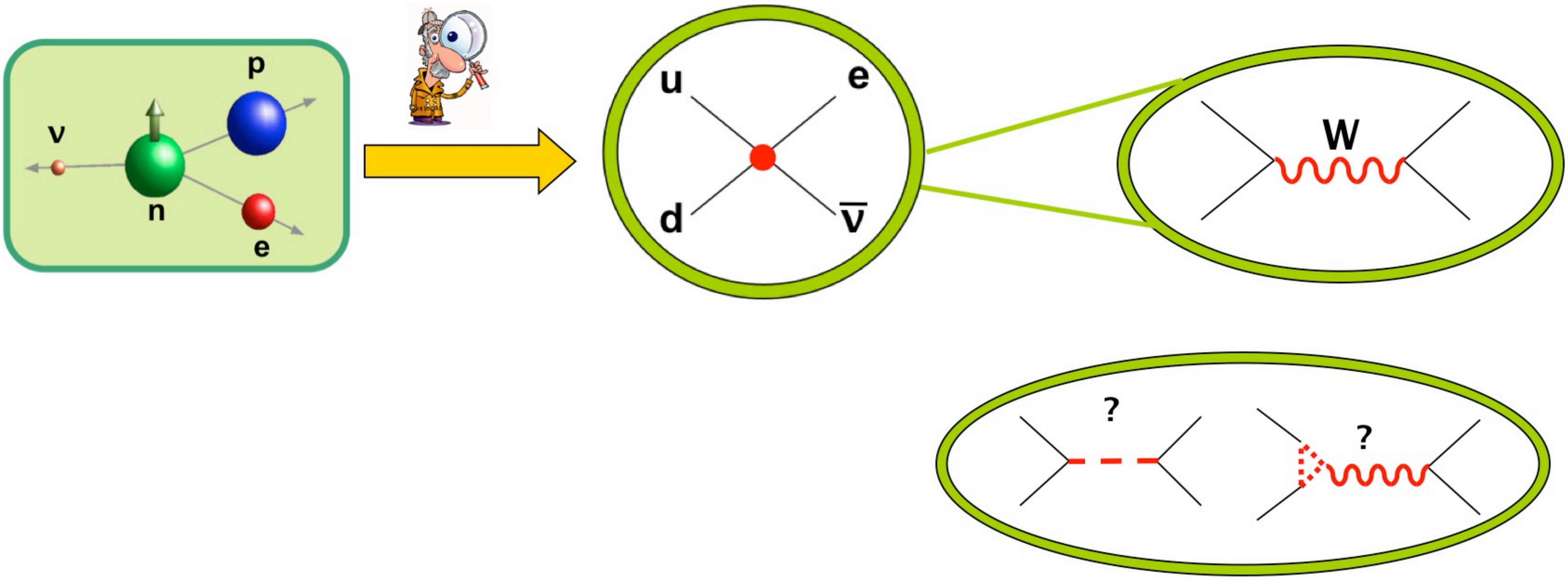

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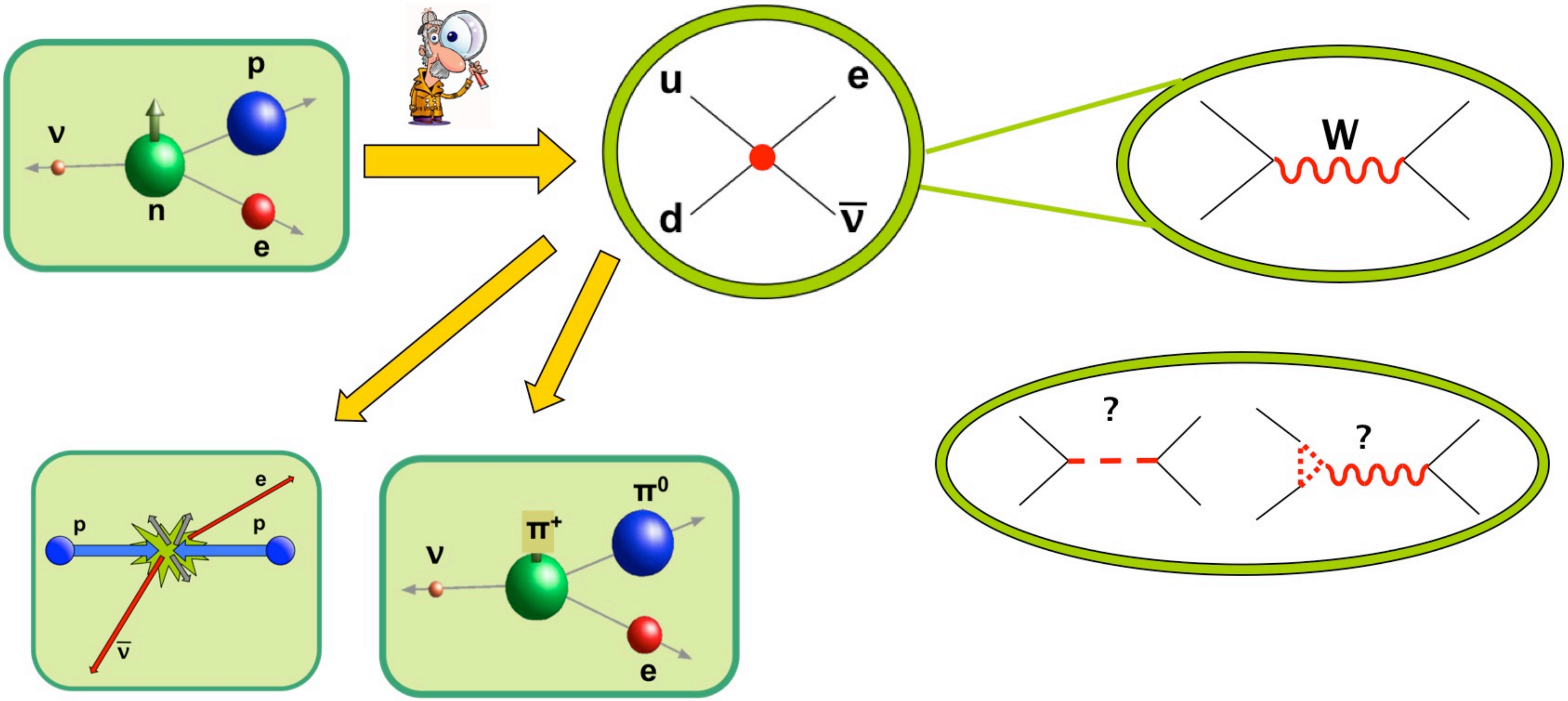
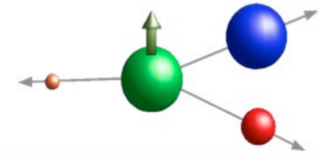


NP searches in beta decays



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

$$
\begin{aligned}
H_{V,A}^{(N)} &= \bar{e}\gamma_\mu(C_V + C'_V\gamma_5)\nu\bar{p}\gamma_\mu n \\
&\quad -\bar{e}\gamma_\mu\gamma_5(C_A + C'_A\gamma_5)\nu\bar{p}\gamma_\mu\gamma_5 n + \text{H.c.} \\
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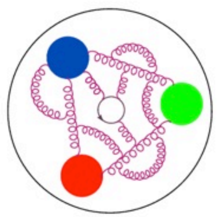
\end{aligned}
$$

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

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

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

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



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

Hadronic-level parameter (from experiment/th)

Hadronization (from lattice/th)

Quark-level parameter

Question: ?

How well do we know them?
Is that OK?

NP searches in beta decays

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

Message:

Use the nucleon-level Lagrangian to compare among nuclear/ neutron experiments [no need to care about FFs at that level]
But translate your results to the quark-language to reach the HEP community (pions, LHC, …)

Question:

$C_i \approx$ (Form factor) $\times$ ϵ

How well do we know them?
Is that OK?

?

Message:

Form factors are very important!

Hadronic-level parameter (from experiment/th)

Hadronization (from lattice/th)

Quark-level parameter

Outline

- Introduction and motivation; ✓
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  - Phenomenology;
- LHC searches;

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

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

[MGA & Martin Camalich, PRL112 (2014)*]*

Form factors in β decay

$C_i \sim g_i \times \varepsilon_i$

$\langle p|\bar{u}\gamma_\mu d|n\rangle \longrightarrow g_V = 1$

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

SM (up to $[\Delta M/M]^2$ effects)

$\langle p|\bar{u}d|n\rangle \longrightarrow g_S$

~~$\langle p|\bar{u}\gamma_5 d|n\rangle \longrightarrow g_P$~~

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

bSM

We don't keep corrections…

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

	g_S	g_T
Adler et al.'1975 (quark model)	0.60(40)	1.45(85)
PNDME 2011	1.05(35)	0.80(40) *(average)*
LHPC 2012	1.08(32)	1.04(02)
PNDME 2013	0.66(24)*	1.09(05)*

Intense activity:

- **Direct lattice calculations;** ***[R. Gupta's talk]***
- **CVC ➔ g_S!**

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

*Not all systematics included in the error.

g_S & the nucleon splitting

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

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

⇓

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

g_S & the nucleon splitting

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

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

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

$g_V \to 1$

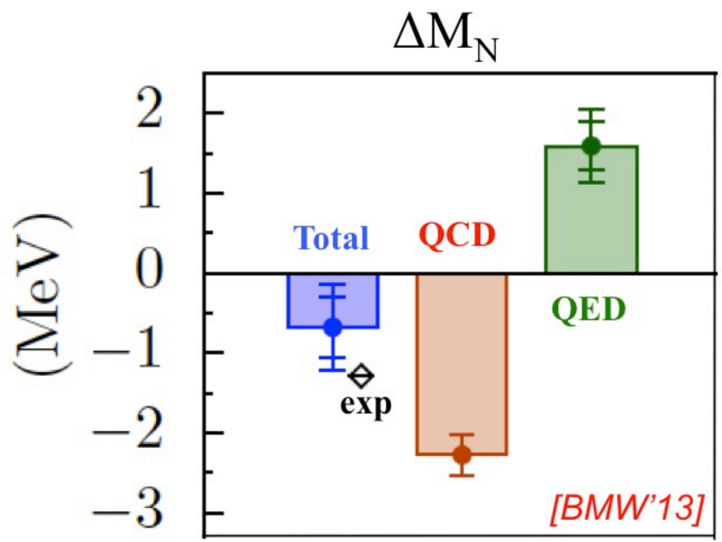
Isospin splitting in the nucleon

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

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

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

Useful connection between two different Lattice efforts!



g_S & the nucleon splitting

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

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

$$g_S = \frac{\left(M_n - M_p\right)_{QCD}}{m_d - m_u} = 0.91(13)$$

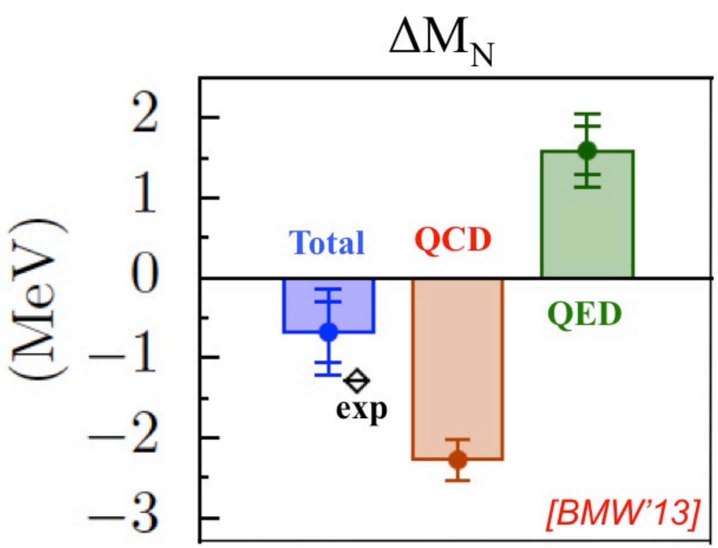
Direct Lattice determinations:

g_S=1.08(32) LHPC Coll.

g_S=0.66(24) PNDME Coll.

$\left(M_n - M_p\right)_{QCD}$ = 2.28(25)(7)(9) MeV *[BMW'2013]*

$m_d - m_u$ = 2.48(25) MeV *[FLAG'2013]*



g_S & the nucleon splitting

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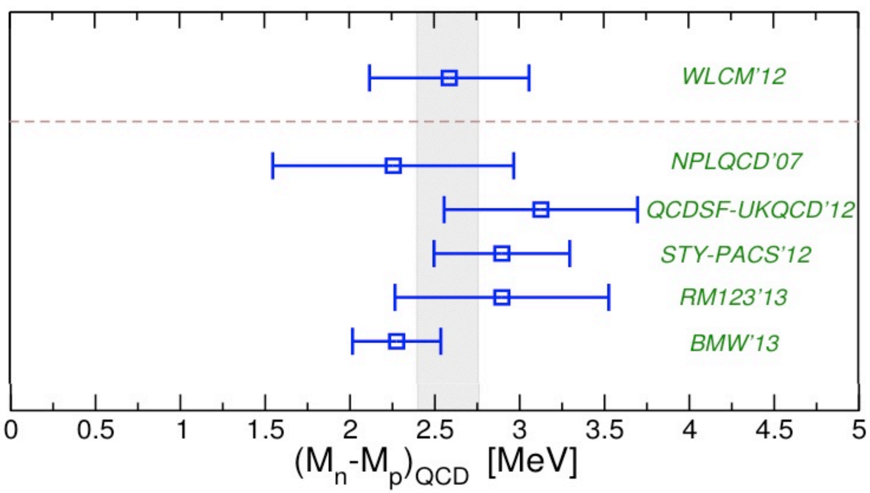
$$m_d - m_u = 2.48(25) \text{ MeV}$$ *[FLAG'2013]*

Already obsolete!

[Thomas et al'2014] $\left(M_n - M_p\right)_{QCD} = 2.33(11)$ MeV

[BMW'2014] $\left(M_n - M_p\right)_{QCD} = 2.52(17)(24)$ MeV

[Erben et al'2014] $\left(M_n - M_p\right)_{QCD} = 2.33(35)$ MeV



g_S & the nucleon splitting

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

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

$$g_S = \frac{\left(M_n - M_p\right)_{QCD}}{m_d - m_u} = 0.91(13) \Rightarrow 1.02(11)$$

Direct Lattice determinations:

g_S=1.08(32) LHPC Coll.

g_S=0.66(24) PNDME Coll.

$\left(M_n - M_p\right)_{QCD} = 2.28(25)(7)$ …

$m_d - m_u = 2.48(25)$ MeV *[FLAG'2013]*

Already obsolete!

[Thomas et al'2014]

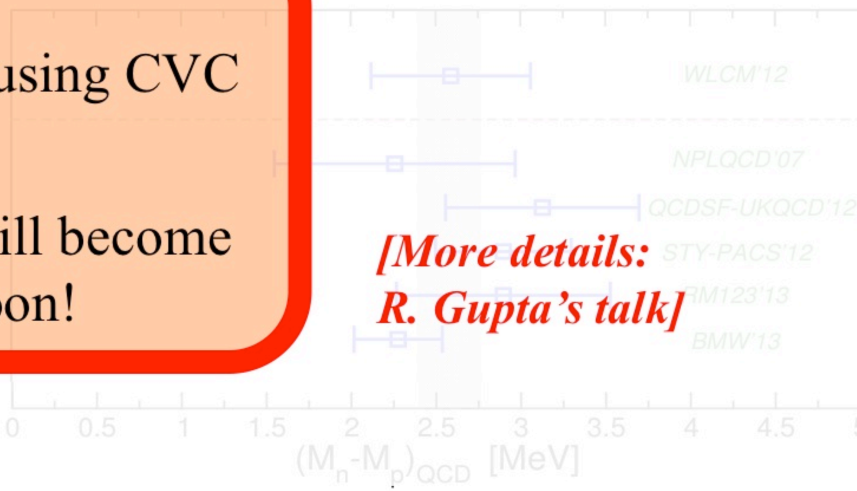
[BMW'2014]

[Erben et al'2014] $\left(M_n - M_p\right)_{QCD} = 2.33(35)$ MeV

Message:

g_S known at 10-15% using CVC

Direct calculations will become competitive soon!



[More details: R. Gupta's talk]

Resuscitating the pseudoscalar interaction

Likewise...

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

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

Implications? It almost compensates the bilinear suppression!

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

"since the nucleons are treated nonrelativistically, the pseudoscalar couplings are omitted"
[Jackson, Treiman & Wyld, 1957]

Message:

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

Outline

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- New Physics searches in beta decays:
  - New form factors; ✓
  - Phenomenology;
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[Cirigliano, MGA & Jenkins, NPB830 (2010)*]*

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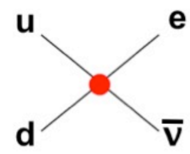
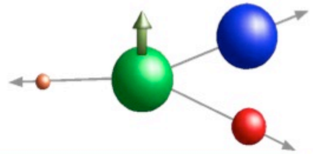
β decay Eff. Lagrangian





After hadronization and at order ε …

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

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

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

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

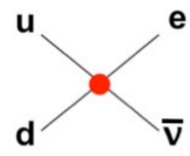
$$g_V \to M_F g_V$$

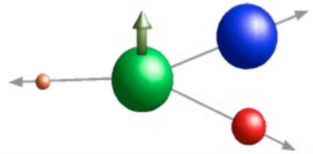
$$g_S \to M_F g_S$$

$$g_A \to M_{GT} g_A$$

$$g_T \to M_{GT} g_T$$

β decay Eff. Lagrangian





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

Lifetime shift ➔ V_{ud} shift

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

$$\mathrm{Re}(\varepsilon_L + \varepsilon_R) \leq 5\cdot 10^{-4}$$

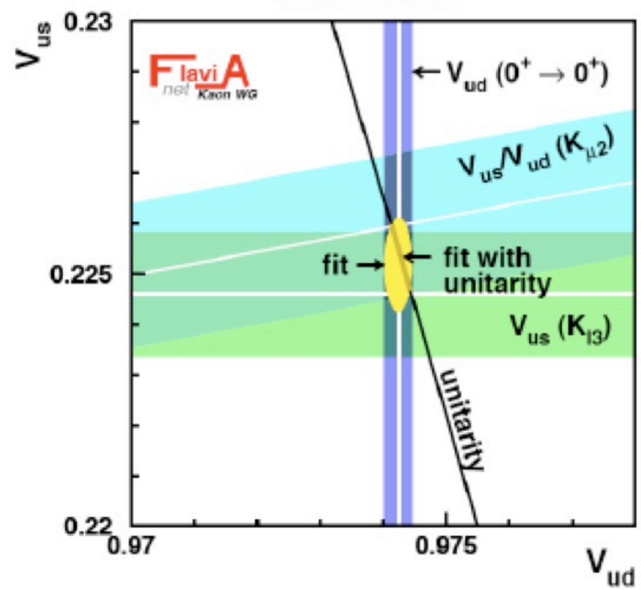
$$\Lambda_{NP} > 11\ \mathrm{TeV}\ (90\%\mathrm{CL})$$

Cirigliano, MGA & Jenkins, NPB830 (2010):

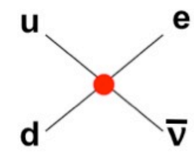
Better than colliders!

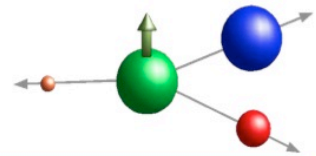
Fermi transitions!
[Talks by Hardy, Blank & Svensson]
Muon decay!
[Pocanic's talk]

arXiv:0907.5386



β decay Eff. Lagrangian





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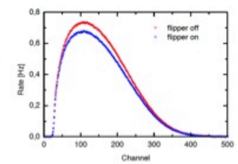
S and T affect the angular distributions and the spectrum!!

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

$$b_{(B)} = \#\varepsilon_S + \#\varepsilon_T$$

- ✓ Direct effect in the spectrum:

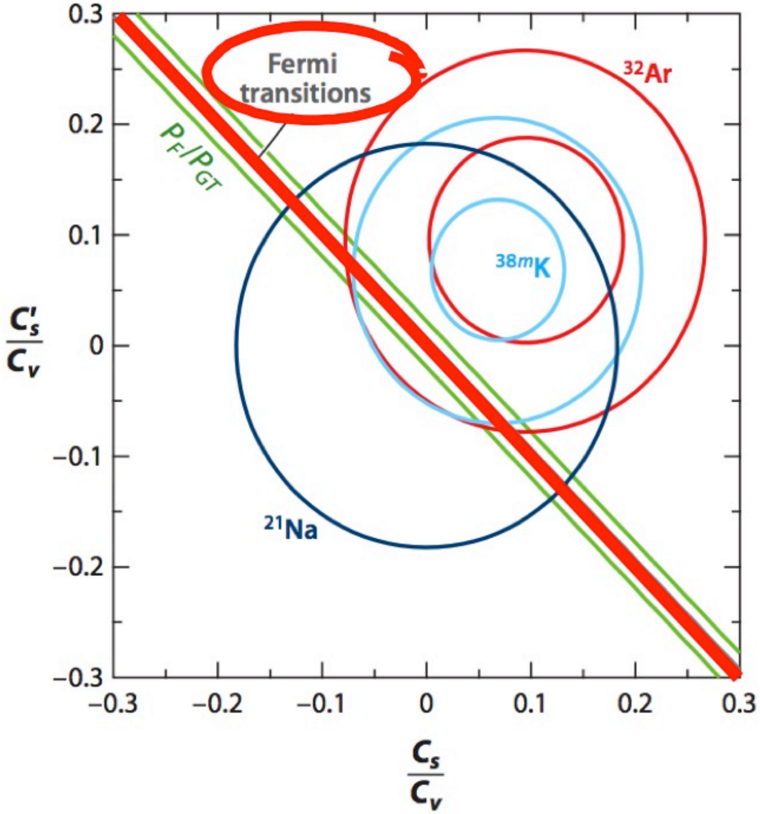


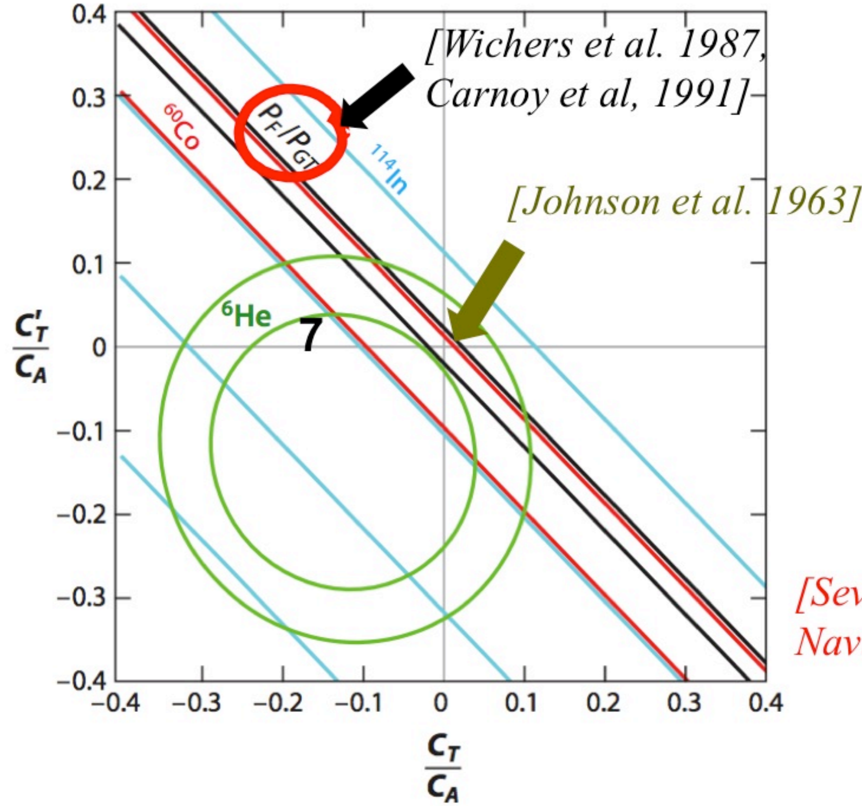
$$\frac{1}{\Gamma}\frac{d\Gamma}{dE_e}$$

[Talks by Naviliat-Cuncic & Severijns]

- ✓ Indirect effect in the asymmetries: $\tilde{X} = \dfrac{X}{1 + b\langle m/E_e\rangle}$ *[A, a, B, … asymmetries]*
- ✓ Indirect effect in the lifetime; *[Hardy & Towner, 2009]*

β decay Eff. Lagrangian





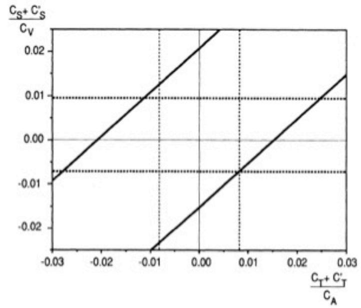
[Severijns & Naviliat-Cuncic, 2011]

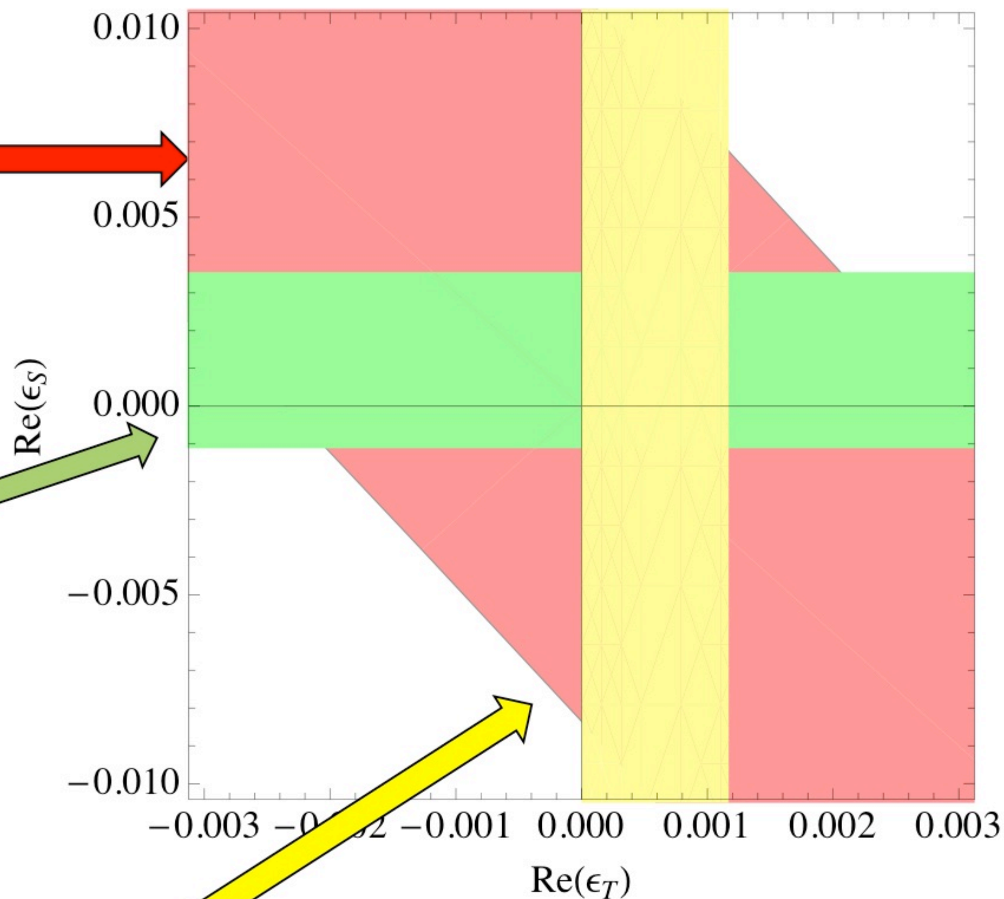
+ Neutron data $= f\,(C_S, C_T,)$ → **Global fit** → $C_S, C_T, \ldots$ → **Form factors** → $\varepsilon_S, \varepsilon_T$

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

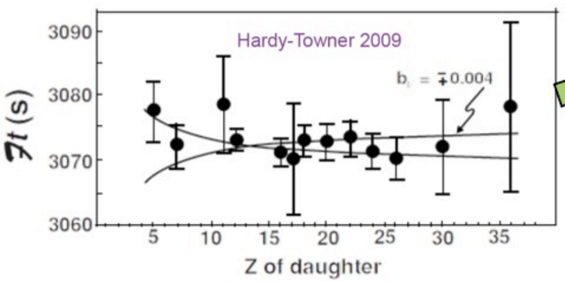
Current limits on S & T from low-E:

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





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



A global fit of nuclear and neutron beta decay data.
[Wauters, Garcia & Hong, 2013]

[Wauters' talk]

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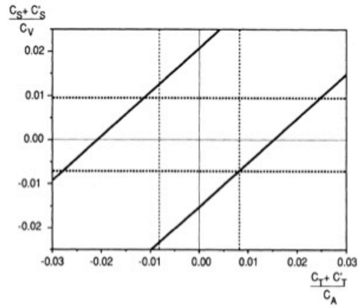
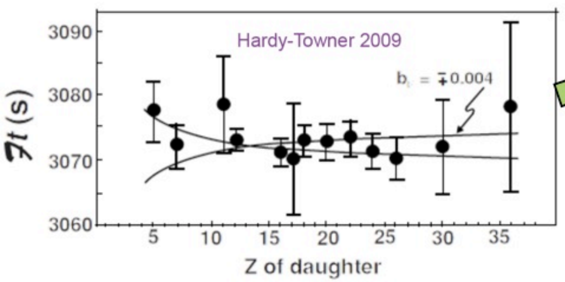
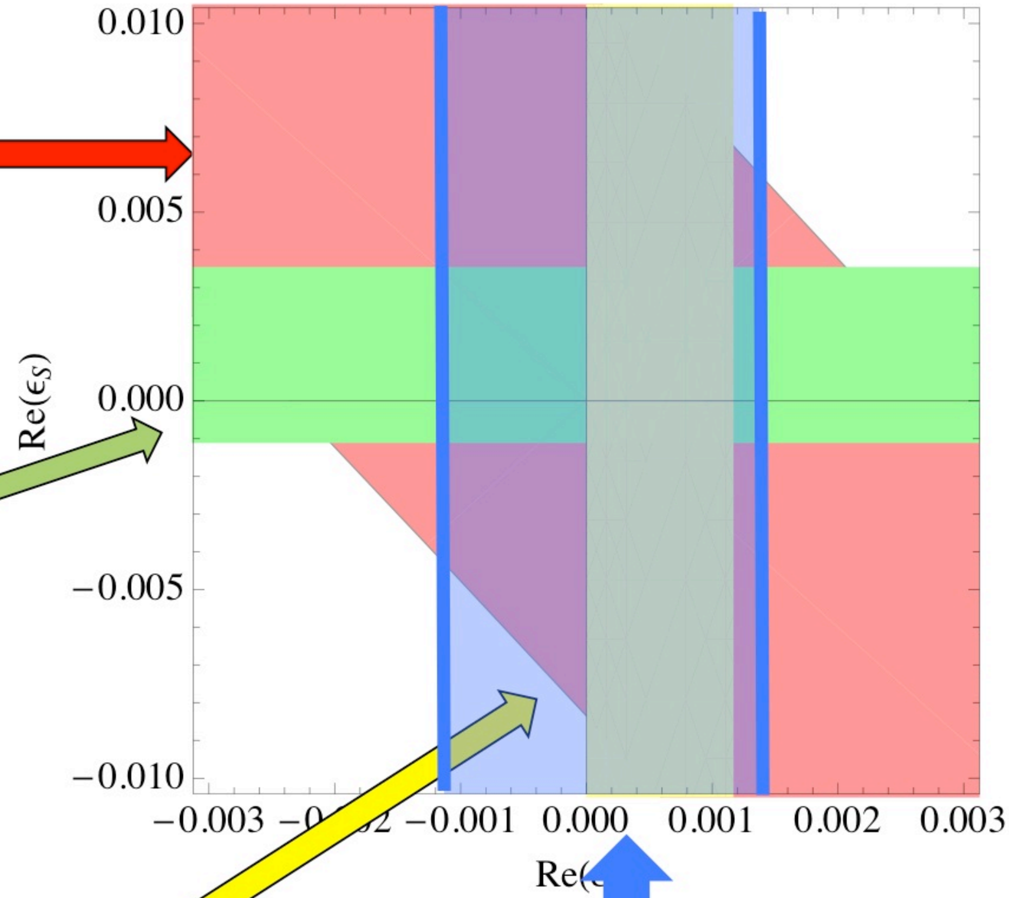


Superallowed nuclear β decays **(b_{0+})**

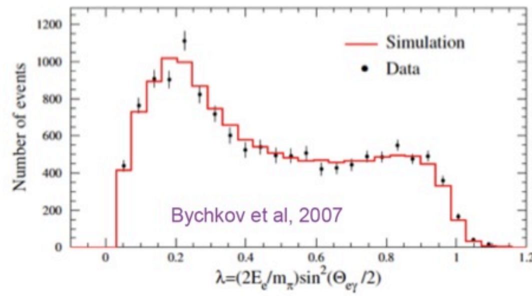




A global fit of nuclear and neutron beta decay data.
[Wauters, Garcia & Hong, 2013]

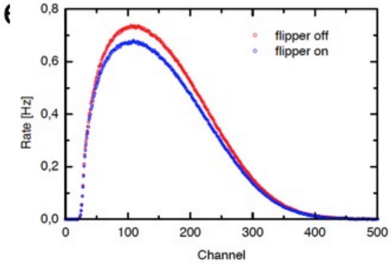
[Wauters' talk]

$\pi \to e\nu\gamma$
(PIBETA´2009)



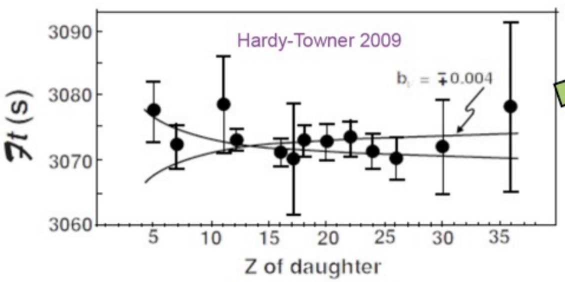
~~Current~~ Future limits on S & T from low-E:

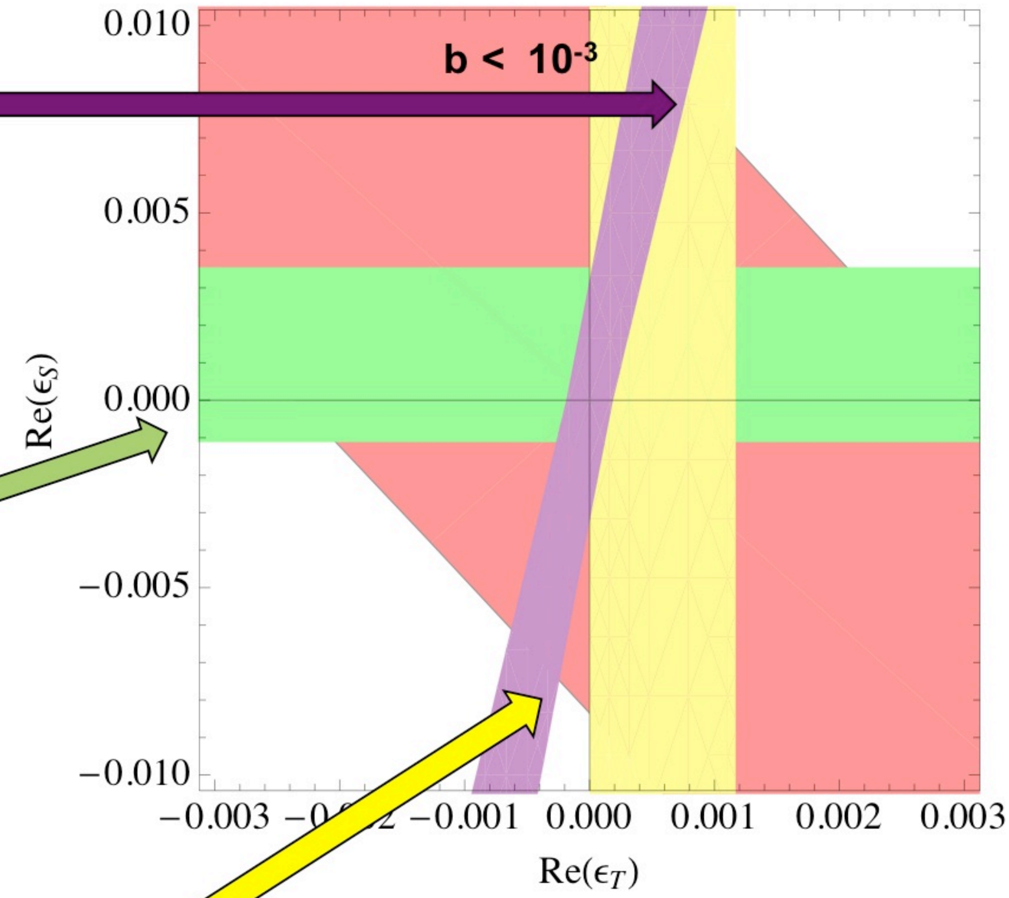
Future neutron decay



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

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





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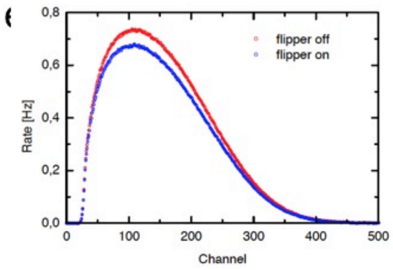

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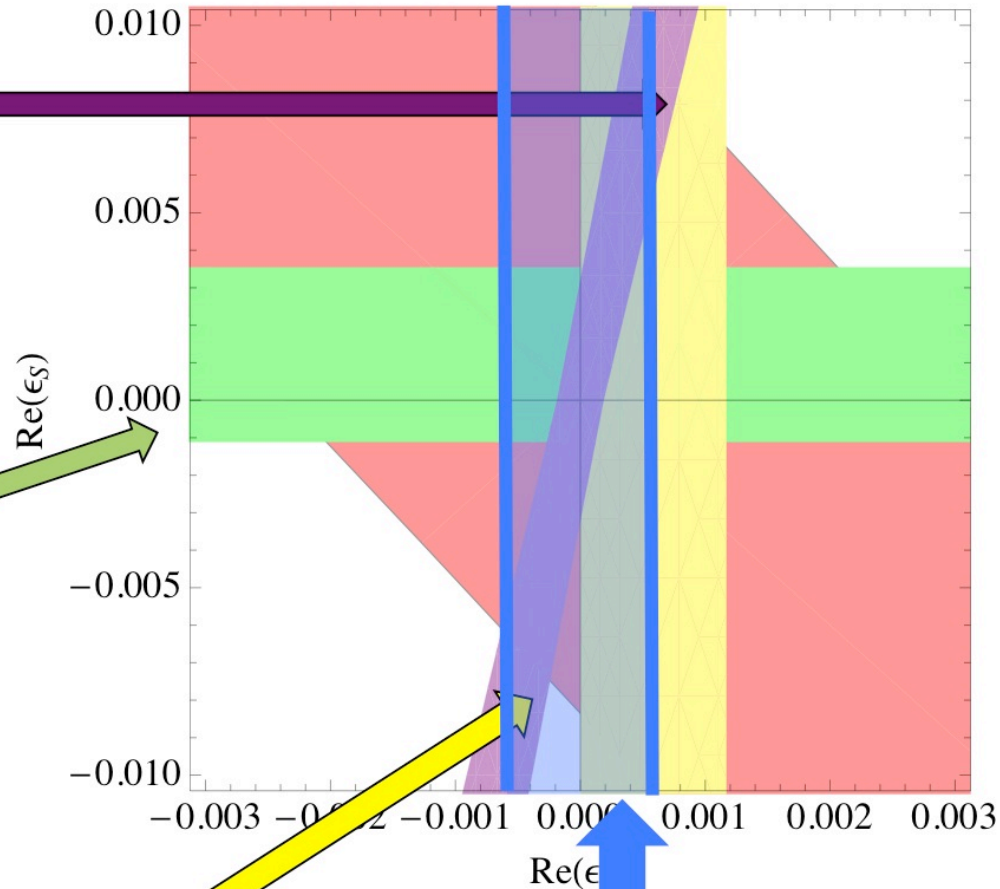

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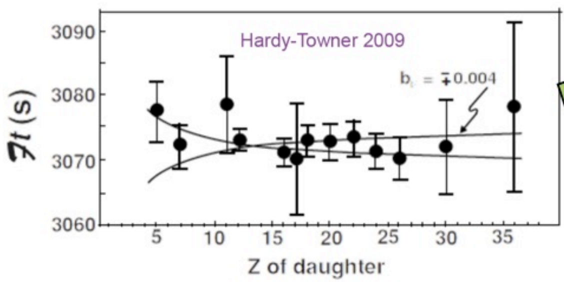
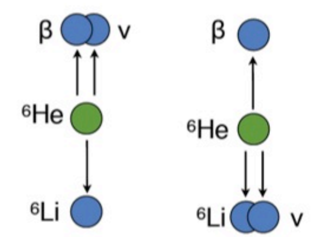


A global fit of nuclear and neutron beta decay data.

[Wauters, Garcia & Hong, 2013]

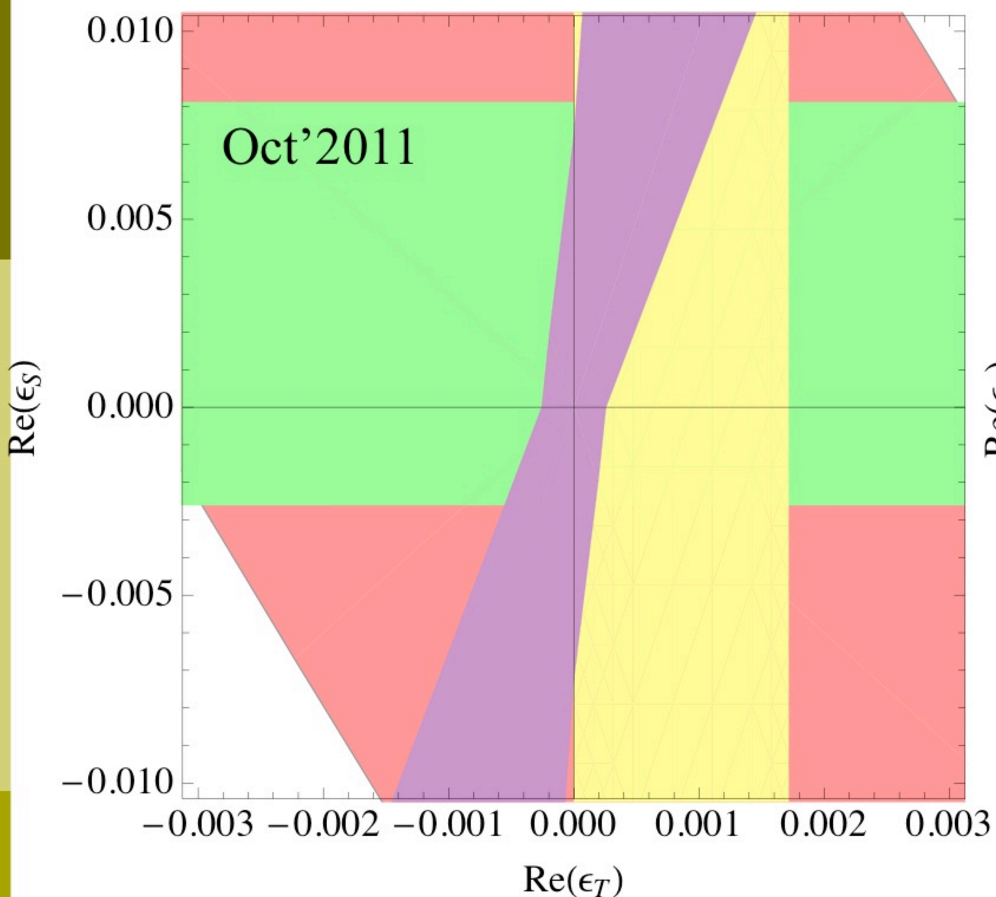
[Wauters' talk]

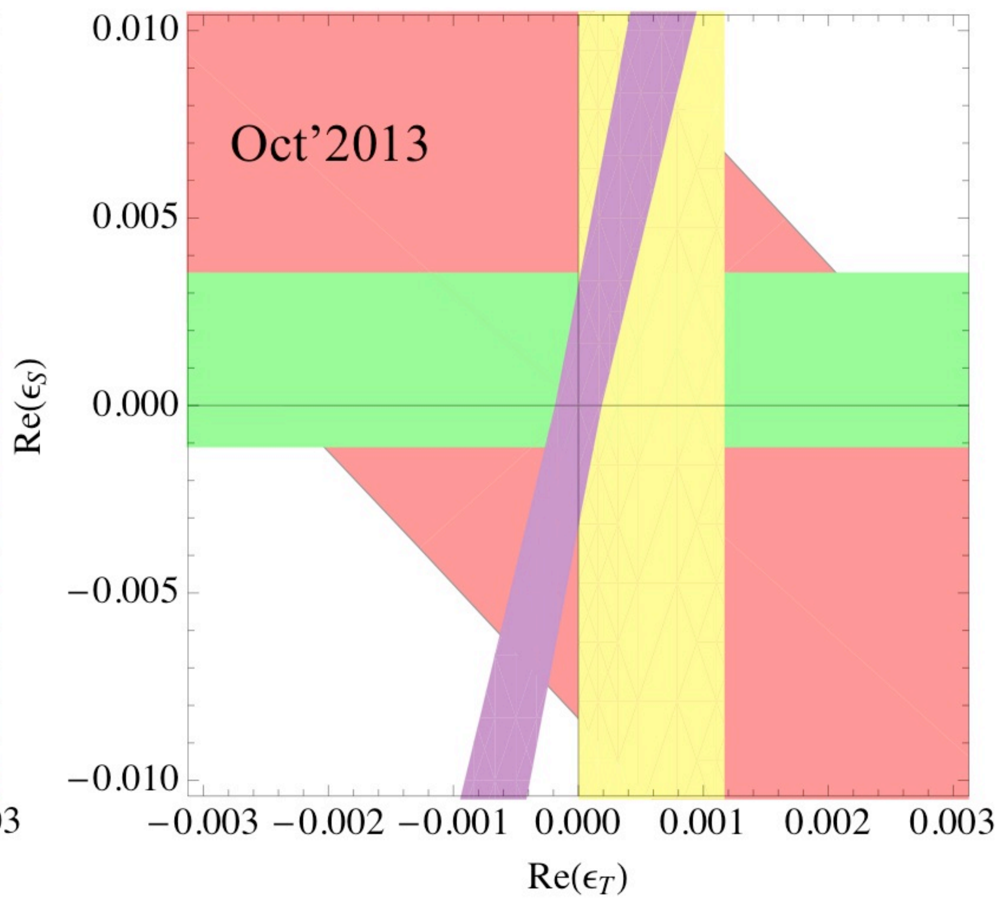
b_{GT} from $\delta a(^6He) \sim 10^{-4}$



[Talks by Mueller & Hass]

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

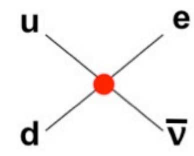


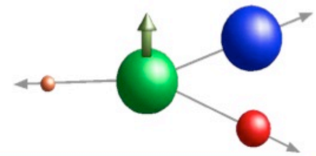


- We are benefiting here from the advance in the FF determinations!
- Conclusion: S,T are at least ~1000x weaker than the V-A Fermi interaction.

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

β decay Eff. Lagrangian





After hadronization and at order ε …

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

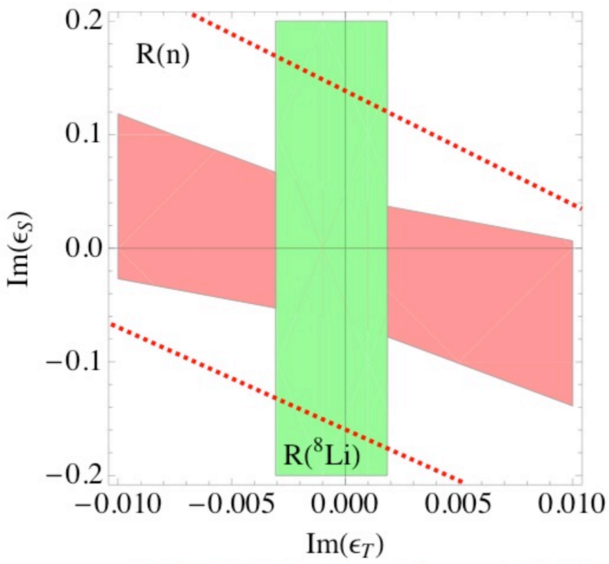
$$+\, g_S\,\epsilon_S\,\bar{e}_R\nu_L\cdot\bar{p}n + 2g_T\,\epsilon_T\,\bar{e}_R\sigma_{\mu\nu}\nu_L\cdot\bar{p}\sigma^{\mu\nu}n_L\Big]$$

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

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

CP violating effects?

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



[MGA & Naviliat-Cuncic, 2013]

D coefficient: Im(ϵ_R)

[Wed's talks by Soldner & Murata]

Outline

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

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

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

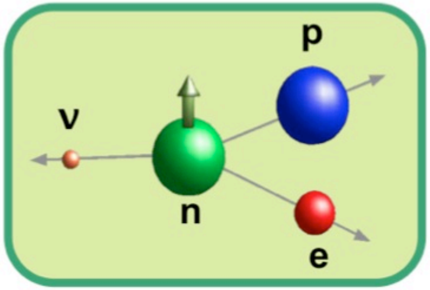
[Cirigliano, MGA & Graesser, JHEP1302 (2013)*]*

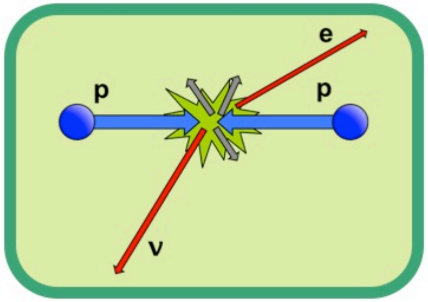
[MGA & Naviliat-Cuncic, Ann. Phys. 525 (2013)*]*

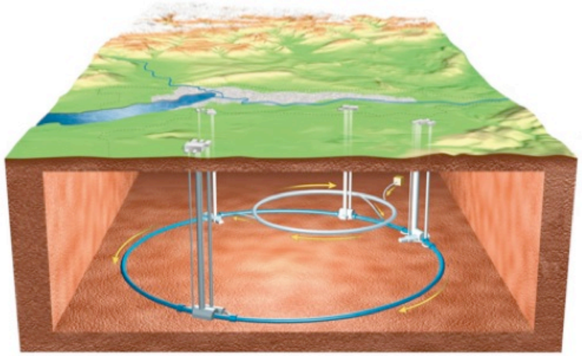
[MGA & Martin Camalich, PRL112 (2014)*]*

What about the LHC?

- These new particles would affect the pp collisions!

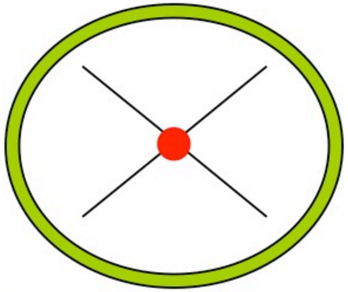


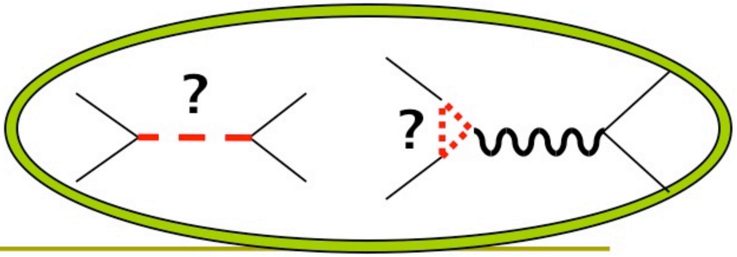




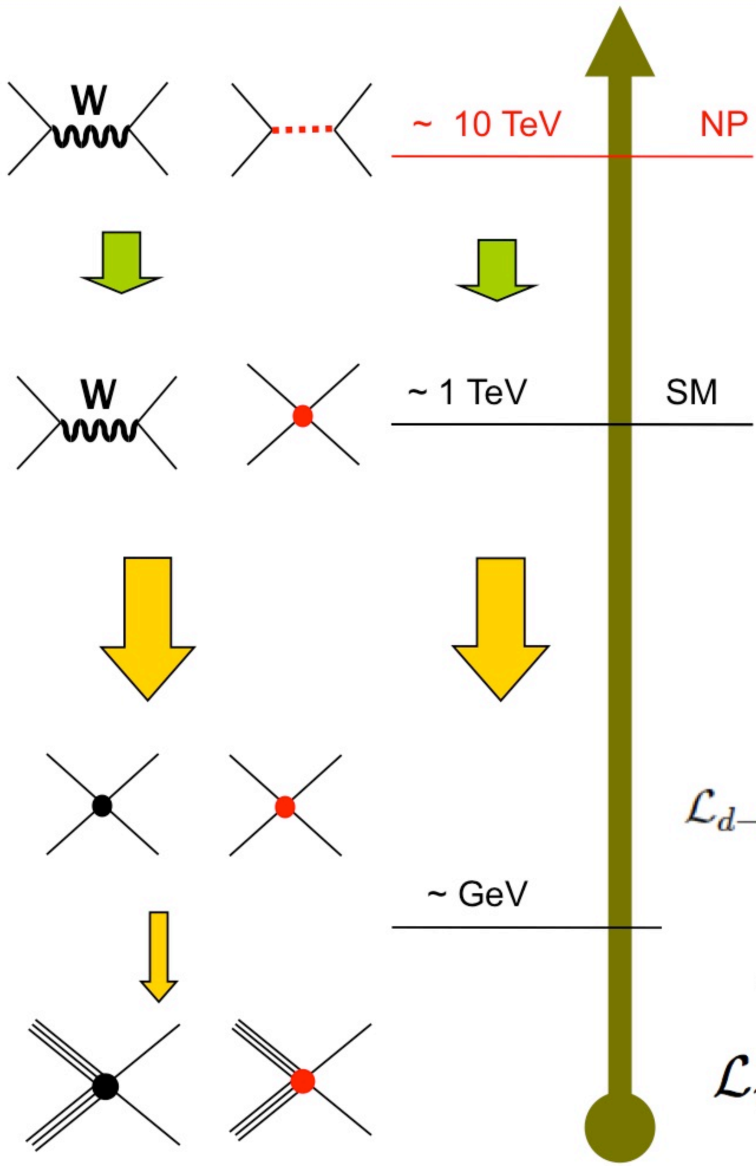
- S,T: In principle low-E experiments are favored (interference ~ m/E), but the LHC is powerful…

- 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!





Effective Lagrangians



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

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

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

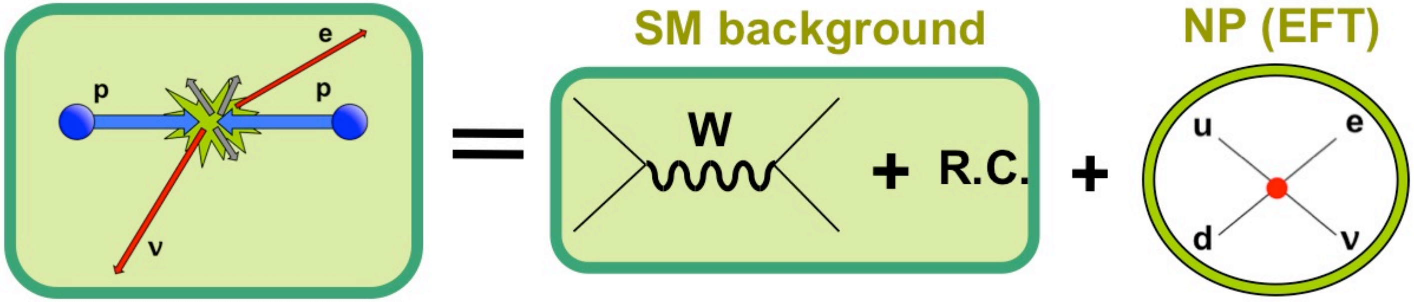
[Cirigliano, MGA, Jenkins'2010, Cirigliano, MGA, Graesser'2012]

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

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

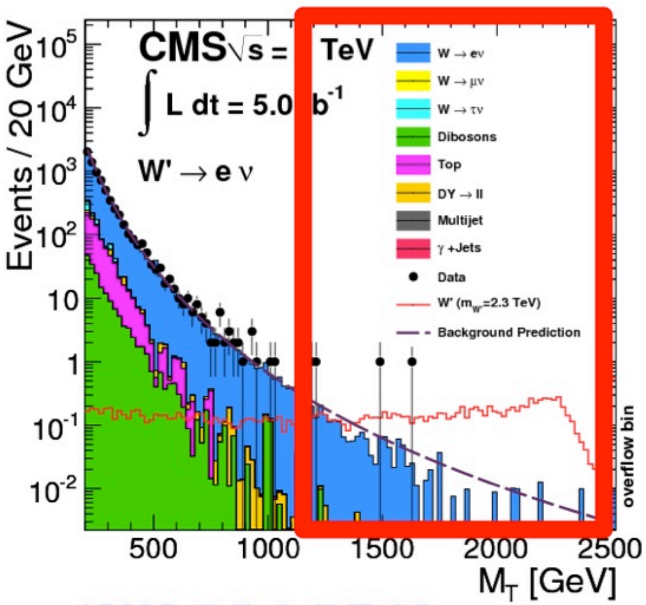
$$\varepsilon_i = f(\alpha_j)$$

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

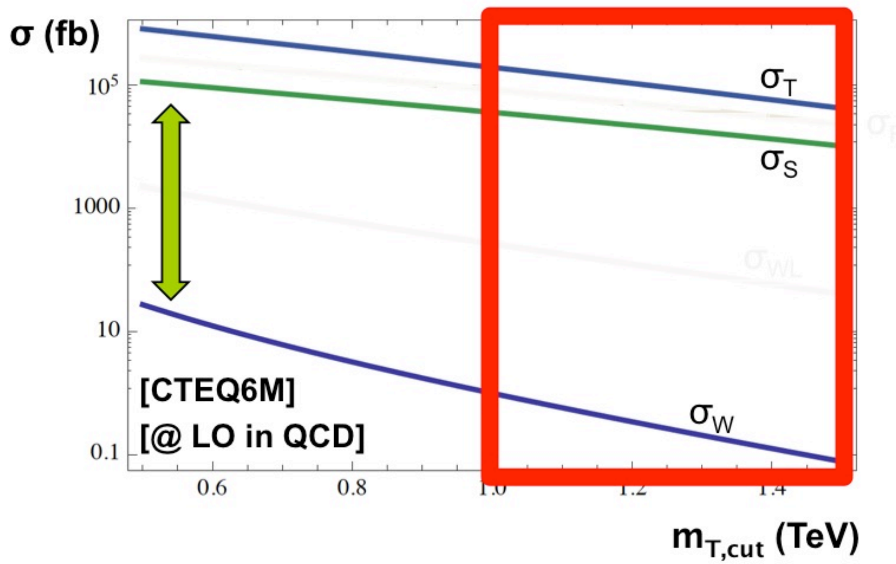


- To suppress the bkg, we look for ***(e+ν)***-events with high m_T:

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



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



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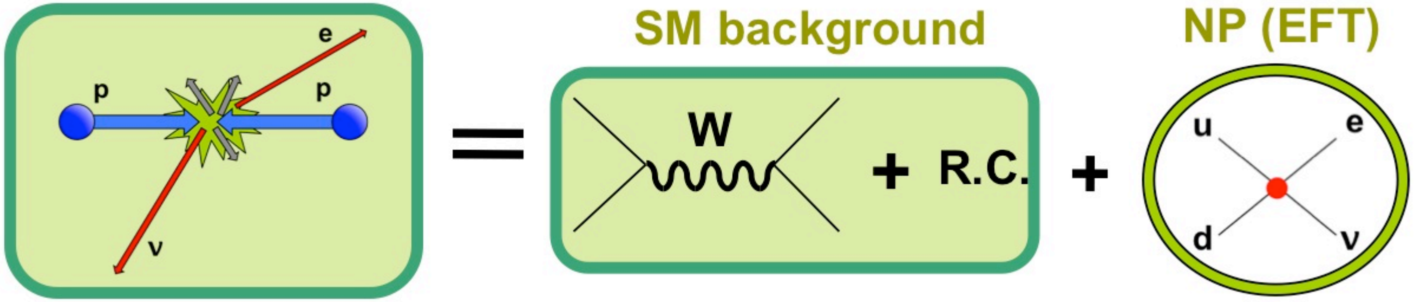

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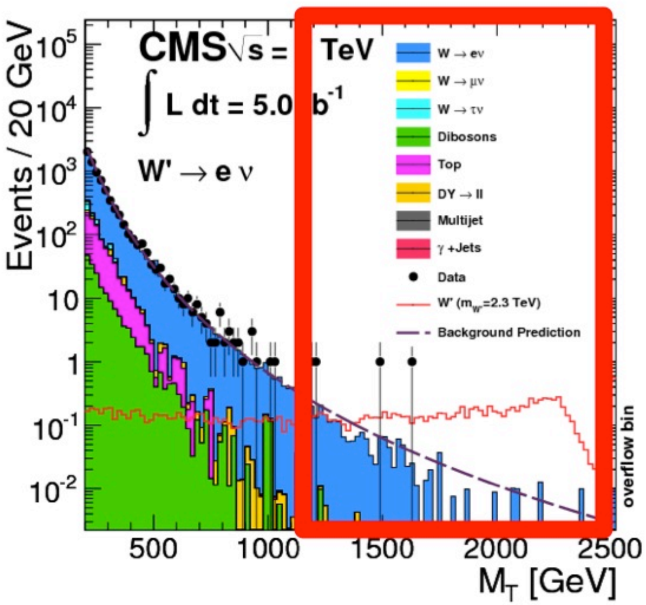

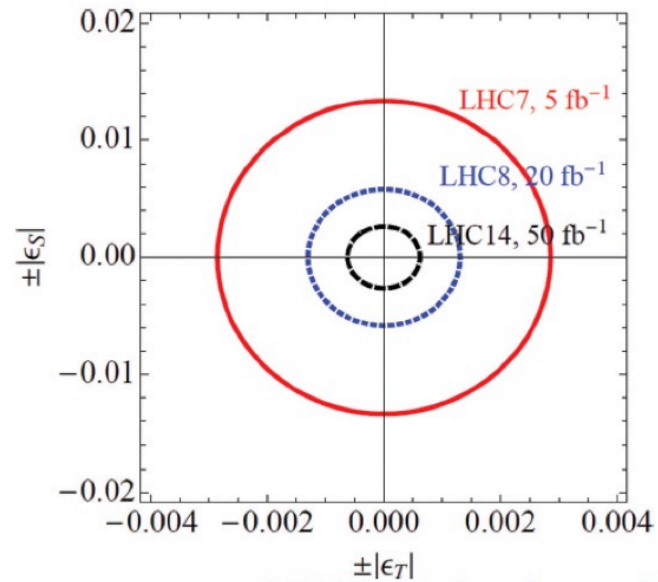

[MGA & Naviliat-Cuncic, 2013]

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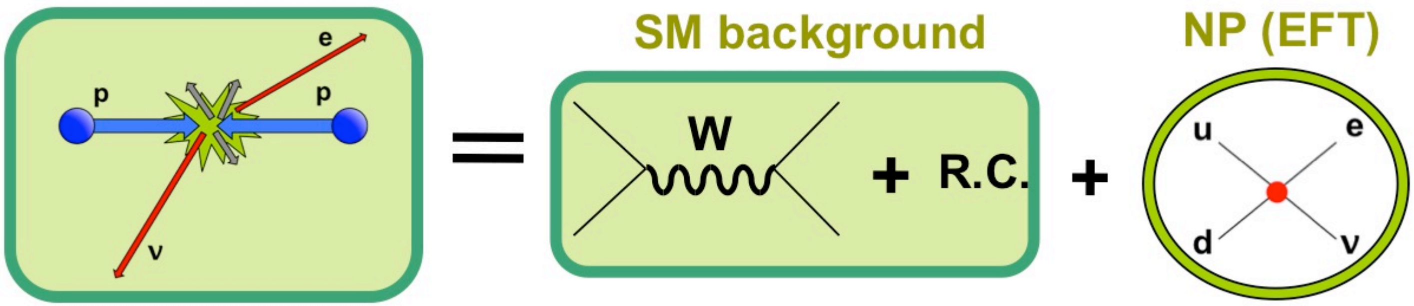

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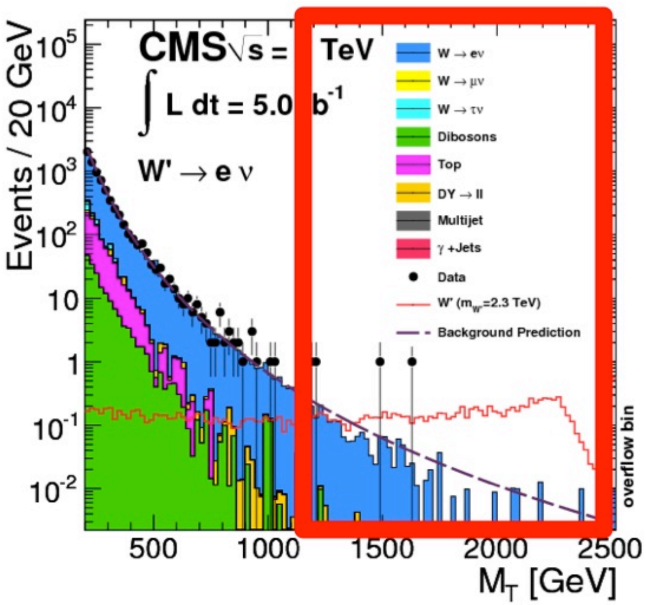
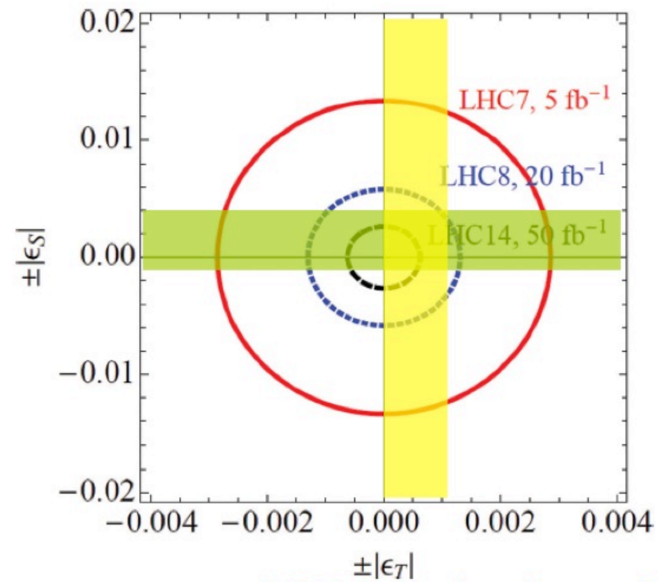
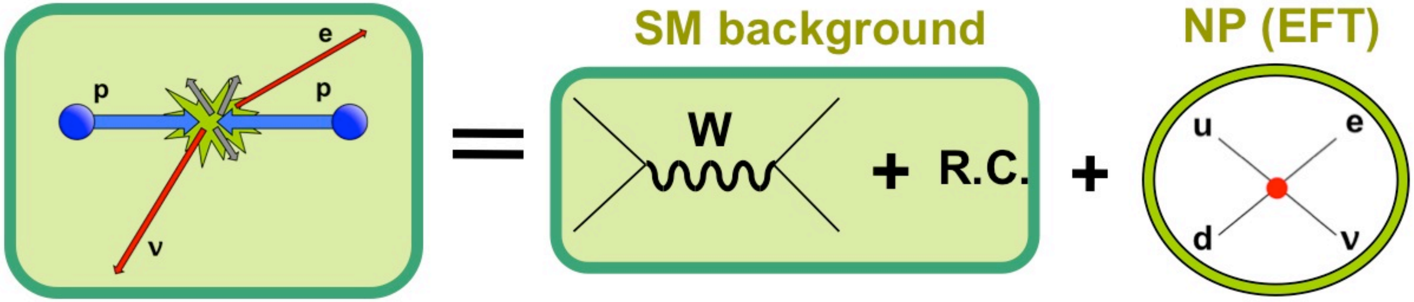




[MGA & Naviliat-Cuncic, 2013]

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



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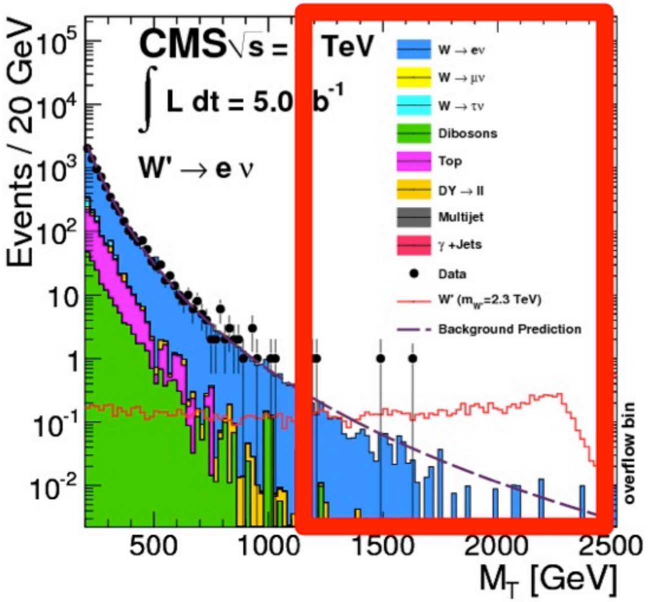

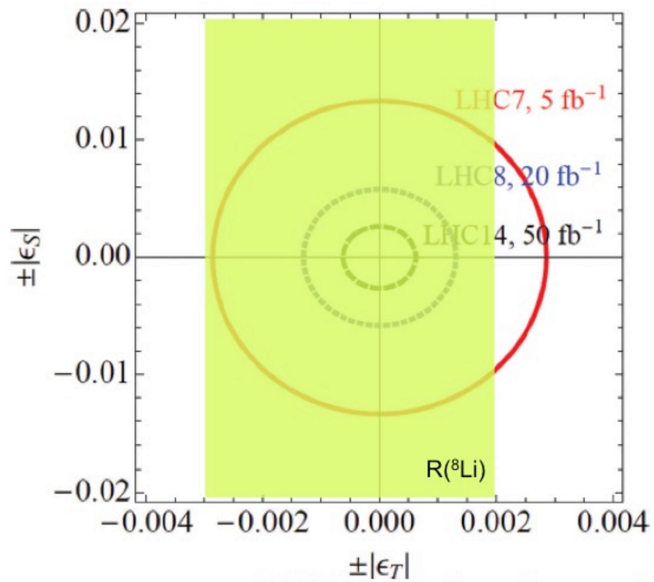

[MGA & Naviliat-Cuncic, 2013]

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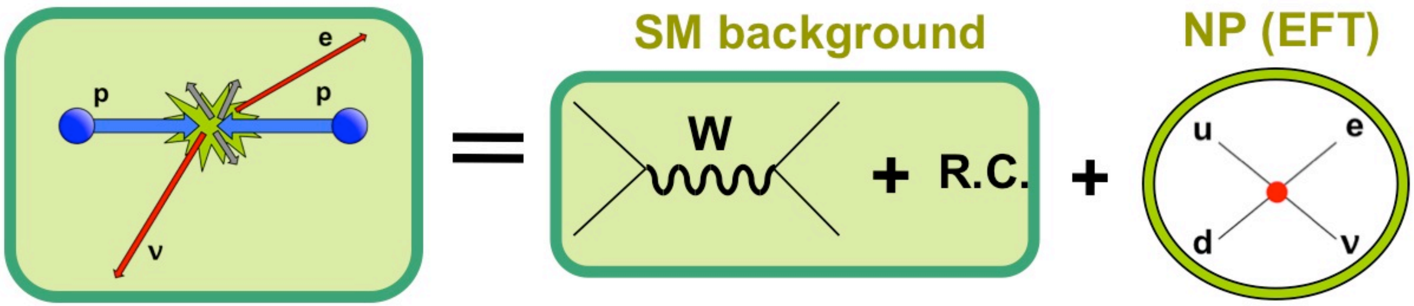
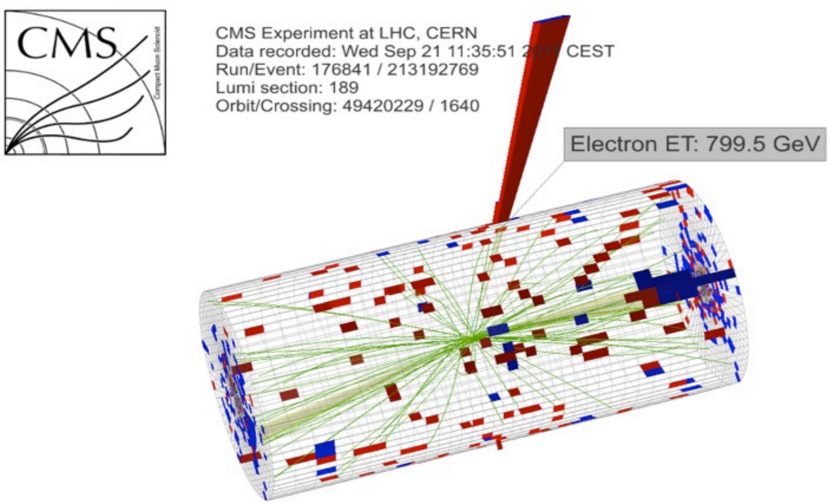
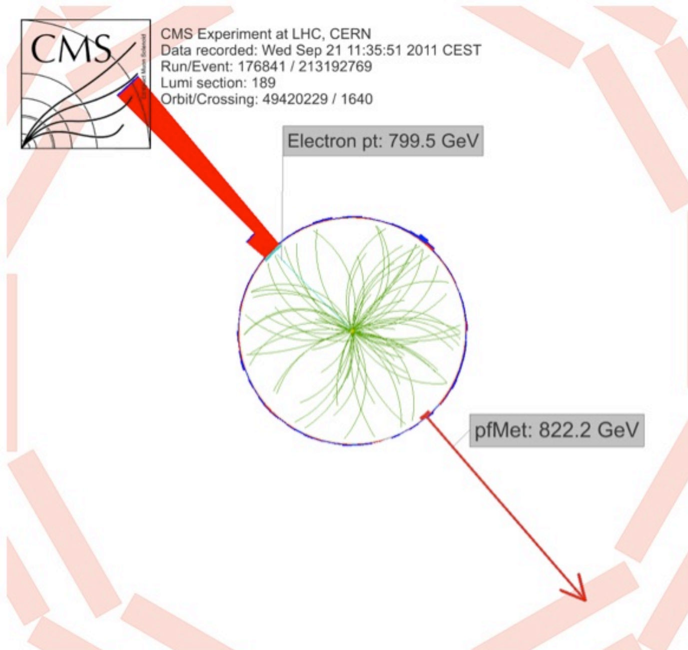


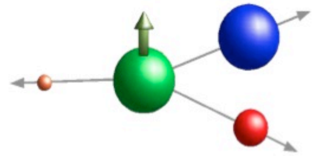


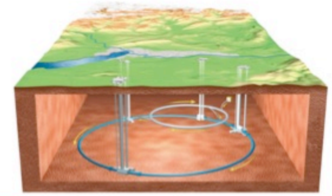


Each event can be characterized by the "transverse mass"

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

Beyond $\varepsilon_{S,T}$





Interesting competition*

ν_L

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

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

Low energy dominates!

ν_R

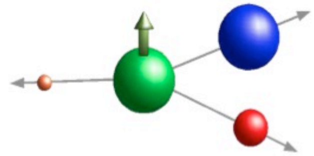
	$\lvert\tilde{\epsilon}_L\rvert$	$\lvert\tilde{\epsilon}_R\rvert$	$\lvert\tilde{\epsilon}_P\rvert$	$\lvert\tilde{\epsilon}_S\rvert$	$\lvert\tilde{\epsilon}_T\rvert$	
Low-E	6	6	0.03	14	3.0	x 10^{-2}
LHC ($e\nu$)	-	0.2	0.6	0.6	0.1	x 10^{-2}

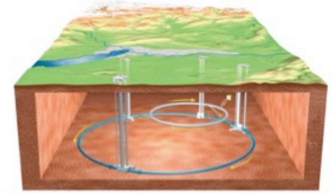
LHC dominates!

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

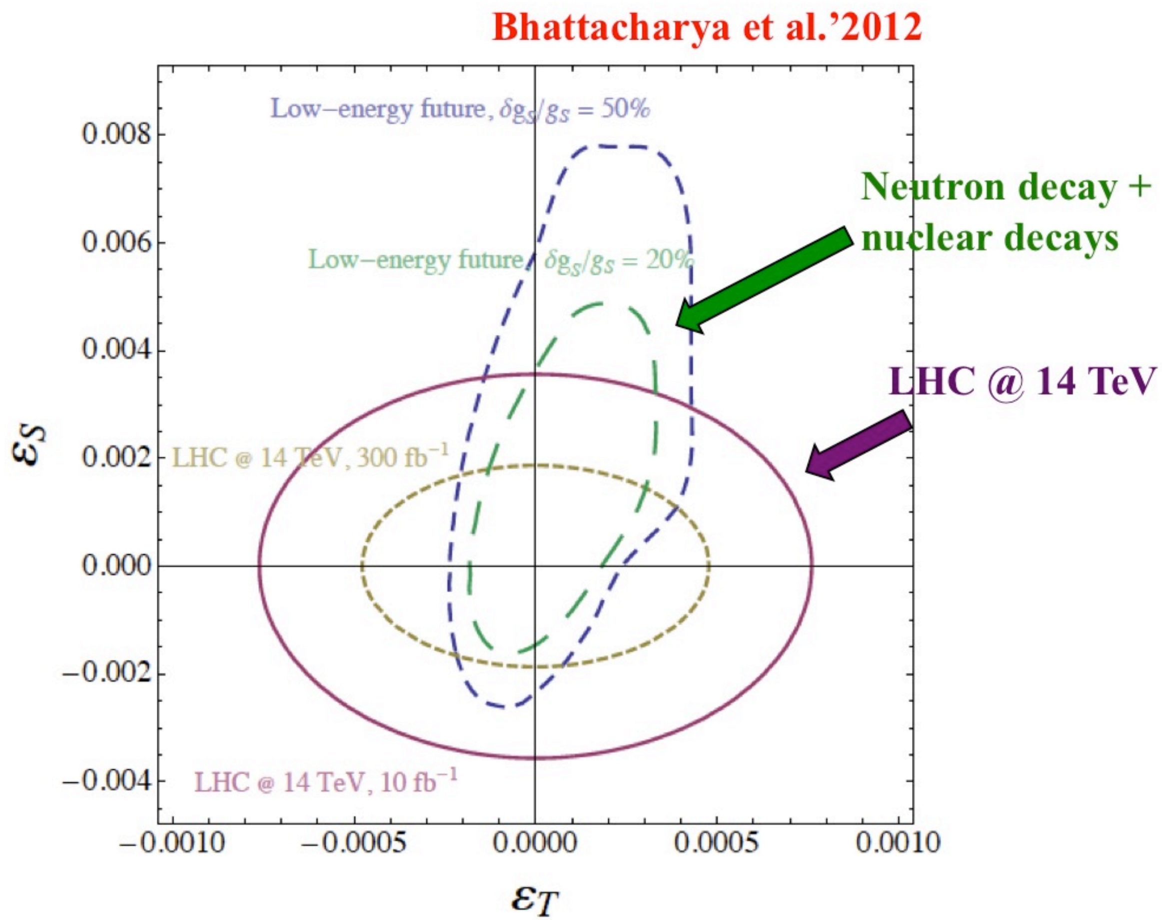
*If the neutrino is an electron neutrino…

β decays vs. the LHC

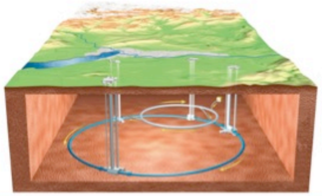


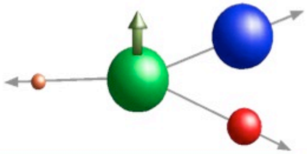


- The competition will continue:
  - New lattice data for the non-standard form factors;
  - New experimental data from beta decays;
  - LHC @ 14 TeV, with higher luminosity;



Conclusions

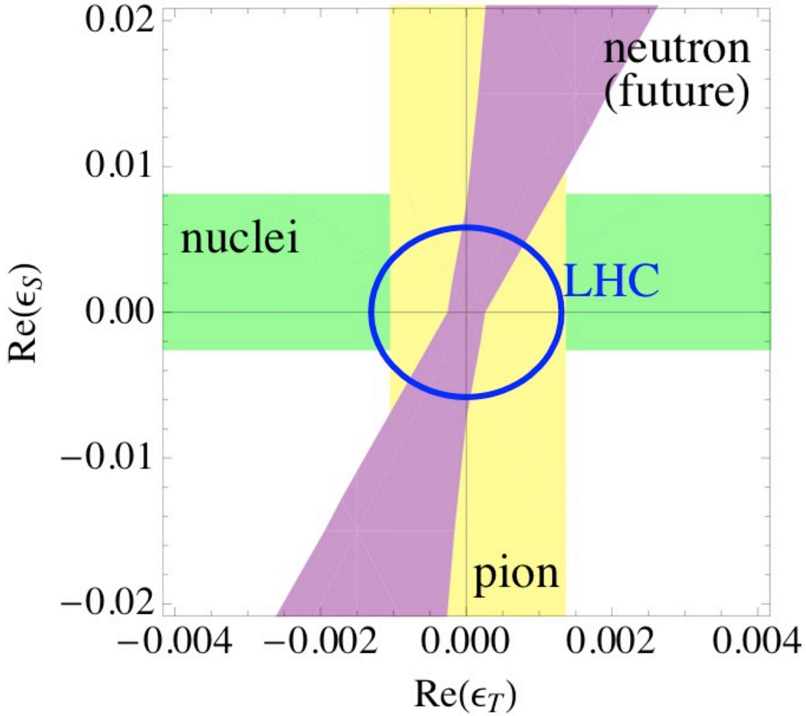




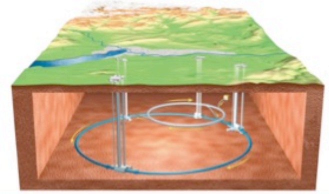
- β decay are sensitive to TeV physics!
  - Intense theoretical activity (form factors);

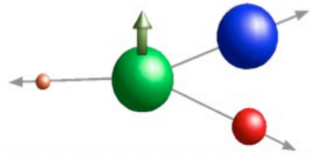
$$g_S = \frac{(M_n - M_p)_{QCD}}{m_d - m_u} = 1.02(11)$$

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



Bonus track

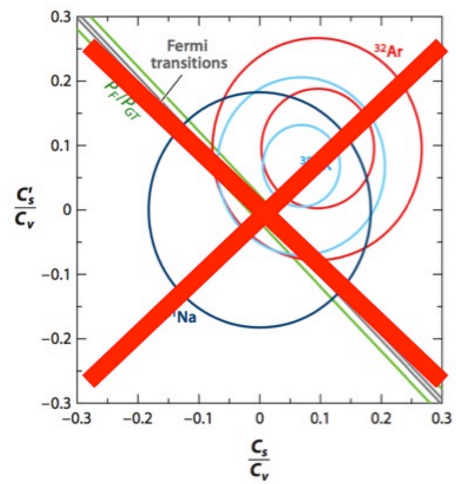




- Any theoretical construction has assumptions.
  EFTs assume e.g. no light new particles.

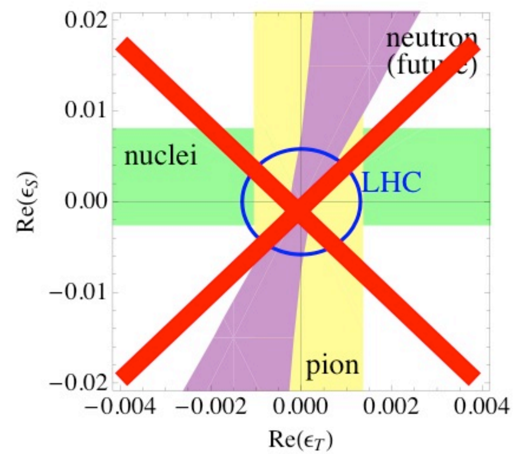
$$
\begin{aligned}
H_{V,A}^{(N)} &= \bar{e}\gamma_\mu (C_V + C_V' \gamma_5)\nu \bar{p}\gamma_\mu n \\
&\quad - \bar{e}\gamma_\mu \gamma_5 (C_A + C_A' \gamma_5)\nu \bar{p}\gamma_\mu \gamma_5 n + \text{H.c.} \\
H_{S,P}^{(N)} &= \bar{e}(C_S + C_S' \gamma_5)\nu \bar{p} n + \text{H.c.} \\
H_T^{(N)} &= \bar{e}\frac{\sigma_{\lambda\mu}}{\sqrt{2}}(C_T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

[Jackson, Treiman & Wyld'1957]



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

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



- Conclusion:
  Don't pay too much attention to theorists.
  Measure and cross your fingers. Nature might surprise us.

Backup slides

Form factors in β decay (SM)

Weinberg'58:

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

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

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

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

$g_A(0)$???

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

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

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

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

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

Form factors in β decay (bSM)

Once we go beyond the SM…

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

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

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

[Weinberg'58]

Now we don't keep corrections…

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

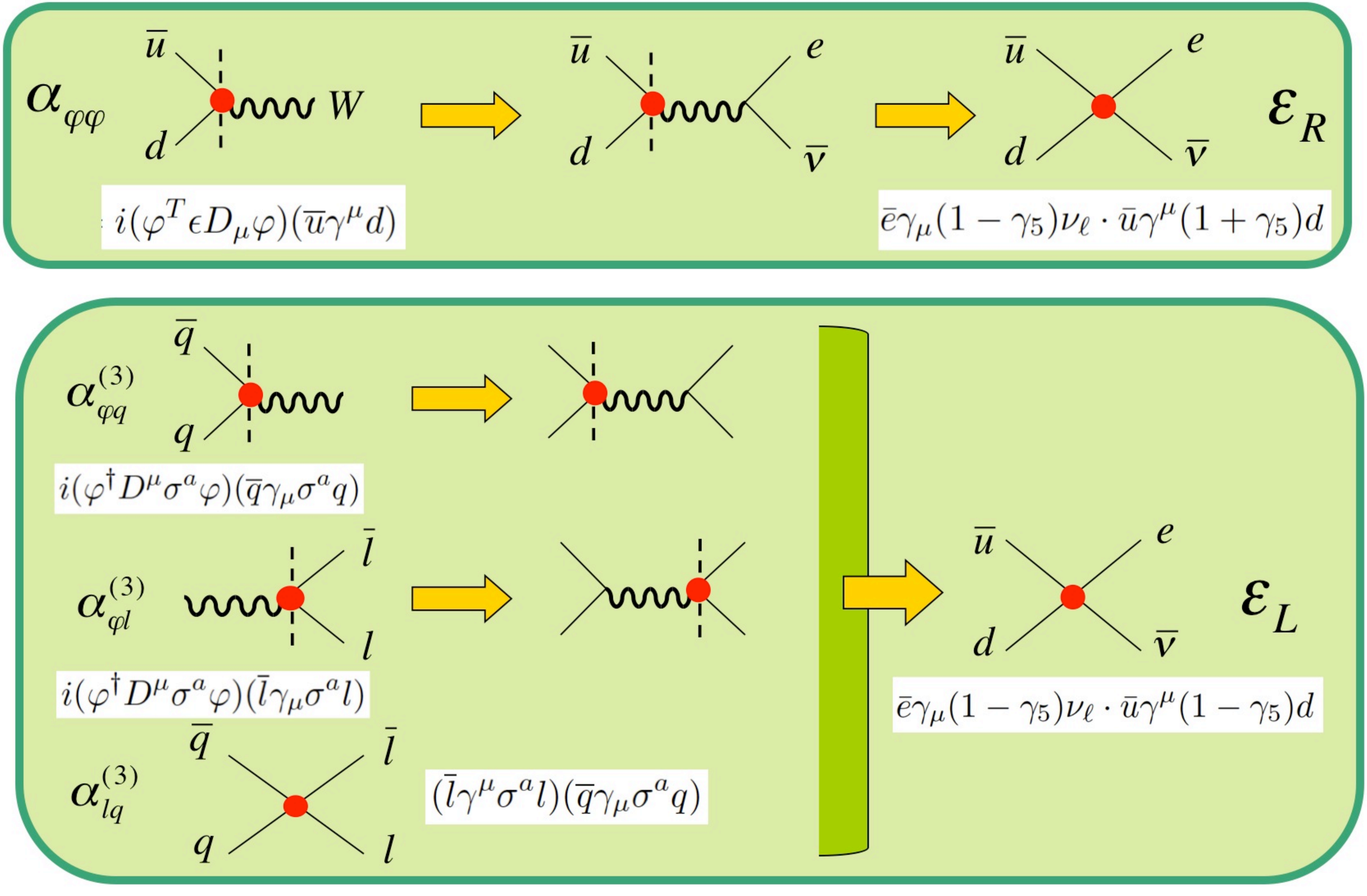
In summary, we have 2 new form factors:

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

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

How well do we know them?

Examples:



$\alpha_{\varphi\varphi}$
$\bar{u}$
d
W
$i(\varphi^T \epsilon D_\mu \varphi)(\overline{u}\gamma^\mu d)$
e
$\bar{\nu}$
ε_R
$\bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1+\gamma_5)d$
$\alpha^{(3)}_{\varphi q}$
$\bar{q}$
q
$i(\varphi^\dagger D^\mu \sigma^a \varphi)(\overline{q}\gamma_\mu \sigma^a q)$
$\alpha^{(3)}_{\varphi l}$
$\bar{l}$
l
$i(\varphi^\dagger D^\mu \sigma^a \varphi)(\bar{l}\gamma_\mu \sigma^a l)$
$\alpha^{(3)}_{lq}$
$(\bar{l}\gamma^\mu \sigma^a l)(\overline{q}\gamma_\mu \sigma^a q)$
ε_L
$\bar{e}\gamma_\mu(1-\gamma_5)\nu_\ell \cdot \bar{u}\gamma^\mu(1-\gamma_5)d$

CKM tests vs. HEP

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

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

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

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

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

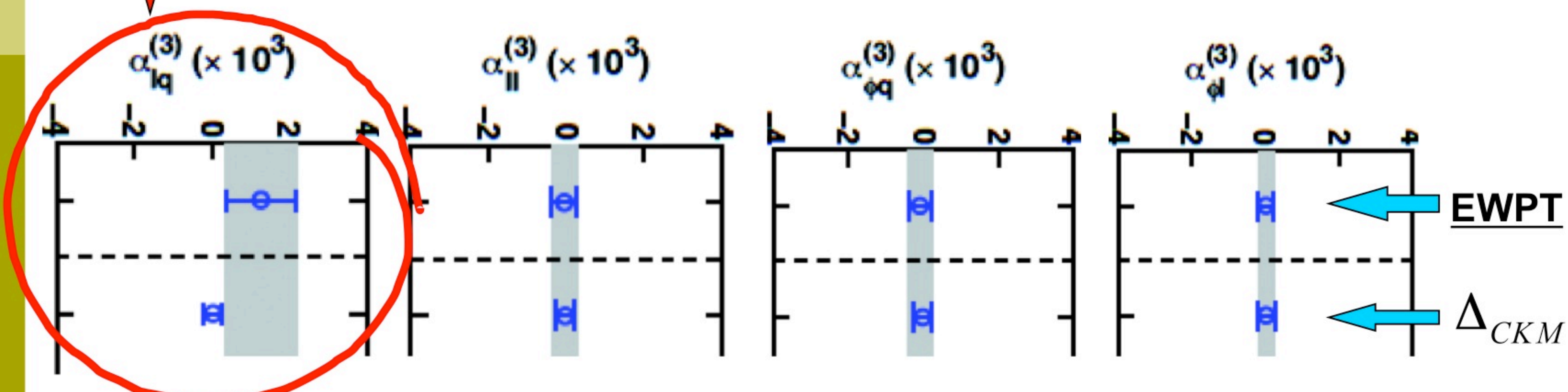
$$O_{\varphi q}^{(3)} = i(\varphi^\dagger D^\mu\sigma^a\varphi)(\bar{q}\gamma_\mu\sigma^a q) + \text{h.c.}$$

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

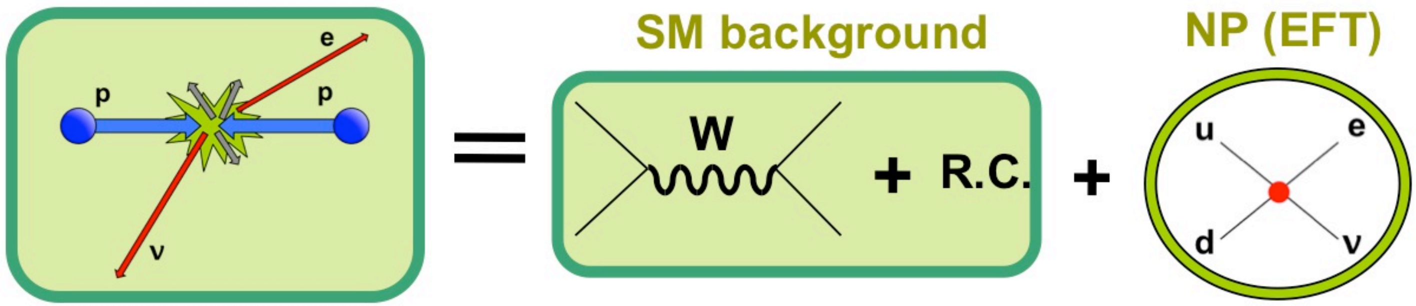
Han & Skiba, PRD71, 2005:

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

5 times less precise!

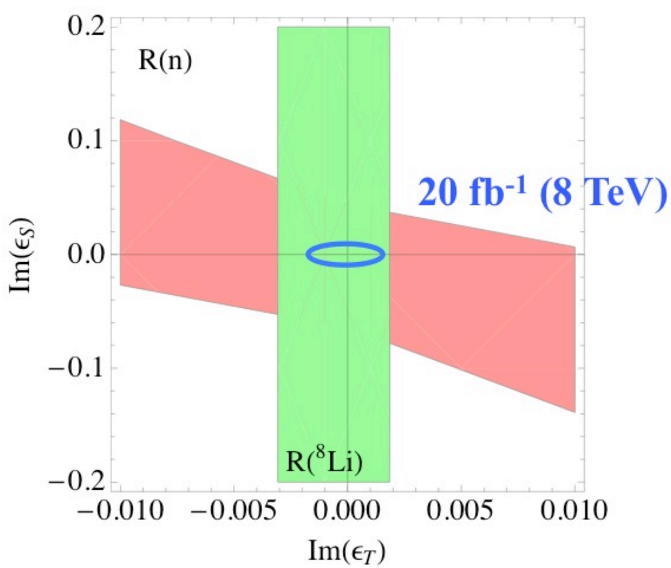


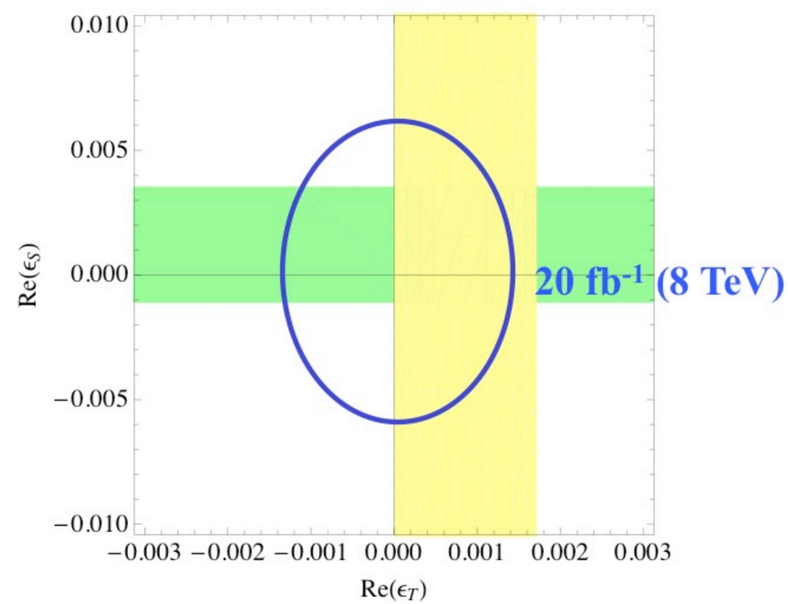
LHC limits on $\varepsilon_{S,T}$



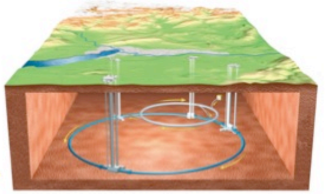
- To suppress the bkg, we look for ***(e+ν)***-events with high m_T:

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



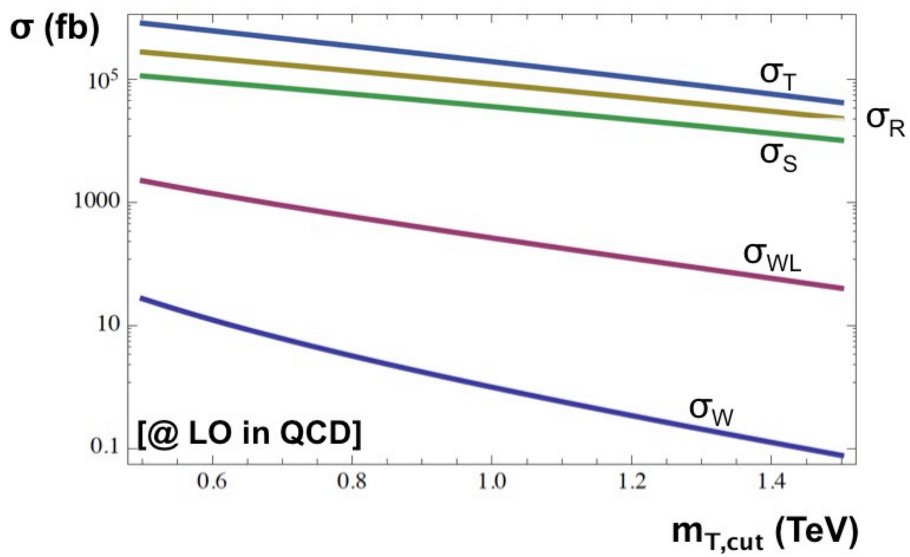


What about the other ε_x?



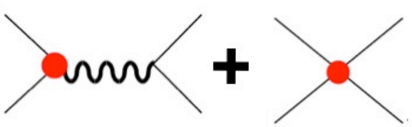
$$\sigma(m_T > \overline{m}_T) = \sigma_W \left[(1+\epsilon_L^{(v)})^2 + |\tilde{\epsilon}_L|^2 + |\epsilon_R|^2\right] - 2\,\sigma_{WL}\,\epsilon_L^{(c)}\left(1+\epsilon_L^{(v)}\right)$$
$$+ \sigma_R \left[|\tilde{\epsilon}_R|^2 + |\epsilon_L^{(c)}|^2\right] + \sigma_S \left[|\epsilon_S|^2 + |\tilde{\epsilon}_S|^2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

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



[Cirigliano, MGA & Graesser, JHEP1302 (2013)]

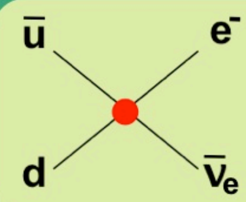
$\epsilon_L = \epsilon_L^{(v)} + \epsilon_L^{(c)}$ =



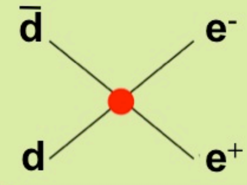
Beyond the $pp \to e\nu X$ channel

- Using SU(2) gauge invariance…

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



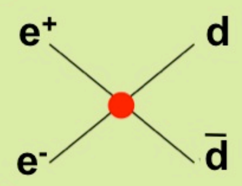
$\Rightarrow pp \to e + MET + X$



$\Rightarrow pp \to e^+ + e^- + X$

A bit better than the [e+MET] channel.

[Cirigliano, MGA & Graesser'2012]



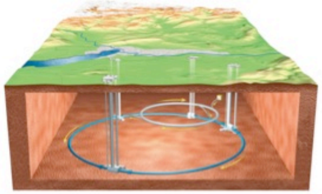
$\Rightarrow e^+e^- \to q\bar{q}$ **LEP!**

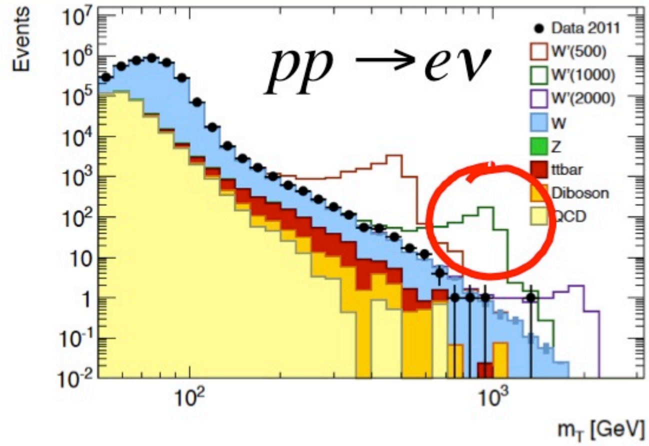
Better than the LHC probing V/A interactions, but not better than CKM unitarity!

[Cirigliano, MGA & Jenkins'2010]

…

Scalar resonance





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

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

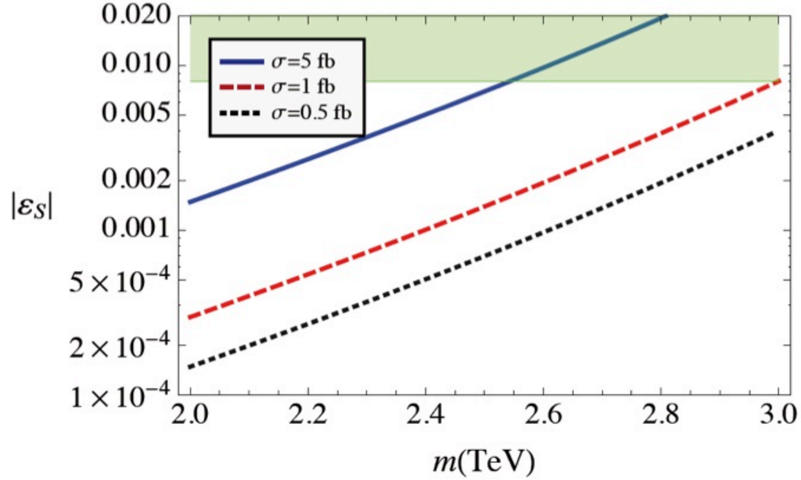
- Then we have a lower-limit value for ε_S:

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

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

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

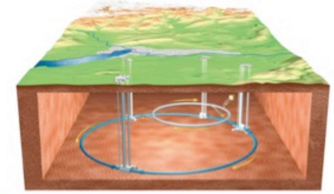
$$\epsilon_S \;=\; 2\lambda_S \lambda_l \frac{v^2}{m^2}$$

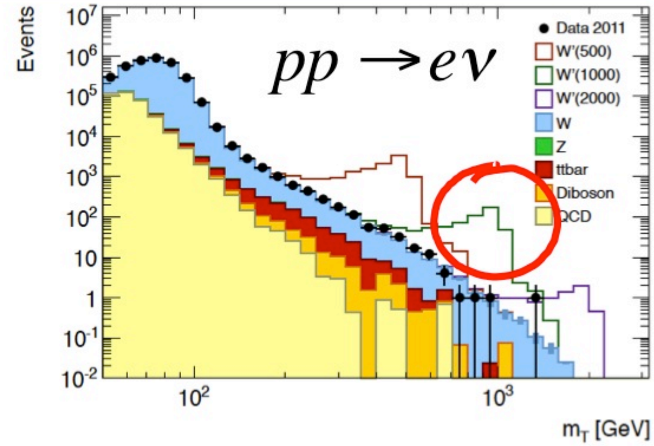


Nice interplay of two experiments separated for so many orders of magnitudes!!!!

[T. Battacharya et al., 2012]

Scalar resonance





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

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- 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]