NSI @ colliders?

S Davidson, V Sanz

arXiv:1108.5320 $\longrightarrow$ PRD

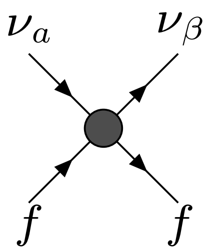
- Intro: what are Non Standard neutrino Interactions?

- $\Big($LEP II bounds on contact interactions of charged leptons
  ...can be extrapolated to NSI on electrons (for a class of models) $\Big)$

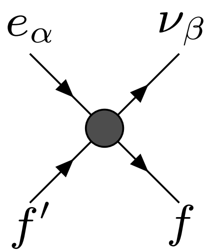
- NSI at the LHC? *IF* NSI are contact interactions at LHC energies (!)
  cross-section is tiny, background even smaller $\Rightarrow$ LHC will see them?

Review — SM ν interactions + NSI

experiment: ν interactions, GeV $\lesssim E_\nu \lesssim 50$ GeV:



(and



)

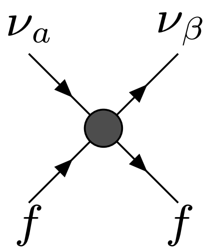
$$\frac{4G_F}{\sqrt{2}}\left[\delta_{\alpha\beta} + \epsilon^f_{\alpha\beta}\right]$$

current bounds from ν interactions : $\varepsilon \lesssim 1 \longrightarrow 10^{-2}$

future ν facilities (νFact) sensitive to $\varepsilon \gtrsim 10^{-3} - 10^{-4}$

Review — SM ν interactions

experiment: ν contact interactions, GeV $\lesssim E_\nu \lesssim 50$ GeV:



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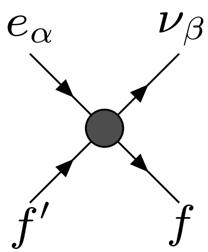

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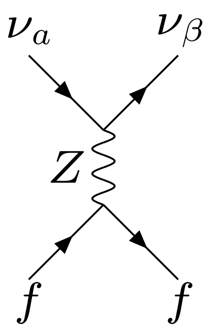
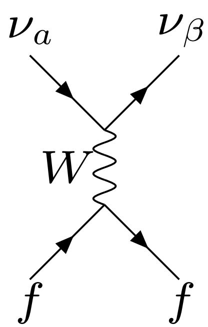
SM

SM:





$$\frac{g^2}{2(p^2 - m_W^2)}\,\delta_{\alpha\beta} = -\delta_{\alpha\beta}\,\frac{g^2}{2m_W^2}\left(1 + \frac{p^2}{m_W^2} + \ldots\right.$$

W,Z, are gauge bosons $\Rightarrow$ flavour diagonal couplings (tree level, flavour eigenstate neutrinos)

Review — SM ν interactions + NSI

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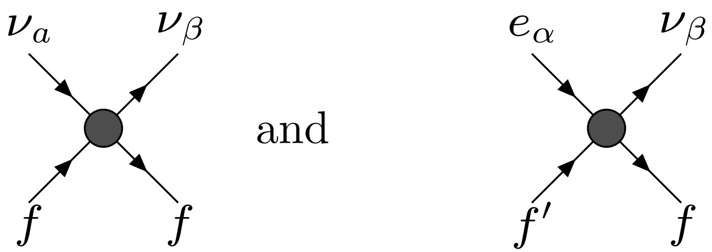


$$\frac{4G_F}{\sqrt{2}}\left[\delta_{\alpha\beta} + \epsilon^f_{\alpha\beta}\right]$$

SM + NSI

SM:

$$\frac{g^2}{2(p^2 - m_W^2)}\,\delta_{\alpha\beta} = -\delta_{\alpha\beta}\,\frac{g^2}{2m_W^2}\left(1 + \frac{p^2}{m_W^2} + \ldots\right.$$

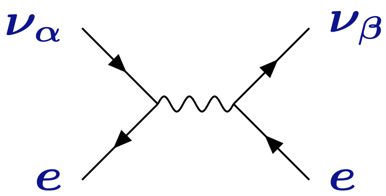
W,Z, are gauge bosons $\Rightarrow$ flavour diagonal couplings (tree level, flavour eigenstate neutrinos)

NSI: add particles from Beyond the SM (BSM), with $M > m_W$

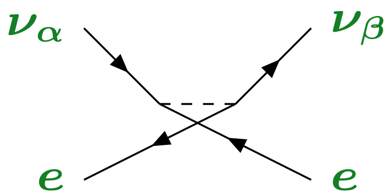
(majorana masses $\Rightarrow$ heavy (?) BSM)

Review — adding BSM that generates NC NSI, at dim six

- To obtain NC NSI on electrons $\sim \varepsilon^{e}_{\alpha\beta} G_F (\overline{\nu}_\beta \gamma^\mu \nu_a)(\overline{e}\gamma_\mu e)$,



and/or



and/or ...

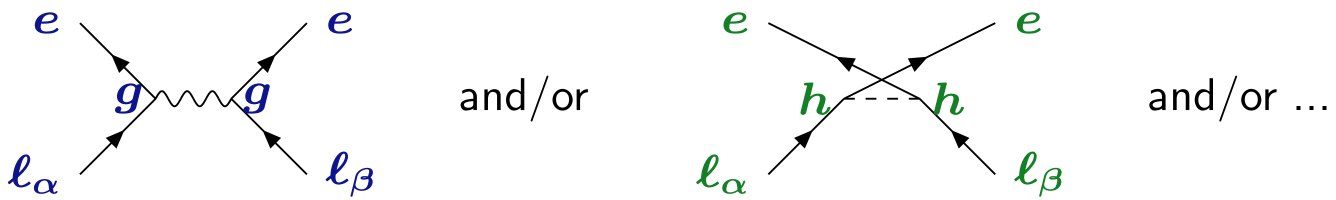
(for time going up) $\quad -\dfrac{g^*_{e\alpha} g_{e\beta}}{t - m_V^2} \qquad \dfrac{h^*_{e\alpha} h_{e\beta}}{u - m_S^2}$

At "dimension six", so $\propto 1/M^2_{BSM}$:

$$\varepsilon_{\alpha\beta} G_F \sim \quad \frac{g^*_{e\alpha} g_{e\beta}}{m_V^2} \qquad -\frac{h^*_{e\alpha} h_{e\beta}}{m_S^2}$$

Review — challenges for BSM that generates NC NSI at dim 6

- To obtain NC NSI on electrons $\sim \varepsilon^{e}_{\alpha\beta} G_F (\overline{\nu}_\beta \gamma^\mu \nu_a)(\overline{e}\gamma_\mu P_R e)$,



: (electroweak is gauge symmetry (proved by LEP: finite loop predictions were observed), so $\ell = \begin{pmatrix} \nu \\ e \end{pmatrix}$

bounds on dim. six NSI from non-observation of charged lepton flavour violation

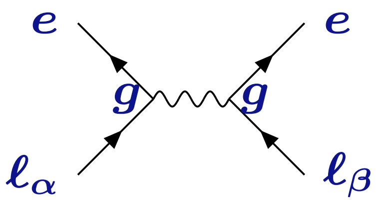
- Avoid charged lepton bounds by assuming NSI arise at dimension *eight*:

$$\frac{1}{\Lambda_8^4}(\overline{e}\gamma^\rho P_X e)(\overline{H\ell}_\alpha \gamma_r H \ell_\beta) \longrightarrow \varepsilon^{fX}_{\alpha\beta} \frac{4G_F}{\sqrt{2}}(\overline{e}\gamma^\rho P_X e)(\overline{\nu}_\alpha \gamma_r \nu_\beta)$$

How to get this (at tree level)?
Can arrange a cancellation at dim 6.

Review — BSM that generates NC NSI, at dimension eight

- To obtain **dimension eight** NC NSI on electrons $\sim \varepsilon^{e}_{\alpha\beta} G_F (\overline{\nu}_\beta \gamma^\mu \nu_a)(\overline{e}\gamma_\mu P_R e)$,



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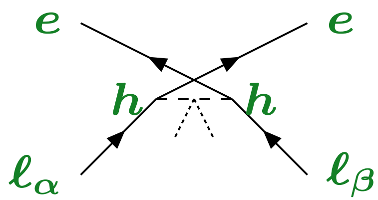

- arrange a cancellation at dim 6: $e.g.$ S and V exchange, with $g^2/m_V^2 = h^2/(2m_S^2)$: Gavela et al Antusch etal

$$-\frac{g^2}{m_V^2 - u}(\overline{e}\gamma^\mu e)(\overline{\ell}\gamma_\mu \ell) \qquad\qquad \frac{h^2}{2(m_S^2 - t)}(\overline{\ell}\gamma^\mu \ell)(\overline{e}\gamma_\mu e)$$

Then suppose a mass splitting in scalar doublet $\propto \lambda^2 v^2$, so cancellation imperfect for ν legs. Get

$$\frac{h^2\lambda^2}{m_S^4}(\overline{e}\gamma^\rho P_X e)(\overline{H\ell_\alpha}\gamma_r H\ell_\beta) \sim \varepsilon^{fX}_{\alpha\beta}\frac{4G_F}{\sqrt{2}}(\overline{e}\gamma^\rho P_X e)(\overline{\nu}_\alpha \gamma_r \nu_\beta)$$

NB: masses, scales, coupling constants for dim 8 NSI

$$\text{if} \quad \frac{4}{\sqrt{2}} G_F \varepsilon = f(h,\lambda,g)\frac{v^2}{m_S^4} \Rightarrow \varepsilon \simeq f(h,\lambda,g)\frac{v^4}{m_S^4}$$

So $\varepsilon > 10^{-4} \Rightarrow \mathbf{m_S} < 2$ TeV (for $f = 1$)
If NSI arise at one loop, then $\varepsilon > 10^{-4} \Rightarrow m_S < 500$ GeV (for $f = 1$)

@ the LHC ?

Neutral current, dimension eight, NSI on quarks
as *contact interactions* at the LHC

$\sqrt{s} = 14$ TeV — what would NSI look like?

- at ν facility energies, have $\varepsilon^{qX}_{\alpha\beta}\frac{4G_F}{\sqrt{2}}(\overline{q}\gamma^\rho P_X q)(\overline{\nu}_\alpha\gamma_r\nu_\beta)$ with $\varepsilon \gtrsim 10^{-4}$
  1. if induced at loop, $\varepsilon \sim v^4/(16\pi^2\Lambda^4) \gtrsim 10^{-4} \Rightarrow \Lambda \lesssim 500$ GeV... LHC should produce the NP in the loop (squarks, etc).
  2. if induced at tree level with dim 6 cancellation (Z', scalar + vector leptoquarks, ...), have $\Lambda \sim m/\lambda \lesssim 2$ TeV. LHC discovery prospects for such particles are model-dep... reach $\sim 3 - 5$ TeV??
  3. Suppose that NSI are contact interactions at the LHC (? some of the new particles involved are beyond the reach of the LHC — *e.g.* $\Lambda^4 = M^2 m^2$, or some couplings $\gg 1$...) can we say anything?

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  3. Suppose that NSI are contact interactions at the LHC (!) (? some of the new particles involved are beyond the reach of the LHC —*e.g.* $\Lambda^4 = M^2 m^2$, or some couplings $\gg 1$...) can we say anything?
     - appeal to the Equivalence Theorem, and replace $v\nu_\alpha \to W^+ e^-_\alpha$.

The Equivalence Theorem and NSI as contact interactions at the LHC

- $(\overline{q}\gamma q)(\overline{\nu}_\alpha \gamma \nu_\beta)$ and the LHC?
  - if induced at loop, $\varepsilon \sim v^4/(16\pi^2\Lambda^4) \gtrsim 10^{-4} \Rightarrow$ LHC should produce the NP in the loop (squarks, etc).
  - if induced at tree level with dim 6 cancellation (Z', scalar + vector leptoquarks, ...), have $\Lambda \lesssim 2$ TeV. LHC discovery prospects are model-dep... reach $\sim 3 - 5$ TeV??
  - Suppose that NSI are contact interactions at the LHC — can we say anything?
    * appeal to the Equivalence Theorem, and replace $v\nu_\alpha \to W^+ e^-_\alpha$.
      - The Equivalence Theorem relates matrix elements of the unbroken electroweak theory ($\langle H \rangle = 0$) to the broken theory
      - (...relativistic W, Z dominated by longitudinal components, who look like goldstones...)
      - In a gauge invariant dim 8 NSI operator

$$H\ell_\alpha = H_0 \nu_\alpha - H_+ e_\alpha$$

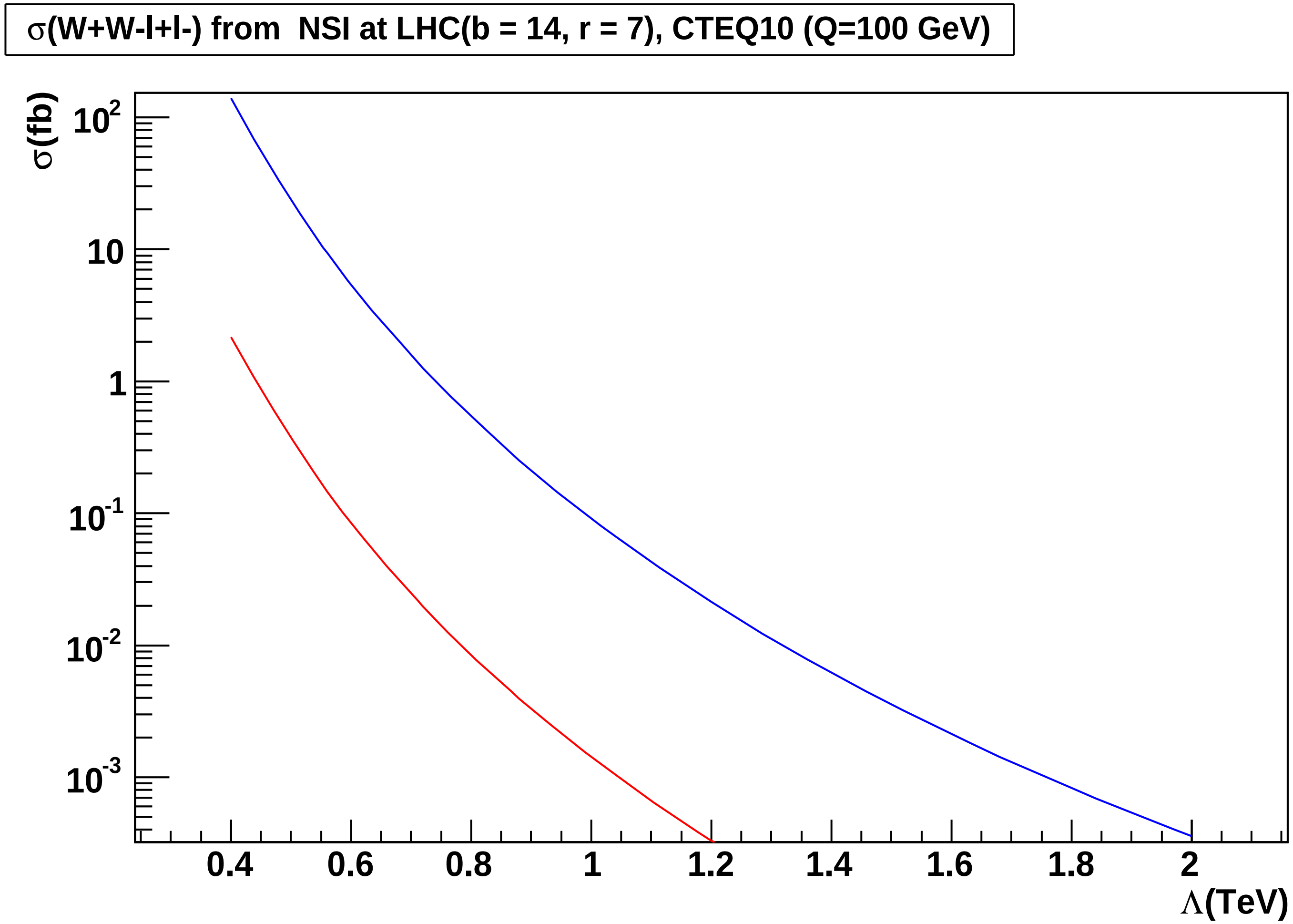
so... $\nu_\alpha v \to W^+ e_\alpha$.

The cross-section $\to W^+W^-e^\pm_\alpha e^\mp_\beta$ corresponding to NSI on quarks

- $(\overline{q}\gamma q)(\overline{\nu}_\alpha\gamma\nu_\beta)$ and the LHC?
  - Suppose that some of the new particles involved are beyond the reach of the LHC ($\Lambda^4 = M^2m^2$, or some couplings $\gg 1$...) can we say anything?
    - appeal to the Equivalence Theorem, and replace $v\nu_\alpha \to W^+L^-_\alpha$.
    - dim analysis suggests (and can calculate in Eq Thm limit)

$$\sigma(pp \to W^+W^-e^+_\alpha e^-_\beta) \sim \int pdfs \times \frac{\hat{s}^3}{\Lambda_8^8} \times massless\ 4 - bdy\ phase\ space$$

$$\sim 10^{-3}\ \text{fb}\frac{\varepsilon^2}{(10^{-4})^2}$$



$$\varepsilon = \frac{v^4}{\Lambda^4} \ ,$$

$\varepsilon = 10^{-4}$ for $\Lambda = 10v$

Ack—cross-section, backgrounds... :(

- $(\overline{q}\gamma q)(\overline{\nu}_\alpha \gamma \nu_\beta)$ and the LHC?
  - Suppose that some of the new particles involved are beyond the reach of the LHC ($\Lambda^4 = M^2 m^2$, or some couplings $\gg 1$...) can we say anything?
    * appeal to the Equivalence Theorem, and replace $v\nu_\alpha \to W^+ L^-_\alpha$.
    * dim analysis suggests

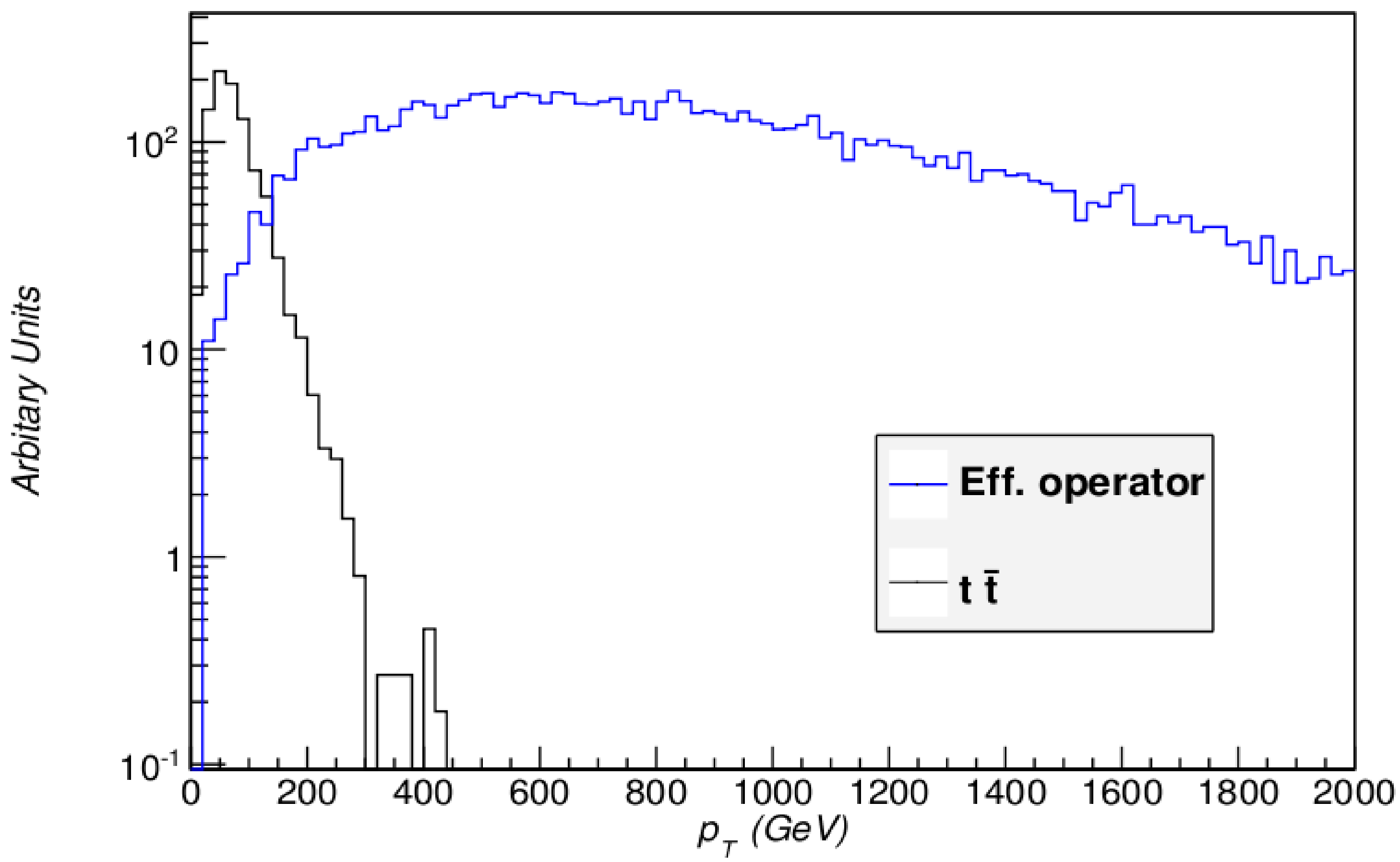
$$\sigma(pp \to W^+W^-\tau^+e^-_\beta) \quad \sim \quad 10^{-3}\ \mathrm{fb}\frac{\varepsilon^2}{(10^{-4})^2}$$

    * Ack : backgrouunds...$\sigma(pp \to t\bar{t}) \sim$ nb $= 10^6$ fb.

$$(pp \to W^+W^-b\overline{b}) \times \frac{1}{200} \longrightarrow (pp \to W^+W^-be^-_\beta)$$

Ack.

EurEEka ! p_T distribution of final states very different... :)



3×10^6 NLO $t\bar{t}$ events: require 3 leptons (e, μ) of $p_T > 400$ GeV, ≤ 10 events survive

Eq Thm caln of $\sigma(pp \to WWe_ae_b)$: same cuts, 70% of NSI events survive.

This works so well, we "anticipate" it works for τs ($i.e.$ withouth the 3ℓ cut)

Summary

- NSI are dimension 8 contact interactions

$$\varepsilon 2\sqrt{2}G_F(\overline{f}\gamma f)(\overline{\nu}_\alpha\gamma\nu_\beta) \sim \frac{1}{\Lambda^4}(\overline{f}\gamma f)(\overline{\ell}_\alpha H^\dagger\gamma H\ell_\beta) \qquad \Rightarrow \varepsilon = \frac{v^4}{\Lambda^4}$$

  for $f \in \{e, u, d\}$. Can obtain these operators without dangerous dim 6 operators:
  -via tree level NP such that the dim 6 coefficients are absent/cancelled
  (in loops)

- *If* NSI are contact interactions at the LHC:
  - the cross-section is tiny, but
  - the final state, of several $p_T \gtrsim 500$ GeV objects, appears background-free? Could even see NSI involving τs?

  Sensitive to $\varepsilon \gtrsim 3 \times 10^{-2}/\sqrt{\mathcal{L}\mathrm{fb}}$ (assuming background-free)
  (If NSI mediators are within LHC reach, maybe it finds them?)

- suppose charged lepton NSI $(\overline{e}\gamma e)(\overline{\nu}_\alpha\gamma\nu_\beta)$ induced at tree level
  - if coefficients of dangerous dimension 6 operators vanish due to a cancellation, at dimension 8 should appear double derivative 4-charged-lepton operators (as well as NSI):

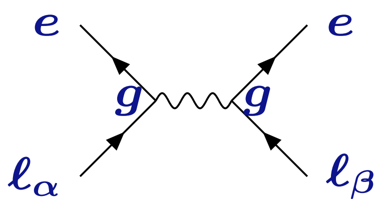
$$\frac{s}{\Lambda^4}(\overline{e}\gamma e)(\overline{L}_\alpha\gamma L_\beta) \qquad \frac{t-u}{\Lambda^4}(\overline{e}\gamma e)(\overline{L}_\alpha\gamma L_\beta)$$

  - bounds from LEP2 on $e^+e^- \to L^+L^-$ translate, with $\mathcal{O}(1)$ factors, to $\varepsilon \lesssim 10^{-2} \to 10^{-3}$.

Back to LEP?

Something new: cancelling charged lepton diagrams only works at zero momentum transfer

- To obtain dim eight NC NSI on electrons $\sim \varepsilon^{e}_{\alpha\beta} G_F (\overline{\nu}_\beta \gamma^\mu \nu_a)(\overline{e}\gamma_\mu e)$,



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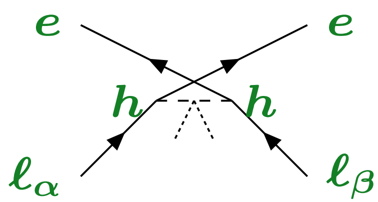

- arrange a cancellation at dim 6: S and V exchange, with $g^2/m_V^2 = h^2/(2m_S^2)$:

Gavela et al
Antusch etal

$$-\frac{g^2}{m_V^2 - u}(\overline{e}\gamma^\mu e)(\overline{\ell}\gamma_\mu \ell) \qquad \frac{h^2}{2(m_S^2 - t)}(\overline{\ell}\gamma^\mu \ell)(\overline{e}\gamma_\mu e)$$

and suppose a mass splitting in scalar doublet $\propto \lambda^2 v^2$, so cancellation imperfect for ν legs.

- BUT for $0 \ll s, t, u \ll m_V^2, m_S^2$, and $g^2/m_V^2 = h^2/2m_S^2$, sum gives

$$-\frac{g^2}{m_V^4}\left(u - \frac{2g^2}{h^2}t\right)(\overline{\ell}\gamma^\mu \ell)(\overline{e}\gamma_\mu e)$$

The cancellation of 4-charged-lepton-interaction only works at zero momentum transfer

$\Rightarrow$ 4-charged-lepton dimension 8 contact interaction, with coefficient $\sim g^2 \frac{s}{m_S^4}, \; h^2 \frac{t-u}{m_S^4}$

(Recall NSI with coefficient $\sim h^2 \lambda^2 \frac{v^2}{m_S^4}$)

Summary so far

- are interested in NSI at dimension eight (to avoid charged lepton bouunds), involving two neutrinos (so can give a matter effect in LBL):

$$\frac{1}{\Lambda_8^4}(\overline{e}\gamma^\rho P_X e)(\overline{H\ell}_\alpha \gamma_r H\ell_\beta) \longrightarrow \varepsilon^{fX}_{\alpha\beta}\frac{4G_F}{\sqrt{2}}(\overline{e}\gamma^\rho P_X e)(\overline{\nu}_\alpha \gamma_r \nu_\beta)$$

- future facilities could be sensitive to $\varepsilon \gtrsim 10^{-3} - 10^{-4}$
- can generate at tree level (its hard to get $\varepsilon \gtrsim 10^{-3}, 10^{-4}$ at loop), by arranging a cancellation of the dimension six operator
- the imperfect cancellation allows at dimension eight:
  the NSI operator $\propto f(g,h,\lambda)v^2/m^4$,
  also the charged-lepton operators$\propto f'(g,h,\lambda)\{s,t-u\}/m^4$
- bounds on charged-lepton operators at $s \ll v^2$ ($\mu \to 3e$, $\tau \to 3\ell$, etc) do not contrain NSI...
  but at LEPII, $s \simeq v^2$ ...

LEP2

LEP2 set bounds, from σ, A_{FB}, on dim six contact interactions ($\sqrt{s} \geq .85 \times (183 \to 209)$GeV)

$$\pm\frac{4\pi}{\Lambda^2_{6,\pm}}(\overline{e}\gamma^\mu P_X e)(\overline{f}_\alpha \gamma_\mu P_Y f_\alpha) \qquad \overline{f}_\alpha f_\alpha \in \{e^+e^-, \mu^+\mu^-, \tau^+\tau^-\}$$

Translate to dimension 8 double-derivative operators, with same legs but coefficients $\propto \frac{s}{\Lambda_8^4}, \frac{t-u}{\Lambda_8^4}$

Translate to dimension 8 NSI operators, with coefficient $\propto \frac{v^2}{\Lambda_8^4}$ by assuming $\frac{s}{\Lambda_8^4}, \frac{t-u}{\Lambda_8^4} \simeq \frac{v^2}{\Lambda_8^4}$

$(\overline{e}\gamma^\mu P_X e)(\overline{\ell}\gamma_\mu P_Y \ell)$	bound	ε
$e^+e^- \to e^+e^-$		
XY=LL	$\Lambda_{6+} \gtrsim 10.3$ TeV	$\lesssim 3.7 \times 10^{-3}$
LL	$\Lambda_{6-} \gtrsim 8.3$ TeV	$\lesssim 5.6 \times 10^{-3}$
RL	$\Lambda_{6+} \gtrsim 8.8$ TeV	$\lesssim 4.7 \times 10^{-3}$
RL	$\Lambda_{6-} \gtrsim 12.7$ TeV	$\lesssim 2.4 \times 10^{-3}$
$e^+e^- \to \mu^+\mu^-$		
XY=LL	$\Lambda_{6+} \gtrsim 8.1$ TeV	$\lesssim 5.9 \times 10^{-3}$
LL	$\Lambda_{6-} \gtrsim 9.5$ TeV	$\lesssim 4.3 \times 10^{-3}$
RL	$\Lambda_{6\pm} \gtrsim 6.3$ TeV	$\lesssim 9.1 \times 10^{-3}$
$e^+e^- \to \tau^+\tau^-$		
XY=LL	$\Lambda_{6+} \gtrsim 7.9$ TeV	$\lesssim 6.2 \times 10^{-3}$
LL	$\Lambda_{6-} \gtrsim 5.8$ TeV	$\lesssim 1.1 \times 10^{-2}$
RL	$\Lambda_{6+} \gtrsim 6.4$ TeV	$\lesssim 9.1 \times 10^{-3}$
RL	$\Lambda_{6-} \gtrsim 4.6$ TeV	$\lesssim 1.8 \times 10^{-2}$

$$\varepsilon = v^4/\Lambda^4$$

Many $\mathcal{O}(1)$ factors!!
$\varepsilon_{\alpha\alpha} \lesssim 10^{-2} - 10^{-3}$

OPAL — bounds on flavour-changing contact interactions at LEP2!

The OPAL experiment saw one $e^+e^- \to e^\pm\mu^\mp$ event at $\sqrt{s} = 189 - 209$ GeV, and published limits on $\sigma(e^+e^- \to e^\pm\mu^\mp, e^\pm\tau^\mp, \tau^\pm\mu^\mp)$.

Naively, "no point" in doing LFV at LEP2 because better bounds on dim 6 contact interactions from $\mu \to 3e$, $\tau \to 3\ell$.

Gives stronger bounds on double-derivative dimension 8 LFV operators than LEP1 (not competing with the Z peak) or rare decays.

$\Rightarrow$ calculate σ for double-derivative dimension 8 operators... and get

$(\overline{e}\gamma^\mu P_X e)(\overline{\ell}\gamma_\mu P_Y \ell)$	ε
$e^+e^- \to e^\pm\mu^\mp$ $\forall\ XY$	$\lesssim 8.7 \times 10^{-3}$
$e^+e^- \to e^\pm\tau^\mp$ $\forall\ XY$	$\lesssim 1.6 \times 10^{-2}$
$e^+e^- \to \tau^\pm\mu^\mp$ $\forall\ XY$	$\lesssim 1.5 \times 10^{-2}$

Summary

- Neutral current NSI can arise as dimension 8 contact interactions

$$\varepsilon 2\sqrt{2} G_F (\overline{f}\gamma f)(\overline{\nu}_\alpha \gamma \nu_\beta) \sim \frac{1}{\Lambda^4}(\overline{f}\gamma f)(\overline{\ell}_\alpha H^\dagger \gamma H \ell_\beta) \qquad \Rightarrow \varepsilon = \frac{v^4}{\Lambda^4}$$

  for $f \in \{e, u, d\}$. Two ways to obtain these operators without dangerous dim 6 operators:
  - with tree level NP such that the dim 6 coefficients are absent/cancelled
  - in loops. (?use the quadratic GIM mechanism, suppresses FCNC by making them dim 8...?)
- suppose such NSI on electrons $(\overline{e}\gamma e)(\overline{\nu}_\alpha \gamma \nu_\beta)$ induced at tree level
  - if coefficients of dangerous dimension 6 operators vanish due to a cancellation, at dimension 8 could appear double derivative 4-charged-lepton operators (as well as NSI):

$$\frac{s}{\Lambda^4}(\overline{e}\gamma e)(\overline{L}_\alpha \gamma L_\beta) \qquad \frac{t-u}{\Lambda^4}(\overline{e}\gamma e)(\overline{L}_\alpha \gamma L_\beta)$$

  - Bounds from LEP2 on $e^+e^- \to L^+L^-$ translate to $\varepsilon \lesssim 10^{-2} \to 10^{-3}$.