$0\nu\beta\beta$ vs LNV at LHC

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Based on:

J.C. Helo, M. Hirsch, H. Päs, S. Kovalenko; arXiv:1307.4849

J.C. Helo, M. Hirsch, H. Päs, S. Kovalenko; Phys.Rev. D88 011901

F. Bonnet, M. Hirsch, T. Ota, W. Winter, JHEP03 (2013) 055

Contents

- Lepton number violation

$$(A, Z) \to (A, Z+2) + 2e^-$$

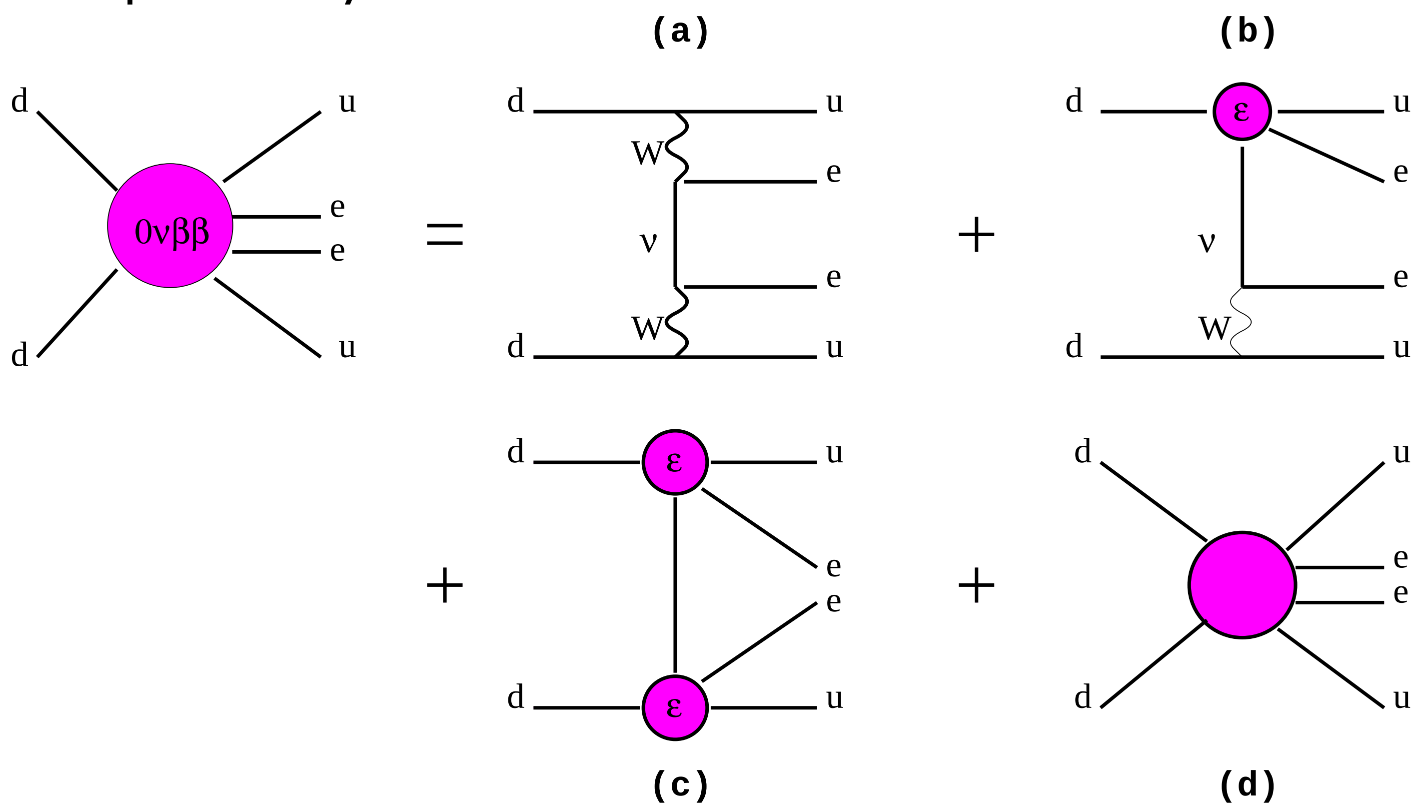
- Neutrino Mass Mechanism

$$T_{1/2}^{\beta\beta 0\nu} \propto m_{\beta\beta}^{-2} \quad ; \quad m_{\beta\beta} = \sum_{i=1}^{3} |m_{\nu_i} U_{ei}^2|$$

- Sensitive to extensions of SM:
  Left-Right, SUSY RPV, LQ, Sterile neutrinos, Color sextet diquarks, ..etc.
  For a review: Deppish et al . Arxiv: 1208.0727
- Schether-Valle Theorem: Observation of $0\nu\beta\beta$ implies neutrinos are Majorana. Phys. Rev. D. 25 2951 (1982)
  However it won't be easily interpreted as evidence for any specific model.

Lorentz-invariant description

Graphically:



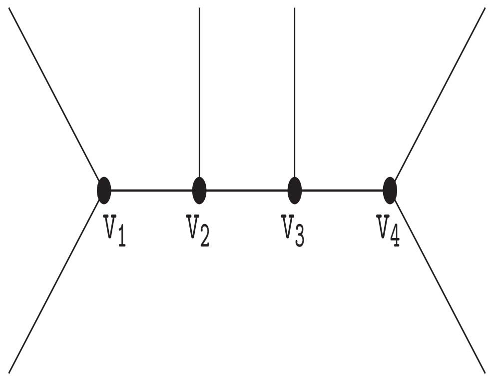
⇒ (a) mass mechanism

⇒ (b) long-range part: H. Päs et al. PLB453 (1999)

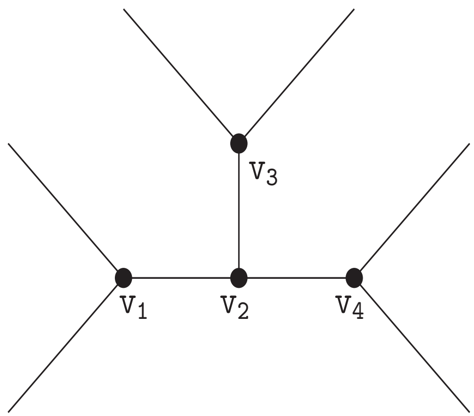
⇒ (d) short-range part: H. Päs et al. PLB498 (2001)

Tree-level topologies

Topology-I:

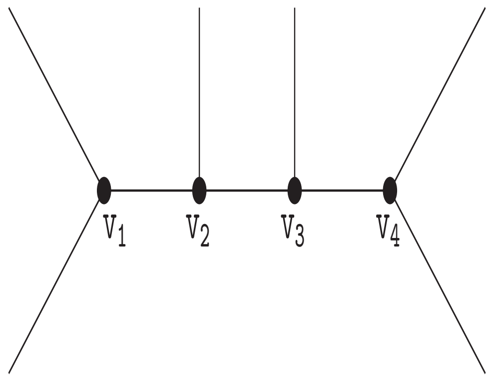


Topology-II:

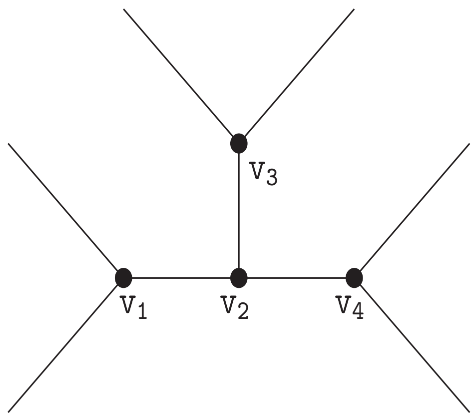


Tree-level topologies

Topology-I:

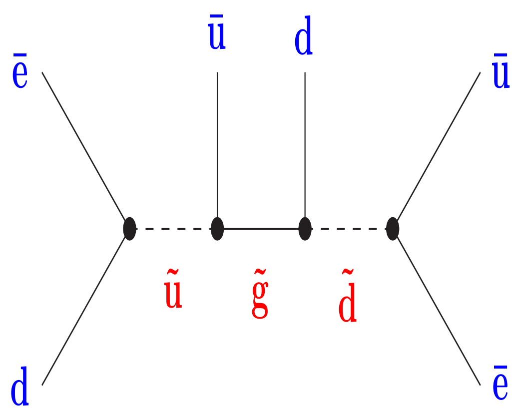


Topology-II:

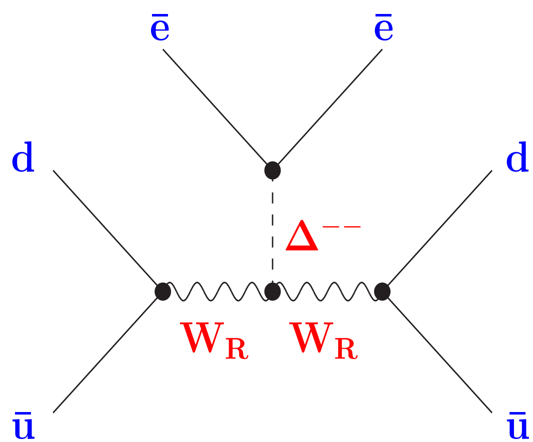


Examples:

RPV squark exchange:

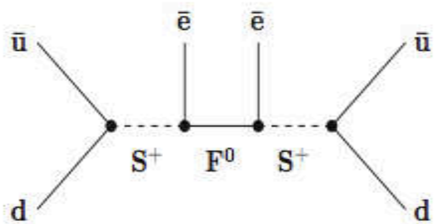


LR symmetric model:

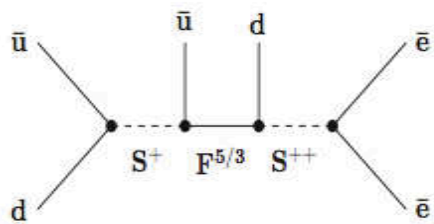


Bonnet et al, JHEP03 (2013) 055; arXiv:1212.3045

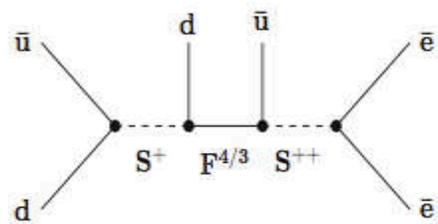
T-I: SFS, part-I



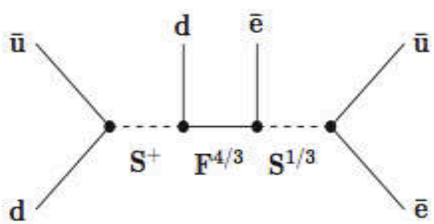
T-I-1-i: $(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$



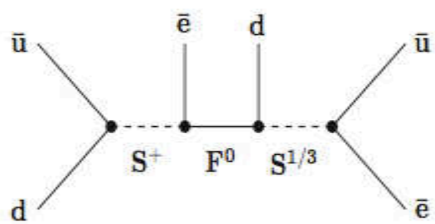
T-I-1-ii-a: $(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$



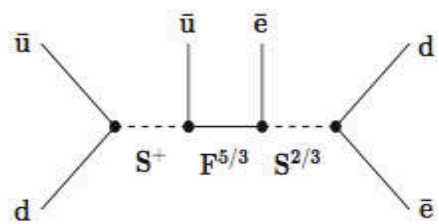
T-I-1-ii-b: $(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$



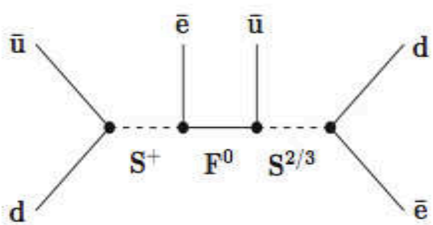
T-I-2-i-a: $(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$



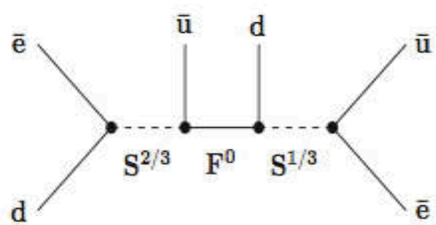
T-I-2-i-b: $(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$



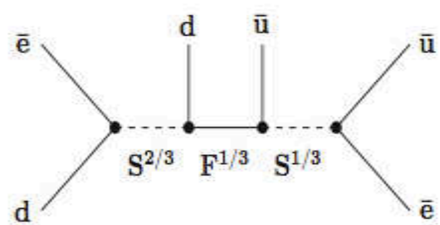
T-I-2-ii-a: $(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$



T-I-2-ii-b: $(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$

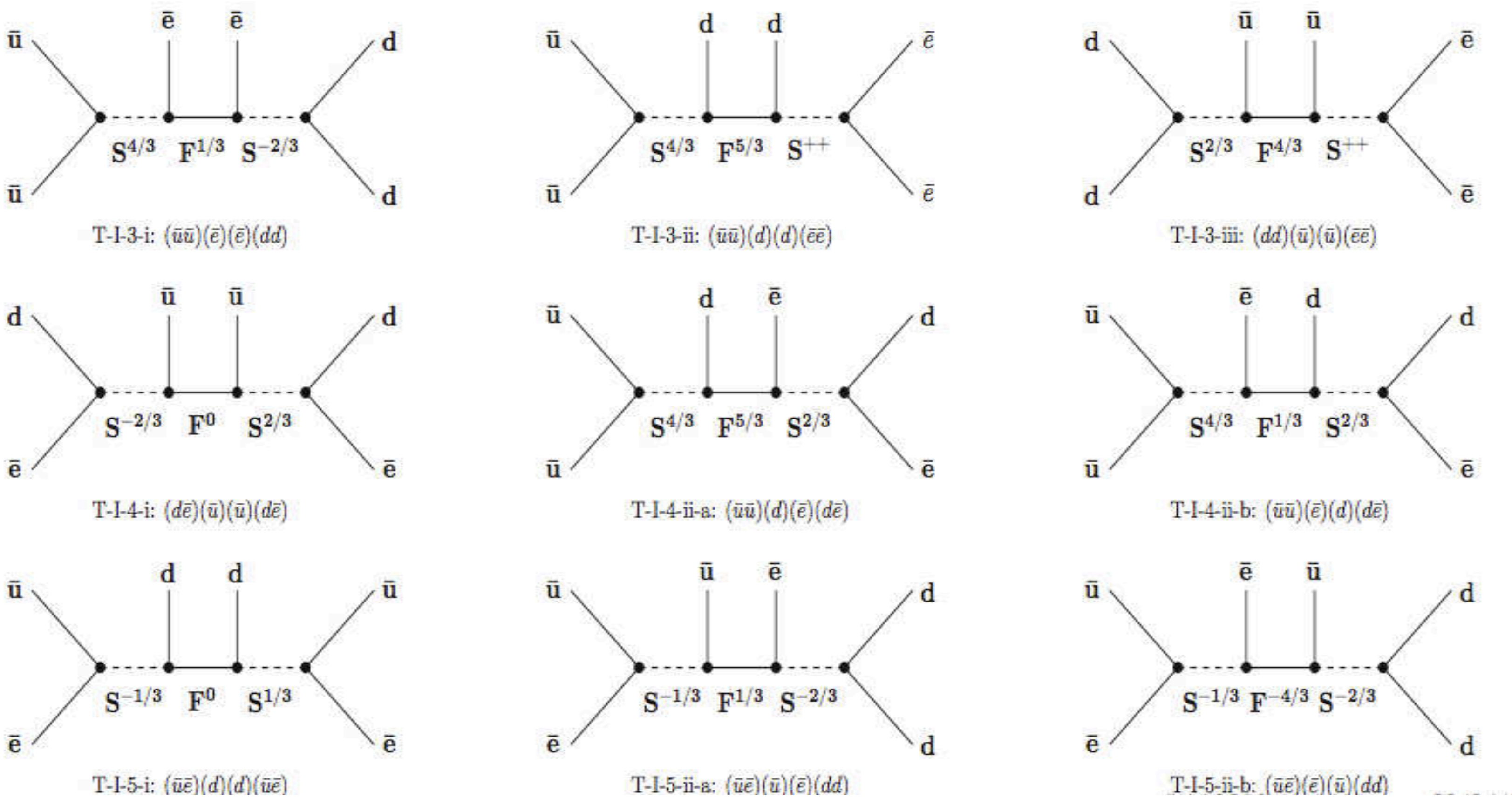


T-I-2-iii-a: $(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$



T-I-2-iii-b: $(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$

T-I: SFS, part-II



T-I: Decomposition

#	Decomposition	Mediator $(Q_{\rm em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(-1, \mathbf{1}\oplus\mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+1/3, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+2/3, \mathbf{3})$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$

18 decompositions in total

$\times$ SFS, VFS and VFV

$\times$ # of different chirality insertions P_L and P_R

Dec. has at least one S_{+1}, S^{DQ} or S^{LQ}

Bonnet et al. JHEP03 (2013) 055

T-I: Decomposition

#	Decomposition	Mediator $(Q_{em}, SU(3)_c)$			RPV SUSY:
		S or V_ρ	ψ	S' or V'_ρ	
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(-1, \mathbf{1} \oplus \mathbf{8})$	$\Leftarrow \tilde{e} - \chi - \tilde{e}$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$	
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	$\Leftarrow \tilde{e} - \chi - \tilde{d}$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1} \oplus \mathbf{8})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+2/3, \mathbf{3})$	$\Leftarrow \tilde{e} - \chi - \tilde{u}$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	$\Leftarrow \tilde{u} - \chi/\tilde{g} - \tilde{d}$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+1/3, \overline{\mathbf{3}})$	
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$	
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3}_a \oplus \overline{\mathbf{6}}_s)$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$	
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+2/3, \mathbf{3})$	$\Leftarrow \tilde{u} - \chi/\tilde{g} - \tilde{u}$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$	
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(+2/3, \mathbf{3})$	
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, \mathbf{1} \oplus \mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$	$\Leftarrow \tilde{d} - \chi/\tilde{g} - \tilde{d}$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_a \oplus \mathbf{6}_s)$	

T-I: Decomposition

#	Decomposition	Mediator $(Q_{\rm em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{0}, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{-1}, \mathbf{1}\oplus\mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(\mathbf{+1/3}, \overline{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{+1/3}, \overline{\mathbf{3}})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(\mathbf{+2/3}, \mathbf{3})$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{+2/3}, \mathbf{3})$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(\mathbf{-2/3}, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{+1/3}, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(\mathbf{-2/3}, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3_a}\oplus\overline{\mathbf{6}}_{\mathbf{s}})$	$(\mathbf{+1/3}, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(+4/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$	$(+1/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$	$(-2/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(+2/3, \mathbf{3_a}\oplus\overline{\mathbf{6}}_{\mathbf{s}})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(\mathbf{-2/3}, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{+2/3}, \mathbf{3})$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$	$(+5/3, \mathbf{3})$	$(\mathbf{+2/3}, \mathbf{3})$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(+4/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$	$(+1/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$	$(\mathbf{+2/3}, \mathbf{3})$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(\mathbf{-1/3}, \mathbf{3})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{+1/3}, \overline{\mathbf{3}})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(\mathbf{-1/3}, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$	$(-2/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(\mathbf{-1/3}, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(-2/3, \overline{\mathbf{3}}_{\mathbf{a}}\oplus\mathbf{6_s})$

Leptoquarks

T-I: Decomposition

#	Decomposition	Mediator $(Q_{\rm em}, SU(3)_c)$ S or V_ρ	ψ	S' or V'_ρ
1-i	$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{0}, \mathbf{1}\oplus\mathbf{8})$	$(\mathbf{-1}, \mathbf{1}\oplus\mathbf{8})$
1-ii-a	$(\bar{u}d)(\bar{u})(d)(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
1-ii-b	$(\bar{u}d)(d)(\bar{u})(\bar{e}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
2-i-a	$(\bar{u}d)(d)(\bar{e})(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+4/3, \overline{\mathbf{3}})$	$(+1/3, \overline{\mathbf{3}})$
2-i-b	$(\bar{u}d)(\bar{e})(d)(\bar{u}\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-ii-a	$(\bar{u}d)(\bar{u})(\bar{e})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
2-ii-b	$(\bar{u}d)(\bar{e})(\bar{u})(d\bar{e})$	$(+1, \mathbf{1}\oplus\mathbf{8})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$
2-iii-a	$(d\bar{e})(\bar{u})(d)(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
2-iii-b	$(d\bar{e})(d)(\bar{u})(\bar{u}\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(-1/3, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+1/3, \overline{\mathbf{3}})$
3-i	$(\bar{u}\bar{u})(\bar{e})(\bar{e})(dd)$	$(\mathbf{+4/3}, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(\mathbf{-2/3}, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$
3-ii	$(\bar{u}\bar{u})(d)(d)(\bar{e}\bar{e})$	$(\mathbf{+4/3}, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2, \mathbf{1})$
3-iii	$(dd)(\bar{u})(\bar{u})(\bar{e}\bar{e})$	$(\mathbf{+2/3}, \mathbf{3}_{\rm a}\oplus\overline{\mathbf{6}}_{\rm s})$	$(+4/3, \overline{\mathbf{3}})$	$(+2, \mathbf{1})$
4-i	$(d\bar{e})(\bar{u})(\bar{u})(d\bar{e})$	$(-2/3, \overline{\mathbf{3}})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+2/3, \mathbf{3})$
4-ii-a	$(\bar{u}\bar{u})(d)(\bar{e})(d\bar{e})$	$(\mathbf{+4/3}, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+5/3, \mathbf{3})$	$(+2/3, \mathbf{3})$
4-ii-b	$(\bar{u}\bar{u})(\bar{e})(d)(d\bar{e})$	$(\mathbf{+4/3}, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(+2/3, \mathbf{3})$
5-i	$(\bar{u}\bar{e})(d)(d)(\bar{u}\bar{e})$	$(-1/3, \mathbf{3})$	$(0, \mathbf{1}\oplus\mathbf{8})$	$(+1/3, \overline{\mathbf{3}})$
5-ii-a	$(\bar{u}\bar{e})(\bar{u})(\bar{e})(dd)$	$(-1/3, \mathbf{3})$	$(+1/3, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$	$(\mathbf{-2/3}, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$
5-ii-b	$(\bar{u}\bar{e})(\bar{e})(\bar{u})(dd)$	$(-1/3, \mathbf{3})$	$(-4/3, \mathbf{3})$	$(\mathbf{-2/3}, \overline{\mathbf{3}}_{\rm a}\oplus\mathbf{6}_{\rm s})$

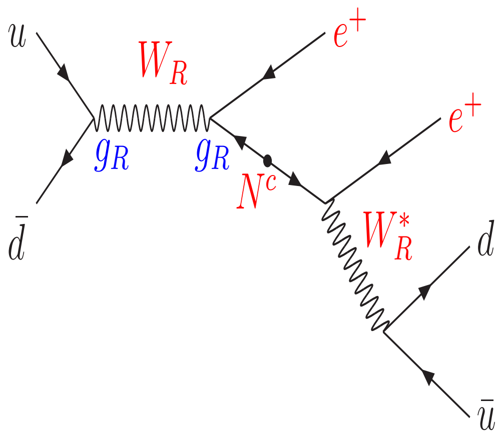
Di-quarks

$\mathcal{III}.$

LNV @ LHC

Example: W_R @ LHC

$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$:



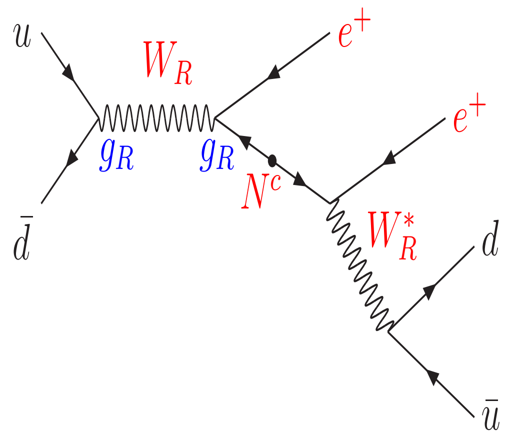
Keung & Senjanovic, 1983

Signal:

di-lepton + jets, **no** $\not{E}_T$

Example: W_R @ LHC

$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$:

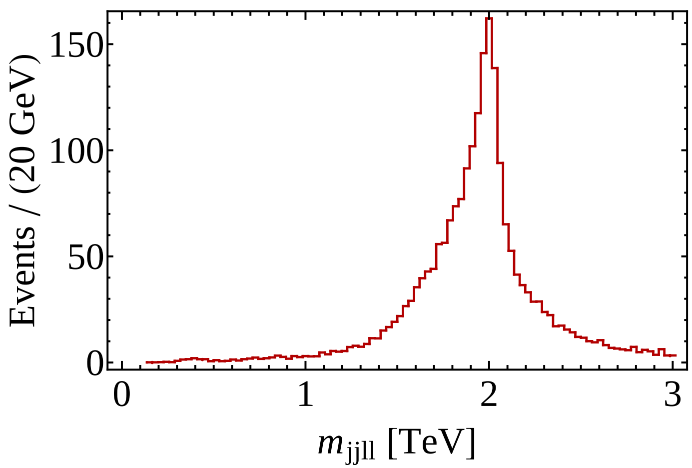


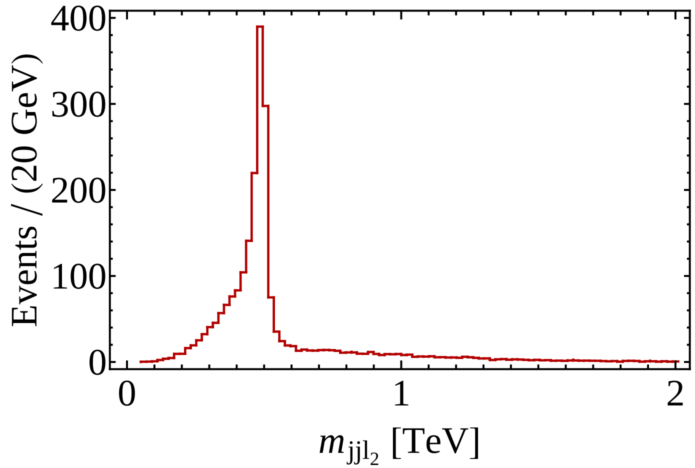
Keung & Senjanovic, 1983

Signal:

di-lepton + jets, **no** $\not{E}_T$

Plot from: S.P. Das et al., PRD **86**

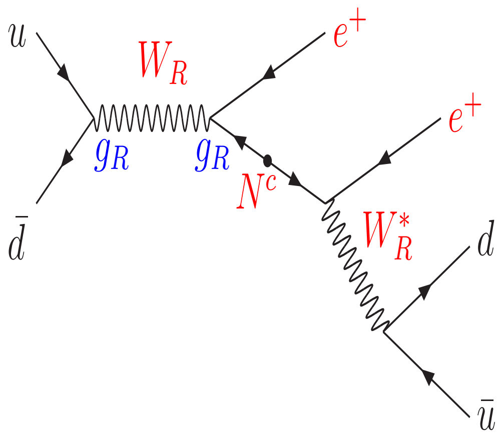




$\Rightarrow$ Assumes $\mathcal{L} = 30$ fb^{-1} at $\sqrt{s} = 14$ TeV

Example: W_R @ LHC

$(\bar{u}d)(\bar{e})(\bar{e})(\bar{u}d)$:



Keung & Senjanovic, 1983

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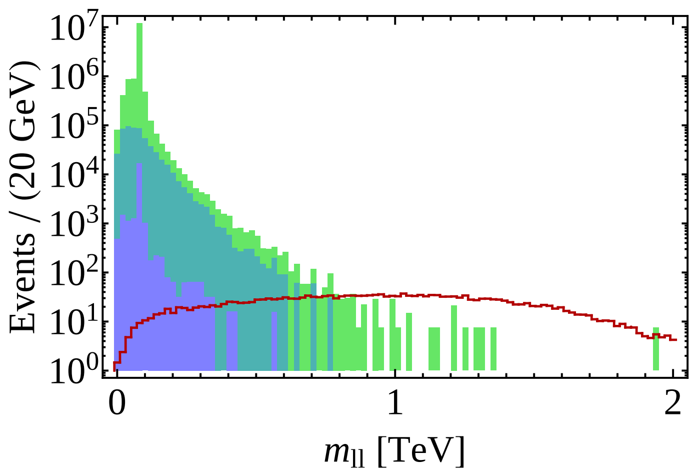
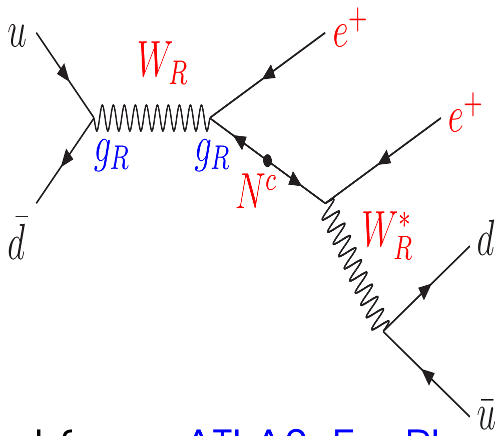


$\Rightarrow$ Assumes $\mathcal{L} = 30$ fb^{-1} at $\sqrt{s} = 14$ TeV

Example: W_R @ LHC

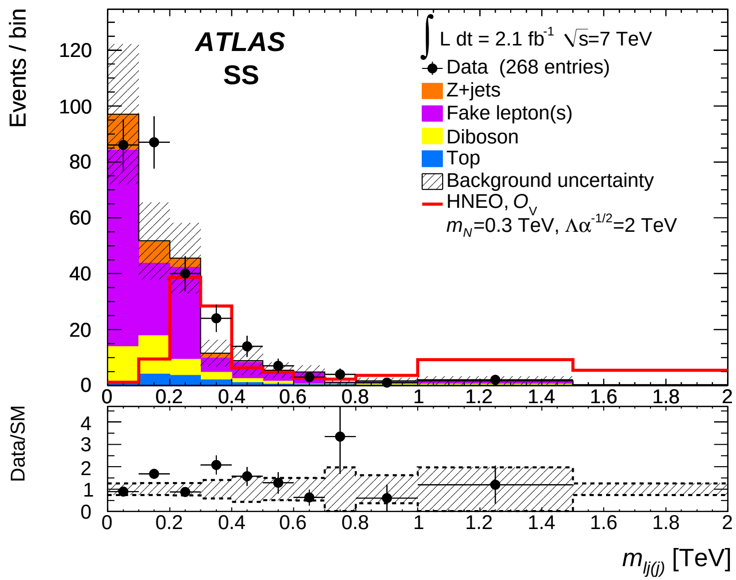


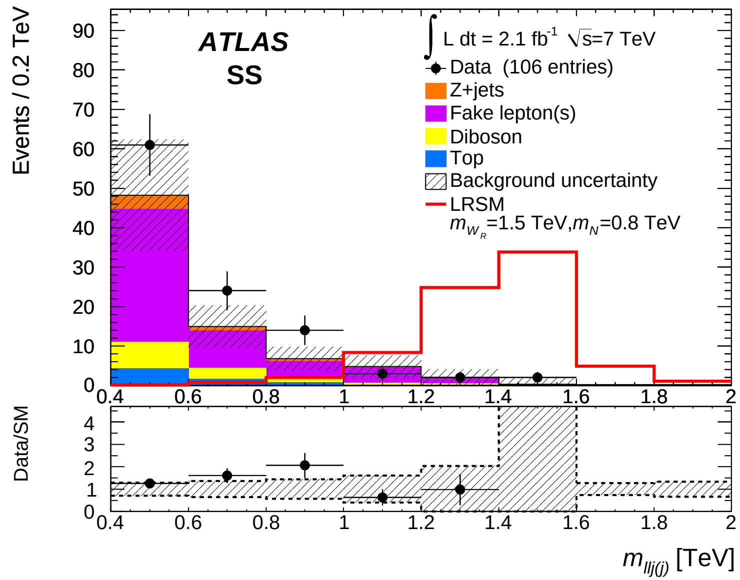
Keung & Senjanovic, 1983

Signal:

di-lepton + jets, **no** $\not{E}_T$

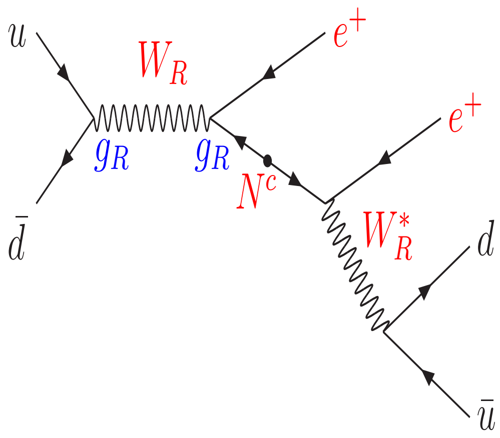
Plot from: ATLAS, Eur.Phys.J C72:





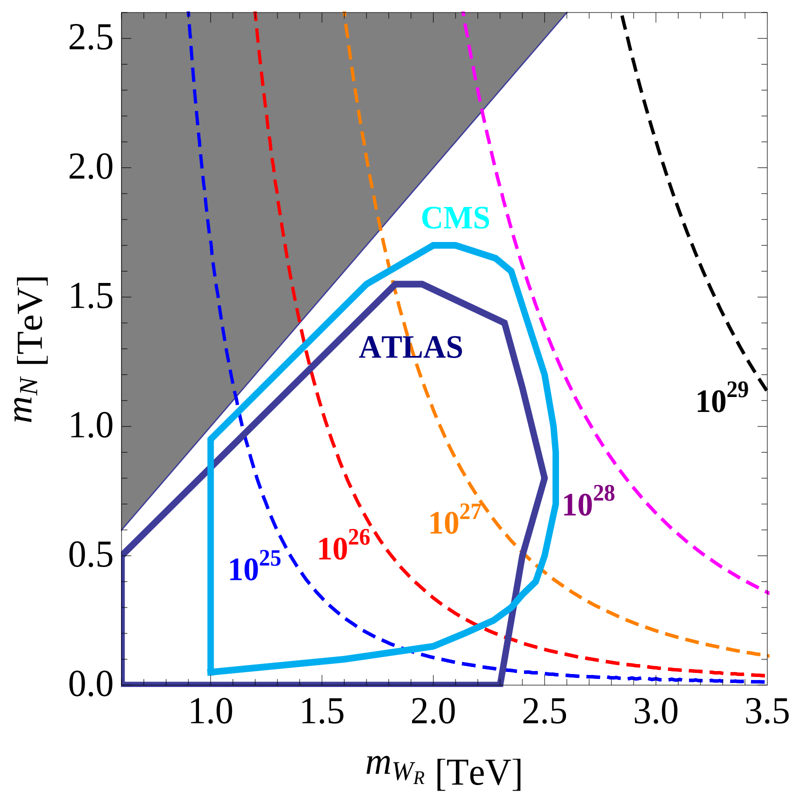
$\Rightarrow$ Assumes $\mathcal{L} = 2.1$ fb^{-1} at $\sqrt{s} = 7$ TeV

Example: W_R @ LHC



Signal:

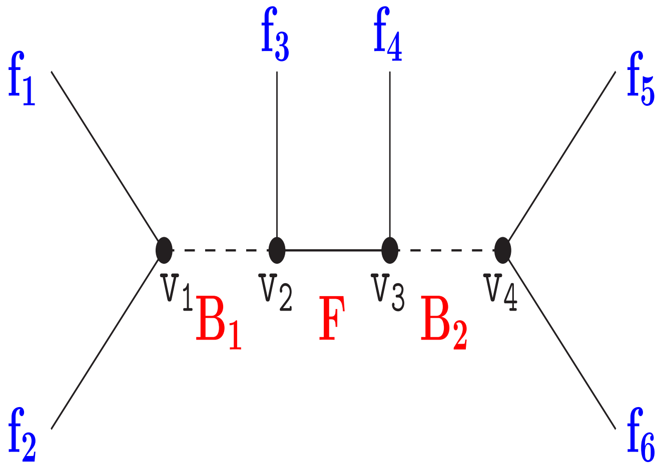
di-lepton + jets, **no** $\not{E}_T$



CMS (and ATLAS) with $\sqrt{s} = 8$ TeV:
Non-observation gives stringent limits on short-range W_R diagrams for $0\nu\beta\beta$ decay.

Assumes: $g_R = g_L$!

$0\nu\beta\beta$ versus LHC

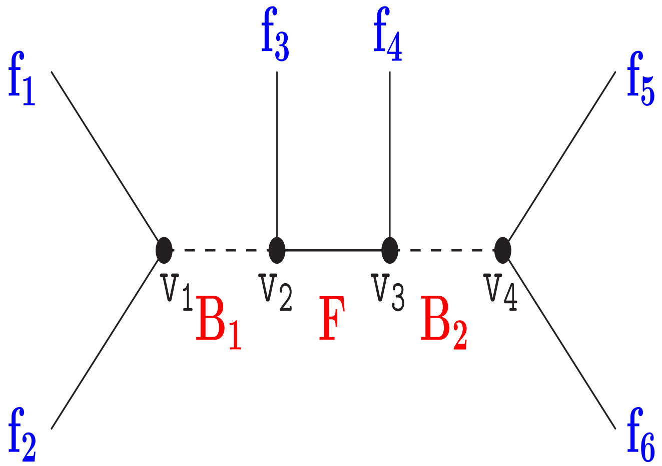


$$\mathcal{A}_I^{0\nu\beta\beta} \propto \frac{g_1 g_2 g_3 g_4}{m_{B_1}^2 m_F m_{B_2}^2} = \frac{g_{eff}^4}{M_{eff}^5}.$$

Define:

$g_{eff} = (g_1 g_2 g_3 g_4)^{1/4}$
$M_{eff} = (m_{B_1}^2 m_F m_{B_2}^2)^{1/5}$

$0\nu\beta\beta$ versus LHC



$$\mathcal{A}_I^{0\nu\beta\beta} \propto \frac{g_1 g_2 g_3 g_4}{m_{B_1}^2 m_F m_{B_2}^2} = \frac{g_{eff}^4}{M_{eff}^5}.$$

Define:

$$g_{eff} = (g_1 g_2 g_3 g_4)^{1/4}$$
$$M_{eff} = (m_{B_1}^2 m_F m_{B_2}^2)^{1/5}$$

$\Rightarrow$ Compare to LHC:

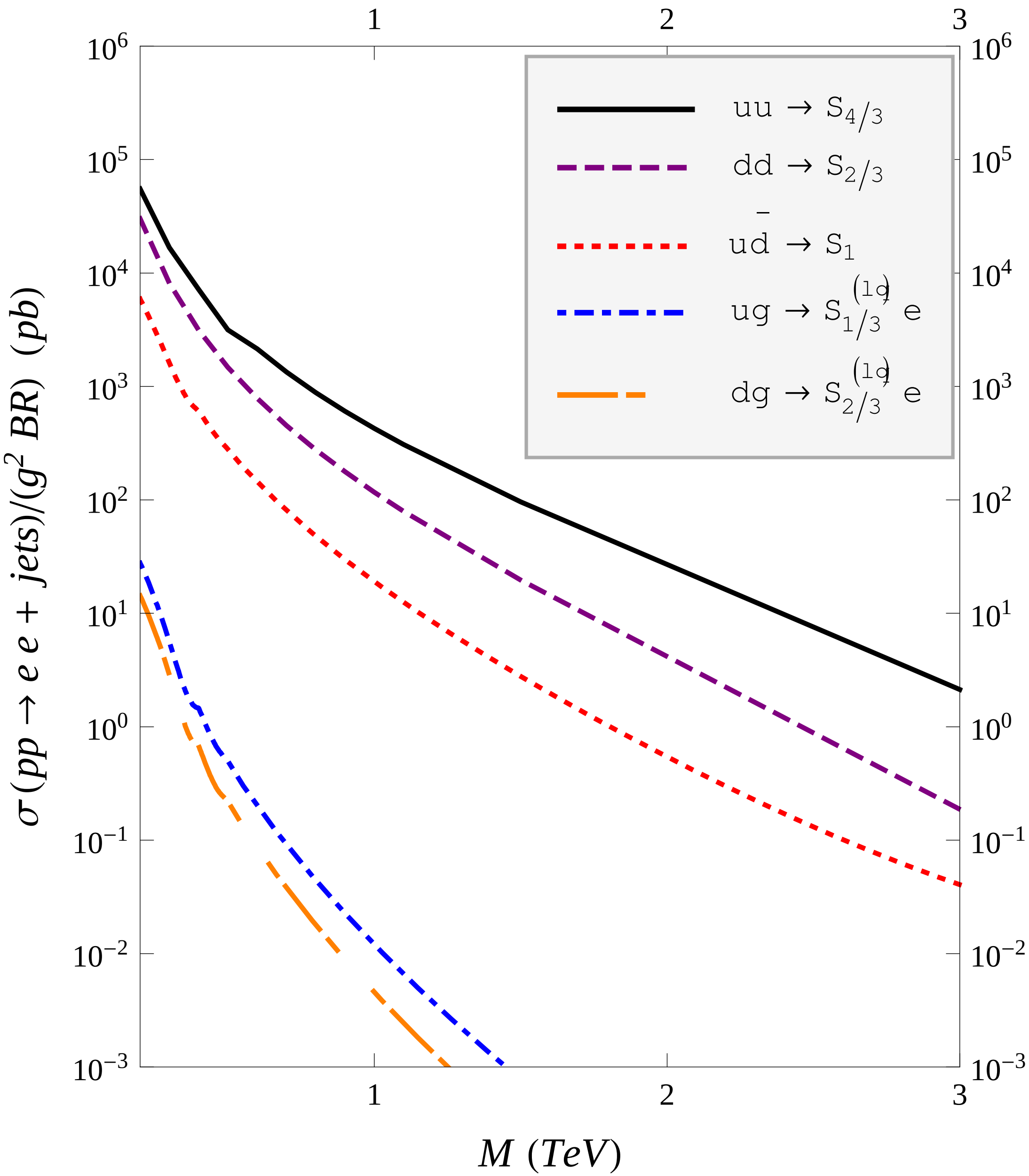
$$\#\text{events}(e^{\pm}e^{\pm}jj) \quad : \quad \sigma(pp \to B_1) \times Br(B_1 \to F + f_3) \times Br(F \to f_4 f_5 f_6)$$

$\Rightarrow$ Heavy F, once produced on-shell, will decay

$\Rightarrow$ $\sigma(pp \to B_1)$ depends on m_{B_1} and g_1, but not on m_{B_2} nor g_3, g_4

$\Rightarrow$ $Br(B_1 \to F + f_3)$ depends on m_{F_1} and g_2, but not on m_{B_2} nor g_3, g_4

Cross sections for $\sqrt{s} = 8$ TeV



Note:

Event rate scales as:

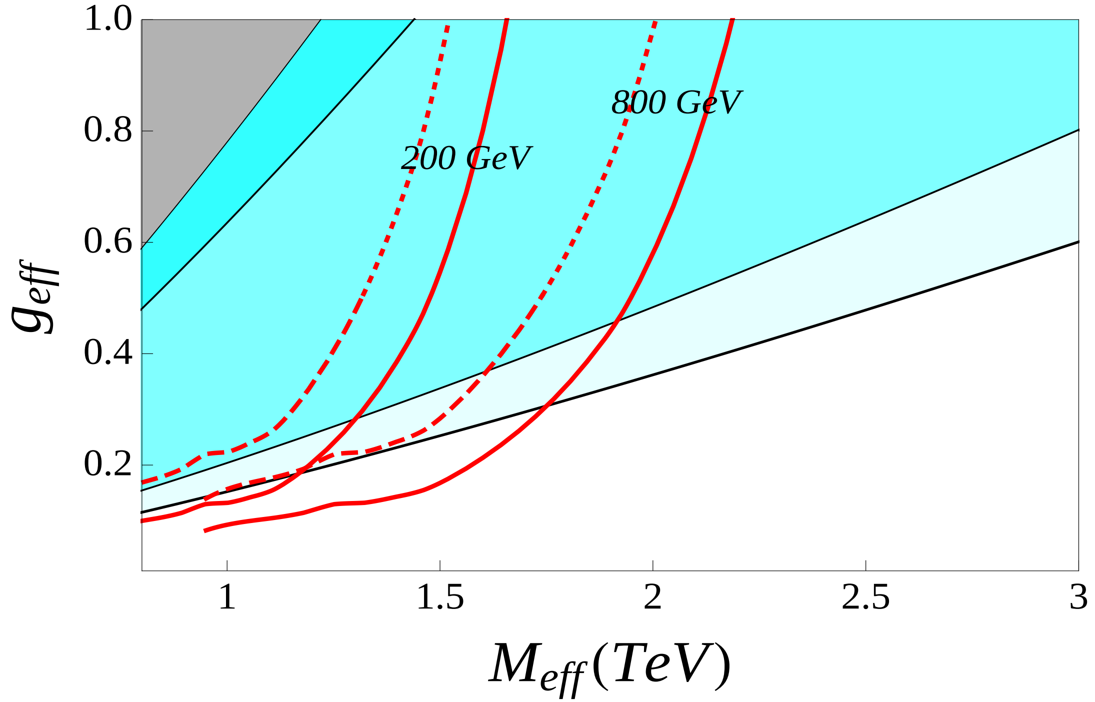
events $\propto g_1^2 \times$Br$(eejj)$

Calculated with CalcHEP and MadGraph

These 5 x-sections (+ vector ones) cover - in principle - all T-I cases!

Status for $\sqrt{s} = 8$ TeV

Case T-I-i-1 with SFS $\Rightarrow (\bar{u}d) - S_{+1} - (e) - N - (e) - S_{+1} - (\bar{u}d)$:



grey: $T^{0\nu\beta\beta}_{1/2} \leq 10^{25}$ ys

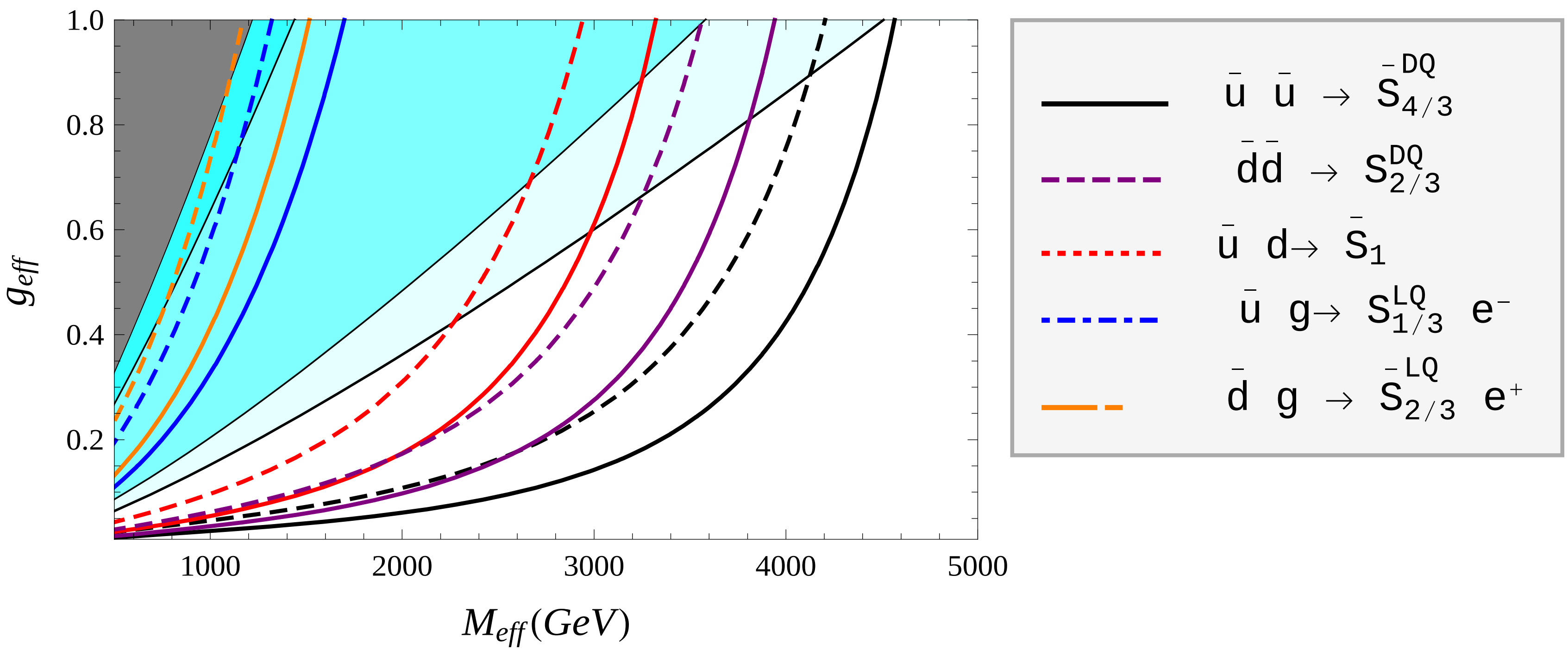
cyan: $T^{0\nu\beta\beta}_{1/2} \leq 10^{26} - 10^{27}$ ys

$\Rightarrow$ Red lines: CMS-EXO-12-017-pas upper limit on:

$$\sigma(pp- > e^+e^+jj) \lesssim (3 - 10) \text{ fb}$$

$\Rightarrow$ Full lines assume $Br(S_{+1}- > e^+e^+jj) = 10^{-1}$
Dashed lines assume $Br(S_{+1}- > e^+e^+jj) = 10^{-2}$

Forecast for $\sqrt{s} = 14$ TeV



⇒ Estimation of the Bkg: We use a simple scaling of Bkg. at 8 TeV.

⇒ Assume an statistic of $300 fb^{-1}$

⇒ $m_F = 200$ GeV (pessimistic case!)

⇒ Full lines: Br$= 10^{-1}$, dashed lines Br$= 10^{-2}$

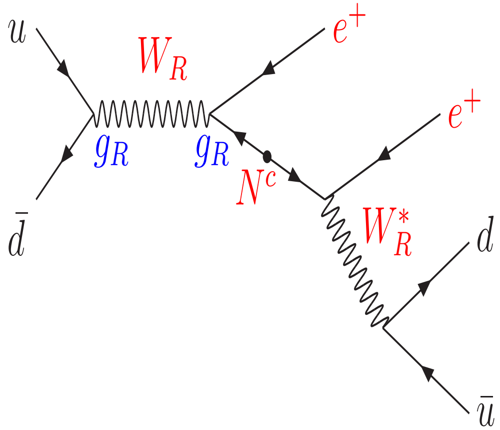
If a positive signal is found,

Can one distinguish different LNV models?

(i) Invariant mass peaks

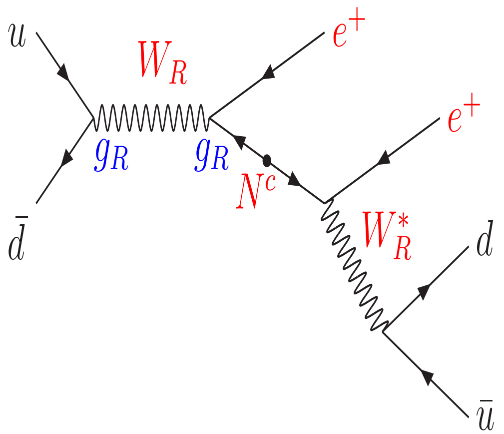
(ii) Charge asymmetry

Invariant mass peaks

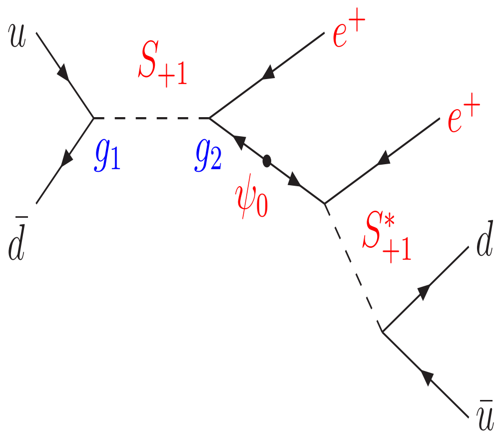


$$p^2_{eejj} = m^2_{W_R}$$
$$p^2_{e_2jj} = m^2_N$$

Invariant mass peaks

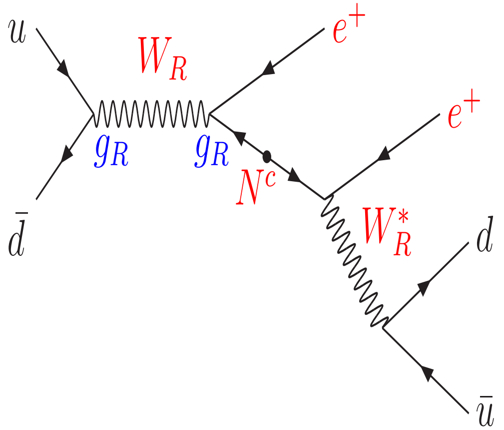


$$p^2_{eejj} = m^2_{W_R}$$
$$p^2_{e_2jj} = m^2_N$$

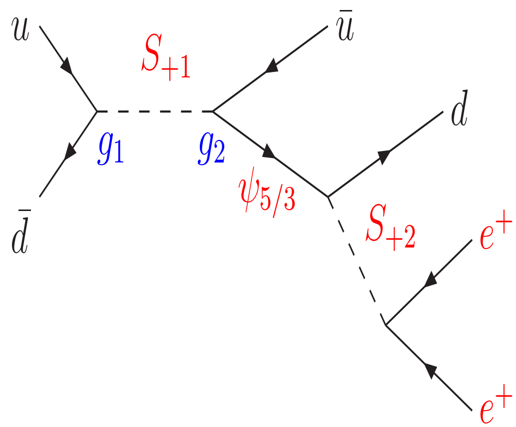


$$p^2_{eejj} = m^2_{S_{+1}}$$
$$p^2_{e_2jj} = m^2_{\psi_0}$$

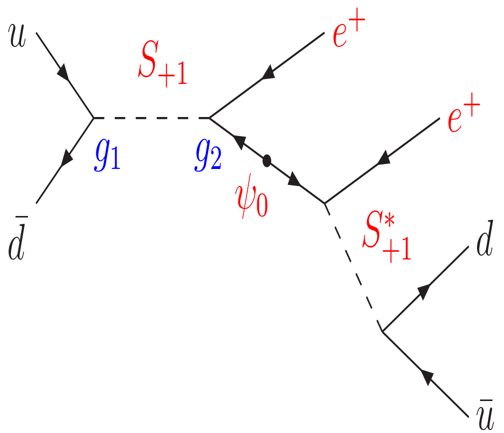
Invariant mass peaks



$$p_{eejj}^2 = m_{W_R}^2$$
$$p_{e_2jj}^2 = m_N^2$$

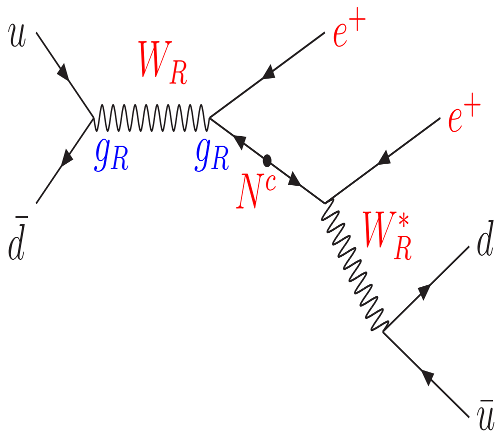


$$p_{eejj}^2 = m_{S_{+1}}^2$$
$$p_{eej_2}^2 = m_{\psi_{5/3}}^2$$
$$p_{ee}^2 = m_{S_{+2}}^2$$

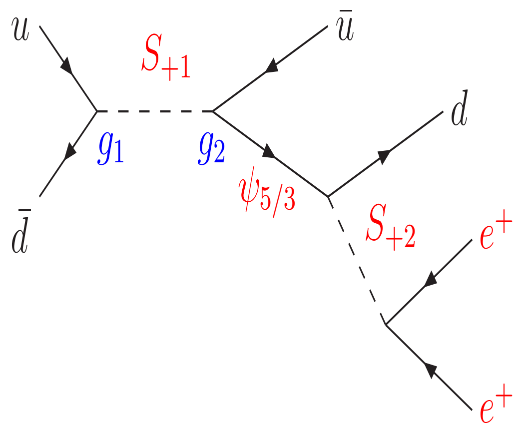


$$p_{eejj}^2 = m_{S_{+1}}^2$$
$$p_{e_2jj}^2 = m_{\psi_0}^2$$

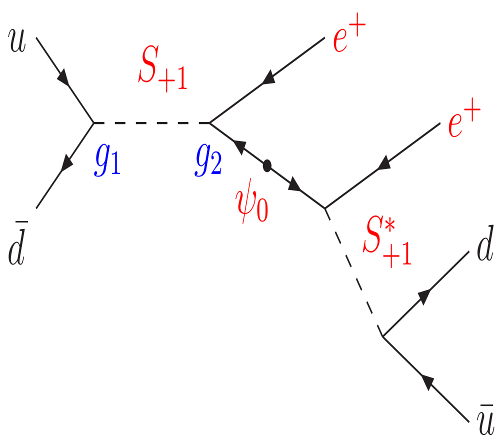
Invariant mass peaks



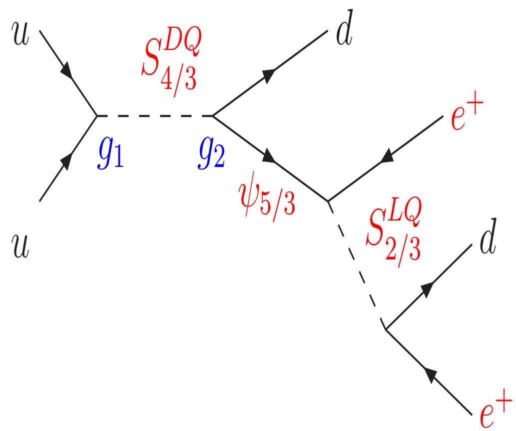
$$p^2_{eejj} = m^2_{W_R}$$
$$p^2_{e_2jj} = m^2_N$$



$$p^2_{eejj} = m^2_{S_{+1}}$$
$$p^2_{eej_2} = m^2_{\psi_{5/3}}$$
$$p^2_{ee} = m^2_{S_{+2}}$$

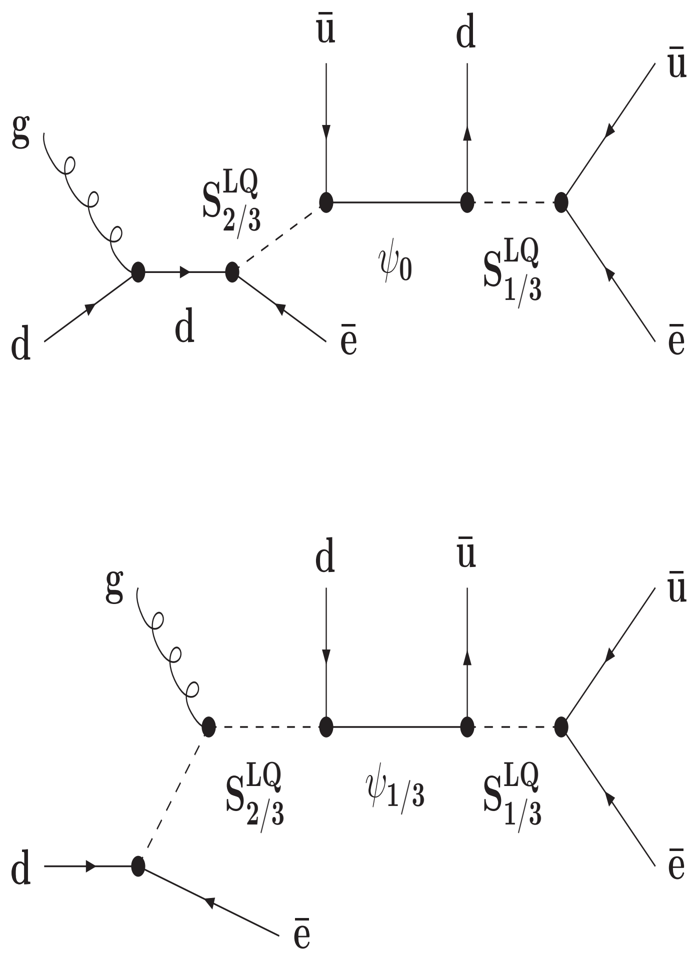


$$p^2_{eejj} = m^2_{S_{+1}}$$
$$p^2_{e_2jj} = m^2_{\psi_0}$$



$$p^2_{eejj} = m^2_{S^{DQ}_{4/3}}$$
$$p^2_{eej_2} = m^2_{\psi_{5/3}}$$
$$p^2_{e_2j_2} = m^2_{S^{LQ}_{2/3}}$$

Mass peaks: Leptoquarks



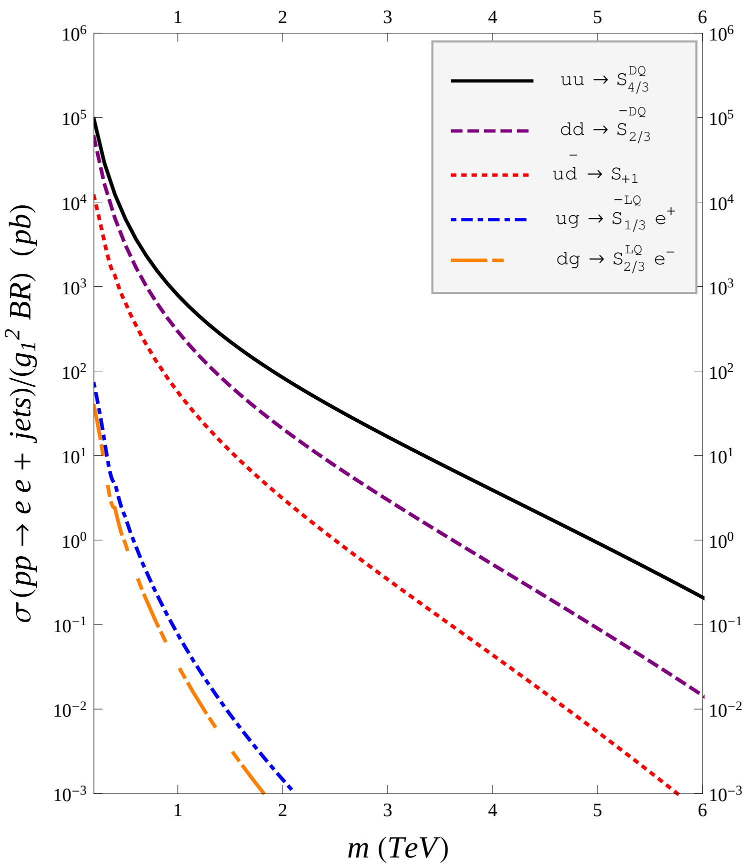
Only example!

No peak in p^2_{eejj}!

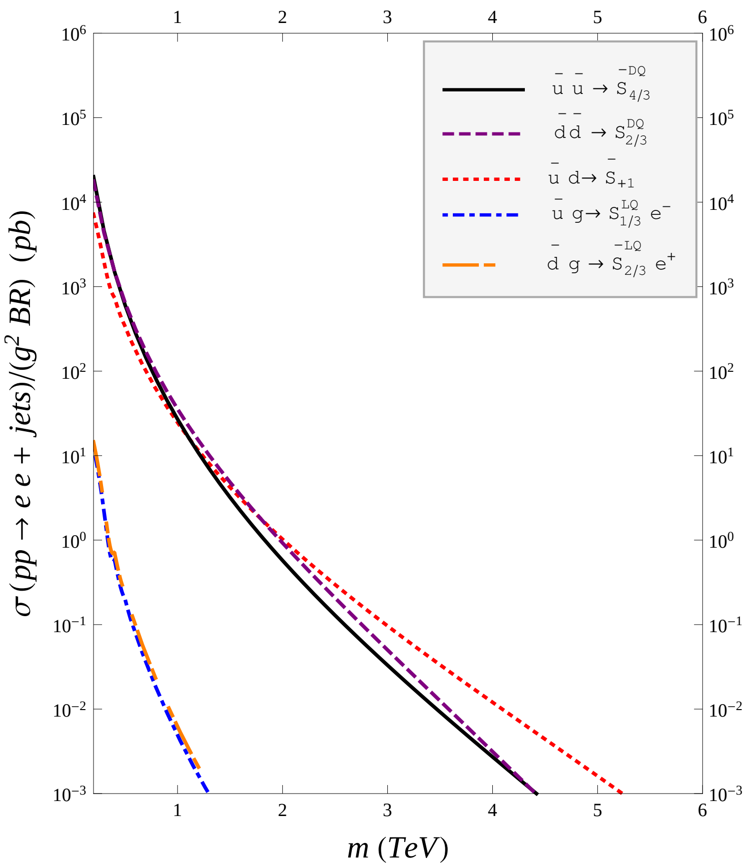
$$p^2_{ejjj} = m^2_{S^{LQ}_{2/3}}$$
$$p^2_{ej_2j_3} = m^2_\psi$$
$$p^2_{ej_3} = m^2_{S^{LQ}_{1/3}}$$

Cross sections for $\sqrt{s} = 14$ TeV

"Dominant" sign producion:



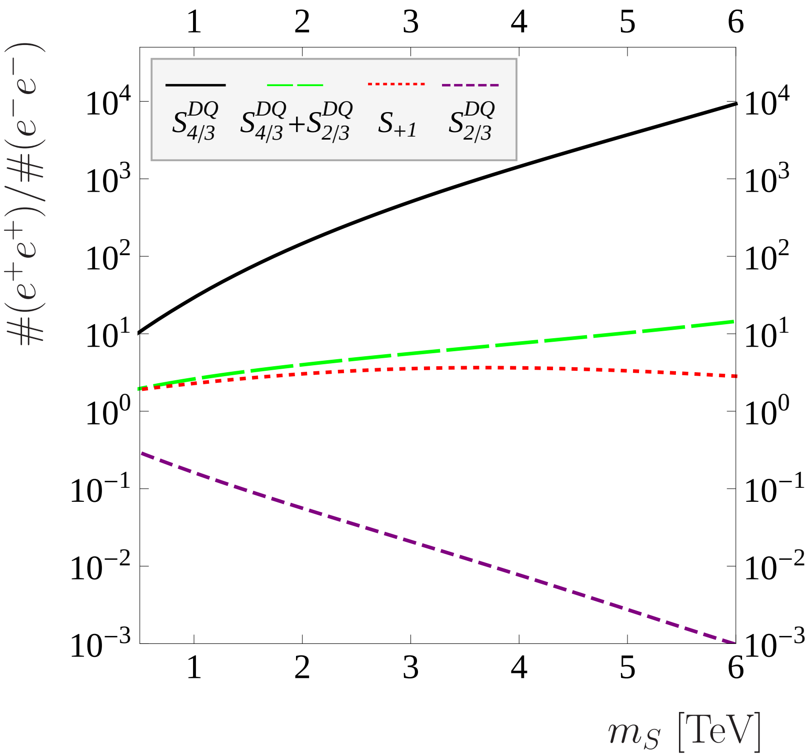
"wrong" sign production:



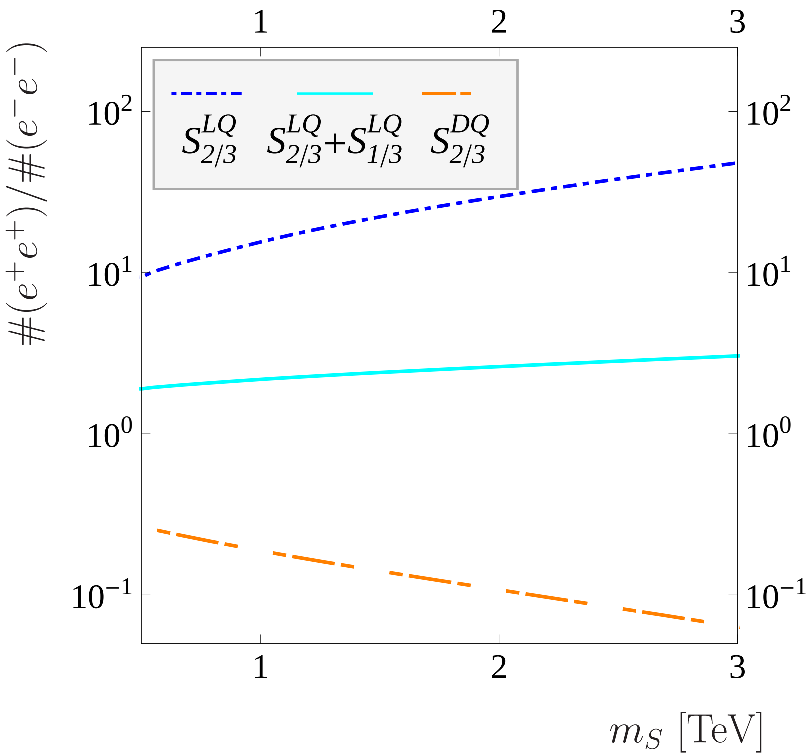
$\Rightarrow$ Number of $e^- e^-$-like and $e^+ e^+$-like events differ, depending on scalar!

Charge asymmetry

Diquark (and S_{+1}) cases:



Leptoquark cases:



⇒ (red) S_{+1} like LR-symmetric model: $x_{CA} \simeq [2.3.5]$

⇒ x_{CA} can be very different in general case!

Conclusions

⇒ We have compared the discovery potential of LNV signals at the LHC with the sensitivity of current and future $0\nu\beta\beta$ experiments. (TeV particle exchange).

⇒ With the exception of some leptoquark mechanisms a $0\nu\beta\beta$ decay signal corresponding to a half life in the range $10^{26} - 10^{27}$ yrs should imply a positive LNV signal at the LHC. The non-observation of a positive signal at the LHC would rule out a short-range mechanism for $0\nu\beta\beta$ in most cases

⇒ IF $0\nu\beta\beta$ decay is discovered:
Which is the dominant mechanism?

→ short range operators: by LHC!

→ charge asymmetry

→ resonance peaks at the invariant mass distribution

⇒ Consequently, if an LNV signal at the LHC would be found it should be possible to identify the dominant contribution of $0\nu\beta\beta$ decay.