Discriminating models with doubly charged Higgs scalars at future colliders: A case study

Janusz Gluza

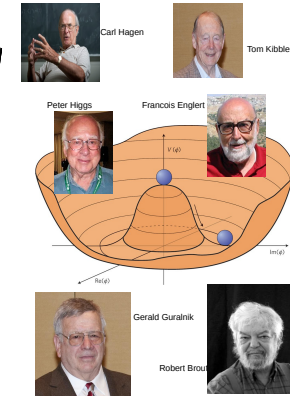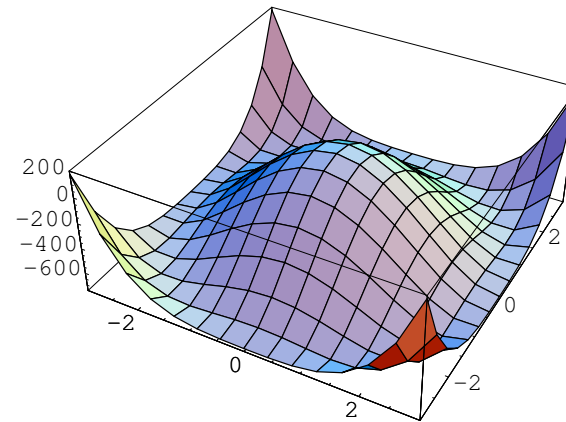General Monthly FCC-ee physics meeting (online)

30 August 2021

One fact and two important questions

❖ **There is a scalar, fundamental particle!**

1. Do we need more of them?

Is Particle Physics scalar landscape so simple? Mount Mayon

(Renowned as the "perfect cone" because of its almost symmetric conical shape)

$$\Phi \equiv \Phi_{SM} = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}$$

$$V = -\mu^2 \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2$$

$$V_{min} = v/\sqrt{2}, v = \sqrt{\mu^2/\lambda} \simeq 250 \text{ GeV}$$

One fact and two important questions

❖ **There is a scalar, fundamental particle!**

1. Do we need more of them?

2. What kind of?

I focus on non-supersymmetric theories.

Not considered many fascinating problems, see e.g.: D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio and A. Strumia, "Investigating the near-criticality of the Higgs boson", https://doi.org/10.1007/JHEP12(2013)089

The 'universe' stability fate phase diagram, https://arxiv.org/abs/1707.08124
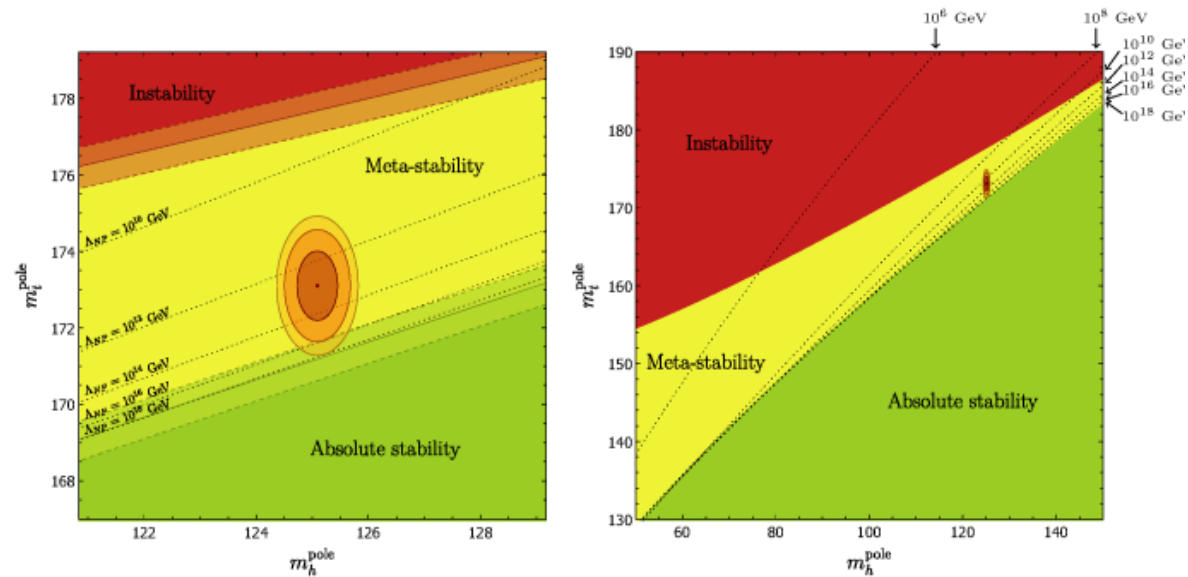
Is BSM needed there? 'The Standard Model of Particle Physics as a Conspiracy Theory and the Possible Role of the Higgs Boson in the Evolution of the Early Universe', F. Jegerlehner, 2106.00862

Extensions of the Standard Model

❖ Left Right Symmetric Model (LRSM)
Extended gauge group: $SU(2)_R \times SU(2)_L \times U(1)_{B-L}$.
In the most popular version for breaking the symmetry two additional triplets are introduced.

$$\Delta_{L,R} = \frac{1}{\sqrt{2}} \begin{pmatrix} \delta^+_{L,R} & \sqrt{2}\delta^{++}_{L,R} \\ v_{L,R} + h_{L,R} + iz_{L,R} & -\delta^+_{L,R} \end{pmatrix}, \ \phi = \begin{pmatrix} \phi^0_1 & \phi^+_1 \\ \phi^-_2 & \phi^0_2 \end{pmatrix}.$$

❖ Higgs Triplet Model (HTM)
One additional $SU(2)_L$ triplet

$$\Delta = \frac{1}{\sqrt{2}} \begin{pmatrix} \delta^+_\Delta & \sqrt{2}\delta^{++} \\ v_\Delta + h_\Delta + iz_\Delta & -\delta^+_\Delta \end{pmatrix}$$

$$
\begin{aligned}
V_{HTM} \quad = \quad & -m_\Phi^2 \left(\Phi^\dagger \Phi\right) + \frac{\lambda}{4}\left(\Phi^\dagger \Phi\right)^2 + M_\Delta^2 \left(\Delta^\dagger \Delta\right) \\
+ \quad & \left[\mu \left(\Phi^T i\sigma_2 \Delta^\dagger \Phi\right) + \text{h.c.}\right] \\
& + \lambda_1 \left(\Phi^\dagger \Phi\right)\left(\Delta^\dagger \Delta\right) + \lambda_2 \left[\left(\Delta^\dagger \Delta\right)\right]^2 \\
+ \quad & \lambda_3 \left[\left(\Delta^\dagger \Delta\right)^2\right] + \lambda_4 \Phi^\dagger \Delta \Delta^\dagger \Phi \,.
\end{aligned}
$$

$$
\Phi \quad = \quad \frac{1}{\sqrt{2}}\begin{pmatrix} \sqrt{2}\delta_\Phi^+ \\ v_\Phi + h_\Phi + iz_\Phi \end{pmatrix}, \; \Delta = \frac{1}{\sqrt{2}}\begin{pmatrix} \delta_\Delta^+ & \sqrt{2}\delta^{++} \\ v_\Delta + h_\Delta + iz_\Delta & -\delta_\Delta^+ \end{pmatrix}\,.
$$

$$
M_{H^{\pm\pm}}^2 = \frac{\mu v_\Phi^2}{\sqrt{2}v_\Delta} - \frac{\lambda_4}{2}v_\Phi^2 - \lambda_3 v_\Delta^2
$$

$$
\begin{aligned}
V_{MLRSM}=&-\mu_1^2\left(Tr[\phi^\dagger\phi]\right)-\mu_2^2\left(Tr[\tilde{\phi}\phi^\dagger]+Tr[\tilde{\phi}^\dagger\phi]\right)-\mu_3^2\left(Tr[\Delta_L\Delta_L^\dagger]+Tr[\Delta_R\Delta_R^\dagger]\right)\\
&+\lambda_1\left(\left(Tr[\phi\phi^\dagger]\right)^2\right)+\lambda_2\left(\left(Tr[\tilde{\phi}\phi^\dagger]\right)^2+\left(Tr[\tilde{\phi}^\dagger\phi]\right)^2\right)+\lambda_3\left(Tr[\tilde{\phi}\phi^\dagger]Tr[\tilde{\phi}^\dagger\phi]\right)\\
&+\lambda_4\left(Tr[\phi\phi^\dagger]\left(Tr[\tilde{\phi}\phi^\dagger]+Tr[\tilde{\phi}^\dagger\phi]\right)\right)+\rho_1\left(\left(Tr[\Delta_L\Delta_L^\dagger]\right)^2+\left(Tr[\Delta_R\Delta_R^\dagger]\right)^2\right)\\
&+\rho_2\left(Tr[\Delta_L\Delta_L]Tr[\Delta_L^\dagger\Delta_L^\dagger]+Tr[\Delta_R\Delta_R]Tr[\Delta_R^\dagger\Delta_R^\dagger]\right)+\rho_3 Tr[\Delta_L\Delta_L^\dagger]Tr[\Delta_R\Delta_R^\dagger]\\
&+\rho_4\left(Tr[\Delta_L\Delta_L]Tr[\Delta_R^\dagger\Delta_R^\dagger]+Tr[\Delta_L^\dagger\Delta_L^\dagger]Tr[\Delta_R\Delta_R]\right)\\
&+\alpha_1\left(Tr[\phi\phi^\dagger]\left(Tr[\Delta_L\Delta_L^\dagger]+Tr[\Delta_R\Delta_R^\dagger]\right)\right)\\
&+\alpha_2\left(Tr[\phi\tilde{\phi}^\dagger]Tr[\Delta_R\Delta_R^\dagger]+Tr[\phi^\dagger\tilde{\phi}]Tr[\Delta_L\Delta_L^\dagger]\right)\\
&+\alpha_2^*\left(Tr[\phi^\dagger\tilde{\phi}]Tr[\Delta_R\Delta_R^\dagger]+Tr[\tilde{\phi}^\dagger\phi]Tr[\Delta_L\Delta_L^\dagger]\right)\\
&+\alpha_3\left(Tr[\phi\phi^\dagger\Delta_L\Delta_L^\dagger]+Tr[\phi^\dagger\phi\Delta_R\Delta_R^\dagger]\right)\\
&+\beta_1\left(Tr[\phi\Delta_R\phi^\dagger\Delta_L^\dagger]+Tr[\phi^\dagger\Delta_L\phi\Delta_R^\dagger]\right)+\beta_2\left(Tr[\tilde{\phi}\Delta_R\phi^\dagger\Delta_L^\dagger]+Tr[\tilde{\phi}^\dagger\Delta_L\phi\Delta_R^\dagger]\right)\\
&+\beta_3\left(Tr[\phi\Delta_R\tilde{\phi}^\dagger\Delta_L^\dagger]+Tr[\phi^\dagger\Delta_L\tilde{\phi}\Delta_R^\dagger]\right)
\end{aligned}
$$

Our aim and strategy for tracing VEV scales: eV or TeV

HTM	MLRSM
Type II See-Saw	Three heavy neutrinos
$SU(2) \times U(1)$	$SU(2)_R \times SU(2)_L \times U(1)_{B-L}$ $W_1,\, W_2,\, Z_1,\, Z_2,\, \gamma$
$h,\, H,\, A,\, H^{\pm},\, H^{\pm\pm}$	$h,\, H_1,\, H_2,\, H_3,\, A_1,\, A_2$ $H_1^{\pm},\, H_2^{\pm},\, H_1^{\pm\pm},\, H_2^{\pm\pm}$
$v_\Delta \lesssim$ GeV	$v_L = 0$ $v_R \gtrsim$ TeV

HTM

$$\mu = 1.7 \times 10^{-7}, \quad \lambda = 0.519, \quad \lambda_1 = 0.519, \quad \lambda_2 = 0, \quad \lambda_3 = -1, \quad \lambda_4 = 0.$$

$$M_h = 125.3 \text{ GeV}, \qquad M_H = 700 \text{ GeV}, \qquad M_{H^{\pm}} = 700 \text{ GeV}, \qquad M_{H^{\pm\pm}} = \mathbf{700 \text{ GeV}}.$$

MLRSM

$$\lambda_1 = 0.129, \ \rho_1 = 0.0037, \ \rho_2 = 0.0037, \ \rho_3 - 2\rho_1 = 0.015, \ \alpha_3 = 4.0816, \ 2\lambda_2 - \lambda_3 = 0.$$

$$M_{H_0^0} = 125.3 \text{ GeV}, \qquad M_{H_1^0} = 10 \text{ TeV}, \qquad M_{H_2^0} = 600 \text{ GeV}, \qquad M_{H_3^0} = 605.4 \text{ GeV},$$

$$M_{H_1^{\pm\pm}} = \mathbf{700 \text{ GeV}}, \qquad M_{H_2^{\pm\pm}} = \mathbf{700 \text{ GeV}}, \qquad M_{H_1^{\pm}} = 654.4 \text{ GeV}, \qquad M_{H_2^{\pm}} = 10\,003.1 \text{ GeV}.$$

The case study: 'Discriminating the HTM and MLRSM models in collider studies via doubly charged Higgs boson pair production and the subsequent leptonic decays',
Chinese Physics C, JG, M.Kordiaczynska, T.Srivastava,
https://iopscience.iop.org/article/10.1088/1674-1137/abfe51
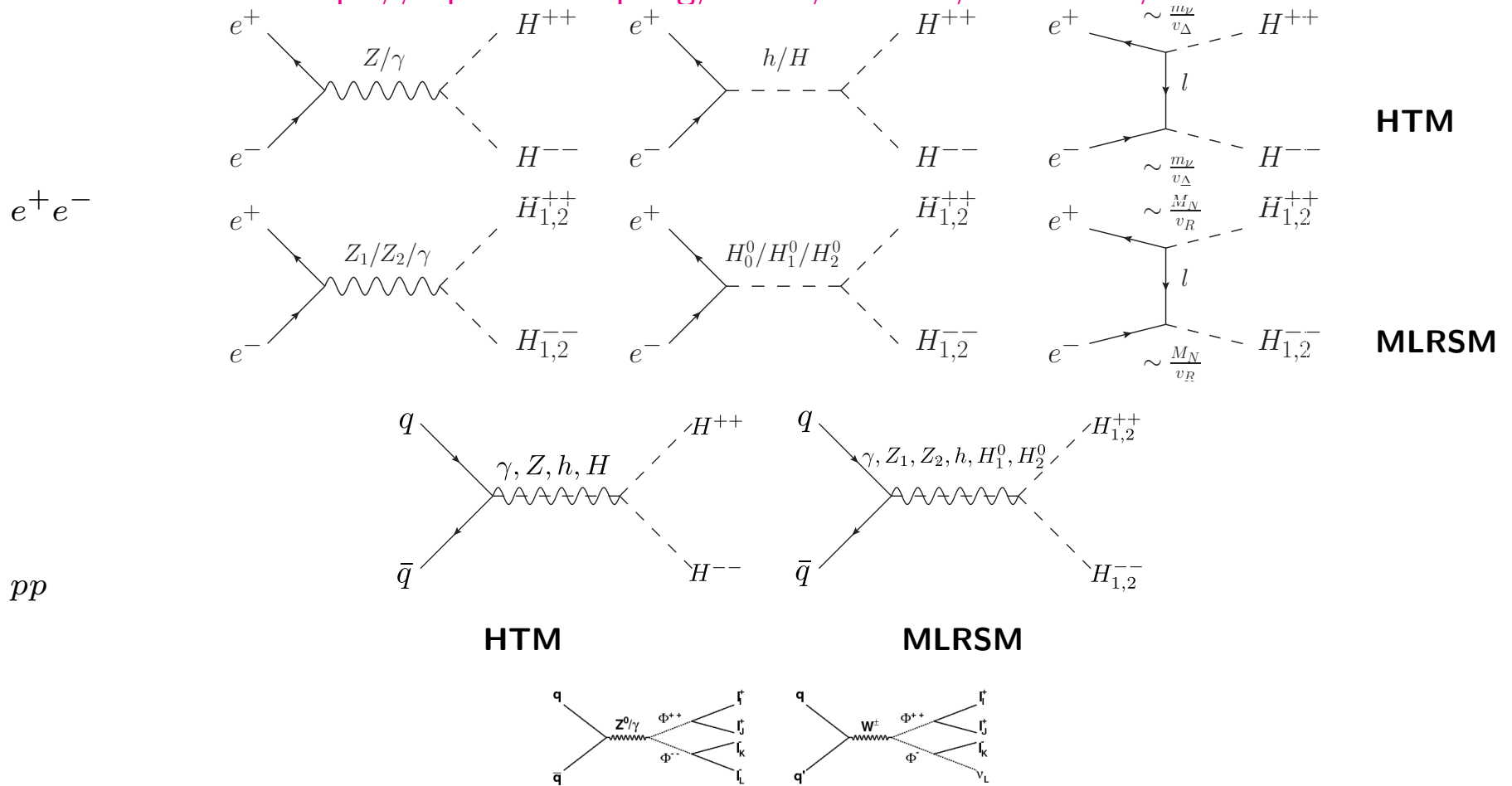
Present bounds on the doubly charged scalar masses

BR	ll	ee	$e\mu$	$\mu\mu$
0.01	216.3	249.2	216.3	309.7
0.02	279.4	310.9	300.0	335.7
0.03	308.5	323.7	316.6	367.5
0.04	316.8	333.9	329.5	418.2
0.05	324.3	342.5	339.5	434.1
0.1	473.7	478.5	473.7	480.7
0.2	493.5	613.7	573.1	557.9
0.3	518.1	638.9	648.0	683.4
0.4	645.4	658.4	671.7	714.6
0.5	662.7	691.5	690.0	734.0
0.6	679.6	752.6	749.3	754.4
0.7	695.6	755.8	776.5	808.3
0.8	753.3	758.3	805.8	839.4
0.9	756.8	761.9	829.4	857.8
1.0	763.8	768.3	846.2	874.7

Lowest limits on a mass of the doubly charged scalar boson $M_{H_L^{\pm\pm}}$ for different branching ratios
ATLAS Collaboration, 1710.09748.

LHC bounds on the doubly charged scalar masses
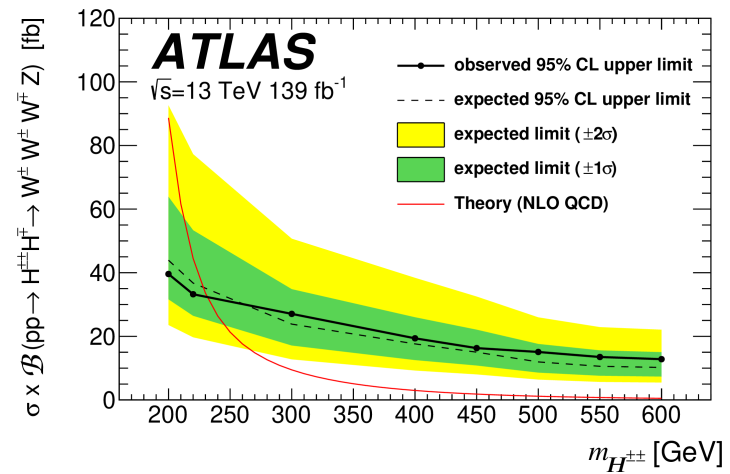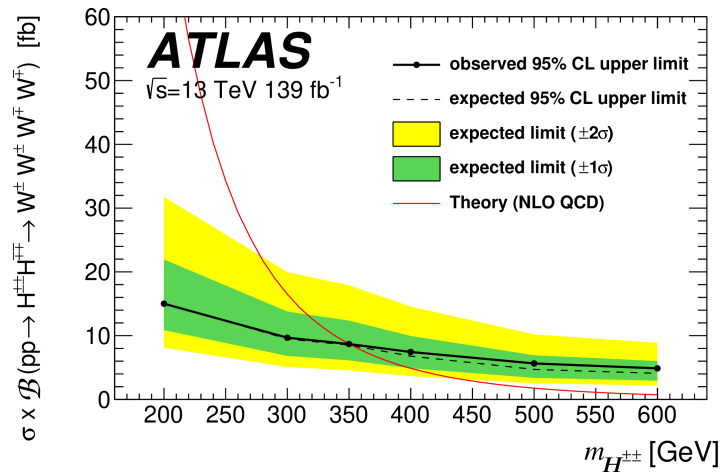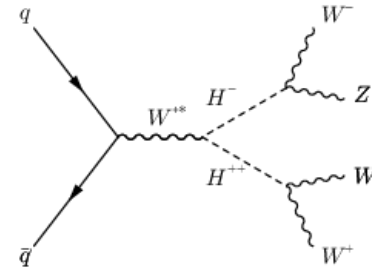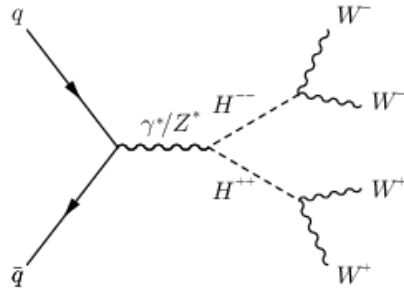
$H^{\pm\pm}$ bosons are excluded at 95% C.L. up to 350 GeV and 230 GeV for the pair and associated production modes, 2101.11961.

Low energy constraints on VEVs

Plenty of them, but of special importance is the ρ parameter

❖ Parameter ρ

$$\rho = \frac{J_{NC}}{J_{CC}} = \frac{M_W^2}{M_Z^2 \cos^2 \theta_W} = 1.00037 \pm 0.00023$$

$\rho_{exp} = 1$, with a very good accuracy.
Can be expressed by VEVs and multiplet isospins

$$\rho = \frac{\sum_i \left(t_i(t_i + 1) - t_{3i}^2 \right) v_i}{2 \sum_i t_{3i}^2 v_i}$$

❖ It is automatically one for doublet Higgs fields, for example, for the SM doublet $\phi : (t, t_3) = (\frac{1}{2}, \pm\frac{1}{2})$: $\rho = 1$.

❖ For an additional $SU(2)_L$ triplet, T. Rizzo,
https://journals.aps.org/prd/abstract/10.1103/PhysRevD.21.1404:

$$\rho = \frac{1 + \frac{2v_\Delta}{v_\phi}}{1 + \frac{4v_\Delta}{v_\phi}} \longrightarrow v_{\Delta\text{max}} = 1.7 \text{ GeV (at } 2\sigma), v_L \sim 0.$$

As we can seen, $\rho_{exp} = 1$ with a very good accuracy, it is automatically one for doublet Higgs fields, $(t, t_3) = (1/2, \pm 1/2)$.

Curiosity: Can we obtain $\rho_{exp} = 1$ independently of v_i values?

Rizzo showed that it happens for values which satisfies the equation $3t_3^2 = t(t+1)$, so, e.g. $(1/2, \pm 1/2)$, next is $(3, \pm 2)$ - 7-plet (note, usual triplet models $(\Phi^0, \Phi^-, \Phi^{--})$ gives $\rho \neq 1$):

$$(\Phi^+, \Phi^0, \Phi^-, \Phi^{--}, ..., \Phi^{------})$$

TABLE III. Values of t^H and t_3^H which yield $\kappa^2 = 1$ for $t_3^H \leqslant 28$ $(t = \frac{1}{2})$.

t^H	$\lvert t_3^H \rvert$
$\frac{1}{2}$	$\frac{1}{2}$
3	2
$\frac{25}{2}$	$\frac{15}{2}$
48	28

Why does $\rho \neq 1$ matters?

Important for specific models, link: hep-ph/9909242.
$\Delta\rho = \epsilon_1$ (Altarelli, ...), $\Delta\rho \simeq T$ (Peskin, Takeuchi).

Confronting electroweak precision measurements with New Physics models

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[2] DESY Zeuthen, Platanenallee 6, 15738 Zeuthen, Germany

Abstract. Precision experiments, such as those performed at LEP and SLC, offer us an excellent opportunity to constrain extended gauge model parameters. To this end, it is often assumed that in order to obtain more reliable estimates, one should include the sizable one-loop standard model (SM) corrections, which modify the Z^0 couplings as well as other observables. This conviction is based on the belief that the higher order contributions from the "extension sector" will be numerically small. However, the structure of higher order corrections can be quite different when comparing the SM with its extension; thus one should avoid assumptions which do not take account of such facts. This is the case for all models with $\rho_{\text{tree}} \equiv M_W^2/(M_Z^2 \cos^2\Theta_W) \neq 1$. As an example, both the manifest left–right symmetric model and the $SU(2)_L \otimes U(1)_Y \otimes \tilde{U}(1)$ model, with an additional Z' boson, are discussed, and special attention to the top contribution to $\Delta\rho$ is given. We conclude that the only sensible way to confront a model with the experimental data is to renormalize it self-consistently. If this is not done, parameters which depend strongly on quantum effects should be left free in fits, though essential physics is lost in this way. We should note that the arguments given here allow us to state that at the level of loop corrections (indirect effects) there is nothing like a "model-independent global analysis" of the data.
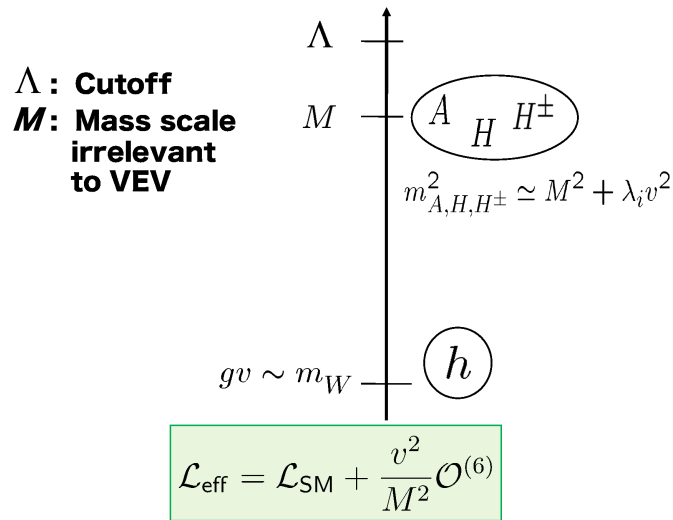
$$(\Delta\rho)_{SM} \simeq \frac{m_t^2}{M_W^2};$$

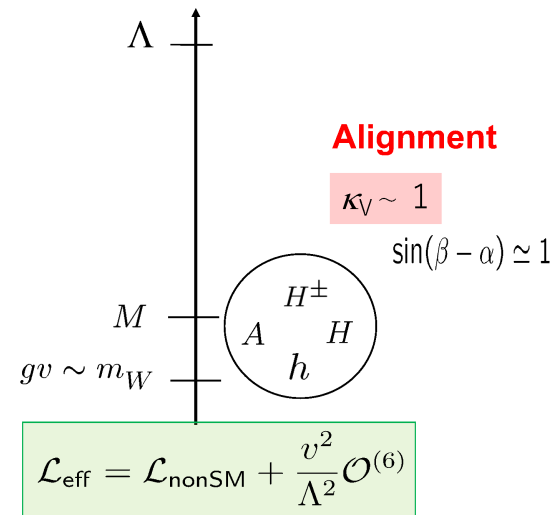$$(\Delta\rho)_{LRM} \simeq \frac{m_t^2}{M_{W_2}^2 - M_{W_1}^2};$$

$$(\Delta\rho)_{HTM} \simeq \ln\frac{m_t^2}{M_W^2};$$

$$G_\mu(\text{fixed}) \sim \frac{g^2}{M_W^2}, M_W \to \infty \Longrightarrow g \to \infty$$

BSM and new scales, S. Kanemura, FCC November Week 2020
https://indico.cern.ch/event/923801

Two Possibilities satisfying current data

Λ : Cutoff
M : Mass scale
  irrelevant
  to VEV

Λ

M $\left(\begin{array}{c} A \ \ H^\pm \\ H \end{array}\right)$

$m^2_{A,H,H^\pm} \simeq M^2 + \lambda_i v^2$

$gv \sim m_W$ $\left(h\right)$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{SM}} + \frac{v^2}{M^2}\mathcal{O}^{(6)}$$

Effective Theory is the SM
Decoupling

Λ

Alignment

$\boxed{\kappa_V \sim 1}$

$\sin(\beta - \alpha) \simeq 1$

M $\left(\begin{array}{c} H^\pm \\ A \quad H \\ h \end{array}\right)$

$gv \sim m_W$

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_{\text{nonSM}} + \frac{v^2}{\Lambda^2}\mathcal{O}^{(6)}$$

Effective Theory is an extended Higgs sector
Alignment without decoupling   8

LFV: $H^{\pm\pm} - l - l'$ coupling

$$\mathcal{L}_Y = \frac{1}{2} f_{\ell\ell'} L_\ell^T C^{-1} i\sigma_2 \Delta L_{\ell'} + \text{h.c.} \longrightarrow \mathcal{L}_\nu = \frac{1}{2} \bar{\nu}_\ell \frac{v_\Delta}{\sqrt{2}} f_{\ell\ell'} \nu_{\ell'}$$
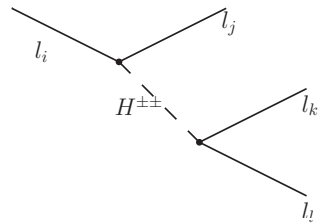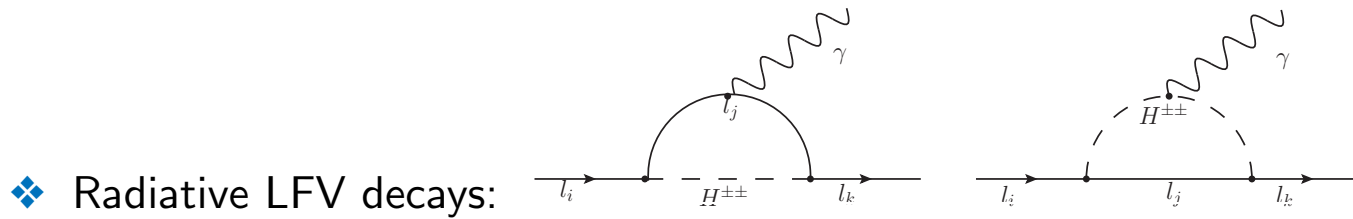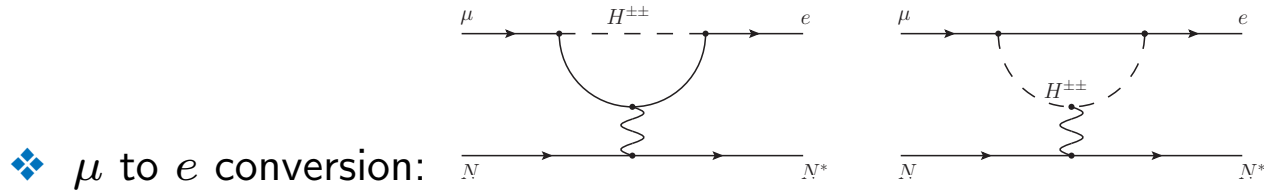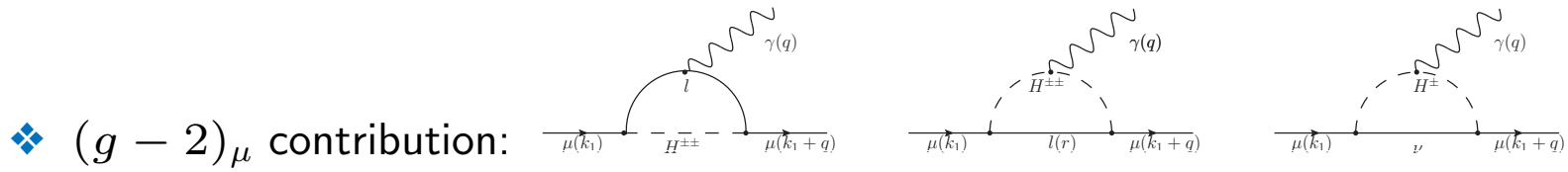

$H^{\pm\pm}$

l

l'
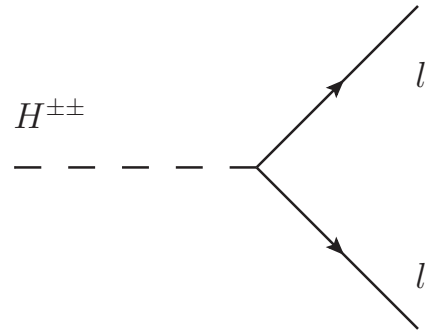
$$\boxed{f = \frac{1}{\sqrt{2}v_\Delta} V_{PMNS}^* D_\nu V_{PMNS}^\dagger} \qquad\qquad D_\nu = \tfrac{1}{2} \text{diag}\{m_1, m_2, m_3\}$$

$$V_{\text{PMNS}} = \begin{bmatrix} c_{12}c_{13}e^{i\alpha_1} & s_{12}c_{13}e^{i\alpha_2} & s_{13}e^{-i\delta_{CP}} \\ (-s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_1} & (c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_2} & s_{23}c_{13} \\ (s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_1} & (-c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta_{CP}})e^{i\alpha_2} & c_{23}c_{13} \end{bmatrix},$$

$$v_\Delta \iff f_{ll'} \iff \text{Neutrino parameters}$$

$\theta_{12}, \theta_{23}, \theta_{13}, \delta_{\text{CP}}, \alpha_{1,2}, m_1, m_2, m_3$

❖ $(g-2)_\mu$ contribution:

❖ μ to e conversion:

❖ Radiative LFV decays:


❖ LFV three body decays :

Lower bounds on the triplet vacuum expectation value v_Δ (in eV) for different values of Majorana phases and doubly charged scalar mass $M_{H\pm\pm} = 700$ GeV.

Lower bounds on the triplet vacuum expectation value v_Δ (in eV) for various values of Majorana phases and doubly charged scalar mass $M_{H^{\pm\pm}} = 700$ GeV. The most strict limit is coming from the LFV processes named with the numerical value. The triplet VEV v_Δ is primarily bounded by experimental limits on $\mu \to eee$ and $\mu \to e\gamma$ dacays. The first four rows present results for the best fit of neutrino oscillation data. The last row shows the range of the lowest possible v_Δ for oscillation parameters within the $\pm 2\sigma$ range and Majorana phases within the entire 2π angle. All values in the table are in eV.

α_1	α_2	NH			IH		
		$m_{v_0} = 0$	$m_{v_0} = 0.01$	$m_{v_0} = 0.071$	$m_{v_0} = 0$	$m_{v_0} = 0.01$	$m_{v_0} = 0.066$
0	0	$1.04\ \mu \to e\gamma$	$1.60\ \mu \to eee$	$6.45\ \mu \to eee$	$3.36\ \mu \to eee$	$3.74\ \mu \to eee$	$7.47\ \mu \to eee$
0	$\frac{\pi}{2}$	$1.04\ \mu \to e\gamma$	$1.15\ \mu \to eee$	$7.48\ \mu \to eee$	$4.92\ \mu \to eee$	$4.99\ \mu \to eee$	$8.09\ \mu \to eee$
$\frac{\pi}{2}$	0	$1.04\ \mu \to e\gamma$	$1.04\ \mu \to e\gamma$	$6.68\ \mu \to eee$	$4.92\ \mu \to eee$	$5.06\ \mu \to eee$	$8.56\ \mu \to eee$
$\frac{\pi}{2}$	$\frac{\pi}{2}$	$1.04\ \mu \to e\gamma$	$1.71\ \mu \to eee$	$5.61\ \mu \to eee$	$3.36\ \mu \to eee$	$3.09\ \mu \to eee$	$3.15\ \mu \to eee$
Oscillations $\pm 2\sigma$			$0.93 \div 10.31$			$1.07 \div 11.38$	

HTM: $v_\Delta \sim eV$, not more than ~ 1.7 GeV.

Low energy intensity frontiers: Competition (and complementarity to HEP
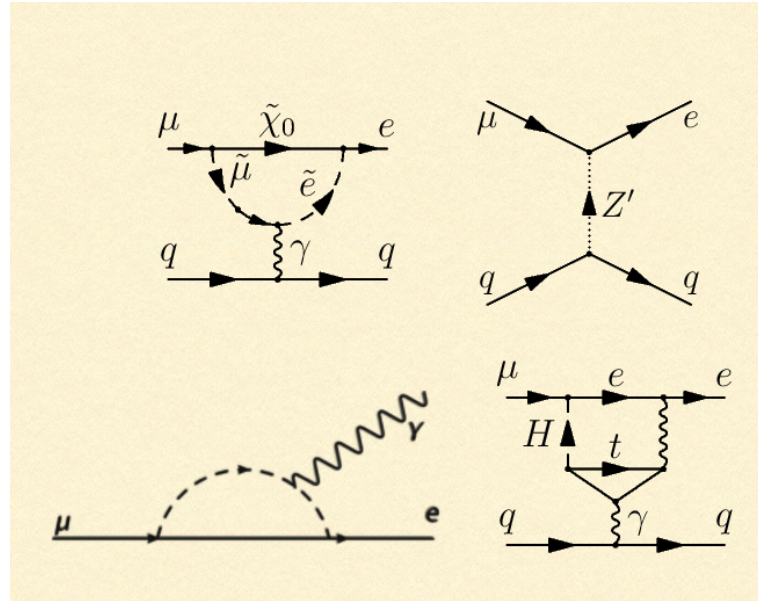
$m_\mu \sim 200 \ m_e$

$R^{\mu \to e} < 7 \cdot 10^{-13}$, expected 4 orders of magnitude improvement,

Sensitivity to NP $\sim$ 10 000 TeV!

MLRSM, **pluses**

Start: 1973-1974,

Pati, Salam, Senjanovic, Mohapatra

Gauge group $SU(2)_L \otimes SU(2)_R \otimes U(1)_{B-L}$

(i) restores left-right symmetry to e-w interactions

$$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}, \quad \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix}$$

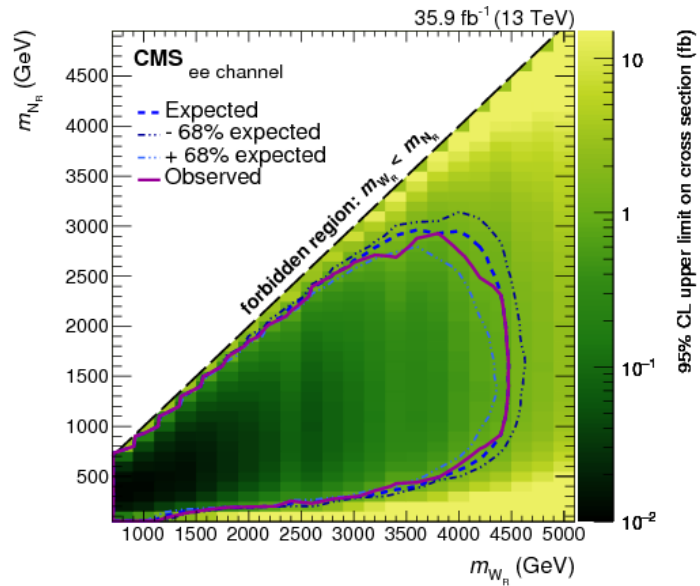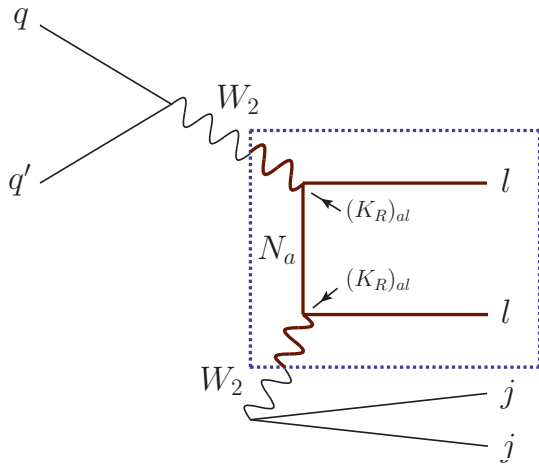(ii) hypercharge interpreted as a difference of baryon and lepton numbers

$$Q = T_{3L} + T_{3R} + \frac{B-L}{2}$$

$$
\begin{array}{ccc}
W_L^{\pm}, W_L^0 & & W_1^{\pm}, W_2^{\pm} \\
W_R^{\pm}, W_R^0 & \rightarrow [SSB?] & Z_1, Z_2 \\
B^0 & & \gamma
\end{array}
$$

(iii)

$$M_\nu = \begin{pmatrix} M_L(v_L) & M_D(\kappa_{1,2}) \\ M_D^T & M_R(v_R) \end{pmatrix}, v_L \ll \kappa_{1,2} \ll v_R, M_R(m_N) = \sqrt{2} h_M v_R.$$

Upper limits on the 'golden' $pp \to eejj$ cross section (Senjanovic-Keung, 1983).

CMS, ATLAS simplify analysis by neglecting heavy neutrino mixings and the CP phases (destructive interferences release the constraints, https://doi.org/10.1016/j.physletb.2015.06.077).

We use the CMS (strict) bounds to constrains the $H^{++}H^{--}$ production processes.

$e^+e^- \to H^{++}H^{--}$ with low energy and LHC bounds, $m_{H^{\pm\pm}} = 700$ GeV, $\sqrt{s} = 1.5$ TeV

HTM

$f \sim \dfrac{m_\nu}{v_\Delta}$

MLRSM

$h_M \sim \dfrac{m_N}{v_R}$
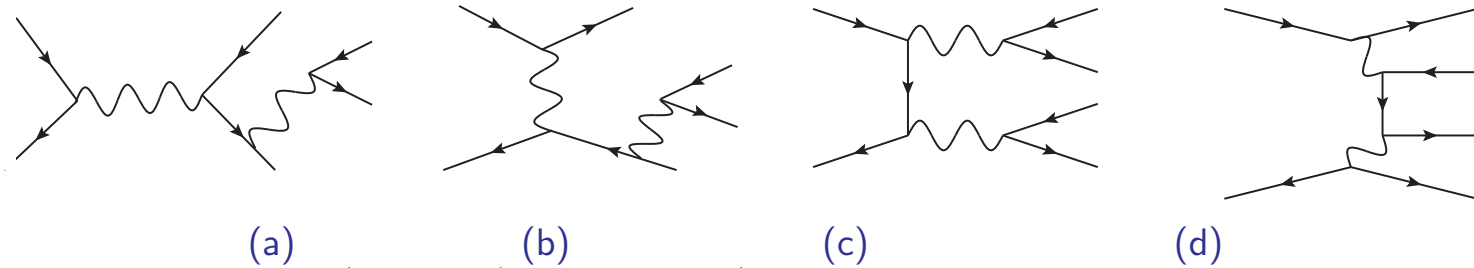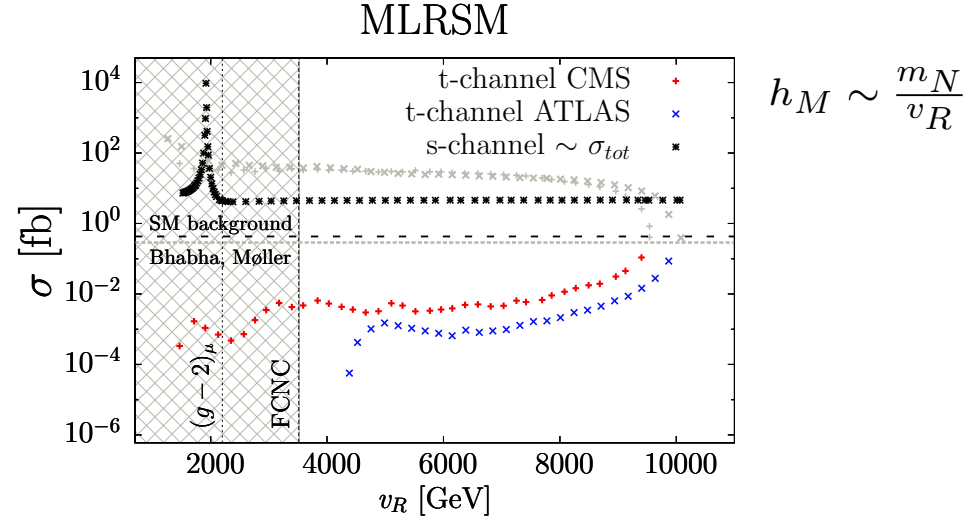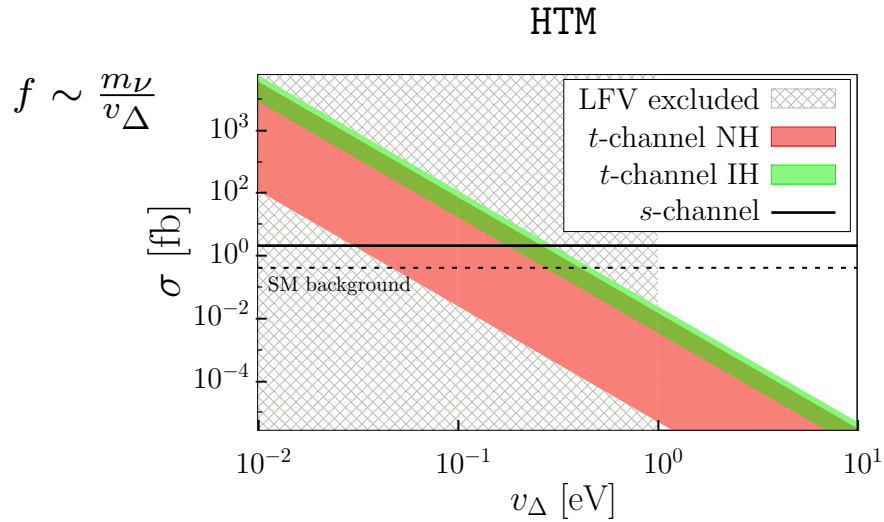
Four lepton background diagrams: $e^+e^- \to e^+e^-$ with FSR e^+e^- pair emission (a) and (b); with Z/γ^* production (c) and with multiperipheral processes (d).

$$pp \to H^{++}H^{--}$$
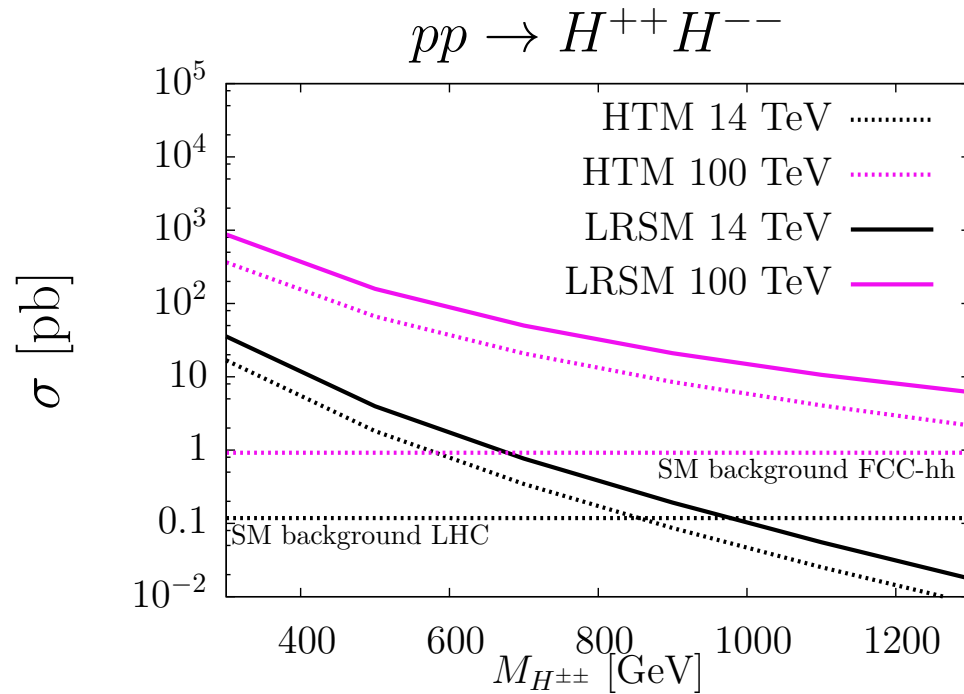
Process	Energy	$t\bar{t}(Z/\gamma^*)$	$(Z/\gamma^*)(Z/\gamma^*)$	TOTAL
$\sigma(pp \to 4l)$ [fb]	14 TeV	0.060	0.054	0.114
	100 TeV	0.58	0.20	0.78

SM background. For the inclusive $t\bar{t}$ process the QCD NLO k-factor is 2.2, accordingly, for $t\bar{t}(Z/\gamma^*)$ it is $k = 1.6$, for $(Z/\gamma^*)(Z/\gamma^*)$ it is $k = 1.5$.

Individual channel contributions, HL-LHC, FCC-hh

Model	Process $pp \rightarrow$	14 TeV				100 TeV			
		γ	Z_1	Z_2	scalars	γ	Z_1	Z_2	scalars
MLRSM	$H_1^{++} H_1^{--}$	63%	36%	$< 1\%$	$\ll 1\%$	43%	27%%	30%	$\ll 1\%$
	$H_2^{++} H_2^{--}$	74%	25%	$\sim 1\%$	$\ll 1\%$	68%	9%	23%	$\ll 1\%$
HTM	$H^{++} H^{--}$	65%	35%	—	$\ll 1\%$	62%	38%	—	$\ll 1\%$

SM background: $e^+e^- \to 4l$				
4e	No cuts: $\sigma = 2.1$ fb After cuts: $\sigma = 0.13$ fb, N = **200**			
4μ	No cuts: $\sigma = 0.07$ fb After cuts: $\sigma = 0.005$ fb, N = **8**			

| BSM signal: $e^+e^- \to H^{++}H^{--} \to 4l$		HTM		MLRSM	
		NH	IH	$v_R = 6$ TeV	$v_R = 15$ TeV
4e	No cuts:	0.19 fb	0.53 fb	0.06 fb	0.924 fb
	After cuts:	0.02 fb N=**30**	0.06 fb N=**90**	0.007 fb N=**10**	0.113 fb N=**169**
4μ	No cuts:	0.22 fb	0.19 fb	0.06 fb	0.33 fb
	After cuts:	0.08 fb N=**120**	0.08 fb N=**120**	0.03 fb N=**38**	0.137 fb N=**205**

$e^+e^- \to H^{++}H^{--} \to 4l$ for $M_{H^{\pm\pm}} = 700$ GeV and $\sqrt{s} = 1.5$ TeV. "N" estimates a number of final events with the assumed luminosity $L = 1500 \ fb^{-1}$.

Kinematic cuts

❖ The Parton Distribution Function (PDF) CTEQ6L1

❖ Initially to select a lepton, CALCHEP, PYTHIA, $|\eta| < 2.5$ and $p_T > 10$ GeV

❖ Detector efficiency cut for leptons is as follows:
  ◇ For electron (either e^- or e^+) detector efficiency i s 0.7 (70%);
  ◇ For muon (either μ^- or μ^+) detector efficiency i s 0.9 (90%).

❖ Smearing of electron energy and muon p_T are done

❖ Lepton-lepton separation. $\Delta R_{ll} \geq 0.2$

❖ Lepton-photon separation cut is also applied: $\Delta R_{l\gamma} \geq 0.2$ with all the photons having $p_{T\gamma} > 10$ GeV;

❖ Lepton-jet separation: The separation of a lepton with all the jets should be $R_{lj} \geq 0.4$, otherwise that lepton is not counted as lepton. Jets are constructed from hadrons using PYCELL within the PYTHIA.

❖ Hadronic activity cut. This cut is applied to take only pure kind of leptons that have very less hadronic activity around them. Each lepton should have hadronic activity, $\frac{\sum p_{T_{hadron}}}{p_{T_l}} \leq 0.2$ within the cone of radius 0.2 around the lepton.

❖ Hard p_T cuts: $p_{Tl_1} > 30$ GeV, $p_{Tl_2} > 30$ GeV, $p_{Tl_3} > 20$ GeV, $p_{Tl_4} > 20$ GeV.

❖ Missing p_T cut. Since 4-lepton final state is without missing p_T, missing p_T cut is not applied while for 3-lepton final state there is a missing neutrino, so missing p_T cut ($p_T > 30$ GeV) is applied.

❖ Z-veto is also applied to suppress the SM background. This has larger impact while reducing the background for four-lepton without missing energy.

SM background: $pp \to 4l$				
$4e$	No cuts: $\sigma = 9.1$ [102.6] fb After cuts: $\sigma = 0.0071$ [0.153] fb, N = **28 [3825]**			
4μ	No cuts: $\sigma = 9.1$ [100.6] fb After cuts: $\sigma = 0.022$ [0.62] fb, N = **88 [15 167]**			

BSM signal: $pp \to H^{++}H^{--} \to 4l$		HTM		LRSM	
		NH	IH	$v_R = 6$ TeV	$v_R = 15$ TeV
$4e$	No cuts:	0.0038 fb [0.39 fb]	0.0109 fb [1.11 fb]	0.0029 fb [0.87 fb]	0.136 fb [19.6 fb]
	After cuts:	0.00032 fb N=**1.3** [0.020 fb] [N=**484**]	0.00092 fb N=**3.7** [0.059 fb] [N=**1459**]	0.00026 fb N=**1.1** [0.0407 fb] [N=**1032**]	0.0116 fb N=**45** [0.98 fb] N=**[24 492]**
4μ	No cuts:	0.0092 [1.086 fb]	0.0039 fb [0.48 fb]	0.0029 fb [0.87 fb]	0.136 fb [19.6 fb]
	After cuts:	0.0031 N=**11.5** [0.202 fb] [N=**5057**]	0.00132 fb N=**5.3** [0.090 fb] [N=**2262**]	0.001 fb N=**4** [0.181 fb] [N=**4509**]	0.048 fb N=**180** [3.9 fb] N=**[97 199]**

Signals over background can be better seen with distributions
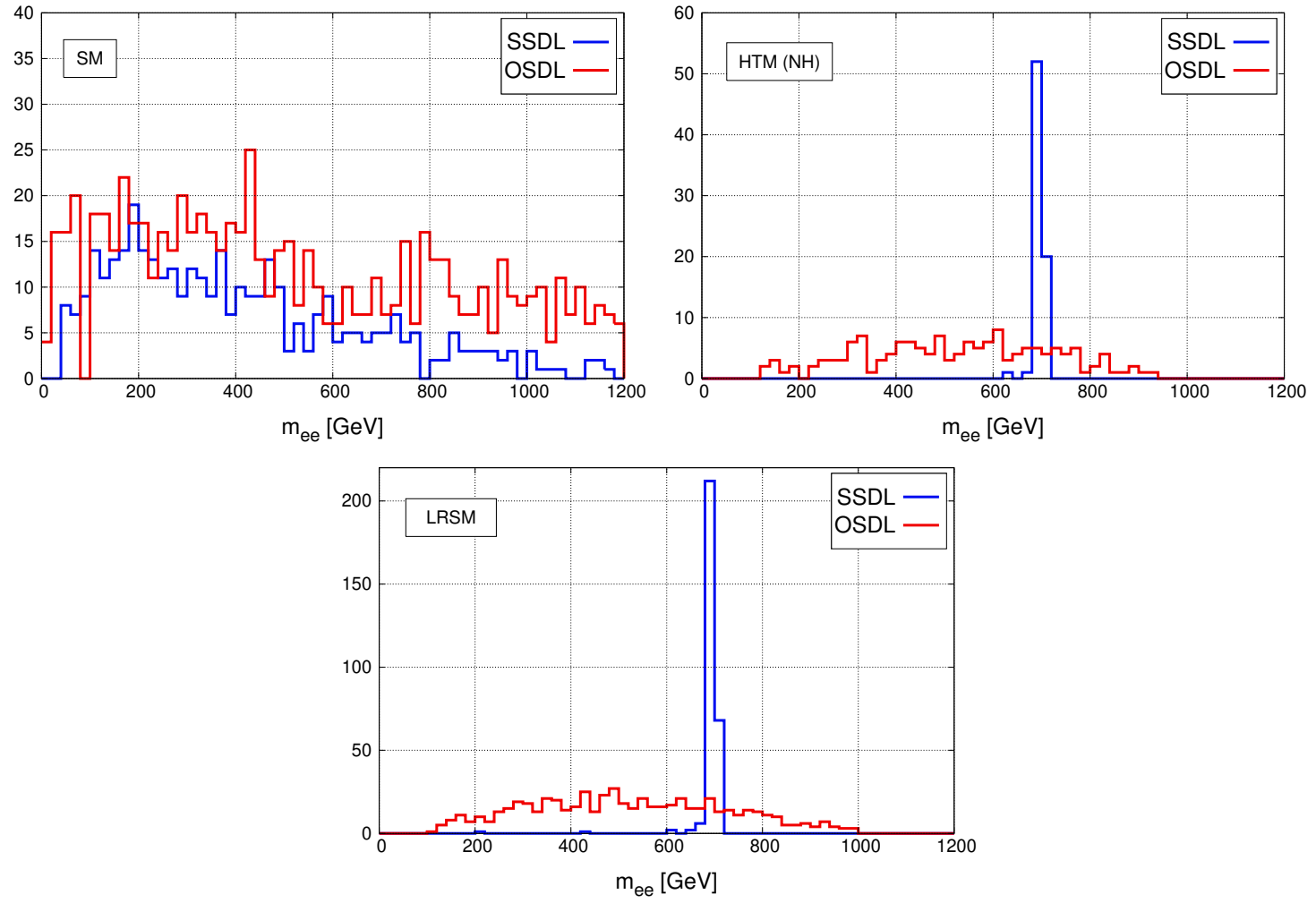
$+ \Delta R_{ee} \ ...$

Summary

❖ $H^{\pm\pm}$ physics is a very interesting option for investigating BSM signals, we focused on the one process, $e^+e^-/pp \to H^{\pm\pm}H^{\mp\mp} \to 4l$.

❖ HL-LHC and FCC-hh can test different $H^{\pm\pm}$ scenarios, CP-violating effects (in scalar and lepton sectors) and low-energy constraints are important and can be discuss in details further.

❖ Elaborating actual models can help to extract observables and connections with effective models.

Backup slides

$M_{H^{\pm\pm}} = 700$ GeV, $M_{H^\pm} = 620$ GeV

$M_{H^{\pm\pm}} = M_{H^\pm}$
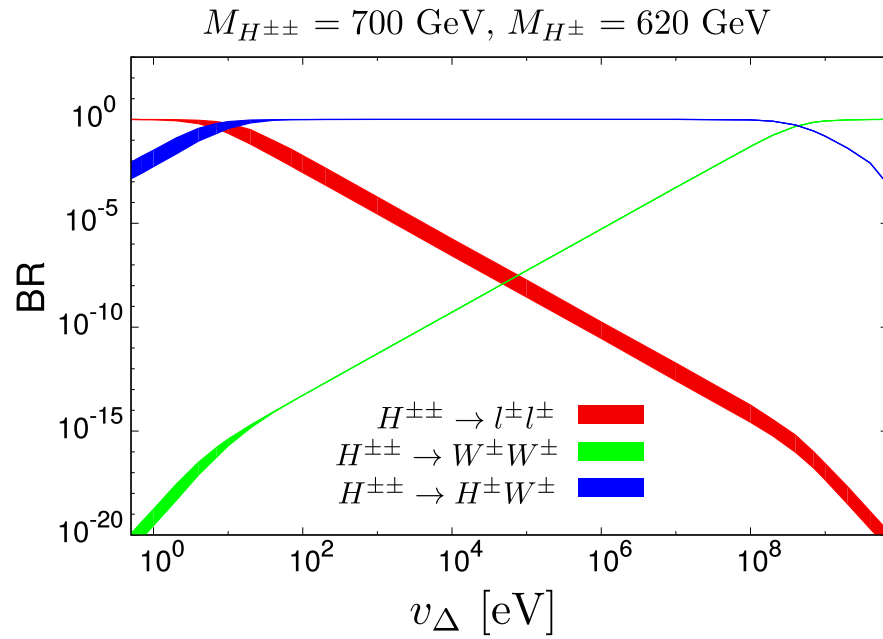
(a)
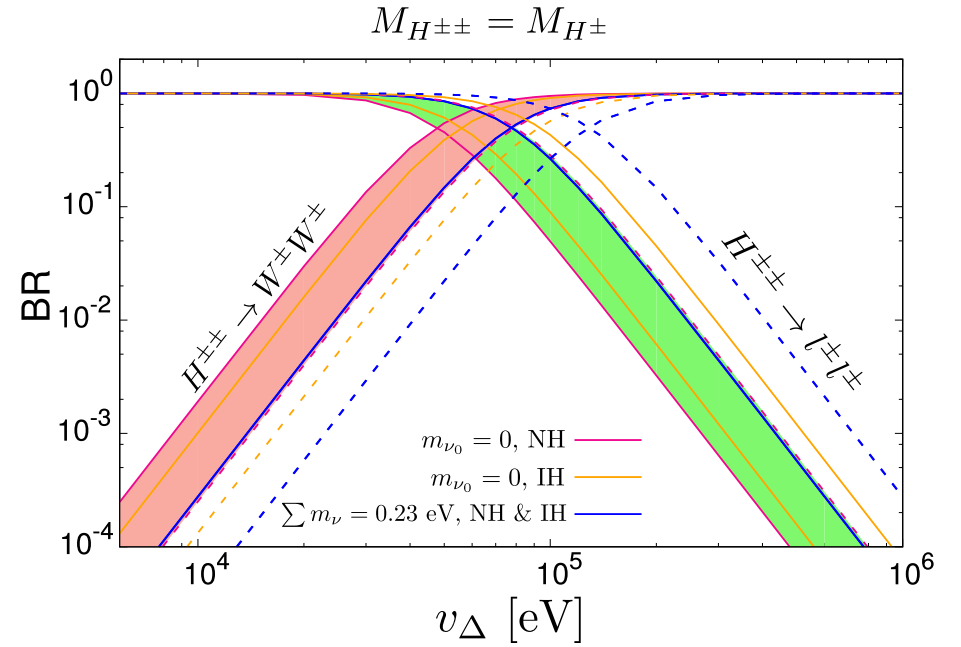
(b)

Used BRs for $M_{H_{1,2}^{\pm\pm}}=$ 700 GeV

	ee	$\mu\mu$	$ee + \mu\mu$
BR$_{H_1^{\pm\pm}}$	0.5	0.3	0.7
BR$_{H_2^{\pm\pm}}$	1.0	0.8	1.0

Maximum branching ratios for $H_{1,2}^{\pm\pm} \to XX$ and $M_{H_{1,2}^{\pm\pm}}=$ 700 GeV. Results for $H_1^{\pm\pm}$ coincides with slide 10. Branching ratios for $H_2^{\pm\pm}$ are due to right-handed leptonic couplings as analysed by ATLAS, EPJC'2018.

Used `HTM` benchmarks

$M_{H^{\pm\pm}}$	$H^{\pm\pm} \to XX$	HTM			
		NH		IH	
700 GeV ()	ee_{max} $BR < 0.5$	BR=0.283	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = \frac{\pi}{2}$ $m_{\nu_0} = 0.071$ eV	BR=0.475	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = \frac{\pi}{2}$ $m_{\nu_0} = 0$
	$\mu\mu_{\text{max}}$ $BR < 0.3$	BR=0.3	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = 0$ $m_{\nu_0} = 0.025$ eV	BR=0.3	$\alpha_1 = 0$ $\alpha_2 = 0$ $m_{\nu_0} = 0.066$ eV
1000 GeV ($\bullet$)	ee_{max}	BR=0.283	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = \frac{\pi}{2}$ $m_{\nu_0} = 0.071$ eV	BR=0.475	$\alpha_1 = \frac{\pi}{2}$ $\alpha_2 = \frac{\pi}{2}$ $m_{\nu_0} = 0$
	$\mu\mu_{\text{max}}$	BR=0.438	$\alpha_1 = 0$ $\alpha_2 = 0$ $m_{\nu_0} = 0.015$ eV	BR=0.3	$\alpha_1 = 0$ $\alpha_2 = 0$ $m_{\nu_0} = 0.066$ eV

Chosen parameter set for maximum branching ratios BR($H^{\pm\pm} \to ee$) and BR($H^{\pm\pm} \to \mu\mu$) and for the best fit neutrino parameters.

Used `MLRSM` benchmarks

$M_{H^{\pm\pm}_{1,2}}$	MLRSM				$H^{\pm\pm}_{1,2} \to$
	$v_R = 6$ TeV		$v_R = 15$ TeV		
700 GeV	$\mathrm{BR}^{ee,\mu\mu}_{H^{\pm\pm}_{1,2}} = 0.123$	$M_{N_1} = 250$ $M_{N_2} = 250$ $M_{N_3} = 620$	$\mathrm{BR}^{ee}_{H^{\pm\pm}_{1,2}} = 0.5$ $\mathrm{BR}^{\mu\mu}_{H^{\pm\pm}_{1,2}} = 0.25$	$M_{N_1} = 1300$ $M_{N_{2,3}} = 918$	$4e$
			$\mathrm{BR}^{\mu\mu}_{H^{\pm\pm}_{1,2}} = 0.3$ $\mathrm{BR}^{ee}_{H^{\pm\pm}_{1,2}} = 0.4$	$M_{N_1} = 1300$ $M_{N_{2,3}} = 1130$	4μ
1000 GeV	$\mathrm{BR}^{ee,\mu\mu}_{H^{\pm\pm}_{1,2}} = 0.123$	$M_{N_1} = 250$ $M_{N_2} = 250$ $M_{N_3} = 620$	$\mathrm{BR}^{ee,2}_{H^{\pm\pm}_{1,2}} \sim 1$	$M_{N_1} = 2867$ $M_{N_{2,3}} = 300$	$4e$
			$\mathrm{BR}^{\mu\mu}_{H^{\pm\pm}_{1,2}} \sim 1$	$M_{N_2} = 5000$ $M_{N_{1,3}} = 300$	4μ

`MLRSM` parameters which maximize separately the branching ratios $\mathrm{BR}(H^{\pm\pm} \to ee)$ and $\mathrm{BR}(H^{\pm\pm} \to \mu\mu)$ for $v_R = 6$ TeV and $v_R = 15$ TeV. A scenario with $v_R = 6$ TeV has been covered already by the LHC analysis. The heavy neutrino masses for $v_R = 6$ TeV fulfill the low energy constraints. M_{N_1} is mostly restricted by the Møller scattering, while M_{N_2} is bounded by $(g-2)_\mu$.

$M_{H^{\pm\pm}_{1,2}}$ [GeV]	$v_R = 6$ TeV	$v_R = 15$ TeV
700	$M_{N_1} < 803$ GeV	$M_{N_1} < 2007$ GeV
1000	$M_{N_1} < 1147$ GeV	$M_{N_1} < 2867$ GeV

Upper limits on the heavy neutrino masses for different sets of doubly charged Higgs boson and the triplet VEV v_R, taking into account low energy LFV constraints and SM processes (Bhabha, Møller).

'Production of the Doubly Charged Higgs Boson in Association with the SM Gauge Bosons and/or Other HTM Scalars at Hadron Colliders'
B. Dziewit, M. Kordiaczyńska, T. Srivastava, https://doi.org/10.1088/1674-1137/abfe51

	Process	Cross section [pb]		Process	Cross section [pb]
$I)$	$pp \to H^{\pm\pm} W^{\mp}$	$\sim 10^{-22}$ $(\sim 10^{-20})$	$II)$	$pp \to H^{\pm\pm} H^{\mp}$	8.13×10^{-5} (8.78×10^{-3})
$III)$	$pp \to H^{\pm\pm} Z W^{\mp}$	$\sim 10^{-12}$ (2.7×10^{-9})	$IV)$	$pp \to H^{\pm\pm} Z H^{\mp}$	6.29×10^{-7} (1.56×10^{-4})
$V)$	$pp \to H^{\pm\pm} W^{\mp} W^{\mp}$	$\sim 10^{-10}$ (1.87×10^{-9})	$VI)$	$pp \to H^{\pm\pm} W^{\mp} h$	$\sim 10^{-12}$ (3.47×10^{-8})
$VII)$	$pp \to H^{\pm\pm} W^{\mp} H$	1.35×10^{-6} (2.44×10^{-4})	$VIII)$	$pp \to H^{\pm\pm} W^{\mp} H^{\mp}$	2.88×10^{-6} (6.81×10^{-4})
$IX)$	$pp \to H^{\pm\pm} h H^{\mp}$	1.07×10^{-7} $)$ $(1.63 \times 10^{-6}$	$X)$	$pp \to H^{\pm\pm} H H^{\mp}$	$\sim 10^{-29}$ $(\sim 10^{-26})$
$XI)$	$pp \to H^{\pm\pm} H^{\mp} H^{\mp}$	$\sim 10^{-31}$ $(\sim 10^{-28})$			

Cross section for a production of a single $H^{\pm\pm}$ boson with associated SM gauge bosons and other HTM scalars at the pp colliders in $2 \to 2$ and $2 \to 3$ processes. Cross sections are calculated for $\sqrt{s} = 14$ TeV (100 TeV). Charged scalar masses are degenerated, $M_{H^{\pm\pm}} = M_{H^{\pm}} = 1000$ GeV.

Models consistency, beyound the tree level

"Left-Right Symmetry at LHC and Precise 1-Loop Low Energy Data", J. Chakrabortty et al, JHEP 1207 (2012) 038
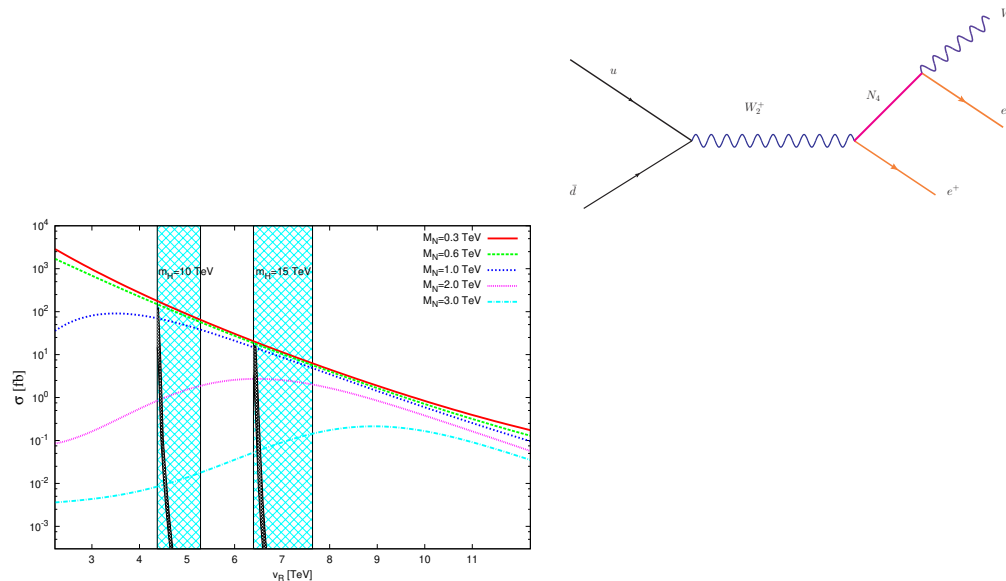
Muon decay constrain parameter space of a model $\frac{G_F}{\sqrt{2}} = \frac{e^2}{8(1-M_W^2/M_Z^2)M_W^2}(1 + \Delta r).$

M. Czakon, J. Gluza, M. Zrałek, Nucl. Phys. **B573** (2000) 57 and
M. Czakon, J. Gluza, J. Hejczyk, Nucl. Phys. **B642** (2002) 157-172.