In quest of Right-Handed Currents [RHC]

W poszukiwaniu niestandardowych cząstek w LHC oraz przyszłych akceleratorach

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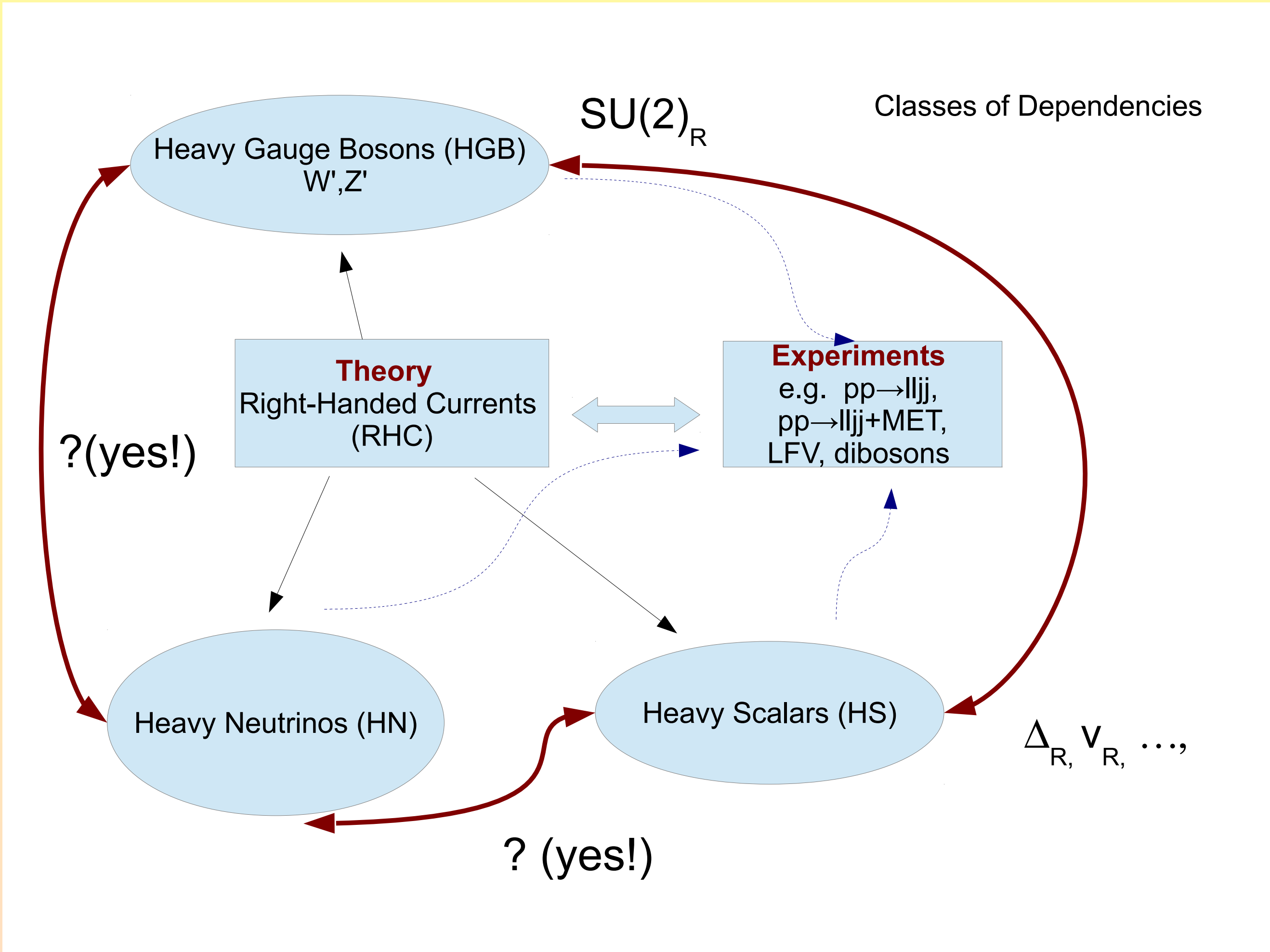
RHC includes plenty of connected issues



LHC-1 excess data

A few deviations from the SM predictions reported by the ATLAS and CMS Collaborations in invariant mass distributions near 2 TeV:

(i) a 3.4σ excess at $\sim$2 TeV in the ATLAS search interpreted as a W' boson decaying into $WZ \to jj$, The mass range with significance above 2σ is ~ 1.9–2.1 TeV; the global significance is 2.5σ - see pdf.

(ii) A CMS search for jj resonances without distinguishing between the W- and Z-tagged jets, a 1.4σ excess at $\sim$1.9 TeV - see pdf

(iii) a 2.8σ excess in the 1.8 – 2.2 TeV bin in the CMS search for a W' and a heavy "right-handed" neutrino, N_R, through the $W' \to N_R\, e \to eejj$ process - see pdf

(iv) a 2.2σ excess in the 1.8 – 1.9 TeV bin in the CMS search for $W' \to Wh^0$, where the SM Higgs boson, h^0, is highly boosted and decays into $b\bar{b}$, while $W \to \ell\nu$ - see pdf

(v) a $\sim 2\sigma$ excess at ~ 1.8 TeV in the CMS dijet resonance search - see pdf. The ATLAS search in the same channel has yielded only a 1σ excess at 1.8 TeV - see pdf

They can be kind of the "edge" effects which will smear out with LHC-2, however...

Theory vs experiment

Three examples:

(i) "Symmetry Restored in Dibosons at the LHC?" Johann Brehmer, JoAnne Hewett, Joachim Kopp, Thomas Rizzo, Jamie Tattersall, see e-Print: arXiv:1507.00013

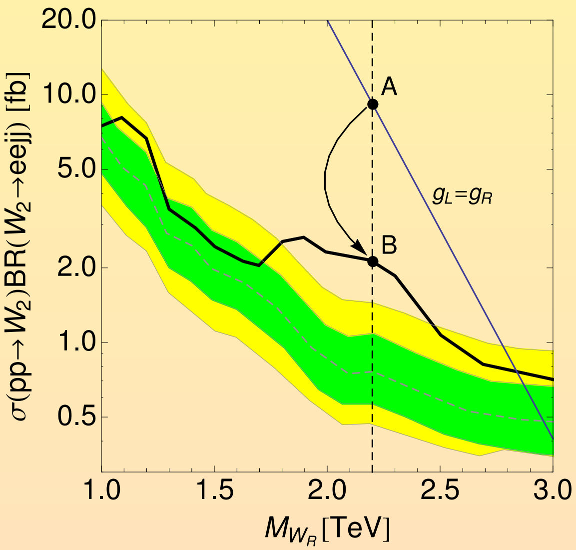
(ii) "Reconciling the 2 TeV Excesses at the LHC in a **Linear Seesaw** Left-Right Model" F. Deppisch, L. Graf, S. Kulkarni, Suchita, S. Patra, W. Rodejohann, N. Sahu, U. Sarkar, see e-Print: arXiv:1508.05940

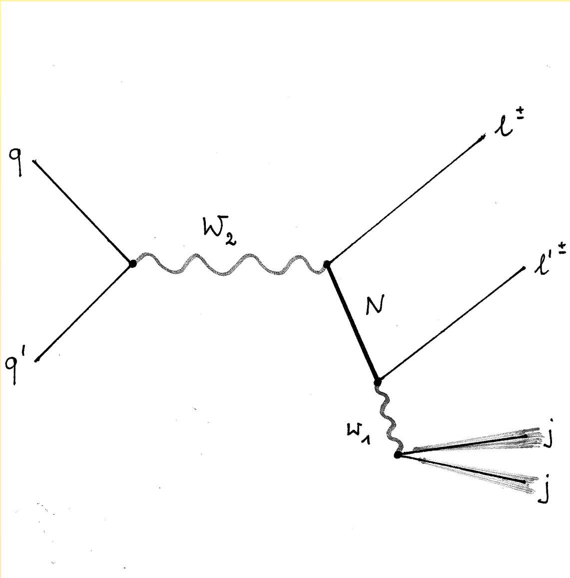
(iii) "Unified explanation of the $eejj$, diboson and dijet resonances at the LHC", P. S. Bhupal Dev,R. N. Mohapatra, see e-Print: arXiv:1508.02277

In (ii) linear seesaw is favorable, in (iii) inverse seesaw is favorable over seesaw I

Our work: first detailed insight into heavy neutrino mass and mixing structures - meaning of interferences

(iv) "Heavy neutrinos and the $pp \to lljj$ CMS data" JG, Tomasz Jeliński, see e-Print: arXiv:1504.05568





CMS: degenerate neutrinos with trivial mixing matrices, $M_N = M_{W_2}/2$,

ATLAS: even more restricted analysis, comment later on

Parity restoration, a lot of theoretical and experimental activity (triggered by LHC)

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

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

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

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

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

The minimal Higgs sector consists of two triplets and one bidoublet

$$\Delta_{L,R} = \begin{pmatrix} \delta^+_{L,R}/\sqrt{2} & \delta^{++}_{L,R} \\ \delta^0_{L,R} & -\delta^+_{L,R}/\sqrt{2} \end{pmatrix},$$

$$\Phi = \begin{pmatrix} \phi^0_1 & \phi^+_1 \\ \phi^-_2 & \phi^0_2 \end{pmatrix}.$$

with vacuum expectation values allowed for the neutral particles

$$\frac{v_L}{\sqrt{2}} = \langle \delta^0_L \rangle,$$

$$\text{new HE scale}: \frac{v_R}{\sqrt{2}} = \langle \delta^0_R \rangle,$$

$$\text{SM VEV scale}: \sqrt{\kappa_1^2 + \kappa_2^2}$$

$$\frac{\kappa_1}{\sqrt{2}} = \langle \phi^0_1 \rangle,$$

$$\frac{\kappa_2}{\sqrt{2}} = \langle \phi^0_2 \rangle.$$

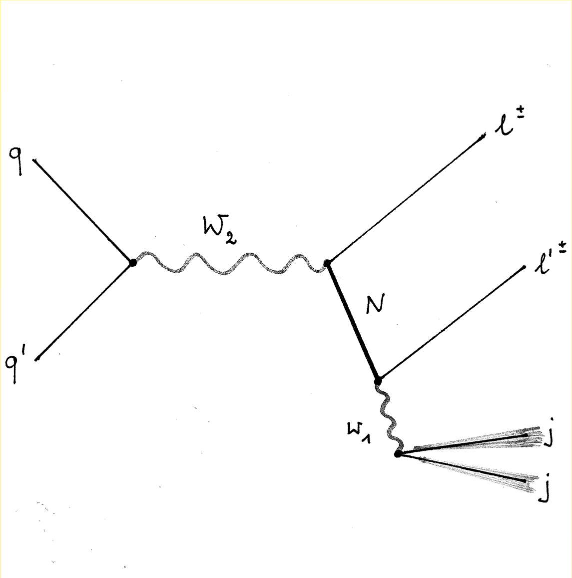
Right-handed currents

$$\mathcal{L} \supset \frac{g_L}{\sqrt{2}}\overline{N}_a\gamma^\mu P_R(K_R)_{aj}l_j W^+_{2\mu} + \text{h.c.}$$

$$M_\nu = \begin{pmatrix} 0 & M_D \\ M_D^T & M_R \end{pmatrix}, \qquad U \approx \begin{pmatrix} 1 & 0 \\ 0 & K_R^\dagger \end{pmatrix},$$

- heavy gauge bosons $Z_2, W_2^\pm$,
  $M_{Z_2} = 0.783 v_R$, $M_{W_2} = 0.461 v_R$.
- heavy neutrinos N_i, $m_{N_i} = \sqrt{2} h_{M_i} v_R$,
- Higgs particles, neutral, charged and doubly charged.
  $\Rightarrow$ one bidoublet and two triplets.
- Right triplet gets VEV: $v_R \Rightarrow$ LR symmetry broken to SM symmetry.
- v_R determines the energy scale. Usually it is assumed to be of order of few TeV.

“Heavy neutrinos and the $pp \to lljj$ CMS data”



Experimental data:

1. Ratio of opposite-sign (OS) $pp \to e^\pm e^\mp jj$ to the same-sign (SS) $pp \to e^\pm e^\pm jj$ leptons as observed is:
$$r = \frac{N_{SS}}{N_{OS}} = \frac{1}{13},$$
2. No excess in the $\mu\mu$ channel
3. Overall excess in lljj production, interpreted by CMS with $g_L = g_R$

e-Print: arXiv:1504.05568

All the above facts can be reconciled with data if non-degenerate heavy neutrinos with CP phases and mixings are taken into account, e.g.

$$M_{N_{1,3}} = 0.925\,\mathrm{TeV}, \quad M_{N_2} = 10\,\mathrm{TeV}, \quad K_R = \begin{pmatrix} \cos\theta_{13} & 0 & \sin\theta_{13} \\ 0 & 1 & 0 \\ -e^{i\phi_3}\sin\theta_{13} & 0 & e^{i\phi_3}\cos\theta_{13} \end{pmatrix}.$$

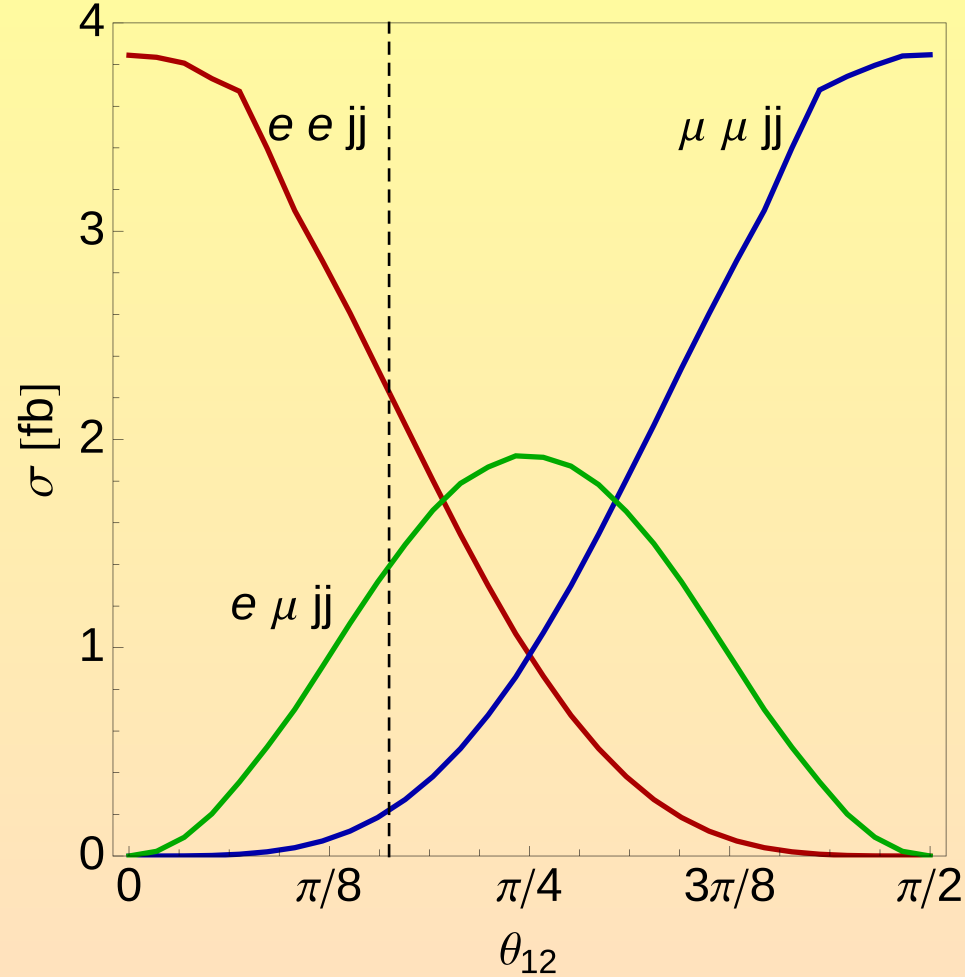
$$\mathcal{L}_{CC} = \frac{g_L}{\sqrt{2}}\overline{N}_a\gamma^\mu P_R(K_R)_{aj} l_j W^+_{2\mu} + \mathrm{h.c.}$$

$$N_e = \cos\theta_{13}N_1 + \sin\theta_{13}N_3 \tag{1}$$

$$N_\mu = N_2 \tag{2}$$

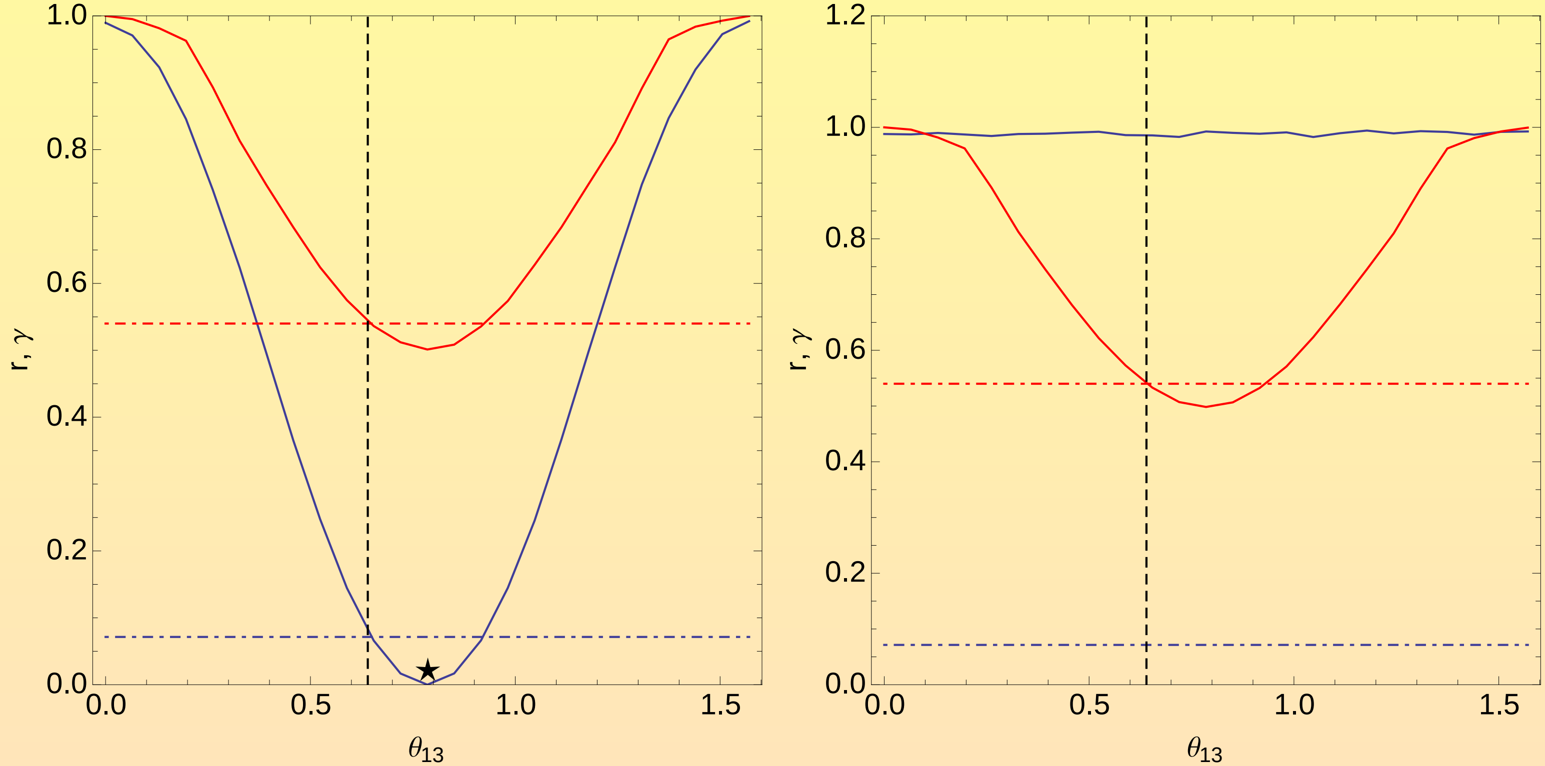
$$N_\tau = -e^{i\phi_3}\sin\theta_{13}N_1 + e^{i\phi_3}\cos\theta_{13}N_3 \tag{3}$$

There is no a problem with $\mu \to e\gamma$ here.



Here example with supressed $\mu\mu jj$ and too big $e\mu jj$.

Effect of mass splitting: $M_1 - M_2$, $r = \frac{1}{13}, \gamma = 0.54$



Kicked Dirac states (pseudo-Dirac, quasi-Dirac,..., phase-Dirac):

$$N_\alpha \quad = \quad \Omega(\cos\theta N_1 + e^{i\phi}\sin\theta N_2)$$

Three comments

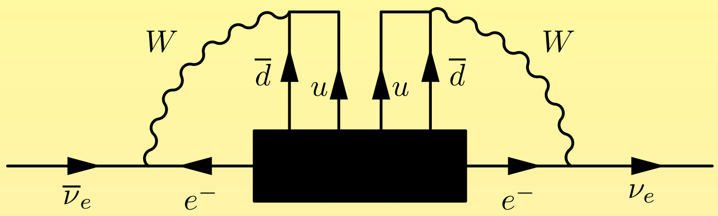
- *For Majorana neutrinos* the same number of SS and OS events is expected,

and

as CMS indicates strongly that $r << 1$,

then

Dirac-type of neutrinos must be involved.



Basically this statement is true, though it can lead to some misinterpretations. However, this logic can be misleading. In principle, that no lepton number violation is observed does not necesserarily mean that Dirac neutrinos are there. Only opposite is true, if lepton number is violated then Majorana neutrinos are there.

In fact, two possibilities (unpublished)

(i) phase-Dirac type of neutrino, compounds of two Majorana degenerate heavy mass states with not maximal mixing and non-trivial CP phase

(ii) non-degenerate heavy Majorana mass states

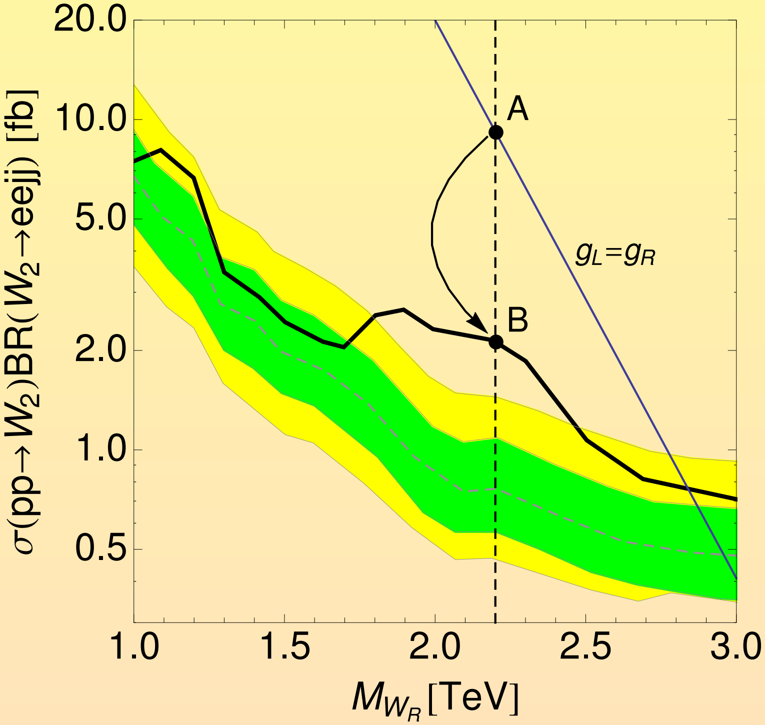
- ATLAS casus

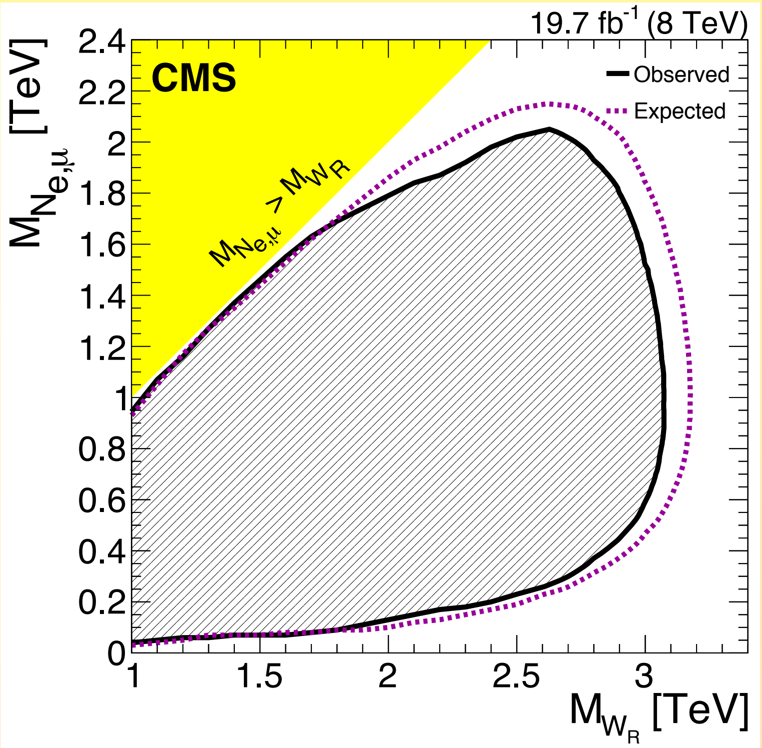
if experimentalists would trust intuition of theoreticians and we assume that heavy Majorana neutrinos exist then to check it experimentally, enough is to find lepton number violating events, in our process these are SS dileptons. However, if no SS signals are found, then possibility that neutrinos are of Dirac type is missed. And this seems to be exactly the ATLAS collaboration case.

see, Dobrescu et al work: “Right-handed neutrinos and the 2 TeV W’ boson”
P. Coloma, B. A. Dobrescu and J. Lopez-Pavon, arXiv:1508.04129

- they assume $r = 0$ and pure Dirac neutrinos

❖ Third remark





Degenerate heavy neutrino masses without neutrino mixings is a very narrow option (leading to simplified exclusion plots).

2012, Polish popular journal

"Father, and what is it, this Higgs boson?"

Mohapatra, Senjanovic (1980); Deshpande, Gunion, Kayser, Olness, 1991

$$
\begin{aligned}
&\mathcal{L}_{Higgs} = \\
&-\mu_1^2 Tr[\Phi^\dagger\Phi] - \mu_2^2(Tr[\tilde{\Phi}\Phi^\dagger] + Tr[\tilde{\Phi}^\dagger\Phi]) - \mu_3^2(Tr[\Delta_L\Delta_L^\dagger] + Tr[\Delta_R\Delta_R^\dagger]) \\
&+\lambda_1 Tr[\Phi\Phi^\dagger]^2 + \lambda_3(Tr[\tilde{\Phi}\Phi^\dagger]Tr[\tilde{\Phi}^\dagger\Phi]) \\
&+\rho_1(Tr[\Delta_L\Delta_L^\dagger]^2 + Tr[\Delta_R\Delta_R^\dagger]^2) \\
&+\rho_2(Tr[\Delta_L\Delta_L]Tr[\Delta_L^\dagger\Delta_L^\dagger] + Tr[\Delta_R\Delta_R]Tr[\Delta_R^\dagger\Delta_R^\dagger]) \\
&+\rho_3(Tr[\Delta_L\Delta_L^\dagger]Tr[\Delta_R\Delta_R^\dagger]) \\
&+\alpha_3(Tr[\Phi\Phi^\dagger\Delta_L\Delta_L^\dagger] + Tr[\Phi^\dagger\Phi\Delta_R\Delta_R^\dagger]) + \ldots
\end{aligned}
$$

invariant under the symmetry $\Delta_L \leftrightarrow \Delta_R, \quad \Phi \leftrightarrow \Phi^\dagger$.

Physical scalars

- 4 neutral scalars: H_0^0, H_1^0, H_2^0, H_3^0,
  (the first can be considered to be the light Higgs of the SM),

- 2 neutral pseudo-scalars: A_1^0, A_2^0,

- 2 charged scalars: $H_1^{\pm}, H_2^{\pm}$,

- 2 doubly-charged scalars: $H_1^{\pm\pm}, H_2^{\pm\pm}$.

This is a complicated model, we consider the simplest, Minimal Left-Right Symmetric model (MLRSM)

AIM of investigations:

- apply low-energy as well as high energy experimental limits on model parameters, plus theoretical consistency
- with these restrictions at hand:
  What kind of signals can we expect at LHC/FCC for charged Higgs particles productions and decays?

Studies including FCC-hh:

- G. Bambhaniya, J. Chakrabortty, J. Gluza, T. Jeliński and R. Szafron,
  "Search for doubly charged Higgs bosons through VBF at the LHC and beyond ,"
  e-Print: arXiv:1504.03999, to appear in PRD.
- G. Bambhaniya, J. Chakrabortty, J. Gluza, T. Jeliński and M. Kordiaczyńska,
  "Lowest limits on the doubly charged Higgs boson masses in the minimal left-right symmetric model,"
  e-Print: arXiv:1408.0774, Phys. Rev. D **90** (2014) 9, 095003

Related studies:

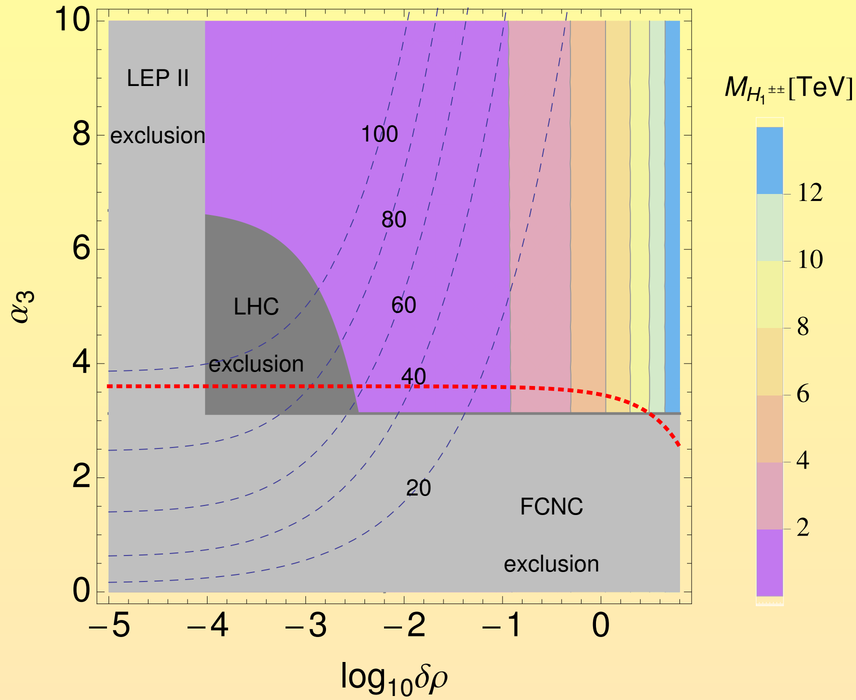
- G. Bambhaniya, J. Chakrabortty, J. Gluza, M. Kordiaczyńska and R. Szafron,
  "Left-Right Symmetry and the Charged Higgs Bosons at the LHC,"
  e-Print: arXiv:1311.4144, JHEP **1405** (2014) 033
- J. Chakrabortty, J. Gluza, R. Sevillano, R. Szafron,
  "Left-Right Symmetry at LHC and Precise 1-Loop Low Energy Data"
  e-Print: arXiv:1204.0736, JHEP **1207** (2012) 038.
- J. Chakrabortty, P. Konar, T. Mondal, "Constraining a class of B-L extended models from vacuum stability and perturbativity"
  e-Print: arXiv:1308.1291, Phys.Rev. D89 (2014) 056014.

Constraints, dependences: theory and experiment

Naturally, $m_H^{\pm,0} \propto v_R$.

❖ 124.7 GeV $< M_{H_0^0} < 126.2$ GeV

$$
\begin{aligned}
M^2_{H_0^0} &\simeq 2\kappa_+^2\lambda_1 - \frac{\alpha_1^2}{2\rho_1}, \\
M^2_{H_1^0}(FCNC) &\simeq \frac{1}{2}\alpha_3 v_R^2 && FCNC > 10 \text{ TeV}, \\
M^2_{H_2^0} &\simeq 2\rho_1 v_R^2 \\
M^2_{H_1^\pm}(LHC) &= \frac{1}{2}v_R^2\delta\rho + \frac{1}{4}\alpha_3\kappa_+^2, && (\delta\rho = \rho_3 - 2\rho_1) \\
M^2_{H_1^{\pm\pm}}(LHC) &= \frac{1}{2}\left[v_R^2\delta\rho + \alpha_3\kappa_+^2\right], \\
M^2_{H_2^{\pm\pm}}(LHC) &= 2\rho_2 v_R^2 + \frac{1}{2}\alpha_3\kappa_+^2. && LHC < 1 \text{ TeV}
\end{aligned}
$$



masses (in GeV)

$M_{H_0^0} = 125,$

$M_{H_1^0} = 10431, \quad M_{H_2^0} = 27011, \quad M_{H_3^0} = 384$

$M_{A_1^0} = 10437, \quad M_{A_2^0} = 384$

$M_{H_1^\pm} = 446, \quad M_{H_2^\pm} = 10433$

$M_{H_1^{\pm\pm}} = 500, \quad M_{H_2^{\pm\pm}} = 500$

parameters

$\lambda_1 = 0.13, \quad \lambda_3 = 1$

$\alpha_3 = 3.4$

$\rho_1 = 5.7, \quad \rho_2 = 1.15 \times 10^{-3}, \quad \rho_3 = 11.40$

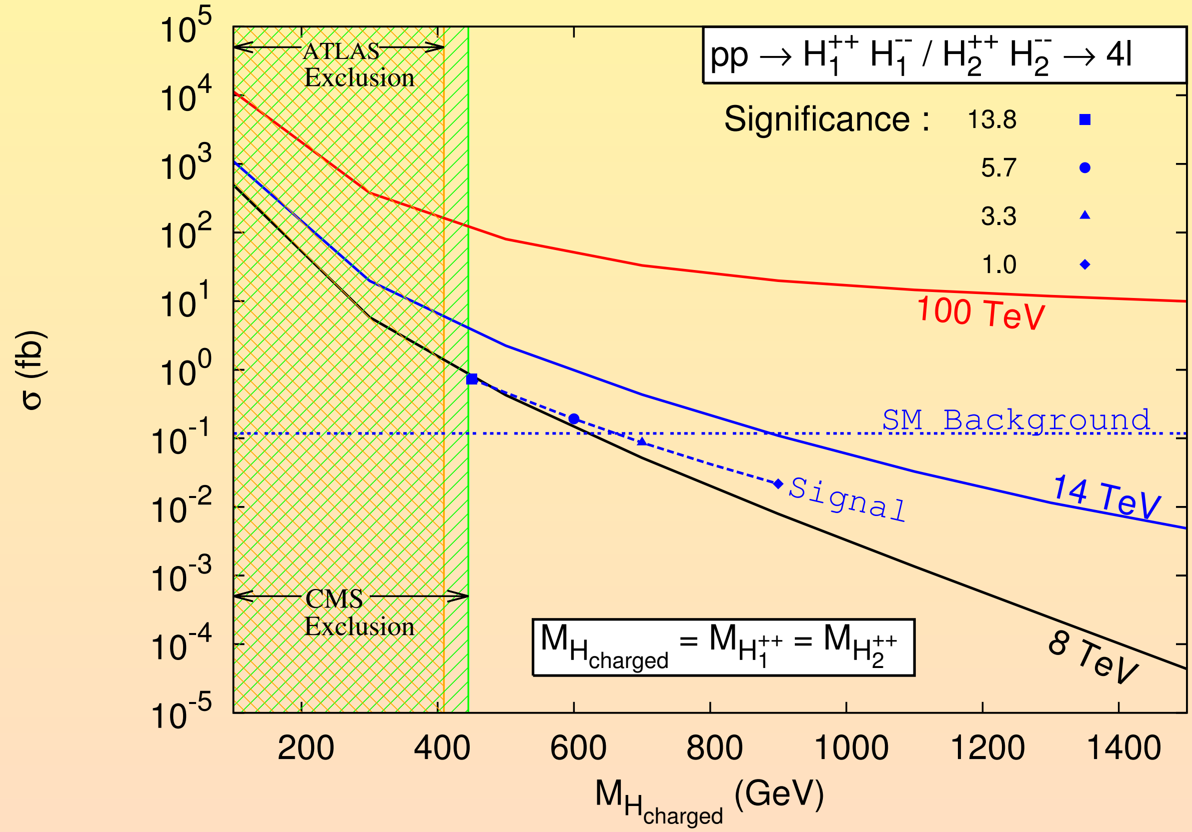
Conclusions:

- only region <u>below</u> the red dotted line is allowed. That line corresponds to the the stability condition.
- $M_{H_1^{\pm\pm}} - M_{H_1^\pm} < M_{W_1^\pm}$, hence on-shell $H_1^{\pm\pm}$ cannot decay to $H_1^\pm$ and $W_1^\pm$

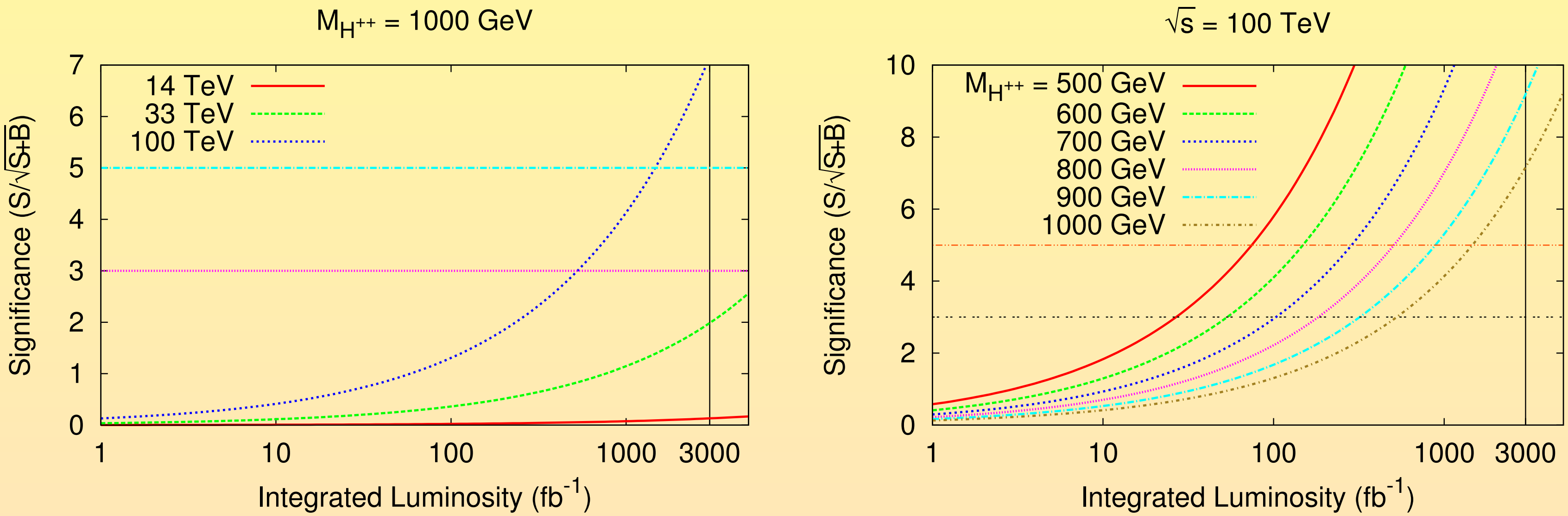
Doubly charged Higgses production (Drell-Yan)

$$m_{H_{1,2}^{\pm\pm}} = 600 \text{ GeV} :$$

$$\sigma(pp \to H_{1,2}^{++} H_{1,2}^{--} \to l_i{}^+ l_i{}^+ l_j{}^- l_j{}^-) \quad = \quad 0.144(0.9498)\ fb \text{ for } \sqrt{s} = 8(14) \text{ TeV}.$$



Doubly charged Higgs bosons production (Vector Boson Fusion with 2 jets)



- Left: 1 TeV doubly charged scalar can be probed with a significance of 5 only with 100 the TeV collider with luminosity at least 1000 fb^{-1}
- Right: significance at the level of 7 can be reached for $M_{H^{\pm\pm}} = 1\,\mathrm{TeV}$ and $\sqrt{s} = 100$ TeV with integrated luminosities around 3000 fb^{-1}.

Summary

- We are in an exciting moment, there is still a lot of place at LHC on many potential discoveries, including GUT models, and additional scalar particles
- Discovery of doubly charged Higgs particles would be something incredibly new and would define new directions in physics (e.g. issue of supersymmetry)
- FCC-hh opens up a very wide range of Higgs boson masses which can be explored.

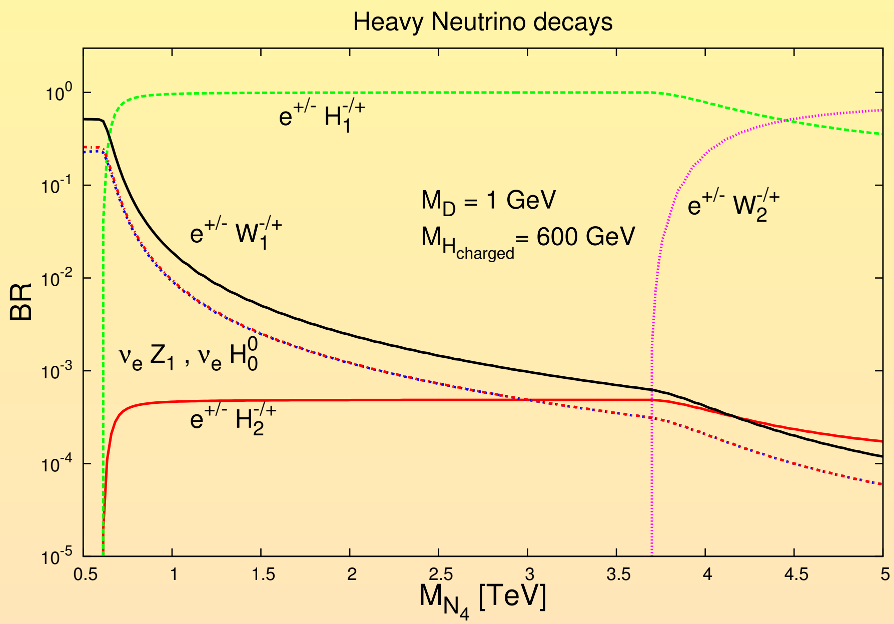
Further plans (~ 2 years):

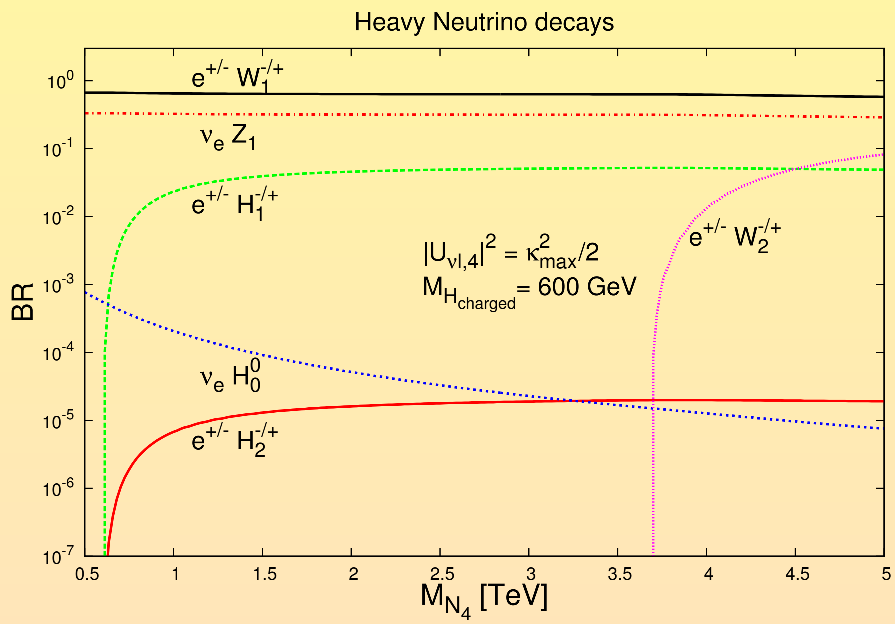
- finding mass benchmarks and branching ratios for Higgs bosons within various scenarios containing triplet scalar fields, taking into account correlations between model parameters and constraints coming from low energy processes
- investigating production and decay processes at FCC-hh, FCC-eh, FCC-ee with a focus on phenomenology of doubly charged Higgs bosons
- investigating possible ways to discriminate among different models with Higgs triplet particles

Backup slides

Decays scenarios

Lowering Higgs mass spectrum below 1 TeV influences decay channels.

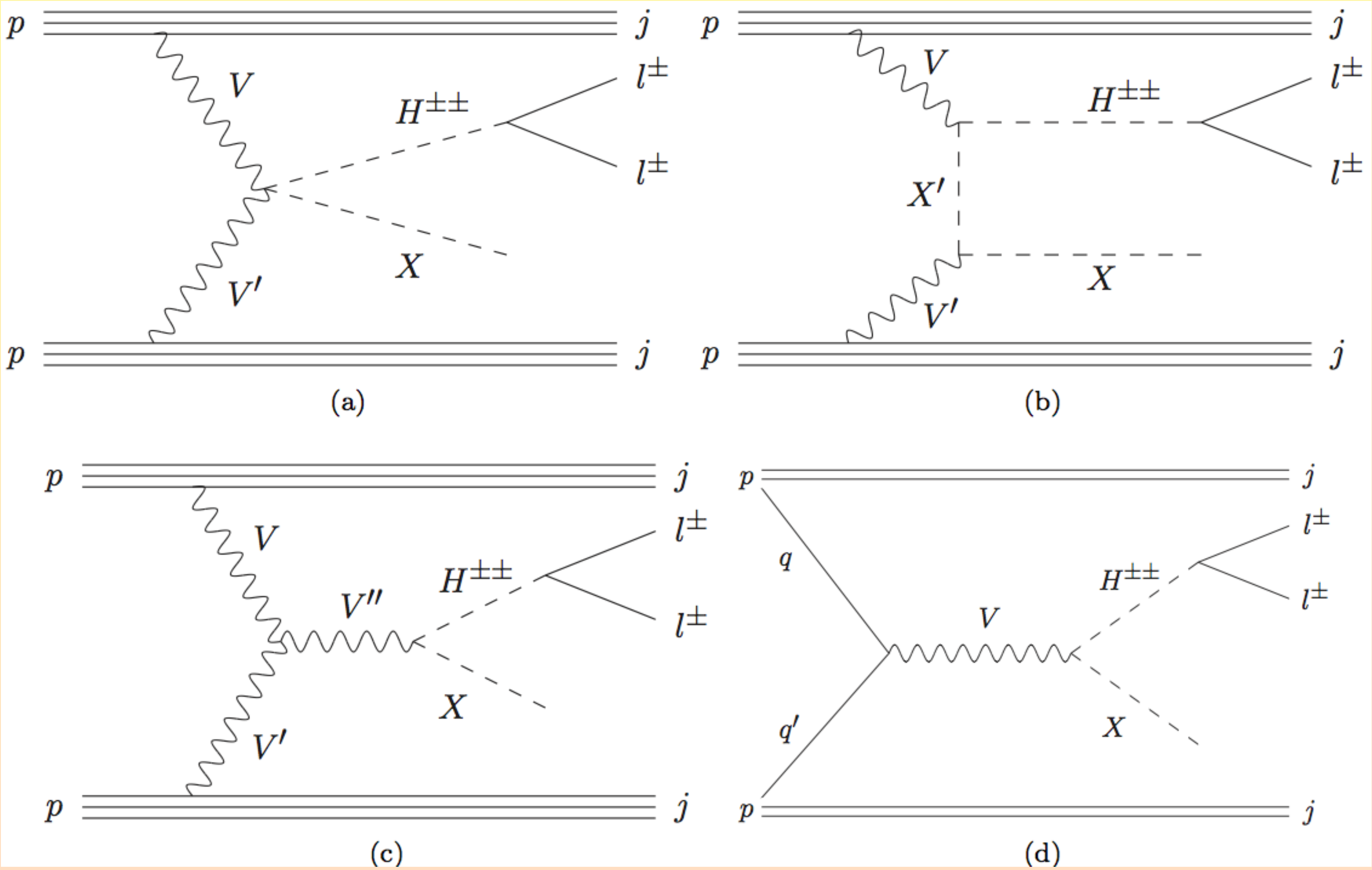




Kinematic cuts for H^{++} studies

- 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 is 0.7 (70%);
  - ♢ For muon (either μ^- or μ^+) detector efficiency is 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.

Vector Boson Fusion with 2 jets



Inverse see-saw

Dev, Mohapatra:

In the original inverse seesaw proposal, the lepton number violation is small, being directly proportional to the light neutrino masses.

the generalized inverse seesaw neutrino mass matrix in the flavor basis $\{\nu^C, N, S^C\}$ is given by

$$\mathcal{M} = \begin{pmatrix} 0 & M_D & 0 \\ M_D^\mathsf{T} & \mu_R & M_N^\mathsf{T} \\ 0 & M_N & \mu_S \end{pmatrix}$$

$$M_{N_{1,2}} \simeq \frac{1}{2}\left[\mu_R \pm \sqrt{\mu_R^2 + 4M_N^2}\right] ,$$

For $\mu_R \ll M_N$, $N_{1,2}$ - pseudo-Dirac pair

For $\mu_R \gg M_N$, N_1 - purely Majorana with $M_{N_1} = \mu_R$

Thus, for intermediate values of μ_R, we can have scenarios with varying degree of lepton number breaking.