Searching left-right (super)symmetry at the LHC

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This talk should answer the questions

- What is left-right symmetry?
- How do you build a left-right symmetric model?
- What are the new particles that could potentially be discovered?
- How can you find them at the LHC?

What is left-right symmetry?

- The basic idea of left-right (LR) symmetry is that parity is a symmetry of Nature, which is spontaneously broken in weak interactions (Pati, Salam PRD10 (1974) 275; Mohapatra, Pati PRD11 (1975) 566)
- The gauge group must be extended to include right-handed weak interactions
- The generalization of electric charge is $Q = I_{3L} + I_{3R} + (B - L)/2$
- The gauge group of left-right symmetric models is $SU(3)_c \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$
- The gauge group of left-right symmetry can come *e.g.* from the breaking of SO(10)

Left-right symmetry solves a number of problems

A number of the problems of the Standard Model are solved in a natural way by LR symmetry:

- parity violation has a dynamical origin
- LR symmetry requires right-handed neutrinos implying that neutrino masses are natural in LR models
- since you may impose parity, the QCD θ-term is absent at tree-level and is generated only at two loops thus offering a solution of the strong CP problem without the axion

The supersymmetric version has also some advantages to MSSM:

- due to the $B - L$ symmetry, we do not need to impose R-parity by hand to avoid proton decay
- there are quite many possible dark matter candidates, especially the right-handed sneutrino
- the tree-level Higgs mass bound is $\sqrt{2}m_W$ instead of m_Z

Right-handed matter is in doublets

We shall now start building the model. I shall describe only the mainstream cases, there are lots of variants on the market.

- It is a very well established experimental fact that left-handed quarks and leptons form doublets of $SU(2)_L$
- Left-right symmetry then implies that we should have also right-handed doublets for quarks and leptons
- This requires new particles, right-handed neutrinos
- A bare mass term for ν_R is forbidden — it violates $U(1)_{B-L}$ — so implementing a seesaw mechanism is not straightforward

The Higgs sector is very different from the SM

- As left-handed matter is in doublets of $SU(2)_L$ and right-handed matter in doublets of $SU(2)_R$, the Higgs field that give mass to fermions must be a bidoublet $(2, 2)$ of $SU(2)_L \times SU(2)_R$
- After EWSB the LR models have two CP-even, one CP-odd and a charged Higgs with Yukawa couplings to fermions — like 2HDM
- If both of the neutral components have VEVs, there is a mixing between W_L and W_R, which is known to be small, hence the second neutral Higgs is (nearly) inert
- In addition you need something to break left-right symmetry, the most common solutions are $SU(2)_R$ triplet scalars with $B - L = -2$ (LR symmetry then requires a triplet of $SU(2)_L$ scalars, too) or $SU(2)_R$ doublets with $B - L = -1$
- The triplet solution allows a more straightforward implementation of neutrino masses (mass for ν_R from the triplet, then type-I), the doublet solution needs the inverse seesaw mechanism

The supersymmetric version can have a light doubly charged Higgs

The SUSY version of left-right symmetry has the following features:

- You need a second bidoublet to generate the correct mass pattern for fermions (the charge-conjugated field cannot be used), both of these should have an inert neutral component
- Due to two bidoublets you have several nearly degenerate higgsinos (4 neutral + 2 charged)
- The triplets should have $B - L = \pm 2$ to avoid gauge anomalies
- A singlet is necessary to allow a high enough scale for LR breaking
- With triplets, the lighter right-handed doubly charged Higgs mass is exactly zero in the gaugeless limit, mass comes essentially from loops (or nonrenormalizable terms) and hence is somewhat small

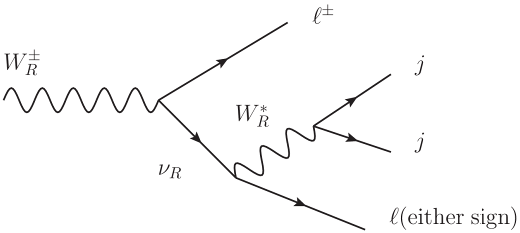
Left-right symmetry might be discovered in many ways

The new particles include:

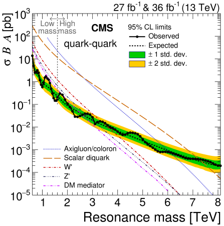
- New, heavy gauge bosons
- Right-handed neutrinos
- Neutral or charged Higgs bosons coupling to SM fermions
- $SU(2)_R$ breaking sector: neutral, charged or even doubly charged Higgses
- In the SUSY version also the superpartners of all of these

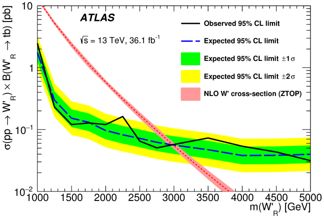
It is easier to find the W_R

- The new gauge bosons include a right-handed charged $W_R^{\pm}$ and a neutral Z', which is a mixture of W_R^0, W_L^0 and B_{B-L}
- The Z' is always a lot heavier than $W_R^{\pm}$ so the production cross section is lower, in addition $Z' \to \ell^+\ell^-$ suppressed compared to a Z'_{SSM}
- There are two certain decay modes for the W_R, dijet (always largest BR) and $hW_L^{\pm}$ (BR at 1–2%), others depend on the spectrum
- If RH neutrinos are lighter than W_R, the decay leads to $\ell\ell jj$ in both opposite-sign and same-sign dilepton channels (Keung, Senjanovic PRL50 (1983) 1427)



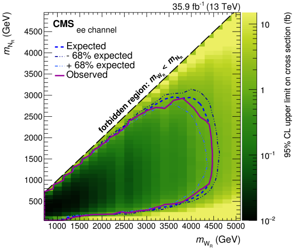
Dijet searches give a robust bound

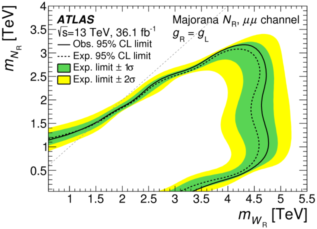




- Dijet searches usually given in terms of W'_{SSM}, which assumes that $g_R = g_L$, all $W_R \to \ell\nu_R$ modes are kinematically allowed and no decay modes to Higgs+gauge bosons or superpartners are allowed (but *e.g.* ATLAS $W_R \to tb$ analysis assumes leptonic modes are absent)
- If leptonic decay modes are forbidden, the bound of 3.4/3.6 TeV becomes ~ 4 TeV, additional decay modes may allow masses of ~ 3 TeV
- Jets originating from a multi-TeV particle are highly boosted, so even tops are single fat jets, background from standard QCD/$t\bar{t}$

Leptonic bounds are more stringent but depend on RH neutrino mass

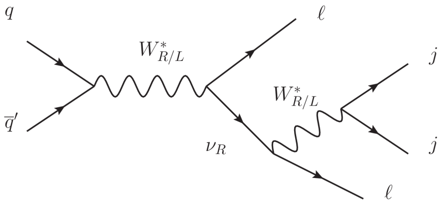




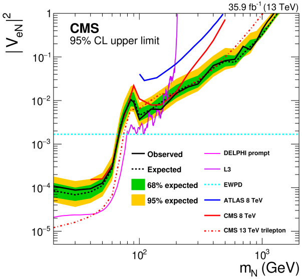
- The $\ell\ell jj$ signature has less SM background than the dijet searches, especially with same-sign leptons
- If $m(\nu_R) > m(W_R)$ for one or all generations, the decay mode is either suppressed or absent
- On the other hand if ν_R is light, the ℓjj get boosted within a rather narrow cone so the second lepton will not pass the isolation criterion $\Rightarrow$ not possible to exclude the full parameter space

Right-handed neutrino production is highly suppressed

- Although the RH neutrinos are not gauge singlets, their couplings with SM gauge bosons vanish in the limit, where there is no mixing between ν_L/ν_R, W_L/W_R and Z/Z' (the gauge group breaks to $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$)
- The RH neutrinos can be possibly found in the $\ell\ell jj$ channel through the nonresonant W_R portal (suppressed by m_{W_R}) or the W_L portal (suppressed by ν_L–ν_R mixing)
- The $Z' \to \nu_R \nu_R \to 2\ell + 4j$ portal less sensitive due to the higher Z' mass



The limits on left-right neutrino mixing are weak



- LHC has not been able to exceed LEP limits at low RH neutrino masses
- At higher masses the limits are very weak, in general one would expect mixing to be of the order $m^2_{W_L}/m^2_{W_R}$ or less so essentially these measurements do not constrain the parameter space of LR models

The bidoublet Higgs phenomenology is a special case of 2HDM

We write the bidoublet Higgs in the standard 2×2 form

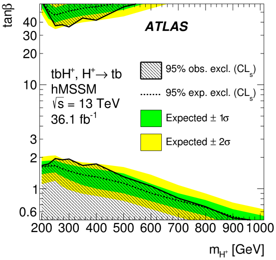
$$\Phi = \begin{pmatrix} \phi_1^0 & \phi_2^+ \\ \phi_1^- & \phi_2^0 \end{pmatrix} \to \begin{pmatrix} v/\sqrt{2} & 0 \\ 0 & v' e^{i\alpha}/\sqrt{2} \end{pmatrix}, \quad \text{need}: \quad v \gg v' \simeq 0$$

and the Yukawa couplings as

$$\mathcal{L} = \overline{Q}_{L,i}^T (F_{ij}\Phi + G_{ij}\Phi^c) Q_{R,j} + \overline{L}_{L,i}^T (f_{ij}\Phi + g_{ij}\Phi^c) L_{R,j} + \text{h.c.}$$

- The heavier neutral Higgses couple to quarks with the "wrong" Yukawa couplings, *i.e.* to the bottom quark with the top Yukawa and vice versa
- The charged Higgs couplings to quarks are $(m_u - m_d)/2 + \gamma^5 (m_u + m_d)/2$
- This would be identical to 2HDM in the alignment limit with $\tan\beta = 1$
- If there are two bidoublets like in SUSY, the low-energy phenomenology is similar to MSSM with general $\tan\beta$, usually the rest of the states are heavier

Heavy Higgs searches are sensitive to the one-bidoublet model

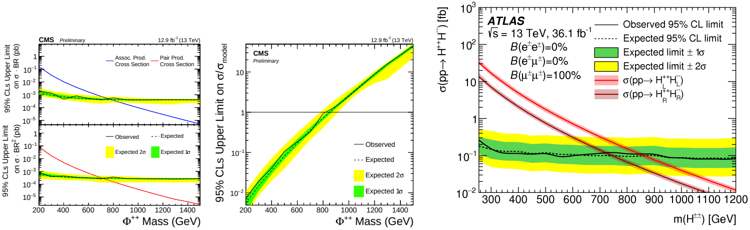


- The searches for heavy Higgses constrain the one-bidoublet version to the decoupling regime, $m_{H,A,H^\pm} \gtrsim 700$ GeV
- On the other hand this was expected as the smallness of FCNC requires the other states of the same bidoublet to be heavier
- In models with two bidoublets the usual constraints for 2HDM apply so also lighter BSM Higgses may be around

The triplet model has doubly charged Higgses

- If LR symmetry is broken with triplets, the most striking feature are the doubly charged Higgses $H^{\pm\pm}$
- The usual VEV hierarchy is $v_L \ll v \ll v_R$ so that the left-handed triplet is nearly inert so $H^{\pm\pm} \to W^\pm W^\pm$ is practically absent and the only decay mode is to same-sign leptons
- Production usually in pairs through Drell-Yan process, also associated production with a singly charged triplet Higgs is possible (the light doubly charged Higgs in SUSY an exception)
- Production cross sections of left- and right-handed doubly charged Higgses differ, for RH $H^{\pm\pm}$ a suppression of roughly 50%
- Branching ratios correlated to neutrino mass pattern — $H_R^{\pm\pm}$ decays dominantly to the flavor of the heaviest RH neutrino

Light doubly charged Higgs bosons excluded — a challenge for minimal left-right SUSY

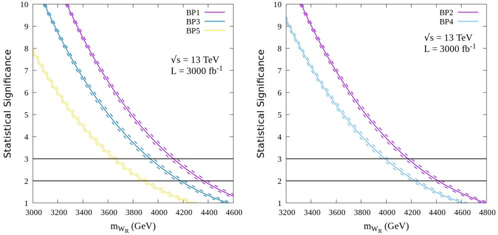


- If the doubly charged Higgs decays solely to electrons or muons the bounds are $\mathcal{O}(600)$ GeV or better, for taus 396 GeV for $H_L^{\pm\pm}$, around 300 GeV for $H_R^{\pm\pm}$, but branching ratio bounds to electron and muon final states still strong
- The SUSY version has a light doubly charged Higgs, this excludes quite a lot of the available parameter space

Dark matter constraints make superpartner searches difficult

- There are basically three categories of dark matter candidates: gauginos, higgsinos and right-handed sneutrinos
- Assuming a single sub-TeV dark matter component we have a mostly bino-like gaugino at $\sim m_h/2$, a set of degenerate bidoublet higgsinos close to 700 GeV or a RH sneutrino above 250 GeV — the lower end of the last one being at the border of direct detection limits
- For all candidates mono-X searches or direct chargino-neutralino production are not sensitive, the Higgs invisible decay width might be with a future collider (would be $\sim 0.5\%$)

Multilepton + high MET searches are sensitive to W_R decays to superpartners



- It seems that the best chances of producing superpartners is through the decays of W_R, the branching ratio to bidoublet higgsinos is $4/3$ times that to leptons (usually $\sim 20\%$)
- In general we expect a large amount of MET and especially in the case of a sneutrino LSP, leptons in the final state
- The dark matter candidate has an impact on the flavor content — sneutrino LSP tends to result in leptons of a single flavor, while gauginos are flavor blind

Summary

- Left-right symmetric models are based on $SU(3)_C \times SU(2)_L \times SU(2)_R \times U(1)_{B-L}$ and the spontaneous breaking of parity
- Even the minimal version requires a rather large particle content, some of which might be accessible at the LHC
- The LHC has pushed the LR breaking scale up to several TeV's

References/further reading

Experimental searches:
W_R: 1703.09127 (ATLAS/jj), 1801.07893 (ATLAS/tb), 1806.00843 (CMS/jj), 1803.11116 (CMS/lljj), 1809.11105 (ATLAS/lljj)
ν_R: 1806.10905 (CMS/nonresonant)
$H^{\pm\pm}$: CMS-PAS-HIG-16-036 (CMS), 1710.09748 (ATLAS)
Model building/phenomenology:
Alternative models: hep-ph/0301041 (no bidoublets), PRD36 (1987) 878 (inverse seesaw)
SUSY models: hep-ph/9306290, hep-ph/9511391, hep-ph/9703434, 0807.0481
Higgs: hep-ph/0107121, 1602.05947 (without SUSY), 1408.2423, 1412.8714 (SUSY)
CP violation: hep-ph/9511391, hep-ph/9604445
Dark matter: 1702.02112, 1810.03891