

LHC phenomenology of general $SU(2) \times SU(2) \times U(1)$ models

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24th of April 2012

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[arXiv:1203.5314v1 \[hep-ph\]](https://arxiv.org/abs/1203.5314v1)



Definition and motivation

- $SU(2) \times SU(2) \times U(1)$ are models with extended gauge group
- additional $SU(2)$:
 $SU(2)_L \times U(1)_Y \rightarrow \text{SU}(2)_1 \times \text{SU}(2)_2 \times U(1)_X \equiv G(221)$
- $SU(2)$ appear in $SO(10)$, E_6 breaking or string theory compactifications
- bottom-up:
 - ▶ extended gauge group is a viable extension of the SM
 - ▶ additional $SU(2)$ is next-to-minimal
- I will argue that $G(221)$ models are:
 - ▶ simple
 - ▶ reachable
 - ▶ distinguishable

Symmetry breaking patterns

- we need to break $SU(2)_1 \times SU(2)_2 \times U(1)_X \rightarrow U(1)_{\text{em}}$
- pattern I: left-right, fermio-, lepto- and hadro-phobic
 - ▶ $SU(2)_1 \equiv SU(2)_L$ and $SU(2)_2 \times U(1)_X \rightarrow U(1)_Y$
 - ★ doublet: $\Phi \sim (1, 2, \frac{1}{2})$, $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \textcolor{violet}{u} \end{pmatrix}$
 - ★ triplet: $\Phi \sim (1, 3, 1)$ $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ \textcolor{violet}{u} & 0 \end{pmatrix}$
 - ▶ $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$
 - ★ $H \sim (2, \bar{2}, 0)$, $\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \textcolor{violet}{v} \cos \beta & 0 \\ 0 & \textcolor{violet}{v} \sin \beta \end{pmatrix}$
- pattern II: un-unified, non-universal
 - ▶ $SU(2)_1 \times SU(2)_2 \rightarrow SU(2)_L$ and $U(1)_X \equiv U(1)_Y$
 - ★ $\Phi \sim (2, \bar{2}, 0)$, $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} \textcolor{violet}{u} & 0 \\ 0 & \textcolor{violet}{u} \end{pmatrix}$
 - ▶ $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$
 - ★ $H \sim (1, 2, \frac{1}{2})$, $\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \textcolor{violet}{v} \end{pmatrix}$

Un-unified (UU) and Non-universal (NU) models

- breaking pattern I, 2 free parameters $\{\tan \varphi \equiv g_2/g_1, x \equiv u^2/v^2\}$
- transformation properties of SM fermions:

Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
UU	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	Y_{SM} for all fermions.
NU	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1^{st}, 2^{nd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1^{st}, 2^{nd}}$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3^{rd}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3^{rd}}$	Y_{SM} for all fermions.

- couplings:
 - UU: if $C_L^{W'}(q) = x$ then $C_L^{W'}(l) \approx -1/x$, $C_R^{W'} = 0$, $C_R^{Z'} \approx 0$
 - NU: if $C_L^{W'}(1^{st}, 2^{nd}) = x$ then $C_L^{W'}(3^{rd}) \approx -1/x$, $C_R^{W'} = 0$, $C_R^{Z'} \approx 0$
- masses: $M_{Z'}^2/M_{W'}^2 = 1 + \mathcal{O}(1/x)$
- observable in: $\ell^+ \ell^-$, $\ell^\pm \nu$, $t\bar{t}$ and $t\bar{b}$

Left-right (LR) and Hadro-phobic (HP) models

- breaking pattern II, 3 free parameters $\{\tan \varphi \equiv g_X/g_2, x \equiv u^2/v^2, \sin 2\beta\}$
- two realizations of the breaking pattern: -D, -T
- transformation properties of SM fermions:

Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
LR	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, $-\frac{1}{2}$ for leptons.
HP	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix}$	Y_{SM} for quarks, $-\frac{1}{2}$ for leptons.

- couplings:
 - ▶ LR: $C_L^{W'} \approx 0; C_{L(R)}^{Z'} \text{ sizeable}$
 - ▶ HP: $C_L^{W'} \approx 0, C_R^{W'}(q) = 0; C_{L(R)}^{Z'} \text{ sizeable}$
- masses: $M_{Z'}^2/M_{W'}^2 > 1$, up to ~ 10 (-D), ~ 14 (-T)
- observable in: $\ell^+ \ell^-$, $t\bar{t}$, $t\bar{b}$ and possibly $\ell^\pm \nu$ (not studied)



Lepto-phobic (LP) and Fermio-phobic (FP) models

- breaking pattern II, 3 free parameters $\{\tan \varphi \equiv g_X/g_2, x \equiv u^2/v^2, \sin 2\beta\}$
- two realizations of the breaking pattern: -D, -T
- transformation properties of SM fermions:

Model	$SU(2)_1$	$SU(2)_2$	$U(1)_X$
LP	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}$	$\frac{1}{6}$ for quarks, y_{SM} for leptons.
FP	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}$		y_{SM} for all fermions.

- couplings:
 - ▶ LP: $C_L^{W'} \approx 0, C_R^{W'}(l) = 0; C_{L(R)}^{Z'}$ sizeable
 - ▶ FP: $C_L^{W'} \approx 0, C_R^{W'}(q) = C_R^{W'}(l) = 0; C_{L(R)}^{Z'}$ sizeable
- masses: $M_{Z'}^2/M_{W'}^2 > 1$, up to ~ 10 (-D), ~ 14 (-T)
- observable in: $\ell^+ \ell^-$, $t\bar{t}$, $t\bar{b}$ but not in $\ell^\pm \nu$

Exclusion limits from EWPO

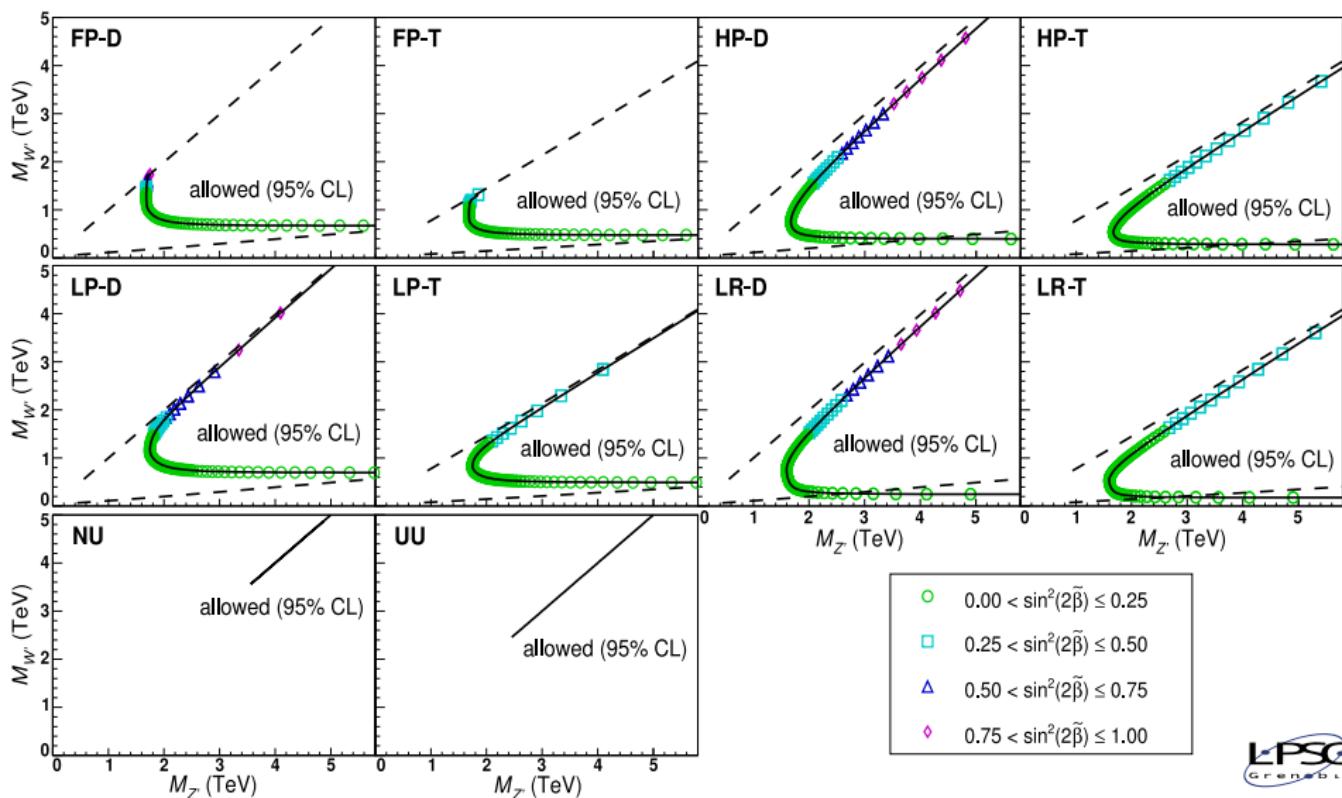
Procedure

- theoretical assumptions:
 - ▶ generation-diagonal and perturbative gauge couplings (smaller than $\sqrt{4\pi}$)
 - ▶ minimal (doublet, triplet or bidoublet) Higgs sector with VEV hierarchy
 $u \gg v$
 - ▶ negligible influence of additional fermions required for anomaly cancellation (UU)
- 2/3 free parameters fit to 37 observables, the most important being:
 - ▶ total hadronic cross section at Z pole
 - ▶ b-quark forward-backward asymmetry
 - ▶ neutrino-nucleno deep inelastic scattering cross section
 - ▶ parity-violating weak charge of Caesium 133
- low-energy constraints requiring information on the flavor structure, like $\text{BR}(b \rightarrow s\gamma)$, voluntarily omitted
- for more information see: K. Hsieh, K. Schmitz, J. -H. Yu and C. -P. Yuan, Phys. Rev. D **82**, 035011 (2010)



Exclusion limits from EWPO

Exclusion limits in the $M_{W'}$, $M_{Z'}$ plane



LHC phenomenology

Goal and simulation setup

- goal:

- study cross sections of $\ell^+ \ell^-$, $\ell^\pm \nu$, $t\bar{t}$ and $t\bar{b}$ production
- investigate cross section correlations

- assumptions:

- after the 2013-2014 shutdown: $\sqrt{s} = 14 \text{ TeV}$, $L = 10 - 100 \text{ fb}^{-1}$
- $V_R = V_{\text{CKM}}$

- simulation details:

- Pythia 6.4 supplemented by W/W' interference
- standard ATLAS cuts, no detector simulation
- cut on $M_{I(T)}$ close to the mass of the new heavy gauge boson (see next slide)

- NLO effects:

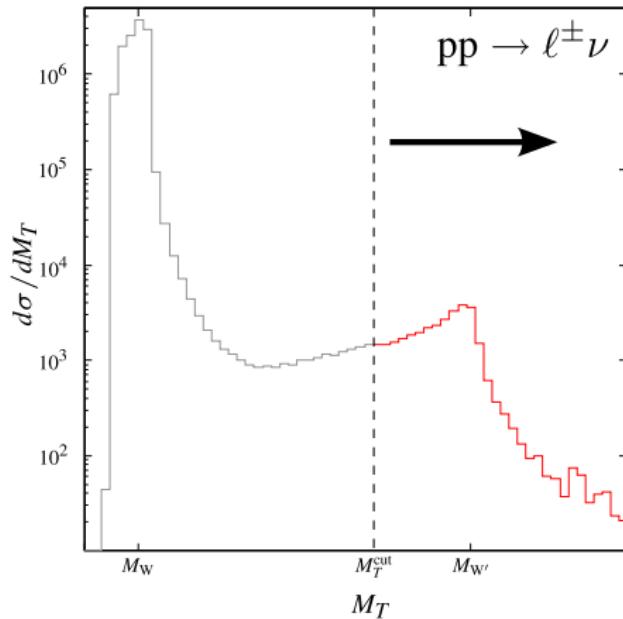
- NLO QCD available only for leptonic final states, not used for consistency
- K-factors modest ($\sim 30\%$) and largely model-independent



LHC phenomenology

Cross section calculation

- we calculate cross sections of $\ell^+\ell^-$, $\ell^\pm\nu$, $t\bar{t}$ and $t\bar{b}$ channels:

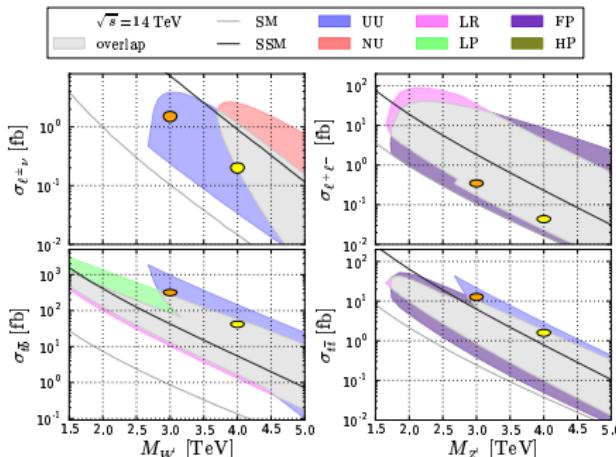


- we reconstruct:
 - M_I for $\ell^+\ell^-$, $t\bar{t}$ and $t\bar{b}$
$$M_I = \sqrt{p_3^2 + p_4^2}$$
 - M_T for $\ell^\pm\nu$
$$M_T = \sqrt{p_{T_W}^2 + M_W^2}$$
- $$\sigma = \int_{M_{I(T)}^{\text{cut}}} \frac{d\sigma}{dM_{I(T)}}$$
where $M_{I(T)}^{\text{cut}} = 0.75M_{W'}$

LHC phenomenology

Cross sections

- cross sections are evaluated for all the allowed values of free parameters

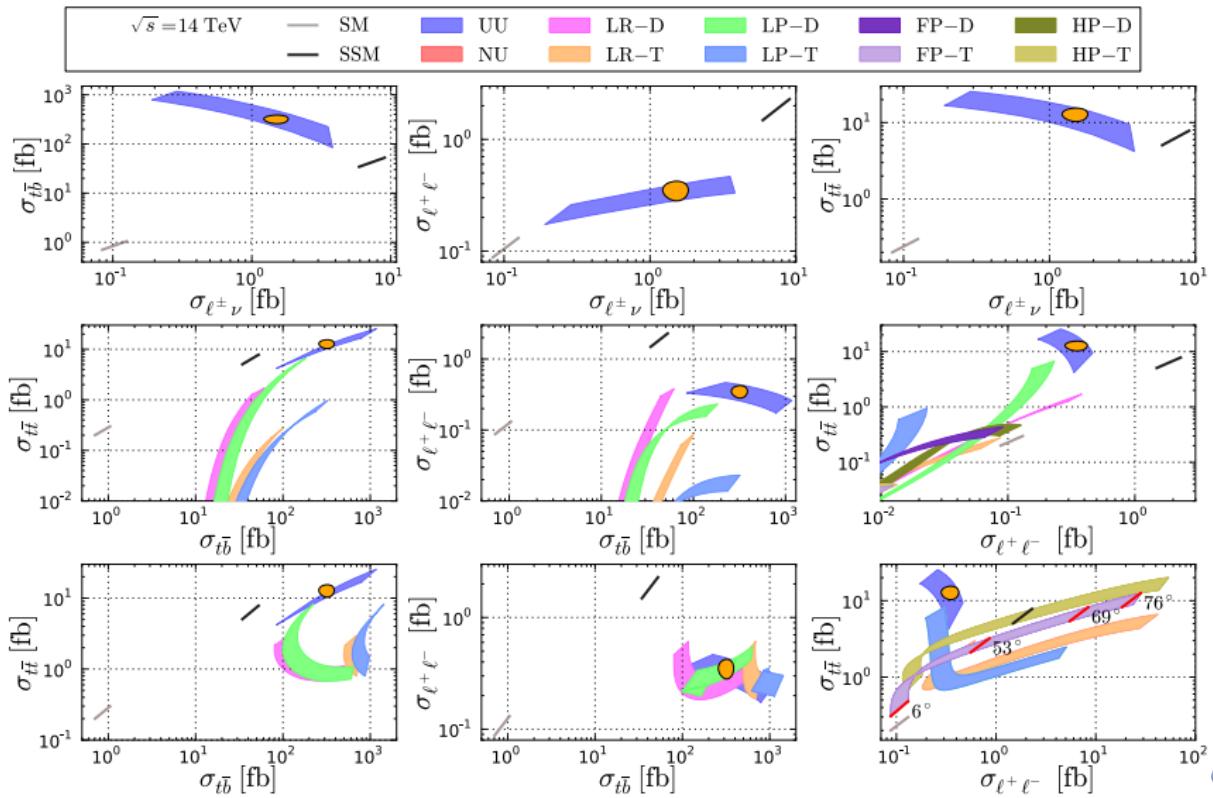


- gray area \equiv overlap of any two regions
- doublet (-D) and triplet (-T) models grouped
- ellipses: realizations of UU model for $M_{W'(Z')} = 3, 4 \text{ TeV}$
- measurement errors: mass $\pm 0.1 \text{ TeV}$, $\sigma \pm 20\%$

- cross sections accessible at LHC for masses up to 5 TeV
- large overlaps between different models

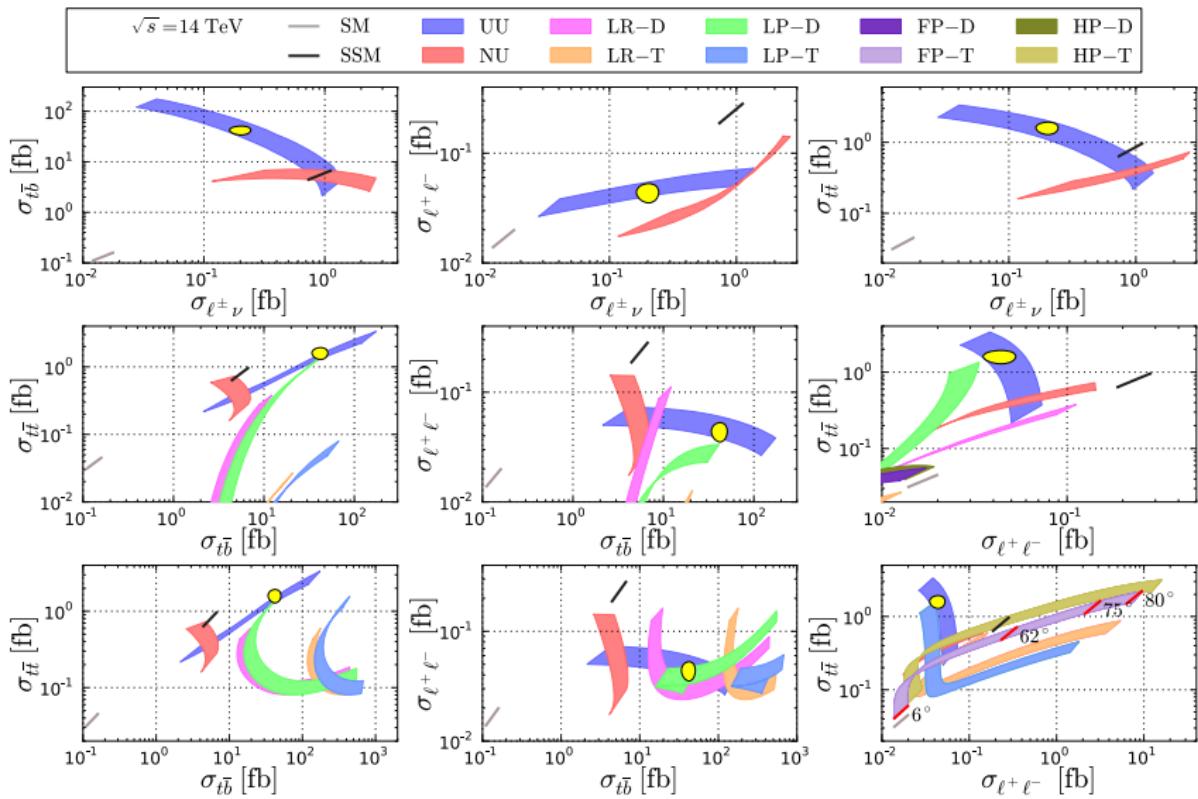
LHC phenomenology

Cross section correlation for $M_{W'} = 3 \pm 0.1$ TeV or $M_{Z'} = 3 \pm 0.1$ TeV



LHC phenomenology

Cross section correlation for $M_{W'} = 4 \pm 0.1$ TeV or $M_{Z'} = 4 \pm 0.1$ TeV



Conclusions and outlook

- **G(221)** models provide good candidates for SM extensions
 - ▶ *simple*: models with 2-3 free parameters
 - ▶ *easily observable*: W' , Z' in resonant s-channel production of $\ell^+\ell^-$, $t\bar{t}$, $t\bar{b}$, $\ell^\pm\nu$
 - ▶ *reachable*: at $\sqrt{s} = 14$ TeV, $L = 100 \text{ fb}^{-1}$ masses up to 5 TeV will be probed
 - ▶ *distinguishable*: **correlations** of cross sections may well lead to a unique identification
- possible extensions
 - ▶ other observables: asymmetries, interference, widths
 - ▶ NLO QCD corrections to hadronic final state
- other experiments
 - ▶ phenomenology of **G(221)** in UHE neutrino interactions in the atmosphere at Pierre Auger Observatory with *F. Lyonnet, F. Montanet and M. Tartare* – coming soon!

Mass measurement error

- it is sufficient to measure mass in one channel
- we verified that the statistical error is below 0.1 TeV

$$\Delta M \approx \Gamma / \sqrt{\sigma L}$$

- resolution:

- ▶ e^+e^- : current $\sim 2\text{-}3\%$, goal $< 2\%$
- ▶ $t\bar{t}$: current $\sim 6\%$ (in boosted regime, c.f. talk of A. Hinzmann), goal ?
- ▶ $t\bar{b}$: a little better than $t\bar{t}$
- ▶ $e^\pm\nu$: worse than e^+e^- , better than $t\bar{t}$ and $t\bar{b}$



LHC phenomenology

Cross section correlation for $M_{W'} = 3 \pm 0.2$ TeV or $M_{Z'} = 3 \pm 0.2$ TeV

