

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

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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  $SU(2)$ :  
 $SU(2)_L \times U(1)_Y \rightarrow SU(2)_1 \times SU(2)_2 \times U(1)_X \equiv G(221)$
- new gauge bosons:  $W'$ ,  $Z'$
- $SU(2)$  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
- LHC phenomenology: simple, reachable, distinguishable

# Introduction

SM	G(221)												
$\begin{array}{c} \text{SU}(2)_L \\ \times \\ \text{U}(1)_Y \end{array}$	$\rightarrow$	$W^1, W^2, W^3,$	$\rightarrow$	$W^\pm, Z, \gamma$	$\rightarrow$	$\begin{array}{c} \text{SU}(2)_1 \\ \times \\ \text{SU}(2)_2 \\ \times \\ \text{U}(1)_X \end{array}$	$\rightarrow$	$W_1^1, W_1^2, W_1^3,$	$\rightarrow$	$W_2^1, W_2^2, W_2^3,$	$\rightarrow$	$\begin{array}{c} W^\pm, Z, \gamma, \\ W'^\pm, Z' \end{array}$	$X$

- @LHC:  $pp \rightarrow \gamma/Z/\text{Z}' \rightarrow \ell^+\ell^-$ ,  $pp \rightarrow W/\text{W}' \rightarrow \ell^\pm\nu$
- realizations of G(221):
  - ▶ transformation properties, e.g.:

$$\begin{array}{ccc} \text{SM} & & \text{Model } \in \text{G(221)} \\ \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (2, Y) & \begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (2, 1, X) & \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1, 2, X) \\ Q = T^3 + Y/2 & & Q = T_1^3 + T_2^3 + X/2 \end{array}$$

- ▶ breaking pattern

# 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

- ▶  $SU(2)_1 \times SU(2)_2 \rightarrow SU(2)_L$  and  $U(1)_X \equiv U(1)_Y$ 
  - ★  $\Phi \sim (2, \bar{2}, 0)$ ,  $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} u & 0 \\ 0 & u \end{pmatrix}$
- ▶  $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$ 
  - ★  $H \sim (1, 2, \frac{1}{2})$ ,  $\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$

- pattern II

- ▶  $SU(2)_1 \equiv SU(2)_L$  and  $SU(2)_2 \times U(1)_X \rightarrow U(1)_Y$ 
  - ★ doublet:  $\Phi \sim (1, 2, \frac{1}{2})$ ,  $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ u \end{pmatrix}$
  - ★ triplet:  $\Phi \sim (1, 3, 1)$   $\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 & 0 \\ u & 0 \end{pmatrix}$
- ▶  $SU(2)_L \times U(1)_Y \rightarrow U(1)_{\text{em}}$ 
  - ★  $H \sim (2, \bar{2}, 0)$ ,  $\langle H \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} v \cos \beta & 0 \\ 0 & v \sin \beta \end{pmatrix}$

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

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

Model

UU	$\begin{pmatrix} u_L \\ d_L \end{pmatrix} \sim (2, 1, X)$	$\begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (1, 2, X)$
NU	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{1^{\text{st}}, 2^{\text{nd}}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{1^{\text{st}}, 2^{\text{nd}}} \sim (2, 1, X)$	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}_{3^{\text{rd}}}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}_{3^{\text{rd}}} \sim (1, 2, X)$

- 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  $C_L^{W'}(1^{\text{st}}, 2^{\text{nd}}) = x$  then  $C_L^{W'}(3^{\text{rd}}) \approx -1/x$ ,  $C_R^{W'} = 0$ ,  $C_R^{Z'} \approx 0$
- 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

- pattern II, three 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

LR	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (2, 1, X)$	$\begin{pmatrix} u_R \\ d_R \end{pmatrix}, \begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \sim (1, 2, X)$
HP	$\begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (2, 1, X)$	$\begin{pmatrix} \nu_R \\ e_R \end{pmatrix} \sim (1, 2, X)$

- 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  $\sim 10$  (-D),  $\sim 14$  (-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

- pattern II, three 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

$$\begin{array}{ll} \text{LP} & \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (2, 1, X) \quad \begin{pmatrix} u_R \\ d_R \end{pmatrix} \sim (1, 2, X) \\ \text{FP} & \begin{pmatrix} u_L \\ d_L \end{pmatrix}, \begin{pmatrix} \nu_L \\ e_L \end{pmatrix} \sim (2, 1, X) \end{array}$$

- 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  $\sim 10$  (-D),  $\sim 14$  (-T)
- observable in:  $\ell^+ \ell^-$ ,  $t\bar{t}$ ,  $t\bar{b}$  but not in  $\ell^\pm \nu$



# Sequential Standard Model (SSM) – not a G(221) model

- benchmark model often used in experimental searches
- $W'$  and  $Z'$  couple to SM fermions as  $W$  and  $Z$
- $M_{Z'}/W'$  free parameters
- we assume  $M_{Z'} = M_{W'}$

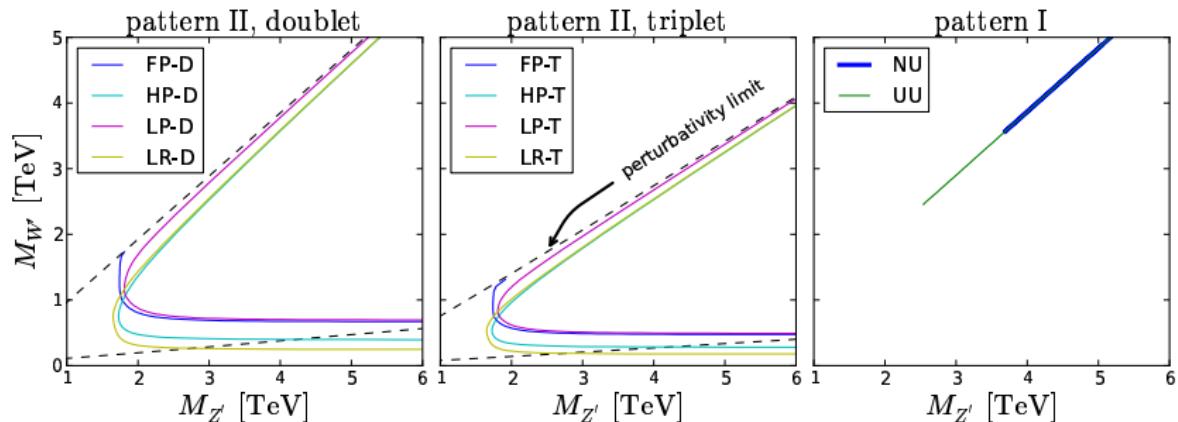
# Exclusion limits from EWPO

## Procedure

- K. Hsieh, K. Schmitz, J. -H. Yu and C. -P. Yuan, Phys. Rev. D **82**, 035011 (2010)
- 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  $\text{BR}(\text{b} \rightarrow \text{s}\gamma)$ , voluntarily omitted

# Exclusion limits from EWPO

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



pattern II: LR  $\equiv$  Left-Right, LP  $\equiv$  Lepto-Phobic, HP  $\equiv$  Hadro-Phobic, FP  $\equiv$  Fermio-Phobic | -D  $\equiv$  doublet, -T  $\equiv$  triplet

pattern I: NU  $\equiv$  Non-Universal, UU  $\equiv$  Un-unified

- pattern I:  $M_{W'}/Z'$  excluded below  $\sim 2.5$  ( $\sim 3.6$ ) TeV for UU (NU)
- pattern II:  $M_{W'} \sim 200$  GeV,  $M_{Z'} \sim 1.7$  GeV

# LHC phenomenology

## Goal and simulation setup

- goal:

- ▶ cross sections of  $\ell^+\ell^-$ ,  $\ell^\pm\nu$ ,  $t\bar{t}$  and  $t\bar{b}$  production @ LO
  - ★ investigate the LHC reach
  - ★ possibility to distinguish among G(221) models

- 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

- note about NLO:

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



# LHC phenomenology

## Observable

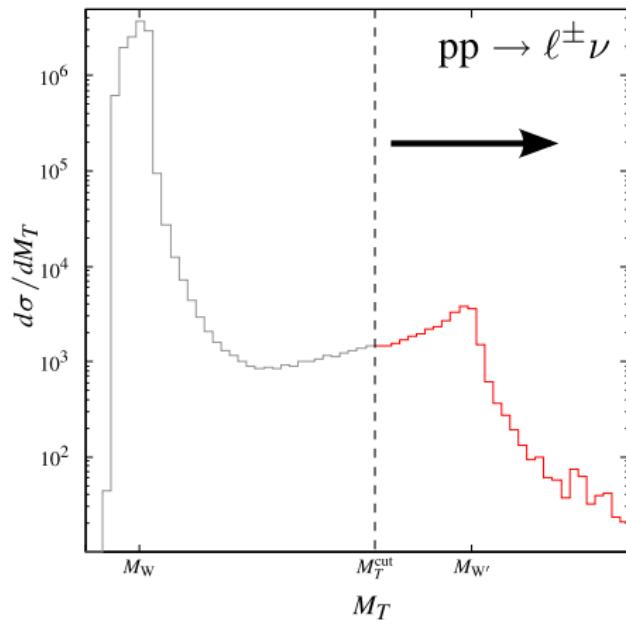
- observable:  $\sigma = \int_{M_{I(T)}^{\text{cut}}} \frac{d\sigma}{dM_{I(T)}}$  where  $M_{I(T)}^{\text{cut}} = 0.75M_{Z'(\text{W}')}}$

- $M_I$  for  $\ell^+\ell^-$ ,  $t\bar{t}$  and  $t\bar{b}$

$$M_I = \sqrt{p_3^2 + p_4^2}$$

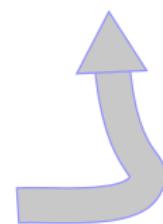
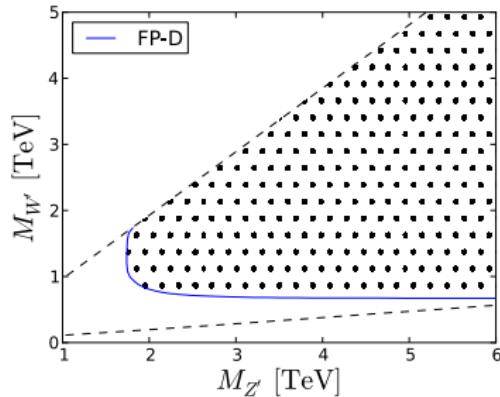
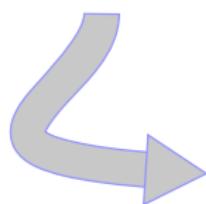
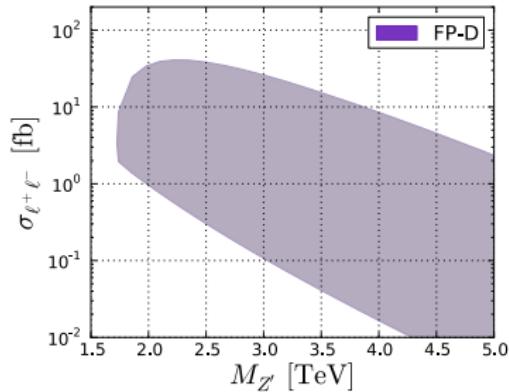
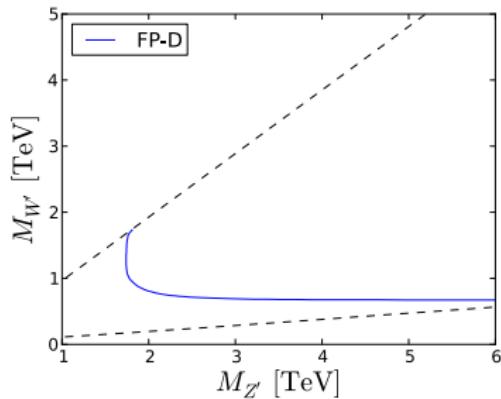
- $M_T$  for  $\ell^\pm\nu$

$$M_T = \sqrt{p_{T_W}^2 + M_W^2}$$



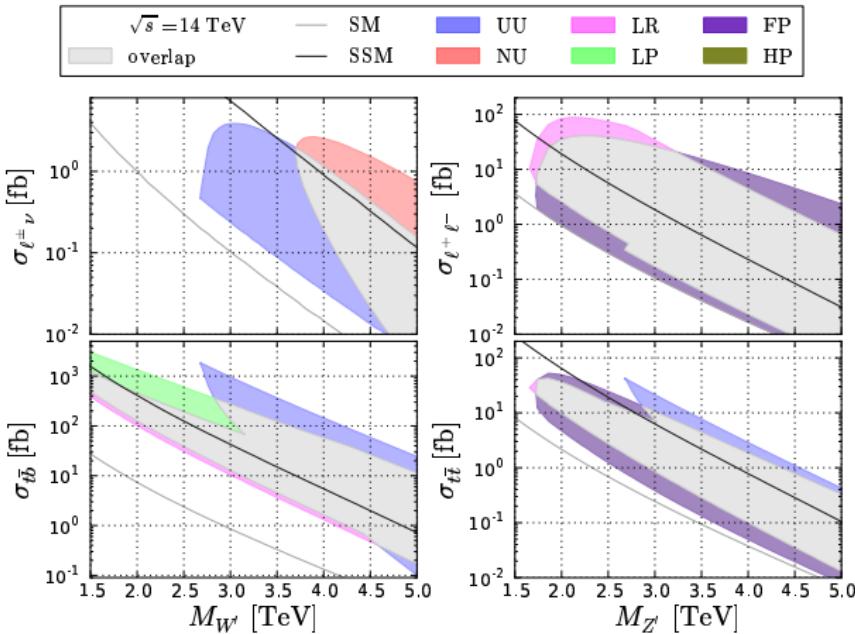
# LHC phenomenology

From exclusion limits to cross section regions



# LHC phenomenology

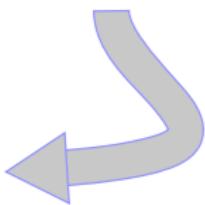
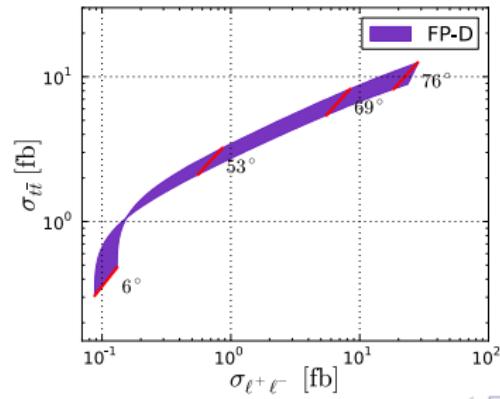
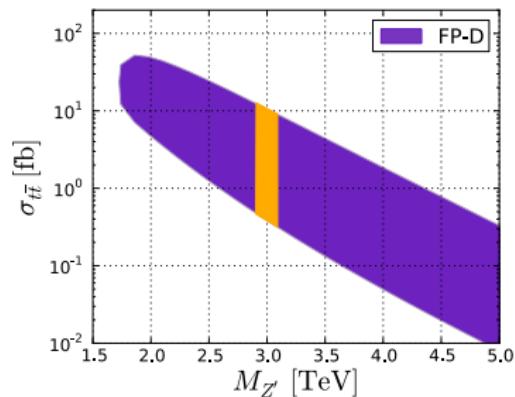
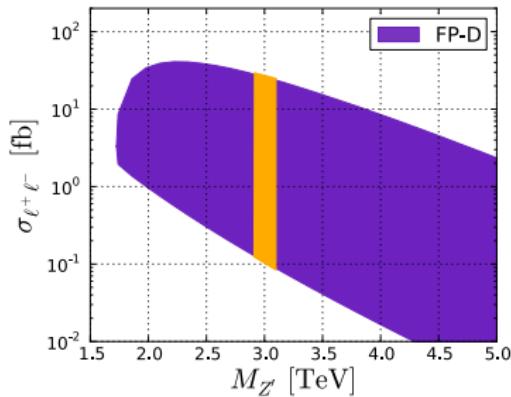
## Cross section regions



- **G(221)** accessible @LHC for masses up to 5 TeV
- difficult to distinguish among **G(221)**

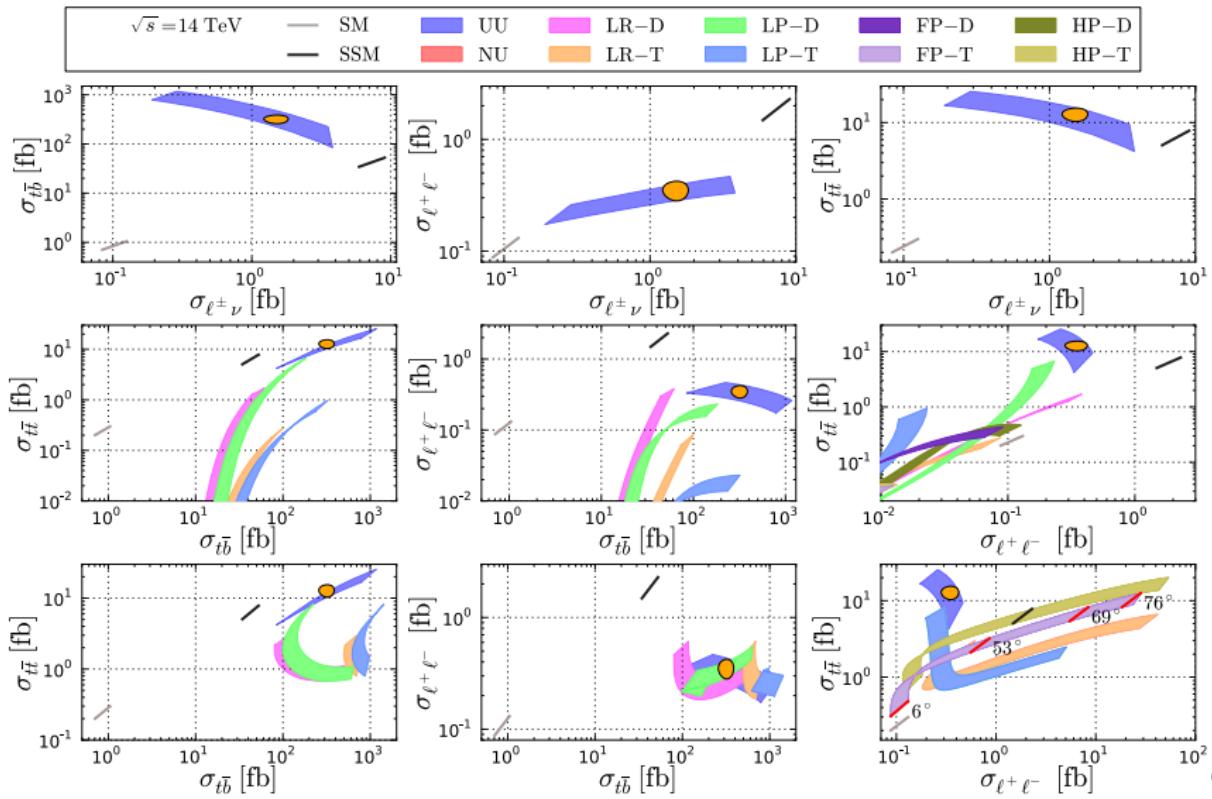
# LHC phenomenology

From cross section regions to correlations



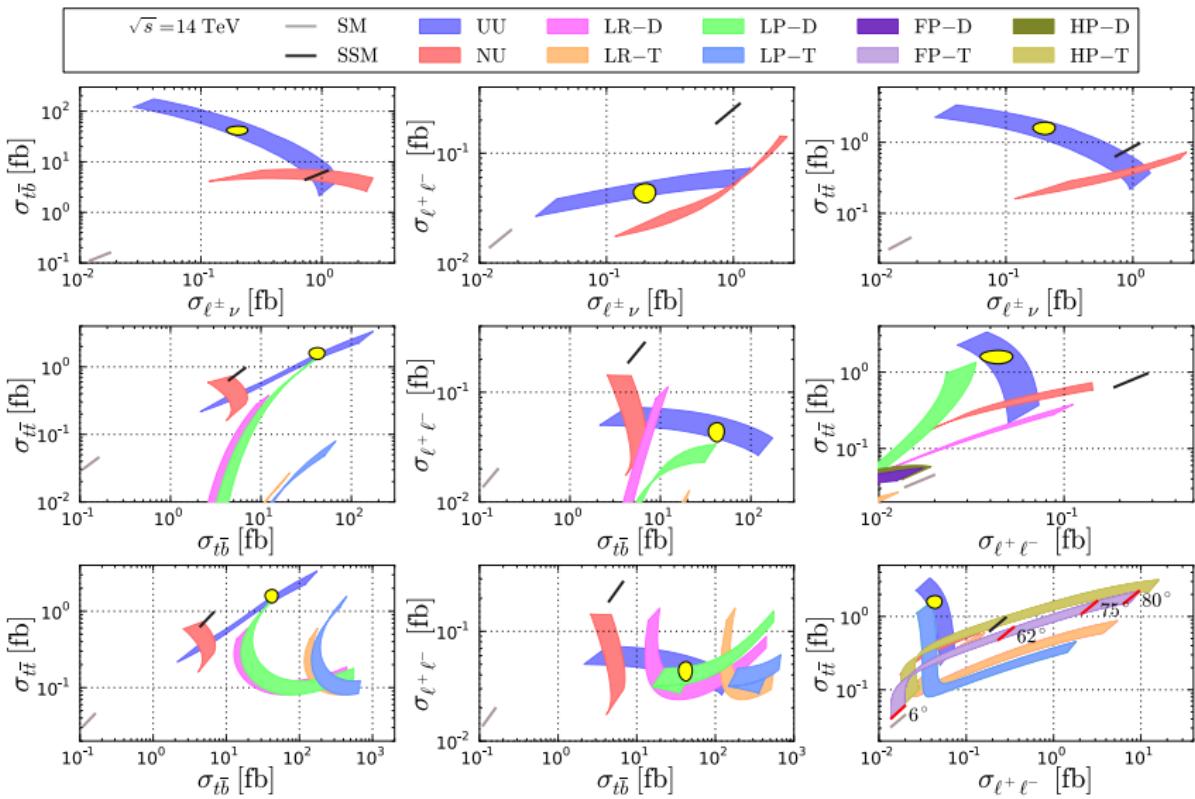
# LHC phenomenology

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



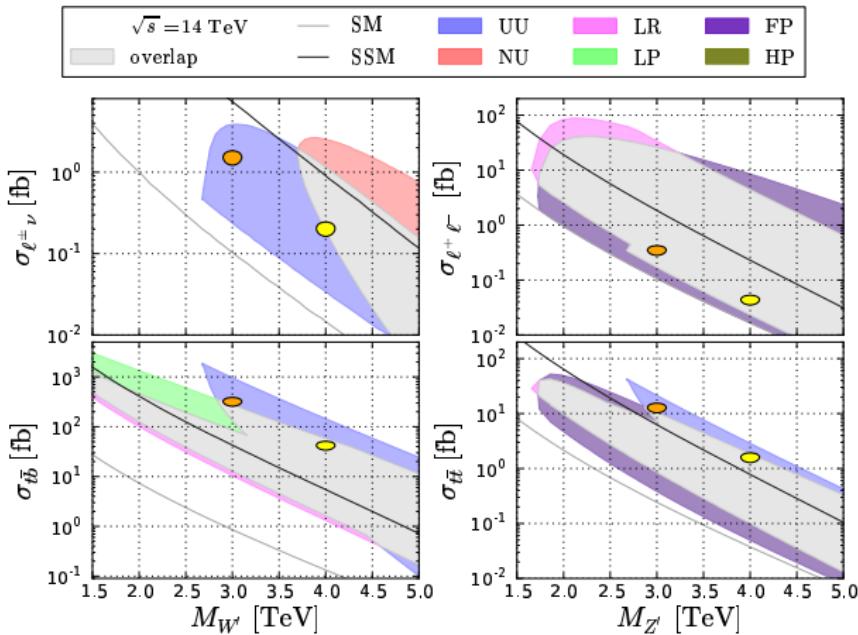
# LHC phenomenology

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



# LHC phenomenology

## Cross section regions



# 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
- future plans
  - ▶ 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!

# 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)



# 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

