# Phenomenology of the 3-3-1 Models

Work in progress with
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# Outline

# Introduction

## The Original 3-3-1 Model: Motivation

Gauge symmetry group: $SU(3)_C \times SU(3)_L \times U(1)_X$

$$Q_1 = \begin{pmatrix} u_L \\ d_L \\ D_L \end{pmatrix} \quad Q_2 = \begin{pmatrix} c_L \\ s_L \\ S_L \end{pmatrix} \quad Q_3 = \begin{pmatrix} b_L \\ t_L \\ T_L \end{pmatrix}$$

$$Q_{1,2} \in (3, 3, -1/3) \quad Q_3 \in (3, \bar{3}, 2/3)$$

$$\ell = \begin{pmatrix} \ell_L \\ \nu_\ell \\ \bar{\ell}_R \end{pmatrix} \quad \ell \in (1, \bar{3}, 0) \quad (\ell = e,\ \mu,\ \tau)$$

Cancellation of the $SU(3)_L$ anomaly:

$$+9(Q_1) + 9(Q_2) - 9(Q_3) + (-3 \times 3)(L_i) = 0 \qquad \Longrightarrow \qquad N_C = N_F$$

P. H. Frampton, Phys.Rev.Lett. 69 (1992) 2889-2891
Singer, Valle and Schechter, Phys.Rev. D22 (1980) 738
Pisano and Pleitez, Phys.Rev. D46 (1992) 410-417

# Outline

# The 3-3-1 Model

Scalars:

$$\chi = \begin{pmatrix} \chi^A \\ \chi^B \\ \chi^0 \end{pmatrix} \in (1,3,X_\chi) \qquad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{-B} \end{pmatrix} \in (1,3,X_\rho) \qquad \eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta^{-A} \end{pmatrix} \in (1,3,X_\eta)$$

$$Q^A = \frac{1}{2} + \frac{\sqrt{3}}{2}\beta_{Q_{em}} \qquad Q^B = -\frac{1}{2} + \frac{\sqrt{3}}{2}\beta_{Q_{em}}$$

$$\mathbb{Q}_{em} = \mathbb{T}^3 + \beta_{Q_{em}}\mathbb{T}^8 + \mathbb{X} \qquad \beta_{Q_{em}} = \frac{n}{\sqrt{3}}\,, \quad n = \pm 1, \pm 2, \pm 3$$

$$X_\chi = \beta_{Q_{em}}/\sqrt{3} \qquad X_\rho = \frac{1}{2} - \frac{\beta_{Q_{em}}}{2\sqrt{3}} \qquad X_\eta = -\frac{1}{2} - \frac{\beta_{Q_{em}}}{2\sqrt{3}}$$

$$\begin{aligned} V = {} & m_1\,\rho^*\rho + m_2\,\eta^*\eta + m_3\,\chi^*\chi \\ & + \lambda_1(\rho^*\rho)^2 + \lambda_2(\eta^*\eta)^2 + \lambda_3(\chi^*\chi)^2 \\ & + \lambda_{12}\rho^*\rho\,\eta^*\eta + \lambda_{13}\rho^*\rho\,\chi^*\chi + \lambda_{23}\eta^*\eta\,\chi^*\chi \\ & + \zeta_{12}\rho^*\eta\,\eta^*\rho + \zeta_{13}\rho^*\chi\,\chi^*\rho + \zeta_{23}\eta^*\chi\,\chi^*\eta \\ & + \sqrt{2}f_{\rho\eta\chi}\rho\,\eta\,\chi \end{aligned}$$

# The Particle Content

Recall:

$$\chi = \begin{pmatrix} \chi^A \\ \chi^B \\ \chi^0 \end{pmatrix} \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{-B} \end{pmatrix} \quad \eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta^{-A} \end{pmatrix}$$

Charges:

$$Q^A = \frac{1}{2} + \frac{\sqrt{3}}{2}\beta_{Q_{em}} \,, \quad Q^B = -\frac{1}{2} + \frac{\sqrt{3}}{2}\beta_{Q_{em}}$$

The electromagnetic charge operator:

$$\mathbb{Q}_{em} = \mathbb{T}^3 + \beta_{Q_{em}}\mathbb{T}^8 + \mathbb{X}$$

Values of $\beta_{Q_{em}}$:

$$\beta_{Q_{em}} = \frac{n}{\sqrt{3}} \,, \quad n = \pm 1, \pm 2, \pm 3$$

- quantization of the electromagnetic charge requires $\beta_{Q_{em}}$ to be fractional
- positive definiteness of the mass of the extra $Z^{'}$ gives extra constraints on $n$

# The Particle Content

## The scalars

Recall:

$$\chi = \begin{pmatrix} \chi^A \\ \chi^B \\ \chi^0 \end{pmatrix} \quad \rho = \begin{pmatrix} \rho^+ \\ \rho^0 \\ \rho^{-B} \end{pmatrix} \quad \eta = \begin{pmatrix} \eta^0 \\ \eta^- \\ \eta^{-A} \end{pmatrix}$$

$$\beta_{Q_{em}} = \pm\frac{1}{\sqrt{3}} \qquad Q_A = 1, \quad Q_B = 0$$

$$Q_A = 0, \quad Q_B = -1$$

$$\beta_{Q_{em}} = \pm\frac{2}{\sqrt{3}} \qquad Q_A = 3/2, \quad Q_B = 1/2$$

$$Q_A = -1/2, \quad Q_B = -3/2$$

$$\beta_{Q_{em}} = \pm\sqrt{3} \qquad Q_A = 2, \quad Q_B = 1$$

$$Q_A = -1, \quad Q_B = -2$$

# The Sextet

- The charged leptons acquire an antisymmetric mass matrix from the Higgs triplet.
- This is not sufficient to give arbitrary mass to the leptons.
- A second, symmetric contribution comes from an additional sextet:

$$\sigma = \begin{pmatrix} \sigma_1^{++} & \sigma_1^{+}/\sqrt{2} & \sigma^{0}/\sqrt{2} \\ \sigma_1^{+}/\sqrt{2} & \sigma_1^{0} & \sigma_2^{-}/\sqrt{2} \\ \sigma^{0}/\sqrt{2} & \sigma_2^{-}/\sqrt{2} & \sigma_2^{--} \end{pmatrix} \in (1,6,0) \qquad \left(\beta_{Q_{em}} = \pm\sqrt{3}\right)$$

$$\mathcal{L}^{Yuk}_{l,\,triplet} = G^{\eta}_{ab}\, l^i_a \cdot l^j_b\, \eta^{*k} \epsilon^{ijk} + \mathrm{h.c.} \qquad \mathcal{L}^{\mathrm{Yuk.}}_{\mathrm{l,sextet}} = \mathrm{G}^{\sigma}_{\mathrm{ab}} \mathrm{l}^{\mathrm{i}}_{\mathrm{a}} \cdot \mathrm{l}^{\mathrm{j}}_{\mathrm{b}} \sigma^{*}_{\mathrm{i,j}}$$

P. H. Frampton, Phys.Rev.Lett. 69 (1992) 2889-2891

# The Spontaneous Symmetry Breaking Pattern

## Higgs and Goldstone bosons

| | | |
|---|---|---|
| Re$\rho_0$, Re$\eta_0$, Re$\chi_0$ | 3 scalars: $h$, $H_2$, $H_3$ | 3 d.o.f. |
| Im$\rho_0$, Im$\eta_0$, Im$\chi_0$ | 1 pseudoscalar $H_0$, 2 Goldstones | 3 d.o.f. |
| $\rho^+$, $\eta^-$ | $H^\pm$, $G^\pm$ | (2+2) d.o.f. |
| $\eta^{-A}$, $\chi^A$ | 1 scalar, 1 Goldstone (complex) | (2+2) d.o.f. |
| $\rho^{-B}$, $\chi^B$ | 1 scalar, 1 Goldstone (complex) | (2+2) d.o.f. |

$SU(3)_C \times SU(3)_L \times U(1)_X$ symmetry:

#generators $= 8 + 8 + 1 = 17$

#Goldstone bosons $= 8$

#Physical scalars $= 10$

$SU(3)_C \times U(1)_{em}$ unbroken symmetry

# The Spontaneous Symmetry Breaking Pattern

## The vector bosons

$SU(3)_L \times U(1)_X$ symmetry $\Rightarrow$ 9 gauge bosons
1 photon + 8 bosons that acquire mass: $W^{\pm}_{\mu}$, $Z_{\mu}$ and 5 BSM vector bosons
Mixing among the gauge bosons:

$$W_{\mu} = W^a_{\mu} T^a = \frac{1}{2} \begin{bmatrix} W^3_{\mu} + \frac{1}{\sqrt{3}} W^8_{\mu} & \sqrt{2} W^+_{\mu} & \sqrt{2} Y^{Q_Y}_{\mu} \\ \sqrt{2} W^-_{\mu} & -W^3_{\mu} + \frac{1}{\sqrt{3}} W^8_{\mu} & \sqrt{2} V^{Q_V}_{\mu} \\ \sqrt{2} Y^{-Q_Y}_{\mu} & \sqrt{2} V^{-Q_V}_{\mu} & -\frac{2}{\sqrt{3}} W^8_{\mu} \end{bmatrix}$$

$$W^{\pm}_{\mu} = \frac{1}{\sqrt{2}} \left( W^1_{\mu} \mp i W^2_{\mu} \right)$$

$$Y^{\pm Q_Y}_{\mu} = \frac{1}{\sqrt{2}} \left( W^4_{\mu} \mp i W^5_{\mu} \right)$$

$$V^{\pm Q_V}_{\mu} = \frac{1}{\sqrt{2}} \left( W^6_{\mu} \mp i W^7_{\mu} \right)$$

$W^3_{\mu}$, $W^8_{\mu}$, $X_{\mu}$

Mixing in the neutral sector:

1. $X_{\mu}$ and $W^8_{\mu}$ mix to give $B_{\mu}$ and $\tilde{Z}'_{\mu}$
2. $B_{\mu}$, $\tilde{Z}'_{\mu}$ and $W^3_{\mu}$ mix to give $Z_{\mu}$, $A_{\mu}$ and $Z'_{\mu}$

In the limit of $v_{\chi} >> v_{\rho}, v_{\eta}$ there is no mix of the $Z'$ with $B_{\mu}$ and $W^3_{\mu}$.

# Outline

# Bilepton Signatures

Corcella, Corianò, Costantini, Frampton, PLB 773 (2017) 544, arXiv:1707.01381

$\beta = \pm\sqrt{3}$: the 5 BSM gauge bosons in the model are:

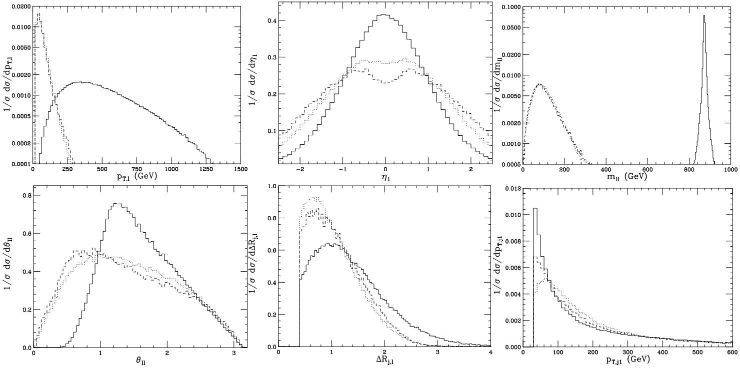
- a $Z'$
- 2 $SU(2)_L$ doublets: $(Y^{--}, Y^{-})$ and $(Y^{++}, Y^{+})$ (with lepton number $L = \pm 2$)

Signature for the doublets: same signe leptons.
Analysis: $pp \to Y^{++}Y^{--} \to (\ell^+\ell^+)(\ell^-\ell^-)jj$

| Benchmark Point | | |
|---|---|---|
| $m_{h_1} = 125.1$ GeV | $m_{h_2} = 3172$ GeV | $m_{h_3} = 3610$ GeV |
| $m_{a_1} = 3595$ GeV | | |
| $m_{h_1^\pm} = 1857$ GeV | $m_{h_2^\pm} = 3590$ GeV | |
| $m_{h_1^{\pm\pm}} = 3734$ GeV | | |
| $m_{Y^{\pm\pm}} = 873.3$ GeV | $m_{Y^\pm} = 875.7$ GeV | |
| $m_{Z'} = 3229$ GeV | | |
| $m_D = 1650$ GeV | $m_S = 1660$ GeV | $m_T = 1700$ GeV |

# Bilepton Signatures

Corcella, Corianò, Costantini, Frampton, PLB 773 (2017) 544, arXiv:1707.01381

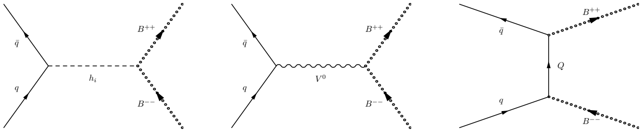



(a) Lepton transverse momentum distribution; (b) Lepton pseudorapidity distribution, (c) Same-sign lepton-pair invariant mass; (d) Angle between same-sign leptons; (e) Invariant opening angle $\Delta R_{j\ell}$ between the hardest jet and its closest lepton; and (f) $p_T$ of the hardest jet $j_1$. The solid histograms are the bilepton signals, the dashes correspond to the $ZZ$ background, the dots to $t\bar{t}Z$ processes.

# Bileptons: Scalars vs. Vectors

Corcella, Corianò, Costantini, Frampton, PLB 785 (2018) 73, arXiv:1806.04536

- Model: $\beta_{Q_{em}} = \pm\sqrt{3}$
- Analysis: $pp \to Y^{++}Y^{--}(H^{++}H^{--}) \to (\ell^+\ell^+)(\ell^-\ell^-)$
- Assumption on the BRs: $BR(Y^{\pm\pm} \to \ell^\pm\ell^\pm) \simeq BR(H^{\pm\pm} \to \ell^\pm\ell^\pm) \simeq 1/3$




- Numerical analysis for a benchmark point (see next slide)
- Total cross sections @LHC 13 TeV:
  - $\sigma(pp \to YY \to 4\ell) \simeq 4.3$fb;
  - $\sigma(pp \to HH \to 4\ell) \simeq 0.3$fb
- Differences are due to the spin of the Y/H.
- Background: $\sigma(pp \to Z \to 4\ell) \simeq 6.1$fb (after cuts)

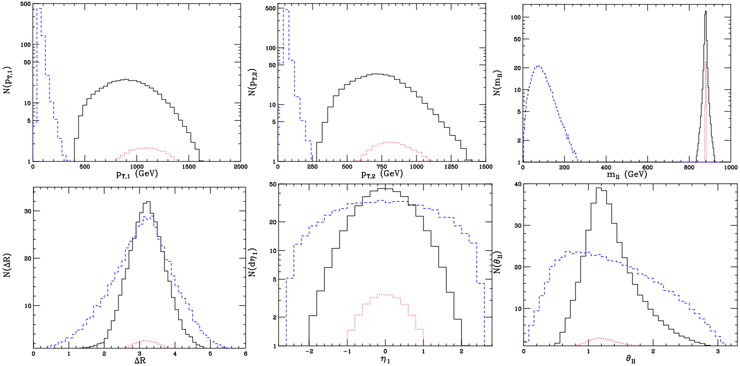
# Bileptons: Scalars vs. Vectors

Corcella, Corianò, Costantini, Frampton, PLB 785 (2018) 73, arXiv:1806.04536

| Benchmark Point | | |
|---|---|---|
| $m_{h_1} = 126.3$ GeV | $m_{h_2} = 1804.4$ GeV | $m_{h_3} = 2474.0$ GeV |
| $m_{h_4} = 6499.8$ GeV | $m_{h_5} = 6528.1$ GeV | |
| $m_{a_1} = 1804.5$ GeV | $m_{a_2} = 6496.0$ GeV | $m_{a_3} = 6528.1$ GeV |
| $m_{h_1^\pm} = 1804.5$ GeV | $m_{h_2^\pm} = 1873.4$ GeV | $m_{h_3^\pm} = 6498.1$ GeV |
| $m_{h_1^{\pm\pm}} = 878.3$ GeV | $m_{h_2^{\pm\pm}} = 6464.3$ GeV | $m_{h_3^{\pm\pm}} = 6527.7$ GeV |
| $m_{Y^{\pm\pm}} = 878.3$ GeV | $m_{Y^\pm} = 881.8$ GeV | $m_{Z'} = 3247.6$ GeV |
| $m_D = 1650.0$ GeV | $m_S = 1660.0$ GeV | $m_T = 1700.0$ GeV |

# Bileptons: Scalars vs. Vectors

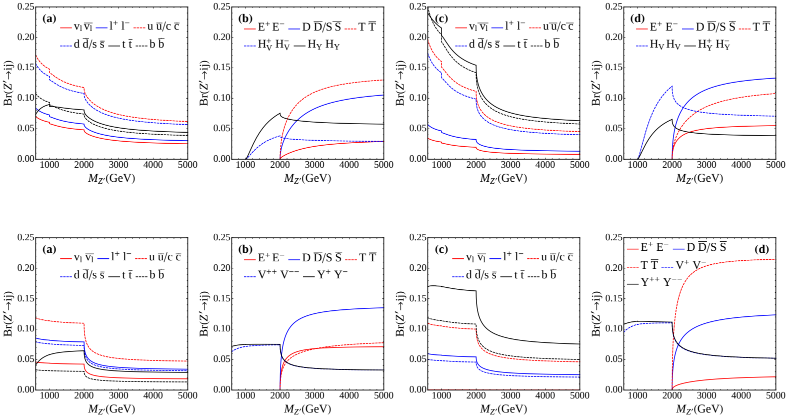
Corcella, Corianò, Costantini, Frampton, PLB 785 (2018) 73, arXiv:1806.04536




Distributions of the transverse momentum of the hardest (a) and next-to-hardest lepton (b), same-sign lepton invariant mass (c), invariant opening angle between the two hardest leptons (d), rapidity of the leading lepton (e), polar angle between same-sign leptons (f). The solid blue histograms are the spectra yielded by vector bileptons, the red dots correspond to scalar doubly-charged Higgs bosons, the blue dashes to the *ZZ* Standard Model background. Black solid: YY; red dotted: HH; blue dotted: ZZ (SM bkg)

# Phenomenology of the $Z'$

Branching ratios:

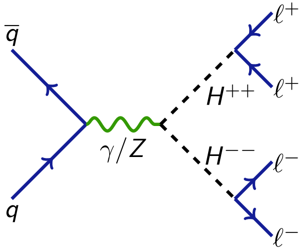



$\beta_{Q_{em}} = -1/\sqrt{3}, 1/\sqrt{3}, -\sqrt{3}, \sqrt{3}$; $m_F = 1$ TeV, $m_{H^\pm} = 500$ GeV.

Cao and Zhang, arXiv:1611.09337

# Experimental constraints

## Doubly charged scalar searches




- Signature: same-sign lepton pairs
- Assumptions on the branching ratios
- Narrow width approximation

ATLAS 7 TeV:

- Eur.Phys.J. C72 (2012) 2244

CMS 7 TeV:

- Eur.Phys.J. C72 (2012) 2189

ATLAS 13 TeV:

- Eur.Phys.J. C78 (2018) no.3, 199

CMS 13 TeV:

- CMS-PAS-HIG-16-036

# Experimental constraints

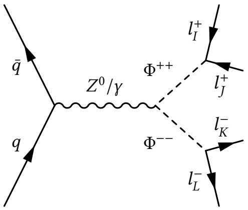
## Doubly charged scalar searches: CMS

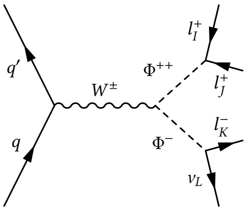
Search for a scalar triplet $S = \begin{pmatrix} S^+ & \sqrt{2}S^{++} \\ \sqrt{2}S^0 & -S^+ \end{pmatrix}$ with degenerate masses.

12.9 $\mathrm{fb}^{-1}$ of integrated luminosity at 13 TeV

Channels:

- Pair production with decays $S^{++}S^{--} \to \ell^+\ell^+\ell^-\ell^-$
- Associated production with decays $S^{\pm\pm}S^{\mp} \to \ell^{\pm}\ell^{\pm}\ell^{\mp}\nu$




CMS-PAS-HIG-16-036

# Experimental constraints

## Doubly charged scalar searches: CMS

- $S_L^{\pm\pm}$ decaying at 100% to $ee$, $\mu\mu$, $\tau\tau$, $e\mu$, $e\tau$, $\mu\tau$;
- Benchmark points:

| Benchmark Point | $ee$ | $e\mu$ | $e\tau$ | $\mu\mu$ | $\mu\tau$ | $\tau\tau$ |
|---|---|---|---|---|---|---|
| BP1 | 0 | 0.01 | 0.01 | 0.30 | 0.38 | 0.30 |
| BP2 | 1/2 | 0 | 0 | 1/8 | 1/4 | 1/8 |
| BP3 | 1/3 | 0 | 0 | 1/3 | 0 | 1/3 |
| BP4 | 1/6 | 1/6 | 1/6 | 1/6 | 1/6 | 1/6 |

Lower bounds on the mass of the $S_L^{\pm\pm}$ - observed (expected) 95% CL:

| Benchmark | AP [GeV] | PP [GeV] | Combined [GeV] |
|---|---|---|---|
| 100% $\Phi^{\pm\pm} \to ee$ | 734 (720) | 652 (639) | 800 (785) |
| 100% $\Phi^{\pm\pm} \to e\mu$ | 750 (729) | 665 (660) | 820 (810) |
| 100% $\Phi^{\pm\pm} \to \mu\mu$ | 746 (774) | 712 (712) | 816 (843) |
| 100% $\Phi^{\pm\pm} \to e\tau$ | 568 (582) | 481 (543) | 714 (658) |
| 100% $\Phi^{\pm\pm} \to \mu\tau$ | 518 (613) | 537 (591) | 643 (708) |
| 100% $\Phi^{\pm\pm} \to \tau\tau$ | 479 (483) | 396 (419) | 535 (544) |
| Benchmark 1 | 613 (649) | 519 (548) | 723 (715) |
| Benchmark 2 | 670 (671) | 465 (554) | 716 (723) |
| Benchmark 3 | 706 (682) | 531 (562) | 761 (732) |
| Benchmark 4 | 639 (639) | 496 (539) | 722 (704) |

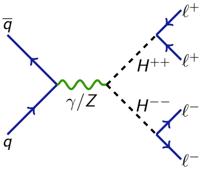
$S_R^{\pm\pm}$ may have similar kinematic properties, but potentially very different production cross sections. No associate production.

CMS-PAS-HIG-16-036

# Experimental constraints

## Doubly charged scalar searches: ATLAS

$36.1\,\mathrm{fb}^{-1}$ of integrated luminosity at 13 TeV.




Scenarios:

- $\sum_{i,j=e,\mu} \mathcal{B}(S^{\pm\pm} \to \ell_i \ell_j) = 100\%$
  - $m\left(S_L^{\pm\pm}\right)$ between 770 GeV and 870 GeV @ 95% C.L.
  - $m\left(S_R^{\pm\pm}\right)$ between 660 GeV and 760 GeV @ 95% C.L.
- $\mathcal{B}(S^{\pm\pm} \to \ell_i \ell_j) > 10\%$ (decays to $\tau$ and $W$ are possible)
  - $m\left(S_L^{\pm\pm}\right)$ larger than 450 GeV @ 95% C.L.
  - $m\left(S_R^{\pm\pm}\right)$ larger than 320 GeV @ 95% C.L.

Eur.Phys.J. C78 (2018) no.3, 199

# Outline

# Physical Parameters vs. Lagrangian Parameters

## The Neutral Sector – Scalars

$$\mathcal{M}_h^2 = \begin{pmatrix} \kappa \tan\beta v_\chi^2 + 2\lambda_1 v^2 \cos^2\beta & \lambda_{12} v^2 \cos\beta \sin\beta - \kappa v_\chi^2 & v_\chi v(\lambda_{13}\cos\beta - \kappa \sin\beta) \\ \lambda_{12} v^2 \cos\beta \sin\beta - \kappa v_\chi^2 & \kappa \cot\beta v_\chi^2 + 2\lambda_2 v^2 \sin^2\beta & v_\chi v(\lambda_{23}\sin\beta - \kappa\cos\beta) \\ v_\chi v(\lambda_{13}\cos\beta - \kappa\sin\beta) & v_\chi v(\lambda_{23}\sin\beta - \kappa\cos\beta) & 2\lambda_3 v_\chi^2 + \kappa v^2 \cos\beta\sin\beta \end{pmatrix}$$

$$H = (\mathrm{Re}\,\rho^0,\, \mathrm{Re}\,\eta^0,\, \mathrm{Re}\,\chi^0) \quad \longmapsto \quad \mathrm{h} = (\mathrm{h}_1,\, \mathrm{h}_2,\, \mathrm{h}_3): \qquad \mathrm{h_i} = \mathcal{R}^{\mathrm{S}}_{\mathrm{ij}} \mathrm{H_j}$$

$$\mathcal{R}^S = \begin{pmatrix} \cos\alpha_2\cos\alpha_3 & \cos\alpha_3\sin\alpha_1\sin\alpha_2 - \cos\alpha_1\sin\alpha_3 & \cos\alpha_1\cos\alpha_3\sin\alpha_2 + \sin\alpha_1\sin\alpha_3 \\ \cos\alpha_2\sin\alpha_3 & \cos\alpha_1\cos\alpha_3 + \sin\alpha_1\sin\alpha_2\sin\alpha_3 & \cos\alpha_1\sin\alpha_2\sin\alpha_3 - \cos\alpha_3\sin\alpha_1 \\ -\sin\alpha_2 & \cos\alpha_2\sin\alpha_1 & \cos\alpha_1\cos\alpha_2 \end{pmatrix}$$

$$\hat{\mathcal{M}}_h^2 = (\mathcal{R}^S)^T \cdot \mathcal{M}_h^2 \cdot \mathcal{R}^S$$

Diagonalization conditions:

$$\hat{\mathcal{M}}^2_{h;1,1} = m^2_{h_1} \qquad \hat{\mathcal{M}}^2_{h;2,2} = m^2_{h_2} \qquad \hat{\mathcal{M}}^2_{h;3,3} = m^2_{h_3}$$

$$\hat{\mathcal{M}}^2_{h;1,2} = 0 \qquad \hat{\mathcal{M}}^2_{h;1,3} = 0 \qquad \hat{\mathcal{M}}^2_{h;2,3} = 0$$

# Physical Parameters vs. Lagrangian Parameters

## The Neutral Sector – Pseudoscalars

$$A = (\mathrm{Im}\,\rho^0, \mathrm{Im}\,\eta^0, \mathrm{Im}\,\chi^0) \quad \longmapsto \quad \mathrm{a} = (\mathrm{a}_{\mathrm{G_Z}}, \mathrm{a}_{\mathrm{G_{Z'}}}, \mathrm{a}_1): \qquad \mathrm{a_i} = \mathcal{R}^{\mathrm{P}}_{\mathrm{ij}} \mathrm{A_j}$$

$$\mathcal{M}_a^2 = \begin{pmatrix} \kappa v_\chi^2 \tan\beta & \kappa v_\chi^2 & \kappa v_\chi v \sin\beta \\ \kappa v_\chi^2 & \kappa v_\chi^2 \cot\beta & \kappa v_\chi v \cos\beta \\ \kappa v_\chi v \sin\beta & \kappa v_\chi v \cos\beta & \kappa v^2 \cos\beta \sin\beta \end{pmatrix}$$

It follows a relation between $\kappa$ and the mass of the pseudoscalar $m_{a_1}^2$:

$$m_{a_1}^2 = \kappa (v_\chi^2 \csc\beta \sec\beta + v^2 \cos\beta \sin\beta)$$

$+$ Diagonalization conditions $\quad \Longrightarrow \quad \lambda_i(m_{h_i}, m_{a_1}, \alpha_i)$

# Physical Parameters vs. Lagrangian Parameters

## The Charged Sector

$$H^- = ((\rho^+)^*, \eta^-) \quad \longmapsto \quad h^- = (h^-_{G_W}, h^-_1) : \qquad h^-_i = \mathcal{R}^C_{ij} H^-_j$$

$$m^2_{h_1^\pm} = \frac{1}{2}\zeta_{12} v^2 + \kappa v_\chi^2 \csc\beta \sec\beta \quad \Longrightarrow \quad \zeta_{12}$$

$$H^A = ((\eta^{-A})^*, \chi^A) \quad \longmapsto \quad h^A = (h^A_{G_{V^A}}, h^A_1) : \qquad h^A_i = \mathcal{R}^A_{ij} H^A_j$$

$$m^2_{h_1^{\pm A}} = \frac{1}{4}(\zeta_{23} + 2\kappa \cot\beta)\left(2v_\chi^2 + v^2 - v^2\cos 2\beta\right) \quad \Longrightarrow \quad \zeta_{23}$$

$$H^B = ((\rho^{-B})^*, \chi^B) \quad \longmapsto \quad h^B = (h^B_{G_{V^B}}, h^B_1);: \qquad h^B_i = \mathcal{R}^B_{ij} H^B_j$$

$$m^2_{h_1^{\pm B}} = \frac{1}{4}(\zeta_{13} + 2\kappa \tan\beta)\left(2v_\chi^2 + v^2 - v^2\cos 2\beta\right) \quad \Longrightarrow \quad \zeta_{13}$$

# Triviality and Perturbative Unitarity Constraints

Triviality:

- Require that the couplings are perturbative

$$\lambda_i < 4\pi$$

Perturbative Unitarity:

- It is a constraint from the scattering amplitudes.
- It does not depend on $\beta_{Q_{em}}$.
- One has to calculate the amplitudes of all the $2 \to 2$ processes;
- take the $s \to \infty$ limit;
- arrange the amplitudes in a matrix;
- project onto the $J = 0$ partial waves;
- diagonalize and impose $|\mathrm{Re}(\lambda_{max})| \leq \frac{1}{2}$.

Lee, Quigg, Thacker, Phys.Rev. D16 (1977) 1519

Luscher and Weisas, Phys. Lett. 212B (1988) 472

# Perturbative Unitarity Constraint

Partial-wave decomposition:

$$a_J = \frac{1}{32\pi}\int_{-1}^{1} d\cos\theta \mathcal{A}(s,\theta) P_J(\cos\theta)$$

$P_J$ are the Legendre Polynomials:

$$P_0(x) = 1 \qquad P_1(x) = x \qquad P_2(x) = \frac{3}{2}x^2 - \frac{1}{2} \qquad \text{etc.}$$

The strongest constraint comes from the $J = 0$ partial wave:

$$a_0 = \frac{1}{32\pi}\int_{-1}^{1} d\cos\theta \mathcal{A}(s,\theta)$$

# Perturbative Unitarity Constraint

## SM example

Calculate the $2 \to 2$ amplitudes in the $s \to \infty$ limit:

$$W_L^+ W_L^- \to W_L^+ W_L^-$$
$$HZ_L \to W_L^+ W_L^-$$
$$HZ_L \to HH$$
$$HZ_L \to Z_L Z_L$$
$$HZ_L \to W_L^+ W_L^-$$

$$Z_l Z_L \to Z_L Z_L$$
$$Z_L Z_L \to W_L^+ W_L^-$$
$$HH \to HH$$
$$HH \to Z_L Z_L$$
$$HH \to W_L^+ W_L^-$$

Project them on $J = 0$;
diagonalize the matrix:

$$t \simeq \frac{-G_F m_H^2}{4\pi\sqrt{2}} \begin{bmatrix} 1 & \frac{1}{\sqrt{8}} & \frac{1}{\sqrt{8}} & 0 \\ \frac{1}{\sqrt{8}} & \frac{3}{4} & \frac{1}{4} & 0 \\ \frac{1}{\sqrt{8}} & \frac{1}{4} & \frac{3}{4} & 0 \\ 0 & 0 & 0 & \frac{1}{\sqrt{8}} \end{bmatrix}$$

Eigenvalues:

$$\frac{-G_F m_H^2}{4\pi\sqrt{2}} \times \left(\frac{3}{2}, \frac{1}{2}, \frac{1}{2}, \frac{1}{2}\right)$$

$$m_H^2 \leq \frac{4\pi\sqrt{2}}{3G_F}$$

Lee, Quigg, Thacker, Phys.Rev. D16 (1977) 1519

# Limits from Higgs Measurements

## Constraints from the observed Higgs boson $h$:

$$m_h = 125\text{GeV}$$

Couplings with the vector bosons: $\cos\alpha_2 \times \cos\alpha_3 \geq 0.8$

The angle $\alpha_1$ remains substantially free.

## Constraints on the vevs:

- 2 light vevs: $v_\rho$, $v_\eta$
- 1 heavy vev: $v_\chi$

$$v_\rho^2 + v_\eta^2 = v_{SM}^2 \equiv (246\text{GeV})^2$$

while the heavy $v_\chi$ is free.

# The triviality constraint: results

Look at the couplings $\lambda_i$ and $\zeta_i$ in the large $v_\chi$ limit and require $\lambda_i, \zeta_i < 4\pi$

- From $\zeta_{12}$ we get that $m_{H_0}$ is close to $m_{H_W}$: $\frac{2(m_{H_0}^2 - m_{H_W}^2)}{v_{SM}^2} \leq 4\pi$
- From $\zeta_{13}$ and $\zeta_{23}$ we only get $m_{H_V}, m_{H_Y} < v_\chi$ ($m_{H_V}, m_{H_Y}$ almost unconstrained)
- From the $\lambda_i$ we get that the splitting between $m_{H_0}$, $m_{H_2}$ and $m_{H_3}$ is small (from ratios of the form: $\frac{2(m_{H_2}^2 - m_{H_3}^2)}{v_{SM}^2}$)
- The requirement $\cos\alpha_2 \times \cos\alpha_3 \geq 0.8$ is translated into $\frac{v_\eta}{v_\rho} < 0.4$, or lower for more stringent constraint on $\alpha_2, \alpha_3$.

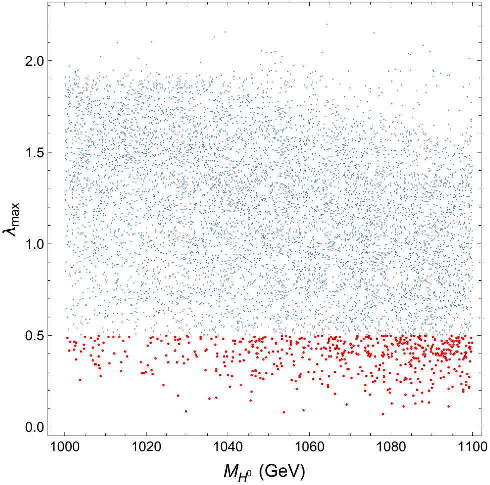
Conclusion: the heavy scalars have a compressed spectrum:

$$m_i \sim 1\text{TeV} \quad \Rightarrow \quad \Delta m \sim 200\text{GeV}$$
$$m_i \sim 2\text{TeV} \quad \Rightarrow \quad \Delta m \sim 100\text{GeV}$$

etc.

The higher the masses, the more compressed the spectrum.

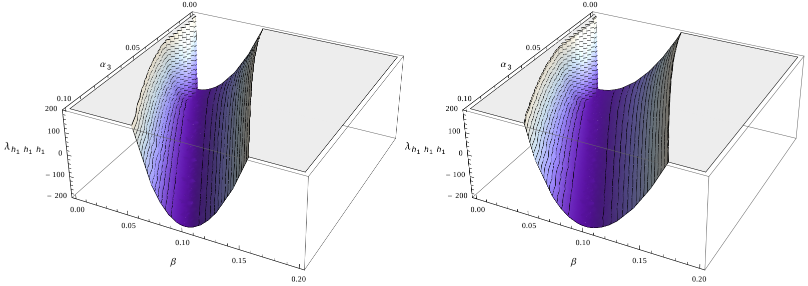
# Triviality + perturbative unitarity: preliminary results



# Outline

# Study of the Higgs Trilinear Coupling

$$\lambda_{h_1 h_1 h_1} = i\Big[ m_{h_1}^2 \frac{-3\left(v_\chi \cos^3\alpha_2 \left(\cos^3\alpha_3 \sec\beta + \sin^3\alpha_3 \csc\beta\right) - v \sin^3\alpha_2\right)}{v_\chi v} + m_{a_1}^2 \frac{24 \csc\beta \sec\beta}{v_\chi v \left(8 v_\chi^2 + v^2(1-\cos 4\beta)\right)} \left(v_\chi^2 \cos^2\alpha_2 \sin^2(\alpha_3-\beta) - v^2 \sin^2\alpha_2 \sin^2\beta \cos^2\beta\right) \times \left(v_\chi \cos\alpha_2 \sin(\alpha_3+\beta) + v \sin\alpha_2 \sin\beta \cos\beta\right)\Big]$$




Higgs canion: $v_\chi = 4$ TeV, $m_{a_1} = 2.5$ TeV, $v_\chi = 4$ TeV, $m_{a_1} = 2$ TeV

# Collider Simulations

- Exotic quark phenomenology
- Benchmark points for the simulations?
- Can we generalize? Simplified Models

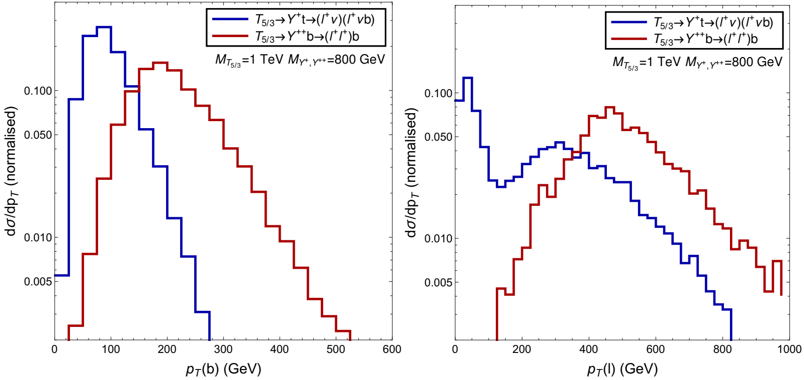
## $T_{5/3}$ pair production

Experimental searches for $pp \to T_{5/3}\bar{T}_{5/3} \to W^+W^-t\bar{t}$

Complementary searches:

- $pp \to T_{5/3}\bar{T}_{5/3} \to Y^{++}Y^{--}b\bar{b}$
- $pp \to T_{5/3}\bar{T}_{5/3} \to V^+V^-t\bar{t}$
- Doubly and singly charged heavy scalars: $Y^{\pm\pm}/V^{\pm} \to S^{\pm\pm}/S^{\pm}$

# Simulations: $T_{5/3}$ quarks



# Summary

- The 331 Model is a minimal extension of the SM gauge group, that addresses the flavour problem.
- The spectrum contains BSM scalars, fermions and gauge bosons.
- We have studied the parameter space in terms of the physical parameters: masses and mixing angles.
- The triviality constraint forces the spectrum of the Higgs bosons to compressed configurations.
- The perturbative unitarity constraint does not show any specific pattern, but excludes efficiently and uniformely many points of the parameter space.
- There is a lot of room for collider studies; in particular, we are planning to study different decay modes of the $T_{5/3}$ exotic quark.