Vector and Axial-vector Resonances in composite models of the Higgs boson

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Outline

- *A brief review of Composite Higgs Models*
- *Model implementation of Spin-1 resonances in SU(4)/Sp(4)*
- *Phenomenology at LHC and 100 TeV Collider*
- *Conclusion and future outlooks*

Composite Higgs Model

What is Composite Higgs? > PNGB from strong dynamics

Original one: SU(5)/SO(5) gives 14 pNGBs; Higgs mass protected by "shift symmetry";
EWSB triggered by vacuum misalignment.

[Georgi, Kaplan 1984]

Global symmetry broken at TeV scale with f >> v, EWPT vs "Naturalness"

Top quark mass can be generated via partial compositeness

SM fermion couples to strong sector: $\lambda\psi_{SM}\mathcal{O}_{CFT}$

[Contino, Nomura, Pomarol 2003; Agashe, Contino, Pomarol, 2004]

Minimal CHM based on fundamental dynamics requires SU(4)/Sp(4)

Give rise to one Higgs doublet plus one singlet

Fundamental Theory

Underlying dynamics is $Sp(2N_c)_{TC}$ gauge theory with 4 Weyl techni-quarks:

[Galloway, Evans, Luty, Tacchi, 2010 ; Cacciapaglia, Sannino, 2014]

$$\mathcal{L} = -\frac{1}{4} F^a_{\mu\nu} F^{a\mu\nu} + \bar{Q}_j (i\sigma^\mu D_\mu) Q_j - M^{ij} Q_i Q_j + h.c.$$

$$M_Q = \begin{pmatrix} \mu_L \, i\sigma_2 & 0 \\ 0 & \mu_R \, i\sigma_2 \end{pmatrix} , \quad \textit{techni-quark mass}$$

Minimal choice : $\boxed{Sp(2) \sim SU(2)}$

Bound states will form in the IR:

$$(\pi^a, \sigma) \; : \; \langle QQ \rangle = \mathbf{6}_{SU(4)} \to \mathbf{5}_{Sp(4)} \oplus \mathbf{1}_{Sp(4)} \qquad \textit{compsoite scalars}$$

$$(\rho^i_\mu, a^k_\mu) \; : \; \langle \bar{Q} \sigma^\mu Q \rangle = \mathbf{15}_{SU(4)} \to \mathbf{10}_{Sp(4)} \oplus \mathbf{5}_{Sp(4)} \qquad \textit{composite vectors}$$

For $N_c \geq 2$, add 6 techni-quarks $\chi_j \Rightarrow$ *coloured pNGBs* plus *top partners*.

[Barnard, Gherghetta, Ray, 2014; Ferretti, 2014; Cacciapaglia, Cai, Deandra, Flacke, Lee, Parolini, 2015]

[Belyaeav, Cacciapaglia, Cai, Flacke, Parolini, Serodio, 2015]

How to implement vector resonances in EFT ?

Hidden Symmetry

Using Hidden symmetry techniques, one can extend the global symmetry to be:

$$SU(4)_0 \times SU(4)_1 \to Sp(4)$$

Composite fermions?

$\pi_0^a, \tilde{W}, B$

SM fermions

$$K = e^{ik^i V^i / f_K}$$

$\pi_1^a, \rho_\mu^i, a_\mu^k$

elementary sector

strong sector

π_0^a, π_1^a, k^i: 20 Nambu-Goldstone bosons, 15 eaten by V^i, A^a

3 eaten by W, Z, two physical scalars remain: h, η.

Model Setup

We adopt the CCWZ formalism and define *2 sets of pions* for enhanced global symmetry:

[Coleman, Wess, Zumino, 1969; Callan, Coleman, Wess, Zumino, 1969; Bando, Kugo, Yamawaki, 1988]

$$U_0 = \exp\left[\frac{i\sqrt{2}}{f_0}\sum_{a=1}^{5}(\pi_0^a Y^a)\right]$$

$$U_1 = \exp\left[\frac{i\sqrt{2}}{f_1}\sum_{a=1}^{5}(\pi_1^a Y^a)\right]$$

Project Maurer-Cartan forms into:

$$\textit{broken direction} \Rightarrow p_{\mu\,i} = 2\sum_a Tr(Y_a U_i^\dagger D_\mu U_i)\,Y_a$$

$$\textit{unbroken direction} \Rightarrow v_{\mu\,i} = 2\sum_a Tr(V_a U_i^\dagger D_\mu U_i)\,V_a$$

Thus $v_{\mu,i}$ transform like gauge bosons and $p_{\mu,i}$ transform homogeneously.

Effective Lagrangian

$$\mathcal{L} = -\frac{1}{2g^2}\,\mathrm{Tr}\,W_{\mu\nu}W^{\mu\nu} - \frac{1}{2g'^2}\,\mathrm{Tr}\,B_{\mu\nu}B^{\mu\nu} - \frac{1}{2\tilde{g}^2}\,\mathrm{Tr}\,\mathcal{F}_{\mu\nu}\mathcal{F}^{\mu\nu}$$

$$+ \frac{1}{2}\kappa_{G_0}(\sigma) f_0^2\ \mathrm{Tr} p_{0\mu} p_0^\mu + \frac{1}{2}\kappa_{G_1}(\sigma) f_1^2\ \mathrm{Tr} p_{1\mu} p_1^\mu + r[\sigma] f_1^2\ \mathrm{Tr} p_{0\mu} K p_1^\mu K^\dagger$$

$$+ \frac{1}{2}\kappa_K(\sigma) f_K^2\ \mathrm{Tr}\ \mathcal{D}^\mu K\ \mathcal{D}_\mu K^\dagger + \frac{1}{2}\partial_\mu\sigma\partial^\mu\sigma - \mathcal{V}(\sigma)$$

pion kinetic terms

normal CCWZ terms

Axial partial compositeness

Vector partial compositeness

composite vectors: $\mathcal{F}_\mu = \sum_{a=1}^{10} \mathcal{V}_\mu^a V_a + \sum_{a=1}^{5} \mathcal{A}_\mu^a Y_a .$

$$K = \exp\left[ik^i V^i / f_K\right]\ , \quad D_\mu K = \partial_\mu K - i v_{0\mu} K + i K v_{1\mu}$$

The K field is to break $Sp(4)_0 \times Sp(4)_1$ into the diagonal final $Sp(4)$.

Physical Pions

Due to the r term, we need to rotate *2 sets of pions* into orthogonal unitary basis,

$$\begin{aligned}\pi_0^a &= \pi_P^a \frac{1}{\sqrt{1 - r^2 f_1^2/f_0^2}} \\ \pi_1^a &= \pi_U^a - \pi_P^a \frac{r f_1/f_0}{\sqrt{1 - r^2 f_1^2/f_0^2}}\end{aligned}$$

π_P is associated with physical scalars and π_U is NG boson eaten by x_0^μ and $\widetilde{x}_0^\mu$.

Unitary basis $\Rightarrow$ no bilinear mixing in terms of $\partial_\mu h\ x_0^\mu$ and $\partial_\mu \eta\ \widetilde{x}_0^\mu$

Since $v^2 = (f_0^2 - r^2 f_1^2) \sin^2\theta$, with EWSB, there is no divergence in the pion rotation.

Model Spectrum

One charged state of exact mass M_V does not mix with $\tilde{W}$ and $\tilde{B}$; Neutral Sector gives a massless photon.

$$M^2_{W^+} = \frac{1}{4}g^2v^2 + \mathcal{O}\left(\frac{g}{\widetilde{g}}\right)^4, \quad M_{S^+} = M^2_V \qquad M^2_Z = \frac{1}{4}(g^2+g'^2)v^2 + \mathcal{O}\left(\frac{g}{\widetilde{g}}\right)^4$$

$$M^2_{A^+} = M^2_A\left(1+\frac{r^2\left(\frac{g}{\widetilde{g}}\right)^2 s^2_\theta}{2}\right) + \mathcal{O}\left(\frac{g}{\widetilde{g}}\right)^4 \qquad M^2_{A^0} = M^2_A\left(1+\frac{r^2\left(\frac{g^2+g'^2}{\widetilde{g}^2}\right) s^2_\theta}{2}\right) + \mathcal{O}\left(\frac{g}{\widetilde{g}}\right)^4$$

$$M_{V^+} = \frac{1}{4}M^2_V\left(\frac{g^2(\cos(2\theta)+3)}{\widetilde{g}^2}+4\right) + \mathcal{O}\left(\frac{g}{\widetilde{g}}\right)^4 \qquad M_{V^0,S^0} = M^2_V\left[1+\frac{g^2+g'^2}{4\widetilde{g}^2}\left(1+c^2_\theta \pm \mathcal{O}(1)\right)\right] + \mathcal{O}\left(\frac{g}{\widetilde{g}}\right)^4$$

There are additional no mixing states $\widetilde{s}^{\pm,0}_\mu$, $\widetilde{v}^0_\mu$, x^0_μ and $\widetilde{x}^0_\mu$, with masses:

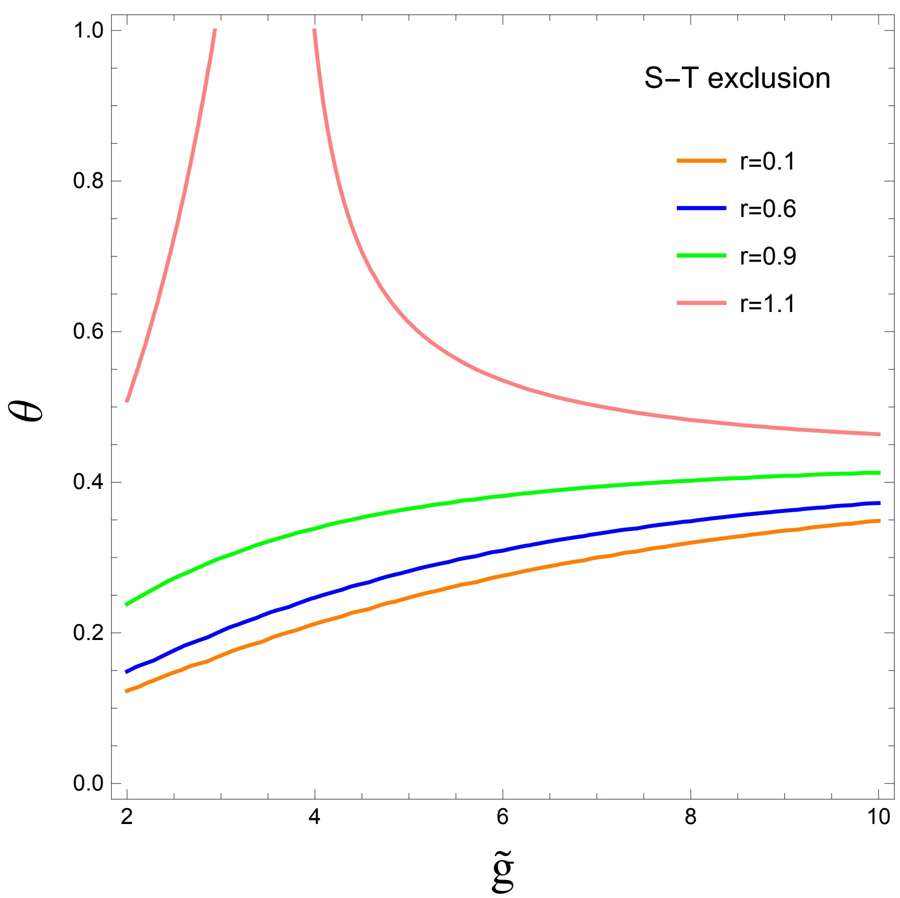
$$M_{\widetilde{s}} = M_{\widetilde{v}^0} = M_V \quad \text{and} \quad M_{x^0} = M_{\widetilde{x}^0} = M_A\,.$$

Typical HVV couplings:

$$c_{hW^+W^-} \simeq \frac{2M^2_W}{v}c_\theta = c^{\mathrm{SM}}_{hW^+W^-}c_\theta\,, \quad c_{hZZ} \simeq \frac{2M^2_Z}{v}c_\theta = c^{\mathrm{SM}}_{hZZ}c_\theta$$

Electroweak Precision Tests

The S-T is exploited to exclude the unfavored region in the parameter space.



$$S = -\frac{4s_W^2}{\alpha_{EW}}\frac{g^2\left(r^2-1\right)s_\theta^2}{2\tilde{g}^2+g^2\left[2+(r^2-1)s_\theta^2\right]} + \frac{1}{6\pi}s_\theta^2\log\left(\frac{\Lambda}{m_h}\right)$$

$$T = -\frac{3}{8\pi\cos^2\theta_W}s_\theta^2\ln\frac{\Lambda}{m_h}$$

$r \simeq 1$: a partial cancellation occurs in S parameter, in certain range of $\tilde{g}$, there is no bound for the θ angle.

$r < 1$: EWPT typically requires $\theta < 0.2$.

stronger than Higgs coupling constraint !

Fermion Currents

Field	Fermion currents	P	C	G	GP
Massive spin-1 $\mathcal{V}_\mu$ (unbroken generators)					
v^+	$\overline{D}\gamma^\mu U$				
v^0	$\frac{1}{\sqrt{2}}\left(\overline{U}\gamma^\mu U - \overline{D}\gamma^\mu D\right)$	$-$	$-$	$-$	$+$
v^-	$\overline{U}\gamma^\mu D$				
$\tilde{v}^0$	$\sqrt{2}\cos\theta\,\Im\left(U^T C\gamma^\mu D\right) + \frac{1}{\sqrt{2}}\sin\theta\left(\overline{U}\gamma^\mu U + \overline{D}\gamma^\mu D\right)$	$-$	$-$	$+$	$-$
s^+	$\cos\theta\left(\overline{D}\gamma^\mu\gamma^5 U\right) + \frac{i}{2}\sin\theta\left(U^T C\gamma^\mu\gamma^5 U - \overline{D}\gamma^\mu C\gamma^5\overline{D}^T\right)$				
s^0	$-\frac{1}{\sqrt{2}}\cos\theta\left(\overline{U}\gamma^\mu\gamma^5 U - \overline{D}\gamma^\mu\gamma^5 D\right) - \sqrt{2}\sin\theta\,\Im\left(U^T C\gamma^\mu\gamma^5 D\right)$	$+$	$+$	$+$	$+$
s^-	$\cos\theta\left(\overline{U}\gamma^\mu\gamma^5 D\right) + \frac{i}{2}\sin\theta\left(\overline{U}\gamma^\mu C\gamma^5\overline{U}^T - D^T C\gamma^\mu\gamma^5 D\right)$				
$\tilde{s}^+$	$\frac{i}{2}\left(U^T C\gamma^\mu\gamma^5 U + \overline{D}\gamma^\mu C\gamma^5\overline{D}^T\right)$				
$\tilde{s}^0$	$\sqrt{2}\,\Re\left(U^T C\gamma^\mu\gamma^5 D\right)$	$+$	$-$	$-$	$-$
$\tilde{s}^-$	$\frac{i}{2}\left(\overline{U}\gamma^\mu C\gamma^5\overline{U}^T + D^T C\gamma^\mu\gamma^5 D\right)$				
Massive spin-1 $\mathcal{A}_\mu$ (broken generators)					
a^+	$\frac{i}{2}\cos\theta\left(U^T C\gamma^\mu\gamma^5 U - \overline{D}\gamma^\mu C\gamma^5\overline{D}^T\right) - \sin\theta\left(\overline{D}\gamma^\mu\gamma^5 U\right)$				
a^0	$-\sqrt{2}\cos\theta\,\Im\left(U^T C\gamma^\mu\gamma^5 D\right) + \frac{1}{\sqrt{2}}\sin\theta\left(\overline{U}\gamma^\mu\gamma^5 U - \overline{D}\gamma^\mu\gamma^5 D\right)$	$+$	$+$	$+$	$+$
a^-	$\frac{i}{2}\cos\theta\left(\overline{U}\gamma^\mu C\gamma^5\overline{U}^T - D^T C\gamma^\mu\gamma^5 D\right) - \sin\theta\left(\overline{U}\gamma^\mu\gamma^5 D\right)$				
x^0	$\sqrt{2}\,\Re\left(U^T C\gamma^\mu D\right)$	$-$	$+$	$-$	$+$
$\tilde{x}^0$	$\frac{1}{\sqrt{2}}\cos\theta\left(\overline{U}\gamma^\mu U + \overline{D}\gamma^\mu D\right) - \sqrt{2}\sin\theta\,\Im\left(U^T C\gamma^\mu D\right)$	$-$	$-$	$+$	$-$

P-Parity : $U \xrightarrow{P} i\gamma^0 U, \qquad D \xrightarrow{P} i\gamma^0 D$

C-Parity : $U \xrightarrow{C} -i\gamma^2 U^*, \qquad D \xrightarrow{C} -i\gamma^2 D^*$

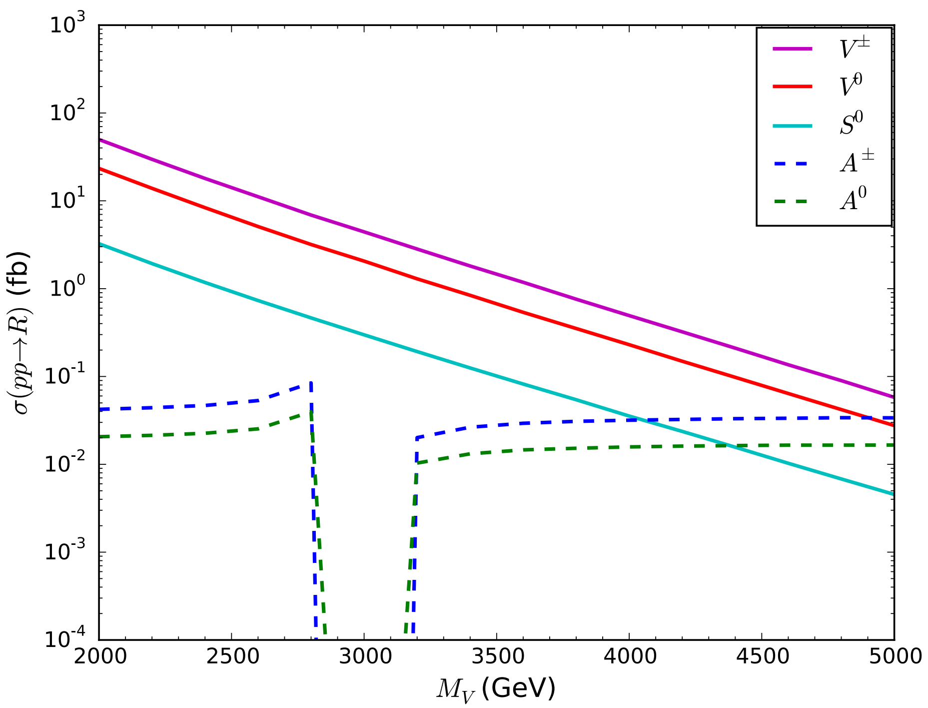
G-Parity : $U \xrightarrow{G} -\gamma^2 D^*, \qquad D \xrightarrow{G} \gamma^2 U^*$

Under the parity operation: a vector fermion-current has $CP = +$; and a pseudo-vector fermion-current has $CP = -$.

The GP is a good symmetry and being selection rule for decays. Only the tilded fields and η are odd under this parity.

Cross Section @ LHC Run II

Drell-Yan production

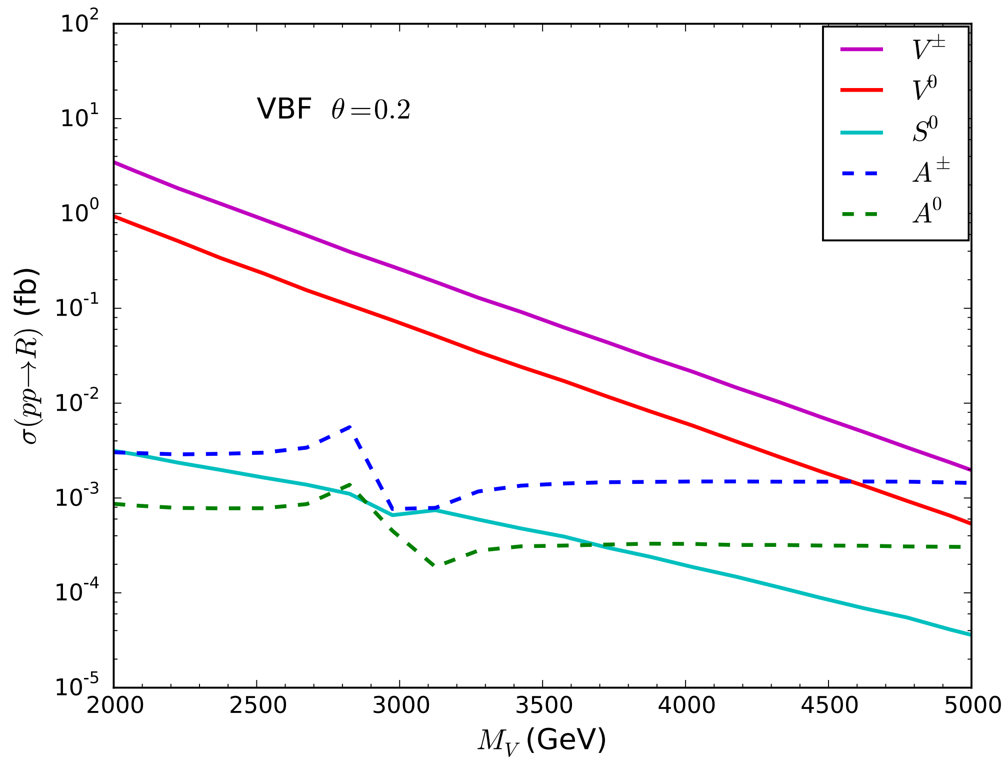


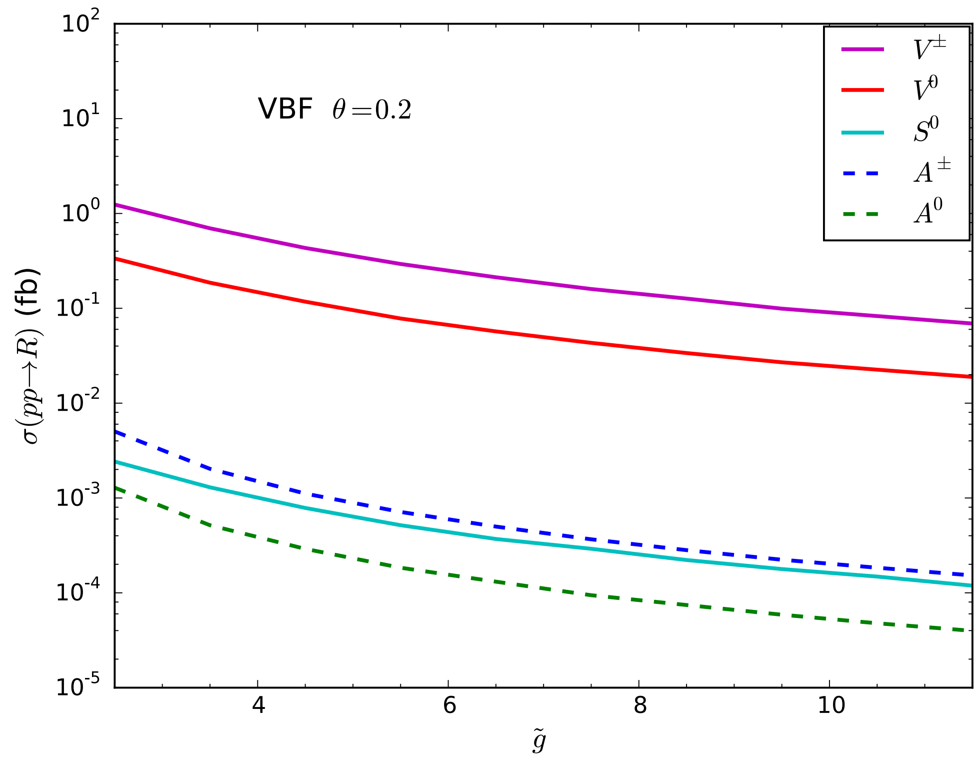
The benchmark point: $M_A = 3$ TeV, $\tilde{g} = 3.0$, $r = 0.6$ and $\theta = 0.2$.

No S^+ state can be directly produced since it is purely composite.

For $M_V = M_A$, cross sections of axial resonances turn out to be zero.

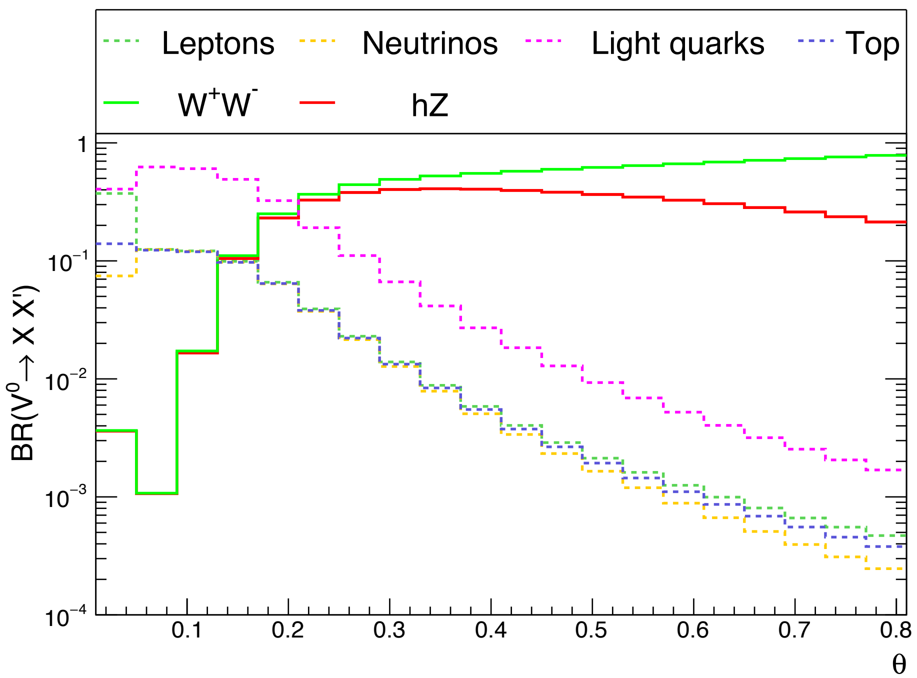
One Feynrule Model is implemented for this SU(4)/Sp(4) model, available at http://hepmdb.soton.ac.uk/hepmdb:0416.0200 we consider normal VBF topology + t-channel radiation diagrams as a gauge invariant set.

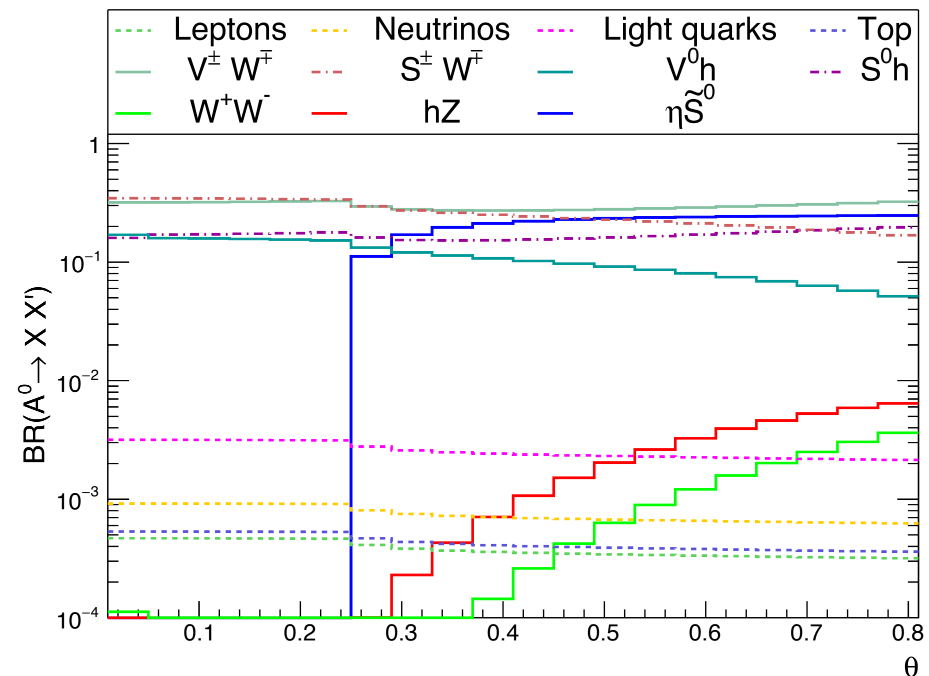




In LHC Run-II, VBF is subdominant and the cross section decreases with $\tilde{g}$.

$M_V < M_A$ Scenario

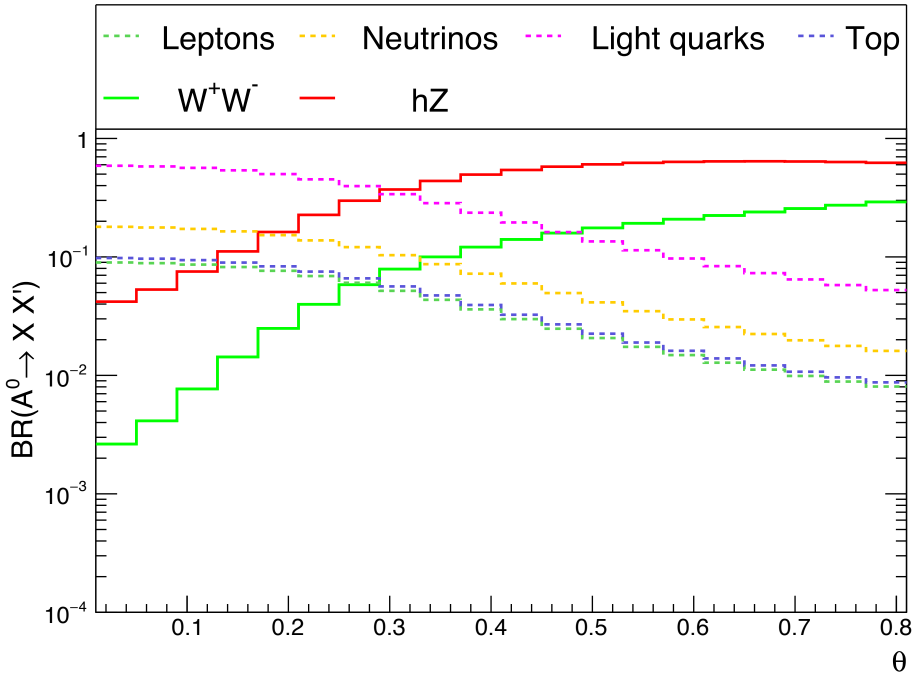


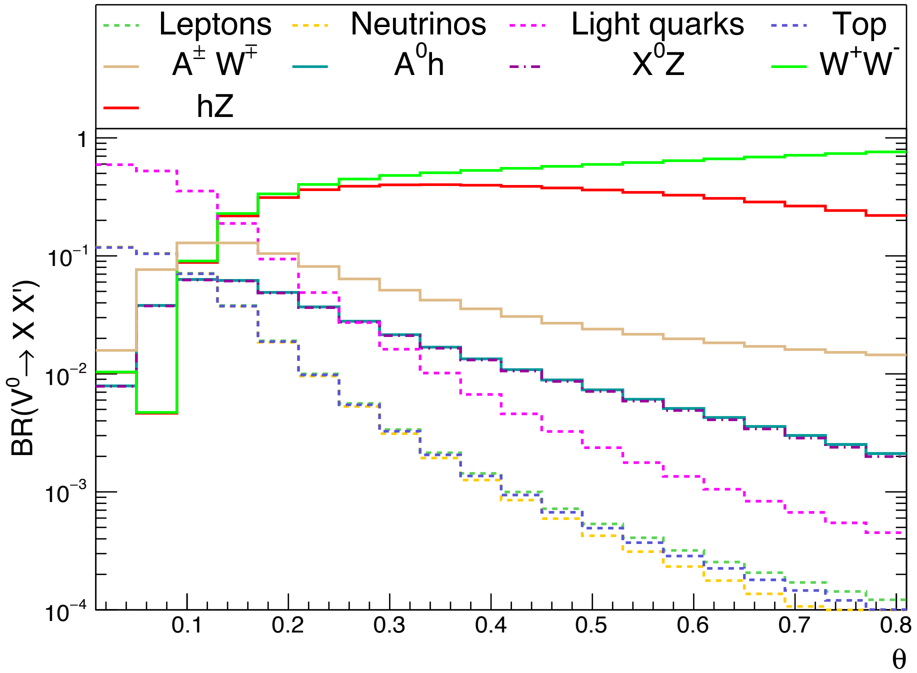


V^0 mainly decays into SM fermions and dibosons and Higgs.

Cascade decay: $A^0 \to \eta \tilde{S}^0 \to 2\eta + Z$, $\eta \to t\bar{t}$. multi-tops events.

$M_A < M_V$ Scenario

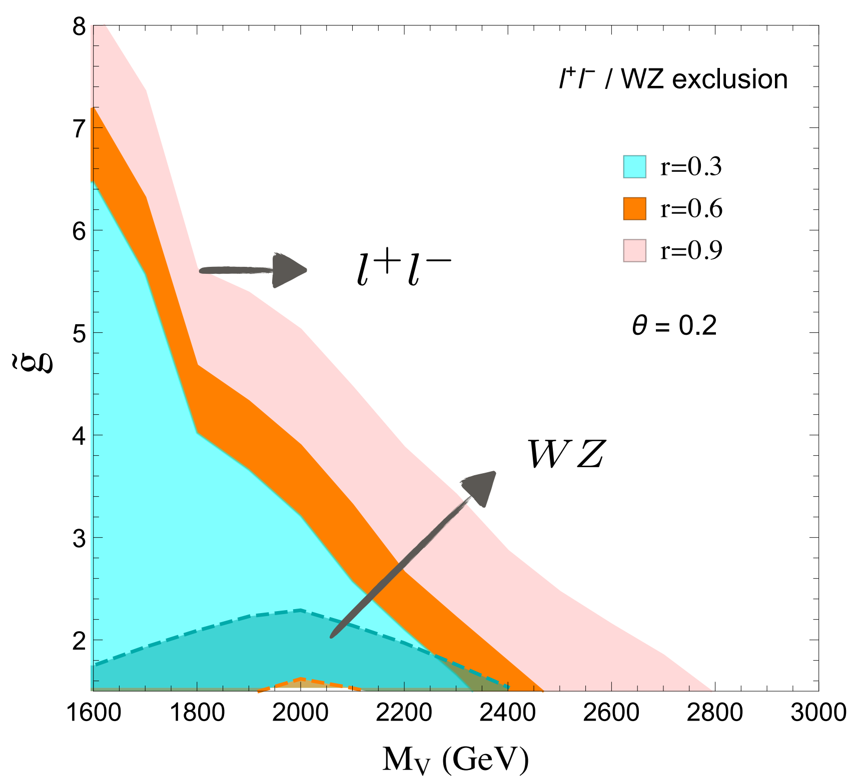


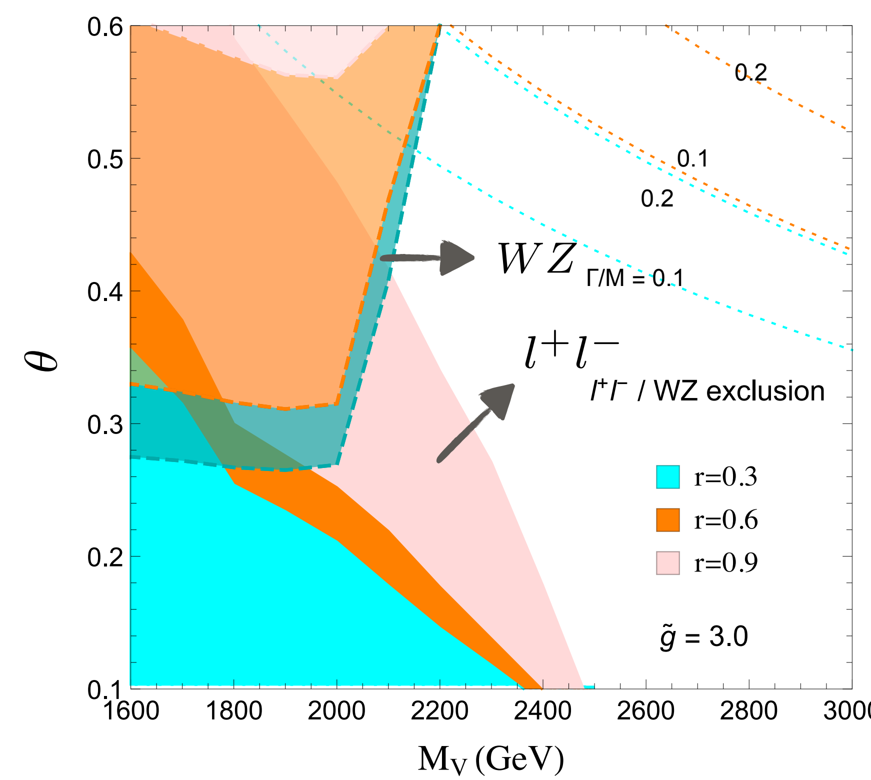


A^0 mainly decays into SM fermions and dibosons and Higgs.

Direct Bounds - LHC Run II

Recasted from ATLAS measurement, with dilepton bound in solid line and WZ bound in dashed line.





The l^+l^- and WZ are complementary to each other.

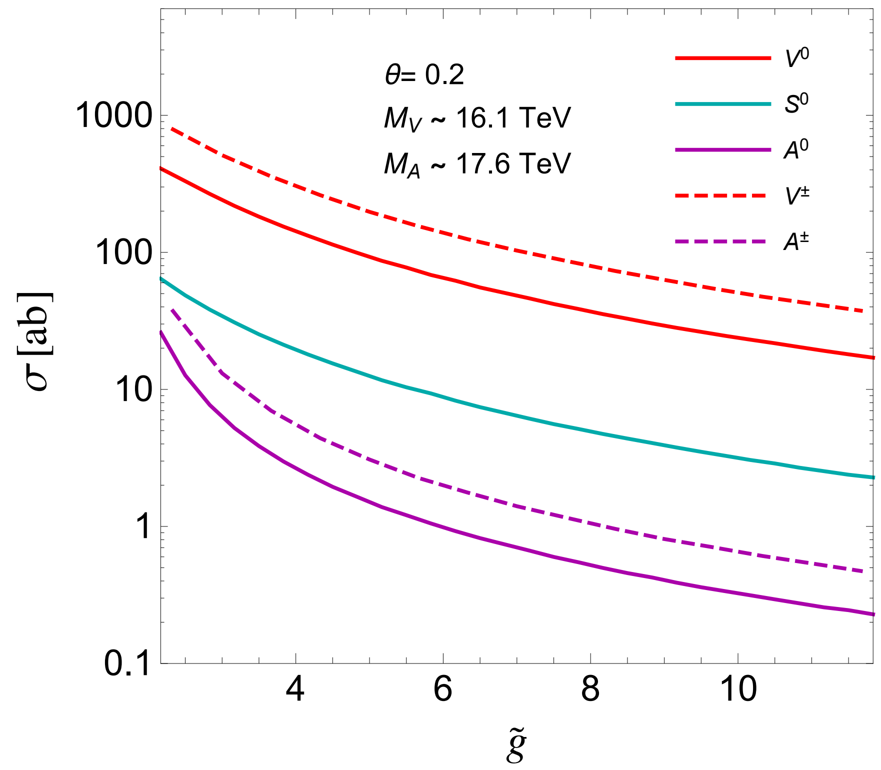
The dilepton exclusion imposes quite strong bound $\Rightarrow M_V \gtrsim 2.5$ TeV !

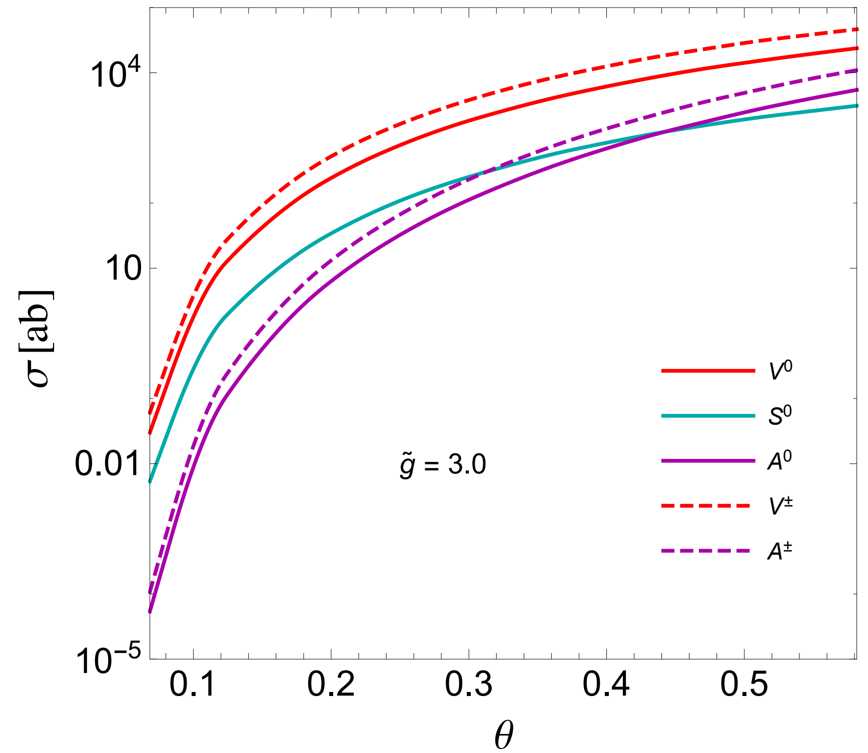
Future100 TeV Collider

Using Lattice benchmark point: $M_V = 3.2/\sin\theta$ TeV, $M_A = 3.5/\sin\theta$ TeV.
[Arthur, Drach, Hansen, Pica, Sannino 2016]

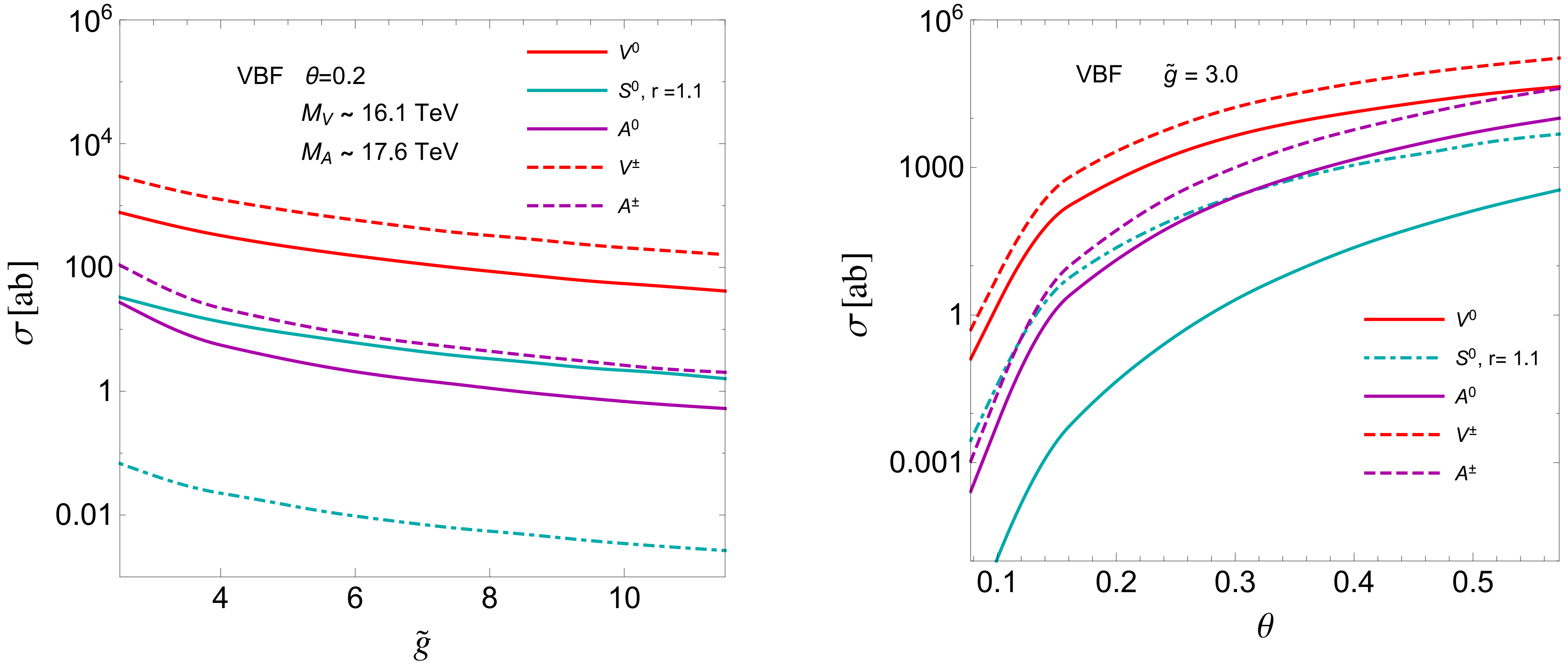
$\sigma_R \lesssim \mathcal{O}(1)$ fb for $\theta \sim 0.2$, with an integrated luminosity $3 - 30ab^{-1}$ per year.
[Richter, 2014; Rizzo, 2015]

Drell-Yan production





At 100 TeV, Vector Boson Fusion plays an important role due to the collinear enhancement, with $\sigma_{VBF} > \sigma_{Drell-Yan}$ for $V^{\pm,0}$ and $A^{\pm,0}$ resonances.



Conclusion and Outlook

- Spin-1 resonances are implemented in a SU(4)/Sp(4) CHM using Hidden symmetry techniques; Composite fermions not included yet.

- S parameter can be well protected due to a partial cancellation.

- The CP parities are illustrated in terms of fermion currents from a fundamental gauge theory.

- At LHC Run-II, the Drell-Yan process imposes a stringent bound. However at 100 TeV collider, some VBF channels become dominant.

- Searching for signatures related to such resonances is possible to unveil EWSB mechanism.

Back up Slides

UV theory and IR Bound States

	$Sp(2N_c)$	$SU(3)_c$	$SU(2)_L$	$U(1)_Y$	SU(4)	SU(6)	U(1)
Q	$\Box$	$\mathbf{1}$	$\mathbf{2}$	1	4	0	$-3(N_c-1)q_\chi$
$Q^\dagger$	$\Box$	$\mathbf{1}$	$\mathbf{1}$	$1/2$ $-1/2$			
χ	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\mathbf{3}$	$\mathbf{1}$	x	$\mathbf{1}$	$\mathbf{6}$	q_χ
$\chi^\dagger$	$\begin{smallmatrix}\Box\\\Box\end{smallmatrix}$	$\bar{\mathbf{3}}$	$\mathbf{1}$	$-x$			

	spin	SU(4)×SU(6)	Sp(4)×SO(6)	names
QQ	0	$(\mathbf{6},\mathbf{1})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{5},\mathbf{1})$	σ π
$\chi\chi$	0	$(\mathbf{1},\mathbf{21})$	$(\mathbf{1},\mathbf{1})$ $(\mathbf{1},\mathbf{20})$	σ_c π_c
χQQ	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_1^1 ψ_1^5
$\chi\bar{Q}\bar{Q}$	1/2	$(\mathbf{6},\mathbf{6})$	$(\mathbf{1},\mathbf{6})$ $(\mathbf{5},\mathbf{6})$	ψ_2^1 ψ_2^5
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{1},\bar{\mathbf{6}})$	$(\mathbf{1},\mathbf{6})$	ψ_3
$Q\bar{\chi}\bar{Q}$	1/2	$(\mathbf{15},\bar{\mathbf{6}})$	$(\mathbf{5},\mathbf{6})$ $(\mathbf{10},\mathbf{6})$	ψ_4^5 ψ_4^{10}
$\bar{Q}\sigma^\mu Q$	1	$(\mathbf{15},\mathbf{1})$	$(\mathbf{5},\mathbf{1})$ $(\mathbf{10},\mathbf{1})$	a ρ
$\bar{\chi}\sigma^\mu\chi$	1	$(\mathbf{1},\mathbf{35})$	$(\mathbf{1},\mathbf{20})$ $(\mathbf{1},\mathbf{15})$	a_c ρ_c

$$\frac{1}{\Lambda^2}\bar{t}_L\chi QQ$$

Top partial compositeness