

# Production of heavy vector resonances at the LHC

Convegno informale di fisica teorica - Sestri Levante 2009

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# Outline

- 1 Introduction to the model: heavy vectors in Higgs-less models
- 2 Double heavy vectors production via gauge boson fusion at the LHC
- 3 Double heavy vectors production via Drell-Yan annihilation at the LHC
- 4 Conclusions

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## The slogan

### Slogan

*The bad news is that the Higgs doesn't exist.  
The good news is that you don't need him.*

## Why we need the Higgs boson?

- To explain the Electroweak Symmetry Breaking  $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$

We can assume that a doublet (the Higgs) with  $Y = \frac{1}{2}$  and  $V = -\frac{m^2}{2}H^2 + \frac{\lambda}{4}H^4$  gets a VEV in its lower component which is neutral under  $Q = Y + T_3$

### In formulae

$$H = \begin{pmatrix} h^+ \\ h^0 \end{pmatrix} = \frac{e^{i\pi^a T^a}}{v} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}$$

So the four vectors  $W_\mu^\pm$ ,  $W_\mu^3$  and  $B_\mu$  eat the three Goldstones, giving massive  $W_\mu^\pm$  and  $Z_\mu$

### In formulae

$$\begin{aligned} |D_\mu \langle H \rangle|^2 &= \left| \frac{gW_\mu^a \sigma^a + g'B_\mu \sigma^3}{2} \begin{pmatrix} 0 \\ \frac{v}{\sqrt{2}} \end{pmatrix} \right|^2 \\ &= \frac{g^2 v^2}{4} W^+ W^- + \frac{v^2}{8} (W_\mu^3 \ B_\mu) \begin{pmatrix} g^2 & -gg' \\ -gg' & (g')^2 \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix} \end{aligned}$$

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 $W_L W_L \rightarrow W_L W_L$  scattering without the Higgs boson

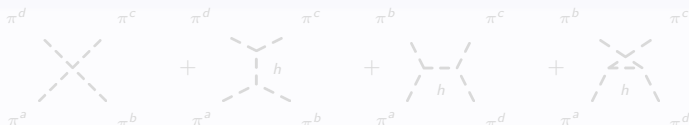
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$$= \frac{s}{v^2} \delta^{ab} \delta^{cd} + \frac{t}{v^2} \delta^{ac} \delta^{bd} + \frac{u}{v^2} \delta^{ad} \delta^{bc}$$

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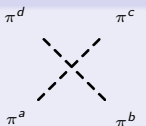


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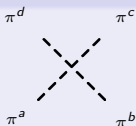


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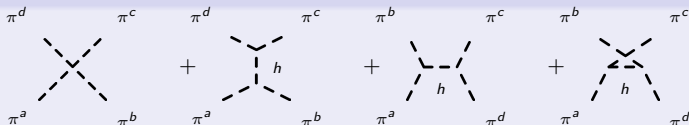
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- To explain the Electroweak Symmetry Breaking  $SU(2)_L \otimes U(1)_Y \rightarrow U(1)_{em}$   
 Inspired in chiral QCD we can consider an exponential representation of  $SU(2)$

In formulae

$$U(x) = e^{\frac{i\pi^a(x)T^a}{v}} \quad U \rightarrow g_R U g_L^\dagger, \quad g_{L,R} \in SU(2)_{L,R}$$

The masses for  $W_\mu^\pm$  and  $Z_\mu$  are generated by the zero order of the non-linear chiral Lagrangian

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$$\mathcal{L}_X^{(2)}(U) = \frac{v^2}{4} \langle D_\mu U (D^\mu U)^\dagger \rangle, \quad (1)$$

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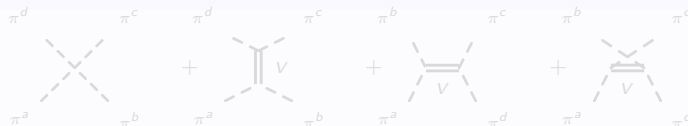
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## Why we don't need an Higgs boson

- To keep  $S$ -matrix unitarity in longitudinal  $WW$  scattering up to a higher cut-off  $\Lambda$

Unitarity is preserved up to  $\Lambda \approx 3\text{TeV}$  if an heavy vector resonance exchange contribute to the  $W_L W_L \rightarrow W_L W_L$

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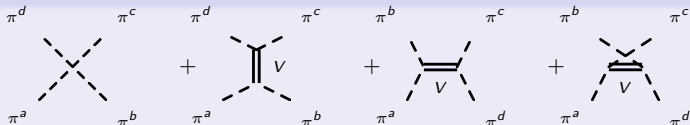
$$\begin{aligned}
 &= \left[ \frac{s}{v^2} - \frac{G_V^2}{v^4} \left[ 3s + M_V^2 \left( \frac{s-u}{t-M_V^2} + \frac{s-t}{u-M_V^2} \right) \right] \right] \delta^{ab} \delta^{cd} \\
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## The Electroweak Chiral Lagrangian with two heavy vectors

- The kinetic term for the heavy vectors

The heavy vector resonances can be described by antisymmetric tensor fields

In formulae

$$\mathcal{L}_{kin}(\hat{R}^{\mu\nu}) = -\frac{1}{2} \langle \nabla_\mu \hat{R}^{\mu\nu} \nabla^\rho \hat{R}_{\rho\nu} \rangle + \frac{M_R^2}{4} \langle \hat{R}^{\mu\nu} \hat{R}_{\mu\nu} \rangle, \quad \hat{R}^{\mu\nu} = \hat{A}^{\mu\nu}, \hat{V}^{\mu\nu}, \quad (2)$$

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- The most fundamental is the antisymmetric tensor description (G. Ecker et al., Phys. Rev. Lett. B 223 425 (1989); Nucl. Phys. B 321 (1989) 311).

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- At high energy the contact term Lagrangian can be neglected since it gives a contribution of order  $g^2$ .

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## Production of a single heavy vector

- Widely studied
- Vector boson fusion is the most relevant process  
 The amplitudes grow with the C.M. energy
- Drell-Yan annihilation processes also relevant for the LHC
- Cross sections appetible to the LHC in few years

### Result

$$\sigma(pp \rightarrow Vqq) \approx \text{few } pb$$

$$N = \sigma(pp \rightarrow Vqq) \times L(\text{few years}) \approx \text{some events}$$

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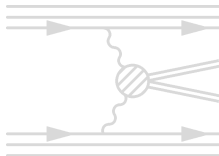
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$$\sigma(pp \rightarrow Vqq) \approx \text{few } pb$$

$$N = \sigma(pp \rightarrow Vqq) \times L(\text{few years}) \approx \text{some events}$$

## Production of a couple of heavy vectors

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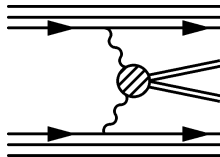
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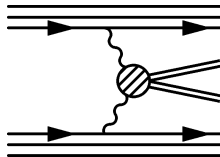
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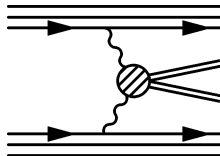
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## The Effective Vector Boson Approximation

- At high energy the Effective Vector Boson Approximation works quite well  
 The EVBA is similar to the Effective Photon Approximation: the gauge bosons  $G$  have a luminosity into the quarks

In formulae

$$f_{q/G_{\pm}}(x) = \frac{1}{16\pi^2} \left[ \frac{|v_q^G \mp a_q^G|^2 + |v_q^G \pm a_q^G|^2 (1-x)^2}{x} \right] \ln \left( \frac{\hat{s}}{M_G^2} \right), \quad (7a)$$

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# The Effective Vector Boson Approximation

- The total cross section is thus given by the convolution of the “partonic” cross section  $GG' \rightarrow VV'$  with these luminosities and with the pdfs.

## In formulae

$$\begin{aligned}
 & \sigma^{pp \rightarrow G_\lambda G'_{\lambda'}, qq \rightarrow VV' qq} (s) \\
 &= \int_{\frac{4M_V^2}{s}}^1 dz \left\{ \sum_{i,j} \int_z^1 \frac{dy}{y} \int_y^1 \frac{dx}{x} \left[ f_{q_i}(x, \mu^2) f_{q_j}\left(\frac{y}{x}, \mu^2\right) + f_{\bar{q}_i}(x, \mu^2) f_{\bar{q}_j}\left(\frac{y}{x}, \mu^2\right) \right. \right. \\
 &+ f_{\bar{q}_i}(x, \mu^2) f_{q_j}\left(\frac{y}{x}, \mu^2\right) + f_{q_i}(x, \mu^2) f_{\bar{q}_j}\left(\frac{y}{x}, \mu^2\right) \left. \right] \left[ \int_{\frac{z}{y}}^1 \frac{dx'}{x'} f_{q_i/G_\lambda}(x') f_{q_j/G'_{\lambda'}}\left(\frac{z}{x'}\right) \right] \\
 &\times \left[ \frac{1}{64\pi z s \left(\frac{zs}{4} - M_G^2\right)} \int_{\hat{t}_{min}}^{\hat{t}_{max}} d\hat{t} |\mathcal{A}(G_\lambda G'_{\lambda'} \rightarrow VV')|^2 \right] \Bigg\}. \tag{8}
 \end{aligned}$$

## The amplitudes

- The amplitudes for the longitudinal-longitudinal vector boson fusion grow with the C.M. energy

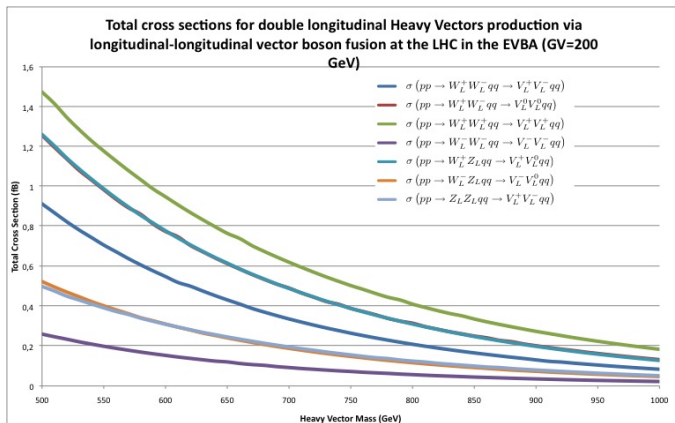
### In formulae

$$\begin{aligned}
 & \mathcal{A} \left( W_L^a W_L^b \rightarrow V_L^c V_L^d \right) \\
 &= \frac{u-t}{2v^2} \left( \delta^{ac} \delta^{bd} - \delta^{ad} \delta^{bc} \right) + \frac{G_V^2}{v^4} \left[ \frac{s(M_V^2+t)^2}{t(s-4M_V^2)} \delta^{ad} \delta^{bc} + \frac{s(M_V^2+u)^2}{u(s-4M_V^2)} \delta^{ac} \delta^{bd} \right. \\
 & \quad \left. - \frac{s}{(s-4M_V^2)} \left( \frac{(M_V^2+t)^2}{t} + \frac{(M_V^2+u)^2}{u} \right) \delta^{ab} \delta^{cd} \right], \tag{9}
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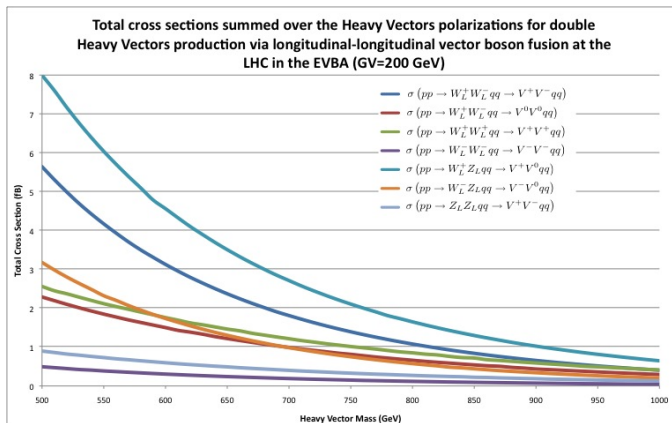
## The total cross sections in the EVBA: $pp \rightarrow G_L G_L' qq \rightarrow V_L V_L' qq$

- Total cross section for double longitudinal heavy vectors production via longitudinal-longitudinal vector boson fusion at the LHC (14 TeV of CM energy) in the EVBA for  $G_V = 200$  GeV



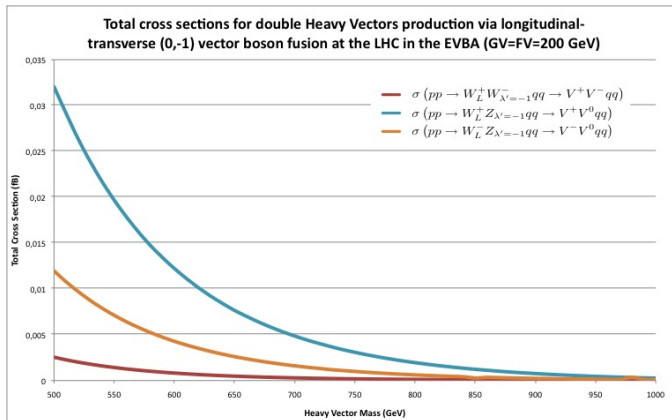
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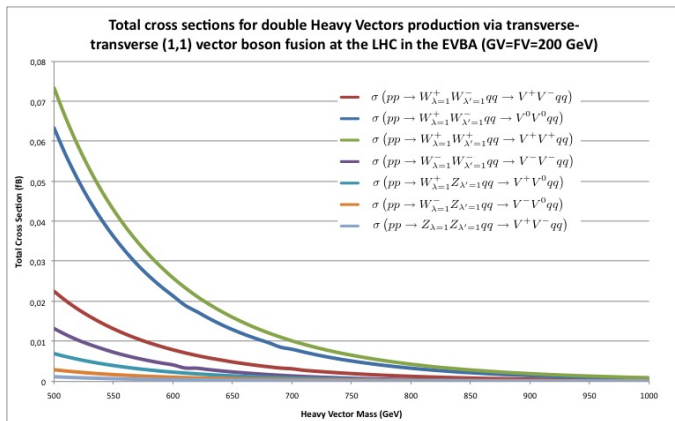
# The total cross sections in the EVBA: $pp \rightarrow G_T G'_L qq \rightarrow V_L V'_L qq$

- An example of the total cross sections for double heavy vectors production via longitudinal-transverse vector boson fusion at the LHC (14 TeV of CM energy) in the EVBA for  $F_V = G_V = 200$  GeV



# The total cross sections in the EVBA: $pp \rightarrow G_T G'_T qq \rightarrow V_L V'_L qq$

- An example of the total cross sections for double heavy vectors production via transverse-transverse vector boson fusion at the LHC (14 TeV of CM energy) in the EVBA for  $F_V = G_V = 200$  GeV



## Going beyond the EVBA

- Although the EVBA works well at high energy it is well known that it can give an overestimate of the true cross section
- It is impossible to make kinematical cuts on the transverse momenta of the outgoing quarks in the EVBA
- It is necessary to go beyond the EVBA making the exact calculation in which the gauge bosons are correctly taken off-shell
- The model in the vector representation can be simply implemented into CalcHEP
- CalcHEP allows the automation of the exact calculation and generates partonic events
- With parton shower and hadronization utility like Pythia the final state can be studied

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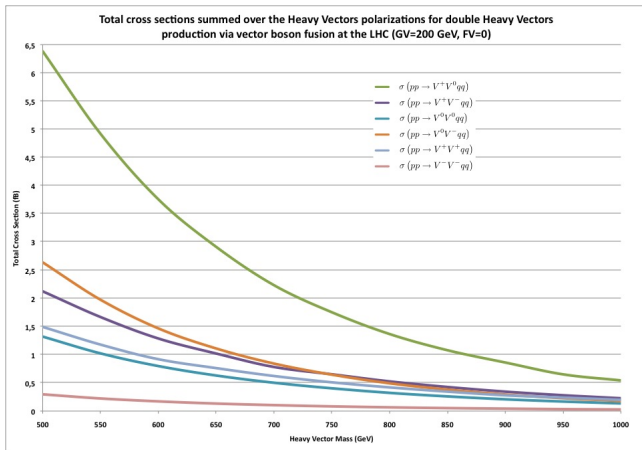
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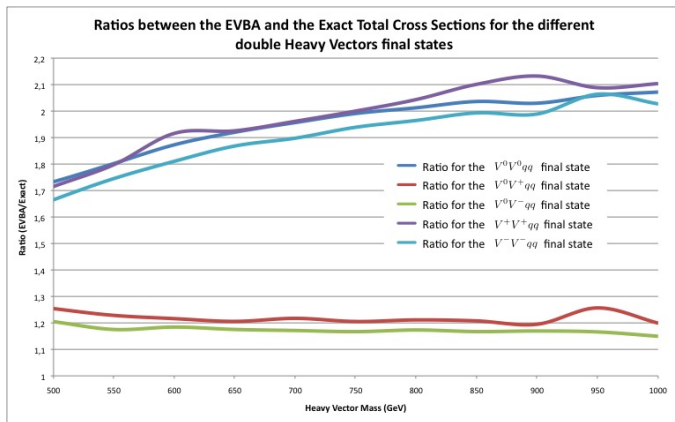
## Results for the Exact total cross sections

- The exact total cross section can be computed with CalcHEP



## EVBA vs exact calculations

- The ratios between the EVBA and the exact total cross sections are between 1.1 to 2.2 in agreement with the expected overestimate



## Drell-Yan double production

- A couple of heavy vector resonances can be produced via  $q\bar{q}$  annihilation
- These processes are more favorable from a phase space point of view:  $2 \rightarrow 2$
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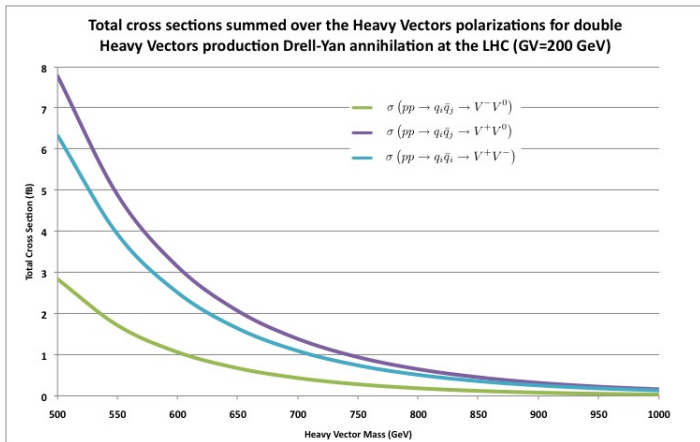


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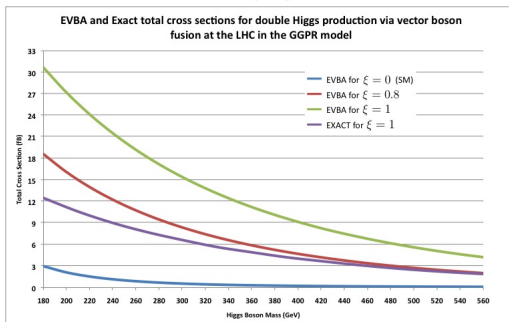
## Drell-Yan double production: results

- The cross sections for the Drell-Yan production of two heavy vectors



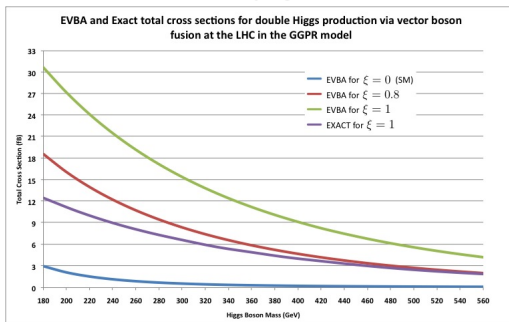
## The composite Higgs model

- The strongly interacting Higgs model of G. F. Giudice, C. Grojean, A. Pomarol and R. Rattazzi (JHEP 0706:045) was studied in the framework of double Higgs production at  $\xi = 1$
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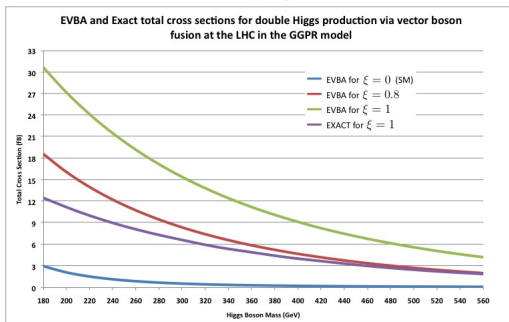
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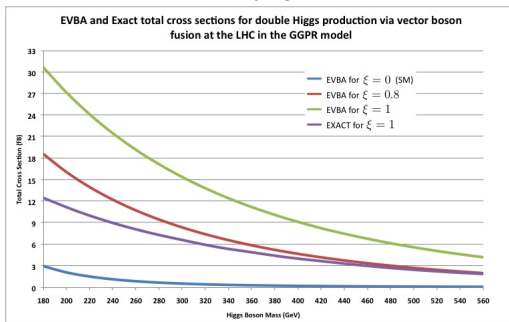
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