Heavy Vector production at LHC in the Chiral Lagrangian formulation with massive spin one fields.

Antonio Enrique Cárcamo Hernández
Scuola Normale Superiore, Pisa, Italy.

Frascati Spring School 2009, Young Researches Workshop

Outline

Motivation

Effective Chiral Lagrangian formulation with massive spin 1 fields is motivated by:

- Absence of experimental evidence of the Higgs boson.
- Need of an Effective Field Theory description of the Standard Model.
- Need of keeping unitarity of the longitudinal W boson scattering under control up to energies of the order of TeV.
- Chiral perturbation theory in QCD which describes SSB in strong interactions.

Outline

Effective Chiral Lagrangian with massive spin 1 fields.

The following $SU(2)_L \times SU(2)_R$ invariant Lagrangian at $O(p^2)$ describing the coupling of heavy fields $V^{\mu\nu}$ and $A^{\mu\nu}$ to Goldstone bosons and Standard Model gauge fields, invariant under parity is considered [1]:

$$
\begin{aligned}
\mathcal{L} \;=\;& \frac{v^2}{4} Tr\left(D_\mu U \left(D^\mu U\right)^\dagger\right) - \frac{1}{2} Tr\left(\nabla^\lambda V_{\lambda\mu} \nabla_\nu V^{\nu\mu} - \frac{1}{2} M_V^2 V_{\mu\nu} V^{\mu\nu}\right) \\
& - \frac{1}{2} Tr\left(\nabla^\lambda A_{\lambda\mu} \nabla_\nu A^{\nu\mu} - \frac{1}{2} M_A^2 A_{\mu\nu} A^{\mu\nu}\right) \\
& + \frac{iG_V}{2\sqrt{2}} Tr\left(V^{\mu\nu}\left[u_\mu, u_\nu\right]\right) + \frac{F_V}{2\sqrt{2}} Tr\left[V^{\mu\nu}\left(uW_{\mu\nu}u^\dagger + u^\dagger B_{\mu\nu} u\right)\right] \\
& + \frac{F_A}{2\sqrt{2}} Tr\left[A^{\mu\nu}\left(uW_{\mu\nu}u^\dagger - u^\dagger B_{\mu\nu} u\right)\right]
\end{aligned}
\tag{1}
$$

where the covariant derivate ∇_μ acting on the $V_{\mu\nu}$ and $A_{\mu\nu}$ antisymmetric spin one tensor fields is defined as:

$$\nabla_\mu R = \partial_\mu R + [\Gamma_\mu, R], \qquad R = V, A \tag{2}$$

with Γ_μ the connection which contains Goldstone bosons and the Standard Model Gauge fields and is given by:

$$\begin{aligned} \Gamma_\mu &= \frac{1}{2}\left[u^\dagger\left(\partial_\mu - i\widehat{B}_\mu\right)u + u\left(\partial_\mu - i\widehat{W}_\mu\right)u^\dagger\right] \\ u &= \exp\left(i\frac{\phi(x)}{2v}\right), \qquad \widehat{W}_\mu = \frac{g}{2}\tau^a W^a_\mu \\ \widehat{B}_\mu &= \frac{g'}{2}\tau^3 B_\mu \end{aligned} \tag{3}$$

Besides that, we have that the term u_μ which transforms like a triplet is given by:

$$u_\mu = u_\mu^\dagger = iu^\dagger D_\mu U u^\dagger = iu^\dagger\left(\partial_\mu U - i\widehat{B}_\mu U + iU\widehat{W}_\mu\right)u^\dagger \tag{4}$$

It is important to mention that under the group $SU(2)_L \times SU(2)_R$, U has the following transformation property:

$$U \rightarrow g_R U g_L^\dagger, \qquad g_{L,R} \in SU(2)_{L,R} \tag{5}$$

While under $SU(2)_{L+R}$, we have that U transforms as:

$$U \rightarrow hUh^\dagger, \qquad h \in SU(2)_{L+R} \tag{6}$$

Moreover, we have that R and $\nabla_\mu R$ have the following transformation properties under the group $SU(2)_L \times SU(2)_R$:

$$R \rightarrow hRh^\dagger, \qquad \nabla_\mu R \rightarrow h\nabla_\mu Rh^\dagger, \qquad h \in SU(2)_{L+R} \tag{7}$$

And the antisymmetric spin one tensor fields $V_{\mu\nu}$ and $A_{\mu\nu}$ are given by:

$$V_{\mu\nu} = \frac{1}{\sqrt{2}}\sum_{a=1}^{3}\tau^a V_{\mu\nu}^a, \qquad A_{\mu\nu} = \frac{1}{\sqrt{2}}\sum_{a=1}^{3}\tau^a A_{\mu\nu}^a \tag{8}$$

Outline

Scattering amplitude for the process $\pi^a\pi^b \to \pi^c\pi^d$.

The scattering amplitude for the process $\pi^a\pi^b \to \pi^c\pi^d$ is:

$$\begin{aligned} A\left(\pi^a\pi^b \to \pi^c\pi^d\right) &= A\left(\pi^a\pi^b \to \pi^c\pi^d\right)_{\pi^4} + A\left(\pi^a\pi^b \to \pi^c\pi^d\right)_V \\ &+ A\left(\pi^a\pi^b \to \pi^c\pi^d\right)_W \\ &= A\left(s,t,u\right)\delta^{ab}\delta^{cd} + A\left(t,s,u\right)\delta^{ac}\delta^{bd} \\ &+ A\left(u,t,s\right)\delta^{ad}\delta^{bc} \end{aligned} \tag{9}$$

where $A\left(s,t,u\right)$ is given by:

$$\begin{aligned} A\left(s,t,u\right) &= \frac{s}{v^2} + \frac{g^2}{2}\left(1 - \frac{s^2}{ut}\right) \\ &- \frac{G_V^2}{v^4}\left[3s + M_V^2\left(\frac{s-u}{t-M_V^2} + \frac{s-t}{u-M_V^2}\right)\right] \end{aligned} \tag{10}$$

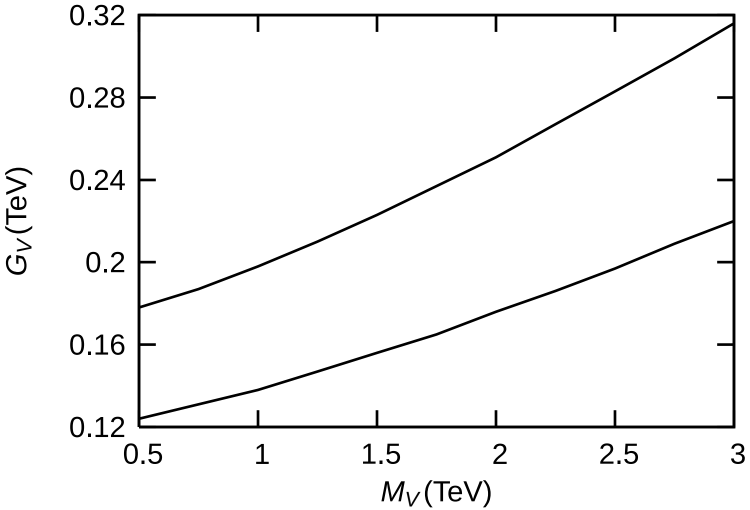

Figure 1: Strongest unitarity constraint in the (M_V, G_V) **plane for the process** $\pi^a\pi^b \longrightarrow \pi^c\pi^d$ **at** $\sqrt{s} = 3TeV$.

Outline

Scattering amplitude for the process $\pi^a\pi^b \to V_L^c V_L^d$.

The scattering amplitude for the process $\pi^a\pi^b \to V_L^c V_L^d$ is:

$$
\begin{aligned}
A\left(\pi^a\pi^b \to V_L^c V_L^d\right) &= A\left(\pi^a\pi^b \to V_L^c V_L^d\right)_{\pi^2V^2} \\
&+ A\left(\pi^a\pi^b \to V_L^c V_L^d\right)_{\pi} + A\left(\pi^a\pi^b \to V_L^c V_L^d\right)_{W} \\
&= A(s,t,u)\,\delta^{ab}\delta^{cd} + B(s,t,u)\,\delta^{ac}\delta^{bd} \\
&+ B(s,u,t)\,\delta^{ad}\delta^{bc}
\end{aligned}
\tag{11}
$$

where $A(s,t,u)$ and $B(s,t,u)$ are given by:

$$
\begin{aligned}
B(s,t,u) &= \frac{u-t}{2v^2} + \frac{G_V^2 s\left(u+M_V^2\right)^2}{v^4 u\left(s-4M_V^2\right)} + \frac{g^2F_V^2 u\left(u+M_V^2\right)^2}{4v^2u^2\left(s-4M_V^2\right)} \\
&- \frac{g^2G_V^2\left[M_V^4 s + ut\left(t-u-2M_V^2\right) + u\left(t^2+u^2\right)\right]}{4v^2u^2\left(s-4M_V^2\right)}
\end{aligned}
$$

$$
A(s,t,u) = -\left(B(s,t,u) + B(s,u,t)\right)
$$

Outline

Total cross sections at LHC for the processes $qq \to G_\kappa G_{\kappa'} qq \to VVqq$.

In the framework of the effective vector boson approximation one has that the total cross section for the process $qq \to G_\kappa G_{\kappa'} qq \to VVqq$ where $G = W, Z$ can be written as:

$$
\begin{aligned}
\sigma_{qq\to G_\kappa G_{\kappa'} qq\to VVqq}(s) &= \int_{\frac{2M_V}{\sqrt{s}}}^{1} dx \int_{\frac{2M_V}{\sqrt{s}}}^{1} dy f_{p/G_\kappa}(x) f_{p/G_{\kappa'}}(y) \\
&\times \sigma_{G_\kappa G_{\kappa'}\to VV}(xys) \\
&= \int_{\frac{4M_V^2}{s}}^{1} dz \left.\frac{dL}{dz}\right|_{pp/G_\kappa G_{\kappa'}} \sigma_{G_\kappa G_{\kappa'}\to VV}(zs)
\end{aligned}
$$

Where $\left.\frac{dL}{dz}\right|_{pp/G_\kappa G_{\kappa'}}$ is the luminosity of the G_κ vector bosons in a proton-proton system given by:

$$\begin{aligned}\left.\frac{dL}{dz}\right|_{pp/G_\kappa G_{\kappa'}} &= \sum_{i,j}\int_z^1 \frac{dy}{y}\int_y^1 \frac{dx}{x}\left\{q_i\left(x,\mu^2\right) q_j\left(\frac{y}{x},\mu^2\right)\right. \\ &+ \bar{q}_i\left(x,\mu^2\right)\bar{q}_j\left(\frac{y}{x},\mu^2\right) \\ &+ \left. q_i\left(x,\mu^2\right)\bar{q}_j\left(\frac{y}{x},\mu^2\right) + \bar{q}_i\left(x,\mu^2\right) q_j\left(\frac{y}{x},\mu^2\right)\right\} \\ &\quad \times \left.\frac{dL}{d\xi}\right|_{q_i q_j/G_\kappa G_{\kappa'}}\left(\xi = \frac{z}{y}\right)\end{aligned}$$

where i and j are flavour index, $\mu \simeq O\left(2M_V\right)$ is the factorization scale

$\left.\frac{dL}{d\xi}\right|_{q_iq_j/G_\kappa G_{\kappa'}}$ is the effective luminosity for emission of a pair of gauge bosons G_κ and $G_{\kappa'}$ from a pair of quarks q_i and q_j defined as:

$$\left.\frac{dL}{d\xi}\right|_{q_iq_j/G_\kappa G_{\kappa'}}(\xi) = \int_\xi^1 \frac{dx}{x} f_{q_i/G_\kappa}(x)\, f_{q_j/G_{\kappa'}}\left(\frac{\xi}{x}\right) \qquad (12)$$

being $f_{q_i/G_\kappa}(x)$ the G_κ distribution in a quark q_i, with $\kappa = -1, 0.1$. In the case of longitudinal polarized gauge boson, the splitting function $f_{q_i/G_0}(x)$, for very high energies such that $E >> M_G$, is given by:

$$f_{q_i/G_{\kappa=0}}(x) = \frac{C_V^2 + C_A^2}{4\pi^2}\frac{1-x}{x} \qquad (13)$$

While in the case of transverse polarized gauge boson, the corresponding spliting function is given by:

$$f_{q_i/G_{\kappa=\pm 1}}(x) = \frac{1}{16\pi^2}\left[\frac{(C_V \mp C_A)^2 + (C_V \pm C_A)^2(1-x)^2}{x}\right] \times \ln\left(\frac{\widehat{s}}{M_G^2}\right) \tag{14}$$

where $\widehat{s} = zs$ is the center of mass energy of the incoming quarks, being $s = 196\,(TeV)^2$ the square of ther center of mass energy of the proton-proton system.

We also have that C_V and C_A are the vector and axial couplings for the quark-quark-gauge boson interaction. For $G = W$, we have:

$$C_V = -C_A = \frac{g}{2\sqrt{2}} = \frac{\sqrt{\pi\alpha(M_Z)}}{\sin\theta_W\sqrt{2}}, \qquad \alpha(M_Z) = \frac{1}{128} \tag{15}$$

and for $G = Z$:

$$C_V = \frac{\sqrt{\pi\alpha(M_Z)}}{\sin\theta_W \cos\theta_W}\left(T_{3L} - 2Q\sin^2\theta_W\right) \tag{16}$$

$$C_A = \frac{g}{2\cos\theta_W}T_{3L} = \frac{\sqrt{\pi\alpha(M_Z)}}{\sin\theta_W\cos\theta_W}T_{3L} \tag{17}$$

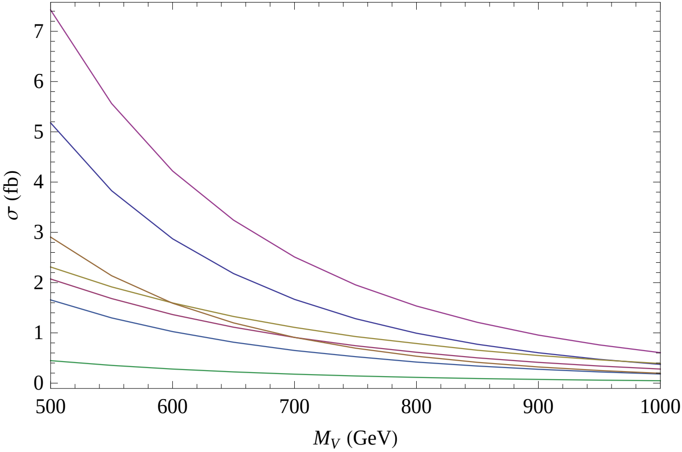

Figure 1: Total cross sections at LHC for the vector production process $W_L^+Z_L \to V^+V^0$, $W_L^+W_L^- \to V^+V^-$, $W_L^-Z_L \to V^-V^0$, $W_L^+W_L^+ \to V^+V^+$, $W_L^+W_L^- \to V^0V^0$, $Z_LZ_L \to V^+V^-$ and $W_L^-W_L^- \to V^-V^-$ from longitudinal gauge boson fusion.

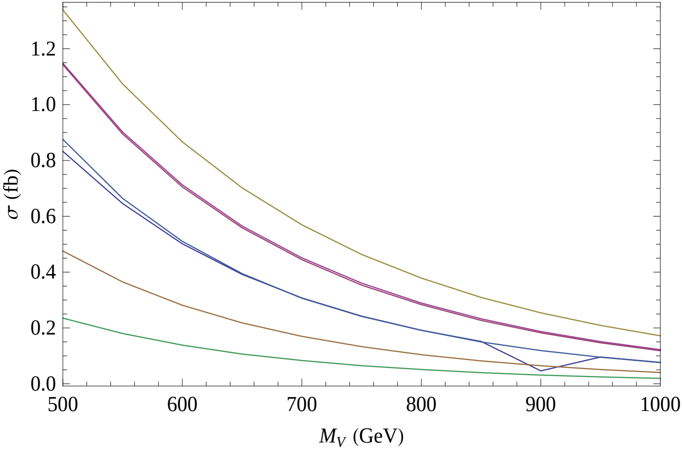

Figure 2: Total cross sections at LHC for the longitudinal vector production process $W_L^+W_L^+ \to V_L^+V_L^+$, $W_L^+Z_L \to V_L^+V_L^0$, $W_L^+W_L^- \to V_L^0V_L^0$, $Z_LZ_L \to V_L^+V_L^-$, $W_L^+W_L^- \to V_L^+V_L^-$, $W_L^-Z_L \to V_L^-V_L^0$ and $W_L^-W_L^- \to V_L^-V_L^-$ from longitudinal gauge boson fusion.

Process	$\sigma\,(fb)$	Process	$\sigma\,(fb)$
$W_L^+W_L^- \to V_L^+V_L^-$	0.83	$W_L^+W_L^- \to V^+V^-$	5.18
$W_L^+W_L^- \to V_L^0V_L^0$	1.14	$W_L^+W_L^- \to V^0V^0$	2.07
$W_L^+W_L^+ \to V_L^+V_L^+$	1.34	$W_L^+W_L^+ \to V^+V^+$	2.31
$W_L^-W_L^- \to V_L^-V_L^-$	0.24	$W_L^-W_L^- \to V^-V^-$	0.45
$Z_LZ_L \to V_L^+V_L^-$	0.88	$Z_LZ_L \to V^+V^-$	1.66
$W_L^+Z_L \to V_L^+V_L^0$	1.15	$W_L^+Z_L \to V^+V^0$	7.42
$W_L^-Z_L \to V_L^-V_L^0$	0.48	$W_L^-Z_L \to V^-V^0$	2.91

Table 1: Total cross sections at LHC for the processes of longitudinal and vector production by longitudinal vector boson fusion at $M_V = 500$GeV.

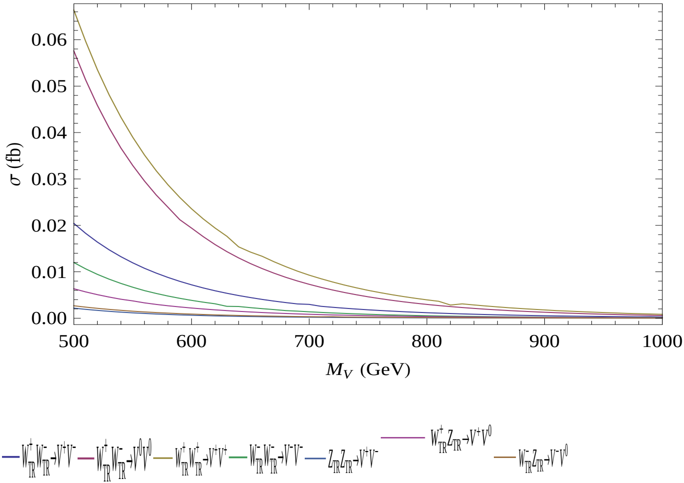

Figure 3: Total cross sections at LHC for the vector production processes by transverse gauge boson fusion. Right-right polarization case.

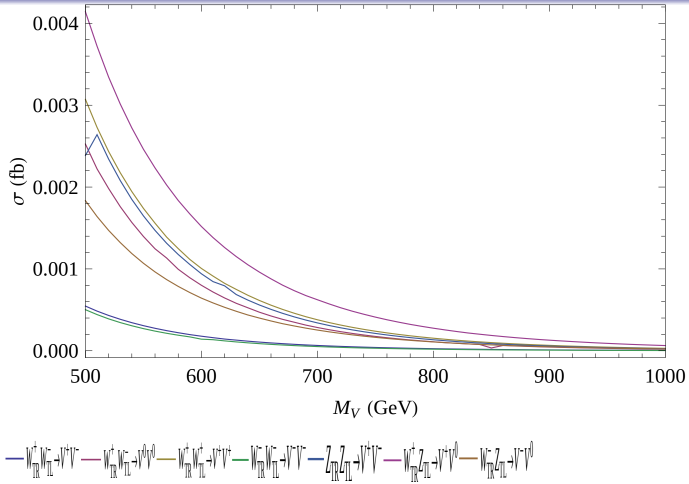

Figure 4: Total cross sections at LHC for the vector production processes by transverse gauge boson fusion. Right-left polarization case.

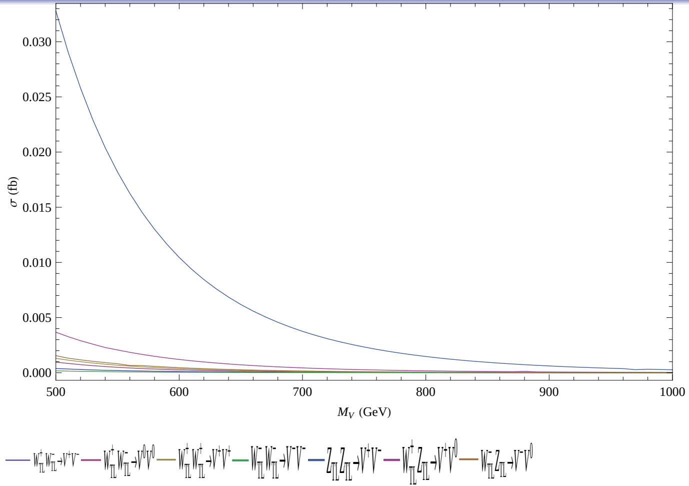

Figure 5: Total cross sections at LHC for the vector production processes by transverse gauge boson fusion. Left-left polarization case.

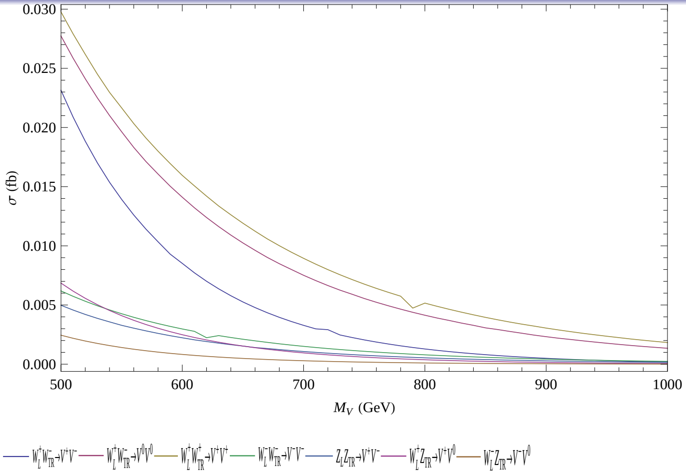

Figure 6: Total cross sections at LHC for the vector production processes by longitudinal-transverse right polarized gauge boson fusion.

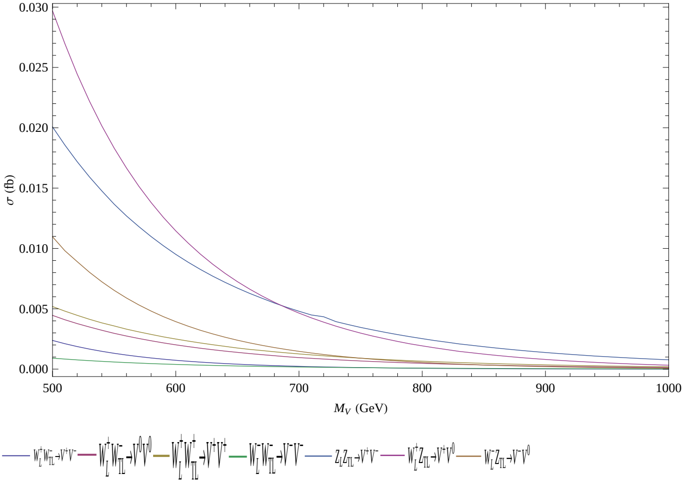

Figure 7: Total cross sections at LHC for the vector production processes by longitudinal-transverse left polarized gauge boson fusion.

Outline

Total cross sections at LHC for vector production by Drell Yan Mechanism.

The squared amplitude for the processes $q\bar{q} \to V^+V^-$ and $q_i\bar{q}_j \to V^{\pm}V^0$ with $i = u, c, j = d, s, b$ or $j = u, c, i = d, s, b$ summed over the polarization states of V's and over the spin states of the quarks and antiquarks is given by:

$$\sum_{\xi,\xi',\chi,\chi'} \left|A\left(q\bar{q} \to V^+V^-\right)\right|^2$$

$$= \frac{g^4}{M_V^2}\left[\frac{\left(g_V^2+g_A^2\right)\left(\cos^2\theta_W - \sin^2\theta_W\right)^2}{8\cos^4\theta_W\left(\hat{s}-M_Z^2\right)^2} + \frac{2Q^2\sin^4\theta_W}{\hat{s}^2}\right.$$

$$\left. + \frac{2Qg_V\sin^2\theta_W\left(\cos^2\theta_W - \sin^2\theta_W\right)}{\cos^2\theta_W\hat{s}\left(\hat{s}-M_Z^2\right)}\right] f\left(\hat{s},\hat{t},\hat{u}\right)$$

$$\sum_{\xi,\xi',\chi,\chi'} \left| A\left(q_i\overline{q}_j \rightarrow V^+V^0\right)\right|^2 = \frac{g^4\left|V_{ij}\right|^2}{8M_V^2\left(\widehat{s}-M_W^2\right)^2} f\left(\widehat{s},\widehat{t},\widehat{u}\right)$$

where $f\left(\widehat{s},\widehat{t},\widehat{u}\right)$ is givwen by:

$$\begin{aligned} f\left(\widehat{s},\widehat{t},\widehat{u}\right) &= \widehat{s}\left(\widehat{s}-4M_V^2\right)\left(\widehat{s}+3M_V^2\right) \\ &-2M_V^2\left[\left(\widehat{t}-\widehat{u}\right)^2-4\widehat{s}M_V^2\right] \\ &-\frac{1}{2}\left(\widehat{t}+\widehat{u}\right)\left[\widehat{s}\left(\widehat{t}+\widehat{u}\right)+\left(\widehat{t}-\widehat{u}\right)^2\right] \end{aligned}$$

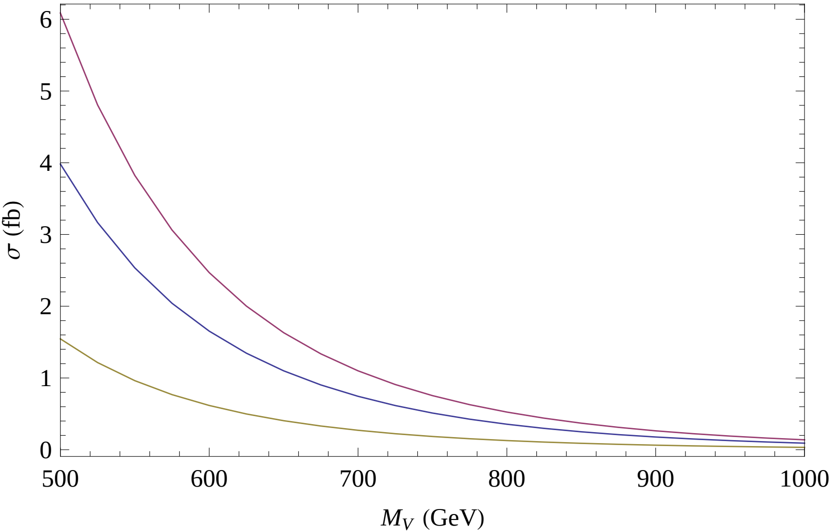

Figure 8: Total cross sections at LHC for the V^+V^-, V^+V^0 and V^-V^0 vector production, respectively by Drell Yan Mechanism.

Outline

Cross section for the V^+V^- production in e^+e^- collisions.

The squared amplitude for the process $e^+e^- \to V^+V^-$ summed over the polarization states of V's and over the spin states of the electron and positron is given by:

$$\sum_{\xi,\xi',\chi,\chi'} \left|A\left(e^+e^- \to V^+V^-\right)\right|^2$$

$$= \frac{g^4}{M_V^2}\left[\frac{\left(g_V^2+g_A^2\right)\left(\cos^2\theta_W-\sin^2\theta_W\right)^2}{8\cos^4\theta_W\left(\widehat{s}-M_Z^2\right)^2}+\frac{2\sin^4\theta_W}{\widehat{s}^2}\right.$$

$$\left.-\frac{2g_V\sin^2\theta_W\left(\cos^2\theta_W-\sin^2\theta_W\right)}{\cos^2\theta_W\widehat{s}\left(\widehat{s}-M_Z^2\right)}\right]f\left(\widehat{s},\widehat{t},\widehat{u}\right)$$

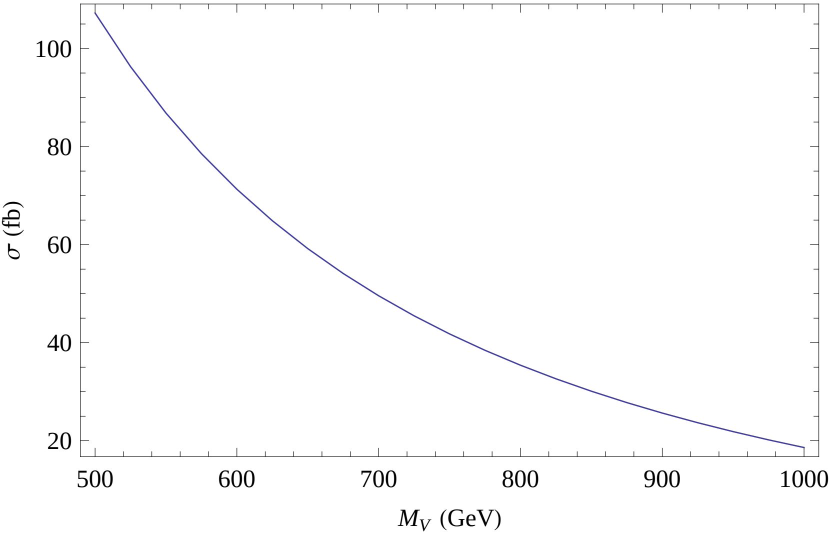

Figure 9: Cross section for the V^+V^- vector production in e^+e^- collisions at $\sqrt{s} = 3$TeV.

Outline

Conclusions.

- The transverse polarization states and the interference between longitudinal and transverse polarization states of V give a significant contribution to the total cross section for vector production.
- The most relevant vector production processes at LHC are longitudinal vector boson fusion and Drell Yang mechanism.
- Transverse polarization states of gauge bosons are irrelevant for vector production.
- Charged vector production process in e^+e^- collisions is very promising.

References

- R. Barbieri, G. Isidori, V. S. Rychkov and E. Trincherini, hep-ph/0806.1624v1.
- G. Ecker et al, Phys. Rev. Lett. **B 223** (1989) 425; Nucl. Phys. **B 321** (1989) 311
- M. J. Herrero, hep-ph/9601286v1.
- S. Dawson, Nucl. Phys. **B 249** (1985) 42, hep-ph/9901280v1.
- C. Quigg, hep-ph/0704.2232v2.
- A. Djouadi, hep-ph/0503172v2.
- A. V. Manohar, hep-ph/9606222v1.
- A. Pich, hep-ph/9806303v1.