WW scattering at LHC

Saurabh D. Rindani

Physical Research Laboratory
Ahmedabad

From Strings to LHC, Goa
8 January, 2007

Outline

1. Introduction
   - Unitarity limit
   - Equivalence Theorem
2. $W_L W_L$ scattering beyond Higgs mechanism
   - Electroweak chiral Lagrangians
   - Higgless models
3. $W_L W_L$ scattering at LHC
   - Backgrounds
   - Distinguishing the signal
   - Equivalent vector-boson approximation
   - Isolating WW scattering
4. Some other issues
5. Summary

Introduction

- The SM Higgs boson will be seen at LHC
- If not, implication for SM is that the Higgs is very heavy
- Higgs mass greater than 1 TeV or so implies violation of perturbative unitarity for WW scattering
- WW interactions become strong
- Possibility of resonance(s) or some other new physics

Introduction

- The SM Higgs boson will be seen at LHC
- If not, implication for SM is that the Higgs is very heavy
- Higgs mass greater than 1 TeV or so implies violation of perturbative unitarity for WW scattering
- WW interactions become strong
- Possibility of resonance(s) or some other new physics

Why I would be very sad if a Higgs boson were discovered

H. Georgi (Harvard U.) 1993.

In *Kane, G.L. (ed.): Perspectives on Higgs physics* 337-342

Higgs and WW scattering

- Amplitudes with massive spin-1 particles have bad high-energy behaviour

$$\varepsilon_L^{\mu}(k) \approx \frac{k^{\mu}}{m_V}$$

- This can make theory non-renormalizable
- In theories with spontaneous symmetry breaking, high-energy behaviour is better
- Higgs exchange can cancel bad high-energy behaviour
- If Higgs mass is too high ($s << m_H^2$), amplitude can be large:

  $\Longrightarrow$ Strong gauge sector
- Can be studied with $W_L W_L$ scattering

Unitarity limit

- SM relation

$$m_H^2 = -2\mu^2 = 2\lambda v^2 = \lambda\sqrt{2}/G_F$$

- Since v and G_F are fixed from experiment, large m_H means large λ.
- For $m_H \gtrsim (G_F/\sqrt{2})^{-1}$, perturbation theory is not valid.
- This corresponds to $m_H \approx 300$ GeV
- A limit may be obtained from unitarity, if the tree amplitudes are to be valid at high energies.

(Dicus & Mathur 1973; Lee, Quigg & Thacker 1977)

Limit from perturbative unitarity

- In the absence of Higgs, or for a very heavy Higgs, the conditions for partial-wave unitarity

$$|a_\ell| \leq 1; \ |\Re a_\ell| \leq \frac{1}{2}.$$

are violated for

$$s > 16\pi v^2 \approx (1.2 \ \mathrm{TeV})^2$$

- Above this energy, perturbative unitarity breaks down
- *WW* scattering becomes strong implying effects like resonances
- Alternatively, new physics restores unitarity
- In the standard model, unitarity gives an upper limit on the Higgs mass:

$$m_H < \left(4\sqrt{2}\pi/G_F\right)^{1/2} \approx 1.2 \ \mathrm{TeV}.$$

WW scattering and symmetry breaking

- Vector boson scattering amplitudes at high energies may be calculated using the equivalence theorem valid to all orders in gauge and symmetry breaking interactions (Cornwall, Levin & Tiktopoulose 1974; Vayonakis 1976; Lee, Quigg & Thacker 1977; Chanowitz & Gaillard 1985; Veltman 1990 ...)
- The equivalence theorem states that at higher energy ($s >> m_W^2$), scattering amplitudes for scattering of longitudinal gauge bosons are equal to the amplitudes for scattering of the corresponding “would-be" Goldstone scalars at high energy ($s >> m_W^2$)

$$
\begin{aligned}
M(W_L W_L \rightarrow W_L W_L) &= M(ww \rightarrow ww) \\
M(Z_L Z_L \rightarrow Z_L Z_L) &= M(zz \rightarrow zz) \\
M(W_L Z_L \rightarrow W_L Z_L) &= M(wz \rightarrow wz) \\
M(W_L W_L \rightarrow Z_L Z_L) &= M(ww \rightarrow zz)
\end{aligned}
$$

Low energy theorems

- Goldstone boson interactions are governed by low-energy theorems for energy below the symmetry breaking scale ($s << m^2_{\rm SB}$)
- Low energy theorems are analogous to those obtained for $\pi\pi$ scattering in the chiral Lagrangian

  (S. Weinberg)
- Thus, when there is no light Higgs (with $m_H < 1$ TeV or so), the low-energy theorems combined with equivalence theorem can predict $W_L W_L$ scattering amplitudes from the symmetries of the theory to leading order in $s/m^2_{\rm SB}$
- The specific theory for symmetry breaking then shows up at the next higher order in $s/m^2_{\rm SB}$

Models with no light Higgs

- In the absence of light Higgs, $W_L W_L$ interactions become strong
- Violation of unitarity is prevented in different ways, depending on the model
- Models can have extra fermions and extra gauge interactions, which give additional contributions to $W_L W_L$ scattering, e.g., resonances
- An example is techni-rho resonance in techni-color model, or new MVB's in Higgsless models
- A no-resonance scenario is described in a chiral Lagrangian (EWCL) model, where one can write effective bosonic operators
- Unitarization can be built in by the use of Padé approximants or K matrix method and these can generate resonance kind of behaviour

Electroweak chiral Lagrangian

- Terms in the chiral lagrangian must respect (spontaneously broken) $SU(2)_L \times U(1)$ gauge symmetry.
- Experiment demands that the Higgs sector also approximately respect a larger, $SU(2)_L \times SU(2)_C$ symmetry, though the $SU(2)_C$ custodial symmetry is broken by the Yukawa couplings and the $U(1)$ gauge couplings.
- The chiral lagrangian is thus constructed using the dimensionless unitary unimodular matrix field $U(x)$, which transforms under $SU(2)_L \times SU(2)_C$ as $(2,2)$.
- Pieces of the chiral Lagrangian in $M_H \to \infty$ limit of the linear theory at tree level are:

$$\mathscr{L}_0 \equiv \frac{1}{4} f^2 Tr[(D_\mu U)^\dagger (D^\mu U)] - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{2} Tr W_{\mu\nu} W^{\mu\nu},$$

Electroweak chiral Lagrangian

- An additional dimension-two operator allowed by the $SU(2)_L \times U(1)$ symmetry:

$$\mathscr{L}_1{}' \equiv \frac{1}{4}\beta_1 g^2 f^2 [Tr(TV_\mu)]^2.$$

- This term, which does not emerge from the $M_H \to \infty$ limit of the renormalizable theory at tree level, violates the $SU(2)_C$ custodial symmetry even in the absence of the gauge couplings.
- It is the low energy description of whatever custodial-symmetry breaking physics exists, and has been integrated out, at energies above roughly $\Lambda_\chi \equiv 4\pi f \simeq 3\text{TeV}$.
- At tree level, $\mathscr{L}_1{}'$ contributes to the deviation of the ρ parameter from unity.

Electroweak chiral Lagrangian

- At the dimension-four level, there are a variety of new operators that can be written down.
- Making use of the equations of motion, and first restricting attention to CP-invariant operators, the list can be reduced to eleven independent terms:

$$\mathscr{L}_1 \equiv \frac{1}{2}\alpha_1 g g' B_{\mu\nu} Tr(TW^{\mu\nu}) \qquad \mathscr{L}_2 \equiv \frac{1}{2} i\alpha_2 g' B_{\mu\nu} Tr(T[V^\mu, V^\nu])$$

$$\mathscr{L}_3 \equiv i\alpha_3 g Tr(W_{\mu\nu}[V^\mu, V^\nu]) \qquad \mathscr{L}_4 \equiv \alpha_4 [Tr(V_\mu V_\nu)]^2$$

$$\mathscr{L}_5 \equiv \alpha_5 [Tr(V_\mu V^\mu)]^2 \qquad \mathscr{L}_6 \equiv \alpha_6 Tr(V_\mu V_\nu) Tr(TV^\mu) Tr(TV^\nu)$$

$$\mathscr{L}_7 \equiv \alpha_7 \; Tr(V_\mu V^\mu) Tr(TV_\nu) Tr(TV^\nu) \qquad \mathscr{L}_8 \equiv \frac{1}{4}\alpha_8 \, g^2 \, [Tr(TW_{\mu\nu})]^2$$

$$\mathscr{L}_9 \equiv \frac{1}{2} i\alpha_9 g Tr(TW_{\mu\nu}) Tr(T[V^\mu, V^\nu]) \qquad \mathscr{L}_{10} \equiv \frac{1}{2}\alpha_{10} [Tr(TV_\mu) Tr(TV_\nu)]^2$$

$$\mathscr{L}_{11} \equiv \alpha_{11} g \varepsilon^{\mu\nu\rho\lambda} \; Tr(TV_\mu) Tr(V_\nu W_{\rho\lambda})$$

Unitarization

- Low energy theorems predict $W_L W_L$ scattering to the leading order, s/m_{SB}^2, given the symmetries of the theory.
- Higher orders in s/m_{SB}^2 depend on the theory.
- In EWCL, one can build in unitarity at a given order by using a non-perturbative modification, which reduces to the original amplitude at the perturbative level
- Write a low-energy expansion as $a(s) = a^{\mathrm{LET}}(s) + a^{(1)}(s)$
- At the lowest order Padé approximant gives

$$a^{\mathrm{Pade}}(s) = \frac{a^{\mathrm{LET}}(s)}{1 - \frac{a^{(1)}(s)}{a^{\mathrm{LET}}(s)}}$$

- K matrix method gives

$$a^{K}(s) = \frac{a^{\mathrm{LET}}(s) + \mathrm{Re}a^{(1)}(s)}{1 - ia^{\mathrm{LET}}(s) + \mathrm{Re}a^{(1)}}$$

- Both satisfy unitarity by construction to the relevant order

Higgless models

- A number of Higgsless models have been proposed recently
  [C. Csaki et al., Phys. Rev. D 69, 70 (2004), Phys. Rev. Lett. 92 (2004), Y. Nomura, JHEP 11 (2003)]
- Symmetry breaking is achieved by appropriate boundary conditions
- They differ in spatial dimensions, 5 in the original versions, 4 in the "deconstructed" versions
- They differ in embedding of SM fermions
- New weakly coupled particles appear at TeV scale and postpone unitarity violation

Higgless models

- A version of the model with modified fermion sector can raise the scale of unitarity violation by at least a factor of 10 without running conflict with precision electroweak constraints.
- In the absence of Higgs, new massive vector boson propagators contribute to *WW* scattering
- The bad high energy behaviour of *WZ* scattering, for example, is cancelled by the contribution of the MVBs because of coupling constant sum rules:

$$g_{WWZZ} = g^2_{WWZ} + \Sigma_i (g^{(i)}_{WZV})^2$$

$$2(g_{WWZZ} - g^2_{WWZ})(M_W^2 + M_Z^2) + g^2_{WWZ} \frac{M_Z^4}{M_W^2}$$

$$= \Sigma_i (g^{(i)}_{WZV})^2 \left[3(M_i^{\pm})^2 - \frac{(M_Z^2 - M_W^2)^2}{(M_i^{\pm})^2} \right]$$

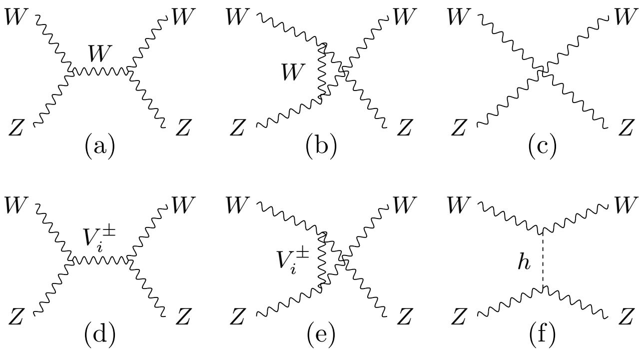


FIG. 1. Diagrams contributing to the $W^\pm Z \to W^\pm Z$ scattering process: (a), (b) and (c) appear both in the SM and in Higgsless models, (d) and (e) only appear in Higgsless models, while (f) only appears in the SM.

Higgless models

- Unitarity is violated at a scale

$$\Lambda \approx \frac{3\pi^4}{g^2}\frac{M_W^2}{M_1^\pm} \approx 5 - 10\ \mathrm{TeV}$$

- The first MVB should appear below 1 TeV, and thus accessible at LHC
- In the approximation that the first state V_1 saturates the sum rules, its partial width is given by

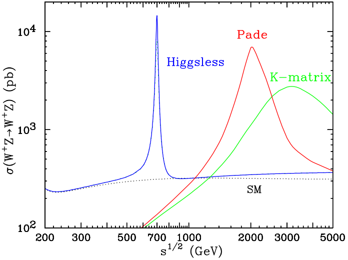
$$\Gamma(V_1^\pm \to W^\pm Z) \approx \frac{\alpha (M_1^\pm)^3}{144 s_W^2 M_W^2}$$

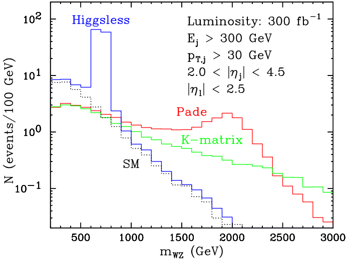
- For $M_1^\pm = 700$ GeV, the width is about 15 GeV
- In SM, there is no resonance in $W^\pm Z$ scattering

WZ scattering in Higgsless model

Cross section for $W^{\pm}Z$ scattering as a function of $\sqrt{s}$ is shown in Higgsless models and two "unitarization models" which attempt to mimic the physics of technicolor type theories.

(EWCL + Padé approximant or K-matrix)

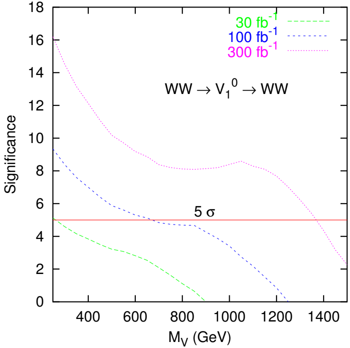




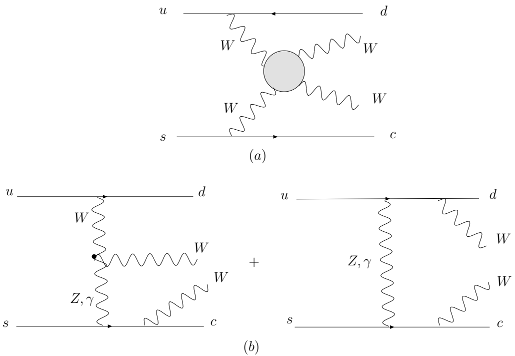
WW scattering in Higgsless model

WW resonance V_1^0 of 1 TeV needs 300 fb$^-$1 at LHC

(R. Malhotra, hep-ph/0611380)



WW contribution vs. others



(b)

Backgrounds

- Backgrounds are of two types:
  1. Bremsstrahlung processes – which do not contribute to VV scattering
  2. Processes which fake VV final state
- It is important to understand the first inherent background, and device cuts which may enhance the signal.
- However, it may be possible to live with it – provided VV scattering signal is anyway enhanced because it is strong. In that case, one simply makes predictions for the combined process of $PP \to VV + X$
- The second background is crucial to take care of, otherwise we do not know if we are seeing a VV pair in the final state or not.

Experimental backgrounds

- Background processes: $q\bar{q} \to W^+W^-X$, $gg \to W^+W^-X$
- $t\bar{t}$ + jet, with top decays giving W^+W^- pair
  Electroweak-QCD process W^+ + jets can mimic the signal when the invariant mass of the two jets is around m_W
- Potential background from QCD processes $q\bar{q}, gg \to t\bar{t}X, Wt\bar{b}$ and $t\bar{t}$ +jets), in which a W can come from the decay of t or $\bar{t}$.
- W boson pairs produced from the intrinsic electroweak process $q\bar{q} \to q\bar{q}W^+W^-$ tend to be transversely polarized
- Coupling to W^+ of incoming quark is purely left-handed
- Helicity conservation implies that outgoing quark follows the direction of incoming quark for longitudinal W, and it goes opposite to direction of incoming quark for transverse (left-handed) W
- Hence outgoing quark jet is less forward in background than in signal event, and tagging of the forward jet can help

Axial gauge vs. unitary gauge vs. EVBA vs. exact results

- The feasibility of extracting WW scattering from experiment and comparison of EVBA with exact results was recently studied by (Accomando et al., Phys. Rev. D 74 (2006))
- It is known that when W's are allowed to be off mass shell, amplitude grows faster with energy, as compared to when they are on shell (Kleiss & Stirling, 1986)
- Problem of bad high-energy behavious of WW scattering diagrams can be avoided by the use of axial gauge (Kunszt and Soper 1988)
- In axial gauge, Goldstone and gauge fields mix, with the gauge propagator given by

$$\left(-g_{\mu\nu} + \frac{q_\mu n_\nu + n_\mu q_\nu}{q \cdot n} - \frac{n^2}{(q \cdot n)^2} q_\mu q_\nu\right) (q^2 - m_W^2)^{-1}$$

Axial gauge vs. unitary gauge vs. EVBA vs. exact results

Accomando et al. examine

- Role of choice of gauge in WW fusion
- Reliability of EVBA
- Determination of regions of phase space, in suitable gauge, which are dominated by the signal (WW scattering diagrams)

Results show that

- WW scattering digrams do not constitute the dominant contribution in any gauge or phase space region
- There is no substitute to the complete amplitude for studying WW fusion process at LHC

Equivalent vector-boson approximation

- Equivalent photon approximation (Weizsäcker-Williams approximation) relates cross section for a charged particle beam (virtual photon exchange) to cross section for real photon beam:

$$\sigma = \int dx\, \sigma_\gamma(x) f_{q/\gamma}(x)$$

- Photon distribution with momentum fraction x in a charged-particle beam of energy E:

$$f_{e/\gamma}(x) = \frac{q^2\alpha}{2\pi x} \ln\left(\frac{E}{m_e}\right) [x + (1-x)^2]$$

- This is generalized to a process with weak bosons (Dawson; Kane et al.; Lindfors; Godbole & Rindani):

$$f_{e/V_\pm}(x) = \frac{\alpha}{2\pi x} \ln\left(\frac{E}{m_V}\right) \left[(v_f \mp a_f)^2 + (1-x)^2 (v_f \pm a_f)^2\right]$$

$$f_{e/V_L}(x) = \frac{\alpha}{\pi x}(1-x)\left[v_f^2 + a_f^2\right]$$

Effective vector boson approximation

Use of effective vector boson approximation entails:

- Restricting to vector boson scattering diagrams
- Neglecting diagrams of bremsstrahlung type
- Putting on-shell momenta of the vector bosons which take part in the scattering
- Note that the on-shell point $q_{1,2}^2 = M_{V_{1,2}}^2$ is outside the physical region $q_{1,2}^2 \leq 0$.
- Approximating the total cross section of the process $f_1 f_2 \to f_3 f_4 V_3 V_4$ by the convolution of the vector boson luminosities $\mathscr{L}_{Pol_1 Pol_2}^{V_1 V_2}(x)$ with the on-shell cross section:

$$\sigma(f_1 f_2 \to f_3 f_4 V_3 V_4) = \int dx \sum_{V_1, V_2} \sum_{pol_1 pol_2} \mathscr{L}_{pol_1 pol_2}^{V_1 V_2}(x) \times \sigma_{pol}^{on}(V_1 V_2 \to V_3 V_4, x s_{qq})$$

Here $x = M(V_1 V_2)^2 / s_{qq}$, while $M(V_1 V_2)$ is the vector boson pair invariant mass and s_{qq} is the partonic c.m. energy.

Improved Equivalent vector-boson approximation

- Even if only dominant (?) longitudinal polarization is kept, EVBA overestimates the true cross section
- Transverse polarization contribution is found to be comparable to longitudinal one (Godbole & Rindani)
- Improved EVBA (Frederick, Olness& Tung), going beyond the leading approximation still overestimates the cross section (Godbole & Olness)
- Further improvements have been attempted (Kuss & Spiesberger)

WW contribution vs. others

No Higgs

	$\sigma(pb)$		
Gauge	All diagrams	WW diagrams	ratio WW/all
Unitary	$1.86\ 10^{-2}$	6.67	358
Feynman	$1.86\ 10^{-2}$	0.245	13
Axial	$1.86\ 10^{-2}$	$3.71\ 10^{-2}$	2

Table: No Higgs contribution, using the CTEQ5 Pdf set with scale M_W

$M_H = 200$ GeV

	$\sigma(pb)$		
Gauge	All diagrams	WW diagrams	ratio WW/all
Unitary	$8.50\ 10^{-3}$	6.5	765
Feynman	$8.50\ 10^{-3}$	0.221	26
Axial	$8.50\ 10^{-3}$	$2.0\ 10^{-2}$	2.3

Table: M_h =200 GeV Higgs and $M(WW) > 300$ GeV .

WW invariant mass distribution

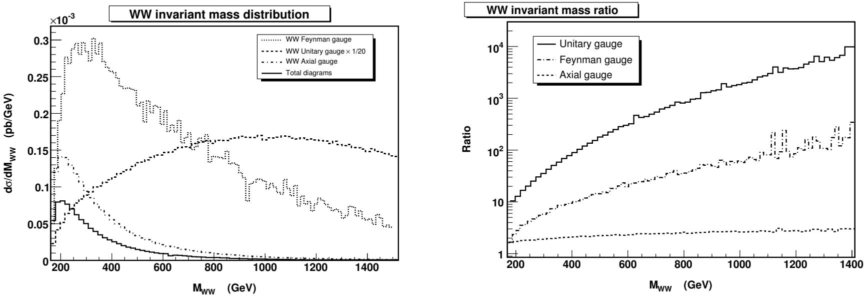


Figure: Distribution of $d\sigma/dM_{WW}$ for the process $PP \to us \to cdW^+W^-$ for All diagrams, WW diagrams and their ratio in Unitary, Feynman and Axial gauge in the infinite Higgs mass limit. The Unitary gauge data in the left hand plot have been divided by 20 for better presentation.

Comparison with EVBA results: WW invariant mass

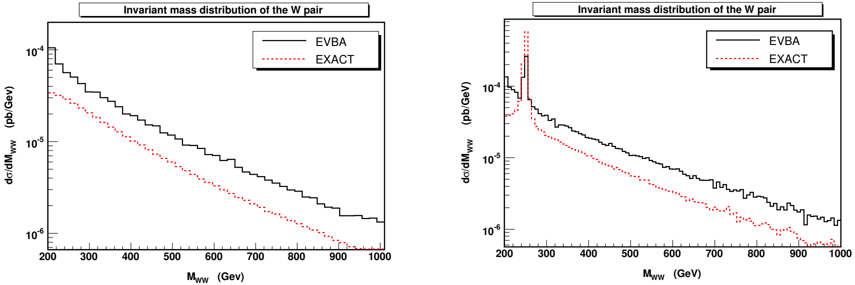


Figure: WW invariant mass distribution $M(WW)$ for the process $us \to dcW^+W^-$ with EVBA (black solid curve) and with exact complete computation (red dashed curve) for no Higgs (left) and M_h=250 GeV (right)

Comparison with EVBA: Total cross section

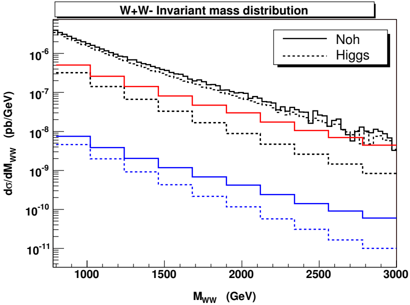
M_h	EVBA (pb)	EXACT (pb)	Ratio
∞	$3.90\ 10^{-2}$	$1.78\ 10^{-2}$	2.17
130 GeV	$3.94\ 10^{-2}$	$1.71\ 10^{-2}$	2.3
250 GeV	$4.61\ 10^{-2}$	$4.09\ 10^{-2}$	1.12
500 GeV	$4.42\ 10^{-2}$	$2.5\ 10^{-2}$	1.77

Table: Total cross sections computed with EVBA and exact computation and their ratio for the process $us \to cdW^+W^-$ at fixed CM energy $\sqrt{s} = 1$ TeV.

θ_{cut}	EVBA (pb)	EXACT (pb)	Ratio
10°	$4.42\ 10^{-2}$	$2.5\ 10^{-2}$	1.77
30°	$1.33\ 10^{-2}$	$2.06\ 10^{-2}$	0.64
60°	$6.06\ 10^{-3}$	$1.28\ 10^{-2}$	0.47

Table: Total cross section in EVBA and exact computation and their ratio for different angular cuts. The CM energy is $\sqrt{s} = 1$ TeV and the Higgs mass M_h=500 GeV.

Large invariant mass region



The WW invariant mass distribution in $PP \to us \to cdW^+W^-$ for no Higgs mass (solid curves) and for M_h=200 GeV (dashed curve). The two intermediate (red) curves are obtained imposing cuts shown below.

The two lowest (blue) curves refer to the process $PP \to us \to cd\mu^-\overline{\nu}_\mu e^+\nu_e$ with further acceptance cuts: $E_l > 20$ GeV, $p_{T_l} > 10$ GeV , $|\eta_l| < 3$.

E(quarks)$>$ 20 GeV
P_T(quarks,W)$>$ 10 GeV
$2 < |\eta(\text{quark})| < 6.5$
$|\eta(\text{W})| < 3$

Table: Selection cuts applied

Some other issues

- Before comparing predictions of new physics predictions, it is necessary to compute more accurately higher order corrections from SM
- It is known that electroweak corrections can be large
- Bloch-Norksieck cancellation does not take place for electroweak processes because of mixing of representations of $SU(2)$ and $U(1)$

  (Ciafaloni, Ciafaloni, Comelli)
- This gives large logarithmic corrections
- For $e^+e^- \to \nu_e \overline{\nu}_e W^+ W^-$, radiative corrections are negative, typically 10%, increasing with energy reaching -20% and -50% at ILC and CLIC respectively

  (E. Accomando, A. Denner, S. Pozzorini, hep-ph/0611289)
- Need to examine the failure of EVBA – is it related to mixing of representations?

Summary

- In the absence of a light Higgs, WW interactions become strong at TeV scales
- Study of WW scattering can give information of the electroweak symmetry breaking sector and discriminate between models
- In general there are large cancellations between the scattering and bremsstrahlung diagrams
- Hence extraction of WW scattering contribution from the process $PP \to W^+W^-X$ needs considerable effort
- EVBA overestimates the magnitude in most kinematic distributions
- Cuts have to be chosen with care to reduce the background