Vector Boson Scattering and Higgs studies at LHC and ILC from a six fermion perspective

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Outline

- Introduction and motivations
- The PHANTOM project
- Phenomenological studies at LHC and ILC

Introduction

Two decades of comparisons with precision data have established the Standard Model as the very successful gauge theory of electroweak and strong interactions

However, at present we do not have yet any evidence of the mechanism responsible for the breaking of the electroweak symmetry (fundamental Higgs scalar(s)? Dynamical symmetry breaking? Extra dimensions?)

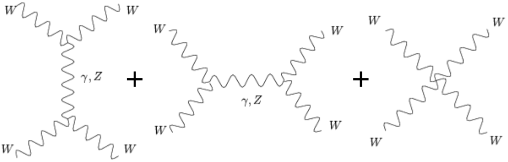
It is commonly agreed that the TeV scale holds clues to address the question of Electroweak Symmetry Breaking (EWSB) and to understand the origin of masses

Tevatron has started to explore the TeV region

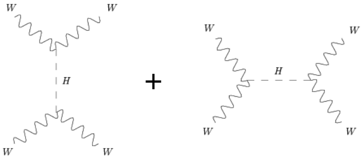
LHC and ILC will complete the picture

Why the TeV scale?

Without a Higgs, the scattering of longitudinally polarized vector bosons has a bad UV behaviour $\therefore$ *violation of perturbative unitarity*



$$\mathcal{M}_{\not{H}} \sim G_F \, s$$



$$\mathcal{M}_H \sim -G_F \, s$$

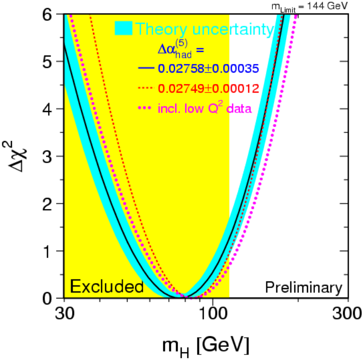
$$\mathcal{M}_{\not{H}} + \mathcal{M}_H \sim \sqrt{2}\, G_F \, M_H^2 \left(\frac{s}{s - M_H^2} + \frac{t}{t - M_H^2} \right)$$

A light Higgs boson unitarizes Vector Boson Scattering

What if no Higgs is found?

EWSB at the TeV scale

The search for Higgs boson(s) represents a direct approach



Limit from direct search:
$M_H > 114.4$ GeV

Upper bound from SM global fit:
$M_H < 182$ GeV (95% CL)

Precision electroweak data favour a *light* Higgs boson

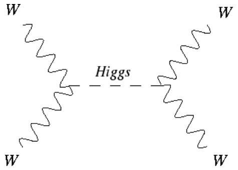
EWSB at the TeV scale

A complementary approach consists in studying the scattering of longitudinally polarized weak bosons

↪ at high energies, they recall their origins as Goldstone bosons and reflect the EWSB dynamics

Different models result in markedly different predictions at high energy

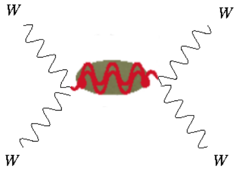
Weakly-coupled scattering



e.g.: SM with a light Higgs, SUSY

VS

Strongly-coupled scattering



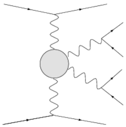
e.g.: Technicolor, Higgless models

Model-independent probe of EWSB (and possible new physics)

The six-fermion perspective

No beam of on-shell heavy bosons will be available in reality...

The only chance to measure boson-boson scattering at LHC (and any other collider) is by extrapolation from *six-fermion* final states



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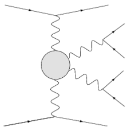

But a consistent definition of *scattering signal* is problematic for several reasons:

- the scattering bosons are *off shell*
  $\hookrightarrow$ differences among predictions about on-shell scattering and the actual results

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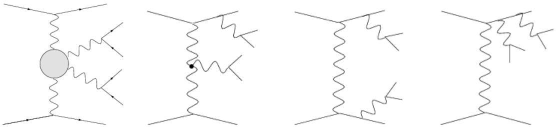


But a consistent definition of *scattering signal* is problematic for several reasons:

- the scattering bosons are *off shell*
  $\hookrightarrow$ differences among predictions about on-shell scattering and the actual results
- the *scattering* contributions are not separately gauge invariant
  $\hookrightarrow$ cannot isolate consistently a *VBS signal* from its *irreducible background* (severe gauge cancellations at work)

The possibility to extract some information about the behaviour of boson-boson scattering cannot prescind from a full six-parton calculation

The scattering signal is fully encompassed into $\mathcal{O}(\alpha^6_{EM})$ diagrams, but in general the amplitude gets additional contributions even at tree level: $\mathcal{O}(\alpha^4_{EM}\alpha^2_S)$, $\mathcal{O}(\alpha^2_{EM}\alpha^4_S)$ ...

$\because$ QCD is a major source of background at LHC

up to hundreds parton-level processes to be evaluated,
up to thousands Feynman diagrams for each process
strongly demand for a *complete* (all processes and all diagrams)
and *dedicated* (efficient) Monte Carlo tool

PHANTOM

$^{(*)}$ PHAct New TOrino Montecarlo

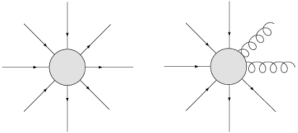
PHANTOM 1.0

Ballestrero, Belhouari, G.B., Kashkan, Maina

Event generator dedicated to six-parton physics at pp, $p\bar{p}$ and e^+e^- colliders

- Exact tree-level matrix elements at $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$
- Full coverage of Standard Model processes at fixed order

$$\begin{matrix} pp \\ p\bar{p} \\ e^+e^- \end{matrix} \longrightarrow \left\{ \begin{matrix} 6f \\ 5f + g \\ 4f + 2g \end{matrix} \right.$$



Holds the signal of

- Higgs production via Vector Boson Fusion $qqH \to qqVV$ ...
- Vector Boson Scattering $WW \to WW, WZ \to WZ$ ...
- Triple Gauge Boson production
- triple/quadruple-vertex EW interactions

together with all EW+QCD irreducible background at FO $t\bar{t}$, $VV + 2j$ ...

Main features

Efficient

- fast *modular* evaluation of helicity amplitudes (with PHACT)
- new integration technique merging *multichannel* with an *adaptive* routine (VEGAS): *iterative-adaptive multichannel*

User friendly

- automatic set-up of reactions managed by PERL scripts
- possibility of unweighted generation of any number of processes at the same time (*oneshot* mode)

Les Houches ready

- interface to pdf's and showering/hadronization via Les Houches Accord; new Les Houches Event File (LHEF) format

All-in-one

- one dedicated tool for 6f physics at hadron and e^+e^- colliders

My contributions to PHANTOM:

- *virtual-gluon* matrix elements

  calculation of $\mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$ contributions to all processes with 8 external fermions

- extension of the *multichannel* apparatus

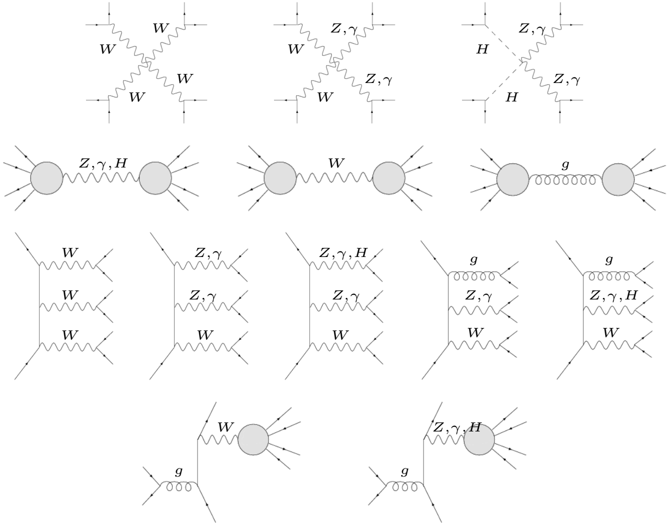
  development of new phase-space mappings designed to integrate efficiently amplitudes with external gluons

- upgrade to LC physics

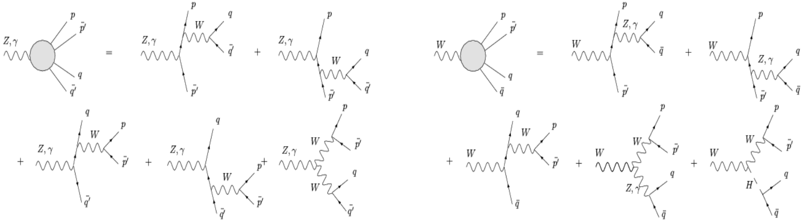
  extension to all reactions initiated by e^+e^- at $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$, including effects of Initial State Radiation (ISR) and beamstrahlung relevant for Linear Collider phenomenology

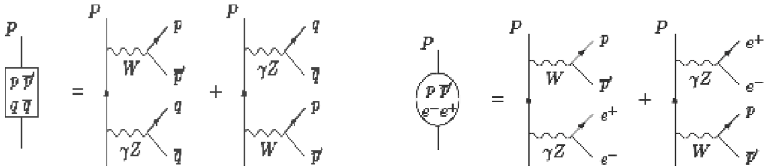
Matrix-element calculation

Example: diagrams with 8 external fermions



Examples of subdiagrams





Physics studies on Vector Boson Scattering at LHC

Purpose

Investigate the possibility of discovering *strong scattering* effects in the semileptonic $\mu\nu$ channel ($pp \to 4j\ \mu\bar{\nu}_\mu$) by means of a complete parton-level analysis at

$$\underbrace{\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)}_{\text{PHANTOM}} + \underbrace{\mathcal{O}(\alpha_{EM}^2 \alpha_S^4)\ [V + 4jets]}_{\text{MadEvent}}$$

Two-step approach:

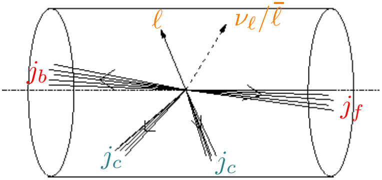
1. study the characteristics of VBS from a *six fermion* viewpoint
   $\hookrightarrow$ define a VBS signature
2. include the QCD irreducible background
   $\hookrightarrow$ search for kinematical differences between *VBS* events and QCD background

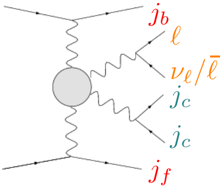
Predictions of SM with a light Higgs are compared with the benchmark scenario $M_H \to \infty$ (*no-Higgs*)

The VBS signature

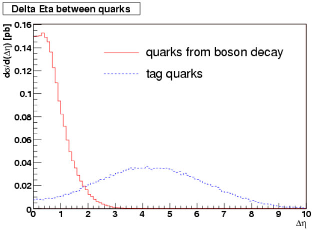
A *signature* is not a *signal*

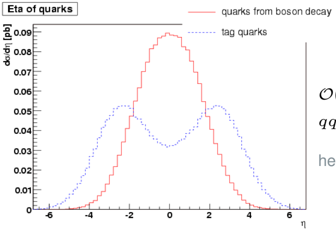
A possible definition of VBS signature at LHC:





- two tag jets forward/backward
- two jets and two leptons in the central region (with invariant mass cuts)



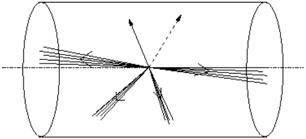


$\mathcal{O}(\alpha_{EM}^6)$

$qq \rightarrow qqq\ell\nu_\ell$

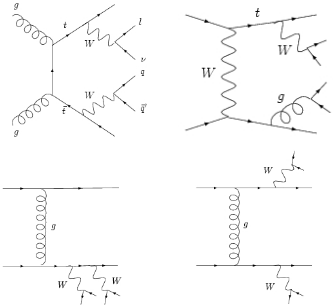
hep-ph/0512219

Enhance VBS



- cut on the pseudorapidity of the two forward/backward jets (η_{j_f}, η_{j_b})
- cut on the invariant mass of the central jets ($M_{j_c j_c}$)

Suppress QCD background

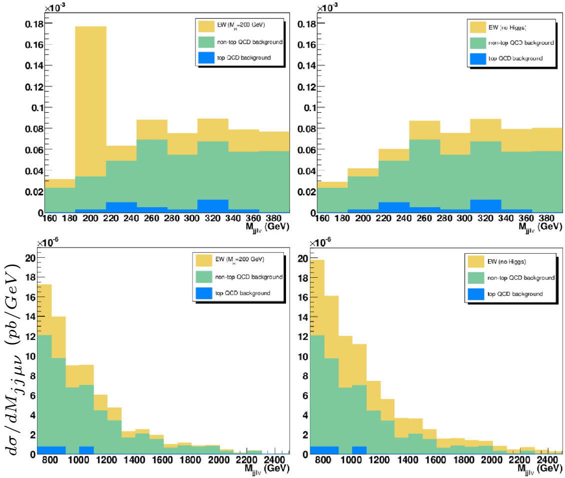


- exploit *b-tagging* + cuts on invariant mass to avoid top contributions
- cut on p_T and pseudorapidity of the lepton pair ($\eta_{l\nu}$)
- cut on the invariant mass of *leptons + tag jet* ($M_{j_f l\nu}, M_{j_b l\nu}$)

PHANTOM results $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4\alpha_S^2)$

Comparison between $\mathcal{O}(\alpha_{EM}^6)$ and $\mathcal{O}(\alpha_{EM}^4\alpha_S^2)$ contributions

$M_H = 200$ GeV $\qquad M_H = \infty$



Basic acceptance cuts:

$E(l) > 20\,GeV \quad p_T(l) > 10\,GeV$

$|\eta_l| < 3$

$E(j) > 20\,GeV \quad p_T(j) > 10\,GeV$

$|\eta_j| < 6.5 \quad m_{jj} > 20\,GeV$

Selection cuts:

b-veto for $|\eta| < 1.5$ with efficiency 80%

$|M(jjj;j\ell\nu) - M_{top}| > 15GeV$

$70\,GeV < M_{j_cj_c} < 100\,GeV$

$M(j_fj_b) < 70GeV \quad M(j_fj_b) > 100GeV$

$|\eta_{j_f} - \eta_{j_b}| > 4 \quad |\eta(\mu\nu)| \le 2$

$p_T(\mu\nu) > 100\,GeV$

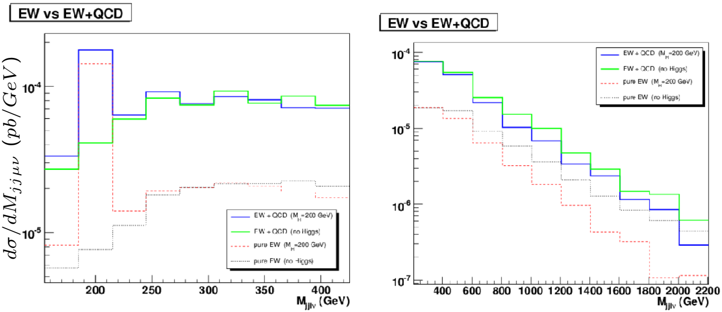
min $(M_{j_fl\nu}, M_{j_bl\nu}) > 250\,GeV$

Top background under control

$VV + 2j$ still non negligible

PHANTOM results $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$

Difference between *light-Higgs* and *no-Higgs* scenarios

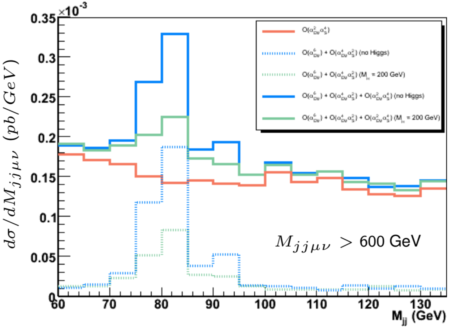


Number of expected events after one year of high luminosity ($\mathcal{L} = 100\ \text{fb}^{-1}$):

$\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4 \alpha_S^2)$	no Higgs		$M_H = 200$ GeV		
	σ	events	σ	events	ratio
$M_{j_c j_c \ell\nu} > 0.8$ TeV	7.61 fb	761 ± 28	5.14 fb	514 ± 23	1.481
$M_{j_c j_c \ell\nu} > 1.2$ TeV	2.53 fb	253 ± 16	1.73 fb	173 ± 13	1.462
$M_{j_c j_c \ell\nu} > 1.6$ TeV	1.00 fb	100 ± 10	0.55 fb	55 ± 7	1.818

Preliminary results at $\mathcal{O}(\alpha_{EM}^6) + \mathcal{O}(\alpha_{EM}^4\alpha_S^2) + \mathcal{O}(\alpha_{EM}^2\alpha_S^4)$

Invariant mass of the two central jets



Basic acceptance cuts:

$p_T(\ell) > 20\ GeV$ $\quad p_T(j) > 30\ GeV$

$|\eta_l| < 3$ $\quad |\eta_j| < 6.5$ $\quad m_{jj} > 60\ GeV$

Selection cuts:

b-veto for $|\eta| < 1.5$ with efficiency 80%

$|M(jjj;j\ell\nu) - M_{top}| > 15 GeV$

$70\ GeV < M_{j_c j_c} < 100\ GeV$

$M(j_f j_b) < 70 GeV$ $\quad M(j_f j_b) > 100 GeV$

$\Delta\eta(j_f j_b) > 4.0$

$\Delta\eta(Vj) > 0.9$ $\quad \Delta\eta(VV) < 3.0$

$p_T(miss) > 100\ GeV$ $\quad |\eta(\mu)| < 1.5$

Work in progress...

With the best set of cuts, so far we have obtained:

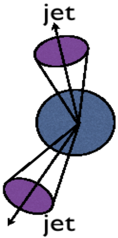
	no Higgs		M_H = 200 GeV		
	σ	events*	σ	events*	ratio
$M_{j_c j_c \ell\nu} >$ 0.8 TeV	3.61 fb	361 ± 19	2.75 fb	275 ± 17	1.32
$M_{j_c j_c \ell\nu} >$ 1.0 TeV	2.06 fb	206 ± 14	1.41 fb	141 ± 12	1.46
$M_{j_c j_c \ell\nu} >$ 1.2 TeV	1.24 fb	124 ± 11	0.74 fb	74 ± 9	1.69

* after one year of high luminosity running ($\mathcal{L}$ = 100 fb^{-1})

Effect of requiring a minimum ΔR separation among partons on the number of expected events (relevant to achieve separation of hadron jets):

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$$

no ΔR cut			
M_{cut}	*no Higgs*$^{(*)}$	$M_H = 200\,GeV^{(*)}$	Ratio
800 GeV	361	275	1.32
1.0 TeV	206	141	1.46
1.2 TeV	124	74	1.69
$\Delta R = 0.3$			
800 GeV	297	242	1.23
1.0 TeV	145	112	1.30
1.2 TeV	70	49	1.43



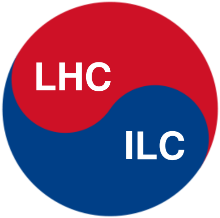
* after one year of high luminosity running ($\mathcal{L} = 100\ \text{fb}^{-1}$)

To evidentiate new physics low ΔR cuts should be studied!

Intermezzo: the LHC/ILC physics interplay

Higher reach in energy

- many more channels open (but not clean)
- possible direct production of new heavy particles



Higher reach in accuracy

- precision measurements
- indirect effects of new particles

The two colliders yield complementary informations

We are interested in extending to ILC our analyses on Boson-Boson Scattering and alternative EWSB scenarios

Physics studies on Vector Boson Fusion at ILC

Several studies in this direction have already appeared

Barger, Cheung, Han, Phillips '95 ...

W^+W^- fusion is a sensitive probe of the dynamics of EWSB: different models predict different ratios $\sigma(W^+W^- \to W^+W^-)/\sigma(W^+W^- \to ZZ)$

Principal backgrounds:

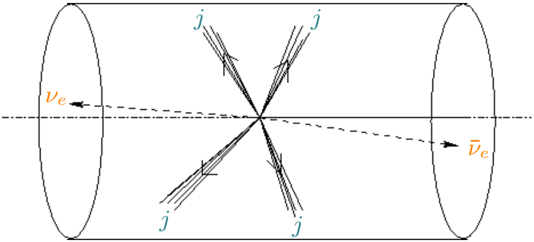
$e^+e^- \to e^+e^-W^+W^-$, e^+e^-ZZ , $e^{\pm}\nu W^{\pm}Z$ (with undetected $e^{\pm}$)

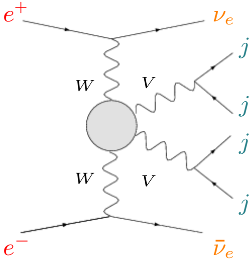
$e^+e^- \to ZW^+W^- \to \nu\bar{\nu}W^+W^-$ (Z-resonant channel)

A case study: $e^+e^- \to \nu_e\bar{\nu}_e\, 4j$

At LHC the selection of events with two tag jets widely separated in η (*forward/backward tagging*) is a well established technique for enhancing the scattering contributions.

The LHC definition of *VBS signature* cannot be applied to this context!





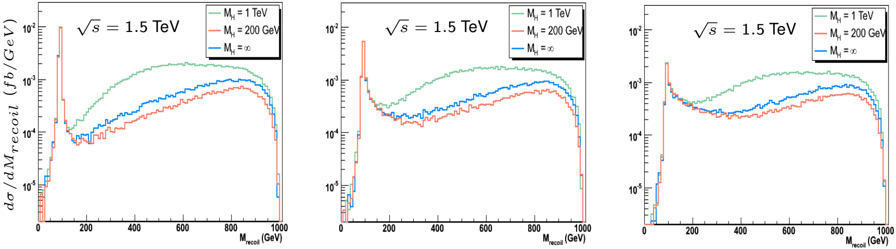
Focus on:

- four-jet invariant mass (M_{4j}): holds information about M_{VV}
- *recoil* four-jet mass (M_{recoil}): complementary to M_{4j}, related to the total missing momentum (neutrinos + initial-state radiation)

PHANTOM results at $\mathcal{O}(\alpha_{EM}^6)$

Effect of initial-state radiation on *recoil mass* distribution (W^+W^- resonant final states)

no radiation ISR ISR+beamstrahlung

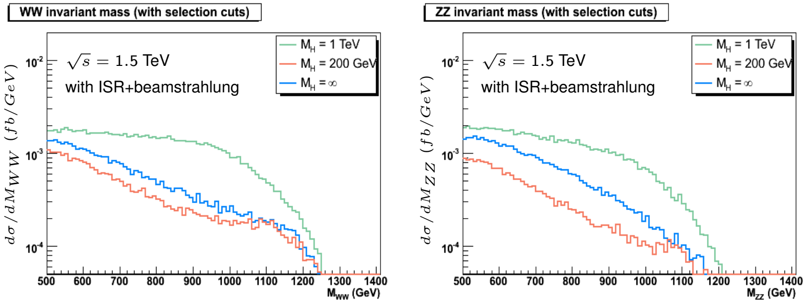


Selection cuts:

$M_{jj} > 40$ GeV; $M_{VV} > 500$ GeV; $p_T(V) > 150$ GeV; $|\cos\theta_V| < 0.8$;

50 GeV $< p_T(WW) <$ 300 GeV; 20 GeV $< p_T(ZZ) <$ 300 GeV

Effect of selection cuts on W^+W^- and ZZ invariant mass distributions



Selection cuts:

$M_{jj} > 40$ GeV; $M_{WW} > 500$ GeV; $p_T(W) > 150$ GeV; $|\cos\theta_W| < 0.8$;

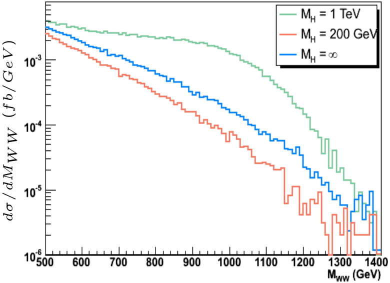
$M_{recoil} > 200$ GeV; 50 GeV $< p_T(WW) <$ 300 GeV

Visible effects of *non-scattering* contributions invalidate the separation between *light-Higgs* and *infinite-Higgs* scenarios at high VV invariant masses

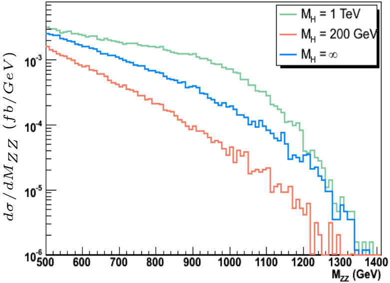
How much is *forward/backward tagging* relevant to suppressing non-scattering contributions?

Imagine we could tag the two neutrinos...

W^+W^- resonant final states



ZZ resonant final states



Selection cuts:

$$M_{jj} > 40 \text{ GeV}; \ M_{ZZ} > 500 \text{ GeV}; \ |\Delta\eta(\nu_e\bar{\nu}_e)| > 3.8; \ |\eta(V)| < 2$$

Summary and perspectives

Vector Boson Scattering has a great potential as a probe of the EWSB mechanism (and of possible new physics which lies behind)

The only consistent way to compare theory and data is to adopt a six-fermion perspective

PHANTOM will provide a more accurate answer on the possibility of detecting signals of EWSB through analyses of VBS at LHC and future colliders

Future projects

- complete analysis on semileptonic channel at LHC $\mu\nu, \mu^+\mu^-$
- focus on new channels $\mu^+\mu^-\mu^+\mu^-, \mu\nu\mu\nu$ ...
- beyond the Standard Model: alternative models of VV scattering
  Butterworth, SILH ...