Strong vector boson scattering at the LHC

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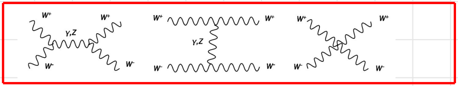
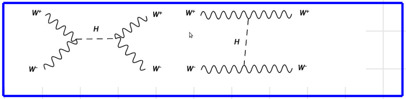
Electroweak Symmetry Breaking And Vector Boson Scattering

- The mechanism responsible for EW symmetry breaking must still be unveiled. In the SM: weak isospin doublet with one scalar field in the real spectrum, the Higgs Boson, which is in good agreement with precision data if light enough.
- The SM presents many problems, including quantum instabilities directly related to a scalar field. In particular the *naturalness* problem has inspired many alternative theories beyond the SM.
- The longitudinal Vector Boson Scattering (VBS) is an important process in the investigation of the SB sector. LVBS amplitudes grow with energy, eventually violating unitarity. The role of the Higgs boson is to control this bad behavior, in its absence new physics must intervene in order to restore unitarity.





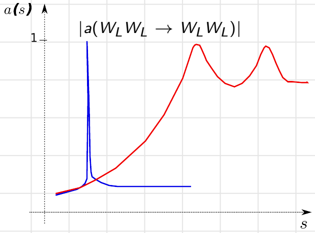
$$\rightarrow a_0(s) \sim \frac{s}{16\pi v^2} - \frac{s}{16\pi v^2}\frac{s}{s-m_H^2}$$

LET: Universal.

Higgs?: simplest possibility among many.

The scale in which the SB intervene determines the strength of interactions in the SB sector...

1. For $\Lambda_{SB} \lesssim 1$ TeV $\rightarrow$ below unitarity limit
   - SB sector is weakly coupled (small amplitudes);
   - perturbative methods work;
   - e.g.: SM Higgs Boson, SUSY
2. $\Lambda_{SB} \gtrsim 1$ TeV
   - SB sector is strongly coupled (large amplitudes);
   - QCD-like resonance spectrum;
   - e.g.: Dynamical Symmetry Breaking(Walking Technicolor...), Warped Extra-Dimensions...



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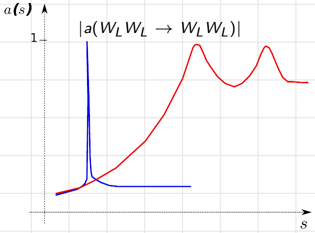

In many cases these new resonances will be out of the reach of the LHC and the only experimental signature will be an excess of events in the large mass domains.

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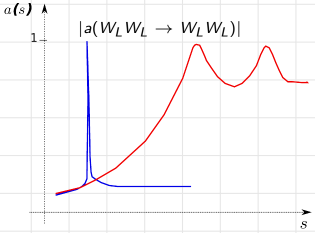

Benchmark scenarios with no heavy resonances:

- NO HIGGS
- SILH Strongly-Interacting Light Higgs

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Phenomenological description of high energy region of VBS through

Unitarization Models

and possible resonances.

Benchmark scenarios with no heavy resonances:

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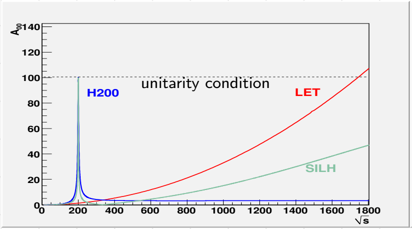
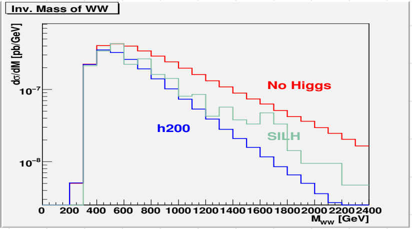
- SILH Strongly-Interacting Light Higgs

NO HIGGS and SILH Giudice et al, hep-ph/0703164

Elastic scattering amp $|A(W_L W_L \to W_L W_L)|$ $PP \to 2jWW \to 2j\ell^+\ell^-\nu\nu$





- Benchmark for strong EWSB models. Excess of events larger than in SILH models and smaller than when in presence of resonances.

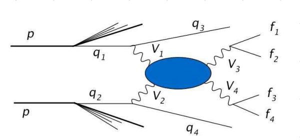
- The Higgs can be a pseudo GB of a new strong sector - postpone violation of unitarity to be controlled by the new strong sector. E.g: Little Higgs and Holographic Higgs;

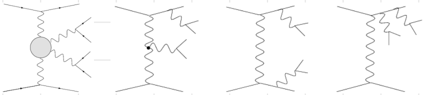
$$\frac{1}{p^2 - m_H^2} \to \frac{1}{1+\xi c_H} \frac{1}{p^2 - m_H^2}$$

Our goal is to estimate the power of the LHC in discriminating between the SM and alternative strong-EWSB scenarios through VBS.

Our approach to this goal is: 1- calculation, 2- study of signal and background and 3- statistical treatment.

1- calculation: PHANTOM Ballestrero et al, hep-ph/0801.3359 and the six-partons in the final state perspective;





- We can observe VB only through its decay to fermions;
- Non trivial signal definition: We have to use complete calculations in order to
  - account for all irreducible backgrounds
  - avoid approximations like EVBA and NWA (most of VBS studies)
  - deal with large gauge cancellations

The 7 channels:

totally leptonic

$PP \to jj\ell^+\ell^-\ell'\nu$

$PP \to jj\ell^\pm\ell^\pm\nu\nu$

$PP \to jj\ell^+\ell^-\ell^+\ell^-$

$PP \to jjW^+W^- \to jj\ell^+\ell^-\nu\nu$

$PP \to jjZZ \to jj\ell^+\ell^-\nu\nu$

semi-leptonic

$PP \to jjjj\ell\nu$

$PP \to jjjj\ell^+\ell^-$

Initial Cuts
$p_T(\ell) > 20$ GeV
$\lvert\eta(\ell)\rvert < 3$
$M(\ell^+\ell^-) > 20$ GeV $M(\ell^+\ell^-) > 250$ GeV ($2jW^+W^-$) 76 GeV $< M(\ell^+\ell^-) <$ 106 GeV ($2jZZ$)
$p_T(j) > 30$ GeV
$\lvert\eta(j)\rvert < 6.5$
$M(j_f j_b) > 100$ GeV
$\lvert\Delta\eta(j_f j_b)\rvert > 3$

- Complete partonic study of all channels, perturbative order $\mathcal{O}(\alpha_{EM}^6)$ (signal and EW backg), $\mathcal{O}(\alpha_{EM}^4\alpha_s^2)$ (VV+2j backg) and $\mathcal{O}(\alpha_{EM}^2\alpha_s^4)$ (V+4j backg, for the two semileptonic channels, with MADEVENT);
- Each channel corresponds to many individual processes, with $j \equiv q, g$ and $\ell \equiv e, \mu$. Millions of events for each channel;
- Study of the high mass region of VV-system, $M(VV)$, in $\ell\nu + 4j$, $\ell^+\ell^- + 4j$ and $\ell^+\ell^-\ell'\nu + 2j$ channels (hep-ph/0909.3838), $\ell\ell$-system in $WW \to 2\ell 2\nu + 2j$ channels and of $M_T(ZZ)$ in $ZZ \to 2\ell 2\nu + 2j$ channel (hep-ph/1011.1514);
- In strong SB sectors, an excess of events in the high mass region is expected. We want to see this excess looking at the appropriate phase space region.

2- Study of signal and background

Basic signature:

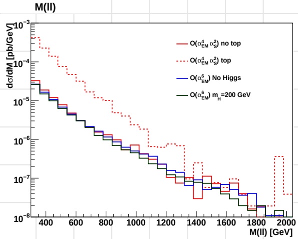
- tag-jets: two high energetic jets in forward-backward direction;
- two pairs of fermions associated with the two bosons in the central region with high P_T;
- bosons approximately back-to-back in respect to azimuthal plane;
- few color activity close to bosons...

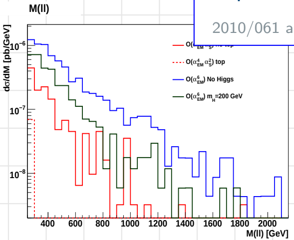
Each channel has its particular properties, e.g:

$$PP \to 2jW^+W^- \to 2j\ell^+\ell^-\nu\nu$$

Hadronic issue: boosted objects in semi-leptonic channels.

Experimental analysis: (CMS AN 2010/061 and CMS AN 2007/005).

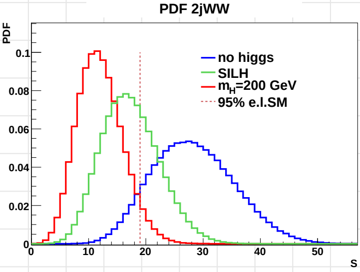




$M(jj) > 1000$ GeV
$\Delta\eta(jj) > 4.8$
$\lvert\eta(\ell)\rvert < 2.00$
$p_T(\ell) > 40$ GeV
$max\lvert\eta(j)\rvert > 2.5$
$\lvert\eta(j)\rvert > 1.3$
$E(j) > 180$ GeV
$\Delta\eta(\ell;j) > 0.8$ (and $\Delta R(\ell;j) > 1$)
$M(\ell;j) > 180$ GeV
$\Delta P_T(\ell^+,\ell^-) > 220$ GeV
$\cos(\delta\phi_{\ell\ell}) < -0.6$

3- Statistical treatment

Counting experiment: number of events observed in each scenario, S. Subjected to statistical fluctuations (Poissonian) and theoretical error due to parton distribution and scale dependence (prediction smeared by $\pm 30\%$).



$L = 200 fb^{-1}$

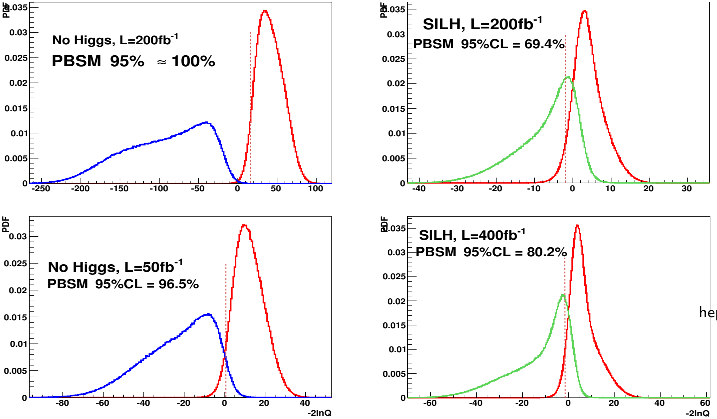
$M(\ell\ell) > 500$ GeV

$PNOH@95\%CL = 90.8\%$

$PSILH@95\%CL = 35.3\%$

Combination of all 7 channels

- For the combination of many channels we used as statistical test the likelihood ratio, which gives a natural generalization of the one-dimensional 95% exclusion limit;
- Likelihood ratio defined as $Q(\mathbf{S}; \bar{\mathbf{S}}_{BSM}, \bar{\mathbf{S}}_{SM}) = P(\mathbf{S}; \bar{\mathbf{S}}_{BSM})/P(\mathbf{S}; \bar{\mathbf{S}}_{\mathbf{SM}})$.



hep-ph/1011.1514

Unitarization Models

Aim to describe higher energy regions of VBS by forcing divergent amplitudes to satisfy the unitarity condition keeping the low energy behavior. Main ingredients are:

1. EWChL, describes the EW interaction at low energies,
   $\mathcal{L} = \frac{v^2}{4} Tr\left[(D_\mu \Sigma)^\dagger D^\mu \Sigma\right]$ (W,Z masses, LET) $\Sigma = exp(i\frac{\sigma\cdot\omega(x)}{v^2})$
   $+\alpha_4[TrV_\mu V_\nu]^2 + \alpha_5[TrV_\mu V^\mu]^2$ (higher order operators) $V_\mu = (D_\mu\Sigma)\Sigma^\dagger$
   $-\frac{1}{2}\sigma(m_\sigma^2 + \partial^2)\sigma + \sigma j_\sigma + \cdots$ (explicit resonances)
   $+$ standard YM terms
   We can compute the scattering amplitudes of Goldstone Bosons, e.g:
   $A^{tree}(\omega^+\omega^- \to zz) = \frac{s}{v^2} + 4\alpha_4\frac{t^2+u^2}{v^4} + 8\alpha_5\frac{s^2}{v^4} + \cdots,$
2. To study unitarity issues, it is always convenient to expand GB elastic scattering in terms of partial wave amplitudes of definitive angular momenta, J, and isospin, I (associated with the custodial symmetry $SU(2)_{L+R}$ group).
   $a_{IJ}(s) = a_{IJ}^{(1)}(s) + a_{IJ}^{(2)}(s) + \mathcal{O}(s^3);$
3. Elastic unitarity condition, $Im\hat{a}_{IJ}(s) = |\hat{a}_{IJ}(s)|^2;$
4. GB Equivalence Theorem,
   $A(\omega^+\omega^- \to zz) \approx A(W_L^+W_L^- \to Z_L Z_L) \qquad s \gg M_W^2.$

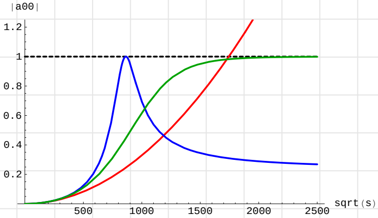
Unitarization of partial waves keeping the low energy behavior.

- K-matrix scheme: $a_{IJ}(s) \rightarrow \frac{1}{Re(1/a_{IJ}(s))-i}$
  We have studied the scenario No Higgs unitarized, which includes only the LET part and no extra parameters. We intend it as a lower limit for all kinds of strong SB sector with no resonances around.
- Inverse Amplitude Method: $a_{IJ}(s) \rightarrow \frac{a^{(1)}_{IJ}(s)}{1-a^{(2)}_{IJ}(s)/a^{(1)}_{IJ}(s)}$
  We have studied three scenarios of different chiral parameters including the one loop part of elastic GB scattering. Widely and succefully used in pion-pion scattering, predicting resonances.

scenario	α_4	α_5
IAM A	0.0	0.003
IAM B	0.002	-0.003
IAM D	0.008	0.0

For some values of the chiral coefficients the partial amplitudes present poles that can be dynamically interpreted as resonances.

One example of KM and IAM (also shown LET)



Off-Shell Implementation of Unitarization Models

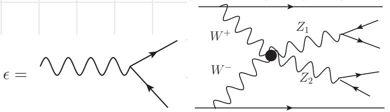
It has been proposed (Chanowitz, hep-ph/9512358) and implemented in the WIZARD MC (Kilian et al, hep-ph/0806.4145) an off-shell realization of UM; however, only on-shell phenomenological studies have been performed so far, relying on EVBA and NWA. We have independently implemented complete 6 fermions final state UM in PHANTOM and studied their phenomenological implications.

- Notice that the SM without Higgs already contains the LET part. Subtract LET part from on-shell amplitudes $\Delta A_{IJ}(s) = \hat{A}_{IJ}(s) - A_{IJ}^{LET}(s)$;
- Identify the process looking at the incoming and outcoming particles;
- Translate A_{IJ} into individual scattering amplitudes, e.g.: $\Delta A(W_L^+ W_L^- \to Z_L Z_L) = 4\left[\frac{v^4}{12s^2}(\Delta A_{00}(s) - \Delta A_{20}(s)) - \frac{5v^4}{6s^2}(\Delta A_{02}(s) - \Delta A_{22}(s))\right]\frac{s^2}{v^4} + \left[\frac{5v^4}{s^2}(\Delta A_{02}(s) - \Delta A_{22}(s))\right]\frac{t^2+u^2}{v^4}$
- Embed elastic amplitude as effective quartic coupling, identifying the factors s^2, t^2 and u^2 with appropriate contraction of polarization vectors, e.g. in $W_L^+ W_L^- \to Z_L Z_L$

$s^2 \to 4 M_W^2 M_Z^2\ \epsilon^+ \cdot \epsilon^-\ \epsilon^1 \cdot \epsilon^2$

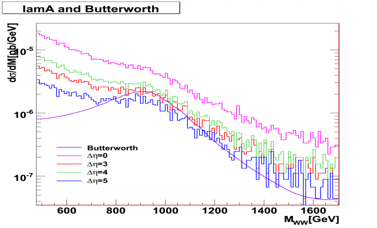
$t^2 \to 4 M_W^2 M_Z^2\ \epsilon^+ \cdot \epsilon^1\ \epsilon^- \cdot \epsilon^2$

$u^2 \to 4 M_W^2 M_Z^2\ \epsilon^+ \cdot \epsilon^2\ \epsilon^- \cdot \epsilon^1$



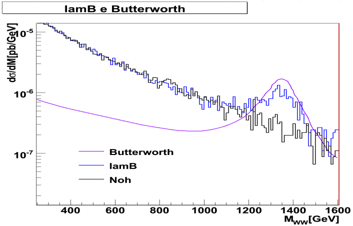
Results for Unitarization Models

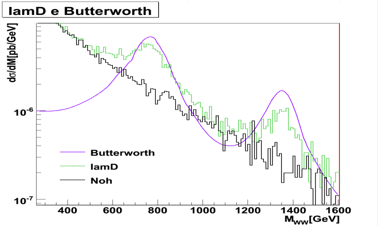
Comparison with previous study (Butterworth et al, hep-ph/0201098) based on on-shell amplitudes and EVBA:



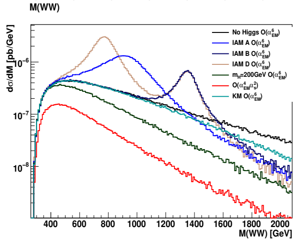
$\Delta\eta(jj) > 4$

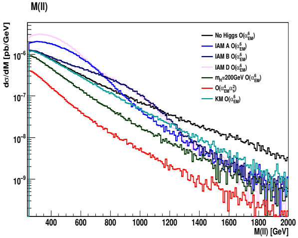
no top processes





$2jWW \to 2j\ell^+\ell'^-\nu\nu$





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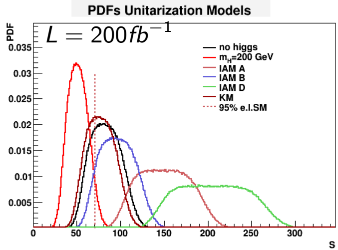
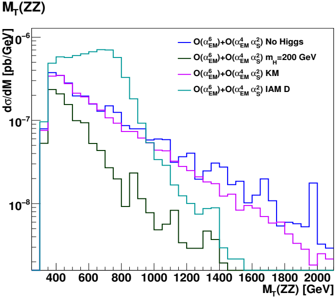


- It is not possible to have access to the resonace peaks in this channel due to the presence of two neutrinos;
- In the presence of resonance(IAM scenarios), the probability to find evidence of a strong sector through an excess of event is high;
- No Higgs unitarized by KM yields similar results to No Higgs - violation of unitarity suppressed by parton distribution at LHC energy scales.

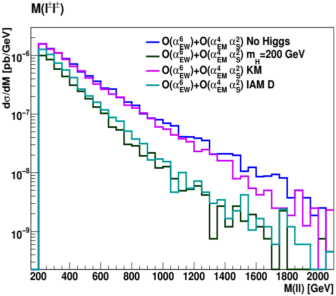
Results for Unitarization Models

$2jZZ \rightarrow 2j\ell^+\ell^-\nu\nu$



76 GeV $< M(\ell^+\ell^-) <$ 106 GeV
$\Delta\eta(jj) > 4.5$
$M(jj) >$ 800 GeV
$\Delta\eta(\ell j) > 1.3$
$missP_t >$ 120 GeV
$\Delta P_T(\ell^+\ell^-, \not{p}_T) >$ 290 GeV
$P_T(\ell^+\ell^-) >$ 120 GeV
$\eta(j) > 1.9$

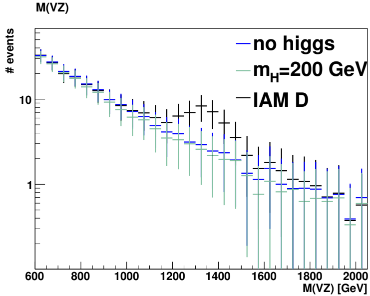
$2j\ell^\pm\ell^\pm\nu\nu$



$M(\ell^\pm\ell^\pm) >$ 200 GeV
$\Delta\eta(jj) > 4.5$
$max\|\eta(j)\| > 2.5$
$\|\eta(j)\| > 1.$
$\|\eta(\ell)\| < 2.5$
$p_T(\ell) >$ 50 GeV
$minp_T(j) <$ 120 GeV
$\Delta R(\ell j) > 1.5$
$\|\vec{p_T}(\ell_1) - \vec{p_T}(\ell_2)\| >$ 150 GeV
$\cos(\delta\phi_{\ell\ell}) < -0.6$

Looking for resonances

$2j3\ell\nu$ (IAM D) $\quad L = 200 fb^{-1}$



$\Delta\eta(jj) > 4$
$M(jj) > 100$ GeV

- In many cases, it will be tough to detect heavy resonances;
- On the other hand, it is very probable that we will observe high rates at high masses;
- Indicating we should look for heavy resonances, eventually in the SLHC.

Conclusion

Measuring the number of events in the high energy region of VBS will be extremely important anyway...

- If there are resonances around, at least one channel will yield a big excess that will very probably be observed at LHC, and a further effort must be done to find the resonances (can be hard or easy);
- Even if resonances are totally out of the reach of LHC, an excess of events at least as big as the No Higgs unitarized scenario should be observed. $L \approx 50 fb^{-1}$, $PNOH@95\%CL = 96.5\%$, should be enough to find this indication of a strong sector, encouraging the search for heavy resonances, eventually in a SLHC;
- Even if we observe a Higgs, it is important to study high energy VBS to understand its nature. In the limiting case studied scenario of SILH models, it may be necessary a big effort to go to very high luminosities, $L = 400 fb^{-1}$, $PSILH@95\%CL = 80.2\%$;
- In some models, a light Higgs sector can be very difficult to observe (see e.g: Van der Bij, hep-ph/0804.3534), and the consequent absence of strong VBS at high energies will push us to look harder for missed Higgses in the low energy regime, eventually in the ILC.