Multi Higgs and Vector boson production beyond the Standard Model

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Outline

- Perturbative unitarity in $2 \to n$ processes
- Motivation: Strong electroweak symmetry breaking and multi "pions" production
- General parametrizations for a strong electroweak sector and interpretations
- Sensitivity of $2 \to 3$ and $2 \to 4$ processes to anomalous couplings with/without using equivalence theorem
- Interpretation on MCHM
- Cross sections and LHC sensitivity

Prelude: Perturbative unitarity in 2 → n processes and scales for mass generation

- The perturbative unitarity bound for generic 2 → n processes, asuming s wave dominance, is given by

$$\sigma(2 \to n) < \frac{4\pi}{s}$$

- Therefore, neglecting possible phase space integration effects, any 2 → n amplitude that respects perturbative unitarity have to depend of the center of mass energy like

$$A(2 \to n) \sim s^{1-n/2}$$

Strong electroweak symmetry breaking, equivalence theorem and multi "pions" production

- Even with the recent discovery of the Higgs boson the question of the nature of EWSB remains open
- If EW is broken by an new strong interaction the dynamics of the Goldstone bosons can be described by a QCD-like chiral Lagrangian bellow TeV scale

$$\mathcal{L}_{NL\sigma M} = \frac{v^2}{4}\mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] \qquad U = e^{\frac{i\vec{\tau}\cdot\vec{\pi}}{v}}$$

- Therefore all the amplitudes goes like $A_{NL\sigma M}(2 \to n) \sim \frac{s}{v^n}$

A remarkable feature of this description is that in principle we can have big cross sections for processes with high multiplicity final state

M. Chanowitz and M. Gaillard '85

D. Morris, R. Peccei and R. Rosenfeld

Reality:
Power counting X phase space suppression

- The relativistic phase space for n-body final states,

$$R_n(s) = \int \prod_{i=1}^{n} \frac{d^3 p_i}{(2\pi)^3 (2E_i)^3} (2\pi)^4 \delta^4(\sqrt{s} - \sum_{i=1}^{n} p_i) = \frac{(2\pi)^{4-3n} (\pi/2)^{n-1}}{(n-1)!(n-2)!} s^{n-2}$$

- We estimate that the perturbativity description of 2 → n processes is broken at scale (again neglecting strong effects from phase space integration on the amplitude)

$$\Lambda_n = \left[\frac{2(n-1)!(n-2)!}{(2\pi)^{3-3n} (\pi/2)^{n-1}} \right]^{\frac{1}{2n}} v.$$

In the absence of a higgs $W_L W_L \rightarrow W_L W_L$ scaterings violates perturbative unitarity at ~ 1.2 TeV

2 → 4 events loose perturbative unitarity at ~ 2.5 TeV

* Dicus He '00

Anomalous Higgs couplings and partial unitarization

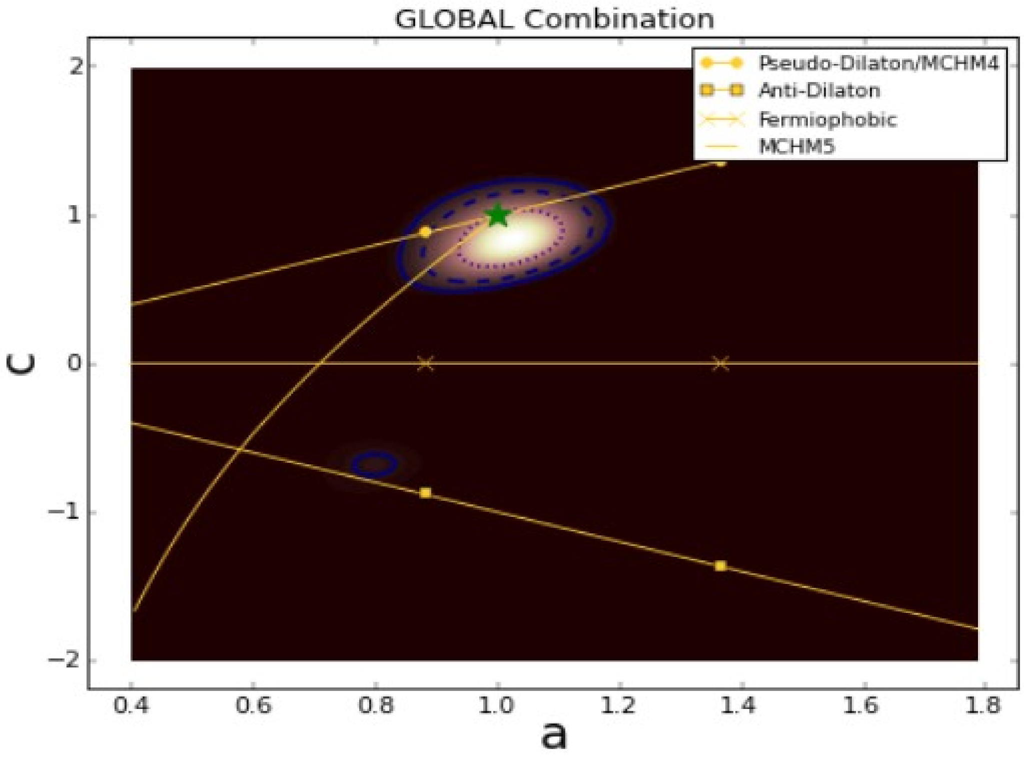
- The simplest way of restore unitarity (linearize the model) is to add a scalar with a rigid structure of couplings to the nonlinear piece…
- If not full EW sector linearization, we delay the violation → General parametrization for Higgs-Goldstones sector

$$
\begin{aligned}
\mathcal{L}_{\text{eff}} &= \frac{v^2}{4}\left(1 + 2a\frac{h}{v} + b\frac{h^2}{v^2} + b_3\frac{h^3}{v^3} + \cdots\right) \mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] \\
&+ \frac{1}{2}(\partial_\mu h)^2 - \frac{1}{2}m_h^2 h^2 - d_3 \lambda v h^3 - d_4 \frac{\lambda}{4} h^4 + \cdots
\end{aligned}
$$

The purpose of this work is study the present/future (LHC/...) sensitivity to higgs anomalous couplings on EW sector at hadron colliders.

Cross sections and LHC sensitivity

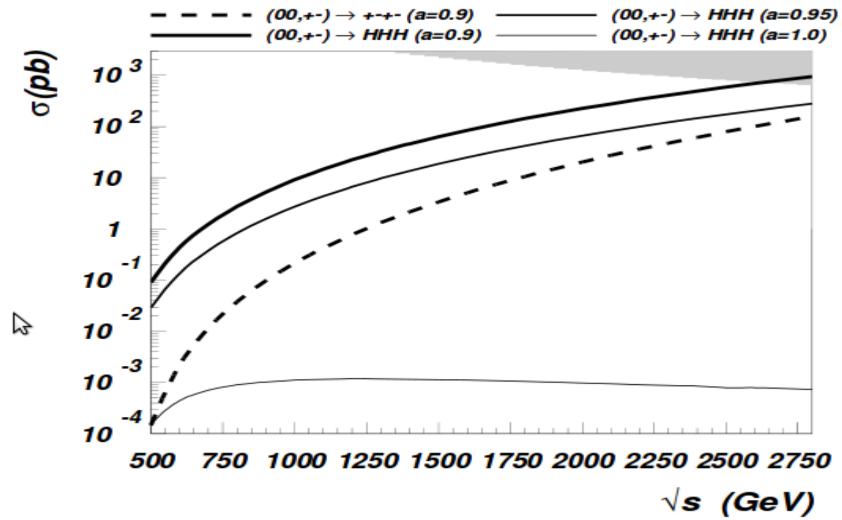
- We recall limits on this parametrization for a 125 GeV Higgs.
  - Combination of bb, tautau, ZZ, WW, and diphoton final states, dependence with higgs anomalous couplings to fermions.
  - Data of Moriond 13 conference

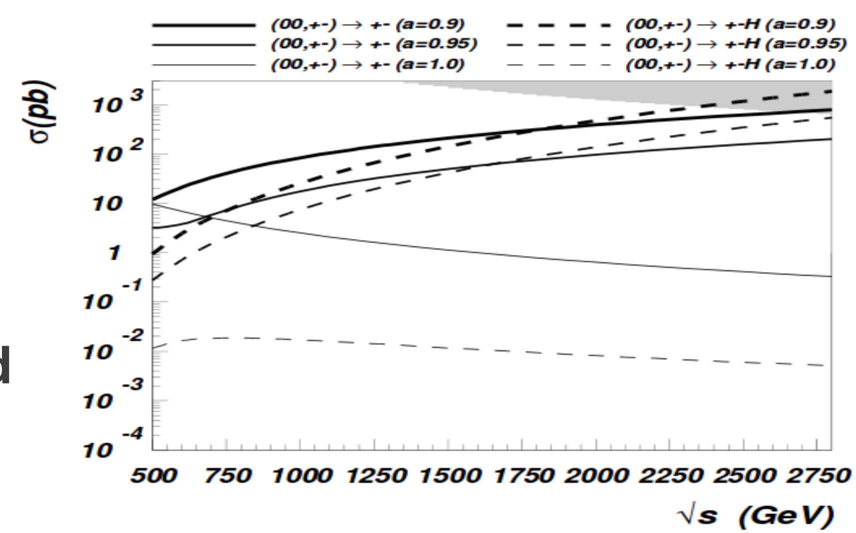


J. Ellis and T. You '13

Anomalous Higgs couplings and partial unitarization Using equivalence theorem

- We probe the sensitivity of the partonic **2-pi**, **pi-pi-h**, **4-pi** and **hhh** channels with "**a**" parameter (holds dominant energy dependence), by using a full automated calculation (CalcHep)
  - $2 \rightarrow 4$ processes have strong suppression of the phase space
  - $2 \rightarrow 3$ processes start to be compatible with $2 \rightarrow 2$ processes at TeV scale,
    - the violation of perturbativity happens at lower scale (for a same "a")





@ high energies small "a" deviations lead to big enhancement on partonic longitudinal scattering

Sensitivity of 2 → 3 processes to anomalous couplings Full partonic scatterings

- We probe **VV**, **VVh**, **hh** and **hhh** channels, at fixed CM energy,
  - We test only the sensitivity with a (dominant energy dependence)

channel	$a = b = 1$ (SM)	$a = 0.9; b = 1$
$00 \to +-$	0.13	295
$ZZ \to W^+W^-$	610	655
$00 \to +-h$	2.0×10^{-3}	350
$ZZ \to W^+W^-h$	10.9	46.2
$00 \to hh$	0.18	158
$ZZ \to hh$	7.61	15.7
$00 \to hhh$	4.9×10^{-4}	112
$ZZ \to hhh$	4.65×10^{-2}	13.6

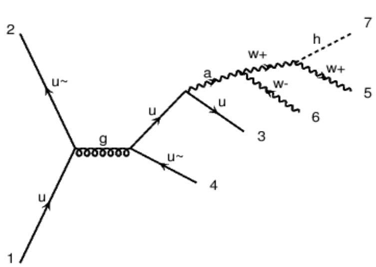
Comparison of $2 \to 2$ and $2 \to 3$ cross sections (in picobarns) at $\sqrt{s} = 2$ TeV

* For processes with VV on initial state the longitudinal component is 1/9 of full cross section – consistent results with equivalence theorem

Cross sections and LHC sensitivity

In a full automated pp initiated calculation Is indeed difficult to separate the topologies that arises from VBF,

Higher the multiplicity of gauge bosons on final state of a given process → bigger the interference with diagrams that do not suffer from violation of perturbative unitarity … e.g. WWh



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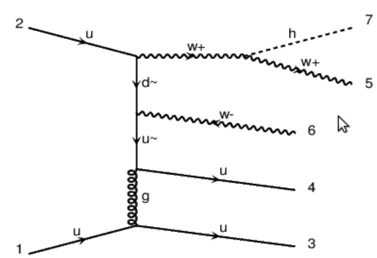

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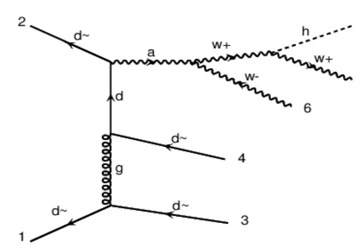


…

Cross sections and LHC sensitivity

Actually, on real life is difficult to separate the topologies that arises purely from VBF,

In order to try select VBF topologies we can use from cuts,

Classical VBF cuts	**Less strong VBF cuts**
The jets are forward and energetic (recovering effective W approximation)	A. Belyaev et all 0708.2588
$P_{T_j} > 30\,\mathrm{GeV}$	$E_j > 300\,\mathrm{GeV}$
$\|\eta_j\| < 5$	$\|\Delta\eta_{jj}\| > 4$
$\Delta R = \sqrt{\Delta\phi_{jj}^2 + \Delta\eta_{jj}^2} > 0.4$	

Cross sections and LHC sensitivity

- Cleanest 2 → 3 channel to prospect on strong sector is the one with only h's final state
- On WWh channels we see even a decrease of the cross section, as expected
  - On one side the modification of the parameters enhances the longitudinal CS (spoiling unitarization). On other side although it decreases the couplings of higgs/quarks with transverse polarization.

Process	14 TeV with (without) VBF cuts		33 TeV with (without) VBF cuts	
	a=1.0 b=1.0	a=0.9 b=1.0	a=1.0 b=1.0	a=0.9 b=1.0
$pp \to jjW^+W^-$	95.2 (1820)	99.3 (1700)	512 (5120)	540 (5790)
$pp \to jjW^+W^-h$	0.011 (0.206)	0.0088 (0.172)	0.0765 (0.914)	0.0626 (0.758)
$pp \to jjhhh$	1.16×10^{-4} (3.01×10^{-4})	0.0566 (0.0613)	0.00115 (0.00165)	1.85 (1.46)

Table 2: Cross section (in fb) for $pp \to jjW^+W^-$, $pp \to jjW^+W^-h$ and $pp \to jjhhh$ processes evaluated with Madgraph5.

We need to have enough energy in order to actually produce the final states → stronger pdf supression → not big overwall cross sections

Addendum: Interpretation on Minimal Composite Higgs Model

- On MCHM the Higgs field arise as a Pseudo GB of SO(5)/SO(4) global symmetry, broken at scale f

$$v = f \sin\theta$$

  - General structure of EW sector on MCHM

$$\frac{f^2}{4}\sin^2\left(\theta + \frac{h(x)}{f}\right)\mathrm{Tr}\left[\partial_\mu U \partial^\mu U^\dagger\right] \longrightarrow \quad a = \sqrt{1-\xi} \quad b = 1-2\xi \quad b_3 = -\frac{4}{3}\xi\sqrt{1-\xi}$$

  - Higgs potential depend on the fermionic representations

$$c = d_3 = \sqrt{1-\xi}\,, \qquad c_2 = -\frac{\xi}{2}\,, \qquad \text{MCHM4, spinorial representation},$$

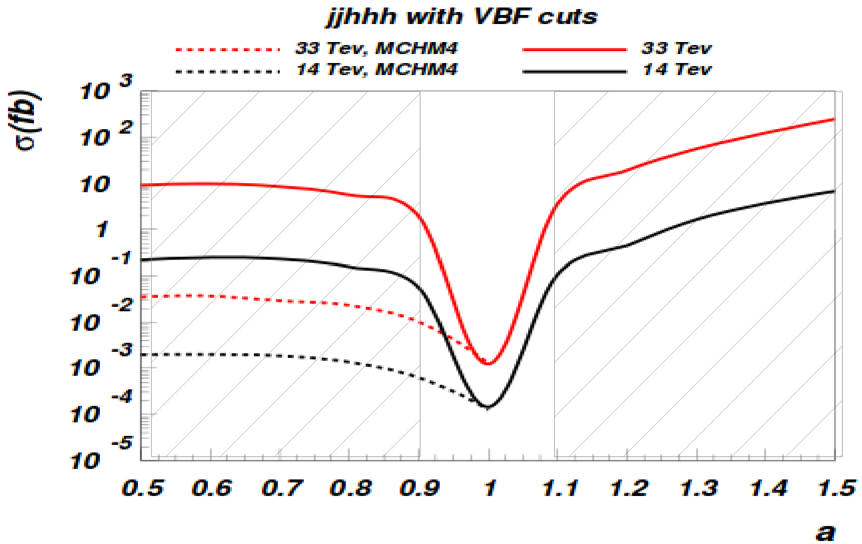
$$c = d_3 = \frac{1-2\xi}{\sqrt{1-\xi}}\,, \qquad c_2 = -2\xi\,, \qquad \text{MCHM5, fundamental representation}.$$

Agashe, Contino and Pomarol '05

Contino, Da Rold and Pomarol '07

Triple Higgs production @ LHC

- If we assume free anomalous couplings, we achieve cross section enhancements factors of O(10^3), after VBF cuts,
- In MCHM we have an hidden h → -h symmetry, that prevents large enhancements at this channel.



To probe seriously the potential discovery of the signal (on future) a more detailed kinematic study would be needed, beyond the scope of this work

Conclusions and prospects

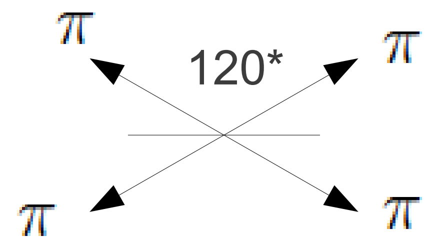
- In this study we verified the impact of anomalous couplings of higgs boson on higher multiplicity multiboson production, neglecting the effect of possible new resonances.
- We checked that processes like $2 \rightarrow 3$ longitudinal bosons/ higgs are the most promising to probe small deviations of higgs couplings, due the stronger cancellations required to recover unitarity. They become important as the usually studied $2 \rightarrow 2$ scatterings at reachable CM energy ~ TeV.
- However, in real pp events the contribution of transverse polarization on final state can dilute the enhancement of longitudinal cross section.
- The cleanest channel to probe generic higgs couplings deviations @ future LHC , with $2 \rightarrow 3$ hard processes is $p\, p \rightarrow hhh\, jj$

  (without a more evolved kinematic study)

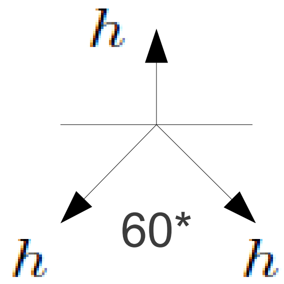
Thanks!

Analytical expressions for some high boson multiplicity amplitudes in specific kinematic configurations, using equivalence theorem

$$\mathcal{M}_{00;00+-} \propto \frac{1}{v^4}\left[72s\left(13a^4 - a^2(7b+5) - 1\right) + 3m_h^2\left(1580a^4 - 378a^3d_3 - 3a^2(245b+131) - 74\right) + \frac{m_h^4}{s}\left(9774a^4 - 3087a^3d_3 - a^2(4494b+1289) + 52\right) + \cdots\right]$$



$$\mathcal{M}_{00;hhh} \propto \frac{1}{4v^3}\left[s\left(-4a^3 + 4ab - 3b_3\right)\right) - m_h^2\left(-8a^3 + 8ab + 3b_3\right) + \frac{4m_h^4}{s}\left(a^3 + ab - 6b_3 - 3a^2d_3\right) + \cdots\right]$$



$$\mathcal{M}_{00;+-h} \propto \frac{a}{192v^3}\left[s\left(-1 + 2a^2 - b\right) + \frac{m_h^2}{4}\left(-164 + 386a^2 - 213b - 9ad_3\right) - \frac{3m_h^4}{2s}\left(-262 + 291a^2 - 93b + 81ad_3\right) + \cdots\right]$$