Studying Electroweak Symmetry Breaking through Vector Boson Scattering at the LHC

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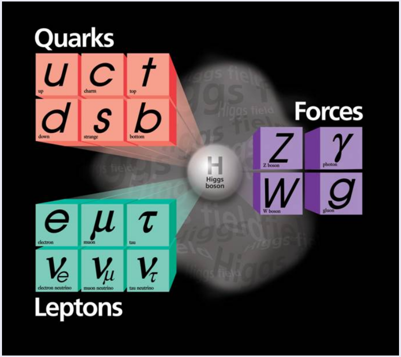
Outline

The Standard Model

The Standard Model(SM) is a $SU(3)_C x SU(2)_L x U(1)_Y$ gauge theory of the strong and electroweak interactions



A Short History of Electroweak Interaction(EW)

- **1961:** Glashow unifies Weak and Electromagnetic interactions under $SU(2)_L xU(1)_Y$ gauge theory
- **1967-1968:** Weinberg and Salam shows that Spontaneous Symmetry Breaking(SSB) can give W/Z mass, preserving the gauge symmetry
- **1971-1972:** t'Hooft and Veltman proves that a gauge theory with SSB is renormalizable.
- **1973-2007:** Electroweak theory has passed extensive testing, but still no clue if EWSB mechanism is correct !

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The Electroweak Interactions

The fundamental lagrangian of nature:

$$\mathcal{L} = \bar{q} i \not{D} q + \bar{l} i \not{D} l - \frac{1}{4}(F^a_{\mu\nu})^2$$
$$+ |D_\mu \phi|^2 - V(\phi)$$
$$-(\lambda_u^{ij} \bar{u}^i_R \phi . Q^i_L + \lambda_d^{ij} \bar{d}^i_R \phi . Q^i_L + \lambda_l^{ij} \bar{e}^i_R \phi^* . L^i_L + h.c.)$$

1. The first line is the pure $SU(2)_L x U(1)_Y$ gauge theory
2. The second line describes the Higgs scalar field ϕ which is the agent of EWSB, giving W/Z mass.
3. The third line contains the Yukawa couplings of Higgs to quarks and leptons, that gives them mass.

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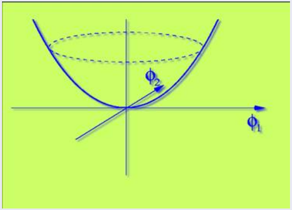
The Higgs Mechanism

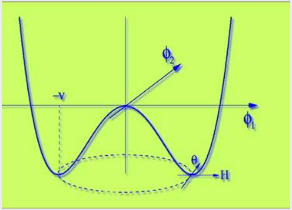
Higgs mechanism implements EWSB based on a relativistic generalization of the Ginzburg-Landau phenomenological potential:

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4 \qquad (\lambda > 0)$$

Unbroken($\mu^2 > 0$)



Broken($\mu^2 < 0$)



The Higgs Mechanism

Spontaneous symmetry breaking(SSB) occurs when we choose one stable minimum of the potential(vacuum)

Unbroken: $SU(2)_L x U(1)_Y$

- 3 massless $SU(2)_L$ vector bosons
- 1 massless $U(1)_Y$ vector
- 1 self-interacting Higgs doublet

Broken: $U(1)_{EM}$

- 3 massive vector bosons: W^+, W^-, Z^o
- 1 massless boson: γ
- 1 real scalar: Higgs
- Fermion masses

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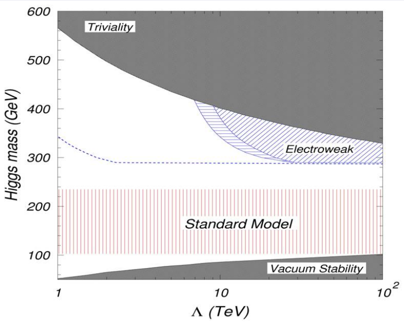
Limits on the Higgs Mass

1. Theoretical bounds: the classic triumvirate of Higgs mass "constraints"
   - Unitarity
   - Vacuum Stability
   - Triviality
2. Experimental limits:
   - Direct searches at LEP and Tevatron
   - Electroweak data global fit

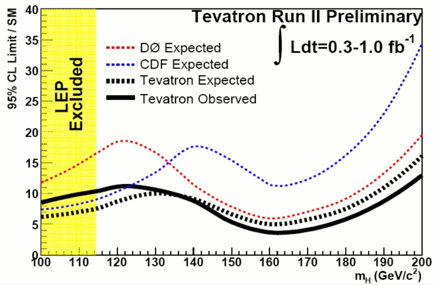
Theoretical Bounds on the Higgs Mass



The hatched regions marked "Electroweak" and dashed line are ruled out by EW data(Kolda&Murayama,hep-ph/0003170)

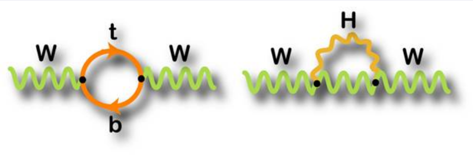
Higgs Mass Exclusion Limits

- Direct searches performed at LEP excludes a Higgs boson lighter than 114.4 GeV (95%CL)
- Searches at Tevatron gives the following exclusion limits



Constrains on Higgs Mass from Data

- EW precision data involves mainly light quarks and leptons and Higgs coupling to them is very small
- Most important constrains on Higgs mass comes from quantities like m_W, m_t, Γ_Z and Z asymmetries
- Higgs enters precision EW predictions through vacuum polarization diagrams



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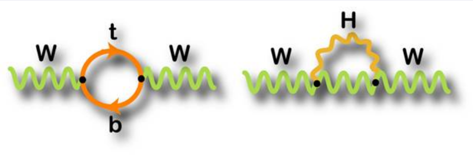

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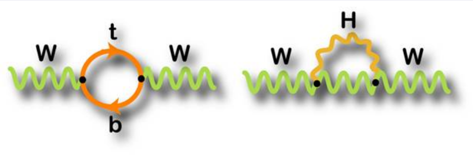


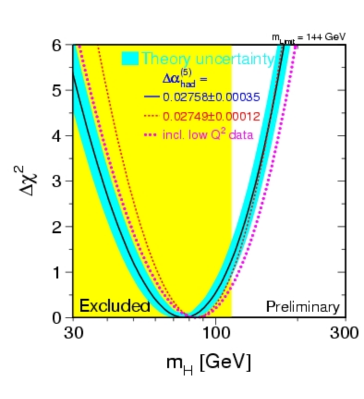
W Mass Radiative Correction

One loop radiative corrections to the m_W expression:

$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}G_\mu sin^2(\theta_W)}(1 + \Delta r)$$

$$\Delta r \simeq \frac{3G_\mu}{8\sqrt{2}\pi^2} m_t^2 + \frac{2G\mu}{16\pi^2} m_W^2 \left[\frac{11}{3} \ln \left(\frac{m_H^2}{m_W^2} \right) + ... \right]$$

Electroweak Data Global Fit



- Data favours a light higgs: minimum at $76^{+33}_{-24} GeV (68\% CL)$
- SM Higgs mass lower than 144GeV with 95%CL (182GeV with LEP limit)
- IMPORTANT: fit valid only if EWSB mechanism is correct !

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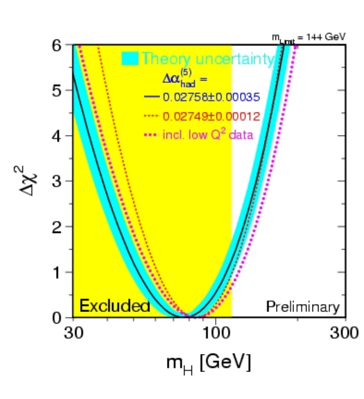

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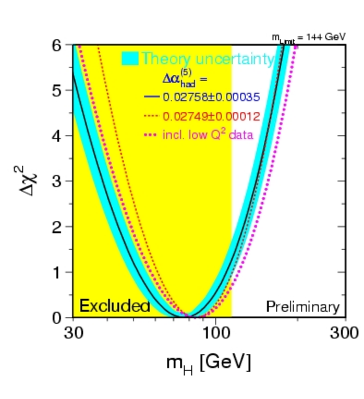

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"Criticisms" of the EWSB Mechanism

- EW theory uses an AD HOC minimal Higgs sector choice, but there are other options...
- Higgs mass radiative corrections has quadratic divergences $\Rightarrow$ naturalness and fine tunning "problems"
- Higgs creates a vacuum energy density $\rho_H = m_H^2 v^2/8 > 10^8 GeV^4$ (GR cosmological constant). Observation suggests that $\rho_{vac} < 10^{-46} GeV^4$!
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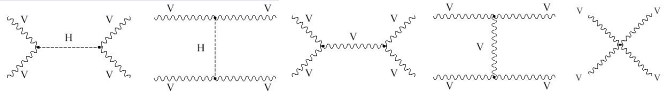
Vector Boson(VV) Scattering at the LHC

- Vector boson scattering is a key process to probe EWSB
- In absence of the Higgs, the scattering amplitude for vector bosons scattering violates unitarity above 1 TeV

$$A(V_L V_L \rightarrow V_L V_L) \sim \frac{1}{\nu} \frac{s^2}{(s - m_H^2)} \frac{t^2}{(t - m_H^2)} - s - t$$



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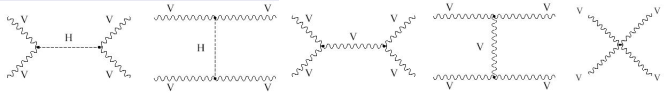

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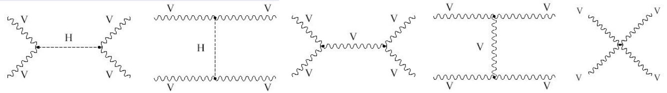

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Possible Scenarios at the LHC

1. If a Higgs is discovered, one must verify if longitudinally polarized vector bosons are weakly coupled at high energies.
2. If no Higgs is found or if it has a very high mass, there are many possibilities:
   - Strongly coupled *VV* with an excess in it's cross section and/or appearance of ressonances like in low energy QCD
   - New physics like Little Higgs, Walking Technicolor, Extra Dimensions ...

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Measurement of VV Scattering

The signature of VV scattering events is quite unique, allowing to suppress the main backgrounds like W/Z+jets and $t\bar{t}$.

- Particles coming from W/Z decay have high p_T
- Two very energetic and forward tag jets
- M_{VV} gives the energy scale of the scattering process
- Measure VV scattering cross section as a function M_{VV} and look for deviations from EW theory at high energy

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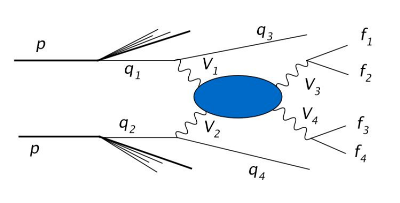
Simulation of VV Scattering

- To explore EWSB through *VV* scattering one needs a precise knowledge of it's EW cross section
- Choice of the Monte Carlo generator is therefore a key aspect of this study
- The general diagram describing *VV* scattering has six fermions in the final state(LO)



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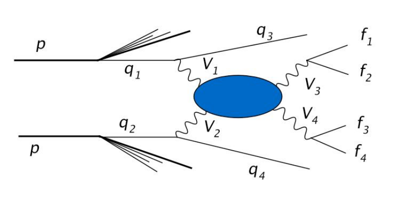

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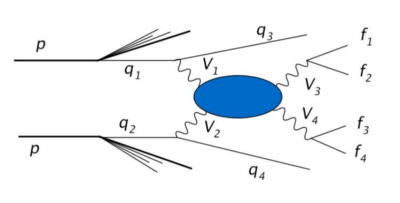

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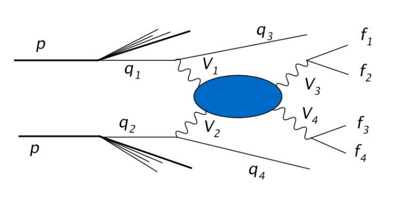
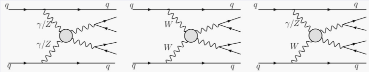


PHANTOM: Monte Carlo

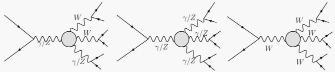
- Fast dedicated event generator with efficient phase space mapping
- Exact LO matrix elements (no prod⊗decay or EVBA)
- Implements vector boson off shellness to describe amplitude away from Higgs ressonance
- Includes complete set of diagrams $O(\alpha^6)$ and $O(\alpha^4\alpha_s^2)$
- Takes into account interference between signal and irreducible background
- Follows Les Houches protocol $\Rightarrow$ can be interfaced with Pythia for showering/hadronization

PHANTOM Diagrams

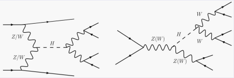
VV Scatering



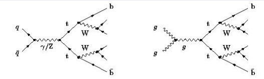
VV Coupling



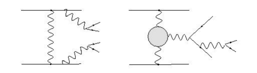
Higgs Production



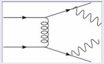
Top Production



Non-Ressonant



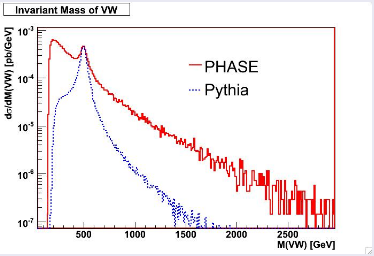
VV+jets Production



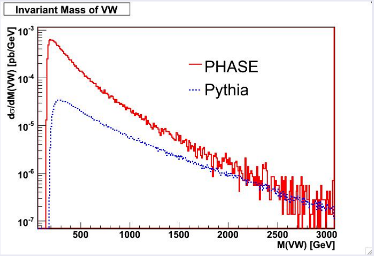
PHANTOM versus PYTHIA

PYTHIA ($qq->4ql\nu$) has only LL polarization and uses EVBA aproximation

Higgs Mass: m_H=500GeV



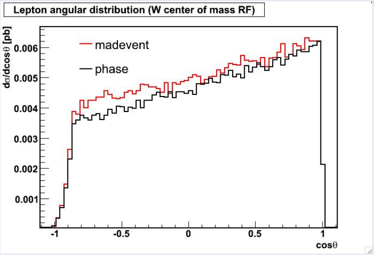
No Higgs



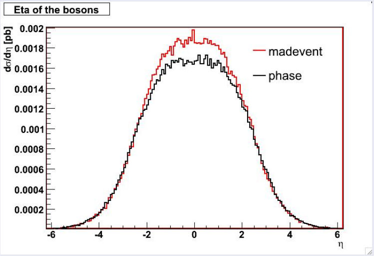
PHANTOM versus MADEVENT

MADEVENT ($qq->qqWV$) in production times decay aproximation. Full calculation is very time consuming !

Lepton Angular Distribution



Vector Boson Rapidity



PHANTOM: "Signal Definition"

- **Signal:** Six fermions VV scattering process $O(\alpha^6)$
- **Irreducible Background:** Same perturbative order $O(\alpha^6)$ and same final state as the signal(ex: non-ressonant, 3-boson and EW top production)
- **Reducible Background:** Different perturbative order and same final state(ex: VV+jets , V+jets and QCD top production)

PHANTOM: "Signal Definition"

PROBLEM

Signal and irreducible background must be generated together due to quantum interference $\Rightarrow$ need a posteriori "signal definition"

SOLUTION

Define cuts to select a phase space region where signal contribution is enhanced over irreducible background

Signal Cross Sections(No Higgs Scenario)

Semi-Leptonic decay modes

- $VW \rightarrow qq\mu\nu/e\nu$ (158fb)
- $VZ \rightarrow qq\mu\mu/ee$ (16.4fb)

Leptonic decay modes

- $WW \rightarrow \mu\nu\mu\nu$ oposite sign (9.52fb)
- $WW \rightarrow \mu\nu\mu\nu$ same sign (4.30fb)
- $ZW \rightarrow \mu\mu\mu\nu$ (1.20fb)
- $ZZ \rightarrow \mu\mu\mu\mu$ (0.180fb)

Background Cross Sections

Main backgrounds comes from $t\bar{t}$, $VV + jets$ and $V + jets$

ALPGEN backgrounds

WW	
SIGNAL	
$M_h = 500$ GEV	$\sigma = 60$ FB
$No - Higgs$	$\sigma = 20$ FB
BACKGROUND	
TOP–TOP	$\sigma = 6.2 \times 10^5$ FB
W+JETS	$\sigma = 7.7 \times 10^4$ FB
WW	$\sigma = 1.1 \times 10^3$ FB

ZZ+ZW	
SIGNAL	
$M_h = 500$ GEV	$\sigma = 9.1$ FB/ 0.7 FB
$No - Higgs$	$\sigma = 1.7$ FB/ 1.4 FB
BACKGROUND	
TOP–TOP	$\sigma = 6.2 \times 10^5$ FB
Z+JETS	$\sigma = 1.4 \times 10^7$ FB
ZZ	$\sigma = 6.6 \times 10^5$ FB
WZ	$\sigma = 6.6 \times 10^5$ FB

Example Analysis: $ZZ \rightarrow \mu\mu\mu\mu$

- Golden channel for Higgs discovery($m_H > 2M_Z$)
- Allows full reconstruction of the m_{ZZ} and precise measurement of $\frac{d\sigma}{dm_{ZZ}}$
- Unique signature: 2 isolated high p_T muon pairs from Z decay + two tag jets + no missing ET
- Very low cross section ! (high luminosity measurement)
- Main backgrounds:ZZ+njets, $t\bar{t}$+njets and $Zb\bar{b}$

Example: $ZZ \rightarrow \mu\mu\mu\mu$ Signal Definition

- 4 isolated muons with $p_T > 20GeV$ and $|\eta| < 2.4$
- 2 reconstructed Z's within the mass window of $10GeV$
- 2 tag jets with $m_{JJ} > 900Gev$
- Veto events with more than 4 muons
- Veto events with more than 2 jets

Summary

- *VV* scattering is a "NO LOOSE" probe of the EWSB mechanism at LHC
- Even if a Higgs boson is found, it will be important to verify if longitudinally polarized vector bosons are weakly coupled
- If the Higgs boson does not exist or has a very large mass, the cross section for $M_{VV} > 1\,TeV$ will deviate from the SM
- Measurement of the large M_{VV} region could provide information on the existence of the Higgs boson independently of its direct observation
- Expect the unexpected !

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