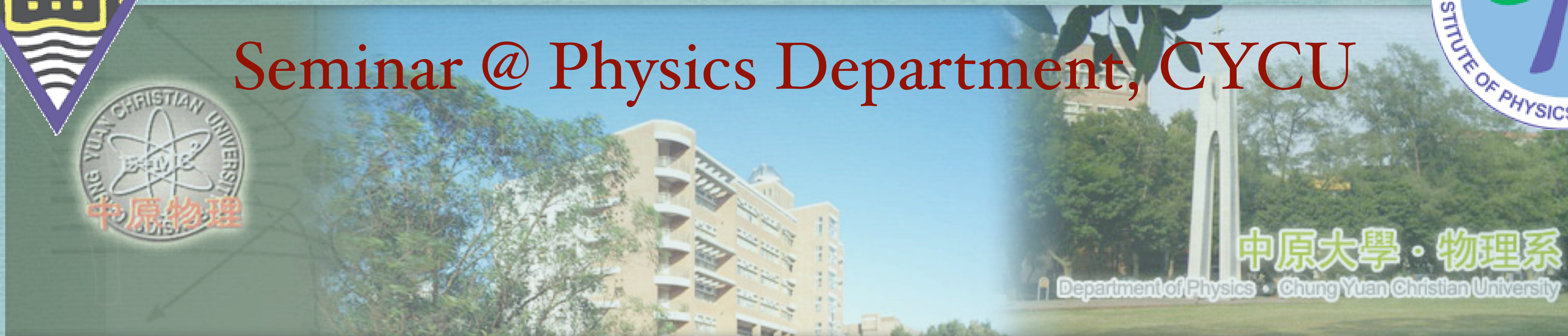
Seminar @ Physics Department, CYCU



PARTIALLY STRONG WEAK GAUGE BOSON SCATTERING

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Outline

- Lightning review of EWSB in SM
- Vector boson scattering as a probe of EWSB
- Effects of an extended Higgs sector
- LHC signals of partially strong scatterings
- Summary

LHC Expectations

- The LHC experiments will starts by the end of this year. What do we expect to see in a couple of years?
  1. Some or a lot of new particles (SUSY, KK modes, fourth generation, Z', W', etc) are observed [most exciting scenario] $\Rightarrow$ collect data for next 20 years to fix parameters in models, happily ever forever
  2. Nothing new is found [perplexing scenario] $\Rightarrow$ difficult to explain to the public but something deep to think about
  3. Only a SM-like Higgs boson is measured [most boring one] $\Rightarrow$ Switch to do cosmology, astro-particle physics, biophysics, ...

Questions of Interest

- An important task of the LHC physics is to understand the EWSB in elementary particle physics.
- What if we detect only a light Higgs boson at the LHC?
- Can we claim that we understand EWSB then?
- Is it the SM Higgs boson, or does it belong to a larger Higgs sector?
- In the latter case, what would be clear and direct ways to figure it out in experiments (assuming that we cannot probe and detect the other degrees of freedom directly for some reason)?

Possible Answers

- Some recent works suggest to study its decays in detail in order to pin down its couplings to SM fermions.

Giudice, Grojean, Pomarol, Rattazzi 2007
Mantry, Trott, Wise 2007; Randall 2007

- Another direction is to study its interactions with the weak gauge bosons through weak gauge boson scatterings at high energies.
- These two approaches are complementary to each other. Nevertheless, the latter is more direct than the former.

Unitarity Constraints

- General consideration of the *S*-matrix theory
  ⇒ Scattering amplitude (or cross section) cannot grow with energy
- Violation of the unitarity indicates the breakdown of an effective theory.
  ⇒ A more complete theory must come in to save the situation.
  ⇒ The scale of new physics is around or below the unitarity-violating scale.

Unitarity Problem in Fermi Theory

- Consider the scattering of $\nu_\mu + e^- \longrightarrow \nu_e + \mu^-$. The cross section to the lowest order is given by

$$\sigma_{tot}(\nu_\mu e^- \to \nu_e \mu^-) = \frac{G_F^2}{\pi} s$$

where only the lowest partial wave (l=0) contributes and unitarity in quantum mechanics requires

$$\frac{G_F^2}{\pi} s \leq \frac{\pi}{2E_{\rm cm}^2} \;\Rightarrow\; E_{\rm cm} \leq \left(\frac{\pi\sqrt{2}}{4G_F}\right)^{\frac{1}{2}} \simeq 310 \text{ GeV}$$

where $E_{\rm cm}$ is the scattering energy in the CM frame.

- This signals a breakdown scale for the theory.
$\Rightarrow$ New degrees of freedom (the W bosons in this case) must emerge at or around this scale to save the trouble.

Minimal Higgs Model

- In the Higgs sector, the scalar potential is given by

$$\begin{aligned} V(\mathbf{w},h) &= \frac{\lambda}{4}\left[(\mathbf{w}^2+h^2)-v^2\right]^2 \\ &\rightarrow \frac{\lambda}{4}(\mathbf{w}^2+h^2)^2+\lambda v h(\mathbf{w}^2+h^2)+\frac{m_h^2}{2}h^2 \end{aligned}$$

  after h acquires a VEV, where $m_h^2 = 2\lambda v^2$.
  [This mimics the pre-QCD σ model ($\mathbf{w}\rightarrow\boldsymbol{\pi}$ and $h\rightarrow\sigma$).]
- After introducing the $SU(2)_L\times U(1)_Y$ gauge interactions, the massless Goldstone fields **w** then become the longitudinal modes of the gauge bosons, W_L and Z_L, through the Higgs mechanism.

Equivalence Theorem

Cornwall, Levin, Tiktopoulos 1974; Vayonakis 1976;
Lee, Quigg, Thacker 1976; Chanowitz and Gaillard 1985;
Gounaris, Kogerler, Neufeld 1986; He, Kuang, Li 1992, 1994

- At high energies, the longitudinal components of the weak bosons recall their identities as the Goldstone modes and interact according to the Higgs potential.
- At the tree level, the high-energy ($E \gg M_W$) scattering amplitudes for longitudinally polarized W's and Z's in the unitary gauge are equivalent to those for the corresponding w and z Goldstone bosons in the 't Hoot-Feynman gauge

$$\mathcal{M}(W_L(p_1), W_L(p_2), ...)_U = \mathcal{M}(w(p_1), w(p_2), ...)_F + \mathcal{O}(M_W/E) \ .$$

- The weak gauge boson scatterings at high energies thus reveal the nature of EWSB.

Longitudinal Polarization

- In the CM frame of the scattering process ($V = W$ or Z)
  $$V_L(p_1)V_L(p_2) \longrightarrow V_L(k_1)V_L(k_2)$$
  the polarization of the weak gauge boson of $V_L(p_1)$, for example, can be written as
  $$\epsilon_L^\mu(p_1) \simeq \frac{p_1^\mu}{M_W} - \frac{2M_W}{s} p_2^\mu \ ,$$
  $$\sim \frac{E}{M_W} \qquad \sim \frac{M_W}{E}$$
  where $s = (p_1+p_2)^2$.

- This is good for studying terms of $O(E^0)$ or above.
- Remark: we use the exact expression for polarization vectors in all our numerical calculations.

Partial-Wave Expansion

- The scattering amplitude can be decomposed into partial waves as

Lee, Quigg, Thacker 1977

$$\mathcal{M}(s,t) = 16\pi \sum_J (2J+1) a_J(s) P_J(\cos\theta) \ ,$$

where the J-th partial-wave coefficient may be written as

$$a_J = A_4 \left(\frac{E}{M_W}\right)^4 + A_2 \left(\frac{E}{M_W}\right)^2 + A_0 \left(\frac{E}{M_W}\right)^0 \ ;$$

where E is the scattering energy in the CM frame.

- The amplitudes do not grow with E in the SM because:
  - the A_4 terms vanish among purely gauge diagrams; and
  - the cancellations of A_2 terms involve the Higgs boson.
- The situation will become different if the electroweak sector is extended...

Unitarity Violation

- Even within the SM, the tree-unitarity may be violated if the Higgs mass m_h is greater than ~ 1 TeV.
  $\Rightarrow$ large λ and thus quantum corrections;
  i.e., failure of Born approximation
  $\Rightarrow$ strongly interacting Higgs sector
  $\Rightarrow$ expect to see a spectrum of resonances as strong interactions in the GeV regime.
- On the other hand, if a light Higgs boson is discovered, it could indicate that weak interactions remain weak at all energies.

Partial Unitarity Violation

- In many extensions of the SM, several Higgs bosons participate in the EWSB together.
- We consider the scenario that only one of them is sufficiently light and detectable at colliders, whereas the others are too heavy to probe.
- The tree-unitarity may be violated at energies between the light Higgs boson and the heavy ones as the scattering cross sections have effectively $(E/M_W)^2$ growth in the intermediate scale [no $(E/M_W)^4$ terms still].

Example: THDM

- Take as one example the two-Higgs doublet model (THDM) where two scalar doublets are simultaneously involved in the EWSB.
- The *ΦVV* couplings in this case are:

	SM	THDM
g_{hVV}	$g_{hVV}^{\rm SM}$	$g_{hVV}^{\rm SM}\sin(\beta-\alpha)$
g_{HVV}	0	$g_{hVV}^{\rm SM}\cos(\beta-\alpha)$

- In general, we parameterize the coupling deviation as

$$g_{hVV}=\sqrt{\delta}\,g_{hVV}^{\rm SM}\;, \qquad (\delta<1)$$

and assume that the other heavy degrees of freedom decouple for the illustration purpose.

Another Example

Giudice, Grojean, Pomarol, Rattazzi 2007

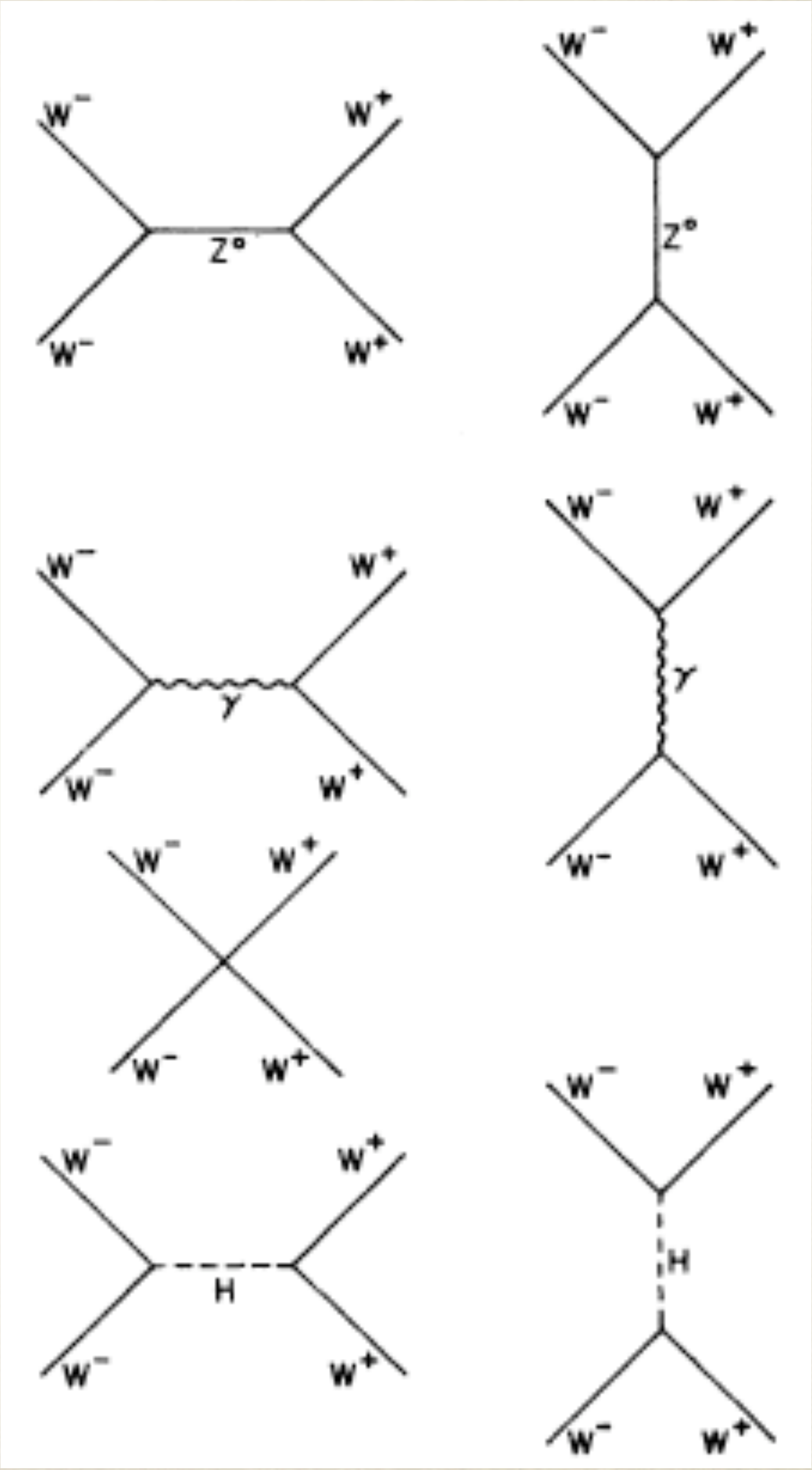
- In a composite-like model for the light Higgs boson, the ratio g_{hVV}/g_{hVV}^{SM} is assumed to be smaller than 1.
- Other heavier degrees of freedom are integrated out, leaving their effects in an effective Lagrangian with an explicit UV cutoff.
- Partial widths of the light Higgs boson will be affected.
- Weak gauge boson scatterings receive contributions of higher-dimensional effective operators that grow with energy until the cutoff is reached.

Remarks

- Using the conventional $\gamma\gamma$ and $b\underline{b}$ decay modes of the light Higgs boson to hunt for new physics becomes difficult.
- The $\gamma\gamma$ mode is suppressed when g_{hWW} is smaller than its SM value.
- The $b\underline{b}$ mode also suffers from the reduced g_{hWW} coupling because the associate production of $W^{\pm}h$ gets smaller.
- While these modes become less useful, the $W_L W_L$ scattering enjoys its partial growth.

$W_L^+ W_L^- \to W_L^+ W_L^-$

- As an explicit example, consider this process in the SM in the $s \gg m_h^2, M_W^2$ limit.
- Tree-level Feynman diagrams in the unitarity gauge:
  - 1 four-point interaction;
  - Z and γ in s and t channels; and
  - Higgs boson in s and t channels.
- Other $V_L V_L \to V_L V_L$ scatterings have similar structures.



$W_L^+ W_L^- \to W_L^+ W_L^-$

- Individual amplitudes of gauge diagrams:

$$
\begin{aligned}
i\mathcal{M}_4 &= i\frac{g^2}{4M_W^4}\left[s^2 + 4st + t^2 - 4M_W^2(s+t) - \frac{8M_W^2}{s}ut\right] \\
i\mathcal{M}_t^{\gamma+Z} &= -i\frac{g^2}{4M_W^4}\left[(s-u)t - 3M_W^2(s-u) + \frac{8M_W^2}{s}u^2\right] \\
i\mathcal{M}_s^{\gamma+Z} &= -i\frac{g^2}{4M_W^4}\left[s(t-u) - 3M_W^2(t-u)\right]
\end{aligned}
$$

- Individual diagrams in the first two categories grow like $(E/M_W)^4$!
- The sum of them nicely cancel with each other to remove such a divergence with energy.

$W_L^+ W_L^- \to W_L^+ W_L^-$

- However, there is still an $O((E/M_W)^2)$ divergence in the sum, which needs a sufficiently light Higgs boson to cure:

$$\sim \left(\frac{E}{M_W}\right)^2$$

$$
\begin{aligned}
i\mathcal{M}^{\text{gauge}} &= -i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) , \\
i\mathcal{M}^{\text{Higgs}} &= -i\frac{g^2}{4M_W^2}\left[\frac{(s-2M_W^2)^2}{s-m_h^2} + \frac{(t-2M_W^2)^2}{t-m_h^2}\right] \\
&\simeq i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) . \\
\Rightarrow &\quad \text{complete } (E/M_W)^2 \text{ cancellation}
\end{aligned}
$$

- The success of SM is thus seen to rely on nice relations among gauge bosons couplings (due to gauge invariance) and a suitable Higgs boson (depending on EWSB structure).

$W_L^+ W_L^- \to W_L^+ W_L^-$

- However, the story changes dramatically if $g_{hVV} = \sqrt{\delta}\, g_{hVV}^{\rm SM}$ as assumed:

$$
\begin{aligned}
i\mathcal{M}^{\rm gauge} &= -i\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) \ , \\
i\mathcal{M}^{\rm Higgs} &= -i\,\delta\frac{g^2}{4M_W^2}\left[\frac{(s-2M_W^2)^2}{s-m_h^2} + \frac{(t-2M_W^2)^2}{t-m_h^2}\right] \\
&\simeq i\,\delta\frac{g^2}{4M_W^2}u + \mathcal{O}\left((E/M_W)^0\right) \ . \\
\Rightarrow &\quad \text{only } \textit{partial}\ (E/M_W)^2 \text{ cancellation}
\end{aligned}
$$

- This gives rise to the “bad” high-energy behavior in the scattering cross section.

Remarks

- In the SM, the scattering amplitude still contains an $O((E/M_W)^0)$ term given by:

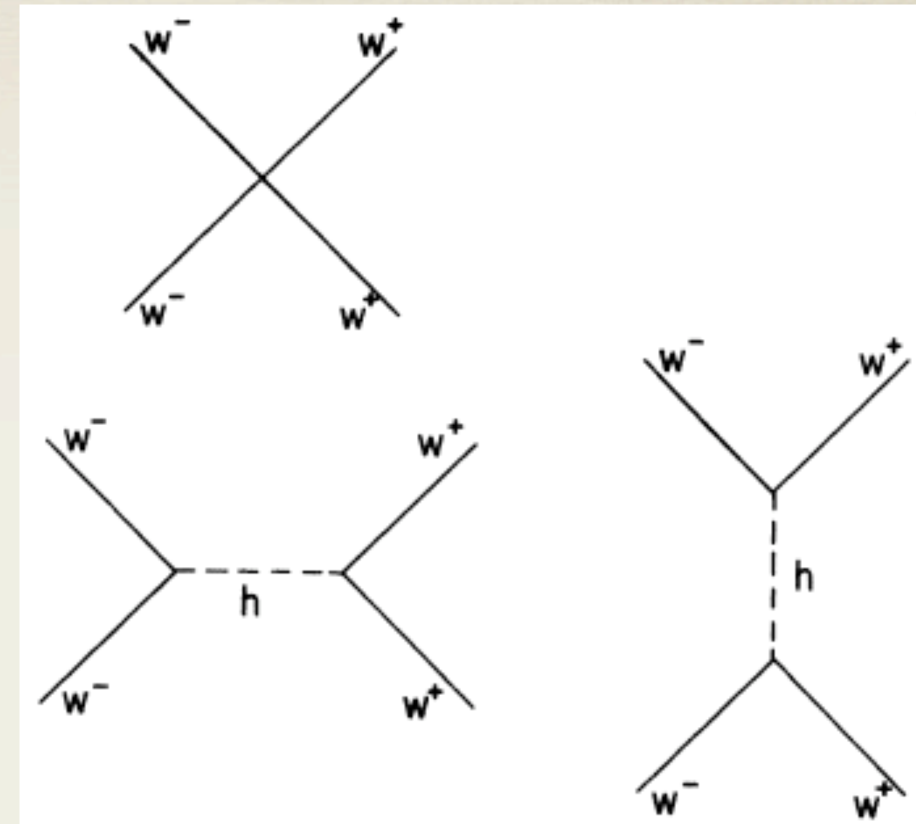
$$i\mathcal{M}_{\rm tot} \quad = \quad i\frac{g^2}{4M_W^4}m_h^2\left[\frac{s}{s \quad m_h^2}+\frac{t}{t \quad m_h^2}\right]$$

  which is proportional to the Higgs boson mass squared.

- One can therefore obtain an upper bound on m_h from the partial-wave analysis.
- The most stringent upper bound actually comes from a combination of different $V_L V_L$ scattering channels and turns out to be about 1 TeV.

Remarks

- The same SM results can also be readily obtained using the equivalence theorem.
- One only needs to consider the scattering of the corresponding Goldstone bosons.
  ⇒ fewer diagrams and simpler Feynman rules
- With suitable changes, this method can be extended to extensions of the SM.



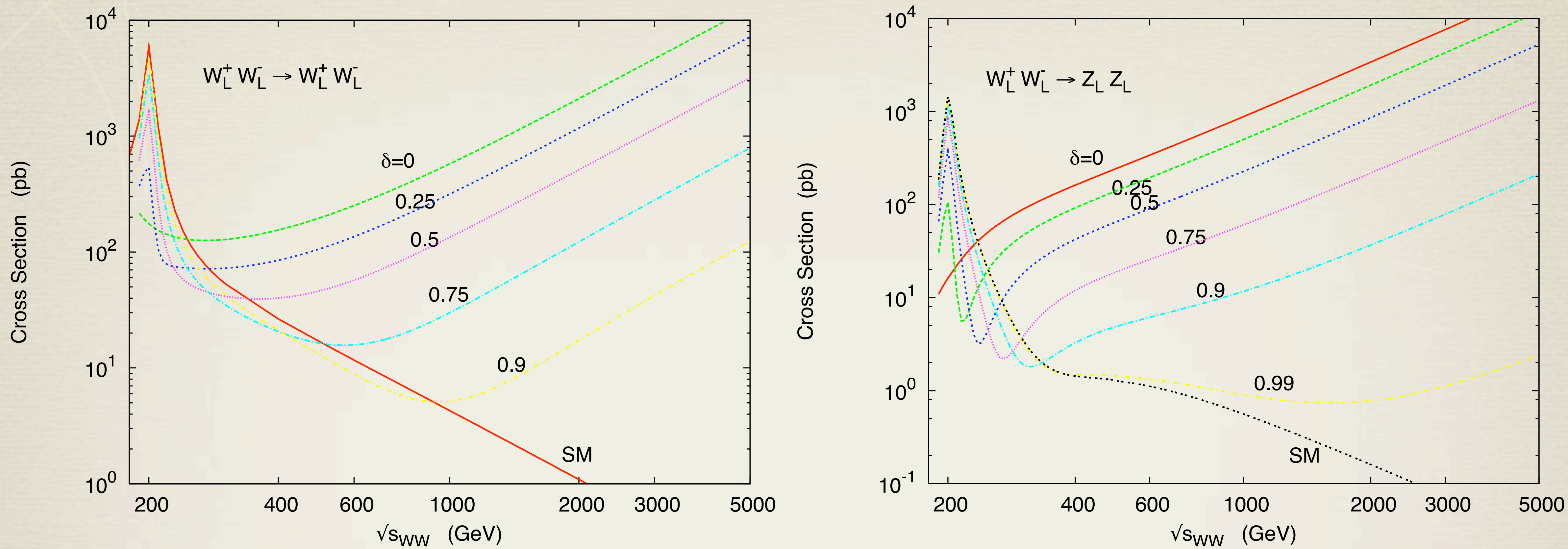
Scattering Channels

- The following channels are studied:

Channel	Gauge	Higgs
$W_L^+ W_L^- \to W_L^+ W_L^-$	x,s,t	s,t
$W_L^+ W_L^- \to Z_L Z_L$	x,t,u	s
$Z_L Z_L \to Z_L Z_L$	—	s,t,u
$W_L^\pm Z_L \to W_L^\pm Z_L$	x,s,u	t
$W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm$	x,t,u	t,u

- Cross sections of the first two resonant channels grow with energy as it goes above the light Higgs boson mass.
- Cross sections of the last two non-resonant channels increase in a less dramatic way.
- The $Z_L Z_L \to Z_L Z_L$ channel is suppressed from SM by δ because it is purely Higgs-mediated.

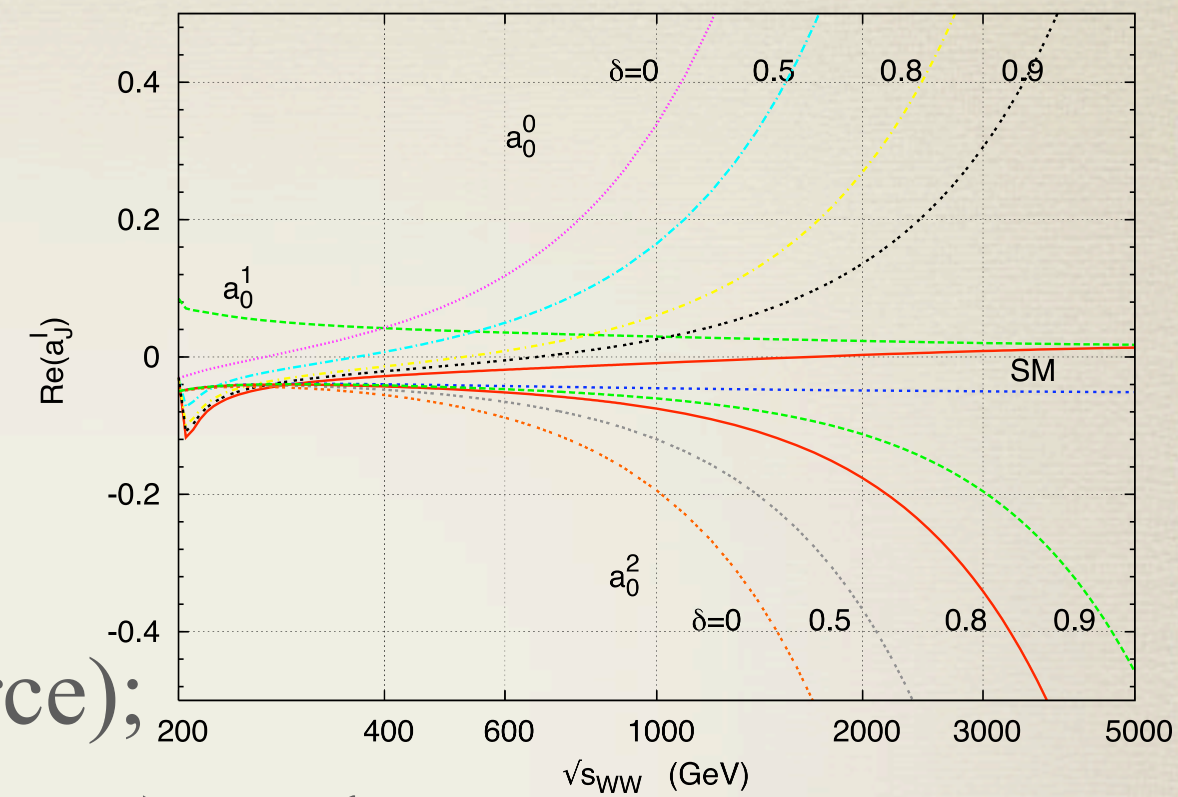
Cross Sections



- Scattering cross sections of $W_L^+W_L^- \to W_L^+W_L^-$ (L) and $W_L^+W_L^- \to Z_LZ_L$ (R) as functions of the scattering energy.
- Assume $m_h = 200$ GeV and an angular cut $|\cos\theta| \leq 0.8$.
- The turn-over effect is different from SM both qualitatively and quantitatively, even if effects of heavy Higgs bosons of TeV masses are included.

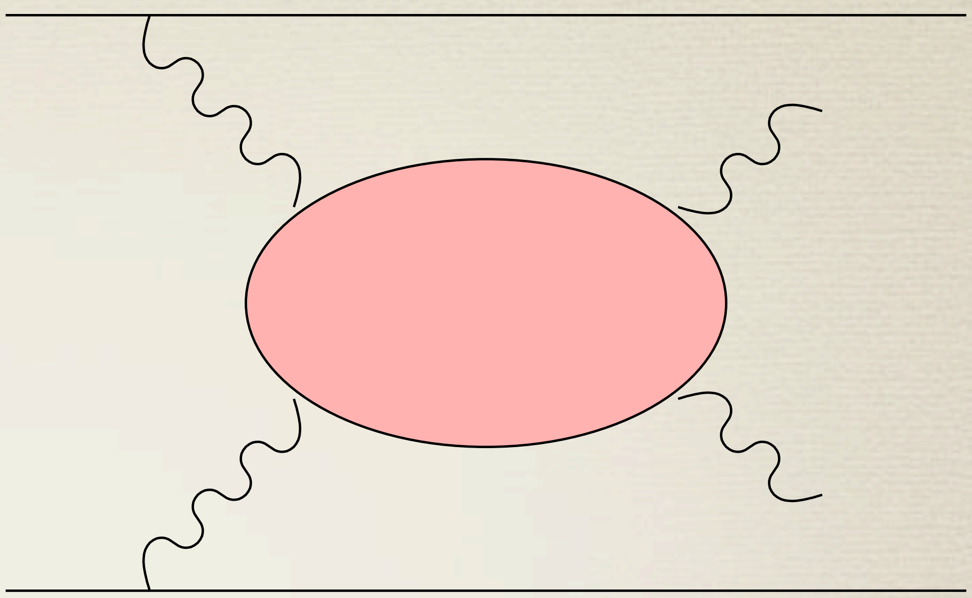
Partial-Wave Amps

- Re(a_J^I) with $J = 0$ and isospin $I = 0, 1, 2$ for various δ :
- Unitarity demands that
  $|\text{Re}(a_0^I)| \le 1/2$.
- At high energies:



  - a_0^0's are positive (attractive force);
  - a_0^2's stay negative (repulsive force); and
  - a_0^1's are close to 0 (irrelevant, odd function of cosθ).
- Unitarity violation is delayed for finite δ compared to the case with a heavy Higgs. Though the LHC may not be able to directly probe these coefficients at such high energies, their growing behavior at low energies should be discernible.

Effective W Approximation



- At LHC, the weak gauge bosons in the initial state are radiated off the jets from the colliding protons.
- We employ the so-called effective W approximation (EWA)

$$f_{q\to W_L(x)} \sim \frac{1-x}{x}$$

Dawson 1985

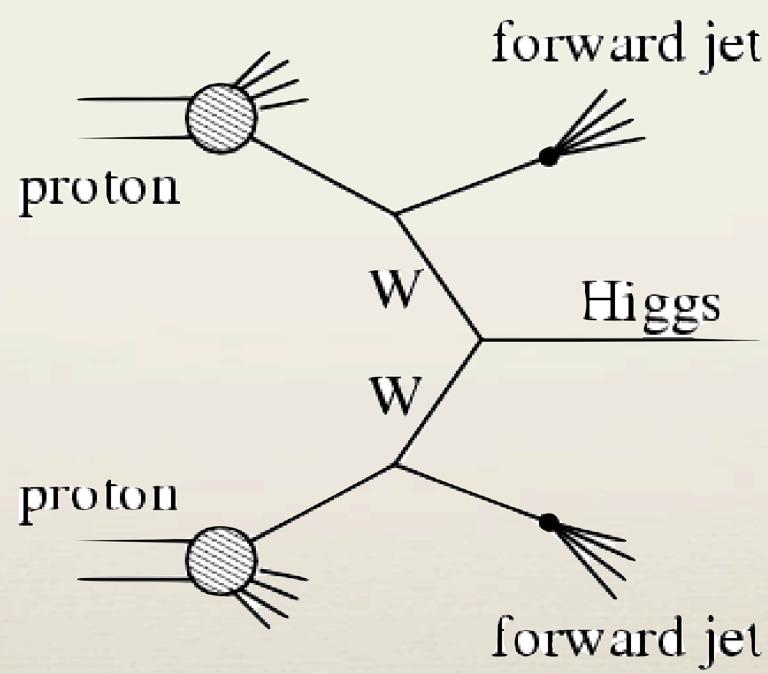
up to some coupling factors depending upon the types of the quark and the gauge boson.

- The same approximation is used to the Z boson as well.
- The radiation probability peaks when $x\to0$ and vanishes when $x\to1$.

Enhancing S/B

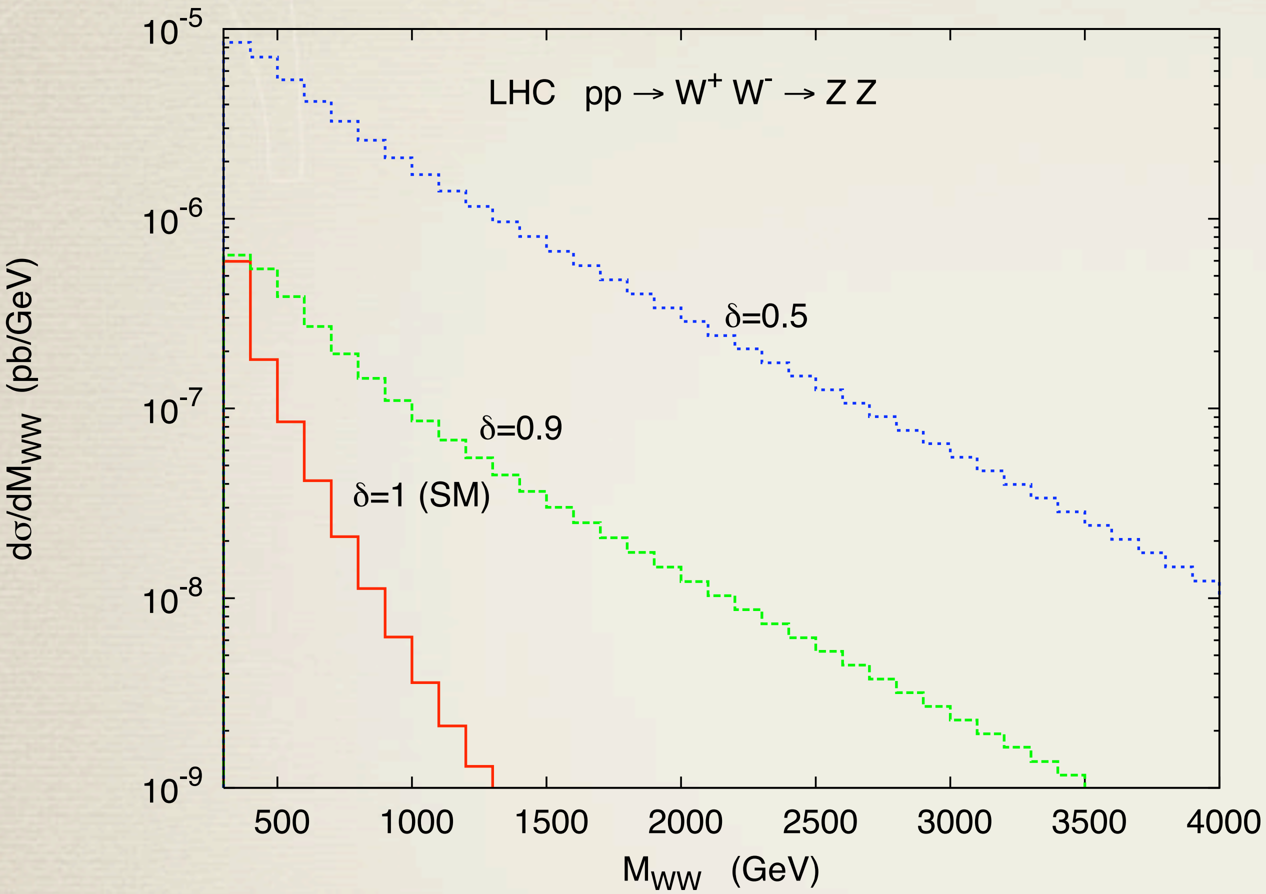
Bagger et al 1994, 1995

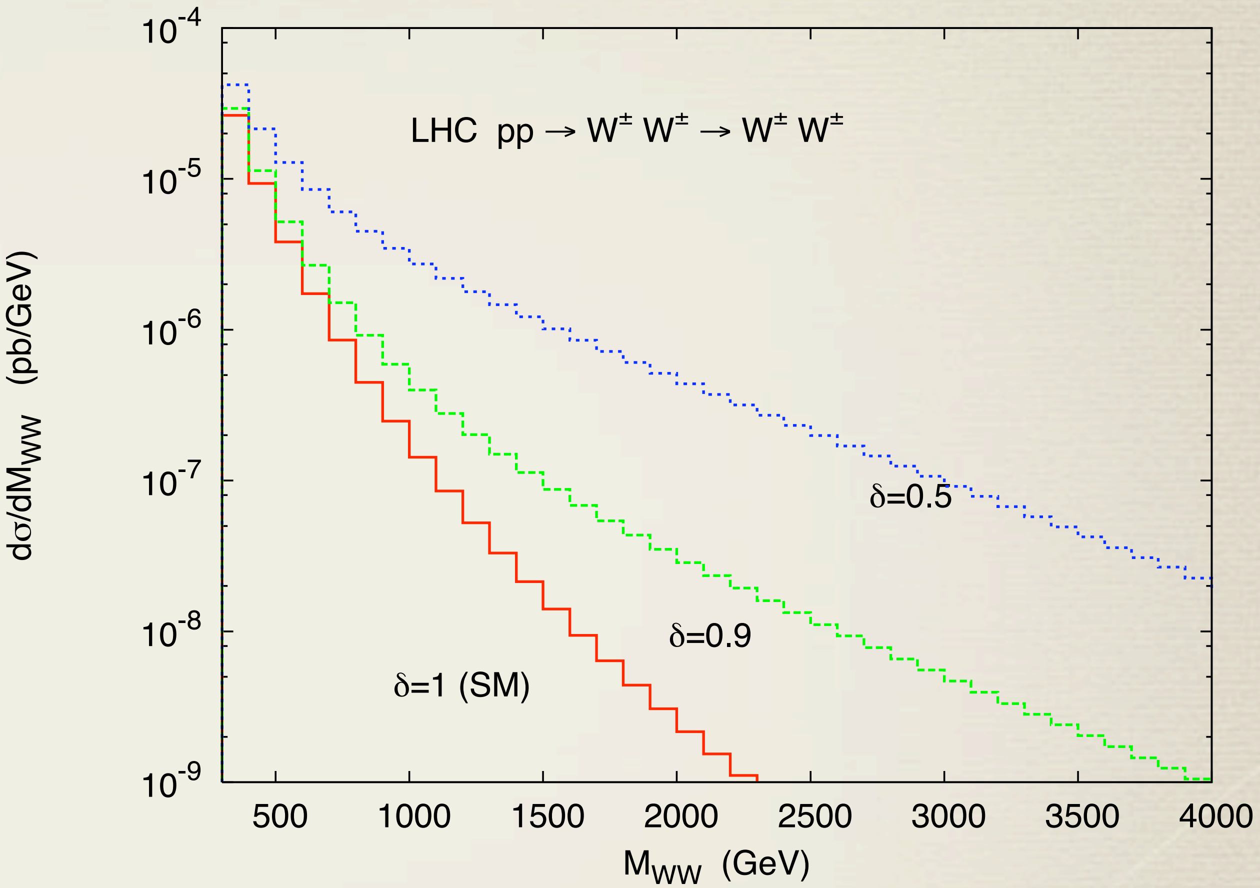
- A good part of initial energy is carried away by the jets.
  ⇒ energetic forward jets
  ⇒ large rapidity gap ($|\eta|>2$) [meaning little hadronic activity in central region]
  ⇒ use central jet veto and forward jet tagging
- A very similar idea had been proposed for Higgs production through VBF.



Diff. x-sec @ LHC

- Invariant mass distribution using naive EWA:





- The difference from the SM can be significant (even for δ as large as 0.9), provided that the UV-completing degrees of freedom are sufficiently heavy.

LHC Signals

- Study the leptonic final states of the above-mentioned scattering channels to avoid QCD background.
- Focus on $WW \to \ell\nu\ell\nu$ and $ZZ \to \ell^+\ell^-\ell^+\ell^- + \ell\ell\nu\nu$

Table 1: Event rates for longitudinal weak gauge boson scattering at the LHC with a yearly luminosity of 100 fb^{-1} using the EWA for $\delta = 1$ (SM), 0.9, 0.5 and 0 (No Higgs). Branching ratios for the leptonic final states are summed for $\ell = e$ and μ. We set $m_h = 200$ GeV and $M_{WW}^{\min} = 300$ GeV.

Subprocess	Number of Events			
	$\delta = 1$ (SM)	0.9	0.5	0 (No Higgs)
$W_L^\pm W_L^\pm \to W_L^\pm W_L^\pm \to \ell^\pm\nu\ell^\pm\nu$	21	26	57	118
$W_L^\pm W_L^\mp \to W_L^\pm W_L^\mp \to \ell^\pm\nu\ell^\mp\nu$	8	7	17	67
$W_L^\pm Z_L \to W_L^\pm Z_L \to \ell^\pm\nu\ell^+\ell^-$	4	5	13	33
$W_L^+ W_L^- \to Z_L Z_L \to \ell^+\ell^-\ell^+\ell^-$	0.04	0.12	2	9
$W_L^+ W_L^- \to Z_L Z_L \to \ell^+\ell^-\nu\bar{\nu}$	0.25	0.74	12	50
$Z_L Z_L \to Z_L Z_L \to \ell^+\ell^-\ell^+\ell^-$	0.4	0.32	0.08	0
$Z_L Z_L \to Z_L Z_L \to \ell^+\ell^-\nu\bar{\nu}$	2.4	2	0.5	0

Work in Progress

Cheung, Chiang, Hsiao, and Yuan

- In models with a massive Z' gauge boson associated with an extra U(1) symmetry, the ZWW, $ZZWW$, and hZZ couplings are necessarily modified due to the Z-Z' mixing, assuming no fine-tuning.
- In contrast, the hWW coupling remains intact.
- Partial growth of the longitudinal weak gauge boson scattering at high energies behaves not only as $(E/M_W)^2$, but even as $(E/M_W)^4$!
- Detailed study of the high-energy behavior for all scattering channels can help us determine whether this is the case.

Summary

- Supposing that only a light Higgs boson is detected and it is not fully responsible for the EWSB, we expect discernible energy-growing behavior of VV scatterings at the LHC.
- The cross sections increase until the other heavier Higgs bosons or UV-completing parts come to unitarize the amplitudes.
- The LHC signature is excess production of longitudinal gauge boson pairs in the large invariant mass region from their leptonic decays.
- By careful comparison of measured event rates, we should be able to deduce how much the g_{hVV} couplings deviate from the SM values.