WW scattering in the era of post-Higgs-boson discovery

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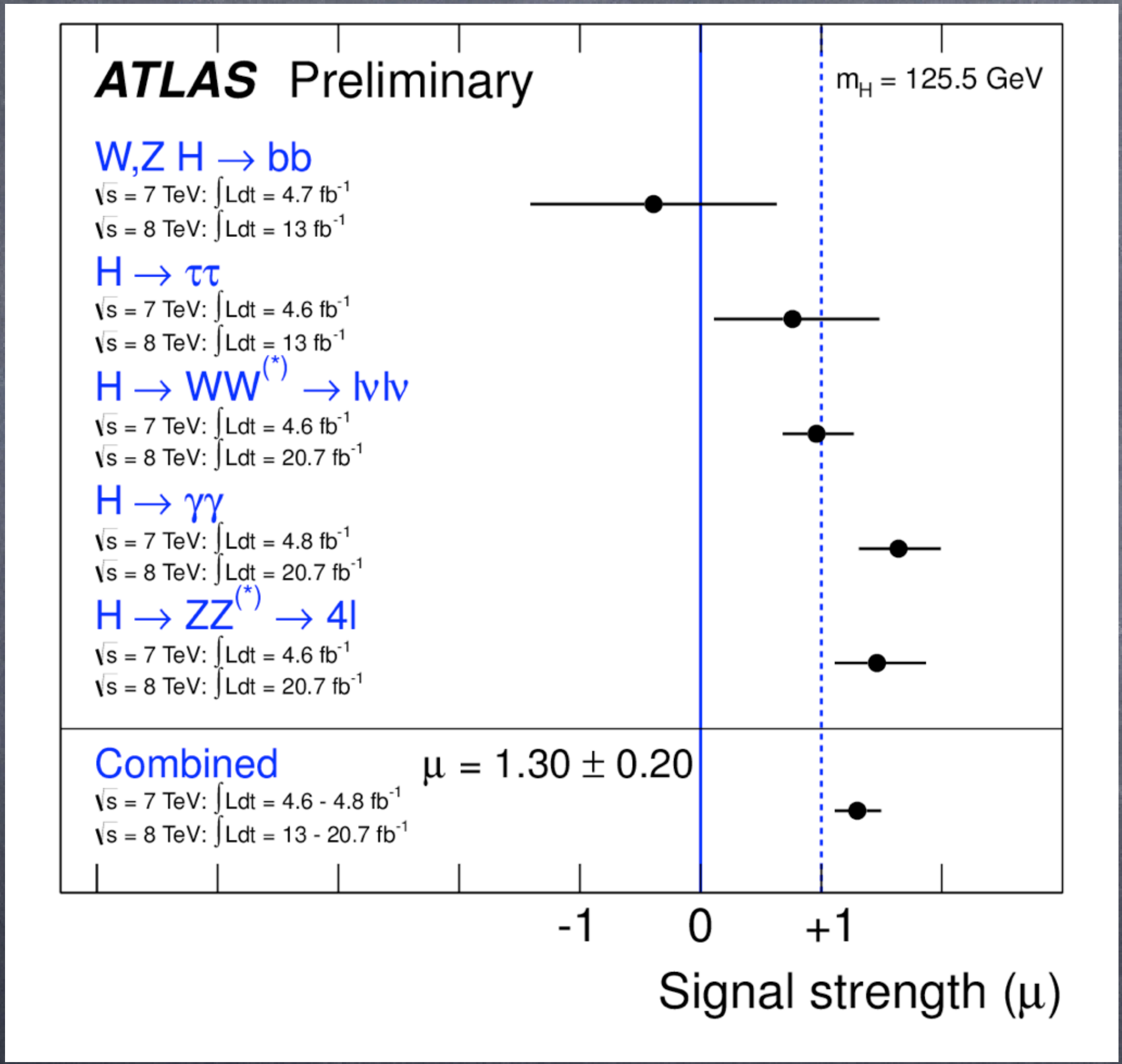
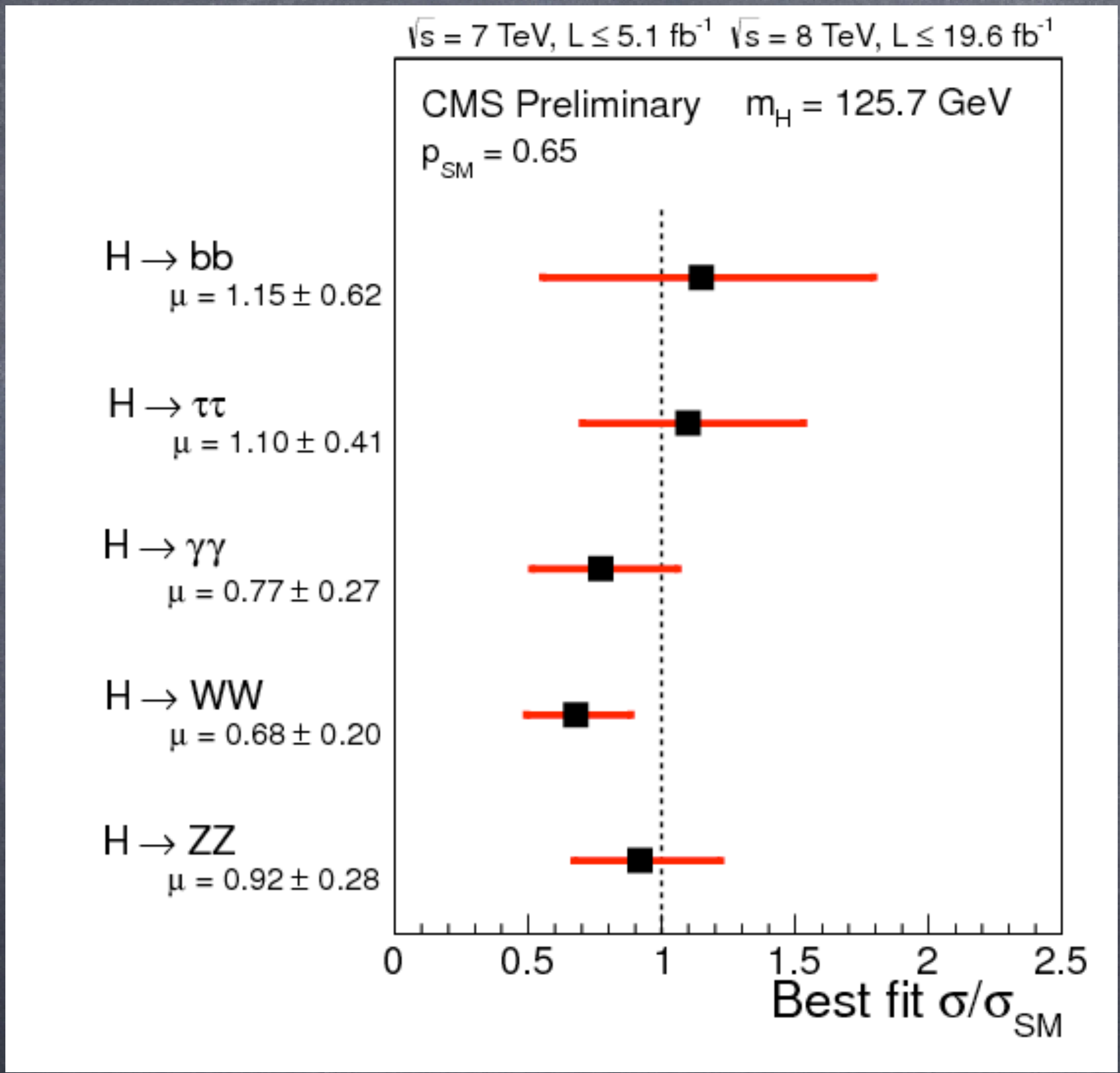
What do we know for the new boson from LHC ?





√s = 7 TeV, L ≤ 5.1 fb-1 √s = 8 TeV, L ≤ 19.6 fb-1
CMS Preliminary
mH = 125.7 GeV
pSM = 0.65
H → bb
μ = 1.15 ± 0.62
H → ττ
μ = 1.10 ± 0.41
H → γγ
μ = 0.77 ± 0.27
H → WW
μ = 0.68 ± 0.20
H → ZZ
μ = 0.92 ± 0.28
0
0.5
1
1.5
2
2.5
Best fit σ/σSM

Motivation :

- Is the new 125-126 GeV boson a lone player responsible for the full EWSB ? (Is the simplest SM enough?)
- May the additional Higgs bosons play a partial role in EWSB as well ? (Do we need the "New Physics" ex: 2HDM, Little Higgs model,Strongly-Interacting Light Higgs Model?)

WW fusion

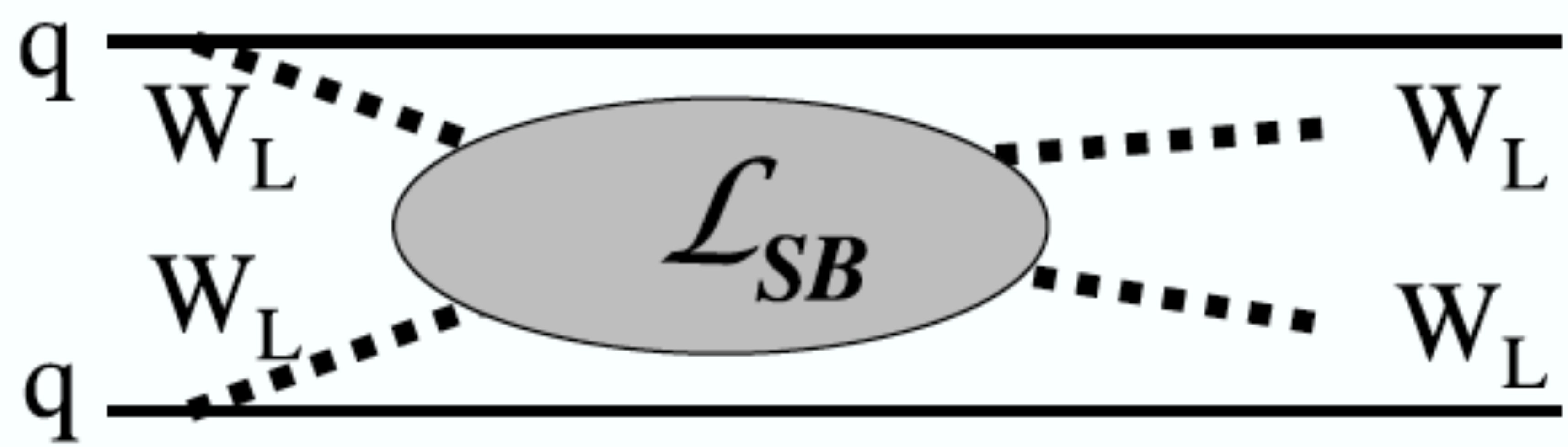


Figure 1: $W_L W_L$ fusion.

Basic Ideas

- The WW scattering becomes strong when the extra Higgs bosons are very heavy.
- The modified gauge-Higgs coupling may lead to incomplete cancellation and thus the partial growth in the scattering amplitudes in the intermediate energy range.

Method :

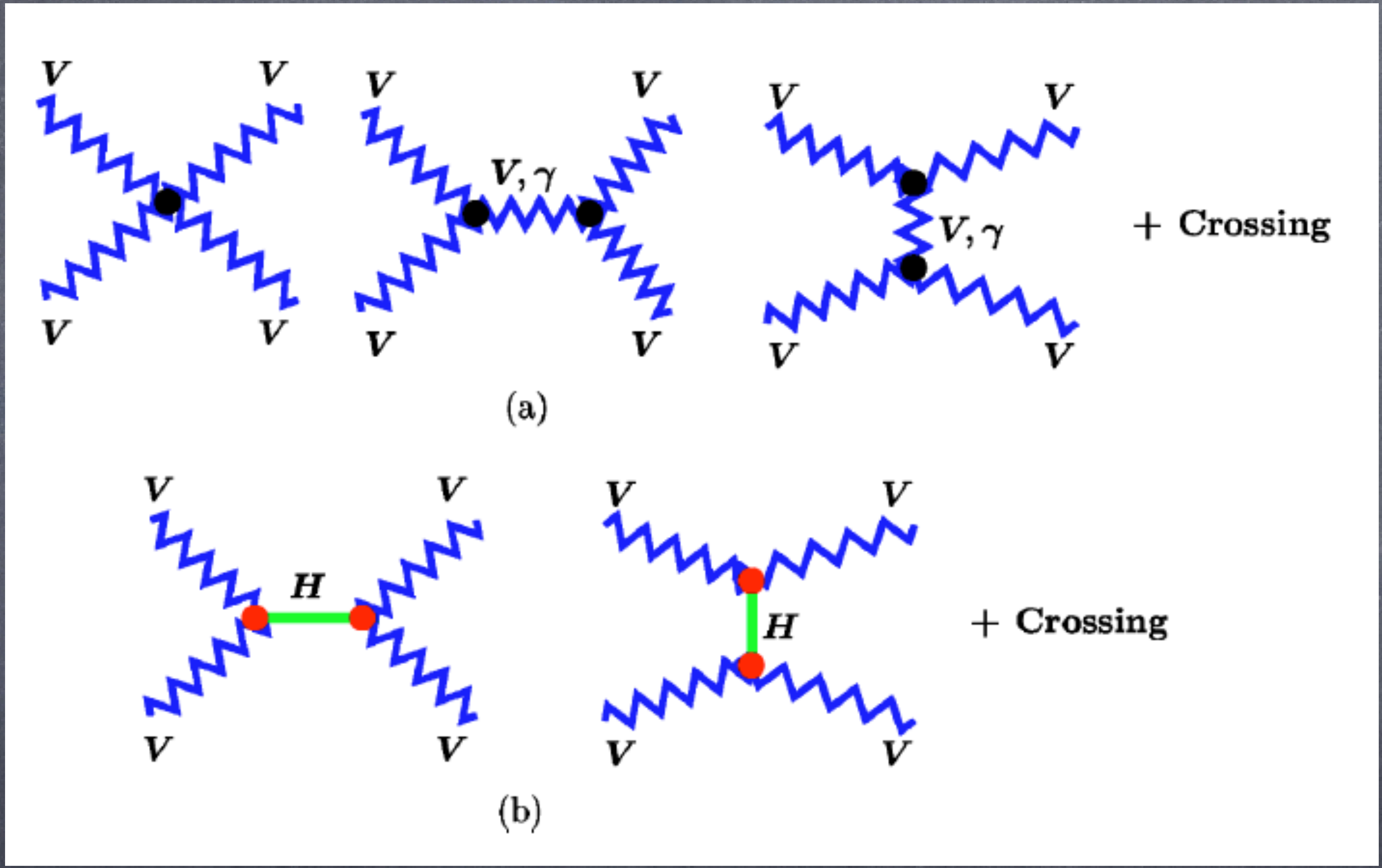
- We use WW scattering to investigate such a possibility, using 2HDM as a prototype.
- We set the light CP-even Higgs boson h is at 125 GeV while the heavy CP-even Higgs boson H is at 2 TeV.
- These 2 CP-even Higgs bosons couple to the vector boson with reduced strengths

$$g_{hWW} = \sin(\beta - \alpha) g_{hWW}^{SM} \qquad g_{HWW} = \cos(\beta - \alpha) g_{hWW}^{SM}$$

- $$g_{hWW}^2 + g_{HWW}^2 = (g_{hWW}^{SM})^2$$

- where $tan\beta$ is the ratio of the VEVs of the two CP-even neutral Higgs bosons and α the mixing angle between the two CP-even neutral Higgs bosons.
- At low energy only one light CP-even Higgs boson is relevant.

Feynman diagrams for VV scattering



- cite : PRD 67, 114024 (2003)

WW SCATTERING AMPLITUDES

$$i\mathcal{M}^{\text{gauge}} = i\mathcal{M}_t^{\gamma+Z} + i\mathcal{M}_s^{\gamma+Z} + i\mathcal{M}_4$$
$$= -i\frac{g^2}{4m_W^2}u + O((E/m_W)^0).$$

$$i\mathcal{M}^{\text{Higgs}} = -i\frac{C_v^2 g^2}{4m_W^2}\left[\frac{(s-2m_W^2)^2}{s-m_h^2} + \frac{(t-2m_W^2)^2}{t-m_h^2}\right],$$
$$\simeq i\frac{C_v^2 g^2}{4m_W^2}u,$$

- These two amplitudes are approximated in the limit of $s \gg m_h^2, m_W^2$
- Only if C_v is exactly equal to 1 as in SM can the bad energy-growing term be delicately cancelled between the gauge diagrams and the Higgs diagrams.

The current data constrain [4]

$$C_v \equiv \frac{g_{hWW}}{g_{hWW}^{\mathrm{SM}}} = 0.96^{+0.13}_{-0.15}.$$

- Nevertheless, it is not unreasonable that the value of C_v could deviate from the central value by **2 sigma**, then the C_v could be as low as 0.66.

Unitarity Limit

- We analyze the partial-wave coefficients of the scattering amplitudes to determine when unitarity is violated.
- Unitarity demands : $|Rea_0^I| \leq 1/2$
- The most severe violation of unitarity is in the a_0^0 channel.
- We define $C_v \equiv \sqrt{\delta}$

Unitarity Limit

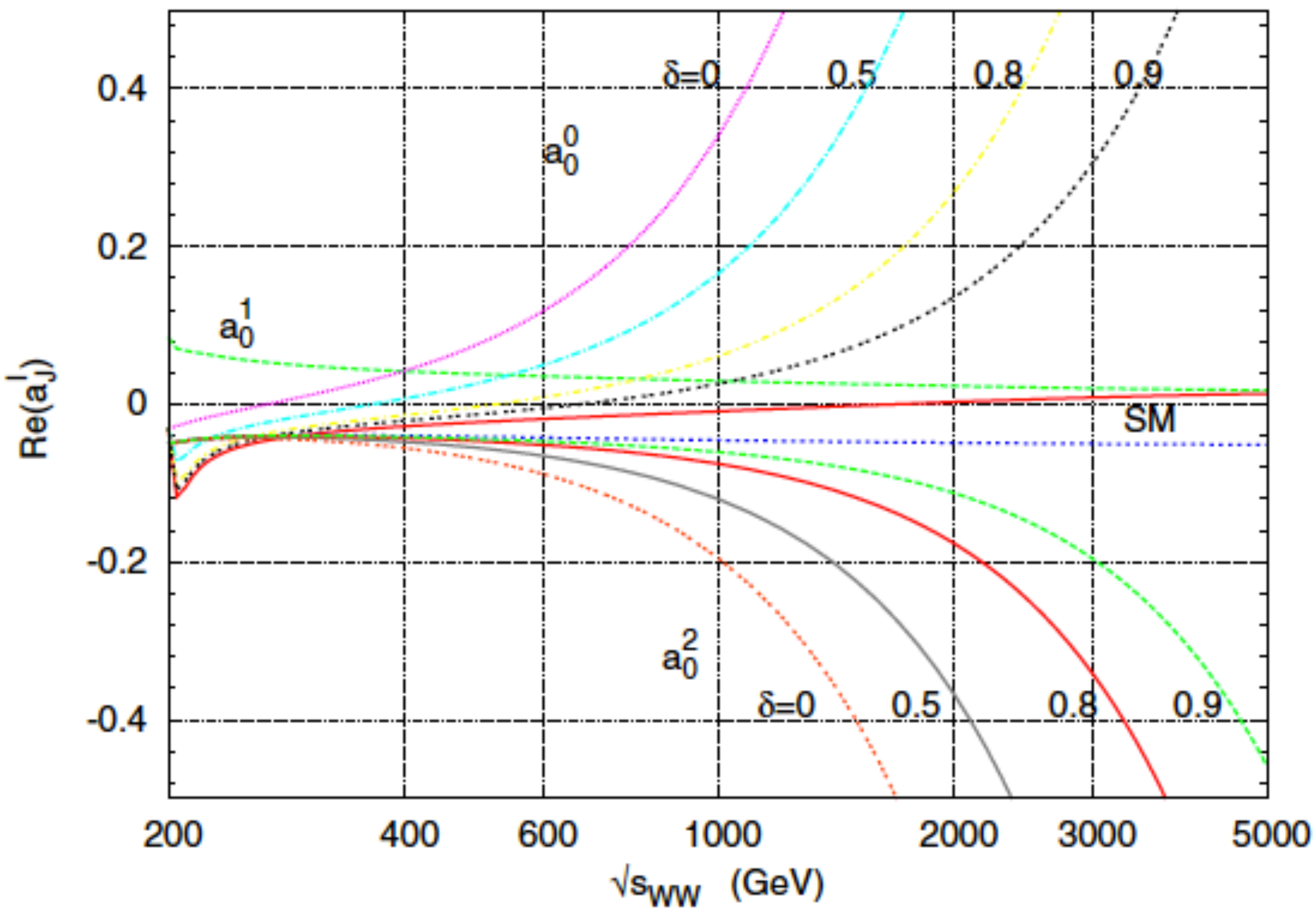
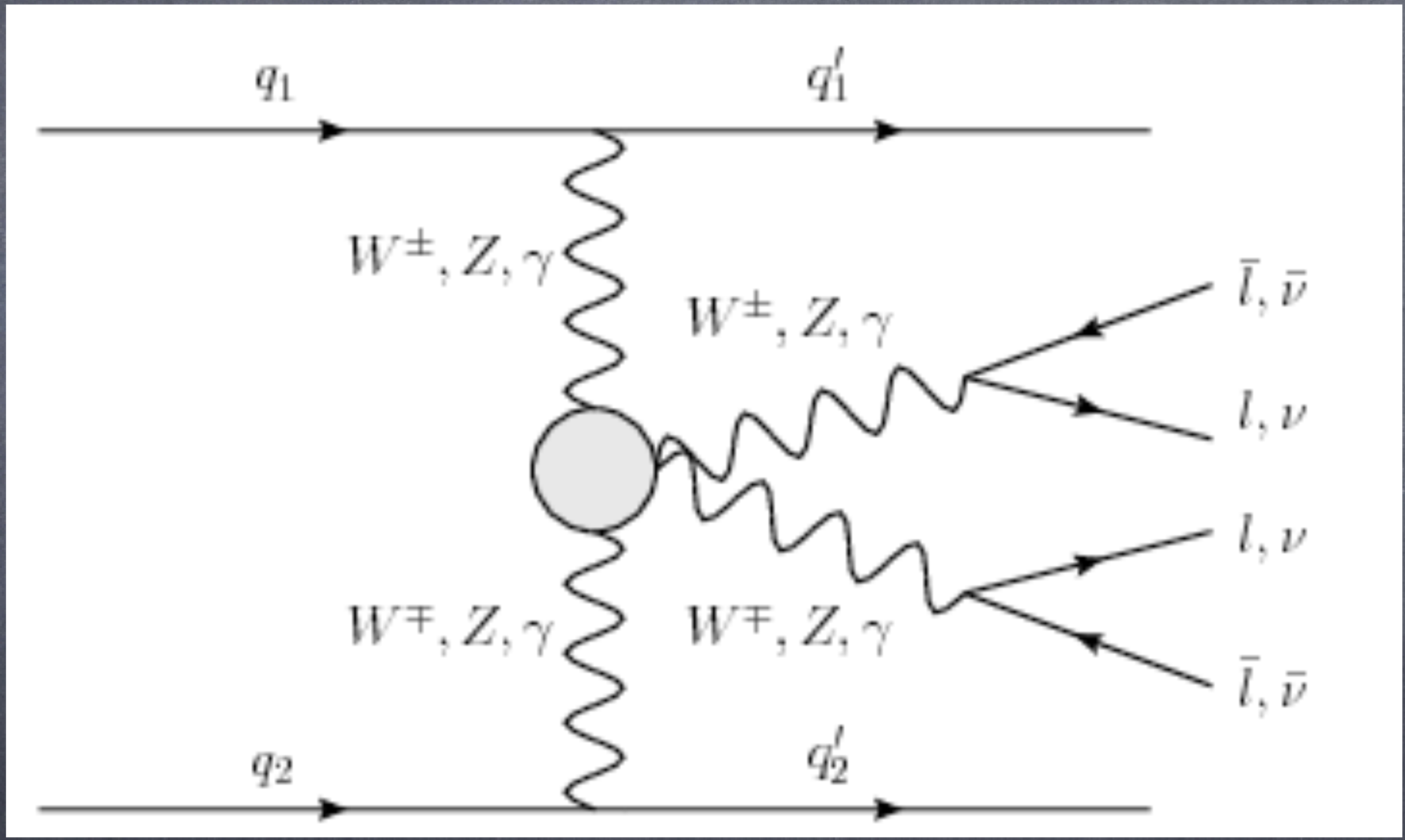


FIG. 2 (color online). The partial-wave coefficients $a_0^{0,1,2}$ versus the CM energy $\sqrt{s_{WW}}$ for various $\delta = 0$-0.9.

Vector Boson Fusion (VBF)



How to separate the VBF diagrams among all the other non-VBF ones ?

- We choose the pure leptonic decay modes of the final state weak bosons as the tagging modes, this will avoid the large hadronic backgrounds at the LHC.

- The QCD background can be greatly suppressed by tagging a forward-going jet. This forward-jet tagging will also suppress the transverse component of the initial V, so that the initial state V will be essentially V_L .

- The EW background can be suppressed by detecting isolated leptons with large transverse momentum in the central rapidity region, especially requiring the two final state leptons to be nearly back to back.
- These leptonic cuts also suppress the V_T contributions in the final state.

Numerical Results

- Experimental Cuts for VBF :
- (i) The appearance of 2 energetic forward jets with large spatial separation.
- (ii) The leptonic decay products of the W or Z bosons are enhanced at the large invariant mass region.

- Cuts for the 2 jets in selecting the VBF events

$$E_{T_{j1,j2}} > 30 \text{ GeV}, \qquad |\eta_{j1,j2}| < 4.7,$$
$$\Delta\eta_{12} = |\eta_{j1} - \eta_{j2}| > 3.5, \qquad \eta_{j1}\eta_{j2} < 0, \tag{8}$$

where $E_{T_{j1,j2}}$ and $\eta_{j1,j2}$ are the transverse energies and pseudorapidities, respectively, of the two forward jets, and

$$M_{jj} > 500 \text{ GeV} \tag{9}$$

on their invariant mass M_{jj} at $\sqrt{s} = 13$ TeV.

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- Cuts for the leptonic decay modes

TABLE I. Leptonic cuts on the leptonic decay products of the diboson channels: W^+W^-, $W^\pm W^\pm$, $W^\pm Z$, and ZZ.

W^+W^-	$W^\pm W^\pm$	$W^\pm Z$	ZZ
$p_{T_\ell} > 100$ GeV	$p_{T_\ell} > 100$ GeV	$p_{T_\ell} > 100$ GeV	$p_{T_\ell} > 50$ GeV
$\lvert y_\ell \rvert < 2$	$\lvert y_\ell \rvert < 2$	$\lvert y_\ell \rvert < 2$	$\lvert y_\ell \rvert < 2$
$M_{\ell^+\ell^-} > 250$ GeV	$M_{\ell^\pm\ell^\pm} > 250$ GeV	$M_{3\ell} > 375$ GeV	$M_{4\ell} > 500$ GeV

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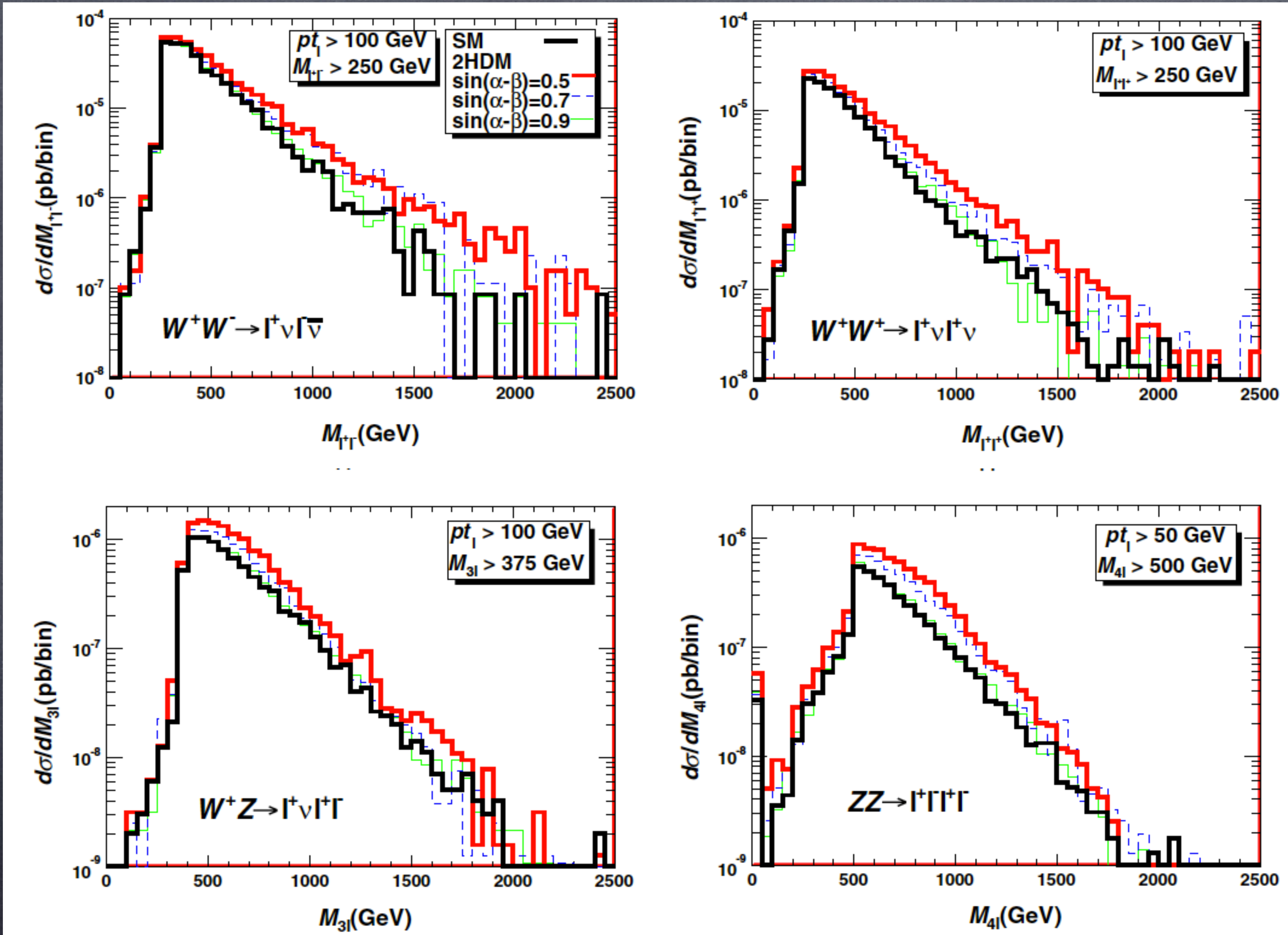
TABLE II. Cross sections in fb in various diboson channels under the jet cuts in Eqs. (8) and (9) and leptonic cuts listed in Table I.

Channels	Cross sections (fb) $\sin(\beta-\alpha)=0.5$	0.7	0.9	SM ($C_v = 1$)
$W^+W^- \to \ell^+\nu\ell^-\bar{\nu}$	0.51	0.46	0.40	0.39
$W^+W^+ \to \ell^+\nu\ell^+\nu$	0.20	0.17	0.14	0.14
$W^-W^- \to \ell^-\bar{\nu}\ell^-\bar{\nu}$	0.083	0.075	0.070	0.069
$W^+Z \to \ell^+\nu\ell^+\ell^-$	0.016	0.013	0.011	0.010
$W^-Z \to \ell^-\bar{\nu}\ell^+\ell^-$	1.0×10^{-2}	8.5×10^{-3}	7.6×10^{-3}	7.4×10^{-3}
$ZZ \to \ell^+\ell^-\ell^+\ell^-$	8.4×10^{-3}	6.4×10^{-3}	4.6×10^{-3}	4.4×10^{-3}



pt_l > 100 GeV
M_l+l- > 250 GeV
SM
2HDM
sin(α-β)=0.5
sin(α-β)=0.7
sin(α-β)=0.9
W+W- → l+νl-ν̄
dσ/dM_l+l-(pb/bin)
M_l+l-(GeV)
pt_l > 100 GeV
M_l+l+ > 250 GeV
W+W+ → l+νl+ν
dσ/dM_l+l+(pb/bin)
M_l+l+(GeV)
pt_l > 100 GeV
M_3l > 375 GeV
W+Z → l+νl+l-
dσ/dM_3l(pb/bin)
M_3l(GeV)
pt_l > 50 GeV
M_4l > 500 GeV
ZZ → l+l-l+l-
dσ/dM_4l(pb/bin)
M_4l(GeV)

Conclusion

- The detailed studies of longitudinal weak gauge boson scattering at the LHC can provide useful hints of new physics at a higher scale (~2TeV), despite only a light Higgs boson (125~126GeV) has been discovered.

END

- Thank You ! !

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