Weak Gauge Boson Scattering in the Era of Post-Higgs-Boson Discovery

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Rencontres du Vietnam, *Windows on the Universe*
August 11 - 17, 2013
ICISE, Quy Nhon, Vietnam

About the New Boson

- A new resonance is found around 125 - 126 GeV at the LHC.
- Decay Modes:
  -- WW*, ZZ* modes are consistent with SM
  -- Fermionic modes $(\tau^+\tau^-, \mu^+\mu^-, b\bar{b})$ is about 3σ, needs more statistics
  -- Diphoton signal strength
  ATLAS (1.55 of SM) versus CMS (0.77 of SM)
  -- Zγ not seen yet!
- Spin is consistent with 0^+, while 0^-, 2^+ are disfavoured!

Theoretical Questions

- Suppose we detect only a light Higgs boson (m_h ~ 125-126 GeV) and nothing else at the LHC. [Nightmare Scenario?]
- Can we declare EWSB is completely understood?
- Is it the SM Higgs boson or does it belong to a larger Higgs sector?
- In the latter case, assuming that we cannot probe and detect the other degrees of freedom directly, how can we be sure there is a larger Higgs (or perhaps other gauge) sector?

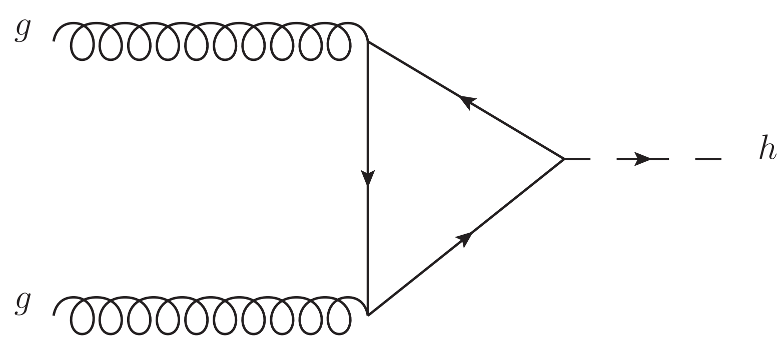
Outline

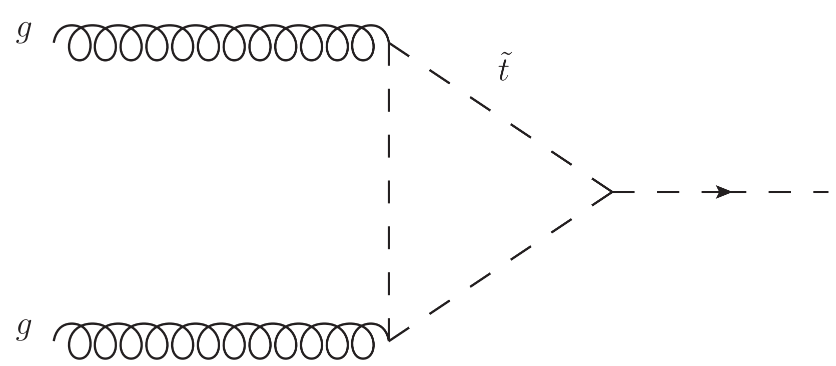
- Vector Boson Fusion and Electroweak Symmetry Breaking
- Vector Boson Fusion in Two Higgs Doublet Model
- Results

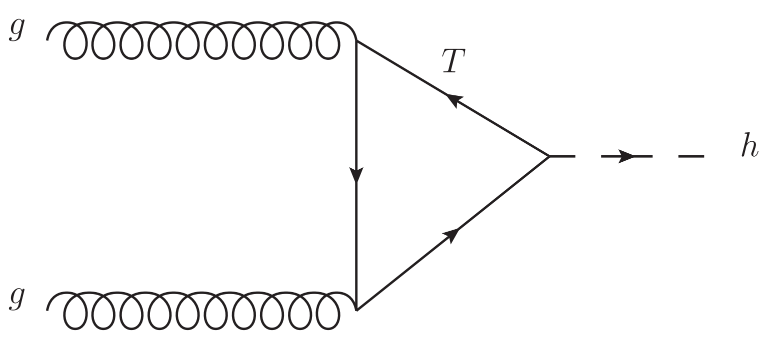
Based on:
(1) Chang, Cheung, Lu, TCY, 1303.6335 PRD87, 093005 (2013) [post-Higgs discovery]
(2) Cheung, Chiang, TCY, 0803.2661 PRD78, 051701 (2008) [pre-Higgs discovery]

Vector Boson Fusion and Electroweak Symmetry Breaking

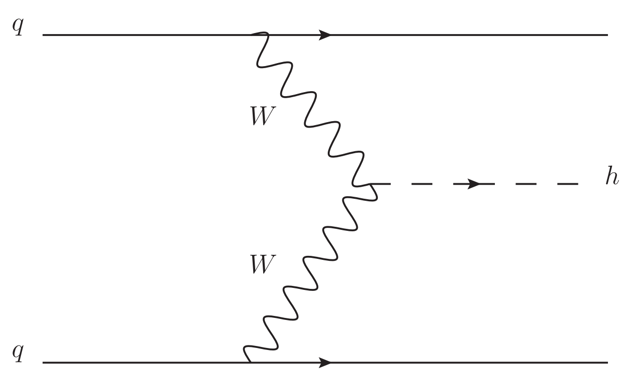
- For most models, except for the FP Higgs, gluon fusion is the dominant production mechanism ($\sigma(gg \to h_{SM}) \approx$ 20 pb for 125 GeV Higgs at LHC8). But the gluon fusion can involve other exotic colored particles:







- On the other hand, VBF is the cleanest channel to probe EWSB via hVV couplings:



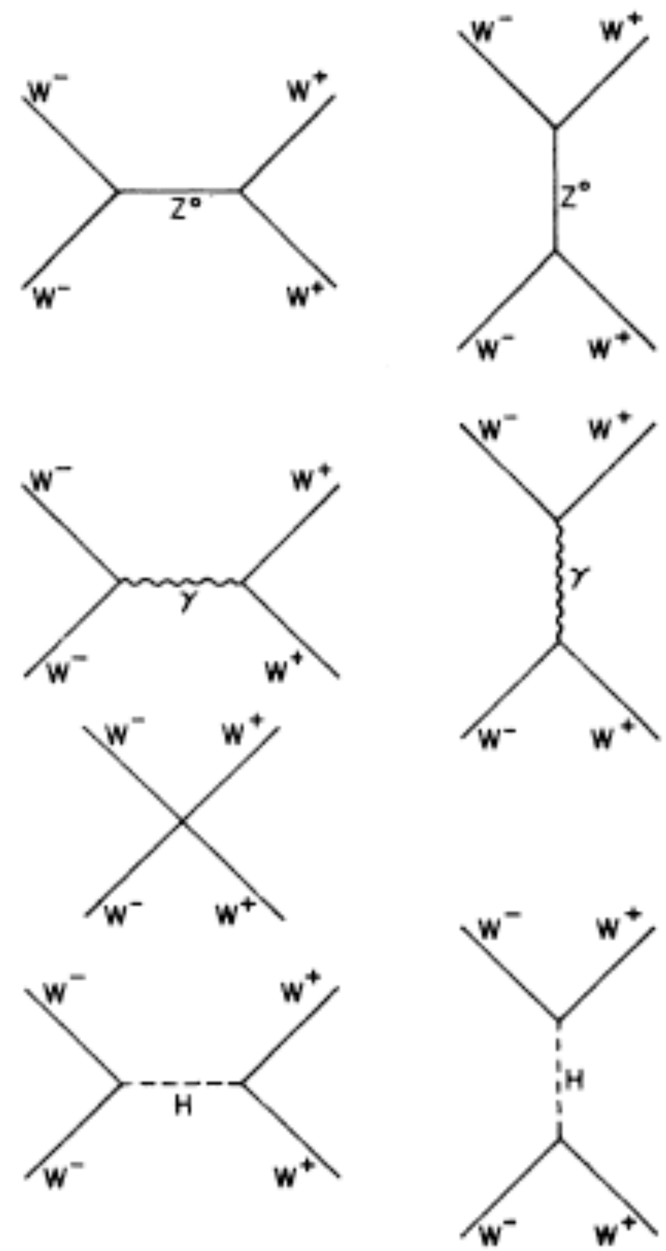
which gives two energetic forward jets, which can be tagged experimentally.

- Before kinematical cuts, VBF cross section is ≈ 8% of gluon fusion for 125 GeV Higgs at LHC8, while Higgs-strahlung is ≈ 5%.

- Two classes of events:
  (i) *Inclusive* diphoton events $\gamma\gamma X$ receives contributions from gluon fusion, VBF, associated production with $W/Z/t\bar{t}$.
  (ii) *Exclusive* $jj\gamma\gamma$ events receives contributions from VBF and associated production.
- We can use the forward jet-tag to suppress the associated production.
- By combining the measurements of *inclusive* $\gamma\gamma X$ production and *exclusive* $jj\gamma\gamma$ VBF production we can obtain useful information about different production mechanisms and models.

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

- As an 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:
  - 4 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 diagrams.



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

- Individual amplitudes of gauge diagrams:

$$i\mathcal{M}_4 = i\frac{g^2}{4M_W^4}\left[s^2+4st+t^2-4M_W^2(s+t)-\frac{8M_W^2}{s}ut\right]$$

$$i\mathcal{M}_t^{\gamma+Z} = -i\frac{g^2}{4M_W^4}\left[(s-u)t-3M_W^2(s-u)+\frac{8M_W^2}{s}u^2\right]$$

$$i\mathcal{M}_s^{\gamma+Z} = -i\frac{g^2}{4M_W^4}\left[s(t-u)-3M_W^2(t-u)\right]$$

- Individual diagrams grow like $(E/M_W)^4$!
- The sum of them nicely cancel with each other to remove such a bad high energy terms.
- For Z′ model, even these $(E/M_W)^4$ terms do not cancel completely. See Cheung, Chiang, Hsiao, TCY, 0911.0734

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

$$i\mathcal{M}^{\text{gauge}} = -i\frac{g^2}{4M_W^2}u+\mathcal{O}\left((E/M_W)^0\right) ,$$

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

$$\simeq i\frac{g^2}{4M_W^2}u+\mathcal{O}\left((E/M_W)^0\right) .$$

$\Rightarrow$ complete $(E/M_W)^2$ cancellation

- 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).

Vector Boson Fusion in Two Higgs Doublet Model

Higgs *Impostors*

- Fermiophobic Higgs
- 2HDM (Type I, II, III, IV, Inert Higgs Doublet, ...)
- SUSY (MSSM, NMSSM, PMSSM, UMSSM, ...)
- Radion, Dilaton
- Etc

2HDM - Type II

- In Type II, one doublet couples only to down-type quarks and another doublet couples to the up-type quarks. No tree level FCNC.

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \; H_d = \begin{pmatrix} H_d^+ \\ H_d^0 \end{pmatrix} \longrightarrow \langle H_u \rangle = \begin{pmatrix} 0 \\ v_u \end{pmatrix}, \; \langle H_d \rangle = \begin{pmatrix} 0 \\ v_d \end{pmatrix}$$

- After EWSB, there are two CP-even (h, H), one CP-odd (A), and a pair of charged Higgs bosons ($H^{\pm}$).
- The 6 parameters of the model in the CP-conserving case include

$$m_h, \; m_H, \; m_A, \; m_{H^+}, \; \tan\beta \equiv \frac{v_u}{v_d}, \; \alpha$$

- Type II Couplings of the Higgs bosons to fermions:

	$t\bar{t}$	$b\bar{b}$	$\tau^-\tau^+$
h:	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$
H:	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$
A:	$-i\cot\beta\,\gamma_5$	$-i\tan\beta\,\gamma_5$	$-i\tan\beta\,\gamma_5$

- Couplings of the Higgs bosons to gauge bosons:

$$(hW^+W^-, hZZ) = ig\sin(\beta-\alpha)(m_W, \frac{m_Z}{\cos\theta_W})\, g^{\mu\nu} \, .$$

- Production via gluon fusion can be enhanced at large tan β with the bottom quark contribution.
- Decay width into γγ receives contributions from W, t, and $H^{\pm}$ loops. Since W loop dominates, we want to make the hWW coupling as large as possible, i.e. sin (β-α) = 1. So along

$$\alpha \approx 0 \quad \text{and} \quad \text{moderately large } \tan\beta$$

can achieve enhancement to γγ width.

Ferreira, Santos, Sher, Silva 1112.3277, 1201.0019; Burdman, Haluch, Matheus 1112.3961; Chen, He 1202.3072; Arhrib, Benbrik, Chen 1205.5536; Cheon, Kang 1207.1083; Chang, Kang, Lee, Lee, Park, Song 1210.3439; Chen, Dawson 1301.0309; Celis, Ilisie, Pich, 1302.4022; Chiang, Yagyu 1303.0168; ... ...

Ferreira, Santos, Sher, Silva 1112.3277; 1305.4587

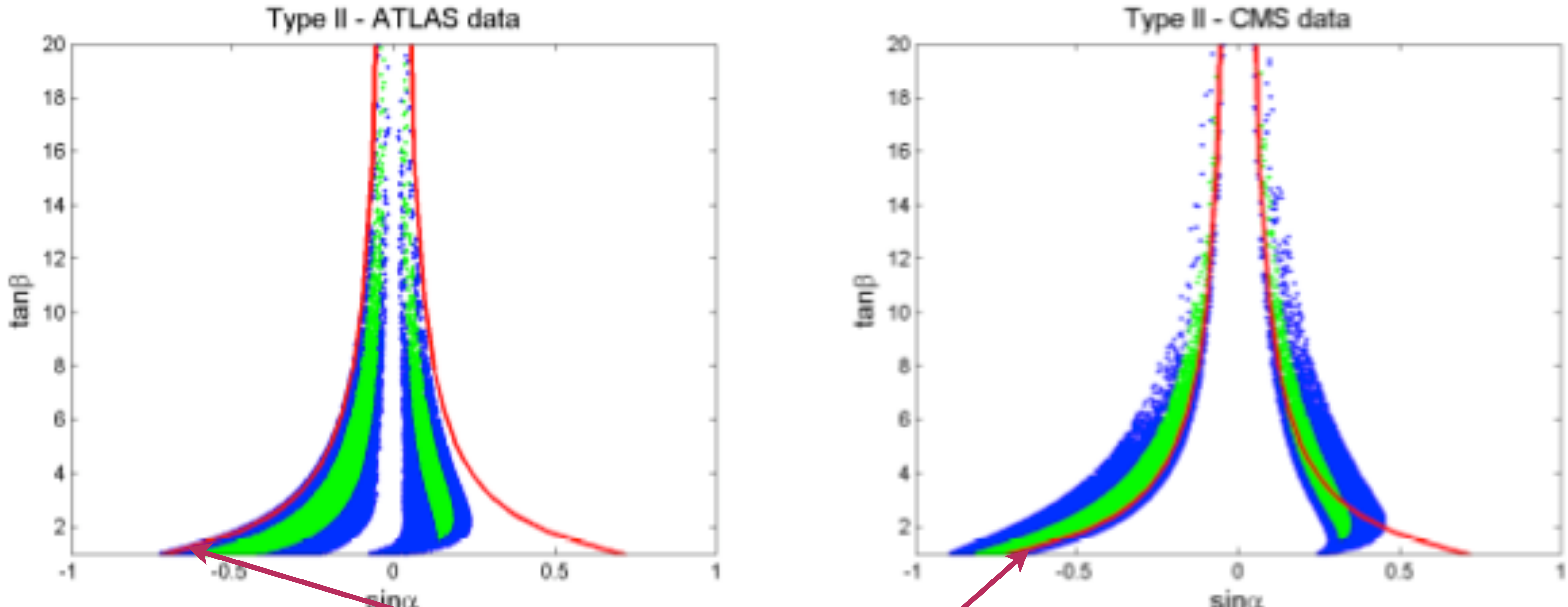


Figure 2: Points in the $(\sin\alpha, \tan\beta)$ plane that passed all the constraints in model type II using the ATLAS data analysis (left) and using the CMS data analysis (right) at 1σ in green (light grey) and 2σ in blue (dark grey). Also shown are the lines for the SM limit $\sin(\beta-\alpha)=1$ (negative $\sin\alpha$) and for the limit $\sin(\beta+\alpha)=1$.

- For other 2HDM of Type I, III (Lepton Specific), and IV (Flipped), see Chen and Dawson 1301.0309; Chen, Dawson, and Sher 1305.1624

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

- If one assumes instead

$$g_{hVV} = \sqrt{\delta}\, g_{hVV}^{\rm SM}$$

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

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

- Take as one example the two-Higgs doublet model (2HDM) where two scalar doublets are simultaneously involved in the EWSB.
- The HVV 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 suppressed coupling as

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

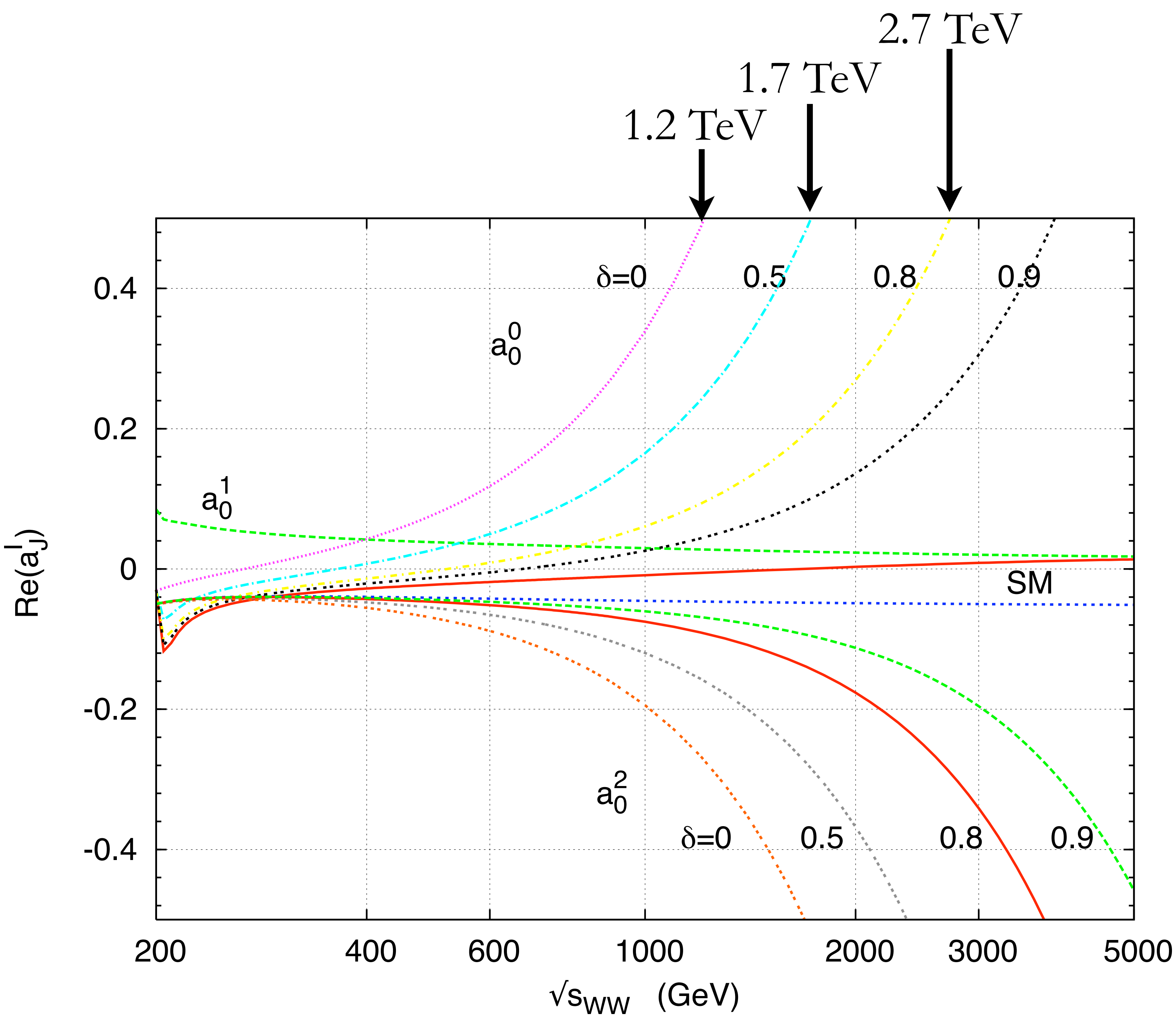
and assume that the other heavy degrees of freedom decouple for the illustration purpose.

- Current LHC data constrain is [Cheung et al, 1302.3794; Rohini's talk]

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

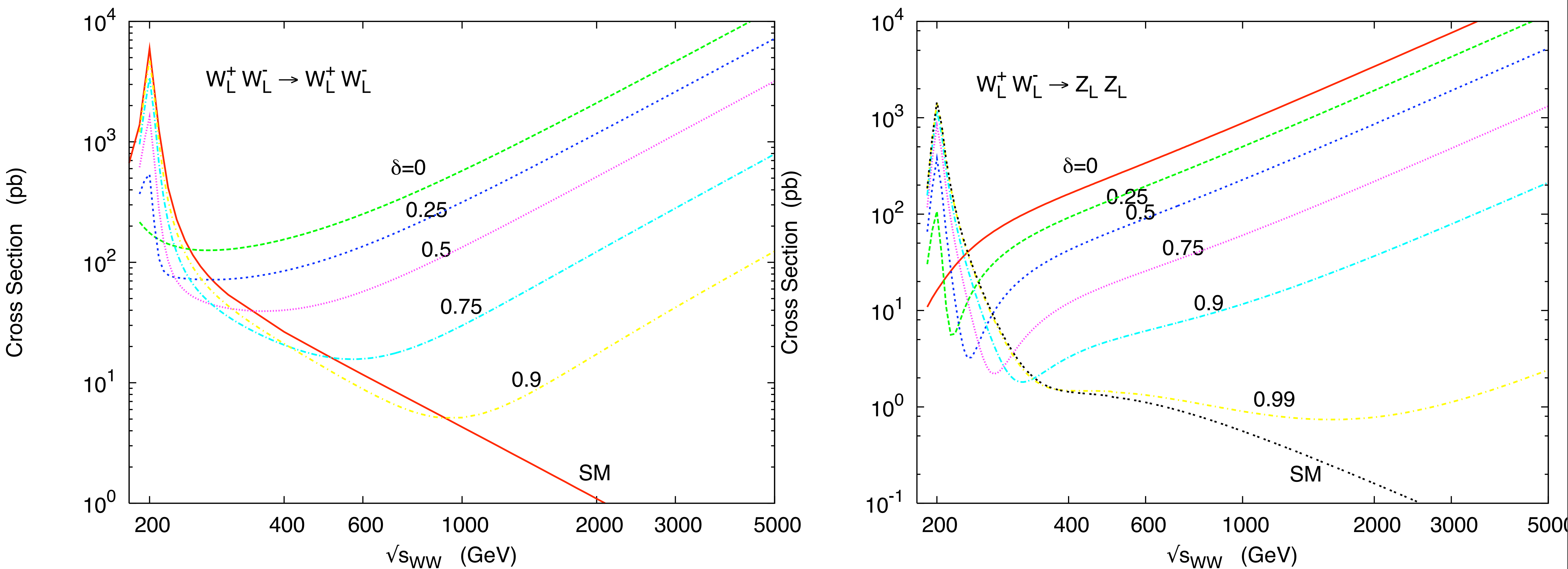
Partial-Wave Amplitudes

- $\mathrm{Re}(a_J^I)$ with $J = 0$ (S-wave) and isospin $I = 0, 1, 2$ for various δ :
- Unitarity demands that $|\mathrm{Re}(a_0^I)| \leq 1/2$.
- 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 $\cos\theta$).
- Though the LHC will not be able to directly probe these coefficients at such high energies, their growing behavior at intermediate energies might be discernible.



Cheung, Chiang, TCY, 0803.2661

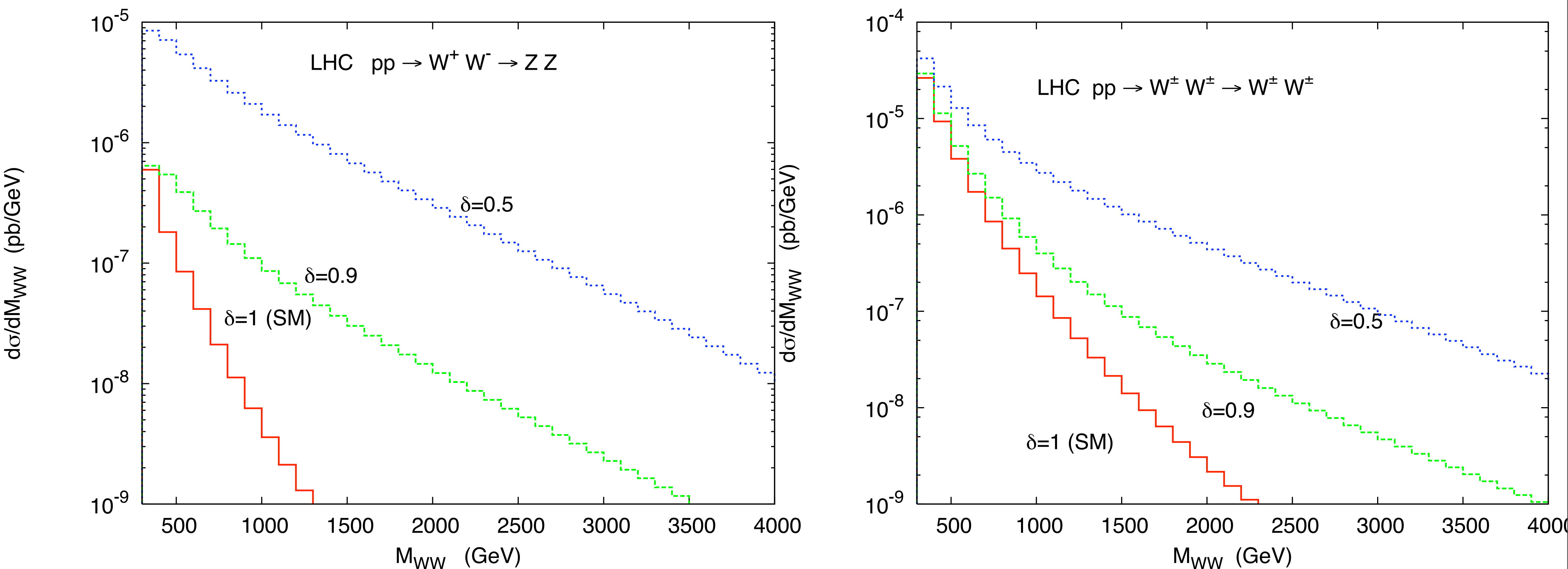
Total Cross Sections



- Scattering cross sections of $W_L^+ W_L^- \to W_L^+ W_L^-$ (L) and $W_L^+ W_L^- \to Z_L Z_L$ (R) as functions of the scattering energy.
- The turn-over effect is different from SM both qualitatively and quantitatively, even if effects of heavy Higgs bosons of TeV masses are included.

Cheung, Chiang, TCY, 0803.2661

Invariant Mass Distribution @ 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.
- Such enhancement in large invariant mass of the VV pair in the cross sections may be manifested at the large invariant mass of its leptonic decay products.

Cheung, Chiang, TCY, 0803.2661

VBF Selection Cuts & Final State Leptonic Cuts

- The most distinguished feature of VBF at hadronic colliders is the appearance of two energetic forward jets separated by a large pseudo-rapidity difference

$$E_{T_{j_1,j_2}} > 30\,\text{GeV}, |\eta_{j_1,j_2}| < 4.7, \Delta\eta_{12} = |\eta_{j_1} - \eta_{j_2}| > 3.5, \eta_{j_1}\eta_{j_2} < 0$$

- High invariant mass M_{jj} cut suppresses W(Z)h → (jj) h associated production which has $M_{jj} \approx m_{W,Z}$

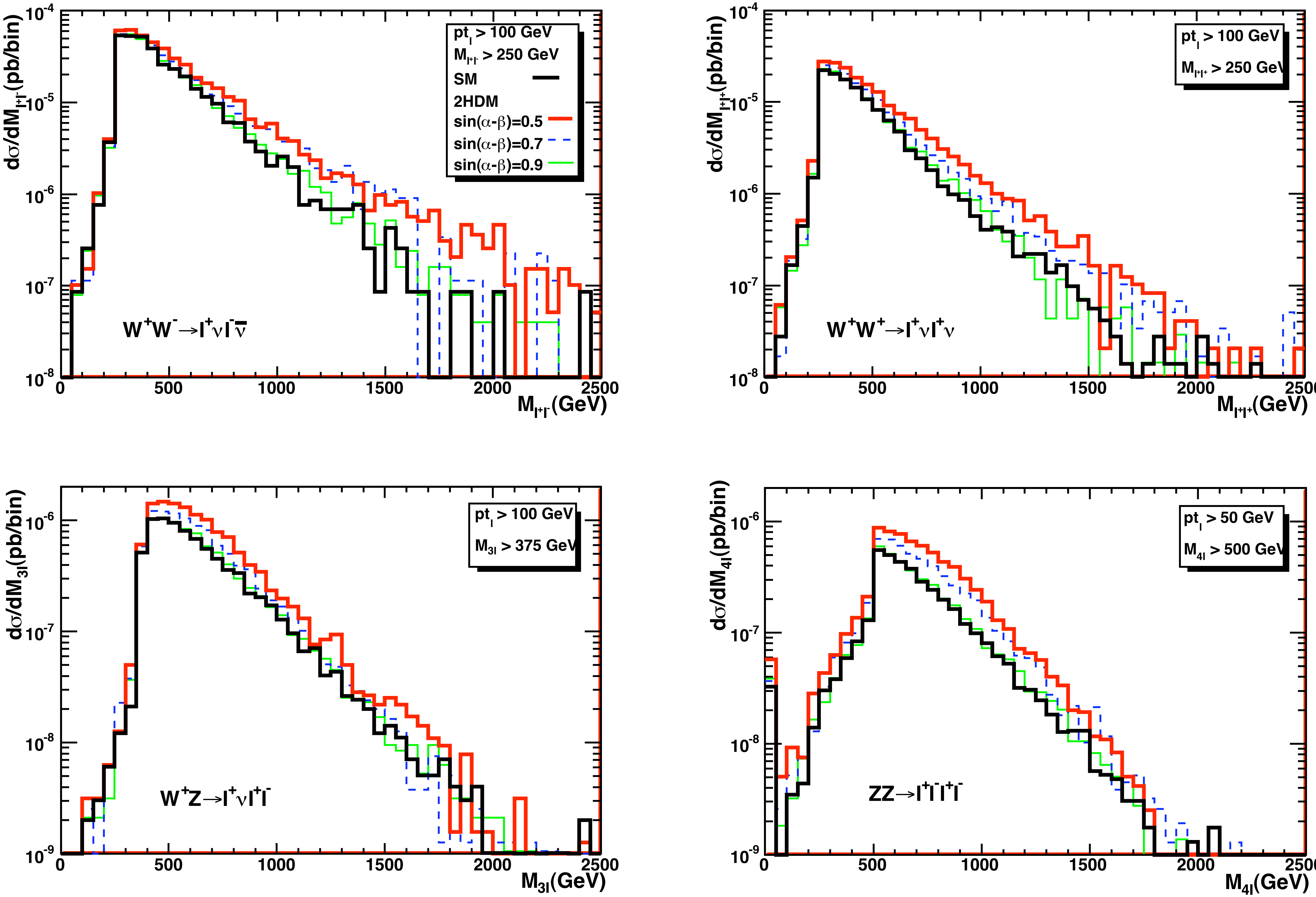
$$M_{jj} > 500\ \text{GeV}$$

- Final state leptonic cuts depend on diboson channels

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

2,3,4 Leptonic Final State Invariant Mass Distribution of VV Scattering in 2HDM



Chang, Cheung, Lu, TCY, 1303.6335

Cross Sections

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.

	Cross Sections (fb)			
Channels	$\sin(\beta-\alpha)=0.5$	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}

Summary

- Despite a SM-like Higgs is found, many Higgs impostors are possible.
- More data is need to verify this is the SM Higgs or distinguish it from other mimickers live nearby or far away.
- VBF is the second most important production mechanism for Higgs:
  (1) useful to distinguish Higgs impostors
  (2) probe EWSB directly
- Using 2HDM as a prototype, we demonstrate partially strong VBF can show up at the LHC.
- Perhaps we should not be too pessimistic.