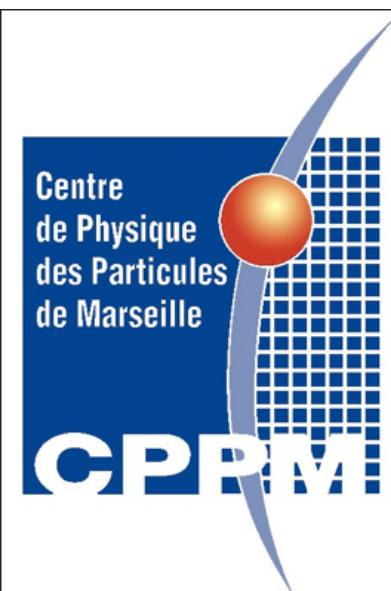


# HWW and Quartic Gauge Couplings studies using WWW events



Yanwen Liu

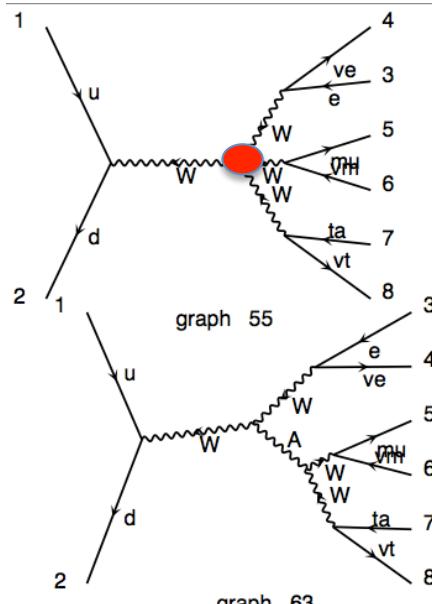
CPPM, on leave of absence from  
Univ. of Sci. and Tech. of China

GDR Terascale, 15 May 2013  
Universite Montpellier II



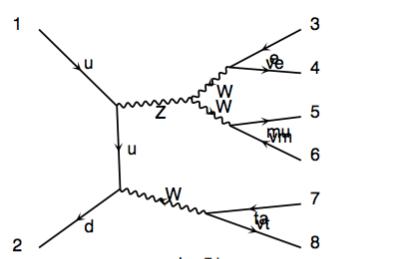
# WWW production

- Preferred definition: “W” as short note of “lv”.

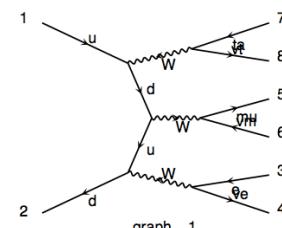


PRD78, 094012 (2008)

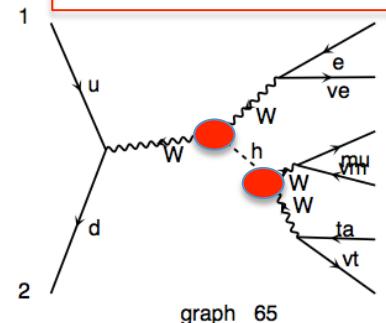
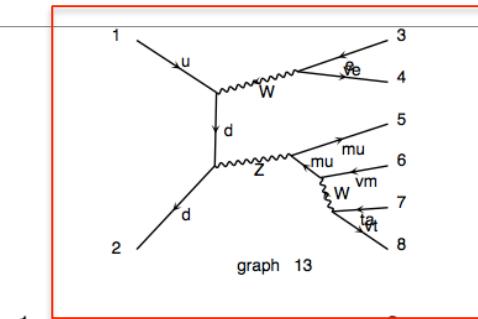
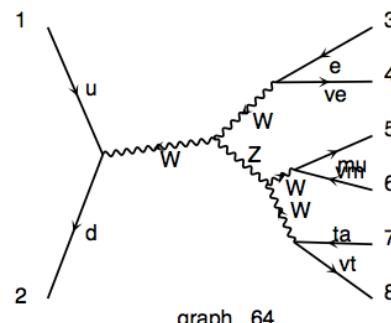
one boson attached to the fermion-line at initial state.



Two bosons attached to fermion line at initial state



3



No sign of 3 Ws

The **4-W vertex** never directly measured!  
Sensitive to **HWW** couplings.

# PART 1

## HWW couplings

- [16] For other analyses of the  $X$  particle couplings, see: D. Carmi, A. Falkowski, E. Kuflik and T. Volanski, arXiv:1202.3144 [hep-ph]; A. Azatov, R. Contino and J. Galloway, JHEP **1204** (2012) 127 [hep-ph/1202.3415]. J.R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, arXiv:1202.3697 [hep-ph]; P. P. Giardino, K. Kannike, M. Raidal and A. Strumia, arXiv:1203.4254 [hep-ph]; T. Li, X. Wan, Y. Wang and S. Zhu, arXiv:1203.5083 [hep-ph]; M. Rauch, arXiv:1203.6826 [hep-ph]; J. Ellis and T. You, JHEP **1206** (2012) 140, [arXiv:1204.0464 [hep-ph]]; A. Azatov, R. Contino, D. Del Re, J. Galloway, M. Grassi and S. Rahatlou, arXiv:1204.4817 [hep-ph]; M. Klute, R. Lafaye, T. Plehn, M. Rauch and D. Zerwas, arXiv:1205.2699 [hep-ph]; D. Carmi, A. Falkowski, E. Kuflik and T. Volansky, arXiv:1206.4201 [hep-ph]; M. J. Dolan, C. Englert and M. Spannowsky, arXiv:1206.5001 [hep-ph]; J. Chang, K. Cheung, P. Tseng and T. Yuan, arXiv:1206.5853 [hep-ph]; S. Chang, C. A. Newby, N. Raj and C. Wanotayaroj, arXiv:1207.0493 [hep-ph]; I. Low, J. Lykken and G. Shaughnessy, arXiv:1207.1093 [hep-ph]; T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia, arXiv:1207.1344 [hep-ph]; P. P. Giardino, K. Kannike, M. Raidal and A. Strumia, arXiv:1207.1347 [hep-ph]; M. Montull and F. Riva, arXiv:1207.1716 [hep-ph]; J. R. Espinosa, C. Grojean, M. Muhlleitner and M. Trott, arXiv:1207.1717 [hep-ph]; D. Carmi, A. Falkowski, E. Kuflik, T. Volansky and J. Zupan, arXiv:1207.1718 [hep-ph]; S. Banerjee, S. Mukhopadhyay and B. Mukhopadhyaya, JHEP **bf 10** (2012) 062, [arXiv:1207.3588 [hep-ph]]; F. Bonner, T. Ota, M. Rauch and W. Winter, arXiv:1207.4599 [hep-ph]; T. Plehn and M. Rauch, arXiv:1207.6108 [hep-ph]; A. Djouadi, arXiv:1208.3436 [hep-ph]; B. Batell, S. Gori and L. T. Wang, arXiv:1209.6832 [hep-ph]; G. Cacciapaglia, A. Deandrea, G. D. La Rochelle and J-B. Flament, arXiv:1210.8120 [hep-ph]; E. Masso and V. Sanz, arXiv:1211.1320 [hep-ph]; T. Corbett, O. J. P. Eboli, J. Gonzalez-Fraile and M. C. Gonzalez-Garcia, arXiv:1211.4580 [hep-ph]; R. Tito D'Agnolo, E. Kuflik and M. Zanetti, arXiv:1212.1165 [hep-ph]; A. Azatov and J. Galloway, arXiv:1212.1380 [hep-ph]; D. Choudhury, R. Islam, A. Kundu and B. Mukhopadhyaya, arXiv:1212.4659 [hep-ph]; R. S. Gupta, M. Montull and F. Riva, arXiv:1212.5240 [hep-ph]; B. Dumont, U. Ellwanger, J. F. Gunion and S. Kraml, arXiv:1212.5244 [hep-ph]; J. S. Lee and P-Y. Tseng, arXiv:1302.3794 [hep-ph].

**Left: Reference of  
J. Ellis and T. You 1303.2879v1**

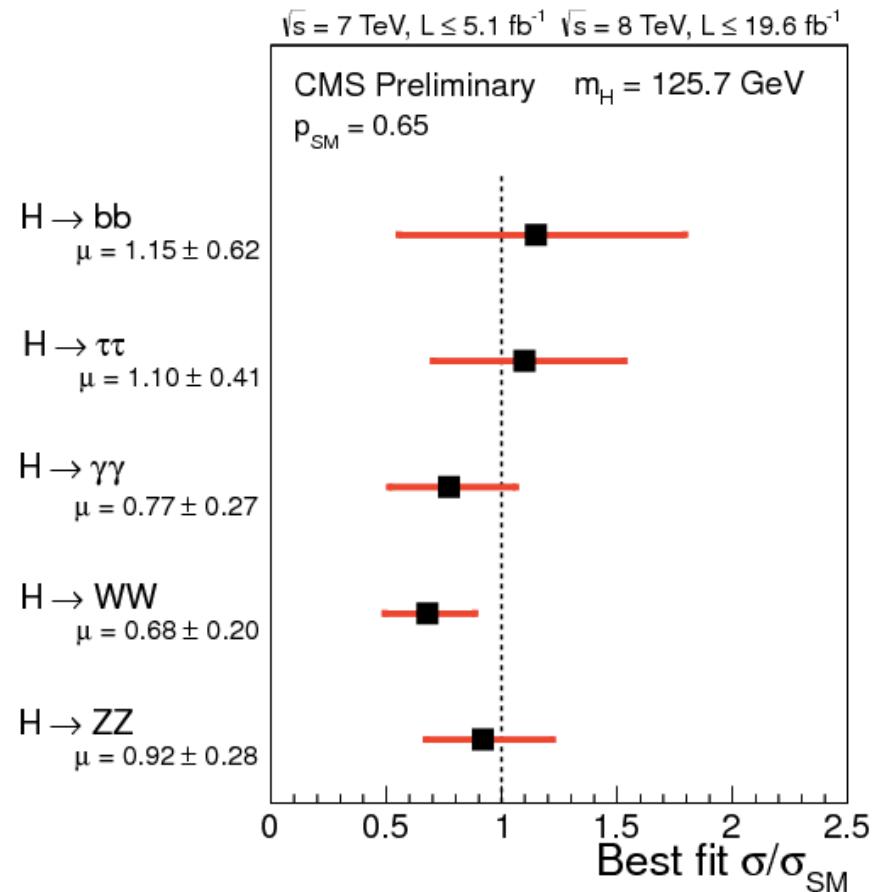
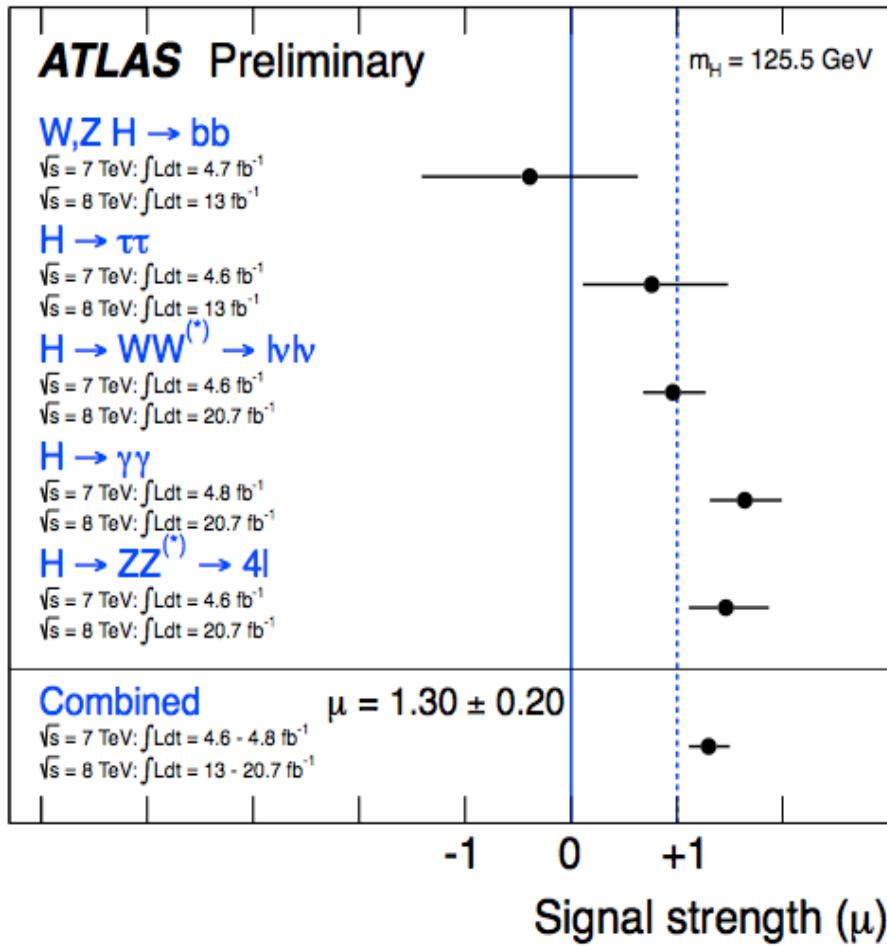


Lots of **re-interpretation** of published data.

Better if analyzers and theorists **work together** – propose/investigate more sensitive observables

See also Eboli talk at Moriond EWK 2013 and talks of Higgs sessions yesterday.

# LHC Higgs Yields



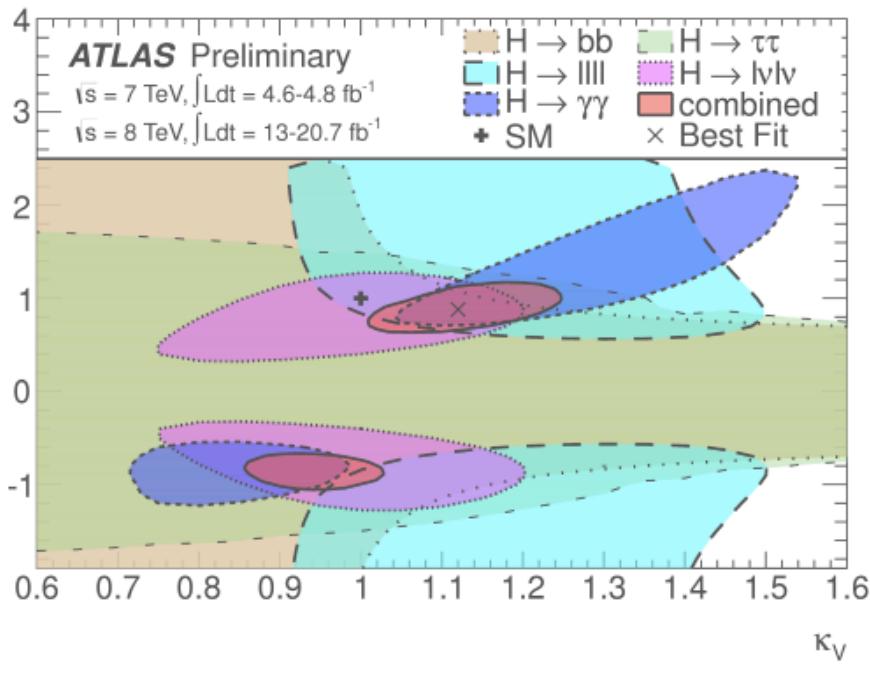
# LHC Higgs Couplings

$$\kappa_V = \kappa_W = \kappa_Z$$

$$\kappa_F = \kappa_t = \kappa_b = \kappa_\tau = \kappa_g$$

68% CL contours

$\kappa_F$



$$\sigma(gg \rightarrow H) * \text{BR}(H \rightarrow \gamma\gamma) \sim \frac{\kappa_F^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

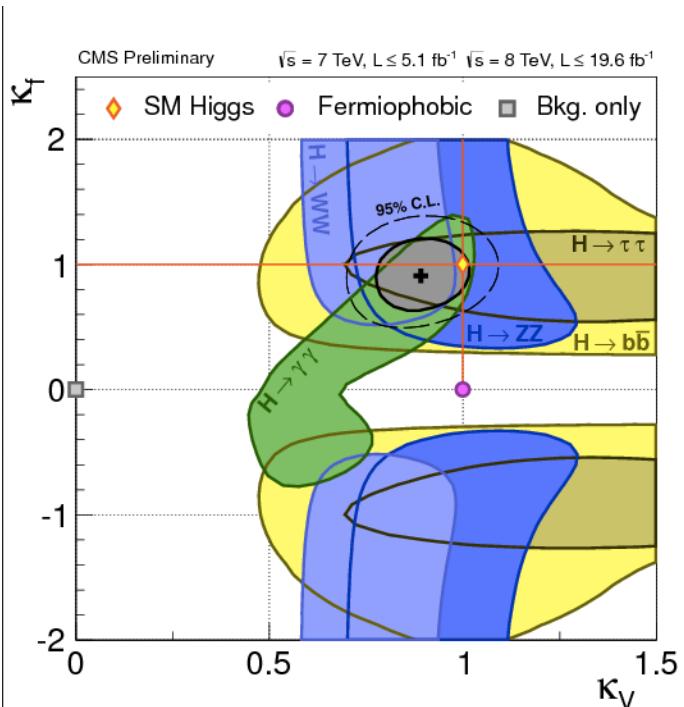
$$\sigma(qq' \rightarrow qq'H) * \text{BR}(H \rightarrow \gamma\gamma) \sim \frac{\kappa_V^2 \cdot \kappa_\gamma^2(\kappa_F, \kappa_V)}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(gg \rightarrow H) * \text{BR}(H \rightarrow ZZ^{(*)}, H \rightarrow WW^{(*)}) \sim \frac{\kappa_F^2 \cdot \kappa_V^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \rightarrow qq'H) * \text{BR}(H \rightarrow ZZ^{(*)}, H \rightarrow WW^{(*)}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

$$\sigma(qq' \rightarrow qq'H, VH) * \text{BR}(H \rightarrow \tau\tau, H \rightarrow b\bar{b}) \sim \frac{\kappa_V^2 \cdot \kappa_F^2}{0.75 \cdot \kappa_F^2 + 0.25 \cdot \kappa_V^2}$$

CMS Preliminary  $\sqrt{s} = 7 \text{ TeV}, L \leq 5.1 \text{ fb}^{-1}$   $\sqrt{s} = 8 \text{ TeV}, L \leq 19.6 \text{ fb}^{-1}$



Effective field theory approach to parameterize low energy effects of physics at higher scale.  
 [arXiv:1207.1344 and references herein ]

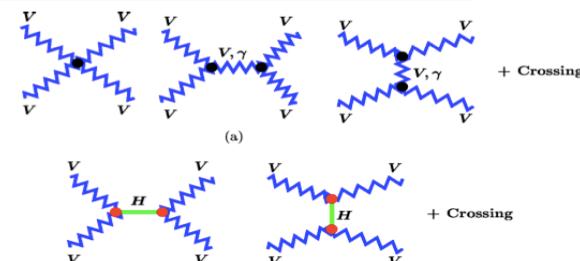
Considering most general dimension-6 operators that preserves symmetry of  $SU(3)_c \times SU(2)_L \times U(1)_Y$

$$\begin{aligned} \mathcal{L}_{\text{eff}}^{\text{HVV}} = & g_{Hgg} HG_{\mu\nu}^a G^{a\mu\nu} + g_{H\gamma\gamma} HA_{\mu\nu} A^{\mu\nu} + g_{HZ\gamma}^{(1)} A_{\mu\nu} Z^\mu \partial^\nu H + g_{HZ\gamma}^{(2)} HA_{\mu\nu} Z^{\mu\nu} \\ & + g_{HZZ}^{(1)} Z_{\mu\nu} Z^\mu \partial^\nu H + g_{HZZ}^{(2)} HZ_{\mu\nu} Z^{\mu\nu} + g_{HZZ}^{(3)} HZ_\mu Z^\mu \\ & + g_{HWW}^{(1)} (W_{\mu\nu}^+ W^{-\mu} \partial^\nu H + \text{h.c.}) + g_{HWW}^{(2)} HW_{\mu\nu}^+ W^{-\mu\nu} + g_{HWW}^{(3)} HW_\mu^+ W^{-\mu} \end{aligned}$$

$$\begin{aligned} g_{HWW}^{(1)} &= \left( \frac{gM_W}{\Lambda^2} \right) \boxed{\frac{f_W}{2}}, \\ g_{HWW}^{(2)} &= - \left( \frac{gM_W}{\Lambda^2} \right) \boxed{f_{WW}}, \end{aligned}$$

EW bound from  $\Delta S$  and  $\Delta T$ :  
 $-6 \leq f_W/\Lambda^2 \leq 5 \text{ [TeV}^{-2}\text{]}$   
 Phys. Rev. D67,114024(2003)

Proposing measurement of VBS  $W^+W^+$   
 Discussing about perspective of  $300 \text{ fb}^{-1}$



16

7

# Perspective for VBS

$pp \rightarrow W^+ W^+ jj \rightarrow l^+ \nu l^+ \nu jj$

| $m_H$ (GeV) | $f_W/\Lambda^2$ (TeV $^{-2}$ ) |         |         |         |         |     |         |         |         |         |         |
|-------------|--------------------------------|---------|---------|---------|---------|-----|---------|---------|---------|---------|---------|
|             | -4.0                           | -3.0    | -2.0    | -1.4    | -1.0    | 0.0 | 0.85    | 1.2     | 2.0     | 3.0     | 4.0     |
| 115         | 117(9.4)                       | 72(6.7) | 38(3.7) | 26(2.2) | 20(1.1) | 15  | 20(1.1) | 25(2.0) | 42(4.2) | 78(7.1) | 129(10) |
| 130         | 118(9.5)                       | 72(6.7) | 38(3.7) | 26(2.2) | 20(1.1) | 15  | 20(1.1) | 25(2.0) | 42(4.2) | 78(7.1) | 130(10) |



# of events for 300 fb $^{-1}$  of pp collisions at 14 TeV , in bracket: S/sqrt(S+B)

$pp \rightarrow W^+ W^+ jj \rightarrow l^+ \nu l^+ \nu jj$

| $m_H$ (GeV) | $f_{WW}/\Lambda^2$ (TeV $^{-2}$ ) |         |         |         |         |    |     |         |         |         |         |
|-------------|-----------------------------------|---------|---------|---------|---------|----|-----|---------|---------|---------|---------|
|             | -4.0                              | -3.0    | -2.2    | -1.6    | 0.0     |    | 1.6 | 2.2     | 3.0     | 4.0     |         |
| 115         |                                   | 47(4.7) | 33(3.1) | 25(2.0) | 19(0.9) | 15 |     | 20(1.1) | 26(2.2) | 33(3.1) | 48(4.8) |
| 130         |                                   | 48(4.8) | 33(3.1) | 25(2.0) | 19(0.9) | 15 |     | 20(1.1) | 26(2.2) | 34(3.1) | 49(4.9) |

B : Number of events with No anomalous coupling

S: Number of events with anomalous coupling - B

No consideration of other background.

Same sign WW production from VBS in progress at ATLAS.

For WWW production:

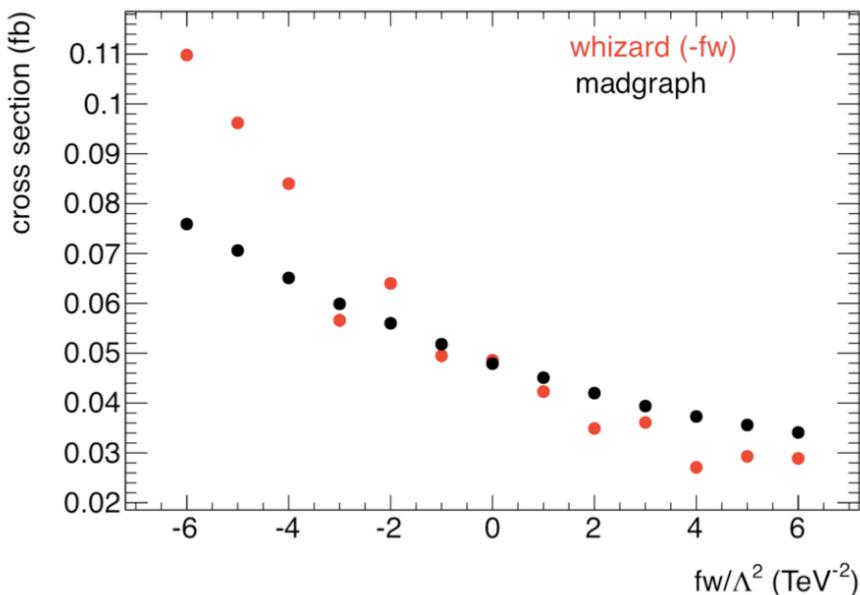
# In need of a reliable generator

Requested WHIZARD authors to implement the HVV anomalous couplings.

Implemented fw and fww with FeynRules + Madgraph on our own.

Comparing cross section of  $pp \rightarrow W^+H \rightarrow WWW^* \rightarrow \text{leptons}$  (considering 1 lepton generation)

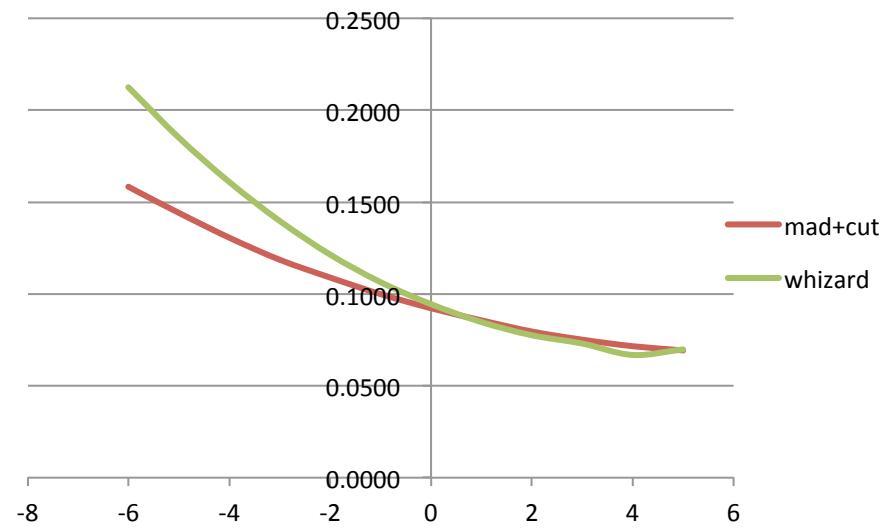
No closure yet.



Aug. 2012 : whizard release 2.1

WHIZARD different sign convention for fw

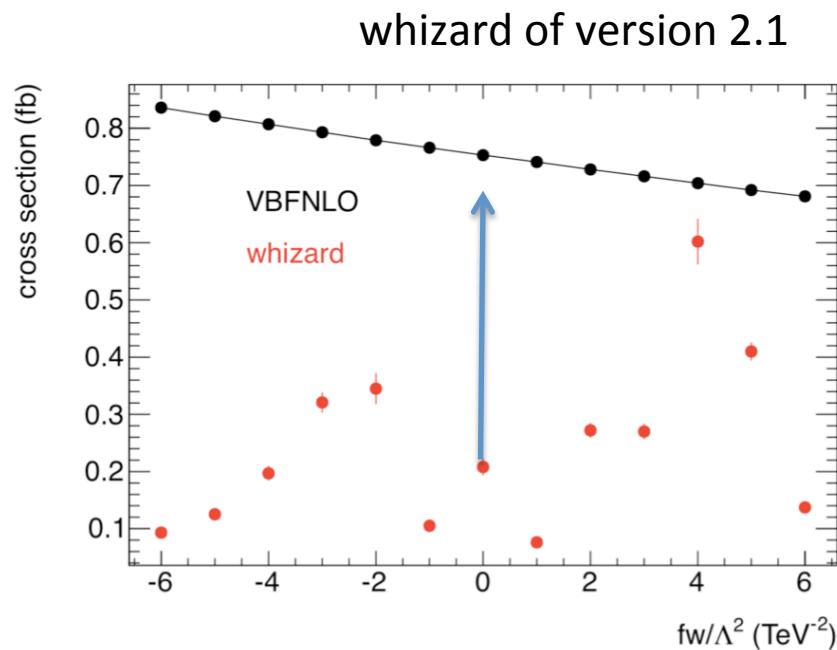
Madgraph code unchanged. different final state cuts



whizard patch of Nov 2012

# VBFNLO vs. WHIZARD

- VBFNLO: process  $105 \text{ pp} \rightarrow Hjj \rightarrow W+W-jj \rightarrow l_1 v_{l1} l_2 v_{l2} jj$   
has HVV anomalous couplings.
  - Cuts:  $|\eta_j| < 4.5$  2jets,  $p_{t,j} > 20 \text{ GeV}$   $|\eta_l| < 2.5$ ,  $p_{t,l} > 10 \text{ GeV}$ .  
 $\Delta R(l,l) > 0.4$   $M_{jj} > 600 \text{ GeV}$ .
  - LO: **0.752+/-0.002 fb**    NLO:**0.642+/-0.023fb**
- whizard: pr,pr > pr,pr,e1,N1,E2,n2  
 $\{\$restrictions="5+6+7+8\sim H"\}$ 
  - pr=u:d:c:s:U:D:C:S, alphas=0, model=SM
  - cross section = **0.679+/-0.018 fb**



# Some expectations from 2012 data

Using **VBFNLO**, lepton  $p_T > 10$  GeV,  $|\eta| < 2.5$ ,  $\Delta R(l,l) > 0.4$

$\sigma = 1.34 \text{ fb}$  (considering only e and  $\mu$  decays)

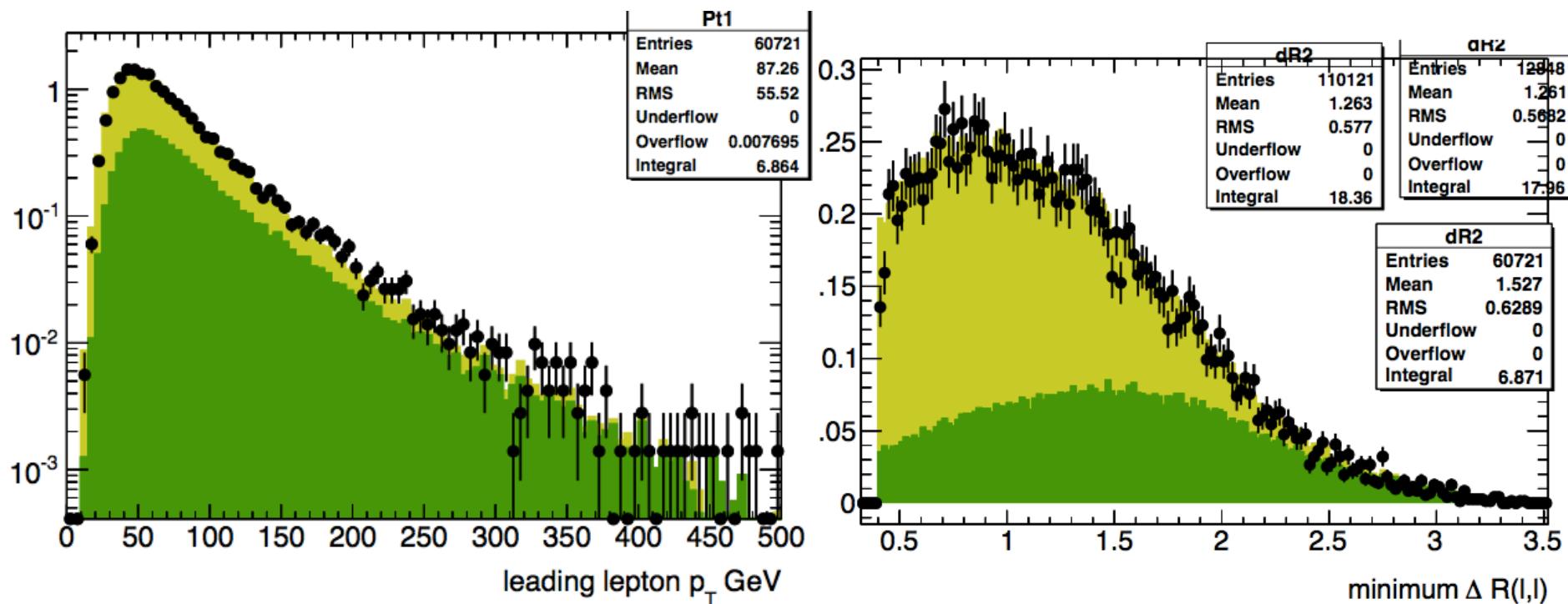
$\sim 27$  events for  $20 \text{ fb}^{-1}$

2/3 from WH

W+W+W-  
point:VBFNLO

Green:WWW  
Yellow:W+H

Arbitrary norm.



# CMS public results on existing data

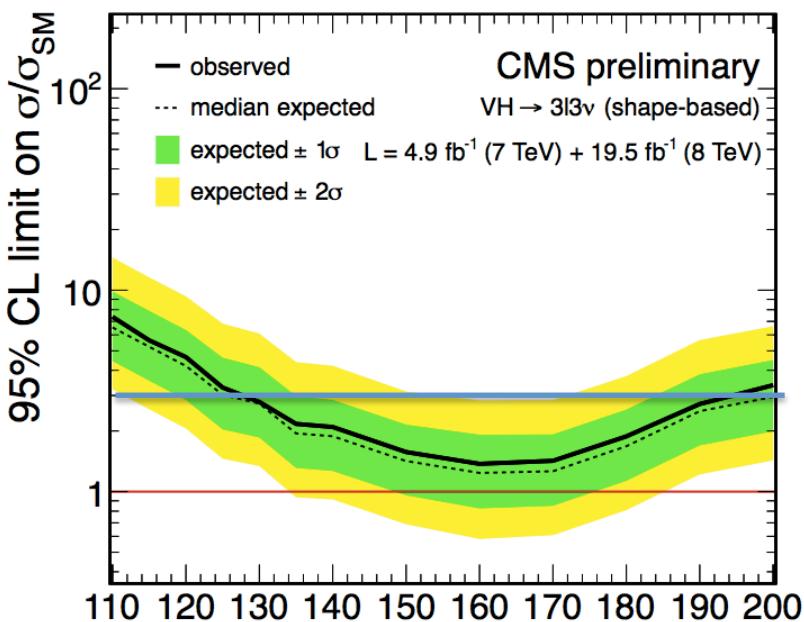
Different signal definitions: including also Higgs- $\rightarrow\tau\tau$ .

Lepton pT thresholds: 20, 10, 10 GeV

Veto if any jets with pT > 40 GeV

Veto on “soft-muon” and “b-jet” tags.

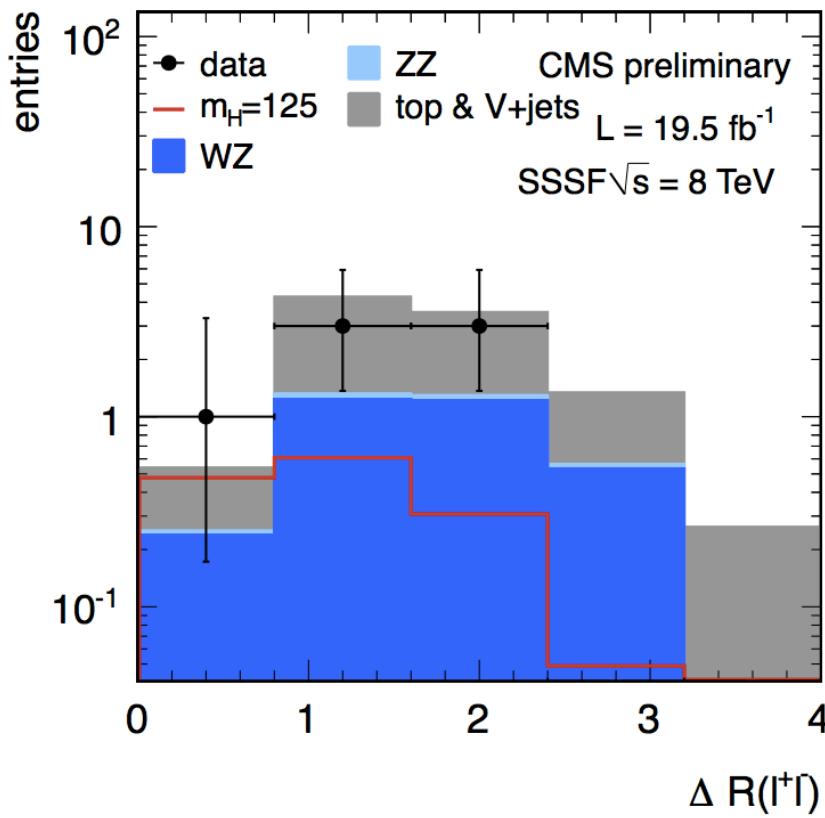
MET > 40 GeV (OSSF) or > 30 GeV for (SSSF)



|      | WH( $\rightarrow\tau\tau$ ) (125) | WH( $\rightarrow WW$ ) (125) | data | all bkg.         | WZ               | fakes           |
|------|-----------------------------------|------------------------------|------|------------------|------------------|-----------------|
| OSSF | $0.27 \pm 0.05$                   | $1.97 \pm 0.22$              | 33   | $33.45 \pm 1.16$ | $24.12 \pm 0.52$ | $7.29 \pm 1.03$ |
| SSSF | $0.21 \pm 0.04$                   | $0.92 \pm 0.16$              | 6    | $6.95 \pm 0.85$  | $1.72 \pm 0.14$  | $4.64 \pm 0.84$ |

**OSSF:** events with **Opposite Sign Same Flavor** leptons.

**SSSF :** everything else



# PART 2

# Quartic Gauge Couplings

# Anomalous Quartic Gauge Coupling

Linear implementation

Higgs field

$$\mathcal{L}_{S,0} = \frac{f_0}{\Lambda^4} \left[ (D_\mu \Phi)^\dagger D_\nu \Phi \right] \times \left[ (D^\mu \Phi)^\dagger D^\nu \Phi \right]$$

$$\mathcal{L}_{S,1} = \frac{f_1}{\Lambda^4} \left[ (D_\mu \Phi)^\dagger D^\mu \Phi \right] \times \left[ (D_\nu \Phi)^\dagger D^\nu \Phi \right]$$

J. Reuter

[at LHCEWWG 2013.4](#)

Integrating out resonances

Consider leading order effects of resonances on EW sector:

$$\mathcal{L}_\Phi = z [\Phi (M_\Phi^2 + DD) \Phi + 2\Phi J] \Rightarrow \mathcal{L}_\Phi^{\text{eff}} = -\frac{z}{M^2} JJ + \frac{z}{M^4} J(DD)J + \mathcal{O}(M^{-6})$$

► Simplest example: scalar singlet  $\sigma$ :

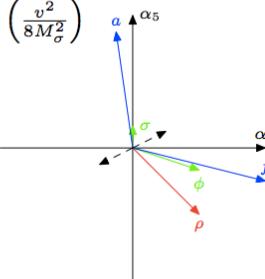
$$\mathcal{L}_\sigma = -\frac{1}{2} [\sigma (M_\sigma^2 + \partial^2) \sigma - g_\sigma v \sigma \text{tr} [\mathbf{V}_\mu \mathbf{V}^\mu] - h_\sigma \text{tr} [\mathbf{T} \mathbf{V}_\mu] \text{tr} [\mathbf{T} \mathbf{V}^\mu]]$$

► Effective Lagrangian  $\mathcal{L}_\sigma^{\text{eff}} = \frac{v^2}{8M_\sigma^2} \{g_\sigma \text{tr} [\mathbf{V}_\mu \mathbf{V}^\mu] + h_\sigma \text{tr} [\mathbf{T} \mathbf{V}_\mu] \text{tr} [\mathbf{T} \mathbf{V}^\mu]\}^2$

► leads to **anomalous quartic couplings**

$$\alpha_5 = g_\sigma^2 \left( \frac{v^2}{8M_\sigma^2} \right) \quad \alpha_7 = 2g_\sigma h_\sigma \left( \frac{v^2}{8M_\sigma^2} \right) \quad \alpha_{10} = 2h_\sigma^2 \left( \frac{v^2}{8M_\sigma^2} \right)$$

| Resonance                                  | $\sigma$       | $\phi$          | $\rho$                                       | $f$            | $a$            |
|--|----------------|-----------------|--|----------------|----------------|
| $\Gamma[g^2 M^2 / (64\pi v^2)]$            | 6              | 1               | $\frac{4}{3} \left( \frac{v^2}{M^2} \right)$ | $\frac{1}{5}$  | $\frac{1}{30}$ |
| $\Delta\alpha_4[(16\pi\Gamma/M)(v^4/M^4)]$ | 0              | $\frac{1}{4}$   | $\frac{3}{4}$                                | $\frac{5}{2}$  | $-\frac{5}{8}$ |
| $\Delta\alpha_5[(16\pi\Gamma/M)(v^4/M^4)]$ | $\frac{1}{12}$ | $-\frac{1}{12}$ | $-\frac{3}{4}$                               | $-\frac{5}{8}$ | $\frac{35}{8}$ |



WHIZARD Choice:

Non-linear implementation

Goldstone fields

$$\Sigma(x) = \exp \left( i \frac{\varphi^a(x) \tau^a}{v} \right)$$

$$D_\mu \Sigma \equiv \partial_\mu \Sigma + ig \frac{\tau^a}{2} W_\mu^a \Sigma - ig' \Sigma \frac{\tau^3}{2} B_\mu$$

$$V_\mu \equiv (D_\mu \Sigma) \Sigma^\dagger$$

$$\mathcal{L}_4^{(4)} = \alpha_4 [\text{Tr} (V_\mu V_\nu)]^2$$

$$\mathcal{L}_5^{(4)} = \alpha_5 [\text{Tr} (V_\mu V^\mu)]^2$$

Added a light Higgs

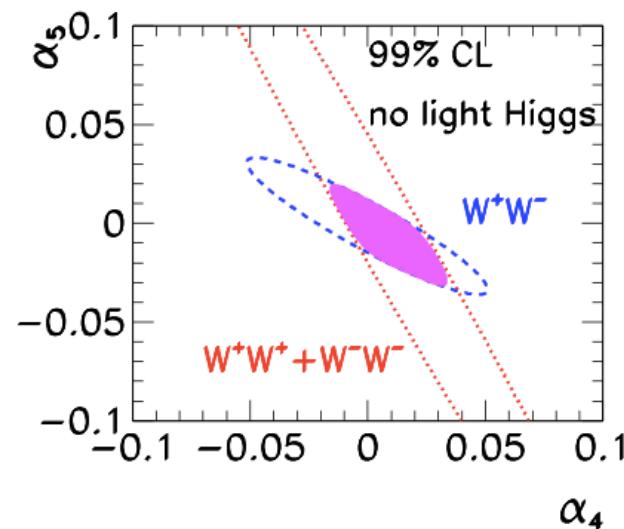
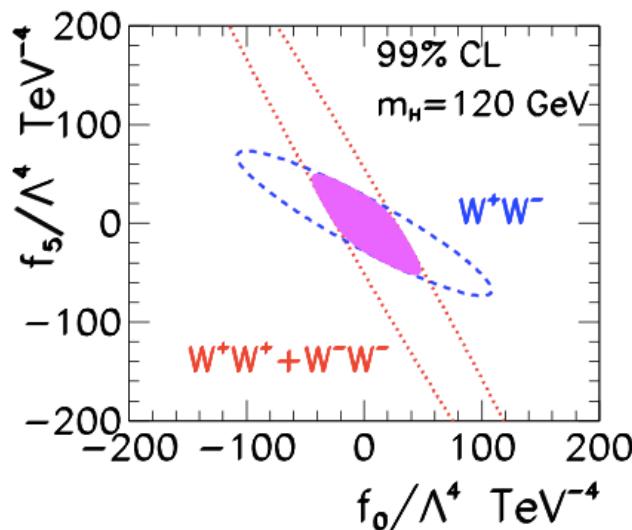
# Constraints

For  $\Lambda=2\text{TeV}$ , 99% CL  
low energy bounds :

$$\begin{aligned} -5.2 < f_0 \times 10^{-3} &< 9.0 \\ -13 < f_1 \times 10^{-3} &< 22 \end{aligned}$$

$$\begin{aligned} -0.32 < \alpha_4 &< 0.085 , \\ -0.81 < \alpha_5 &< 0.21 . \end{aligned}$$

Expected limits for  $100 \text{ fb}^{-1}$  of LHC data



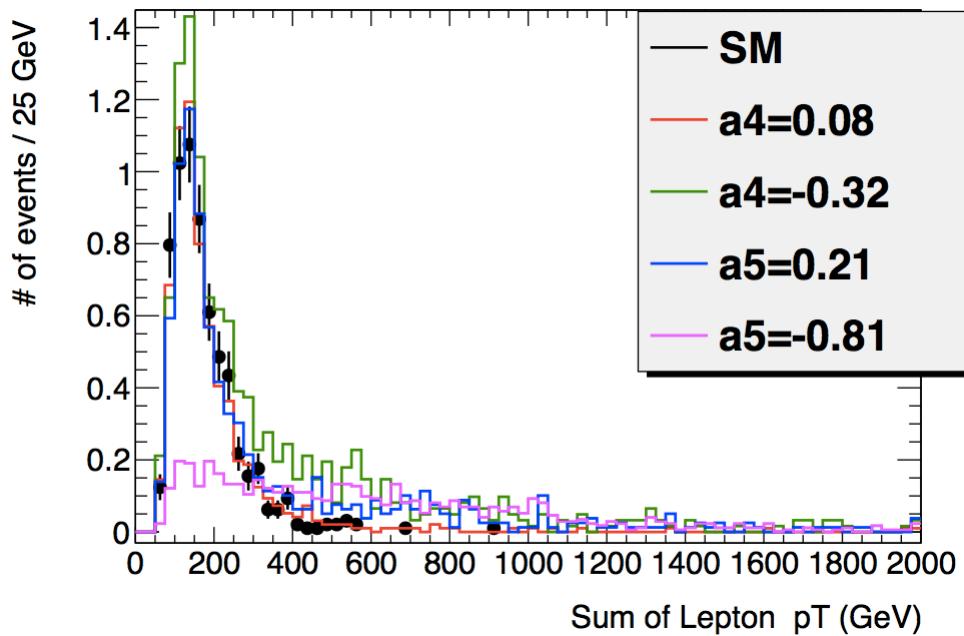
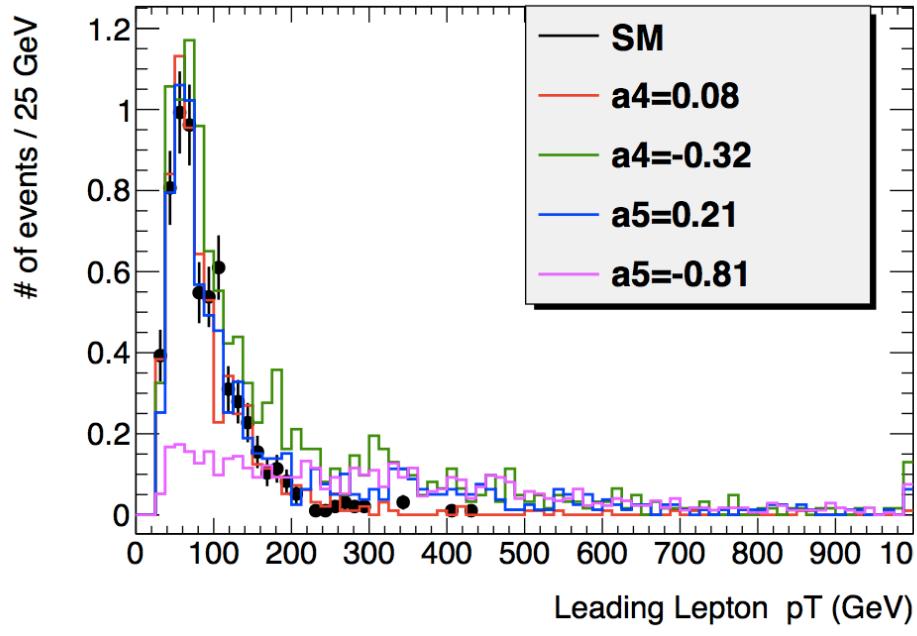
# Effect on WWW production@8TeV

- WHIZARD(LHEF) => PYTHIA8(decay+PS+UE)

| a4    | a5    | cross section(fb) | 3-lepton events |
|-------|-------|-------------------|-----------------|
| 0     | 0     | 51.7              | 6.3             |
| 0.08  | 0     | 51.9              | 6.4             |
| -0.32 | 0     | 81.3              | 11.3            |
| 0     | 0.21  | 63.1              | 8.2             |
| 0     | -0.81 | 28.9              | 4.7             |

Last column: lepton  $pT > 25, 10, 10$  GeV,  $|\eta| < 2.5$ , normalized to  $20 \text{ fb}^{-1}$

# kinematic distributions



Anomalous couplings enhance the high PT region, in general.  
Normalized to  $20 \text{ pb}^{-1}$

# Conclusions

- For Higgs Couplings : currently only using event yields in different production/decay modes.
- **Differential distributions** should improve sensitivities. **Need reliable MC generators.**  
More relevant for LHC Run 2!
- Quartic Gauge couplings ~never directly measured, now measurable at LHC.

More on next slide.

# Some events

**Helmholtz Alliance**

**PHYSICS AT THE TERASCALE**

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**Anomalous Quartic Gauge Couplings**

**30 September - 2 October 2013**  
TU Dresden

**Topics**

- aGG in VV, gg->VV, and WW
- Theory status of all SM processes
- aGG and BSM physics
- Anomalous couplings in EFT
- Partially strong VV scattering
- Unitarity issues
- Status of experimental studies for 13/14 TeV
- Monte Carlo generators

Organizing Committee: Matthew Herndon (U Wisconsin), Christophe Grojean (CERN), Barbara Jäger (U Mainz), Michael Kobel (TU Dresden), Sabine Lammers (Indiana U), Yurii Maravin (Kansas State U), Kalanand Mishra (FNAL), Jürgen Reuter (DESY), Thomas Schöderer-Sadenius (DESY), Anja Vest (TU Dresden)

Registration deadline: 15 September 2013

Contact: [enacm@desy.de](mailto:enacm@desy.de)  
For more information and in order to register please go to:

<http://www.terascale.de/aqgc2013>

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**Participants List**

## Electroweak Measurements at the Energy Frontier

Duke Workshop

February 18-20, 2013

**Snowmass Energy Frontier Workshop**  
April 3-6, 2013 • Brookhaven National Laboratory

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Snowmass Energy Frontier Workshop

# **BACK-UP SLIDES START HERE**

# Settings in Whizard

- used model : SM\_ac
- process definition:
  - `pr, pr => E1, n1, e1, N1, E2, n2 { $restrictions = "3+4 ~ Wp && 5+6+7+8 ~ H" }`
- process scale:
  - `scale = 240 GeV`
- beam specification
  - `sqrts = 8000 GeV`
  - `beams = p,p => lhapdf { $lhapdf_file = "cteq6l.LHpdf" }`
- define reasonable cuts (in .sin script)
  - `none`
- set some parameters in .sin script (same values in Madgraph):
  - `ms = 0. # s-quark mass`
  - `mc = 0. # c-quark mass`
  - `me = 0.`
  - `mmu = 0.`
  - `GF = 1.166370e-05`
  - `mH = 125 GeV`
  - `wH = 4.03e-03 GeV`
  - `mW = 79.82436 GeV`
  - `wW = 2.085 GeV`
  - `mZ = 91.18760 GeV`
  - `wZ = 2.4952 GeV`
  - `mtop = 172 GeV`
  - `wtop = 1.508336 GeV`
  - `mb = 4.7 GeV`
  - `alphas = 0.1184`

# Settings in Madgraph

- used model: o6final\_UFO (We defined it by adding the anomalous coupling term into SM Lagrangian)
- command used for generating the process
  - generate p p > W+ H, W+ > e+ ve, H > e+ ve mu- vm~ QCD=0
- collider type and energy
  - 1 = lpp1 ! beam 1 type (0=NO PDF)
  - 1 = lpp2 ! beam 2 type (0=NO PDF)
  - 4000 = ebeam1 ! beam 1 energy in GeV
  - 4000 = ebeam2 ! beam 2 energy in GeV
- pdf choice
  - 'cteq6l1' = pdlabel ! PDF set
- renormalization scales
  - F = fixed\_ren\_scale ! if .true. use fixed ren scale
- cuts with decay products
  - 10 = cpl\_decaysim ! cut for the photon leptons  
2.5 = etal ! max rap for the charged leptons  
0.4 = drll ! min distance between leptons