Higgs J/CP projections for Run2 and HL-LHC (ATLAS+CMS)

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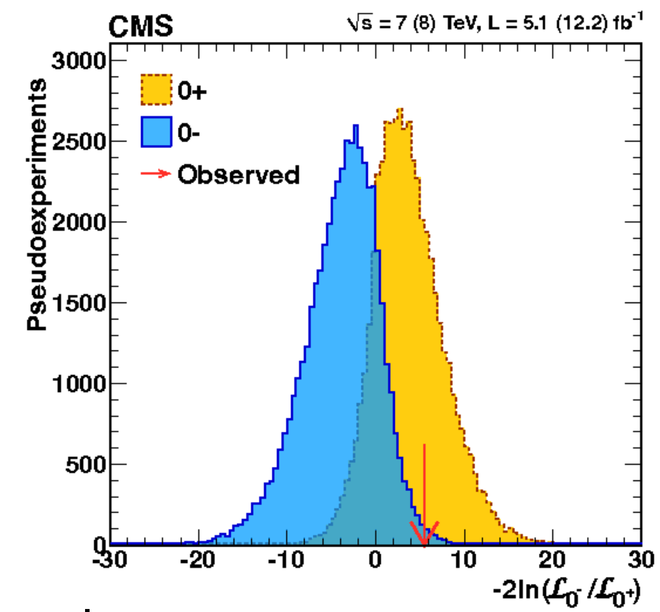
Fermilab

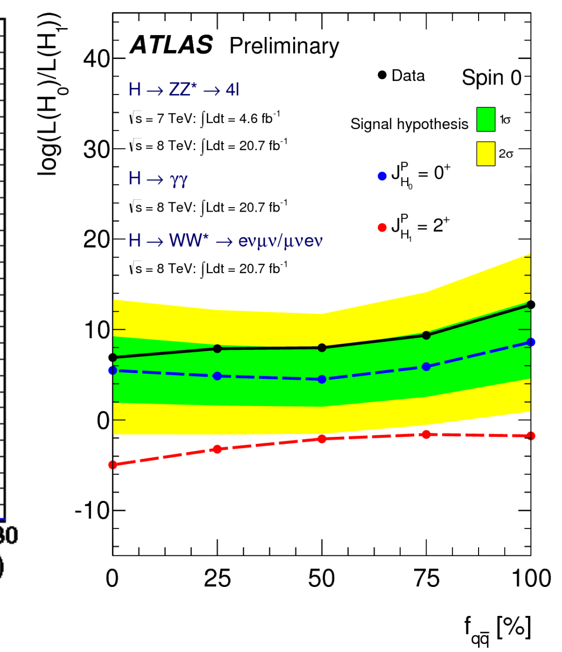
On behalf of the CMS & ATLAS Collaborations

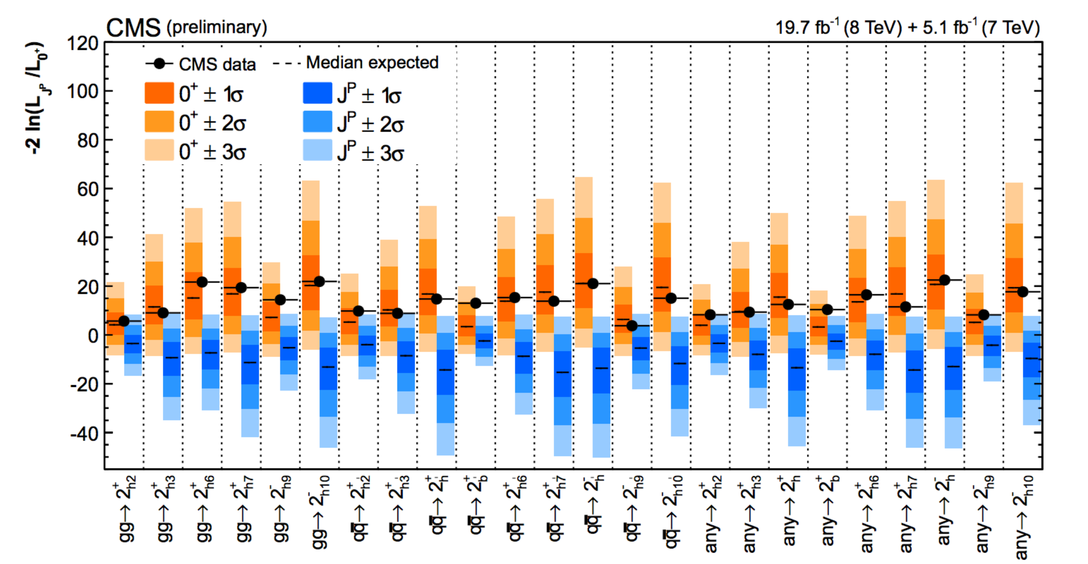
BSM Higgs @ LPC - Monday November 3, 2014

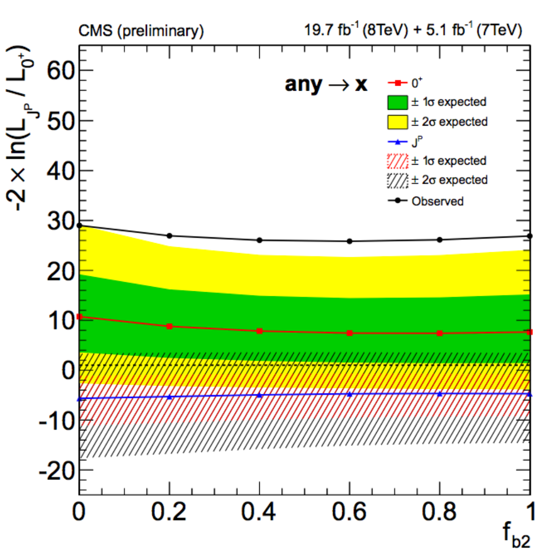
Introduction

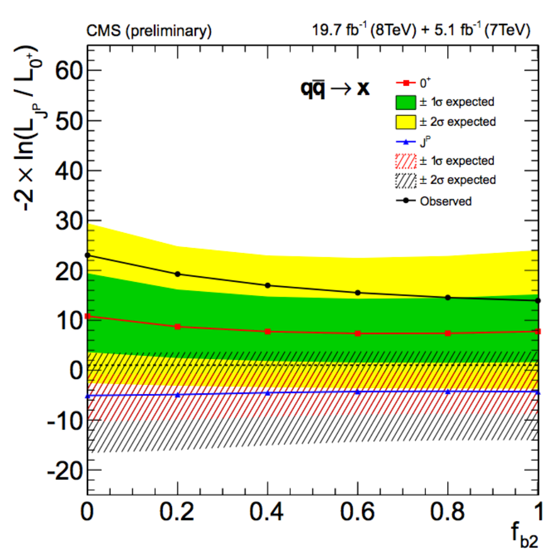
- J^{CP} studies encompass a significant breadth of measurements
  - Spin-parity hypothesis testing
  - anomalous CP couplings
- Largely within the three main discovery channels
  - $H\rightarrow\gamma\gamma$ (spin-2 tests)
    $H\rightarrow ZZ\rightarrow 4l$ & $H\rightarrow WW\rightarrow 2l2\nu$ (spin-0, spin-1, spin-2 tests, anomalous couplings)

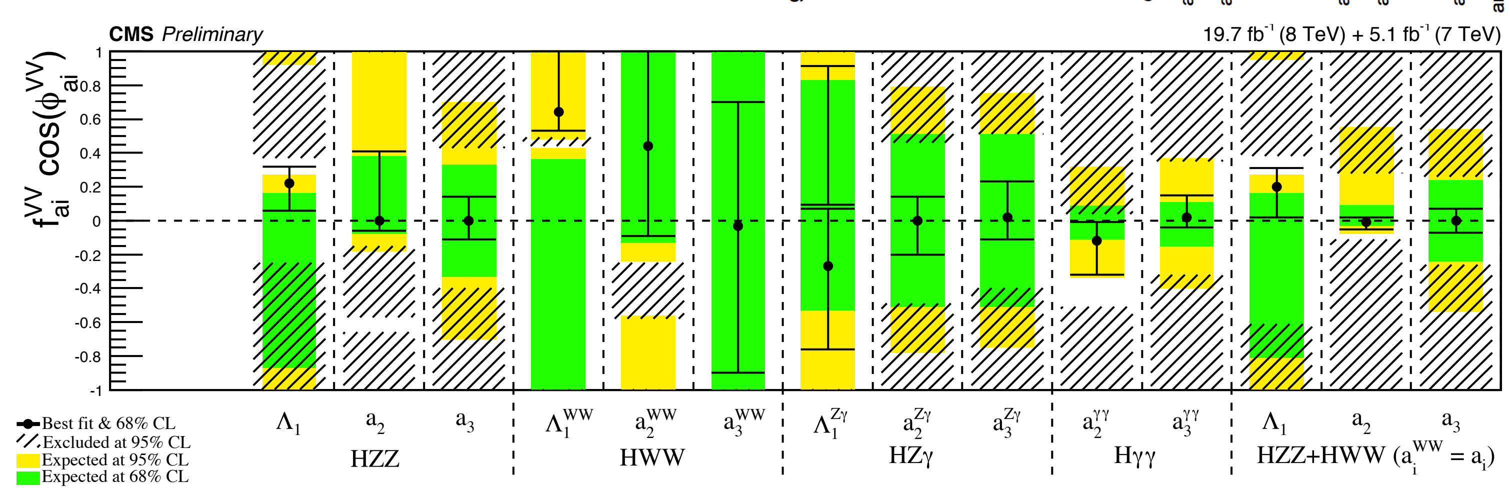












HVV Tensor Structure

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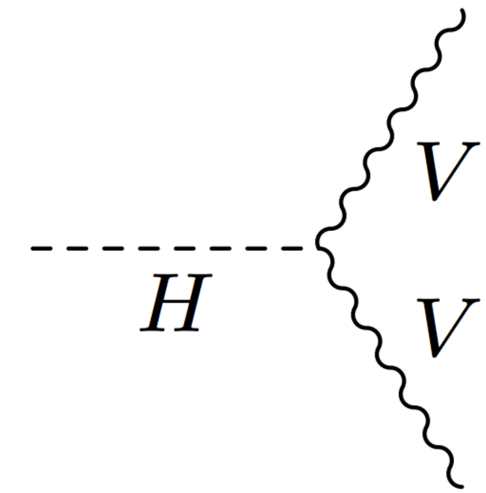
- Current JCP measurements exploit di-boson decays — *channels which have significant signal sensitivity*



- Anomalous couplings are parameterized as:

CMS:

$$A(X_{J=0} \to V_1 V_2) \sim v^{-1}\left(\left[a_1 - e^{i\phi_{\Lambda_1}} \frac{q^2_{Z_1} + q^2_{Z_2}}{(\Lambda_1)^2}\right] m_Z^2 \epsilon^*_{Z_1} \epsilon^*_{Z_2} + a_2 f^{*(Z_1)}_{\mu\nu} f^{*(Z_2),\mu\nu} + a_3 f^{*(Z_1)}_{\mu\nu} \tilde{f}^{*(Z_2),\mu\nu} + a_2^{Z\gamma} f^{*(Z)}_{\mu\nu} f^{*(\gamma),\mu\nu} + a_3^{Z\gamma} f^{*(Z)}_{\mu\nu} \tilde{f}^{*(\gamma),\mu\nu} + a_2^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} f^{*(\gamma_2),\mu\nu} + a_3^{\gamma\gamma} f^{*(\gamma_1)}_{\mu\nu} \tilde{f}^{*(\gamma_2),\mu\nu}\right)$$

ATLAS: $A(H \to VV) \sim (a'_1 M_H^2 g_{\mu\nu} + a'_2 (q_1 + q_2)_\mu (q_1 + q_2)_\nu + a'_3 \epsilon_{\mu\nu\alpha\beta} q^\alpha q^\beta) \epsilon_1^{*\mu} \epsilon_2^{*\nu}$

$$g_1 = a'_1 \frac{m_H^2}{m_V^2} + a'_2 \frac{s}{m_V^2} \quad ; \quad g_2 = -\frac{1}{2} a'_2 \quad ; \quad g_4 = -\frac{1}{2} a'_3$$

**Will focus on the ZZ couplings in this talk

Notation

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- More convenient notation defines parameters which are functions of cross sections

  - anomalous couplings are redefined to a unit interval:
    e.g. fa3 = 1, fa2 = 0 for pure pseudoscalar
    fa3 = fa2 = 0 for SM Higgs (up to EW corrections)

$$f_{a3} = \frac{|a_3|^2\sigma_3}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/\left(\Lambda_1\right)^4} \qquad \phi_{a3} = \arg\left(\frac{a_3}{a_1}\right)$$

$$f_{a2} = \frac{|a_2|^2\sigma_2}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/\left(\Lambda_1\right)^4} \qquad \phi_{a2} = \arg\left(\frac{a_2}{a_1}\right)$$

$$f_{\Lambda 1} = \frac{\tilde{\sigma}_{\Lambda_1}/\left(\Lambda_1\right)^4}{|a_1|^2\sigma_1 + |a_2|^2\sigma_2 + |a_3|^2\sigma_3 + \tilde{\sigma}_{\Lambda_1}/\left(\Lambda_1\right)^4} \qquad \phi_{\Lambda 1},$$

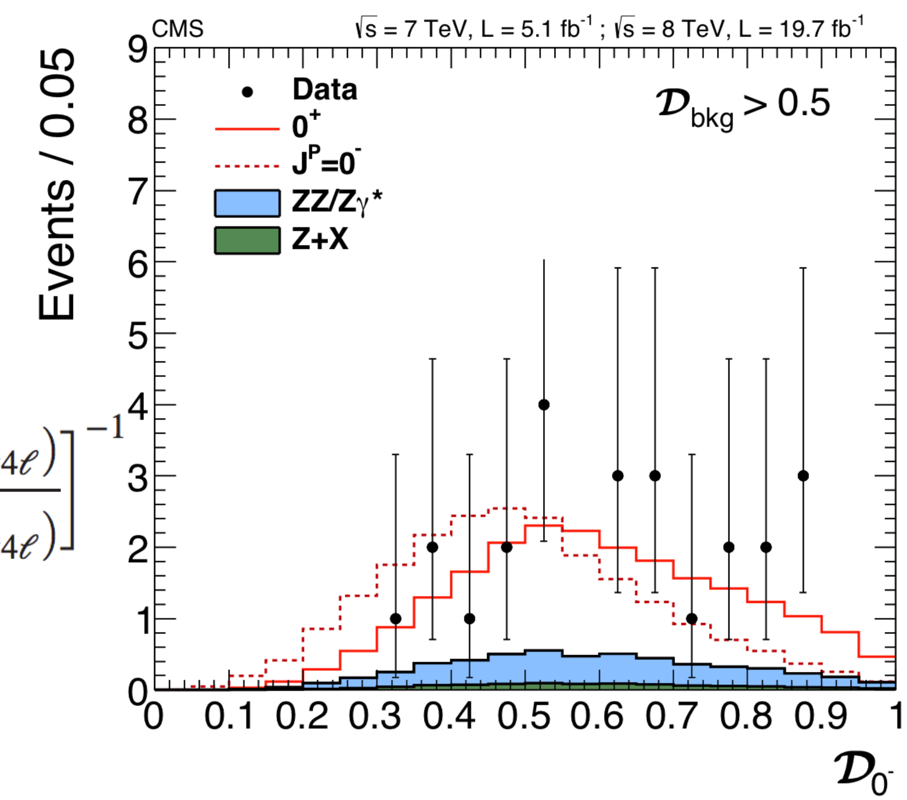
where σ_i is the cross section of the process corresponding to $a_i = 1, a_{j\neq i} = 0$, while $\tilde{\sigma}_{\Lambda_1}$ is the effective cross section of the process corresponding to $\Lambda_1 > 0, a_{j\neq\Lambda_1} = 0$, given in units fb $\cdot$ GeV^4.

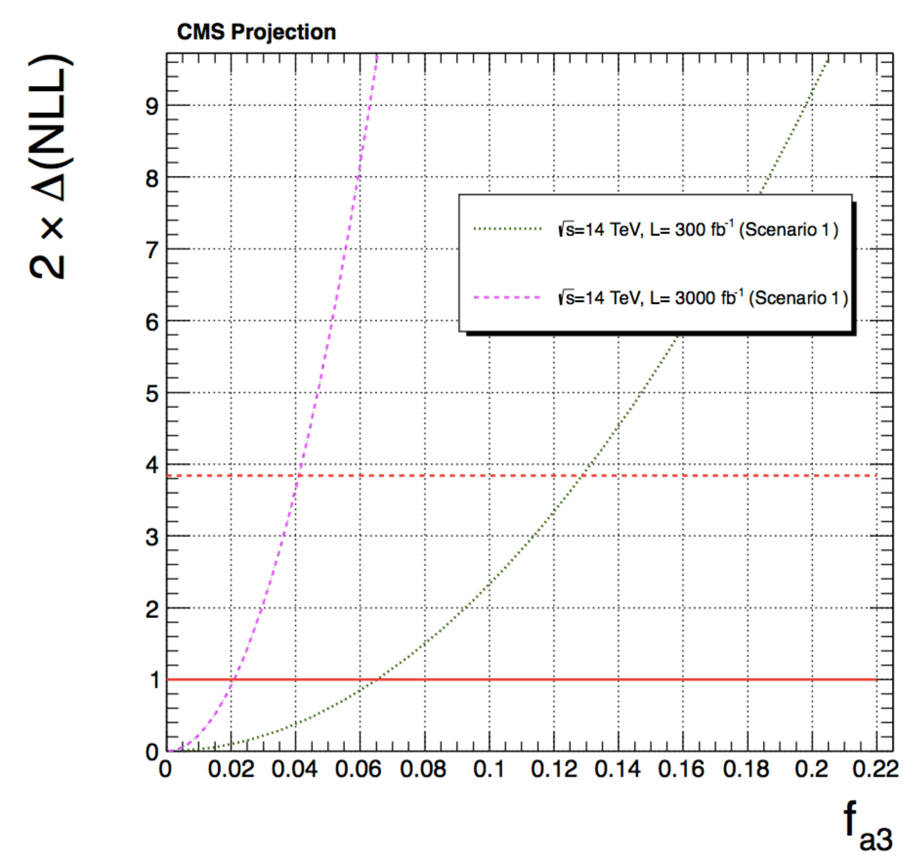
H→ZZ @ CMS

- Projections out to 300/fb & 3000/fb
  - fits are performed with templates in which events are described by 2D distributions of kinematic discriminants:

$$\mathcal{D}_{\rm bkg} = \left[1 + \frac{\mathcal{P}^{\rm kin}_{\rm bkg}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm bkg}(m_{4\ell})}{\mathcal{P}^{\rm kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell}) \times \mathcal{P}^{\rm mass}_{\rm sig}(m_{4\ell}|m_{0^+})}\right] \quad \mathcal{D}_{J^P} = \left[1 + \frac{\mathcal{P}^{\rm kin}_{J^P}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}{\mathcal{P}^{\rm kin}_{0^+}(m_{Z_1}, m_{Z_2}, \vec{\Omega}|m_{4\ell})}\right]^{-1}$$

  - signals model with LO MC
  - scaling up all background predictions
  - all systematic uncertainties are assumed to be the same: *still dominated by statistical uncertainties*
  - can reach 95% C.L. upper limits of fa3 < 0.13 (0.04)





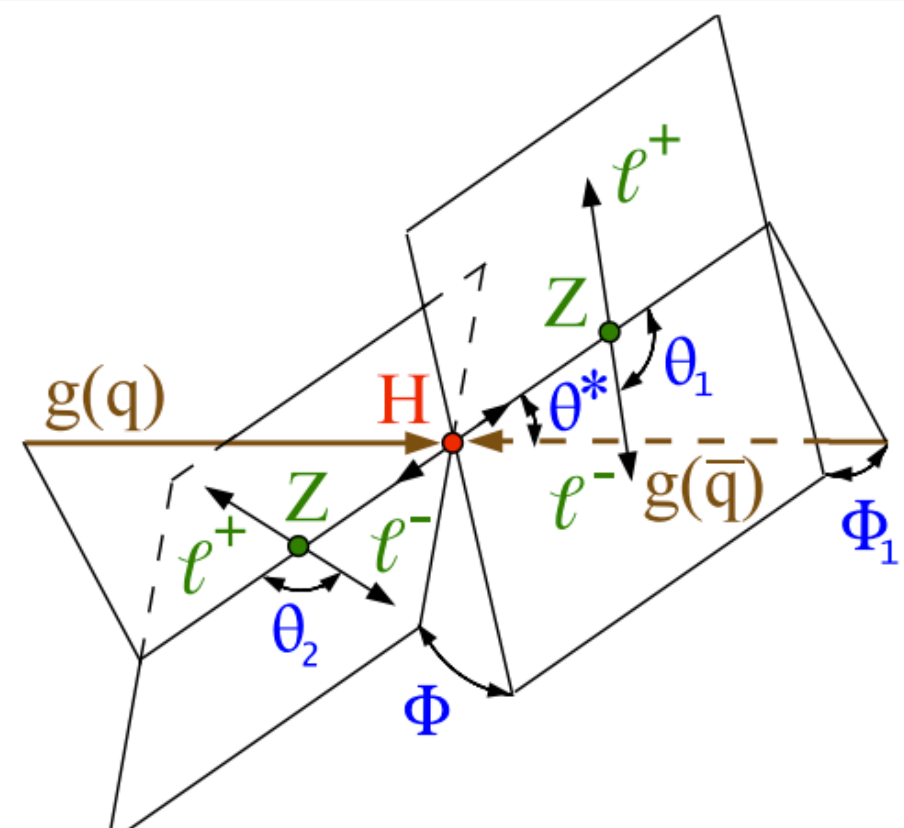
***Note, this measurement assumes that f_{a2} and ϕ_{a2} are fixed to zero*

H→ZZ @ ATLAS

- Exploring sensitivity to g2 & g4 couplings @ 300 & 3000/fb
    - background: assuming qq->ZZ background scaled up to account for irreducible background
    - signal: LO MC - reweighing to morph signal hypothesis
- Fitting either
    - templates based on ME-based kinematic discriminants
    - fully correlated 8D likelihood
      (including approx. detector effects)
- Systematics uncertainties approximated to be: *3% luminosity, 5% signal and background yields (lepton reco ε), and 9.4% (7.4%) for 300/fb (3000/fb) for background yield*

Observable	Sensitivity
$\ln \frac{\lvert ME(g_1=1,g_2=0,g_4=0)\rvert^2}{\lvert ME(g_1=0,g_2=0,g_4=1)\rvert^2}$	$\lvert g_4\rvert/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=0,g_4=-2+2i)\rvert^2}{\lvert ME(g_1=1,g_2=0,g_4=2+2i)\rvert^2}$	$\Re(g_4)/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=0,g_4=2-2i)\rvert^2}{\lvert ME(g_1=1,g_2=0,g_4=2+2i)\rvert^2}$	$\Im(g_4)/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=0,g_4=0)\rvert^2}{\lvert ME(g_1=1,g_2=1,g_4=0)\rvert^2}$	$\lvert g_2\rvert/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=-1+i,g_4=0)\rvert^2}{\lvert ME(g_1=1,g_2=1+i,g_4=0)\rvert^2}$	$\Re(g_2)/g_1$
$\ln \frac{\lvert ME(g_1=1,g_2=1-i,g_4=0)\rvert^2}{\lvert ME(g_1=1,g_2=1+i,g_4=0i)\rvert^2}$	$\Im(g_2)/g_1$

ATLAS-PHYS-PUB-2013-013

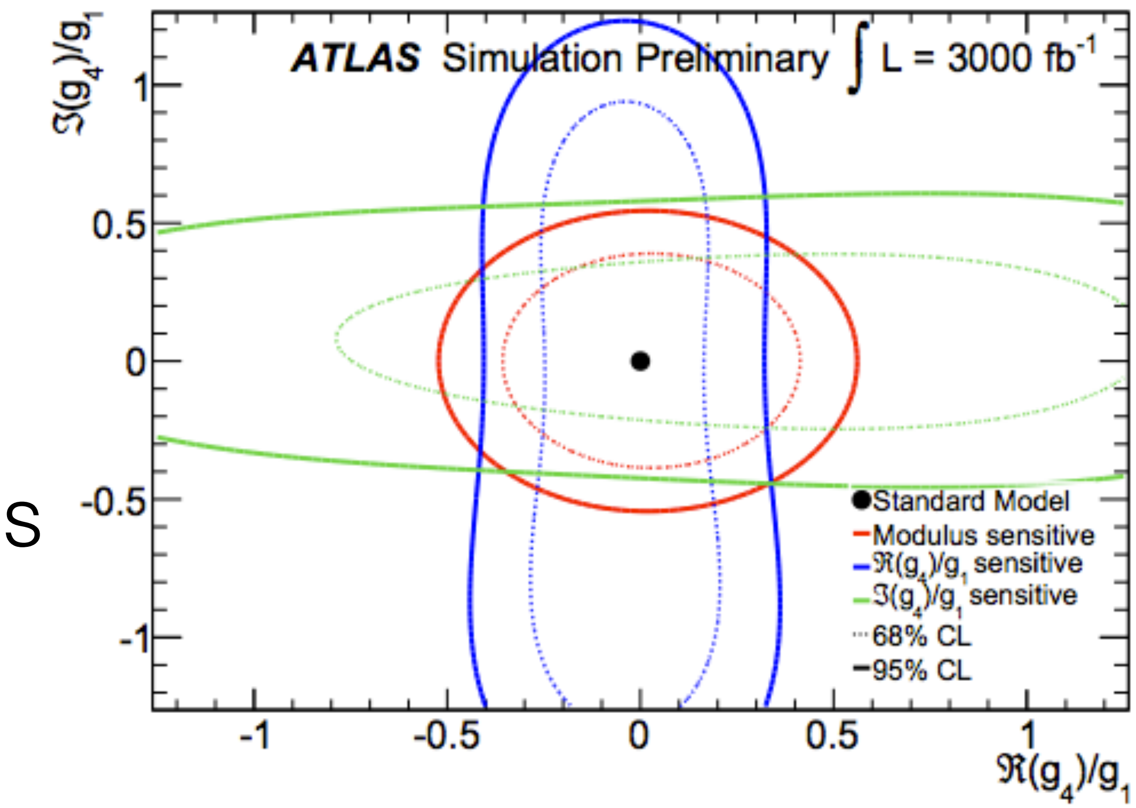


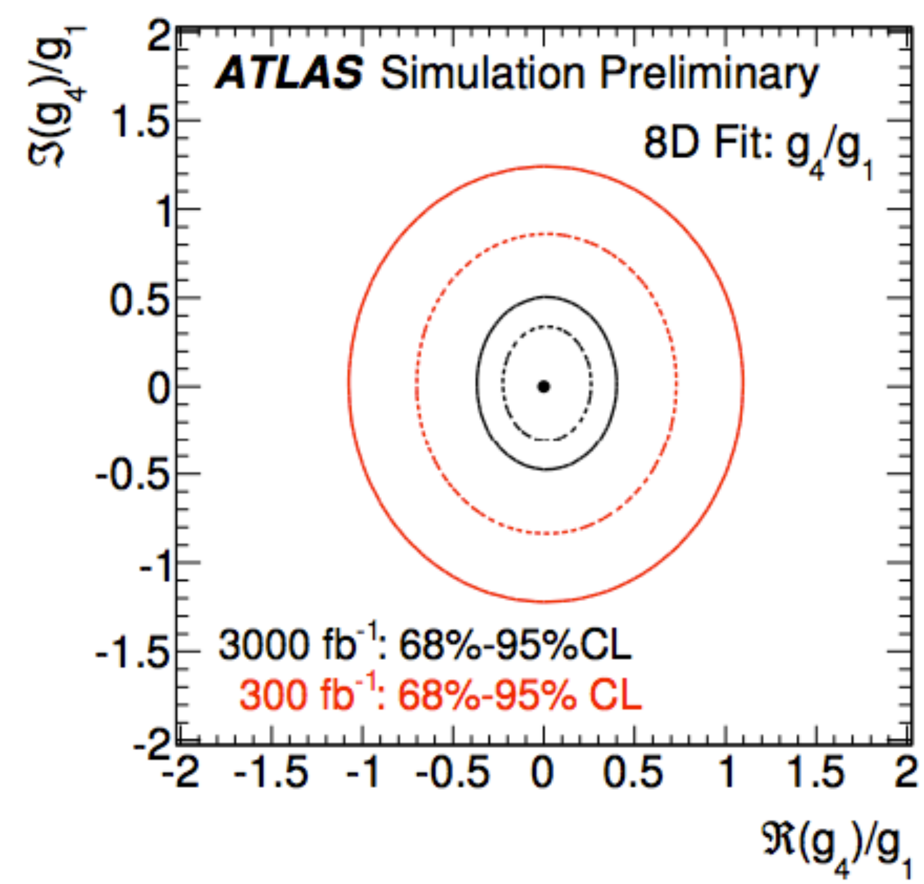
Final State	Signal	Background
$4e$	871	474
4μ	1186	641
$2e2\mu$	1035	574
$2\mu 2e$	867	431

expected yields (115<m_{4l}<130)

CP violating interactions

- Likelihood scan in real and imaginary projection of g_4/g_1
  - KD fits show that phase of anomalous couplings can play an important role
    - *note this can also be parameterized by extending templates' dimensionality a la CMS*
  - 8D - correlation less between the real and imaginary projections - *simultaneously parameterizes kinematics in term of magnitude & phase of anomalous couplings*





Higher Dim. CP even interactions

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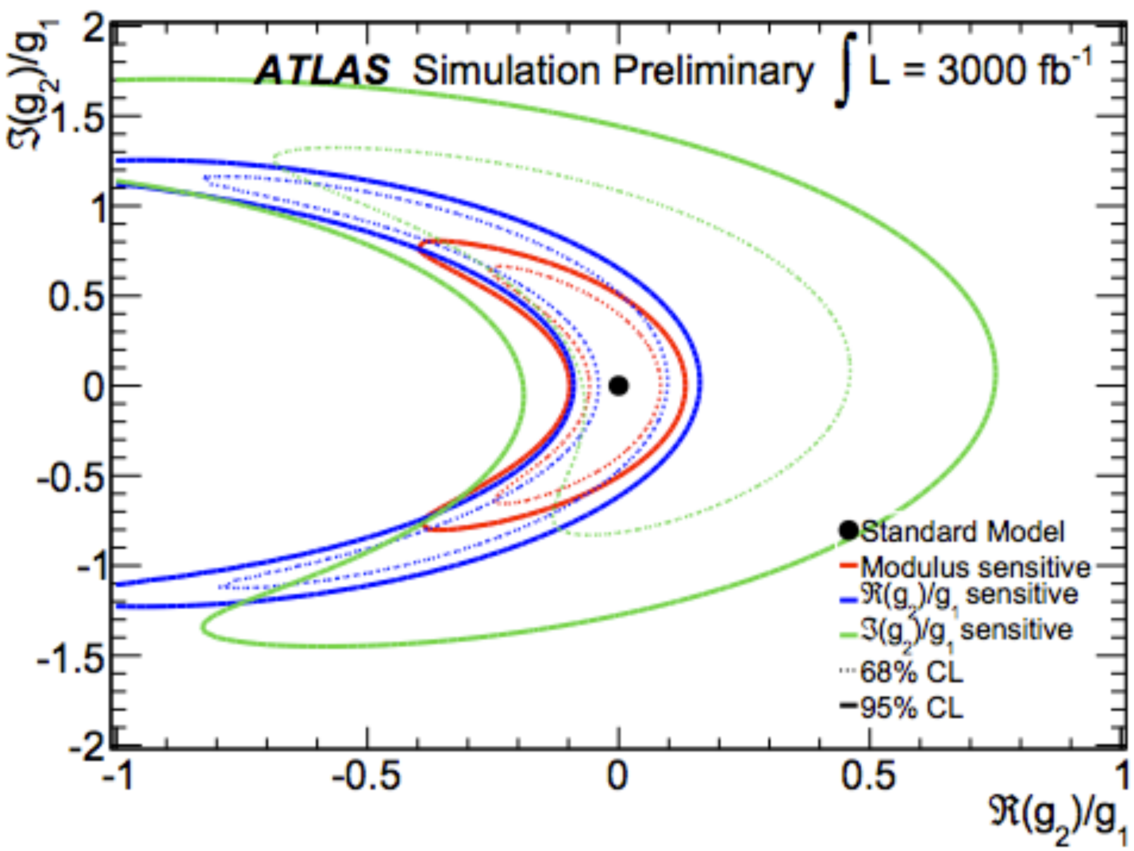
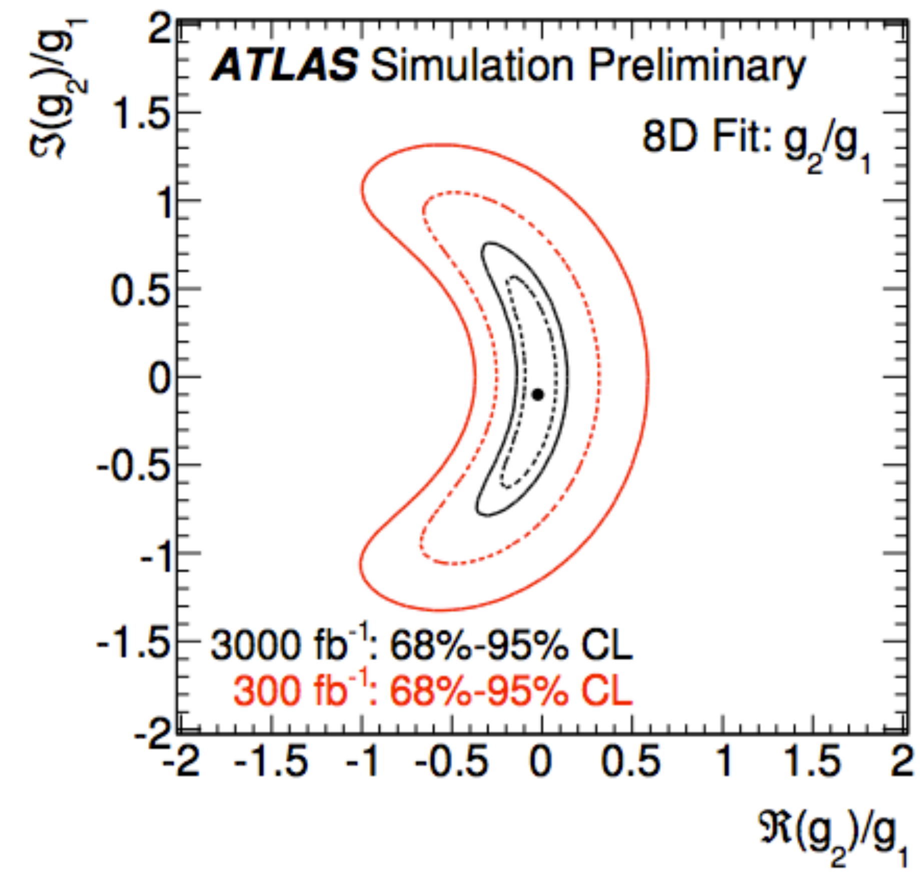
- Similar qualitative comparison between the two methods





Luminosity	$\|g_4\|/g_1$	$\Re(g_4)/g_1$	$\Im(g_4)/g_1$	$\|g_2\|/g_1$	$\Re(g_2)/g_1$	$\Im(g_2)/g_1$
300 fb^{-1}	1.03	(-1.01, 1.01)	(-1.02, 1.02)	1.39	(-0.88, 0.38)	(-1.13, 1.13)
3000 fb^{-1}	0.49	(-0.34, 0.26)	(-0.34, 0.48)	0.81	(-0.33, 0.11)	(-0.73, 0.75)

ME sensitive fits

Luminosity	$\|g_4\|/g_1$	$\Re(g_4)/g_1$	$\Im(g_4)/g_1$	$\|g_2\|/g_1$	$\Re(g_2)/g_1$	$\Im(g_2)/g_1$
300	1.20	(-0.88, 0.91)	(-1.02, 1.05)	1.02	(-0.84,0.44)	(-1.19, 1.18)
3000	0.60	(-0.30, 0.33)	(-0.39, 0.42)	0.60	(-0.30,0.11)	(-0.71, 0.68)

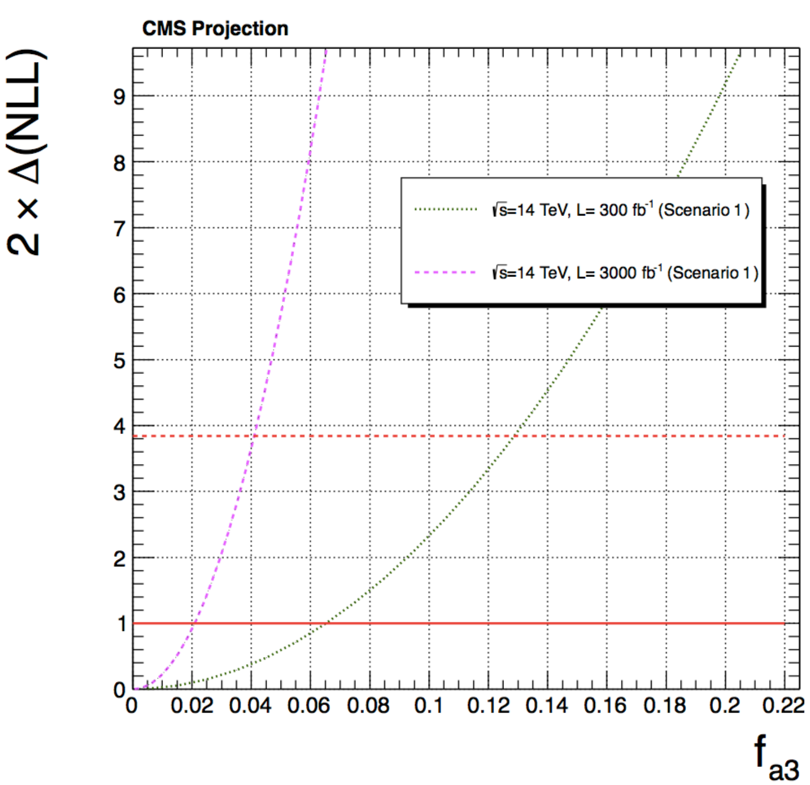
8D fits

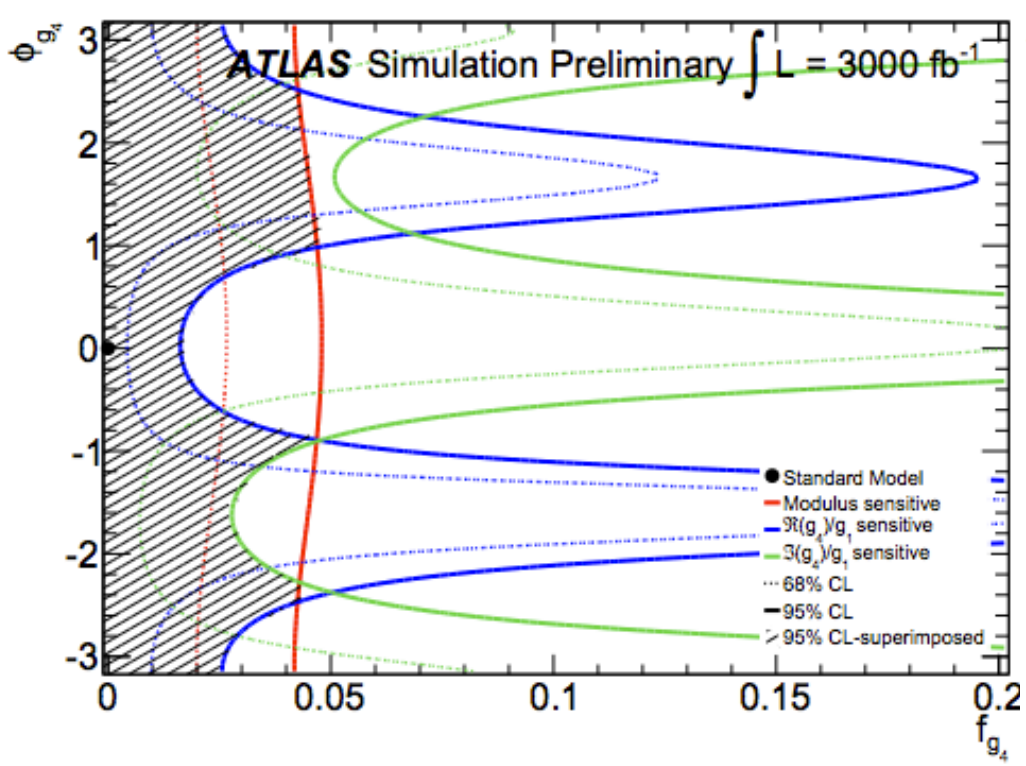
ATLAS-PHYS-PUB-2013-013

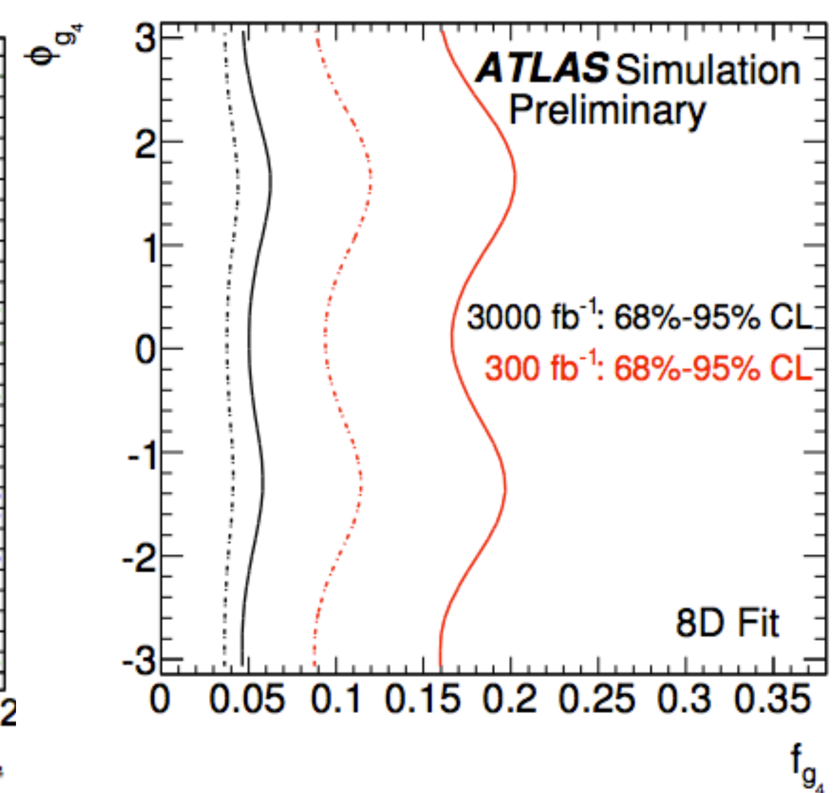
Comparisons

- ATLAS analysis also produced likelihood scan as a function of f_{ai} & ϕ_i

- $f_{a3} = f_{g4}$ — comparable results between ATLAS and CMS
  ($f_{a3} < 0.04$ @ 95% C.L.)







NOTE: the parameterization used in CMS is equivalent to the ATLAS modulus sensitive variable

Snowmass

- Set of results showing potential sensitivity in many collider scenarios

1

Higgs working group report

Conveners: Sally Dawson (BNL), Andrei Gritsan (Johns Hopkins), Heather Logan (Carleton), Jianming Qian (Michigan), Chris Tully (Princeton), Rick Van Kooten (Indiana)

Authors: A. Ajaib, A. Anastassov, I. Anderson, D. Asner, O. Bake, V. Barger, T. Barklow, B. Batell, M. Battaglia, S. Berge, A. Blondel, S. Bolognesi, J. Brau, E. Brownson, M. Cahill-Rowley, C. Calancha-Paredes, C.-Y. Chen, W. Chou, R. Clare, D. Cline, N. Craig, K. Cranmer, M. de Gruttola, A. Elagin, R. Essig, L. Everett, E. Feng, K. Fujii, J. Gainer, Y. Gao, I. Gogoladze, S. Gori, R. Goncalo, N. Graf, C. Grojean, S. Guindon, H. Haber, T. Han, G. Hanson, R. Harnik, S. Heinemeyer, U. Heintz, J. Hewett, Y. Ilchenko, A. Ishikawa, A. Ismail, V. Jain, P. Janot, S. Kanemura, S. Kawada, R. Kehoe, M. Klute, A. Kotwal, K. Krueger, G. Kukartsev, K. Kumar, J. Kunkle, M. Kurata, I. Lewis, Y. Li, L. Linssen, E. Lipeles, R. Lipton, T. Liss, J. List, T. Liu, Z. Liu, I. Low, T. Ma, P. Mackenzie, B. Mellado, K. Melnikov, A. Miyamoto, G. Moortgat-Pick, G. Mourou, M. Narain, H. Neal, J. Nielsen, N. Okada, H. Okawa, J. Olsen, H. Ono, P. Onyisi, N. Parashar, M. Peskin, F. Petriello, T. Plehn, C. Pollard, C. Potter, K. Prokofiev, M. Rauch, T. Rizzo, T. Robens, V. Rodriguez, P. Roloff, R. Ruiz, V. Sanz, J. Sayre, Q. Shafi, G. Shaughnessy, M. Sher, F. Simon, N. Solyak, J. Strube, J. Stupak, S. Su, T. Suehara, T. Tanabe, T. Tajima, V. Telnov, J. Tian, S. Thomas, M. Thomson, K. Tsumura, C. Un, M. Velasco, C. Wagner, S. Wang, S. Watanuki, G. Weiglein, A. Whitbeck, K. Yagyu, W. Yao, H. Yokoya, S. Zenz, D. Zerwas, Y. Zhang, Y. Zhou

Abstract

This report summarizes the work of the Energy Frontier Higgs Boson working group of the 2013 Community Summer Study (Snowmass). We identify the key elements of a precision Higgs physics program and document the physics potential of future experimental facilities as elucidated during the Snowmass study. We study Higgs couplings to gauge boson and fermion pairs, double Higgs production for the Higgs self-coupling, its quantum numbers and *CP*-mixing in Higgs couplings, the Higgs mass and total width, and prospects for direct searches for additional Higgs bosons in extensions of the Standard Model. Our report includes projections of measurement capabilities from detailed studies of the Compact Linear Collider (CLIC), a Gamma-Gamma Collider, the International Linear Collider (ILC), the Large Hadron Collider High-Luminosity Upgrade (HL-LHC), Very Large Hadron Colliders up to 100 TeV (VLHC), a Muon Collider, and a Triple-Large Electron Positron Collider (TLEP).

arXiv:1310.8361v2

- One of the most complete set of recent studies on constraining CP-mixtures

Other Production Mechanisms

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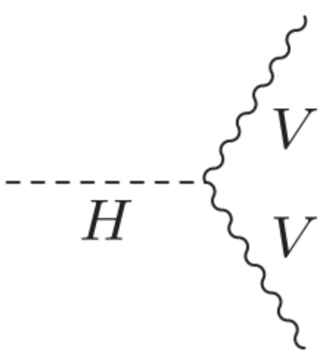
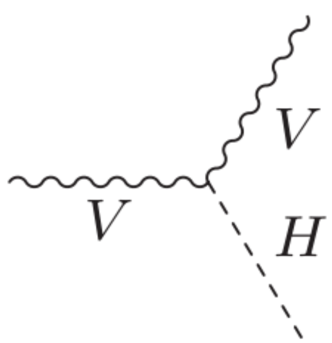
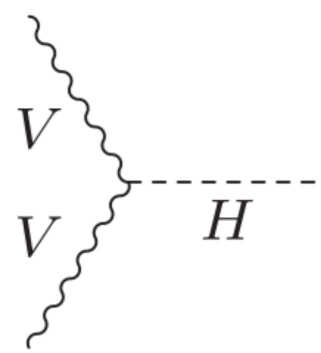
- As sensitivity to other production mechanisms become significant, new opportunities arise



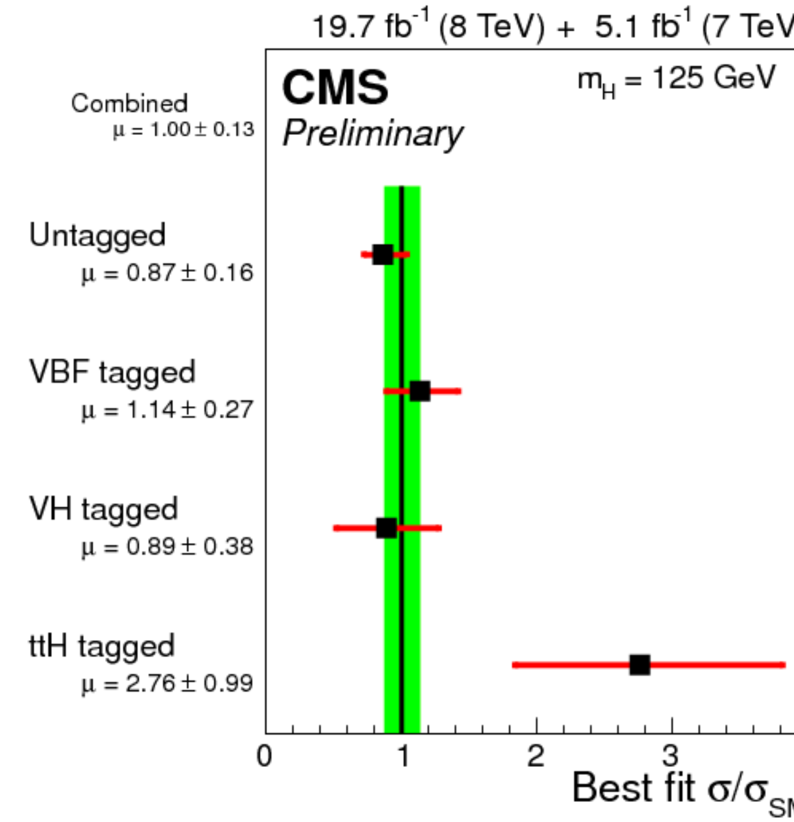
H→ZZ, H→WW



associated prod.

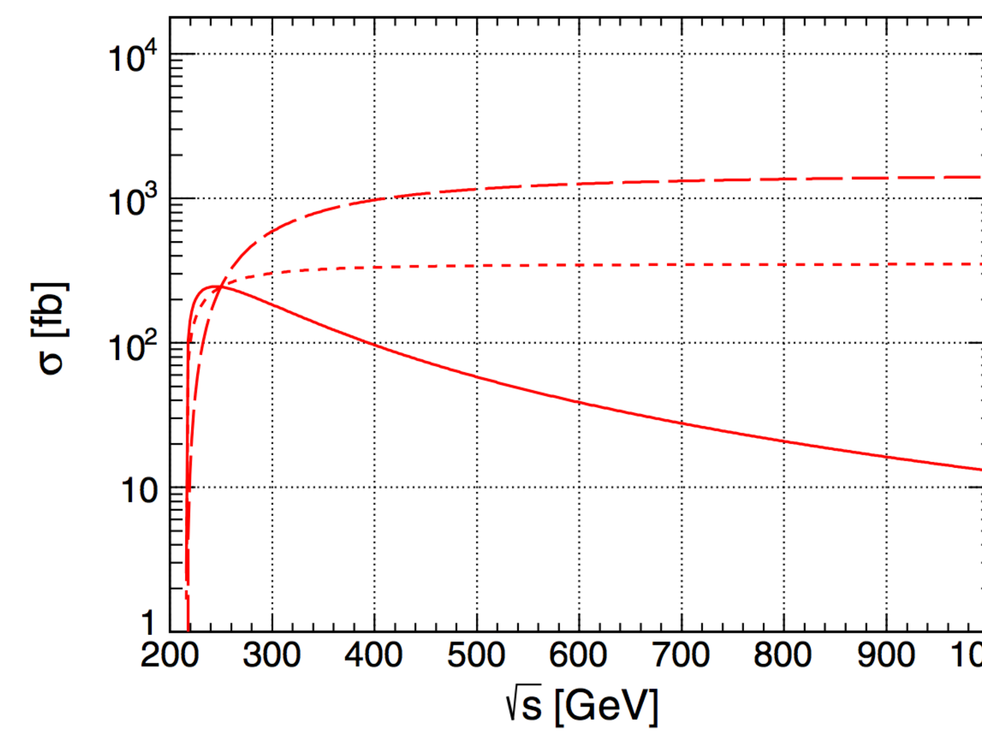


VBF



CMS-PAS-HIG-14-009

- 0^--like events have an enhancement at large $\sqrt{s}$ - leading to increased sensitivity in associated production and VBF production channels



center-of-mass energy dependence for associated production of different scalars, ***no q² dependence***

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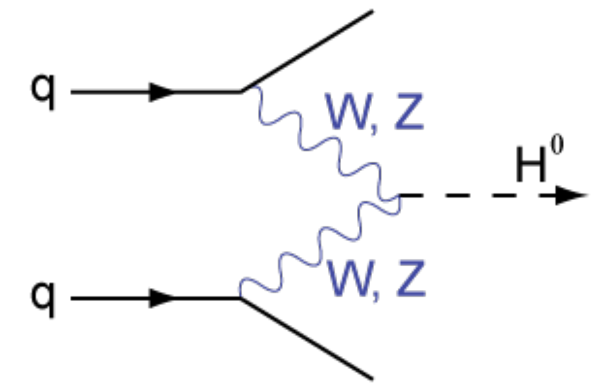
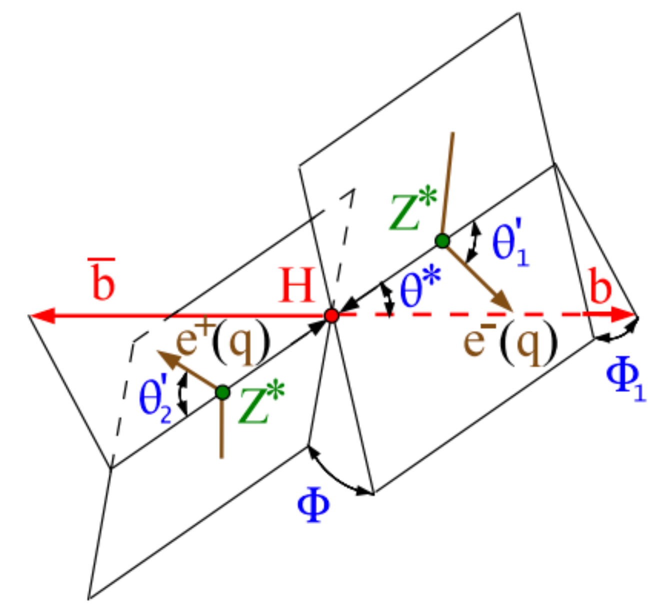
Weak Boson Fusion

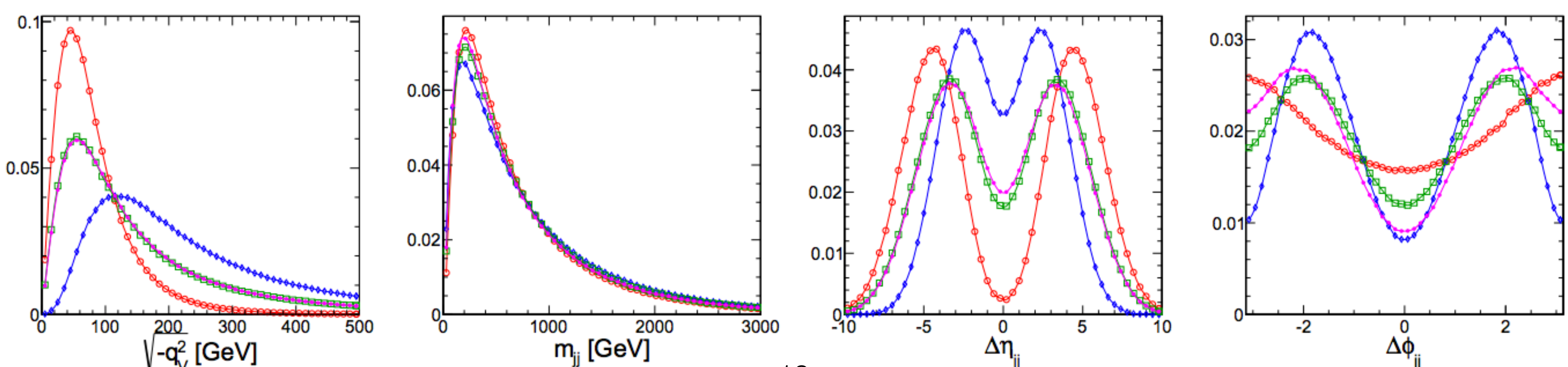
- Well known that $\Delta\phi$ and $\Delta\eta$ reflect the tensor structure of the HVV couplings



- Strong discrimination power in m_{V^*}
  - result of enhanced cross section at large values of m_{V^*} for a pseudoscalar - *susceptible to presence of q^2-dependent couplings*



- Angular distributions which are critical for distinguishing phases



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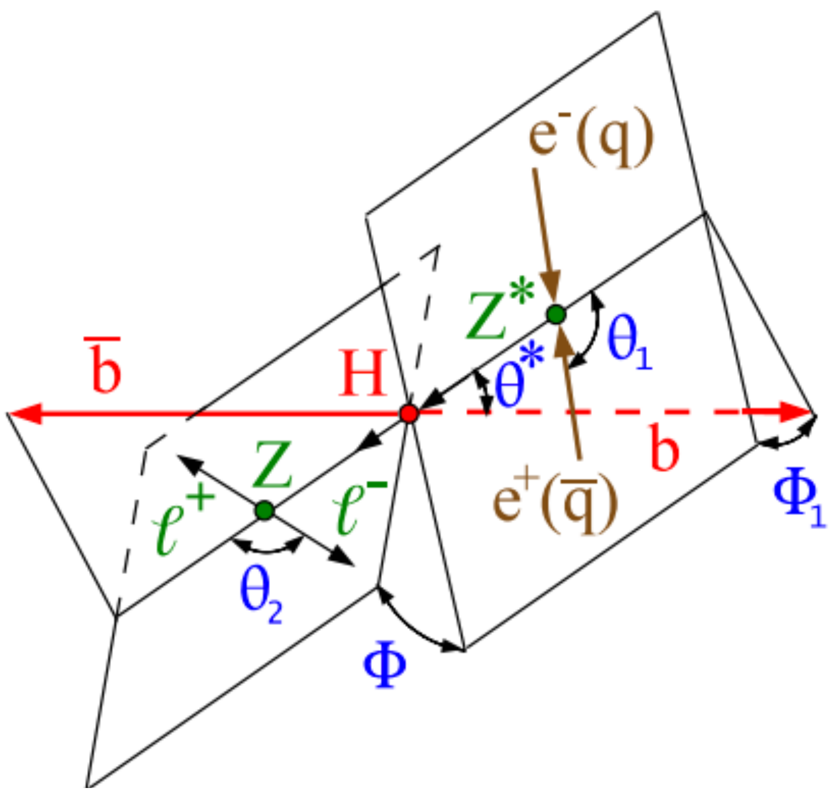
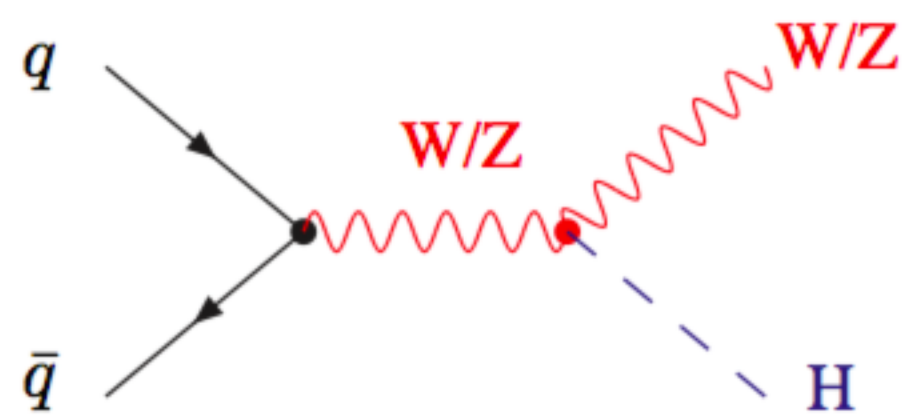
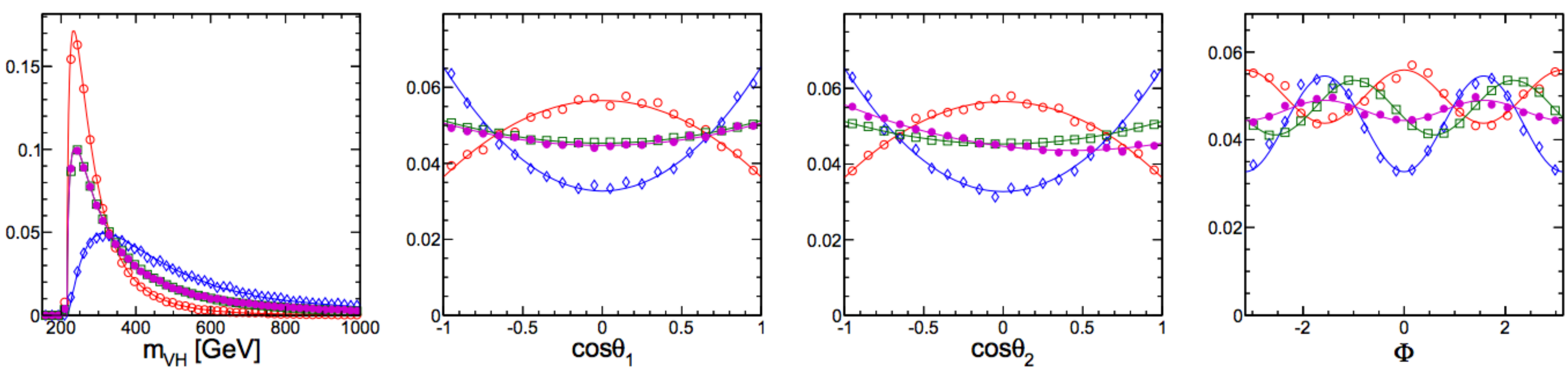
Associated Prod.

- Qualitatively similar to VBF production







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Future Outlook for LHC

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- Projections out to 300/fb & 3000/fb show strong sensitivity to CP-violating HVV interactions

  - Associated production: assuming only Z→Z(ll)H(bb)

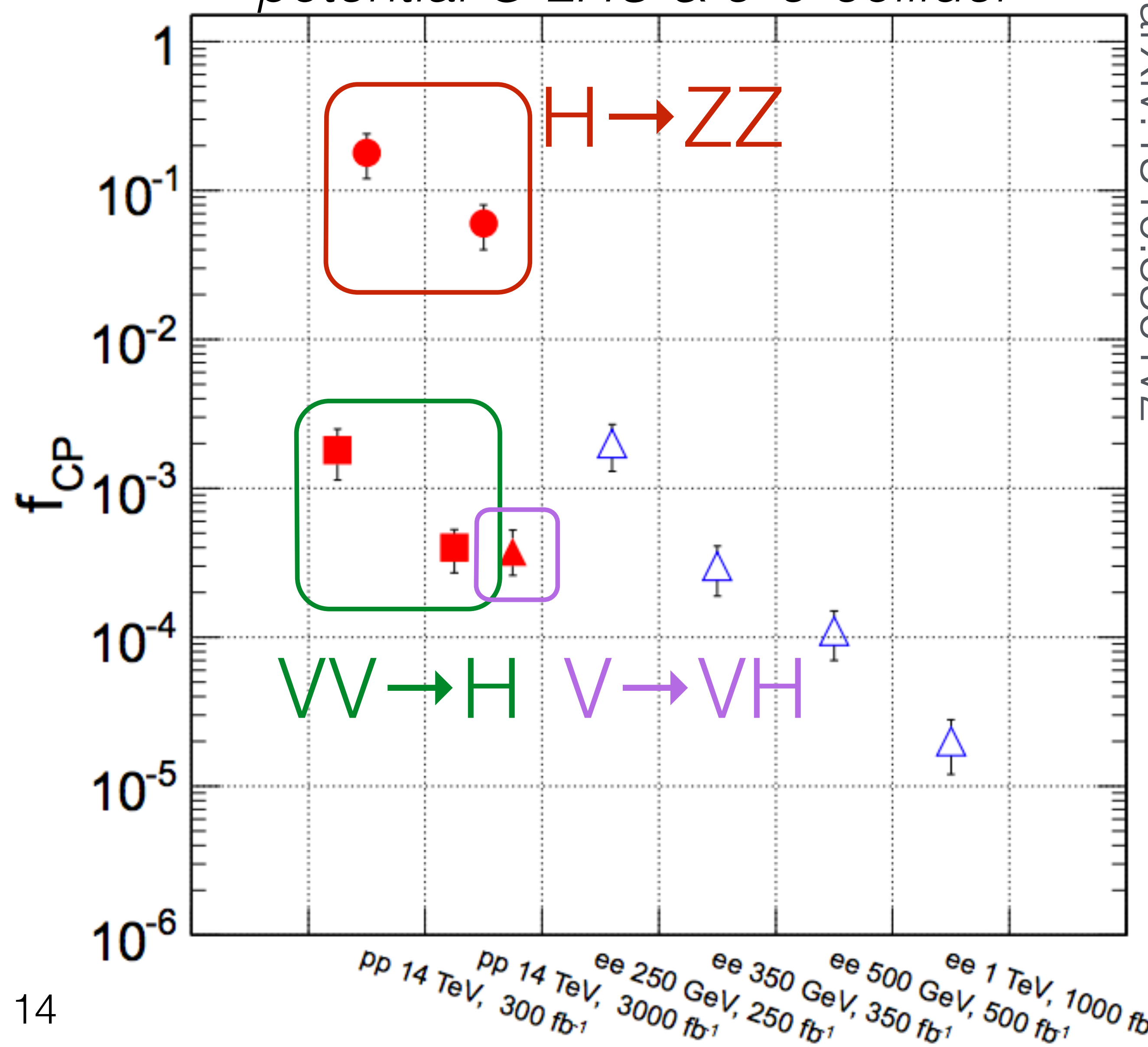
  - VBF production: assuming H(γγ) + H(ZZ)

  →dominant sensitivity from associated and VBF production mechanisms!

$$f_{CP} = \frac{|a_3|^2 \sigma_3^{H\to ZZ}}{\Sigma |a_i|^2 \sigma_i^{H\to ZZ}}$$

$$e.g. \quad \frac{\sigma_3^{H\to ZZ}}{\sigma_1^{H\to ZZ}} \sim 0.160$$

Summary of projections for discovery potential @ LHC & e+e- collider



arXiv:1310.8361v2

Fermion Coupling

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Collider E (GeV) $\mathcal{L}$ (fb^{-1})	pp 14,000 300	pp 14,000 3,000	e^+e^- 250 250	e^+e^- 350 350	e^+e^- 500 500	e^+e^- 1,000 1,000	$\gamma\gamma$ 126 250	$\mu^+\mu^-$ 126	target (theory)
spin-2^+_m	$\sim 10\sigma$	$\gg 10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$	$>10\sigma$			$>5\sigma$
$VVH^\dagger$	0.07	0.02	✓	✓	✓	✓	✓	✓	$< 10^{-5}$
$VVH^\ddagger$	$4\cdot 10^{-4}$	$1.2\cdot 10^{-4}$	$7\cdot 10^{-4}$	$1.1\cdot 10^{-4}$	$4\cdot 10^{-5}$	$8\cdot 10^{-6}$	–	–	$< 10^{-5}$
$VVH^\diamond$	$7\cdot 10^{-4}$	$1.3\cdot 10^{-4}$	✓	✓	✓	✓	–	–	$< 10^{-5}$
ggH	0.50	0.16	–	–	–	–	–	–	$< 10^{-2}$
$\gamma\gamma H$	–	–	–	–	–	–	0.06	–	$< 10^{-2}$
$Z\gamma H$	–	✓	–	–	–	–	–	–	$< 10^{-2}$
$\tau\tau H$	✓	✓	0.01	0.01	0.02	0.06	✓	✓	$< 10^{-2}$
ttH	✓	✓	–	–	0.29	0.08	–	–	$< 10^{-2}$
$\mu\mu H$	–	–	–	–	–	–	–	✓	$< 10^{-2}$

† estimated in $H \to ZZ^*$ decay mode

‡ estimated in $V^* \to HV$ production mode

$^\diamond$ estimated in $V^*V^* \to H$ (VBF) production mode

arXiv:1310.8361v2

Conclusions

- Great prospects for constraining Higgs tensor structure in future LHC runs!
  - traditional channels are great avenues to continue carving out parameter space of anomalous couplings
  - Both CMS & ATLAS are building up campaigns to measure/constrain couplings of the HZZ vertex:

	|g		|g	
	300/fb	3/ab	300/fb	3/ab
ATLAS	1.20 (0.20)	0.60 (0.06)	1.02 (0.29)	0.60 (0.12)
CMS	(0.14)	(0.04)	—	—

- New prospects lie on the horizon: $V^* \to VH$ & $VBF \to H$

Backup

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HZZ @ ATLAS

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ME sensitive Fits

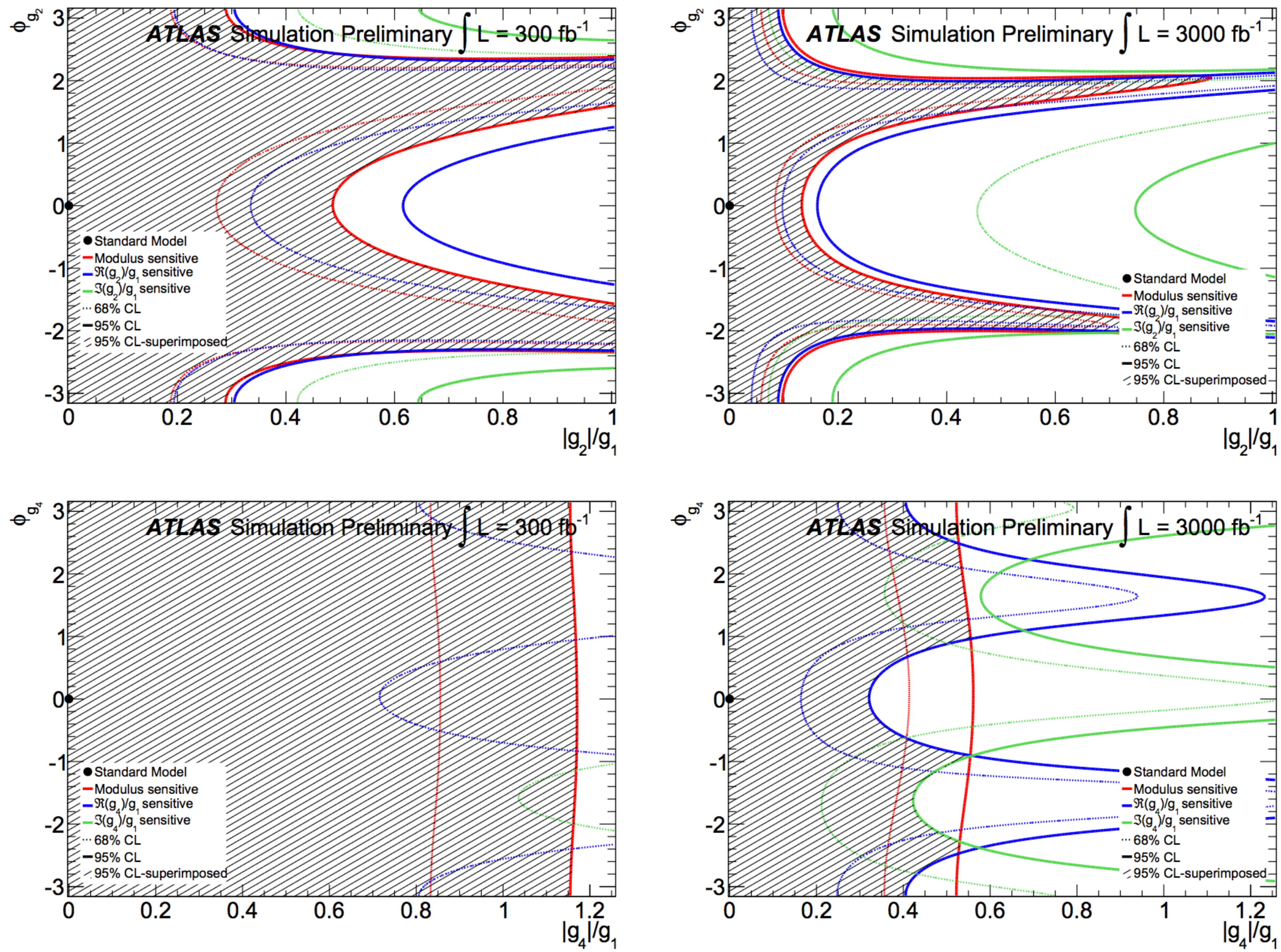

Figure 5: Results of the ME-observable fit for Standard Model signal at 300 fb^{-1} and 3000 fb^{-1}. **Top row:** Results of the g_2-sensitive fits projected onto the $(|g_2|/g_1, \phi_{g_2})$ plane. **Bottom row:** Results of the g_4-sensitive fits projected onto the $(|g_4|/g_1, \phi_{g_4})$ plane. The shaded area corresponds to the most restrictive exclusion of the three observables.