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Golden Probe of Electroweak Symmetry Breaking

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CPAD INSTRUMENTATION FRONTIER 2016 AT CALTECH, 8-10 OCT. : NEW TECHNOLOGIES FOR DISCOVERY II

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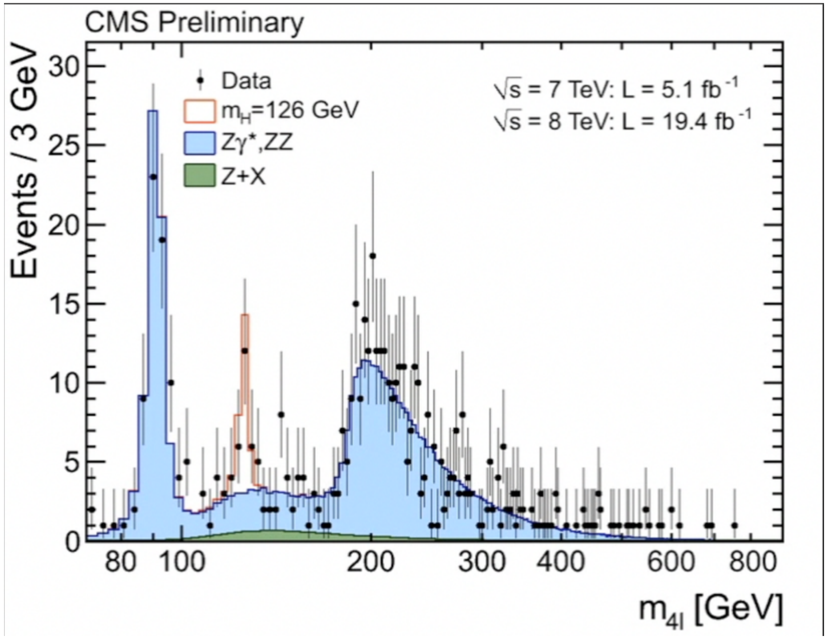
Papers:

arXiv:1609.02159
arXiv:1505.01168
arXiv:1503.05855
arXiv:1404.1336

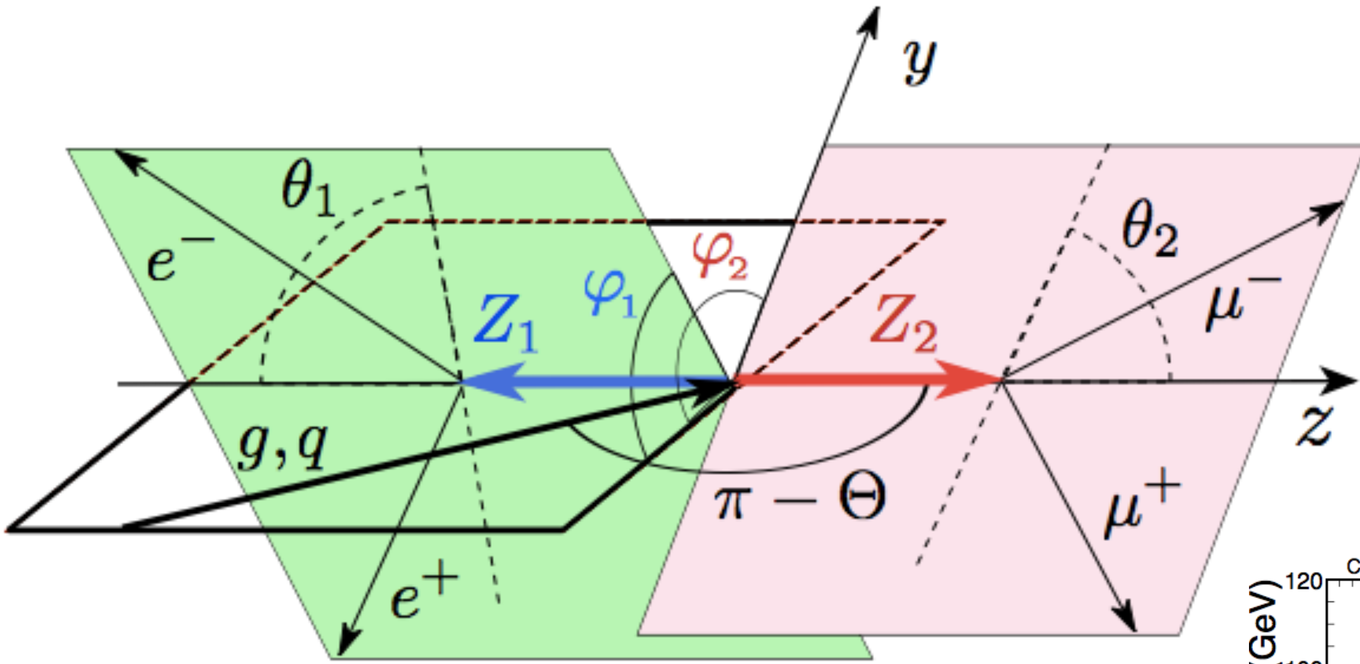
The Higgs Golden Channel

- It has been known since the dawn of the Standard Model that the rare decay h -> 4l is both the cleanest mode and the one containing the most information in the final state

- Even with low statistics, it was an unimpeachable discovery channel in 2012, especially since at 126 GeV the SM background is both small and flat



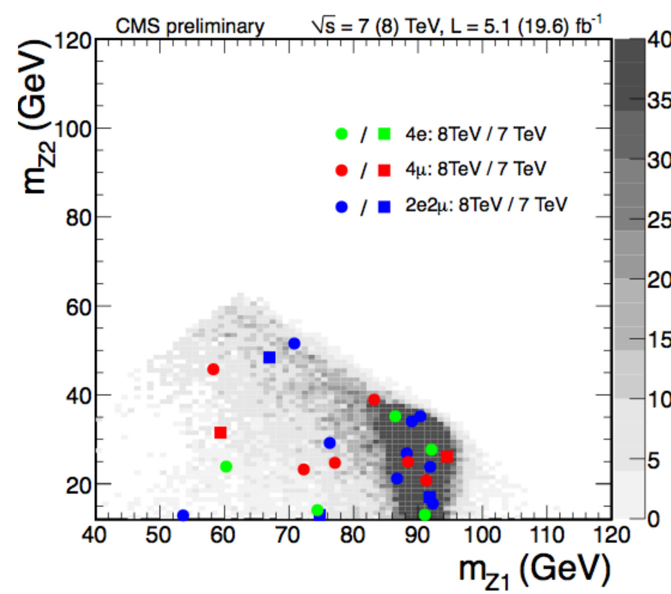
Golden channel angles and masses



A gold mine of information, since the decay amplitudes depend on 5 angles and the two dilepton invariant masses

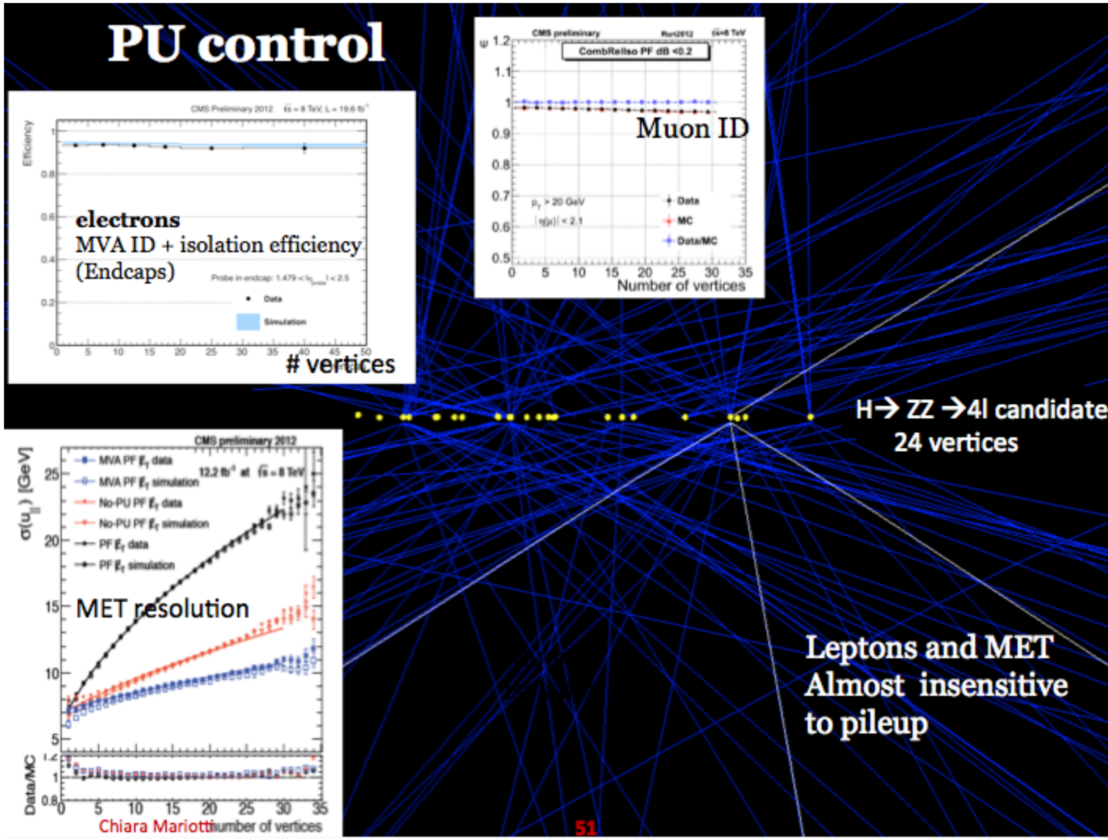
Production effects are decoupled modulo small effects from phase space acceptance

A. De Rujula, JL, C. Rogan, M. Pierini, M. Spiropulu, arXiv:1001.5300



Golden Channel and pileup

- If you zoom in and show the soft tracks, even the Golden Channel looks like a mess
- So far this has not been a problem
- But emphasizes the need for the phase 2 upgrades to keep this performance through 3 ab^{-1}



Higgs Factories?

TABLE I: Summary of collider options considered for the production of a Higgs boson with the mass of 125 GeV. Collider center-of-mass energy, integrated luminosity, cross sections for relevant production modes and decay channels are shown. Reconstructed efficiencies are estimated using selection criteria described in the text and relate the number of produced and reconstructed events (N_{prod} and N_{reco}). In several cases we also show fractions f_{jet} of events with two associated jets with $p_T > 30$ GeV and $\Delta R_{jj} > 0.5$.

collider	energy	$\int \mathcal{L}dt$ (fb^{-1})	production	σ (fb)	decay	$\sigma \times \mathcal{B}$ (fb)	N_{prod}	N_{reco}	f_{jet}
pp	14 TeV	3000	$gg \to H$	49850	$H \to ZZ^* \to 4\ell$	6.23	18694	5608	0.1
pp	14 TeV	3000	$V^*V^* \to H$	4180	$H \to ZZ^* \to 4\ell$	0.52	1568	470	0.6
pp	14 TeV	3000	$W^* \to WH$	1504	$H \to ZZ^* \to 4\ell$	0.19	564	169	0.5
pp	14 TeV	3000	$Z^* \to ZH$	883	$H \to ZZ^* \to 4\ell$	0.11	331	99	0.5
pp	14 TeV	3000	$t\bar{t} \to t\bar{t}H$	611	$H \to ZZ^* \to 4\ell$	0.08	229	69	1.0
pp	14 TeV	3000	$V^*V^* \to H$	4180	$H \to \gamma\gamma$	9.53	28591	8577	0.6
pp	14 TeV	3000	$Z^* \to ZH$	883	$H \to b\bar{b}$, $Z \to \ell\ell$	34.3	102891	690	–
e^+e^-	250 GeV	250	$Z^* \to ZH$	240	$H \to b\bar{b}$, $Z \to \ell\ell$	9.35	2337	1870	–
e^+e^-	350 GeV	350	$Z^* \to ZH$	129	$H \to b\bar{b}$, $Z \to \ell\ell$	5.03	1760	1408	–
e^+e^-	500 GeV	500	$Z^* \to ZH$	57	$H \to b\bar{b}$, $Z \to \ell\ell$	2.22	1110	888	–
e^+e^-	1 TeV	1000	$Z^* \to ZH$	13	$H \to b\bar{b}$, $Z \to \ell\ell$	0.51	505	404	–
e^+e^-	250 GeV	250	$Z^*Z^* \to H$	0.7	$H \to b\bar{b}$	0.4	108	86	–
e^+e^-	350 GeV	350	$Z^*Z^* \to H$	3	$H \to b\bar{b}$	1.7	587	470	–
e^+e^-	500 GeV	500	$Z^*Z^* \to H$	7	$H \to b\bar{b}$	4.1	2059	1647	–
e^+e^-	1 TeV	1000	$Z^*Z^* \to H$	21	$H \to b\bar{b}$	12.2	12244	9795	–

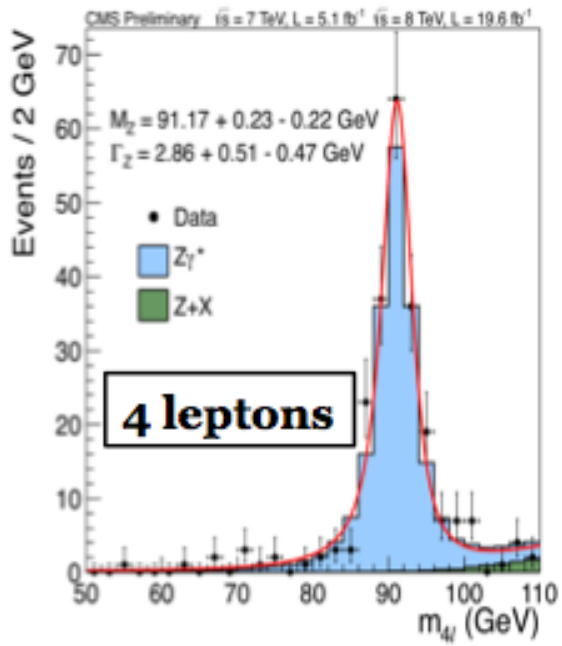
Not quite LEP scale numbers

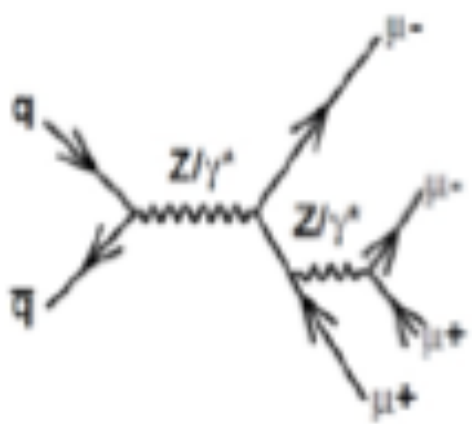
But we can do a lot by making the most of the information in the events

I. Anderson, S. Bolognesi, F. Caola, Y. Gao, A. Gritsan, C. Martin, K. Melnikov, M. Schulze, N. Tran, A. Whitbeck, Y. Zhou, arXiv:1309.4819

Golden channel precision

- At CMS (and even ATLAS) electrons and muons are measured with exquisite precision
- Don't believe it? Look at the extracted mass of the Z from its rare 4-lepton decays!
- Compare to PDG value M_Z = 91.188 +-0.002





momentum scale:

0.1% for muons

0.2% for electrons of 35<pT<50 up to 1.5% at low pT

Lepton resolution= 1 - 2%
uncertainty: 20%

Validated in situ with Z(4l)

Talk by Chiara Mariotti

A question for the HL-LHC era

Can we extract the **signs** of Higgs couplings?

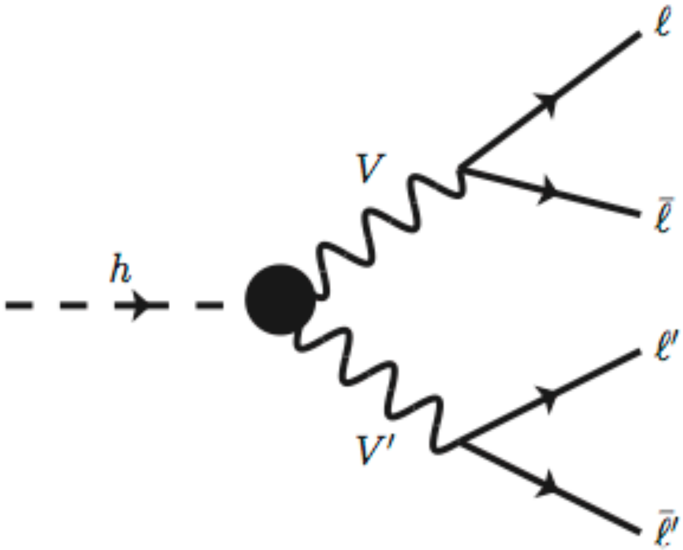
This sounds hard, since it requires sensitivity to either

- Interference of tree-level SM couplings with loop-level SM couplings
- Interference of tree-level SM couplings with BSM couplings

The rest of this talk is showing you two examples where this can be done in the Golden Channel with HL-LHC

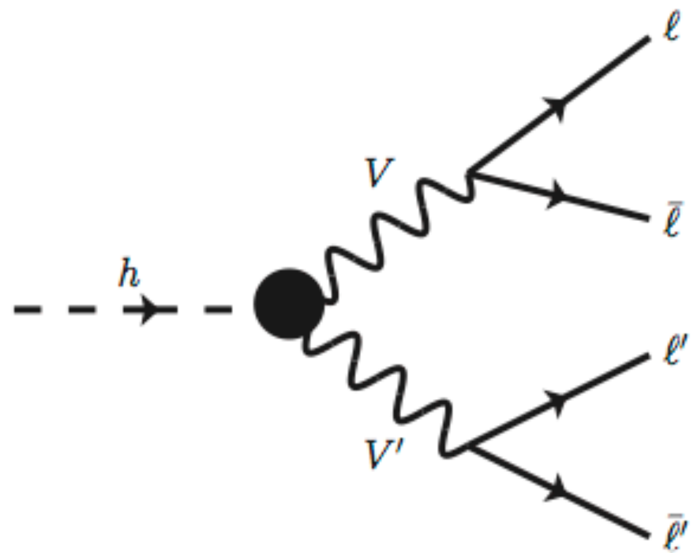
Golden channel is not just ZZ

- Consists of the $h \to VV' \to 4\ell$ decay where $4\ell = 2e2\mu, 4e, 4\mu$ and $VV' = ZZ, Z\gamma, \gamma\gamma$ (where Z, γ are in general off-shell)



Golden channel beyond tree level

- Consists of the $h \to VV' \to 4\ell$ decay where $4\ell = 2e2\mu, 4e, 4\mu$ and $VV' = ZZ, Z\gamma, \gamma\gamma$ (where Z, γ are in general off-shell)



- Can parametrize the hVV' couplings with following Lagrangian

$$\mathcal{L} \supset \frac{h}{4v}\Big(2A_1^{ZZ} m_Z^2 Z^\mu Z_\mu + A_2^{ZZ} Z^{\mu\nu} Z_{\mu\nu} + A_3^{ZZ} Z^{\mu\nu} \widetilde{Z}_{\mu\nu}$$
$$+\ 2A_2^{Z\gamma} F^{\mu\nu} Z_{\mu\nu} + 2A_3^{Z\gamma} F^{\mu\nu} \widetilde{Z}_{\mu\nu} + A_2^{\gamma\gamma} F^{\mu\nu} F_{\mu\nu} + A_3^{\gamma\gamma} F^{\mu\nu} \widetilde{F}_{\mu\nu}\Big)$$

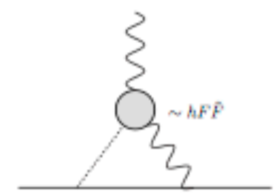
(For SM at tree level we have $A_1^{ZZ} = 2$ and all others zero)

Motivation: The Need for Direct Probes of CP Violation

- Many indirect constraints on CPV:
  - Constraints from EWPD
  - Measurements of $h \to SM$ decay rates
  - The most severe constraints come from EDMs
- But all of these are indirect and rely on model dependent assumptions

Even here you need to close the circle, since EDM constraints assume 1st gen Higgs couplings that you can't measure

γ operator:
already severely constrained by e and q EDMs
McKeen, Pospelov, Ritz '12



- Can parametrize the *hVV′* couplings with following Lagrangian

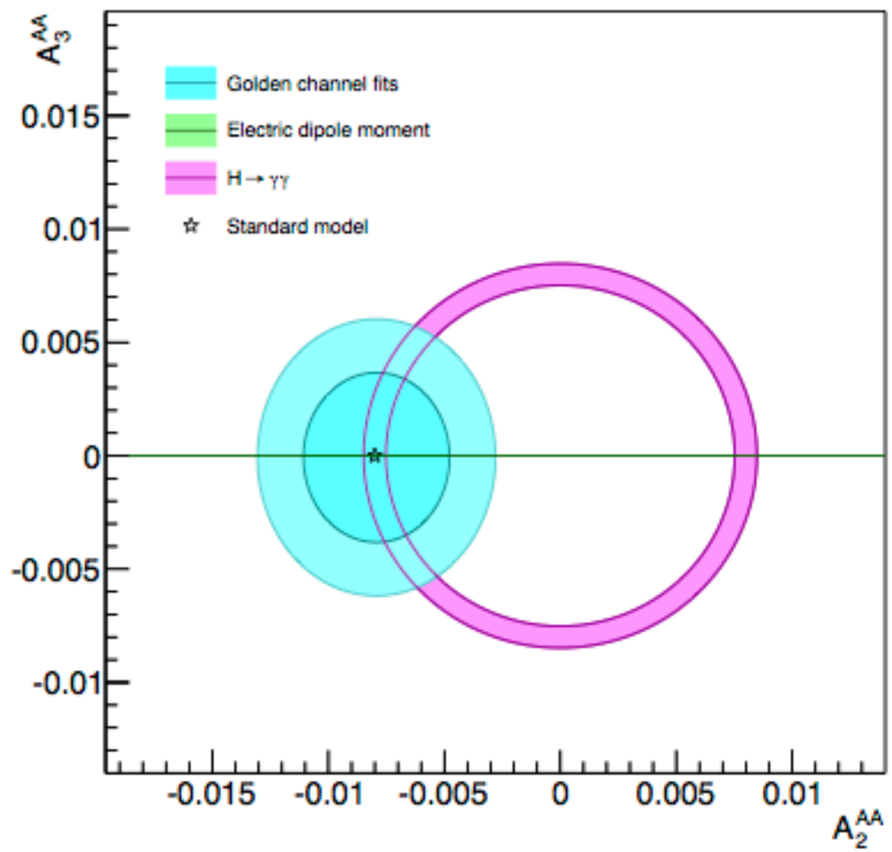
$$\mathcal{L} \supset \frac{h}{4v}\Big(2A_1^{ZZ} m_Z^2 Z^\mu Z_\mu + A_2^{ZZ} Z^{\mu\nu} Z_{\mu\nu} + A_3^{ZZ} Z^{\mu\nu}\tilde{Z}_{\mu\nu} + 2A_2^{Z\gamma} F^{\mu\nu} Z_{\mu\nu} + 2A_3^{Z\gamma} F^{\mu\nu}\tilde{Z}_{\mu\nu} + A_2^{\gamma\gamma} F^{\mu\nu} F_{\mu\nu} + A_3^{\gamma\gamma} F^{\mu\nu}\tilde{F}_{\mu\nu}\Big)$$

(For SM at tree level we have $A_1^{ZZ} = 2$ and all others zero)

Golden Channel vs. $h \to \gamma\gamma$ and EDMs: $\vec{A}_o = (0,0,0,0,-0.008,0)$

- What can be done with $\sim 3000 fb^{-1}$ in golden channel vs. $h \to \gamma\gamma$?

(Y. Chen, R. Harnick, RVM: arXiv:1404.1336)



- LHC should *directly* establish CP nature of Higgs couplings to $\gamma\gamma$!

The Custodial Nature of the Higgs Boson

- To a very good approximation, we have at tree level:

$$\rho_{tree} \equiv \frac{m_W^2}{c_W^2 m_Z^2} = 1$$

- Implies a 'custodial' global $SU(2)_C$ symmetry of the EW gauge boson mass matrix and Higgs scalar sector (P. Sikivie, L. Susskind, et. al (1980))

A W/Z boson transforms as a triplet under custodial symmetry, so a pair of W's or Z's transforms like:

$$\mathbf{3} \times \mathbf{3} = \mathbf{1} + \mathbf{3} + \mathbf{5}$$

Taking into account parity, custodial symmetry thus requires that any 0^+ boson that couples to WW/ZZ is either in a singlet or a 5-plet of $SU(2)_C$ (or a mixture)

- Custodial fiveplet can be found in custodial Higgs triplet models

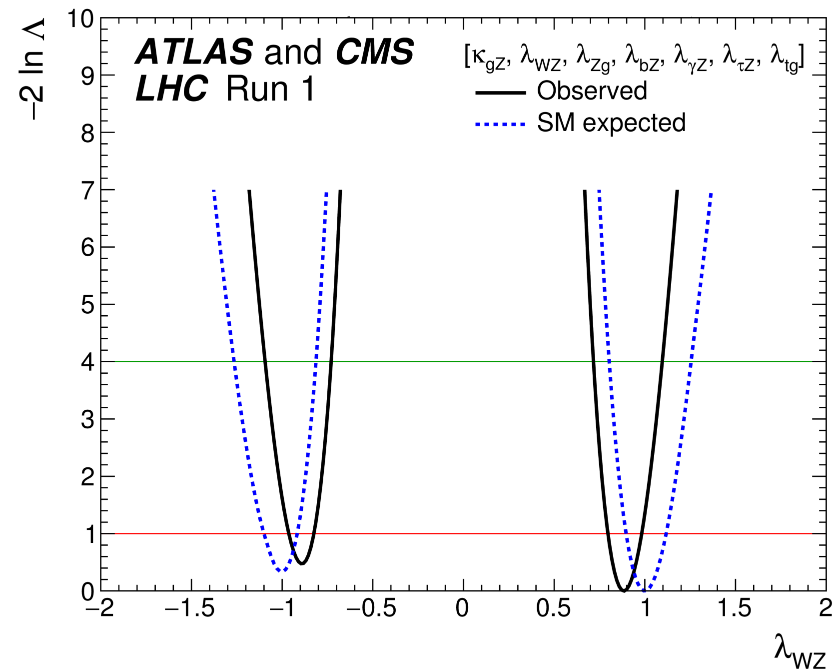
(H. Georgi and M. Machacek (1985), S. Gori, M. Quiros, et.al: 1308.4025, 1409.5737)

Nonstandard custodial properties affect both the magnitude and sign of $\lambda_{WZ} = g_W/g_Z$

$$\lambda_{WZ} = +1 \quad \text{(custodial singlet)}, \quad \lambda_{WZ} = -1/2 \quad \text{(custodial fiveplet)}$$

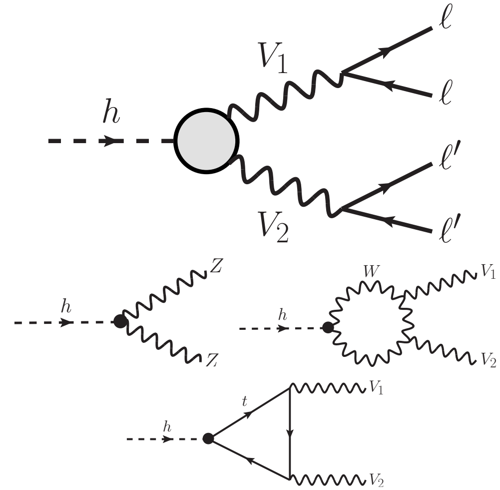
I. Low, JL, arXiv:1005.0872

ATLAS and CMS already constrain the magnitude of $\lambda_{WZ} = g_W/g_Z$ **but how can we measure tne sign?**



Loop effects in Higgs to four lepton decays

- The *W* and top loops contribute to effective hVV couplings which mediate $h \to 4\ell$ decays
- dominated by tree level hZZ mediated amplitude



- Can study the nature of the top and *W* couplings to the Higgs

(for study focusing on top couplings see Y. Chen, D. Stolarski, R. Vega-Morales: 1505.01168)

$$\mathcal{L}_{ZW} \supset \frac{h}{v}\Big(g_Z m_Z^2 Z^\mu Z_\mu + 2 g_W m_W^2 W^{\mu+} W_\mu^-\Big)$$

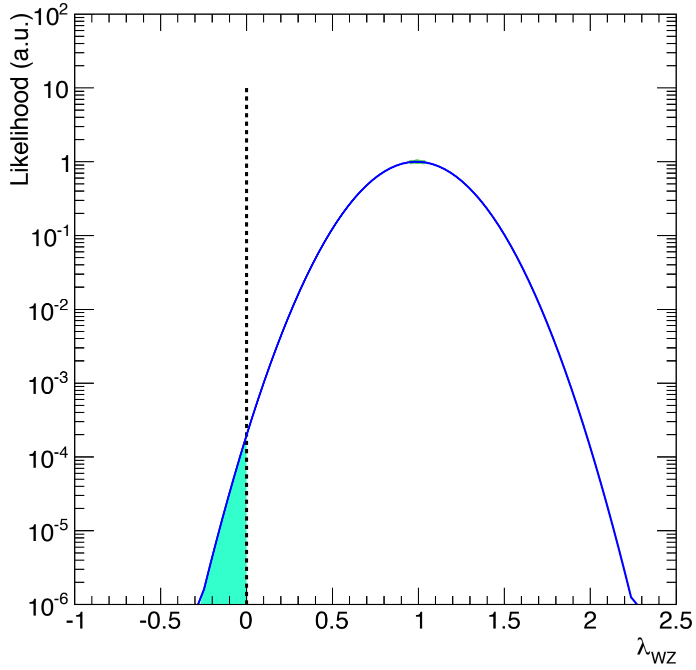
$$\mathcal{L}_t \supset \frac{m_t}{v} h\bar{t}(y_t + i\tilde{y}_t\gamma^5)t$$

- Interference between tree level hZZ amplitude and loop diagrams allows us to probe top CP properties and the ratio $\lambda_{WZ} = g_W/g_Z$

Pinning the Sign Down at the LHC

- Can perform a likelihood shape analysis to perform a 'sign test'

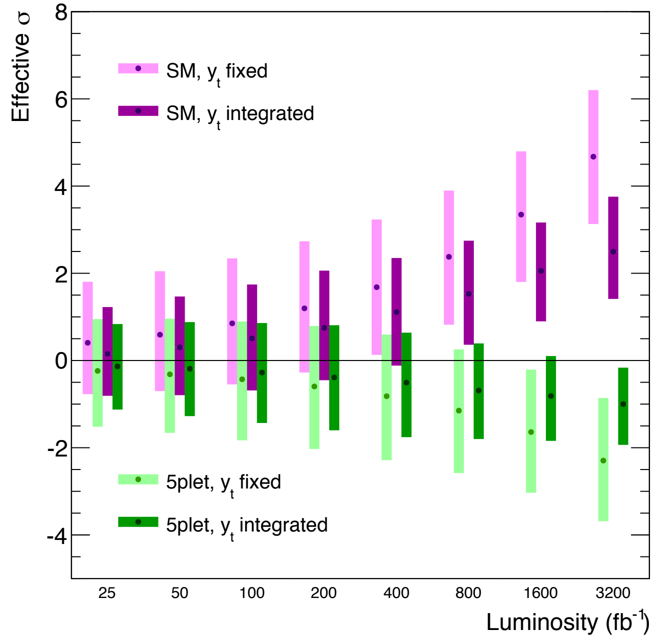
(Y. Chen, J. Lykken, M. Spiropulu, D. Stolarski, R. Vega-Morales: 1608.02159)



Pinning the Sign Down at the LHC

- Crucially, can establish the sign independently of top quark sector

(Y. Chen, J. Lykken, M. Spiropulu, D. Stolarski, R. Vega-Morales: 1608.02159)



- Does not rely on combining multiple measurements to establish sign
- Rate information not used in likelihood ⇒ largely independent of production uncertainties

Conclusion

- There is a lot more that can be done with the Higgs golden channel, and many groups are exploring the possibilities
- The prospect of measuring Higgs interference effects directly at HL-LHC is exciting
- This prospect relies on maintaining detector performance through the high luminosity era