HIGGS LOOK-ALIKES AT THE LHC

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OUTLINE

- Higgs look-alikes: nonstandard spin and CP
- Higgs look-alikes: nonstandard electroweak but custodially symmetric
- Higgs look-alikes: nonstandard everything

References:

Higgs look-alikes:

- Alvaro De Rujula, J.L., Maurizio Pierini, Chris Rogan, Maria Spiropulu, arXiv:1001.5300
- Y. Gao, A. Gritsan, Z. Guo, K. Melnikov, M. Schulz, N. V. Tran, arXiv:1001.3396
- Ian Low and J.L., arXiv:1005.0872

see also R. Lafaye, T. Plehn, M. Rauch, D. Zerwas, M. Duehrssen, arXiv:0904.3866
and Stephen Godfrey and Ken Moats, arXiv.1003.3033

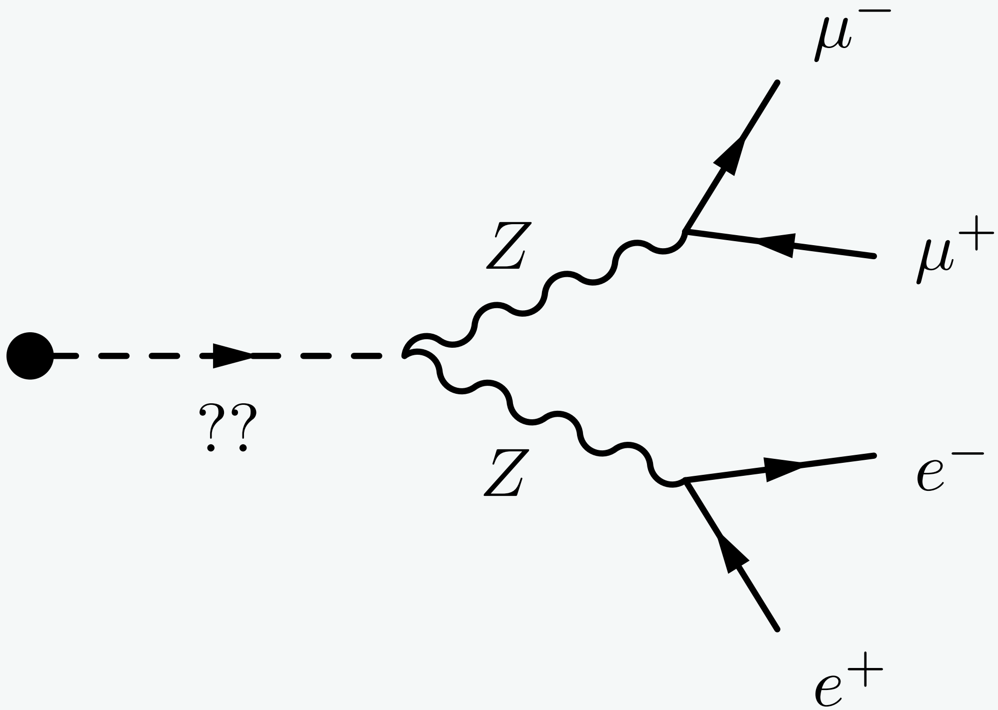
MSSM Higgs with general dimension 6 operators:

- Marcela Carena, K.C. Kong, Eduardo Ponton, Jose Zarita, arXiv:0909.5434, and TBA

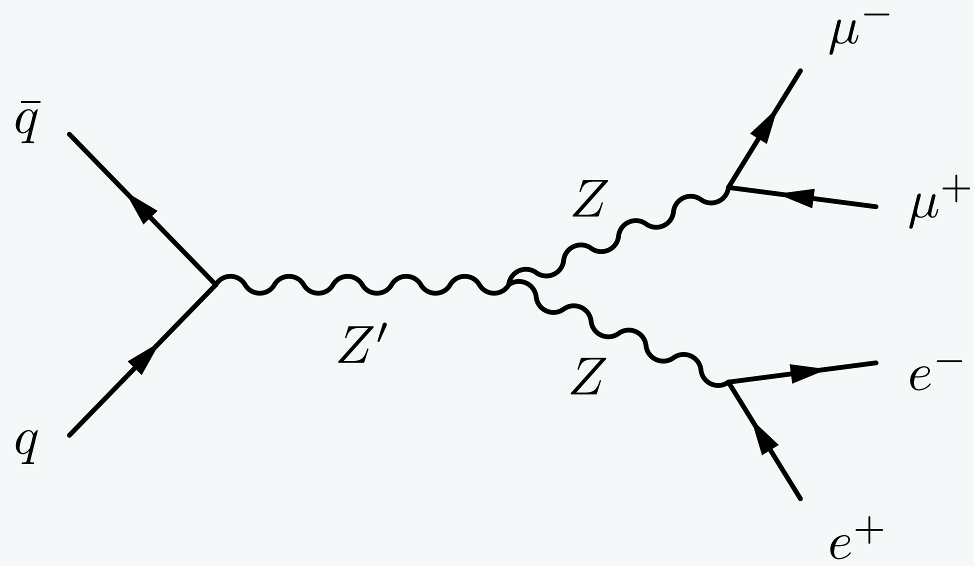
Higgs look-alikes

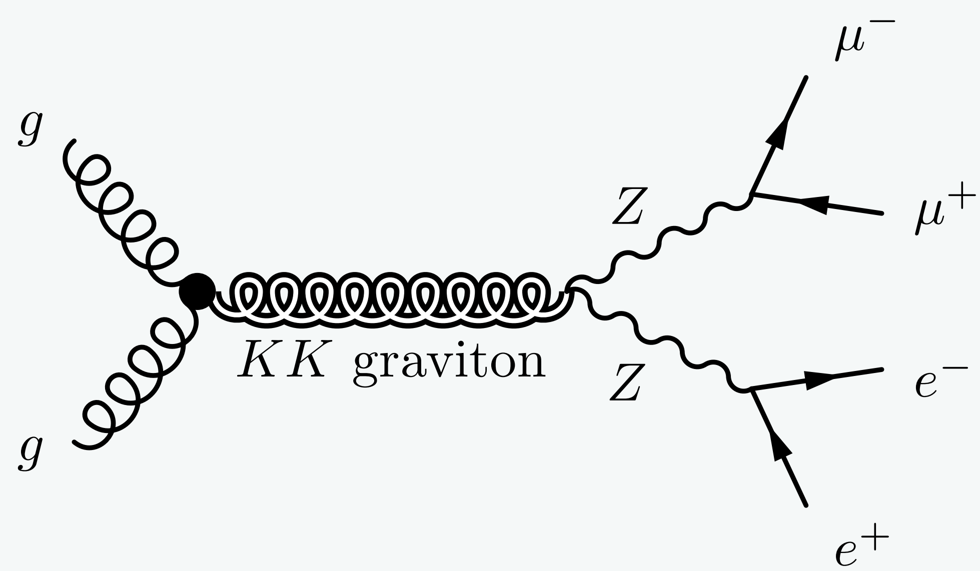
- **Suppose your favorite LHC experiment sees a resonant signal**

- **How do we determine that this is the neutral CP-even spin 0 component of a $(\mathbf{2_L}, \mathbf{2_R})$ of $\mathbf{SU(2)_L \times SU(2)_R}$ predicted by the Standard Model, or a look-alike?**



We need to exclude other spins, etc



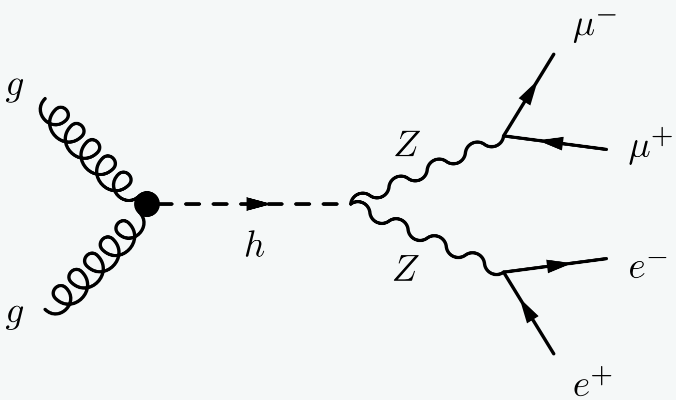


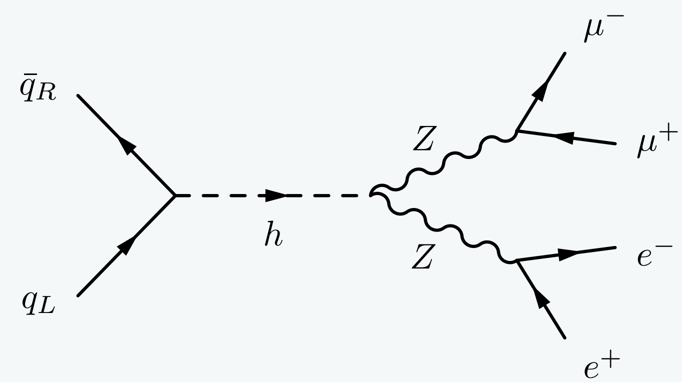
The post-discovery LHC Higgs challenge

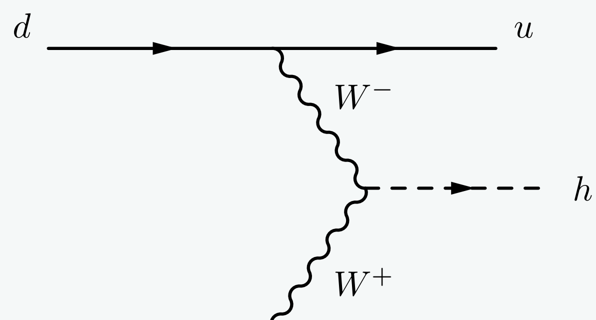
- **You have ~100 signal events that could be a Higgs**
- **How many Higgs look-alike candidates can you eliminate *at or around the time of discovery?***
- **A simpler question: How many Higgs look-alike candidates can you eliminate at or around the time of discovery *by looking at distributions and correlations in the 4 lepton final state?***

Factorizing the problem

- ☑ **Distributions and correlations in the 4 lepton final state**
- **Production (gluon fusion, VBF, ...)**
- **Correlations with signals (or lack of signals) in other channels**





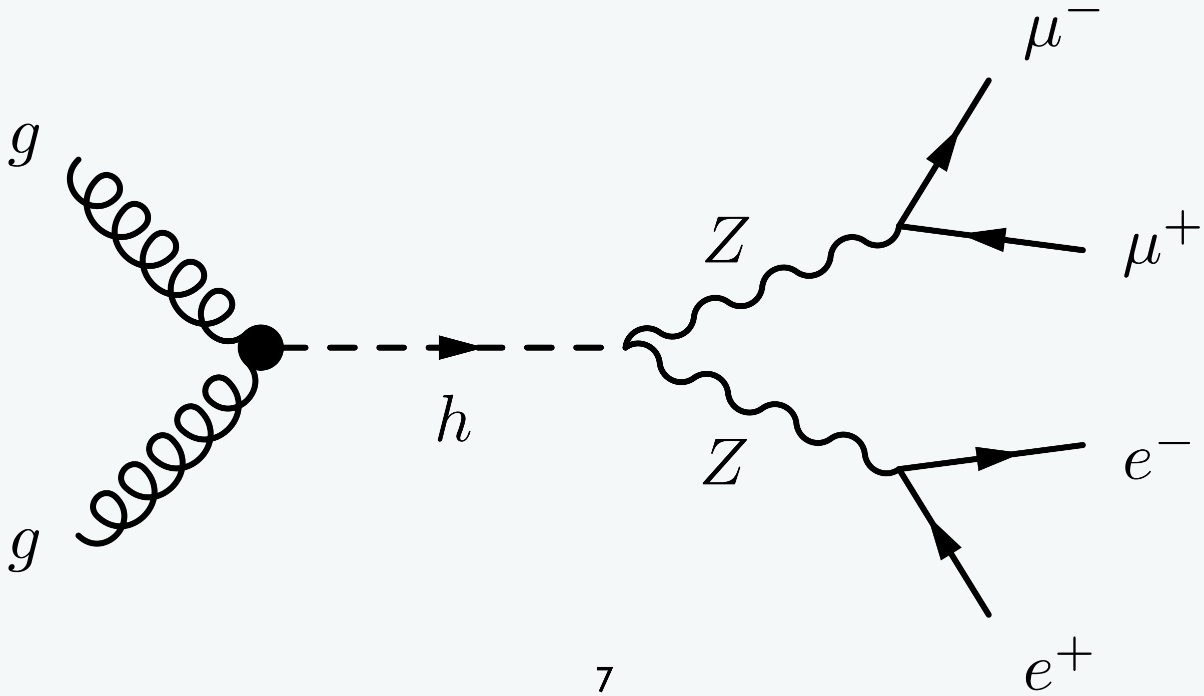


The golden Higgs channel at the LHC

- **The leptonic decay $\mathbf{h \to ZZ \to 4\ell}$ has a small branching fraction but provides a (relatively) clean and fully-reconstructable final state**

- **The Z bosons don't have to be on shell**

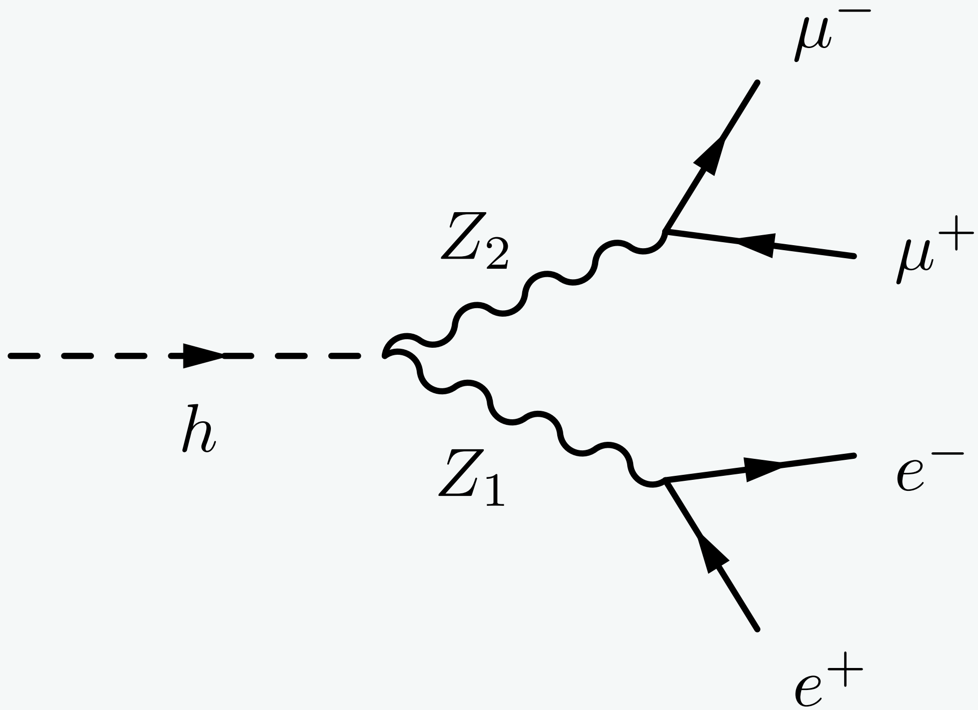
- **Relevant for SM Higgs mass above about ~ 130 GeV**



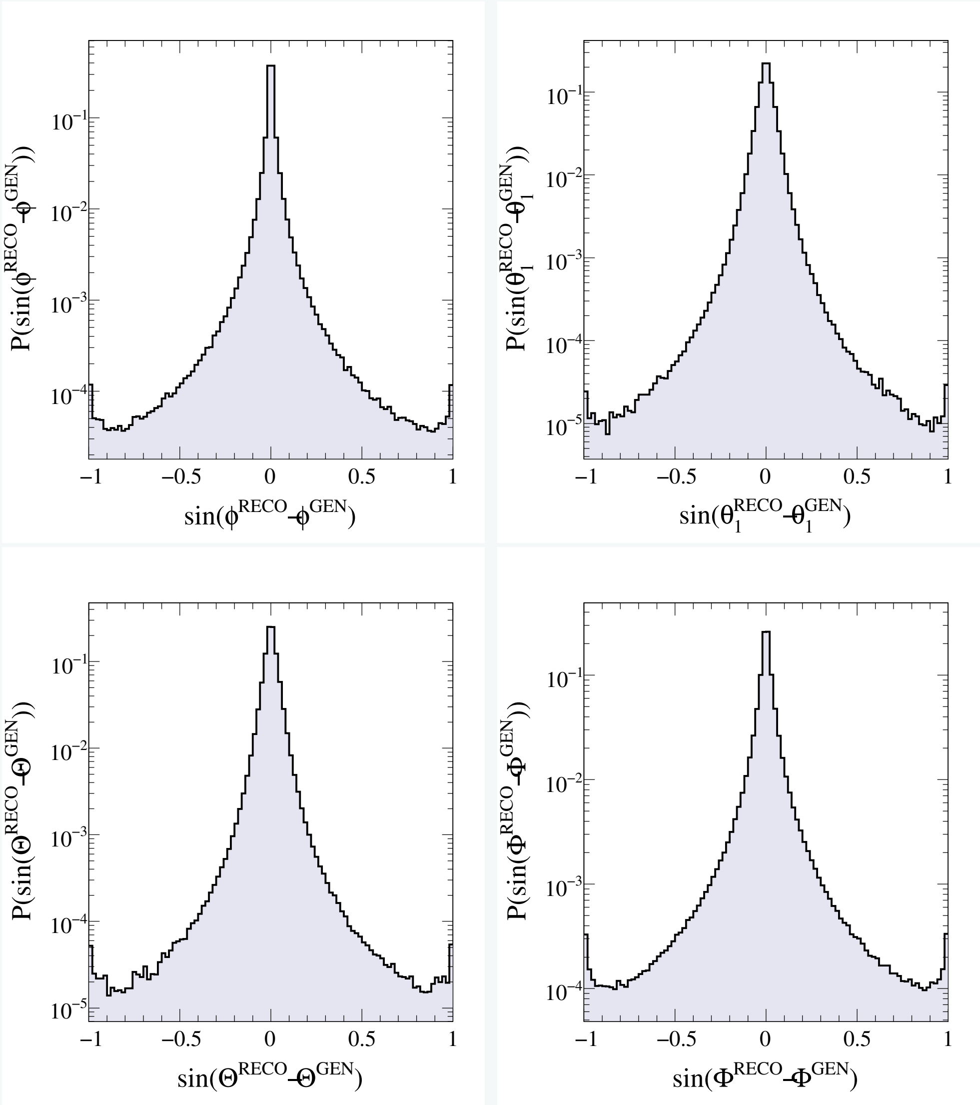
The 12 observables of the fully reconstructed event

- Treating the leptons as massless, there are 12 momentum components per event measured in the final state

- Each event is fully reconstructable in terms of these 12 observables



ATLAS and CMS can measure the 4-lepton final state with exquisite precision



So you can choose any basis you want for your 12 observables without losing experimental realism

The 12 observables of the fully reconstructed event

- To get from the lab frame to the Higgs rest frame, I need to specify a boost and the direction of the boost, which is given by two angles:

$$\gamma_\mathbf{h}, \theta_\mathbf{h}, \phi_\mathbf{h}$$

- I need to specify the reconstructed Higgs mass

$$\mathbf{M_h}$$

- In the Higgs rest frame, by convention, take the positive z-axis to be along the direction of motion of $\mathbf{Z_2}$, then use two angles to specify the direction of one of the incoming partons (note 2-fold ambiguity)

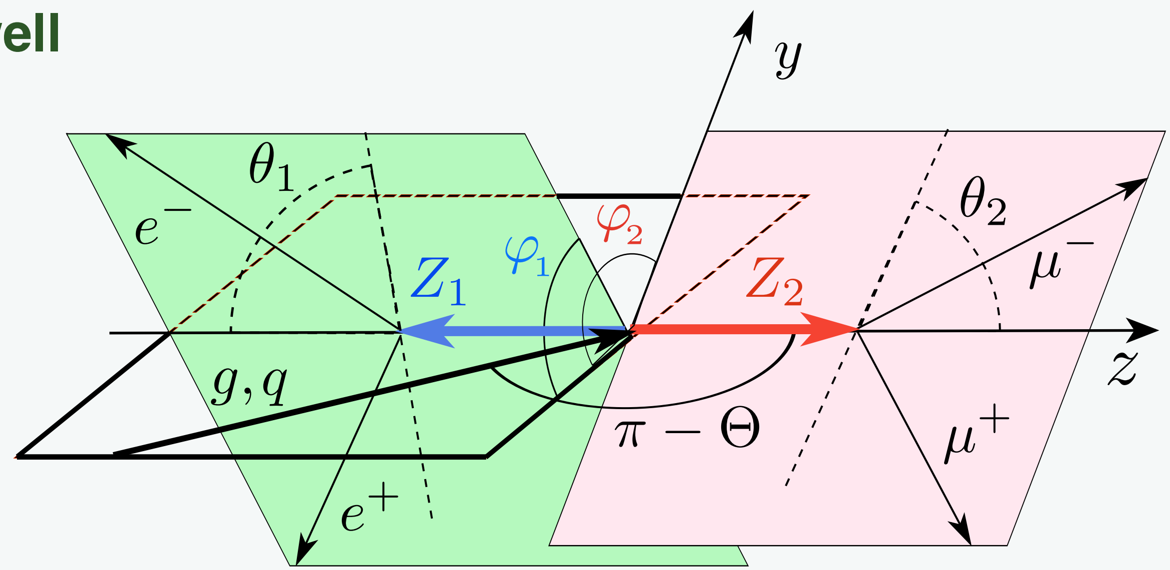
$$\boldsymbol{\Theta}, \; \boldsymbol{\Phi}$$

- Z decay involves another pair of angles measured in the Z rest frame, with the polar angle measured wrt the z-axis defined above. We also need the two boosts from the Higgs rest frame to the Z rest frames, γ_1, γ_2 , which is equivalent to specifying the (possibly off-shell) Z masses:

$$\mathbf{m_1}, \theta_\mathbf{1}, \phi_\mathbf{1}, \quad \mathbf{m_2}, \theta_\mathbf{2}, \phi_\mathbf{2}$$

8 angles!

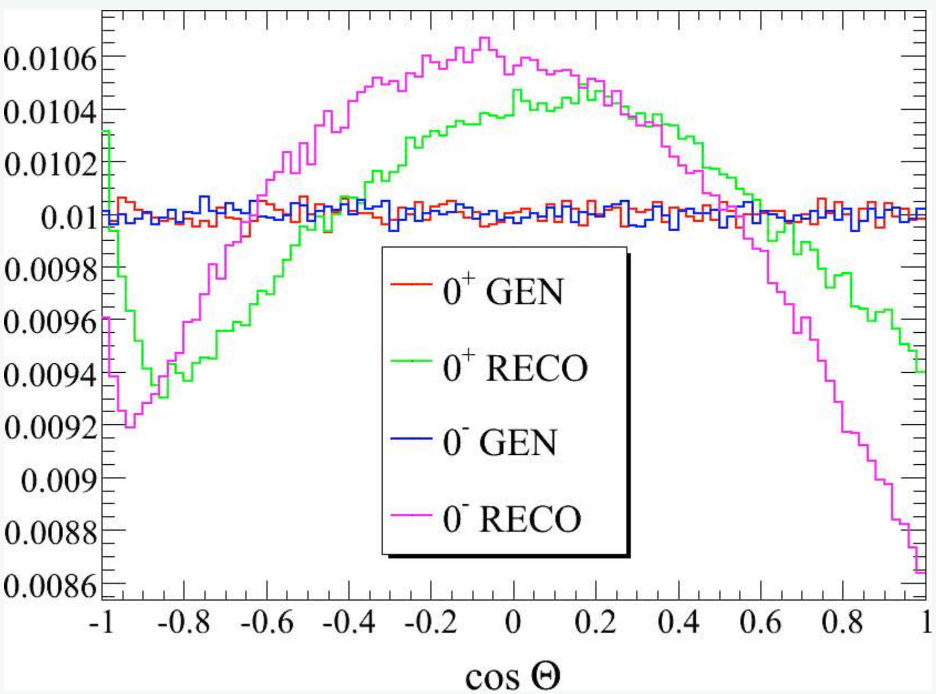
- **In the spirit of factorization, we will (for now) ignore the two production angles** $\theta_{\mathbf{h}},\ \phi_{\mathbf{h}}$
- **If the resonance is a spin 0 particle, the signal distribution will be isotropic (i.e. flat) in the** $\mathrm{h} \to \mathbf{ZZ}$ **angles** $\mathbf{\Theta},\ \mathbf{\Phi}$
- **Twenty-year-old common wisdom says that therefore we should ignore these angles as well**
- **Is this reasonable?**

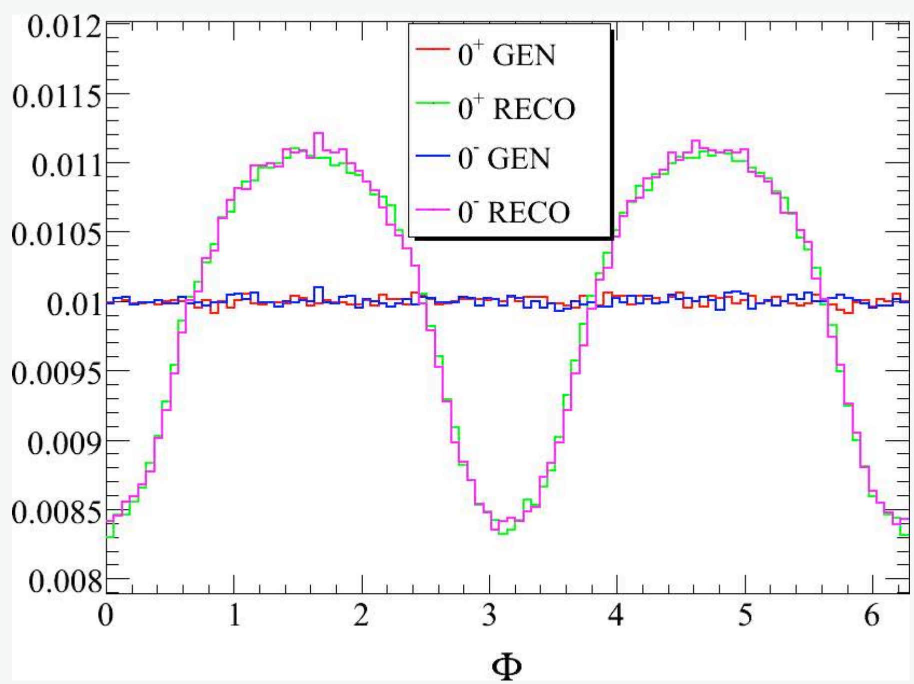


No!

- If we want to test that the Higgs is a Higgs, and not a higher spin look-alike, then we should use the $h \to ZZ$ angles Θ, Φ as discriminators

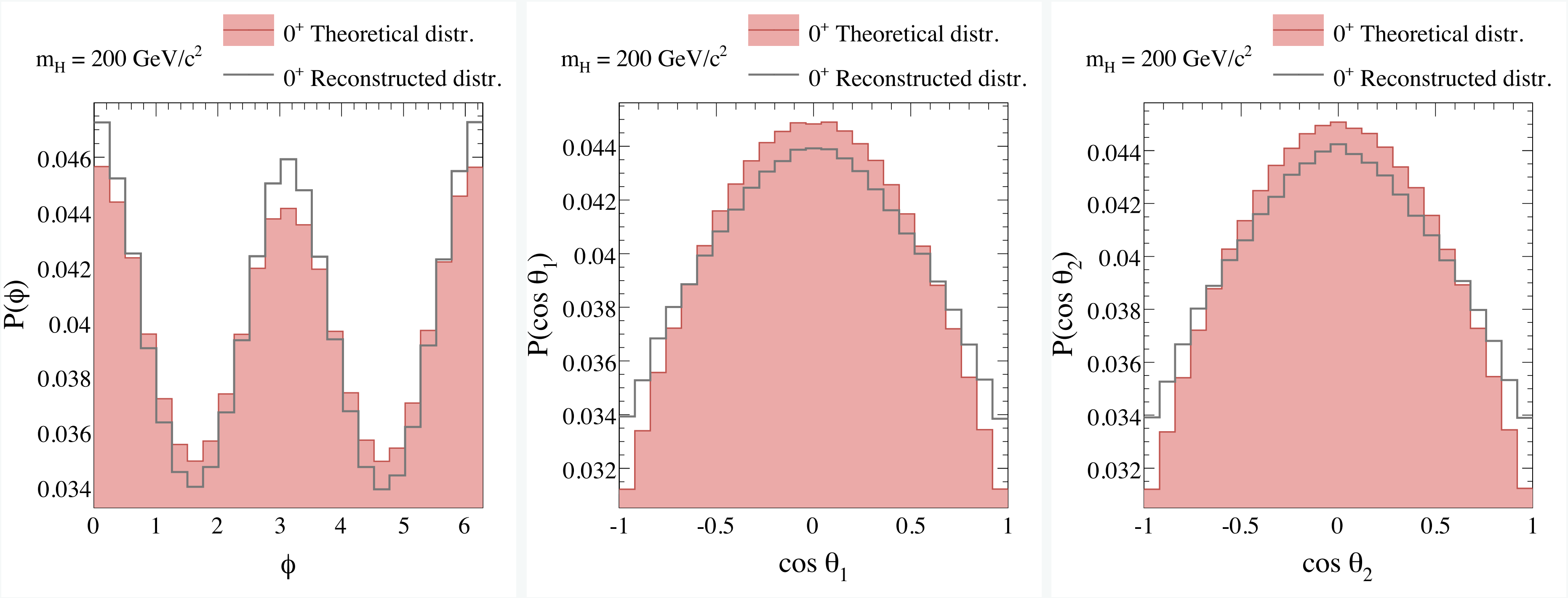
- Furthermore, even for the spin 0 case, it is NOT TRUE that the distributions are flat in these angles, after we take into account realistic detector effects:



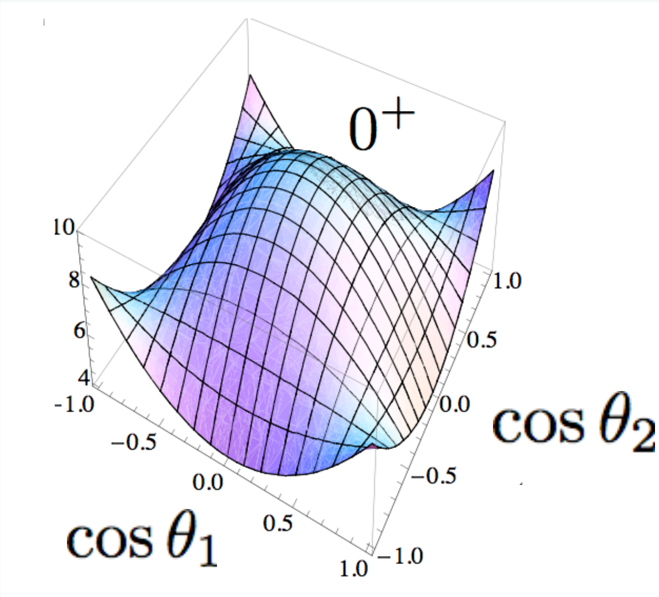


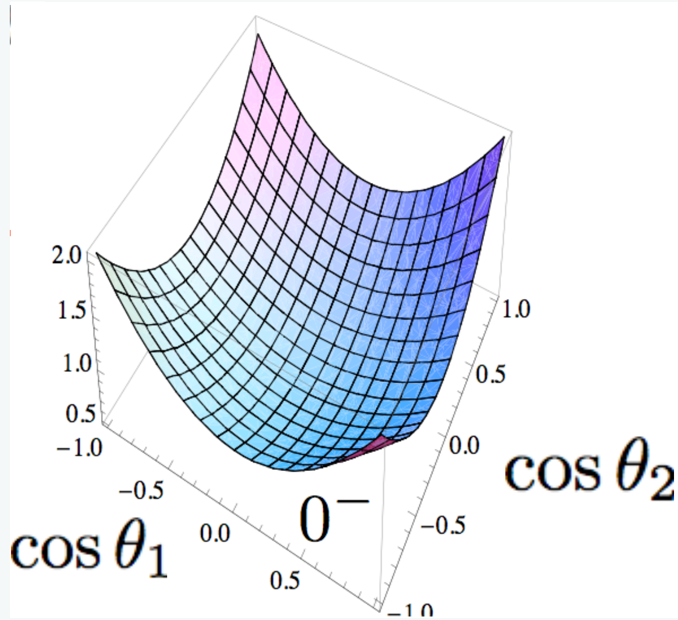
- **For the three nontrivial $\mathbf{ZZ \rightarrow \mu^- \mu^+ e^- e^+}$ decay angles θ_1, θ_2, ϕ, detector effects flatten the polar distributions slightly and sharpen the azimuthal distribution slightly**

- **Higher order corrections have similar (computable) effects**

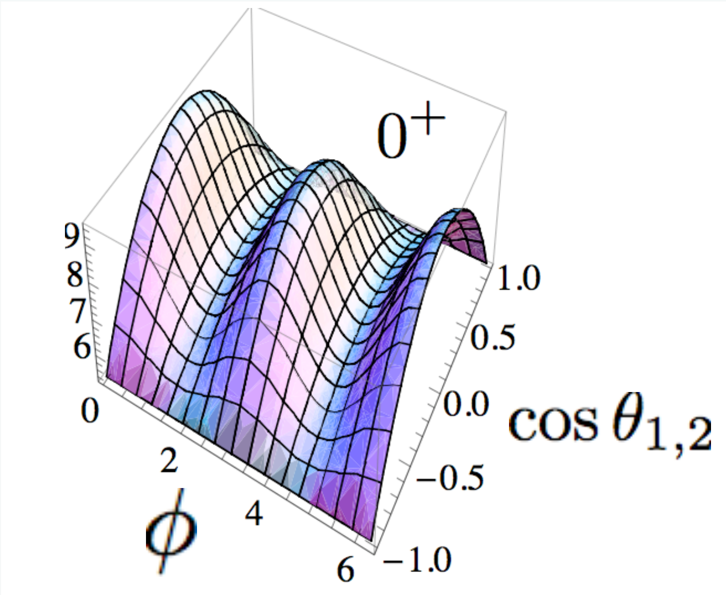


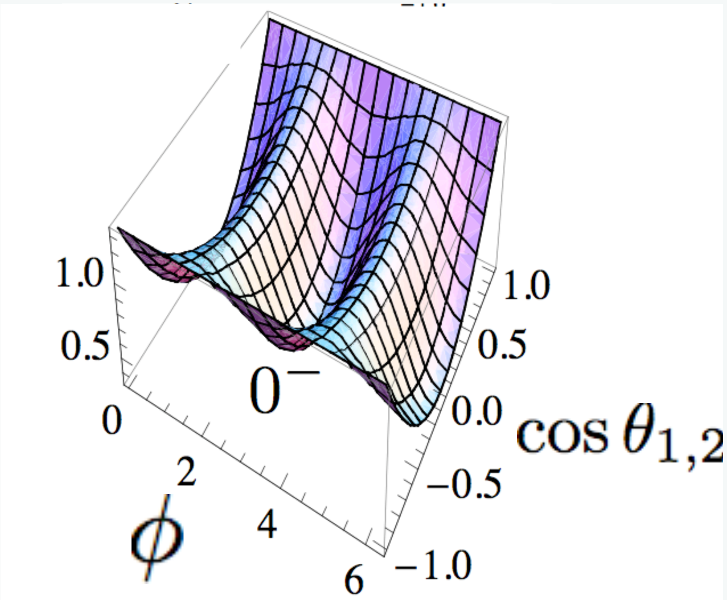
Correlations are important





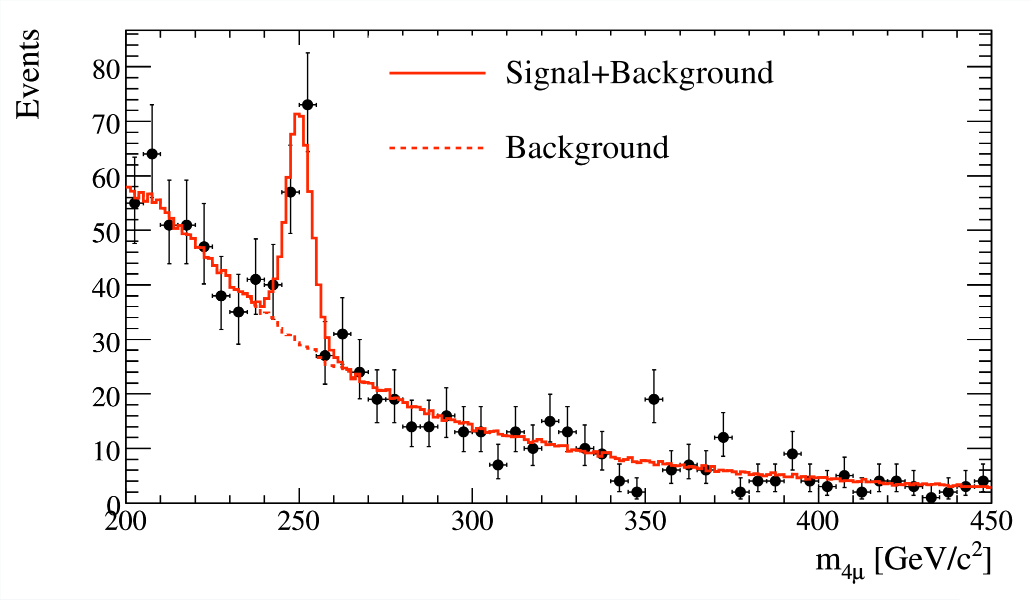
$m_H = 200$ GeV

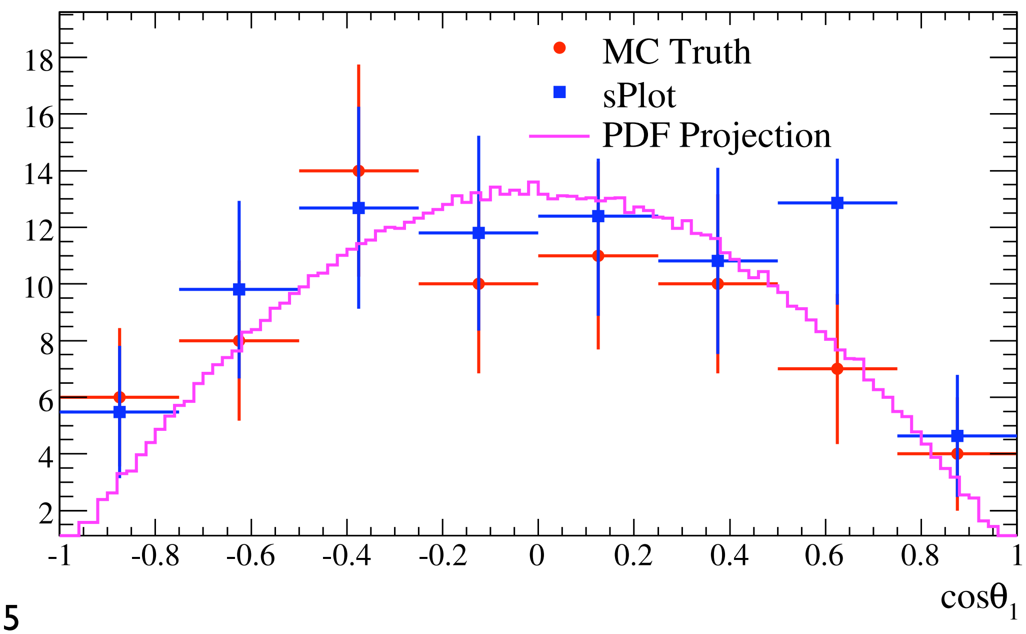




What about the backgrounds?

- Although there is a fairly large irreducible background from ZZ production, this can be “subtracted” using a fit+weighting scheme called sPlots





General couplings of Higgs Look-alikes to ZZ

- Allow couplings up to dimension 6
- Allow spin 0, 1, 2, and all possible C and P
- Note includes derivative couplings as would occur e.g. from expanding the form factor of a composite spin 0

$$\mathbf{L^0_{\mu\nu} = X\, g_{\mu\nu} - (Y + iZ)\frac{p^h_\mu p^h_\nu}{M_Z^2} + (P + iQ)\epsilon_{\mu\nu\rho\sigma}\frac{p_1^\rho p_2^\sigma}{M_Z^2}}$$

$$\mathbf{L_1^{\mu\nu\rho} = X(g^{\mu\nu}p_1^\rho + g^{\mu\rho}p_2^\nu) + (P + iQ)\epsilon^{\mu\nu}_{\rho\sigma}(p_1^\sigma - p_2^\sigma)}$$

$$\mathbf{L_2^{\mu\nu\rho\sigma} = M_h^2\, X_0\, g^{\mu\rho}g^{\nu\sigma} + (X_1 + iY_1)(p_1^\nu p_2^\rho g^{\sigma\mu} + p_2^\mu p_1^\rho g^{\sigma\nu})}$$
$$\mathbf{+(X_2 + iY2)g^{\mu\nu}p_1^\rho p_2^\sigma + (P + iQ)\epsilon^{\rho\mu\nu}_\alpha(p_1^\alpha p_2^\sigma - p_2^\alpha p_1^\sigma)}$$

fully-differential decay widths (tree level)

- **SM Higgs**

$$\frac{d\Gamma[0^+]}{dc_1\,dc_2\,d\phi} \propto m_1^2\,m_2^2\,m_H^4\Big[1+c_1^2c_2^2+(\gamma_b^2+c^2)s_1^2s_2^2$$
$$+2\gamma_a\,c\,s_1s_2\,c_1c_2+2\eta^2(c_1c_2+\gamma_a\,c\,s_1s_2)\Big]\,. \qquad (14)$$

- **pure 1-**

$$4m_1^2m_2^2X^2\gamma_b^2\Big[g_1S^2s_1^2s_2^2\left(2\ell_0^2m_d^4-\ell^2m_H^2\left[m_1^2\cos(2\varphi_1)+m_2^2\cos(2\varphi_2)\right]\right)$$
$$+g_1\ell^2m_H^2(1+C^2)\left[2m_2^2s_1^2+2m_1^2s_2^2-(m_1^2+m_2^2)s_1^2s_2^2\right]+4\ell\ell_0g_1m_Hm_d^2\,C\,S\left[m_1c_1s_1s_2^2\sin\varphi_1-m_2c_2s_2s_1^2\sin\varphi_2\right]$$
$$-2\ell^2m_H^2m_1m_2s_1s_2\left((1+C^2)(g_1c_1c_2-g_{\sigma\sigma})\cos(\varphi_1-\varphi_2)+S^2(g_1c_1c_2+g_{\sigma\sigma})\cos(\varphi_1+\varphi_2)\right)\Big]\,.$$

- **pure 1+**

$$P^2\Big[\ell^2g_1m_H^2S^2s_1^2s_2^2\left[M_2^4m_1^2\cos(2\varphi_1)+M_1^4m_2^2\cos(2\varphi_2)\right]$$
$$+8\ell_0^2m_1^2m_2^2m_d^4S^2\left[g_1\left(c_1^2+c_2^2+s_1^2s_2^2\sin(\varphi_1-\varphi_2)^2\right)+2g_{\sigma\sigma}c_1c_2\right]$$
$$+(1+C^2)\ell^2g_1m_H^2\left[2M_1^4m_2^2s_1^2+2M_2^4m_1^2s_2^2-(M_2^4m_1^2+M_1^4m_2^2)s_1^2s_2^2\right]$$
$$-8\ell\ell_0m_Hm_d^2m_1m_2C\,S\left[M_2^2m_1s_2\left(g_1c_2s_1^2\sin\varphi_1\cos(\varphi_1-\varphi_2)+c_1(g_1c_1c_2+g_{\sigma\sigma})\sin\varphi_2\right)\right.$$
$$\left.-M_1^2m_2s_1\left(g_1c_1s_2^2\sin\varphi_2\cos(\varphi_1-\varphi_2)+c_2(g_1c_1c_2+g_{\sigma\sigma})\sin\varphi_1\right)\right]$$
$$+2\ell^2m_H^2M_1^2M_2^2m_1m_2s_1s_2\left[(1+C^2)(g_1c_1c_2-g_{\sigma\sigma})\cos(\varphi_1-\varphi_2)-S^2(g_1c_1c_2+g_{\sigma\sigma})\cos(\varphi_1+\varphi_2)\right]\Big]\,.$$

Hypothesis testing with likelihood ratios

- Statistical approach - Neyman-Pearson hypothesis test:
  - Each ‘experiment’ corresponds to some number of observed signal events, N
  - Each event, i, corresponds to a set of observables, $\vec{X}_i$
  - Construct likelihoods for the two different hypotheses based on the multidimensional PDF’s P_{0+} and P_{0-}

$$\mathcal{L}_{0+} = \prod_{i}^{N} P_{0+}(\vec{X}_i) \qquad \mathcal{L}_{0-} = \prod_{i}^{N} P_{0-}(\vec{X}_i)$$

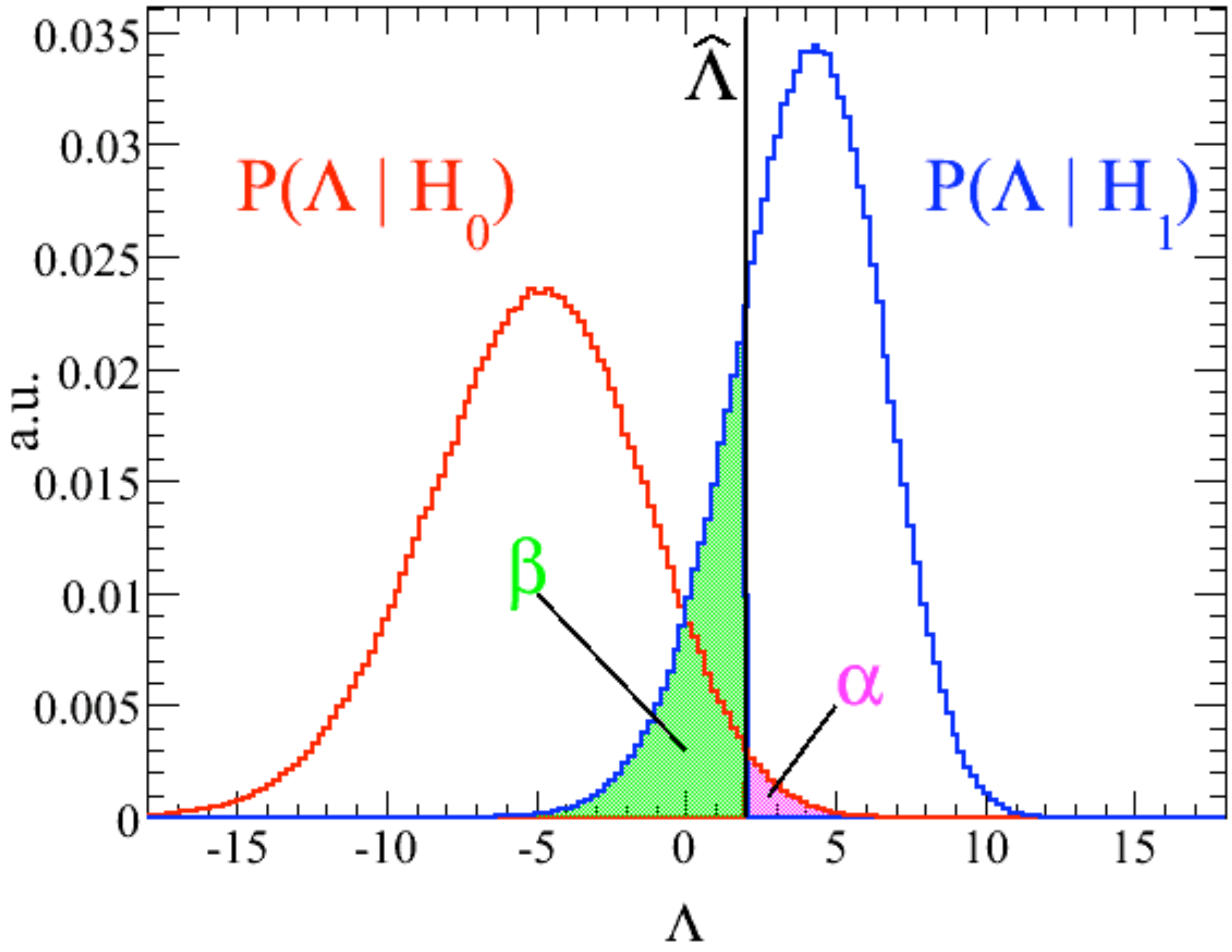
  - Construct a test-statistic based on those likelihoods

$$\Lambda = \log\left(\mathcal{L}_{0+}/\mathcal{L}_{0-}\right)$$

Hypothesis testing with likelihood ratios

$$H_0 = 0^- \quad H_1 = 0^+ \quad \Lambda = \log\left(\mathcal{L}_{0+}/\mathcal{L}_{0-}\right)$$

Neyman-Pearson (NP) simple hypothesis test



Risk of the 1st type:

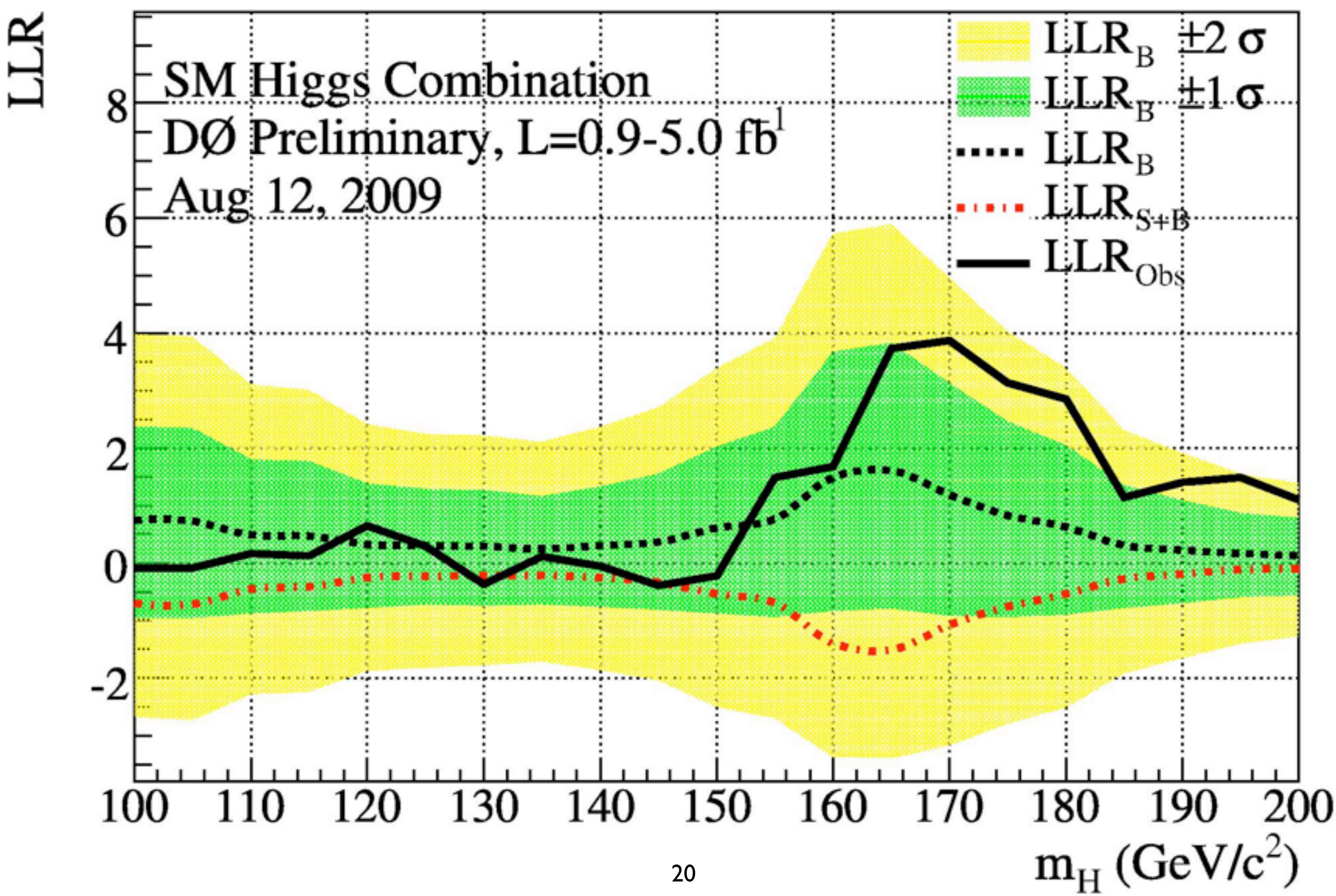
$$\alpha = \int_{\hat{\Lambda}}^{\infty} P(\Lambda|H_0)d\Lambda$$

Risk of the 2nd type:

$$\int_{-\infty}^{\hat{\Lambda}} P(\Lambda|H_1)d\Lambda = \beta$$

Power of the test: $1-\beta$

Example of hypothesis testing: Higgs or no Higgs?



Example: 0^+ vs. 0^-

- Consider the case when we are trying to distinguish between 0^+ vs. 0^- resonances:

$$\gamma_a = \frac{1}{2m_1 m_2}\left[m_H^2 - m_1^2 - m_2^2\right]$$

$$\cos\theta_i = c_i,\ \sin\varphi = s$$

$$\eta \equiv \frac{2\, c_v\, v_a}{(c_v^2 + c_a^2)} \approx 0.15$$

The standard Higgs, $J^{PC} = 0^{++}$

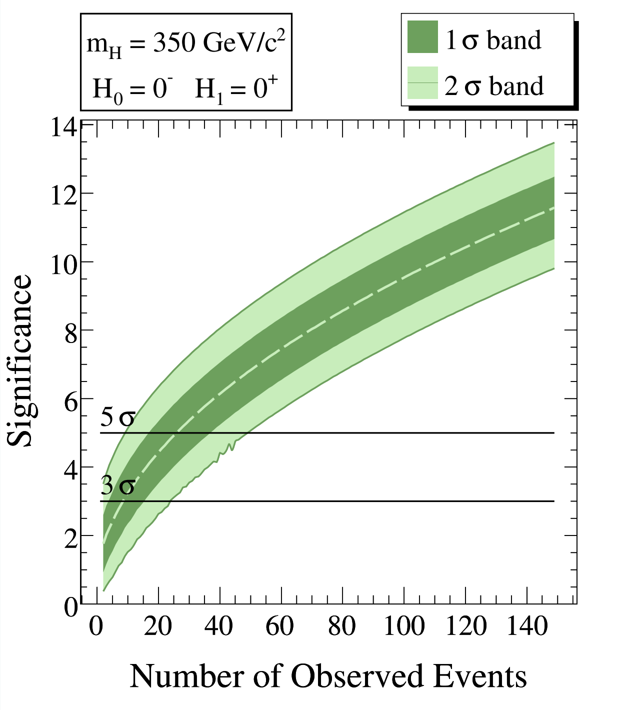
$$|\mathcal{M}[0^+]|^2 \equiv \frac{d\Gamma[0^+]}{dc_1\, dc_2\, d\varphi} \propto m_1^2\, m_2^2$$
$$\{2\,(c_1 c_2 + c\, s_1 s_2 \gamma_a)\,\eta^2 + s_1^2 s_2^2 \gamma_a^2$$
$$+\frac{1}{2}\left[\left(2\, c^2 - 1\right)\, s_1^2 s_2^2 + \left(c_1^2 + 1\right)\left(c_2^2 + 1\right)\right]$$
$$+2\, c\, c_1 c_2 s_1 s_2 \gamma_a\}$$

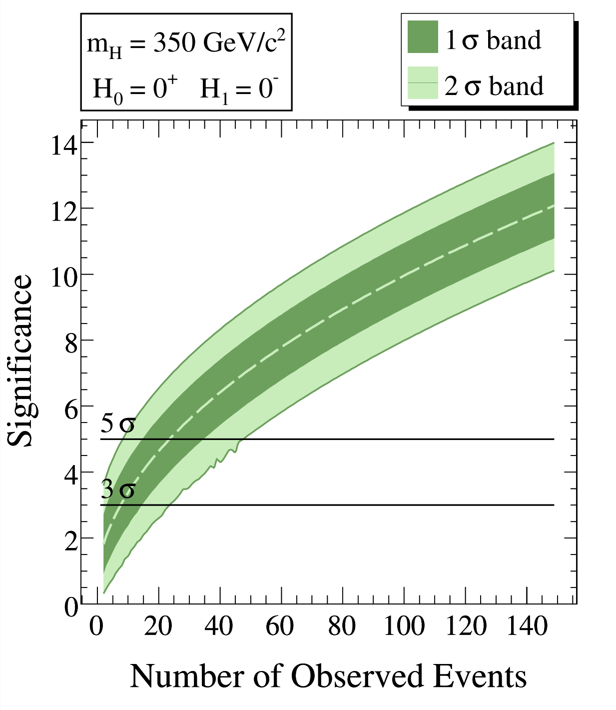
VS

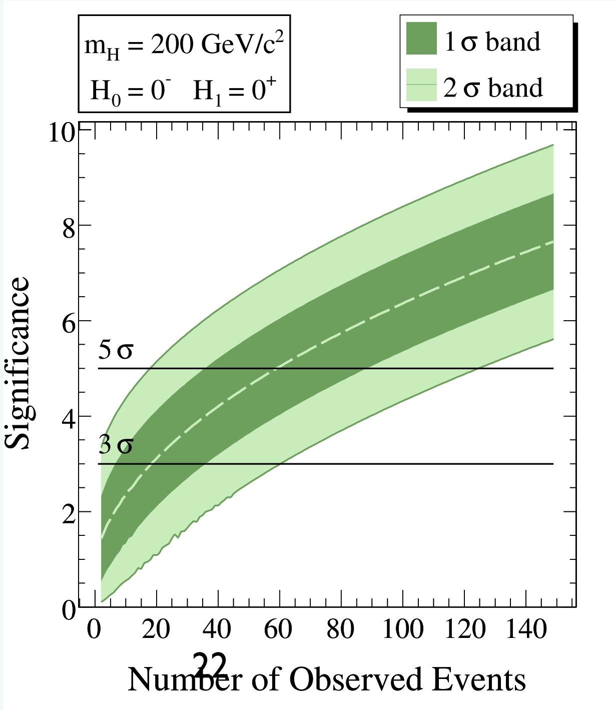
A pure pseudoscalar, $J^{PC} = 0^{-+}$

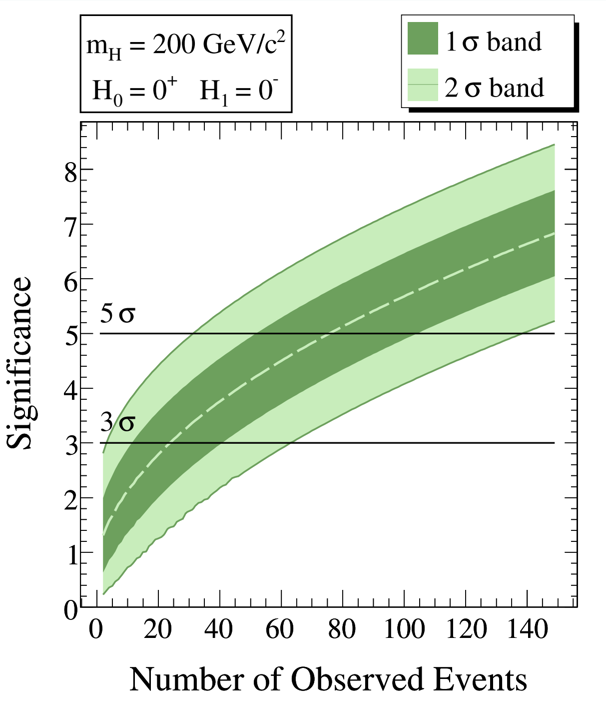
$$|\mathcal{M}[0^-]|^2 \equiv \frac{d\Gamma[0^-]}{dc_1\, dc_2\, d\varphi} \propto m_1^4\, m_2^4\, \gamma_b^2$$
$$\left(c_1^2 c_2^2 + 2\,\eta^2\, c_1 c_2 - c^2 s_1^2 s_2^2 + 1\right)$$

Simple hypothesis test results, 0+ versus 0-









0+ versus a little bit of mixed CP

$$\mathcal{L}_{\mu\alpha} \propto \cos(\xi_{XP})\, g_{\mu\alpha} + \sin(\xi_{XP})\, \epsilon_{\mu\alpha p_1 p_2}/M_Z^2$$

how small an admixture can I exclude when in fact it is an SM Higgs?

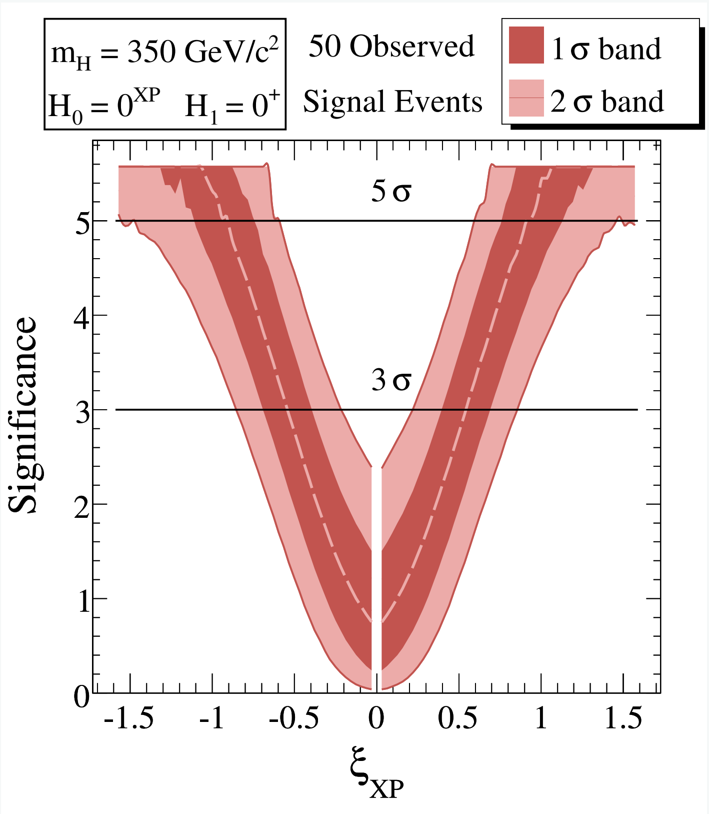


FIG. 37: Significance for excluding values of ξ_{XP} in the CP-violating J=0 hypothesis in favor of the 0^+ one, assumed to be correct, for m_H=350 GeV/c^2 and N_S=50. The dashed line corresponds to the median of the significance. The 1 and 2 σ bands correspond to 68% and 95% confidence intervals centered on the median value.

how large does the admixture have to be before I will be able to exclude the SM?

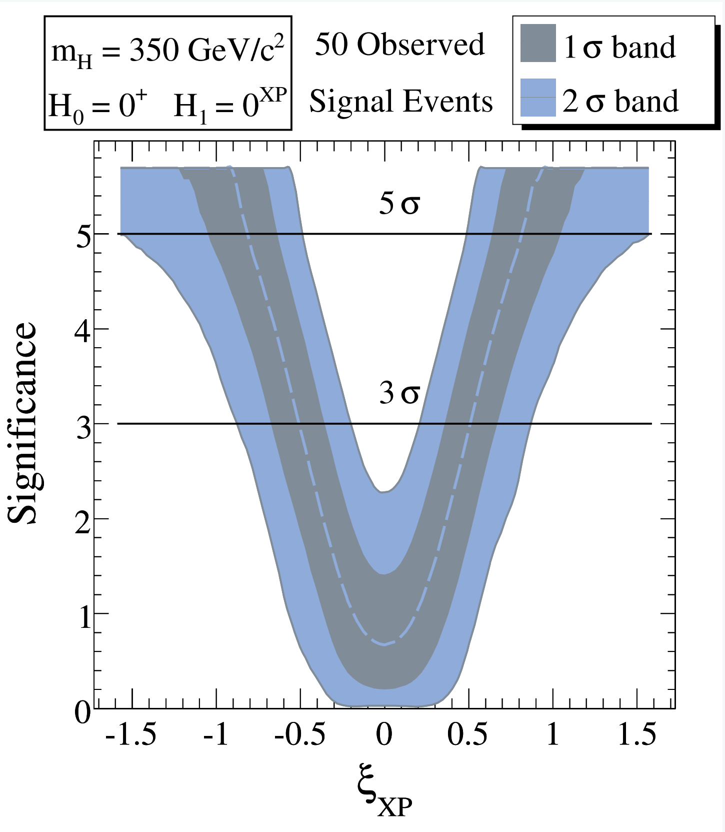
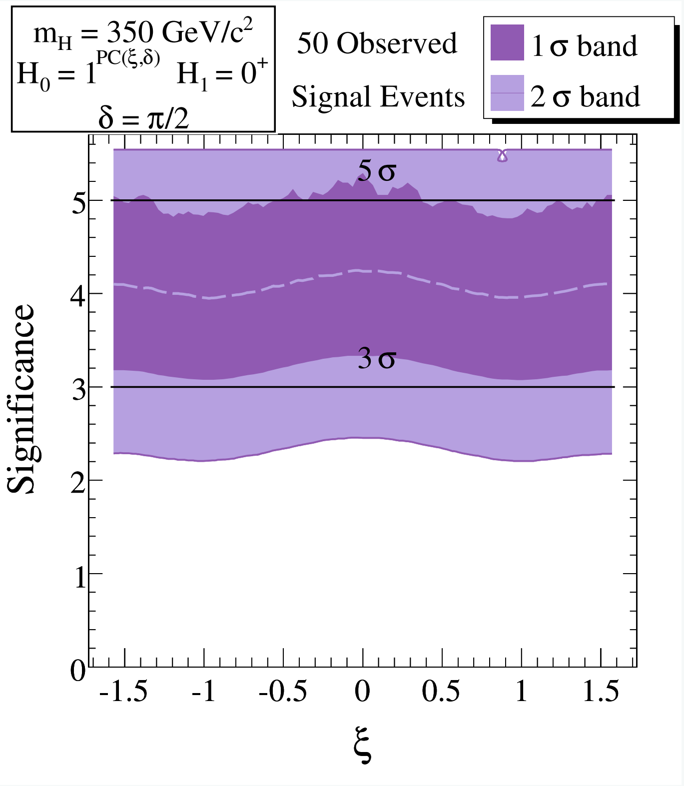


FIG. 38: The significance for excluding a pure 0^+ in favor of a CP-violating HZZ coupling ($\xi_{XP} \neq 0$), assuming the latter to be correct, with ξ_{XP} given by its x-axis values. Example for N_S=50, m_H=350 GeV/c^2. Dashed line and bands as in Fig. 37.

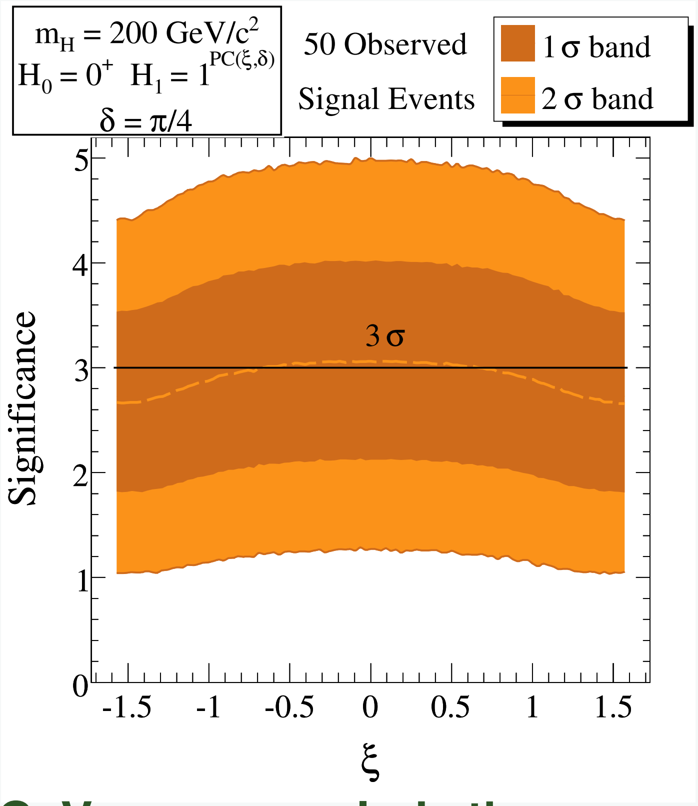
0+ versus any possible spin 1 look-alike

$$\mathcal{L}^{\rho\mu\alpha} \propto \cos\xi\,(g^{\rho\mu}p_1^{\alpha} + g^{\rho\alpha}p_2^{\mu}) + e^{i\delta}\sin\xi\,\epsilon^{\rho\mu\alpha}(p_1 - p_2)$$

how well do I exclude arbitrary spin 1 when in fact I have a SM Higgs?



how well do I exclude an SM Higgs when in fact I have some arbitrary spin 1?



for SM Higgs masses (145, 200, 350) GeV we can exclude the general spin 1 hypothesis at 5 sigma with (60, 200, 85) signal events

discriminating Higgs look-alikes at the moment of discovery

- **number of signal events required for (median) 3 sigma discrimination:**

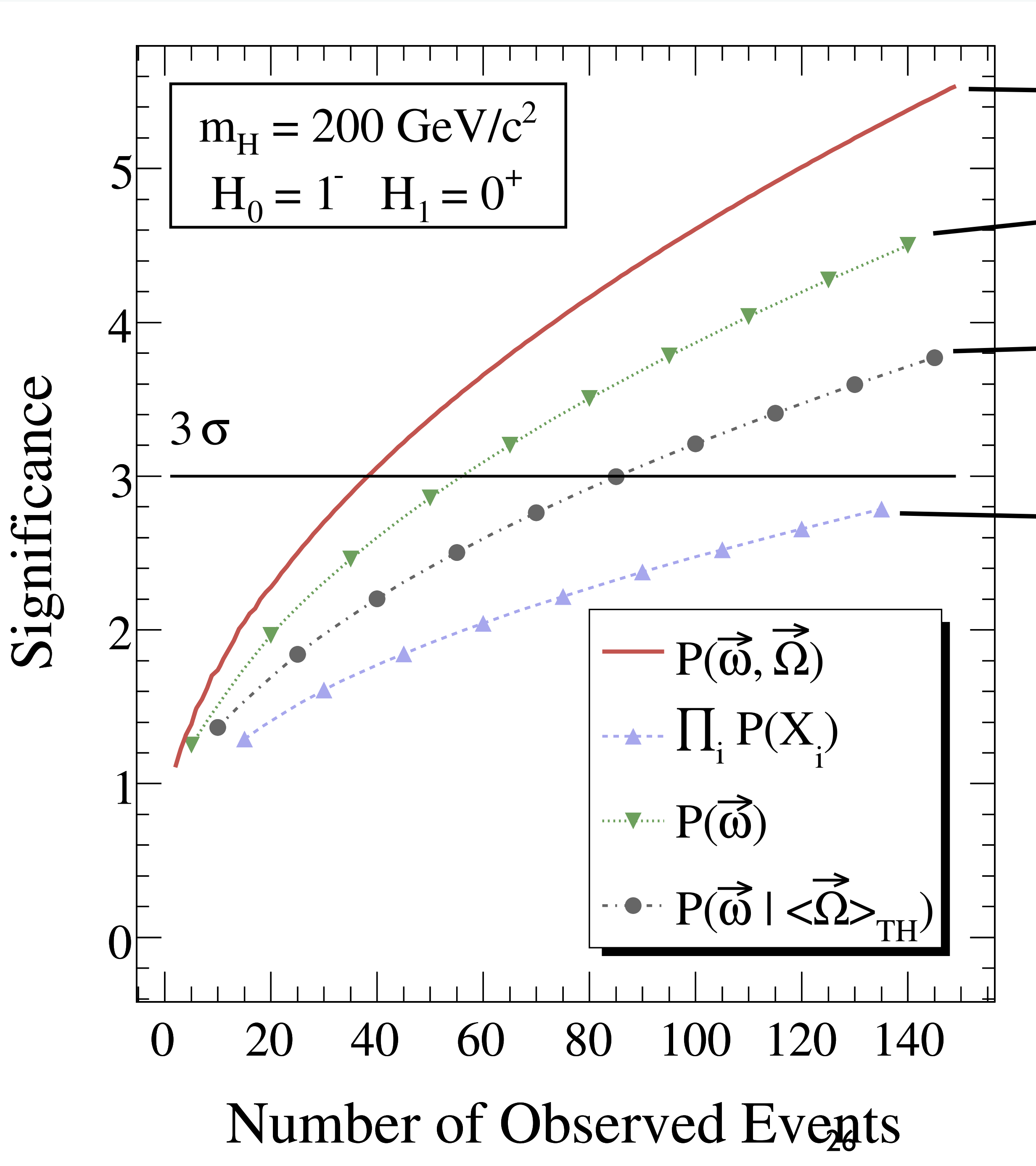
$\mathbb{H}_0 \Downarrow \mathbb{H}_1 \Rightarrow$	0^+	0^-	1^-	1^+
0^+	–	17	12	16
0^-	14	–	11	17
1^-	11	11	–	35
1^+	17	18	34	–

TABLE I: Minimum number of observed events such that the median significance for rejecting $\mathbb{H}_0$ in favor of the hypothesis $\mathbb{H}_1$ (assuming $\mathbb{H}_1$ is right) exceeds $3\,\sigma$ with m_H=145 GeV/c^2.

$\mathbb{H}_0 \Downarrow \mathbb{H}_1 \Rightarrow$	0^+	0^-	1^-	1^+	2^+
0^+	–	24	45	62	86
0^-	19	–	19	19	38
1^-	40	18	–	90	48
1^+	56	19	85	–	66
2^+	86	45	54	70	–

TABLE III: Minimum number of observed events such that the median significance for rejecting $\mathbb{H}_0$ in favor of the hypothesis $\mathbb{H}_1$ (assuming $\mathbb{H}_1$ is right) exceeds $3\,\sigma$ with m_H=200 GeV/c^2.

The importance of using all the information



All angles+correlations

All angles, no correlations

Just the $\mathbf{ZZ \to \mu^-\mu^+e^-e^+}$ angles θ_1, θ_2, ϕ

Same as above, and integrating over the $\mathbf{h \to ZZ}$ angles Θ, Φ

The importance of using all the information

- **Should also put the production information back in (how to handle the uncertainties?)**

- **Should also use NLO to compute the likelihoods (do these calculations exist for all the possible look-alikes?)**

- **Should also include the other possible decay channels!**

we have to measure other decay modes to determine the electroweak properties of the putative Higgs

Higgs electroweak look-alikes

- OK so you discovered a neutral resonance and used the first 20 events in the ZZ golden mode to exclude higher spins, large CP admixtures, etc.

- But is this particle the SM Higgs of electroweak symmetry breaking?

- Can we pin down the electroweak properties of the neutral resonance by measuring its branching fractions into electroweak vector bosons?

$$\mathbf{h} \to \mathbf{W^+W^-},\ \mathbf{ZZ},\ \gamma\gamma,\ \mathbf{Z}\gamma$$

  - what look-alikes should we worry about?
  - do we need to measure all four branching fractions?

Higgs electroweak look-alikes

$$\mathbf{h \to W^+W^-,\ ZZ,\ \gamma\gamma,\ Z\gamma}$$

- **Can do a general analysis making one additional assumption: the look-alike electroweak sector still respects custodial symmetry**

- **Thus the only look-alikes we have to worry about transform like some $(\mathbf{N_L},\ \mathbf{N_R})$ under the global $\mathbf{SU(2)_L \times SU(2)_R}$ of which custodial $\mathbf{SU(2)_C}$ is the diagonal remnant after EWSB**

Go to Ian Low's talk this afternoon!!

what look-alikes should we worry about?

$$\mathbf{h \rightarrow W^+W^-,\ ZZ,\ \gamma\gamma,\ Z\gamma}$$

- $(\mathbf{1_L},\ \mathbf{1_R})$ **an electroweak singlet with dimension 5 couplings to VV**
- $(\mathbf{2_L},\ \mathbf{2_R})$ **the SM case**
- $(\mathbf{3_L},\ \mathbf{3_R})$ **the custodial symmetry preserving combination of a real and a complex $\mathbf{SU(2)_L}$ triplet**
- $(\mathbf{4_L},\ \mathbf{4_R})$ **some weird thing nobody bothers to talk about**

In the last three cases we have dimension 4 couplings to WW and ZZ

do we need to measure all four branching fractions?

$$\mathbf{h} \rightarrow \mathbf{W^+W^-},\ \mathbf{ZZ},\ \gamma\gamma,\ \mathbf{Z}\gamma$$

Yes

m_S (GeV)	$Br(\gamma\gamma/WW)$	$Br(ZZ/WW)$	$Br(Z\gamma/WW)$
115	2.7×10^{-2} (2.7×10^{-2})	5.1×10^{-2} (0.11)	39 (9.0×10^{-3})
120	1.7×10^{-2} (1.7×10^{-2})	5.7×10^{-2} (0.11)	35 (8.2×10^{-3})
130	7.8×10^{-3} (7.8×10^{-3})	6.7×10^{-2} (0.13)	26 (6.7×10^{-3})
140	4.0×10^{-3} (4.0×10^{-3})	7.1×10^{-2} (0.14)	18 (5.1×10^{-3})
150	2.0×10^{-3} (2.0×10^{-3})	6.4×10^{-2} (0.12)	10 (3.5×10^{-3})
170	1.6×10^{-4} (1.6×10^{-4})	1.4×10^{-2} (2.3×10^{-2})	0.81 (4.1×10^{-4})

TABLE II: *Ratios of branching fractions for an electroweak singlet scalar when $Br(\gamma\gamma/WW)$ is tuned to the SM value. The value in the parenthesis is for the corresponding SM prediction.*

what happens if you have violations of the custodial symmetry in the “Higgs” sector?

- **This is more complicated...**
- **But there is a general analysis for the case of the MSSM**
- **Here you have to consider all operators up to dimension 6**

See the slides from Jose Zurita’s talk yesterday!!

what happens if you have violations of the custodial symmetry in the “Higgs” sector?

- There are generically violations of custodial symmetry at both tree level and loop level (and perhaps cancellations)

- There are also generic custodial-preserving effects that, e.g. raise the Higgs mass

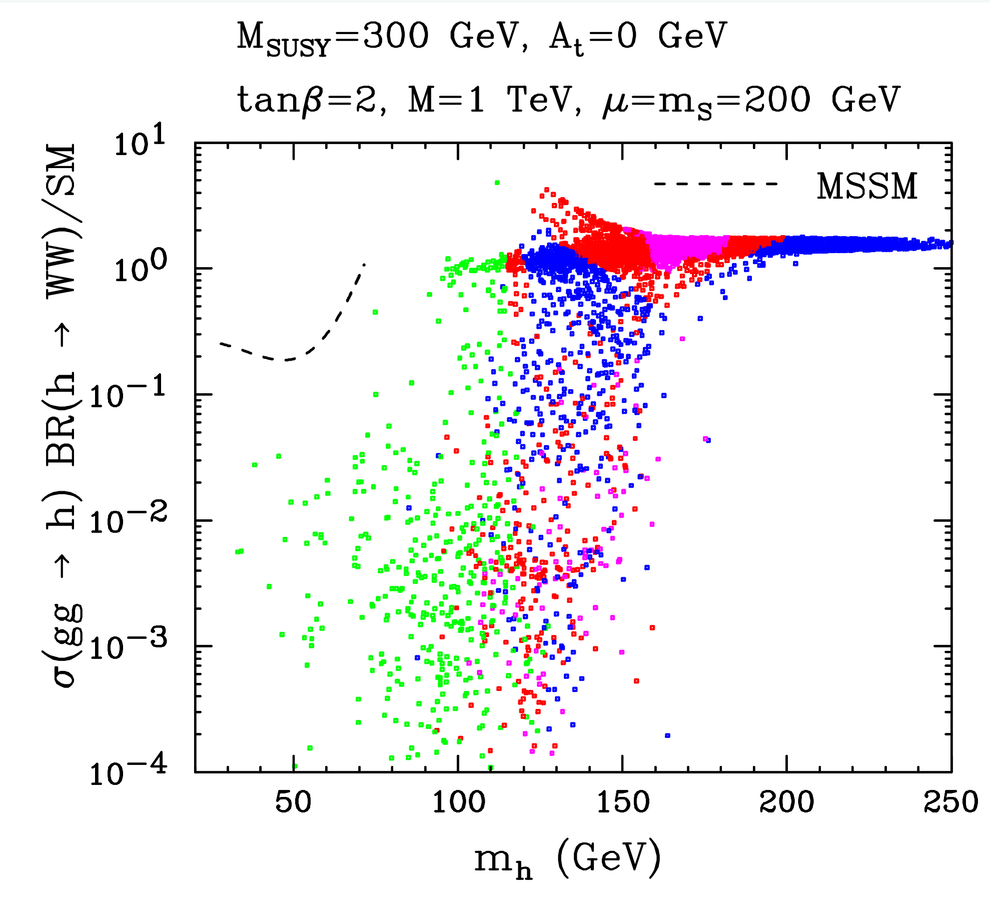
Custodially violating (treel level) :

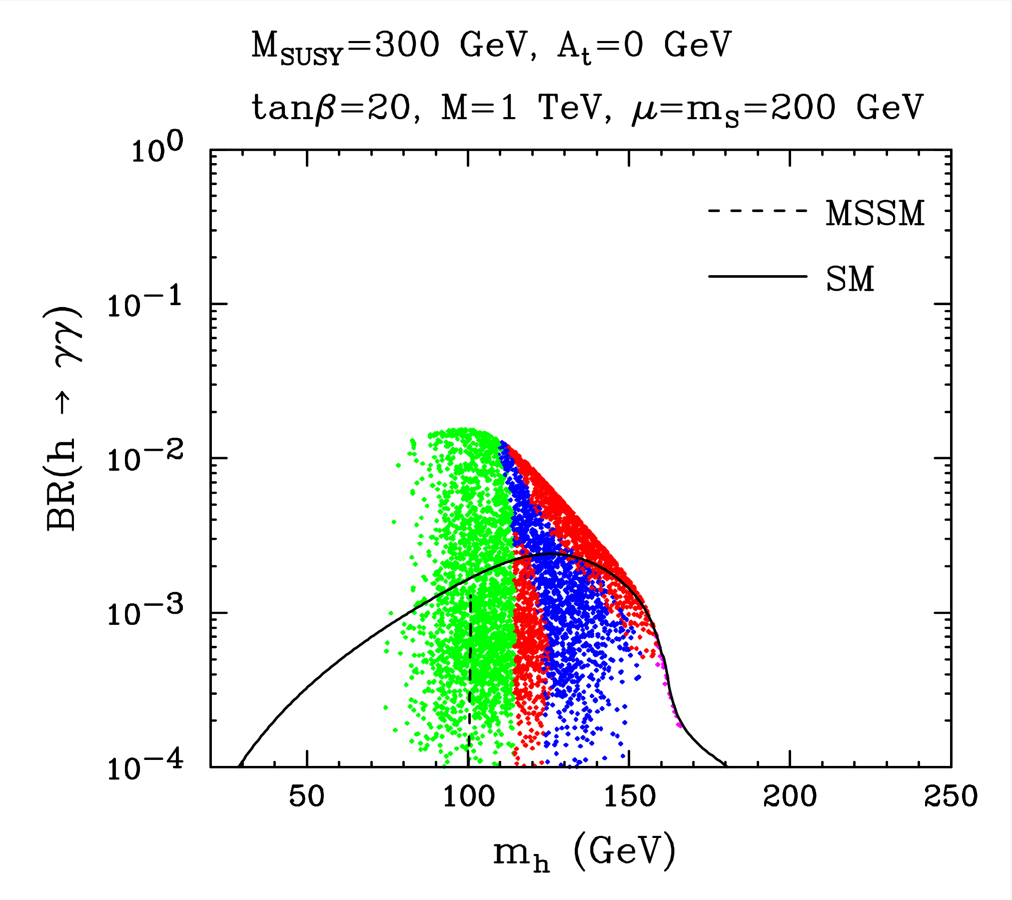
$$\Delta K^{\mathrm{CV}} = \frac{c_1}{2|M|^2}(H_d^\dagger e^{2V} H_d)^2 + \frac{c_2}{2|M|^2}(H_u^\dagger e^{2V} H_u)^2 + \frac{c_3}{|M|^2}(H_u^\dagger e^{2V} H_u)(H_d^\dagger e^{2V} H_d)$$

Custodially preserving (tree level) :

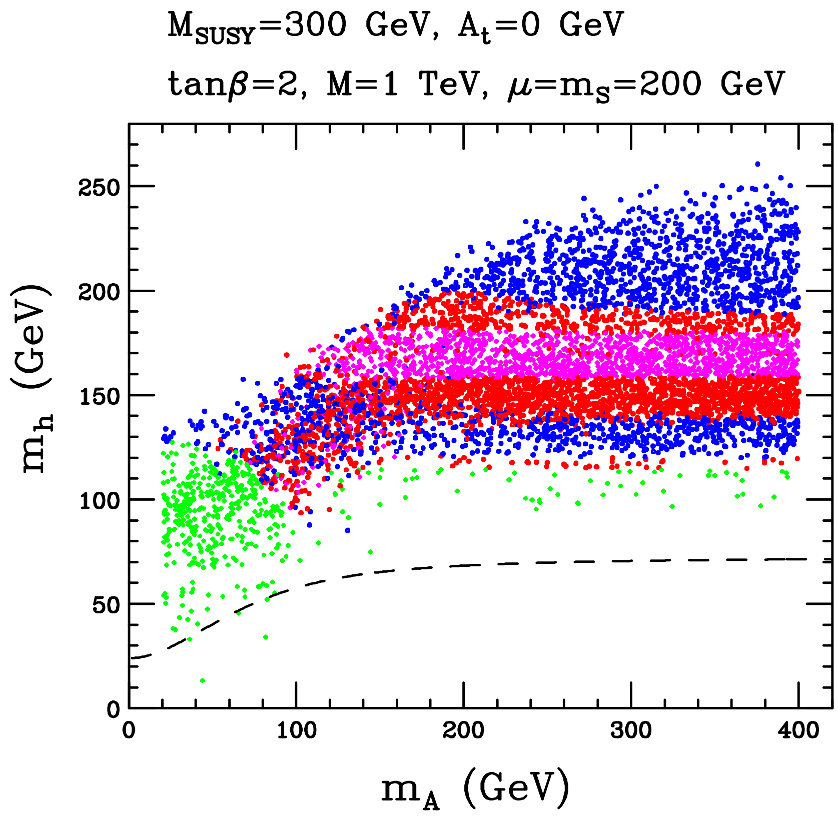
$$\Delta K^{\mathrm{Cust}} = \frac{c_4}{|M|^2}|H_u H_d|^2 + \left[\frac{c_6}{|M|^2} H_d^\dagger\, e^{2V} H_d + \frac{c_7}{|M|^2} H_u^\dagger\, e^{2V} H_u\right](H_u H_d) + \mathrm{h.c.}$$

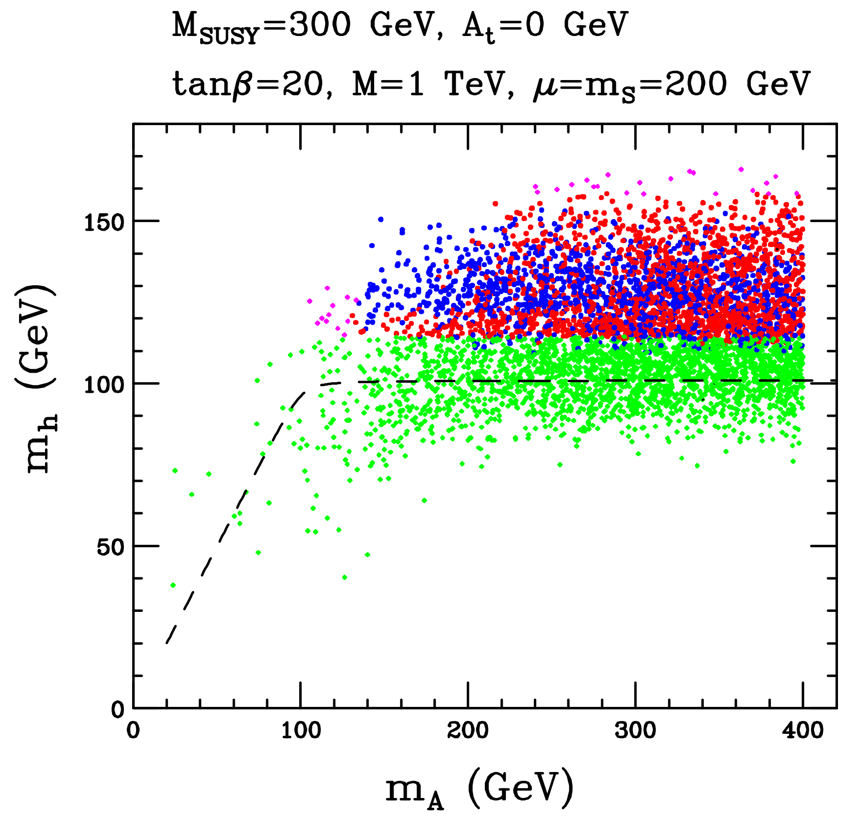
large differences in the branching fractions to VV, compared to the MSSM or SM





also changes the bounds from LEP and Tevatron Higgs searches





Excluded by LEP

Tevatron upgrade → $10\ \mathrm{fb}^{-1} + 50\%$ efficiency in $b\bar{b}$, WW

Excluded by Tevatron

Allowed

Conclusion

- The LHC will (we hope) discover Higgs-like resonances
- We have powerful tools to figure out the identity of what we find
- Most of this does not require 1 ab-1 or an ILC, but it will require (i) more work to get ready, (ii) multi-channel searches, (iii) luck