The Higgs Boson in the Golden Channel

University of Virginia
Particle Physics Seminar
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University of Florida
Based on

1108.2274/ JHEP 1111 (2011) 027
JSG, Kumar, Low, Vega-Morales

1210.0896/ PRD 87 (2013) 055006
Avery, Bourilkov, Chen, Cheng, Drozdetskiy, JSG, Korytov,
Matchev, Milenovic, Mitselmakher, Park, Rinkevicius, and Snowball

1304.4936 / PRL 111 (2013) 041801
JSG, Lykken, Matchev, Mrenna, Park

1310.1397
Chen, Cheng, JSG, Korytov, Matchev, Milenovic, Mitselmakher,
Park, Rinkevicius, Snowball
Outline

- Discovering the Higgs in $H \rightarrow ZZ^* \rightarrow 4 \ell$
- General information
- The Matrix Element Method
- Measuring Higgs Properties
- Geolocation
- Interference
Why look at $H \rightarrow ZZ^* \rightarrow 4 \ell$?
The Standard Model Higgs

A major motivation for the Higgs is to give mass to the W and Z bosons.

\[ \Phi(x) = \left( \begin{array}{c} \theta_2 + i\theta_1 \\ \frac{1}{\sqrt{2}}(v + H) - i\theta_3 \end{array} \right) = \frac{e^{i\theta_4(x)\tau^a(x)/\nu}}{\sqrt{2}} \left( \begin{array}{c} 0 \\ \frac{1}{\sqrt{2}}(v + H(x)) \end{array} \right) \]

The \( |D_\mu \Phi|^2 \) term in the Lagrangian gives both

\[ -\frac{\sqrt{g_1^2 + g_2^2}}{8}v^2g_{\mu\nu}Z^\mu Z^\nu = -\frac{1}{2}M_Z^2g_{\mu\nu}Z^\mu Z^\nu \]

and

\[ -\frac{\sqrt{g_1^2 + g_2^2}}{8}(2vH)g_{\mu\nu}Z^\mu Z^\nu = -\frac{M_Z^2}{v}g_{\mu\nu}HZ^\mu Z^\nu \]

unsuppressed tree level HZZ coupling—strength determined by \( M_Z \)

cf. Djouadi, (2005); Dawson, Gunion, Haber, Kane (1989)
In the Standard Model, the Higgs is also the source of fermion masses.

\[ \mathcal{L}_F = -\frac{1}{\sqrt{2}} \lambda_e (\bar{\nu}_e, \bar{e}_L) \begin{pmatrix} 0 \\ v + H \end{pmatrix} e_R + \cdots \]

\[ = -\frac{1}{\sqrt{2}} \lambda_e (v + H) \bar{e}_L e_R + \cdots \]

Since the fermion mass comes from \( v \), the coupling of a massive fermion to the Higgs is given by

\[ \lambda_f = y_f = \frac{\sqrt{2} m_f}{v} \]

\( v = 246 \text{ GeV} \), so other than the top quark, all SM fermions couple relatively weakly to the Higgs.

So “if” \( 2 M_Z < M_H < 2 m_t \), (i.e. the Higgs has an on-shell two body decays into \( Zs \) but not tops) \( H \rightarrow ZZ \) sizable (actually even if \( M_H > 2 m_t \)).
Time Machine to 2011

We’re going to pretend that we haven’t discovered the Higgs

Don’t worry, we’ll re-discover it in about 15 minutes.

Really I want to introduce the study of the Higgs with the $4 \ell$ final state without assuming $m_H \approx 125 \text{ GeV}$
If $M_H \gtrsim 200$ GeV, decays to $WW$ and $ZZ$ dominate, even above $2 m_t$.

For $M_H \lesssim 2 M_W$, decays to $WW^*$ and $ZZ^*$ still important because with $H \rightarrow b \bar{b}$ one has to contend with huge QCD backgrounds.
Time Machine to 2011

- Clearly, if $M_H \gtrsim 200$ GeV, we should focus on $ZZ$, $WW$ final states.
- Of these, $H \rightarrow ZZ \rightarrow 4 \ell$ is the unique fully leptonic, fully reconstructable final state.
The Golden Channel

Leptons are comparatively easy to reconstruct and measure in detectors (QCD makes life hard)

Downside is $Z \rightarrow \ell^+ \ell^- \ (\ell = e, \mu)$ is only $\approx 1/16$, so leptonic branching fractions cost us a factor of $\approx 260$

So what do $S$ and $S/B$ look like, taking into account the irreducible (LO) $q \bar{q} \rightarrow Z (Z/Z^*/g^*) \rightarrow 4 \ell$ background?
\[ \langle N \rangle \text{ for } 2.5 \text{ fb}^{-1} \text{ at } 7 \text{ TeV} \]

\[ 1108.2274 \]
\[ \langle N \rangle \text{ for } 2.5 \text{ fb}^{-1} \text{ at } 7 \text{ TeV} \]

1108.2274

8.78 fb is spread over wide range of \( m_{4\ell} \).

Relevant background cross section for a given Higgs mass is substantially smaller.
\[ <N> \text{ for } 2.5 \text{ fb}^{-1} \text{ at } 7 \text{ TeV} \]

1108.2274

Background is relatively small, but remember Higgs is wide when \( M_H > 2 M_Z \)
Taking background with $m_{4\ell}$ within $2\Gamma_H$ of $M_H$.

<table>
<thead>
<tr>
<th>$m_h$(GeV)</th>
<th>$\sigma$(fb)</th>
<th>$\epsilon$</th>
<th>$\langle N \rangle$</th>
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<tr>
<td>175</td>
<td>0.218</td>
<td>0.512</td>
<td>0.279</td>
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<td>0.958</td>
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<tr>
<td>350</td>
<td>0.600</td>
<td>0.708</td>
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<table>
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<tr>
<th>$m_h$(GeV)</th>
<th>B</th>
<th>S/B</th>
<th>S/$B^{1/2}$</th>
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<tbody>
<tr>
<td>Background</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>220</td>
<td>0.94</td>
<td>1.9</td>
<td>1.9</td>
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<tr>
<td>250</td>
<td>1.1</td>
<td>1.4</td>
<td>1.5</td>
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<tr>
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<tr>
<td>350</td>
<td>1.1</td>
<td>0.98</td>
<td>1.0</td>
</tr>
</tbody>
</table>

$\langle N \rangle$ for $2.5$ fb$^{-1}$ at 7 TeV

1108.2274
High Higgs Masses

- For a heavy SM Higgs $S/ B$ is fine ($\sim 1$)
- But $S$ is small

How can we get the most significance from a small number of events, if $M_H$ is large?
Use the “Matrix Element Method”

Multivariate Analysis (MVA) which uses the likelihood for all kinematic variables calculated from theory

Uses all available information in an optimal way
In general, assume we have \( N \) events \( \{x_1, x_2, \ldots, x_N\} \)

and we have a model for the process that generates the events \( P(\alpha, x) \), where \( \alpha \) are parameters of the model

Then we can find best fit values for the parameters by maximizing the likelihood function (also \( P \)) with respect to the parameters, \( \alpha \)

i.e. we maximize

\[
P(\alpha, x_1) \times P(\alpha, x_2) \times P(\alpha, x_3) \ldots \times P(\alpha, x_N)
\]

with respect to the parameters \( \alpha \)

(Really people use \( 2 \times \log \) likelihood since it translates more directly to p-values, \( \sigma \), etc.)
Matrix Element Method

In particle physics, the likelihood/ probability function $P(\alpha, x)$ is the differential cross section

$$P(p_{i\text{vis}} | \alpha) = \frac{1}{\sigma_\alpha} \int dx_1 dx_2 \frac{f_1(x_1) f_2(x_2)}{2sx_1x_2} \times \left[ \prod_{i \in \text{final}} \int \frac{d^3p_i}{(2\pi)^3 2E_i} \right] |M_\alpha(p_i)|^2 \prod_{i \in \text{vis}} \delta(p_i - p_{i\text{vis}})$$
In particle physics, the likelihood/probability function $P(\alpha, x)$ is the differential cross section

$$P(\mathbf{p}_{i}^{\text{vis}} | \alpha) = \frac{1}{\sigma_{\alpha}} \int dx_1 dx_2 \frac{f_1(x_1) f_2(x_2)}{2sx_1 x_2} \times \left[ \prod_{i \in \text{final}} \int \frac{d^3p_i}{(2\pi)^3 2E_i} \right] |M_{\alpha}(p_i)|^2 \prod_{i \in \text{vis}} \delta(p_i - p_{i}^{\text{vis}})$$

Normalized by the total cross section after acceptances and efficiencies

So that the integral over kinematic variables gives 1.
Matrix Element Method

- In general need to integrate over momentum of invisible particles (neutrinos, neutralinos)

- and take into account finite detector resolution by integrating over “transfer functions” that describe how likely the observed momenta is given the true momenta

- For $H \rightarrow ZZ \rightarrow 4\ell$, we can ignore these complications (except possibly for $m_{4\ell}$)
Improving the Sensitivity of Higgs Boson Searches in the Golden Channel

Quantified the extent to which sensitivity in Golden Channel could be increased using the Matrix Element Method
To calculate differential cross section in a way that also gives a qualitative understanding, we used helicity amplitudes

\[
\Delta \lambda = \pm 2: \quad A^{\Delta \sigma}_{\pm \mp} = -\sqrt{2}(1 + \beta_1 \beta_2),
\]

\[
\Delta \lambda = \pm 1: \quad A^{\Delta \sigma}_{\pm 0} = \frac{1}{\gamma_2(1 + x)} \left[ (\Delta \sigma \Delta \lambda) \left( 1 + \frac{\beta_1^2 + \beta_2^2}{2} \right) - 2 \cos \Theta ight. \\
\left. - (\Delta \sigma \Delta \lambda)(\beta_2^2 - \beta_1^2)x - 2x \cos \Theta - (\Delta \sigma \Delta \lambda) \left( 1 - \frac{\beta_1^2 + \beta_2^2}{2} \right)x^2 \right]
\]

\[
A^{\Delta \sigma}_{0 \pm} = \frac{1}{\gamma_1(1 - x)} \left[ (\Delta \sigma \Delta \lambda) \left( 1 + \frac{\beta_1^2 + \beta_2^2}{2} \right) - 2 \cos \Theta ight. \\
\left. - (\Delta \sigma \Delta \lambda)(\beta_2^2 - \beta_1^2)x + 2x \cos \Theta - (\Delta \sigma \Delta \lambda) \left( 1 - \frac{\beta_1^2 + \beta_2^2}{2} \right)x^2 \right]
\]

\[
\Delta \lambda = 0: \quad A^{\Delta \sigma}_{\pm \pm} = -(1 - \beta_1 \beta_2) \cos \Theta - \lambda_1 \Delta \sigma (1 + \beta_1 \beta_2)x,
\]

\[
\Delta \lambda = 0: \quad A^{\Delta \sigma}_{00} = 2\gamma_1 \gamma_2 \cos \Theta \left[ ((1 - x)\beta_1 + (1 + x)\beta_2) \sqrt{\frac{\beta_1 \beta_2}{1 - x^2}} - (1 + \beta_1^2 \beta_2^2) \right]
\]
\[
\Delta \lambda = \pm 2 : \quad A_{\pm \mp}^{\Delta \sigma} = -\sqrt{2}(1 + \beta_1 \beta_2),
\]

\[
\Delta \lambda = \pm 1 : \quad A_{\pm 0}^{\Delta \sigma} = \frac{1}{\gamma_2(1 + x)} \left[ (\Delta \sigma \Delta \lambda) \left(1 + \frac{\beta_1^2 + \beta_2^2}{2}\right) - 2 \cos \Theta 
- (\Delta \sigma \Delta \lambda)(\beta_2^2 - \beta_1^2)x - 2x \cos \Theta - (\Delta \sigma \Delta \lambda) \left(1 - \frac{\beta_1^2 + \beta_2^2}{2}\right) x^2 \right]
\]

\[
\Delta \lambda = 0 : \quad A_{0 \pm}^{\Delta \sigma} = \frac{1}{\gamma_1(1 - x)} \left[ (\Delta \sigma \Delta \lambda) \left(1 + \frac{\beta_1^2 + \beta_2^2}{2}\right) - 2 \cos \Theta 
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\]

\[
\Delta \lambda = 0 : \quad A_{00}^{\Delta \sigma} = 2\gamma_1 \gamma_2 \cos \Theta \left[ \left( (1 - x)\beta_1 + (1 + x)\beta_2 \right) \sqrt{\frac{\beta_1 \beta_2}{1 - x^2}} - (1 + \beta_1^2 \beta_2^2) \right]
\]

\[\star \quad \text{i.e. we broke the calculation up into the amplitude for qq (or gg -> H) -> ZZ for each choice of Z helicity}\]

\[\star \quad \text{and the amplitude for Zs of a given helicity to decay to a fermion of specified helicity and angles in the Z rest frame}\]
\[ \Delta \lambda = \pm 2 : \quad A_{\pm \mp}^{\Delta \sigma} = -\sqrt{2}(1 + \beta_1 \beta_2) , \]
\[ \Delta \lambda = \pm 1 : \quad A_{\pm 0}^{\Delta \sigma} = \frac{1}{\gamma_2(1 + x)} \left[ (\Delta \sigma \Delta \lambda) \left(1 + \frac{\beta_1^2 + \beta_2^2}{2}\right) - 2 \cos \Theta \right. \]
\[ \left. - (\Delta \sigma \Delta \lambda)(\beta_2^2 - \beta_1^2)x - 2x \cos \Theta - (\Delta \sigma \Delta \lambda) \left(1 - \frac{\beta_1^2 + \beta_2^2}{2}\right)x^2 \right] \]
\[ \Delta \lambda = 0 : \quad A_{\pm \pm}^{\Delta \sigma} = -(1 - \beta_1 \beta_2) \cos \Theta - \lambda_1 \Delta \sigma(1 + \beta_1 \beta_2)x , \]
\[ \Delta \lambda = 0 : \quad A_{00}^{\Delta \sigma} = 2\gamma_1 \gamma_2 \cos \Theta \left[(1 - x)\beta_1 + (1 + x)\beta_2\right] \sqrt{\frac{\beta_1 \beta_2}{1 - x^2} - (1 + \beta_1^2 \beta_2^2)} \]

* Values shown are for general M_1, M_2

(Zs not necessarily on-shell)
The on-shell limit of our expressions reproduces the above results.

In high energy limit $+-$ and $-+$ dominate

All amplitudes are, in general, non-vanishing.
For signal, only ++, --, and 00 are non-zero
(due to spin-zero nature of Higgs)

00 dominates in high energy limit
So additional ability to distinguish signal from background (beyond $m_{41}$) comes from differences in helicity amplitudes.
Moving forward to July 2012...
Discovery Plots in $4\ell$

CMS-PAS-HIG-12-016

ATLAS-CONF-2012-092

CMS Preliminary $\sqrt{s} = 7$ TeV, $L = 5.05$ fb$^{-1}$; $\sqrt{s} = 8$ TeV, $L = 5.26$ fb$^{-1}$

- Data
- $Z+X$
- $Z\gamma^{\ast}Z$
- $m_{H}=126$ GeV
- $m_{H}=350$ GeV

ATLAS Preliminary

$H\rightarrow ZZ^{\ast}\rightarrow 4\ell$

S/B is in the 1-2 range.

Discovery!!!

S/B is in the 1-2 range.
Matrix Element Method/ MELA

CMS used MELA KD

MELA = Matrix Element Likelihood Analysis

KD = Kinematic Discriminant: ratio involving signal and background likelihoods

Quantifies how “signal-like” events are.

Contours give expected distribution for background events

\[ KD = \frac{P_s}{P_s + P_b} \]

CMS-PAS-HIG-12-016
MELA

Used analytic expressions for signal

POWHEG templates for background $< 2 \, M_Z$
(at discovery time-- now use analytic expressions from
Chen, Tran, and Vega-Morales (2012))

Our analytic expressions (from 1108.2274) for
background $> 2 \, M_Z$!
Success of MELA motivates the use of the MEM in experimental analyses

Not always best to use totally analytic expressions for likelihoods

Is there a safe (from bugs!), efficient way to develop codes for performing the Matrix Element Method in any given channel?
There has been a major effort in the theory community toward the automatization and generalization of the MC tools.

Increasingly one can go automatically from Lagrangian to events (calculating matrix elements along the way) for an arbitrary model.
The same chain of tools can be run in a different direction:

We can use standard tools to automatically generate code which finds the signal and background squared matrix elements.

Can be done for an arbitrary signal hypothesis and virtually any background.
MadWeight is an existing tool along these lines

Artoisenet, Mattelaer (2008)
Artoisenet, Lemaitre, Maltoni, Mattelaer (2010)

Good for many processes, but currently cannot do $H \to ZZ \to 4\ell$
MEKD

- With members of the UF CMS group and Myeonghun Park, created a publicly available tool (MEKD) to calculate differential cross sections, etc. for performing the Matrix Element Method in the Golden Channel.

- Using well-verified, publicly available packages to automatically generate the matrix-element calculating code.

- With as many options/ features relevant to analyses involving the golden channel as possible.
$M_2$ is a very good variable, though the Matrix Element Method outperforms all single variable analyses.
Why $M_2$ is a Good Variable

$f_{11}$ is SM Higgs 1310.1397

$M_2 > 12$ GeV from cuts, without cuts, would be singular in limit of massless leptons
Same Method: Different Physics

- MEM increased sensitivity for high mass Higgs because of different ZZ helicity amplitudes.
- MEM increased sensitivity for lower (actual) Higgs mass because signal is ZZ* while background is Zγ*.
- In both cases, the driver of MVA sensitivity can be clearly related to physics.
- Interestingly, in each case different physics drives the sensitivity.
Back to the Future...
Having discovered “a Higgs”, we want to measure its properties, in particular its couplings to Z bosons

**Goal 1**: Be as general as possible (reduce model dependence)

**Goal 2**: Use as few parameters as possible (keep things manageable)

To provide a useful framework for presenting experimental results, projections, etc.
Preliminaries

We consider a scalar, $X$, which is a linear combination of CP eigenstates $H (0^+)$ and $A (0^-)$

$$X \equiv H \cos \alpha + A \sin \alpha$$

In general, $X$ is not a CP eigenstate

- $\alpha = 0$ corresponds to pure $0^+$
- $\alpha = \pi/2$ corresponds to pure $0^-$

We assume that the other mass eigenstate is heavy and can be ignored.
Effective Theory

We write down general CP-conserving couplings of the H and the A to two Z’s

(CP violation will come from mixing)

\[
\mathcal{L} \ni \left\{ \begin{array}{c}
- \frac{M_Z^2}{v} H Z^\mu \hat{f}^{(H)}_{\mu \nu} Z^\nu \\
- \frac{1}{2} H F^{\mu \nu} \hat{f}^{(H)}_{\mu \nu \rho \sigma} F_{\rho \sigma} \\
- \frac{1}{2} A F^{\mu \nu} \hat{f}^{(A)}_{\mu \nu \rho \sigma} F_{\rho \sigma}
\end{array} \right. 
\]

The \( f \) are form factors which generate operators with different symmetry properties.
Form Factors

- CP even couplings which must violate gauge invariance
  \[ \hat{f}^{(H)}_{\mu\nu} \equiv g_1 g_{\mu\nu} + \frac{g_5}{\Lambda^2} \left( \partial_{\mu} \partial_{\nu} + g_{\mu\nu} \partial_\rho \partial_\rho \right) + \frac{g_6}{\Lambda^2} g_{\mu\nu} \left( \Box + \Box \right) + \mathcal{O} \left( \frac{1}{\Lambda^4} \right) \]
  Note: \( g_5, g_6 \) operators are dimension-5*

- CP even couplings which may preserve gauge invariance
  \[ \hat{f}^{(H)}_{\mu\nu\rho\sigma} \equiv \frac{g_2}{\Lambda} g_{\mu\rho} g_{\nu\sigma} + \frac{g_3}{\Lambda^3} g_{\mu\rho} \partial_{\nu} \partial_{\sigma} + \mathcal{O} \left( \frac{1}{\Lambda^5} \right) \]

- CP Odd Couplings (which preserve gauge invariance)
  \[ \hat{f}^{(A)}_{\mu\nu\rho\sigma} = \frac{g_4}{\Lambda} \varepsilon_{\mu\nu\rho\sigma} + \mathcal{O} \left( \frac{1}{\Lambda^5} \right) \]
Keeping only the lowest dimensional terms from each of the three form factors we obtain the following Lagrangian for the coupling of the mass eigenstate $X$ to two $Z$ bosons.

\[
\mathcal{L} = X \left[ \kappa_1 \frac{m_Z^2}{v} Z_\mu Z^\mu + \frac{\kappa_2}{2v} F_{\mu\nu} F^{\mu\nu} + \frac{\kappa_3}{2v} F_{\mu\nu} \tilde{F}^{\mu\nu} \right]
\]

These operators cover all possible Lorentz structures in the amplitude

\[
A(X \rightarrow V_1 V_2) = v^{-1} \epsilon_1^* \epsilon_2^* \left( a_1 g_{\mu\nu} m_X^2 + a_2 q_\mu q_\nu + a_3 \epsilon_{\mu\nu\alpha\beta} q_1^\alpha q_2^\beta \right)
\]

Gao, Gritsan, Guo, Melnikov, Schulze, Tran (2010)
De Rújula, Lykken, Pierini, Rogan, Spiropulu (2010)
Bolognesi, Gao, Gritsan, Melnikov, Schulze, Tran, Whitbeck (2012)
Lagrangians must be real, so the $\kappa$’s must be real.

The amplitude receives corrections from loops:

- Contributions from heavy particle loops are real.
- Contributions from light particle loops are complex.
  - These complex contributions can be mimicked with complex $\kappa$’s.
Real or Complex? That is the Question

- Lagrangians must be real, so the $\kappa$'s must be real
- The amplitude receives corrections from loops
  - Contributions from heavy particle loops are real
  - Contributions from light particle loops are complex
    - These complex contributions can be mimicked with complex $\kappa$'s

Generally these contributions are subdominant! (see 1310.1397)
Consider \( \kappa_1, \kappa_2, \kappa_3 \) real

Measured rate implies correlations among couplings

Defines an ellipsoidal “pancake” in \( \kappa \) space

Larger (smaller) total rate: pancake inflated (deflated), but shape stays the same

Removes one degree of freedom
Consider $\kappa_1, \kappa_2, \kappa_3$ real

Measured rate implies correlations among couplings

Defines an ellipsoidal “pancake” in $\kappa$ space

Larger (smaller) total rate: pancake inflated (deflated), but shape stays the same

Helpful when maximizing likelihoods

$$\Gamma(X \rightarrow ZZ) = \Gamma_{SM} \sum_{i,j} \gamma_{ij} \kappa_i \kappa_j$$

(Tree level) SM: $(\kappa_1, \kappa_2, \kappa_3) = (1, 0, 0)$
Parametrizing the Pancake 1

- Different points on the pancake correspond to different admixtures of Higgs couplings, but constant rate.
- How should we parametrize the surface of the pancake?
- One choice: spherical coordinates in $\kappa$ space

\[
\begin{align*}
\kappa_1 &= \kappa \sin \theta \cos \phi \\
\kappa_2 &= \kappa \sin \theta \sin \phi \\
\kappa_3 &= \kappa \cos \theta
\end{align*}
\]

Map of $\kappa$ as function of $\theta$ and $\phi$
Parametrizing the Pancake 2

- Alternatively one can change variables to deform the pancake into an “equal rate sphere”

- This involves a linear transformation:

  We go from to using

  \[
  \begin{align*}
  x_1 &= \kappa_1 - 0.25 \kappa_2 \\
  x_2 &= 0.17 \kappa_2 \\
  x_3 &= 0.19 \kappa_3
  \end{align*}
  \]

  DF, before cuts
Geolocating the Higgs

Any given value of $(\kappa_1, \kappa_2, \kappa_3)$, corresponding to a given rate, maps to a point on the sphere
Cuts and Efficiencies

If we use the values of $\gamma_{ij}$ before cuts to construct our sphere, then we find significant variation in the acceptance x efficiency at different points on the sphere.

- Efficiency varies from $\sim 35\%$ to $\sim 55\%$
- $p_T > 7$ GeV  
  $|\eta| < 2.5$ for electrons
- $p_T > 5$ GeV  
  $|\eta| < 2.4$ for muons
- $M_1 > 40$ GeV
- $M_2 > 12$ GeV
Cuts and Efficiencies

The main driver of the changes in efficiency on the sphere seems to be the invariant mass of the less massive intermediate $Z^*$ ($M_2$)

(Choi, Miller, Muhlleitner, and Zerwas, 2003),
(Godbole, Miller, and Muhlleitner, 2007),
(Boughezal, LeCompte, and Petriello, 2012), etc.

I’ll say more about $M_2$ distributions later!
Example Analysis

* We illustrate the use of the sphere for displaying results with a toy analysis

* We generate 1000 pseudoexperiments

  * 300 DF signal events for each of 4 benchmark points (∼300 fb⁻¹ at 14 TeV): three pure states and one completely mixed state

  * Impose cuts (p_T, |η|, M_{Z1}, M_{Z2})

  * Find the point on the sphere that maximizes the likelihood for each pseudoexperiment and plot

1304.4936
Example Analysis

Note: a point and its antipode are effectively equivalent

1304.4936
### Other Spheres

\[ \mathcal{L} = X \left[ \kappa_1 \frac{m_Z^2}{v} Z_\mu Z^\mu + \frac{\kappa_2}{2v} F_{\mu\nu} F^{\mu\nu} + \frac{\kappa_3}{2v} F_{\mu\nu} \tilde{F}^{\mu\nu} \right] \]

- **Scenario 1**: \( \kappa_1 = 0 \). \( \kappa_2 \) and \( \kappa_3 \) arbitrary and complex.
  
  Coupling can be gauge invariant.
  
  Example: X is SM singlet.

- **Scenario 2**: \( \kappa_2 = 0 \). Mixing of SM scalar and pseudoscalar.

- **Scenario 3**: \( \kappa_3 = 0 \). Arbitrary CP-even scalar.
Example: Scenario 2

- Now we allow $\kappa_1, \kappa_3$ to be complex

$$\mathcal{L} = X \left[ \kappa_1 \frac{m_Z^2}{v} Z_\mu Z^\mu + \frac{\kappa_2}{2v} F_{\mu\nu} F^{\mu\nu} + \frac{\kappa_3}{2v} F_{\mu\nu} \tilde{F}^{\mu\nu} \right]$$

- Degrees of freedom: 2 magnitudes and 2 phases
- One overall phase is irrelevant
- We can call relative phase $\phi_{13}$
- Rate restricts overall magnitude of couplings
- Remaining degree of freedom is ratio of couplings

$$x_{13} = \frac{|\kappa_3|^2}{|\kappa_1|^2 + |\kappa_3|^2} = \sin^2 \theta_{13}$$

1304.4936
Geolocating Conclusions

- While many operators may affect the coupling of a scalar to bosons, it is reasonable to focus on three lowest dimensional operators from each class of couplings.
- Overall rate eliminates one degree of freedom.
- We propose the following scenarios all of which involve two degrees of freedom:
  - Three real couplings (general mixture of $0^+_m$, $0^+_h$, $0^-$)
  - $\kappa_1 = 0$, $\kappa_2$, $\kappa_3$ complex: $\theta_{23}$, $\phi_{23}$
  - $\kappa_2 = 0$, $\kappa_1$, $\kappa_3$ complex: $\theta_{13}$, $\phi_{13}$
  - $\kappa_3 = 0$, $\kappa_1$, $\kappa_2$ complex: $\theta_{12}$, $\phi_{12}$
Importance of Interference

- We saw from the above that it is important to look for the Higgs on the entire Earth, not just along the Prime Meridian or the Equator.

- Interference effects between operators can increase sensitivity to non-SM couplings, give sensitivity to sign of couplings (relative to SM).

- If non-SM coupling are discovered, can study if there is one particle with e.g. scalar and pseudoscalar couplings, or two not-quite-degenerate CP-eigenstates.

Greenwich, UK
Importance of Interference

One thing we’ve found is that the $M_2$ distribution changes dramatically as we vary $\kappa_1$ and $\kappa_2$ due to the effect of interference:

Peak of $M_2$ distribution displays “first order phase transition” from $\kappa_1$-$\kappa_2$ interference, no such feature when considering $\kappa_1$ and $\kappa_3$
Distribution (unit normalized on left) of $M_2$ due to pure $\kappa_i$ ($f_{ii}$) and from $\kappa_1-\kappa_2$ interference ($f_{12}$)

Note: $f_{12}$ relatively large, negative.

\[
\frac{d^2 \Gamma}{dM_{Z_1} dM_{Z_2}} = \frac{1}{v} \sum_{i,j} \kappa_i \kappa_j F_{ij}(M_{Z_1}, M_{Z_2}; M_X)
\]
\[ \theta = \arctan(\frac{\kappa_2}{\kappa_1}) \]
Projections
Projections

![Graphs showing expected 2σ exclusion and 5σ observation for ratio $\kappa_2/\kappa_1$ using interference-sensitive D($X; 0^\circ$) and interference-insensitive D($0^\circ_0; 0^\circ$).]
Brief Conclusions

“Golden” $H \rightarrow ZZ^* \rightarrow 4 \ell$ useful channel both in Higgs discovery and in the measurement of Higgs properties.

The Matrix Element Method has been useful for optimizing sensitivity in this channel. Physically transparent (for an MVA).

I’ve described a public tool for golden channel analyses and presented a useful framework for the interpretation of results.

Exciting times are also ahead as we measure the couplings of the Higgs!
Thanks!!!
backup slides
Expressions for change of variables

\[ x_i = \sum_j O_{ij} \kappa_j \]

where \( O_{21} = O_{31} = O_{32} = 0 \) and

\[
O_{1i} = \frac{\gamma_{1i}}{\sqrt{\gamma_{11}}}, \quad (i = 1, 2, 3)
\]

\[
O_{2i} = \frac{\gamma_{11}\gamma_{2i} - \gamma_{12}\gamma_{1i}}{\sqrt{(\gamma_{11}\gamma_{22} - \gamma_{12}^2)\gamma_{11}}}, \quad (i = 2, 3)
\]

\[
O_{33} = \sqrt{\det ||\gamma_{ij}||}/(\gamma_{11}\gamma_{22} - \gamma_{12}^2)
\]

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Top two and bottom left plots show $\kappa$ values on the sphere.
## Rates for various processes

<table>
<thead>
<tr>
<th>Process</th>
<th>$\gamma_{11}$</th>
<th>$\gamma_{22}$</th>
<th>$\gamma_{33}$</th>
<th>$\gamma_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X \to ZZ \ (DF')$</td>
<td>1</td>
<td>0.090</td>
<td>0.038</td>
<td>-0.250</td>
</tr>
<tr>
<td>$X \to ZZ \ (SF)$</td>
<td>1</td>
<td>0.081</td>
<td>0.032</td>
<td>-0.243</td>
</tr>
<tr>
<td>$X \to \gamma\gamma$</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>$X \to WW$</td>
<td>1</td>
<td>0.202</td>
<td>0.084</td>
<td>-0.379</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Process</th>
<th>$\gamma_{11}$</th>
<th>$\gamma_{22}$</th>
<th>$\gamma_{33}$</th>
<th>$\gamma_{12}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$X \to ZZ \ (DF')$</td>
<td>1</td>
<td>0.101</td>
<td>0.037</td>
<td>-0.277</td>
</tr>
</tbody>
</table>

- **Avoid variable efficiencies:** use $\gamma_{ij}$ after cuts
- **Note also that $\gamma_{ij}$ are substantially different in the same flavor and different flavor cases**
Matrix Element Method

In particle physics, the likelihood/ probability function $P(\alpha, x)$ is the differential cross section

$$P(p_i^{vis}|\alpha) = \frac{1}{\sigma_{\alpha}} \int dx_1 dx_2 \frac{f_1(x_1)f_2(x_2)}{2sx_1x_2} \times \left[ \prod_{i\in\text{final}} \int \frac{d^3p_i}{(2\pi)^3 2E_i} \right] |M_\alpha(p_i)|^2 \prod_{i\in\text{vis}} \delta(p_i - p_i^{vis})$$

Only LO here: for extension to extra radiation/ NLO/ parton showers see

Alwall, Freitas, Mattelaer (2010)
Campbell, Giele, Williams (2012)
Campbell, Ellis, Giele, Williams (2013)