Mad-Maximizing Higgs Pair Analyses

arXiv: 1311.2591 (Plehn, Schichtel, Wiegand)
arXiv: 16xx.xxxx (FK, Plehn, Schichtel)

work with Tilman Plehn and Peter Schichtel

Felix Kling

THE UNIVERSITY OF ARIZONA
Fermilab

Pheno 2016
**Introduction**

- **2012**: LHC found Higgs
  - no new physics found (so far)
  - let’s analyze all its properties
Introduction

- **2012:** LHC found Higgs
  - no new physics found (so far)
  - let’s analyze all its properties

- **Higgs Potential:** \( V(\Phi) = -\mu \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \)
Introduction

- **2012**: LHC found Higgs
  - no new physics found (so far)
  - let’s analyze all its properties
- **Higgs Potential**: \( V(\Phi) = -\mu \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \)
  - not measured yet
Introduction

- **2012**: LHC found Higgs
  - no new physics found (so far)
  - let’s analyze all its properties

- **Higgs Potential**: \( V(\Phi) = -\mu \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \)
  - not measured yet

- **Higgs Pair Production**:
  - \( \sigma(gg \rightarrow hh) = 34 \text{ fb} \) arXiv 1401.7340
  - \( bb\gamma\gamma \) most promising
Introduction

- **2012:** LHC found Higgs
  - no new physics found (so far)
  - let’s analyze all its properties

- **Higgs Potential:** \( V(\Phi) = -\mu \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \)
  - not measured yet

- **Higgs Pair Production:**
  - \( \sigma(gg \rightarrow hh) = 34 \text{ fb} \)
  - \( bb\gamma\gamma \) most promising

- **Previous Studies:**
  - arXiv 0310056 (Baur et. al.)
    - Pre-LHC study
  - arXiv 1206.5001 (Dolan et. al.)
  - arXiv 1212.5581 (Baglio et. al.)
    - Cut based analysis
  - arXiv 1311.1931 (Barger et. al.)
    - First multivariate analysis
Introduction

- **2012**: LHC found Higgs
  - no new physics found (so far)
  - let’s analyze all its properties
- **Higgs Potential**: \[ V(\Phi) = -\mu \Phi^\dagger \Phi + \lambda (\Phi^\dagger \Phi)^2 \]
  - not measured yet
- **Higgs Pair Production**:
  - \( \sigma(gg \rightarrow hh) = 34 \text{ fb} \)
  - \( bb\gamma\gamma \) most promising

- **Previous Studies**:
  - arXiv 0310056 (Baur et. al.)
    - Pre-LHC study
  - arXiv 1206.5001 (Dolan et. al.)
  - arXiv 1212.5581 (Baglio et. al.)
    - Cut based analysis
  - arXiv 1311.1931 (Barger et. al.)
    - First multivariate analysis

---

**How good can we be?**

**MadMax**
MadMax

I bin

cut

B only
S+B
N_B, N_{S+B}

# events

kin. variable

Felix Kling
Mad-Maximizing Higgs Pair Analyses
MadMax

I bin

# events

kin. variable

cut

B only
S+B

N_B, N_{S+B}

likelihood distribution

gaussian

ρ

N_B, N_{S+B}, N_{cut}

Felix Kling

Mad-Maximizing Higgs Pair Analyses
MadMax

B only
S+B

# events vs. kin. variable

likelihood distribution

gaussian

significance $\sigma$

$N_{B}$, $N_{S+B}$

$\rho$ vs. $N_{cut}$

Felix Kling

Mad-Maximizing Higgs Pair Analyses

The University of Arizona
MadMax

likelihood distribution

\[ \mathcal{N}_{S+B,i} \quad \mathcal{N}_{B,i} \]

\[ \sigma^2 = \sum_{bins} \sigma_i^2 \]

Felix Kling

Mad-Maximizing Higgs Pair Analyses
The log-likelihood ratio $q$ is the most powerful hypothesis test.

Neyman-Pearson

The log-likelihood ratio $q$ is the most powerful hypothesis test.
The log-likelihood ratio $q$ is the most powerful hypothesis test.

$$ q = \log \frac{L(\vec{x}|H_{S+B})}{L(\vec{x}|H_B)} $$
The log-likelihood ratio $q$ is the most powerful hypothesis test.

Neyman-Pearson

The log-likelihood ratio $q$ is the most powerful hypothesis test.

$$q = \log \frac{L(\bar{x}|H_{S+B})}{L(\bar{x}|H_B)}$$
Mad-Maximizing Higgs Pair Analyses

\[ q = \log \frac{L(x|H_{S+B})}{L(x|H_B)} \]
- single event log-likelihood ratio

\[ dq(x) = \log \frac{L(x|H_{S+B})}{L(x|H_B)} = -n_s + \log \left( 1 + \frac{d\sigma_S(x)}{d\sigma_B(x)} \right) \]
- single event log-likelihood ratio

\[ dq(x) = \log \frac{L(x|H_{S+B})}{L(x|H_B)} = -n_s + \log \left( 1 + \frac{d\sigma_S(x)}{d\sigma_B(x)} \right) \]

- calculate distribution via Monte Carlo

- Modified version of MG5

see 1311.2591 or ask Peter Schichtel
MadMax

- single event log-likelihood ratio

\[ dq(x) = \log \frac{L(x|H_{S+B})}{L(x|H_B)} = -n_s + \log \left(1 + \frac{d\sigma_S(x)}{d\sigma_B(x)}\right) \]

- calculate distribution via Monte Carlo

\[ dq(x) = \log \frac{L(x|H_{S+B})}{L(x|H_B)} = \text{single event likelihood distribution} \]

\[ dq_S dq_B \]

\[ q = \log \frac{L(\vec{x}|H_{S+B})}{L(\vec{x}|H_B)} \]

Modified version of MG5

see 1311.2591 or ask Peter Schichtel

single event log-likelihood distribution

\[ \frac{d\sigma_S}{dq} \quad \frac{d\sigma_B}{dq} \]
- single event log-likelihood ratio
\[
dq(x) = \log \frac{L(x|H_{S+B})}{L(x|H_B)} = -n_s + \log \left(1 + \frac{d\sigma_S(x)}{d\sigma_B(x)}\right)
\]

- calculate distribution via Monte Carlo

\[\text{Modified version of MG5} \quad \xrightarrow{\text{see 1311.2591 or ask Peter Schichtel}}\]

single event likelihood distribution
\[\frac{d\sigma_S}{dq}, \frac{d\sigma_B}{dq}\]

\[\text{LEPStat4LHC}\]

full probability distribution \[\rho_B(q), \rho_{S+B}(q)\]
- single event log-likelihood ratio

\[ dq(x) = \log \frac{L(x|H_{S+B})}{L(x|H_B)} = -n_s + \log \left( 1 + \frac{d\sigma_S(x)}{d\sigma_B(x)} \right) \]

- calculate distribution via Monte Carlo

→ Modified version of MG5

see 1311.2591 or ask Peter Schichtel

single event likelihood distribution

\[ \frac{d\sigma_S}{dq} \quad \frac{d\sigma_B}{dq} \]

\[ dq(x) = \log L(x|H_{S+B}) - \log L(x|H_B) = n_s + \log \left( 1 + \frac{d\sigma_S(x)}{d\sigma_B(x)} \right) \]

- obtain maximum significance \( Z \)

\[ \text{CL}(q^*) = \int_{q^*}^{\infty} dq' \rho_B(q') = \frac{1}{2} \left( 1 - \text{erf} \left( \frac{Z}{\sqrt{2}} \right) \right) \]
Higgs Pairs

**Signal:** both box and triangle diagram

→ Higgs self coupling sensitive to $\lambda$

\[
g_{hhh} = \lambda v
\]
### Higgs Pairs

**Signal:** both box and triangle diagram

→ Higgs self coupling sensitive to $\lambda$

**Background:**

<table>
<thead>
<tr>
<th>continuum</th>
<th>resonant</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb\gamma\gamma$</td>
<td>$ZH \rightarrow bb\gamma\gamma$</td>
</tr>
<tr>
<td>$bb_j\gamma$</td>
<td></td>
</tr>
<tr>
<td>$jj\gamma\gamma$</td>
<td></td>
</tr>
</tbody>
</table>
### Higgs Pairs

**Signal:** both box and triangle diagram

- $\rightarrow$ Higgs self coupling sensitive to $\lambda$

**Background:**

- continuum: $bb\gamma\gamma$, $bbj\gamma$, $jj\gamma$
- resonant: $ZH \rightarrow bb\gamma\gamma$

see 1603.06896 (CMS)
Higgs Pairs

**Signal:** both box and triangle diagram

\[ \rightarrow \text{Higgs self coupling sensitive to } \lambda \]

**Background:**

- continuum: \( bb, bbj, jj, \gamma\gamma \)
- resonant: \( ZH \rightarrow bb\gamma\gamma \)

**Smearing:** MadMax \( \rightarrow \) parton level study

\[ \rightarrow \text{modify propagator} \]

\[ \frac{1}{p^2 - m^2 - i\Gamma} \rightarrow e^{-\left(\frac{\sqrt{p^2 - m}^2}{4\sigma^2}\right)} \]

gaussian width

- Simulation model
- Parametric model
- \( \sigma_{\text{eff}} = 1.94 \text{ GeV} \)
- FWHM = 3.50 GeV

\( \text{arXiv:1411.4362 (photons)} \)
\( \text{CMS-PAS-HIG-15-005 (bottom)} \)
### Higgs Pairs

**Signal:** both box and triangle diagram

→ Higgs self coupling sensitive to $\lambda$

**Background:**

<table>
<thead>
<tr>
<th>Continuum</th>
<th>Resonant</th>
</tr>
</thead>
<tbody>
<tr>
<td>$bb\gamma\gamma$</td>
<td>$ZH\gamma$</td>
</tr>
<tr>
<td>$bbj\gamma$</td>
<td>$jj\gamma\gamma$</td>
</tr>
</tbody>
</table>

see 1603.06896 (CMS)

**Smearing:** MadMax → parton level study

→ modify propagator

**Efficiencies:**

- **b-tagging**
  - arXiv:1309.1057

- **fake photons**
  - CERN-LHCC-2015-010
High Luminosity LHC: $\mathcal{L} = 3000 \text{ fb}^{-1}$
High Luminosity LHC: $\mathcal{L} = 3000$ fb$^{-1}$
Higgs Pairs - Results

High Luminosity LHC: $\mathcal{L} = 3000$ fb$^{-1}$

CMS diphoton trigger
Higgs Pairs - Results

High Luminosity LHC: \( \mathcal{L} = 3000 \ \text{fb}^{-1} \)

CMS diphoton trigger

differential cross section including efficiencies

\[ p_{T,\gamma}^{max} \]
High Luminosity LHC: $\mathcal{L} = 3000 \text{ fb}^{-1}$

CMS diphoton trigger

differential cross section including efficiencies

Higgs Pairs - Results

CMS diphoton trigger

differential cross section including efficiencies

find regions with high significance

same for all other kinematic variables
Higgs Pairs - Results

High Luminosity LHC: $\mathcal{L} = 3000 \text{ fb}^{-1}$

Total Significance $Z = 4.76$
Higgs Pairs - Results

Measuring $\lambda$:

$\lambda = 5\lambda_{SM}$

$Z = 3.21$

different region of parameter space carry significance

$\lambda = \lambda_{SM}$

$Z = 4.76$
Measuring $\lambda$:

![Graph showing the measurement of $\lambda$](image-url)
Measuring $\lambda$:

![Graph showing the measurement of $\lambda$.](image-url)
Higgs Pairs - Results

Measuring $\lambda$:

![Graph showing results for measuring $\lambda$. The graph displays three lines: $\sigma_S$, $\sigma_S \times 10$ (including efficiencies), and $\sigma_B$ (including efficiencies). The x-axis represents $\lambda/\lambda_{SM}$, and the y-axis represents $\sigma$ in [fb].]
Higgs Pairs - Results

Measuring $\lambda$:

![Graph showing the measurement of $\lambda$ with significances and efficiencies.](image)
Conclusion and Outlook

MadMax

- maximum significance
- fully differential significance
  → track regions of significance
- automated and fast

Higgs Pair Analysis

Outlook

- test signal hypotheses: \( S_2 + B \) vs. \( S_1 + B \)
- explicit particle smearing