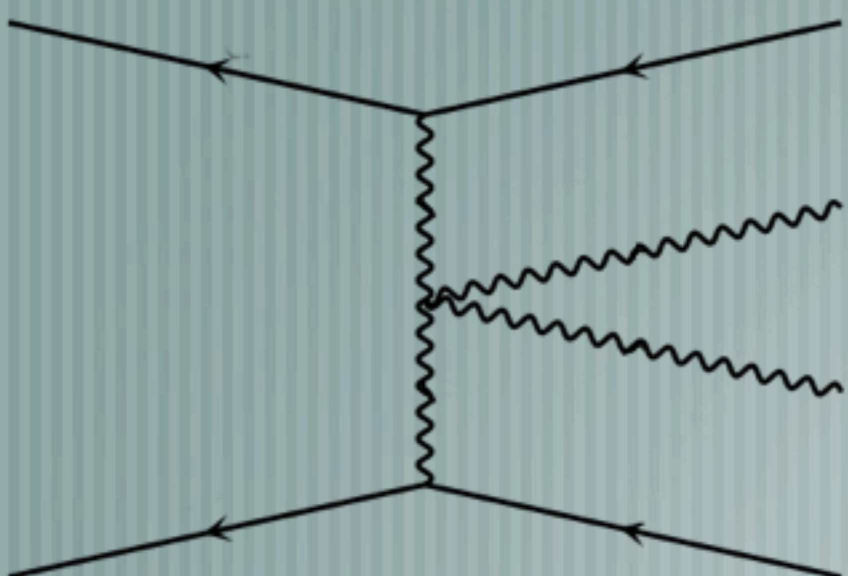
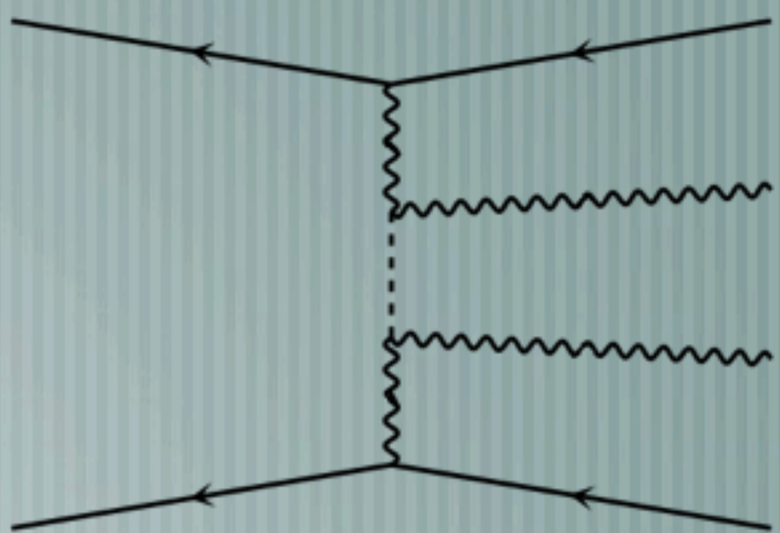
High Energy WW Scattering at the LHC



James (Jamie) Gainer
University of Florida
August 19, 2013



LPC Workshop on Gauge Boson Couplings

- Mostly

  arXiv:1212.3598

  Phys. Rev. D88 (2013) 017302

  with Ayres Freitas

- Not a general overview– apologies!!!

So I won't say much about...

- (Dicus and Mathur, 1973)
- (Veltman, 1977)
- (Lee, Quigg, Thacker, 1977)
- (van der Bij and Veltman, 1984)
- (Duncan, Kane, and Repko, 1986)
- (Dicus and Vega, 1986)
- (Kleiss and Stirling, 1988)
- (Barger, Cheung, Han, and Phillips, 1990)
- (Baur and Glover, 1990)
- (Dicus, Gunion, and Vega, 1991)
- (Dicus, Gunion, Orr, and Vega, 1992)
- (Bagger et al., 1994)
- (Bagger et al., 1995)
- (Iordanidis and Zeppenfeld, 1998)
- (Butterworth, Cox, and Forshaw, 2002)
- (Alboteanu, Kilian, and Reuter, 2008)
- (Englert, Jäger, Worek, and Zeppenfeld, 2009)
- (Ballestrero, Bevilacqua, and Maina, 2009)
- (Ballestrero, Bevilacqua, Franzosi, and Maina, 2009)
- (Aad et al., 2009)
- (Ballestrero, Franzosi, and Maina, 2011).
- (Doroba et al., 2012).
- Et cetera...

Outline

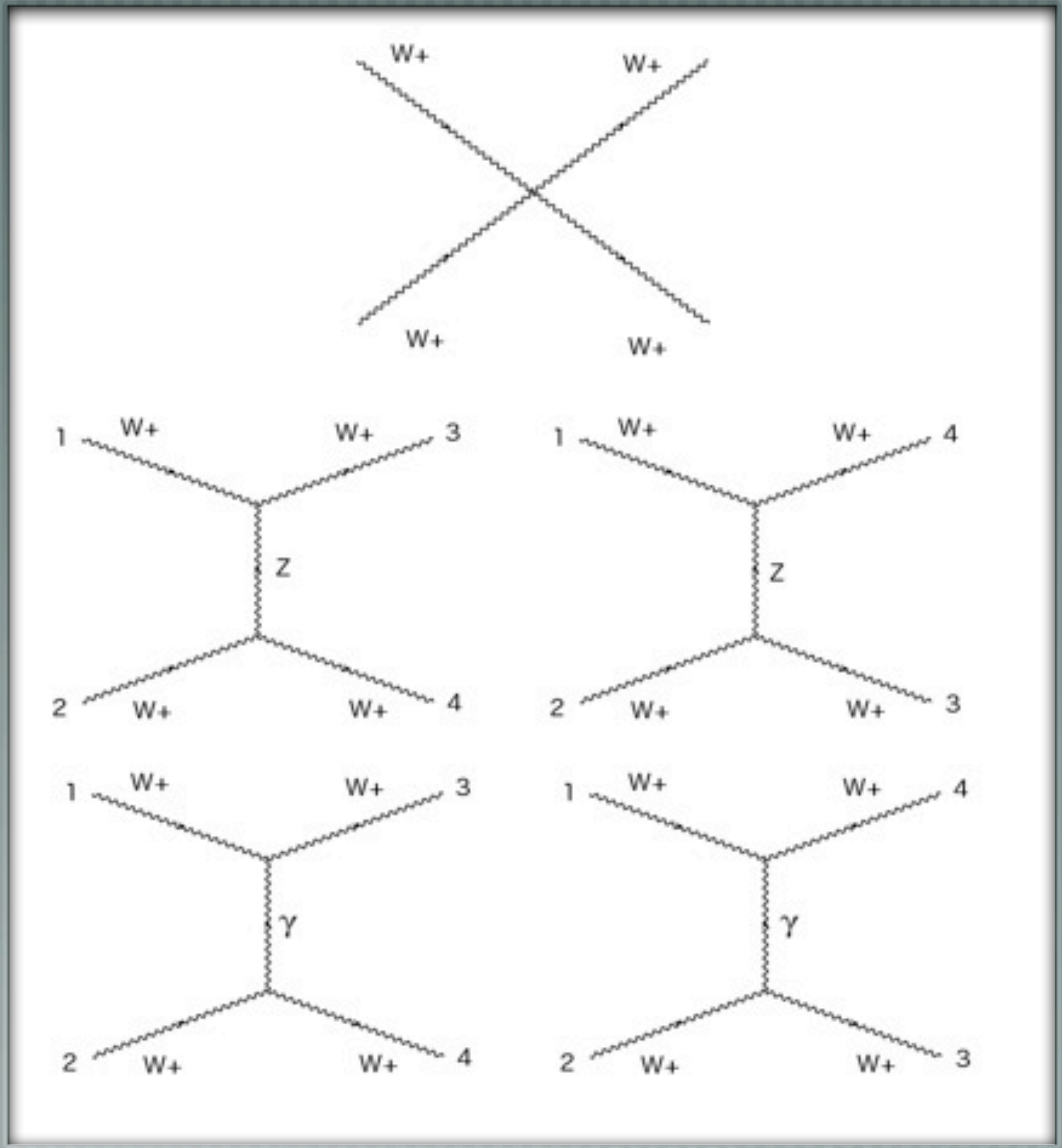
- Why Study WW Scattering?
  - How to Study WW Scattering
- The Matrix Element Method
- Our Analysis
- Results
- Possible Systematic Effects and Future Work

Why Study WW Scattering?

- In the SM without the Higgs, the amplitude for t-channel $W_L W_L$ scattering at high energies is proportional to s, and hence violates unitarity
- unitarity can be restored by including the SM Higgs
- or e.g. strongly coupled new physics at a few TeV

Gauge Theory Diagrams

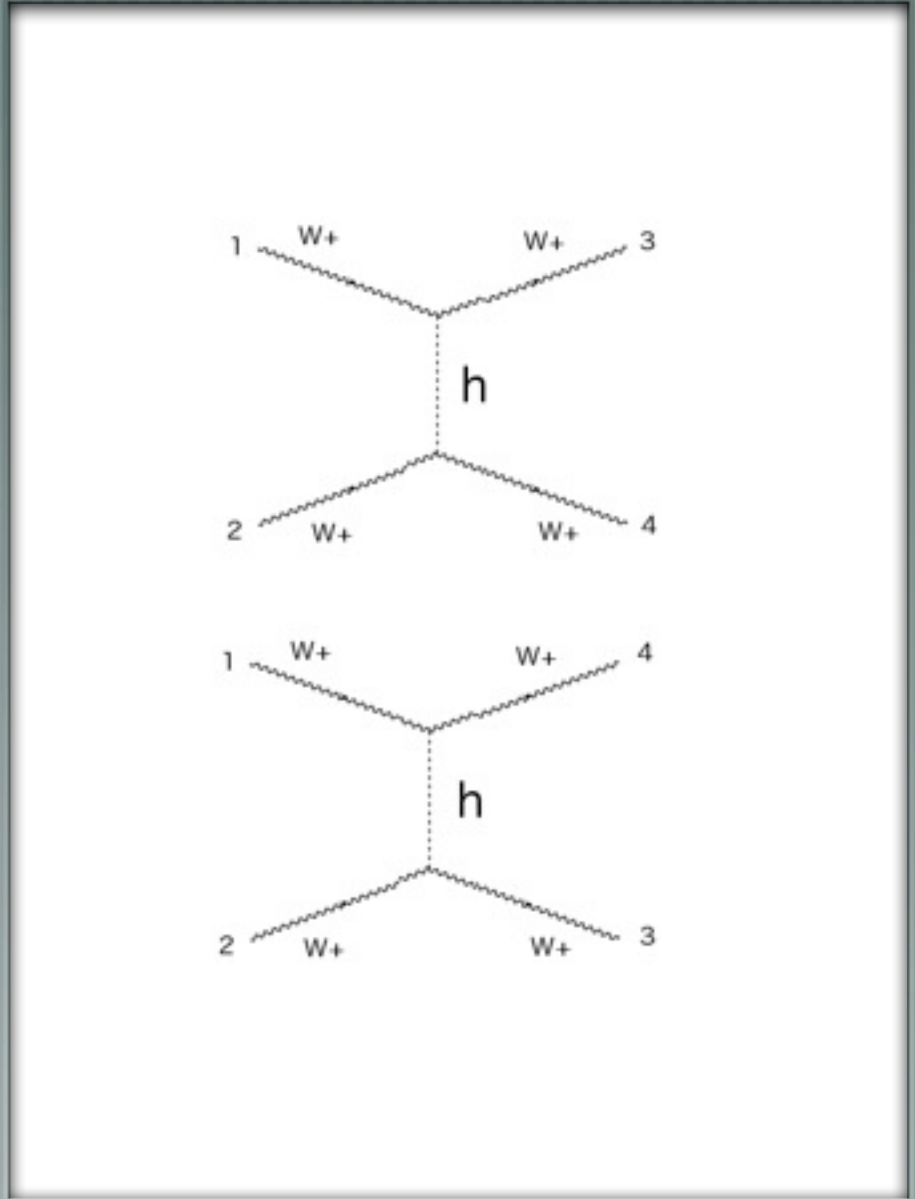
$$\mathcal{M}_{\text{Gauge}} = \frac{1}{v^2}(t+u)$$



Higgs Diagrams

$$\mathcal{M}_{\text{Higgs}} = \frac{-1}{v^2}\left(\frac{t^2}{t-m_H^2} + \frac{u^2}{u-m_H^2}\right)$$

$$\lim_{s\to\infty} \mathcal{M}_{\text{Higgs}} = \frac{-1}{v^2}(t+u)$$



Unitarity Restored

- Both gauge and Higgs diagrams give a contribution to the amplitude which grows linearly with s for s→∞
- However the sum of the gauge and Higgs contributions

$$\mathcal{M}_{\text{Gauge}} + \mathcal{M}_{\text{Higgs}} = \frac{-m_H^2}{v^2}\left(\frac{t}{t-m_H^2} + \frac{u}{u-m_H^2}\right)$$

approaches a constant as s→∞

- So unitarity is restored by the inclusion of the SM Higgs

Unitarity Restored

- Historically, this provided a clear argument that there was either an SM-like Higgs or e.g. strong coupling at the scale of a few TeV
- Pointed out relatively early...

From Dicus and Mathur (1973)

In the Weinberg theory,[6] we consider the processes $\nu\bar{\nu} \to WW$, $ZZ \to ZZ$, $\nu_e\bar{\nu}_e \to \nu_\mu\bar{\nu}_\mu$, $WZ \to WZ$, and $e^+e^- \to \mu^+\mu^-$. The best bounds come from the process $ZZ \to ZZ$ with all the Z longitudinal. We find

$$m_Z < 1550 \text{ GeV},$$

$$m_\phi < 1020 \text{ GeV}.$$

m_W is also bounded by 1550 GeV since, for mass values this large, it is approximately equal to m_Z.

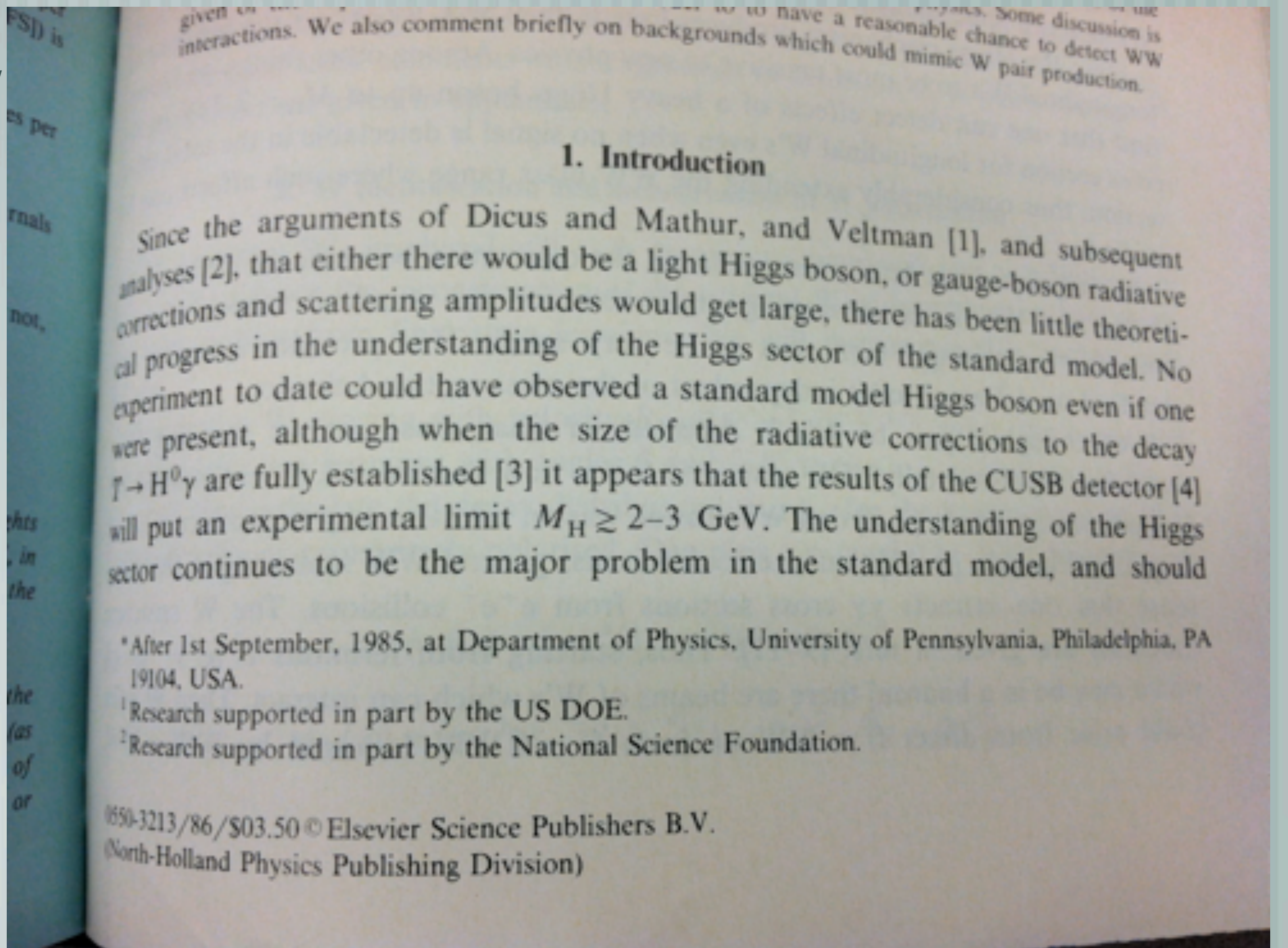
(WW scattering described elsewhere in paper; I found this passage striking.)

Unitarity Restored

- Thus there was a clear argument that there was either an SM-like Higgs or e.g. strong coupling at the scale of a few TeV
- Pointed out relatively early

From Duncan, Kane, and Repko (1986)

"... it appears that the results of the CUSB detector will put an experimental limit $M_H \leq$ 2-3 GeV..."



interactions. We also comment briefly on backgrounds which could mimic W pair production.

1. Introduction

Since the arguments of Dicus and Mathur, and Veltman [1], and subsequent analyses [2], that either there would be a light Higgs boson, or gauge-boson radiative corrections and scattering amplitudes would get large, there has been little theoretical progress in the understanding of the Higgs sector of the standard model. No experiment to date could have observed a standard model Higgs boson even if one were present, although when the size of the radiative corrections to the decay $\Upsilon \to H^0\gamma$ are fully established [3] it appears that the results of the CUSB detector [4] will put an experimental limit $M_H \geq 2$–3 GeV. The understanding of the Higgs sector continues to be the major problem in the standard model, and should

*After 1st September, 1985, at Department of Physics, University of Pennsylvania, Philadelphia, PA 19104, USA.
[1] Research supported in part by the US DOE.
[2] Research supported in part by the National Science Foundation.

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(North-Holland Physics Publishing Division)

There has been some experimental progress in the meantime...

Do we still need to study WW Scattering?

- **Yes!**
- Probing hWW couplings at high energies.
  - different energy regime
  - complementary to s-channel Higgs production and decay
- Even small departures from the SM demand additional new physics and may suggest its scale

Not Quite SM Higgs

- If the hWW coupling is scaled by k, then

$$\mathcal{M}_{\text{Higgs}} = k^2 \mathcal{M}_{\text{SM Higgs}}$$

$$\lim_{s \to \infty} \mathcal{M}_{\text{Gauge}} + \mathcal{M}_{\text{Higgs}} = \frac{1-k^2}{v^2}(t+u)$$

and unitarity is again violated

Two Higgs Doublet Models

- Let k = cos ξ. (ξ = α - β.)

- If we add a second Higgs, H, for which the HWW coupling is sin ξ × SM coupling then the linear dependence on s in the s→∞ is again cancelled:

$$\lim_{s\to\infty} \mathcal{M}_{\text{Gauge}} + \mathcal{M}_h + \mathcal{M}_H \approx \frac{1-\cos^2\xi - \sin^2\xi}{v^2}(t+u)$$

- This is a feature of Two Higgs Doublet Models

Two Higgs Doublet Models

- Natural connection to SUSY:
  the Higgs sector of the MSSM is a THDM

- More general possibilities exist for THDM beyond the MSSM

- Predicts a second (mostly) CP-even neutral Higgs
  (which unitarizes WW scattering),
  a CP-odd Higgs, charged Higgses. Neutral states mix.

Strongly Interacting Light Higgs Models

- Another possibility is that there is a new sector responsible for EWSB
- In the SILH paradigm (Giudice, Grojean, Pomerol, and Rattazzi, 2007) this new sector is parameterized by
  - a coupling g_ρ with $g_{SM} \lesssim g_\rho \lesssim 4\pi$
  - a mass scale m_ρ, which describes the mass scale of the particles in the new sector
- e.g. Little Higgs fits into this general class of models

Strongly Interacting Light Higgs Models

- We obtain a scale f (roughly analogous to the pion decay constant in the limit where the theory is QCD-like):

$$m_\rho = g_\rho f$$

- The couplings of the W and Z bosons to the “light Higgs”, which here is a psuedo-Goldstone boson of some new sector symmetry are scaled by

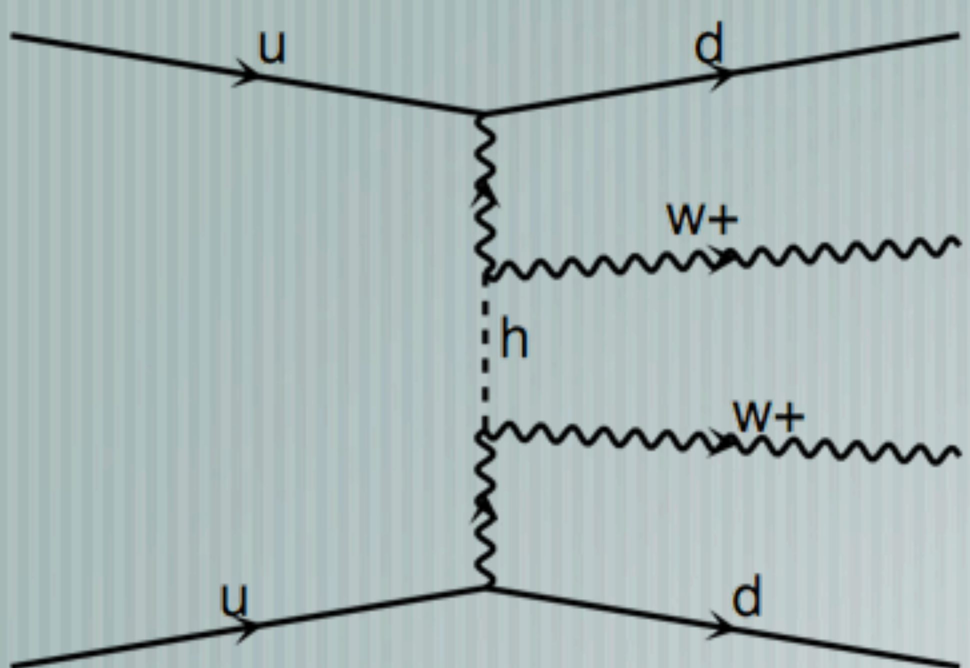
$$1/\sqrt{1 - c\,v^2/f^2}$$

where c is order 1 (and dependent on the details of the new sector).

New States, New Scales

- So as in the THDM, the modification of the hWW coupling in the SILH would affect the amplitude for WW scattering at high energies
- Should suggest a scale for new physics (roughly!)
- Cannot to discriminate between THDM and SILH in the limit of a very heavy Heavy Higgs mass
  - sensitivity is to k, unless other states are light enough to contribute directly to the WW scattering amplitude

How to Study WW Scattering



$q\bar{q} \rightarrow WWjj$ at the LHC

```
mg5>generate p p > W+ W+ j j HIG=2
INFO: Trying process: u u > w+ w+ d d HIG=2
INFO: Process has 102 diagrams
INFO: Trying process: u u > w+ w+ d s HIG=2
INFO: Trying process: u u > w+ w+ s s HIG=2
INFO: Trying process: u c > w+ w+ d d HIG=2
INFO: Trying process: u c > w+ w+ d s HIG=2
INFO: Process has 51 diagrams
INFO: Trying process: u c > w+ w+ s s HIG=2
INFO: Crossed process found for u d~ > w+ w+ d u~, reuse diagrams.
INFO: Crossed process found for u d~ > w+ w+ s c~, reuse diagrams.
INFO: Crossed process found for u s~ > w+ w+ d c~, reuse diagrams.
INFO: Process c u > w+ w+ d s added to mirror process u c > w+ w+ d s
INFO: Trying process: c c > w+ w+ d d HIG=2
INFO: Trying process: c c > w+ w+ d s HIG=2
INFO: Trying process: c c > w+ w+ s s HIG=2
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INFO: Crossed process found for c s~ > w+ w+ d u~, reuse diagrams.
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INFO: Process d~ c > w+ w+ s u~ added to mirror process c d~ > w+ w+ s u~
INFO: Crossed process found for d~ d~ > w+ w+ u~ u~, reuse diagrams.
INFO: Crossed process found for d~ s~ > w+ w+ u~ c~, reuse diagrams.
INFO: Process s~ u > w+ w+ d c~ added to mirror process u s~ > w+ w+ d c~
INFO: Process s~ c > w+ w+ d u~ added to mirror process c s~ > w+ w+ d u~
INFO: Process s~ c > w+ w+ s c~ added to mirror process c s~ > w+ w+ s c~
INFO: Process s~ d~ > w+ w+ u~ c~ added to mirror process d~ s~ > w+ w+ u~ c~
INFO: Crossed process found for s~ s~ > w+ w+ c~ c~, reuse diagrams.
12 processes with 918 diagrams generated in 3.189 s
Total: 12 processes with 918 diagrams
```

of course many other diagrams contribute (many do not involve WW scattering)

How to Study WW Scattering

- To probe the diagrams that involve WW scattering, demand forward and backward jets (large $|\eta|$ and $\Delta\eta$)
- Many previous analyses have either used either the total number of events or single variable distributions.
- Challenge: cross sections are smallish (O(fb)).
(Especially small for the cleaner same sign WW channel.)
Need to extract as much information as possible from each event.

What We Did

- The Matrix Element Method is a technique which uses all available kinematic information for maximum sensitivity

- So we looked at how well one could do in discriminating various scenarios from SM-125 using the MEM in same sign WW scattering at the 14 TeV LHC

- I'll describe our procedure in more detail after describing the MEM

The Matrix Element Method

The Matrix Element Method

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

- The Matrix Element Method is the use of the full event-by-event likelihood.
- This likelihood is essentially the normalized differential cross section, evaluated for the particular kinematics of an event.

The Matrix Element Method

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

- The normalization involves a total cross section taking into account acceptances, etc.
  - when one integrates over the kinematic variables (momenta of final state particles), one obtains 1.

The Matrix Element Method

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

- The model dependence of this quantity is mostly in the (squared) matrix element, which is a function of model parameters, α.

- Note that the matrix element is a function of the true momenta $\mathbf{p}_i$ not the observed momenta $\mathbf{p}_i^{\text{vis}}$

The Matrix Element Method

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

- The expression naturally also includes phase space factors and integrals for final state particles
- Here the delta functions on the far right mean we only need to integrate over invisible final state particles (like neutrinos)

The Matrix Element Method

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

- In the expression for the likelihood here, the transfer function is a delta function
- This is a simplification.
- In general, one has some Gaussian-like function.
- Need to actually perform integrals for visible particles as well.

The Matrix Element Method

$$\chi^2 = -2\ln(\mathcal{L}) = -2\sum_{n=1}^{N} \ln \mathcal{P}(\mathbf{p}^{\mathsf{vis}}_{n,i}|\alpha)$$

- The event-by-event likelihood can be used to calculate the log likelihood for N events
- and in turn a value for χ^2 (if there are sufficient events)
- We will use this expression to obtain $\Delta\chi^2$ between the SM with 125 GeV Higgs and various alternative hypotheses

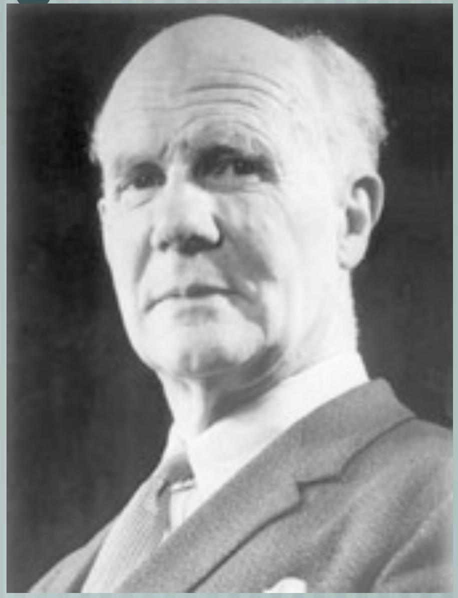
The Matrix Element Method

Pros

- Uses as close as possible to exact likelihood for all parameters.
  Optimal sensitivity.
- More transparent than BDTs, Neural Nets

Con

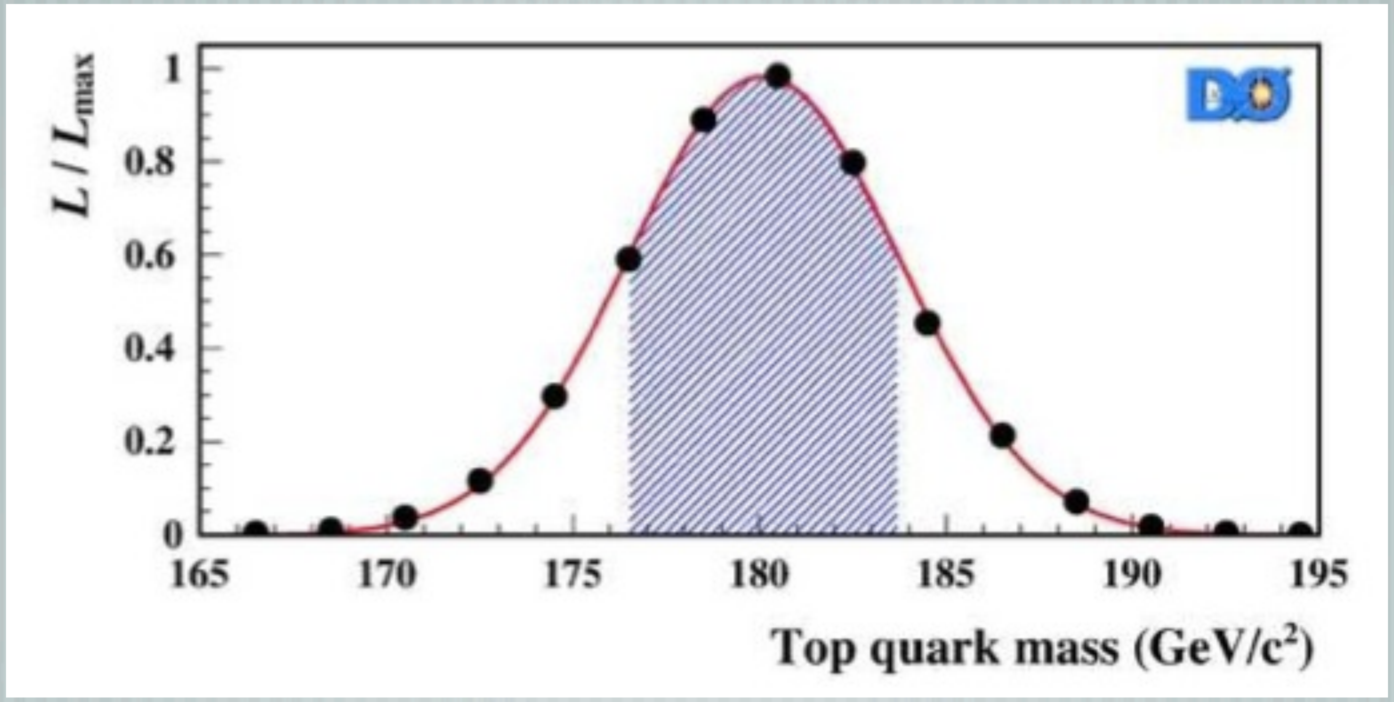
- Computationally intensive.
  Many integrals!

Actually Neyman and Pearson were roughly the same age. Google works in mysterious ways...

The Matrix Element Method

- Much use in the study of **top quark** properties at the Tevatron (D0 '99, '04, '08; CDF '06, '08; Fiedler et al. '10; ...)
- and in **B Physics** (Dunietz, Quinn, Snyder, Toki, and Lipkin, 1991), (Kramer and Palmer, 1992), (Gritsan and Smith, 2012)



The Matrix Element Method

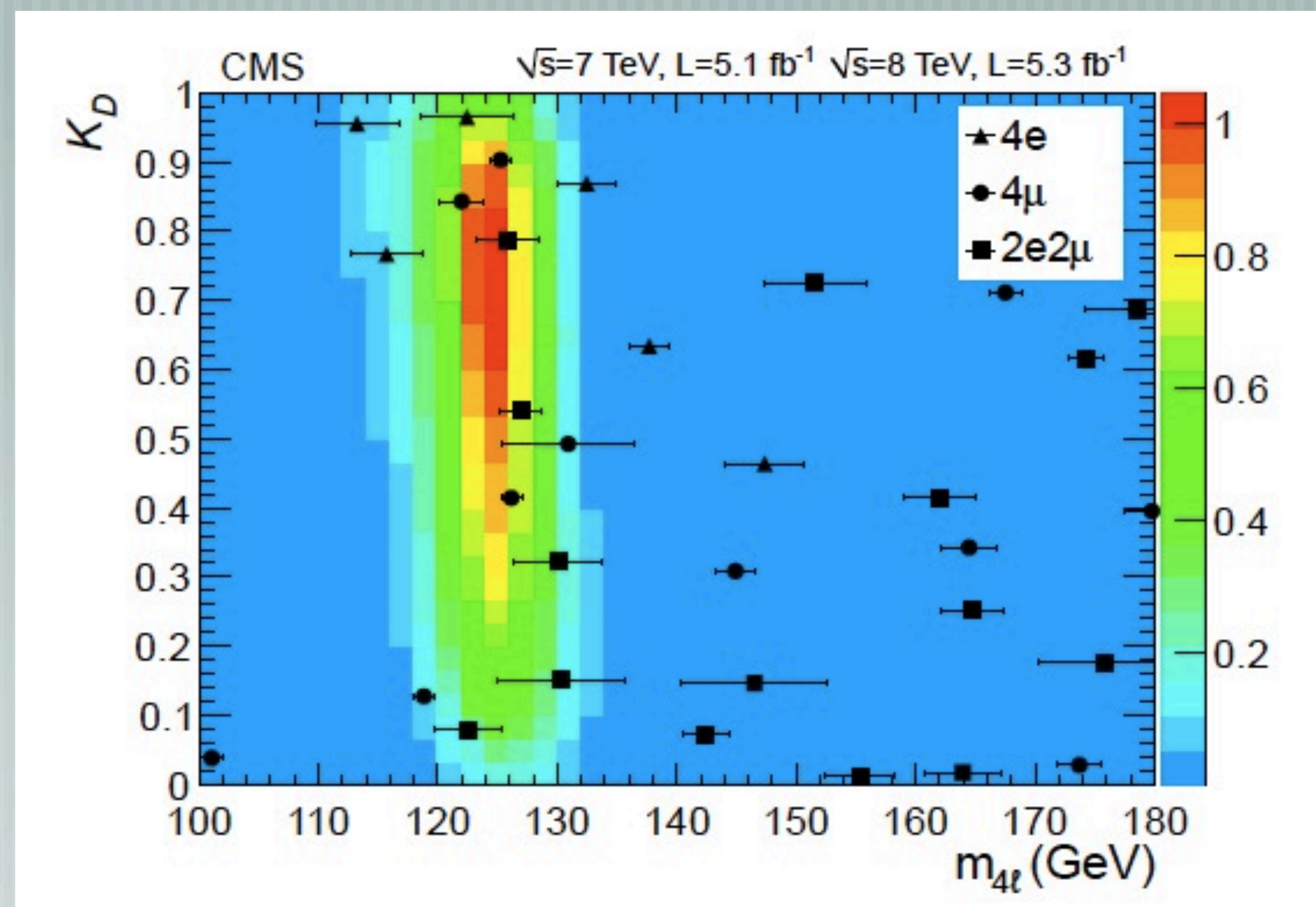
Much phenomenological study in $H \rightarrow ZZ^* \rightarrow 4\ell$

- (Gao, Gritsan, Guo, Melnikov, Schulze, and Tran, 2010)
- (De Rujula, Lykken, Pierini, Rogan, and Spiropulu, 2010)
- (Gainer, Kumar, Low, and Vega-Morales, 2011)
- (Campbell, Giele, and Williams, 2012)
- (Stolarski and Vega-Morales, 2012)
- (Bolognesi, Gao, Gritsan, Melnikov, Schulze, Tran, and Whitbeck, 2012)
- (P. Avery et al., 2012)
- (Gainer, Lykken, Matchev, Mrenna and Park, 2013)
- (Modak, Sahoo, Sinha, and Cheng, 2013)
- Et cetera...

The Matrix Element Method

Exciting part of Higgs discovery in $H \to ZZ^* \to 4\ell$

- Via the **MELA** framework used in Higgs discovery in CMS.
- **MELA**, **JHUGen** and **MEKD** (all MEM-based) used for further Higgs studies at the LHC

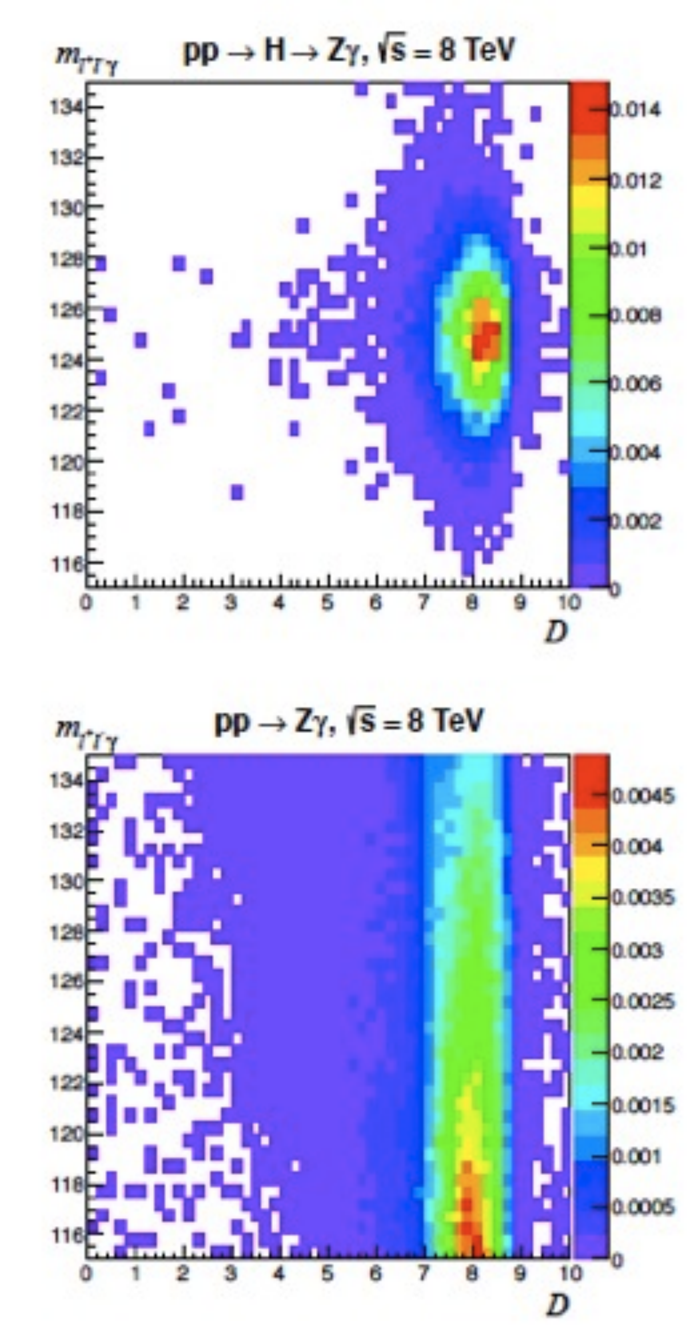


CMS 2012

The Matrix Element Method

Other MEM Higgs Studies...

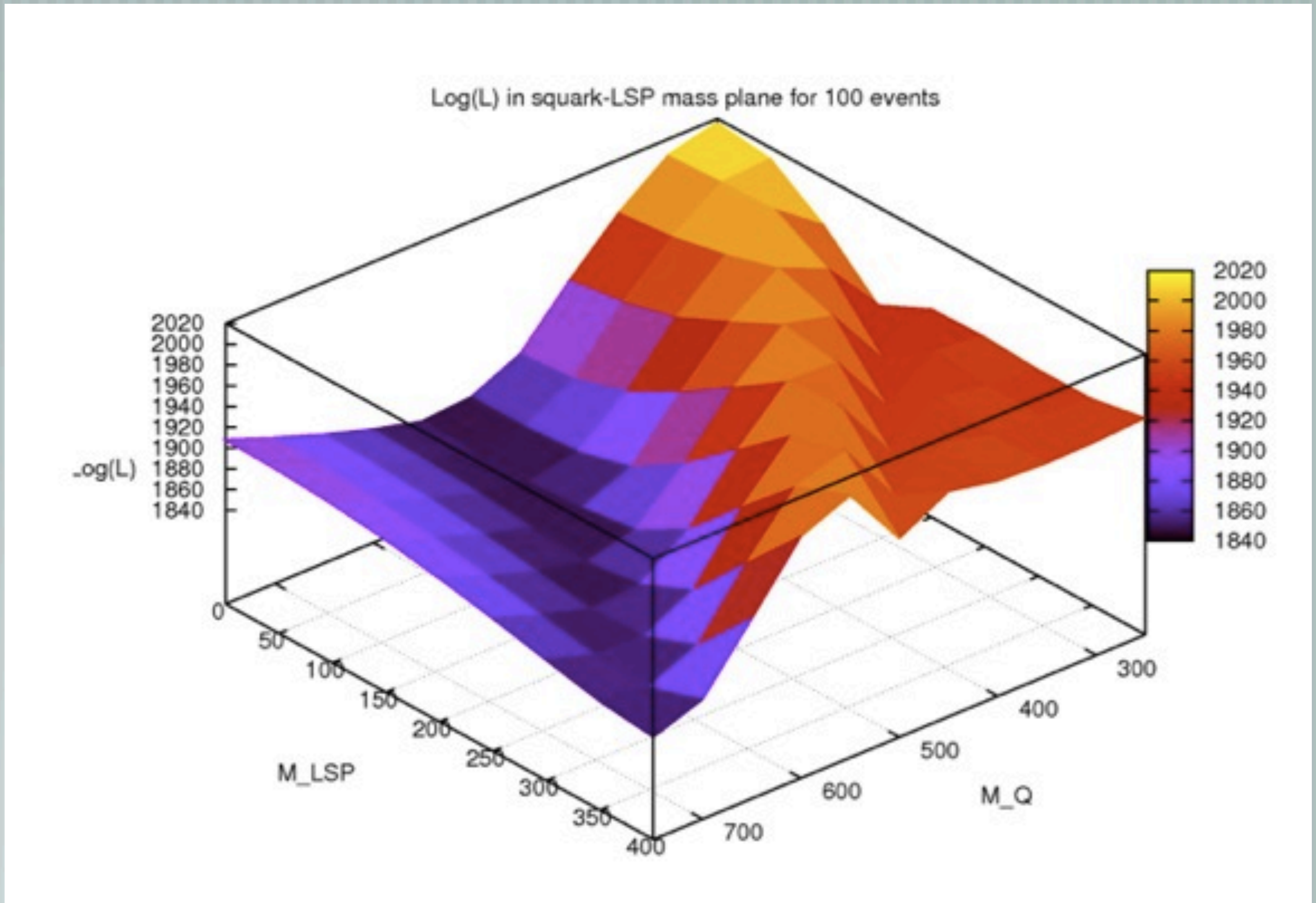
- (Cranmer and Plehn, 2007)
- (Hsu et al., 2007)
- (Aaltonen et al., 2009);
- (Therhaag, 2009);
- (Gainer, Keung, Low, and Schwaller, 2012)
- (Andersen, Englert, and Spannowsky, 2012)
- (Campbell, Ellis, Giele, and Williams, 2013)
- (Artoisenet, de Aquino, Maltoni, and Mattelaer, 2013)
- (Artoisenet et al., 2013)
- Et cetera...



The Matrix Element Method

BSM MEM

- (Alwall, Freitas, and Mattelaer, 2009
- (Chen and Freitas, 2011)
- (Gedalia et al., 2012)



(Alwall, Freitas, and Mattelaer, 2009)

Our Procedure

- For each analysis we used 100 parton-level leptonic same sign WW+2j events generated with MadGraph/MadEvent using the hypothesis of the SM with a 125 GeV Higgs
  - σ = 0.59 fb at 14 TeV, so ≈ 170 fb^{-1} (somewhat more at 13 TeV).
- Delta functions for transfer functions in MEM calculation
- Obtained $\Delta\chi^2$ using the MEM.
  - Compared with an analysis using only m_{ll}

Our Procedure

- Evaluate MEM likelihood using
private code (with diagrams generated by FeynArts 3.3)

- Verify using MadWeight, (Artoisenet, Lemaître, Maltoni, and Mattelaer, 2010)

Preselection Cuts

- In principle, if (MEM) likelihood includes all possible backgrounds, no need for cuts

- Due to finite computing power and a desire not to model reducible backgrounds (more on this later) we applied pre-selection cuts

Preselection Cuts

- Acceptance $|\eta_\ell| < 2.5 \quad |\eta_j| < 5$

  $p_{\mathrm{T},\ell} > 20\ \mathrm{GeV} \quad p_{\mathrm{T,j}} > 30\ \mathrm{GeV}$

- Isolation $\Delta R_{jj,\ell j,\ell\ell} > 0.4$

- VBF topology $|\eta_{j_1} - \eta_{j_2}| > 4 \quad |\eta_j| > 1$

  $m_{j_1 j_2} > 100\ \mathrm{GeV}$

- Reducible top pair backgrounds $m_{\ell j} > 190\ \mathrm{GeV}$

Reducible Top Pair Backgrounds

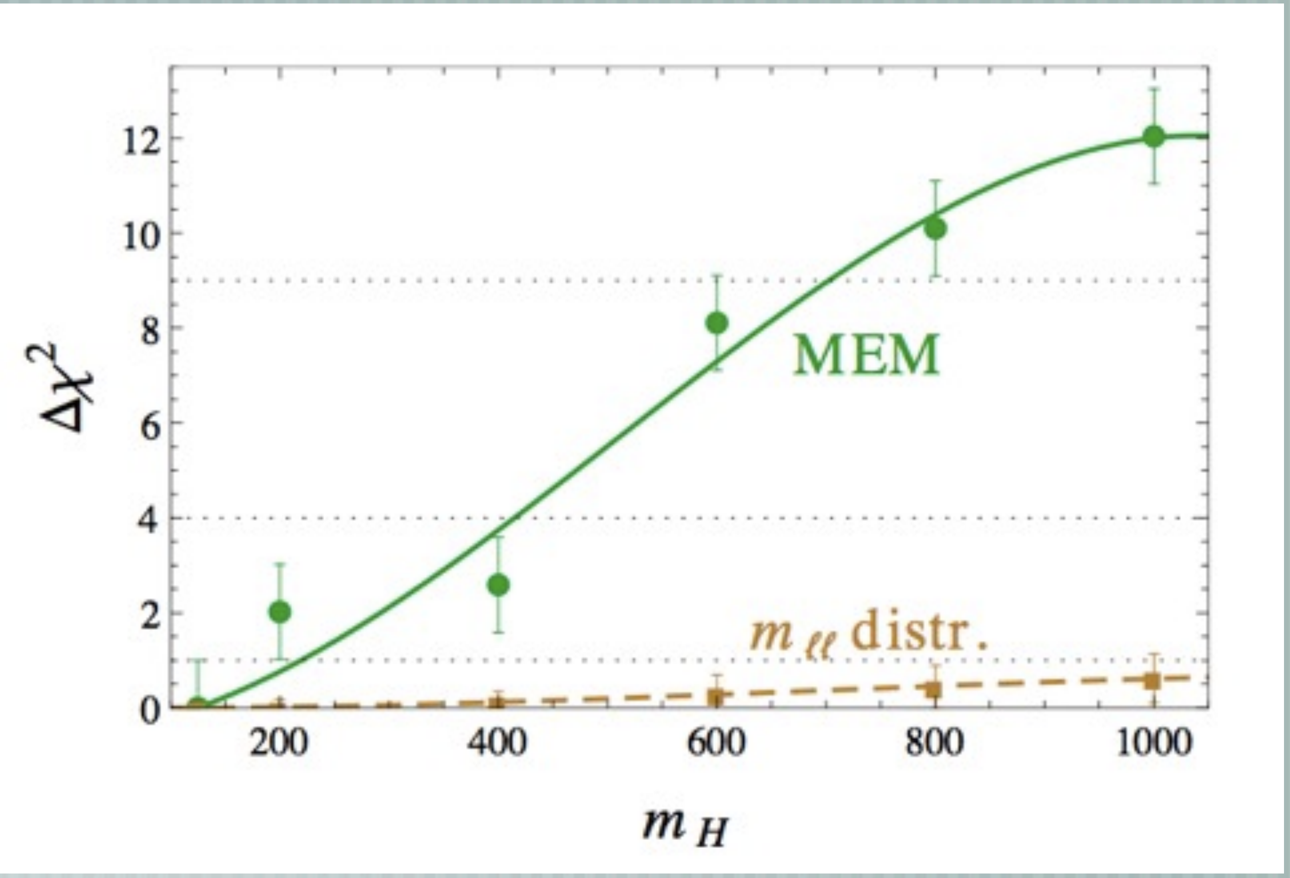
- Contribution from leptonic top decays with charge misidentification
  - also contribution from leptonic B decays
- Small fraction of $t\bar{t}$ events, but $t\bar{t}$ cross section is large
- This background is discussed in more detail in (Doroba et al. 2012)
- The invariant mass cut reduces cross section by a factor of 4

Results

- We looked at 3 scenarios
  - SM with varying Higgs mass
  - THDM with varying heavy Higgs mass and ξ
  - SILH with varying k = $1/\sqrt{1 - c\,v^2/f^2}$

Results: SM

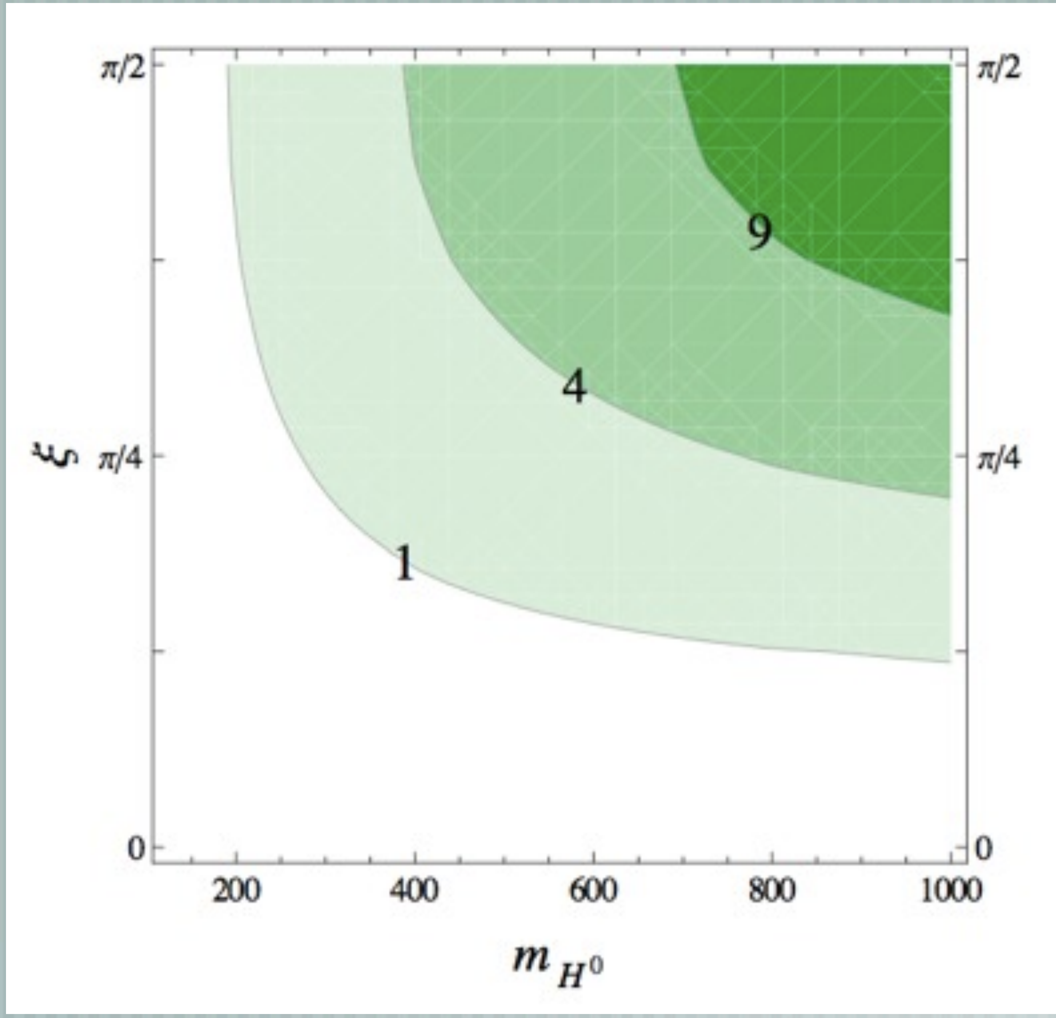
- Here we determine the extent to which other SM Higgs masses are disfavored with respect to 125 GeV in this channel



- Of course we know $m_H \approx 125$ GeV

- Illustrates the procedure and gives a more intuitive measure of sensitivity

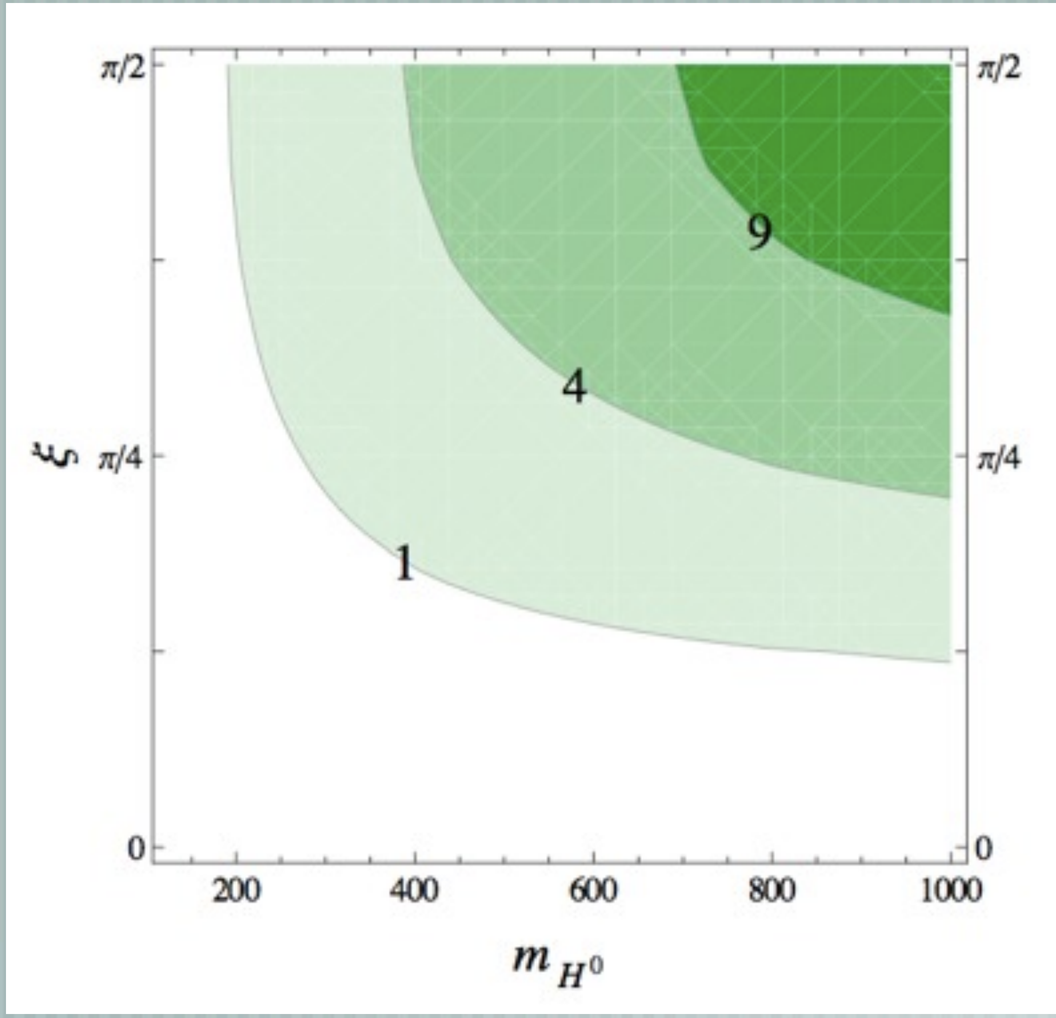
Results: THDM



$\Delta\chi^2$ contours

Here we determine the extent to which various values of $\xi = \alpha - \beta$ and heavy Higgs mass are disfavored with respect to the SM

Results: THDM

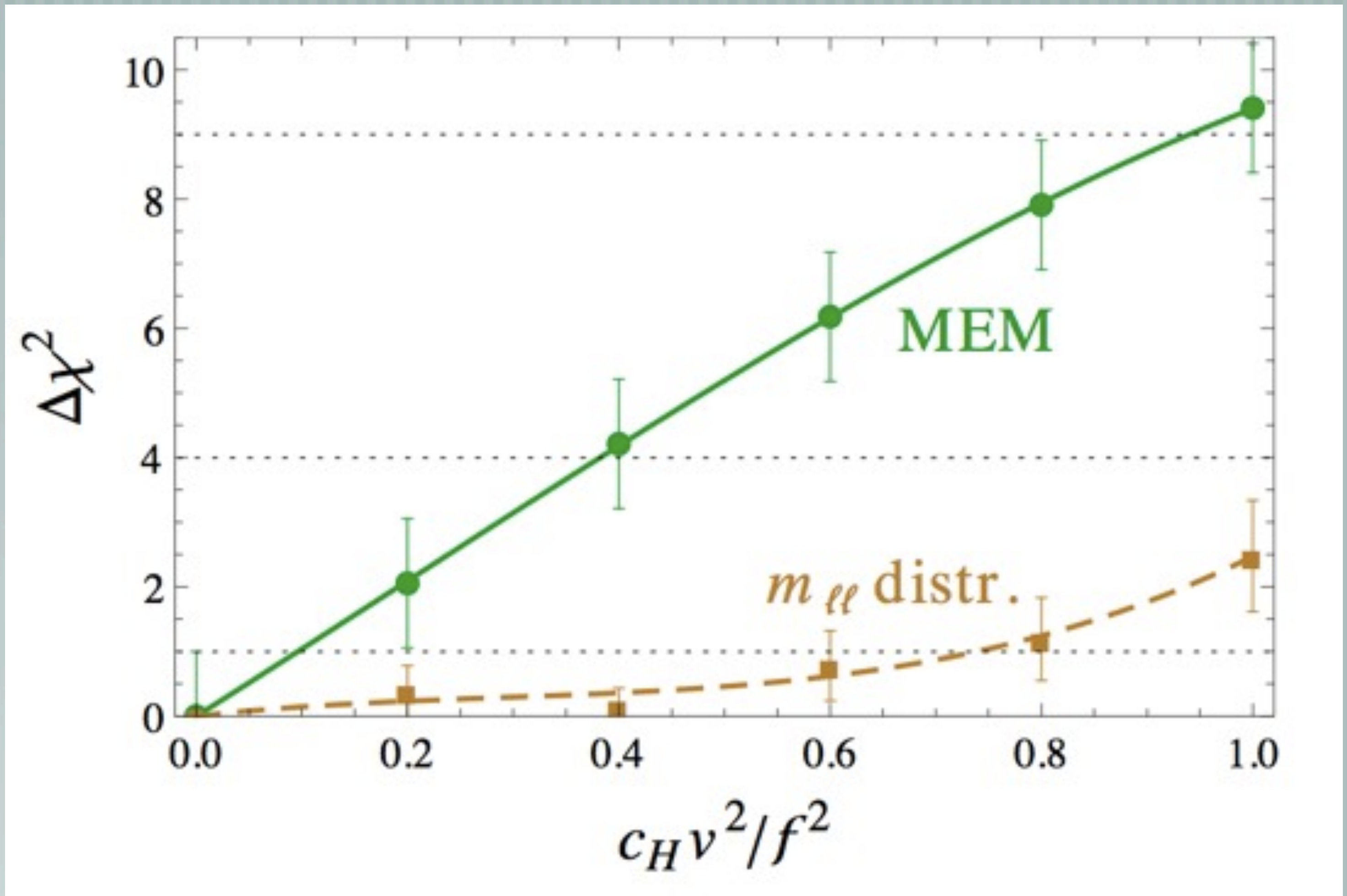


$\Delta\chi^2$ contours

- Note:
  - $\xi = 0$ reproduces the SM hWW coupling
  - $\xi = \pi/2$ reproduces the SM with heavy Higgs mass
- Heavy Higgs mass dependence because lighter heavy Higgses cancel more of the $\sim t + u$ behavior of the WW scattering amplitude at the energies probed

Results: SIHL

- Finally we determine the extent to which the scaling of the hWW coupling found e.g. in SILH models is disfavored with respect to the SM



hWW coupling scales like

$$1/\sqrt{1 - c\,v^2/f^2}$$

So discrimination increases monotonically with cv^2/f^2

Jet Energy

- Largest systematic error is related to the measurement of final state particle momenta, especially jets and especially energy
  - Can incorporate jet smearing functions and
  - treat the overall jet energy scale as a free parameter in the fit
- This would lead to a substantial increase in computing time
- Sensitivity of the MEM should not be significantly reduced.

Reducible Backgrounds

- We discussed (and used preselection cuts to control) the reducible background from $t\,\bar{t}$.
- Another reducible background from W + 3j events where one jet fakes an (appropriately charged) lepton (M. Schmitt)
- If electron fake rate from jets is 10^{-4}, then rate for this background may be ~15% of signal rate
- Need a more detailed look at this from the experimental side
- Can fake rate be made low enough using more stringent reconstruction criteria for electrons?
- If not, can include in the likelihood.. but more work, potential systematic errors, parameters.

NLO and PDFs

- **NLO** effects generally small for VBF processes (Jäger, Oleari, and Zeppenfeld, 2009)
  - World experts on the MEM at NLO are in this building cf. (Campbell, Giele, and Williams, 2012), (Campbell, Ellis, Giele, and Williams, 2013)
  - Procedure for including extra radiation: (Alwall, Freitas, and Mattelaer, 2011)
  - Inclusion of parton showers: (Soper and Spannowsky, 2011), (Soper and Spannowsky, 2012)
- **PDF** errors are already relatively small, but should become much smaller with LHC data

Future Work

- Opposite sign case
- Improved handling of systematic effects (where pheno-level tools are appropriate)
- Probing other departures from SM hWW couplings.
- All (except maybe systematics) conceptually straightforward.

Stay tuned!!!