High-energy WW scattering with the MEM

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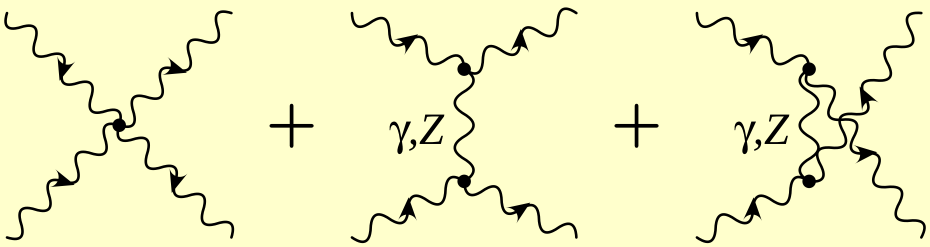
in collaboration with J. Gainer, arXiv:1211.xxxx

1. Vector-boson scattering and unitarity
2. Matrix Element Method
3. WW scattering and MEM
4. Conclusions

Vector-boson scattering and unitarity

- Recent discovery of bosonic resonance with mass 125–126 GeV
  $\longrightarrow$ consistent with SM Higgs
- Still large uncertainty on its properties and details of EWSB
  - More information from improved rate/BR measurements
  - Direct test of role in EWSB through high-energy VV scattering

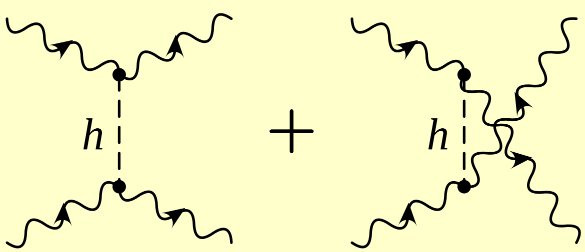
Example: $W_L^+ W_L^+ \to W_L^+ W_L^+$



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

$\longrightarrow$ Grows linearly for $s \to \infty$

SM Higgs contribution:



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

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

Unitarity and EWSB

Other examples of unitary-restoring physics:

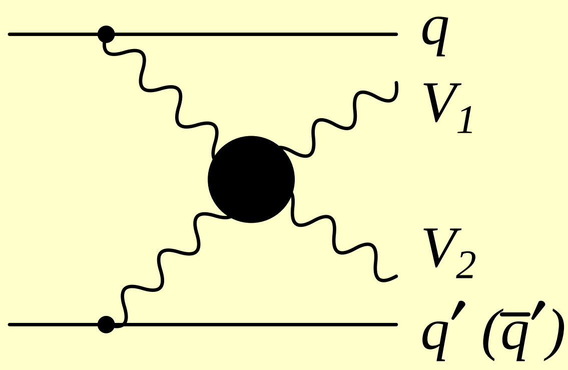
- Extended Higgs sectors (2 Higgs doublets, SUSY, etc.)
- Spin-1 resonances (Higgs-less)
- Technicolor (σ, ρ techni-mesons)
- Composite Higgs with modified couplings compared to SM + heavy resonances (Little Higgs, etc.)
- Higgs with non-perturbative self-coupling
- ...

Some models disfavored by electroweak precision and LHC data

$\longrightarrow$ Independent check through VV scattering desirable
$VV = W^+W^+,\ W^+W^-,\ W^\pm Z,\ ZZ$

Existing work

Production at hadron colliders:



1. Apply smart cuts on vector-boson fusion (VBF) topology:
   $\longrightarrow$ two jets with large rapidity gap
2. Count events or analyze m_{VV}

Problem: typical event rate $\sim$ 0.1–0.5 fb at $\sqrt{s} = 14$ TeV

Duncan, Kane, Repko '86
Dicus, Vega '86
Kleiss, Stirling '88
Barger, Cheung, Han, Phillips '90
Baur, Glover '90
Dicus, Gunion, Vega '91
Dicus, Gunion, Orr, Vega '92
Bagger et al. '94,'95
Iordanidis, Zeppenfeld '98
Butterworth, Cox, Forshaw '02
Alboteanu, Kilian, Reuter '08
Englert, Jäger, Worek, Zeppenfeld '09
Ballestrero, Bevilacqua, Maina '09
ATLAS '09
Ballestrero, Franzosi, Maina '11
Doroba et al. '12
and others...

Matrix Element Method

Matrix Element Method (MEM):

Kondo '88,'91
Dalitz, Goldstein '92
DØ collaboration '99,'04

Likelihood that measured event, $\mathbf{p}_i^{\text{vis}}$, agrees with theoretical matrix element M_α:

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

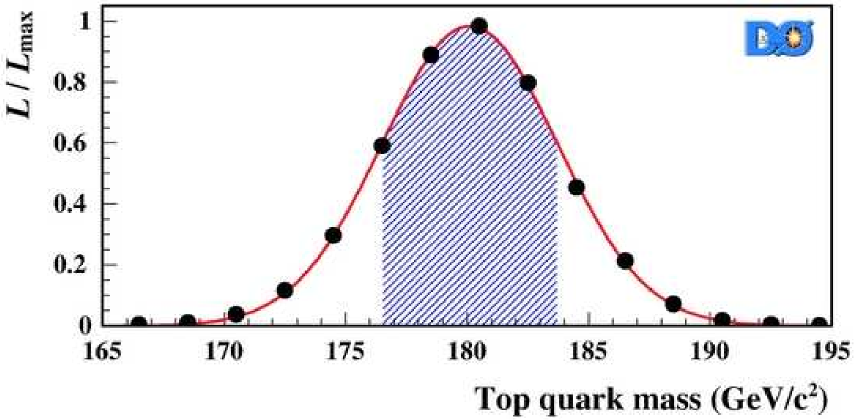
For sample of N events:

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

(+) Uses complete event information
(+) Effective for small event samples
(+) Works well also with invisible final-state objects

Applications of MEM

Top physics at Tevatron:



DØ '99,'04,'08,... CDF '06,'08,...

Fiedler et al. '10

Applications of MEM

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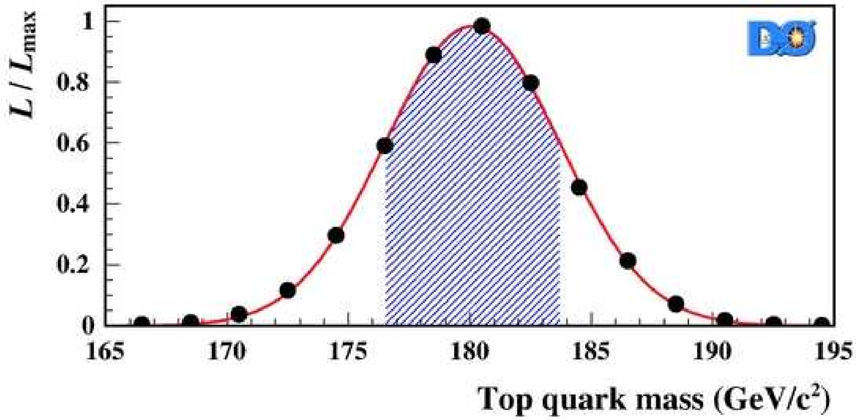

DØ '99,'04,'08,... CDF '06,'08,...
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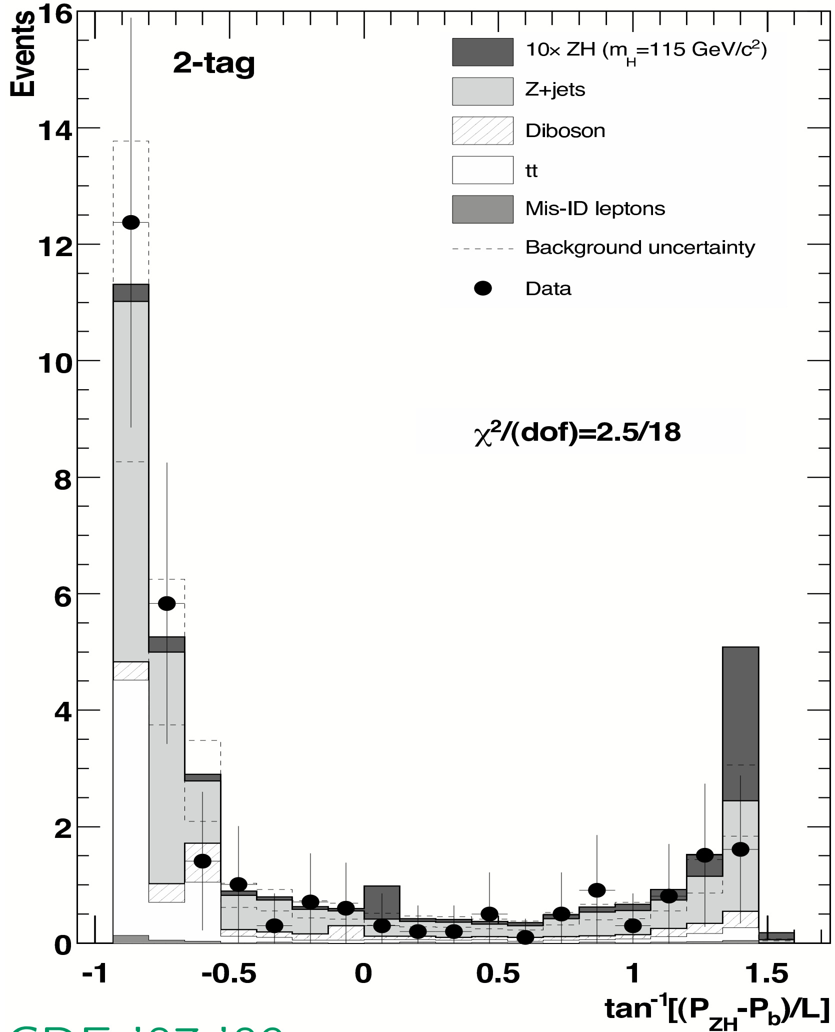
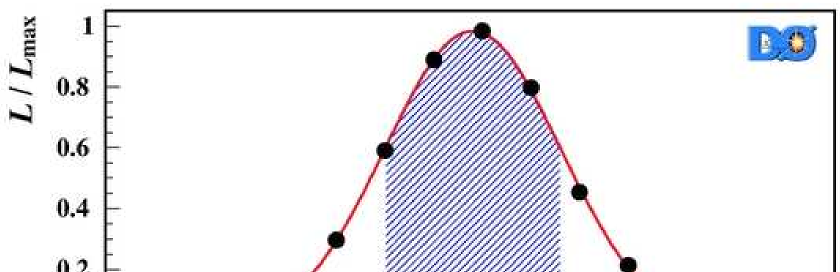
Higgs searches at Tevatron/LHC:



CDF '07,'09
Therhaag '09
Gainer, Kumar, Low, Vega-Morales '11

Applications of MEM

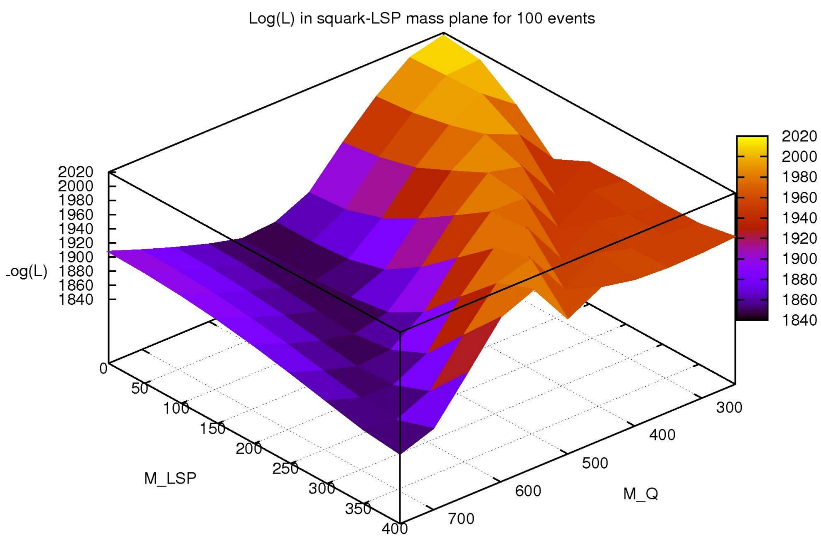
Top physics at Tevatron:



DØ

Fie

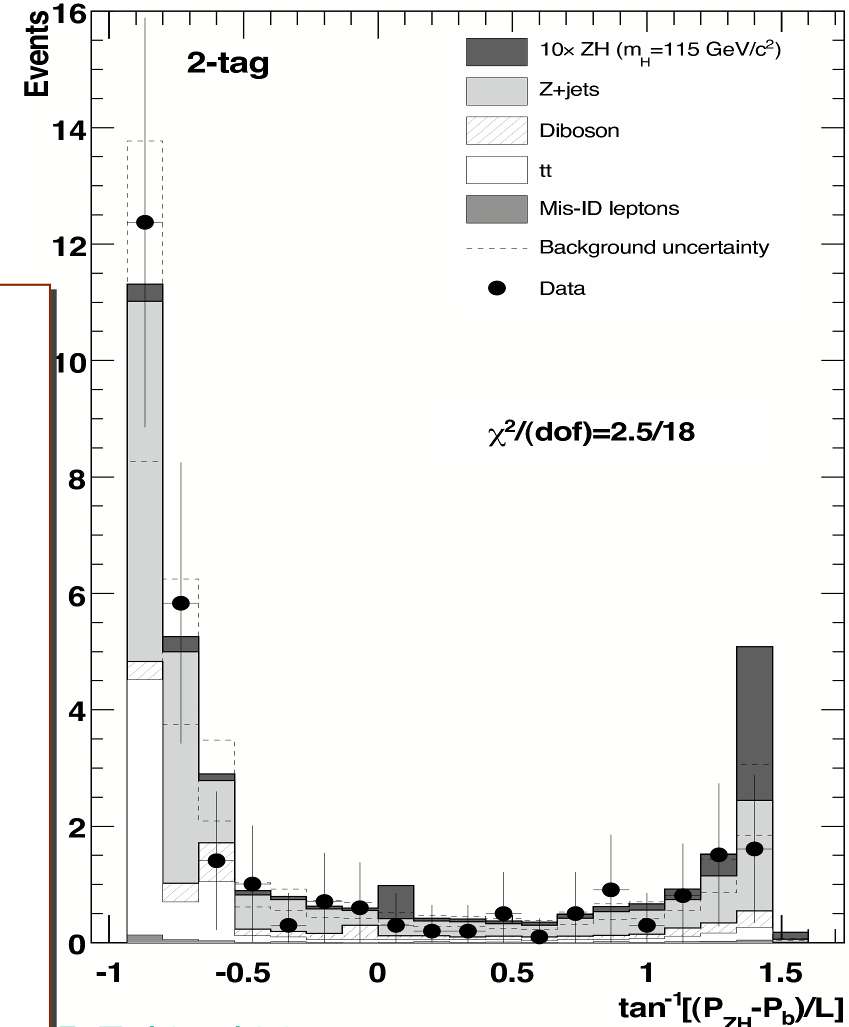
Model discimination and mass measurement for new physics:



Alwall, Freitas, Mattelaer '09

Chen, Freitas '10

Higgs searches at Tevatron/LHC:



DF '07,'09

herhaag '09

ainer, Kumar, Low, Vega-Morales '11

WW scattering and MEM

First step: $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$ $\quad (\ell^{(\prime)} = e, \mu)$

(−) Relatively low event rate

(−) Final state cannot be reconstructed kinematically

(+) Clean final state (no jet ambiguity)

(+) Low background

Main backgrounds:

- Intrinsic $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$
  (contributions without $W_L^+W_L^+$ scattering)
- $pp \to t\bar{t} \to jj\ell^+\ell'^-\nu_\ell\bar{\nu}_{\ell'}$ — Doboda et al. '12
  (due to wrong charge identification for $\mathcal{O}(1\%)$ of hard lepton tracks)

Implementation of MEM for WW scattering

Partonic process: $q\bar{q} \to q'\bar{q}'W^+W^+ \to q'\bar{q}'\ell^+\ell'^+\nu_\ell\nu_{\ell'}$ $(q, q' = u, d, s, c)$

- Only diagrams with two on-shell W^+
  (Remainder is negligible, see Doboda et al. '12)
- Analysis at parton-level
  (inclusion of jet smearing functions is easy but computing intensive)
  DØ '04, Fiedler et al. '10

- Private code for likelihood weights and cross-section normalization
- MADGRAPH/MADEVENT/MADWEIGHT for cross-checks
- Simulation of "experimental" input events with MADEVENT/
  ($m_h = 125$ GeV)

Implementation of MEM for WW scattering

Preselection cuts:

$p_{\mathrm{T},\ell} > 20$ GeV	$p_{\mathrm{T,j}} > 30$ GeV	$\lvert\eta_\ell\rvert < 2.5$	$\lvert\eta_j\rvert < 5$	(acceptance)
$\Delta R_{jj,\ell j,\ell\ell} > 0.4$				(isolation)
$\lvert\eta_{j_1} - \eta_{j_2}\rvert > 4$	$\lvert\eta_j\rvert > 1$	$m_{j_1 j_2} > 100$ GeV		(VBF cuts)
$m_{\ell j} > 190$ GeV				($t\bar{t}$ bkgd.)

↖ 25% signal eff.

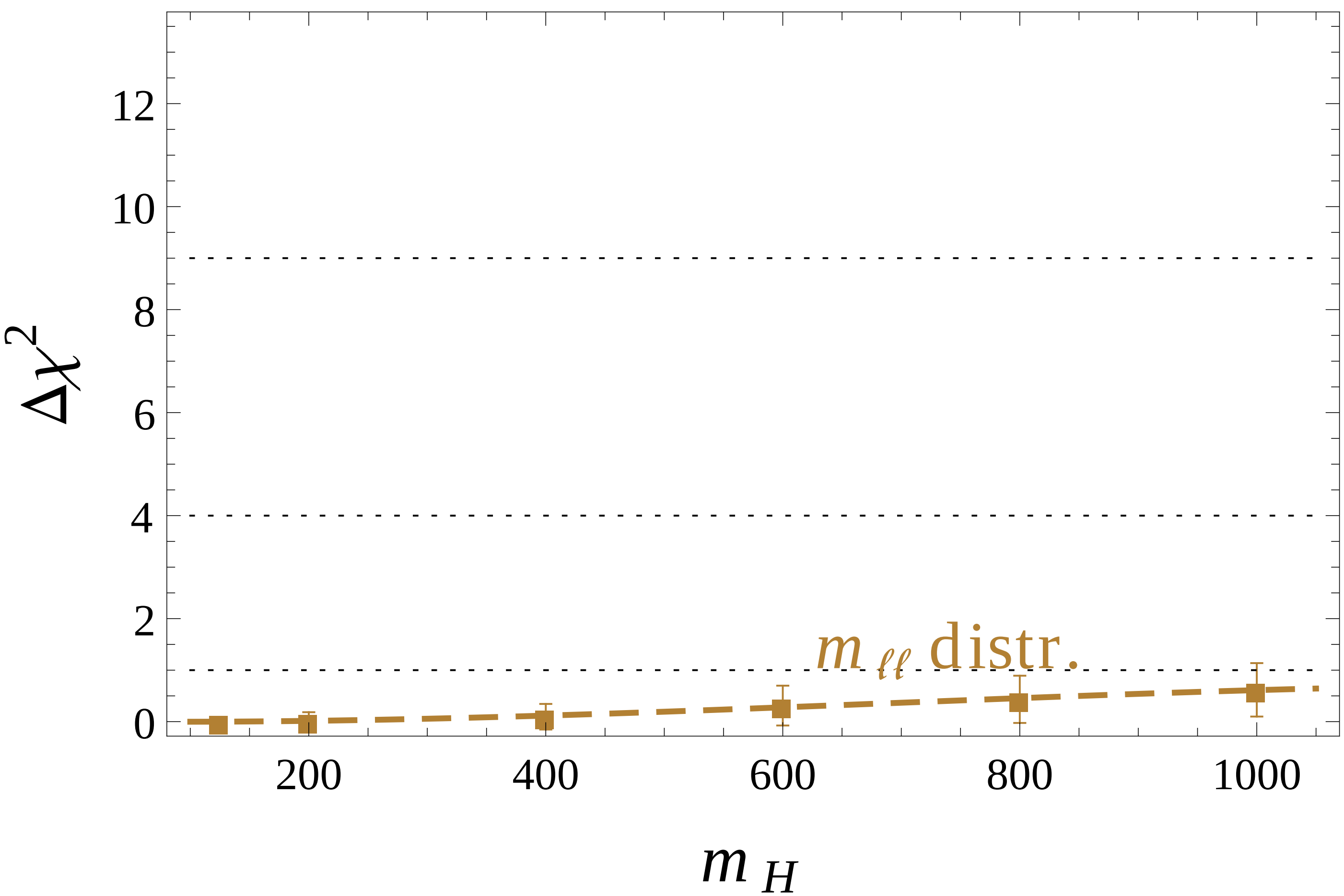
SM cross-section ($\sqrt{s} = 14$ TeV): $\sigma = 0.59$ fb

$\longrightarrow$ 100 events with $\mathcal{L} \sim 170$ fb^{-1}

Results SM

MEM: 100 events at $\sqrt{s} = 14$ TeV for $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$

Traditional analysis: $m_{\ell\ell}$ distribution, 2 bins for $m_{\ell\ell} \in [0, 1000]$ GeV, (same event sample)



Results: SM

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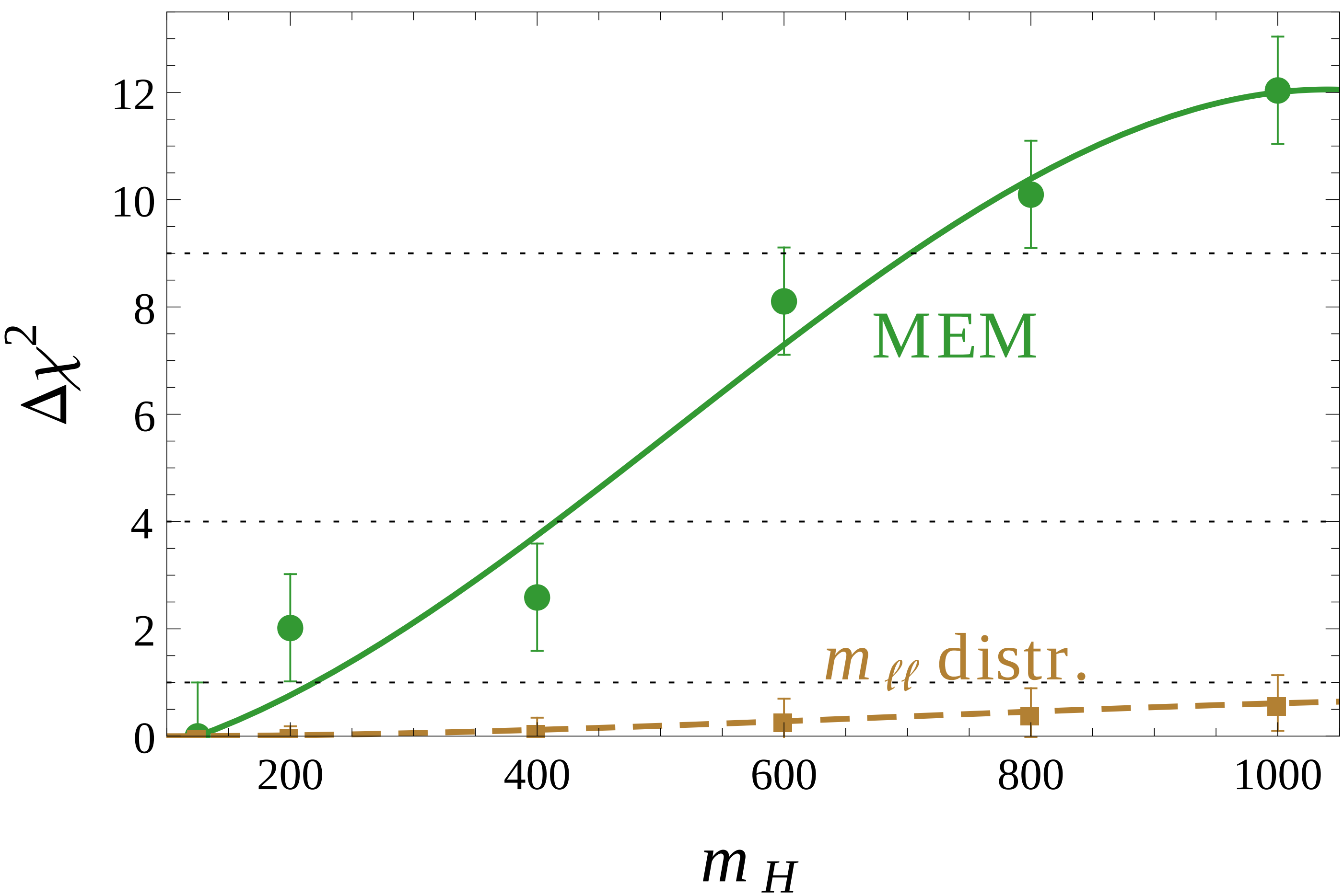


Two Higgs Doublet Model (THDM)

Higgs-like particle with $m = 125$ GeV has been observed

$\longrightarrow$ Could be one of two CP-even Higgs states h^0 and H^0 ($m_{h^0} = 125$ GeV)

$\longrightarrow$ Both needed for complete unitarization

Mixing angles:

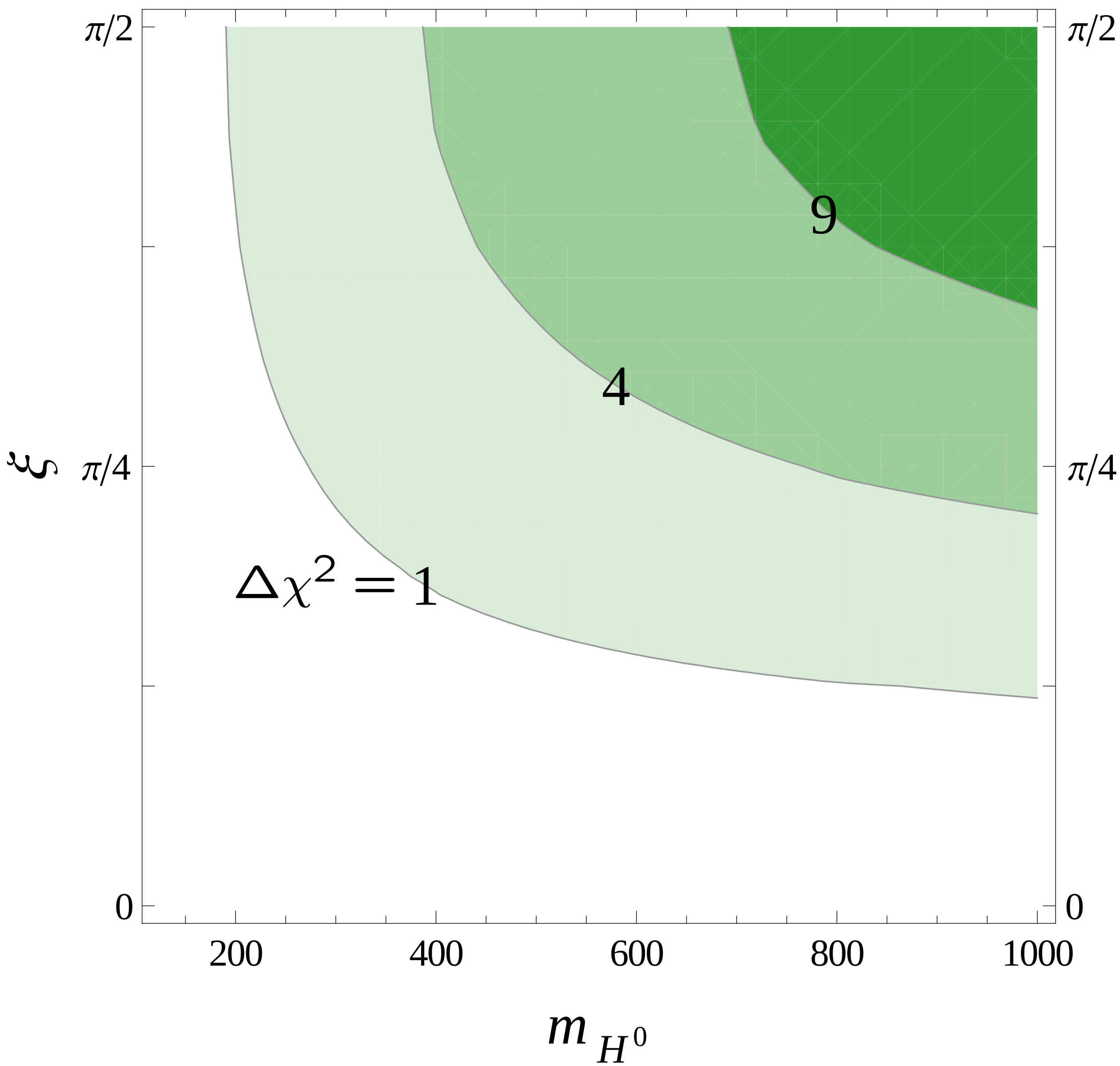
$$h^0 = \cos\alpha\ H_1^0 - \sin\alpha\ H_2^0$$
$$H^0 = \sin\alpha\ H_1^0 + \cos\alpha\ H_2^0$$

$$\frac{g(h^0WW)_{\text{THDM}}}{g(HWW)_{\text{SM}}} = \cos(\beta-\alpha) \equiv \cos\xi$$

$$\tan\beta = \langle H_2^0\rangle / \langle H_1^0\rangle$$

$$\frac{g(H^0WW)_{\text{THDM}}}{g(HWW)_{\text{SM}}} = \sin(\beta-\alpha) \equiv \sin\xi$$

Results: THDM



100 events
$\sqrt{s} = 14$ TeV

Strongly Interaction Light Higgs (SILH)

Class of models with strong dynamics at $\Lambda \sim 4\pi f > 1$ TeV
and light composite Higgs boson
(here $m_H = 125$ GeV)

Guidice, Grojean, Pomarol, Ratazzi '07

- Higgs couplings to SM particles reduced by $1/\sqrt{1 - c\,v^2/f^2}$, $c \sim \mathcal{O}(1)$
- Full unitarization for $M_{WW} \to \infty$ by heavy resonances ($m \sim$ few $\times f$)
  $\longrightarrow$ May be beyond reach of LHC
- Special case of THDM with

  $m_{H^0} \to \infty$

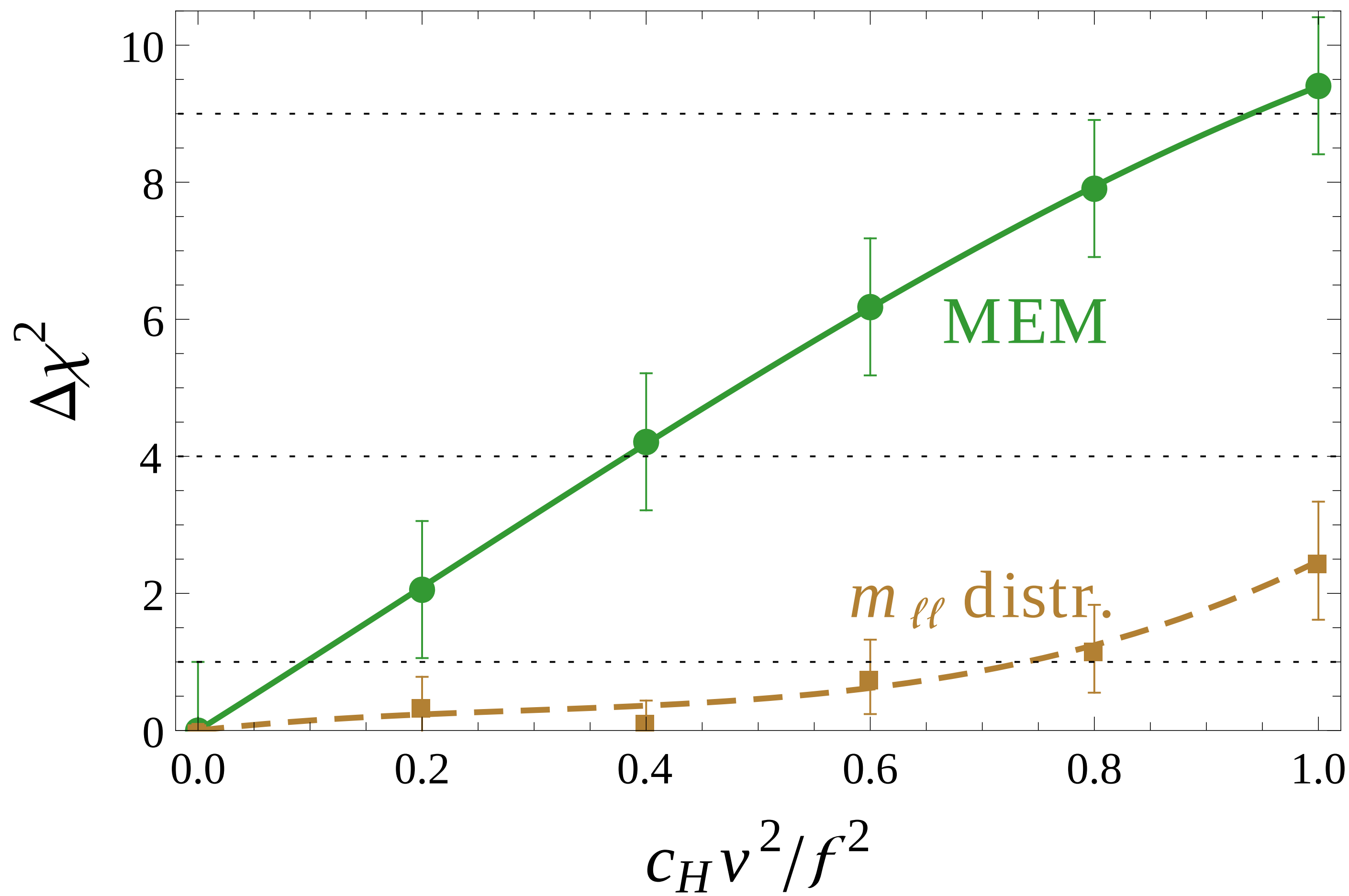
  $\cos\xi = 1/\sqrt{1 - c\,v^2/f^2}$

Results: SILH

MEM: 100 events at $\sqrt{s} = 14$ TeV for $pp \to jjW^+W^+ \to jj\ell^+\ell'^+\nu_\ell\nu_{\ell'}$

Traditional analysis: $m_{\ell\ell}$ distribution, 2 bins for $m_{\ell\ell} \in [0, 1000]$ GeV,

(results compatible with Ballestrero, Franzosi, Maina '11)



Conclusions

- High-energy VV scattering central for testing mechanism of EWSB

- MEM significantly improves sensitivity compared to traditional analysis methods
  → Demonstrated with MEM fits for W^+W^+ in three models: SM, THDM, SILH
  → Extension to other models conceptually simple (matrix elements from FEYNARTS/) Hahn

- Does not require resolution of a resonance
  → Useful for “nightmare” scenarios with very broad resonances

- Systematic uncertainties:
  - Jet energy scale: can include as free parameter in fit DØ ’04
  - QCD corr.: small (few %) for VBF Jäger, Oleari, Zeppenfeld ’09
  - Quark/antiquark PDFs: can obtain from Drell-Yan