(Non)-Standard Model Higgs Boson

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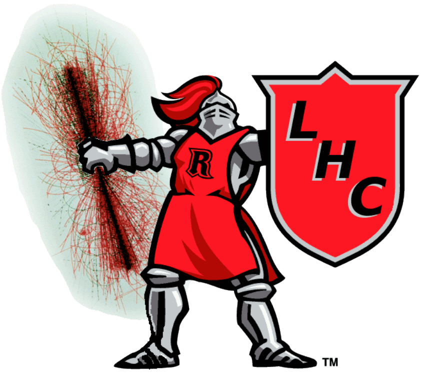


October 1, 2012

Experimental Investigation of the

Higgs Sector Has Begun !!

Outline:

Extra (Heavy) Higgs in Standard Channels

Higgs -> Multi-Leptons
- Standard Model Higgs
- Multiple Higgs – Extended Higgs Sector

Higgs in Association with New Physics
- Higgs -> $\gamma\gamma$ + X
- top -> charm + Higgs

Higgs -> $\gamma\gamma$, ZZ*, Zγ
- The New Precision EW Physics

Measuring Time Reversal Violation in the
- Higgs -> ZZ* -> l l l l Channel

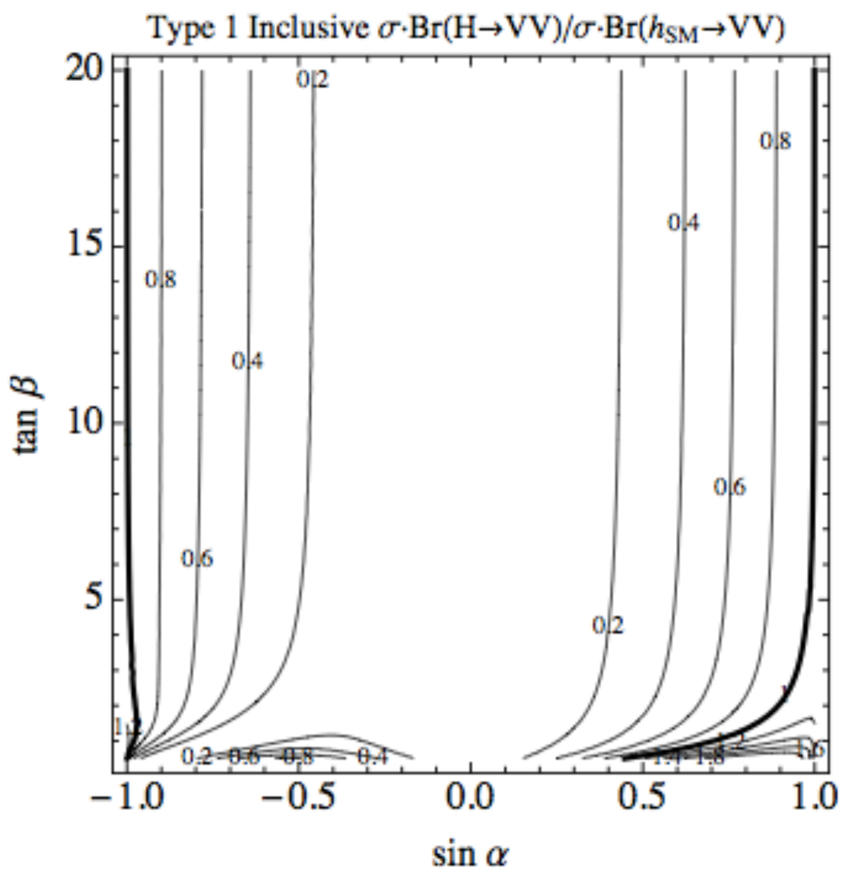
Reconstructing the Higgs Mass in the
- Higgs -> WW* -> l ν l ν Channel

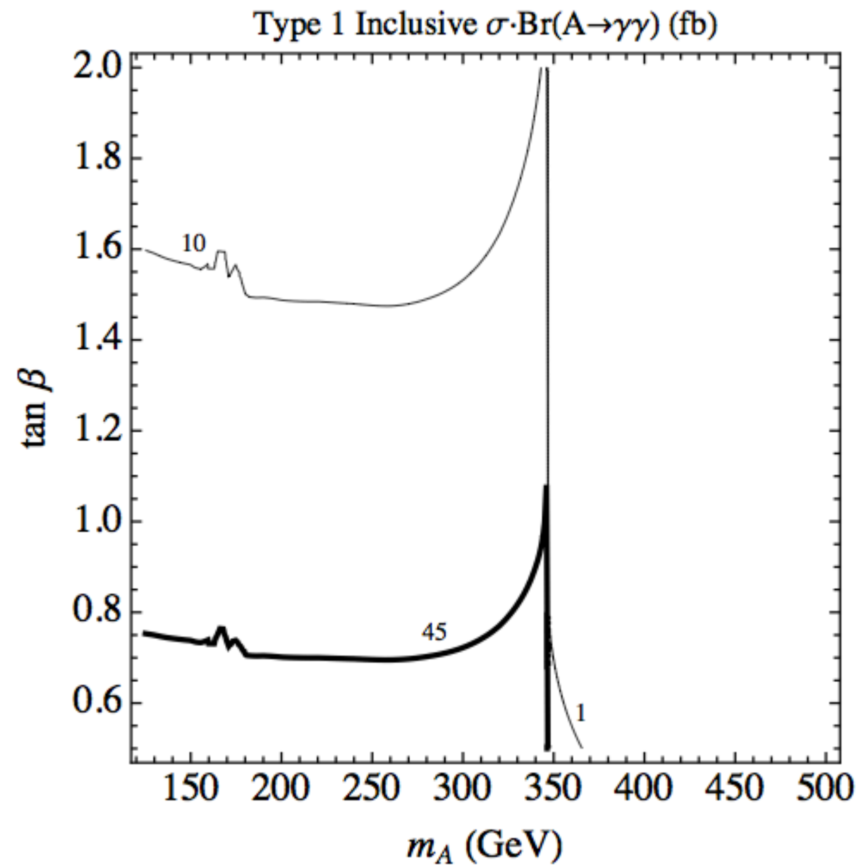
Displaced Higgs

Extra (Heavy) Higgs Bosons in Standard Higgs Channels

(Craig, ST)

H -> VV (mixes with h) and H,A -> $\gamma\gamma$



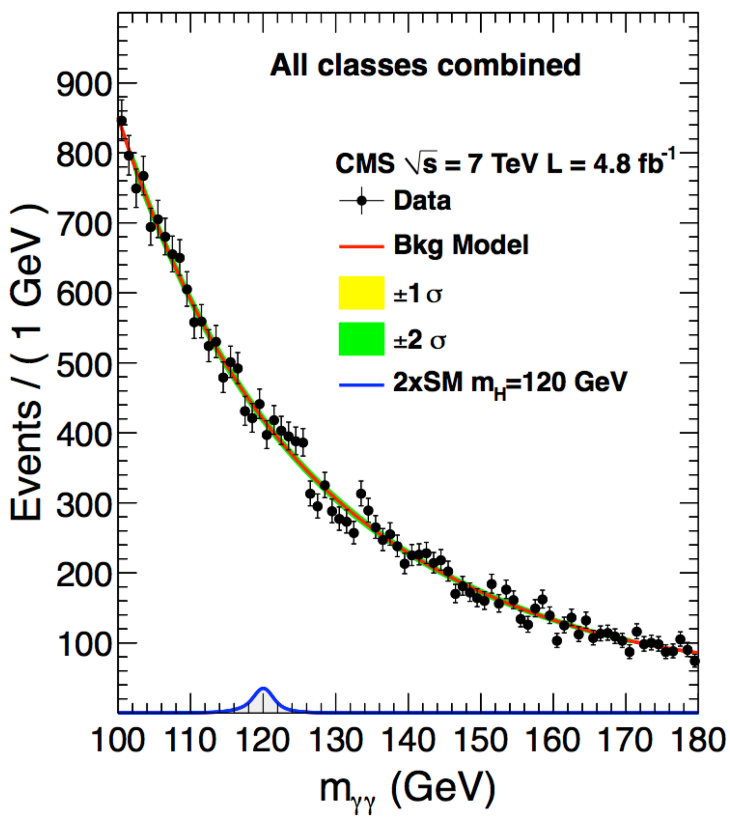


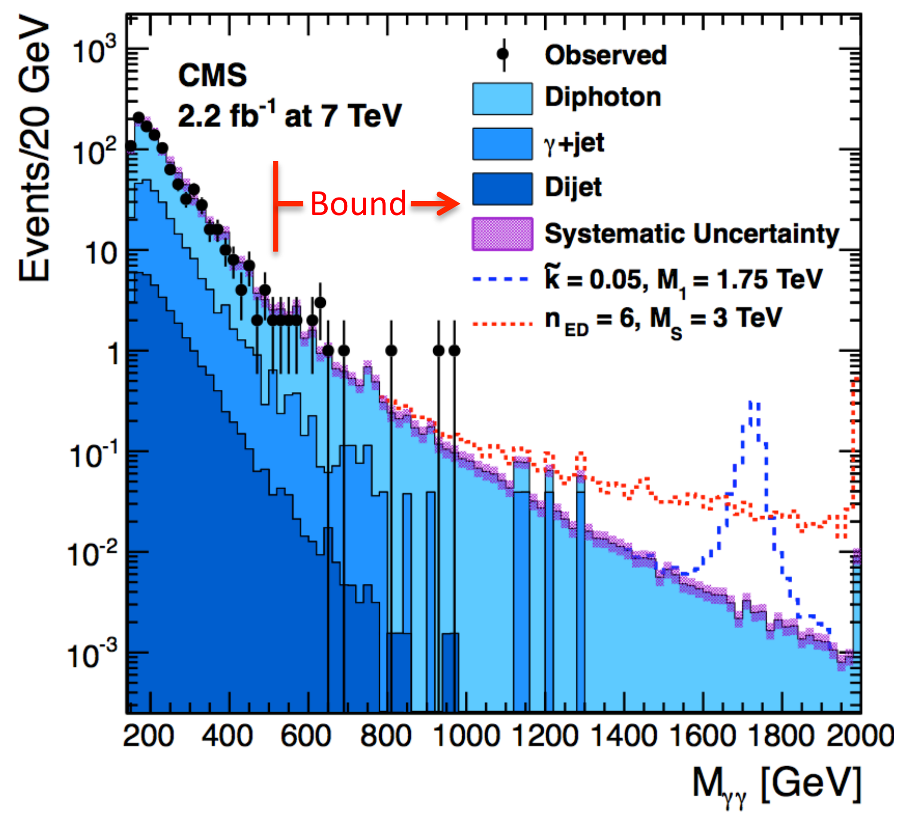
m_H = m_h = 400 GeV
Note: H Width reduced wrt h_{SM}

σ . Br(h -> $\gamma\gamma$) = 45 fb
for m_h = 125 GeV

Extra (Heavy) Higgs Bosons in Standard Higgs Channels

h, H ,A -> γγ





Multi-Lepton Signatures

(CMS)

157 Channels – Signal / Control Regions + Kinematics

Backgrounds: Irreducible + Fake + …

MET + H_T Analysis 7 TeV 5 fb^{-1}

Selection	N(τ)=0		N(τ)=1		N(τ)=2	
	obs	expect	obs	expect	obs	expect
4ℓ Lepton Results						
4ℓ >50,H_T >200,noZ	0	0.017 ± 0.005	0	0.08 ± 0.06	0	0.6 ± 0.6
4ℓ MET>50,H_T > 200, Z	0	0.20 ± 0.04	0	0.25 ± 0.11	0	0.7 ± 1.0
4ℓ MET>50,H_T <200,noZ	1	0.19 ± 0.07	3	0.56 ± 0.16	1	1.4 ± 0.6
4ℓ MET>50,H_T <200, Z	1	0.74 ± 0.20	4	2.2 ± 0.6	0	1.1 ± 0.7
4ℓ MET<50,H_T >200,noZ	0	0.006 ± 0.001	0	0.13 ± 0.08	0	0.25 ± 0.07
4ℓ MET<50,H_T >200, Z	1	0.78 ± 0.31	0	0.52 ± 0.20	0	1.13 ± 0.42
4ℓ MET<50,H_T <200,noZ	1	2.4 ± 1.0	5	3.7 ± 1.2	17	10.5 ± 3.2
4ℓ MET<50,H_T <200, Z	33	35 ± 14	20	16.1 ± 4.9	62	42 ± 16
3ℓ Lepton Results						
3ℓ MET>50,H_T >200,no-OSSF	2	1.5 ± 0.5	33	30.3 ± 9.6	15	13.5 ± 2.6
3ℓ MET>50,H_T <200,no-OSSF	7	6.5 ± 2.3	159	140 ± 37	82	106 ± 16
3ℓ MET<50,H_T >200,no-OSSF	1	1.2 ± 0.7	16	16.5 ± 4.5	18	31.9 ± 4.8
3ℓ MET<50,H_T <200,no-OSSF	14	11.6 ± 3.6	446	354 ± 55	1006	1025 ± 171
3ℓ MET>50,H_T >200,noZ	8	4.8 ± 1.3	16	31.0 ± 9.5	–	–
3ℓ MET>50,H_T >200, Z	20	17.8 ± 6.0	13	24.0 ± 4.9	–	–
3ℓ MET>50,H_T <200,noZ	30	25.9 ± 7.3	114	106 ± 27	–	–
3ℓ MET<50,H_T >200,noZ	11	4.4 ± 1.5	45	51.8 ± 6.2	–	–
3ℓ MET>50,H_T <200, Z	141	126 ± 47	107	115 ± 16	–	–
3ℓ MET<50,H_T >200, Z	15	18.4 ± 4.5	166	244 ± 24	–	–
3ℓ MET<50,H_T <200,noZ	123	142 ± 36	3721	2906 ± 412	–	–
3ℓ MET<50,H_T <200, Z	657	749 ± 181	17857	15516 ± 2421	–	–
Total	1066	1148 ± 191	22725	19557 ± 2457	1201	1235 ± 173
Total 4ℓ	37	39 ± 15	32	23.6 ± 5.1	80	58 ± 16
Total 3ℓ	1029	1109 ± 191	22693	19533 ± 2457	1121	1177 ± 172
Total	1066	1148 ± 191	22725	19557 ± 2457	1201	1235 ± 173

Multi-Lepton Signals of Higgs

(Contreras-Compana, Craig, Gray, Kilic, Park, Somalwar, ST)

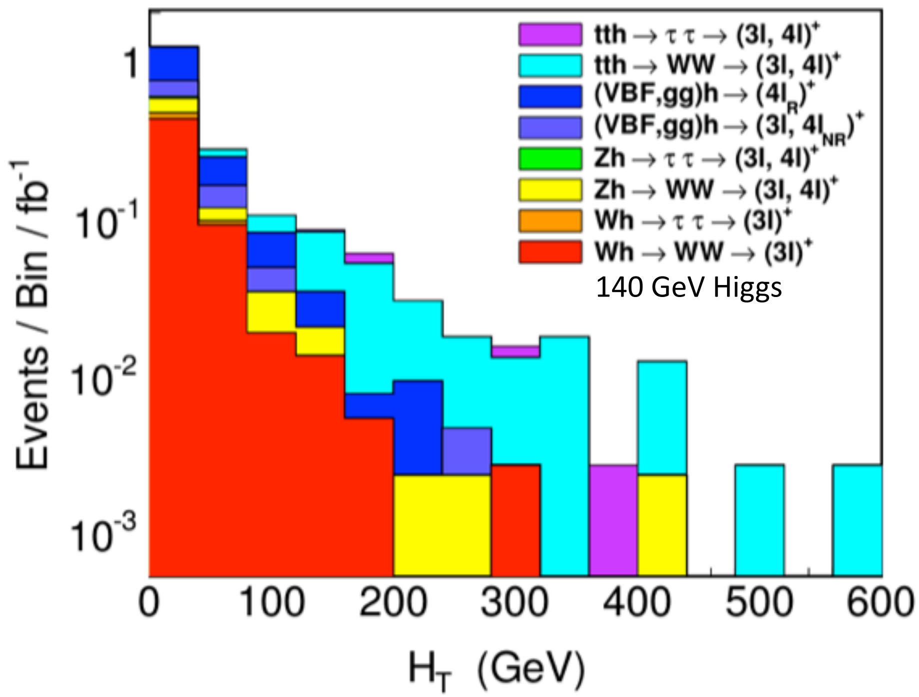
Higgs Final States Will Eventually Contaminate Multi-lepton Search …

Turn Around – Multi-Leptons as Search for Higgs

h : (120-150) GeV

(11 Signal Topologies)

Production	Decay
$gg \to h$	$h \to 4\ell$
$VBF \to h$	$h \to 4\ell$
$q\bar{q} \to Wh$	$Wh \to WWW, W\tau\tau, WZZ$
$q\bar{q} \to Zh$	$Zh \to ZWW, Z\tau\tau, ZZZ$
$t\bar{t}h$	$t\bar{t}h \to t\bar{t}WW, t\bar{t}\tau\tau, t\bar{t}ZZ$



Multi-Lepton Non-Resonant Channels Exceed Resonant 4 Lepton Channel

Signal Spread Out over Many Channels
Minimal Significance in Any Given Channel

Multi-Lepton Signals of Higgs

(Contreras-Compana, Craig, Gray, Kilic, Park, Somalwar, ST)

Higgs Final States Will Eventually Contaminate
Multi-lepton Search …

Turn Around – Multi-Leptons as Search for Higgs
No Kinematic Optimization

h : (120-150) GeV
(11 Signal Topologies)

Production	Decay
$gg \to h$	$h \to 4\ell$
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$q\bar{q} \to Wh$	$Wh \to WWW, W\tau\tau, WZZ$
$q\bar{q} \to Zh$	$Zh \to ZWW, Z\tau\tau, ZZZ$
$t\bar{t}h$	$t\bar{t}h \to t\bar{t}WW, t\bar{t}\tau\tau, t\bar{t}ZZ$

Estimated σ / σ_{SM} Limit 5 fb^{-1}

	120 GeV	130 GeV	140 GeV	150 GeV
All Contributions				
Standard Model Higgs	4.3	2.7	2.0	1.8
Fermi-phobic Higgs	2.2	2.3	2.9	3.0
b-phobic Higgs	1.6	1.4	1.4	1.5
Non-resonant Contributions				
Standard Model Higgs	5.8	3.8	3.0	2.6
Fermi-phobic Higgs	2.2	2.4	3.1	3.2
b-phobic Higgs	2.0	2.0	2.1	2.2

Multi-Lepton Non-Resonant
Channels Exceed Resonant
4 Lepton Channel

Calculated $A(m_h)$ for All Topologies
Exclusive Combination - (extrapolation)
(c.f. CDF Simplified Model Topology Study)

Signal Spread Out over Many Channels
Minimal Significance in Any Given Channel

Illustrates Power of Multi-Channel
Multi-Lepton Search

Multi-Lepton Signals of Multiple Higgs

(Craig, Evans, Gray, Park, Kilic, Somalar, ST)

Higgs Final States Will Eventually Contaminate Multi-lepton Search …

$$\sigma \cdot \mathrm{Br} \cdot \mathcal{A}(pp \to f) = \sum_t \sigma(pp \to t)\mathcal{A}(pp \to t \to f) \prod_a \mathrm{Br}_a(t \to f)$$

$h/A/H^{\pm}/H$:
125/230/230/500 GeV
(105 Signal Topologies)

Production	Decay
$gg \to h$	$h \to 4\ell$
$VBF \to h$	$h \to 4\ell$
$gg \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZb\bar{b}, ZZWW, 4Z, ZZ\tau\tau$
	$H \to AA \to 4\tau$
	$H \to AA \to \tau\tau Zh \to \tau\tau ZWW, \tau\tau Z\tau\tau, \tau\tau Zb\bar{b}, \tau\tau ZZZ$
	$H \to AA \to ZhZh \to ZZWWWW, ZZWW\tau\tau, ZZWWb\bar{b}, ZZ\tau\tau b\bar{b}, ZZ\tau\tau\tau\tau$
	$H \to AA \to ZhZh \to ZZb\bar{b}b\bar{b}, ZZZZb\bar{b}, ZZZZ\tau\tau, ZZZZWW, ZZZZZZ$
	$H \to H^+H^- \to WhWh \to WWWWWW, WWWW\tau\tau, WWWWb\bar{b}, WW\tau\tau\tau\tau$
	$H \to H^+H^- \to WhWh \to WW\tau\tau b\bar{b}, WWZZb\bar{b}, WWWWZZ, WWZZZZ, WWZZ\tau\tau$
	$H \to H^+H^- \to \tau\nu Wh \to \tau\nu WWW, \tau\nu W\tau\tau, \tau\nu WZZ$
	$H \to H^+H^- \to tbWh \to tbWWW, tbW\tau\tau, tbWZZ$
	$H \to ZA \to Z\tau\tau$
	$H \to ZA \to ZZh \to ZZ\tau\tau, ZZWW, ZZb\bar{b}, ZZZZ$
$VBF \to H$	$H \to 4\ell$
	$H \to hh \to 4W, WW\tau\tau, 4\tau, ZZb\bar{b}, ZZWW, 4Z, ZZ\tau\tau$
	$H \to AA \to 4\tau$
	$H \to AA \to \tau\tau Zh \to \tau\tau ZWW, \tau\tau Z\tau\tau, \tau\tau Zb\bar{b}, \tau\tau ZZZ$
	$H \to AA \to ZhZh \to ZZWWWW, ZZWW\tau\tau, ZZWWb\bar{b}, ZZ\tau\tau b\bar{b}, ZZ\tau\tau\tau\tau$
	$H \to AA \to ZhZh \to ZZb\bar{b}b\bar{b}, ZZZZb\bar{b}, ZZZZ\tau\tau, ZZZZWW, ZZZZZZ$
	$H \to H^+H^- \to WhWh \to WWWWWW, WWWW\tau\tau, WWWWb\bar{b}, WW\tau\tau\tau\tau$
	$H \to H^+H^- \to WhWh \to WW\tau\tau b\bar{b}, WWZZb\bar{b}, WWWWZZ, WWZZZZ, WWZZ\tau\tau$
	$H \to H^+H^- \to \tau\nu Wh \to \tau\nu WWW, \tau\nu W\tau\tau, \tau\nu WZZ$
	$H \to H^+H^- \to tbWh \to tbWWW, tbW\tau\tau, tbWZZ$
	$H \to ZA \to Z\tau\tau$
	$H \to ZA \to ZZh \to ZZ\tau\tau, ZZWW, ZZb\bar{b}, ZZZZ$
$gg \to A$	$A \to Zh \to ZWW, Z\tau\tau, ZZZ$
$q\bar{q} \to Wh$	$Wh \to WWW, W\tau\tau, WZZ$
$q\bar{q} \to Zh$	$Zh \to ZWW, Z\tau\tau, ZZZ$
$t\bar{t}h$	$t\bar{t}h \to t\bar{t}WW, t\bar{t}\tau\tau, t\bar{t}ZZ$
$t\bar{t}A$	$t\bar{t}A \to t\bar{t}\tau\tau$
	$t\bar{t}A \to t\bar{t}Zh \to t\bar{t}ZWW, t\bar{t}Z\tau\tau, t\bar{t}Zb\bar{b}, t\bar{t}ZZZ$

Sensitivity Beyond Standard Searches

…

Multi-Lepton Signals of Multiple Higgs

(Craig, Evans, Gray, Park, Kilic, Somalar, ST)

Higgs Final States Will Eventually Contaminate Multi-lepton Search …

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$t\bar{t}h$	$t\bar{t}h \to t\bar{t}WW, t\bar{t}\tau\tau, t\bar{t}ZZ$
$t\bar{t}A$	$t\bar{t}A \to t\bar{t}\tau\tau$
	$t\bar{t}A \to t\bar{t}Zh \to t\bar{t}ZWW, t\bar{t}Z\tau\tau, t\bar{t}Zb\bar{b}, t\bar{t}ZZZ$

Sensitivity Beyond Standard Searches

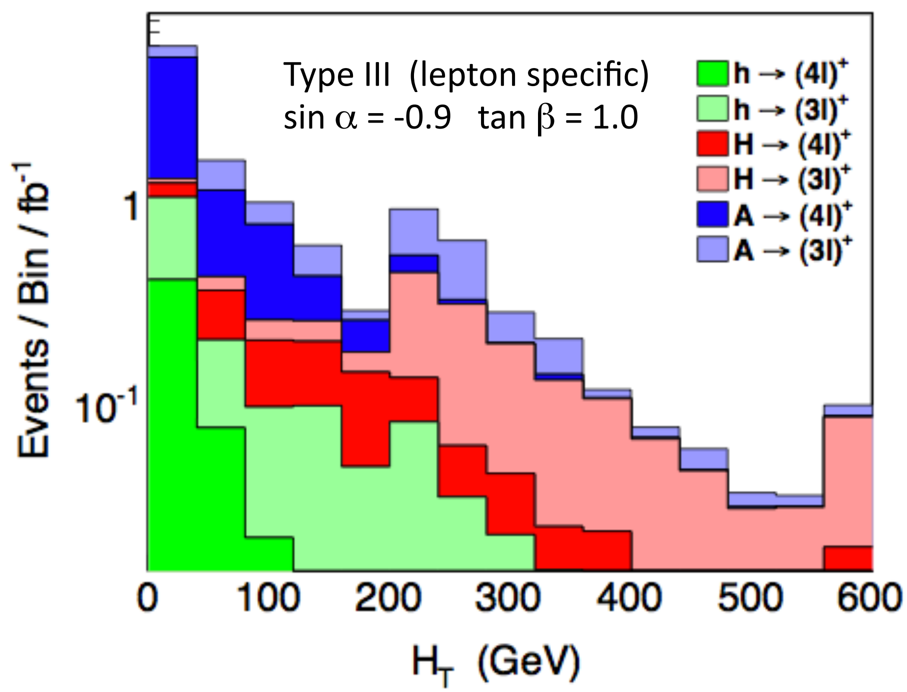
…

Multi-Lepton Signals of Multiple Higgs

(Craig, Evans, Gray, Park, Kilic, Somalar, ST)

Higgs Final States Will Eventually Contaminate
Multi-lepton Search …

$h/A/H^{+-}/H$:
125/230/230/500 GeV
(105 Signal Topologies)



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Sensitivity Beyond
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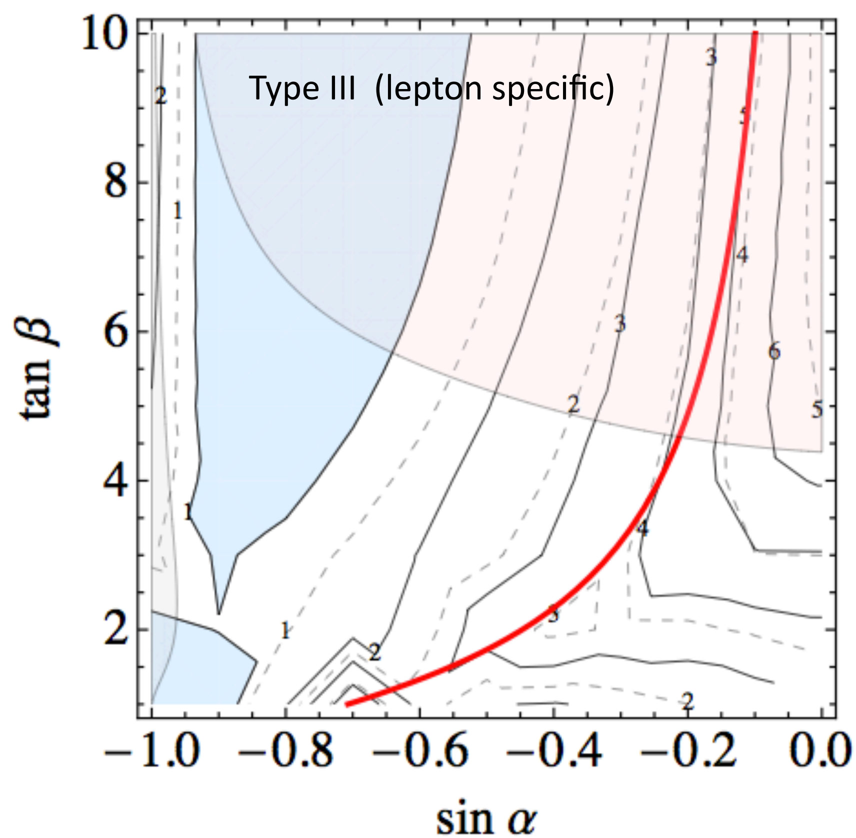


Blue Multi-Lepton Excluded
Gray H ->VV Excluded

Higgs in Association with New Physics

(Gershtein, Chou, Y. Kats, ST)

Use 125 GeV Higgs as Calibration to Search for New Physics

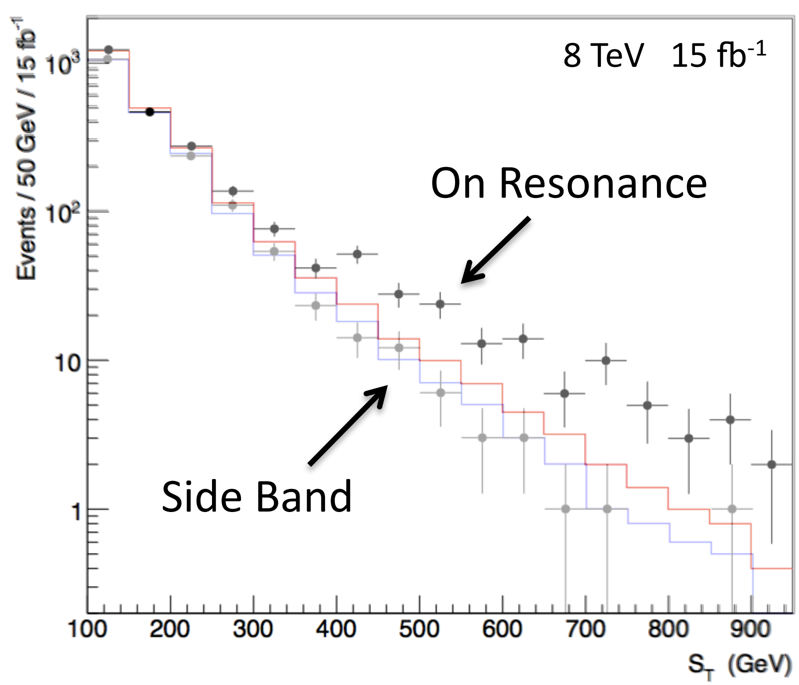
$h \to \gamma\gamma$ + X (On-Resonance + Upper and Lower Side Bands)

↳ Even Blunt Variables Suffice + More focused + …

Stop Pair Production 250 GeV
with stop -> b + Higgsino and
Higgsino -> h + Goldstino

Many other Examples …

Compare SM tth benchmark



Blue = Side Band Background
Red = On Resonance SM Higgs + Background + Stop -> h + X

Higgs in Association with New Physics

(Craig, Evans, Gray, Park, Somalwar, ST, Walker)

Use 125 GeV Higgs as Calibration to Search for New Physics

h -> WW*, ZZ*, $\tau\tau$ -> Multi-Leptons + X

tt Pair Production with

t -> c h and t -> leptonic

5 fb^{-1} Multi-Lepton 7 TeV Data:

Br(t -> c h) < 2.7%

(with b-tags in progress)

First Use of Higgs Boson to Search for New Physics in Existing Data

First Direct Probe of Flavor Violation in Higgs sector (for fermion that is most strongly coupled to Higgs Sector)

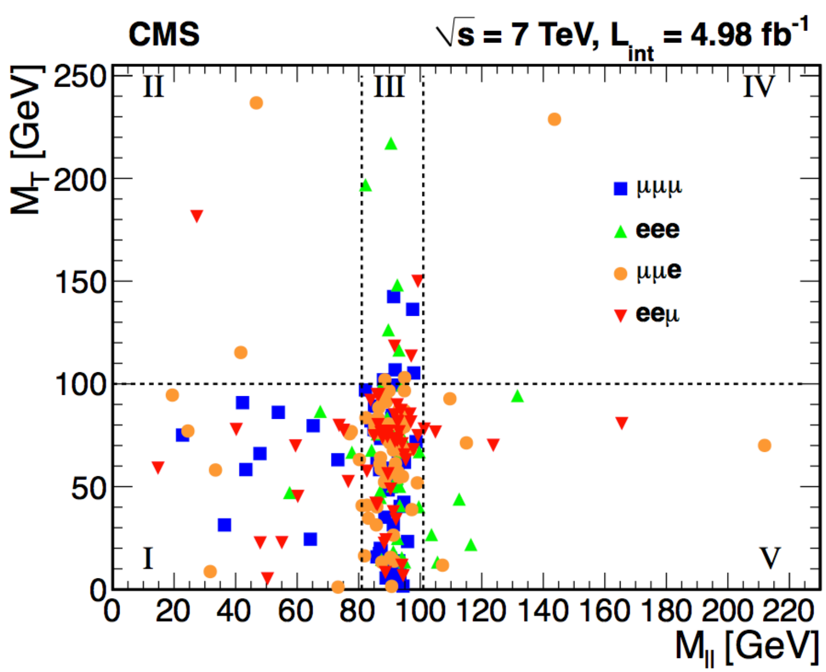
Higgs in Association with New Physics

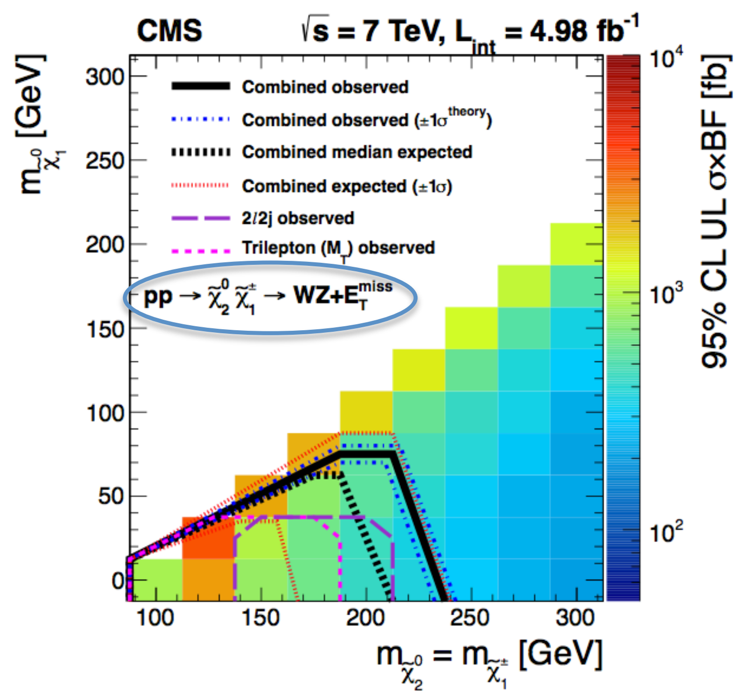
(CMS)

Use 125 GeV Higgs as Calibration to Search for New Physics

h -> WW*, ZZ*, ττ -> Multi-Leptons + X

$\chi^{+-}\chi^0$ -> h W $\chi^0\chi^0$ -> Multi-Leptons + MET (Expect 8 TeV Sensitivity)





σ.Br : The Importance of Ratios

Certain Systematics Cancel in Ratios

Inclusive: All Production Modes - Different Final States

Exclusive: Different Production Modes – Same Final State

Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

- σ . Br (Initial -> h -> Final)

Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

Best Channels:

σ . Br (Inclusive -> h ->
Resonant Final)

Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

$$\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)}$$

<u>Best Channels</u>: (Ratios)

σ . Br (Inclusive -> h -> Resonant Final)

Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

$$\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)} \simeq \left.\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)}\right|_{\mathrm{SM}} \left[1+\mathcal{O}\left(\frac{\alpha}{4\pi v^2}\frac{M^2}{\xi}\right)\right]$$

<u>Best Channels</u>: (Ratios)

σ . Br (Inclusive -> h -> Resonant Final)

Renormalizable SM + D=6 Operators

H = ‹H› + h

$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\;H^\dagger W_{\mu\nu} H\;B^{\mu\nu}$$

$$\frac{g_1^2 \xi_{S_{11}}}{2M^2}\;H^\dagger H\;B_{\mu\nu}B^{\mu\nu}$$

$$\frac{g_2^2 \xi_{S_{22}}}{2M^2}\;H^\dagger H\;W_{\mu\nu}W^{\mu\nu}$$

Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

$$\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)} \simeq \frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)}\bigg|_{\mathrm{SM}} \left[1+\mathcal{O}\left(\frac{\alpha}{4\pi v^2}\frac{M^2}{\xi}\right)\right]$$

Best Channels: (Ratios)

σ . Br (Inclusive -> h -> Resonant Final)

Renormalizable SM + D=6 Operators

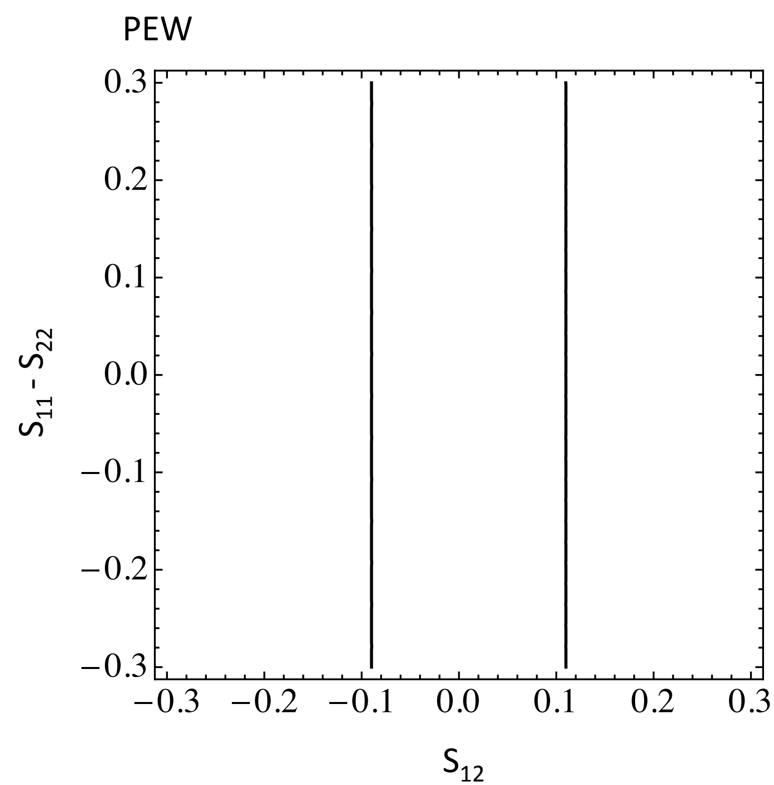
H = ‹H› + h

$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\; H^\dagger W_{\mu\nu} H\; B^{\mu\nu}$$

$$\frac{g_1^2 \xi_{S_{11}}}{2M^2}\; H^\dagger H\; B_{\mu\nu}B^{\mu\nu}$$

$$\frac{g_2^2 \xi_{S_{22}}}{2M^2}\; H^\dagger H\; W_{\mu\nu}W^{\mu\nu}$$



Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

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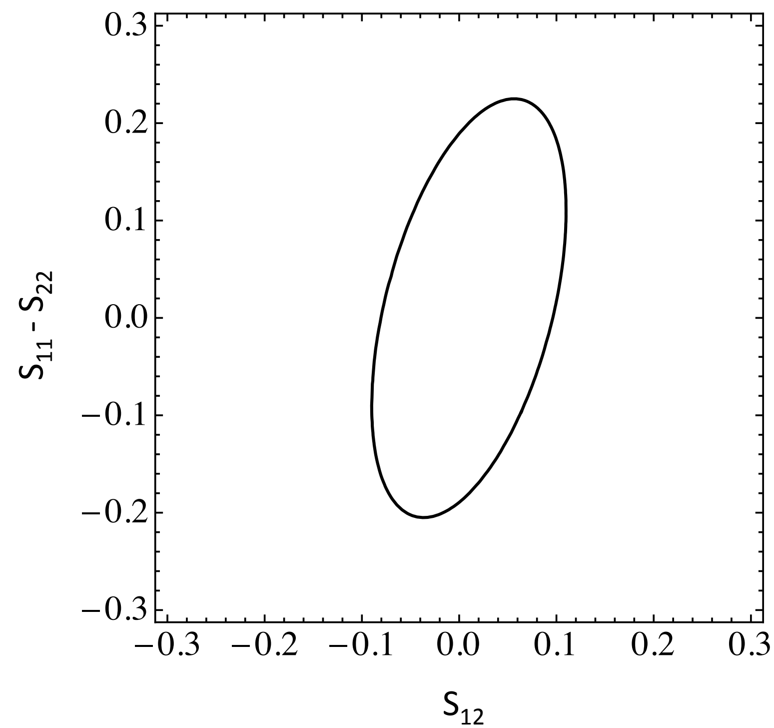
$$\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)} \simeq \left.\frac{\mathrm{Br}(h \to \gamma\gamma)}{\mathrm{Br}(h \to ZZ)}\right|_{\mathrm{SM}} \left[1 + \mathcal{O}\left(\frac{\alpha}{4\pi v^2}\frac{M^2}{\xi}\right)\right]$$

Best Channels: (Ratios)

σ . Br (Inclusive -> h -> Resonant Final)

PEW + 100 % Uncertainty Br(h->γγ)/Br(h->ZZ)



Renormalizable SM + D=6 Operators

H = ‹H› + h

$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\;H^\dagger W_{\mu\nu} H\; B^{\mu\nu}$$

$$\frac{g_1^2 \xi_{S_{11}}}{2M^2}\;H^\dagger H\; B_{\mu\nu} B^{\mu\nu}$$

$$\frac{g_2^2 \xi_{S_{22}}}{2M^2}\;H^\dagger H\; W_{\mu\nu} W^{\mu\nu}$$

Systematics: Statistics, Resonant-Continuum Separation + Interference, …

Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

$$\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)} \simeq \left.\frac{\mathrm{Br}(h\to\gamma\gamma)}{\mathrm{Br}(h\to ZZ)}\right|_{\mathrm{SM}} \left[1+\mathcal{O}\left(\frac{\alpha}{4\pi v^2}\frac{M^2}{\xi}\right)\right]$$

Best Channels: (Ratios)

σ . Br (Inclusive -> h -> Resonant Final)

Renormalizable SM + D=6 Operators

H = ‹H› + h

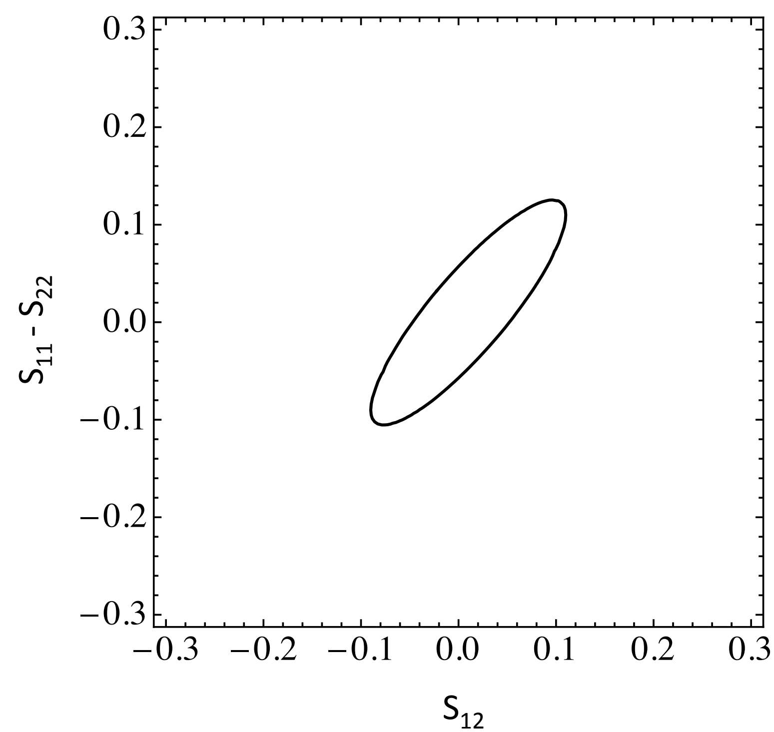
$$\frac{\xi_T}{M^2}(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\ H^\dagger W_{\mu\nu} H\ B^{\mu\nu}$$

$$\frac{g_1^2 \xi_{S_{11}}}{2M^2}\ H^\dagger H\ B_{\mu\nu}B^{\mu\nu}$$

$$\frac{g_2^2 \xi_{S_{22}}}{2M^2}\ H^\dagger H\ W_{\mu\nu}W^{\mu\nu}$$

PEW + 30 % Uncertainty Br(h->γγ)/Br(h->ZZ)



Systematics: Statistics, Resonant-Continuum Separation + Interference, …

Precision Physics Through the Higgs

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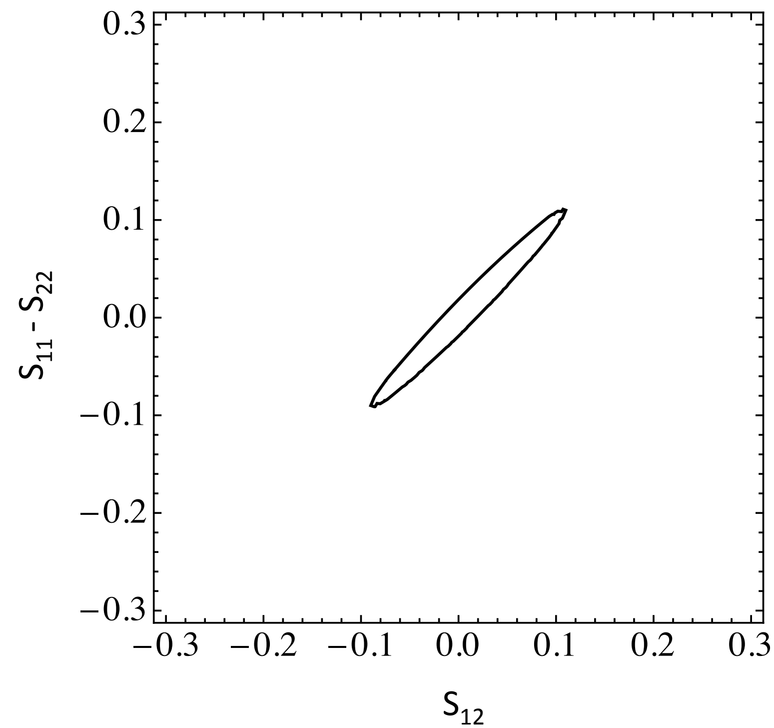
Best Channels: (Ratios)

σ . Br (Inclusive -> h -> Resonant Final)

PEW + 10 % Uncertainty Br(h->γγ)/Br(h->ZZ)



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Systematics: Statistics, Resonant-Continuum Separation + Interference, …

Precision Probes of New Physics

(Craig, ST)

Electroweak Observables

G_F, m_W, m_Z, Γ_Z, A_{FB}, ...

Renormalizable SM +
D=6 Operators

H = <H>

$$\frac{\xi_T}{M^2}\,(H^\dagger D_\mu H)(H^\dagger D^\mu H)$$

$$\frac{g_1 g_2 \xi_{S_{12}}}{M^2}\;H^\dagger W_{\mu\nu} H\;B^{\mu\nu}$$

PDG

S = 0.01 +- 0.10

T = 0.03 +- 0.11

Systematics: m_t, $\ln(m_h)$, α_S , ...

Measuring Time Reversal Violation in Higgs -> ZZ* -> l l l l

(Park, ST)

12 Dimensional Phase Space

Mass Variable	$m_{\ell\ell\ell'\ell'}$	$(0,\infty)$	Relevant
Center of Mass Variables	$y_{\ell\ell\ell'\ell'}$	$[0,\infty)$	Relevant
	$\pi_{T\ell\ell\ell'\ell'}$	$[0,\infty)$	Transverse Irrelevant
	Azimuth	–	Irrelevant
Production Variables	$\lvert\cos\theta_{\ell\ell-\ell'\ell'}\rvert$	$[0,1]$	Relevant
	$\zeta'_{\ell\ell-\ell'\ell'}$	$[0,\infty)$	Transverse Irrelevant
Decay Variables	$\cos\Theta_{\ell^+\ell'^-}$	$[-1,1]$	Relevant
	ρ	$(0,\frac{1}{2})$	Threshold Irrelevant
	ξ	$[0,1)$	Threshold Irrelevant
	$\mathcal{P}_{\ell\ell}$	$[0,1]$	Threshold Irrelevant
	$\mathcal{P}_{\ell'\ell'}$	$[0,1]$	Threshold Irrelevant
	$\tau_{\ell\ell-\ell'\ell'}$	$[-1,1]$	Threshold Irrelevant

→ Interesting Information (Mass Variable)

→ Interesting Information (Production Variables)

→ Most of the Interesting Information in Irrelevant Kinematic Variables

$$\tau_{\ell^+\ell^-\ell'^+\ell'^-} \equiv \frac{\epsilon_{\mu\nu\rho\sigma}\, p^{\mu}_{\ell^+} p^{\nu}_{\ell^-} p^{\rho}_{\ell'^+} p^{\sigma}_{\ell'^-}}{m^4_{\ell^+\ell^-\ell'^+\ell'^-}}$$

Odd Under Time Reversal

Measuring Time Reversal Violation in Higgs -> ZZ* -> l l l l

(Park, ST)

hZZ Coupling Through <u>Both</u> T-even + T-odd Couplings

Renormalizable SM + D=6 Operators

H = ‹H› + h

$$\frac{g_1 g_2 \tilde{\xi}_{S_{12}}}{M^2} H^\dagger W_{\mu\nu} H \tilde{B}^{\mu\nu}$$

$$\frac{g_1^2 \tilde{\xi}_{S_{11}}}{2M^2} H^\dagger H B_{\mu\nu} \tilde{B}^{\mu\nu}$$

$$\frac{g_2^2 \tilde{\xi}_{S_{22}}}{2M^2} H^\dagger H W_{\mu\nu} \tilde{W}^{\mu\nu}$$

Enhance Asymmetry with Specific Kinematic Structure of Interference Term

$$\widetilde{\mathcal{T}}_{\ell^+\ell^-\ell'^+\ell'^-} \equiv \tau_{\ell^+\ell^-\ell'^+\ell'^-} \, \widetilde{\mu}_{\ell^+\ell^-\ell'^+\ell'^-}$$

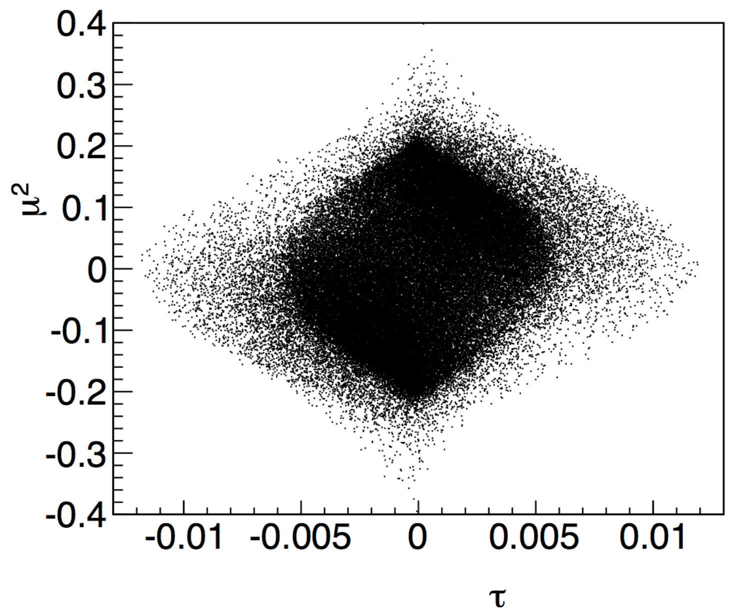
$$\widetilde{\mu}_{\ell^+\ell^-\ell'^+\ell'^-} \equiv \frac{m^2_{\ell^+\ell'^+} - m^2_{\ell^+\ell'^-} - m^2_{\ell^-\ell'^+} + m^2_{\ell^-\ell'^-}}{m^2_{\ell^+\ell^-\ell'^+\ell'^-}}$$

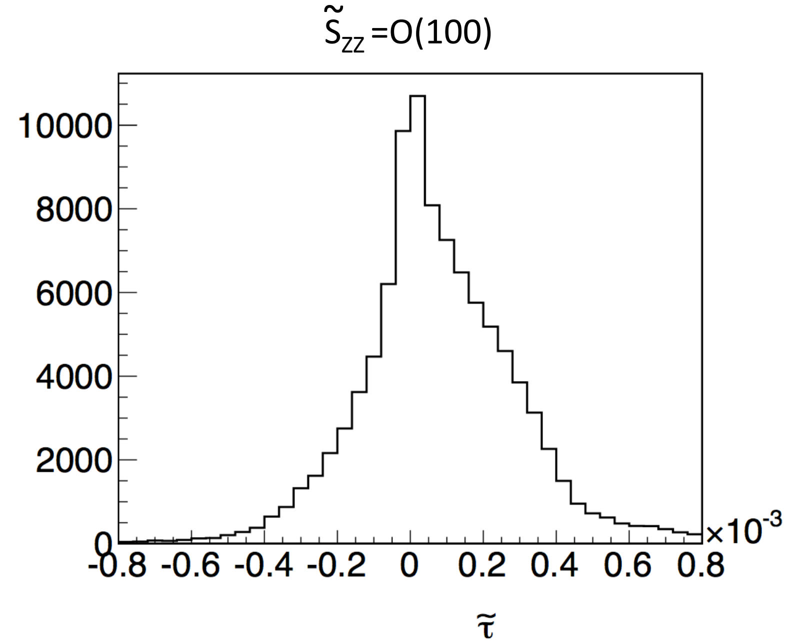
$$\tau_{\ell^+\ell^-\ell'^+\ell'^-} \equiv \frac{\epsilon_{\mu\nu\rho\sigma}\, p^\mu_{\ell^+} p^\nu_{\ell^-} p^\rho_{\ell'^+} p^\sigma_{\ell'^-}}{m^4_{\ell^+\ell^-\ell'^+\ell'^-}}$$

Odd Under Time Reversal

Measuring Time Reversal Violation in Higgs -> ZZ* -> l l l l

(Park, ST)





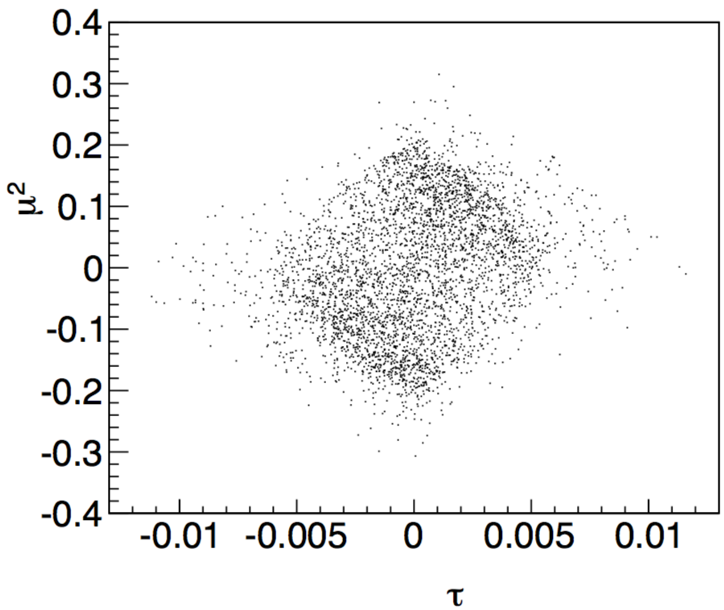
Asymmetry Vanishes for Pure Scalar
or Pure Pseudo-Scalar Coupling

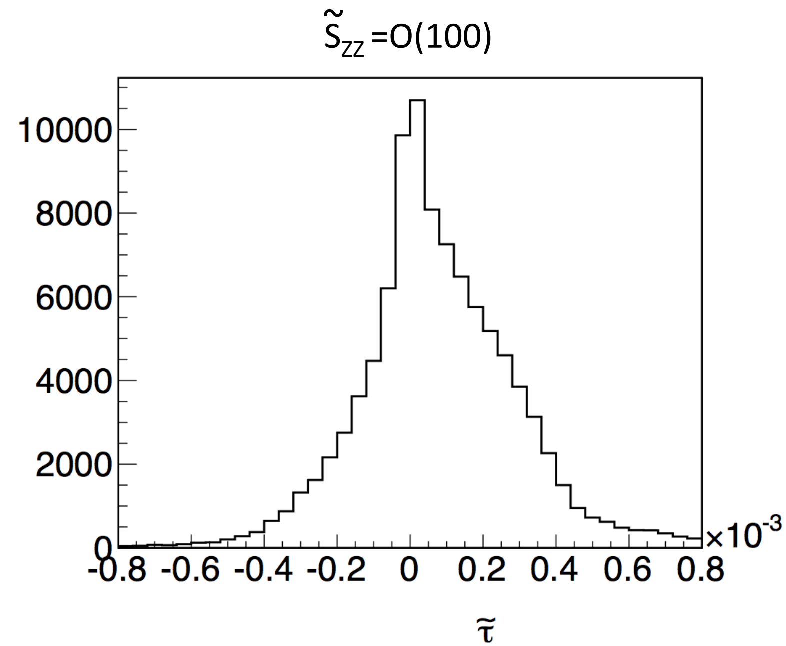
Luminosity >> ab^{-1} to go beyond EDM bounds
But Interesting Direct Probe of
T-Violation in Higgs Sector

$$\widetilde{T}_{\ell^+\ell^-\ell'^+\ell'^-} \equiv \tau_{\ell^+\ell^-\ell'^+\ell'^-}\ \widetilde{\mu}_{\ell^+\ell^-\ell'^+\ell'^-}$$

Measuring Time Reversal Violation in Higgs -> ZZ* -> l l l l

(Park, ST)





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Reconstructing the Higgs Mass in the Higgs -> WW* -> l ν l ν Channel

(Park, ST)

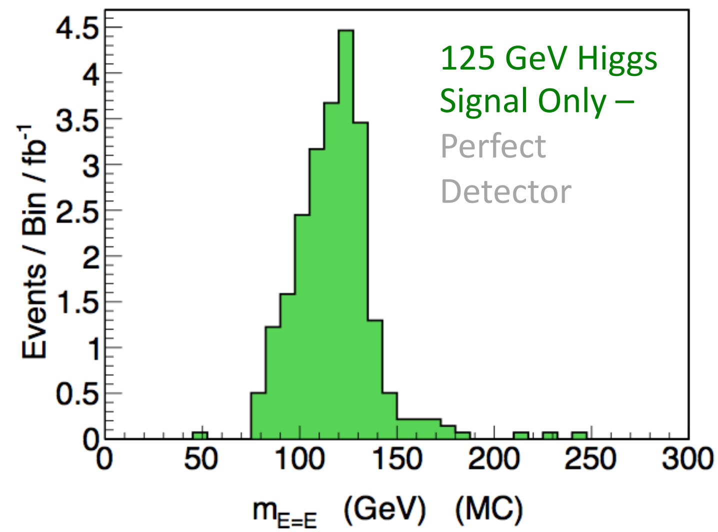
Most of the Phase Space Distribution Near Threshold

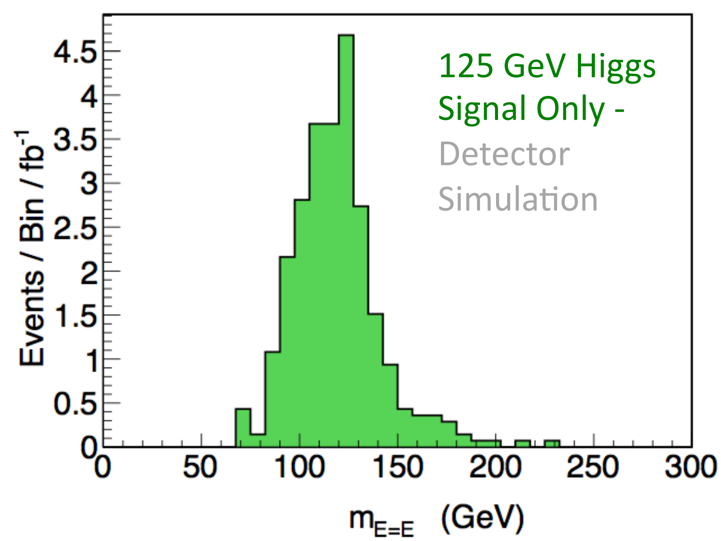
At Threshold:
$E_{l-} = E_{l+}$ In Higgs Rest Frame

Boost to this Frame – form $m_{E=E}$ Without Using MET

Systematically Improve Threshold Approximation by

1. Transverse Re-Boosting
2. Threshold Corrections





Reconstructing the Higgs Mass in the Higgs -> WW* -> l ν l ν Channel

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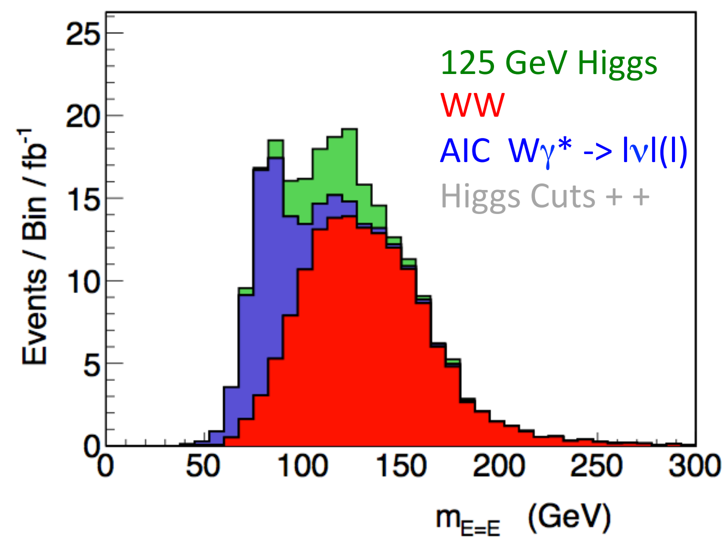
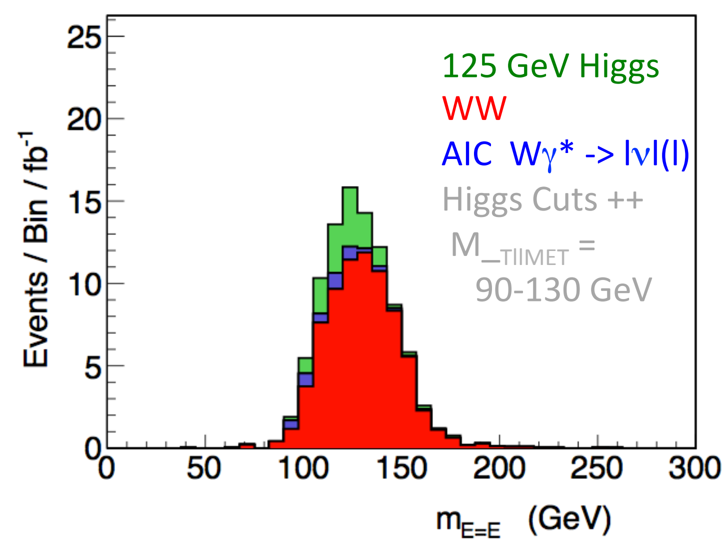




Probing New Physics Through Displaced Higgs

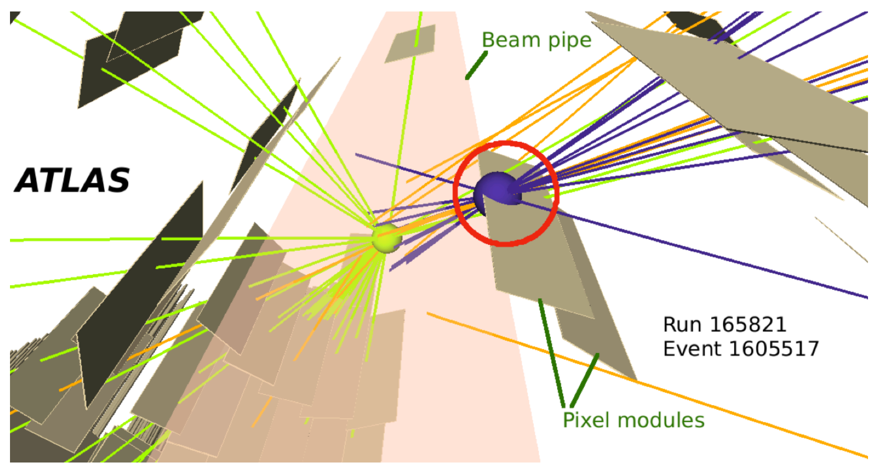
(Matchev, Sarid, ST)

Higgsino -> h / Z + Goldstino

O(100) TeV SUSY Breaking Scale
Long Lived – Displaced Higgs / Z

Large Negative Impact Parameter (LNIP) b-jets

ATLAS Displaced Vertex Search
35 pb^{-1} – Single muon trigger



Experimental Investigation of the Higgs Sector has Begun !!

Search for Extended Higgs Sectors in
  Standard Higgs Search Channels

Use the Higgs to Search for New Physics
  Multi-Leptons
  $\gamma\gamma$ Resonance + X
  …

Probe Symmetries in the Higgs Sector
  Flavor Violation
  Time Reversal Violation

Higgs -> $\gamma\gamma$, ZZ* , Zγ
  The New Precision Physics (Will Complement + Surpass Old PEW)

Higgs -> WW* Mass Reconstruction

Displaced Higgs / Z :
  Higgsino -> Higgs / Z + Goldstino

Much Much More …

Extra Slides