Electroweak Scale Physics at the Electroweak Scale

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Primary Focus of Run II at the LHC

Electroweak Scale Physics at
the Electroweak Scale

Uncover Physics in the Higgs Sector
Underlying Electroweak Symmetry Breaking

Preview What's Ahead by Way of
Ongoing Work on Run I at the LHC

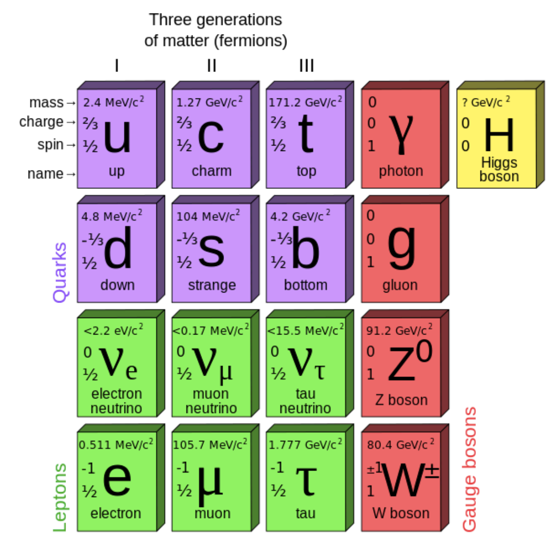
Minimal Renormalizable Standard Model

Predictive

Incredibly Successful !!

Sectors:

- Gauge
- Yukawa
- Higgs



Minimal Renormalizable Standard Model

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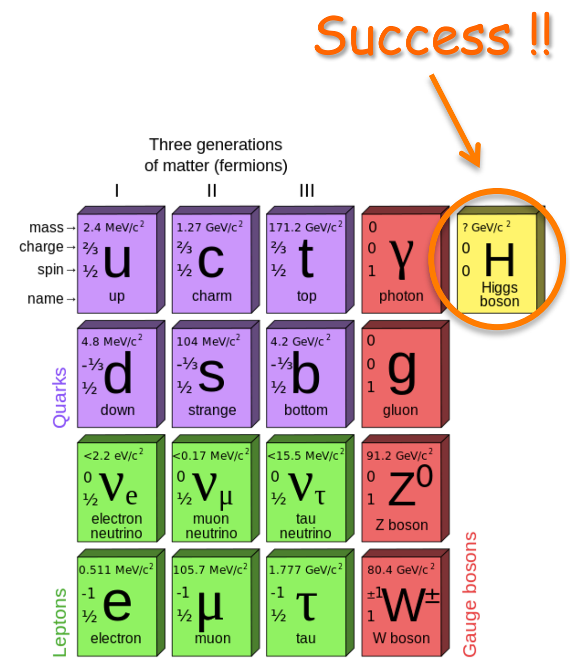


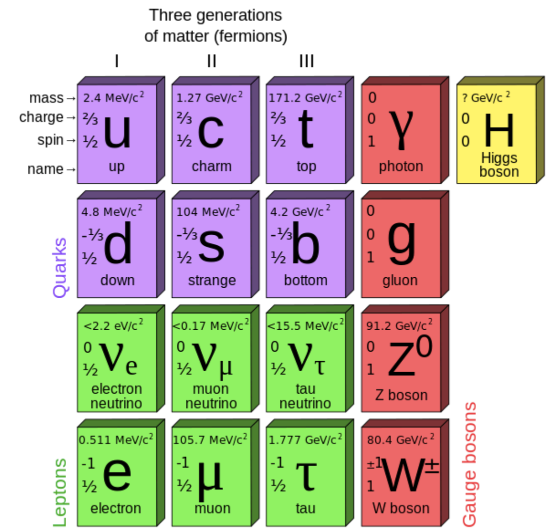
Minimal Renormalizable Standard Model

Predictive

Incredibly Successful !!

Supplement by Non-Renormalizable Interactions

Gravity
Neutrino Mass Operators



Search for New Physics at the Electroweak Scale

. Physics of ElectroWeak
Symmetry Breaking

. Quantum Space-Time Dimensions
(Super-Space)
. Identity of Dark Matter
. New Flavor Changing Interactions +
Origin of Flavor
. New Symmetries
. New Forces
. Origin of Cosmic Baryon Asymmetry
. Dark Hidden Sectors
...

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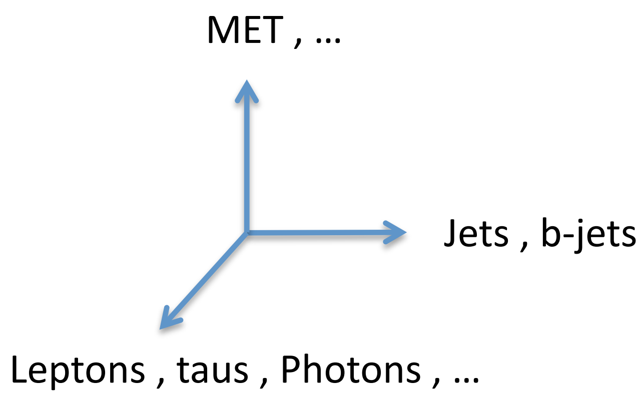
Search for New Physics

Signature Space



Search for New Physics

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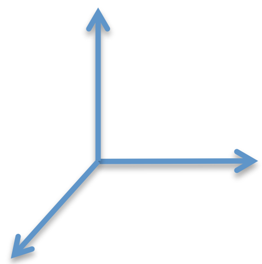

Searches are Built <u>Around</u>
SM (+fake) Backgrounds –

Design Searches Away from
"Origin" of Signature Space
Along Some Axis or Axes

		σ (fb) 7 TeV
W		100,000,000
Z		30,000,000
tt		150,000
WW		40,000
WZ		17,000
ZZ		6,500
h inclusive		17,900
ttW		150
ttZ		100
WWW		60
ttWW		2
$\tilde{w}\tilde{w}$	(150 GeV)	1000
	(400 GeV)	10
$\tilde{g}\tilde{g}$	(1 TeV)	10

Search for New Physics

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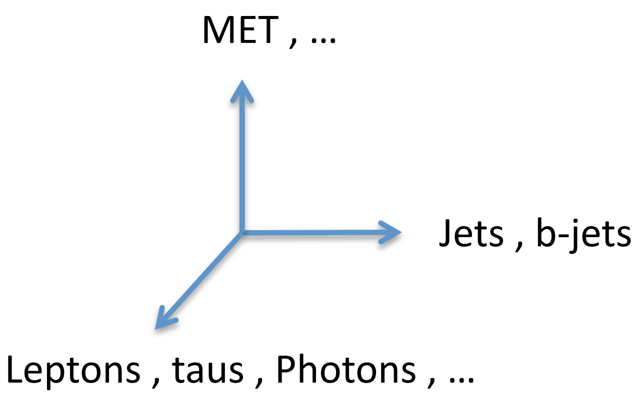

Discovery Potential Evolves:

Luminosity Increases
(Production + Rare Decays)

Control over Backgrounds Improves

Analysis Techniques Improve

Identified/Reconstructed Objects Improves W, Z, top, Higgs

	σ (fb) 7 TeV
W	100,000,000
Z	30,000,000
tt	150,000
WW	40,000
WZ	17,000
ZZ	6,500
h inclusive	17,900
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WWW	60
ttWW	2
$\tilde{w}\tilde{w}$ (150 GeV)	1000
(400 GeV)	10
$\tilde{g}\tilde{g}$ (1 TeV)	10

Search for New Physics at the Electroweak Scale

Higgs Sector

Mass Scale O(100-200) GeV

$SU(2)_L$ $U(1)_Y$ Interactions

σ(pp -> Higgs Sector -> Electroweak)$_{LHC}$ = O(pb)

Higgs Identified Object
(New Opportunities for Searches)

Focused on Electroweak Physics at the Electroweak Scale

LHC Sensitivity to Electroweak Physics in Higgs Sector Just Beginning …

7+8 TeV 25 fb^{-1}

Reached an Important Milestone !

Search for Electroweak Scale Physics in the Higgs Sector

- Higgs Rate Measurements

- Search for Additional States Directly in the Higgs Sector

- Searching for New Physics Produced in Association with Higgs

- Search for Additional States Related to the Higgs Sector

New CMS Results
PAS next week

- Searching for New Physics Produced from Decay of Higgs

- Precision Higgs Measurements to Search for New Physics

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Discovered Un-Anticipated High p_T Electroweak Process

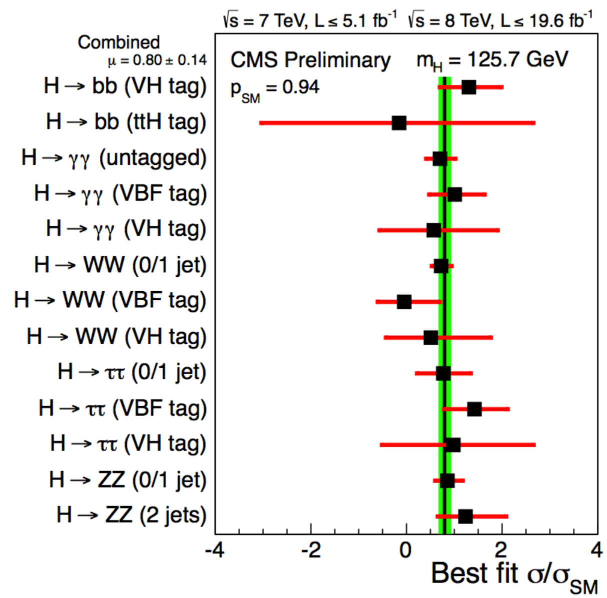
(Single Example Run I)

Higgs Boson Rate Measurements

Number of Channels Observed + Measured

Many Many More Eventually …

	Inclusive	VBF	Vh	tth
$\gamma\gamma$	X	X	X	X
ZZ*	X	X	X	X
WW*	X	X	X	X
$\tau\tau$	X	X	X	X
bb			X	X
Z γ	X	X	X	
$\mu\mu$	X	X	X	X



Higgs Boson Rate Measurements

Signals of New Physics in
SM Higgs Rate Measurements

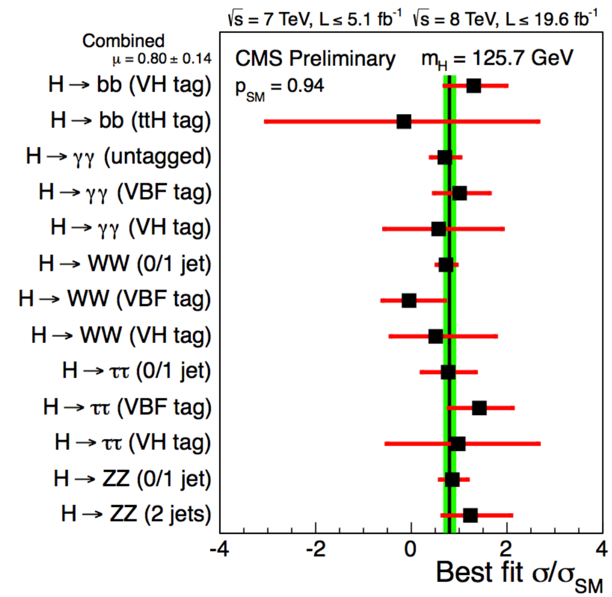
Deviations in SM Higgs Couplings

- Fit to SM Couplings

- Effective Operator Analysis

- Specific Underlying
  Theoretical Framework

Extended Higgs Sector
Supersymmetry
…



Any Deviations at Discovery Level
are by Definition Large …

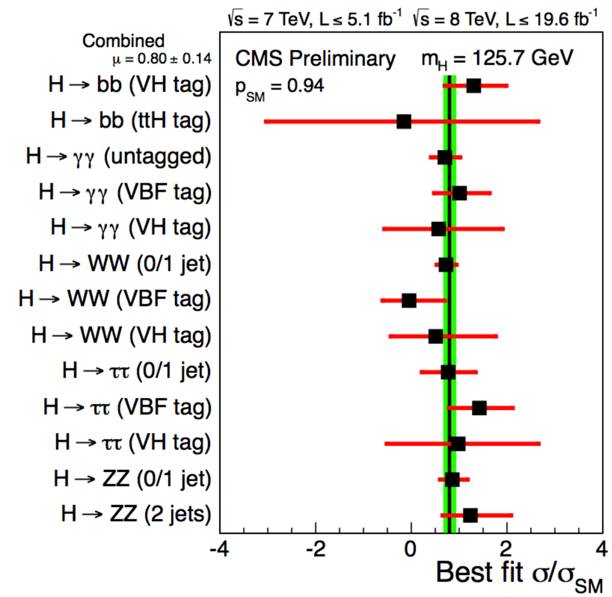
Higgs Boson Rate Measurements

Modifications of SM Higgs Rate Measurements

Specific Underlying Framework

h -> aa	O(10+)	$(m_h/f)^4$
Higgs Mixing	O(1)	$(m_h/M)^2$
Yukawa Form Factor	O(1)	$(m_h/M)^2$
Partner Loops	O(1)	$(m_h/M)^2$

(No Loop Suppression !)



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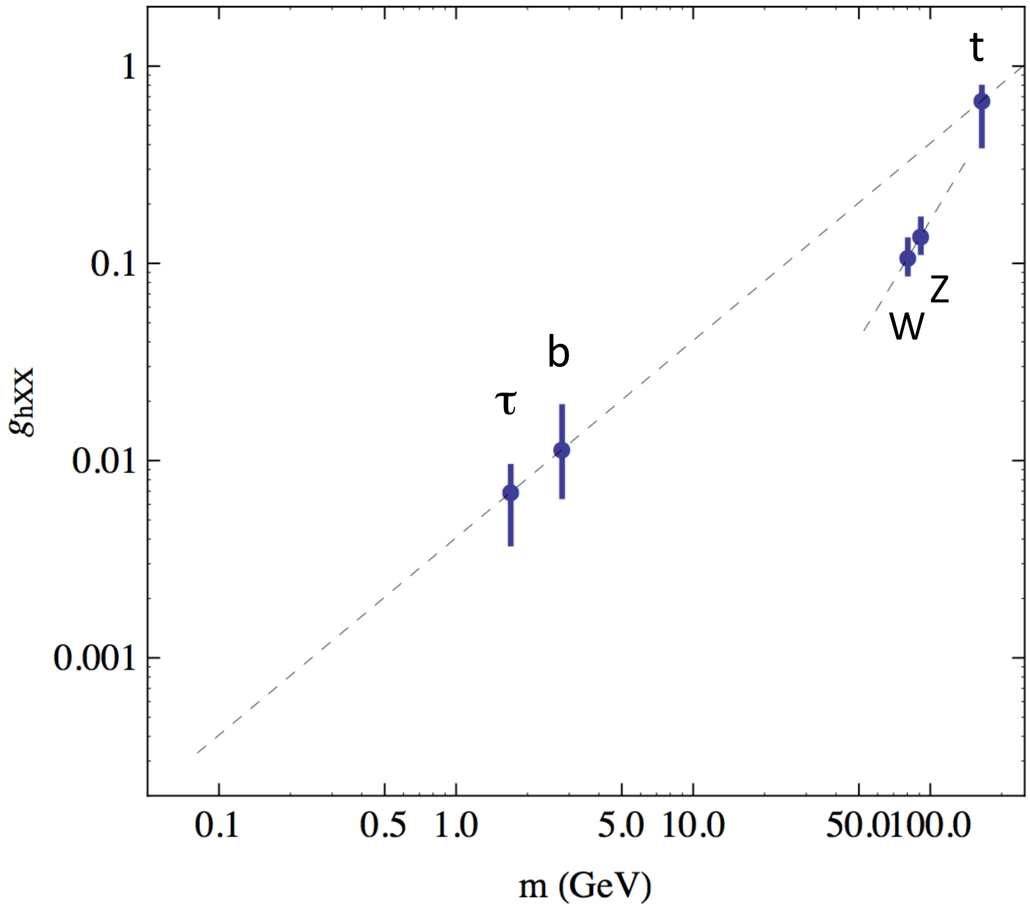
Higgs Boson Rate Measurements

It's the Higgs Boson !!



CMS Global Fits
(Pre-Moriond 2013)

Re-interpreted Loop
Couplings in terms of
W and top Couplings

$g_{hXX} = (m_X/v)^n$

n = 1 Fermion
n = 2 Boson

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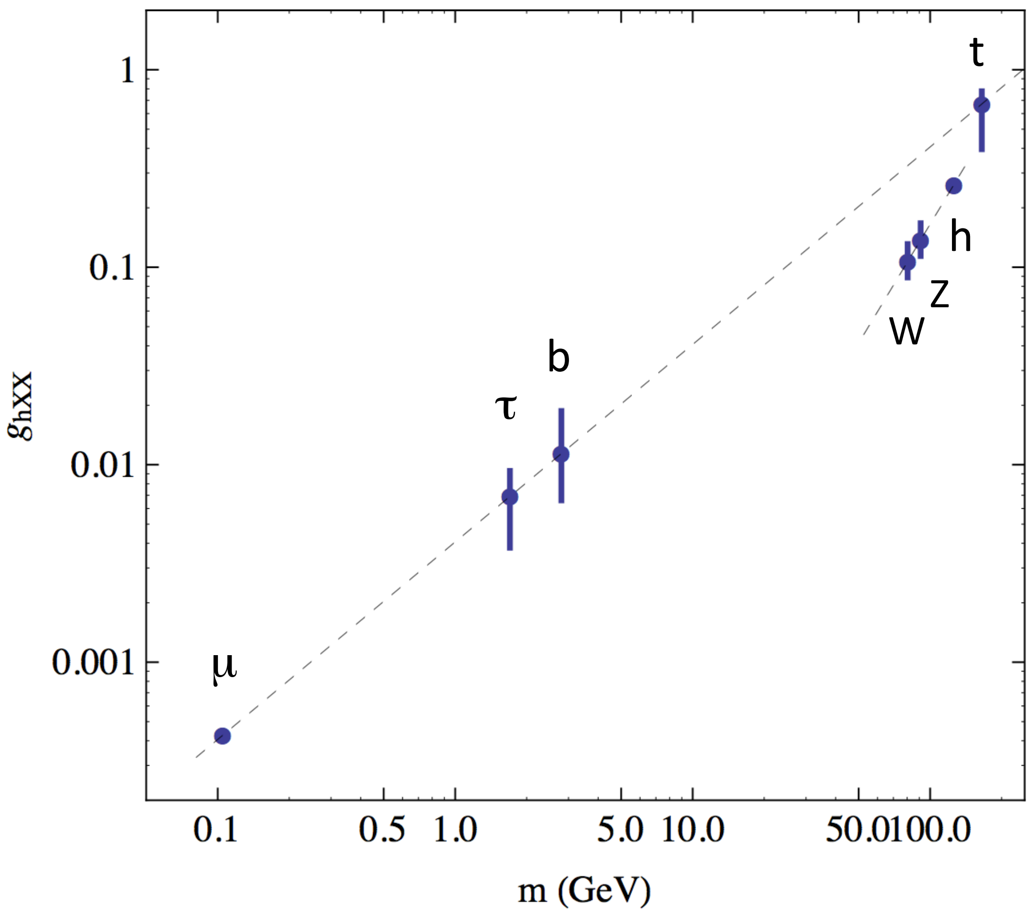

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Precision Probes of New Physics

Electroweak Observables

G_F, m_W, m_Z, Γ_Z, $A_{Z\text{-}FB}$, ...

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 , ...

Precision Physics Through the Higgs

(Craig, ST)

Higgs Observables

σ . Br (Initial -> h -> Final)

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<u>Best Channels</u>:

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

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

Best Channels: (Ratios)

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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)

Renormalizable SM + D=6 Operators

H = ‹H› + h

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

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

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

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

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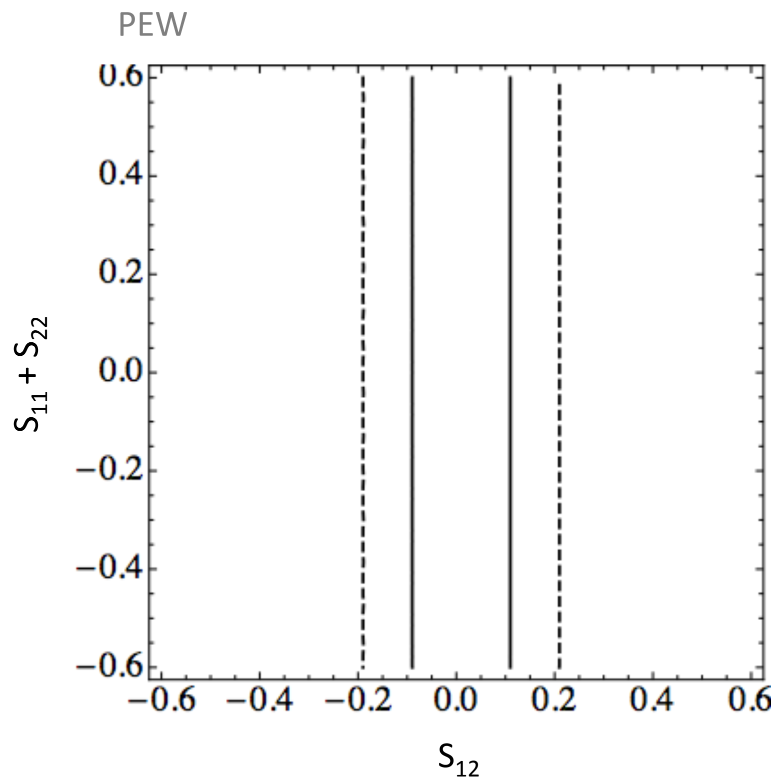

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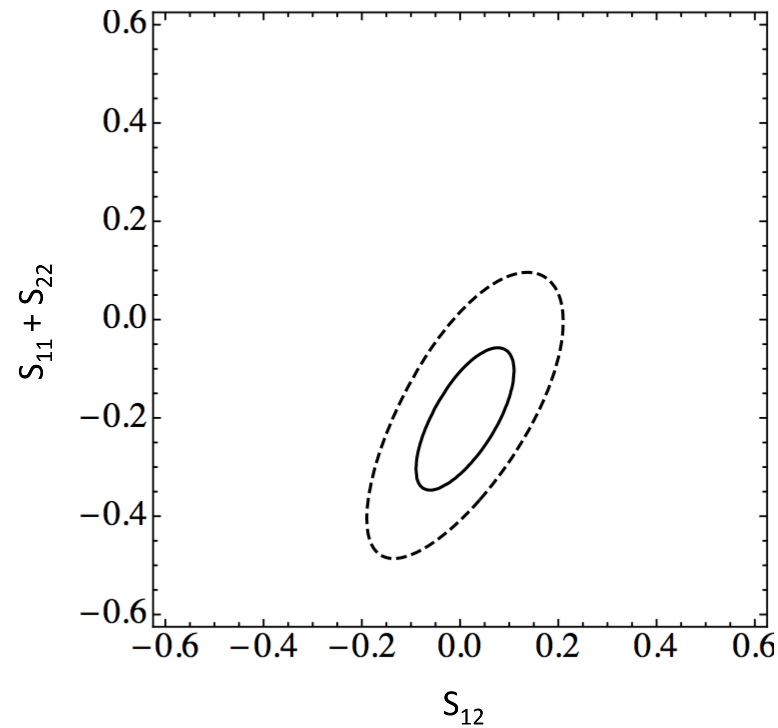
Best Channels: (Ratios)

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

PEW + CMS 5 + 12(5) fb^{-1} 7 + 8 TeV



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

Precision Physics Through the Higgs

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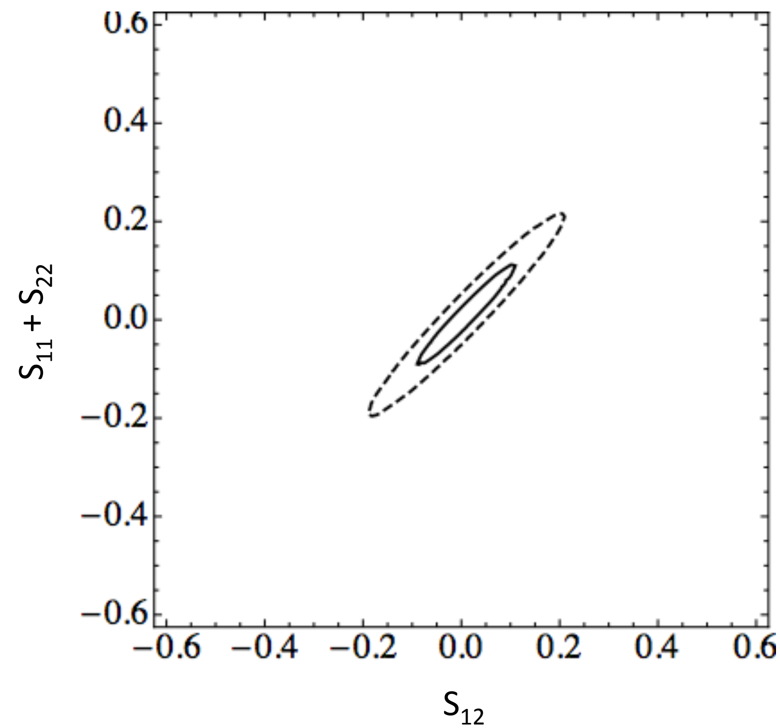
PEW + 5% Uncertainty Br(h->γγ)/Br(h->ZZ)



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Searching for 2nd Higgs Doublet in SM Higgs Boson Rate Measurements

(Craig, ST)

Two Higgs Doublets h, A, H, H+-

h-H mix

Large modifications of h couplings Possible

Four Discrete Two Doublet Models that Satisfy Glashow-Weinberg Condition

Two Parameters, α , β

$$\tan\beta \equiv |\langle\Phi_2^0\rangle/\langle\Phi_1^0\rangle|$$

$$\begin{pmatrix} \sqrt{2}\ \mathrm{Re}(\Phi_2^0) - v_2 \\ \sqrt{2}\ \mathrm{Re}(\Phi_1^0) - v_1 \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

Four couplings

(see paper for correlations)

(MSSM)

	2HDM I	2HDM II	2HDM III	2HDM IV
u	Φ_2	Φ_2	Φ_2	Φ_2
d	Φ_2	Φ_1	Φ_2	Φ_1
e	Φ_2	Φ_1	Φ_1	Φ_2

	2HDM I	2HDM II	2HDM III	2HDM IV
hVV	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$	$\sin(\beta-\alpha)$
hQu	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$	$\cos\alpha/\sin\beta$
hQd	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$
hLe	$\cos\alpha/\sin\beta$	$-\sin\alpha/\cos\beta$	$-\sin\alpha/\cos\beta$	$\cos\alpha/\sin\beta$
HVV	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$	$\cos(\beta-\alpha)$
HQu	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$	$\sin\alpha/\sin\beta$
HQd	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$
HLe	$\sin\alpha/\sin\beta$	$\cos\alpha/\cos\beta$	$\cos\alpha/\cos\beta$	$\sin\alpha/\sin\beta$
AVV	0	0	0	0
AQu	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

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AVV	0	0	0	0
AQu	$\cot\beta$	$\cot\beta$	$\cot\beta$	$\cot\beta$
AQd	$-\cot\beta$	$\tan\beta$	$-\cot\beta$	$\tan\beta$
ALe	$-\cot\beta$	$\tan\beta$	$\tan\beta$	$-\cot\beta$

Alignment Limit:

h mass Eigenstate || Expectation Values

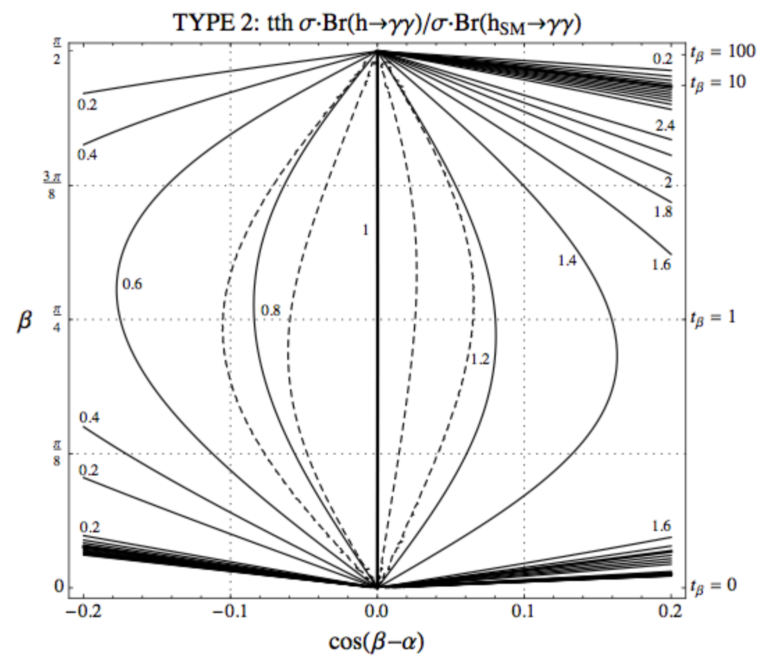
$\cos(\beta - \alpha) = 0$

h couplings = h_{SM} couplings

Searching for 2^{nd} Higgs Doublet in SM Higgs Boson Rate Measurements

(Craig, Galloway, ST)

Two Higgs Doublets h-H mix



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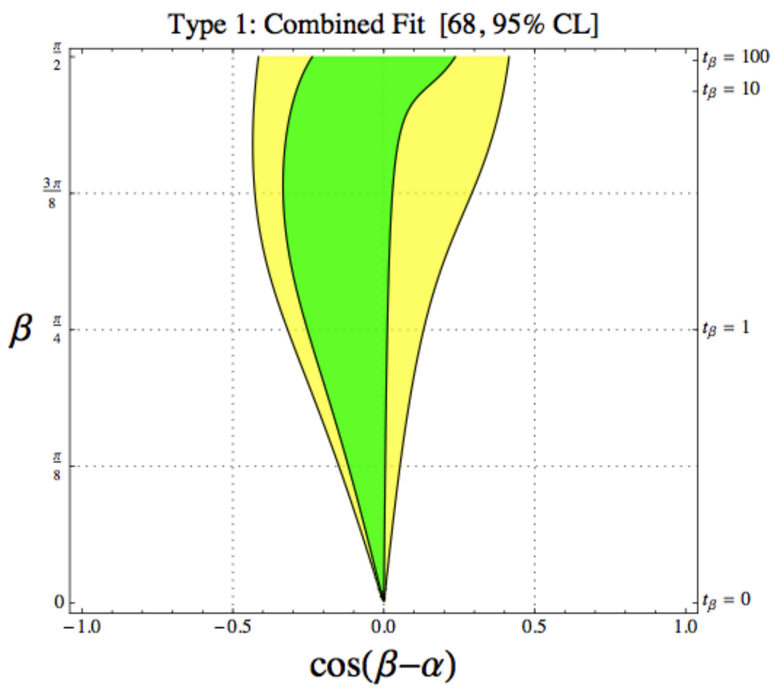

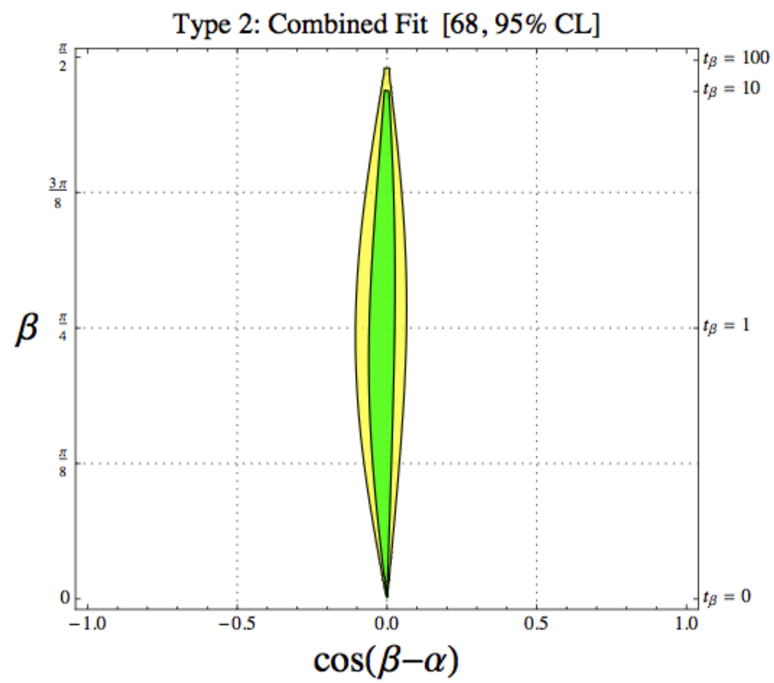

hQd , hQu $\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$

hQd $\sin(\beta-\alpha) - \tan\beta\cos(\beta-\alpha)$

hQu $\sin(\beta-\alpha) + \cot\beta\cos(\beta-\alpha)$

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Experimentally:

h Couplings ~ h_{SM} Couplings

Theoretically for 2HDM Implies:

Type I – Close to Alignment Limit
Type II – Very Close to Alignment Limit

Implications for Proximity to
Decoupling Limit - (Model Dependent)

Implications for A,H,H+- Couplings
Direct Searches …

Direct Searches for 2nd Higgs Doublet

(Craig, Evans, Kilic, Park, ST)

Two Higgs Doublets h, A, H, H^{+-}

Consider Spectrum:

$2\, m_h < m_A \sim m_H \sim m_{H+-} < 2\, m_t$

splittings < $O(m_W)$

Leading Topologies with Unsuppressed Production Cross Sections Near Alignment Limit

Second Higgs Doublet Decay Topology	Alignment Limit
$H \to WW, ZZ$	–
$H, A \to \gamma\gamma$	✓
$H, A \to \tau\tau, \mu\mu$	✓
$H, A \to tt$	✓
$A \to Zh$	–
$H \to hh$	–
$t \to H^{\pm}b$	✓

Checkmark = Constant in Alignment Limit
Dash = Vanishes in Alignment Limit

Direct Searches for 2nd Higgs Doublet

(Craig, Evans, Kilic, Park, ST)

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$H, A \rightarrow tt$	✓
$A \rightarrow Zh$	–
$H \rightarrow hh$	–
$t \rightarrow H^{\pm}b$	✓

SM Higgs Search Channels

Non-Standard Channels

Checkmark = Constant in Alignment Limit
Dash = Vanishes in Alignment Limit

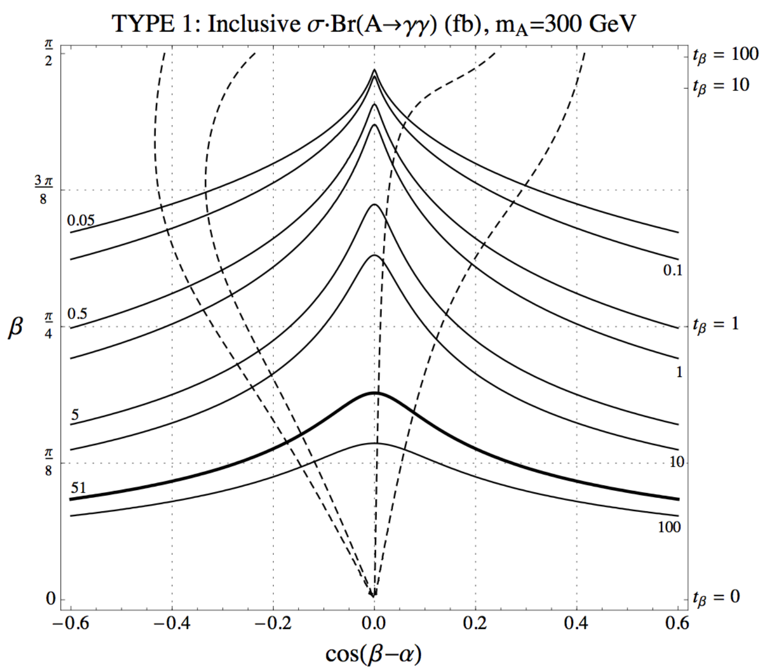
Direct Searches for 2nd Higgs Doublet

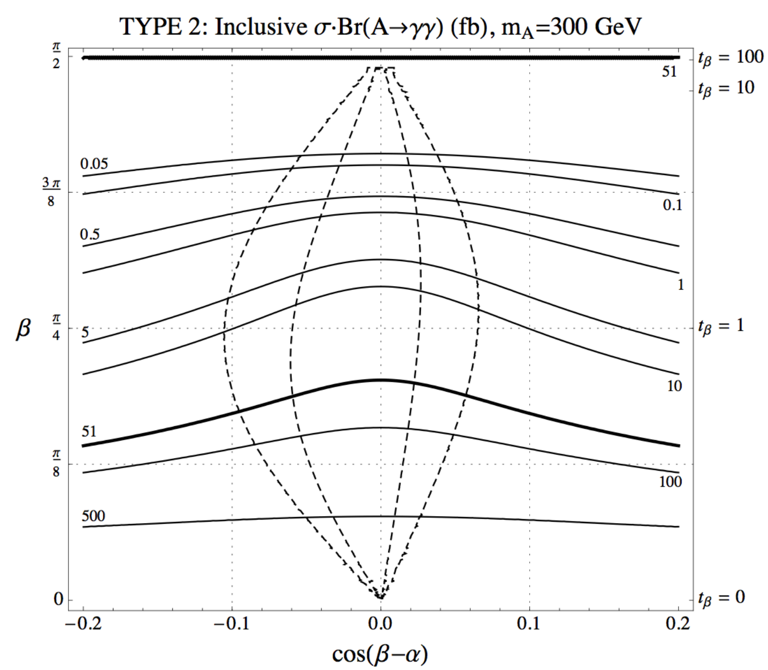
(Craig, Galloway, ST)

Two Higgs Doublets h, A, H, H^{+-}

gg -> A,H -> γγ

σ . Br(A -> γγ) = few . σ . Br(H -> γγ)





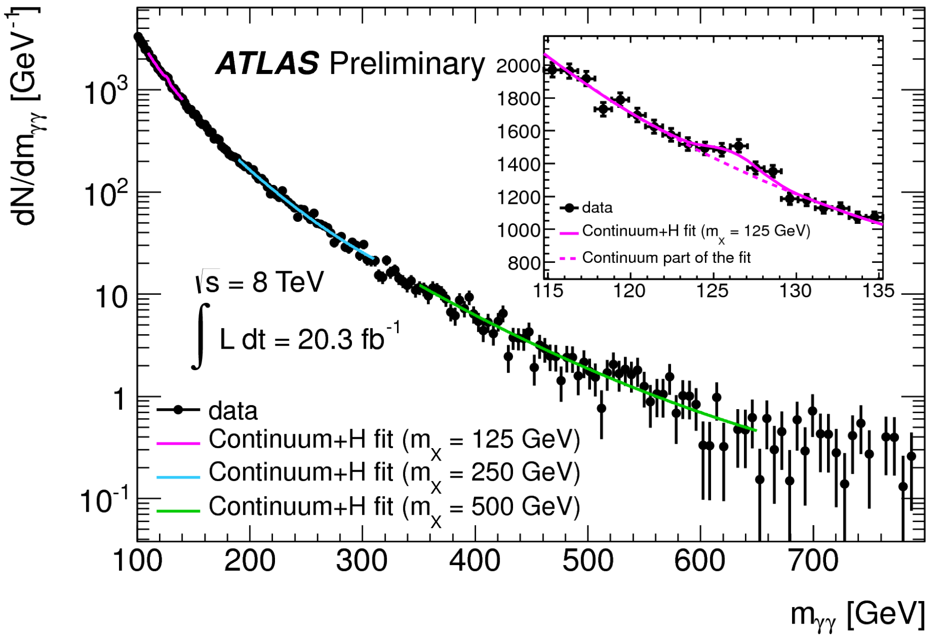
σ . Br(h_{SM} -> γγ) = 51 fb
for m_h = 125 GeV

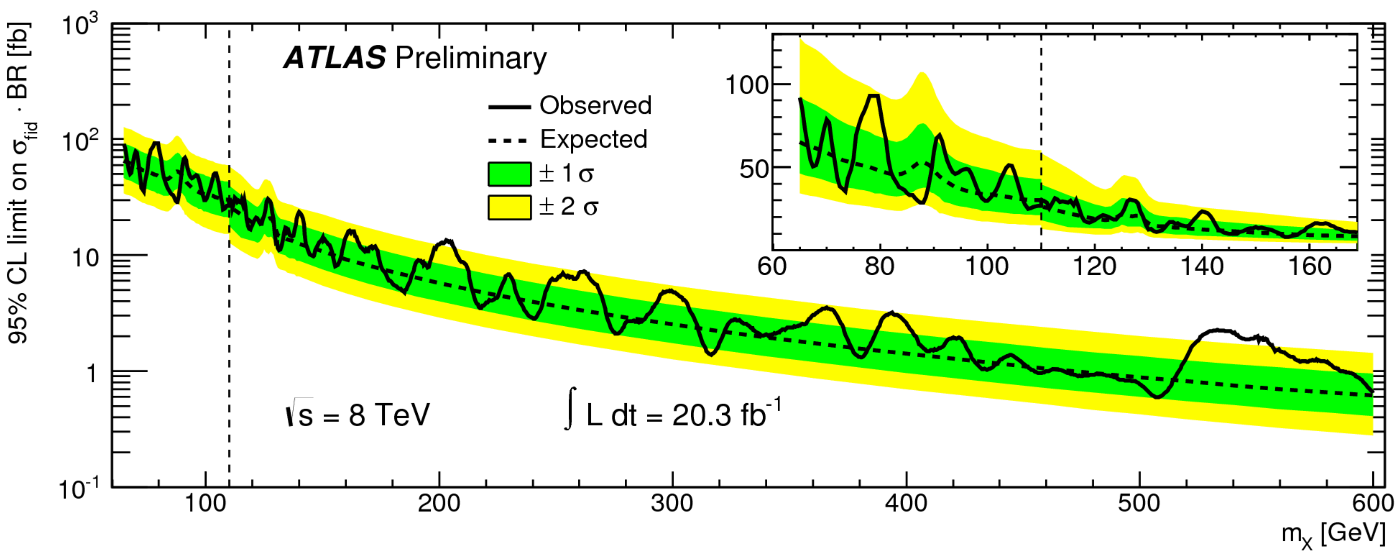
Direct Searches for 2nd Higgs Doublet

Two Higgs Doublets h, A, H, H^{+-}

$gg \to A,H \to \gamma\gamma$

σ . Br($h_{SM} \to \gamma\gamma$) < 5 fb
for m_A = 300 GeV



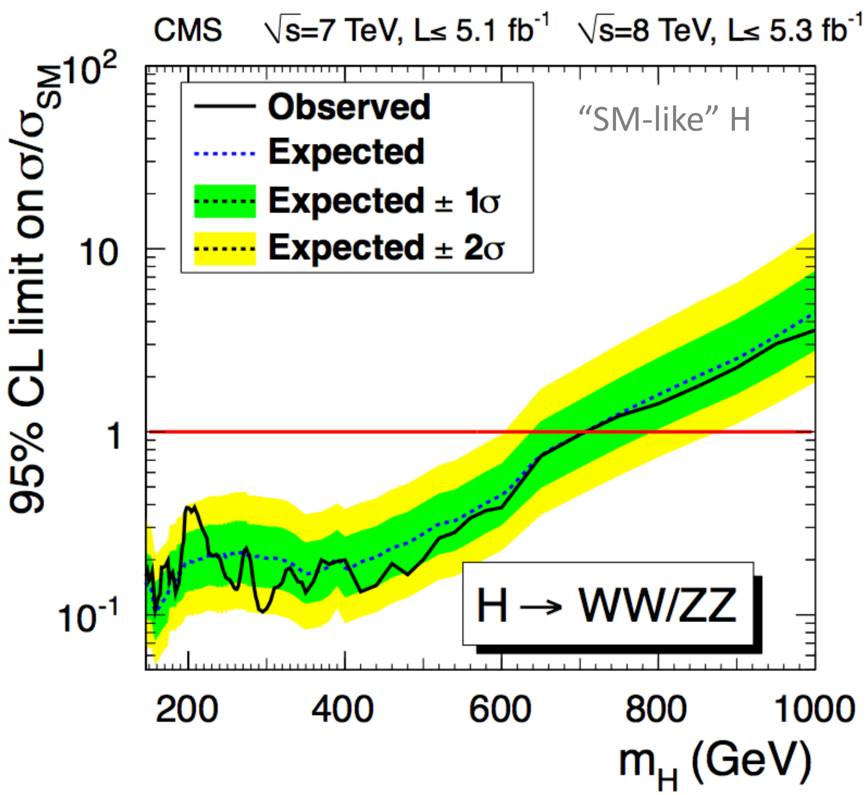


Direct Searches for 2nd Higgs Doublet

(CMS)

Two Higgs Doublets h, A, H, H^{+-}

h – H mix   gg -> H -> WW, ZZ

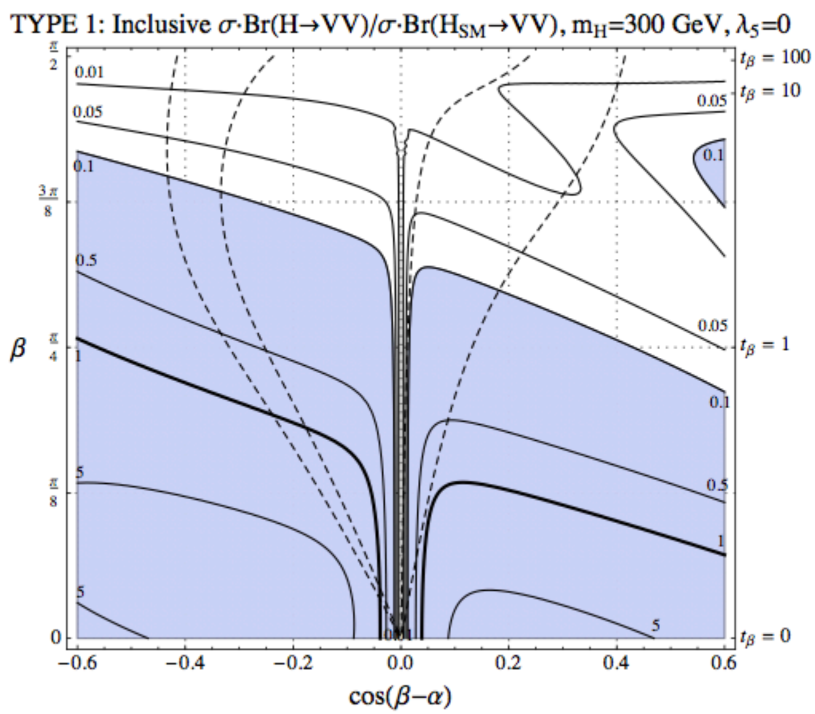


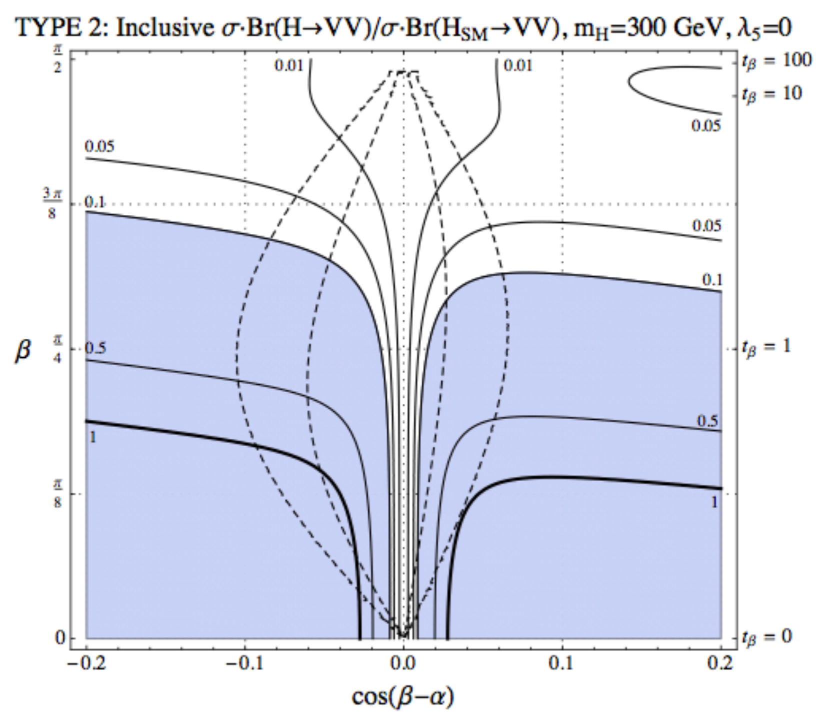
Direct Searches for 2nd Higgs Doublet

(Craig, Galloway, ST)

Two Higgs Doublets h, A, H, H^{+-}

h – H mix gg -> H -> WW, ZZ





Could do a bit better with Narrow Width H-> ZZ->l lll Search

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

(Park, ST)

Much 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

$$\eta_0 = \frac{1}{2}\ln\left[\frac{E_{T_{\ell+}}e^{\eta_{\ell+}} - E_{T_{\ell-}}e^{\eta_{\ell-}}}{E_{T_{\ell-}}e^{-\eta_{\ell-}} - E_{T_{\ell+}}e^{-\eta_{\ell+}}}\right]$$

$$\Xi_0 = e^{2\eta_0} = \frac{E_{T_{\ell+}}e^{\eta_{\ell+}} - E_{T_{\ell-}}e^{\eta_{\ell-}}}{E_{T_{\ell-}}e^{-\eta_{\ell-}} - E_{T_{\ell+}}e^{-\eta_{\ell+}}}$$

$$m = \begin{cases} 4E_{T_j}\cosh\left(\eta_j - \frac{1}{2}\ln\Xi_0\right) & \Xi_0 > 0 \\ 4iE_{T_j}\left|\sinh\left(\eta_j - \frac{1}{2}\ln(-\Xi_0)\right)\right| & \Xi_0 < 0 \end{cases}$$

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

(Park, ST)

Much of the Phase Space Distribution Near Threshold

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

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$m_{E=E}$ Without Using MET

Systematically Improve Threshold Approximation by

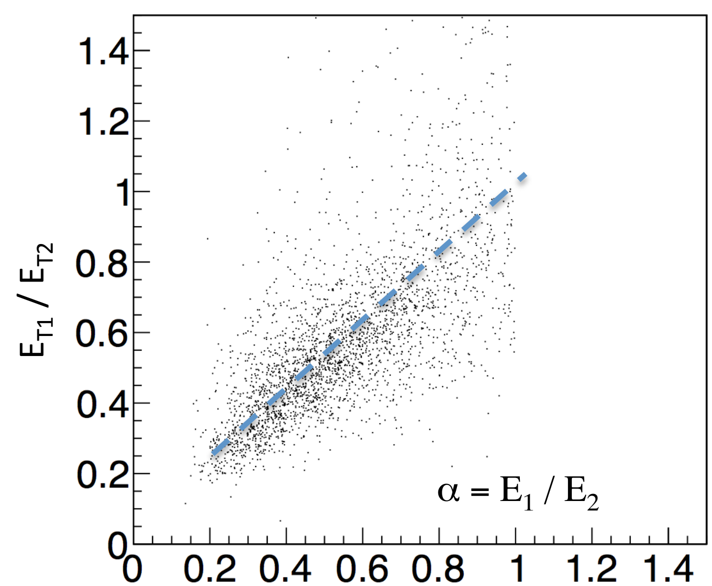
1. Threshold Corrections
   $\alpha = E_1 / E_2$

2. Iterative Transverse Reboosting - $p_{T\text{-Higgs}} \neq 0$

$$\eta_0 = \frac{1}{2}\ln\left[\frac{E_{T_{\ell_2}}e^{\eta_{\ell_2}} - \alpha E_{T_{\ell_1}}e^{\eta_{\ell_1}}}{\alpha E_{T_{\ell_1}}e^{-\eta_{\ell_1}} - E_{T_{\ell_2}}e^{-\eta_{\ell_2}}}\right]$$

$$\Xi_0 = e^{2\eta_0} = \frac{E_{T_{\ell_2}}e^{\eta_{\ell_2}} - \alpha E_{T_{\ell_1}}e^{\eta_{\ell_1}}}{\alpha E_{T_{\ell_1}}e^{-\eta_{\ell_1}} - E_{T_{\ell_2}}e^{-\eta_{\ell_2}}}$$

$$m = \begin{cases} 2(\alpha+1)E_{T_1}\cosh\left(\eta_1 - \frac{1}{2}\ln\Xi_0\right) & \Xi_0 > 0 \\ 2(\alpha+1)iE_{T_1}\left|\sinh\left(\eta_1 - \frac{1}{2}\ln(-\Xi_0)\right)\right| & \Xi_0 < 0 \end{cases}$$



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

(Park, ST)

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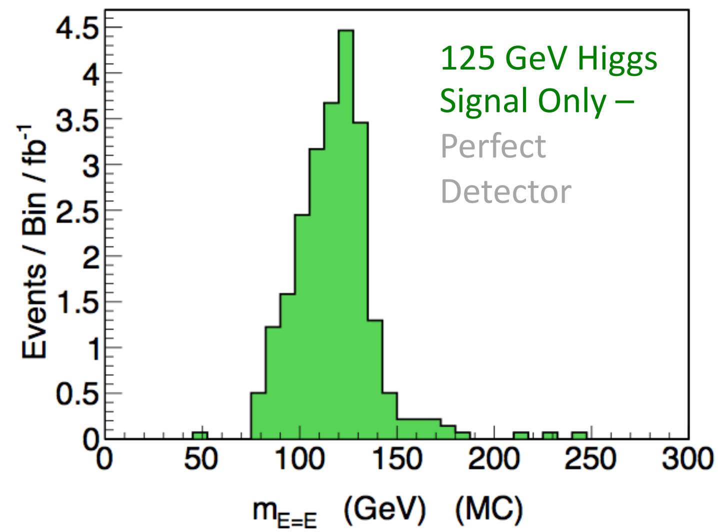

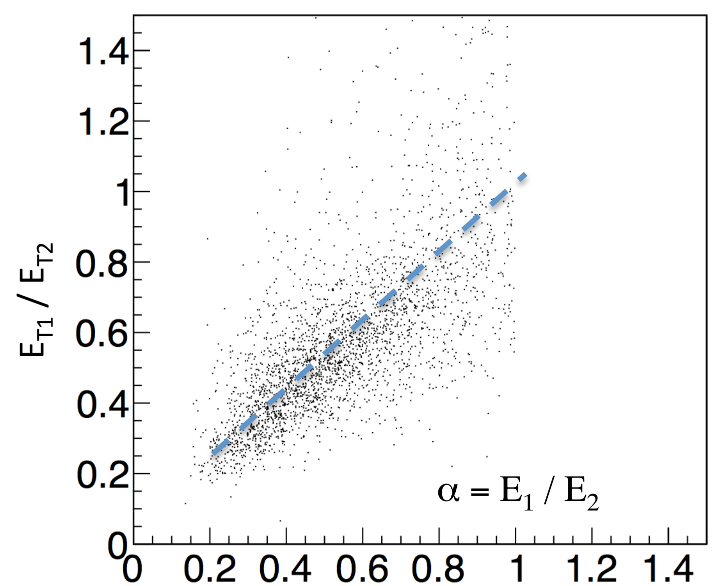

Reconstructing the Higgs Mass in the Higgs -> WW* -> l ν l ν Channel

(Park, ST)

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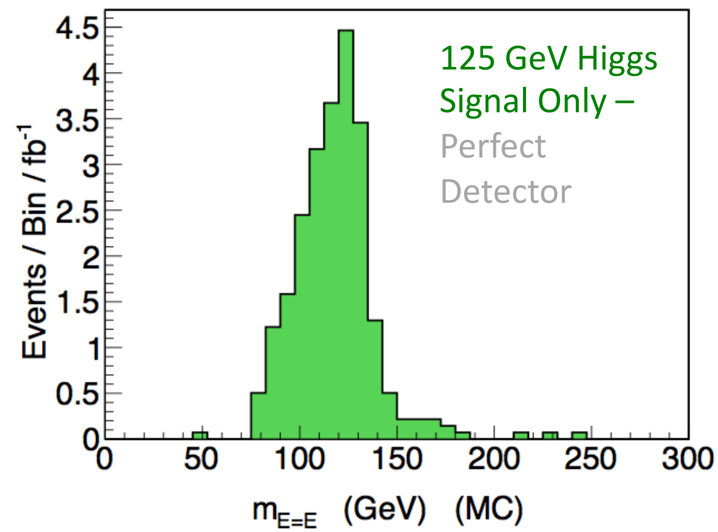
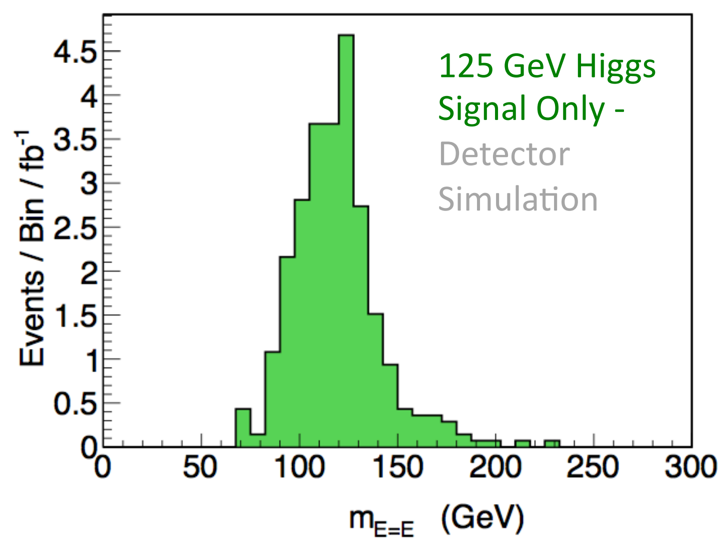




Reconstructing the Higgs Mass in the Higgs -> WW* -> l ν l ν Channel

(Park, ST)

Much of the Phase Space Distribution Near Threshold

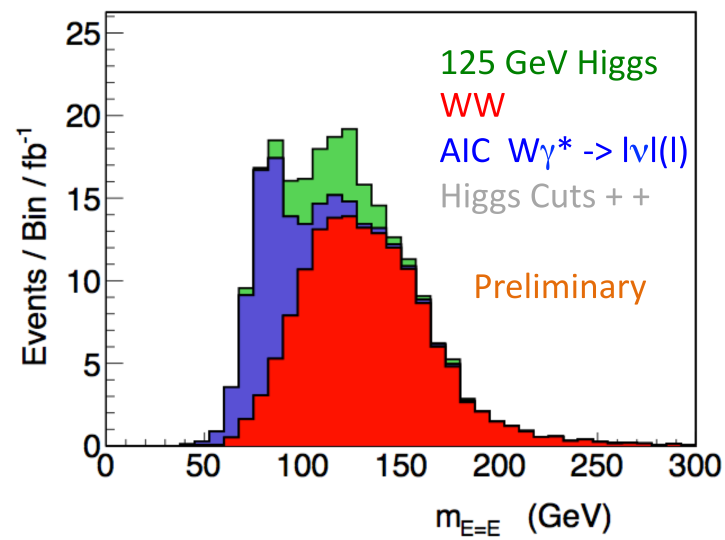
At Threshold:
$E_{l-} = E_{l+}$ In Higgs Rest Frame

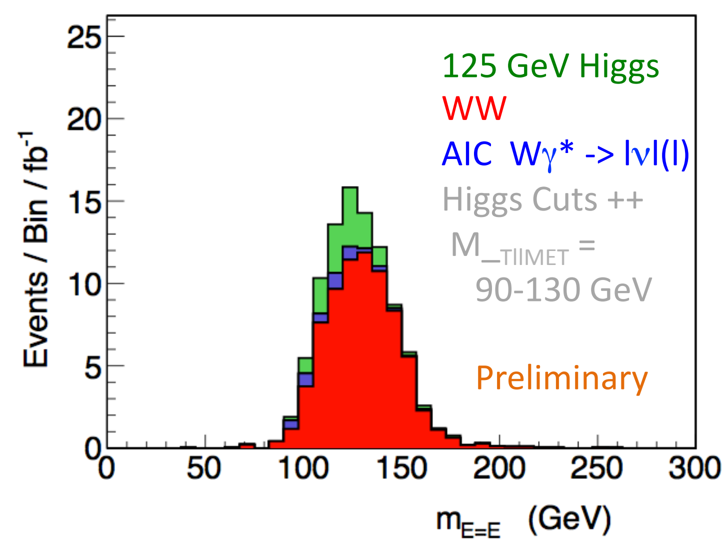
Boost to this Frame - form $m_{E=E}$ Without Using MET

Systematically Improve Threshold Approximation by

1. Threshold Corrections
   $\alpha = E_1 / E_2$

2. Iterative Transverse Reboosting - $p_{T\text{-Higgs}} \neq 0$





Reconstructing the 2nd Higgs Mass in the Higgs -> WW* -> l ν l ν Channel

(Park, ST)

Much of the Phase Space Distribution Near Threshold

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

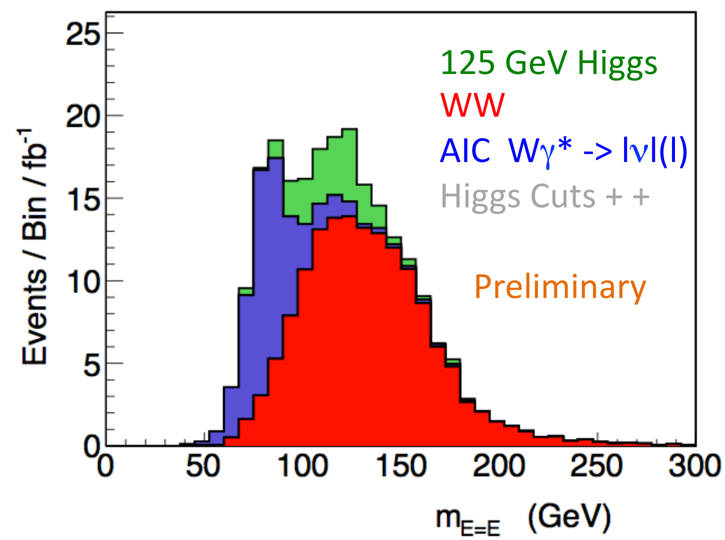
Boost to this Frame - form $m_{E=E}$ <u>Without</u> Using MET

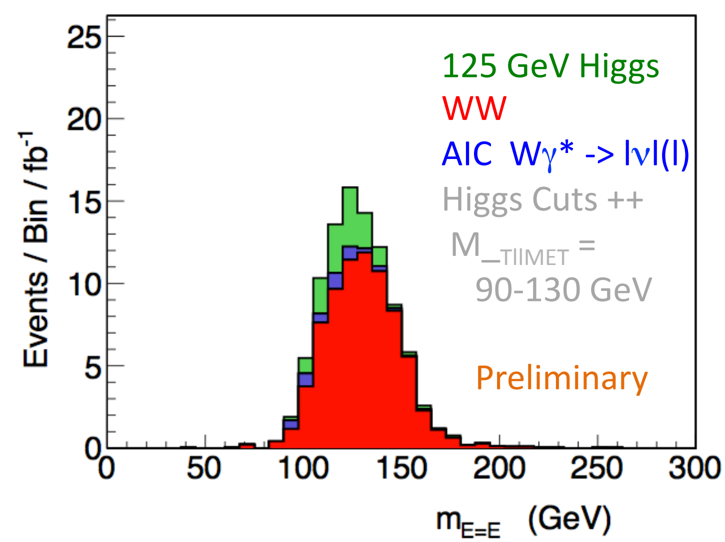
Systematically Improve Threshold Approximation by

1. Threshold Corrections
   $\alpha = E_1 / E_2$

2. Iterative Transverse Rebooosting - $p_{T\text{-Higgs}} \neq 0$

Search for H -> WW
130 - 160 GeV

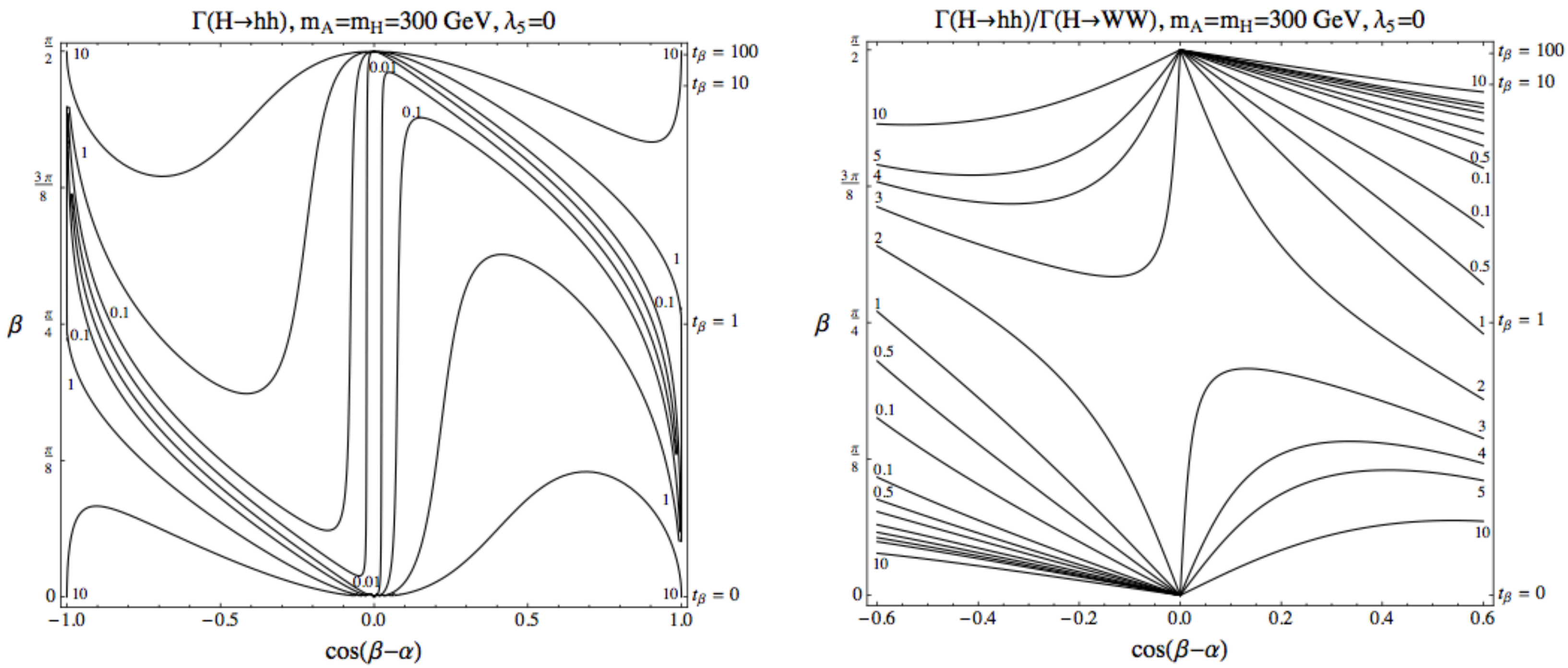




Direct Searches for 2nd Higgs Doublet

Two Higgs Doublets h, A, H, H^{+-}

gg -> H -> hh

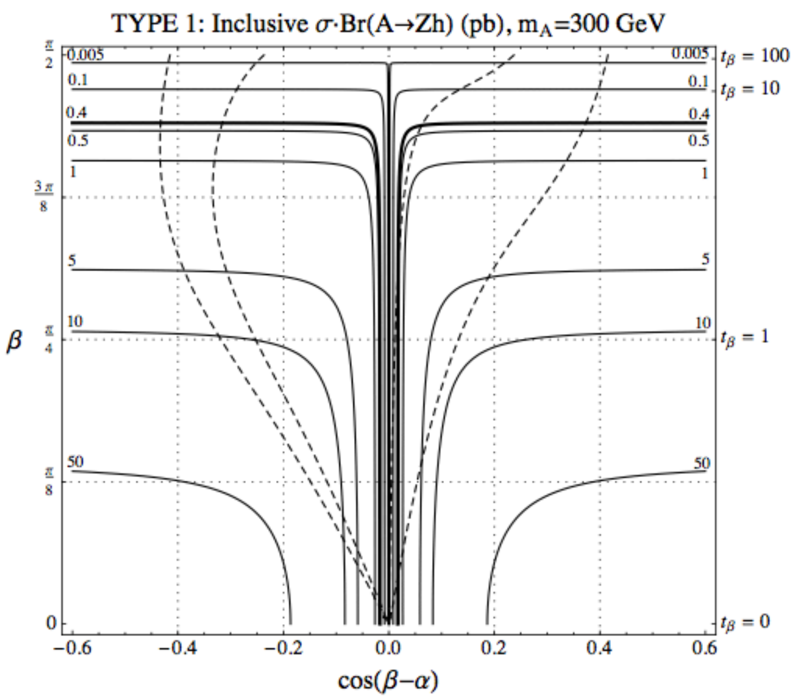


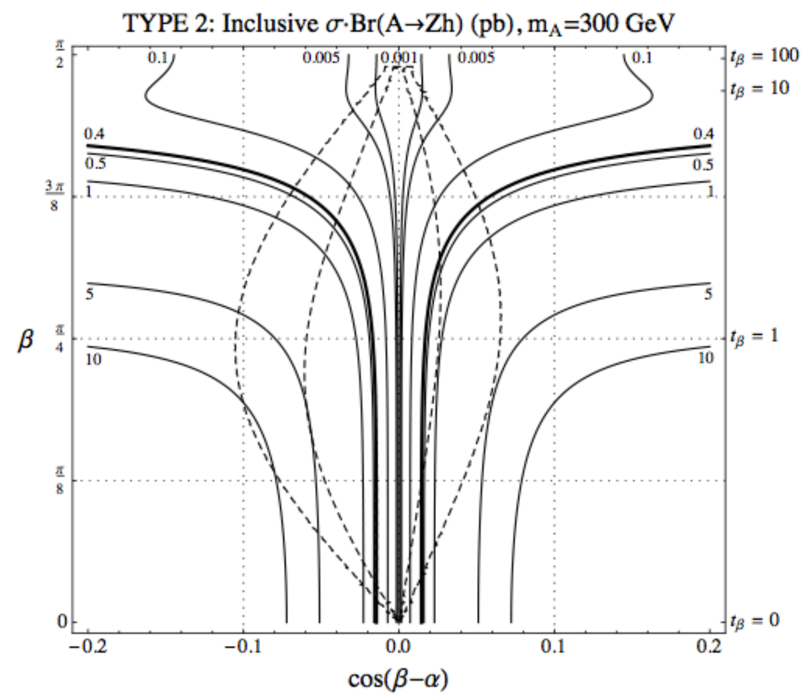
Direct Searches for 2^{nd} Higgs Doublet

(Craig, Galloway, ST)

Two Higgs Doublets h, A, H, H^{+-}

gg -> A -> Zh





Direct Searches for 2^{nd} Higgs Doublet

Two Higgs Doublets h, A, H, H^{+-}

gg -> H -> hh , gg -> A -> Zh

hh Decay Modes

hh	WW	ZZ	$\tau\tau$	bb	$\gamma\gamma$
WW					
ZZ					
$\tau\tau$					
bb					
$\gamma\gamma$					

Leptons +X
Di-Photons + X
Quad-b-jets

Zh Decay Modes

Zh	WW	ZZ	$\tau\tau$	bb	$\gamma\gamma$
$\ell\ell$					
$\nu\nu$					
jj					

Leptons + X
Di-Photons + X
Di-b-jets + X

Direct Multi-Lepton Search for 2nd Higgs Doublet

Two Higgs Doublets h, A, H, H^{+-} (CMS)

gg -> H -> hh , gg -> A -> Zh

Extremely Sensitive Probes
for New Physics

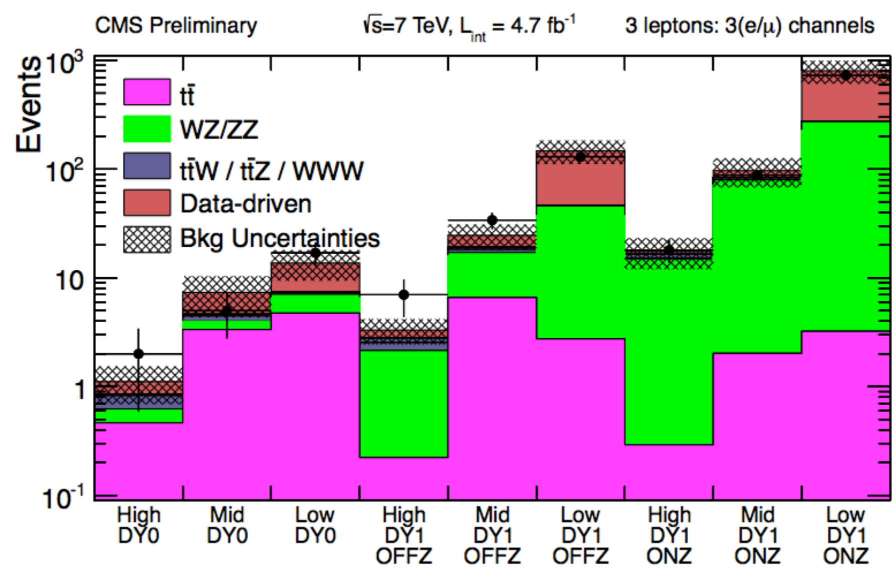
Exclusive Channels Based on

All Flavor + Charge Combinations
Two or More Leptons (and taus)
HT, MET, ST, …
b-tags, … , jets
Kinematics Discriminants + …

Events -> Channels Lowest to
Highest Background Exclusively

Maximizes Sensitivity
(Given Signal may Overlap with
Low Background Channels)

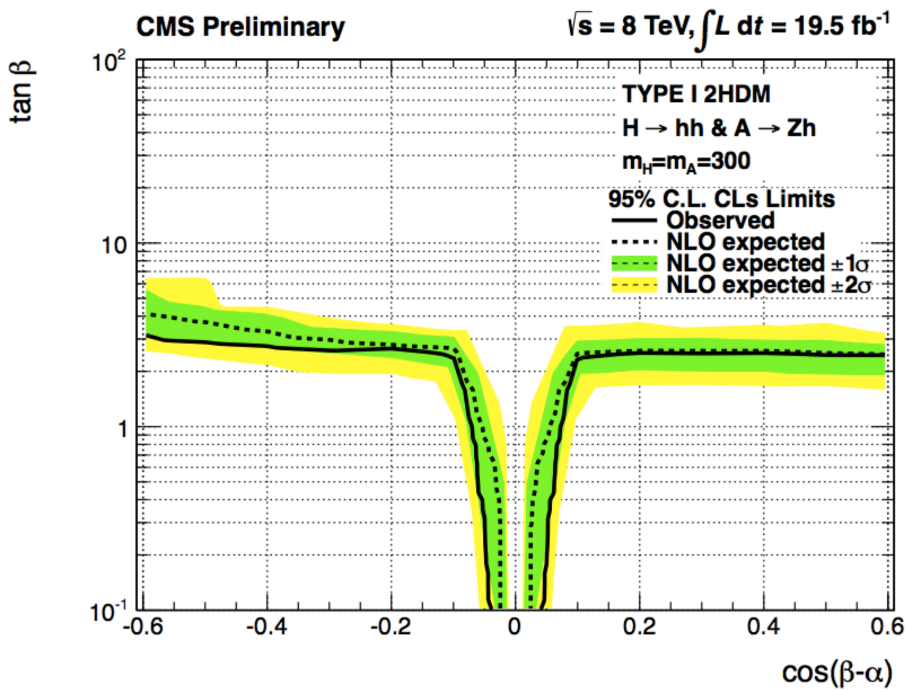
Exclusive Combination of All
(100's) of Channels

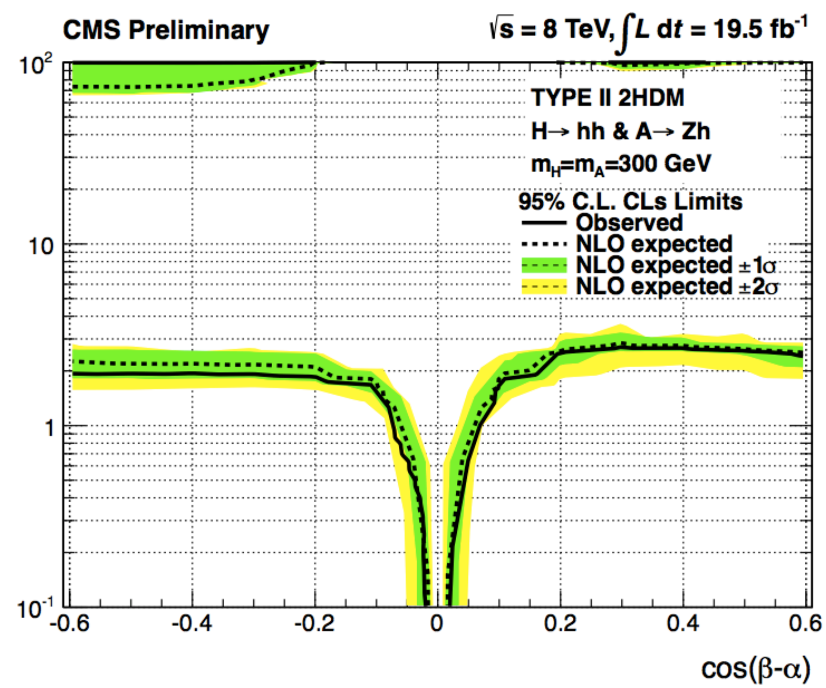


Direct Multi-Lepton Search for 2nd Higgs Doublet

Two Higgs Doublets h, A, H, H^{+-} (CMS)

gg -> H -> hh , gg -> A -> Zh





Multi-Lepton Search for A->Zh

Tri-Leptons OSSF + Third Lepton

WZ -> 3 Leptons - Dominant Background

Zh Decay Modes

Zh	WW	ZZ	$\tau\tau$	bb	$\gamma\gamma$
$\ell\ell$					
$\nu\nu$					
jj					

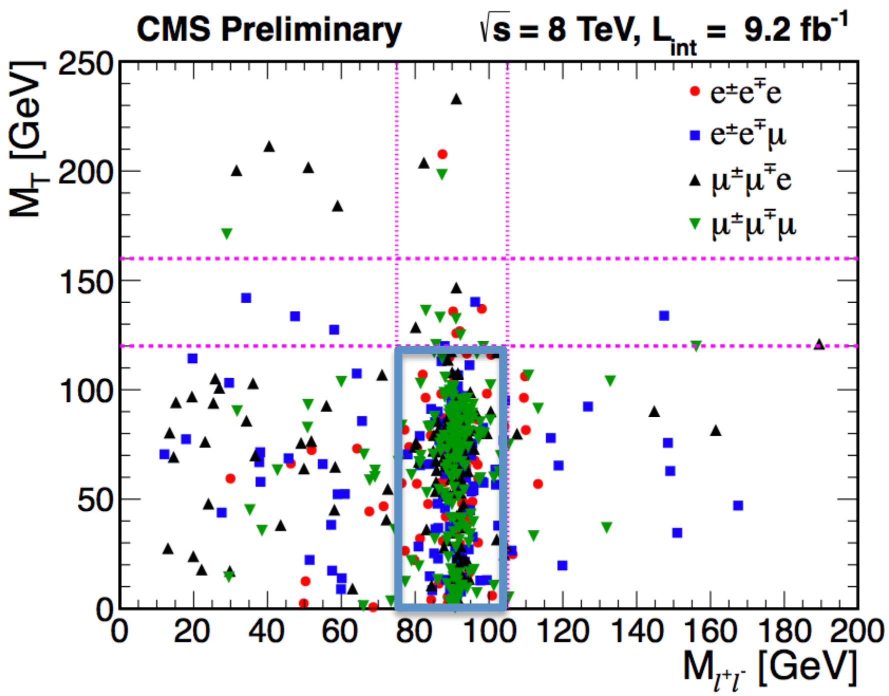
Includes Tri-Leptons + X

Multi-Lepton Search for A->Zh

(CMS ; Craig, Evans, Park, ST)

Tri-Leptons OSSF + Third Lepton

WZ -> 3 Leptons - Dominant Background



gg -> A -> Zh -> (ll)(lνjj)

Lands Right on Top of WZ Background in m_T - m_{ll}

2 Extra Jets

Can Completely Reconstruct Kinematics

Searching for Non-Standard Production of Higgs

Use 125 GeV Higgs as Calibration to Search for New Physics

$h \to WW^*, ZZ^*, \tau\tau, bb, \gamma\gamma$

tt Pair Production with

$t \to c\, h$ and $t \to W$

Wh	WW	ZZ	$\tau\tau$	bb	$\gamma\gamma$
$\ell\nu$					
jj					

Leptons + X
Di-Photons + X

Searching for Non-Standard Production of Higgs

Use 125 GeV Higgs as Calibration to Search for New Physics

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

(CMS)

tt Pair Production with

t -> c h and t -> leptonic

8 TeV 20 fb^{-1}

Br(t -> c h) < 0.0056

7 TeV 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)

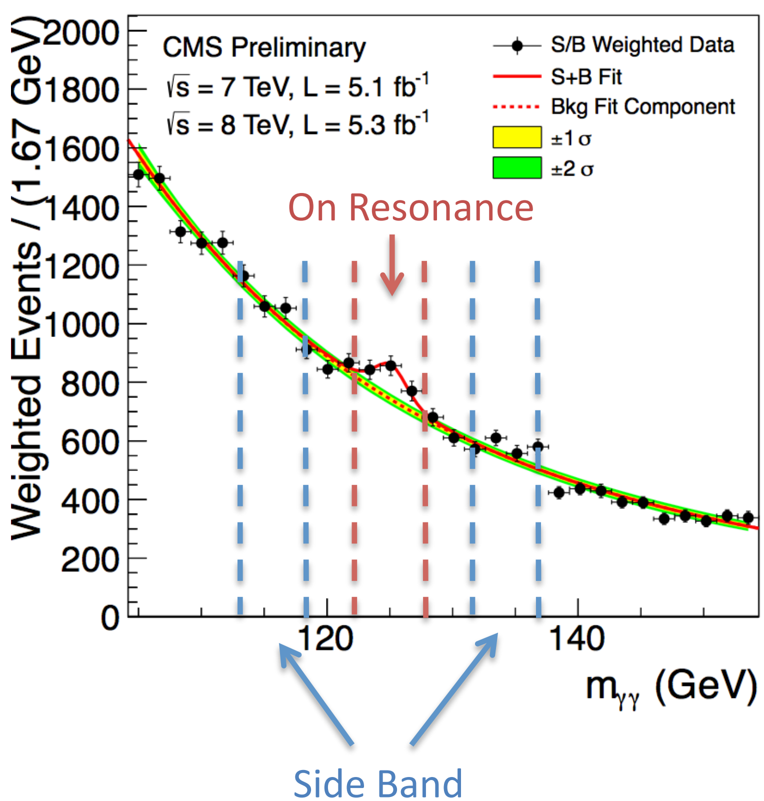
Using Higgs to Discover New Physics

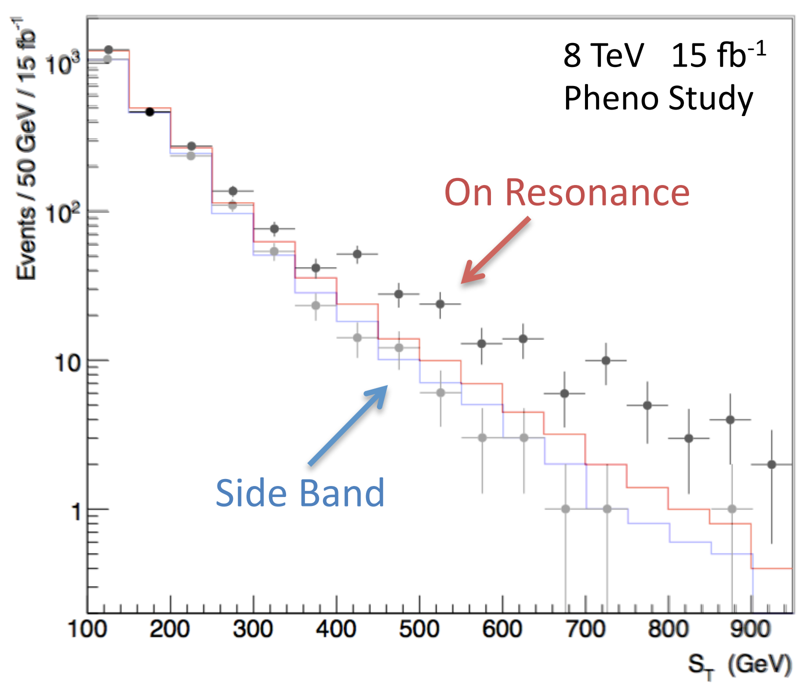
(CMS ; Gershtein, Baker, Y. Kats, ST)

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 + …





Blue = Side Band Background

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

Using Higgs to Discover New Physics

(CMS ; Gershtein, Baker, 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 + …

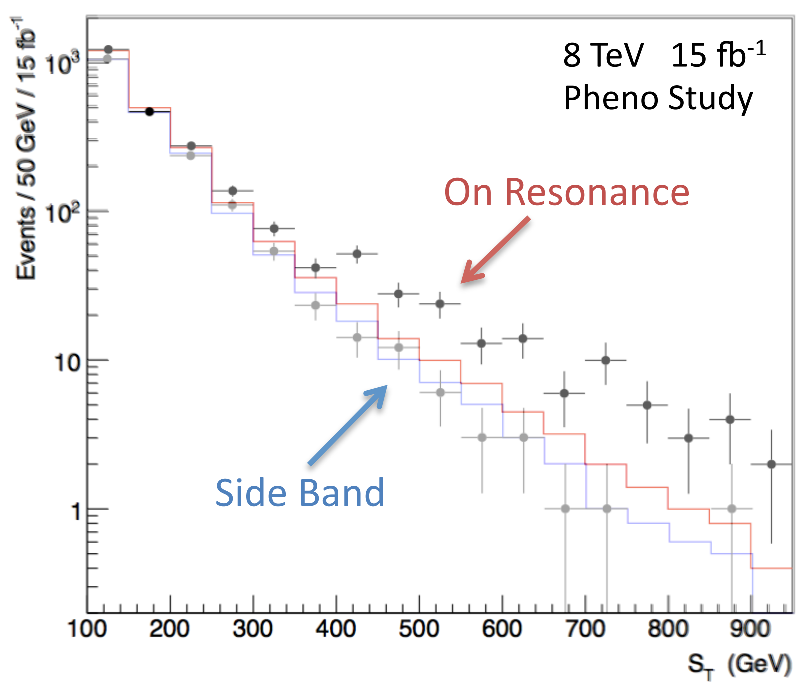
Natural Higgsino NLSP

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

Many other Examples …

More Focused ->

X = Multi-Channel Analysis



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

Search for Additional States Related to Higgs Sector

Higgs Partners $\tilde{H}$

(CMS)

$\tilde{H} \to (h,Z)\,\tilde{G}$ $\tilde{H}\tilde{H} \to (h,Z)(h,Z)\,\tilde{G}\tilde{G}$

hh Decay Modes

hh	WW	ZZ	$\tau\tau$	bb	$\gamma\gamma$
WW					
ZZ					
$\tau\tau$					
bb					
$\gamma\gamma$					

Leptons +X
Di-Photons + X
Quad-b-jets

Zh Decay Modes

Zh	WW	ZZ	$\tau\tau$	bb	$\gamma\gamma$
$\ell\ell$					
$\nu\nu$					
jj					

Leptons + X
Di-Photons + X
Di-b-jets + X

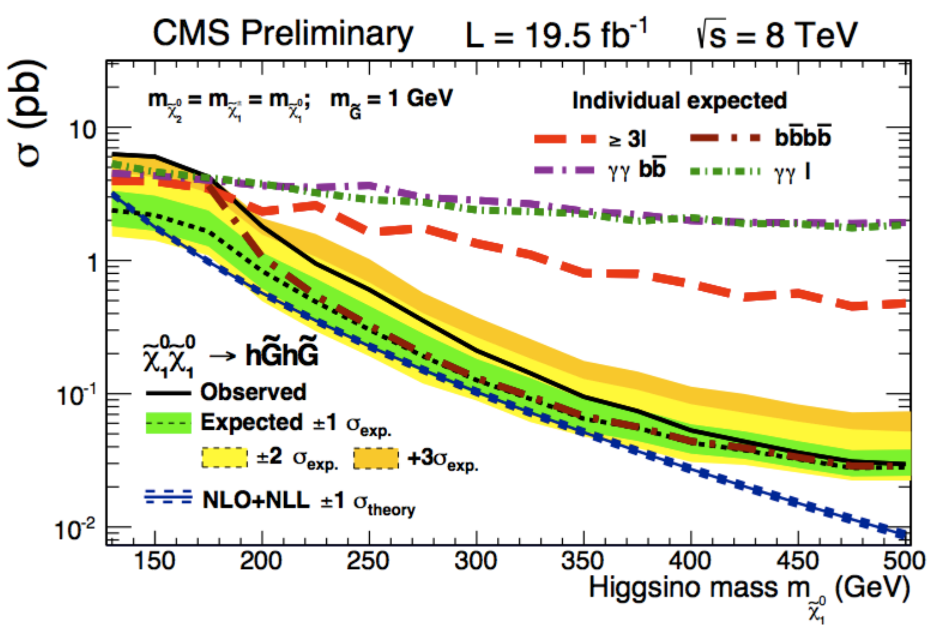
Search for Additional States Related to Higgs Sector

Higgs Partners $\tilde{H}$ (CMS)

$\tilde{H} \to (h,Z)\,\tilde{G}$ $\quad$ $\tilde{H}\tilde{H} \to (h,Z)(h,Z)\,\tilde{G}\tilde{G}$

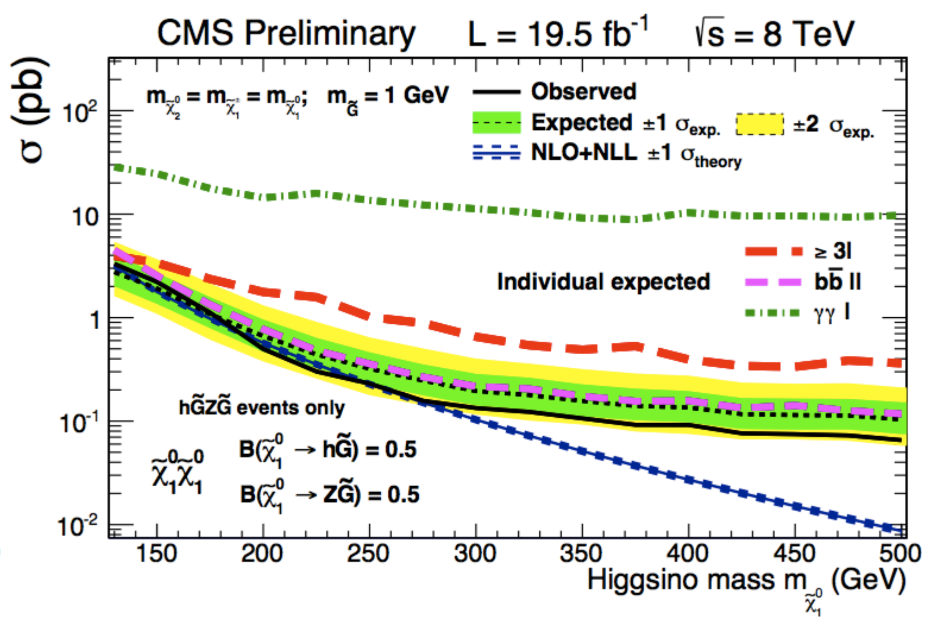
New CMS Result
PAS next week

$\tilde{H}\tilde{H} \to hh\,\tilde{G}\tilde{G}$



New CMS Result
PAS next week

$\tilde{H}\tilde{H} \to hZ\,\tilde{G}\tilde{G}$



Search for Additional States Related to Higgs Sector

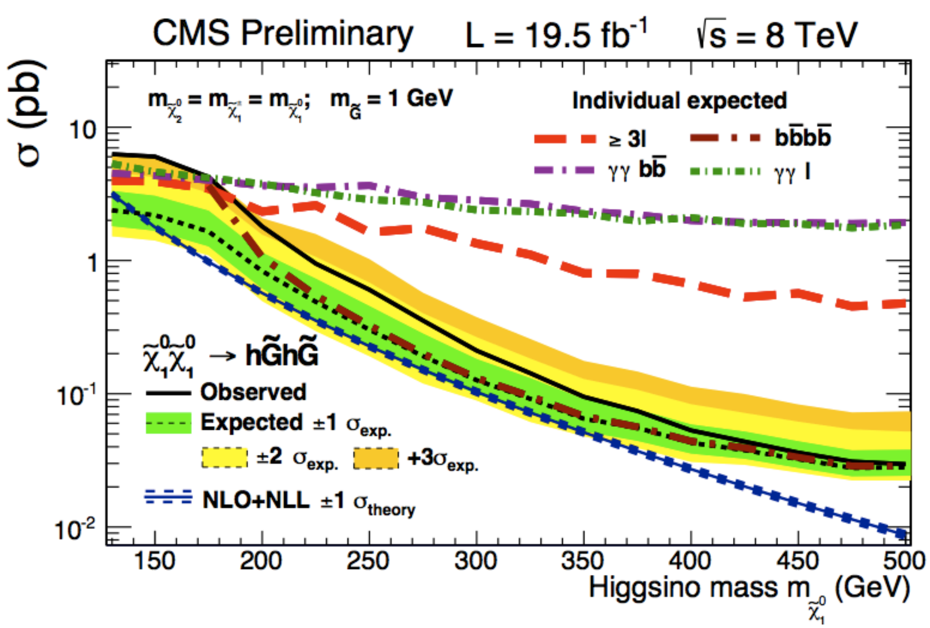
Higgs Partners $\tilde{H}$

(CMS)

$\tilde{H}$ -> (h,Z) $\tilde{G}$ $\tilde{H}\tilde{H}$ -> (h,Z)(h,Z) $\tilde{G}\tilde{G}$

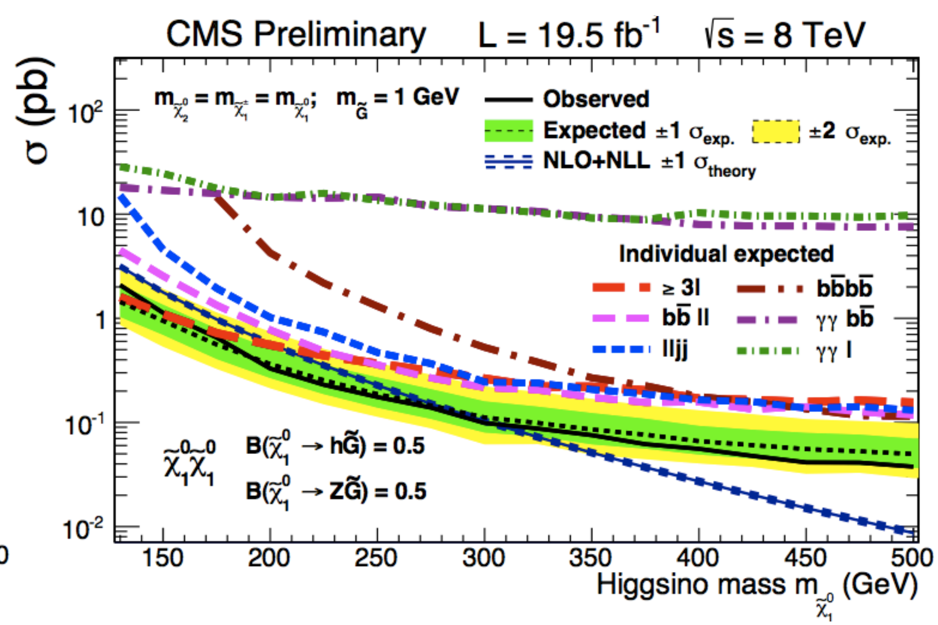
New CMS Result
PAS next week

$\tilde{H}\tilde{H}$ -> hh $\tilde{G}\tilde{G}$



New CMS Result
PAS next week

$\tilde{H}\tilde{H}$ -> (hh,hZ,ZZ) $\tilde{G}\tilde{G}$



Search for Additional States Related to Higgs Sector

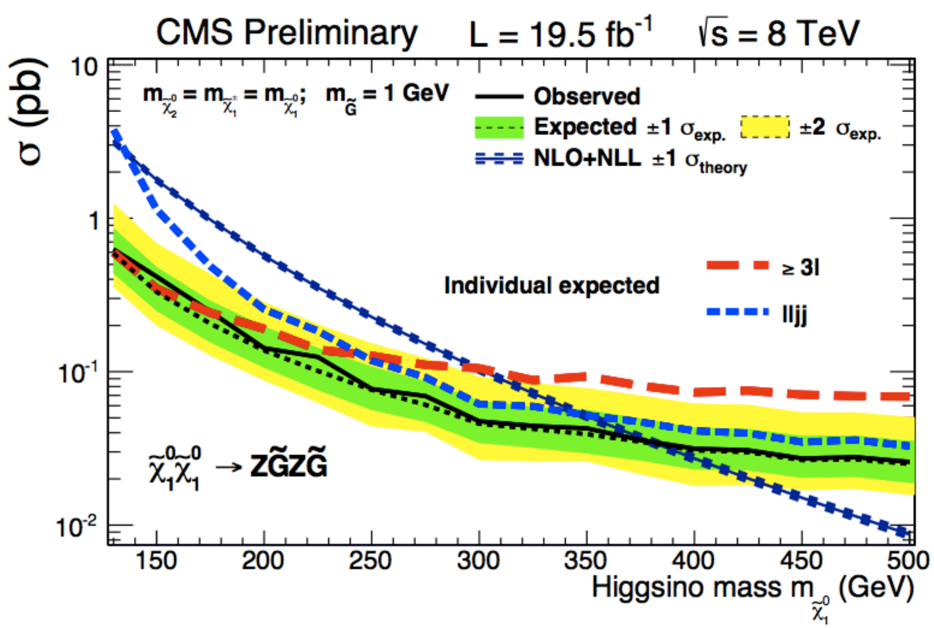
Higgs Partners $\tilde{H}$

(CMS)

$\tilde{H} \to (h,Z)\,\tilde{G}$ $\tilde{H}\tilde{H} \to (h,Z)(h,Z)\,\tilde{G}\tilde{G}$

New CMS Result
PAS next week

$\tilde{H}\tilde{H} \to ZZ\,\tilde{G}\tilde{G}$



Search for Additional States Related to Higgs Sector

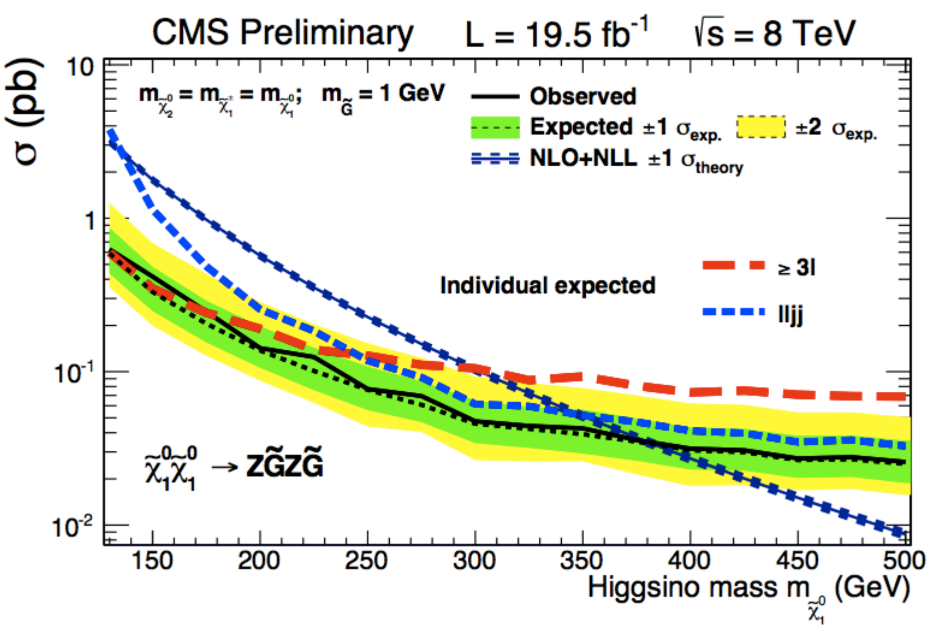
Higgs and Electroweak Partners $\tilde{H}$, $\tilde{W}$ (CMS)

$\tilde{H} \to (h,Z)\ \tilde{G}$ $\tilde{H}\tilde{H} \to (h,Z)(h,Z)\ \tilde{G}\tilde{G}$

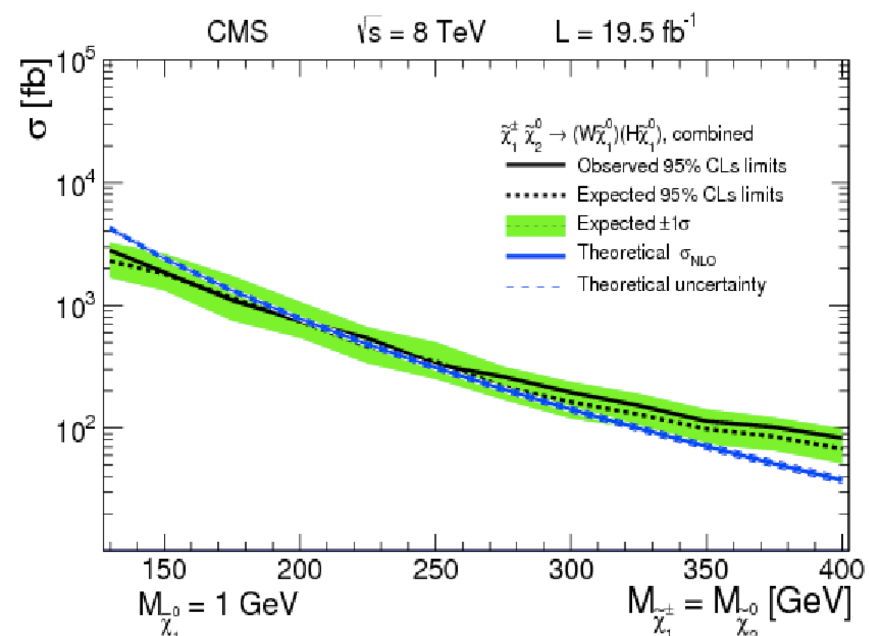
$W \to (W,h,Z)\ G$ $\tilde{W}\tilde{W} \to (W,h,Z)(W,h,Z)\ \tilde{G}\tilde{G}$

New CMS Result
PAS next week

$\tilde{H}\tilde{H} \to ZZ\ \tilde{G}\tilde{G}$



$WW \to Wh\ \tilde{G}\tilde{G}$



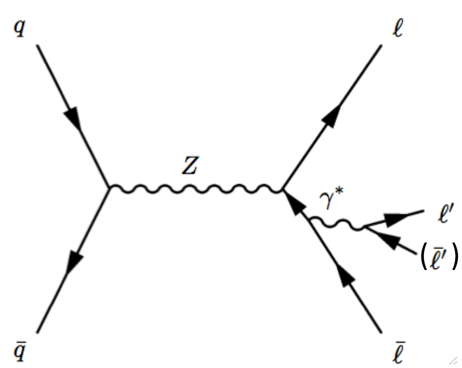
Electroweak Signatures Multi-Leptons

(CMS; Kilic, Park, …)

Sensitive to Extremely Rare Processes

Un-Anticipated Process –

Largest Source: Z -> l l γ* -> l l l (l)
(Others)



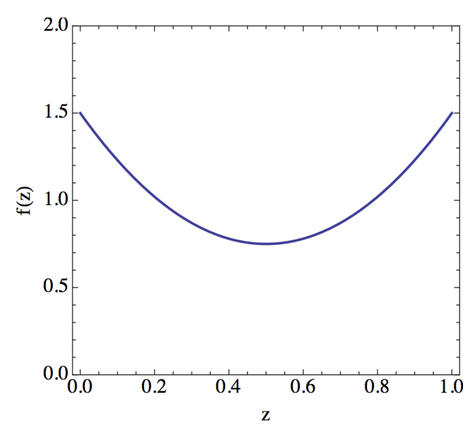
Asymmetric Internal Conversion
γ* -> e(e) , μ(μ)

Compare External Conversion
in Material γ -> e(e)

Standard MC's Don't Capture IR Singular Region of Phase Space

$$m_{\ell\ell}\frac{d\mathcal{P}(\gamma^* \to \ell\ell)}{dm_{\ell\ell}} = \frac{2}{3}\frac{\alpha}{\pi}\left(1 - \frac{4m_\ell^2}{m_{\ell\ell}^2}\right)^{1/2}\left(1 + \frac{2m_\ell^2}{m_{\ell\ell}^2}\right)$$

Momentum
Fraction
Distribution

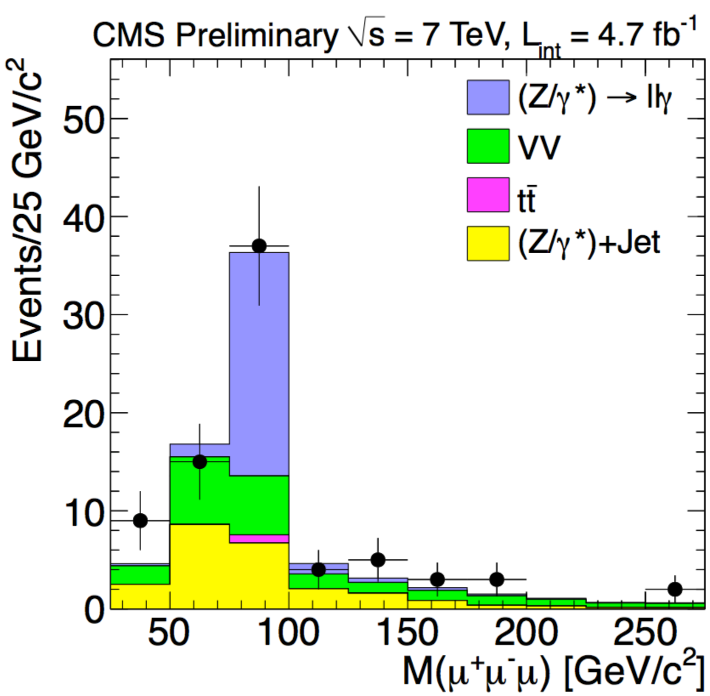


Electroweak Signatures Multi-Leptons (CMS)

Sensitive to Extremely Rare Processes

Un-Anticipated Process –

Largest Source: Z -> l l γ* -> l l l (l)
(Others)



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Developed Special Purpose AIC MG MC

First Observed in Multi-Dimensional
Dalitz Distribution O(few) Events

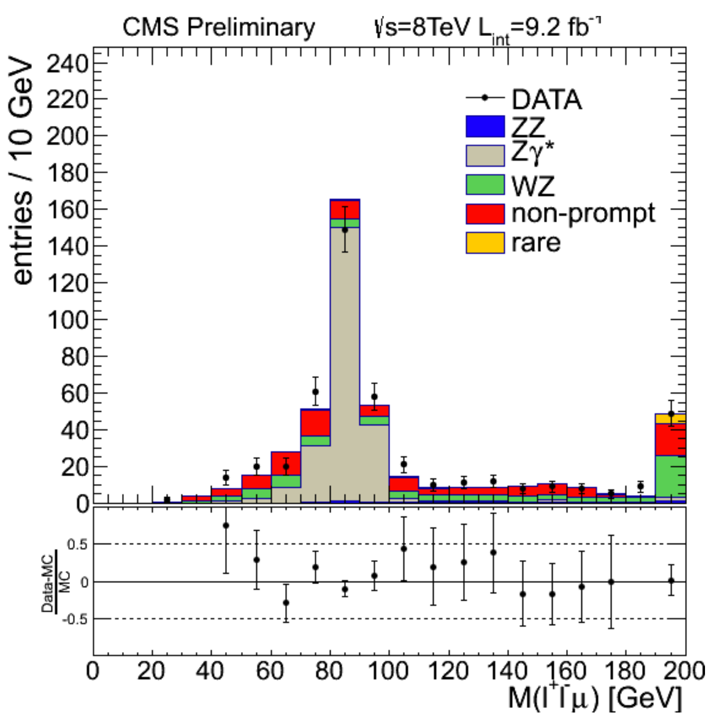
First Observation of Z -> lll(l)

Electroweak Signatures Multi-Leptons (CMS)

Sensitive to Extremely Rare Processes

Un-Anticipated Process –

Largest Source: $Z \to l\,l\,\gamma^* \to l\,l\,l\,(l)$
(Others)



Asymmetric Internal Conversion
$\gamma^* \to e(e)$, $\mu(\mu)$

Compare External Conversion
in Material $\gamma \to e(e)$

Standard MC's Don't Capture IR Singular Region of Phase Space

$$m_{\ell\ell}\frac{d\mathcal{P}(\gamma^*\to\ell\ell)}{dm_{\ell\ell}} = \frac{2}{3}\frac{\alpha}{\pi}\left(1-\frac{4m_\ell^2}{m_{\ell\ell}^2}\right)^{1/2}\left(1+\frac{2m_\ell^2}{m_{\ell\ell}^2}\right)$$

Developed Special Purpose AIC MG MC

First Observed in Multi-Dimensional
Dalitz Distribution O(few) Events

First Observation of $Z \to lll(l)$

Electroweak Signatures Multi-Leptons

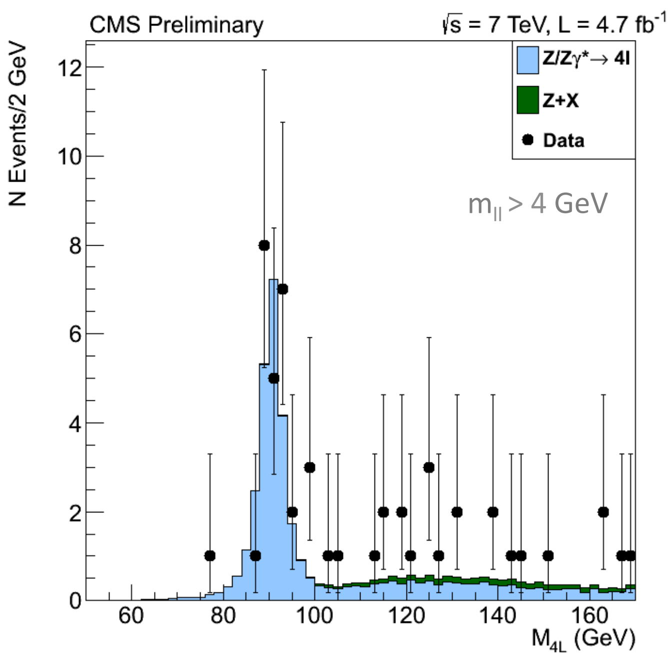
(CMS)

Sensitive to Extremely Rare Processes

Un-Anticipated Process –

Largest Source: $Z \to l\,l\,\gamma^* \to l\,l\,l\,(l)$

(Others)



Asymmetric Internal Conversion

$\gamma^* \to e(e)$, $\mu(\mu)$

Compare External Conversion

in Material $\gamma \to e(e)$

Standard MC's Don't Capture IR Singular Region of Phase Space

$$m_{\ell\ell}\frac{d\mathcal{P}(\gamma^*\to\ell\ell)}{dm_{\ell\ell}} = \frac{2}{3}\frac{\alpha}{\pi}\left(1-\frac{4m_\ell^2}{m_{\ell\ell}^2}\right)^{1/2}\left(1+\frac{2m_\ell^2}{m_{\ell\ell}^2}\right)$$

Developed Special Purpose AIC MG MC

First Observed in Multi-Dimensional Dalitz Distribution O(few) Events

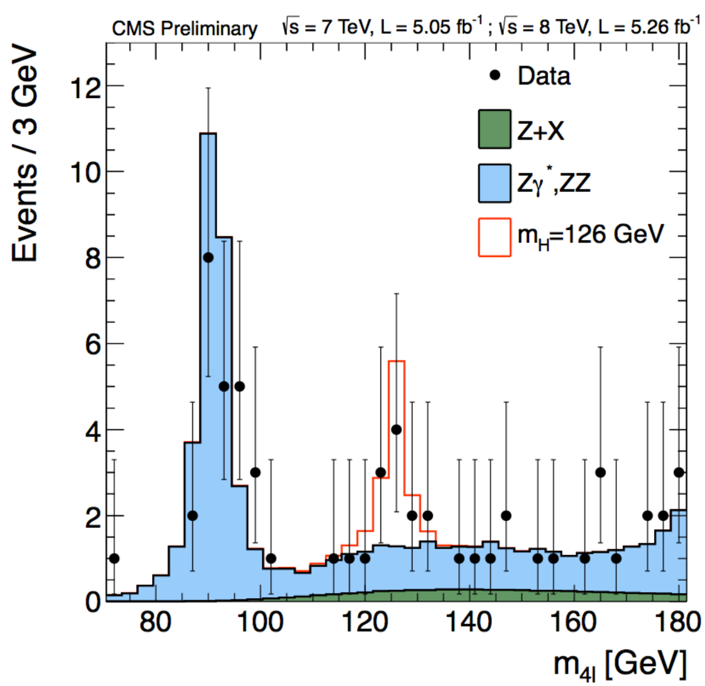
First Observation of $Z \to lll(l)$, $llll$

Electroweak Signatures Multi-Leptons (CMS)

Sensitive to Extremely Rare Processes

Un-Anticipated Process –

Largest Source: Z -> l l γ^* -> l l l (l)
(Others)



Asymmetric Internal Conversion
γ^* -> e(e) , $\mu(\mu)$

Compare External Conversion
in Material γ -> e(e)

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Used in Higgs -> llll as "calibration"

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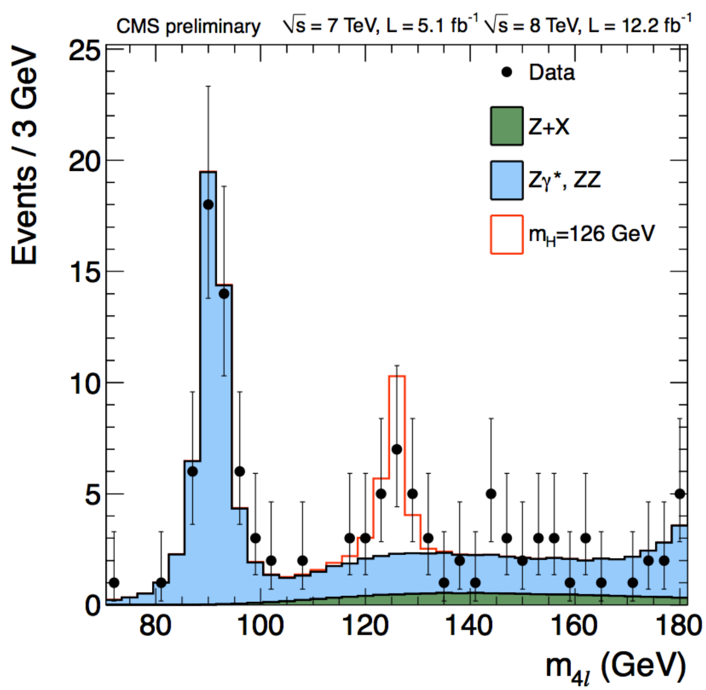

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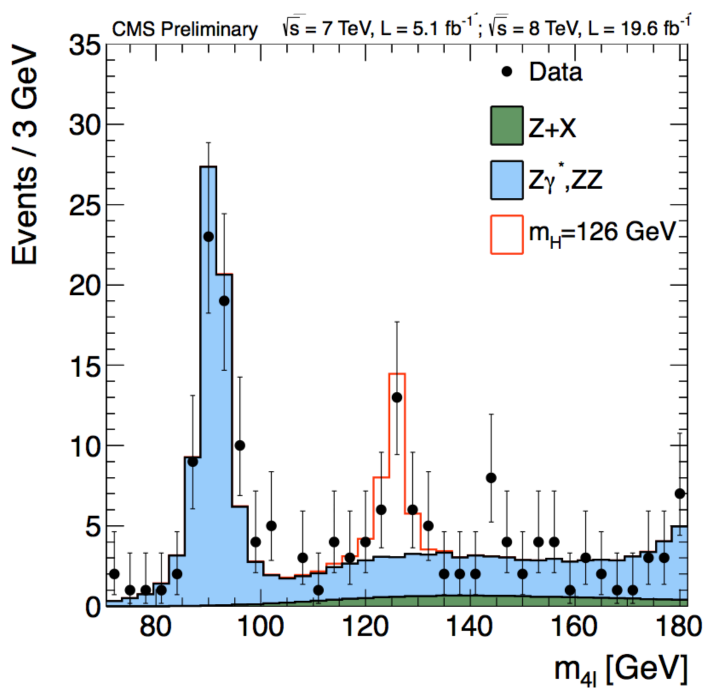

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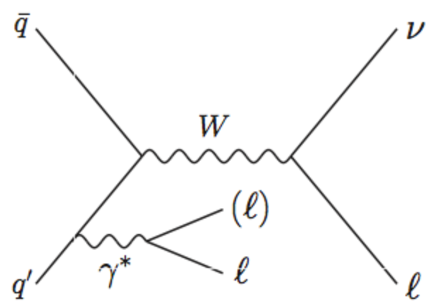
Higgs -> WW: Asymmetric Internal Conversion

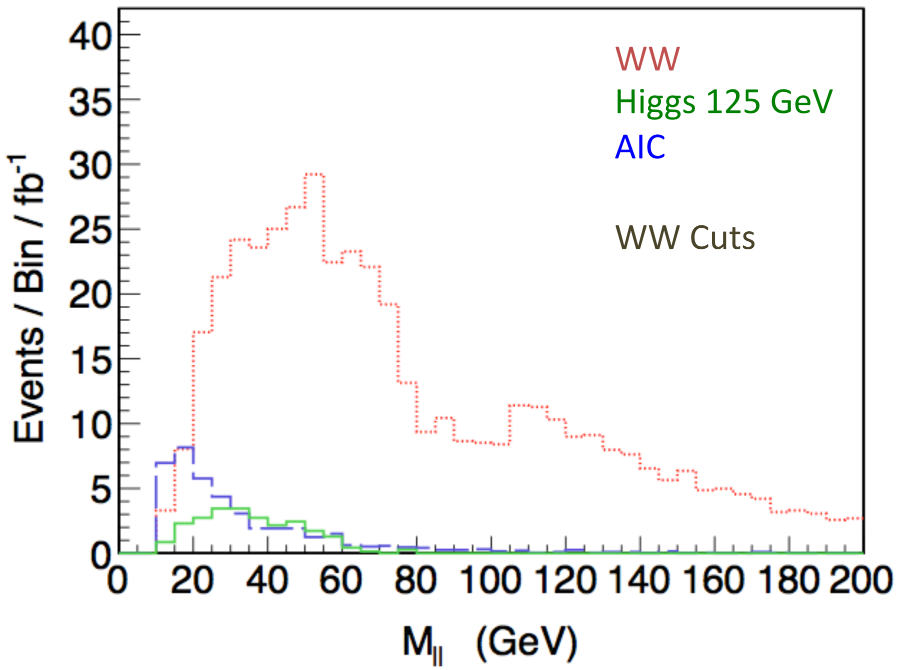
H -> WW -> l ν l ν

(Gray, Kilic, Park, Somalwar, ST)

Un-Anticipated Process – "Fake" Lepton Background

W γ* -> l ν l (l) + …
(Comparable to Higgs Signal)





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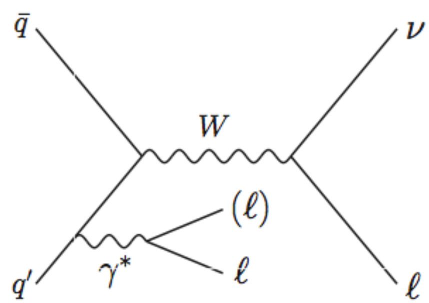

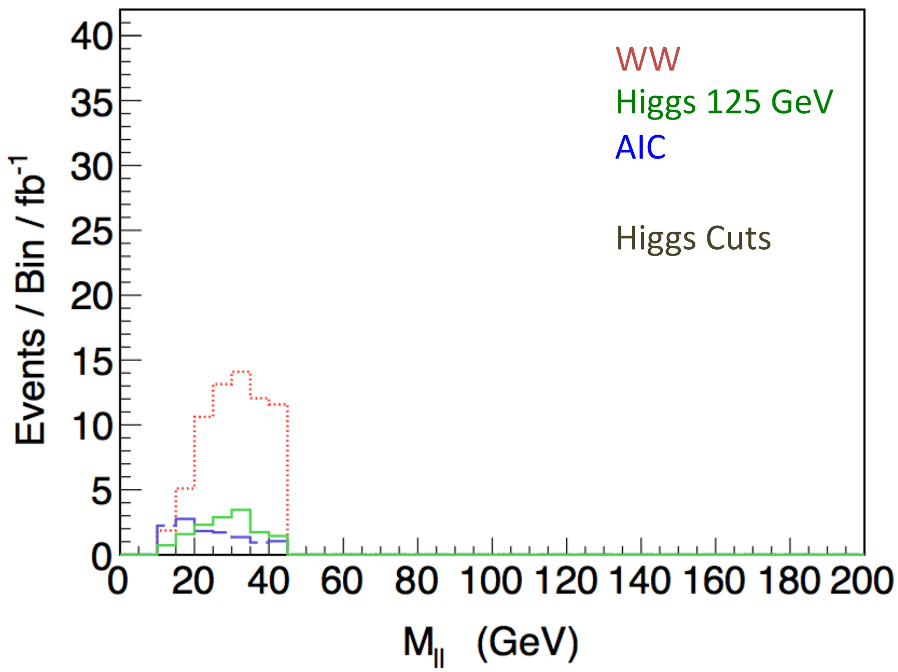

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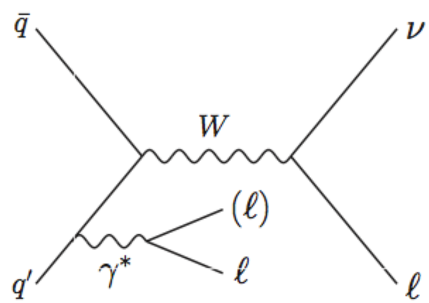
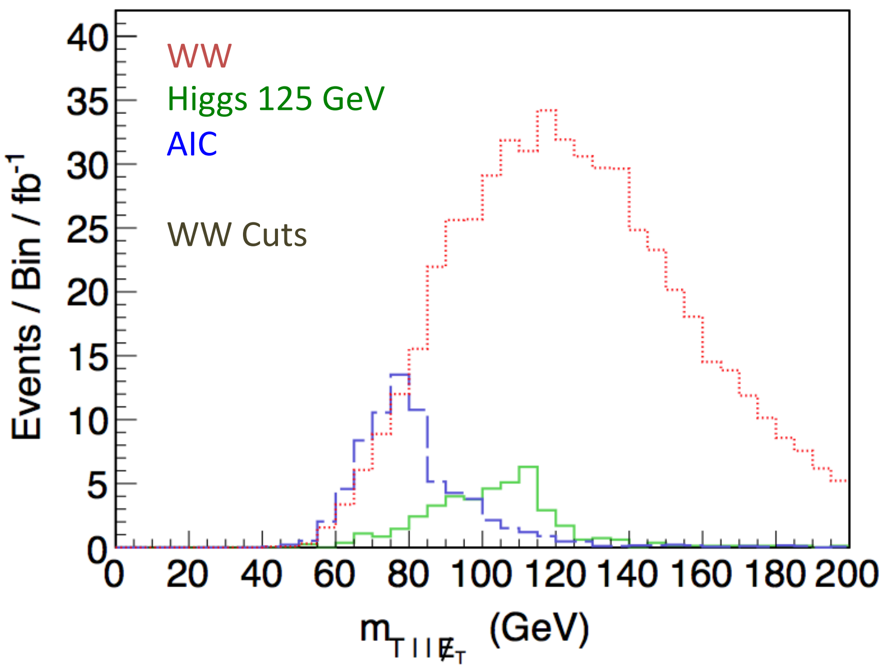




Experimental Investigation of ElectroWeak Physics at the ElectroWeak Scale has (Finally) Begun !!

Search for New Physics in Higgs Rate Measurements
Relatively Large Deviations Possible (Expected)

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

Search for Extended Higgs Sectors in
Standard Channels H,A -> $\gamma\gamma$, ZZ, WW, …

Search for Extended Higgs Sector in
New Channels H->hh , A->Zh, …

Search for New Higgs Production Processes
Multiple Channels, Kinematics, Higgs Tagging, …
Higgs -> $\gamma\gamma$ Resonance + X

Search for New States Related to Higgs (SUSY)
Multiple Channels, Kinematics, Higgs Tagging, …
Higgs -> $\gamma\gamma$ Resonance + X

Discovered Un-Anticipated high p_T Electroweak Physics Process
Asymmetric Internal Conversion

Experimental Investigation of ElectroWeak Physics at the ElectroWeak Scale has (Finally) Begun !!

7+8 TeV 25 fb^{-1}	Sufficient to <u>Begin</u> the Exploration of Electroweak Physics at the Electroweak Scale
13-14 TeV 100's fb^{-1}	Should be Sufficient to <u>Thoroughly</u> Explore Electroweak Physics at the Electroweak Scale

Stay Tuned !

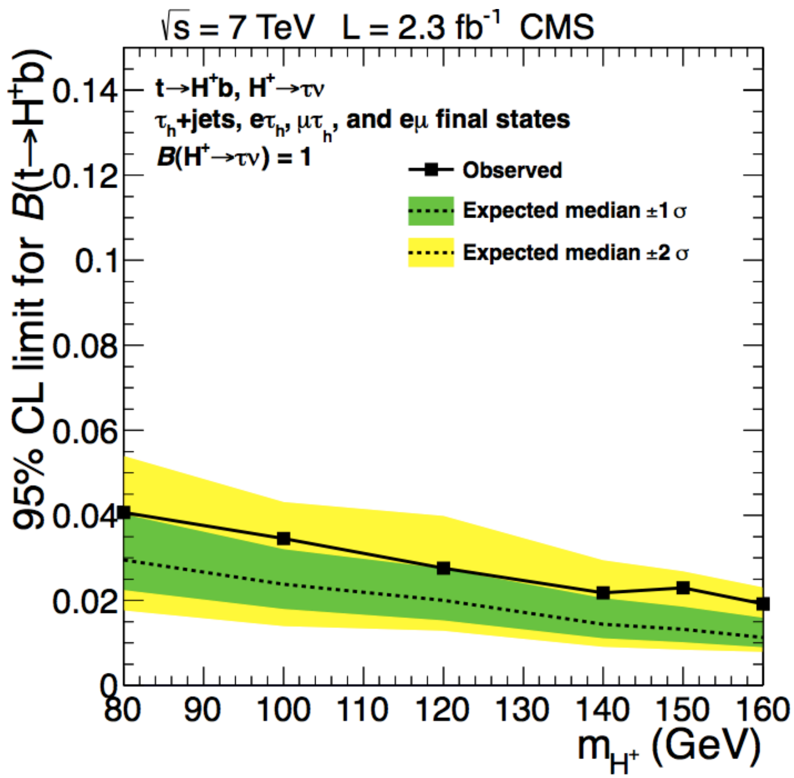
Extra Slides

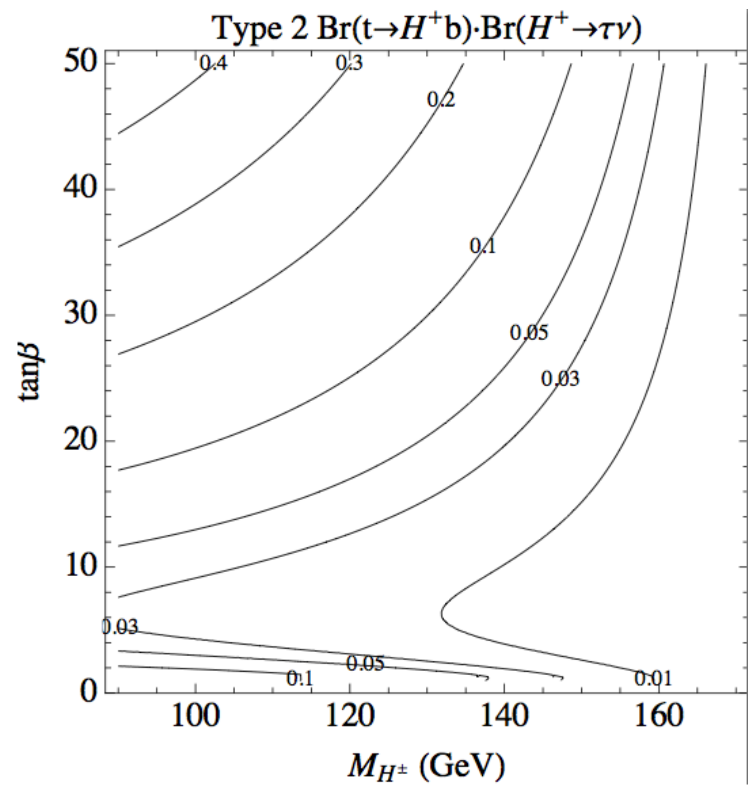
Direct Searches for 2nd Higgs Doublet

(CMS)

Two Higgs Doublets h, A, H, H^{+-}

t -> H^{+-}b H^{+-} -> τ ν



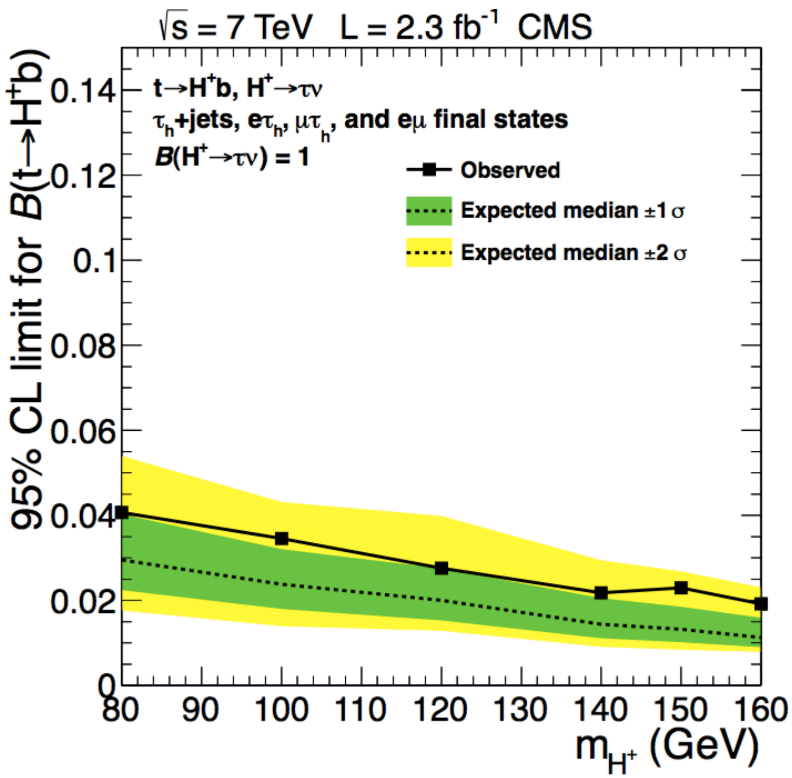


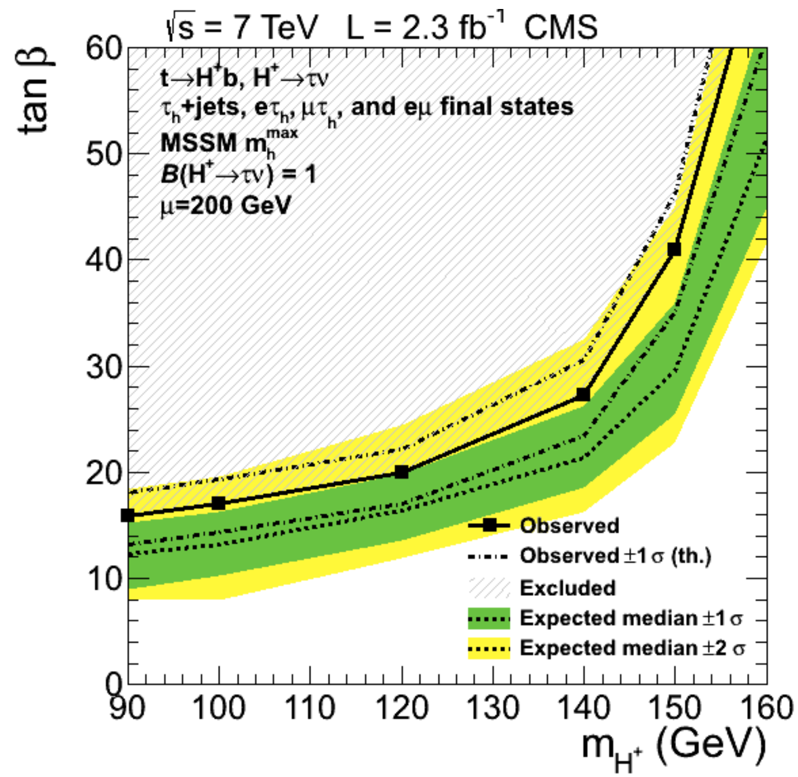
Direct Searches for 2nd Higgs Doublet

(CMS)

Two Higgs Doublets h, A, H, H^{+-}

$t \rightarrow H^{+-}b$ $H^{+-} \rightarrow \tau\ \nu$



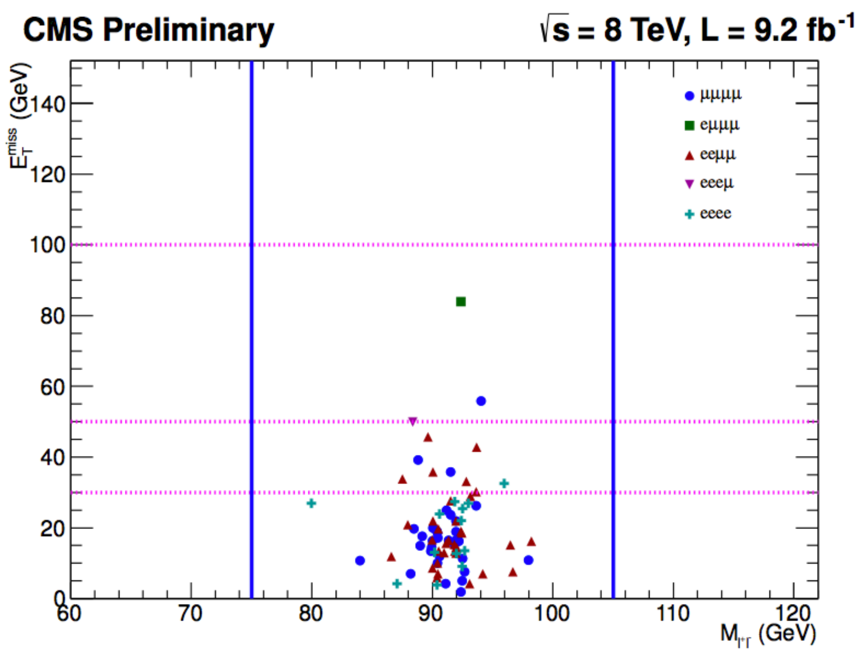


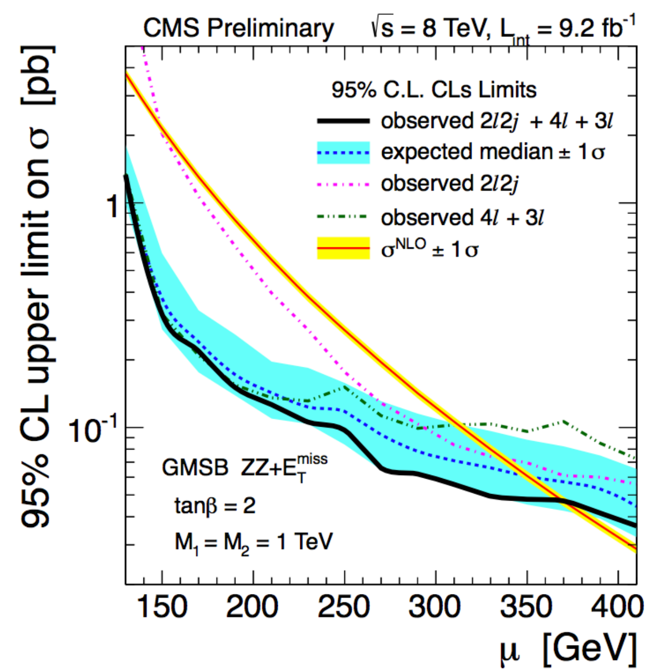
Higgsino Signatures Multi-Leptons

(CMS)

Sensitive to Extremely Rare Processes

Higgsino -> Z , h + Goldstino





SUSY, 2nd Higgs Doublet -> WZ, ZZ ,Wh, Zh, hh, …

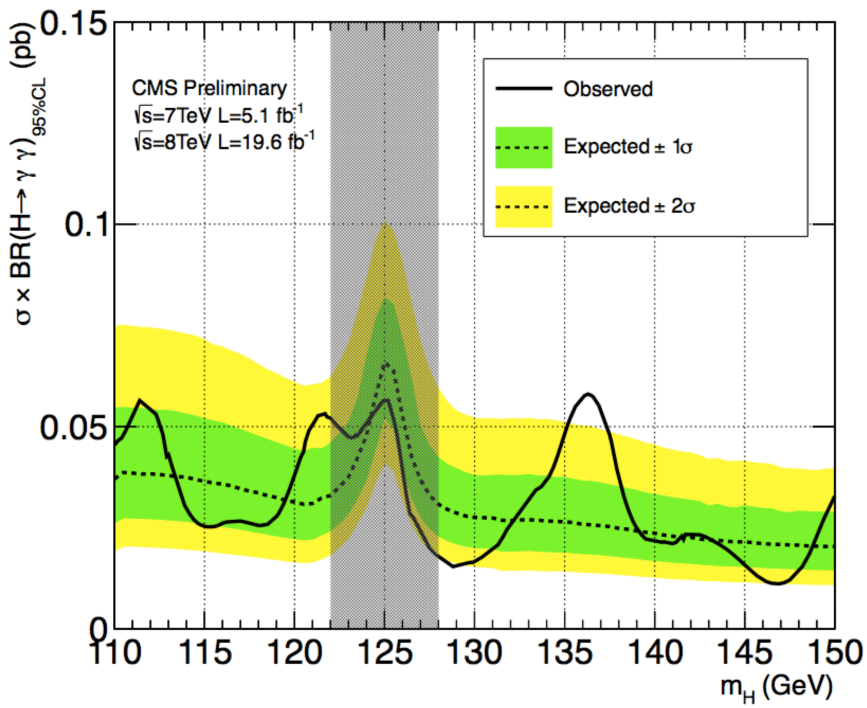
Kinematic Discriminants
(20 fb^{-1} sensitivity)

Direct Searches for 2nd Higgs Doublet

(CMS ; Craig, ST)

Two Higgs Doublets h, A, H, H^{+-}

A,H -> $\gamma\gamma$



2HDM Predictions

	Type I	Type II
$\dfrac{\sigma \,.\, Br(A \to \gamma\gamma)}{\sigma \,.\, Br(H \to \gamma\gamma)}$	~ 6	~ 3

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