Searching for neutral Higgs bosons in non-standard channels

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Motivation

- A SM-Higgs like resonance has been observed at the LHC
- The Higgs sector may also have extra scalars and pseudo-scalars.
- The $\tau\tau$-channel is the standard mode of searching for such particles.
- Examples of models with suppressed $A/H \to \tau\tau$ rates:
  - Enhanced $b\bar{b}$ couplings in 2HDM and MSSM.
    JHEP 1207 (2012) 091 w/ M. Carena, S. Gori, A. Juste, C. Wagner & L-T. Wang
  - Enhance ZA couplings in NMSSM like models.
    JHEP 1302 (2013) 152 w/ S. Chang

Searching Non-Standard Higgses with enhanced $b\bar{b}$ rates

Higgs Sector in 2HDMs

- The Neutral components acquire vevs and their ratio is $\tan\beta = v_u/v_d$.
- Neglecting CP violation in the Higgs sector, electroweak breaking leaves:

  1 CP odd Higgs A
  1 charged Higgs $H^{\pm}$, and
  2 CP even Higgs bosons h, H
- One CP-even (SM-like) Higgs has SM strength couplings to gauge bosons.
- The other CP-even (Non-Standard) Higgs has suppressed couplings to gauge bosons.

Couplings to b-quarks and τ-leptons in 2HDMs

- General 2HDM Higgs fermions couplings are

$$\begin{aligned}\mathcal{L}_{\text{Yuk}} &= y_u\, H_u\bar{Q}U + y_d\, H_d\bar{Q}D + \tilde{y}_u\, H_d^\dagger\bar{Q}U \\ &+ \tilde{y}_d\, H_u^\dagger\bar{Q}D + y_\ell\, H_d\bar{L}E + \tilde{y}_\ell\, H_u^\dagger\bar{L}E + h.c.\end{aligned}$$

- d-type fermion couplings to Non-standard Higgses are:

$$g_{H/Af\bar{f}} \simeq \frac{\bar{m}_f}{v}\tan\beta^f_{\text{eff}}$$

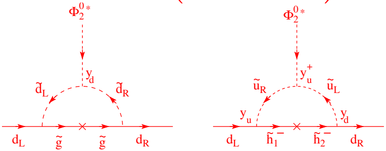
where for $f = b, \tau$

$$\begin{aligned}\tan\beta^f_{\text{eff}} &= \frac{\tan\beta}{1+\epsilon_f\tan\beta}\left(1-\frac{\epsilon_f}{\tan\beta}\right) \\ \epsilon_f &= \frac{\tilde{y}_f}{y_f}\end{aligned}$$

Fermion couplings in the MSSM

- Including 1-loop effects, both quarks couple to both the Higgs bosons so that:

$$-\mathcal{L}_{eff} = \bar{d}_R^0 \hat{\mathbf{Y}}_{\mathbf{d}} [\Phi_d^{0*} + \Phi_u^{*0} \left(\hat{\epsilon}_{\mathbf{0}} + \hat{\epsilon}_{\mathbf{Y}} \hat{\mathbf{Y}}_{\mathbf{u}}^{\dagger} \hat{\mathbf{Y}}_{\mathbf{u}} \right)] d_L^0 + h.c.$$



and have the structure:

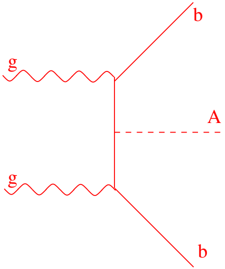
$$\epsilon_0^I \approx \frac{2\alpha_s}{3\pi} M_3 \mu C_0(m_{\tilde{d}_1^I}^2, m_{\tilde{d}_2^I}^2, M_3^2)$$

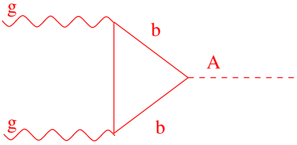
$$\epsilon_Y \approx \frac{1}{16\pi^2} A_t \mu C_0(m_{\tilde{t}_1}^2, m_{\tilde{t}_2}^2, \mu^2)$$

$$\epsilon_\tau \approx \frac{3\alpha_2}{8\pi} \mu M_2 C_0(M_{\tilde{\tau}_1}^2, M_{\tilde{\tau}_2}^2, M_1^2)$$

Kolda, Babu, Buras, Roszkowski...

Non-standard Higgs boson production and decay





Gunion et.al. ’94, Balazs et.al, Diaz-Cruz et.al., & Huang et.al. ’98, Campbell et.al. ’03, Dawson et.al. ’03

- General b and τ couplings are

$$g_{Abb} \simeq \frac{m_b \tan\beta^b_{\rm eff}}{v}; \, g_{A\tau\tau} \simeq \frac{m_\tau \tan\beta^\tau_{\rm eff}}{v}$$

contd...

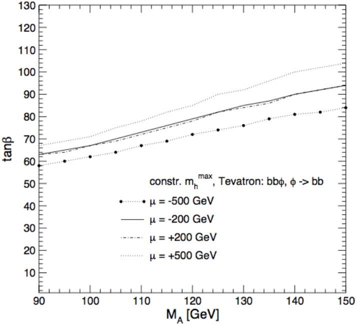
- Enhanced production and decay modes:

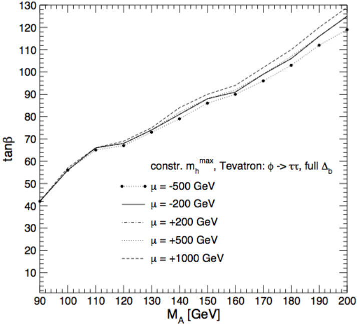
$$\frac{\sigma(b\bar{b} \to A)}{\sigma(b\bar{b}h)_{\rm SM}} \mathcal{BR}(A \to b\bar{b}) \propto \frac{9(\tan\beta^b_{\rm eff})^4}{(\tan\beta^\tau_{\rm eff})^2 + 9(\tan\beta^b_{\rm eff})^2} ,$$

$$\frac{\sigma(gg, b\bar{b} \to A)}{\sigma(gg, b\bar{b} \to h)_{\rm SM}} \mathcal{BR}(A \to \tau\tau) \propto \frac{(\tan\beta^\tau_{\rm eff})^2(\tan\beta^b_{\rm eff})^2}{(\tan\beta^\tau_{\rm eff})^2 + 9(\tan\beta^b_{\rm eff})^2} ,$$

- In the MSSM the $b\bar{b}$ channel has greater model dependence than $\tau\tau$.

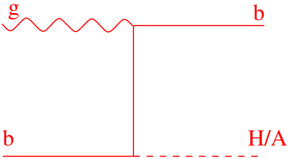
Carena et.al. '05





Non-Standard Higgs into 3b: Production and Decay

- $\tan\beta^{\tau}_{\rm eff}$ can be small compared to $\tan\beta^{b}_{\rm eff}$ ⇒ weaker reach in the $\tau\tau$ channel.
- The $H/A \to b\bar{b}$ can be enhanced enough to make it competitive with the clean $\tau\tau$ channel.
- In addition to the 4b-final state we also have:



- 3b channel can be important at 14 TeV LHC for mSUGRA

Cao et.al. ’09, Baer et. al. ’11

Signal and Background Simulation

- Simulation used MG5 interfaced with Pythia 6.4.
- QCD background: Separately simulated the 3b+X and 2b+j+X where X= 1,2j
- Used k_t matching, with matching scale of 30 GeV.
- Background separation into bbj and $3b$ samples does not model b jets with p_T below $\sim$ 40 GeV very well.
- b-jets are clustered using anti-k_T with $\Delta R = 0.4$.
- Jet energy smearing of $100\%/\sqrt{E/\mathrm{GeV}}$.
- We assume a constant b-tagging efficiency of 60%, a c-jet mis-tag rate of 10% and a light-jet mis-tag rate of 1%.
- Low mis-tag rate of c- and light-jets leads to the bbj and $3b$ backgrounds being comparable

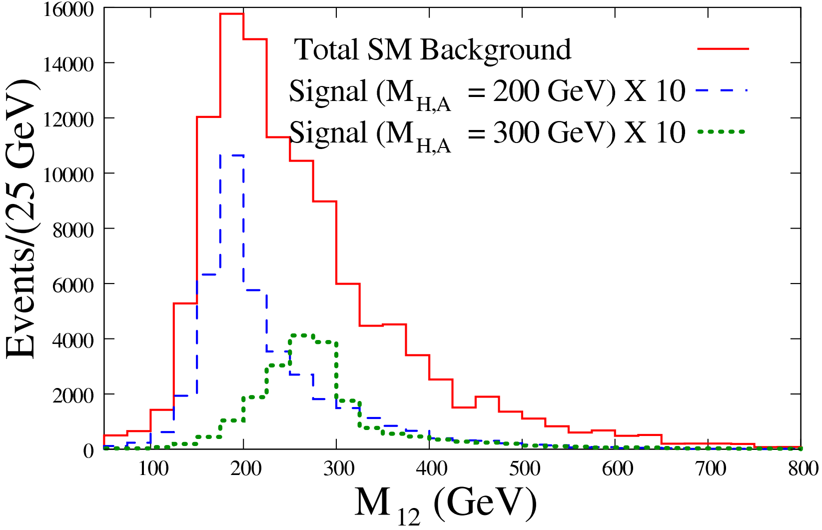
Selection I vs Selection II

- Selection I: Exactly 3 *b*-tagged jets with $p_T > 60$ GeV and $|\eta| < 2.0$.
- Selection II: Exactly 3 *b*-tagged jets with $p_T^{b_1} > 130$ GeV, $p_T^{b_{2,3}} > 50$ GeV and $|\eta| < 2.0$.
- Require M_{12}, M_{13} or M_{23} within 25 GeV window of Higgs mass.

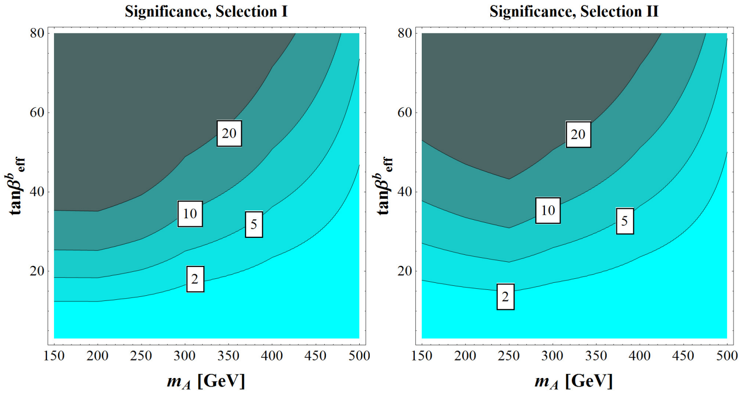
For $\tan\beta_{\mathrm{eff}}^{b} = 30$ @ 30 fb^{-1} 7 TeV LHC

	Selection I		Selection II	
	S/B	$S/\sqrt{B}$	S/B	$S/\sqrt{B}$
$m_A = 150$ GeV	0.06	14.1	0.047	6.2
$m_A = 200$ GeV	0.057	14.4	0.048	7.9
$m_A = 300$ GeV	0.035	7.3	0.038	6.8
$m_A = 400$ GeV	0.027	3.4	0.028	3.3

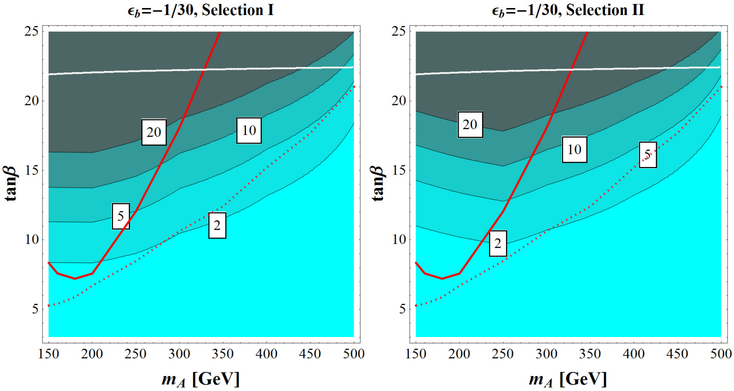
Signal and Background Distributions for tan $\beta = 30$



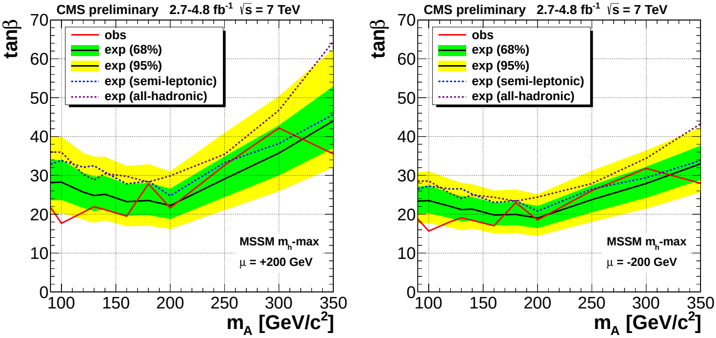
Reach in the general 2HDM Model



The 3b vs $\tau\tau$ in the MSSM



CMS Analysis



HCP Nov. 2012

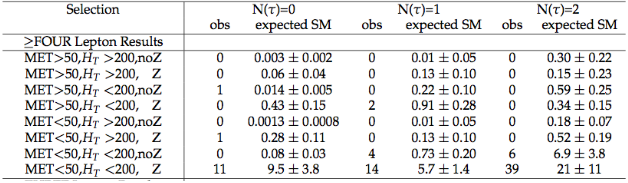
Conclusions

- The $A \to \tau\tau$ LHC search puts weak limits on regions of large $\tan\beta_{\text{eff}}^{b}$ and small $\tan\beta_{\text{eff}}^{\tau}$ in 2HDMs.
- The $A/H \to b\bar{b}$ is a complementary channel that probes parametric scenarios of large $\tan\beta_{\text{eff}}^{b}$.
- The reach of the $A/H \to b\bar{b}$ channel is limited by low S/B for low to moderate $\tan\beta_{\text{eff}}^{b}$, but can be powerful at large $\tan\beta_{\text{eff}}^{b}$.

Search for Non-Standard Higgs in the $H \rightarrow ZA$ channel

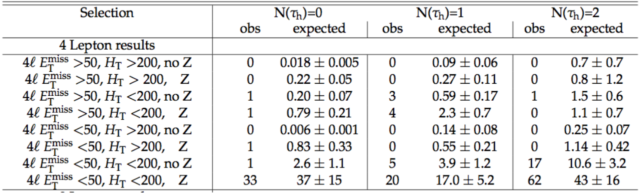
Motivation: excess in the $2\ell+$ 0 ,1 and 2 τ_h's

- CMS 2011: 2.1 fb^{-1} @ 7 TeV **CMS-PAS-SUS-11-013**



Selection	N(τ)=0		N(τ)=1		N(τ)=2	
	obs	expected SM	obs	expected SM	obs	expected SM
≥FOUR Lepton Results						
MET>50,H_T >200,noZ	0	0.003 ± 0.002	0	0.01 ± 0.05	0	0.30 ± 0.22
MET>50,H_T >200, Z	0	0.06 ± 0.04	0	0.13 ± 0.10	0	0.15 ± 0.23
MET>50,H_T <200,noZ	1	0.014 ± 0.005	0	0.22 ± 0.10	0	0.59 ± 0.25
MET>50,H_T <200, Z	0	0.43 ± 0.15	2	0.91 ± 0.28	0	0.34 ± 0.15
MET<50,H_T >200,noZ	0	0.0013 ± 0.0008	0	0.01 ± 0.05	0	0.18 ± 0.07
MET<50,H_T >200, Z	1	0.28 ± 0.11	0	0.13 ± 0.10	0	0.52 ± 0.19
MET<50,H_T <200,noZ	0	0.08 ± 0.03	4	0.73 ± 0.20	6	6.9 ± 3.8
MET<50,H_T <200, Z	11	9.5 ± 3.8	14	5.7 ± 1.4	39	21 ± 11

- CMS 2012: 4.8 fb^{-1} @ 7 TeV **arXiv:1204.5341**



Selection	N(τ_h)=0		N(τ_h)=1		N(τ_h)=2	
	obs	expected	obs	expected	obs	expected
4 Lepton results						
4ℓ E_T^{miss} >50, H_T >200, no Z	0	0.018 ± 0.005	0	0.09 ± 0.06	0	0.7 ± 0.7
4ℓ E_T^{miss} >50, H_T > 200, Z	0	0.22 ± 0.05	0	0.27 ± 0.11	0	0.8 ± 1.2
4ℓ E_T^{miss} >50, H_T <200, no Z	1	0.20 ± 0.07	3	0.59 ± 0.17	1	1.5 ± 0.6
4ℓ E_T^{miss} >50, H_T <200, Z	1	0.79 ± 0.21	4	2.3 ± 0.7	0	1.1 ± 0.7
4ℓ E_T^{miss} <50, H_T >200, no Z	0	0.006 ± 0.001	0	0.14 ± 0.08	0	0.25 ± 0.07
4ℓ E_T^{miss} <50, H_T >200, Z	1	0.83 ± 0.33	0	0.55 ± 0.21	0	1.14 ± 0.42
4ℓ E_T^{miss} <50, H_T <200, no Z	1	2.6 ± 1.1	5	3.9 ± 1.2	17	10.6 ± 3.2
4ℓ E_T^{miss} <50, H_T <200, Z	33	37 ± 15	20	17.0 ± 5.2	62	43 ± 16

Theoretical Implications of Signal

- The multi-lepton channel is sensitive to SM Higgs decay modes and with 5 fb^{-1} of data, the region $120 \leq m_h \leq 150$ GeV can be probed at 95% C.L.

E. Contreras-Compana, et.al. ’12

- The CMS 2012 multi-lepton data puts limits on $\mathcal{BR}(t \to ch) < 2.7\%$

N. Craig et.al. ’12

- It also leads to constraints on 2HDM’s when multiple-channels from h, H, A and $H^{\pm}$ decay modes.

N. Craig et.al. ’13

Example: The NMSSM

- The superpotential has the form

$$W = W_{\text{Yuk}} + \lambda \hat{H}_u \hat{H}_d \hat{S} + \frac{\kappa}{3}\hat{S}^3$$

with soft terms

$$V_{\text{soft}} = m^2_{H_u}|H_u|^2 + m^2_{H_d}|H_d|^2 + m^2_S|S|^2 + \sqrt{2}\left(m_\lambda S H_u H_d - \frac{m_\kappa}{3}S^3\right)$$

with $m_\kappa \equiv -\kappa A_\kappa/\sqrt{2}$ and $m_\lambda \equiv \lambda A_\lambda/\sqrt{2}$

- In the basis where scalar basis (h_v^0, H_v^0, h_s^0) and the pseudo-scalar basis (A_v^0, A_s^0)

$$\mathcal{L}^{\text{Kin}}_{\text{Higgs}} \quad \subset \quad -\frac{g_2}{2c_{\theta_W}} Z^\mu (c_{\theta_A} A_1^0 - s_{\theta_A} A_2^0) \overleftrightarrow{\partial_\mu} \left(s_{2\beta} h_v^0 + c_{2\beta} H_v^0\right)$$

where the h_v is direction that acquires a VEV.

- $H \to Z\tau^+\tau^-$ Has been studied in context of explaining LEP anomalies.

Dermisek '08, Dermisek and Gunion '09

Higgs mass of Benchmark points

Model	λ	κ	t_β	A_λ (GeV)	A_κ (GeV)	A_t (TeV)	μ_{eff} (GeV)	$M_{\tilde{q}}$ (TeV)
BM1	0.71	1.10	1.5	-11.0	-8.0	0.0	160	0.5
BM2	0.71	1.10	1.5	-9.1	-7.0	0.0	166	0.5
BM3	0.67	0.78	1.5	-4.2	-40.6	0.0	170	0.5

Model	$m_{H_1^0}$ (GeV)	$m_{H_2^0}$ (GeV)	$m_{A_1^0}$ (GeV)	$m_{H^\pm}$ (GeV)	$g^{\mathrm{red.}}_{t\bar{t}H_1^0}$	$g^{\mathrm{red.}}_{t\bar{t}H_2^0}$
BM1	125.2	270	8.9	266	0.982	-0.691
BM2	125.1	283	19.7	278	0.984	-0.690
BM3	124.5	252	117	248	0.992	-0.668

Higgs couplings of Benchmark points

$\mathcal{BR}$ of H_1^0	$b\bar{b}$	$\gamma\gamma$	WW^*	ZZ^*	$A_1^0 A_1^0$
BM1	0.63	2.6×10^{-3}	0.19	2.1×10^{-2}	2.9×10^{-3}
BM2	0.61	2.5×10^{-3}	0.18	2.0×10^{-2}	4.3×10^{-2}
BM3	0.64	2.7×10^{-3}	0.18	2.0×10^{-2}	0.0

$$\mathcal{BR} : \gamma\gamma_{\rm SM} = 2.28 \times 10^{-3};\ WW^*_{\rm SM} = 2.15 \times 10^{-1};\ ZZ^*_{\rm SM} = 2.64 \times 10^{-2}$$

$\mathcal{BR}$ of H_2^0	$b\bar{b}$	$H_1^0 H_1^0$	ZA_1^0	$A_1^0 A_1^0$
BM1	4.5×10^{-3}	5.6×10^{-4}	0.78	0.17
BM2	4.3×10^{-3}	4.9×10^{-4}	0.70	0.16
BM3	1.9×10^{-2}	1.7×10^{-6}	0.78	0.19

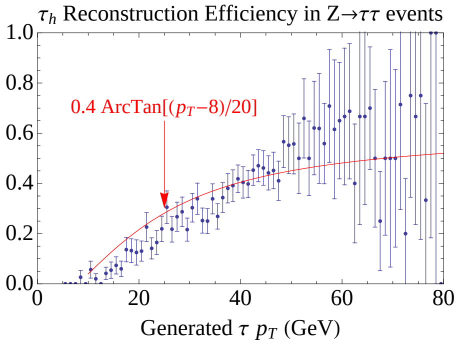
$\mathcal{BR}$ of A_1^0	$\tau\tau$	$b\bar{b}$	gg	Signal Rate (μ)
BM1	0.74	0.0	0.12	0.28
BM2	5.9×10^{-2}	0.92	1.1×10^{-2}	5.7×10^{-3}
BM3	9.1×10^{-2}	0.87	2.9×10^{-2}	0.01

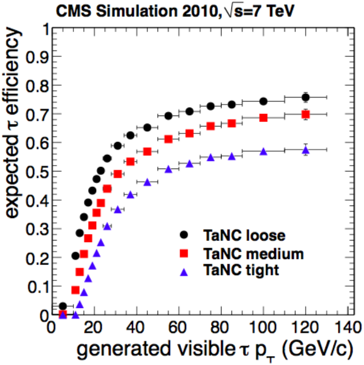
Event Simulation

- Simulation used Pythia8.170 for *pp* collisions.
- Include the effects of ISR, FSR, multiple interactions and fragmentation.
- The Z-bosons were allowed to decay only into e, μ, τ.
- No detector simulator was used, but instead implemented an CMS-like τ_h reconstruction algorithm.
- Trigger requirements:
  - *1-lepton:* muon (electron) has a $p_T > 35\,(85)$ GeV
  - *2-lepton:* $p_T^1 \geq 20$ GeV and $p_T^2 \geq 10$ GeV.
- Lepton identification: $p_T \geq 8$ GeV and $|\eta| \leq 2.1$.
- Lepton isolation: $I_{\mathrm{Rel}} = E_{\mathrm{cone}}/E_\ell \leq 0.15$, where
  $E_\ell =$ energy of lepton and
  $E_{\mathrm{cone}} =$ energy in a $\Delta R = 0.3\,(0.4)$ for muons (electrons).

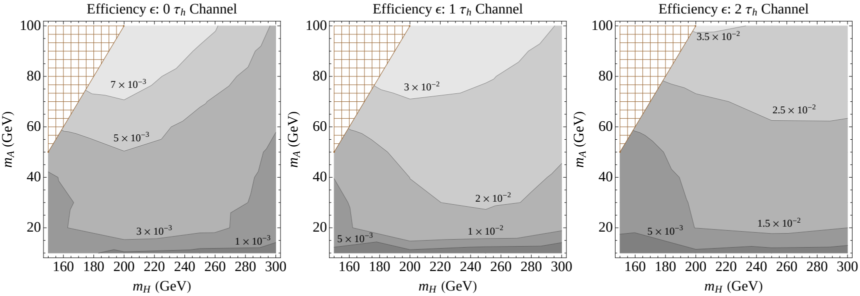
τ_h reconstruction

- τ_h **reconstruction**: 1-pronged track with $p_T \geq 8.0$ GeV.
- τ_h **isolation**: $E_{\rm ann}/E_{\rm cone} \leq 0.15$ where,
  $E_{\rm ann}$ = energy in $0.1 < \Delta R \leq 0.3$
  $E_{\rm cone}$ = energy in $\Delta R \leq 0.1$.





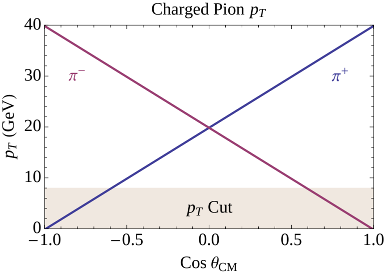
$Z\tau\tau$ efficiency in



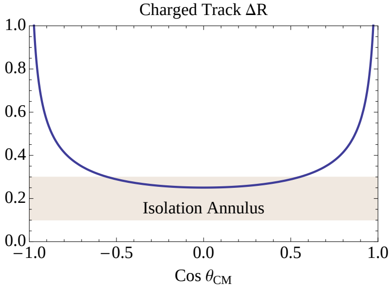
$$\epsilon = \frac{\text{Number of events to pass cuts}}{\text{Number of events generated}}$$

Toy-Model for τ_h reconstruction

$m_H = 200$ GeV and $m_A = 10$ GeV



Charged Pion p_T



Charged Track ΔR

θ_{CM} = Angle of π^+ in rest frame of A when $\tau^+ \to \pi^+ \bar{\nu}_\tau$

p_T is measured in the H rest frame

ΔR = the angle between the two charged tracks.

Limits of signal due to CMS data

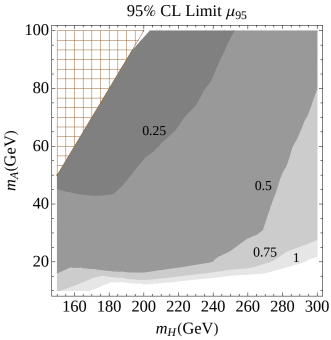
- Due to low statistics we assume a Poisson distribution for the number of events.
- We assume the background errors are gaussian
- The maximum allowed number of signal events at 95% C.L. (S_{95}^{Max}) is found by solving

$$\int_0^\infty dB \frac{\Gamma(N_{\mathrm{obs}}+1, S_{95}^{\mathrm{Max}}+B)}{N_{\mathrm{obs}}!} \frac{1}{\mathcal{N}_B} \exp\left[-\frac{(B-\mu_B)^2}{2\sigma_B^2}\right] = 0.05$$

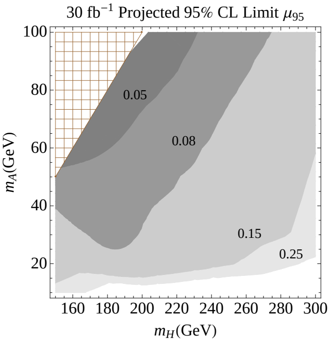
- The bounds on σ_{sig}, normalized to σ_{SM} is

$$\mu_{95}^i \equiv \frac{S_{95}^{i\,\mathrm{Max}}}{\sigma_{\mathrm{H_{SM}}} \times \mathcal{BR}(Z \to l^+l^-) \times \epsilon^i \times \mathcal{L}}$$

contd.



7 TeV



8 TeV

1-τ_h constraint is the strongest due to large $\epsilon_{1\tau_h}$ and $N_{obs}^{\mathrm{CMS}} \sim N_{bkg}$

H and A Mass reconstruction in the $2\tau_h$ channel

- Transverse Mass:

$$\begin{aligned} m_A^T &= \sqrt{p_V^2 + 2(E_V E_+^T - p_V^T \cdot p_+^T)} \\ m_H^T &= \sqrt{(p_V + p_Z)^2 + 2((E_V + E_Z)E_+^T - (p_V^T + p_Z^T) \cdot p_+^T)} \end{aligned}$$

where $m_i^T \leq m_i$

Barr et. al., 2009

- Collinear Mass: Solve kinematics under assumption that neutrinos are collinear with the visible momenta

$$\lambda_1 \, p_{V_1}^T + \lambda_2 \, p_{V_2}^T = p_+^T.$$

where by assumption λ_i's are positive.

Ellis et. al., 1987

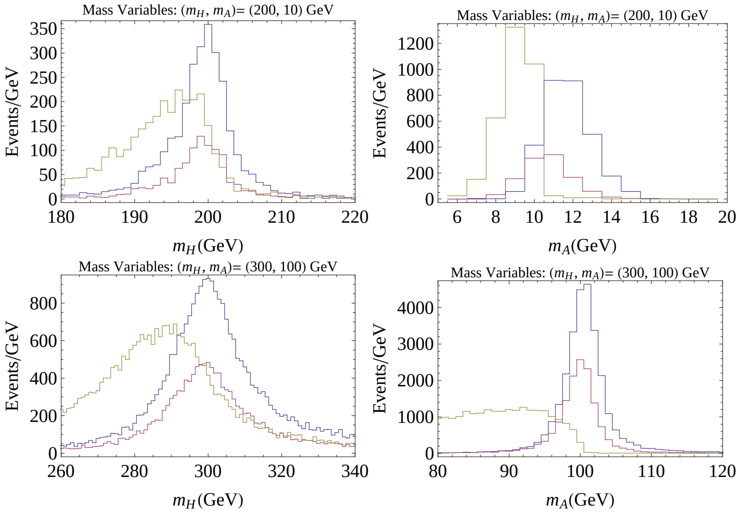
H and A Trial Mass Reconstruction in the $2\tau_h$ channel

- The 8 kinematic constraint equations are:

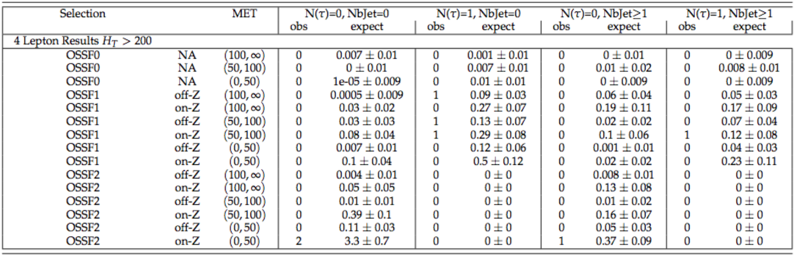
$$
\begin{aligned}
&p_{\nu_1}^2 = 0 = p_{\nu_2}^2\\
&\left(p_{\nu_1} + p_{V_1}\right)^2 = m_\tau^2 = \left(p_{\nu_2} + p_{V_2}\right)^2\\
&m_A^2 = \left(p_{\nu_1} + p_{V_1} + p_{\nu_2} + p_{V_2}\right)^2\\
&m_H^2 = \left(p_Z + p_{\nu_1} + p_{V_1} + p_{\nu_2} + p_{V_2}\right)^2\\
&p_{\nu_1}^x + p_{\nu_2}^x = p_+^x\\
&p_{\nu_1}^y + p_{\nu_2}^y = p_+^y
\end{aligned}
$$

- However 10 unknowns p_{ν_i}, m_H and m_A.
- Solve for the mean values of m_H and m_A where solutions exist.

Comparison of Mass reconstructions



Latest CMS analysis



Selection		MET	N(τ)=0, NbJet=0		N(τ)=1, NbJet=0		N(τ)=0, NbJet≥1		N(τ)=1, NbJet≥1	
			obs	expect	obs	expect	obs	expect	obs	expect
4 Lepton Results $H_T > 200$										
OSSF0	NA	$(100,\infty)$	0	0.007 ± 0.01	0	0.001 ± 0.01	0	0 ± 0.01	0	0 ± 0.009
OSSF0	NA	$(50,100)$	0	0 ± 0.01	0	0.007 ± 0.01	0	0.01 ± 0.02	0	0.008 ± 0.01
OSSF0	NA	$(0,50)$	0	1e-05 ± 0.009	0	0.01 ± 0.01	0	0 ± 0.009	0	0 ± 0.009
OSSF1	off-Z	$(100,\infty)$	0	0.0005 ± 0.009	1	0.09 ± 0.03	0	0.06 ± 0.04	0	0.05 ± 0.03
OSSF1	on-Z	$(100,\infty)$	0	0.03 ± 0.02	0	0.27 ± 0.07	0	0.19 ± 0.11	0	0.17 ± 0.09
OSSF1	off-Z	$(50,100)$	0	0.03 ± 0.03	1	0.13 ± 0.07	0	0.02 ± 0.02	0	0.07 ± 0.04
OSSF1	on-Z	$(50,100)$	0	0.08 ± 0.04	1	0.29 ± 0.08	0	0.1 ± 0.06	1	0.12 ± 0.08
OSSF1	off-Z	$(0,50)$	0	0.007 ± 0.01	0	0.12 ± 0.06	0	0.001 ± 0.01	0	0.04 ± 0.03
OSSF1	on-Z	$(0,50)$	0	0.1 ± 0.04	0	0.5 ± 0.12	0	0.02 ± 0.02	0	0.23 ± 0.11
OSSF2	off-Z	$(100,\infty)$	0	0.004 ± 0.01	0	0 ± 0	0	0.008 ± 0.01	0	0 ± 0
OSSF2	on-Z	$(100,\infty)$	0	0.05 ± 0.05	0	0 ± 0	0	0.13 ± 0.08	0	0 ± 0
OSSF2	off-Z	$(50,100)$	0	0.01 ± 0.01	0	0 ± 0	0	0.01 ± 0.02	0	0 ± 0
OSSF2	on-Z	$(50,100)$	0	0.39 ± 0.1	0	0 ± 0	0	0.16 ± 0.07	0	0 ± 0
OSSF2	off-Z	$(0,50)$	0	0.11 ± 0.03	0	0 ± 0	0	0.05 ± 0.03	0	0 ± 0
OSSF2	on-Z	$(0,50)$	2	3.3 ± 0.7	0	0 ± 0	1	0.37 ± 0.09	0	0 ± 0

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But visible $p_T^\tau \geq 20$ GeV $\Rightarrow$ reduced efficiencies.

Conclusion

- The possibility of enhanced $H \to ZA \to Z\tau^+\tau^-$ decay exists.
- The NMSSM example scenario needs low tan β and large pseudo-scalar mixing.
- The efficiencies for detecting such a scenario are the largest in the $1\tau_h$ and $2\tau_h$ channel.
- The shape of the efficiency curves is due to an interplay between the isolation and $\min(p_T)$ cuts.
- For low m_A a boosted τ strategy similar to Englert et. al., '11 may be needed.

contd...

- 1-τ_h is the most constraining of the channels.
- The projected reach with 30 fb^{-1} CMS data could probe a large region interesting parameter space.
- For such decays the trial mass reconstruction method is more efficent than the transverse and collinear approaches.
- The phenomenology of non-Standard Higgs bosons can be quite rich and appear in many channels other than $\tau\tau$.