CMS searches for non-SM Higgs

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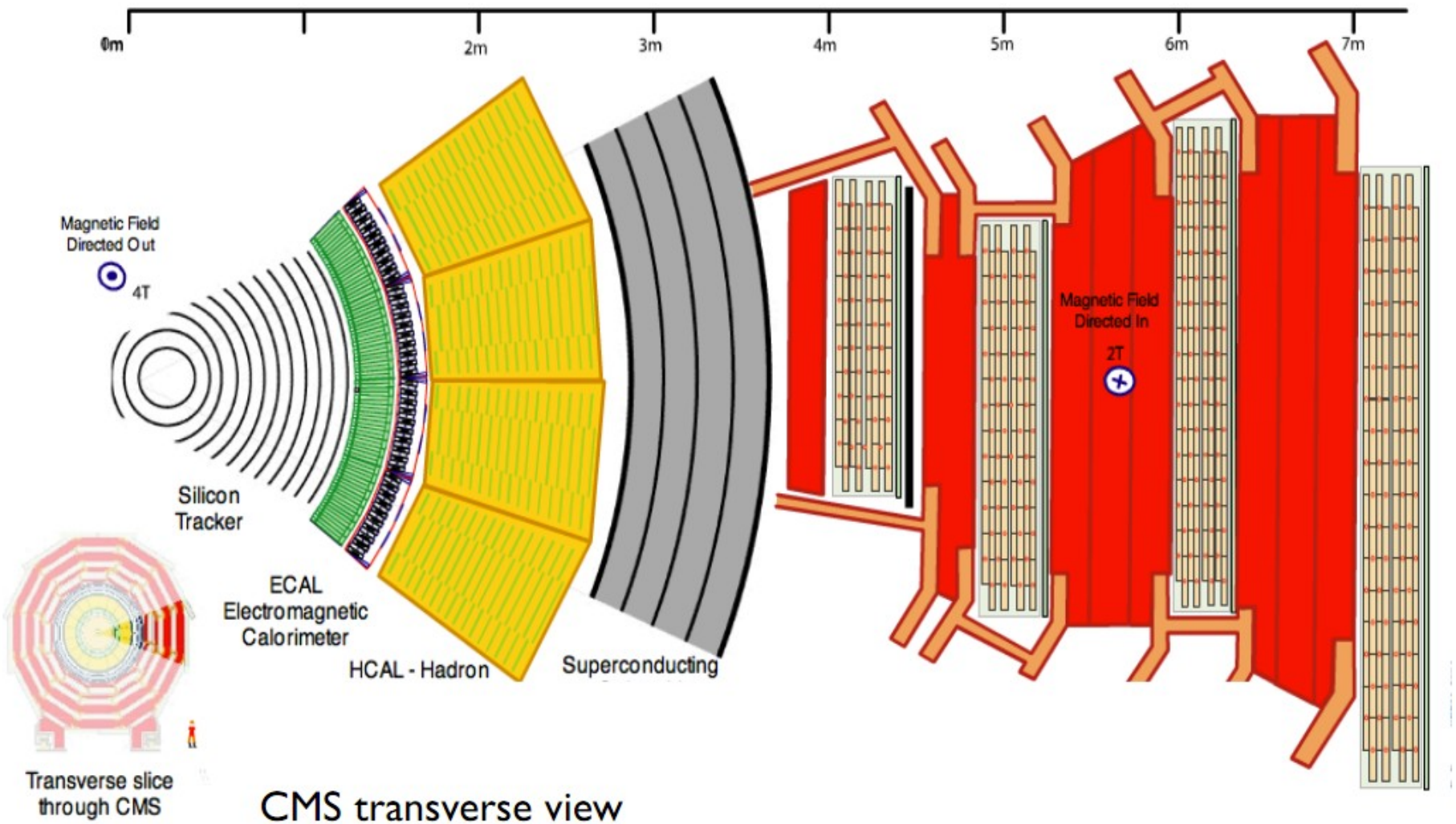
Outline

- Higgs searches in Supersymmetry scenarios:
  - Neutral Higgs
  - Charged Higgs
  - NMSSM light Higgs
- SM4
- Fermiophobic Higgs
- H^{++}
- Higgs to long-lived particles

The current scenario

- With this year data, LHC experiments should either discover or exclude the Higgs within the SM scenario
- Both cases could simply not be the end of the story
- If we do find the Higgs
  - Is it the SM Higgs? Could be MSSM
  - Is there only one Higgs? → (N)MSSM
- If we don't find the Higgs
  - Has it different couplings?
    - MSSM, Fermiophobic, SM4
  - The Higgs sector has a more sophisticated structure
    - MSSM, Doubly charged Higgs
  - Maybe its mass is lighter?
    - NMSSM
  - Or its decays are “hidden” to our experimental setup

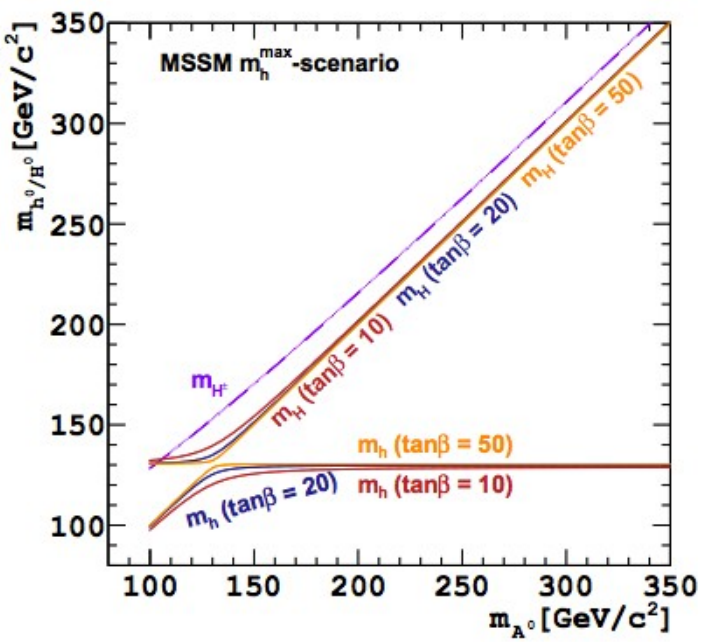
CMS experiment



MSSM searches

The MSSM Higgs sector

- In MSSM you end up with two Higgs doublets
- This leads to a more complicated scalar sector:
  - A light neutral CP-even state (h), two charged states ($H^{\pm}$), a heavy neutral CP-even state (H) and a neutral CP-odd state (A)
- Effectively, one can describe the entire sector with two parameters, usually m_A and the ratio of the vev for the two doublets ($\tan\beta$)

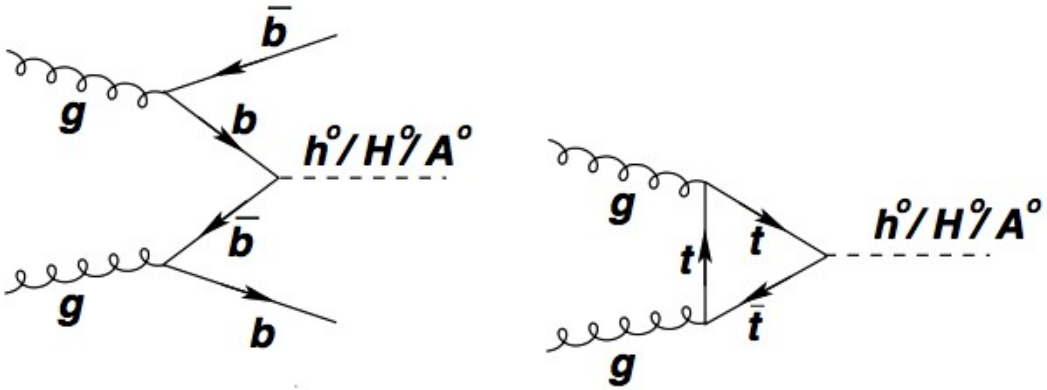


Note that for large $\tan\beta$

- For m_A < 130 GeV, A and h are nearly degenerate
- For m_A > 130 GeV, A and H are nearly degenerate, and m_h ~ 130 GeV

Neutral MSSM Higgs boson

- b-quark coupling enhanced in MSSM: $g_{b\bar{b}H}^{MSSM} = \tan\beta \cdot g_{b\bar{b}H}^{SM}$
- Associated production dominates over gluon-gluon fusion



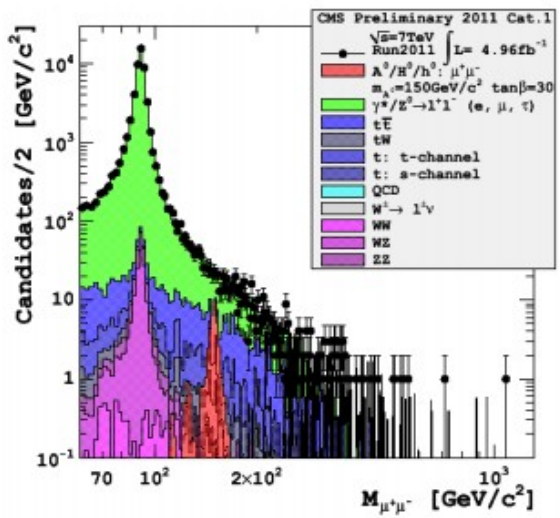
- Lepton decays have lower BR, but higher sensitivity at LHC
- ττ dominates, but μμ cleaner

Search for MSSM $\Phi^0 \rightarrow \mu^+\mu^-$

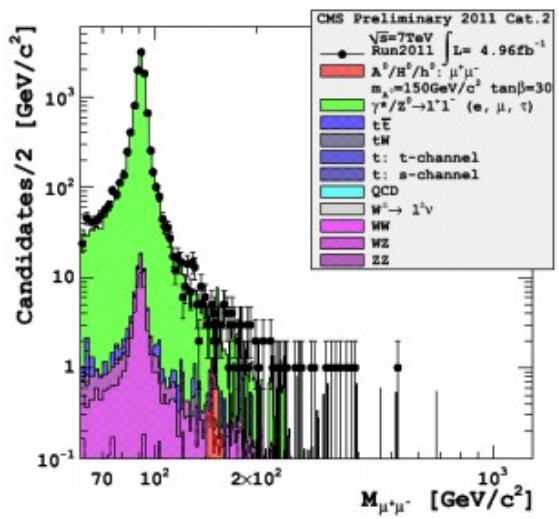
- Look for events with two muons and low missing E_T (< 30 GeV)
- Divide events into three (non-overlapping) categories:
  - Cat1: Events with at least 1 b-tagged jet
  - Cat2: Events with no b-tagged jet but an additional muon
  - Cat3: Events with no b-tagged jet and no muons (g-g fusion)
- Muon selection:
  - $|\eta| < 2.1$
  - $N_{hits} > 10$ ($N_{pix} > 0$)
  - $p_{T,1} > 30$ and $p_{T,2} > 20$ GeV
  - $\chi^2/ndof < 10$
  - $|d_{xy}| < 0.02$ and $|d_z| < 15$ cm
  - Isolation: Sum of momenta and calorimeter energy < 10% of muon p_T

Background contributions

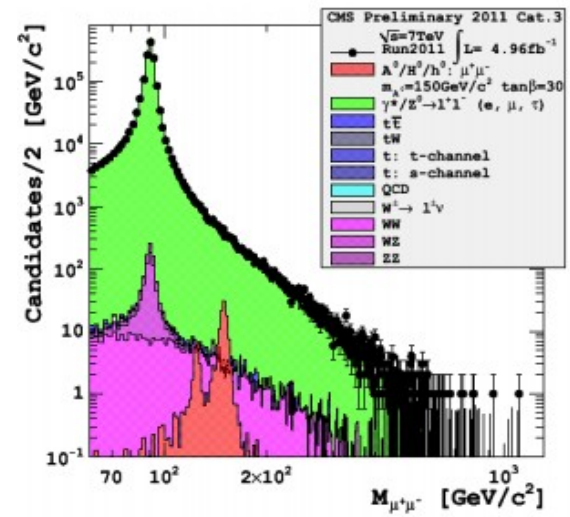
Cat1 : b-tag



Cat2 : no b-tag, +1 muon



Cat3 : no b-tag, no muon



- bbZ irreducible background to the analysis
- tt important for Cat1
- WW for Cat3
- Other backgrounds considered: Z->2l, WZ, ZZ, W, QCD, single t

Signal and background parametrization

- Separate parameterization for the three categories
- Signal: shape fitted from MC and fixed in data:

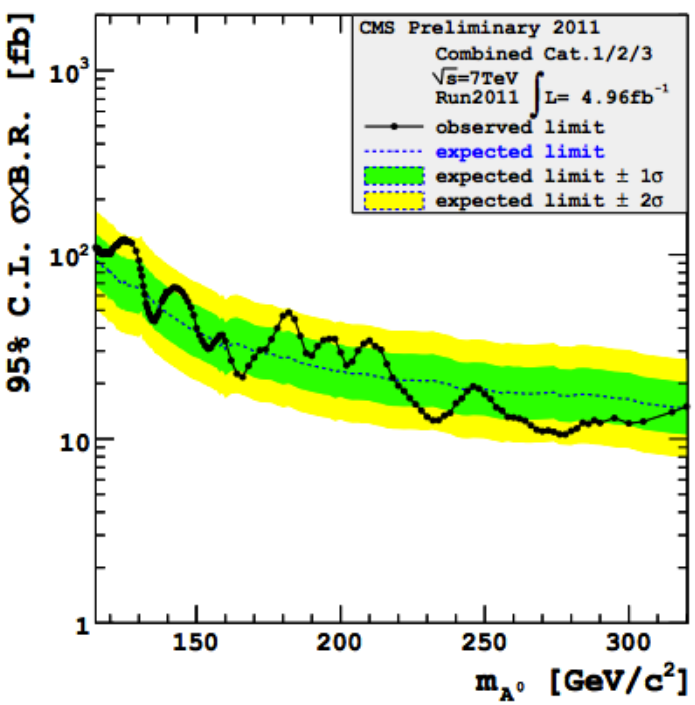
$$F_{sig} = a \cdot F_{BWh^0} + b \cdot F_{BWH^0} + (1 - a - b) \cdot F_{BWA^0}$$

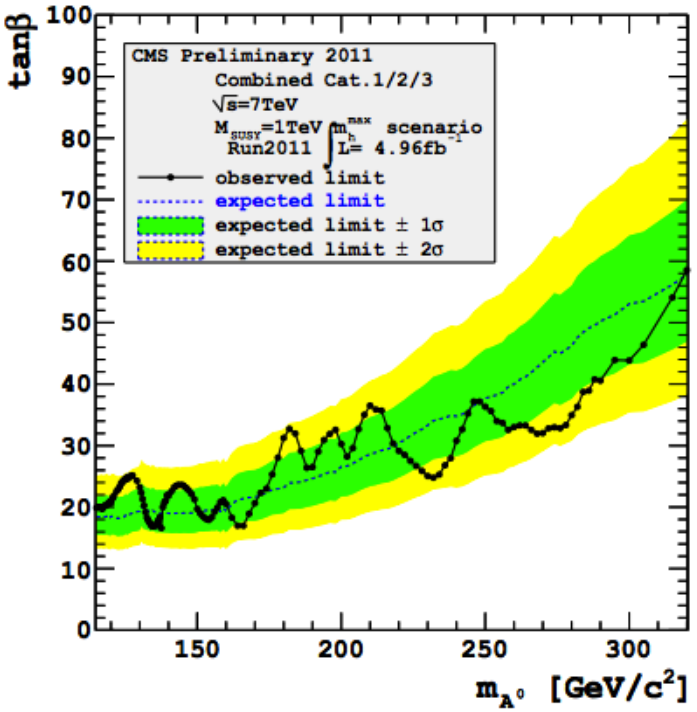
- Background: fitted to data

$$F_{bkg} = e^{\lambda x} \left(\frac{f_{BWZ^0}}{N_{norm1}} \cdot \frac{\Gamma_{Z^0}}{(x - M_{Z^0})^2 + \frac{\Gamma_{Z^0}^2}{4}} + \frac{(1 - f_{BWZ^0})}{N_{norm2}} \cdot \frac{1\mathrm{GeV}/c^2}{x^2} \right)$$

where $x = M_{\mu\mu}$

Results for $\Phi^0 \rightarrow \mu^+\mu^-$





Main sources of systematics

- Theoretical cross sections (~20%)
- Renormalization and factorization scales (~10%)
- b-tagging efficiency (~4%)
- Luminosity (~2%)

ArXiv:1202.4083
Submitted to PLB

Search for $\Phi^0 \rightarrow \tau^+\tau^-$

- Search in three independent final states: $e\tau_h$, $\mu\tau_h$ and $e\mu$
- Adronically decaying taus reconstructed with particle-flow algorithm using HPS
- Tau candidates are typically isolated for signal
- Low transverse mass for tau tracks (neutrinos are ~ collinear)
- Split the sample into two categories:
  - b-Tagged: at most one jet with $p_T > 30$ and one b-tagged jet with $p_T > 20$ GeV
  - Non b-tagged: at most one jet with $p_T > 30$ and no b-tagged jet with $p_T > 20$ GeV

Event selection

$e\tau_h$ channel

Process	MSSM Non B-Tag	MSSM B-Tag
$Z \to \tau\tau$	13115 ± 908	126 ± 8
Fakes	6482 ± 305	101 ± 9
W+jets	5441 ± 377	32 ± 2
$Z \to ll$	6029 ± 646	26 ± 3
$t\bar{t}$	44 ± 7	69 ± 10
Di-Boson	98 ± 21	1 ± 1
Total Background	31208 ± 2264	355 ± 35
$H \to \tau\tau$	44 ± 4	4 ± 1
Data	32062	391
Signal Efficiency		
$gg \to \phi$	9.17e-03	8.22e-05
$gg \to bb\phi$	9.75e-03	1.34e-03

Event selection

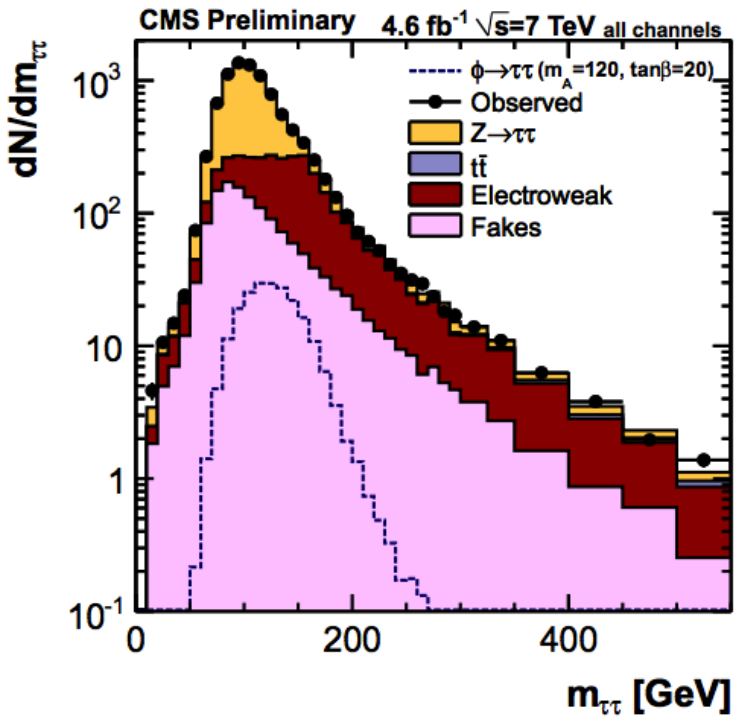
- For adronic taus final states:
  - $p_{T,e} > 20$ or $p_{T,\mu} > 17$ GeV
  - Oppositely charged τ_h with $p_T > 20$ GeV
- For eμ final state:
  - $p_{T,1} > 20$ GeV and $p_{T,2} > 10$ GeV

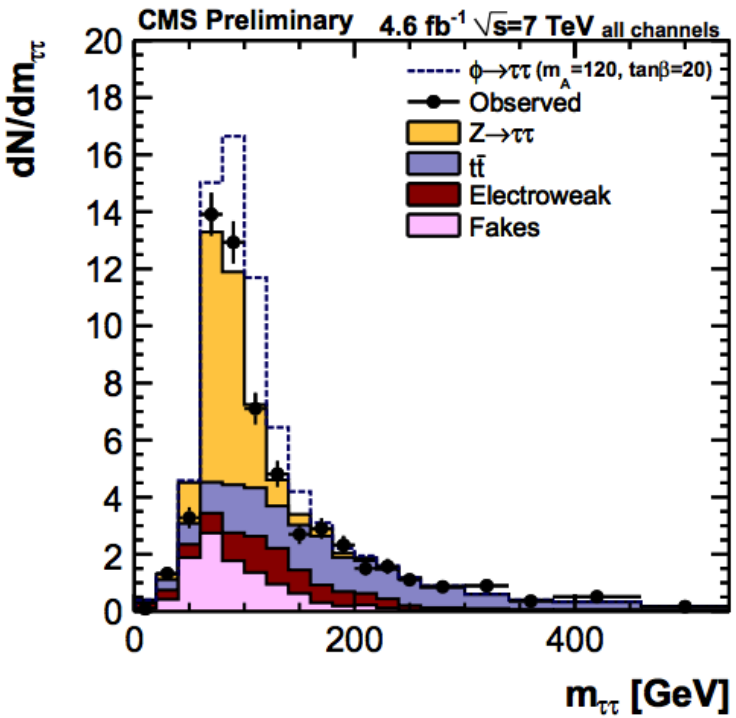
Calculate Higgs candidate invariant mass with maximum likelihood technique

- Neutrinos momentum free parameter of the fit
- Includes tau decay phase-space and tau transverse momentum probability density
- Resolution of ~ 21% at 130 GeV

Background composition

No b-tag



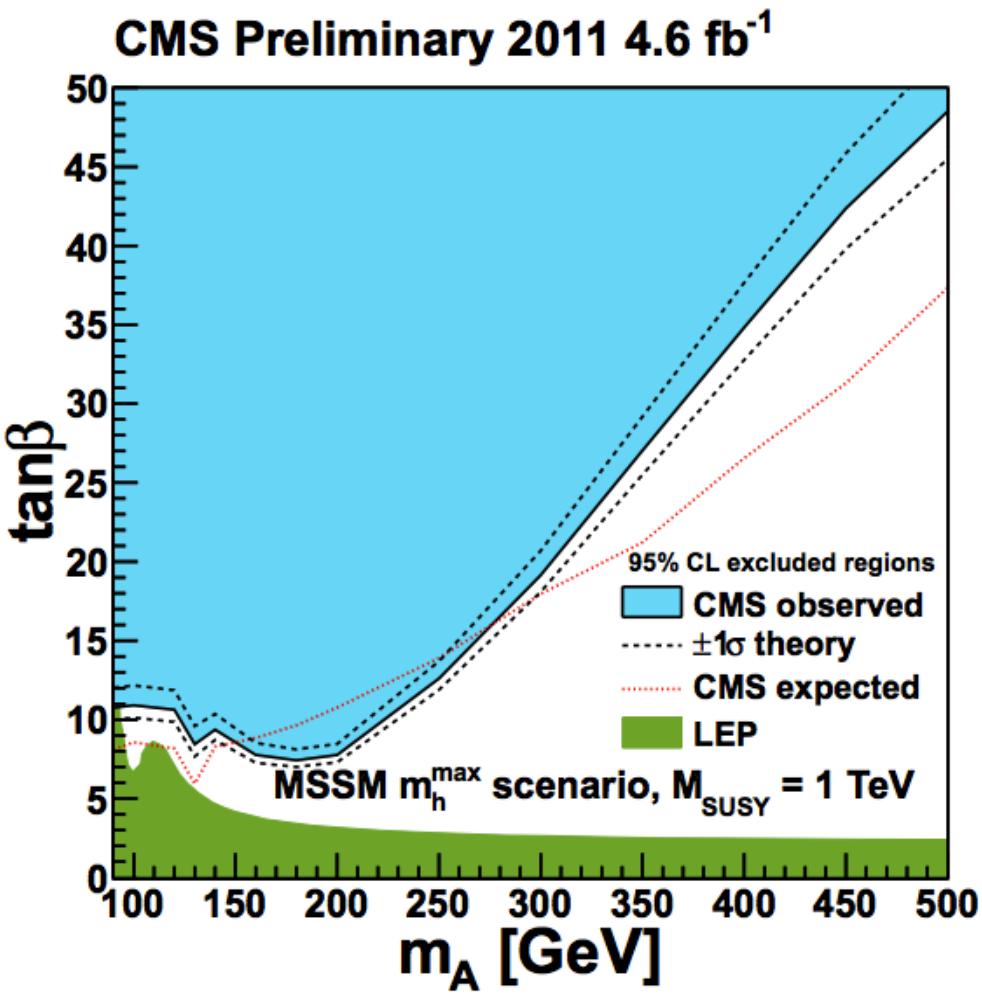


b-tag

Sources of background

- Main source is $Z \to \tau\tau$, irreducible
  - Reconstruct from data $Z \to \mu\mu$, with muons replaced by simulated taus
- Multijet events with one jet misidentified as muon or electron, and another as a τ_h
- tt pair production
- Z production

$\Phi^0 \rightarrow \tau^+\tau^-$ results



Limits obtained with

- M_{SUSY} = 1 TeV
- Stop mixing parameter $X_t = 2M_{SUSY}$
- Higgsino mass μ = 200 GeV
- Gluino mass M_g = 800 GeV
- Stop and sbottom trilinear couplings $A_b = A_t$

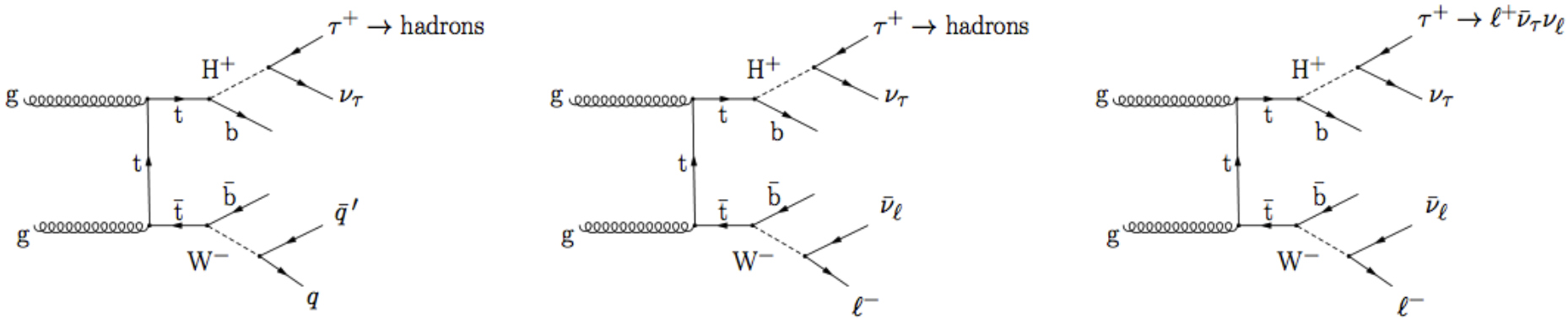
Main systematic effects:

- Background normalization
- b-tag efficiency
- Luminosity

CMS PAS HIG-11-019
Submitted to JHEP

Charged Higgs searches

- If $m_{H+} < m_t - m_b$, then the main production mechanism at LHC is $pp \rightarrow ttX \rightarrow H^+W^-bb/H^+H^-bb$
- Three different final states: τ_h+jets, $e(\mu)\tau_h$ and $e\mu$



H^+ selection criteria

τ_h+jets

- $p_{T,\tau h}$ > 40 GeV
- At least 3 jets with p_T > 30 GeV
- At least one of the jets must be b-tagged
- Events with e(μ) with p_T > 15 GeV rejected
- Cut on tau polarization to suppress W contamination
- Missing E_T > 50 GeV and $\Delta\phi(p_T^{\tau_h}, E_T^{miss}) < 160°$

τ_h+e(μ)

- $p_{T,\tau h}$ > 20 GeV
- $p_{T,e(\mu)}$ > 35 (30) GeV
- At least two jets with p_T > 35 (30) GeV
- At least one of the jets must be b-tagged
- Lepton isolation < 10(20)%*p_T
- Missing E_T > 45 (40) GeV

eμ

- p_T > 20 GeV
- At least two jets with p_T > 30 GeV
- $m_{e\mu}$ > 12 GeV
- Lepton isolation < 15%*p_T

Expected and observed events

Source	$N_{ev}^{\tau_h+jets} \pm$ stat. $\pm$ syst.
$HH + WH$, $m_{H^+} = 120\,GeV$, $\mathcal{B}(t \to H^+b) = 0.05$	$51 \pm 4 \pm 8$
multijets (from data)	$26 \pm 2 \pm 1$
EWK+$t\bar{t}$ τ (from data)	$78 \pm 3 \pm 11$
EWK+$t\bar{t}$ no-τ	$6.0 \pm 3.0 \pm 1.2$
residual $Z/\gamma^* \to \tau\tau$	$7.0 \pm 2.0 \pm 2.1$
residual $WW \to \tau\nu_\tau\tau\nu_\tau$	$0.35 \pm 0.23 \pm 0.09$
Total expected background	$119 \pm 5 \pm 12$
Data	130

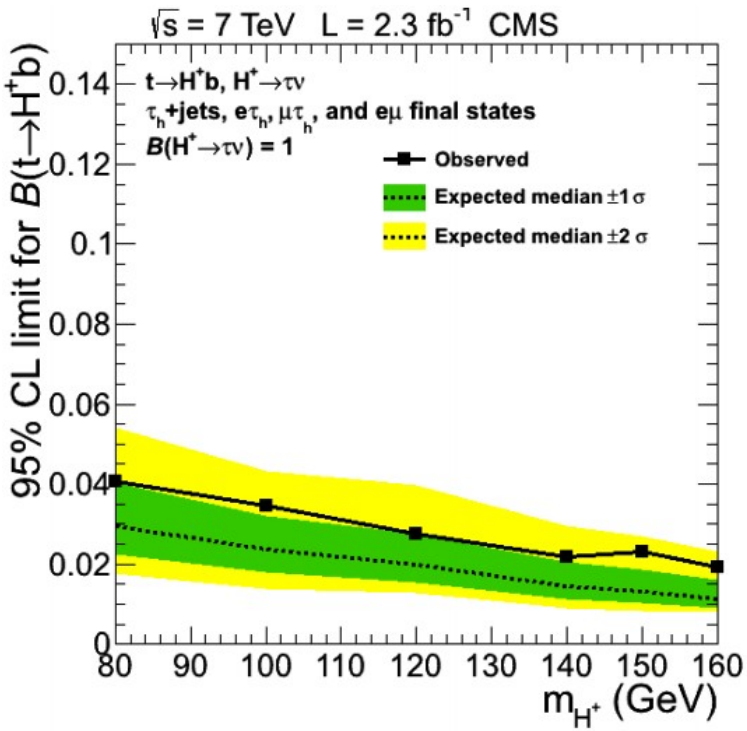
Source	$N_{ev}^{e\tau_h} \pm$ stat. $\pm$ syst.	$N_{ev}^{\mu\tau_h} \pm$ stat. $\pm$ syst.
HH+HW, $m_{H^+} = 120\,GeV$, $\mathcal{B}(t \to H^+b) = 0.05$	$51 \pm 3 \pm 8$	$89 \pm 4 \pm 13$
misidentified τ (from data)	$54 \pm 6 \pm 8$	$89 \pm 9 \pm 11$
$t\bar{t} \to WbW\bar{b} \to \ell\nu b\, \tau\nu\bar{b}$	$100 \pm 3 \pm 14$	$162 \pm 4 \pm 23$
$t\bar{t} \to WbW\bar{b} \to \ell\nu b\, \ell\nu\bar{b}$	$9.0 \pm 0.9 \pm 1.8$	$13.0 \pm 1.2 \pm 2.5$
$Z/\gamma^* \to ee, \mu\mu$	$4.8 \pm 1.8 \pm 1.3$	$0.7 \pm 0.7 \pm 0.7$
$Z/\gamma^* \to \tau\tau$	$17.0 \pm 3.3 \pm 3.0$	$26.0 \pm 4.3 \pm 6.1$
single top quark	$7.9 \pm 0.4 \pm 1.1$	$13.5 \pm 0.5 \pm 1.9$
diboson	$1.3 \pm 0.1 \pm 0.2$	$2.0 \pm 0.2 \pm 0.3$
Total expected background	$194 \pm 8 \pm 20$	$306 \pm 11 \pm 32$
Data	176	288

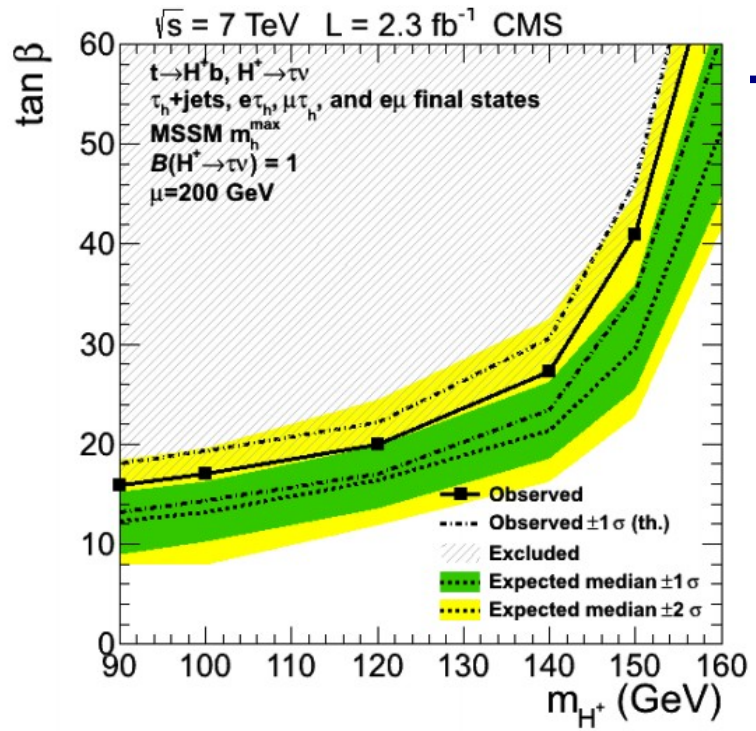
Source	$N_{ev}^{e\mu} \pm$ stat. $\pm$ syst.
HH+WH, $m_{H^+} = 120\,GeV$, $\mathcal{B}(t \to H^+b) = 0.05$	$125 \pm 9 \pm 13$
$t\bar{t}$ dileptons	$3423 \pm 35 \pm 405$
other $t\bar{t}$	$23 \pm 3 \pm 3$
$Z/\gamma^* \to \ell\ell$	$192 \pm 12 \pm 19$
W+jets	$14 \pm 6 \pm 2$
single top quark	$166 \pm 3 \pm 18$
diboson	$48 \pm 2 \pm 5$
Total expected background	$3866 \pm 38 \pm 406$
Data	3875

Main background contributions:

- In τ_h+jets: multijet events with large missing E_T and jets misidentified as taus or b-jets
- W+jets/Z+jets, diboson
- tt pair production, tW

H^+ search results





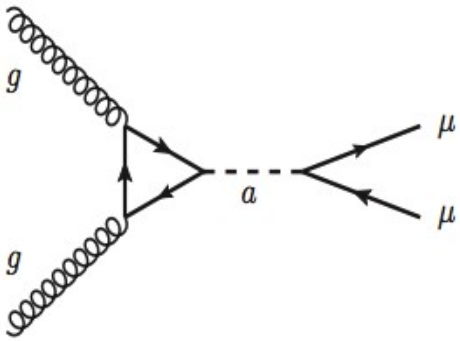
Systematic uncertainties on event yields (%) for m_{H+} = 120 GeV

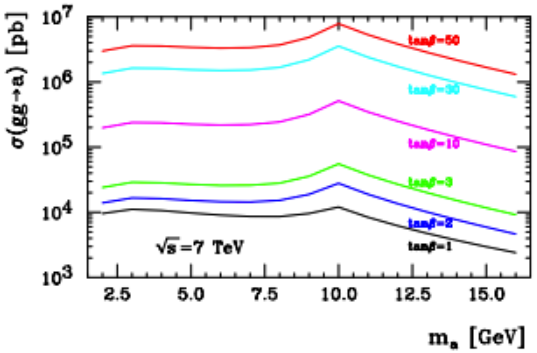
	HH	WH	$t\bar{t}$	DY($\ell\ell$)	W+jets	Single top	diboson
JES+JER+E_T^{miss}	2.1	2.0	2.0	6.0	10.8	4.0	6.5
cross section		$^{+7}_{-10}$		4.3	5.0	7.4	4.0
pileup modeling	4.5	4.5	5.0	5.5	4.0	5.5	5.5
MC stat	5.3	7.9	1.0	6.5	42.9	1.9	4.3
luminosity	2.2						
dilepton selection	2.5						

NMSSM

Search for a light pseudoscalar Higgs boson

- Extends MSSM by adding a complex singlet field
- Solve the μ-term problem (when you break the symmetry, you generate an effective μ-term of the electroweak scale)
- You end up with three CP-even scalars (h_1, h_2, h_3), two CP-odd scalars (a_1, a_2) and two charged scalars ($H^{\pm}$)
- It is very natural for a_1 to have a mass of ~ $2m_B$
  - Would allow a CP-even Higgs with SM-like WW/ZZ couplings with a mass below the nominal LEP limits (h → aa → 4j/4tau)



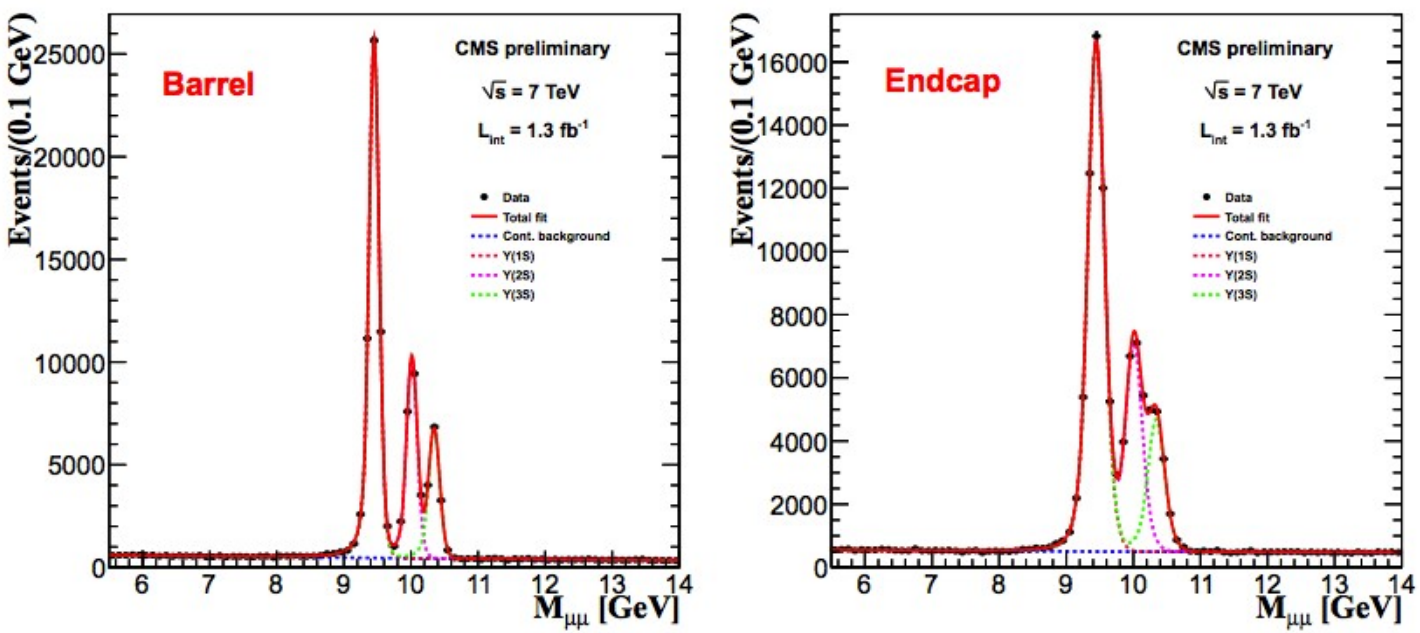


Search for a → μμ

- Dimuon channel suppressed, but cleaner
- Narrow resonance → experimental resolution dominates
- Mainly background from continuum
- Signal σxBR ~ 1-30 pb
  - Avoid the Y region (σxBR ~ nb)
- Barrel and endcap considered as two separate channels and then combined into the final result
  - Exploit better resolution in barrel
- Search for the resonance in two regions: 5.5 – 9 GeV/c^2 (Region 1) and 11.5 – 14 GeV/c^2 (Region 2)
- Low p_T muons → dedicated dimuon trigger with special cuts optimized for this analysis

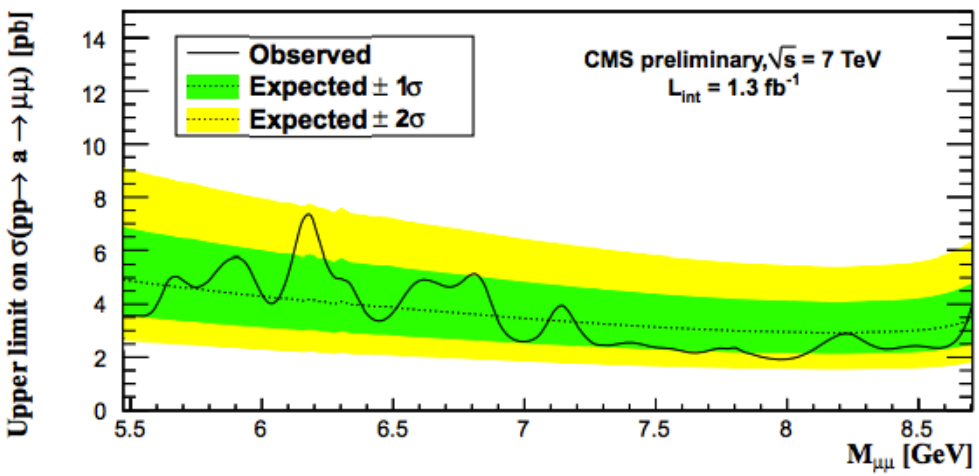
Event selection

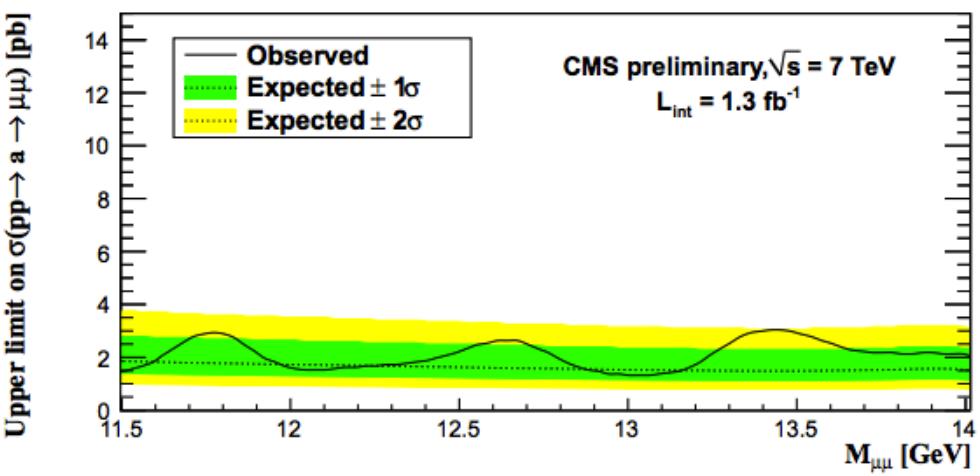
- $p_T(\mu) > 5.5$ GeV/c , $|\eta|(\mu) < 2.4$
- Number of hits per track > 10 (>0 in pixel)
- Track χ^2/ndof < 1.8
- Muon isolation < 0.2
- If more than one candidate is present, choose the highest χ^2 probability



Determination of the UL

- We perform a scan of the invariant mass below/above the Ys
- In each step, a gaussian signal peak is centered in the bin of the scan and the sample is refitted
- Since no significant signal, we put an UL on σxBR



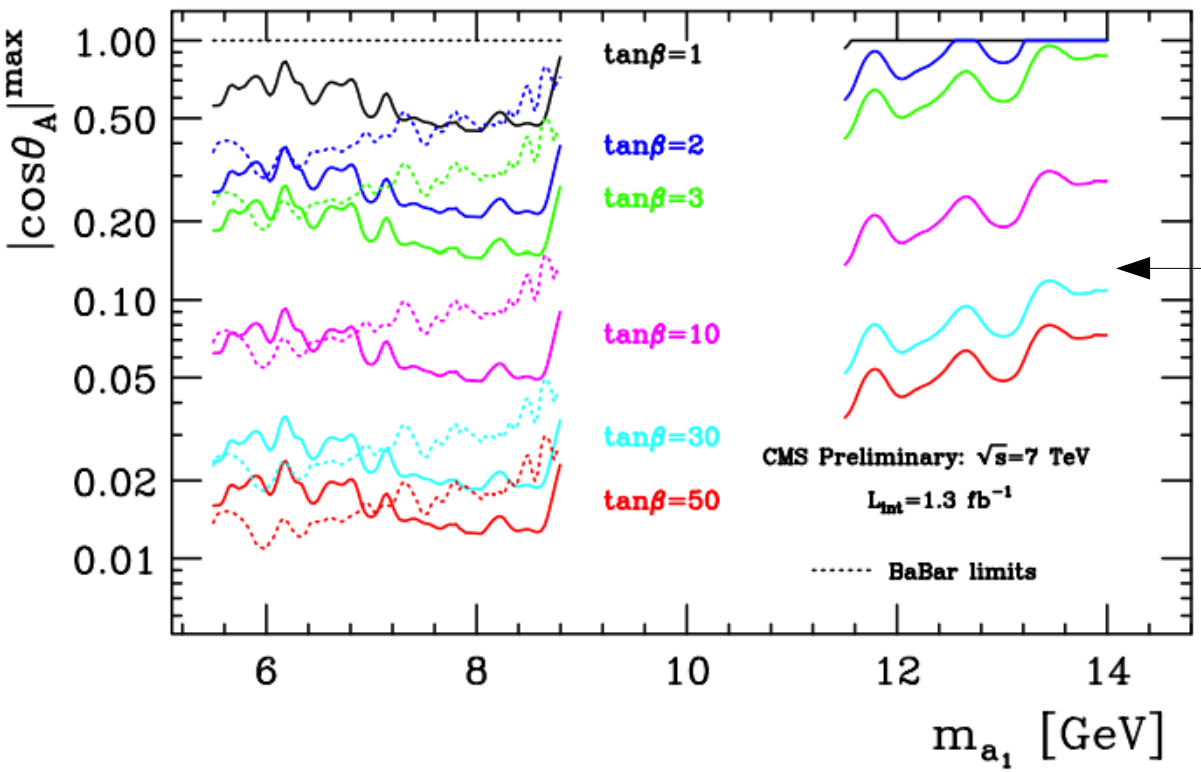


Limits on $|\cos\theta_a|$

- Within NMSSM, the mass eigenstate representing the light Higgs is ~ a singlet:

$$a_1 = \cos(\theta_a)\, a_{MSSM} + \sin(\theta_a)\, a_S$$

- Coupling of a with μμ is proportional to $\cos(\theta_a)\tan\beta$



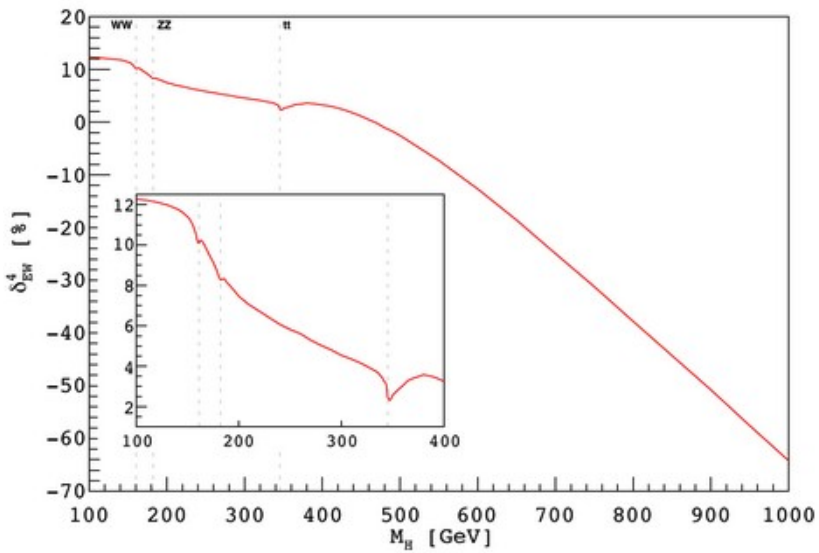
No previous measurement above the Υ(3S) threshold

SM4

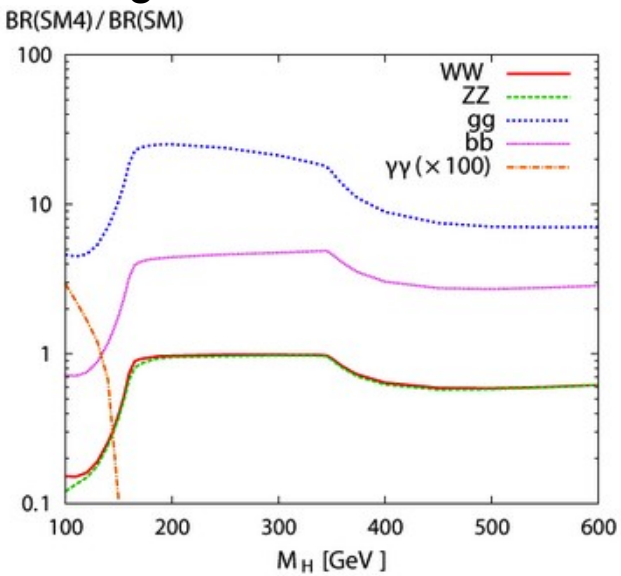
Higgs and a 4th generation

Adding a 4th generation to SM changes the gluon-gluon production cross section and the BR of the decays

NLO EWK correction to gg production

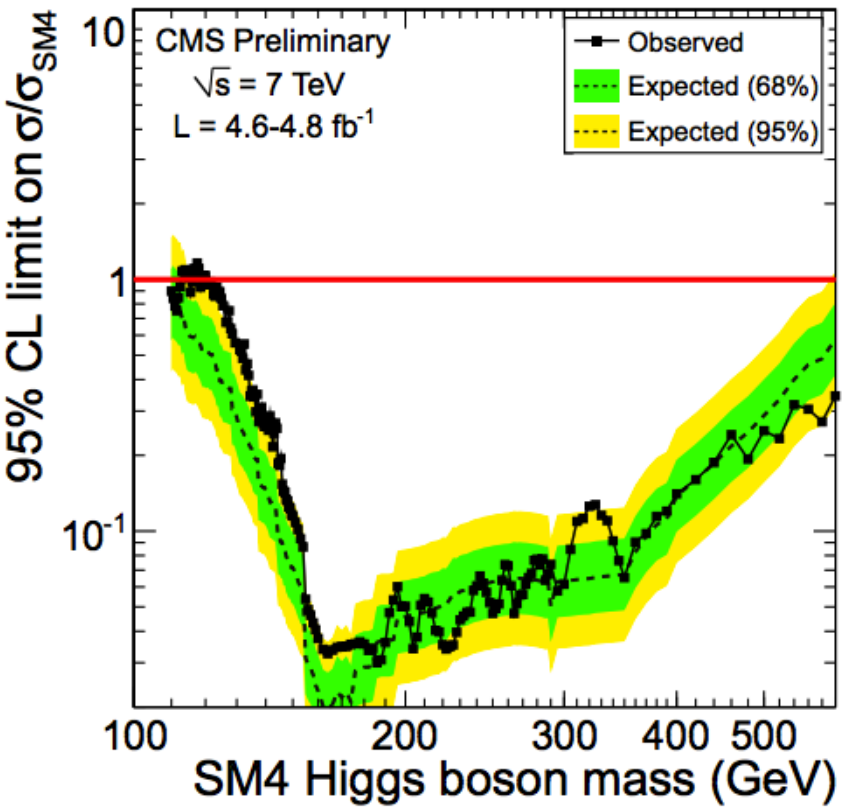


Ratio of BRs in SM4 and SM using NLO EWK corrections



Tables and numbers provided by the LHC Cross Section Working Group

SM4 results



Higgs within SM4 scenario excluded in range 120-600 GeV

Assumes

- $M_{D4} = M_{L4} = 600$ GeV
- $M_{U4} - M_{D4} = [1 + 1/5*\ln(M_H/115) * 50 \text{ GeV}]$

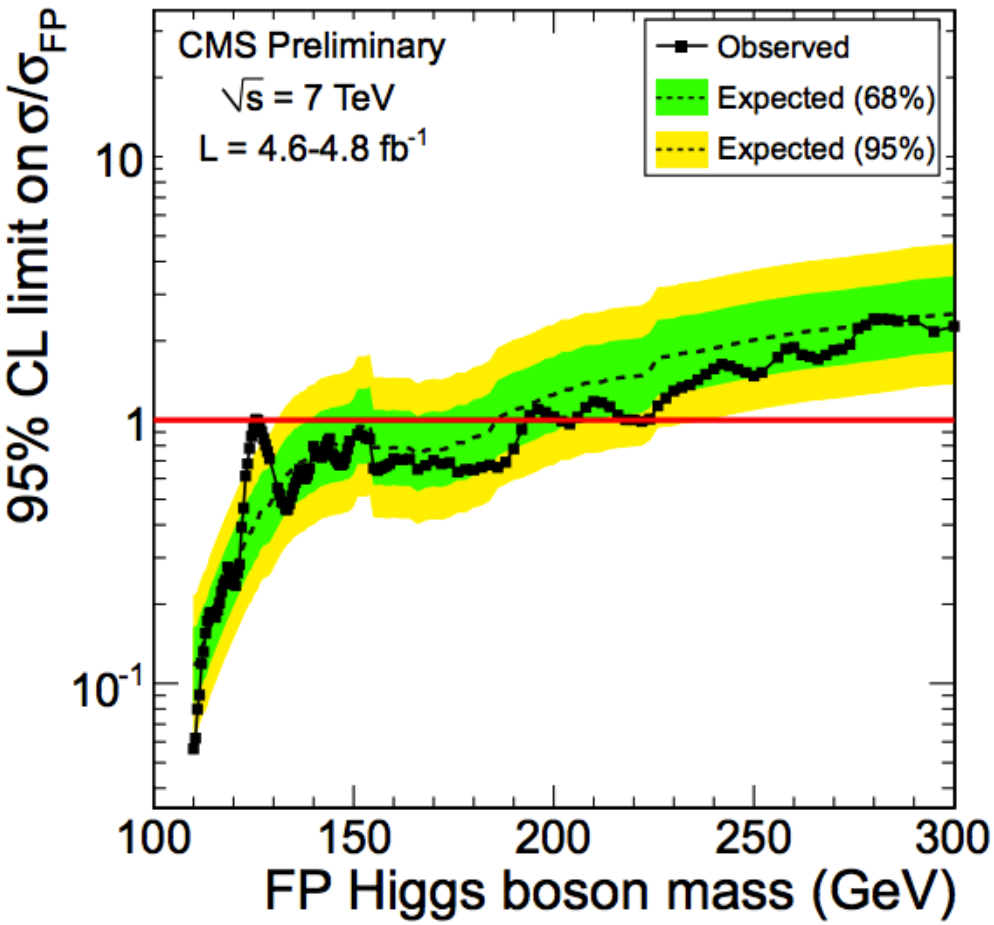
Given the changes in BRs, at low mass the channel that contributes the most is $H \rightarrow \tau\tau$

Fermiophobic Higgs

Fermiophobic Higgs searches

- Higgs only coupled to bosons at tree level
- This enhances the γγ BR at low mass by an order of magnitude
- The cross section suppressed (only VBF and associated production)
- Analysis similar to H → γγ, H → ZZ and H → WW within SM, but focus on VBF and VH signatures
  - VBF: Two jets with E_T > 30 (20) GeV, separation of Δη > 3.5 and m_{jj} > 350 GeV
  - VH: Muons/electrons with p_T > 20 GeV and ΔR > 1 with photons. Veto on Z mass for γe
- All other selection criteria are very similar to SM searches (see Chiara M. talk)

Fermiophobic Higgs results



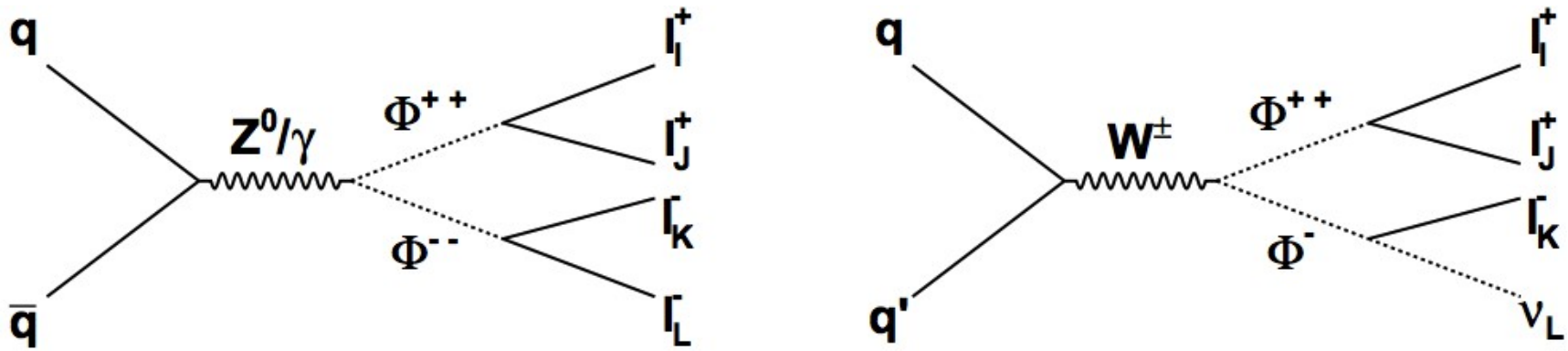
Fermiophobic Higgs excluded at 95% CL in range 110-192 GeV

Excess at 125 still present, but too weak to be compatible with fermiophobic Higgs signal

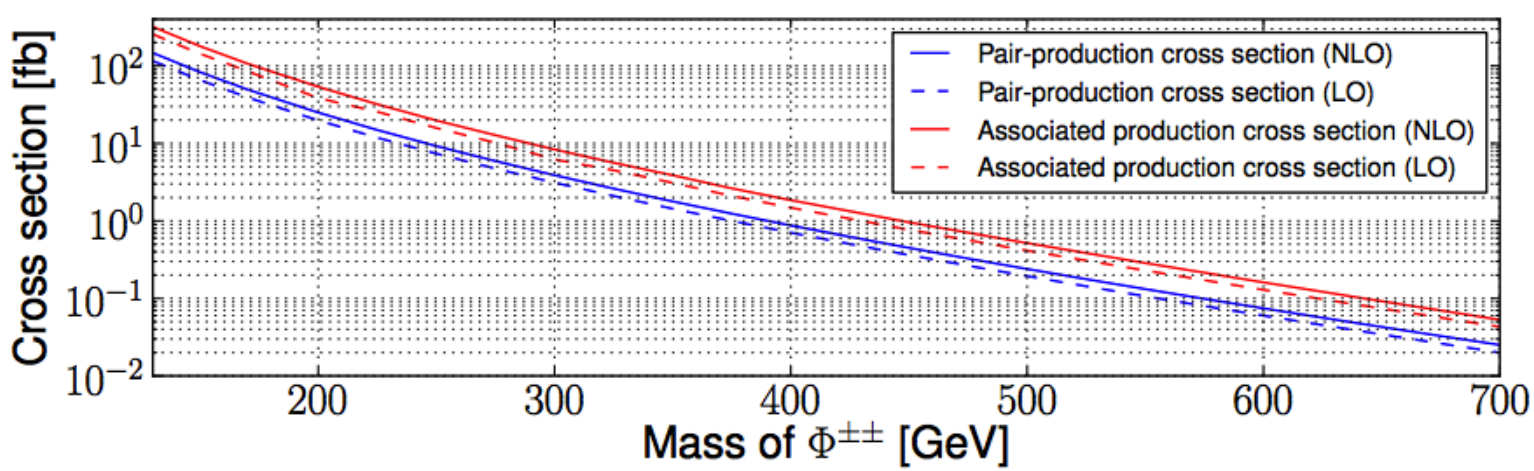
Doubly charged Higgs

H^{++} searches

- Type-II seesaw mechanism generates one triplet scalar field containing a Φ^{++} scalar
- This can be seen at LHC via pair production or associated production



- We search these topologies including at most one (two) τ_h for the associated (pair) production



Selection criteria

Variable	$ee, e\mu, \mu\mu$	$e\tau, \mu\tau$
$\sum p_T$	$> 1.1 \cdot m_{\Phi^{++}} + 60\,\text{GeV}$	$> 0.85 \cdot m_{\Phi^{++}} + 125\,\text{GeV}$
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	$> 80\,\text{GeV}$	$> 80\,\text{GeV}$
$\Delta\varphi$	$< m_{\Phi^{++}}/600\,\text{GeV} + 1.95$	$< m_{\Phi^{++}}/200\,\text{GeV} + 1.15$
E_T^{miss}	none	$> 20\,\text{GeV}$
Mass window	$[0.9 \cdot m_{\Phi^{++}}; 1.1 \cdot m_{\Phi^{++}}]$	$[m_{\Phi^{++}}/2; 1.1 \cdot m_{\Phi^{++}}]$

Three leptons final states

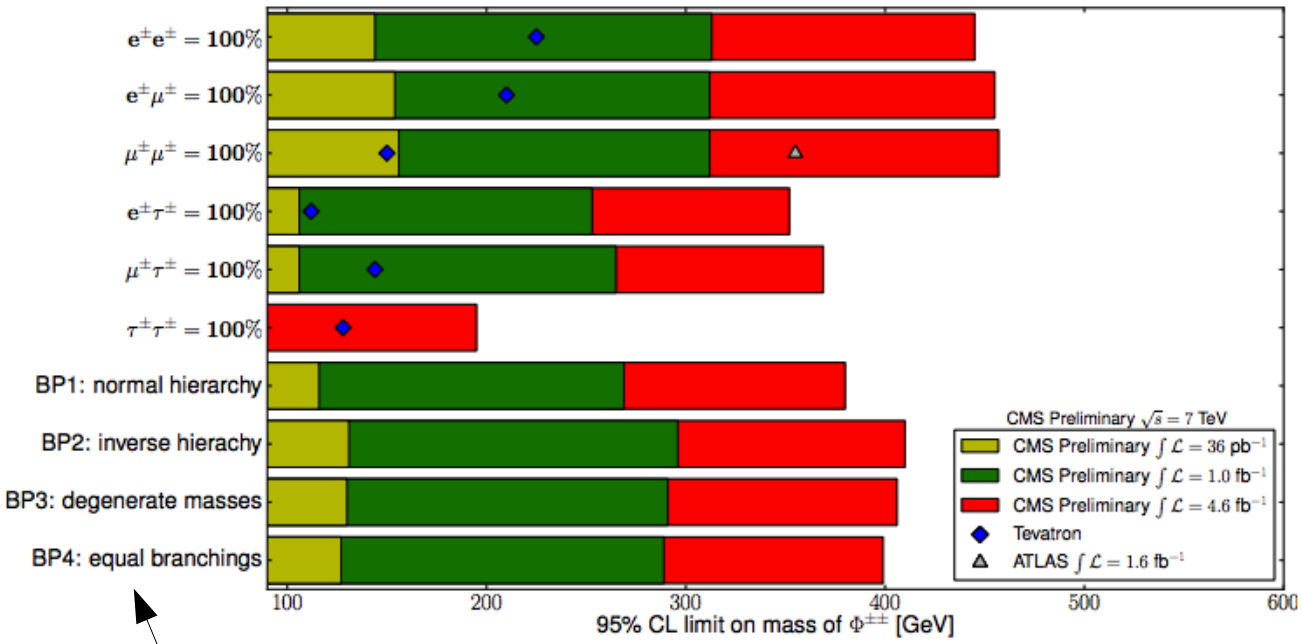
Variable	$ee, e\mu, \mu\mu$	$e\tau, \mu\tau$
$\sum p_T$	$> 0.6 \cdot m_{\Phi^{++}} + 130\,\text{GeV}$	$> m_{\Phi^{++}} + 100\,\text{GeV}$ or $> 400\,\text{GeV}$
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	none	$> 10\,\text{GeV}$
Mass window	$[0.9 \cdot m_{\Phi^{++}}; 1.1 \cdot m_{\Phi^{++}}]$	$[m_{\Phi^{++}}/2; 1.1 \cdot m_{\Phi^{++}}]$

Four leptons final states

Variable	3τ	4τ
$\sum p_T$	$> m_{\Phi^{++}} - 10\,\text{GeV}$ or $> 200\,\text{GeV}$	$\sum p_T > 120\,\text{GeV}$
$\lvert m(\ell^+\ell^-) - m_{Z^0}\rvert$	$> 50\,\text{GeV}$	$> 50\,\text{GeV}$
$\Delta\varphi$	< 2.1	< 2.5
E_T^{miss}	$> 40\,\text{GeV}$	none
Mass window	$[m_{\Phi^{++}}/2 - 20; 1.1 \cdot m_{\Phi^{++}}]$	none

Final states with τ_h

H^{++} results



Several benchmark points tested

Branching ratios

Benchmark point	ee	$e\mu$	$e\tau$	$\mu\mu$	$\mu\tau$	$\tau\tau$
BP1	0	0.01	0.01	0.30	0.38	0.30
BP2	0.50	0	0	0.125	0.25	0.125
BP3	1/3	0	0	1/3	0	1/3
BP4	1/6	1/6	1/6	1/6	1/6	1/6

Systematic uncertainties

Lepton (e or μ) ID and isolation	2%
τ_{had} ID and isolation	6%
τ_{had} energy scale	3%
τ_{had} misid rate	3%
Trigger and primary vertex finding	1.5%
Signal cross section	10%
Luminosity (for signal only)	4.5%
Ratio used in background estimation	5-100%
Statistical uncertainty of observed data events in sideband	10-100%
Statistical uncertainty of signal samples	1-7%

Search for Higgs to long-lived particles

“Hidden” Higgs decays

- Several models predict the existence of massive long-lived particles (split SUSY, weak R-parity violating SUSY, hidden valley models)
- Within these models one can expect the Higgs to decay to these exotic particles, that subsequently have decay vertices very far from the PV
- We search for the possible decay of $H^0 \rightarrow XX$, $X \rightarrow 2l$ (muons or electrons)

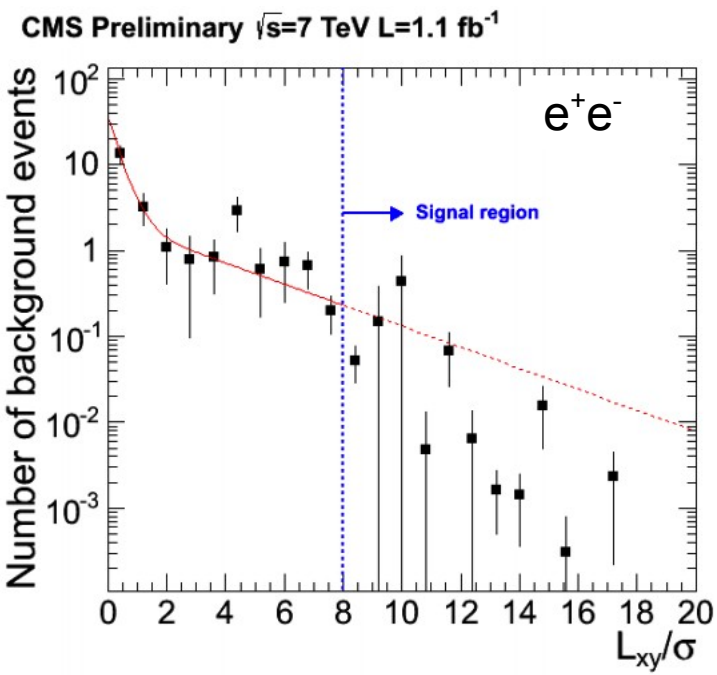
$H^0 \rightarrow XX \rightarrow 4l$ selection

- p_T > 38 (25) GeV for electrons (muons)
- $|\eta| < 2$ (efficiency drops at high η for displaced tracks)
- Require PV with at least 4 tracks to reject cosmics
- Transverse impact parameter significance $|d_0/\sigma| > 3$ (2) for electrons (muons)
- Dimuon vertex χ^2/ndof < 5
- Reject back-to-back muons
- Dimuon transverse momentum collinear with PV
- m_{ll} > 15 GeV to reject J/psi and γ conversions
- Σp_T in isolation cone < 4 GeV
- Dimuon vertex must be 8 (5) standard deviations from PV for electrons (muons)

Background estimation

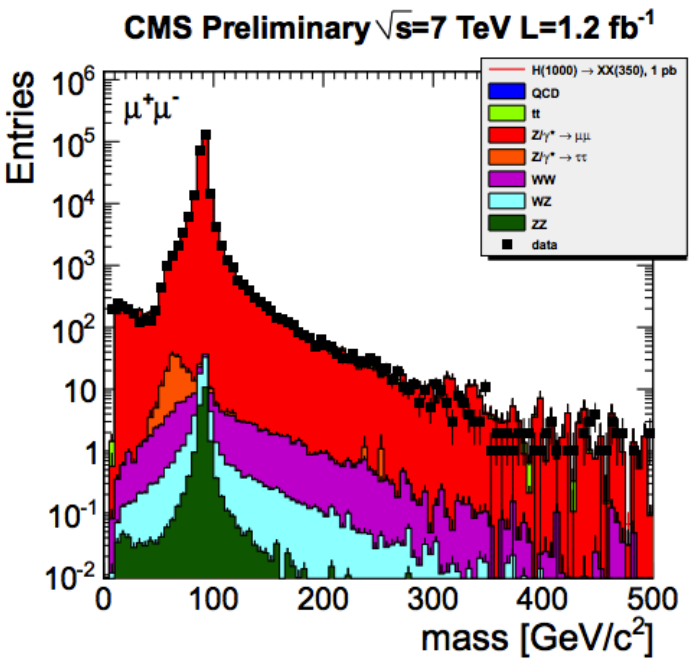
Normalization

Fit the transverse decay length significance (cut removed) and extrapolate in the signal region

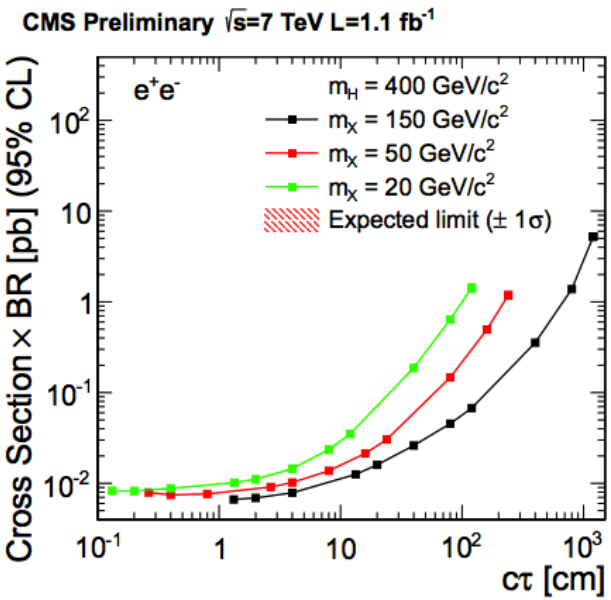


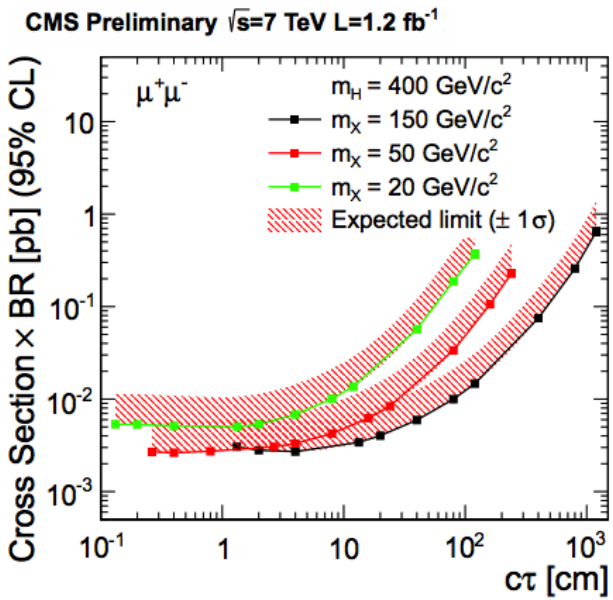
Shape

Invert the decay length significance cut (mass shape not dependent on those selections)



Results for $H^0 \rightarrow XX \rightarrow 4l$





Results depend on m_H and m_X

Few benchmark points provided

Also valid for Z' decays (acceptance slightly different, so small corrections need to be applied)

- Tracking efficiency is the largest systematic (~20%), estimated using data and MC cosmics for muons
  - Electrons assumed to have similar systematic (discrepancy with muons negligible wrt systematic error)
- Trigger efficiency (~10%)

Conclusions

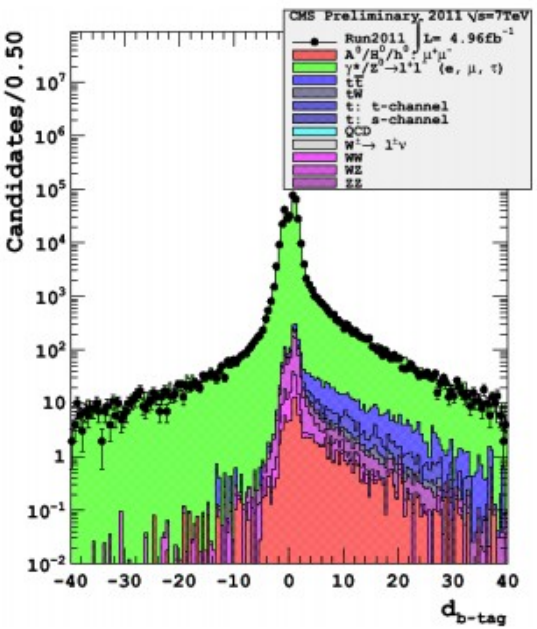
- CMS has a rich BSM Higgs searches program
  - MSSM, NMSSM, SM4, Fermiophobic Higgs, H^{++}
- 2011 data already provided the most stringent constraints to BSM Higgs in the LHC era
  - In some cases, BSM models ruled out
- In most searches, these analyses are relevant independently from a possible discovery of SM-like Higgs this year

<u>New results will be coming out very soon</u>

Backup

B-tagging

- Jets reconstructed with anti-k_T algorithm (R < 0.5)
- $p_{T,jet}$ > 20 GeV and $|\eta_{jet}|$ < 2.4
- Tracks associated to jets ranked in impact parameters significance
- Second largest significance taken as discriminator for the jet



Systematics for $\Phi^0 \rightarrow \mu^+\mu^-$

HLT & μ Rec. Eff. [%]	± 0.1
E_T^{miss} [%]	± 1.8
JES (Cat.1) [%]	$^{+0.3}_{-0.4}$
JES (Cat.2) [%]	$^{+0.02}_{-0.04}$
JES (Cat.3) [%]	$^{+0.4}_{-0.2}$
b-tag [%]	± 3.6
μ_{3rd} [%] as in [22]	± 1.2
pile up [%]	± 1
integrated luminosity [%]	± 2.2
PDF and α_s [%]	± 1 to ± 3
Q-scale [%]	± 5 to ± 13
$\sigma_{A^0/H^0/h^0}$ [%] m_{A^0} and $\tan\beta$ dependent [25] (not for $\sigma \times B.R.$ vs. m_{A^0})	$^{+16}_{-20}$

Systematcs shown as relative error to efficiency

Systematics for fermiophobic Higgs search

Sources of systematic uncertainty		Uncertainty	
Per photon		Barrel	Endcap
Photon identification efficiency		1.0%	2.6%
R_9 >0.94 classification (class migration)		4.0%	6.5%
Energy resolution ($\Delta\sigma/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.22%, 0.61%	0.91%, 0.34%
	$R_9 < 0.94$ (low η, high η)	0.24%, 0.59%	0.30%, 0.53%
Energy scale ($(E_{data} - E_{MC})/E_{MC}$)	$R_9 > 0.94$ (low η, high η)	0.19%, 0.71%	0.88%, 0.19%
	$R_9 < 0.94$ (low η, high η)	0.13%, 0.51%	0.18%, 0.28%
Per event			
Integrated luminosity		4.5%	
Vertex finding efficiency		0.4%	
Trigger efficiency	One or both photons $R_9 < 0.94$ in endcap	0.4%	
	Other events	0.1%	
Dijet selection			
Dijet-tagging efficiency	VBF process	10%	
VH leptonic selection			
Charged lepton identification efficiency		1.0%	
Inclusive 2D analysis			
2D Signal Model - $\pi_T^{\gamma\gamma}$ parametrization		5%	
Production cross sections		Scale	PDF
Vector boson fusion		+0.5% -0.3%	+2.7% -2.1%
Associated production with W/Z		1.8%	4.2%
Decay branching ratio			
$H \to \gamma\gamma$ BR in the FP model		5%	