Non-SM Exotic Higgs: Beyond SM and MSSM

Including results from Tevatron and LHC

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on behalf of CMS/ATLAS/CDF/D0 collaboration

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Higgs session
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Outline

1. Higgs in Standard Model with 4^{th} generation
2. Fermiophobic Higgs
3. Next to Minimal Supersymmetric Standard Model
   - $t \to H^{\pm} b \to (W^{\pm} a_1) b, \quad a_1 \to \tau\tau$
   - $h \to aa \to (4\mu)$
   - $gg \to a \to (2\mu)$
   - $h \to aa \to 4\gamma$
4. Exotic
   - See-Saw Type-II H^{++}
   - Hidden sector
5. Summary

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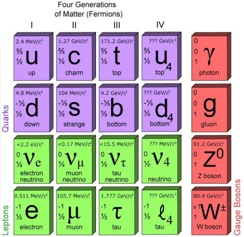
Higgs in Standard Model with 4^{th} generation

Model

- Standard Model with a fourth generation of fermions u_4, d_4, ℓ_4, ν_4;
- not excluded by EWK precision data if mass split not too large $\mathcal{O}(50)$ GeV,



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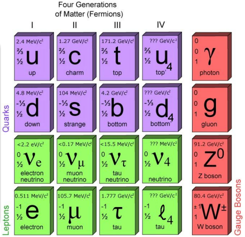
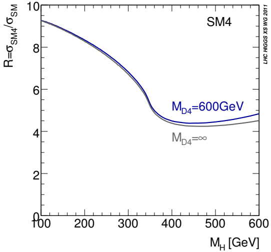
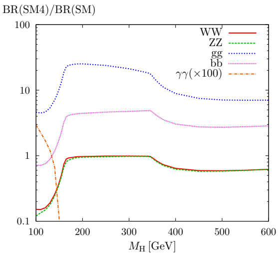


Large impact on production and decay rates

- $\sigma(gg \to H)$ enhanced, VBF and VH negligible;
- $BR(H \to WW/ZZ)$ smaller, $H \to \gamma\gamma$ suppressed, $H \to fermions$ larger





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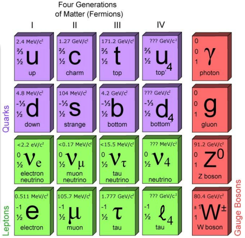

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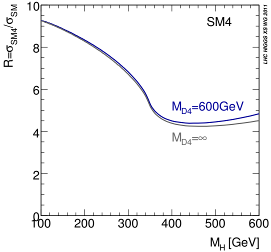
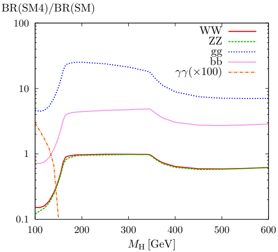
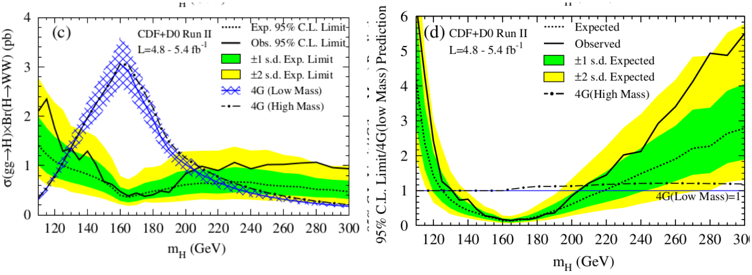




Need re-interpretation of SM(3) results in the context of SM4.

SM4 at Tevatron

- at CDF 4.8 fb^{-1} and D0 5.4 fb^{-1} [1]
  - low mass scenario $m_{\nu_4} = 80\ GeV$, $m_{\ell_4} = 100\ GeV$;
  - high mass scenario $m_{\nu_4} = m_{\ell_4} = 1\ TeV$.
  - $m_{d_4} = 400\ GeV\ m_{u_4} - m_{d_4} = (50 + 10 \cdot \ln(m_H/115))\ GeV$
- Uses only $H \to WW$
- 2 $\ell^{\pm}$ isolated + MET + (0,1,$\geq$2 jets)



Results: $131 < m_{H_{SM4}} < 204\ GeV$ excluded at the 95% CL

SM4 at LHC

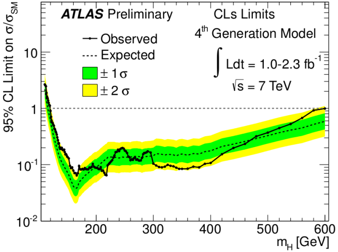
ATLAS 1.0-2.3 fb^{-1} [2]
CMS 4.6-4.8 fb^{-1} [3]

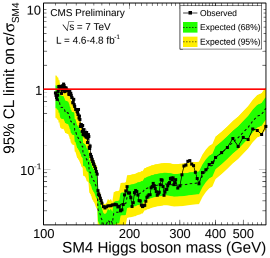
$$m_{\ell_4} = m_{\nu_4} = m_{d_4} = 600\ GeV$$
$$m_{u_4} - m_{d_4} = (50 + 10 \cdot \ln(m_H/115))\ GeV$$

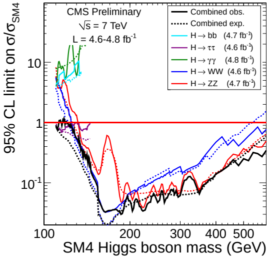
- $H \to \gamma\gamma, bb$ (almost no sensitivity)
- $H \to \tau\tau$
- $H \to WW$
- $H \to ZZ$

Results

ATLAS/CMS each exclude
$120 < m_{H_{SM4}} < 600$ GeV 95% CL







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Fermiophobic Higgs

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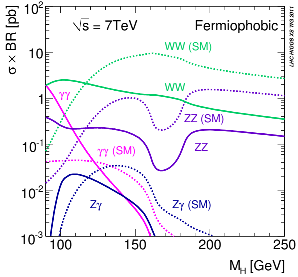


Fermiophobic Higgs

Model

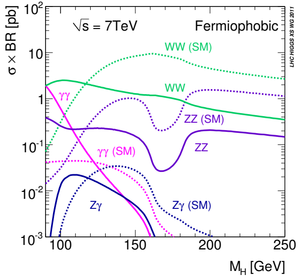
- Possible with extended Higgs sector (2DHM)
- SM-like but **no coupling to fermions**;

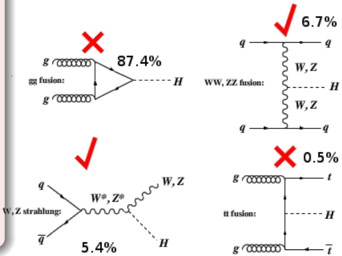
decay $H \to WW, ZZ, \gamma\gamma$

production only via VBF and VH ✓,
no $gg \to H$ nor ttH ✗.

  - Yield $\to \gamma\gamma$ comparable to SM at 125 GeV
  - Higgs is boosted
  - additional signatures: di-jet, lepton, MET

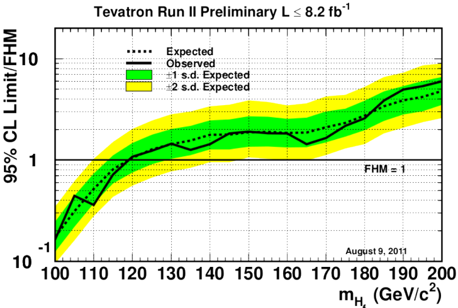
- LEP excluded H_{fp} $M_H < 108.2\ GeV$.





Fermiophobic Higgs at Tevatron

- CDF 8.2 fb^{-1} / D0 8.2 fb^{-1} [4]
- SM Higgs analysis re-optimized to use boosted Higgs
- Channels considered:
  - $H \to \gamma\gamma$
  - $H \to WW \to 2\ell 2\nu$ $(0, 1, \geq 2$ jets$)$
  - $WH \to WWW$
  - $ZH \to ZWW$

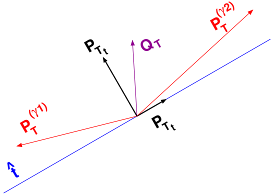


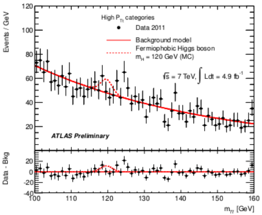
Exclusion: $m_{H_{fp}} < 119$ GeV 95% CL

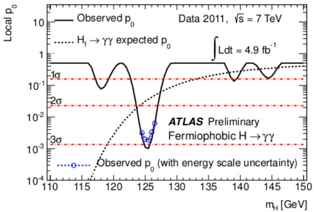
Fermiophobic Higgs at ATLAS

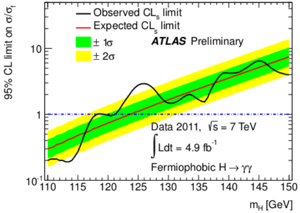
- ATLAS 4.9 fb^{-1} [5]
- $H \to \gamma\gamma$: SM-like selections
- 9 sub-channels
  - η-region: both central, rest
  - converted/unconverted
  - Low/High $P_{T_t}^{\gamma\gamma}$

    $P_{T_t}^{\gamma\gamma}$ $\gamma\gamma$ transverse momentum orthogonal to the $\gamma\gamma$ thrust $(\hat{t})$ axis in the transverse plane
  - $+$ converted γ in transition region









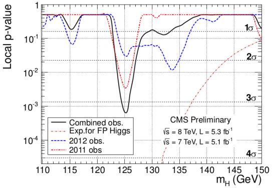
Largest excess $M_H = 125.5$ GeV 1.6σ (LEE):

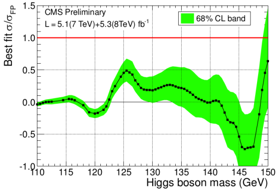
Exclusion for $m_{H_{fp}} \in [110 - 118] \cup [119.5 - 121]$ GeV 95% CL

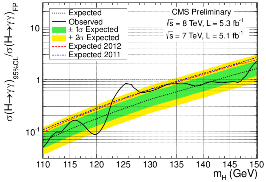
Fermiophobic Higgs at CMS

- CMS 4.9-5.1 fb^{-1} [3] and 5.1+5.3 fb^{-1} [6]
- $H \to WW \to 2\ell^{\pm}2\nu + (2\ jets, \ell)$
- $H \to ZZ$ re-interpretation of SM analysis;
- $H \to \gamma\gamma$, in association with:
  - pair of jets with large $\Delta\eta_{jj}$
  - an isolated muon/electron or large MET
  - untagged (4 sub-channels by η_γ and shower shape)

  2D analysis: $m_{\gamma\gamma}, \pi_T^{\gamma\gamma} = p_T^{\gamma\gamma}/m_{\gamma\gamma}$ to exploit the $H \to \gamma\gamma$ boost.







$M_H = 125.5$ GeV $p_0 = 3.2\sigma$ (w/o LEE effect). Signal strenght too low for a Fermiophobic Higgs hypothesis. $m_{H_{fp}} < 147\,\text{GeV}$ 95% CL

Outline

Next-to-MSSM (nMSSM)

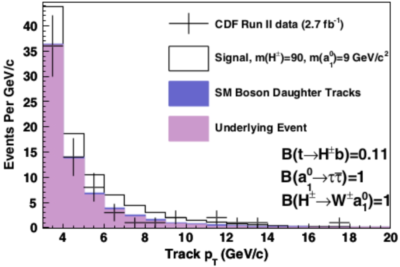
Model

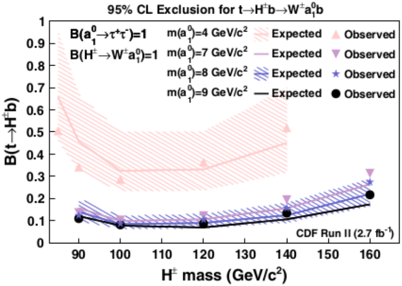
- nMSSM: add one scalar singlet to MSSM.
  - 3 CP-even $h_{1,2,3}$, 2 CP-odd $a_{1,2}$, charged $H^{\pm}$
  - one CP-odd boson (a_1) can be very light $m_{a_1} \lesssim 2m_b$
- solve some problem of MSSM
  - accommodates better $M_H = 125 - 126\,\mathrm{GeV}$
  - no fine-tuning for μ-term (produced by VEV of singlet)
- Production via $gg \to (h, a)$ through t, b triangle loop.
- Channels:
  - $t \to H^{\pm}b \to (W^{\pm}a_1)b \quad a \to \tau\tau$
  - $h \to a_1 a_1 \to 4\mu$
  - $a_1 \to \mu\mu$
  - $h \to a_1 a_1 \to 4\gamma$
- Searches also at B-factory via $\Upsilon(nS) \to \gamma a_1$

nMSSM $t \to H^{\pm} b \to (W^{\pm} a_1) b \quad a_1 \to \tau\tau$

CDF L=2.7 fb^{-1} [7]

- $t\bar{t}$ standard selection: isolated-μ/e+MET +3 jets+b-jets
- τ selection for 1-prong decay: 1 isolated track far from leptons
- signal extraction based on isolated track p_t spectrum
- no excess, limit on $B(t \to H^{\pm} a_1)$ vs $M_H^{\pm}$ for $m_{a_1} = 4 - 9$ GeV





nMSSM $h \to aa \to (4\mu)$

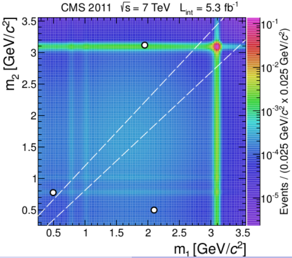
CMS L=5.3 fb^{-1} [9]

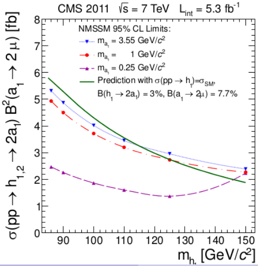
4μ:
- $1\mu(p_t > 17\,\text{GeV},\ |\eta| < 0.9) + 3\mu(p_t > 8\,\text{GeV},\ |\eta| < 2.4)$
- opposite charged μs paired if same vtx and $M_{\mu\mu} < 5\,\text{GeV}$, isolated
- signal when $m_1 \approx m_2$, side bands for background $(\omega, \rho, \phi, J/\psi, \ldots)$
- similar analysis at D0 [8] in $(4\mu, 2\mu 2\tau)$ (L=4.2 fb^{-1})

- Limit on $\sigma(p\bar{p} \to h \to a_1 a_1) \times B^2(a_1 \to 2\mu)$
- Also interpreted in term of Higgs decay with dark-SUSY models

  $h \to 2n_1,\ n_1 \to \gamma_D + n_D,\ \gamma_D \to \mu\mu$

  (n_1 is SUSY lightest neutralino, n_D dark-neutralino, γ_D dark-photon)





nMSSM $gg \to a \to \mu\mu$

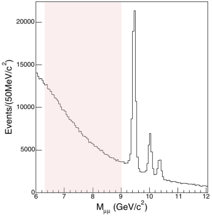
CDF: $L = 0.63\,\text{fb}^{-1}$ [10]. CMS $L = 1.3\,\text{fb}^{-1}$ [11].

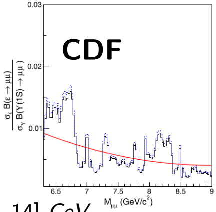
- dedicated exclusive Trigger:
  - 2μ, low p_t^{μ}, same vtx
  - Selection in $M_{\mu\mu}$
- Selection: 2 good $\mu^{\pm}$, isolated, prompt
  - search for narrow resonances for:

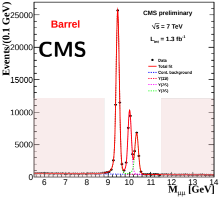
CDF $M_{\mu\mu} \in [6.3 - 9]$ GeV

CMS $M_{\mu\mu} \in [5.5 - 8.8] \cup [11.5 - 14]$ GeV

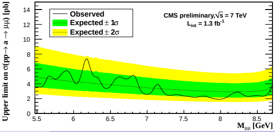
no excess, set limit on $\sigma_a B(a \to \mu\mu)$



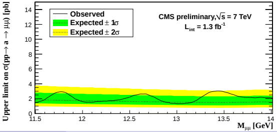




$M_{\mu\mu} \in [5.5 - 8.8]$ GeV



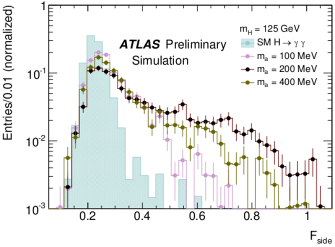
$M_{\mu\mu} \in [11.5 - 14]$ GeV

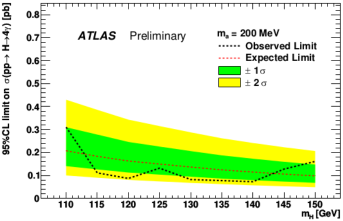


nMSSM $h \to aa \to (\gamma\gamma) + (\gamma\gamma)$

ATLAS $L = 4.9\,\text{fb}^{-1}$ [12]

- Sensitive to very light a:
  - for $M_a < 3m_{\pi^0}$: $a \to \gamma\gamma$ enhanced, very clean signal.
- large boost for a, γ very collinear, seen almost as $H \to \gamma\gamma$
- same analysis as SM $H \to \gamma\gamma$
  - relaxed shower shape requirements on γ
  - allow larger lateral energy leak F_{side}
- limit on $\sigma(h \to aa \to 4\gamma)$ vs $M_h \in [110 - 150]$ GeV for $m_a = 100, 200, 400$ MeV



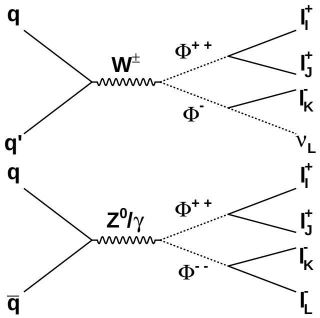


Outline

See-Saw Type-II: H^{++}

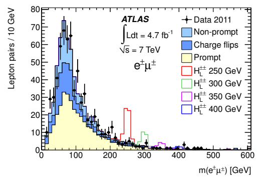
Model: Minimal See-Saw Type II

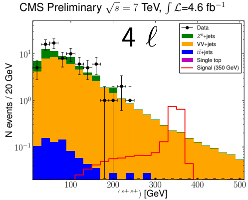
- Additional scalar field, triplet under $SU(2)_L$
- New Higgs-like particles $\phi^{++}, \phi^{+}, \phi^{0}$
- responsible for low neutrino masses via see-saw mechanism
  - Search for ϕ^{++} and ϕ^{+}
  - Produced from W/Z
  - $\phi^{\pm\pm} \to \ell^{\pm}\ell^{\pm}$: same sign leptons signature

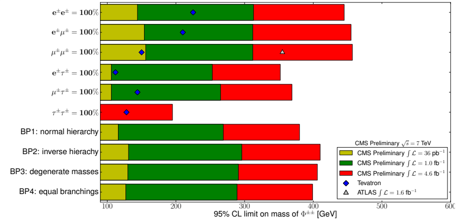


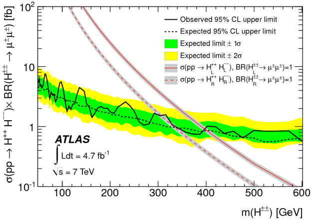
See-Saw Type II: $\phi^{++} \to \ell^{\pm}\ell^{\pm}$

- ATLAS L=4.7 fb^{-1} [13]
  - final states: $e^{\pm}$, $\mu^{\pm}$
  - $M_{H^{\pm\pm}} < 409 - 367\,GeV$ 95% CL for $e^{\pm}e^{\pm}/\mu^{\pm}\mu^{\pm}/e^{\pm}\mu^{\pm}$
- CMS L=4.6 fb^{-1} [14]
  - final states: $e^{\pm}$, $\mu^{\pm}$, $\tau_h^{\pm}$
  - $M_{H^{\pm\pm}} < 455$ for $e^{\pm}$ and $\mu^{\pm}$ combinations
    $M_{H^{\pm\pm}} < 350$ for $e^{\pm}/\mu^{\pm} + \tau_h^{\pm}$
    $M_{H^{\pm\pm}} < 200$ for $\tau_h^{\pm} + \tau_h^{\pm}$







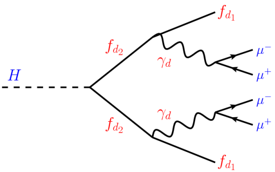


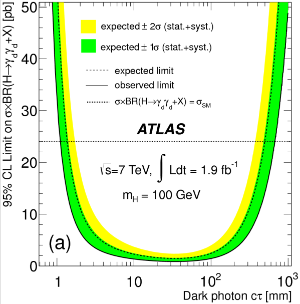
results from D0 [15],CDF [16]

Hidden sector

ATLAS L=1.9 fb^{-1} [17]

- Search for rare H decay into hidden sector
- $H \to 2f_{d_2}$, $f_{d_2} \to f_{d_1}\gamma_d$, $\gamma_d \to \mu\mu$
  - $m_{\gamma_d} = 400$ MeV, long-lived
  - $B(\gamma_d \to \mu\mu) = 45\%$
- Back-to-back pairs of isolated, collinear, displaced $\mu^{\pm}$
- little MET since f_{d_1} are emitted back-to-back
- limit on $\sigma B(H \to 2\gamma_d + X)$ vs $(c\tau)_{\gamma_d}$
  - $BR(H \to 2\gamma_d + X) < 10\%$ for $7(5) < c\tau < 82(159)$ mm for $M_H = 140(100)$ GeV





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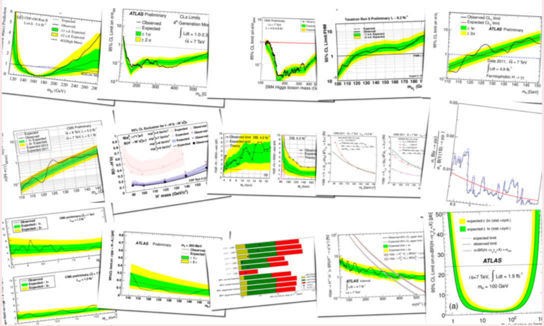
- A rich program of searches for exotic Higgs beyond SM and MSSM,
- including SM4, Fermiophobic SM, nMSSM, SeeSaw models, hidden sector.



Only limits, so far;
but stay tuned.

Bibliography I

[1] CDF and D0 Collaboration. Combined tevatron upper limit on $gg \to h \to W^+W^-$ and constraints on the higgs boson mass in fourth-generation fermion models. *Phys. Rev. D*, 82:011102, Jul 2010.

[2] ATLAS Collaboration. Update of the combination of higgs boson searches in pp collisions at sqrt(s) = 7 tev with the atlas experiment at the lhc. Technical Report ATLAS-CONF-2011-135, CERN, Geneva, Sep 2011.

[3] CMS Collaboration. Combination of sm, sm4, fp higgs boson searches. *CMS Physics Analysis Summary*, CMS-PAS-HIG-12-008, 2012.

[4] The CDF and D0 Collaborations and the Tevatron New Physics and Higgs Working Group. Combined cdf and d0 upper limits on fermiophobic higgs boson production with up to 8.2 fb-1 of ppbar data. *FERMILAB-CONF-11-413-E*, 2011.

[5] ATLAS Collaboration. Search for a fermiophobic Higgs boson in the diphoton decay channel with the ATLAS detector. *Eur.Phys.J.*, C72:2157, 2012.

[6] CMS Collaboration. Higgs to gamma gamma, fermiophobic. *CMS Physics Analysis Summary*, CMS-PAS-HIG-12-022, 2012.

[7] CDF Collaboration. Search for a very light *cp*-odd higgs boson in top quark decays from $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. *Phys. Rev. Lett.*, 107:031801, Jul 2011.

[8] D0 Collaboration. Search for next-to-minimal supersymmetric higgs bosons in the $h \to aa \to \mu\mu\mu\mu$, $\mu\mu\tau\tau$ channels using $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV. *Phys. Rev. Lett.*, 103:061801, Aug 2009.

[9] CMS collaboration. Search for new light bosons in decays of a non-standard-model higgs boson to two pairs of muons in proton-proton collisions at sqrt(s) = 7 tev. Technical Report CERN-PH-EP-2012-292. CMS-EXO-12-003, CERN, Geneva, Oct 2012.

[10] CDF Collaboration. Search for narrow resonances lighter than υ mesons. *The European Physical Journal C - Particles and Fields*, 62:319–326, 2009. 10.1140/epjc/s10052-009-1057-4.

Bibliography II

[11] CMS Collaboration. Search for a light pseudoscalar boson in the dimuon channel. *CMS Physics Analysis Summary*, CMS-PAS-HIG-12-004, 2012.

[12] ATLAS collaboration. Search for a higgs boson decaying to four photons through light cp-odd scalar coupling using 4.9 fb^{-1} of 7 TeV *pp* collision data taken with atlas detector at the lhc. Technical Report ATLAS-CONF-2012-079, CERN, Geneva, Jul 2012.

[13] ATLAS Collaboration. Search for doubly-charged Higgs bosons in like-sign dilepton final states at $\sqrt{s} = 7$ TeV with the ATLAS detector. 2012.

[14] CMS Collaboration. Inclusive search for doubly charged higgs in leptonic final states with the 2011 data at 7 tev. *CMS Physics Analysis Summary*, CMS-PAS-HIG-12-005, 2012.

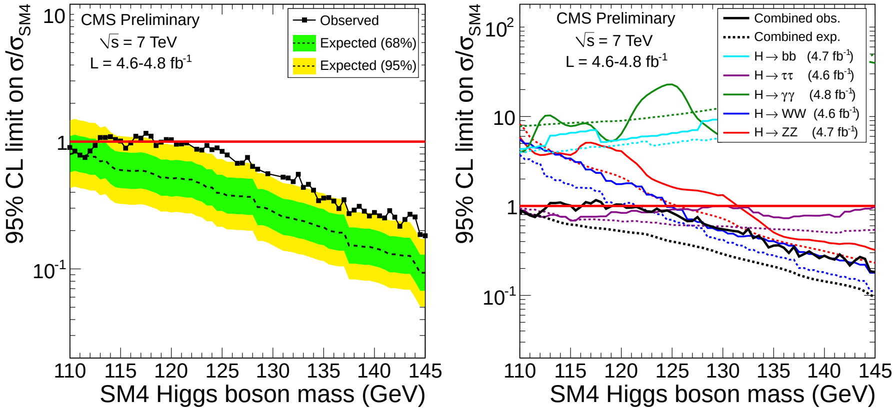
[15] D0 Collaboration. Search for doubly charged higgs boson pair production in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. *Phys. Rev. Lett.*, 108:021801, Jan 2012.

[16] CDF Collaboration. Search for new physics in high p_T like-sign dilepton events at cdf ii. *Phys. Rev. Lett.*, 107:181801, Oct 2011.

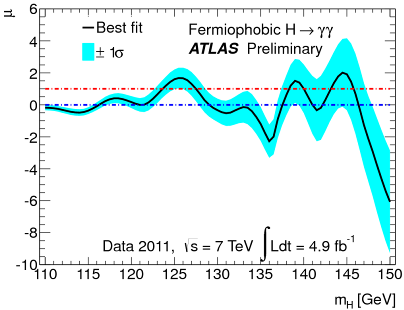
[17] Georges Aad et al. Search for displaced muonic lepton jets from light Higgs boson decay in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. 2012.

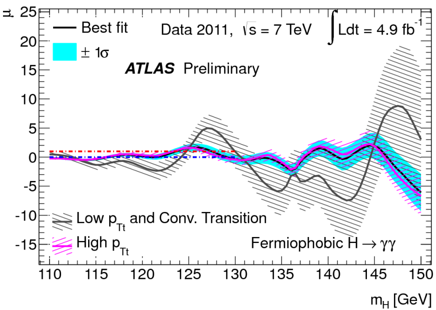
[18] ATLAS collaboration. A search for a light cp-odd higgs boson decaying to $\mu^+\mu^-$ in atlas. Technical Report ATLAS-CONF-2011-020, CERN, 2011.

Higgs in Standard Model with 4th generation



Fermiophobic Higgs at ATLAS



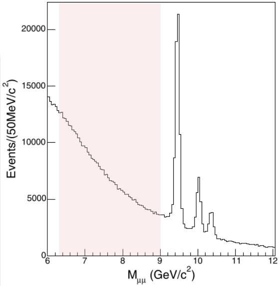


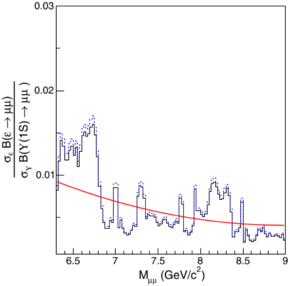
nMSSM $a \to \mu\mu$ at CDF

CDF: $L = 0.63\,\text{fb}^{-1}$ [10].

- Trigger:
  - $2\mu,\ p_t^{\mu} > 3\,\text{GeV}$
  - $M_{\mu\mu} > 5\,\text{GeV}$
  - $\delta(z_{vtx}) < 5\,\text{cm}$
  - dynamic pre-scale
- Selection: 2 good $\mu^{\pm}$, isolated, prompt
  - search for narrow resonances for $M_{\mu\mu} < M_{\Upsilon(1S)}$
  - Gaussian shape with expected detector resolution
- $M_{\mu\mu} \in [6.3 - 9]$ GeV

no excess, set limit on $\frac{\sigma_a B(a\to\mu\mu)}{\sigma_{\Upsilon(1S)} B\Upsilon(1S)\to\mu\mu}$

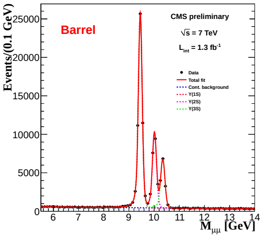


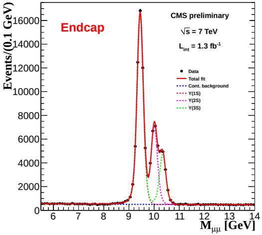


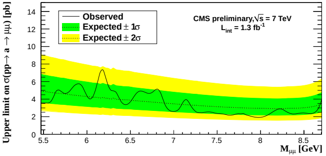
nMSSM $a \to \mu\mu$ at CMS

CMS $L = 1.3\,\text{fb}^{-1}$ [11].

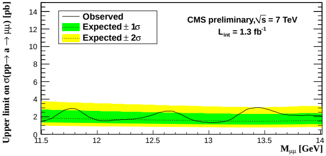
- $\sigma(gg \to a)_{LHC} \approx 4.5\sigma_{Tevatron}$
  - Trigger: $2\mu^{\pm}$, $p_t > 3.5$ GeV, $p_t^{\mu\mu} > 6$ GeV $M_{\mu\mu} \in [5 - 14]$ GeV, same vtx, pre-scale=2
  - Background: $\Upsilon(nS)$+continuous
  - Fit separately $M_{\mu\mu}$ for barrel and end-cap
- $M_{\mu\mu} \in [5.5 - 8.8] \cup [11.5 - 14]$ GeV
  - excluding the $\Upsilon(nS)$ peaks
- Similar search in ATLAS L=35.4 pb^{-1} [18]





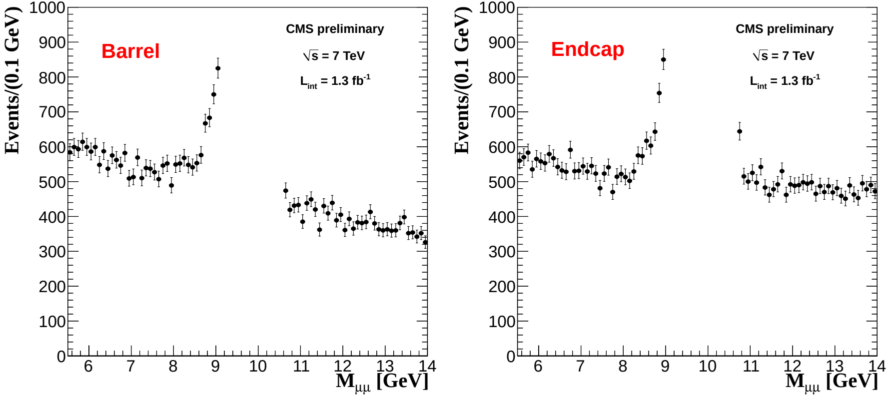


$M_{\mu\mu} \in [5.5 - 8.8]$ GeV

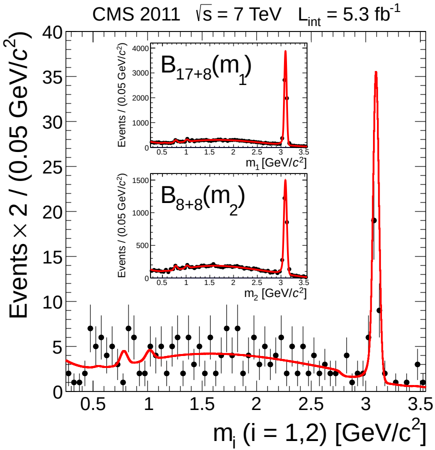


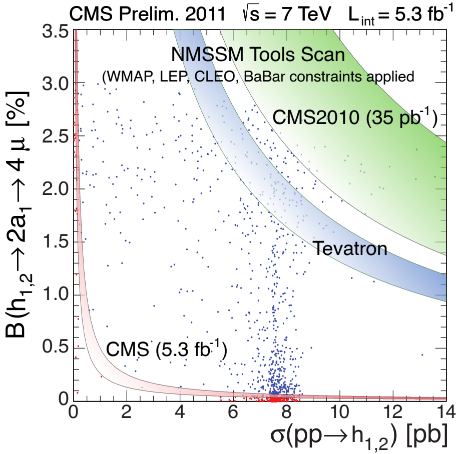
$M_{\mu\mu} \in [11.5 - 14]$ GeV

$gg \to a \to (2\mu)$

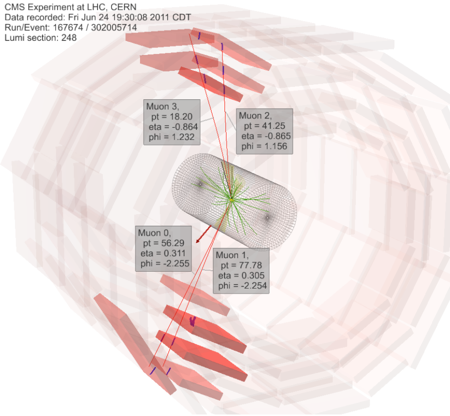

Events/(0.1 GeV)
Barrel
CMS preliminary
√s = 7 TeV
L_int = 1.3 fb^-1
M_μμ [GeV]
Endcap
CMS preliminary
√s = 7 TeV
L_int = 1.3 fb^-1
M_μμ [GeV]

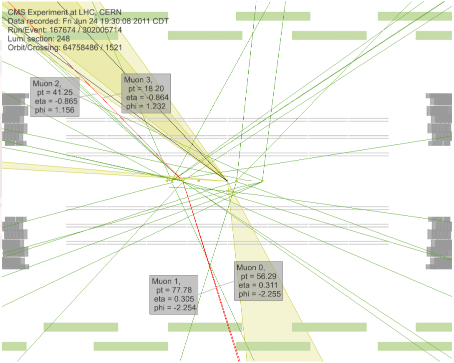
$h \to aa \to (4\mu)$


CMS 2011 √s = 7 TeV L_int = 5.3 fb^-1
Events × 2 / (0.05 GeV/c²)
B_17+8(m_1)
Events / (0.05 GeV/c²)
m_1 [GeV/c²]
B_8+8(m_2)
m_2 [GeV/c²]
m_i (i = 1,2) [GeV/c²]


CMS Prelim. 2011 √s = 7 TeV L_int = 5.3 fb^-1
NMSSM Tools Scan
(WMAP, LEP, CLEO, BaBar constraints applied
CMS2010 (35 pb^-1)
Tevatron
CMS (5.3 fb^-1)
B(h_1,2→2a_1→4 μ) [%]
σ(pp→h_1,2) [pb]

$h \to aa \to (4\mu)$


CMS Experiment at LHC, CERN
Data recorded: Fri Jun 24 19:30:08 2011 CDT
Run/Event: 167674 / 302005714
Lumi section: 248
Muon 3, pt = 18.20 eta = -0.864 phi = 1.232
Muon 2, pt = 41.25 eta = -0.865 phi = 1.156
Muon 0, pt = 56.29 eta = 0.311 phi = -2.255
Muon 1, pt = 77.78 eta = 0.305 phi = -2.254


CMS Experiment at LHC, CERN
Data recorded: Fri Jun 24 19:30:08 2011 CDT
Run/Event: 167674 / 302005714
Lumi section: 248
Orbit/Crossing: 64758486 / 1521
Muon 2, pt = 41.25 eta = -0.865 phi = 1.156
Muon 3, pt = 18.20 eta = -0.864 phi = 1.232
Muon 0, pt = 56.29 eta = 0.311 phi = -2.255
Muon 1, pt = 77.78 eta = 0.305 phi = -2.254

nMSSM $h \to a_1 a_1 \to (4\mu, 2\mu 2\tau)$

D0 L=4.2 fb^{-1} [8]

4μ
- Not enough granularity for $\mu\mu$, so 2(μ+track) isolated pairs, same vtx
- background from resonances $\eta, \phi, J/\psi, \ldots$ and Z/γ^*
- signal $m_1(\mu, track) \approx m_2(\mu, track)$, background from side bands;

$2\mu 2\tau$
- $2\mu, M_{\mu\mu} < 20$ GeV and $\Sigma p_t^{\mu} > 35$ GeV
- plus complex requirement for τ (MET/MET +jet/μ/e)
- signal search in $M_{\mu\mu}$ spectrum

Limit on $\sigma(p\bar{p} \to h) \times B(h \to a_1 a_1)$ vs M_{a_1} and M_h