Searches for BSM Higgs at the LHC

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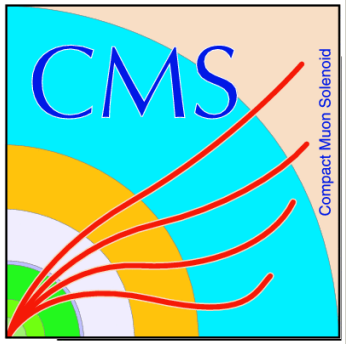
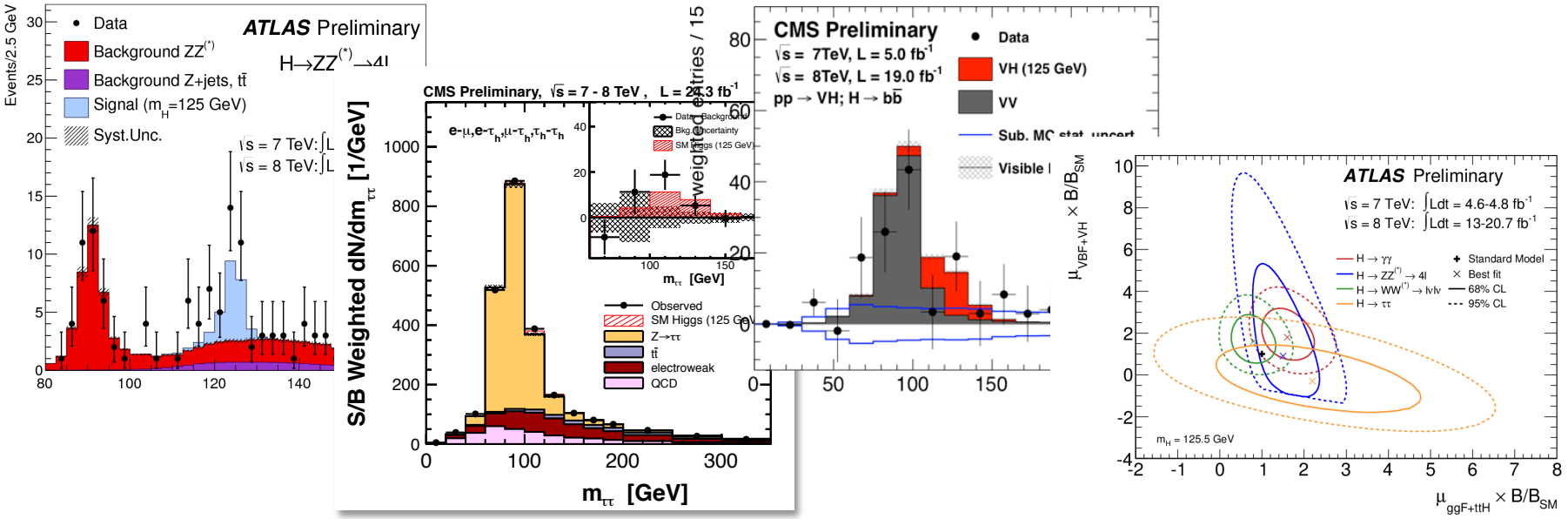
On behalf of the ATLAS and CMS collaborations



Introduction

- A new boson with mass of ~126 GeV was discovered
  - So far, the measured properties are consistent with those of the SM Higgs



- Story is not over… There must be physics beyond the standard model
  - Precision measurement of the discovered boson's properties
  - Searches for additional Higgs bosons

In this talk

- Both ATLAS and CMS have very wide program of BSM Higgs searches
  - Emphasize on the latest results

	ATLAS	CMS
2HDM,HgWW	**ATLAS-CONF-2013-027**	
Fermiophobic & SM4 Higgs		arXiv:1302.1764
Invisible Higgs: ZH	**ATLAS-CONF-2013-011**	**CMS-PAS-HIG-13-018**
h→2a→4μ		**CMS-PAS-HIG-13-010**
WH, H→electron-jets	**arXiv:1302.4403**	
Charged Higgs	**arXiv:1212.3572** ATLAS-CONF-2011-094	**CMS-PAS-HIG-12-052**

Two Higgs Doublet Model

- The simplest extension of the SM
  - Two doublets give rise to 5 physical states
  - New sources of CP-violation

5 Higgs bosons
h^0,H^0 CP-even scalar
A^0 CP-odd pseudo-scalar
H^+,H^- charged

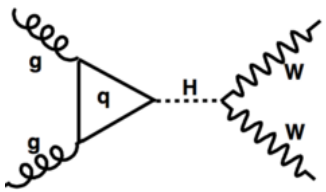
- Four types of 2HDM
  - Type I: Only one doublet couples to fermions
  - Type II: one double couples to down sector and the other one – to up sector
  - Type III and IV differ from I and II by lepton-specific parameters

- At the tree-level described by parameters
  - $\tan\beta = v_2/v_1$
  - α – h-H mixing angle
  - masses of Higgs bosons

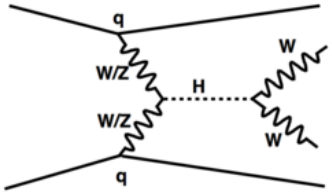
} Limits are set on $\cos\alpha$ – m_H plane for different $\tan\beta$ scenario

2HDM: H→WW→eνμν

- Search for heavy Higgs, H→WW
  - Discovered boson is assumed to be light Higgs A and $H^{\pm}$ are assumed to be heavy

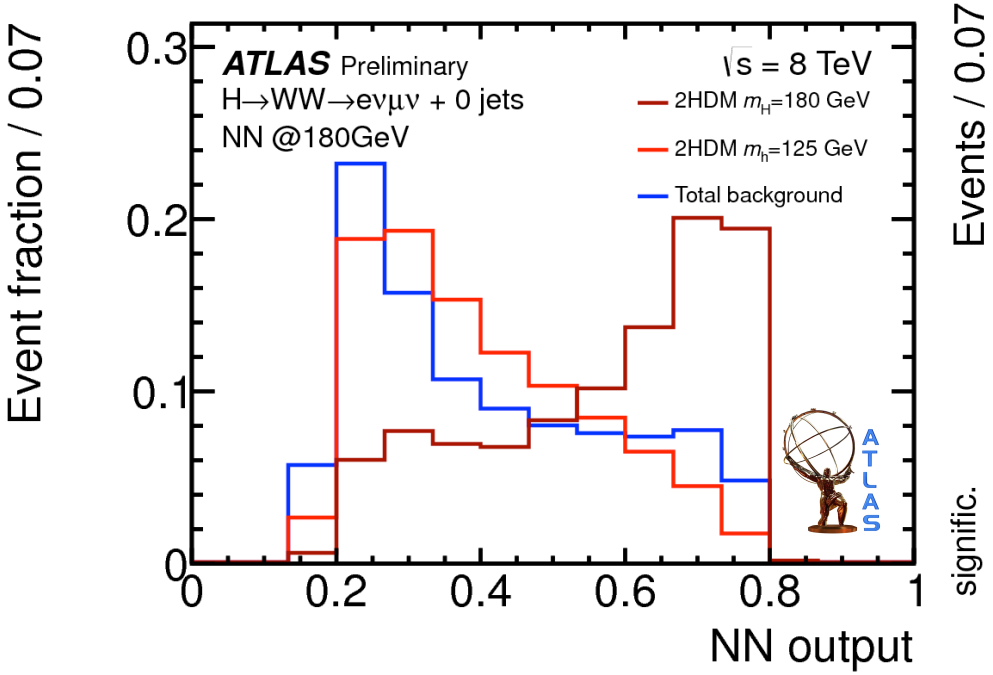


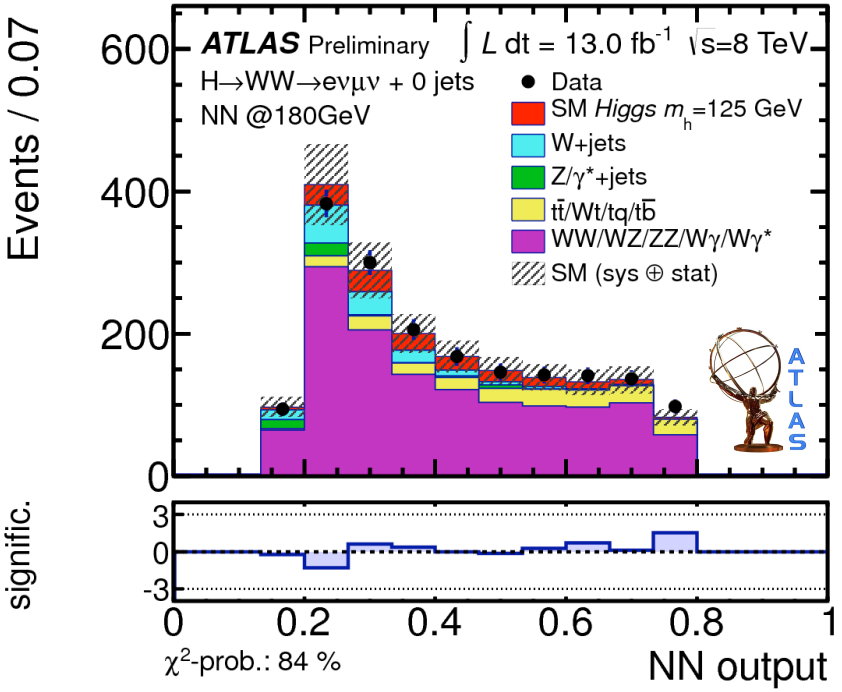
ggF – 0 jet



VBF – 2 jet

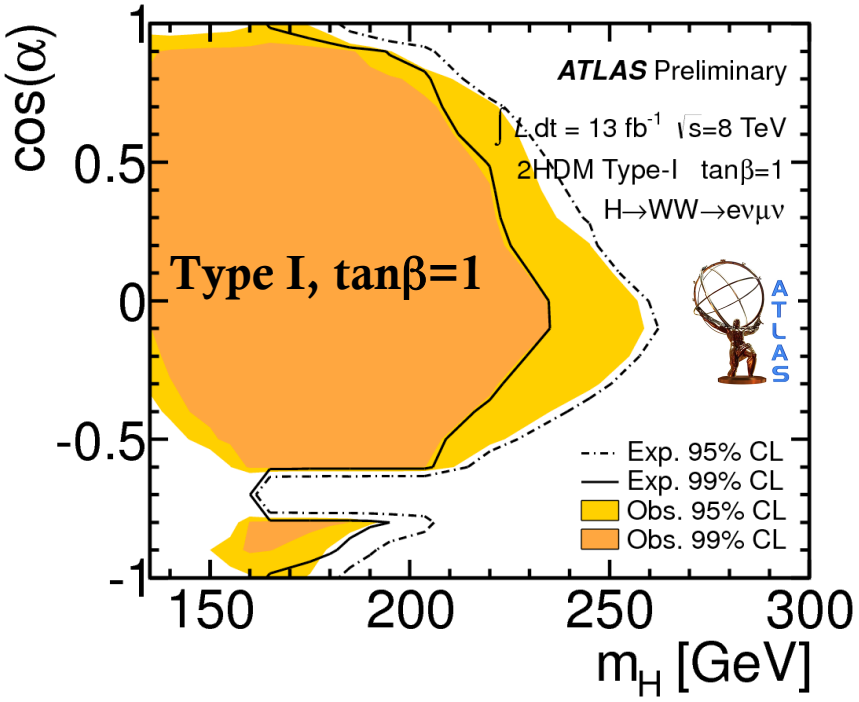
- Analysis is similar to the SM h→WW→ll+MET

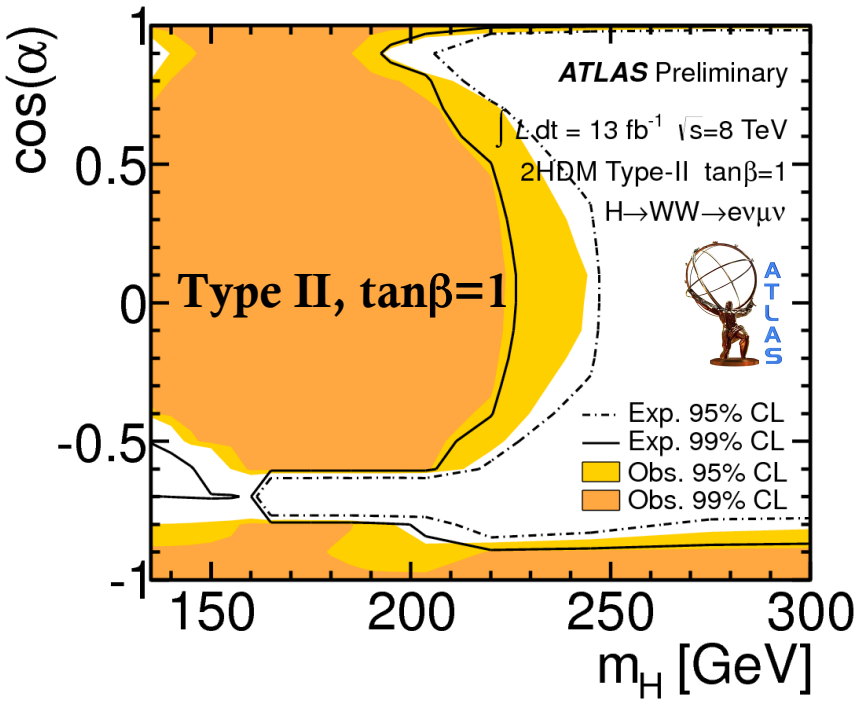




2HDM: H→WW→eνμν

- No evidence for the second Higgs decaying to WW
- Limits are set on both Type I and II 2HDM for tanβ=1,3,6,20 and tanβ=50 (only Type I)
  - Limits for larger tanβ are less constraining cosα-m_H plane





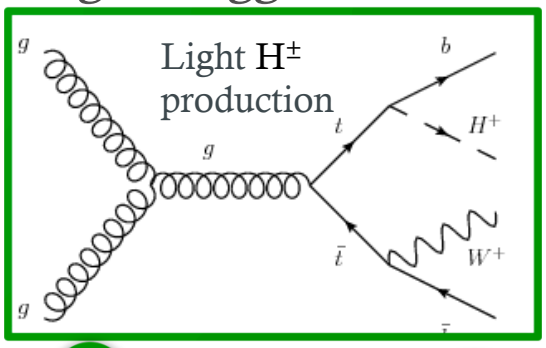
Charged Higgs @ LHC

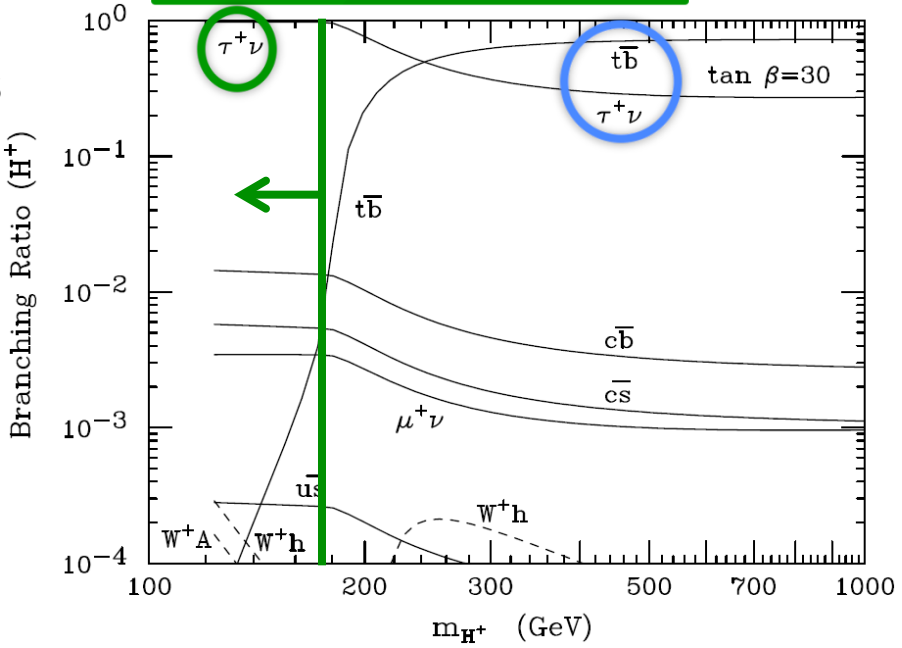
- Various BSM models predict existence of charged Higgs
  - Heavy charged Higgs $m_H > m_{top}$
    - Production: $gg \to tbH^{\pm}$, $bg \to tH^{\pm}$
    - Dominant decays: $H^{\pm} \to tb$, $H^{\pm} \to \tau\nu$

  → Not yet analyzed

  - Light charged Higgs $m_H < m_{top}$
    - Dominant production in top decays
    - Dominant decay
      - $H^{\pm} \to \tau\nu$ – large tanβ

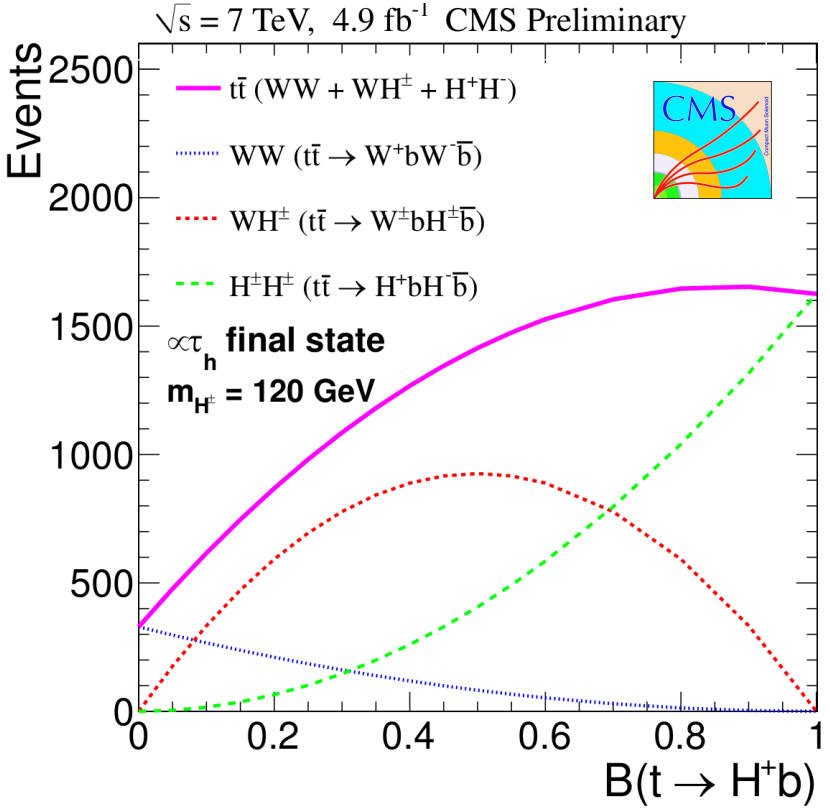
  → Searched in different final states





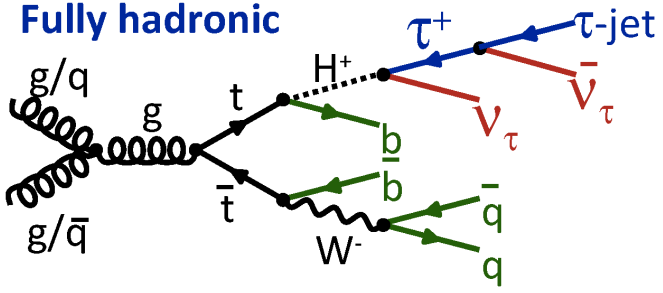
Light Charged Higgs Search

- Search in ttbar decays via WbHb or HbHb
  - Final state with at least one hadronic tau and additional lepton or jets

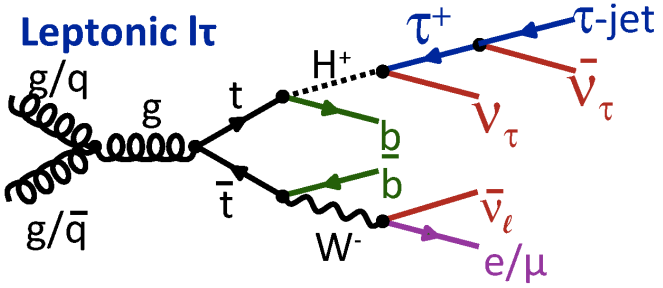


BR(H→τν)=100%

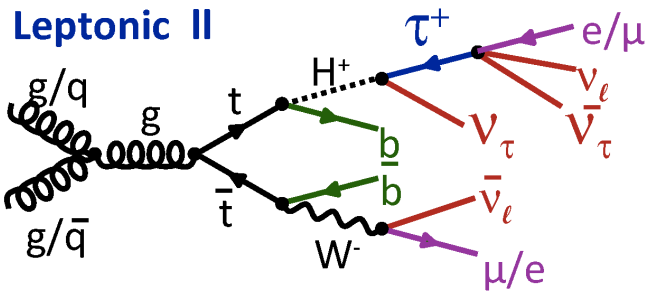
Fully hadronic



Leptonic lτ



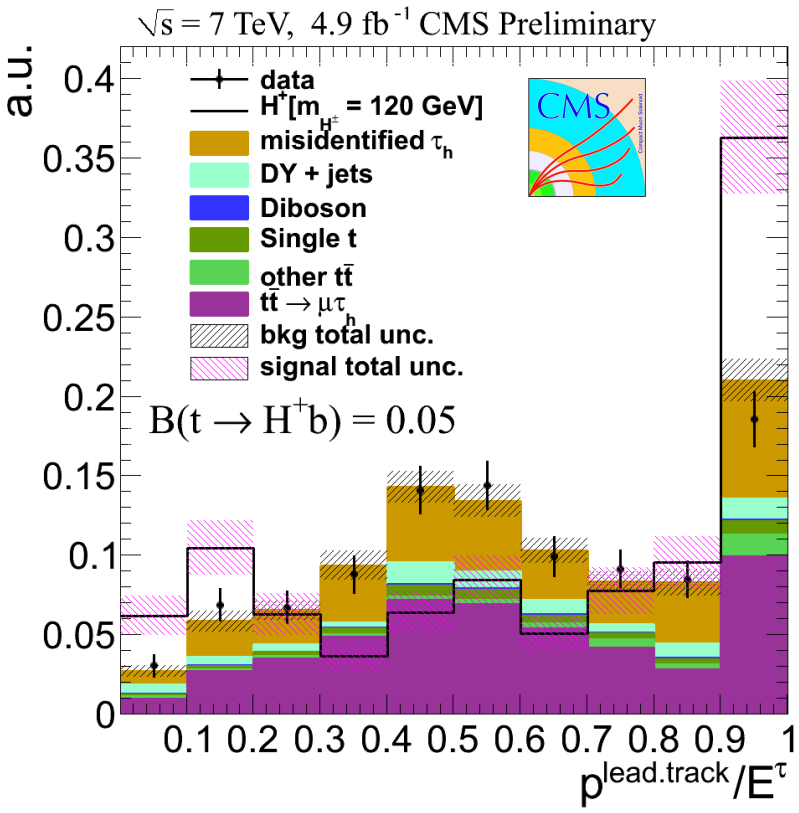
Leptonic ll

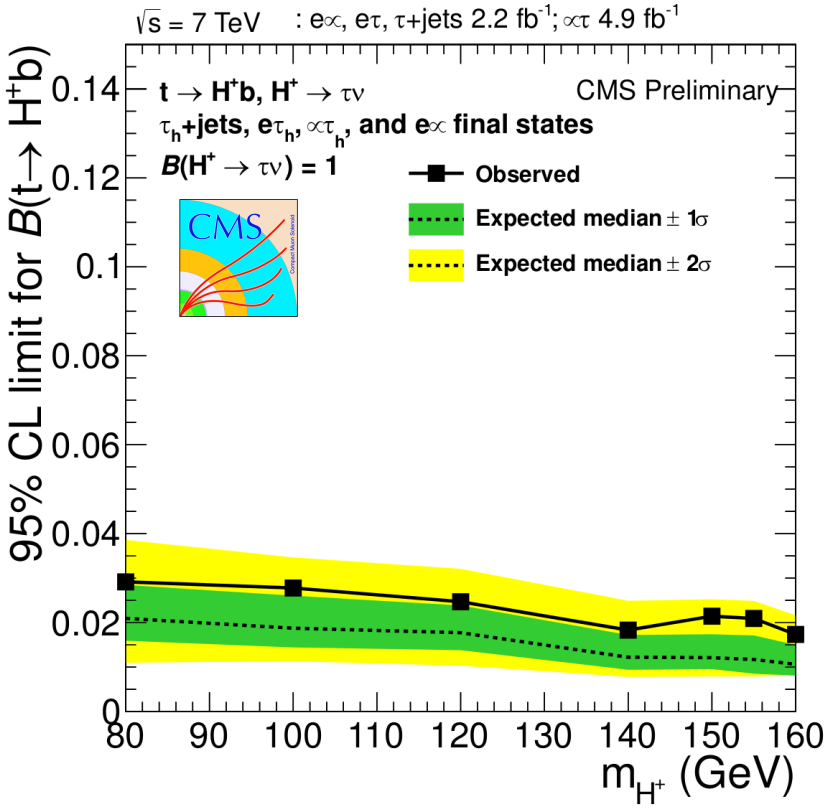


Light Charged Higgs Search

- No evidence of signal above the SM background prediction

Upper limit on BR(t→Hb) set at 2-3%, assuming BR(H→τν)=1 for masses 80–160 GeV

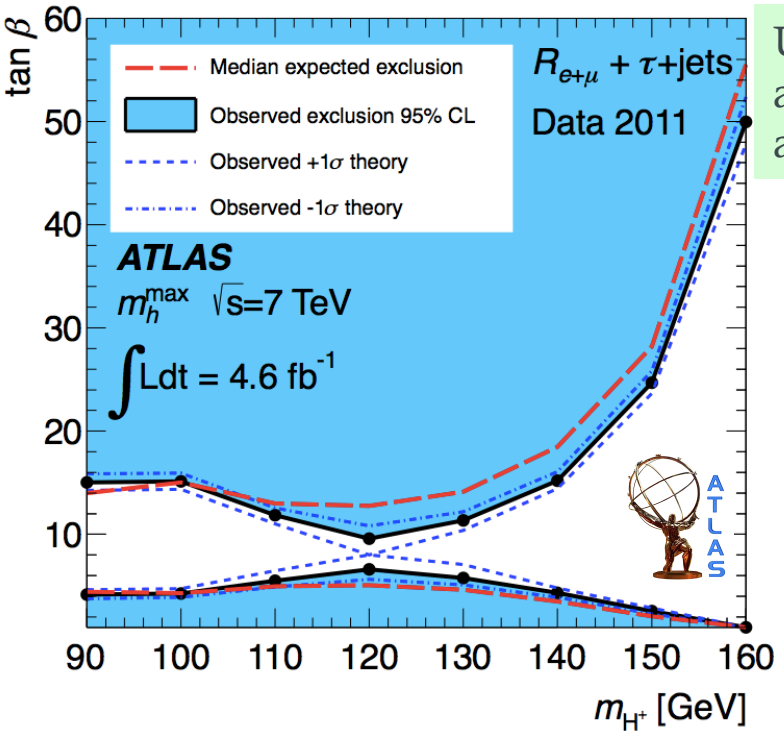




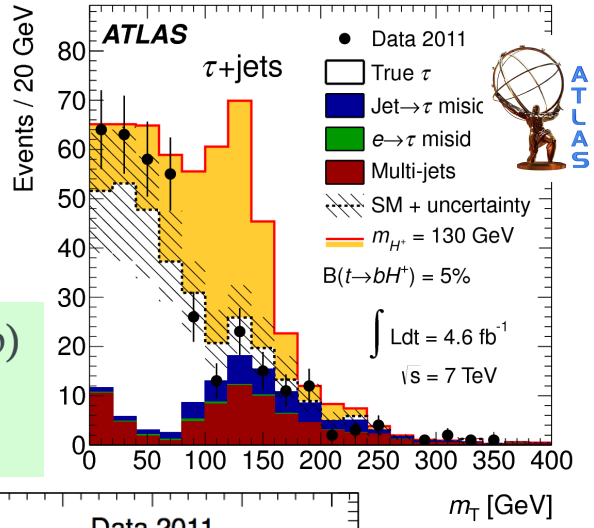
Light Charged Higgs Search

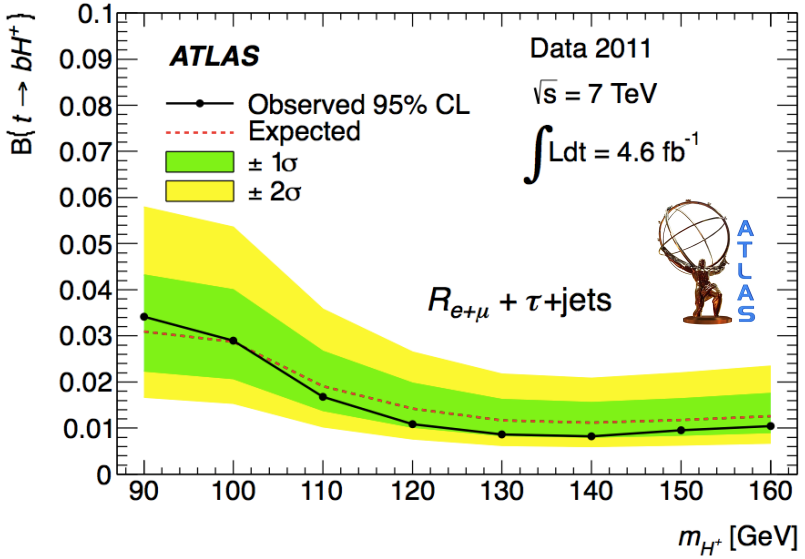
- Similar search for light charged Higgs at ATLAS
  - Improve sensitivity in $l\tau_h$ channels assuming lepton universality

$$R_l = \frac{\mathcal{B}(t\bar{t} \to b\bar{b} + l\tau_{\mathrm{had}} + N\nu)}{\mathcal{B}(t\bar{t} \to b\bar{b} + ll' + N\nu)}$$



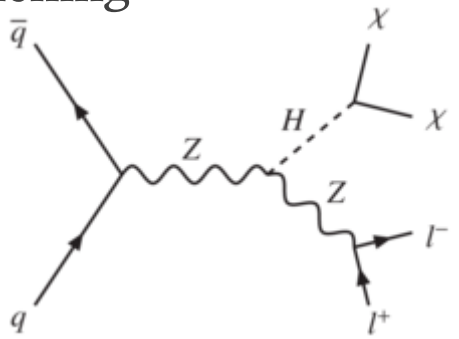
Upper limit on BR(t→Hb) at 0.8-3.4%, assuming B(H→τν)=1



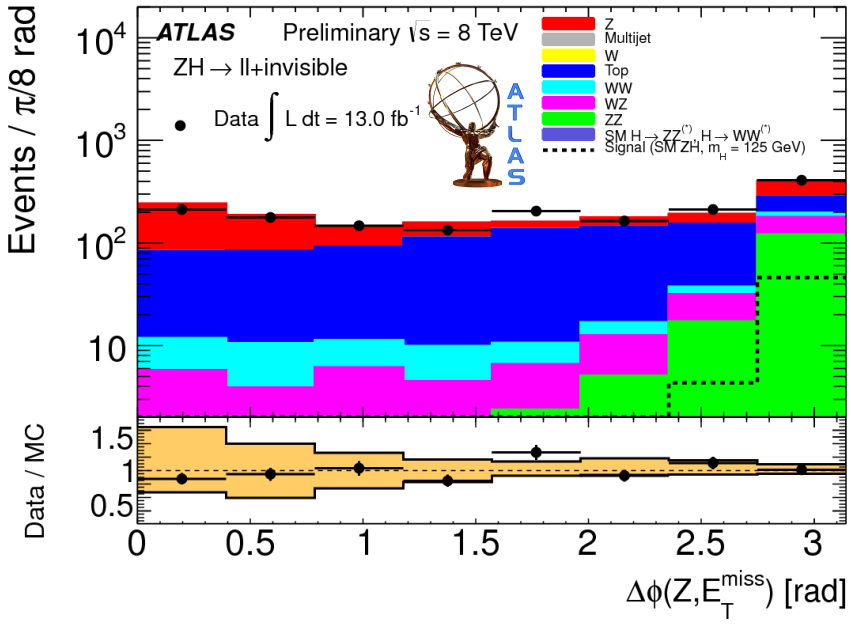


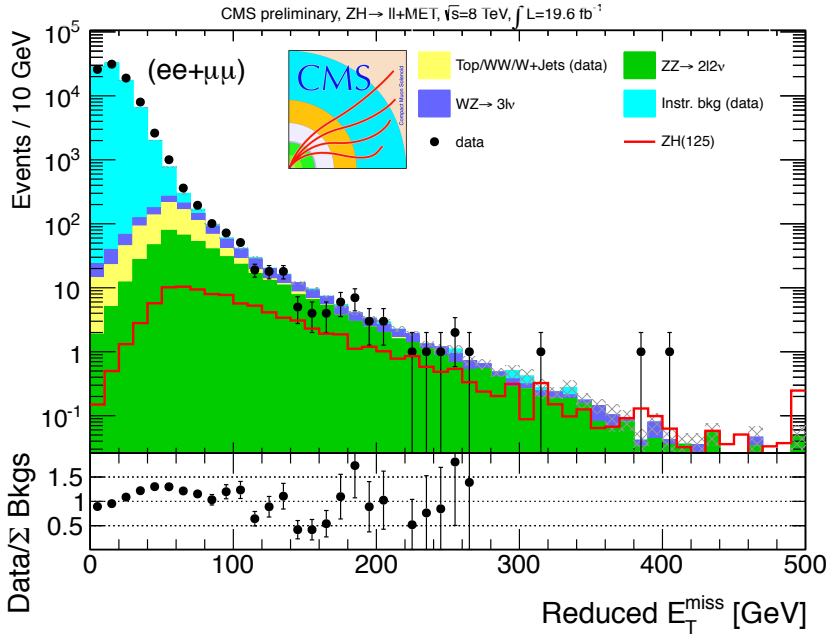
Invisible Higgs

- Various extensions of the SM predict sizable branching fraction of the Higgs to invisible particles
  - Decay to pair of LSPs from SUSY
  - Mixing with graviscalars from ED theories



- Direct search of H→inv in ZH production

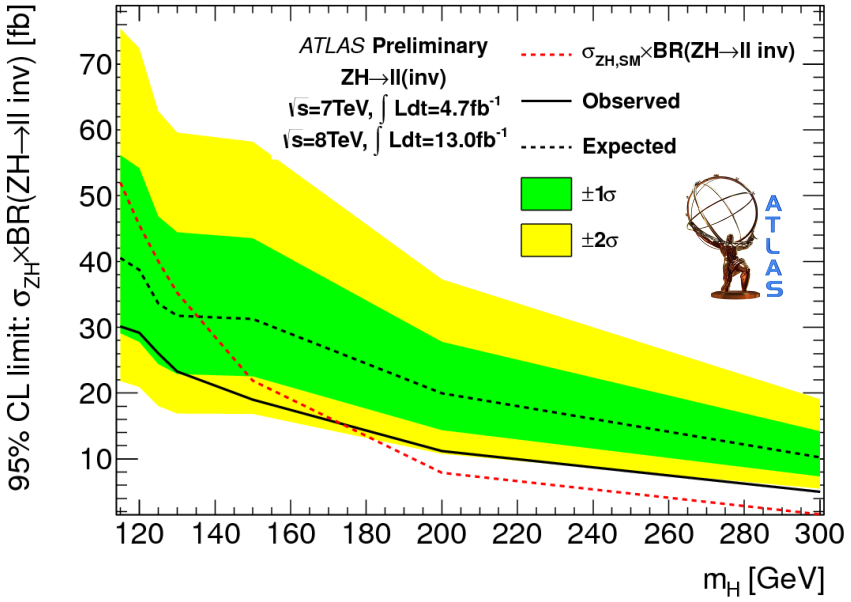


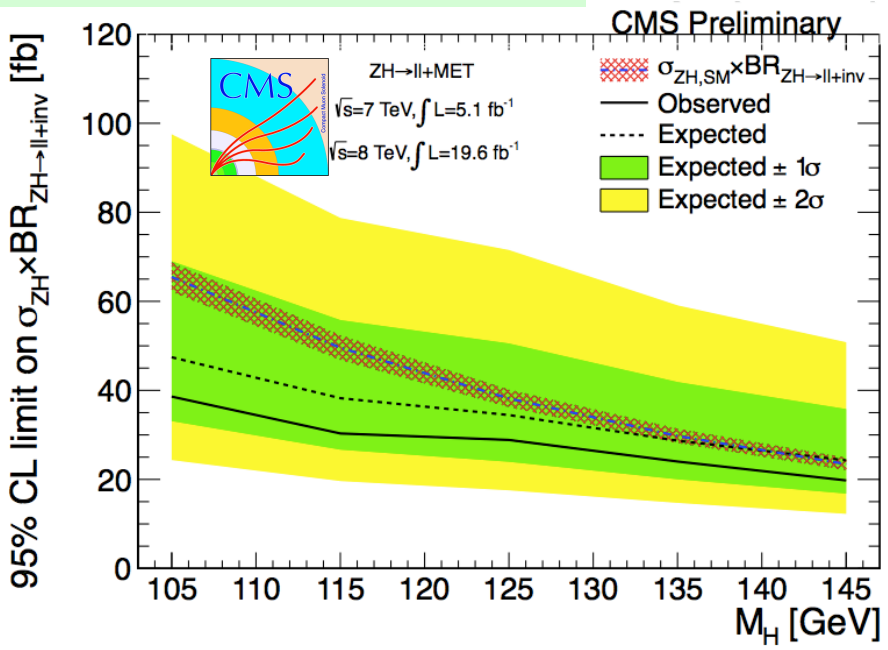


Invisible Higgs

- No excess over the SM expectation
  - Constrain non-SM decay of 125 GeV resonance
  - Search for a Higgs-like boson in 115-300 GeV range

For m_H=125 GeV Higgs boson 95% CL upper limit on the invisible branching fraction is 65%/75%

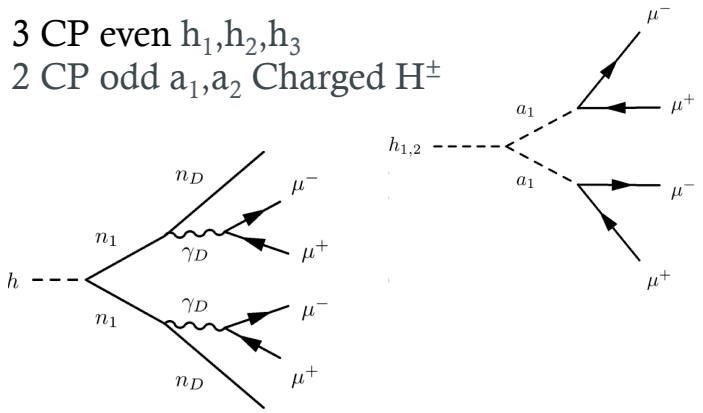


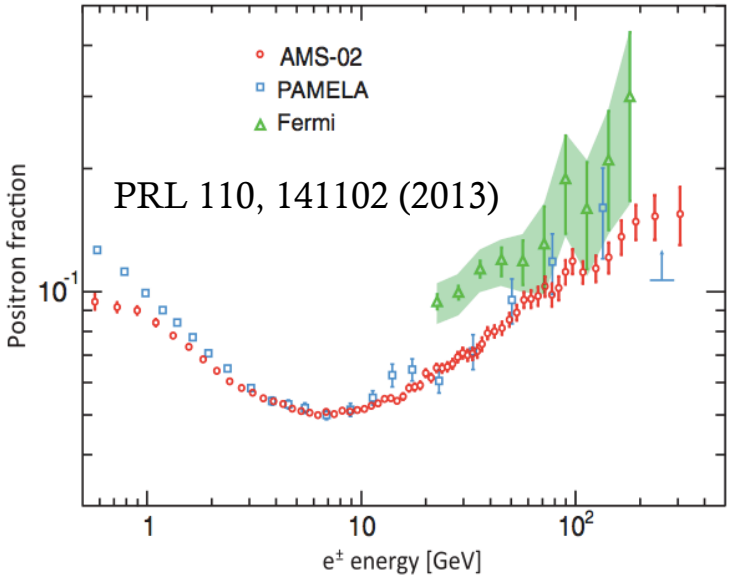


nMSSM & Dark SUSY

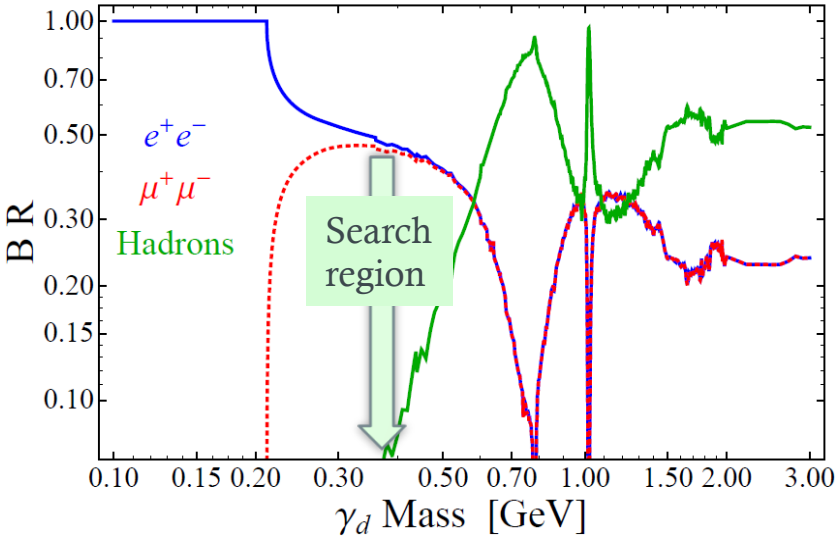
- nMSSM extends minimal SUSY Higgs sector by additional one scalar singlet field
- Dark SUSY models are motivated by observed excess in positron spectra
  - Measurements constrain $m(\gamma_D) \leq O(1\ GeV)$

3 CP even h_1, h_2, h_3
2 CP odd a_1, a_2 Charged $H^{\pm}$



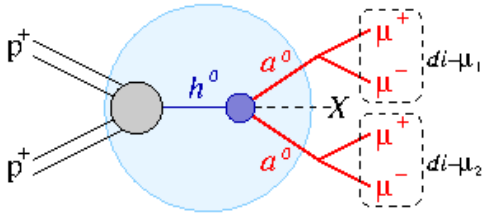


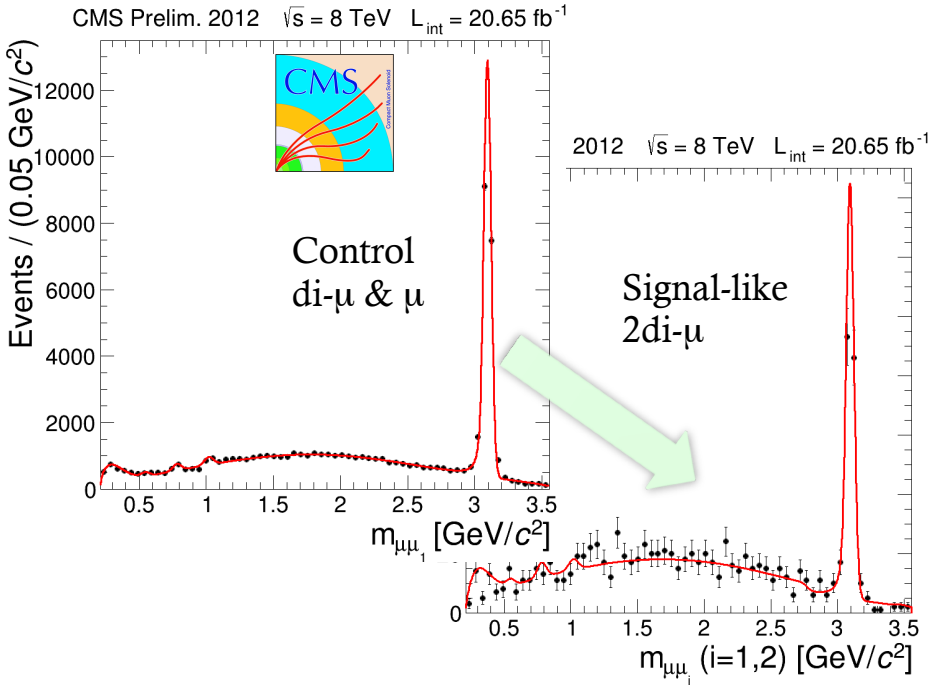
γ_d Branching Ratio

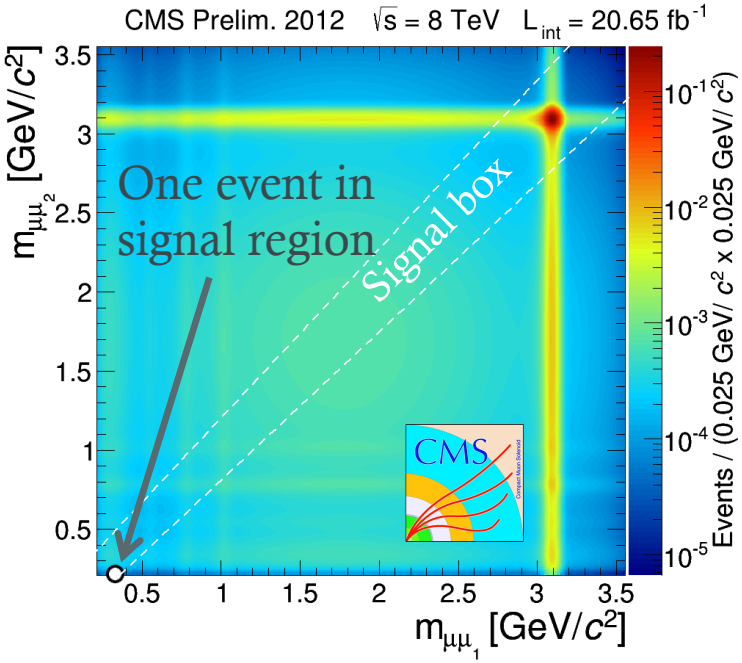


nMSSM Higgs/Dark SUSY Search

- Select events with only two oppositely charged muon-pairs
  - Di-muons, isolated, originate from the same vertex; $m(\text{di-}\mu) < 5$ GeV; $|m(\text{di-}\mu_1) - m(\text{di-}\mu_2)| < 5\sigma$
  - bbbar background templates are obtained from data
    - Fitted with combination of Bernstein polynomials & Crystal Ball

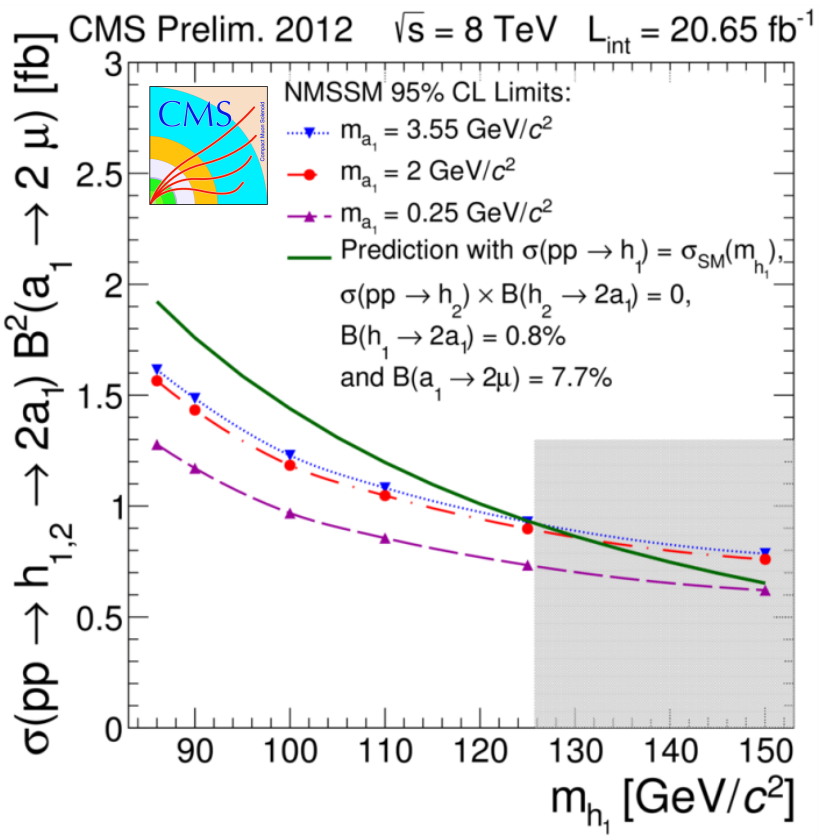


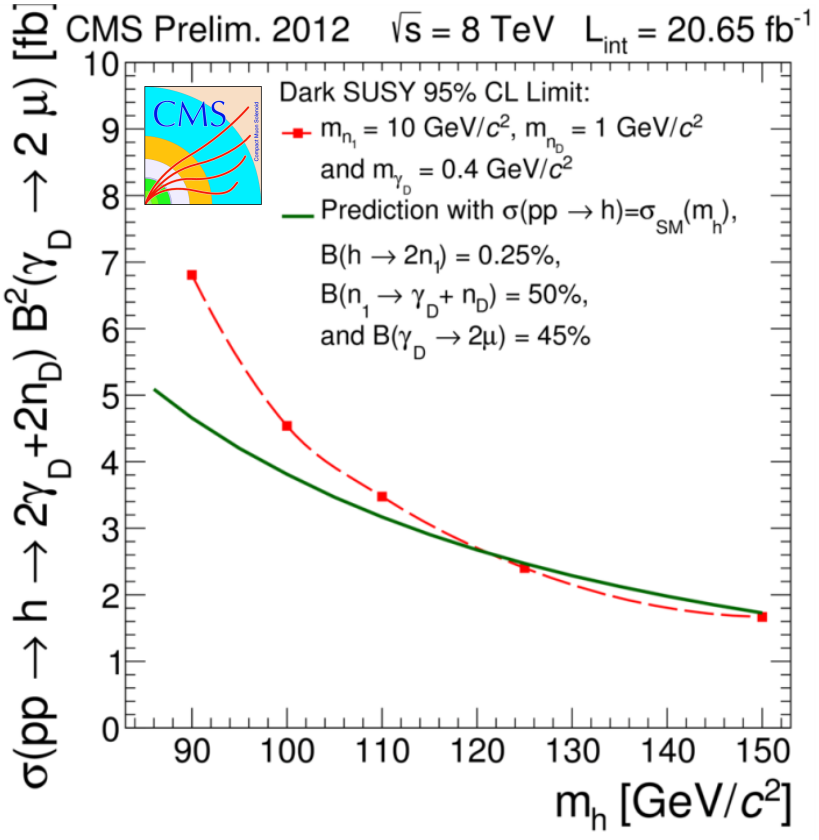




nMSSM Higgs/Dark SUSY Search

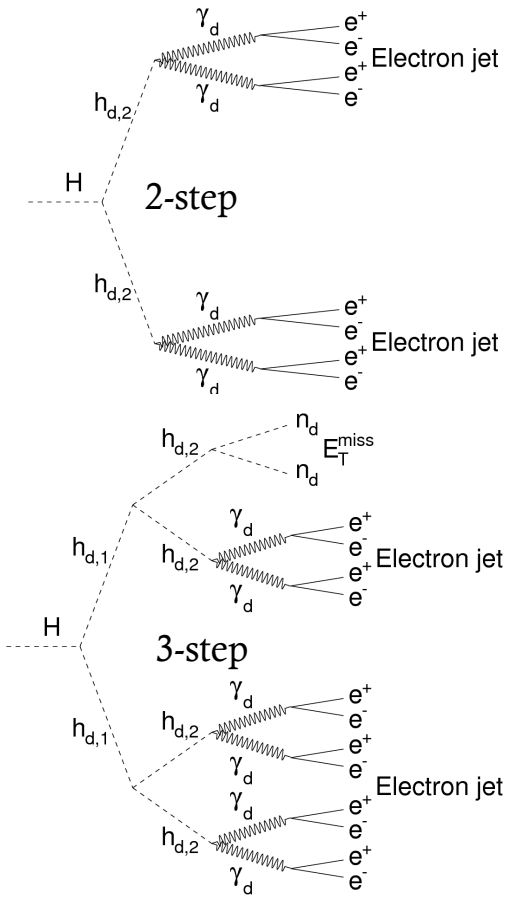
- Limit on nMSSM and SUSY hidden sector as a function of Higgs mass



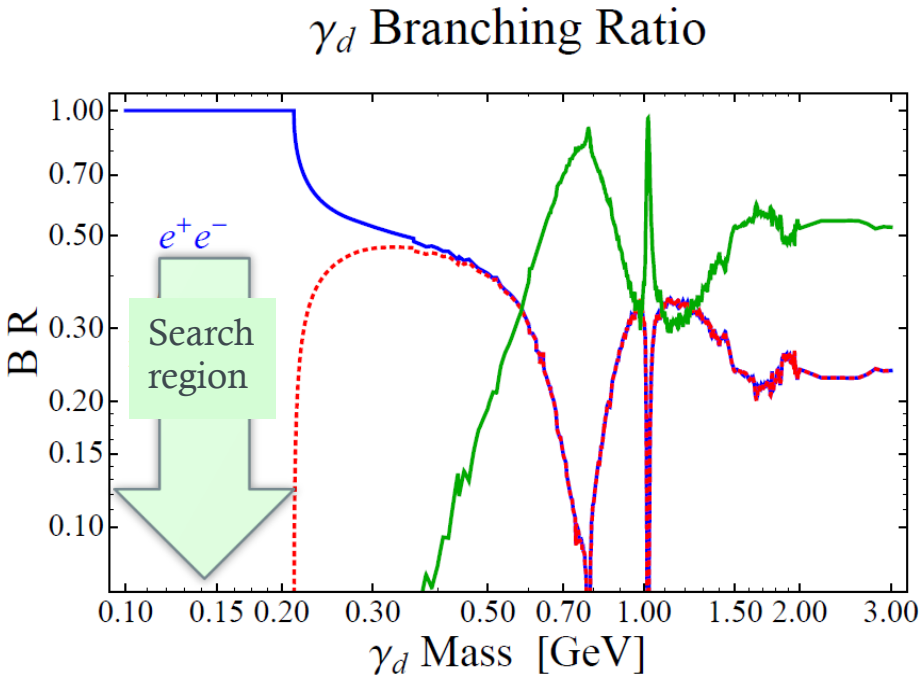


Dark SUSY, Higgs → electron-jets

- Search for WH, H couples to light scalars from hidden sector



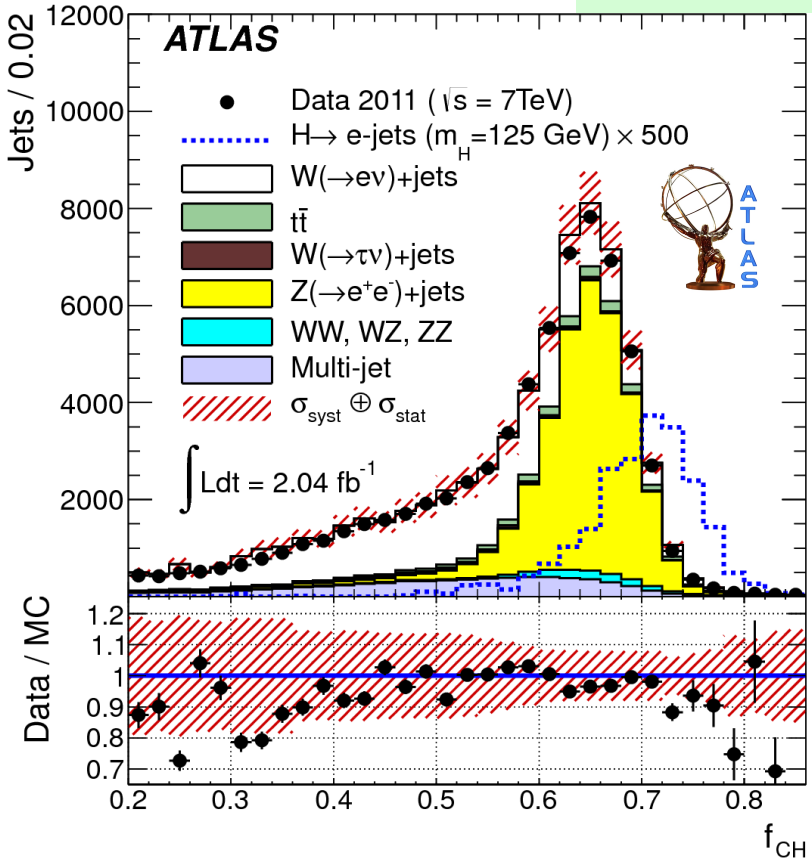
Assuming
- large $\gamma - \gamma_D$ Mixing parameter
  γ_D decays promptly
- $m(h_1) \approx 10$ GeV, $m(h_2) \approx 4$ GeV

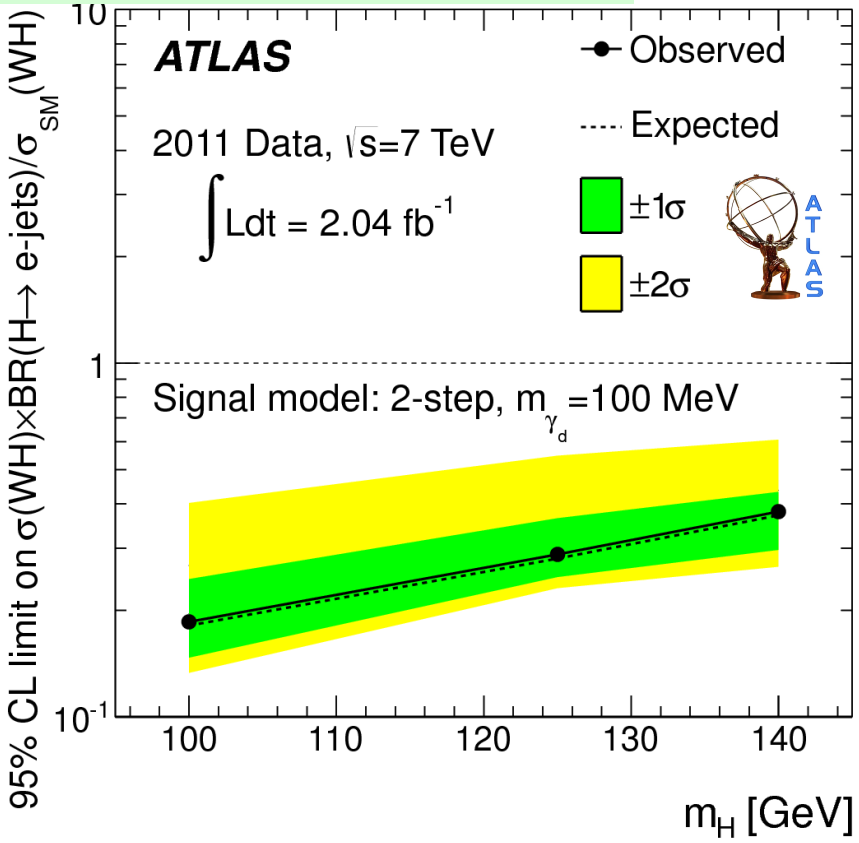


Dark SUSY, Higgs → electron-jets

- Jets with large EM and CH fraction selected as e-jets candidates

Exclude BR(H→ electron-jets) between 24% and 45% for m_H=125 GeV





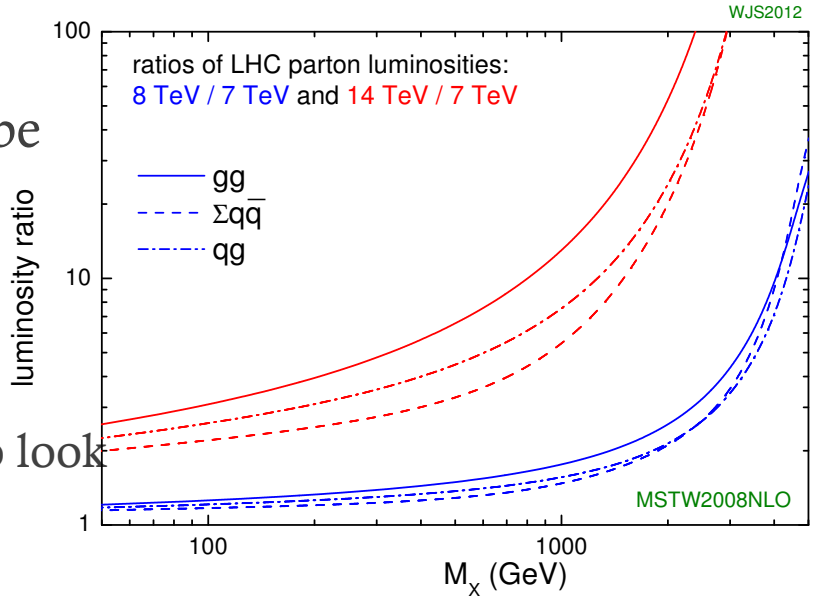
Conclusion

- A very wide spectrum of searches for BSM Higgs is being carried out by both ATLAS and CMS experiments
  - Analyses are using both 7 and/or 8 TeV data
  - So far, no signs of new physics
    - Some models are almost ruled out: Higgsless, FP Higgs, 4th generation
    - Some BSM models are strongly constrained: MSSM mh-max…

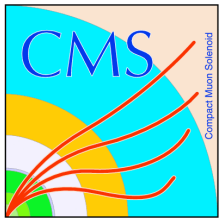
- More BSM Higgs searches based on full Run I data are ongoing and will be completed in the following months

- New territories to explore with Run II data at ~14 TeV

  → Need input from theorists on where to look

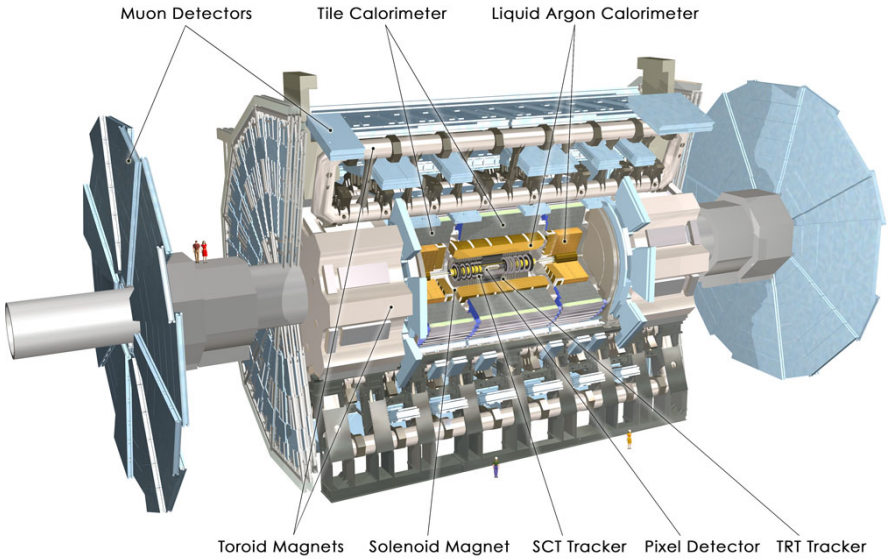


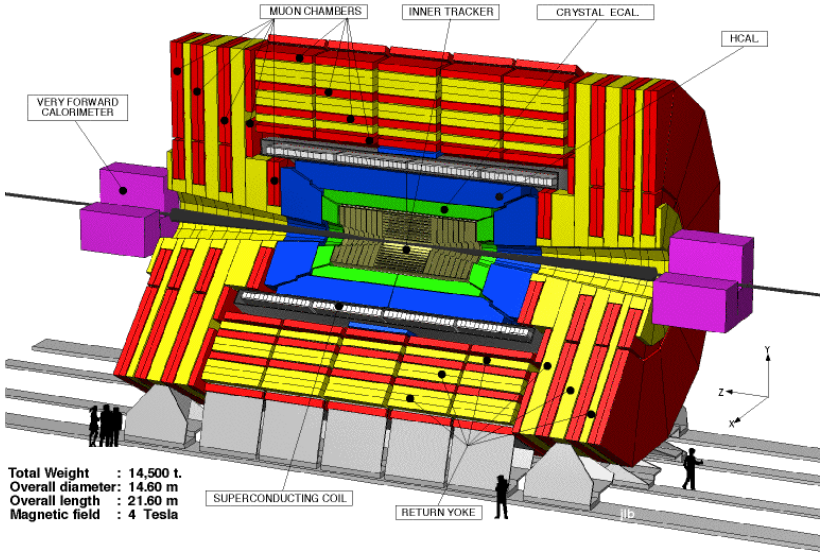
Fermilab

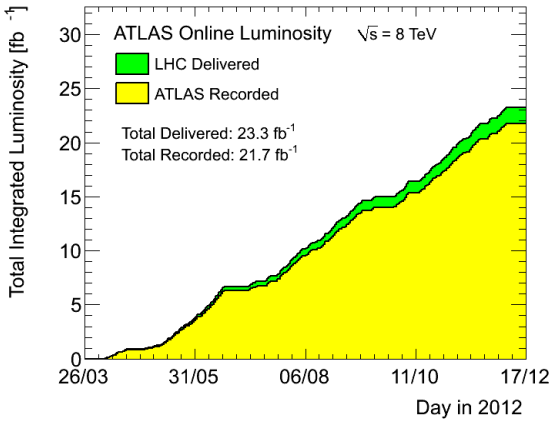


Extra Material

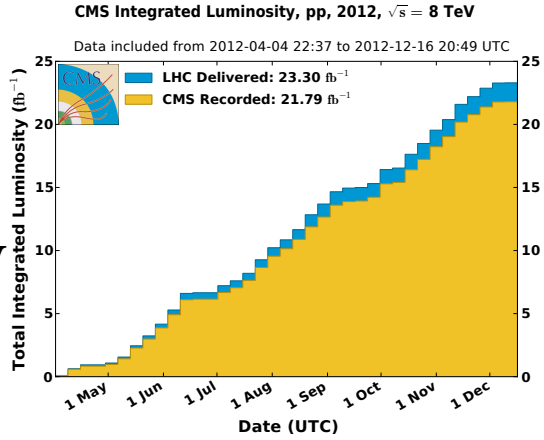
ATLAS & CMS







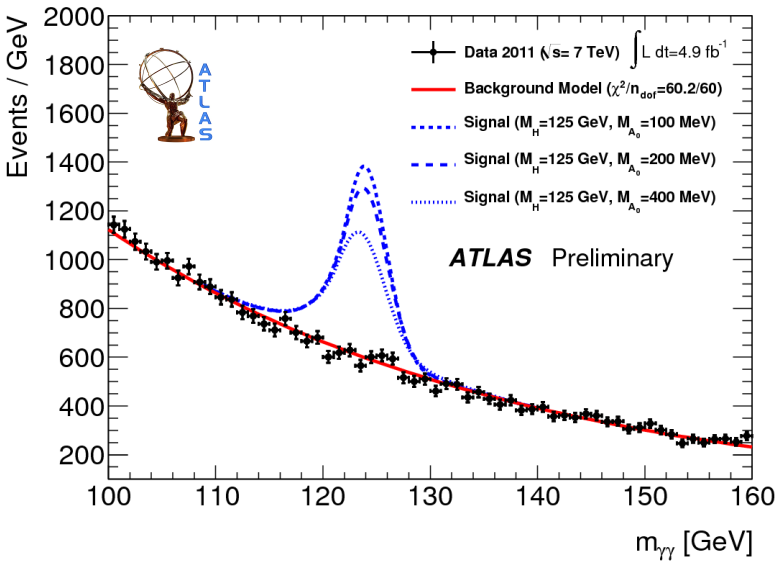
- Excellent performance of both ATLAS and CMS detectors!
  - ~20/fb of data at 8 TeV
  - ~5/fb of data at 7 TeV

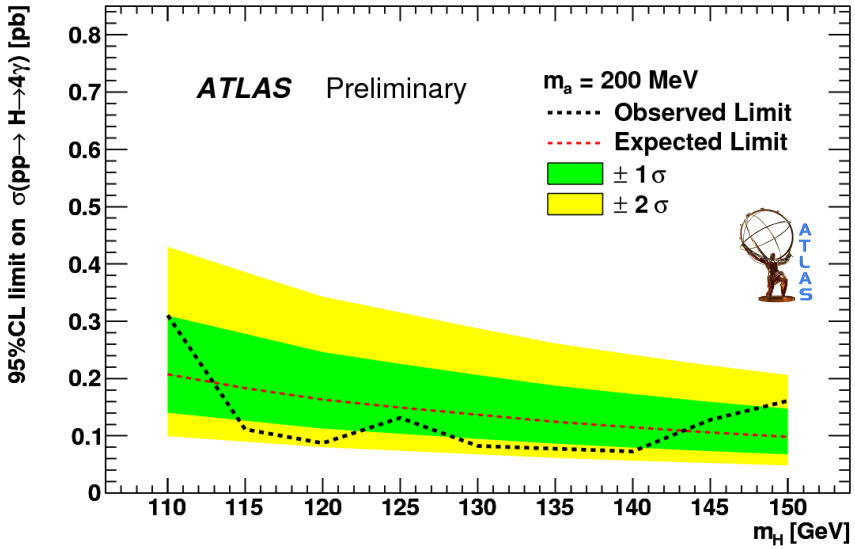


nMSSM Higgs Search

- Model independent search $h \to a_0 a_0 \to \gamma\gamma\gamma\gamma$
  - $m(a_0) \sim O(100\ \text{MeV})$; $a_0 \to \gamma\gamma$ decay very collimated
  - Follow the SM di-photon selection
  - Looser EM shower-shape requirement
- No excess above the SM expectation

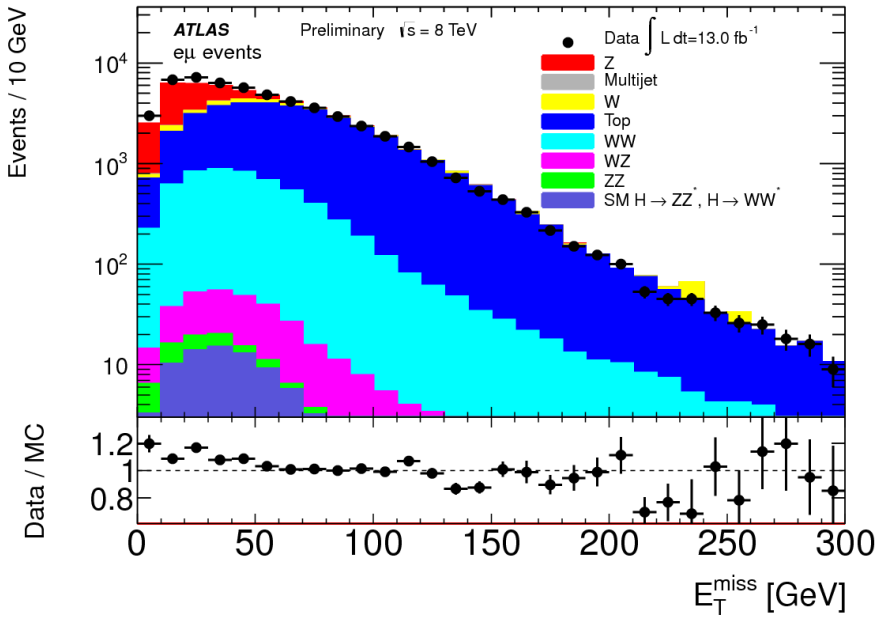
Exclude σxBR >0.1pb (0.2pb) for $m(a_0)$=100,200(400) MeV and m_h = 110-150 GeV

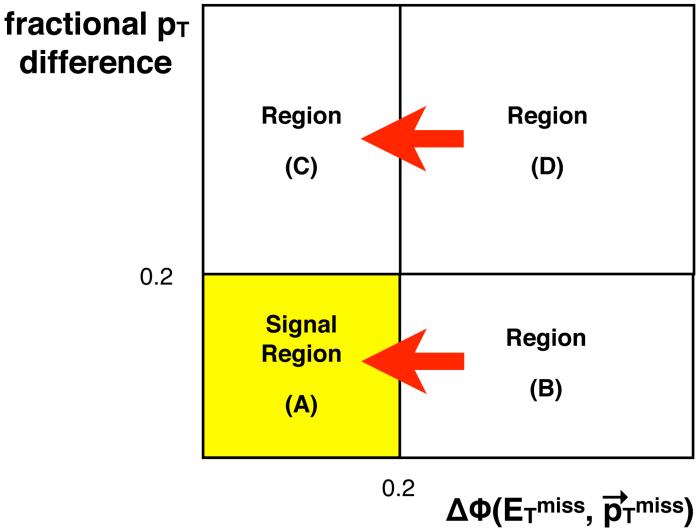




ATLAS: ZH, H->inv

- ZZ, WZ estimated from MC
- WW, ttbar estimated from eμ events in 8 TeV data
- Z background is estimated from data





$$N_A^{\text{est}} = N_B^{\text{obs}} \times \frac{N_C^{\text{obs}}}{N_D^{\text{obs}}} \times \alpha$$

Systematics ZH, H->inv

- ATLAS
- CMS

Process	Estimation method	Uncertainty (%) 2011	2012
ZH Signal	MC	7	6
ZZ	MC	11	10
WZ	MC	12	14
WW	MC	14	not used
Top quark	MC	90	not used
Top quark, WW and $Z \to \tau\tau$	$e\mu$ CR	not used	4
Z	ABCD method	56	51
W + jets, multijet	Matrix method	15	22

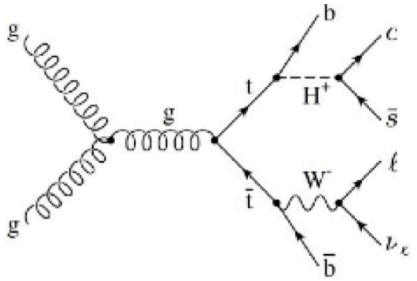
Table 2: Summary of the systematic uncertainties on each background and on the signal yield. The method used to estimate the backgrounds and the associated sources of systematic uncertainties are given. The total systematic uncertainties for each data taking period are given.

Type	Source	Uncertainty(%)
Rate	PDF	4-5
	QCD scale variation (ZH)	7
	QCD scale variation (VV)	7-10
	Luminosity	2.2-4.4
	Lepton Trigger, Reco., Isolation	3
	$Z/\gamma^* \to \ell^+\ell^-$ normalization	100
	Top, WW & W + jets normalization	25-100
Shape	MC statistics: ZH,ZZ,WZ	1-5
	Control sample statistics $Z/\gamma^* \to \ell^+\ell^-$	12-24
	Control sample statistics NRB	53-100
	Pile Up	0.1-0.3
	b-tagging Efficiency	0.2
	Lepton Momentum Scale	1
	Jet Energy Scale, Resolution	1-3
	Unclustered energy	1-4

Table 1: Summary of all systematic uncertainties. The ones assigned as shape uncertainties are propagated to both event rates and to the m_T distributions in the limit calculation.

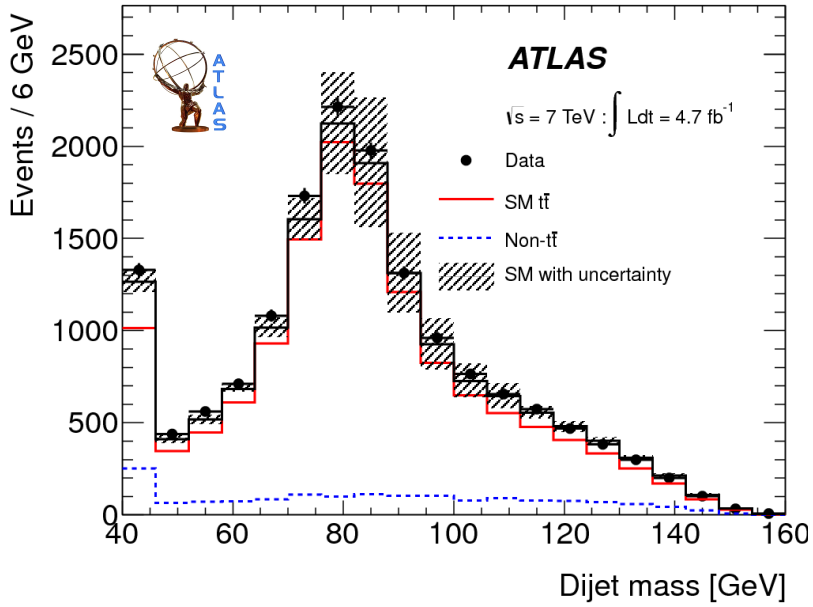
Light Charged Higgs Search

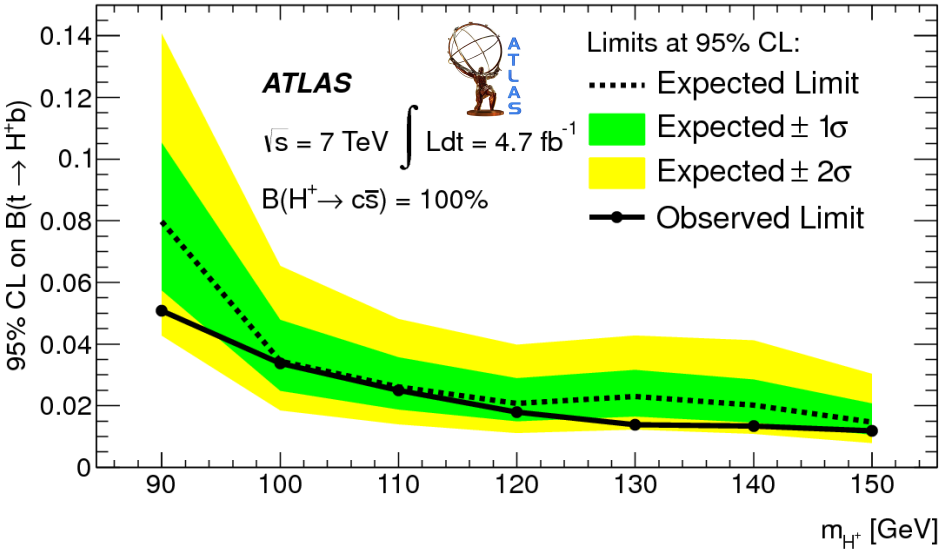
- Search in ttbar decays via WbHb
  - Assuming BR(H→cs)~100%
  - lepton+jets final state
    - At least two b-tagged jets
    - MET, m_T(l,MET)



Sensitive to small tanβ values

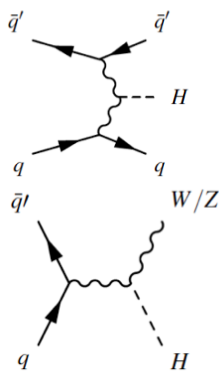
Upper limit on BR(t→Hb) set at 1-5%, assuming BR(H→cs)=1 for masses 90–150 GeV

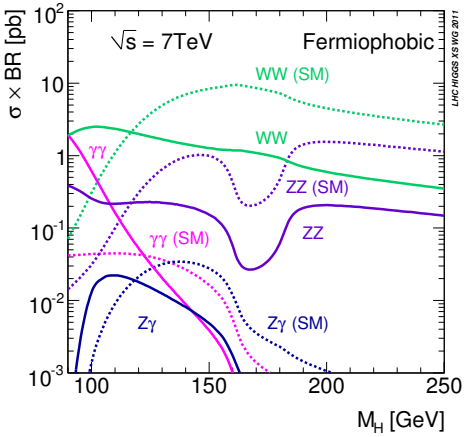


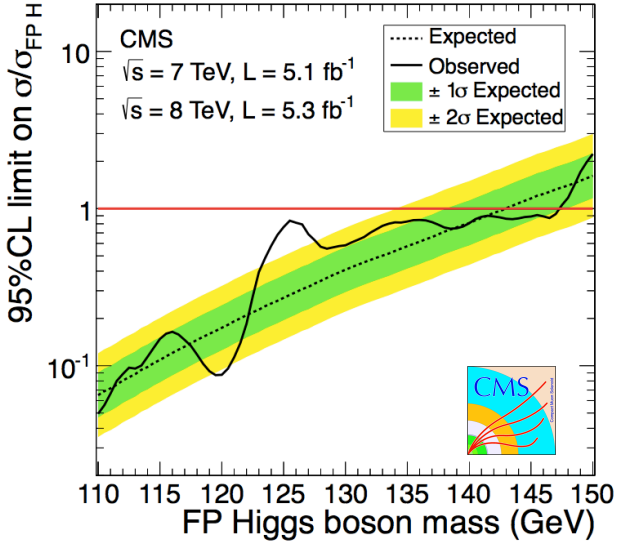


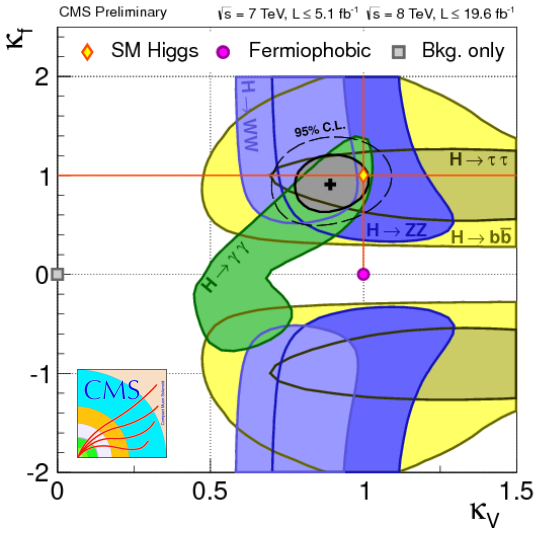
Fermiophobic Higgs

- Various extensions propose Higgs to couple only vector bosons
  - σ x BR(H→γγ) is enhanced significantly
- Search is done in VBF and VH signatures
  - Two forward jets, large M(jj) and large Δη(jj)
  - Isolated electron, muon, and/or MET from V boson decay
  - Consider boosted kinematics of diphoton system







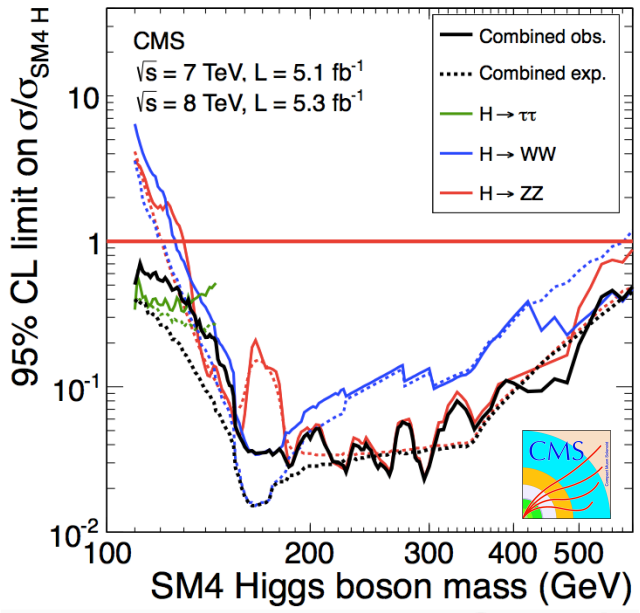


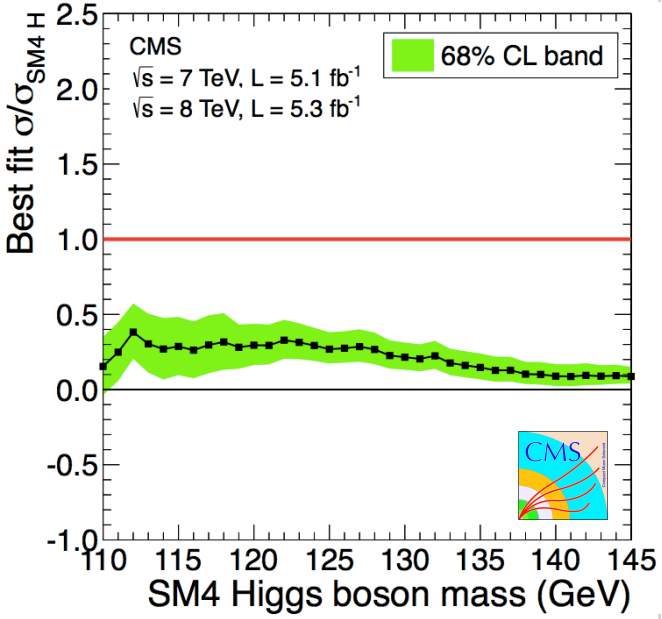
FP Higgs are excluded
- At 95% CL: 110-147 GeV
- At 99% CL: 110-134 GeV

SM4 Higgs

- Presence of 4th generation fermions would have a significant impact on the couplings of the Higgs boson to the SM particles
  - Consider benchmark $m(l_4)=m(\nu_4)=m(d_4)=600$ GeV, mass splitting between up-down type quarks is O(50 GeV)
- Results are obtained by combining searches in individual decay channels

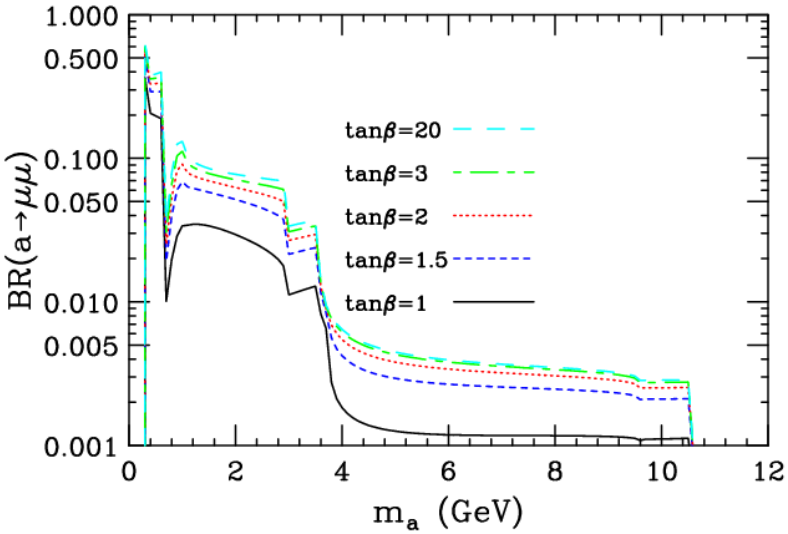
SM4 Higgs is excluded in range 110 – 600 GeV at 99% CL

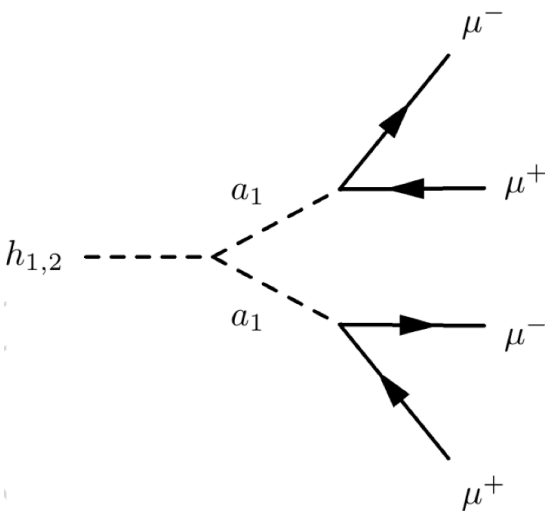




Higgs in nMSSM

- nMSSM extends minimal SUSY Higgs sector by additional one scalar singlet field
  - Gives rise to 3 CP even h_1,h_2,h_3, 2 CP odd a_1,a_2, and charged $H^{\pm}$
    - $h_{1,2} \rightarrow 2a_1$, m(h_1 or h_2) = 126 GeV
    - m(a_1) < $2m_b$ weakly couples to the SM particles

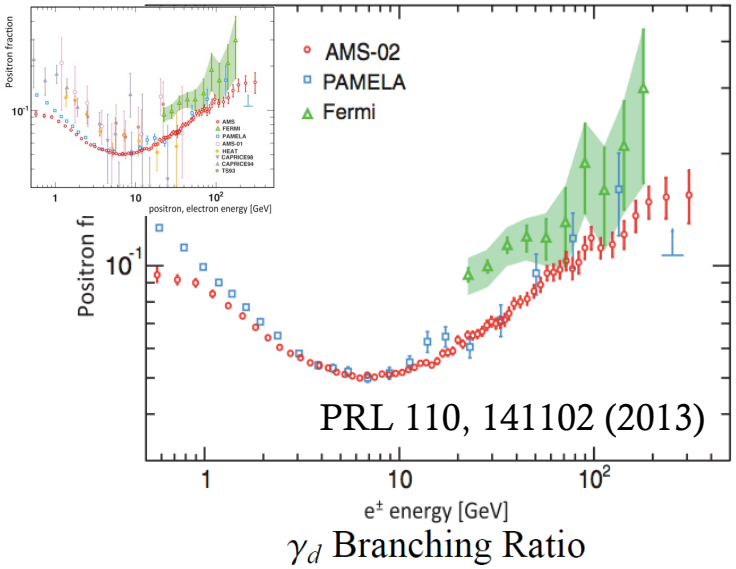




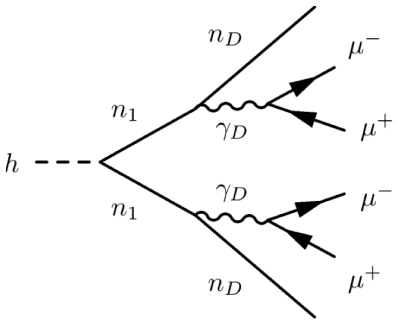
- Search for signature $h_{1,2} \rightarrow 2a_1 \rightarrow 4\mu$
  - 0.25 < m(a_1) < 3.55 GeV ($2m_\mu \leq m(a_1) \leq 2m_\tau$)
  - 90 < m(h_1) < 120-135 GeV
  - m(h_2) > 120 – 135 GeV

Benchmark in Dark SUSY

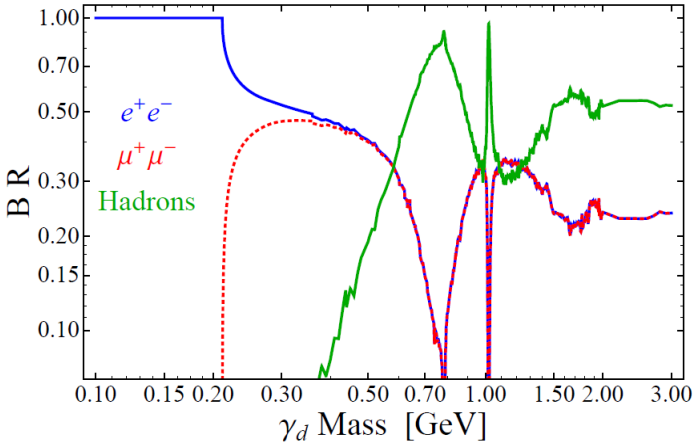
- Dark SUSY models are motivated by observed excess in positron spectra
  - Broken $U(1)_D$ symmetry gives rise to γ_D
    - Measurements in cosmic rays constrain $m(\gamma_D) \leq O(1\ \text{GeV})$
  - The lightest neutralino in visible SUSY spectrum is not stable $n_1 \to n_D + \gamma_D$
  - The SM-like Higgs boson decays via $h \to 2n_1$ if $m(h) > 2m(n_1)$



γ_d Branching Ratio



$h \to 2n_1 \to 2n_D + 2\gamma_D \to 2n_D + 4\mu$

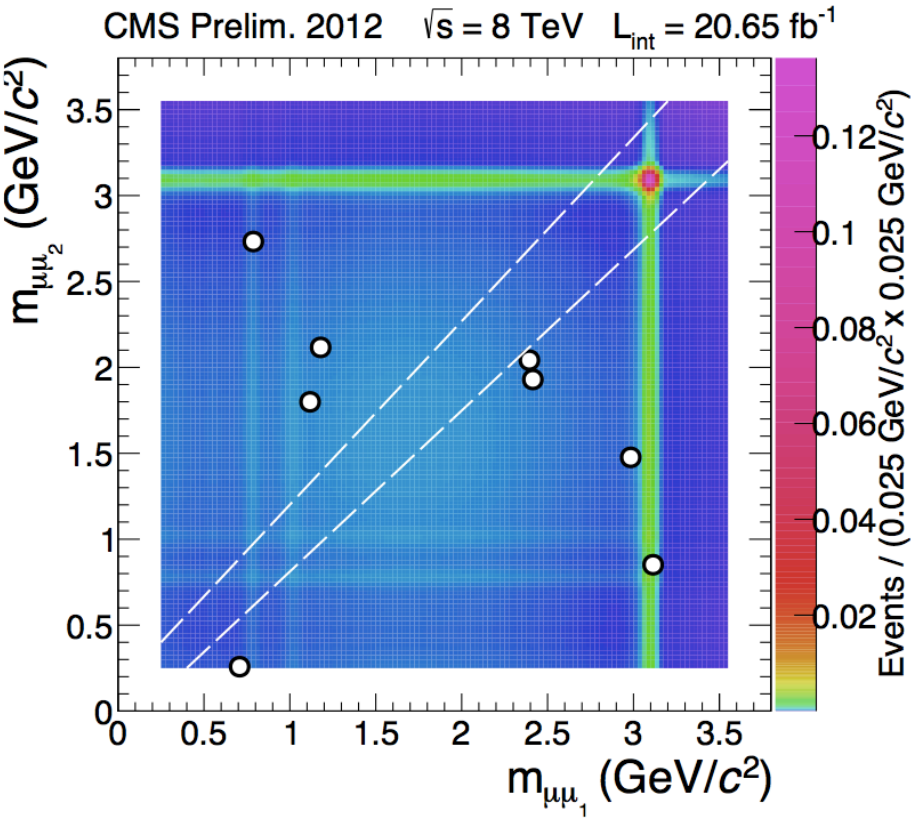


Benchmark:

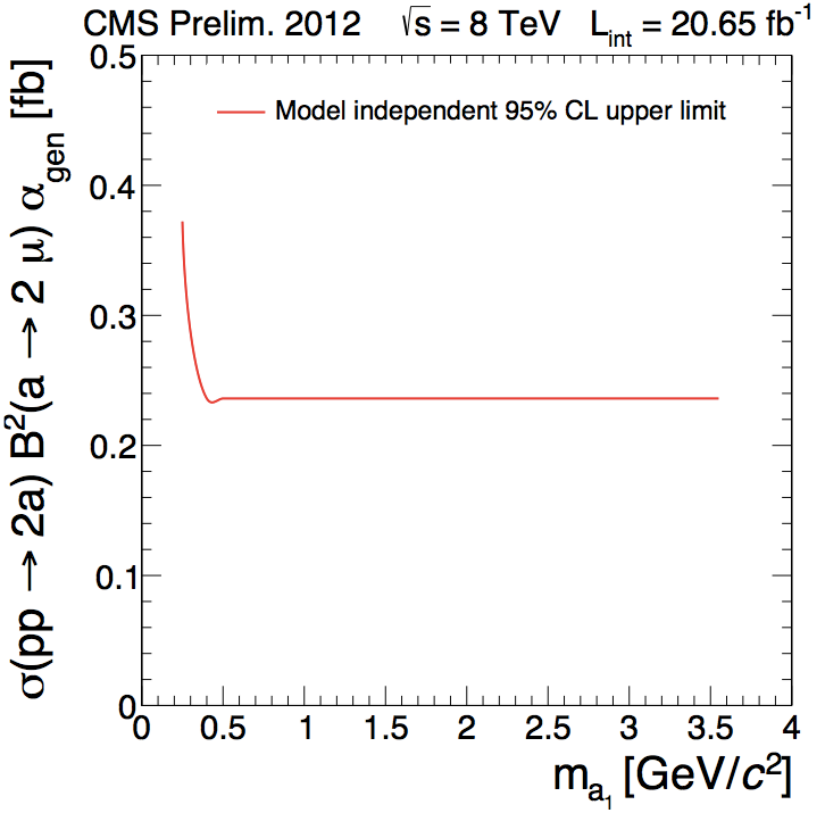
- $m(\gamma_D) \approx 0.4$ GeV, $m(n_1) \approx 10$ GeV, $m(n_D) \approx 1$GeV
- $90 \leq m(h_1) \leq 150$ GeV

nMSSM H->4mu

Data in off-diagonal 2D template



Model independent limit on σxB^2



nMSSM H->4mu

- Efficiency for two benchmark models

Table 1: Event selection efficiencies $\epsilon_{\text{full}}^{MC}(m_{h_1}, m_{a_1})$, as obtained from the full detector simulation, and the geometric and kinematic acceptances $\alpha_{\text{gen}}(m_{h_1}, m_{a_1})$ calculated using generator level information only, with statistical uncertainties for the NMSSM benchmark model. The experimental data-to-simulation scale factors are not applied.

m_{h_1} [GeV/c^2]	90	100	125	125	125	125	125	150
m_{a_1} [GeV/c^2]	2	2	0.25	0.5	1	2	3.55	2
$\epsilon_{\text{full}}^{MC}$ [%]	11.4 ± 0.1	13.8 ± 0.1	35.1 ± 0.2	22.6 ± 0.1	18.9 ± 0.1	18.2 ± 0.1	17.6 ± 0.1	21.5 ± 0.1
α_{gen} [%]	15.9 ± 0.1	19.3 ± 0.1	52.9 ± 0.2	32.0 ± 0.2	27.2 ± 0.2	26.3 ± 0.2	25.9 ± 0.2	32 ± 0.2
$\epsilon_{\text{full}}^{MC}/\alpha_{\text{gen}}$ [%]	71.7 ± 0.9	71.4 ± 0.8	66.4 ± 0.4	70.6 ± 0.6	69.6 ± 0.7	69.3 ± 0.7	68.2 ± 0.7	67.3 ± 0.6

Table 2: Event selection efficiencies $\epsilon_{\text{full}}^{MC}(m_h, m_{\gamma_D})$, as obtained from the full detector simulation, and the geometric and kinematic acceptances $\alpha_{\text{gen}}(m_h, m_{\gamma_D})$ calculated using generator level information only, with statistical uncertainties for a dark-SUSY benchmark model, as obtained from simulation. The experimental data-to-simulation scale factors are not applied.

m_h [GeV/c^2]	90	110	125	150
m_{γ_D} [GeV/c^2]		0.4		
ϵ_{full} [%]	2.4 ± 0.1	4.7 ± 0.1	6.8 ± 0.1	9.8 ± 0.1
α_{gen} [%]	3.5 ± 0.1	6.8 ± 0.1	9.9 ± 0.1	14.6 ± 0.1
$\epsilon_{\text{full}}/\alpha_{\text{gen}}$ [%]	68.9 ± 2.1	68.7 ± 1.5	68.1 ± 1.2	67.3 ± 0.9