Rare Higgs Decays

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Hunting for a Non-Standard Higgs Sector 2014

Outline

- Introduction
- Less rare Higgs decays
- Invisible Higgs decays
- Higgs sector in MSSM
- Higgs sector in NMSSM
- $\mathrm{WH},\ \mathrm{H} \to \mathrm{prompt\ electron-jets}$
- $\mathrm{H} \to \pi_V \pi_V$, $\mathrm{H} \to XX \to 4\ell$ (long-lived particles)
- Uncovered modes

Introduction

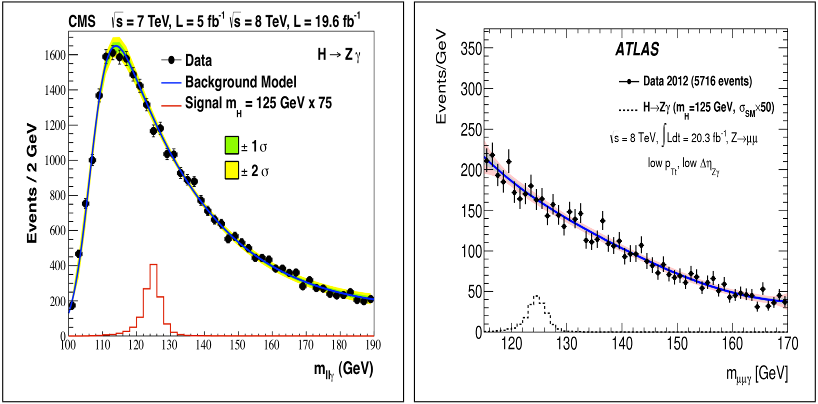
- Several ways to find Physics Beyond the Standard Model (BSM) within the Higgs sector:
  - measuring couplings of known SM Higgs boson decays:
    - main modes: ZZ, WW, $\gamma\gamma$, $\tau\tau$, $b\bar{b}$
    - (less) rare modes: $\mu\mu$, $\mathrm{Z}\gamma$, $\gamma^*\gamma$, ee
    - very difficult modes (at LHC): $s\bar{s}$, $c\bar{c}$, gg
    - couplings: $gg \to \mathrm{H}$, $qq\mathrm{H}$, VH, $\mathrm{t\bar{t}H}$, $tq\mathrm{H}$, $b\bar{b}\mathrm{H}$
  - searching for additional Higgs bosons:
    - direct searches for low mass (pseudo-)scalars (NMSSM...)
    - direct searches for heavy Higgs bosons (2HDM, $H^{\pm\pm}$...)
  - searching for particle decays involving Higgs bosons, e.g.:
    - $t \to c\mathrm{H}$
    - $\tilde{\chi}_1^0 \to \mathrm{H}\tilde{G}$, $\tilde{t}_2 \to \tilde{t}_1\mathrm{H} \to t\tilde{\chi}_1^0\mathrm{H}$, $\tilde{\chi}_1^{\pm}\tilde{\chi}_2^0 \to \mathrm{W}^{\pm}\tilde{\chi}_1^0\mathrm{H}\tilde{\chi}_1^0$
  - searching for rare neutral Higgs boson decays:
    - either forbidden or a branching fraction well below the experimental reach within the SM
- Last item is the main subject of the talk
- Focus on analyses with experimental (public) results, brief mention to other possible (new) searches

Branching Ratios in the SM

Values in % for $m_{\mathrm{H}} = 125$ GeV				
$b\bar{b}$	$\tau^+\tau^-$	$\gamma\gamma$	$\mathrm{W^+W^-}$	ZZ
57.7	6.32	0.23	21.5	2.64
gg	$c\bar{c}$	$s\bar{s}$	$\mu^+\mu^-$	$\mathrm{Z}\gamma$
8.57	2.91	0.025	0.022	0.154

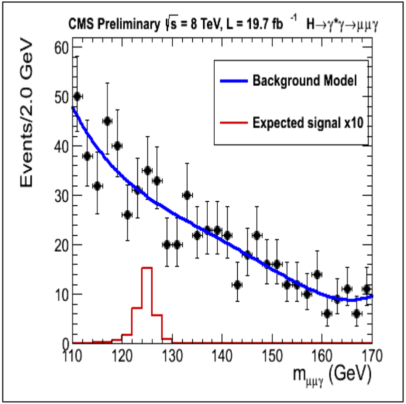
- "Invisible" decays in the SM: $BR(H \to \mathrm{ZZ} \to 4\nu) = 0.1\%$
- $\Gamma(\gamma^*\gamma) \sim 0.06\Gamma(\gamma\gamma)$
- $BR(H \to J/\psi\gamma) \sim 10^{-6}$

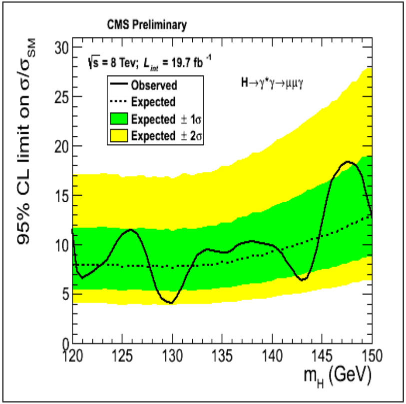
$H \rightarrow Z\gamma$ - ATLAS/CMS



- Two leptons and one photon in the final state
- Relatively simple analysis, but very low expected signal yields
- Split in several categories to improve S/B and mass resolution
- No significance excess over the entire search region
- Cross section limits about 10 times the SM expectation

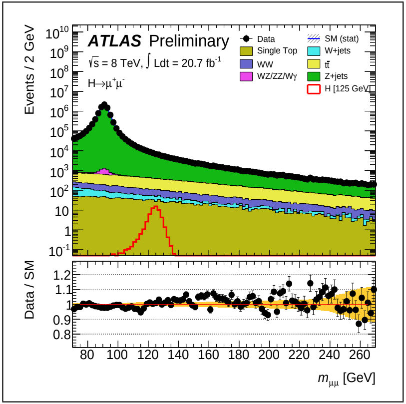
$H \rightarrow \gamma^*(\mu^+\mu^-)\gamma$ - CMS

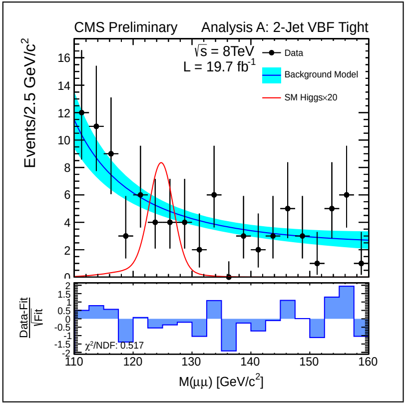




- Two collimated leptons and one photon in the final state
- $m_{\mu\mu} < 20$ GeV
- Cross section limits about 8-10 times the SM expectation

$H \rightarrow \mu^+\mu^-$ - ATLAS/CMS





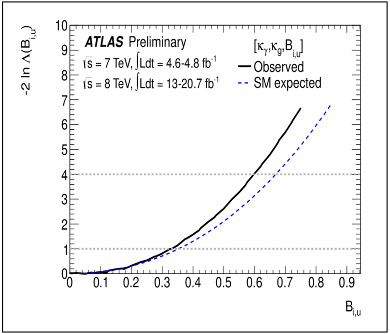
- Two isolated muons in the final state
- Split in several categories to improve S/B and mass resolution
- Cross section limits about 5-8 times the SM expectation

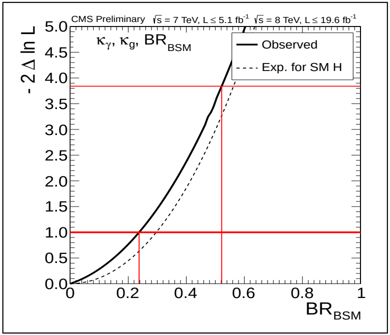
Invisible Higgs Decays

- The most extensive set of rare decays searches by far
- It exists in the SM, but extremely rare: $BR(\mathrm{H} \to \mathrm{ZZ} \to 4\nu) \sim 0.1\%$
- Observation of a large rate would be a sign of BSM:
  - LSPs in SUSY (neutralinos, gravitinos)
  - Graviscalars (large extra-dimensions)
  - Dark Matter (DM) → limits competitive with other DM searches
- Large missing transverse energy ($E_{\mathrm{T}}^{\mathrm{miss}}$) is the general pattern of all these searches
- Several production modes can be studied:
  - $qq\mathrm{H}$ (VBF): two forward/backward jets with high $\Delta\eta_{jj}$ & m_{jj}
  - $\mathrm{Z}(\ell\ell)\mathrm{H}$: two leptons compatible with a Z boson
  - $\mathrm{Z}(b\bar{b})\mathrm{H}$: two b-jets compatible with a Z boson
  - $\mathrm{Z/W}(q\bar{q}')\mathrm{H}$: two jets compatible with a $\mathrm{Z/W}$ boson
  - $gg \to \mathrm{H} + \mathrm{jet}$: one high p_{T} jet
    - standard mono-jet DM search can be re-used for this purpose, no public results yet
  - $\mathrm{W}(\ell\nu)\mathrm{H}$: one isolated high p_{T} lepton, hopeless due to the large $\mathrm{W} + \mathrm{jets}$ background

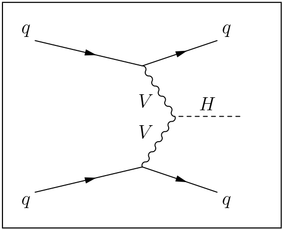
Indirect Limits on Invisible Higgs Decays

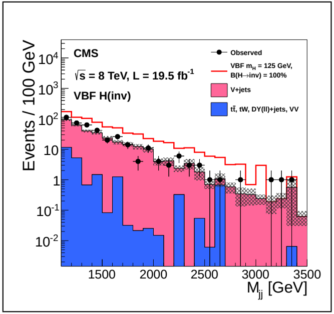
- Using the information from the visible measured Higgs decays modes
- An alternative general scenario can be obtained by allowing for non-vanishing Higgs boson decays beyond the SM ($\mathrm{BR}_{\mathrm{BSM}}$)
- $\kappa_{\mathrm{V}} \leq 1$ must be required
- $\kappa_{\mathrm{H}}^2 = \kappa_{\mathrm{H}}^2(SM)/(1 - \mathrm{BR}_{\mathrm{BSM}})$

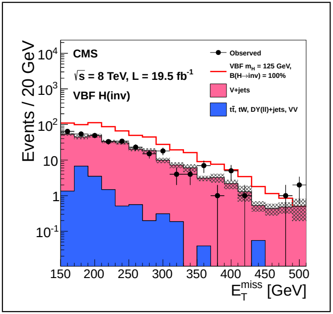




VBF, H $\rightarrow$ invisible (I) - CMS







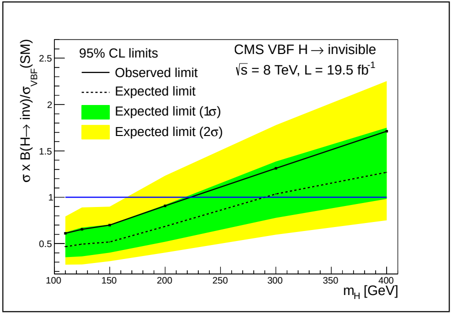
- Search for events with two high p_{T} jets with large $\Delta\eta_{jj}$ and m_{jj}, in addition to large $E_{\mathrm{T}}^{\mathrm{miss}}$
- All main backgrounds ($\mathrm{Z} \rightarrow \nu\nu$, $\mathrm{W} + \mathrm{jets}$, QCD) estimated from data
- Simple cut & count mass-independent approach

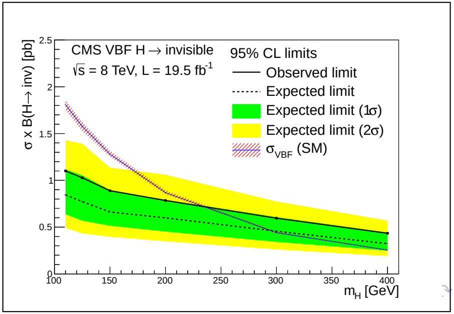
VBF, H → invisible (II) - CMS

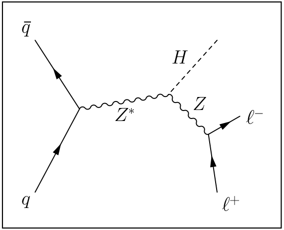
Summary of the estimated number of background and signal events, together with the observed yield. Signal yield is given for $m_{\mathrm{H}} = 125\ \mathrm{GeV}$ and $BR(\mathrm{H} \rightarrow \mathrm{invisible}) = 100\%$

Process	Event yields
$\mathrm{Z}(\nu\nu)$+jets	$99 \pm 29(stat.) \pm 25(syst.)$
$W(\mu\nu)$+jets	$67 \pm 5(stat.) \pm 16(syst.)$
$W(e\nu)$+jets	$63 \pm 9(stat.) \pm 18(syst.)$
$W(\tau_{\mathrm{h}}\nu)$+jets	$53 \pm 18(stat.) \pm 18(syst.)$
QCD multijet	$31 \pm 2(stat.) \pm 23(syst.)$
Other backgrounds	$20.0 \pm 8.2(syst.)$
Total background	$332 \pm 36(stat.) \pm 46(syst.)$
VBF H(inv.)	$210 \pm 30(syst.)$
ggF H(inv.)	$14 \pm 11(syst.)$
Observed data	390
S/B (%)	70

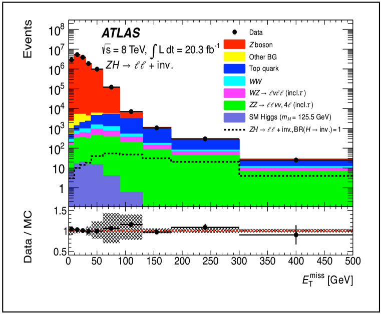
- Mild excess over the expected background, not significant
- Observed (expected) 95% CL BR limit for $m_{\mathrm{H}} = 125\ \mathrm{GeV}$ is 65% (49%)

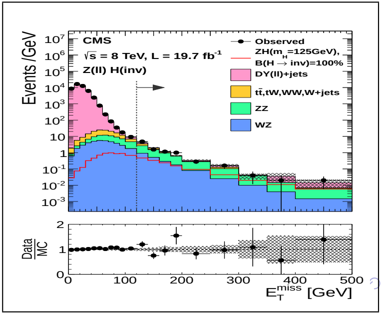






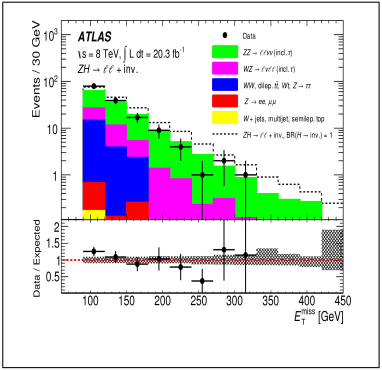
- Search for events with two high p_T isolated leptons compatible with a Z boson, in addition to large E_T^{miss}
- Statistical limited at this point, golden mode for high luminosity
- ZZ and WZ backgrounds from simulation, $t\bar{t}$+WW and Z + jets from data
- Tighter E_T^{miss} requirements in CMS to ∼ completely reject Z + jets

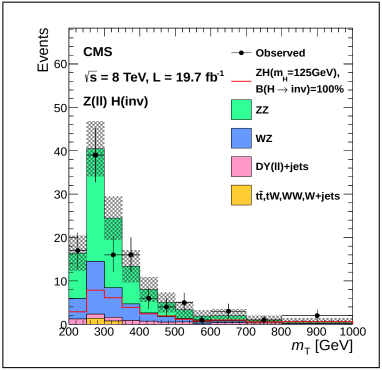




Z($\ell\ell$)H, H $\rightarrow$ invisible (II) - ATLAS/CMS

- ATLAS: observed (expected) 95% CL BR limit for $m_{\mathrm{H}} = 125$ GeV is 75% (62%)
- CMS: observed (expected) 95% CL BR limit for $m_{\mathrm{H}} = 125$ GeV is 83% (86%)

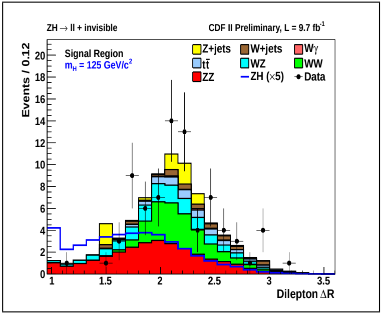


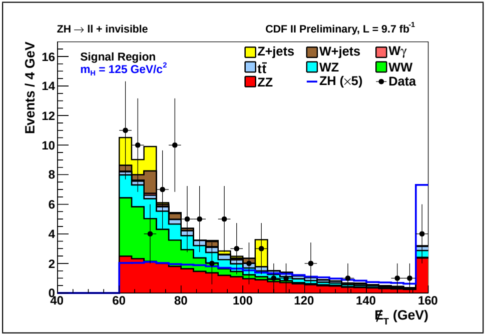


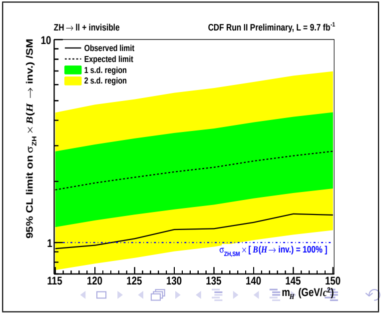
- ~30% excess at low $E_{\mathrm{T}}^{\mathrm{miss}}$ in ATLAS, not consistent with H $\rightarrow$ invisible

Z($\ell\ell$)H, H $\rightarrow$ invisible (III) - CDF

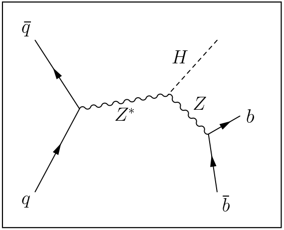
- Analysis performed with the full Tevatron run-II dataset
- Requirements looser than the ones at LHC
- Making use of $\Delta R_{\ell\ell}$ as final discriminant variable



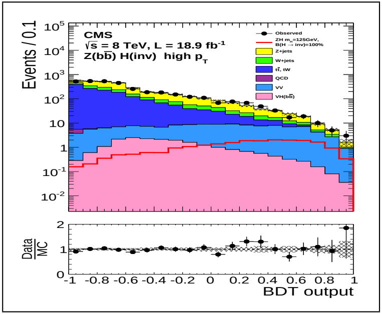


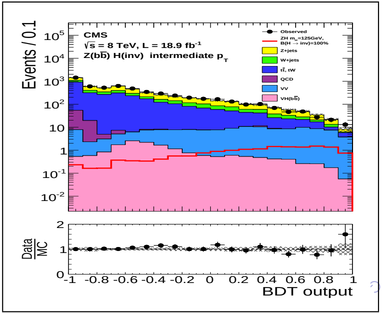


$Z(b\bar{b})H$, $H \rightarrow$ invisible - CMS



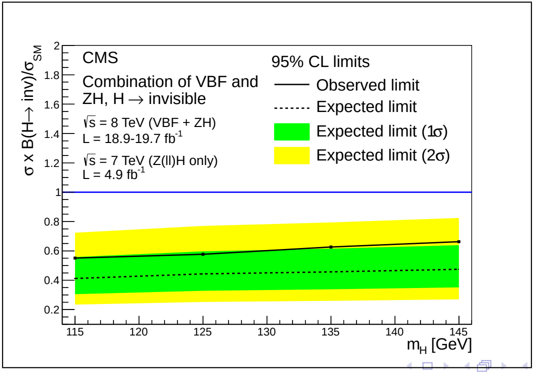
- Search for events with two high p_T b-jets compatible with a Z boson, in addition to large E_T^{miss}
- Split in Z p_T regions to improve signal-to-background ratio
- Built a BDT to separate signal and backgrounds as final discriminant variable
- Observed (expected) 95% CL BR limit for $m_H = 125$ GeV is 182% (199%)





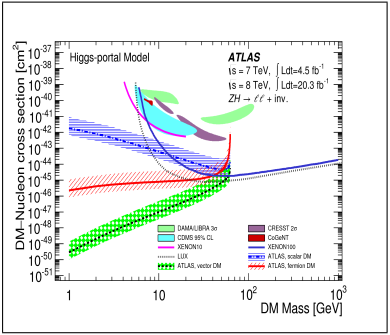
Combined CMS H $\rightarrow$ invisible Result

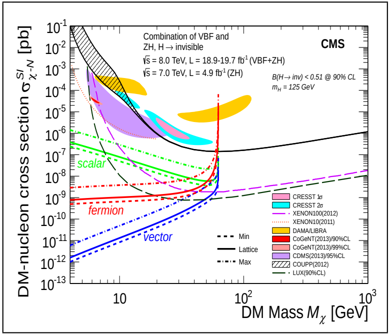
- Paper just released! (arXiv:1404.1344)
- By assuming production cross sections as for the SM, the results of the three individual CMS searches are combined and interpreted as a limit on $BR(\mathrm{H} \rightarrow \mathrm{invisible})$
- Observed (expected) 95% CL BR limit for $m_{\mathrm{H}} = 125$ GeV is 58% (44%)



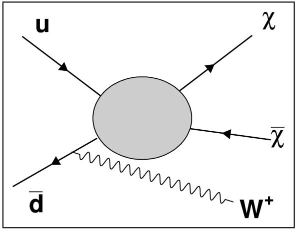
DM Limits Interpretation

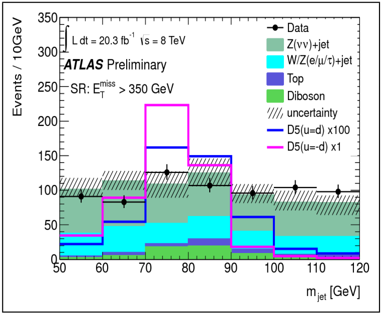
- Limits on the DM-nucleon scattering cross section at 90% CL, extracted from the BR($\mathrm{H} \rightarrow \mathrm{invisible}$) limit in a Higgs-portal scenario, compared to results from direct-search experiments
- Sensitivity competitive with other dedicated searches



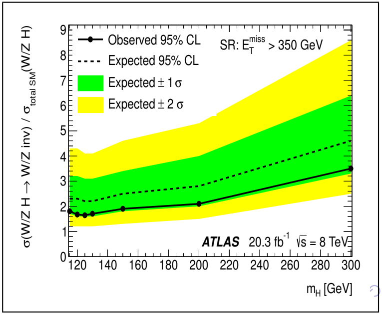


$Z/W(q\bar{q}') + E_T^{miss}$ - ATLAS



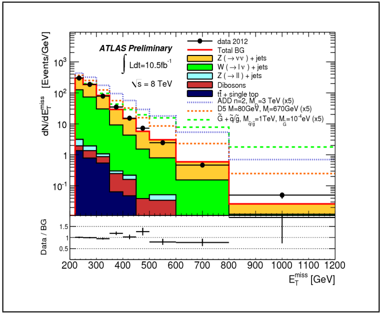


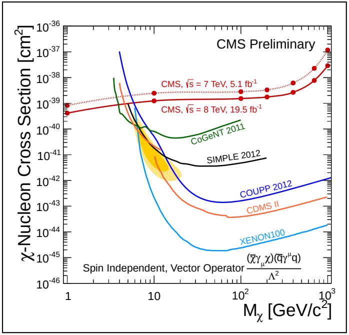
- Search for events with two high p_T light-jets compatible with a Z/W boson, in addition to large E_T^{miss}
- Backgrounds from $V + \text{jets}$, top-quark production, and dibosons
- Using jet sub-structure techniques to identify V bosons
- Upper limits on DM and $H \to \text{invisible}$ scenarios

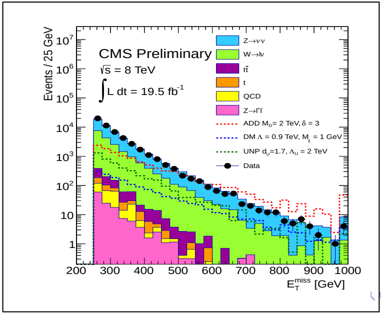


Mono-Jet Searches - ATLAS/CMS

- Search for events with one high p_{T} jet and large $E_{\mathrm{T}}^{\mathrm{miss}}$
- Backgrounds from $\mathrm{V} + \mathrm{jets}$, top-quark production, and dibosons
- Upper limits on DM scenarios, can also be interpreted on $\mathrm{BR}(\mathrm{H} \to \mathrm{invisible})$







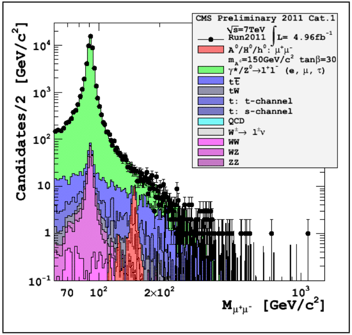
Higgs Sector in MSSM

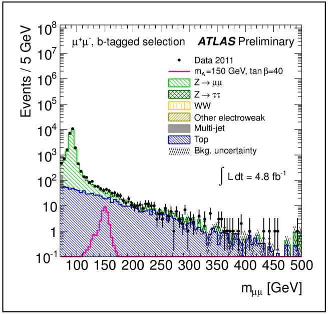
- Higgs sector in SUSY contains two scalar doublets:
  - five physical Higgs bosons:
    - 3 neutral: CP-even $\Phi =$ h & H; CP-odd A
    - 2 charged: $\mathrm{H}^{\pm}$
  - SM-like Higgs boson: h
- Neutral Higgs "Φ" decay modes:
  - $BR(\Phi \rightarrow b\bar{b}) \sim 90\%$
  - $BR(\Phi \rightarrow \tau\tau) \sim 10\%$
  - $BR(\Phi \rightarrow \mu\mu) \sim 0.1\%$
- Two main production modes:
  - $gg \rightarrow \mathrm{H}$
  - $b\bar{b}\mathrm{H}$

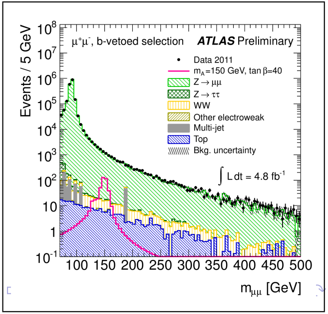
- B-tagged topologies make analyses rather different w.r.t. SM searches
- Observation of $H(125)$ does not exclude a heavy MSSM Higgs boson in a wide range of $tan\beta$, still fits both SM and MSSM
- Signal extraction based on looking for a mass resonance
- Showing $\Phi \rightarrow \mu\mu$ case here, other analyses in Susan Gascon-Shotkin's talk

MSSM $\Phi \to \mu\mu$ (I)

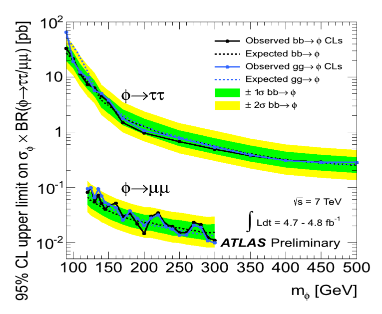
- Search for a $\mu\mu$ mass resonance
- Good mass resolution thanks to the full and clean reconstructed final state
- Split in b-tagged and non b-tagged categories to be sensitive to $gg \to \Phi$ and $b\bar{b}\Phi$ production modes
  - two (three) categories in ATLAS (CMS)
- Main backgrounds: $\mathrm{Z}(b\bar{b})$, $\mathrm{t\bar{t}}$, WW

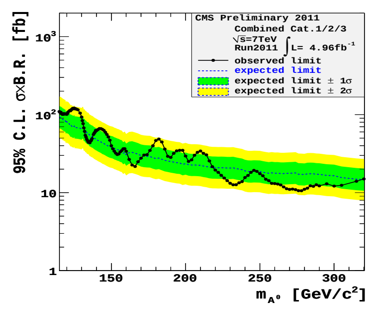


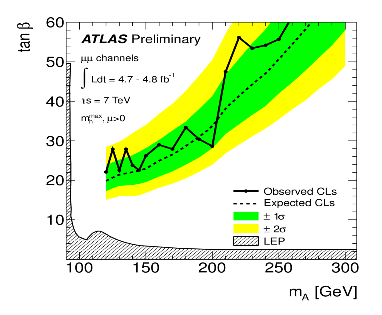


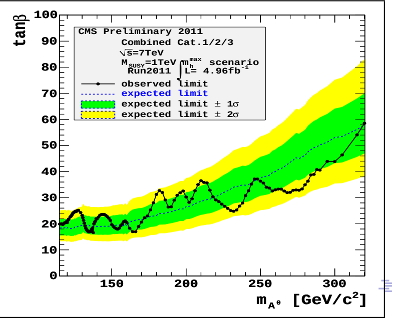


MSSM $\Phi \to \mu\mu$ (II)





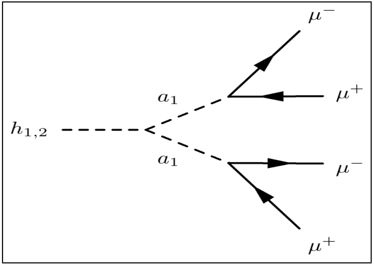




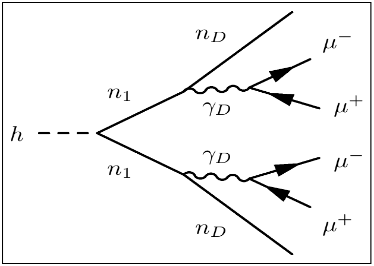
Higgs Sector in NMSSM

- Next to Minimal Supersymmetric Standard Model
  - NMSSM superfields = MSSM superfields + Higgs superfield singlet $\widehat{S}$
  - acommodates better $m_{\mathrm{H}} \sim 125$ GeV
  - seven physical Higgs bosons:
    - 5 neutral: CP-even $\Phi = h_1$,h_2, h_3; CP-odd a_1, a_2
    - 2 charged: $\mathrm{H}^{\pm}$
  - one CP-odd boson (a_1) can be very light, $m_{a_1} < 2m_b$
- Two models interpretation:

NMSSM benchmark

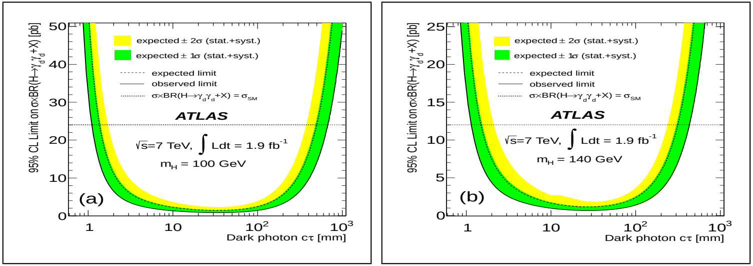


Dark SUSY benchmark



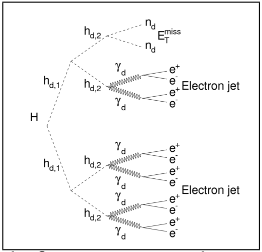
$\mathrm{H} \to 4\mu + X$ (Long-Lived)

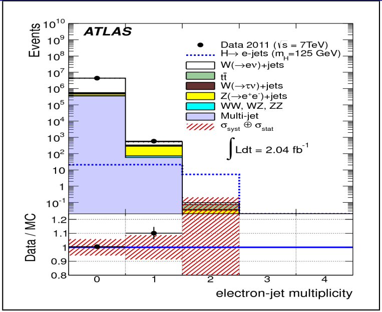
- $\mathrm{H} \to f_{d_2} f_{d_2}$, $f_{d_2} \to f_{d_1} \gamma_d$, $\gamma_d \to \mu\mu$
  - $m_{\gamma_d} = 400$ MeV, long-lived
  - $BR(\gamma_d \to \mu\mu) = 45\%$
- Back-to-back pairs of isolated, collinear, displaced μ
- Little $E_{\mathrm{T}}^{\mathrm{miss}}$ since f_{d_1} are emitted back-to-back
- Limits on $BR(\mathrm{H} \to 4\mu + X)$ vs. $(c\tau)_{\gamma_d}$

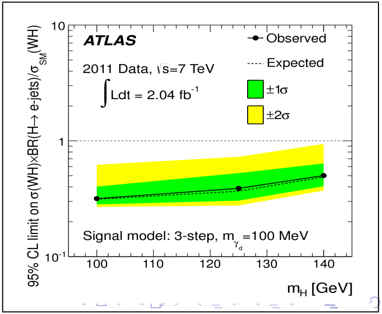


Other NMSSM analyses shown in Susan Gascon-Shotkin's talk

WH, H → prompt electron – jets



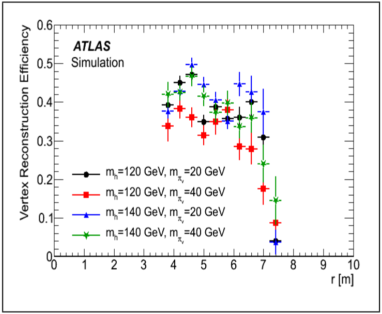


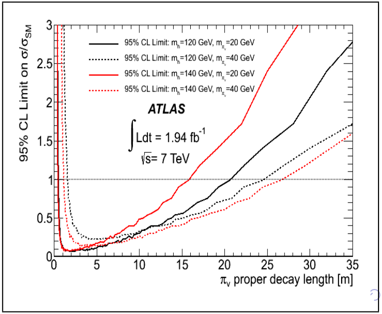


- Search for events with one high-p_T isolated lepton and one or more prompt electron-jets
- Two models:
  - three-step and two-step
  - Each $h_{d,2}$ particle can decay to a pair of dark photons γ_d or stable scalars n_d
- Select events with clusters of electron-like tracks within a jet, very distintive signature

$\mathrm{H} \rightarrow \pi_V \pi_V$ (Long-Lived Particles)

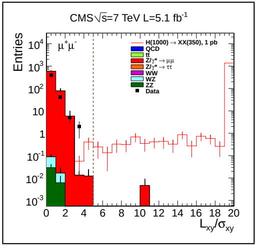
- Search for events compatible with $\mathrm{H} \rightarrow \pi_V \pi_V$
  - π_V is a long-lived neutral particle
  - π_V decays should happen at $r \sim 4 - 8\ m$ (ATLAS muon spectrometer)
- Specialized tracking and vertexing reconstruction algorithms were used
- 0 observed data events to be compared with 0.03 ± 0.02 expected background events

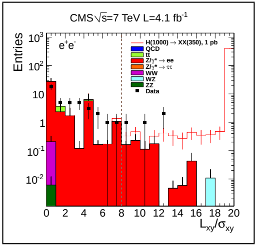


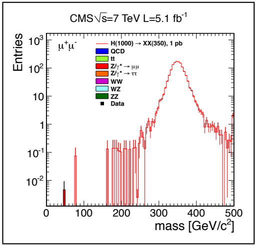


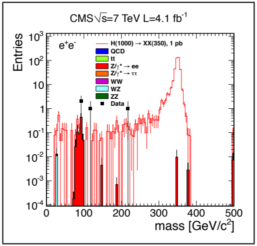
$H \to XX \to 4\ell$ (Long-Lived Particles)

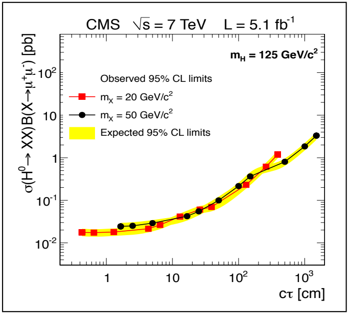
- Search for a pair of oppositely charged isolated leptons originating at a separated secondary vertex
- Leptons with large impact parameter

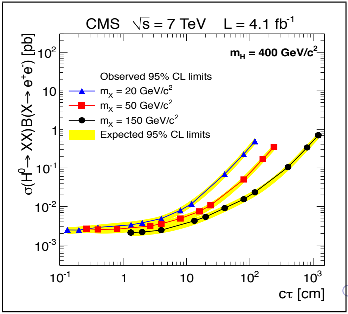










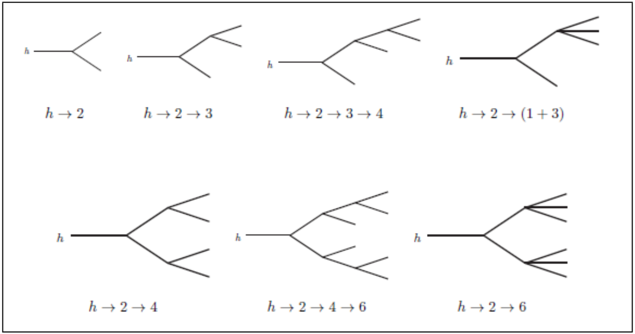


Uncovered Modes (or Not Public Yet)

A summary can be found in e.g. arXiv1312.4992

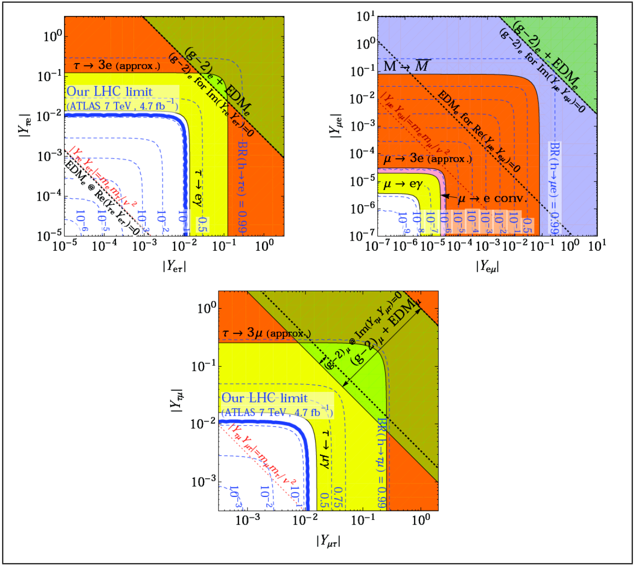
- $\mathrm{H} \to XX \to 4b$
- $\mathrm{H} \to aa \to 2b2\tau/2b2\mu/4\tau/2\tau2\mu$
  - multilepton analyses may be used to put limits on them
- $\mathrm{H} \to XX \to 4j$
- $\mathrm{H} \to XX \to 2j2\gamma$
- $\mathrm{H} \to XX \to 4\gamma$
  - no truly 4γ analysis exists yet
- $\mathrm{H} \to a\mathrm{Z}$
- $\mathrm{H} \to Z_D\mathrm{Z}/\mathrm{Z}_D\mathrm{Z}_D$, with Z_D a new gauge boson
- $\mathrm{H} \to \chi_1\chi_2 \to \gamma/2\gamma + E_{\mathrm{T}}^{\mathrm{miss}}$
- $\mathrm{H} \to \ell/\ell\ell/b\bar{b}/\tau\tau + E_{\mathrm{T}}^{\mathrm{miss}}$
  - SUSY analyses may be used to put limits on them
- $\mathrm{H} \to \mathrm{one/two\ prompt\ leptons - jets} + X$
- Lepton Flavor Violating (LFV) Higgs decays: $\mu\tau$, $e\tau$, $e\mu$

Topologies



- $\mathrm{H} \to 2$: $E_{\mathrm{T}}^{\mathrm{miss}}$
- $\mathrm{H} \to 2 \to 3$: $\gamma/b\bar{b}/\gamma\gamma/\tau\tau/\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$
- $\mathrm{H} \to 2 \to 3 \to 4$: $\chi_1\chi_2/a\chi_1/V\chi_1$
- $\mathrm{H} \to 2 \to (1+3)$: $\ell\ell + E_{\mathrm{T}}^{\mathrm{miss}}$
- $\mathrm{H} \to 2 \to 4$: $aa'/ss'/V_1V_2/aV_1$
- $\mathrm{H} \to 2 \to 4 \to 6$: e.g. leptons plus $E_{\mathrm{T}}^{\mathrm{miss}}$
- $\mathrm{H} \to 2 \to 6$: e.g. R-parity violating neutralinos

A Word about LFV Higgs Decays



- $\mu\tau$, $e\tau$ final states within current LHC reach
- Little sensitivity for $e\mu$ final state

Summary

- Shown a summary of searches on rare Higgs decays:
  - Invisible Higgs decays
  - Higgs Sector in MSSM
  - Higgs Sector in NMSSM
  - $\mathrm{WH,\ H \to prompt\ electron - jets}$
  - $\mathrm{H} \to \pi_V \pi_V$, $\mathrm{H} \to XX \to 4\ell$ (long-lived particles)
- No significant deviations from the SM so far
- Several analyses still in progress using run-I LHC data
- Large number of yet uncovered possible Higgs decays
  - some of them may re-use already existing analyses

Back-Up

References

- ATLAS-HIGG-2013-03, ATLAS-CONF-2013-073, CMS-PAS-HIG-13-013, CMS-PAS-HIG-13-018, CMS-PAS-HIG-13-028, CMS-PAS-HIG-13-030, CDF-11068: $\mathrm{H} \to \mathrm{invisible}$
- EXO-12-048 & ATLAS-CONF-2012-147: mono-jet searches
- CMS-PAS-HIG-12-033: MSSM $\Phi \to b\bar{b}$
- CMS-PAS-HIG-13-021: MSSM $\Phi \to \tau\tau$
- arXiv:1211.6956 & CMS-PAS-HIG-12-011: MSSM $\Phi \to \mu\mu$
- CMS-PAS-HIG-13-010: NMSSM $\mathrm{H} \to 4\mu + X$ short-lived
- ArXiv:1210.0435: NMSSM $\mathrm{H} \to 4\mu + X$ long-lived
- ATLAS-CONF-2012-079: NMSSM $\mathrm{H} \to 4\gamma$
- ArXiv:1302.4403: $\mathrm{WH},\ \mathrm{H} \to \mathrm{prompt\ electron-jets}$
- ArXiv:1203.1303: $\mathrm{H} \to \pi_V \pi_V$
- CMS-PAS-EXO-11-101: $\mathrm{H} \to XX \to 4\ell$
- Uncovered modes: arXiv1312.4992
- LFV: arXiv1209.1397

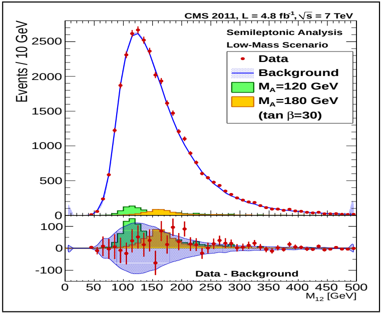
$Z(\ell\ell)H$, $H \to$ invisible - ATLAS vs. CMS Sensitivity

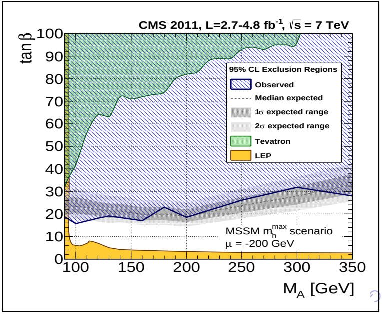
- All the difference in sensitivity comes from E_T^{miss} requirement
- CMS wants to ensure tiny $Z + \text{jets}$ background is left after the full selection, i.e. tighter E_T^{miss} requirement is applied
- Notice all the ATLAS excess of events come from that difficult bin to model
- Long term sensitivity is barely affected since events with large E_T^{miss} are the relevant ones

Variable	ATLAS	CMS
p_T^j > [GeV]	25	30
Jet bin categories	0	0,1
p_T^ℓ > [GeV]	20	20
third lepton veto	applied	applied
$\lvert m_{\ell\ell} - m_Z \rvert <$ [GeV]	15	15
b-tag veto	not applied	applied
$\lvert E_T^{miss} - p_T^{\ell\ell} \rvert / p_T^{\ell\ell} <$	0.2	0.25
$\Delta\phi_{\ell\ell - E_T^{miss}} >$	2.6	2.7
$E_T^{miss} >$ [GeV]	90	120
$\Delta\phi_{\ell\ell} <$	1.7	not applied
Final discriminant	E_T^{miss}	m_T-$\Delta\phi_{\ell\ell}$

MSSM $\Phi \rightarrow b\bar{b}$

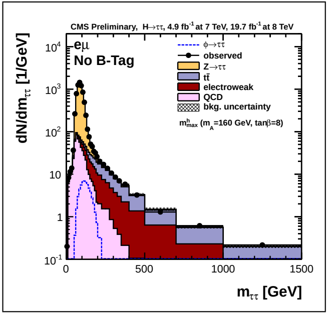
- Highest branching ratio, but very difficult due to the large QCD background:
  - dedicated trigger paths to identify b-tagged jets
  - challenging background estimates
- Two categories of events targeting $b\bar{b}\Phi$ production
  - all hadronic: at least three b-tagged leading jets
  - semileptonic: two b-tagged leading jets plus a soft muon
- Signal extraction from a peak in the M_{12} di-jet mass

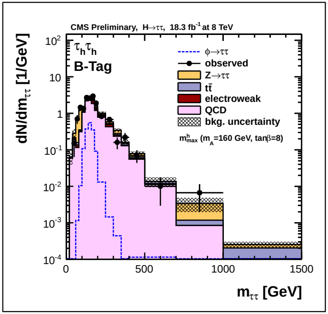




MSSM $\Phi \rightarrow \tau\tau$ (I)

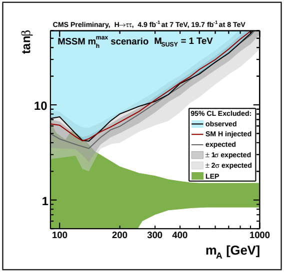
- Search for a $\tau\tau$ mass peak using a maximum likelihood method (∼10-15% mass resolution)
- Five $\tau\tau$ final states are reconstructed: $\mu\tau_h$, $e\tau_h$, $e\mu$, $\mu\mu$, $\tau_h\tau_h$
- Split in b-tagged and non b-tagged categories
  - sensitive to $gg \rightarrow \Phi$ and $b\bar{b}\Phi$ production modes
- Main backgrounds: $Z \rightarrow \tau\tau$, QCD/W + jets, $Z \rightarrow ee/\mu\mu$, $t\bar{t}$, dibosons

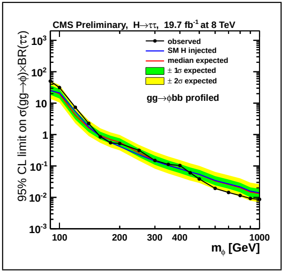


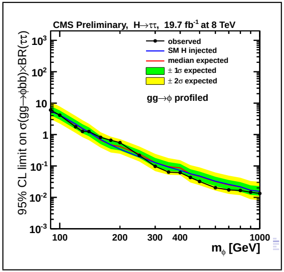


MSSM $\Phi \rightarrow \tau\tau$ (II)

- No significant excess of events over the SM background prediction is observed in any of the categories
- 95% CL upper limits are extracted

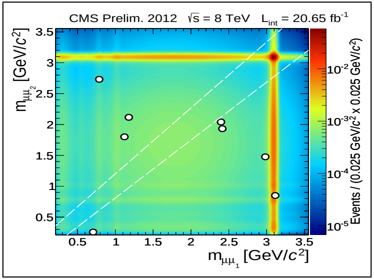




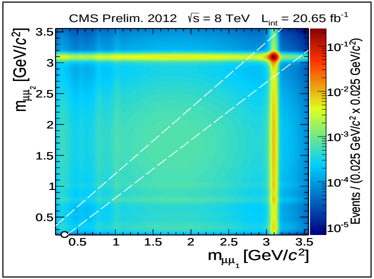


$\mathrm{H} \to 4\mu + X$ (Short-Lived)

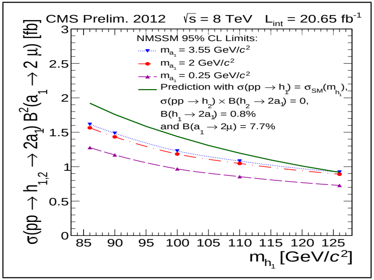
$m_{\mu\mu_1} != m_{\mu\mu_2}$



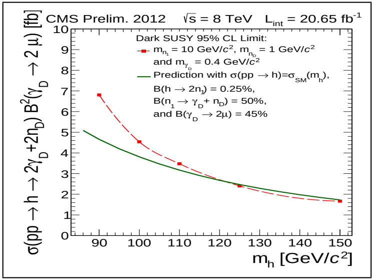
$m_{\mu\mu_1} \sim m_{\mu\mu_2}$



NMSSM benchmark



Dark SUSY benchmark



NMSSM $\mathrm{H} \to 2a \to 4\gamma$

- Sensitive to very light a:
  - for $m_a < 3m_{\pi^0}$, $a \to \gamma\gamma$ enhanced, very clean signal
  - one CP-odd boson (a_1) can be very light, $m_{a_1} < 2m_b$
- Large boost for a, γ very collinear $\to$ seen almost as $\mathrm{H} \to \gamma\gamma$
- Similar analysis as $\mathrm{H} \to \gamma\gamma$:
  - relaxed shower shape requirements on γ
  - allow larger lateral energy leak
- Limits for several m_a values