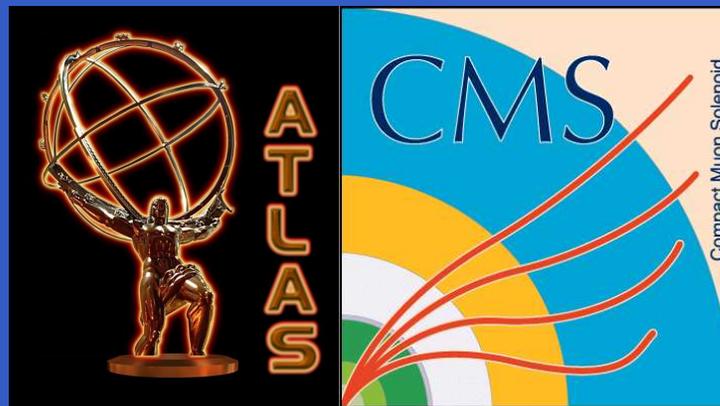
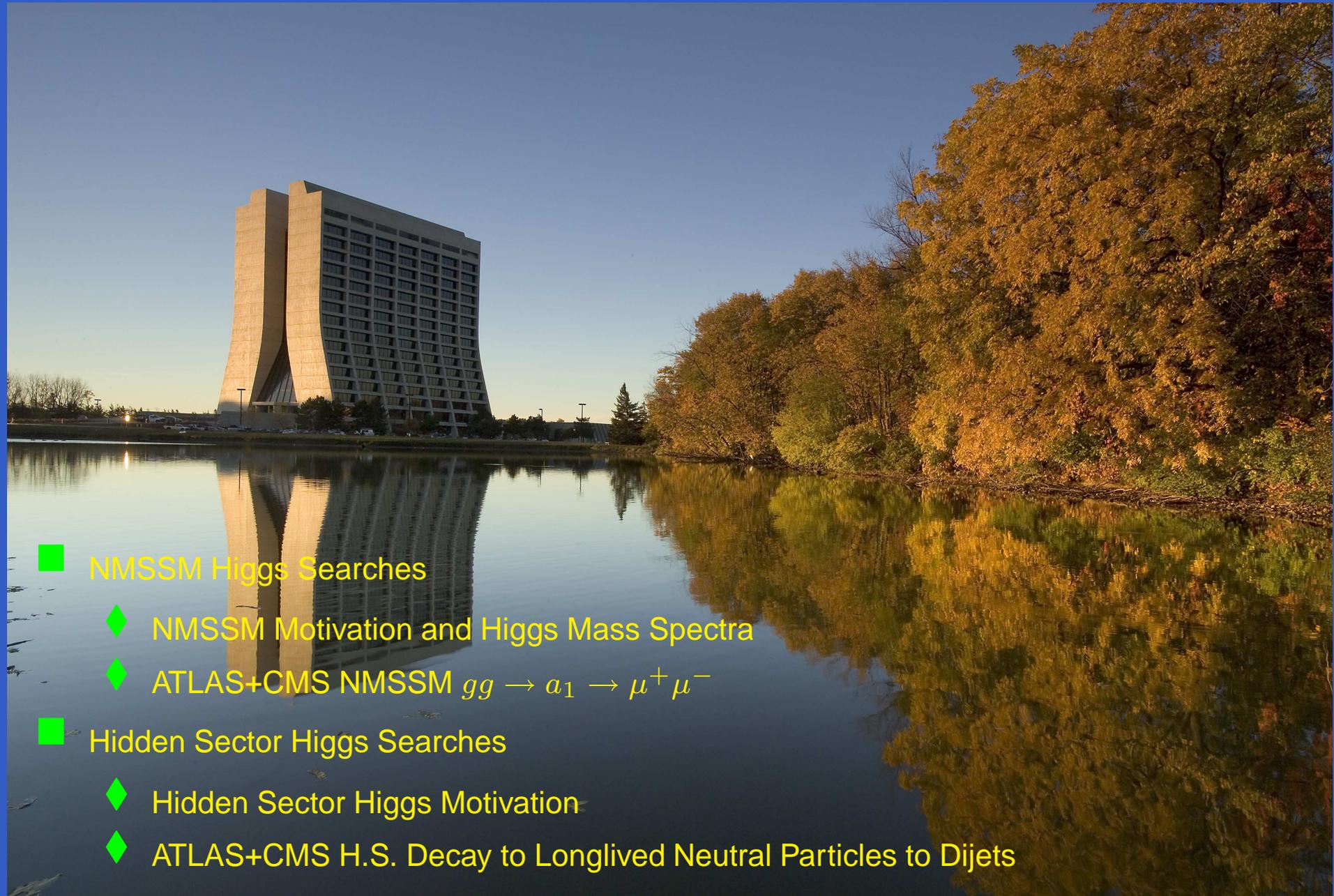


Other Exotic [Hidden Sector and NMSSM] Higgs Decays at the LHC



Chris Potter, for the CMS and ATLAS Collaborations

University of Oregon



- NMSSM Higgs Searches
 - ◆ NMSSM Motivation and Higgs Mass Spectra
 - ◆ ATLAS+CMS NMSSM $gg \rightarrow a_1 \rightarrow \mu^+ \mu^-$
- Hidden Sector Higgs Searches
 - ◆ Hidden Sector Higgs Motivation
 - ◆ ATLAS+CMS H.S. Decay to Longlived Neutral Particles to Dijets

- One singlet superfield S is introduced to the MSSM. An effective μ term is generated $\mu_{eff} = \lambda \langle S \rangle$ at a natural scale.
- The NMSSM superpotential is given by:

$$\mathbf{W} = \lambda \mathbf{S} \mathbf{H}_u \mathbf{H}_d + \frac{\kappa}{3} \mathbf{S}^3$$

- The soft SUSY breaking terms in the NMSSM Lagrangian are

$$V_{soft} = m_{H_d}^2 |H_d|^2 + m_{H_u}^2 |H_u|^2 + m_S^2 |S|^2 + (-\lambda A_\lambda H_u H_d S + \frac{1}{3} A_\kappa \kappa S^3 + h.c.).$$

- Six parameters determine the NMSSM Higgs sector at tree level:

$$\lambda, \kappa, A_\lambda, A_\kappa, \tan \beta \text{ and } \mu_{eff}$$

- The NMSSM Higgs sector has 2 neutral CP-odd, 3 neutral CP-even and 2 charged scalars:

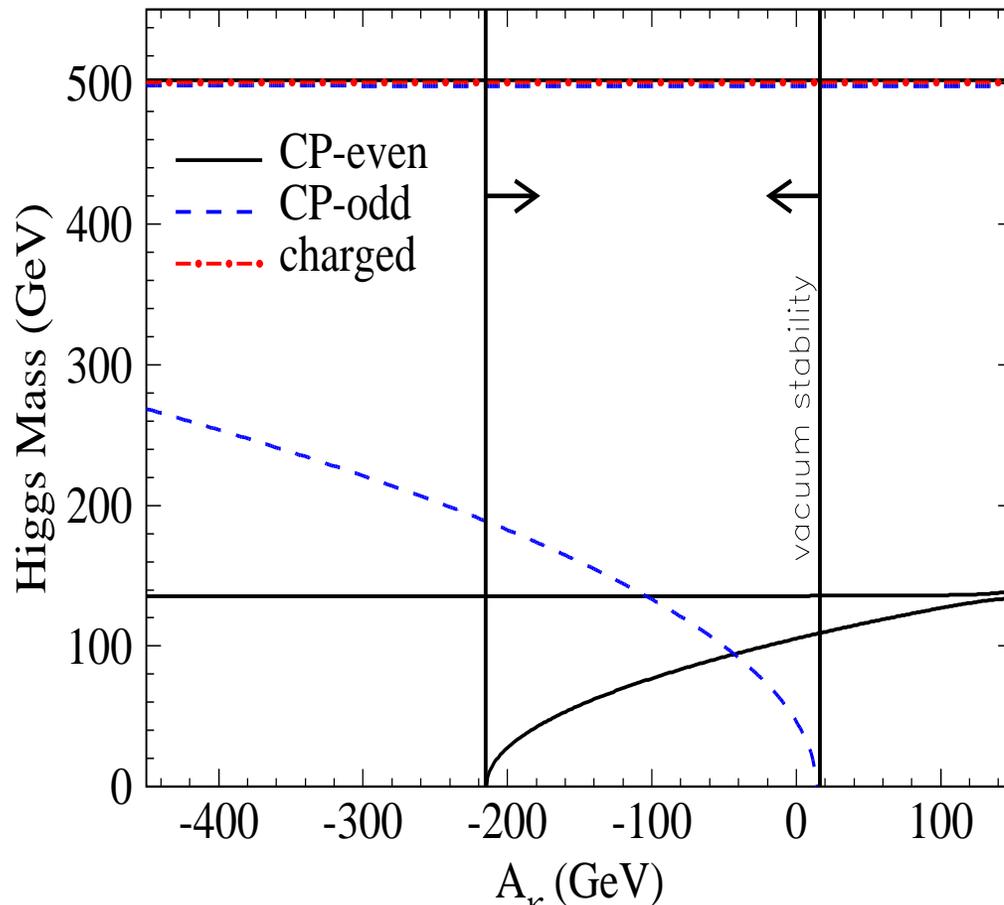
$$a_1, a_2, h_1, h_2, h_3, H^+, H^-$$

NMSSM Higgs Mass Spectrum



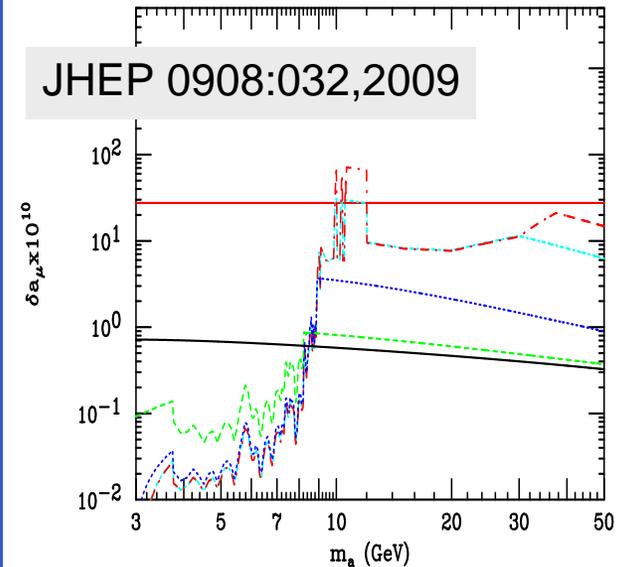
Low mass scalars a_1 and h_1 absent in the MSSM but present in the NMSSM are motivated by the anomalous muon magnetic moment and the LEP excess in the $Zh \rightarrow Zb\bar{b}$ channel.

Nucl.Phys.B681:3-30,2004

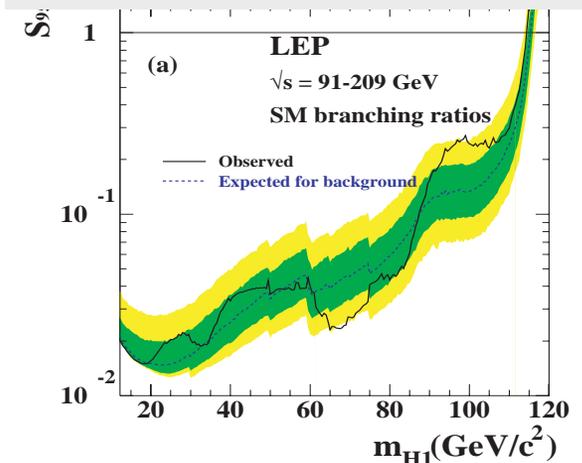


$\lambda = 0.3, \kappa = 0.1, v_s = 3v, \tan \beta = 3, m_A = \mu \tan \beta \approx 470 \text{ GeV}$

JHEP 0908:032,2009



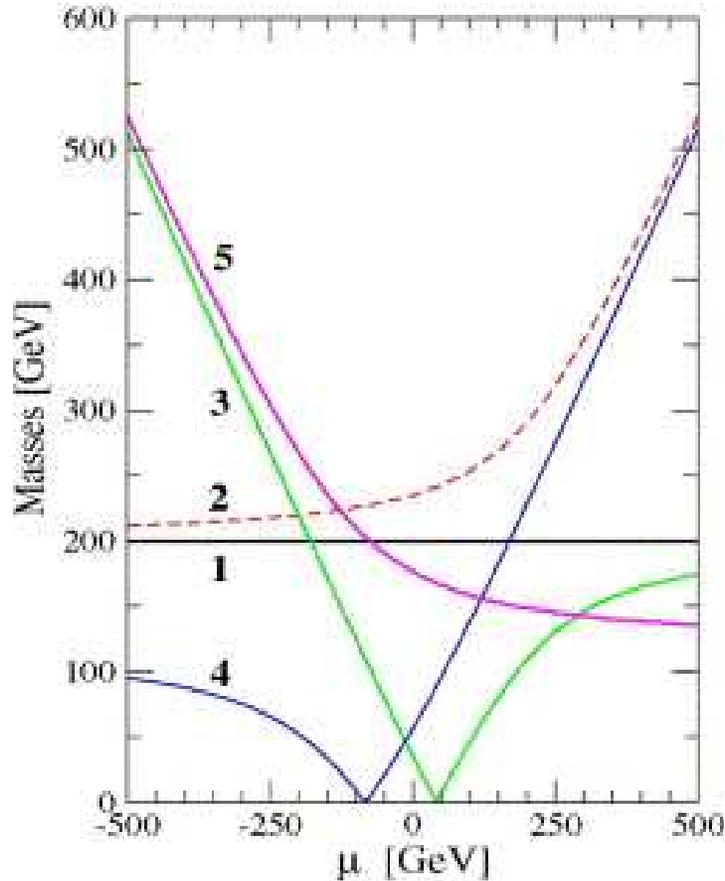
Eur.Phys.J.C47:547-587,2006



NMSSM Neutralino Mass Spectrum

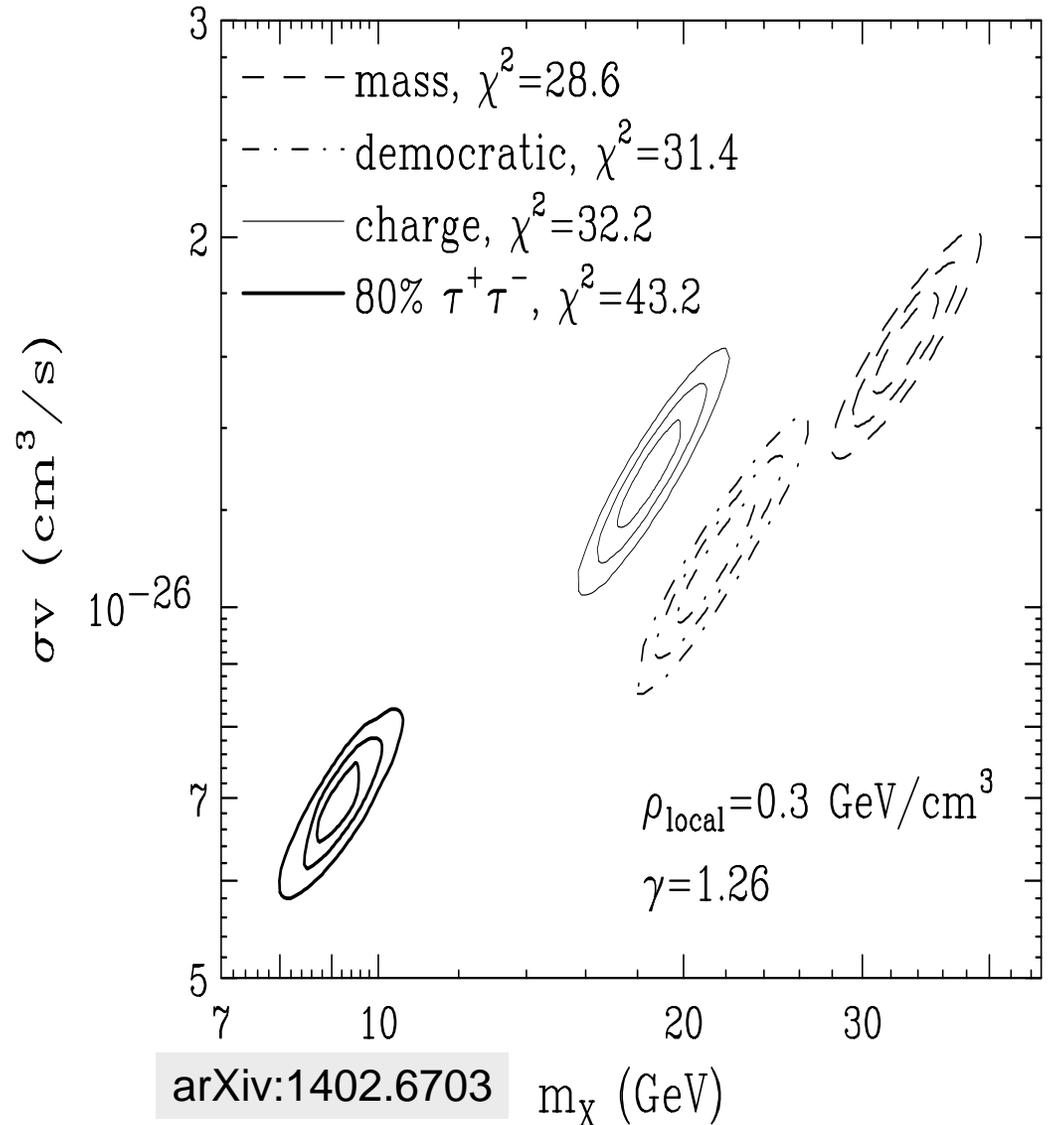


Low mass neutralinos χ absent in the MSSM are motivated by the gamma ray excess in the galactic core and the dark matter relic density as low mass scalars allow $\chi\chi \rightarrow a_1, h_1 \rightarrow q\bar{q}, \ell^+\ell^-$.



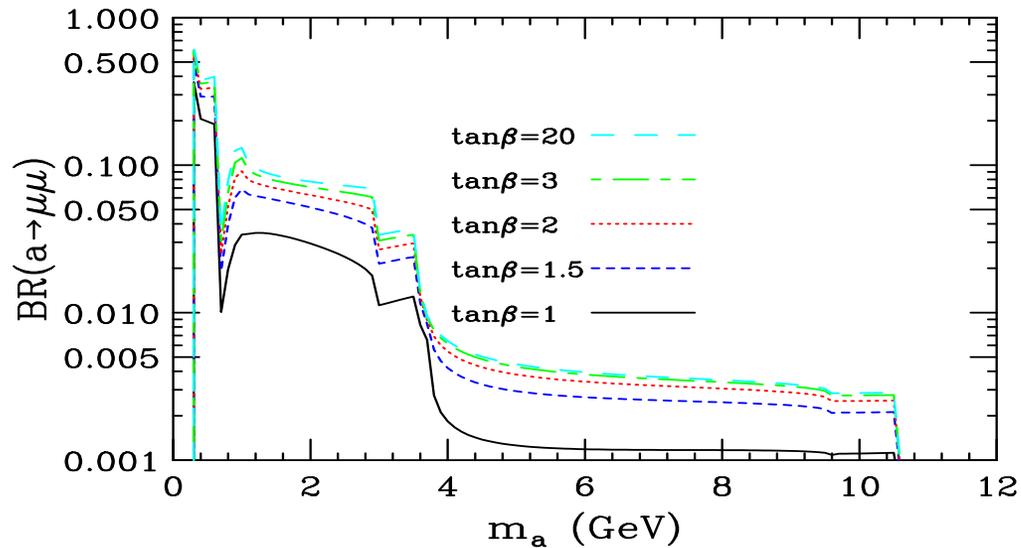
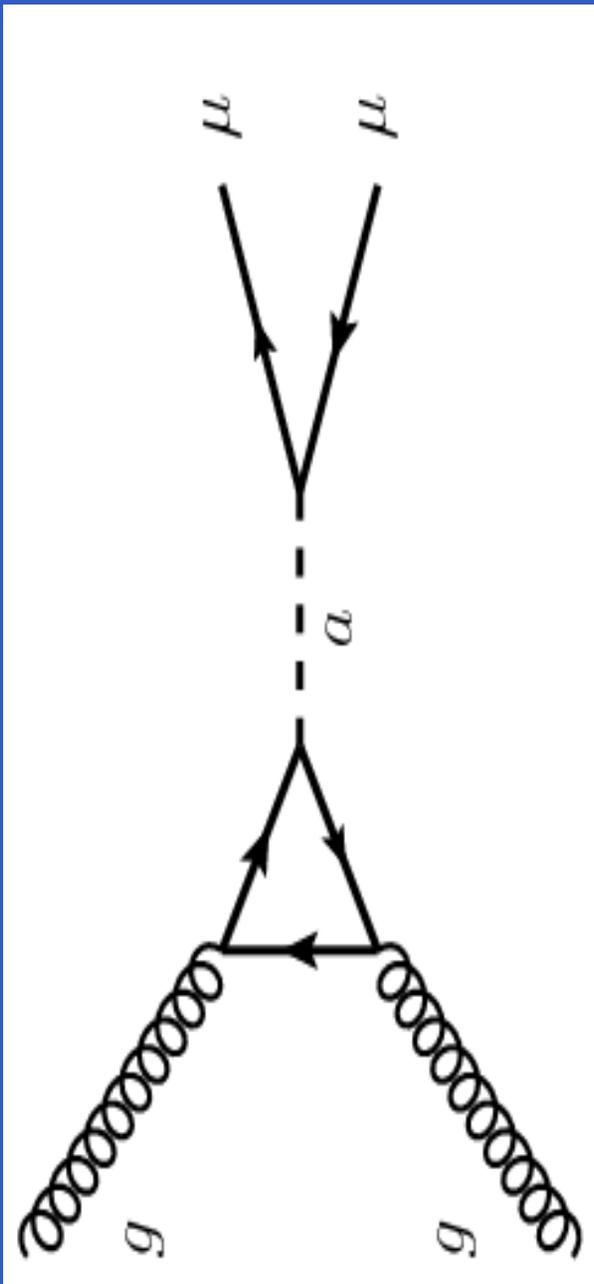
$m_1 = m_2 = 200 \text{ GeV}$, $\mu_\kappa = 120 \text{ GeV}$,
 $\mu_\lambda = 100 \text{ GeV}$

Nucl.Phys.B711:83-111,2005



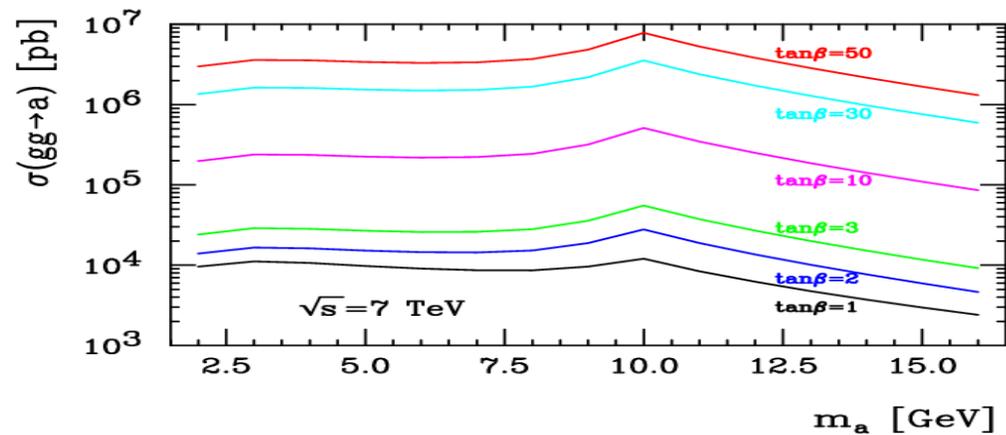
arXiv:1402.6703

NMSSM $gg \rightarrow a_1 \rightarrow \mu^+ \mu^-$ at the LHC



ATLAS-CONF-2011-020

CMS-HIG-12-004



■ Signal Model

- ◆ Pythia 6.4.25 generator used to generate MSSM $A \rightarrow \mu^+ \mu^-$ with CTEQ6 PDF.
- ◆ Fit the signal $m_{\mu^+ \mu^-}$ mass resolution σ and overall efficiency $\epsilon = \epsilon_{acc} \times \epsilon_{trig} \times \epsilon_{sel}$ as a function of $m_{\mu^+ \mu^-}$ to interpolate between generated mass points.

■ Background Model

- ◆ Model is determined from data fit: QCD is fit with degree one polynomial while the $\Upsilon(1, 2, 3s)$ tail are each fit with double Crystal Ball.
- ◆ Crystal Ball parameters are constrained so resolution $\sigma_{\Upsilon(1s)} = \sigma_{\Upsilon(2s)} = \sigma_{\Upsilon(3s)}$ and $\Delta m(\Upsilon(1s), \Upsilon(2s))$ and $\Delta m(\Upsilon(1s), \Upsilon(3s))$ are fixed to world averages.

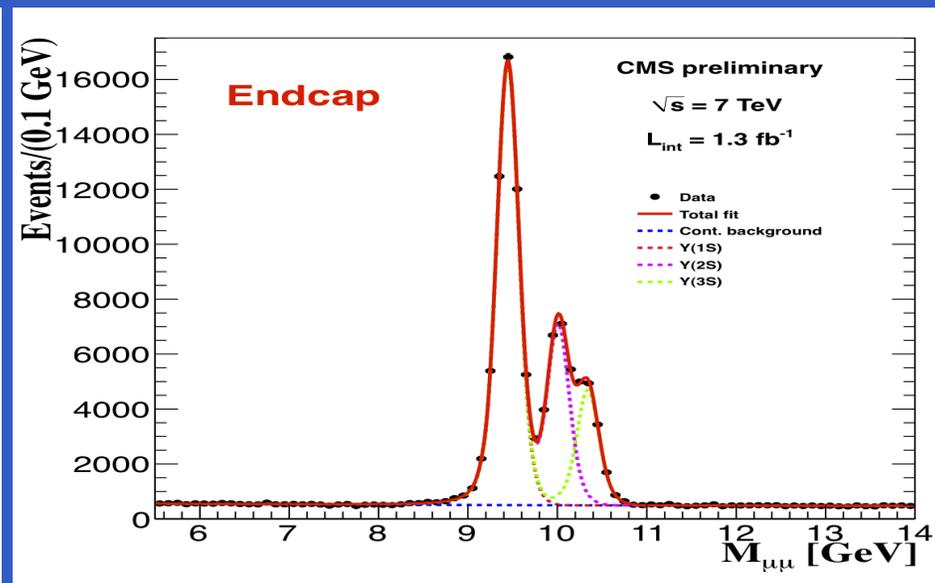
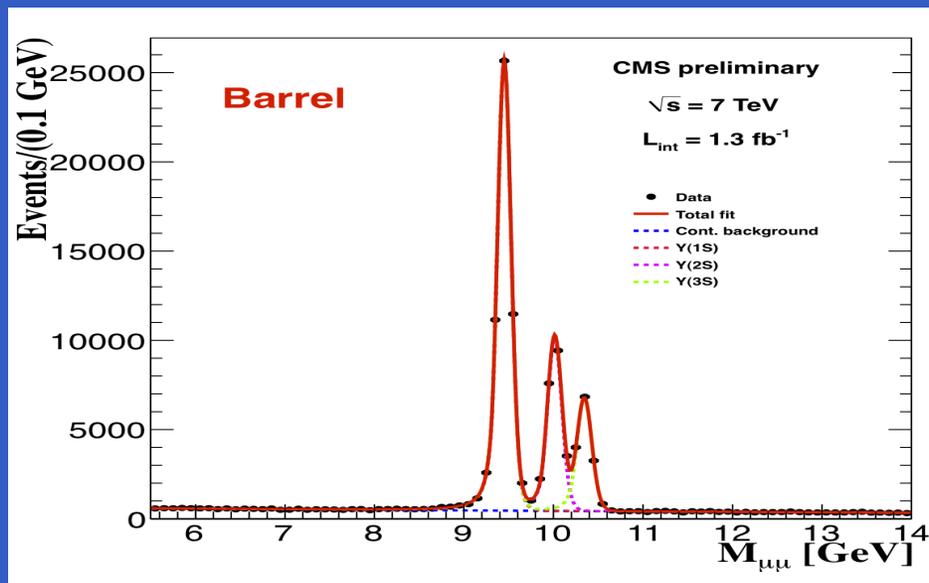
■ Data Selection

- ◆ Trigger on a good primary vertex and two prompt oppositely charged muons with $p_T > 3.5$ GeV, $p_T(\mu^+ \mu^-) > 6$ GeV and $5.5 < m_{\mu^+ \mu^-} < 14$ GeV (prescale 2).
- ◆ Offline selection requires two oppositely charged muons with $|\eta| < 2.4$, $p_T > 5.5$ GeV, relative isolation $I_{rel} < 0.2$ (cone $\Delta R = 0.3$), ≥ 11 pixel hits and track fit $\chi^2/dof < 1.8$.

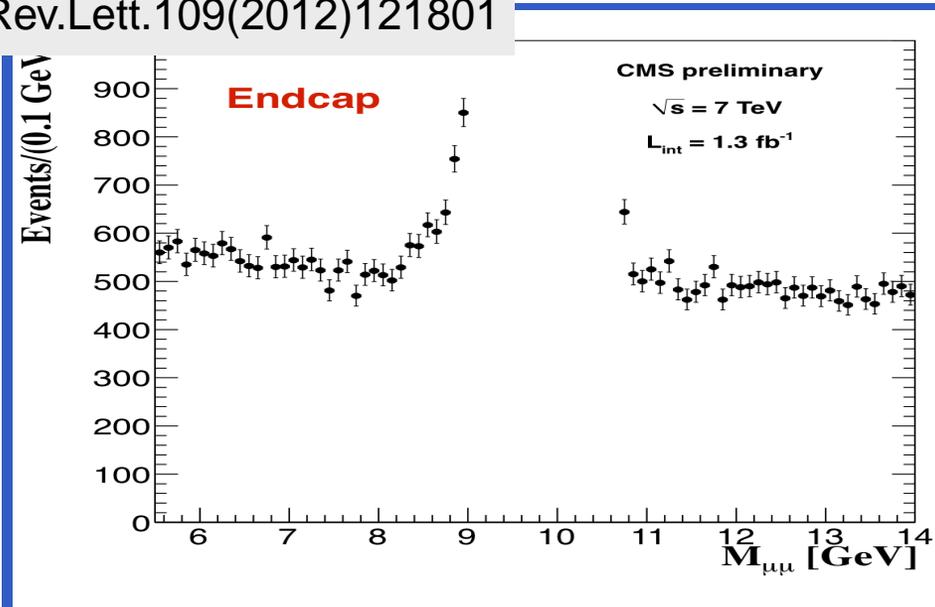
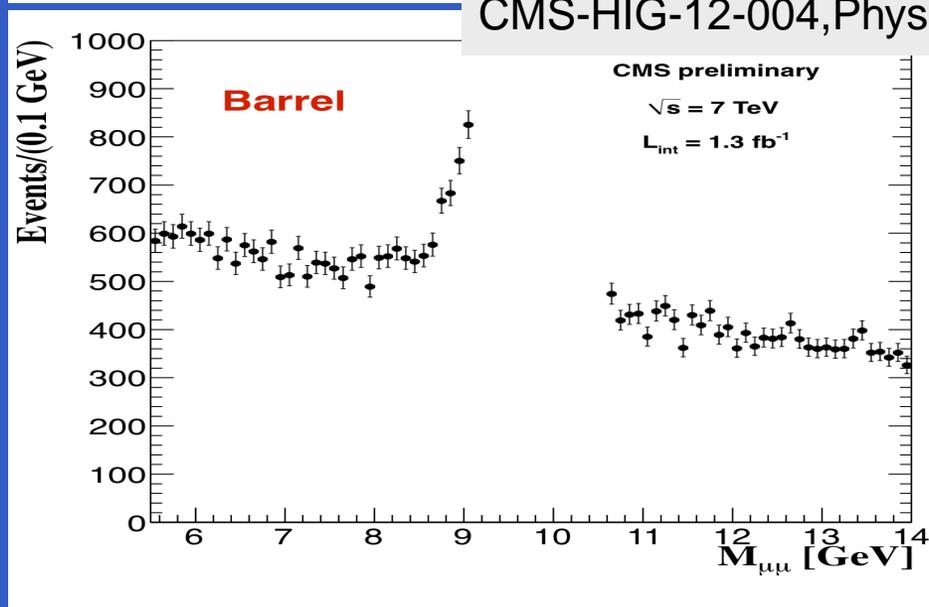
■ Systematic Uncertainties

- ◆ Signal uncertainties of 12% from ϵ , 5% I_{rel} , 11% (4%) barrel (endcap) σ .
- ◆ Background uncertainty of few % from the assumed QCD PDF.

NMSSM $gg \rightarrow a_1 \rightarrow \mu^+ \mu^-$ at CMS (ii)

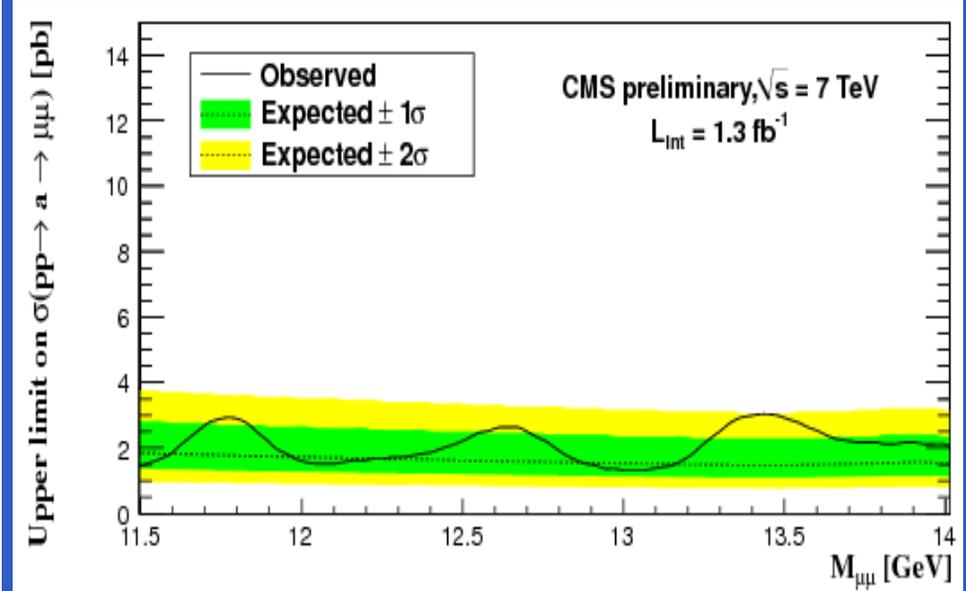
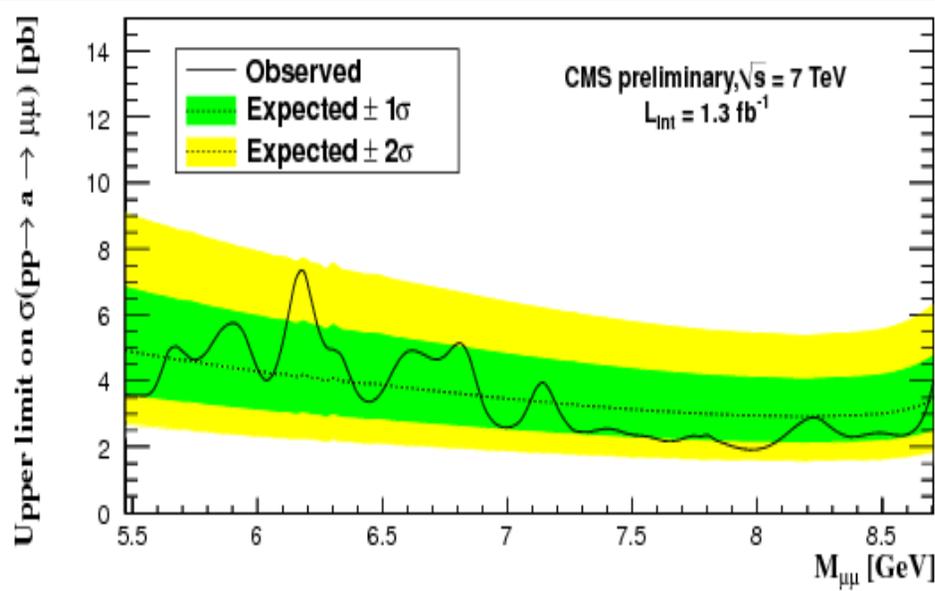


CMS-HIG-12-004, Phys.Rev.Lett. 109(2012)121801

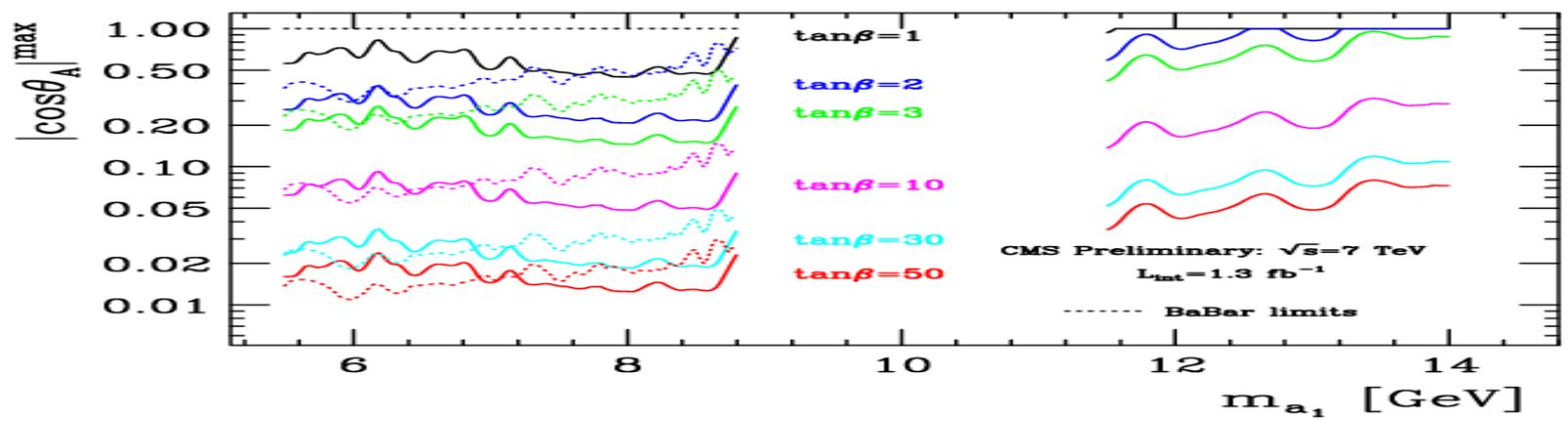


Dimuon invariant mass in the barrel (left) and endcap (right).

NMSSM $gg \rightarrow a_1 \rightarrow \mu^+ \mu^-$ at CMS (iii)

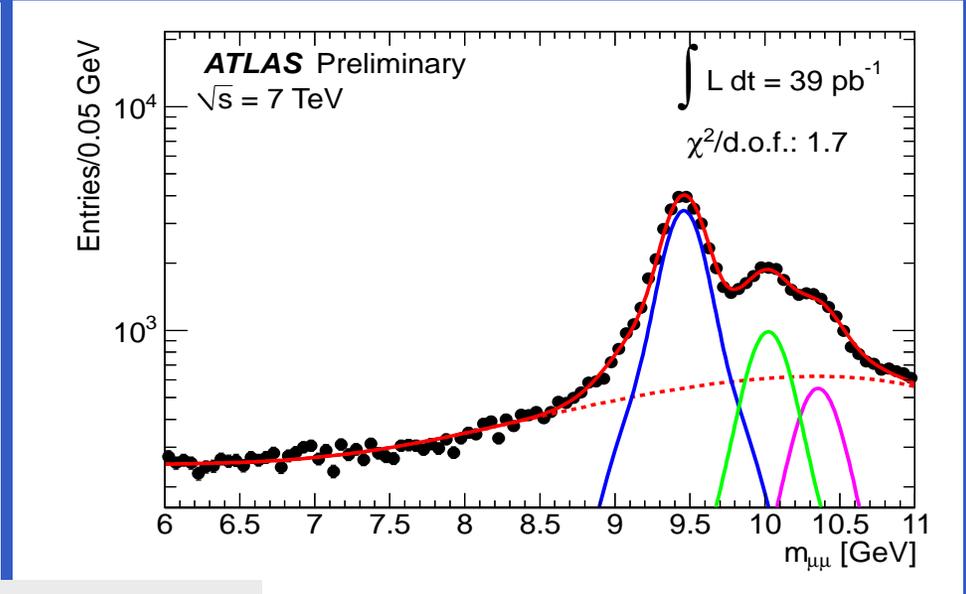
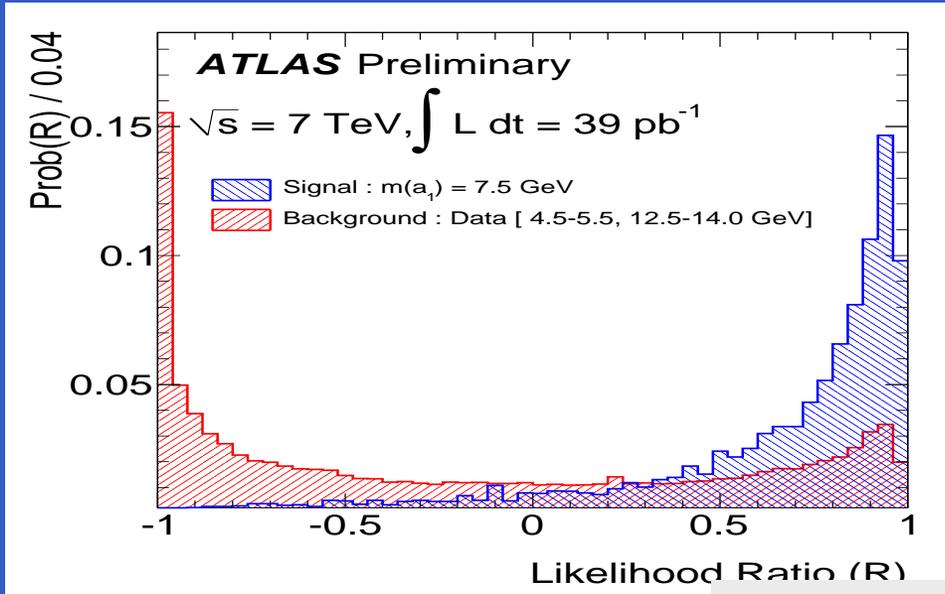


CMS-HIG-12-004, Phys.Rev.Lett. 109(2012)121801

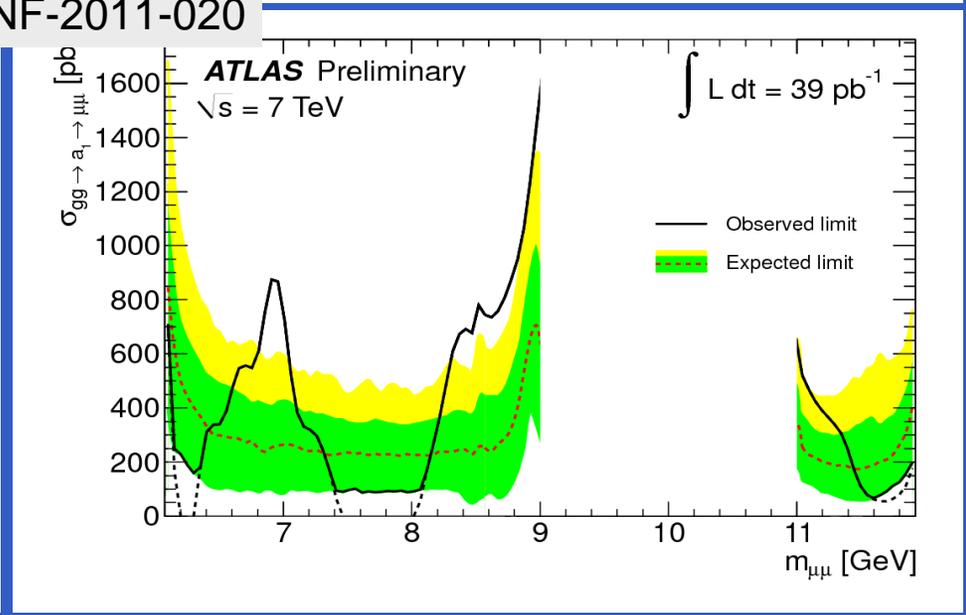
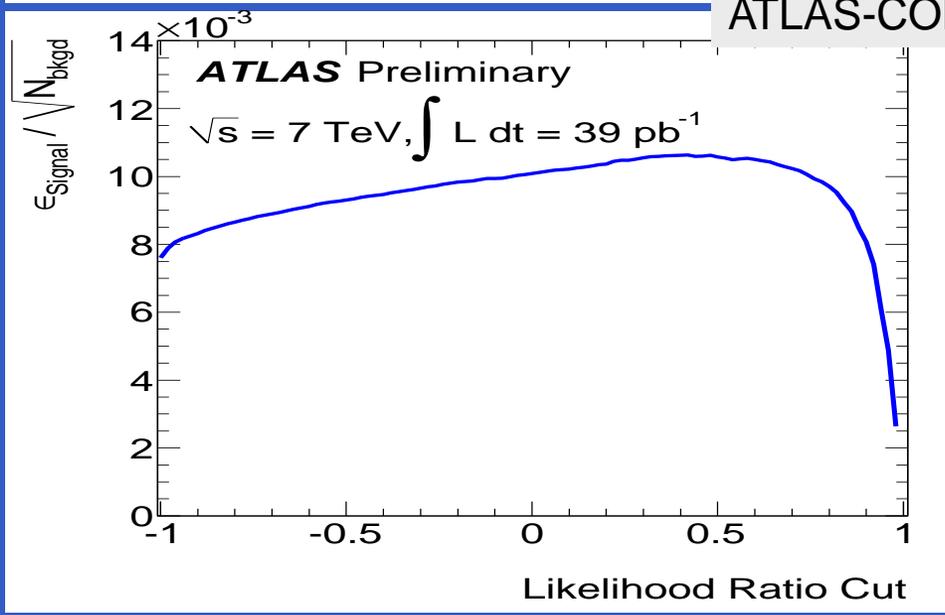


Limits on $\sigma \times BR$ translated to limits on $\cos \theta_A$ ($a_1 = \cos \theta_A a_{MSSM} + \sin \theta_A a_S$).

NMSSM $gg \rightarrow a_1 \rightarrow \mu^+ \mu^-$ at ATLAS

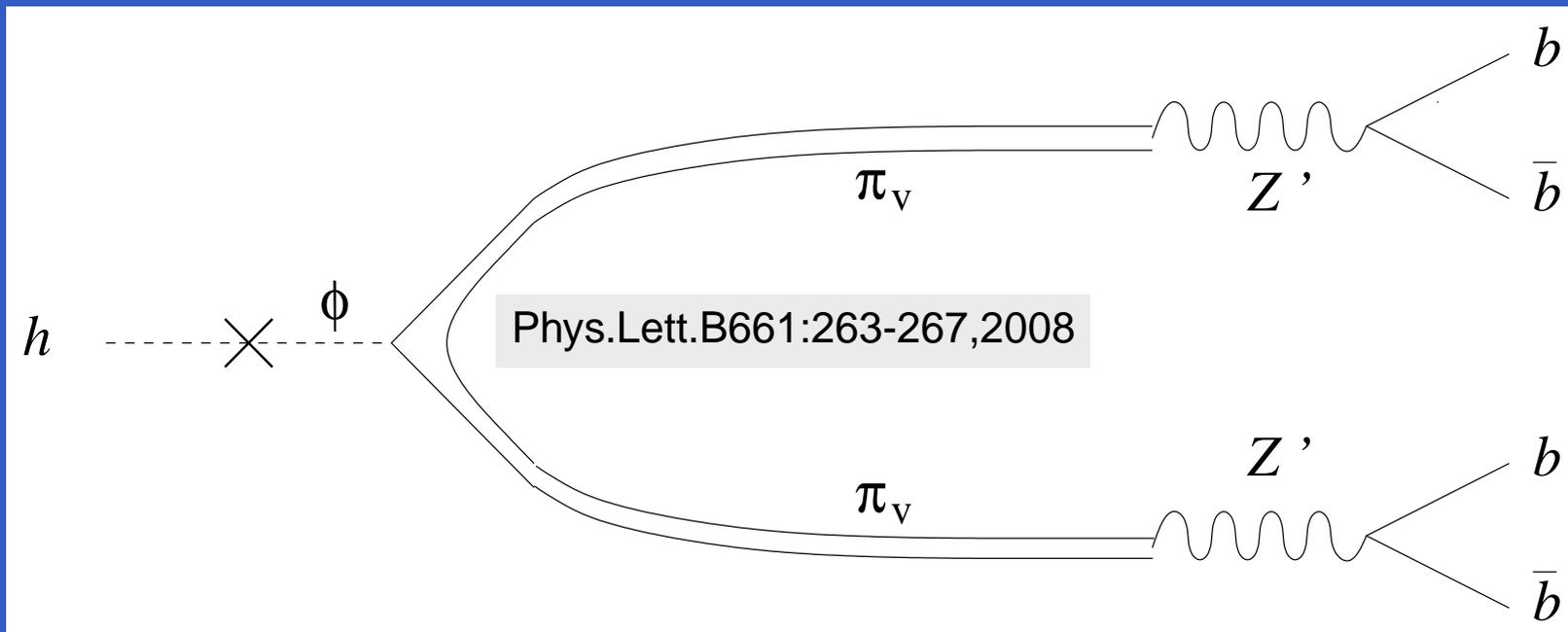


ATLAS-CONF-2011-020



Likelihood ratio and its optimization (left), background fit and limits on $\sigma \times BR$ (right).

Hidden Sector Higgs



- Hidden sector with a non-abelian gauge group where no SM particle is charged.
- Hidden sector consists of a confining gauge group which makes hadrons π_v from hidden sector quarks.
- A scalar ϕ gives mass to the hidden sector quarks and may mix with the SM Higgs.
- Only coupling of the hidden sector to SM is through a heavy Z' , which couples to SM.
- Neutral π_v can have lifetimes of order 100 ps (1ps) for $m_{\pi_v} = 20$ (40) GeV.

Hidden Sector $\Phi_{HS} \rightarrow \pi_\nu \pi_\nu \rightarrow 4j$ at ATLAS (i)



■ Signal Model

- ◆ Pythia8 used to generate $gg \rightarrow \Phi_{HS} \rightarrow 2\pi_\nu$ with longlived $\pi_\nu \rightarrow b\bar{b}, \tau^+\tau^-, c\bar{c}$ with Higgs-like couplings.
- ◆ Masses $m_{\Phi_{HS}} = 100, 126, 140$ GeV, $m_{\pi_\nu} = 10, 20, 25, 40$ GeV depending on $m_{\Phi_{HS}}$.

■ Data Selection

- ◆ Trigger on narrow jets with $E_T > 40$ GeV, no associated tracks and little E_{EM} .
- ◆ Select offline anti- k_T $R = 0.4$ jet with $E_T > 60$ GeV, $|\eta| < 2.5$, $\log_{10}(E_H/E_{EM}) > 1.2$ and no $p_T > 1$ GeV tracks in a cone $R=0.2$ around the jet axis.
- ◆ Select a second offline jet similarly but with relaxed E_T requirement $E_T > 40$ GeV.

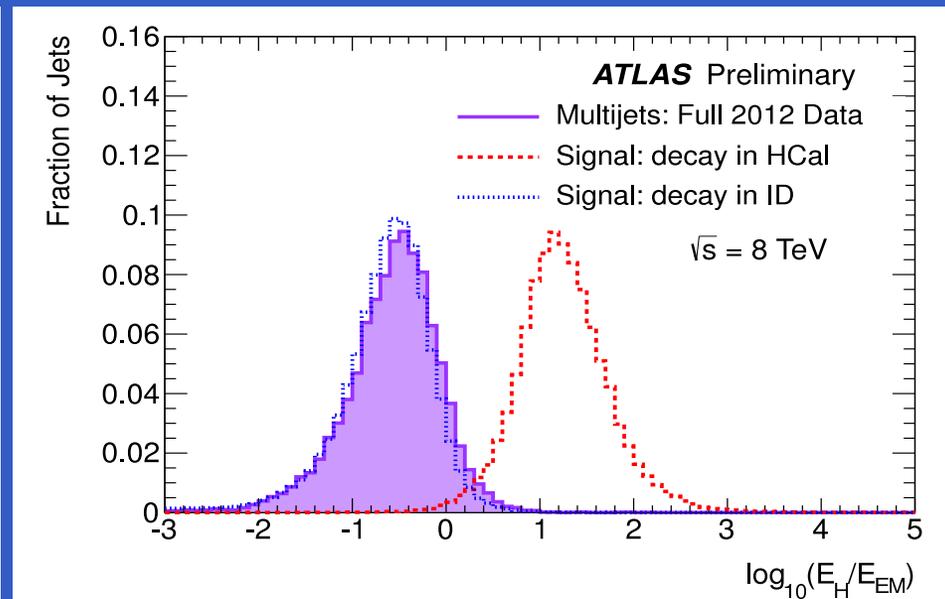
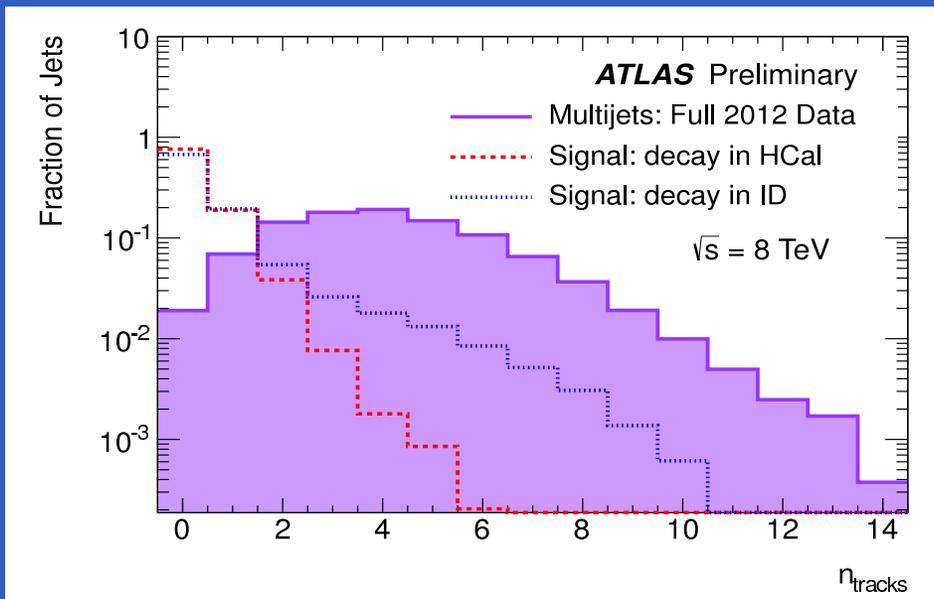
■ Background Model

- ◆ Define a probability P for multijets events to survive the trigger and offline $E_T > 60$ GeV jet requirements and Q to survive the offline $E_T > 40$ GeV jet requirements.
- ◆ Multijets background model is determined from a data fit with Landau PDF for P and exponential PDF for Q .

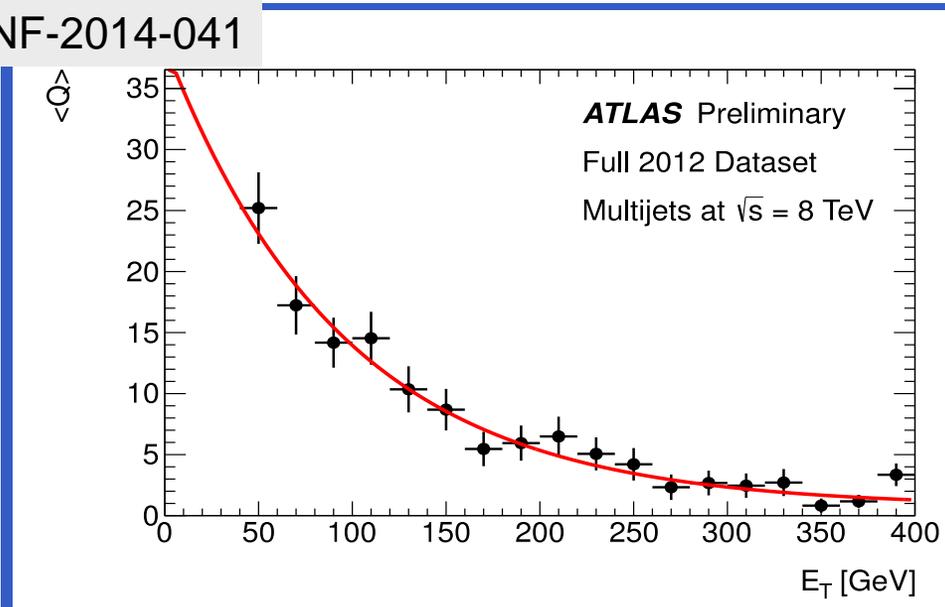
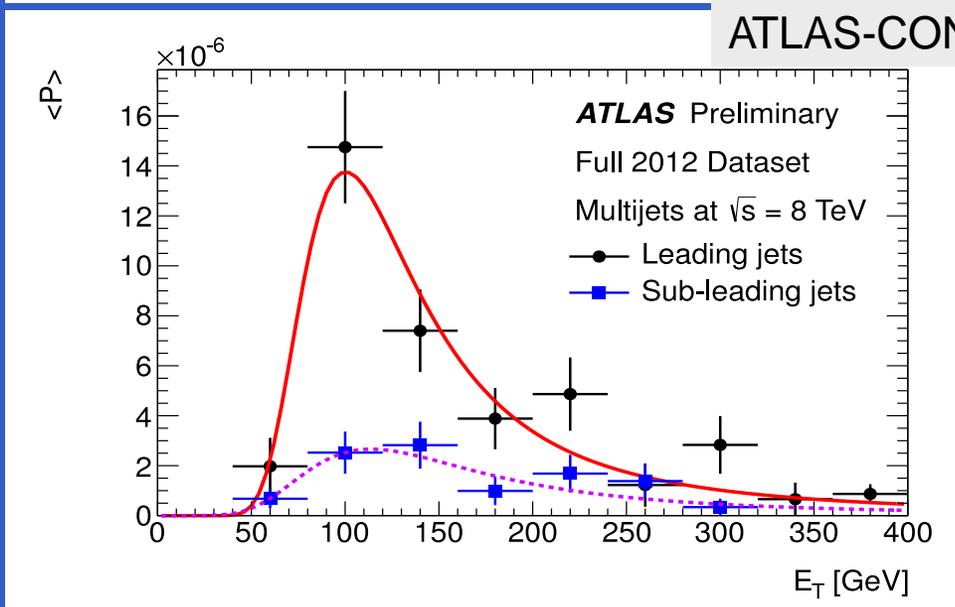
■ Systematic Uncertainties

- ◆ Signal uncertainties dominated by pileup (10%) and production cross section (10%).
- ◆ Secondary uncertainties from JES, trigger, ISR, PDF give overall uncertainties 15-16%.

Hidden Sector $\Phi_{HS} \rightarrow \pi_v \pi_v \rightarrow 4f$ at ATLAS (ii)

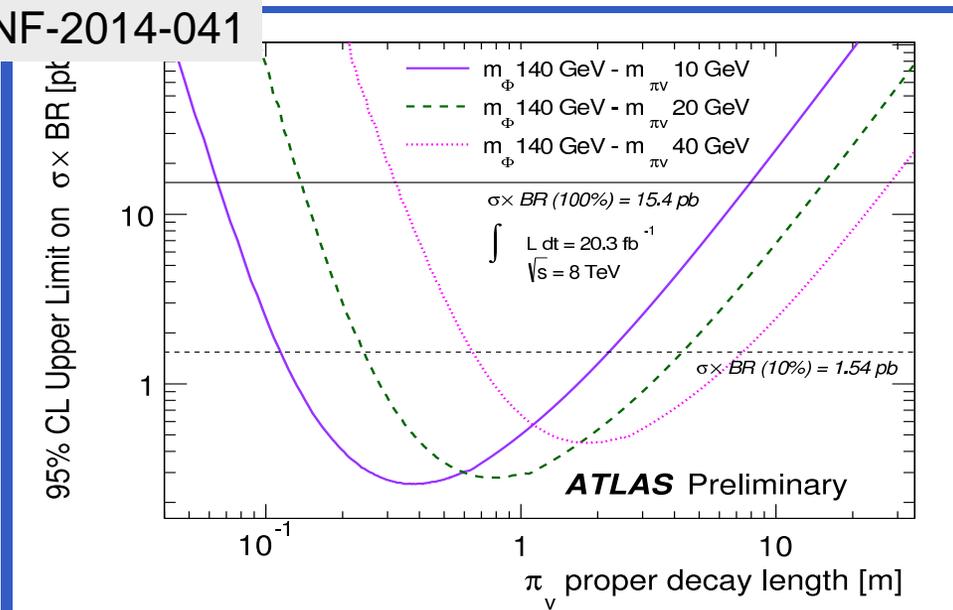
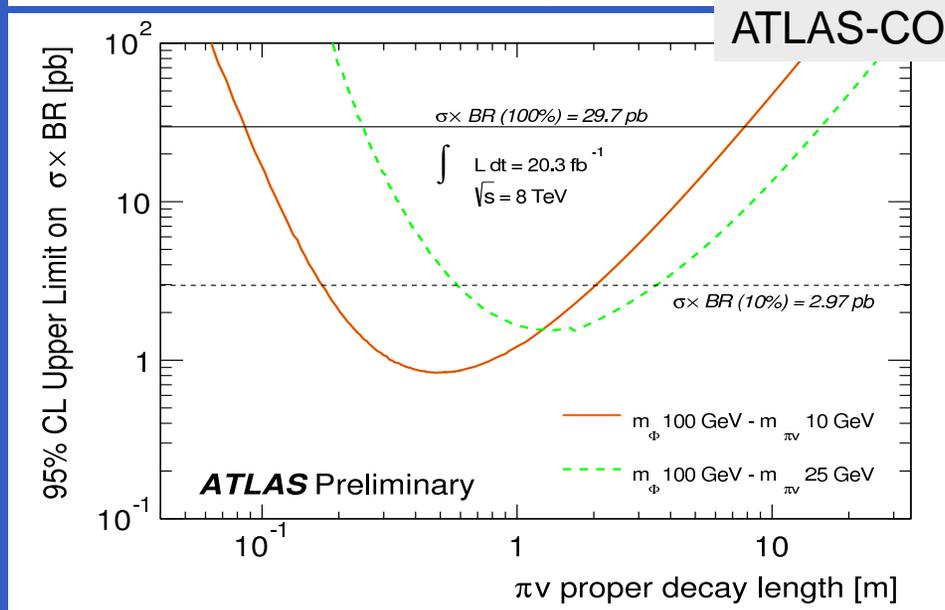
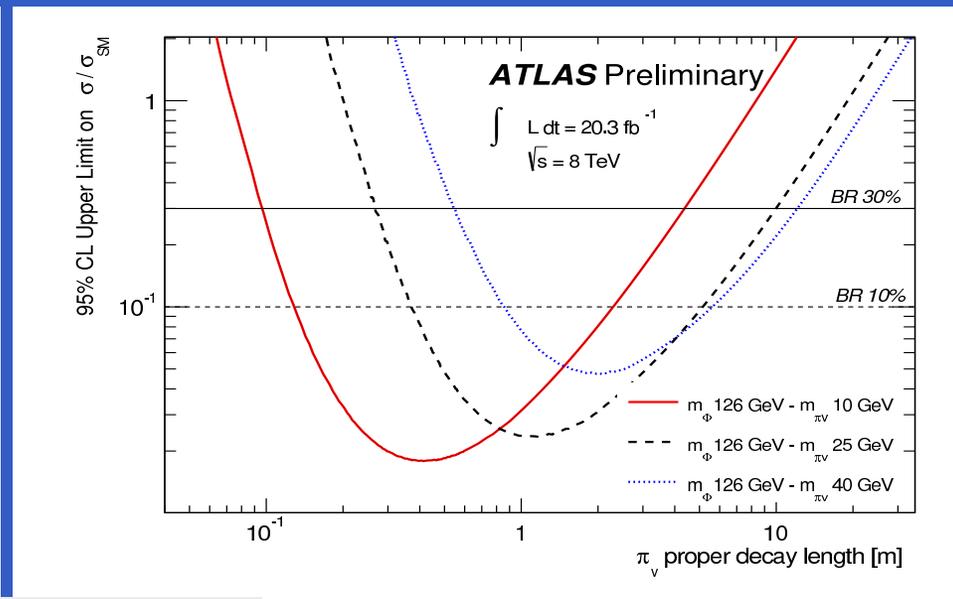
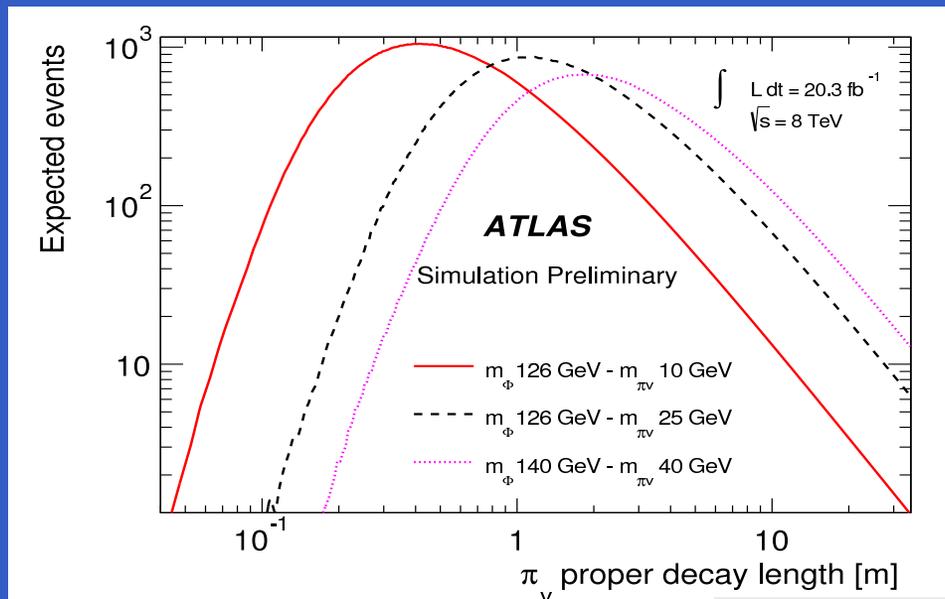


ATLAS-CONF-2014-041



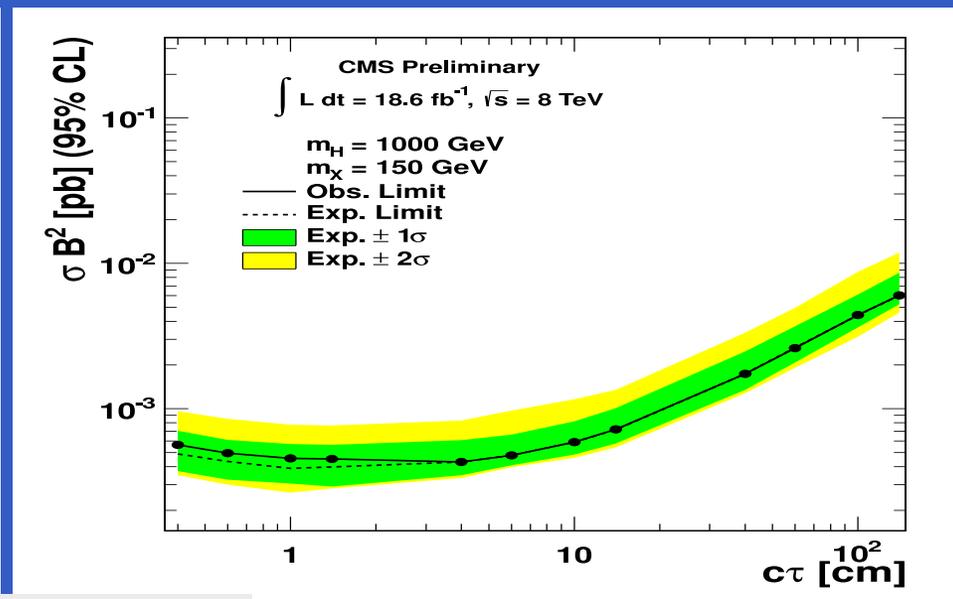
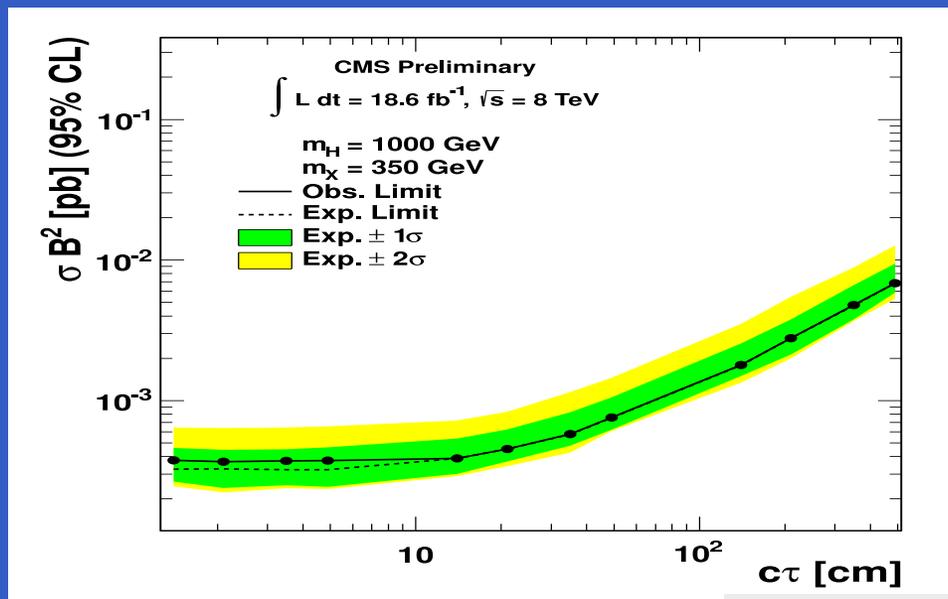
Associated tracks and hadronic component (top), and multijet probabilities P and Q (bottom).

Hidden Sector $\Phi_{HS} \rightarrow \pi_\nu \pi_\nu \rightarrow 4f$ at ATLAS (iii)

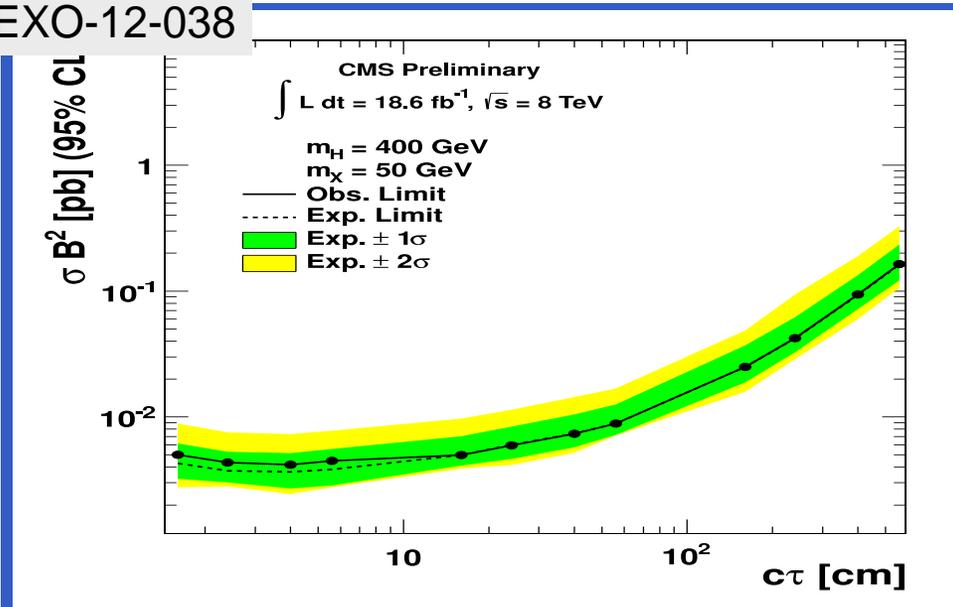
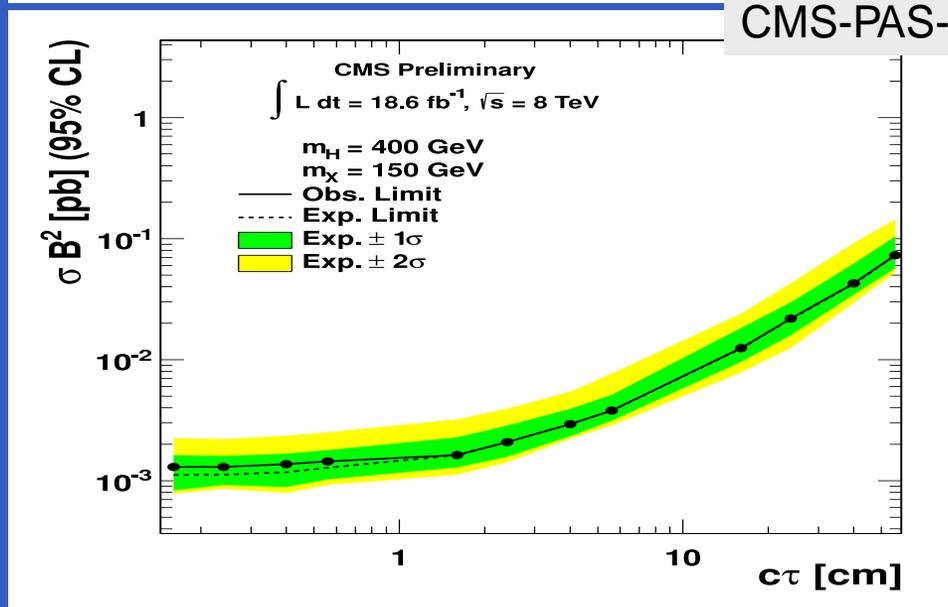


N_{sig}^{exp} vs π_ν decay length and σ/σ_{SM} limits (top), $\sigma \times BR$ limits $m_{\Phi_{HS}} = 100, 140 \text{ GeV}$ (bottom).

Hidden Sector $H^0 \rightarrow X^0 X^0 \rightarrow 4f$ at CMS



CMS-PAS-EXO-12-038



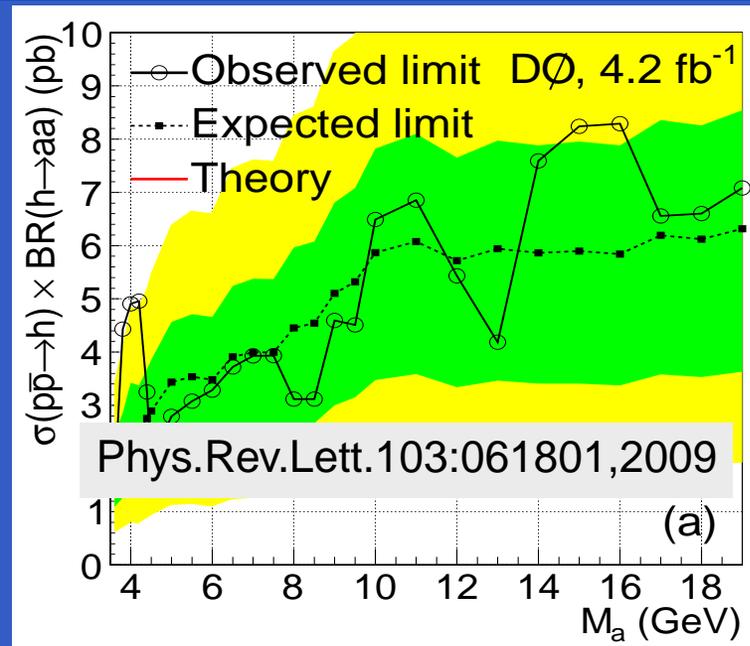
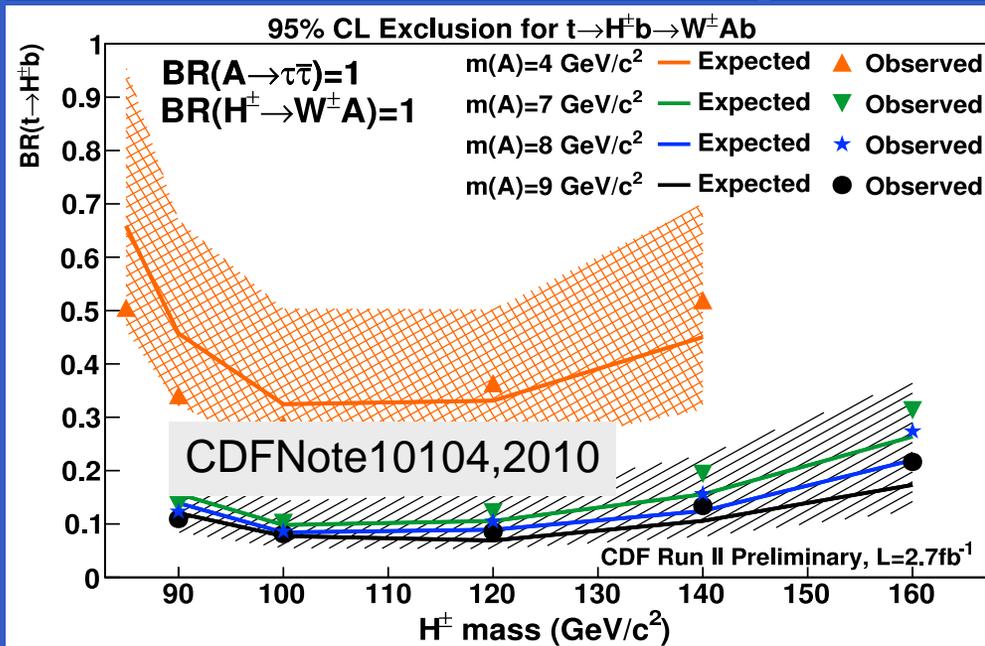
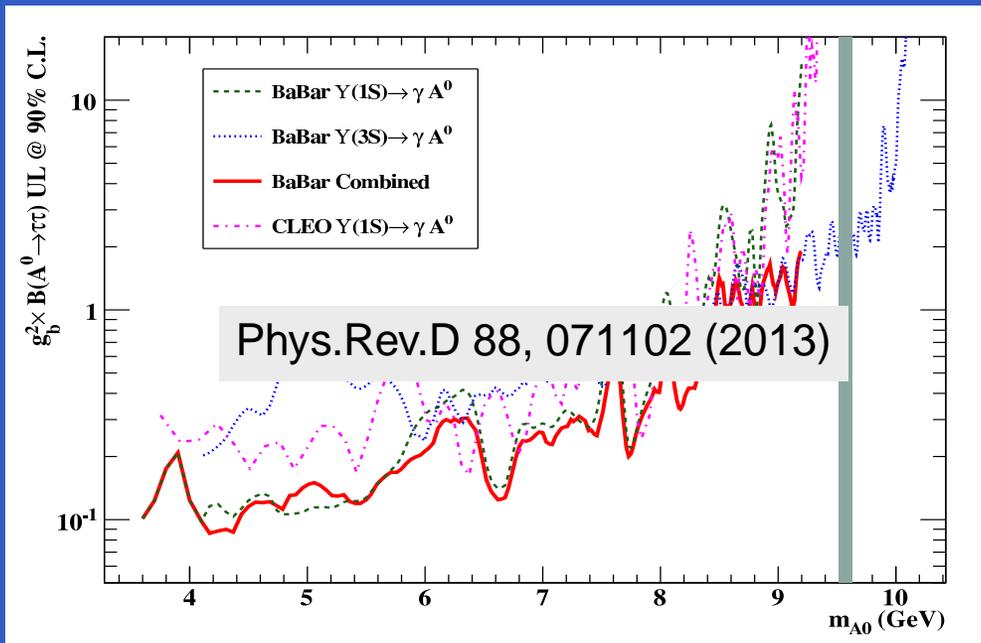
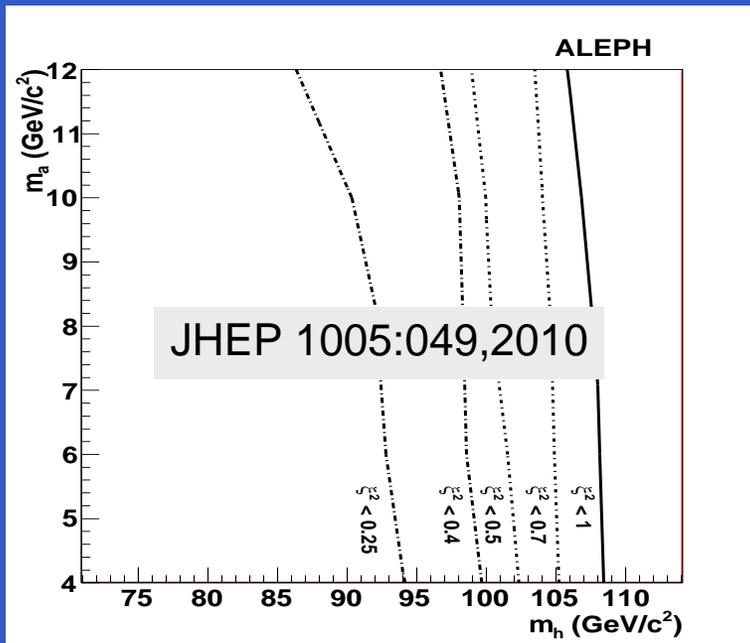
Limits on $\sigma_{pp \rightarrow H^0 \rightarrow 2X^0} \times B(X^0 \rightarrow q\bar{q})$ for $m_{H^0} = 1000 \text{ GeV}$ (top) and $m_{H^0} = 400 \text{ GeV}$ (bottom)

- Couplings of the h_{125} Higgs allow for additional exotic decays, and other Higgs bosons decays are unconstrained.
- The NMSSM provides a solution to the MSSM μ -term problem and includes possibly very light scalars.
- Hidden Sector Higgs decays to longlived neutral particles may be a window to a hidden sector.
- Public searches at the LHC:
 - ◆ NMSSM $gg \rightarrow a_1 \rightarrow \mu^+ \mu^-$ at CMS+ATLAS
 - ◆ NMSSM $h_1 \rightarrow 2a_1 \rightarrow 4\gamma$ at ATLAS (see supplementary slides)
 - ◆ Hidden Sector decays to Longlived Neutral Decays to Dijets at CMS+ATLAS
 - ◆ Hidden Sector decays to Lepton Jets at ATLAS (see supplementary slides)
- Outlook
 - ◆ More LHC Run1 Higgs analyses are underway.
 - ◆ Run2 promises more data and more powerful constraints (or even discovery).

Thanks to the BSMHiggs@LPC organizers,
and bring on Run2!



NMSSM Higgs at Aleph, BaBar, DZero, CDF



■ Signal Model

- ◆ Signal model from MC@NLO generator $a \rightarrow \mu^+ \mu^-$ with CTEQ6.6 PDF.
- ◆ Signal efficiency is $\epsilon = \epsilon_{acc} \times \epsilon_{trig} \times \epsilon_{\mu^+ \mu^-} \times \epsilon_{LR}$.

■ Background Model

- ◆ Model is determined from data fit: QCD is fit with degree four polynomial while the $\Upsilon(1, 2, 3s)$ are each fit with double Gaussian.
- ◆ Gaussian parameters are constrained so resolution $\sigma_{\Upsilon(2,3s)}$ fixed to linear extrapolation from fitted $\Upsilon(1s)$ and $m_{\Upsilon(1,2,3s)}$ are fixed to world averages.

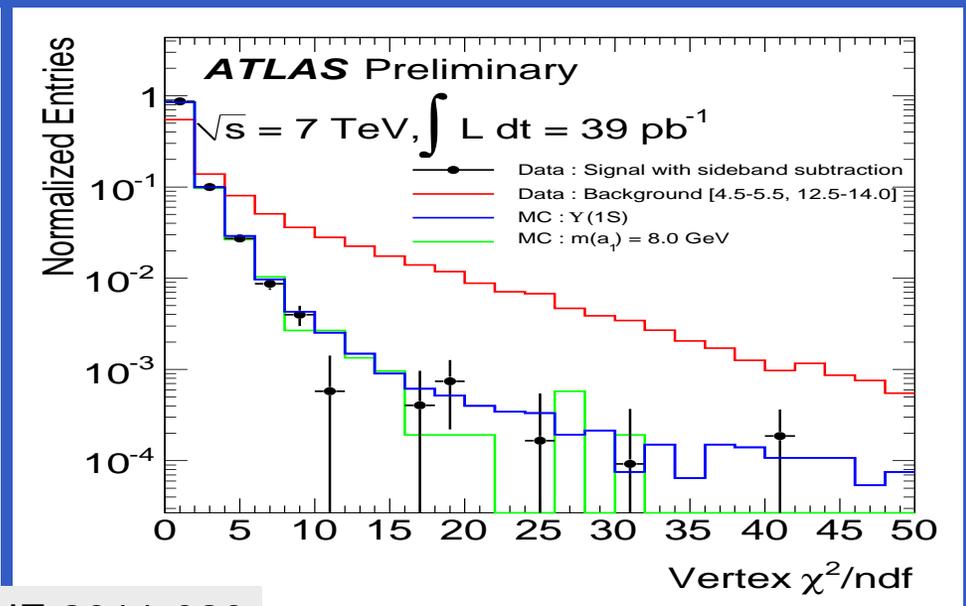
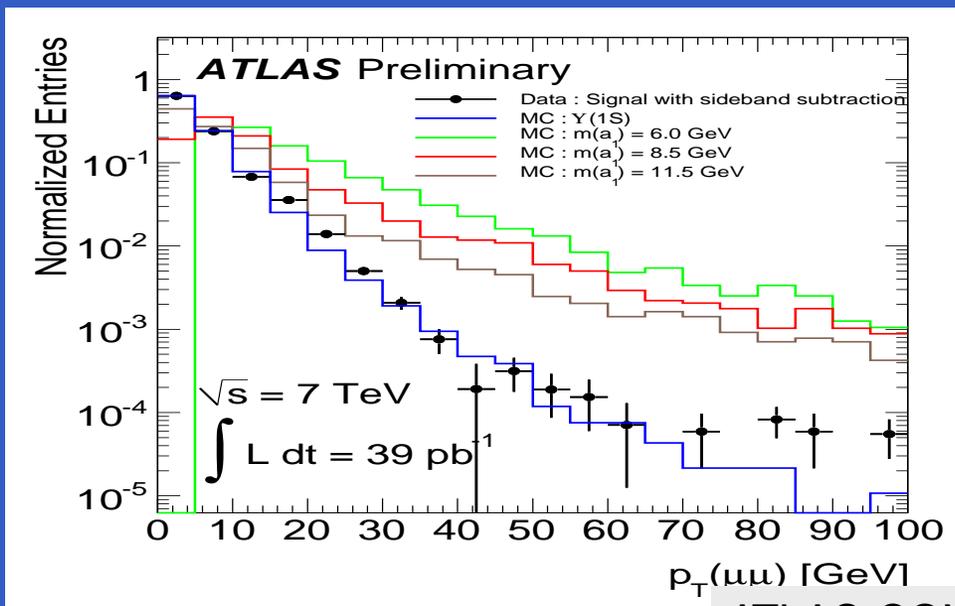
■ Data Selection

- ◆ Trigger on two muons with $p_T > 4$ GeV. Offline muon selection requires two trigger matched oppositely charged muons with $|\eta| < 2.5$, $p_T > 4$ GeV, $4.5 < m_{\mu^+ \mu^-} < 14$ GeV and with track ≥ 6 tracker hits and ≥ 1 pixel hit.
- ◆ A likelihood ratio $R = (1 - \Pi y_i) / (1 + \Pi y_i)$ is constructed with dimuon vertex fit $\chi^2 / ndof$ and calorimeter isolation E_T^{cone20} (cone $\Delta R = 0.2$) from both muons.

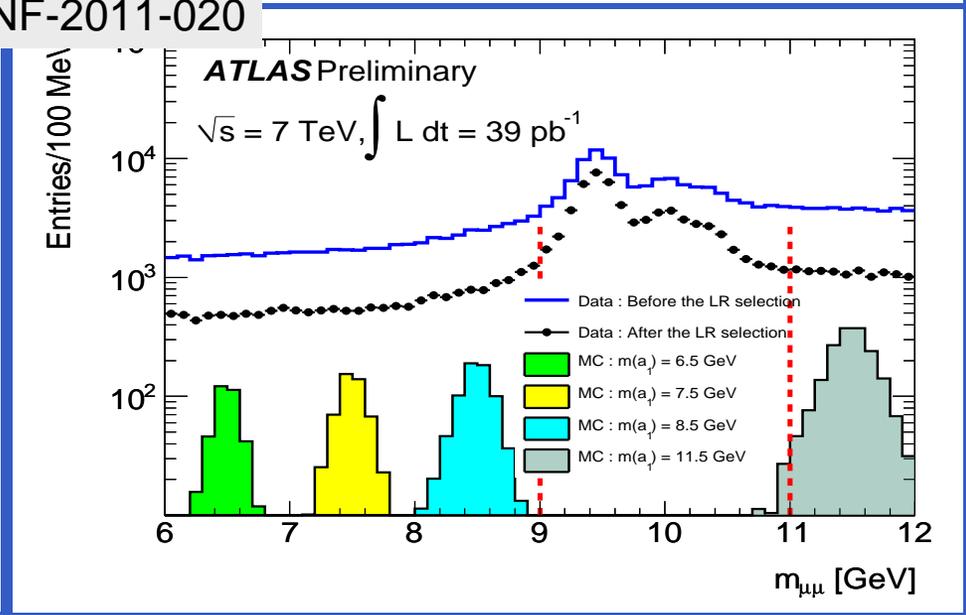
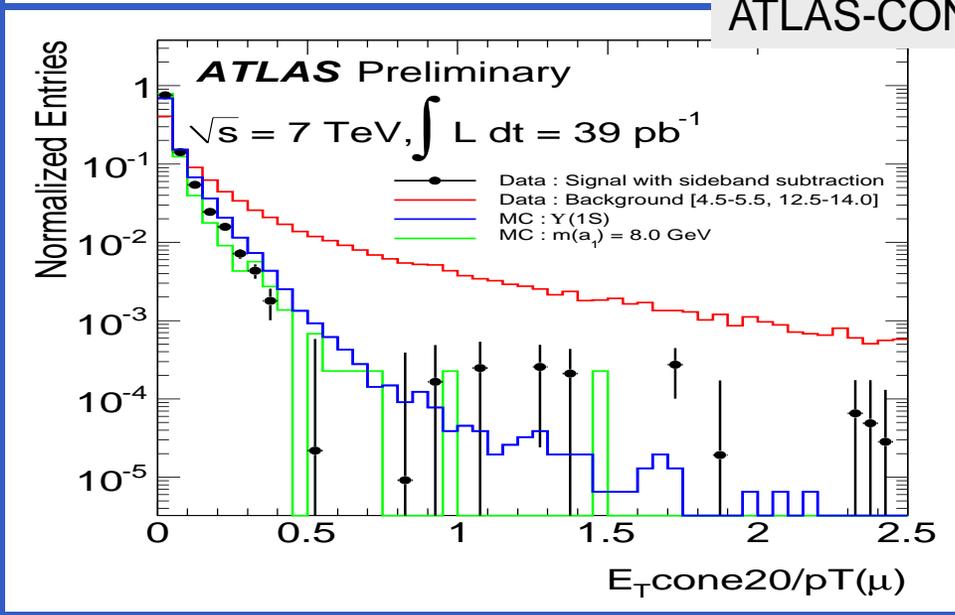
■ Systematic Uncertainties

- ◆ Signal uncertainties 20-67% from ϵ_{acc} from a_1 p_T modeling (MC@NLO vs Pythia).
- ◆ Signal uncertainties 10% from ϵ_{trig} , 14% $\epsilon_{\mu^+ \mu^-}$, 3% ϵ_{LR} .

NMSSM $gg \rightarrow a_1 \rightarrow \mu^+ \mu^-$ at ATLAS (ii)



ATLAS-CONF-2011-020



Muon p_T , dimuon $\chi^2/ndof$, muon relative isolation and dimuon invariant mass.

■ Signal Model

- ◆ Signal generator Powheg/Pythia for gg fusion and VBF , Pythia for Vh and $t\bar{t}h$. Assume SM Higgs cross sections and $100 < m_{a_1} < 400$ MeV with zero a_1 decay length.
- ◆ Fit signal distributions with Crystal Ball PDF and interpolate fit parameters between generated mass points.

■ Background Model

- ◆ Background model from data fit with an exponential PDF outside signal region.
- ◆ Excess seen in the SM $H \rightarrow 2\gamma$ search is not significant with looser γ ID.

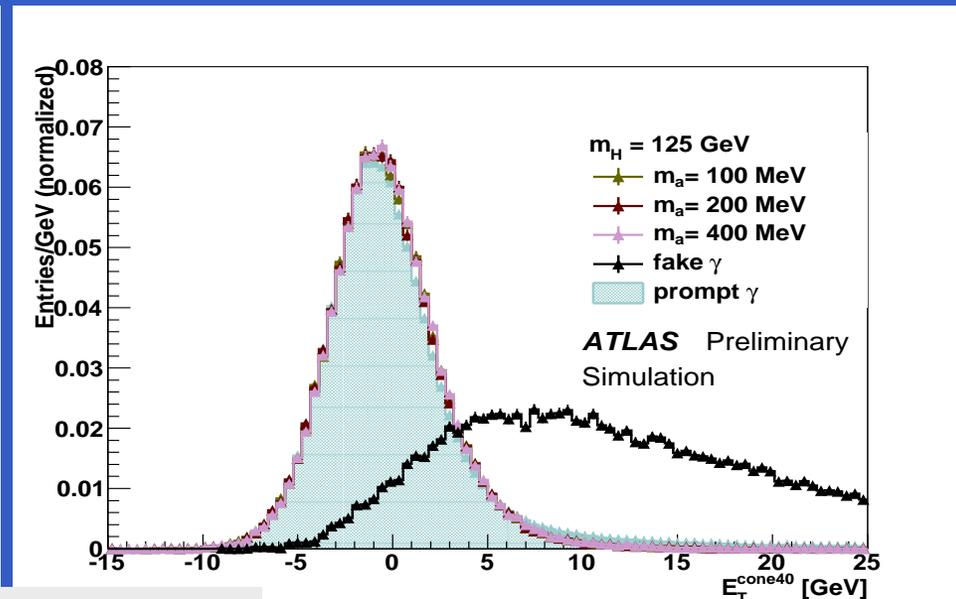
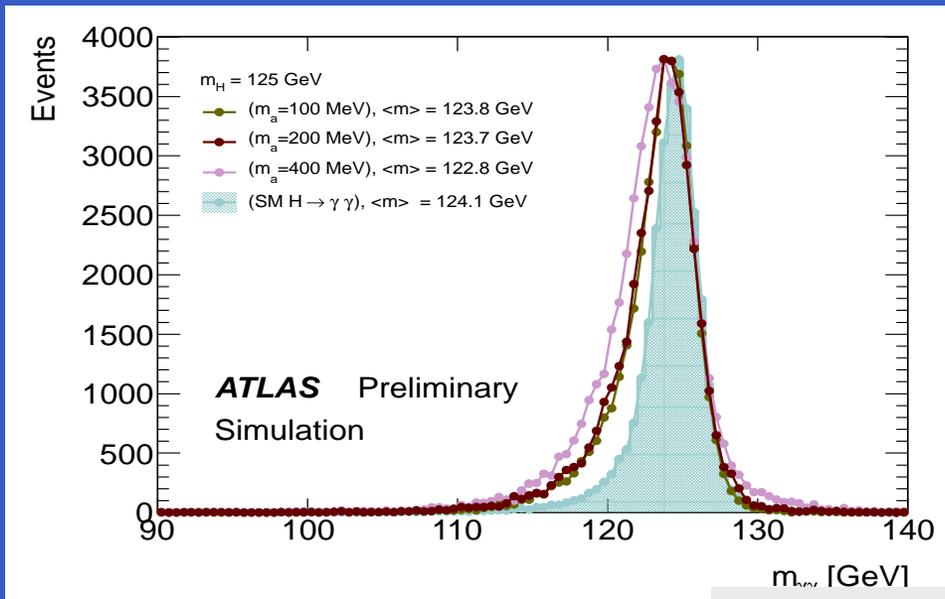
■ Data Selection

- ◆ Trigger on 2γ with $E_T > 20$ GeV with loose shower shape requirements.
- ◆ Offline γ selection requires $E_T > 25, 40$ GeV with $|\eta| < 1.37$ and $1.52 < |\eta| < 2.37$ and γ calorimeter isolation $E_T^{cone40} < 5$ GeV.
- ◆ Remove shower structure requirements on γ ID since highly collimated $a_1 \rightarrow 2\gamma$ are reconstructed as one γ .

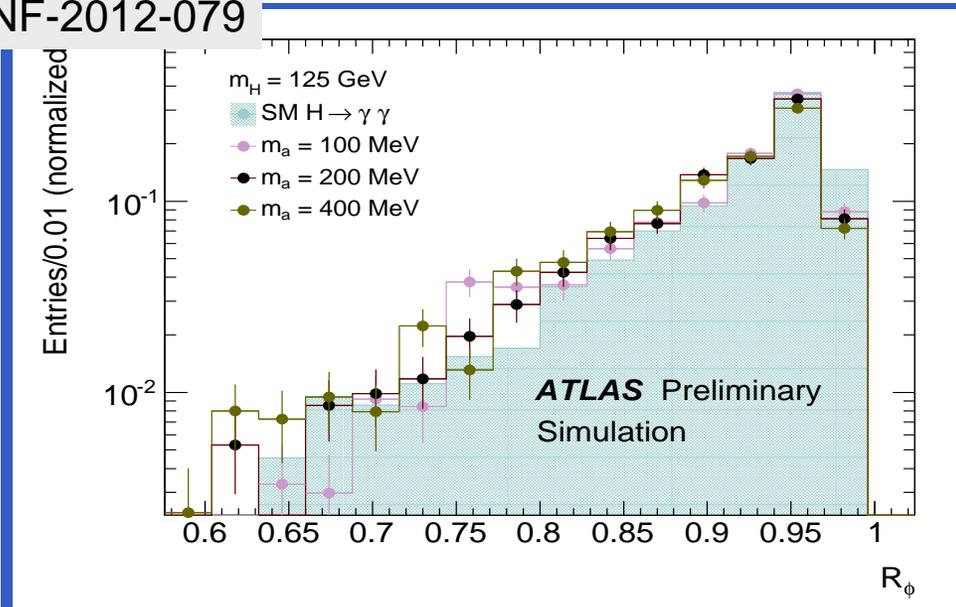
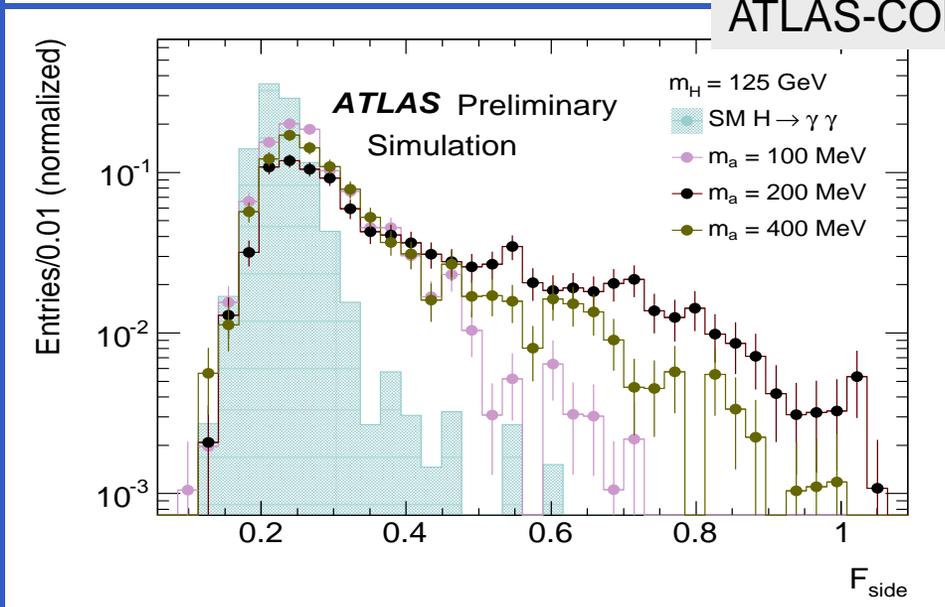
■ Systematic Uncertainties

- ◆ Signal efficiency uncertainty from trigger, γ ID, pileup and calorimeter isolation is 21%.
- ◆ Signal resolution uncertainty from calorimeter resolution and energy calibration is 17%.

NMSSM $h \rightarrow 2a_1 \rightarrow 4\gamma$ at ATLAS (ii)

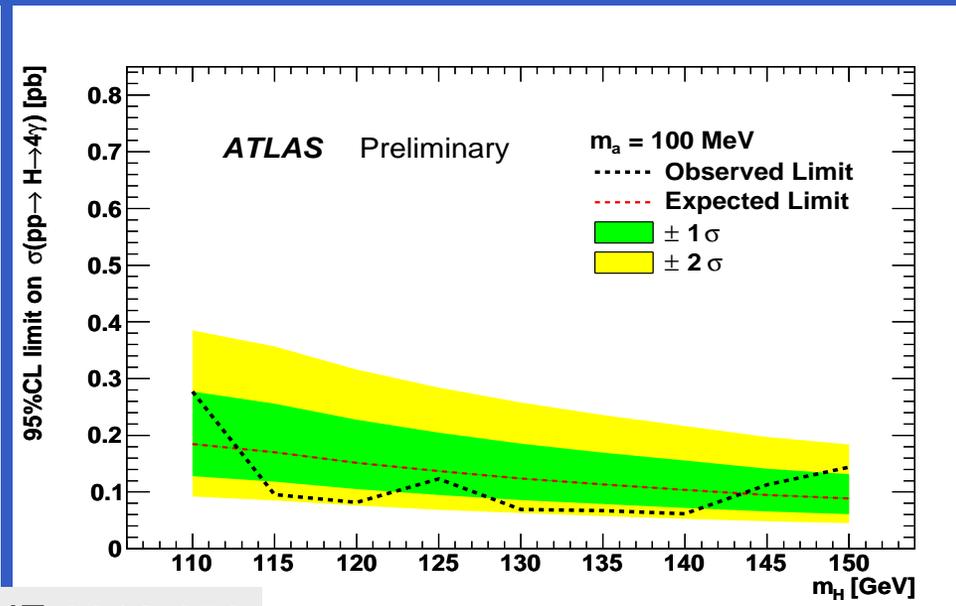
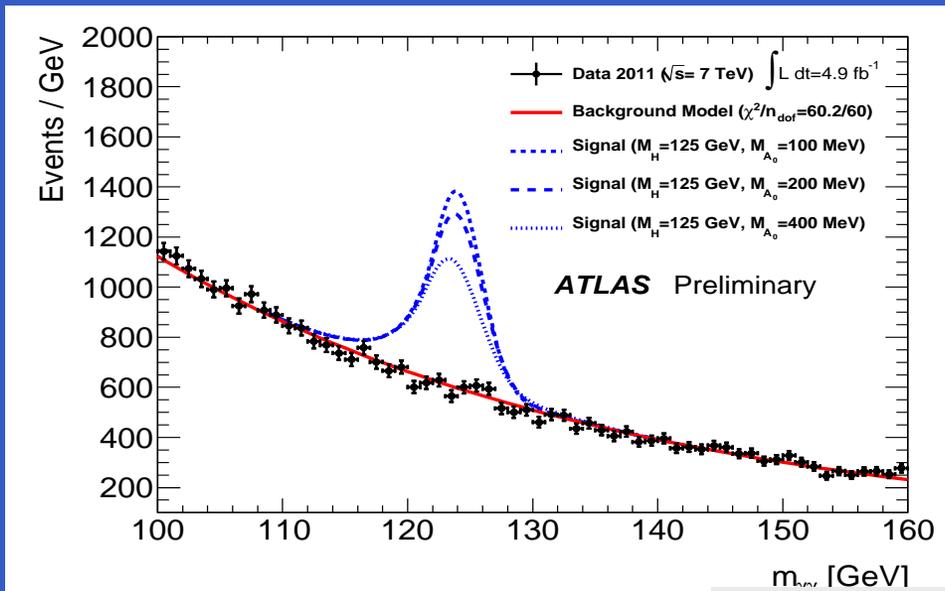


ATLAS-CONF-2012-079

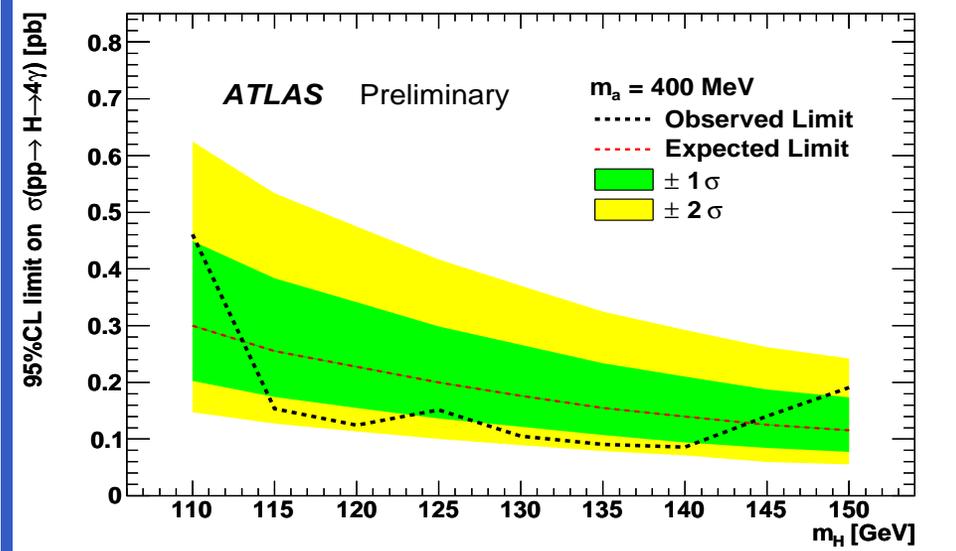
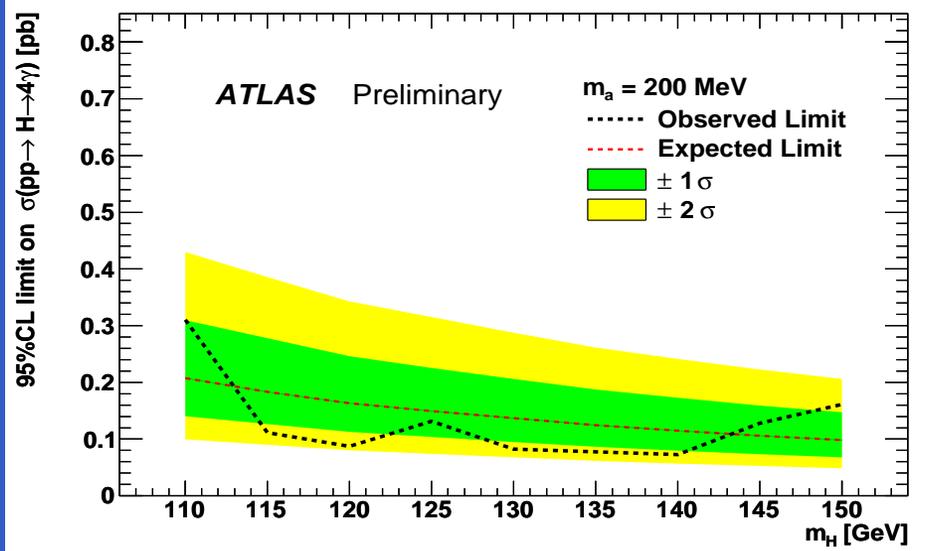


$m_{\gamma\gamma}$ and γ calorimeter isolation (top), and structure and width shower shape variables (bottom).

NMSSM $h \rightarrow 2a_1 \rightarrow 4\gamma$ at ATLAS

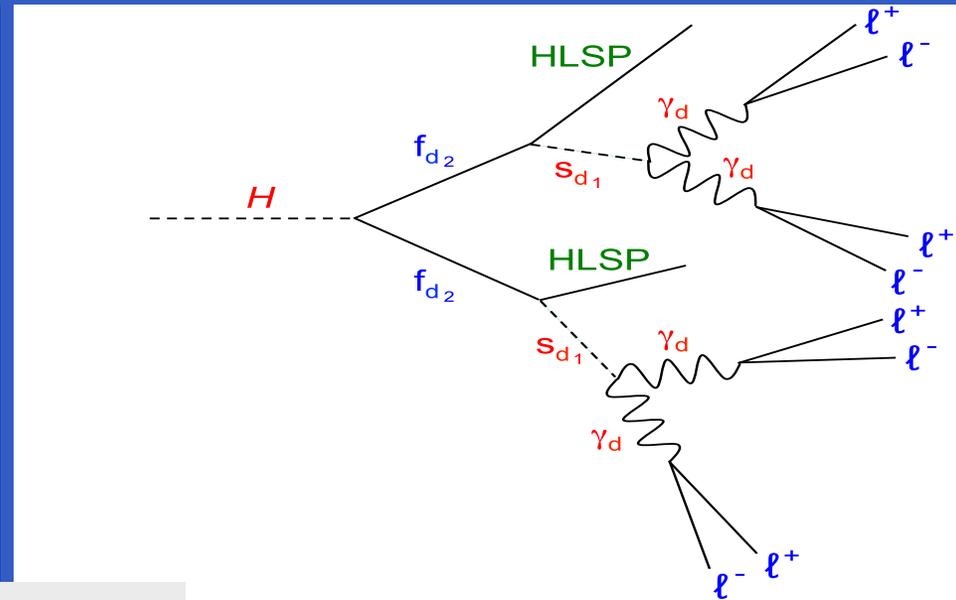
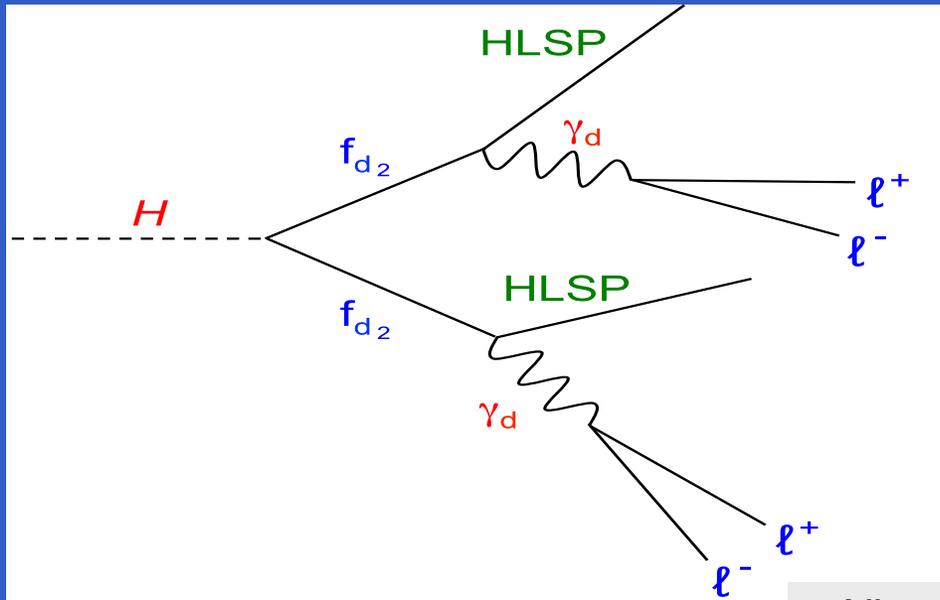


ATLAS-CONF-2012-079

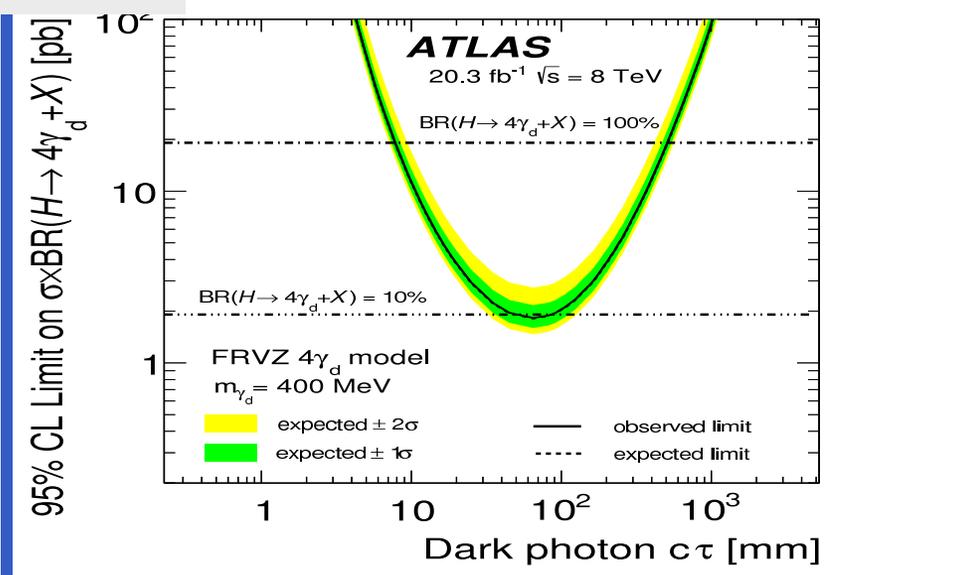
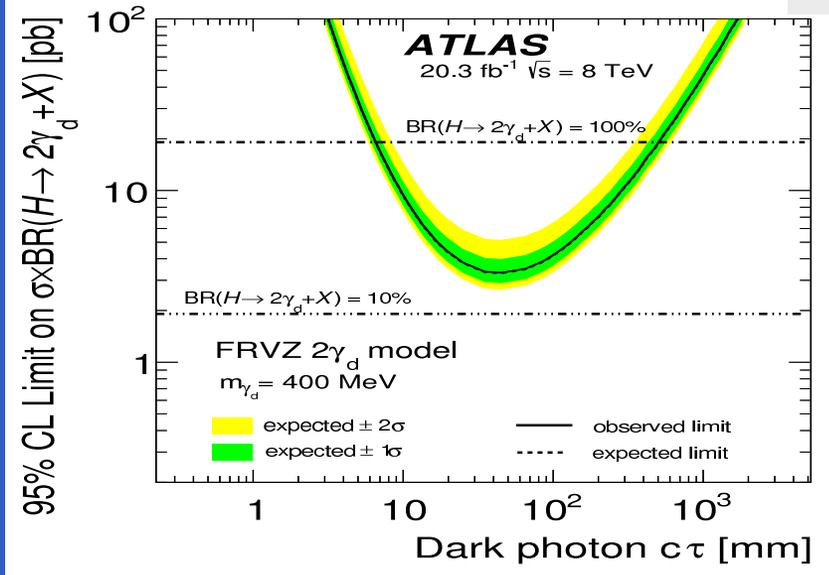


$m_{\gamma\gamma}$ in data with background fit (top left) and CLs limits for $m_a = 100, 200, 400$ MeV.

Hidden Sector $H^0 \rightarrow 2/4\gamma_d \rightarrow LJ_s$ at ATLAS



arXiv:1409.0746



Diagrams for FRVZ decays producing $2\gamma_d$ and $4\gamma_d$ (top), and limits on $\sigma \times BR$ (bottom).

Hidden Sector $H^0 \rightarrow \gamma_d \gamma_d \rightarrow LJs$ at ATLAS (ii)

