

Searches for Higgs bosons and other new physics in BSM

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On behalf of the ATLAS and CMS
Collaborations

Opening up the TeV scale at the LHC

Major goals of the ATLAS and CMS experiments

- Measurement of the new Higgs-like particle
- Precision measurements of non-Higgs SM processes

- Dedicated searches for new physics in the Higgs sector
- Search for new particles and physics processes in the non-Higgs sector

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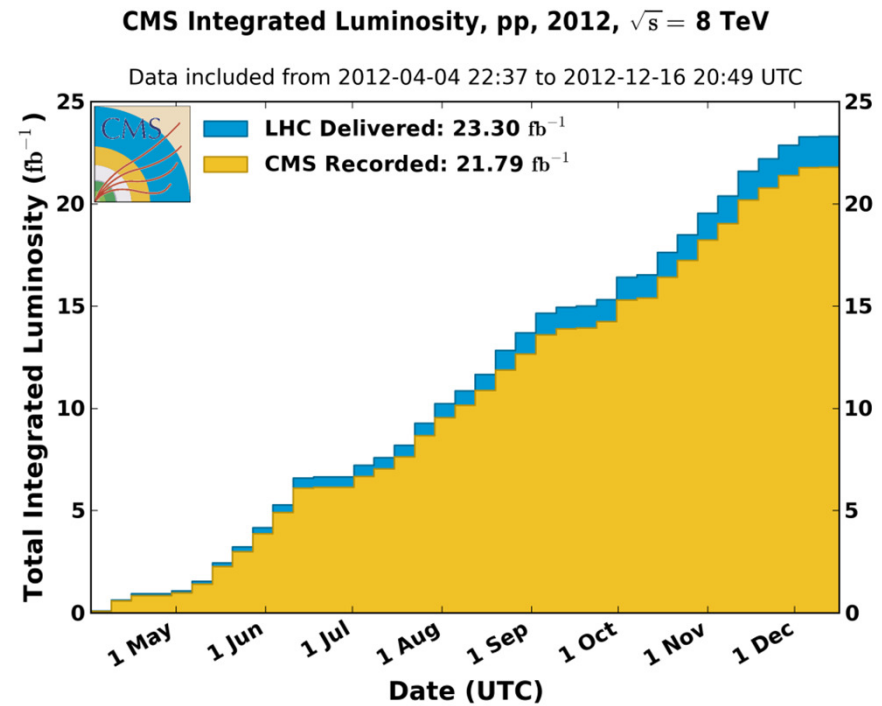
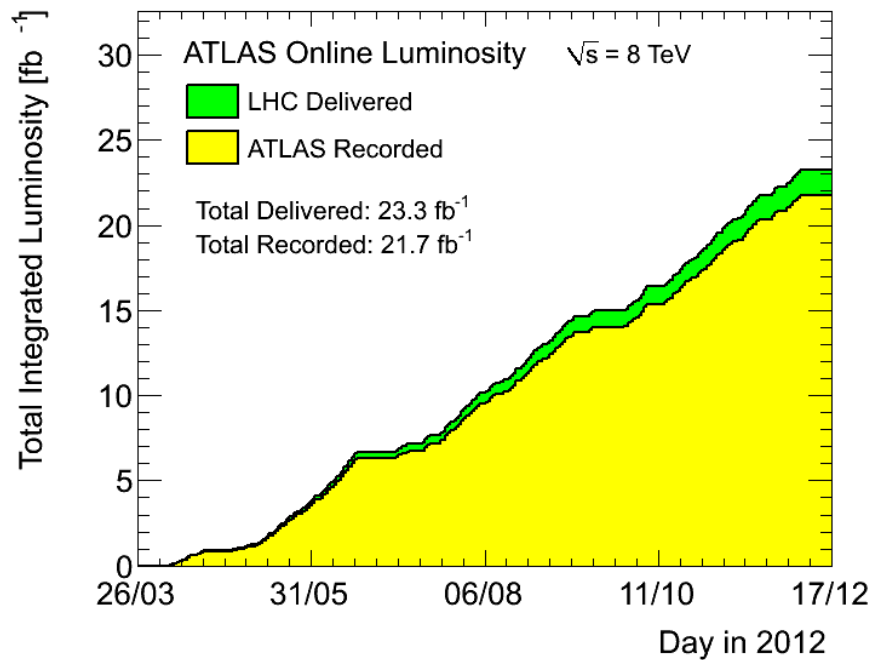
This talk

Accelerator and detector operation

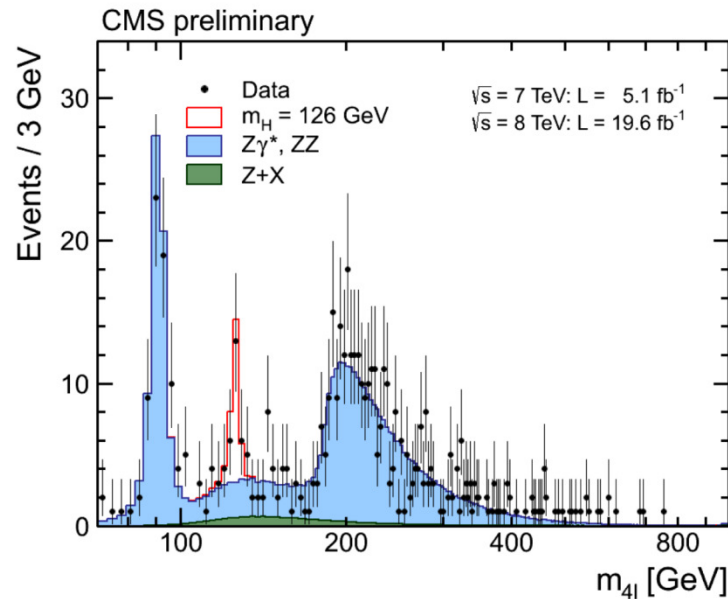
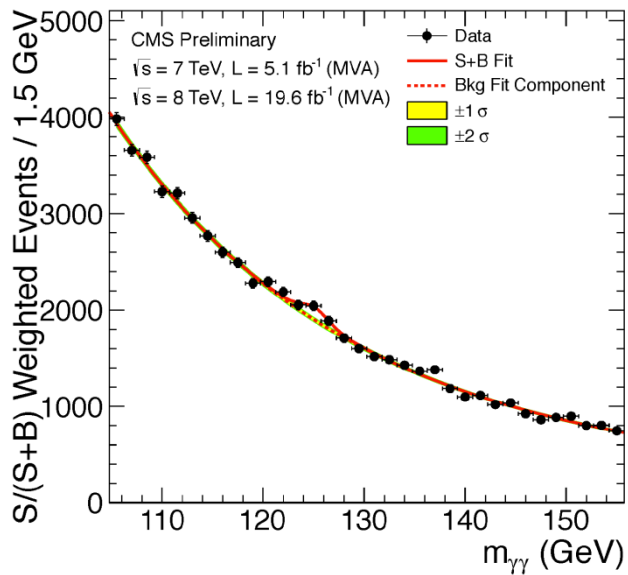
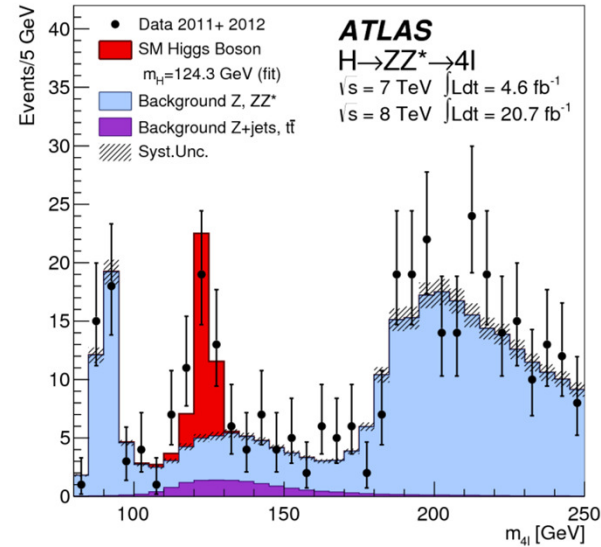
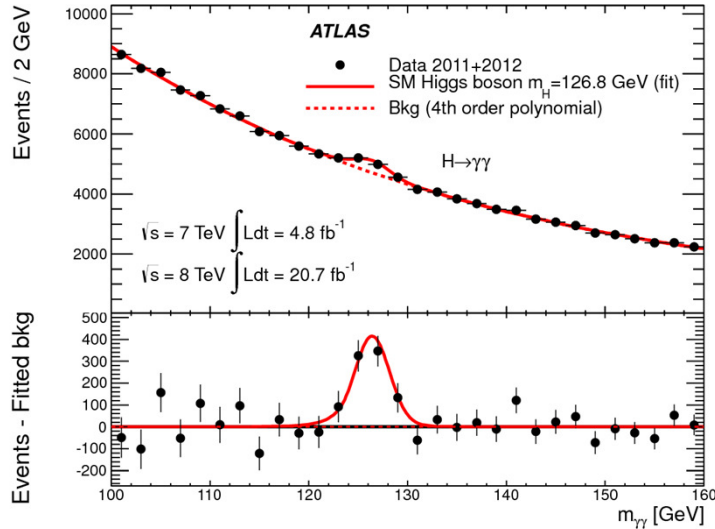
Excellent machine and detector performance

~95% of data recorded

~90% useful for physics



A new boson has been observed!

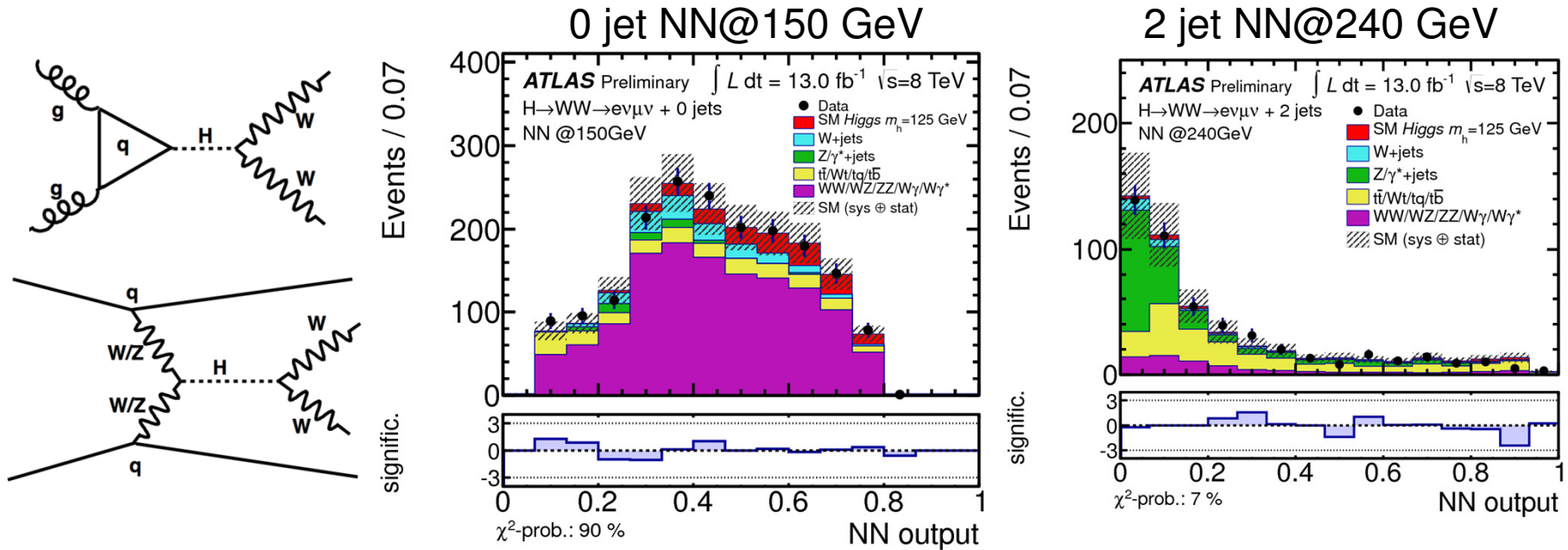


But is it the SM Higgs boson ?

Beyond the SM Higgs sector

- Two Higgs doublet models (eg in MSSM)
 - Generation of baryon asymmetry, ingredient of axion models
 - Extends SM Higgs sector to include two complex Higgs doublets H_1 and H_2
 - Five physical Higgs states: H^+ , H^- , A (CP-odd), H , h (CP-even)
 - Accommodate observed Higgs, $h=125$ GeV
 - $\tan\beta$ (ratio of doublet Vevs) and m_H and mixing angle α
 - Neutral Higgs decay $\rightarrow WW, bb, \tau\tau$
 - Charged Higgs decay $\rightarrow \tau\nu, cs$

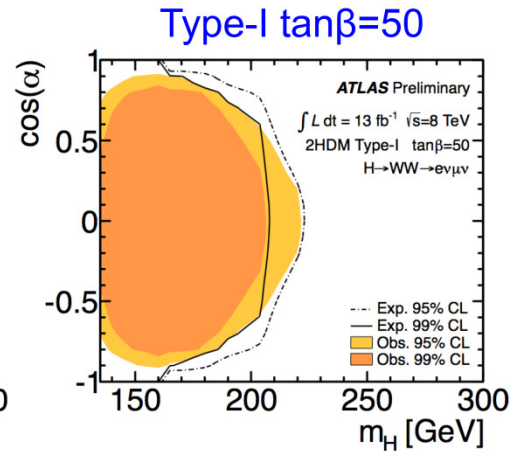
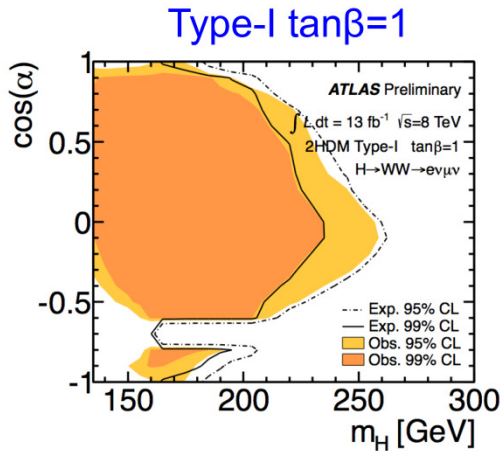
2HDM : H- \rightarrow WW



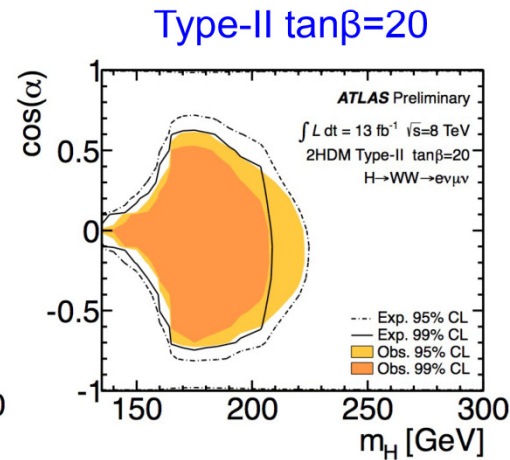
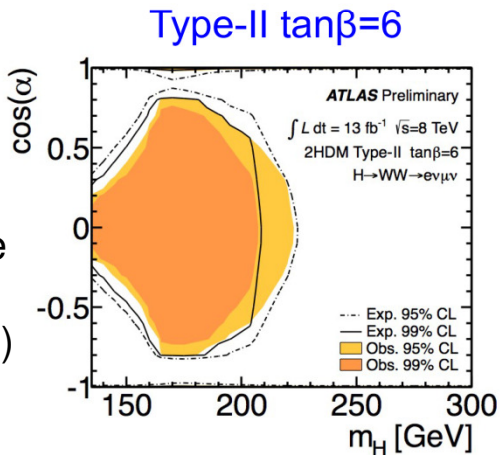
- Search for higher mass CP-even H assuming 125 GeV Higgs is lightest CP-even h of 2HDM
- Preselection based on SM WW analysis: $e+\mu$, high MET
- Split into 0-jet and 2-jet channels
- Final discriminant: neutral networks

2HDM: $H \rightarrow WW$

All quarks couple to one of the doublets



RH-“up-type” (“RH-down-type”) quarks couple to one doublet (the other doublet)

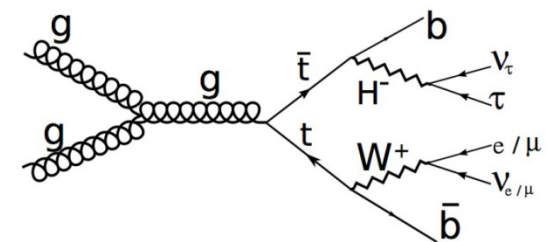
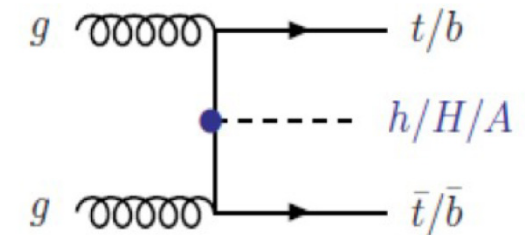
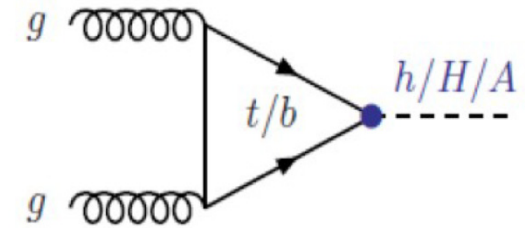


No significant excess

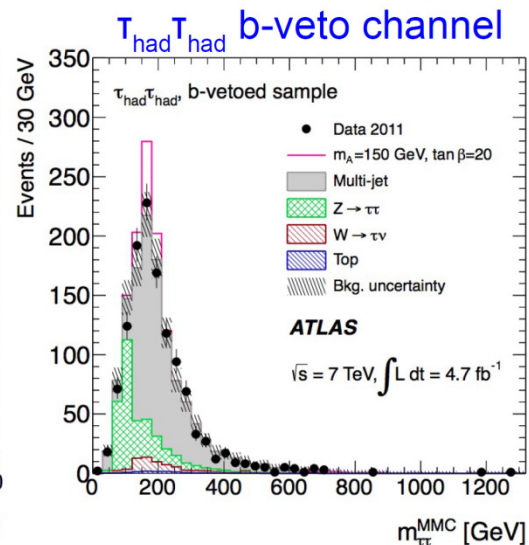
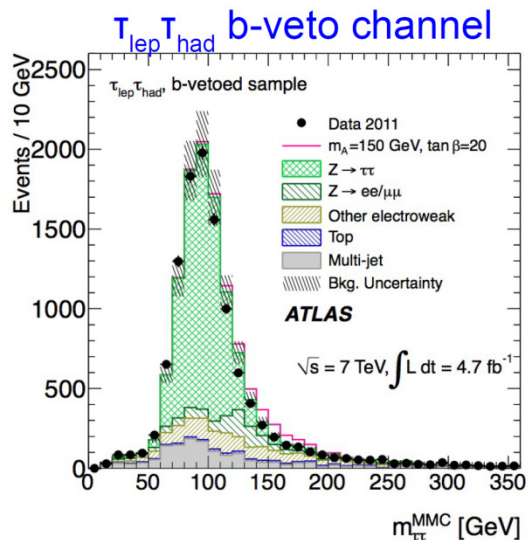
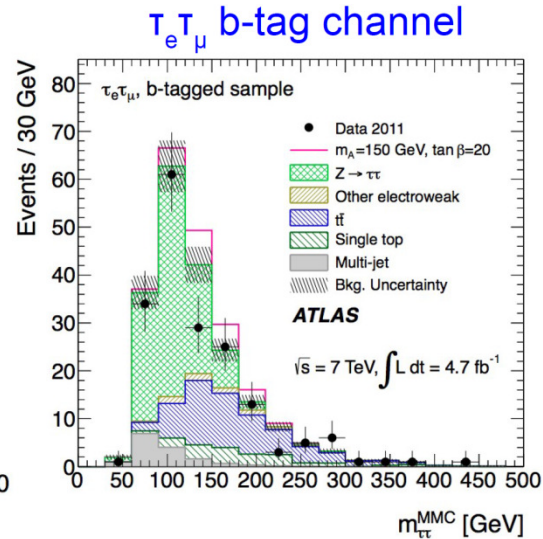
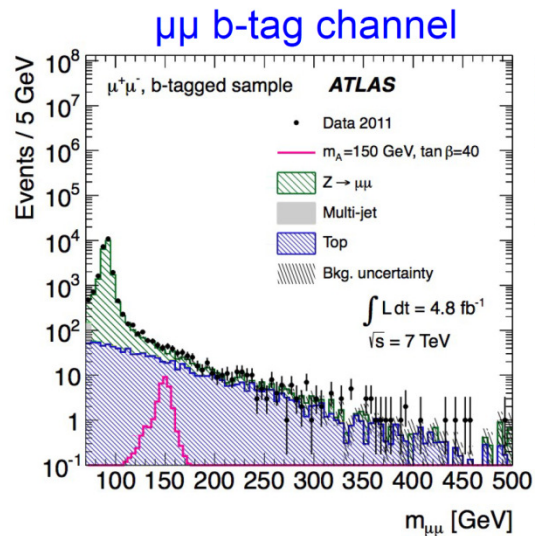
Exclusion limits set separately for Type-I and Type-II 2HDM in $\cos(\alpha) - m_H$ plane at $\tan\beta = 1, 3, 6, 20(50)$

MSSM Higgs sector

- MSSM Higgs sector is a constrained 2HDM at tree level
- Tree level MSSM Higgs sector determined by m_A and $\tan\beta$
- Couplings to b-quarks and τ -leptons enhanced at large $\tan\beta$
- Neutral Higgs searches focus on b-associated and gg-fusion production with $\tau\tau$ or $\mu\mu$ decays
- Charged Higgs searches focus on low mass: production in top decays and decay to $\tau\nu$, $c\bar{s}$

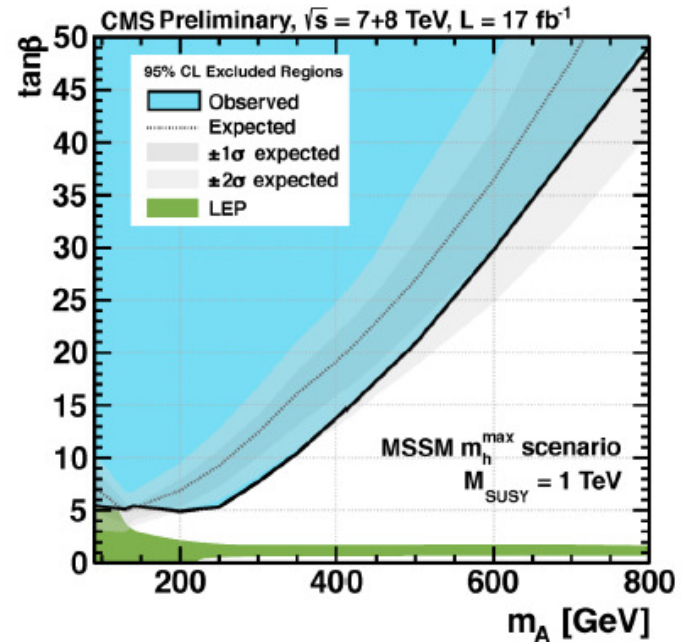
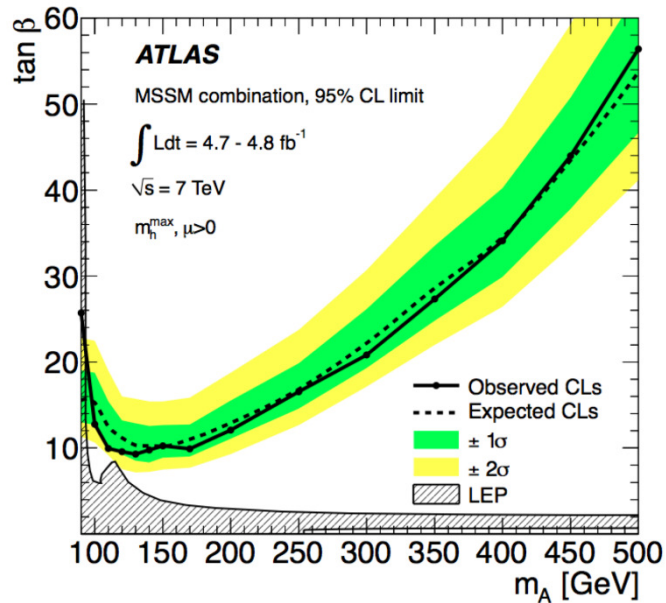


MSSM $H \rightarrow \tau\tau/\mu\mu$



- Categorise by leptonic final state and b-tag/veto
- Di-tau invariant mass reconstructed with likelihood-based method (missing mass calculator)
- $\mu\mu$ parameterised by fitted to data outside of signal window

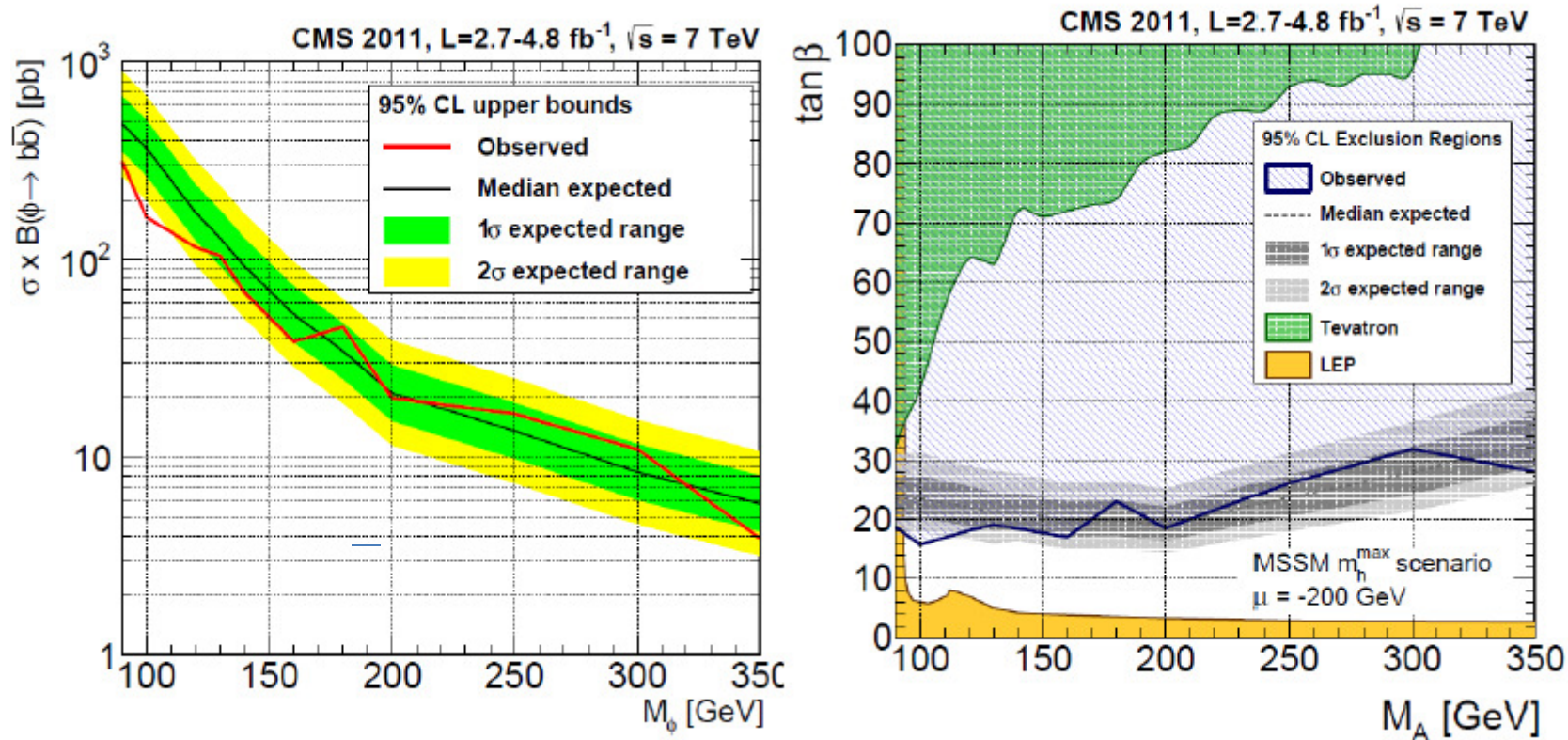
MSSM $H \rightarrow \tau\tau$ or $\mu\mu$



- Large part of parameter space still compatible interpretation of 125 GeV Higgs as a CP-even MSSM Higgs

H \rightarrow bb Exclusion Limits

Arxiv:1302.2892



Upper limit on pp \rightarrow Hb , H \rightarrow bb by fitting observed M12 distribution (invariant mass of leading dijet system).

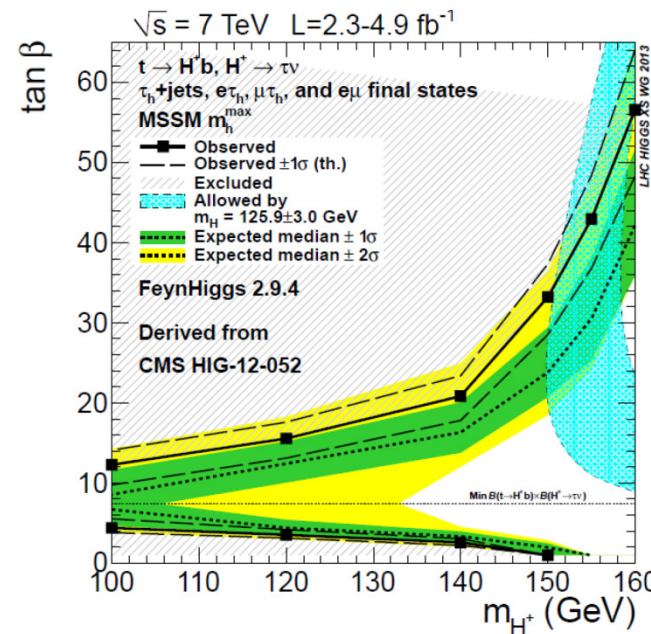
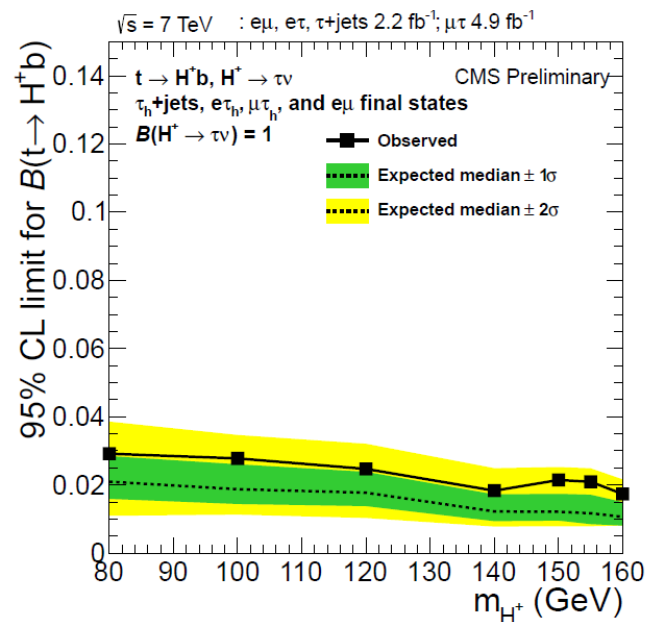
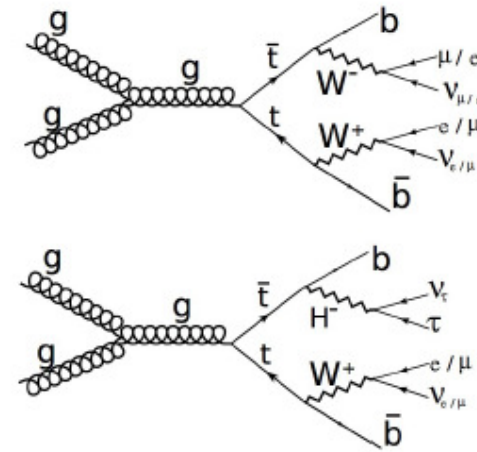
Non-observation of signal excludes region of large $\tan\beta$ in MSSM parameter space

Charged Higgs

Searched for charged Higgs from top quark production

Different final states considered:
 $e\mu$, $e\tau_h$, $\mu\tau_h$, $\tau_h + \text{jets}$

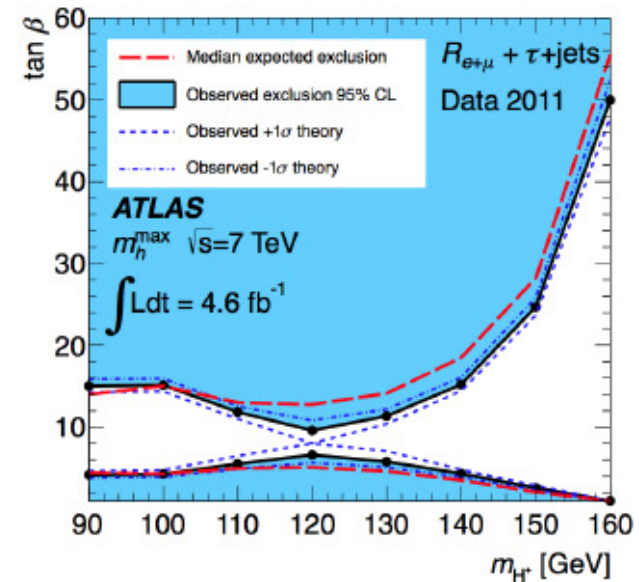
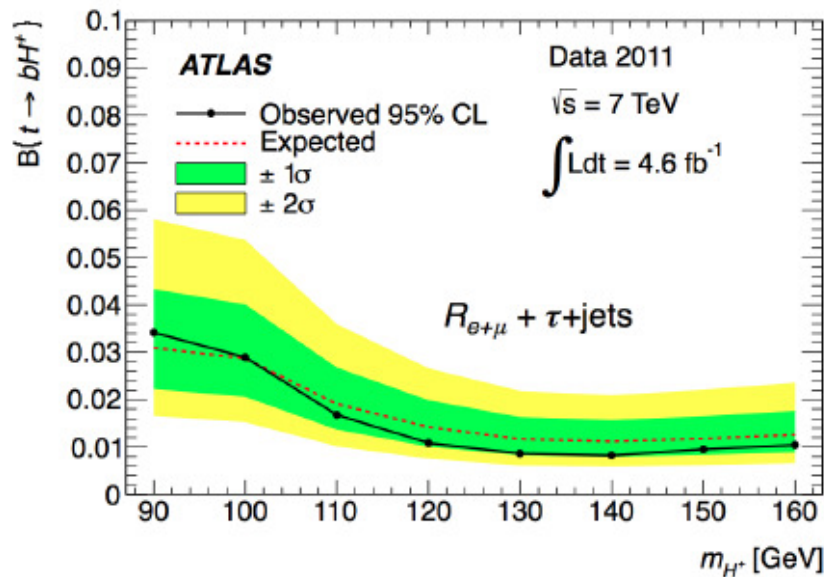
Shape-based analysis using m_T
 $(\tau + E_t^{\text{miss}})$ or $p_T(\text{leading track})/p_T(\tau)$



Excludes large regions of $\tan \beta$ in MSSM space for $M_{H^+}/M_A < M_{\text{top}}$

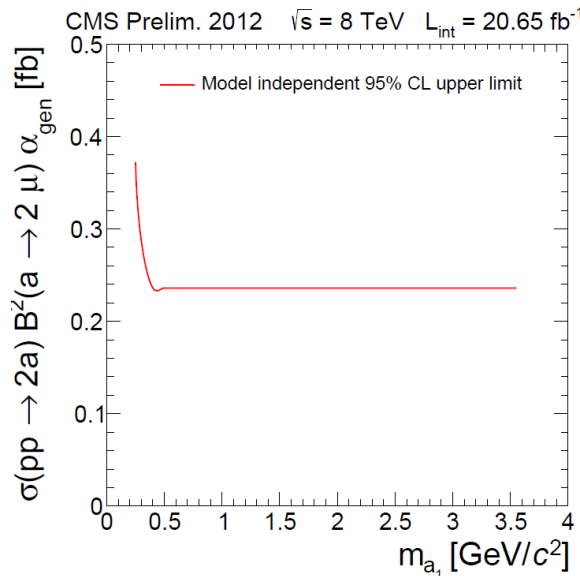
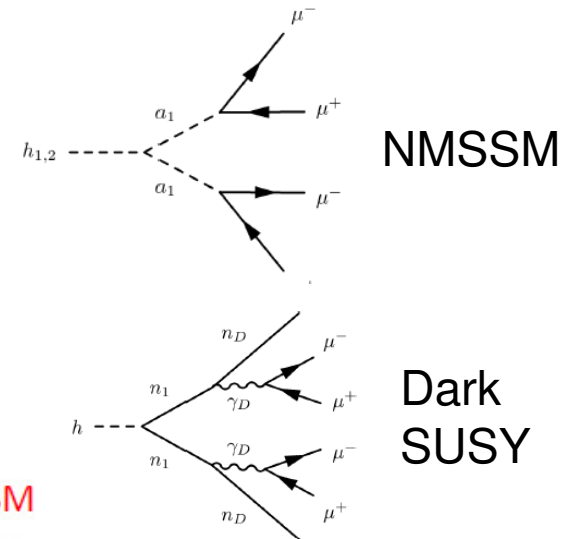
Charged Higgs

- $H^+ \rightarrow \tau \nu$ Combined direct and indirect search
- Direct : τ and W decay hadronically
- Indirect (lepton universality in $t\bar{t}$ events)
 - Look for preferential decay to τ (Light H decays mainly to τ)

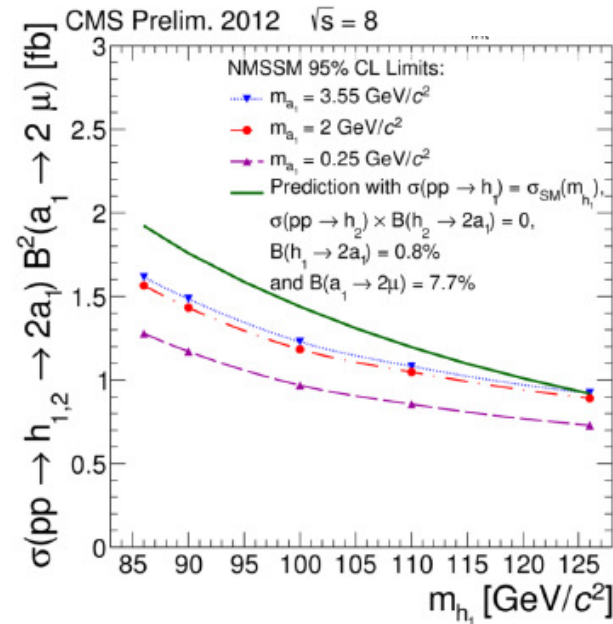


Higgs $\rightarrow 2a + X \rightarrow 4\mu + X$

- $h \rightarrow 2a + X \rightarrow 4\mu + X$
- Decay of Higgs to new light bosons and then boosted muons
- Isolated dimuon peak signature



Model-independent upper limit on $\sigma(pp \rightarrow 2a + X) \times \text{BR}^2(a \rightarrow 2\mu) \times \alpha_{\text{gen}}$
 ($\alpha_{\text{gen}} = \text{acceptance}$)

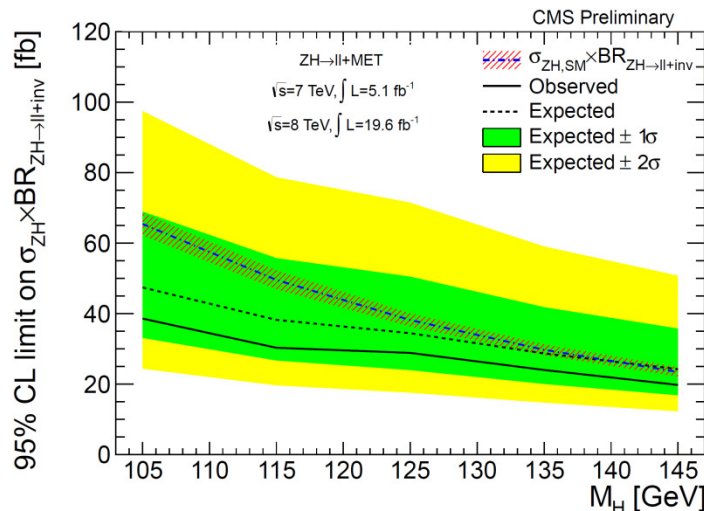
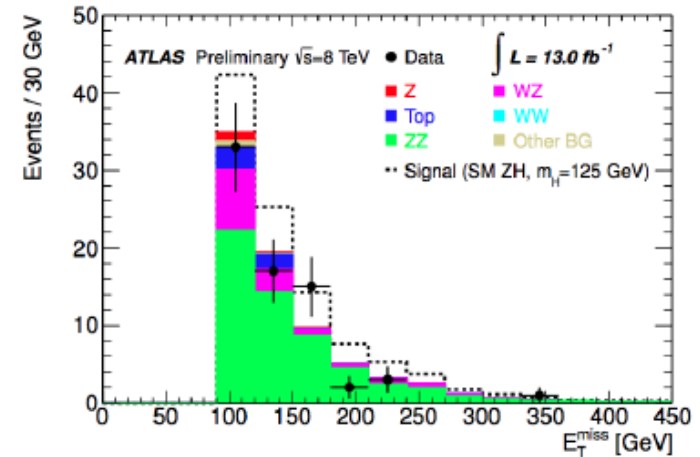
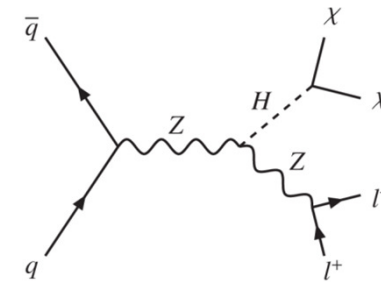


Exclusion limits in NMSSM

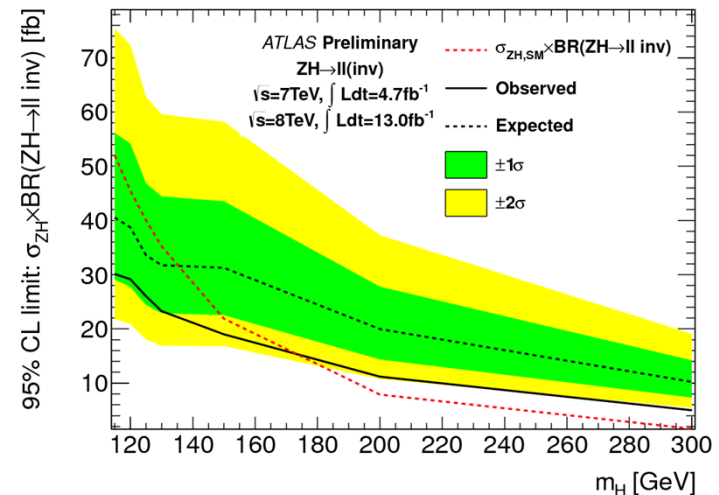
CMS-PAS-HIG-13-010

Invisible Higgs

- Exotic theories, eg, WIMPs give large invisible branching ratio
- $ZH \rightarrow \ell\ell + \text{invisible}$
- Opposite sign lepton pairs with Z-mass constraint + MET balance
- No significant excesses observed



CMS-HIG-13-018



ATLAS-CONF-2013-011

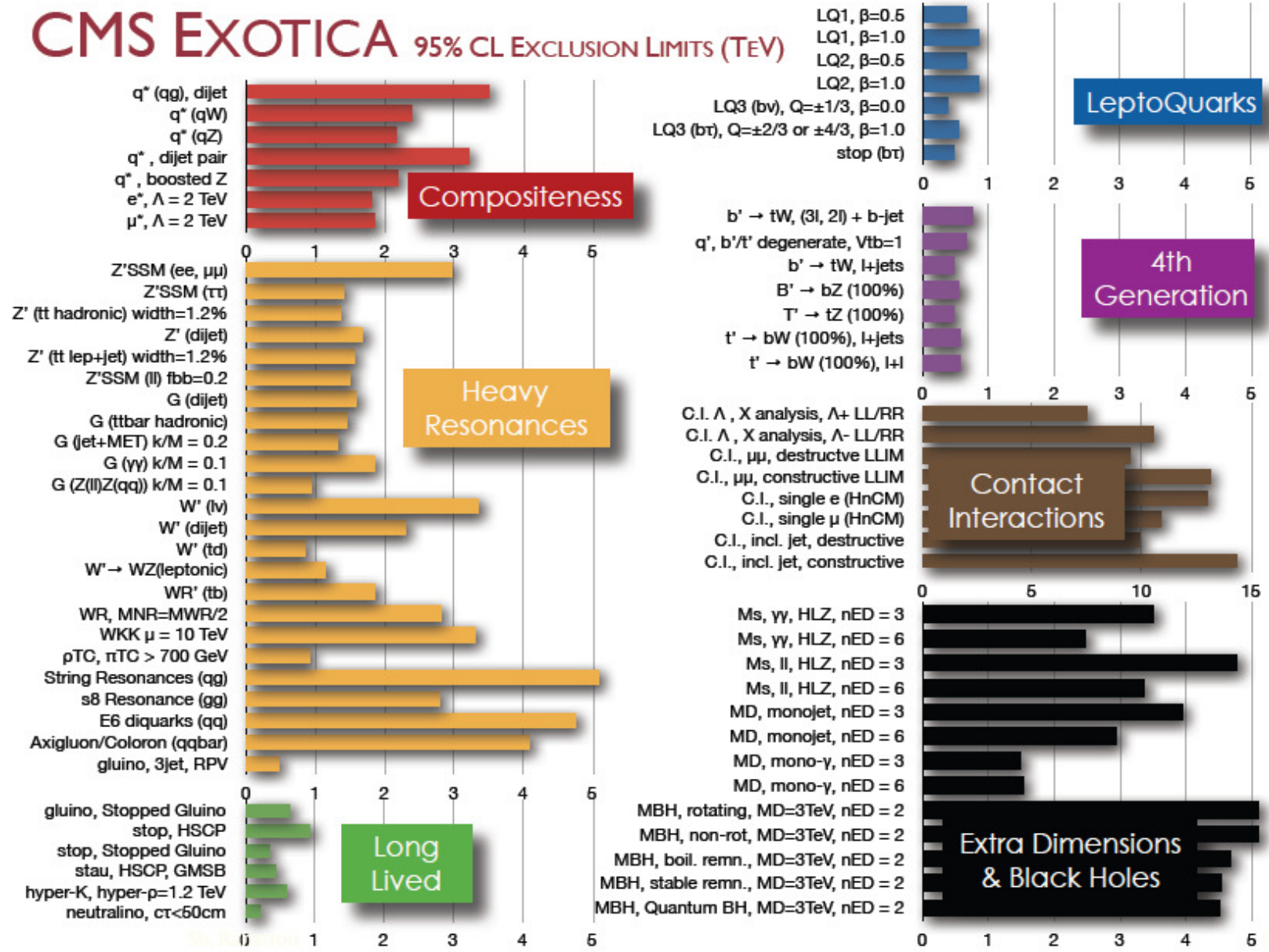
Beyond the Higgs sector

- A SM-like Higgs has been found with mass ~ 125 GeV
 - No current evidence for a non-SM Higgs-like sector
- This causes a headache
 - Up to a new physics scale Λ the Higgs mass is fine-tuned $m_H^2 = m_0^2 + k\Lambda^2$
 - Motivates searches for new physics at the TeV scale to address the naturalness problem
 - Aim to address other outstanding problems implying new TeV physics, eg, dark matter

Searches for Physics beyond the SM

- Two approaches
 - Generic approach based on measurements of various final states associated with high p_T .
 - Observables: leptons, jets, missing transverse energy, energy loss, particle speed, displaced decays
 - Searches inspired by phenomenological models of theories beyond-the-Standard Model
 - Constraints on supersymmetry, extra dimensions models, leptoquarks

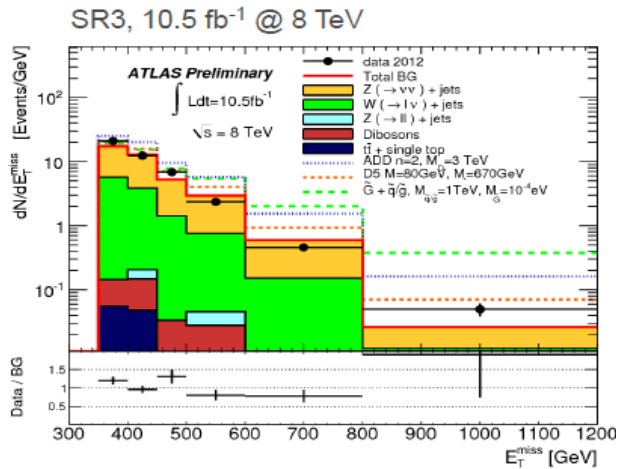
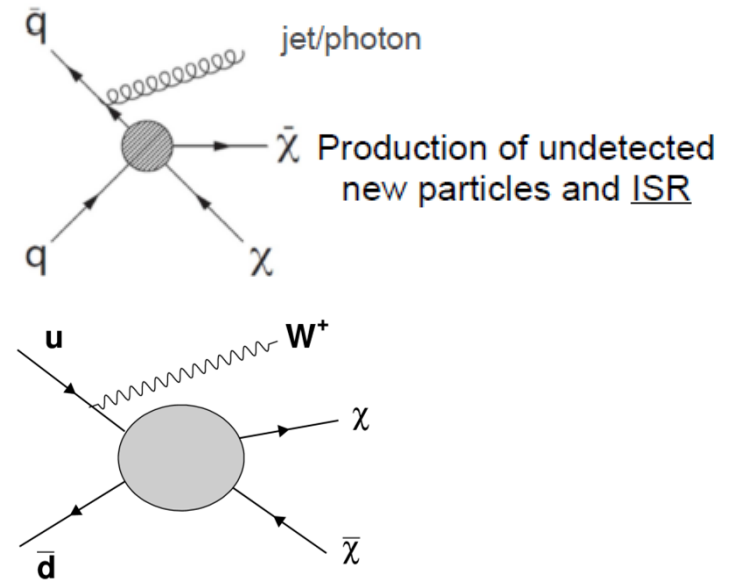
CMS EXOTICA 95% CL EXCLUSION LIMITS (TeV)



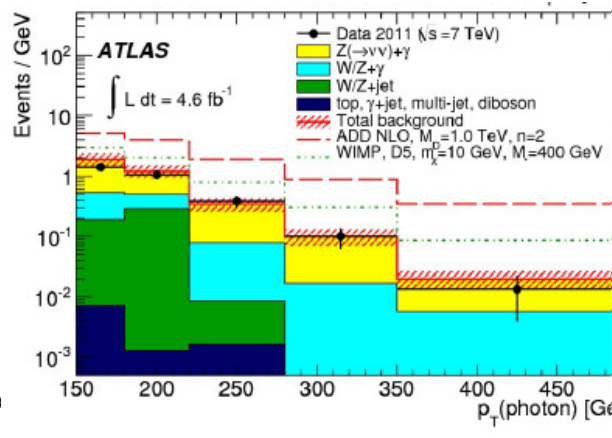
Excluding masses at the TeV-scale

Search for WIMP dark matter + associated final states

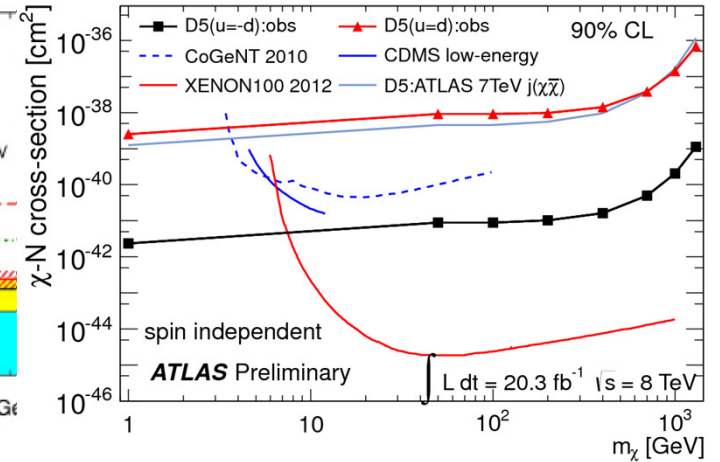
- Sensitive to direct production of WIMP candidates
- Jet/photon, W/Z hadronic decays + MET
- Predicted in models of SUSY and Large Extra Dimensions



ATL-CONF-2012-147
monojet



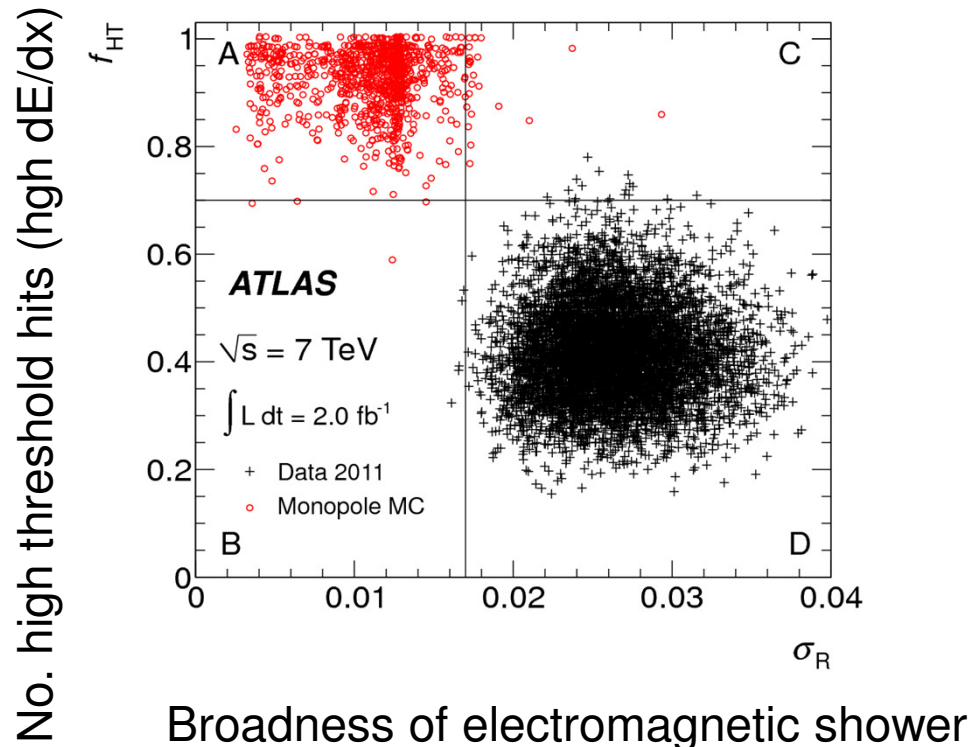
arXiv:1209.4625
monophoton



ATLAS-CONF-2013-073
W/Z hadronic decay

Search for magnetic monopoles

- Existence of monopoles addresses electric charge quantisation (Dirac)
- Monopoles feature generically in models of spontaneous symmetry breaking ('t Hooft)
- LHC opened up the TeV regime for direct searches

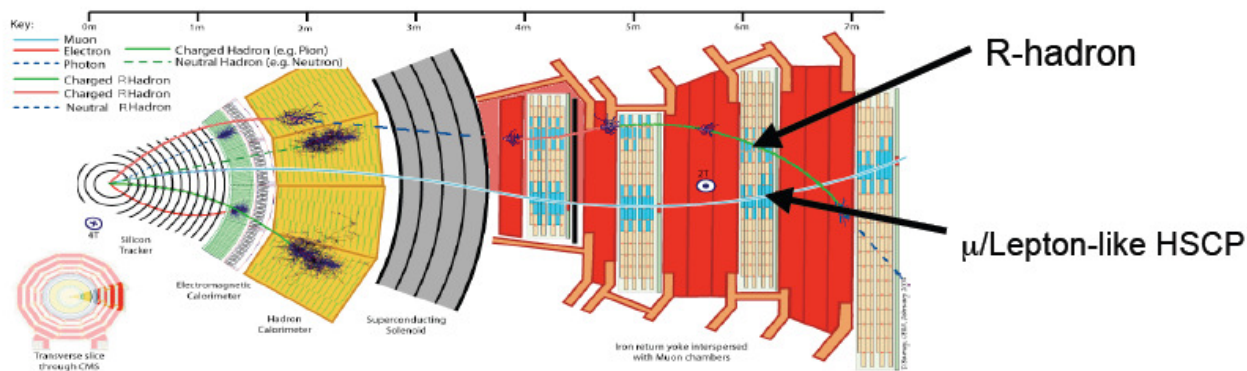


Look for highly ionising objects leaving characteristic energy deposition profiles at ATLAS

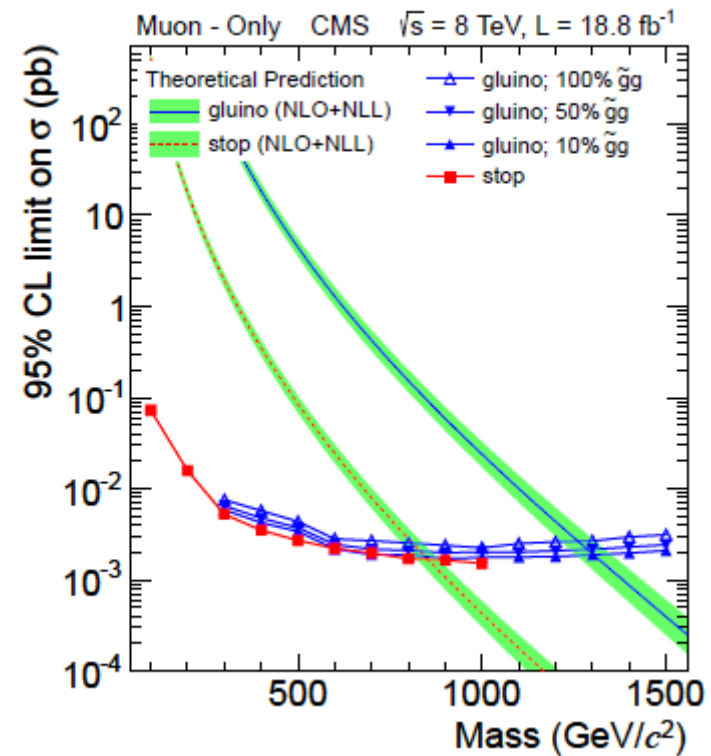
No events observed.

Upper limit of 2pb at 95% CL in the sensitive fiducial region of the search.

Long-lived massive particles

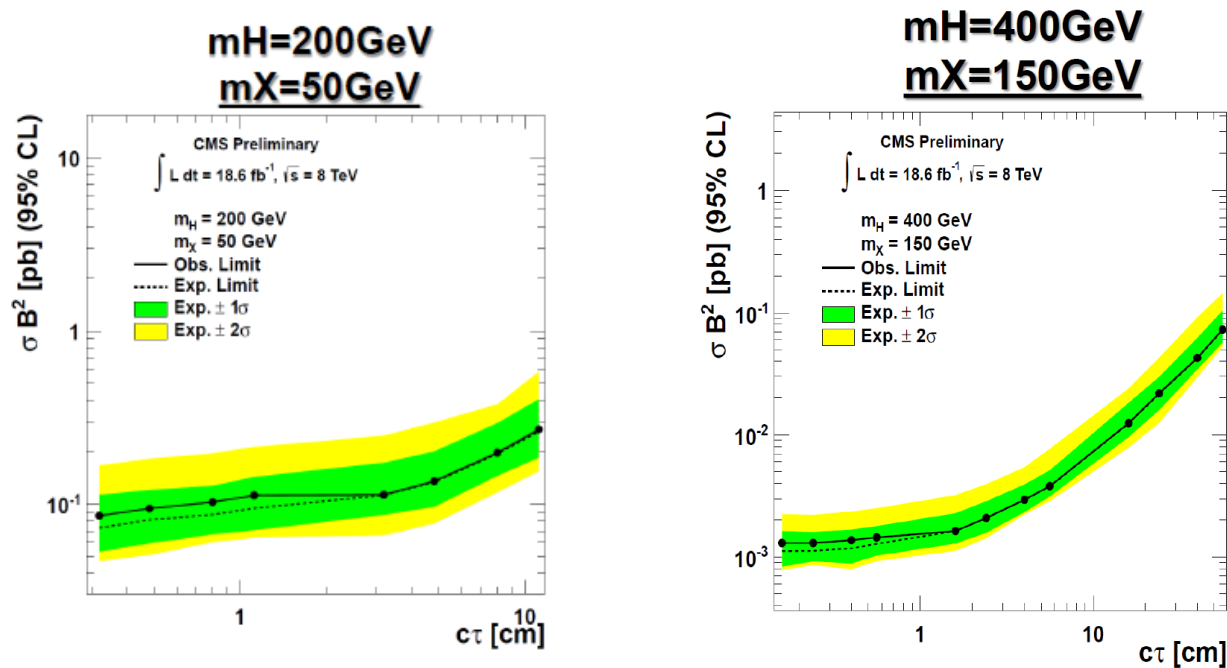


- Look for muon-like (muon trigger) and non-muon-like slow particle (MET trigger)
- Tracker dE/dx and TOF (muon) as discriminants
- Limits up to 1.3 TeV for stable R-hadrons



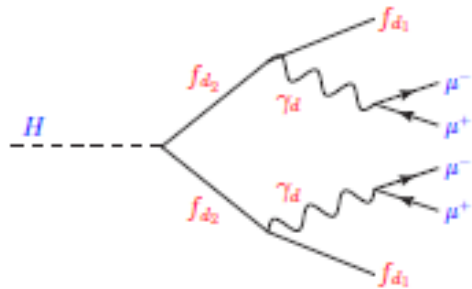
Long-lived neutral particles

- Generic search for long-lived neutral object X^0
 - Model of non-SM Higgs: $H^0 \rightarrow 2X^0 \rightarrow 2(qq)$
 - Displaced Dijets
 - Search optimised for low and high displacement ($L_{xy} < 20\text{cm}$, $L_{xy} > 20\text{cm}$)



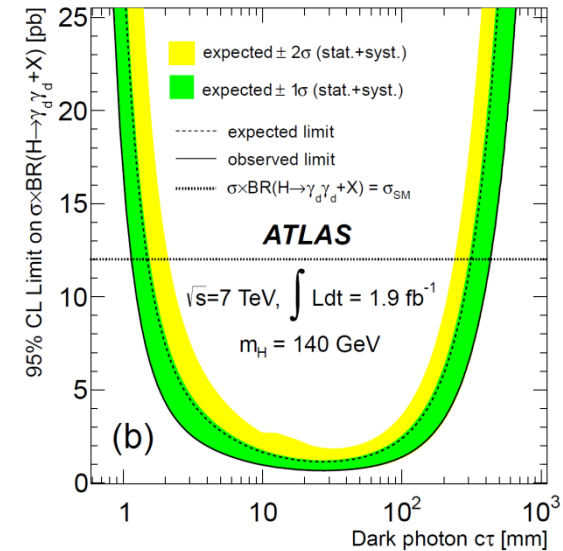
Higgs and long-lived particles

- Higgs to neutral fermions decaying to long-lived bosons and stable neutral fermion
 - Search for collimated muon pairs

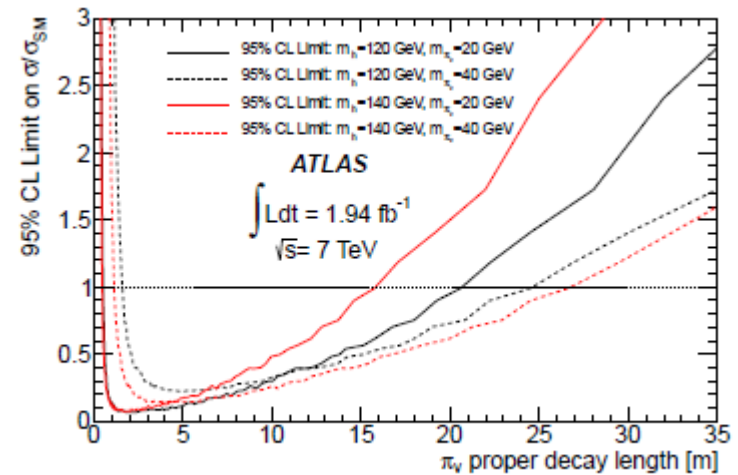


- Higgs to long-lived neutral particles $\pi_\nu \pi_\nu$ decaying to fermion-antifermion pairs

m_{h^0} (GeV)	m_{π_ν} (GeV)	Excluded Region
120	20	$0.50 < c\tau < 20.65$ m
120	40	$1.60 < c\tau < 24.65$ m
140	20	$0.45 < c\tau < 15.8$ m
140	40	$1.10 < c\tau < 26.75$ m



Arxiv:1210.0435

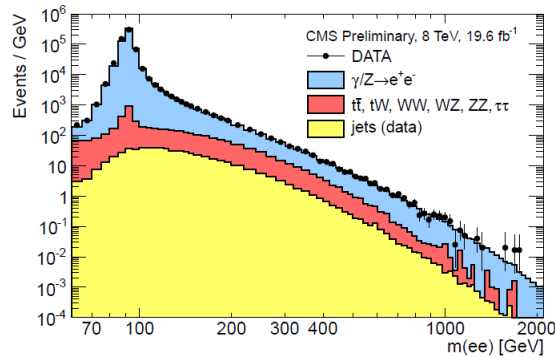


Arxiv:1210.0435

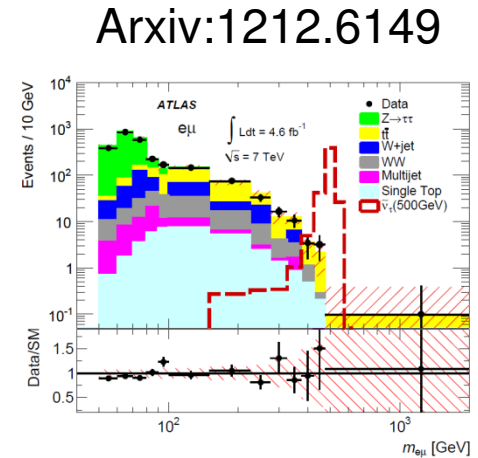
Resonance hunting

- Range of final states
- Sequential SM, RPV SUSY..

e^+e^- resonance

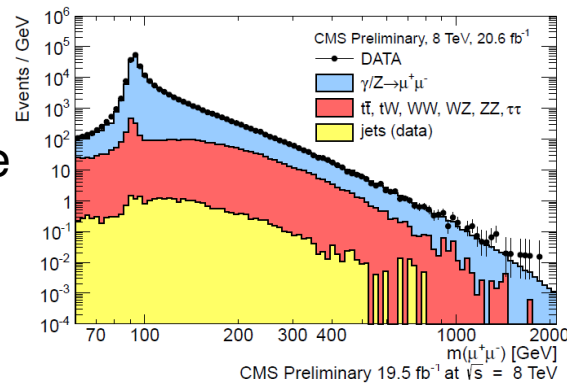


$e\mu$ resonance

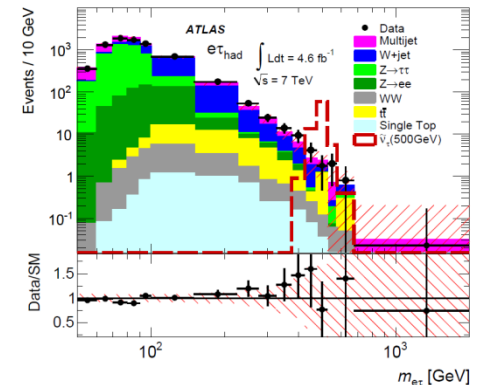


EXO-12-061

$\mu^+\mu^-$ resonance

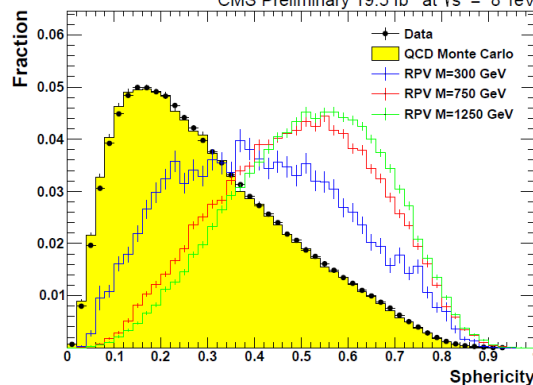


$e\tau$ resonance

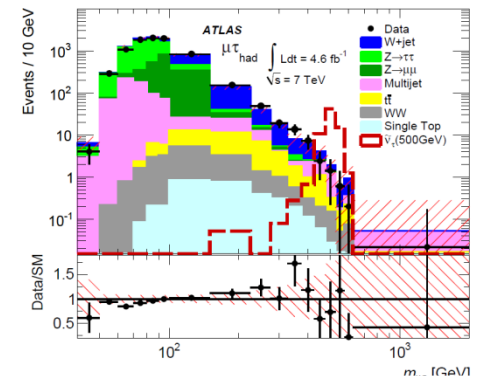


Multijet
High multiplicity

EXO-12-049



$\mu\tau$ resonance



Supersymmetry

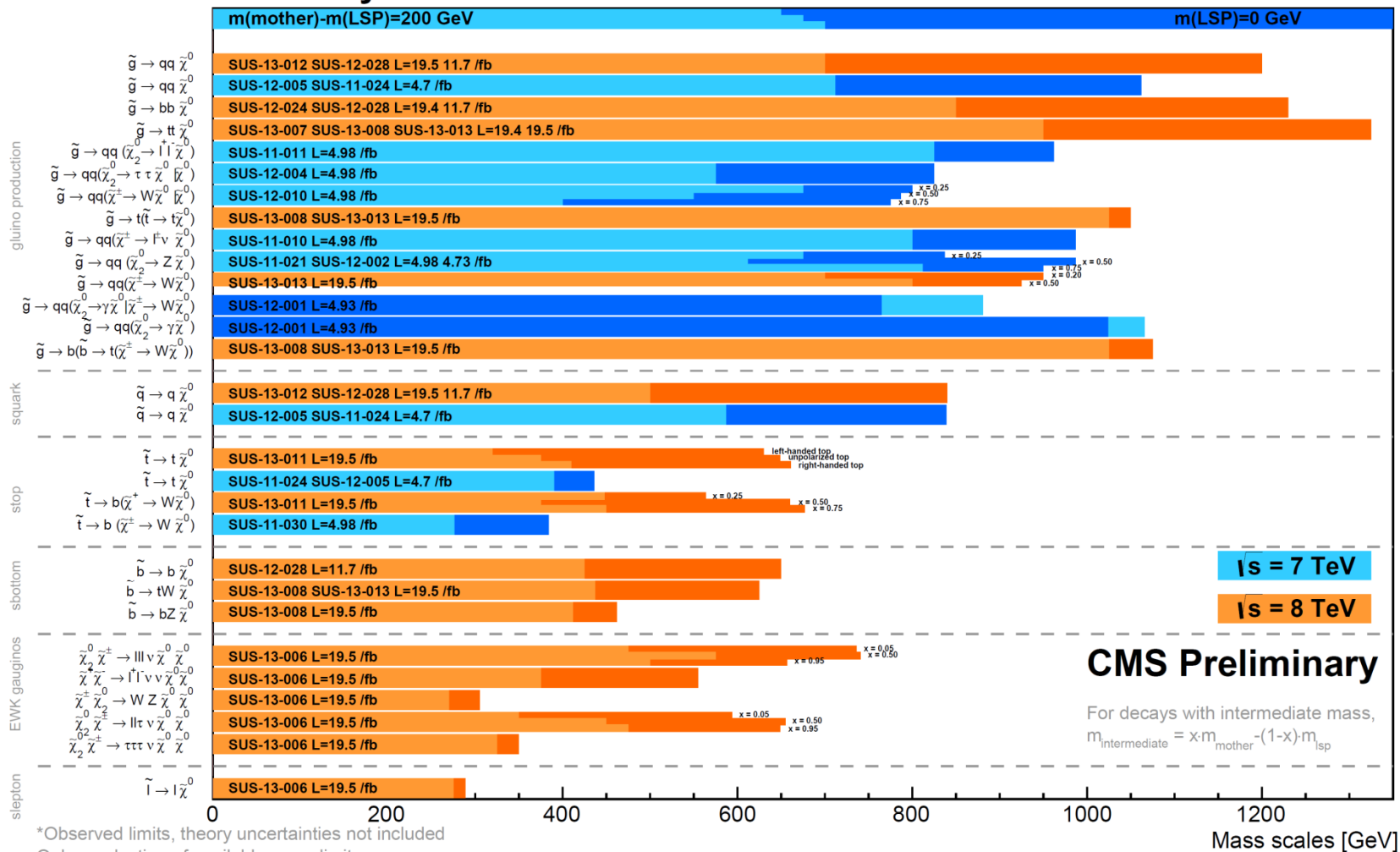
- Addresses a number of deficiencies of the Standard Model
 - Makes the SM Higgs sector less unnatural
 - R-parity conserving SUSY with LSP giving a dark matter candidate

$$\text{Lightest neutralino: } \tilde{\chi}^0 = a_1 \tilde{\gamma} + a_2 \tilde{Z}^0 + a_3 \tilde{H}_1^0 + a_4 \tilde{H}_2^0$$

gaugino Higgsino

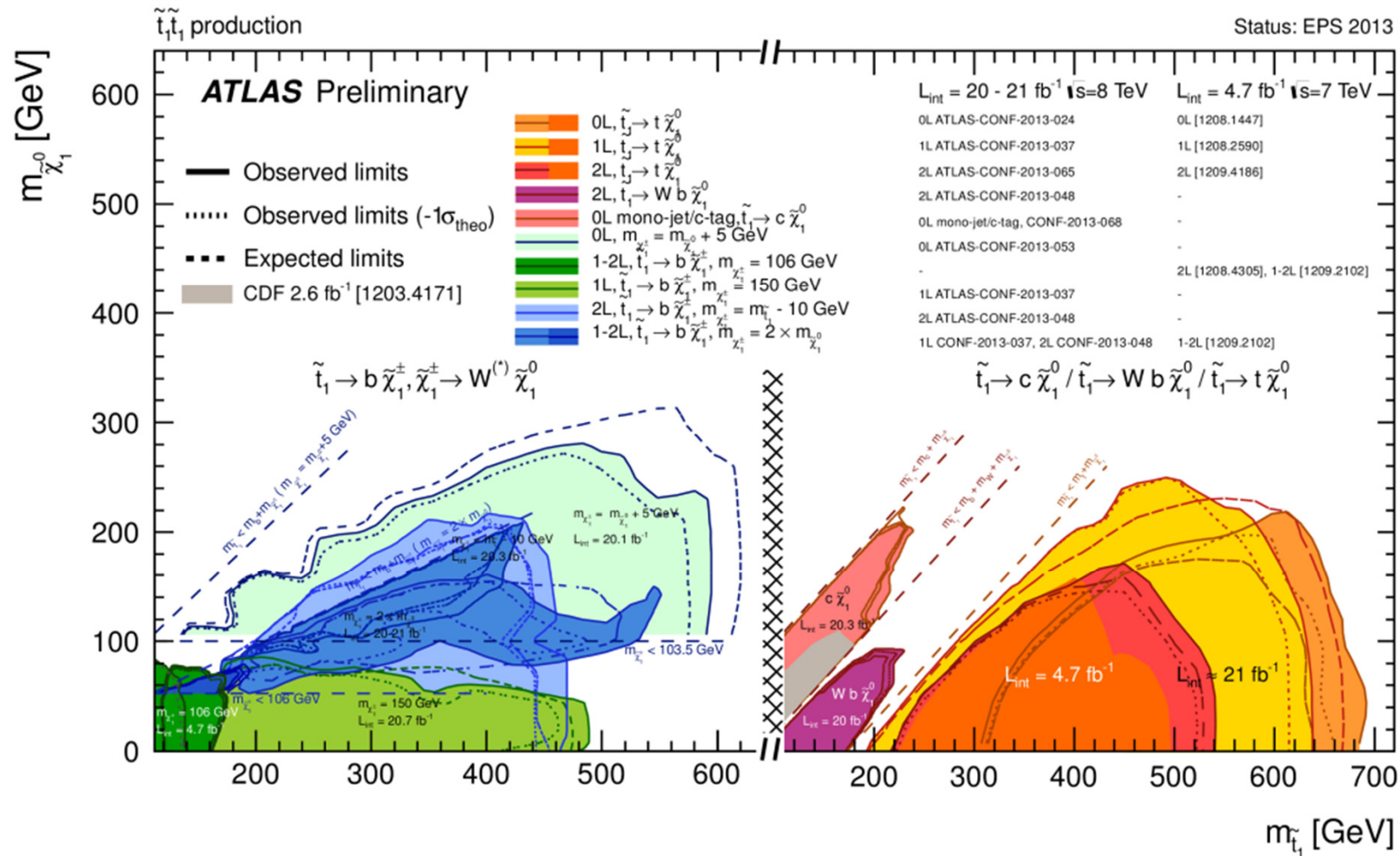
- Approximate unification of the running couplings
- A wide range of SUSY searches undertaken

Summary of CMS SUSY Results* in SMS framework EPSHEP 2013



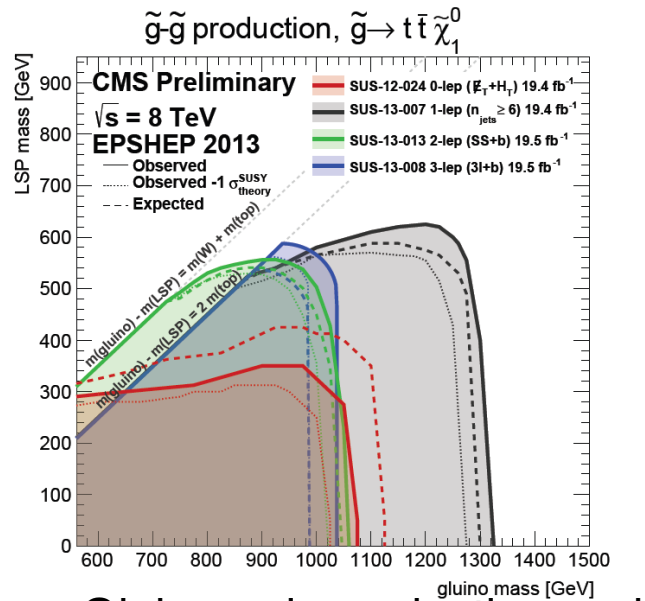
Up to ~1 TeV mass scale for diverse scenarios
 Searches based on event topologies with various lepton/jet multiplicities + MET/event shape selections.

R-parity conserving SUSY

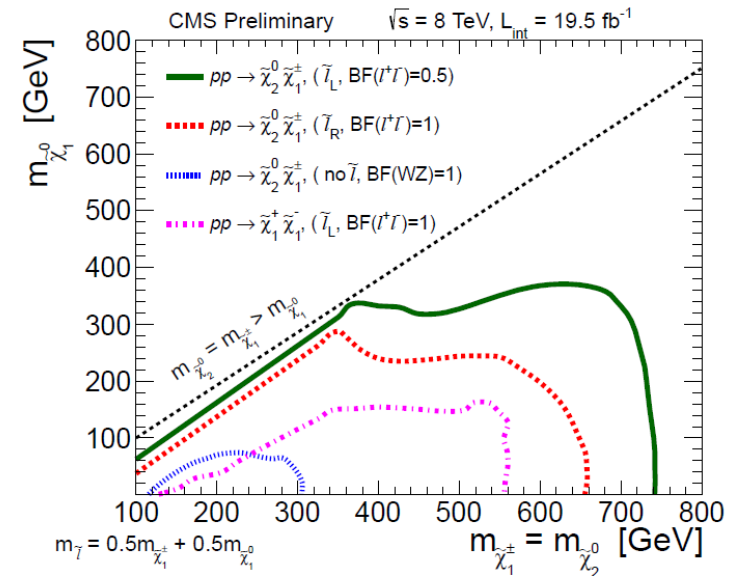


Direct stop production
 Complementary searches
 Parameter space explored with increasing lumi

R-parity conserving SUSY



Glauino pair production and direct decay to WIMPs + top



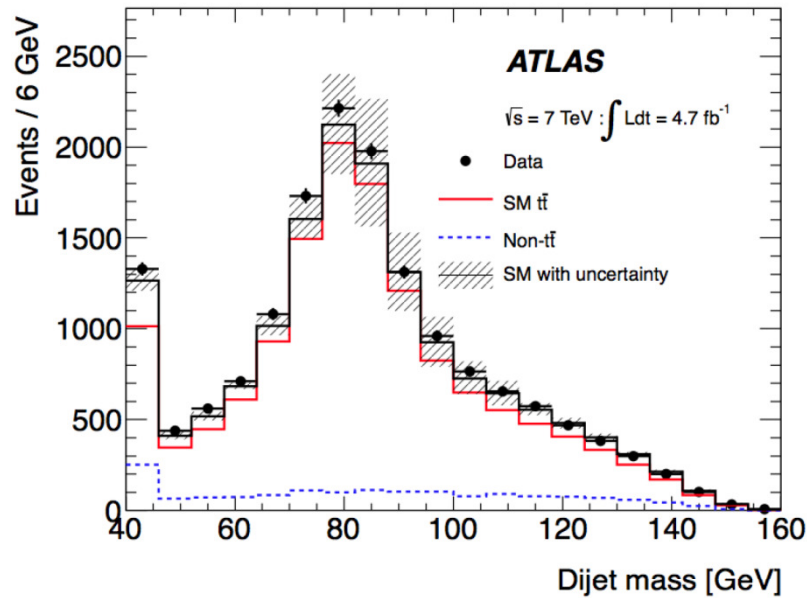
Limits on electroweak production

Summary

- ATLAS and CMS aim for a diverse and comprehensive program of physics beyond the Standard Model
- Impossible to do it justice in one talk
- Searches for evidence of a non-SM Higgs undertaken
- Signature-driven searches and searches motivated by speculative theories made.
- Higher energy LHC with greater lumi will reopen discovery windows...

Spares

$H^{+-} \rightarrow c\bar{s}$



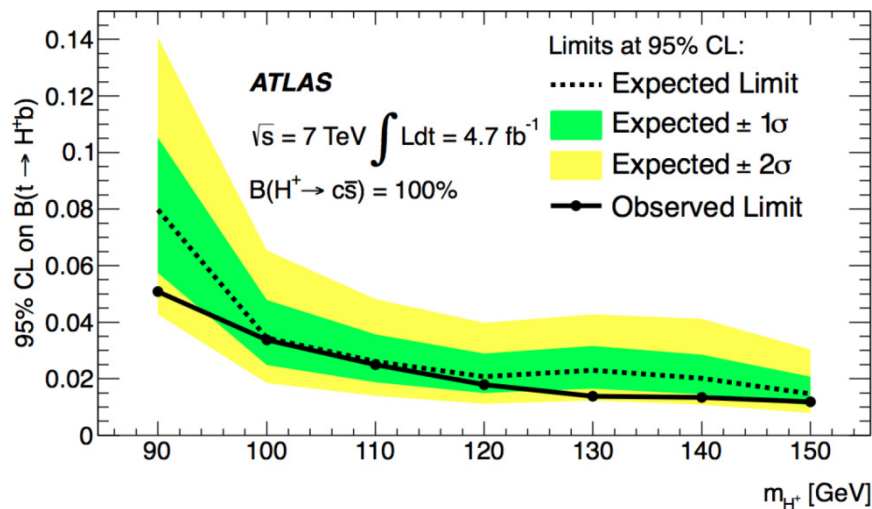
Significant $H^{+-} \rightarrow c\bar{s}$
 at low $\tan \beta$ in
 MSSM

Search in semi-leptonic $t\bar{t}$ channel

- $1e/\mu$ and >3 jets ($>1b$ -jet)

- High MET and m_T

Dijet mass as
 discriminant



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

- Two analysis categories
 - Semileptonic b-decays (with muons)
 - Hadronic b-decays
- Data-driven estimates of major background : strong $b\bar{b}$
- Data consistent with bg prediction
- Mass resolution $\sim 15\%$

