Searches for Beyond SM Higgs @ LHC

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Outline

- MSSM Higgs Searches
    - Neutral Higgs
    - Charged Higgs
- SM4
- Fermiophobic Higgs
- Doubly Charged Higgs
- Light Scalar Higgs (e.g. NMSSM)
- Hidden Higgs Sector (e.g. Higgs to long lived particles)

Introduction

- LHC experiments are becoming more and more sensitive to probe Higgs production
  - The chances are that with this year's data we will be able to exclude or provide evidence for the existence of a SM-like Higgs
  - Nevertheless, the story won't end here
- Suppose we find the SM Higgs
  - Is it really the SM Higgs? → MSSM Higgs

Introduction

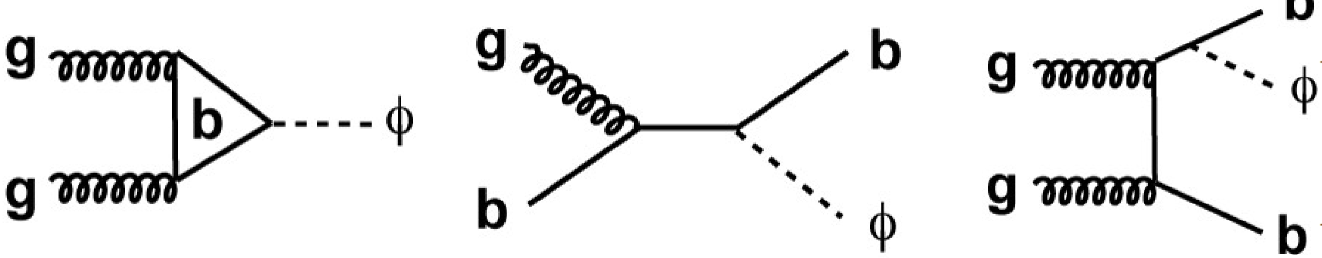
- LHC experiments are becoming more and more sensitive to probe Higgs production
  - The chances are that with this year's data we will be able to exclude or provide evidence for the existence of a SM-like Higgs
  - Nevertheless, the story won't end here
- Suppose there is no SM Higgs found
  - Higgs with different couplings? → MSSM, SM4, fermiophobic
  - More complicated Higgs sector? → MSSM, Doubly charged Higgs
  - Light Scalar Higgs? → NMSSM
  - Hidden Higgs sector? → Higgs to long lived particles

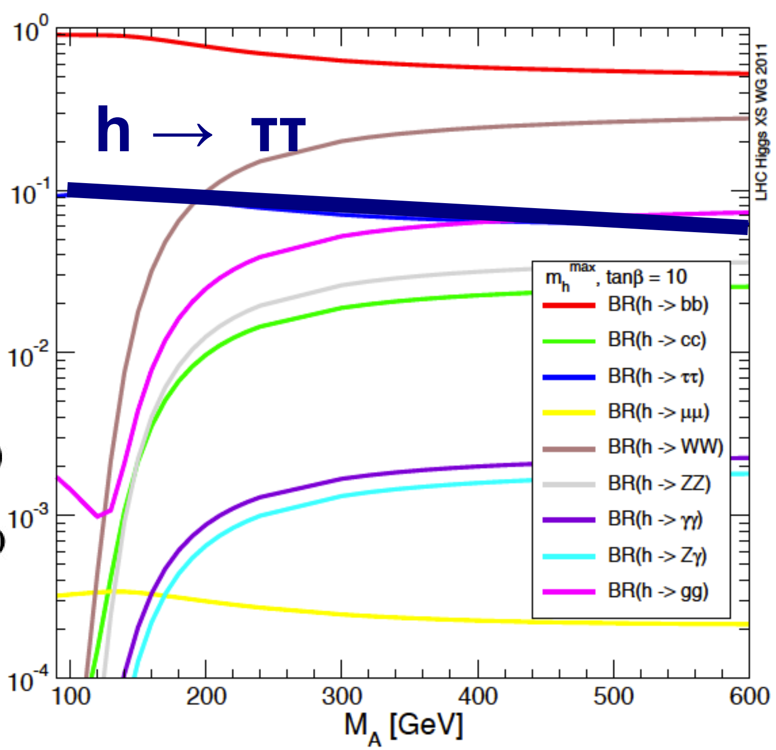
MSSM

- MSSM: a popular and well-studied extension of the SM
  - 5 Higgs bosons: CP-even (h,H), CP-odd (A), charged ($H^{\pm}$)
  - Mass of h < 135 GeV
  - Higgs sector depends only on 2 parameters at tree level (e.g. m_A , $\tan\beta$)

For large parts of the parameter space $H \rightarrow \tau\tau$ and $H^{\pm} \rightarrow \tau^{\pm}\nu$ decays are dominant, WW/WZ decays suppressed

Neutral Higgs produced mainly by gluon fusion, also in association with b-quarks





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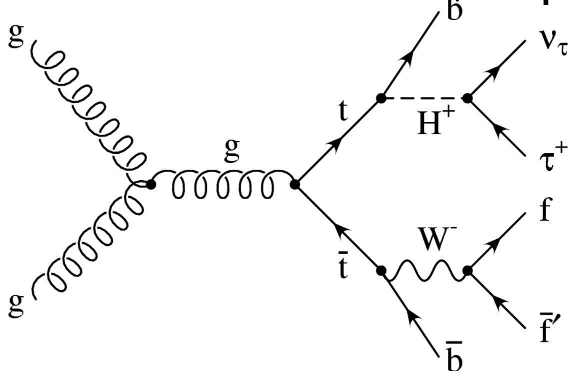
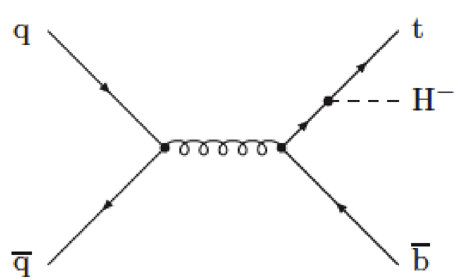
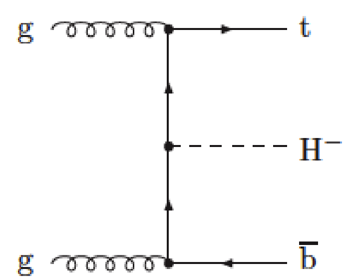
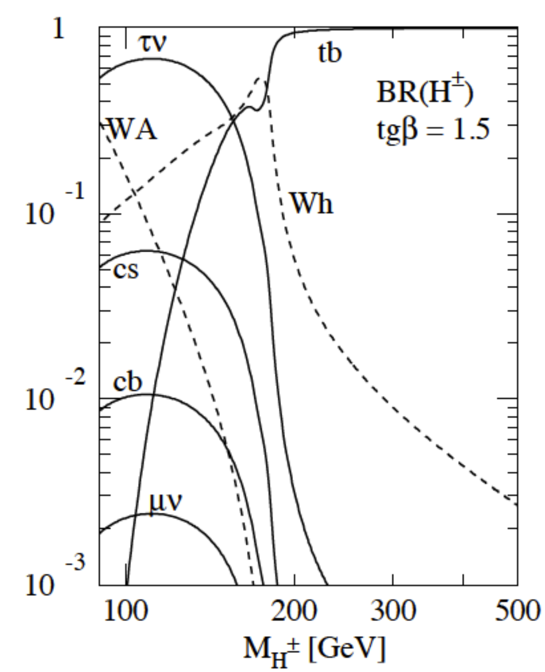
For large parts of the parameter space $H \rightarrow \tau\tau$ and $H^{\pm} \rightarrow \tau^{\pm}\nu$ decays are dominant, WW/WZ decays suppressed

Charged Higgs produced mainly in top decays or in association with tb, depending on its mass





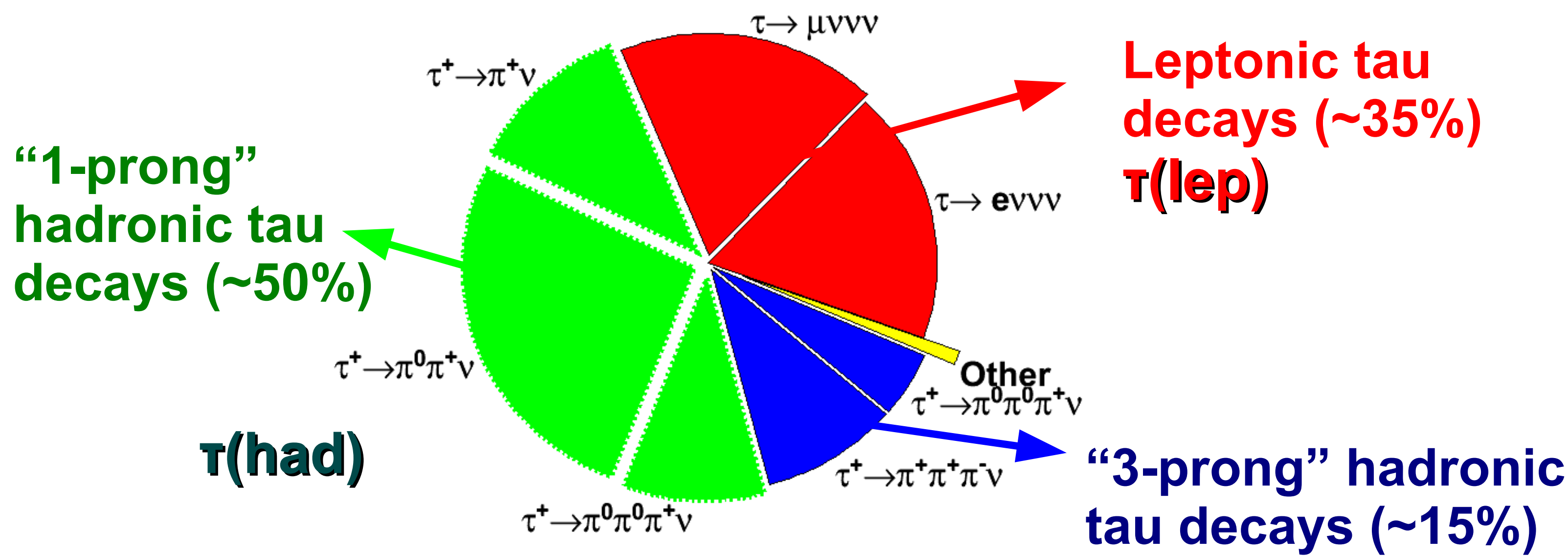


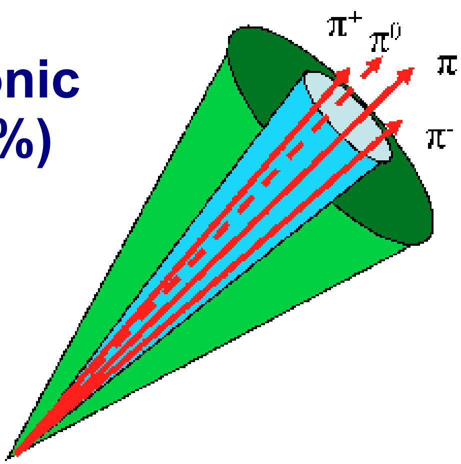


hep-ph/9704448

Taus

- The main search channels for MSSM Higgs involve tau-leptons in the final state: $H\rightarrow\tau\tau$, $H^{\pm}\rightarrow\tau^{\pm}\nu$
- Taus: the only leptons that can decay hadronically

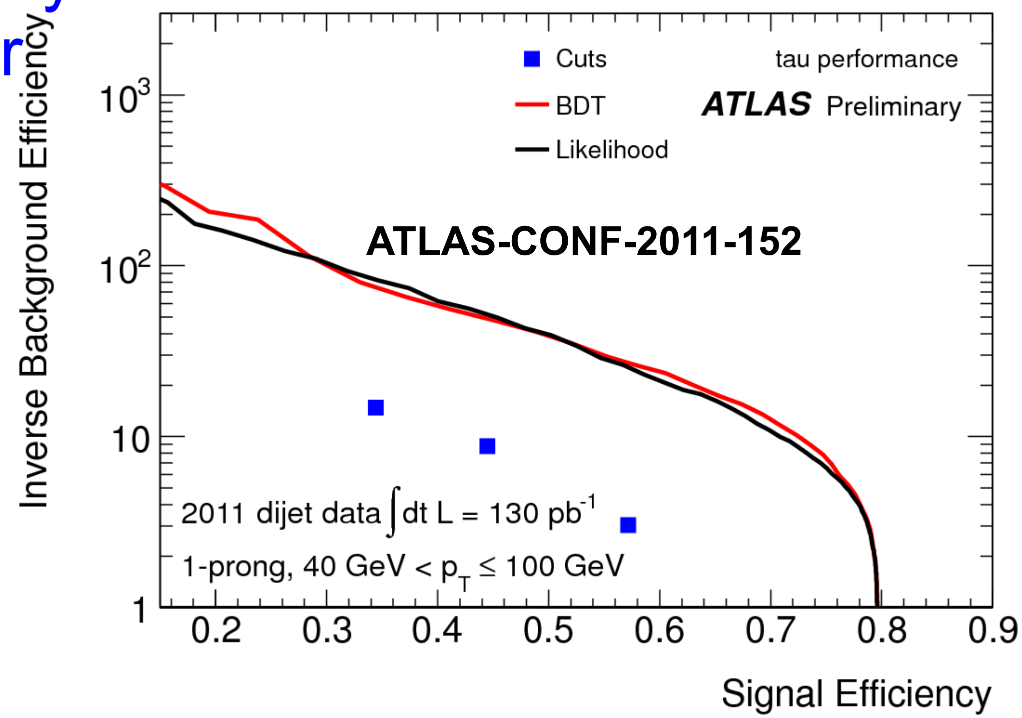




The presence of neutrinos and pions in the final states of hadronic tau decays makes it very challenging to suppress backgrounds from jets faking taus and to reconstruct di-tau invariant mass

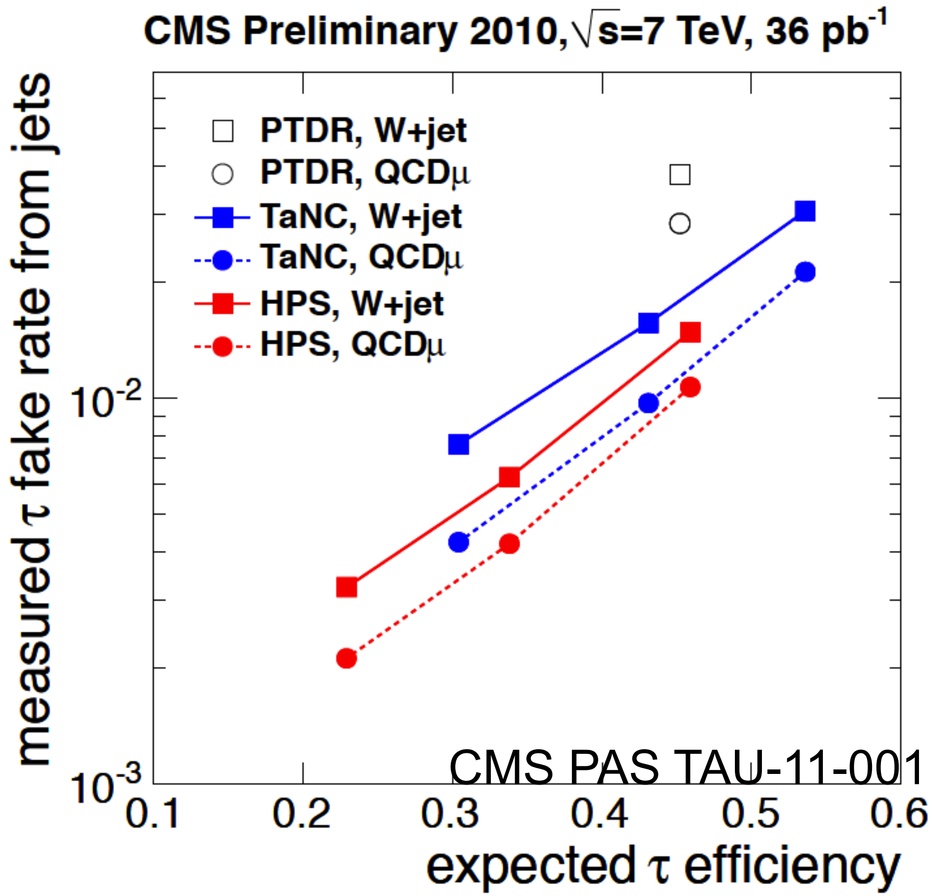
Taus in ATLAS and CMS

- In the experimental jargon "tau reconstruction" refers to hadronically decaying taus
- ATLAS is using a traditional approach to tau reconstruction
  - The "ATLAS tau" is essentially anti-kT clustered calorimeter deposits matched to tracks



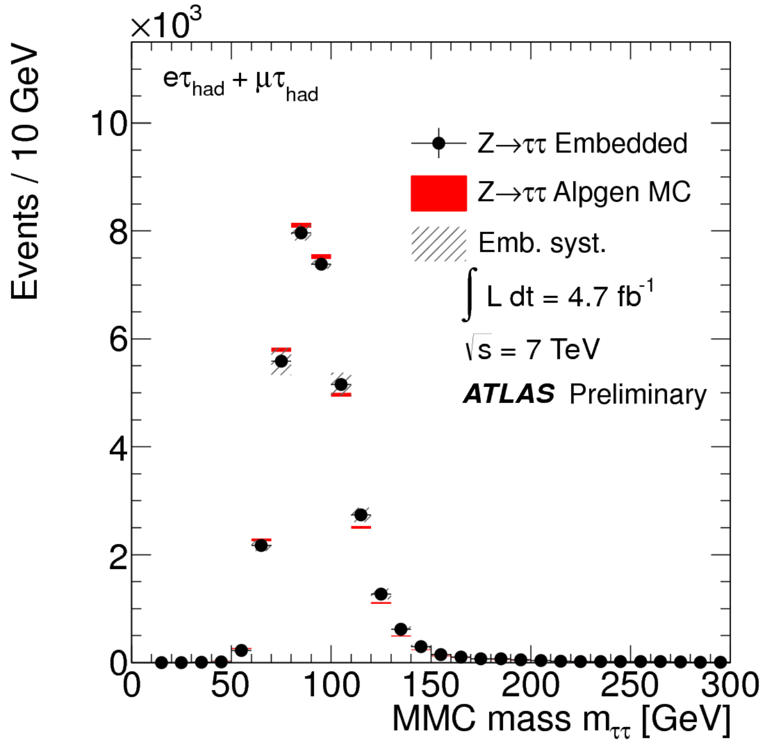
Taus in ATLAS and CMS

- In the experimental jargon "tau reconstruction" refers to hadronically decaying taus
- CMS is using a "particle flow" technique to make taus by clustering particles (photons & pions)



Special Techniques used with Taus

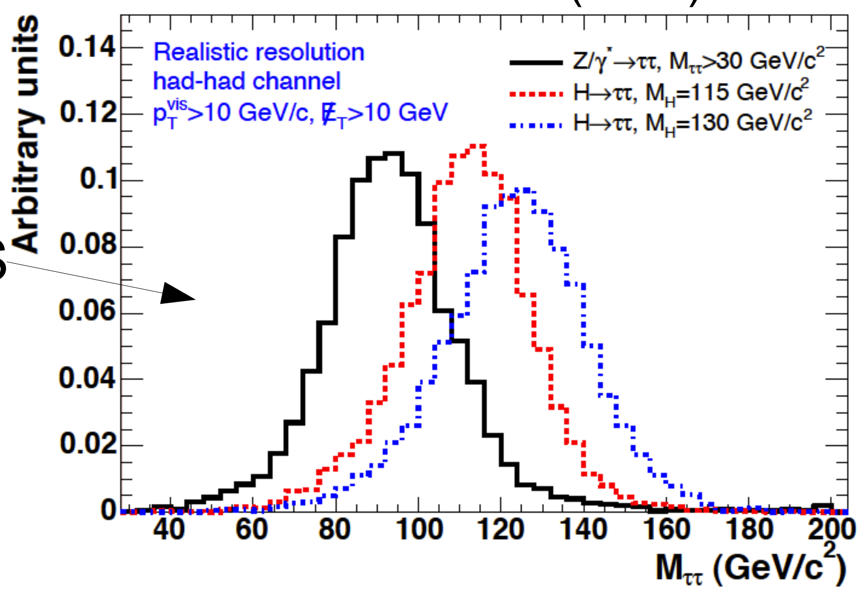
- $Z \rightarrow \tau\tau$ is the most important background source for di-tau final states
  - "τ-embedded" $Z \rightarrow \mu\mu$ data events:
    - semi-data-driven method: select a pure $Z \rightarrow \mu\mu$ event sample from data and then replacing the muons with simulated taus
    - Pile-up, underlying event, kinematics etc directly from data



Special Techniques used with Taus

- Di-tau invariant mass has poor resolution due to the presence of neutrinos in the final state
  - Simplest options: visible and effective mass (mass of visible objects or visible objets+MET)
  - Collinear approximation: assume neutrinos emitted in the same direction as the visible products
  - More advanced techniques: choose the most probable neutrino direction
    - "Missing mass calculator" for ATLAS
    - "SVfit" for CMS CMS-HIG-11-029

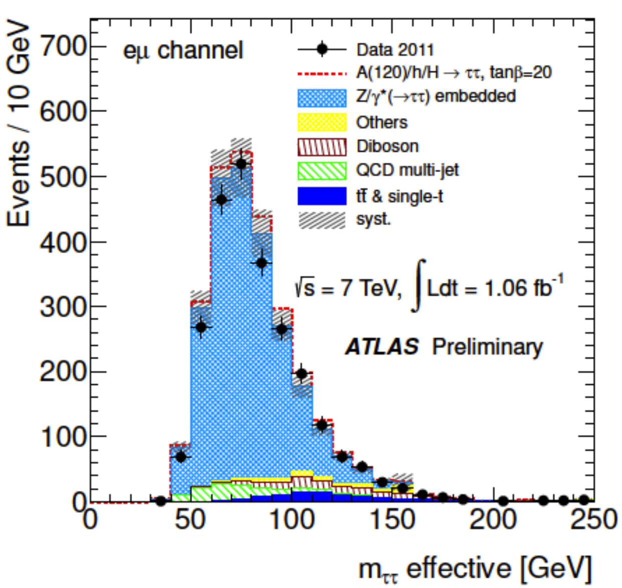
NIM A654 (2011) 481

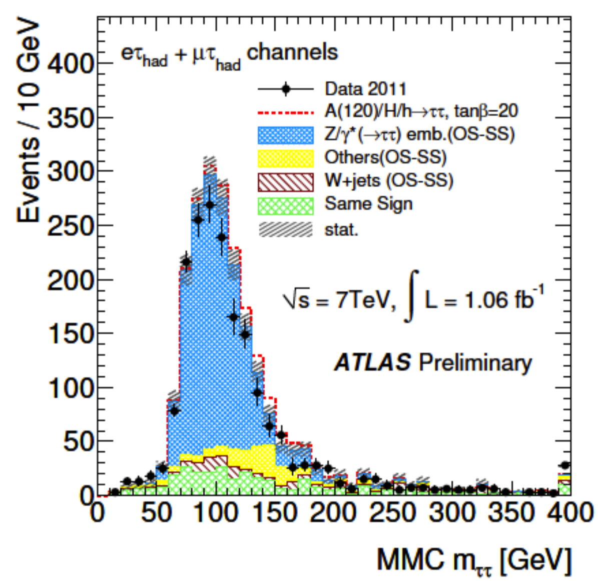


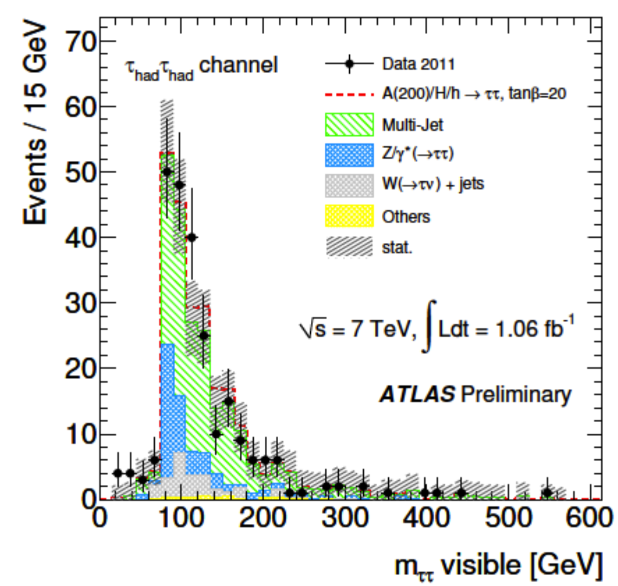
ATLAS Neutral MSSM Higgs Search

ATLAS-CONF-2011-132

τ(lep)τ(lep) using eμ	τ(lep)τ(had)	τ(had)τ(had)
1 isolated e with p_T > 25 GeV	**isolated e / μ** with p_T >25/20 GeV	**2 τhad** with p_T > 30/45 GeV
1 isolated μ with p_T > 20 GeV	exactly **one τhad** with p_T > 20 GeV	
Opposite sign	**Opposite sign**	**Opposite sign**
Sum of lepton pT and MET < 120 GeV, ΔΦ(e,μ)>2	MET > 20 GeV, MT<30 GeV	MET > 25 GeV



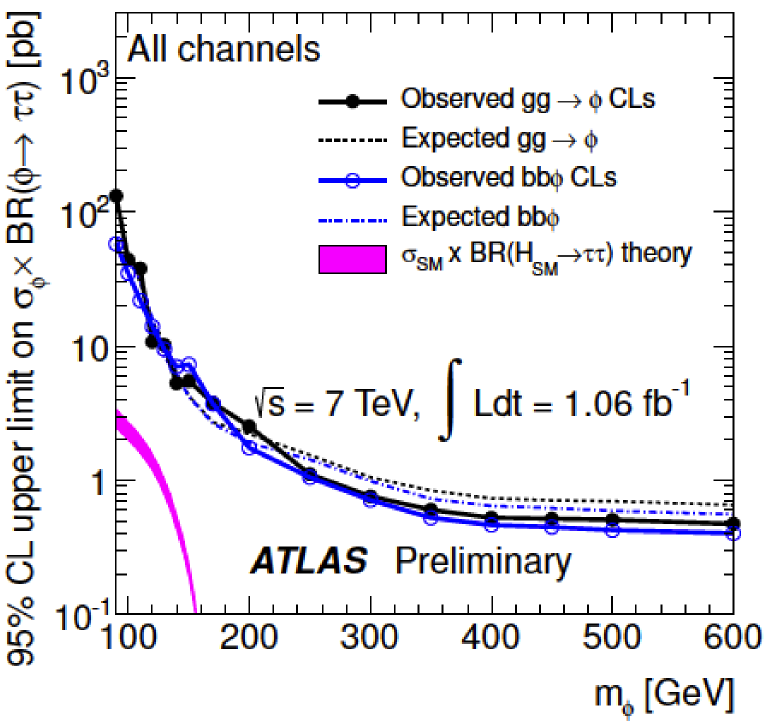




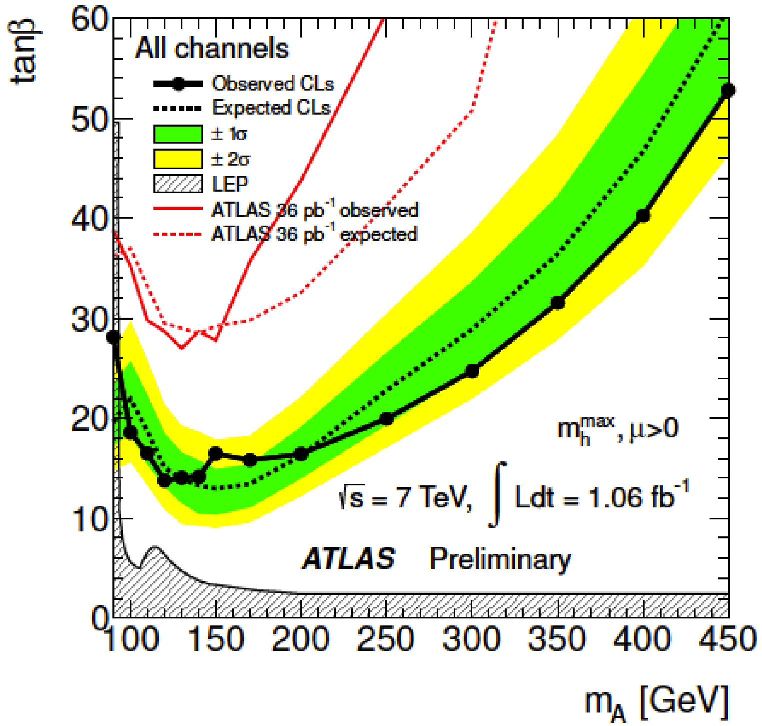
ATLAS Neutral MSSM Higgs Search

- Exclusion Limits: all channels combined

Limit on σ BR(φ → ττ)



"m_A-tanβ" space limit mhmax

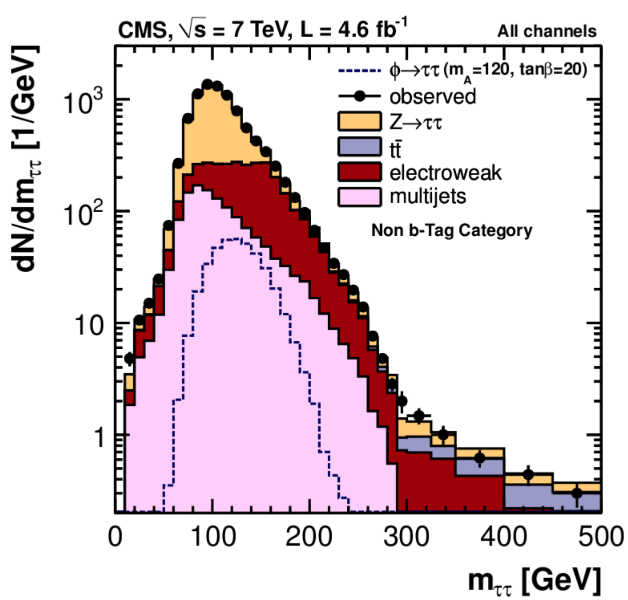


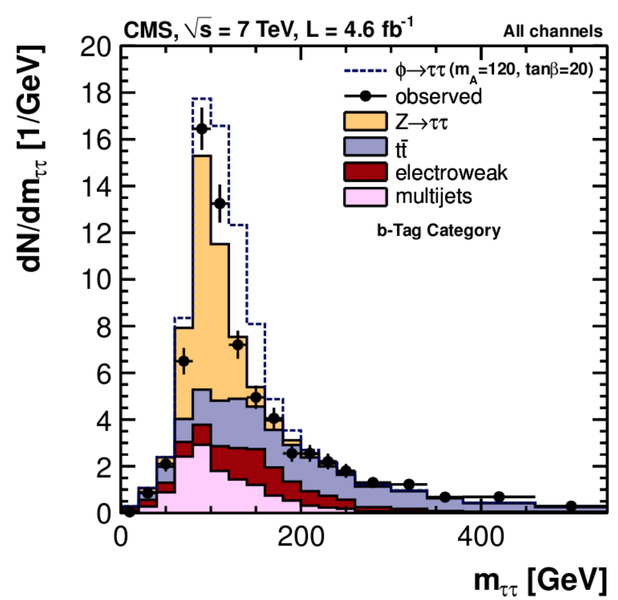
CMS Neutral MSSM Higgs Search

τ(lep)τ(lep) using eμ	τ(lep)τ(had)
isolated e,μ with p_T > 10,20 GeV	**isolated e / μ** with p_T >10/20 GeV
	exactly **one τ_{had}** with p_T > 20 GeV
Opposite sign	
Topological cuts based on MET and tau/lepton momenta	

"b-Tag" category:
"b-Tagged" jet with pT>20 GeV
and at most 1 jet with pT>30 GeV

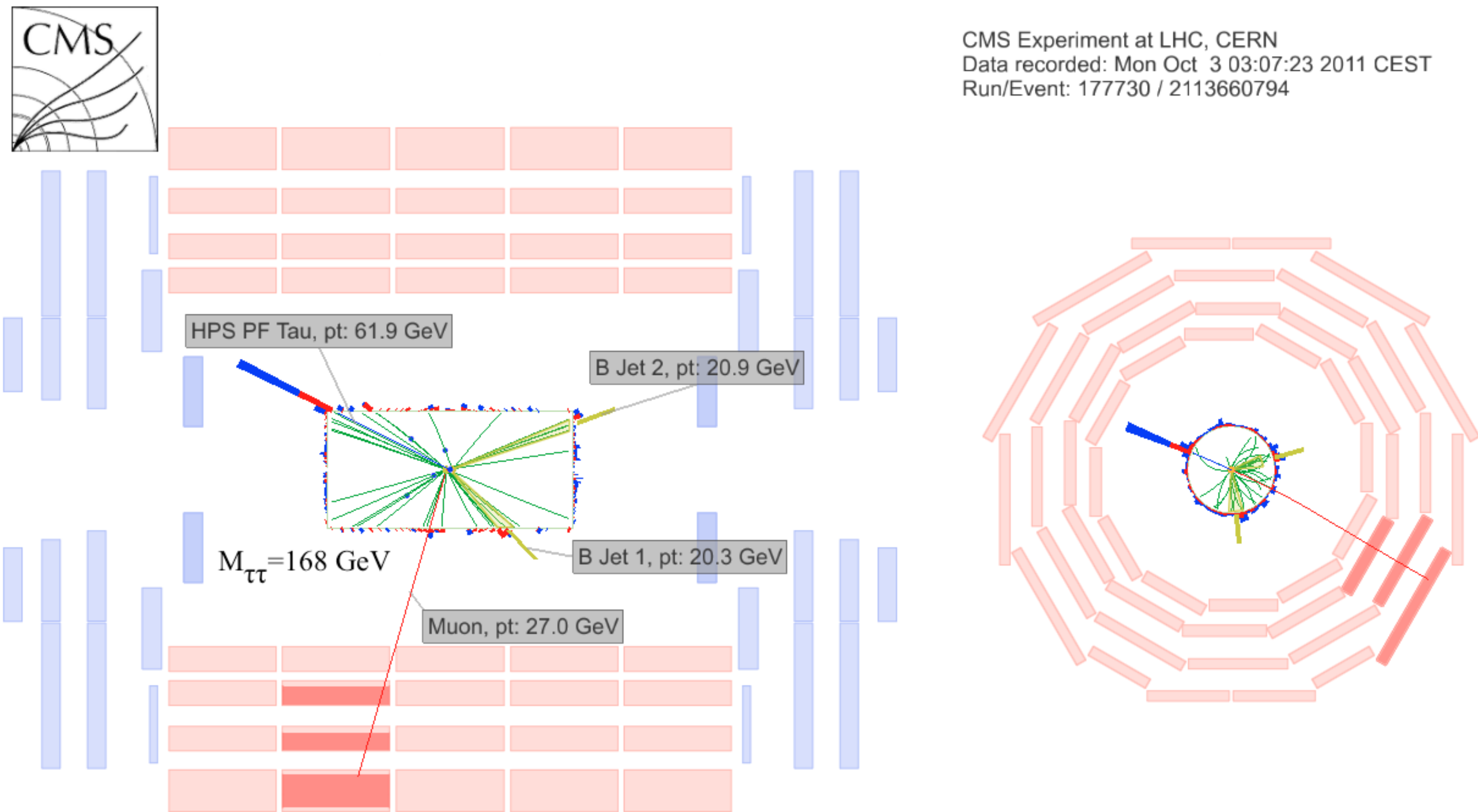
"no b-Tag" category:
No "b-Tagged" jet with pT>20GeV
and at most 1 jet with pT>30 GeV





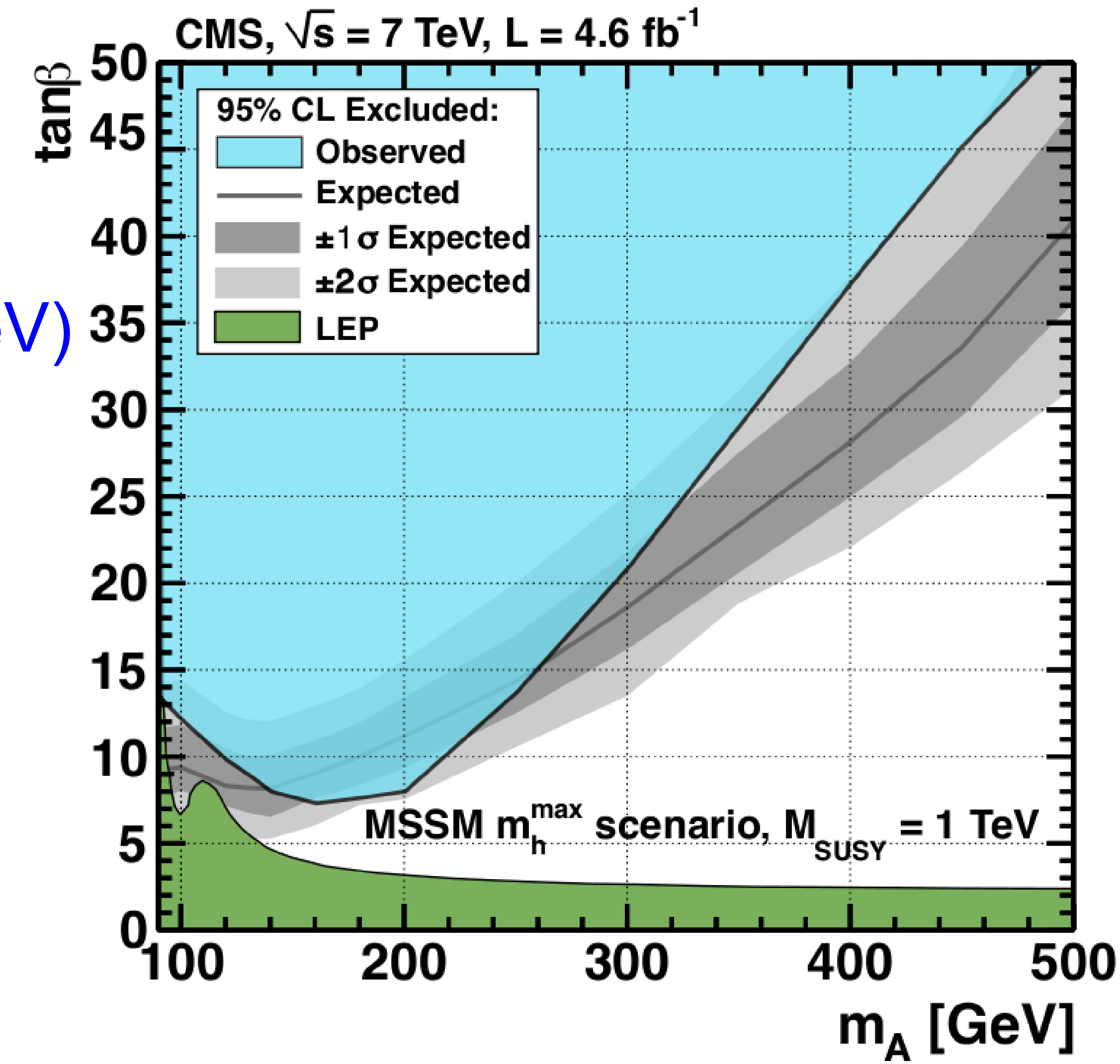
CMS Neutral MSSM Higgs Search

CMS event display of a H → ττ candidate from the b-Tag channel



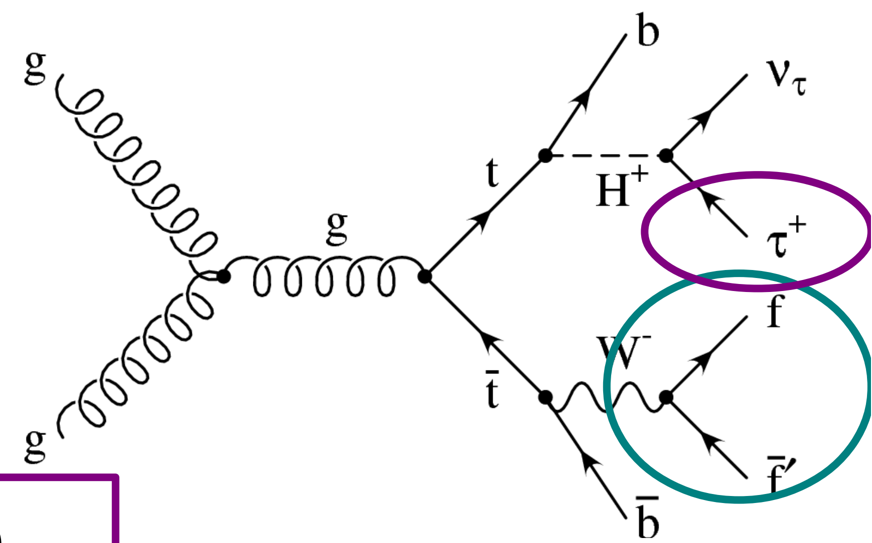
CMS Neutral MSSM Higgs Search

- Exclusion Limit in the mA – tanβ space:
  - About tanβ > 10 for low mass mA (<200 GeV) is excluded



Charged MSSM Higgs

- Search focus on a light charged Higgs produced in top decays
  - Channel topology organized according to W and Higgs decay



tau(had)+W(→lν): tt → bbWH → bb (lν) (τ_{had}ν)
tau(had)+W(→jets): tt → bbWH → bb (qq) (τ_{had}ν)
tau(lep)+W(→jets): tt → bbWH → bb (qq) (τ_{lep}ν)
tau(lep)+W(→lν): tt → bbWH → bb (lν) (τ_{lep}ν)

H → τν

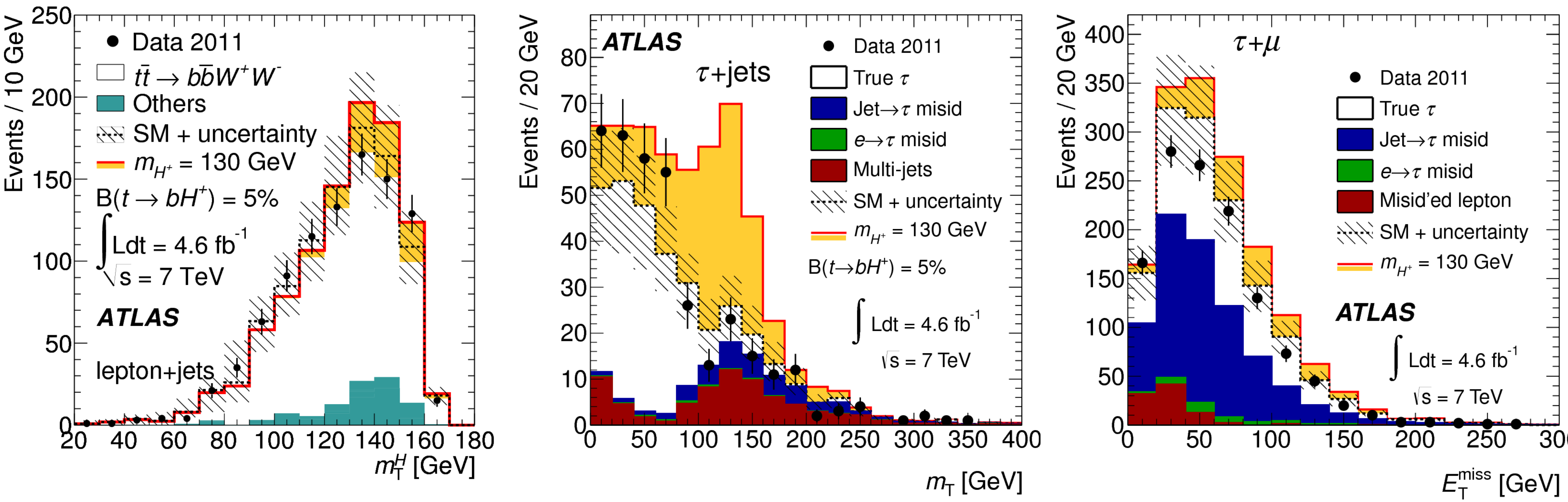
H^+(→cs)+W(→jets): tt → bbWH → bb (qq) (cs)

H → cs

arXiv:1204.2760

ATLAS $H^{\pm} \rightarrow \tau^{\pm}\nu$ search

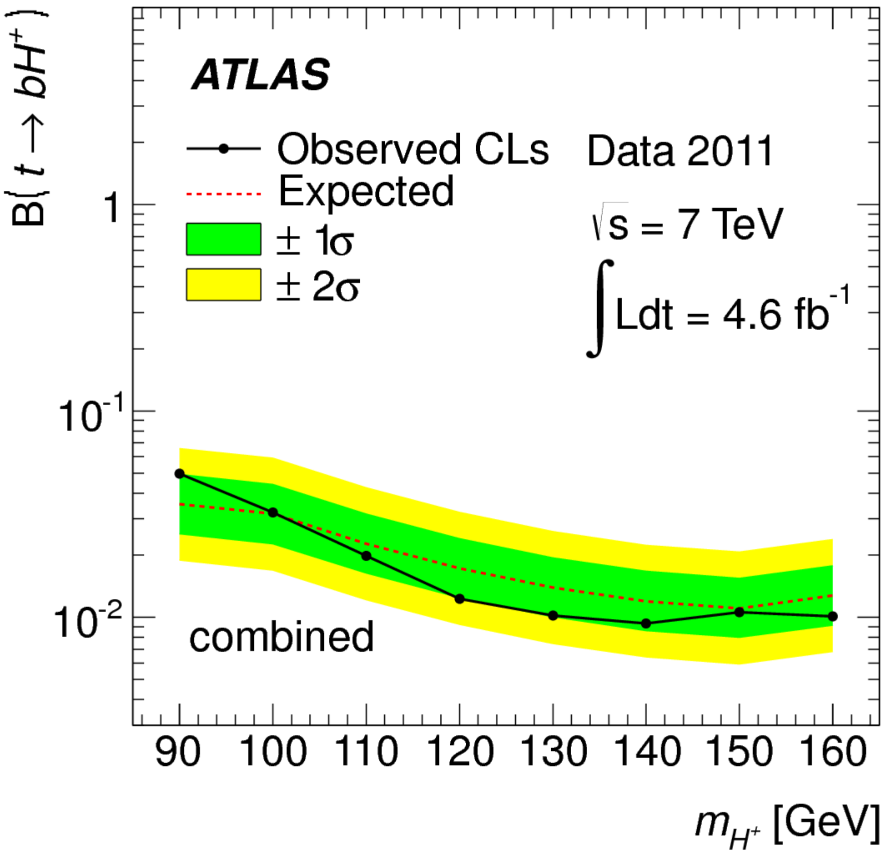
Tau(lep) + W(→ jets)	Tau(had) + W(→ jets)	Tau(had) + W(→ lν)
1 isolated e/μ, pT > 25/20 GeV	1 τ_{had} with pT > 40 GeV	1 isolated e/μ, pT > 25/20 GeV
		1 τ_{had} with pT > 20 GeV
At least 4 jets (pT>20 GeV) with exactly 2 b-tagged	At least 4 jets (pT>20 GeV) with at least 1 b-tagged	At least 2 jets (pT>20 GeV), with at least 1 b-tagged
MET & Topological cuts	MET & Topological cuts	vertex ΣpT > 100 GeV

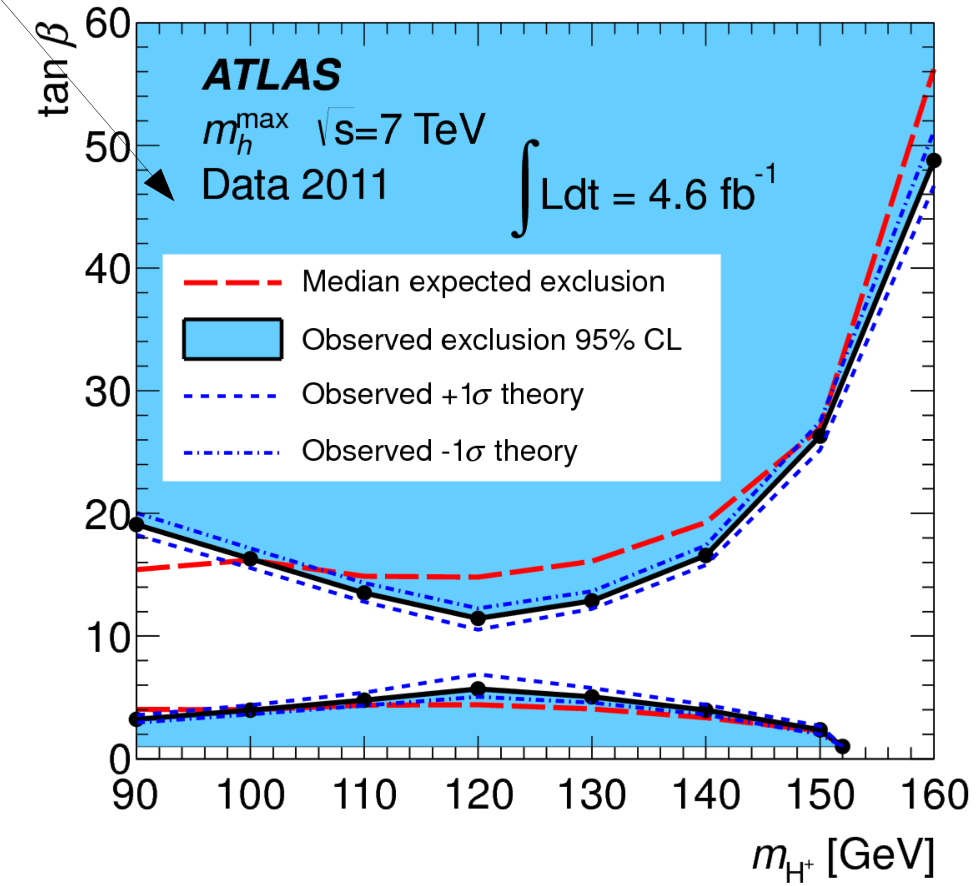


ATLAS $H^{\pm} \rightarrow \tau^{\pm}\nu$ search

arXiv:1204.2760

Low mass H± allowed phase space in the MSSM scenario is heavily constrained now

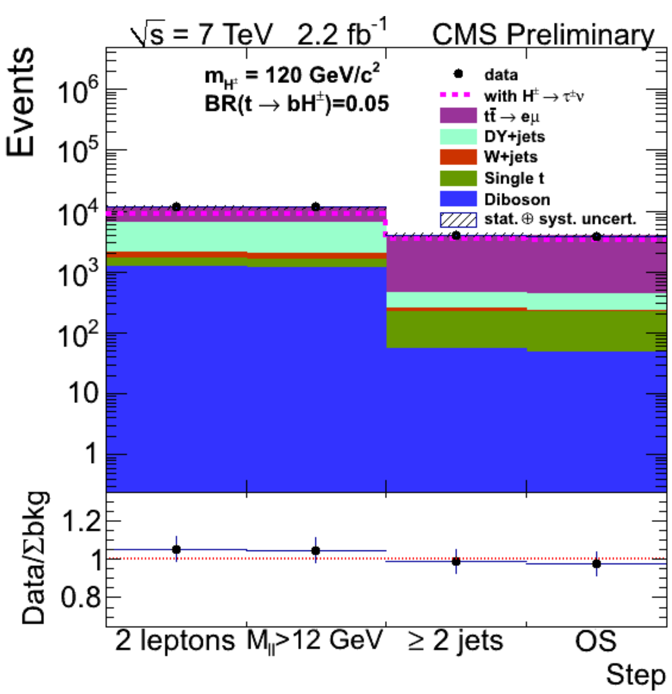


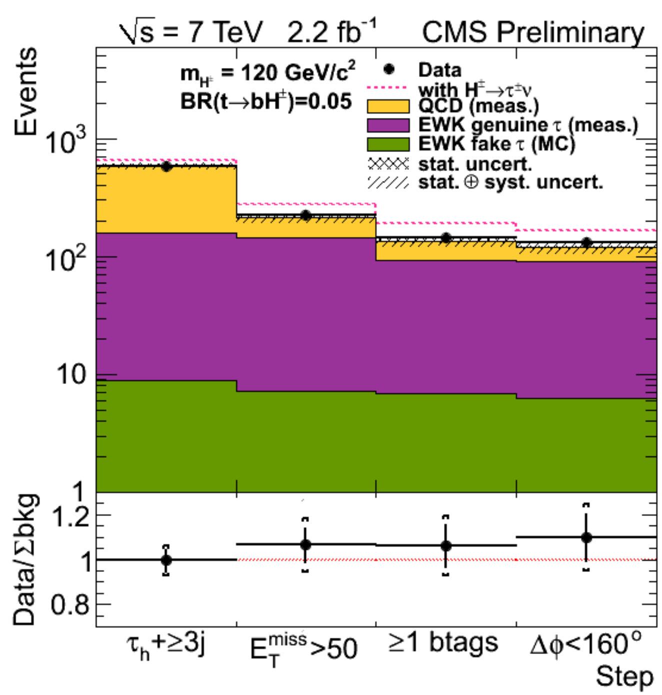


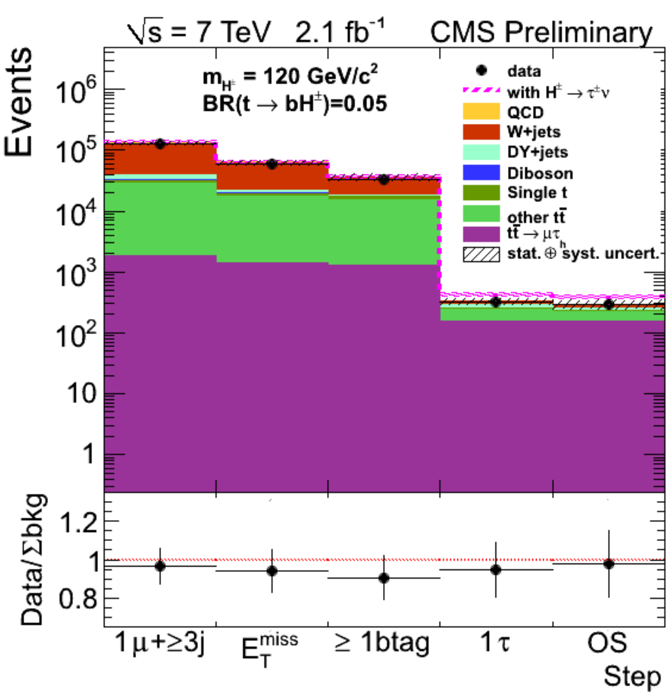
CMS $H^{\pm} \rightarrow \tau^{\pm}\nu$ search

CMS PAS HIG-11-019

Tau(lep) + W(→ lv)	Tau(had) + W(→ jets)	Tau(had) + W(→ lv)
isolated e+μ, pT > 20 GeV	1 τ_{had} with pT > 40 GeV	isolated e or μ, pT > 35/30 GeV
Opposite sign; M(eμ)>12 GeV		1 τ_{had} with pT > 20 GeV
At least 2 jets (pT>30 GeV)	At least 3 jets (pT>30 GeV) with at least 1 b-tagged	At least 2 jets (pT>35/30 GeV), with at least 1 b-tagged
	MET, topological cuts etc	MET and other cuts



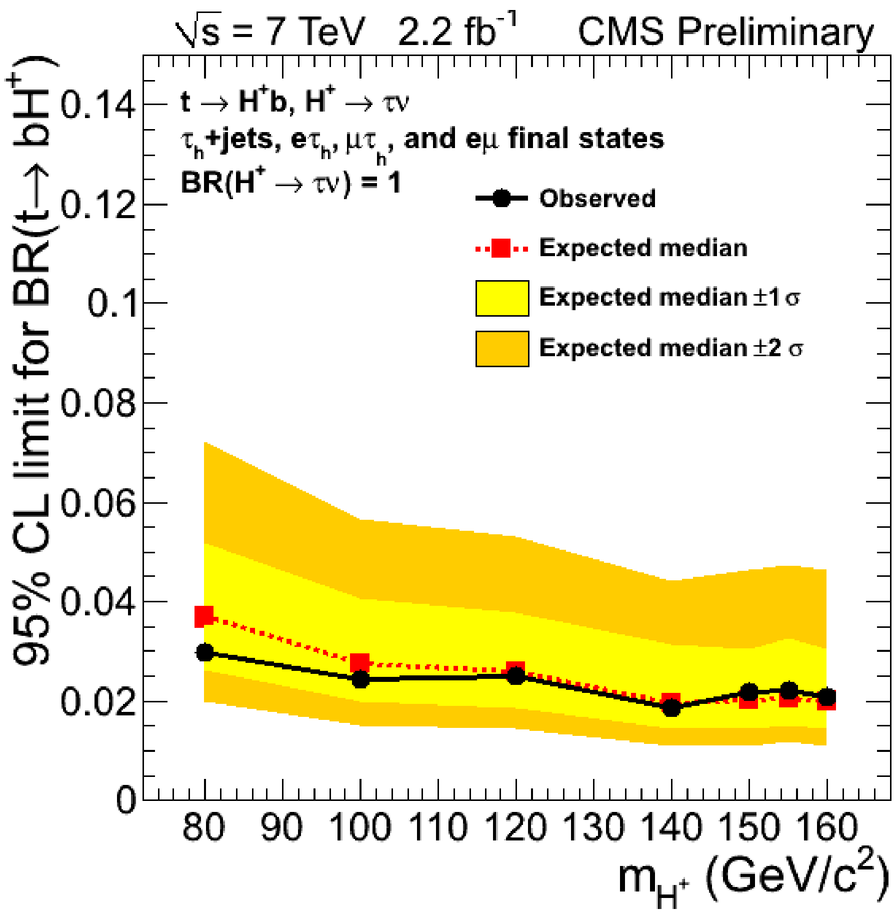


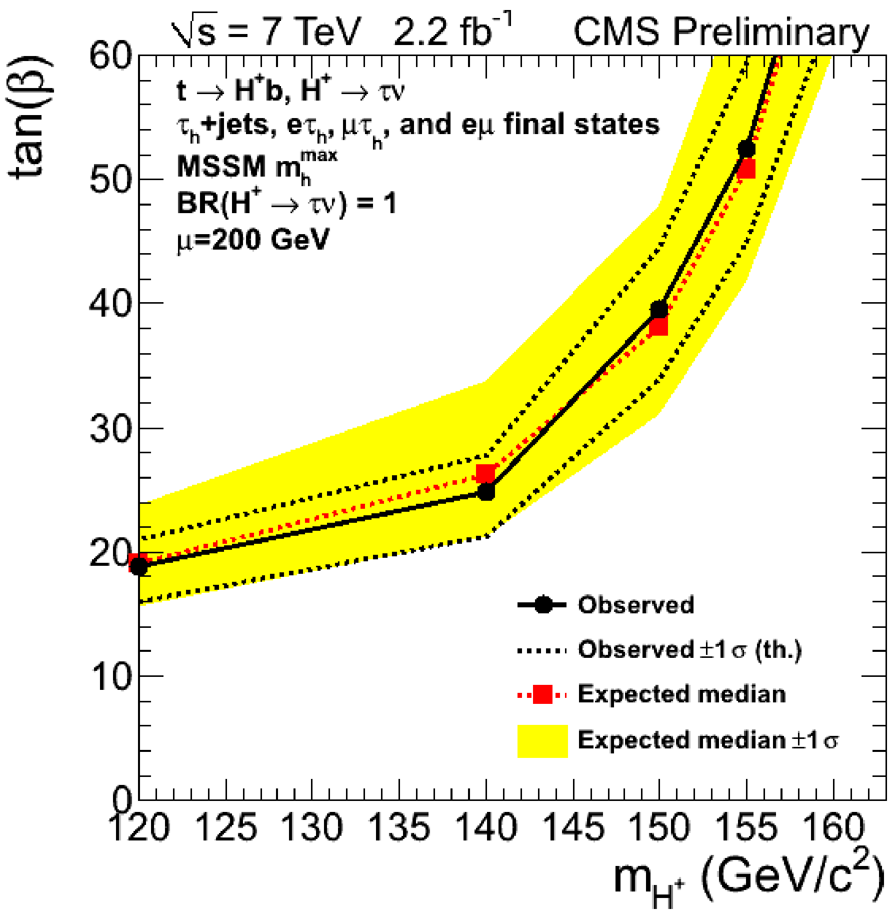


CMS $H^{\pm} \rightarrow \tau^{\pm}\nu$ search

CMS PAS HIG-11-019

- Exclusion Limit (Lumi ~ 2/fb)



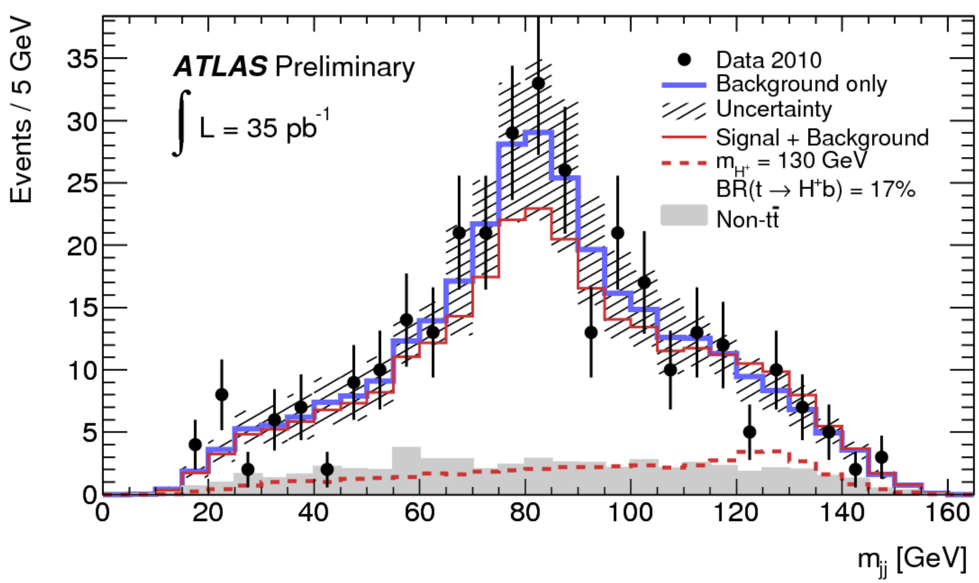


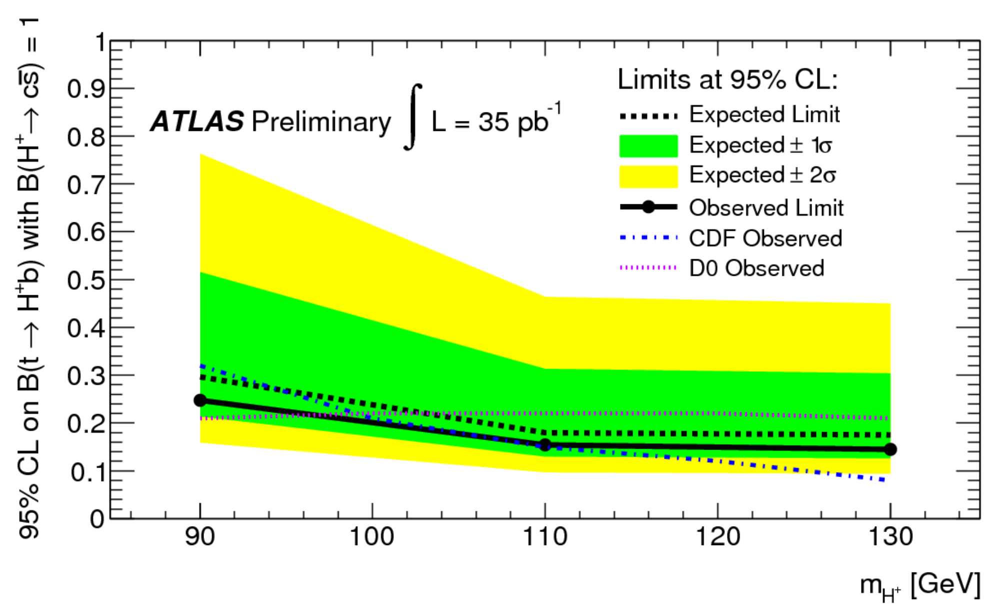
ATLAS $H^+ \rightarrow c\bar{s}$

- Important at low tanβ:
  - Br(H→cs) ~ 40%, tanβ<1, mH+ ~130 GeV
  - Only one ATLAS search with 35/pb

$t\bar{t} \rightarrow bW\, bH^+ \rightarrow b\,(e/mu)\,\nu\ \ b\, cs$
1 isolated e/μ, $p_T > 20$ GeV
At least 4 jets, pT>20 GeV; one b-Tagged jet
MET/MT cuts: MT>25 GeV (e); MT+MET>60GeV

ATLAS-CONF-2011-094

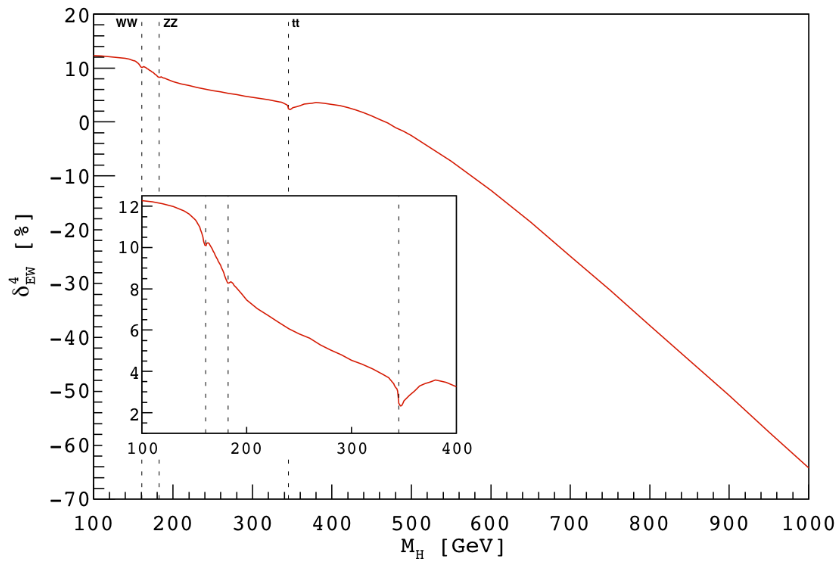




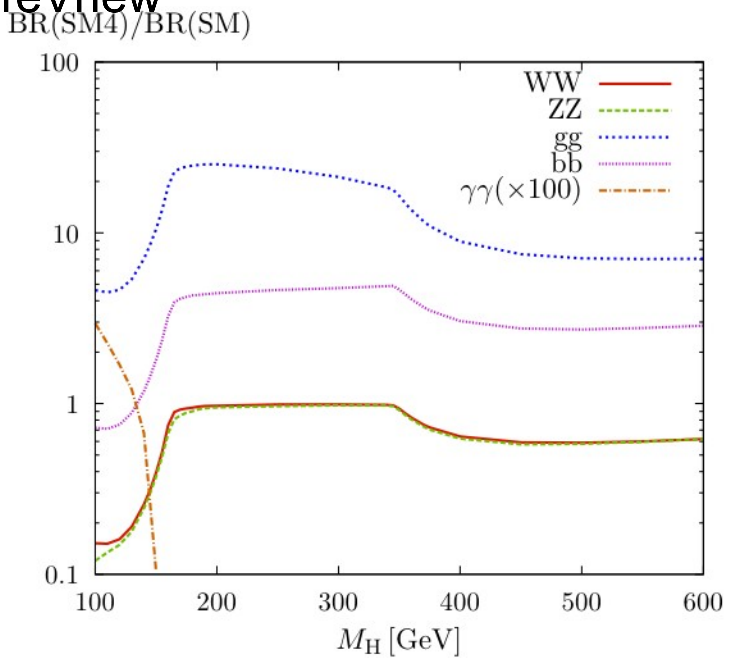
SM4

- An additional 4th generation of fermions modifies the gg fusion production mode and the higgs decay branching ratios

https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SM4At7TeVnew



NLO EW correction to the ggF Higgs production in SM4

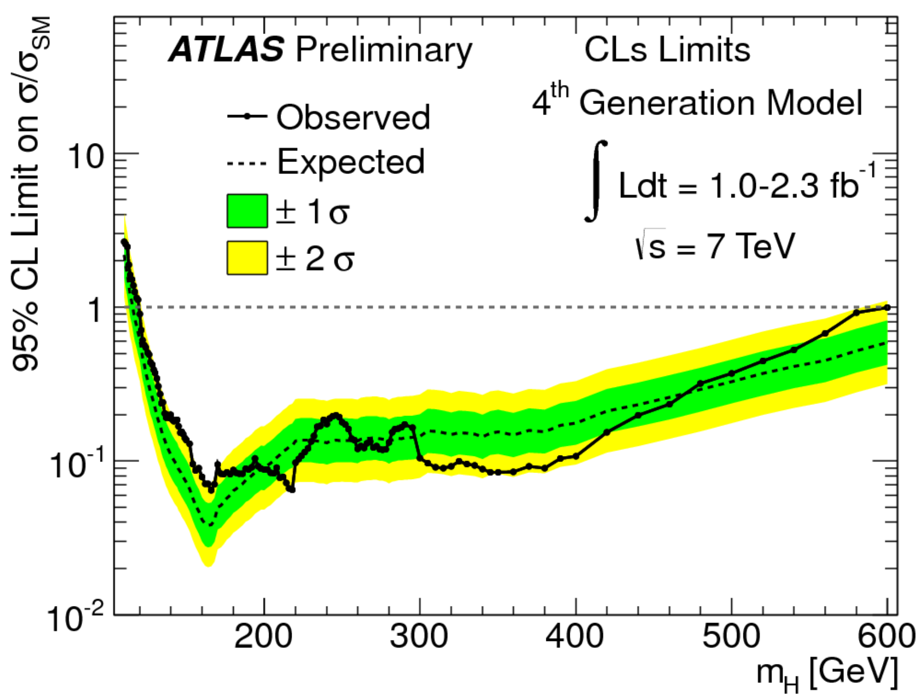


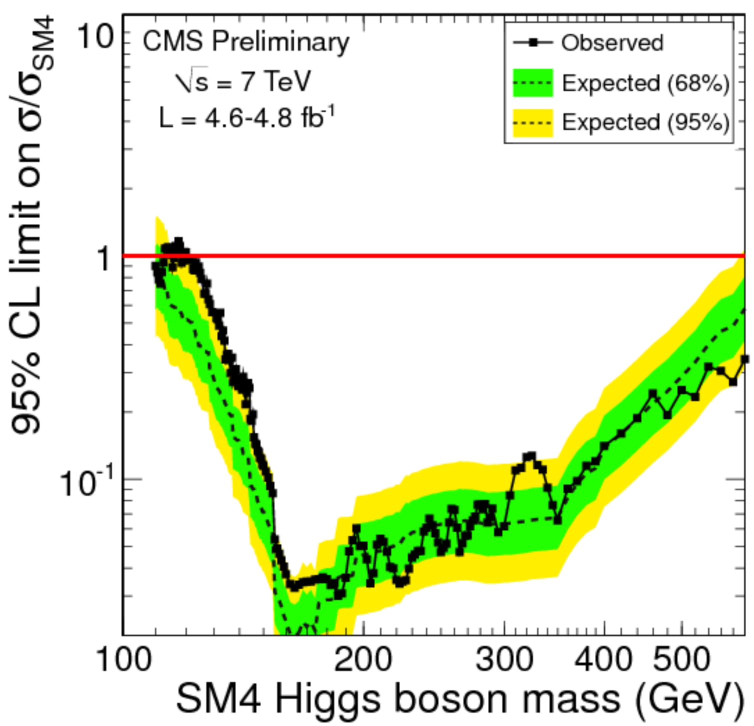
Ratio of BR in SM4/SM calculated with Prophecy4f and HDECAY

$m_{D4} = m_{L4} = 600$ GeV and $m_{U4} - m_{D4} = (50 + 10 \ln(m_H/115))$ GeV

SM4

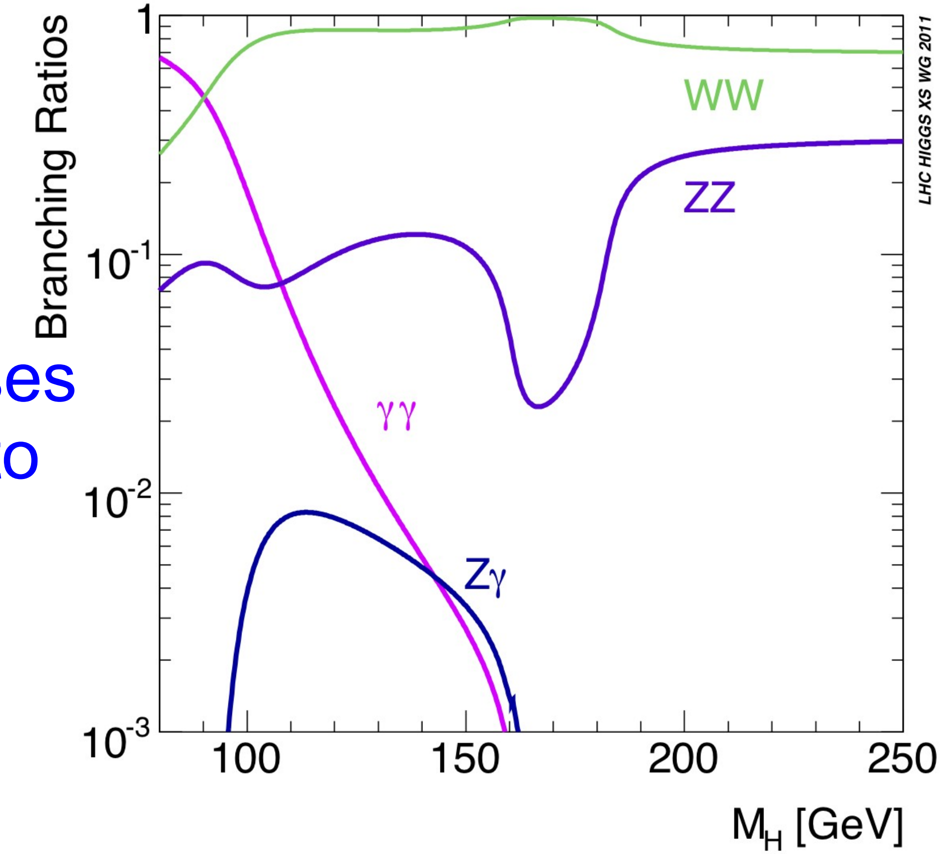
- The enhanced cross section relative to the SM allows an exclusion of large parts of the parameter space
  - Higgs mass range 119-600 GeV excluded





Fermiophobic Higgs

- Fermiophobic Higgs models change considerably Higgs couplings with respect to the SM
  - No couplings to fermions
  - Production via VBF and VH
  - Decay via γγ, ZZ, WW and Zγ
  - ATLAS and CMS search focuses on γγ – searches very similar to SM Higgs → γγ search

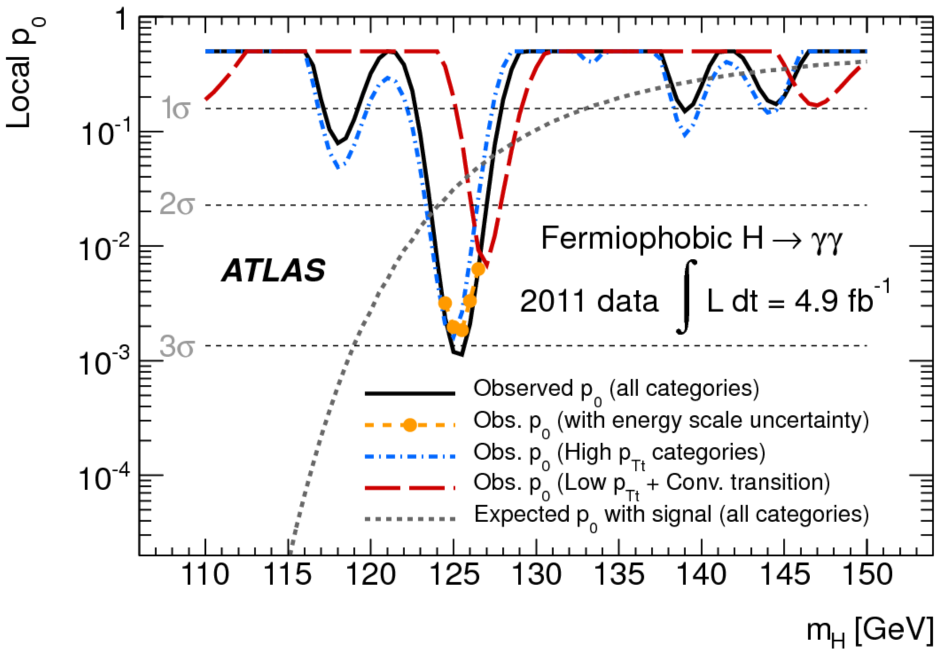


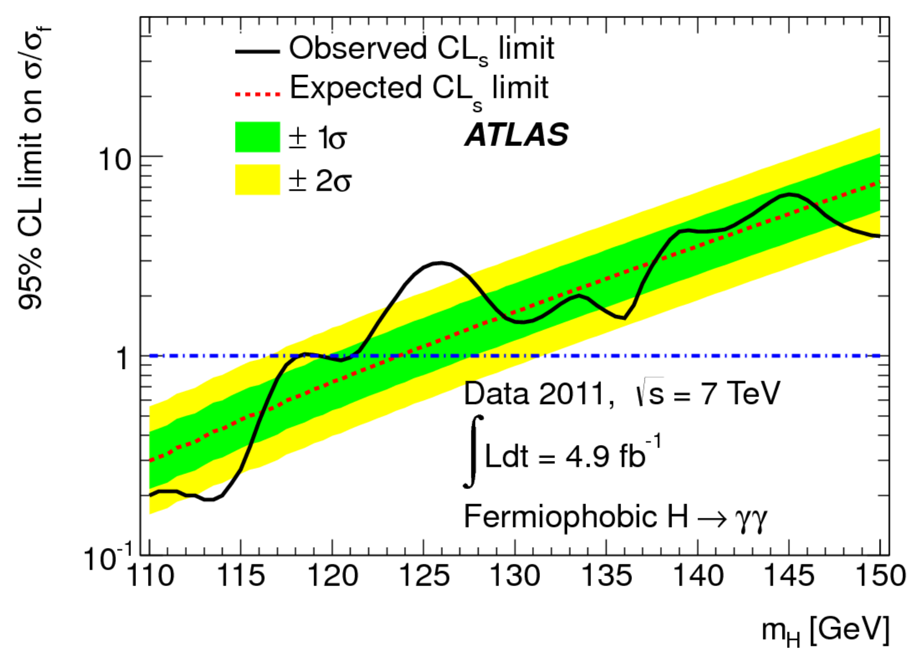
Fermiophobic Higgs Search

arXiv:1205.0701

- ATLAS search

2 photons pT > 40 / 25 GeV
Categories based on conversions, η and di-photon pT
Signal modelled with "crystal ball"+gaussian; bkg with exponential



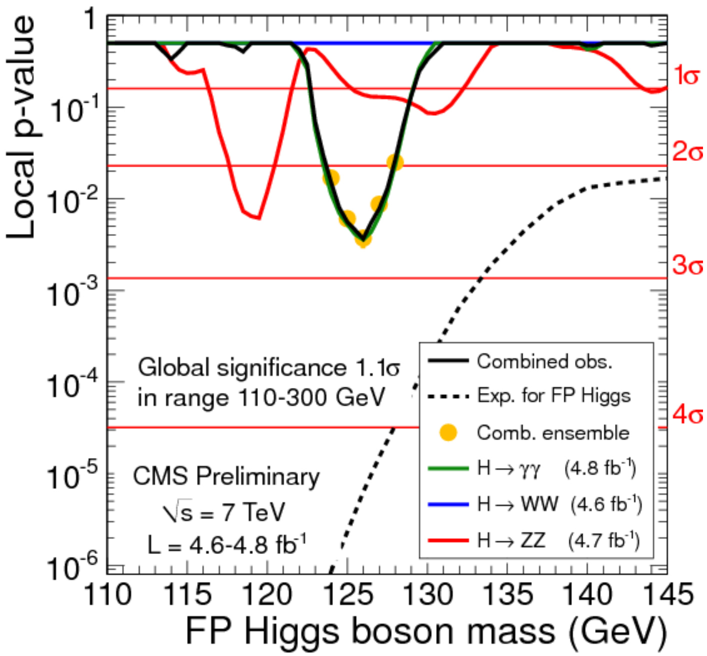


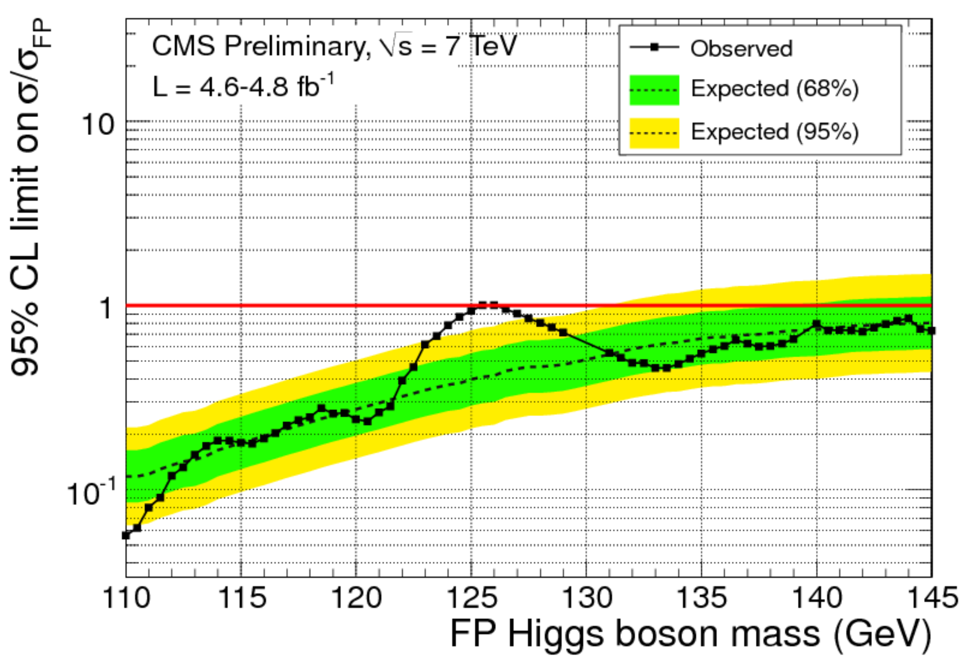
Fermiophobic Higgs Search

- CMS search

CMS PAS HIG-12-002
CMS PAS HIG-12-008

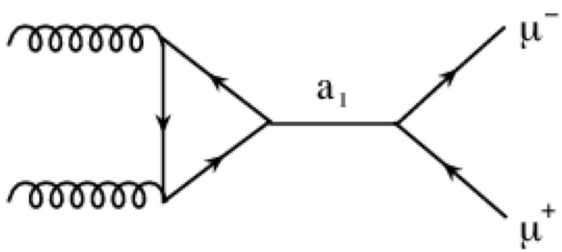
2 photons pT > 40 / 25 GeV
Categories: lepton, di-jet tagged and inclusive
Signal modelled with “crystal ball”+gaussian; bkg with exponential, polynomial or modified power law depending on the category





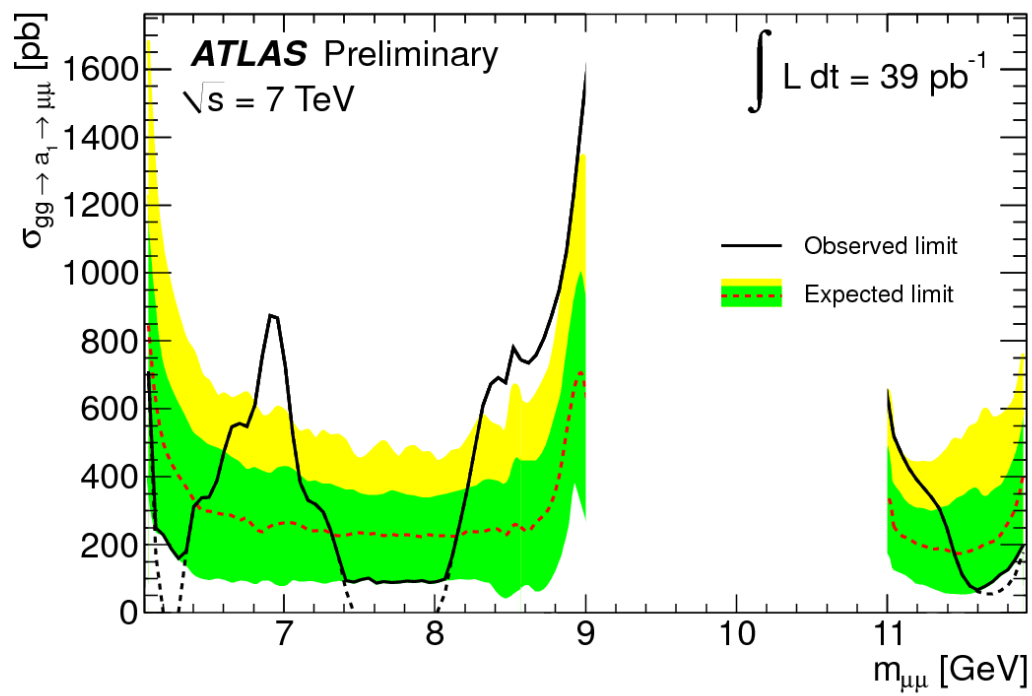
Light Scalar Field (NMSSM)

- Light scalar Higgs boson: NMSSM allows a ~10 GeV CP-odd Higgs with a sizeable BR to a di-muon pair
  - Search for it in the Υ sidebands



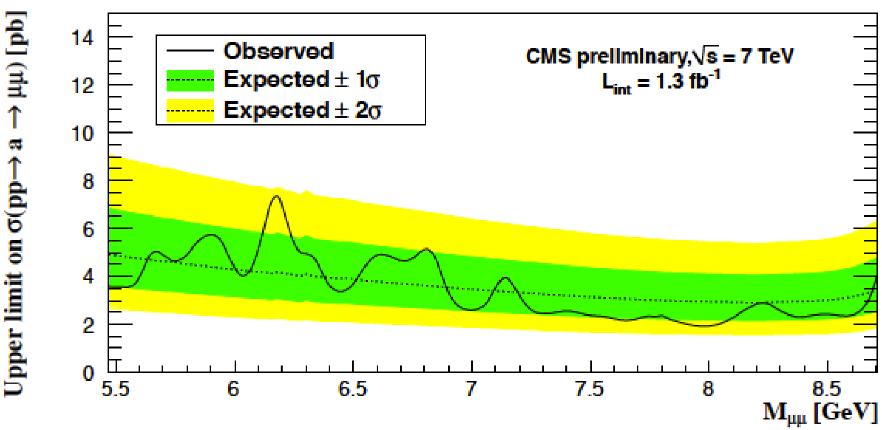
ATLAS-CONF-2011-020

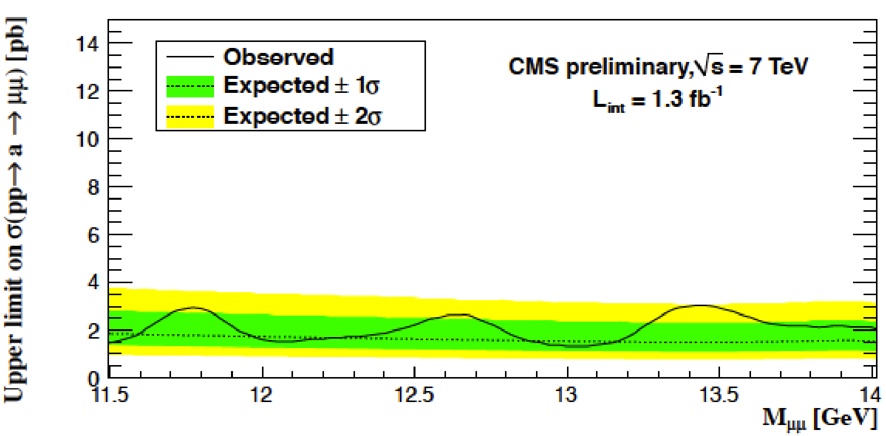
$H \rightarrow \mu\mu$ (NMSSM)
2 isolated μ, p_T > 4 GeV, opposite sign
Multivariate technique to reject muons not coming from the decay of a single particle
Sidebands $m_{\mu\mu}$: 6-9 GeV and 11-12 GeV



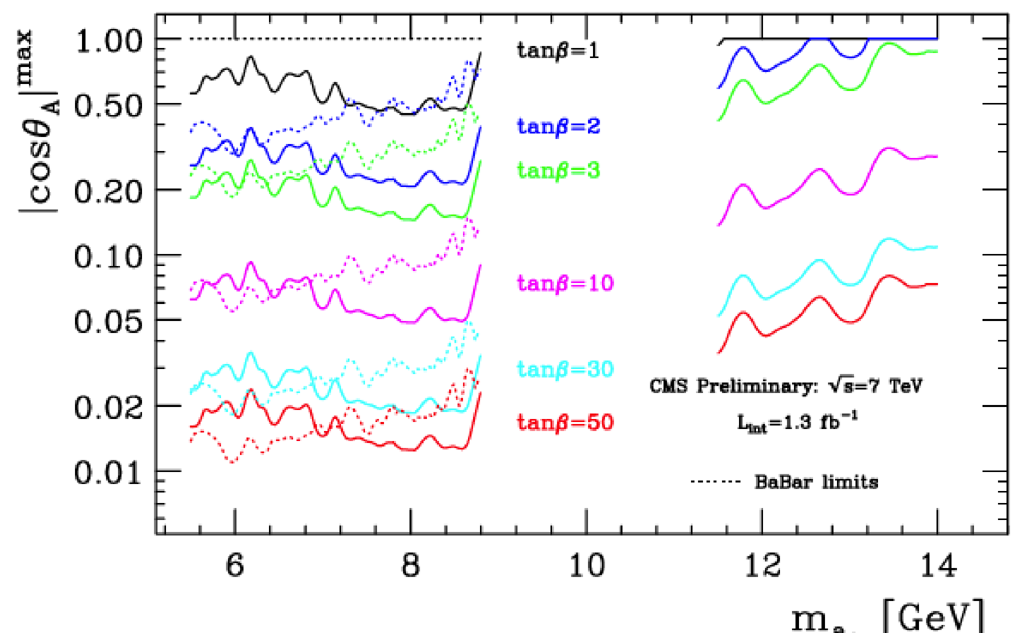
Light Scalar Field (NMSSM)

CMS PAS HIG-12-004



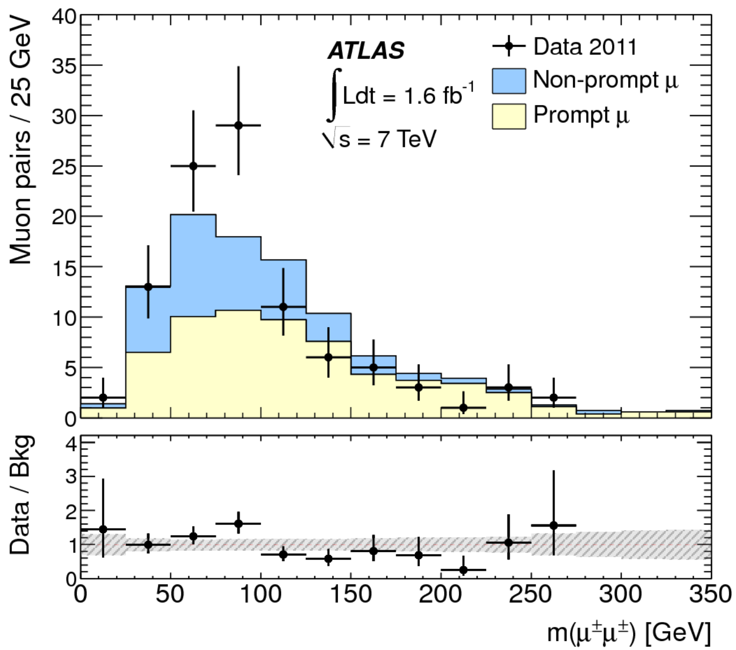


H → μμ (NMSSM)
2 isolated μ, pT > 5.5 GeV, opposite sign
Sidebands $m_{\mu\mu}$: 5-9 GeV and 11-14 GeV



H^{++} Search

- Doubly charged Higgs is predicted by many models
  - "little Higgs" and "seesaw type II" models include triplet (H^0,H^+,H^{++})
  - Possible observation of H^{++} in LHC could provide more insight into neutrino masses
- ATLAS: a generic same sign di-muon spectrum search



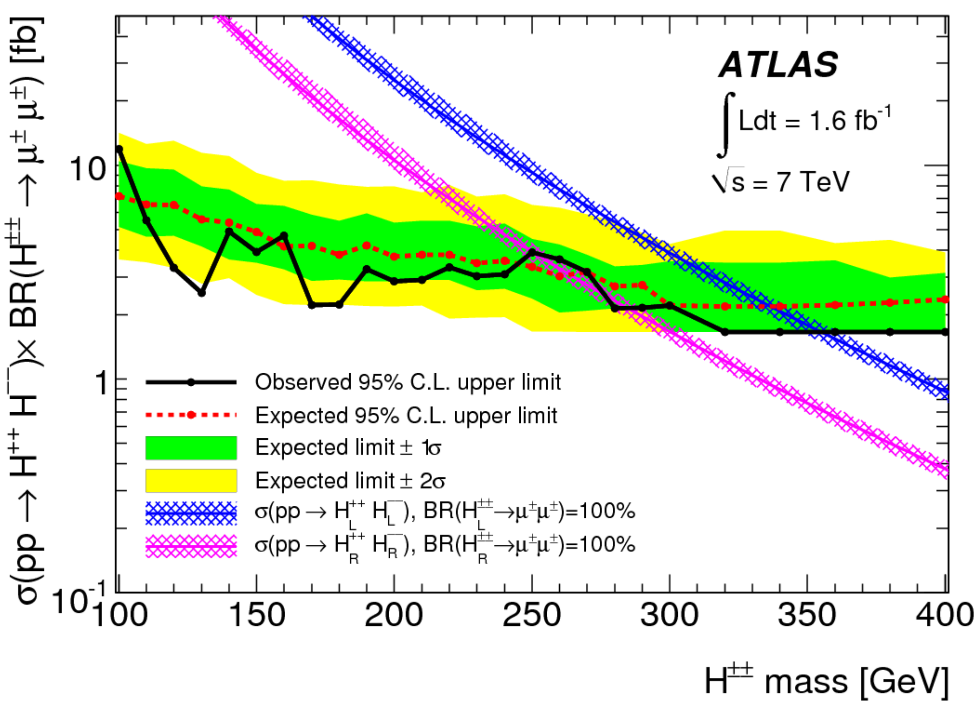
$H^\pm \rightarrow \mu^\pm\mu^\pm$
2 isolated μ, $p_T > 20$ GeV, **same sign**

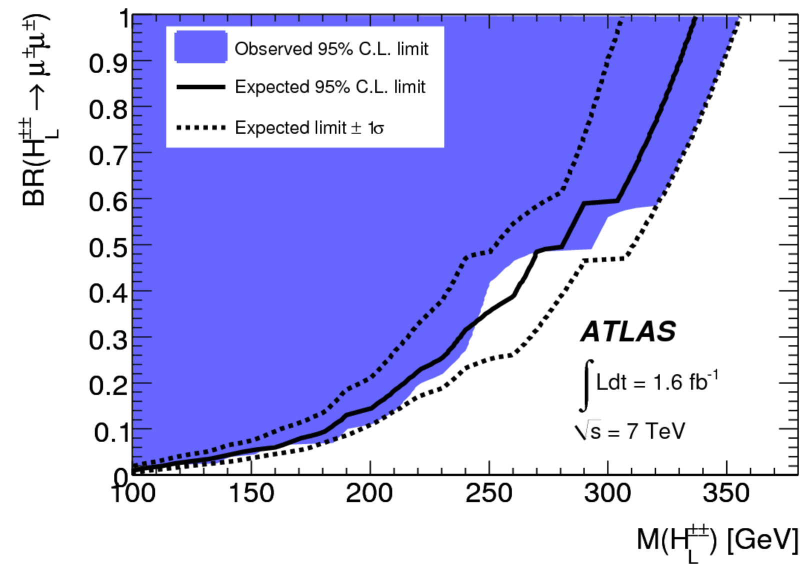
Phys. Rev. D 85, 032004 (2012)

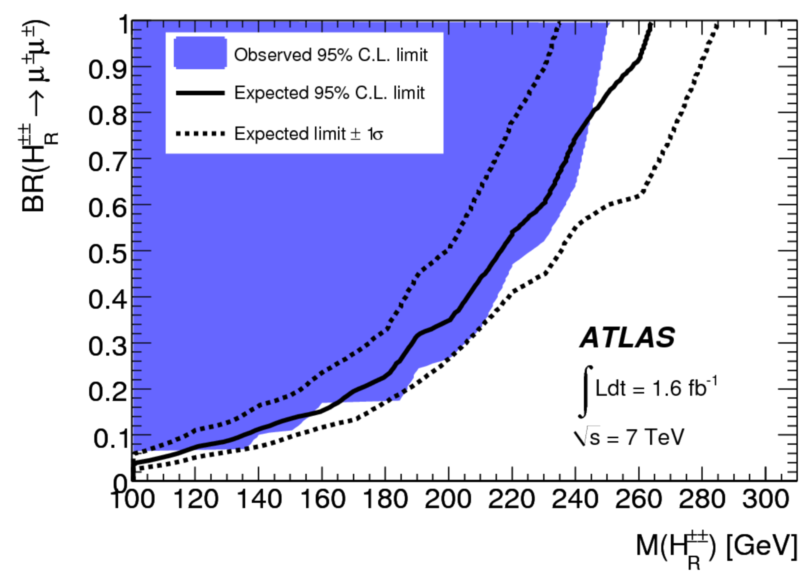
$H^{\pm\pm}$ Search

- ATLAS Exclusion limits

Phys. Rev. D 85, 032004 (2012)



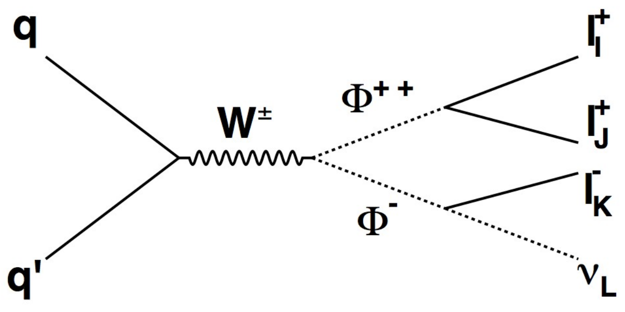


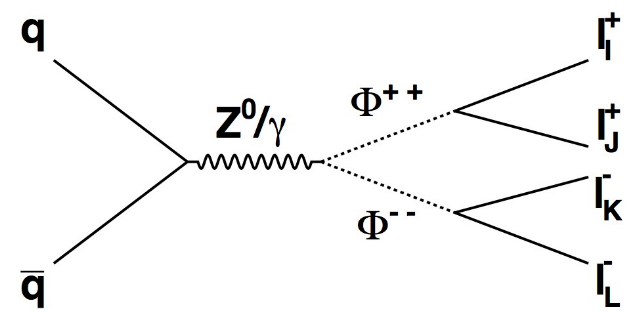


$H^{\pm\pm}$ Search

CMS PAS HIG-12-005

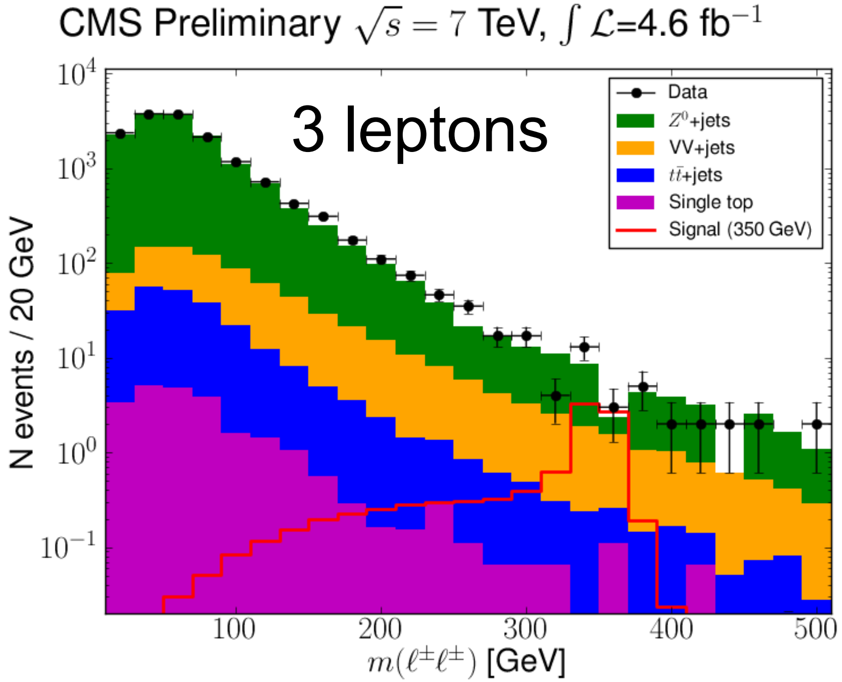
- CMS search: search tailored on 2 mechanisms:





Look for 3-lepton and 4-lepton final states assuming different lepton flavour combinatior

$H^{\pm} \rightarrow \mu\mu$ / ee / eμ / μτ / eτ	
At least 2 isolated leptons with pT > 20, 10 GeV m(ll)<12 GeV rejected	
3-lepton channel → Z-veto → Scalar lepton sum pT, MET etc depending on the assumed higgs mass	4-lepton channel → Similar to 3-lepton channel but less Constraints, since bkgs are lower

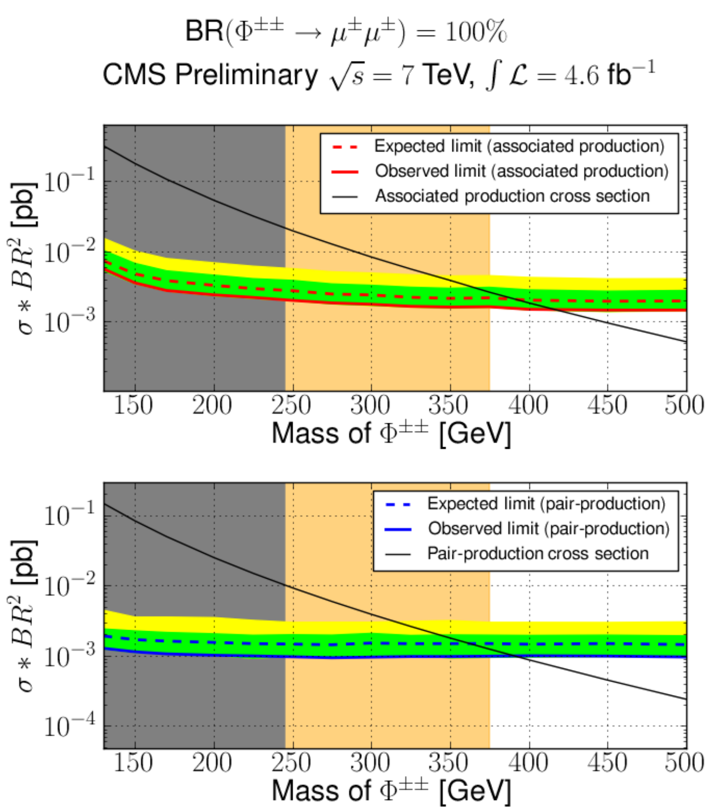


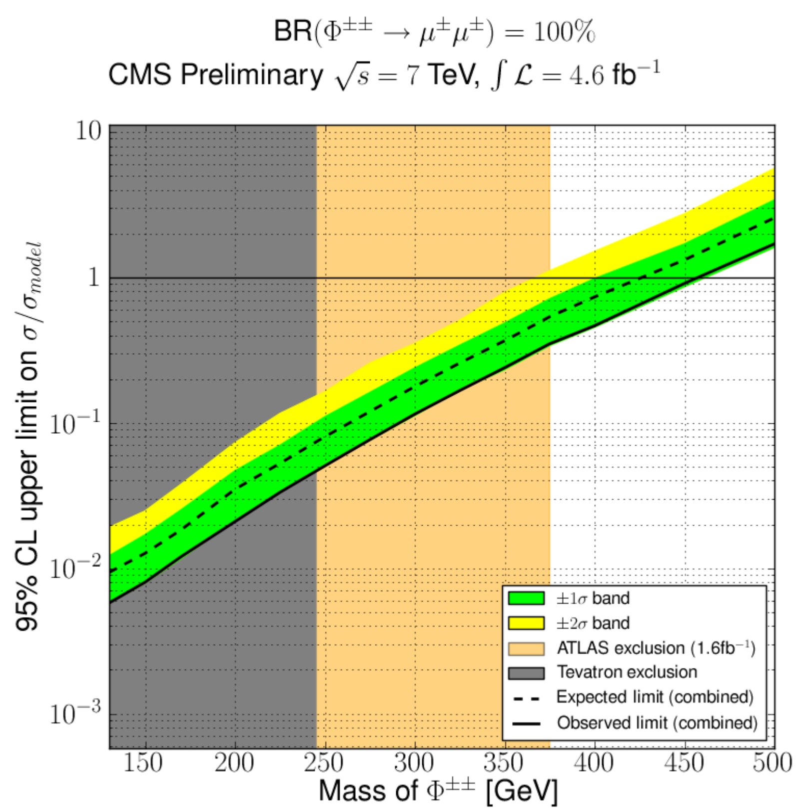
$H^{\pm\pm}$ Search

CMS PAS HIG-12-005

• CMS search: Results

Data interpreted in both "model-independent" (i.e. cross section limits) way and in 4 benchmark points of see-saw type II mechanism (Phys. Rev. D77(2008) 115023)





$H^{\pm\pm}$ Search

CMS PAS HIG-12-005

• CMS search: Results

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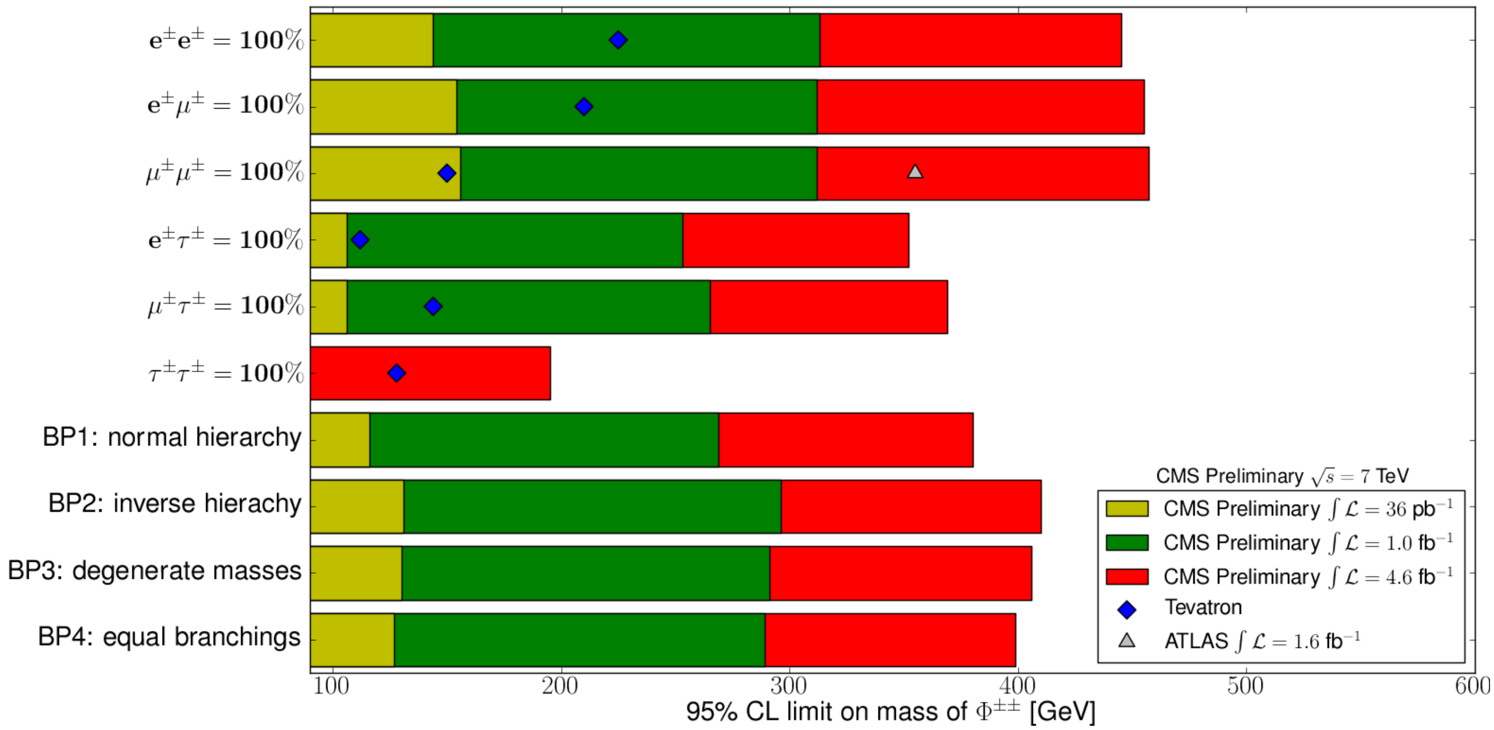


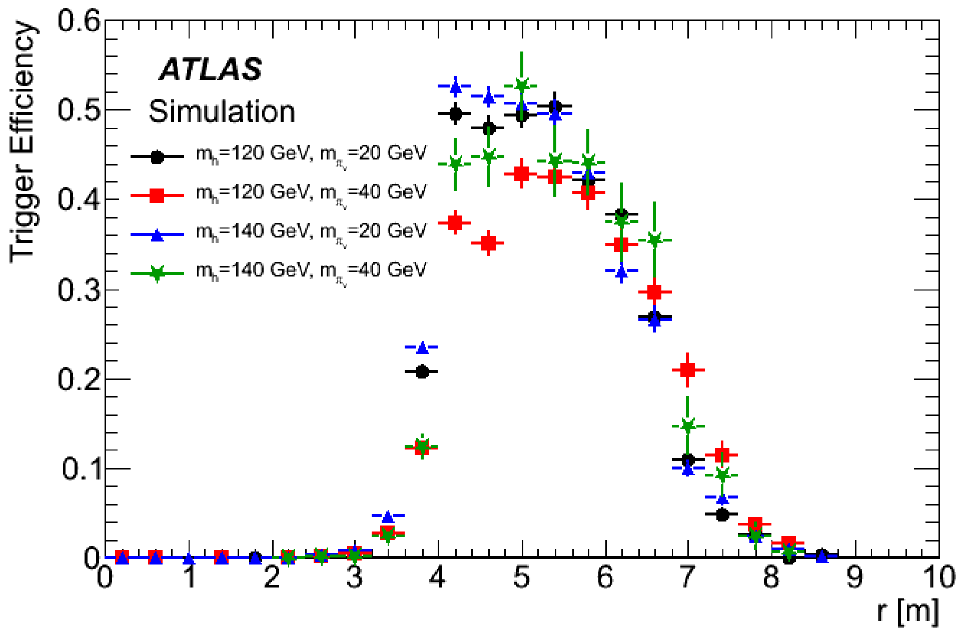
Higgs decaying to long lived particles

- A number of models include higgs decaying to long lived particles
- e.g. “hidden valley model”:
  - SM weakly coupled to a hidden sector by some communicator particle
  - here higgs is the communicator and can decay to long lived particles, which in their turn decay predominantly to bb, cc, ττ pairs

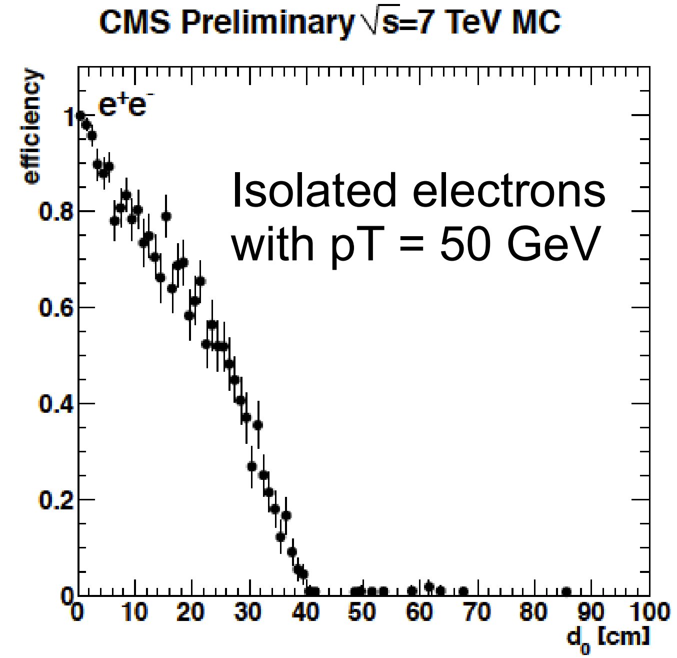
Higgs decaying to long lived particles

- These searches require the development of special techniques

ATLAS dedicated trigger for long lived particles decaying in the outer parts of the detector



Lepton Reconstruction at high transverse impact parameter at CMS



Track transverse impact parameter (cm)

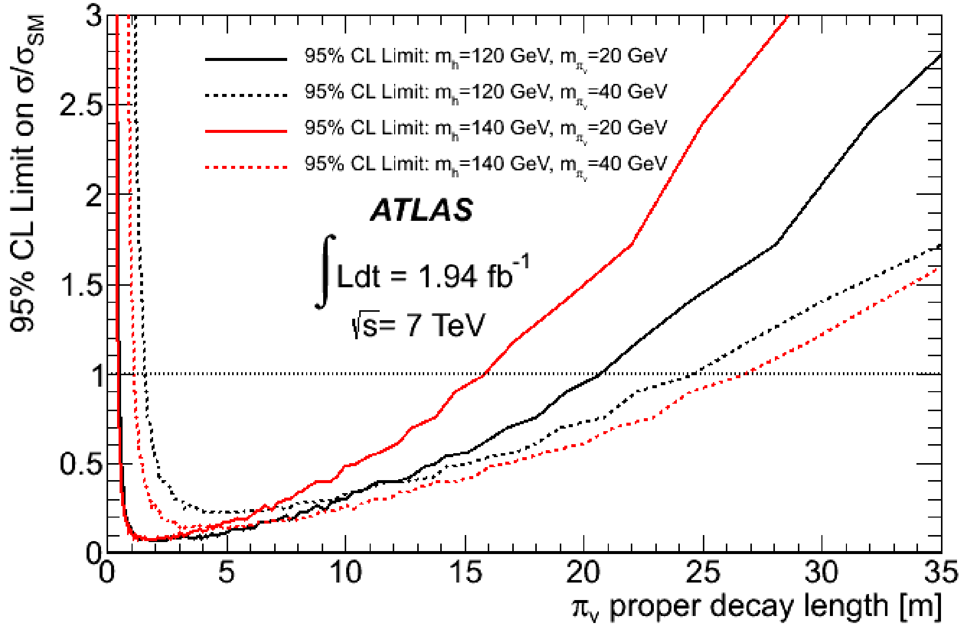
Higgs decaying to long lived particles

- ATLAS Search

arXiv:1203.1303

  - Looking for a light higgs in the “hidden valey” context with the long lived particles decaying the hadronic calorimeter and their decay products are detected in the muon system

m_{h^0} (GeV)	m_{π_v} (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

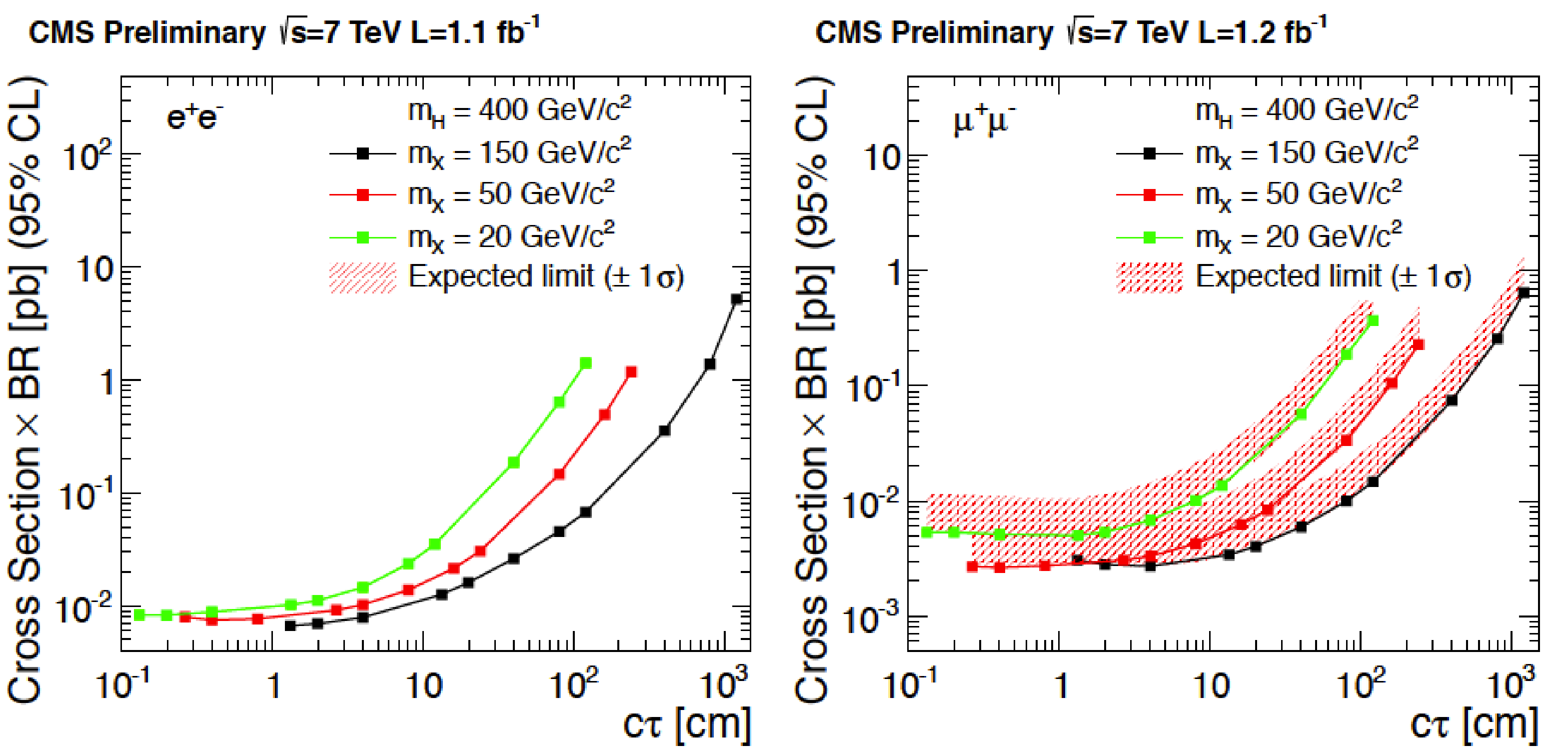


Higgs decaying to long lived particles

- CMS search

CMS PAS EXO-11-004

  - Generic search for the process $H \to XX$ and each $X \to ee$ or $\mu\mu$; each X may decay far from interaction point but well before the first layer of the inner tracking detector; focus on a heavy Higgs



Conclusion

- ATLAS and CMS support a very active BSM Higgs search programme
- LHC has already pushed the constraints further than previous searches
- BSM Higgs searches will continue to be relevant even if a SM(-like) Higgs is observed later this year
- The audience in this workshop can argue much better than me that the Higgs is probably not the SM Higgs
  - I wish they are right!

Many thanks for your attention!!!

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

- Important at low tanβ:
  - Br(H→cs) ~ 40%, tanβ<1, mH+ ~130 GeV
  - But difficult channel...

ATLAS-CONF-2011-094

Use of kinematic fits to improve the separation against W → jj background