Beyond SM Higgs searches @ ATLAS

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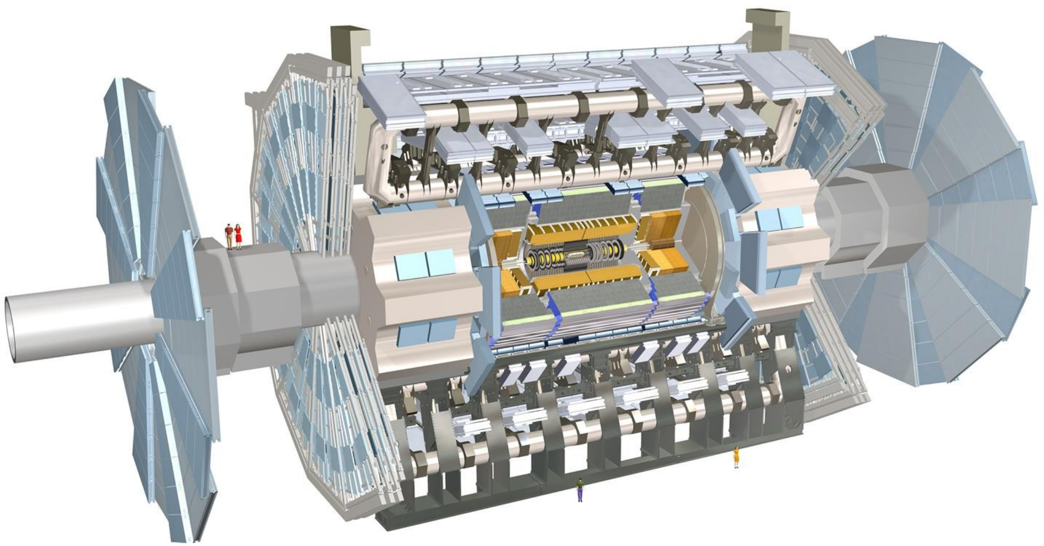
Implications of LHC results for TeV-scale physics,
13-17 July 2012, CERN

Introduction

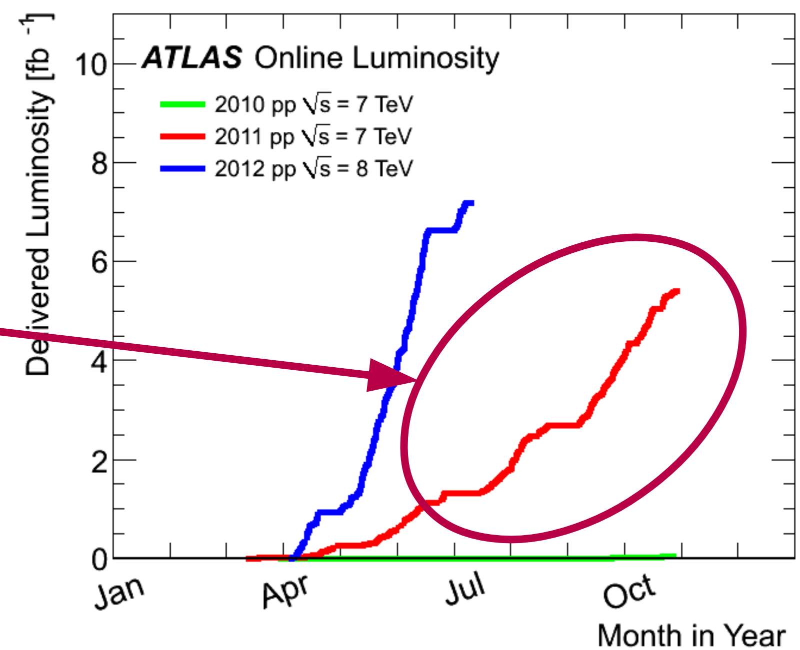
- LHC experiments are currently sensitive to SM Higgs production
  - ATLAS and CMS reported on July 4th the discovery of a new particle at ~ 125 GeV, which is SM-Higgs-like
    - more work (and more data) is still needed to see whether it is indeed SM Higgs
- This doesn't make redundant the BSM Higgs searches:
  - SM-Higgs-like doesn't necessarily mean that is SM → **still compatible with SUSY models like MSSM** (e.g. see arXiv:1112.3026) or with other models (e.g. models involving Higgs decaying to light scalar particles)
  - Besides it is more fun to look for less predictable physics!

ATLAS: Detector & Data



ATLAS: LHC multi-purpose detector with hermetic calorimetry
Ø ~ 25m, L ~ 46m,
~ 90m underground

All searches shown here use pp collision data @ 7 TeV from the 2011 run



2011: a prolific year for the LHC

→ 5.6 fb^{-1} delivered by the LHC
→ 5.3 fb^{-1} recorded by ATLAS

ATLAS BSM Higgs searches

A quick overview of the latest public ATLAS results in BSM Higgs searches

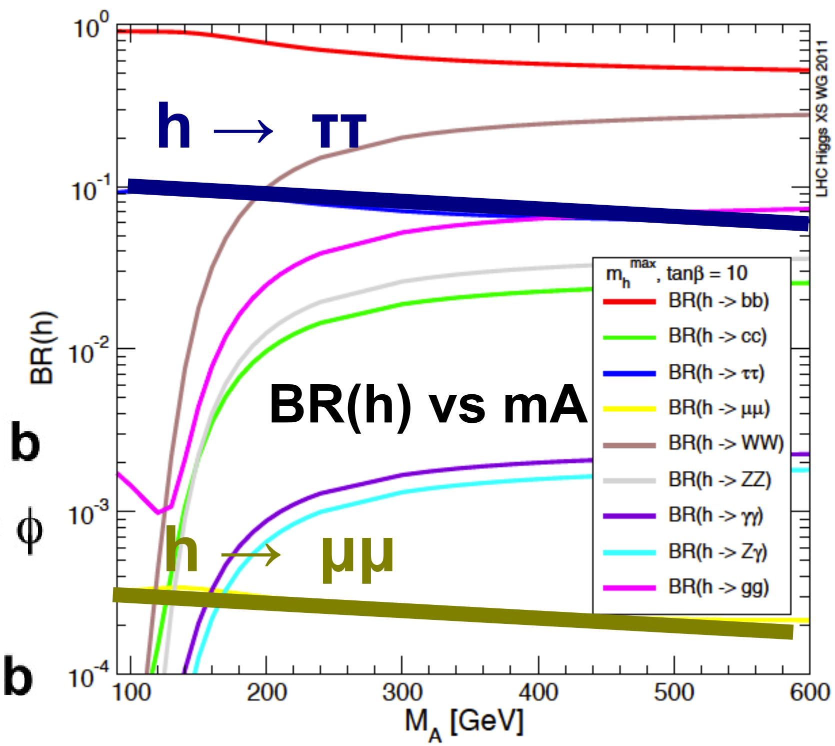
Channel	Dataset (pp@7 TeV)	Reference
MSSM H → ττ / μμ ★	4.7 – 4.8 fb^{-1}	ATLAS-CONF-2012-094
MSSM $H^+ \to \tau^+\nu$ ★	4.7 fb^{-1}	JHEP 1206 (2012) 039
MSSM $H^+ \to cs$	0.035 fb^{-1}	ATLAS-CONF-2011-094
SM with a 4th fermion generation	1.0-2.3 fb^{-1}	ATLAS-CONF-2011-135
Fermiophobic Higgs search ★	4.9 fb^{-1}	arXiv:1205.0701
Light scalar Higgs	0.039 fb^{-1}	ATLAS-CONF-2011-020
Higgs to light scalar particles ★	4.9 fb^{-1}	ATLAS-CONF-2012-079
Doubly Charged Higgs ★	1.6 fb^{-1}	PRD 85, 032004 (2012)
Higgs to long-lived particles ★	1.9 fb^{-1}	PRL 108 (2012) 251801
Higgs to displaced muon jets	1.9 fb^{-1}	ATLAS-CONF-2012-089

Only studies with a ★ will be discussed in this presentation

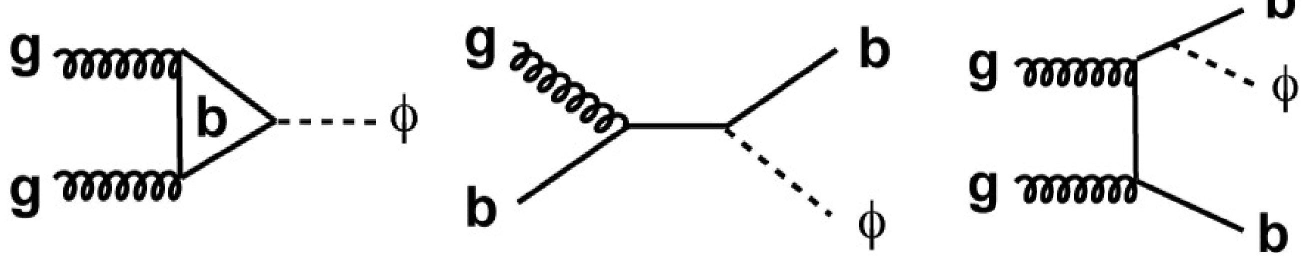
MSSM

- 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 , tanβ)

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



Neutral Higgs produced by gluon fusion or in association with b-quarks



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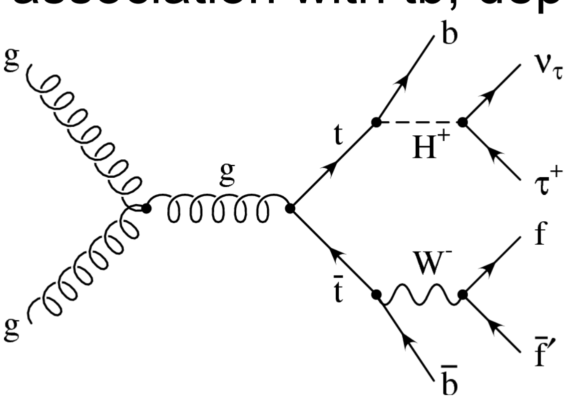
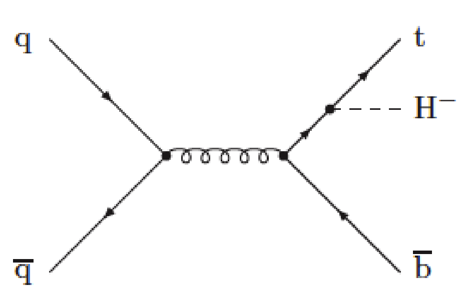
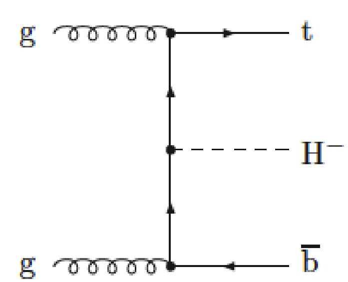
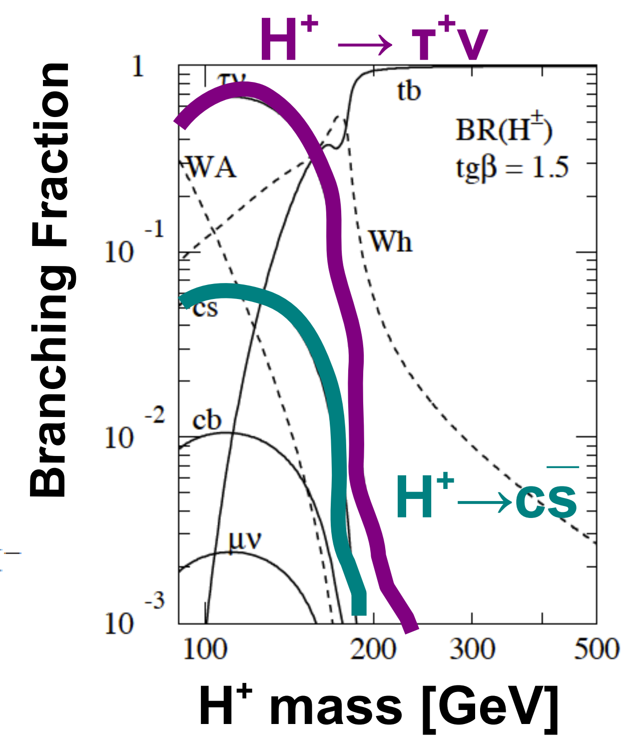
For large parts of the parameter space $H \rightarrow \tau\tau$ and $H^{\pm} \rightarrow \tau^{\pm}\nu$ decays are dominant, WW/WZ decays suppressed

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





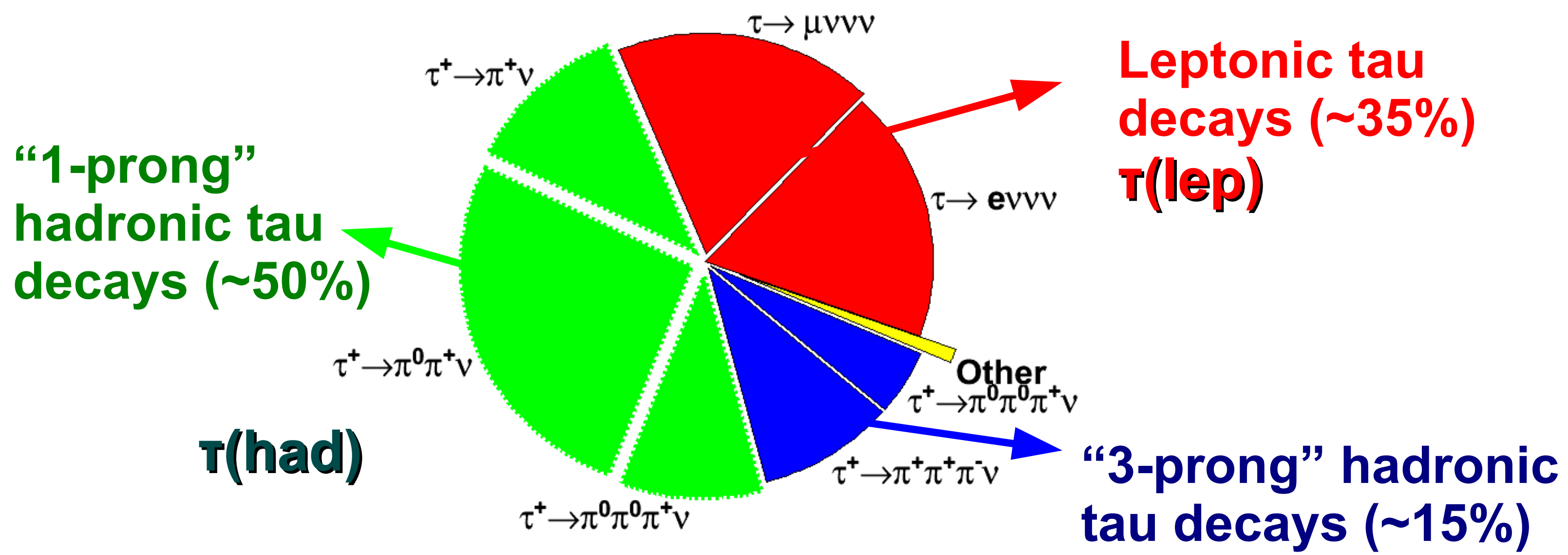


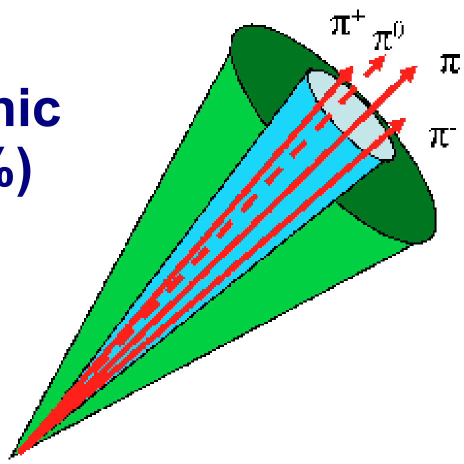


hep-ph/9704448

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





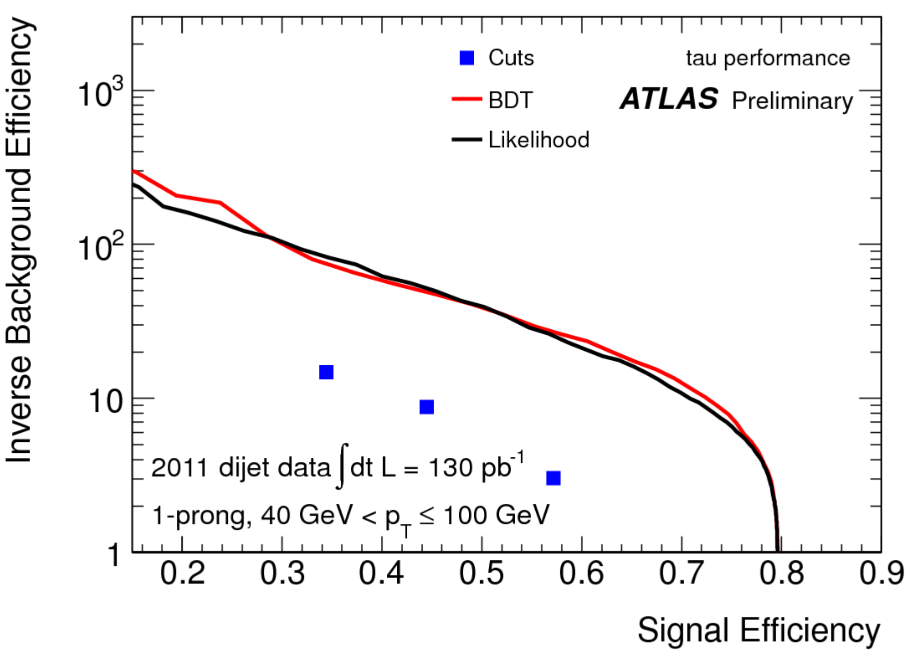
Studies with taus are involved:

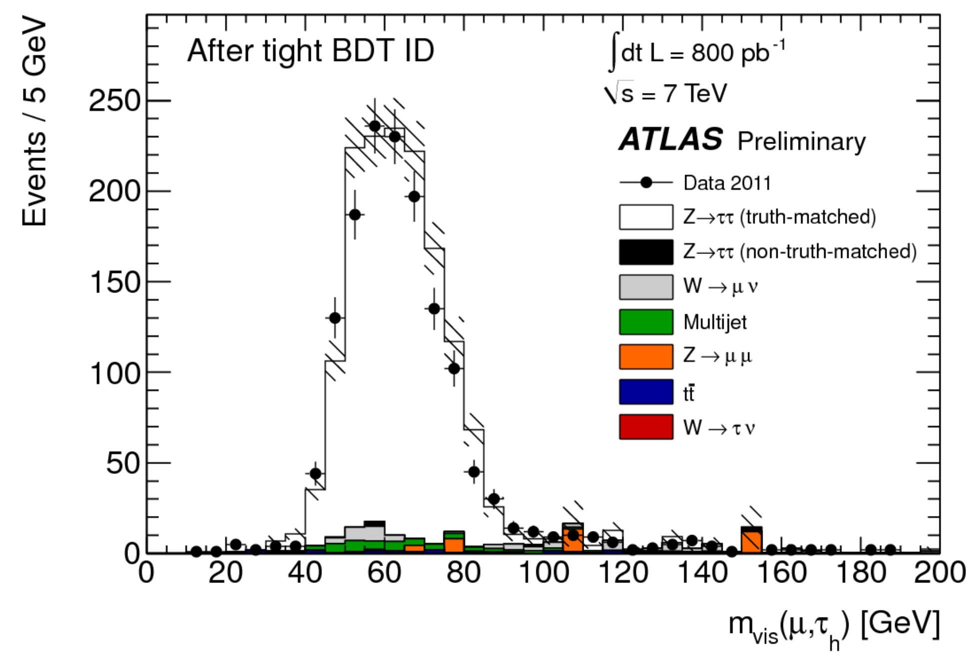
- neutrinos in the final state: challenging to reconstruct di-tau invariant mass without degrading resolution a lot
- pions in τ(had): difficult to separate them from QCD jets

Taus in ATLAS

- “tau reconstruction” refers to hadronically decaying taus
  - “ATLAS tau”: anti-kT clustered calorimeter deposits matched to tracks
  - Low track multiplicity and shower shape is used to discriminate against multi-jet production; efficiency measured in data using Z → ττ and W → τν events

ATLAS-CONF-2011-152





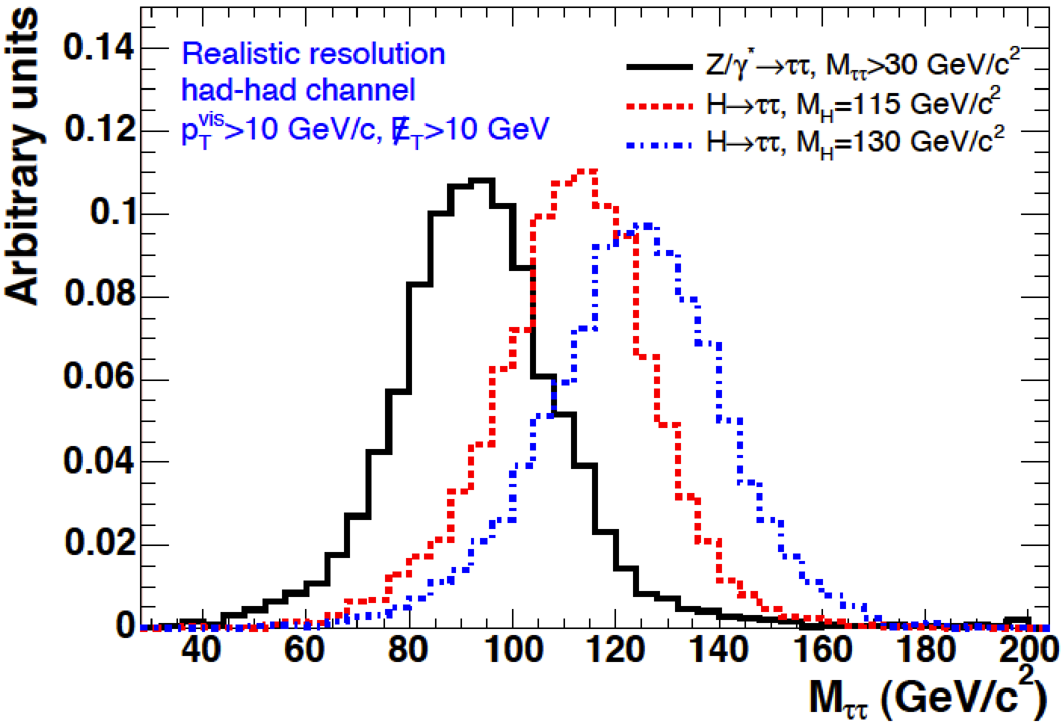
Special Techniques used with Taus

- Di-tau invariant mass has poor resolution due to the presence of neutrinos in the final state
  - Simplest option: **visible mass** (mass of visible objects)
  - More advanced techniques like **Missing Mass Calculator** (MMC)

MMC concept:

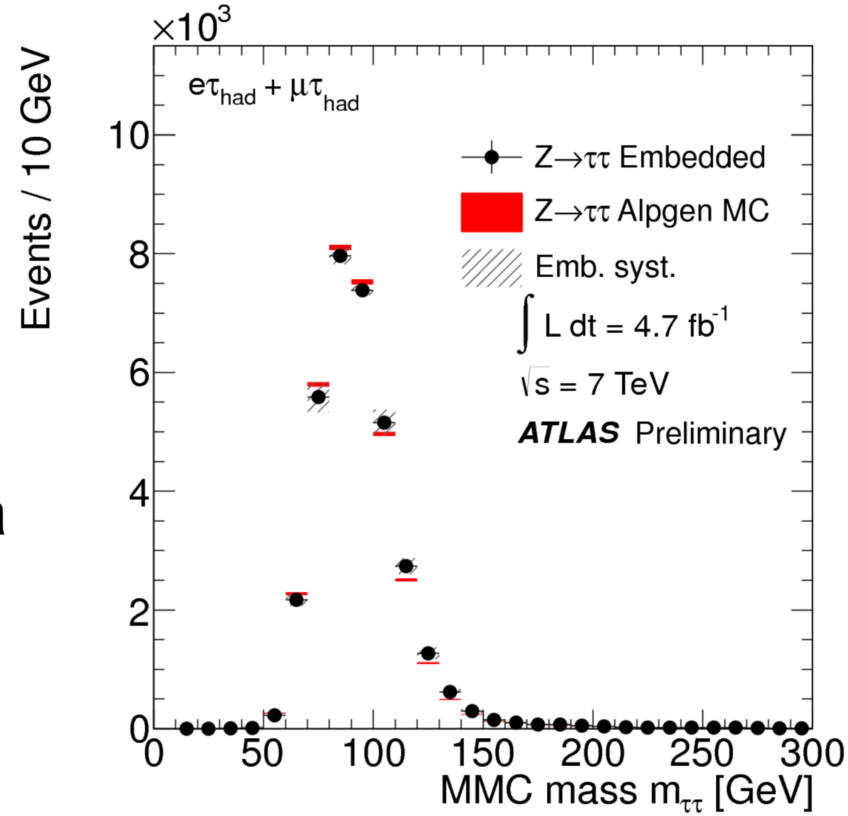
constrain the neutrino momenta using tau decay kinematics to improve resolution

NIM A654 (2011) 481



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 an adequately 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



Embedding techniques can also be used with W or ttbar events

MSSM H → τ τ / μ μ

- H → ττ: the most promising channel to look for neutral MSSM Higgs
  - Final states considered here:
    τ(e)τ(μ): BR ~ 6%
    τ(e)τ(had)+τ(μ)τ(had): 46 %
    τ(had)τ(had): BR ~ 42%
- H → μμ: small BR (~0.04% c.f. ~10% for ττ) but very clean signature and good mass resolution
- Production mode (gg fusion, "b-associated") motivates sample splitting using the presence or absence of b-tagged jets (jet p_T > 20 GeV)
- Use of data-driven methods to control all important backgrounds: (Z → ττ, W+jets, multi-jet events, top)

MSSM H → τ(lep) τ(lep)

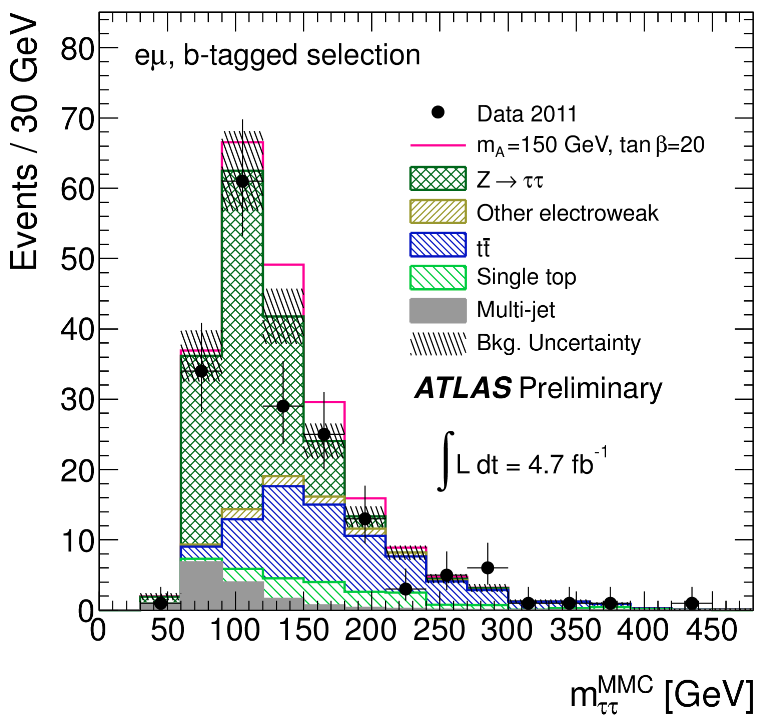
τ(lep)τ(lep) using τ(e)τ(μ) final state

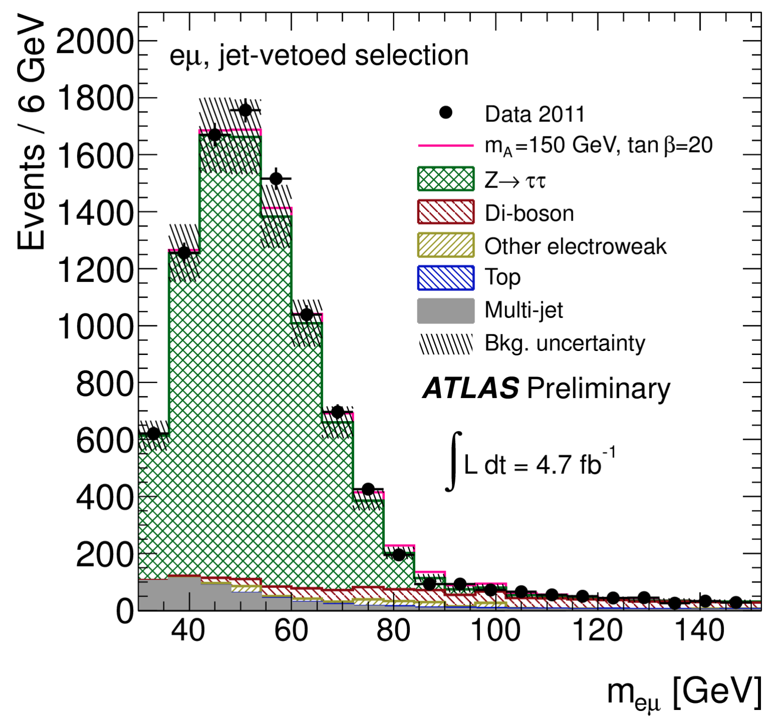
1 isolated e with p_T > 15-24 GeV; **1 isolated μ** with p_T > 10-20 GeV

Opposite sign; ΔΦ(e,μ)>2; m(e,μ)>30 GeV

“b-tagged” sample: exactly 1 b-jet $MET+p_T(e)+p_T(\mu) < 125$; H_T<100 GeV; $\Sigma\cos\Delta\varphi(MET,l)>-0.2$	**“jet-vetoed” sample:** no jets in event

ATLAS-CONF-2012-094

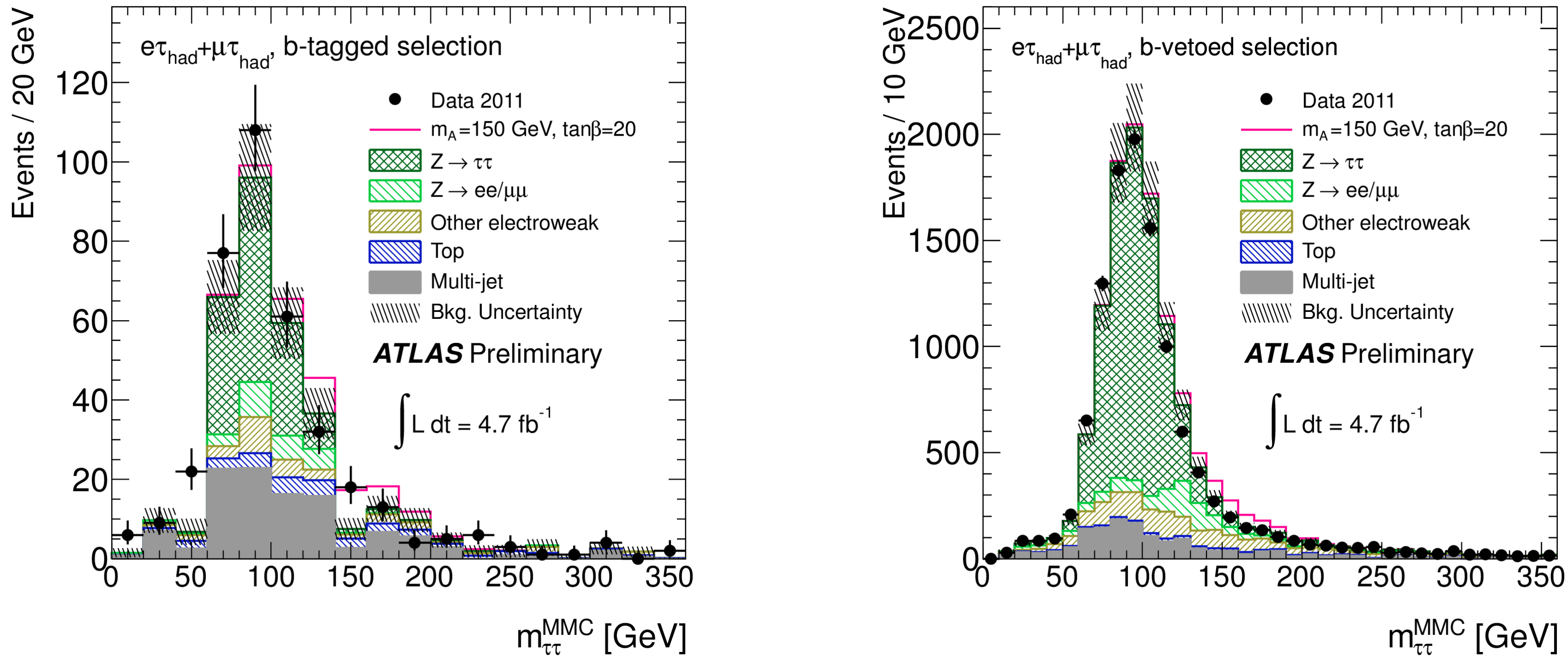




MSSM H → τ(lep) τ(had)

τ(lep)τ(had)	
isolated e / μ with p_T >25/20 GeV; **τhad** with p_T > 20 GeV;	
Opposite sign; M_T < 30 GeV	
"b-tagged" sample: leading jet is a b-jet Leading (b-)jet p_T < 50 GeV	**"b-vetoed" sample:** leading jet not a b-jet MET > 20 GeV

ATLAS-CONF-2012-094



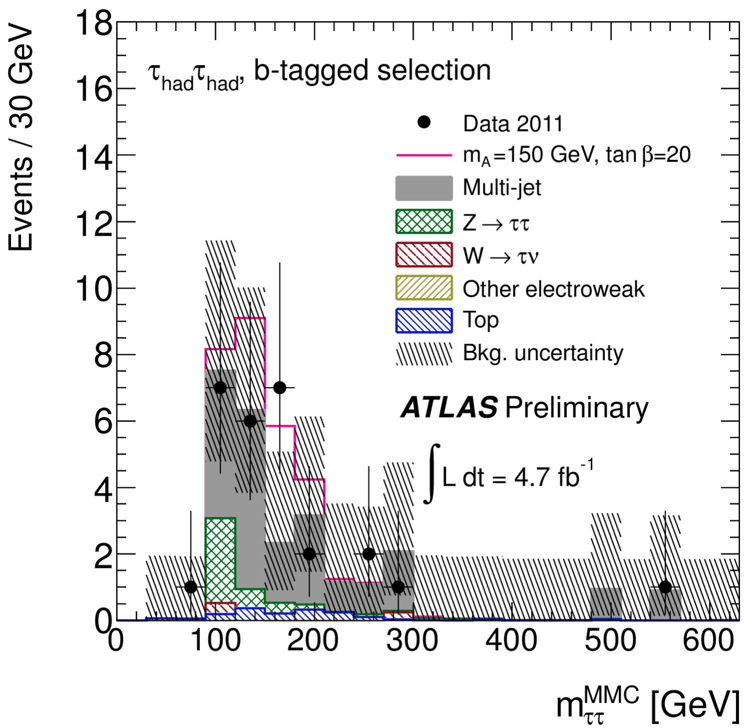
MSSM H → τ(had) τ(had)

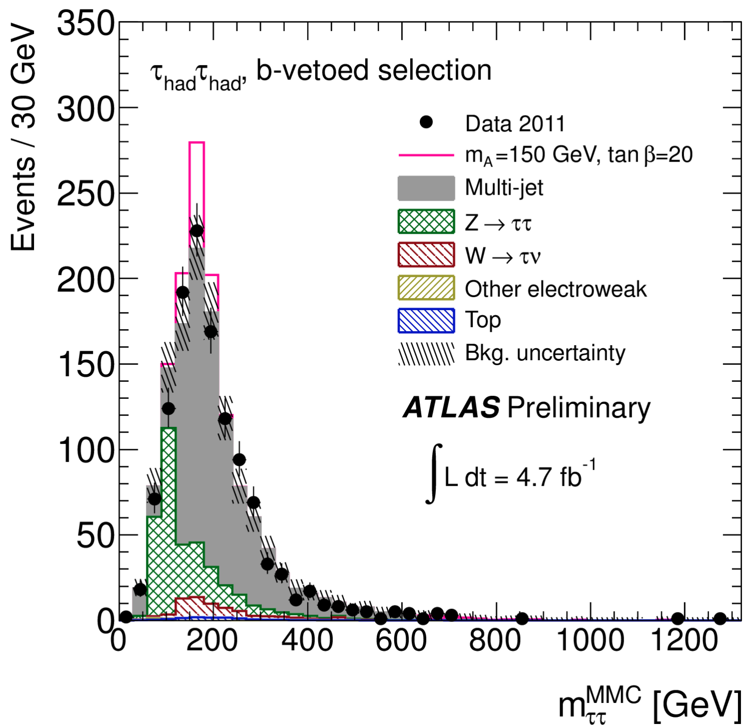
τ(had)τ(had)

2 τhad with p_T > 30/45 GeV; Opposite sign; MET > 25 GeV

"b-tagged" sample: leading jet is a b-jet	**"b-vetoed" sample:** leading jet is a b-jet
Leading (b-)jet p_T < 50 GeV	Leading tau p_T > 60 GeV

ATLAS-CONF-2012-094

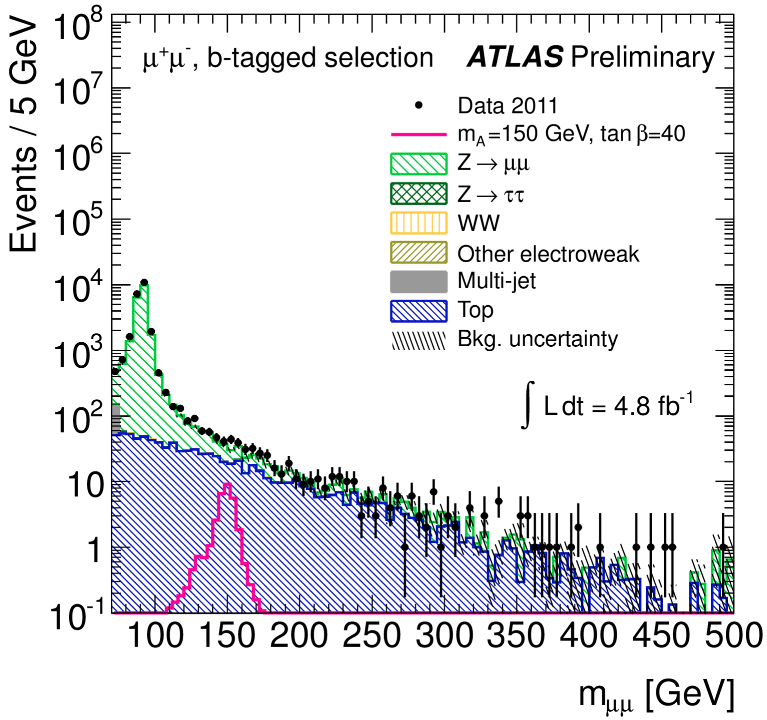


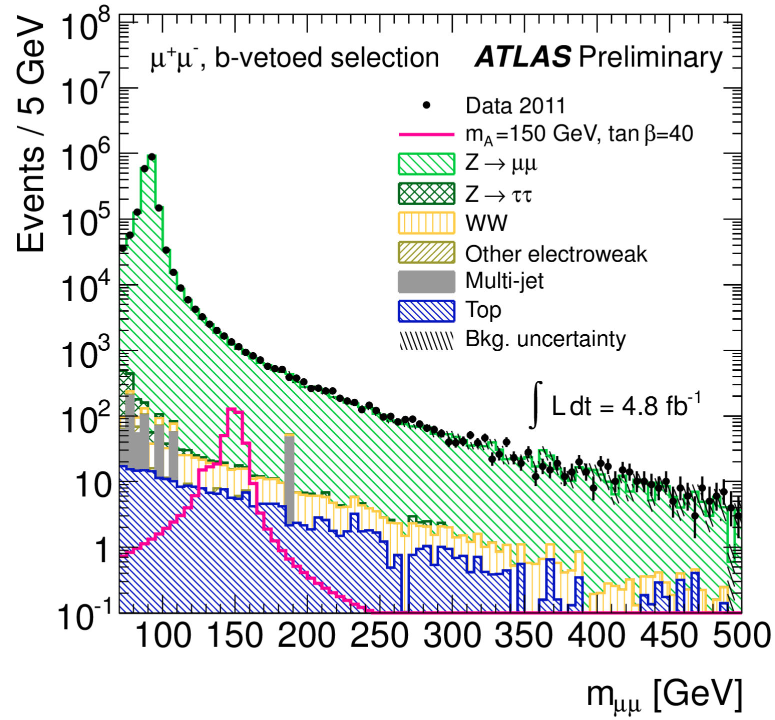


MSSM H → μ μ

μμ	
2 μ with p_T > 15/20 GeV; Opposite sign; MET < 40 GeV; m(μμ) > 70 GeV	
"b-tagged" sample: at least one b-jet	**"b-vetoed" sample:** no b-jet
Bkg model: (Z/γ* interference) ʘ (Gaussian resolution); ʘ = convolution operator	
Signal model: (Breit-Wigner) ʘ (Gaussian resolution)+Landau	

ATLAS-CONF-2012-094





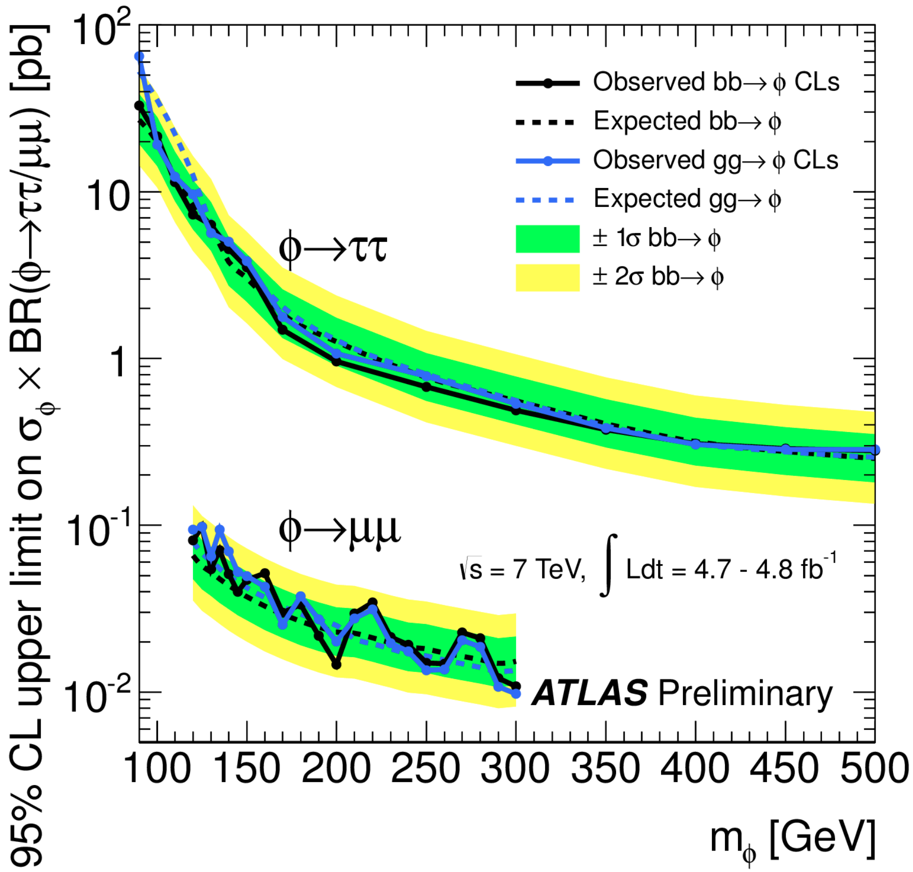
Simulated backgrounds are shown here only for demonstration: not used in the final result

MSSM H → ττ/μμ search

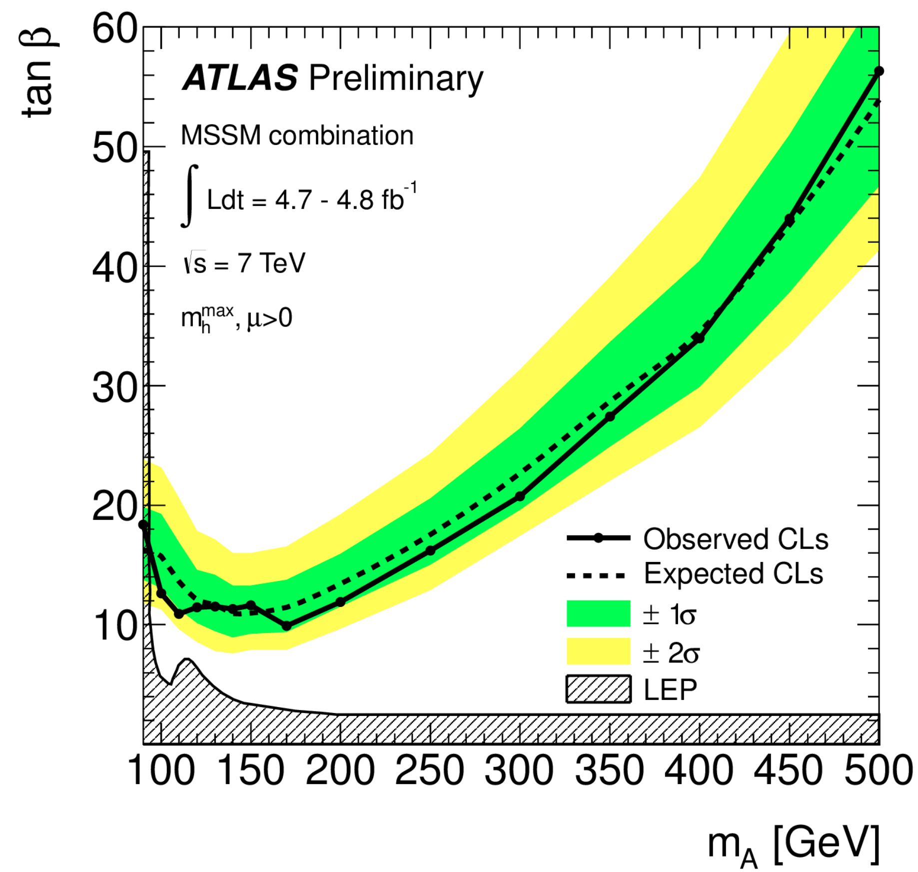
ATLAS-CONF-2012-094

- Exclusion Limits: all channels combined

Limit on σ BR(φ → ττ)

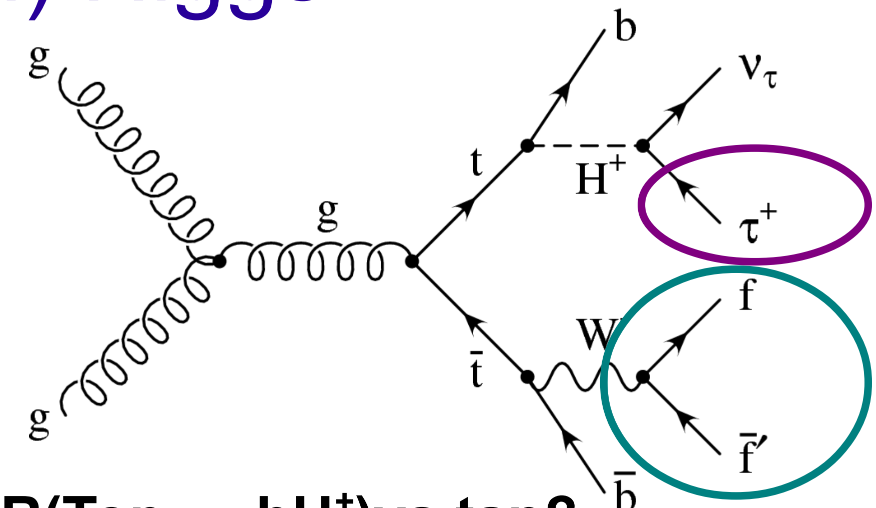


"m_A-tanβ" space limit m_h^{max}



Charged (MSSM) Higgs

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



$H \rightarrow \tau\nu$

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

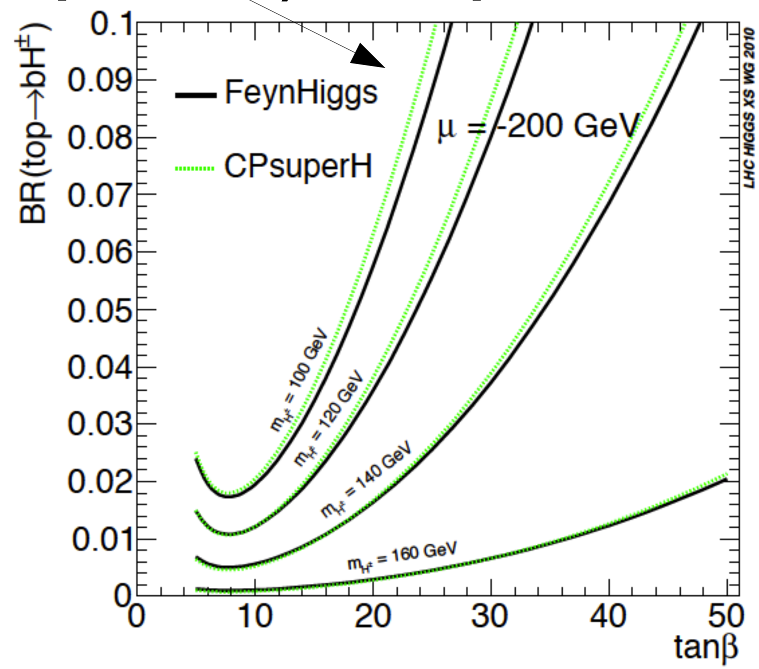
tau(had)+W(→lν): tt → bbWH → bb (lν) (τ_{had}ν)

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

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

Channels studied with full 2011 data

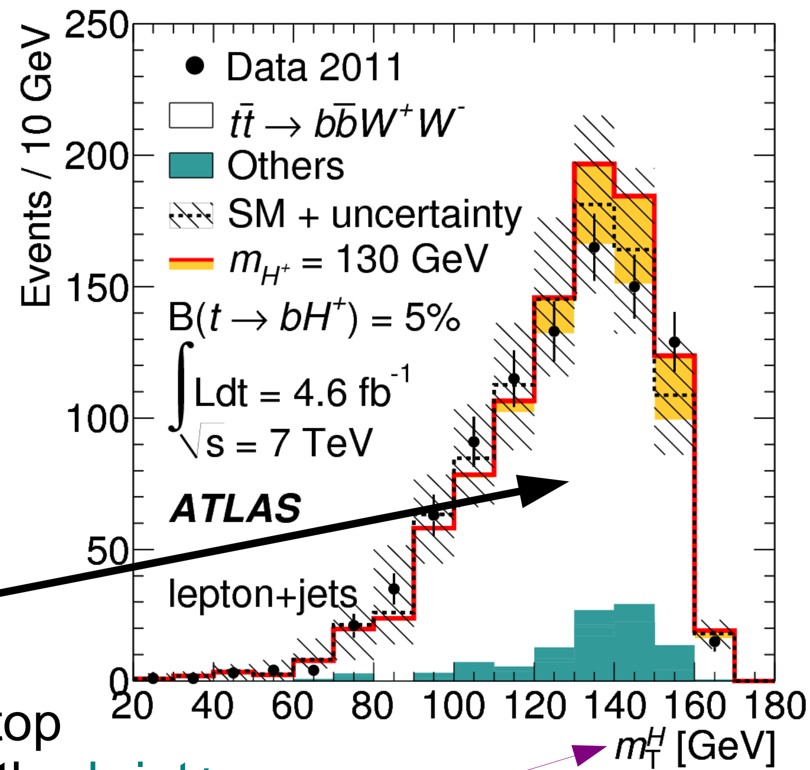
BR(Top → bH⁺)vs tanβ



JHEP 1206 (2012) 039

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

Tau(lep) + W(→ jets)
1 isolated e/μ, p_T > 25/20 GeV
At least 4 jets (p_T>20 GeV) with exactly 2 b-tagged
MET > 40 GeV (tighter if Δφ(lepton,MET) small) $\cos\theta^*_l$ < -0.6; m_T(lepton,MET)<60 GeV



Very challenging to separate signal from tt → bbWW → bb+jj+lν (main background)

Need to use kinematic fit to associate b-jets to the top candidates and define discrimination variables like the b-jet+ charged lepton invariant mass and the Higgs transverse mass

$$\cos\theta^*_l = \frac{2m^2_{bl}}{m^2_{top} - m^2_W} - 1$$

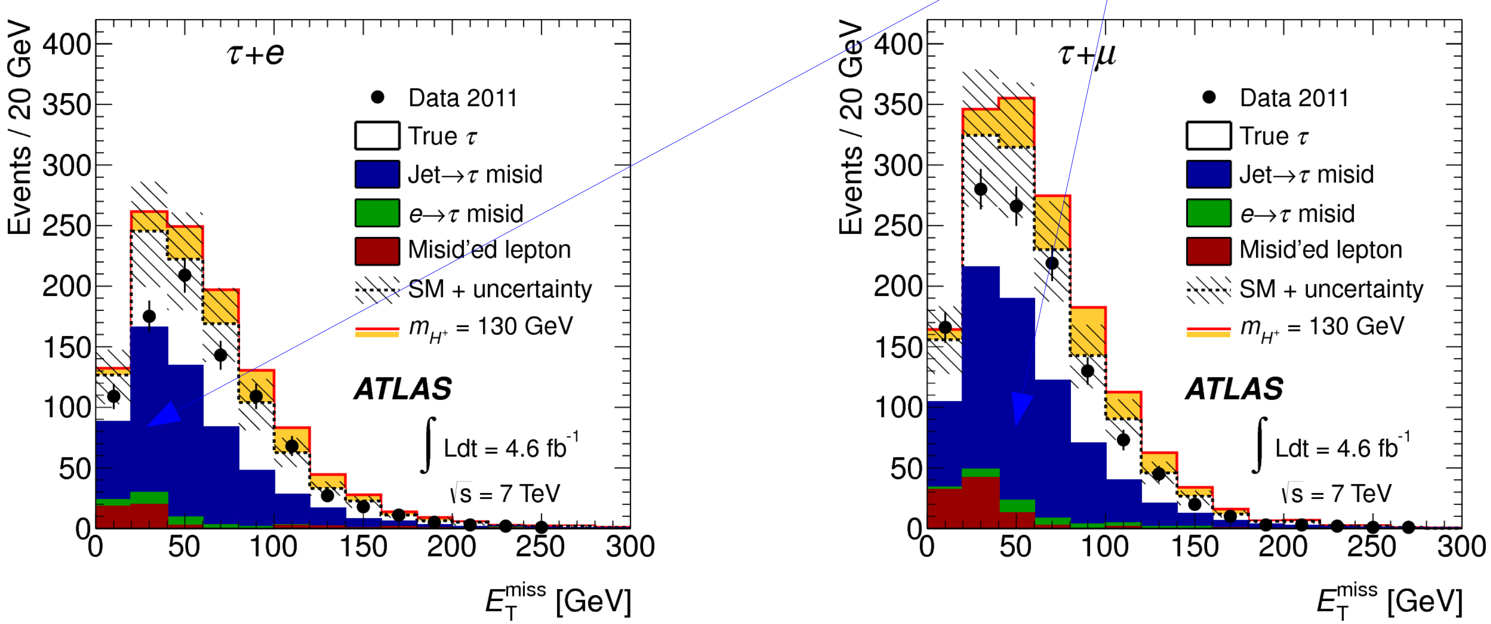
$$(m_T^H)^2 = \left(\sqrt{m^2_{top} + (\vec{p_T}^l + \vec{p_T}^b + \vec{p_T}^{miss})^2} - p_T^b\right)^2 - \left(\vec{p_T}^l + \vec{p_T}^{miss}\right)^2.$$

JHEP 1206 (2012) 039

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

Tau(had) + W(→ lν)
1 isolated e/μ, p_T > 25/20 GeV; 1 τ_{had} with p_T > 20 GeV
At least 2 jets (p_T>20 GeV), with at least 1 b-tagged
vertex Σp_T > 100 GeV

Jet → tau fakes estimated from data



JHEP 1206 (2012) 039

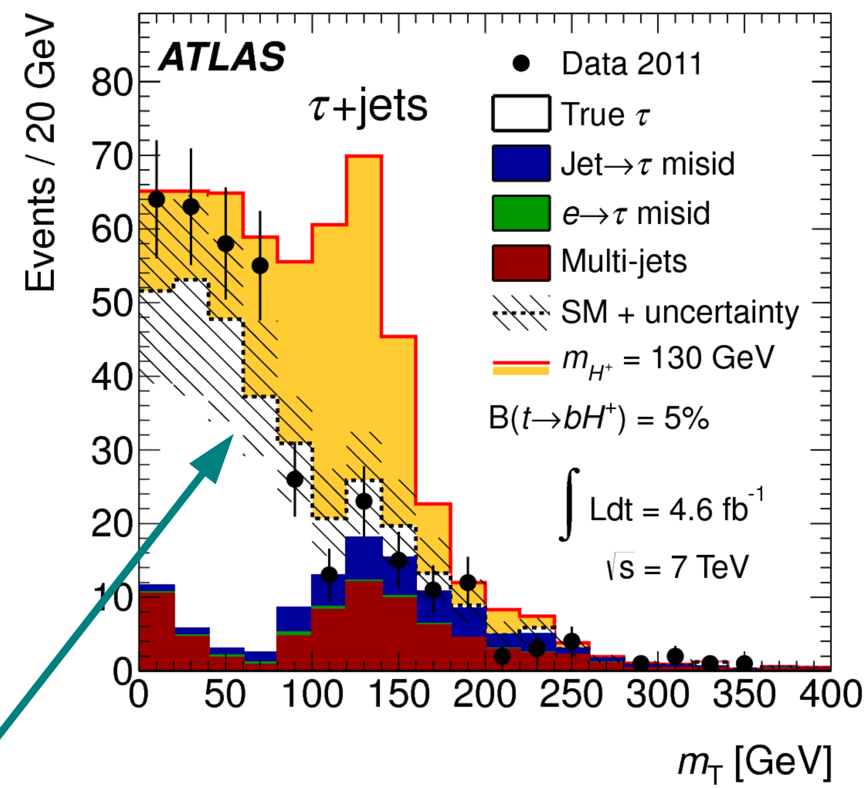
$H^{\pm} \rightarrow \tau^{\pm}\nu$ search

Tau(had) + W(→ jets)
1 τ_{had} with $p_T > 40$ GeV
At least 4 jets (pT>20 GeV) with at least 1 b-tagged
MET > 65 GeV (tighter at high Σ p_T(tracks)) 120 GeV < m(jjb) < 240 GeV

Most sensitive channel

Absence of a light lepton makes triggering on these events less trivial: tau + MET trigger

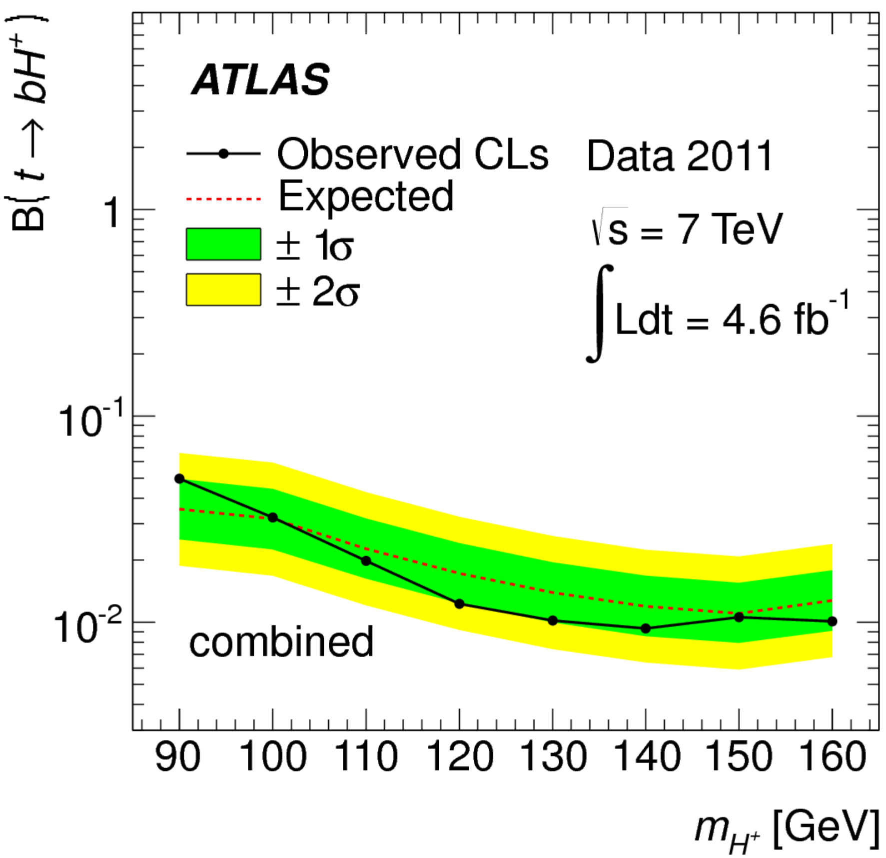
"true tau" background component estimated with an μ-embedded sample

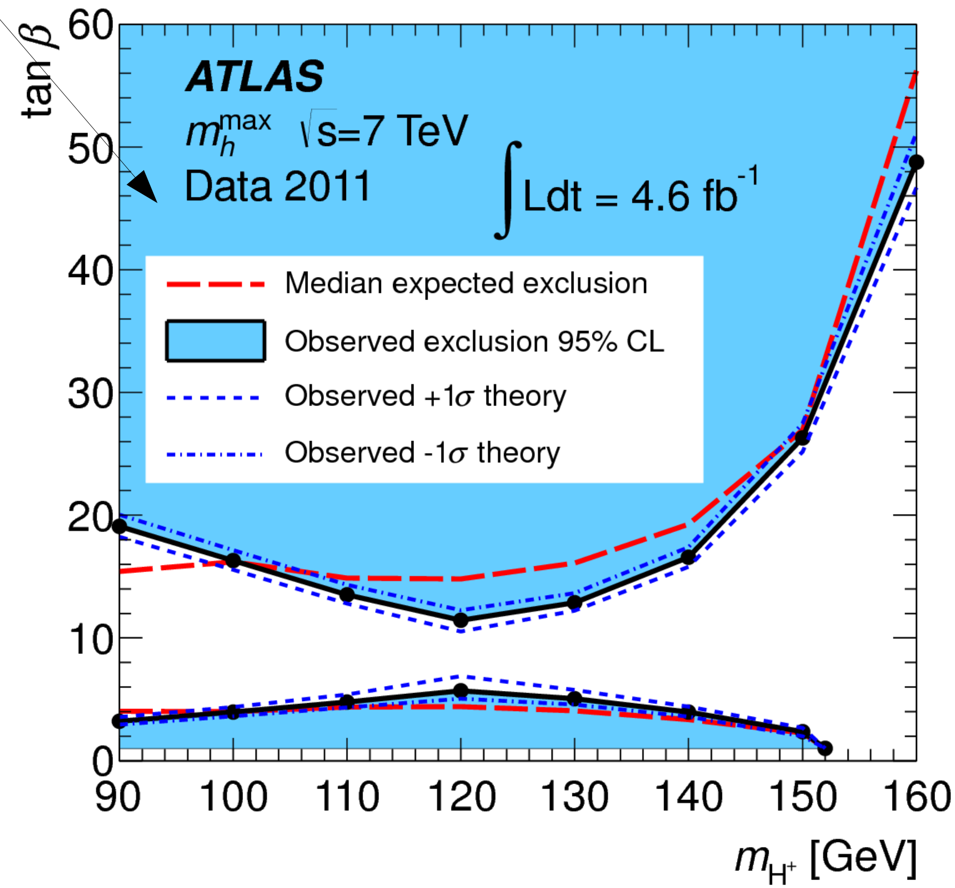


$H^{\pm} \rightarrow \tau^{\pm}\nu$ search

JHEP 1206 (2012) 039

Low mass $H^{\pm}$ allowed phase space in the MSSM scenario is heavily constrained now





Fermiophobic Higgs Search

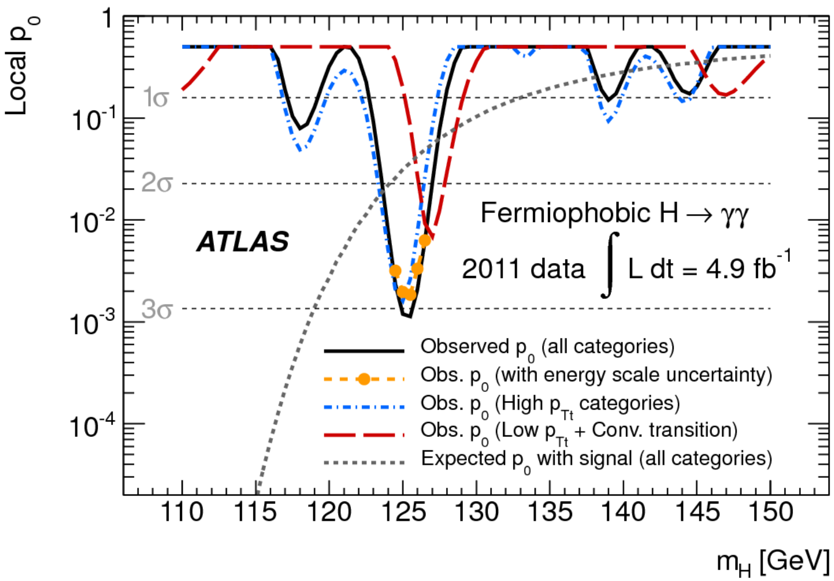
- Fermiophobic Higgs models modify SM Higgs couplings and affect Higgs production & decay
- ATLAS search follows the SM $H \rightarrow \gamma\gamma$ search; only signal model changes

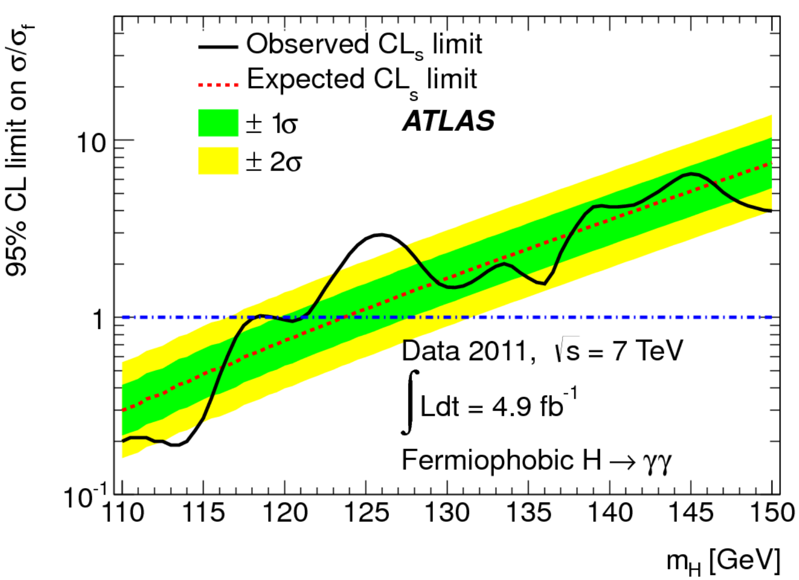
2 photons pT > 40 / 25 GeV

Categories based on conversions, η and di-photon p_T

Signal modelled with "crystal ball" (= gaussian core+power law low-end tail) +gaussian; bkg with exponential

arXiv:1205.0701





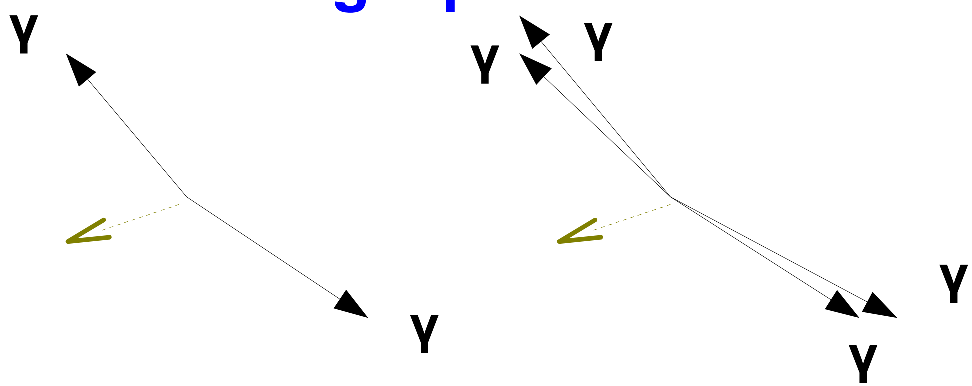
$H \rightarrow aa \rightarrow \gamma\gamma + \gamma\gamma$

ATLAS-CONF-2012-079

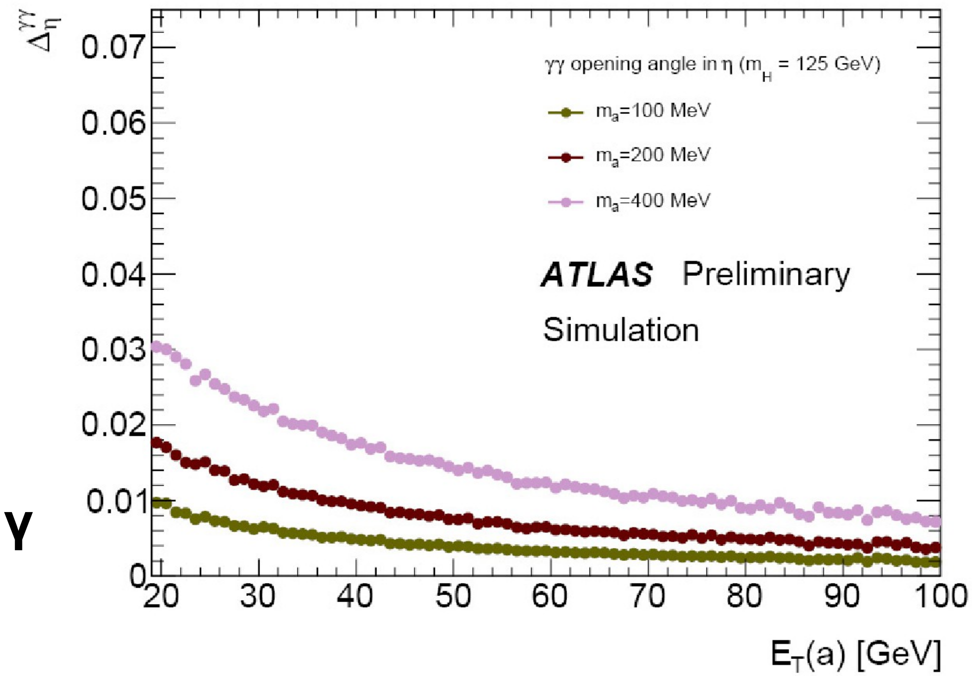
- In some SM extensions Higgs is allowed to decay to light (pseudo)scalar particles, a, which consequently decay to $\gamma\gamma$ without contradicting any current result

e.g. see PRD63(2001)075003, PRD66(2002) 075006

- a is light ~ 100 MeV;
  $\gamma\gamma$ angle very small:
  $\gamma\gamma$-pair is reconstructed as a single photon



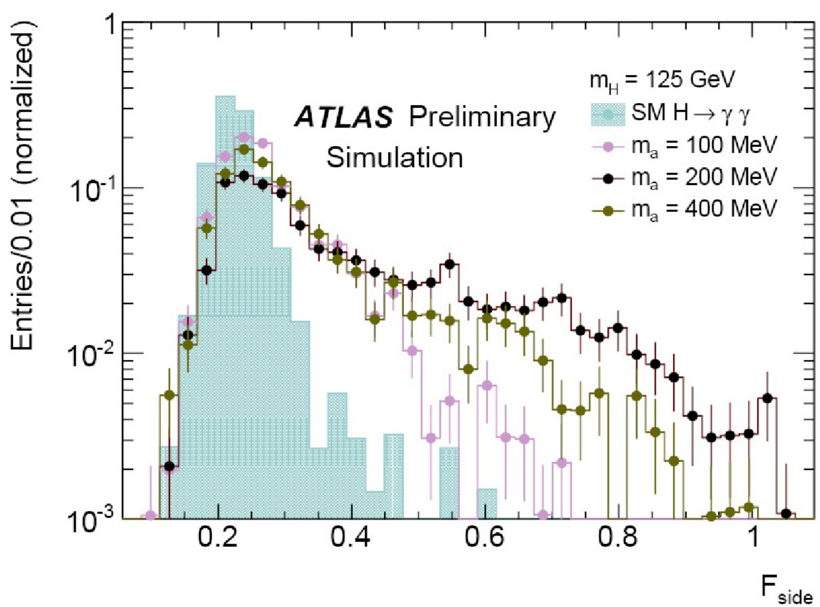
SM Higgs → γγ vs this search



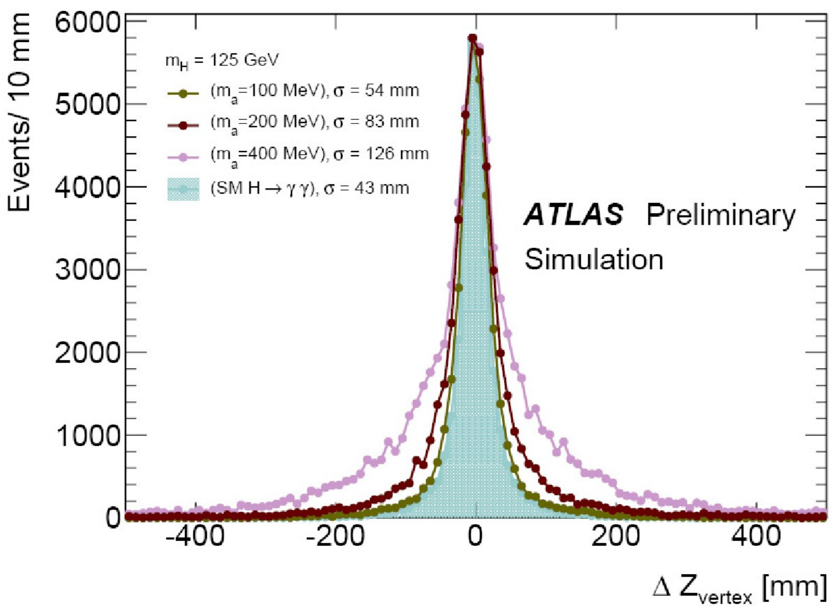
$H \to aa \to \gamma\gamma + \gamma\gamma$

ATLAS-CONF-2012-079

- Dedicated photon ID tuning is needed since a γγ-pair reconstructed as a single photon is different from a single γ: remove affected shower shape variables from photon ID
- Also other properties are affected (e.g. photon pointing)



Electromagnetic shower width measure



Photon pointing to vertex: z resolution

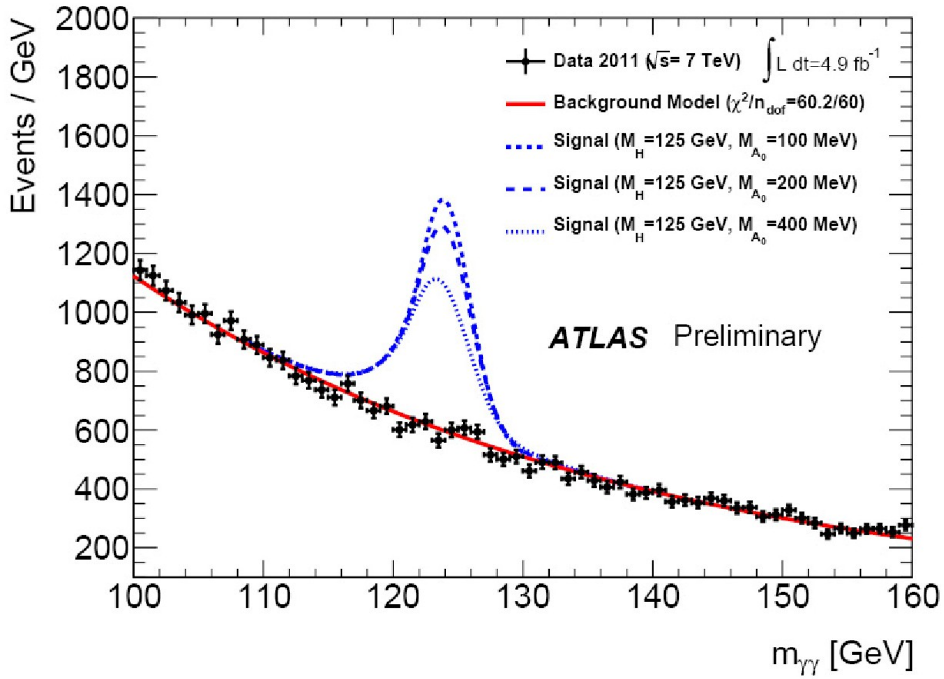
$H \rightarrow aa \rightarrow \gamma\gamma + \gamma\gamma$

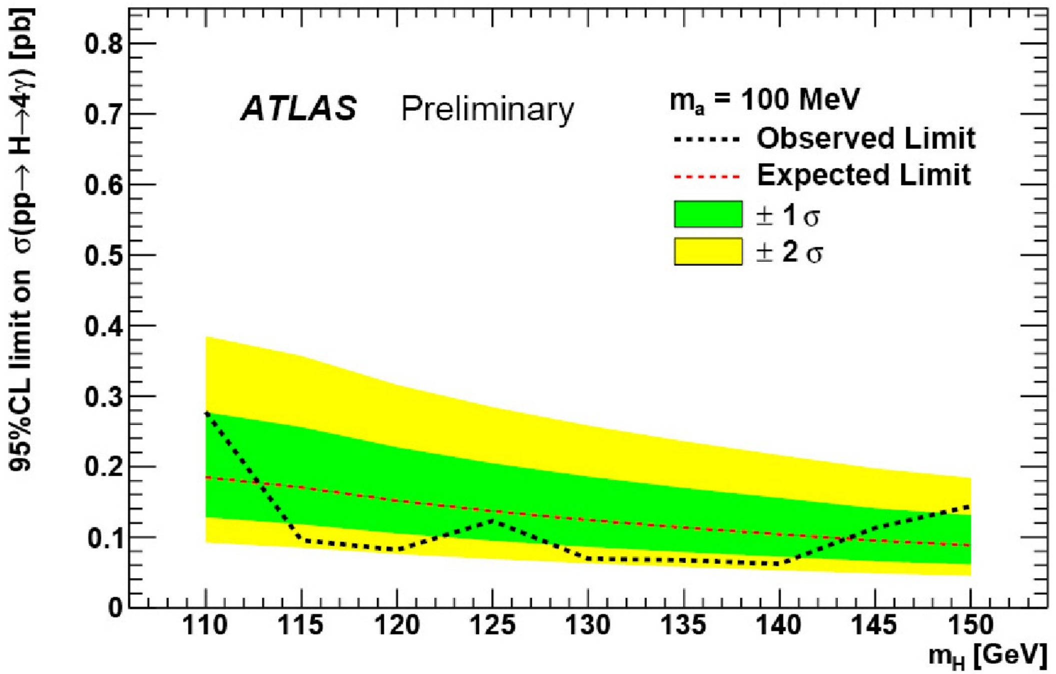
ATLAS-CONF-2012-079

- Search uses events with a γγ pair

2 photons pT > 40 / 25 GeV
No categories; use of dedicated photon ID
Signal modelled with "crystal ball" (= gaussian core+power law low-end tail)+gaussian; bkg with exponential

Cross section limits for m_a : 100-400 MeV and Higgs mass : 110-150 GeV assuming that zero decay length for α





$H^{\pm\pm}$ Search

Phys. Rev. D 85, 032004 (2012)

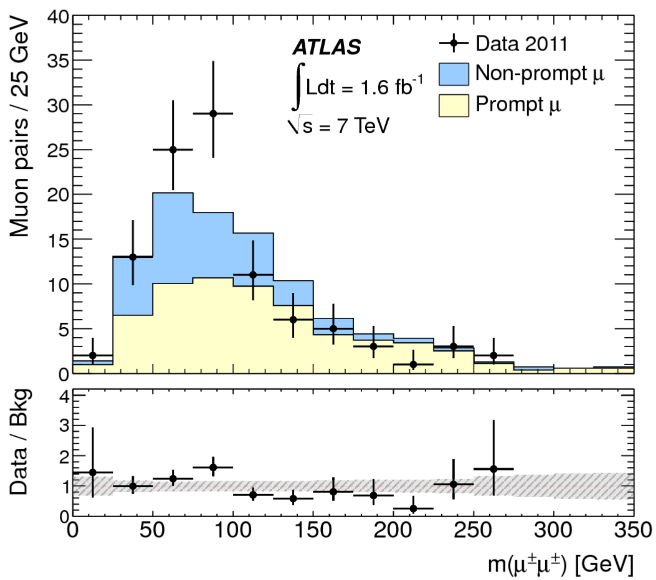
- Doubly charged Higgs is predicted by many models
  - e.g. “little Higgs”, “seesaw type II” include triplet (H^0,H^+,H^{++})
- ATLAS: a generic same sign di-muon spectrum search

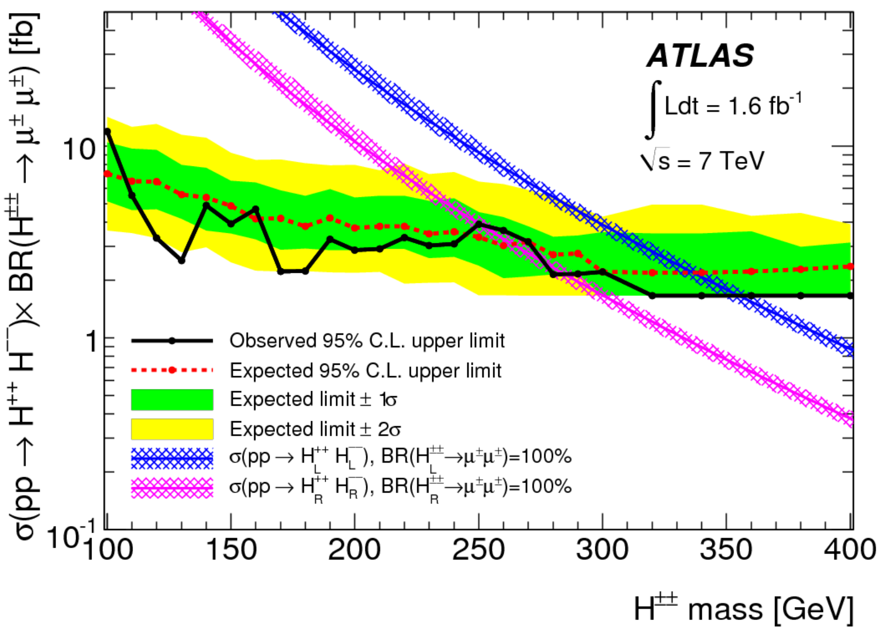
$H^{\pm\pm} \rightarrow \mu^\pm\mu^\pm$

2 isolated μ, $p_T > 20$ GeV, **same sign**

Limit derivation assuming

$qq \rightarrow Z/\gamma^* \rightarrow H^{++}H^{--} \rightarrow \mu^+\mu^+ \mu^-\mu^-$





Higgs decaying to long lived particles

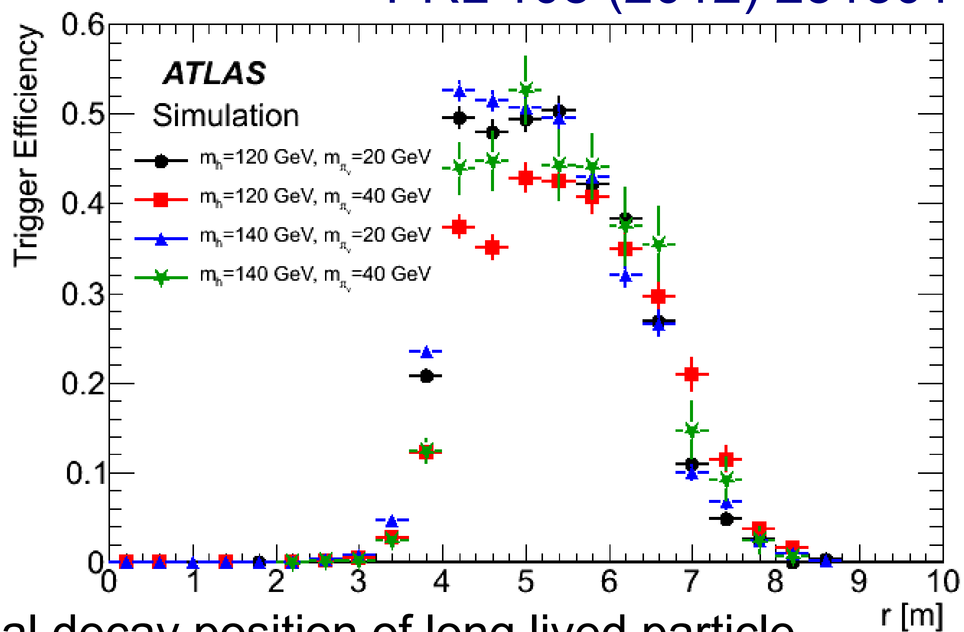
- A number of models include higgs decaying to long lived particles, e.g. “hidden valley model”:
  - SM weakly coupled to a hidden sector by some communicator particle (Higgs, h) which decays to long lived particles π_v

$$h \rightarrow \pi_v \, \pi_v; \;\; \pi_v \rightarrow bb/cc/\tau\tau$$

PRL 108 (2012) 251801

ATLAS has assumed that π_vs decay in the outer calorimeter system and can be detected in the muon chambers

Dedicated trigger has to be developed for such a study



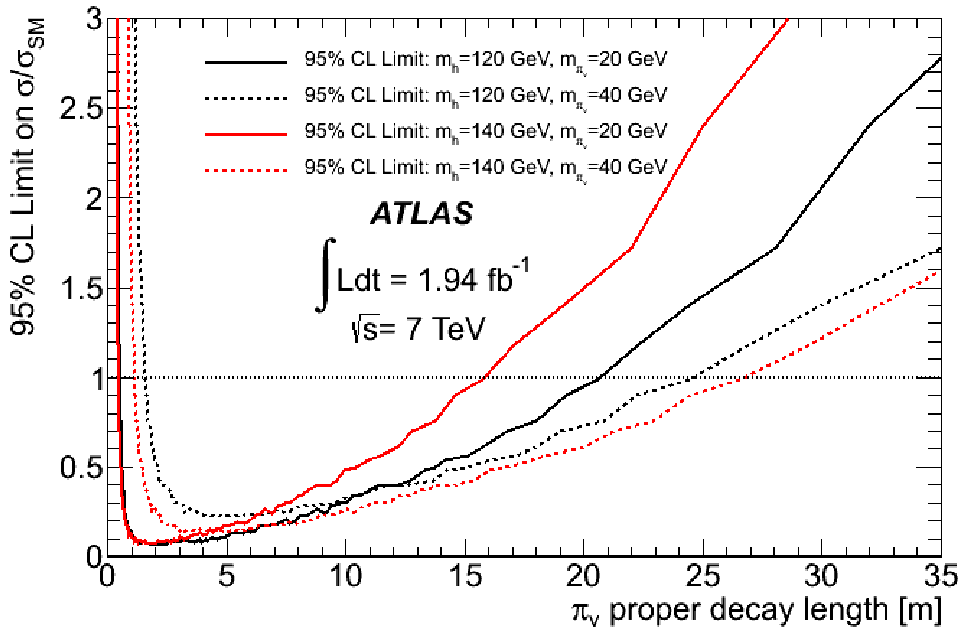
Radial decay position of long lived particle

Higgs decaying to long lived particles

- "Hidden valley" model is used as a benchmark
  - A light Higgs (120-140 GeV) is assumed to be produced as in SM; decay $h \rightarrow \pi_v \pi_v$ is assumed with BR = 100%
  - Signature: two vertices reconstructed in the muon system compatible with the decay of 2 back-to-back particles

PRL 108 (2012) 251801

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



Conclusion

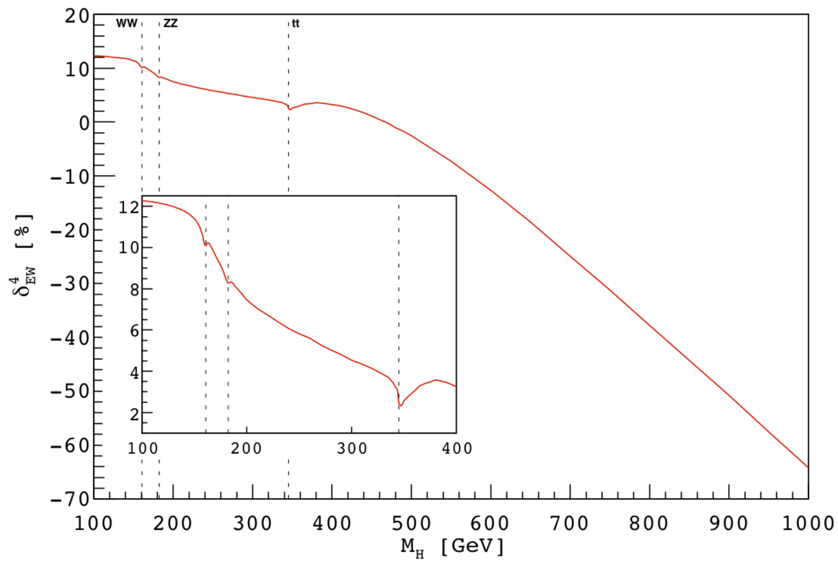
- ATLAS supports a very active BSM Higgs search programme
- LHC is pushing the constraints further than previous searches
- The recent Higgs-like particle discovery provides further motivation to look for BSM Higgs
  - There is a good chance that the Higgs is not a SM Higgs, so stay tuned: many unexpected discoveries may be ahead

Many thanks for your attention!!!

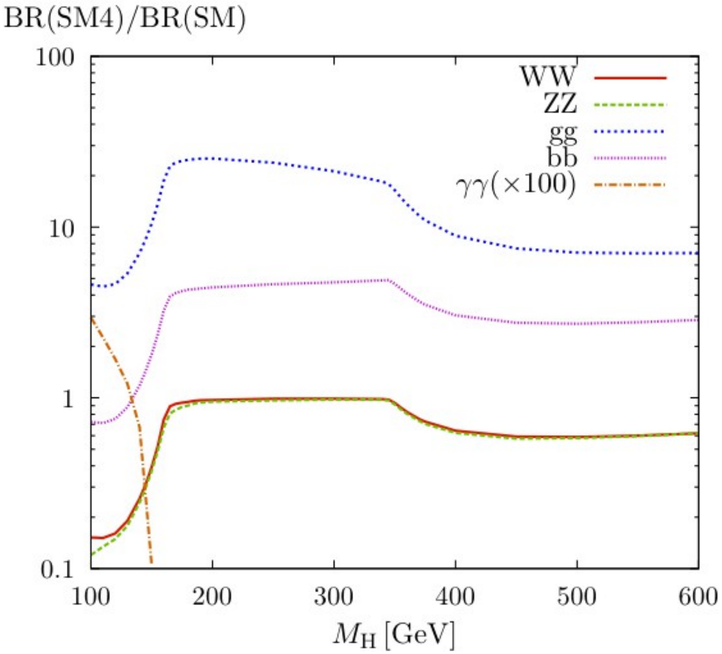
SM4

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

arXiv:1201.3084



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

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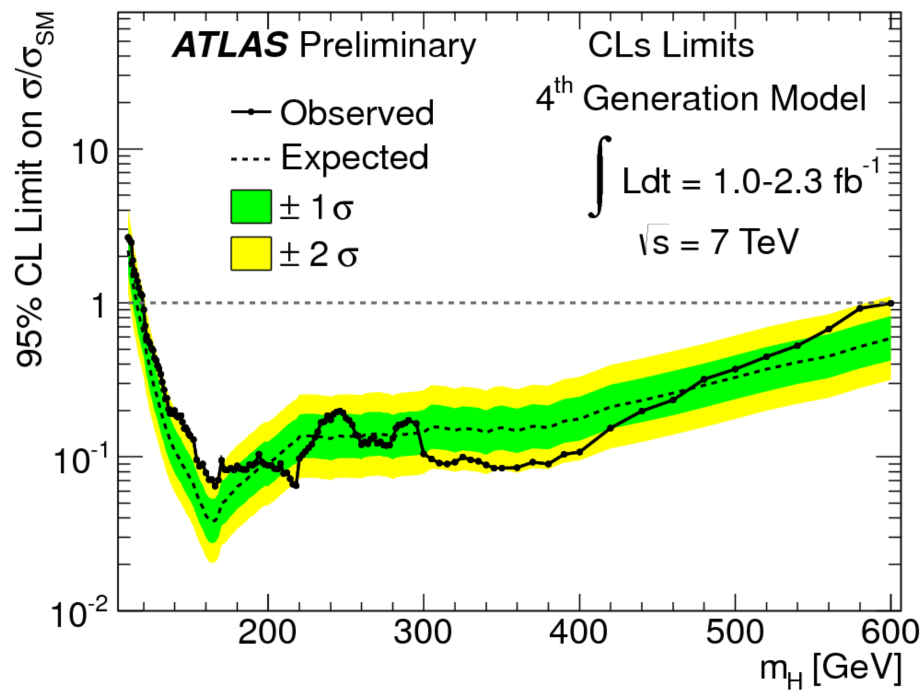
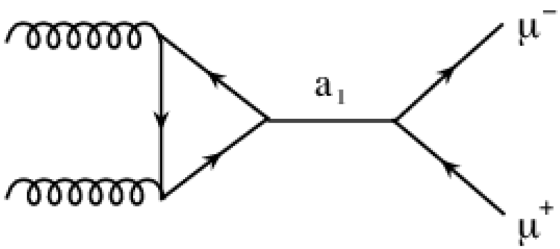


Light Scalar Field (NMSSM)

- 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



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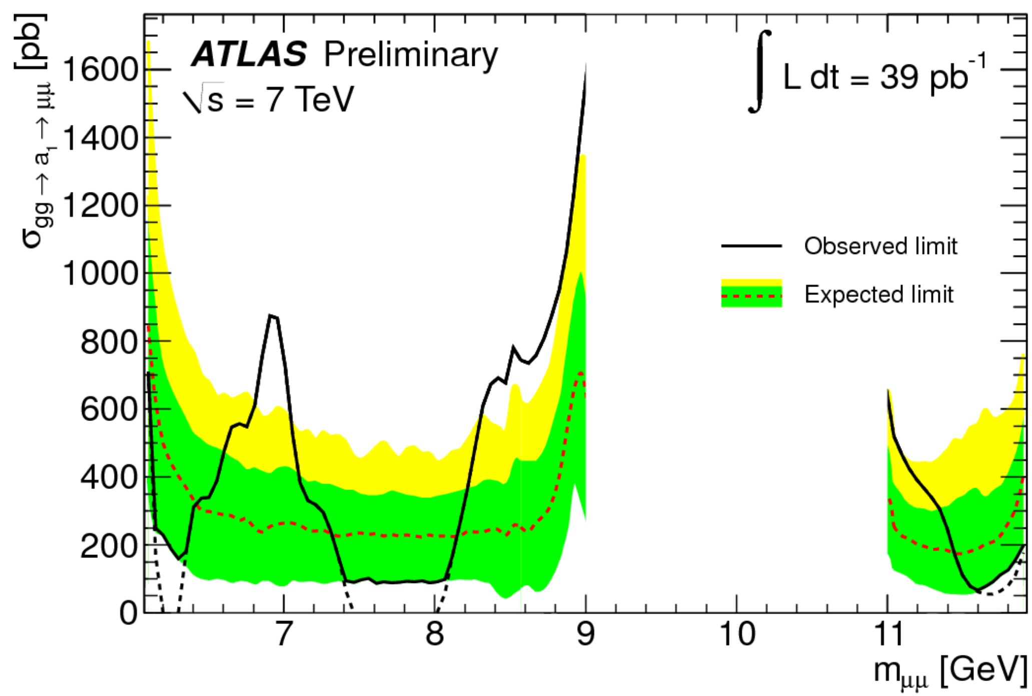

a → μμ (NMSSM)
2 isolated μ, $p_T > 4$ GeV, opposite sign
Multivariate technique to reject muons not coming from the decay of a single particle
Sidebands $m_{\mu\mu}$: 6-9 GeV and 11-12 GeV

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

- Important at low tanβ:
  - Br(H→cs) ~ 40%, tanβ<1, mH^+ ~130 GeV
  - Search using with 35 pb^{-1}

$tt \rightarrow bW\ bH^+ \rightarrow b\ (e/mu)\ \nu\ \ b\ cs$
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

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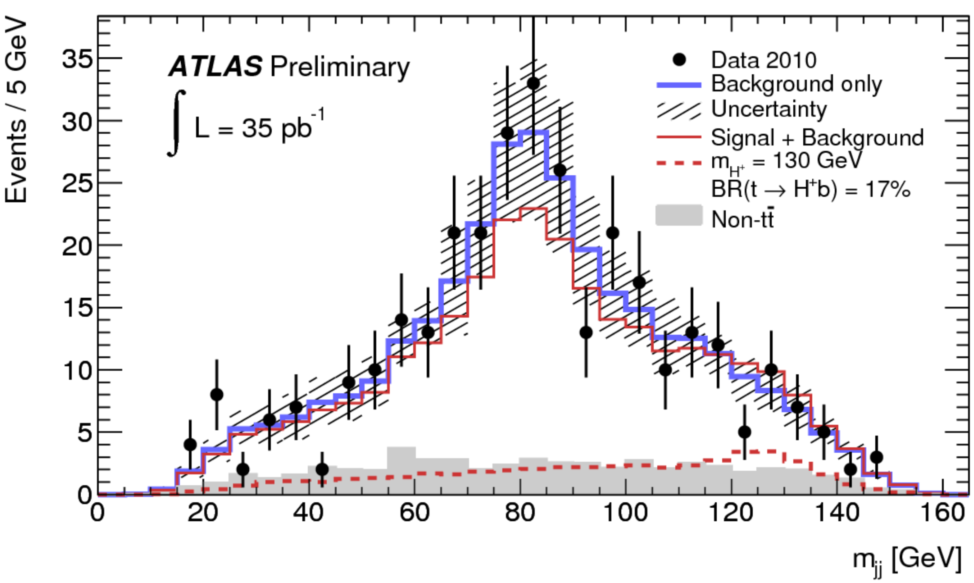

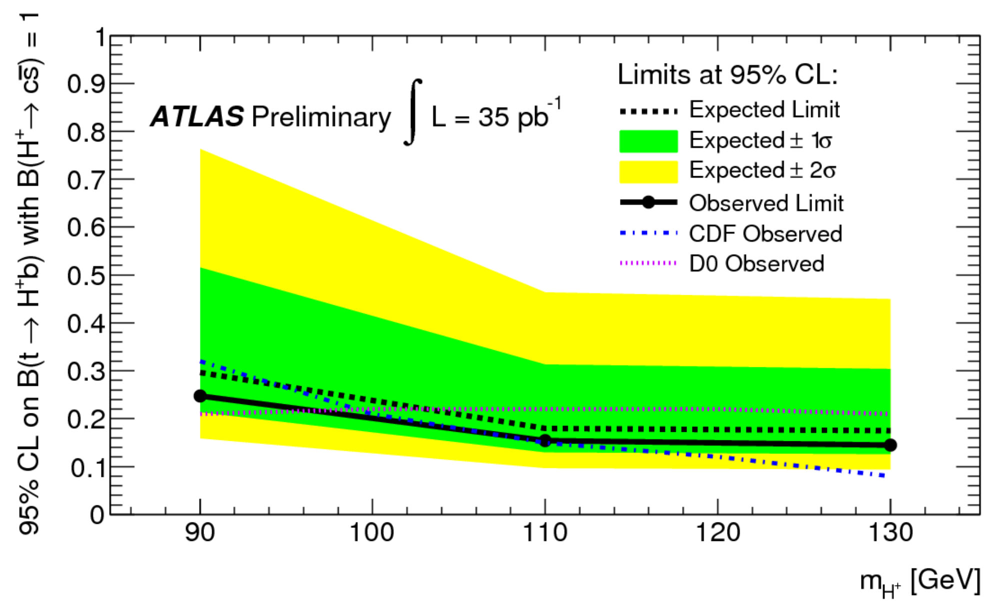

ATLAS $H^+ \rightarrow c\bar{s}$

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

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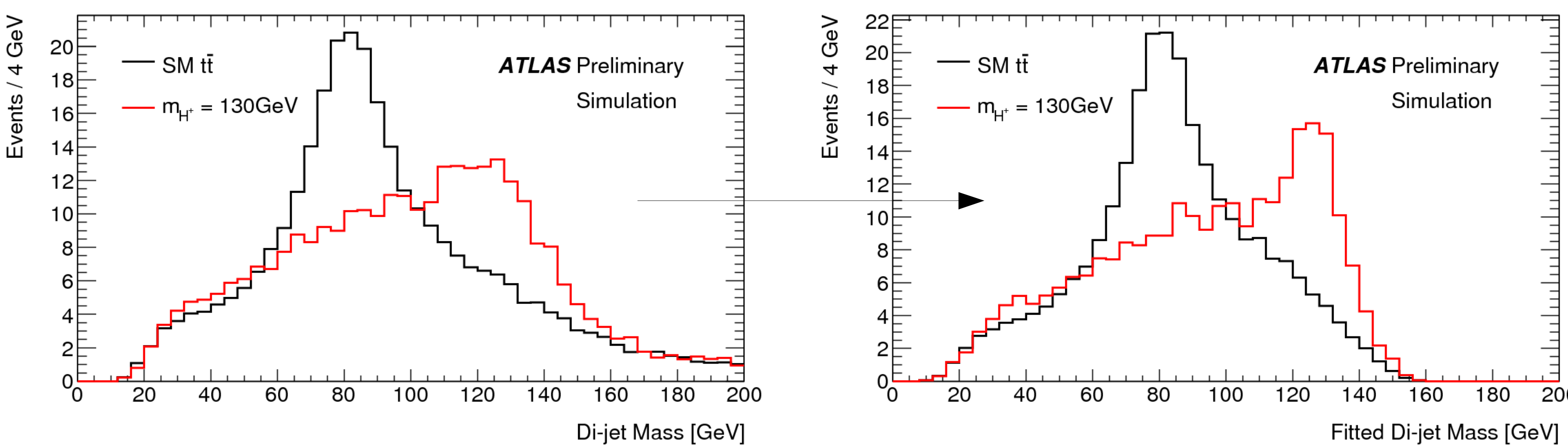
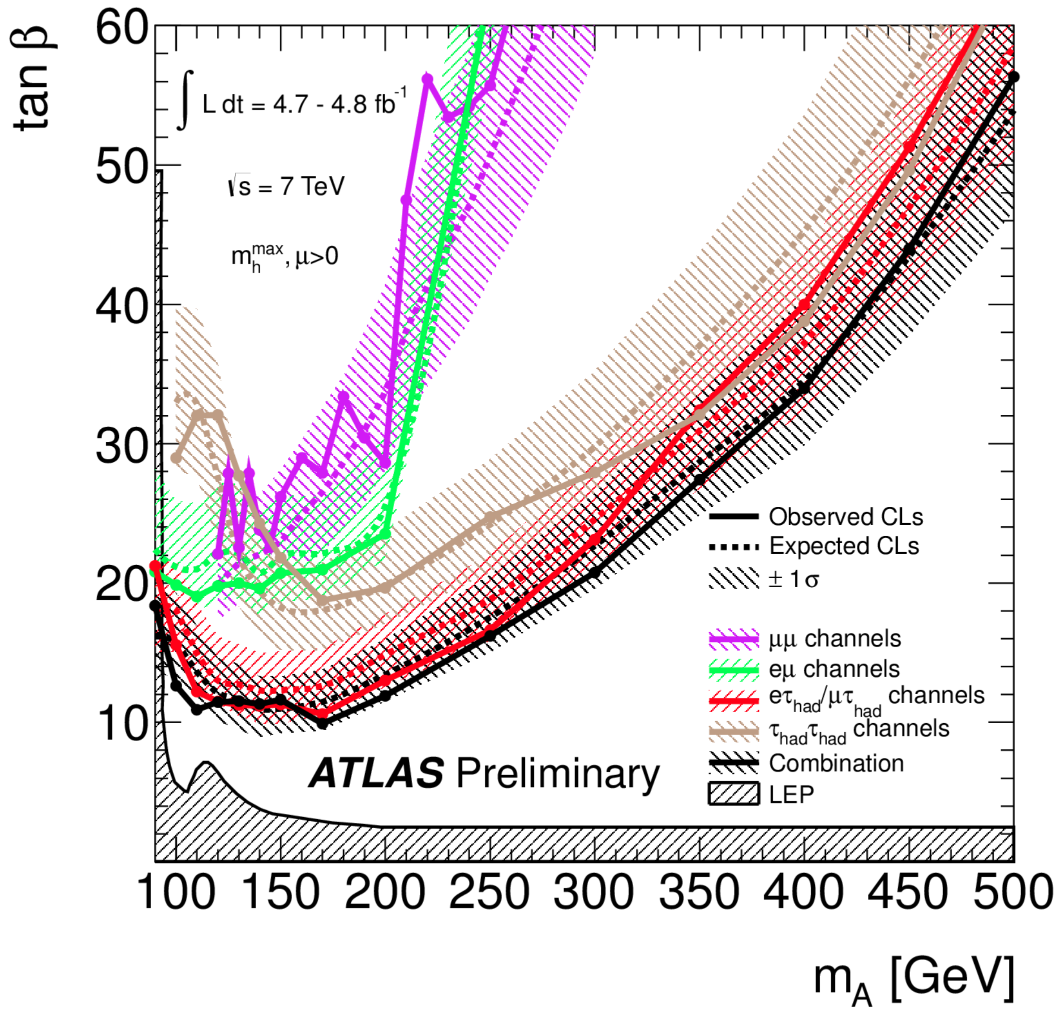
Use of kinematic fits to improve the separation against W → jj background

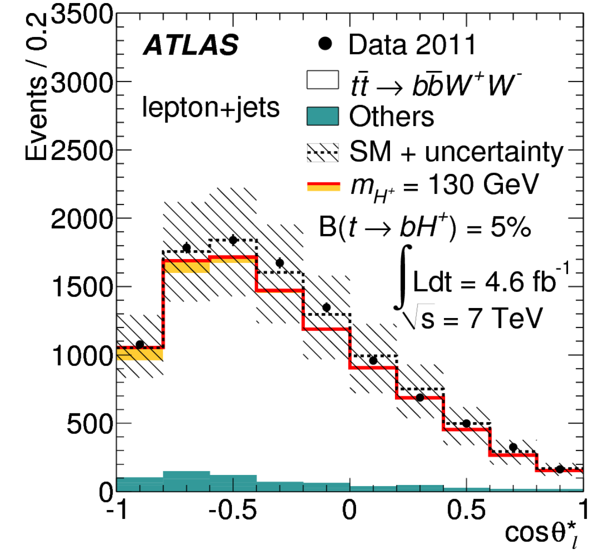


MSSM H → ττ/μμ

Individual channel contribution to the final limit

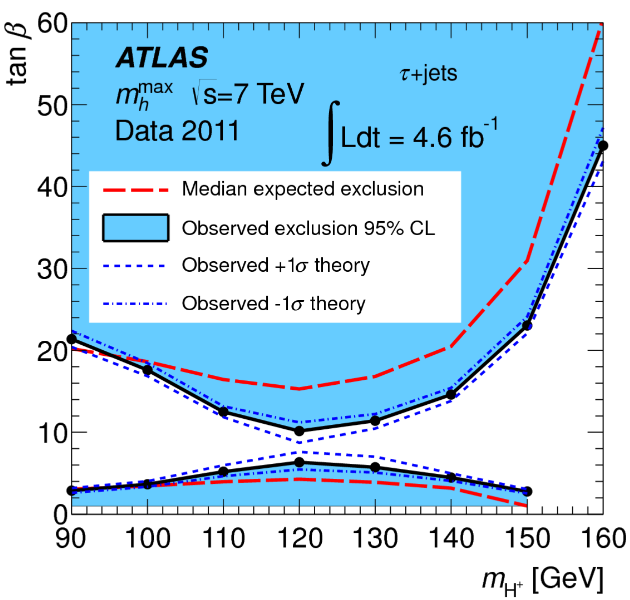


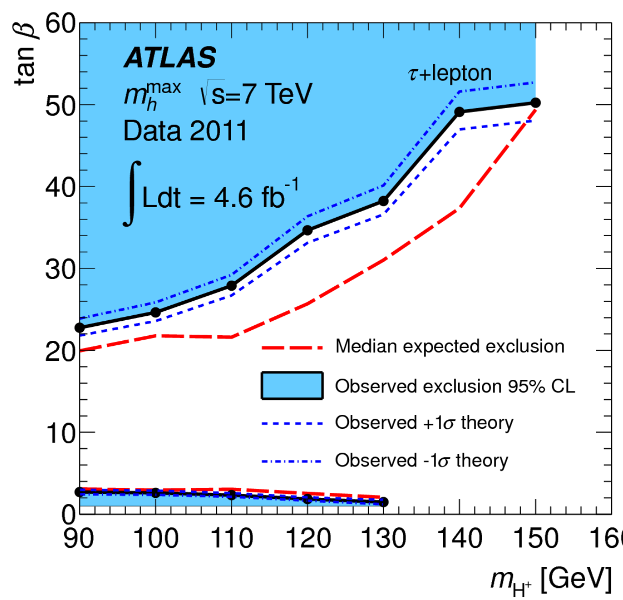
$H^{\pm} \rightarrow \tau^{\pm}\nu$

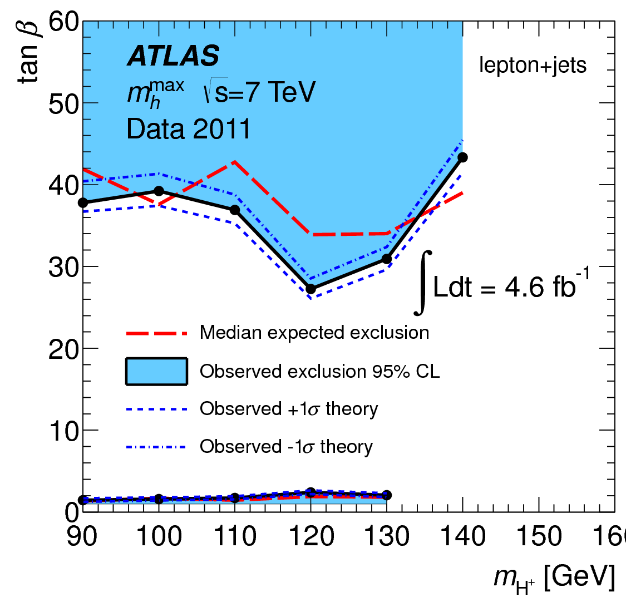


Extra plots for the Charged Higgs search

Individual channel contribution to the final limit







$H \rightarrow aa \rightarrow \gamma\gamma + \gamma\gamma$

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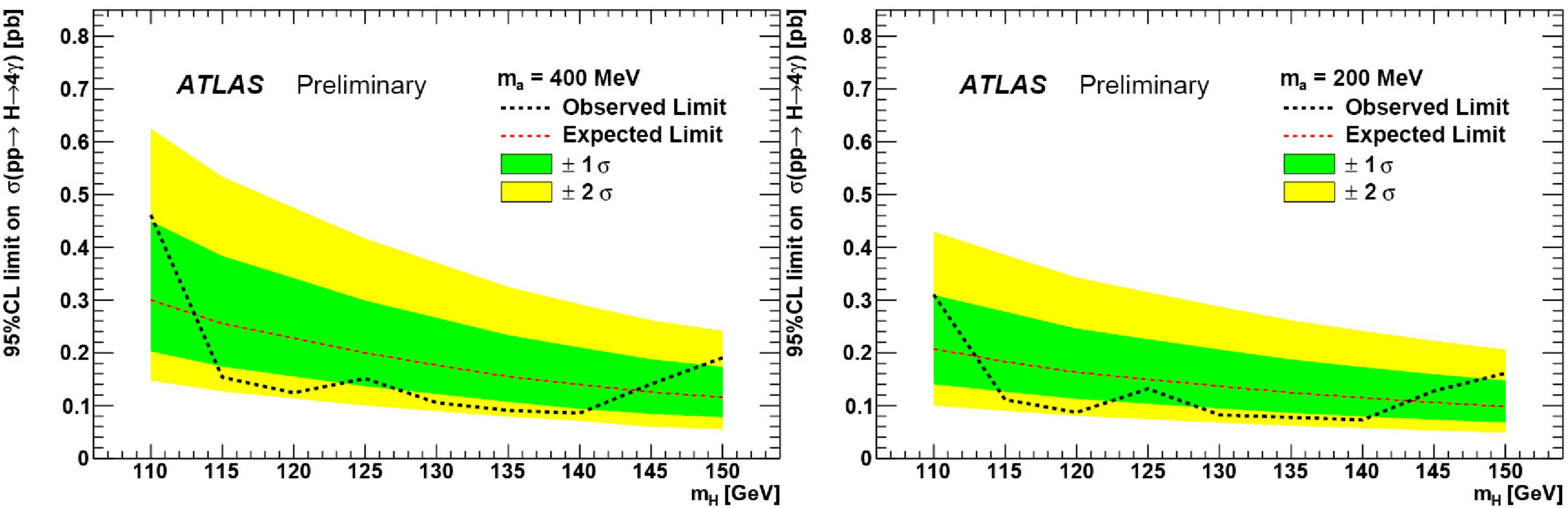
- Limits for other m_a masses



Fermiophobic Higgs

- No couplings to fermions
- Production via VBF and VH
- Decay via γγ, ZZ, WW and Zγ
- ATLAS search focuses on γγ; WW and ZZ also an option