Beyond SM Higgs searches @ ATLAS

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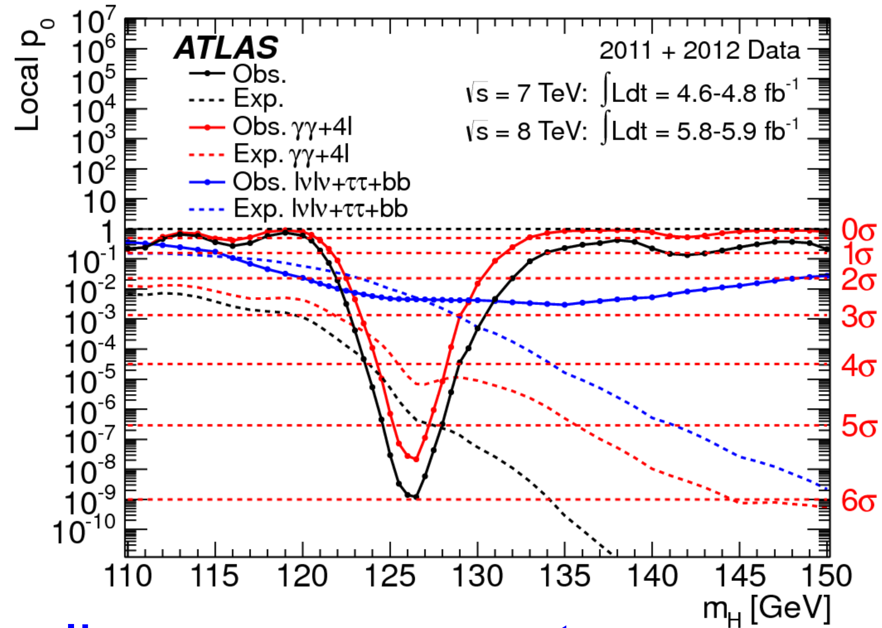
Jan Kochanowski University, Kielce, Poland

Introduction

Phys. Lett. B 716 (2012) 1-29

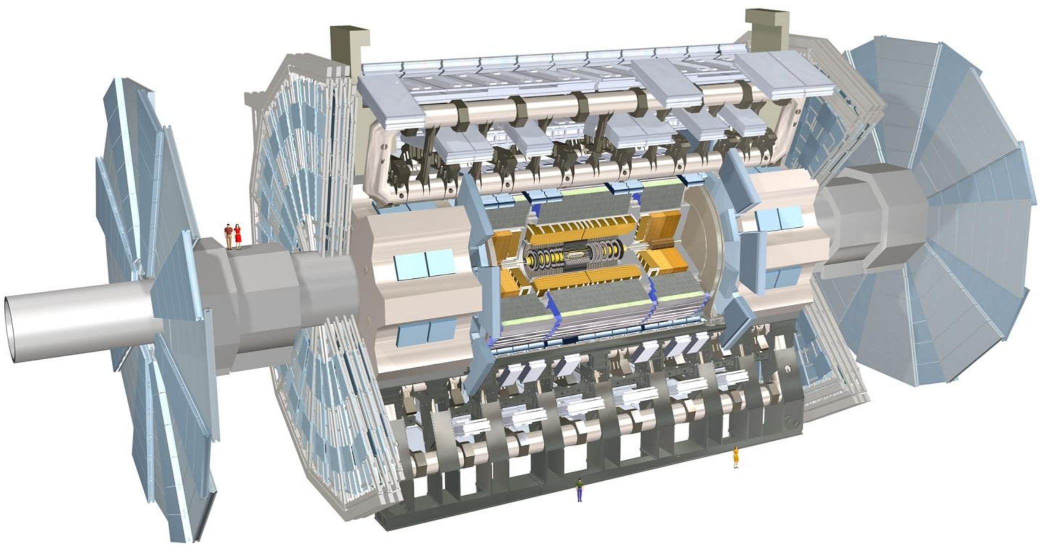


- July 2012: the discovery of a new (SM-Higgs-like) boson
- A "brave new world" lies ahead!

  Is it really the SM Higgs?
  - Lots of properties to be measured:
    fermionic decays, spin, precise coupling measurements, …
  - But note that many BSM physics scenarios predict a SM-like Higgs boson, but with a more complicated Higgs sector

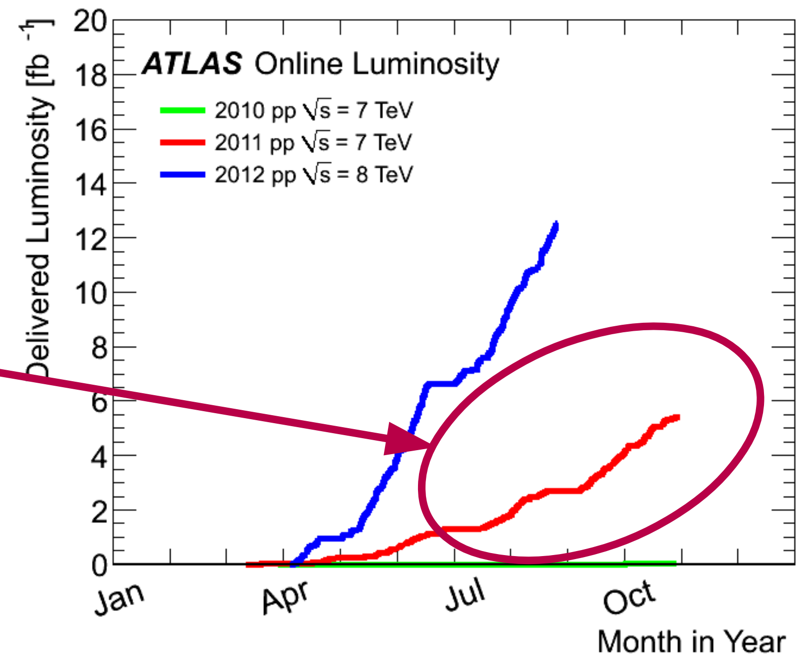
BSM Higgs searches:
→ complementary to the new resonance studies
→ necessary for understanding of the Higgs sector details and the nature of the electroweak symmetry breaking

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	Lumi (7 TeV)	Reference
$H \to \tau\tau$ / $\mu\mu$ (MSSM)	4.7–4.8 fb^{-1}	ATLAS-CONF-2012-094
$H^+ \to \tau^+\nu$	4.6 fb^{-1}	JHEP 1206 (2012) 039
$H^+ \to c\bar{s}$	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 ($a \to \mu\mu$)	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

ATLAS BSM Higgs searches

- Only a few searches will be described here due to the time restrictions
  - SUSY (but not olny) inspired searches:
    - $H \to \tau\tau$ / $\mu\mu$ search
    - Charged Higgs search: $H^{\pm} \to \tau^{\pm}\nu$
  - Examples of more exotic signatures
    - Higgs to light scalar particles
    - Higgs to long-lived particles (lepton jets & π_{v})

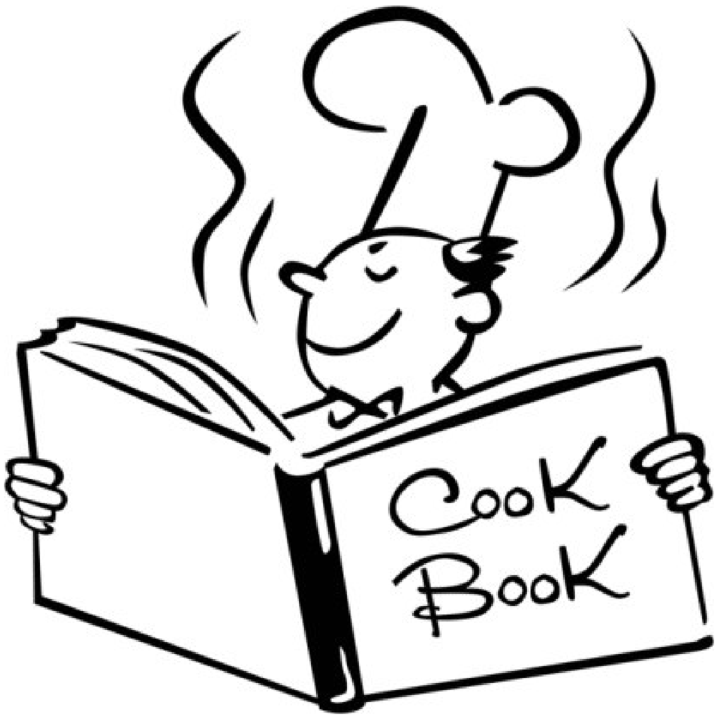
Grandma's recipe for a successful search

- Good old tricks that may do the job!

→ Try to find a simple extension to what you have already

→ Choose a theory which is highly motivated from a physics point of view

→ Keep also in mind that if you have many parameters it is difficult to interpret your data: c.f. SM Higgs search: only one parameter



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SM "Custodial symmetry" restricts our option: 2 Higgs doublet models (2HDM) is a very simple extension

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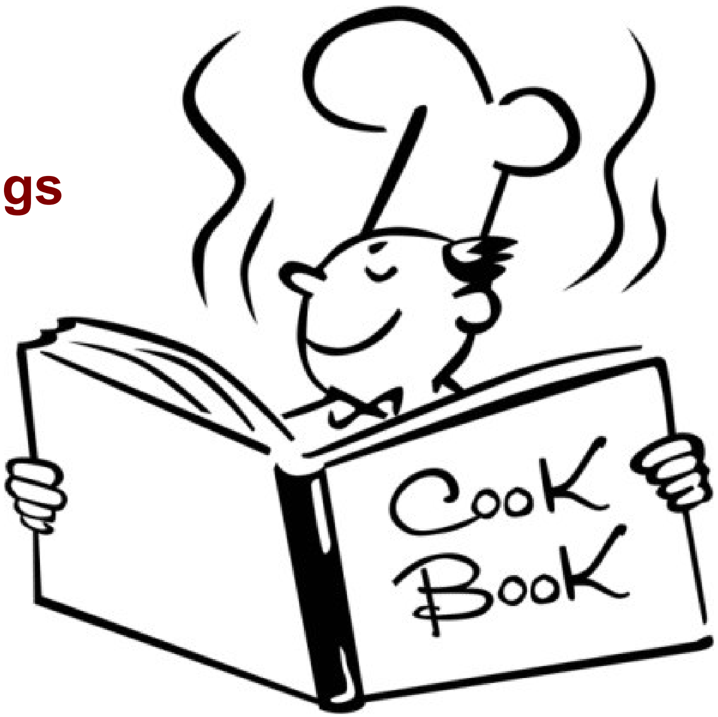

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SUSY can solve many problems: coupling unification, Higgs mass corrections, dark matter, ...

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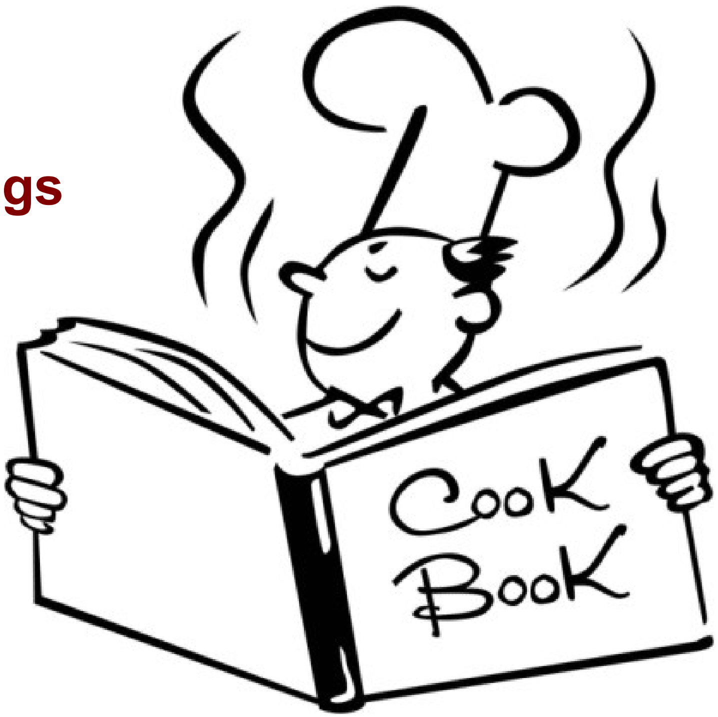
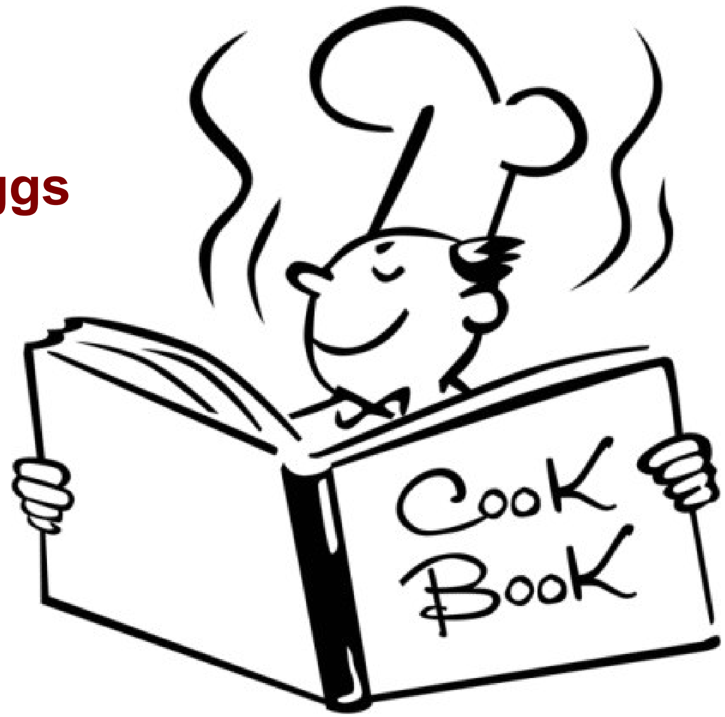


Grandma's recipe for a successful search

- Good old tricks that may do the job!

A not-so-frequent case where all these points are satisfied!



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MSSM (Minimal supersymmetric Standard Model) has a Higgs sector that depends only on 2 parameters at tree level!

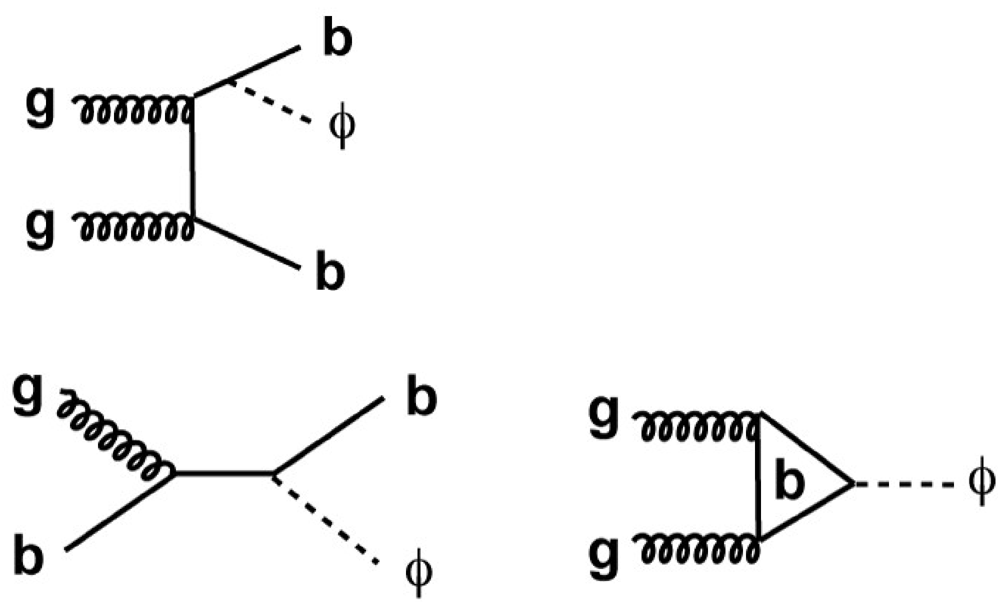
MSSM

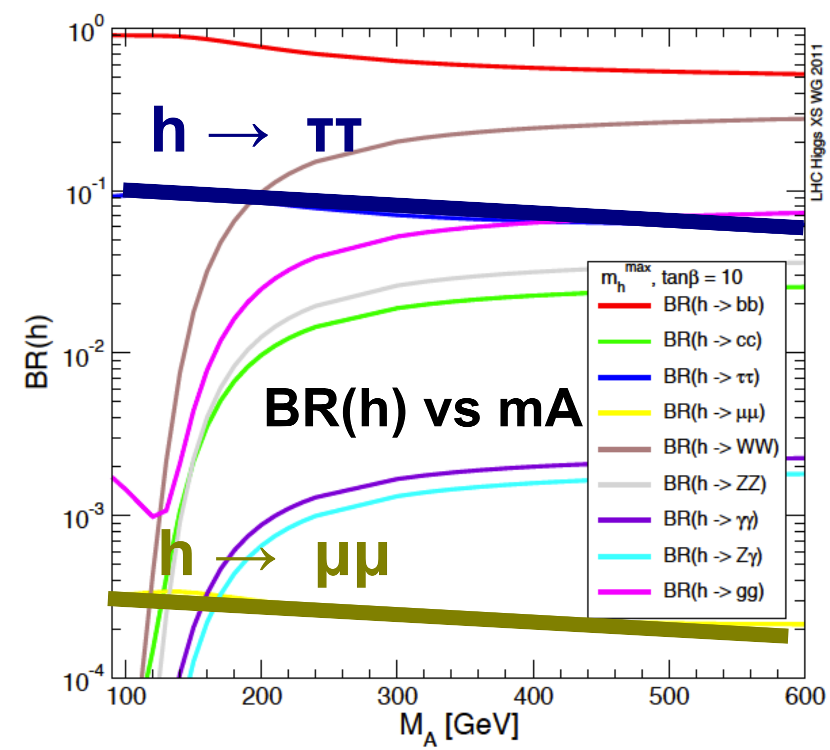
- MSSM (Minimal Supersymmetric Standard Model): a popular and well-studied extension of the SM
  - A specific case of a "type II 2HDM"
    - One Higgs doublet couples to up-quarks, one other to down-quarks
  - Higgs sector:
    - 2 Higgs doublets, 5 Higgs bosons: CP-even (**h**, **H**), CP-odd (**A**), charged (**H$^{\pm}$**)
    - depends only on 2 parameters at tree level: e.g. (m_A , tanβ), where tanβ is the ratio of the Higgs doublet v.e.v.s
  - **MSSM is compatible with the existence of a SM-like Higgs boson at ~126 GeV**

MSSM: Neutral Higgs

Neutral MSSM Higgs Production & Decay

Production through gluon-gluon fusion or in association with b quarks, with the latter being more and more important at high tanβ

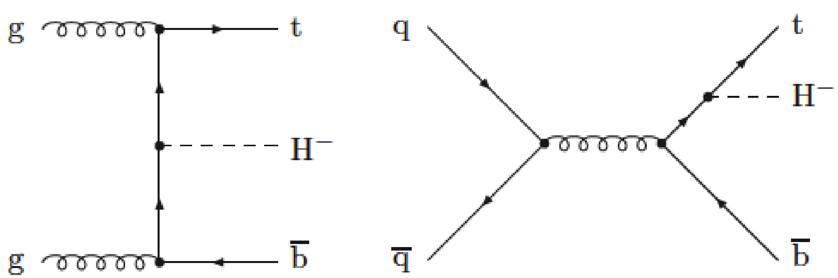




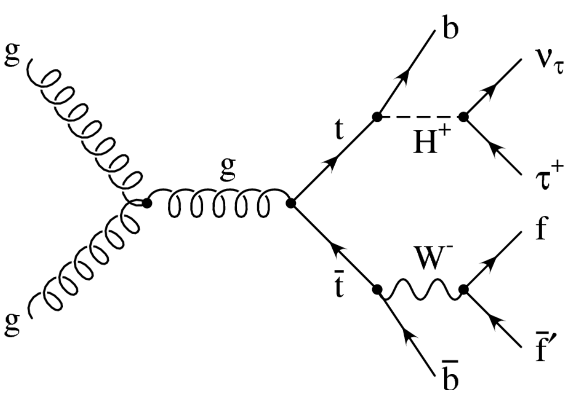
MSSM: Charged Higgs

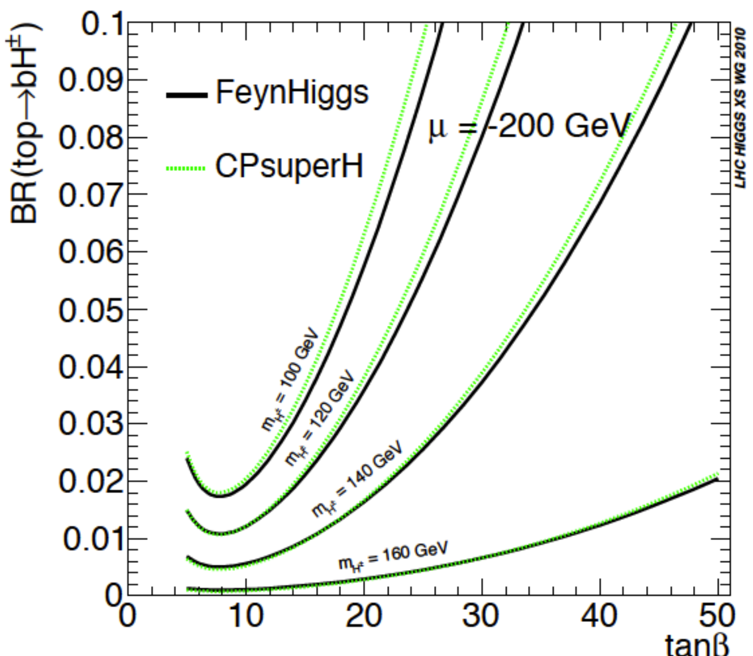
Charged MSSM Higgs Production & Decay

Heavy Charged Higgs

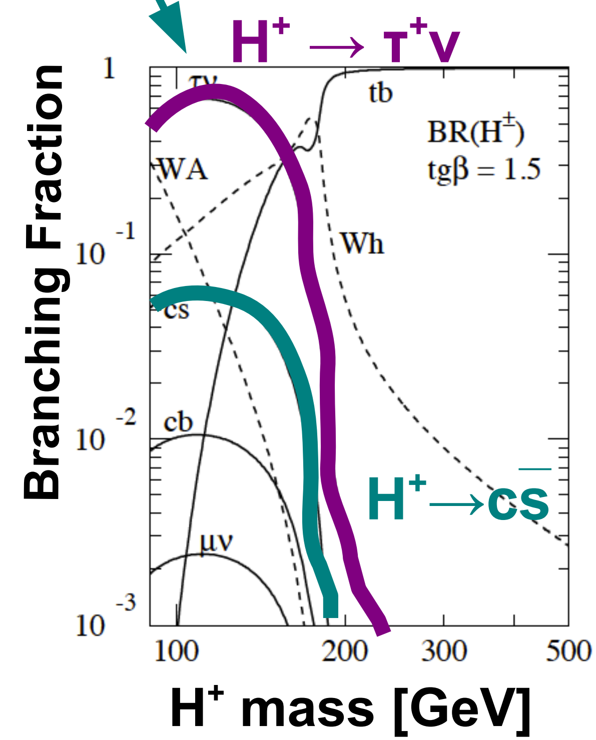


Light Charged Higgs





BR(Top → bH$^+$)vs tanβ



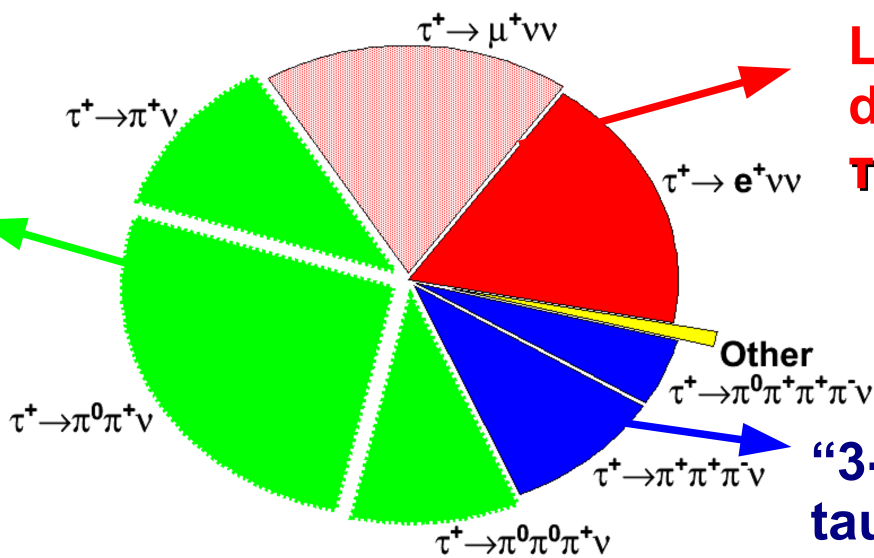
hep-ph/9704448

Taus

- "Golden" MSSM Higgs search channels: **H→ττ, H$^{\pm}$→τ$^{\pm}$ν**
- Taus: the only leptons that can decay hadronically

"1-prong" hadronic tau decays (~50%)

τ(had)



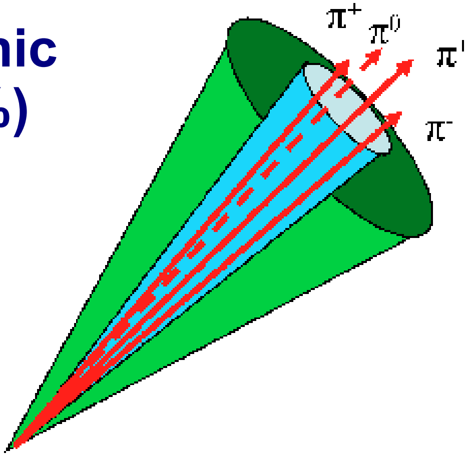
Leptonic tau decays (~35%)

τ(lep)

"3-prong" hadronic tau decays (~15%)

Studies with taus are involved:

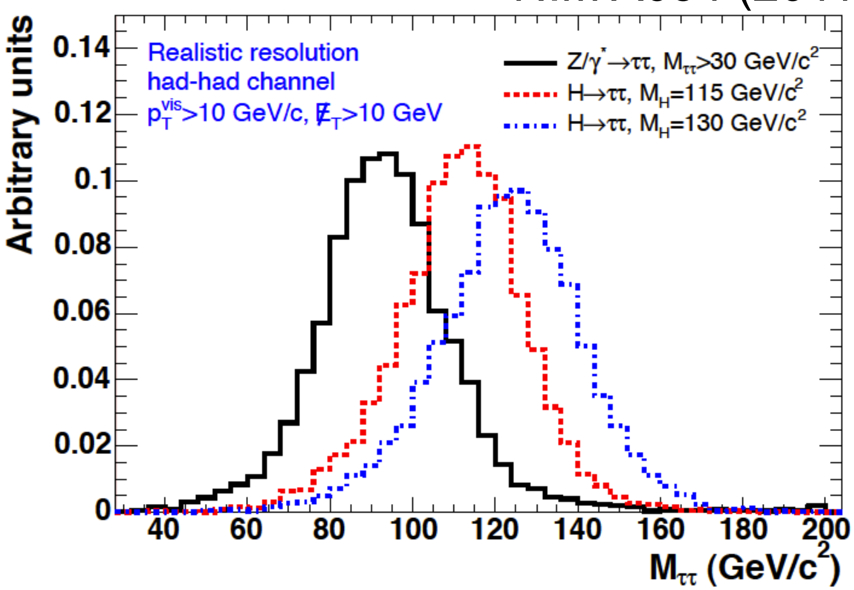
- neutrinos in the final state: degraded di-tau mass resolution
- pions in τ(had): large fake rates from multi-jet production



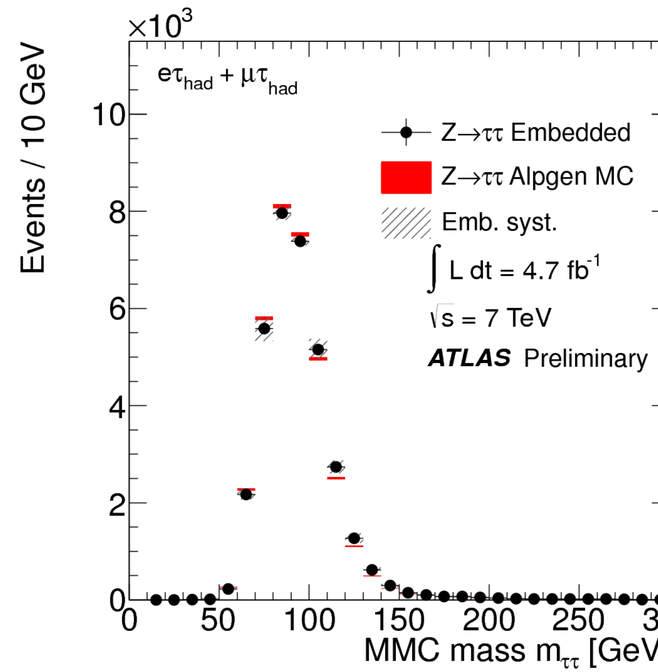
Special Techniques used with Taus

- Di-tau mass resolution: very poor due to the presence of neutrinos in the final state
  - Visible mass (mass of visible objects)
  - "Missing Mass Calculator" (MMC):

Constrain unknown neutrino momenta using τ decay kinematics NIM A654 (2011) 481



- Z → τ τ : very important background source



"τ-embedded" Z → μμ data events: select Z→μμ events from data and replace μ with a simulated τ

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

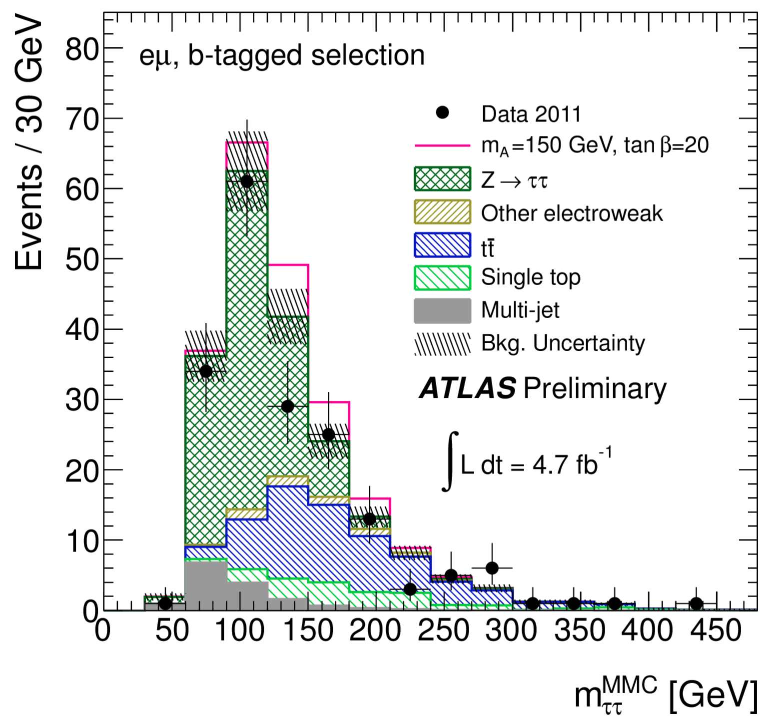
(MSSM) $H \to \tau\, \tau$ / $\mu\, \mu$

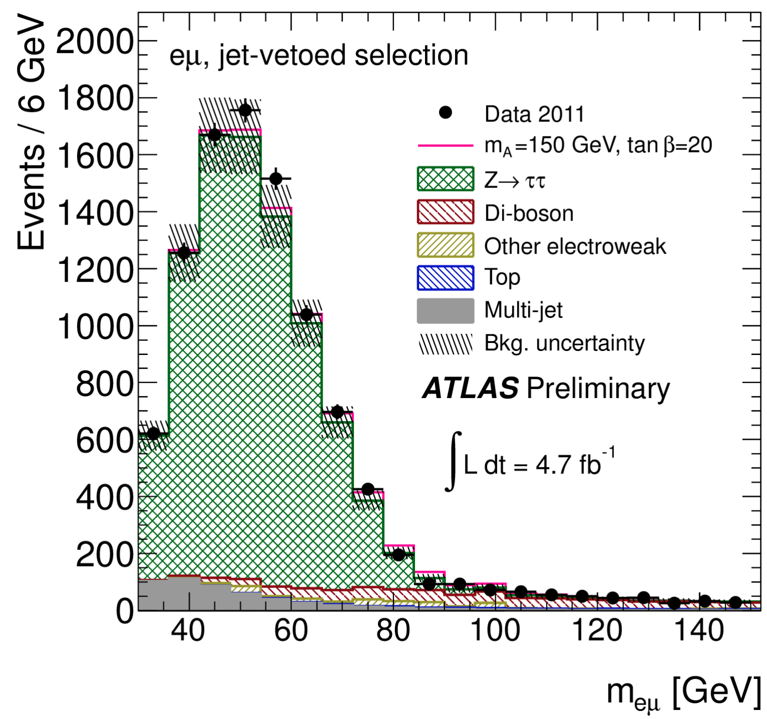
- $H \to \tau\tau$: the most promising channel to look for neutral MSSM Higgs
  - Final states considered here:
    $\tau(e)\tau(\mu)$: BR ~ 6%
    $\tau(e)\tau(had)+\tau(\mu)\tau(had)$: BR ~ 46%
    $\tau(had)\tau(had)$: BR ~ 42%
- $H \to \mu\mu$: small BR (~0.04% c.f. ~10% for $\tau\tau$) but very 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: ($Z \to \tau\tau$, 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(μ) < 125 GeV; H_T<100 GeV; ΣcosΔφ(MET,l)>-0.2	**"jet-vetoed" sample:** no jets in event

ATLAS-CONF-2012-094

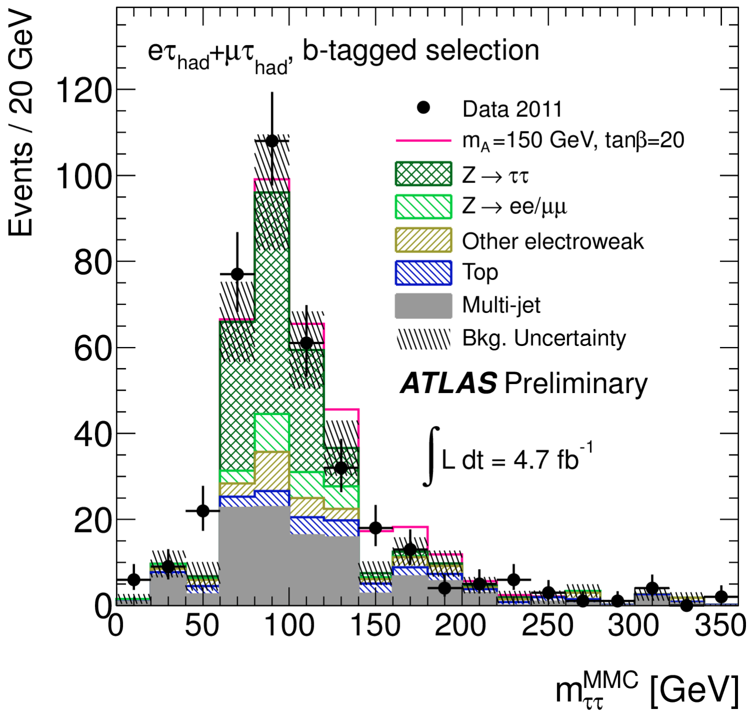


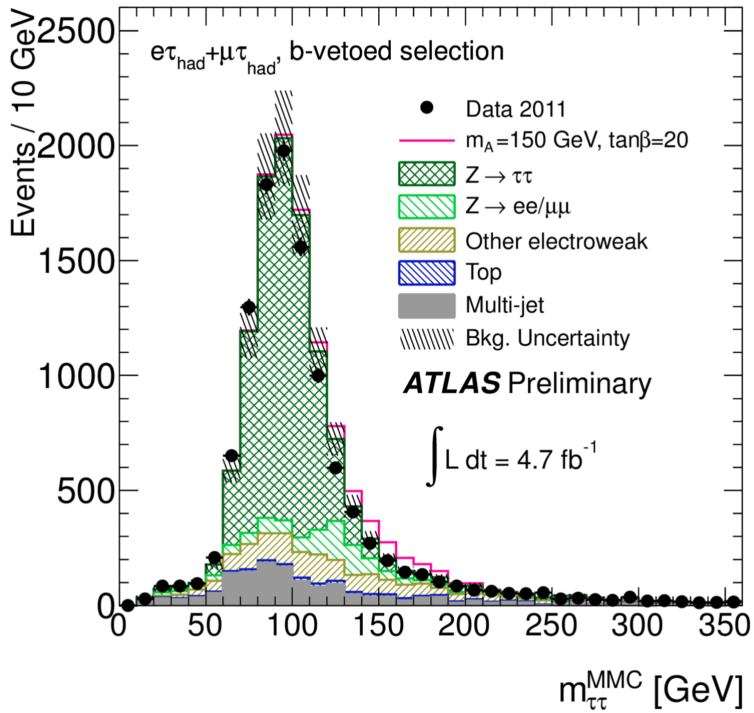


MSSM H → τ(lep) τ(had)

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





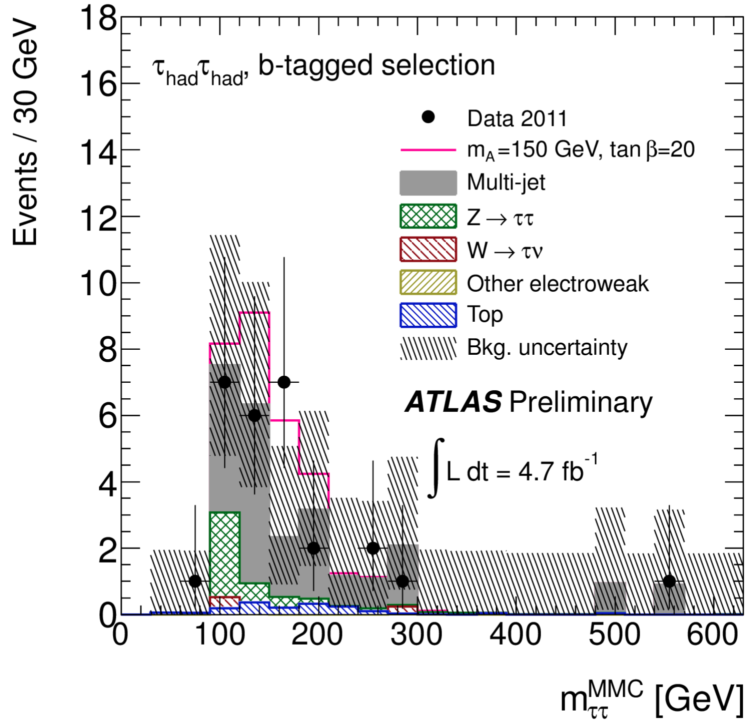
MSSM H → τ(had) τ(had)

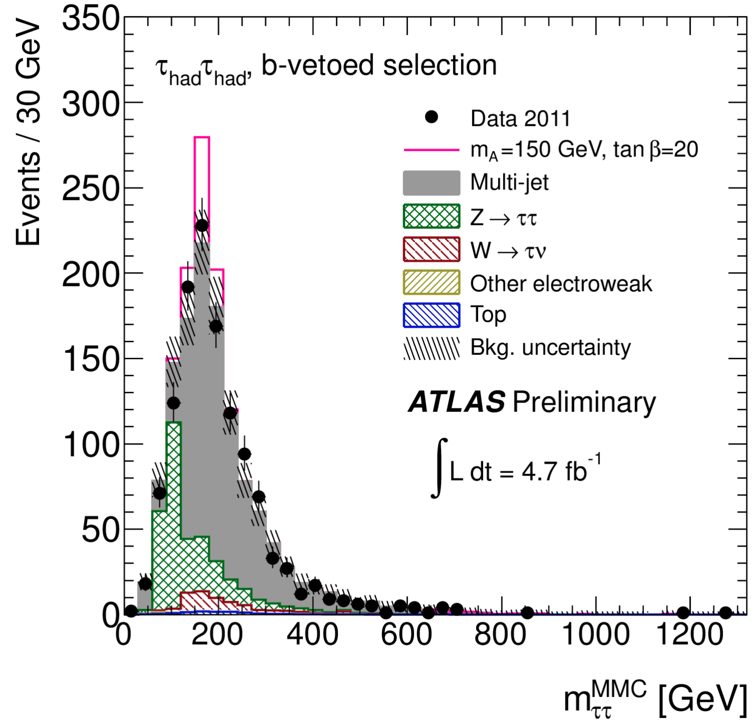
τ(had)τ(had)

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

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

ATLAS-CONF-2012-094

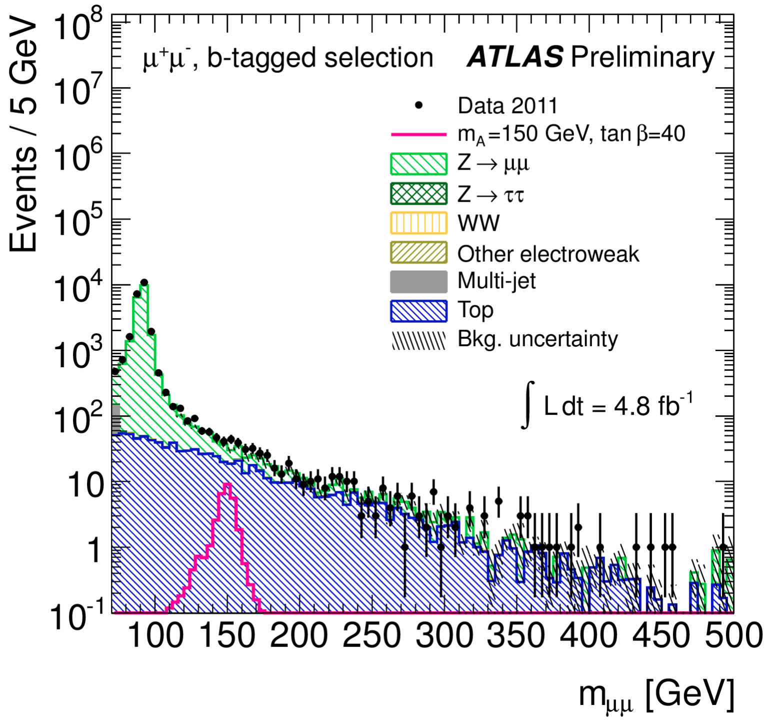


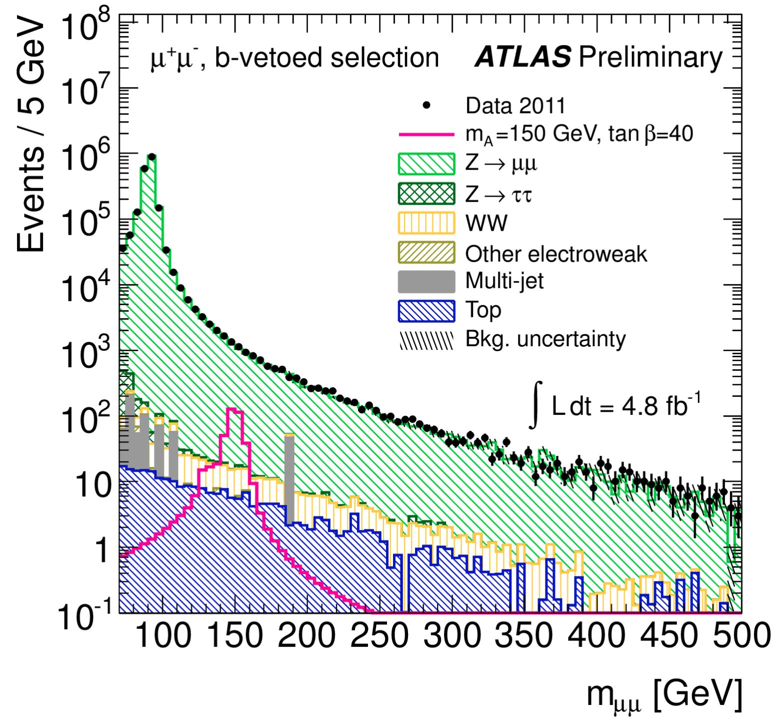


MSSM H → μ μ

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





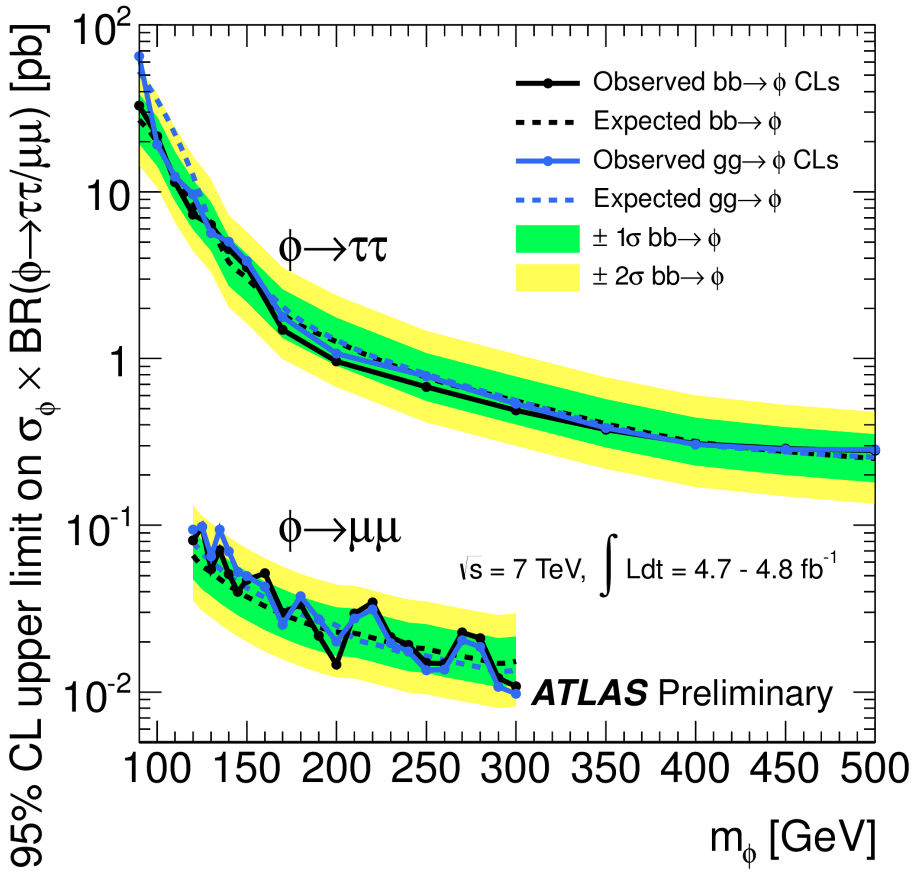
Simulated backgrounds are shown here only for demonstration: not used in the final result

MSSM H → ττ/μμ search

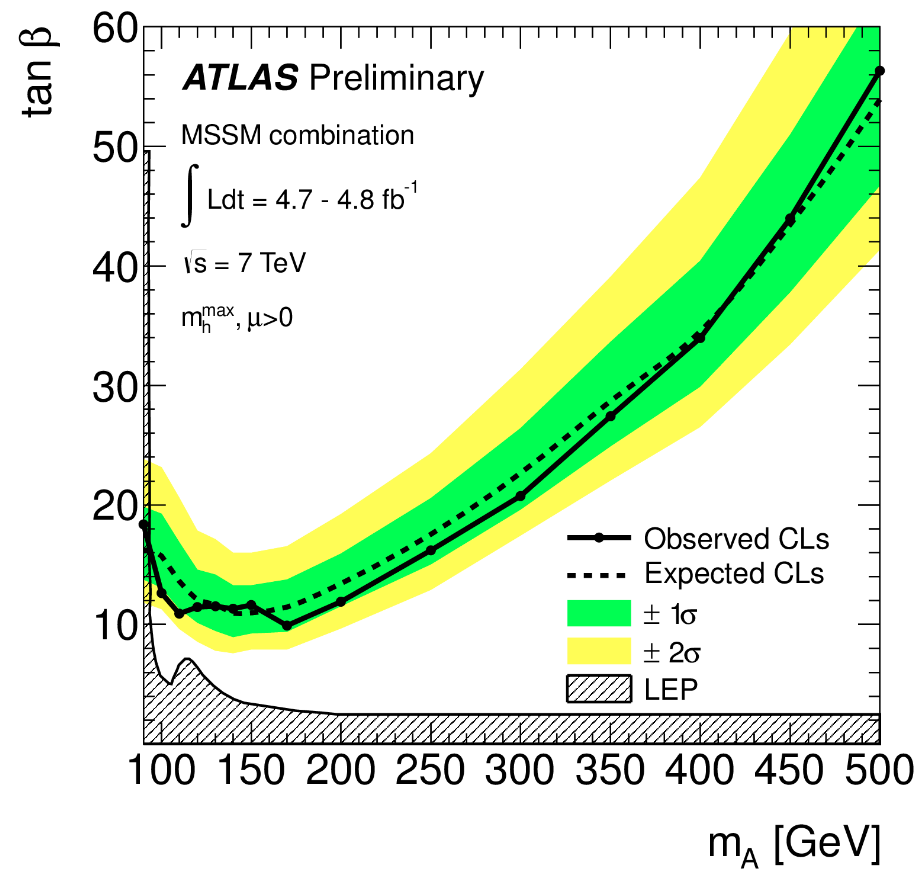
ATLAS-CONF-2012-094

- Exclusion Limits: all channels combined

Limit on σ BR(φ → ττ)



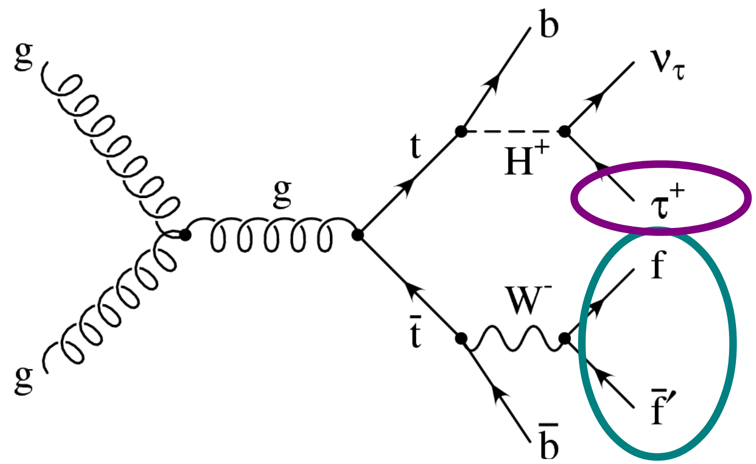
"m_A-tanβ" space limit m_h^{max}



Charged Higgs

Charged Higgs Search

- In “type II 2HDM” (and in MSSM): in large parts of the parameter space light charged Higgs is produced primarily through top decays; BR($H^{\pm} \rightarrow \tau^{\pm}\nu$) is sizeable



Channel topology organized according to W and tau decay

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

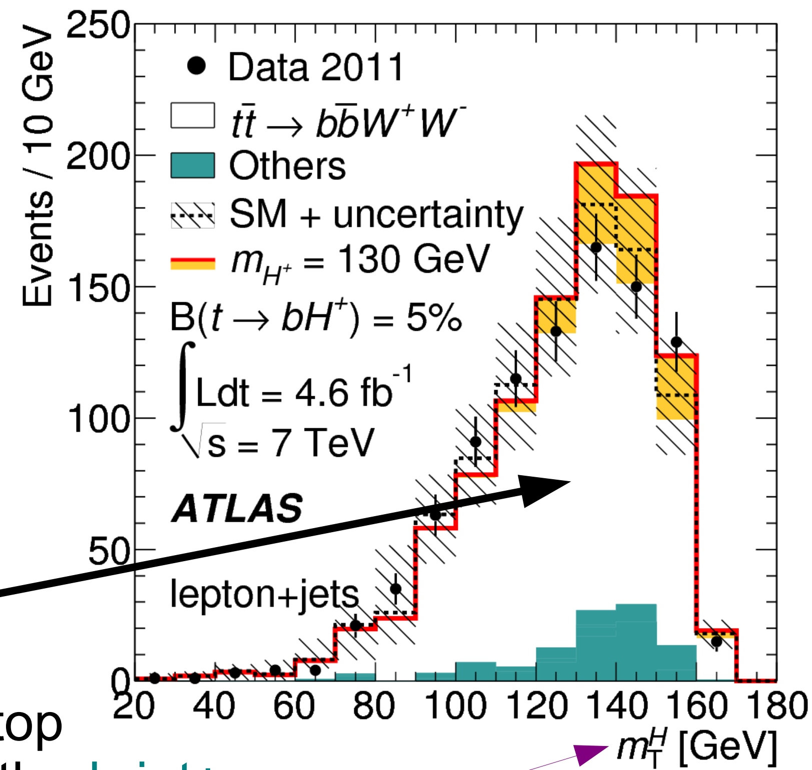
tau(lep)+W(→lν):	$tt \rightarrow bbWH \rightarrow bb\,(l\nu)\,(\tau_{lep}\nu)$	
tau(had)+W(→lν):	$tt \rightarrow bbWH \rightarrow bb\,(l\nu)\,(\tau_{had}\nu)$	BR ~ 14%
tau(had)+W(→jets):	$tt \rightarrow bbWH \rightarrow bb\,(qq)\,(\tau_{had}\nu)$	BR ~ 46%
tau(lep)+W(→jets):	$tt \rightarrow bbWH \rightarrow bb\,(qq)\,(\tau_{lep}\nu)$	BR ~ 25%

Channels studied with full 2011 data

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

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

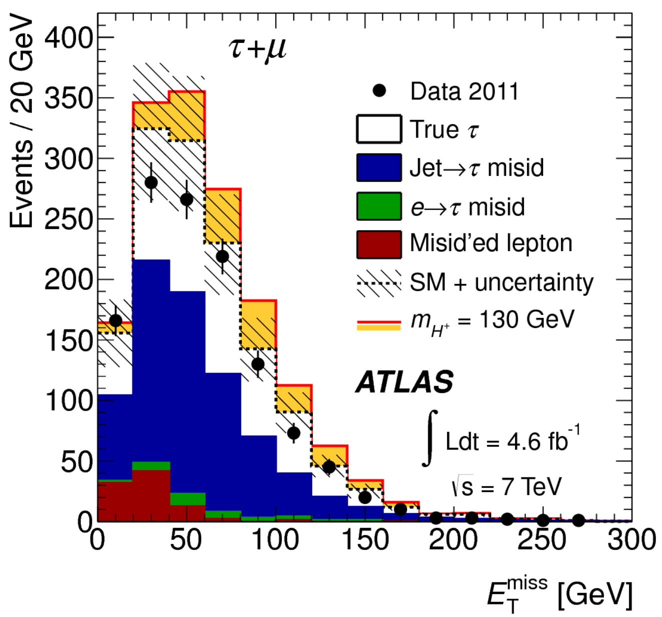
$$(m_T^H)^2 = \left(\sqrt{m^2_{top} + (\vec{p_T}^{\,l} + \vec{p_T}^{\,b} + \vec{p_T}^{\,miss})^2} - p_T^b\right)^2 - \left(\vec{p_T}^{\,l} + \vec{p_T}^{\,miss}\right)^2.$$

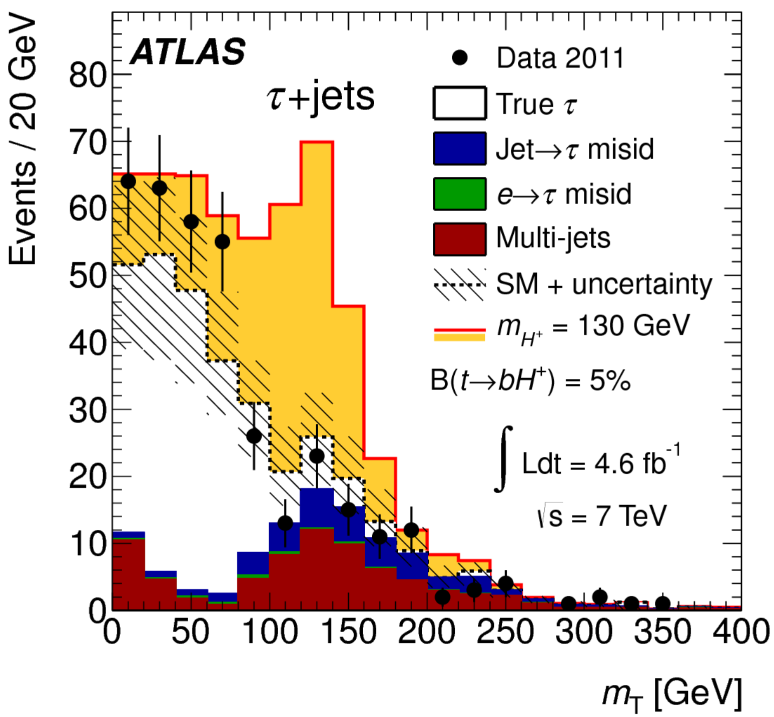
JHEP 1206 (2012) 039

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

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

Tau(had) + W(→ jets)
1 τ_{had} with pT > 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



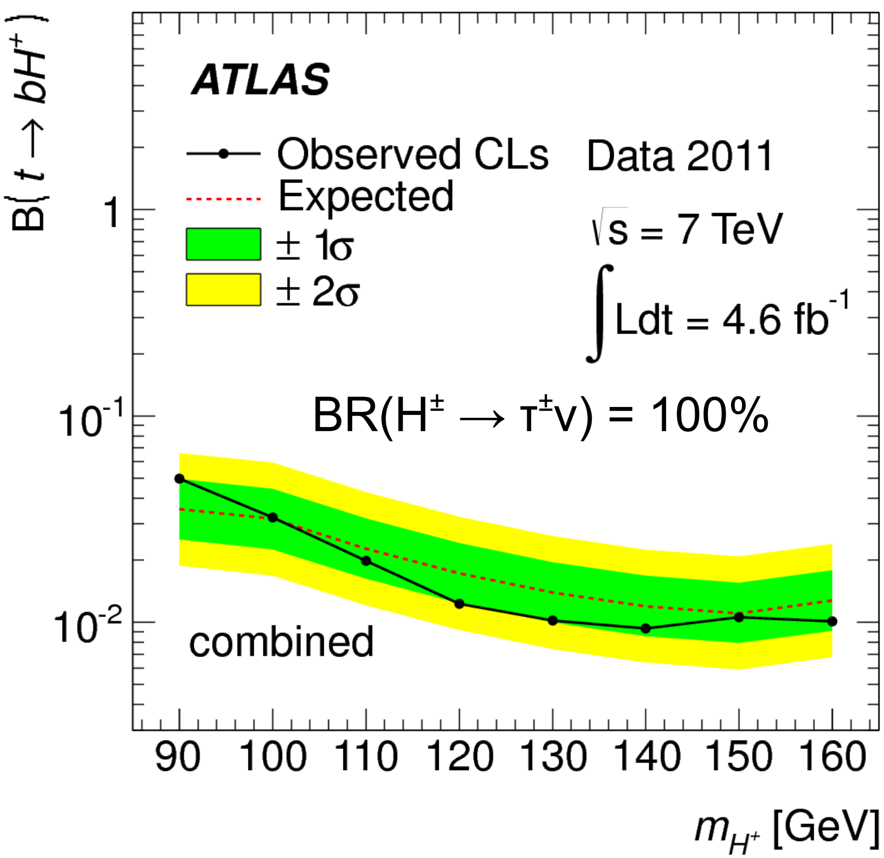


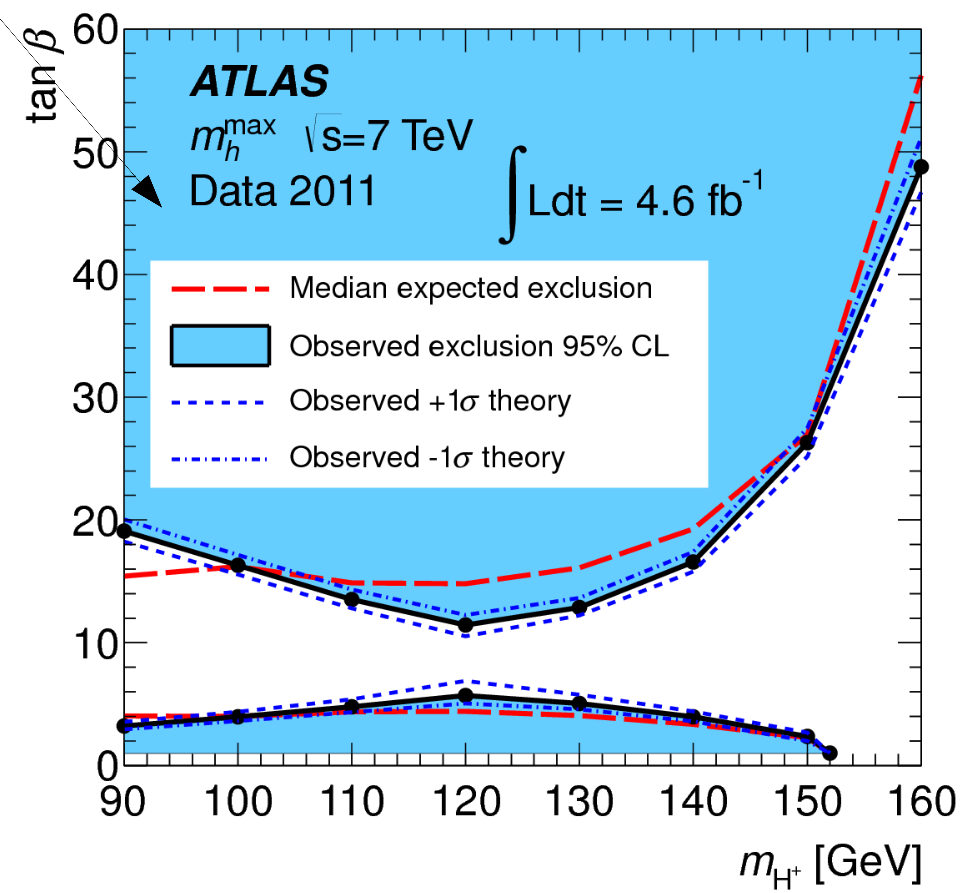
Most sensitive channel, but the absence of a light lepton makes triggering on these events not trivial: tau + MET trigger

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

JHEP 1206 (2012) 039

Search result interpretation in the MSSM: low mass $H^\pm$ allowed phase space is heavily constrained





Higgs to light scalar particles

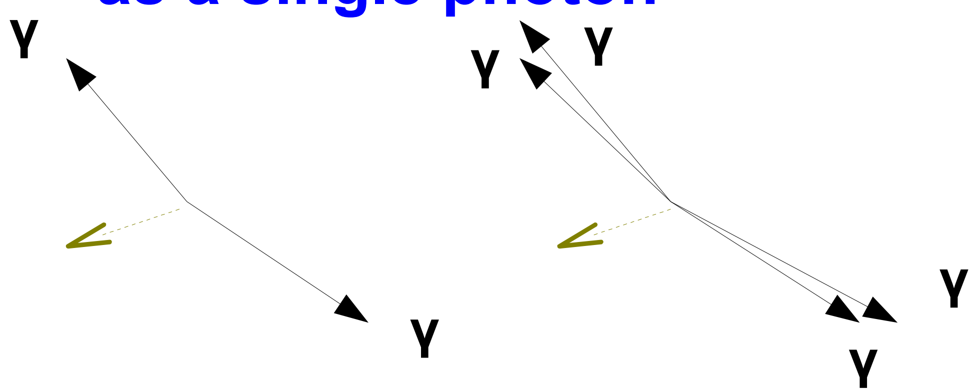
$H \rightarrow aa \rightarrow \gamma\gamma + \gamma\gamma$

ATLAS-CONF-2012-079

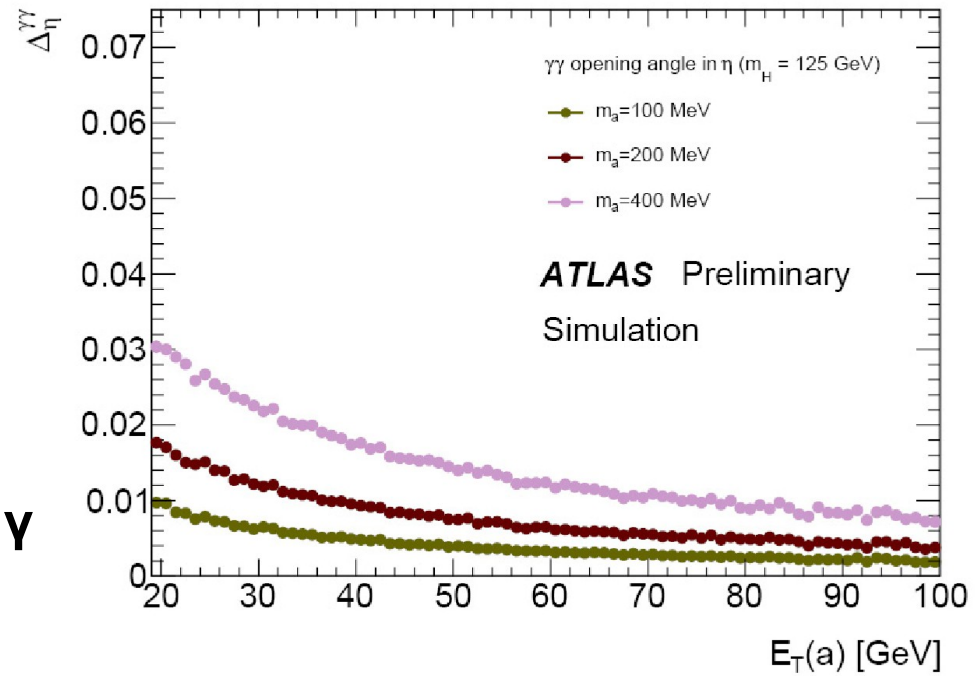
- In some SM extensions (e.g. NMSSM) Higgs is allowed to decay to light (pseudo)scalar particles, a, which consequently decay to $\gamma\gamma$ without contradicting any current result

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 → aa → γγ + γγ

ATLAS-CONF-2012-079

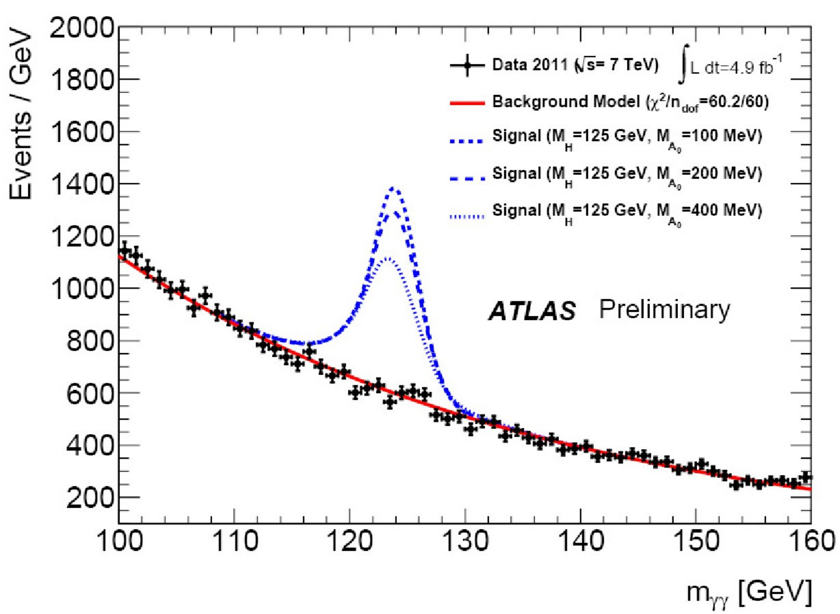
- Search uses events with a γγ pair

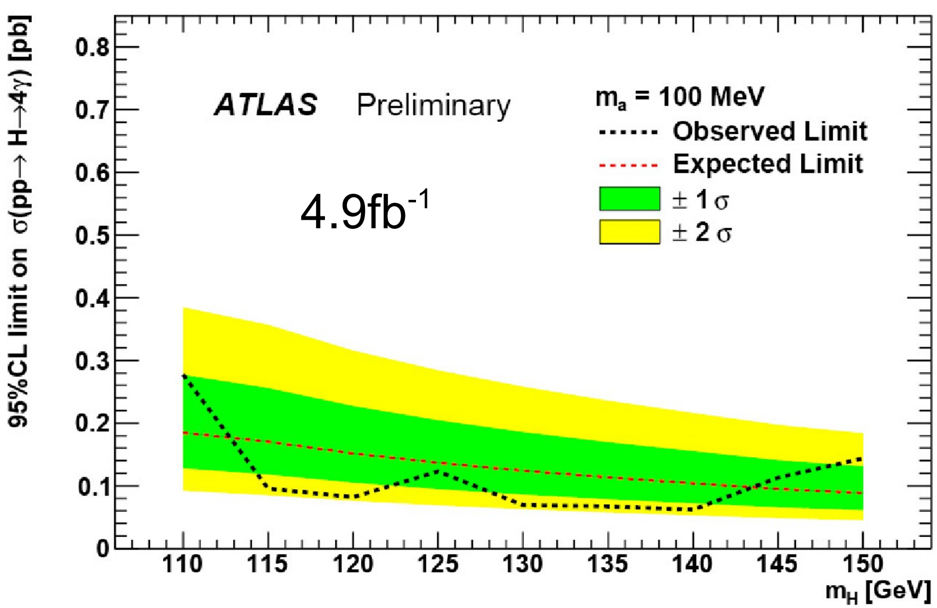
2 photons pT > 40 / 25 GeV

use of dedicated photon ID (shower shape cuts are removed)

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 zero decay length for a





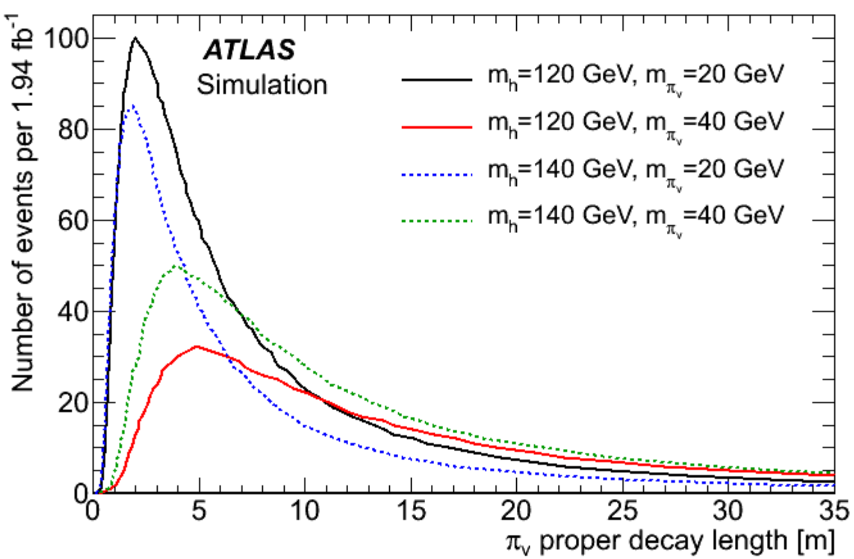
Higgs to long lived particles

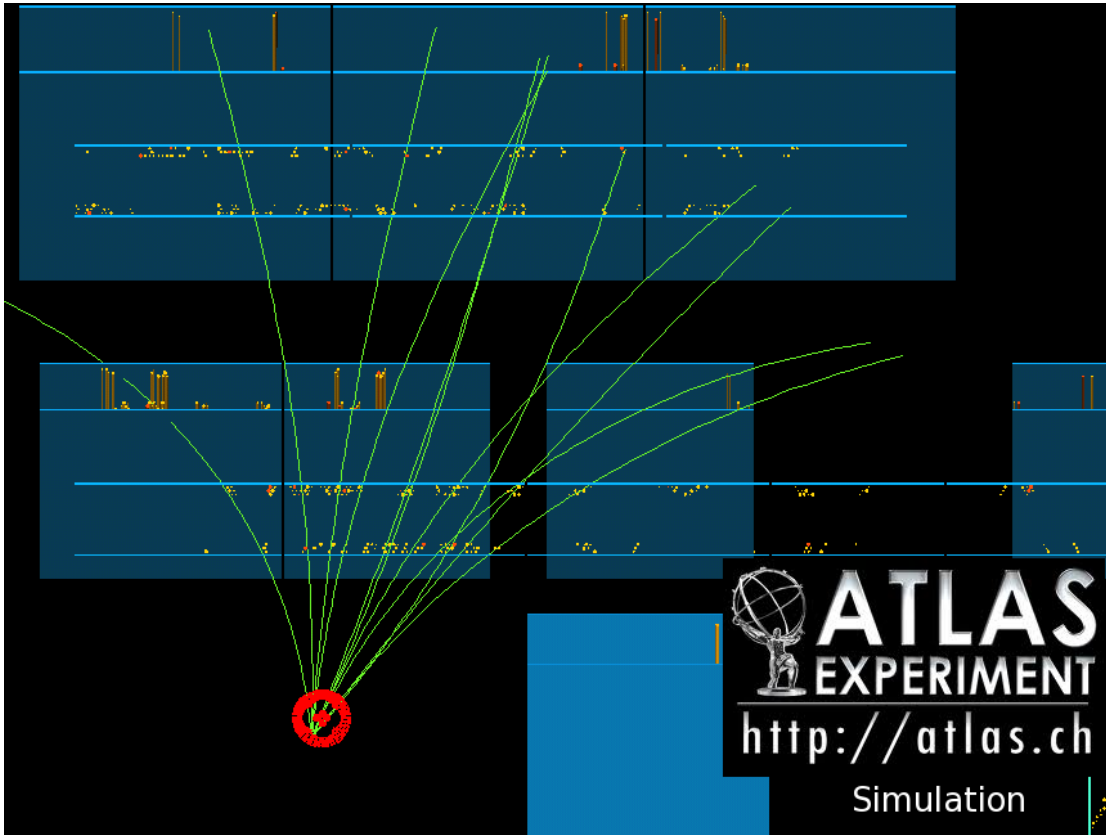
Higgs decaying to long-lived particles

- Higgs decaying to invisible, long-lived "hidden valley" pions π_v, which decay to jets in the outer calorimeter and are detected in the muon system

PRL 108 (2012) 251801

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





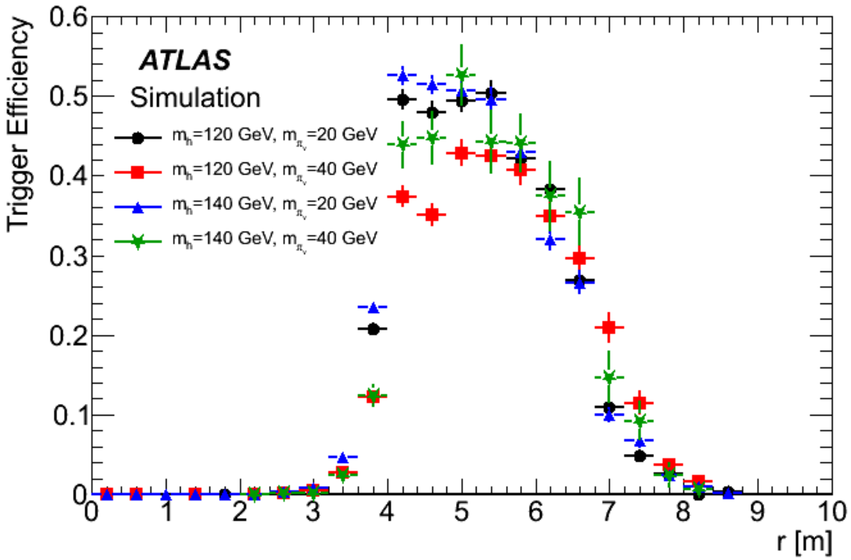
Higgs decaying to long-lived particles

- **$h \rightarrow \pi_v \pi_v$; $\pi_v \rightarrow bb/cc/\tau\tau$**

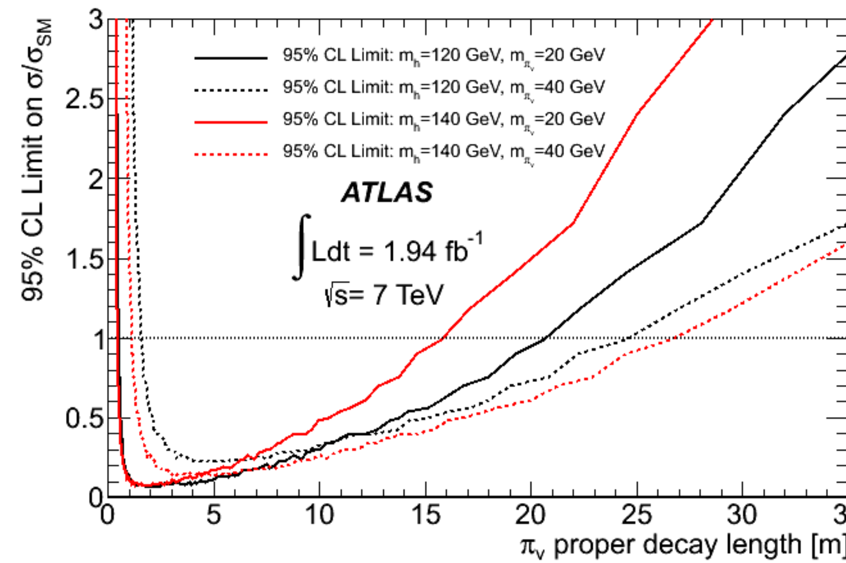
PRL 108 (2012) 251801

Dedicated trigger development to collect candidate events

"hidden valley" model used as benchmark assuming a Higgs produced as in SM, but with a BR ($h \rightarrow \pi_v \pi_v$) = 100%



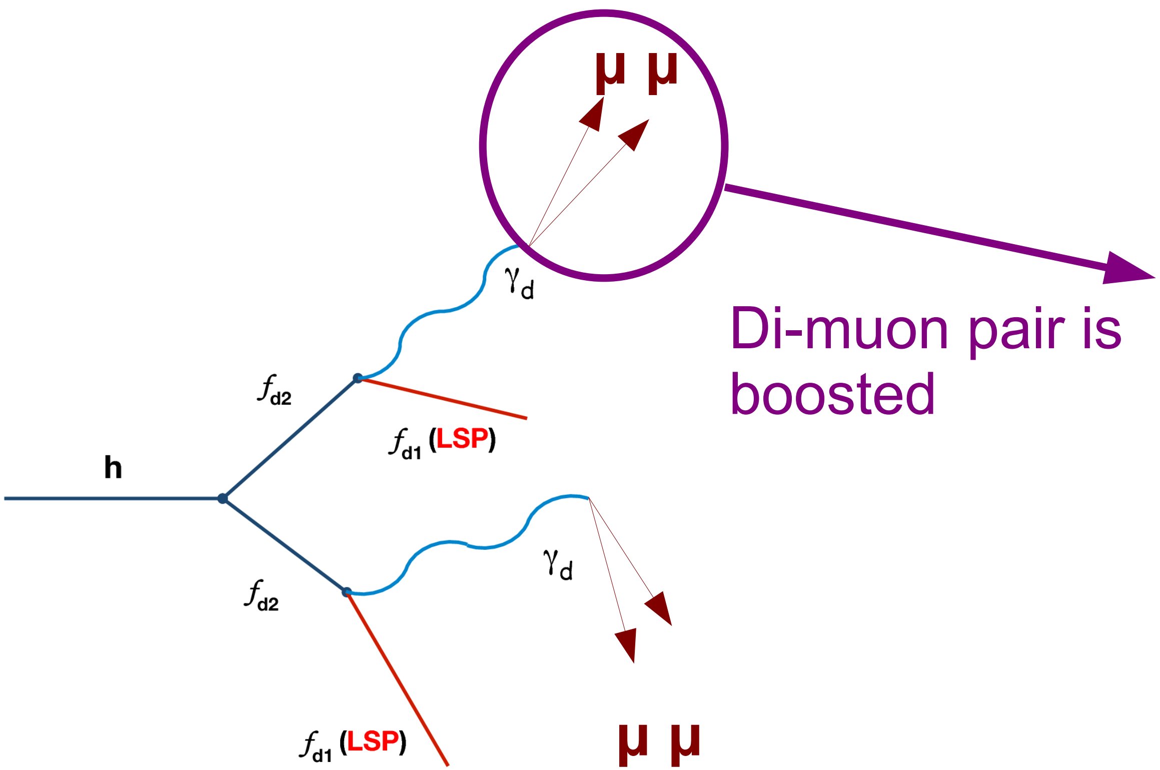
Radial decay position of long lived particle

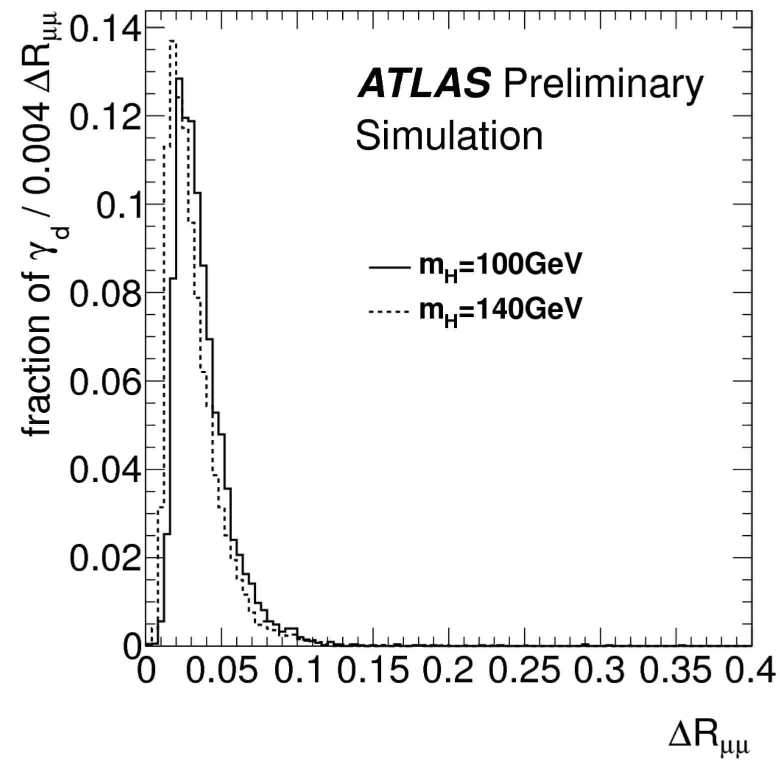


Higgs decaying to long-lived particles

- Higgs decaying to invisible, long-lived particles, which finally produce particles decaying to lepton-jets

ATLAS-CONF-2012-089





Higgs decaying to long-lived particles

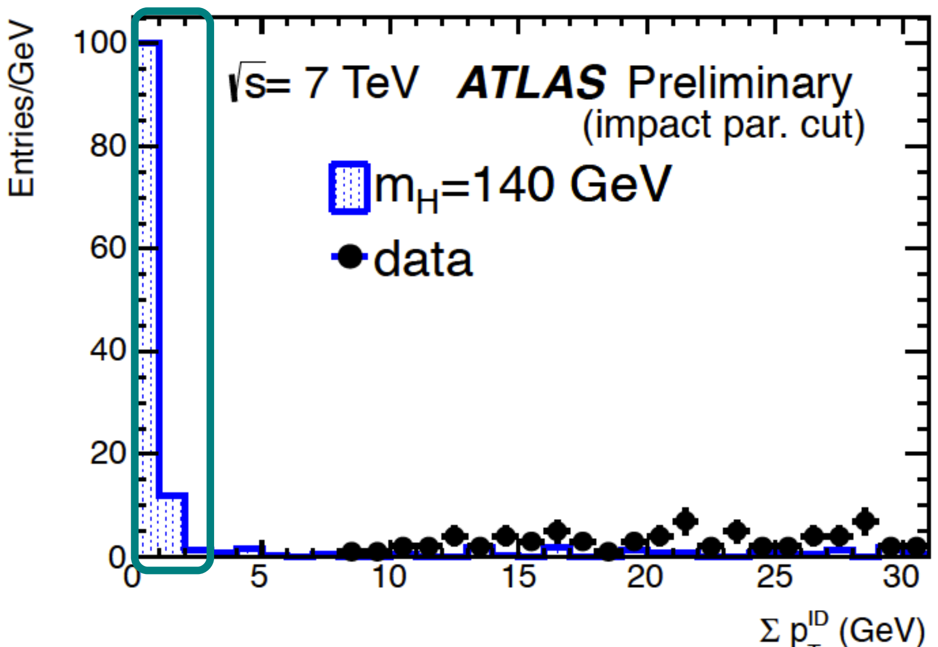
- Higgs to muon jets: results

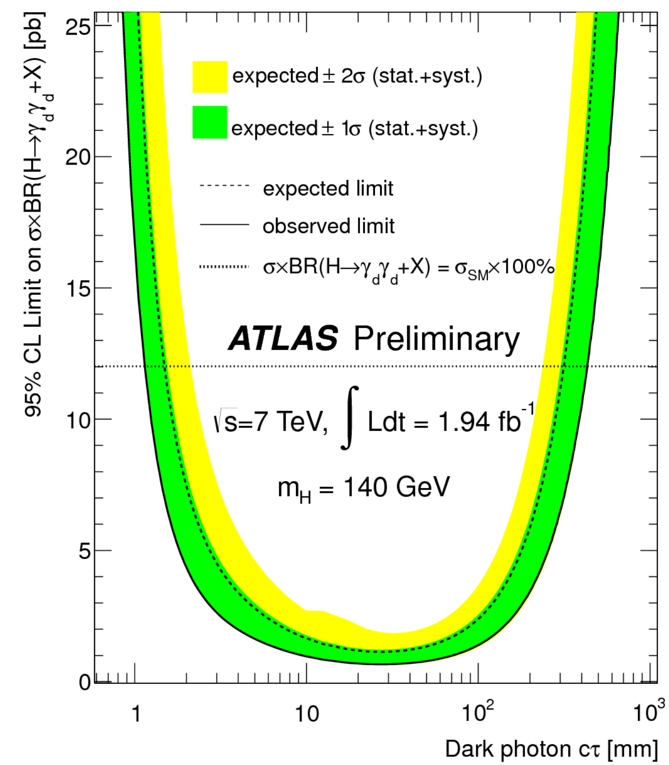
ATLAS-CONF-2012-089

Selecting events using a 3-muon trigger with Muon-System-only muons

Signal region

“hidden valley” model used as benchmark assuming BR ($h \to \gamma_d \gamma_d + X$) = 100%





$\Sigma\ p_T$(ID) : Sum of Inner Tracking Detector track pT in DR < 0.4 around the lepton-jet direction

Conclusion

- The effort to understand whether the recently discovered boson is indeed the long sought SM Higgs boson has started
- Direct searches for BSM Higgs bosons are an important part of this procedure
- ATLAS searches are inspired by a variety of BSM physics scenarios and focus on many different signatures, e.g.
  - $H \to \tau\,\tau$, $H^{\pm} \to \tau^{\pm}\nu$, $H \to aa \to \gamma\gamma + \gamma\gamma$, $H \to \pi_v \pi_v \to$ jets $H \to \gamma_d \gamma_d \to$ lepton jets ,...
  - No hints for a BSM Higgs is found yet: continue to restrict the parameter space of many BSM physics scenarios

Many thanks for your attention!!!

Extra Slides

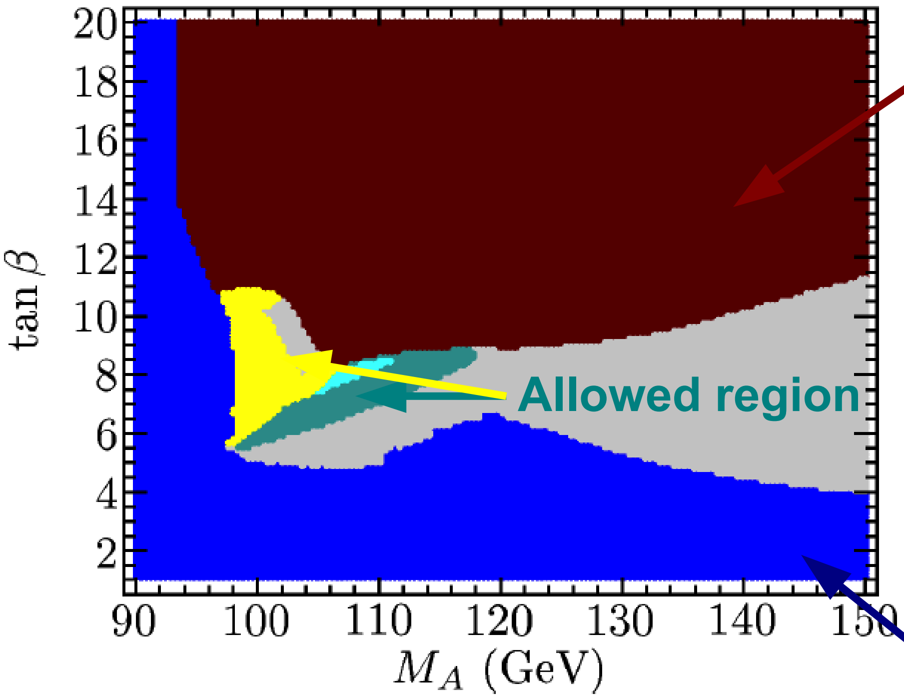
MSSM & SM-like Higgs @ 126 GeV

- MSSM is compatible with a SM-like Higgs boson at ~126 GeV

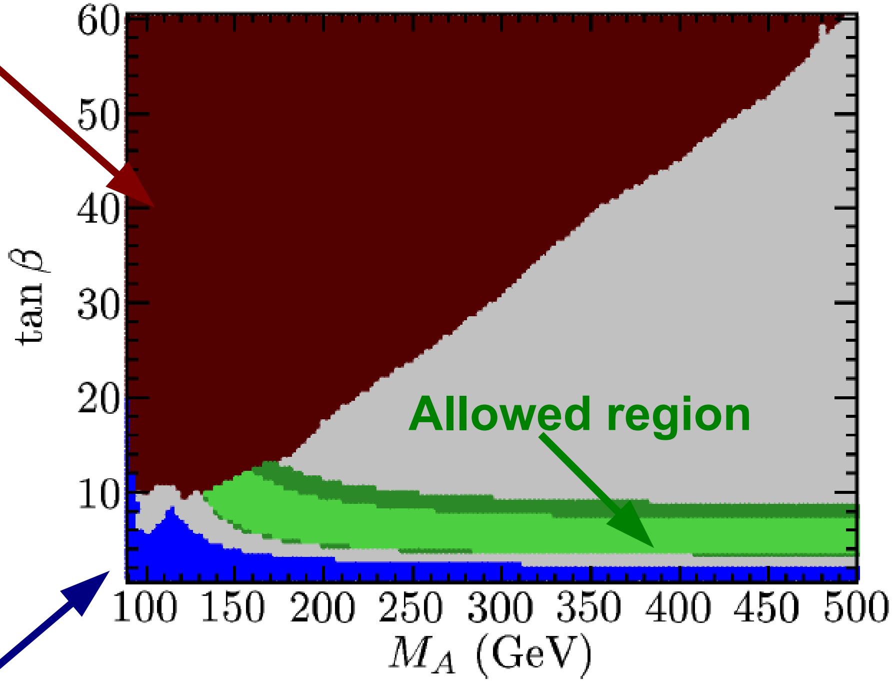
arXiv:1112.3026v3 [hep-ph]
Heinemeyer et al.

Excluded (LHC, Tevatron)

“m_h^{max}”, m(H) ~ 126 GeV



“m_h^{max}”, m(h) ~ 126 GeV



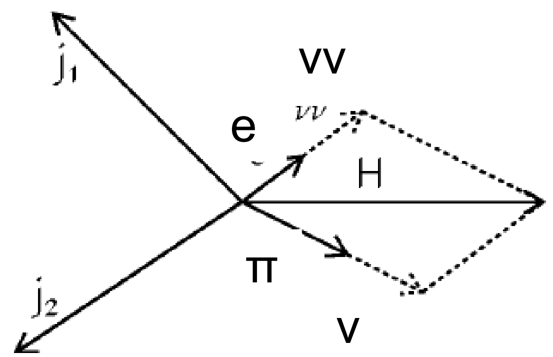
Excluded (LEP)

Missing Mass Calculator

- An extension of the collinear mass approximation
  - Collinear mass: assume that neutrinos are emitted in the same direction as the visible decay products

$$\not{E}_X = P_{\nu 1} \cdot \cos(\theta_1) \cdot \cos(\varphi_1) + P_{\nu 2} \cdot \cos(\theta_2) \cdot \cos(\varphi_2)$$

$$\not{E}_Y = P_{\nu 1} \cdot \cos(\theta_1) \cdot \sin(\varphi_1) + P_{\nu 2} \cdot \cos(\theta_2) \cdot \sin(\varphi_2)$$



  - Missing mass calculator:

→ Write the full equation system: more unknowns than equations

→ parameterise the 3D angle between visible and invisible tau decay products from MC simulation, dθ

→ solve the equation on a grid of the extra unknowns and calculate the most probable choice using the dθ distribution

$$E_x^{miss} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \cos\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \cos\phi_{\text{mis}_2}$$

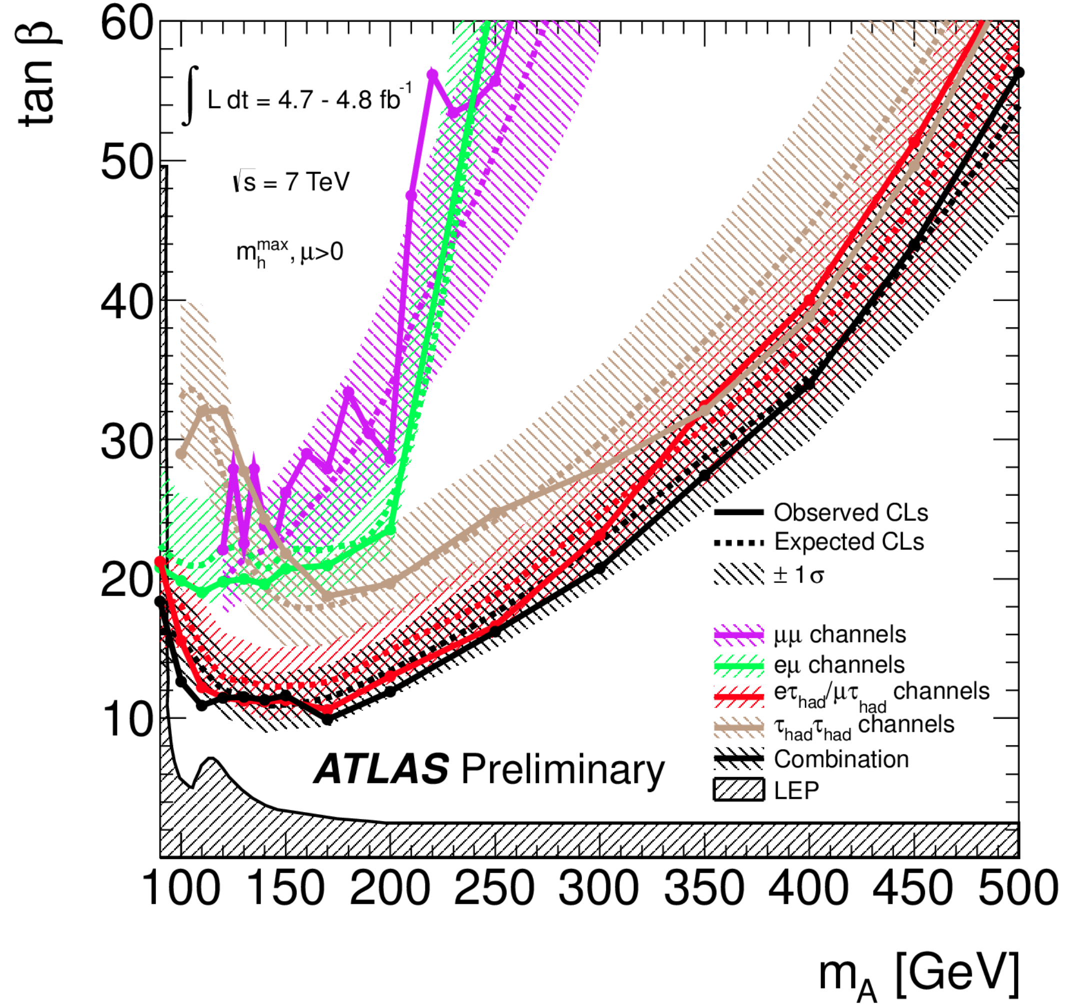
$$E_y^{miss} = p_{\text{mis}_1} \sin\theta_{\text{mis}_1} \sin\phi_{\text{mis}_1} + p_{\text{mis}_2} \sin\theta_{\text{mis}_2} \sin\phi_{\text{mis}_2}$$

$$M_{\tau_1}^2 = m_{\text{mis}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{mis}_1}^2 + m_{\text{mis}_1}^2} - 2 p_{\text{vis}_1} p_{\text{mis}_1} \cos\Delta\theta_{vm_1}$$

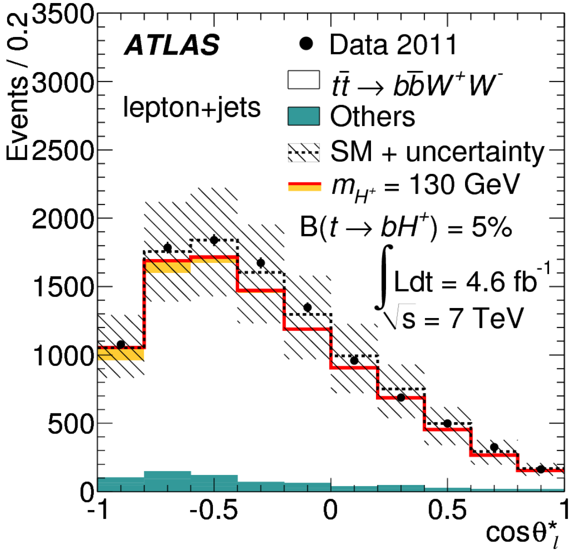
$$M_{\tau_2}^2 = m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2}\sqrt{p_{\text{mis}_2}^2 + m_{\text{mis}_2}^2} - 2 p_{\text{vis}_2} p_{\text{mis}_2} \cos\Delta\theta_{vm_2}$$

MSSM H → ττ/μμ

Individual channel contribution to the final limit

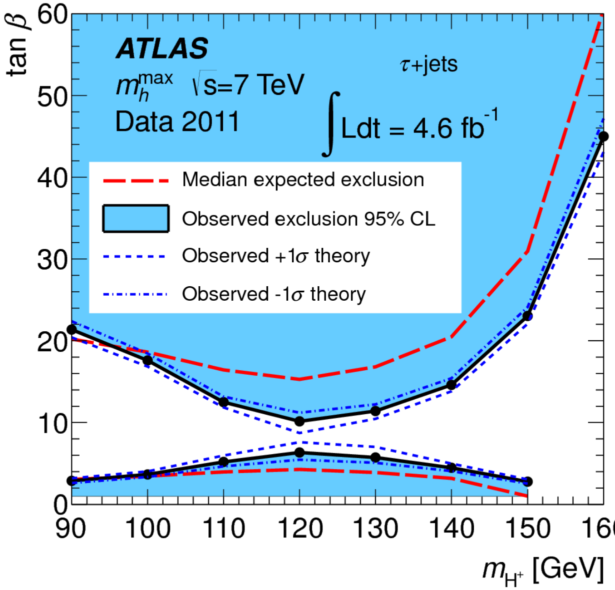


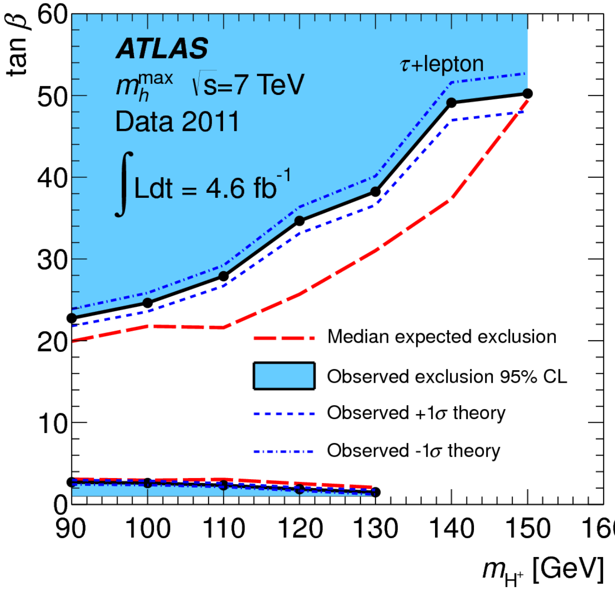
$H^{\pm} \rightarrow \tau^{\pm}\nu$

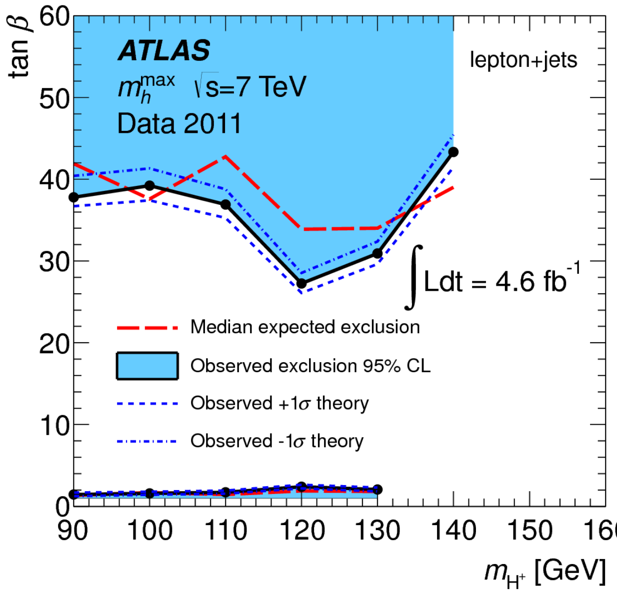


Extra plots for the Charged Higgs search

Individual channel contribution to the final limit



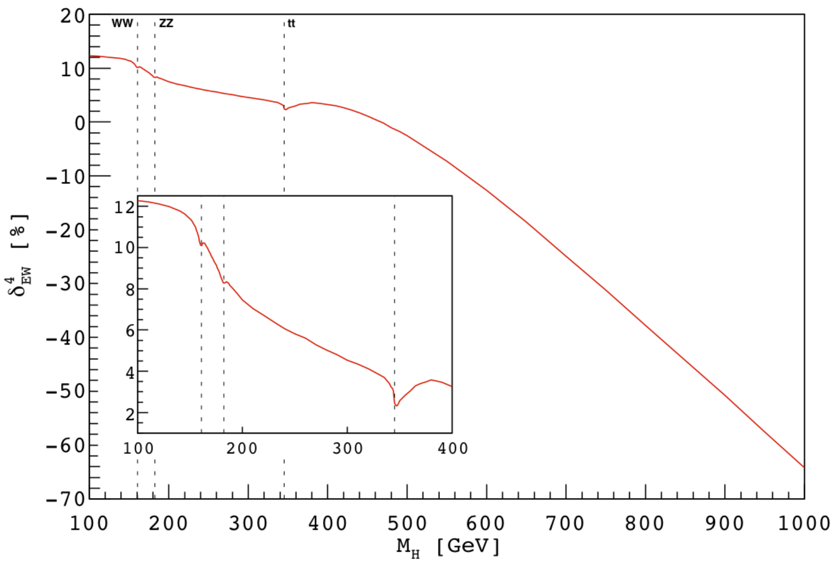




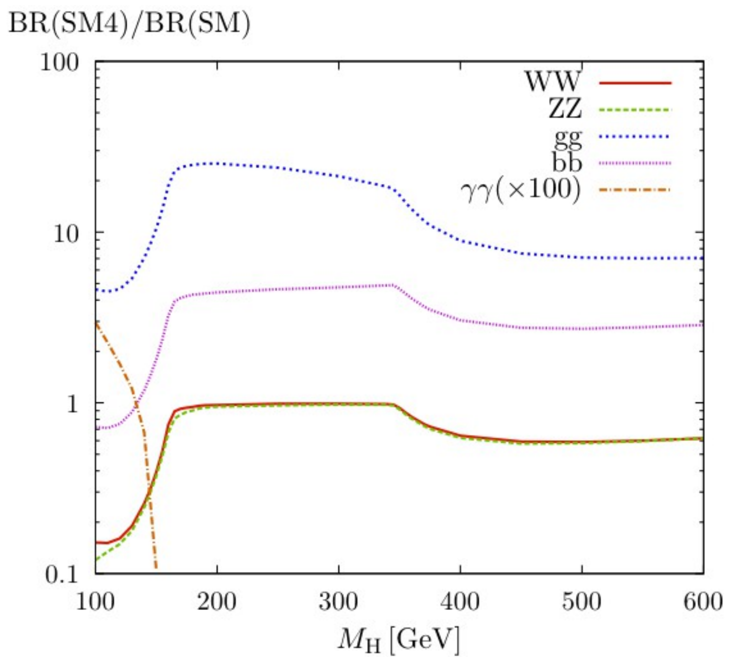
SM4

- 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



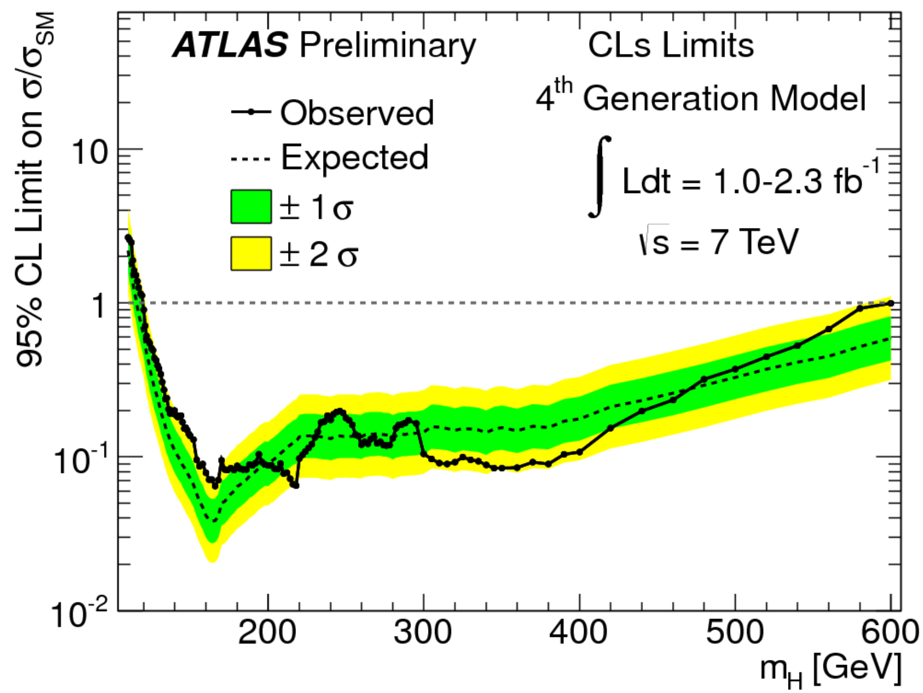
Ratio of BR in SM4/SM calculated with Prophecy4f and HDECAY

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

SM4

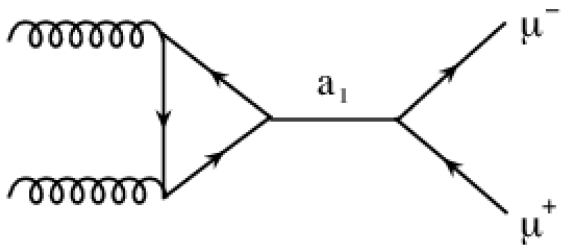
- The enhanced cross section relative to the SM allows an exclusion of large parts of the parameter space
  - Higgs mass range 119-600 GeV excluded

ATLAS-CONF-2011-135



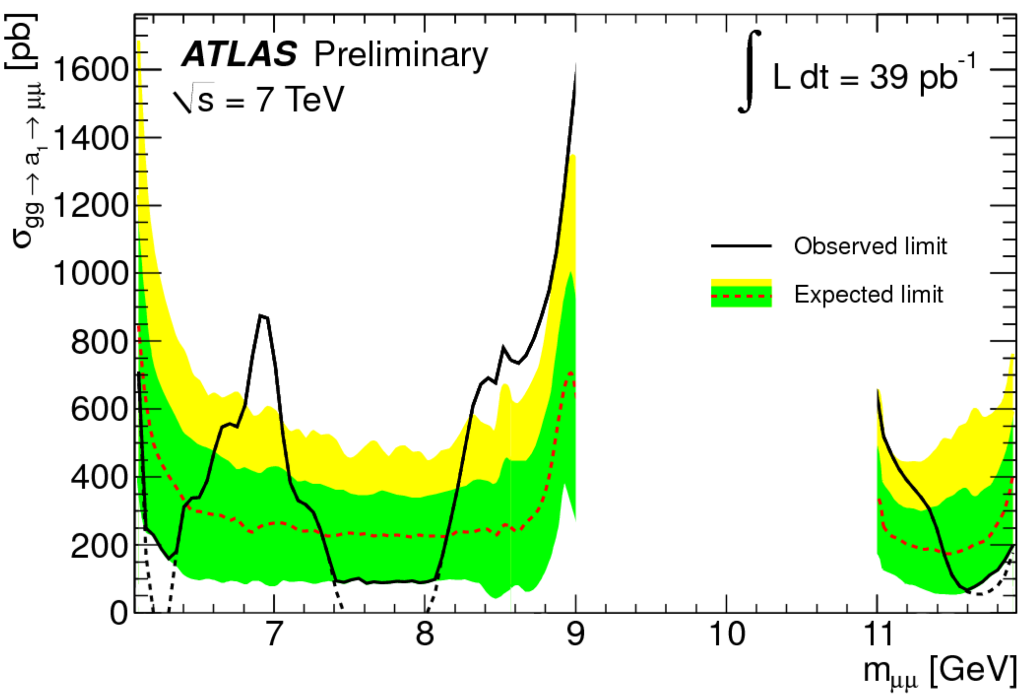
Light Scalar Field

- 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

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

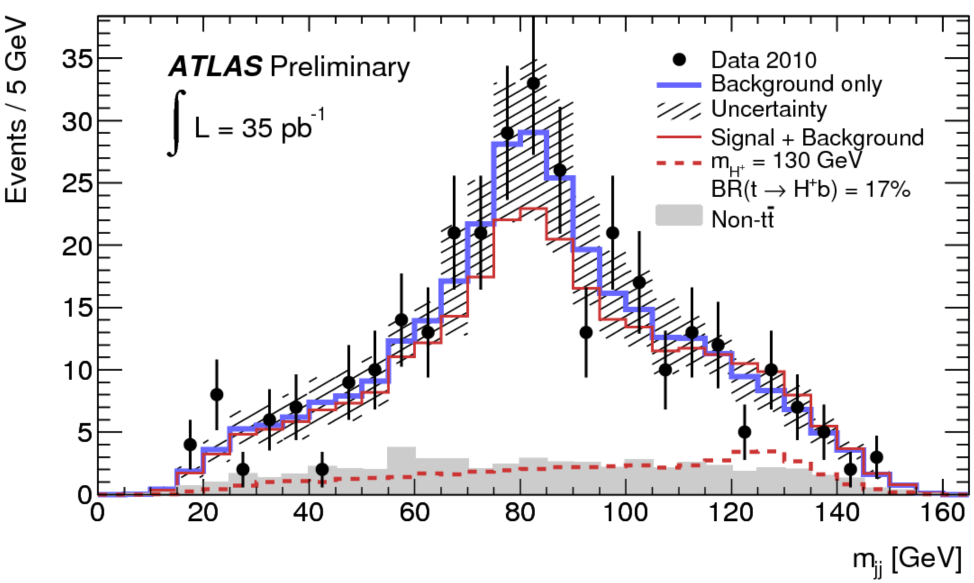


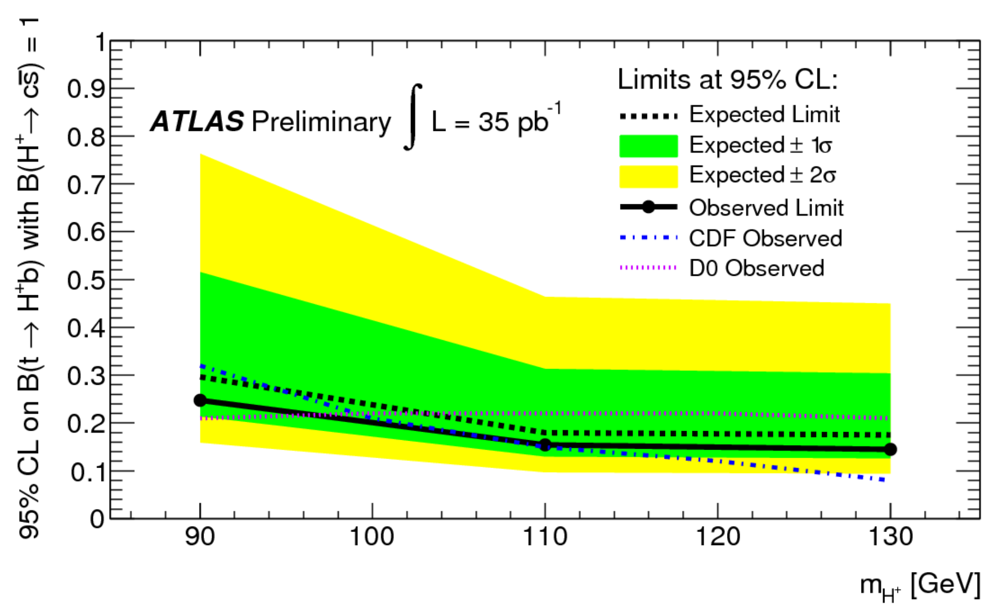
$H^+ \to c\bar{s}$

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

$tt \to bW\ bH^+ \to b\ (e/mu)\ v\ \ b\ cs$
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

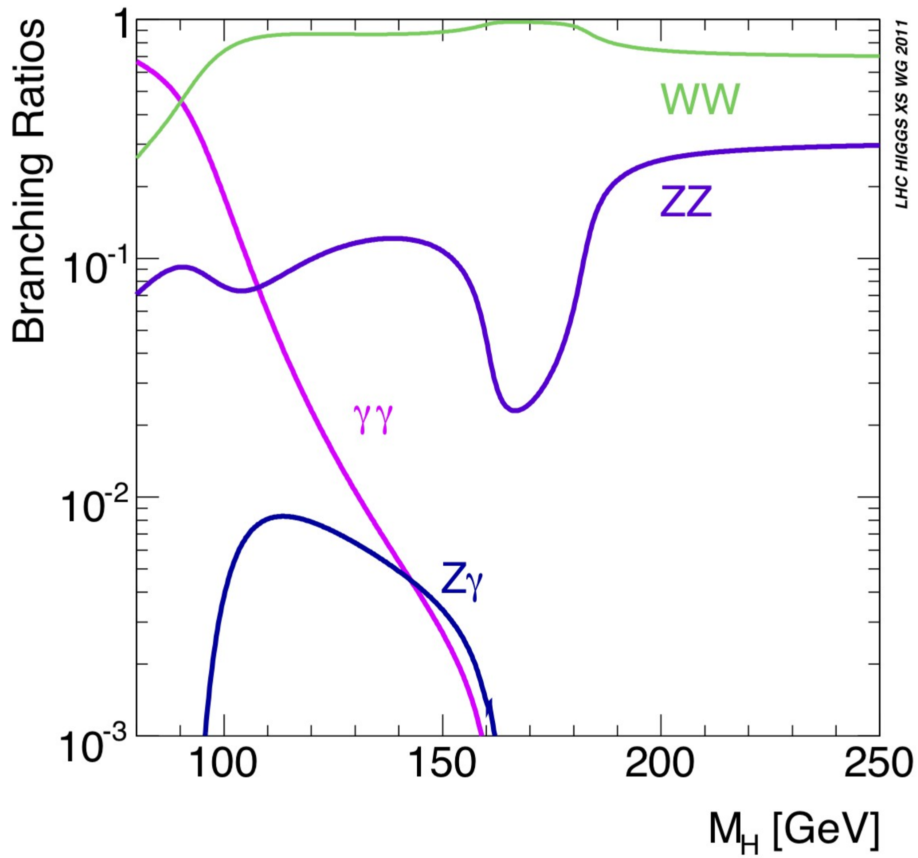
ATLAS-CONF-2011-094





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

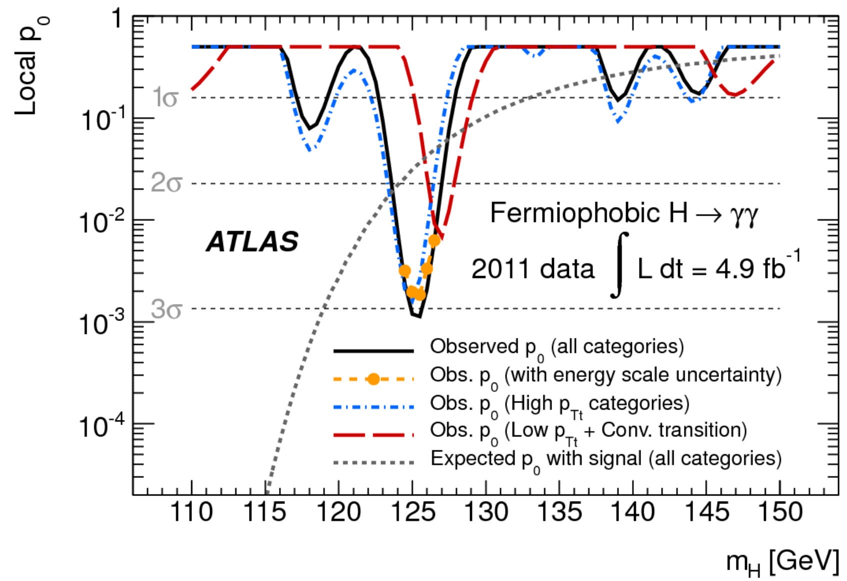


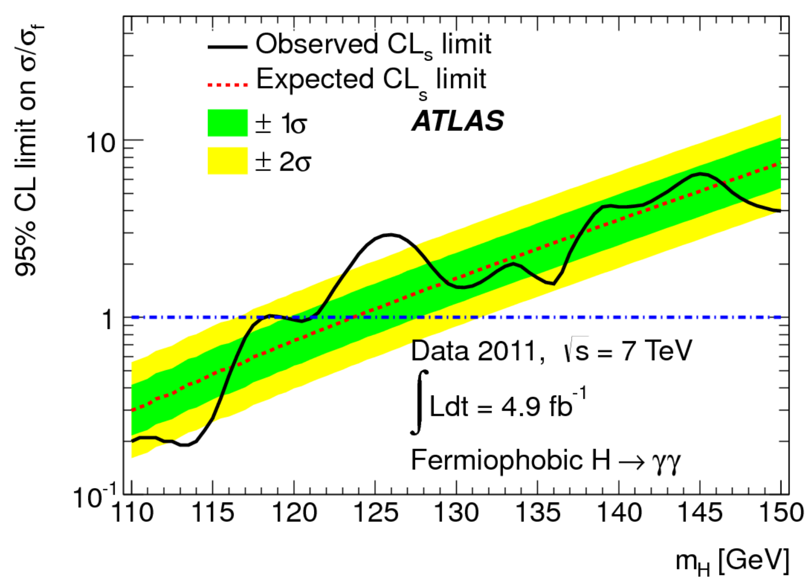
Fermiophobic Higgs Search

- Fermiophobic Higgs models modify SM Higgs couplings and affect Higgs production & decay
- ATLAS search follows the SM H → γγ 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

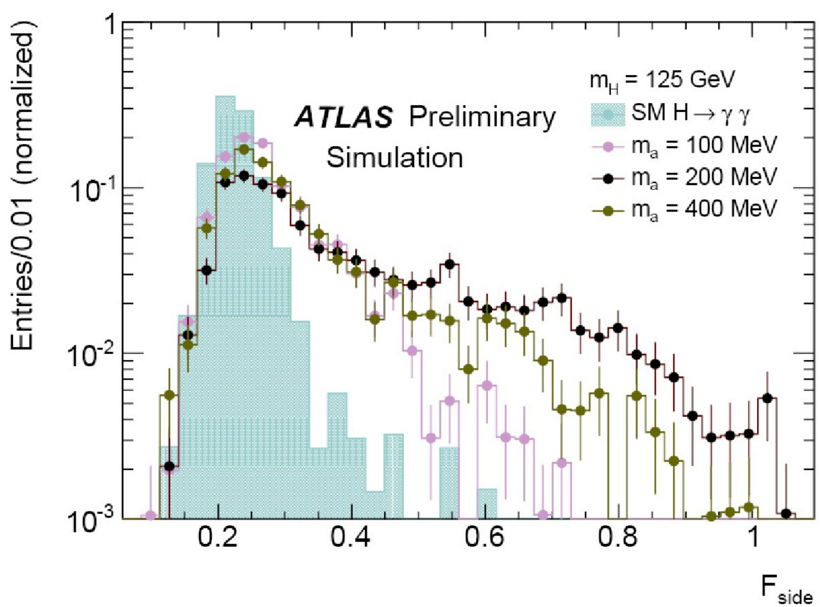




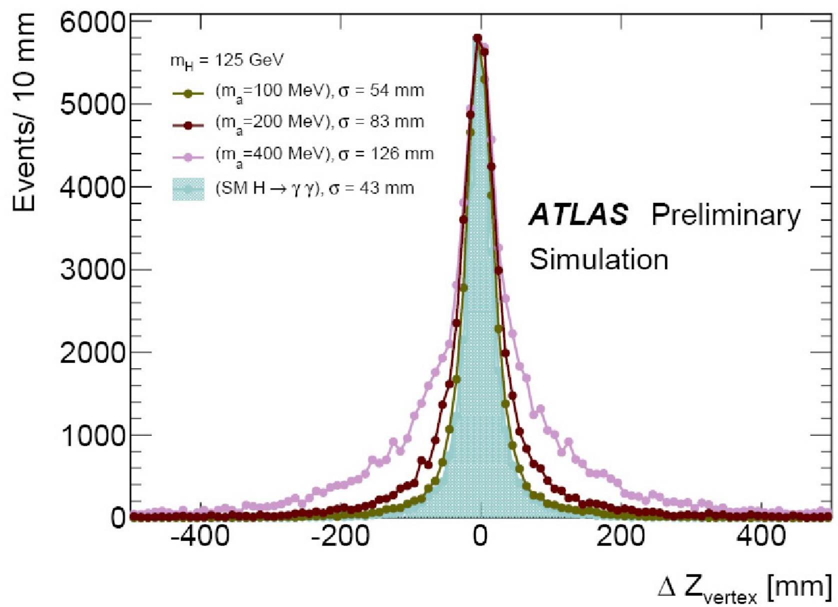
$H \to aa \to \gamma\gamma + \gamma\gamma$

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

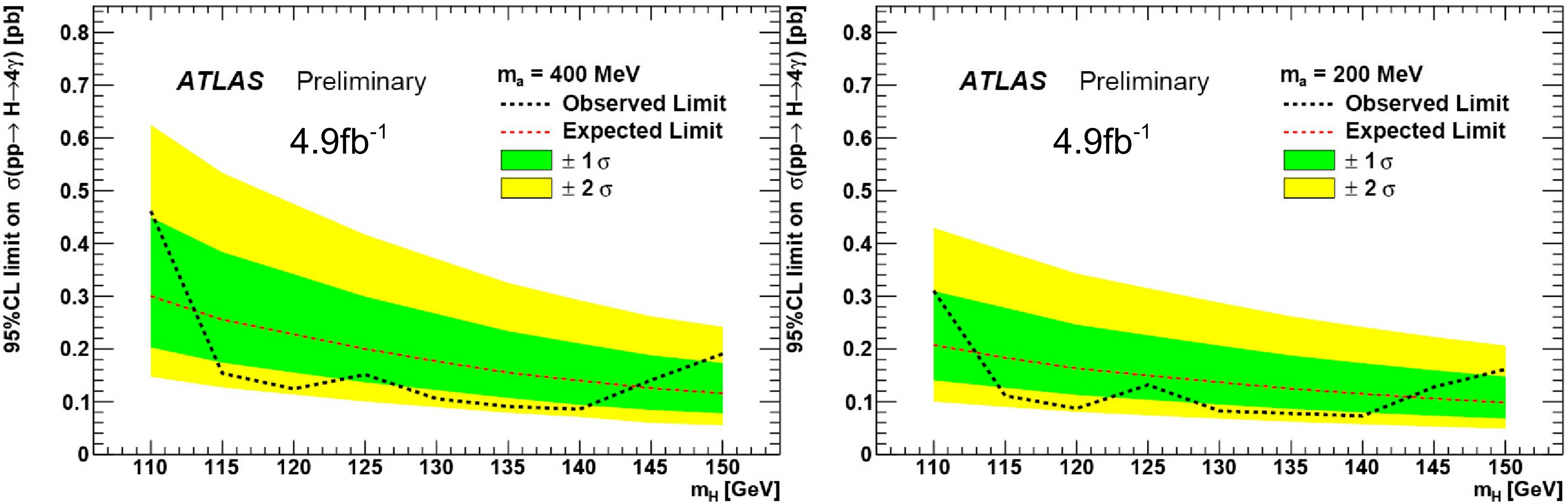


Photon pointing to vertex: z resolution

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

ATLAS-CONF-2012-079

- Limits for other m_a masses



$H^{\pm\pm}$ 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

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