MSSM HIGGS SEARCHES IN ATLAS

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(on behalf of the ATLAS Collaboration)

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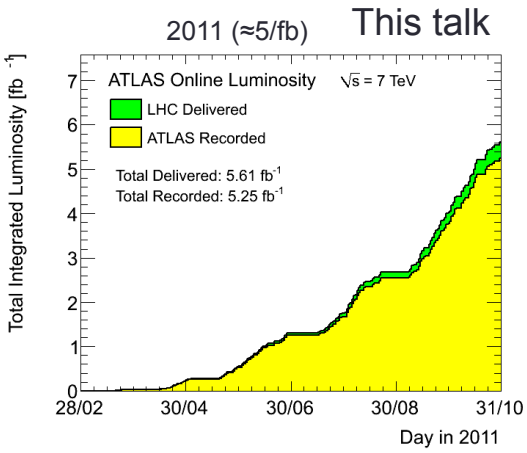
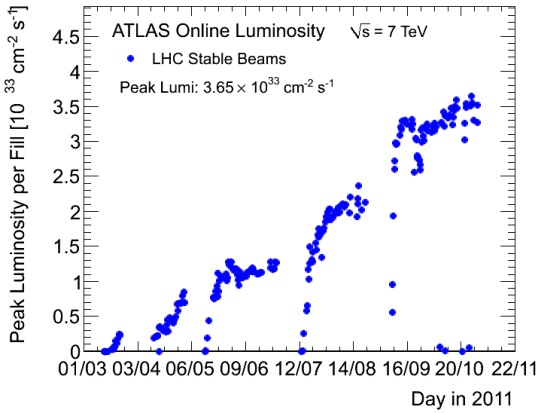
Summary



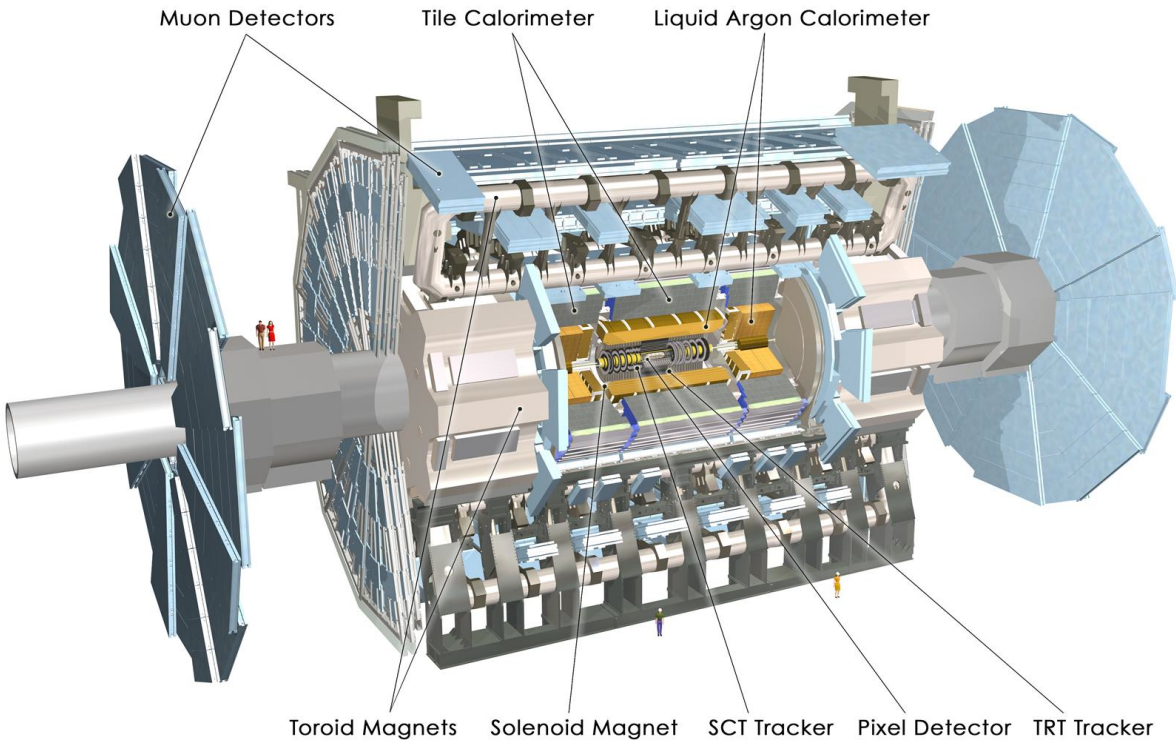


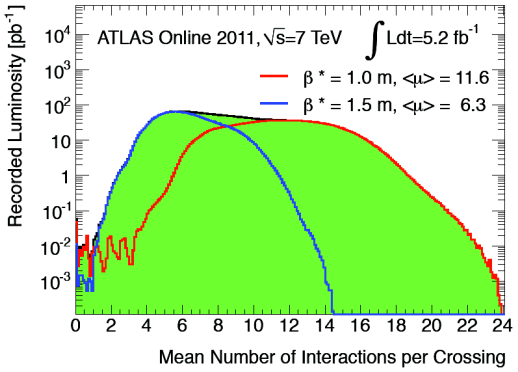
Inst. luminosity
0.4×10^{34} cm^{-2}s^{-1} (2011)

Luminosity weighted <μ>

Average interactions per bunch crossing

ATLAS



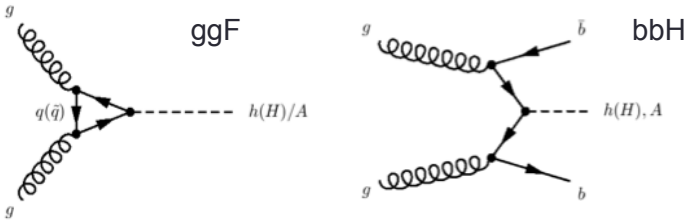


MSSM Higgs Sector

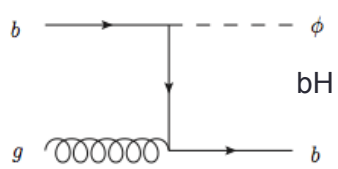
MSSM: simplest low energy SUSY model with rich and simple Higgs phenomenology

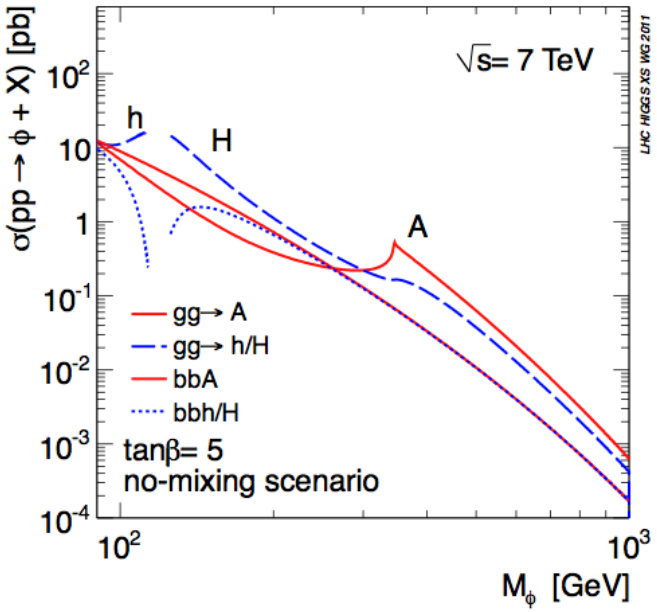
5 physical Higgs particles: A, h, H, H± → Only two parameters: $\tan\beta = v_u/v_d$ m_A

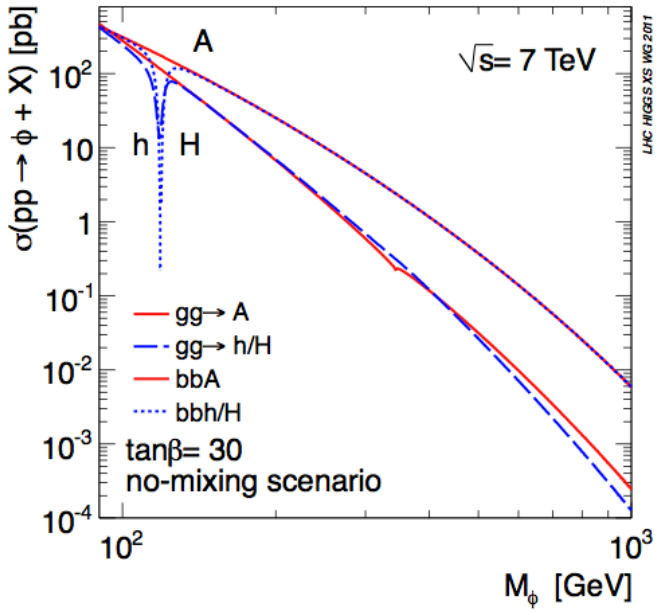
Dominant production modes for neutral MSSM Higgses



Charged MSSM Higgses searched through top quark pair production (see later)

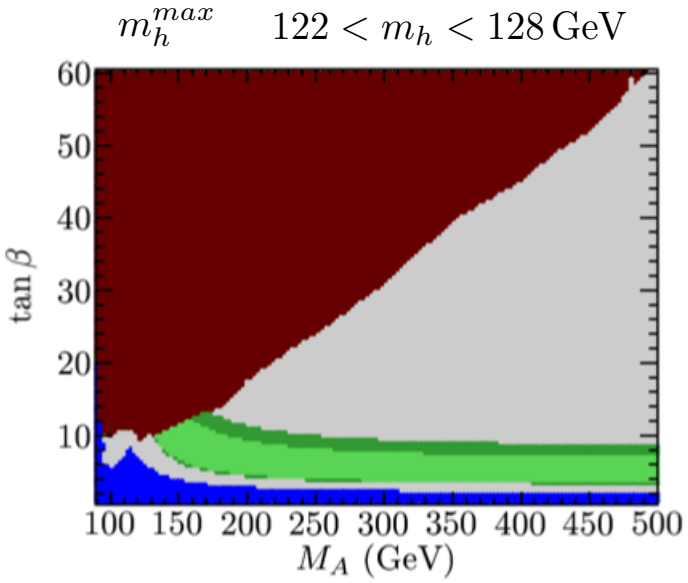




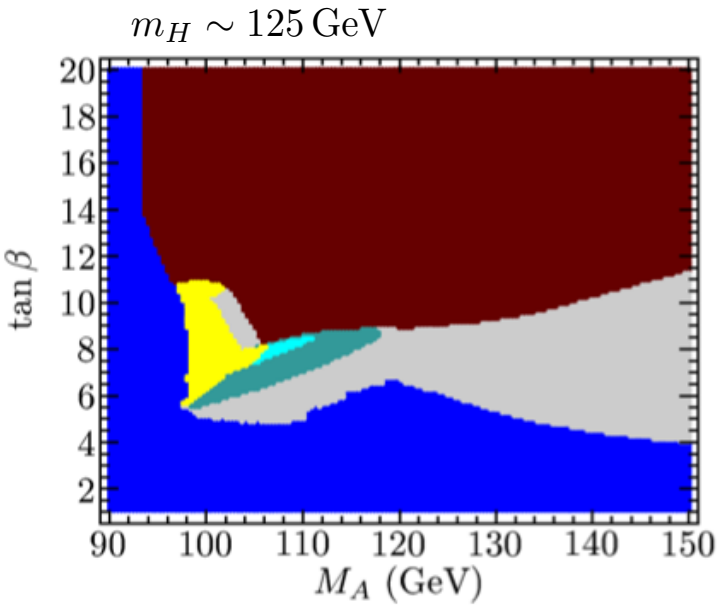


MSSM Higgs Sector

- A new SM-like state observed at 126 GeV
- …but still the MSSM may accommodate the new observed particle, either as h or H



Excluded by LEP
Excluded by Tevatron/LHC
Allowed before observation
Allowed after observation

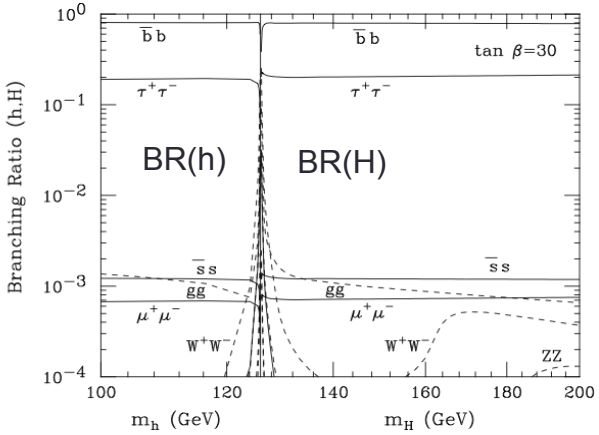


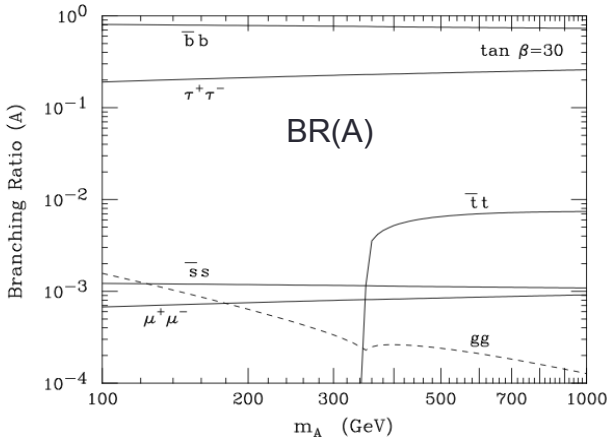
Allowed after observation
σ(H→γγ) 90% of SM

Heinemeyer et. al,
Phys. Lett. B710 (2012) 201

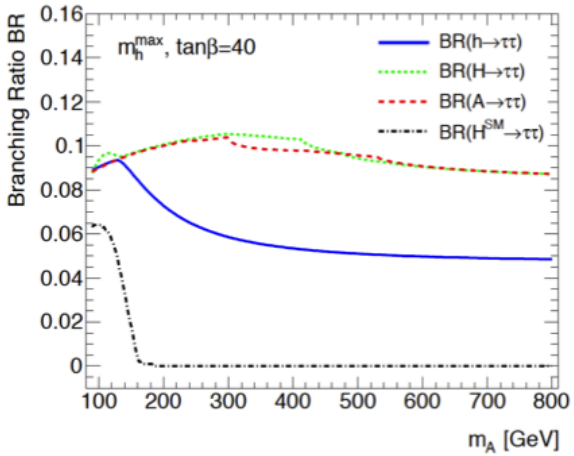
- The MSSM Higgs sector is not ruled out yet

Neutral Higgs Search Strategy





$BR(\phi \to \tau\tau)$

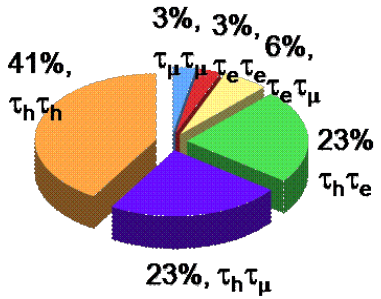


bb (≈90%) ττ (≈10%) μμ (≈0.04%) but clean signature → Over a large fraction of parameter space

- Four different decay modes (OS tau pairs)
- Use final states with and without b-jets (to cover different production modes)
- Similar event selection and strategy as SM search

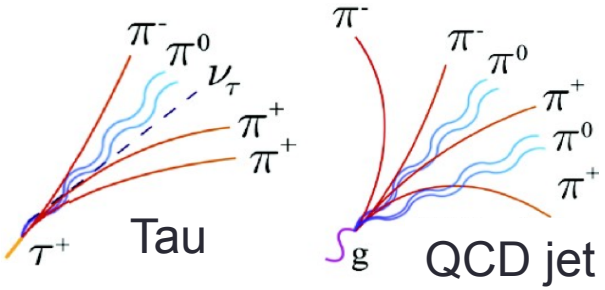
$\tau_e\tau_\mu$ $\tau_\mu\tau_h$ $\tau_e\tau_h$ $\tau_h\tau_h$

(ll) (lh) (hh)

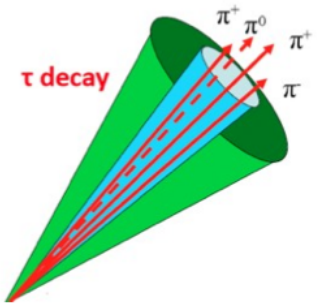


Tau Reconstruction & ID in ATLAS

Tau jet reconstruction



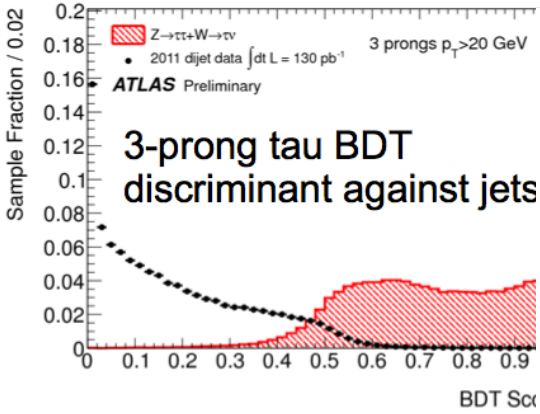
Seed from aK$_T$ jets in calorimeter (ΔR=0.
Associated tracks in ΔR=0.2 of jet axis



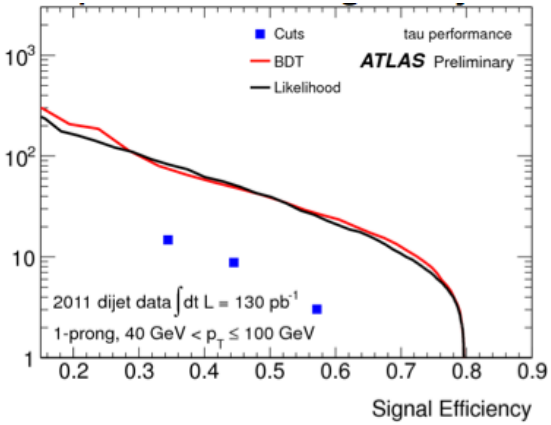
Use MVA BDTs and likelihoods using:
low track multiplicities,
isolation, shower shapes (collimation),
EM/HAD fractions and angular separic

- Discriminate against QCD jets
- Electron/Tau separation

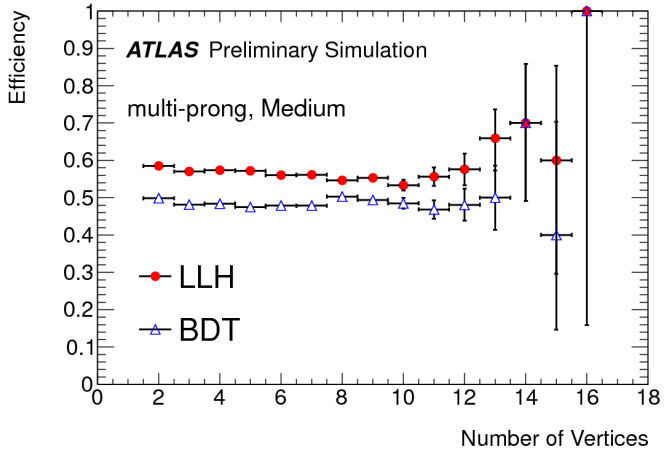
Tau jet identification



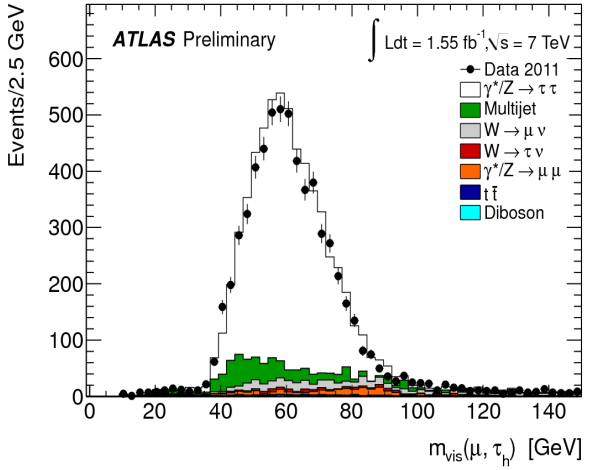
1-prong tau-ID performance against jets



Tau jet ID efficiencies



Tau jets in DATA

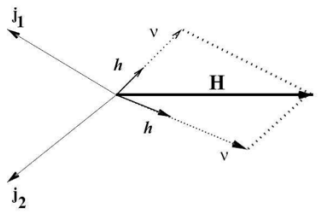


Tau-Tau Invariant Mass Reconstruction

Effective (visible or transverse) mass

$$m_{\tau\tau} = \sqrt{(p_{\mathrm{vis}_1} + p_{\mathrm{vis}_2} + p_{\mathrm{mis}})^2}$$
$$p_{\mathrm{mis}} = (E_T^{\mathrm{mis}}, E_{T_x}^{\mathrm{mis}}, E_{T_y}^{\mathrm{mis}}, 0)$$

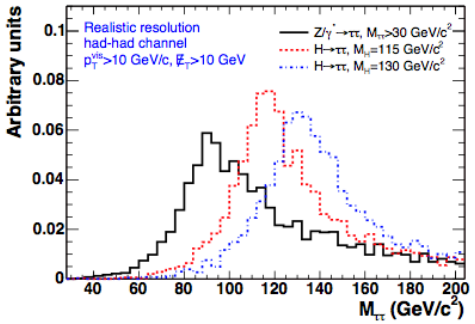
Collinear approximation



$$m_{\tau\tau} = \frac{m_{\mathrm{vis}}}{(x_1 x_2)^{1/2}}$$
$$x_{1,2} = \frac{p_{\mathrm{vis}_{1,2}}}{p_{\mathrm{vis}_{1,2}} + p_{\mathrm{mis}_{1,2}}}$$

$$\not{E}_{T_x} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{vis}_1} \cos\phi_{\mathrm{vis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{vis}_2} \cos\phi_{\mathrm{vis}_2}$$
$$\not{E}_{T_y} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{vis}_1} \sin\phi_{\mathrm{vis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{vis}_2} \sin\phi_{\mathrm{vis}_2}$$

Collinear



MMC (Missing Mass Calculator)

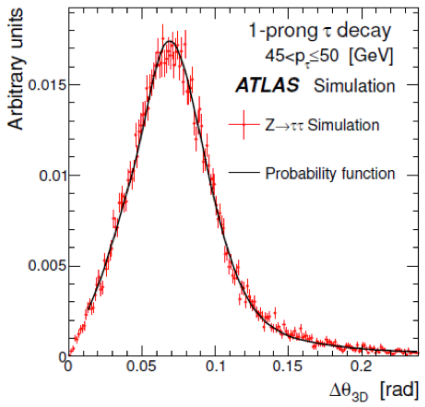
Event by event Mττ
scanning over ν directions according to MC PDFs

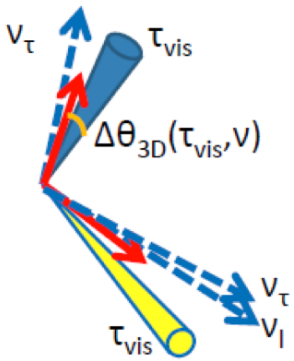
$$\not{E}_{T_x} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{mis}_1} \cos\phi_{\mathrm{mis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{mis}_2} \cos\phi_{\mathrm{mis}_2}$$

$$\not{E}_{T_y} = p_{\mathrm{mis}_1} \sin\theta_{\mathrm{mis}_1} \sin\phi_{\mathrm{mis}_1} + p_{\mathrm{mis}_2} \sin\theta_{\mathrm{mis}_2} \sin\phi_{\mathrm{mis}_2}$$

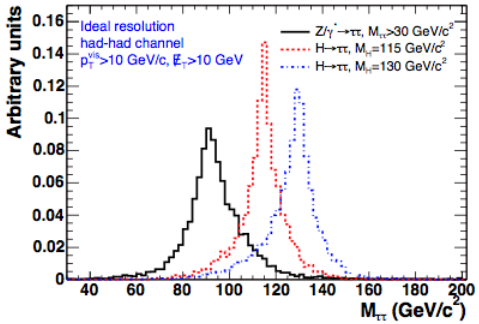
$$M_{\tau_1}^2 = m_{\mathrm{mis}_1}^2 + m_{\mathrm{vis}_1}^2 + 2\sqrt{p_{\mathrm{vis}_1}^2 + m_{\mathrm{vis}_1}^2}\sqrt{p_{\mathrm{mis}_1}^2 + m_{\mathrm{mis}_1}^2} - 2p_{\mathrm{vis}_1} p_{\mathrm{mis}_1} \cos\Delta\theta_{\nu m_1}$$

$$M_{\tau_2}^2 = m_{\mathrm{mis}_2}^2 + m_{\mathrm{vis}_2}^2 + 2\sqrt{p_{\mathrm{vis}_2}^2 + m_{\mathrm{vis}_2}^2}\sqrt{p_{\mathrm{mis}_2}^2 + m_{\mathrm{mis}_2}^2} - 2p_{\mathrm{vis}_2} p_{\mathrm{mis}_2} \cos\Delta\theta_{\nu m_2}$$





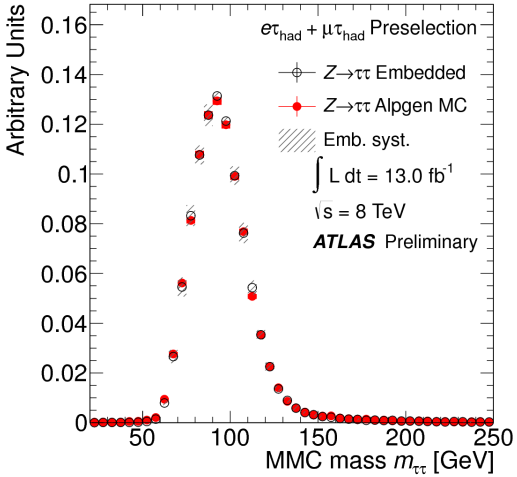
MMC



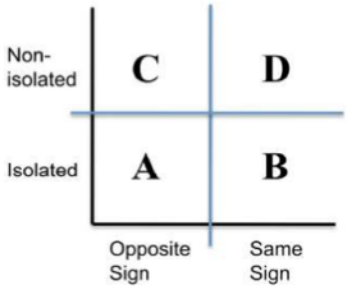
A. Elagin et. al, NIM A 654 (2011) 481

Higgs to TauTau Backgrounds

- Z/γ*→ττ background estimated from data (all channels)
  - Select Z/γ*→μμ and replace the muon response with a tau response from MC
  - Apply selection to the embedded sample
  - Check agreement with Z/γ*→ττ simulation

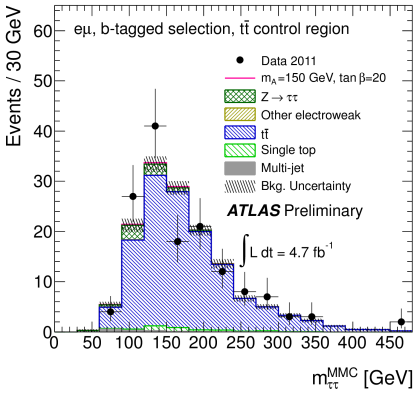


- QCD multijet backgrounds estimated from data (all channels)
  - Data-driven with ABCD method
  - eμ and lh channels: use SS/OS & lepton isolation
  - hh channel: use SS/OS & tau ID severity



$$n_A = n_B \times \frac{n_C}{n_D}$$

- Other backgrounds
  - Top (b-tag samples) from data CR
    - ll and lh channels
  - W+jets also from data CR
    - lh channel



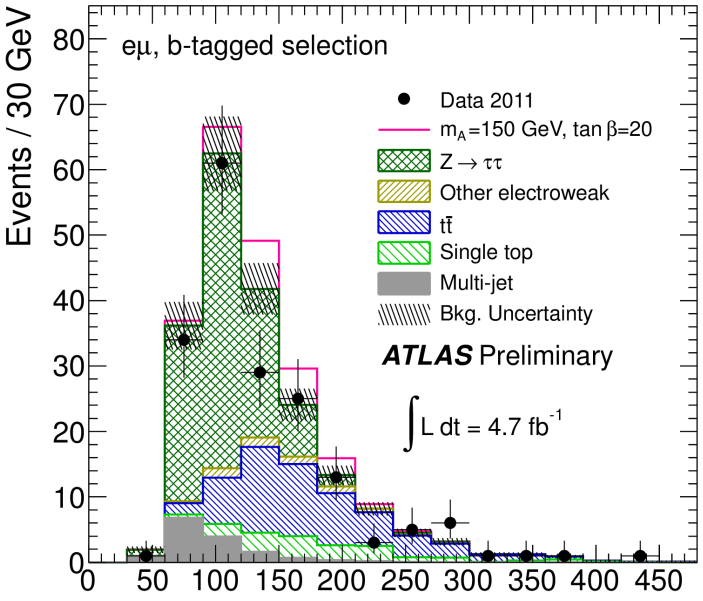
CR (eμ sample, b-tagged): No HT cut, 2 b-tagged jets

$$n_{\text{top}}^{SR} = \alpha_{\text{top}} n_{\text{top}}^{CR}$$

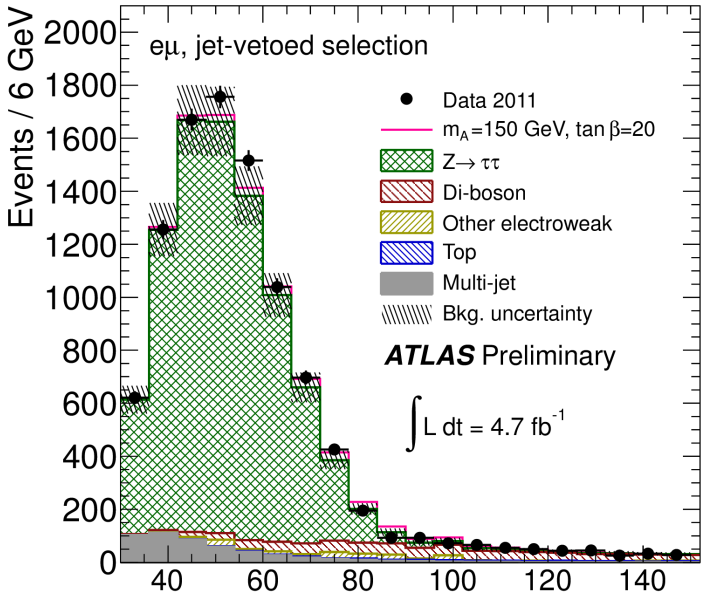
from MC

$H \to \tau^+\tau^-$: Mass Distributions

$H \to \tau_e \tau_\mu$



b-tagged sample



jet-vetoed sample

common: { Exactly two OS leptons (e and μ)
$\Delta\phi(e,\mu) > 2$ $\quad m_{e\mu} > 30\,\mathrm{GeV}$

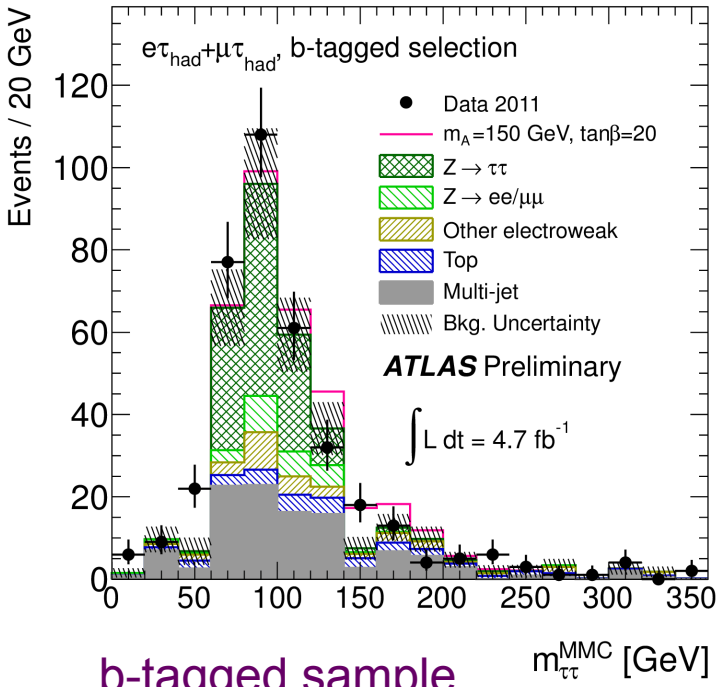
No jets

Only 1 b-tagged jet

$$H_T = \sum_j E_T(j) < 100\,\mathrm{GeV}$$

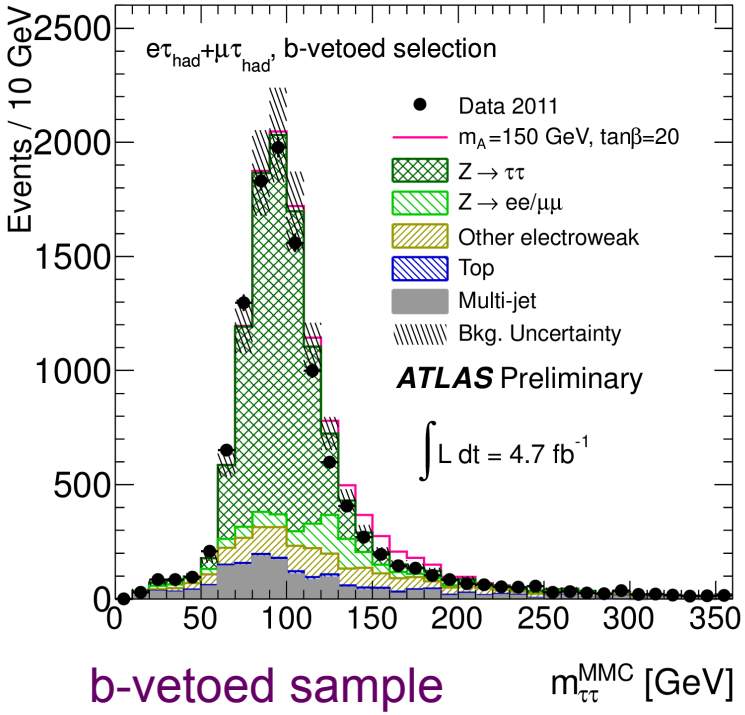
$H\to\tau^+\tau^-$: Mass Distributions

$H\to\tau_{e,\mu}\tau_h$



b-tagged sample

Only 1 b-tagged jet



b-vetoed sample

Leading jet NOT b-tagged

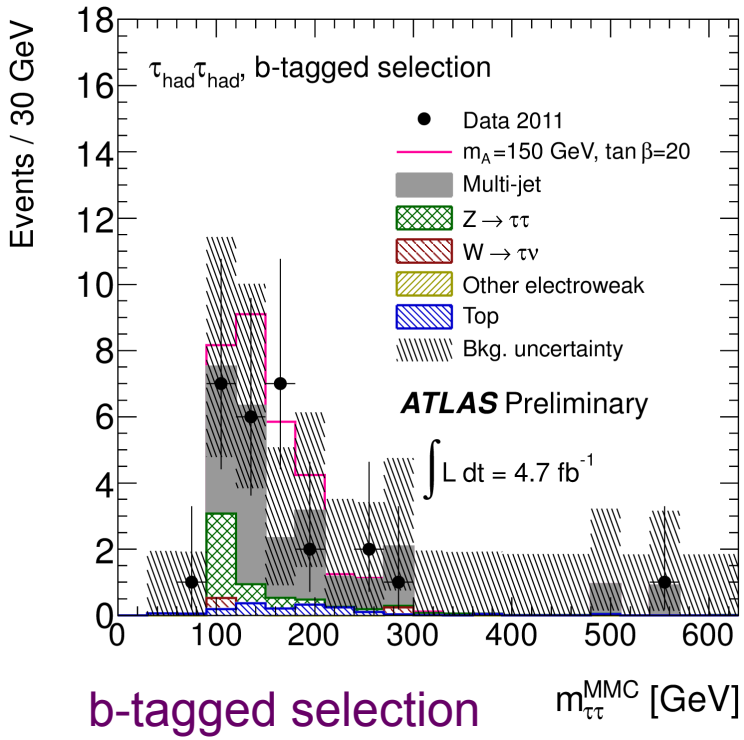
$E_T^{\mathrm{miss}} > 20\,\mathrm{GeV}$

common: Two OS leptons (e or μ) and hadronic tau

$m_T(l, E_T^{\mathrm{miss}}) < 30\,\mathrm{GeV}$

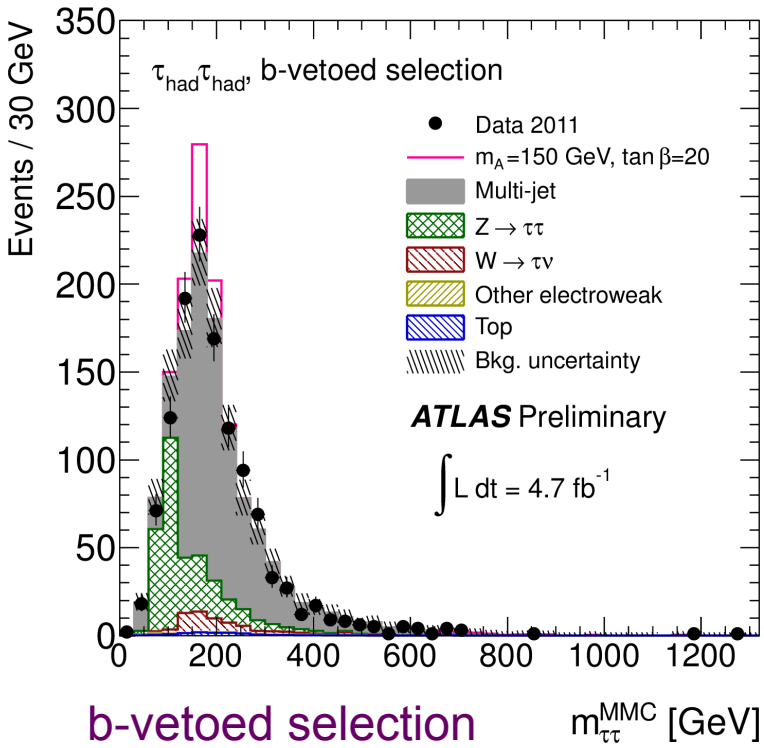
$H\to\tau^+\tau^-$: Mass Distributions

$H\to\tau_h\tau_h$



b-tagged selection

Only 1 b-tagged jet



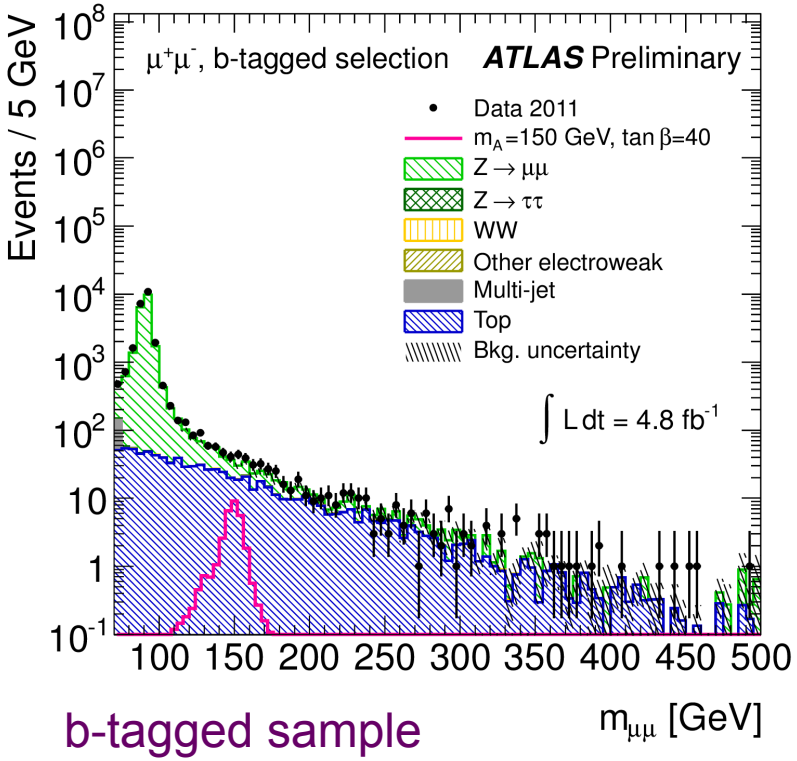
b-vetoed selection

Leading jet NOT b-tagged

common: { Two OS hadronic taus; $E_T^{\text{miss}} > 25\,\text{GeV}$

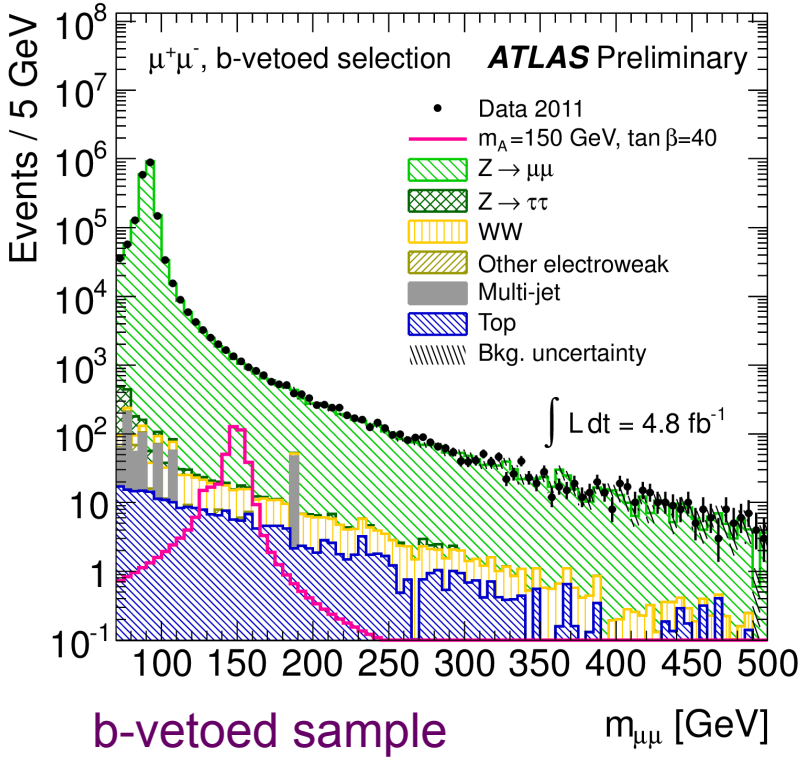
H→μ⁺μ⁻: Mass Distributions

H→μμ



b-tagged sample

≥ 1 b-tagged jet



b-vetoed sample

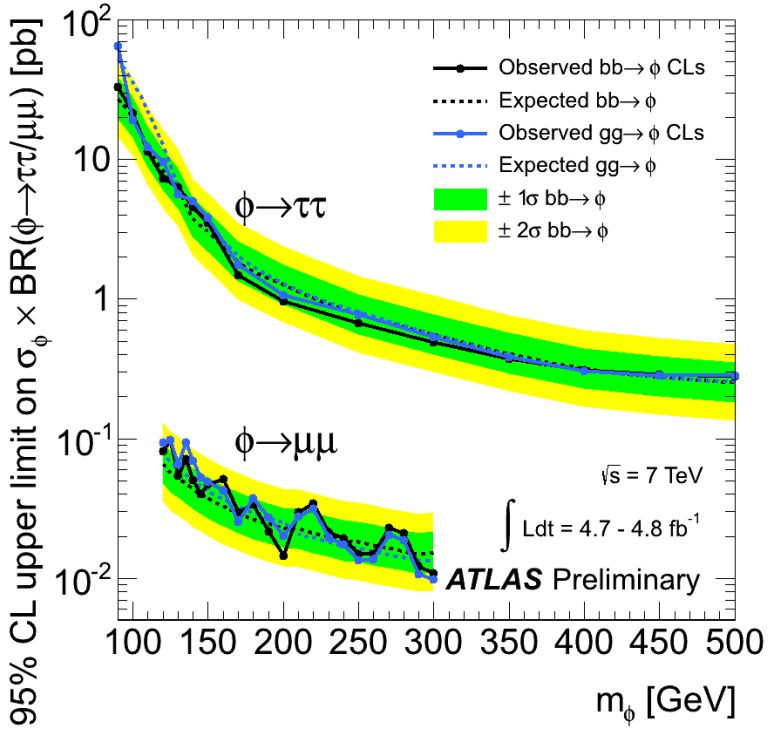
No b-tagged jets

common:
- Two OS muons
- $m_{\mu\mu} > 70\,\mathrm{GeV}$
- $E_T^{\mathrm{miss}} < 40\,\mathrm{GeV}$

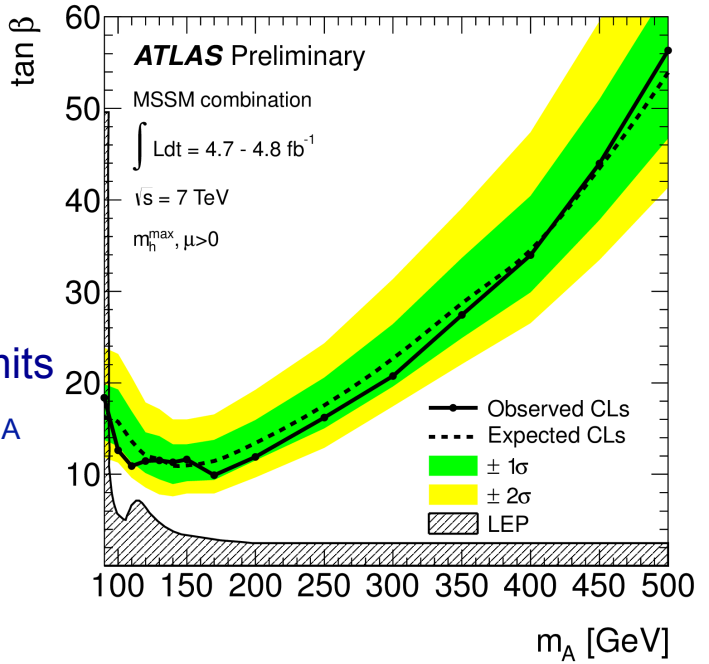
Main backgrounds:
- $Z/\gamma^* \to \mu^+\mu^-$
- Top

H→μ⁺μ⁻,τ⁺τ⁻: Results

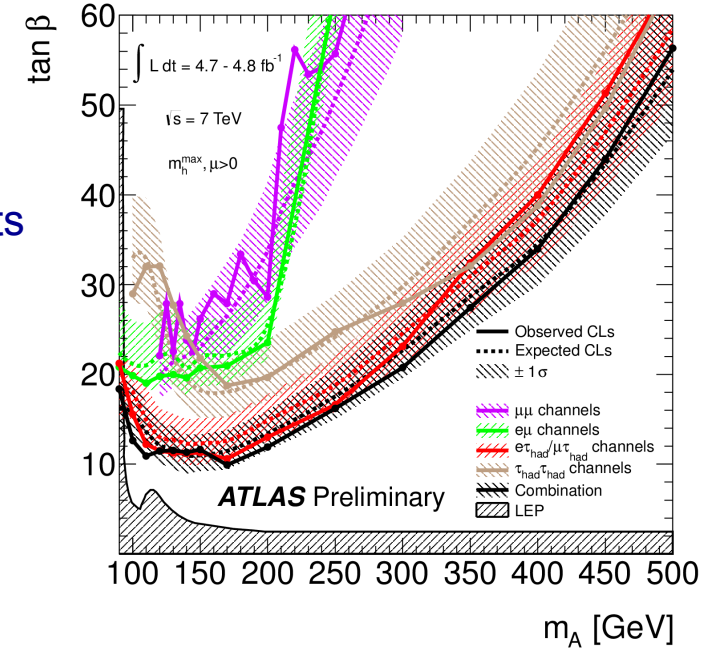
H to μμ, ττ combination results
for the 95% CL limits on σ(φ)×BR(φ→ττ)



Combined limits on tanβ - m_A



Individual limits on tanβ - m_A

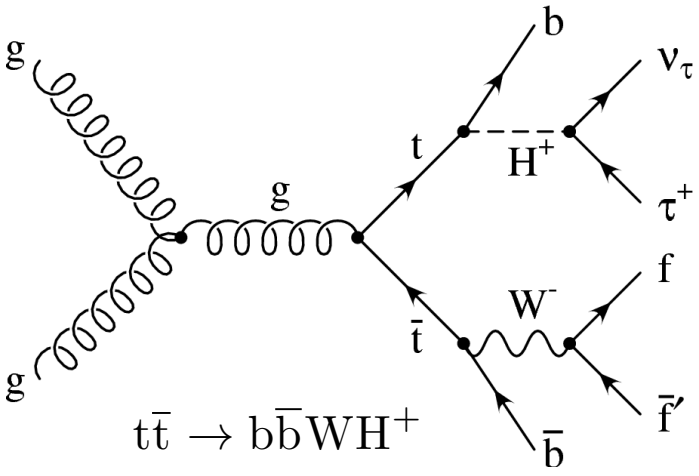


Charged MSSM Higgs

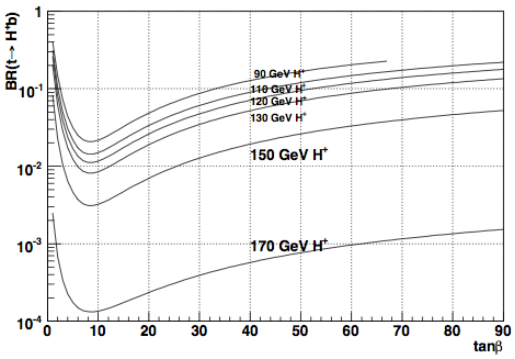
$t \to H^+ b$

$t \to Wb$

competing modes

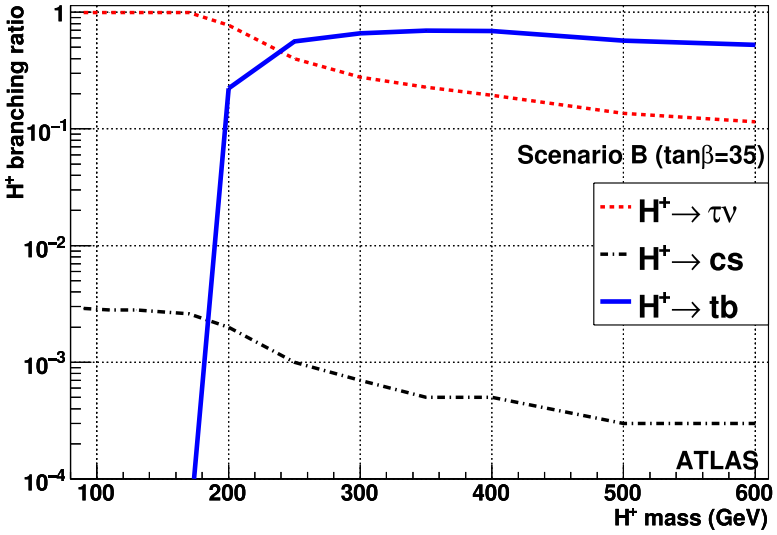


$BR(t \to H^+ b) = f(\tan\beta, m_{H^+})$



$m_{H^+} \lesssim m_t$

$BR(H^+ \to \tau\nu, cs, tb)$



Three different channels with top-pairs

$t\bar{t} \to b\bar{b}WH^+ \to b\bar{b}(q\bar{q}')(\tau_{lep}\nu)$ → Lepton+jets selection

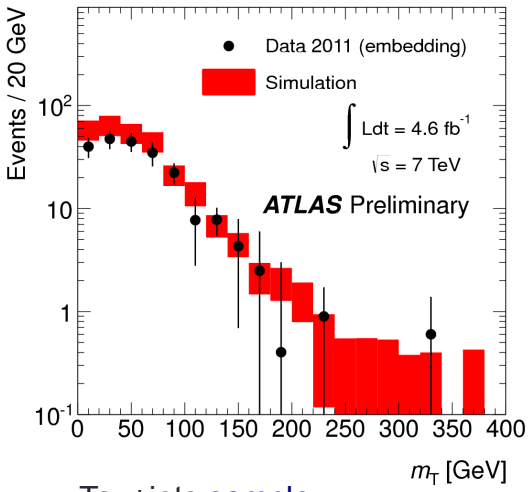
$t\bar{t} \to b\bar{b}WH^+ \to b\bar{b}(l\nu)(\tau_{had}\nu)$ → Tau+leptons selection

$t\bar{t} \to b\bar{b}WH^+ \to b\bar{b}(q\bar{q}')(\tau_{had}\nu)$ → Tau+jet selection

$m_{H^+} \lesssim m_t$ { $H^+ \to \tau\nu$ dominant; $H^+ \to c\bar{s}$

Charged MSSM Higgs Backgrounds

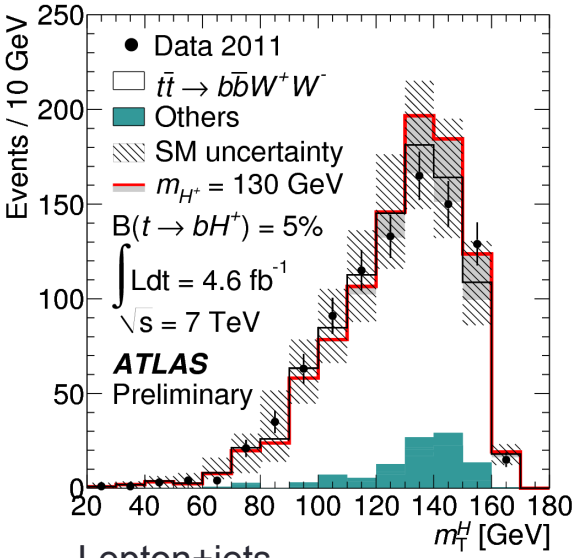
- Misidentified leptons (data driven)
  - Present in the lepton+jets and tau+lepton samples
  - Jets misidentified as isolated leptons
- Electrons and jets misidentified as tau(had) (data driven)
  - Present in the tau+lepton and tau+jets samples
- Backgrounds with true tau(had) (data driven)
  - Present in the tau+lepton and tau+jets sample
  - Select a CR with μ+jets and replace the muon response with a tau response from MC
  - Apply selection to the embedded sample
  - Check agreement with simulation
- Multijet background
  - Present in the tau+jets sample
  - Estimated from mE_T in CR



Tau+jets sample

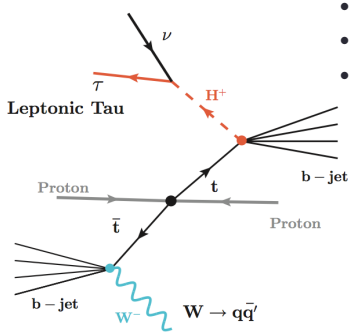
$H^+ \to \tau\nu$

Charged MSSM Higgs Search Strategies



Lepton+jets

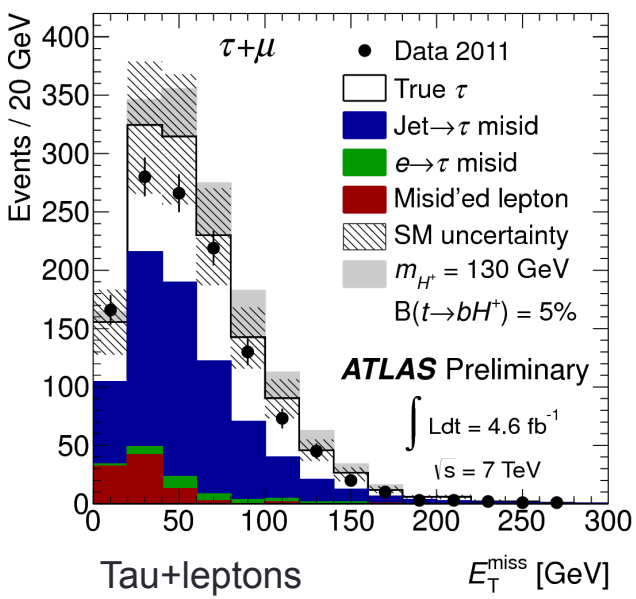
- 1 lepton
- 4 jets (2 b-tagged)
- $E_T^{\text{miss}} > 40\,\text{GeV}$
- Topological cuts



Discriminating variables

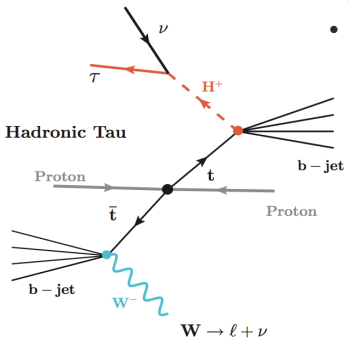
$$(m_T^H)^2 = \left(\sqrt{m_{\text{top}}^2 + (\vec{p}_T{}^l + \vec{p}_T{}^b + \vec{p}_T{}^{\text{miss}})^2} - p_T^b\right)^2 - \left(\vec{p}_T{}^l + \vec{p}_T{}^{\text{miss}}\right)^2$$

$$\cos\theta_l^*$$



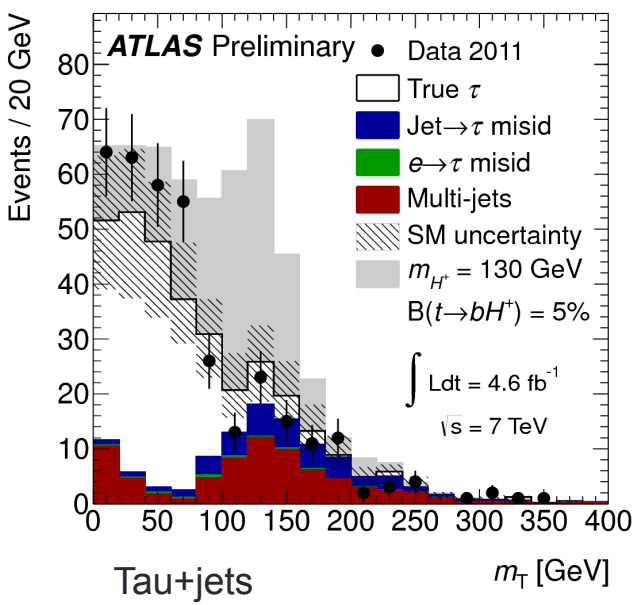
Tau+leptons

- 1 lepton + 1 tau (OS)
- ≥ 2 jets (≥ 1 b-tagged)
- $\sum p_T > 100\,\text{GeV}$



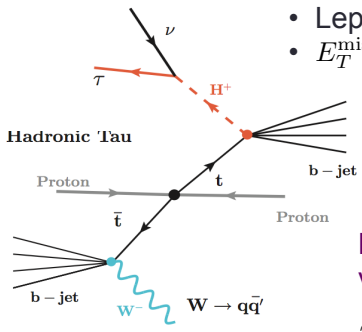
Discriminating variable

E_T^{miss}



Tau+jets

- 1 tau
- ≥ 4 jets (≥ 1 b-tagged)
- Lepton veto
- $E_T^{\text{miss}} > 65\,\text{GeV}$

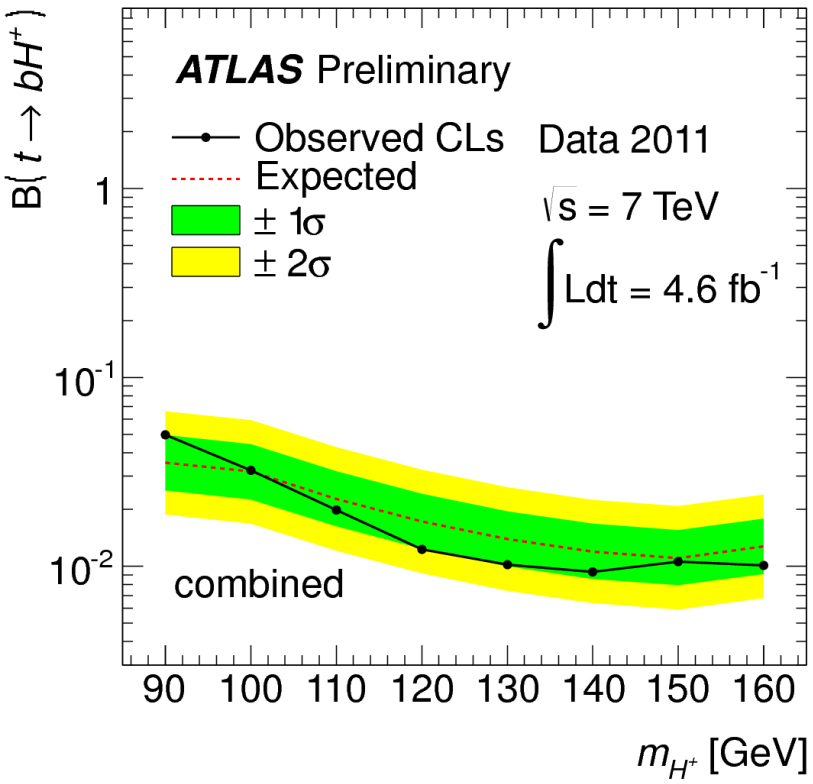


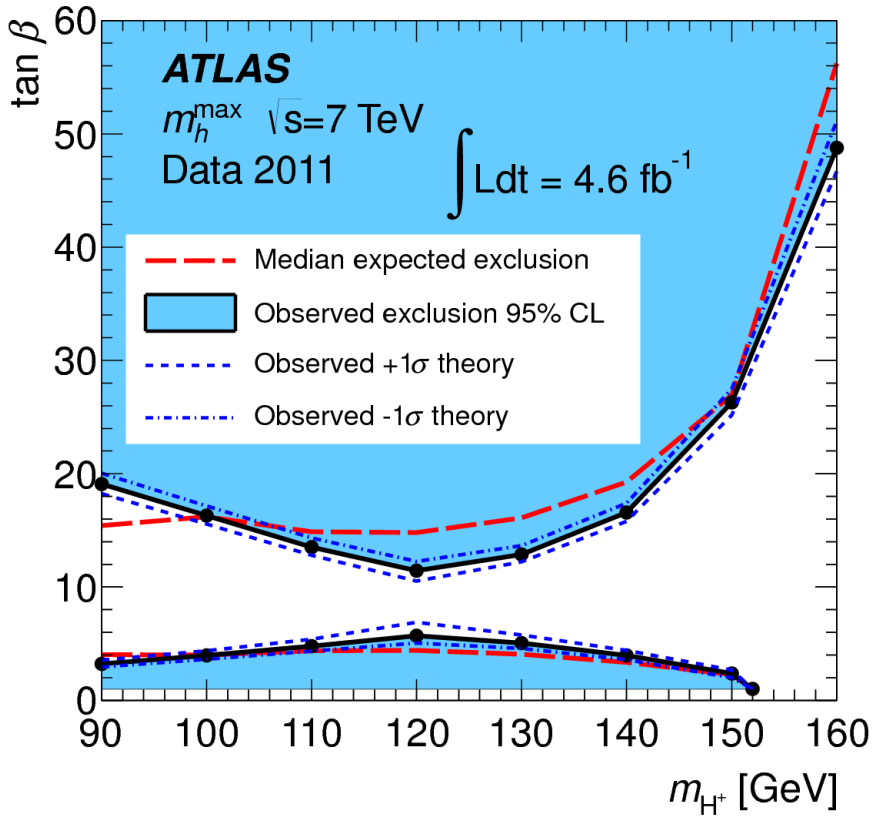
Discriminating variable

$m_T(\tau, mE_T)$

$H^+ \to \tau\nu$

Charged Higgs Search Results





95% CL upper limits on $BR(\mathrm{t} \to \mathrm{H}^{\pm}\mathrm{b})$

Assume $BR(\mathrm{H}^{\pm} \to \tau\nu) = 1$

↳ 5% (90 GeV) to 1% (160 GeV)

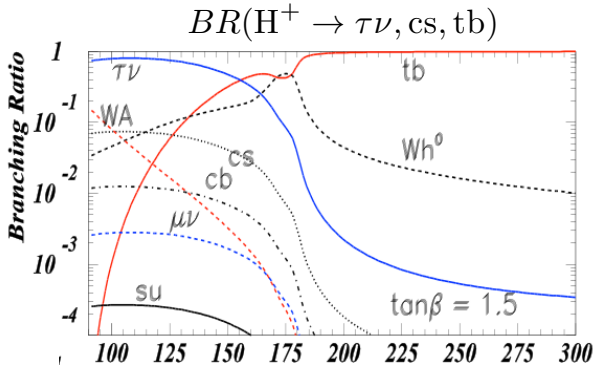
Exclusion region in the tanβ – m_A plane (90-160 GeV)

↳ tanβ > 12-26
tanβ between 1 and 2-6

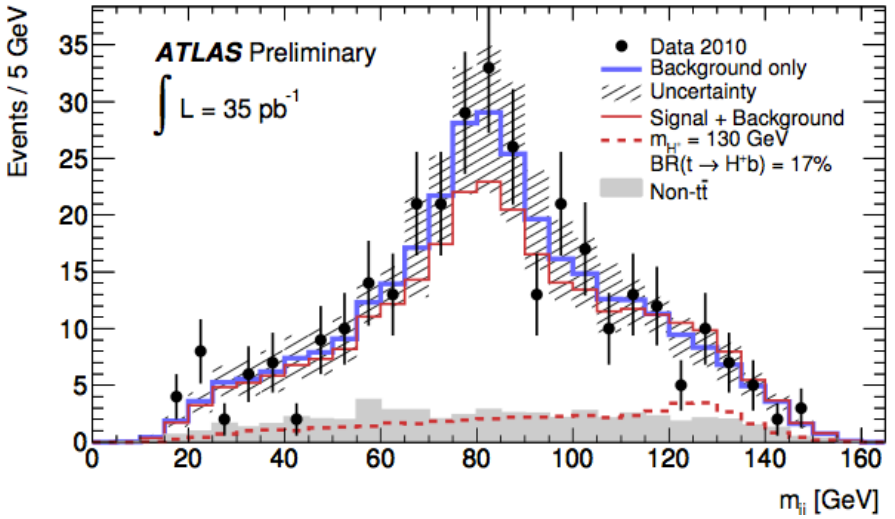
$H^+ \to c\bar{s}$

H^+ to cs(bar) Search

$t\bar{t} \to b\bar{b}WH^+ \to b\bar{b}(\ell\nu)(c\bar{s})$



tanβ < 1 → BR ≈ 40% m(H⁺) = 130 GeV

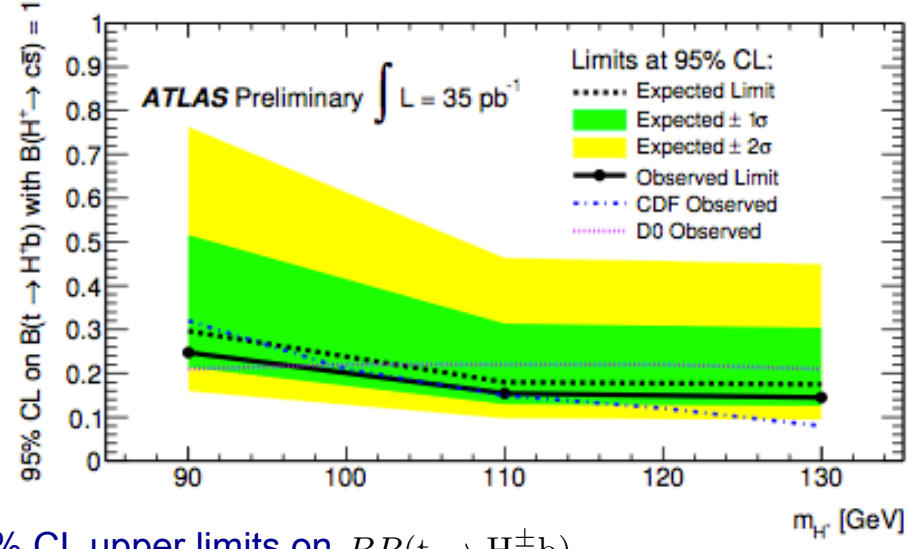


Selection:

- 1 e,μ p_T > 25 (20) GeV
- ≥ 4 jets (2 b-tagged)
- mE_T > 30 (20) GeV
- m_T(l,mET) = m_T(W)

+

Kinematic Fit on top quark decays



95% CL upper limits on $BR(t \to H^{\pm}b)$ = 1

Conclusions

- MSSM Higgs sector still not ruled out by the new SM-like particle discovery
- Importance of tau leptons, not only in the SM but also for new physics with strong coupling to third generation fermions (like MSSM)
- MSSM neutral and charged Higgs sector studied in ATLAS with taus and other decays
  - No evidence of new physics → upper limits and exclusion regions derived
- So far only public results from 2011 (7 TeV) (≈5/fb). In 2012 (8 TeV) we recorded 4 times more data…

Backup Slides

MSSM Higgs Sector

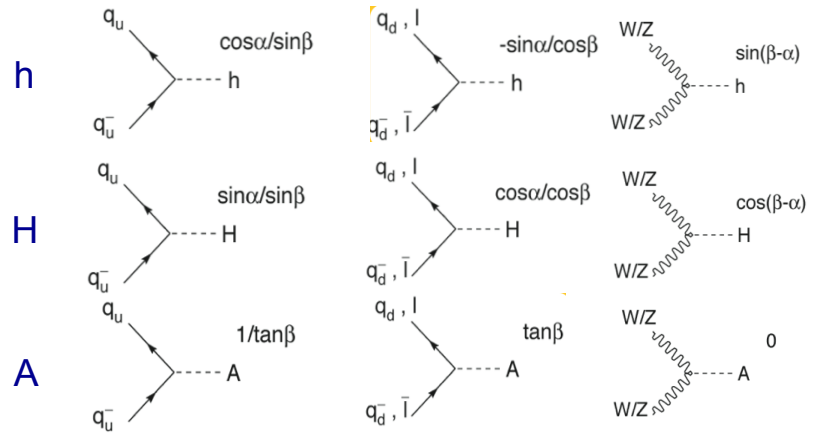
MSSM: simplest low energy SUSY model with rich and simple Higgs phenomenology

5 physical Higgs particles: A, h, H, $H^{\pm}$

TREE LEVEL $m_A \gg m_Z$

$$m_h^2 \simeq m_Z^2 \cos^2 2\beta$$
$$m_H^2 \simeq m_A^2 + m_Z^2 \sin^2 2\beta$$
$$m_{H^\pm}^2 = m_A^2 + m_W^2$$

TREE LEVEL
Couplings to fermions/bosons

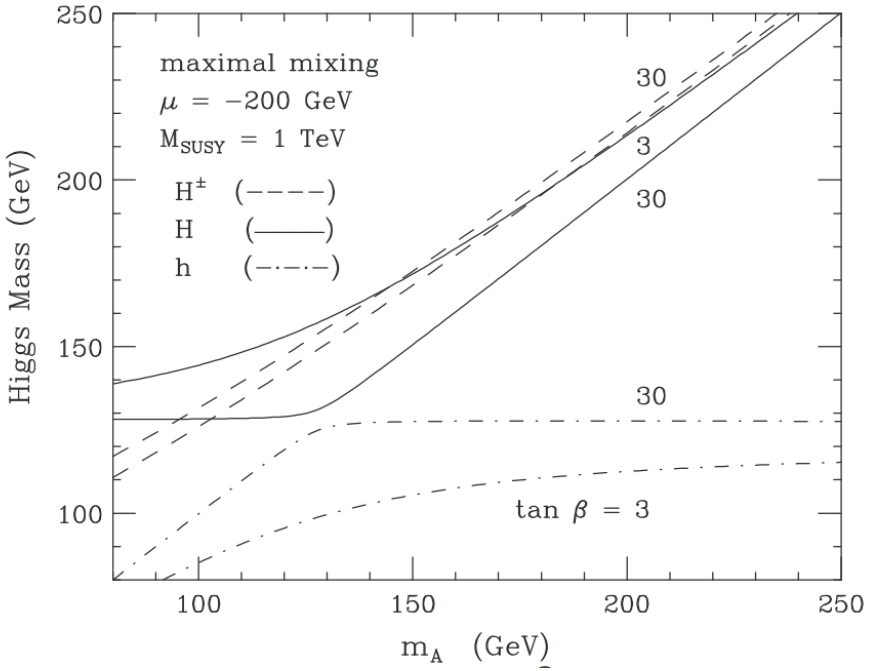


Suppressed for A
Suppressed for either h or H

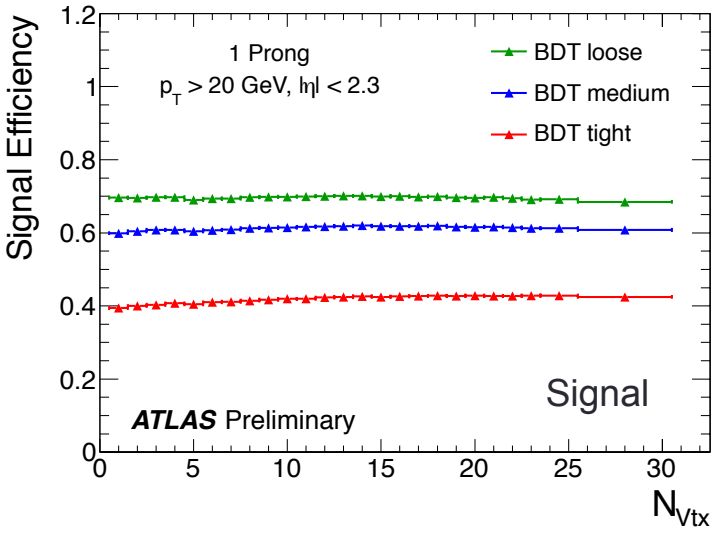
Absent for A
Suppressed for either h or H

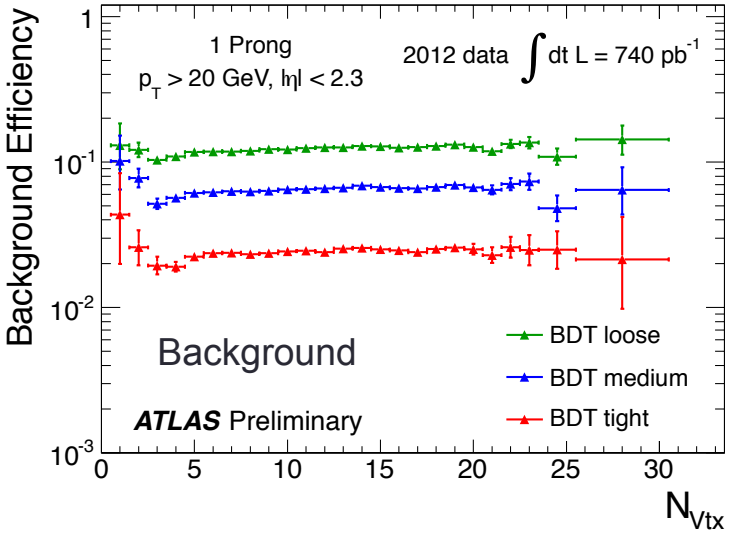
Enhanced for A
Enhanced for either h or H

RADIATIVE CORRECTED MASSES

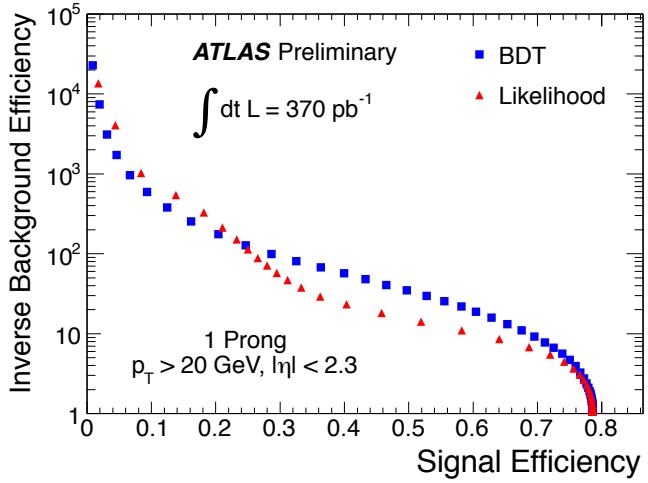


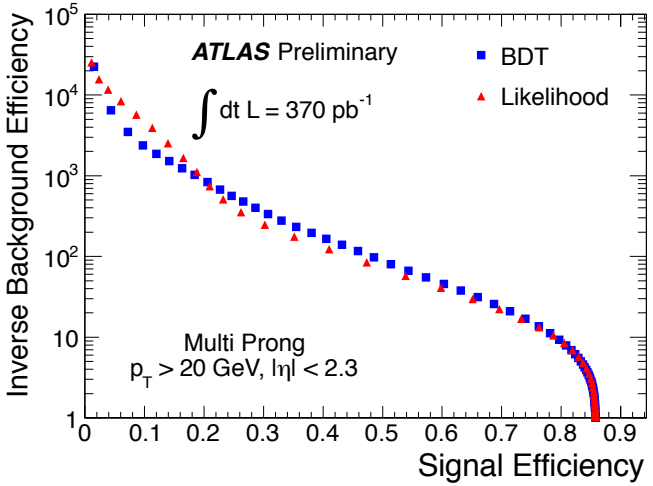
Tau Identification Efficiencies





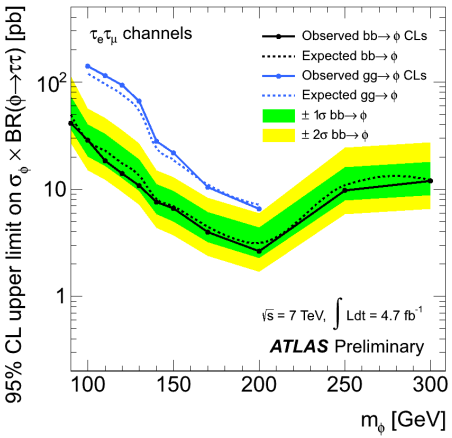
From data
$Z \rightarrow \tau\tau$

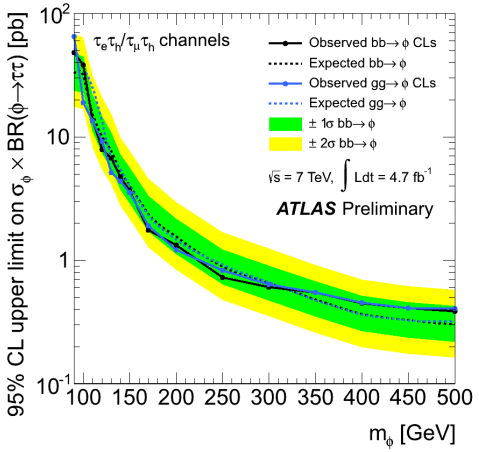


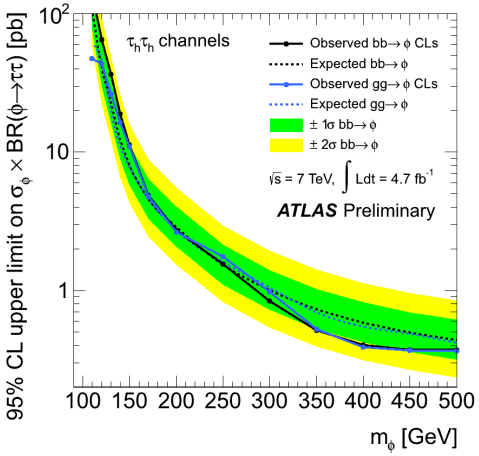


$H \to \tau^+\tau^-$: Results

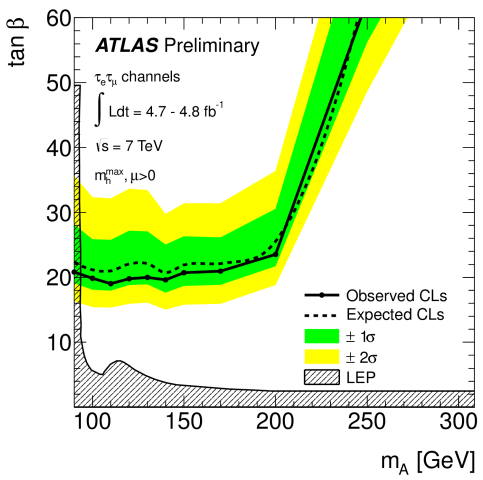
Limits on $\sigma(\varphi) \times BR(\varphi \to \tau\tau)$

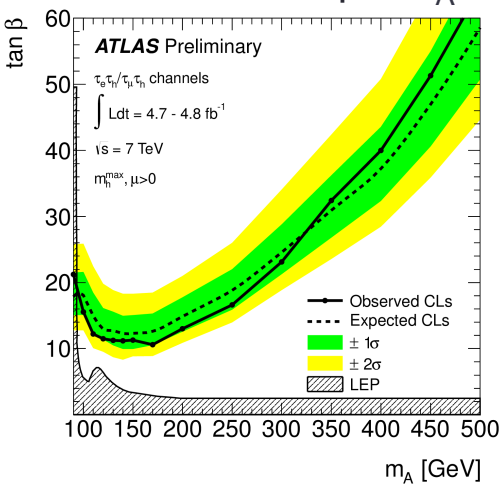


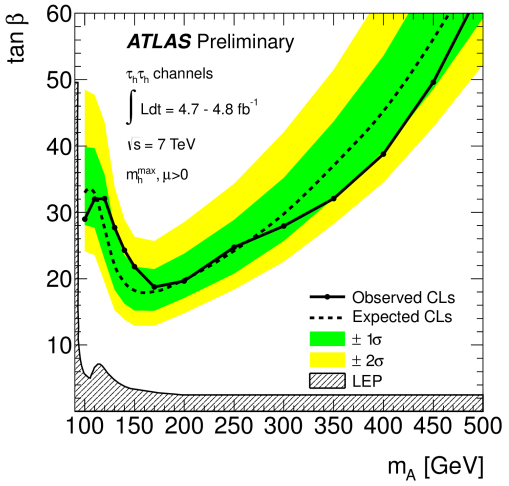




Limits on tanβ - m_A

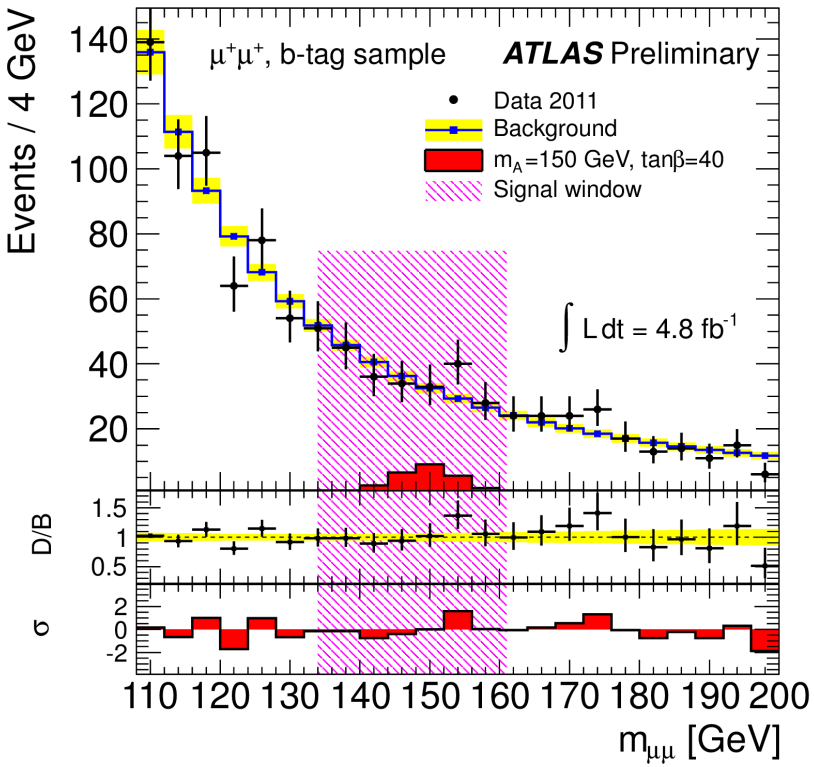




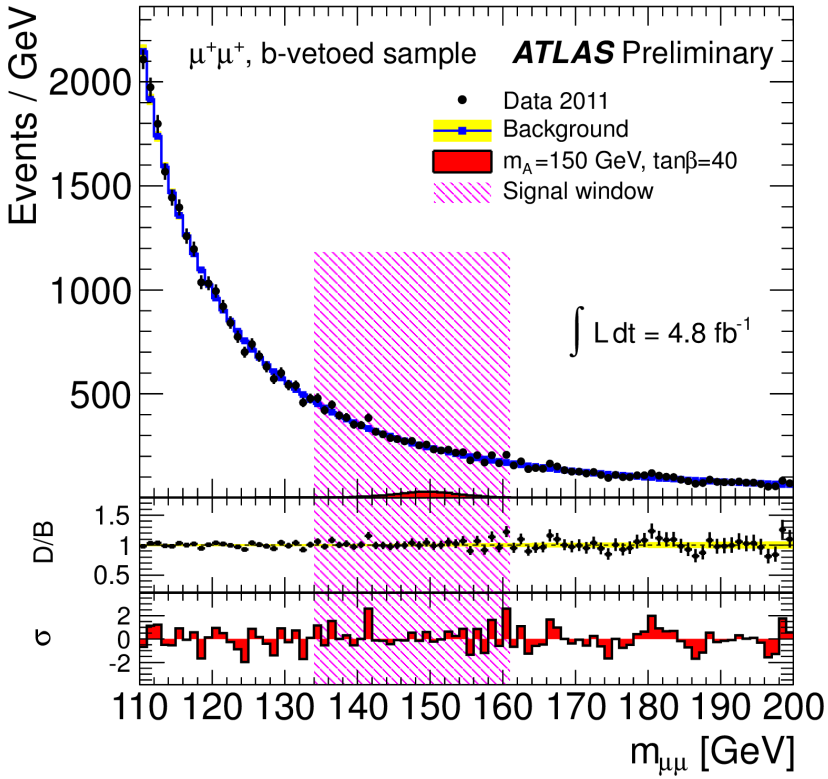


H→μ⁺μ⁻: Mass Distributions

H→μμ



b-tagged sample



b-vetoed sample

Background parametrization from sideband fits to the data

Charged MSSM Higgs Search

- Topological cuts based on χ^2 to select hadronic part of the decay (by combining b-tagged jet and untagged jets amd minimizing th

$$\chi^2 = \frac{(m_{jjb} - m_{\text{top}})^2}{\sigma_{\text{top}}^2} + \frac{(m_{jj} - m_W)^2}{\sigma_W^2}$$

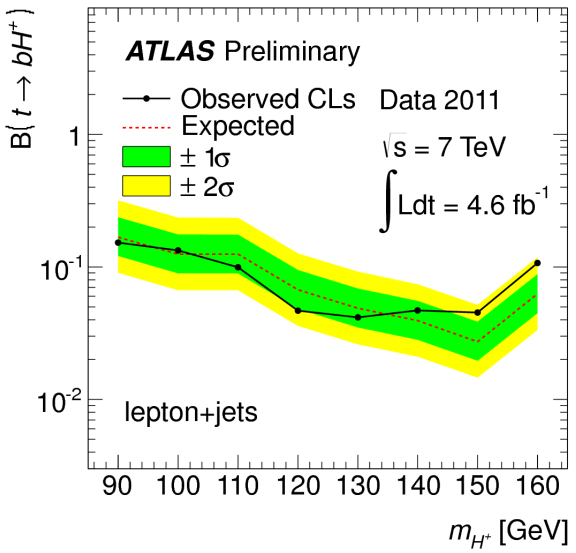
- Use discriminant variables to disantangle Tau lepton decays from H+ (or W) from direct W leptons

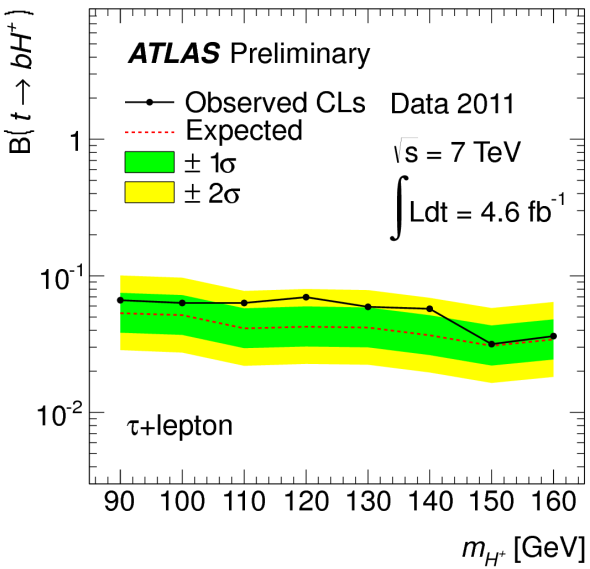
$$\cos\theta_l^* = \frac{2m_{bl}^2}{m_{\text{top}}^2 - m_W^2} - 1 \simeq \frac{4\,p^b \cdot p^l}{m_{\text{top}}^2 - m_W^2} - 1$$

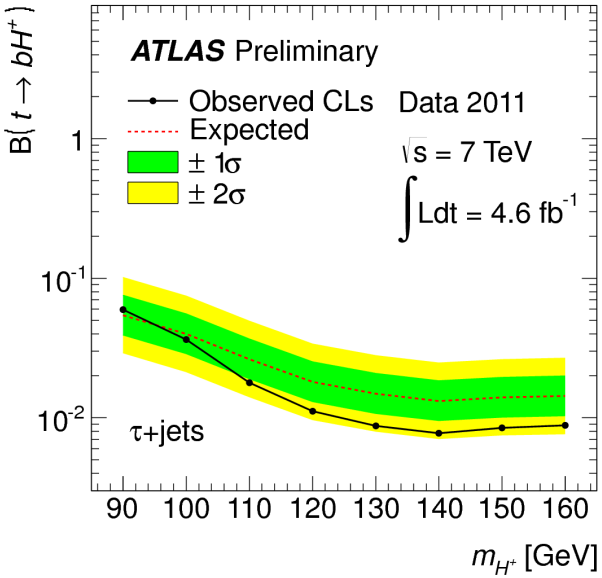
$$(m_{\text{T}}^H)^2 = \left(\sqrt{m_{\text{top}}^2 + (\vec{p}_{\text{T}}^{\,l} + \vec{p}_{\text{T}}^{\,b} + \vec{p}_{\text{T}}^{\,\text{miss}})^2} - p_{\text{T}}^b \right)^2 - \left(\vec{p}_{\text{T}}^{\,l} + \vec{p}_{\text{T}}^{\,\text{miss}} \right)^2$$

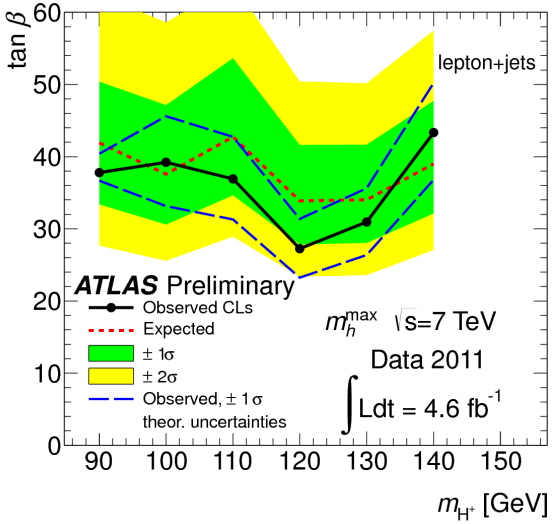
$H^+ \to \tau\nu$

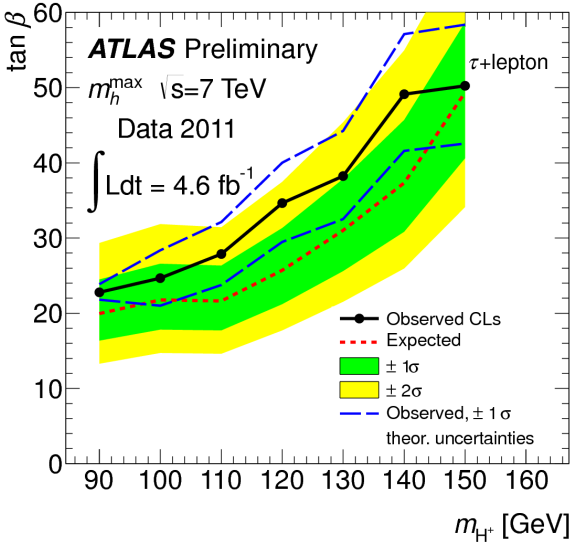
Charged Higgs Search Results

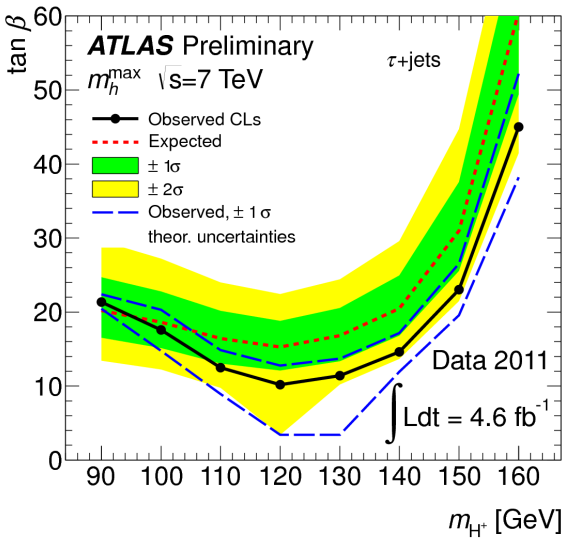






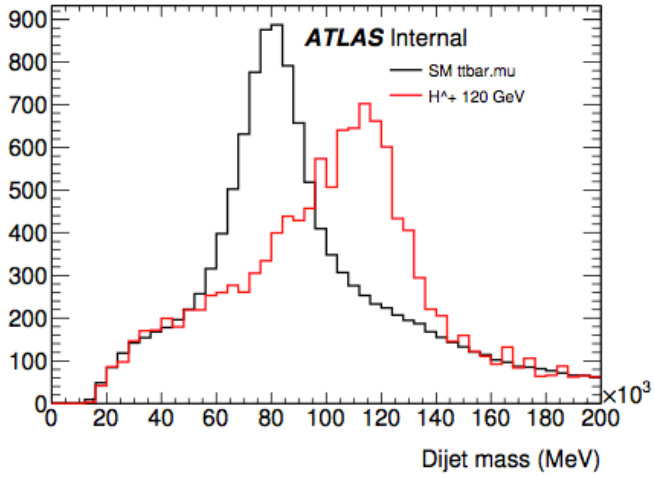


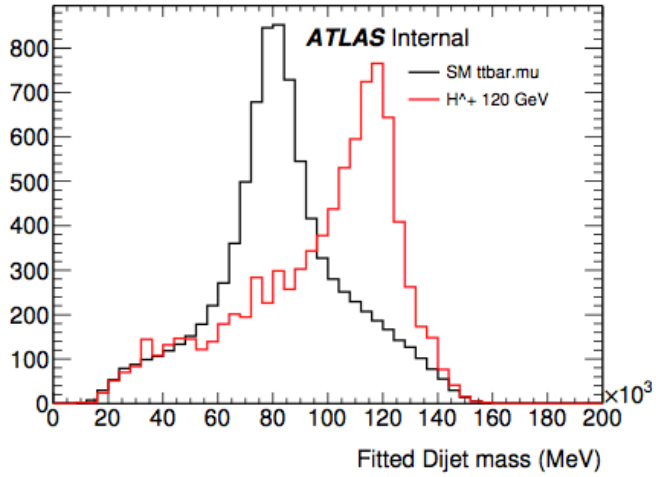




H^+ to cs(bar) Kinematic Fit

Dijet Mass Fitter

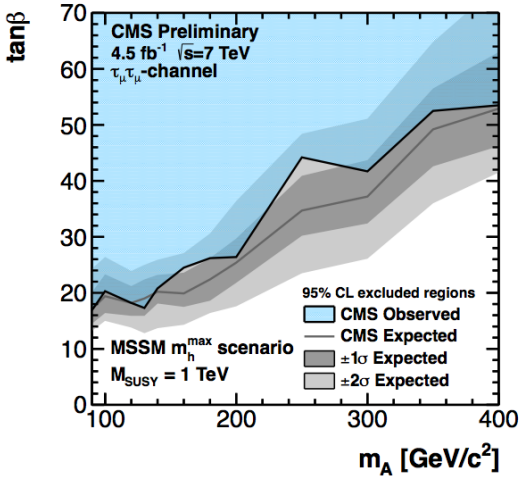




CMS MSSM Neutral Higgs Searches

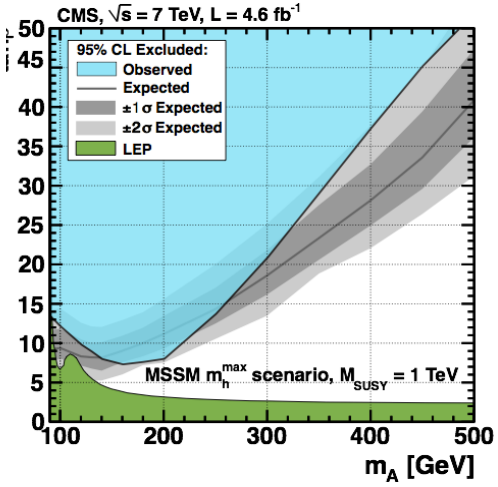
$H \to \tau_\mu \tau_\mu$

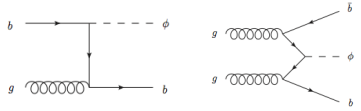
CMS PAS HIG-12-007



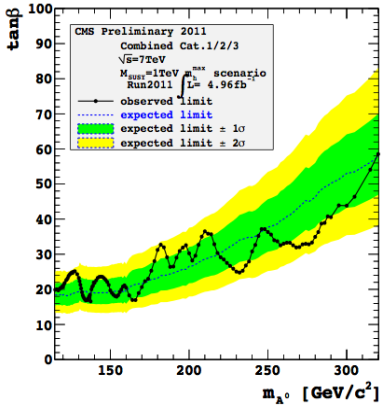
$H \to e\tau_h, \mu\tau_h, e\mu$

CMS arXiv:1202.4083





CMS PAS HIG-12-011



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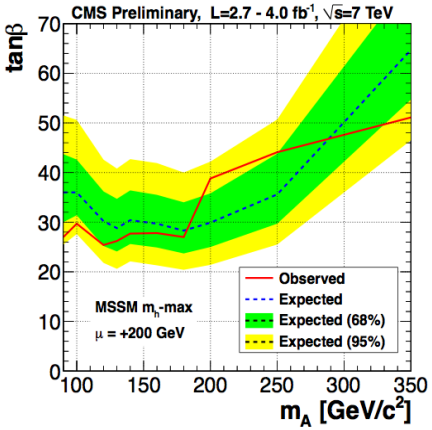
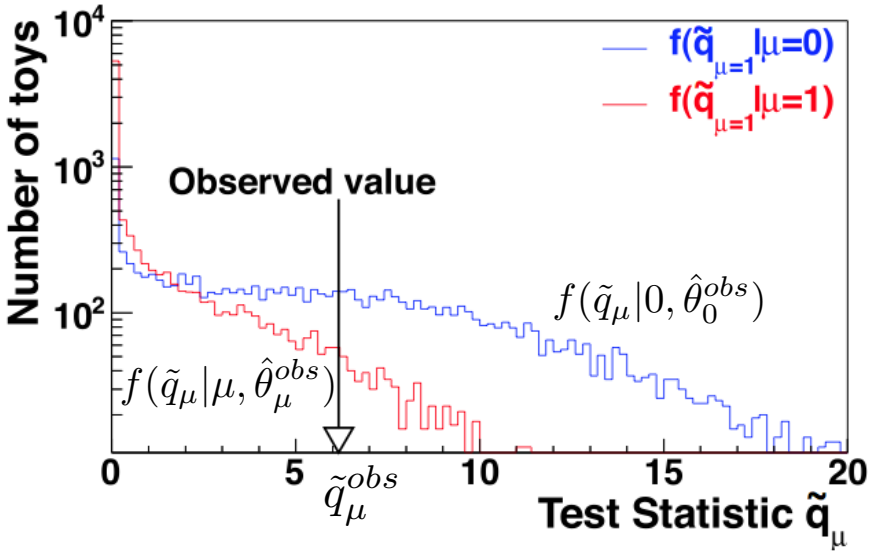


Exclusion Limits at the LHC

Test statistic used for exclusions (hypothesis testing with signal)
profile likelihood ratio:

$$\tilde{q}_\mu = -2\ln\frac{\mathcal{L}(data|\mu,\hat{\theta}_\mu)}{\mathcal{L}(data|\hat{\mu},\hat{\theta})} \qquad 0 \le \tilde{\mu} \le \mu$$

$data$ → • observation
• toy pseudo-experiments



$$p_\mu = CL_{s+b} = P(\tilde{q}_\mu \ge \tilde{q}_\mu^{obs}|s+b) = \int_{\tilde{q}_\mu^{obs}}^{\infty} f(\tilde{q}_\mu|\mu)d\tilde{q}_\mu$$

$$1-p_b = CL_b = P(\tilde{q}_\mu \ge \tilde{q}_\mu^{obs}|b) = \int_{\tilde{q}_\mu^{obs}}^{\infty} f(\tilde{q}_\mu|0)d\tilde{q}_\mu$$

$$\rightarrow \quad CL_s = \frac{CL_{s+b}}{CL_b}$$

95% CL upper limit on μ ($\mu^{95\%CL}$) → Adjust μ until CL_s = 0.05