Search for BSM Higgs Bosons with ATLAS

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On behalf of the ATLAS Collaboration

SEARCH

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Overview

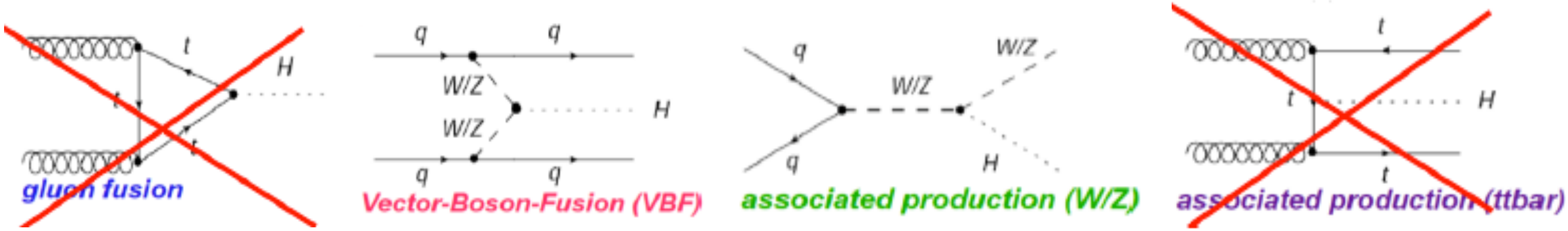
- Fermiophobic $H \to \gamma\gamma$ — New prelim. results (4.9 fb^{-1})
- MSSM neutral $h/H/A \to \tau\tau$
- Charged Higgs bosons

$$\left.\begin{array}{l} H^+ \to \tau_{\mathrm{had}}\nu \\ H^+ \to \tau_{lep}\nu \end{array}\right\} \text{New prelim. results (4.6 fb}^{-1}\text{)}$$

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

- Doubly charged Higgs $H^{++} \to \mu^+\mu^+$ — Published in PRD (1.6 fb^{-1})
- NMSSM $a_1 \to \mu\mu$

Fermiophobic Higgs



- **Suppressed Higgs couplings** to **fermions** in 2HDM and Higgs triplet models

  Here: simple benchmark model (LEP)
  - **no fermion-Higgs couplings**
  - **SM boson-Higgs couplings**

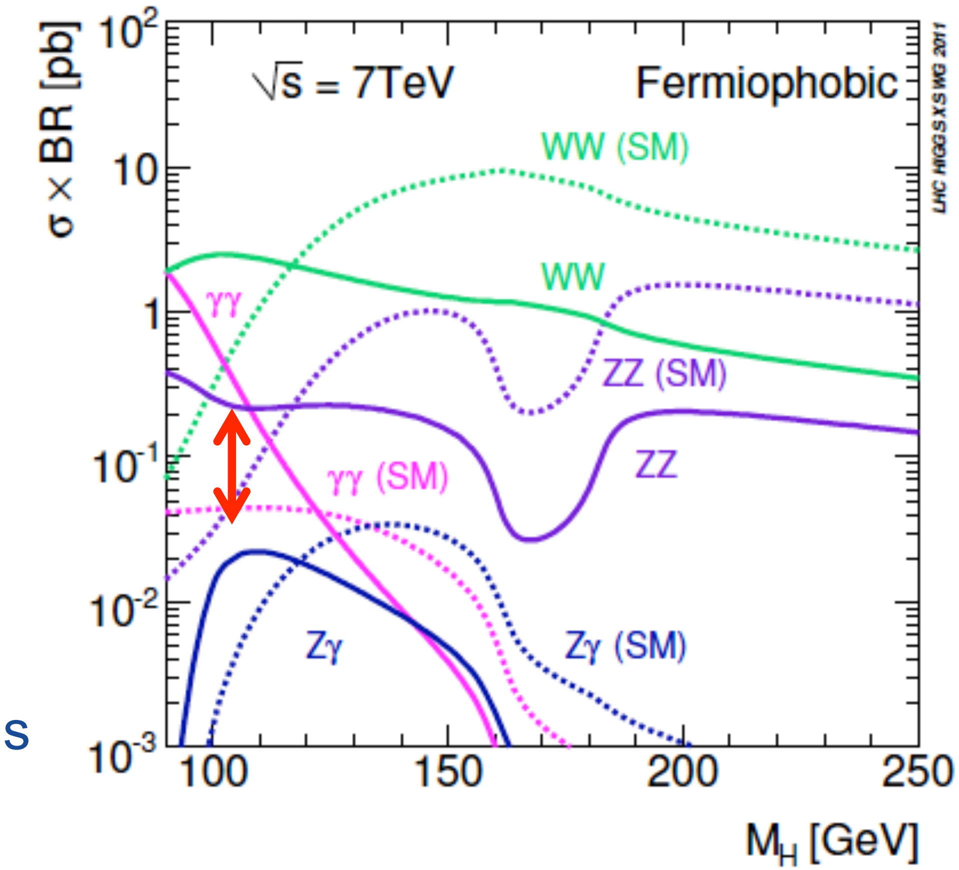
- **Production:** Vector-boson fusion and associated production with W/Z

- **Decays** to γγ, WW, ZZ, Zγ

  Here: focus on **H** → γγ

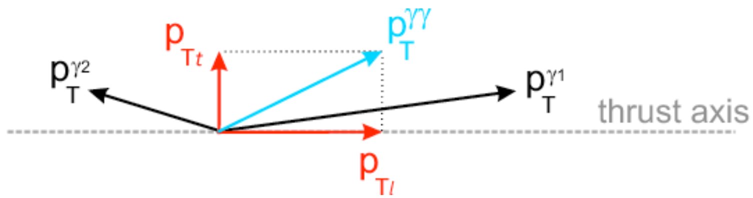
  ⇒ **larger σ×BR** than SM for light Higgs

  ⇒ **higher Higgs** $\mathbf{p_T}$



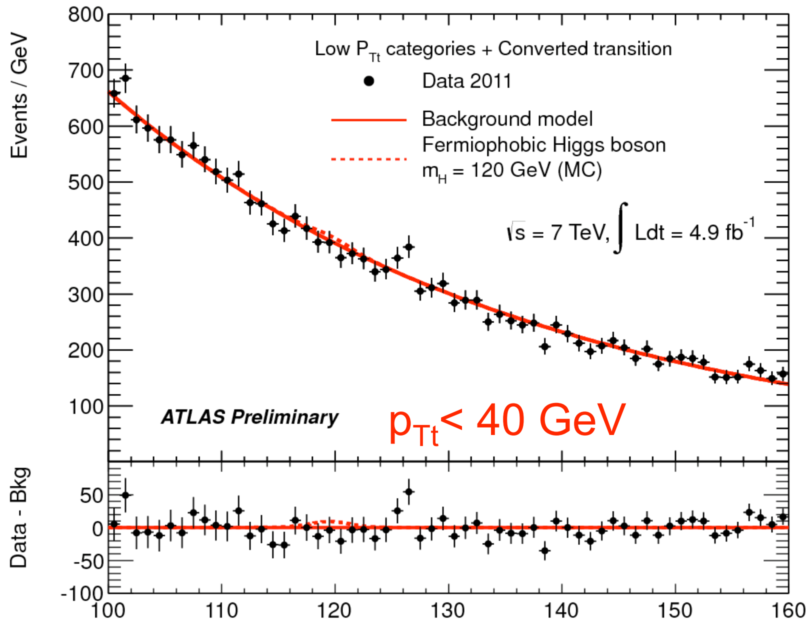
Fermiophobic Higgs → γγ

- **Selection:** (identical to SM H → γγ)
  - **2 isolated photons** with p_T > 40, 20 GeV
  - Di-photon mass: **100 < $m_{\gamma\gamma}$ < 160 GeV**
  - **9 categories** based on
    - presence of γ **conversions**
    - γ calorimeter **impact point**
    - **p_{Tt}**: related to di-photon p_T



- **Signal $m_{\gamma\gamma}$ model**
  Crystal Ball (core) + wide Gaussian (tail)

- **Background $m_{\gamma\gamma}$ model**
  Exponential



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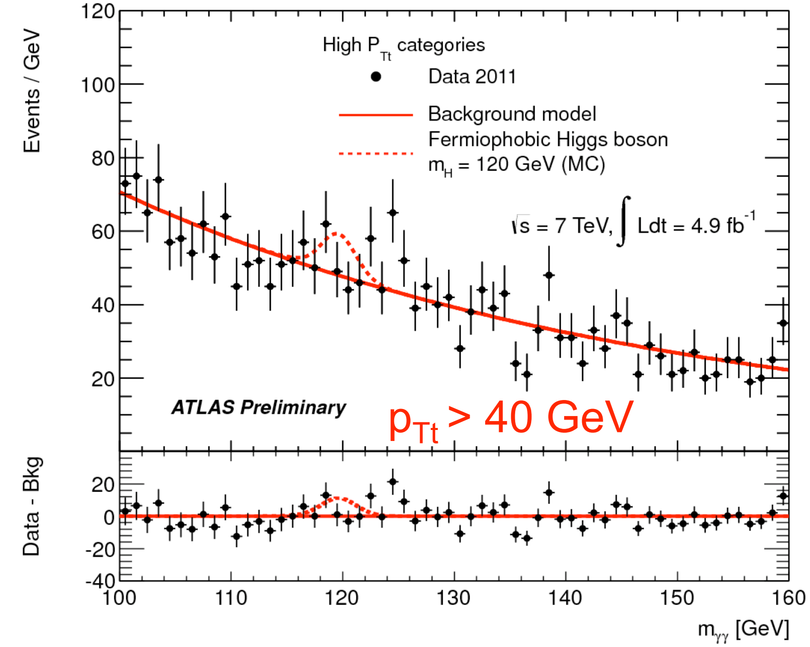
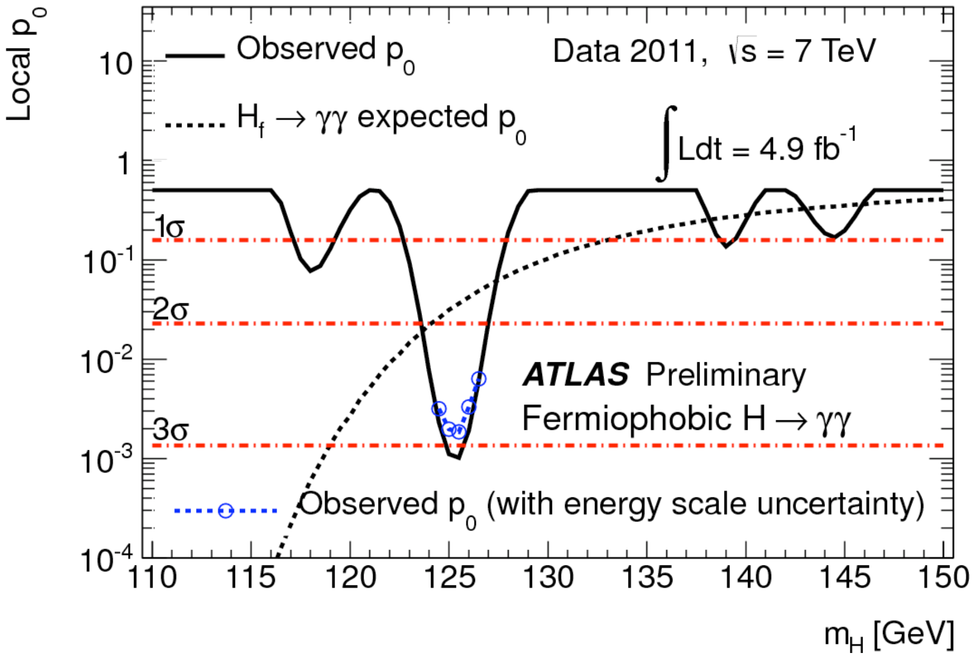


Fermiophobic Higgs → γγ : Exclusion limits



Largest excess at **m_H=125.5 GeV**

Including look-elsewhere effect:

Significance: **1.6σ**

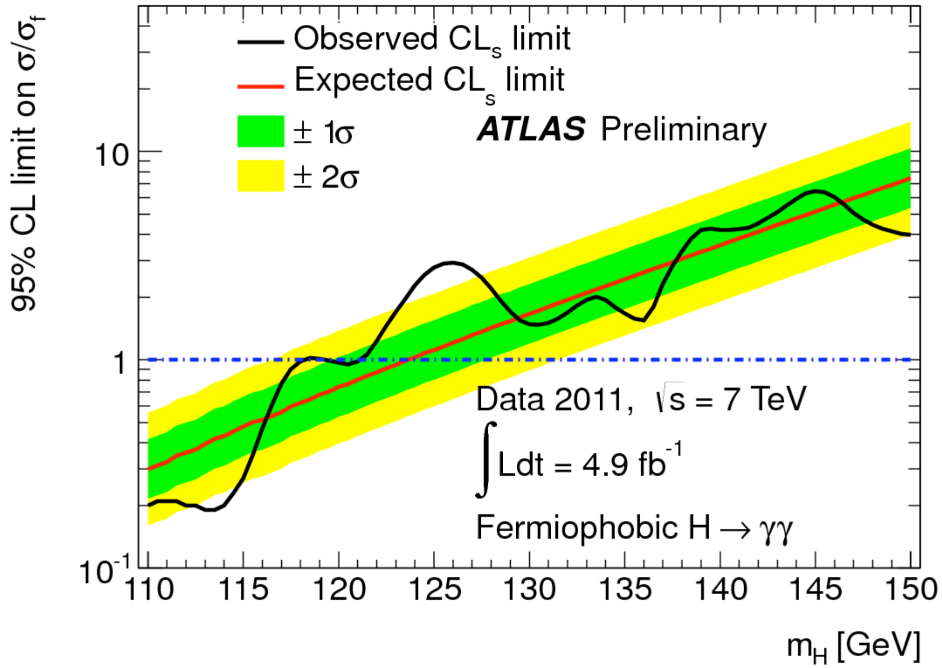
Prob. of background fluctuation: **5%**

Observed m_H exclusion:

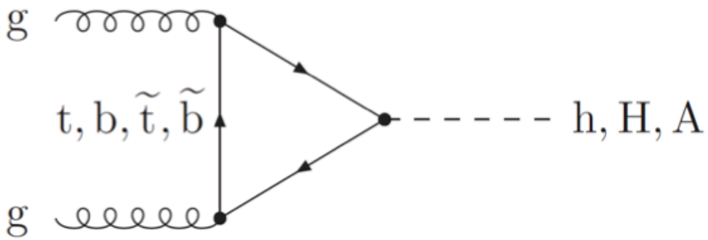
[110.0, 118.0], [119.5, 121.0]

Expected m_H exclusion:

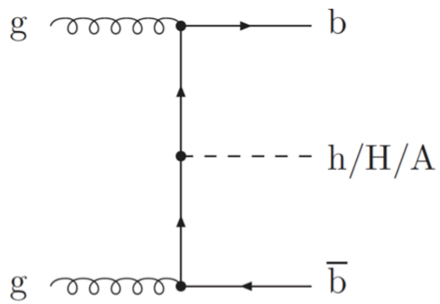
[110.0, 123.5]



Neutral MSSM Higgs

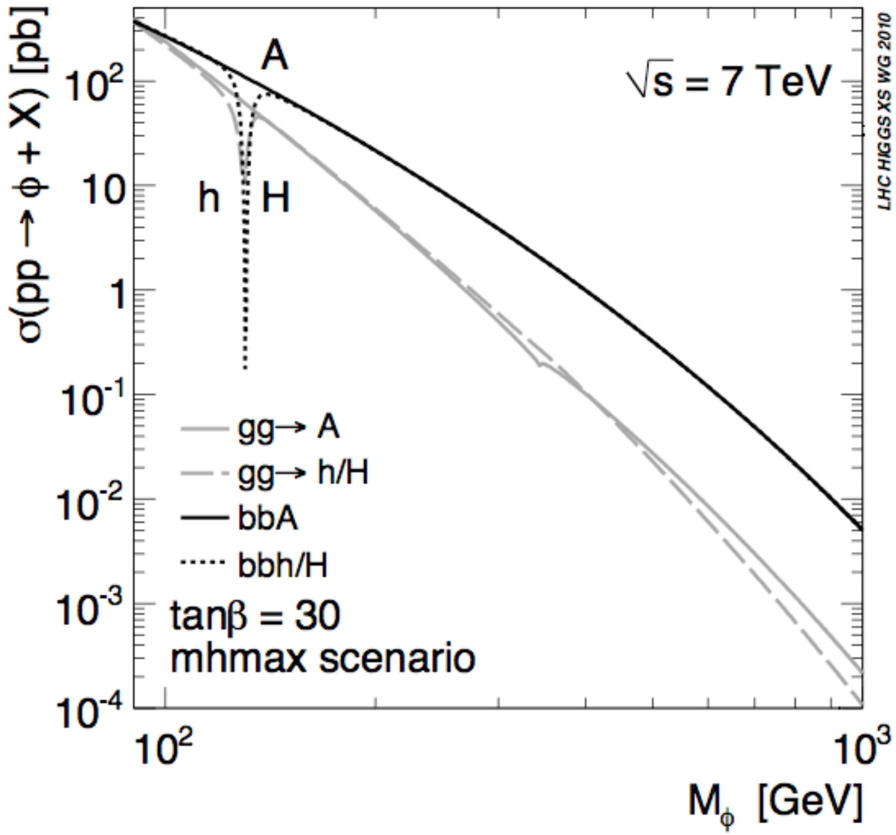


gluon-gluon fusion: gg → h/H/A

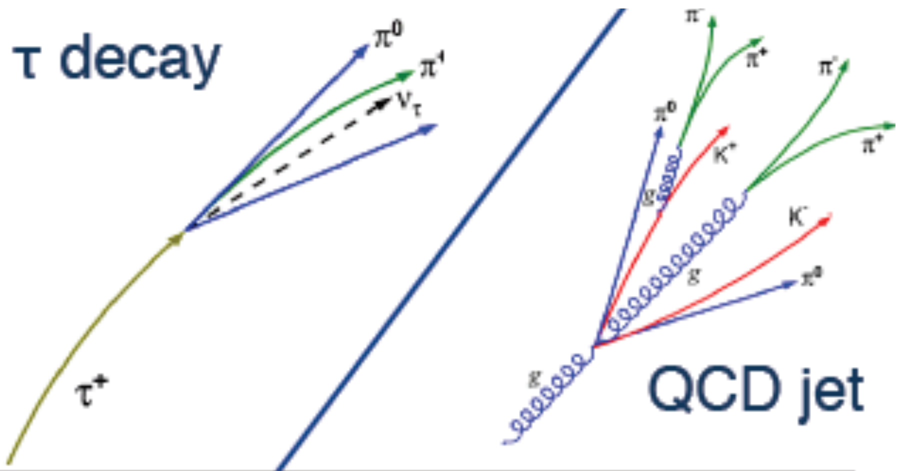


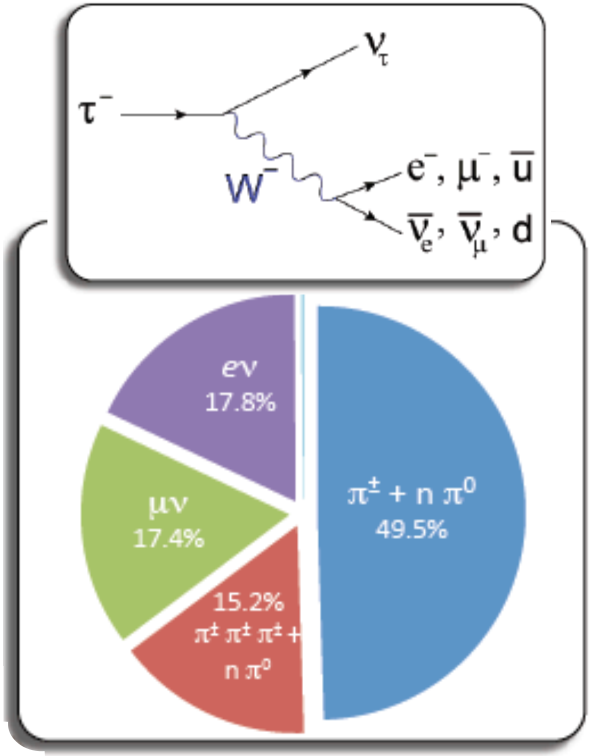
b-associated production: bbh/H/A

- **MSSM** requires 2 Higgs doublets
  ⇒ **5 Higgs bosons:**
  Φ = **h, H, A** ; H^+,H^-
- h/H and A nearly mass degenerate
- 2 parameters at tree level: m_A, tanβ
- **Enhanced couplings to b and τ** in large parts of parameter space
  $\sigma_{bbh/H/A} \propto \tan^2\beta$



Tau signature and identification

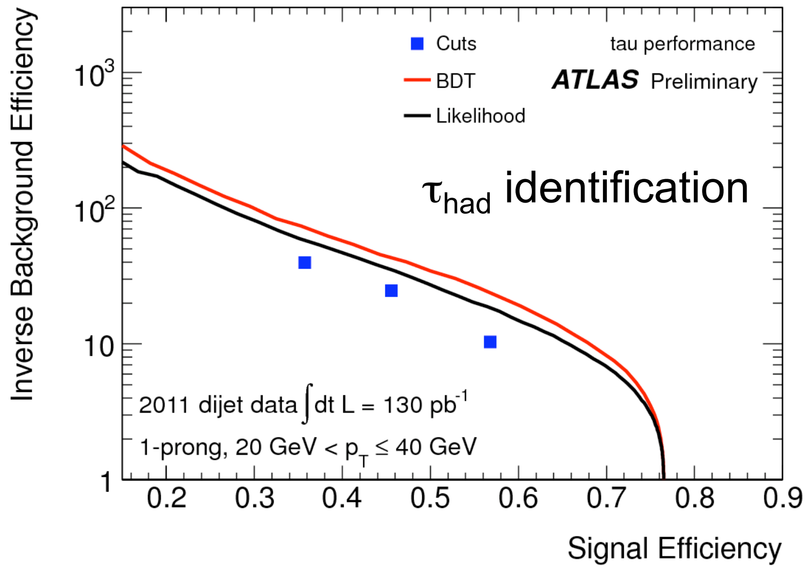




Hadronic τ decay (τ_{had}):

- Narrow, **collimated** jet
- **isolated** energy deposits and tracks
- large electromagnetic component
- **low track multiplicity** (1 or 3)
- high leading track momentum fraction

multivariate identification



Neutral MSSM Higgs : Selection

$e + \mu$

- 1 isolated e with $p_T > 25$ GeV
- 1 isolated μ with $p_T > 20$ GeV
- Opposite charges
- **$E_T^{miss} + p_T^e + p_T^\mu < 120$ GeV**

$\Delta\Phi(e,\mu) > 2.0$ rad

(top, WW, ZZ suppression)

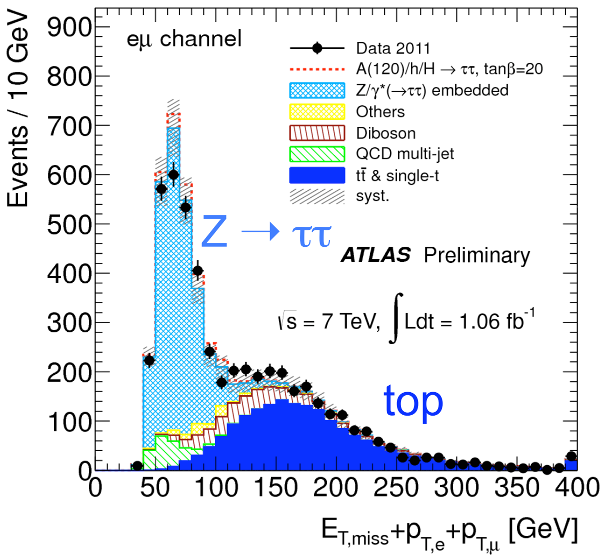
$e/\mu + \tau_{had}$

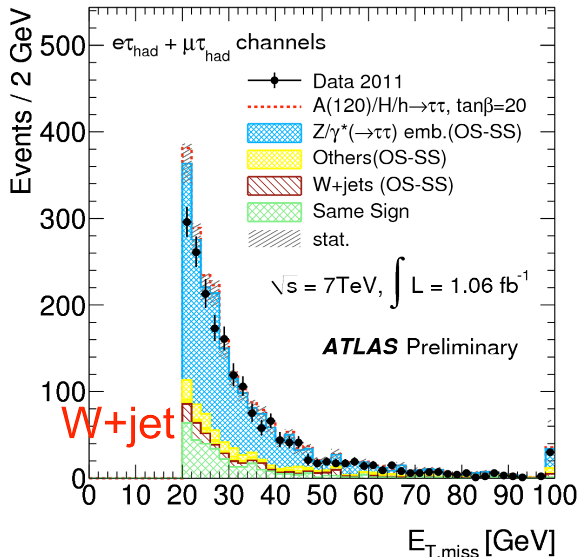
- 1 isolated e / μ with $p_T > 25$ / 20 GeV
- 1 τ_{had} with $p_T > 20$ GeV
- Opposite charges
- **Di-lepton veto** (Z, top)
- **$E_T^{miss} > 20$ GeV** (QCD)
- **$m_T < 30$ GeV** (W)

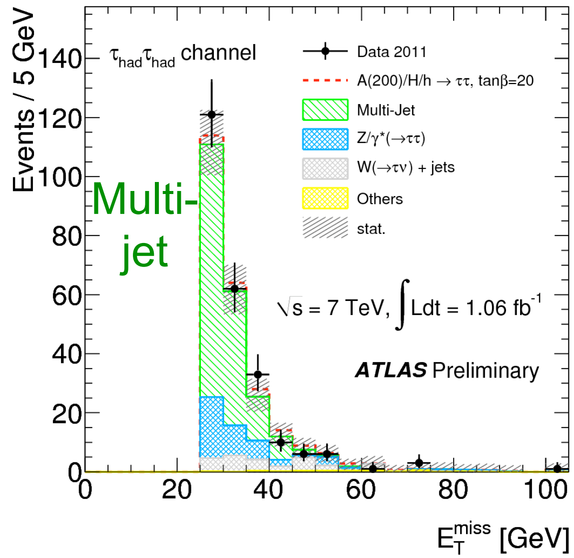
$\tau_{had} + \tau_{had}$

- **Di-τ_{had} trigger**
- 2 τ_{had} with $p_T > 45$ / 30 GeV
- Opposite charges
- **$E_T^{miss} > 25$ GeV**

(QCD suppression)







Neutral MSSM Higgs : Mass reconstruction

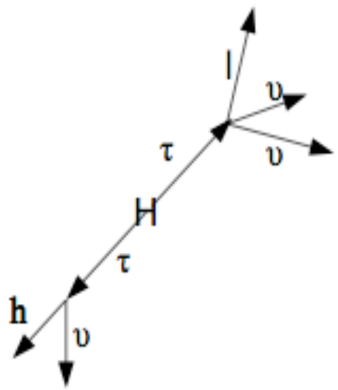
- **Visible mass :** $m_{\tau\tau}^{\text{visible}}$ (invariant mass of visible tau decay products)

- **Effective mass:** $m_{\tau\tau}^{\text{effective}} = \sqrt{(p_{\tau^+} + p_{\tau^-} + p_{\text{miss}})^2}$

$$p_{\text{miss}} = (E_{\text{T}}^{\text{miss}}, E_{\text{x}}^{\text{miss}}, E_{\text{y}}^{\text{miss}}, 0)$$

A.Elagin, P.Murat, A.Pranko, A.Safonov, Nucl. Inst. Meth. A654 (2011) 481

- **Missing mass calculator (MMC):**

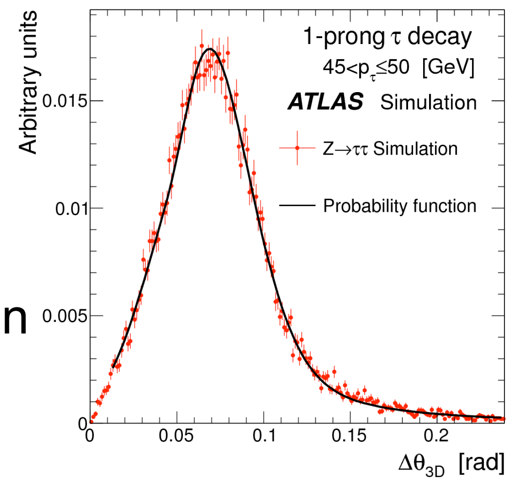


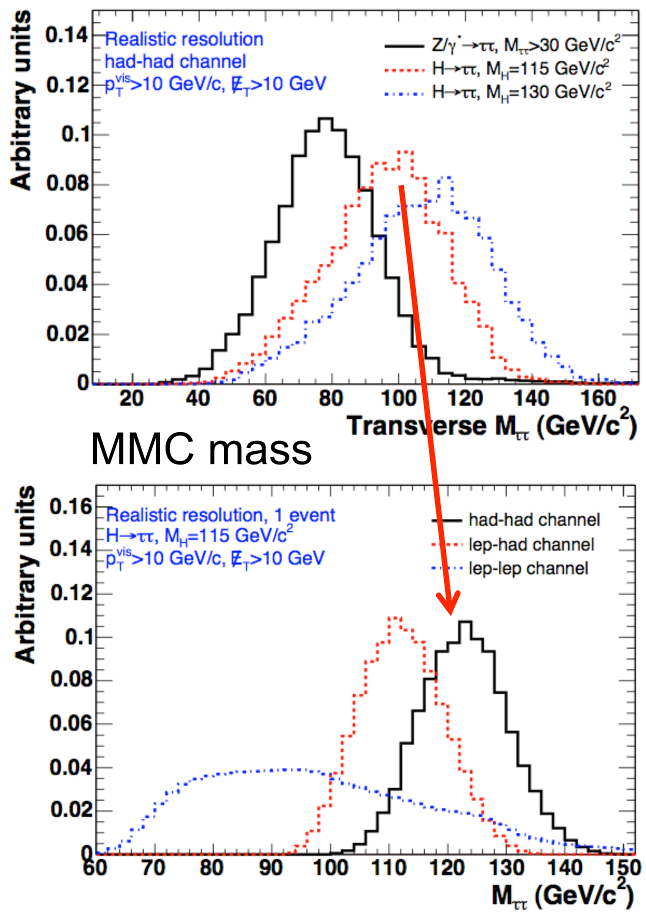
- 7 unknown parameters: two "missing" 3-momenta, $m_{\nu\nu}$
- 4 constraints from E_x^{miss}, E_y^{miss}, $m_{\tau 1}$, $m_{\tau 2}$

⇒ scan over $\Delta\Phi(\nu,l)$, $\Delta\Phi(\nu,h)$, $m_{\nu\nu}$

⇒ weight solution according to probability of 3D angle in solution

⇒ MMC mass = Max. of weighted $m_{\tau\tau}$ distribution

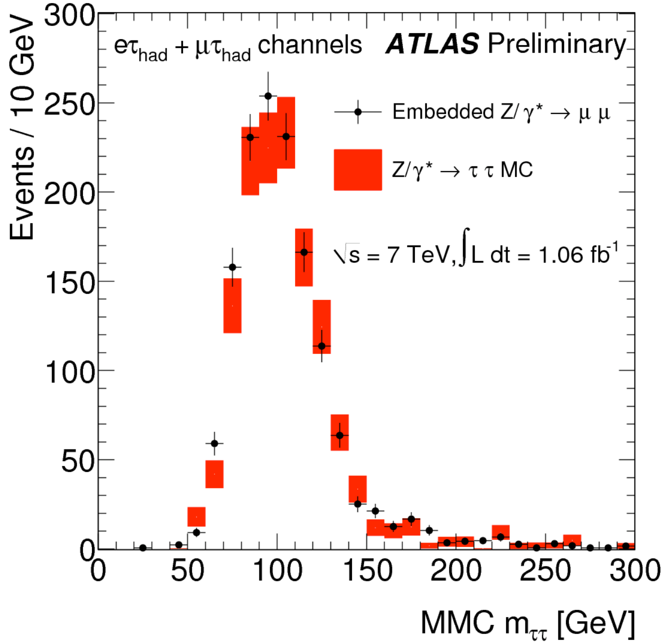




Neutral MSSM Higgs : Background estimation

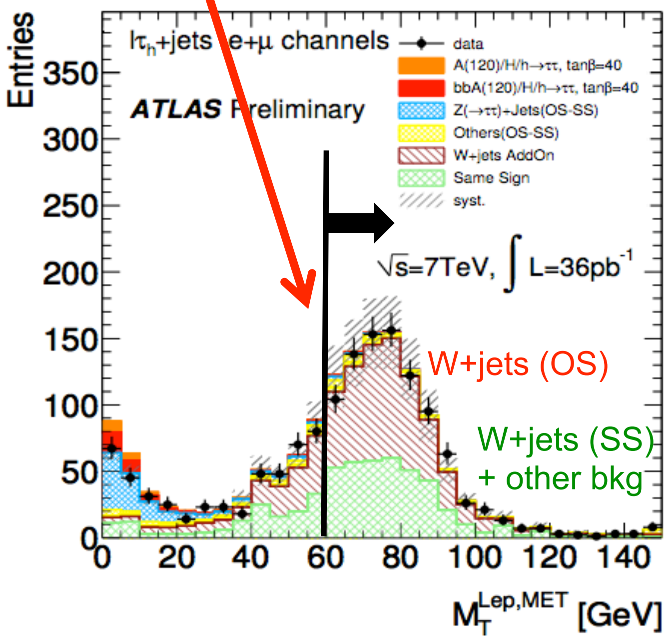
Background estimation based on **data control samples**:

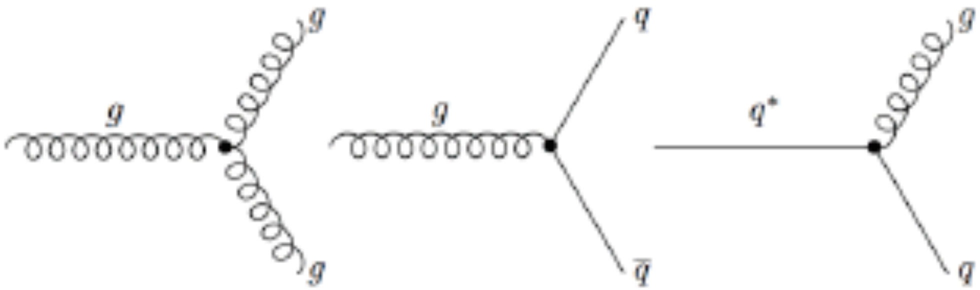
- **$Z/\gamma^* \rightarrow \tau\tau$** from **$\tau$-embedded** **$Z/\gamma^* \rightarrow \mu\mu$** data sample



- **Multijet** background from samples with **same-sign charges** and **low E_T^{miss}** or **inverted lepton isolation**

- **W+jets** from high-$m_T(l, E_T^{miss})$ sample

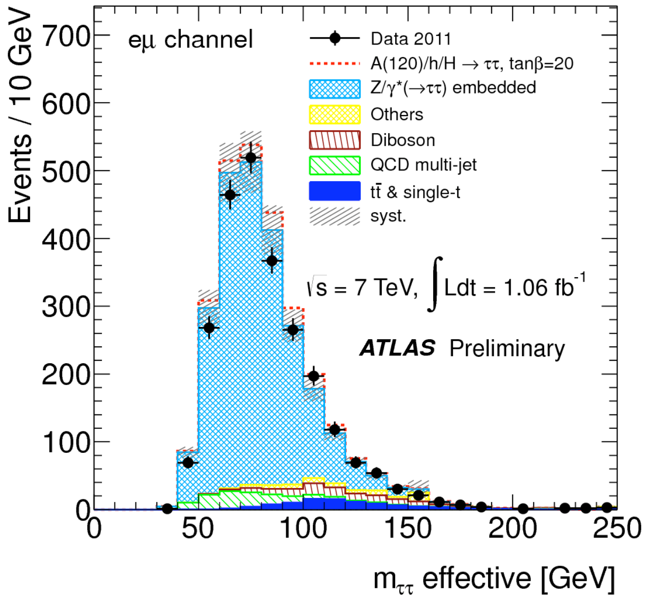




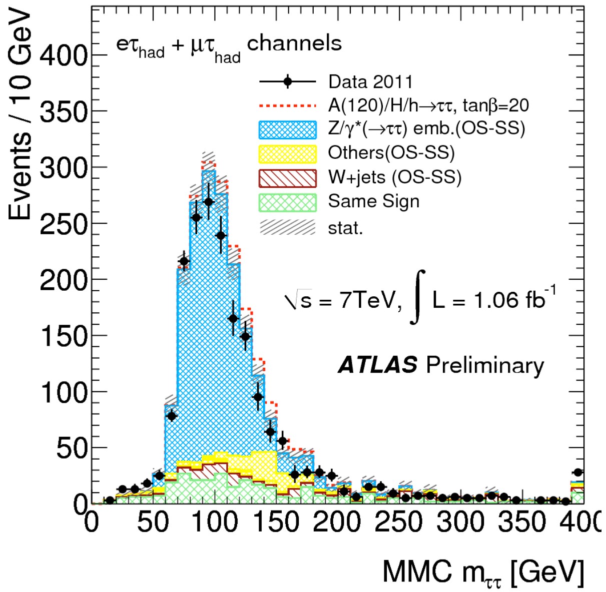
- No significant charge correlation
- Expect no large E_T^{miss}
- Mostly non-isolated or fake leptons

Neutral MSSM Higgs : Results

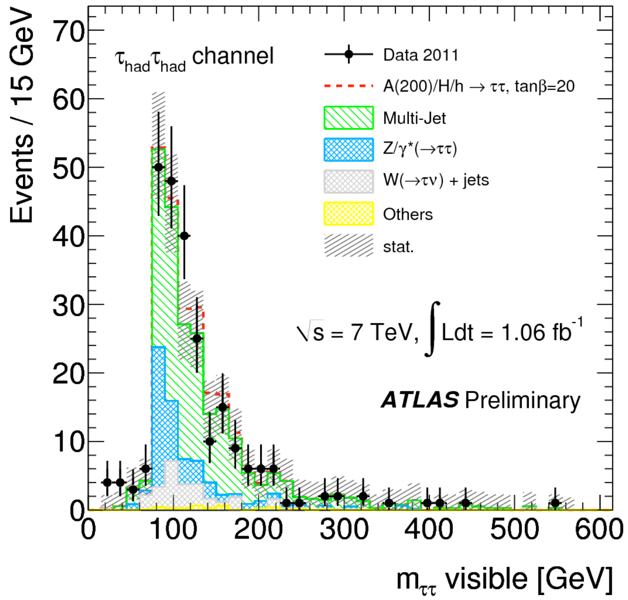
$e + \mu$



$e/\mu + \tau_{had}$



$\tau_{had} + \tau_{had}$

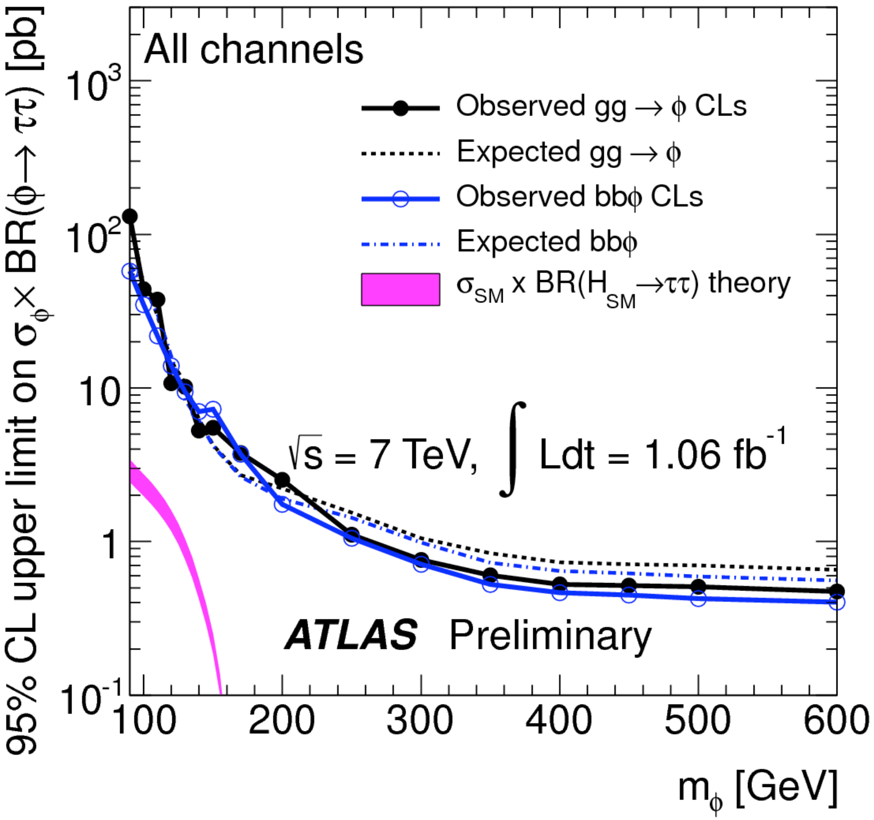


Final state	Exp. Background	Data
$e\mu$	$(2.6 \pm 0.2) \times 10^3$	2472
$\ell\tau_{had}$	$(2.1 \pm 0.4) \times 10^3$	1913
$\tau_{had}\tau_{had}$	233^{+44}_{-28}	245
Sum	$(4.9 \pm 0.6) \times 10^3$	4630

Neutral MSSM Higgs : Exclusion limits

$\sigma \times$ BR ($\Phi \rightarrow \tau\tau$)

- Assume only one resonance (Φ):
  100% gg $\rightarrow \Phi$ or
  100% bbΦ production
  (acceptances similar)
- Useful to test arbitrary models



(m_A, tanβ) plane

- Need to assume specific (c)MSSM scenario
- Here: m_h^{max} scenario

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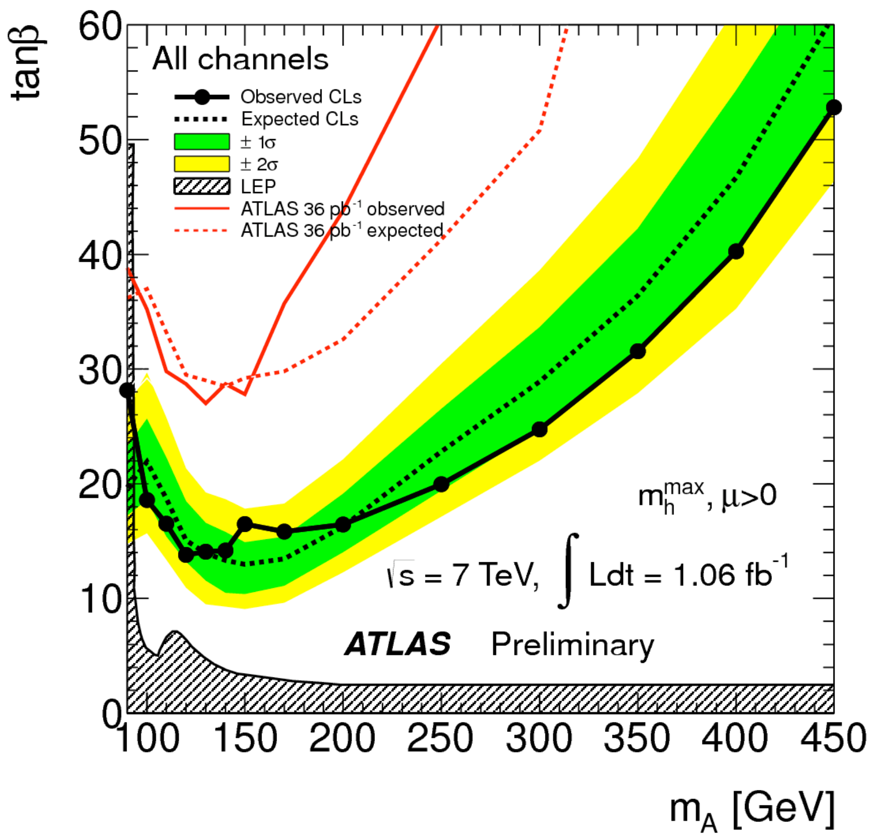
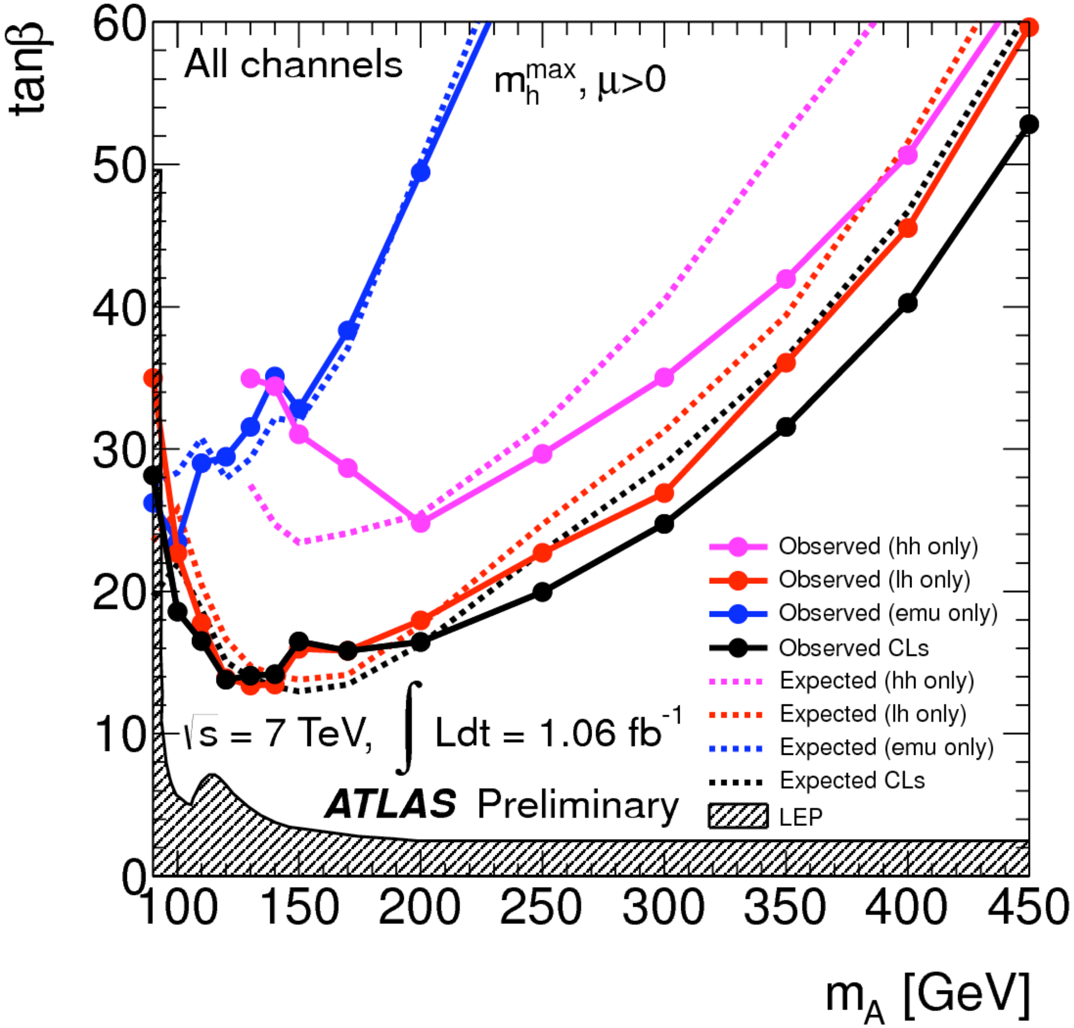


Neutral MSSM Higgs : Exclusion limits

Comparison of search channels



Update to full 4.9 fb^{-1} data set & inclusion of b-tagging in progress!

Charged Higgs

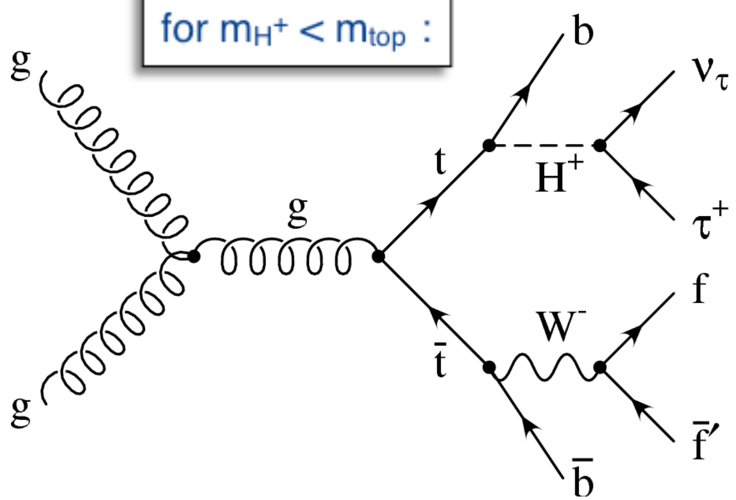
- Predicted in Higgs doublet (e.g. MSSM) and triplet models

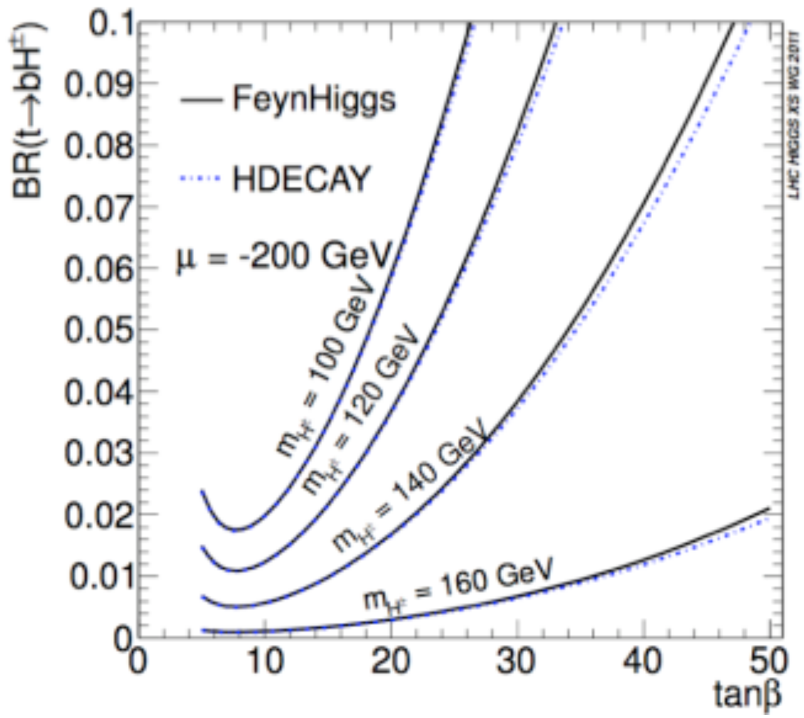
- $m_{H+} < m_t$: dominant **production in top quark decays**

- $m_{H+} > m_t$: gb → tH^+ production important, but more data needed

- for tanβ > 3, **preferred decay mode** is **H → τν** (here: assume BR of 100%)

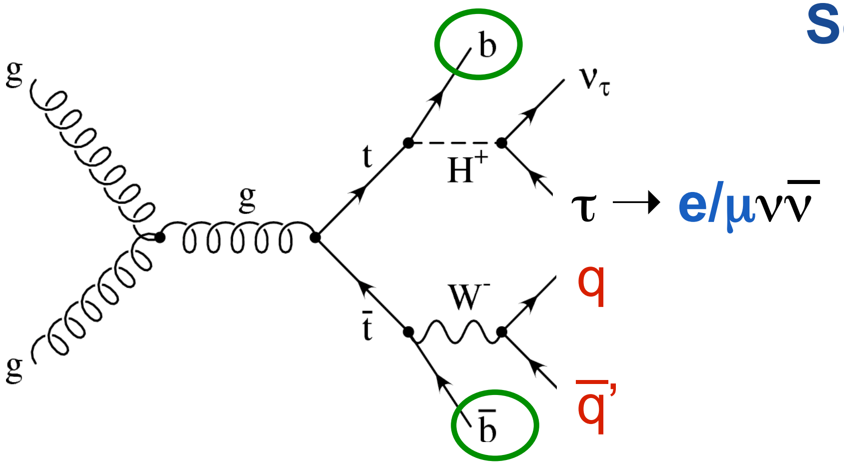
for $m_{H^+} < m_{top}$:





$t\bar{t} \to b\bar{b}H^{\pm}W^{\mp} \to b\bar{b}(\tau_{lep}\nu)(q\bar{q})$	: lepton + jets
$t\bar{t} \to b\bar{b}H^{\pm}W^{\mp} \to b\bar{b}(\tau_{had}\nu)(\ell\nu)$	: τ_{had} + lepton
$t\bar{t} \to b\bar{b}H^{\pm}W^{\mp} \to b\bar{b}(\tau_{had}\nu)(q\bar{q})$	: τ_{had} + jets

Charged Higgs: Lepton + jets channel



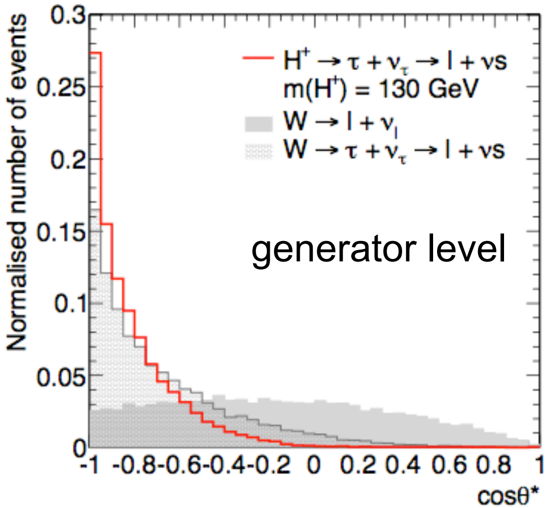
Selection:

- **1 isolated e / μ** with p_T > 25 / 20 GeV
- ≥ 4 jets **(2 b-tagged)** with p_T > 20 GeV
- E_T^{miss} > 40 GeV if $|\Phi_{l,miss}| > \pi/6$
  $E_T^{miss} \times |\sin(\Phi_{l,miss})|$ > 20 GeV if $|\Phi_{l,miss}| < \pi/6$
- Identify **"hadronic side"** by choosing combination of 1 b-jet and 2 light jets that minimizes $\chi^2 = \frac{(m_{jjb} - m_{top})^2}{\sigma_{top}^2} + \frac{(m_{jj} - m_W)^2}{\sigma_W^2}$

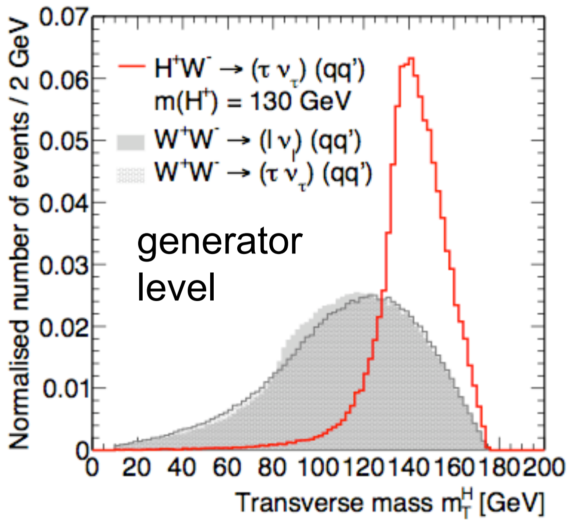
Discriminating variables:

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

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



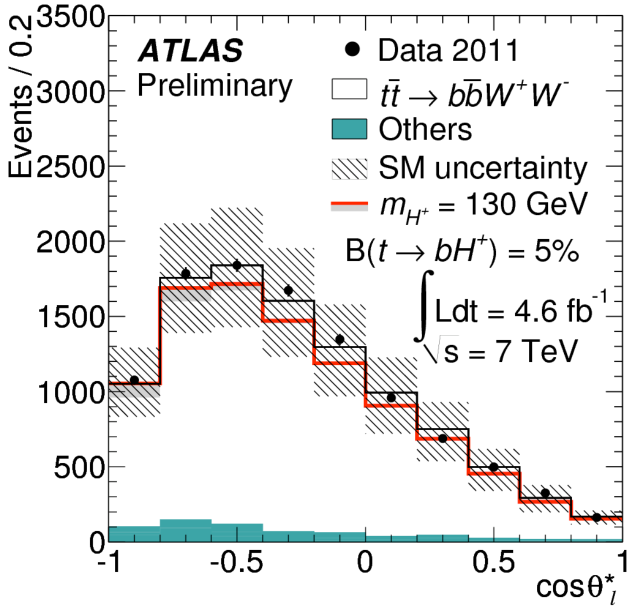
Discriminates between leptons from τ and W

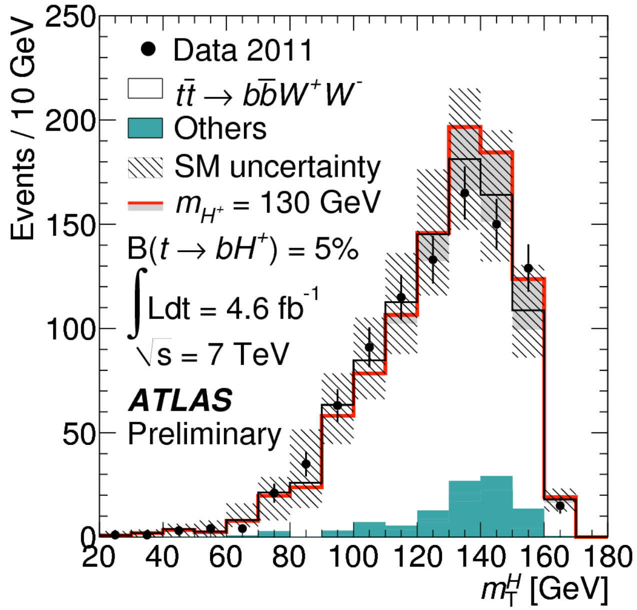


Lower bound ~ mass of charged boson (H^+ or W)

Charged Higgs: Lepton + jets channel

Signal region: $\cos\theta_l^* < -0.6$, $m_T(l, E_T^{miss}) < 60$ GeV





Sample	Event yield (lepton+jets)
$t\bar{t}$	840 ± 20 ± 150
Single top quark	28 ± 2 $^{+8}_{-6}$
W+jets	14 ± 3 $^{+6}_{-3}$
Z+jets	2.1 ± 0.7 $^{+1.2}_{-0.4}$
Diboson	0.5 ± 0.1 ± 0.2
Misidentified leptons	55 ± 10 ± 20
$\sum$ SM	940 ± 22 ± 150
Data	933
$t \to bH^+$ (130 GeV)	120 ± 4 ± 25

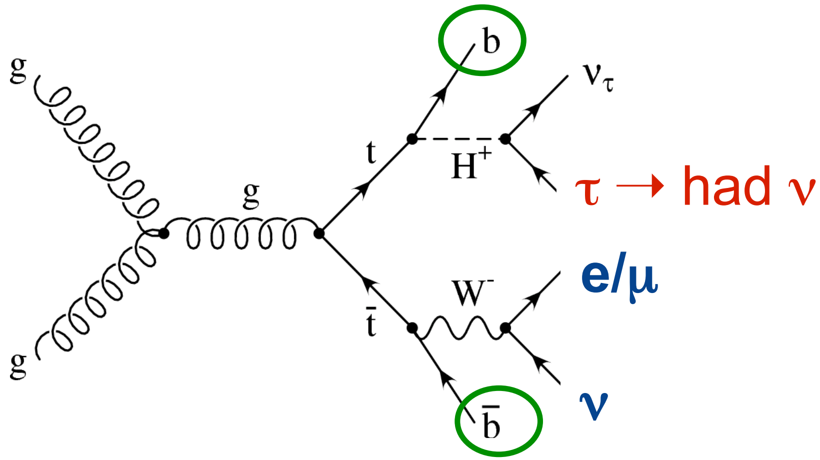
Dominant background from **top pairs**!
Simulated with MC@NLO, normalized in $-0.2 < \cos\theta^*_l < 1$

Misidentified-lepton background determined from control sample with **loosened** lepton ID

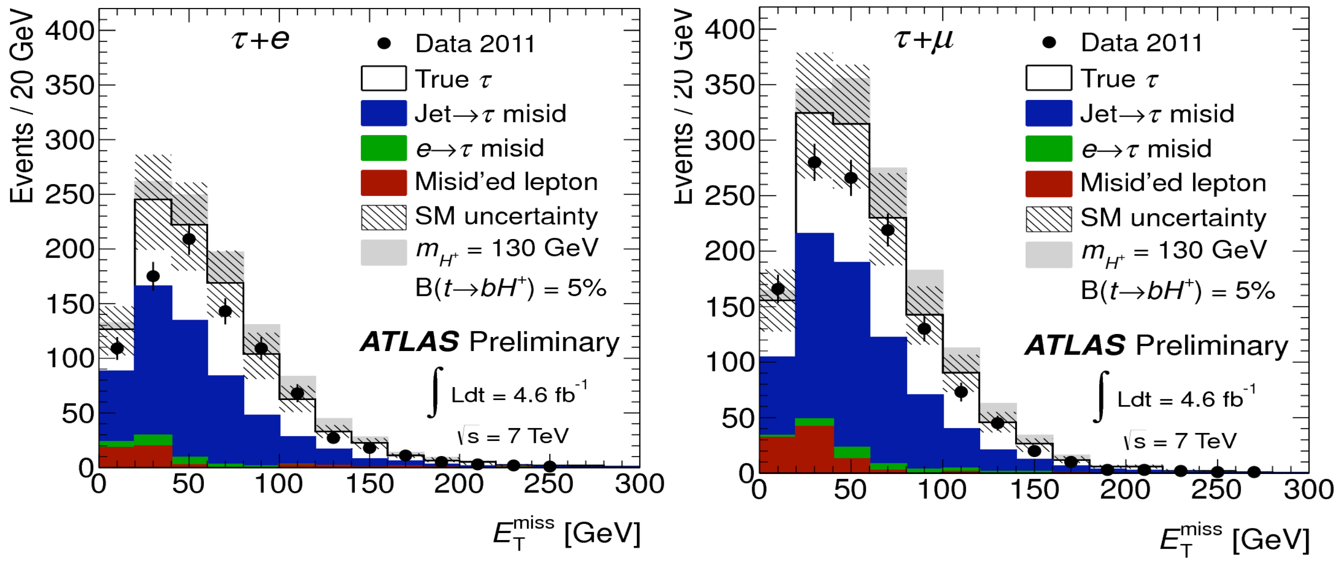
Charged Higgs: τ_{had} + lepton channel

Selection:

- **1 isolated e / μ** with p_T > 25 / 20 GeV
- **1 τ_{had}** with p_T > 20 GeV
- ≥ 2 jets **(≥ 1 b-tagged)** with p_T > 20 GeV
- Sum of primary-vertex track p_T:
  $\Sigma p_T > 100$ GeV



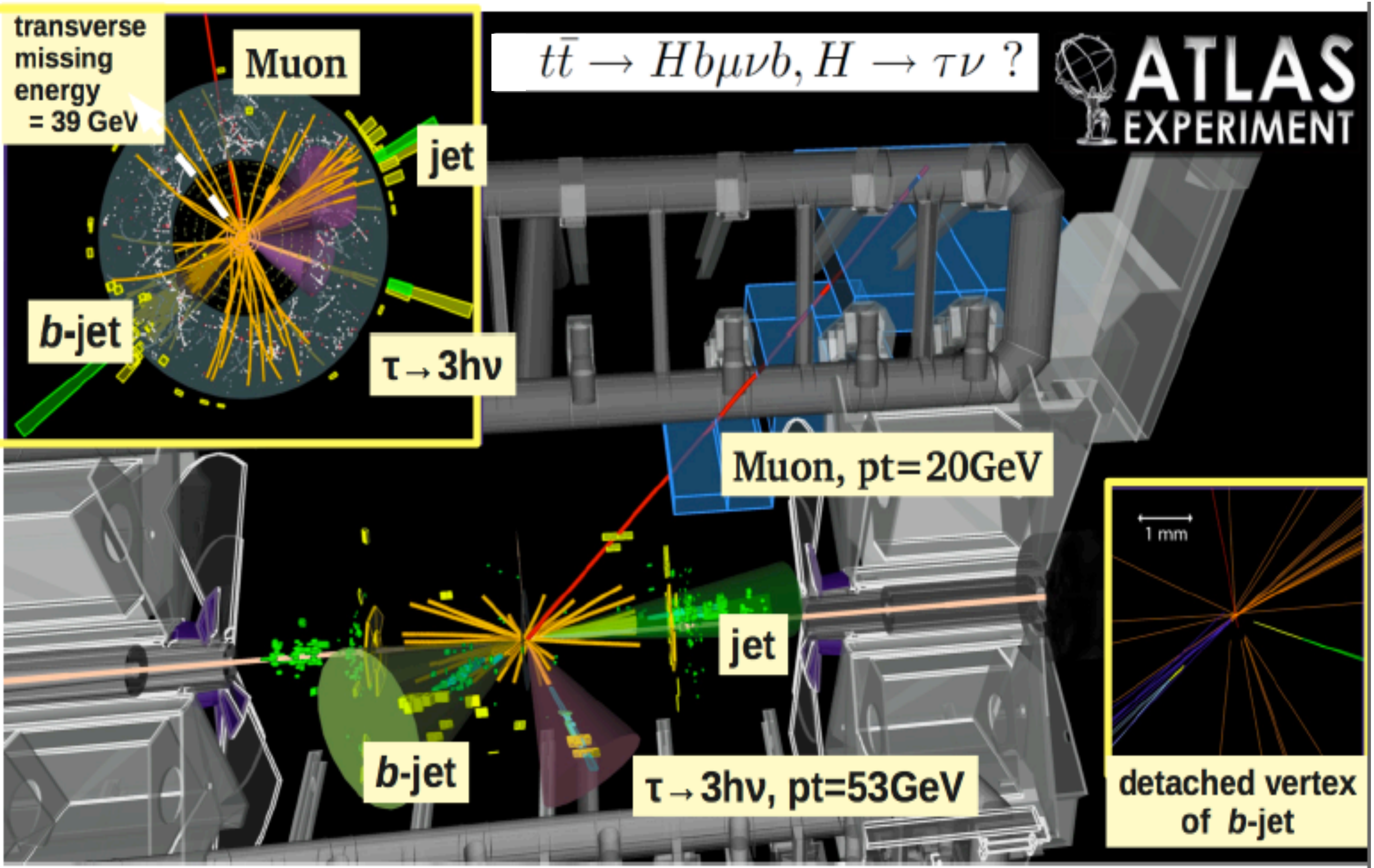
Discriminating variable: E_T^{miss}



- **Background** contributions with **misidentified taus**:
  μ: 0.05%, e: 1%, jets: 55% ; jet → τ_{had} mis-ID measured with W+jets

- **True-tau background** taken from simulation

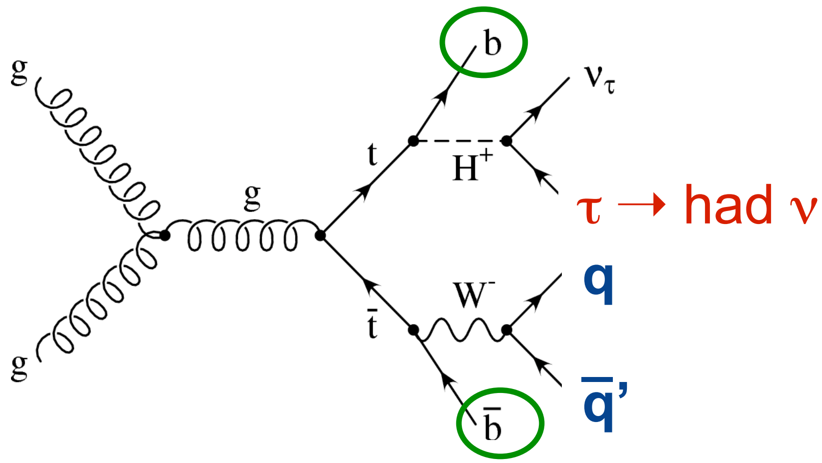
A candidate event in τ_{had} + lepton channel



Charged Higgs: τ_{had} + jets channel

Selection:

- **τ + E_T^{miss} trigger**
- **1 τ_{had}** with p_T > 40 GeV
- $\geq$ 4 jets **($\geq$ 1 b-tagged)** with p_T > 20 GeV
- **E_T^{miss} > 65 GeV**
- **E_T^{miss} significance:** $\frac{E_T^{miss}}{0.5 \cdot \sqrt{\sum p_T}} > 13 \text{ GeV}^{1/2}$
- jjb combination (hightest p_T) consistent m_{top}

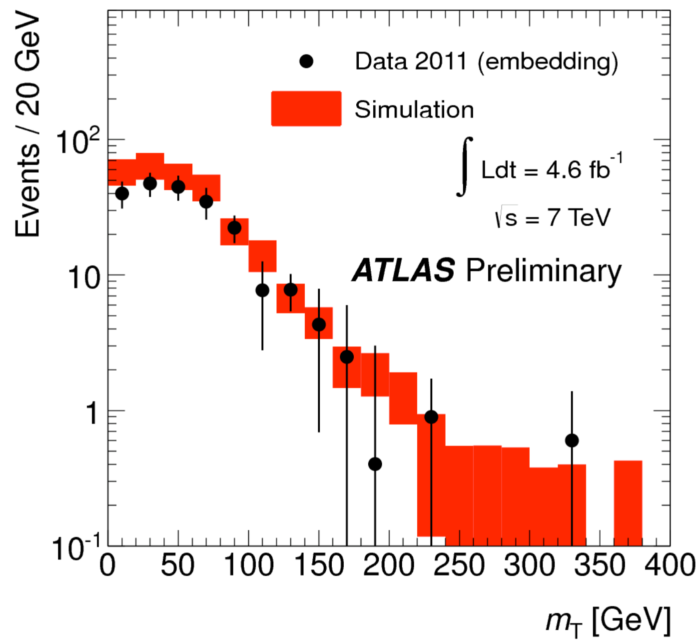


Discriminating variable:

$$m_T = \sqrt{2 p_T^\tau E_T^{miss} (1 - \cos \phi_{\tau,miss})},$$

- **True-tau background** estimated with **τ embedding** in **μ+jets** events (with top-pair like event topology)

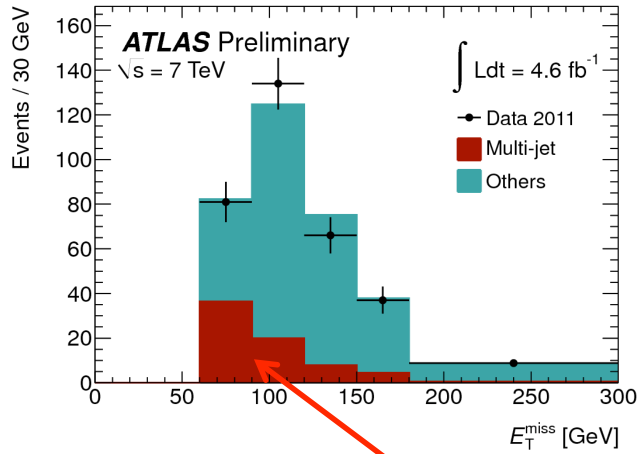
- Mis-id. tau background: as for τ_{had}+lepton



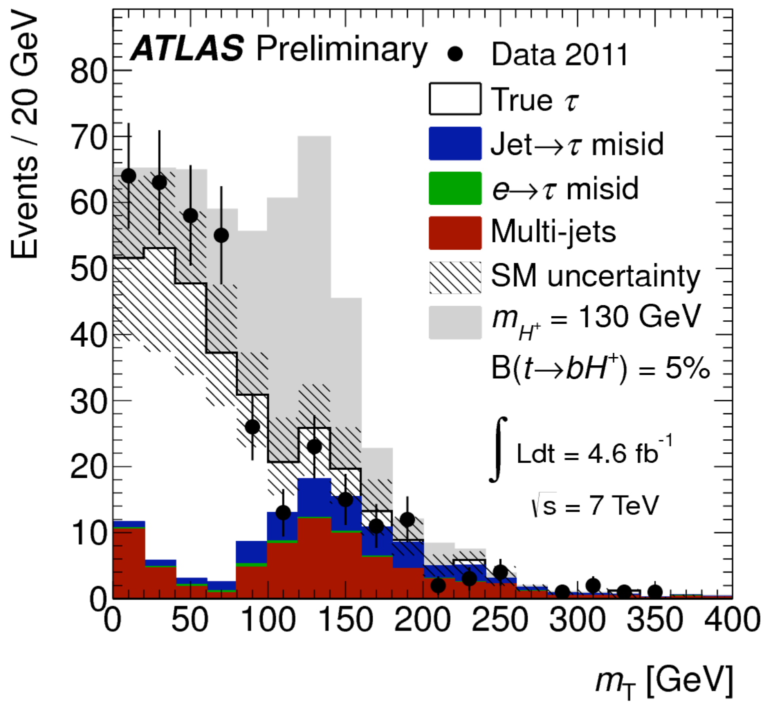
Charged Higgs: τ_{had} + jets channel

Sample	Event yield (τ+jets)
True τ (embedding method)	$210 \pm 10 \pm 44$
Misidentified jet$\rightarrow \tau$	$36 \pm 6 \pm 10$
Misidentified $e \rightarrow \tau$	$3 \pm 1 \pm 1$
Multi-jet processes	$74 \pm 3 \pm 47$
$\sum$ SM	$330 \pm 12 \pm 65$
Data	355
$t \rightarrow bH^{+}$ (130 GeV)	$220 \pm 6 \pm 56$

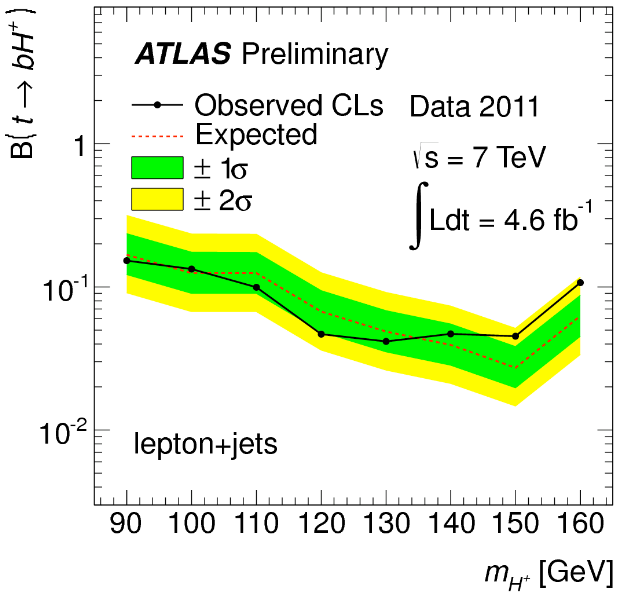
Multijet background estimated by **fitting E_T^{miss} shapes to data**.

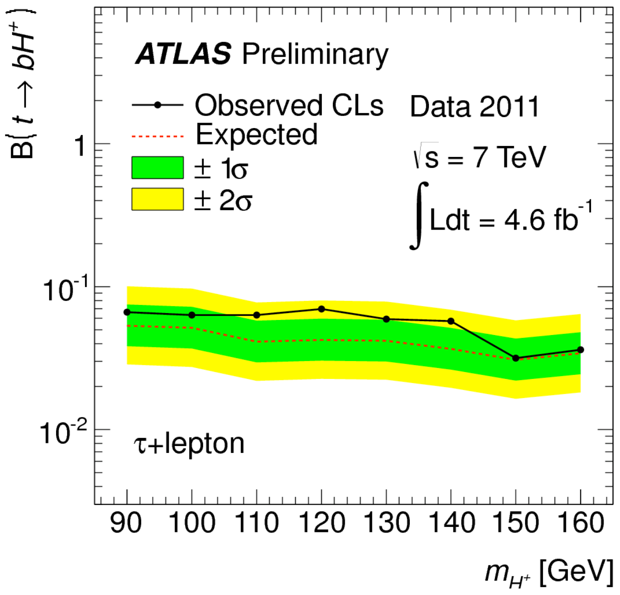


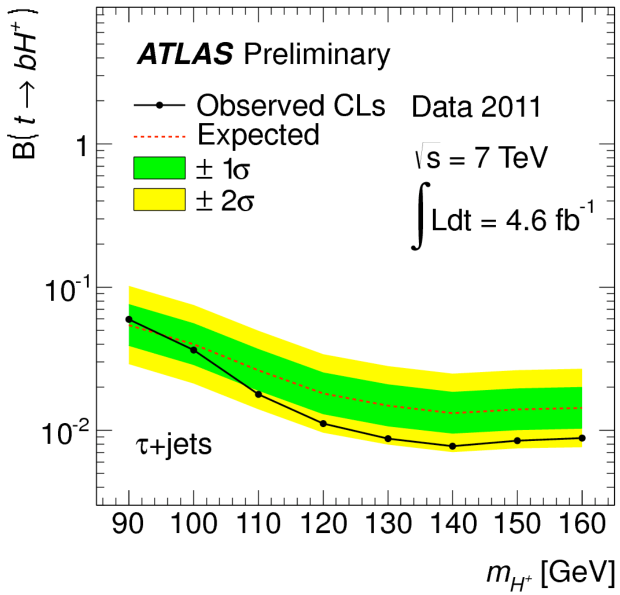
Multijet shape from control sample with inverted τ and b ID



Charged Higgs: Exclusion limits







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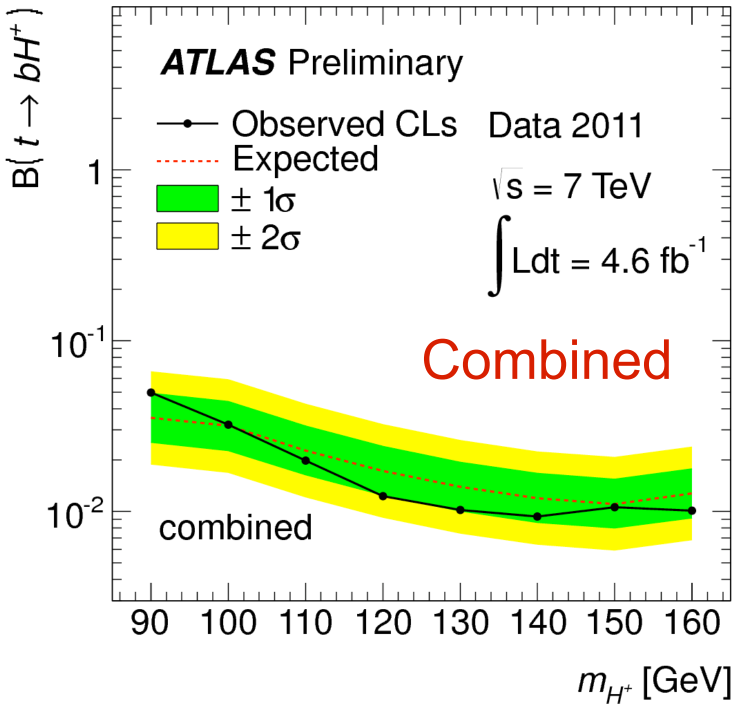
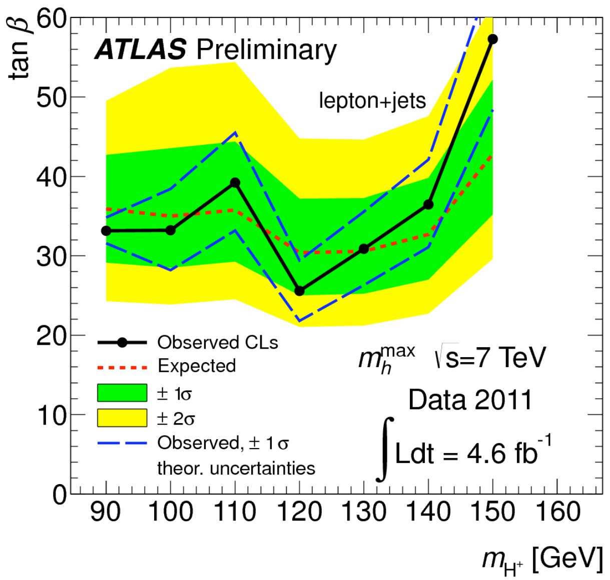
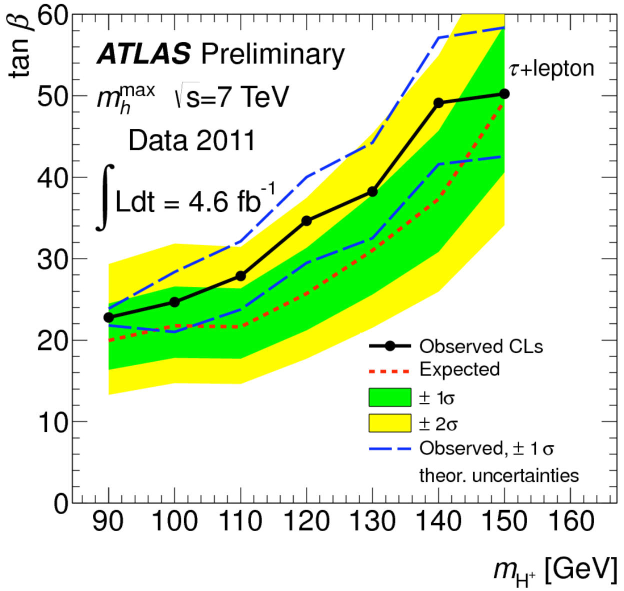


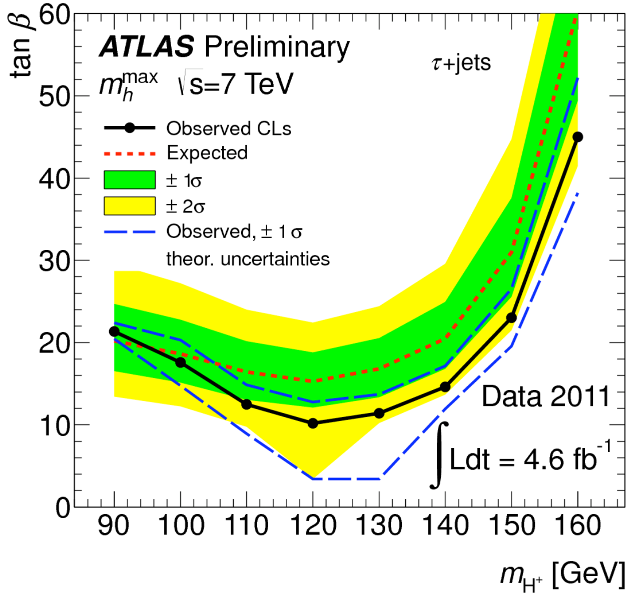
Tevatron limits:

BR < 10-15%

Charged Higgs: Exclusion limits (MSSM)







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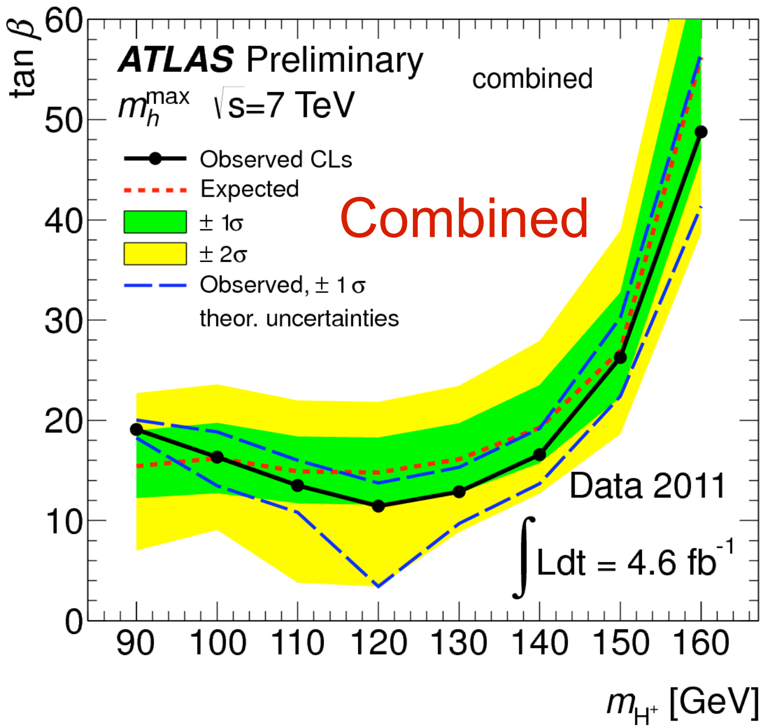
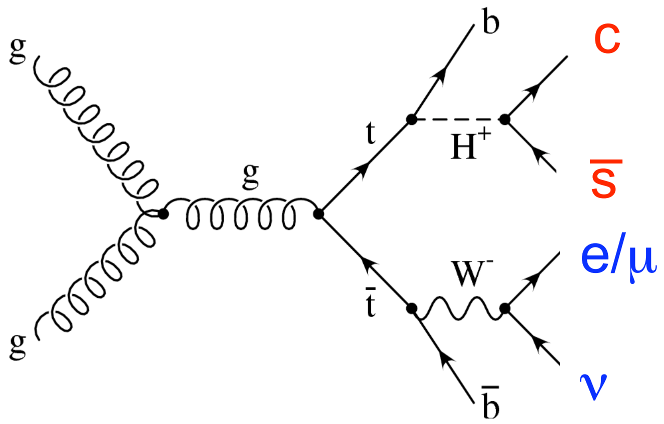
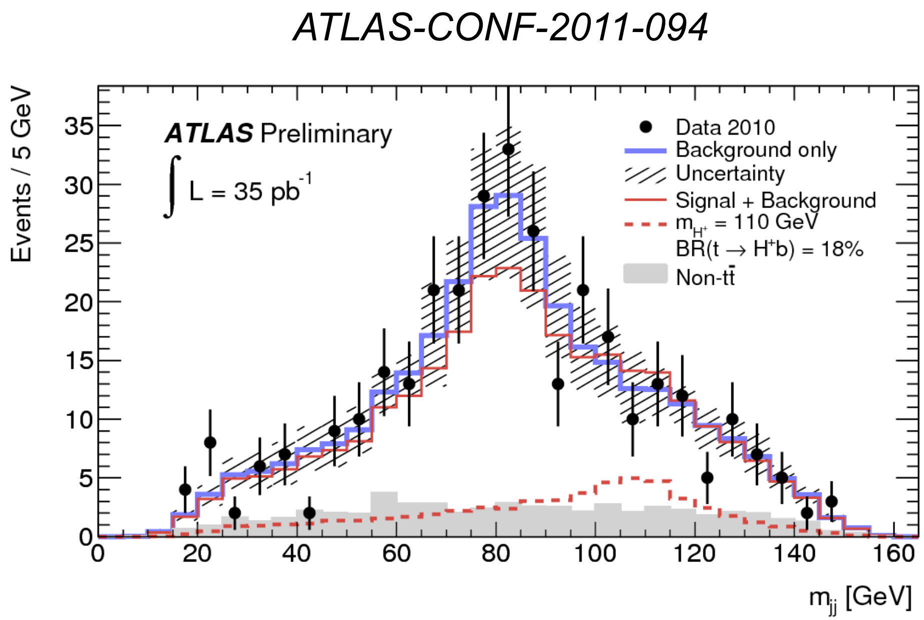


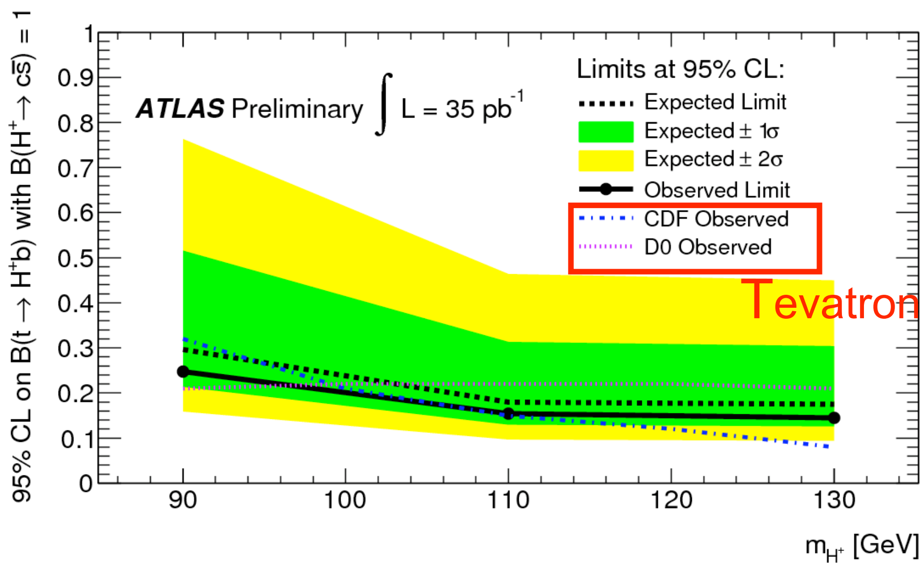
…we will probably be able to rule out low-mass charged Higgs with 2012 data, if it doesn't exist!

Charged Higgs: $H^+ \rightarrow c\bar{s}$

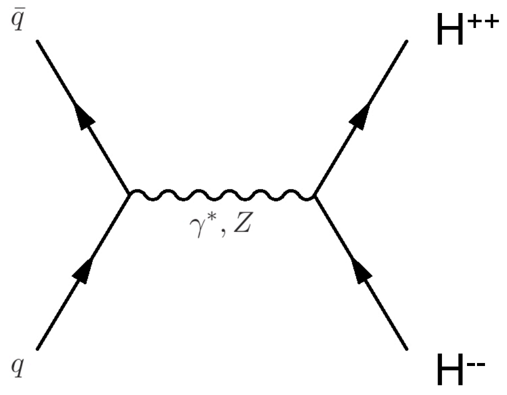


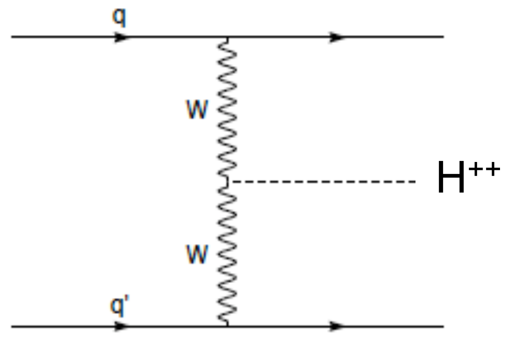


- $H \rightarrow c\bar{s}$ dominates for $\tan\beta < 1$
- Require **large E_T^{miss}** and **m_T** to suppress multijet background
- **Kinematic fit** with **W and top mass contraints** to find best H^+ candidate
- Set limits on $BR(t \rightarrow H^+b)$ assuming $BR(H^+ \rightarrow c\bar{s}) = 100\%$

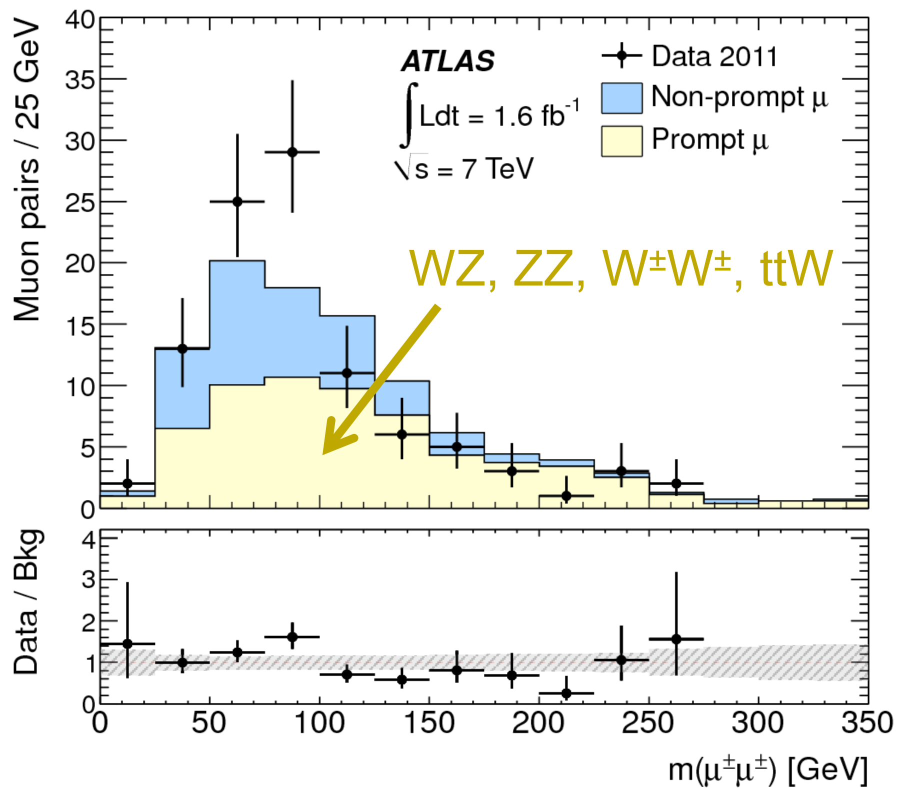


Doubly-charged Higgs





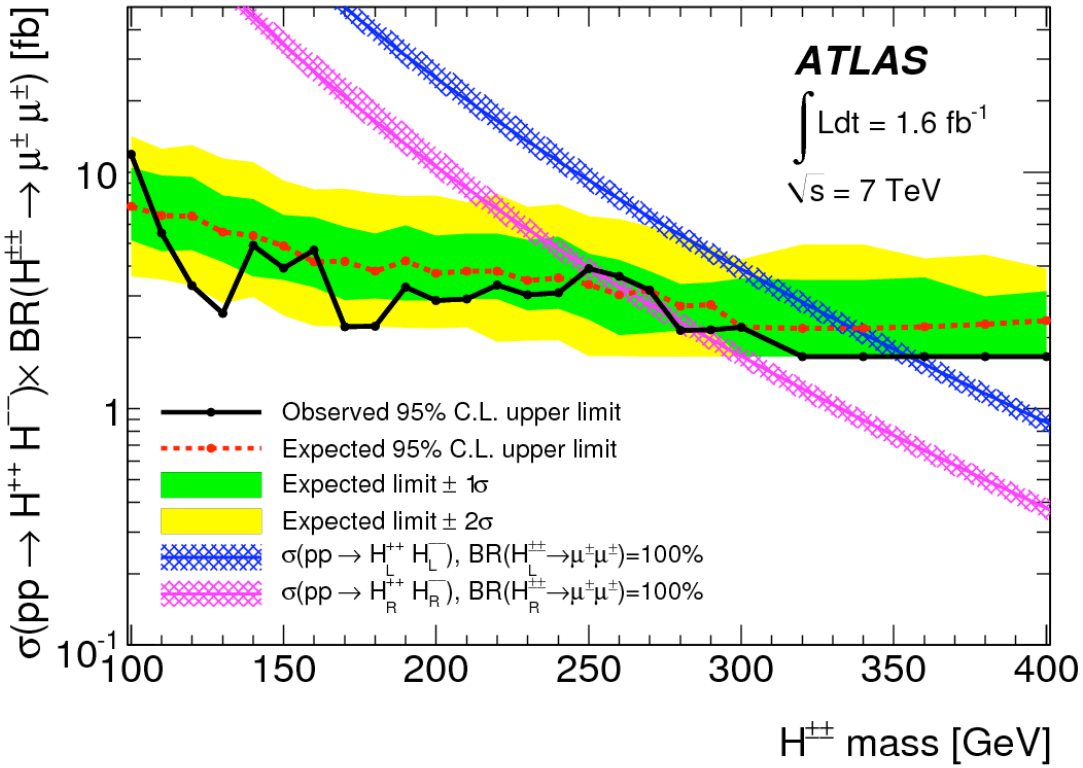
- Relevant e.g. in **Higgs triplet**, **Little Higgs** and **Left-Right Symmetric** models
- Select **μ pairs** with **same-sign charges** and p_T> 20 GeV
- Look for **resonance in $\mu^\pm\mu^\pm$ mass spectrum**
- **No significant excess** over SM background found

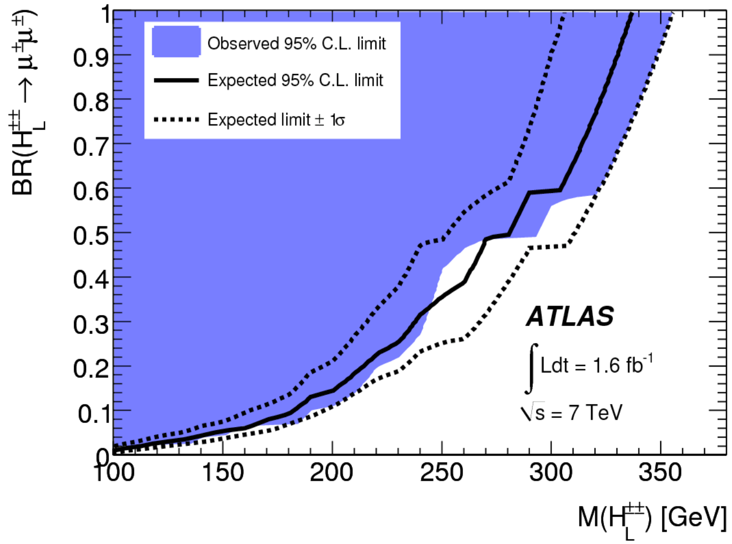


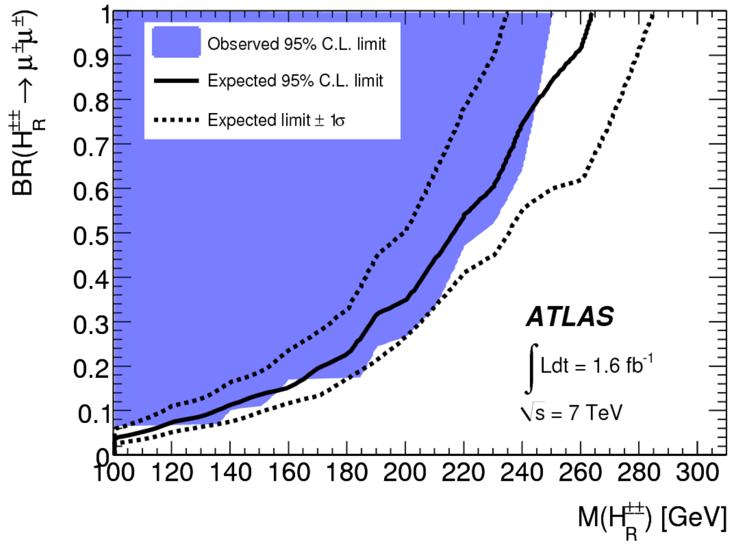
Doubly-charged Higgs: Exclusion limits

Set limits on $H^{++} H^{--}$ pair production via Drell Yan process $pp \rightarrow Z/\gamma^* \rightarrow H^{++} H^{--}$

Assuming predicted cross section, set limits on BR





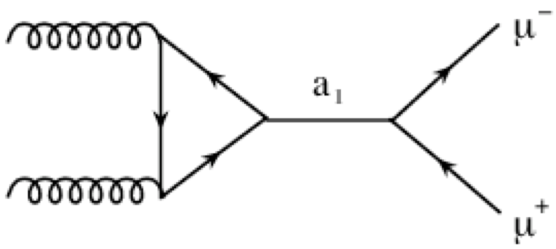


Right-handed Higgs mass < 251 GeV
Left -handed Higgs mass < 355 GeV
@95% CL if $Br(H^{++} \rightarrow \mu^+ \mu^+)=100\%$

Tevatron (CDF) upper limit: 205-245 GeV

Phys.Rev.D 88 (2012) 032004

NMSSM $a_1 \rightarrow \mu^+\mu^-$

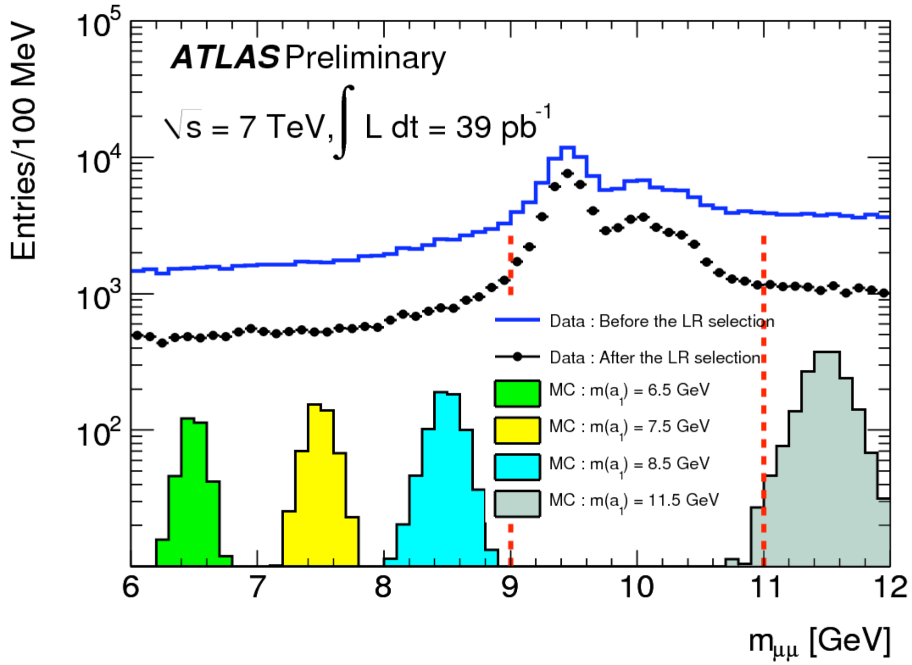


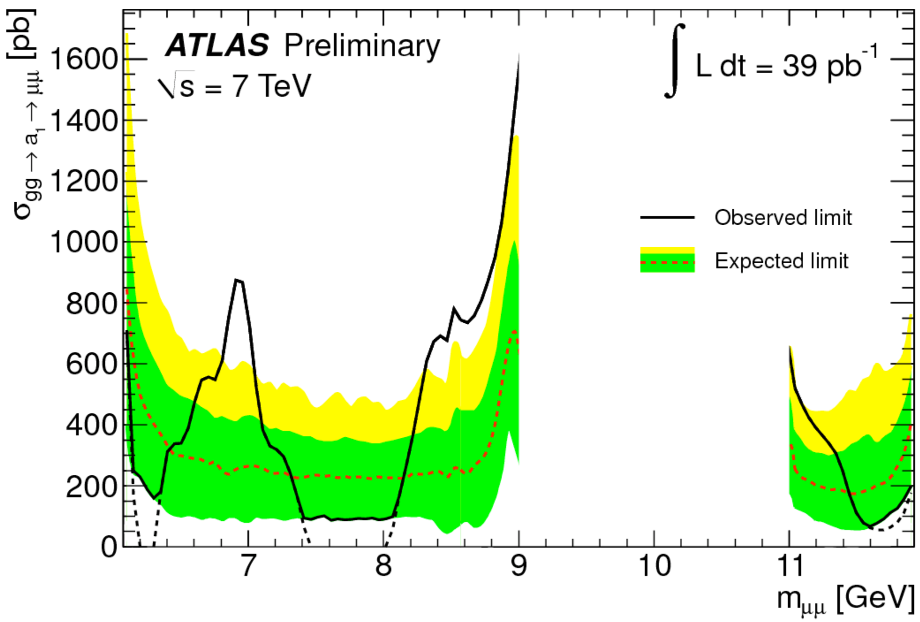
- **NMSSM**: introduces **singlet scalar field** to solve μ problem

  $\Rightarrow$ 3 CP-even scalars (h_1, h_2, h_3)
  2 CP-odd scalars (**a_1**, a_2)
- a_1 can be **very light**!
  $m_{a1} < 2\, m_B$

Analysis:

- Opposite-sign **di-muons** (P_T>4GeV)
- Likelihood ratio selection based on $\mu^+\mu^-$ **vertex χ^2** and **μ isolation**
- Set limits **by fitting to mass spectrum**
- Υ region excluded





ATLAS-CONF-2011-020

Conclusions

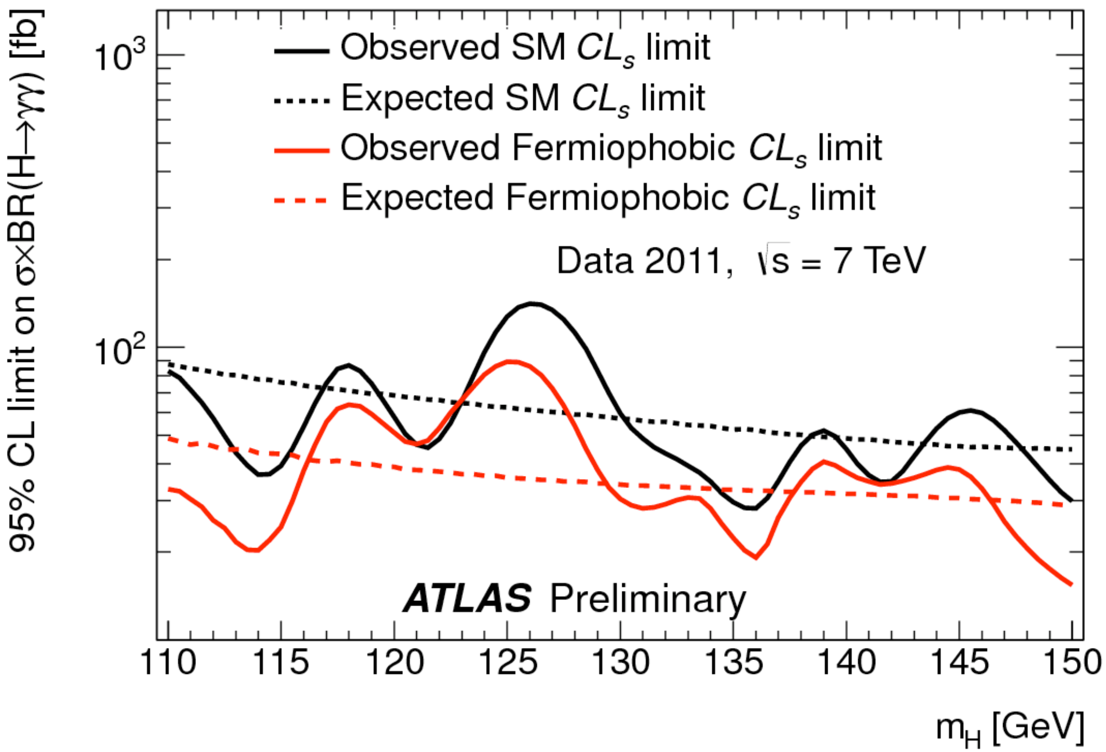
- Various interesting BSM Higgs scenarios are being probed in parallel to SM Higgs search

- No indication for BSM Higgs bosons yet …
  but lots of upper limits on cross sections/branching ratios

- Searches continue with more data and improved methods
  $\Rightarrow$ There is still significant room for BSM Higgs searches for the year ahead … and after!

Backup Slides

Fermiophobic Higgs → γγ : Exclusion limits



Fermiophobic Higgs $\to \gamma\gamma$: Systematics

Signal event yield	
Photon reconstruction and identification	±11%
Effect of pileup on photon identification	±4%
Isolation cut efficiency	±5%
Trigger efficiency	±1%
Higgs boson cross section	±9%
Luminosity	±3.9%
Signal mass resolution	
Calorimeter energy resolution	±12%
Photon energy calibration	±6%
Effect of pileup on energy resolution	±3%
Photon angular resolution	±1%
Signal category migration	
Higgs boson p_T modelling	±1%
Conversion rate	±4.5%
Background model	± (0.1 – 7.9) events

MSSM Higgs sector

- MSSM: 2 Higgs doublets ⇒ 5 Higgs bosons:

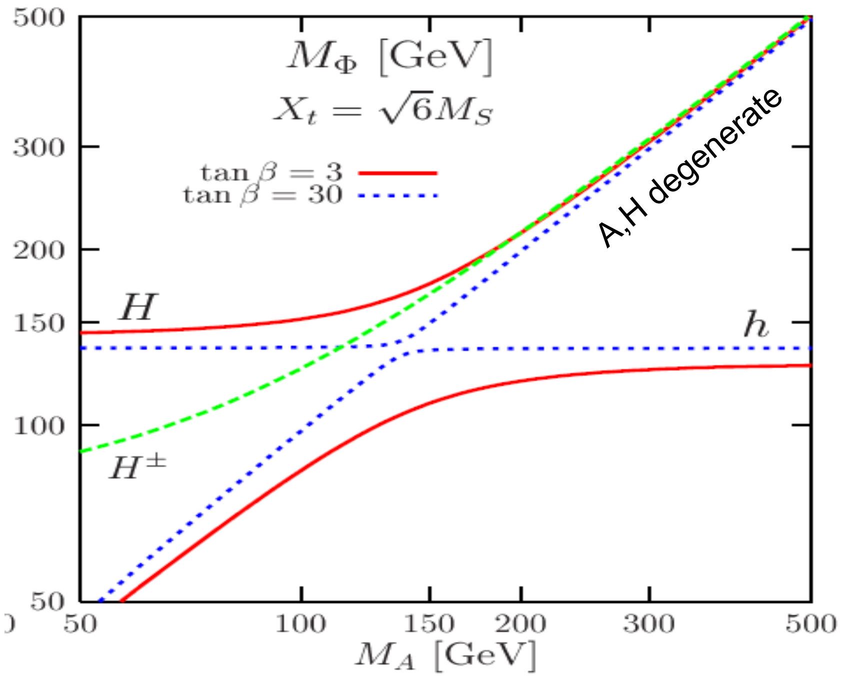
  h^0 (CP=1) , H^0 (CP=1) , A^0 (CP=-1), $H^{\pm}$

- At tree level described by two parameters: m_A, $\tan\beta = v_u/v_d$

- Fixed mass relations at tree level:

$$m^2_{H,h} = \frac{1}{2}\left(m^2_A + m^2_Z \pm \sqrt{(m^2_A + m^2_Z)^2 - 4m^2_Z m^2_A \cos^2 2\beta}\right)$$

$$m^2_h \leq m^2_Z \cos^2 2\beta \leq m^2_Z$$

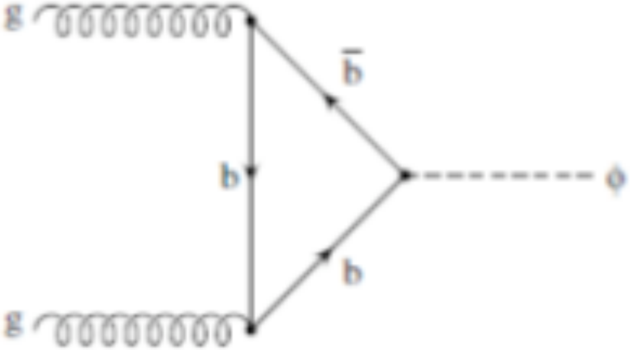


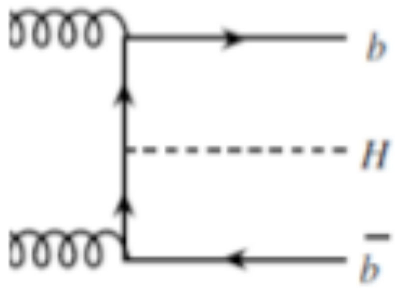
- Upper mass bound modified by radiative corrections (depend on SUSY parameters, e.g. mixing in stop sector)

All parameters except tanβ, m_A fixed in benchmark scenarios:

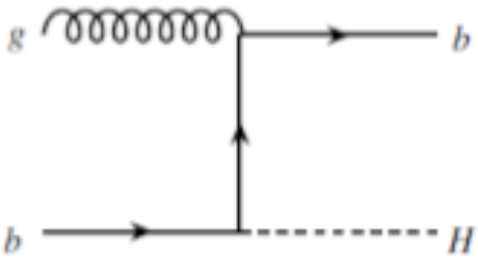
m_h^{max}:	m_h < 133 GeV, maximum allowed mass for h
nomixing:	m_h < 116 GeV, no mixing in stop sector
gluphobic:	m_h < 119 GeV, suppressed gg fusion
small α:	m_h < 123 GeV, suppressed ttbar h, h → bb

MSSM Higgs production

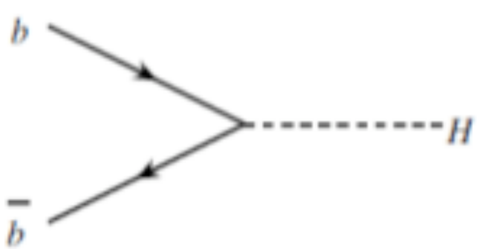




$gg \to b\bar{b}H$



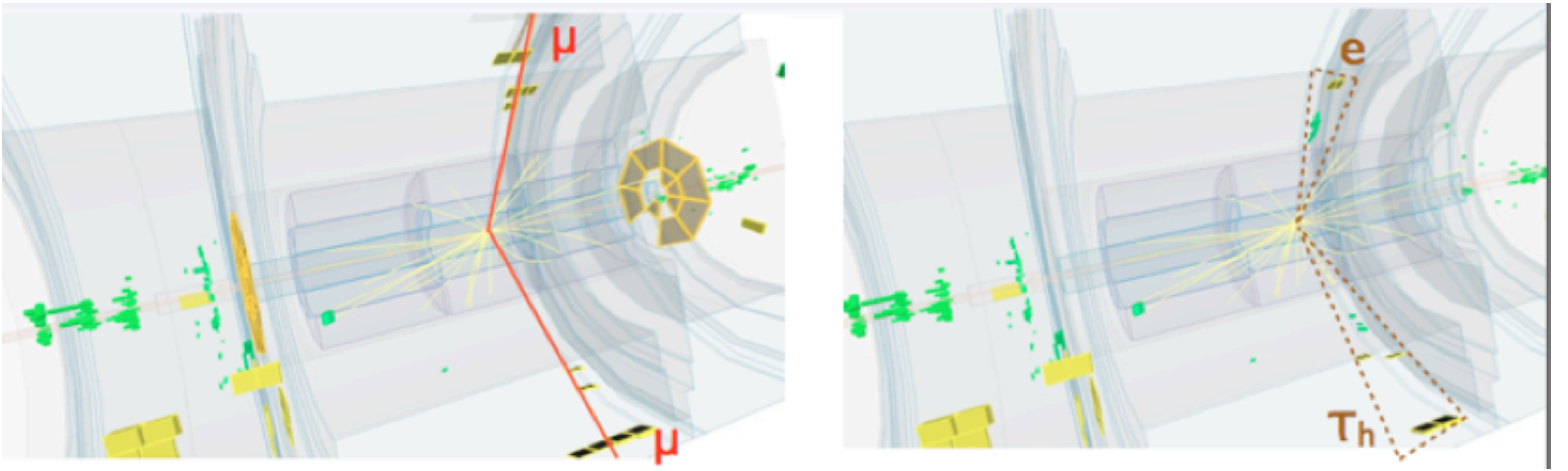
$bg \to bH$



$b\bar{b} \to H$

Estimation of $Z \rightarrow \tau\,\tau$ Background

- Reliable $Z \rightarrow \tau\,\tau$ model important for low-mass Higgs
- Desirable to use real data, but cannot be selected signal-free
- Instead, use high-purity $Z \rightarrow \mu\,\mu$ sample (~ signal-free due to small Higgs-μ coupling)

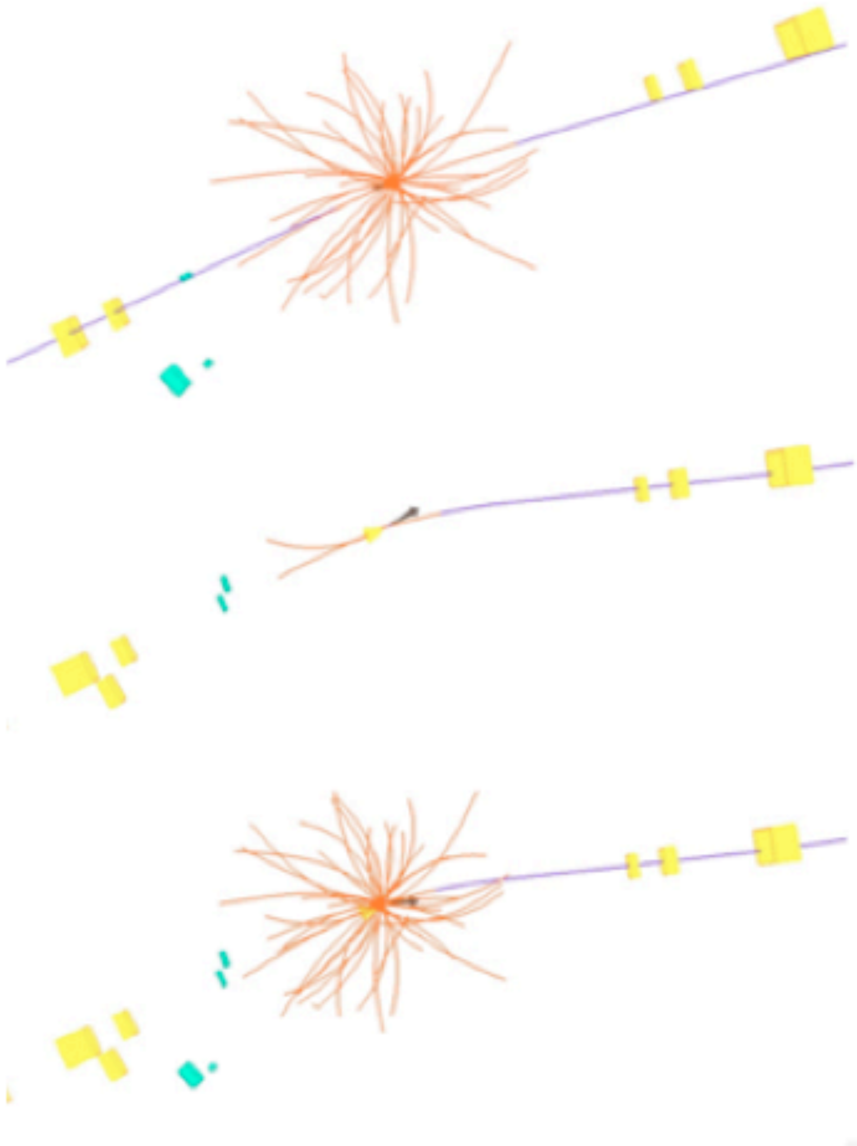


$Z \rightarrow \tau\,\tau$ "Embedding": Method

- In $Z \rightarrow \mu\,\mu$ events, remove muon tracks and nearby calorimeter cells

- Simulate stand-alone $Z \rightarrow \tau\,\tau$ decays with same 4-momenta for the τ's as for the muons (after mass correction)

- Merge into single hybrid event and re-reconstruct objects and E_T^{miss}



Neutral MSSM Higgs: Background Estimation

- Estimate background from same-sign (SS) data sample

$$n_{\mathrm{OS}}^{Bkg} = \boxed{n_{\mathrm{SS}}^{Bkg}} + n_{\mathrm{OS-SS}}^{\mathrm{QCD}} + n_{\mathrm{OS-SS}}^{W} + n_{\mathrm{OS-SS}}^{Z} + n_{\mathrm{OS-SS}}^{\mathrm{other}}$$

$$\approx \boxed{n_{\mathrm{SS}}^{Bkg}} + n_{\mathrm{OS-SS}}^{W} + n_{\mathrm{OS-SS}}^{Z} + n_{\mathrm{OS-SS}}^{\mathrm{other}}$$

- Assumption made for QCD: $\boxed{r_{\mathrm{QCD}} = n(OS)/n(SS) \approx 1}$

Checked with QCD-enhanced sample
- $E_T^{miss} < 15$ GeV
- loosened lepton isolation

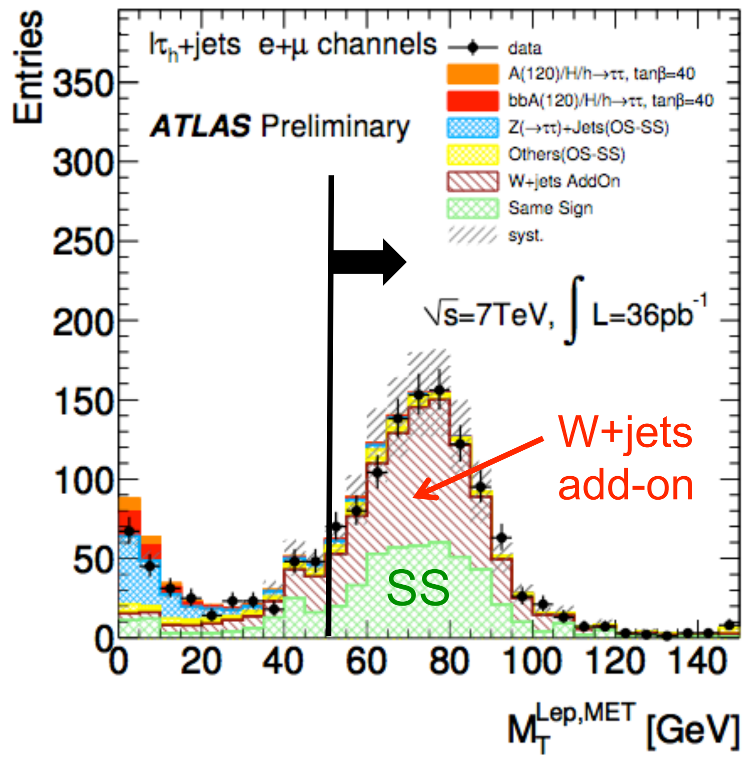
$$r_{\mathrm{QCD}} = 1.16 \pm 0.04^{stat} \pm 0.09^{syst}$$

$$r_{\mathrm{QCD}}^{MC} = 1.06 \pm 0.13^{stat}$$

Neutral MSSM Higgs: Background Estimation

$$n_{\mathrm{OS}}^{Bkg} \approx \boxed{n_{\mathrm{SS}}^{Bkg}} + \underbrace{\boxed{n_{\mathrm{OS-SS}}^{W}} + \boxed{n_{\mathrm{OS-SS}}^{Z}} + \boxed{n_{\mathrm{OS-SS}}^{other}}}_{\text{OS-SS “add-on” due to } r_{OS/SS} \neq 1}$$

- n_{SS} from nominal selection with $Q(\ell)\cdot Q(\tau) = +1$
- $Z \rightarrow \tau^+\tau^-$ and other background OS-SS “add-on” from simulation
- W+jets OS-SS “add-on”: from $M_T > 50$ GeV control sample



Neutral MSSM Higgs: Systematics

Table 4: Uncertainties on the number of selected events for those background contributions that are at least partially estimated from simulation and for a hypothetical signal (m_A = 120 GeV and $\tan\beta = 20$ for the $e\mu$ and $\ell\tau_{had}$ final states and m_A = 200 GeV and $\tan\beta = 20$ for the $\tau_{had}\tau_{had}$ final state). All numbers are given in %. When three numbers are given the first refers to the $e\mu$ final state, the second to the $\ell\tau_{had}$ final states and the third to the $\tau_{had}\tau_{had}$ final state. If an uncertainty does not apply for a certain background, this is indicated by a "-". For the $e\mu$ final state, the uncertainty on the W+jets background is dominated by the statistical component and the systematic uncertainty is neglected; for the $\ell\tau_{\rm had}$ final state the W+jets background is estimated from data.

	W+jets	Di-boson	$t\bar{t}$+ single-top	$Z/\gamma^* \to ee,\mu\mu$	$Z/\gamma^* \to \tau^+\tau^-$	Signal
$\sigma_{inclusive}$	-/-/5	7	10	5/5/-	5	14/14/16
Acceptance	-/-/20	4/2/7	3/2/9	2/14/-	5/14/14	5/7/9
e efficiency	-/-/0.8	4/3.1/0.5	4/3.6/0.3	4/3.1/-	4/3.0/0.5	4/3.6/0.1
μ efficiency	-/-/0.3	2/1.2/0.4	2/1.1/0.0	2/1.3/-	2/1.8/0.4	2/1.0/0.1
τ efficiency and fake rate	-/-/21	-/9.1/15	-/9.1/13	-/48/-	-/9.1/15	-/9.1/15
Energy scales and resolution	-/-/$^{+34}_{-21}$	2/$^{+19}_{-9}$/$^{+26}_{-12}$	6/$^{+5}_{-4}$/12	1/$^{+39}_{-25}$/-	1/11/$^{+63}_{-23}$	1/$^{+30}_{-23}$/$^{+9}_{-8}$
Luminosity	-/-/3.7	3.7	3.7	3.7/3.7/-	3.7	3.7
Total uncertainty	-/-/$^{+45}_{-36}$	10/$^{+23}_{-16}$/$^{+32}_{-22}$	13/15/23	8/$^{+64}_{-56}$/-	9/21/$^{+67}_{-31}$	16/$^{+35}_{-30}$/$^{+26}_{-25}$

H^+: Estimation of mis-ID lepton background

Misidentified-lepton background determined from samples with **tight** (T) and **loose** (L) lepton ID:

$$\begin{aligned} N^L &= N_m^L + N_r^L \\ N^T &= N_m^T + N_r^T \end{aligned}$$

$$\boxed{N_m^T = \frac{p_m}{p_r - p_m}(p_r N^L - N^T)}$$

with $p_r = \dfrac{N_r^T}{N_r^L}$ and $p_m = \dfrac{N_m^T}{N_m^L}$

from $Z \to e^+e^-$ from multi-jets

Charged Higgs: Systematics

Source of uncertainty	Normalisation uncertainty
lepton+jets:	
Generator and parton shower ($b\bar{b}WH^+$, signal region)	10%
Generator and parton shower ($b\bar{b}W^+W^-$, signal region)	8%
Generator and parton shower ($b\bar{b}WH^+$, control region)	7%
Generator and parton shower ($b\bar{b}W^+W^-$, control region)	6%
Initial and final state radiation (signal region)	8%
Initial and final state radiation (control region)	13%
τ+lepton:	
Generator and parton shower ($b\bar{b}WH^+$)	2%
Generator and parton shower ($b\bar{b}W^+W^-$)	5%
Initial and final state radiation	13%
τ+jets:	
Generator and parton shower ($b\bar{b}WH^+$)	5%
Generator and parton shower ($b\bar{b}W^+W^-$)	5%
Initial and final state radiation	19%

Charged Higgs: Systematics

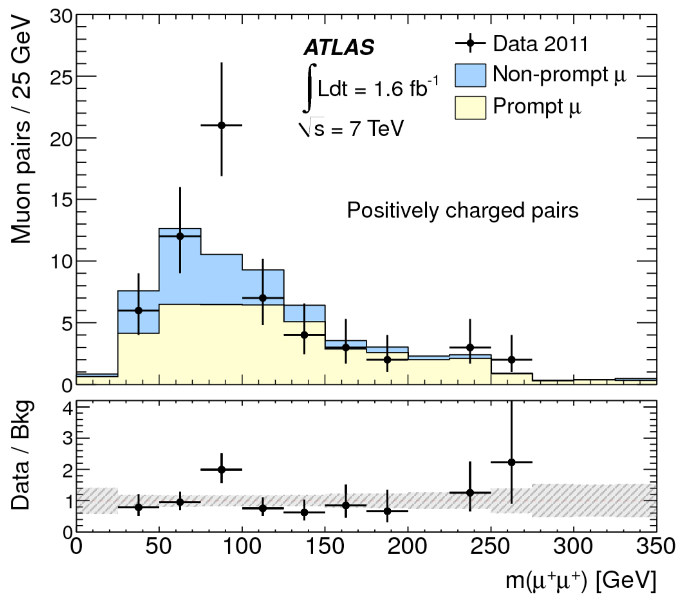
Source of uncertainty	Normalisation uncertainty	Shape uncertainty
lepton+jets: lepton misidentification		
Choice of control region	6%	-
Z mass window	4%	-
Jet energy scale	16%	-
Jet energy resolution	7%	-
Sample composition	31%	-
τ+lepton: jet$\rightarrow$ τ misidentification		
Statistics in control region	2%	-
Jet composition	11%	-
Object-related systematics	23%	3%
τ+lepton: e$\rightarrow$ τ misidentification		
Misidentification probability	20%	-
τ+lepton: lepton misidentification		
Choice of control region	4%	-
Z mass window	5%	-
Jet energy scale	14%	-
Jet energy resolution	4%	-
Sample composition	39%	-
τ+jets: true τ		
Embedding parameters	6%	3%
Muon isolation	7%	2%
Parameters in normalisation	16%	-
τ identification	5%	-
τ energy scale	6%	1%
τ+jets: jet$\rightarrow$ τ misidentification		
Statistics in control region	2%	-
Jet composition	12%	-
Purity in control region	6%	1%
Object-related systematics	21%	2%
τ+jets: e$\rightarrow$ τ misidentification		
Misidentification probability	22%	-
τ+jets: multi-jet estimate		
Fit-related uncertainties	32%	-
$E_{\mathrm{T}}^{\mathrm{miss}}$-shape in control region	16%	-

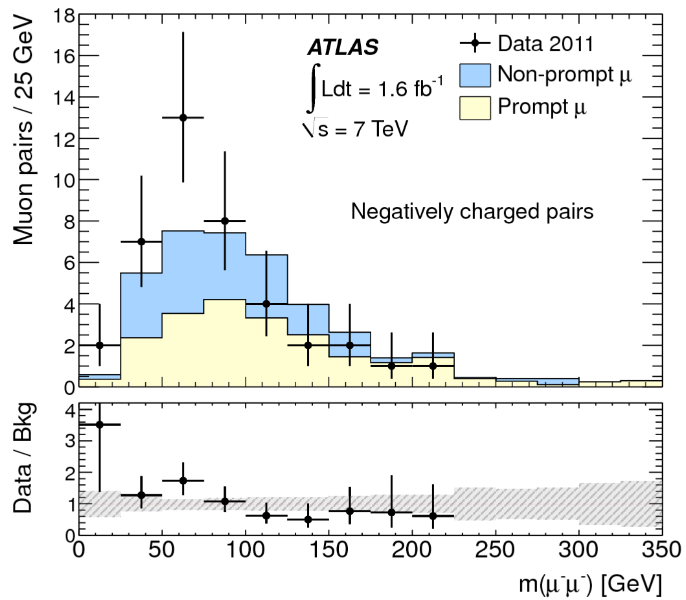
Doubly-Charged Higgs: Event yields

Sample	Number of muon pairs with $m(\mu^\pm\mu^\pm)$			
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV
prompt muons	63.1 ± 7.8	34.9 ± 4.5	9.6 ± 1.6	2.24 ± 0.54
non-prompt muons	$37.5^{+10.3}_{-12.4}$	13.0 ± 4.5	1.8 ± 0.7	0.31 ± 0.18
charge flip	$0^{+2.7}_{-0.0}$	$0^{+0.9}_{-0.0}$	$0^{+0.7}_{-0.0}$	$0^{+0.61}_{-0.00}$
total	$100.6^{+13.2}_{-14.7}$	48.0 ± 6.4	$11.4^{+1.8}_{-1.7}$	$2.56^{+0.83}_{-0.57}$
data	101	32	7	1

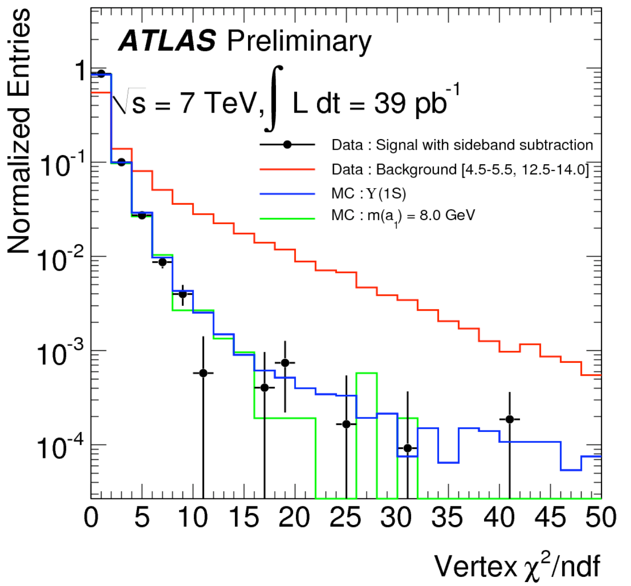
Sample	Number of muon pairs with $m(\mu^+\mu^+)$			
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV
prompt muons	41.2 ± 5.3	23.5 ± 3.2	6.6 ± 1.2	1.33 ± 0.40
non-prompt muons	$20.2^{+5.9}_{-6.9}$	6.3 ± 2.2	1.0 ± 0.4	0.24 ± 0.15
charge flip	$0^{+1.3}_{-0.0}$	$0^{+0.5}_{-0.0}$	$0^{+0.3}_{-0.0}$	$0^{+0.30}_{-0.00}$
total	$61.4^{+8.0}_{-8.7}$	29.8 ± 3.9	7.5 ± 1.3	$1.57^{+0.52}_{-0.42}$
data	61	22	6	1

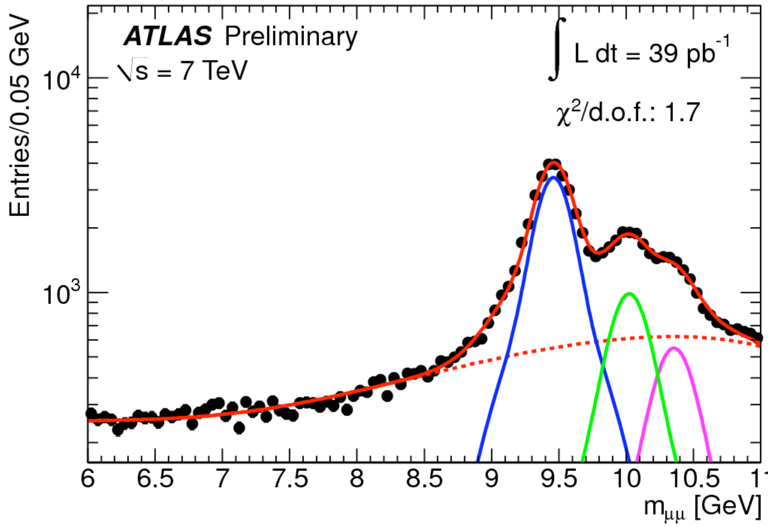
Sample	Number of muon pairs with $m(\mu^-\mu^-)$			
	> 15 GeV	> 100 GeV	> 200 GeV	> 300 GeV
prompt muons	21.9 ± 3.0	11.4 ± 1.8	3.04 ± 0.67	0.91 ± 0.32
non-prompt muons	$17.4^{+4.7}_{-5.8}$	6.8 ± 2.4	0.83 ± 0.38	$0.07^{+0.08}_{-0.07}$
charge flip	$0^{+1.3}_{-0.0}$	$0^{+0.5}_{-0.0}$	$0^{+0.34}_{-0.0}$	$0^{+0.30}_{-0.00}$
total	$39.3^{+5.8}_{-6.5}$	18.2 ± 3.0	$3.87^{+0.84}_{-0.77}$	$0.98^{+0.45}_{-0.33}$
data	40	10	1	0

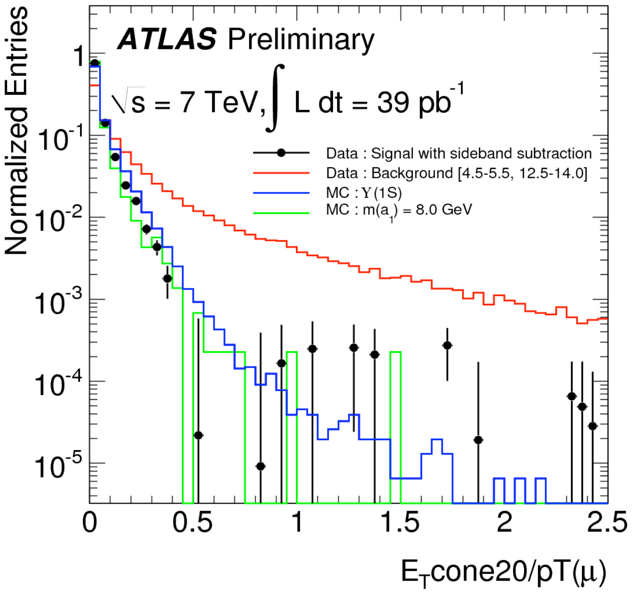


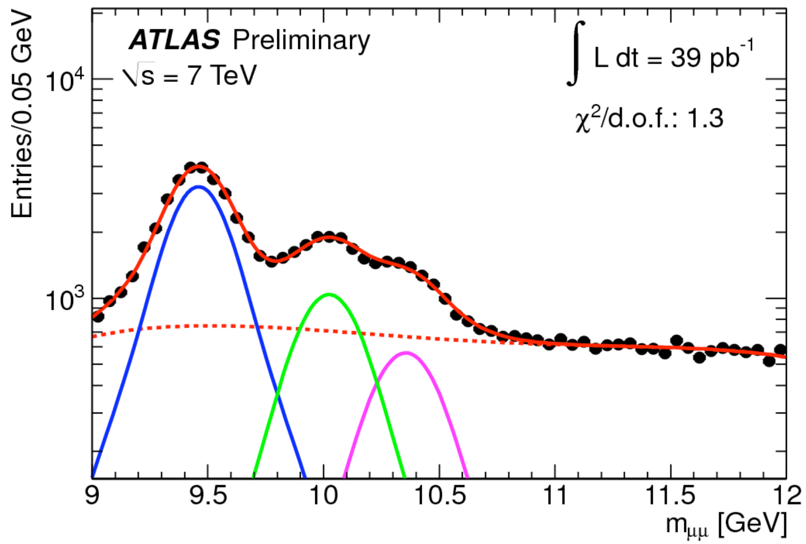


NMSSM $a_1 \to \mu^+\mu^-$: Additional Plots









NMSSM $a_1 \to \mu^+\mu^-$: Systematics

Source	Relative Uncertainty (%) at $m(a_1)$ (GeV)							
	6.0	6.5	7.0	7.5	8.0	8.5	11.0	11.5
Luminosity	± 3							
PYTHIA vs MC@NLO	± 67	± 55	± 49	± 40	± 36	± 32	± 20	± 20
Dimuon Efficiency	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+14}_{-13}$	$^{+15}_{-14}$	$^{+15}_{-14}$
Trigger Correction	± 8							
MC Statistics	± 10	± 10	± 10	± 10	± 10	± 10	± 9	± 9
Likelihood Ratio Modeling	± 3							
Total (Pythia vs MC@NLO)	± 70	± 59	± 53	± 45	± 41	± 37	± 28	± 28