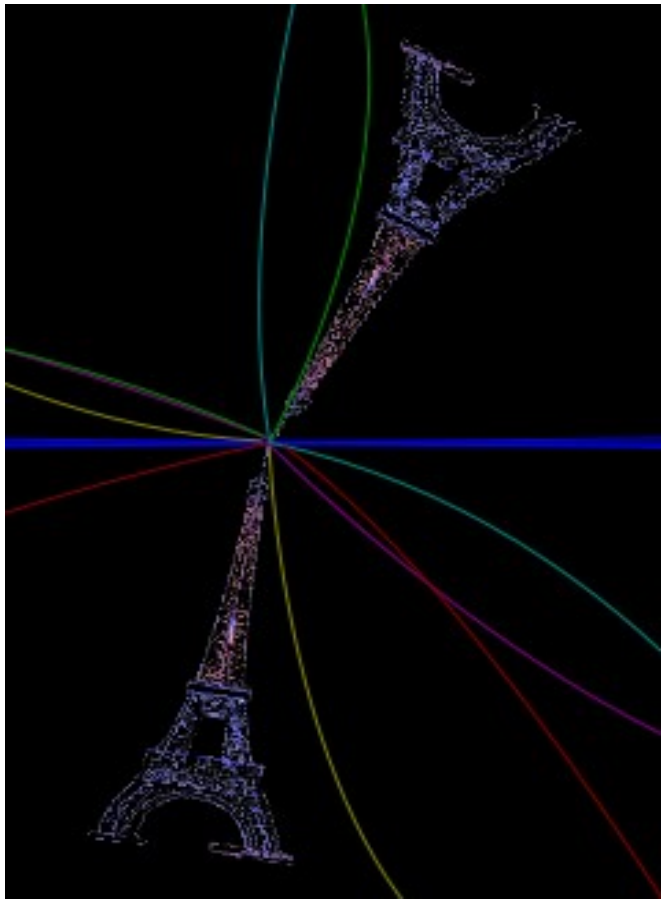
ATLAS Searches for Higgs Bosons Beyond the Standard Model

John Keller (U. of Washington)
on behalf of the
ATLAS Collaboration



Higgs Hunting Workshop
Orsay, France
18 July, 2012

UNIVERSITY OF WASHINGTON

A word from the Director General:

Global Effort → Global Success

Results today only possible due to extraordinary performance of accelerators – experiments – Grid computing

Observation of a new particle consistent with a Higgs Boson (but which one…?)

Historic Milestone but only the beginning

Global Implications for the future

R-D Heuer

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Global Implications for the future

R-D Heuer

- Is it the only one?
- Are the couplings as expected?
- Are there decays we haven't considered?

The ATLAS BSM Higgs suite

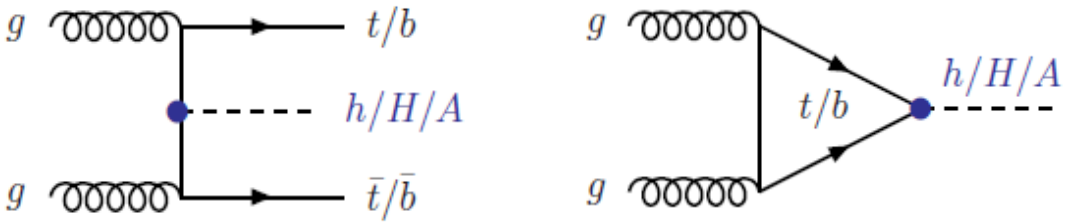
All analyses based on 7 TeV data

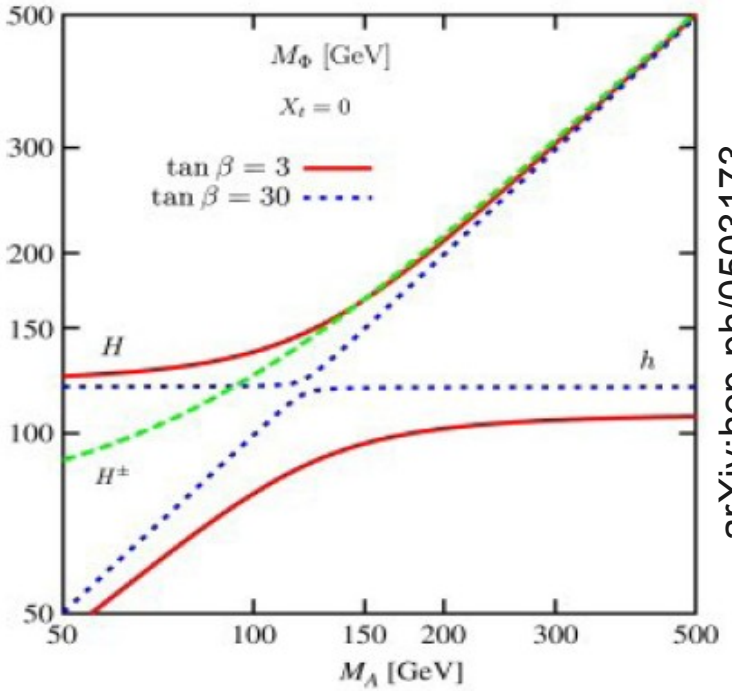
Channel	Lumi (fb^{-1})
Neutral MSSM h/A/H $\rightarrow \mu\mu$	4.8
Neutral MSSM h/A/H $\rightarrow \tau\tau$	4.7
Charged $H^{+} \rightarrow \tau\nu$	4.6
Charged $H^{+} \rightarrow c\bar{s}$	0.035
Doubly-charged $H^{++} \rightarrow ee/\mu\mu$	4.7
NMSSM $a \rightarrow \mu\mu$	0.039
NMSSM $H \rightarrow aa \rightarrow 4\gamma$	4.9
Higgs decays to Hidden Valley pions	1.94
Higgs decays to Muon Jets	1.94
Fermiophobic $H \rightarrow \gamma\gamma$	4.9
SM Higgs with 4^{th} fermion generation	1.0-2.3

*Topics in light blue covered in this talk.

The MSSM Higgs sector

- Two Higgs doublets generate mass separately for up and down-type fermions => 5 physical Higgs states (A, H, h, $H^{\pm}$).
  - Consistent with a SM-like Higgs at 126 GeV.[1]
- Described at tree-level by two parameters: m_A & $\tan\beta = v_2/v_1$.
- Couplings to down-type fermions enhanced for large $\tan\beta$.
- ATLAS has searched in the $\tau\tau$ and $\mu\mu$ decay modes, in final states with and without a b-jet.





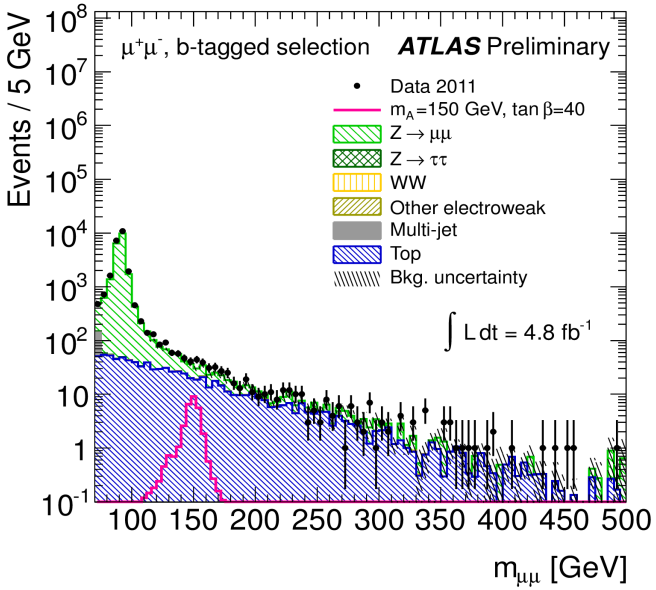
arXiv:hep-ph/0503173

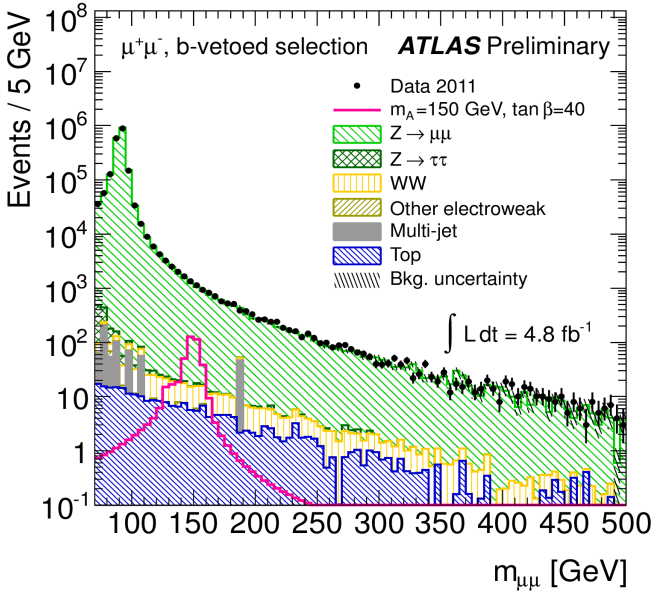
[1] See e.g. http://arxiv.org/abs/1207.1096

MSSM Higgs→μμ: Selection

- At least two opposite-sign muons, p_T > 20, 15 GeV.
- $m(\mu\mu)$ > 70 GeV
- MET < 40 GeV
- Events split by presence or absence of a b-tagged jet.
- Dominant backgrounds: Drell-Yan, $t\bar{t}$ (after b-tag).

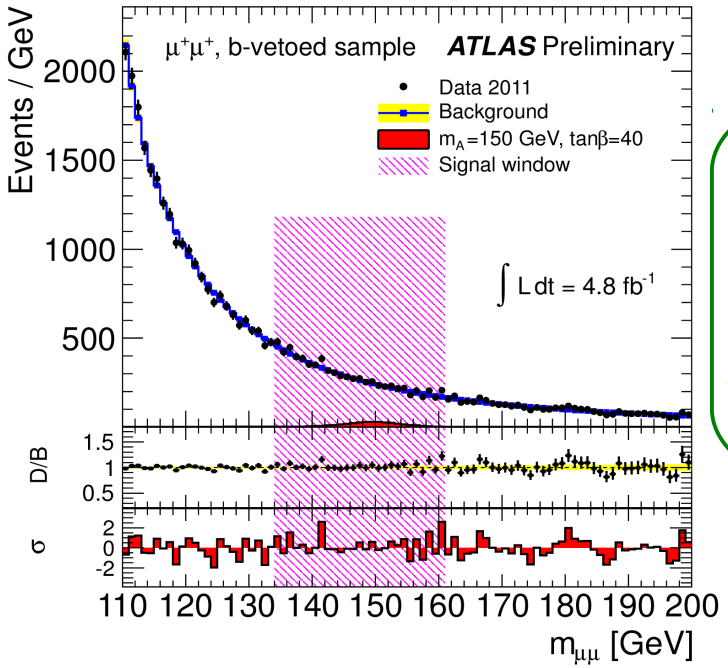
MC prediction shown for illustration only, not used in final result





MSSM Higgs→μμ: Modelling

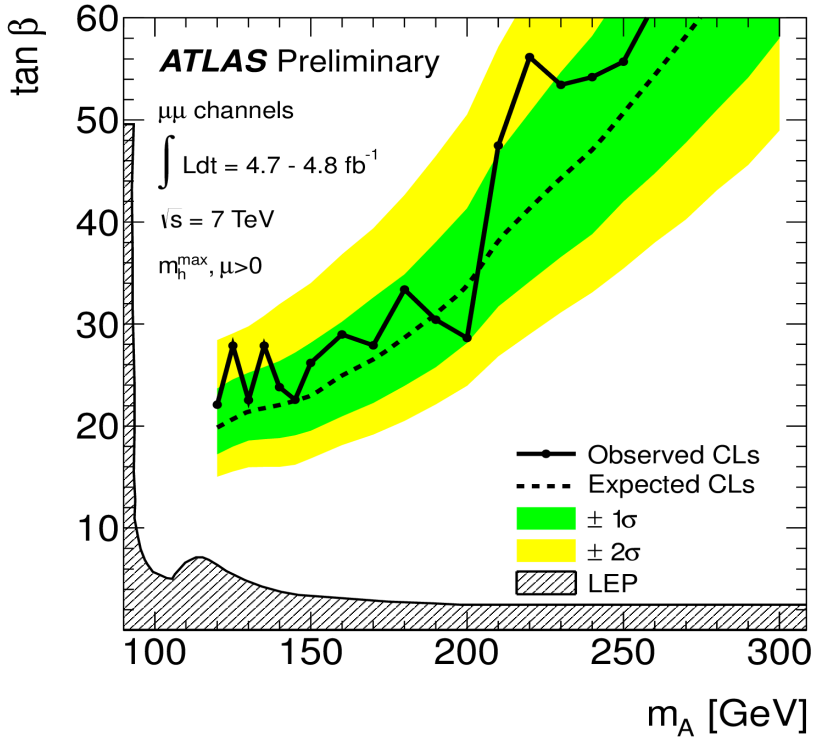
- Signal window chosen for each point in the m_A-tanβ plane.
- Background in the signal region determined by fitting the sidebands with functions below.
- Functional form seen to be robust for many background components.

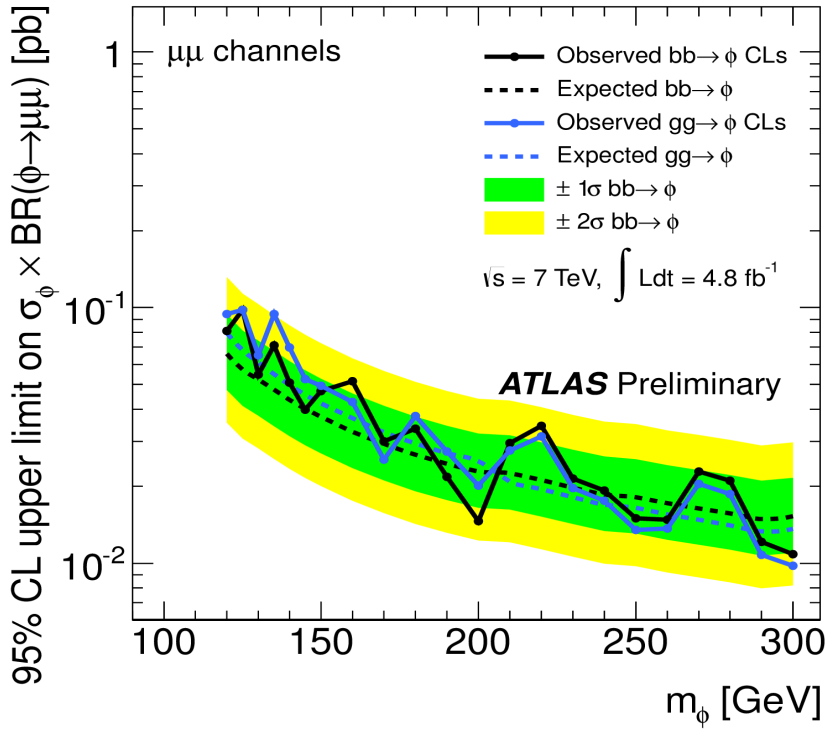


$$f_B(x, N, A, B, M_Z, \Gamma_Z, \sigma) = N \cdot [f_Z(x, A, B, M_Z, \Gamma_Z) \otimes f_{Gauss}(x, \sigma)]$$

$$f_Z(x, A, B, M_Z, \Gamma_Z) = A\frac{1}{x^2} + B\frac{x^2 - M_Z^2}{\left(x^2 - M_Z^2\right)^2 + M_Z^2\Gamma_Z^2} + \frac{x^2}{\left(x^2 - M_Z^2\right)^2 + M_Z^2\Gamma_Z^2}$$

MSSM Higgs→μμ: Results





- No significant deviations observed.
- Upper limits set on tanβ as function of m_A, and on XS*BR of a generic scalar boson.

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MSSM Higgs→ττ: Selection

Channel	$\tau\tau \rightarrow e\mu$	$\tau\tau \rightarrow e\tau_h$ / $\mu\tau_h$	$\tau\tau \rightarrow \tau_h\tau_h$
Pre-selection	-Opposite-sign e & μ -m(e,μ) > 30 GeV -Δφ(e,μ) > 2.0	-Opposite-sign l & τ_h -No additional leptons -$m_T(l,\text{MET})$ < 30 GeV	-Two opposite-sign τ_h -No light leptons -MET > 25 GeV
b-tagged	-Exactly 1 b-jet -MET+p_T(e)+p_T(μ) < 125 GeV -Σcosφ(l,MET) > -0.2 -Σp_T(jets) < 100 GeV	-Leading jet b-tagged -p_T(b-jet) < 50 GeV	-Leading jet b-tagged -p_T(b-jet) < 50 GeV
no b-tag	-No jets with $\lvert\eta\rvert$ < 2.5 -Visible mass window	-Lead jet fails b-tag -MET > 20 GeV	-Lead jet fails b-tag -Lead τ_h p_T > 60 GeV

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Reduce top

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Reduce W + jets

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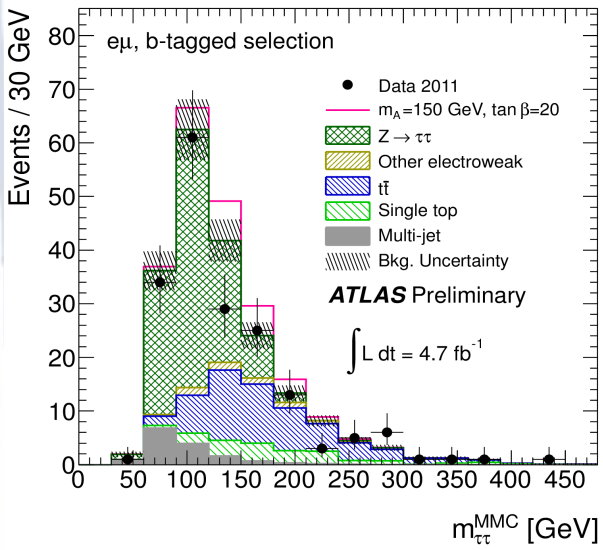
MSSM Higgs→ττ: Selection

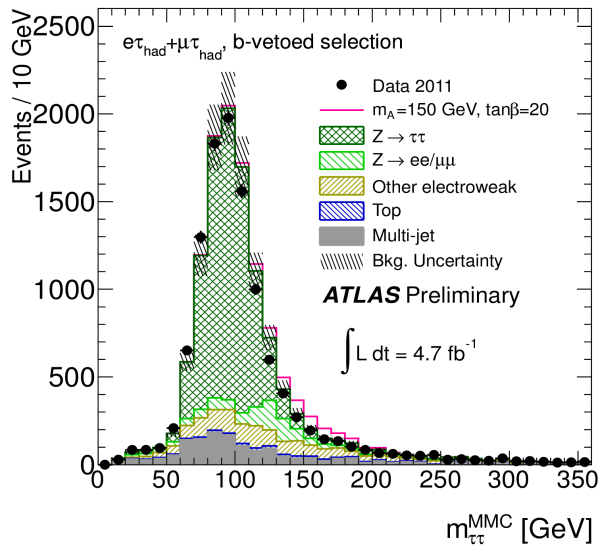
Channel	$\tau\tau \rightarrow e\mu$	$\tau\tau \rightarrow e\tau_h$ / $\mu\tau_h$	$\tau\tau \rightarrow \tau_h\tau_h$
Pre-selection	-Opposite-sign e & μ -m(e,μ) > 30 GeV -Δφ(e,μ) > 2.0	-Opposite-sign l & τ_h -No additional leptons -$m_T(l,\text{MET})$ < 30 GeV	-Two opposite-sign τ_h -No light leptons -MET > 25 GeV
b-tagged	-Exactly 1 b-jet -MET+p_T(e)+p_T(μ) < 125 GeV -Σcosφ(l,MET) > -0.2 -Σp_T(jets) < 100 GeV	-Leading jet b-tagged -p_T(b-jet) < 50 GeV	-Leading jet b-tagged -p_T(b-jet) < 50 GeV
no b-tag	-No jets with $\lvert\eta\rvert$ < 2.5 -Visible mass window	-Lead jet fails b-tag -MET > 20 GeV	-Lead jet fails b-tag -Lead τ_h p_T > 60 GeV

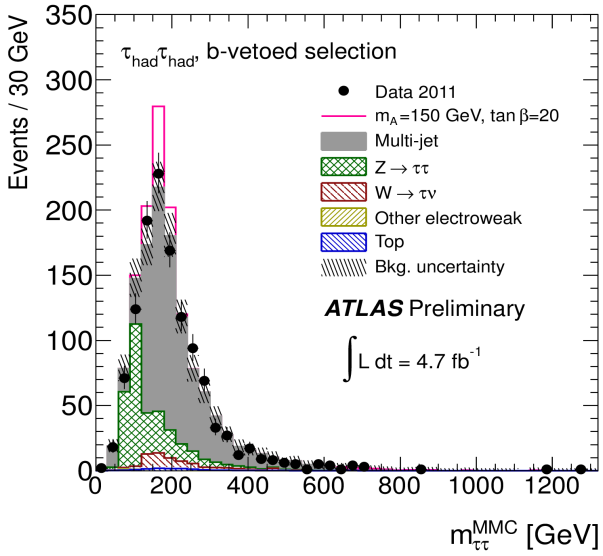
Reduce Multi-jets

MSSM Higgs→ττ: Distributions

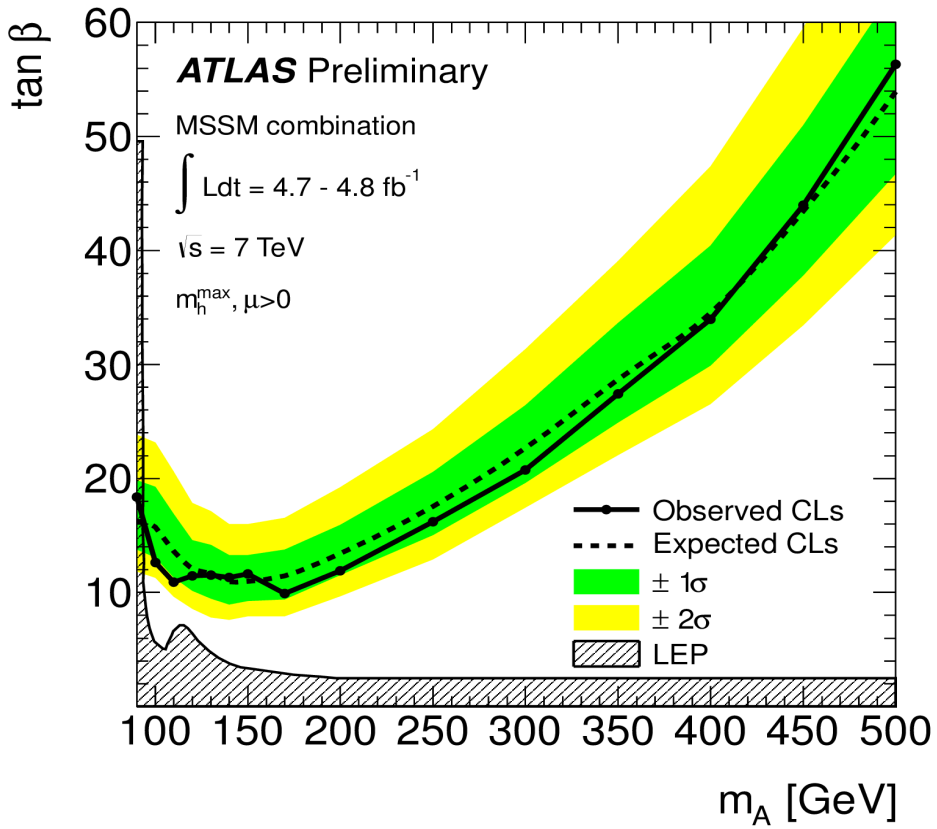
- $Z\to\tau\tau$ estimated from τ-embedded $Z\to\mu\mu$ data.
- Multi-jets taken from (scaled) same-sign events.
- W, $t\bar{t}$, $Z\to ee$ normalized from data control regions.
- Missing Mass Calculator (MMC) used for mass reconstruction.
  - eμ, b-veto channel uses visible mass.
- Details in common with SM analysis; see talk by Jike Wang

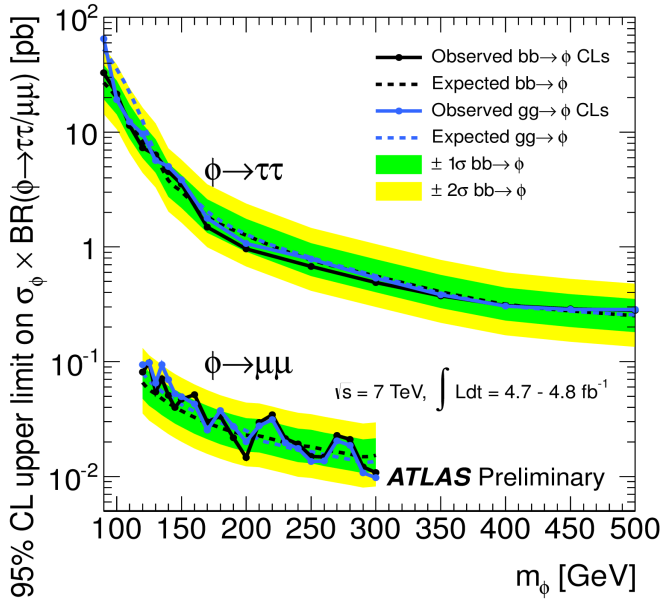


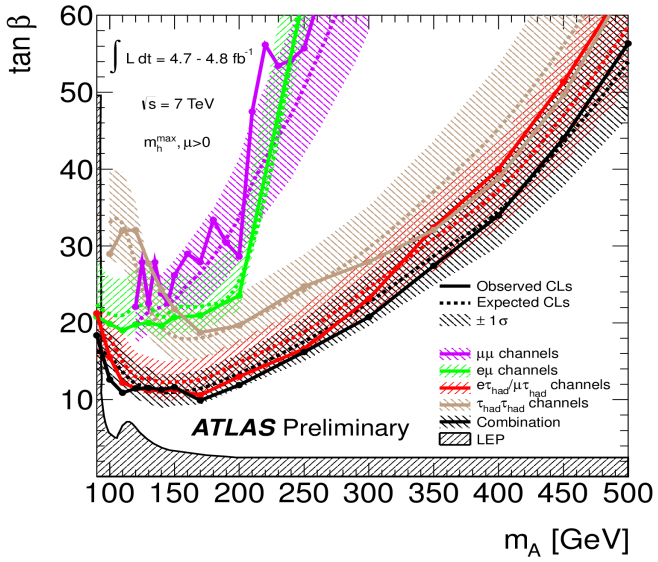




Neutral MSSM: Results







- No significant excess observed.
- Limits set as low as tanβ = 10.

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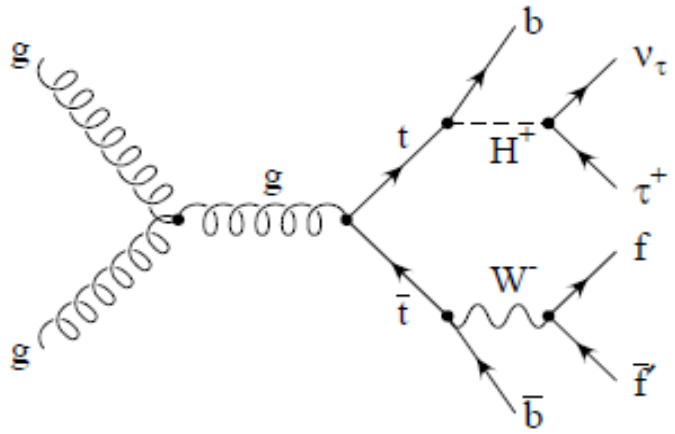
Charged Higgs: Introduction

- For $m_{H^+} < m_t$, charged Higgs produced primarily through top-quark decays.
- $H^+ \to \tau^+ \upsilon$ dominant for $\tan\beta \gtrsim 2$.
- 3 channels considered:



  - $t\bar{t} \to b\bar{b}H^{\pm}W \to b\bar{b}(\tau_{lep}\,\upsilon)(q\bar{q})$: "lepton + jets"
  - $t\bar{t} \to b\bar{b}H^{\pm}W \to b\bar{b}(\tau_{had}\,\upsilon)(l\upsilon)$: "tau + lepton"
  - $t\bar{t} \to b\bar{b}H^{\pm}W \to b\bar{b}(\tau_{had}\,\upsilon)(q\bar{q})$: "tau + jets"

Charged Higgs: Selection

Lepton + Jets

- 1 e or μ
- 4 or more jets (2 b-tagged)
- MET > 40 GeV
  - Tighter at small Δφ(l,MET)
- $\cos\theta_l^*$ < -0.6
- $m_T(l,\text{MET})$ < 60 GeV

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

Tau + Lepton

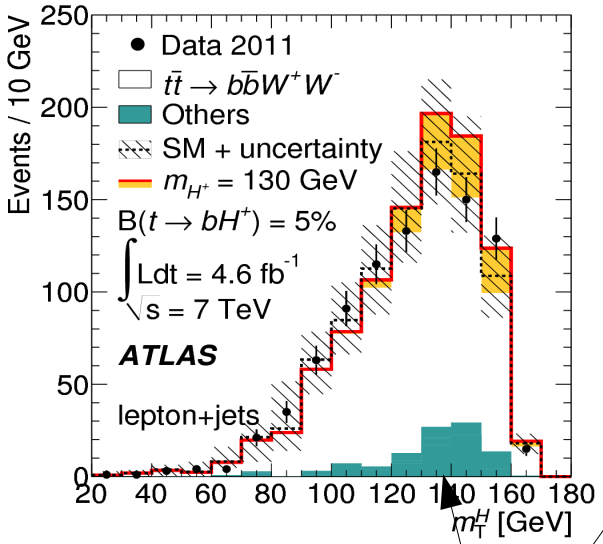
- 1 e or μ, 1 opposite-sign τ
- 2 or more jets (≥1 b-tagged)
- Σp_T(tracks) > 100 GeV

Tau + Jets

- Exactly 1 τ, no other leptons
- 4 or more jets (≥1 b-tagged)
- MET > 65 GeV
  - Tighter at high Σp_T(tracks)
- 120 < m_{jjb} < 240 GeV

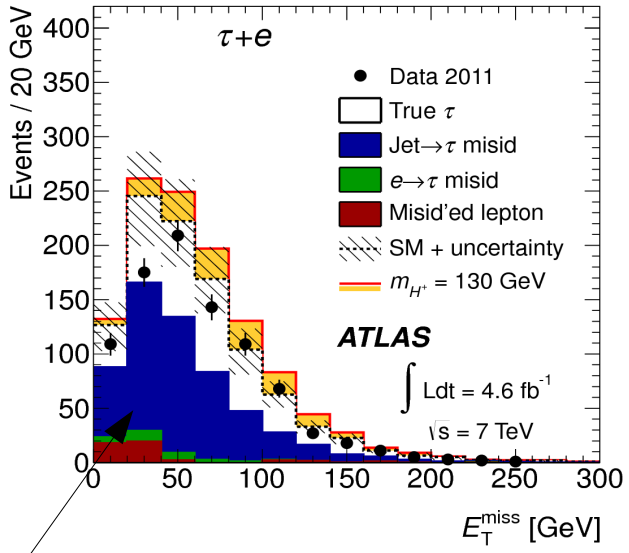
Charged Higgs: Distributions

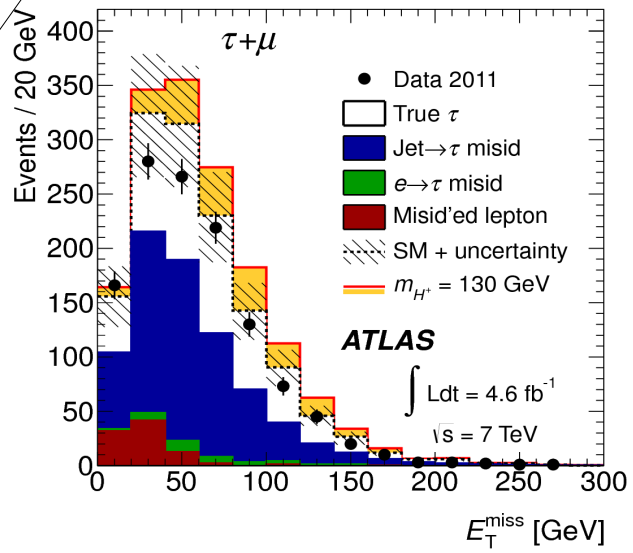
Lepton + jets



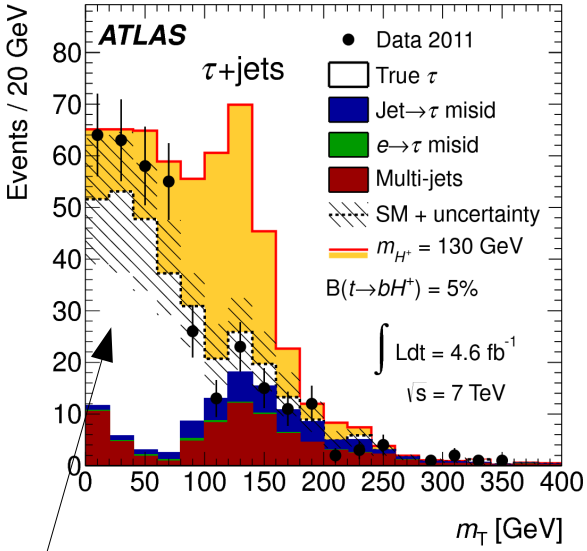
Mis-identified taus & leptons scaled from data

Tau + lepton



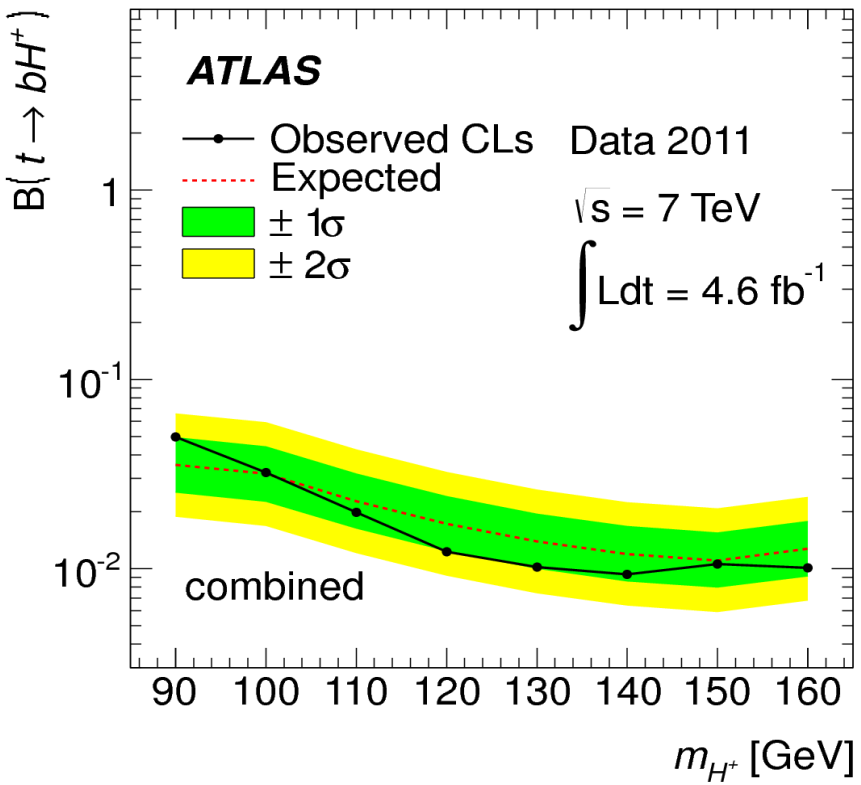


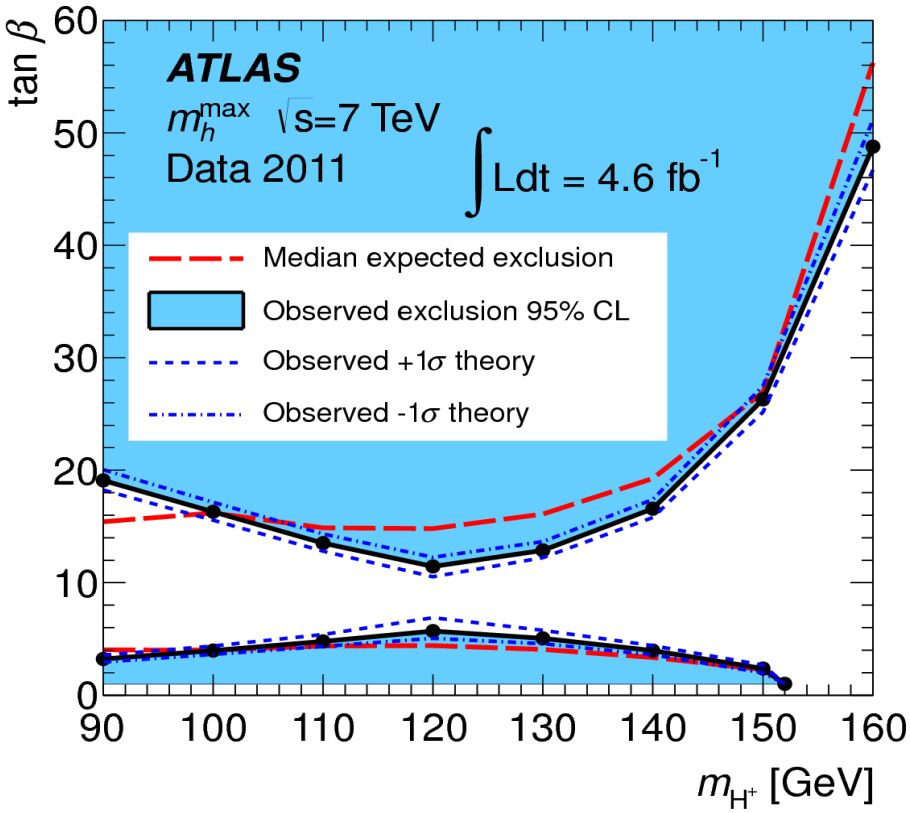
Tau + jets



True tau contribution taken from “embedding”

Charged Higgs: Results





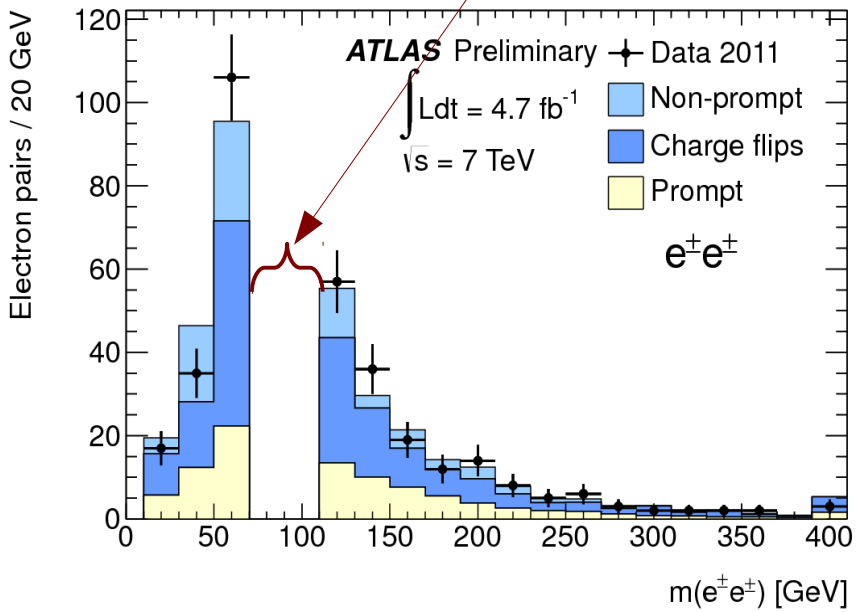
- No significant excess is observed.
- Very little room remaining for a light charged Higgs boson!

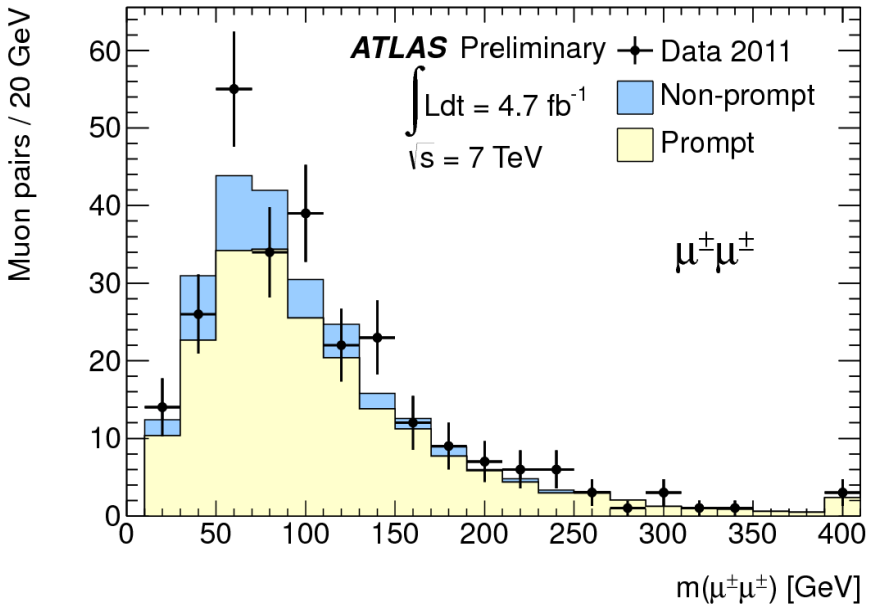
ATLAS-CONF-2012-069

Doubly-charged $H^{++} \rightarrow l^+l^+$ (I)

- Relevant for Little Higgs, Higgs triplet models; many others
  - Results interpreted in model-independent manner
- Events selected with same-sign electron or muon pairs
- Backgrounds from diboson processes, hadronic jets
  - Charge flips negligible for muons, not electrons

Control region for charge mis-ID & conversions





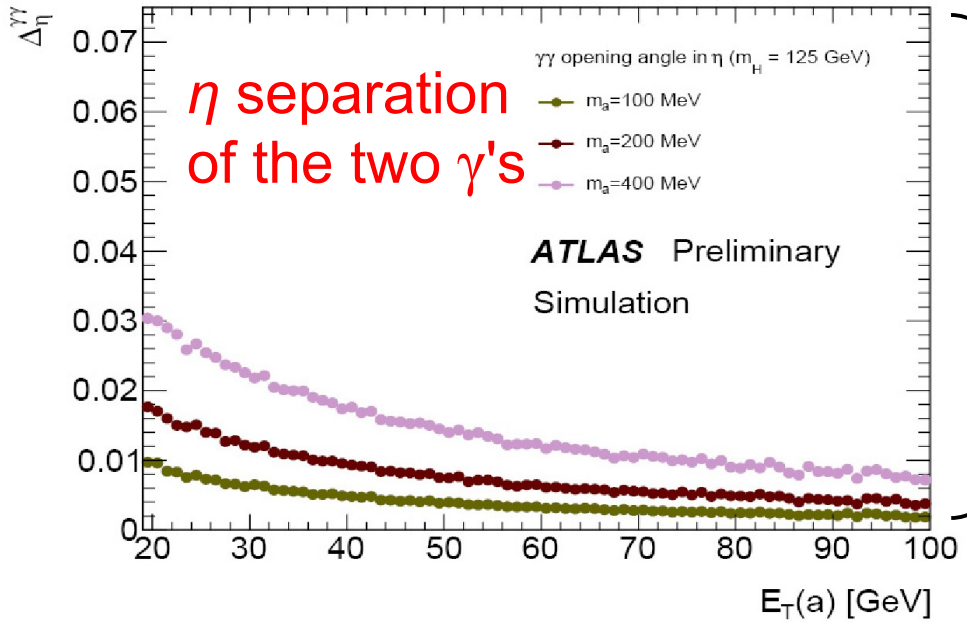
Doubly-charged $H^{++} \to l^+l^+$ (II)

Mass range	95% C.L. upper limit [fb]			
	expected	observed	expected	observed
	$e^{\pm}e^{\pm}$		$\mu^{\pm}\mu^{\pm}$	
$M > 15$ GeV	$45.0^{+17.3}_{-12.0}$	45.7	$23.4^{+8.6}_{-5.8}$	29.1
$M > 100$ GeV	$24.3^{+9.1}_{-7.0}$	25.6	$11.9^{+4.4}_{-2.9}$	14.6
$M > 200$ GeV	$8.8^{+3.2}_{-2.9}$	8.1	$4.2^{+1.8}_{-1.1}$	6.6
$M > 300$ GeV	$4.5^{+1.6}_{-1.3}$	3.9	$2.3^{+0.8}_{-0.7}$	2.5
$M > 400$ GeV	$2.9^{+1.1}_{-0.9}$	2.3	$1.6^{+0.6}_{-0.5}$	1.7
	e^+e^+		$\mu^+\mu^+$	
$M > 15$ GeV	$27.3^{+10.0}_{-7.9}$	23.8	$14.7^{+6.0}_{-3.2}$	14.9
$M > 100$ GeV	$16.2^{+6.0}_{-4.8}$	12.4	$8.2^{+3.2}_{-2.4}$	7.7
$M > 200$ GeV	$6.6^{+2.8}_{-1.5}$	6.5	$3.4^{+1.5}_{-0.7}$	4.2
$M > 300$ GeV	$3.5^{+1.6}_{-0.8}$	2.9	$2.0^{+0.8}_{-0.5}$	2.0
$M > 400$ GeV	$2.4^{+1.1}_{-0.6}$	1.7	$1.5^{+0.6}_{-0.3}$	1.7
	e^-e^-		$\mu^-\mu^-$	
$M > 15$ GeV	$24.6^{+8.5}_{-6.8}$	29.1	$11.9^{+4.4}_{-3.4}$	18.0
$M > 100$ GeV	$12.7^{+4.6}_{-3.9}$	19.9	$5.8^{+2.2}_{-1.9}$	9.8
$M > 200$ GeV	$4.7^{+1.9}_{-1.3}$	4.4	$2.7^{+1.1}_{-0.7}$	4.3
$M > 300$ GeV	$2.8^{+1.1}_{-0.8}$	2.7	$1.4^{+0.7}_{-0.3}$	1.7
$M > 400$ GeV	$1.8^{+1.0}_{-0.4}$	2.2	$1.2^{+0.4}_{-0.0}$	1.1

- No significant excess of events is observed.
- Limits set on fiducial cross-section for new physics processes
  - Signal efficiency estimated using variety of BSM signatures.

$H \rightarrow aa \rightarrow 4\gamma$: Introduction

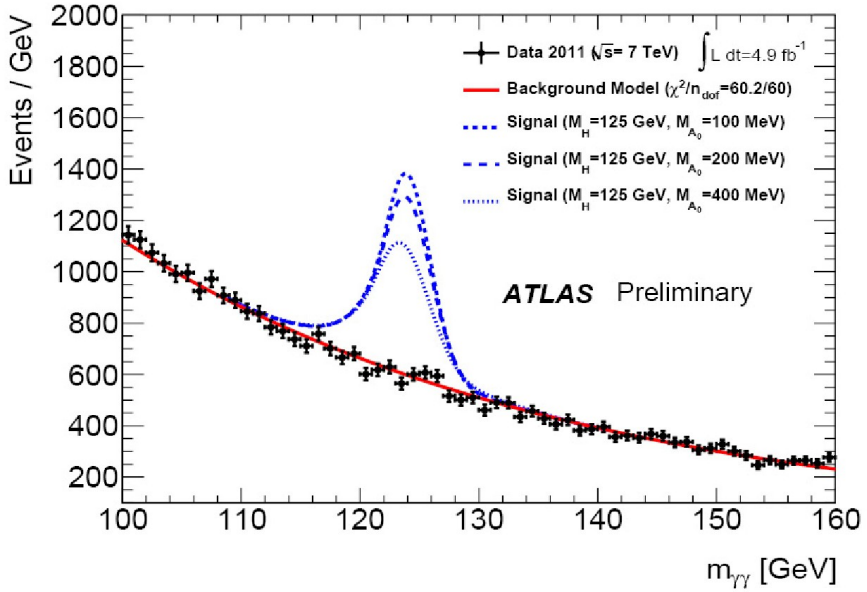
- Many BSM models (e.g. NMSSM) include a light, pseudoscalar Higgs boson *a*, produced directly or via heavy Higgs decays.
- If it is heavily boosted, decay products are tightly collimated
  - Two photons may appear as one!
- Events can enter standard $H \rightarrow \gamma\gamma$ analysis, but the selection is not optimal.

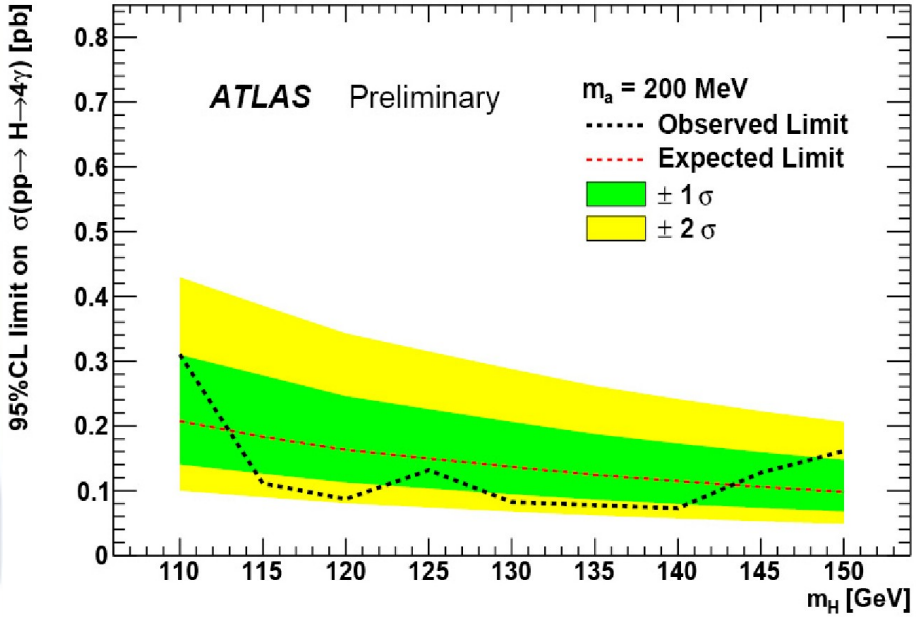


Width in η of an EM cluster for typical unconverted photons

$H \rightarrow aa \rightarrow 4\gamma$: Results

- Selection as in $H \rightarrow \gamma\gamma$, except:
  - Some shower-shape variables removed from photon ID
  - No event categorization applied
- Background fit to exponential





- No excess seen for these selection criteria.
- Limit on σ*BR set as a function of m_H.
  - Sensitivity decreases with higher m_a.

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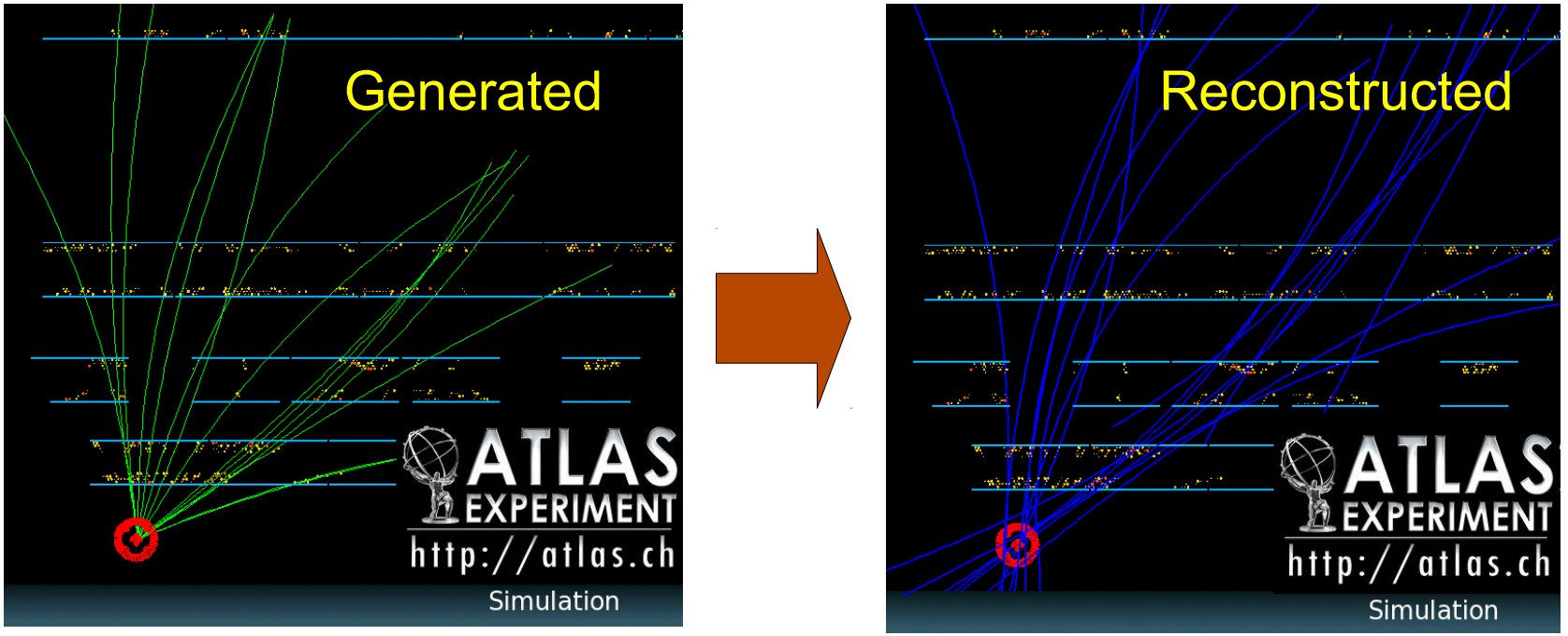
ATLAS-CONF-2012-089

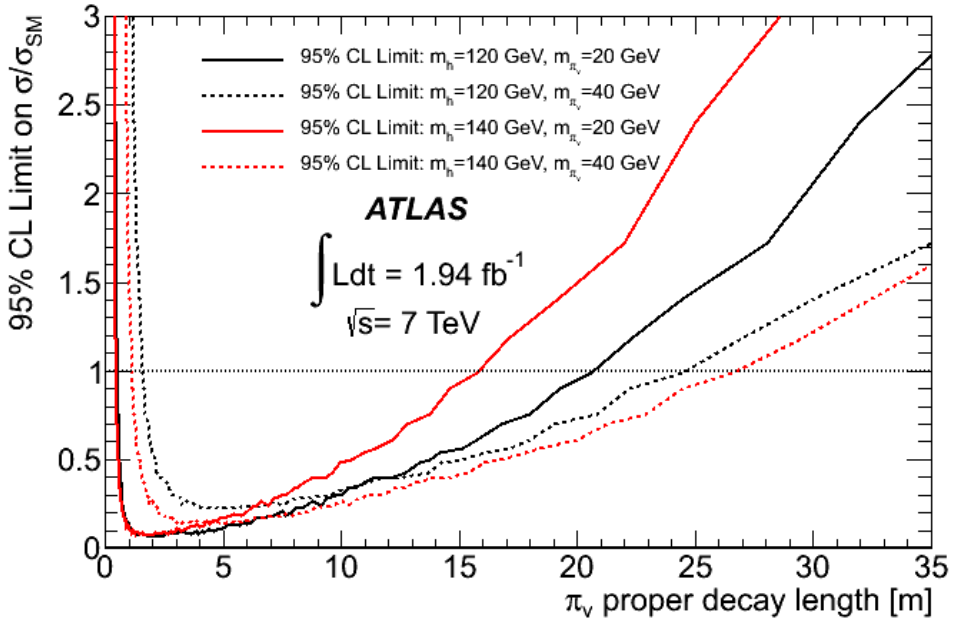
Hidden Valley Higgs decays (I)

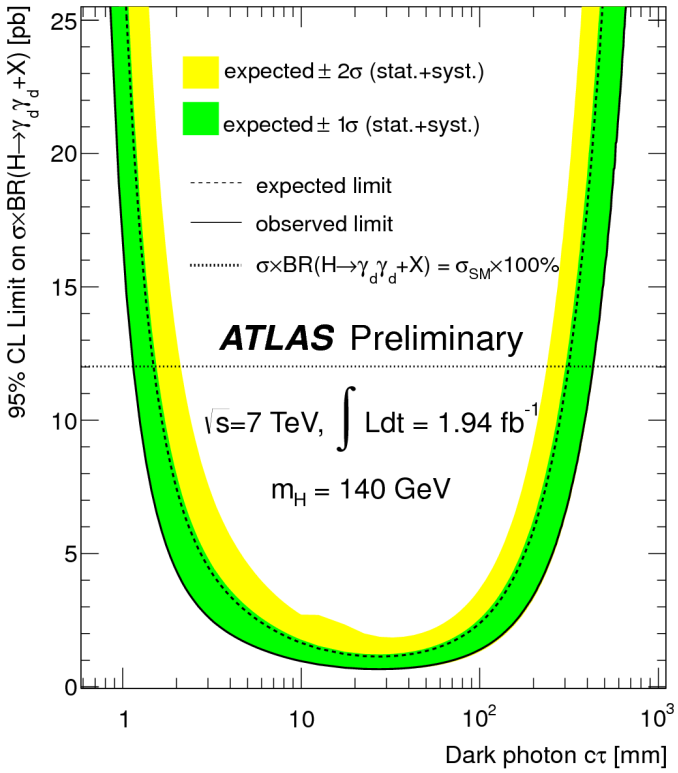
- Benchmark scenario: Higgs serves as communicator to weakly-coupled sector (the "Hidden Valley").
- Hidden sector particles (π_v or γ_d) may have decay length similar to the detector size.
- Missed by standard ATLAS reconstruction: dedicated trigger, tracking, vertexing algorithms needed.



Hidden Valley Higgs decays (II)

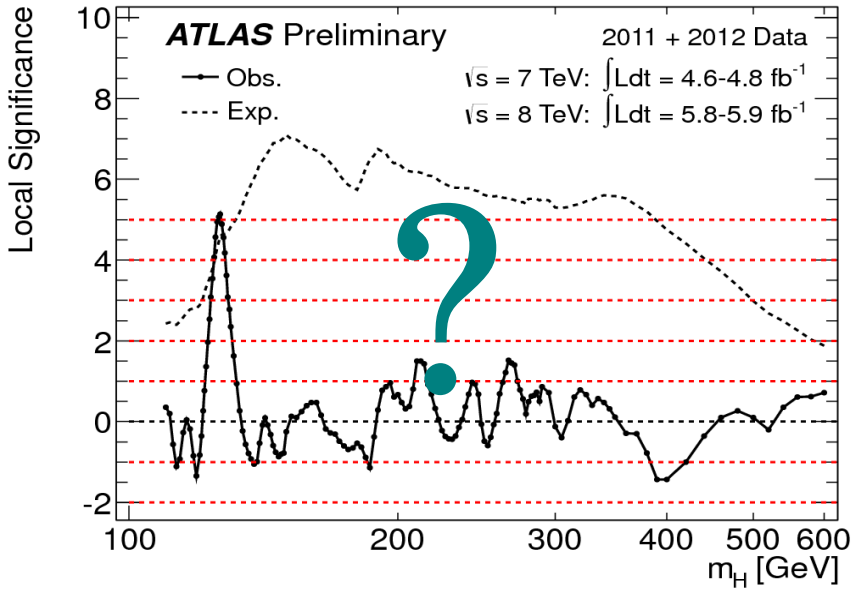
- Two signatures considered: vertices in the muon spectrometer (from $\pi_v \to b\bar{b}$) and displaced Muon Jets (from $\gamma_d \to \mu\mu$).
- No events observed (expected backgrounds: 0.03 and 0.06).
- Limits set on Higgs cross-section as function of π_v or γ_d decay length (from ~1 mm to 30 m).





Summary

- Observation of a peak at 126 GeV makes BSM Higgs searches all the more interesting.
- ATLAS is working hard to determine the nature of the excess, and what is accompanying it (if anything).
- Exciting times are ahead of us: Stay tuned!

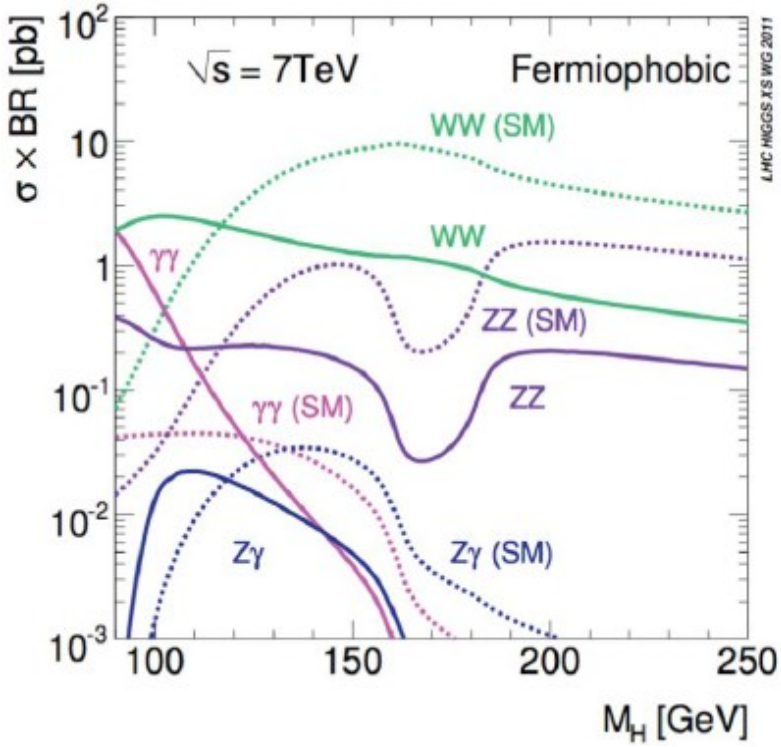


Beyond the Standard Slides

arXiv:1205.0701

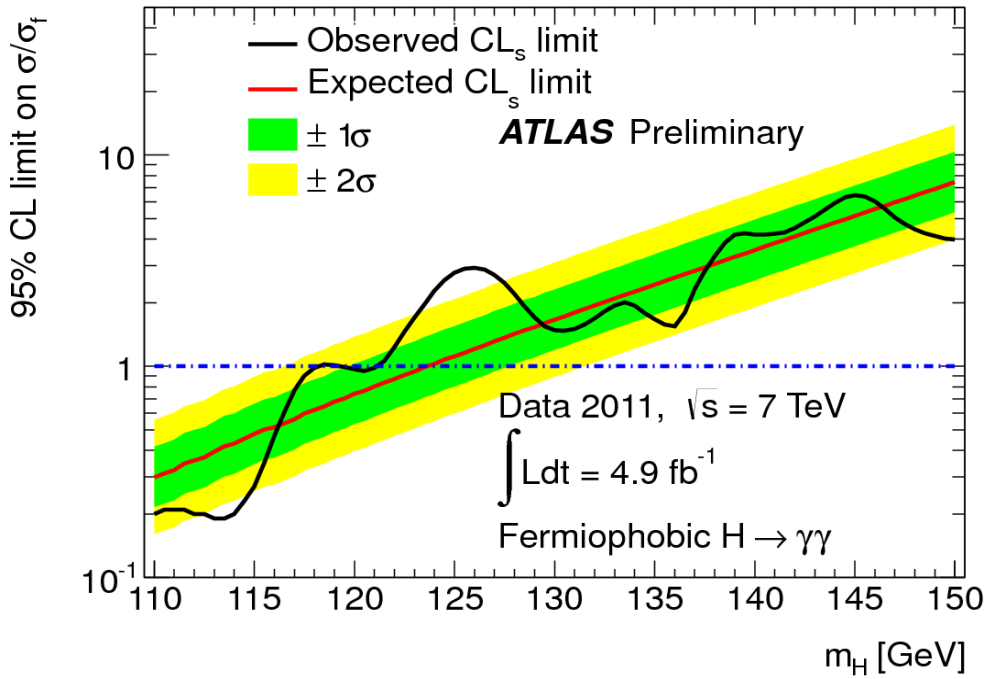
Fermiophobic $H \rightarrow \gamma\gamma$: Introduction

- Benchmark scenario: Higgs couplings to fermions set to 0.
  - Production exclusively through VH, VBF processes.
- Selection identical to 2011 SM $H \rightarrow \gamma\gamma$ analysis:
  - 2 photons (40/25 GeV)
  - 9 categories based on:
    - γ pseudorapidity
    - γ conversions
    - γ p_{Tt} (transverse momentum relative to diphoton thrust axis)



Fermiophobic $H \rightarrow \gamma\gamma$: Results

- FP Higgs excluded in range 110 - 118 and 119.5 – 121 GeV
- Excess observed of 3.1σ at m_H = 125.5 GeV



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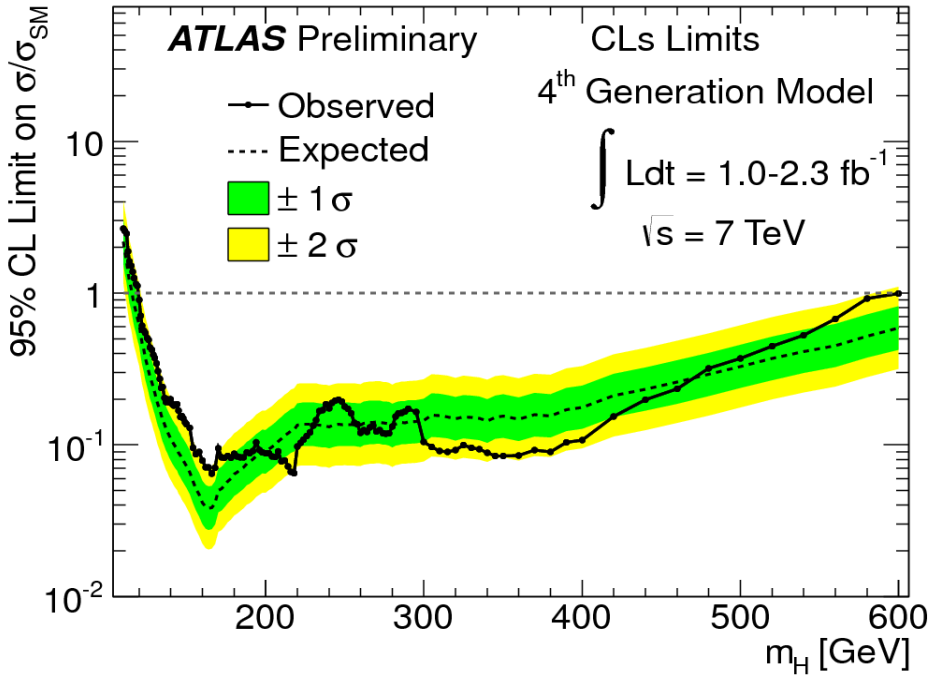
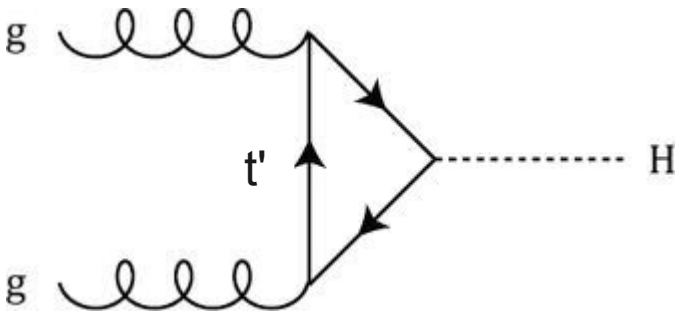
Higgs in 4th-generation models

- 4th generation fermions enhance gluon-fusion loop.
- Early 2011 data sufficient to exclude most parameter space (including m_H = 125 GeV).

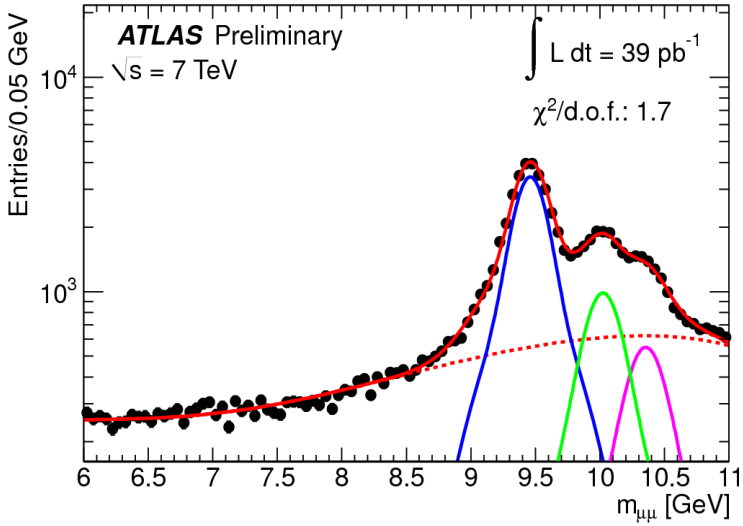


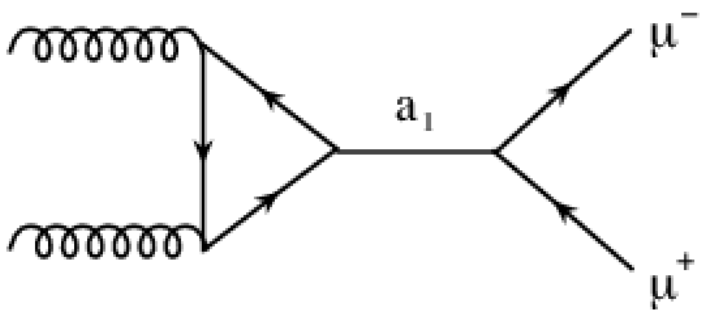


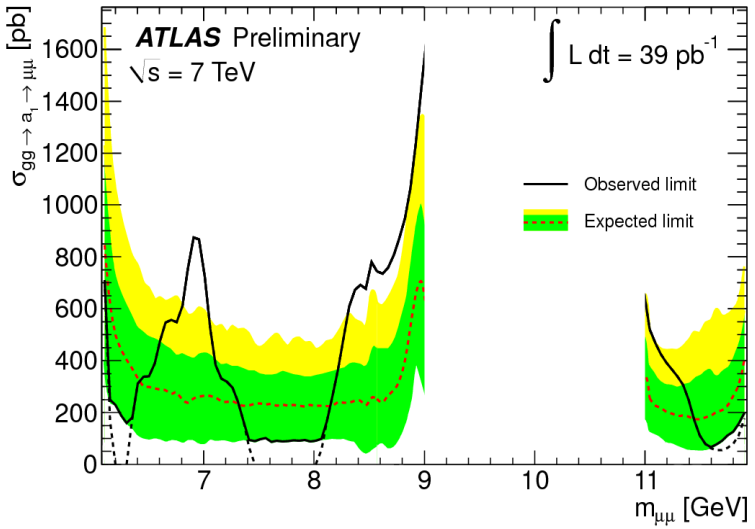
ATLAS-CONF-2011-020

NMSSM $a_1 \rightarrow \mu\mu$

- Direct production of light pseudo-scalar decaying to muons.
- Search for mass bump in the Υ sidebands (6-9 and 11-12 GeV).
- Multivariate selection to reject muons from hadronic decays.
- Background modelled with 4th order polynomail + 3 double-gaussians

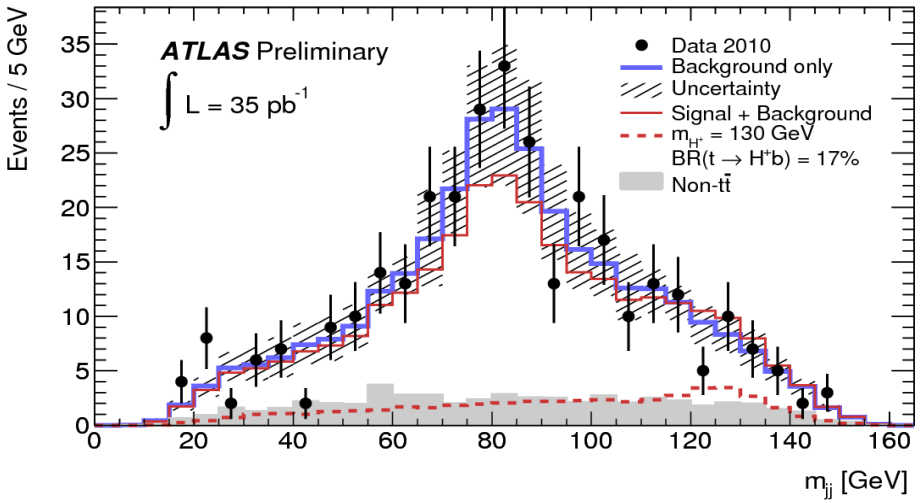


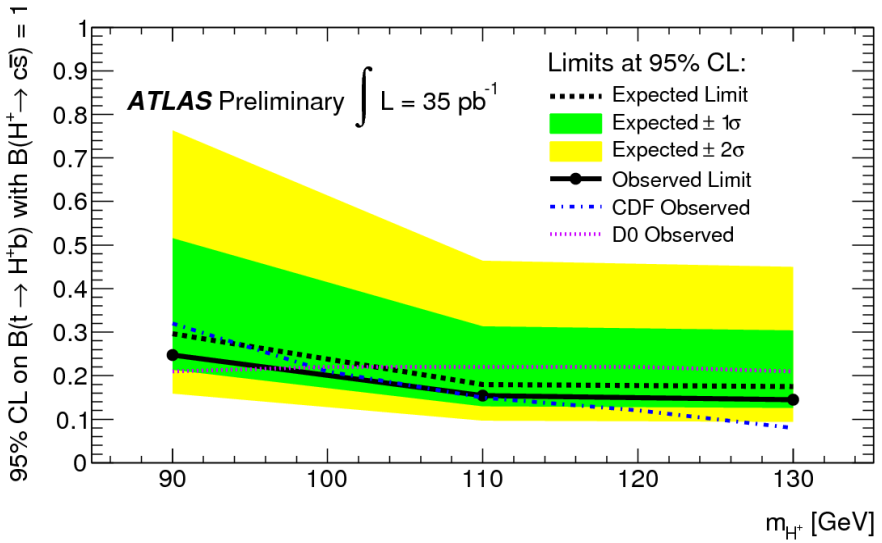




Charged Higgs → $c\bar{s}$

- Significant decay mode for tanβ < 1 (BR ~40%).
- Events selected with a semi-leptonic $t\bar{t}$ decay topology.
- Search for strange shape in the m_{jj} system
  - Jets assigned to H^+ using kinematic fit.
- No departure from SM expectation is observed.

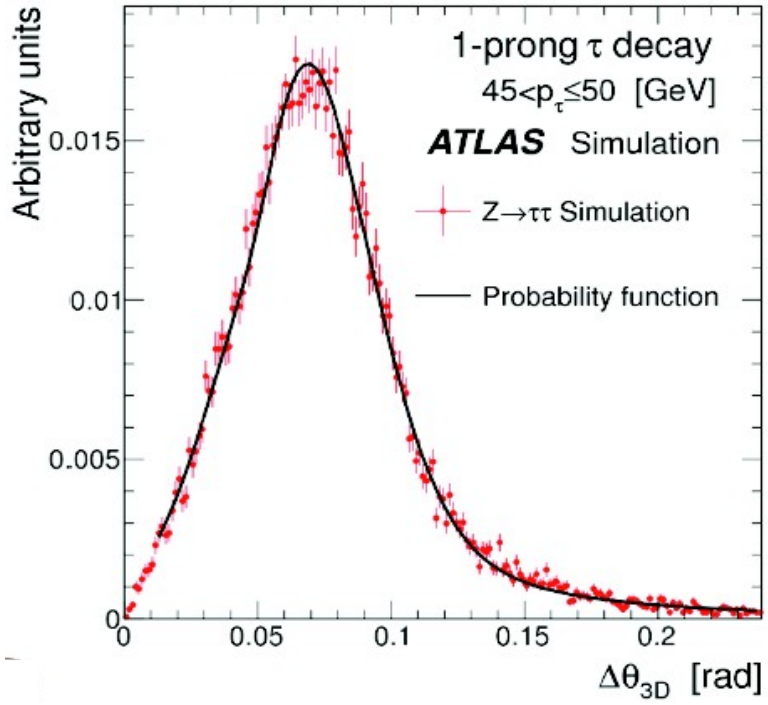




The Missing Mass Calculator

- 4 constraints on mass of di-tau system, but 6-8 unknowns
  - Depending on # of neutrinos in final state

$$
\begin{aligned}
E_x^{\text{miss}} &= p_{\text{miss}_1} \sin\theta_{\text{miss}_1} \cos\phi_{\text{miss}_1} + p_{\text{miss}_2} \sin\theta_{\text{miss}_2} \cos\phi_{\text{miss}_2}, \\
E_y^{\text{miss}} &= p_{\text{miss}_1} \sin\theta_{\text{miss}_1} \sin\phi_{\text{miss}_1} + p_{\text{miss}_2} \sin\theta_{\text{miss}_2} \sin\phi_{\text{miss}_2}, \\
m_\tau^2 &= m_{\text{miss}_1}^2 + m_{\text{vis}_1}^2 + 2\sqrt{p_{\text{vis}_1}^2 + m_{\text{vis}_1}^2}\sqrt{p_{\text{miss}_1}^2 + m_{\text{miss}_1}^2}, \\
&\quad -2p_{\text{vis}_1} p_{\text{miss}_1} \cos\Delta\theta_{\text{vm}_1}, \\
m_\tau^2 &= m_{\text{vis}_2}^2 + 2\sqrt{p_{\text{vis}_2}^2 + m_{\text{vis}_2}^2} \cdot p_{\text{miss}_2}, \\
&\quad -2p_{\text{vis}_2} p_{\text{miss}_2} \cos\Delta\theta_{\text{vm}_2}
\end{aligned}
$$



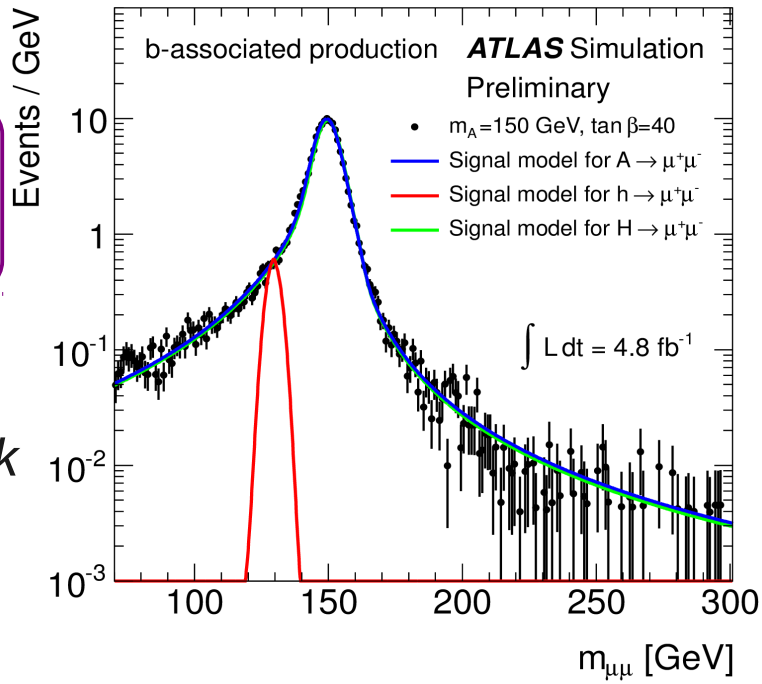
- Ambiguity resolved by scanning the parameter space, calculating the mass for each point, weighting the solution by the likelihood to come from a tau decay.
- Final MMC mass is the peak of the resulting distribution.

A.Elagin, P.Murat, A.Pranko, A.Safonov
arXiv:1012.4686 ; NIM A654 (2011) 481

Signal Modelling in MSSM μμ

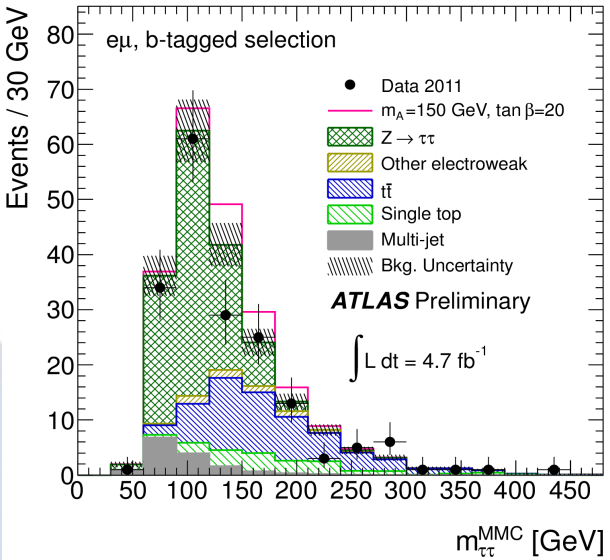
- Signal model different for each point in the m_A-tanβ plane: impractical to simulate signal sample for each point.
- Instead signal is parametrized by Breit-Wigner convoluted with a gaussian, plus a Landau for the asymmetric tail.
- Intermediate signal models obtained by interpolating the fit parameters from simulated points.

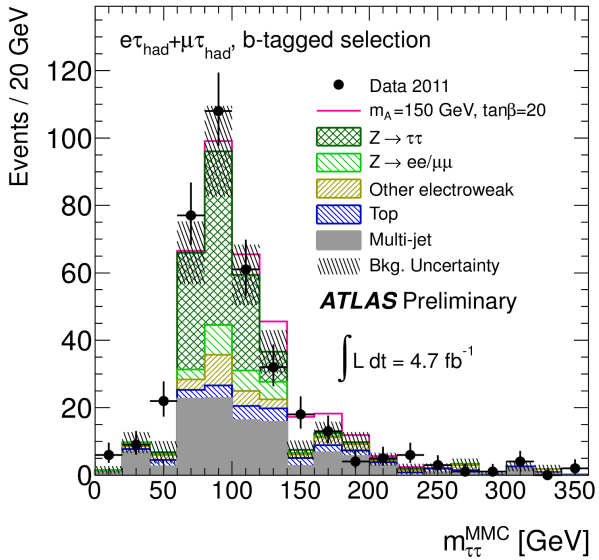
$$N\left[\frac{1}{\left[x^2-M^2\right]^2+M^2\Gamma^2}\otimes f_{Gauss}(x,\sigma)+c\,f_{Landau}(-x,M,\varsigma)\right]$$

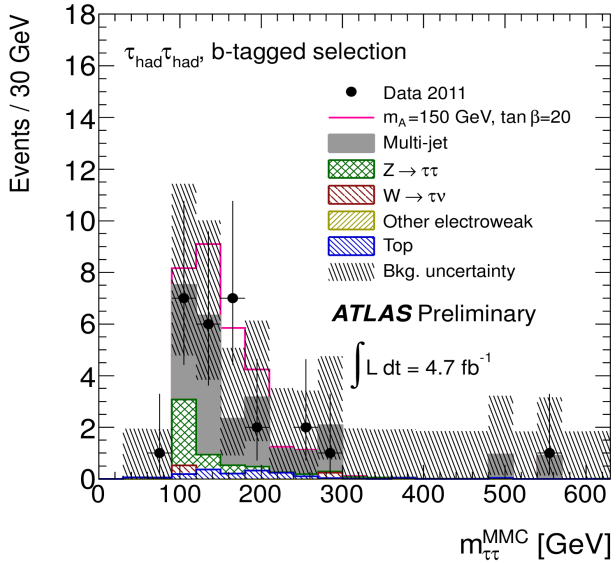


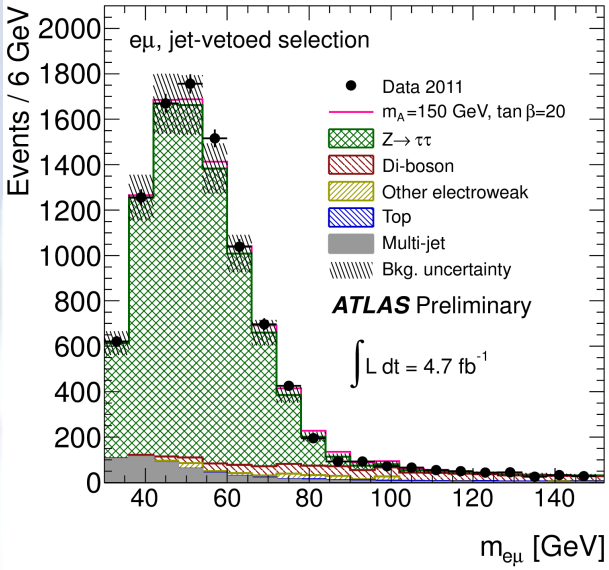
Comparison of simulated signal (black points) with the model obtained from interpolation (blue line)

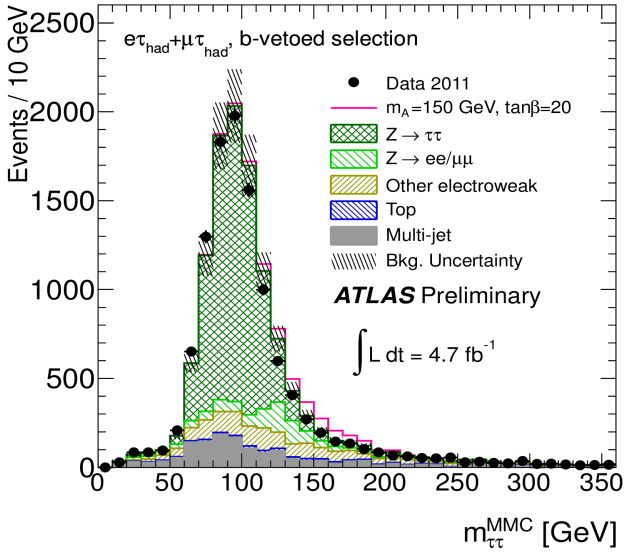
All MSSM $\tau\tau$ mass plots

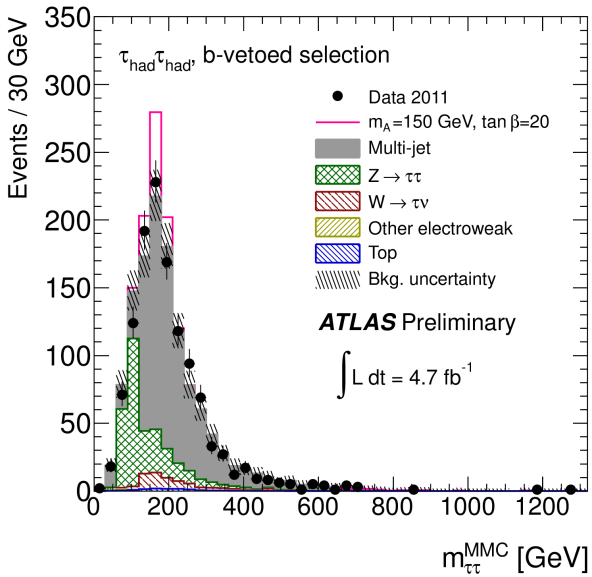




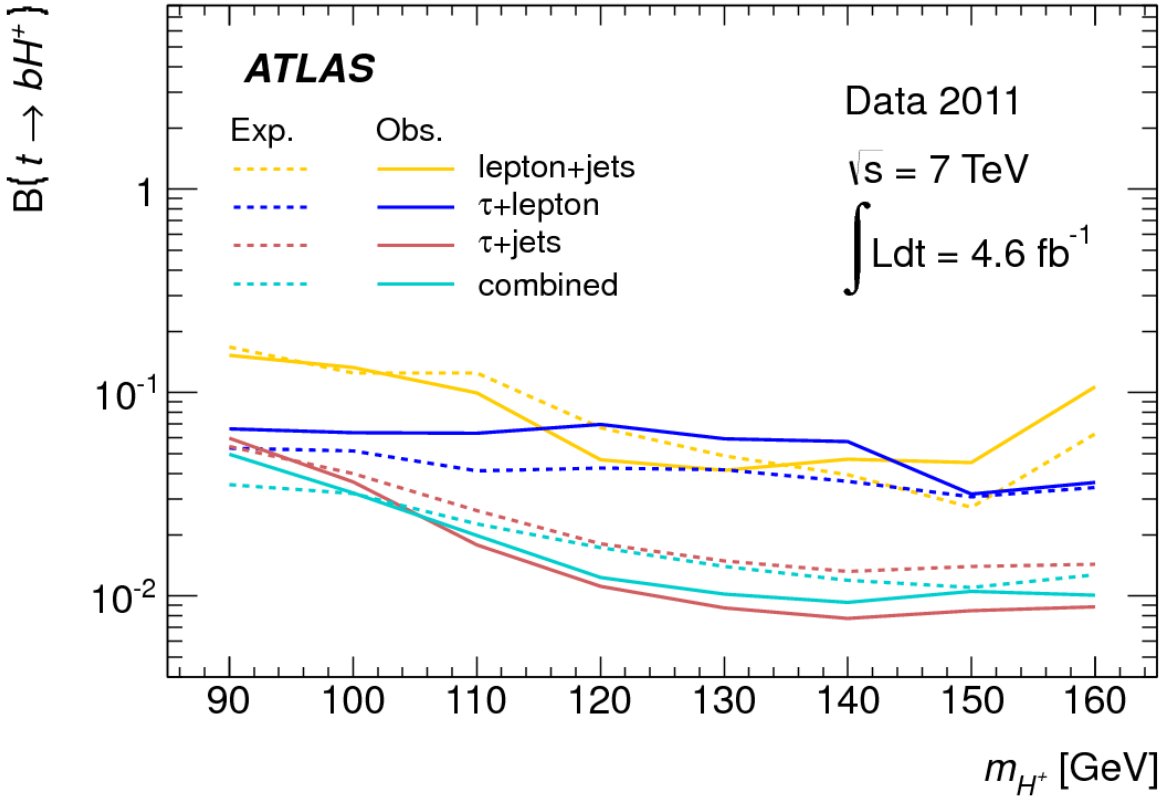






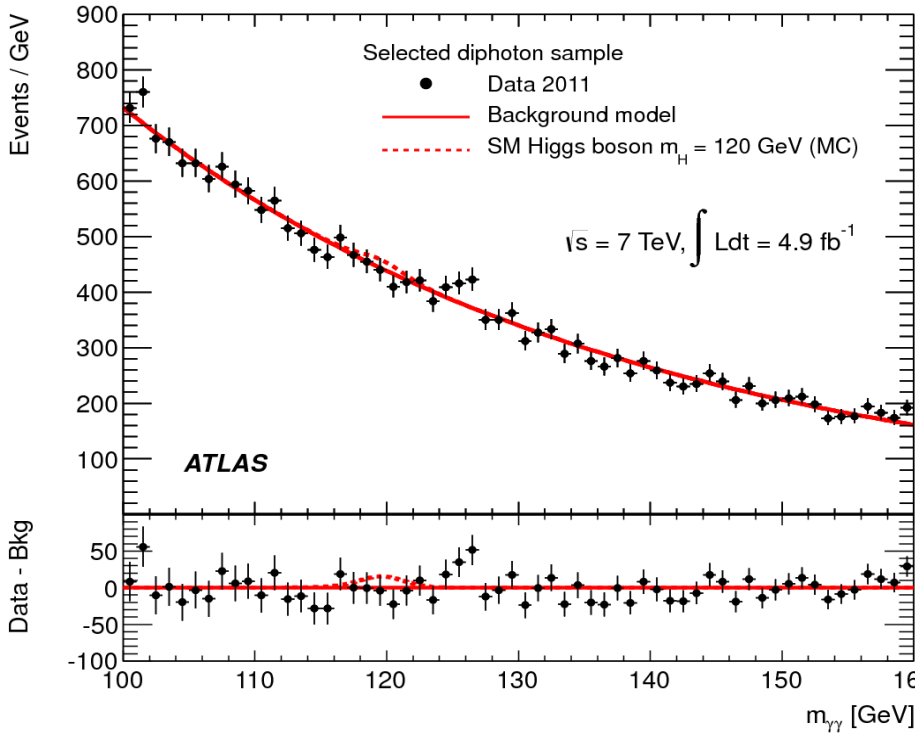


Charged Higgs, individual exclusion

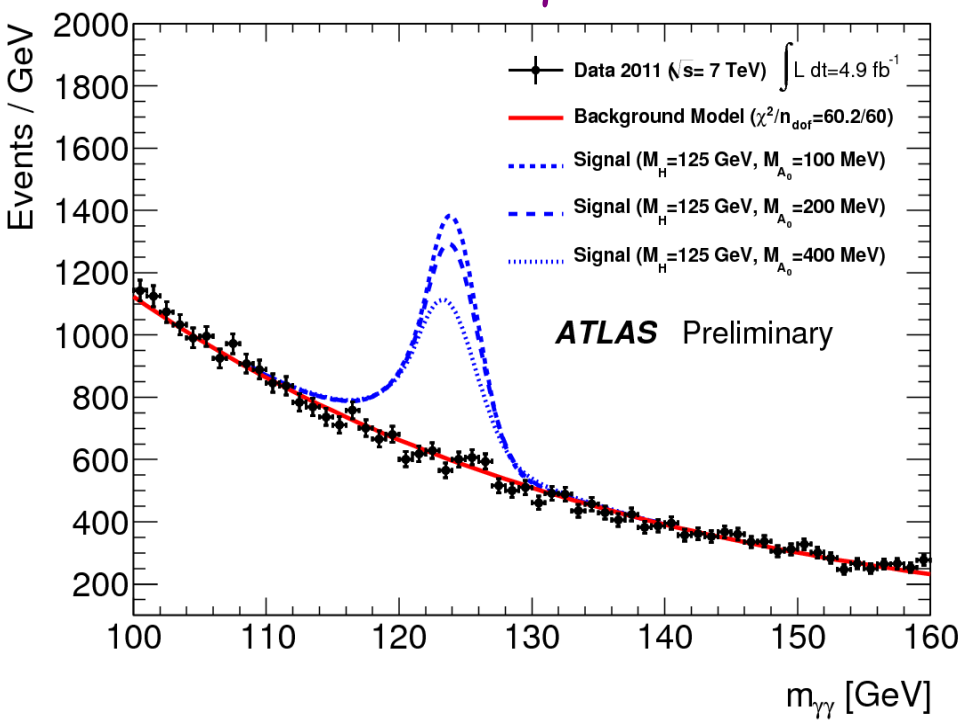


Comparison of diphoton samples

2011 SM, inclusive

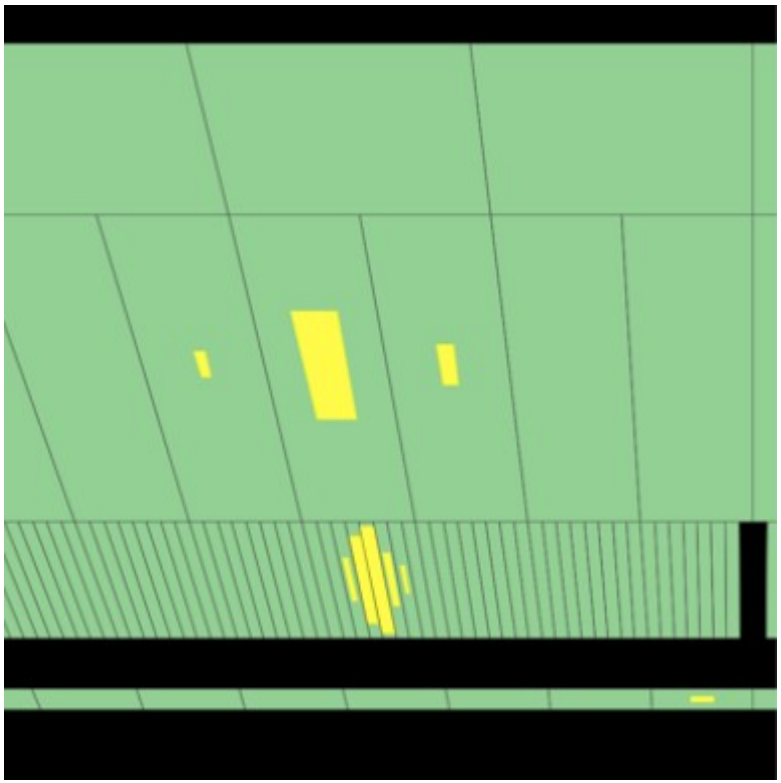


2011 aa→4γ selection

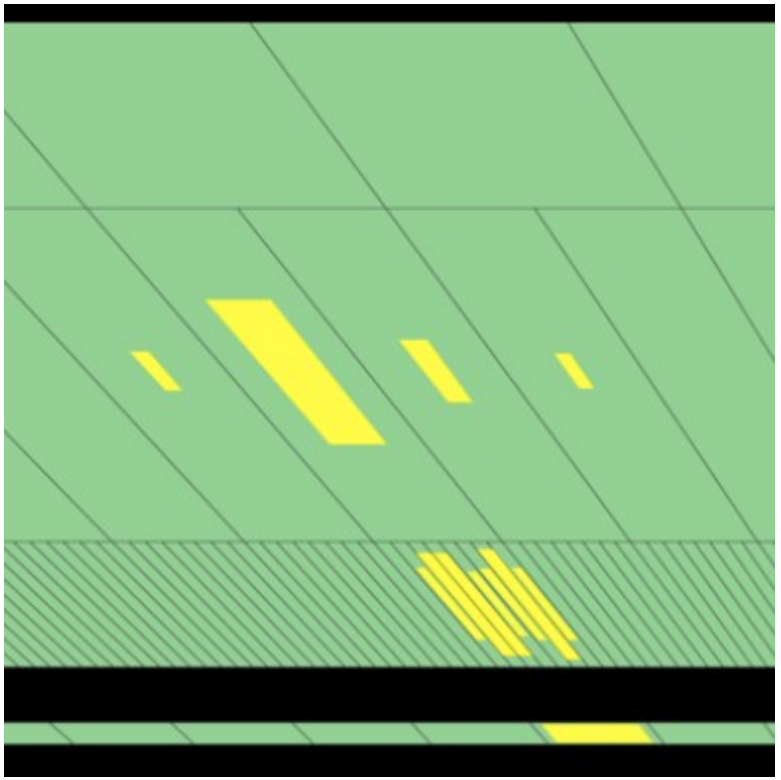


Comparison of the inclusive γγ mass spectrum from standard ATLAS photon ID, and the modified photon ID used in the aa→4γ analysis

Photon - π^0 Comparison



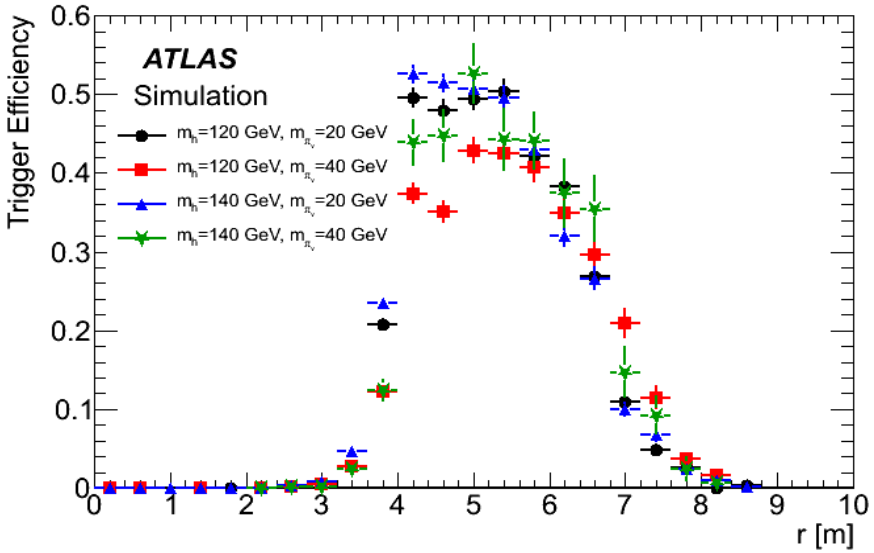
- Corrected isolation: 178 MeV

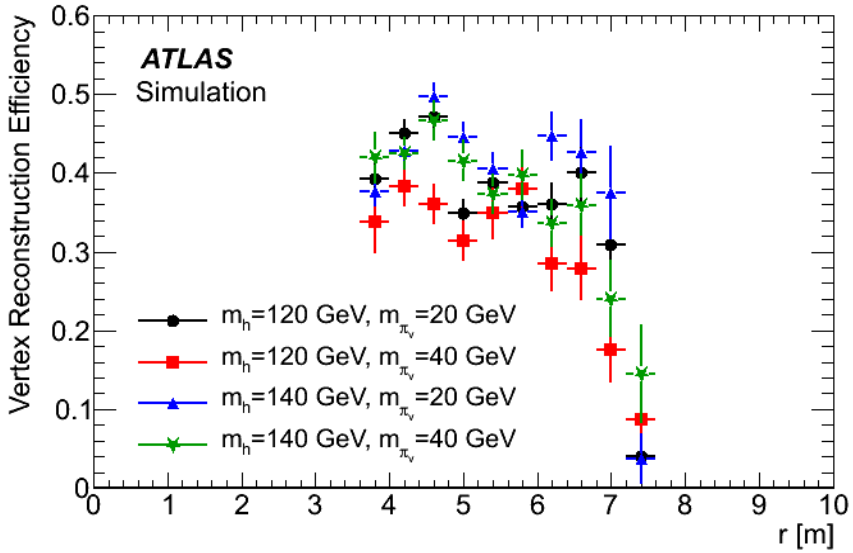


- Corrected isolation: 6.2 GeV

HV trigger & vertex reconstruction

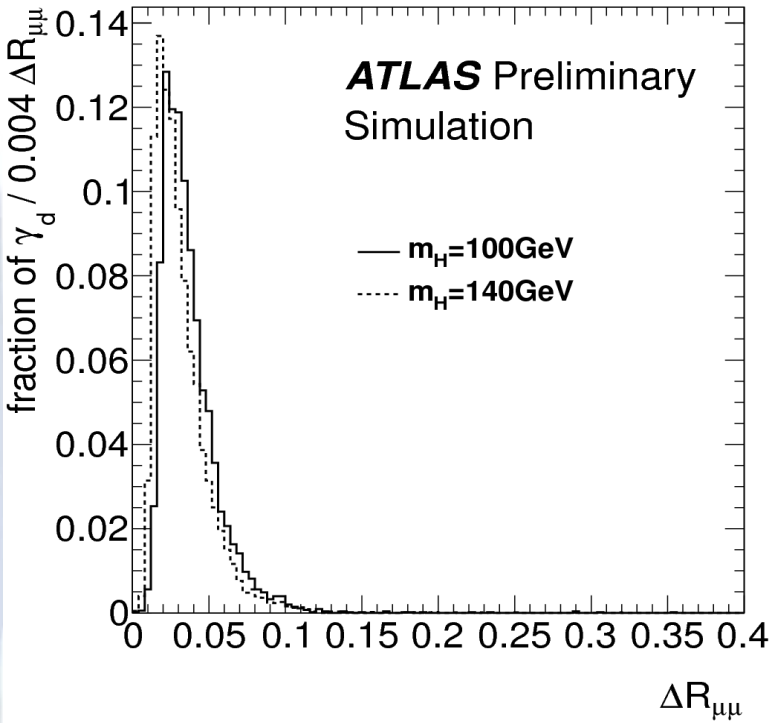
- Vertexing efficiency defined for ROI's which pass the trigger.

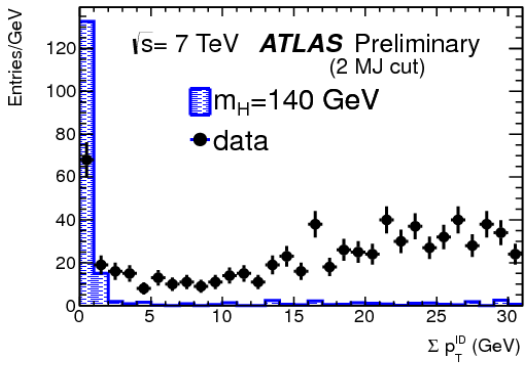


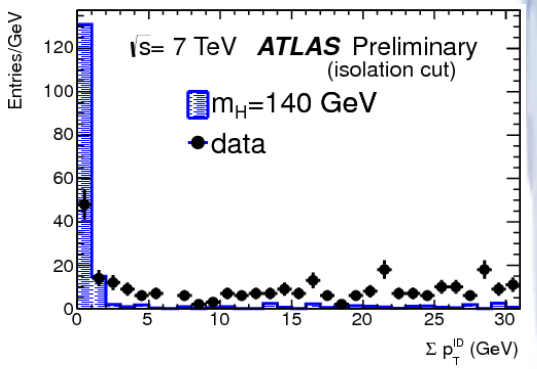


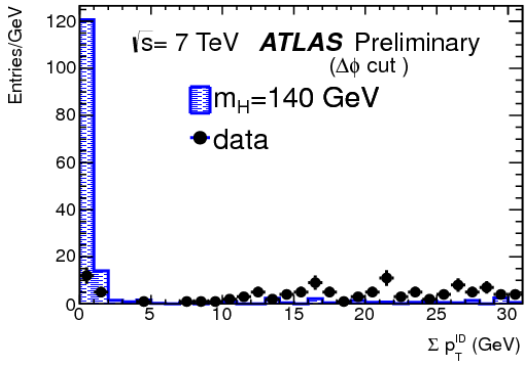
More on Muon Jets

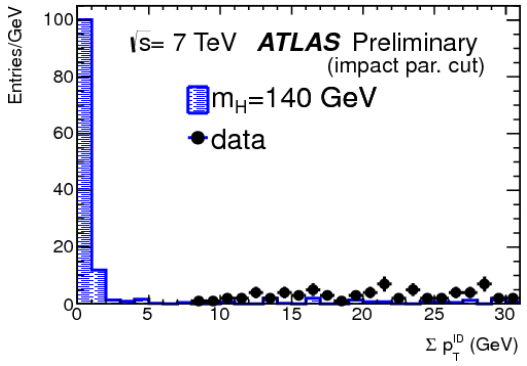
- Muon Jets formed by counting additional muons in a cone of 0.2 around a high p_T muon.











- MJ's must be isolated from calorimeter activity, separated in phi, and (loosely) associated to the primary vertex.
- Finally a cut on 3 GeV on the p_T of nearby ID tracks is applied.

Dark photon reconstruction efficiency