BSM Higgs Searches

What we discussed so far …

PH-EP-2012-323	Search for the neutral Higgs bosons of the Minimal Supersymmetric Standard Model in pp collisions at s = √7 TeV with the ATLAS detector
PH-EP-2012-105	Search for a fermiophobic Higgs boson in the diphoton decay channel with the ATLAS detector
CONF-2012-079	Search for a Higgs boson decaying to four photons through light CP-odd scalar coupling using 4.9 fb^{-1} of 7 TeV pp collision data taken with ATLAS detector
CONF-2011-020	A search for a light CP-Odd Higgs boson decaying to $\mu^+\mu^-$ in ATLAS
PAS HIG-13-010	Search for a non-standard-model Higgs boson decaying to a pair of new light bosons in four-muon final states

BSM Higgs Searches
Still to come today …

PH-EP-2012-347	Search for charged Higgs bosons through the violation of lepton universality in tt events using pp collision data at $\sqrt{s}$ = 7 TeV with the ATLAS experiment
PH-EP-2012-338	Search for a light charged Higgs boson in the decay channel $H^+ \rightarrow cs$ in tt events using pp collisions at $\sqrt{s}$ = 7 TeV with the ATLAS detector
PH-EP-2012-083	Search for charged Higgs bosons decaying via $H^\pm \rightarrow \tau\nu$ in tt events using pp collision data at $s = \sqrt{7}$ TeV with the ATLAS detector
CONF-2013-090	Search for charged Higgs bosons in the τ+jets final state with pp collision data recorded at $\sqrt{s}$=8 TeV with the ATLAS experiment
CONF-2013-011	Search for invisible decays of a Higgs boson produced in association with a Z boson in ATLAS
CONF-2013-067	Search for a high-mass Higgs boson in the H->WW->lvlv decay channel with the ATLAS detector using 21 fb^{-1} of proton-proton collision data
CONF-2013-027	Search for Higgs bosons in Two-Higgs-Doublet models in the $H \rightarrow WW \rightarrow e\nu\mu\nu$ channel with the ATLAS detector

Invisible Higgs Decays

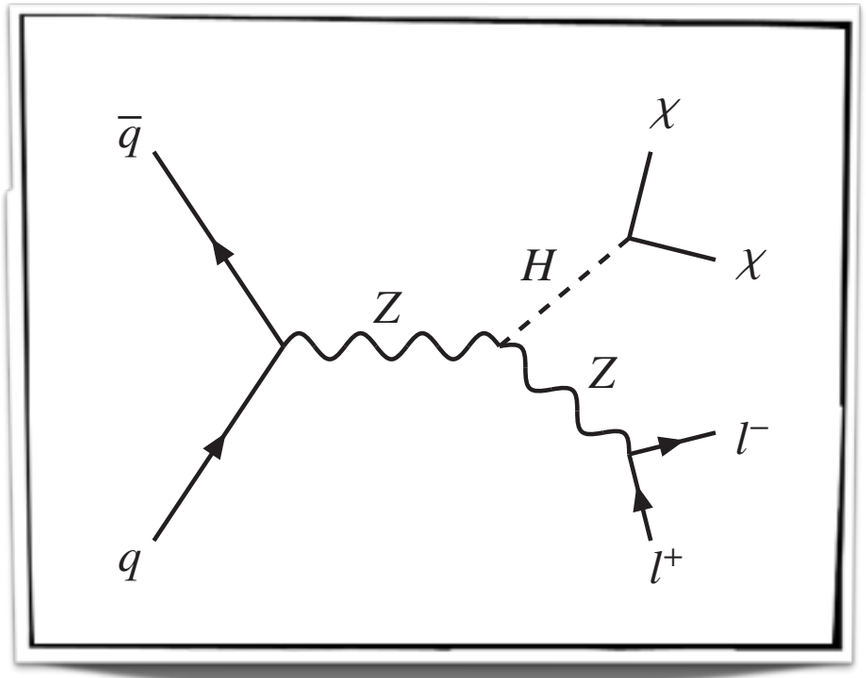
BSM Models:

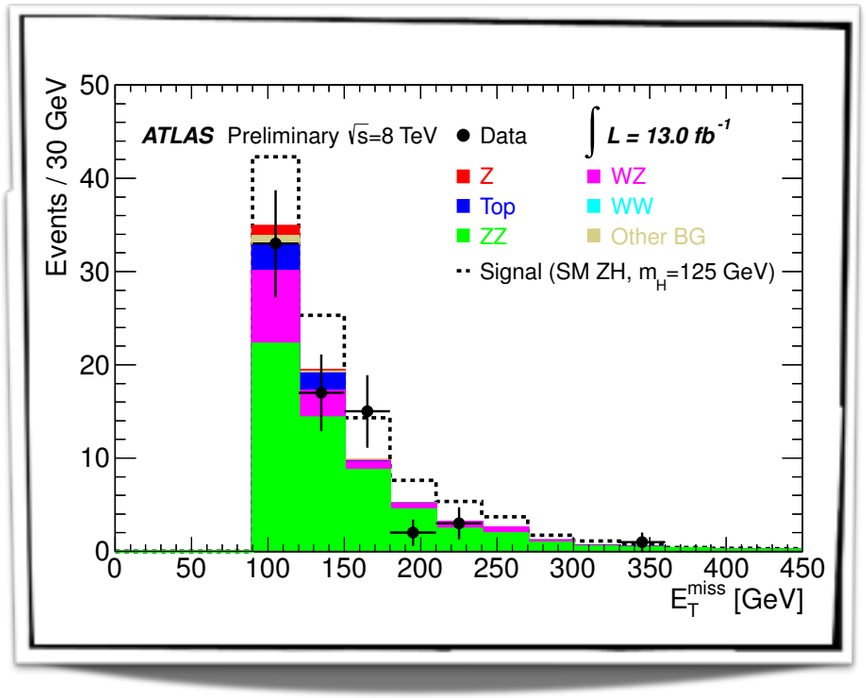
- Supersymmetry – decay to neutralinos
- Extra Dimension – oscillation or decay to graviscalars
- Dark Matter Singlets – decay into dark matter particles

Signature:

Higgs decays invisibly …
to stable or long-lived weakly interacting particles …
i.e. additional final state particles required …

Signal process: ZH production …
Expectation: large missing energy, $E_{T,miss}$ …
Main background: ZZ ➛ llvv …





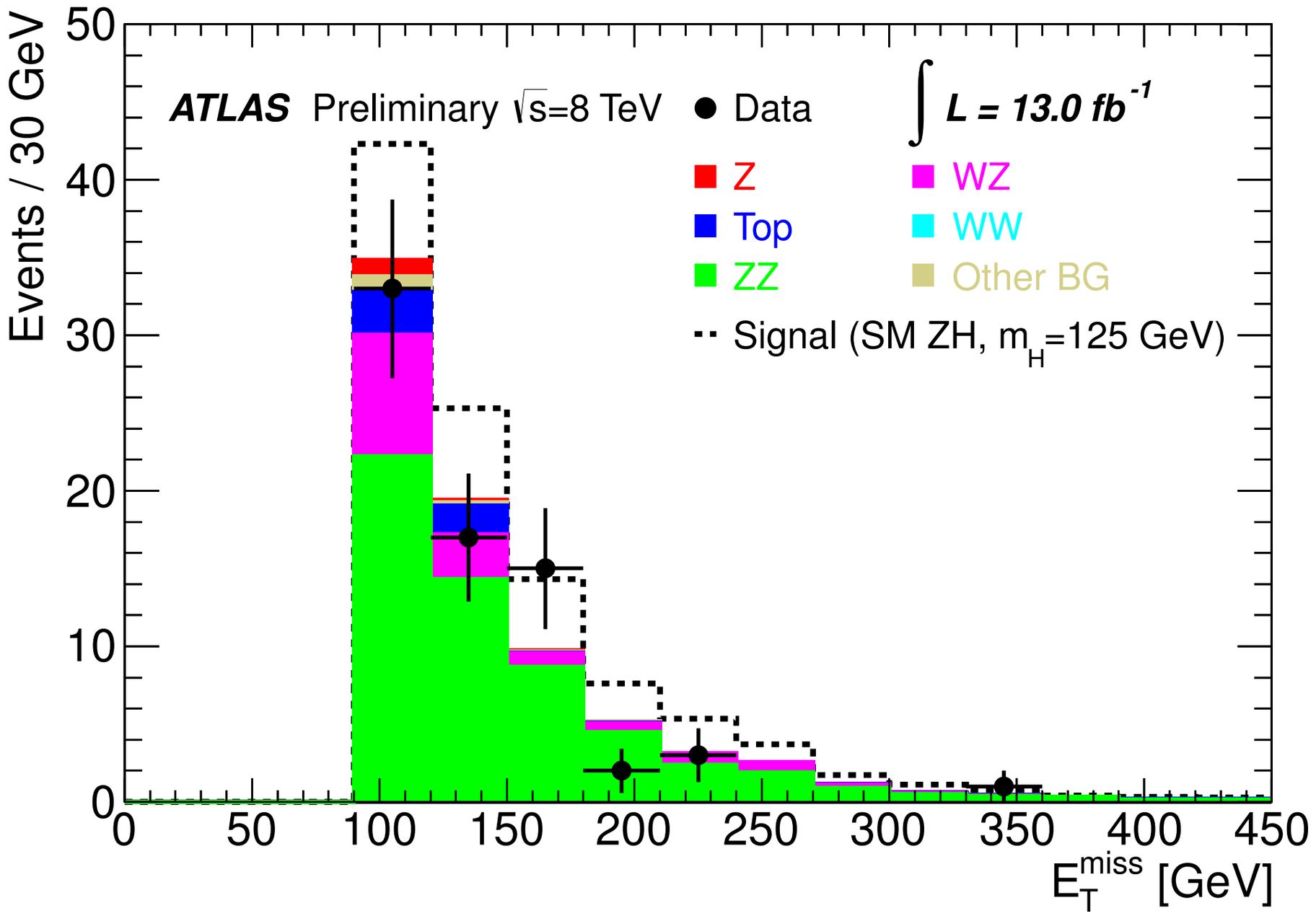
Analysis:

ATLAS : exploration of $E_{T,miss}$ distribution …
CMS : shape analysis of transverse mass m_T …

[ATLAS]

Invisible Higgs Decays

[ATLAS-CONF-2013-011]



Invisible Higgs Decays

[ATLAS-CONF-2013-011]

Event Selection:

Two high p_T electrons/muons …

Leptons isolated …

$|m_Z - m_{ll}| < 15$ GeV

$E_{T,miss} > 90$ GeV

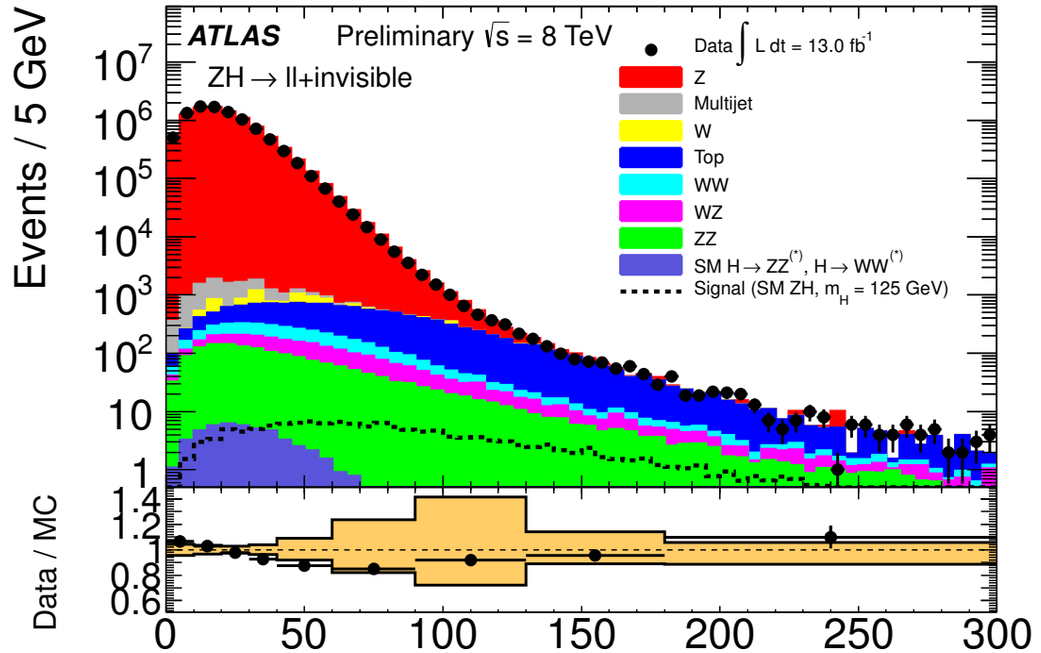
$\Delta\phi(E_{T,miss}, p_{T,miss}) < 0.2$

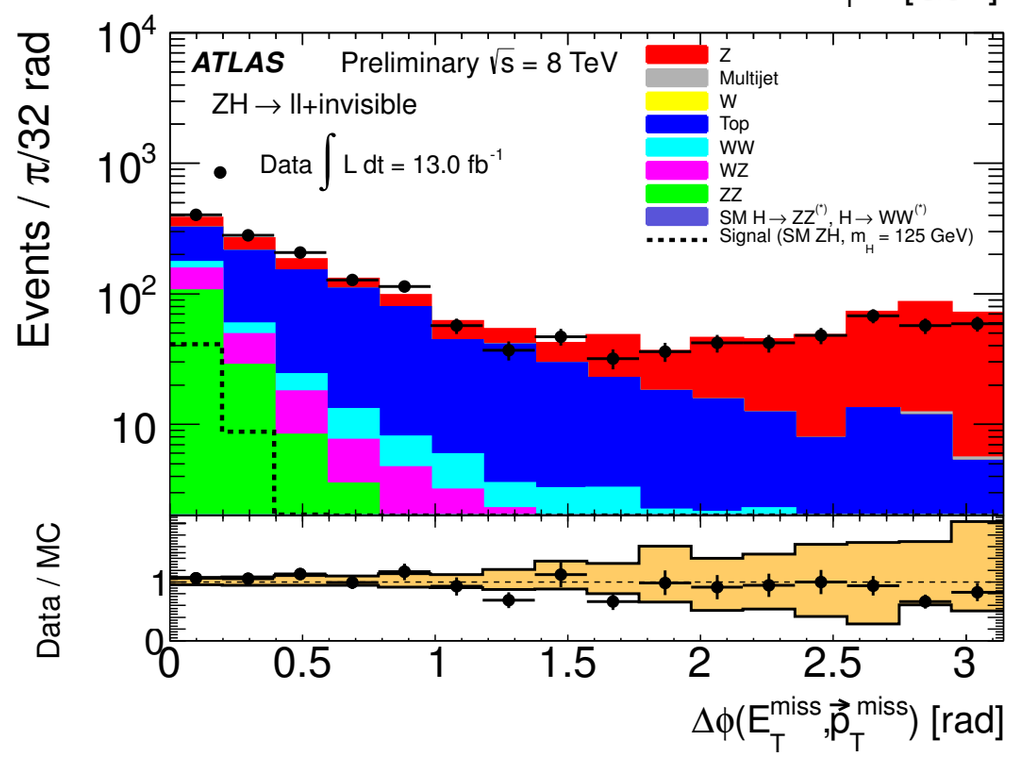
$\Delta\phi(Z, E_{T,miss}) > 2.6$

$\Delta\phi(l,l) < 1.7$

$|E_{T,miss} - p_{T,ll}| / p_T < 0.2$

Jet veto: $p_T > 20$ GeV, $|\eta| < 2.5$





[ATLAS]

Invisible Higgs Decays

[ATLAS-CONF-2013-011]

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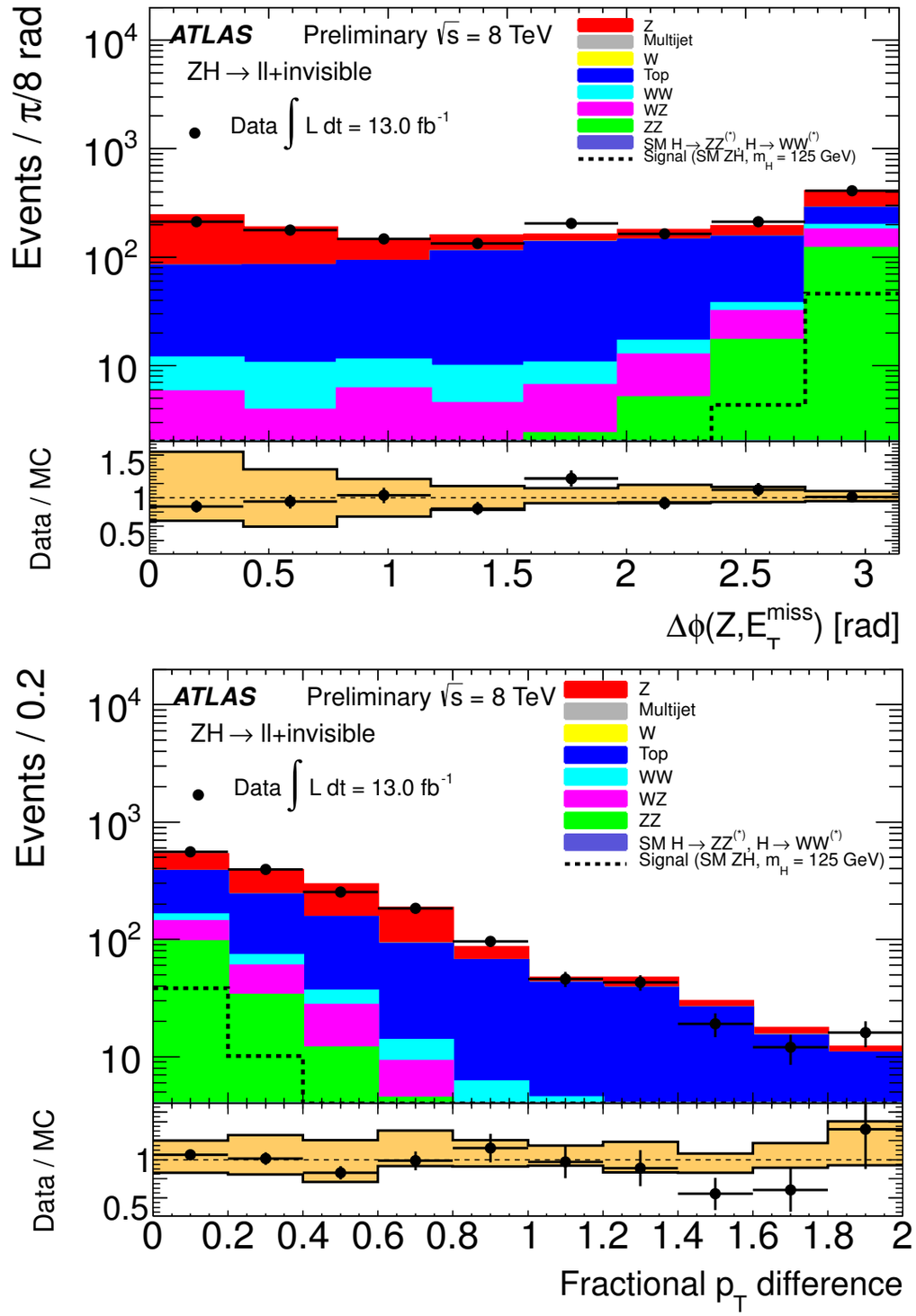
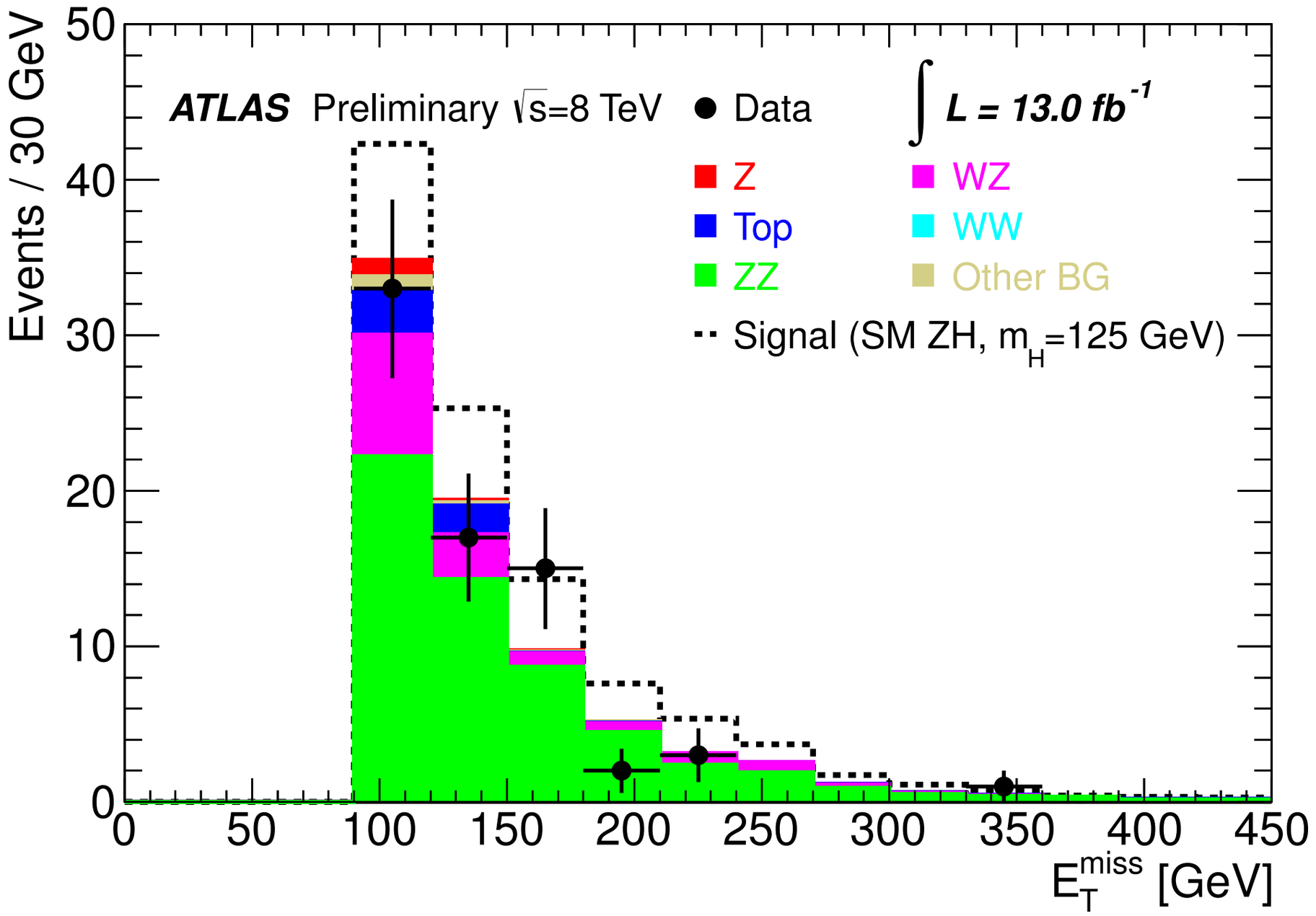


[ATLAS]

Invisible Higgs Decays

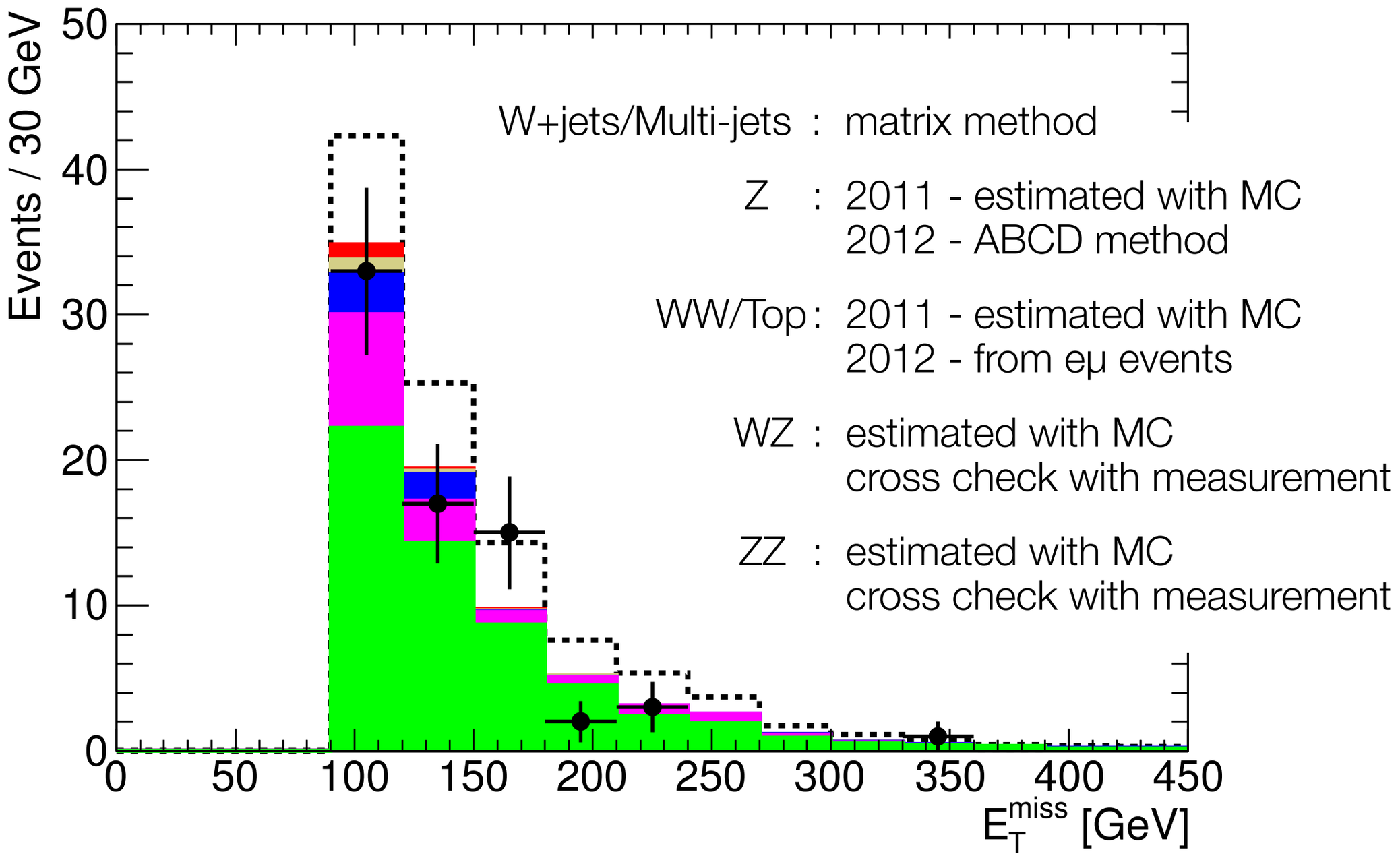
[ATLAS-CONF-2013-011]



[ATLAS]

Invisible Higgs Decays

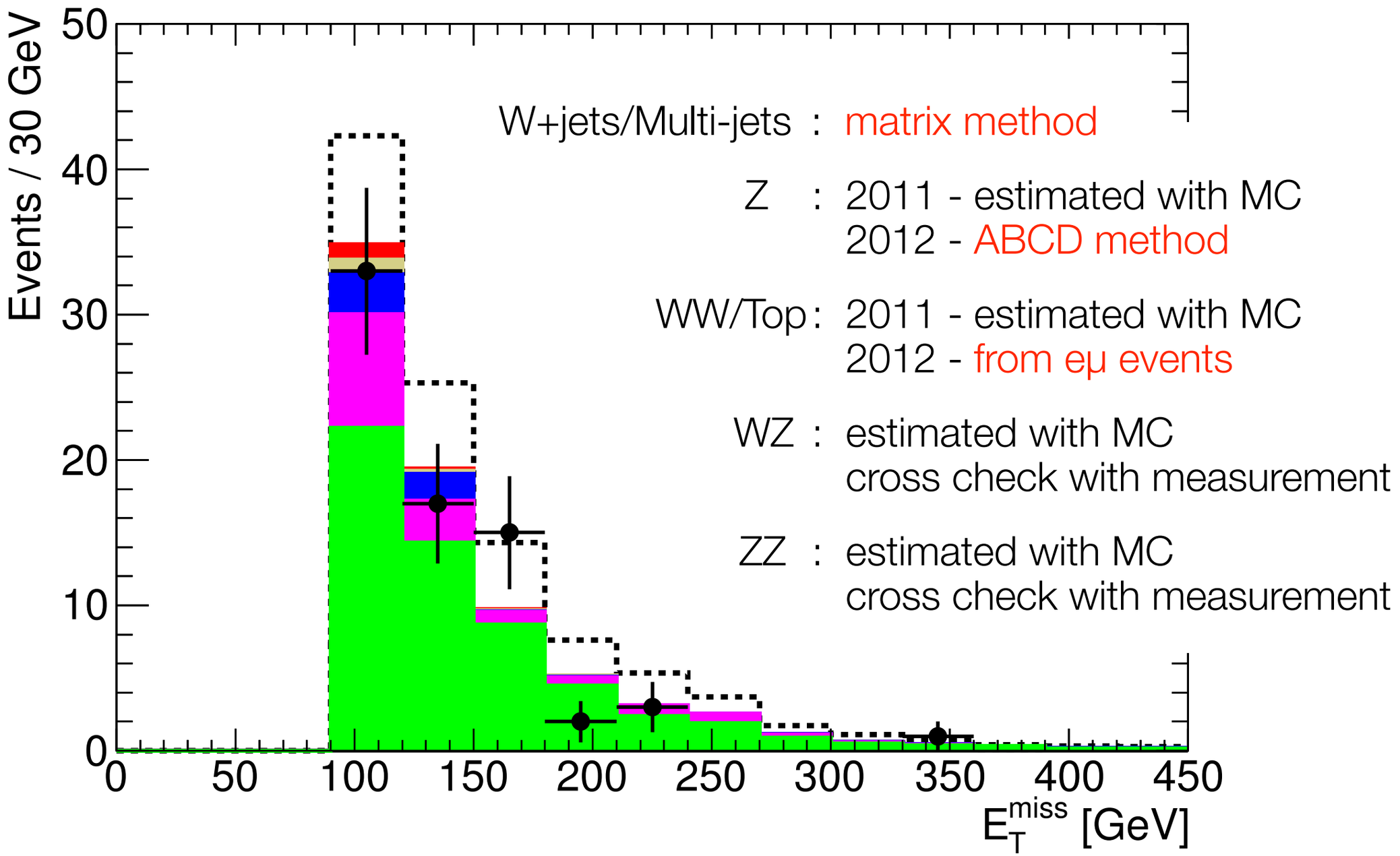
[ATLAS-CONF-2013-011]



[ATLAS]

Invisible Higgs Decays

[ATLAS-CONF-2013-011]



[ATLAS]

Invisible Higgs Decays

Bgr. estimate:

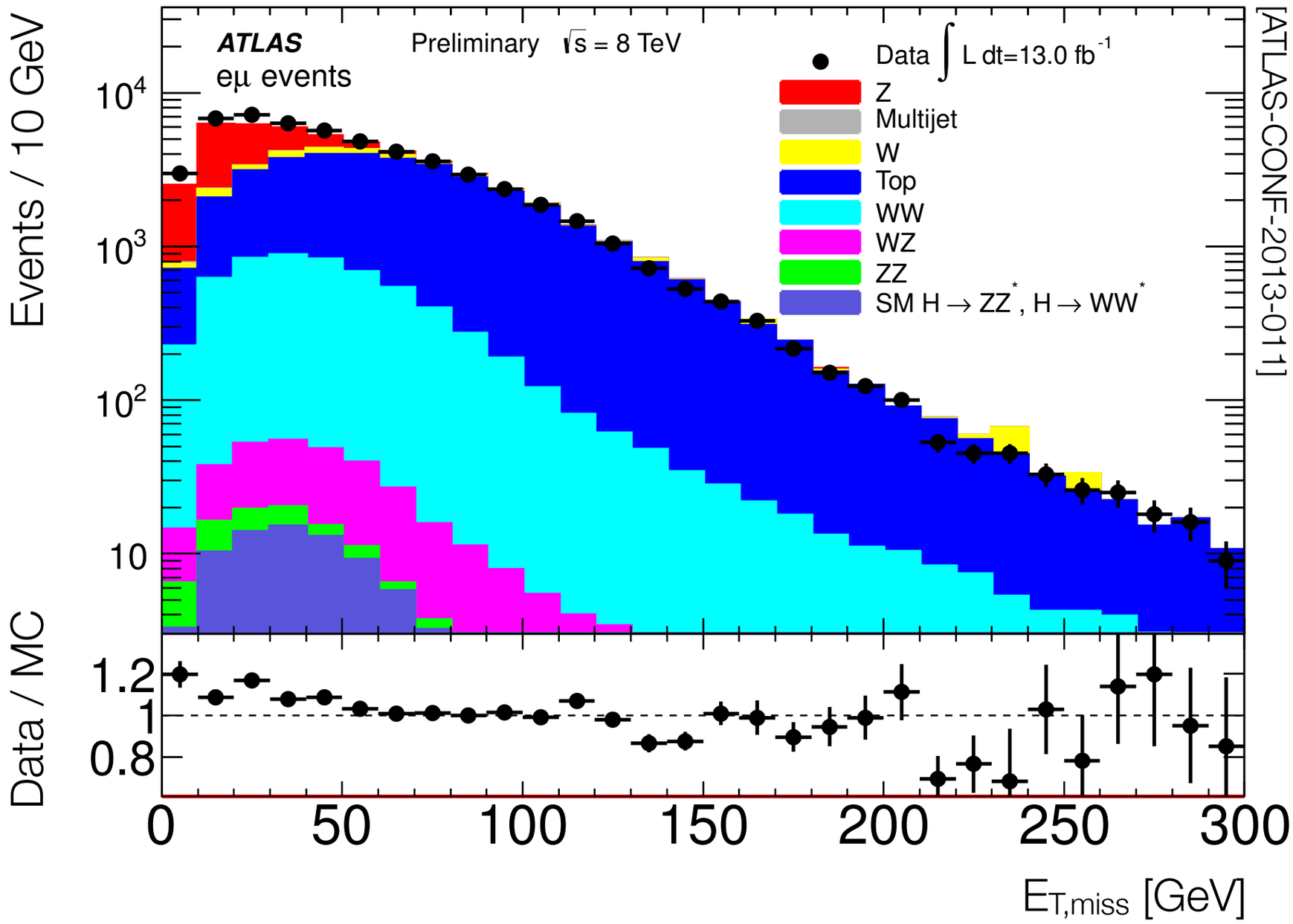
$$N_{ee}^{\mathrm{bkg}} = \frac{1}{2} \times N_{e\mu}^{\mathrm{data,sub}} \times k$$

$$N_{\mu\mu}^{\mathrm{bkg}} = \frac{1}{2} \times N_{e\mu}^{\mathrm{data,sub}} \times \frac{1}{k}$$

with

$$k = \sqrt{\frac{N_{ee}^{\mathrm{data}}}{N_{\mu\mu}^{\mathrm{data}}}}$$

WW/Top Background Estimate
[Selected eμ Control Sample]



Invisible Higgs Decays

[ATLAS]
[ABCD Method]

[ATLAS-CONF-2013-011]

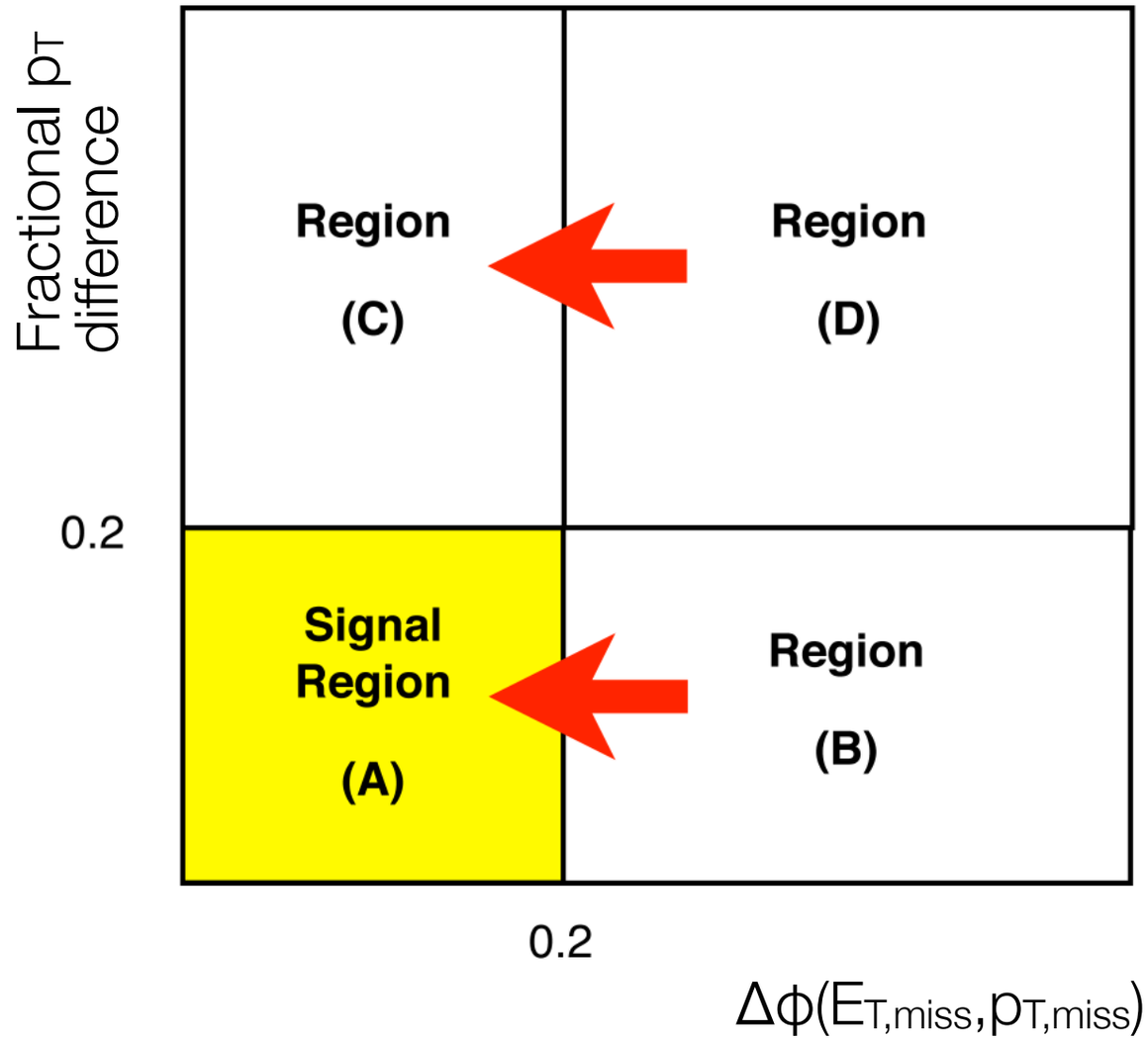
Z Background Estimate
[ABCD Method]

Observed

Estimate

$$N_A^{\text{est}} = N_B^{\text{obs}} \times \frac{N_C^{\text{obs}}}{N_D^{\text{obs}}} \times \alpha$$

Correction
[due to correlations]

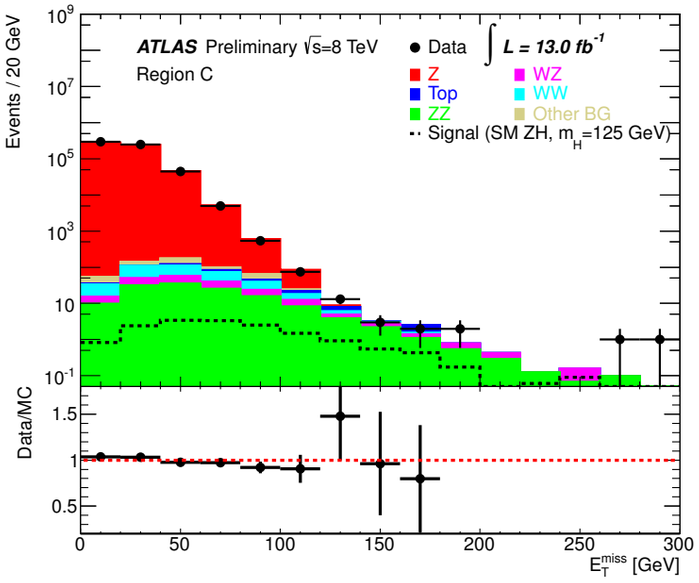


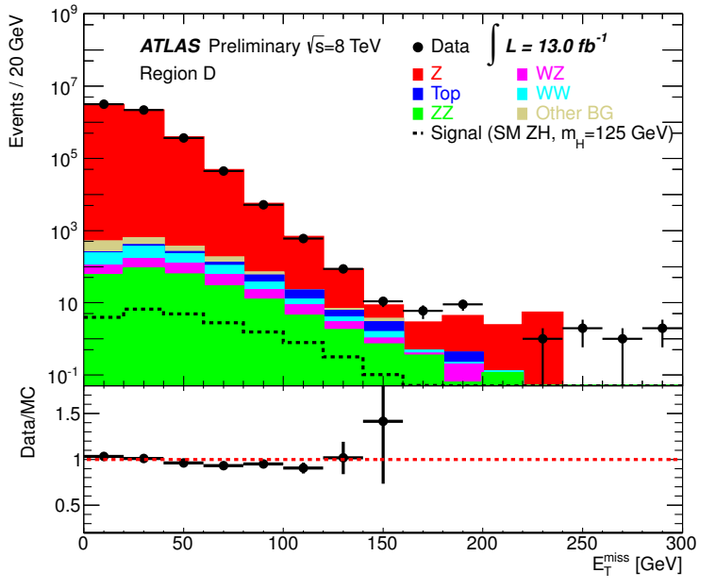
Invisible Higgs Decays

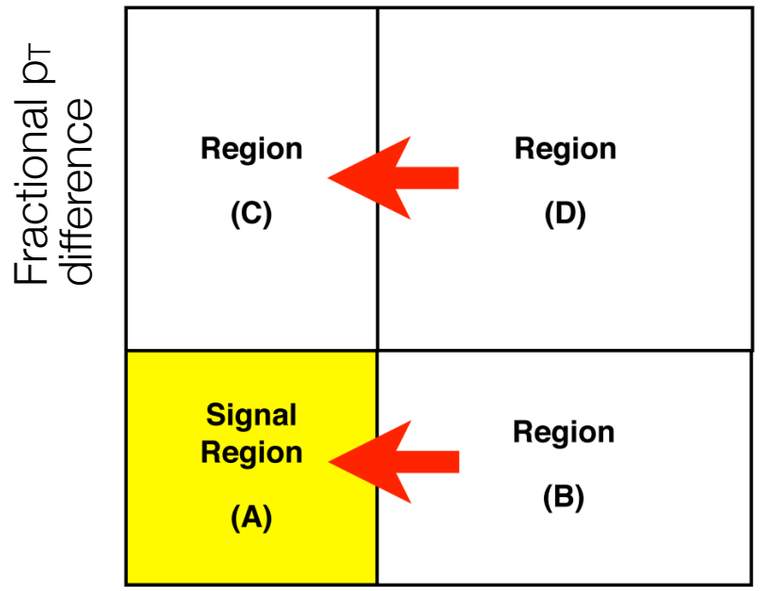
[ATLAS]
[ABCD Method]

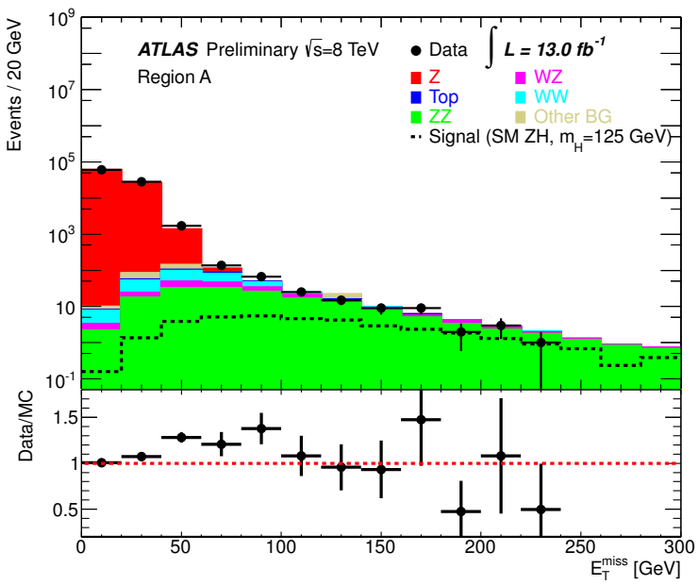
[ATLAS-CONF-2013-011]

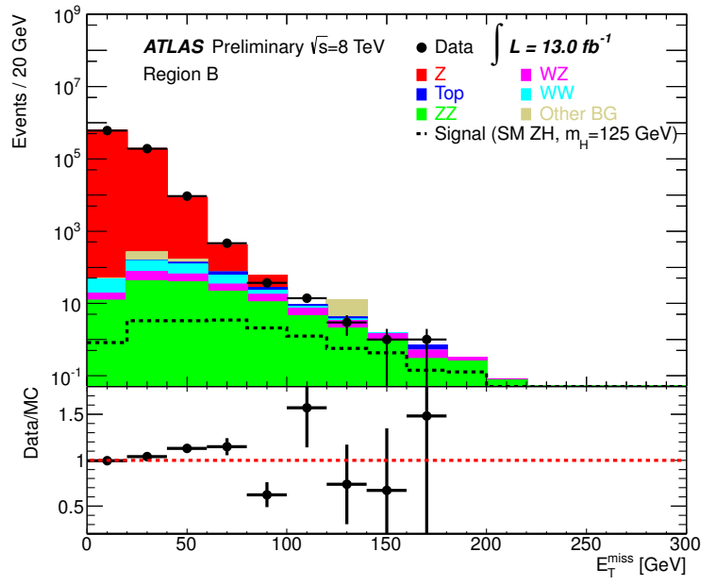
Z Background Estimate
[ABCD Method]











$$N_A^{\text{est}} = N_B^{\text{obs}} \times \frac{N_C^{\text{obs}}}{N_D^{\text{obs}}} \times \alpha$$

Invisible Higgs Decays

[ATLAS]
[Matrix Method]

[ATLAS-CONF-2013-011]

W+jets/Multijet Background Estimate
[Matrix Method]

T: Tight
L: Loose

R: Real
F: Fake

$$\begin{bmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{bmatrix} = \begin{bmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{bmatrix} \times \begin{bmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{bmatrix}$$

selection efficiencies
and fake rates …
[tight wrt loose …]

from data
e.g. from Z ➝ ll or dijets
[p_t dependent]

$$N_{W+\text{jets}} = \sum_i^{N_{\text{events}}} N^i_{RF} \times r^i_1 \times f^i_2 + N^i_{FR} \times f^i_1 \times r^i_2$$

$$N_{\text{multijet}} = \sum_i^{N_{\text{events}}} N^i_{FF} \times f^i_1 \times f^i_2$$

Invisible Higgs Decays

[ATLAS-CONF-2013-011]

Systematics on background estimates
[Processes, methods, uncertainties]

Process	Estimation method	Uncertainty (%) 2011	2012
ZH Signal	MC	7	6
ZZ	MC	11	10
WZ	MC	12	14
WW	MC	14	not used
Top quark	MC	90	not used
Top quark, WW and $Z \to \tau\tau$	$e\mu$ CR	not used	4
Z	ABCD method	56	51
W + jets, multijet	Matrix method	15	22

[ATLAS]

Invisible Higgs Decays

[ATLAS-CONF-2013-011]

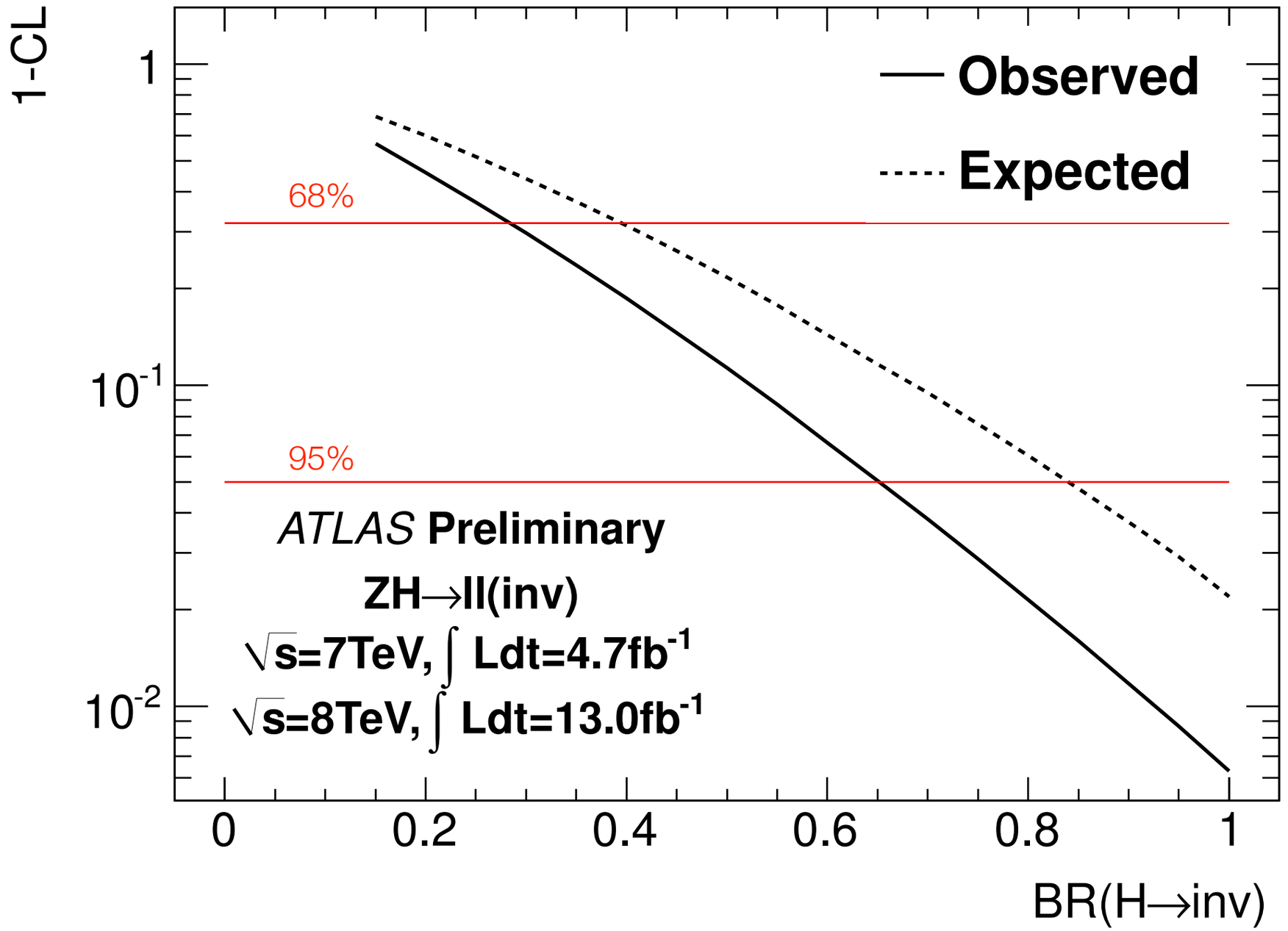
Observed and expected number of events
for 2011 and 2012 data taking periods

Data Period	2011 (7 TeV)	2012 (8 TeV)
ZZ	$23.5 \pm 0.8 \pm 2.5$	$56.5 \pm 1.2 \pm 5.7$
WZ	$6.2 \pm 0.4 \pm 0.7$	$13.9 \pm 1.2 \pm 2.1$
WW	$1.1 \pm 0.2 \pm 0.2$	used $e\mu$ data-driven
Top quark	$0.4 \pm 0.1 \pm 0.4$	used $e\mu$ data-driven
Top quark, WW and $Z \to \tau\tau$ ($e\mu$ data-driven)	used MC	$4.9 \pm 0.9 \pm 0.2$
Z	$0.16 \pm 0.13 \pm 0.09$	$1.4 \pm 0.4 \pm 0.7$
W + jets, multijet	$1.3 \pm 0.3 \pm 0.2$	$1.4 \pm 0.4 \pm 0.3$
Total BG	$32.7 \pm 1.0 \pm 2.6$	$78.0 \pm 2.0 \pm 6.5$
Observed	27	71

[ATLAS]

Invisible Higgs Decays

[ATLAS-CONF-2013-011]



SM Higgs

[m_h =125 GeV]

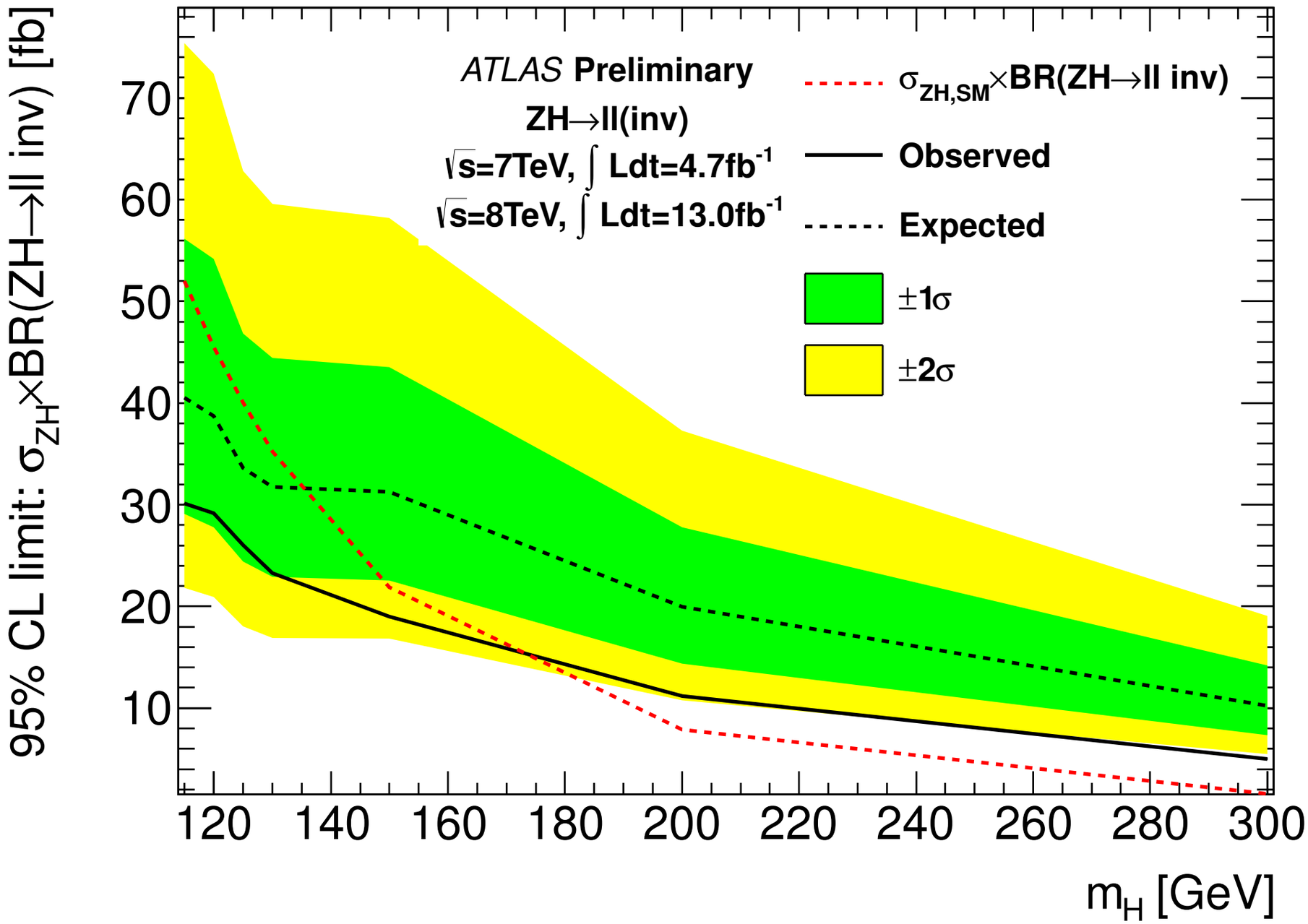
BR < .65

[SM: BR = 0.1%]

[ATLAS]

Invisible Higgs Decays

[ATLAS-CONF-2013-011]



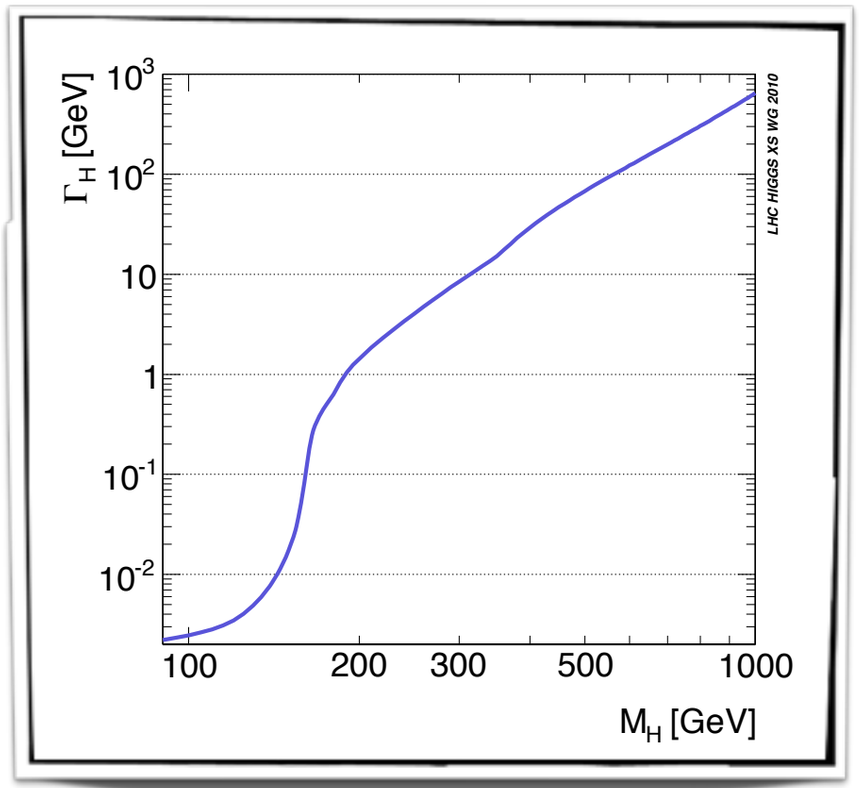
Search for a Heavy Higgs

Search for a second, heavier, CP-even, SM-like Higgs boson …

e.g. predicted by 2HDM models …

Limit setting includes the 125 GeV Higgs boson
and assumes that this is the light scalar, h, of a 2HDM …

PDG



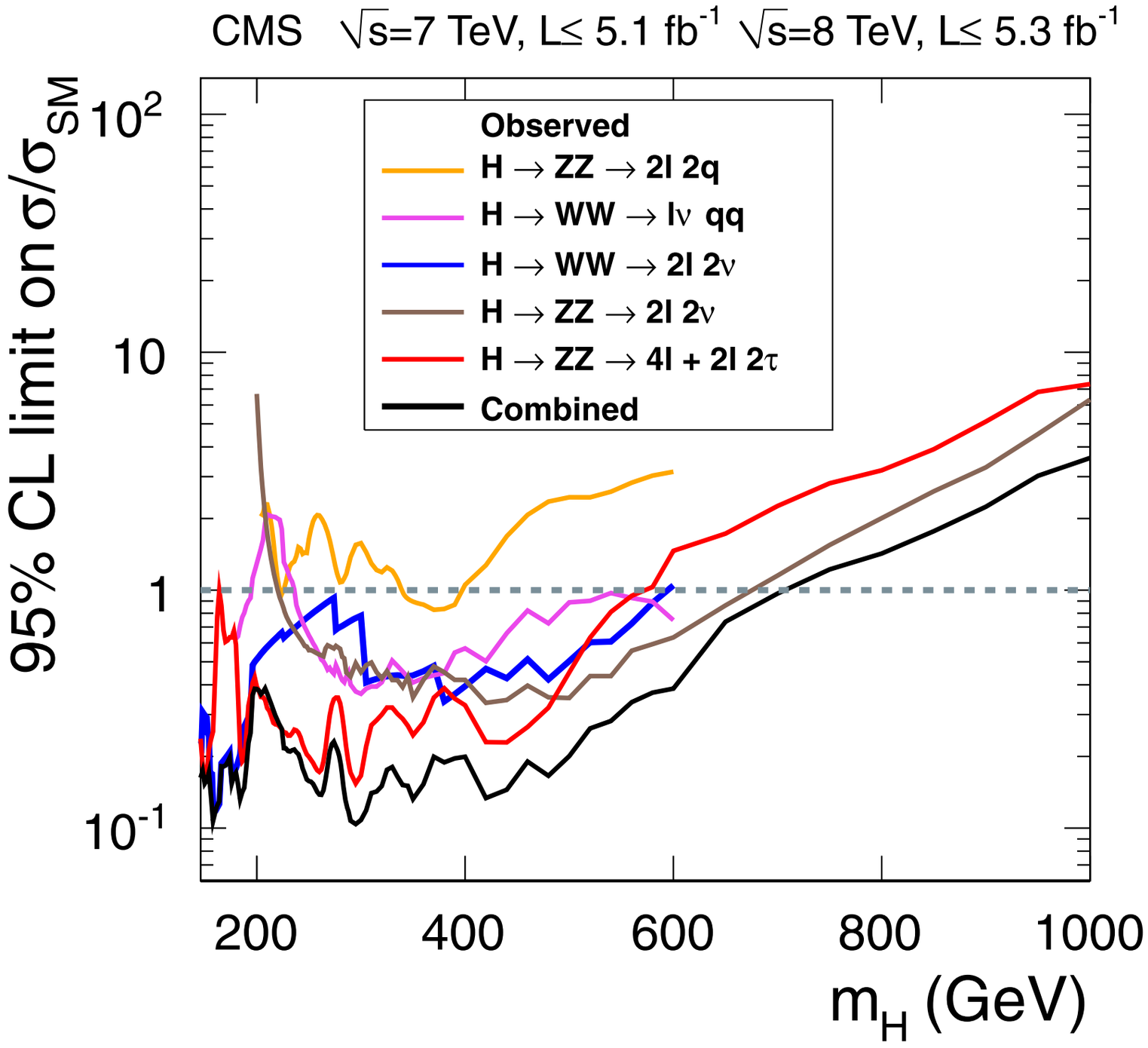
H decay mode	H production	Exclusive final states	No. of channels	m_{H} range [GeV]	m_{H} resolution
$\mathrm{WW} \to \ell\nu\ell\nu$	0/1-jets	$((\mathrm{ee}, \mu\mu), \mathrm{e}\mu) + (0 \text{ or } 1 \text{ jets})$	4	145–600	20 %
$\mathrm{WW} \to \ell\nu\ell\nu$	VBF tag	$((\mathrm{ee}, \mu\mu), \mathrm{e}\mu) + (\mathrm{jj})_{\mathrm{VBF}}$	2	145–600	20 %
$\mathrm{WW} \to \ell\nu\mathrm{qq}$	Untagged	$(\mathrm{e}\nu, \mu\nu) + ((jj)_{\mathrm{W}} \text{ with } 0 \text{ or } 1 \text{ jets})$	4	180–600	5–15 %
$\mathrm{ZZ} \to 2\ell 2\ell'$	Inclusive	$4\mathrm{e}, 4\mu, 2\mathrm{e}2\mu$	3	145–1000	1–2 %
		$(\mathrm{ee}, \mu\mu) + (\tau_{\mathrm{h}}\tau_{\mathrm{h}}, \tau_{\mathrm{e}}\tau_{\mathrm{h}}, \tau_{\mu}\tau_{\mathrm{h}}, \tau_{\mathrm{e}}\tau_{\mu})$	8	200–1000	10–15 %
$\mathrm{ZZ} \to 2\ell 2\mathrm{q}$	Inclusive	$(\mathrm{ee}, \mu\mu) + ((\mathrm{jj})_{\mathrm{Z}} \text{ with } 0, 1, 2\mathrm{b}\text{-tags})$	6	200–600	3 %
$\mathrm{ZZ} \to 2\ell 2\nu$	Untagged	$(\mathrm{ee}, \mu\mu) + 0, 1, 2$ non-VBF jets	6	200–1000	7 %
$\mathrm{ZZ} \to 2\ell 2\nu$	VBF tag	$(\mathrm{ee}, \mu\mu) + (\mathrm{jj})_{\mathrm{VBF}}$	2	200–1000	7 %

[EPJ 73 (2013) 2469]

[CMS]

Search for a Heavy Higgs

[EPJ 73 (2013) 2469]



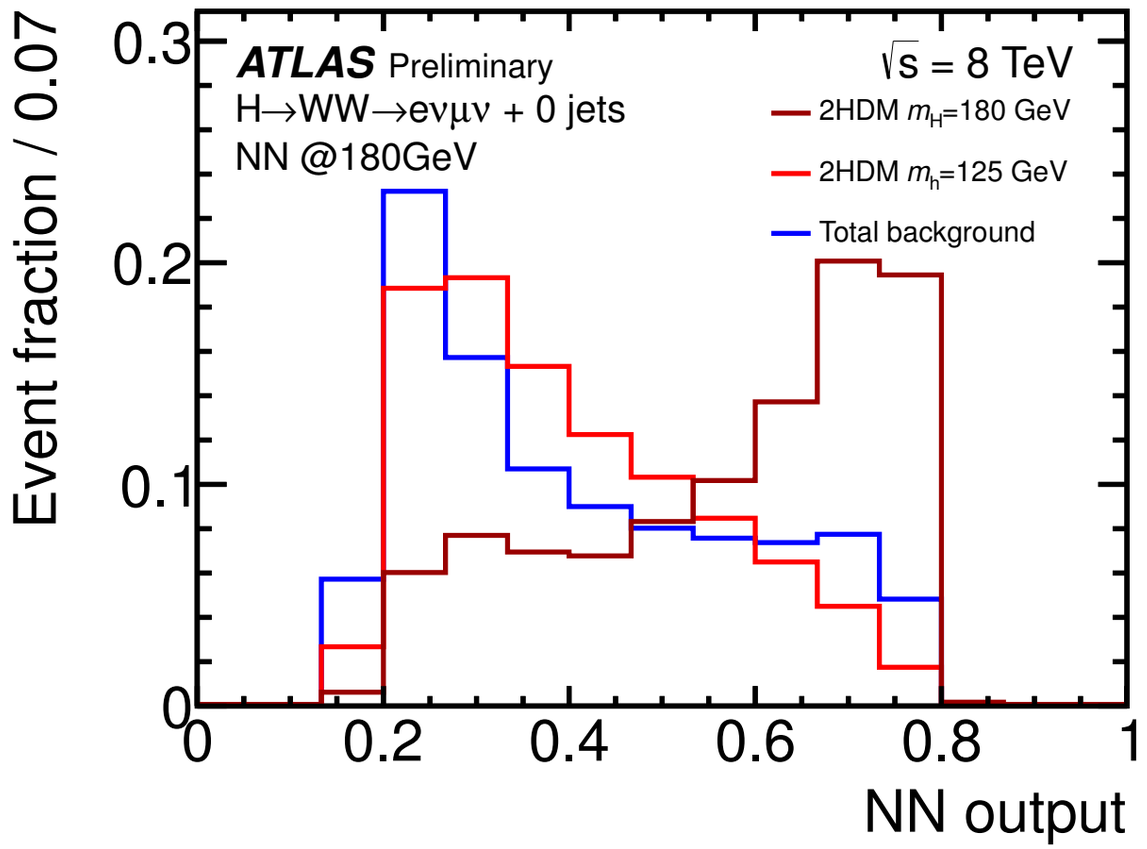
Exclusion:
127 -710 GeV

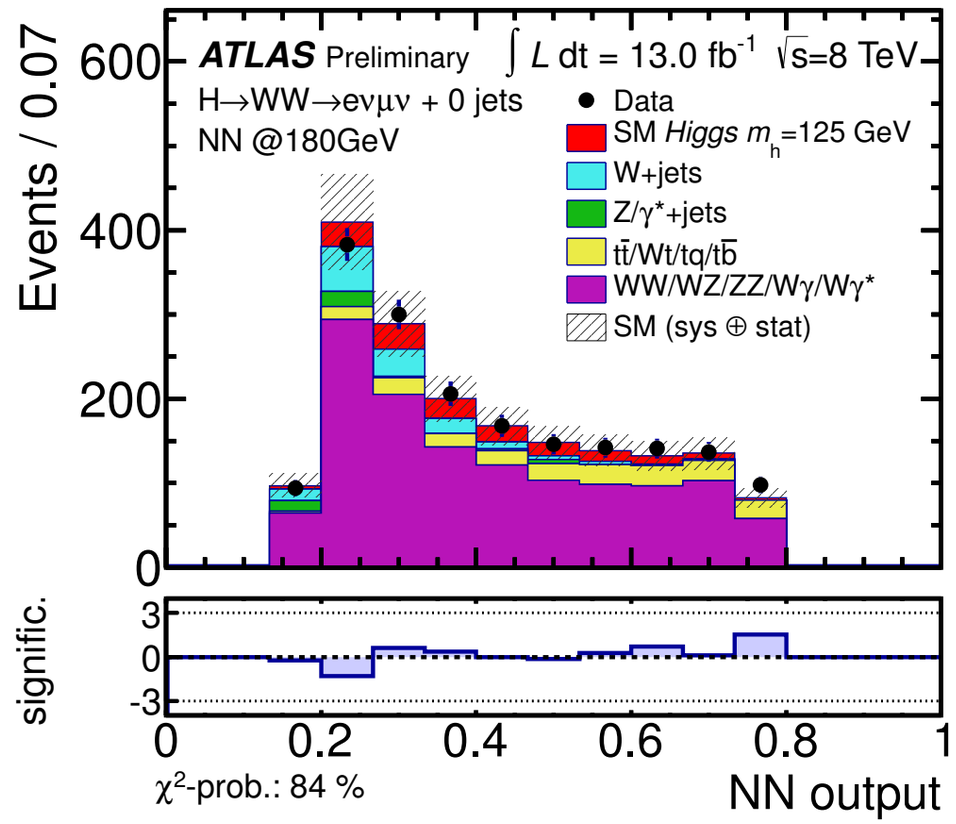
Search for a Heavy Higgs

[ATLAS-CONF-2013-027]

Search for Higgs bosons in 2HDMs in the H ➛ WW ➛ evμv channel …

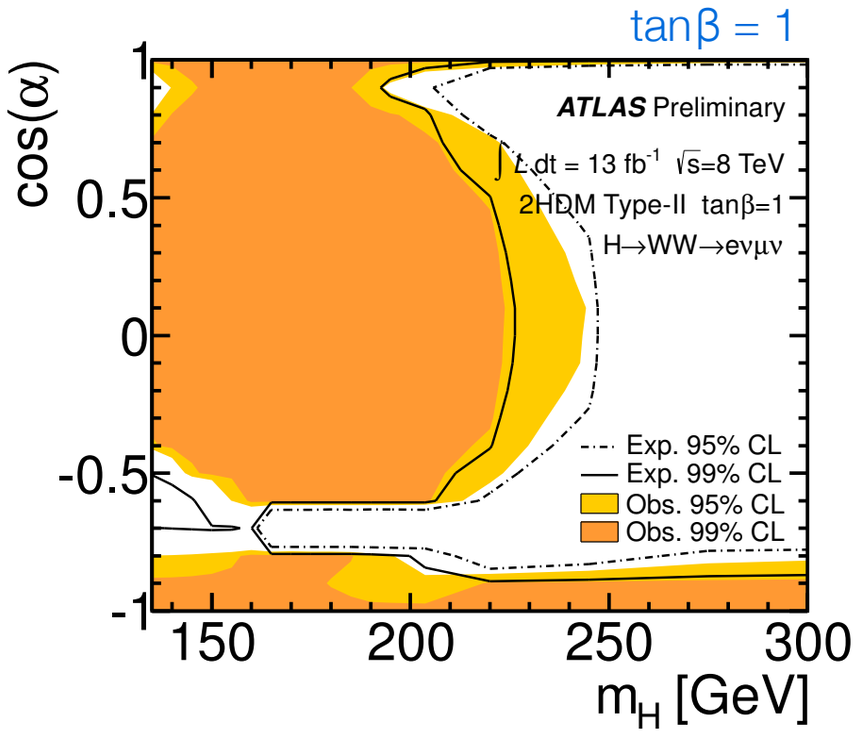
Neural Network techniques are used to maximize the sensitivity …
Low- and high-mass Higgs bosons can be well separated …

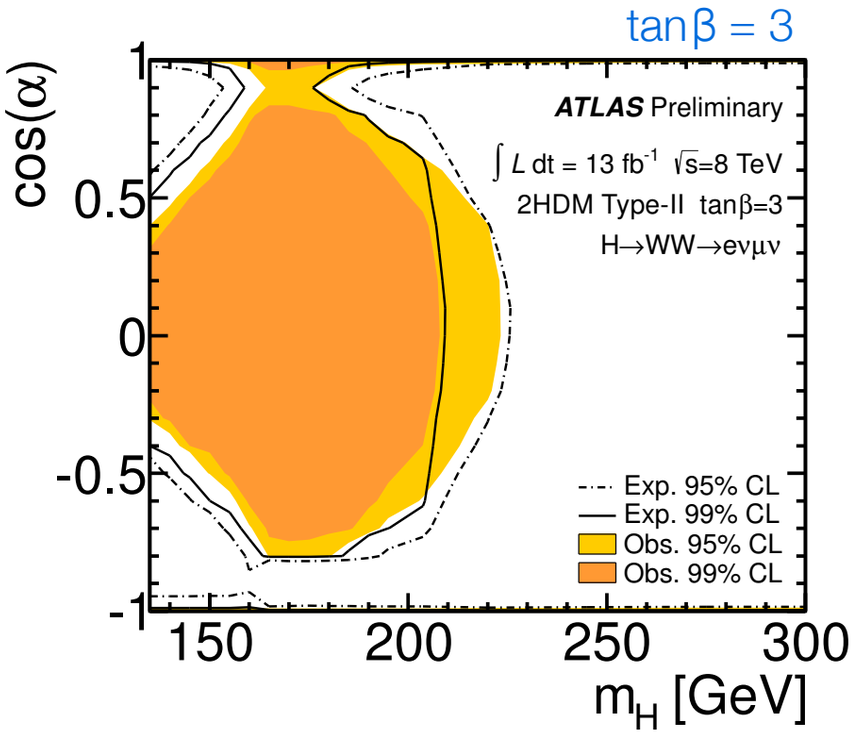




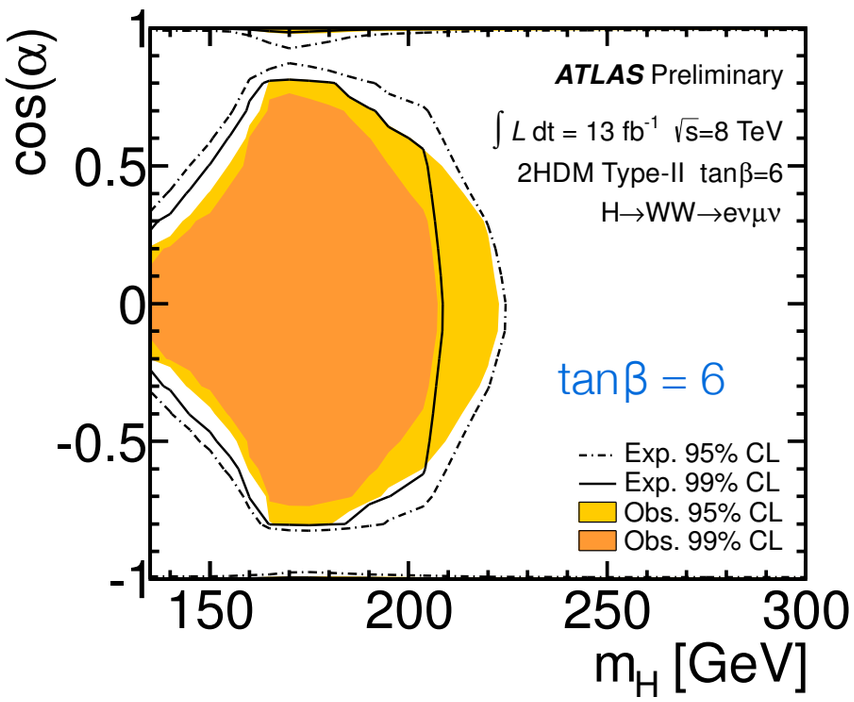
Search for a Heavy Higgs

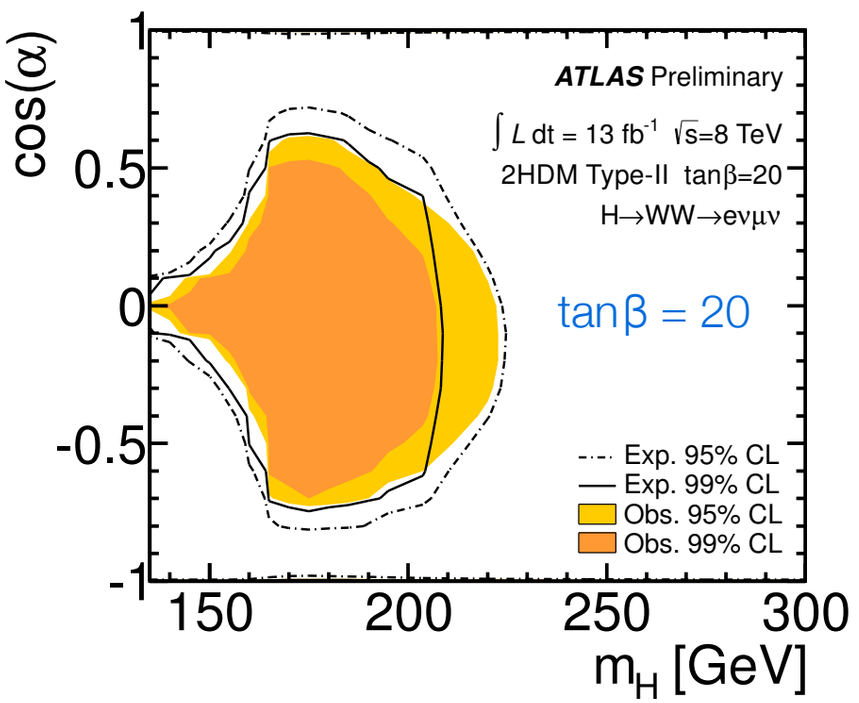
[ATLAS-CONF-2013-027]





Generic 2HDM Type II Model …





LHC BSM Higgs Searches

[Repetition]

BSM Scenarios:

[see e.g. PDG: Status of Higgs Boson Physics]

Supersymmetric Extensions …

One neutral Higgs with close to SM properties (h); two extra neutral Higgs bosons (H,A), one SM-like;
two charged Higgs bosons ($H^{\pm}$); potential departures from SM Higgs decay rates (e.g. h ➛ bb) …

Two Higgs-Doublet Models (2-HDMs)…

Simple extension with 7 free parameters; different types, distinguished based on coupling to fermions …
Type-I: only one doublet couples to fermions; Type-II (SUSY): ϕ_1/ϕ_2 couples to up/down-type fermions …

Composite Higgs Scenarios …

Idea: Higgs is composite bound state; e.g. Little Higgs Models; partial compositeness …
Extra particles at the TeV scale (Z′, W′, …); extra Higgs bosons; charged and doubly charged Higgs bosons …

Higgs Triplet Models …

Add electroweak triplet scalar to SM; motivation: neutrinos acquire Majorana mass …
Extra Higgs bosons, in particular doubly charged Higgs ($H^{\pm\pm}$); fermiophobic Higgs (also for 2HDM) …

Search for a Heavy Higgs

A Generic 2HDM …

Possible Production:

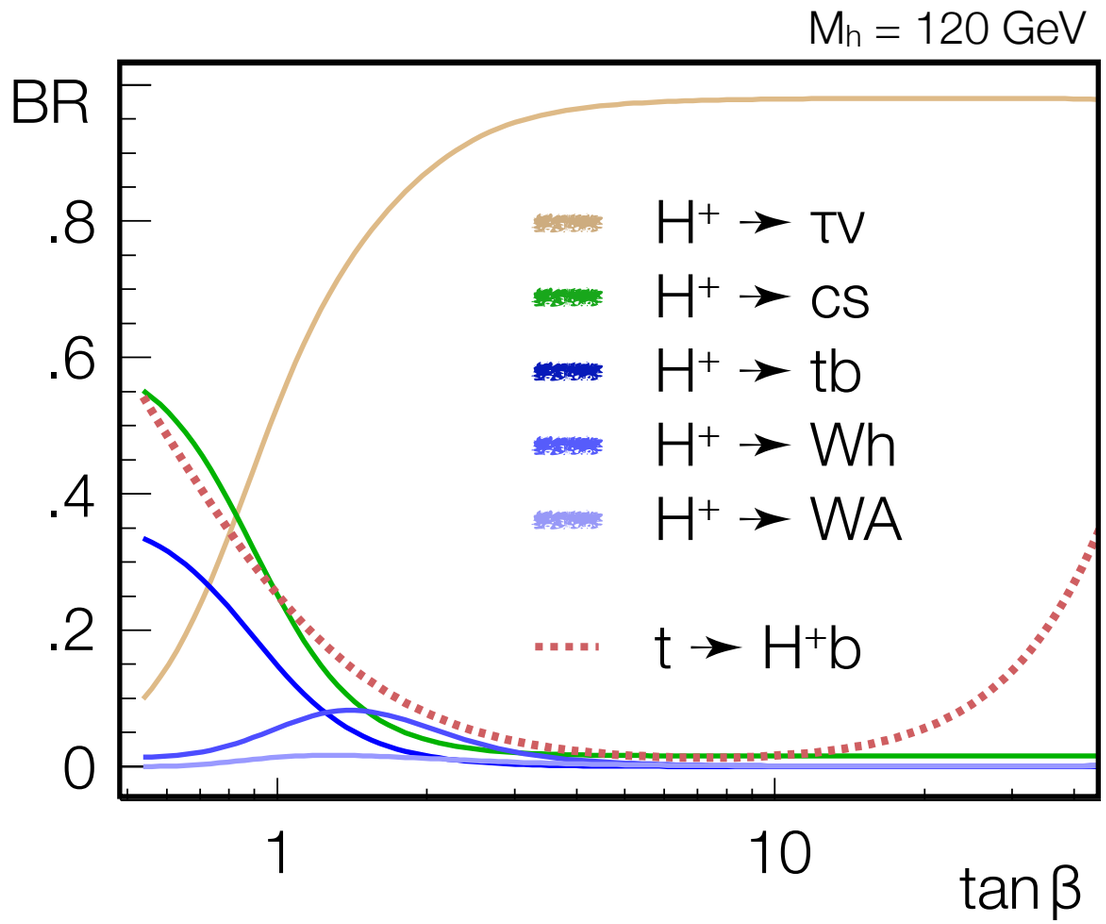
Light H^+ : $gg \rightarrow tt \rightarrow bWbH^+$

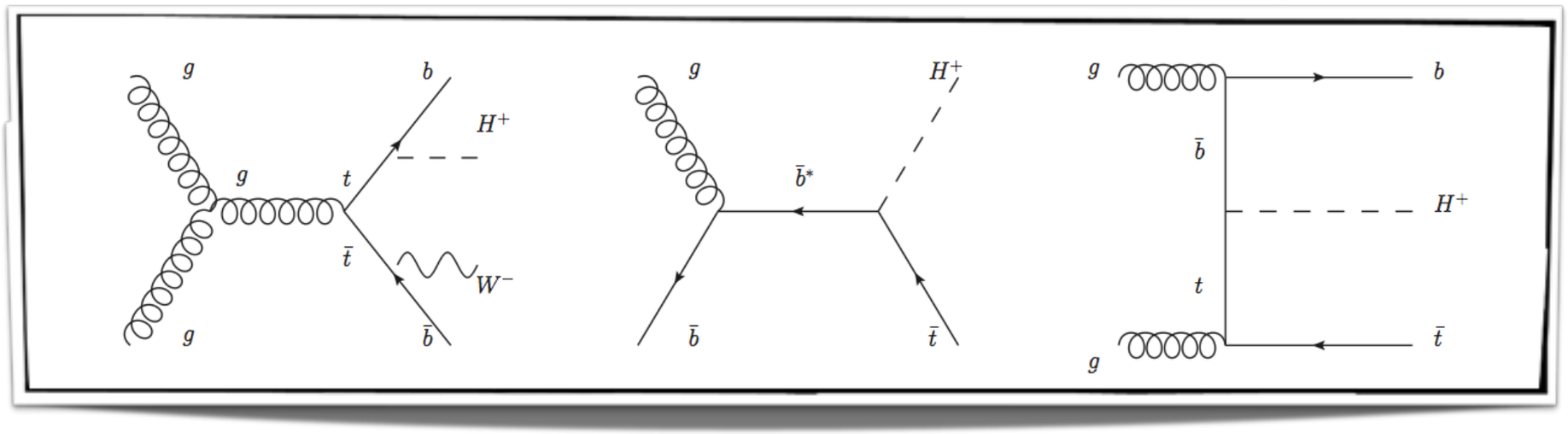
Heavy H^+ : $gb \rightarrow tH^+$ and $gg \rightarrow tbH^+$

Charged Higg Decay:

Light H^+ : Almost exclusively to τν
[at low tanβ predominantly to cs]

Heavy H^+ : tb; τν; $\chi^+\chi^0$





[ATLAS, CMS]

Light Charged Higgs

[JHEP 06 (2012) 039]
[JHEP 07 (2012) 143]
[EPJ C 73 (2013) 2465]

Searches channels …

considering τ-decay

τ_{had} + lepton:

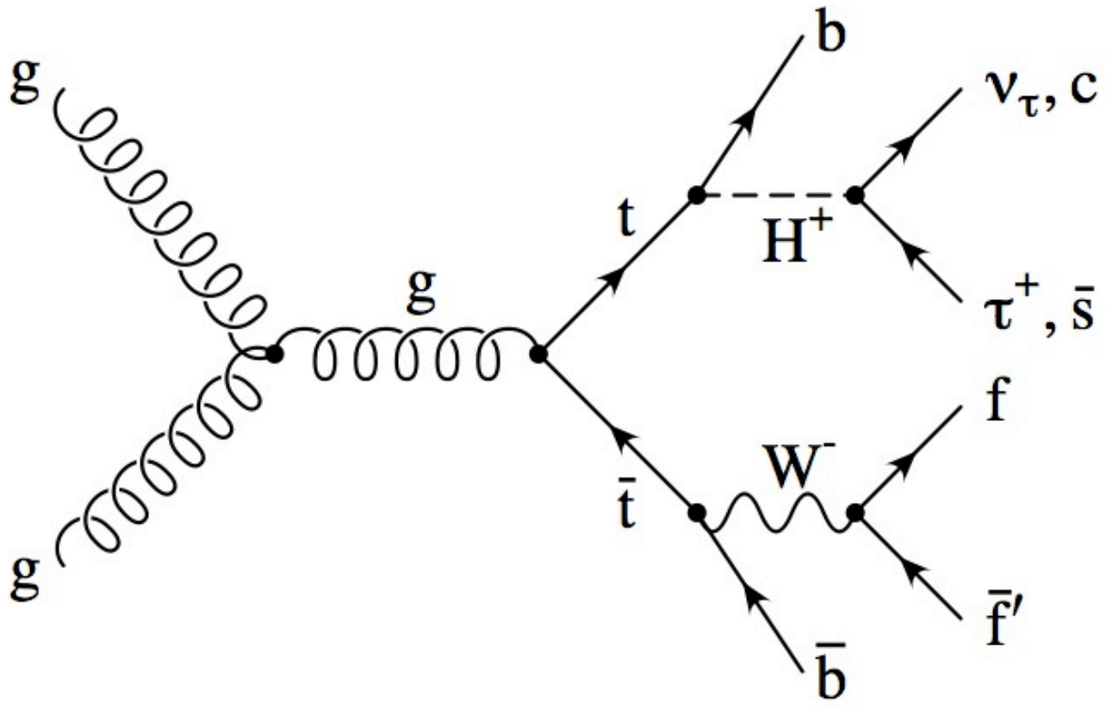
tt ➛ bWbH^+ ➛ bb lν $\tau_{had}\nu$

τ_{had} + jets:

tt ➛ bWbH^+ ➛ bb qq $\tau_{had}\nu$

τ_{lep} + jets:

tt ➛ bWbH^+ ➛ bb qq $\tau_{lep}\nu$



Searches channels …

considering hadronic Higgs decay

e,μ + jets:

tt ➛ bWbH^+ ➛ bb lν cs

W decay: hadronically
H decay : to τ (or charm)

[ATLAS]

Light Charged Higgs, $H^+ \rightarrow \tau\nu$

[JHEP 06 (2012) 039]

τ_{lep} + W(➔ jets)	τ_{had} + W(➔ jets)	τ_{had} + W(➔ lν)
One isolated e/μ p_T > 25/20 GeV	One hadronic τ p_T > 40 GeV	One isolated e/μ p_T > 25/20 GeV
		One hadronic τ p_T > 20 GeV
≥ 4 jets; p_T > 20 GeV exactly 2 b-jets	≥ 4 jets; p_T > 20 GeV at least one b-jet	≥ 2 jets; p_T > 20 GeV at least one b-jet
MET & topological cuts	MET & topological cuts	MET & topological cuts

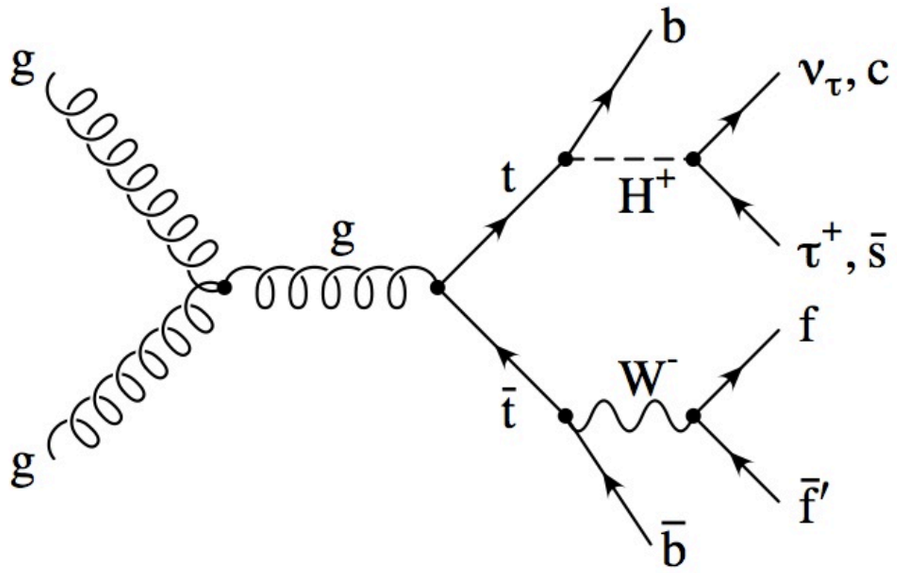
Three Channels

Dominant backgrounds:

ttbar, single-top, multi-jets,W+jets, Z+jets, Di-boson events

Dominant systematics:

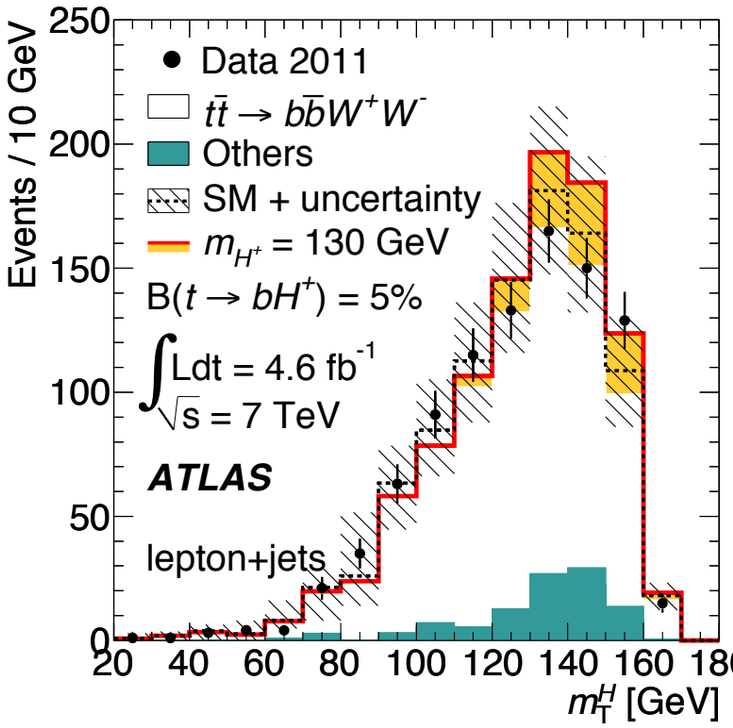
Jet energy resolution/scale, b-tagging efficiency, misidentification probability …



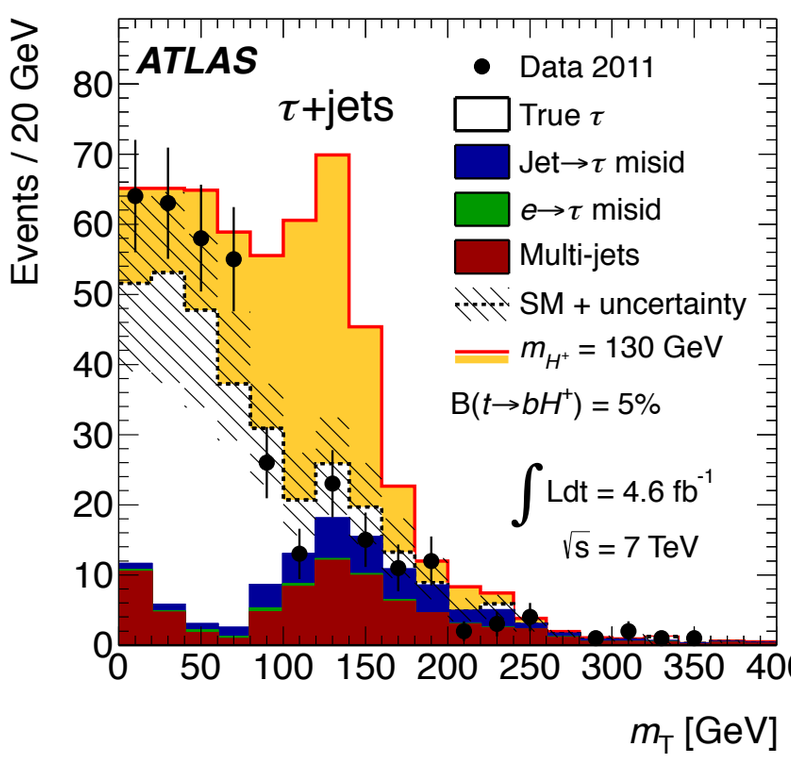
Light Charged Higgs, $H^+ \rightarrow \tau\nu$

[JHEP 06 (2012) 039]

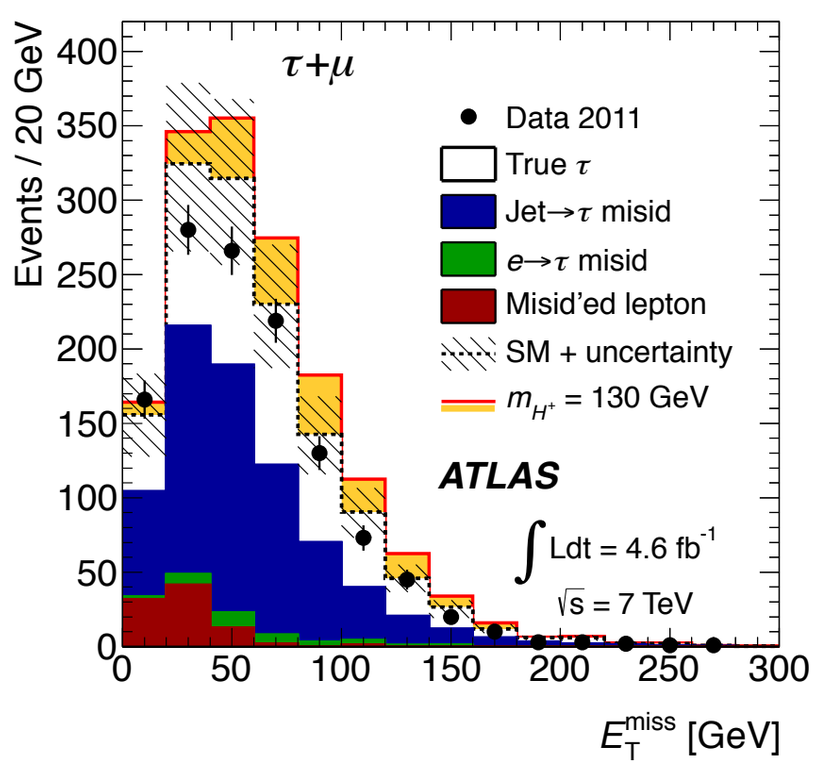
τ_{lep} + W(➛ jets)



τ_{had} + W(➛ jets)



τ_{had} + W(➛ lν)



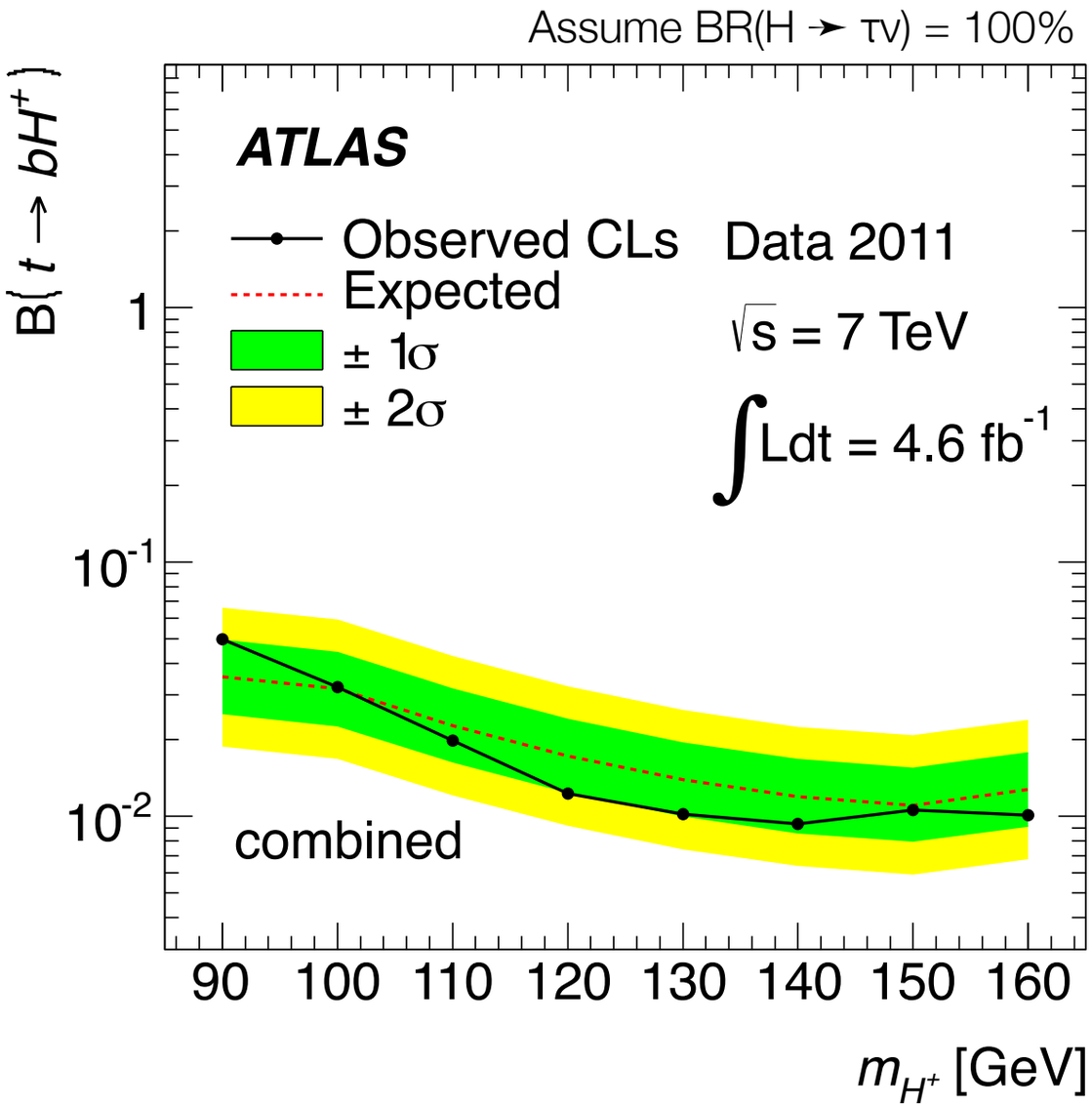
Most sensitive: τ+jets channel …

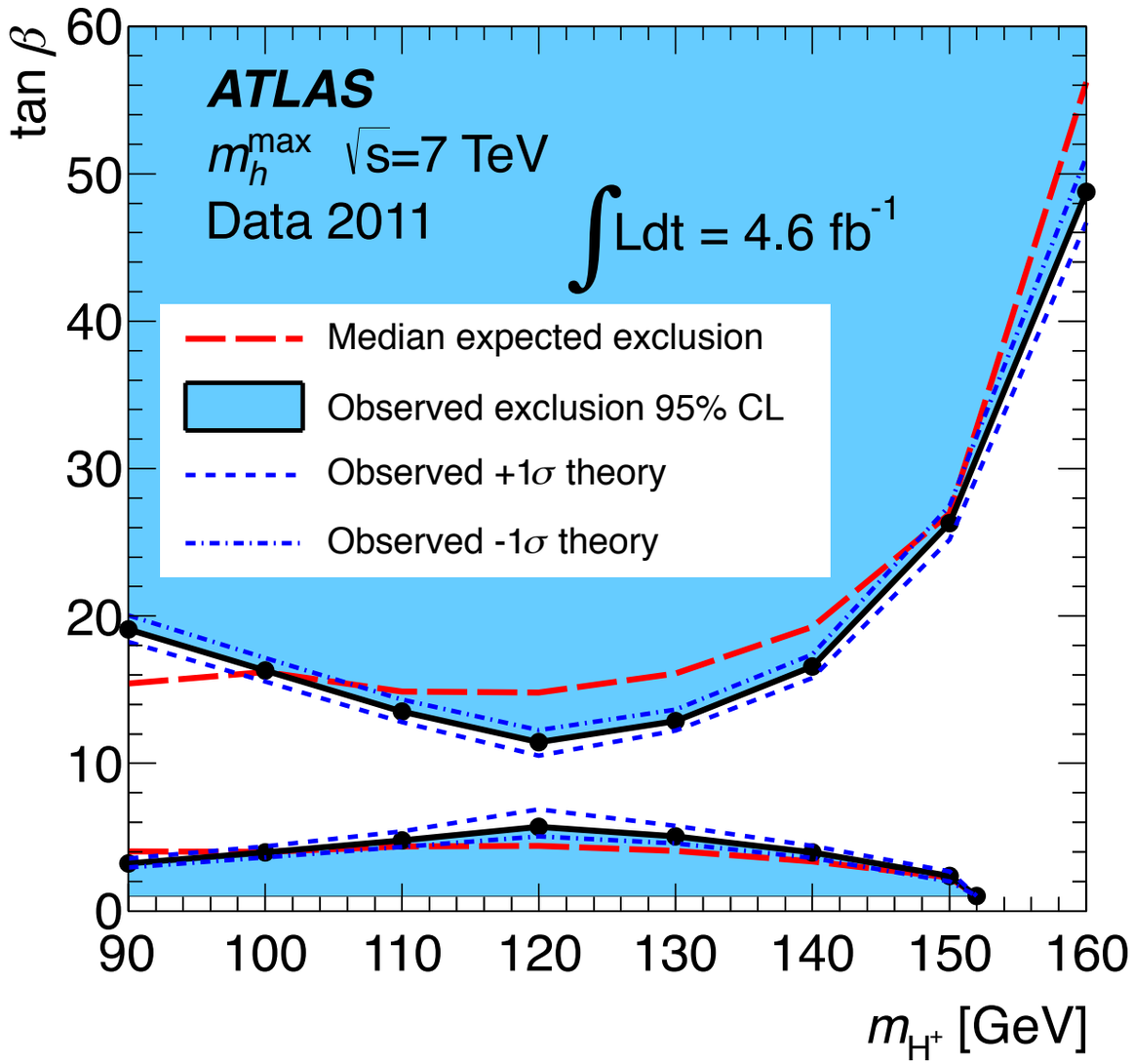
The lepton+jets channel, $H^+ \rightarrow \tau^+\nu \rightarrow l^+\nu\nu\nu$, has a very similar signature to $W^+ \rightarrow l^+\nu$, so rely on kinematics for discrimination of signal and background …

- use cosθ* distribution [W boson polarization from top decay …]
- use charged Higgs transverse mass, $m_{T,H}$, estimate …
- b-jet-to-top association important for both; done with via jjb-mass

Light Charged Higgs, $H^+ \to \tau\nu$

[JHEP 06 (2012) 039]





Statistical analysis: binned likelihood …

Light Charged Higgs, $H^+ \to \tau\nu$

[JHEP 03 (2013) 076]

Investigate Lepton Universality …

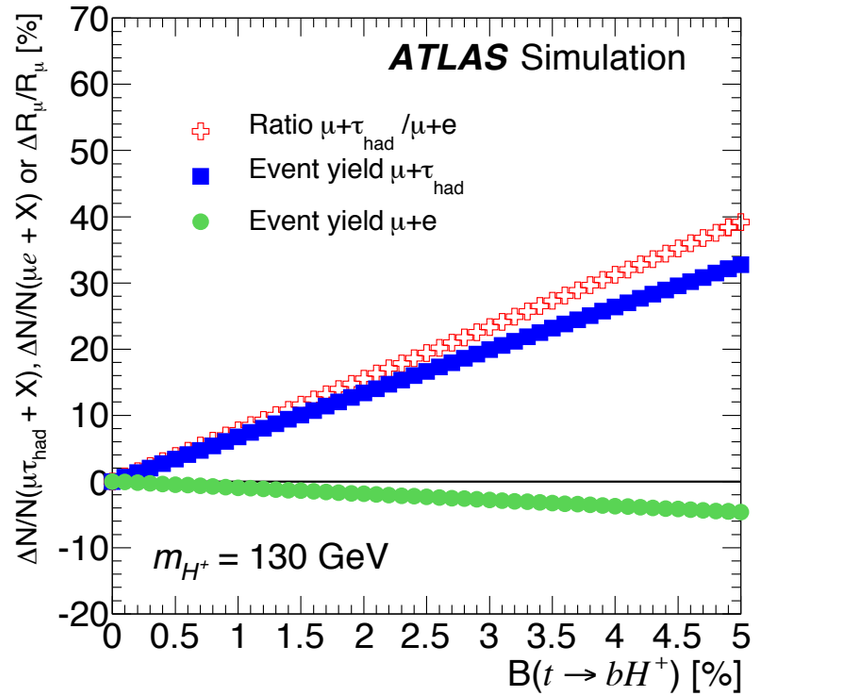
in top-quark decays to search for a charged Higgs

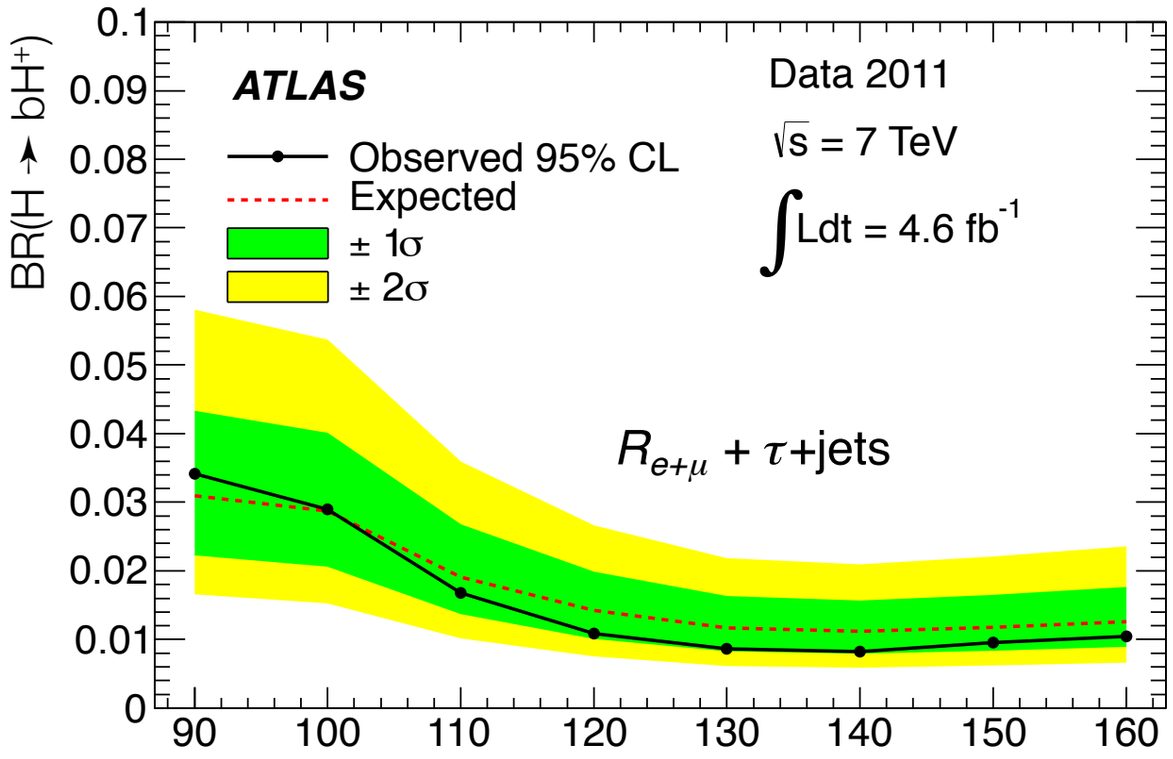
Use:

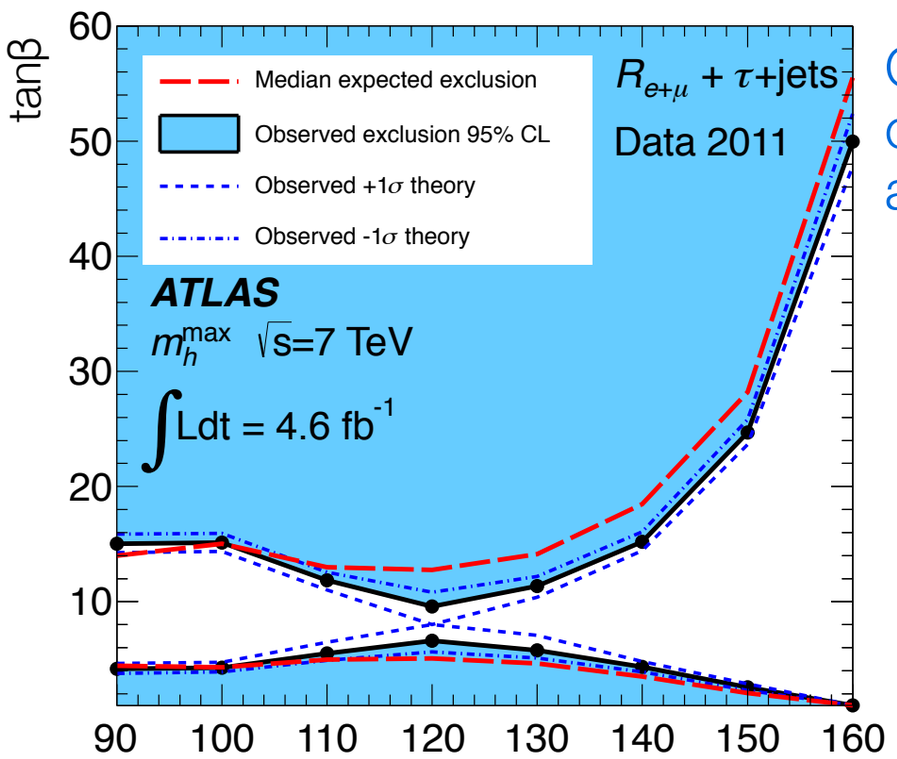
$$R_{e+\mu} = \frac{\mathcal{N}(e+\tau_{\mathrm{had}}) + \mathcal{N}(\mu+\tau_{\mathrm{had}})}{\mathcal{N}(e+\mu) + \mathcal{N}_{\mathrm{OR}}(\mu+e)}$$

triggered by electron trigger

excl. triggered by muon trigger







Combination of $R_{e\mu}$ & τ+jets analyses

Light Charged Higgs, $H^+ \rightarrow cs$

[EPJ C, 73 (2013) 2465]

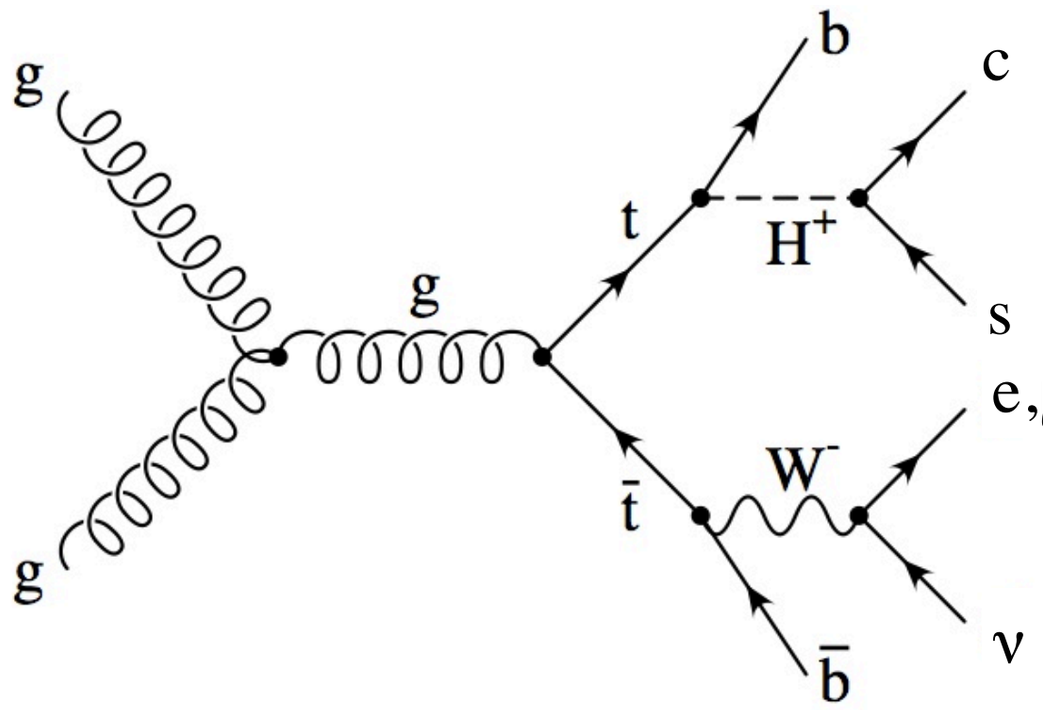
Searches channel …

considering hadronic decay

Light Charged Higgs Search …

Final state allows for full reconstruction of H^+ candidate …

Examine dijet spectrum and look for extra mass peak …



Selection …

Isolated e/μ; $p_T > 20$ GeV

At least 4 jets; $p_T > 20$ GeV; one b-tag

$M_T > 25$ GeV
MET + $M_T > 60$ GeV

Kinematics …

Neutrino momentum from $E_{T,miss}$ calculated by constraining the W-mass …

Solve combinatorics using kinematic χ^2-fit to (blv) and (bjj) systems …
[both required to be the top mass]

Light Charged Higgs, $H^+ \rightarrow cs$

[EPJ C, 73 (2013) 2465]

χ2-distribution
to be minimized …

all jet-p_t to vary within uncertainties

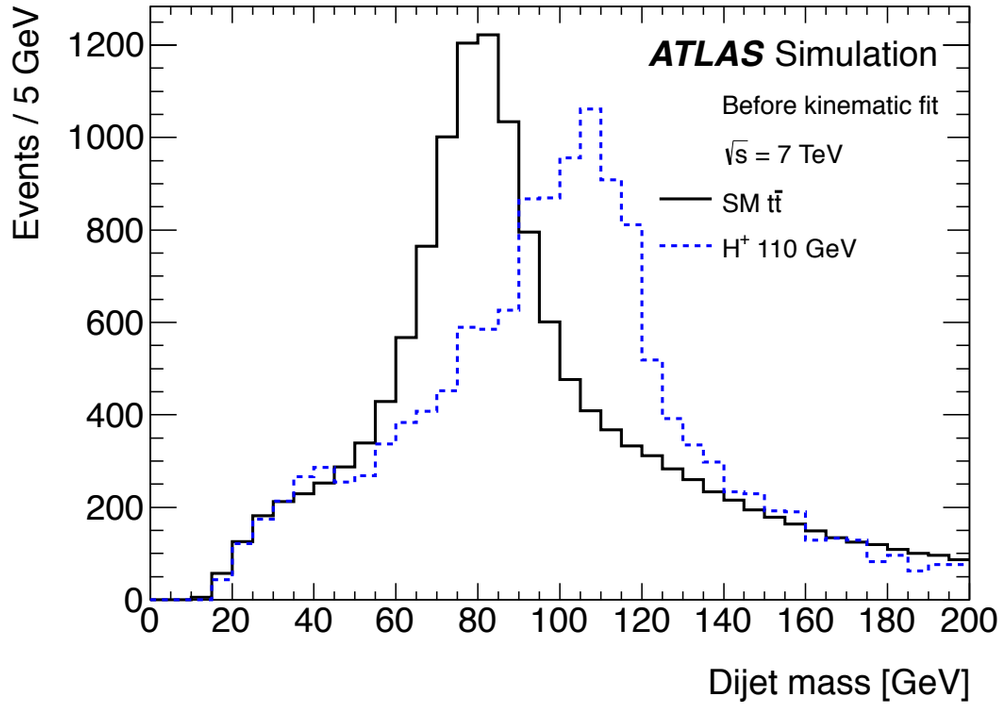
$$\chi^2 = \sum_{i=\ell,4\text{jets}} \frac{(p_{\mathrm{T}}^{i,\mathrm{fit}} - p_{\mathrm{T}}^{i,\mathrm{meas}})^2}{\sigma_i^2}$$

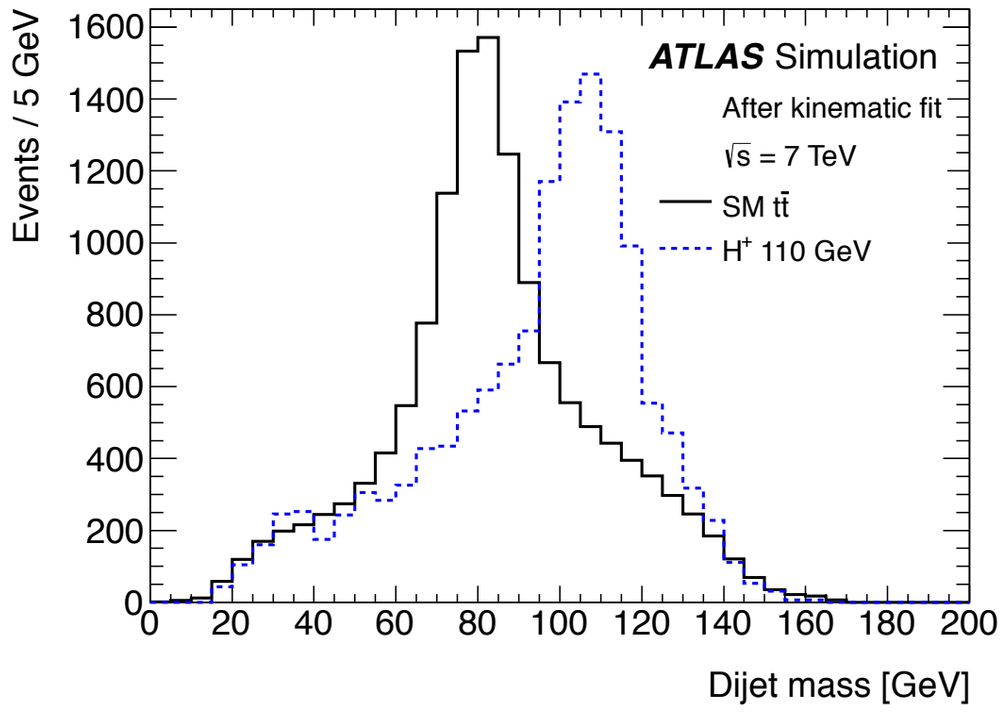
$$+ \sum_{j=x,y} \frac{(p_j^{\mathrm{SEJ,fit}} - p_j^{\mathrm{SEJ,meas}})^2}{\sigma_{\mathrm{SEJ}}^2}$$

$$+ \sum_{k=jjb,b\ell\nu} \frac{(m_k - m_{\mathrm{t}})^2}{\Gamma_t^2}$$

soft jets influencing $E_{T,miss}$

top mass constraints

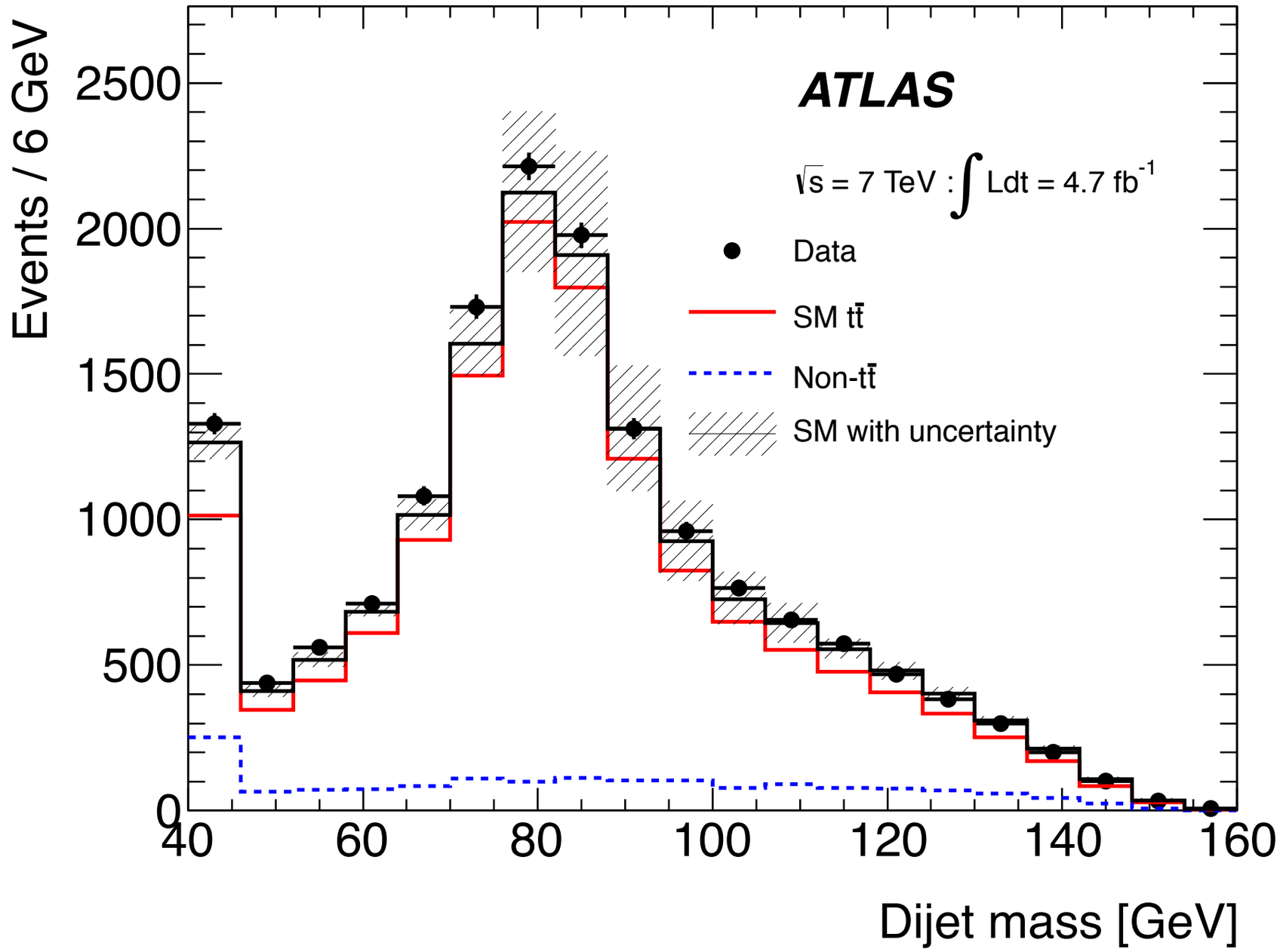




[ATLAS]

Light Charged Higgs, $H^+ \rightarrow cs$

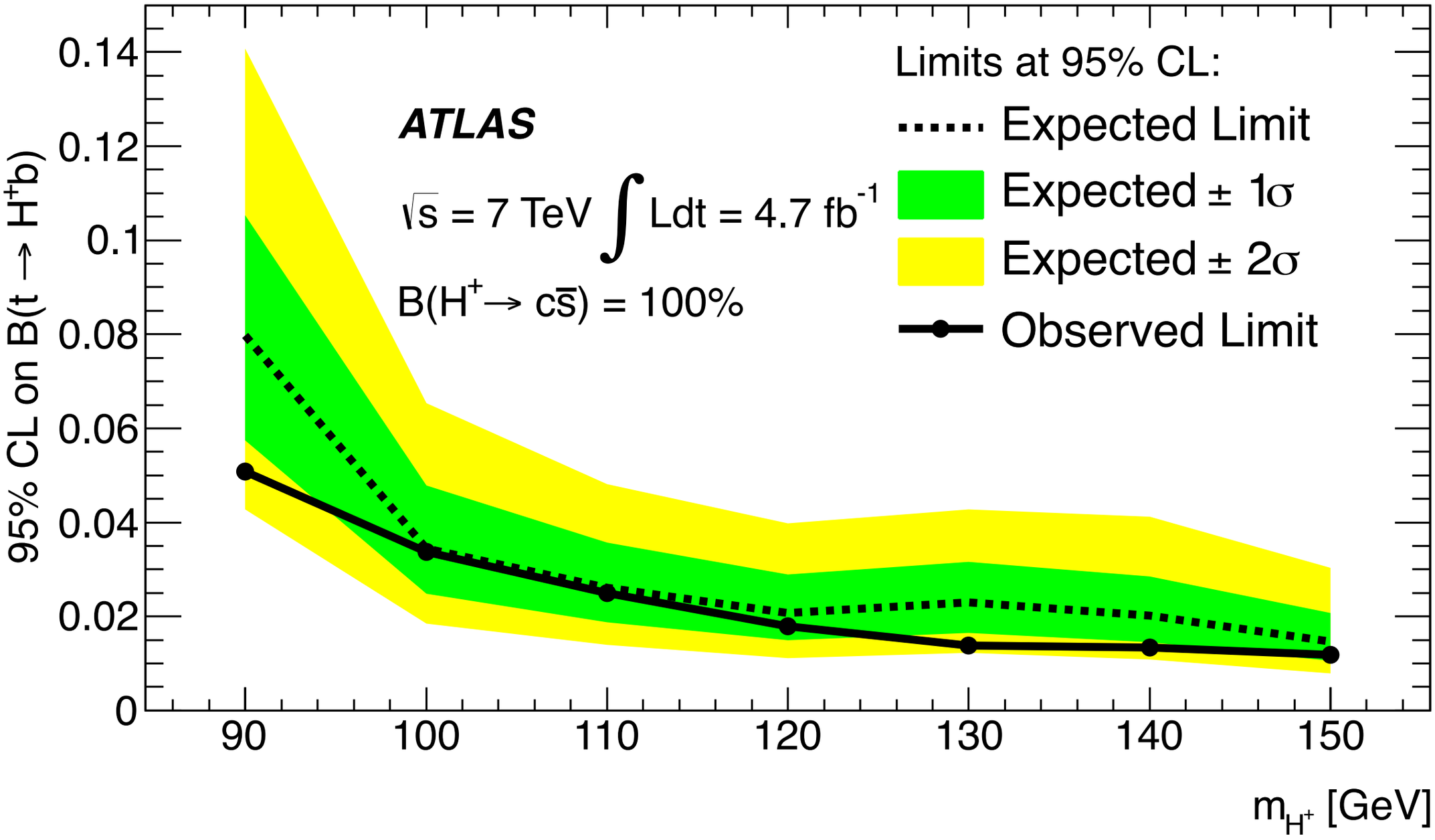
[EPJ C, 73 (2013) 2465]



[ATLAS]

Light Charged Higgs, $H^+ \rightarrow cs$

[EPJ C, 73 (2013) 2465]



[ATLAS]

Light & Heavy Charged Higgs

[ATLAS-CONF-2013-090]

Combined analysis of:

Three- and Four-jet final states
with $H^+ \rightarrow \tau_{had} + \nu$ …

4-jet final state
2 b-tags

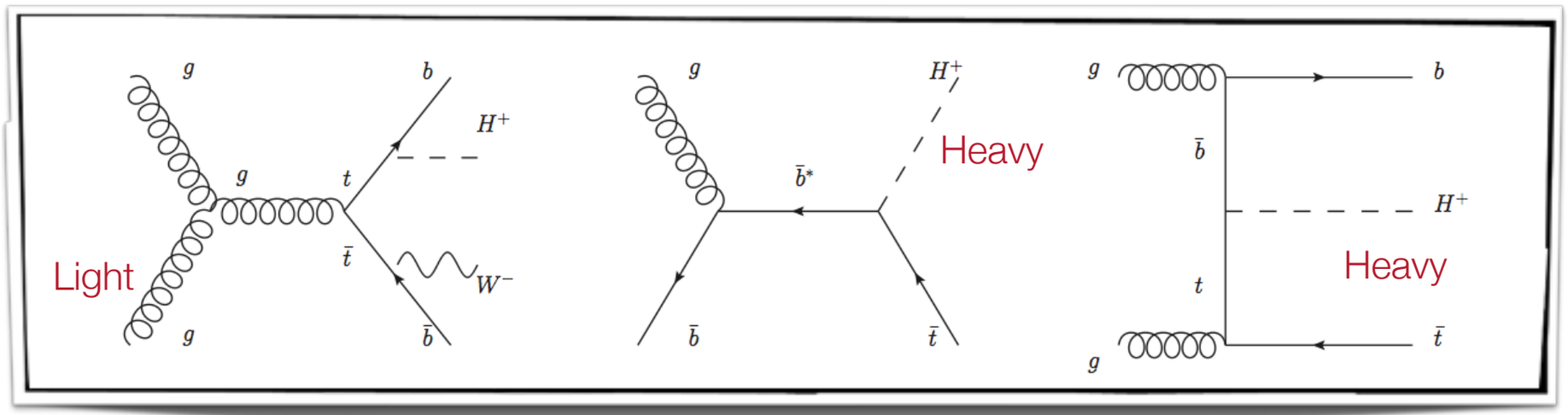
$$t\bar{t} \rightarrow [H^+ b]\,[W^- \bar{b}] \rightarrow [(\tau^+ + \nu_\tau) b]\,[q\bar{q}\bar{b}]$$

3-jet final state
1 b-tags

$$g\bar{b} \rightarrow [\bar{t}]\,[H^+] \rightarrow [q\bar{q}\bar{b}]\,[\tau^+ + \nu_\tau]$$

4-jet final state
2 b-tags

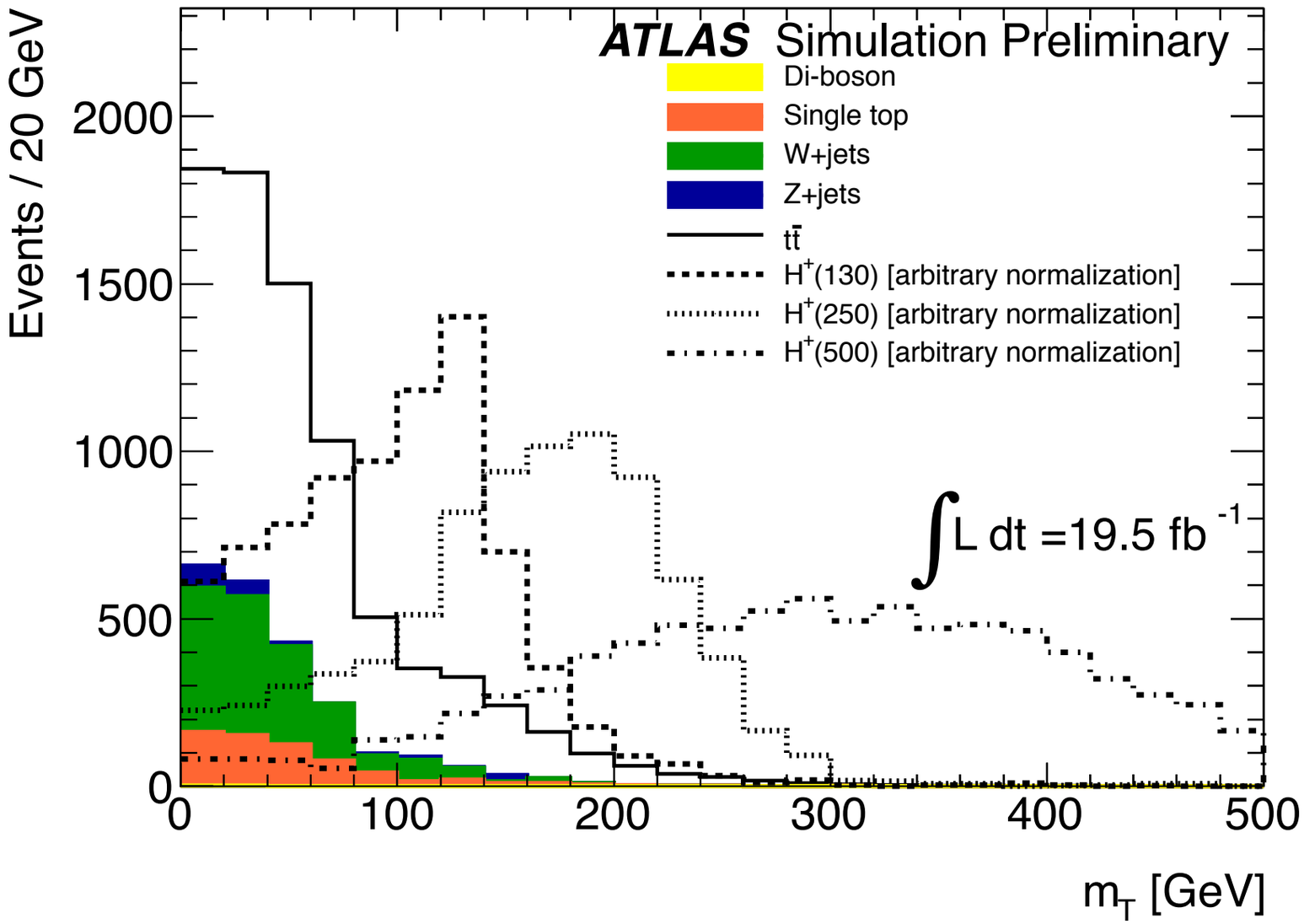
$$gg \rightarrow [\bar{t}b]\,[H^+] \rightarrow [(q\bar{q}\bar{b})b]\,[\tau^+ + \nu_\tau]$$



Light & Heavy Charged Higgs

[ATLAS-CONF-2013-090]

$$m_{\mathrm{T}} = \sqrt{2 p_{\mathrm{T}}^{\tau} E_{\mathrm{T}}^{\mathrm{miss}} (1 - \cos \Delta\phi_{\tau,\mathrm{miss}})}$$



Selection:

≥ 4 (3) jets; on b-tag
for light (heavy) H^+

one hadronic τ
p_T > 40 GeV; no additional τ,e,μ

$E_{T,miss}$ ≥ 65 (80) GeV
for light (heavy) H^+

Transverse mass shows Jacobian peak

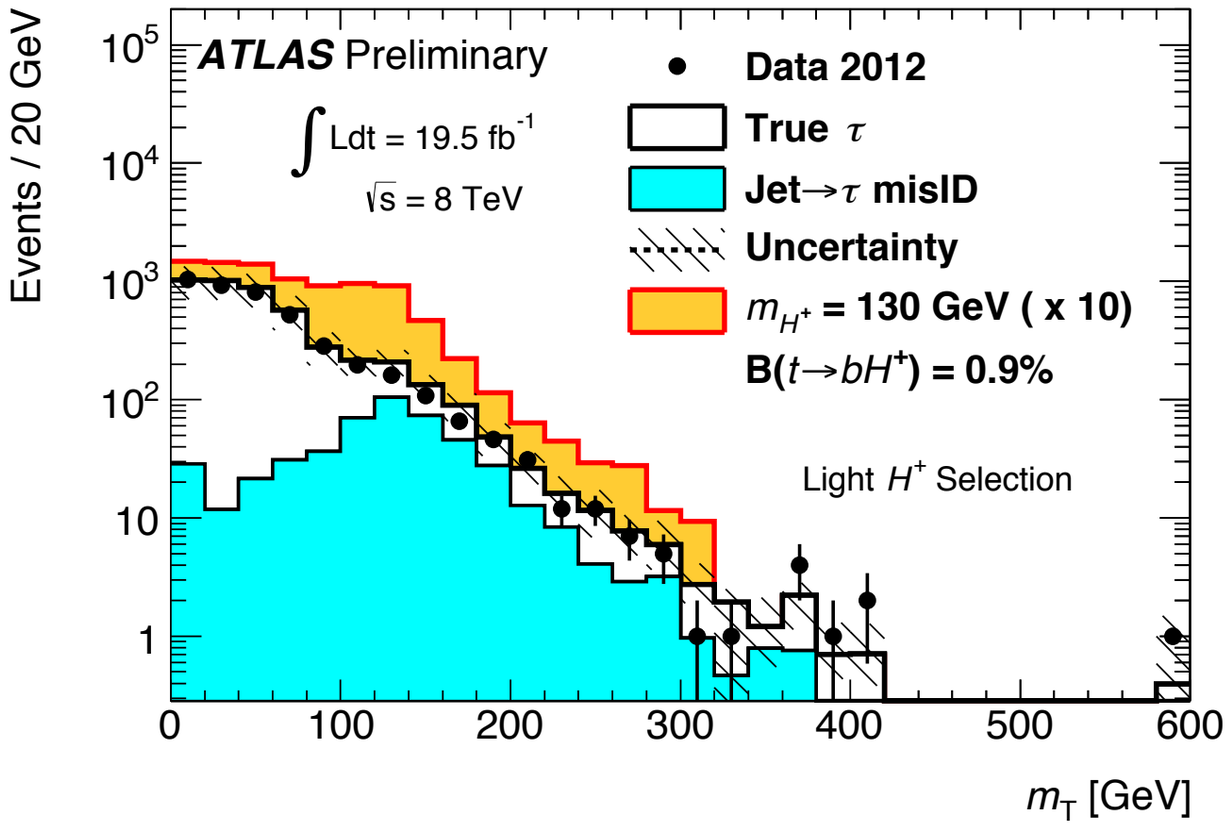
[Edge at H^+-mass …]

[ATLAS]

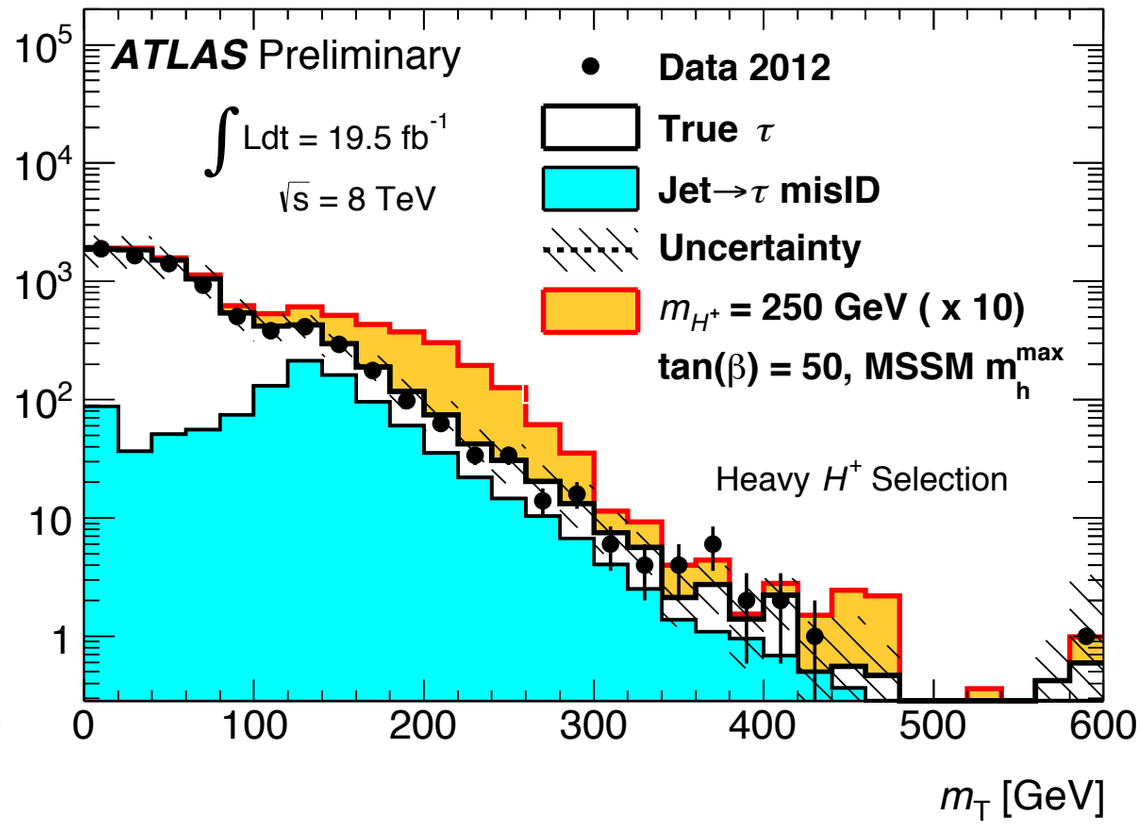
Light & Heavy Charged Higgs

[ATLAS-CONF-2013-090]

Light H^+ Selection



Heavy H^+ Selection



Data and background prediction after final selection …

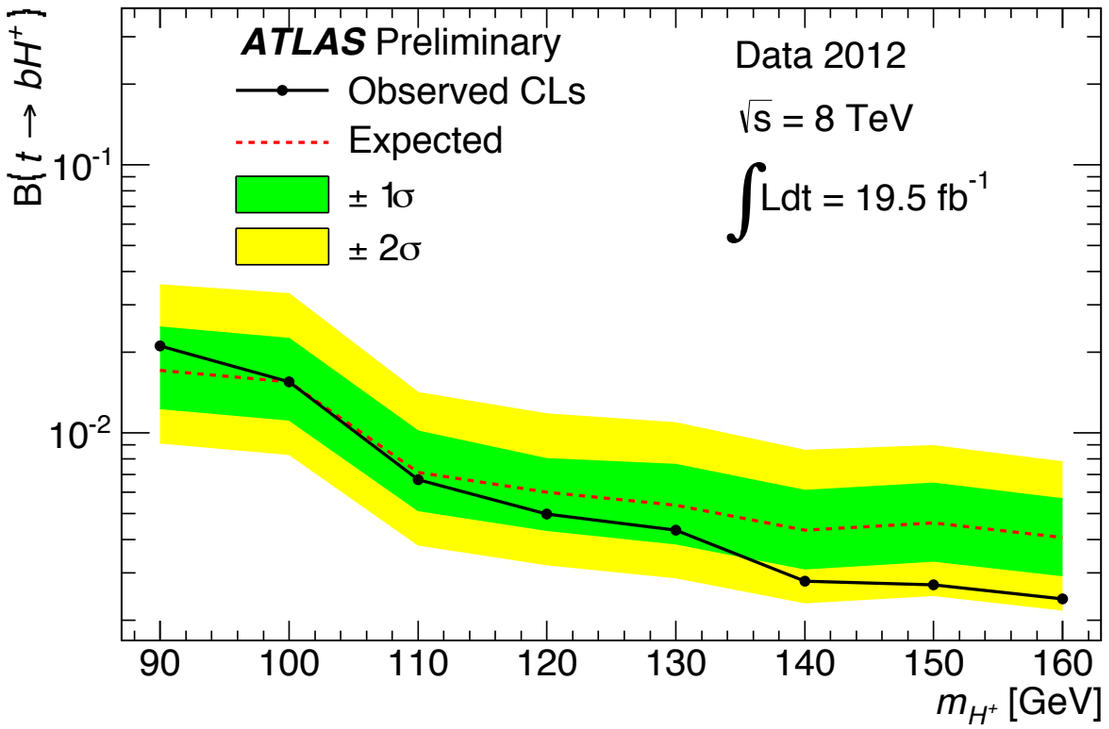
[ATLAS]

Light & Heavy Charged Higgs

[ATLAS-CONF-2013-090]

Light H^+ Selection

[Assume BR($H^+ \to \tau\nu$) = 1]

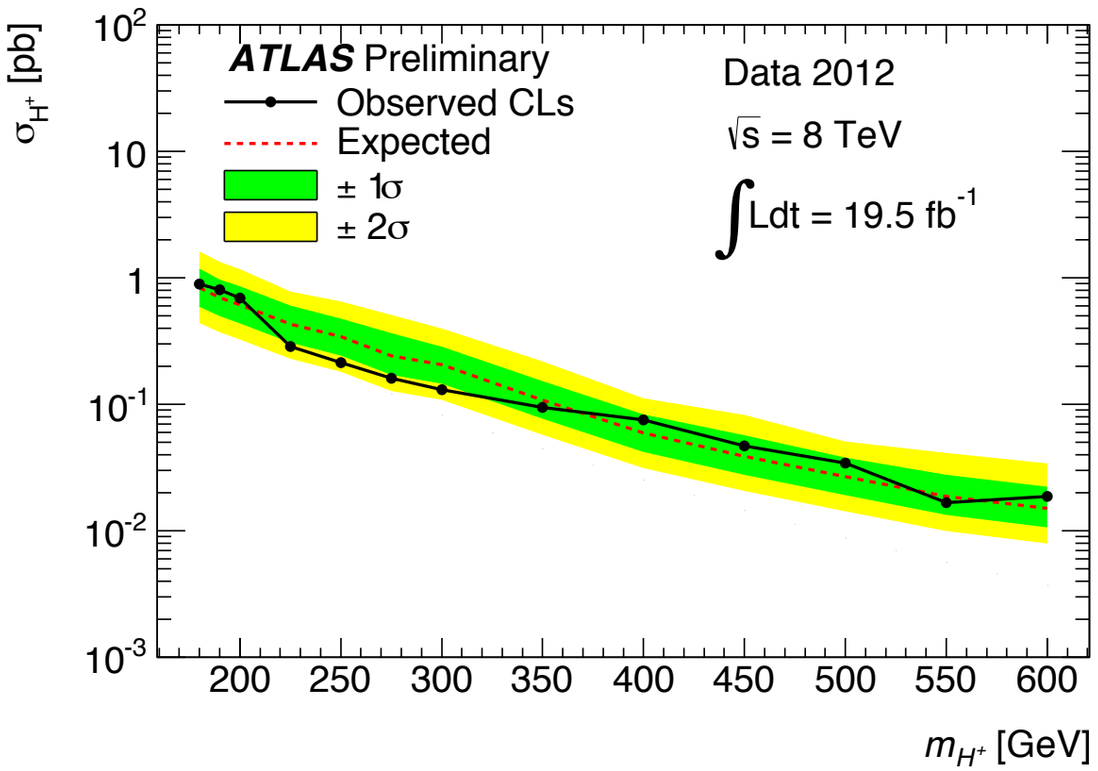


Light Higgs:

Upper limit on B($t \to bH^+$) as
H^+ only produced via top decay

Heavy H^+ Selection

[Assume BR($H^+ \to \tau\nu$) = 1]



Heavy Higgs:

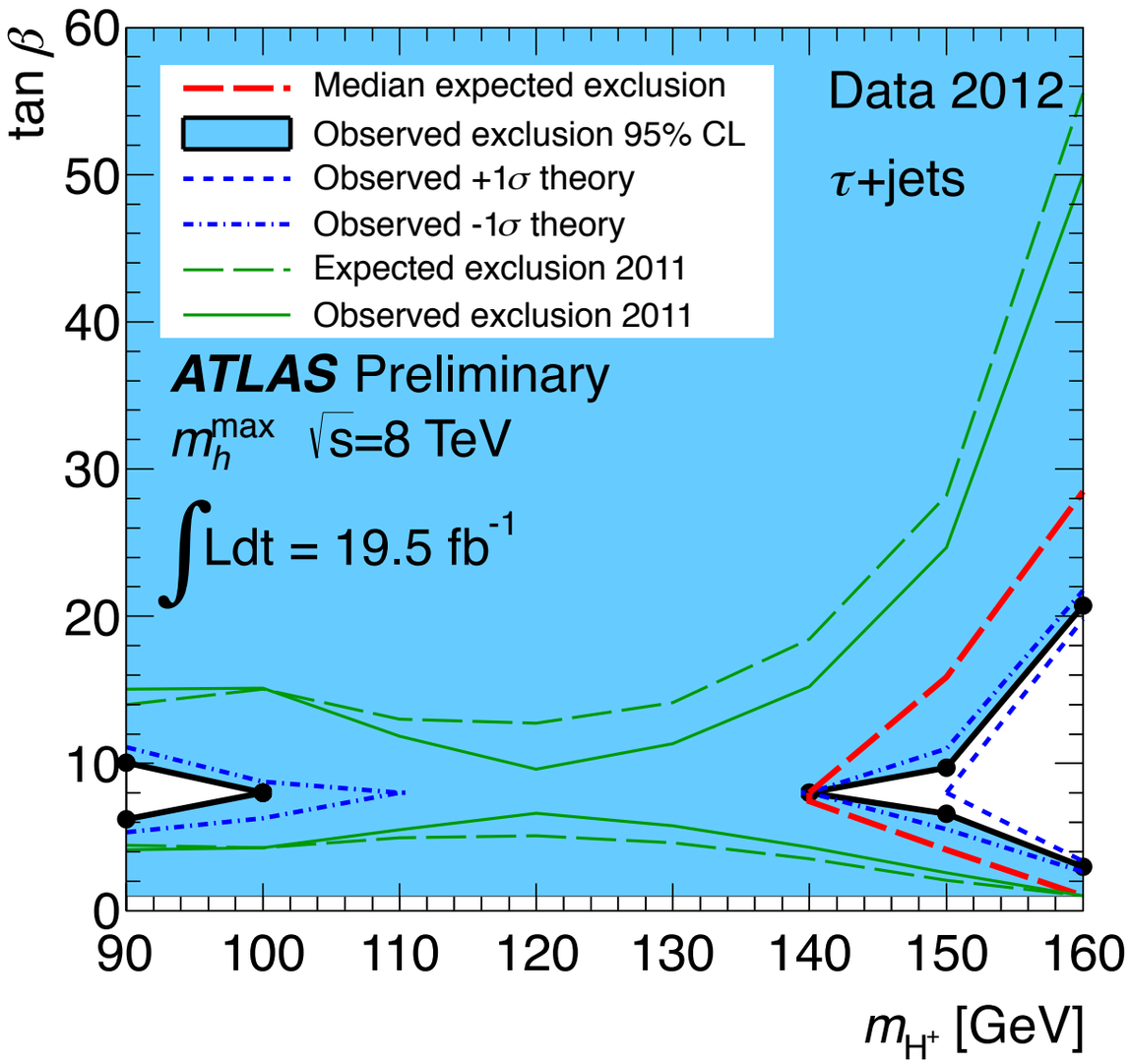
Upper limit on production
cross section of the charged Higgs

[ATLAS]

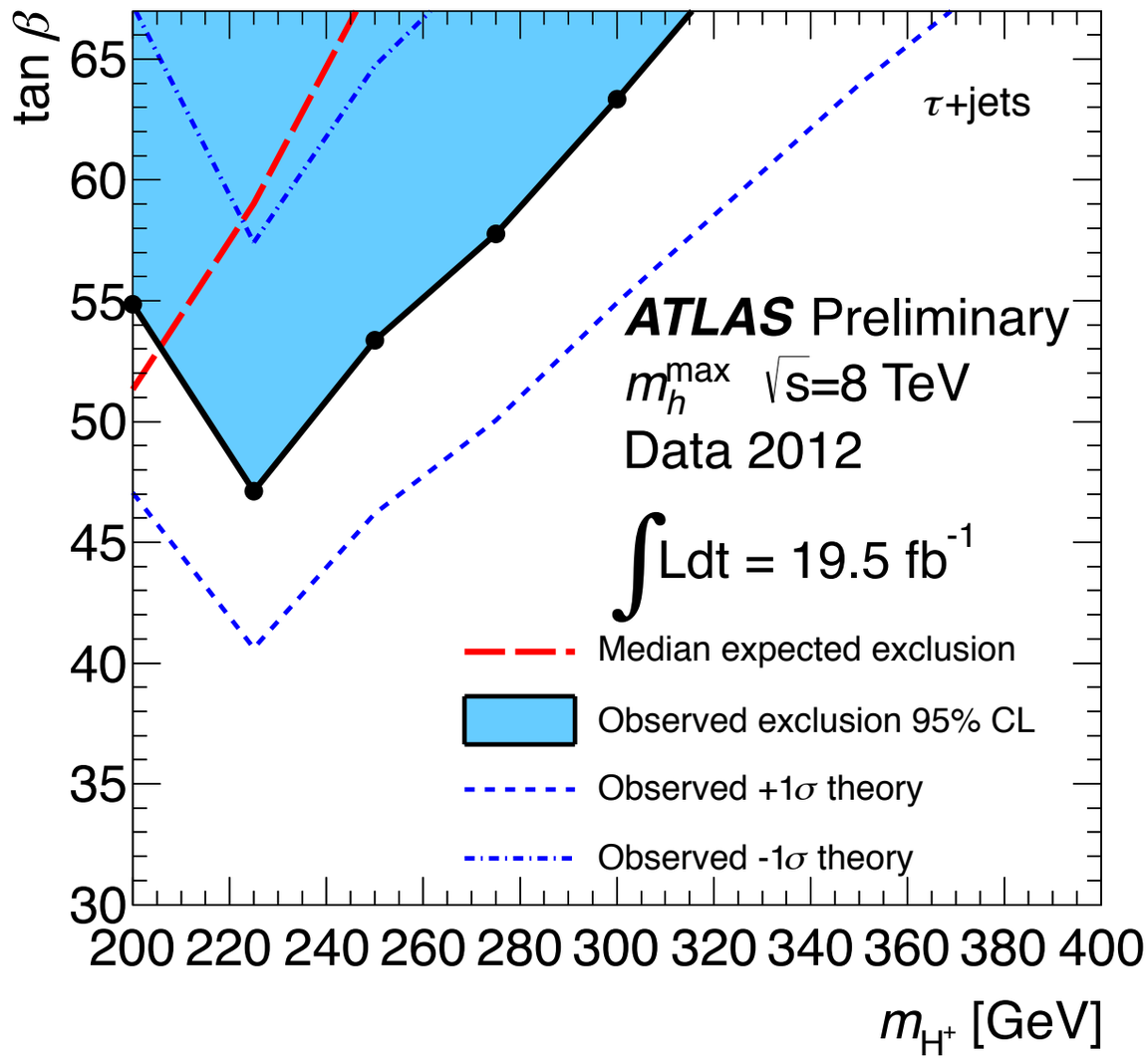
Light & Heavy Charged Higgs

[ATLAS-CONF-2013-090]

Light H^+ Selection



Heavy H^+ Selection



[ATLAS, CMS]

Doubly Charged Higgs

[EPJ C 72 (2012) 2189]
[EPJ C 72 (2012) 2244]

BSM Models:

See-Saw Type II Models …
Little Higgs Models …

Production:

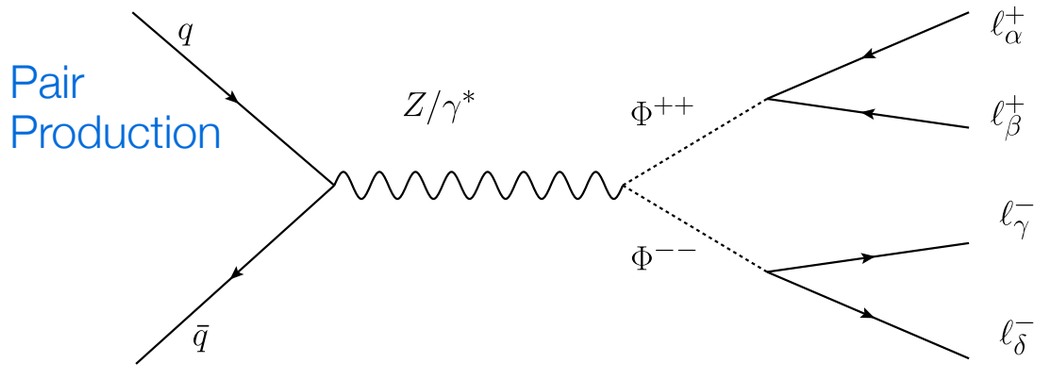
Predominantly via pp ➛ $H^{++}H^{--}$ …
Also: pp ➛ $H^{++}H^{-}$ …

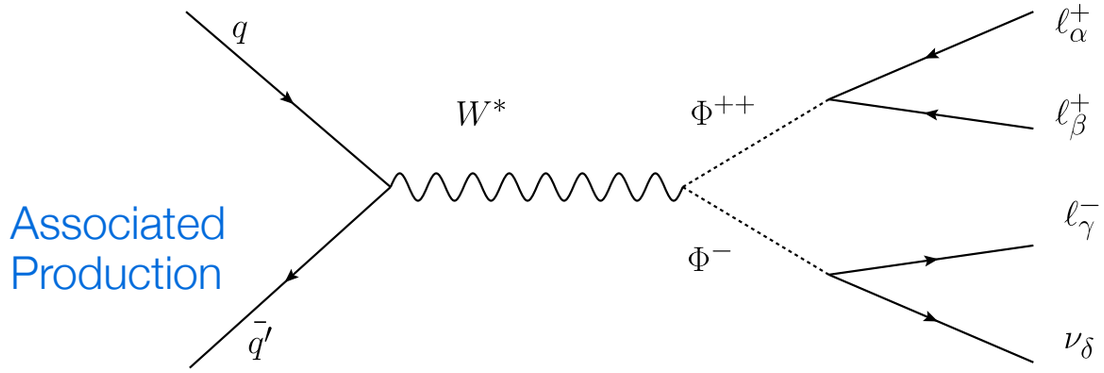
Signature:

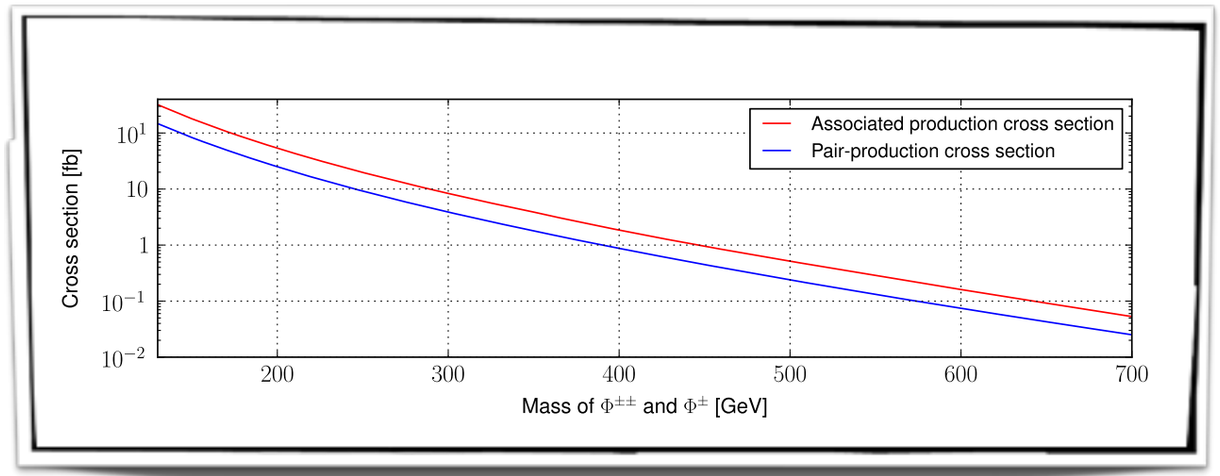
Decay in two like-sign particles …
e.g. two like-sign leptons:

H^{++} ➛ e^+e^+, H^{++} ➛ $\mu^+\mu^+$ …
H^{++} ➛ $e^+\mu^+$, H^{++} ➛ $\mu^+\tau^+$ …

➛ Search for same-sign lepton pairs
in 3- and 4-lepton final states …







[ATLAS]

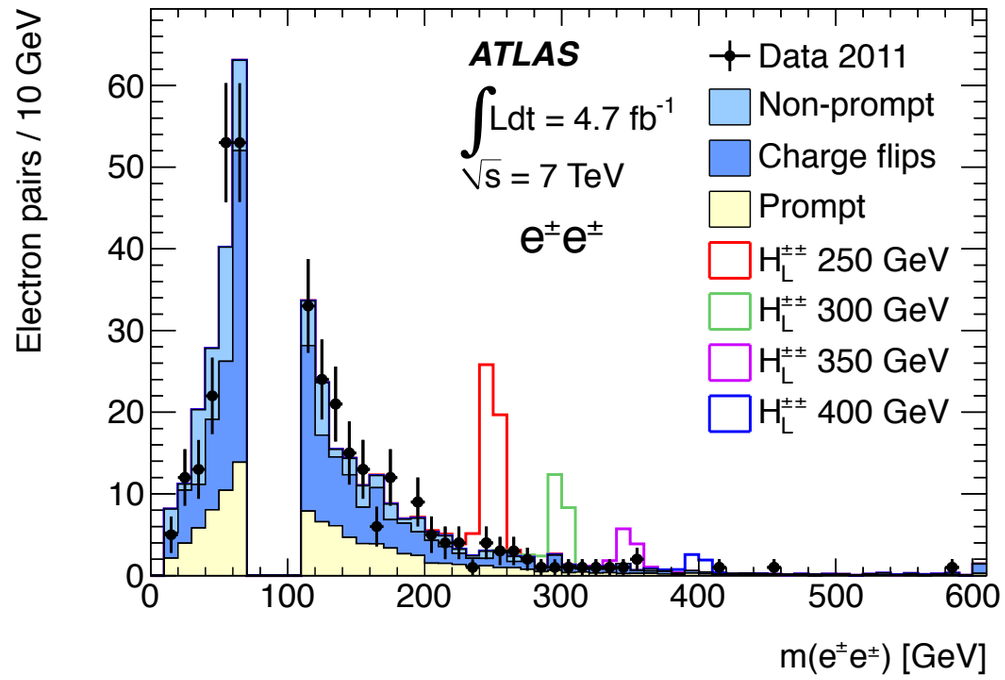
Doubly Charged Higgs

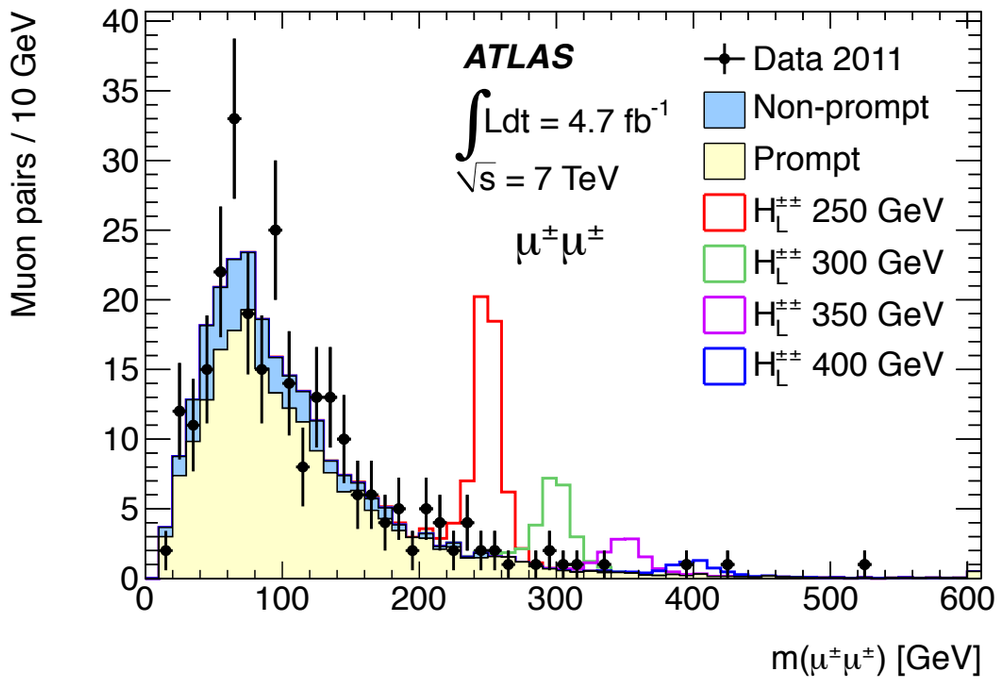
[EPJ C 72 (2012) 2244]

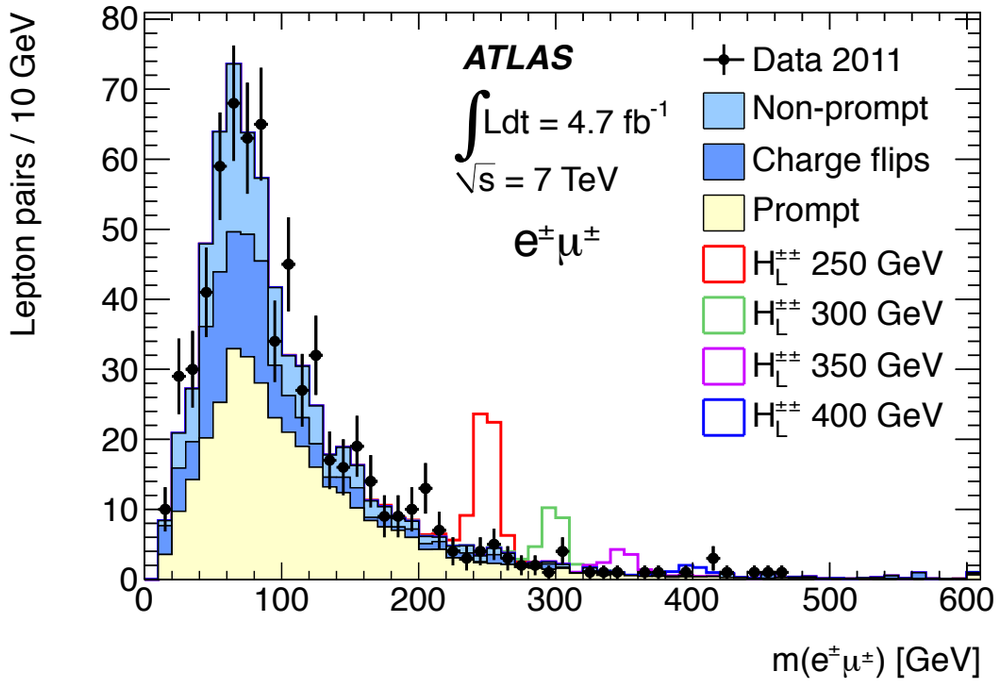
ATLAS:

Generic same-sign
Di-lepton spectrum search
[ee, μμ, eμ]

Background: Prompt muons
[from heavy flavor decays or pions & kaons]







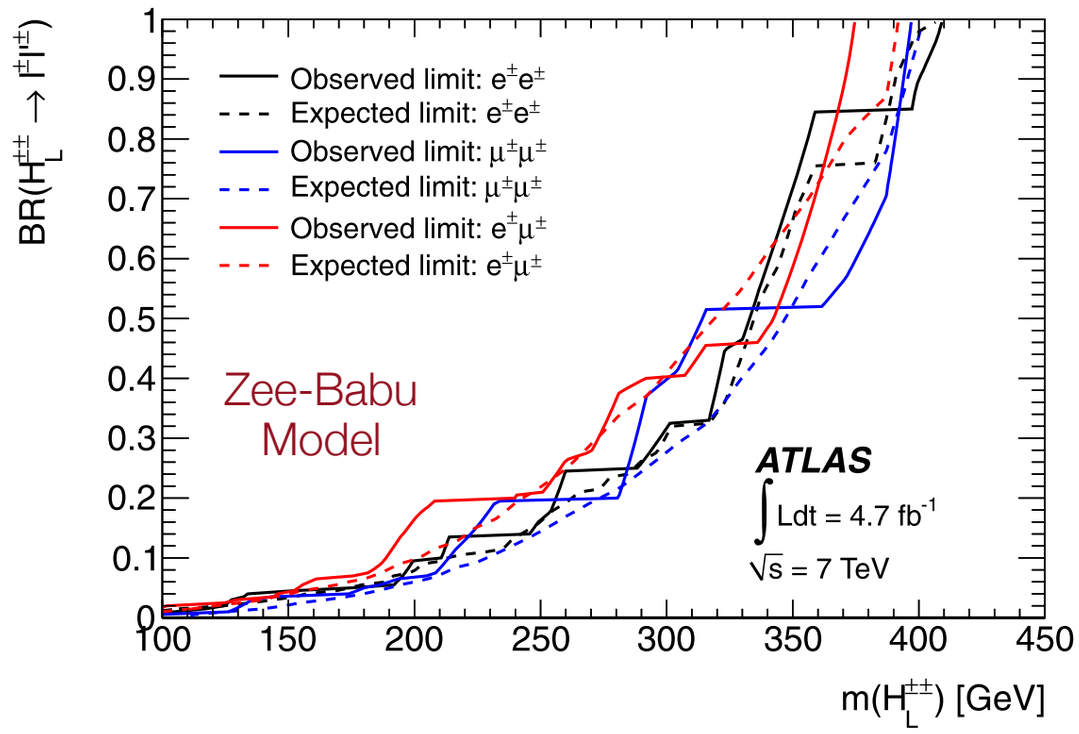
Doubly Charged Higgs

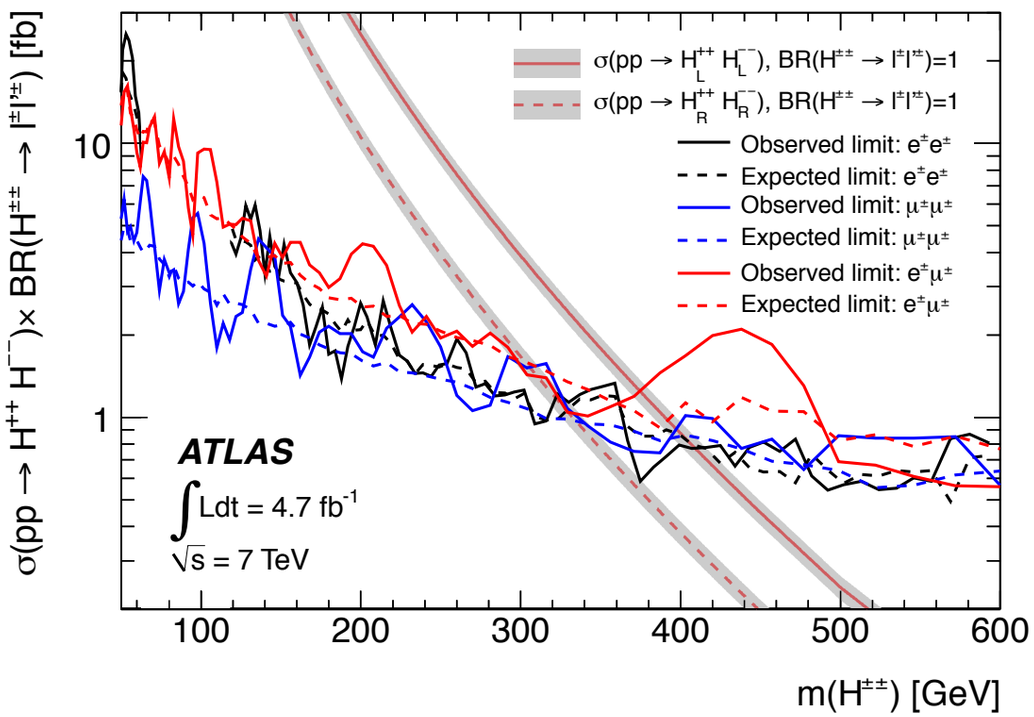
[EPJ C 72 (2012) 2244]

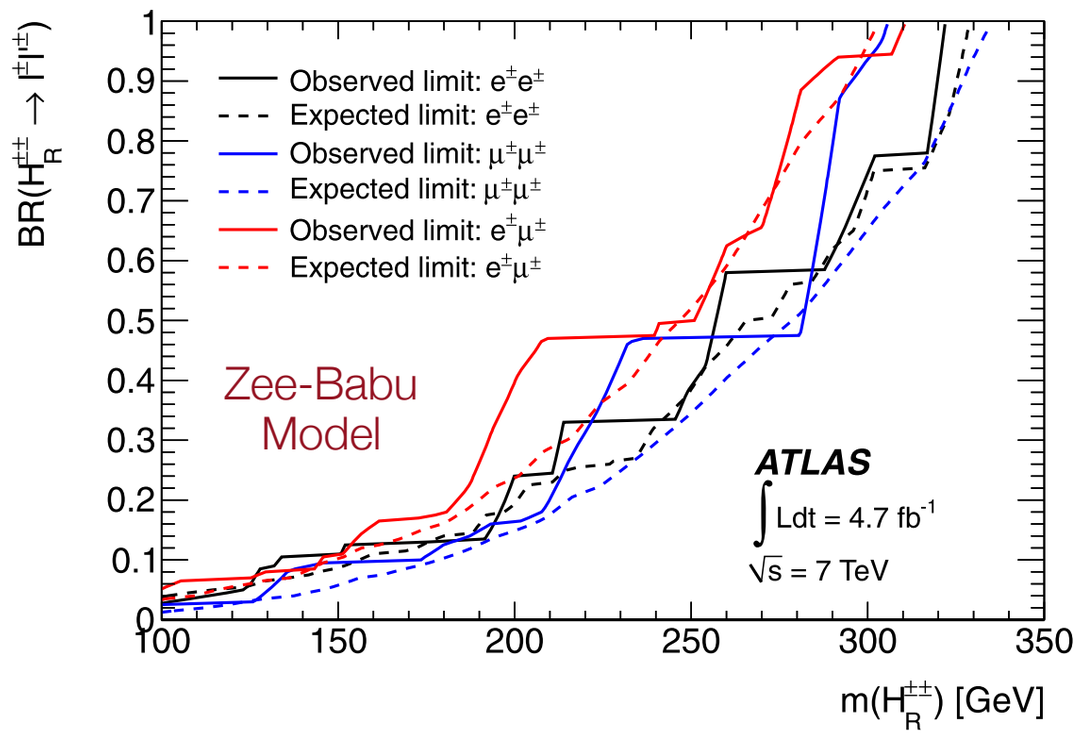
ATLAS:

Assuming $qq \rightarrow Z/\gamma^* \rightarrow H^{++}H^{--}$
decaying to pairs of $\mu^{\pm}\mu^{\pm}$, $e^{\pm}e^{\pm}$, $e^{\pm}\mu^{\pm}$

Limits on $H^{\pm\pm}$ mass
at 375 GeV to 409 GeV; BR=100%







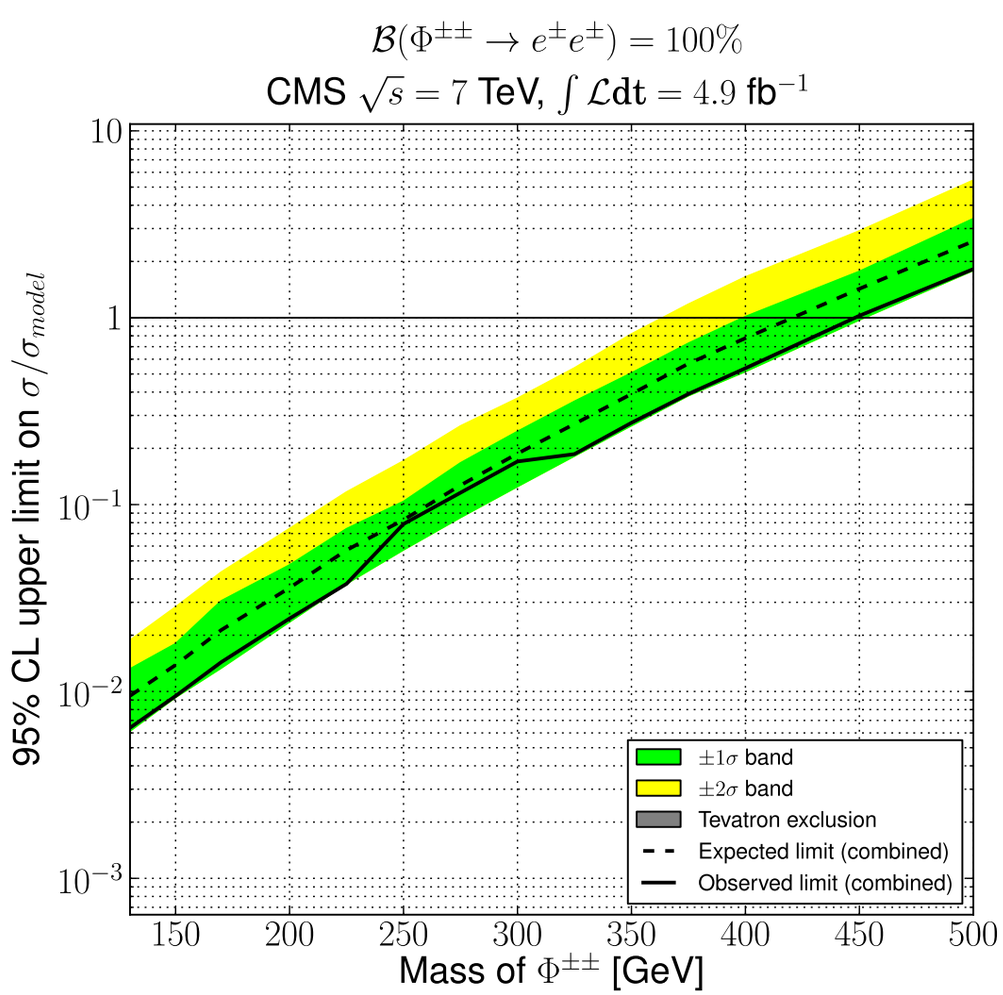
[CMS]

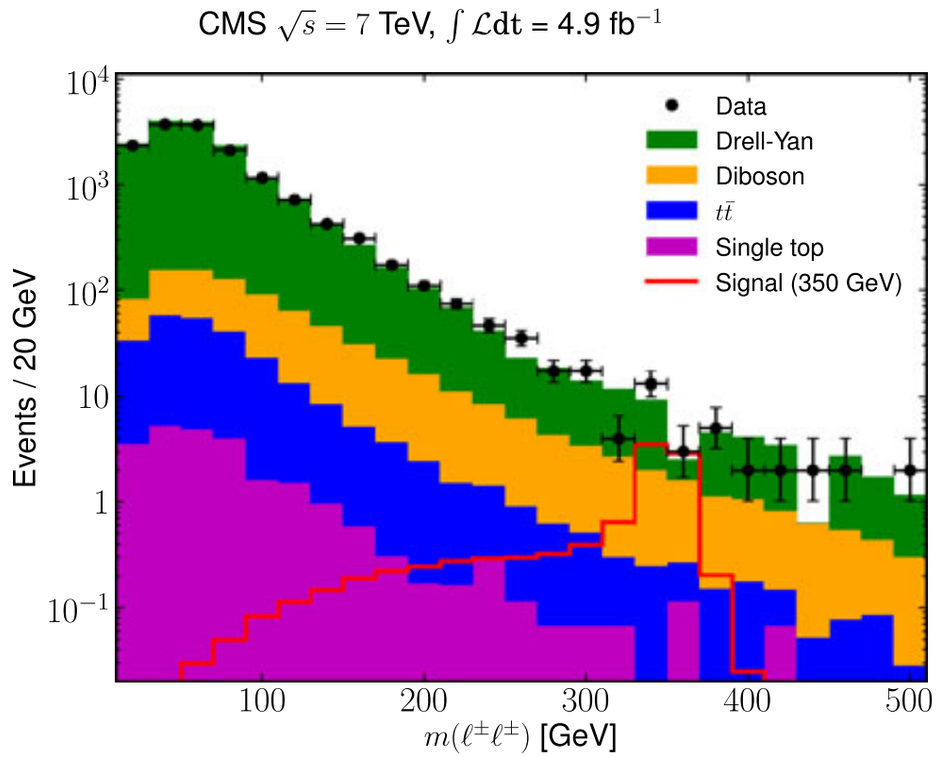
Doubly Charged Higgs

[EPJ C 72 (2012) 2189]

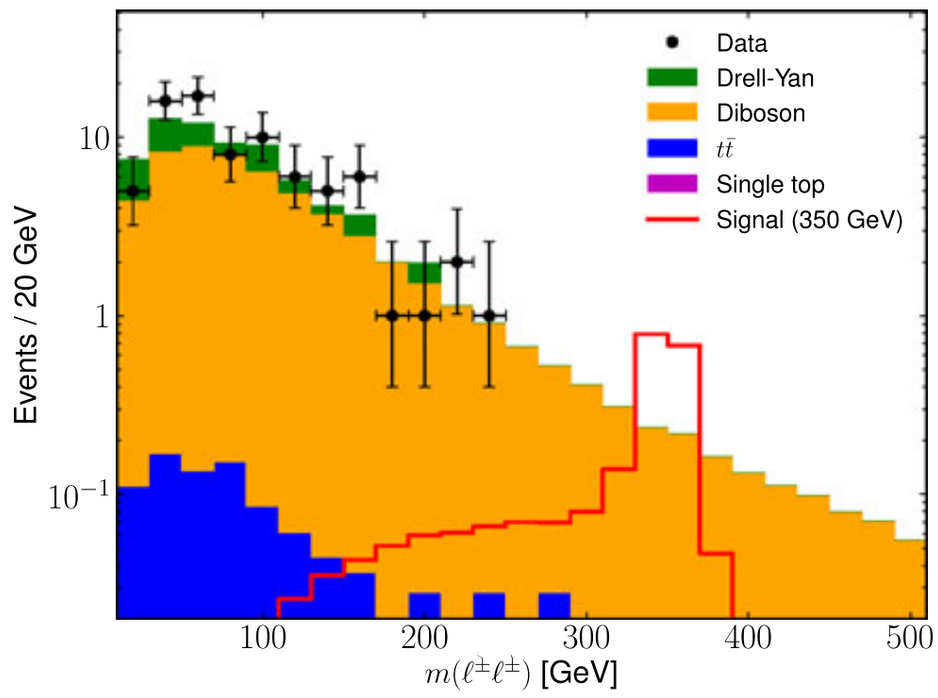
CMS:

3- and 4-lepton final states
with same sign di-leptons …
[ee, μμ, eμ, eτ, eμ, ττ]





3-lepton final state



4-lepton final state