ATLAS SUSY Higgs Searches
(H, A, $H^{\pm}$)

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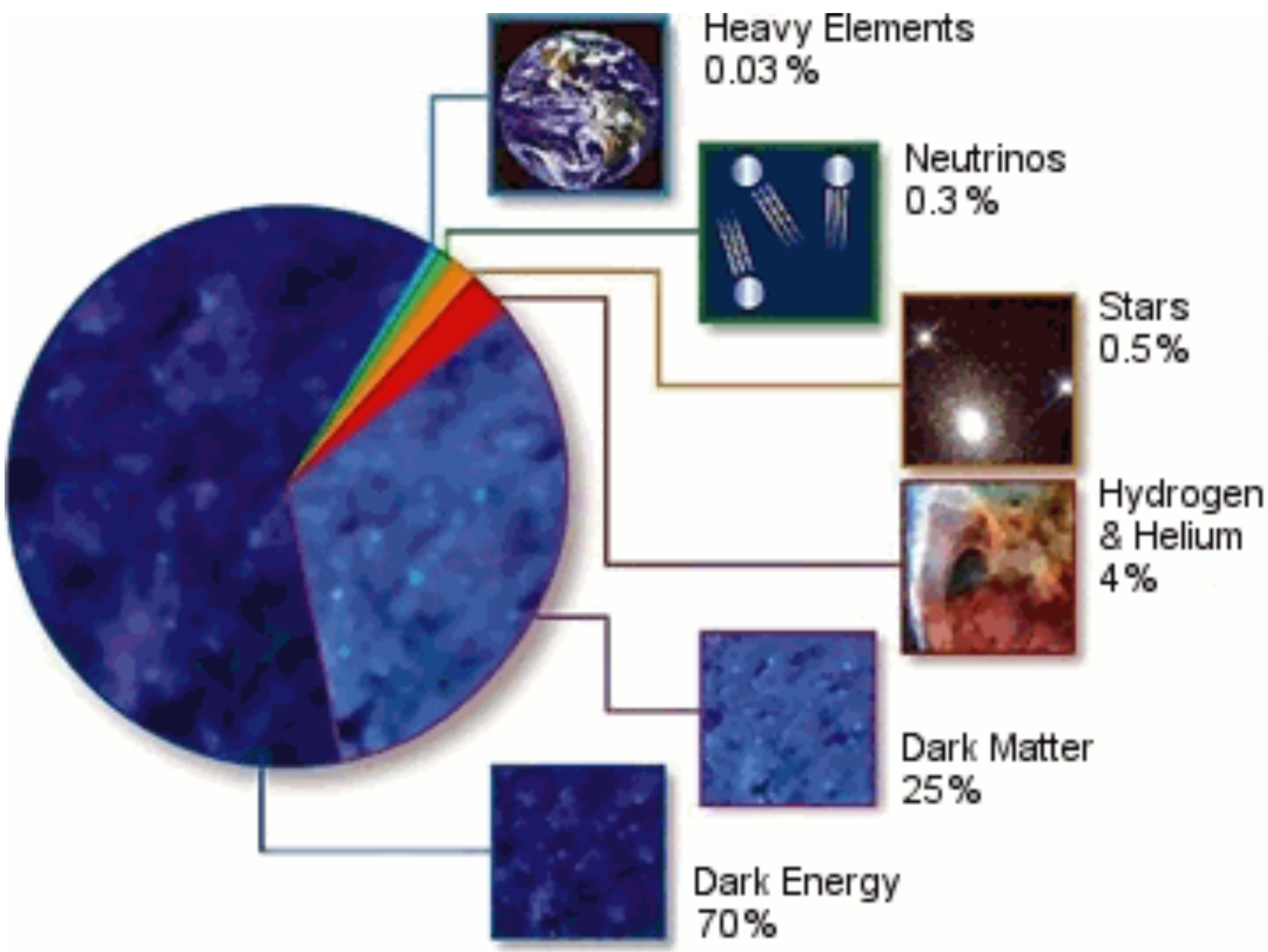
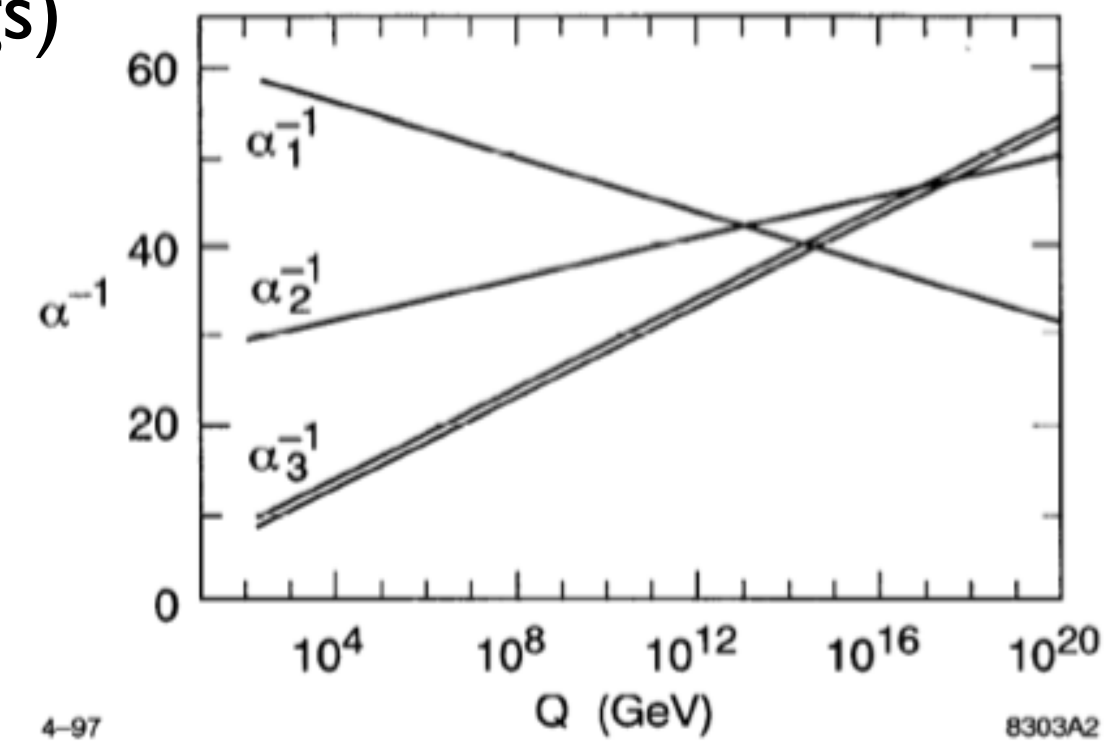
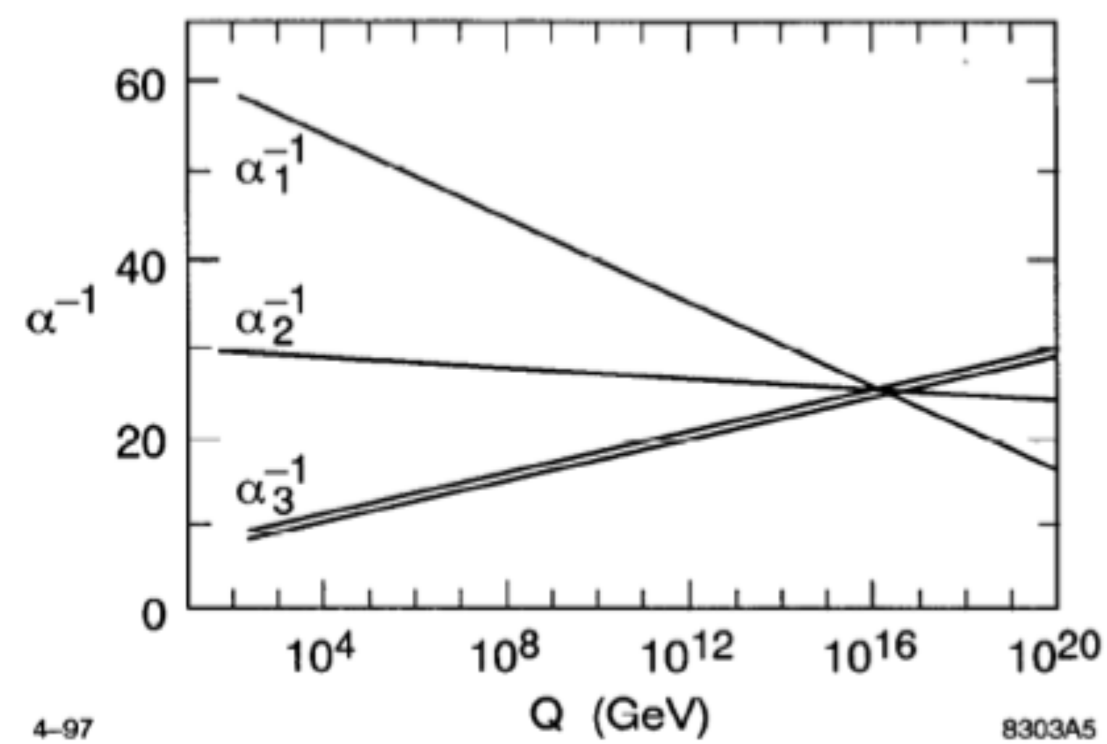
Motivation for Supersymmetry

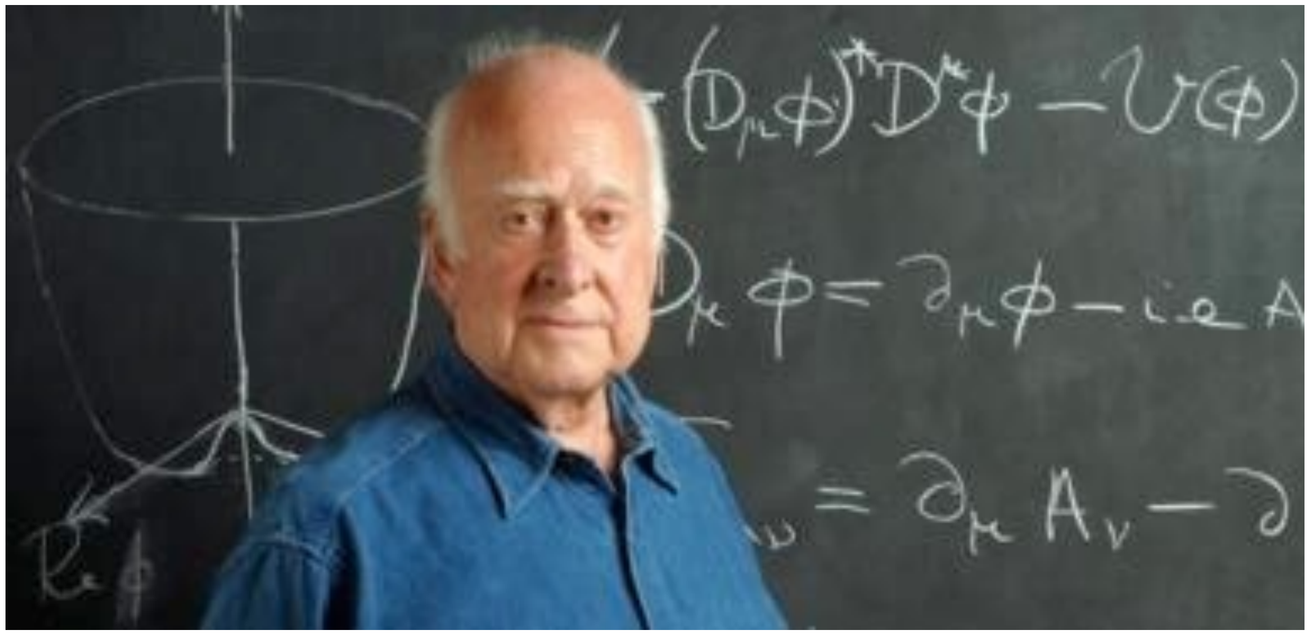
- Naturalness (Hierarchy Problem)
- Unification of the forces (gauge couplings)
- Provides a candidate for Dark Matter



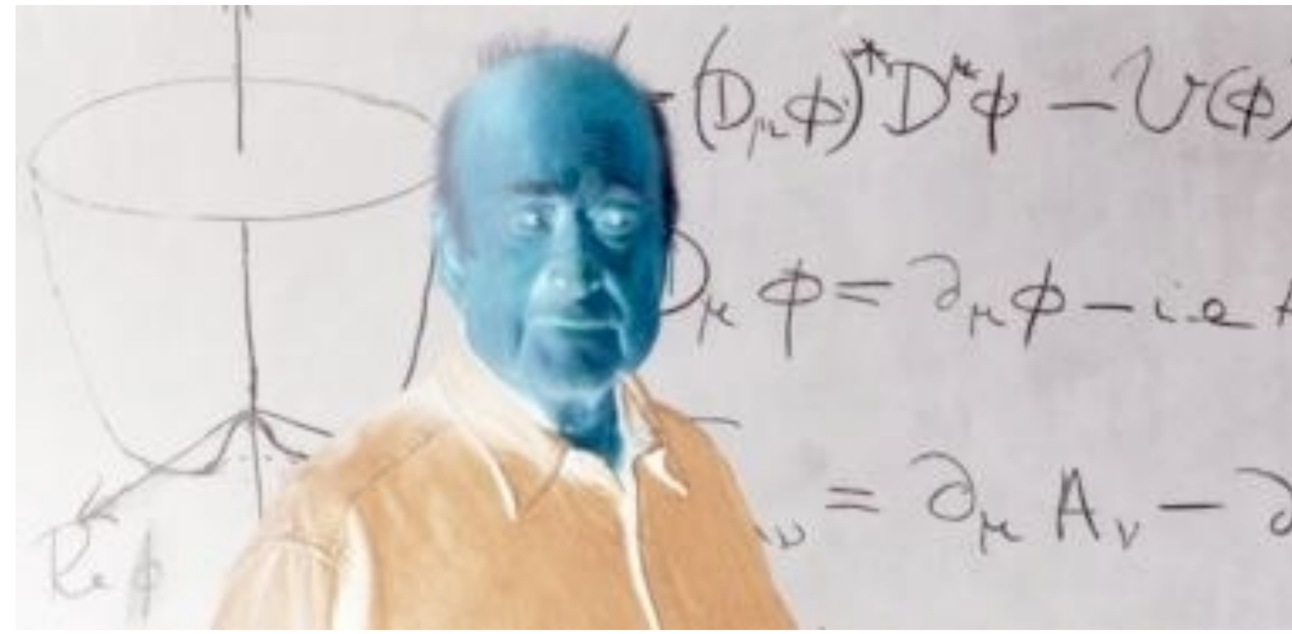




If the (light) Higgs mass is ~125 GeV, what next?



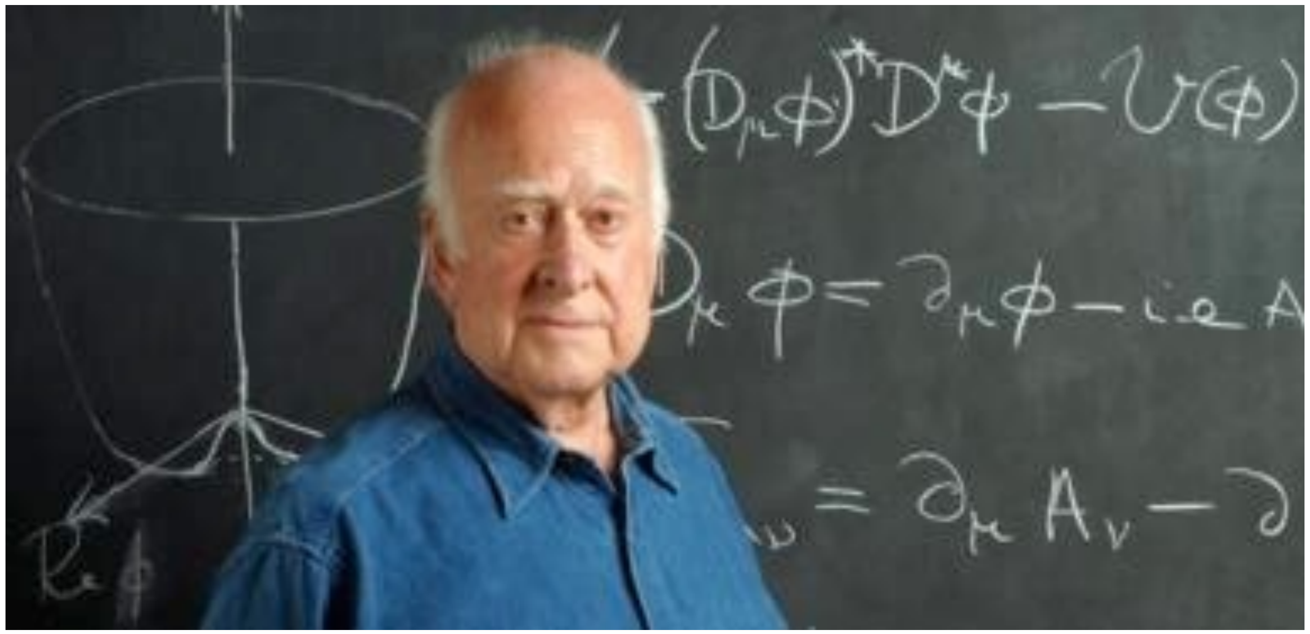
Standard Model Higgs

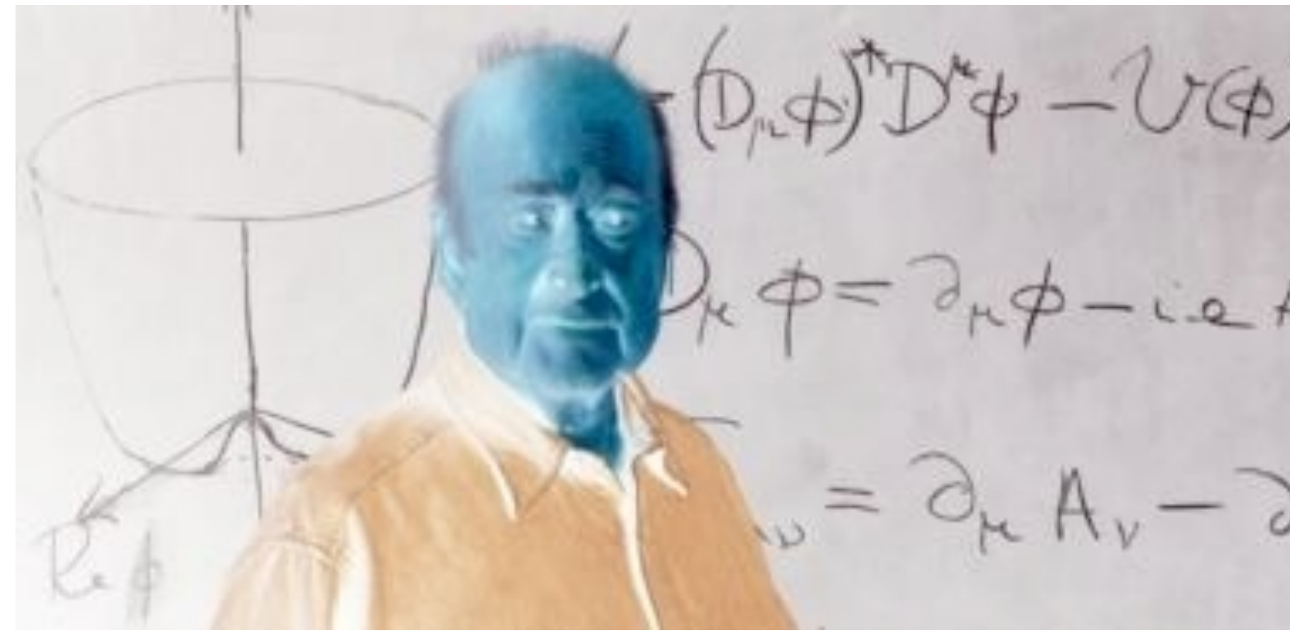


Beyond the SM Higgs

- Suppose that this is not the Standard Model Higgs (focus of many talks in this week's workshop)
  - Higgs with different couplings? ⇒ MSSM, Fermiophobic, Higgs impostor
  - More complicated Higgs sector? ⇒ MSSM, Doubly-charged Higgs, Composite
  - Light scalar Higgs? ⇒ NMSSM
  - Hidden Higgs sector? ⇒ Higgs to long-lived particles
- The MSSM is compatible with a 125 GeV Higgs

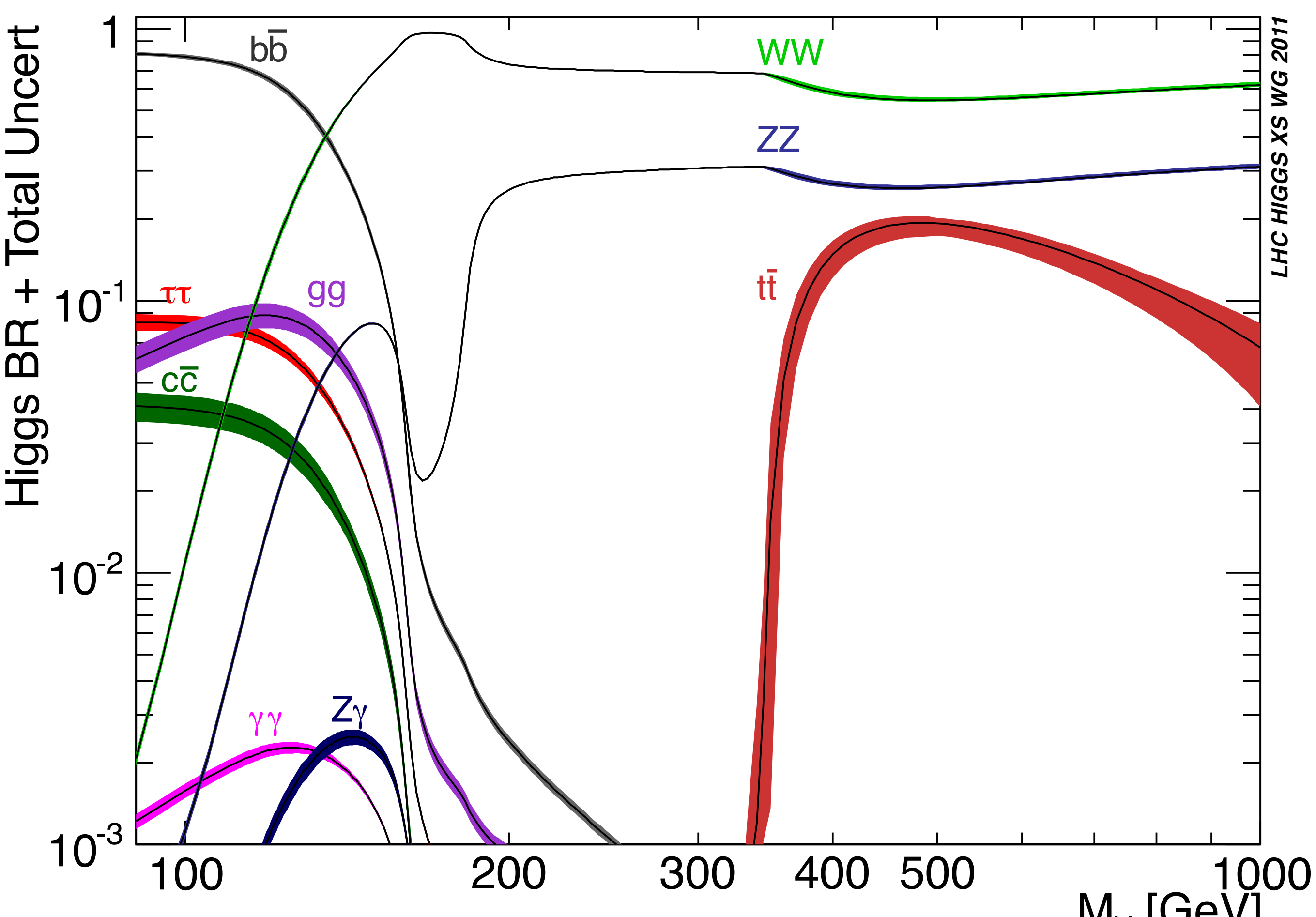
If the (light) Higgs mass is ~125 GeV, what next?

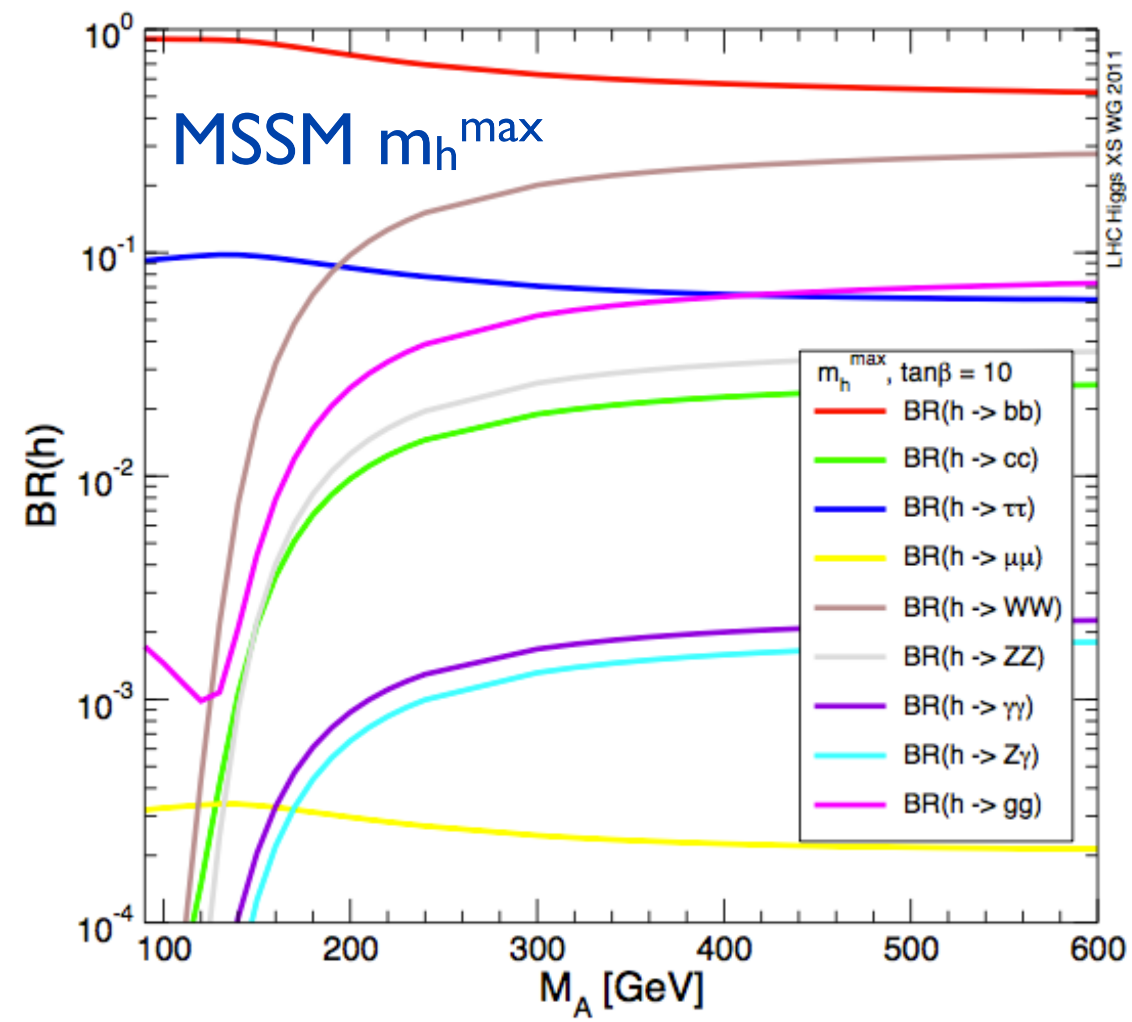




Standard Model Higgs

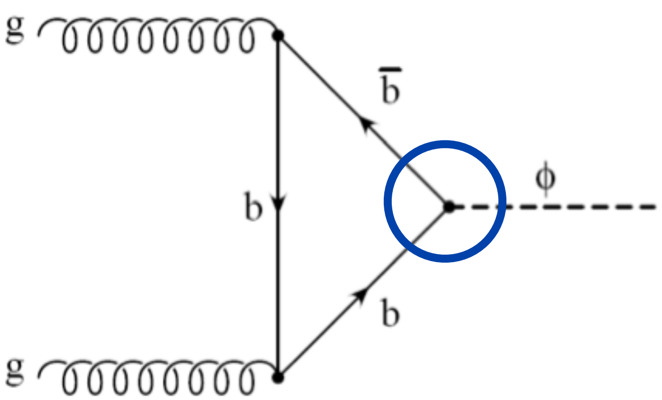
Beyond the SM Higgs

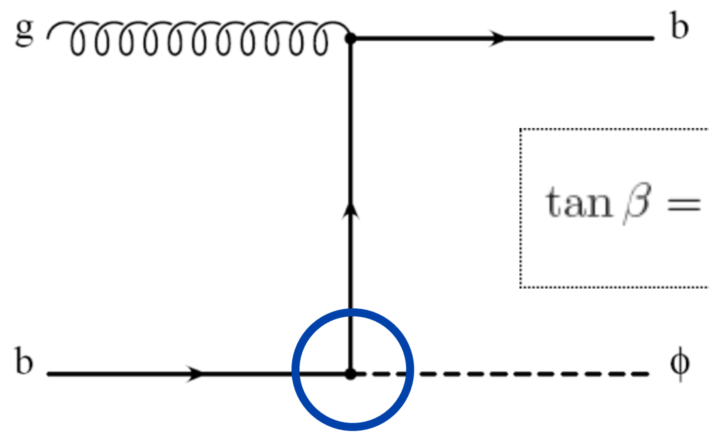




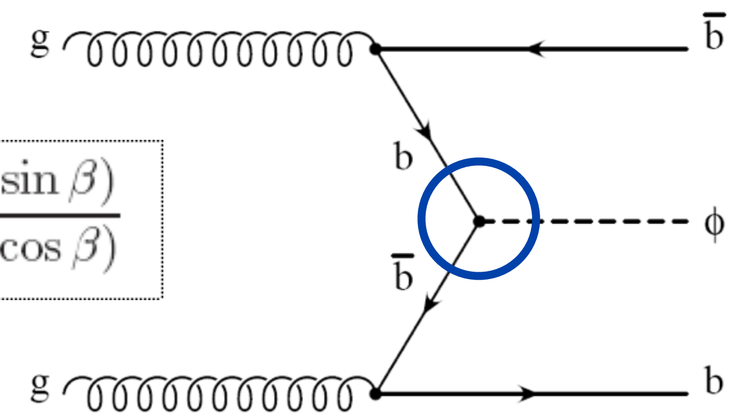
MSSM Higgs Sector

- Consider the case of an MSSM Higgs at the LHC
  - 2 Higgs doublets give rise to 5 physical Higgs bosons: h, H, A, $H^{\pm}$
  - Enhanced coupling to 3rd generation; strong coupling to down-type fermions (at large tanβ get strong enhancements to h/H/A production rates)
  - Diagrams with bbϕ vertex enhanced proportional to $\tan^2\beta$ where ϕ=h,H,A

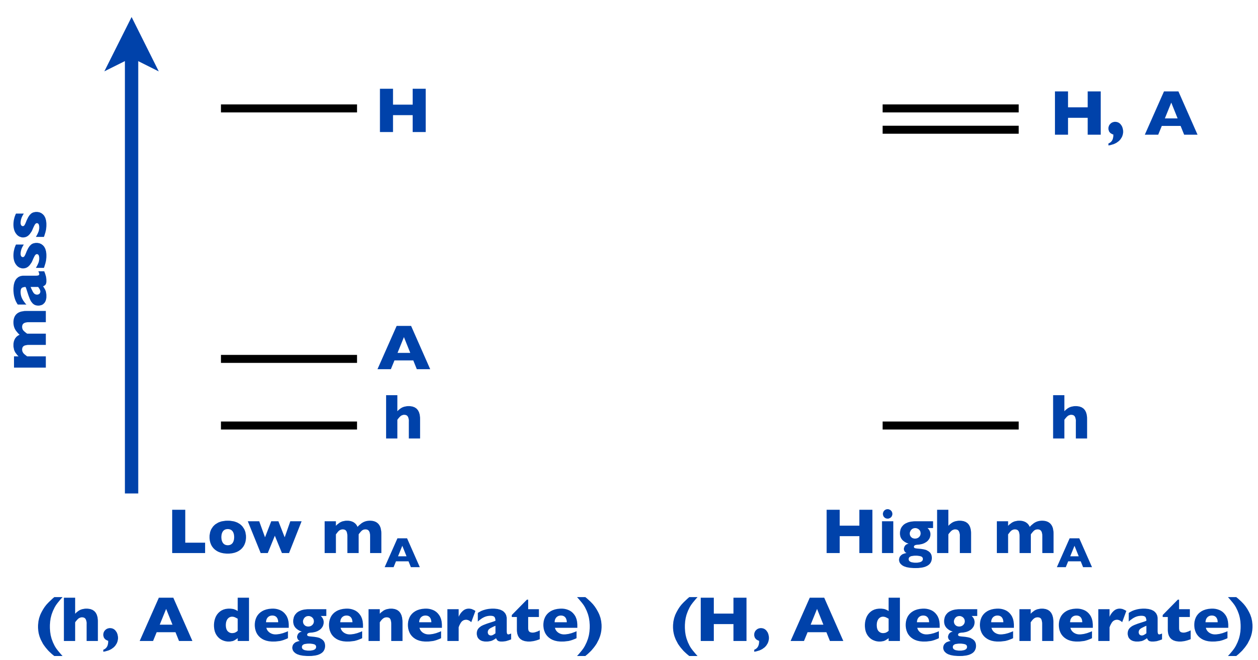


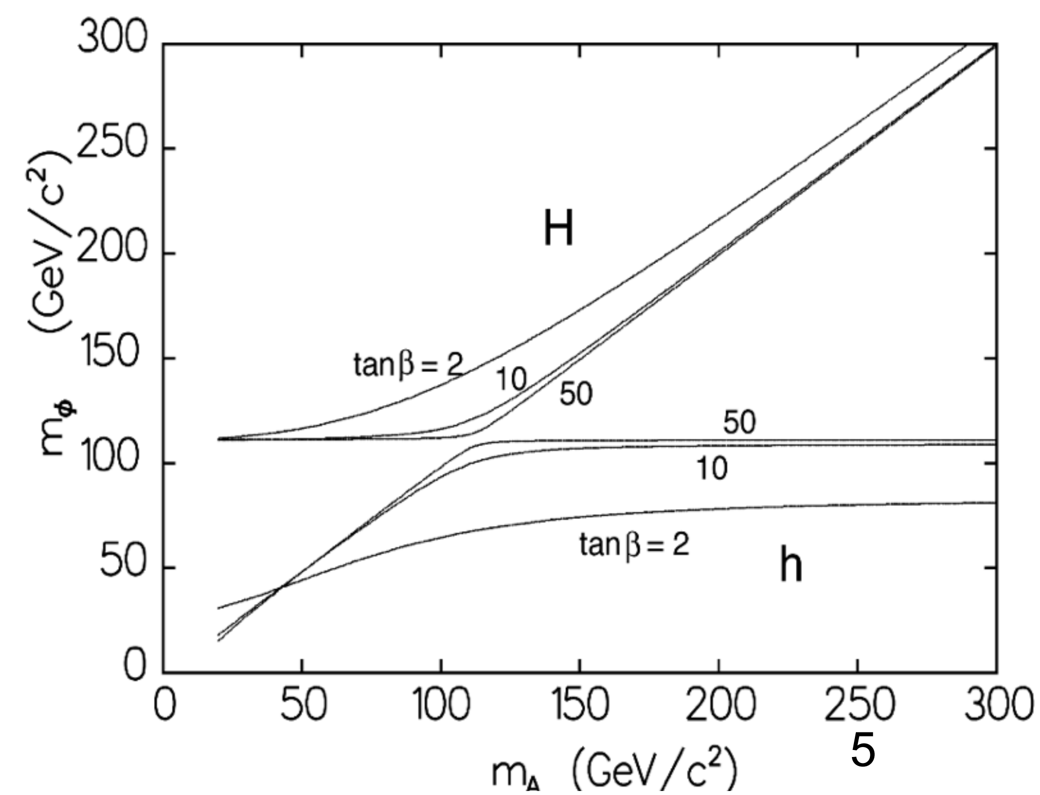


$$\tan\beta = \frac{v_2}{v_1} = \frac{(v\sin\beta)}{(v\cos\beta)}$$



- Can parameterize the masses of the Higgs bosons with two free parameters: tanβ and m_A





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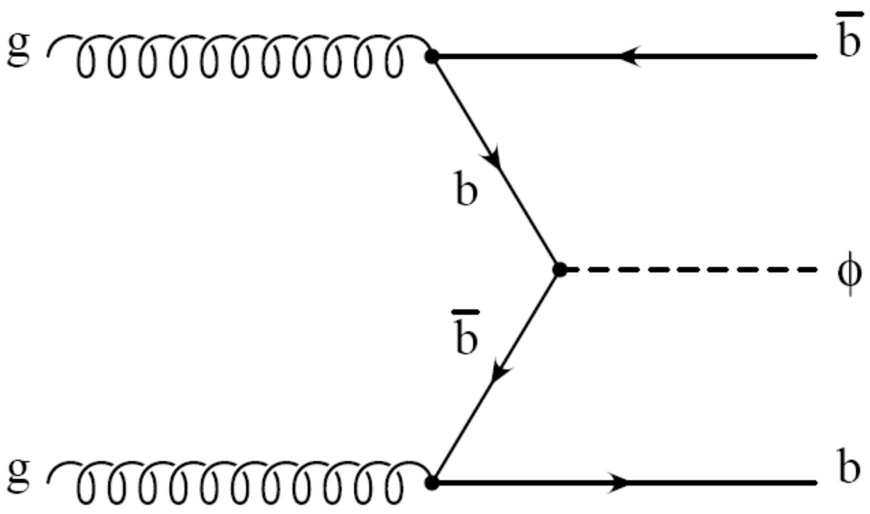
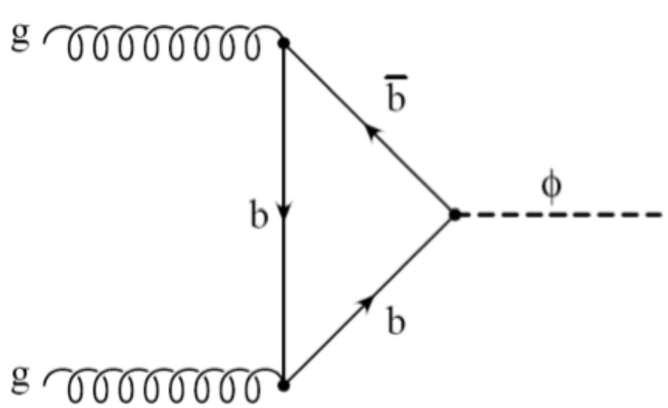
Neutral SUSY Higgs Searches in ATLAS

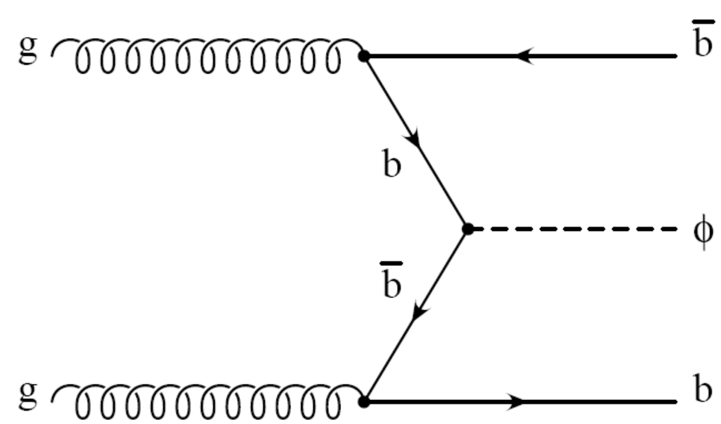


MSSM ϕ=h/A/H

MSSM Higgs Search ($\phi \to \tau^+\tau^-$)

- Latest ATLAS MSSM Neutral Analysis uses ~20 fb^{-1} of 8 TeV data
  - The ττ channel is very important for neutral MSSM searches: has a larger predicted BR than μμ (~10% versus ~0.03%) and less background than the bb channel
- Can use different categories target main production mechanisms
  - "no b-tag" targets gluon-fusion (dominant mode at small tanβ)
  - "b-tag" targets b-associated production (dominant mode at large tanβ)



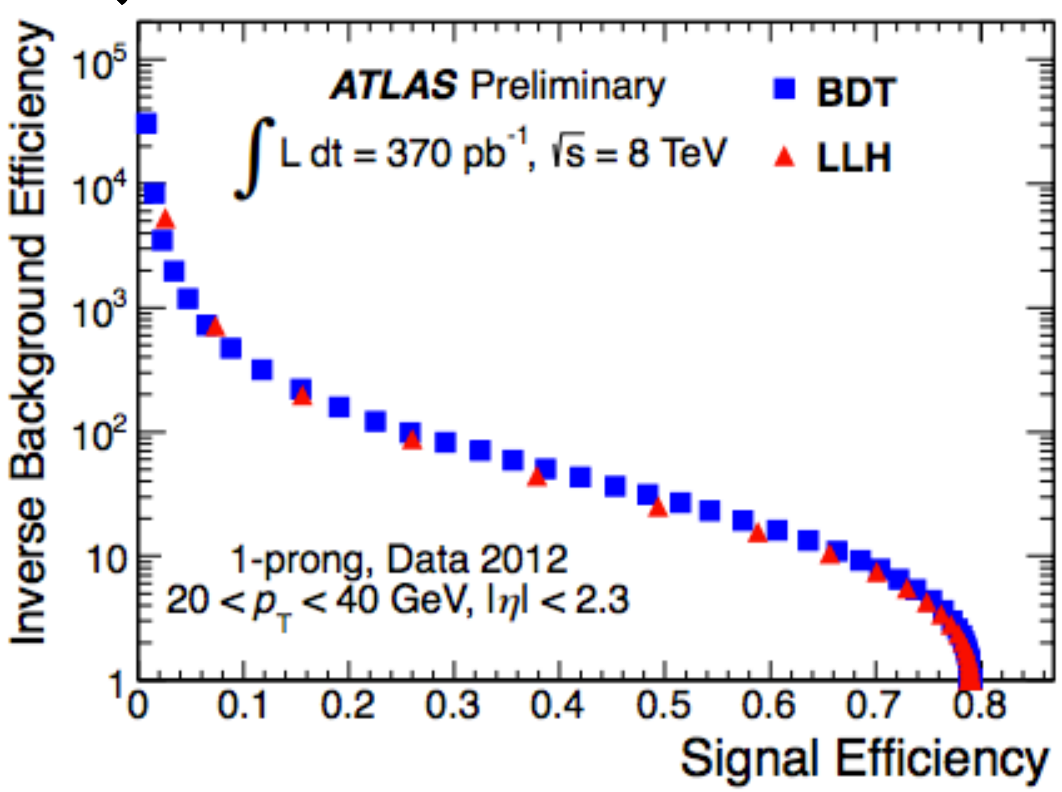


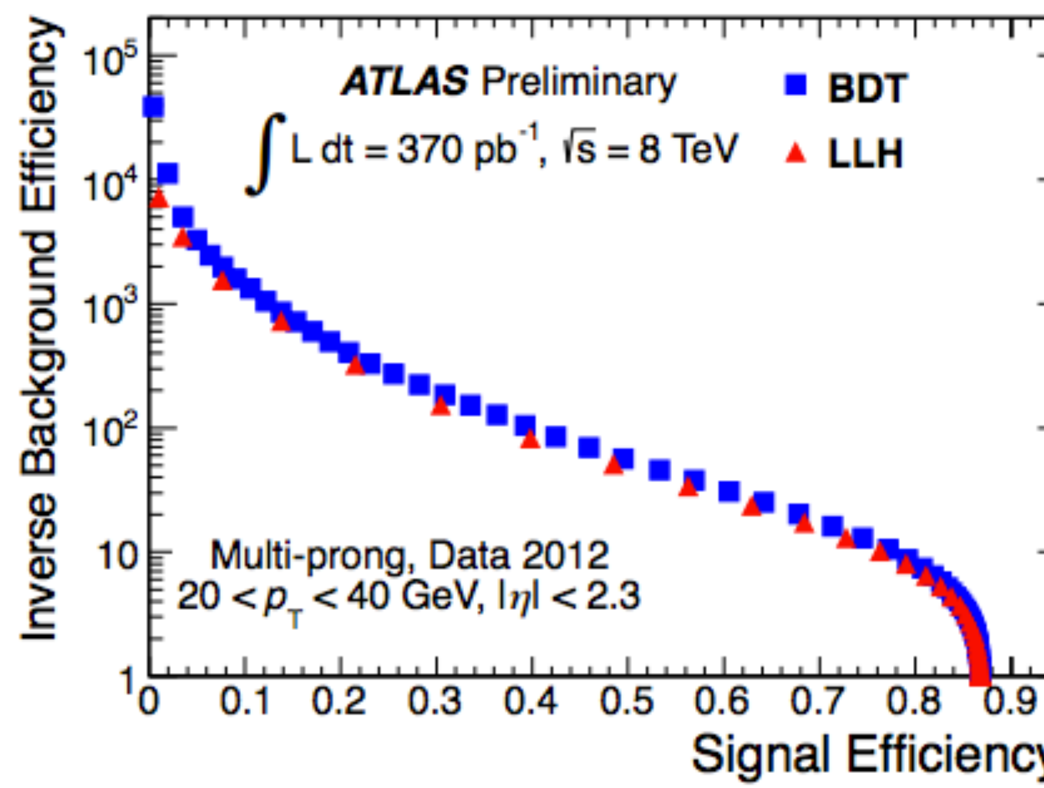
- Three main decay channels, depending on the τ decay
  - lep-lep (e-μ) uses τ decays to e and μ plus neutrinos (~6%)
  - lep-had uses leptonic and hadronic decays (~46%)
  - had-had uses exclusively hadronic decays (~42%)
- Each of these final states has been optimized for a specific Higgs mass range

arXiv:1409.6064

Reconstruction of hadronic τ decays

- The signature of hadronic τ decays are 1 or 3 tracks, collimated jet, possibly EM clusters
- Objects compatible with this signature are reconstructed
  - Seed from jet objects by considering each of them as a τ candidate
  - Identify a vertex consistent with a τ decay
  - Associate tracks within a core cone ($\Delta R \leq 0.2$) of the τ axis to jet objects

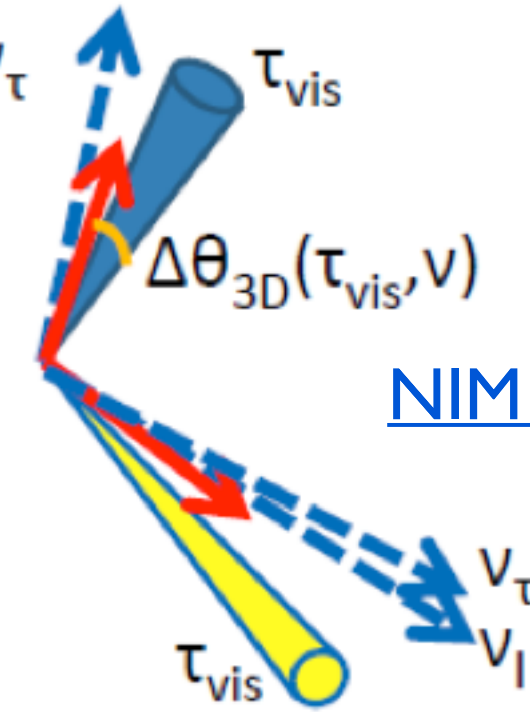




- Backgrounds from QCD jets, electrons and muons are rejected using dedicated algorithms
  ATL-CONF-2013-064
  - Discriminate using tracking information and cluster topology variables

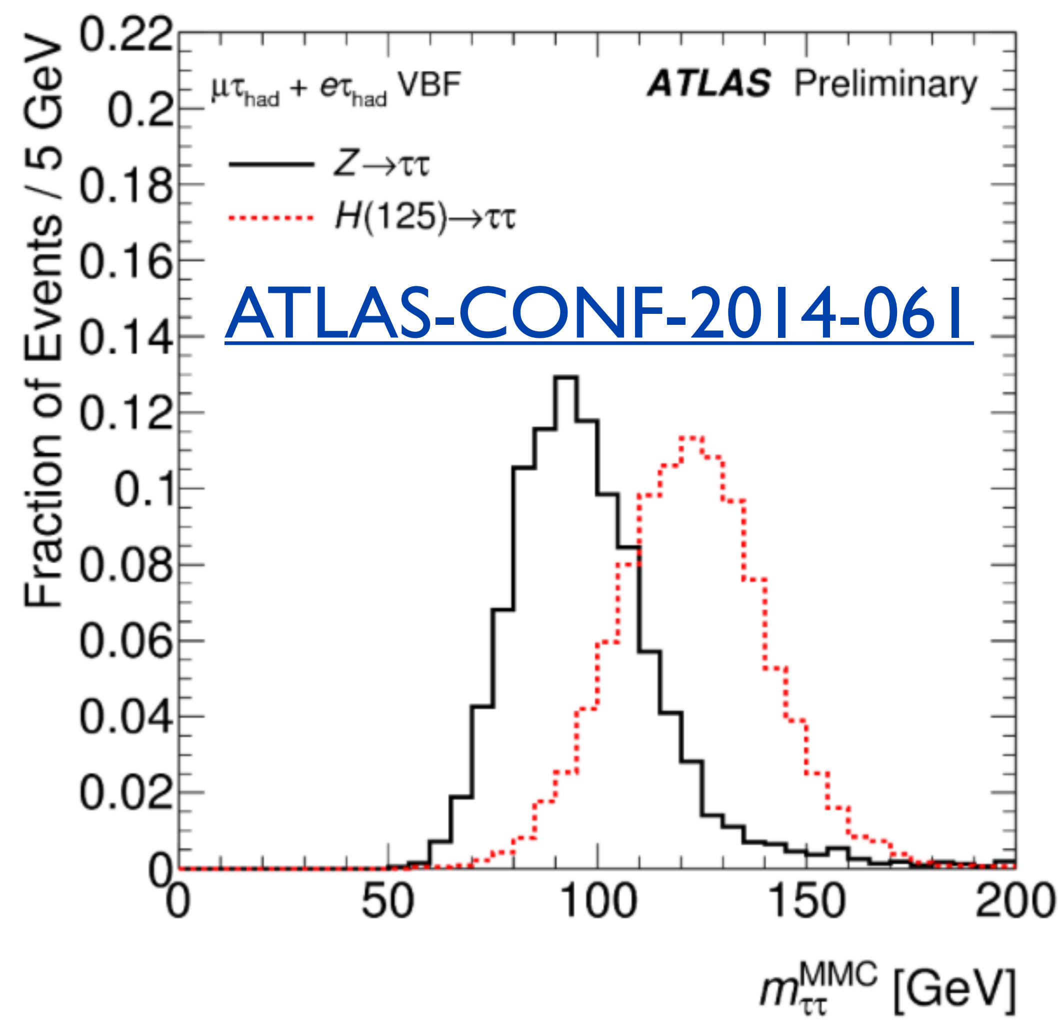
Mass Reconstruction with τ leptons

- Missing Mass Calculator technique
  - A step beyond the "collinear mass"
  - Assume the angle between the neutrinos and the visible hadronic τs (Δθ) is non-zero
  - End up with a system of equations with 6 - 8 unknowns
  - Use a likelihood to solve this under-constrained set of equations



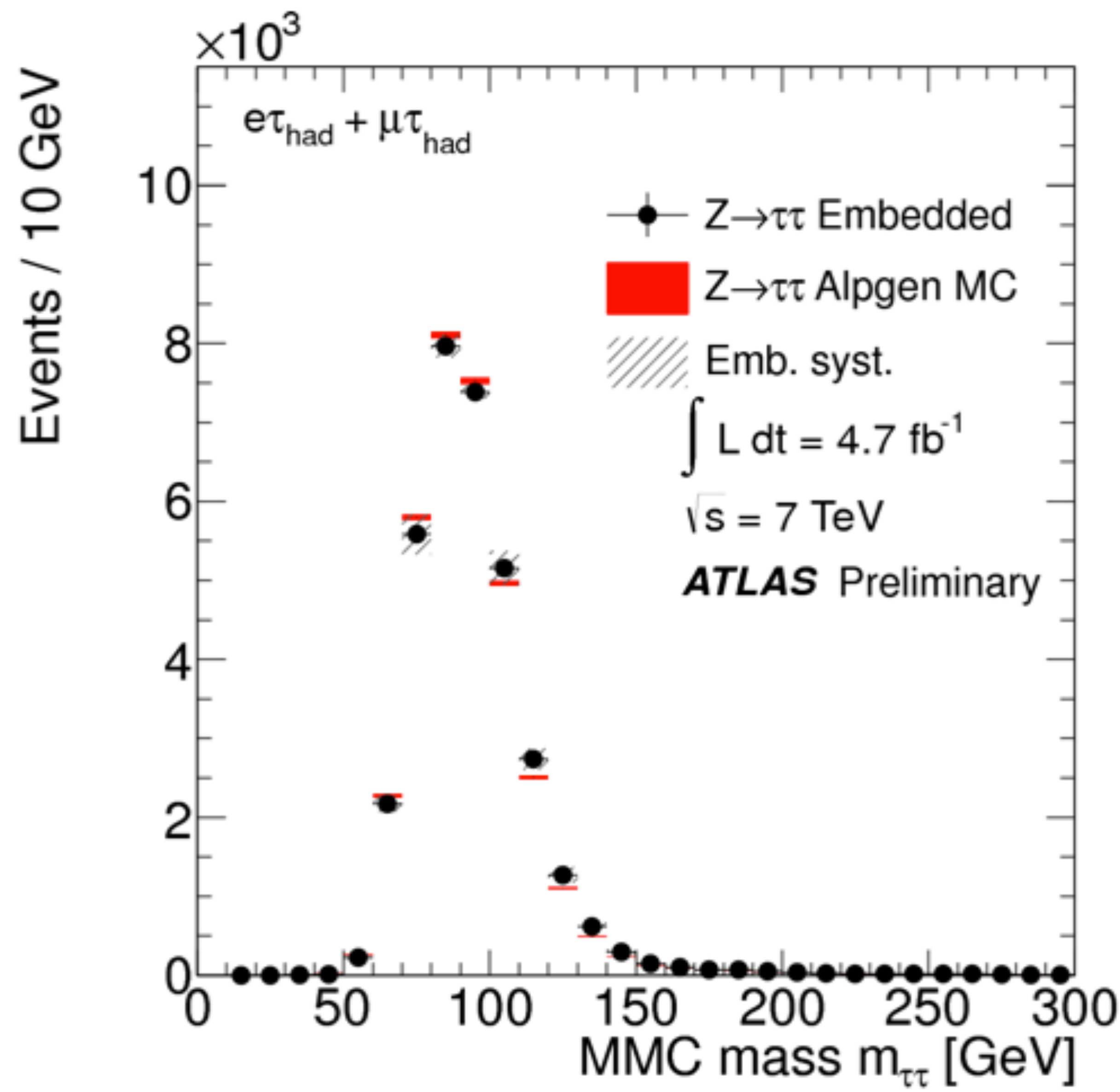
[NIM A654 (2011) 481]

Resolution 14-21%, depending on decay mode



Special Techniques Used with τ leptons

- $Z \to \tau\tau$ is the most important (irreducible) background source for di-τ final states at low mass
- Embedding technique ("τ-embedded" $Z \to \mu\mu$ data events)
- A semi-data-driven method: select an adequately pure $Z \to \mu\mu$ event sample from data and then replace the muons with simulated taus
- Pile-up, underlying event, kinematics, etc. are all taken directly from the data
- ATLAS charged Higgs search also uses embedding for ttbar backgrounds (replace single muon from W decay)

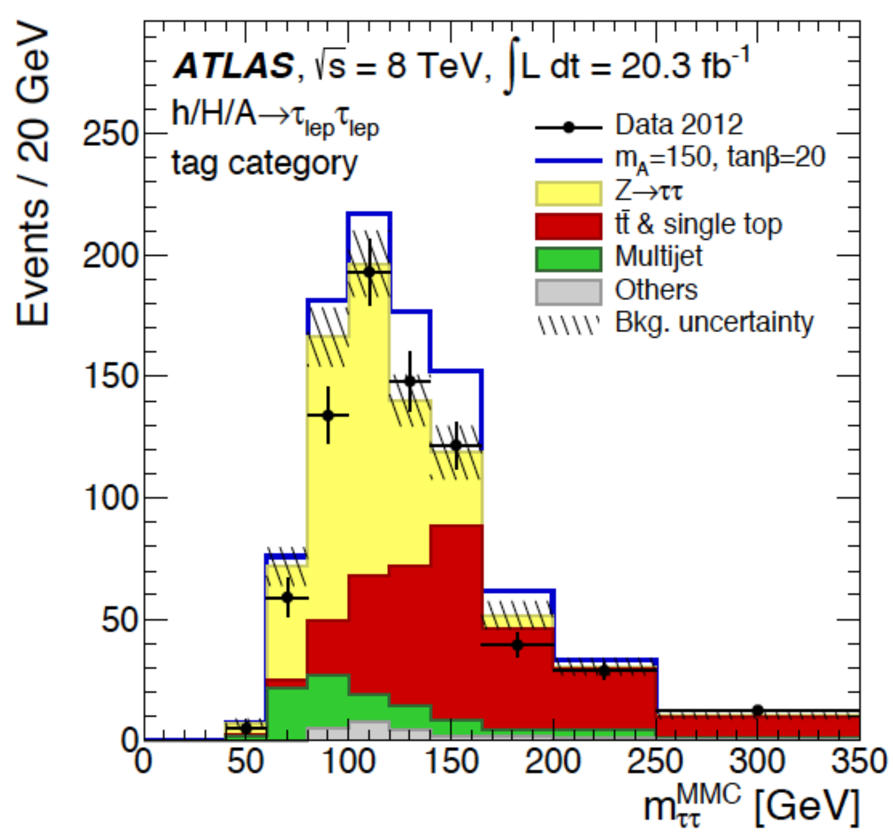


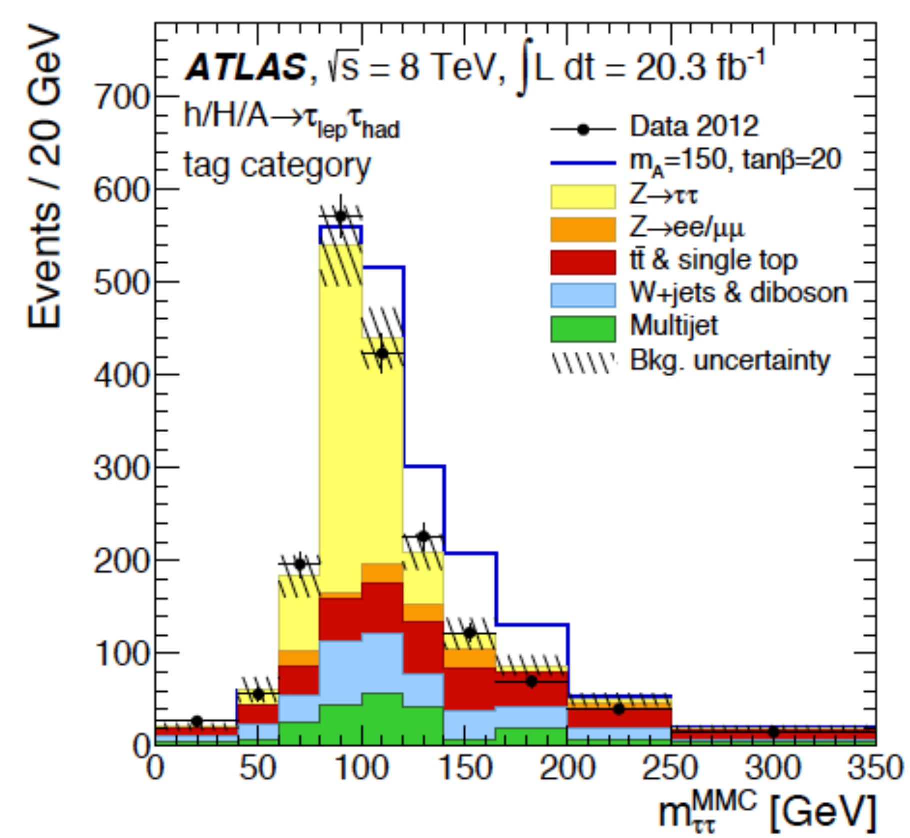
MMC di-τ mass for "tau embedding" and Alpgen simulation

MSSM Higgs Search ($\phi \to \tau^+\tau^-$)

- MSSM Neutral Analyses (three main channels, depending on the τ decay)
  - The e-μ and low-mass lep-had channels are separated into b-tagged and b-vetoed categories arXiv:1409.6064
  - **The e-μ analysis:** Use single e or e-μ triggers; opposite charge; require presence or absence of b-jet; $Z \to \tau\tau$ bkgnd from embedding; ttbar from simulation (normalized to data control region); W+jets, single-top, diboson all from simulation; multi-jets from 2D sideband method
  - **The low-mass lep-had analysis:** Use single e or single μ triggers; $Z \to \tau\tau$ bkgnd from embedding; W+jets, Z(ee,μμ)+jets, ttbar single-top from simulation (normalized to data control region); diboson from simulation

Mass distributions:



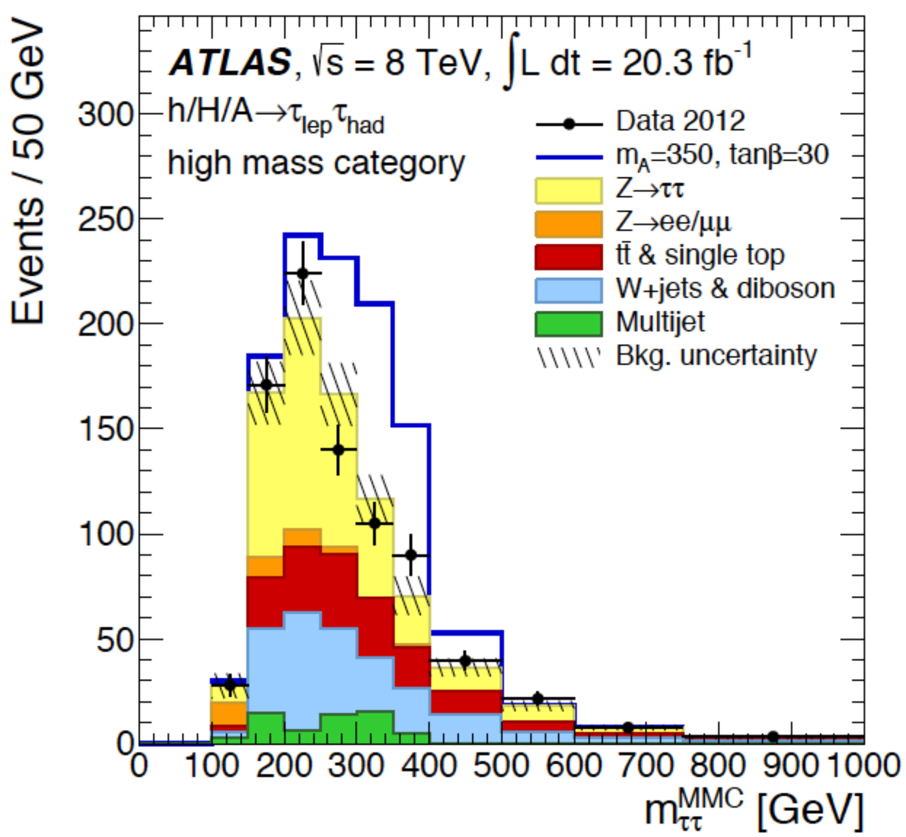


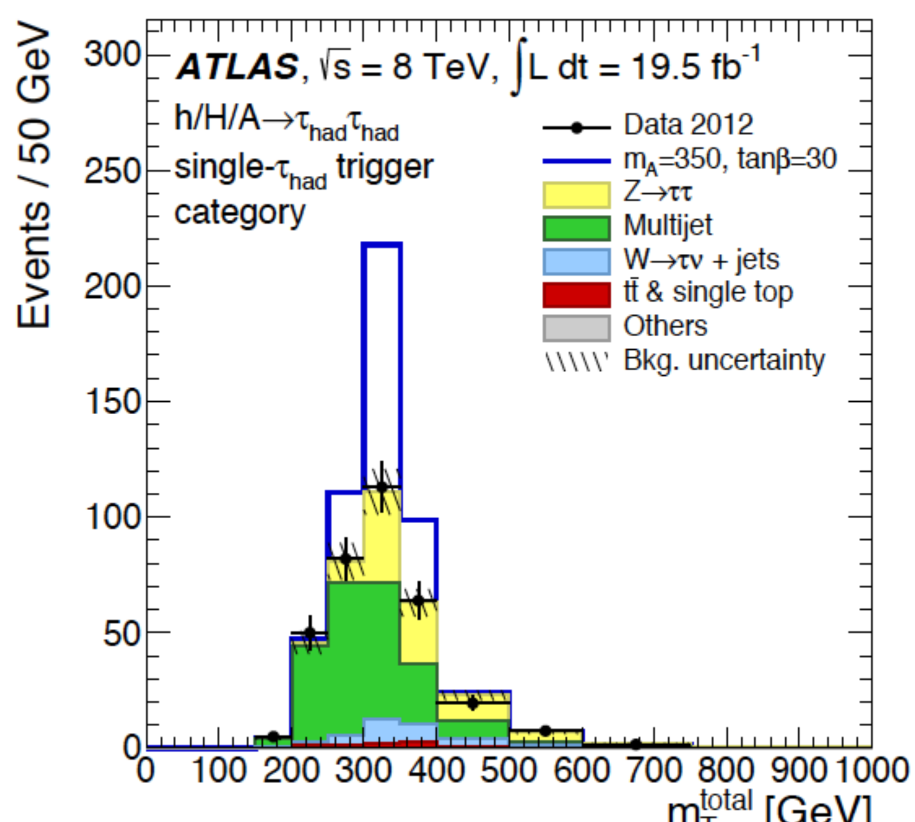
MSSM Higgs Search ($\phi \to \tau^+\tau^-$)

- MSSM Neutral Analyses (three main channels, depending on the τ decay)
  - **The high-mass lep-had analysis:** Targets $m_A \geq 200$ GeV; Use single e or single μ triggers; $Z \to \tau\tau$ bkgnd from embedding; W+jets, Z(ee,$\mu\mu$)+jets, ttbar single-top from simulation (normalized to data control region); diboson from simulation; exploit high-mass kinematics (taus are back-to-back)
  - **The had-had analysis:** Use single and double hadronic τ triggers; $p_T > 50$ GeV, opposite charge; exploit high-mass kinematics (taus are back-to-back); dominant bkgnd is multi-jets and m_T is used as the final discriminant; other bkgnds are Z+jets (due to high trigger thresholds, no embedding used), W+jets, ttbar and diboson

$$m_T^{total} = \sqrt{m_T^2(\tau_1,\tau_2) + m_T^2(\tau_1, E_T^{miss}) + m_T^2(\tau_2, E_T^{miss})}$$

Mass distributions:



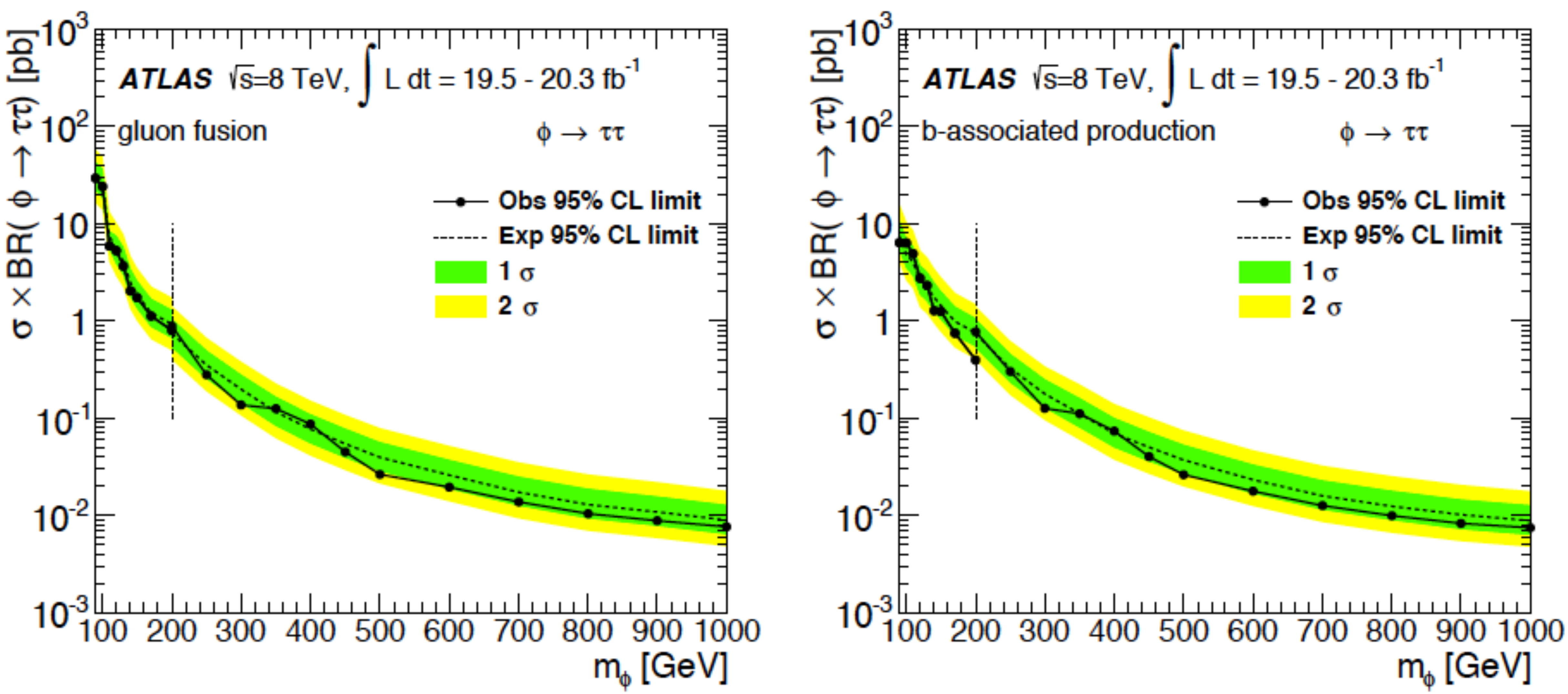


$$m_T = \sqrt{2p_{T1}p_{T2}(1 - \cos\Delta\phi)}$$

arXiv:1409.6064

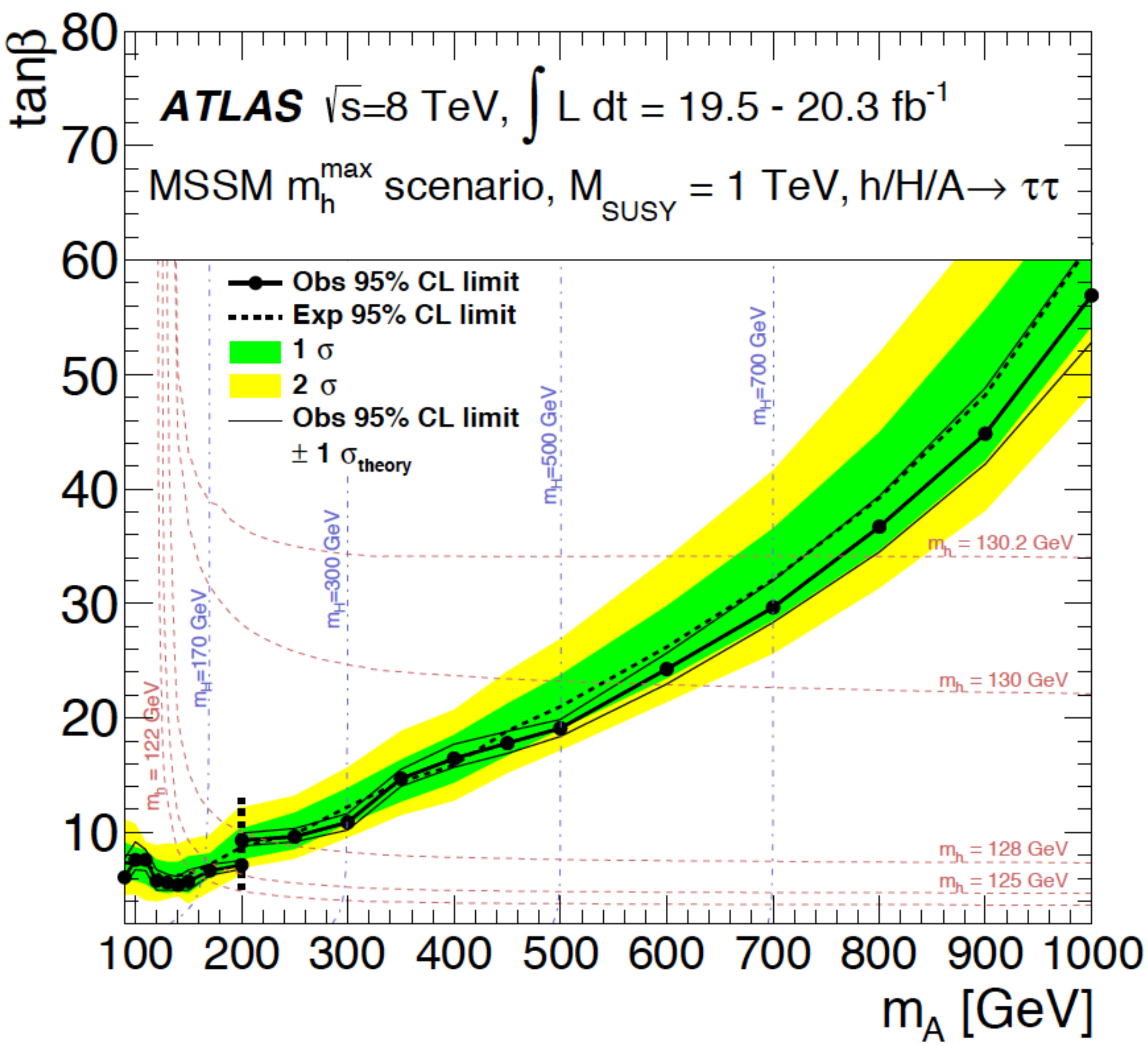
MSSM Neutral Higgs Search

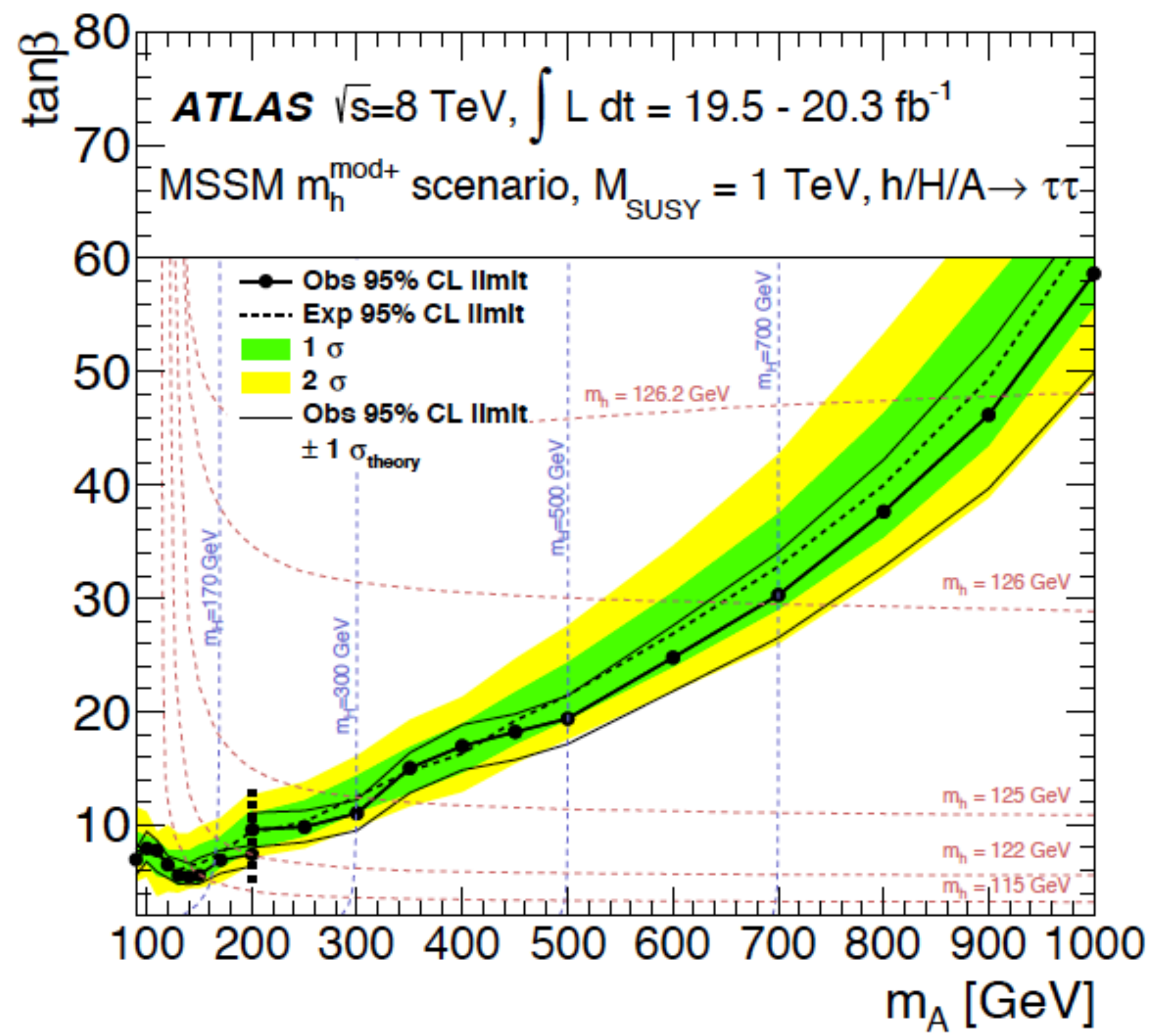
- Statistically combine the τ_{lep}-τ_{had}, τ_{had}-τ_{had}, and τ_{lep}-τ_{lep} channels for one exclusion limit arXiv:1409.6064
- We determine a $\sigma \times BR$ limit ($h/A/H \rightarrow \tau\tau$) for gluon-fusion and b-associated production separately; exclusions range from 30 pb to about 7 fb, depending on the Higgs mass and production mechanism



MSSM Neutral Higgs Search

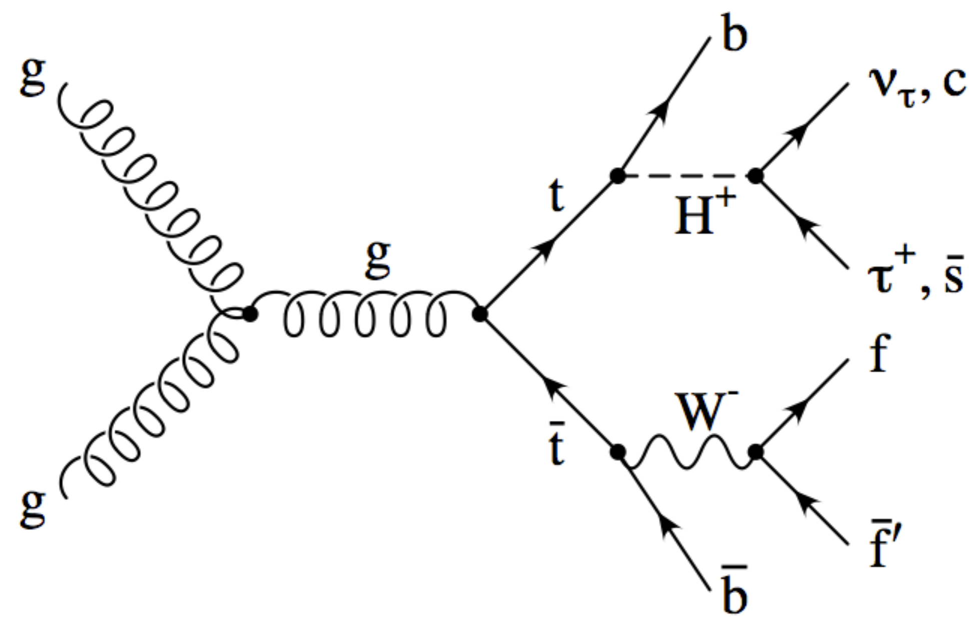
- Statistically combine the τ_{lep}-τ_{had}, τ_{had}-τ_{had}, and τ_{lep}-τ_{lep} channels for one exclusion limit arXiv:1409.6064
- We also show limits in the m_h^{max} and m_h^{mod} benchmark scenarios
- In the m_h^{max} scenario, lowest tanβ constraint excludes tanβ > 5.4 for m_A = 140 GeV





Note: Red dashed lines denote constant m_h mass for a particular scenario

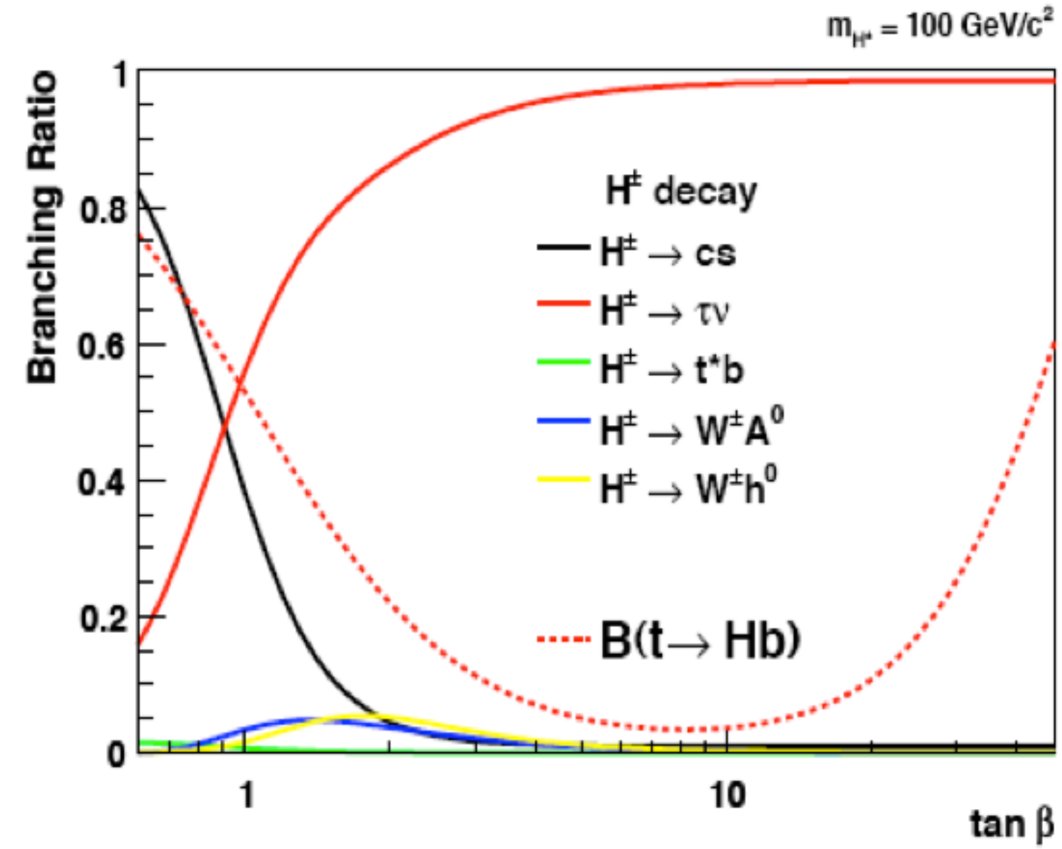
Charged SUSY Higgs Searches in ATLAS



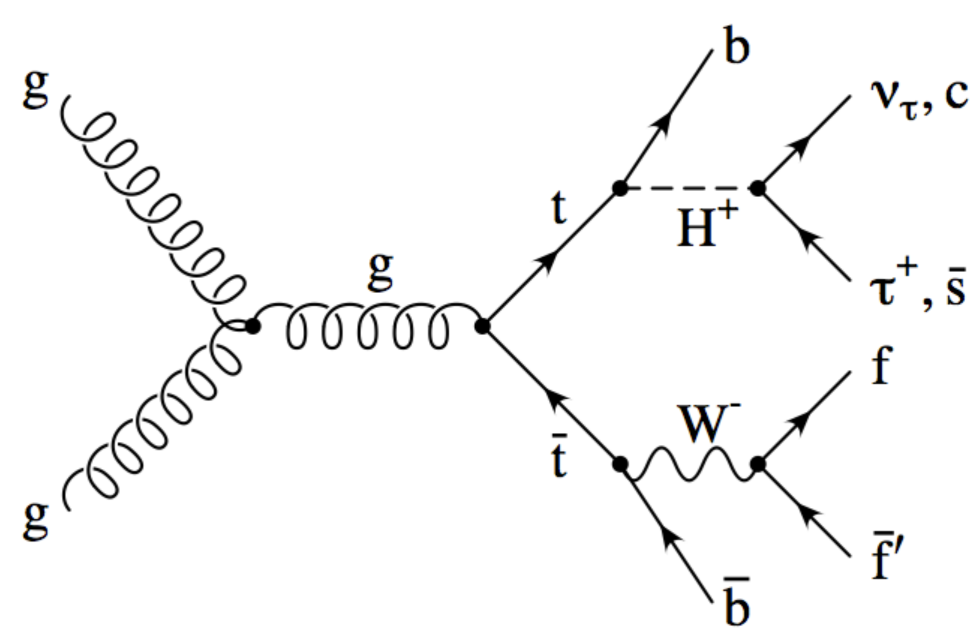
Charged Higgs $H^{\pm}$

Charged MSSM Higgs Searches

- Charged Higgs bosons could be expected from the MSSM Higgs sector
- H+ Production:
  - Light H^+: pp → tt → bW bH$^+$
  - Heavy H^+: gb → tH$^+$ and gg → tbH$^+$
- H+ Decay:
  - Light H^+: Almost exclusively to τν (at low tanβ predominantly to $c\bar{s}$)
  - Heavy H^+: tb; τν; $\chi^+\chi^0$

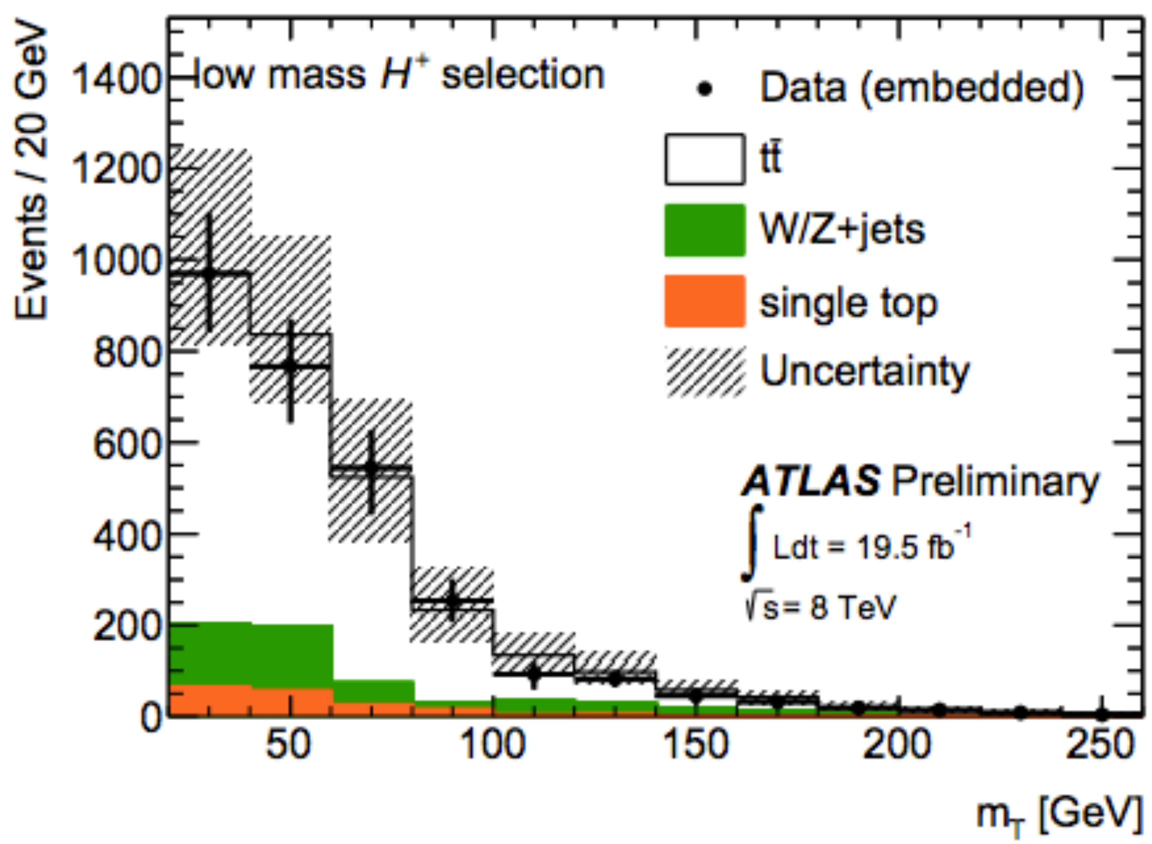


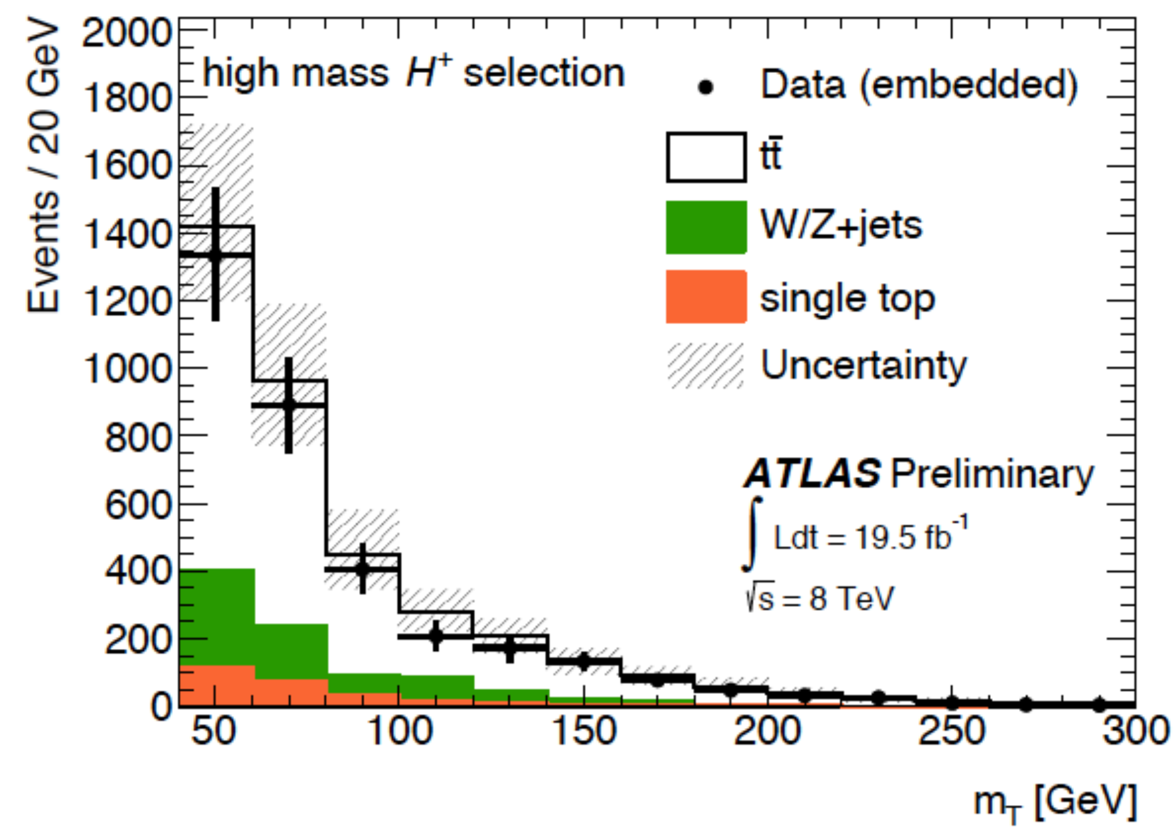
- ATLAS charged Higgs searches with taus:
  - Use final states with τνjjb and τνjjbb
  - tt → [H$^\pm$b][Wb] → [τνb][qqb]
  - gb → [t][H$^\pm$] → [qqb][τν]
  - gg → [tb][H$^\pm$] → [qqbb][τν]



Charged Higgs: $H^+ \to \tau\nu$

- A cut-based analysis on ~20 fb^{-1} of 8 TeV data; only using hadronic taus; separate into low- and high-mass regions
- Again, we use some special techniques [ATLAS-CONF-2014-050]
  - Embedding is used to estimate the dominant background containing true hadronic τ decays; we select a μ+jets sample and replace the μ with a Monte Carlo τ

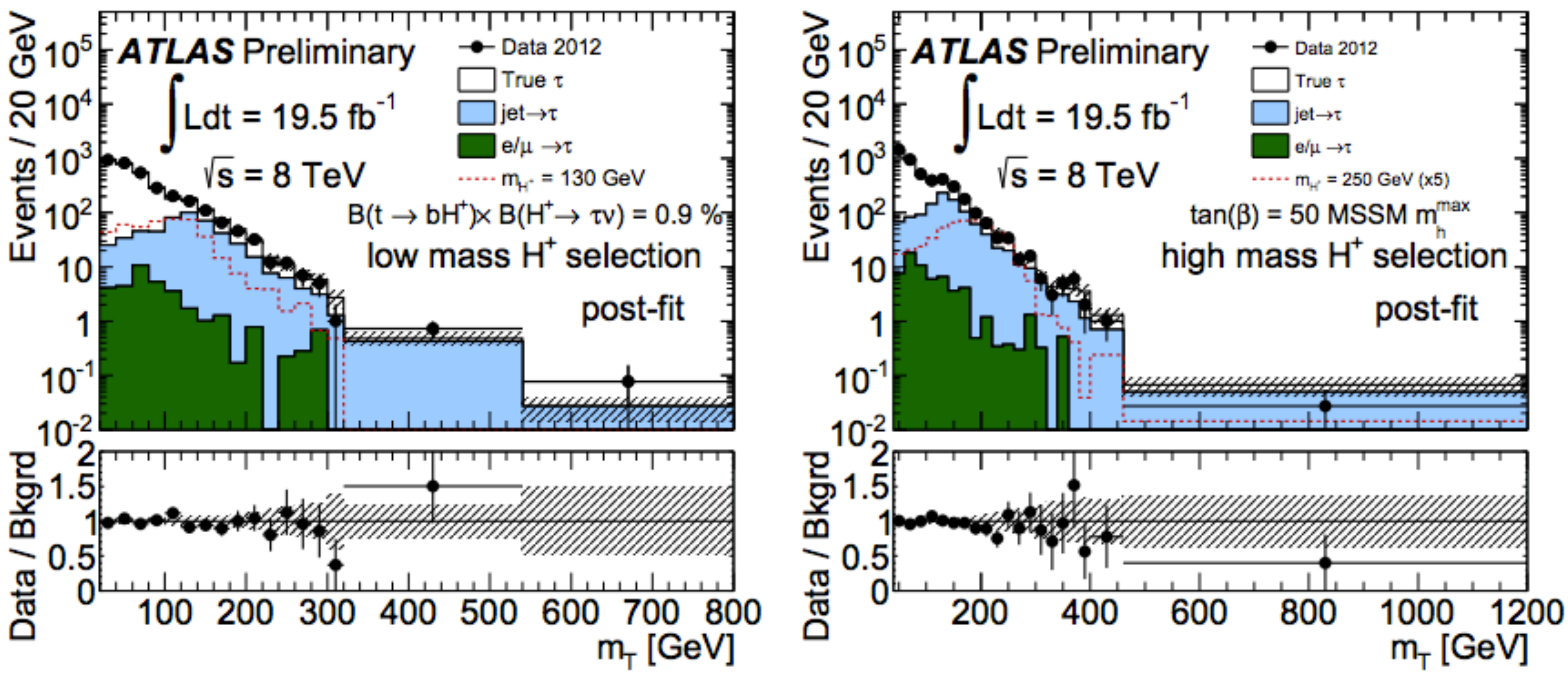




- Use events passing hadronic τ + MET trigger.
- The transverse mass is used as the final discriminating variable

Charged Higgs: $H^+ \rightarrow \tau\nu$

- Backgrounds with jet faking tau are estimated using data-driven control regions
- Backgrounds with e/μ faking tau are small (due to veto algorithms) and are estimated using simulated events
- For an MSSM Charged Higgs in the m_h^{max} scenario, with tanβ = 50, we would expect ~230 events for a 130 GeV H^+ and ~58 events for a 250 GeV H^+

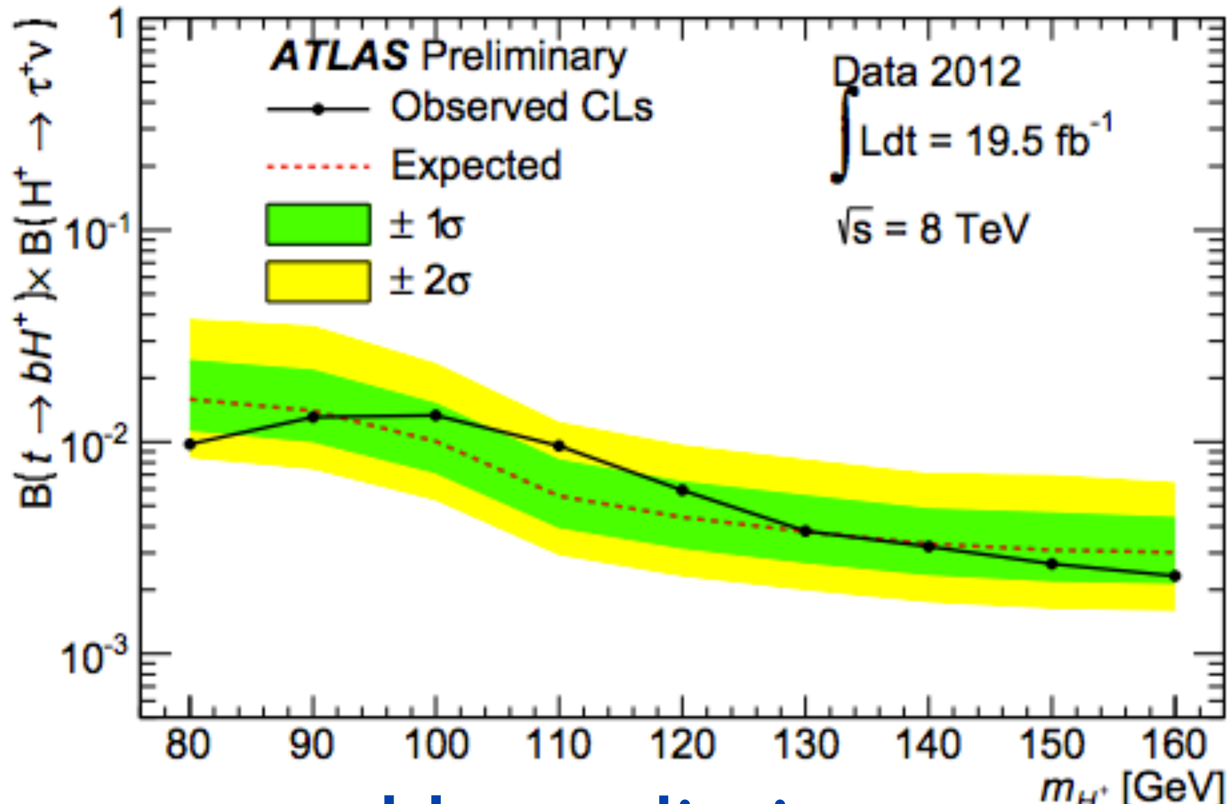


ATLAS-CONF-2014-050

Charged Higgs: $H^+ \to \tau\nu$

- ATLAS Limits on charged Higgs production

Low-mass H^+ selection

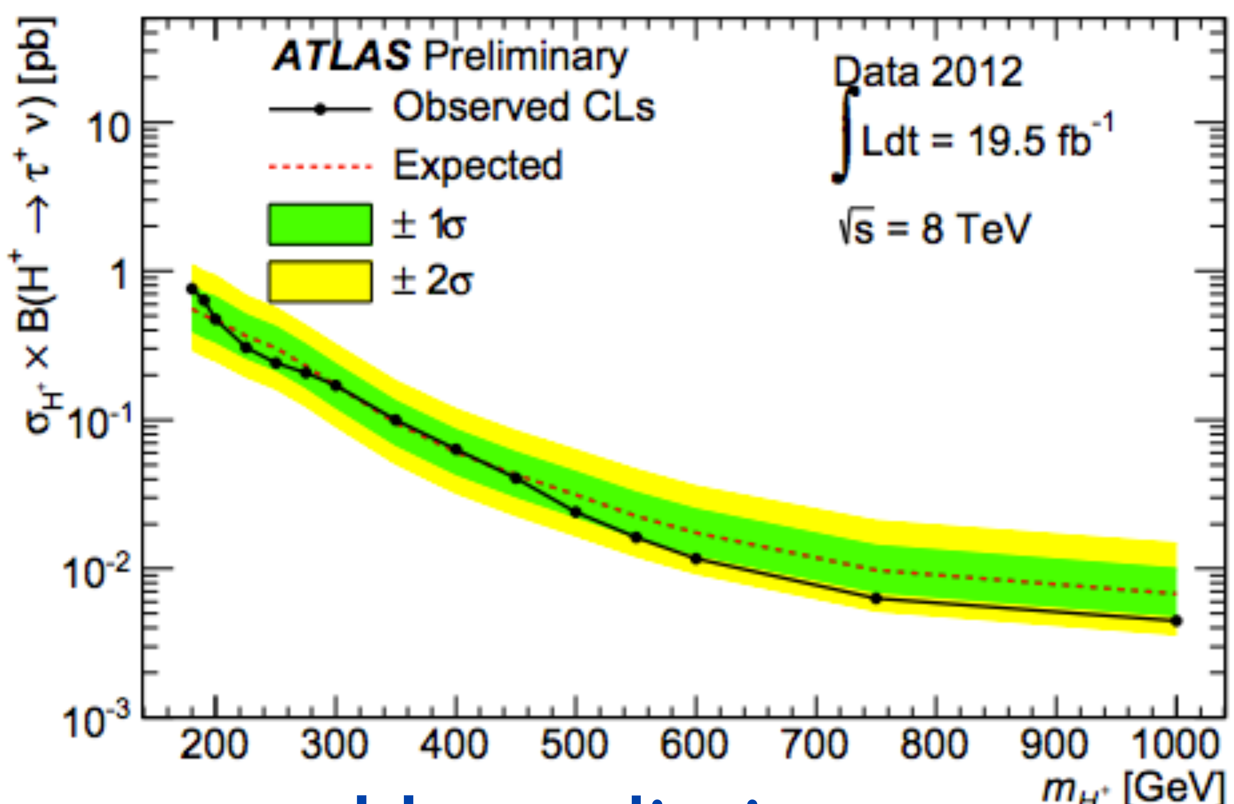


Upper limits on

$BR(t \to bH^+) \times BR(H^+ \to \tau\nu)$

1.3% - 0.23%

High-mass H^+ selection



Upper limits on

$\sigma(pp \to tH^+ + X) \times BR(H^+ \to \tau\nu)$

0.76 pb - 4.5 fb

Note: Additional input from theory regarding the region 160 GeV - 200 GeV would be helpful (no reliable calculation)

ATLAS-CONF-2014-050

Conclusions and Outlook

- During Run-I ATLAS has had a very active search program for Beyond the Standard Model Higgs bosons and we've been exploring the MSSM Higgs sector
  - Some searches in 7 TeV data not shown here (like MSSM $\phi \rightarrow \mu^+\mu^-$ and $H^+ \rightarrow cs$)
  - No hint of an extended Higgs sector just yet; We have already pushed the constraints further than previous searches
  - Even with a SM-like Higgs observed, BSM Higgs searches will continue to be relevant (e.g., there are still regions of MSSM parameter space that are compatible with the observed Higgs at 125 GeV)
- Stay tuned for Run-II of the LHC; these are very exciting times!

Back-up Slides

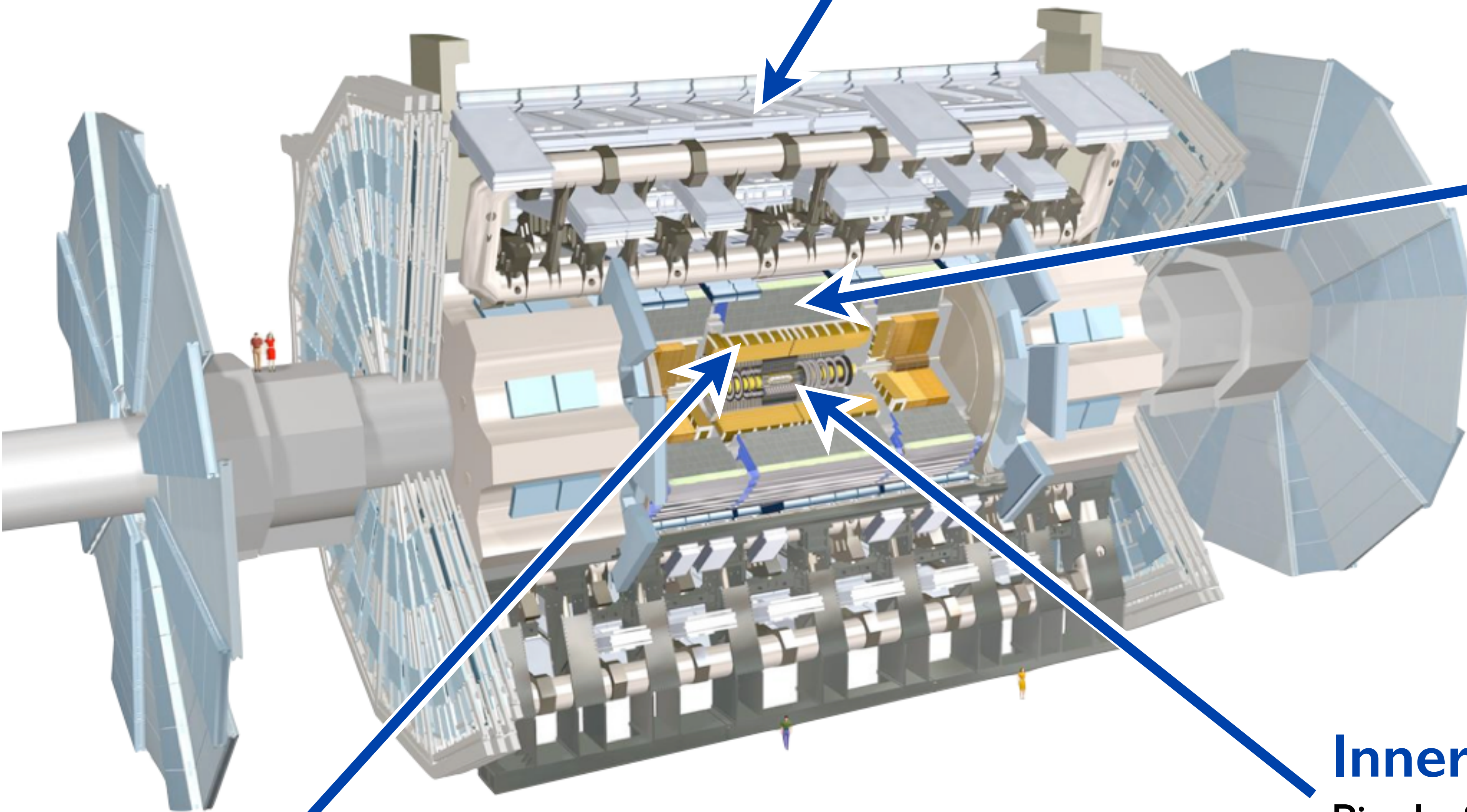
The ATLAS Experiment at the CERN LHC

3-Level Trigger

Reducing the rate from 40 MHz to 200-300 Hz

Muon Spectrometer

($|\eta|<2.7$): Air-core toroids with gas-based muon chambers; Muon trigger and measurement with momentum resolution < 10% up to $p_\mu \sim 1$ TeV



HAD calorimetry

($|\eta|<5$): hermetic and highly segmented; Fe/scintillator Tiles (central), Cu/W-LAr (fwd)

Trigger and measurement of jets and missing E_T

E-resolution:

$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

Inner Detector ($|\eta|<2.5$, B=2T): S

Pixels, Si strips, Transition Radiation detector (straws); Precise tracking and vertexing, allows for e/π separation;

Momentum resolution:

$\sigma/p_T \sim 3.8\times10^{-4}\ p_T\ (\text{GeV}) \oplus 0.015$

i.e. $\sigma/p_T < 2\%$ for $p_T < 35$ GeV

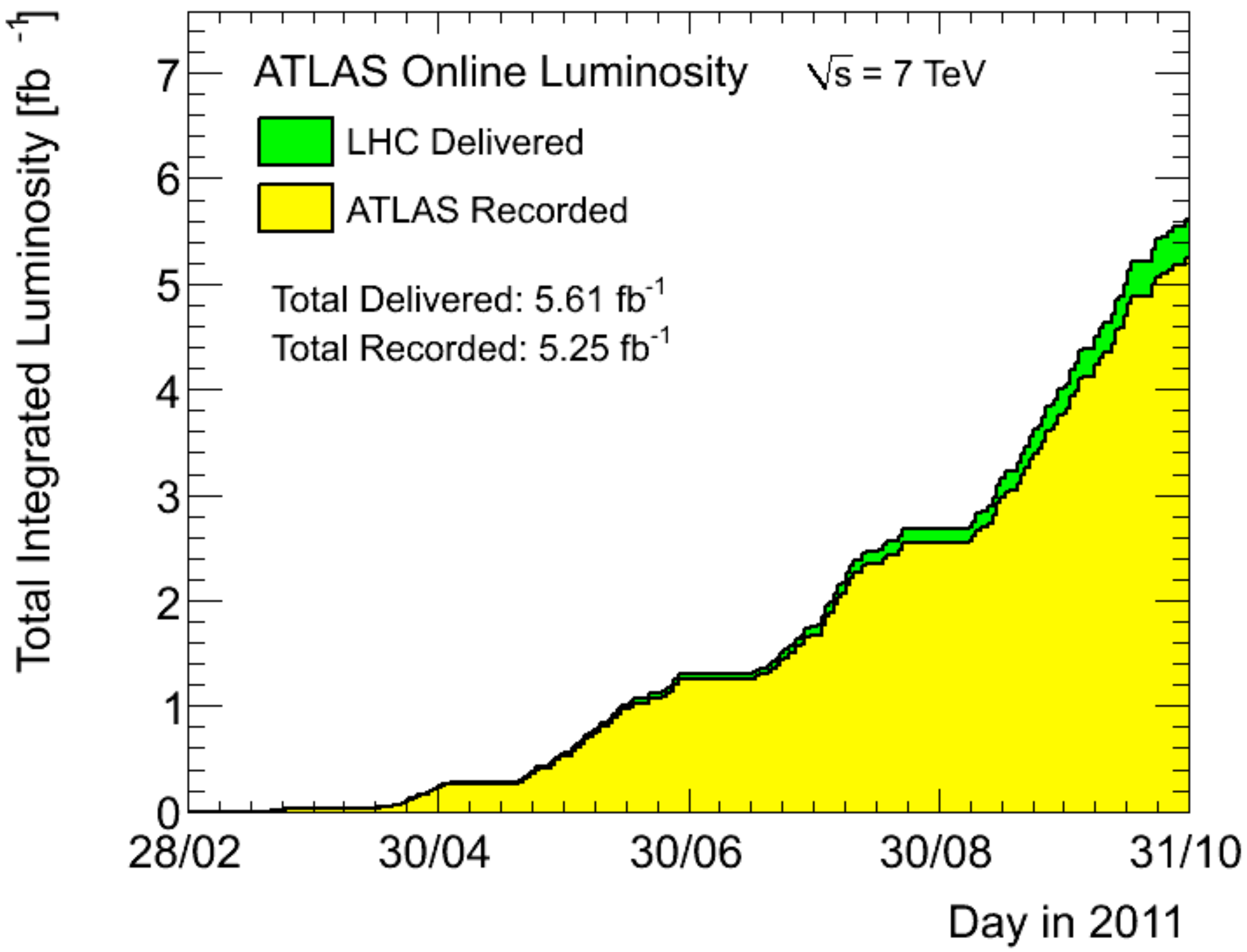
EM Calorimeter ($|\eta|<3.2$):

Pb-LAr Accordion; allows for e/γ triggering, identification and measurement;

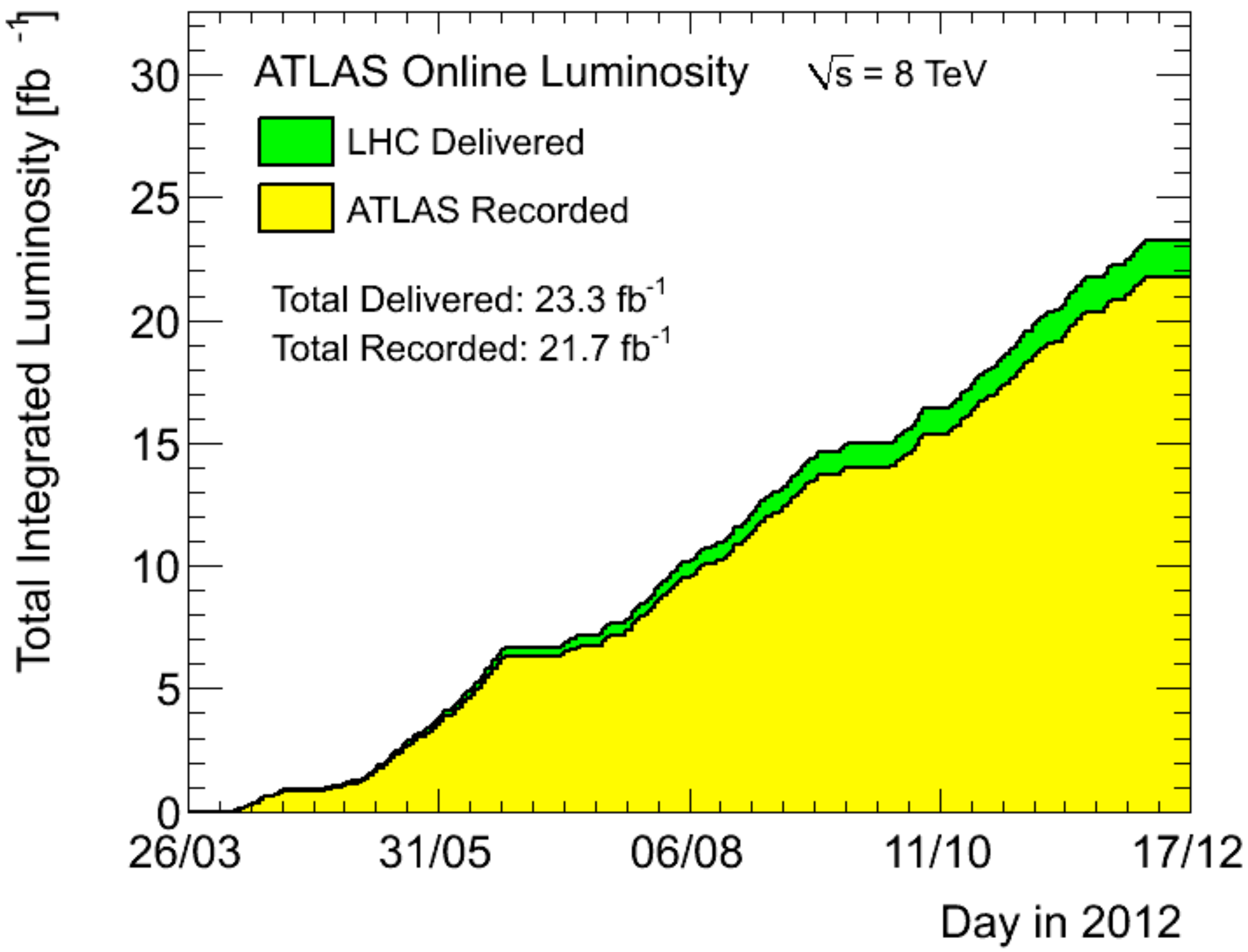
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

ATLAS Datasets

2011 7 TeV



2012 8 TeV



Monte Carlo Generators Used

- Charged Higgs:

Process	Generator	Cross section [pb]	
SM $t\bar{t}$ (inclusive)	MC@NLO	253	[29]
Single top quark t-channel (≥ 1 lepton)	AcerMC	28.4	[30]
Single top quark s-channel (≥ 1 lepton)	MC@NLO	1.8	[31]
Single top quark Wt-channel (inclusive)	MC@NLO	22.4	[32]
$W \to \ell\nu$	ALPGEN	3.6×10^4	[35]
$Z/\gamma^* \to \ell\ell$ with $m(\ell\ell) > 10$ GeV	ALPGEN	1.7×10^4	[36]
WW (≥ 1 electron/muon)	HERWIG	20.9	[37]
ZZ (≥ 1 electron/muon)	HERWIG	1.5	[37]
WZ (≥ 1 electron/muon)	HERWIG	7.0	[37]
H^+ signal ($m_{H^+} = 250$ GeV)	PYTHIA 8	0.2	

Table 1: Cross sections for the simulated processes and reference generators used to model them. For the heavy H^+ signal selection, the value shown is the cross section times $\mathcal{B}(H^+ \to \tau^+\nu)$ for the MSSM m_h^{max} scenario [40], corresponding to $m_{H^+} = 250$ GeV and $\tan\beta = 50$. The low mass signal, which is not included in the table, assumes one H^+ produced per $t\bar{t}$ decay, so it is a fraction of the $t\bar{t}$ cross section. The existing published limit on $\mathcal{B}(t \to bH^+)$ for $m_{H^+} = 130$ GeV is 0.9% [18].

MSSM Benchmarks Used

- Alternative benchmark scenarios

arXiv: 1302.7033v2

m_h^{max}

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 2\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= \sqrt{6}\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

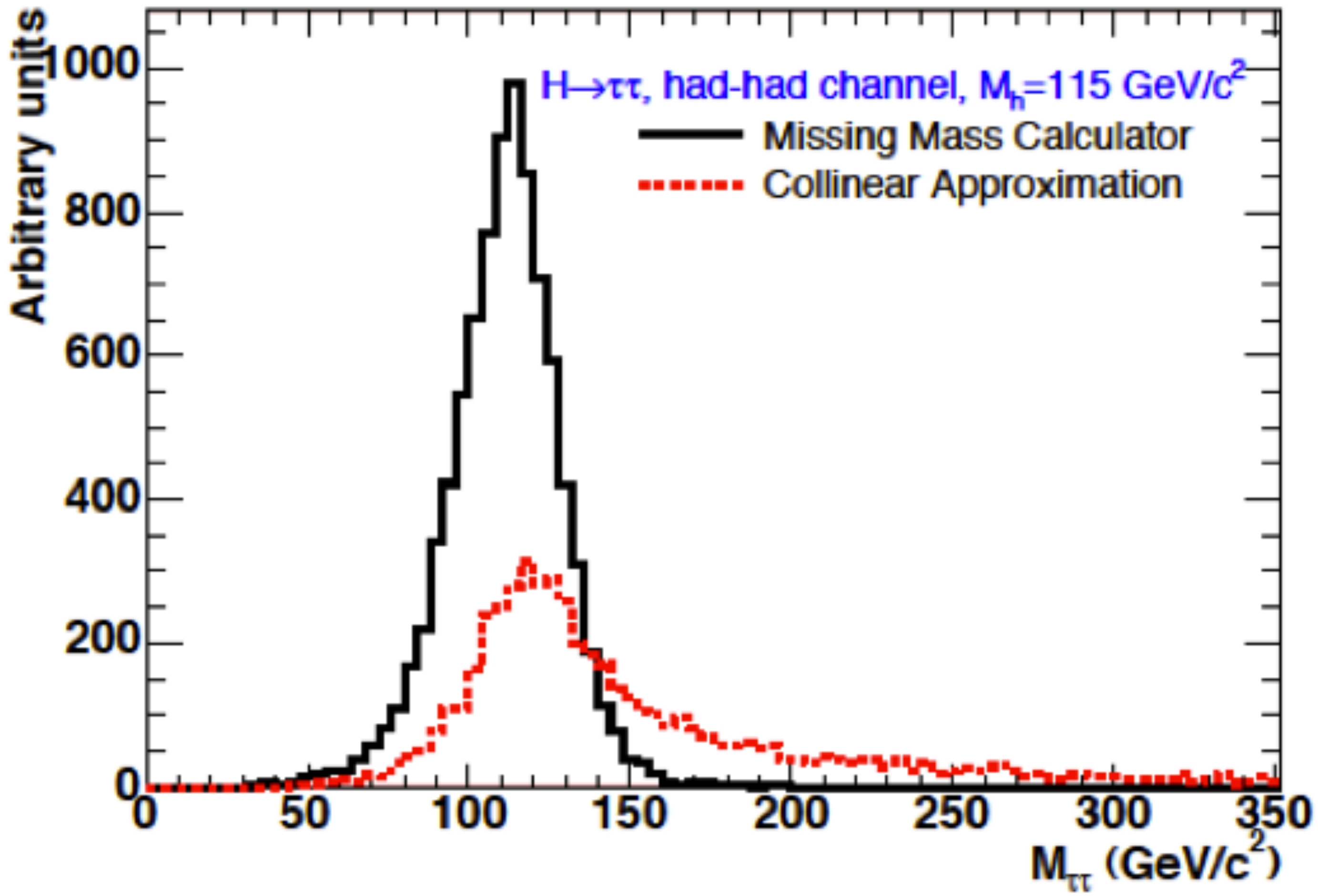
m_h^{mod+}

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 1.6\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

m_h^{mod-}

$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= -1.9\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= -2.2\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau = A_t, \\
m_{\tilde{g}} &= 1500 \text{ GeV}, \\
M_{\tilde{l}_3} &= 1000 \text{ GeV} .
\end{aligned}
$$

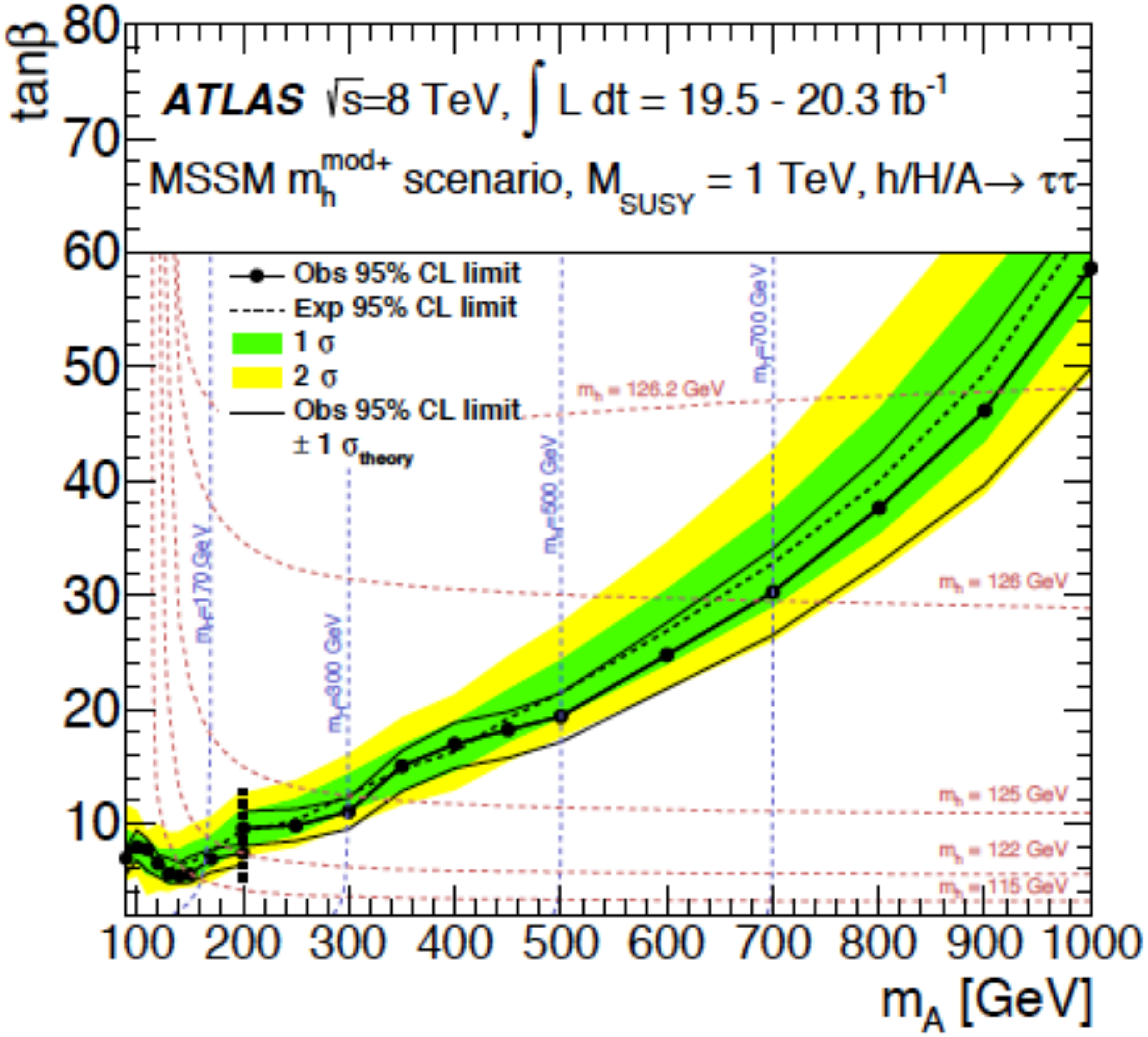
MMC vs Collinear Mass

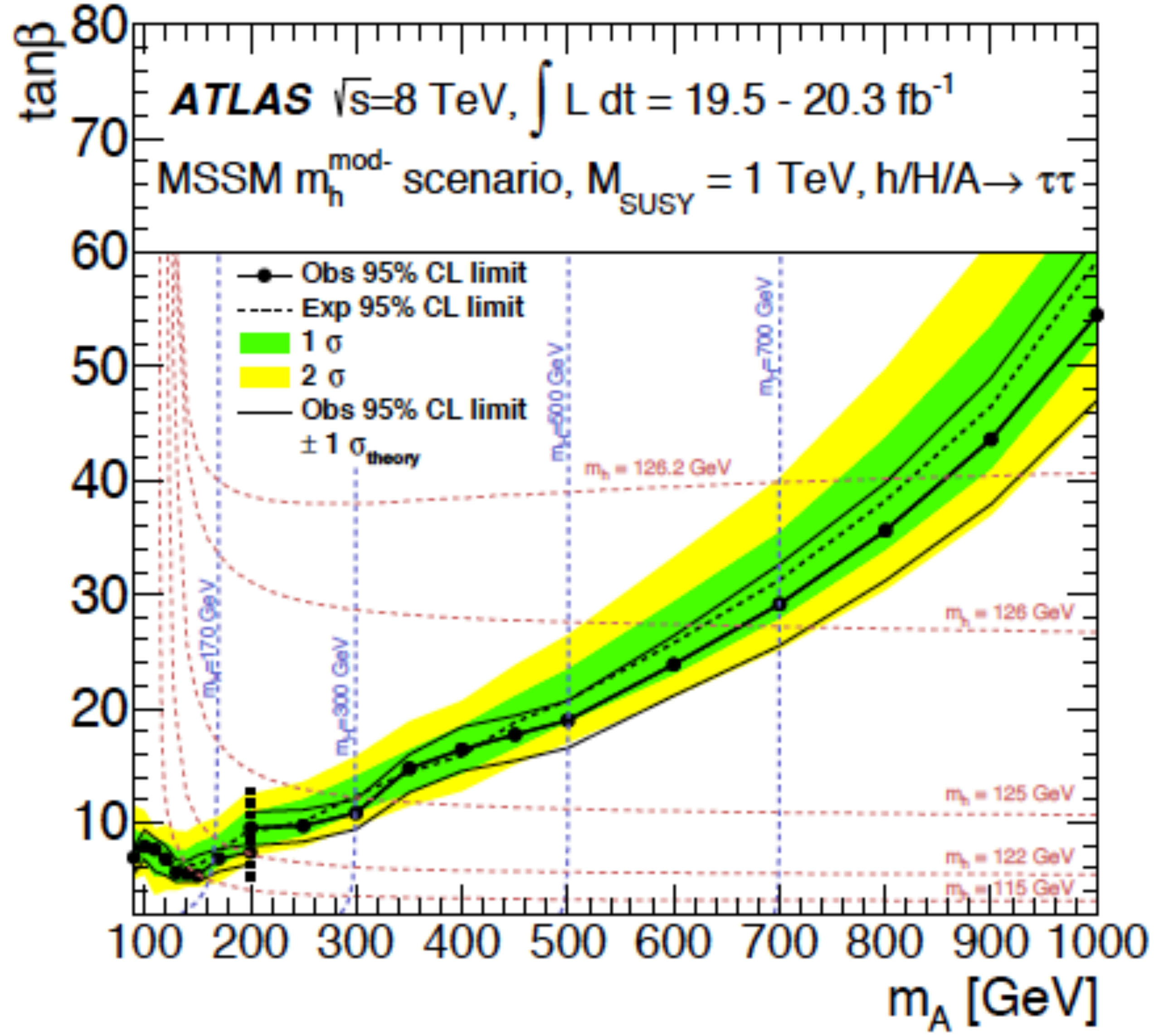


MSSM Neutral Higgs Search at 8 TeV

- Alternative benchmark scenarios

arXiv:1409.6064





MSSM Neutral Higgs Search at 7 TeV

- Combine the τ_{lep}-τ_{had}, τ_{had}-τ_{had}, τ_e-τ_μ and $\mu\mu$ channels for one exclusion limit
  - Limit with the m_h^{max} benchmark scenario
  - Also determine a σ x BR limits

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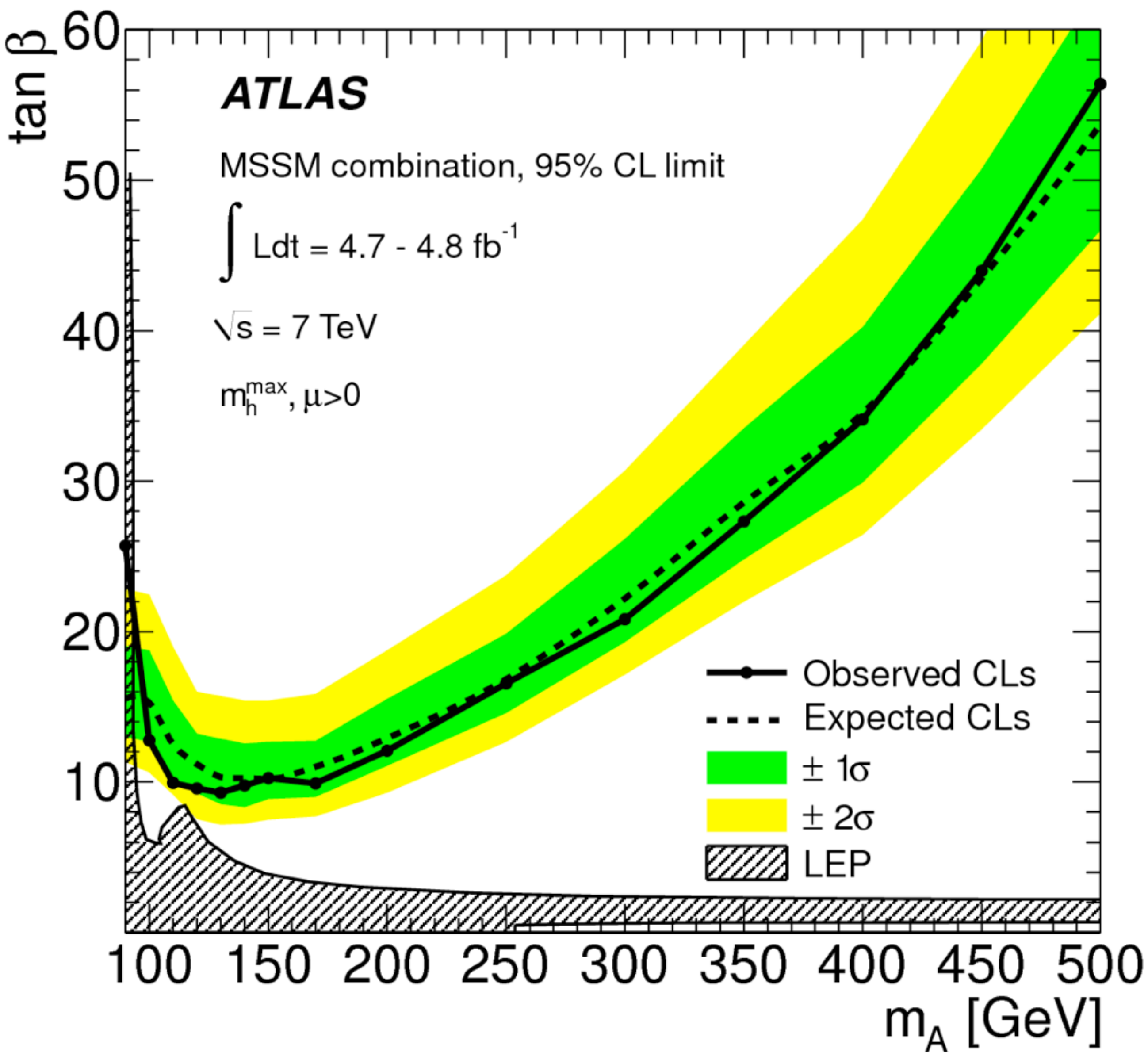
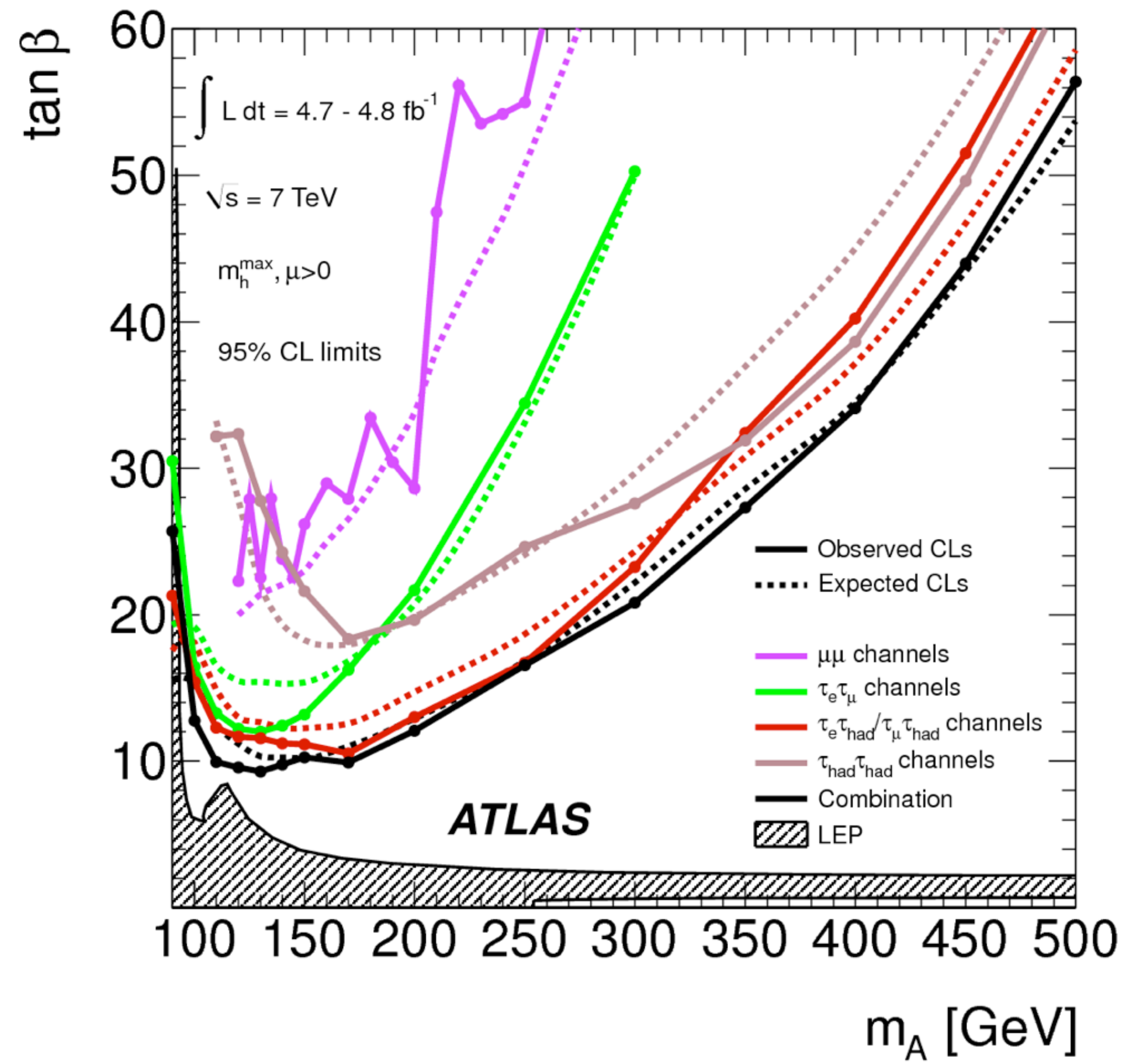




MSSM Neutral Higgs Observed Events (lep-lep)

	Tag category	Veto category
Signal ($m_A = 150$ GeV, $\tan\beta = 20$)		
$h \to \tau\tau$	8.7 ± 1.9	244 ± 11
$H \to \tau\tau$	65 ± 14	882 ± 45
$A \to \tau\tau$	71 ± 15	902 ± 48
$Z/\gamma^* \to \tau\tau$+jets	418 ± 28	54700 ± 3800
Multi-Jet	100 ± 21	4180 ± 670
$t\bar{t}$ and single top	421 ± 46	2670 ± 360
Others	25.8 ± 7.4	4010 ± 280
Total background	965 ± 59	65500 ± 3900
Data	904	65917

Table 1. Number of events observed in the $h/H/A \to \tau_e\tau_\mu$ channel and the predicted background and signal. The predicted signal event yields correspond to the parameter choice $m_A = 150$ GeV and $\tan\beta = 20$. The row labelled "Others" includes events from diboson production, $Z/\gamma^* \to ee/\mu\mu$ and W+jets production. Combined statistical and systematic uncertainties are quoted. The signal prediction does not include the uncertainty due to the cross-section calculation.

MSSM Neutral Higgs Observed Events (lep-had)

Low-mass categories

	Tag category		Veto category	
	e channel	μ channel	e channel	μ channel
Signal ($m_A = 150$ GeV, $\tan\beta = 20$)				
$h \to \tau\tau$	10.5 ± 2.8	10.5 ± 2.6	194 ± 13	192 ± 14
$H \to \tau\tau$	86 ± 26	86 ± 24	836 ± 60	822 ± 61
$A \to \tau\tau$	94 ± 29	94 ± 27	840 ± 64	825 ± 62
$Z \to \tau\tau$+jets	403 ± 39	425 ± 42	31700 ± 2800	38400 ± 3300
$Z \to \ell\ell$+jets ($\ell = e, \mu$)	72 ± 24	33 ± 14	5960 ± 920	2860 ± 510
W+jets	158 ± 44	185 ± 58	9100 ± 1300	9800 ± 1400
Multi-jet	185 ± 35	66 ± 31	11700 ± 490	3140 ± 430
$t\bar{t}$ and single top	232 ± 36	236 ± 34	533 ± 91	535 ± 98
Diboson	9.1 ± 2.3	10.0 ± 2.5	466 ± 40	468 ± 42
Total background	1059 ± 81	955 ± 86	59500 ± 3300	55200 ± 3600
Data	1067	947	60351	54776

MSSM Neutral Higgs Observed Events (lep-had)

High-mass category	
Signal ($m_A = 350$ GeV, $\tan\beta = 30$)	
$h \to \tau\tau$	5.60 ± 0.68
$H \to \tau\tau$	157 ± 13
$A \to \tau\tau$	152 ± 13
$Z \to \tau\tau$+jets	380 ± 50
$Z \to \ell\ell$+jets ($\ell = e,\ \mu$)	34.9 ± 7.3
W+jets	213 ± 40
Multi-jet	57 ± 20
$t\bar{t}$ and single top	184 ± 26
Diboson	30.1 ± 4.8
Total background	900 ± 72
Data	920

Table 2. Numbers of events observed in the $h/H/A \to \tau_{\text{lep}}\tau_{\text{had}}$ channel and the predicted background and signal. The predicted signal event yields correspond to the parameter choice $m_A = 150$ GeV, $\tan\beta = 20$ for the low-mass categories and $m_A = 350$ GeV, $\tan\beta = 30$ for the high-mass category. Combined statistical and systematic uncertainties are quoted. The signal prediction does not include the uncertainty due to the cross-section calculation.

MSSM Neutral Higgs Observed Events (had-had)

	Single-τ_{had} trigger (STT) category	$\tau_{had}\tau_{had}$ trigger (DTT) category
Signal ($m_A = 350$ GeV, $\tan\beta = 30$)		
$h \to \tau\tau$	0.042 ± 0.039	11.2 ± 4.5
$H \to \tau\tau$	95 ± 18	182 ± 27
$A \to \tau\tau$	82 ± 16	158 ± 24
Multi-jet	216 ± 25	6770 ± 430
$Z/\gamma^* \to \tau\tau$	113 ± 18	750 ± 210
$W(\to \tau\nu)$+jets	34 ± 8.1	410 ± 100
$t\bar{t}$ and single top	10.2 ± 4.4	76 ± 26
Others	0.50 ± 0.20	3.40 ± 0.80
Total background	374 ± 32	8010 ± 490
Data	373	8225

Table 3. Number of events observed in the $h/H/A \to \tau_{had}\tau_{had}$ channel and the predicted background and signal. The predicted signal event yields correspond to the parameter choice $m_A = 350$ GeV, $\tan\beta = 30$. The row labelled "Others" includes events from diboson production, $Z \to \ell\ell$ and $W \to \ell\nu$ with $\ell = e, \mu$. Combined statistical and systematic uncertainties are quoted. The signal prediction does not include the uncertainty due to the cross-section calculation.

MSSM Neutral Higgs Systematics (low-mass)

Source of uncertainty	Uncertainty on μ (%)
Lepton-to-τ_{had} fake rate	14
τ_{had} energy scale	12
Jet energy scale and resolution	11
Electron reconstruction & identification	8.1
Simulated backgrounds cross section and acceptance	7.5
Luminosity	7.4
Muon reconstruction & identification	7.2
b-jet identification	6.6
Jet-to-τ_{had} fake rate for electroweak processes ($\tau_{\text{lep}}\tau_{\text{had}}$)	6.2
Multi-jet background ($\tau_{\text{lep}}\tau_{\text{lep}}$, $\tau_{\text{lep}}\tau_{\text{had}}$)	6.1
Associated with the τ-embedded $Z \to \mu\mu$ sample	5.3
Signal acceptance	2.0
$e\mu$ trigger	1.5
τ_{had} identification	0.8

Table 4. The effect of the most important sources of uncertainty on the signal strength parameter, μ, for the signal hypothesis of $m_A = 150$ GeV, $\tan\beta = 5.7$. For this signal hypothesis only the $h/H/A \to \tau_{\text{lep}}\tau_{\text{had}}$ and $h/H/A \to \tau_e\tau_\mu$ channels are used.

MSSM Neutral Higgs Systematics (high-mass)

Source of uncertainty	Uncertainty on μ (%)
$\tau_{\rm had}$ energy scale	15
Multi-jet background ($\tau_{\rm had}\tau_{\rm had}$, $\tau_{\rm lep}\tau_{\rm had}$)	9.8
$\tau_{\rm had}$ identification	7.9
Jet-to-$\tau_{\rm had}$ fake rate for electroweak processes	7.6
$\tau_{\rm had}$ trigger	7.4
Simulated backgrounds cross section and acceptance	6.6
Signal acceptance	4.7
Luminosity	4.1
Associated with the τ-embedded $Z \rightarrow \mu\mu$ sample	1.2
Lepton identification	0.7

Table 5. The effect of the most important sources of uncertainty on the signal strength parameter, μ, for the signal hypothesis of $m_A = 350$ GeV, $\tan\beta = 14$. For this signal hypothesis only the $h/H/A \rightarrow \tau_{\rm lep}\tau_{\rm had}$ and $h/H/A \rightarrow \tau_{\rm had}\tau_{\rm had}$ channels are used.

Charged Higgs ($H^+ \rightarrow \tau\nu$) Observed Events

Sample	Low mass H^+ selection	High mass H^+ selection
True τ_{had} (embedding method)	$2900 \pm 60 \pm 500$	$3400 \pm 60 \pm 400$
Misidentified jet $\rightarrow \tau_{\text{had-vis}}$	$490 \pm 9 \pm 80$	$990 \pm 15 \pm 160$
Misidentified $e \rightarrow \tau_{\text{had-vis}}$	$15 \pm 3 \pm 6$	$20 \pm 2 \pm 9$
Misidentified $\mu \rightarrow \tau_{\text{had-vis}}$	$18 \pm 3 \pm 8$	$37 \pm 5 \pm 8$
All SM backgrounds	$3400 \pm 60 \pm 500$	$4420 \pm 70 \pm 500$
Data	3244	4474
H^+ ($m_{H^+} = 130\,\mathrm{GeV}$)	$230 \pm 10 \pm 40$	
H^+ ($m_{H^+} = 250\,\mathrm{GeV}$)		$58 \pm 1 \pm 9$

Table 2: Expected event yields after all selection criteria and comparison with $19.5\,\mathrm{fb}^{-1}$ of data. The values shown for the signal correspond to $\mathcal{B}(t \rightarrow bH^+) \times \mathcal{B}(H^+ \rightarrow \tau\nu) = 0.9\%$ for the low mass point and $\tan\beta = 50$ in the MSSM m_h^{max} scenario for the high mass point. Both statistical and systematic uncertainties are shown, in this order.

Charged Higgs ($H^+ \to \tau\nu$) Systematics

Source of uncertainty	Low mass H^+ selection	High mass H^+ selection
Muon selection	$< 1\%$	$< 1\%$
Misidentified $\tau_{\text{had-vis}}$	5.6%	5.7%
Fitting function	2.1%	1.8%
Trigger definition	$< 1\%$	$< 1\%$
Residual correlations	1.4%	3.2%
$\tau_{\text{had-vis}}$ energy scale	$< 1\%$	$< 1\%$

Table 3: Effect of systematic uncertainties on the combined trigger efficiencies for a low mass ($m_{H^+} = 130\,\text{GeV}$) and high mass ($m_{H^+} = 250\,\text{GeV}$) signal sample.

Source of uncertainty	Low mass H^+ selection	High mass H^+ selection
True τ_{had}		
Embedding parameters	3.0%	1.8%
Muon isolation	0.3%	2.3%
Parameters in normalisation	2.0%	2.0%
$\tau_{\text{had-vis}}$ identification	2.2%	2.0%
$\tau_{\text{had-vis}}$ energy scale	4.0%	3.6%
$\tau_{\text{had-vis}} + E_{\text{T}}^{\text{miss}}$ trigger	8.3%	8.3%
Jet $\to \tau_{\text{had-vis}}$		
Statistical uncertainty on p_{m}	2.0%	3.4%
Statistical uncertainty on p_{r}	0.5%	0.5%
Jet composition	1.1%	1.9%
$\tau_{\text{had-vis}}$ identification	0.8%	0.6%
e/μ contamination	0.5%	0.7%

Table 4: Dominant systematic uncertainties on the data-driven background estimates. The shift in event yield is given relative to the total background.

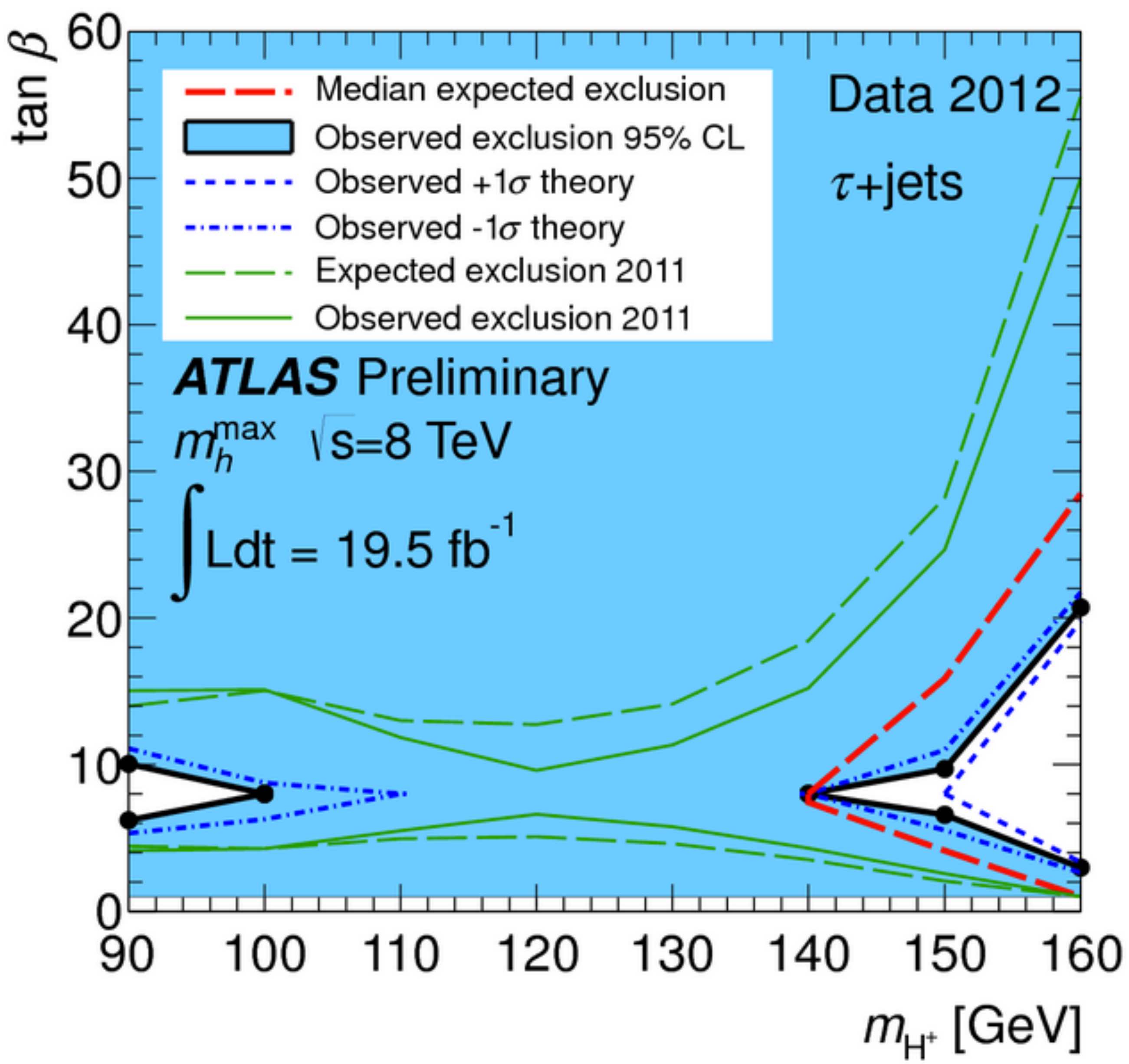
Charged Higgs ($H^+ \rightarrow \tau\nu$) Systematics

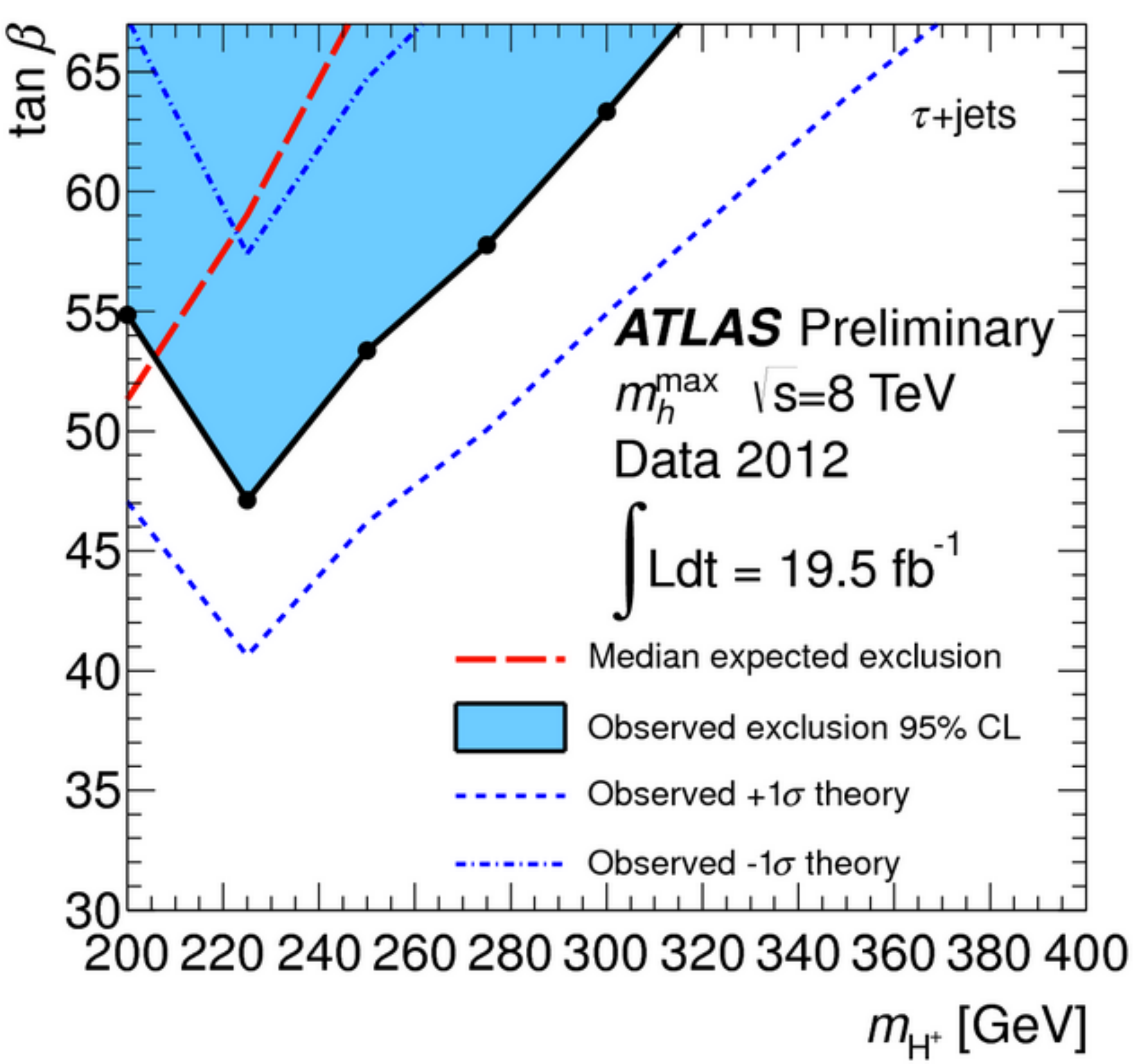
Source of uncertainty	Normalisation uncertainty
Low mass H^+	
Generator model ($b\bar{b}W^-H^+$)	9%
Generator model ($b\bar{b}W^+W^-$)	9%
$t\bar{t}$ cross section	6%
Jet production rate (SM and H^+) (QCD scale)	11%
High mass H^+	
Generator model (H^+)	2–9%
Generator model (SM)	8%
$t\bar{t}$ cross section	6%
Jet production rate (H^+) (QCD scale)	1–2%
Jet production rate (SM) (QCD scale)	11%
H^+ production (4FS vs 5FS)	3–5%

Table 5: Systematic uncertainties arising from $t\bar{t}$ and signal generator modelling, and from the jet production rate. The uncertainties are shown for the $t\bar{t}$ background and the charged Higgs boson signal, for the low and high mass charged Higgs boson selections separately.

Charged Higgs limits in the MSSM (old)

ATLAS-CONF-2013-090





Mass Reconstruction with τ leptons

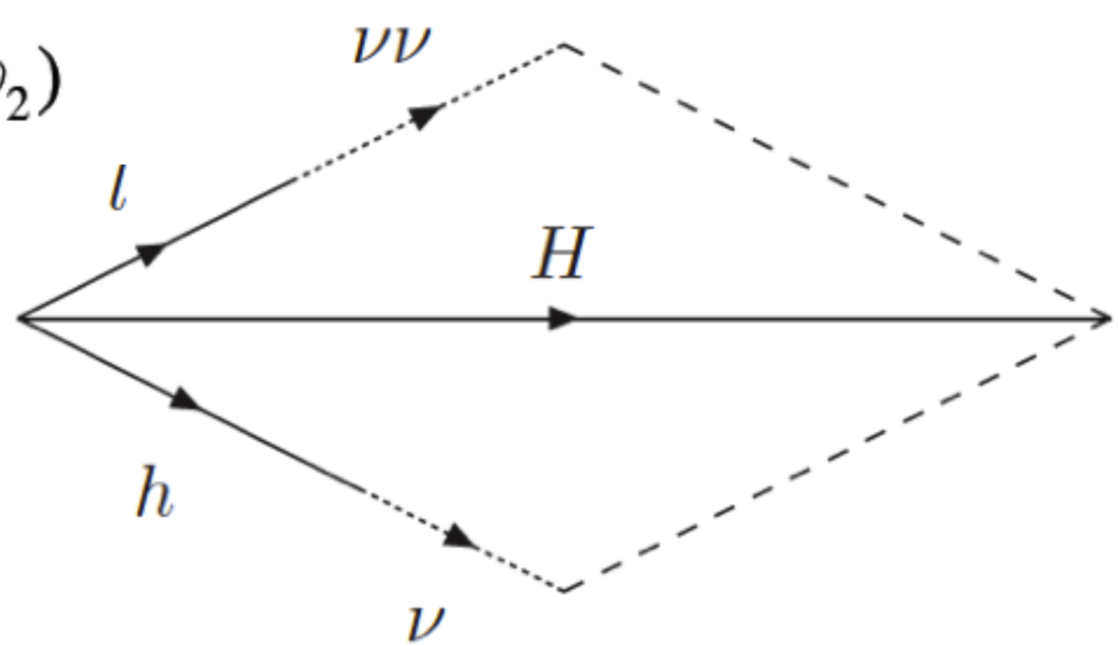
- Visible mass:
  - Invariant mass of the visible τ decay products
- Effective mass
  - Invariant mass of the visible τ decay products + MET
- Collinear mass:
  - Assume that neutrinos are emitted parallel to the visible τ decay products' direction ⇒ 2 equations and 2 unknowns

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

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

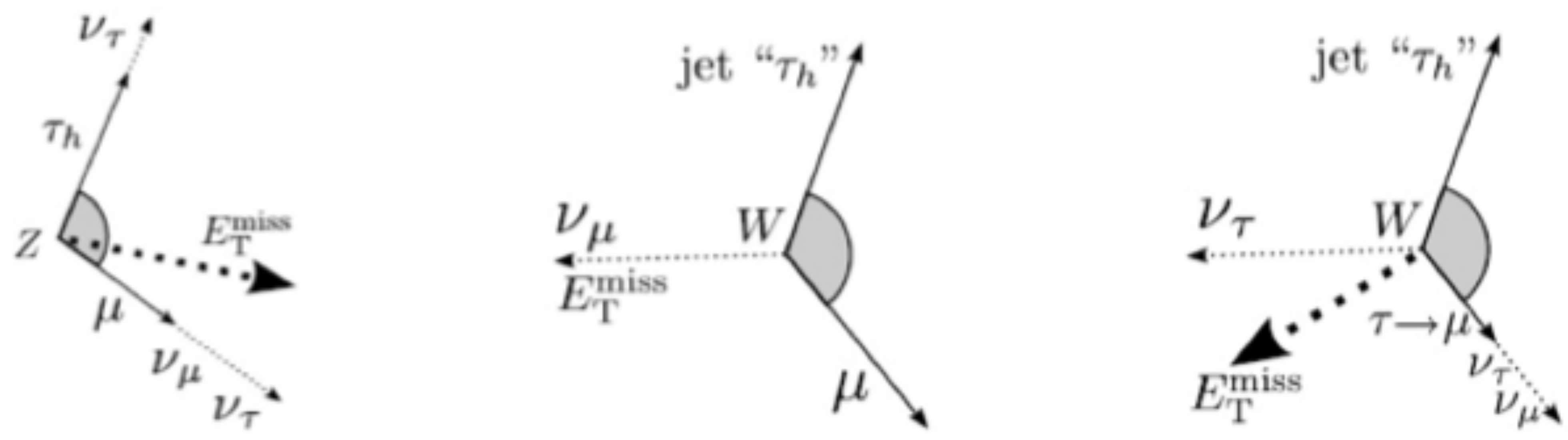
$$m_{collinear} = \frac{m_{vis}}{x_1 x_2}$$

$x_{1,2}$ are the momentum fractions carried away by the visible τ products



SumCosDeltaPhi

SumCosDeltaPhi:



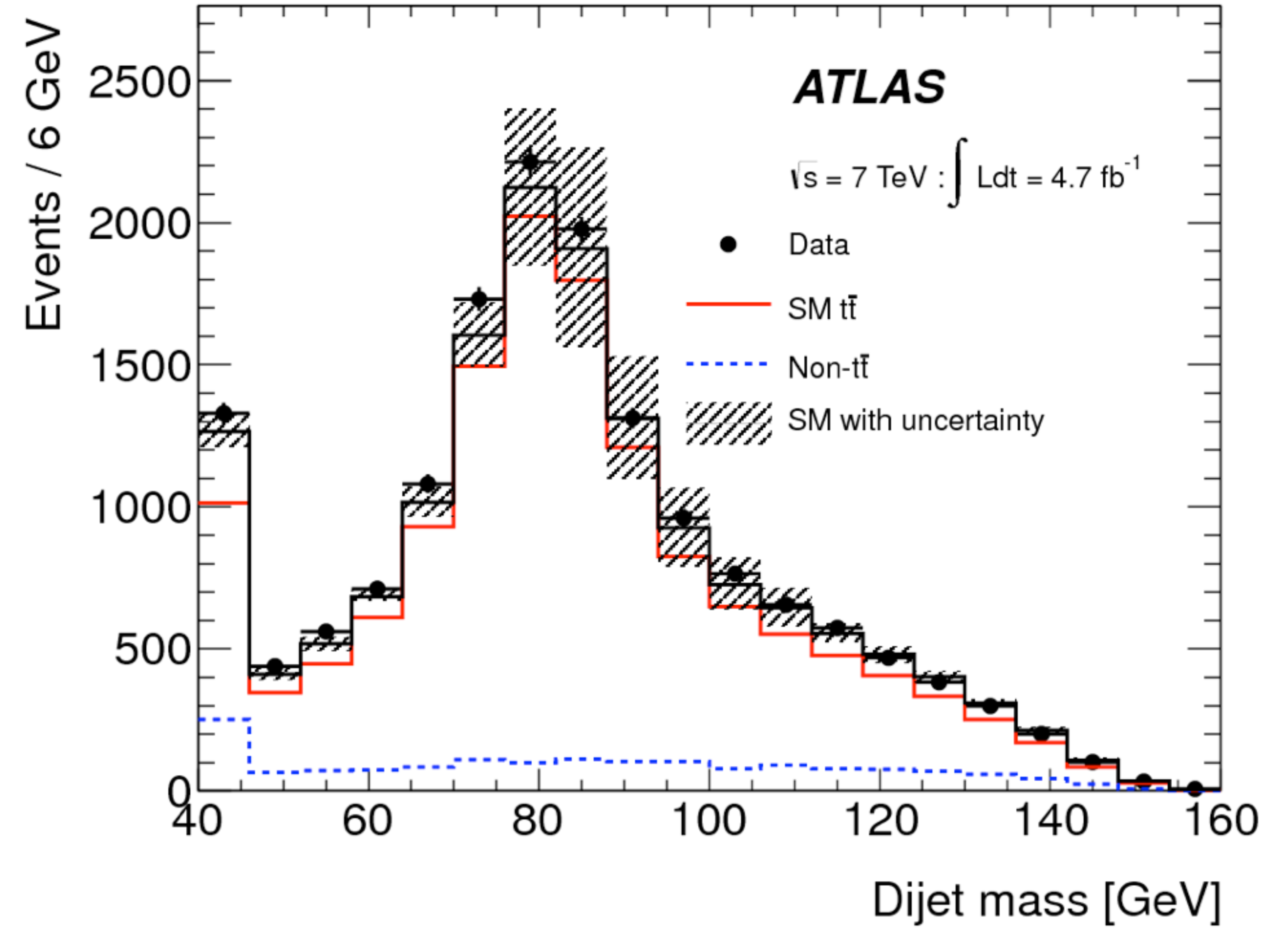
(a) $Z \to \tau\tau \to \mu\tau_h$ (b) $W \to \mu\nu$ (c) $W \to \tau\nu \to \mu\nu\nu\nu$

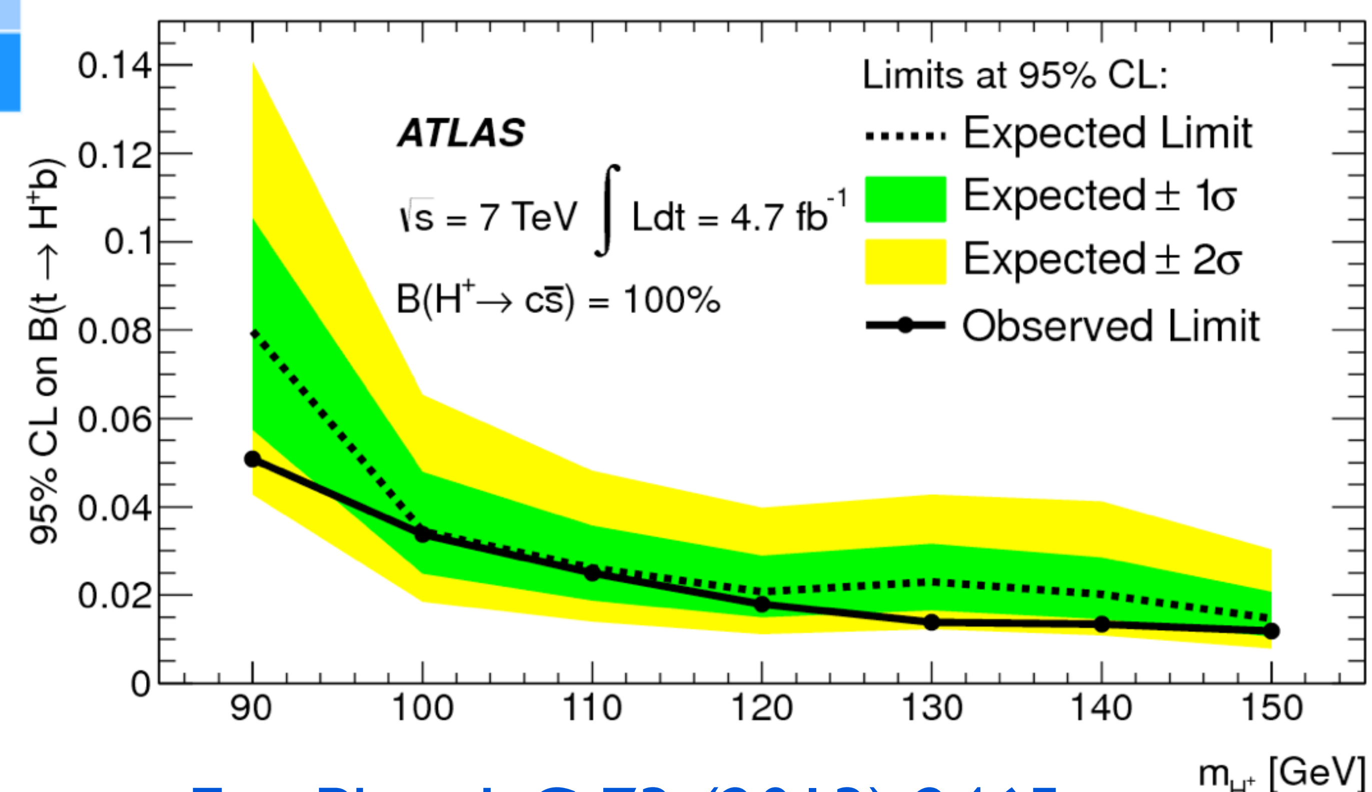
Charged Higgs: $H^+ \rightarrow c\bar{s}$ with 7 TeV data

- Light Higgs: $m(H^{\pm}) < m_t$
- Final state allows for full reconstruction of the H^+ candidates
- Examine the di-jet spectrum and look for a second peak

$tt \rightarrow bW\ bH^+ \rightarrow b\ (e/mu)\ \nu\ \ b\ cs$
1 isolated e/μ, $p_T > 20$ GeV
At least 4 jets, pT>20 GeV; one b-Tagged jet
MET/MT cuts: MT>25 GeV (e); MT+MET>60GeV

$$\chi^2 = \sum_{i=l,4jets} \frac{(p_T^{i,fit} - p_T^{i,meas})^2}{\sigma_i^2} + \sum_{j=x,y} \frac{(p_j^{UE,fit} - p_j^{UE,meas})^2}{\sigma_{UE}^2} + \sum_{k=bjj,bl\nu} \frac{(M_k - M_{top})^2}{\sigma_{top}^2}.$$





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Charged Higgs ($H^+ \to cs$) Events and Systematics

Channel	Muon	Electron
Data	193	130
SM $t\bar{t} \to W^+bW^-\bar{b}$	156^{+24}_{-29}	106^{+16}_{-20}
W/Z + jets	17 ± 6	9 ± 3
Single top	7 ± 1	5 ± 1
Diboson	0.30 ± 0.02	0.20 ± 0.02
QCD multijet	11 ± 4	6 ± 3
Total Expected (SM)	191^{+26}_{-30}	127^{+17}_{-21}
$\mathcal{B}(t \to H^+b) = 10\%$:		
$t\bar{t} \to H^+bW^-\bar{b}$	20^{+3}_{-4}	14^{+2}_{-2}
$t\bar{t} \to W^+bW^-\bar{b}$	127^{+19}_{-23}	86^{+13}_{-16}
Total Expected ($\mathcal{B} = 10\%$)	181^{+21}_{-25}	120^{+14}_{-17}

Systematic Source	
Jet energy scale	+11, −13% (SM $t\bar{t}$) +9, −12% (signal)
b-Jet energy scale	±0.5%
Jet energy resolution	±1%
b-tagging efficiency	+4, −9%
MC generator	±4%
Parton shower	±3%
ISR/FSR	±1%
Additional Interactions	±4%
Luminosity	±3.4%
Electron reconstruction	±1.6%
Muon reconstruction	±0.2%
Electron trigger	±0.2%
Muon trigger	±0.5%
$t\bar{t}$ cross section	+7, −9%
t quark mass	±7%

MSSM Higgs Searches ($\phi \rightarrow \mu^+\mu^-$)

- MSSM $\phi \rightarrow \mu^+\mu^-$ channels
- Small BR but very clean final state
- Main event selection:
  - Lowest unprescaled single muon trigger
  - 2 isolated muons of opposite charge with p_T>20 GeV, $|\eta|$<2.5
  - MET < 40 GeV
- Again, separation into b-tagged and b-vetoed categories
- Total background from sideband fits to di-muon invariant mass spectrum

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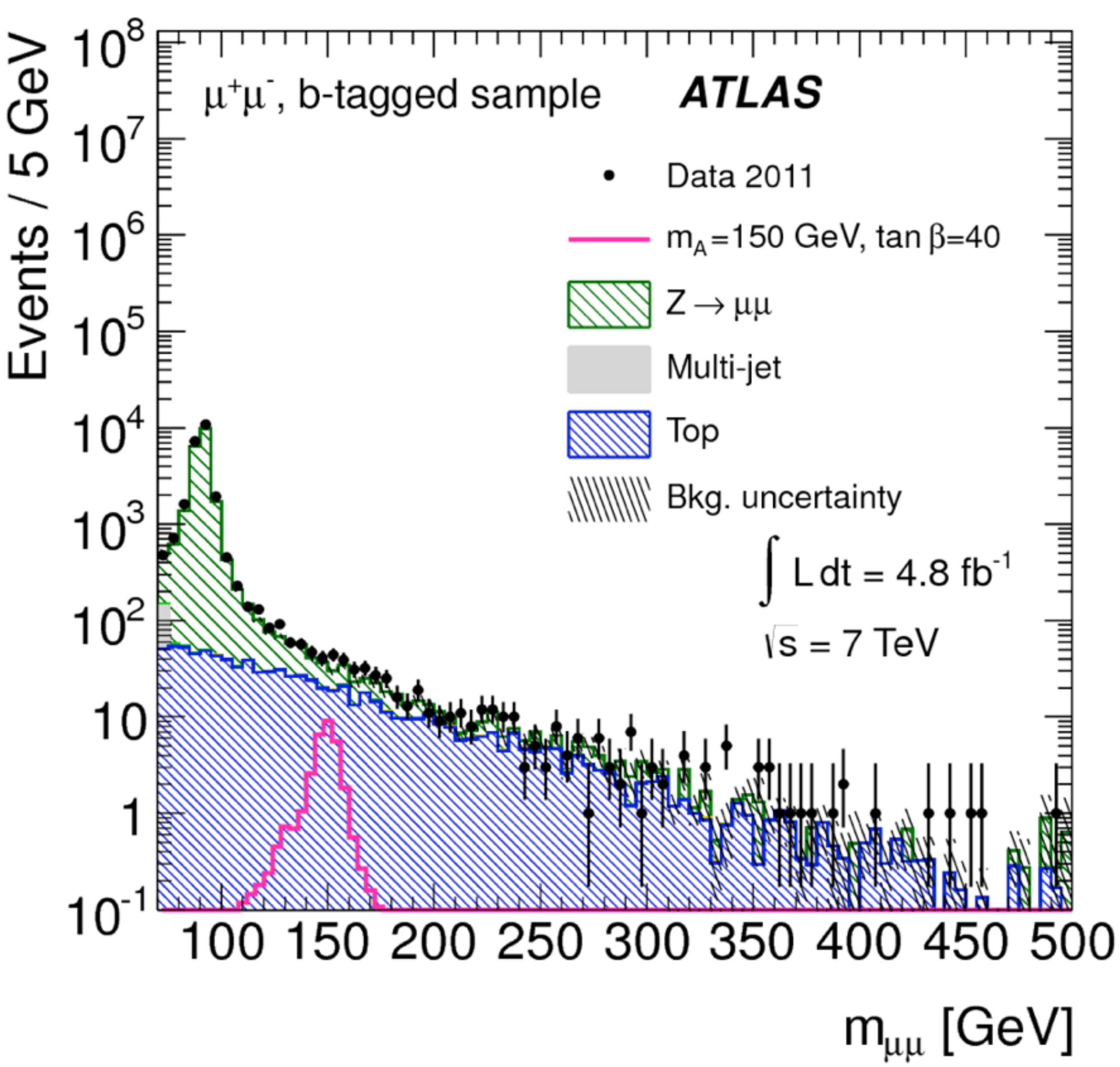

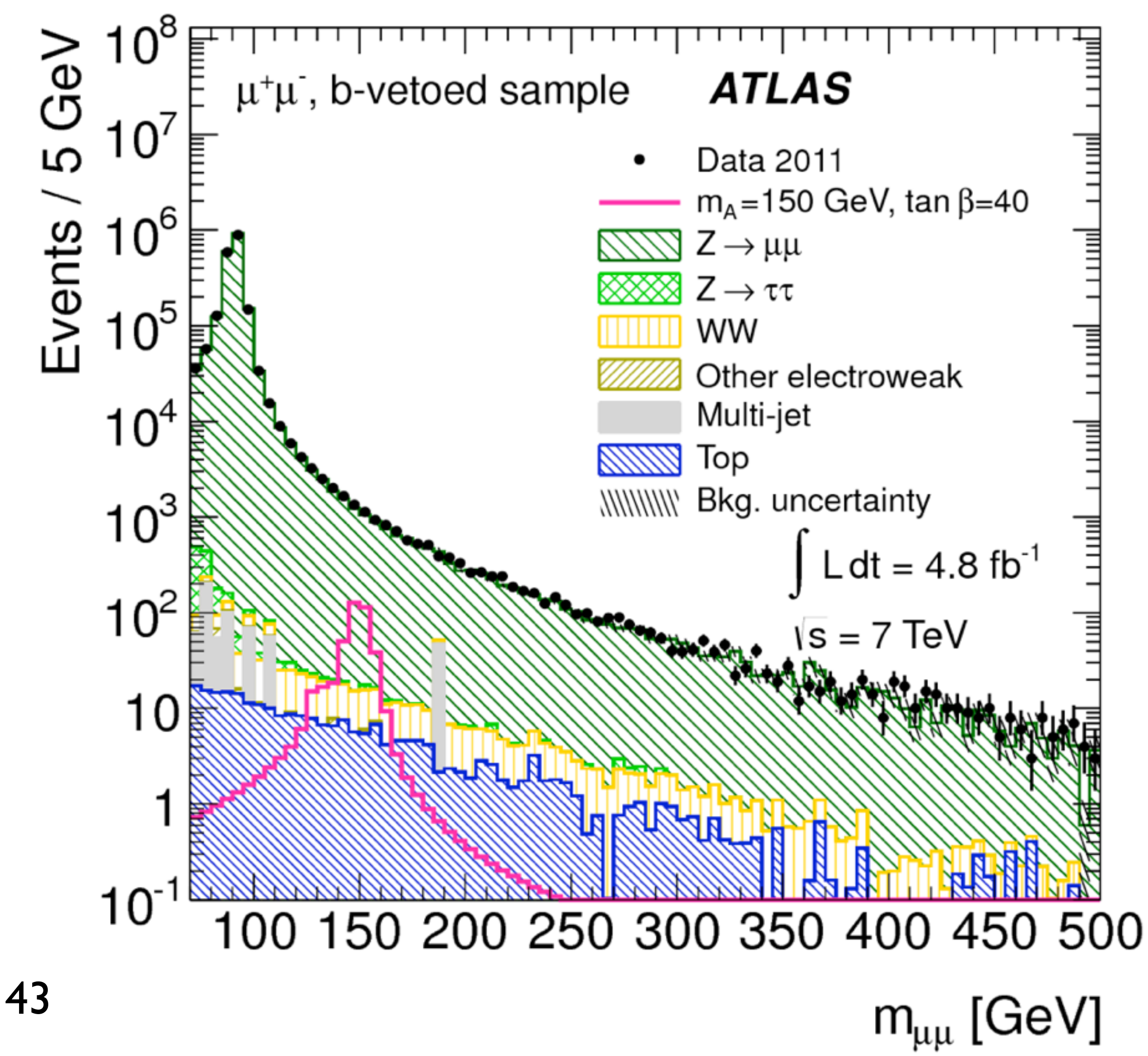

Current τ identification variables in BDT and LLH

Variable	LLH tau ID		BDT tau ID		e-veto	muon veto
	1-prong	3-prong	1-prong	3-prong	1-prong	1-prong
$f_{\mathrm{core}}^{\mathrm{corr}}$	•	•	•	•	•	
$f_{\mathrm{track}}^{\mathrm{corr}}$	•	•	•	•	•	
f_{track}					•	•
R_{track}	•	•	•	•	•	
$S_{\mathrm{lead\ track}}$	•		•			
$N_{\mathrm{track}}^{\mathrm{iso}}$	•		•			
ΔR_{max}		•		•		
$S_{\mathrm{T}}^{\mathrm{flight}}$		•		•		
m_{tracks}		•		•		
f_{EM}					•	•
f_{HT}					•	
$E_{\mathrm{T,max}}^{\mathrm{strip}}$					•	
$f_{\mathrm{HCAL}}^{\mathrm{leadtrk}}$					•	
$f_{\mathrm{ECAL}}^{\mathrm{leadtrk}}$					•	
f_{PS}					•	
$f_{\mathrm{EM}}^{\pi^\pm}$					•	
f_{iso}					•	
R_{Had}					•	

Table 1: Comparison of variables used by the $\tau_{\mathrm{had\text{-}vis}}$ identification algorithms: projective likelihood identification (LLH tau ID), boosted decision tree identification (BDT tau ID), boosted decision tree based electron veto (e-veto) and cut based muon veto (muon veto). Variable definitions can be found in Appendix A.

Current τ identification variables

1. Core energy fraction*

$$f_{\text{core}} = \frac{\sum_{\{\Delta R<0.1\}} E_{\text{T}}^{\text{EM}}(\text{cell})}{\sum_{\{\Delta R<0.2\}} E_{\text{T}}^{\text{EM}}(\text{cell})}$$

2. Leading track momentum fraction*

3. Track radius $R_{\text{track}} = \frac{\sum_{\{\Delta R<0.4\}} p_{\text{T}}(\text{track})\, \Delta R(\text{track, jet})}{\sum_{\{\Delta R<0.4\}} p_{\text{T}}(\text{track})}$

4. Number of isolation tracks $N_{\text{trk}}^{0.2<\Delta R<0.4}$

5. Leading track impact parameter significance $S_{\text{lead track}} = \frac{d_0}{\sigma_{d_0}}$

6. Transverse flight path significance $S_{\text{T}}^{\text{flight}} = \frac{L_{\text{T}}^{\text{flight}}}{\sigma_{L_{\text{T}}^{\text{flight}}}}$

7. Mass of track system

8. Maximum ΔR between jet-axis and core tracks

*has pile-up correction term linear in N(vertex)