Search for a high mass neutral Higgs boson in fermion final states with the ATLAS detector

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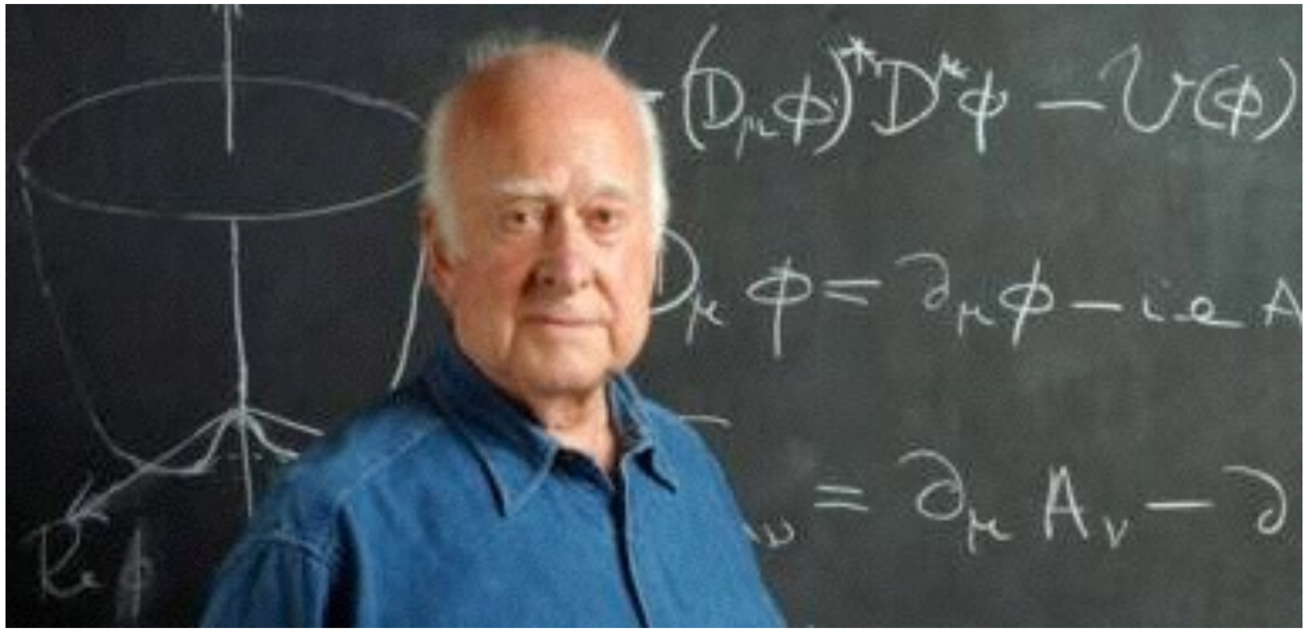
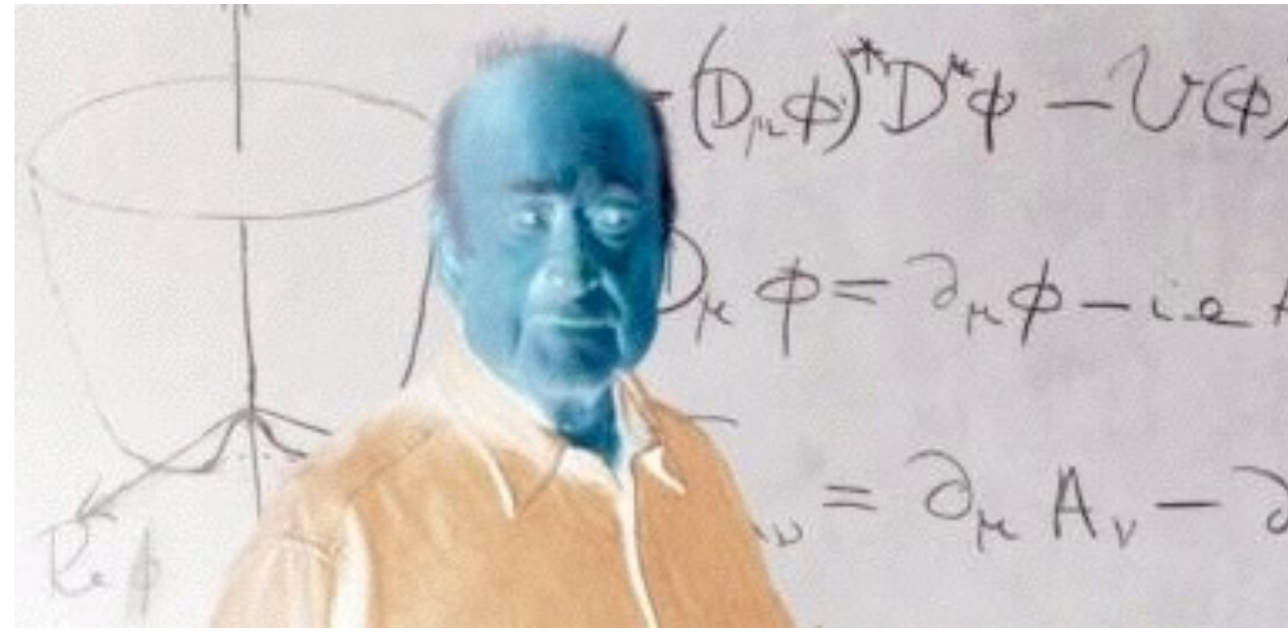
If the (light) Higgs mass is ~125 GeV, what next?



Standard Model Higgs



Beyond the SM Higgs

- Suppose that this is not the Standard Model Higgs… just one of several Higgs bosons?
  - More complicated Higgs sector? ⇒ 2HDM, MSSM, Doubly-charged Higgs, Composite
  - Light scalar Higgs? ⇒ NMSSM
- Searching for additional Higgs bosons at a higher mass (using fermions) is the focus of this talk
- Please see the other low- and high-mass Higgs search talks from ATLAS at ICHEP-2016:
  - Search for a high mass diphoton resonance (Bruno Lenzi; "Joint BSM & Higgs", Friday at 09:00)
  - Search for di-Higgs production (Tulin Varol; "Higgs Physics: 4", Friday at 11:50)
  - Search for high mass Higgs bosons (Karsten Koeneke; "Higgs Physics: 4", Friday at 13:10)
  - Search for the decay of the Higgs boson into two nMSSM pseudo-scalar particles (Lidija Zivkovic; "Higgs Physics: 5", Friday at 15:45)
  - Search for a high mass $Z\gamma$ resonance (Giovanni Marchiori; "Higgs Physics: 6", Friday at 17:50)
  - Charged Higgs boson searches (Carl Gwilliam; "Higgs Physics: 7", Saturday at 09:15)

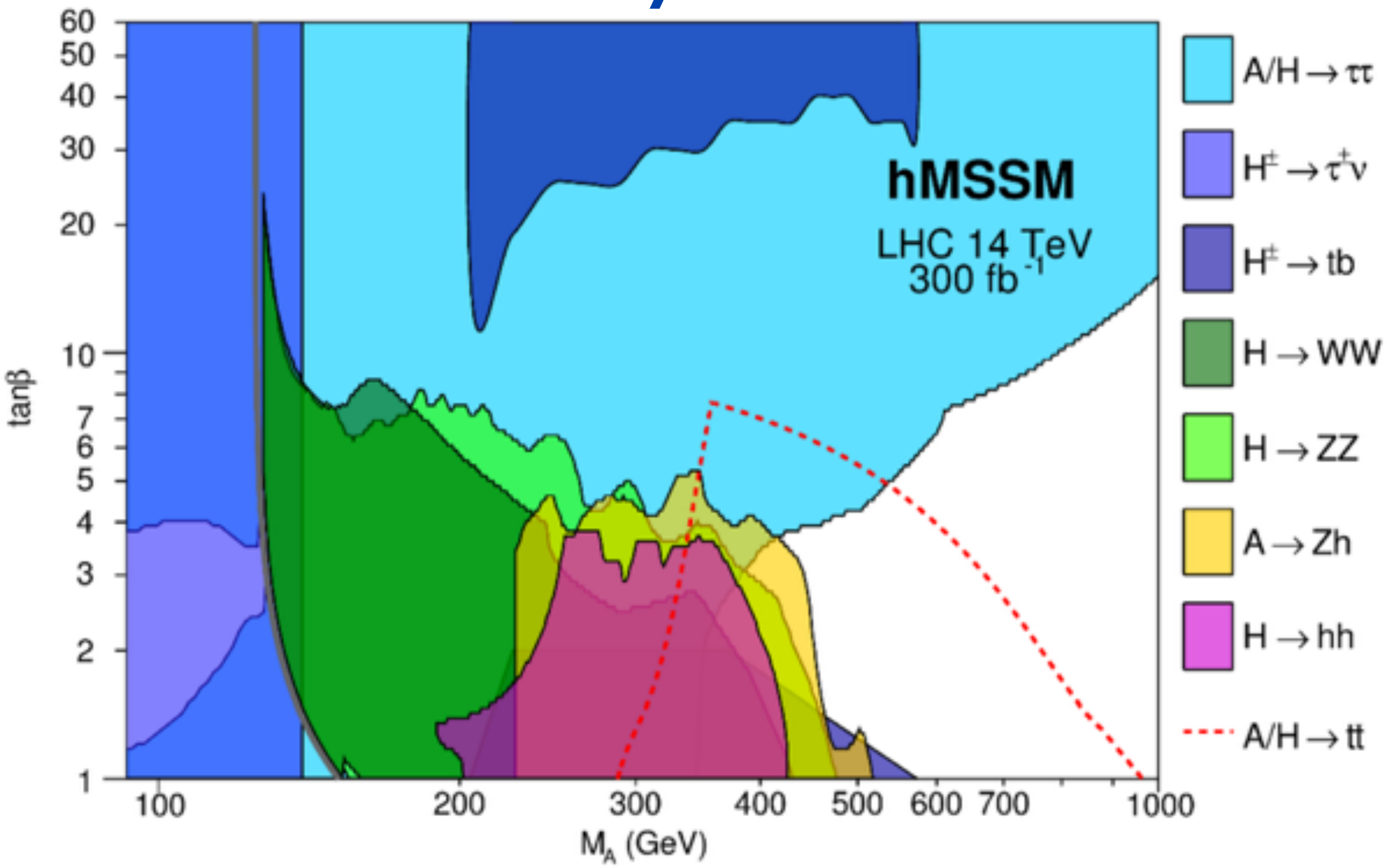
MSSM Higgs Sector and a 125 GeV Higgs

- The MSSM (h, A, H, $H^{\pm}$) is compatible with a 125 GeV Higgs… for example:
  - hMSSM scenario: the measured value of 125 GeV can be used to predict masses and decay branching ratios of the other Higgs bosons
  - m_h^{mod+} scenario: the lightest CP-even Higgs is assigned to be the 125 GeV boson

- We have two new ATLAS high-mass neutral Higgs searches using fermions to show you…
  - A/H to ττ using 13.3 fb^{-1} of 13 TeV pp collision data ATLAS-CONF-2016-085
  - A/H to ttbar using 20.3 fb^{-1} of 8 TeV pp collision data ATLAS-CONF-2016-073

NEW!

Theory projections for 2σ sensitivity are shown

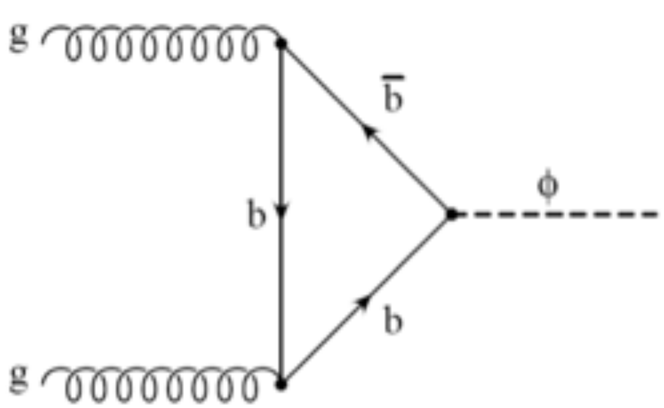


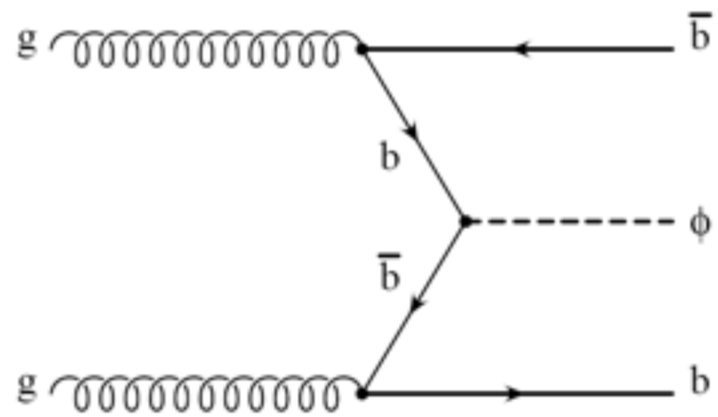
A/H to ττ and A/H to ttbar are each very important channels at mid- to high-m_A

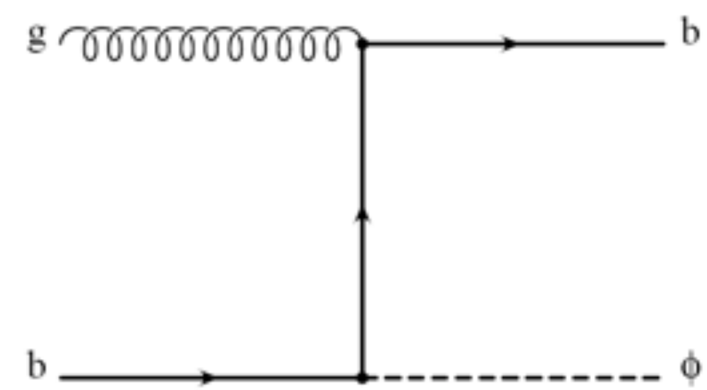
Djouadi, A., Maiani, L., Polosa, A. et al. JHEP 06 (2015) 168

MSSM Higgs Search ($A/H \to \tau^+\tau^-$)

- New ATLAS MSSM neutral Higgs search for ICHEP uses 13.3 fb^{-1} of 13 TeV data
  - 3.2 fb^{-1} from 2015 and 10.1 fb^{-1} from 2016
  - Improvement on the limits from the 2015 result submitted to EPJC: arXiv:1608.00890
- Can use different categories to target main production mechanisms
  - "no b-tag" targets gluon-fusion (dominant mode at small $\tan\beta$)
  - "b-tag" targets b-associated production (dominant mode at large $\tan\beta$)







- Can also separate based on the τ lepton decay mode (here lepton-hadron or hadron-hadron)
  - The addition of a high-MET trigger category in lep-had is new for the 2016 analysis
  - So in total, there are 5 categories considered by the analysis
- Monte Carlo samples used:
  - A/H to $\tau\tau$ signal: Powheg+Pythia8 (ggH) and aMC@NLO + Pythia8 (bbH)
  - Backgrounds:
    - Powheg+Pythia8 (W+jets in lep-had, Z+jets and top)
    - Sherpa (W+jets in had-had and dibosons)

Event Selection for the 5 Categories ($A/H \rightarrow \tau^+\tau^-$)

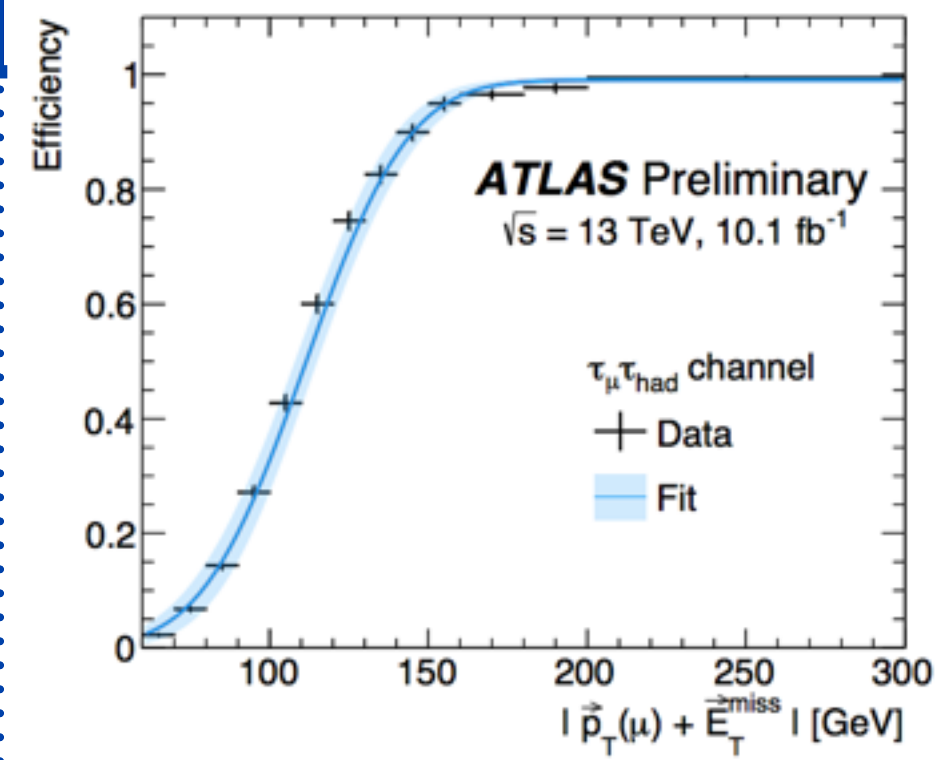
lep-had b-veto	lep-had b-tagged	lep-had high-MET

- For the lep-had analysis:
  - Single lepton triggers
  - Single hadronic tau (55%) with p_T >25 GeV
  - Single isolated electron or muon with p_T >30 GeV
  - Opposite charge
  - Veto events with an additional lepton
  - $\Delta\phi$(tau, e/mu) > 2.4
  - M_T(e/mu, MET) < 40 GeV $m_T(a,b) = \sqrt{2p_T(a)p_T(b)[1-\cos\Delta\phi(a,b)]}$
  - The e-had channel has an m_{vis} < 80 GeV and >110 GeV requirement
  - $N_{b\text{-jets}}$ = 0 (b-veto)
  - $N_{b\text{-jets}} \geq 1$ (b-tag; 77%)

- MET trigger for high-MET category (events with MET > 150 GeV)
- This category introduced due to loss of efficiency for single lepton triggers

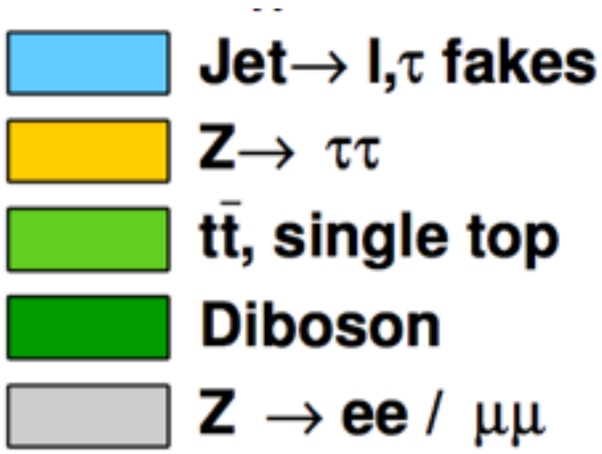
had-had b-veto	had-had b-tagged

- For the had-had analysis:
  - Single tau trigger with threshold of 80 GeV (or 125 GeV; depends on run period)
  - Leading tau (55%) with p_T >110 GeV (or p_T > 140 GeV with the 125 GeV trigger)
  - Second tau (60%) with p_T > 55 GeV (or 65 GeV for b-tagged category)
  - Opposite charge requirement
  - Veto events with a lepton
  - $\Delta\phi(tau_1, tau_2)$ > 2.7
  - $N_{b\text{-jets}}$ = 0 (b-veto)
  - $N_{b\text{-jets}} \geq 1$ (b-tag; 70%)



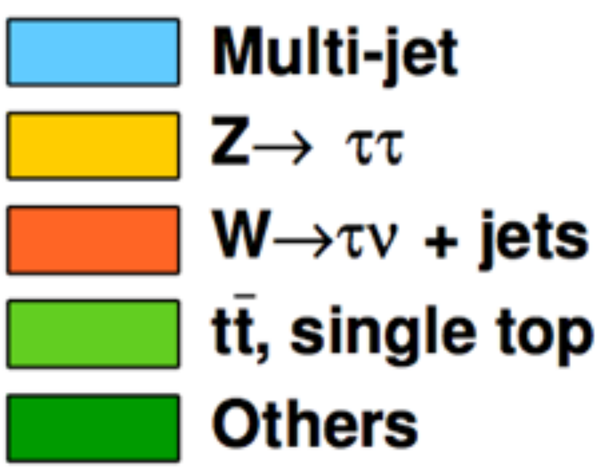
Background Estimation (A/H→$\tau^+\tau^-$)

lepton-hadron final state



- Jets faking leptons (e,μ) and taus are not well modeled in Monte Carlo
  - Separate fake factors are derived from data control regions for W+jets/top and QCD
  - These fake factors are parameterized by tau p_T and number of tracks
  - The fake factors are combined by using a data-driven estimate for the multi-jets fraction taken from the anti-tau ID region (otherwise same as signal region)
  - The combined fake factors are obtained as a function of e/μ, category and hadronic tau p_T

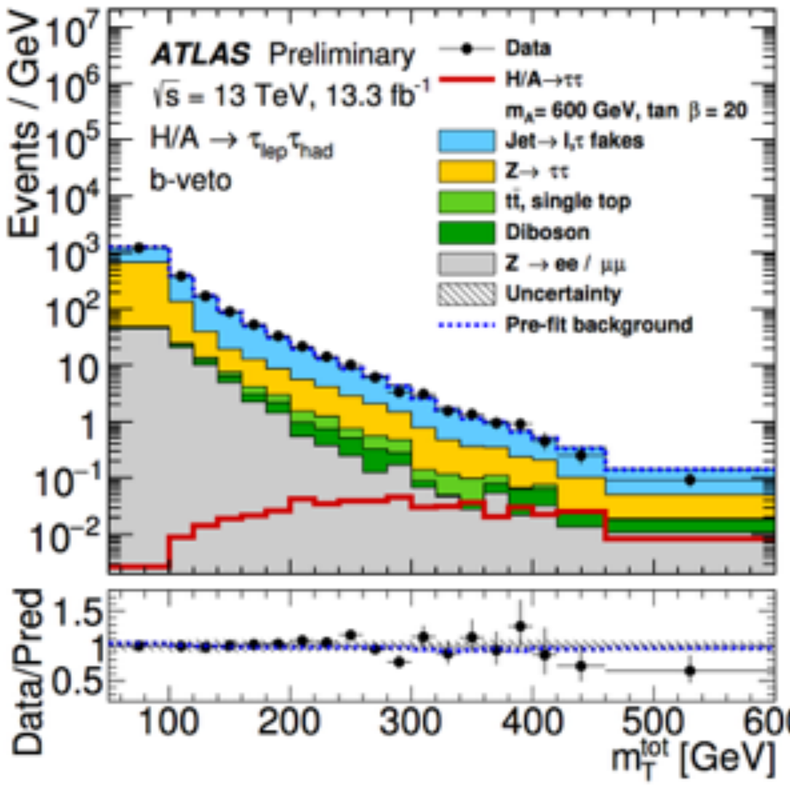
hadron-hadron final state



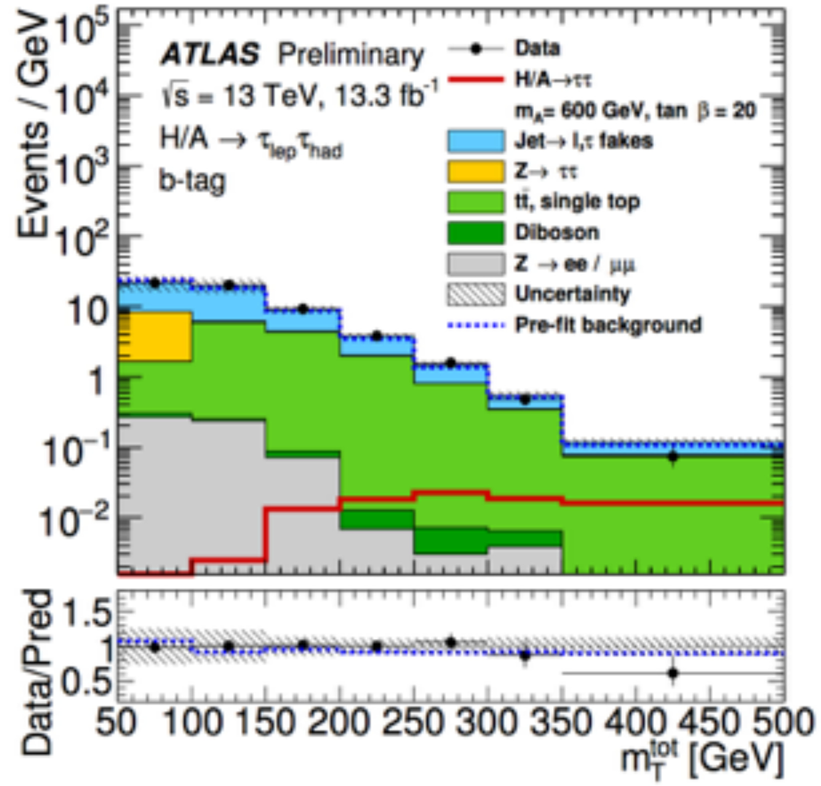
- Multi-jet backgrounds faking taus are not well modeled in Monte Carlo
  - A fake factor is derived from data control regions, and then applied to the anti-ID regions to obtain estimates for the signal regions
  - This fake factor is parameterized by tau p_T and number of tracks
- For W-jets and top backgrounds, different dedicated fake-rate corrections to MC are used
  - These corrections to MC are estimated from data

Post-fit Plots for the 5 Categories ($A/H \rightarrow \tau^+\tau^-$)

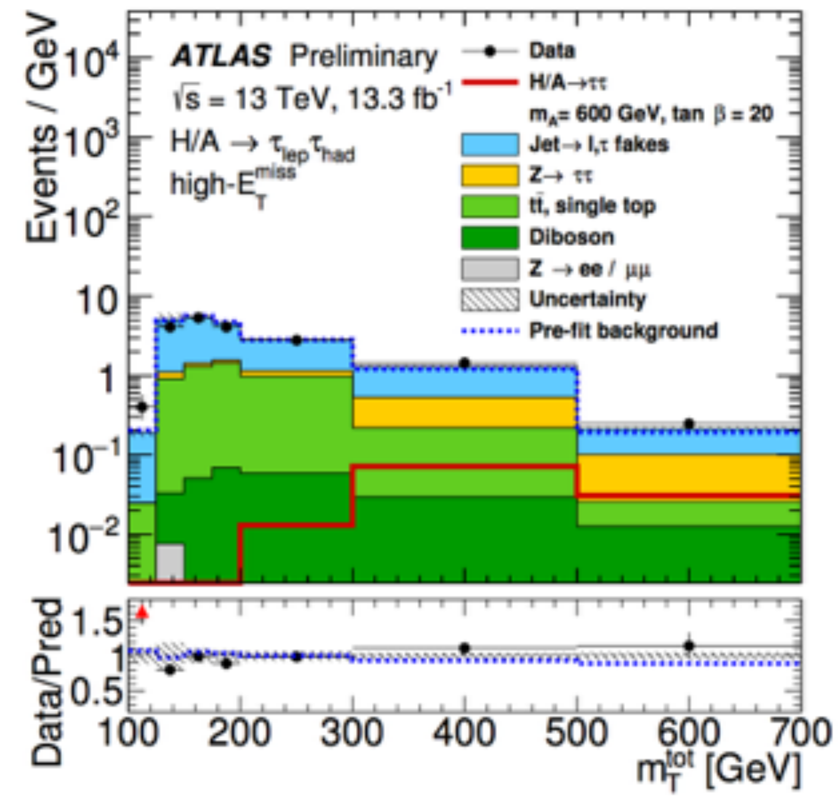
lep-had b-veto



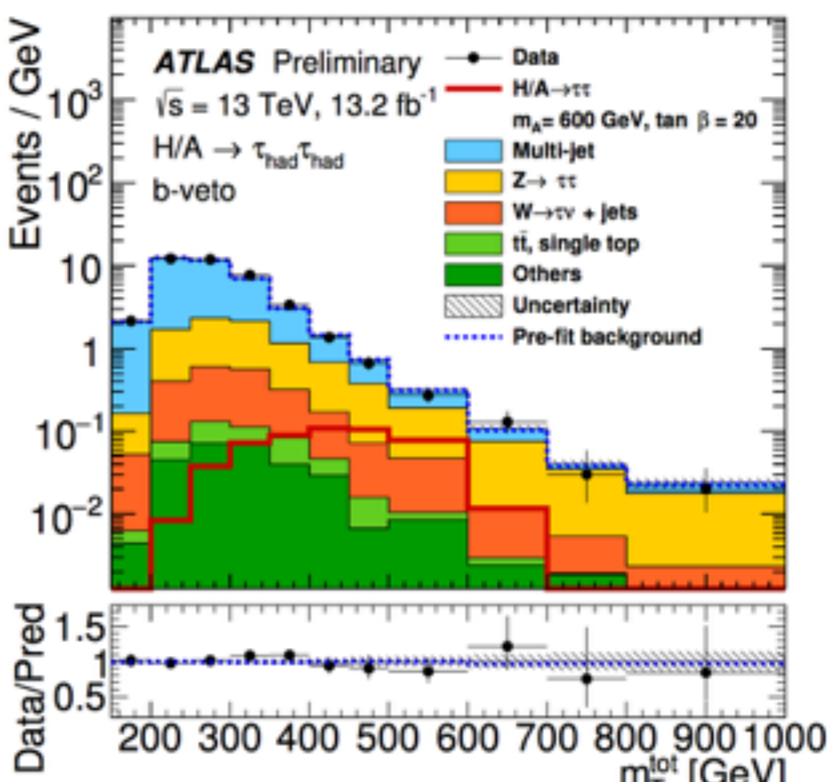
lep-had b-tagged



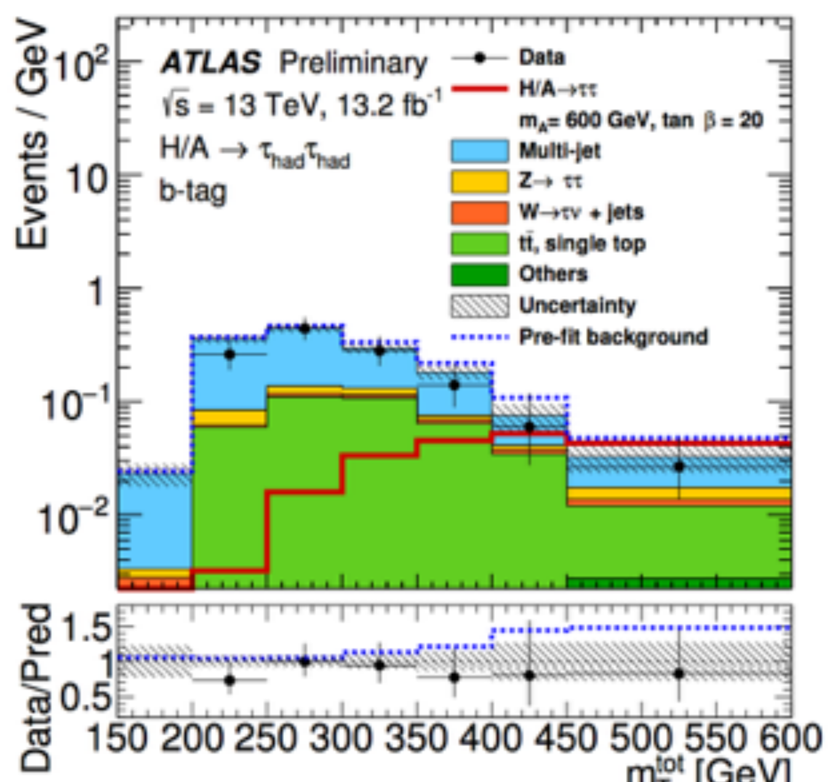
lep-had high-MET



had-had b-veto



had-had b-tagged



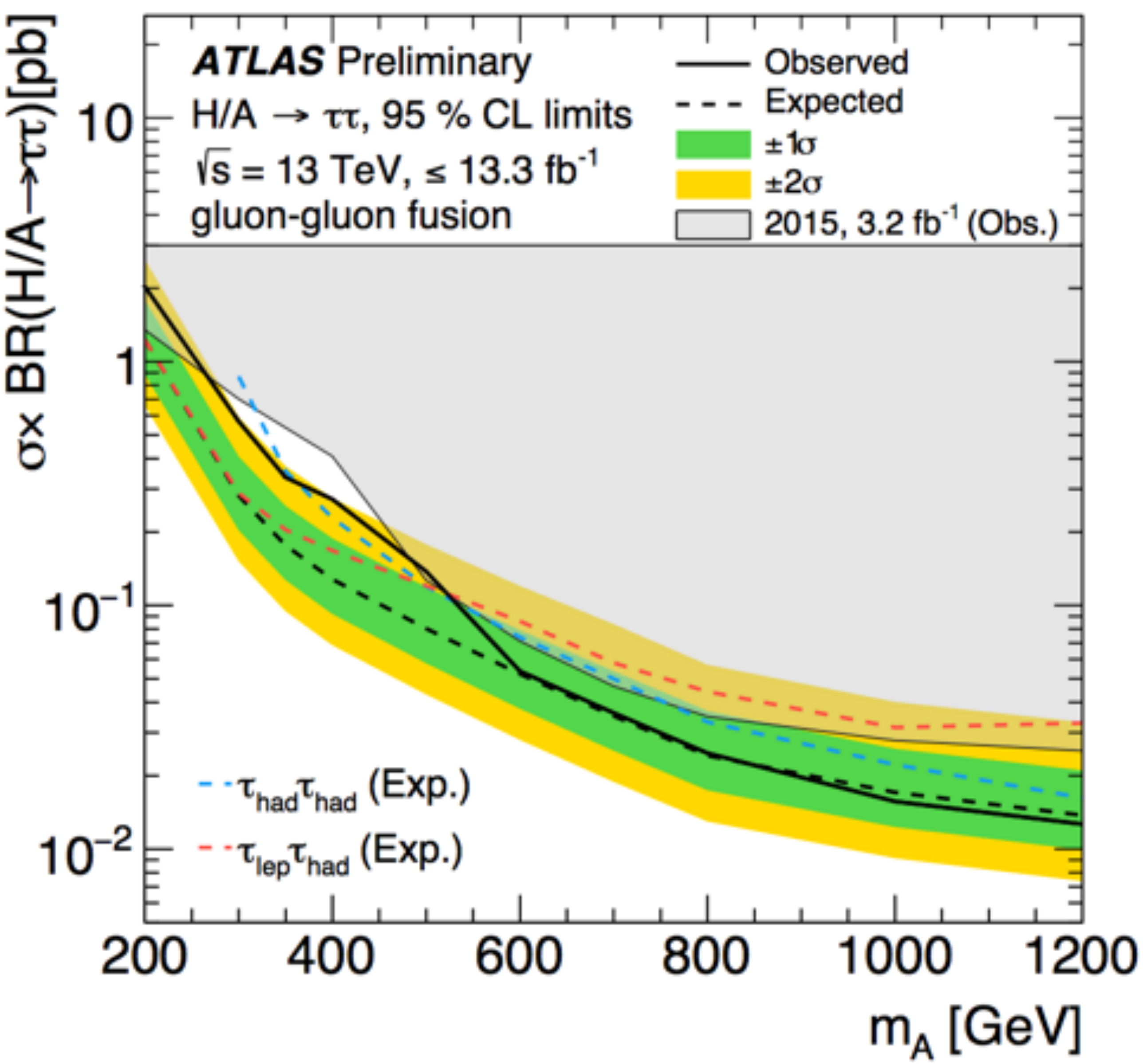
- Discriminant used is the m_T^{tot} variable, as it offers good separation of signal from backgrounds due to fake τs

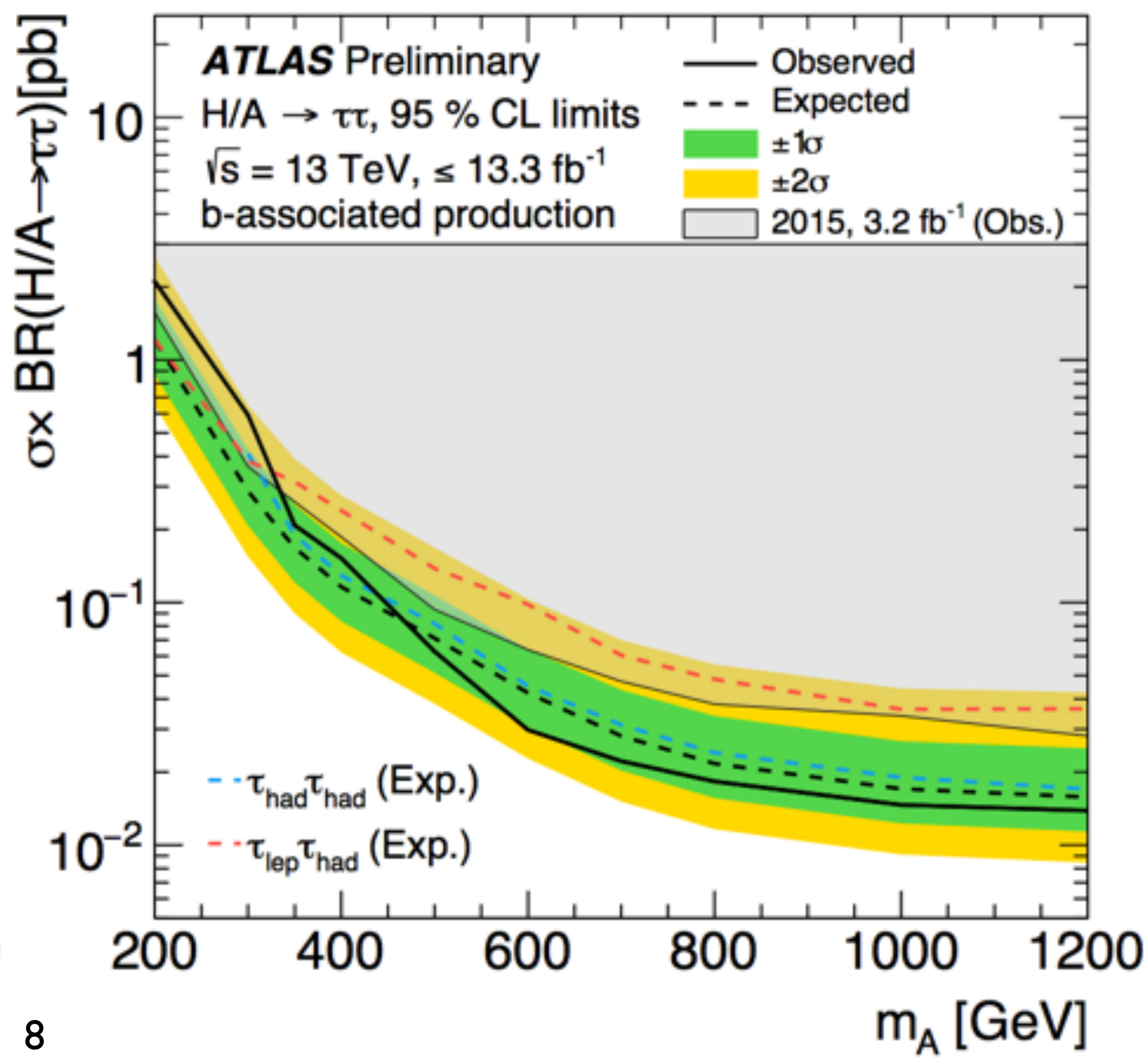
$$m_T^{tot} = \sqrt{m_T^2(E_T^{miss}, \tau_1) + m_T^2(E_T^{miss}, \tau_2) + m_T^2(\tau_1, \tau_2)}.$$

$$m_T(a, b) = \sqrt{2 p_T(a) p_T(b)[1 - \cos\Delta\phi(a, b)]}$$

MSSM Neutral Higgs Search ($A/H \rightarrow \tau^+\tau^-$)

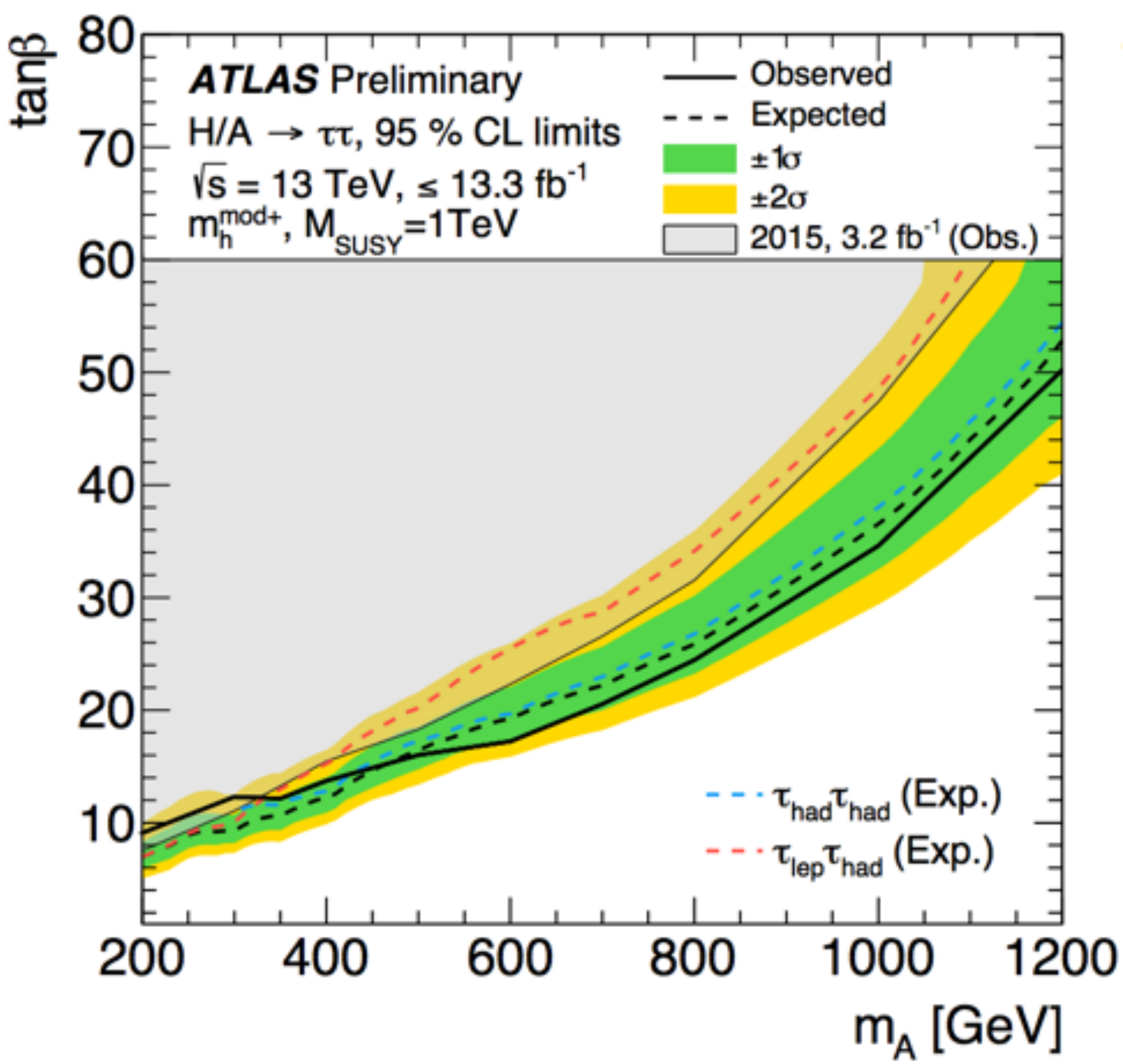
- Dominant systematics: τ energy scale, τ trigger, jet fake-related (lep-had), top modeling (had-had)
- Statistically combine the τ_{lep}-τ_{had} and τ_{had}-τ_{had} channels for one exclusion limit
  - NB: Limit from had-had starts at a higher m_A due to limited acceptance below 300 GeV
- We determine a σ x BR limit ($A/H \rightarrow \tau\tau$) for gluon-fusion and b-associated production separately; exclusions range from ~2.0 pb to 13-14 fb, depending on the Higgs mass and production mechanism

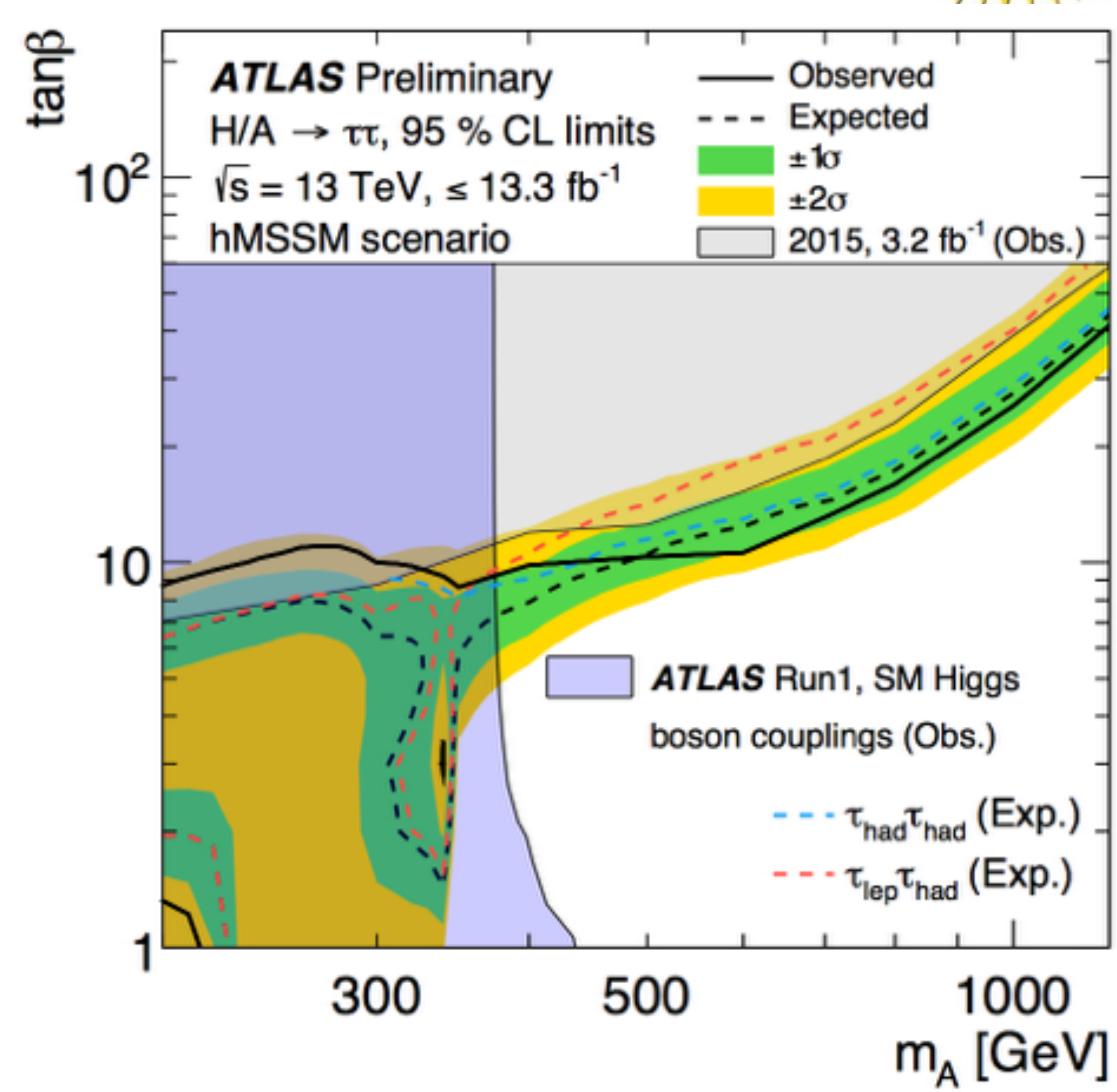




MSSM Neutral Higgs Search ($A/H \rightarrow \tau^+\tau^-$)

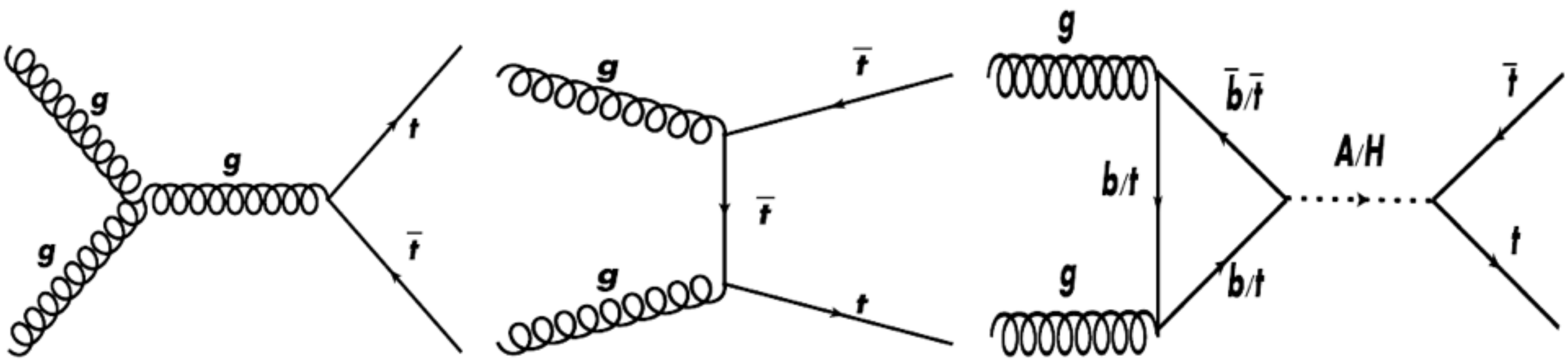
- We also show limits in the m_h^{mod+} and hMSSM benchmark scenarios
- In the m_h^{mod+} scenario, we exclude $\tan\beta > 16$ for $m_A = 600$ GeV and $\tan\beta > 35$ for $m_A = 1$ TeV
- In the hMSSM, we have sensitivity to exclude the low m_A-low $\tan\beta$ corner and the island around 350 GeV. Note: the features around 350 GeV are related to the σ x BR evolution near the A/H→ttbar threshold
- hMSSM plot shows Run-1 couplings exclusion (κ_V, κ_u and κ_d)





High-mass Higgs Search (A/H→ttbar)

- We revisit a Run-1 ttbar resonance search that used 20.3 fb^{-1} of 8 TeV proton-proton collision data: ATLAS collaboration, JHEP 08 (2015) 148
- This analysis uses the ttbar lepton+jets channel, and takes the interference between the signal and ttbar background production modes into account for the first time

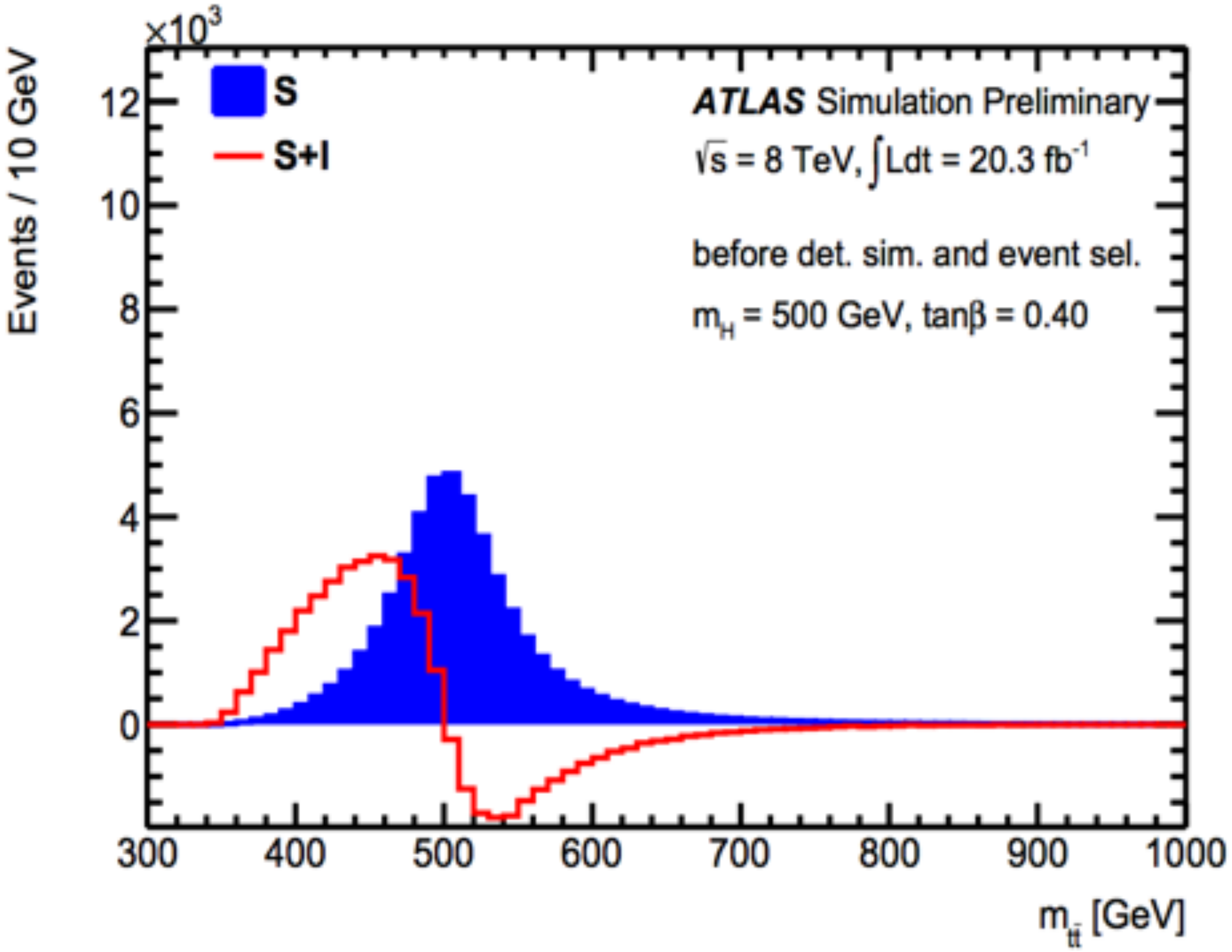


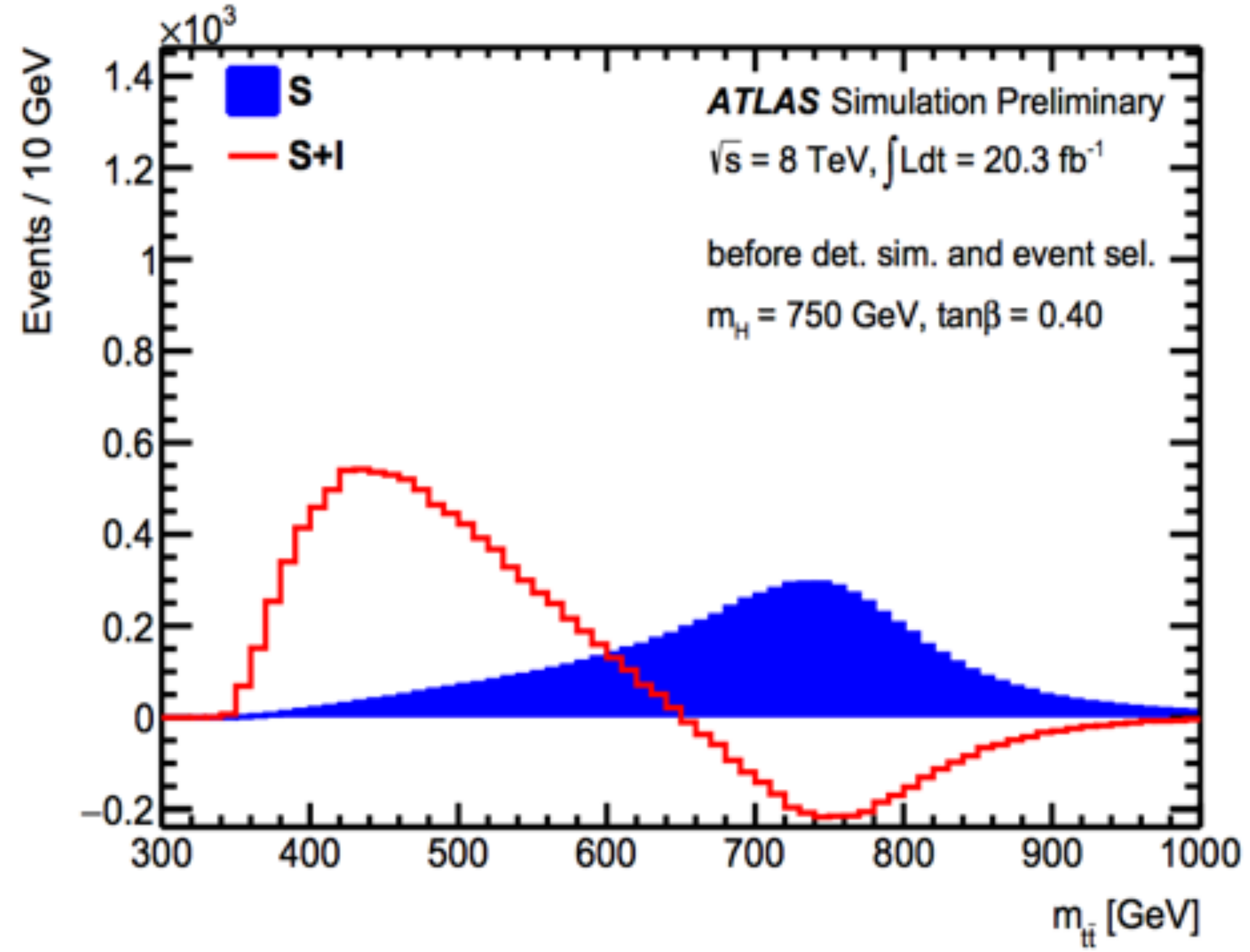
- Monte Carlo samples used:
  - A/H to ttbar signal: MadGraph5+Pythia6
  - Backgrounds:
    - ttbar: Powheg-Box+Pythia6
    - ttbar + V: Madgraph5+Pythia6
    - single top: Powheg+Pythia6
    - W+jets and Z+jets: Alpgen+Pythia6
    - Diboson: Sherpa

MadGraph5 used for both Direct and Indirect A/H signal generation (Direct used; difference taken as a modeling systematic)

Signal Modeling (A/H→ttbar)

- The signal process is simulated using the generator MadGraph5 v2.0.1 with the Higgs Effective Couplings Form Factor model (implements the production of scalar and pseudoscalar particles through loop-induced gluon fusion)
  - Loop contributions from both bottom and top quarks are taken into account
  - Signal shape is distorted from a simple Breit-Wigner peak, to a peak-dip structure
  - Statistical interpretation of measured event rates in data are compared to the total sum of Signal + Interference + Background (S + I + B)
  - The mass of the SM-like Higgs boson, h, is chosen to be 125 GeV and sin(β-α) is set to 1



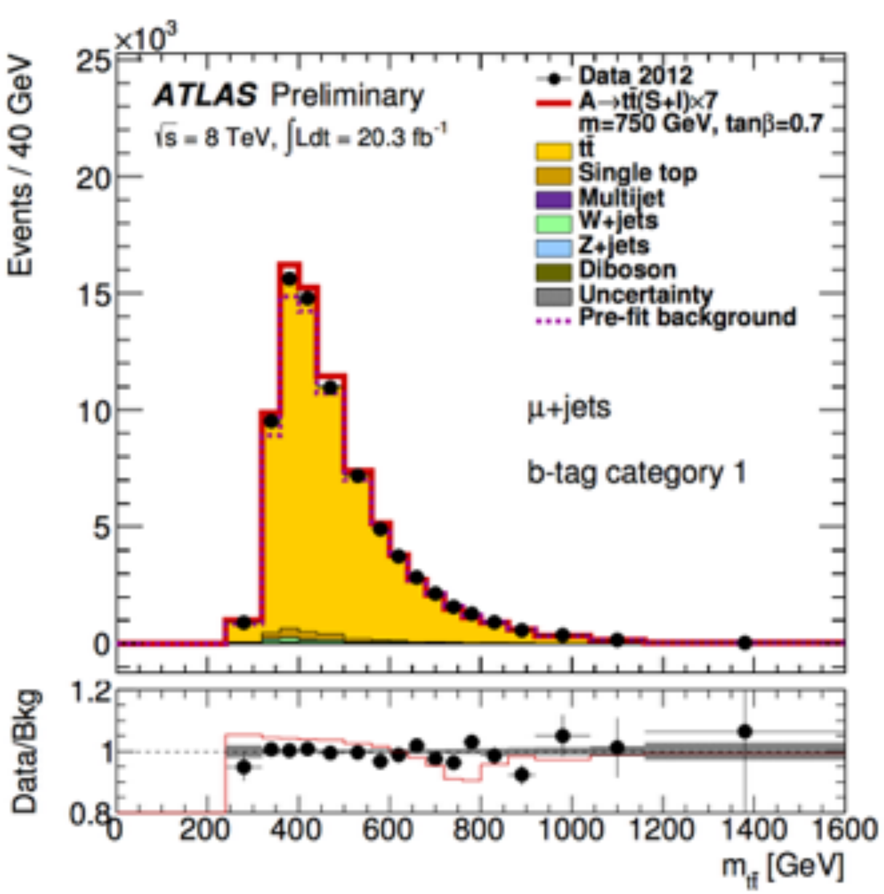


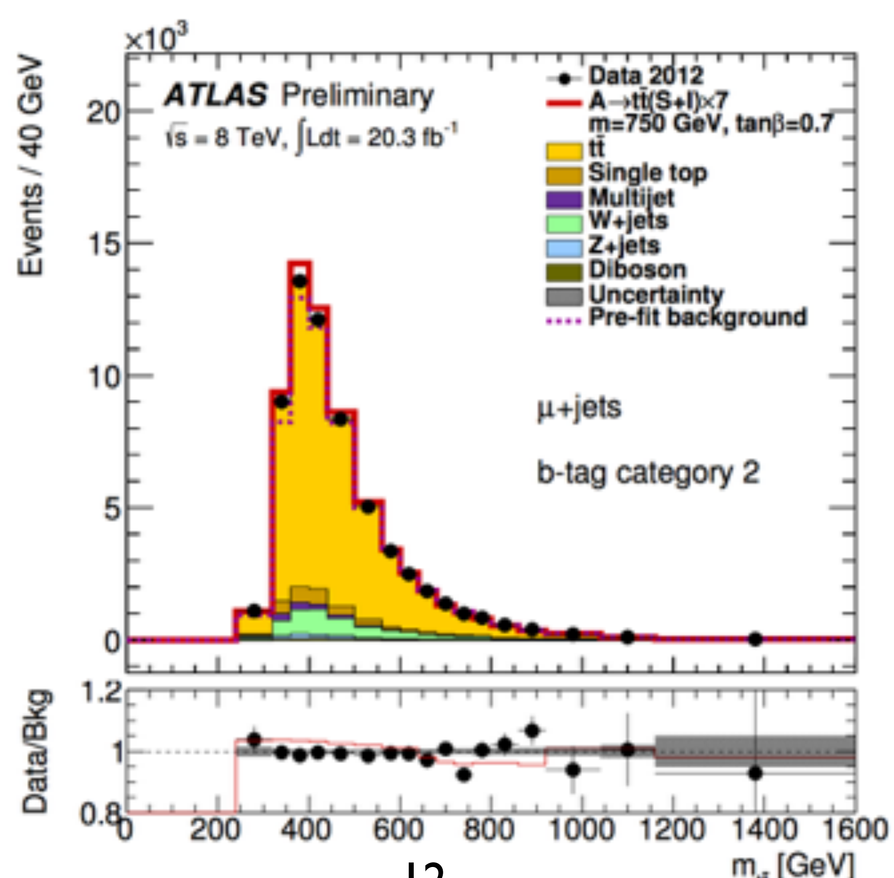
Event Selection / Mass Reconstruction (A/H→ttbar)

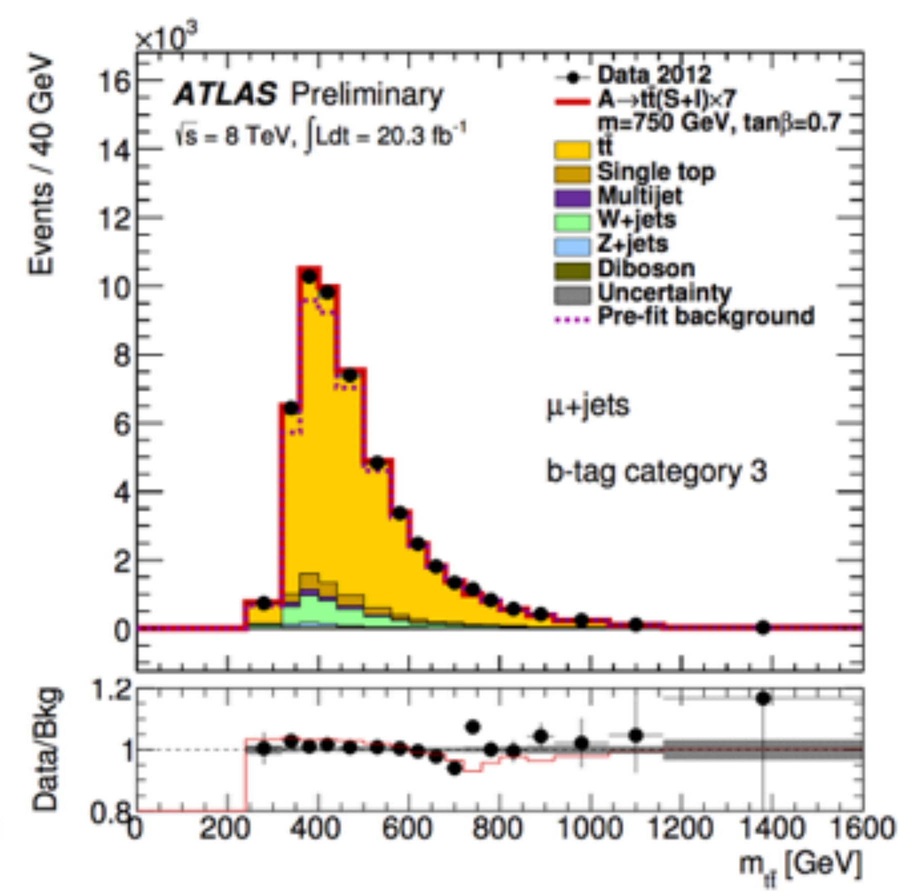
- Analysis targets the ttbar lepton+jets channel (one W to hadrons one to leptons)
  - Single electron or single muon triggers are used—2 categories (one for e; one for μ)
  - One high p_T electron or muon; high MET from the escaping neutrino; presence of at least 4 high p_T jets in the event; at least one jet originating from b quarks must be tagged (70%); Sum of MET and m_T > 60 GeV (multi-jets suppression) $m_T^W = \sqrt{2 \cdot p_T^\ell \cdot E_T^{miss} \cdot (1 - \cos\phi_{\ell\nu})}$
- A chi-squared fit is used for assignment of the decay products, then m_{tt} is reconstructed
  - Events further classified depending on the b-tagged jet(s) assignment—3 categories

$$\chi^2 = \left[\frac{m_{jj} - m_W}{\sigma_W}\right]^2 + \left[\frac{m_{jjb} - m_{jj} - m_{t_h-W}}{\sigma_{t_h-W}}\right]^2 + \left[\frac{m_{j\ell\nu} - m_{t_\ell}}{\sigma_{t_\ell}}\right]^2 + \left[\frac{(p_{T,jjb} - p_{T,j\ell\nu}) - (p_{T,t_h} - p_{T,t_\ell})}{\sigma_{\mathrm{diff}\,p_T}}\right]^2$$

6 categories in total (2 lepton types) x (3 b-tagging classifications)

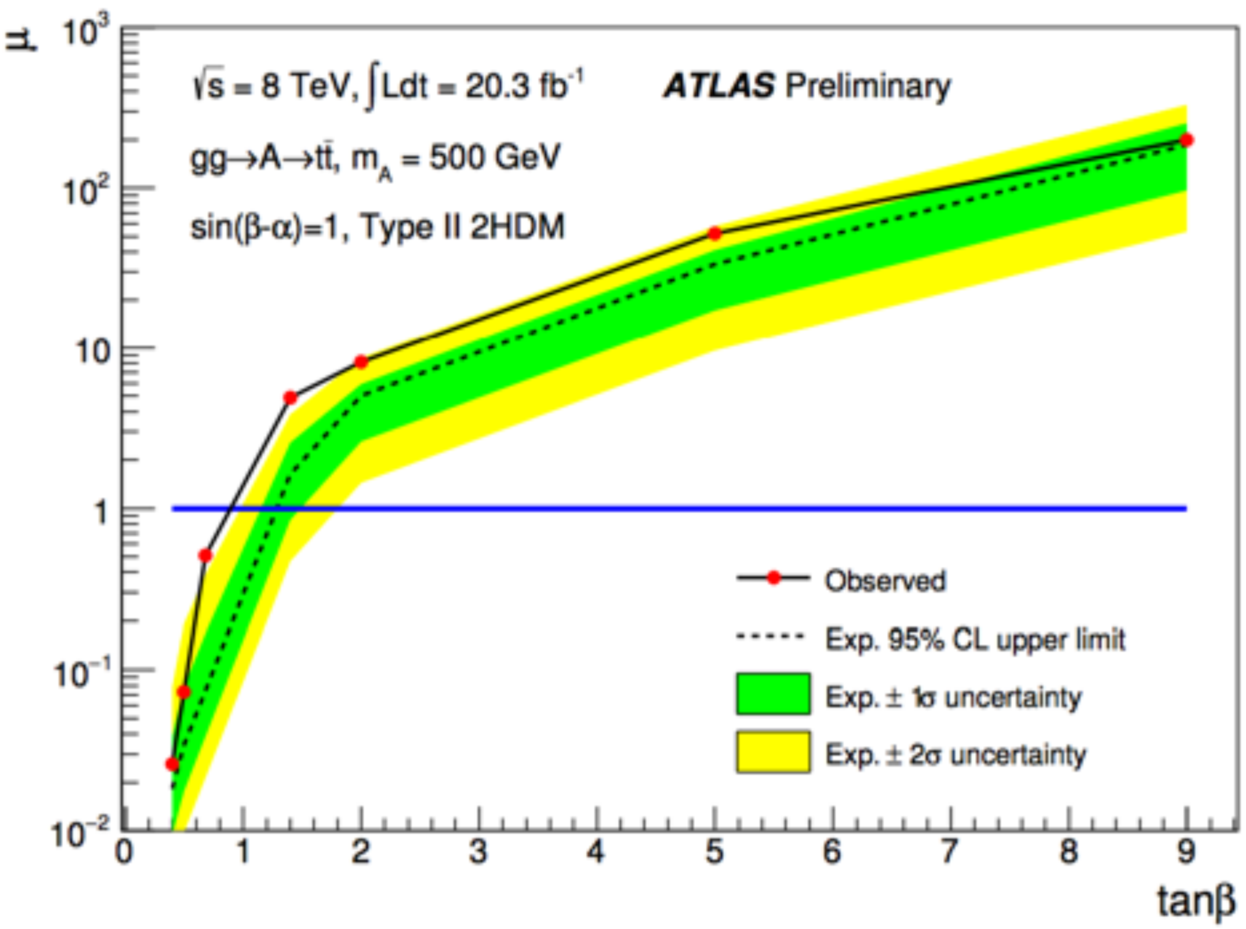


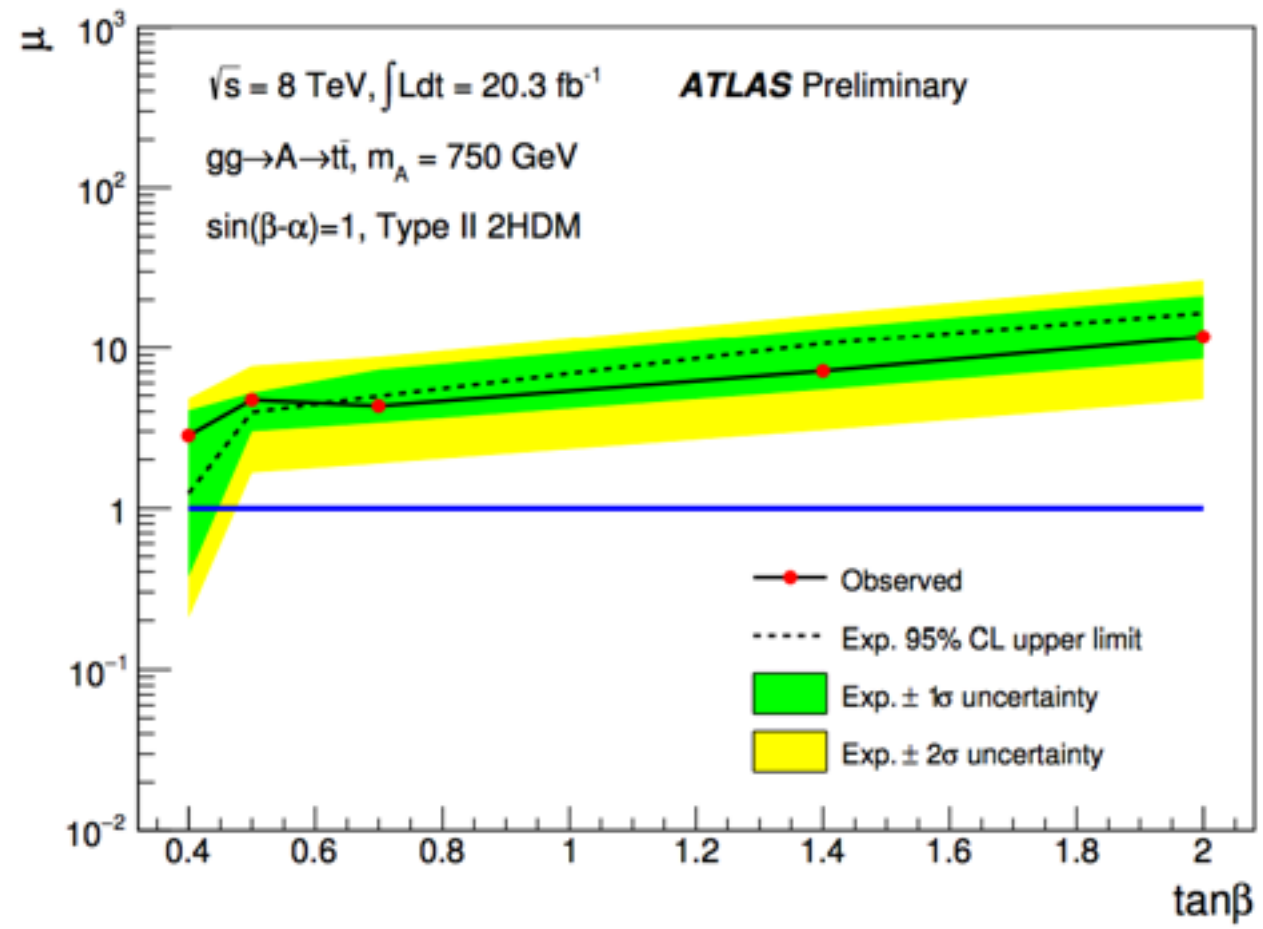




High-mass Higgs Search Results (A/H→ttbar)

- No significant excess over Standard Model background expectations is observed
- We set upper limits on the signal strength parameter μ as a function of the parameter tanβ for a neutral pseudoscalar A with a mass of 500 GeV and 750 GeV
- NB: The blue line at μ=1 corresponds to the signal strength in the Type-II 2HDM

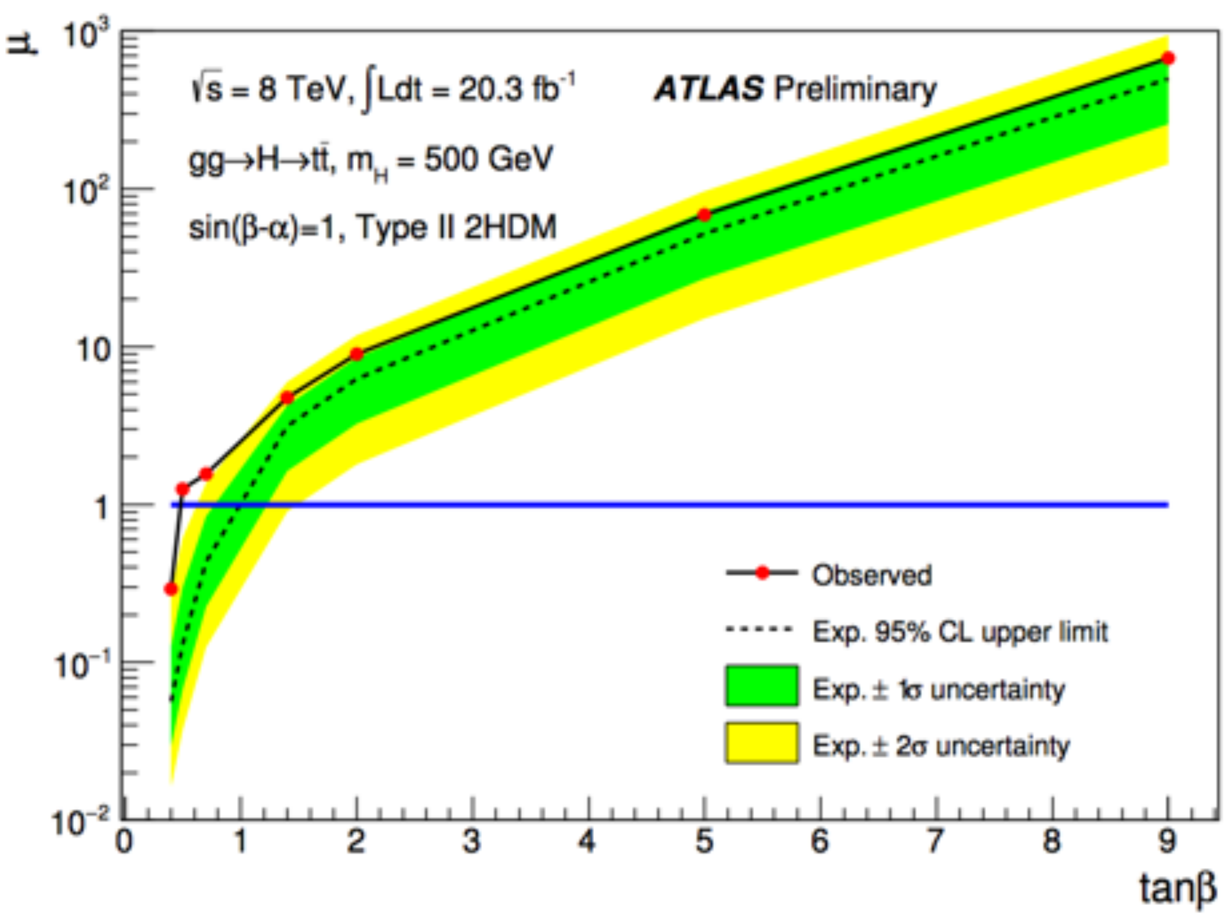


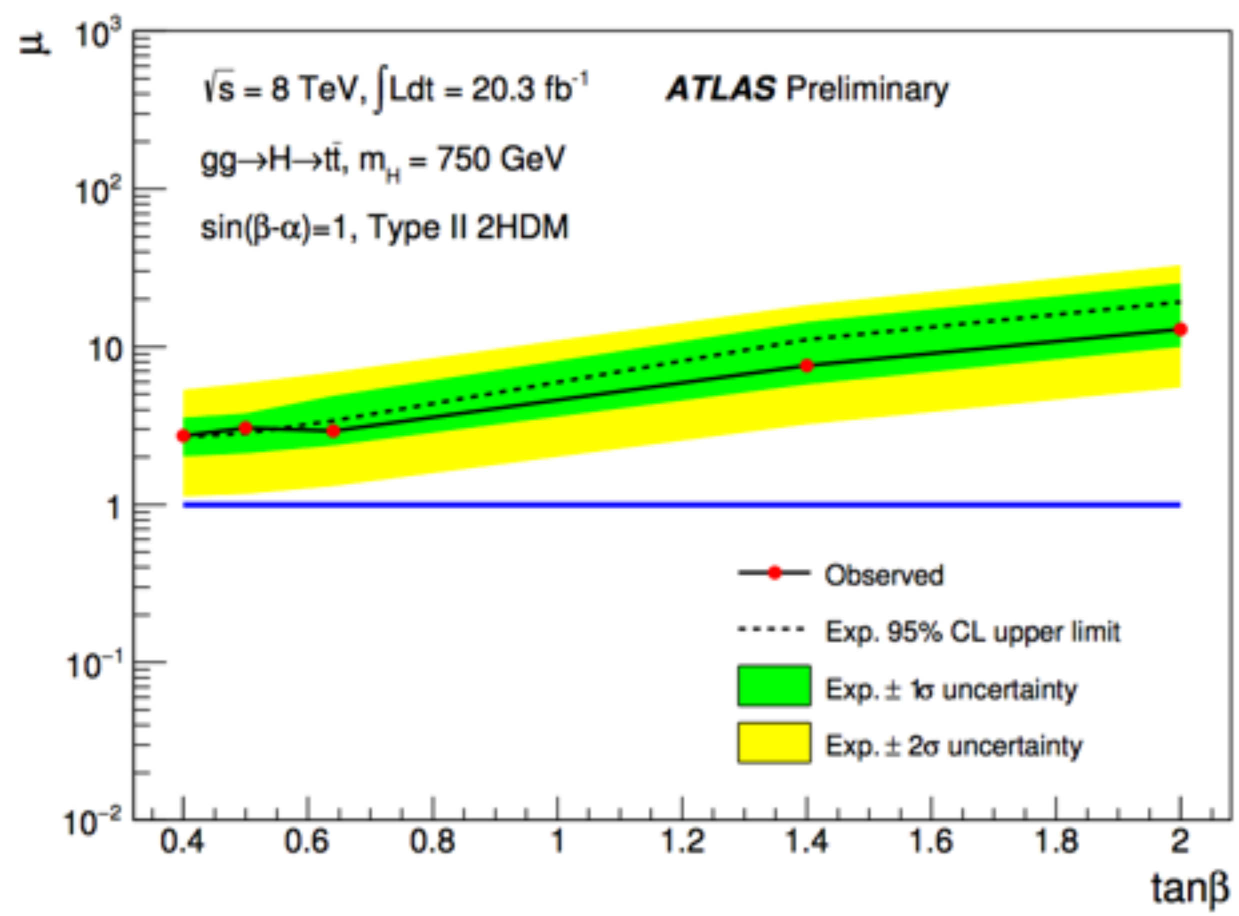


- For a neutral pseudoscalar A, with a mass of m_A=500 GeV, parameter values of tanβ < 0.85 in the Type-II 2HDM are excluded at the 95% CL. No tanβ values can be excluded for the higher mass point at 750 GeV.

High-mass Higgs Search Results (A/H→ttbar)

- No significant excess over Standard Model background expectations is observed
- We set upper limits on the signal strength parameter μ as a function of the parameter tanβ for a neutral scalar H with a mass of 500 GeV and 750 GeV
- NB: The blue line at μ=1 corresponds to the signal strength in the Type-II 2HDM





- For a neutral scalar H, with a mass of m_H=500 GeV, parameter values of tanβ < 0.45 in the Type-II 2HDM are excluded at the 95% CL. No tanβ values can be excluded for the higher mass point at 750 GeV.

Conclusions and Outlook

- ATLAS has performed new searches for high-mass neutral Higgs bosons decaying to fermions
  - The new $A/H \rightarrow \tau\tau$ analysis uses up to 13.3 fb^{-1} of 13 TeV collision data recorded in 2015 and 2016; this result improves on a recent ATLAS paper submitted to EPJC
  - The $A/H \rightarrow$ ttbar analysis is an extension of a Run-1 search in 20.3 fb^{-1} of 8 TeV data and takes the interference between A/H signal and ggF ttbar into account for the first time

- No significant excess is observed in the data from either search, and 95% CL limits are set
  - **$A/H \rightarrow \tau\tau$:** We determine a σ x BR limit for gluon-fusion and b-associated production separately; exclusions range from ~2.0 pb at m_A=200 GeV to 13-14 fb for m_A between 600 GeV and 1 TeV
  - **$A/H \rightarrow \tau\tau$:** We also show limits in the m_h^{mod+} and hMSSM benchmark scenarios; e.g., in the m_h^{mod+} scenario, lowest $\tan\beta$ constraint excludes $\tan\beta > 9$ for m_A = 200 GeV
  - **$A/H \rightarrow$ ttbar:** For a neutral pseudoscalar A, with a mass of m_A=500 GeV, parameter values of $\tan\beta < 0.85$ in the Type-II 2HDM are excluded at the 95% CL.
  - **$A/H \rightarrow$ ttbar:** For a neutral scalar H, with a mass of m_H=500 GeV, parameter values of $\tan\beta < 0.45$ in the Type-II 2HDM are excluded at the 95% CL.

- Stay tuned for more results from Run-II of the LHC; these are very exciting times!

Back-up Slides

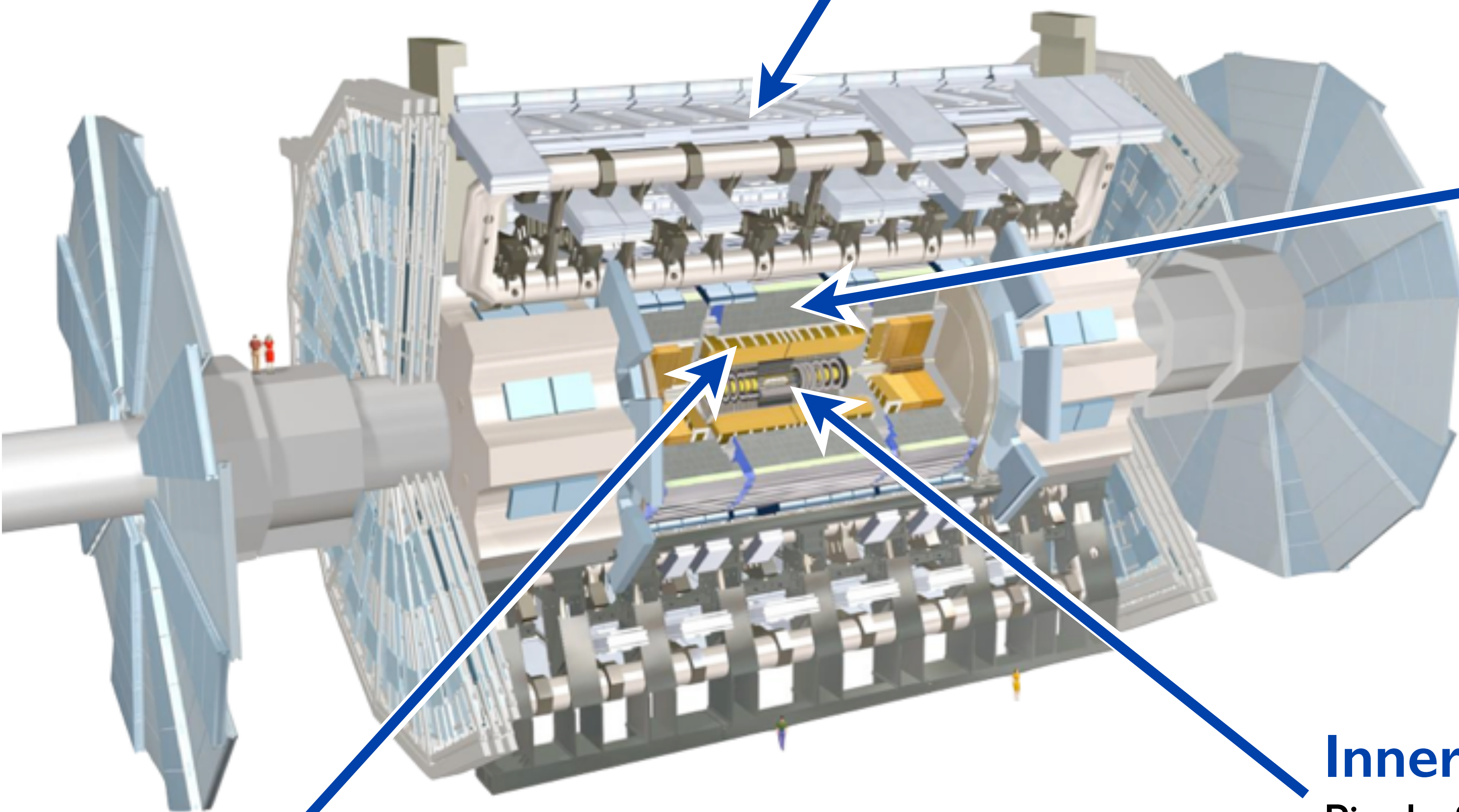
The ATLAS Experiment at the CERN LHC

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

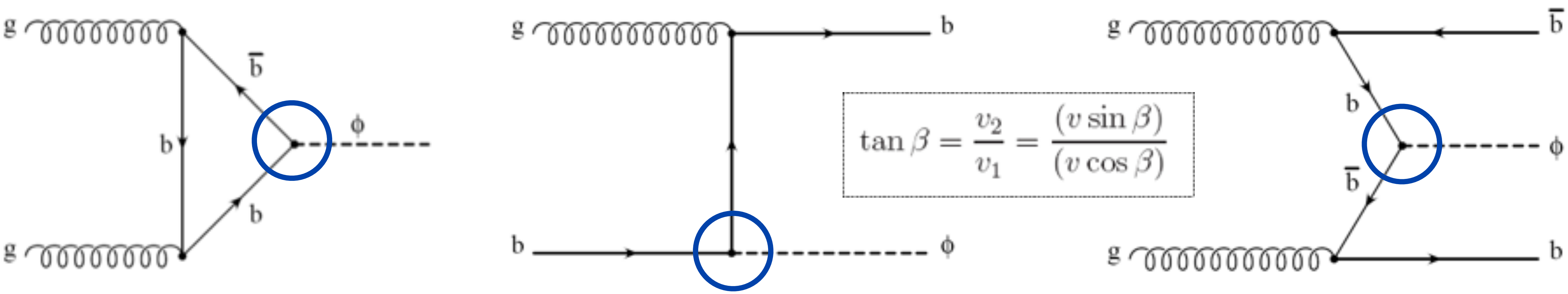
Pixels, Si strips, Transition Radiation detector (straws); Precise tracking and vertexing, allows for e/π separation;
Momentum resolution:
$\sigma/p_T \sim 3.8\times10^{-4}\, p_T\,(\text{GeV}) \oplus 0.015$
i.e. $\sigma/p_T < 2\%$ for $p_T < 35$ GeV

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

Pb-LAr Accordion; allows for e/γ triggering, identification and measurement;
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

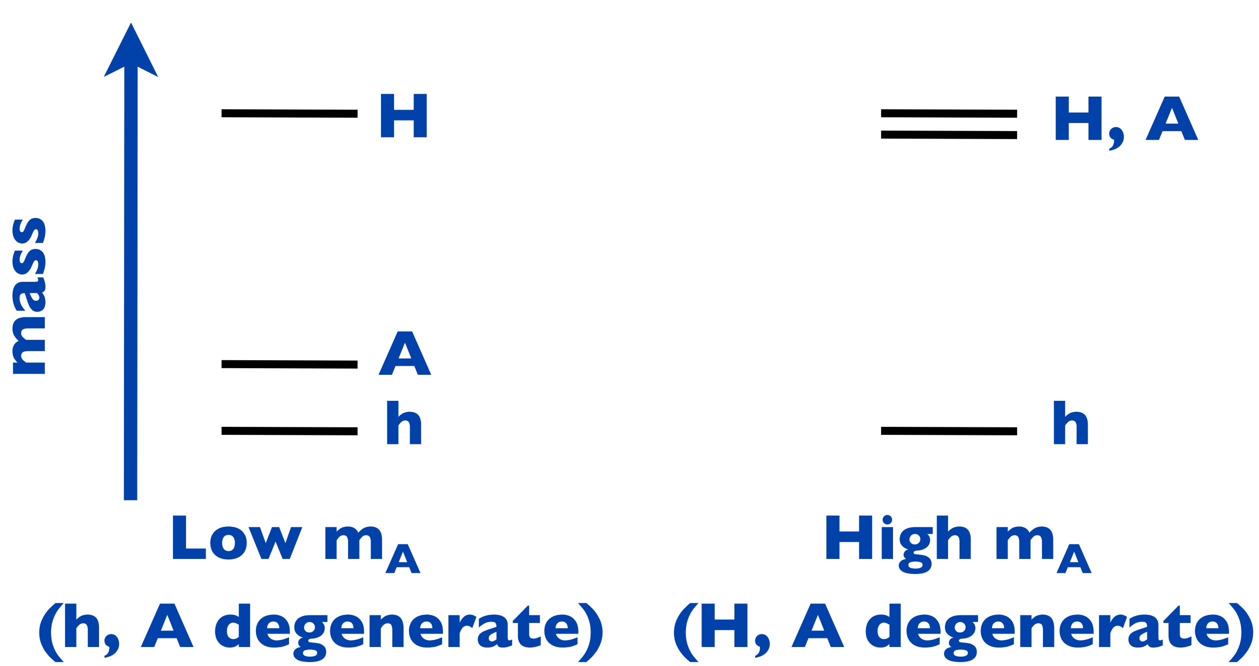
MSSM Higgs Sector

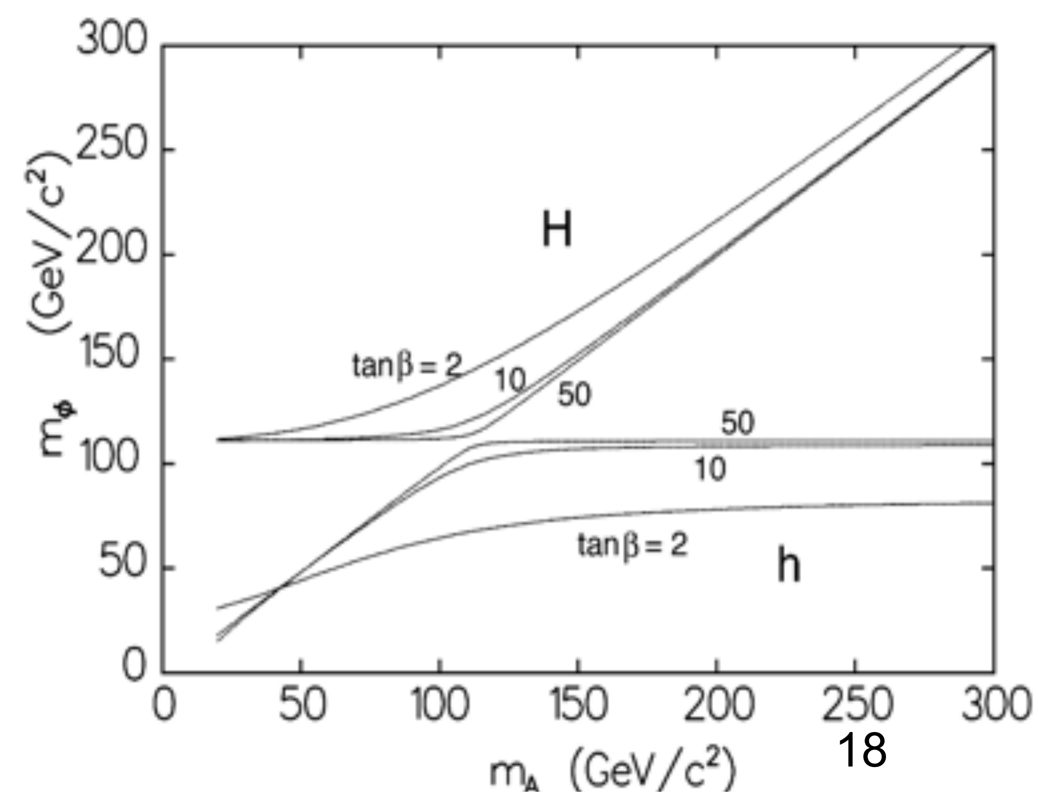
- Consider the case of an MSSM Higgs at the LHC
  - 2 Higgs doublets give rise to 5 physical Higgs bosons: h, H, A, $H^{\pm}$
  - Enhanced coupling to 3rd generation; strong coupling to down-type fermions (at large tanβ get strong enhancements to h/H/A production rates)
  - Diagrams with bbϕ vertex enhanced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





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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+}

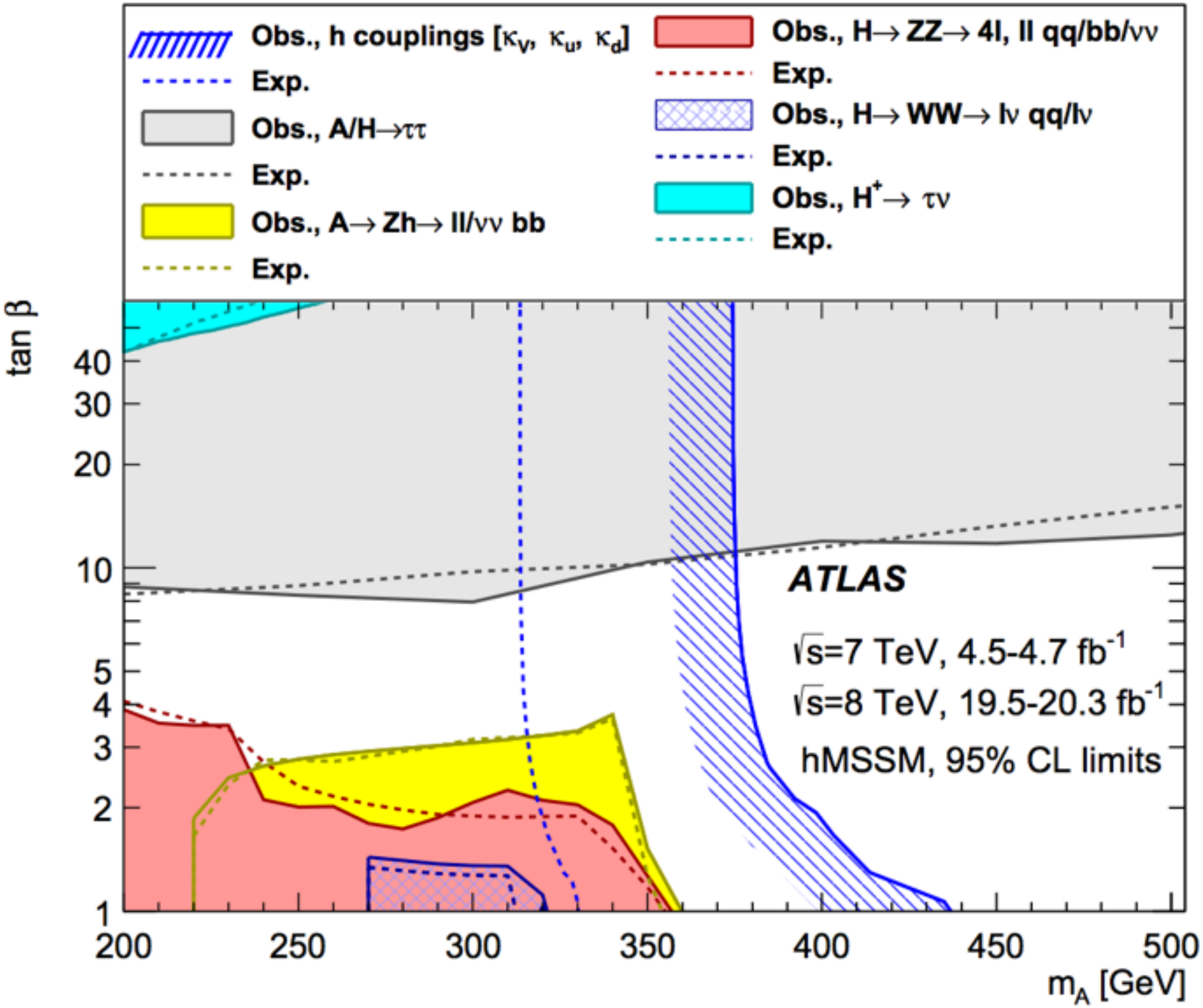
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= 1.5\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= 1.6\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &= A_\tau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

m_h^{mod-}

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

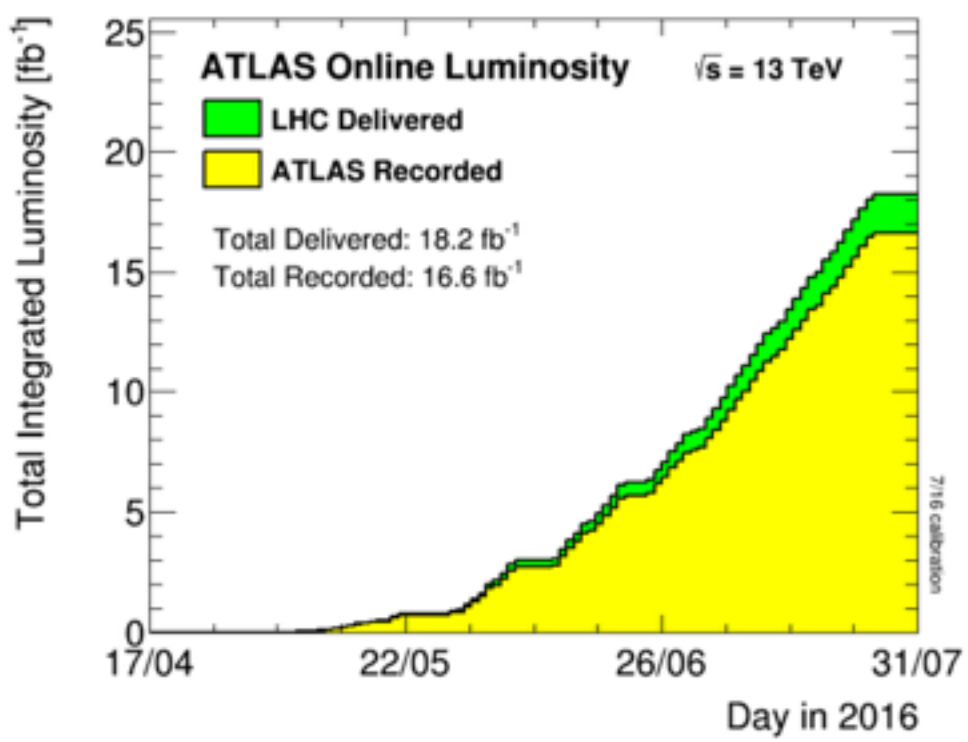
ATLAS Run-1 hMSSM Exclusion

arXiv: 1509.00672

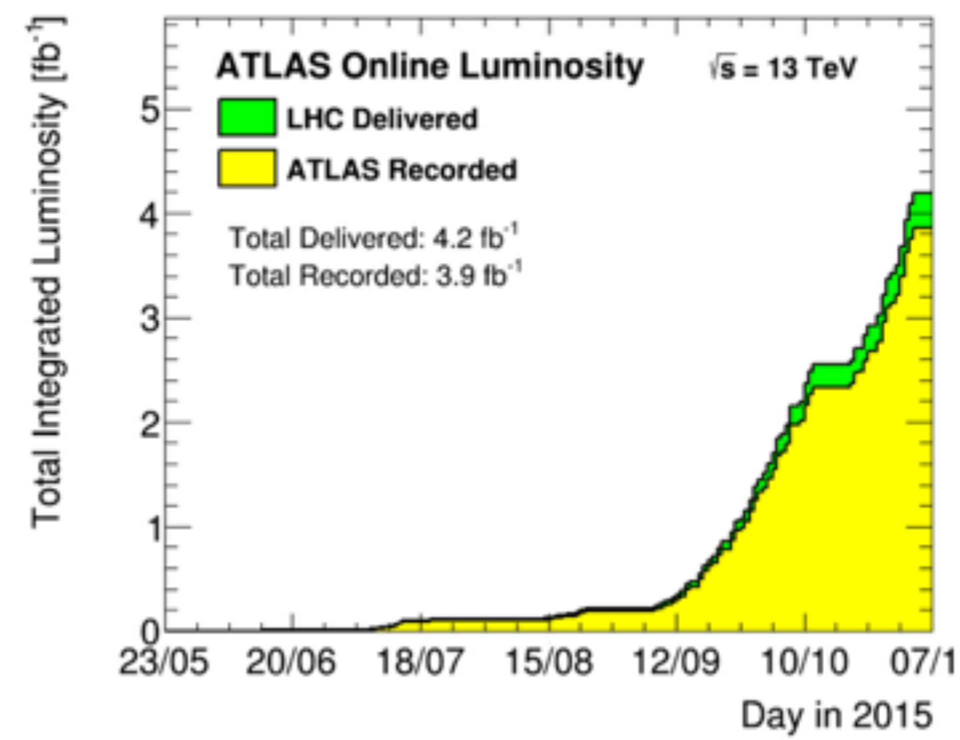


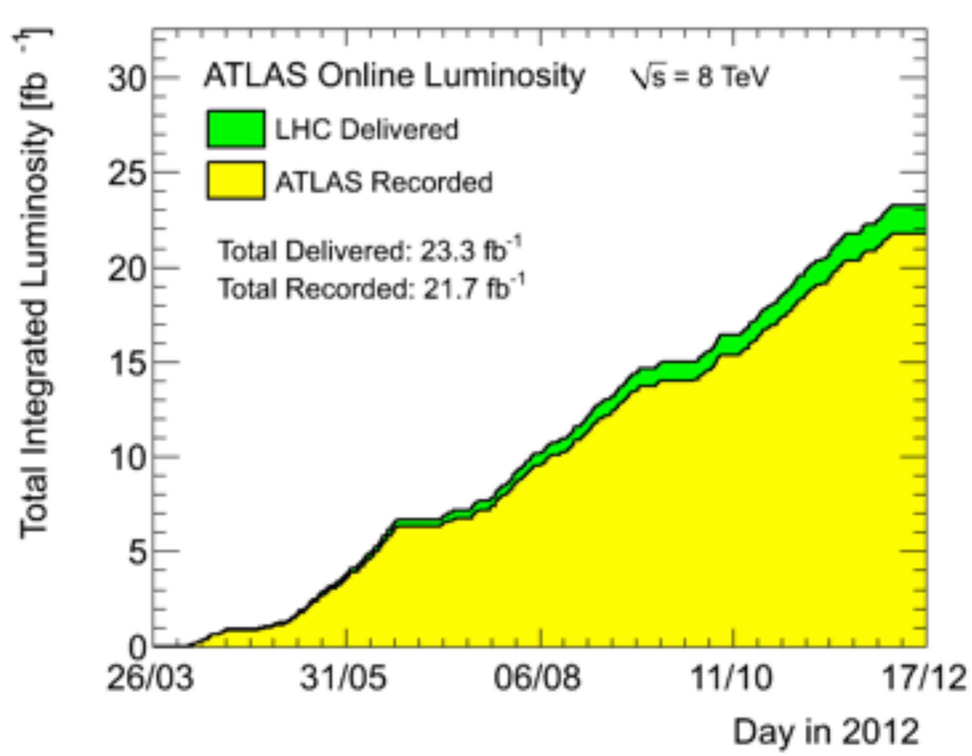
ATLAS Datasets

2016 13 TeV

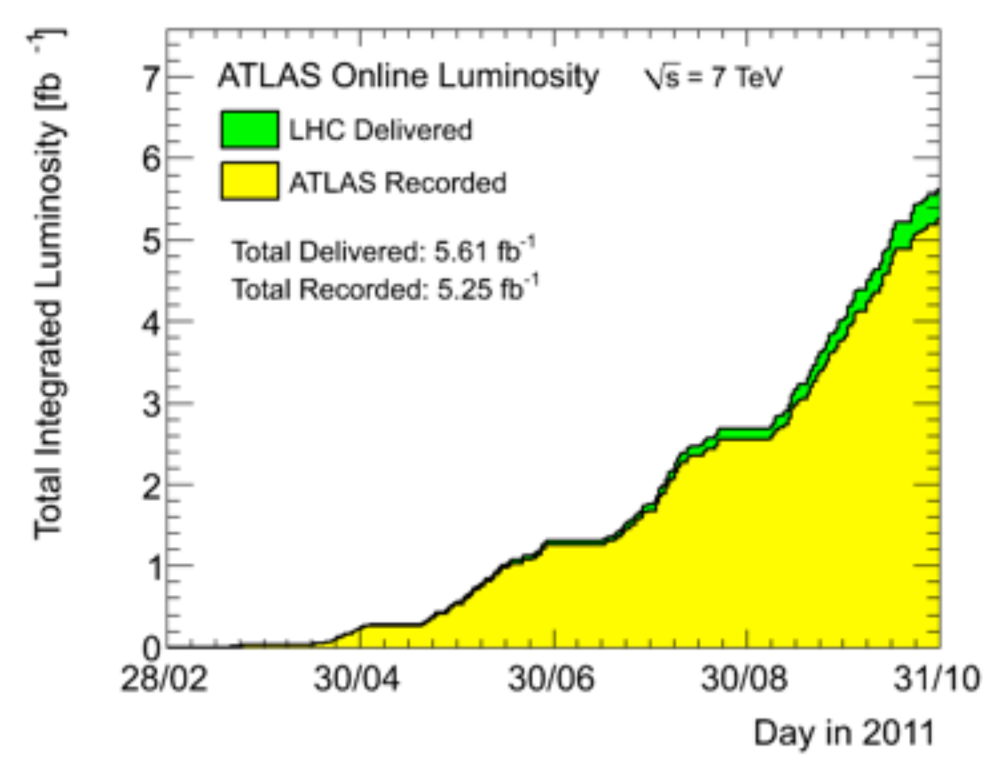


2015 13 TeV





2012 8 TeV



2011 7 TeV

ATLAS Run-1 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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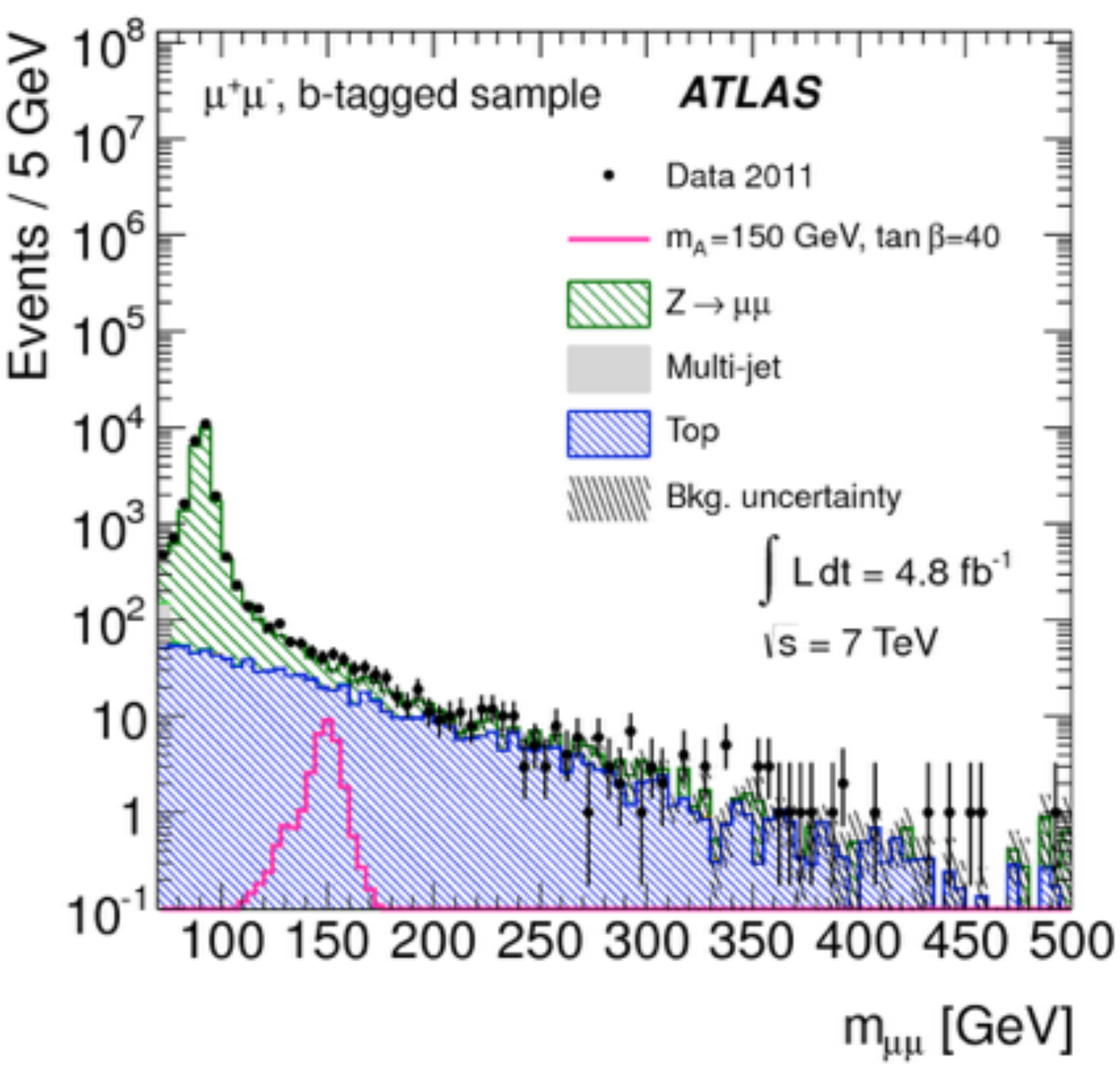
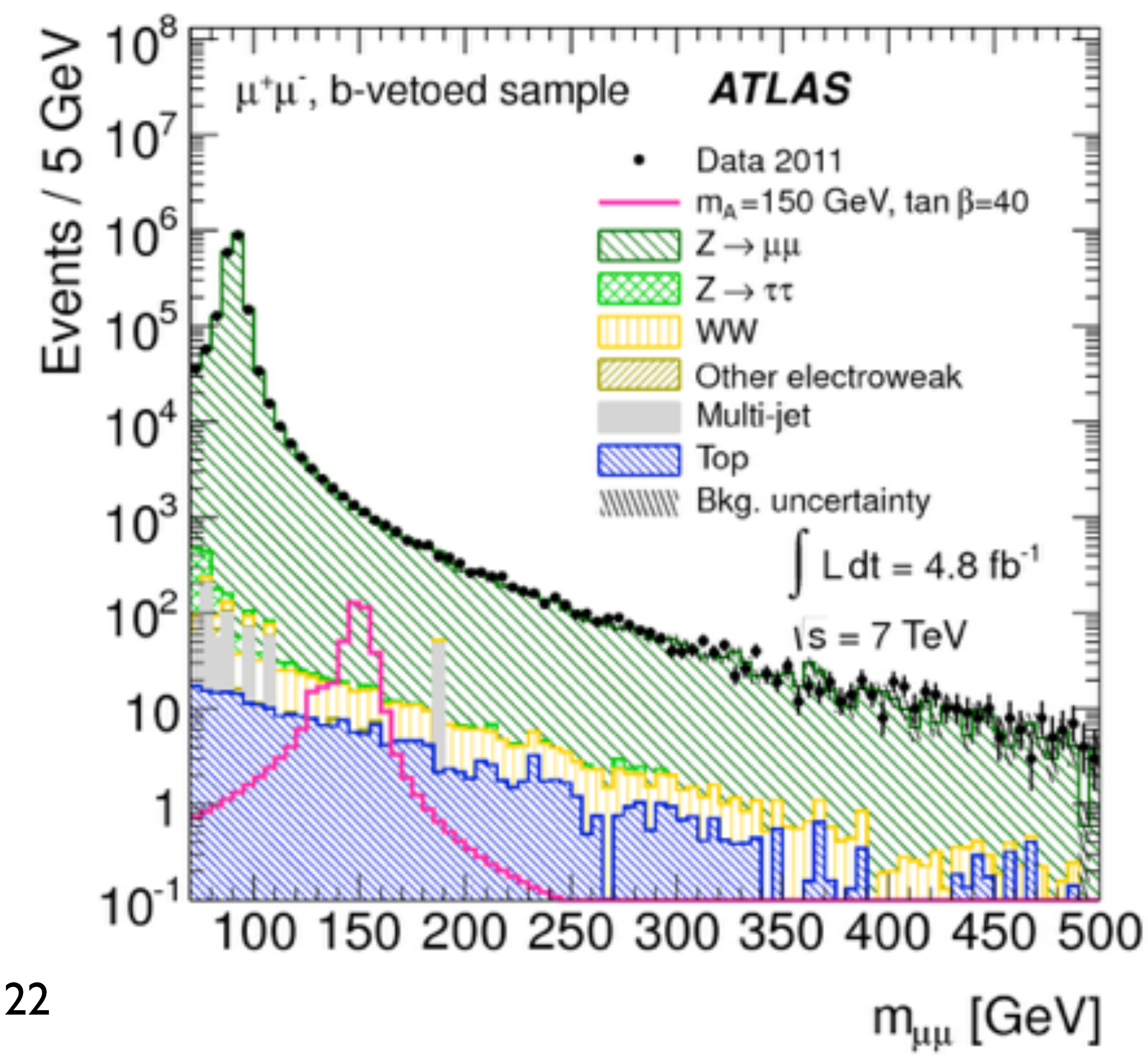
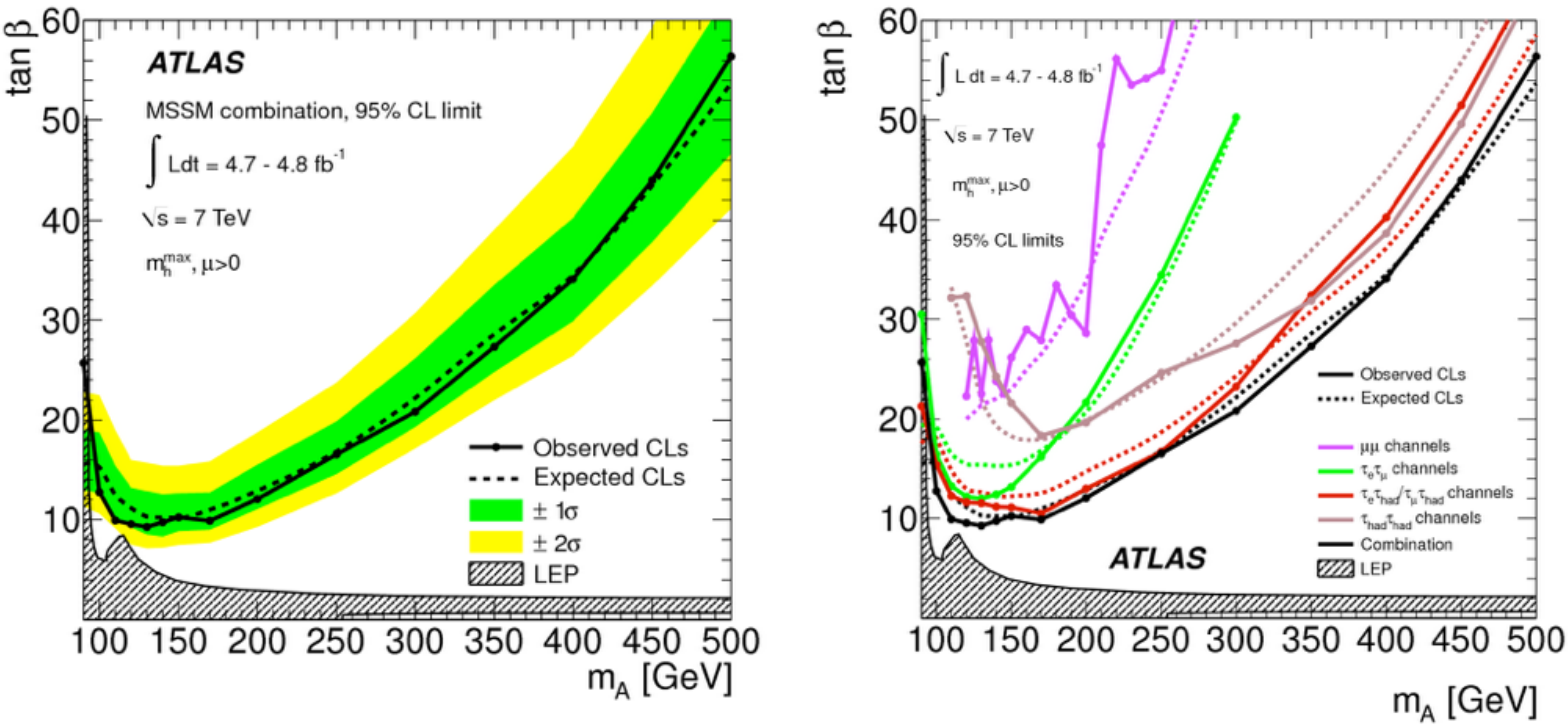




ATLAS Run-1 MSSM Higgs Searches ($\phi \rightarrow \mu^+\mu^-$)

- 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

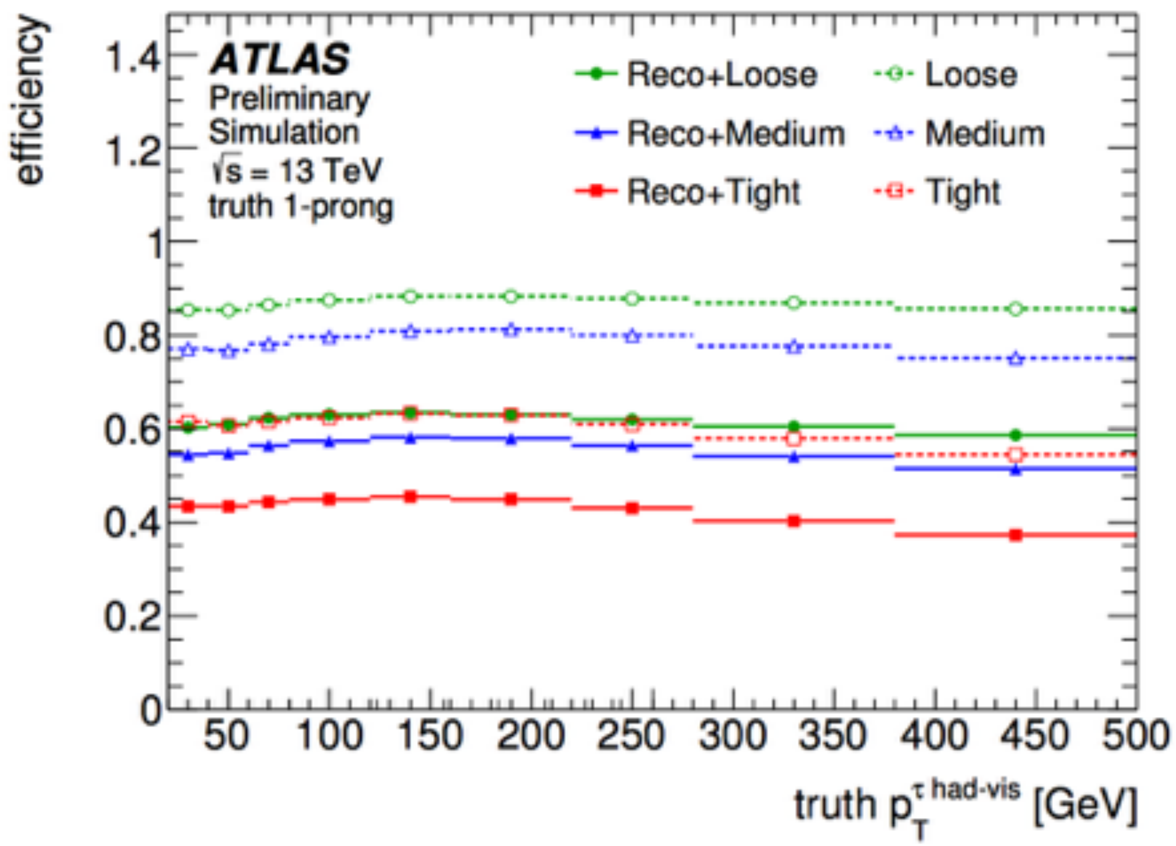
JHEP02 (2013) 095

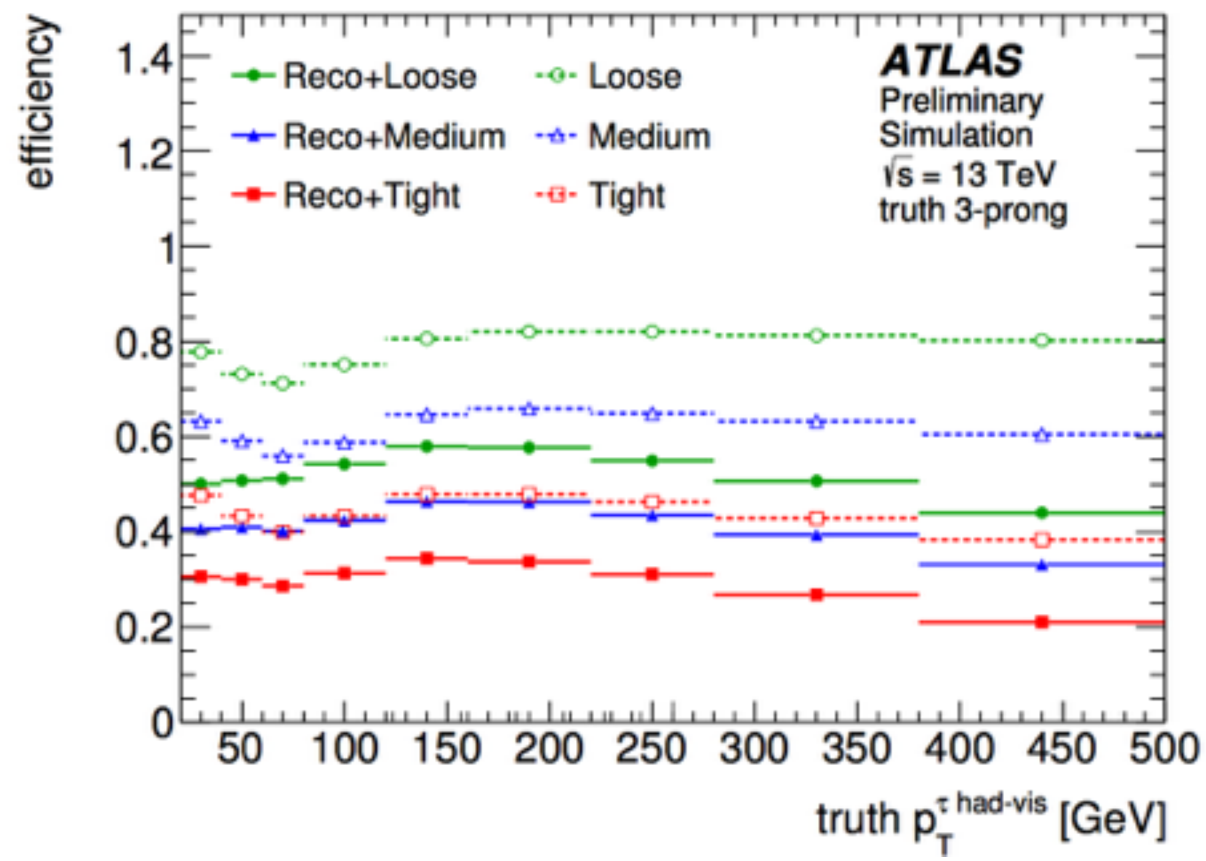


Backup Slides for A/H$\rightarrow\tau^+\tau^-$

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 (e.g., BDT used for rejection of jets) ATL-PHYS-PUB-2015-045
  - Discriminate using tracking information and cluster topology variables

MET Trigger in the lep-had Channel

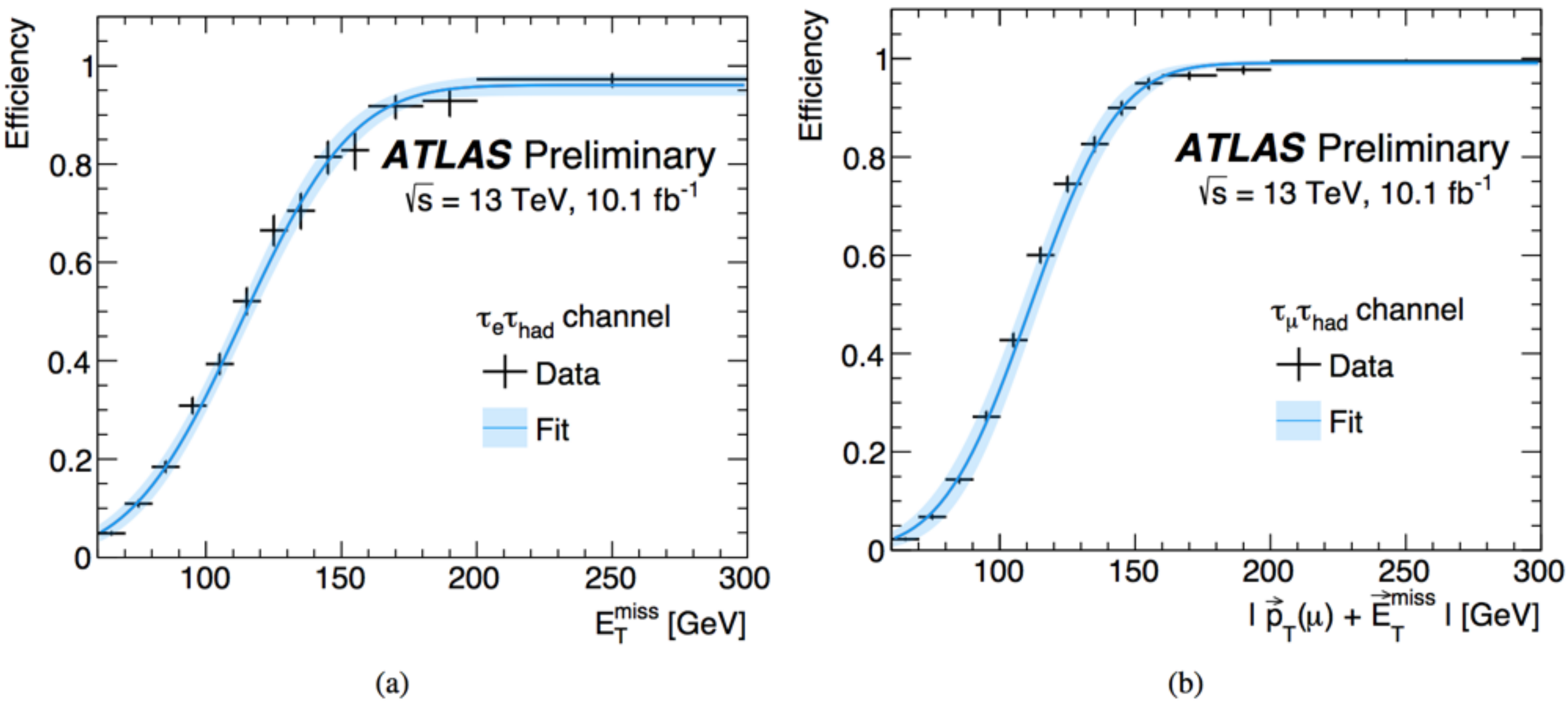


Figure 2: The efficiency of the $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger with a threshold of 90 GeV as measured in data collected in 2016. The data are fit with a sigmoid function and the uncertainties shown are of statistical nature. The fit is shown separately for (a) the $\tau_e\tau_{\mathrm{had}}$ and (b) the $\tau_\mu\tau_{\mathrm{had}}$ channels.

MET Trigger in the lep-had Channel

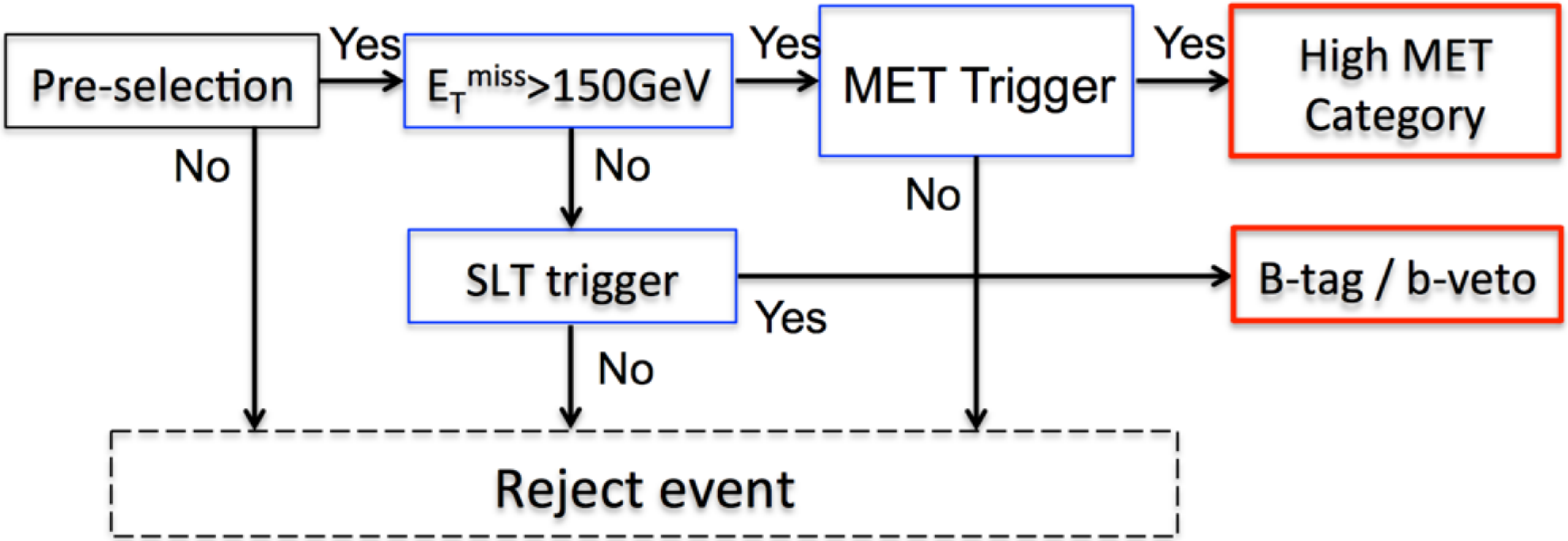


Figure 2: Trigger work flow for lephad analysis.

Systematic Uncertainties

- The main sources of detector-related systematic uncertainties are: tau energy scale, hadronic tau identification and reconstruction, electron veto (lep-had), JES, JER, flavor-tagging, pile-up and tau trigger (had-had)

- Modeling-related systematic uncertainties also exist

- Lep-Had:
  - Jet fakes (fake-factor and rQCD)
  - Top modeling (when looking at m_T^{tot} region)
  - MC signal uncertainties

- Had-Had:
  - Jet fakes (multi-jet, W and top)
  - Top modeling
  - MC signal uncertainties

Source of uncertainty	F_{-} (%)	F_{+} (%)
$t\bar{t}$ background parton shower model	−21	+39
$\tau_{\text{had-vis}}$ energy scale, detector modelling	−10	+12
r_{MJ} estimation b-veto region ($\tau_\mu \tau_{\text{had}}$)	− 5	+ 6
r_{MJ} estimation b-veto region ($\tau_e \tau_{\text{had}}$)	− 2.3	+ 3.0
bbH signal cross-section uncertainty	− 3.8	+ 1.6
Multi-jet background ($\tau_{\text{had}}\tau_{\text{had}}$)	− 2.2	+ 2.6
Jet-to-$\tau_{\text{had-vis}}$ fake rate b-veto region ($\tau_{\text{lep}}\tau_{\text{had}}$)	− 1.3	+ 2.9
$\tau_{\text{had-vis}}$ energy scale, in-situ calibration	− 1.4	+ 1.1
r_{MJ} estimation high-$E_{\text{T}}^{\text{miss}}$ region ($\tau_\mu \tau_{\text{had}}$)	− 1.4	+ 1.0
τ trigger (2016)	− 0.5	+ 1.3
Statistics (data and simulation)	−48	+25

Table 3: Fractional impact of the most important sources of systematic uncertainty on the total uncertainty of the signal strength, for the MSSM signal hypothesis of m_A = 600 GeV, $\tan\beta$ = 20. For each source of uncertainty, $F_\pm = \pm\frac{\sigma^2_{\text{source}}}{\sigma^2_{\text{total}}}$ is defined as the positive (negative) fractional contribution to the signal strength uncertainty.

MSSM Neutral Higgs Observed Events (lep-had)

$\tau_e \tau_{\text{had}}$ channel	b-tag category			b-veto category			high-E_T^{miss} category		
$Z \to \tau\tau$+jets	150	±	40	14200	±	900	13	±	2
Jet $\to \ell, \tau_{\text{had-vis}}$ fakes	770	±	260	20000	±	3900	72	±	9
$Z \to \ell\ell$+jets	20	±	4	1370	±	180	-	±	-
$t\bar{t}$ and single top quark	370	±	30	90	±	14	29	±	3
Diboson	3.0	±	0.6	141	±	13	2.6	±	0.6
Total prediction	1320	±	270	35800	±	4000	117	±	11
Data	1304			35841			123		
m_A = 600 GeV, $\tan\beta$ = 20 ($m_h^{\text{mod+}}$)									
ggH	0.019	±	0.007	1.02	±	0.17	0.32	±	0.06
bbH	4.5	±	0.9	7.2	±	1.5	3.9	±	0.9

MSSM Neutral Higgs Observed Events (lep-had)

$\tau_\mu \tau_{\text{had}}$ channel

	b-tag category			b-veto category			high-E_T^miss category		
$Z \to \tau\tau$+jets	210	±	50	19800	±	1100	91	±	11
Jet $\to \ell, \tau_{\text{had-vis}}$ fakes	960	±	340	18800	±	1900	540	±	60
$Z \to \ell\ell$+jets	10	±	3	1700	±	130	0.22	±	0.08
$t\bar{t}$ and single top quark	350	±	30	85	±	13	187	±	17
Diboson	1.3	±	0.5	190	±	16	14.9	±	2.0
Total prediction	1530	±	350	40600	±	2100	830	±	70
Data	1539			40556			839		
$m_A = 600$ GeV, $\tan\beta = 20$ ($m_h^{\text{mod+}}$)									
ggH	0.010	±	0.004	0.4	±	0.06	1.3	±	0.2
bbH	1.6	±	0.4	3.0	±	0.7	16	±	3

MSSM Neutral Higgs Observed Events (had-had)

$\tau_{\rm had}\tau_{\rm had}$ channel

	b-tag category			b-veto category		
$Z \to \tau\tau$+jets	4.0	±	0.9	340	±	40
Multi-jet	47	±	4	1500	±	60
$W \to \tau\nu$+ jets	1.50	±	0.21	91	±	9
$t\bar{t}$ and single top quark	20	±	6	10	±	6
Others	0.51	±	0.21	14.8	±	2.0
Total prediction	73	±	6	1980	±	40
Data	63			2006		
$m_A = 600$ GeV, $\tan\beta = 20$ ($m_h^{\rm mod+}$)						
ggH	0.042	±	0.014	3.2	±	0.7
bbH	14	±	4	27	±	8

Signal and Control Regions (lep-had)

$\tau_{\text{lep}}\tau_{\text{had}}$ signal region	$\Delta\phi(\tau_{\text{had-vis}},\ell) > 2.4$, $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 40$ GeV, Veto $80 < m_{e,\tau} < 110$ GeV for $\tau_e\tau_{\text{had}}$,
high-$E_{\text{T}}^{\text{miss}}$ category:	$E_{\text{T}}^{\text{miss}}$ ($\lvert\vec{p}_{\text{T}}(\mu) + \vec{E}_{\text{T}}^{\text{miss}}\rvert$)> 150 GeV for $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$),
b-tag/b-veto categories:	fail high-$E_{\text{T}}^{\text{miss}}$ category requirements, $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto category)
b-veto/$t\bar{t}$ fake-factor control region	$m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) > 70$ (60) GeV for $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$), $N_{b\text{-tag}} = 0$ different $\tau_{\text{had-vis}}$ identification for the anti-τ_{had} region
b-tag control region	$N_{b\text{-tag}} \geq 1$, $m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) > 100$ GeV
Multi-jet fake-factor control region	invert e,μ isolation requirement, $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto and high-$E_{\text{T}}^{\text{miss}}$ categories) different $\tau_{\text{had-vis}}$ identification for the anti-τ_{had} multi-jet control region
Multi-jet control region for r_{MJ} estimation	$m_{\text{T}}(\ell, E_{\text{T}}^{\text{miss}}) < 30$ GeV, no e,μ isolation requirement, no $\tau_{\text{had-vis}}$ passing loose identification, $N_{\text{jet}} \geq 1$ and $N_{b\text{-tag}} = 0$ (b-veto category), $N_{\text{jet}} \geq 2$ and $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{\text{jet}} \geq 1$, $N_{b\text{-tag}} = 0$ and $E_{\text{T}}^{\text{miss}}$ ($\lvert\vec{p}_{\text{T}}(\mu) + \vec{E}_{\text{T}}^{\text{miss}}\rvert$)> 150 GeV for $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$) (high-$E_{\text{T}}^{\text{miss}}$ category)

Table 1: Description of the signal and control regions used in the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. For the control regions, only the selection criteria differing from the signal region are enumerated.

Signal and Control Regions (had-had)

$\tau_{\text{had}}\tau_{\text{had}}$ signal region	$\Delta\phi(\tau_{\text{had-vis},1}, \tau_{\text{had-vis},2}) > 2.7$, $N_{b\text{-tag}} \geq 1$ and $p_{\text{T}} > 65$ GeV for the sub-leading $\tau_{\text{had-vis}}$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto category)
Multi-jet fake-factor control region	pass single-jet trigger, leading $\tau_{\text{had-vis}}$ with $p_{\text{T}} > 100$ GeV that fails medium identification, no charge requirements and for leading $\tau_{\text{had-vis}}$ $n_{\text{tracks}} \leq 7$ (b-tag category), $n_{\text{tracks}} = 1,3$ (b-veto category), $\frac{p_{\text{T}}^{\tau_{\text{had-vis},2}}}{p_{\text{T}}^{\tau_{\text{had-vis},1}}} > 0.3$
Fake rate control region	pass single-muon trigger, isolated muon with $p_{\text{T}} > 55$ GeV, $\tau_{\text{had-vis}}$ with $p_{\text{T}} > 50$ GeV, $\Delta\phi(\mu, \tau_{\text{had-vis}}) > 2.4$, $m_{\text{T}}(\mu, E_{\text{T}}^{\text{miss}}) > 40$ GeV $N_{b\text{-tag}} \geq 1$ (b-tag category), $N_{b\text{-tag}} = 0$ (b-veto category)
Same-sign validation region	The two $\tau_{\text{had-vis}}$ objects are required to have the same electric charge

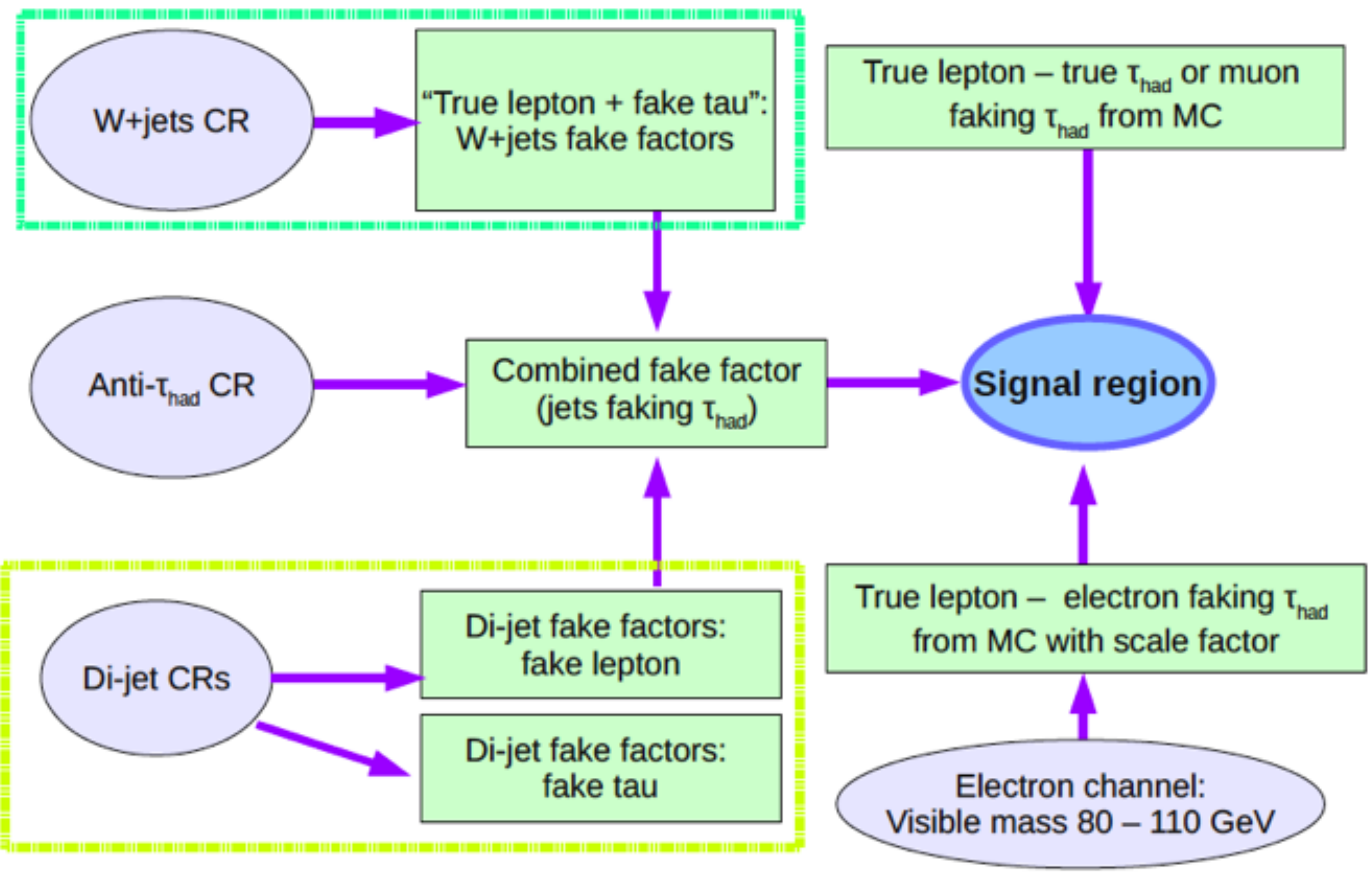
Table 1: Description of the signal and control regions used in the $\tau_{\text{lep}}\tau_{\text{had}}$ and $\tau_{\text{had}}\tau_{\text{had}}$ channels. For the control regions, only the selection criteria differing from the signal region are enumerated.

Background Estimation (lep-had)

$$FF(W + \text{jets}) = \frac{N(\text{pass "medium" tau ID})}{N(\text{fail "medium" tau ID and jet BDT>0.35})},$$

For example, derived in W+jets Control Region

Then... Applied to another Control Region which passed all selection criteria except for the tau ID → **Fake tau estimate for signal region obtained**



tau fakes from

- W+jets or top: high-m_T CR
- QCD multijet: studied in anti-isolation control region
- rQCD: multijet fraction in anti-ID region

Background Estimations in the lep-had Channel

Control Region plots for lep-had:

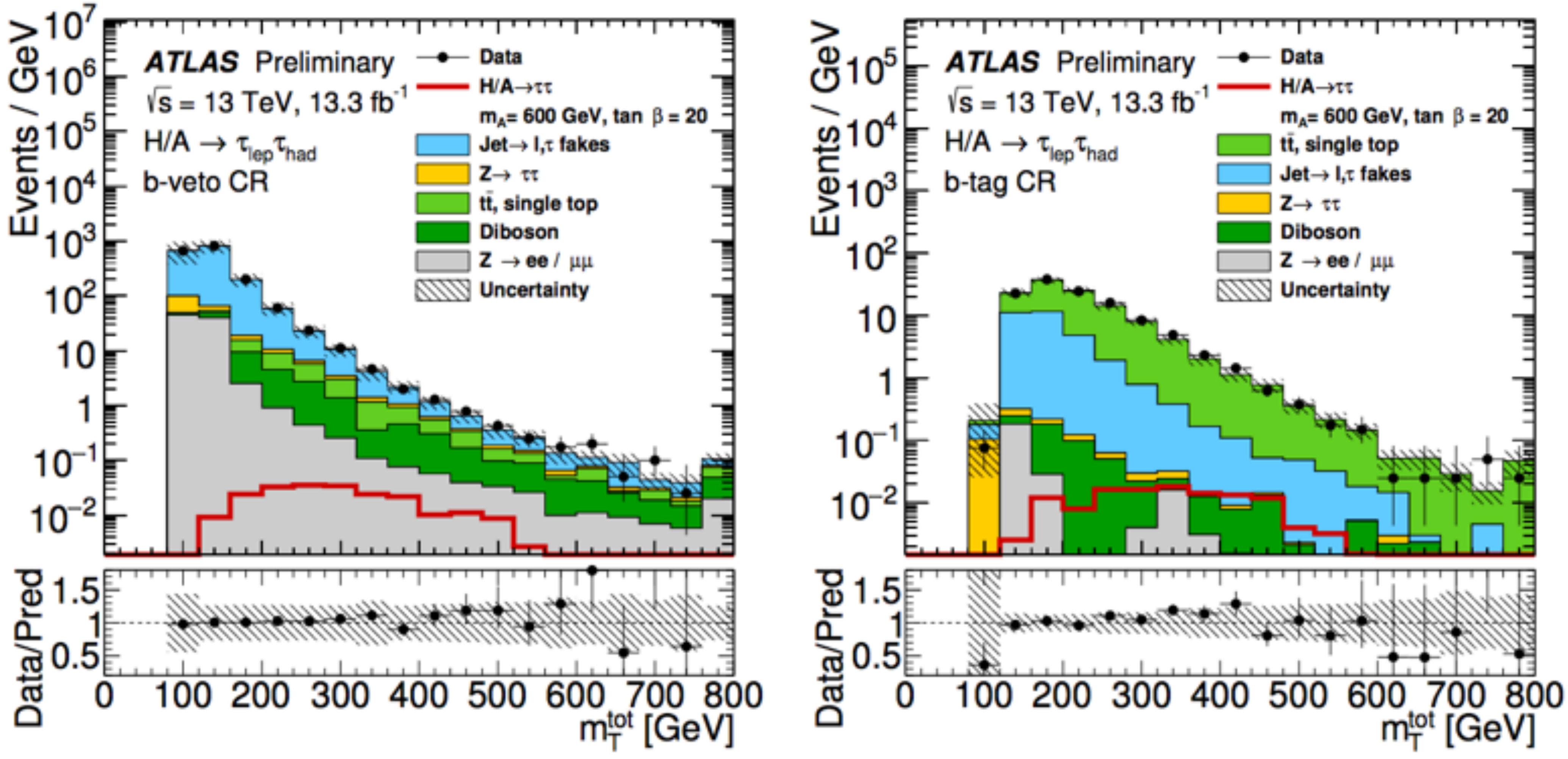


Figure 3: The distributions of m_T^{tot} in (a) the b-veto control region of the $\tau_{lep}\tau_{had}$ channel, (b) the b-tag control region of the $\tau_{lep}\tau_{had}$ channel, (c) the b-veto same-sign validation region of the $\tau_{had}\tau_{had}$ channel and (d) b-tag same-sign validation region of the $\tau_{had}\tau_{had}$ channel. The various control and validation regions are defined in Table 1. The data are compared to the background prediction and a hypothetical MSSM $H/A \rightarrow \tau\tau$ signal (m_A = 600 GeV and tan β = 20). The statistics of the simulated signal samples are limited in the background-dominated regions. The label "Others" in (c) and (d) refers to contributions from diboson, $Z(\ell\ell)$+jets and $W(\ell\nu)$+jets production. The background uncertainty includes statistical and systematic uncertainties. The bins have a varying size and overflows are included in the last bin of the distributions.

Background Estimation (had-had)

Hadhad Jet fake: Fake factor

Jet fake tau background: Multi-jet, W(τν)+jets and top

Multi-jet FF:

- Derived in a dijet enriched region with leading τ failing MEDIUM ID
- Independently for b-tag and b-veto categories
- Additional correction factor for the btag FF derived in Same-Sign CR

W-jet and **Top** FR:

- Derived in a W(μν)+jets (b-veto) and Top (b-tag) enriched region
- Applied to the MC W(τν) +jets and Top (jet->tau fake)

Background Estimations in the had-had Channel

Control Region plots for had-had:

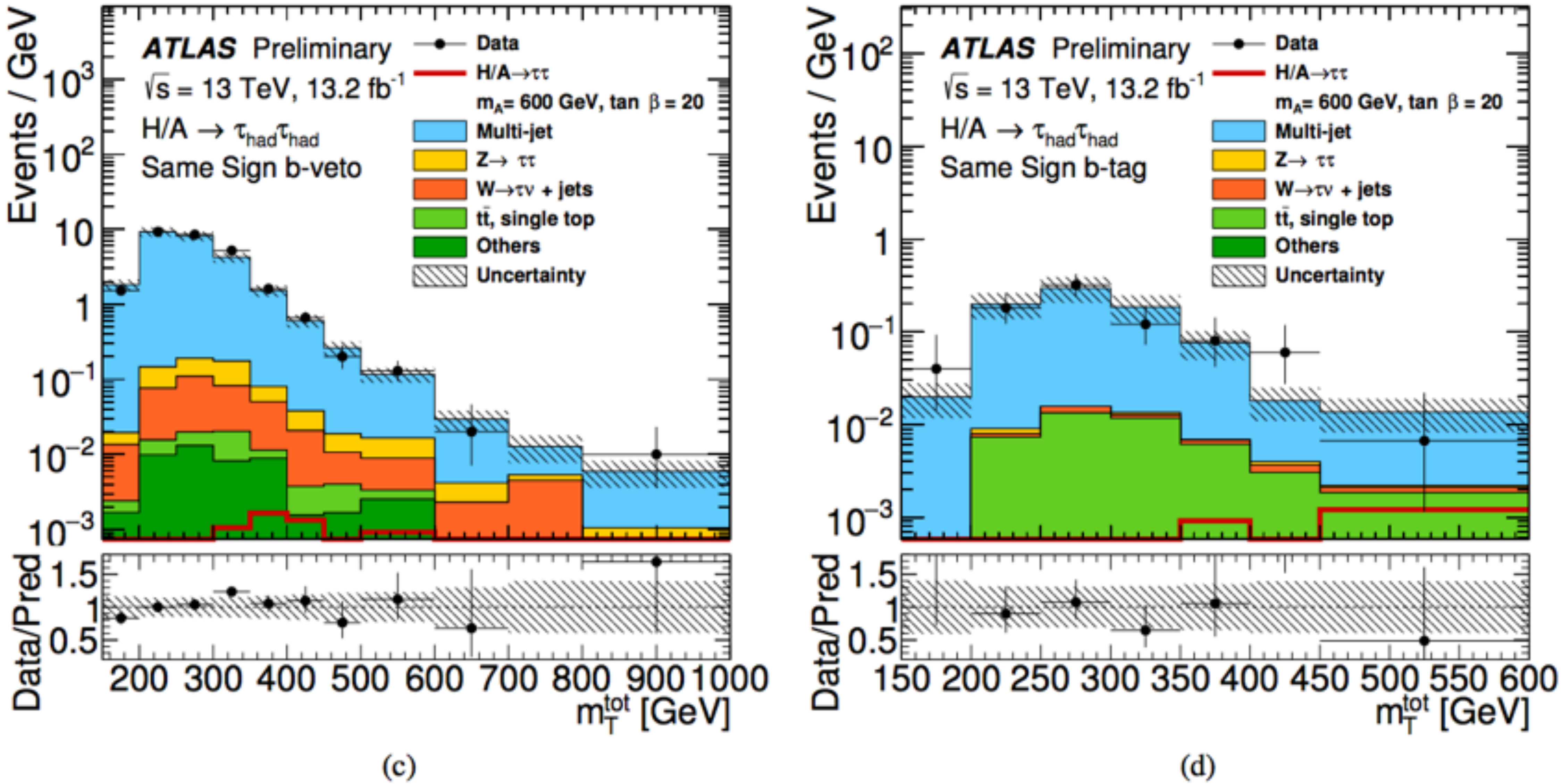
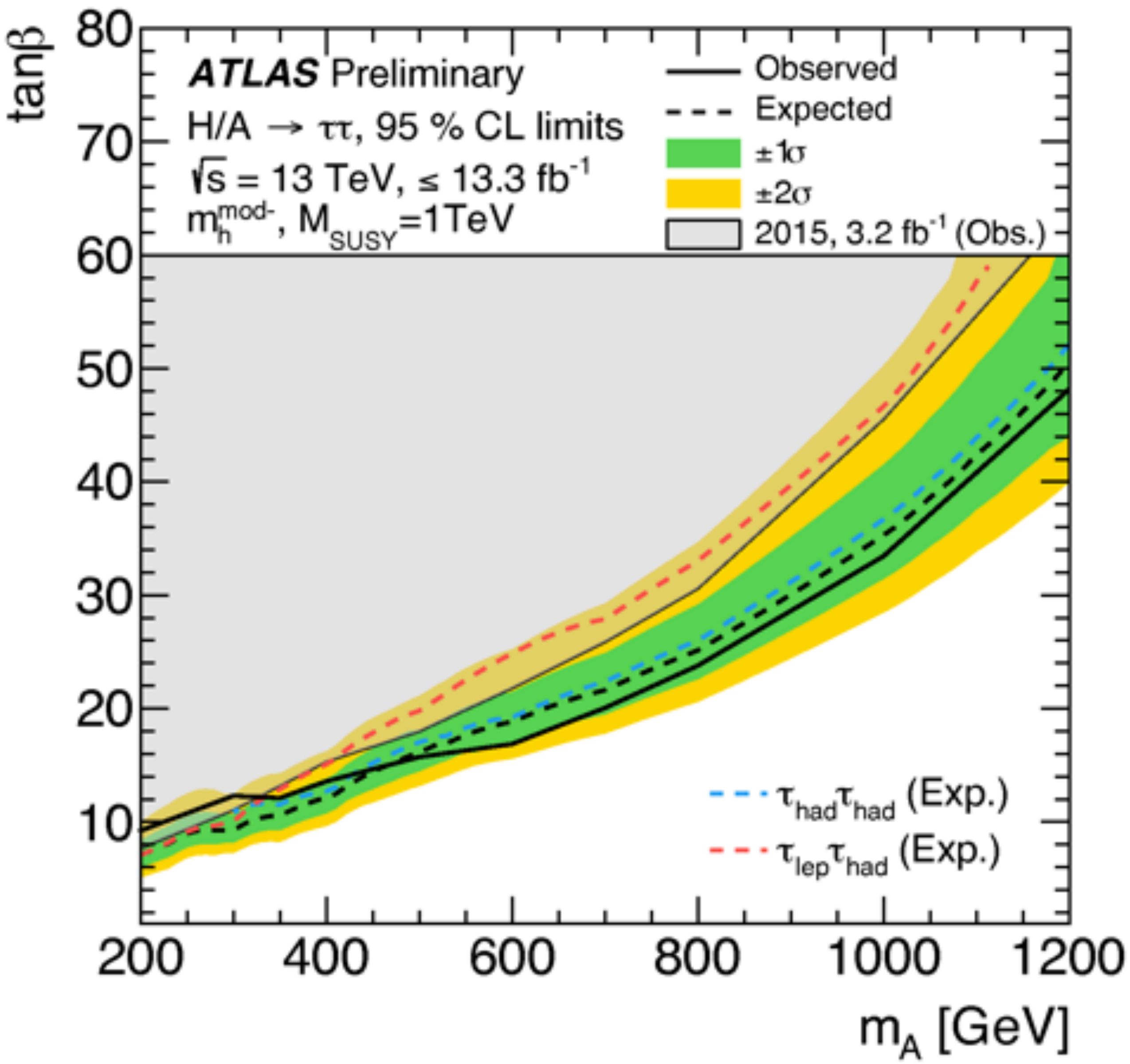
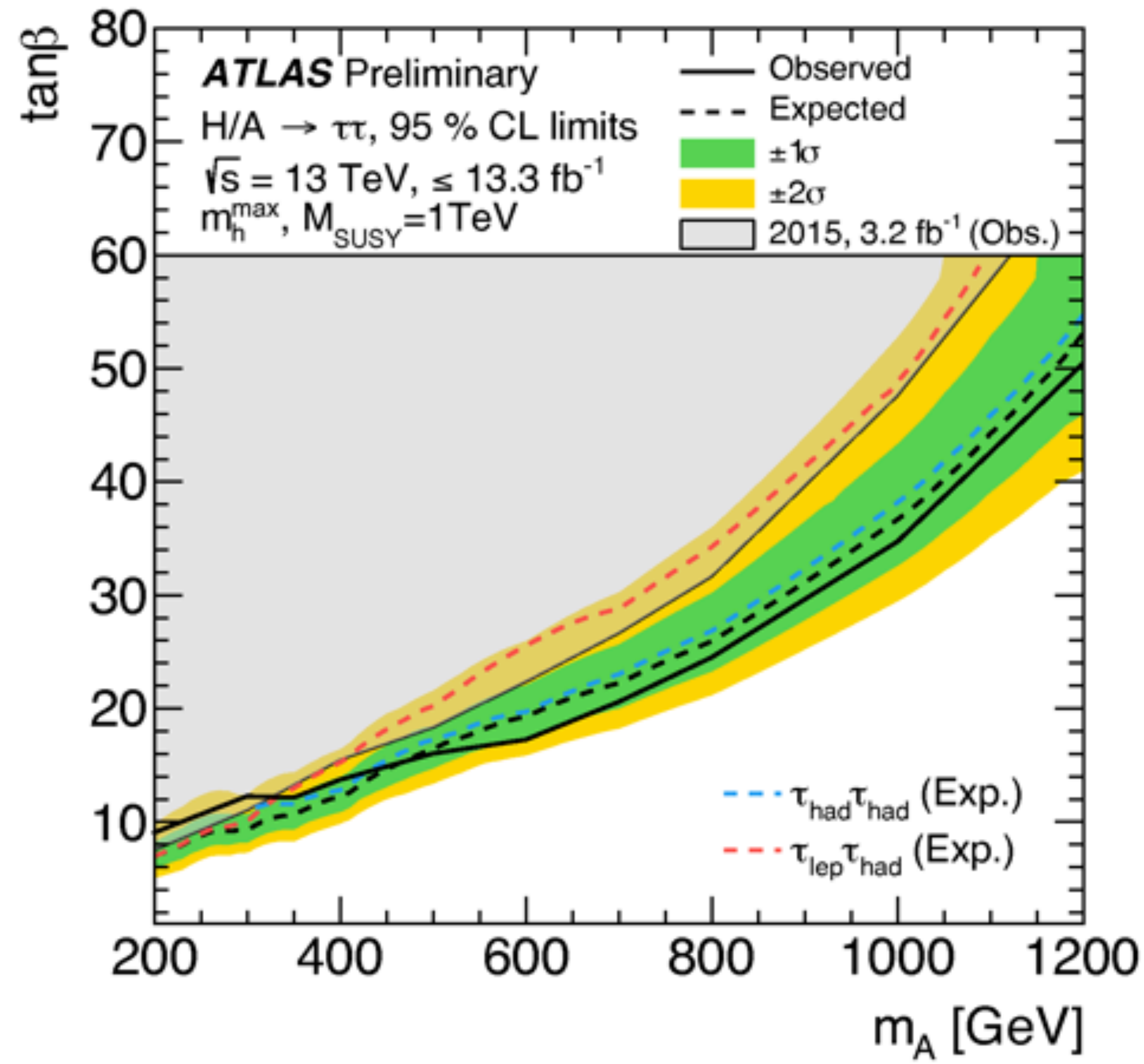


Figure 3: The distributions of $m_{\mathrm{T}}^{\mathrm{tot}}$ in (a) the b-veto control region of the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel, (b) the b-tag control region of the $\tau_{\mathrm{lep}}\tau_{\mathrm{had}}$ channel, (c) the b-veto same-sign validation region of the $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel and (d) b-tag same-sign validation region of the $\tau_{\mathrm{had}}\tau_{\mathrm{had}}$ channel. The various control and validation regions are defined in Table 1. The data are compared to the background prediction and a hypothetical MSSM $H/A \rightarrow \tau\tau$ signal (m_A = 600 GeV and $\tan\beta = 20$). The statistics of the simulated signal samples are limited in the background-dominated regions. The label "Others" in (c) and (d) refers to contributions from diboson, $Z(\ell\ell)$+jets and $W(\ell\nu)$+jets production. The background uncertainty includes statistical and systematic uncertainties. The bins have a varying size and overflows are included in the last bin of the distributions.

MSSM Neutral Higgs Search ($A/H \to \tau^+\tau^-$)





Backup Slides for A/H→ttbar

Monte Carlo for A/H→ttbar

Process	Generator	Cross-section calculation	PDFs
***A/H* signal**	MadGraph5_aMC@NLO [34] + Pythia6	Leading order (LO)	CT10 [35]
Top			
$t\bar{t}$	Powheg-Box [36–39] + Pythia6 [40]	NNLO+NNLL [25–31]	CT10
$t\bar{t} + V$	MadGraph5_aMC@NLO + Pythia6	NLO [41]	CTEQ6L1 [42]
$Wt/s/t$	Powheg-Box [37–39] + Pythia6	NLO [43–45]	CT10
***V*+jets**			
W+jets	Alpgen [46] + Pythia6	Data-driven normalisation	CTEQ6L1
Z+jets	Alpgen + Pythia6	NNLO [47]	CTEQ6L1
Diboson			
$WW/ZZ/WZ$	Sherpa [48–51]	NLO [52]	CT10

Table 1: List of the MC generators, the order of cross-section calculation in QCD, and the PDF sets used in the generation of signal and background processes. All generator versions are the same as those in Ref. [1]. The background from multijet events was estimated in a fully data-driven way (Section 8.)

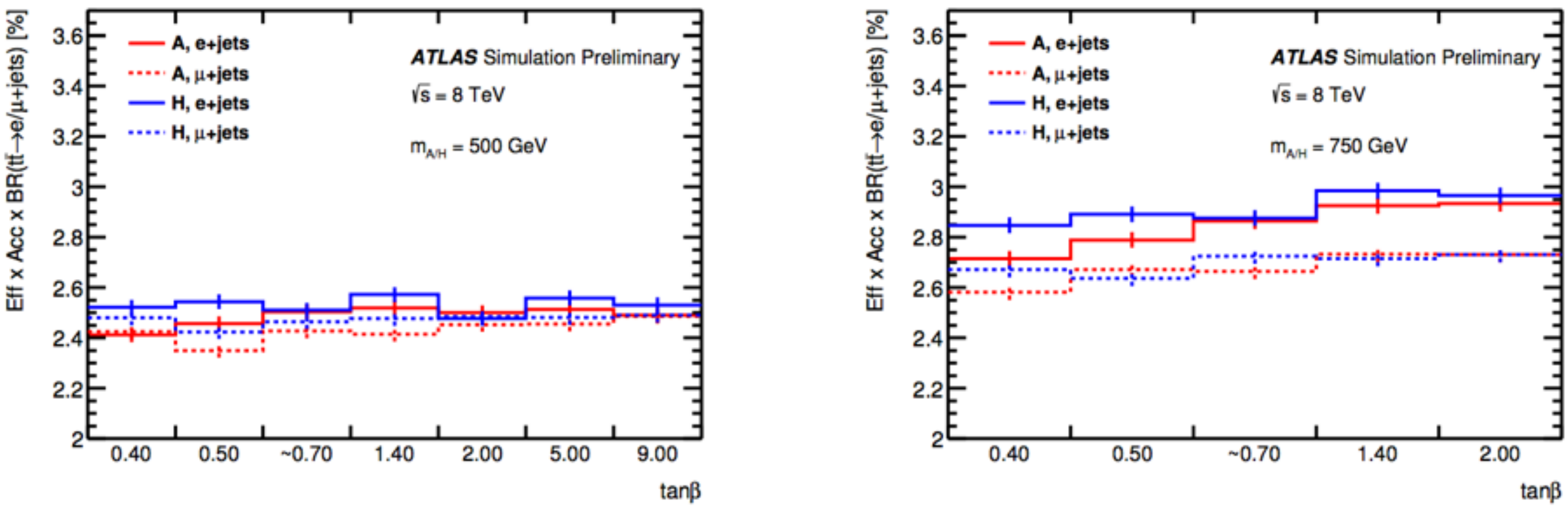
- Backgrounds for W+jets (normalization only) and multi-jets are estimated in a data-driven way
  - For W+jets, data is used to derive scale factors correcting the overall normalisation and the individual flavour fractions in the Alpgen simulation (by comparing with the W boson charge asymmetry in data)
  - For multi-jets, a matrix method, which utilises efficiencies for leptons produced by prompt and non-prompt sources, is used to estimate the background from data (this is used for both the normalization and shape).

Signal Modeling for A/H→ttbar

- Indirect Approach:
  - Two large samples are generated using MadGraph5_aMC@NLO:
    - One sample for the SM ttbar background (B)
    - One sample in which all Feynman diagrams are taken into account (S + I + B)
  - Events selection and reconstruction are applied on each sample separately
  - The m_{tt} invariant mass distributions are obtained
  - The difference of the two resulting histograms (S+I+B) - (B) corresponds to (S+I)
  - Disadvantage: one must generate and simulate a large S+I+B sample at each point in parameter space

- Direct Approach:
  - MadGraph5_aMC@NLO code is modified to remove the SM ttbar matrix element
  - This yields a pure S+I contribution on an event-by-event basis
  - Advantage: SM ttbar background does not need to be generated for each signal parameter point
  - **The direct approach is the one used to generate all S+I samples used for this preliminary result**
  - Difference between direct and indirect is taken as a systematic for the signal modeling uncertainty

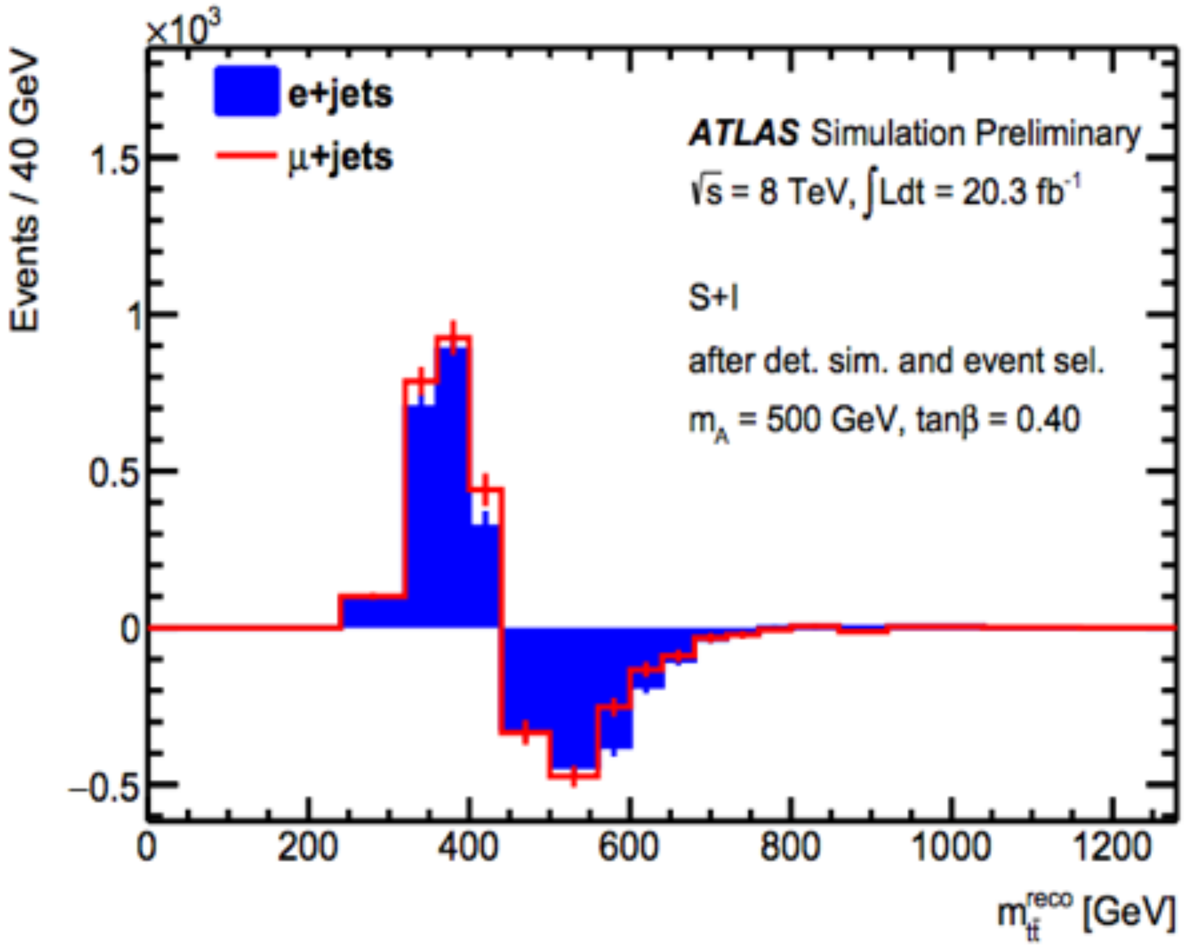
Selection Efficiencies for A/H→ttbar



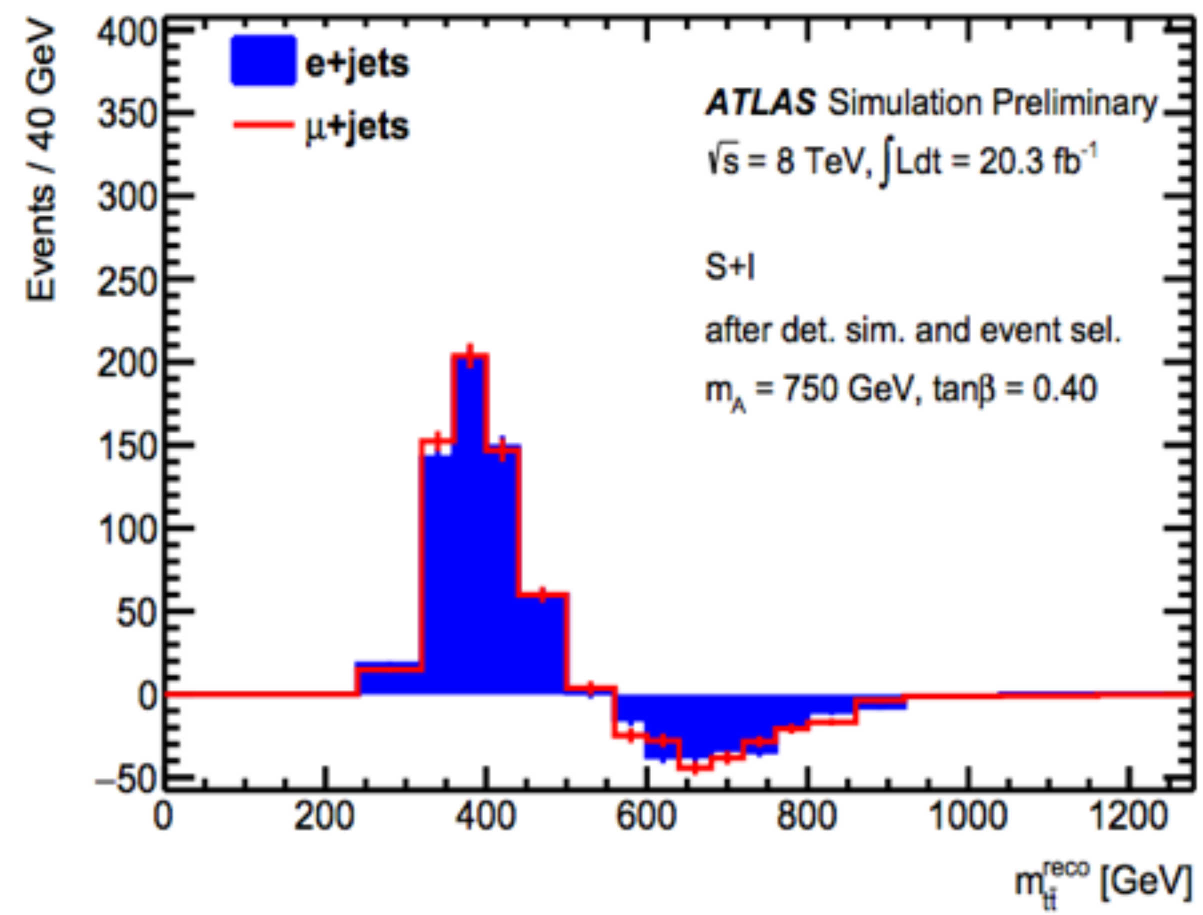
(a) (b)

Figure 4: The selection efficiencies for pure resonant signal samples with resonance masses of (a) 500 GeV and (b) 750 GeV. The *A* and *H* distributions show a difference of less than 5% at 500 GeV and less than 10% at 750 GeV.

Invariant Masses for A/H→ttbar



(a) m_A = 500 GeV, tan β = 0.40



(b) m_A = 750 GeV, tan β = 0.40

Figure 5: Distribution of the $t\bar{t}$ invariant mass, reconstructed with the χ^2 algorithm, for $S + I$ events with a pseudoscalar resonance A that fulfill the e+jets (blue) and μ+jets (red) selections. *Left column*: m_A = 500 GeV for tan β values of (a) 0.4 (c) 0.68 (e) 9.0. *Right column*: m_A = 750 GeV for tan β values of (b) 0.4 (d) 0.7 (f) 2.0. The parameter $\sin(\beta - \alpha)$ is set to unity in all cases. The distributions are normalised to an integrated luminosity of 20.3 fb^{-1}.

Systematic Uncertainties for A/H→ttbar

Source	Impact on $\Delta\mu$	
Object systematic uncertainties		
Jets & $E_{\mathrm{T}}^{\mathrm{miss}}$	+0.22	−0.22
Luminosity	+0.04	−0.03
b-tagging	+0.05	−0.04
Background systematic uncertainties		
Diboson	+0.26	−0.29
Z+jets	+0.21	−0.22
W+jets	+0.15	−0.16
$t\bar{t}$	+0.06	−0.05
Total		
Total systematic uncertainty	+0.41	−0.43
Data statistical uncertainty	+0.12	−0.12
Total uncertainty	+0.43	−0.44

Results for A/H→ttbar

Type	e+jets		μ+jets		Sum	
$t\bar{t}$	95,000	± 11,000	93,000	± 11,000	188,000	± 22,000
Single top quark	3,900	± 500	3,800	± 500	7,700	± 1,000
$t\bar{t}V$	290	± 40	280	± 40	560	± 80
W+jets	6,600	± 2,100	7,200	± 2,300	13,800	± 4,300
Z+jets	1,400	± 620	650	± 250	2,100	± 900
Diboson	320	± 120	310	± 120	630	± 240
Multijet e	5,300	± 1,100	-		5,300	± 1,100
Multijet μ	-		1,060	± 230	1,060	± 30
Total	112,000	± 13,000	106,000	± 12,000	219,000	± 25,000
Data	115,785		110,218		226,003	

Table 2: Data and expected background event yields after the resolved-topology selection. The uncertainty on the expected background yields is derived by summing all systematic uncertainties and the MC statistical uncertainty in quadrature. The expected yields and uncertainties are shown before the profile likelihood fit (described in the text) to the full dataset.

- A binned profile likelihood ratio fit is carried out for the signal parameter μ:

$$\mu \cdot S + \sqrt{\mu} \cdot I + B = \sqrt{\mu} \cdot (S + I) + (\mu - \sqrt{\mu}) \cdot S + B,$$

Post-Fit Plots for A/H→ttbar