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

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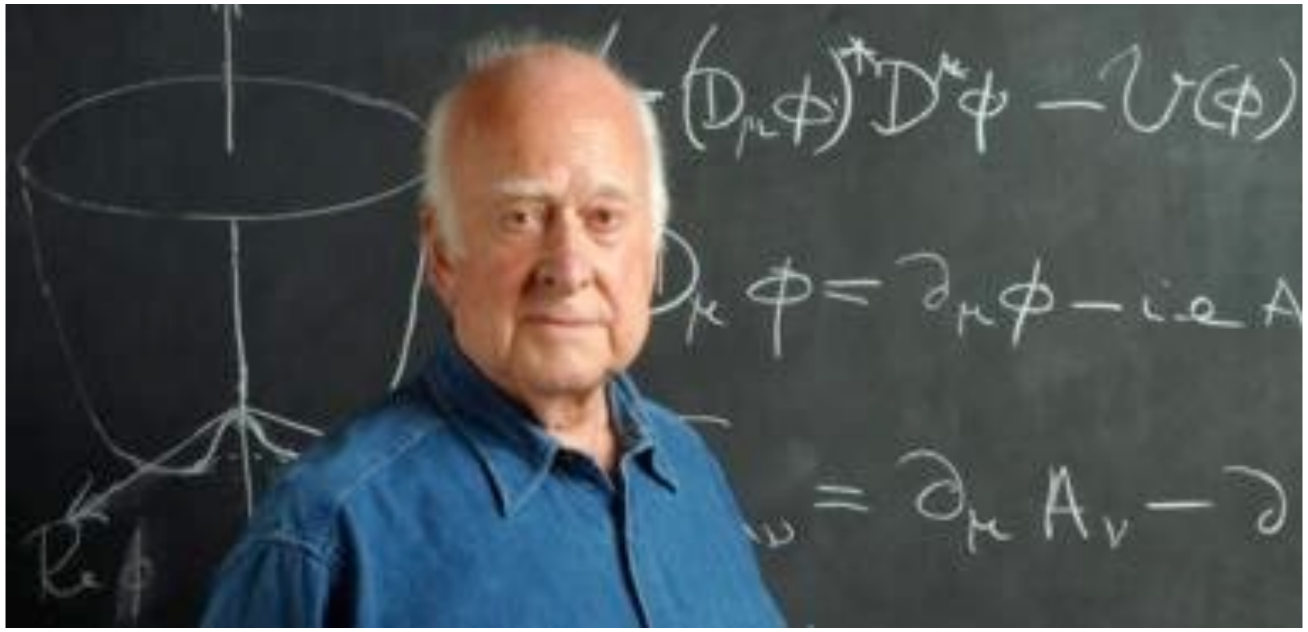
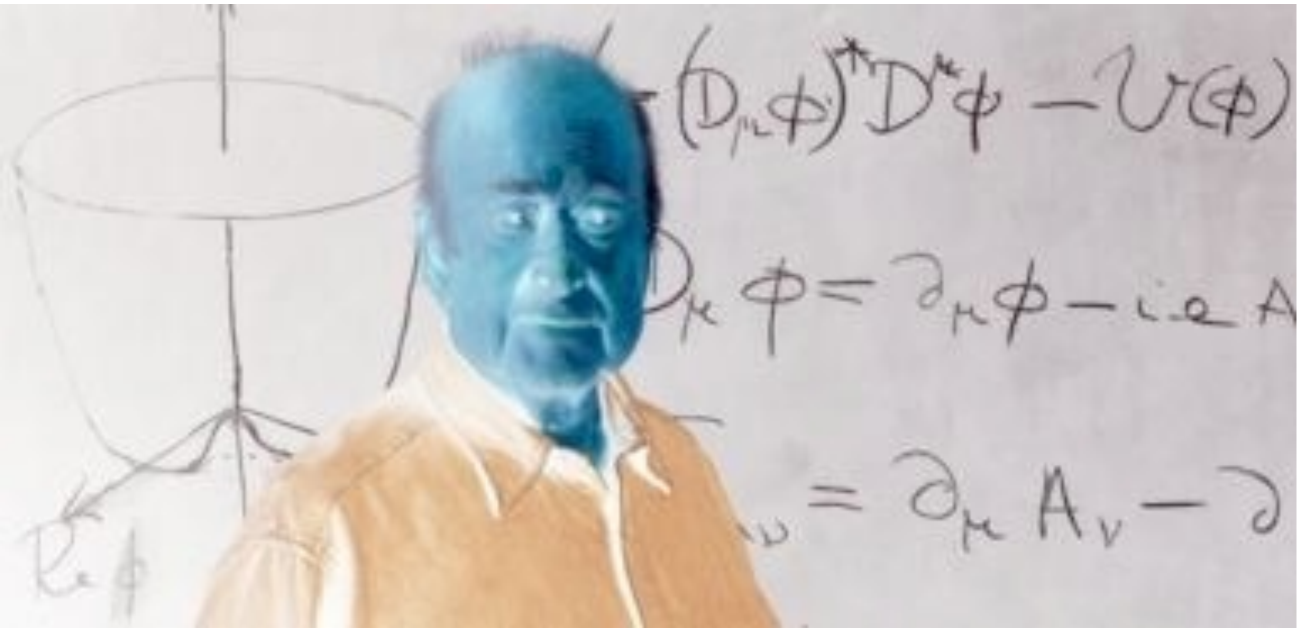
December 14, 2017

SUSY-2017 — Mumbai, India

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



Standard Model Higgs



Beyond the SM Higgs

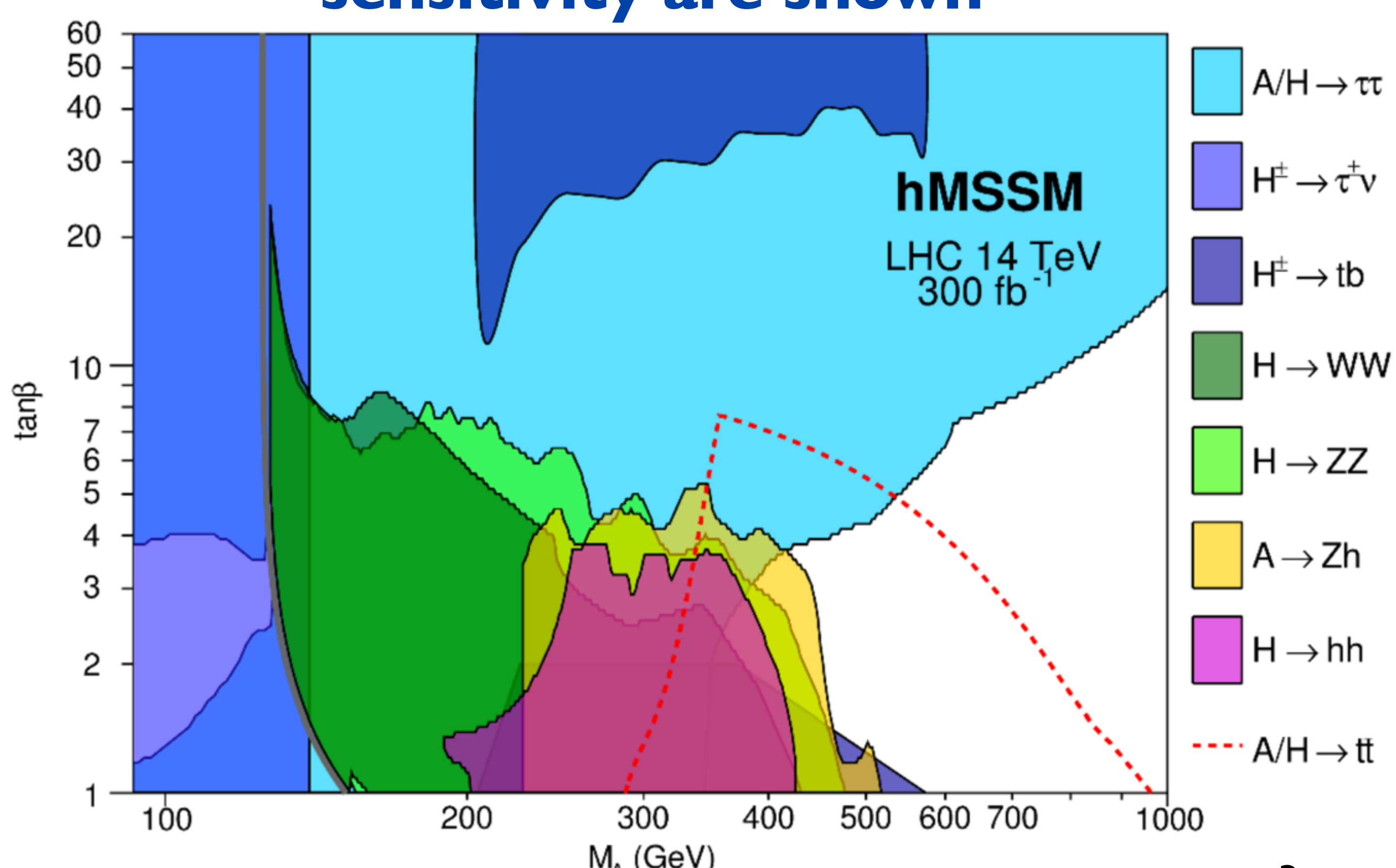
- Suppose that this is not the Standard Model Higgs…
  - Higgs with different couplings? ⇒ 2HDM, ~~Fermiophobic~~, Higgs impostor
  - More complicated Higgs sector? ⇒ MSSM, Doubly-charged Higgs, Composite
  - Light scalar Higgs? ⇒ NMSSM (Next-to-Minimal SUSY extension to SM)
  - Hidden Higgs sector? ⇒ Higgs to long-lived particles / decays into Dark Matter

Neutral MSSM Higgs Searches

- 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 (all SUSY particles are heavy)
  - **m_h^{mod} scenario:** top-squark mixing parameter is chosen such that the mass of the lightest CP-even Higgs boson is close to the mass of the one observed at the LHC (historical)

- Two recent ATLAS high-mass neutral Higgs searches using fermions to show you…
  - A/H to ττ using 36.1 fb^{-1} of 13 TeV pp collision data — arXiv: 1709.07242
  - A/H to ttbar using 20.3 fb^{-1} of 8 TeV pp collision data — PRL 119 (2017) 191803

Theory projections for 2σ sensitivity are shown



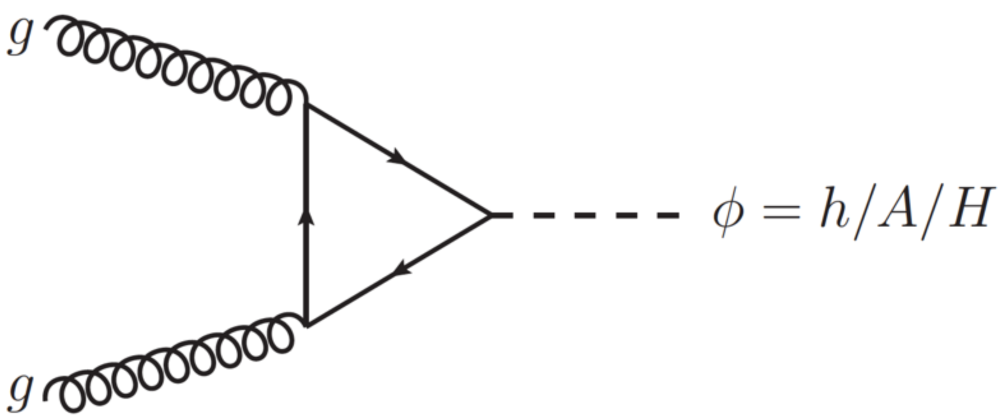
A/H to ττ and A/H to ttbar are each very important channels at mid- to high-m_A

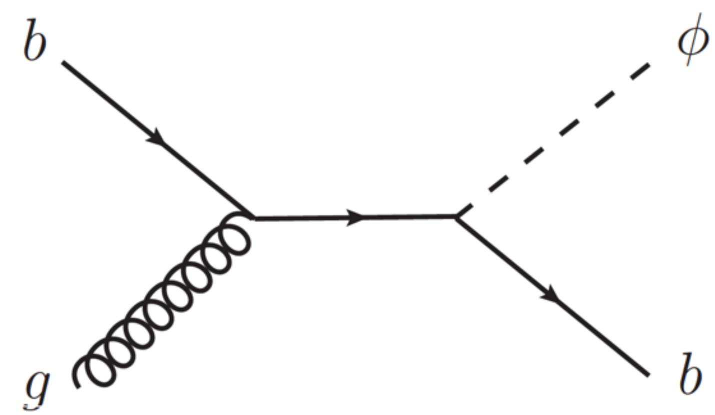
Djouadi, A., Maiani, L., Polosa, A. et al. JHEP 06 (2015) 168

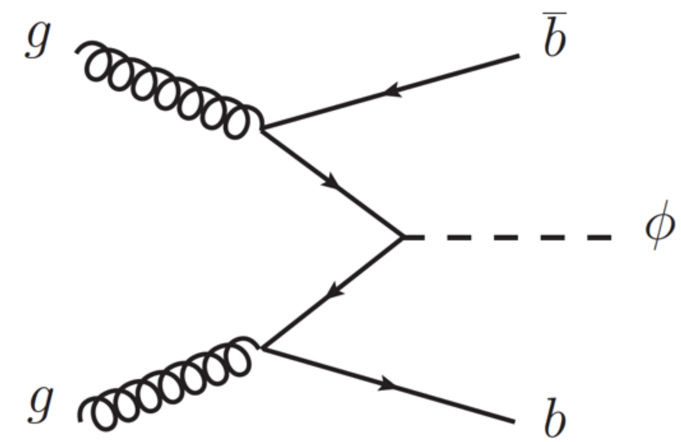
MSSM Higgs Search ($A/H \to \tau^+\tau^-$)

- Latest ATLAS MSSM neutral Higgs search uses 36.1 fb^{-1} of 13 TeV data from Run-2
  - Improvement on our limits from the result published in EPJC: Eur. Phys. J. C (2016) 76: 585
  - New result recently submitted to JHEP: arXiv: 1709.07242

- Can use different categories to target main production mechanisms:
  - "no b-tag" targets gluon-fusion (dominant production mode at small tanβ)
  - "b-tag" (70%) targets b-associated production (dominant production mode at large tanβ)







- Can also separate based on the τ lepton decay mode (for a total of 4 categories):
  - Lepton-Hadron: high-p_T single lepton triggers (e or μ); one hadronic tau (55%)
  - Hadron-Hadron: high-p_T hadronic tau trigger; two hadronic taus (60%, 55%)

- Monte Carlo samples used:
  - A/H to ττ signal: Powheg-Box+Pythia8 (ggH) and MG5_aMC@NLO + Pythia8 (bbH)
  - Backgrounds:
    - Powheg+Pythia8 (Z+jets, W+jets in lep-had, and top)
    - Sherpa (W+jets in had-had and dibosons)

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

lepton-hadron final state

- Jet$\rightarrow\tau$ fake
- $Z/\gamma^*\rightarrow\tau\tau$
- $Z/\gamma^*\rightarrow ll$
- Top
- Diboson

- Largest background: Jets faking taus; not well-modeled in Monte Carlo
  - Separate fake factors are derived from data control regions for W+jets, top and multijets
  - These fake factors are parameterized by tau p_T and number of tracks
- Z+jets, other top and diboson are estimated using Monte Carlo and the ttbar normalization is done using a top-rich control region in the data

hadron-hadron final state

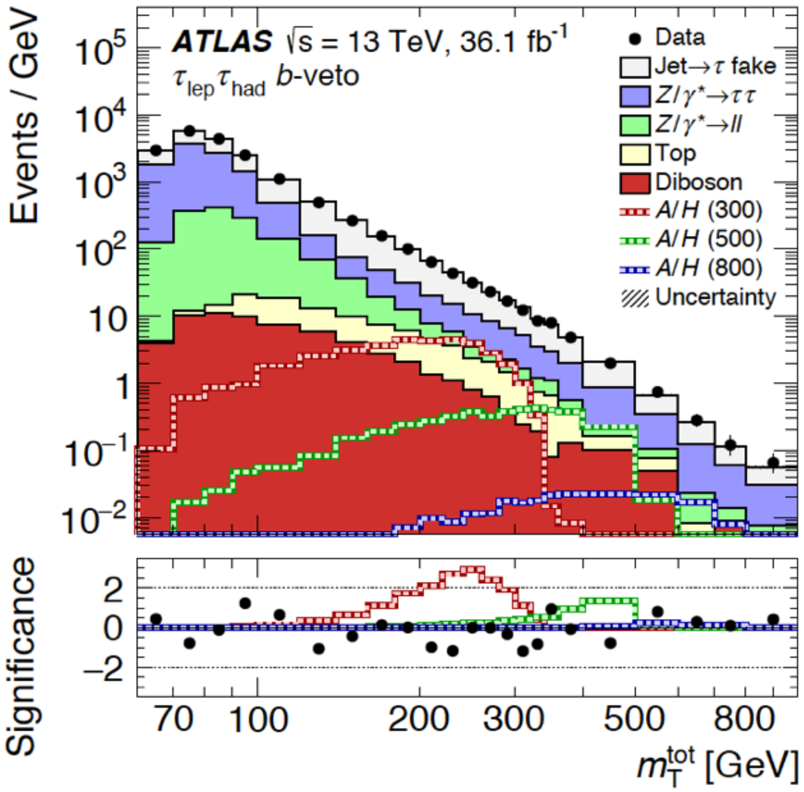
- Multijet
- $Z/\gamma^*\rightarrow\tau\tau$
- $W\rightarrow\tau\nu$
- Top
- Others

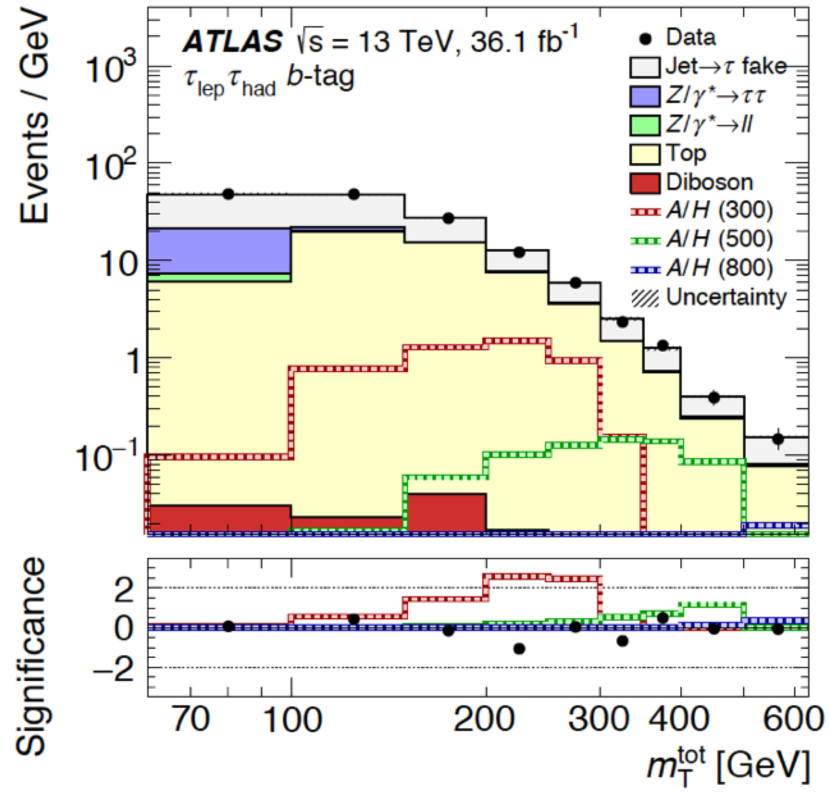
- Largest background: Multi-jets faking taus; not well-modeled in Monte Carlo
  - A fake factor is derived from data control regions, and then applied to the anti-ID regions to obtain estimates for the signal regions
  - This fake factor is parameterized by tau p_T and number of tracks
- For Z+jets,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

arXiv: 1709.07242

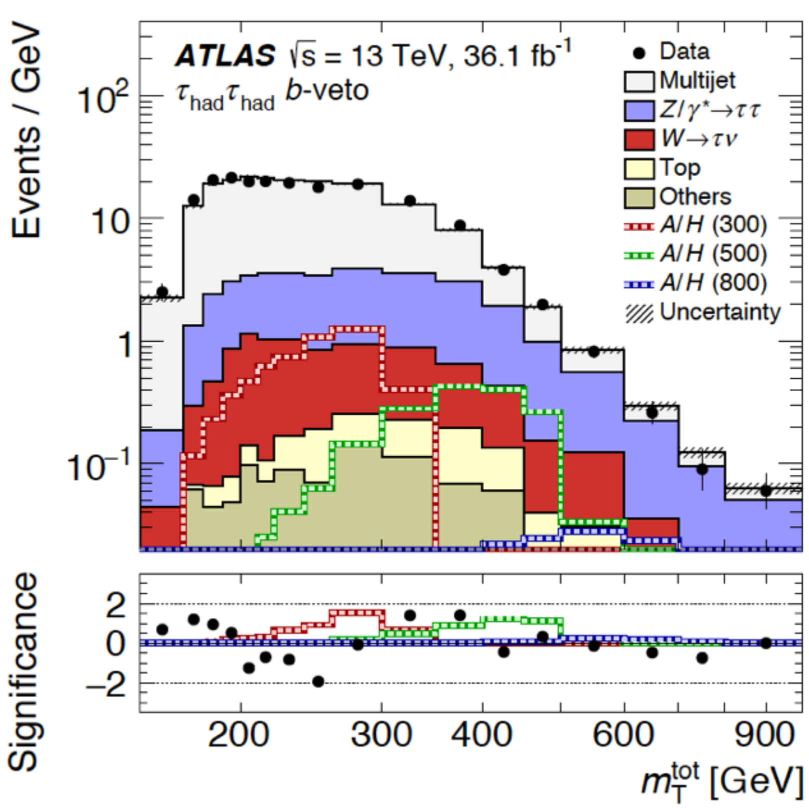
Post-fit Plots for the 4 Categories ($A/H \to \tau^+\tau^-$)

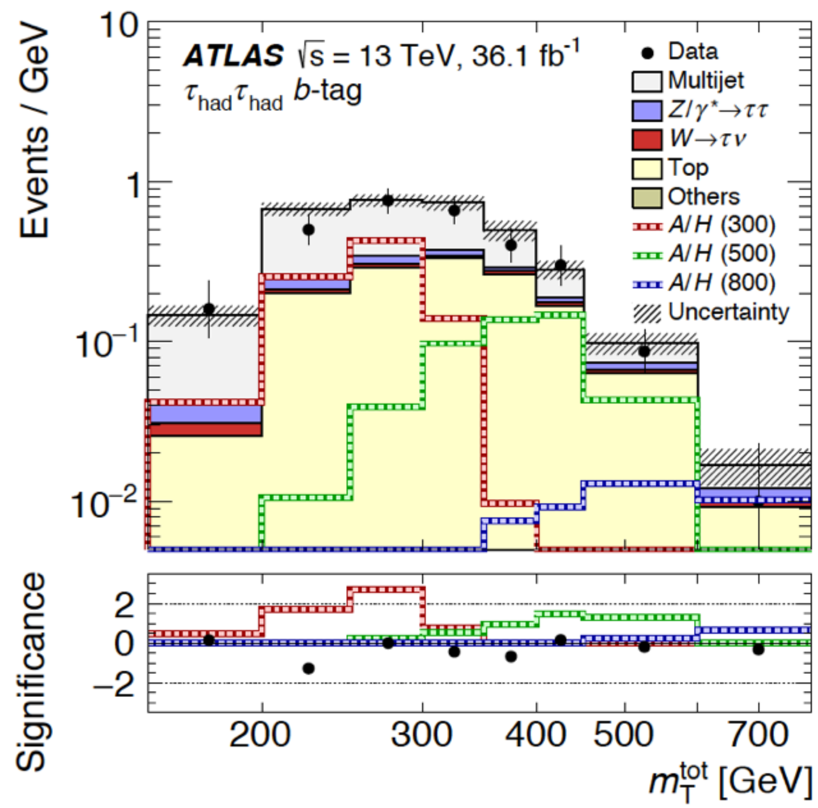
lep-had b-veto | **lep-had b-tagged**





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

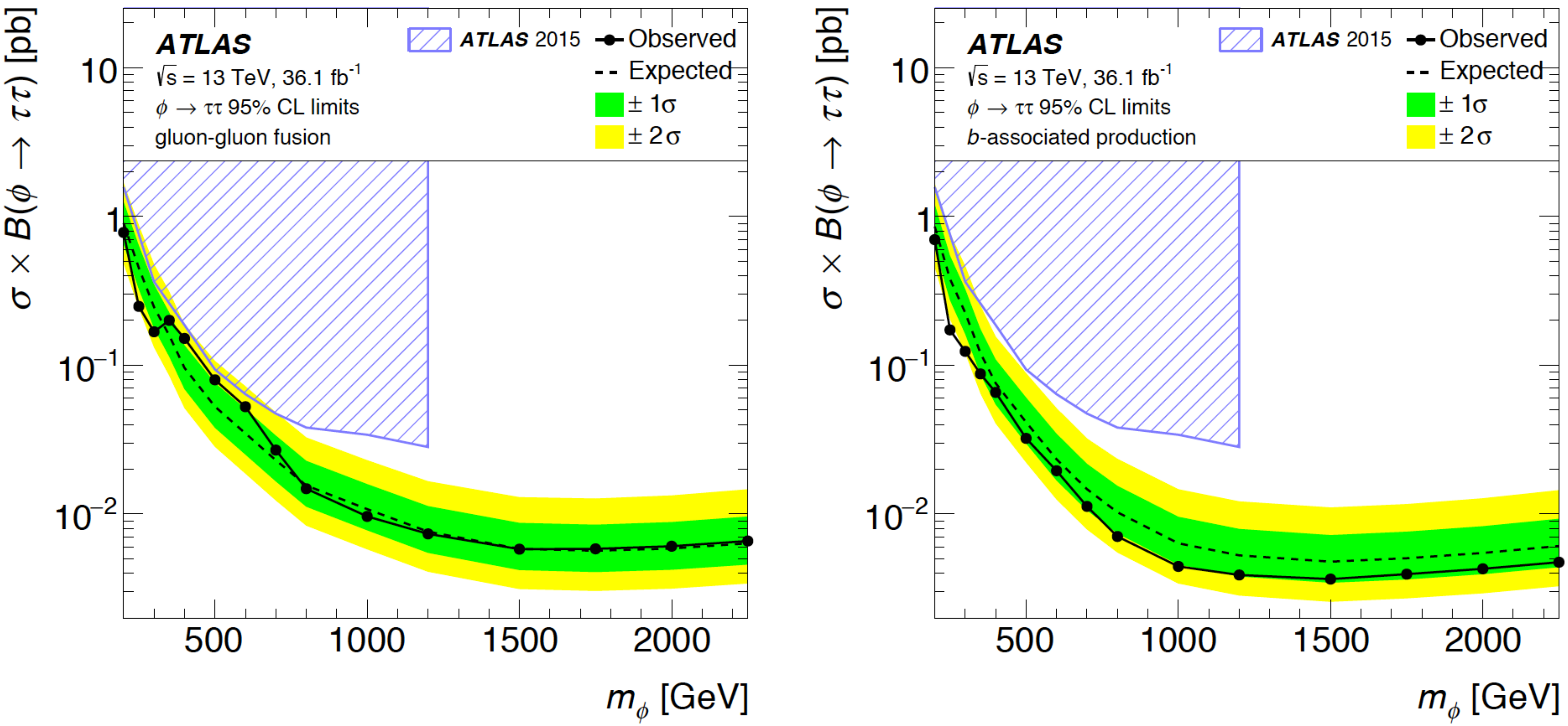
$$m_T^{tot} \equiv \sqrt{(p_T^{\tau_1} + p_T^{\tau_2} + E_T^{miss})^2 - (\mathbf{p}_T^{\tau_1} + \mathbf{p}_T^{\tau_2} + \mathbf{E}_T^{miss})^2}$$

- Signal superimposed with $m_{A/H}$ = 300, 500 and 800 GeV (assuming hMSSM and tanβ = 10)

arXiv: 1709.07242

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

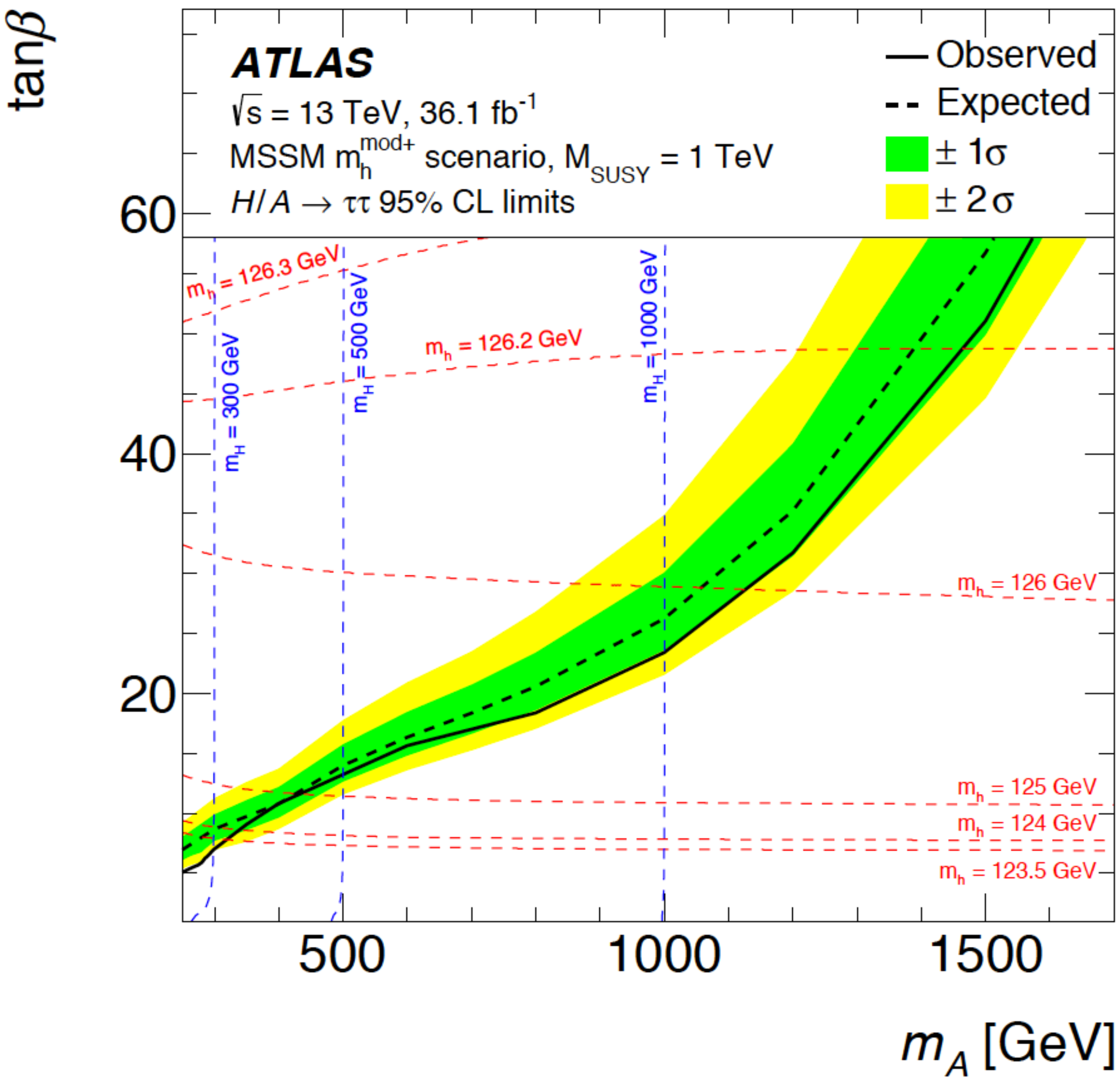
- Dominant systematics: τ energy scale, τ trigger (had-had), τ identification efficiency, fakes
- Statistically combine the τ_{lep}-τ_{had} and τ_{had}-τ_{had} channels for one exclusion limit
- We determine a σ x BR limit ($A/H \to \tau\tau$) for gluon-fusion and b-associated production
- Exclusions range from 0.78 pb – 5.8 fb for gluon-fusion and 0.70 pb – 3.7 fb for b-associated in the range of 200 GeV – 2.25 TeV

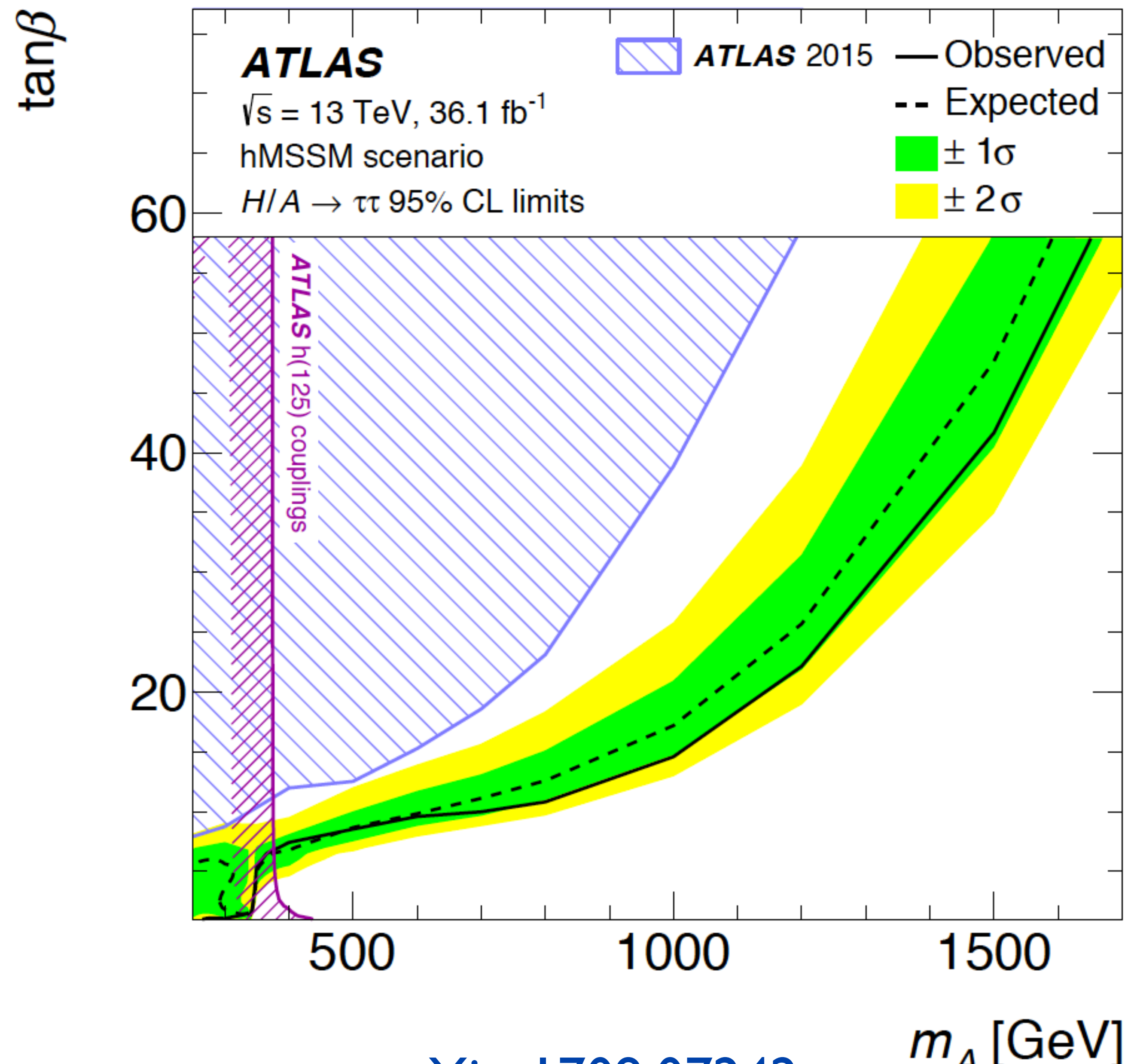


arXiv: 1709.07242

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+}, we exclude tanβ > 5.1 for m_A = 250 GeV and tanβ > 51 for m_A = 1.5 TeV
- In the hMSSM, we have sensitivity to exclude the low m_A-low tanβ 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)

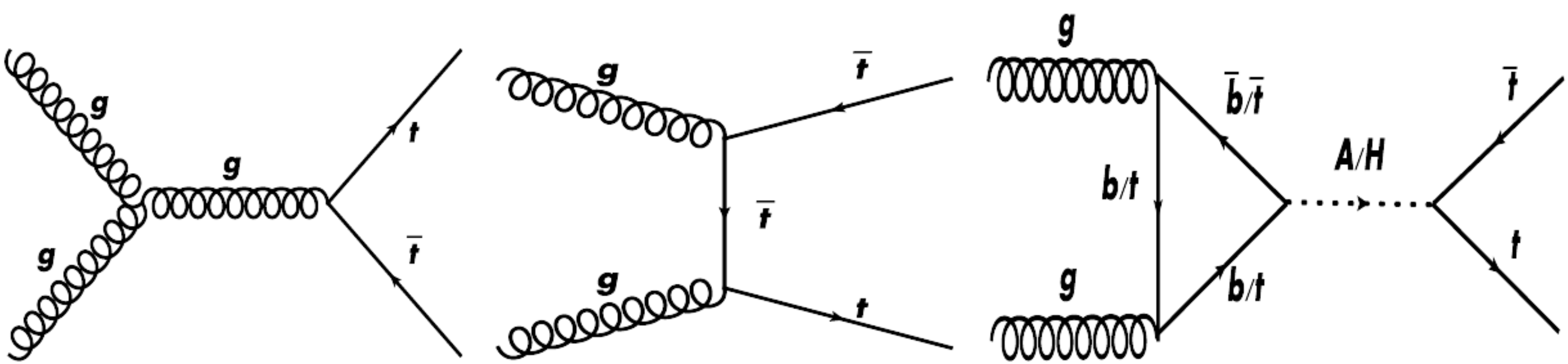




arXiv: 1709.07242

High-mass Higgs Search (A/H→ttbar)

- We revisit a Run-1 generic scalar ttbar resonance search that used 20.3 fb^{-1} of 8 TeV proton-proton collision data: ATLAS collaboration, JHEP 08 (2015) 148
- The 2017 analysis (PRL 119 (2017) 191803) uses the ttbar lepton+jets channel, specifically targets A/H, and takes the interference between the signal and ttbar background production modes into account for the first time

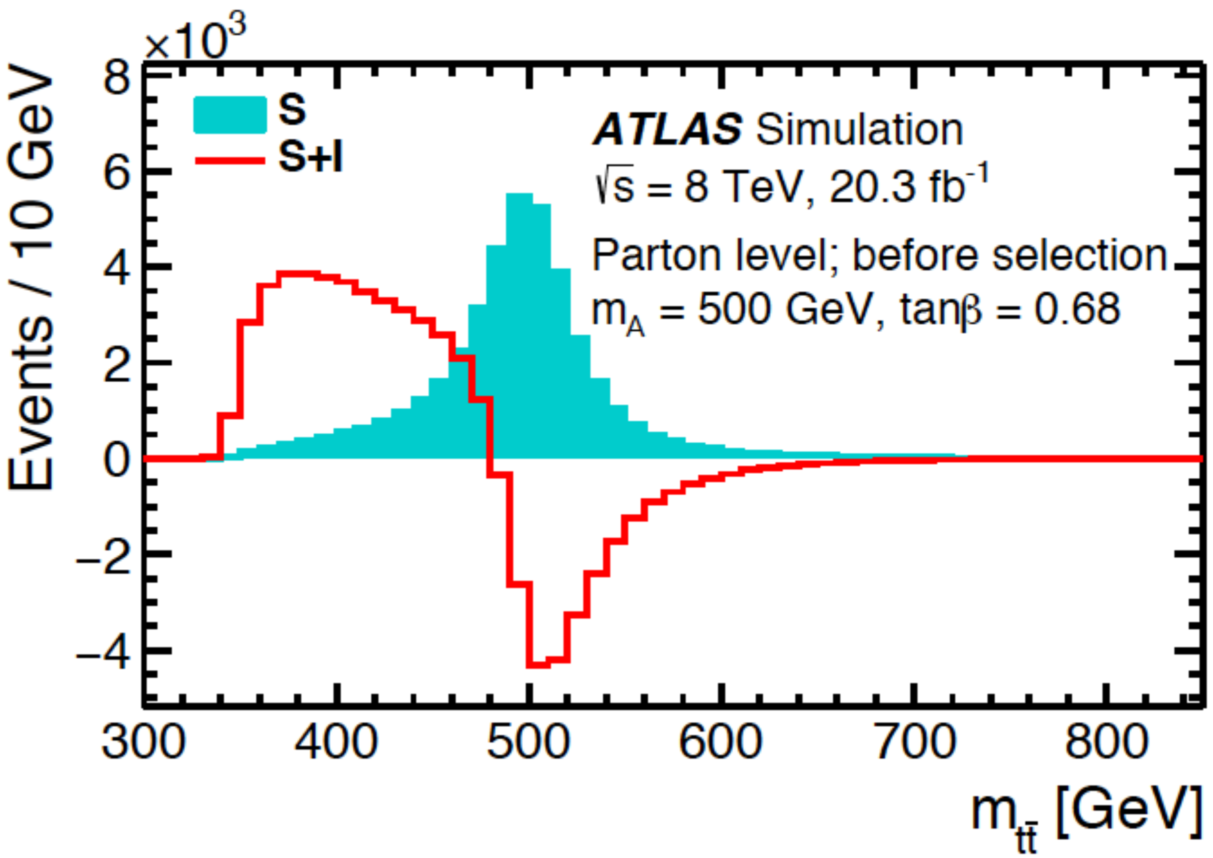


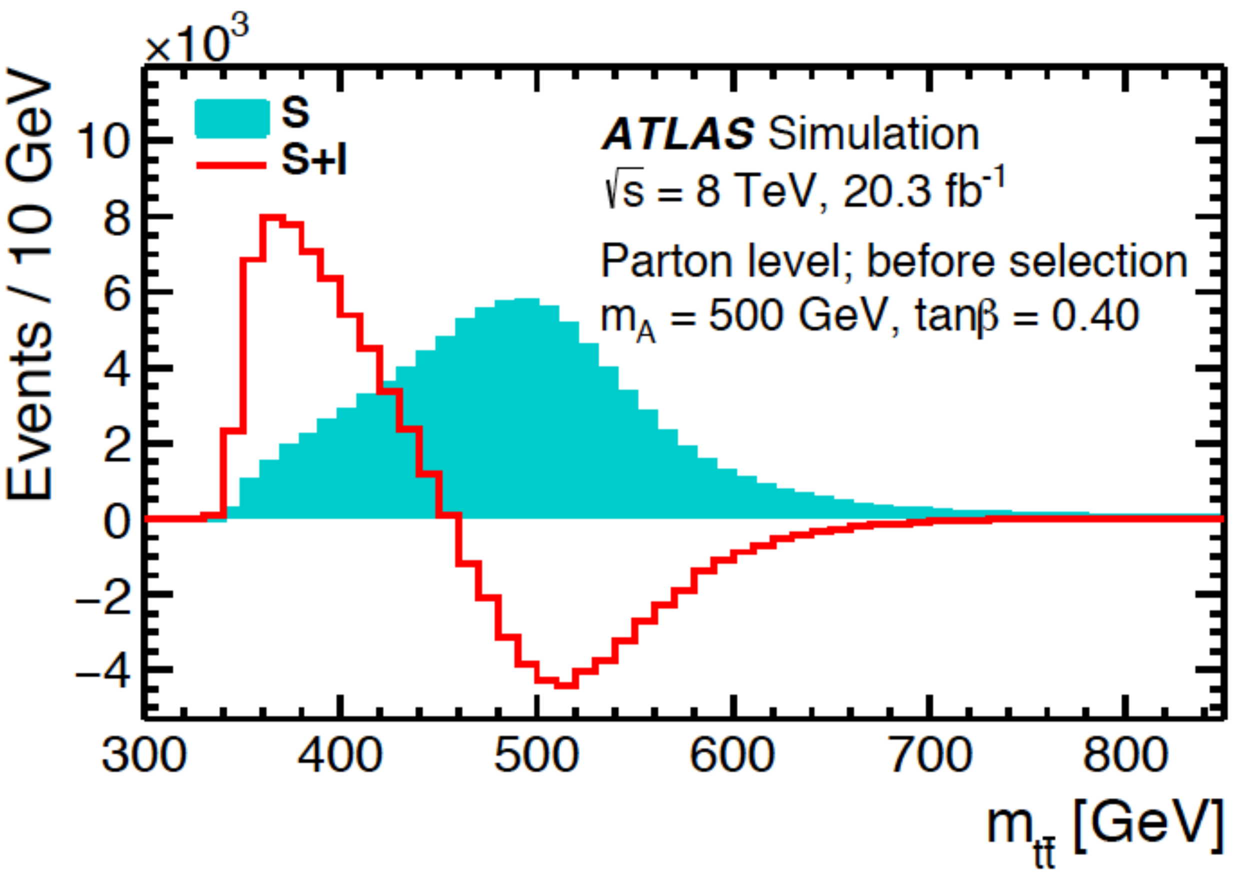
- Monte Carlo samples used:
  - A/H to ttbar signal: MadGraph5+Pythia6
  - Backgrounds:
    - ttbar: Powheg-Box+Pythia6
    - ttbar + V: MadGraph5+Pythia6
    - single top: Powheg+Pythia6
    - W+jets and Z+jets: Alpgen+Pythia6
    - Diboson: Sherpa

MadGraph5 used for both "indirect" (S+I+B) and "direct" (S+I) 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(α-β) is set to 1 (i.e., the "alignment limit", where h has decays as expected in the SM)



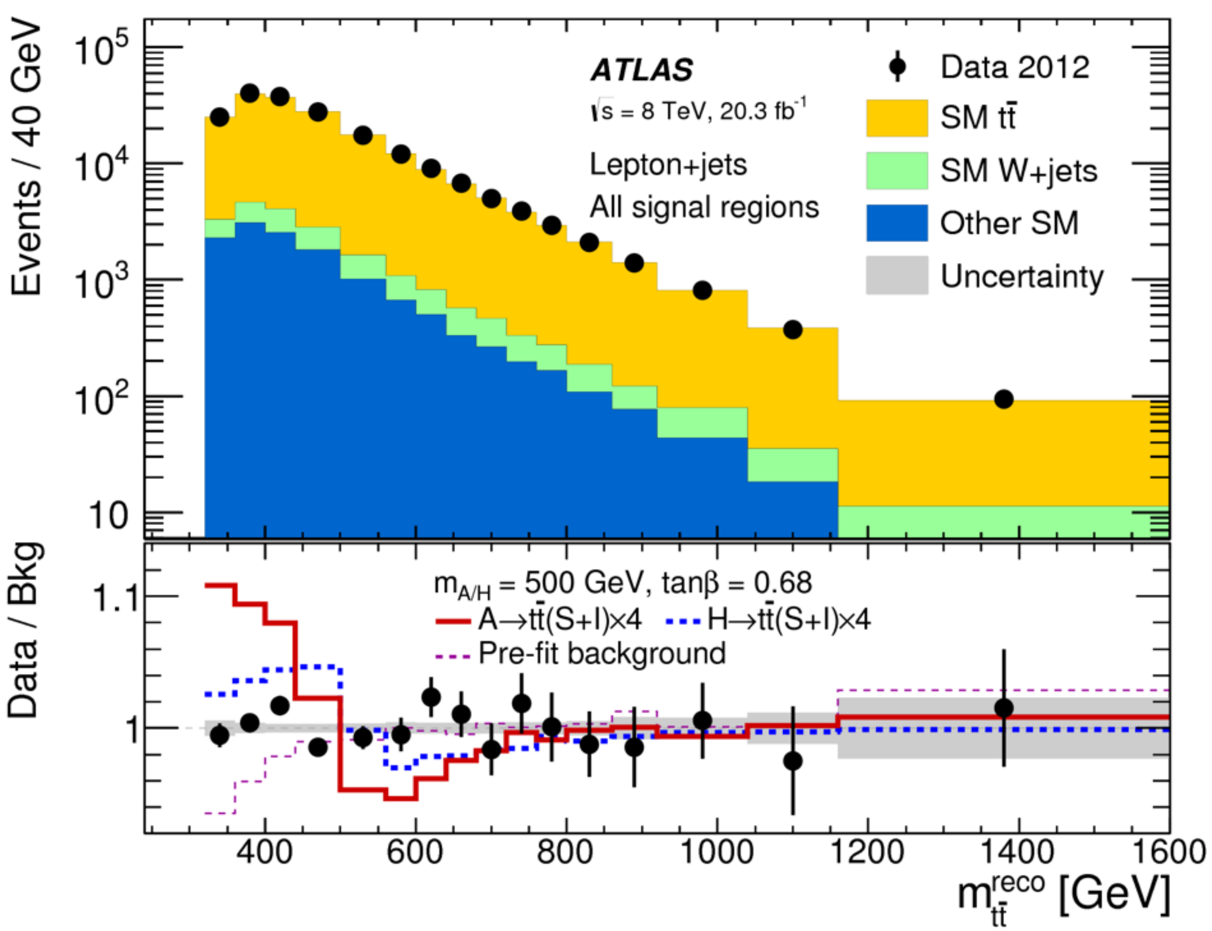


PRL 119 (2017) 191803

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%)

- 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)

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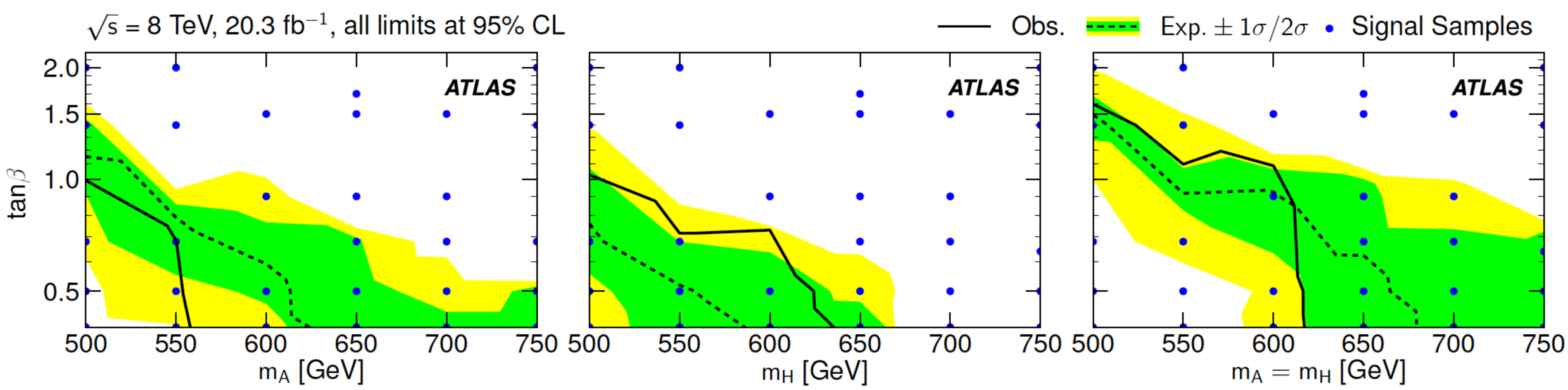
High-mass Higgs Search Results (A/H→ttbar)

- No significant excess or deficit from the Standard Model background expectation is observed
- The 95% CL expected and observed upper limits on the signal strength μ are shown for a Type-II 2HDM in the alignment limit considering only a pseudoscalar A (left), only a scalar H (middle), and the mass-degenerate scenario $m_A = m_H$ (right).
- Blue points indicate parameter values at which signal samples are available. Values at intermediate points are obtained from a linear triangular interpolation. The observed (expected) exclusion region for the Type-II 2HDM (μ = 1) is indicated by a solid (dashed) line.



PRL 119 (2017) 191803

Conclusions and Outlook

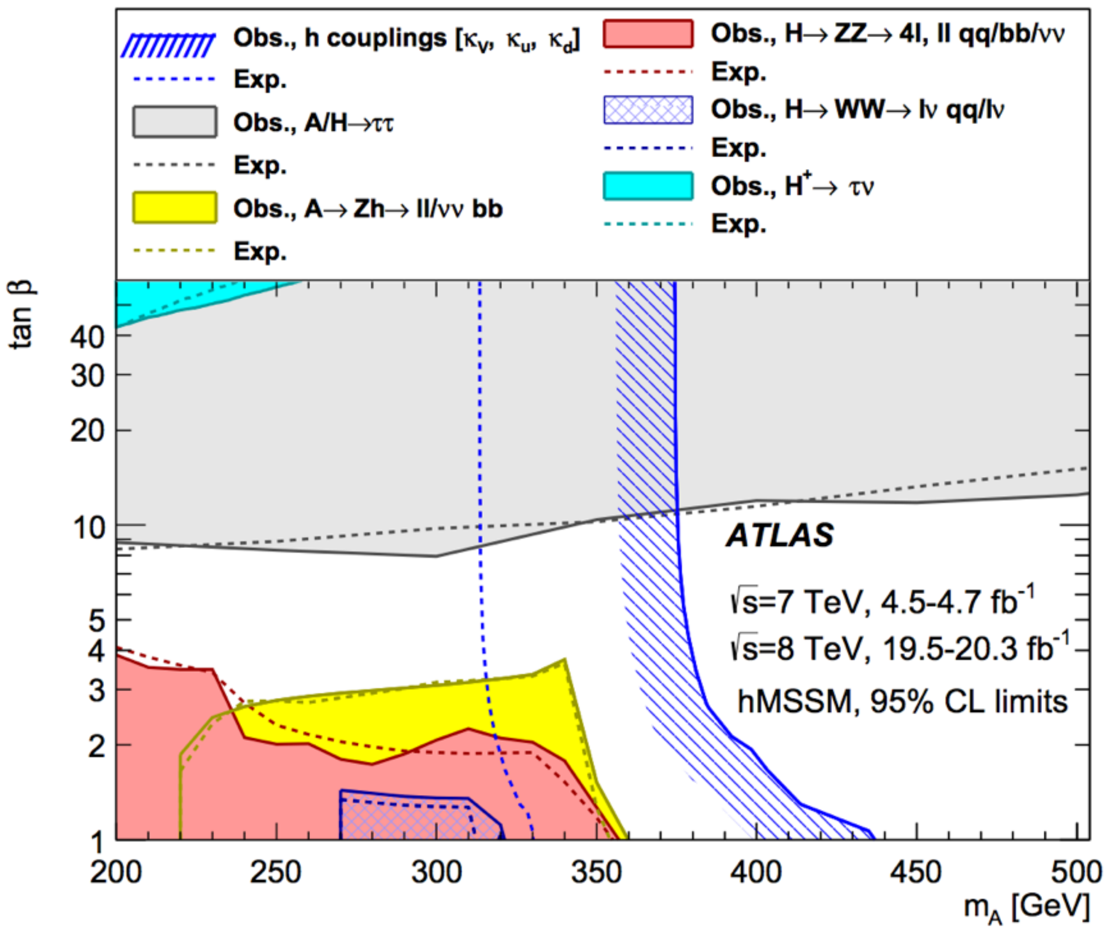
- ATLAS has performed new searches for high-mass neutral Higgs bosons decaying to fermions
  - The new $A/H \rightarrow \tau\tau$ analysis uses up to 36.1 fb^{-1} of 13 TeV collision data recorded during Run-2; this result improves on an earlier ATLAS paper published in EPJC
  - The $A/H \rightarrow$ttbar analysis is an extension of a generic Run-1 scalar ttbar resonance 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

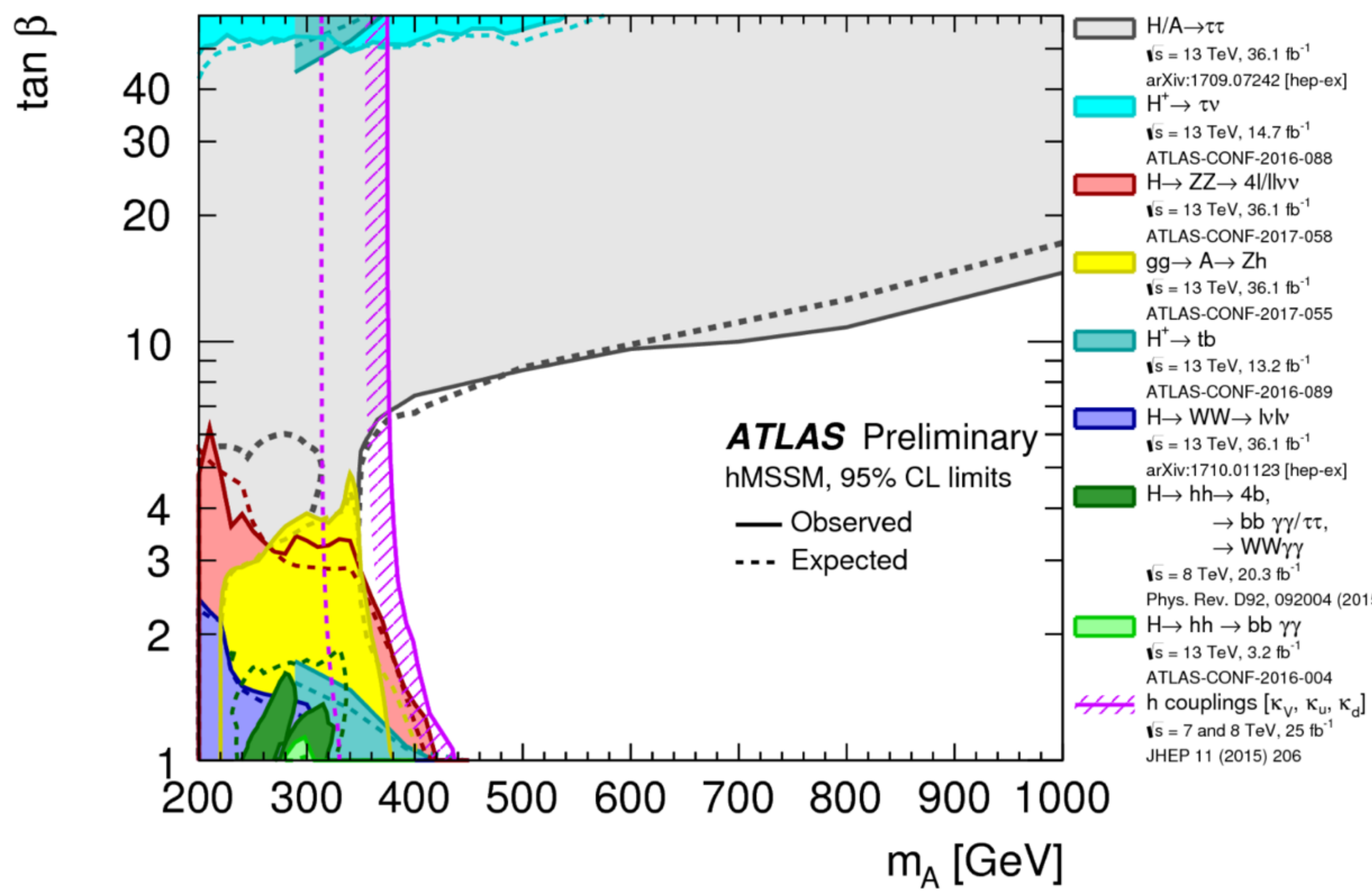
- No significant excess is observed in the data from either search, and 95% CL limits are set
  - **$A/H \rightarrow \tau\tau$:** We determine a $\sigma \times$ BR limit for gluon-fusion and b-associated production separately; exclusions range from 0.70 pb – 3.7 fb for masses in the range of 0.2–2.25 TeV
  - **$A/H \rightarrow \tau\tau$:** We also show limits in the m_h^{mod+} and hMSSM benchmark scenarios; e.g., in the hMSSM scenario the most stringent constraints exclude $\tan\beta > 1.0$ for m_A=0.25 TeV (>42 for m_A=1.5 TeV)
  - **$A/H \rightarrow$ttbar:** For the mass-degenerate case (m_A=m_H) with a mass of 500 GeV, parameter values of $\tan\beta < 1.55$ in the Type-II 2HDM (in the alignment limit) 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

ATLAS Run-1 and Run-II hMSSM Exclusion

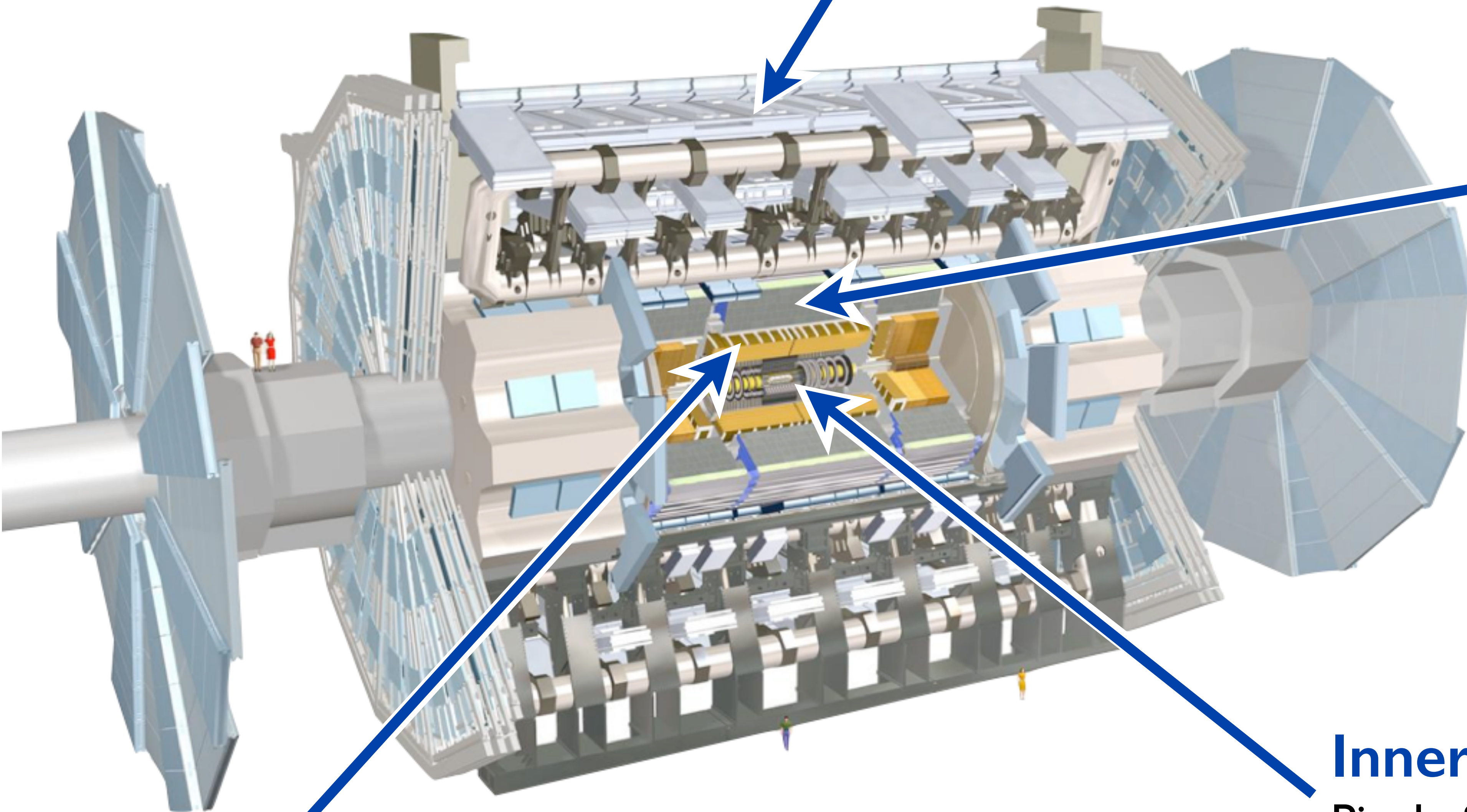




The ATLAS Experiment at the CERN LHC

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_μ ~ 1 TeV



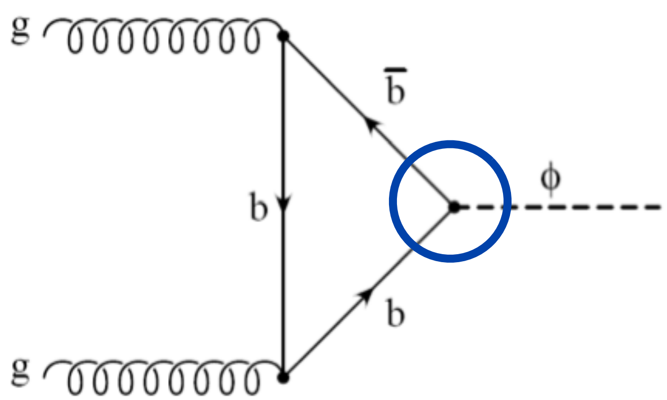
HAD calorimetry
($|\eta|<5$): hermetic and highly segmented; Fe/scintillator Tiles (central), Cu/W-LAr (fwd)
Trigger and measurement of jets and missing E_T
E-resolution:
$\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$

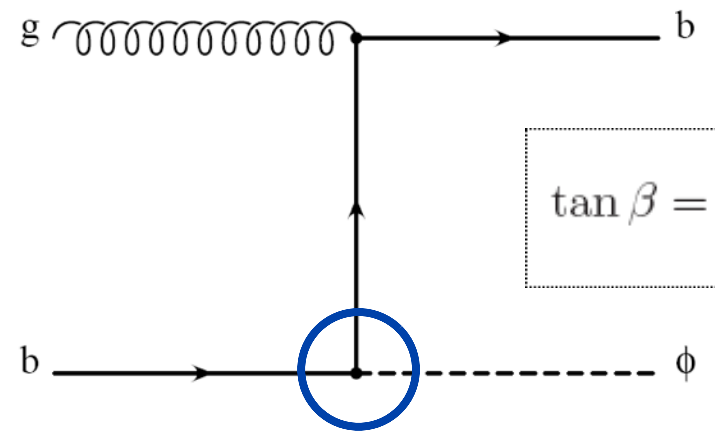
EM Calorimeter ($|\eta|<3.2$):
Pb-LAr Accordion; allows for e/γ triggering, identification and measurement;
E-resolution: $\sigma/E \sim 10\%/\sqrt{E}$

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:
$\sigma/p_T \sim 3.8\text{x}10^{-4}\ p_T\ (\text{GeV}) \oplus 0.015$
i.e. σ/p_T <2% for p_T < 35 GeV

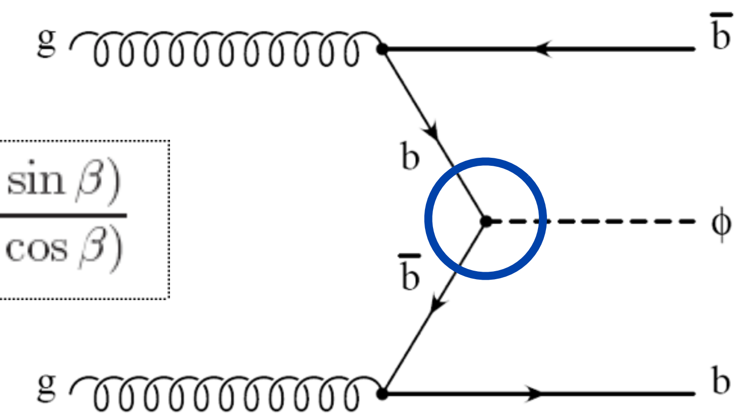
MSSM Higgs Sector

- 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

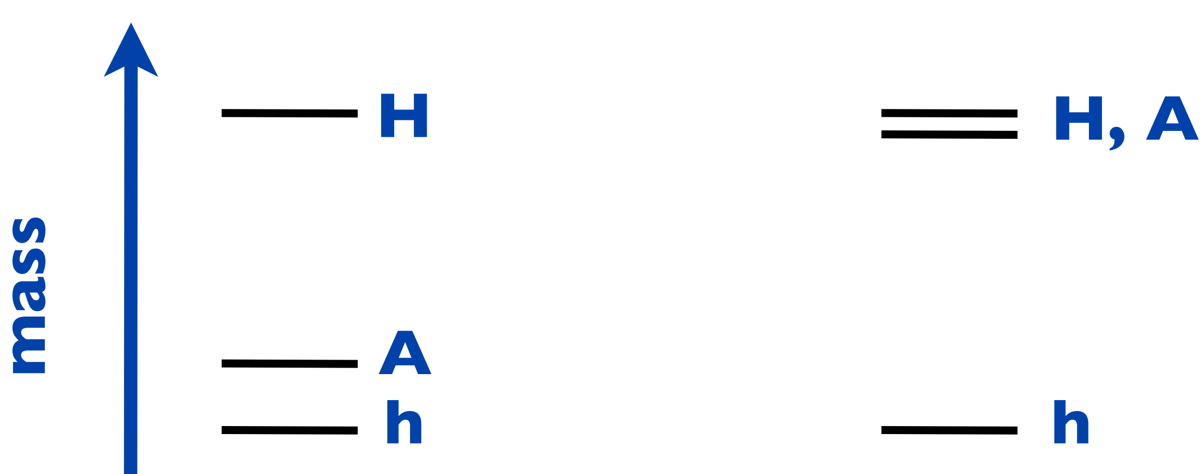




$$\tan\beta = \frac{v_2}{v_1} = \frac{(v\sin\beta)}{(v\cos\beta)}$$

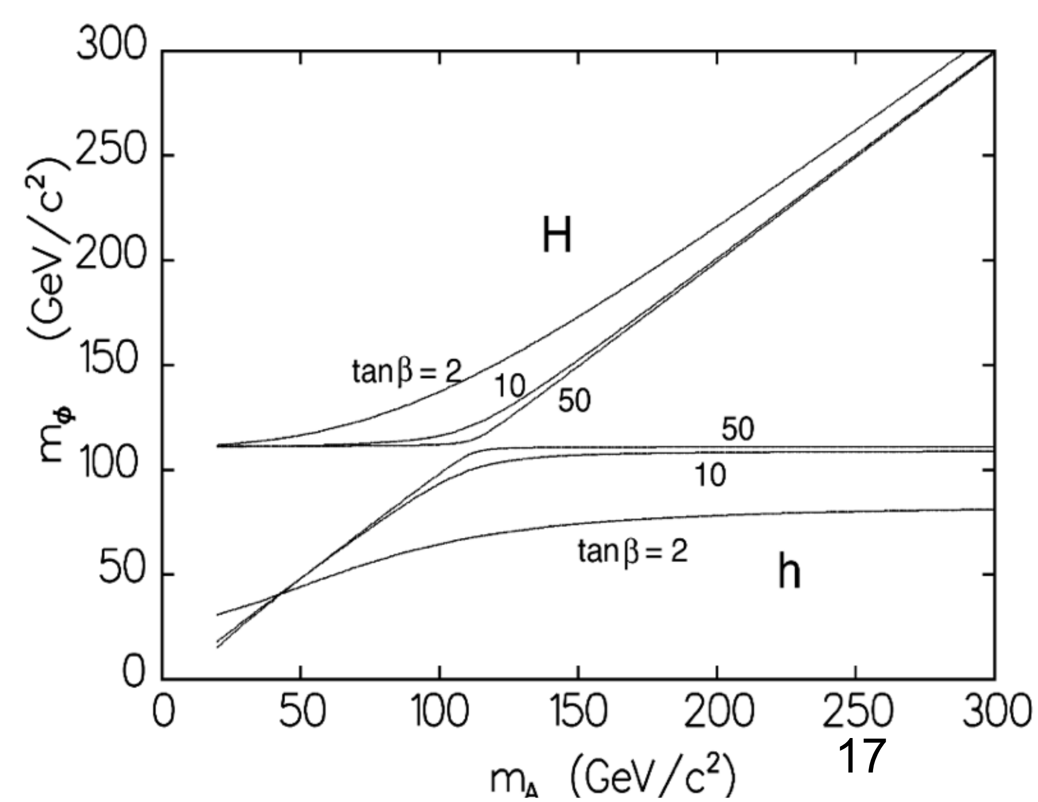


- Can parameterize the masses of the Higgs bosons with two free parameters: tanβ and m_A (at tree level)



Low m_A
(h, A degenerate)

High m_A
(H, A degenerate)



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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+}

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

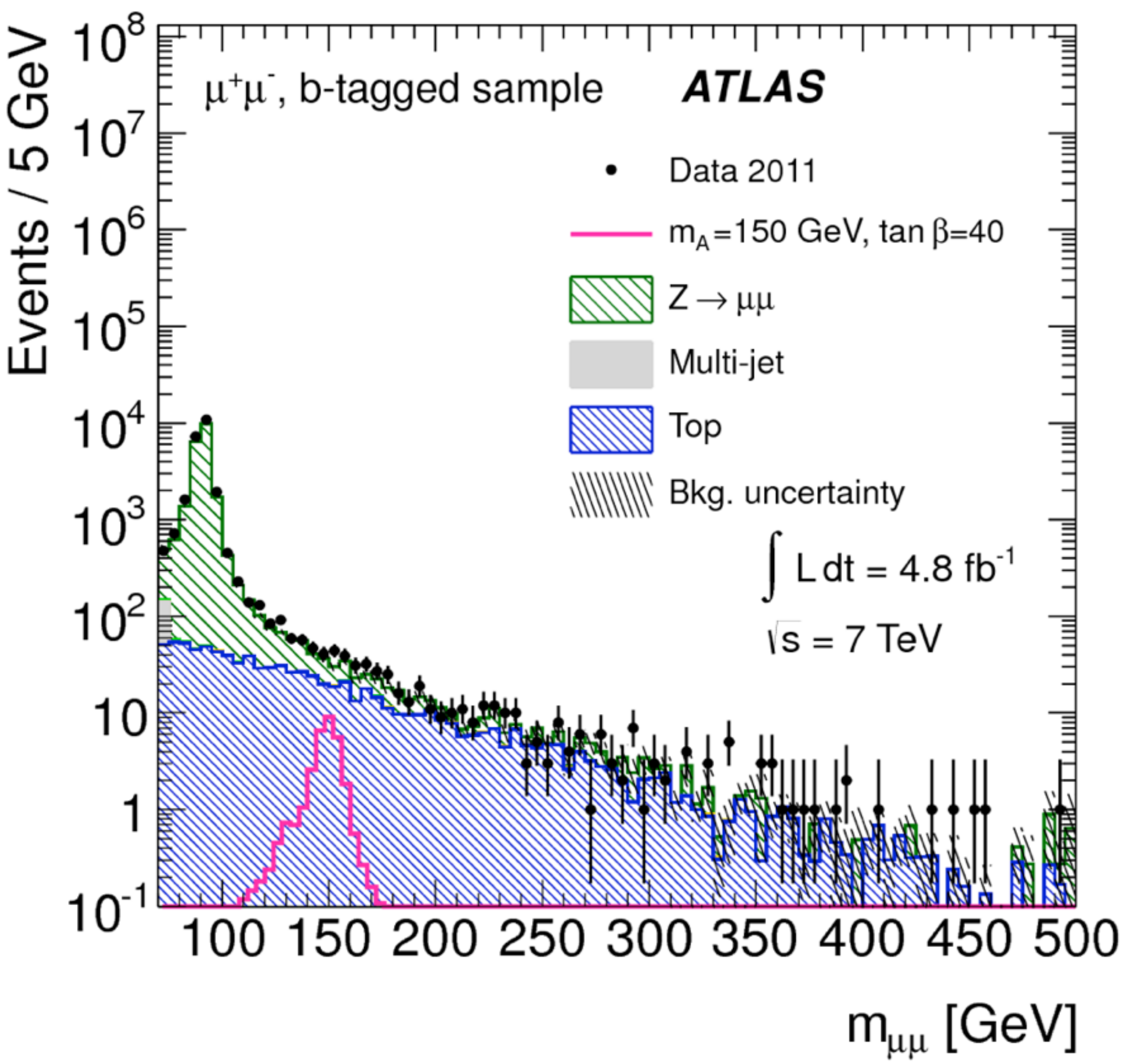
m_h^{mod-}

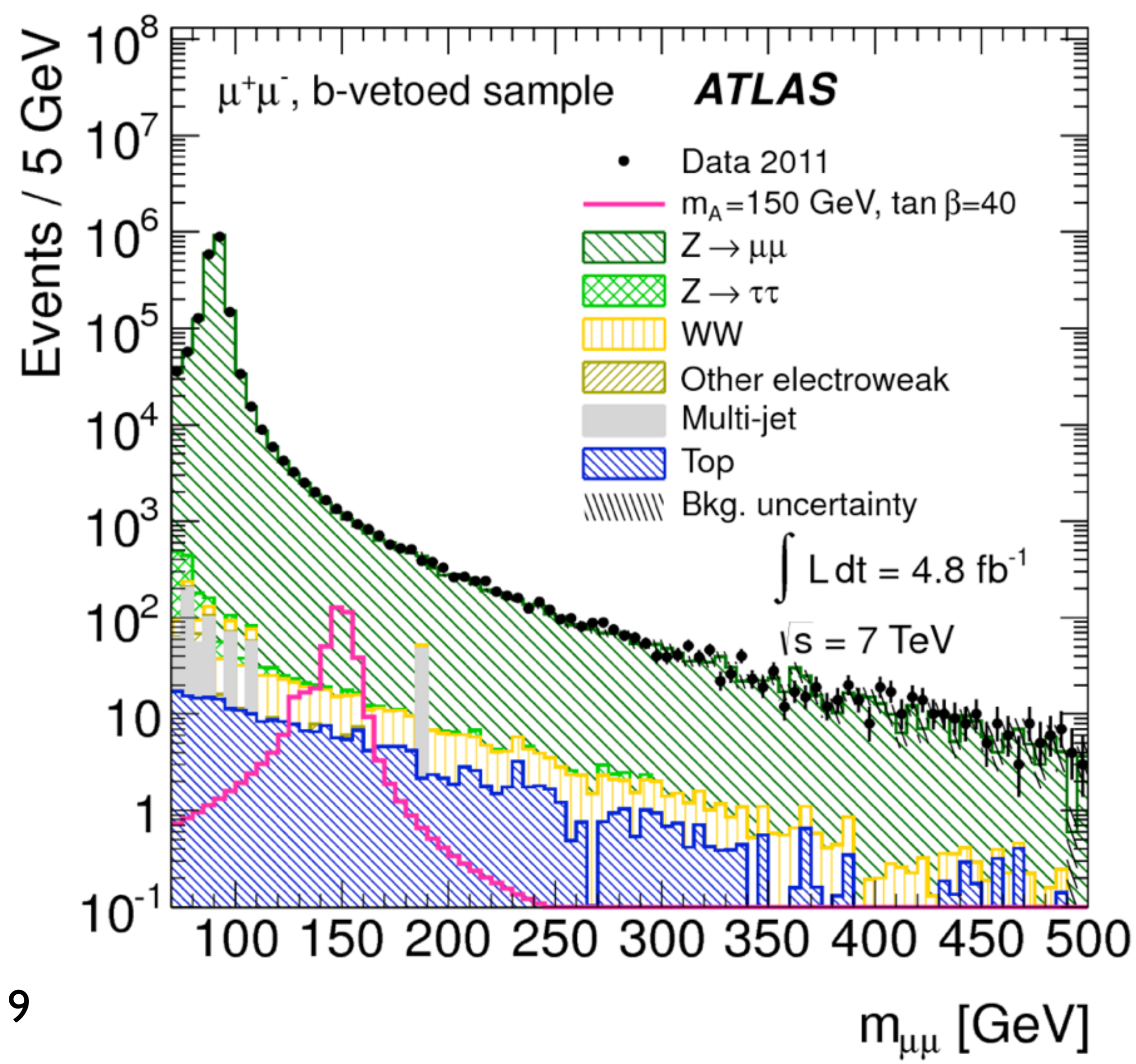
$$
\begin{aligned}
m_t &= 173.2 \text{ GeV}, \\
M_{\text{SUSY}} &= 1000 \text{ GeV}, \\
\mu &= 200 \text{ GeV}, \\
M_2 &= 200 \text{ GeV}, \\
X_t^{\text{OS}} &= -1.9\, M_{\text{SUSY}} \text{ (FD calculation)}, \\
X_t^{\overline{\text{MS}}} &= -2.2\, M_{\text{SUSY}} \text{ (RG calculation)}, \\
A_b &=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

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

- MSSM $\phi \to \mu^+\mu^-$ 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

JHEP02 (2013) 095





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

- 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

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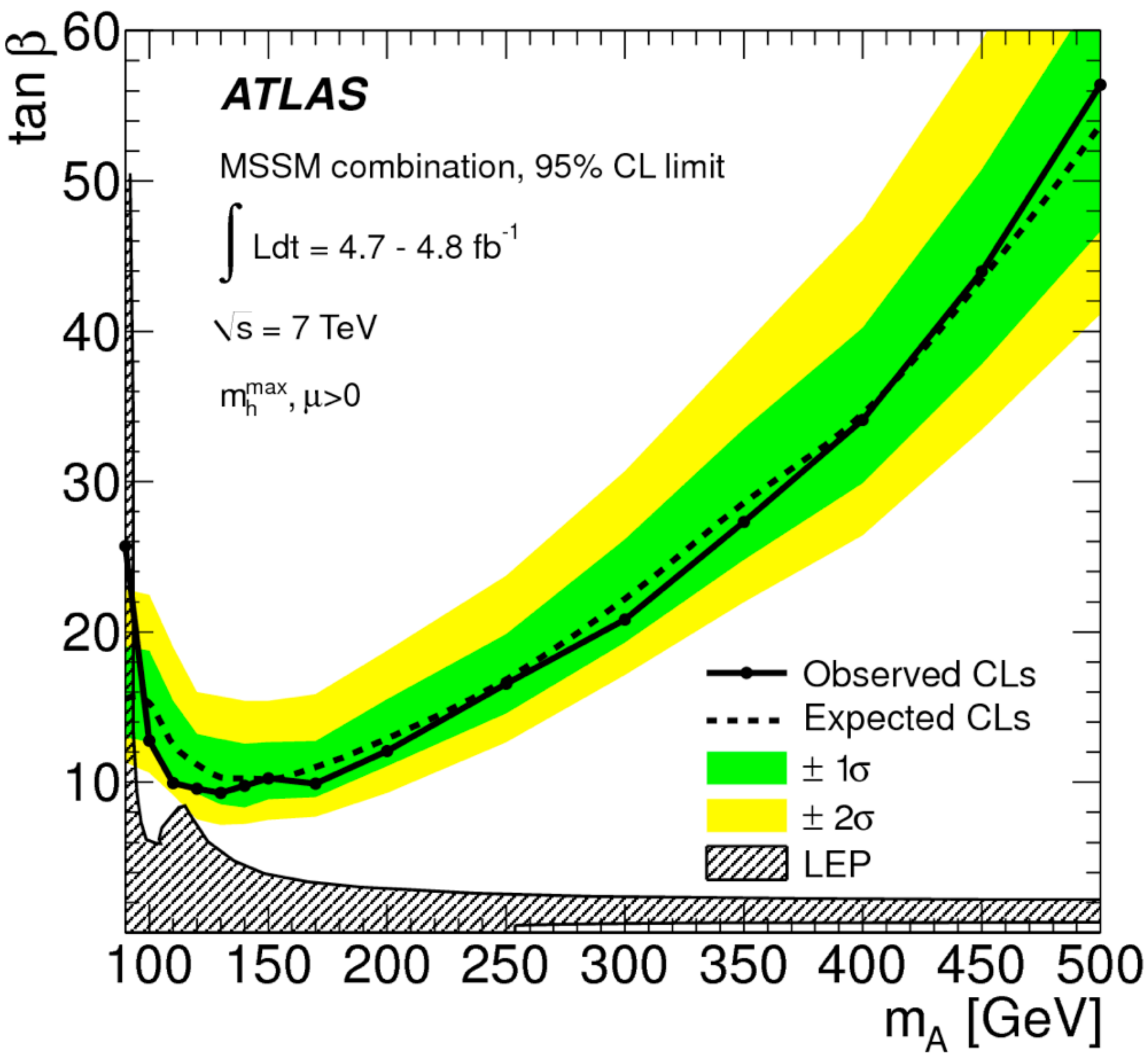
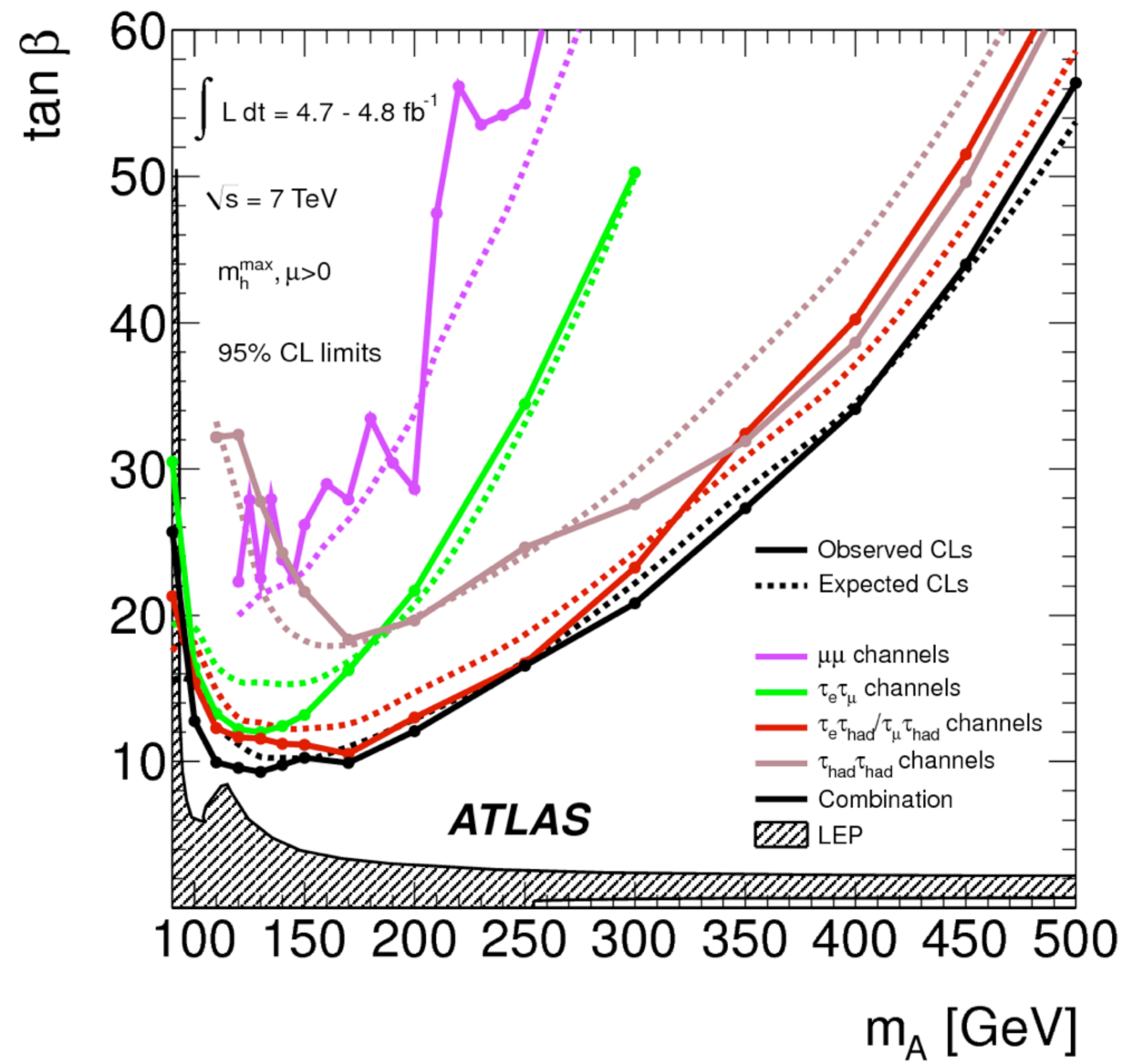
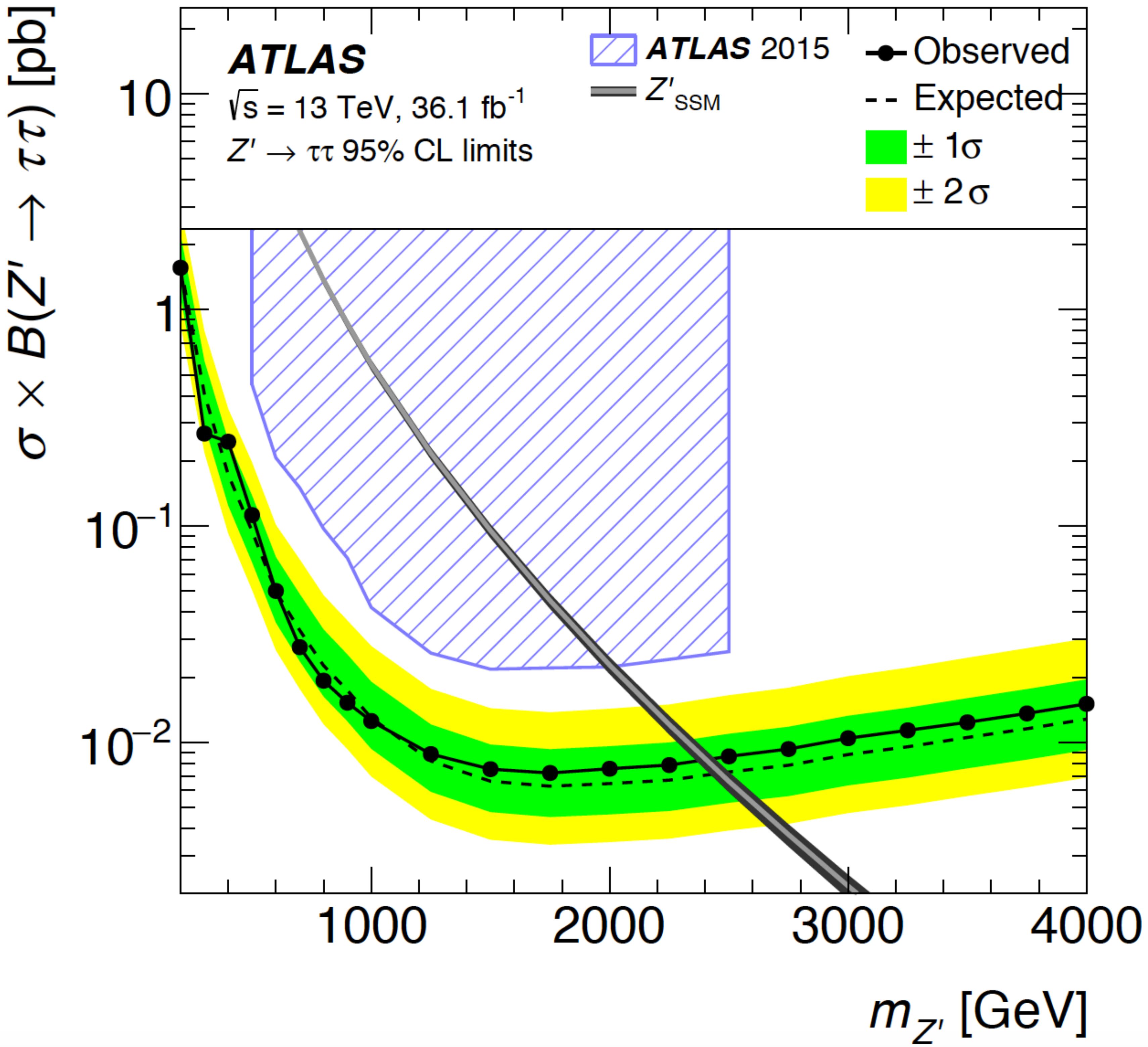




Backup Slides for $A/H \rightarrow \tau^+\tau^-$

$Z' \rightarrow \tau^+\tau^-$ Interpretation



Event Selection for the 4 Categories ($A/H \to \tau^+\tau^-$)

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

- 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; 70%)

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

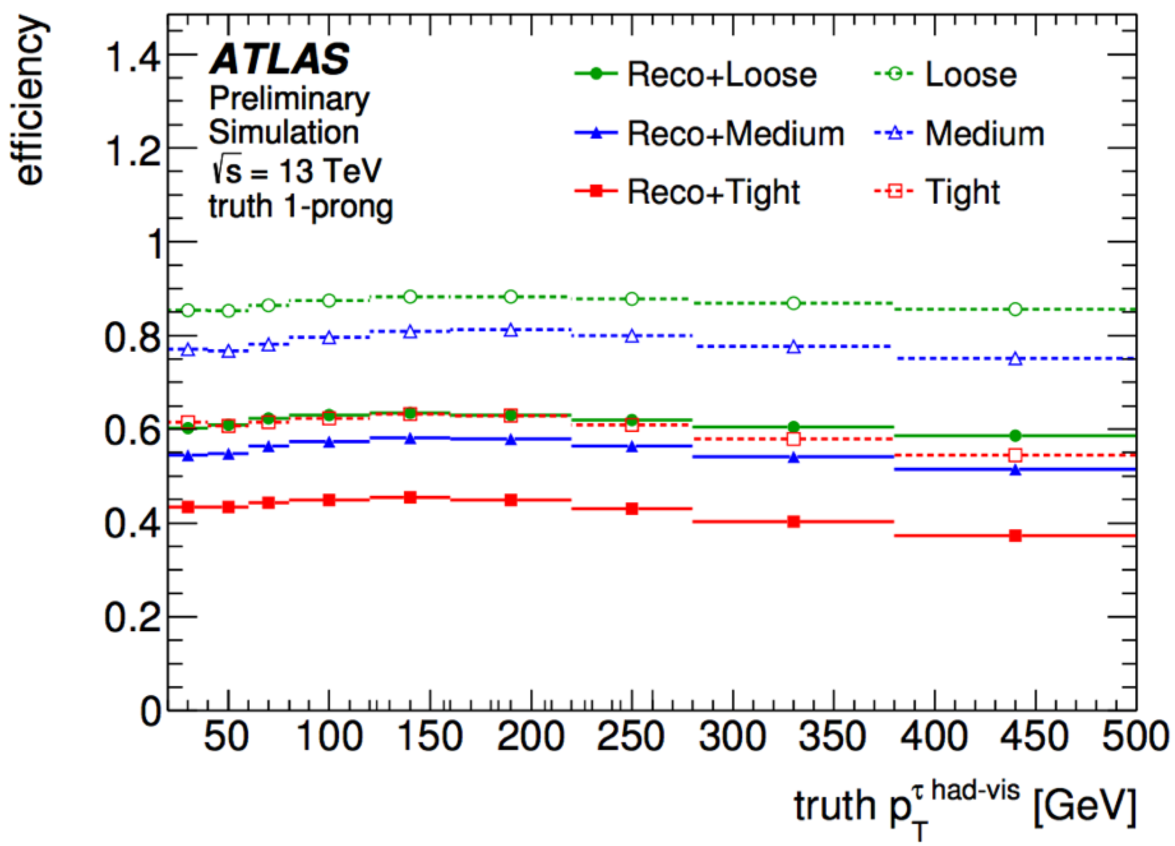
- For the had-had analysis:
  - Single tau trigger with threshold of 80 GeV, 125 GeV or 160 GeV (depends on run period)
  - Leading tau (55%) with p_T at least 5 GeV above the trigger level
  - Second tau (60%) with p_T > 65 GeV
  - Opposite charge requirement
  - Veto events with a lepton
  - $\Delta\phi(tau_1, tau_2) > 2.7$
  - $N_{b\text{-jets}}$ = 0 (b-veto)

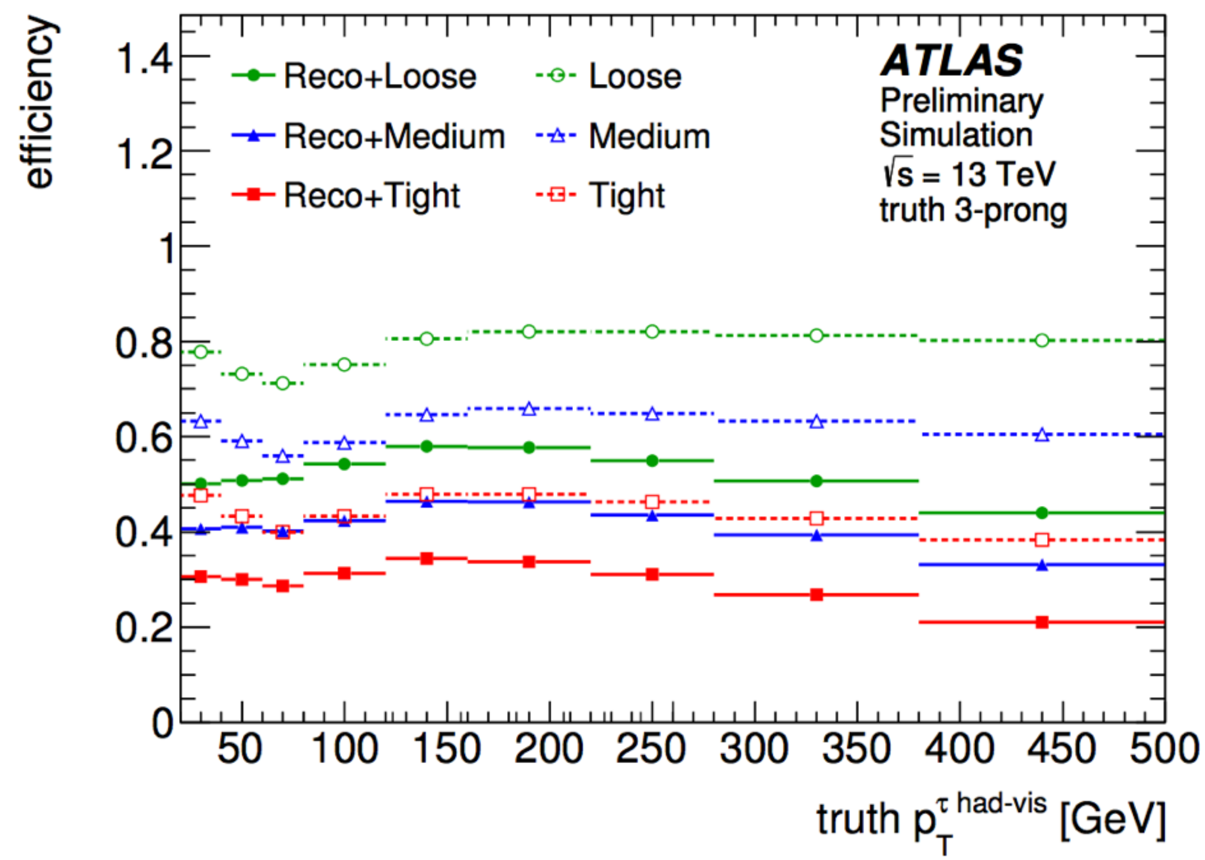
- $N_{b\text{-jets}} \geq 1$ (b-tag; 70%)

Reconstruction of hadronic τ decays

- The signature of hadronic τ decays are 1 or 3 tracks, collimated jet, possibly EM clusters

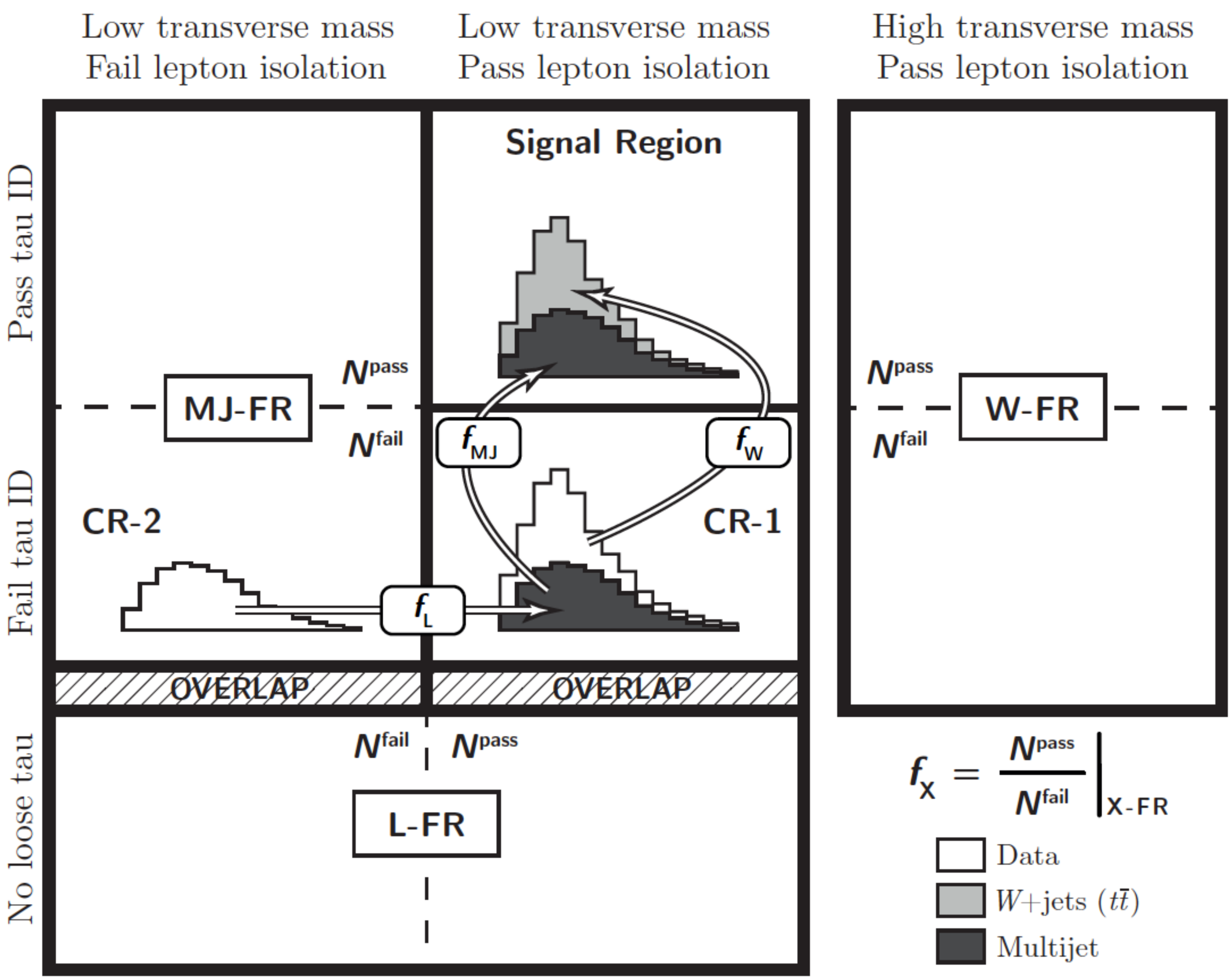
- Objects compatible with this signature are reconstructed
  - Seed from jet objects by considering each of them as a τ candidate
  - Identify a vertex consistent with a τ decay
  - Associate tracks within a core cone ($\Delta R \leq 0.2$) of the τ axis to jet objects





- 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

Background Estimation

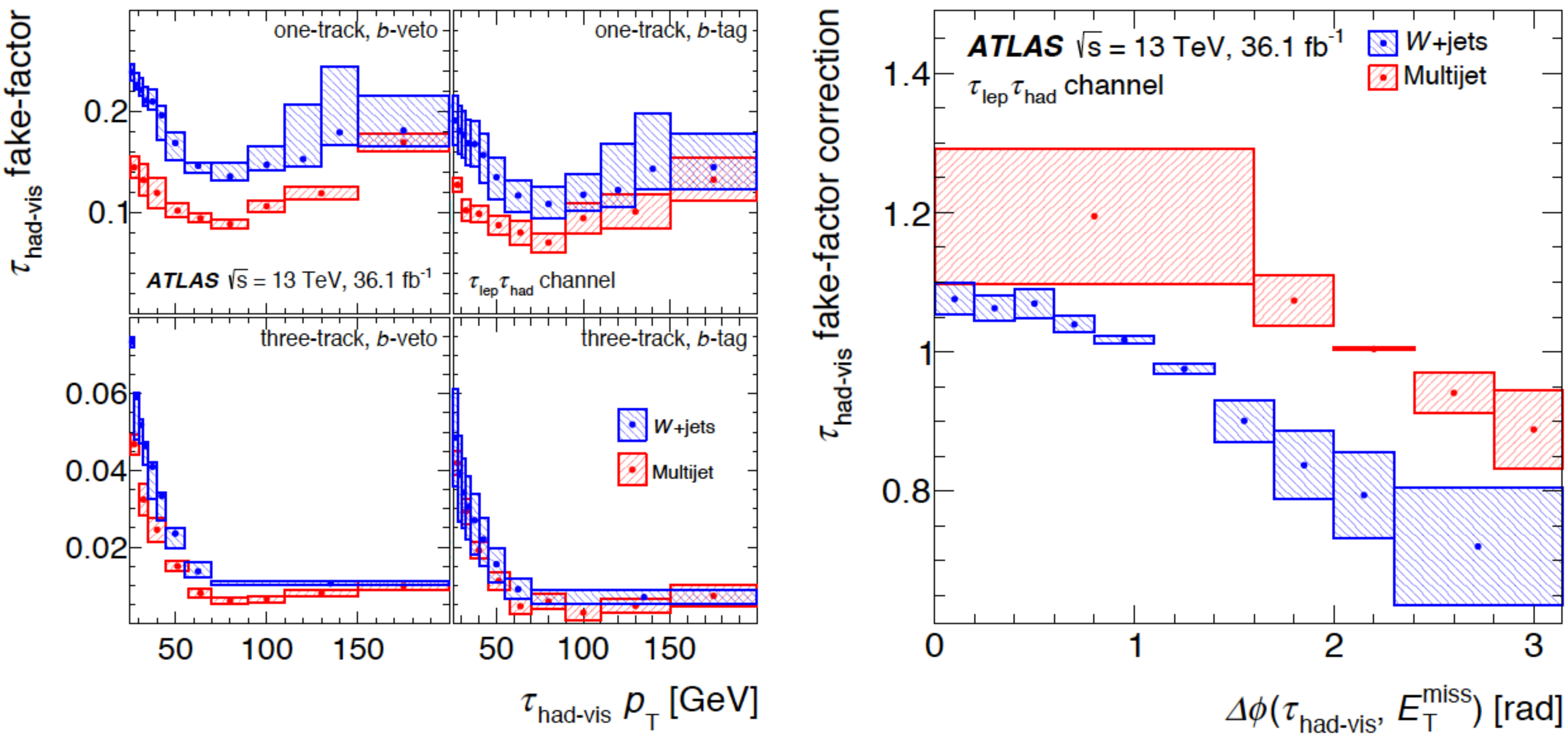


Signal, Control and Fake Regions

Table 1: Definition of signal, control and fakes regions used in the analysis. The symbol ℓ represents the selected electron or muon candidate and τ_1 (τ_2) represents the leading (sub-leading) $\tau_{\text{had-vis}}$ candidate.

Channel	Region	Selection
$\tau_{\text{lep}}\tau_{\text{had}}$	SR	ℓ (trigger, isolated), τ_1 (medium), $q(\ell) \times q(\tau_1) < 0$, $\lvert\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\ell}, \mathbf{p}_{\mathrm{T}}^{\tau_1})\rvert > 2.4$, $m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell}, \mathbf{E}_{\mathrm{T}}^{\text{miss}}) < 40\,\text{GeV}$, veto $80 < m(\mathbf{p}^{\ell}, \mathbf{p}^{\tau_1}) < 110\,\text{GeV}$ ($\tau_e\tau_{\text{had}}$ channel only)
	CR-1	Pass SR except: τ_1 (very-loose, fail medium)
	CR-2	Pass SR except: τ_1 (very-loose, fail medium), ℓ (fail isolation)
	MJ-FR	Pass SR except: τ_1 (very-loose), ℓ (fail isolation)
	W-FR	Pass SR except: $70\,(60) < m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell}, \mathbf{E}_{\mathrm{T}}^{\text{miss}}) < 150\,\text{GeV}$ in $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$) channel
	CR-T	Pass SR except: $m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell}, \mathbf{E}_{\mathrm{T}}^{\text{miss}}) > 110\,(100)\,\text{GeV}$ in the $\tau_e\tau_{\text{had}}$ ($\tau_\mu\tau_{\text{had}}$) channel, b-tag category only
	L-FR	ℓ (trigger, selected), jet (selected), no loose $\tau_{\text{had-vis}}$, $m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\ell}, \mathbf{E}_{\mathrm{T}}^{\text{miss}}) < 30\,\text{GeV}$
$\tau_{\text{had}}\tau_{\text{had}}$	SR	τ_1 (trigger, medium), τ_2 (loose), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\tau_1}, \mathbf{p}_{\mathrm{T}}^{\tau_2})\rvert > 2.7$
	CR-1	Pass SR except: τ_2 (fail loose)
	DJ-FR	jet trigger, τ_1+τ_2 (no identification), $q(\tau_1) \times q(\tau_2) < 0$, $\lvert\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\tau_1}, \mathbf{p}_{\mathrm{T}}^{\tau_2})\rvert > 2.7$ $p_{\mathrm{T}}^{\tau_2}/p_{\mathrm{T}}^{\tau_1} > 0.3$
	W-FR	μ (trigger, isolated), τ_1 (no identification), $\lvert\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\mu}, \mathbf{p}_{\mathrm{T}}^{\tau_1})\rvert > 2.4$ $m_{\mathrm{T}}(\mathbf{p}_{\mathrm{T}}^{\mu}, \mathbf{E}_{\mathrm{T}}^{\text{miss}}) > 40\,\text{GeV}$, b-veto category only
	T-FR	Pass W-FR except: b-tag category only

Background Estimation



(a) $\tau_{\text{had-vis}}$ fake-factors (b) $|\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\tau_{\text{had-vis}}}, \mathbf{E}_{\mathrm{T}}^{\text{miss}})|$ correction

Figure 3: The $\tau_{\text{had-vis}}$ identification fake-factors and the sequential $|\Delta\phi(\mathbf{p}_{\mathrm{T}}^{\tau_{\text{had-vis}}}, \mathbf{E}_{\mathrm{T}}^{\text{miss}})|$ correction in the $\tau_{\text{lep}}\tau_{\text{had}}$ channel. The multijet fake-factors are for the 2016 dataset only. The bands include all uncertainties.

Background Estimation

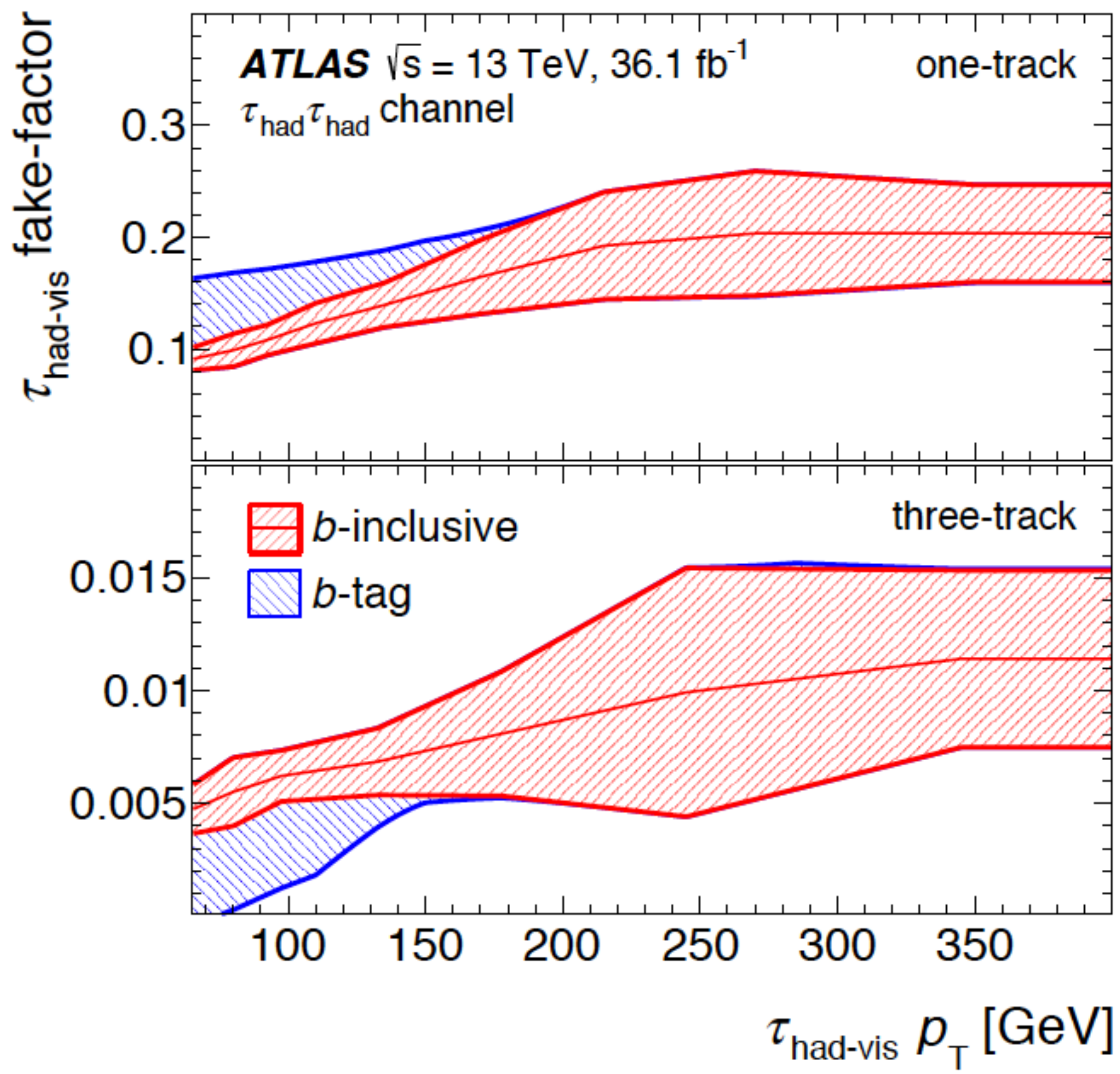
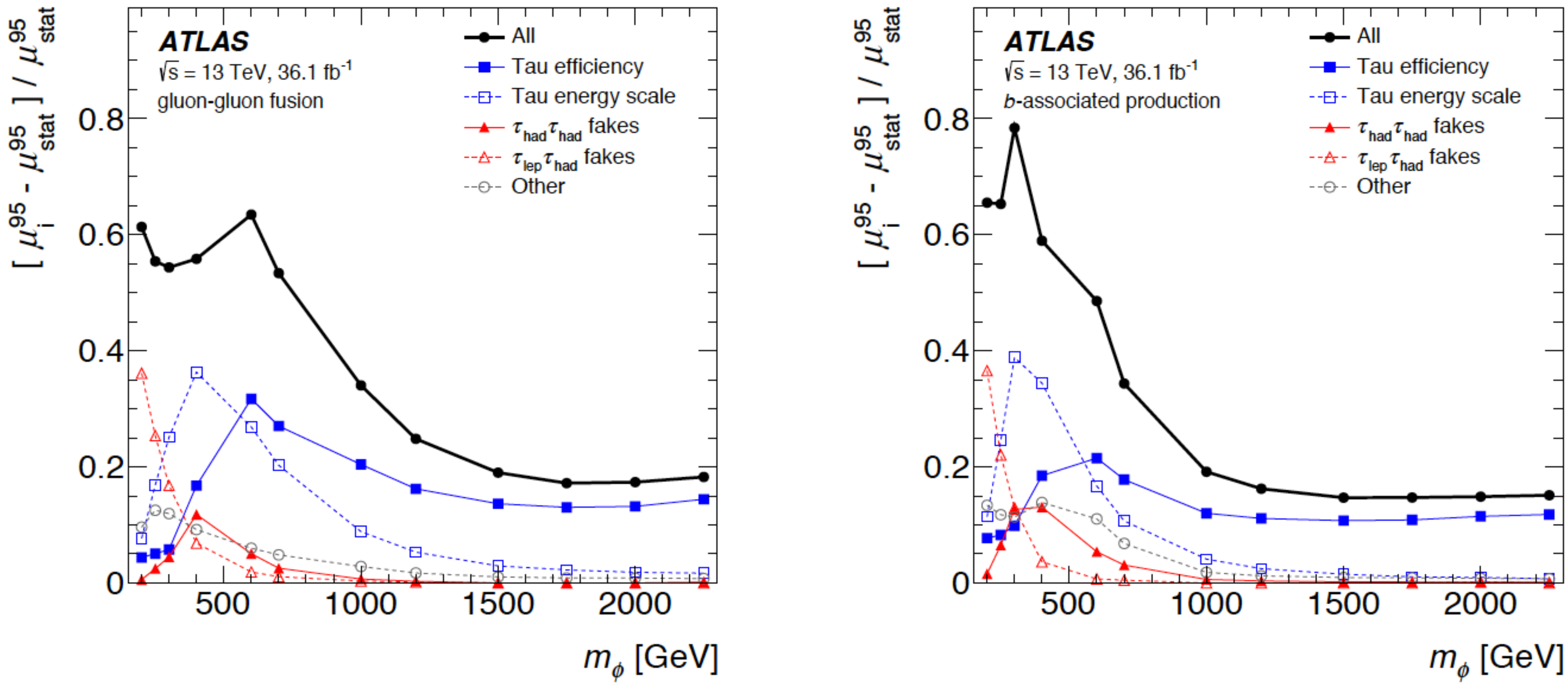


Figure 4: The $\tau_{had\text{-}vis}$ identification fake-factors in the $\tau_{had}\tau_{had}$ channel. The red band indicates the total uncertainty when used with a b-inclusive or b-veto selection. The blue band indicates the additional uncertainty when used with a b-tag selection.

Systematic Uncertainties



(a) gluon–gluon fusion production (b) *b*-associated production

Figure 9: Impact of major groups of systematic uncertainties on the $\phi \to \tau\tau$ 95% CL cross section upper limits as a function of the scalar boson mass, separately for the (a) gluon–gluon fusion and (b) *b*-associated production mechanisms.

$A/H \to \tau^+\tau^-$ Expected and Observed Events

Channel	Process	*b*-veto pre-fit	*b*-veto post-fit	*b*-tag pre-fit	*b*-tag post-fit
$\tau_{lep}\tau_{had}$	$Z/\gamma^* \to \tau\tau$	92 000 ± 11 000	96 400 ± 1600	670 ± 140	690 ± 70
	Diboson	880 ± 100	920 ± 70	6.3 ± 1.7	6.5 ± 1.4
	$t\bar{t}$ and single top-quark	1050 ± 170	1090 ± 130	2800 ± 400	2680 ± 80
	Jet $\to \tau$ fake	83 000 ± 5000	88 800 ± 1700	3000 ± 400	3390 ± 170
	$Z/\gamma^* \to \ell\ell$	15 800 ± 1200	16 200 ± 700	86 ± 21	89 ± 16
	SM Total	193 000 ± 13 000	203 400 ± 1200	6500 ± 600	6850 ± 120
	Data	203 365		6843	
	A/H (300)	720 ± 80	–	236 ± 32	–
	A/H (500)	112 ± 11	–	39 ± 5	–
	A/H (800)	10.7 ± 1.1	–	4.8 ± 0.6	–
$\tau_{had}\tau_{had}$	Multijet	3040 ± 240	3040 ± 90	106 ± 32	85 ± 10
	$Z/\gamma^* \to \tau\tau$	610 ± 230	770 ± 80	7.5 ± 2.9	8.6 ± 1.3
	$W(\to \tau\nu)$+jets	178 ± 31	182 ± 15	4.0 ± 1.0	4.1 ± 0.5
	$t\bar{t}$ and single top-quark	26 ± 9	29 ± 4	60 ± 50	74 ± 15
	Others	25 ± 6	27.4 ± 2.1	1.0 ± 0.5	1.1 ± 0.4
	SM Total	3900 ± 400	4050 ± 70	180 ± 60	173 ± 16
	Data	4059		154	
	A/H (300)	130 ± 50	–	44 ± 19	–
	A/H (500)	80 ± 33	–	28 ± 12	–
	A/H (800)	11 ± 4	–	5.1 ± 2.2	–

Backup Slides for A/H→ttbar

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, lower CPU and storage requirements
  - **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

Systematic Uncertainties for A/H→ttbar

Table 1: Average impact of the dominant uncertainties on the estimated yields for the total background and for a pseudoscalar A with $m_A = 500$ GeV and $\tan\beta = 0.68$ in percent of the nominal value. The spectra of the e+jets and μ+jets channels are added. Only uncertainties with a yield impact $> 0.5\%$ are shown. A bar (–) indicates that an uncertainty is not applicable to a sample.

Systematic uncertainties [%]	Total bkg	S	$S+I$
Luminosity [55]	1.7	1.9	1.9
PDF	2.5	2.1	12
$t\bar{t}$ initial-/final-state radiation	3.2	–	–
$t\bar{t}$ parton shower + fragmentation	4.9	–	–
$t\bar{t}$ normalization	5.7	–	–
$t\bar{t}$ event generator	0.5	–	–
Top quark mass	0.5	2.2	13
Jet energy scale	6.4	4.9	9.3
Jet energy resolution	1.3	1.6	1.7
b-tagging: b-jet efficiency	1.5	1.3	1.1
b-tagging: c-jet efficiency	0.2	0.2	0.8
Electron efficiency	0.3	0.4	0.7
Muon efficiency	0.9	1.0	1.0
Signal MC scales	–	7.3	7.3
Reweighting	–	–	5.0
MC statistical uncertainty	0.5	2.4	11
Total uncertainty	11	10	25

Results for A/H→ttbar

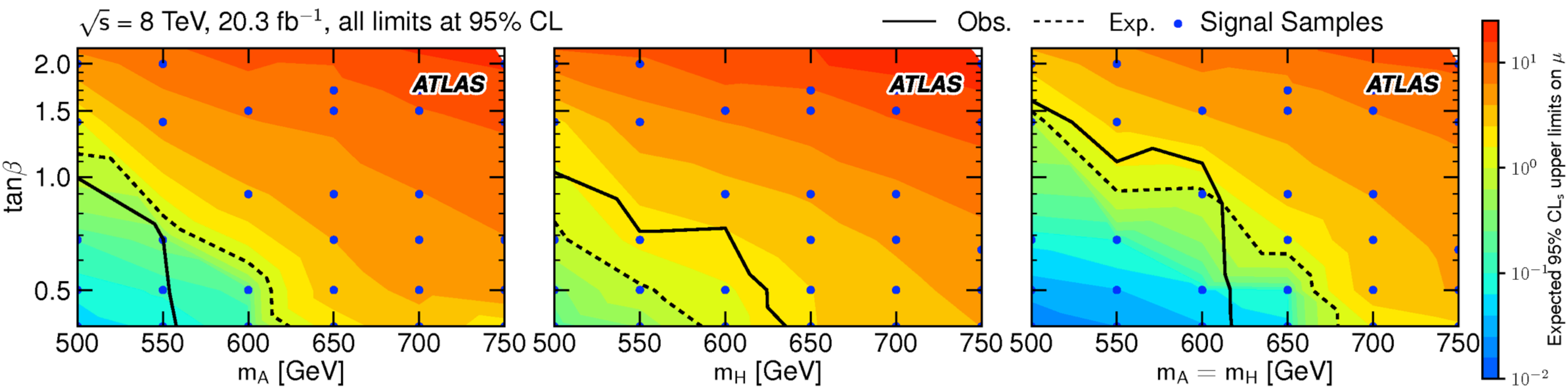
Table 2: Number of events observed in data and expected number of background events after the event selection, before the profile-likelihood fit to the full dataset. The uncertainty in the expected background yields is derived by summing all systematic and statistical uncertainties in quadrature. The "other bkg" component comprises single top quark, $t\bar{t} + W/Z$, Z+jets, diboson and multijet production. Details of the estimation of these backgrounds are given in Ref. [17].

Type	e+jets	μ+jets
$t\bar{t}$	95 000 ± 11 000	93 000 ± 11 000
W+jets	6600 ± 2100	7200 ± 2300
Other bkg.	11 200 ± 1400	6100 ± 600
Total	112 800 ± 13 000	106 300 ± 12 000
Data	115 785	110 218

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

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

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



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

Table 3: The 95% CL observed and expected exclusion limits on $\tan\beta$ for a type-II 2HDM in the alignment limit considering only a pseudoscalar A (left), only a scalar H (middle), and the mass-degenerate scenario $m_A = m_H$ (right). A bar (–) indicates that no value of $\tan\beta \geq 0.4$ is excluded.

Mass		m_A		m_H		$m_A = m_H$	
[GeV]	$\tan\beta$:	obs.	exp.	obs.	exp.	obs.	exp.
500		< 1.00	< 1.16	< 1.00	< 0.77	< 1.55	< 1.50
550		< 0.69	< 0.79	< 0.72	< 0.52	< 1.10	< 0.92
600		–	< 0.59	< 0.73	–	< 1.09	< 0.93
650		–	–	–	–	–	< 0.62