Searches for $t\bar{t}$ resonances

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Top LHC France
Paris, 23–25 May 2018

Motivation

- New particles decaying to $t\bar{t}$ appear in a number of SM extensions
  - Mediators of interactions with dark matter (talks by Andreas and Sabine)
  - Gauge bosons in (topcolour-assisted) technicolour models
  - Kaluza–Klein excitations of gluons and gravitons in models with extra dimensions
  - Additional Higgs bosons in 2HDM, including hMSSM

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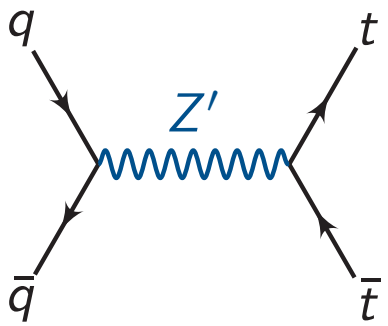
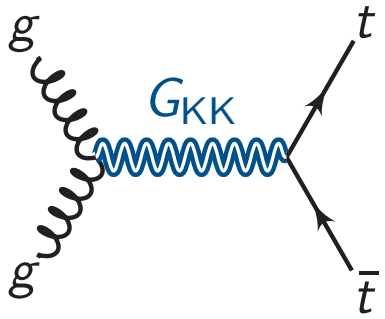
  - Gauge bosons in (topcolour-assisted) technicolour models
  - Kaluza–Klein excitations of gluons and gravitons in models with extra dimensions
  - Additional Higgs bosons in 2HDM, including hMSSM
- Little to no interference with SM $t\bar{t}$ $\Rightarrow$ Experimentally similar
  - $\Phi \to t\bar{t}$ is special and will be considered separately

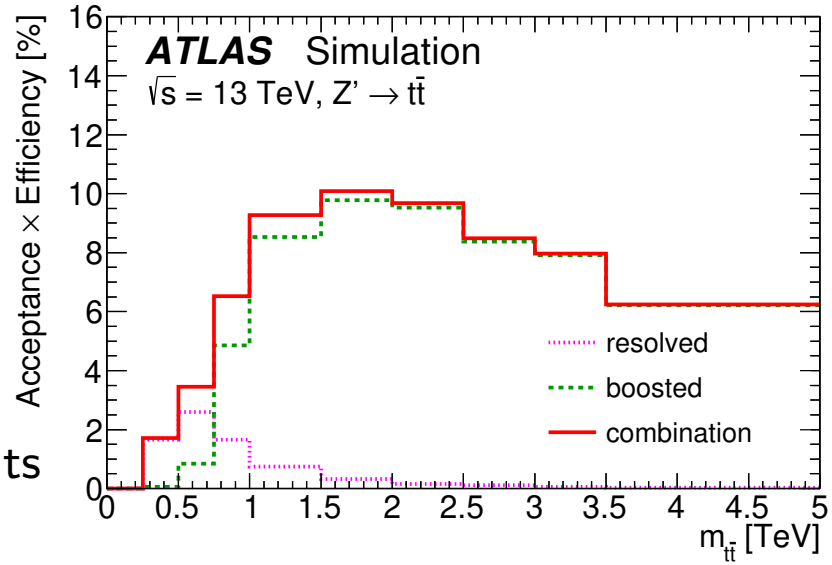




Search for $X \to t\bar{t}$ from ATLAS

New

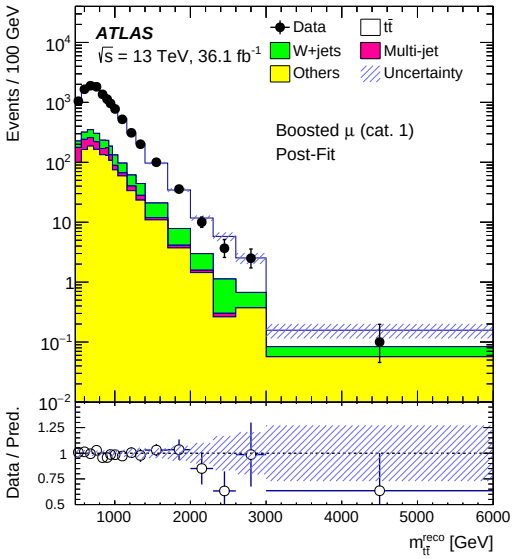
- New search for $X \to t\bar{t}$ from ATLAS[1]
  - $36\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$
  - Target Z' and KK gluons and gravitons
- Exploit ℓ + jets decay channel, $\ell = e, \mu$
  - $p_{\text{T}}^{\ell} > 30\,\text{GeV}$, veto additional e or μ with $p_{\text{T}} > 25\,\text{GeV}$
  - Presence of neutrino: $p_{\text{T}}^{\text{miss}} > 20\,\text{GeV}$, $p_{\text{T}}^{\text{miss}} + m_{\text{T}}^{W} > 60\,\text{GeV}$
- Boosted and resolved topology
- Reconstruct $t\bar{t}$ system and study $m_{t\bar{t}}$ spectrum (next slides)
- Dominant background is SM $t\bar{t}$
- Data-driven estimation of some bkg.
  - Matrix method for multijet QCD
  - Normalization of W + jets components from charge asymmetry

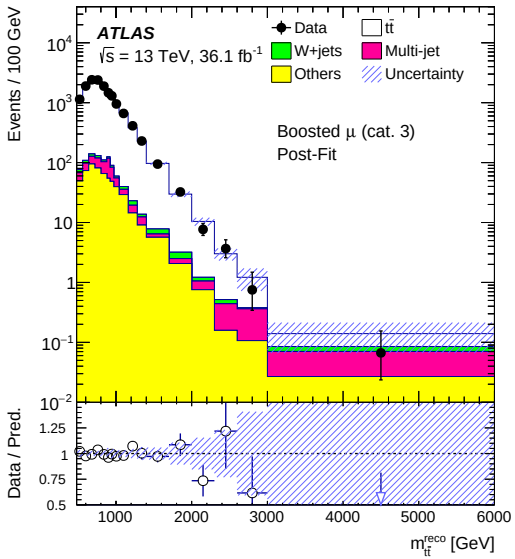


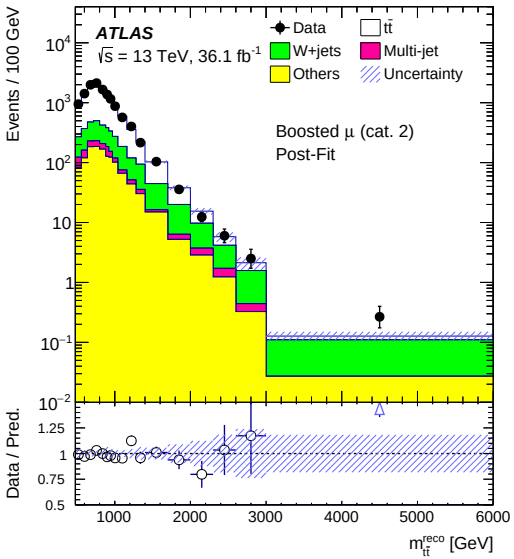
[1] arXiv:1804.10823, submitted to Eur. Phys. J. C

Boosted topology

- Reconstruct $t \to b\ell\nu$ from ℓ and nearby jet
  - Neutrino from $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$ and W mass constraint
- Reconstruct $t \to$ had from top-tagged $\Delta R = 1$ jet
  - Trimmed, $p_{\mathrm{T}} > 300\,\mathrm{GeV}$, $|\eta| < 2$
  - Must be well separated from $t \to b\ell\nu$
- Three b-tag categories
  - Matching (track) b-tagged jet for $t \to b\ell\nu$, $t \to$ had, or both
  - Events w/o matching are rejected

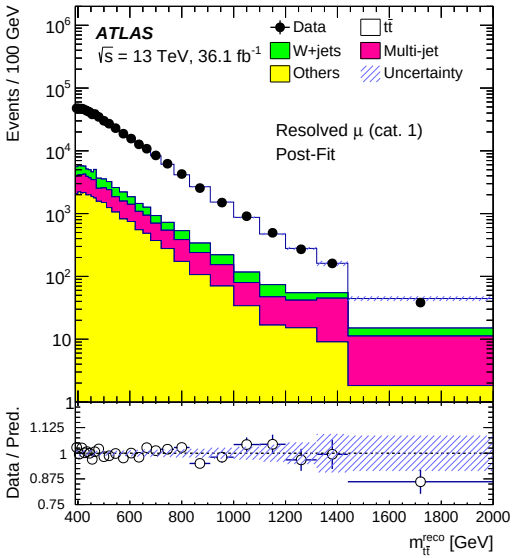


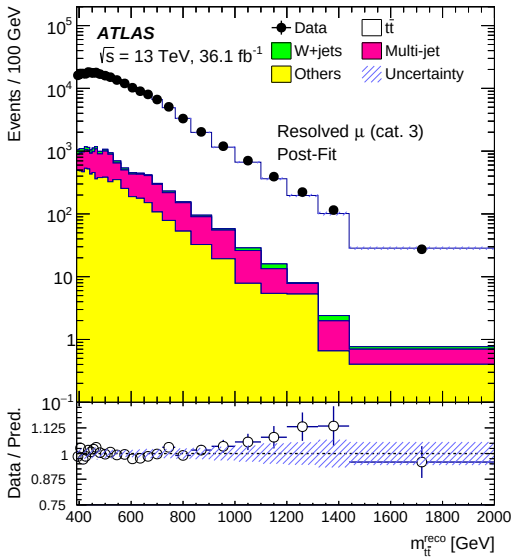


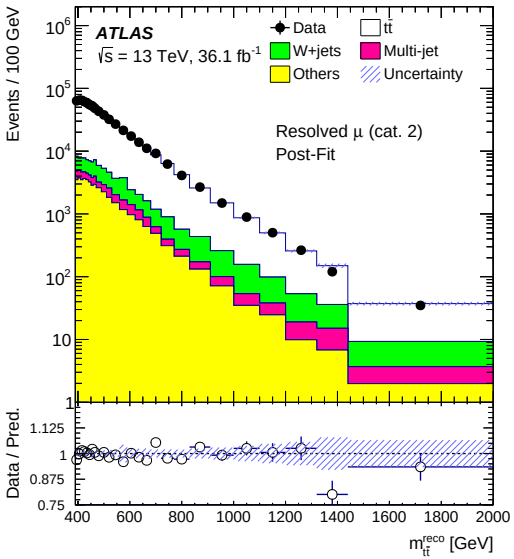


Resolved topology

- Only considered for events not compatible with boosted topology
- Identify four jets in $t\bar{t} \to \ell +$ jets final state
  - Minimize χ^2 based on $m_{t\to b\ell\nu}$, $m_{W\to \text{had}}$, $m_{t\to \text{had}} - m_{W\to \text{had}}$, and $p_{\text{T},t\to b\ell\nu} - p_{\text{T},t\to \text{had}}$
  - Reconstruct ν as before but try all solutions for p_z^ν
  - All jets with $p_\text{T} > 25\,\text{GeV}$, $|\eta| < 2.5$ considered
  - Reject event if smallest χ^2 is above a threshold
- Same three b-tag categories as before are defined



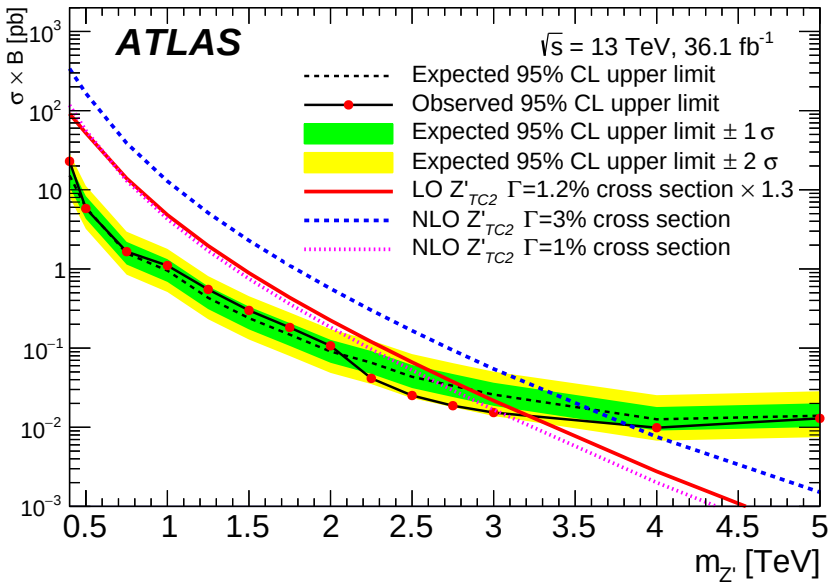




Results

- Fit $m_{t\bar{t}}$ spectrum
  - Boosted and resolved topologies, three b-tag categories
- Data are described well after background-only fit $\Rightarrow$ Set limits on cross sections for $pp \to X \to t\bar{t}$
- Observed exclusion (95% CL):

Model	Excluded mass [TeV]
Z'_{TC2} (1% width)	< 3.0
$Z'_{\mathrm{DM,\,axial}}$	< 1.2
$Z'_{\mathrm{DM,\,vector}}$	< 1.4
G_{KK}	$[0.45, 0.65]$
g_{KK} (15% width)	< 3.8
g_{KK} (30% width)	< 3.7

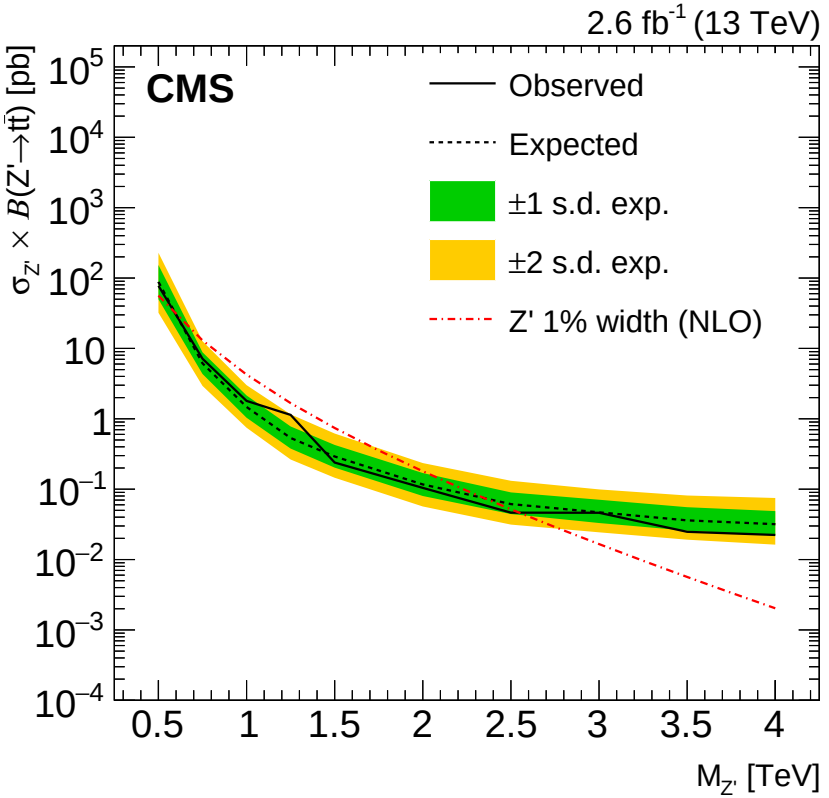


CMS search for $X \to t\bar{t}$

- CMS results[1] shown last time, no updates yet
  - $2.6\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$
- Rather similar approach
  - ℓ + jets channel with boosted and resolved topologies
  - Also include fully hadronic decays in boosted topology
- Observed exclusion (95% CL):

Model	Excluded mass [TeV]
Z' (1% width)	$[0.6, 2.5]$
Z' (10% width)	$[0.5, 3.9]$
Z' (30% width)	$[0.5, 4.0]$
g_{KK}	$[0.5, 3.3]$

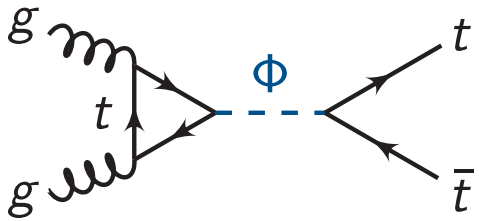
- New results are coming, stay tuned



[1] JHEP 07 (2017) 001

Additional Higgs bosons

- Special interest to $\Phi \to t\bar{t}$ in 2HDM
  - $A \to VV$ forbidden by CP conservation
  - $H \to VV$ suppressed in alignment limit
  - For $m_\Phi \gtrsim 2m_t$, $\tan\beta \lesssim 5$, $\Phi \to t\bar{t}$ is the most interesting channel



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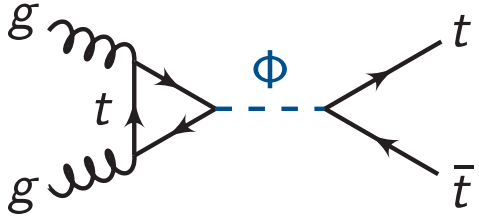
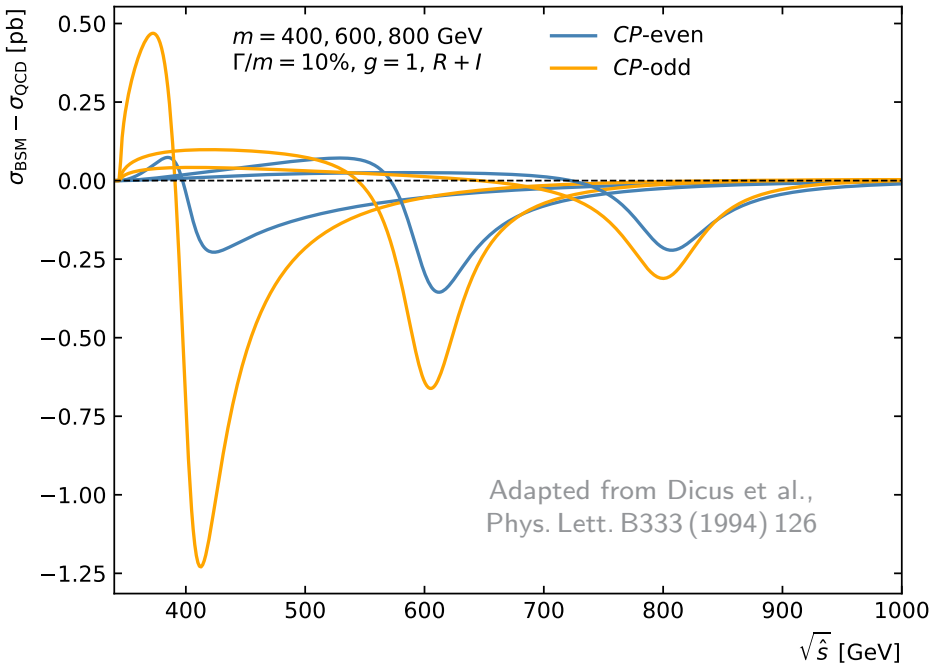
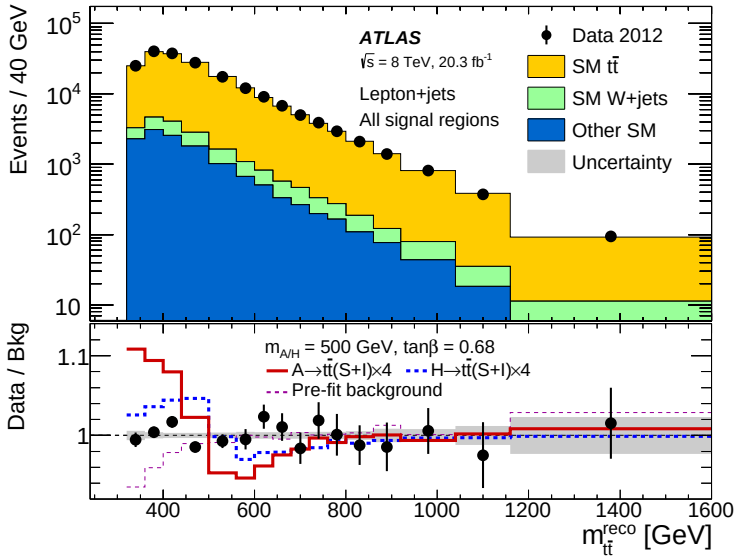


- Interference with SM $t\bar{t}$ distorts $m_{t\bar{t}}$ lineshape drastically
  - Results in a peak–dip or even dip–only structure
  - 'Bump hunting' searches are not appropriate



ATLAS $\Phi \to t\bar{t}$

- Only experimental result is from ATLAS[1]
  - $20.3\,\text{fb}^{-1}$ at $\sqrt{s} = 8\,\text{TeV}$
  - Preliminary version shown last year
- Analysis similar to resolved case in $X \to t\bar{t}$
  - ℓ + jets final state, χ^2-based $t\bar{t}$ reco.
  - Interference taken into account explicitly



[1] PRL 119 (2017) 191803

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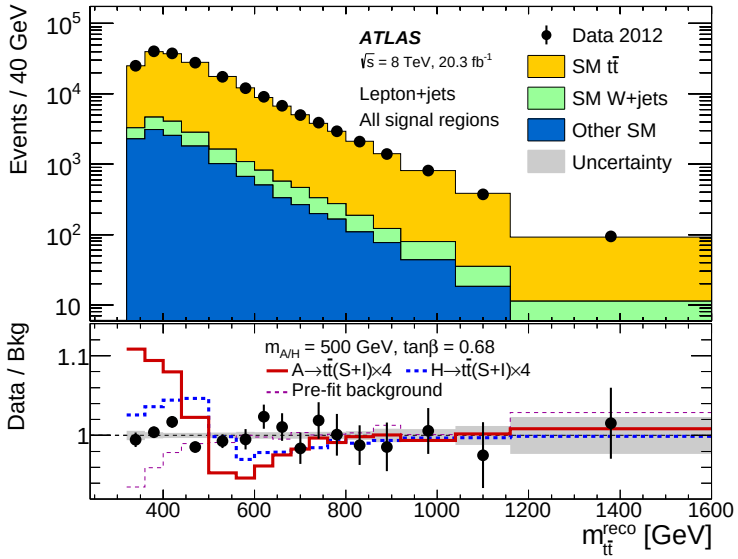
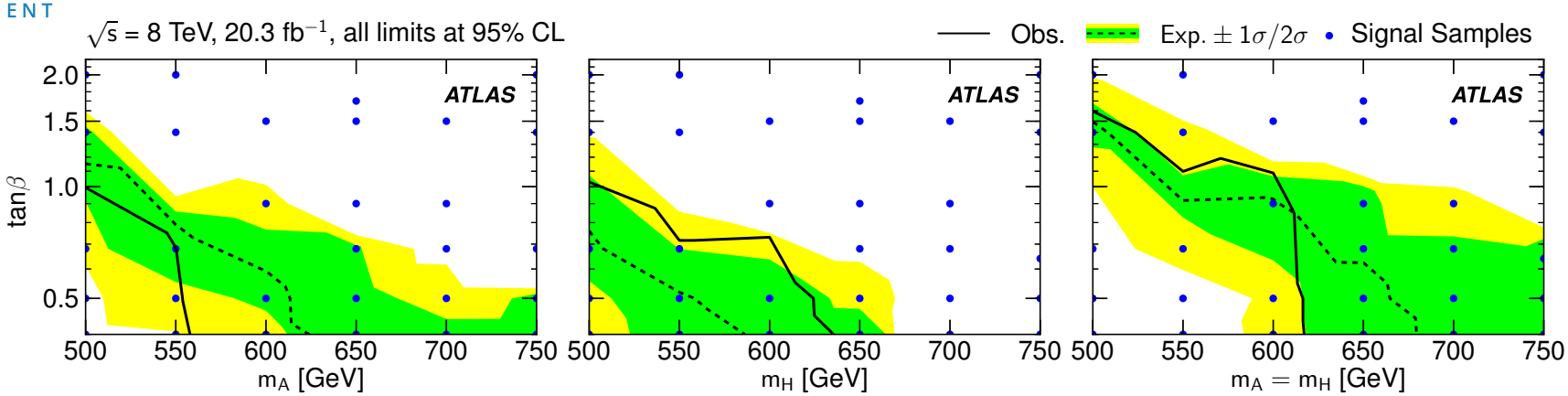
- Analysis similar to resolved case in $X \to t\bar{t}$
  - ℓ + jets final state, χ^2-based $t\bar{t}$ reco.
  - Interference taken into account explicitly
- Upper limits on $\tan\beta$ in 2HDM
  - Alignment limit, three mass hierarchies: $m_A \ll m_H$, $m_H \ll m_A$, $m_A = m_H$



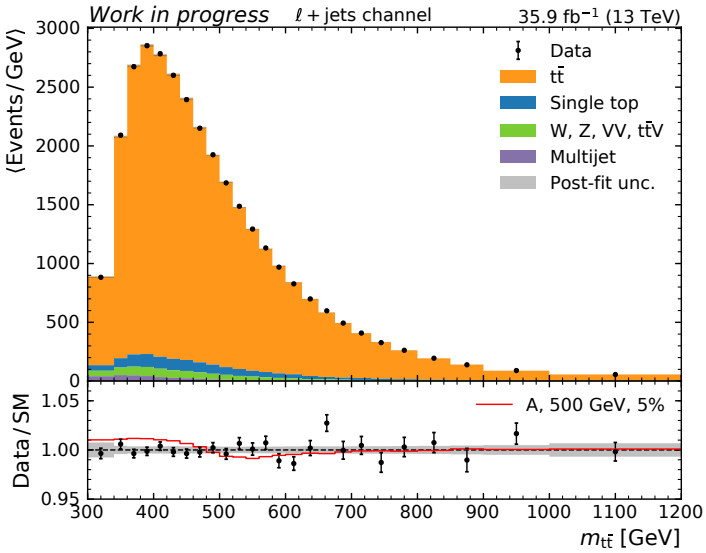


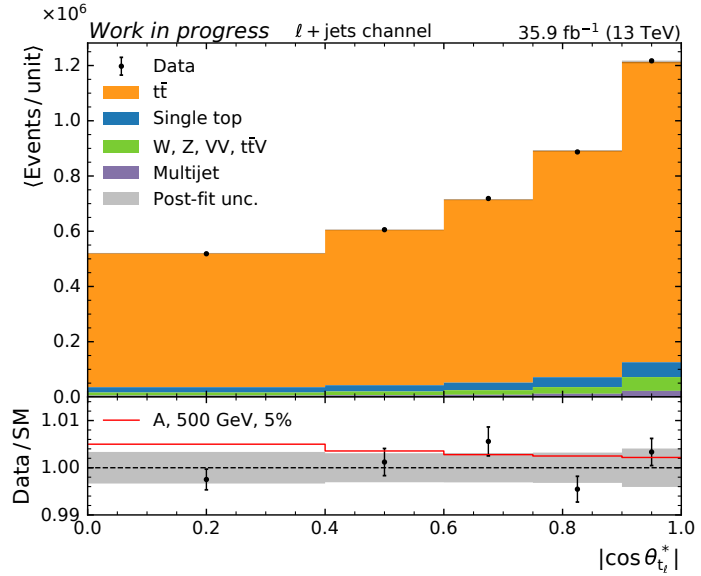
[1] PRL 119 (2017) 191803

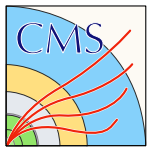
CMS $\Phi \to t\bar{t}$

Work in progress

- There is an on-going search in CMS
  - $35.9\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$
- Interference taken into account explicitly
- Resolved topology
- ℓ + jets channel $(\ell = e, \mu)$
  - Reconstruct ν from $t \to b\ell\nu$ by minimizing $D_\nu = \|\vec{p}_\text{T}^{\,\nu} - \vec{p}_\text{T}^{\,\text{miss}}\|$ respecting constraints from m_W and m_t [1]
  - Reconstruct $t\bar{t}$ by maximizing product of likelihood for D_ν and 2D likelihood for $m_{t\to\text{had}}$ and $m_{W\to\text{had}}$
  - Utilize $m_{t\bar{t}}$ and decay angle of $t_{b\ell\nu}$
    - Angle between $\vec{p}_{t\to b\ell\nu}$ in $t\bar{t}$ rest frame and $\vec{p}_{t\bar{t}}$ in lab frame
    - Reflects spin of the resonance





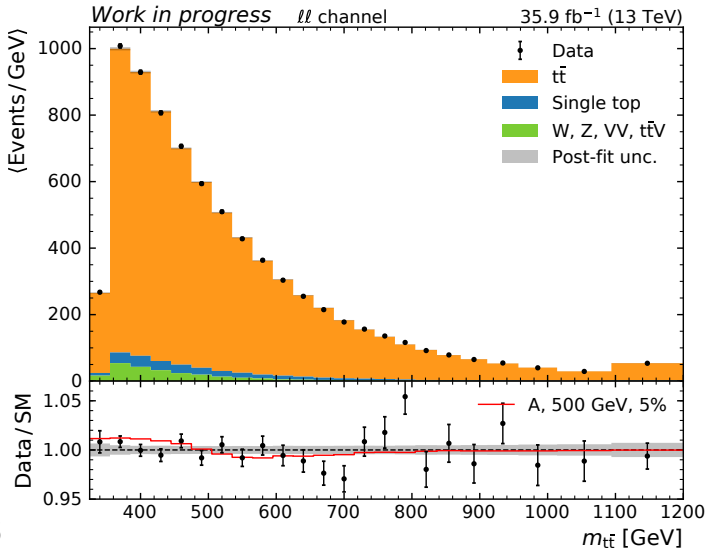


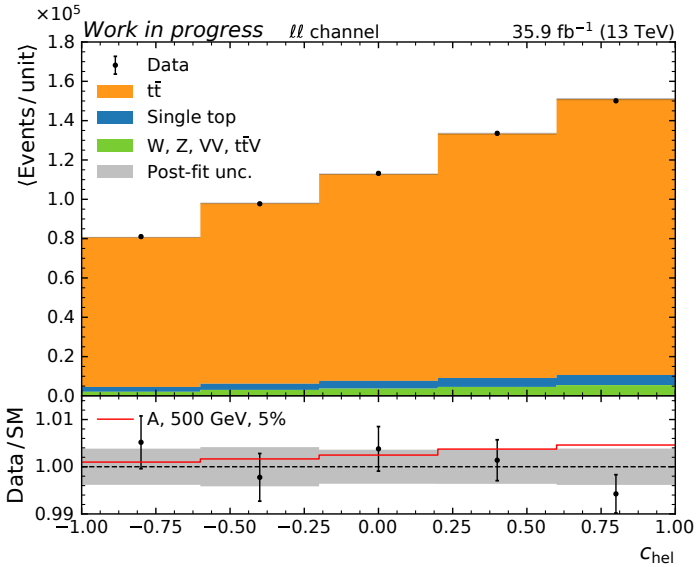
[1] Betchart et al., NIM A 736 (2014) 169

CMS $\Phi \to t\bar{t}$

Work in progress

- $\ell\ell$ channel $(\ell = e, \mu)$
  - Reconstruct neutrinos[1] using constraints from $\vec{p}_{\mathrm{T}}^{\,\mathrm{miss}}$, m_t $(\times 2)$, m_W $(\times 2)$
    - Out of multiple solutions, choose one with smallest $m_{t\bar{t}}$
  - Reconstruct momenta of top quarks by weighting all permutations according to product of likelihoods for $m_{\ell-\bar{b}}$ and $m_{\ell+b}$
    - Smear input momenta within the resolutions
  - Utilize $m_{t\bar{t}}$ and angle between $\vec{p}_{\ell+}$ and $\vec{p}_{\ell-}$ in their respective helicity frames
    - Top quarks are boosted into $t\bar{t}$ rest frame, each lepton is then boosted to rest frame of its parent top quark
    - Sensitive to spin and *CP* state of the resonance





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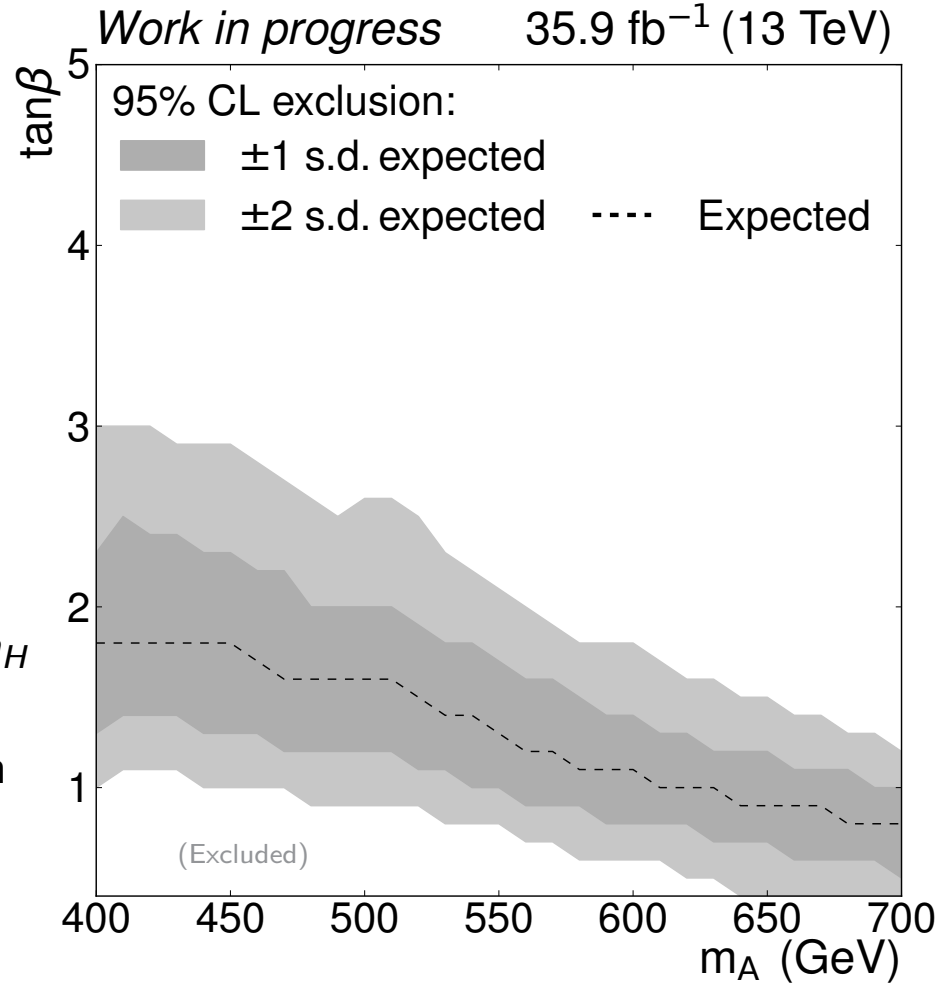
CMS $\Phi \to t\bar{t}$

Work in progress

- Search for signal using 2D distributions of $m_{t\bar{t}}$ and the angles
- Signal is modelled at LO
  - Resonant part R and interference I generated separately
  - Higher-order corrections to $gg\Phi$ form-factor included via k-factors
    - $k_R \sim 2$, $k_I = \sqrt{k_R k_B} \sim 1.8$
- Set constraints in hMSSM
  - Take into account dependence of m_H and $\Gamma_{A/H}$ on m_A and $\tan\beta$
  - Shown is blinded expected exclusion



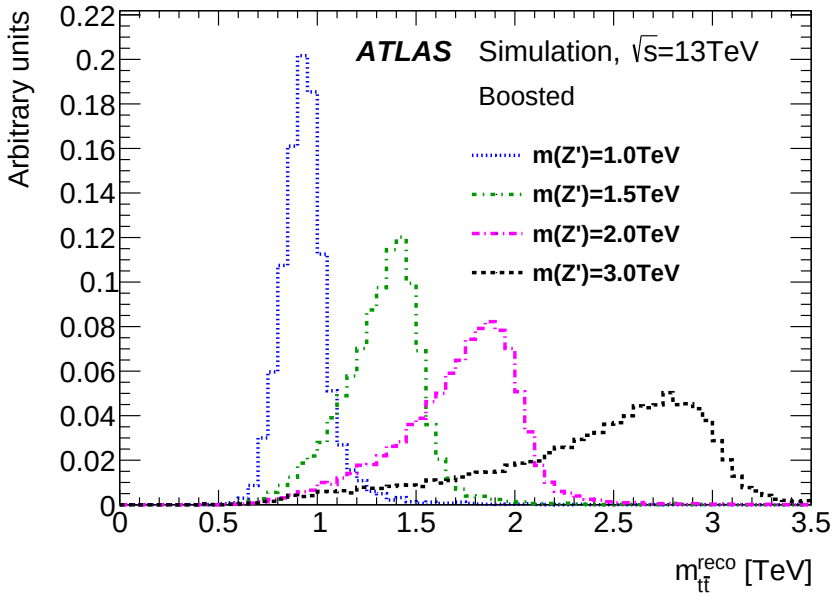
Summary

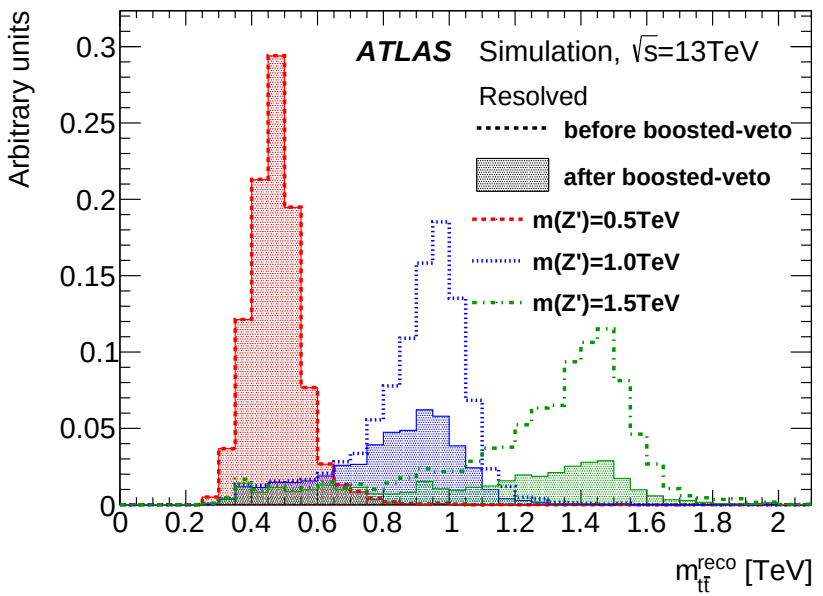
- Many BSM models can manifest themselves with $t\bar{t}$ resonances
- ATLAS and CMS are in multi-TeV regime for spin-1 and 2 particles and are pushing further as more data are collected and analyzed
  - Current limit for 1% Z' is $m_{Z'} > 3.0\,\text{TeV}$
- Experiments are working on $\Phi \to t\bar{t}$ as well
  - First result from ATLAS, CMS is catching up
  - In hMSSM, expect to exclude $\tan\beta \lesssim 2$ to 1 for m_A from 400 to 700 GeV with 2016 data
- Stay tuned for new results!

Additional slides

Reconstructed signal in ATLAS $X \to t\bar{t}$

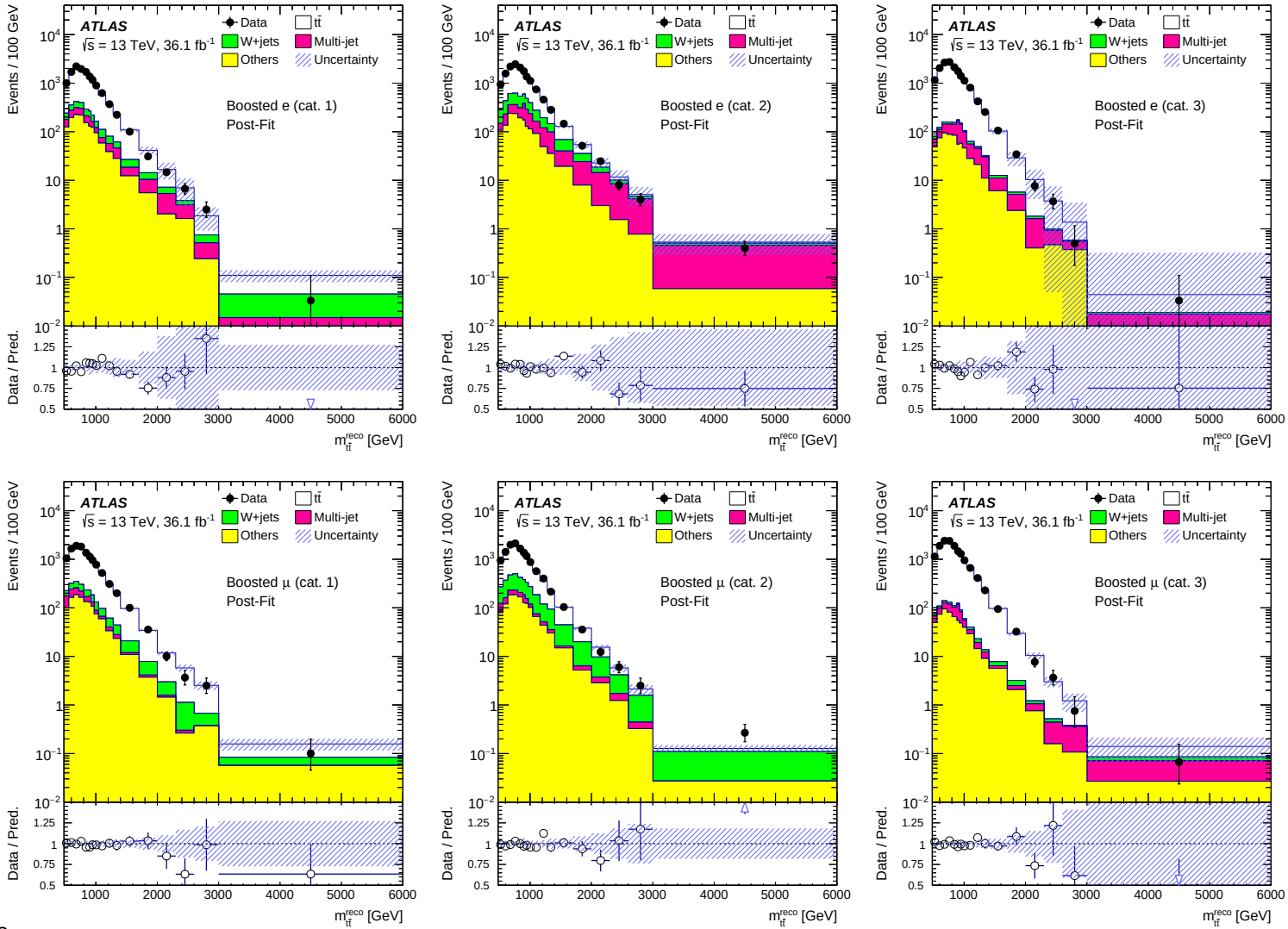
- Reconstructed $m_{t\bar{t}}$ in $Z' \to t\bar{t}$ with $\Gamma = 3\%$





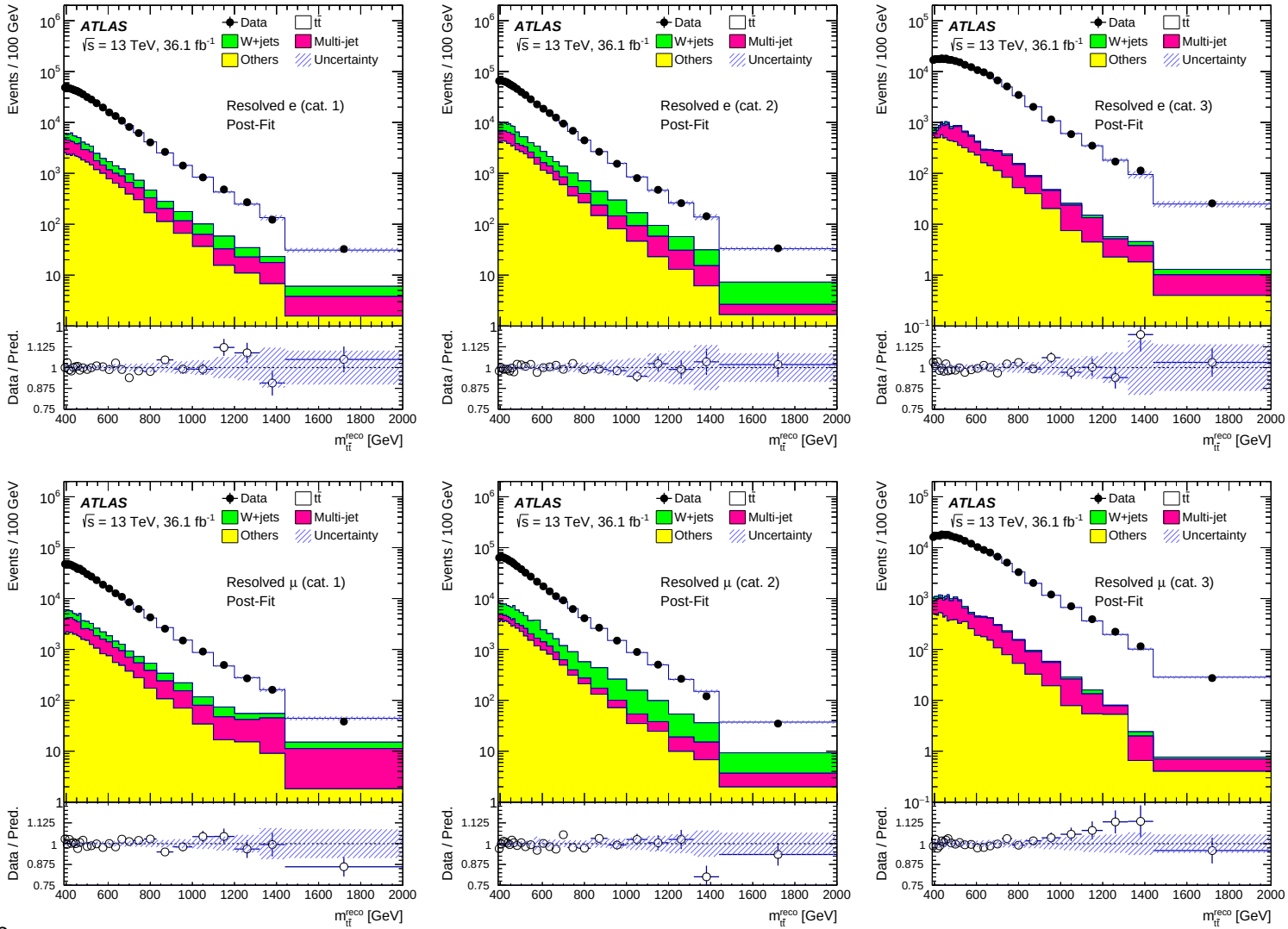
Post-fit $m_{t\bar{t}}$ distributions in ATLAS $X \to t\bar{t}$

- Distributions after b-only fit to data, boosted topology

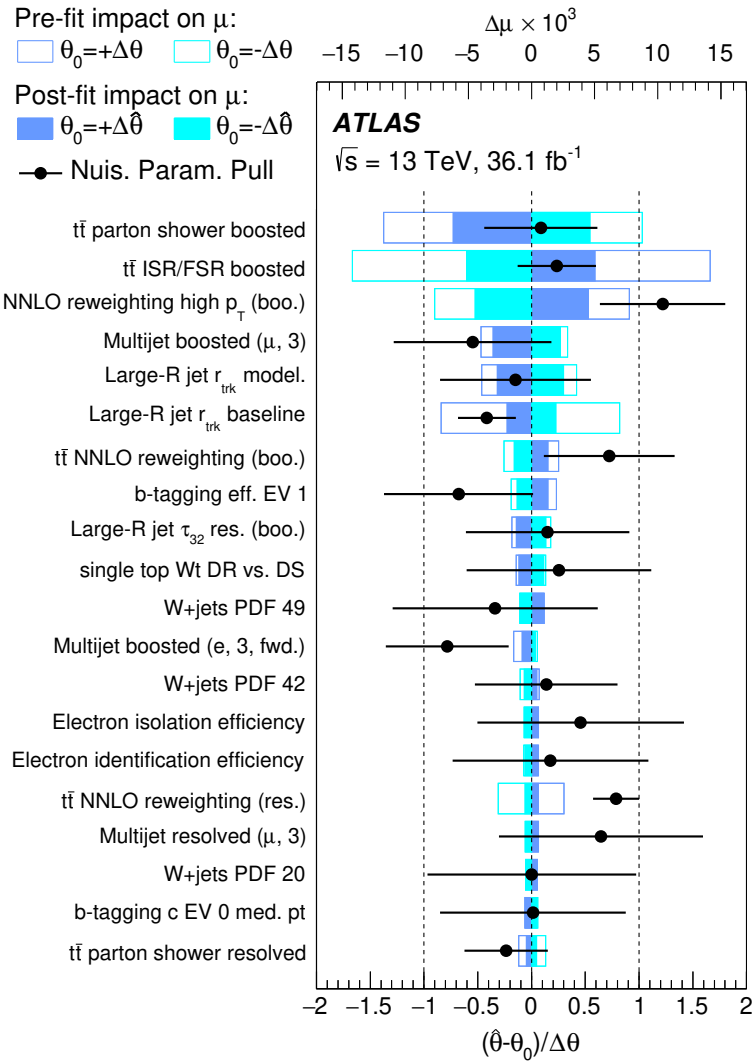


Post-fit $m_{t\bar{t}}$ distributions in ATLAS $X \to t\bar{t}$

- Distributions after b-only fit to data, resolved topology



Uncertainties in ATLAS $X \to t\bar{t}$

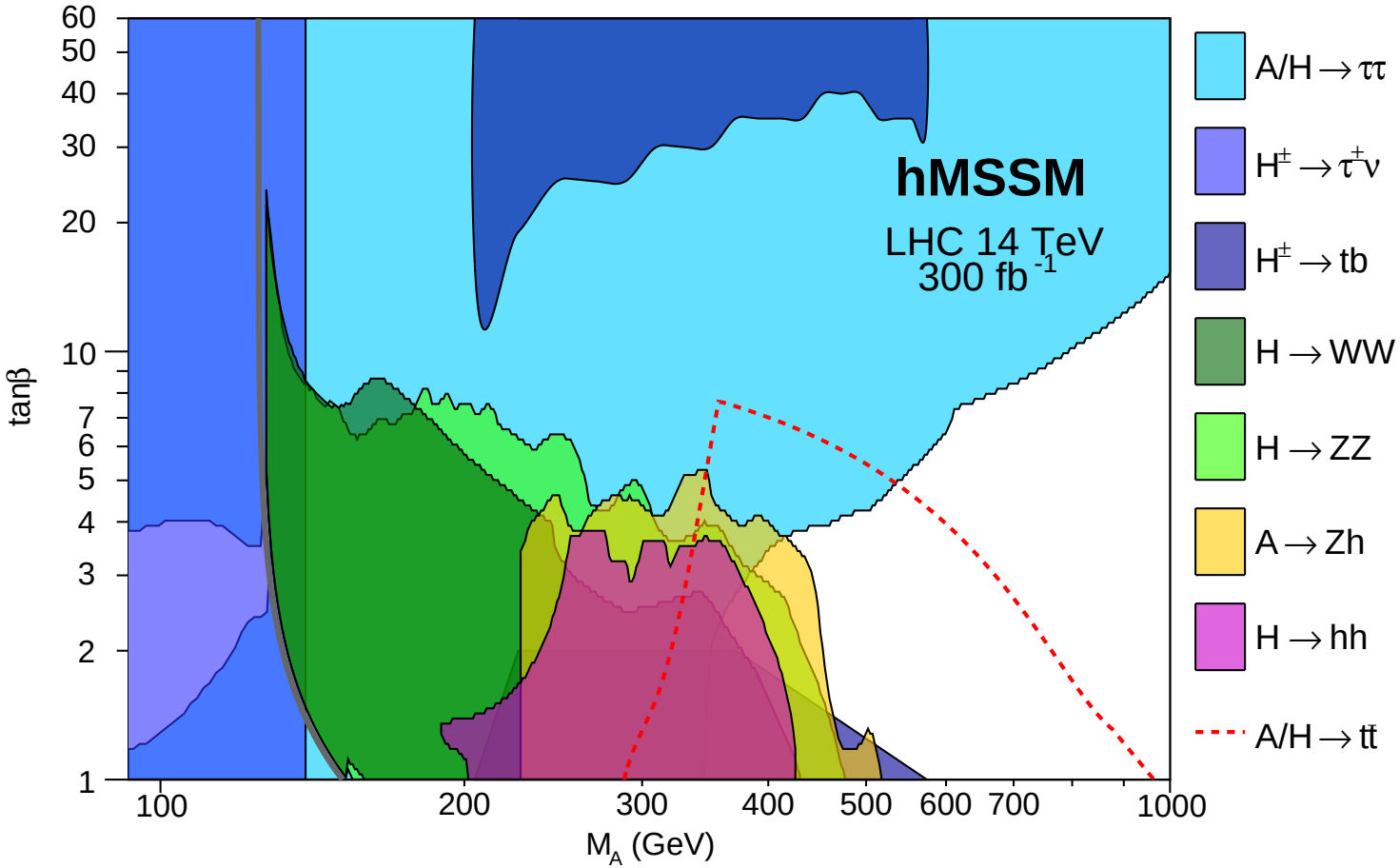


- Impact of main uncertainties on signal strength and event yields

Systematic Uncertainty	Background [%]		Z'_{TC2}, 2 TeV [%]		Z'_{TC2}, 3 TeV [%]	
	resolved	boosted	resolved	boosted	resolved	boosted
$t\bar{t}$ extra QCD radiation	4.0	2.4	–	–	–	–
$t\bar{t}$ QCD NNLO	0.8	7.4	–	–	–	–
$t\bar{t}$ cross-section	5.2	–	–	–	–	–
$t\bar{t}$ generator	1.7	3.8	–	–	–	–
$t\bar{t}$ parton shower	0.6	3.2	–	–	–	–
Multi-jet	2.6	2.7	–	–	–	–
Anti-k_t $R = 0.4$ JER	1.1	0.2	3.2	0.2	1.2	0.2
Anti-k_t $R = 0.4$ JES	5.8	0.9	7.0	0.7	3.6	0.6
Anti-k_t $R = 1.0$ JER	0.1	4.0	5.3	3.7	2.0	4.2
Anti-k_t $R = 1.0$ JES	0.3	6.0	3.7	4.7	2.8	6.0
b-tagging efficiency	3.2	1.8	1.8	1.9	2.3	2.7
b-tagging extrapolation	2.4	2.3	2.0	0.6	1.2	1.8
Luminosity	1.9	1.9	2.1	2.1	2.1	2.1
Pile-up	4.4	0.5	4.4	0.8	3.9	0.5
Total	11.6	12.8	11.7	7.1	7.6	8.7

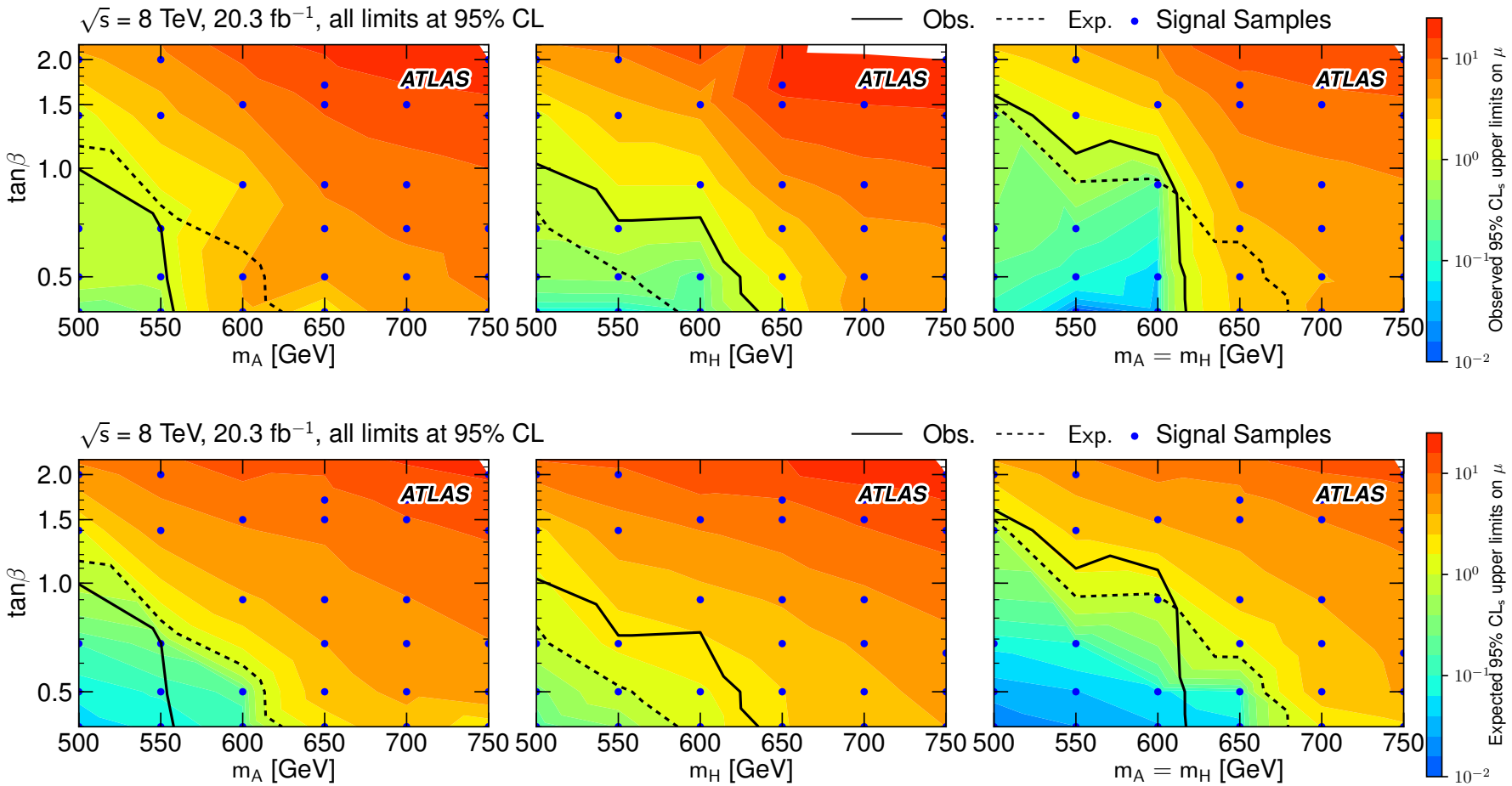
Projected constraints in hMSSM

- Constraints in hMSSM from phenomenological studies [Djouadi et al., JHEP 06 (2015) 168]



Limits on signal strength in ATLAS $\Phi \to t\bar{t}$

- Observed (top) and expected (bottom) upper limits on $\mu = g^4$



Uncertainties in ATLAS $\Phi \to t\bar{t}$

- Impacts on event yields ($m_A = 500\,\text{GeV}$, $\tan\beta = 0.68$)

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