Search for $t\bar{t}H/A \to t\bar{t}t\bar{t}$ in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector

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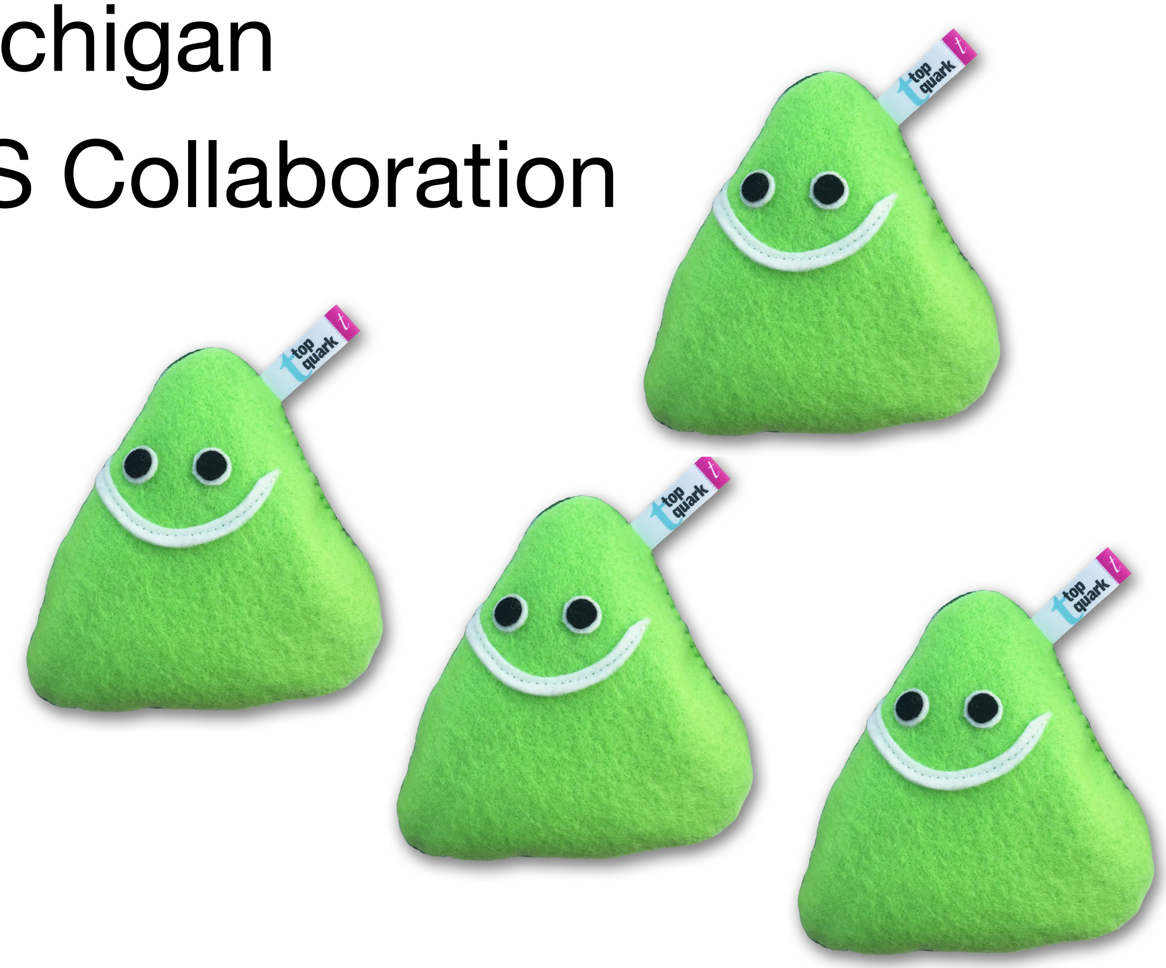
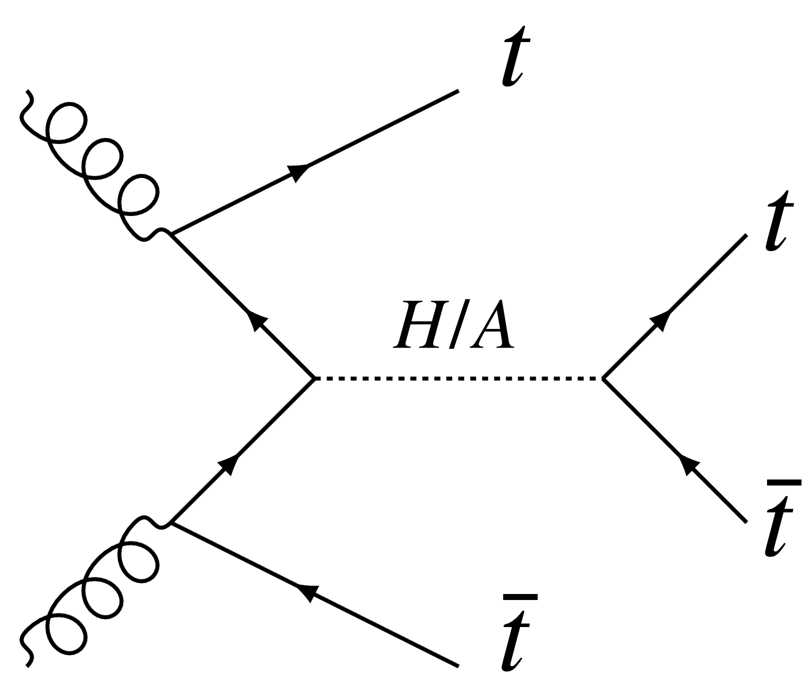
On behalf of the ATLAS Collaboration

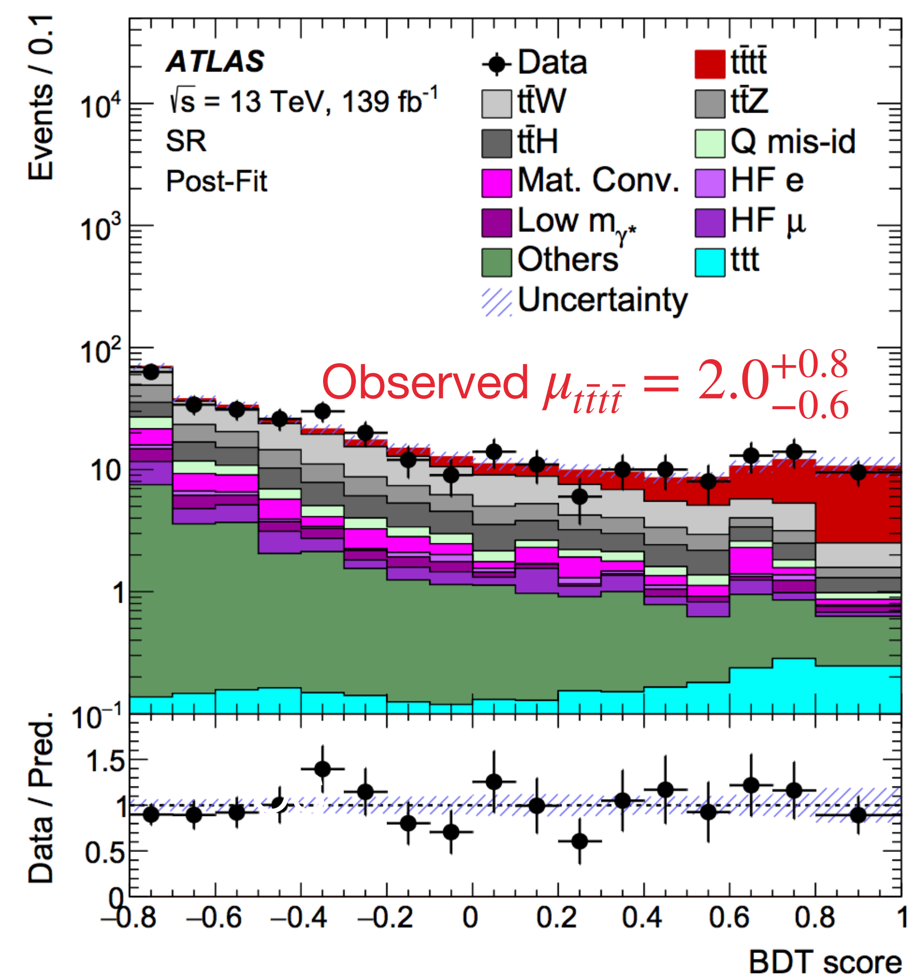


Motivation

- Evidence for SM $t\bar{t}t\bar{t}$ production in the same-sign dilepton and multilepton (SSML) final states was achieved → observed cross section: $\sigma_{t\bar{t}t\bar{t}} = 24^{+7}_{-6}$ fb (twice of expectation!)
- This analysis searches for the heavy Higgs boson in top-associated production mode ($t\bar{t}H/A \rightarrow t\bar{t}t\bar{t}$) from the 2HDM model in the same SSML final state
- Sensitive to the low $\tan\beta$ region with small interference with SM background
  - $A \rightarrow t\bar{t}$ decay mode dominates at the low $\tan\beta$ region (so does $H \rightarrow t\bar{t}$ in the alignment limit)

High jet, b-jet multiplicities and High H_T



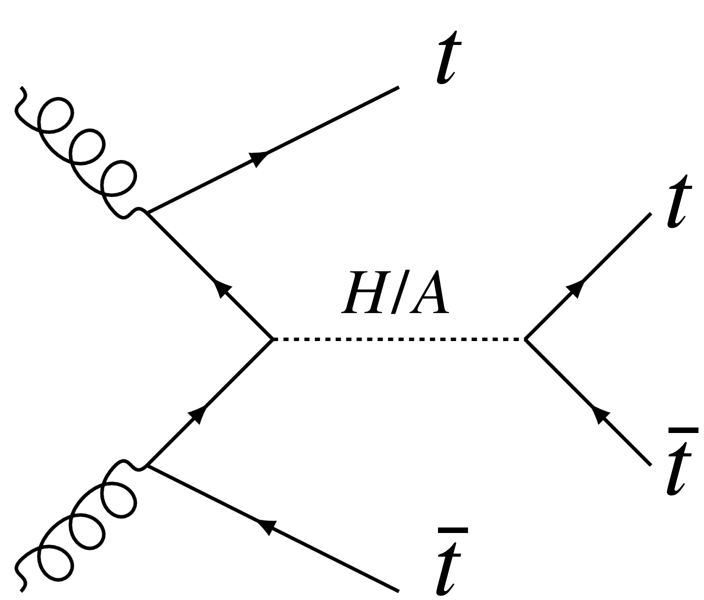


arXiv: 2007.14858

Analysis overview

- Analysis strategy based on the SM $t\bar{t}t\bar{t}$ analysis (paper) with additional upgrades
  - Improved jet reconstruction (particle flow algorithm) and neural net based b-tagging algorithm
  - Multivariate analysis (sequential BDTs) to extract BSM signals
- Main challenges
  - Small signal cross sections and background modeling in extreme kinematic regions
  - Hard to extract BSM $t\bar{t}t\bar{t}$ from highly irreducible ttV and SM $t\bar{t}t\bar{t}$

High jet, b-jet multiplicities and High H_T



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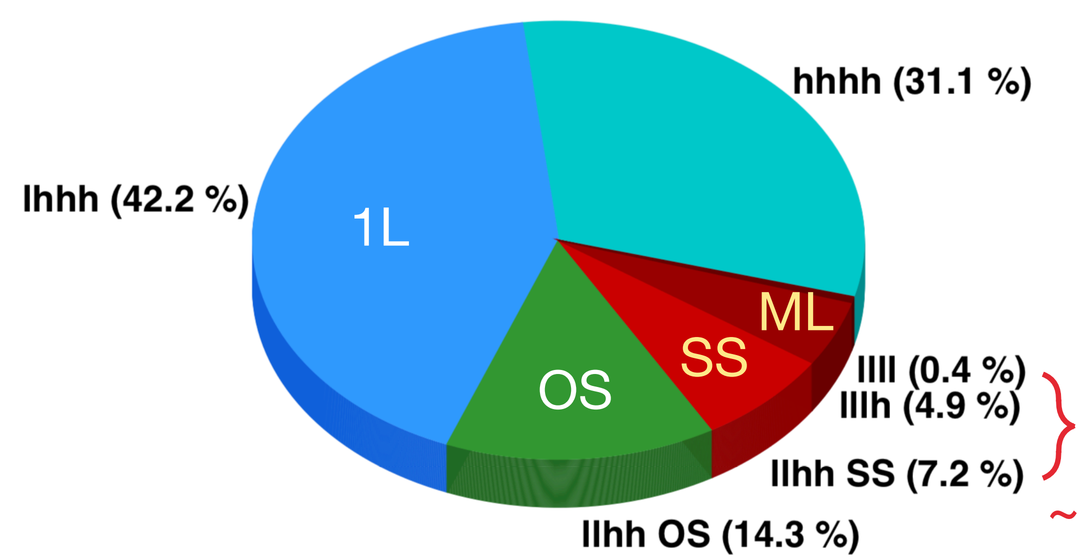
Decay product of 4 W bosons



+ 4 b-jets

~12% for SSML

Analysis strategy

Preselection

Both SS and ML, ≥ 1 b-tagged jet at 77% WP

2 tight leptons

2LSS
- SS ee with ECIDS, Z Veto, $M_{ee} > 15$ GeV
- SS $e\mu$ with ECIDS
- SS $\mu\mu$

ECIDS: MVA decreasing electron charge misID contributions)

≥ 3 tight leptons and Z Veto

ML
- eee
- $ee\mu$
- $e\mu\mu$
- $\mu\mu\mu$

✓ Signal background separation

- Events with $N_{jets} \geq 6, N_{b-jets} \geq 2$ and $H_T = \sum p_T^{\ell} + \sum p_T^{j} \geq 500$ GeV are signal-enriched phase space (baseline SR) in which is used for SM BDT and BSM parametrized-BDT (pBDT) training with XGBoost

✓ Statistical analysis

- In data-blinded stage, estimate the normalization factor for backgrounds with unblinded CRs in the template fit
- Simultaneous fit of CRs and SRs with post-fit background model to get limits on the cross section for the BSM signals

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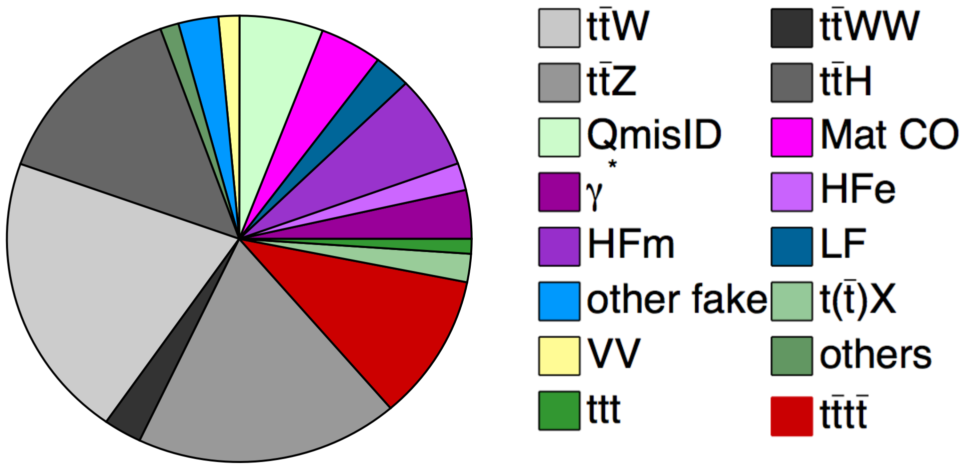
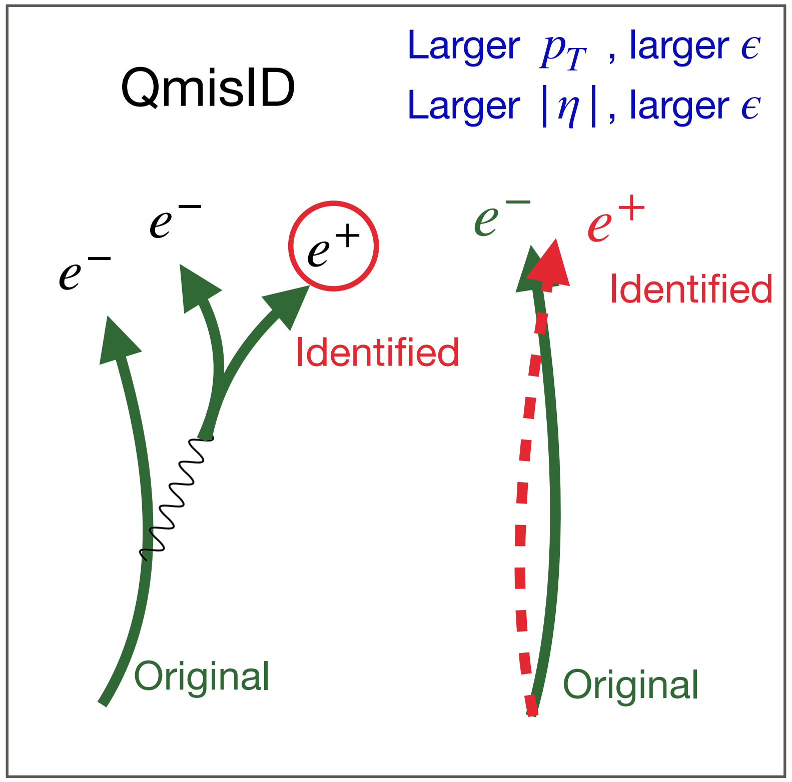
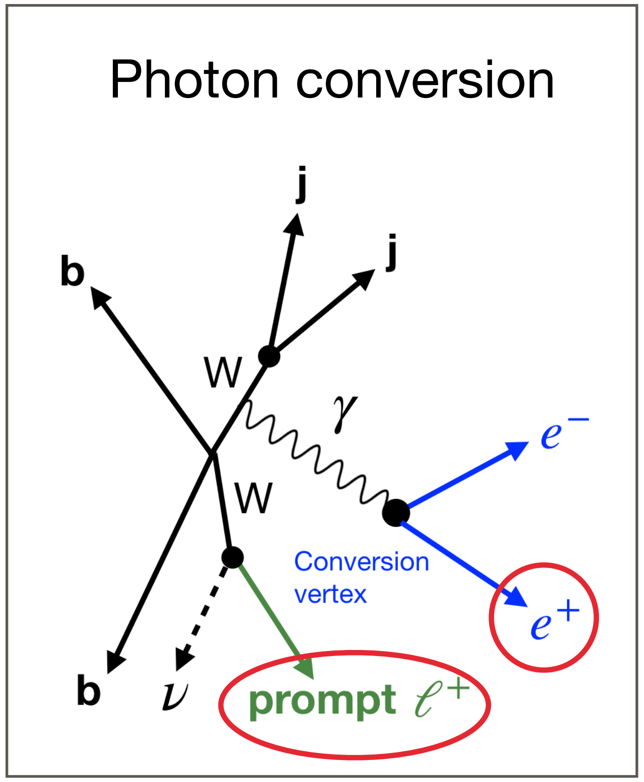
Backgrounds in SSML channel

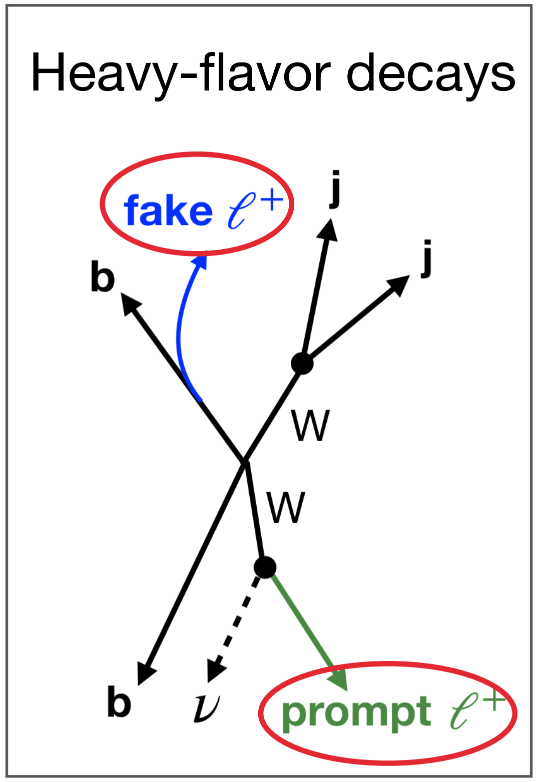
- **Physics processes: (~75%)**
  - SM $t\bar{t}t\bar{t}$ (**constrained to SM with 20% theory uncert.**)
  - $t\bar{t}W$ NLO QCD (**MC corrected to data**)
  - $t\bar{t}Z$, $t\bar{t}H$ and minor processes (**fully taken from MC**)
- **Instrumental and fake backgrounds: (~25%)**
  - Charge mis-identification (**data-driven method**)
  - Non-prompt leptons from heavy-flavor decays and photon conversion (**MC corrected to data in CRs**)
  - Fake leptons from light mesons and quark/gluon jets, and minor backgrounds (**fully taken from MC**)

Baseline SR (Pre-fit) $N_{jets} \geq 6$ & $N_{b-jets} \geq 2$ & $H_T \geq 500$ GeV









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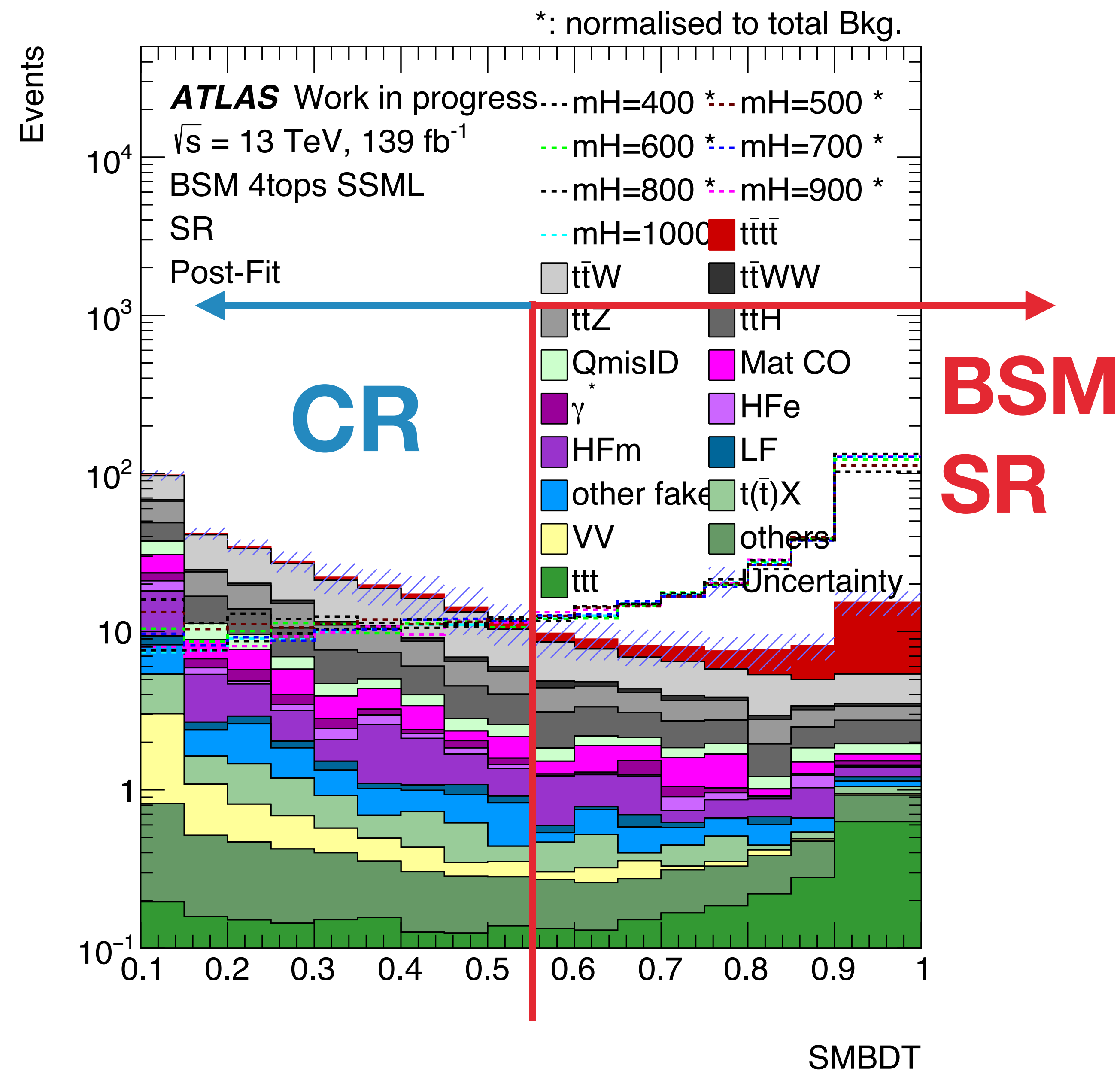
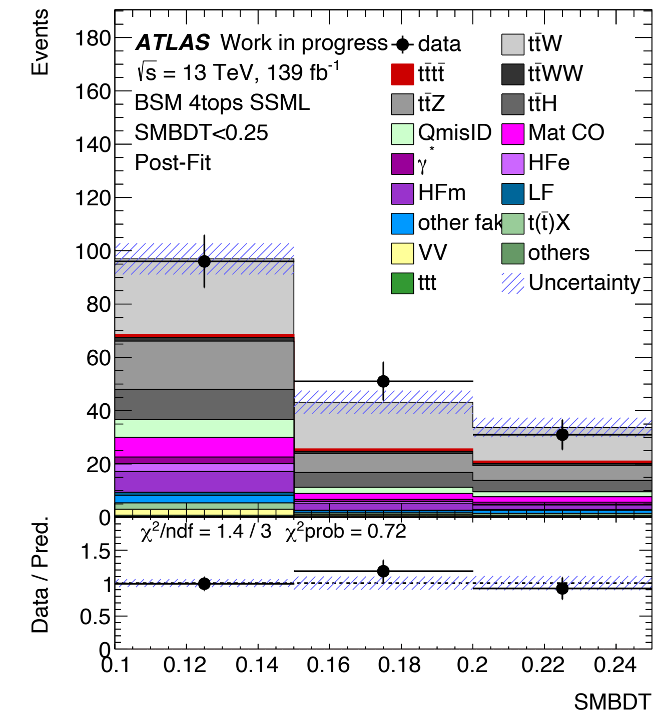
Sequential BDT strategy - SM BDT

- **SM BDT** is trained with SM $t\bar{t}t\bar{t}$ against SM backgrounds using XGBoost package
- Discriminate $t\bar{t}t\bar{t}$-like events from SM background
  - Low SM BDT region for background modeling
  - High SM BDT region for BSM signal extraction

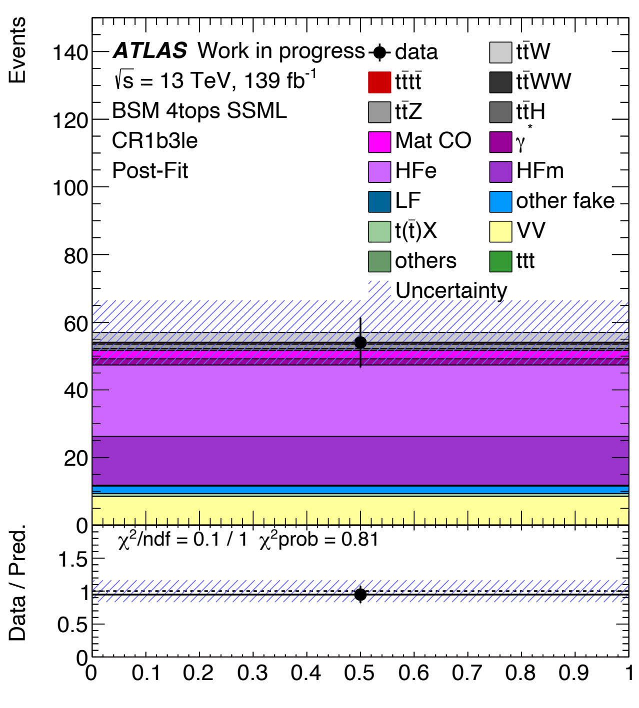


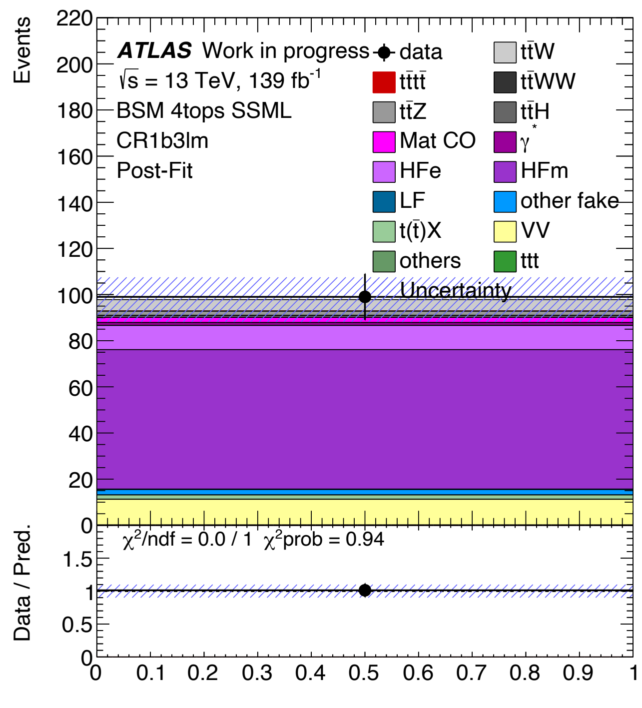
Fake and $t\bar{t}W$ background estimation

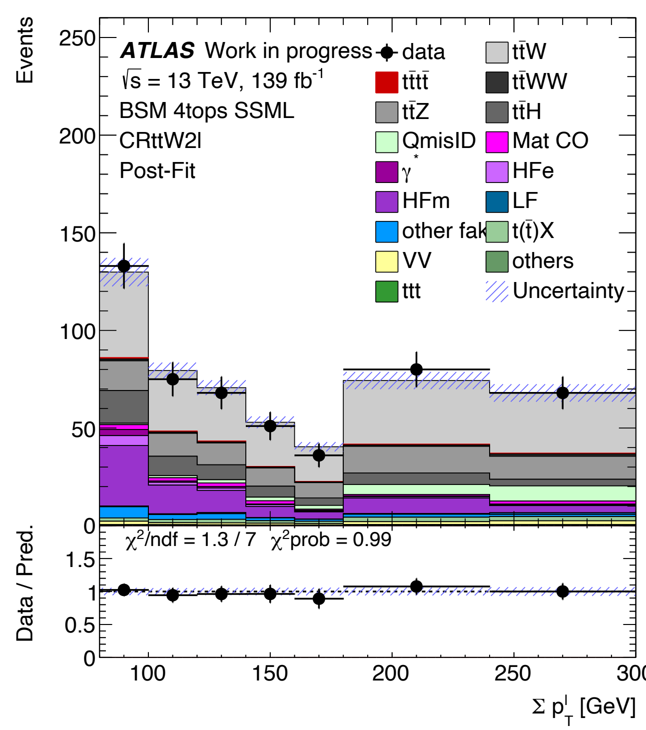
- Template fit to data in 5 control regions to estimate the normalization factors of $t\bar{t}W$ and fake backgrounds
- Low BDT control region was included to make the background modeling close to the unblinding fit setup
  → unblind bins where signal contamination < 5% (**SM BDT < 0.25**) in the template fit

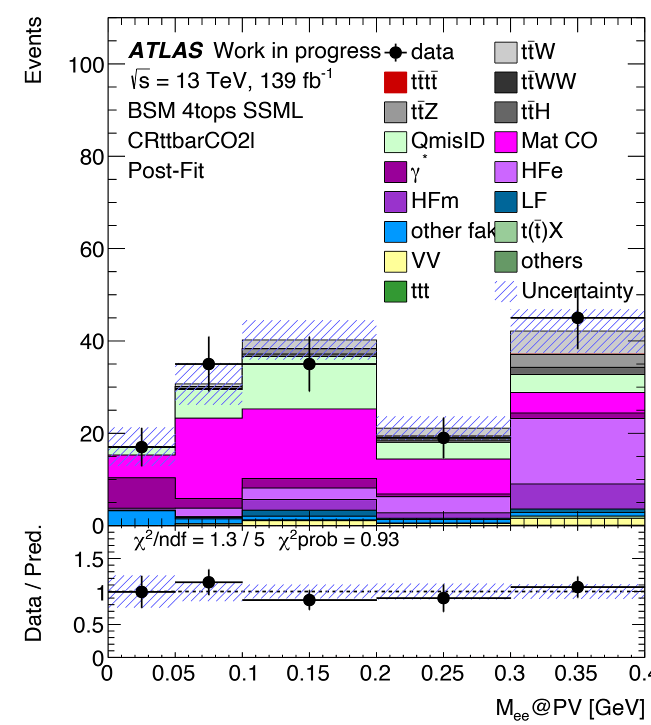


Parameter	NF $t\bar{t}W$	NF CO	NF γ^*	NF HF e	NF HF μ
Value (± Stat.+Syst.)	$1.48^{+0.28}_{-0.27}$	$1.58^{+0.61}_{-0.53}$	$0.62^{+0.61}_{-0.42}$	$0.95^{+0.37}_{-0.35}$	$0.98^{+0.22}_{-0.20}$



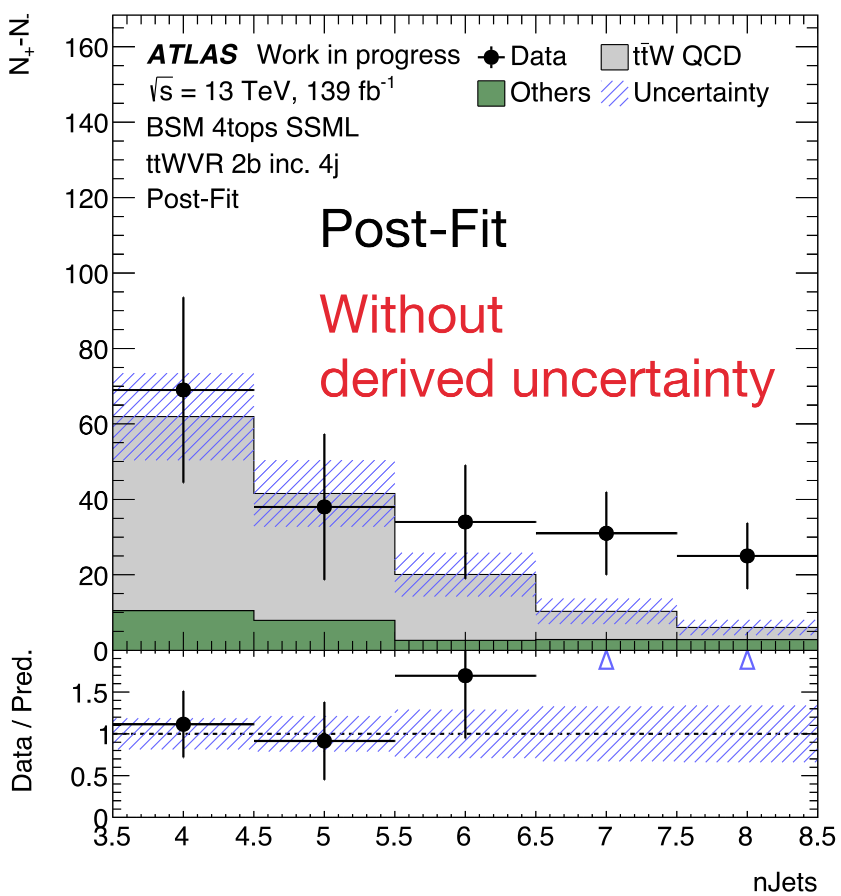


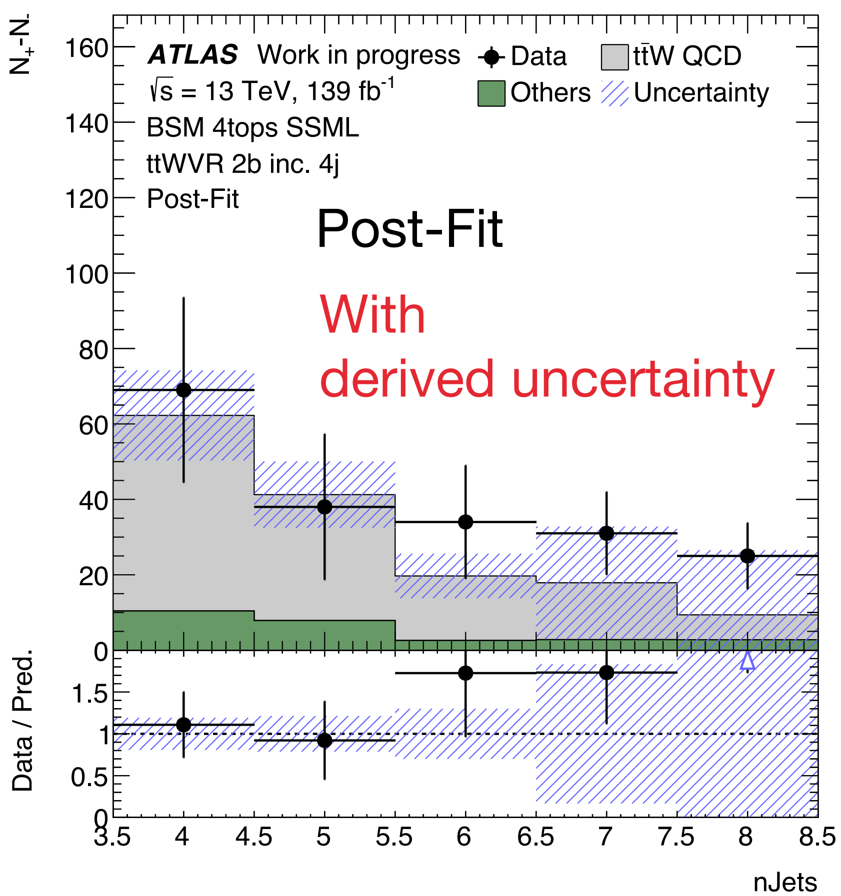




$t\bar{t}W$ validation region

- $t\bar{t}W$ validation region: difference between positively and negatively charged leptons ($N_{++} - N_{--}$) with selection $N_{\rm jets} \geq 4$ and $N_{\rm b-jets} \geq 2$ (no H_T selection)
- Large Data/MC discrepancy in the high $N_{\rm jets}$ region → derive large uncertainty for $t\bar{t}W$
  - Working in progress to update the ttW QCD+EW NLO samples

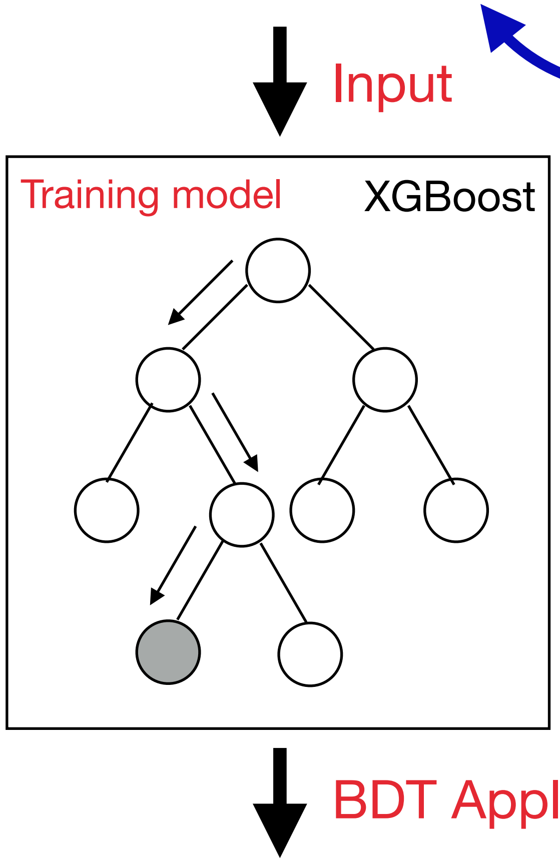




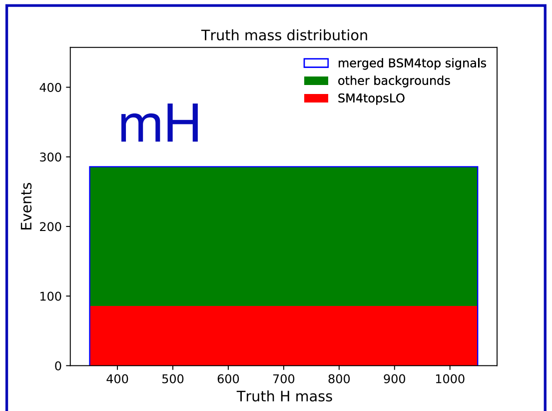
Introduction to parameterized BDT

- Idea of pBDT is from parameterized neural network (ArXiv:1601.07913)

Features = $(\vec{x}, m_H)$

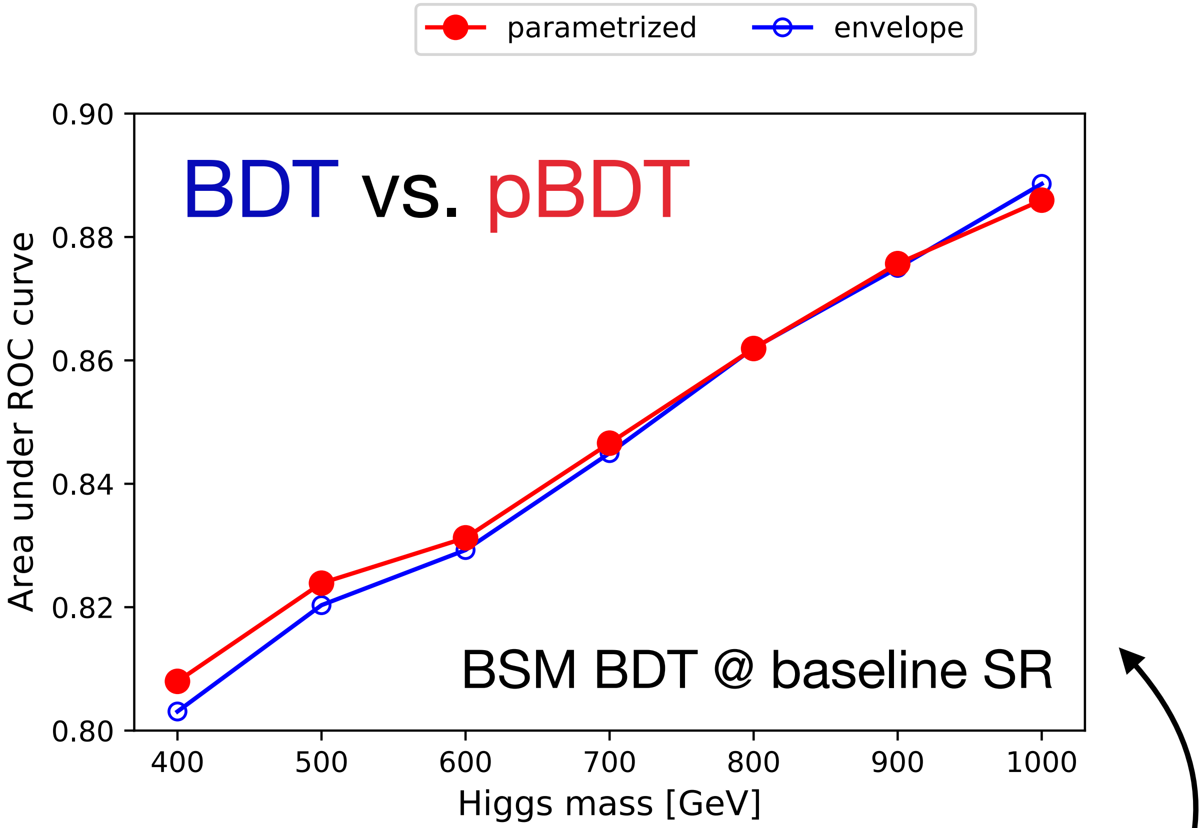


"BSM BDT @ mH=400 GeV"
$= f(\vec{x}, m_H = 400 \text{ GeV})$



- Random mH for bkg
- Same mH distribution on sig and bkg

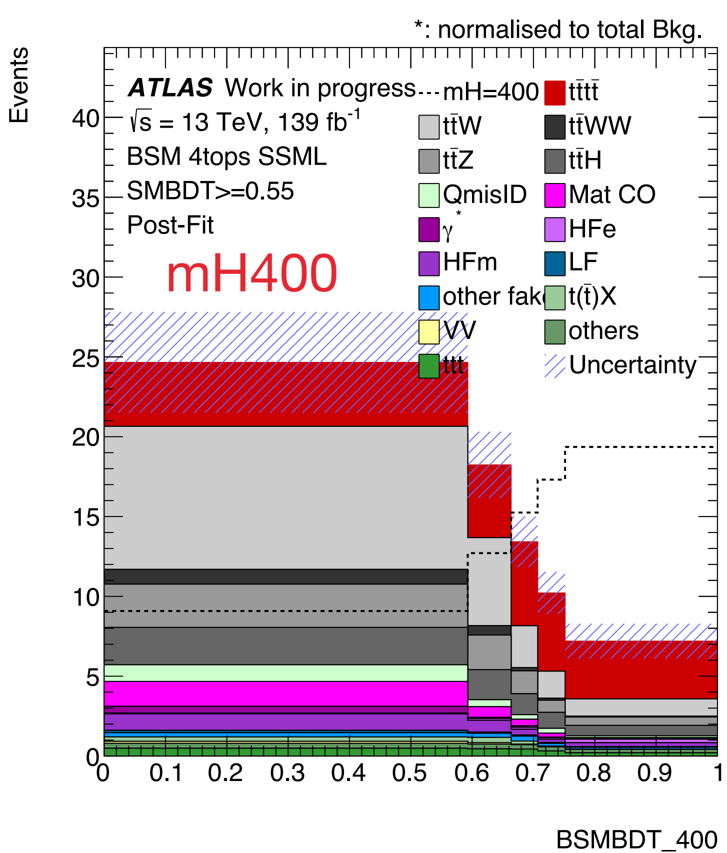
pBDT = $f(m_H, \vec{x})$

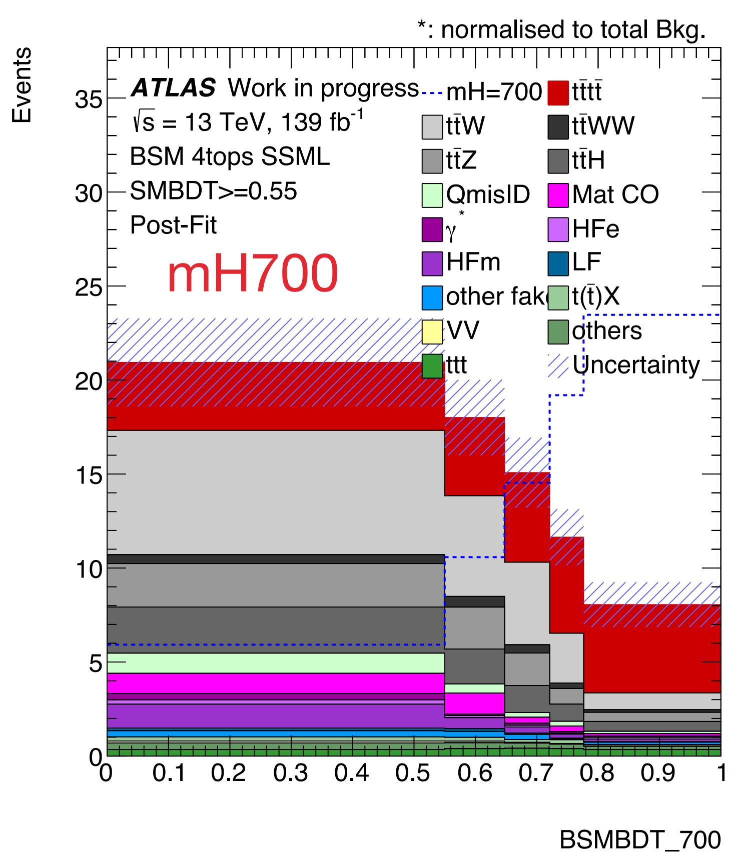


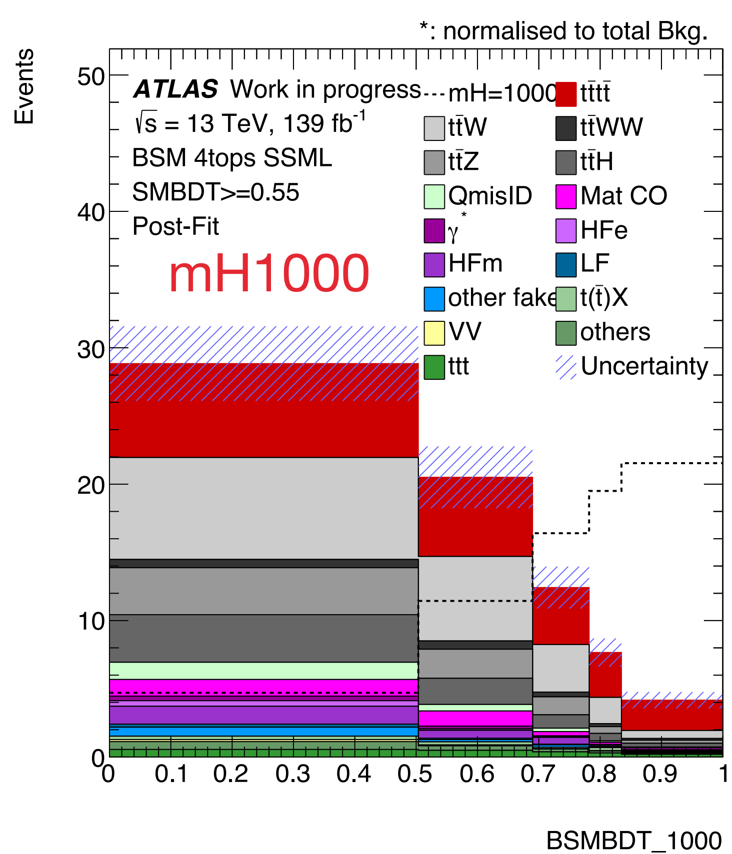
- **BDT at each mass point:** each signal point against all SM backgrounds
- **Parametrized BDT:** merged signals against all SM backgrounds

Sequential BDT strategy - BSM pBDT

- **BSM pBDT** is trained with merged BSM $t\bar{t}t\bar{t}$ and SM backgrounds using XGBoost package
  - Reweigh background contribution to mimic the high SM BDT region in the training
  - SM BDT is used as input variable for BSM pBDT

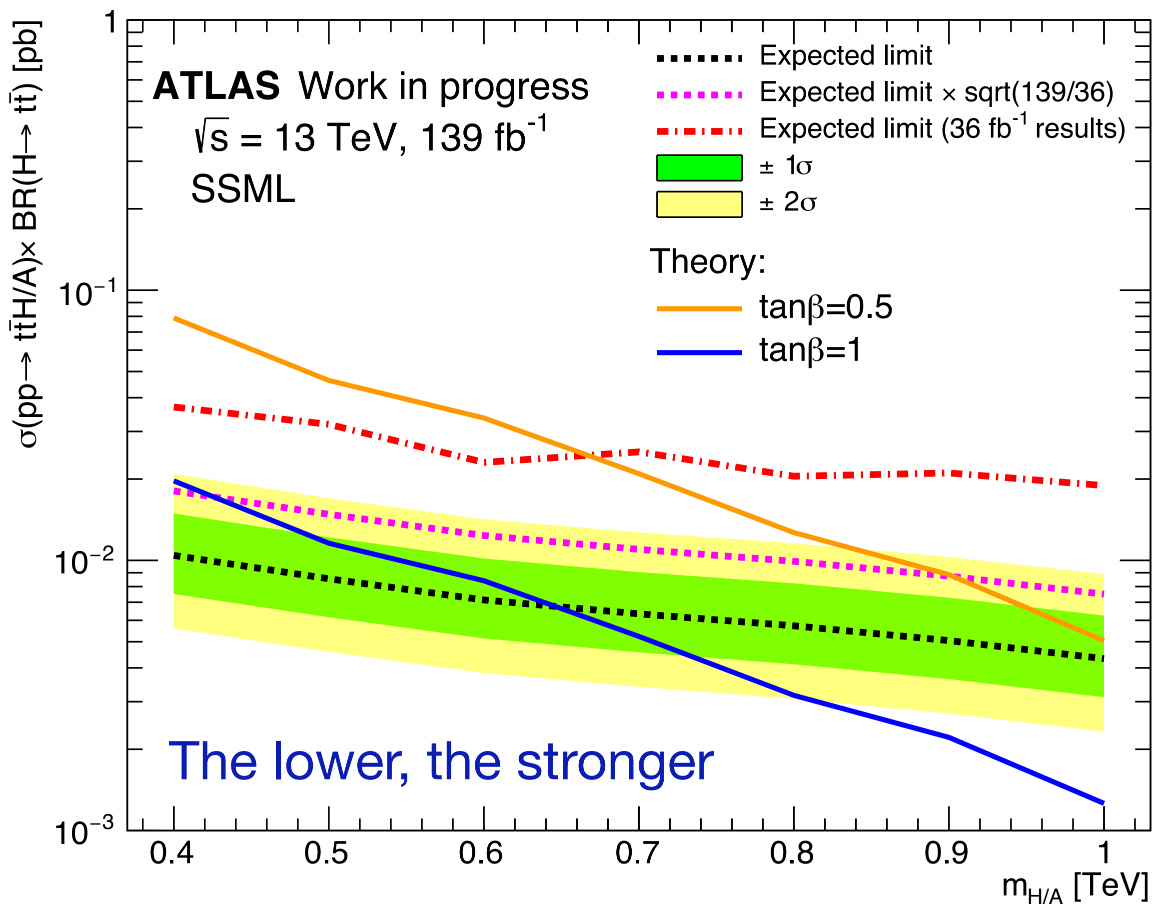


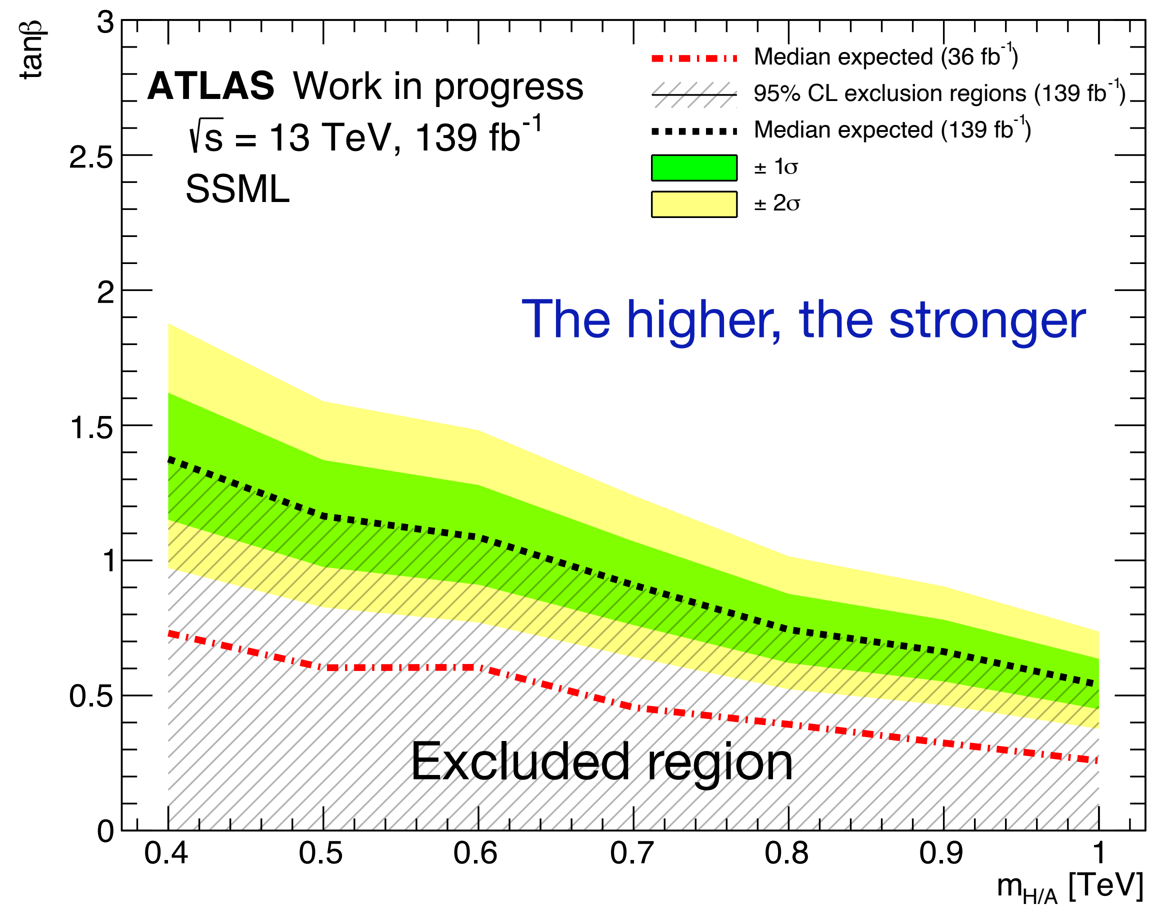




Expected sensitivity

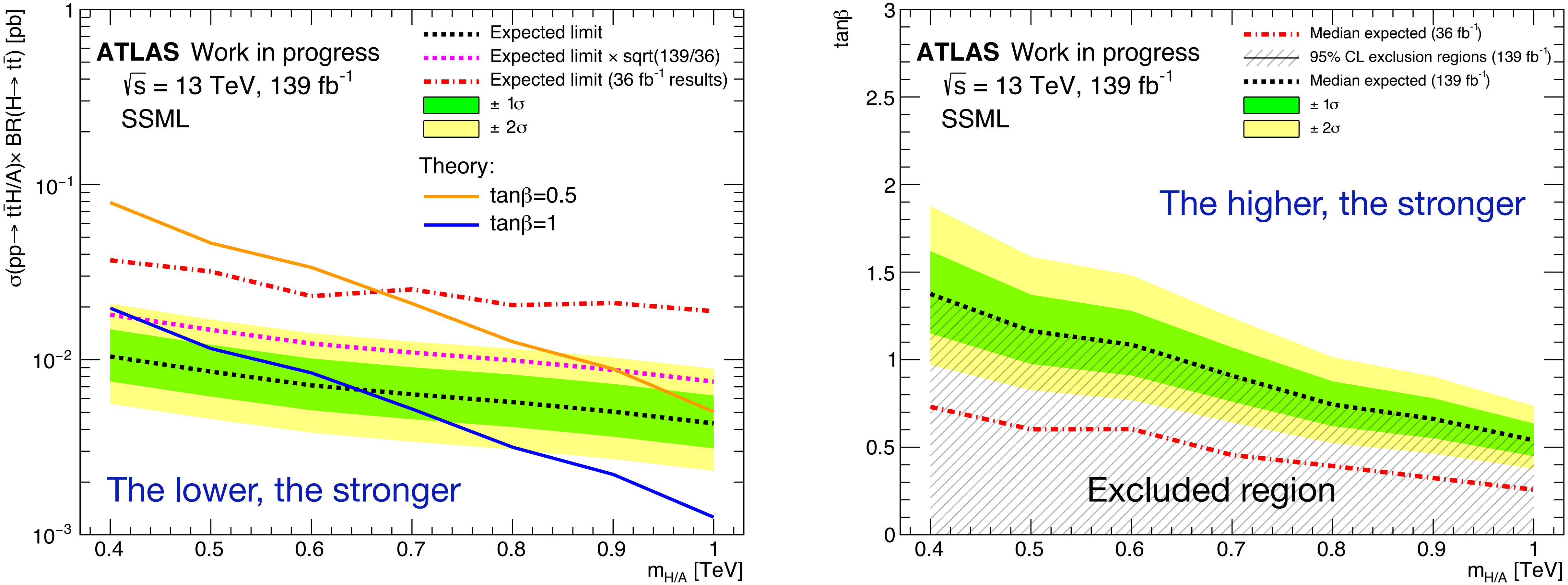
- About 75% stronger than ATLAS 36 fb^{-1} SSML+b-jets analysis (paper)
  - Expected 50% stronger with statistical improvement (4 times more statistics, limits decrease by a factor of 2)
- Exclusion of $\tan\beta = 1$ for mH < 650 GeV and exclusion of $\tan\beta = 0.5$ for mH < 1000 GeV





Summary and outlook

- Mass parameterized BDT is used to extract BSM signals in $t\bar{t}t\bar{t}$ enriched phase space
  - Same performance between pBDT and BDT at each mass point
- Work in progress to improve modeling of SM backgrounds ($t\bar{t}W$, SM $t\bar{t}t\bar{t}$, ...)
  - Plan to update with $t\bar{t}W$ QCD+EW NLO samples to have better description in the high N_{jets} region



Backup

Object selection

- Trigger and object definitions are inherited from SM $t\bar{t}t\bar{t}$ analysis
- Single lepton and di-lepton triggers are used
- Same object definitions but changing to PFlow jets and DL1r b-tagging

Table 13: Overlap removal procedure

Reject	Against	Criteria
Electron	Electron	shared track, $p_{\mathrm{T},1} < p_{\mathrm{T},2}$
Muon	Electron	is Calo-Muon and shared ID track
Electron	Muon	shared ID track
Jet	Electron	$\Delta R < 0.2$
Electron	Jet	$\Delta R < 0.4$
Jet	Muon	`NumTrack` < 3 and (ghost-associated or $\Delta R < 0.2$)
Muon	Jet	$\Delta R < \min(0.4, 0.04 + 10\,\mathrm{GeV}/p_{\mathrm{T}}(\mu))$

Ntuple production with AnalysisBase 21.2.120

Object	Electrons Loose	Electrons Tight	Muons Loose	Muons Tight	Jets	b-jets	E_T^{miss}
p_T [GeV]	> 10	> 28	> 10	> 28	> 25	> 25	$-\sum$ (calib. lep & jet & non-matched tracks at PV)
$\|\eta\|$	< 1.37 or 1.52-2.47		< 2.5		< 2.5	< 2.5	
ID quality	mediumLH ECIDS $(ee, e\mu)$	tightLH ECIDS $(ee, e\mu)$	medium		Anti-k_t (R=0.4) EMPFlow with Jet cleaning + JVT tight	DL1r 77% (CDI: 2020-03-11-Sh228_v3)	Calo-based (Tight WP)
Isolation	none	FCtight	none	FCTightTrackOnly			
Track vertex: $\|d_0/\sigma_{d_0}\|$ $\|\Delta z_0 \sin\theta\|$	< 5 < 0.5 mm		< 3 < 0.5 mm				

Template fit method

- **Fit to data in CRs to estimate the ttW and fake backgrounds**
  - Simultaneously free float the NFs of backgrounds with shape from MC in a fit to data to correct the background estimation
  - 5 Normalization factors: fake electron from HF (HFe), fake muon from HF (HFμ), material conversion (Mat CO), virtual photon conversion (γ^*) and $t\bar{t}W$
- CRlowBDT was included in the template fit in the SM 4top analysis to make the background modeling close to the unblinding fit setup → unblind bins where signal contamination < 5% (**SM BDT < 0.25**) in this region and include in the template fit

Currently Included in the template fit

Region	Channel	N_{jets}	$N_{\text{b-jets}}$	other selection	Fitted variable
CRttbarCO	SSee || SSem	$4 \leq N_{\text{j}} < 6$	≥ 1	$0 < M_{ee}@ConvV < 0.1$ $200 < H_{\text{T}} < 500$	$M_{ee}@PV$
CR1b3Le	eee || eem		$= 1$	$100 < H_{\text{T}} < 250$	1 bin
CR1b3Lm	emm || mmm		$= 1$	$100 < H_{\text{T}} < 250$	1 bin
CRttW2L	SSem || SSmm	≥ 4	≥ 2	$M_{ee} < 0$ or $M_{ee} > 0.1$, $\|\eta(e)\| < 1.5$ for $N_{\text{b}} = 2$, $H_{\text{T}} < 500$ or $N_{\text{j}} < 6$ for $N_{\text{b}} \geq 3$, $H_{\text{T}} < 500$	$\sum p_T(lep)$
CRlowBDT	SS+3L	≥ 6	≥ 2	$H_{\text{T}} > 500$, SM BDT < 0.55†	SM BDT
BSM SR	SS+3L	≥ 6	≥ 2	$H_{\text{T}} > 500$, SM BDT ≥ 0.55	BSM pBDT

* $M_{ee}@ConvV(@PV)$ is defined as the invariant mass between the track associated to e and the closest track at conversion (primary) vertex

† In the template fit, SM BDT < 0.25 is included in the fit. In the realistic Asimov fit, SM BDT < 0.55 is included

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Input variable for SM BDT and BSM pBDT

- Input variable of SM BDT inherited from SM 4top analysis with additionally decorrelating the sum of continuous b-tagging scores into two variables to have better separation between 4top-like events and $t\bar{t}W \geq 7$-jet events
- SM BDT is used in BSM pBDT training

Input variables (SM BDT)
jet_sum_DL1r_Continuous_leadingFour
nJets
deltaR_ll_min
leading_jet_pT
lep_0_pt
leading_bjet_pT
deltaR_ll_sum
HT_jets_noleadjet
jet5_pt
deltaR_bj_min
met_met
deltaR_lb_max
jet1_pt

Input variables (BSM pBDT)
deltaR_ll_min
deltaR_ll_sum
SphericityJets
SphericityXYJets
met_met
HT_all
SMBDT
mH

MVA strategies	BDTs used	Samples used	Parametrized
Sequential BDT	SM BDT	SM 4top vs. bkg	✗
	BSM pBDT	Merged BSM vs. SM 4top (& bkg)	✓

ATLAS EXPERIMENT

Fit setup

✓ **Plain Asimov Fit: (S+B and SRCR with Asimov data)**

- Probe sensitivity (limits) and expected constraints on fitted variables based on pre-fit background model

✓ **Real data CRs-Only Fit: (BOnly and unblinded CROnly, fit with real data)**

- Derive a "close-to-final" post-fit background estimation w/o looking at data in SR
- Template fit method: CRttbarCO, CR1b3Le, CR1b3Lm, CRttW2L

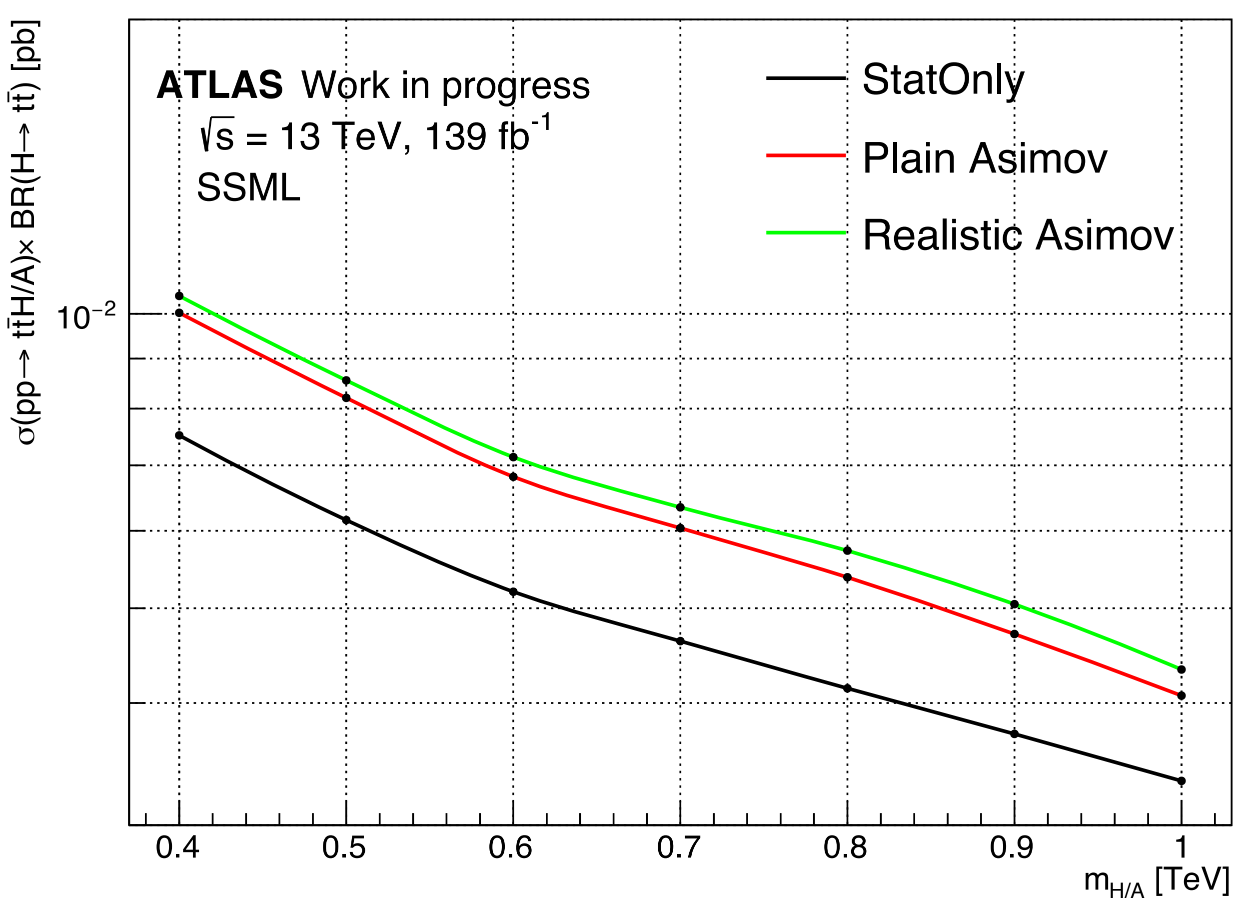
✓ **Realistic Asimov Fit: (S+B and SRCR with Asimov data with $\mu_{\mathrm{BSM}t\bar{t}t\bar{t}}$ free-floating with nominal set to 0)**

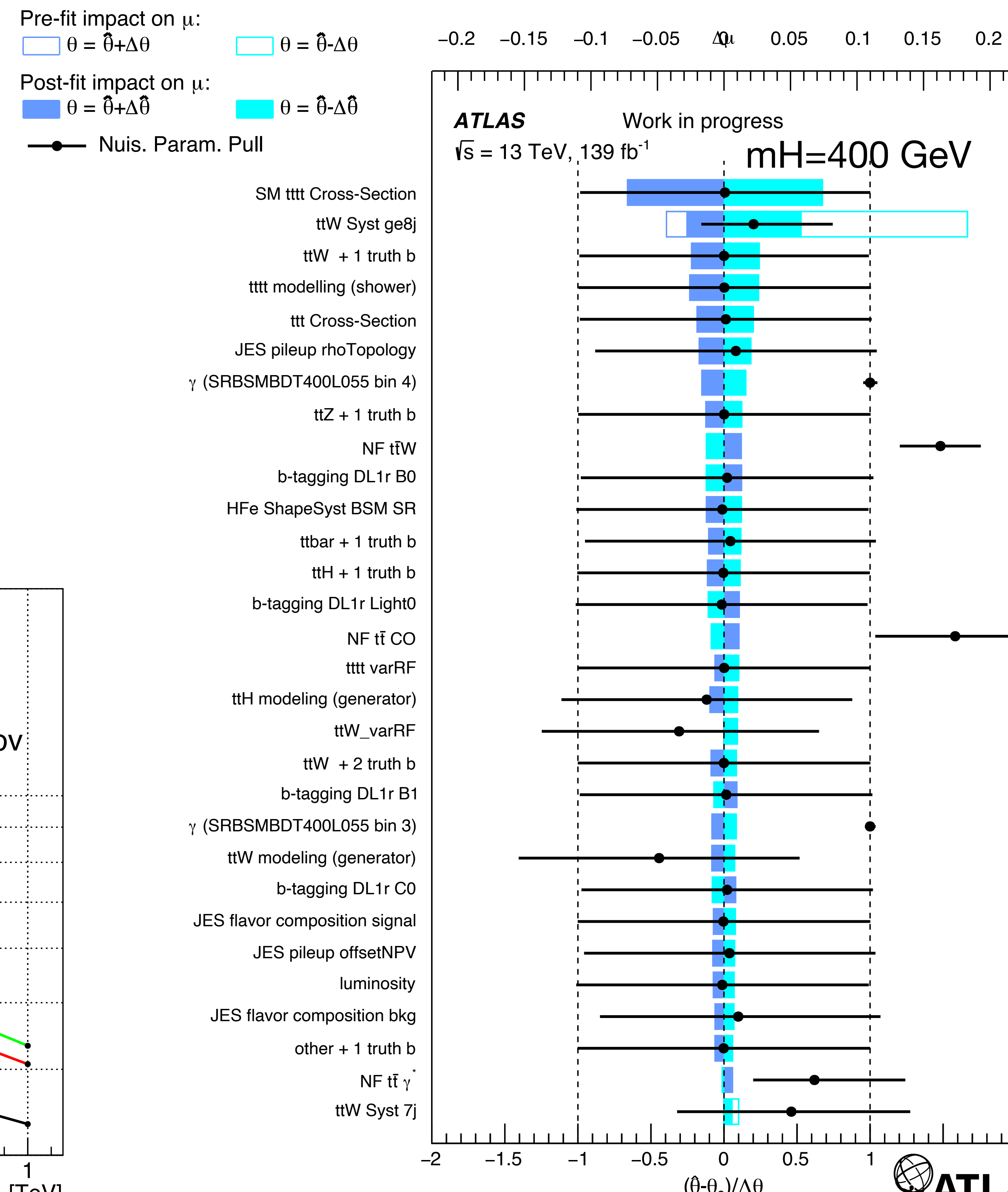
- Use pseudo-data corresponding to post-fit background prediction from Real CRs-Only fit
- Obtain the "close-to-final" values of sensitivity (limits), NP pulls and constraints w/o looking at data in any regions

Fit setup	Control regions	Signal regions	Fitted parameters	$\mu_{\mathrm{BSM}t\bar{t}t\bar{t}}$	Purpose
Plain Asimov	MC	MC	$\alpha_{\mathrm{PlainAsimov}}$	free [μ=0]	expected constraints and sensitivity
Real CRs-Only	data	not included	$\alpha_{\mathrm{CRs\text{-}Only}}$	not included	post-fit bkg
Realistic Asimov	MC[$\alpha_{\mathrm{CRs\text{-}Only}}$]	MC[$\alpha_{\mathrm{CRs\text{-}Only}}$]	$\alpha_{\mathrm{RealisticAsimov}}$	free [μ=0]	expected sensitivity (post-fit bkg injected)

Systematic uncertainties

- Hard to separate SM $t\bar{t}t\bar{t}$, 3top and $t\bar{t}W \geq 8$ jets events from BSM $t\bar{t}t\bar{t}$ signals
- Large impact from SM $t\bar{t}t\bar{t}$, 3top and $t\bar{t}W \geq 8$ jets related systematic uncertainties





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