Search for top-associated pseudoscalar production ($t\bar{t}$ a) in the a → b $\bar{b}$ decay in dileptonic $t\bar{t}$ events

Based on ATLAS Paper HMBS-2024-46 [(CERN-EP-2025-060)]

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Introduction

Motivation

The pseudoscalar **a** is predicted in many BSM models:

- Extended Higgs sectors - e.g., Two-Higgs-Doublet Models (2HDM).
- **a** could mediate dark matter.

Decay and Experimental status

- Previously, ATLAS probed a light pseudoscalar $t\bar{t}$a with a → μ⁺μ⁻ decay mode.
- For $m_a < m_h^{SM}$, a → b b̄ channel is expected to have a significant branching ratio (model dependent).

This Analysis

- **First ATLAS search** for *top-associated* pseudoscalar production t̄t a and tW a with a → b b̄ decay
- **Set limits** on top-Yukawa g_t and on σ × BR

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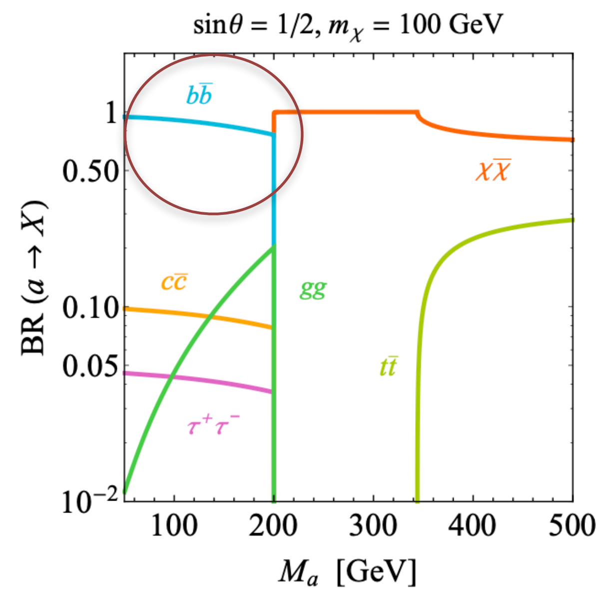


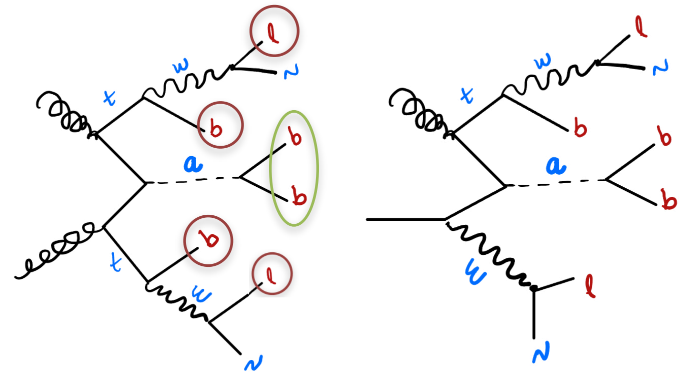
Below SM higgs mass, the a->bb dominates

Signal Model analysis strategy

Light pseudo-scalar a produced with $t\bar{t}$ or tW decaying via a->$b\bar{b}$.
The Yukawa Lagrangian for this channel :

$$\mathscr{L} = -\frac{g_t\, y_t}{\sqrt{2}}\, a\, \bar{t}\, i\gamma^5\, t \; - \; \frac{g_b\, y_b}{\sqrt{2}}\, a\, \bar{b}\, i\gamma^5\, b$$

g_t is a model parameter for the top-a coupling

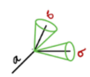


Feynman diagrams of the signal
$2l$ and at least $3bjets$ in the final state

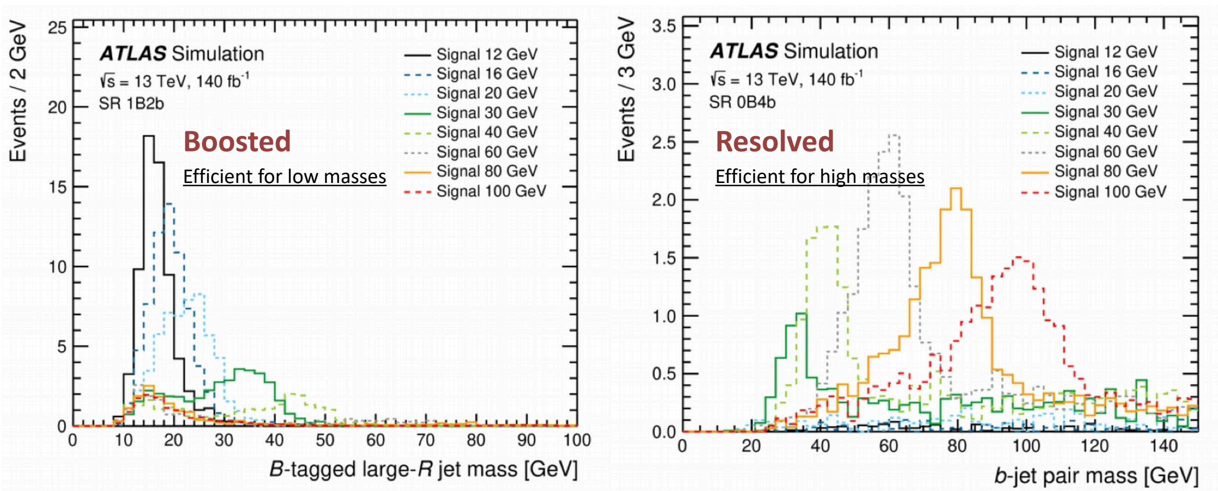
Two mass-dependent kinematic regimes:

Boosted regime:
$m_a = 12{,}16{,}20{,}30$
B quark pair jets are reconstructed as **large-R jet**.

Resolved regime:
$m_a = 30{,}40{,}60{,}80{,}100$
B quark pair are reconstructed as 2 **small-R jets**



The main BGs are :tt+jets, ttW, ttH and ttZ



Good sensitivity for the full mass range

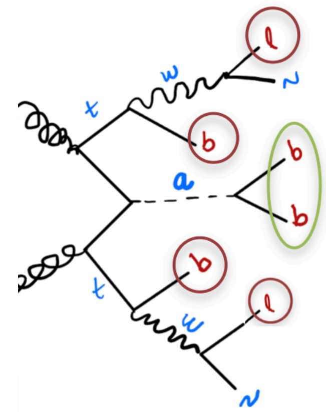
Event selection

Trigger:

Single lepton Triggers combined in a logical OR.

Preselection:

- Two oppositely charged leptons ($ee, \mu\mu, e\mu$), one of them with $p_T > 27GeV$ and satisfies trigger matching.
- $m_{ll} > 15GeV$.
- $|m_{ll} - m_Z| > 8GeV$.

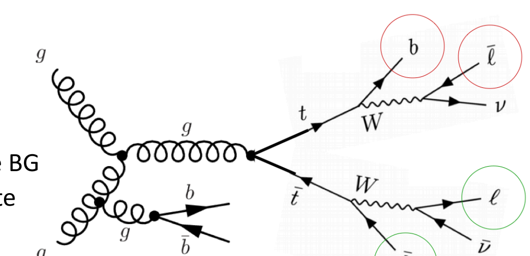


	Region	$R=1$ jets	$R=0.4$ jets	B	b	loose b
Resolved	SR 0B4b	≥ 0	≥ 4	0	≥ 4	–
	SR 0B3b	≥ 0	≥ 3	0	3	–
Boosted	SR 1B2b	≥ 1	≥ 2	1	≥ 2	–
	SR 1B1b+1bL	≥ 1	≥ 2	1	1	≥ 1
	CR 0B2b+1bL	≥ 0	≥ 3	0	2	≥ 1

Requiring only two tight tagged jets removes most of the a-> b $\bar{b}$ events

b = small-R tight DL1r, B = large-R DeXTer

Feynman diagrams of a possible BG
Mimicking the signal final state



*also c-jets
and light-jets

Data-driven corrections for $t\bar{t}$ MC simulation (mc reweighting)

Heavy flavour normalization

Improve the description of $t\bar{t}$+HF jets

kinematic reweighting

Improve the transverse momenta of leptons and jets

Heavy flavor normalization

The fraction of extra **b** and **c** jets in $t\bar{t}$+jets is mis-modeled—so we calibrate it with data.

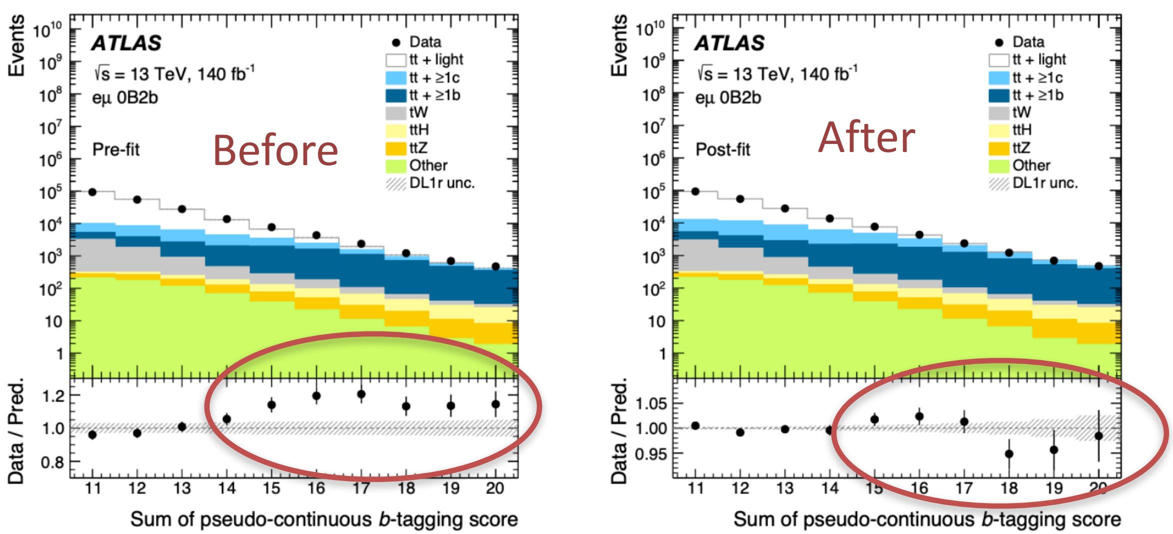
CR 0B2b+1bL is used in the **eμ** final state.

sumPCBTag score: Add the pseudo-continuous DL1r b-tag score of **every** jet.
b-jet->large score-> sum increases
Light flavor jet->small score

Scale factors extracted from the fit for each jet flavor

HF category	Norm. factor
$t\bar{t}$+light, tW	0.91 ± 0.03
$t\bar{t}+\geq 1c$	1.58 ± 0.14
$t\bar{t}+\geq 1b$	1.13 ± 0.07

1-D variable fit to correct for under-molded heavy flavor component in MC



MC needed:
60% more c-jets
13% more b-jets

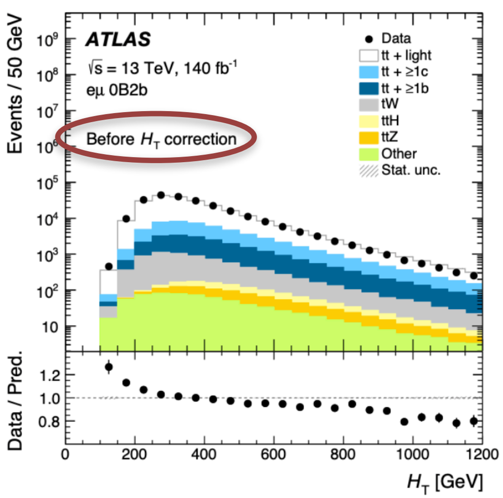
post-fit ratio flat around 1.0 → HF composition aligned

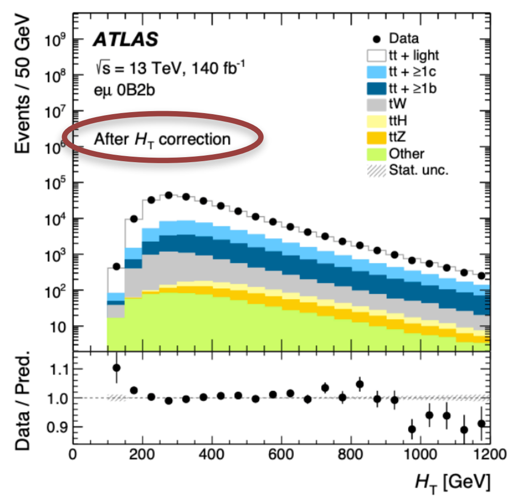
Kinematic reweighting

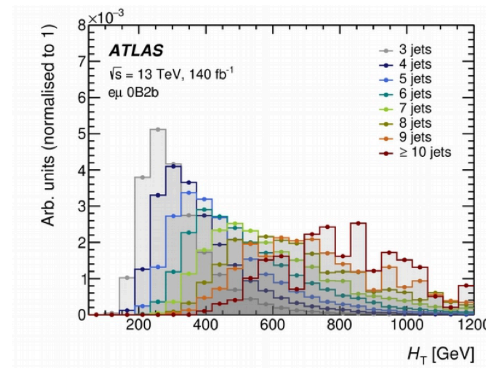
After HF normalization, In the MC events, every **extra jet** tends to push H_t **too high**, so data/MC drifts upward with jet multiplicity.

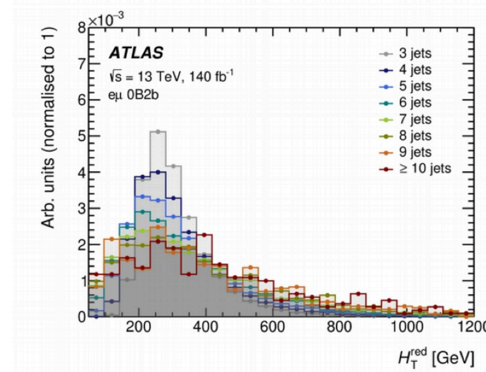
- Build **Hyperbolic reweighting map** in the (H_T, N_{jets}) plane to derive data driven corrections for $t\bar{t}$+light/c +Wt MC samples.
- **Goal:** Cancels the per-jet HT offset

$\mathbf{H_t} = \Sigma p_t(jets) + \Sigma p_t(leptons) + \Sigma E_T^{miss}$









HF scaling fixes flavour; H_t reweighting flattens event 'hardness'—combined, they give a background model that agrees with data before the NN fit

The offset in H_T is mitigated in H_T^{red} (after correction)
Reflecting the actual hardness of the event rather than the number of jets

Event Reconstruction(BDT)

Rank all possible jet–lepton and jet–jet combinations and pick the ones most likely to be a true $t\bar{t}$ or a->$b\bar{b}$ decay

Signal/BG discrimination(NN)

sees the **right top quarks and (potential) pseudoscalar**
And does the signal and Background discrimination

BDT

t
t

Two independent BDTs trained across all mass points:

$t\bar{t}$

BDT Input:

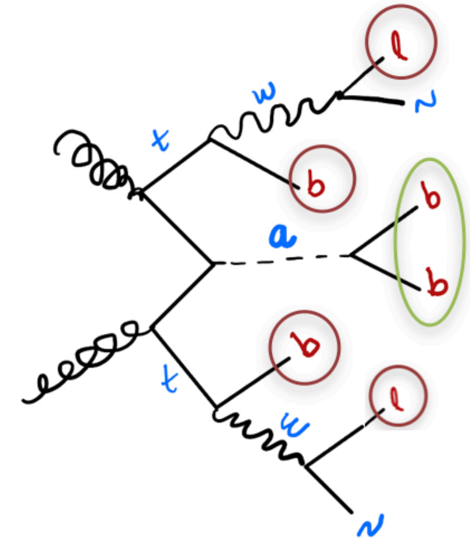
- N_{jets} , N_{bjets}
- Lepton kinematics : η, p_T
- Jet kinematics: η, p_T, jet index, b-tag score
- lj, jj pairs kinematics: $\eta, p_T, m, \Delta R$

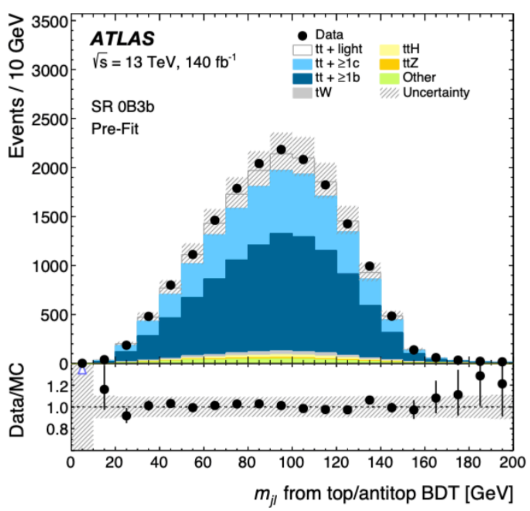
a

BDT Input:

- N_{jets} , N_{bjets}, sumPCBTag
- Jet kinematics: η, p_T, jet index, b-tag score

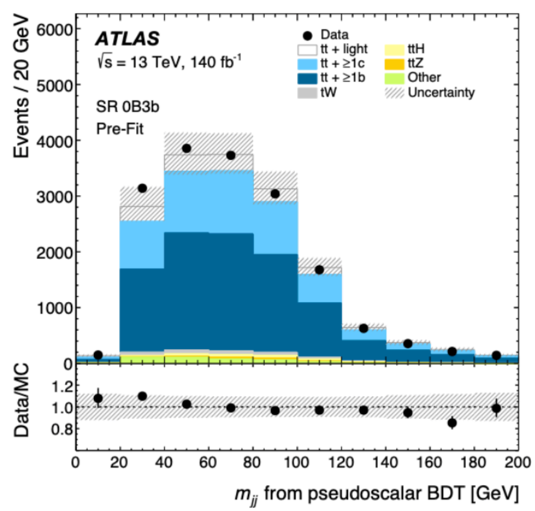
BDTs output: **BDT score** for lj, jj pairs and their kinematic variables





(a) m_{jl} (top)

Reconstructed mass of the highest-BDT-score ℓb-pair



(b) m_{jj} (pseudoscalar)

Reconstructed mass of the highest-BDT-score jj-pair

With the BDTs giving us clean top and bb candidates, we now feed those kinematics—and the BDT scores—into a **mass-parameterised Neural Network** that will make the final **signal-versus-background decision**

Signal/BG Discrimination with NNs

One NN is trained for each SR and for a specific mass point

Input: BDT scores, reconstructed masses, event level kinematics.

Output: score 0->1 (BG->signal)

Final maximum likelihood fit:

Run for every m_a hypothesis (12 – 100 GeV).

Inputs to the fit:

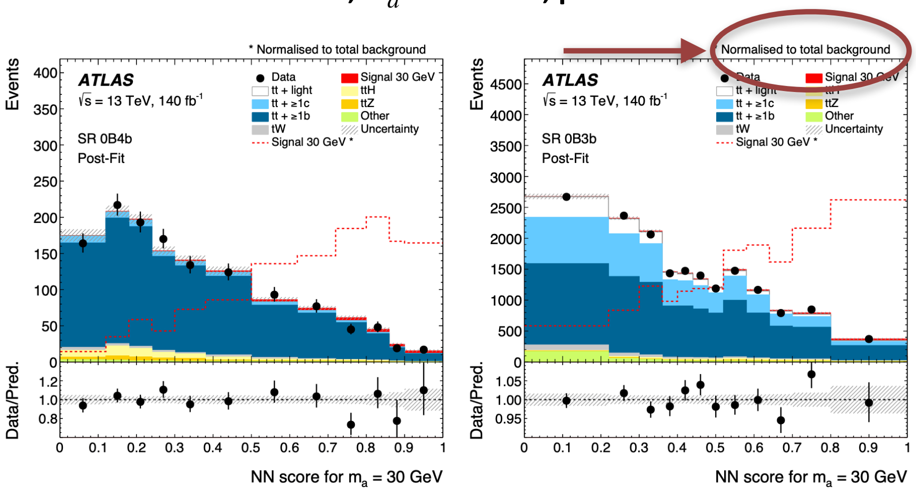
- **4 Signal Regions** → binned **NN-score** histograms
- **1 Control Region** (eμ 0B2b1bL) → **sumPCBTag** histogram

Free parameters:

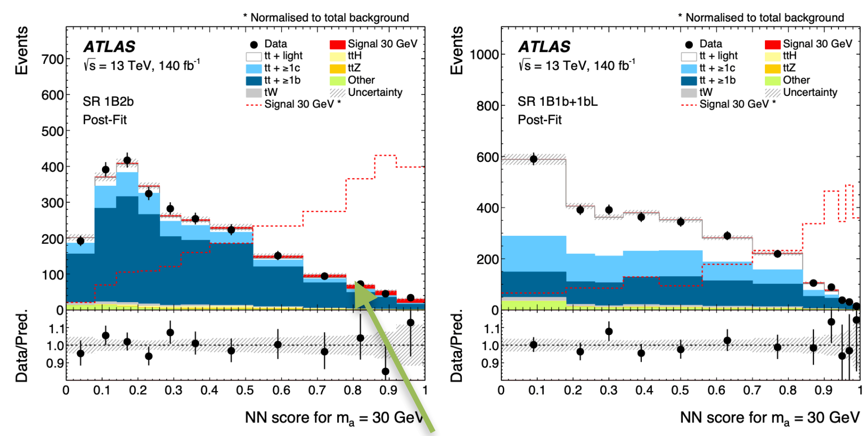
1. **Signal strength μ:** scale on $\sigma(t\bar{t}a)$ x BR
2. **Background scale factors:**
   - $k(t\bar{t}+light, tW), k(t\bar{t}+\geq 1c), k(t\bar{t}+\geq 1b)$

$$pred = \frac{BG}{BG + signal(fitted)}$$

Boosted, $m_a = 30GeV$, post-fit



Resolved, $m_a = 30GeV$,post-fit

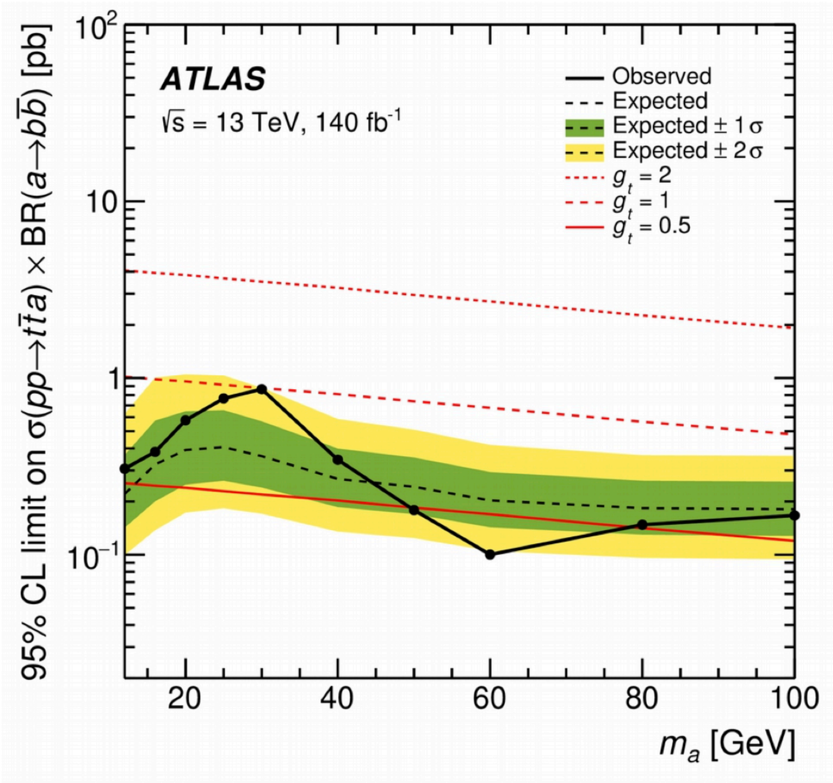


Data/MC agreement at the high score tail

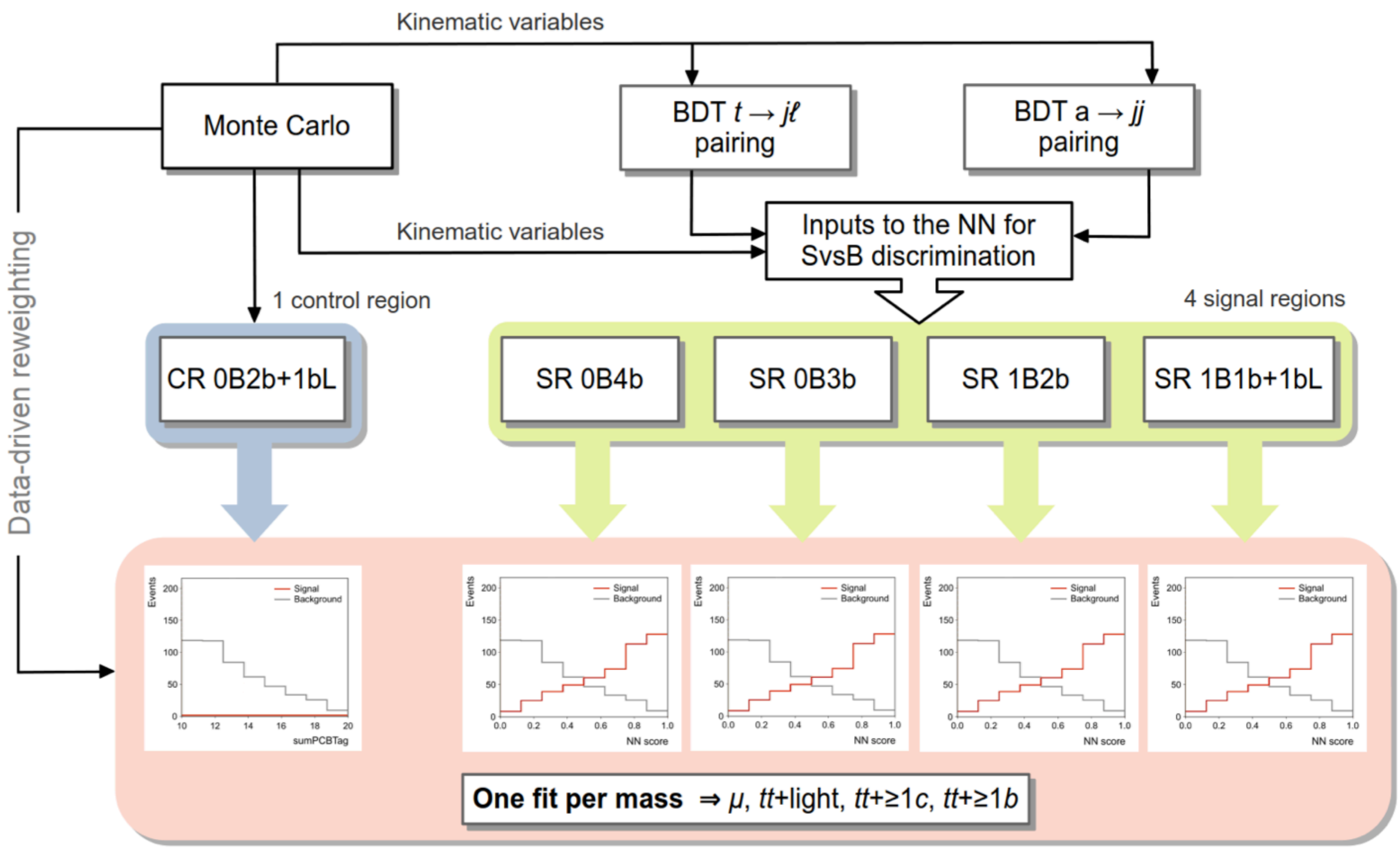
$$\sigma_{postfit}(m_a = 30GeV) = 46 \pm 24 \text{ fb}$$

Results: Exclusion limits

- No significant excess observed in the whole mass Range.
- largest excess is at $m_a = 30GeV: 2.0\sigma$.
- Red lines show the signal cross section for different values of g_t in the 2HDM_a model.
- Assume BR(a->$b\bar{b}$)=100%.
- $g_t \geq 1$ excluded for all masses.
- $g_t \geq 0.5$ excluded from 50-80 GeV.



RECAP:Analysis strategy



Conclusions

- **Dataset**: full ATLAS Run-2 pp data at $\sqrt{s} = 13$ TeV (139 fb^{-1}).
- **Target Process**: $\bar{t}t\,a$ / tW a , a → $\bar{b}b$ in the di-leptonic channel.
- **Mass range**: $m_a =$ **12-100** GeV, covering **boosted** (large-R B-jets) and **Resolved** (small-R b-jets) topologies.
- **Results**:
  - Assume BR(a->$b\bar{b}$)=100%.
  - **Exclude** $50 < m_a < 80$ **GeV for coupling** $g_t = 0.5$.
  - Exclude all masses (12-100) GeV for $g_t = 1$.
- **Significance**: **No significant excess** , max local deviation 2.0 σ at $m_a = 30$ GeV.
- **Impact**: **first ATLAS limits on $\bar{t}t$ a production with a → $\bar{b}$b**; complements earlier ATLAS searches that probed leptonic a decays.

Back up slides

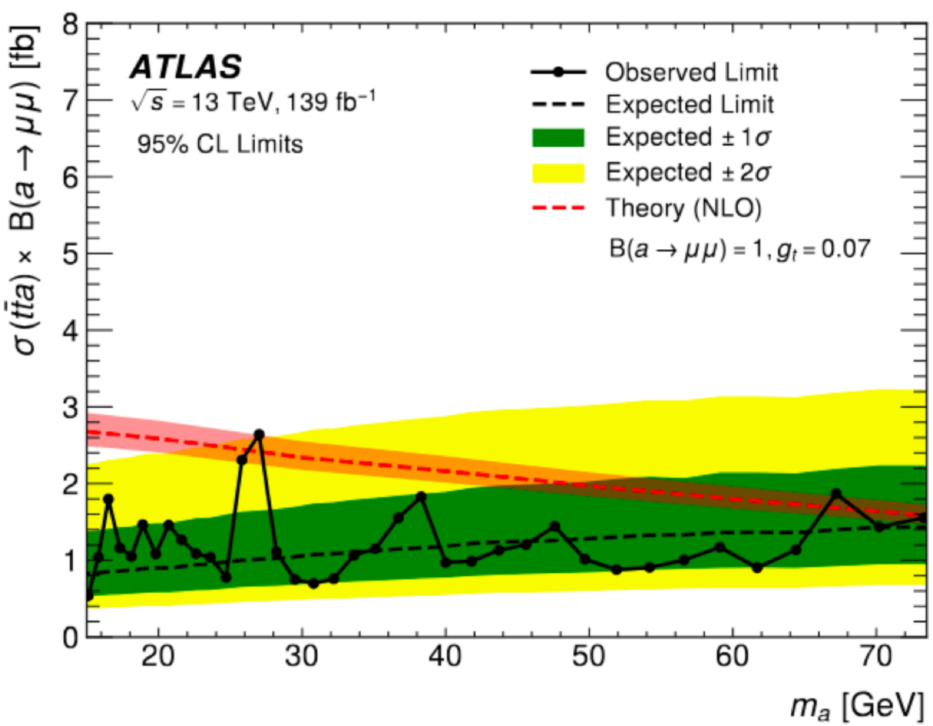
List of uncertainties

- *12 GeV (boosted)*: **Data statistics + large-R b-tag (DeXTer)** drive the error.
- **Heavy-flavour theory** – $t\bar{t}+b$ sets the modelling floor, especially above 30 GeV.
- All other detector effects (pile-up, lepton, E^Tmiss, small-R DL1r) are **sub-percent**.
- *30 GeV* : **Systematics take over** – DeXTer (18 fb) and **$t\bar{t}+b$ modelling** (13 fb)

Fitted cross section [fb]	m_a = 12 GeV $\hat{\sigma}$ = 9	m_a = 30 GeV $\hat{\sigma}$ = 46	m_a = 80 GeV $\hat{\sigma}$ = −6.1
Uncertainty source	$\Delta\hat{\sigma}$	$\Delta\hat{\sigma}$	$\Delta\hat{\sigma}$
Data statistics	6.1	11.0	6.0
MC statistics	2.4	4.2	1.8
Luminosity & pile-up	0.1	0.4	0.1
Jet reconstruction	0.5	4.9	1.2
Lepton reconstruction	<0.1	<0.1	<0.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction	<0.1	0.3	<0.1
Track reconstruction	4.1	1.5	0.1
DL1r	0.4	3.5	1.4
DeXTer	4.2	18	1.1
Modelling signal	1.7	7.5	1.3
Modelling $t\bar{t}+b$	2.7	13	5.5
Modelling $t\bar{t}+c$	0.9	1.8	1.4
Modelling $t\bar{t}$+light	0.8	2.0	2.2
Modelling tW	0.3	0.7	0.6
Modelling ttH	0.1	0.3	0.2
Modelling ttZ	0.1	0.2	1.0
Norm factors	0.7	6.7	4.7
Reweighting	<0.1	<0.1	<0.1
Total systematic uncertainty	8.0	22	7.8
Total uncertainty	10	24	9.7

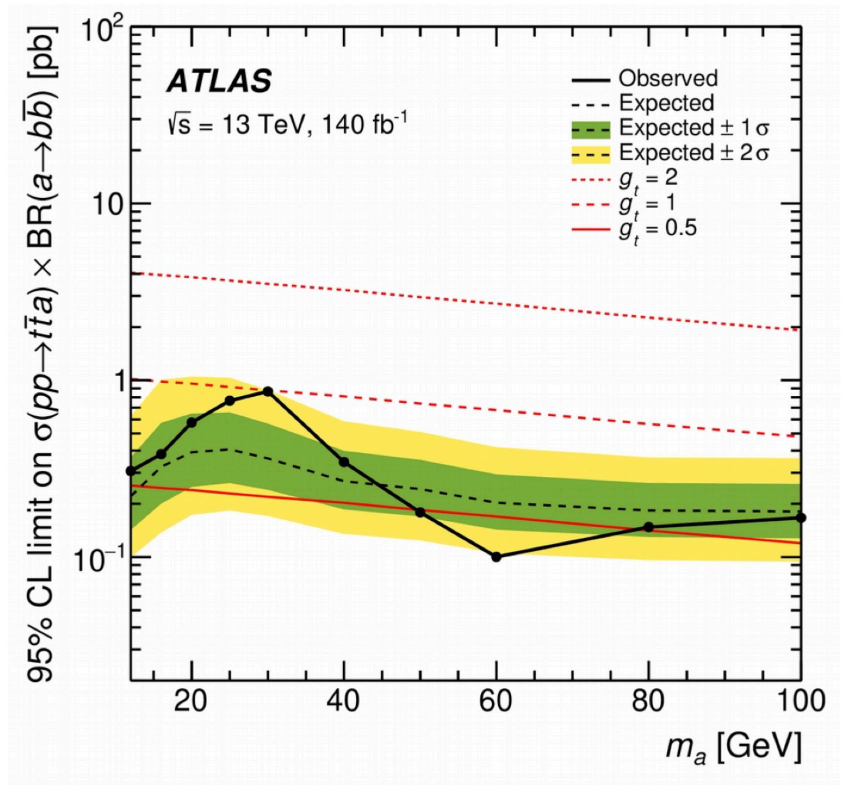
COMPARISON WITH PREVIOUS ATLAS RESULT

Previous study



[Phys. Rev. D 108 (2023) 092007](https://doi.org/10.1103/PhysRevD.108.092007)

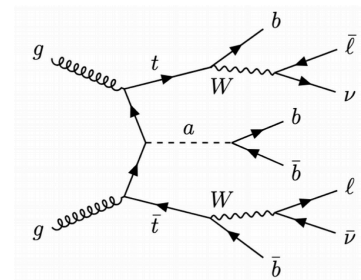
This study



ATLAS DETECTOR

- **Brief Overview:**
  - Inner Detector (ID): Tracking ($|\eta| < 2.5$), 2 T solenoid.
  - Calorimeters: EM and Hadronic ($|\eta| < 4.9$).
  - Muon Spectrometer (MS): Muon tracking ($|\eta| < 2.7$), toroidal magnets.
  - Trigger System: L1 and HLT.
- **Coordinate System:** ATLAS uses a right-handed system. Pseudorapidity $\eta = -\ln\tan(\theta/2)$. Angular distance $\Delta R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$.

Signal and Background samples



- **Data:**
  - Full Run 2 pp collision data at $\sqrt{s} = 13\,\text{TeV}$.
  - Integrated Luminosity: $140.1(12)\,\text{fb}^{-1}$.
- **Signal Simulation ($t\bar{t}a$, tWa with $a \to b\bar{b}$):**
  - `MG5_aMC@NLO` (NLO for $t\bar{t}a$, LO for tWa).
  - m_a points: 12, 16, 20, 25, 30, 40, 50, 60, 80, 100 GeV.
- **Background Simulation:**
  - Dominant: $t\bar{t}$ + jets (esp. $t\bar{t}$+HF using `PowhegBox`).
  - Others: Single top, $t\bar{t}H$, $t\bar{t}V$ ($V = W, Z$), V+jets, Diboson.
- Pileup simulation and reweighting applied. Geant4 (FS) and Fast Simulation (AF2).

Objects definition

- **Electrons:**
  - $p_T > 10\,\text{GeV}$, $|\eta| < 2.47$ (excluding $1.37 < |\eta| < 1.52$).
  - `TightLH` ID, `PLVLoose` PromptLeptonTagger.
  - Impact parameters: $|z_0 \sin\theta| < 0.5\,\text{mm}$, $|d_0/\sigma(d_0)| < 5$.
- **Muons:**
  - $p_T > 10\,\text{GeV}$, $|\eta| < 2.5$.
  - `Medium` quality, `PLVLoose` PromptLeptonTagger.
  - Impact parameters: $|d_0/\sigma(d_0)| < 3$, $|z_0 \sin\theta| < 0.5\,\text{mm}$.
- **Missing Transverse Momentum (E_T^{miss}):**
  - momentum imbalance in the transverse plane calculated from selected objects + soft term from tracks.

Objects Overlap removal

- **Standard Overlap Removal:** e/μ, e/jet, μ/jet.
- **Electron–jet overlap removal**
  - Discard electrons that share a track with a muon.
  - Remove the closest small-R jet if $\Delta R(e,j) < 0.2$; otherwise, if the jet is within $\Delta R < 0.4$, discard the electron.
- **Muon–jet overlap removal**
  - Require $\Delta R(\mu,j) > 0.4$ from the nearest small-R jet.
  - If that jet has ≥ 3 tracks, keep the jet and discard the muon; otherwise, discard the jet (preserves efficiency for energetic muons).
- `DeXTer` **Jet Handling:**
  - Small-R jets eligible for `DeXTer` ($p_T > 20\,\text{GeV}$, isolated in $R = 0.8$ reclustered jet).
  - If pass `DeXTer Loose` WP $\rightarrow$ Large-R B-tagged jet, removed from small-R list.
  - Else $\rightarrow$ kept as small-R jet.
  - Large-R jet overlap with leptons ($\Delta R = 0.8$).

Jets definition

b-jets:

- jets originating from a single b-hadron.
- Anti-k_t algorithm, R=0.4.
- identified using DL1r tagger.
- μ in jet p_T correction is performed. (where the soft muons are lost during the overlap removal are added back to the four momentum).
- loose b-jet->85% DL1r WP
- tight b-jet: 70% WP

B-jets:

- boosted bb pair identified as one single object.
- Anti-k_t algorithm, R=0.4)
- identified using Dexter tagger.
- μ in jet p_T correction and DNN mass correction.

BDT and NN full inputs

BDT

Top quark/antiquark reconstruction BDT

Object	Variables
Full event	N_{jets}, $N_{b\text{-jets}}$
$j\ell$ pair (test, aux.)	m, p_{T}, η, ΔR
Lepton (test, aux.)	p_{T}, η
Jet (test, aux.)	p_{T}, η, b-tag score, jet index
$t\bar{t}$ pair	m, p_{T}, η, ΔR, $\Delta\phi$
jj pair	ΔR

Pseudoscalar reconstruction BDT

Object	Variables
Full event	N_{jets}, $N_{b\text{-jets}}$, `sumPCBTag`
jj pair	m, p_{T}, η, E, ϕ, ΔR
Jet (1st, 2nd)	p_{T}, η, b-tag score, jet index

NN

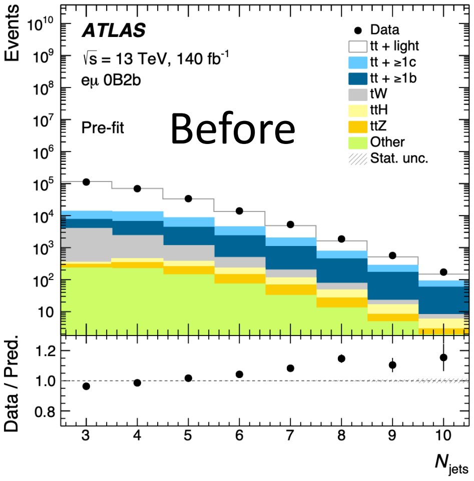
Object	Variables
BDT $t \to j\ell$	Score, $p_{\mathrm{T}}^{j\ell}$, $\Delta R_{j\ell}$, $\Delta\eta_{j\ell}$, $\Delta\phi_{j\ell}$, jet ID
BDT $a \to jj$	Score, p_{T}^{jj}, η_{jj}, m_{jj}, ΔR_{jj}, $\Delta\eta_{jj}$, $\Delta\phi_{jj}$, jet ID
Small-R jets	p_{T}, η, b-tagging score p_{T}^{bb}, m_{bb}, m_{bbb}, m_{bbbb}, ΔR_{bb}, $\Delta\eta_{bb}$, $\Delta\phi_{bb}$, $\Delta\phi_{E_{\mathrm{T}}^{\text{miss}},b}$
Large-R jets	p_{T}, η ΔR_{Bb}, $\Delta\phi_{E_{\mathrm{T}}^{\text{miss}},B}$
Leptons	$\Delta R_{\ell\ell}$, $\Delta\eta_{\ell\ell}$, $\Delta\phi_{\ell\ell}$, $\Delta\phi_{E_{\mathrm{T}}^{\text{miss}},\ell}$ $\Delta R_{\ell\ell,bb}$, $\Delta R_{\ell\ell,B}$, $\Delta R_{\ell\ell,b}$
Event	N_{jets}, $H_{\mathrm{T}}^{\text{jets}}$, $E_{\mathrm{T}}^{\text{miss}}$

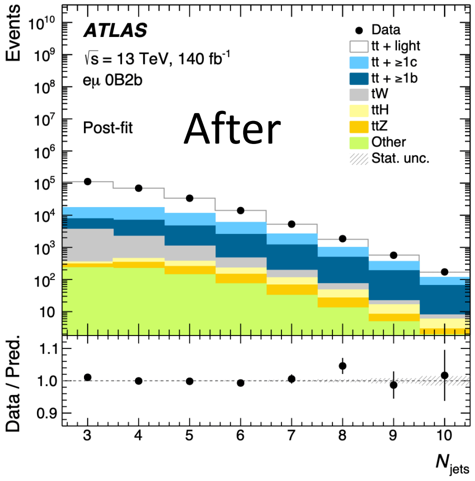
JET MULTIPLICITY CORRECTIONS

- Heavy-flavour reweighting also fixes the **inclusive jet count** (N_{jets}), previously mismodelled in $t\bar{t}$ MC.
- Apply the three normalisation factors from the table.
- Result: markedly improved data–MC agreement in `sumPCBTag` *and* N_{jets} distributions.

To reduce N_{jets} dependency when duping the kinematic re-weighting.
Not spoil the data/MC agreement achieved after HF corrections .
a reduced HT is introduced:

$$H_{\mathrm{T}}^{\mathrm{red}}(n) = H_{\mathrm{T}} - (n-3)\Delta H_{\mathrm{T}}(n),$$





List of systematics

Experimental uncertainties:

- **Luminosity**
- **Pileup modeling**
- **Leptons** (e,μ): Trigger, reconstruction, identification, isolation, Energy/momentum scale resolution
- **Jets**: Jet vertex tagging, jet energy scale and resolution, DL1r and dexter flavour tagging.
- **Tracks**:Track selection efficiency, AK8 track jet mass scale correction uncertainties.
- **MET**

Modelling uncertainties (sample-specific)

Systematic	Signal	tt+jets	tW	ttH	ttZ
(μ_r, μ_f)	✓	✓	✓	✓	✓
FSR/ISR		✓	✓	✓	
PDF+α_s	✓	✓	PDF ME only	✓	PDF ME only
Gen. alternative		pThard=1	MG_aMC@NLO	MG_aMC@NLO	Sherpa
PS alternative	Herwig7	Herwig7	Herwig7	Herwig7	
DS alternative			✓		
RW uncertainties		✓	✓		

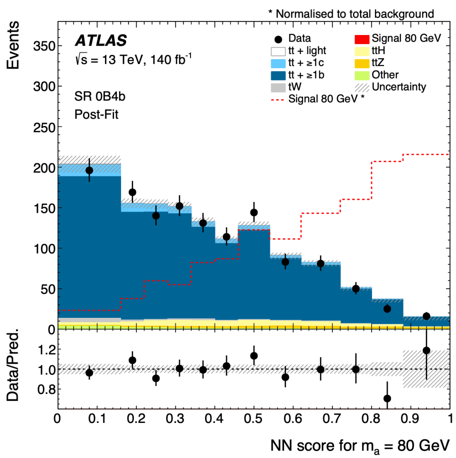
LHC workshop

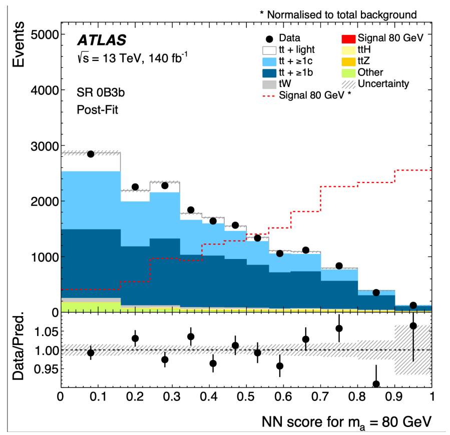
Post-fit event yields in all signal and control regions for $m_a = 30$ GeV

Sample	SR 0B4b	SR 0B3b	SR 1B2b	SR 1B1b+1bL	CR 0B2b+1bL
Signal 30	28±14	180±98	71±31	35±16	110±63
$t\bar{t}$+light	5±2	1400±320	130±24	1100±180	17000±3000
$t\bar{t}+\geq 1c$	58±21	4700±1200	380±140	740±230	12000±3500
$t\bar{t}+\geq 1b$	1093±47	9820±700	1758±97	815±70	5510±650
tW	22±12	360±140	46±20	64±17	830±220
$t\bar{t}H$	62±9	222±22	31±4	14±12	136±13
$t\bar{t}Z$	27±6	120±22	15±3	11±2	128±25
Other	14±2	394±35	47±4	78±10	1060±120
Total pred.	1300±35	17000±130	2500±50	2900±53	36000±190
Data	1301	17242	2479	2866	36350

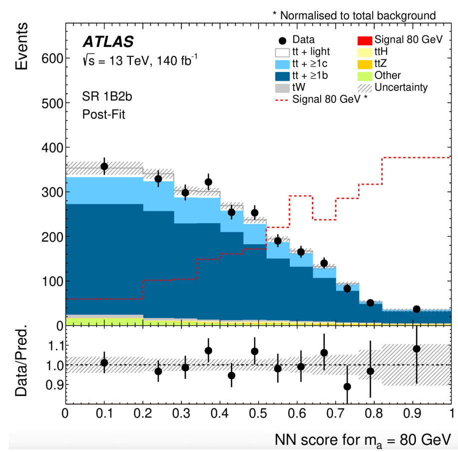
Final fit : NNs post-fit scores for $m_a = 80$ GeV

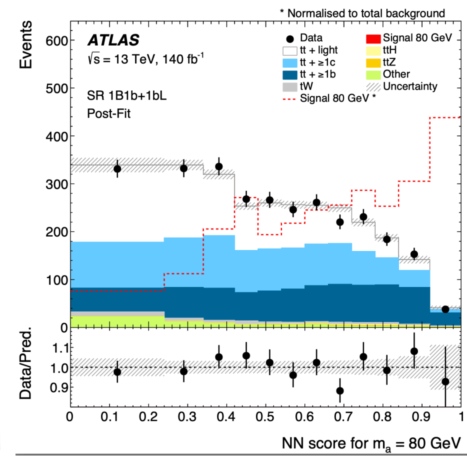
Resolved





Boosted





$$\sigma_{postfit}(m_a = 80GeV) = -6.1 \pm 9.7fb$$

pseudoscalar a

- **2HDM:**

  Add a second Higgs doublet->after EWSB we get: h(SM-like), H(heavy even), A->a (CP-odd), $H^{\pm}$.

- **Couplings:**

Yukawa $\propto$ **fermion mass**, a couples strongest to top and b-quarks.

- a->$b\bar{b}$ highest BR.
- **DM mediator** : $\lambda_\chi a \bar{\chi} i\gamma_5 \chi$

Back ground processes mimicking the signal

a)$t\bar{t}$**+jets** same two real top quarks->identical di-lepton kinematics+ additional hard jet, or g->$b\bar{b}$ fakes the a->$b\bar{b}$ pair

b) Single-top tW

- Contains **one real top** and a **W** that often decays leptonically, giving the same ($\ell^+\ell^-$, ≥3 jets, ≥1 b-tag) topology.
- Mistagged light jets can supply the second "b" needed.

C) $t\bar{t}$H(H→bb⁻)

- Two tops **plus** a true **b $\bar{\text{b}}$ resonance** at ~125 GeV—the nearest SM look-alike to our a->$b\bar{b}$

D) $t\bar{t}$ Z(Z→bb⁻ or ℓ+ℓ–)

- Same top pair.
- If Z->$b\bar{b}$ Z→$b\bar{b}$, gives extra b-jets;
- if Z→ℓℓ same dilepton kinematics.

This CR is a good CR, because it mirrors the signal topology
Requiring only 2 tight b tagged jets , Remove most of a->bb events

More about NN

- **Simultaneous binned ML fit** in:
  - 4 SRs $\rightarrow$ NN score (mass–parameterised).
  - 1 CR $\rightarrow$ `sumPCBTag`.
- **Parameter of interest**: signal strength $\mu = \dfrac{\sigma_{\text{meas.}}}{\sigma_{\text{theo.}}}$.
- **Free background normalisations**:

$$k(t\bar{t} + \text{light}, tW),\ k(t\bar{t}+ \geq 1c),\ k(t\bar{t}+ \geq 1b)$$

- **Likelihood**: product of Poisson terms over every histogram bin + priors for nuisance parameters (Gaussian, log-normal or Poisson).
- **Fit result**: maximise $\mathcal{L}(\mu, \theta)$ over μ and all nuisances θ.