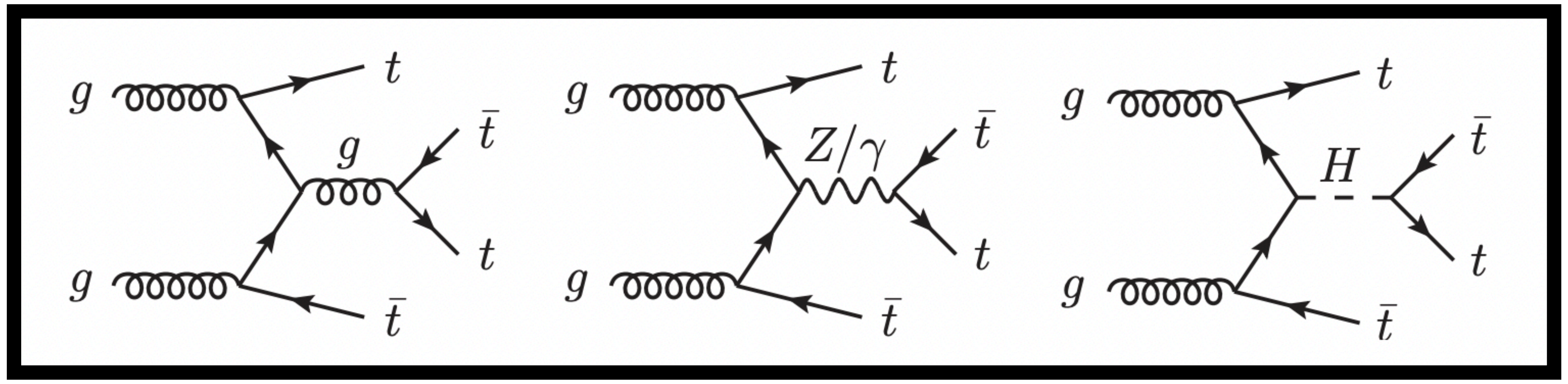


HIGGS 2023 - BEIJING

30 NOVEMBER 2023

RYAN ROBERTS FOR THE ATLAS COLLABORATION

MEASUREMENT OF THE HIGGS COUPLING TO TOP QUARKS WITH FOUR-TOP-QUARK PRODUCTION

Eur. Phys. J. C 83 (2023) 496

Auxiliary Material

TOP YUKAWA COUPLING

$$\mathscr{L} = -\frac{1}{\sqrt{2}} y_t \kappa_t \bar{t} \left(\cos\alpha + i\gamma_5 \sin\alpha\right) th$$

Potential BSM top-Higgs couplings parameterized by the coupling strength κ_t and CP mixing angle α. In the SM, $\kappa_t = 1$ and $\alpha = 0$.

- The top Yukawa is a direct probe of mass generation from EWSB and relevant to the hierarchy of the SM.
- Top is the heaviest SM fermion with mass near the EW scale; top Yukawa coupling is order 1.
- Modified by many BSM extensions to Higgs sector.
- Possible source of CP violation.
- Key contributor to loop induced gluon fusion single and di-Higgs production, diphoton Higgs decay.
- Central part of Higgs physics!

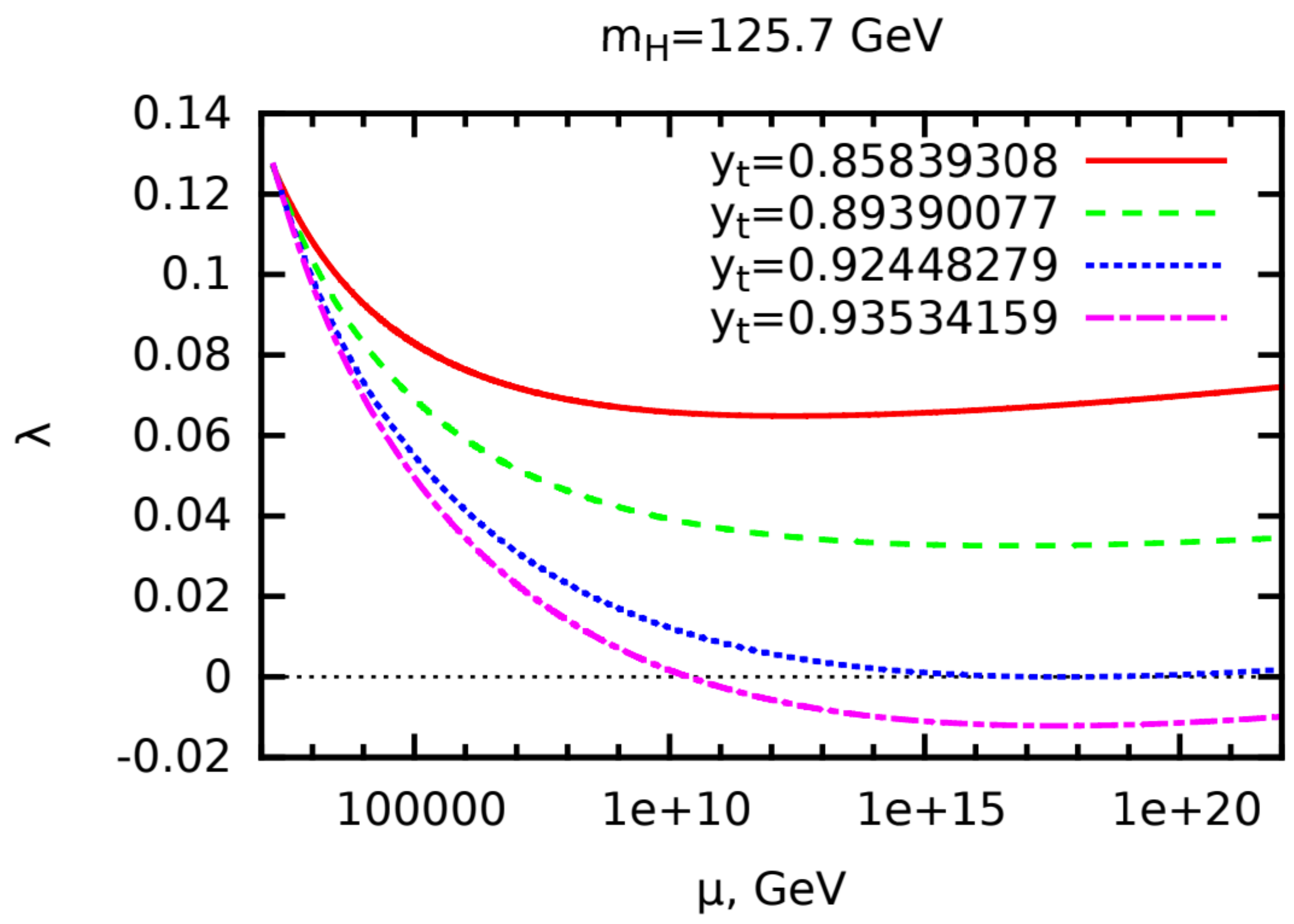


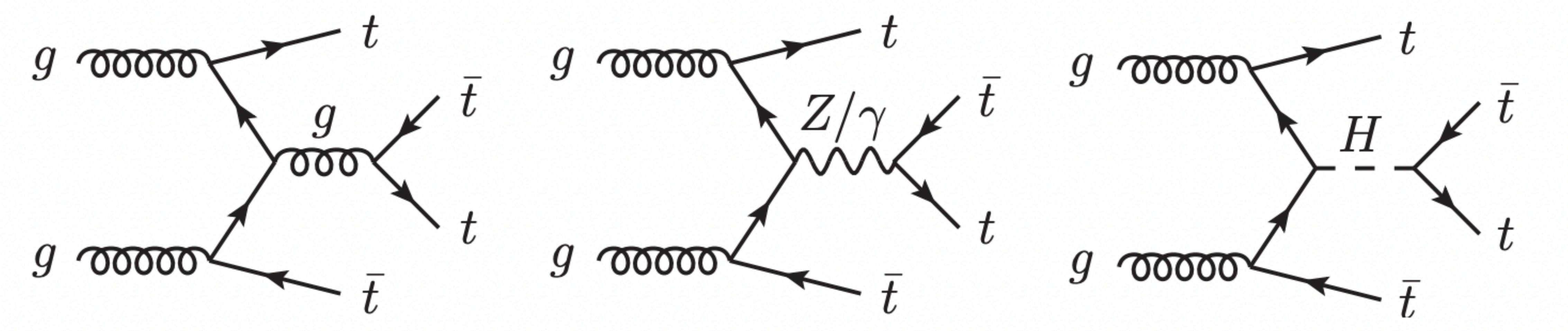
FIG. 1. Renormalization group running of the Higgs coupling constant λ for the Higgs mass $M_h = 125.7$ GeV and several values of the top quark Yukawa $y_t(\mu = 173.2\,\text{GeV})$.

J.Exp.Theor.Phys. 120 (2015) 3, 335-343

MEASURING THE TOP YUKAWA WITH 4 TOPS

- Rare process with **QCD** and **EW** contributions, including **off-shell Higgs** mediator.
- Cross section flat for small values of κ_t with a steep rise above 1.5.
- Quartic and quadratic terms in κ_t.

SM Predictions		$\sigma_{t\bar{t}t\bar{t}}$ [fb]
LO	JHEP 02 (2018) 031	$7.6^{+4.9}_{-2.7}$
NLO (QCD+EW)	JHEP 02 (2018) 031	$12.0^{+2.2}_{-2.5}$
NLO+NLL′	Phys. Rev. Lett. 131, 211901	$13.4^{+1.0}_{-1.8}$



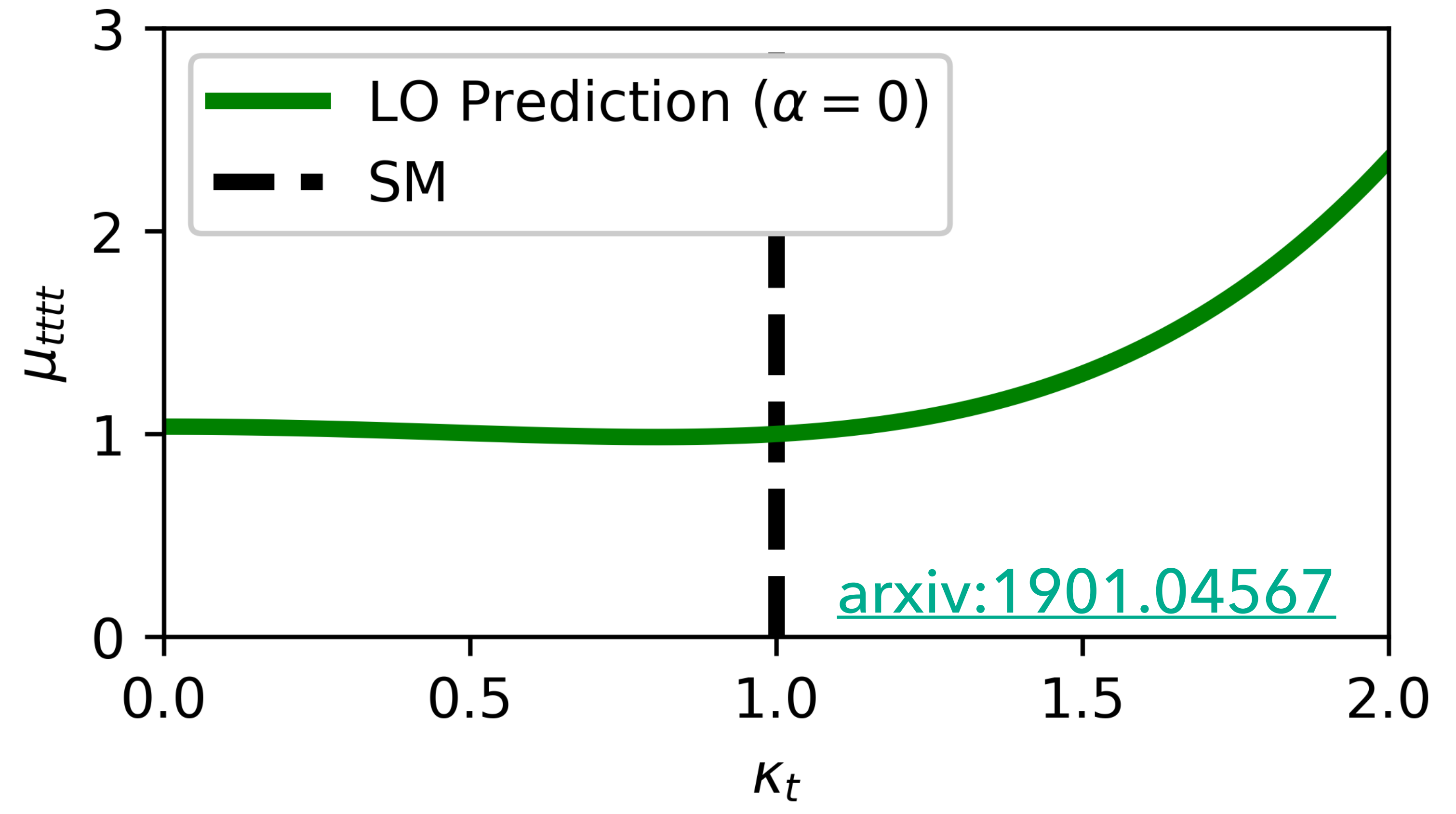
LO QCD only: 6.83 fb

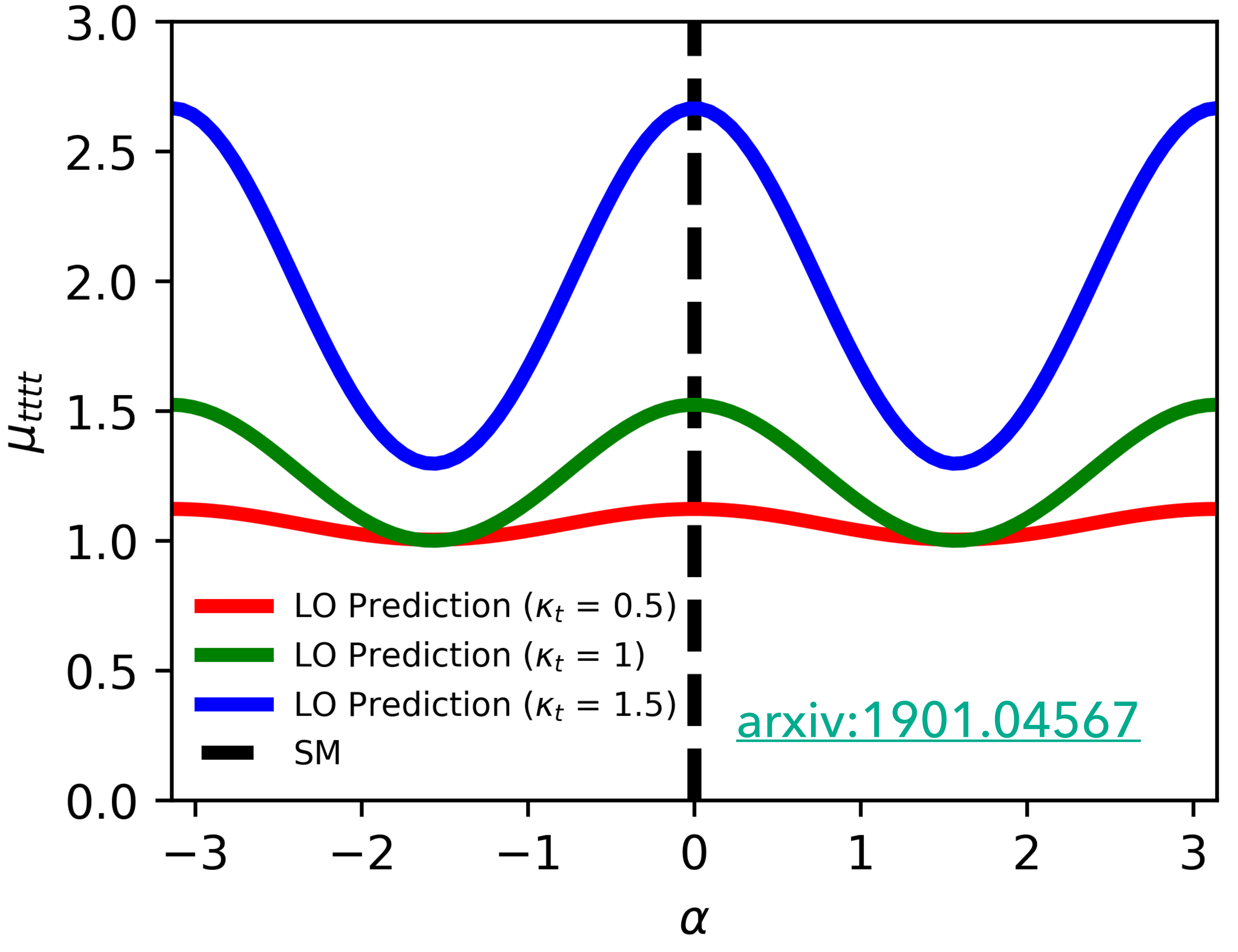
LO QCD+EW: 7.59 fb

LO QCD+Z: 10.00 fb

H/(g+Z) Interference: -1.52 fb

LO Higgs only: 1.17 fb





Dependence of the $t\bar{t}t\bar{t}$ cross-section on the top Yukawa coupling.

ATLAS EXPERIMENT

COMPARISON WITH OTHER APPROACHES

* NLO cross-section. BR is same sign lepton + $\geq 3\ell$ channels after τ decays.
† NLO fiducial cross-section. $H \to \gamma\gamma$ BR with no top decays.

Four Tops

- Most sensitive at high κ_t.
- Potentially affected by BSM mediators.
- Off-Shell: Independent of Higgs width.
- $\sigma \times \mathrm{BR} = 1.5\ \mathrm{fb}^*$ (JHEP 02 (2018) 031).
- Template based signal and background modeling.
- Dominant uncertainties: stat, $t\bar{t}t\bar{t}$ modeling, $t\bar{t}W$ modelling, b-tagging.

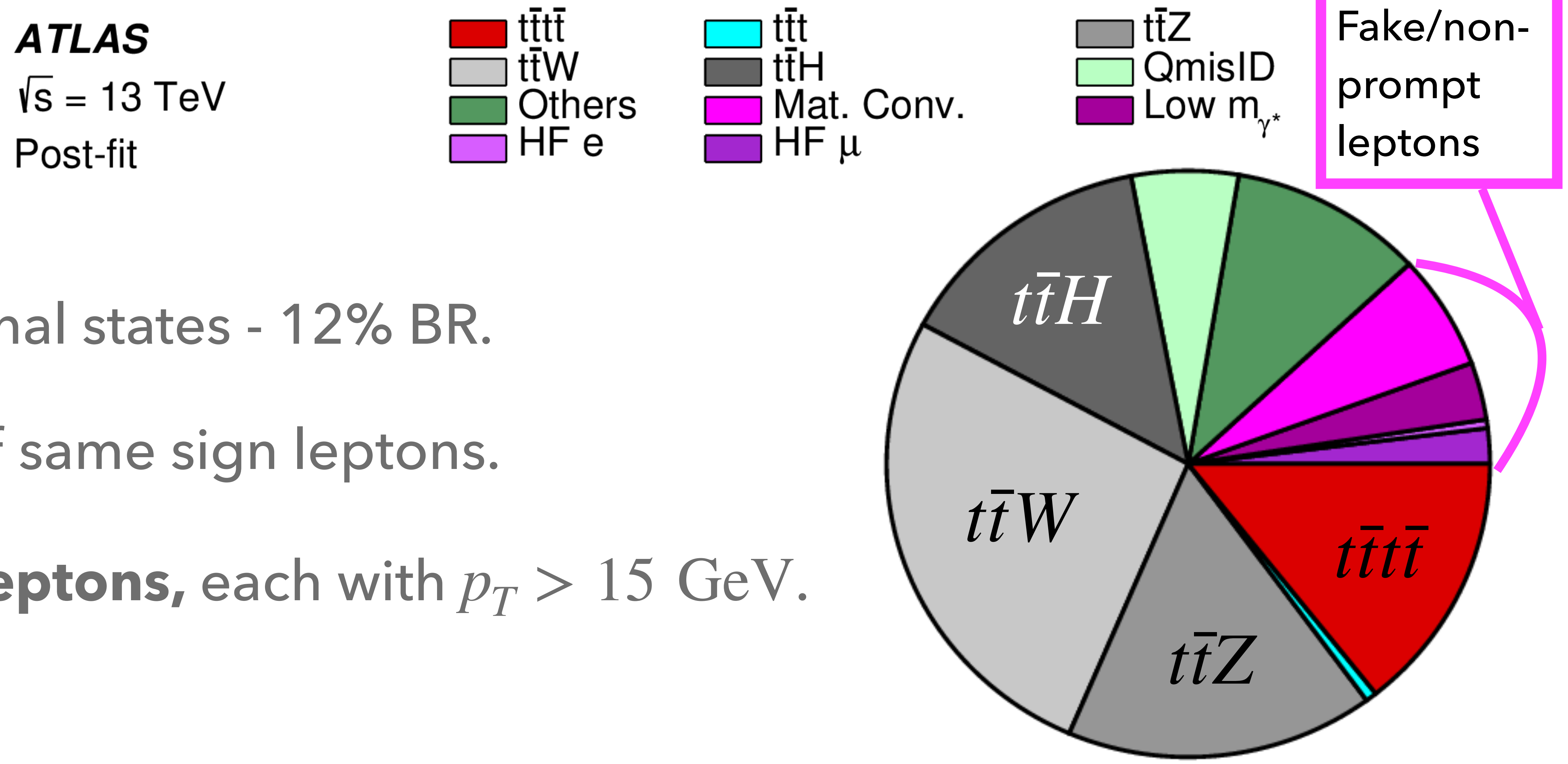
ttH($H \to \gamma\gamma$)

- Most sensitive at low κ_t.
- Other Higgs couplings, possible BSM, enter through decay.
- On-Shell: Positively identify the Higgs by its mass.
- $\sigma \times \mathrm{BR} = 1.1\ \mathrm{fb}^\dagger$ (JHEP 07 (2023) 088).
- Analytic signal and background modeling.
- Dominant uncertainties: stat, $t\bar{t}H$ modeling, jet systematics, photon systematics.

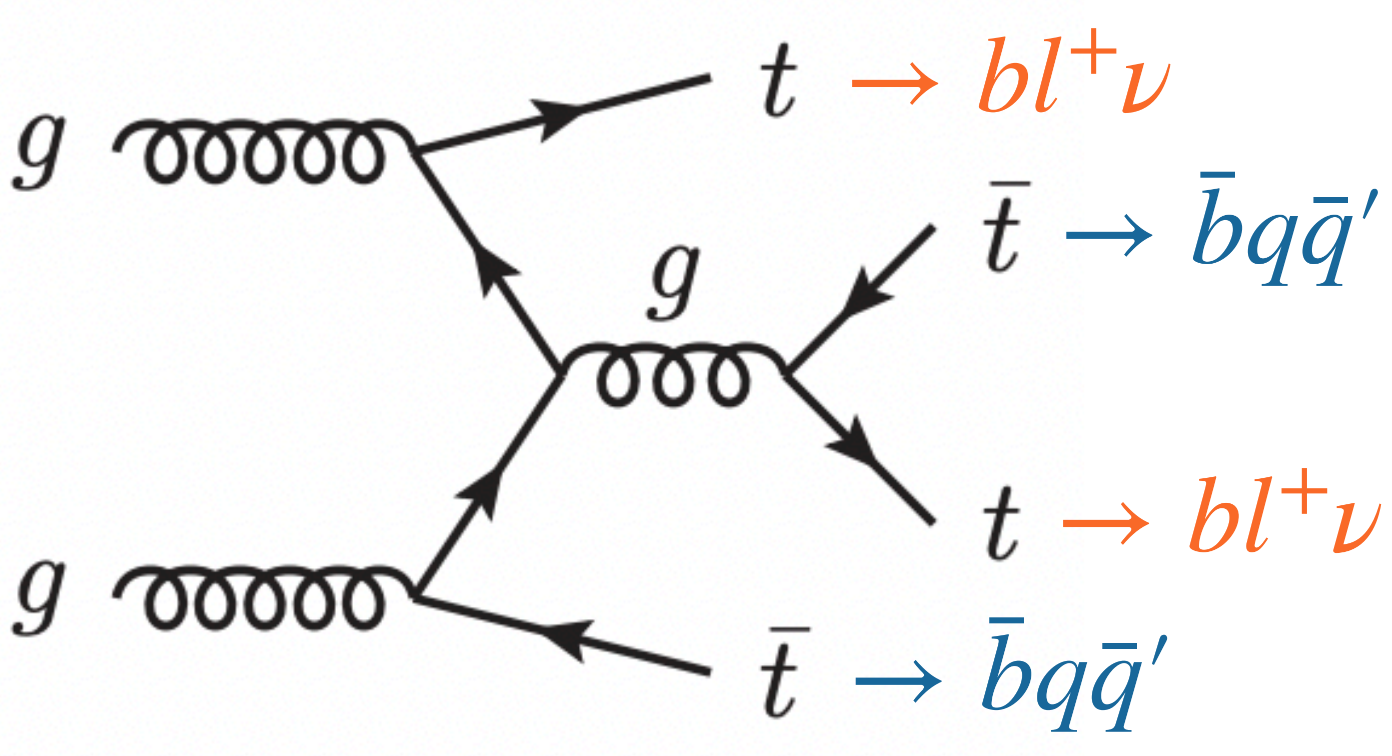
Measurements in different channels face **different challenges** and make **different assumptions**. Multiple complementary measurements give us a more complete picture.

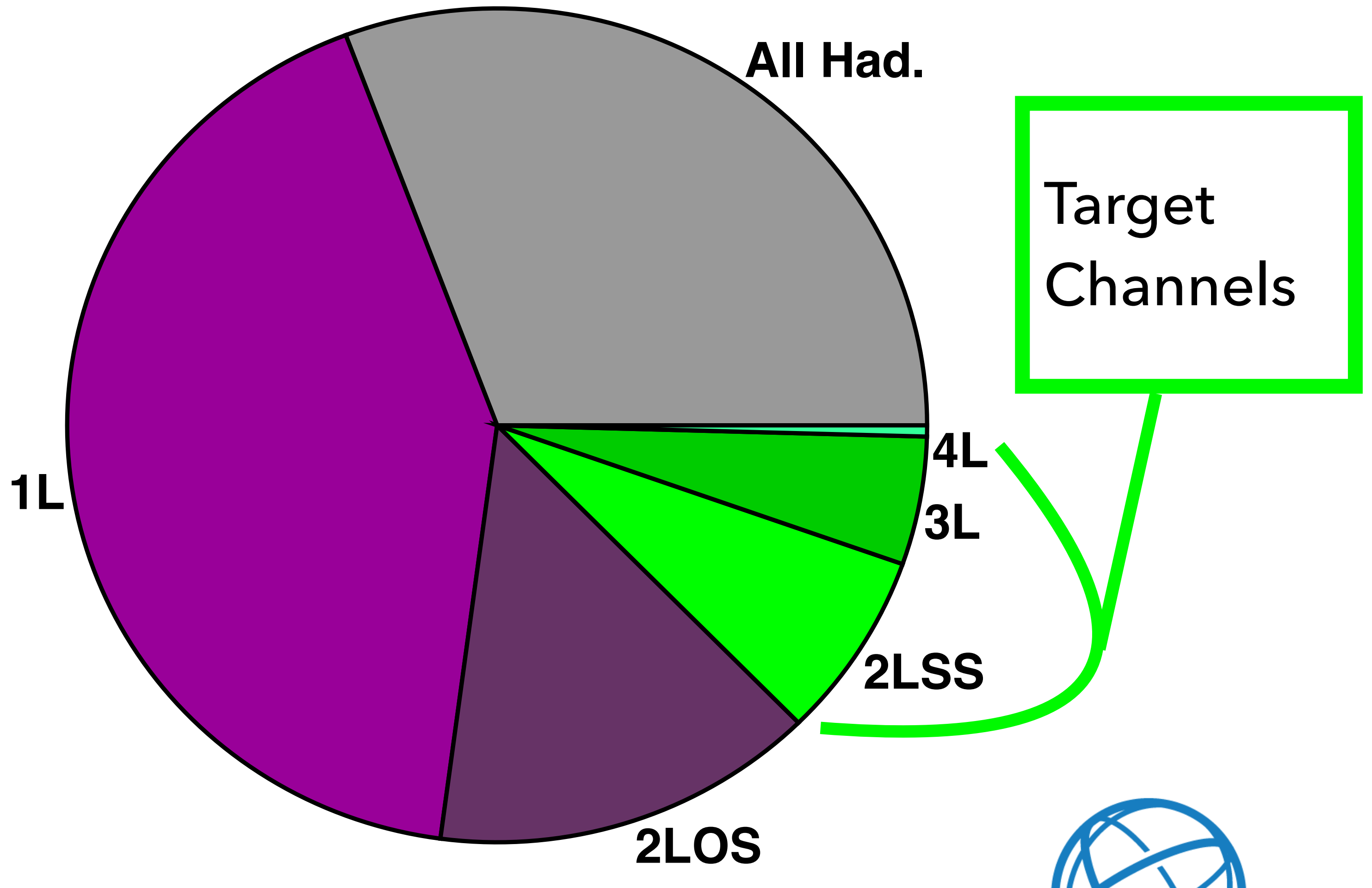
SIGNAL REGION SELECTION

- Targeting the same sign dilepton (2LSS) and three lepton (3L) final states - 12% BR.
  - Most sensitive channel due to background rejection power of same sign leptons.
- Trigger on single lepton with $p_T > 28$ GeV, require **same sign leptons,** each with $p_T > 15$ GeV.
- **Z veto** on opposite sign muon pairs, all electron pairs.
- Looking for high multiplicity, high mass final state: ≥ **6 jets**, ≥ **2 b-jets**, $H_T > 500$ GeV.
- Overall selection efficiency for 2LSS/3L $t\bar{t}t\bar{t}$ events is 18%.
- Also define 8 control regions to constrain background model.



Signal Region Composition



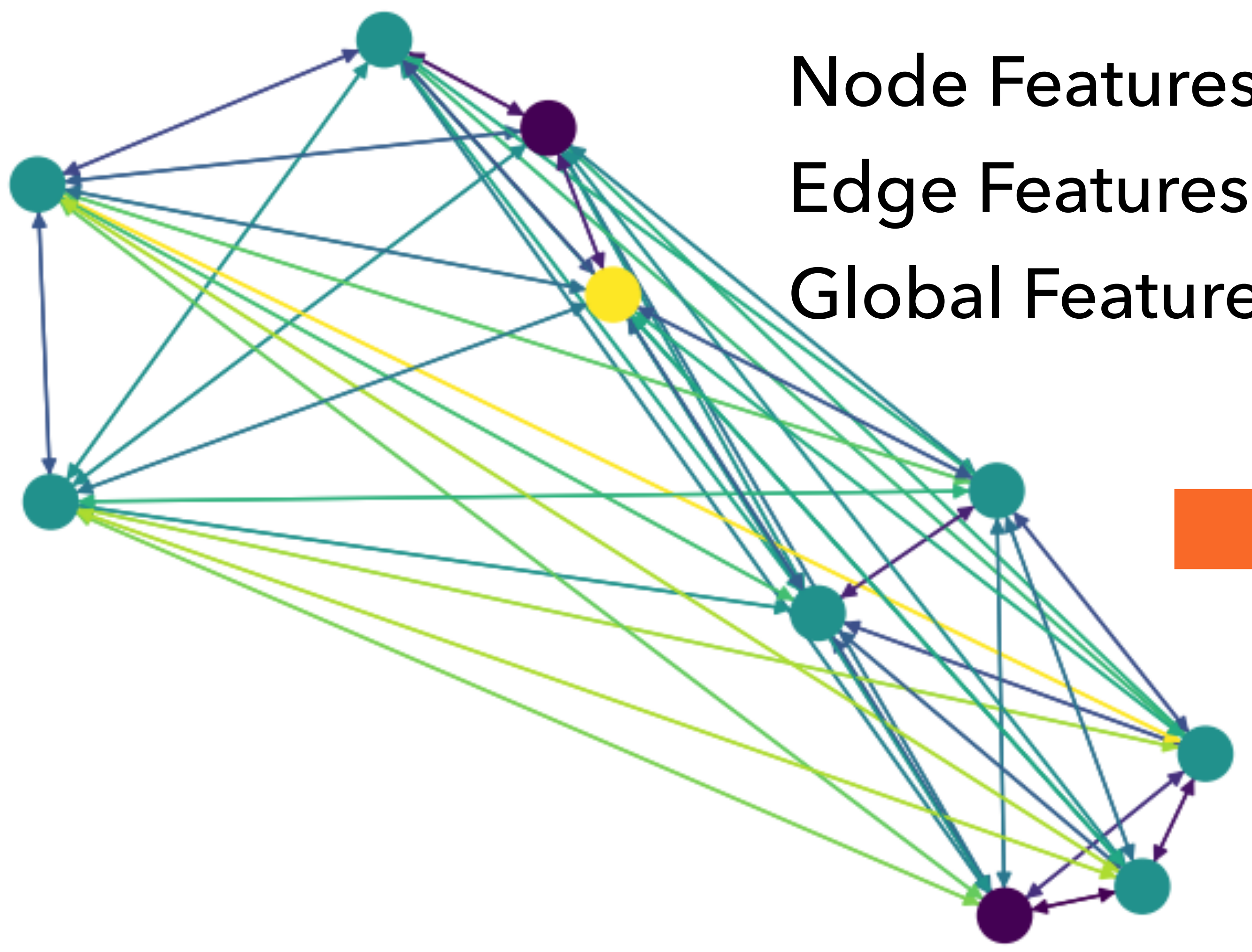


$t\bar{t}t\bar{t}$ **Branching Ratios**

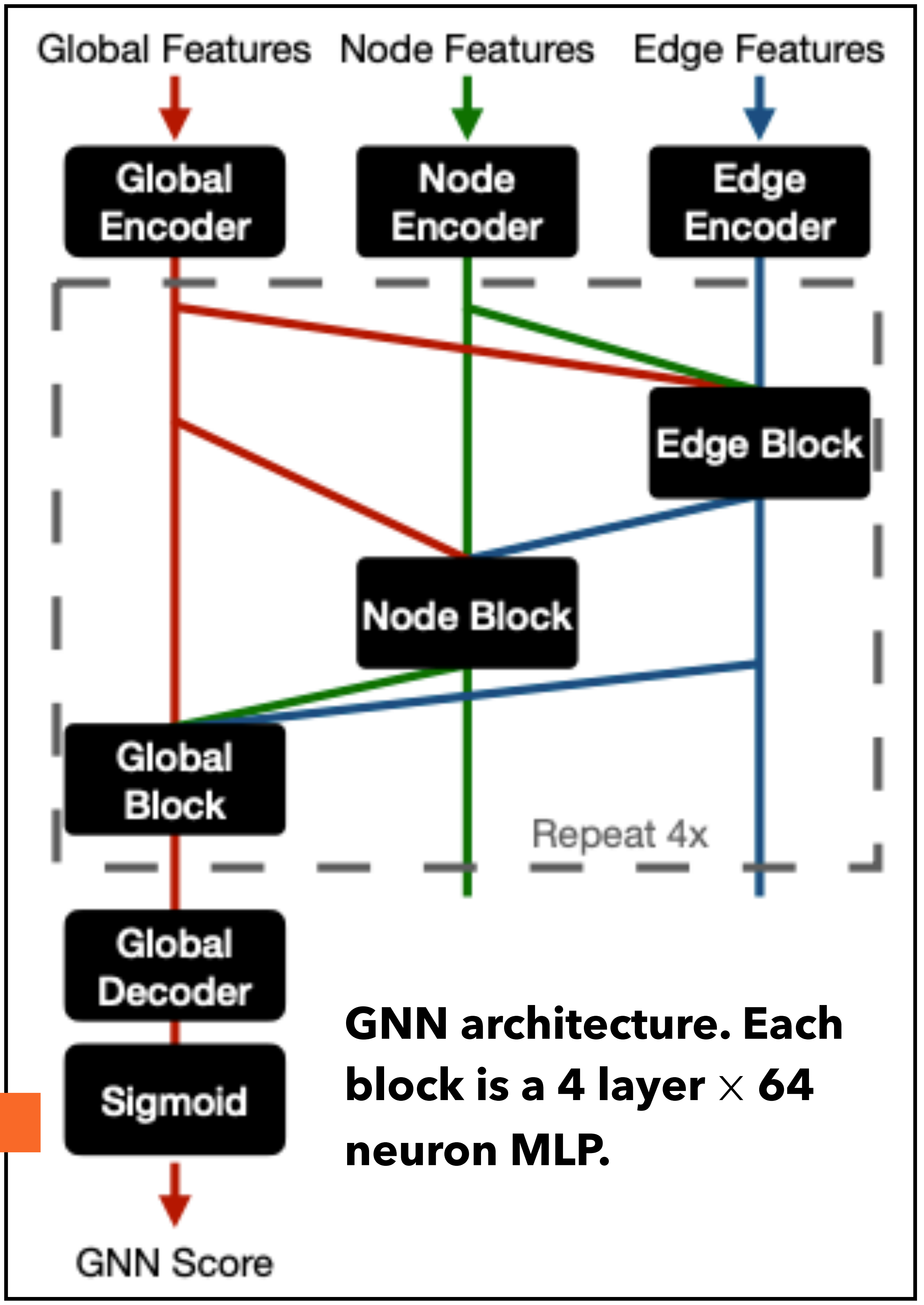
SIGNAL/BACKGROUND SEPARATION

- A **Graph Neural Network** (GNN) is trained to separate $t\bar{t}t\bar{t}$ from backgrounds in the signal region.
- Each event becomes a fully connected graph with jets, leptons, and missing transverse energy as nodes.
- Message passing architecture allows network to learn complex features of the four top process.

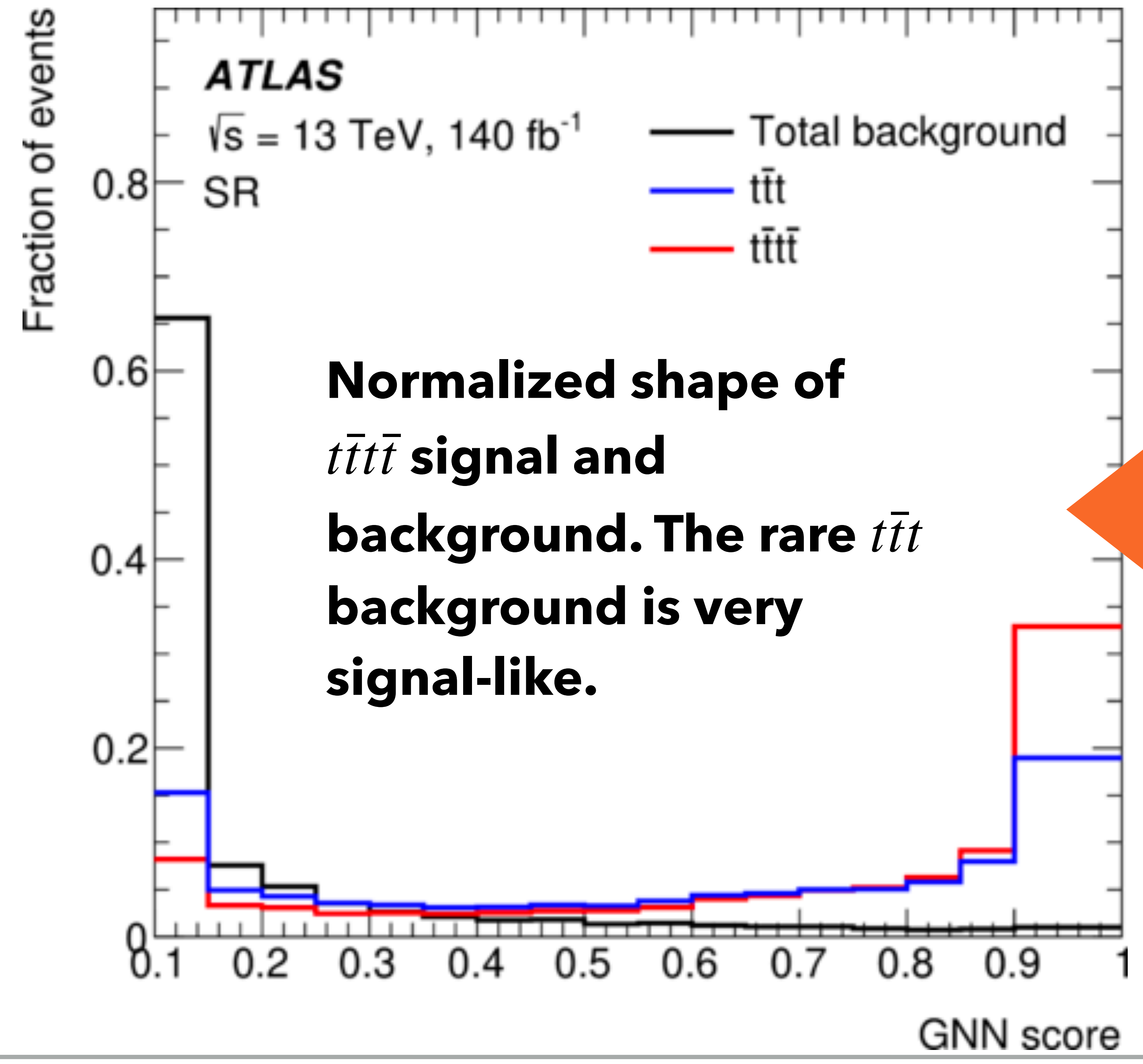
Node Features: $p_T, \eta, \phi, E, btag, q, PID$
Edge Features: $\Delta\eta, \Delta\phi, \Delta R$
Global Feature: N_{jets}



Example Graph of $t\bar{t}t\bar{t}$ Event
Node color indicates particle type, edge color indicates ΔR



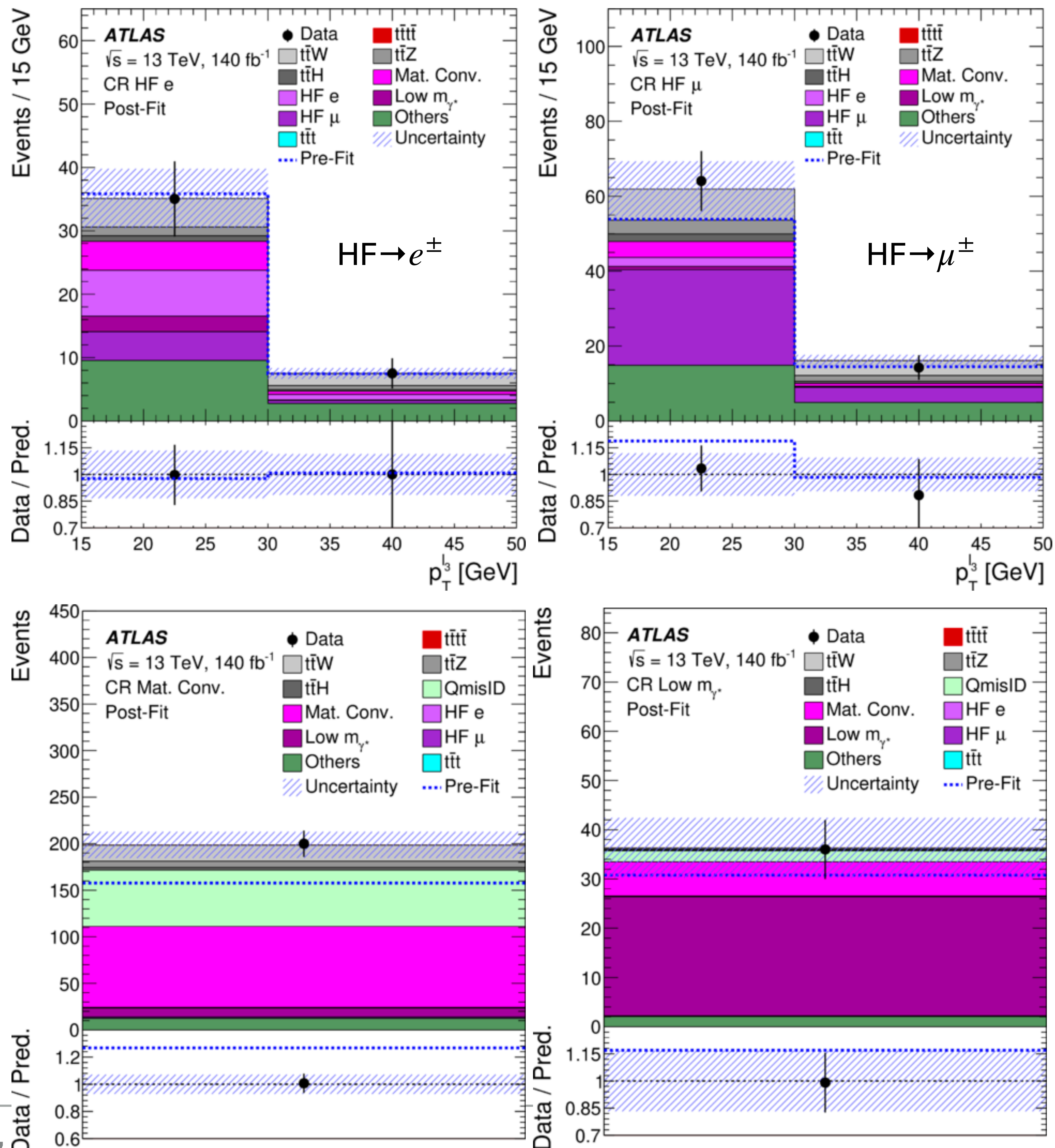
GNN architecture. Each block is a 4 layer $\times$ 64 neuron MLP.



Normalized shape of $t\bar{t}t\bar{t}$ signal and background. The rare $t\bar{t}t$ background is very signal-like.

BACKGROUNDS WITH FAKE AND NON-PROMPT LEPTONS

- Fake leptons, material conversion, leptons from heavy flavor decays, or charge misidentification allow $t\bar{t}$ to enter 2LSS channel.
- Charge misidentification extrapolated from data in opposite sign region.
- Non-prompt leptons from heavy flavor decays and photon conversions use templates from MC with floating normalizations constrained by control regions.



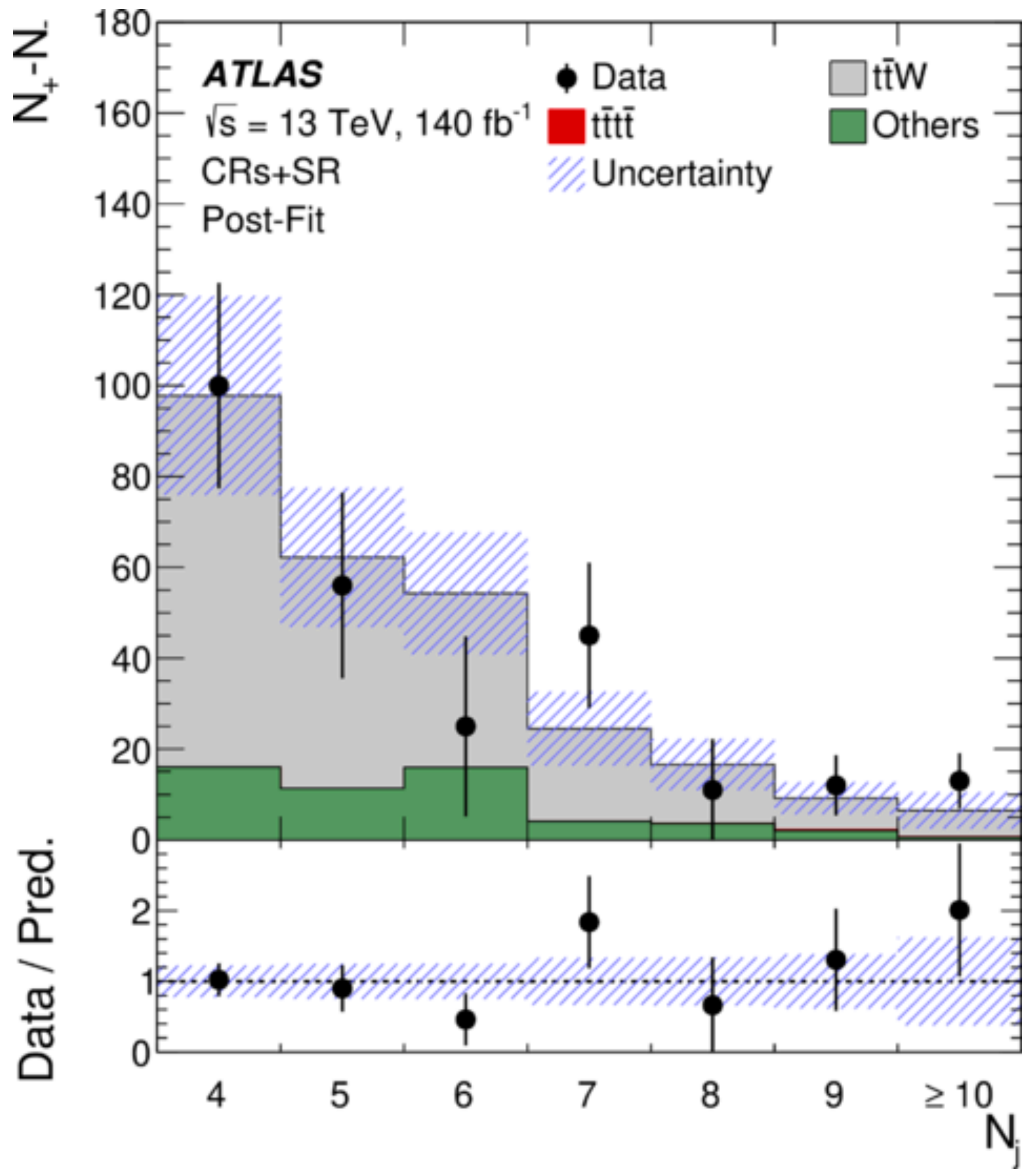
Material Conversions

Virtual Photons

$t\bar{t}W$ BACKGROUND

- $t\bar{t}W$ modeling seen to be problematic in e.g. [JHEP 07 (2023) 219]() ($t\bar{t}W$), [ATLAS-CONF-2019-045]() ($t\bar{t}H$).
- Semi data-driven approach with templates for each jet multiplicity and sign of the $W^{\pm}$.
- Jet multiplicity distributions $N_{\pm}(j)$ fit to analytic distribution in control regions.
- 2 scaling parameters, (a_0, a_1), and 2 normalizations, $(N_{+}(4), N_{-}(4))$ constrained in 4 $t\bar{t}W$ control regions.

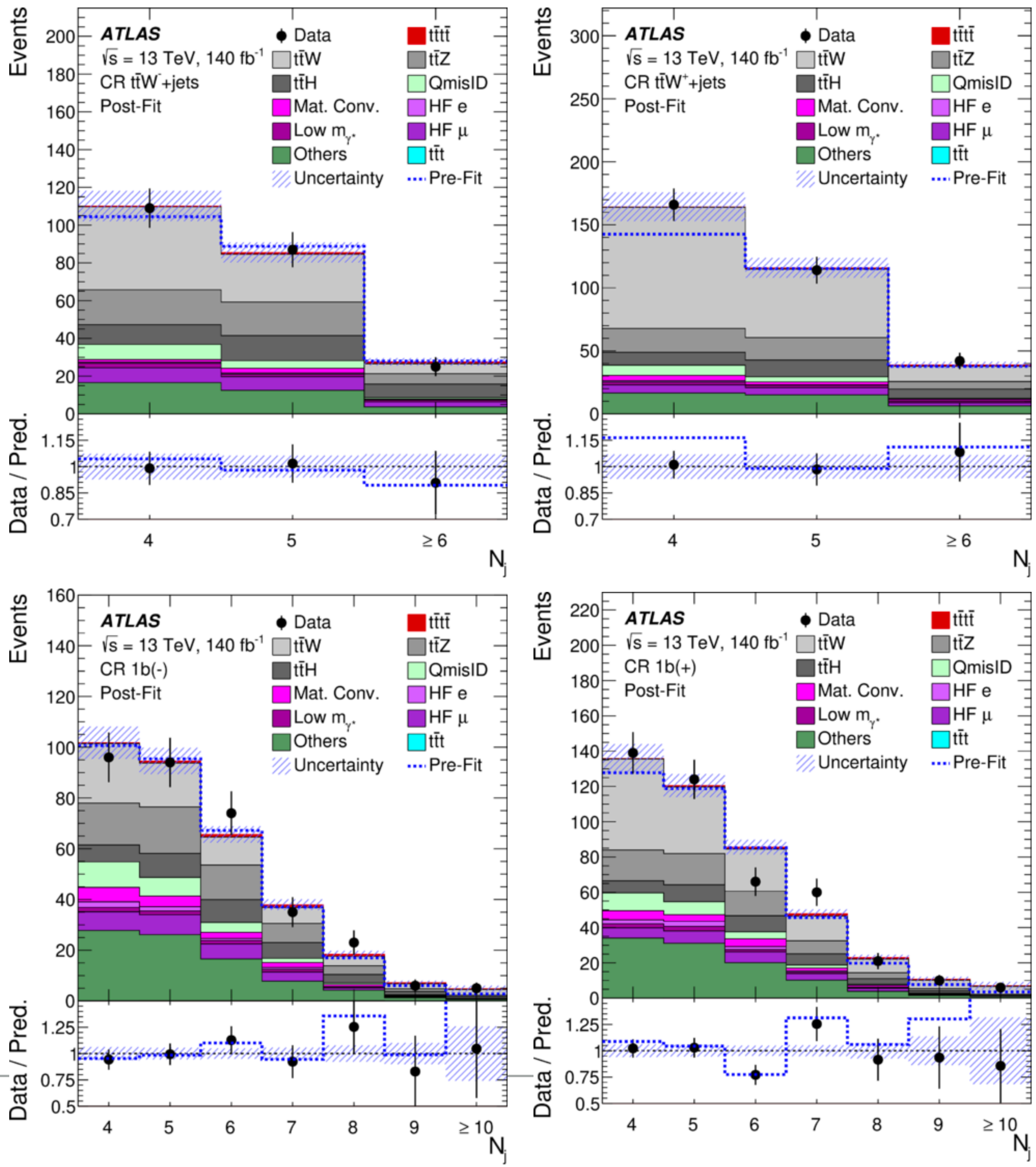
$$R(j) = \frac{N_{\pm}(j+1)}{N_{\pm}(j)} = a_0 + \frac{a_1}{1+(j-4)}$$



Charge Subtracted data distribution in $t\bar{t}W$ and Signal Regions

$t\bar{t}W$ Control Regions

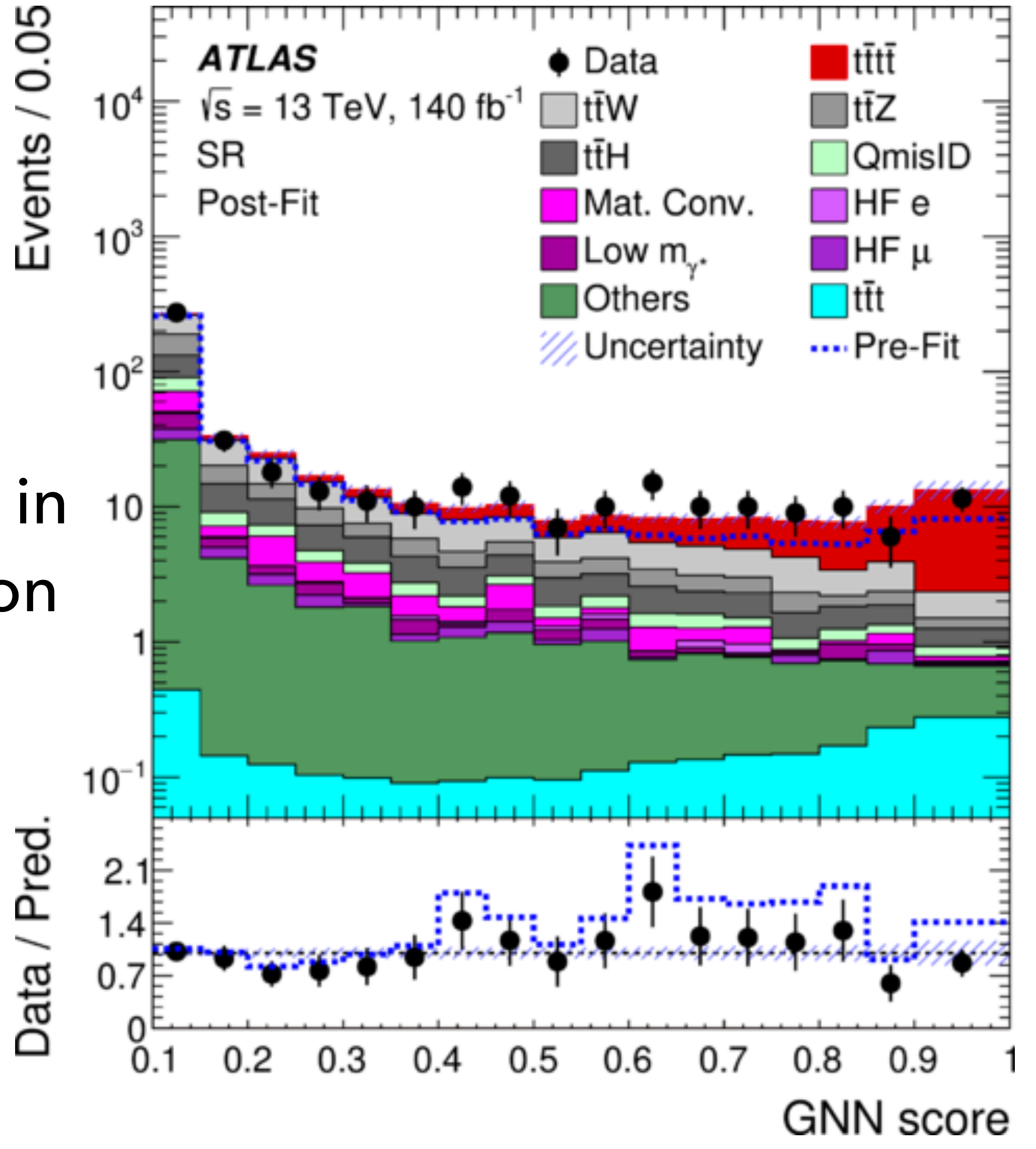
$t\bar{t}W^{-}$ $t\bar{t}W^{+}$

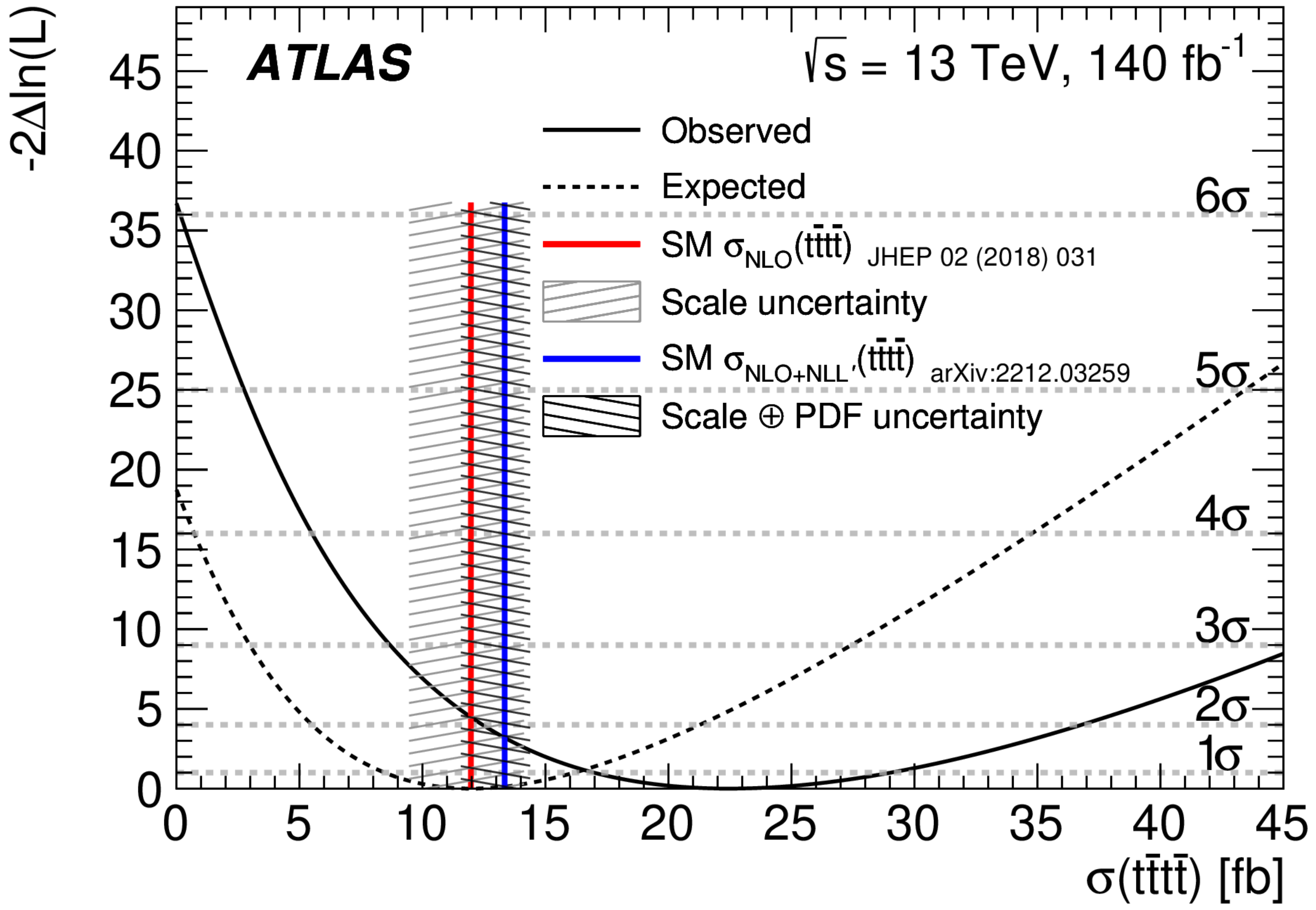


SM MEASUREMENT – RESULTS

- $\sigma_{t\bar{t}t\bar{t}} = 22.7^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\text{ fb} = 22.5\,^{+6.6}_{-5.5}\text{ fb}$
- $\mu_{t\bar{t}t\bar{t}} = 1.9 \pm 0.4(\text{stat})\,^{+0.7}_{-0.4}(\text{syst}) = 1.9\,^{+0.8}_{-0.5}$
- 6.1σ (4.3σ) observed (expected) significance.
- SM Compatibility: 1.8σ (1.7σ) w.r.t. NLO (NLO+NLL SM).

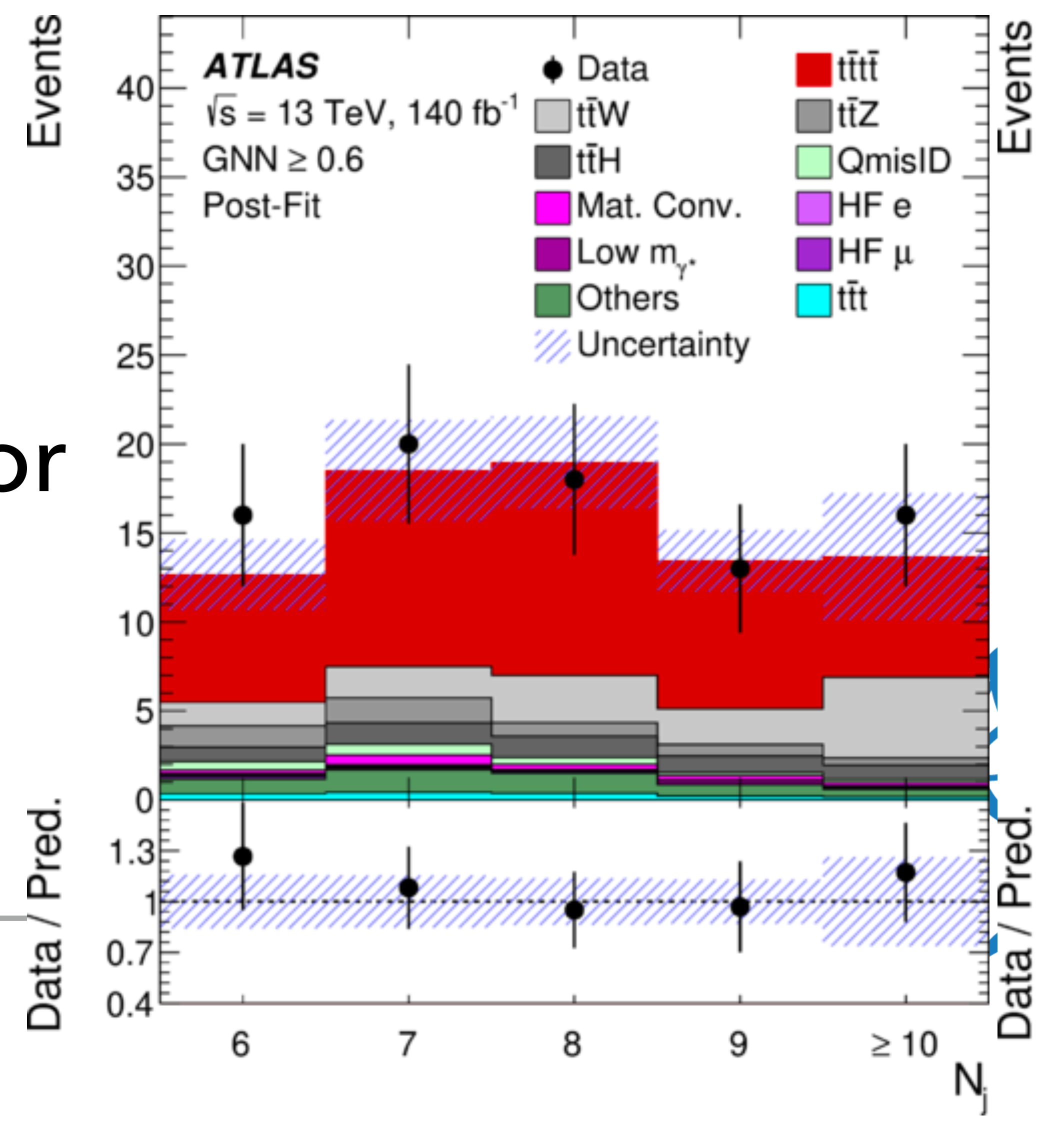
GNN Distribution in Signal Region

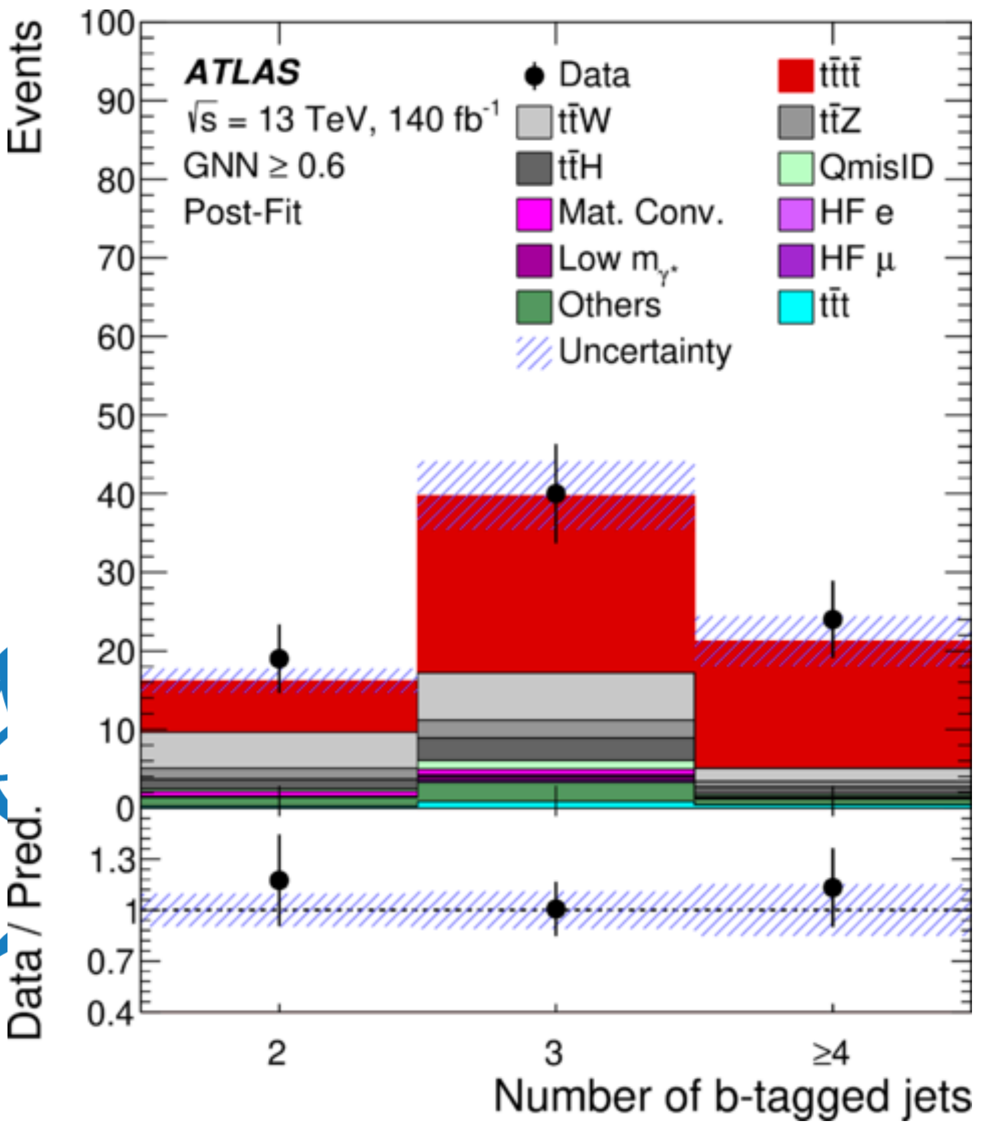




Likelihood scan of $t\bar{t}t\bar{t}$ cross-section.

Jet, b-jet multiplicity for GNN>0.6



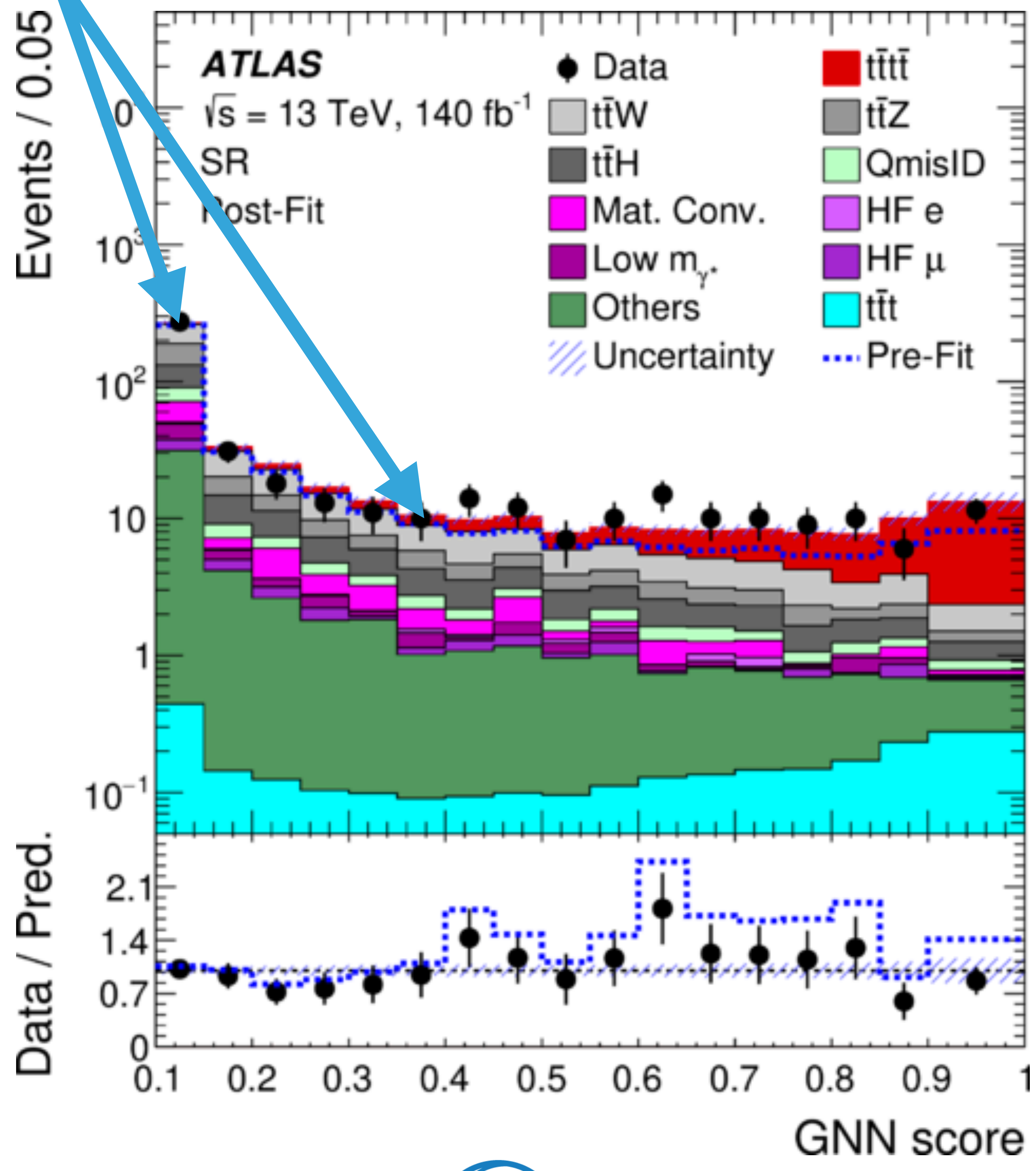


YUKAWA MEASUREMENT – TECHNIQUE

$$N(\kappa_t, \alpha) = N(1,0)\Big(1 + C_1(\kappa_t^4 \cos^4 \alpha - 1) + C_2\kappa_t^4 \cos^2 \alpha \sin^2 \alpha + C_3\kappa_t^4 \sin^4 \alpha + C_4(\kappa_t^2 \cos^2 \alpha - 1) + C_5\kappa_t^2 \sin^2 \alpha\Big)$$

arxiv:1901.04567

Parameterize each bin.



- Simulated signal points at 6 values of the top Yukawa coupling. Dominant effect is cross-section variation.
- In each bin, parameterize signal yield as a function of κ_t and α.
- 2 possible treatments of $t\bar{t}H$ background.
  - Fully parameterize in terms of κ_t, α.
  - Floating normalization for $t\bar{t}H$.

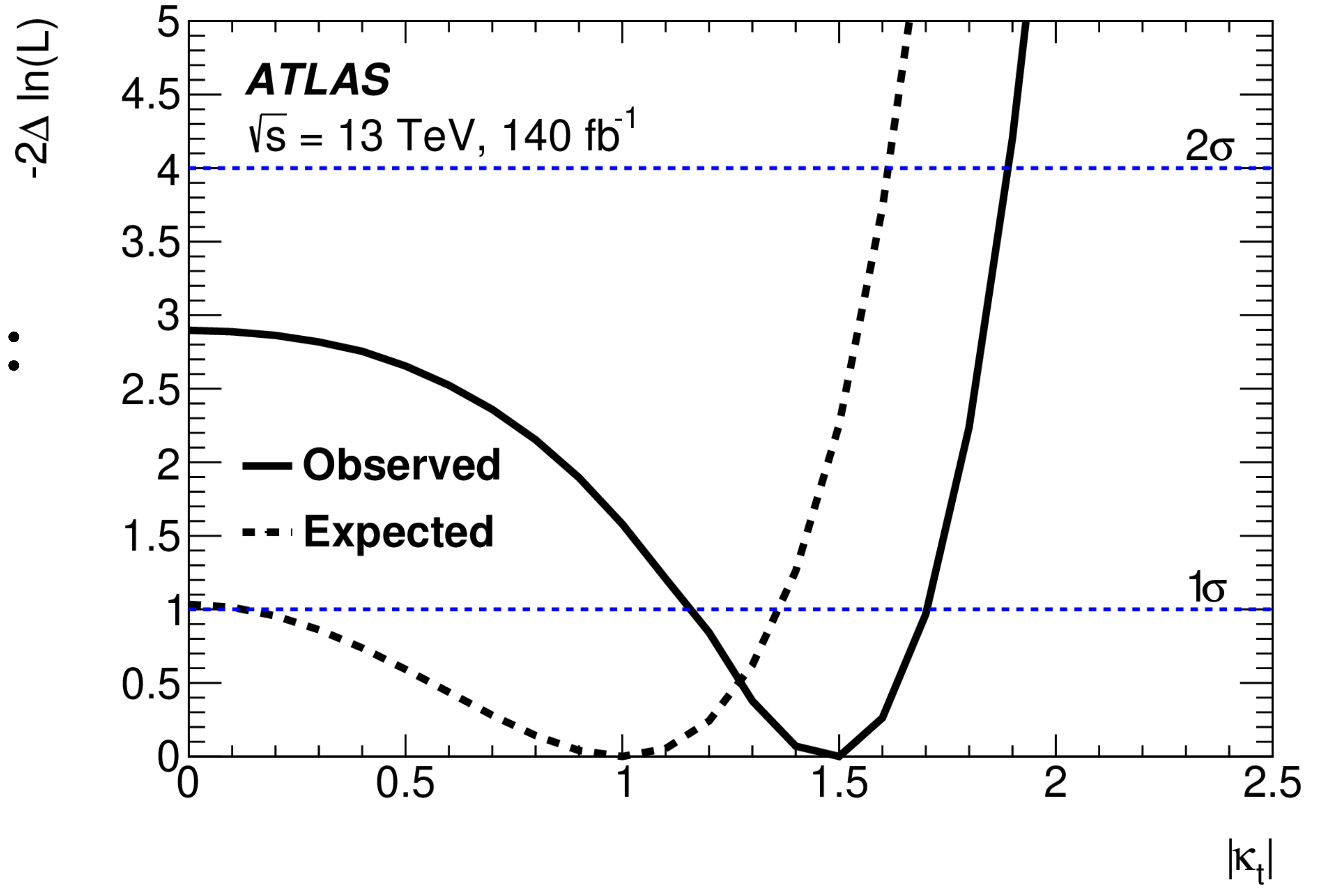
YUKAWA MEASUREMENT – RESULTS

- Mild excess in signal-like events over SM results in weaker than expected limits on κ_t.

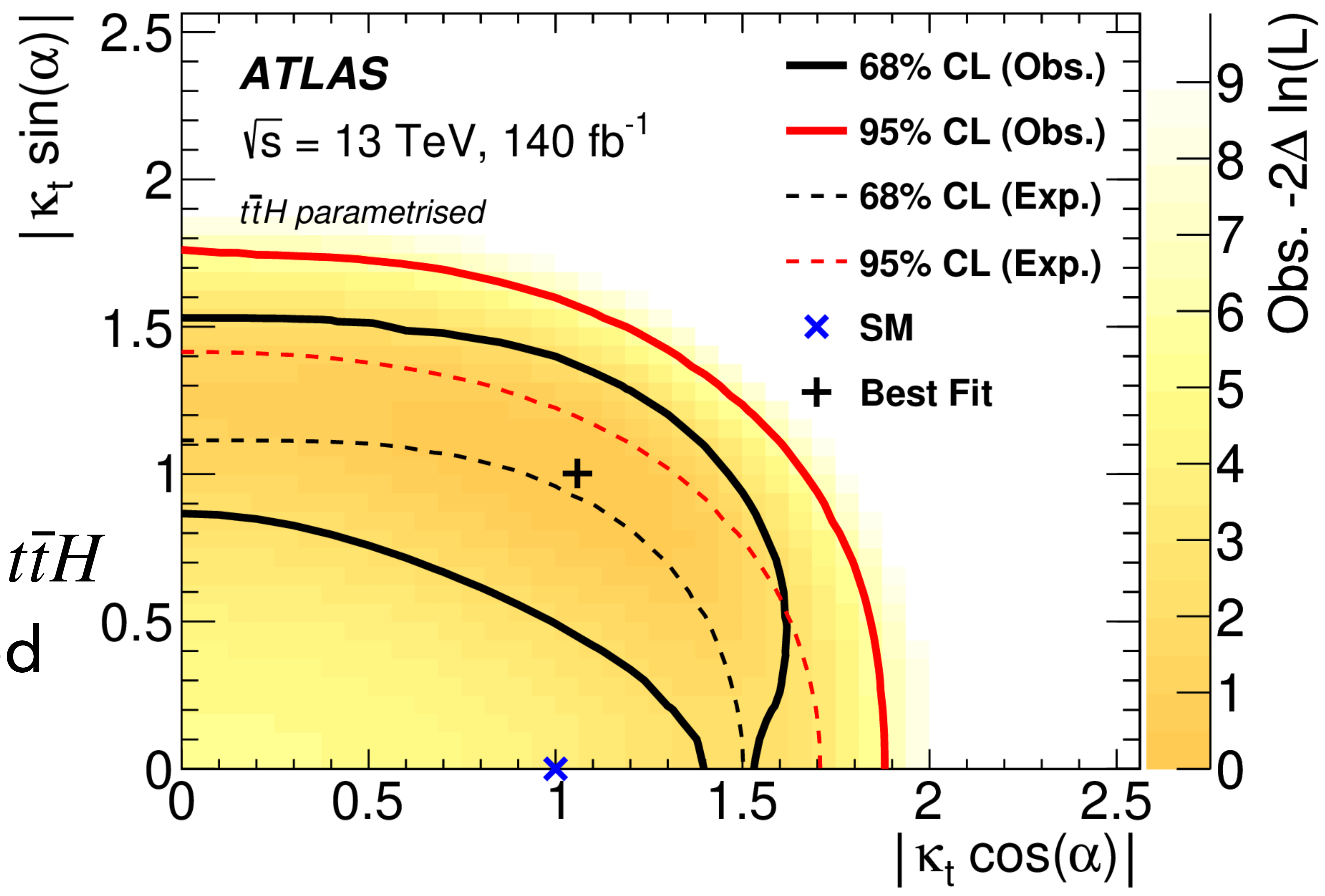
$t\bar{t}H$ Parameterized:

$|\kappa_t| < 1.8\ (1.6)$

Obs. (Exp.)



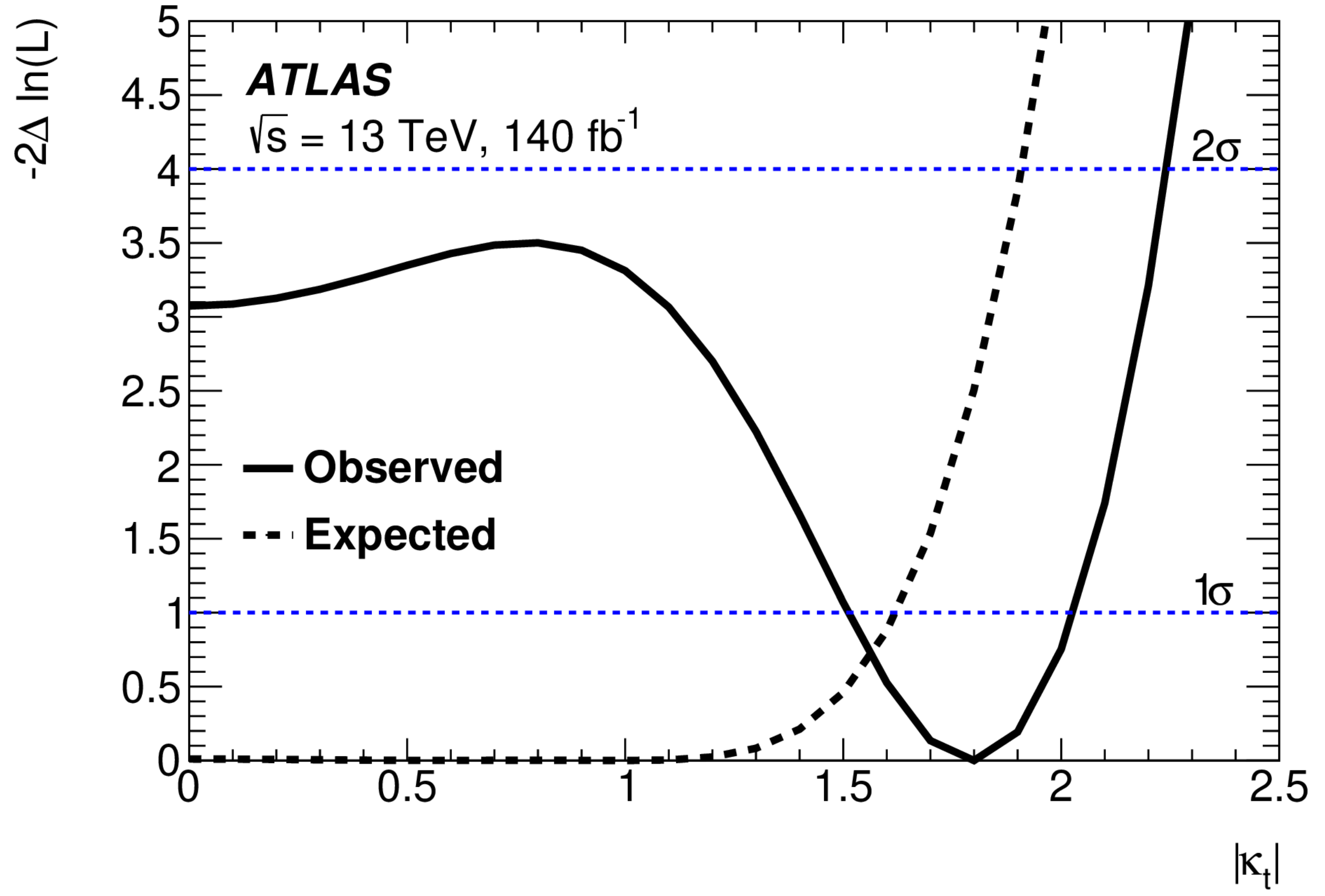
2D Limit Contours for $(|\kappa_t|, \alpha)$ with $t\bar{t}H$ parameterized



$t\bar{t}H$ not Parameterized:

$|\kappa_t| < 2.2\ (1.8)$

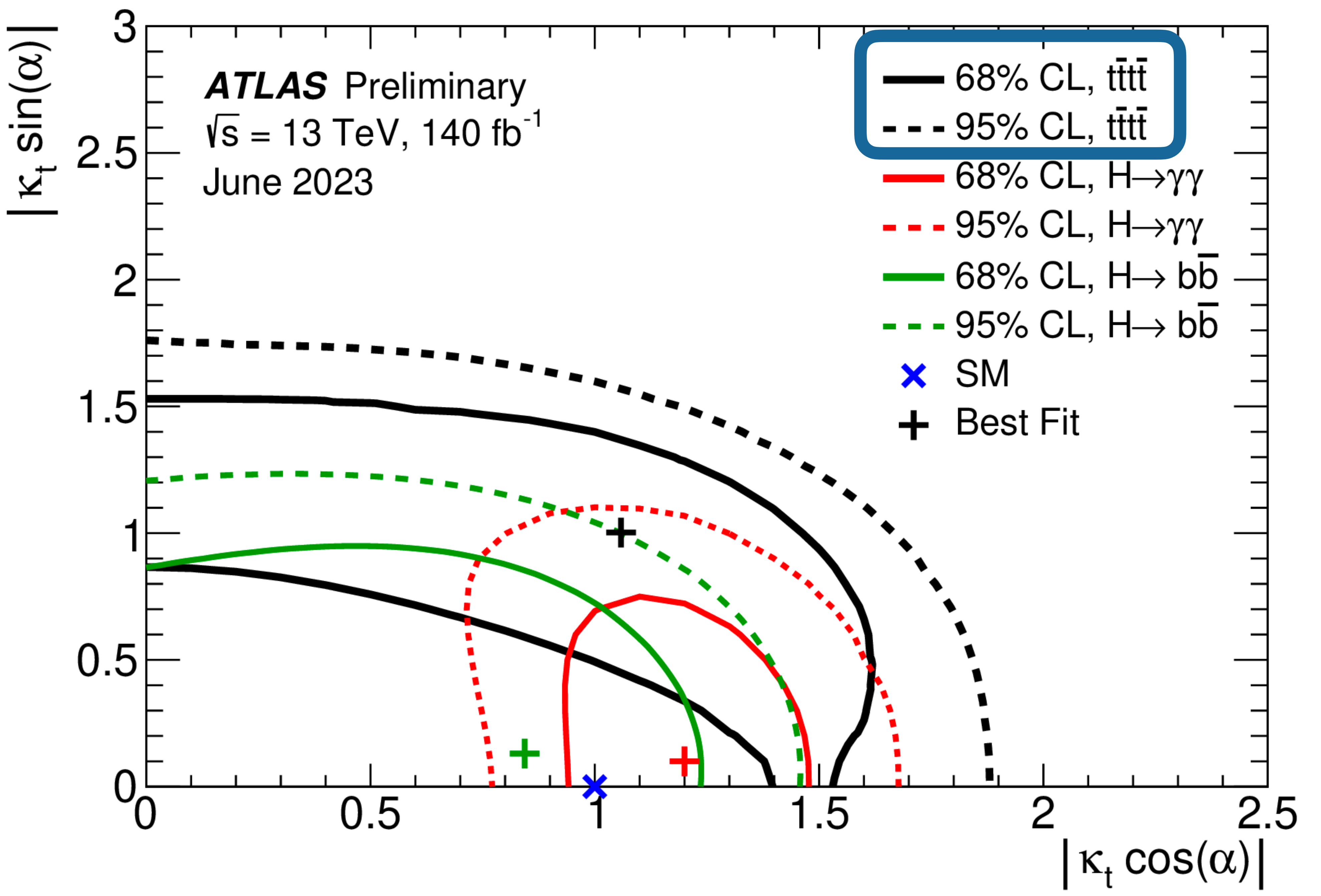
Obs. (Exp.)



OUTLOOK

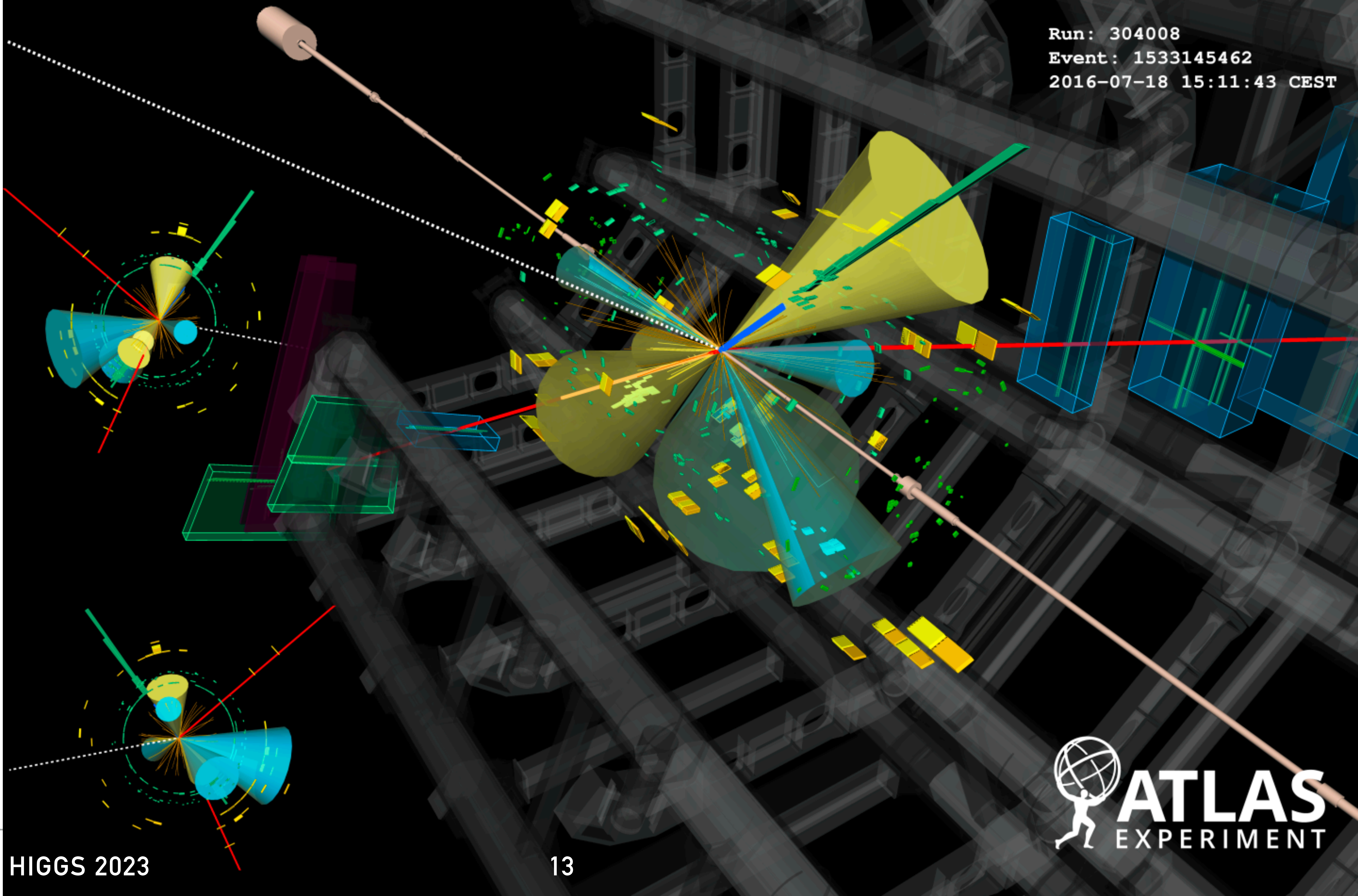
- $t\bar{t}t\bar{t}$ provides a very different window into the top-Higgs interaction compared to $t\bar{t}H$ measurements or measurements of κ_g and κ_γ.
- The cross-section measurement has prospects for improvement in future runs from increased statistics and from improved modeling of $t\bar{t}t\bar{t}$, $t\bar{t}t$, and $t\bar{t}W$.
- The top Yukawa determination can also benefit from simultaneously targeting $t\bar{t}t\bar{t}$ and $t\bar{t}H$.

ATL-PHYS-PUB-2023-013



Overlay of 2D limits on κ_t and λ from measurements of $t\bar{t}t\bar{t}$ and $t\bar{t}H$ in ATLAS.

THANKS!


Run: 304008
Event: 1533145462
2016-07-18 15:11:43 CEST
ATLAS
EXPERIMENT

BACKUP

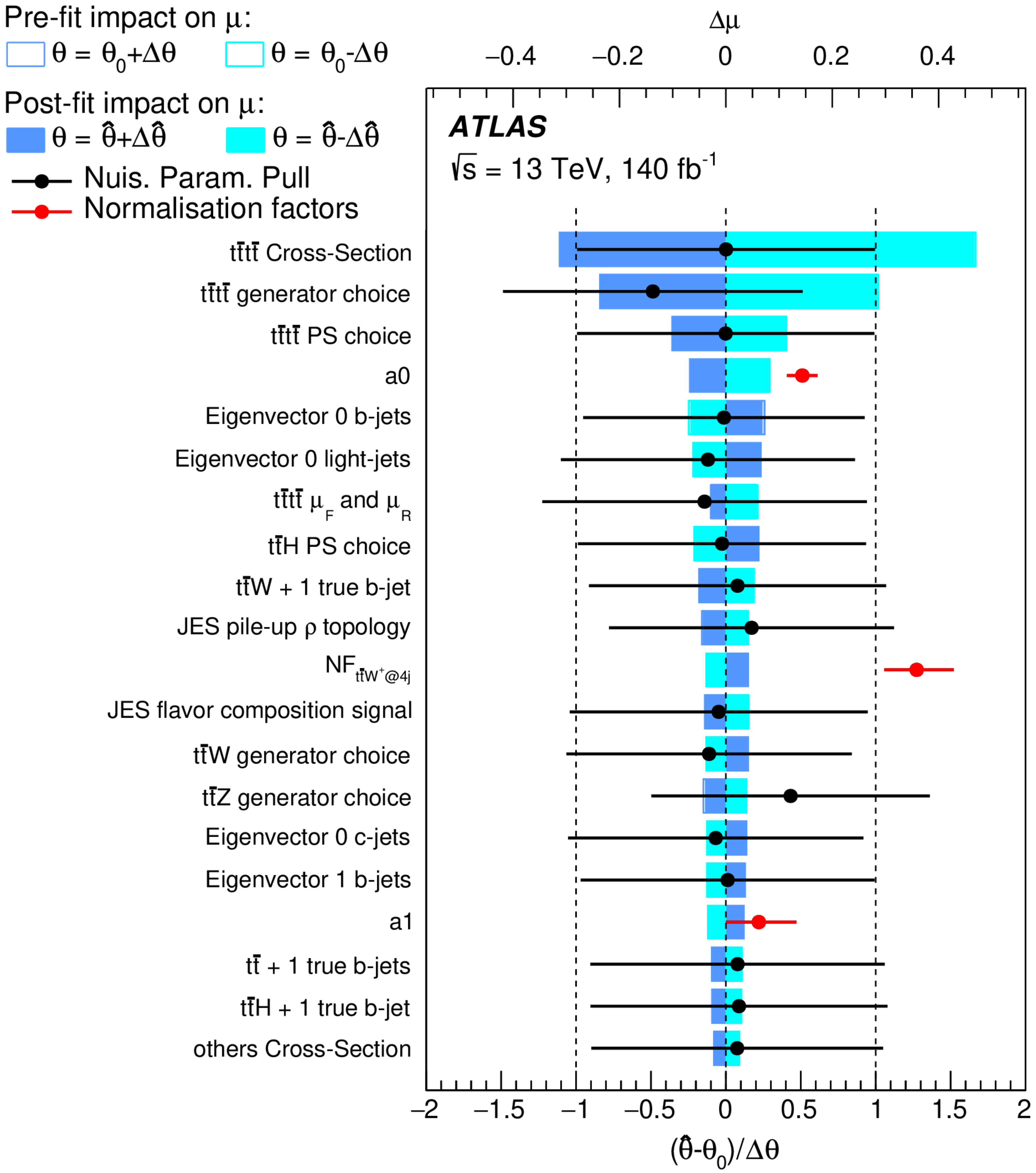
FULL SELECTION DETAILS

Region	Channel	N_j	N_b	Other selection	Fitted variable
CR Low m_{γ^*}	SS, ee or eμ	$4 \leq N_\mathrm{j} < 6$	≥ 1	ℓ_1 or ℓ_2 is from virtual photon (γ^*) decay ℓ_1 and ℓ_2 are not from photon conversion	counting
CR Mat. Conv.	SS, ee or eμ	$4 \leq N_\mathrm{j} < 6$	≥ 1	ℓ_1 or ℓ_2 is from photon conversion	counting
CR HF μ	e$\mu\mu$ or $\mu\mu\mu$	≥ 1	$= 1$	$100 < H_\mathrm{T} < 300$ GeV $E_\mathrm{T}^\mathrm{miss} > 50$ GeV total charge $= \pm 1$	$p_\mathrm{T}^{\ell_3}$
CR HF e	eee or eeμ	≥ 1	$= 1$	$100 < H_\mathrm{T} < 275$ GeV $E_\mathrm{T}^\mathrm{miss} > 35$ GeV total charge $= \pm 1$	$p_\mathrm{T}^{\ell_3}$
CR $t\bar{t}W^+$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_\mathrm{T} < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_\mathrm{T} < 500$ GeV total charge > 0	N_j
CR $t\bar{t}W^-$+jets	SS, eμ or $\mu\mu$	≥ 4	≥ 2	$\lvert\eta(e)\rvert < 1.5$ when $N_b = 2$: $H_\mathrm{T} < 500$ GeV or $N_j < 6$ when $N_b \geq 3$: $H_\mathrm{T} < 500$ GeV total charge < 0	N_j
CR 1b(+)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_\mathrm{T} > 500$ GeV total charge > 0	N_j
CR 1b(-)	2LSS+3L	≥ 4	$= 1$	ℓ_1 and ℓ_2 are not from photon conversion $H_\mathrm{T} > 500$ GeV total charge < 0	N_j
SR	2LSS+3L	≥ 6	≥ 2	$H_\mathrm{T} > 500$ GeV	GNN score

MONTE CARLO SIMULATION DETAILS

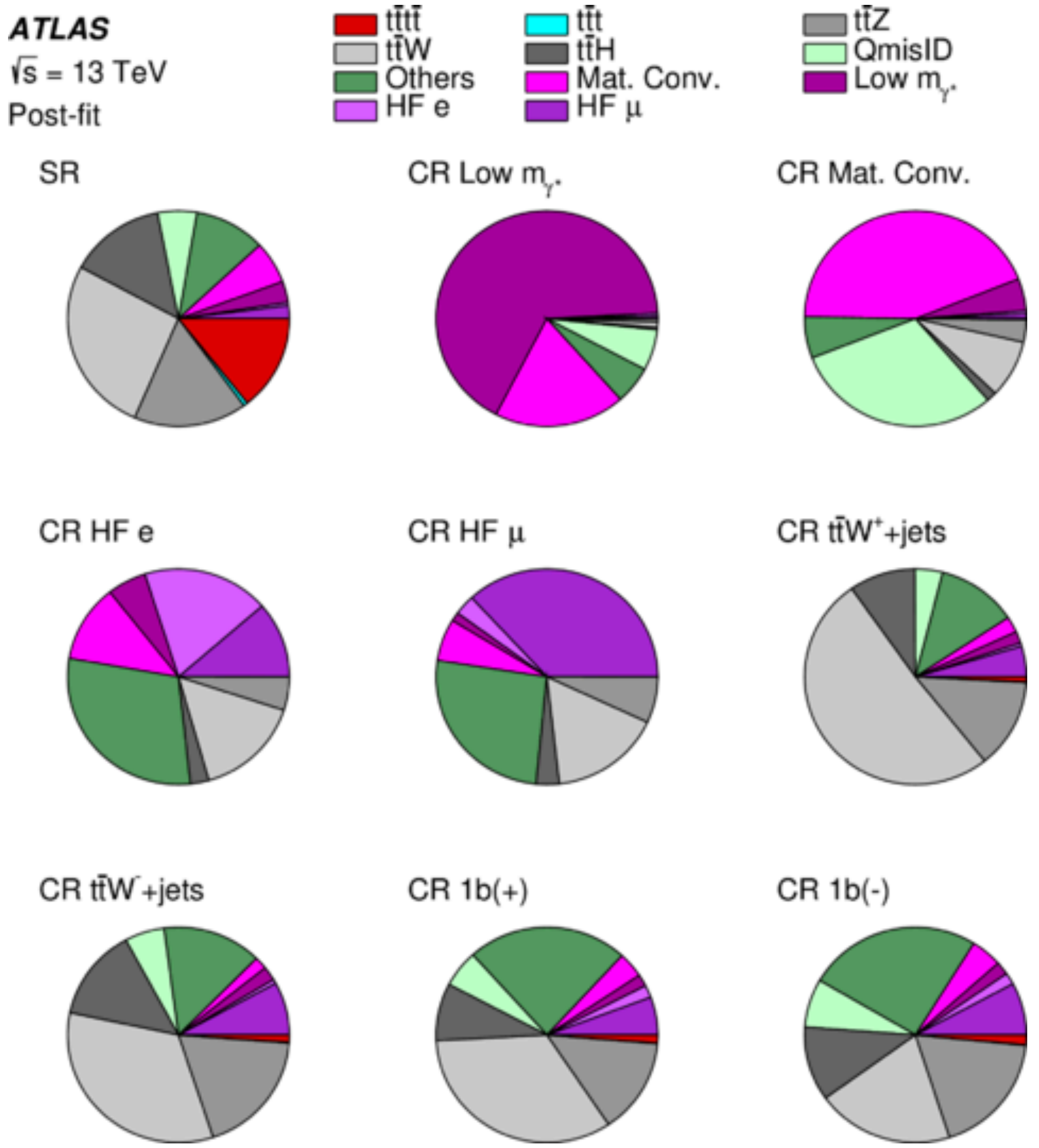
Process	Generator	ME order	PDF	Parton shower	Tune
$t\bar{t}t\bar{t}$	MadGraph5_aMC@NLO	NLO	NNPDF3.1nlo	Pythia8	A14
	(MadGraph5_aMC@NLO)	(NLO)	(MMHT2014 LO)	(Herwig7)	(H7UE)
	(Sherpa 2.2.11)	(NLO)	(NNPDF3.0nnlo)	(Sherpa)	(Sherpa)
	(MadGraph5)	(LO)	(MMHT2014 LO)	(Pythia8)	(A14)
$t\bar{t}t\bar{t}$ κ_t	MadGraph5	LO	MMHT2014 LO	Pythia8	A14
$t\bar{t}t\bar{t}$ EFT	MadGraph5	LO	MMHT2014 LO	Pythia8	A14
$t\bar{t}t$	MadGraph5	LO	NNPDF2.3lo	Pythia8	A14
$t\bar{t}W$	Sherpa 2.2.10	MEPS@NLO	NNPDF3.0nnlo	Sherpa	Sherpa
	(MadGraph5_aMC@NLO)	(FxFx)	(NNPDF2.3lo)	(Pythia8)	(A14)
$t\bar{t}W$ EW	Sherpa 2.2.10	LO	NNPDF3.0nnlo	Sherpa	Sherpa
	(MadGraph5)	(LO)	(NNPDF2.3lo)	(Pythia8)	(A14)
$t\bar{t}Z/\gamma^*$	MadGraph5_aMC@NLO	NLO	NNPDF3.0nlo	Pythia8	A14
	(Sherpa 2.2.11)	(MEPS@NLO)	(NNPDF3.0nnlo)	(Sherpa)	(Sherpa)
$t\bar{t}H$	PowhegBox	NLO	NNPDF3.0nlo	Pythia8	A14
	(PowhegBox)	(NLO)	(NNPDF3.0nlo)	(Herwig7)	(H7UE)
	(MadGraph5_aMC@NLO)	(NLO)	(NNPDF3.0nlo)	(Pythia8)	(A14)
$t\bar{t}$	PowhegBox	NLO	NNPDF3.0nlo	Pythia8	A14
Single-top	PowhegBox	NLO	NNPDF3.0nlo	Pythia8	A14
tWZ	MadGraph5_aMC@NLO	NLO	NNPDF3.0nlo	Pythia8	A14
tZq	MadGraph5	LO	NNPDF2.3lo	Pythia8	A14
$t\bar{t}VV$	MadGraph5	LO	NNPDF2.3lo	Pythia8	A14
V	Sherpa 2.2.1	MEPS@NLO	NNPDF3.0nnlo	Sherpa	Sherpa
VV,VVV	Sherpa 2.2.2	MEPS@NLO	NNPDF3.0nnlo	Sherpa	Sherpa
VH	Pythia8	LO	NNPDF2.3lo	Pythia8	A14

SYSTEMATICS



Uncertainty source	$\Delta\mu$	
Signal modelling		
$t\bar{t}t\bar{t}$ cross-section	+0.53	−0.27
$t\bar{t}t\bar{t}$ generator choice	+0.33	−0.22
$t\bar{t}t\bar{t}$ parton showering	+0.14	−0.08
Other $t\bar{t}t\bar{t}$ modelling	+0.07	−0.04
Background modelling		
$t\bar{t}H$+jets modelling	+0.08	−0.06
$t\bar{t}W$+jets modelling	+0.08	−0.06
$t\bar{t}Z$+jets modelling	+0.05	−0.03
Other background modelling	+0.04	−0.04
Non-prompt leptons modelling	+0.04	−0.03
$t\bar{t}t$ modelling	+0.02	−0.02
Charge misassignment	+0.01	−0.00
Instrumental		
Jet flavour tagging (b-jets)	+0.10	−0.06
Jet uncertainties	+0.09	−0.06
Jet flavour tagging (light-flavour jets)	+0.08	−0.05
Jet flavour tagging (c-jets)	+0.04	−0.03
Simulation sample size	+0.04	−0.02
Other experimental uncertainties	+0.04	−0.02
Luminosity	+0.02	−0.01
Total systematic uncertainty	+0.65	−0.39
Statistical		
Intrinsic statistical uncertainty	+0.35	−0.32
$t\bar{t}W$+jets normalisation and scaling factors	+0.12	−0.09
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.04	−0.02
Total statistical uncertainty	+0.39	−0.36
Total uncertainty	+0.76	−0.53

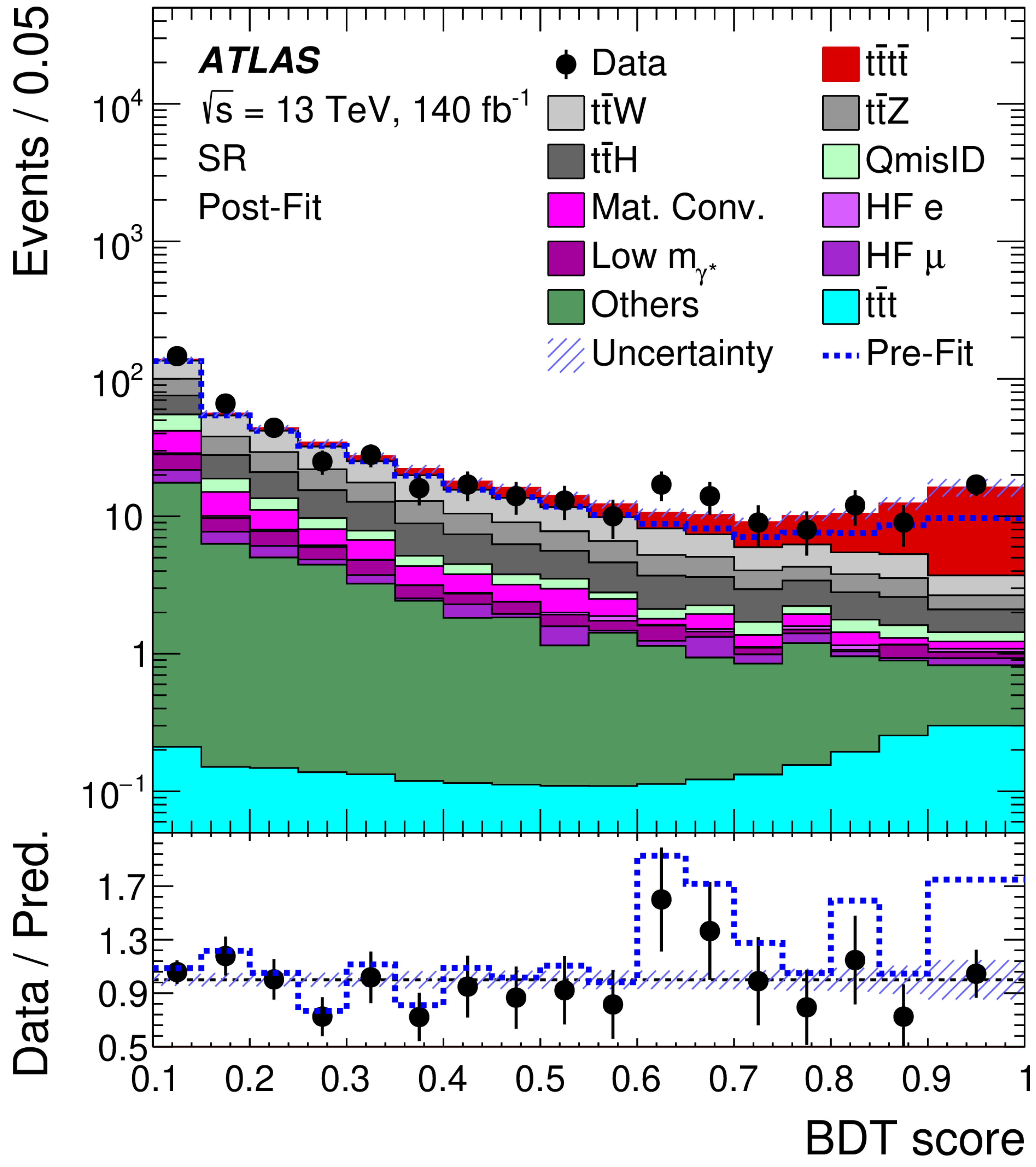
FULL BACKGROUND COMPOSITION AND YIELDS



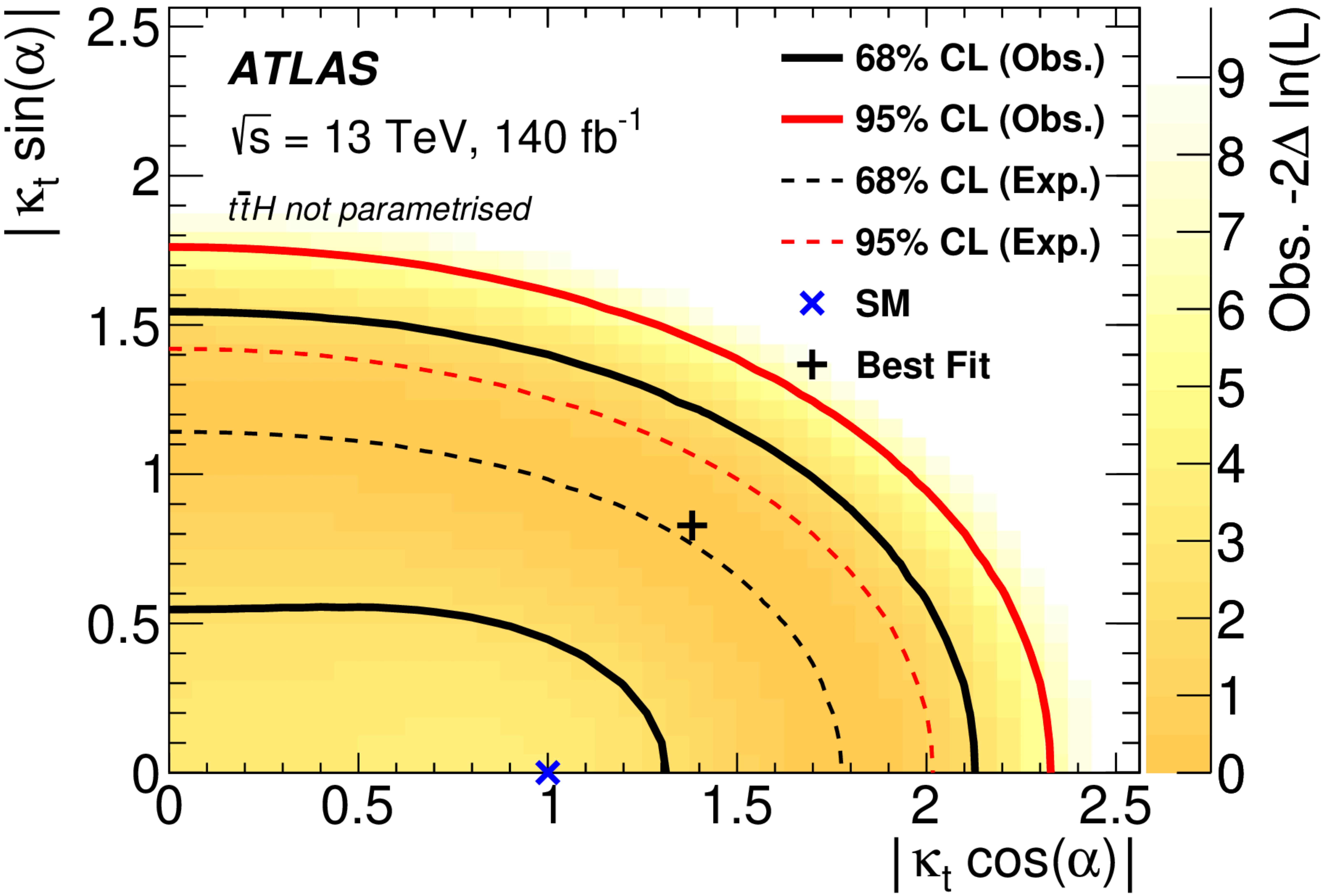
	Pre-fit		Post-fit	
	SR	GNN≥0.6	SR	GNN≥0.6
$t\bar{t}W$	130 ± 40	9 ± 4	127 ± 35	12 ± 4
$t\bar{t}Z$	72 ± 15	3.4 ± 1.8	79 ± 15	4.4 ± 2.0
$t\bar{t}H$	65 ± 11	4.6 ± 1.3	68 ± 10	5.0 ± 1.4
QmisID	27 ± 4	1.78 ± 0.26	27 ± 4	1.80 ± 0.24
Mat. Conv.	16.5 ± 2.3	0.73 ± 0.25	30 ± 8	1.4 ± 0.5
HF e	3.1 ± 1.0	0.4 ± 0.5	2.3 ± 2.4	0.3 ± 0.4
HF μ	7.1 ± 1.2	0.31 ± 0.15	9 ± 4	0.41 ± 0.22
Low m_{γ^*}	14.1 ± 2.0	0.52 ± 0.19	15 ± 5	0.56 ± 0.22
Others	47 ± 11	3.9 ± 1.2	50 ± 10	4.3 ± 1.2
$t\bar{t}t$	2.9 ± 0.9	1.5 ± 0.5	2.9 ± 0.9	1.5 ± 0.5
Total bkg	390 ± 50	26 ± 5	412 ± 21	32 ± 4
$t\bar{t}t\bar{t}$	38 ± 4	25.2 ± 3.2	69 ± 15	45 ± 10
Total	430 ± 50	51 ± 7	480 ± 19	77 ± 8
Data	482	83	482	83

BDT CROSSCHECK

- Cross-check fit performed with Boosted Decision Tree akin to that used in [cite evidence].
- 6.0σ (3.9σ) observed expected significance of $t\bar{t}t\bar{t}$ signal.



2D FIT WITH $t\bar{t}H$ NOT PARAMETERIZED



NORMALIZATION FACTORS

Fake/non-prompt background	$\mathrm{NF}_{\mathrm{Mat.\ Conv.}}$	$\mathrm{NF}_{\mathrm{Low}\ m_{\gamma^*}}$	$\mathrm{NF}_{\mathrm{HF}\ e}$	$\mathrm{NF}_{\mathrm{HF}\ \mu}$
Value	$1.80^{+0.47}_{-0.41}$	$1.08^{+0.37}_{-0.31}$	$0.66^{+0.75}_{-0.46}$	$1.27^{+0.53}_{-0.46}$

$t\bar{t}W$ background	a_0	a_1	$\mathrm{NF}_{t\bar{t}W^+(\mathrm{4jet})}$	$\mathrm{NF}_{t\bar{t}W^-(\mathrm{4jet})}$
Value	0.51 ± 0.10	$0.22^{+0.25}_{-0.22}$	$1.27^{+0.25}_{-0.22}$	$1.11^{+0.31}_{-0.28}$