Institut de Física d'Altes Energies

Funded by the European Union

MARIE SKŁODOWSKA-CURIE ACTIONS

Measurements and searches for $t\bar{t}t\bar{t}$ production with ATLAS and CMS experiments

Quake Qin (IFAE)

on behalf of the ATLAS and CMS collaborations

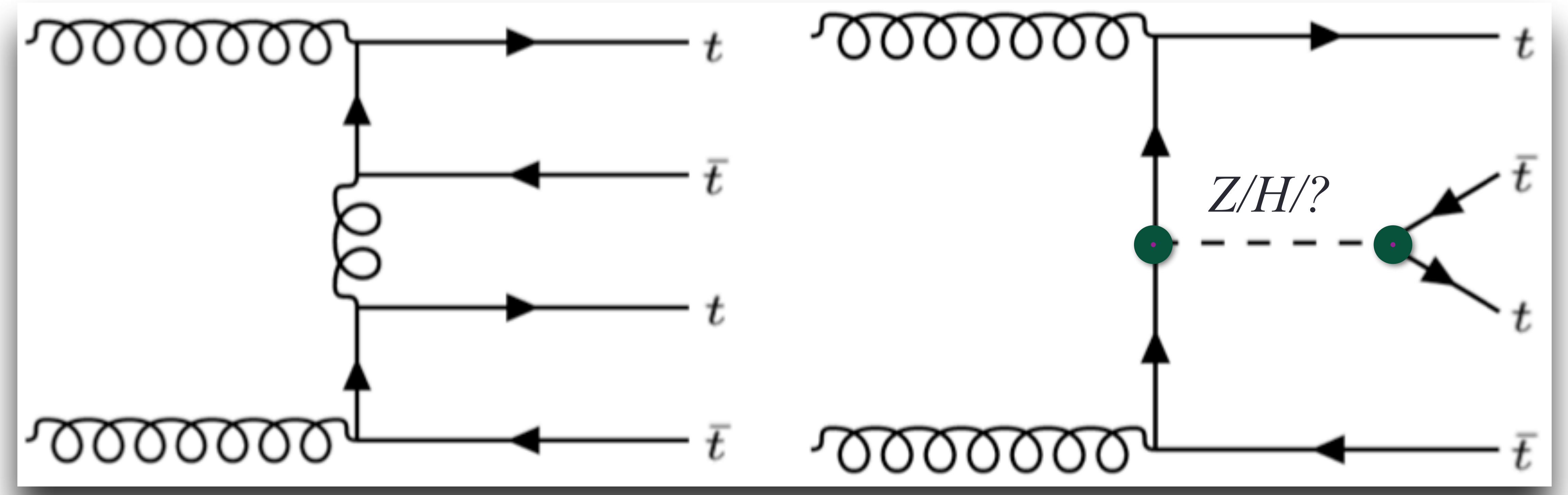
17th International Workshop on Top Quark Physics (2024)

ATLAS EXPERIMENT

CMS

Introduction

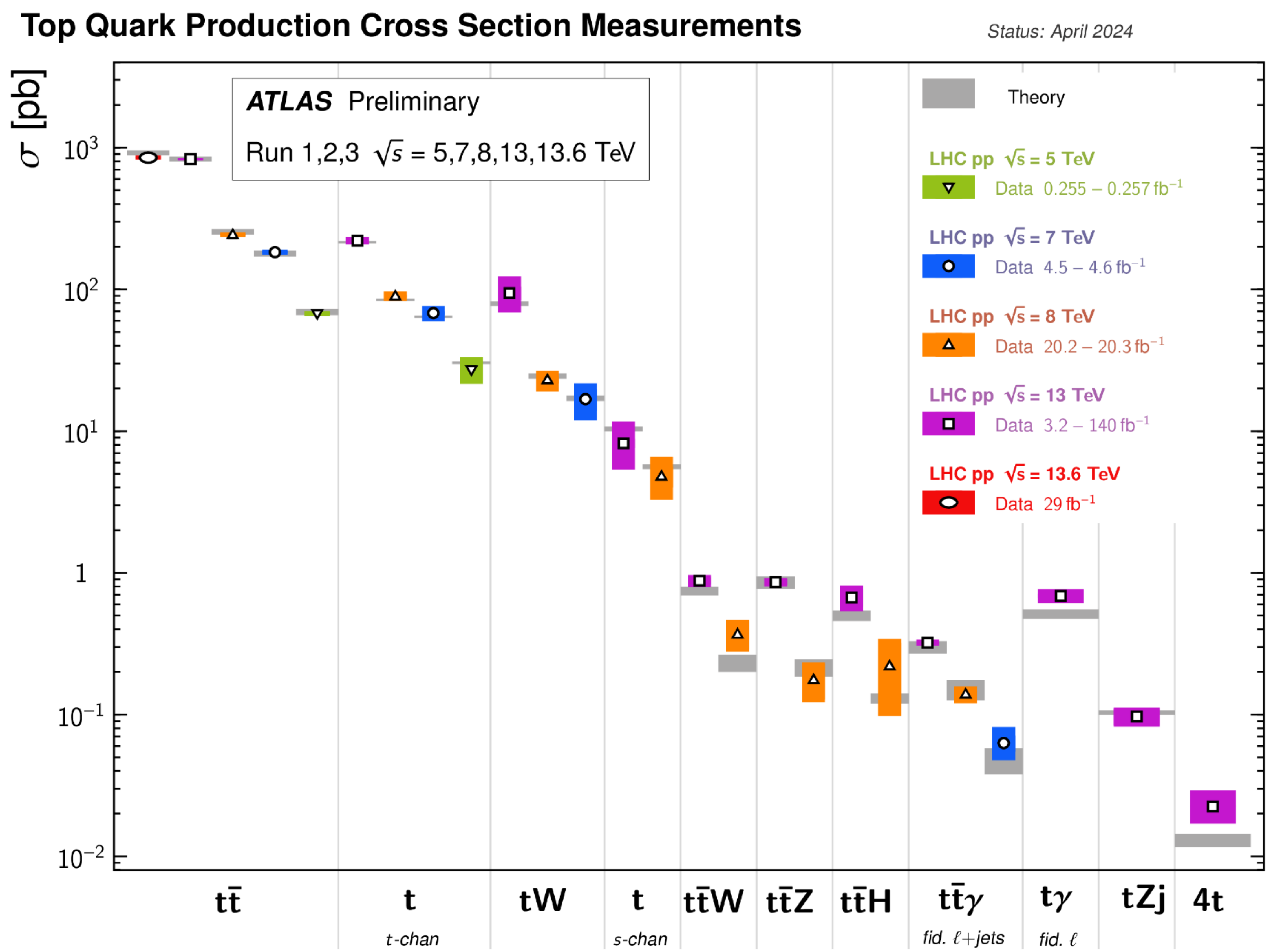
- $t\bar{t}t\bar{t}$ production is a rare process, in 13 TeV pp collisions:
  - NLO QCD+EW: $11.97^{+18\%}_{-21\%}$ fb (R. Frederix, D. Pagani, M. Zaro)
  - adding NLL' resummation: $13.37^{+3.6\%}_{-11.4\%}$ fb (M. Beekveld, A. Kulesza, L. Valero)
- Sensitive to heavy new physics, top-Yukawa coupling, and a number of four-fermion operators in EFT



Leading: $\mathcal{O}(\alpha_S^4)$

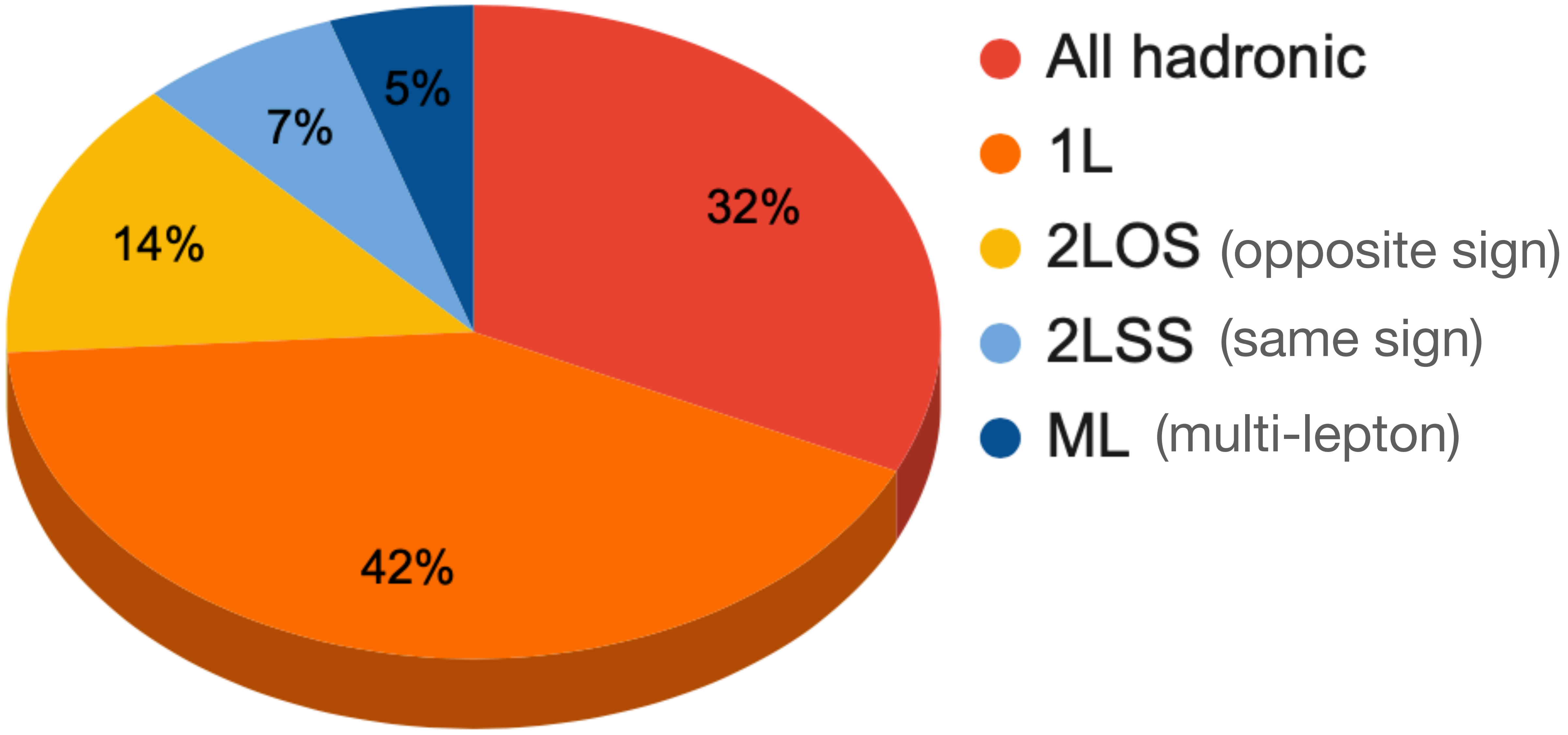
Sub-leading: $\mathcal{O}(\alpha_S^2 y_t^2)$, $\mathcal{O}(\alpha_S^2 \alpha^2)$

ATL-PHYS-PUB-2024-006

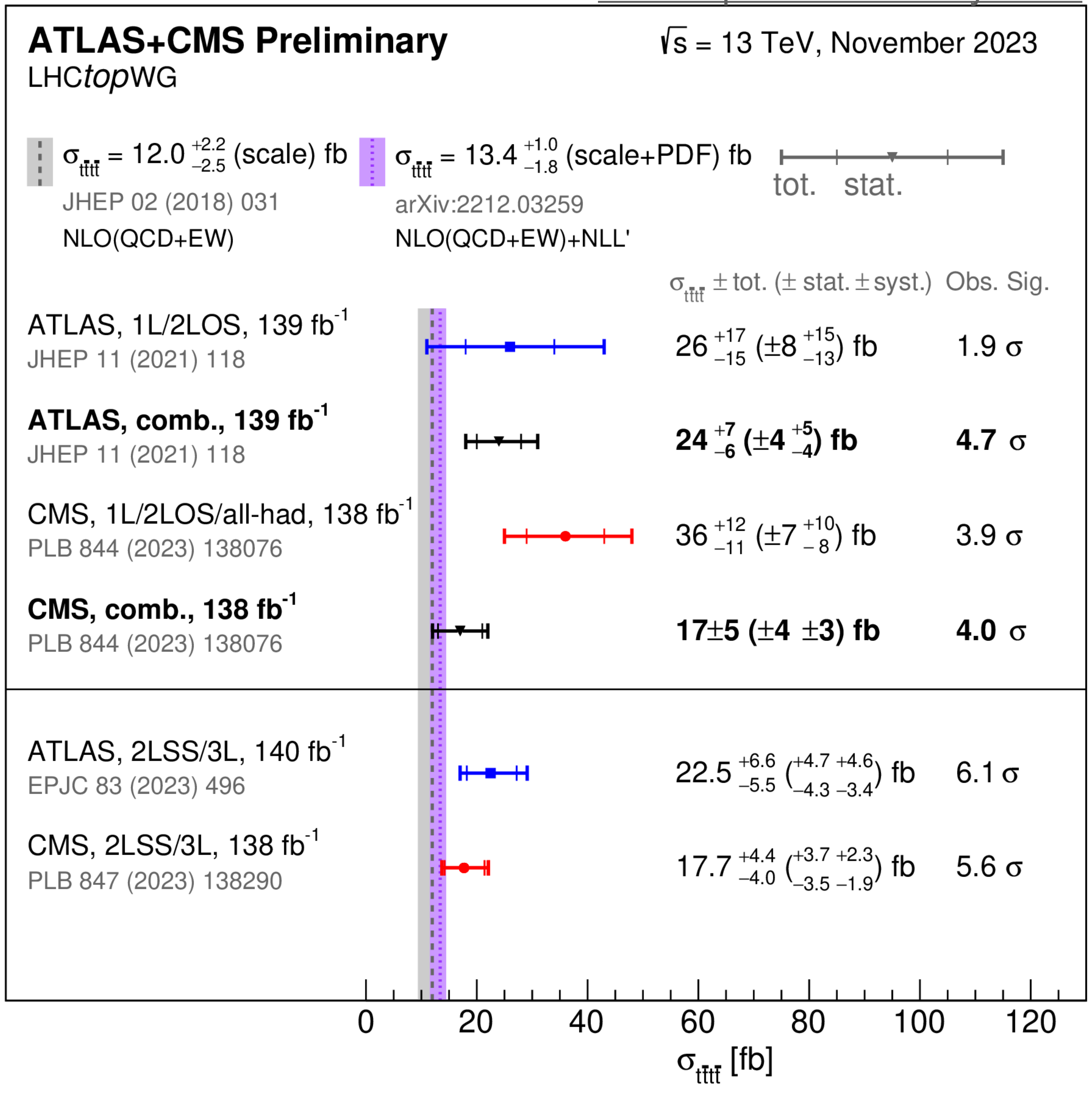


State of the art

- Measurements and searches in all channels



LHC Top WG Summary Plots



State of the art

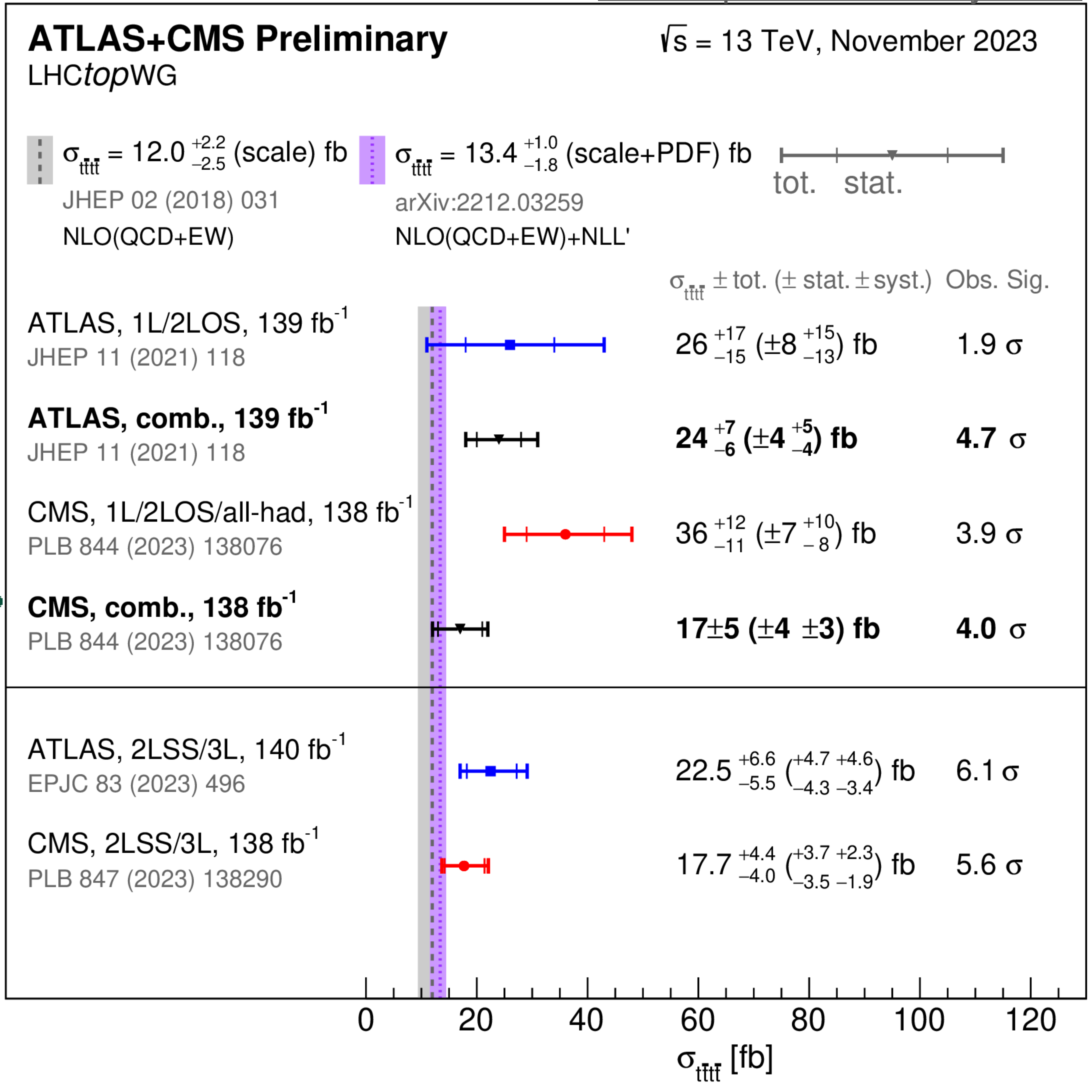
- Measurements and searches in all channels

Combination of
- 1L/2LOS
- 2LSS/ML EPJC 80 (2020)

Combination of
- 1L/2LOS/all-had
- 2LSS/ML EPJC 80 (2020) 75

Observation in 2LSS/ML by ATLAS and CMS

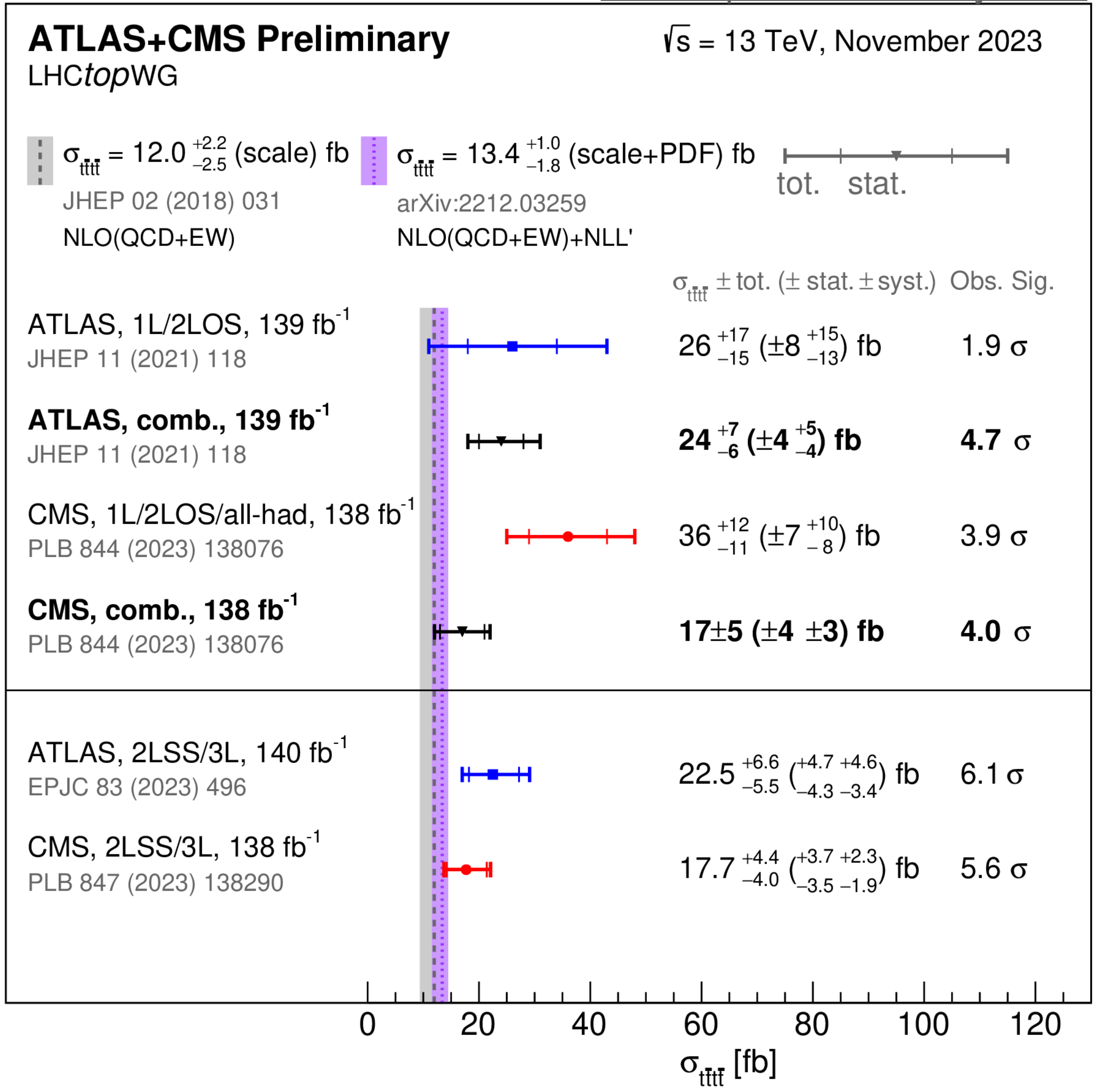
LHC Top WG Summary Plots



State of the art

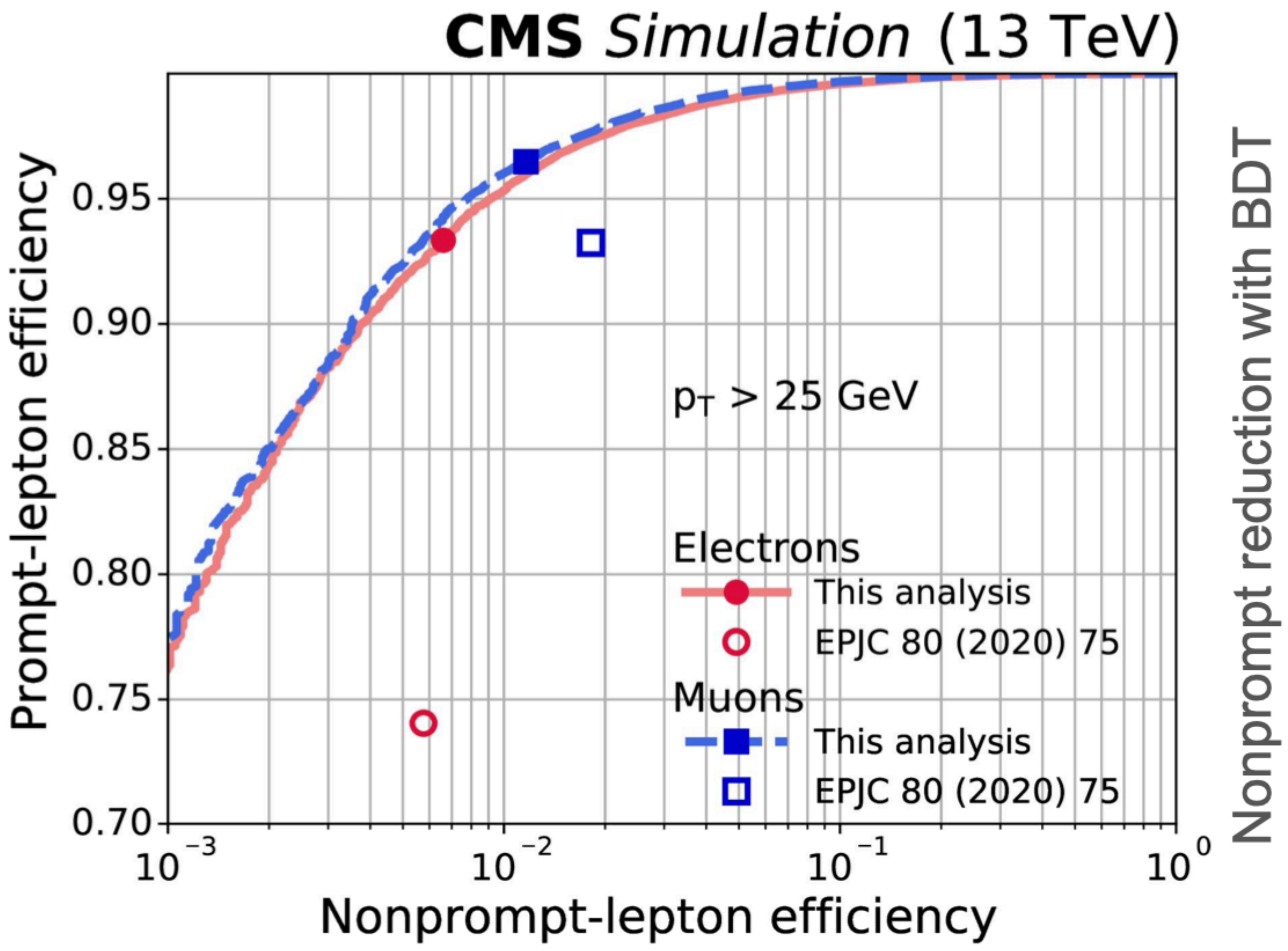
- Measurements and searches in all channels
- BSM searches
  - ATLAS
    - 1L/2LOS channels (submitted to EPJC)
    - 2LSS/ML channels (JHEP 07 (2023) 203)
    - resonance search using 1L events (EPJC 84 (2024) 157)
  - CMS
    - dedicated search using partial Run 2 data (EPJC 77 (2017) 578)
    - interpretation of previous 2LSS/ML results (EPJC 80 (2020) 75) to constrain heavy resonances
  - Reinterpretation of EFT and Yukawa coupling in various ATLAS/CMS measurements

LHC Top WG Summary Plots

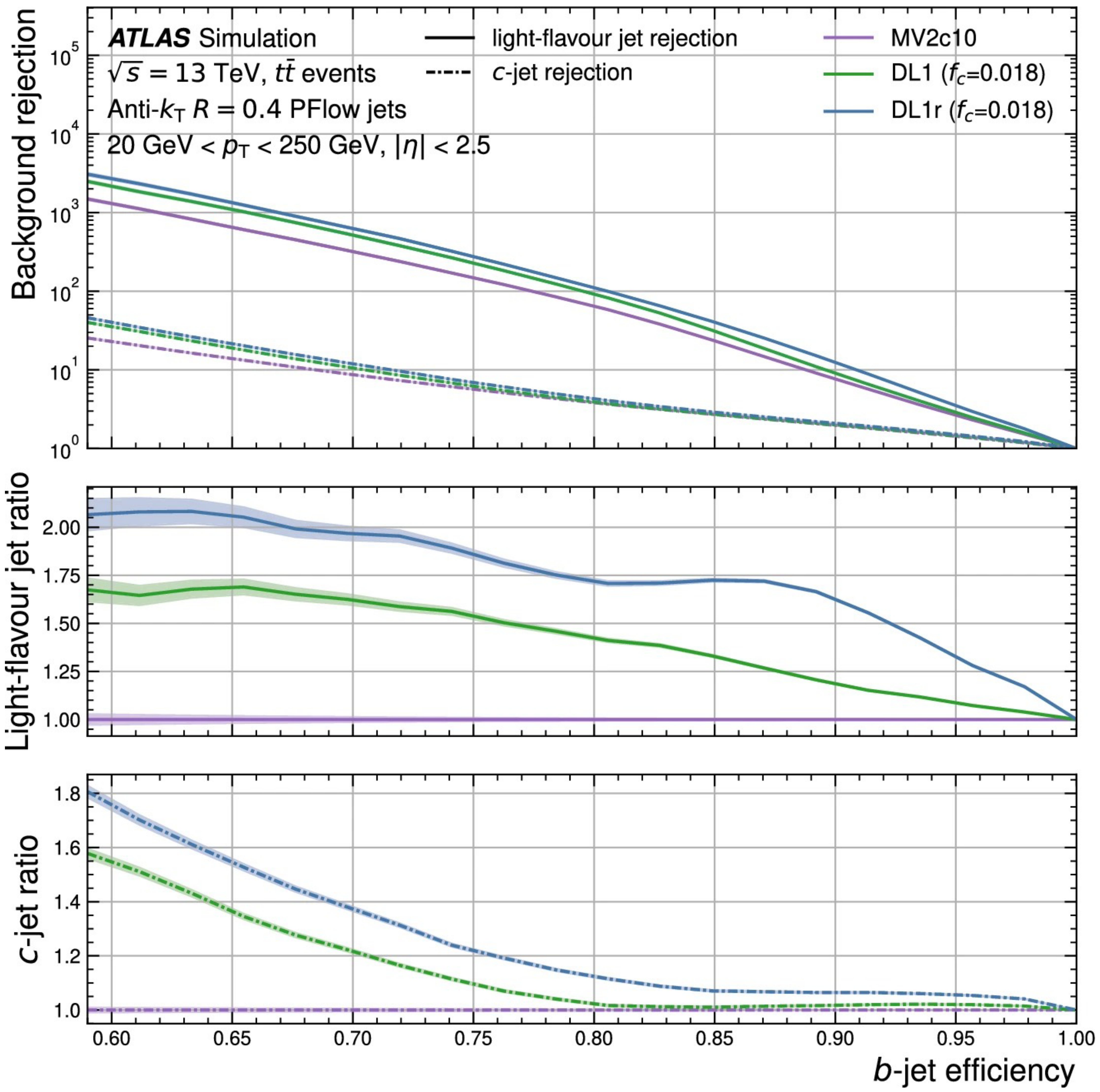


Path to the observation

- Re-analysis of Run 2 data
- Both ATLAS and CMS used 2LSS/ML channel
- Benefited from the improved lepton/b-jet identification and selection

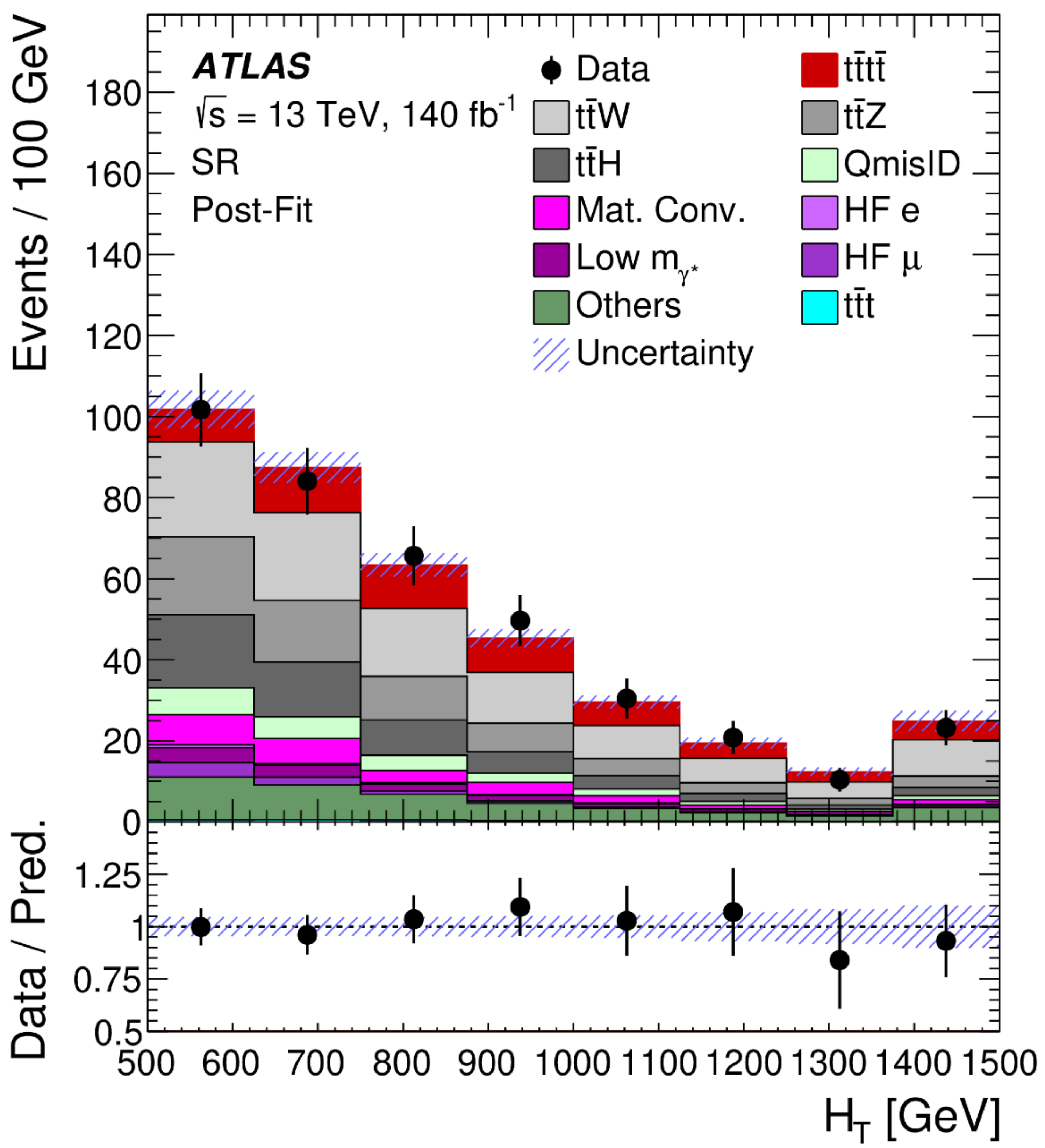


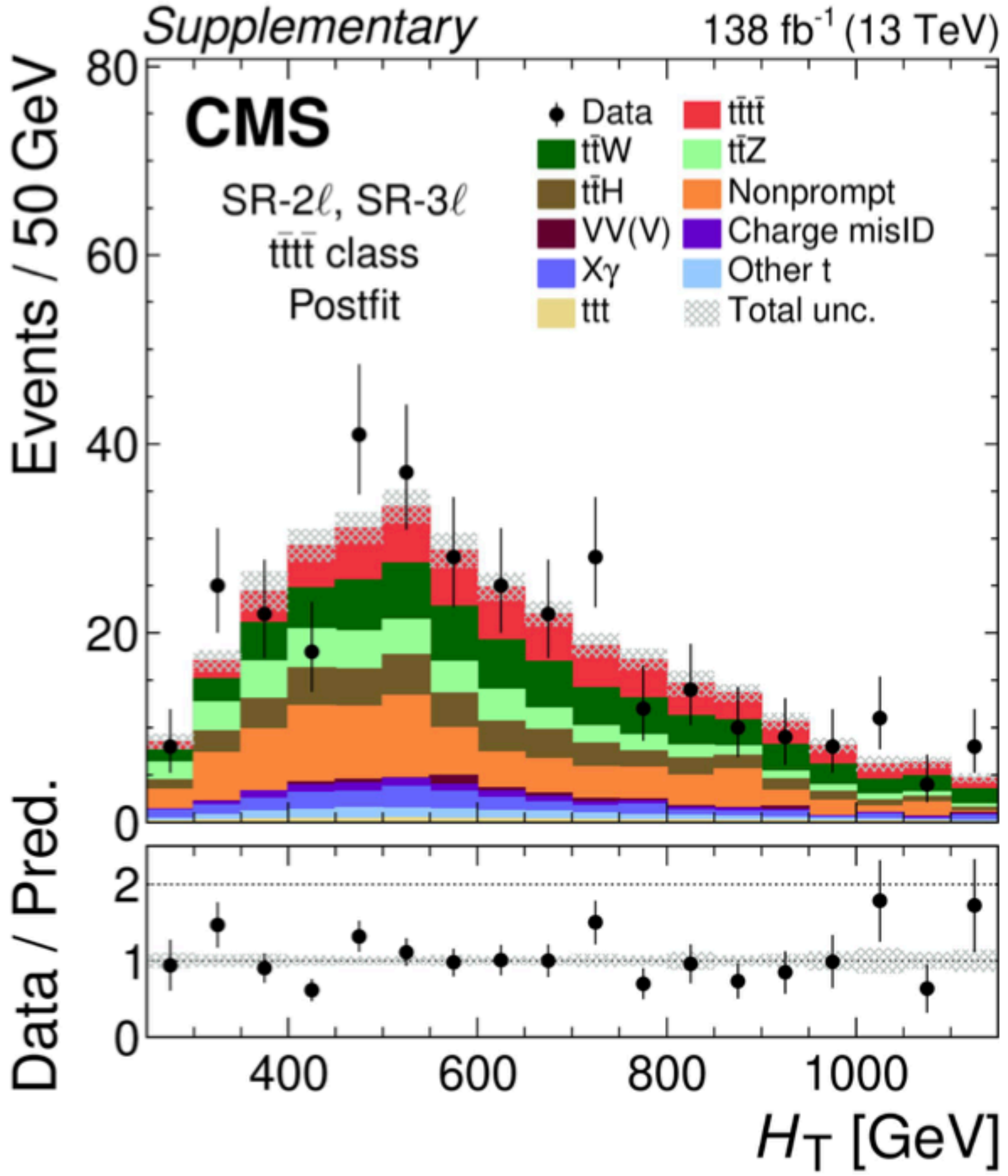
EPJC 83 (2023) 681



Path to the observation

- 2LSS/ML channels have a complicated background composition
- **Reducible** background - mostly from $t\bar{t}$
  - events with non-prompt/fake and charge mis-identified (QmisID) leptons
- **Irreducible** background: $t\bar{t}W/t\bar{t}Z/t\bar{t}H$





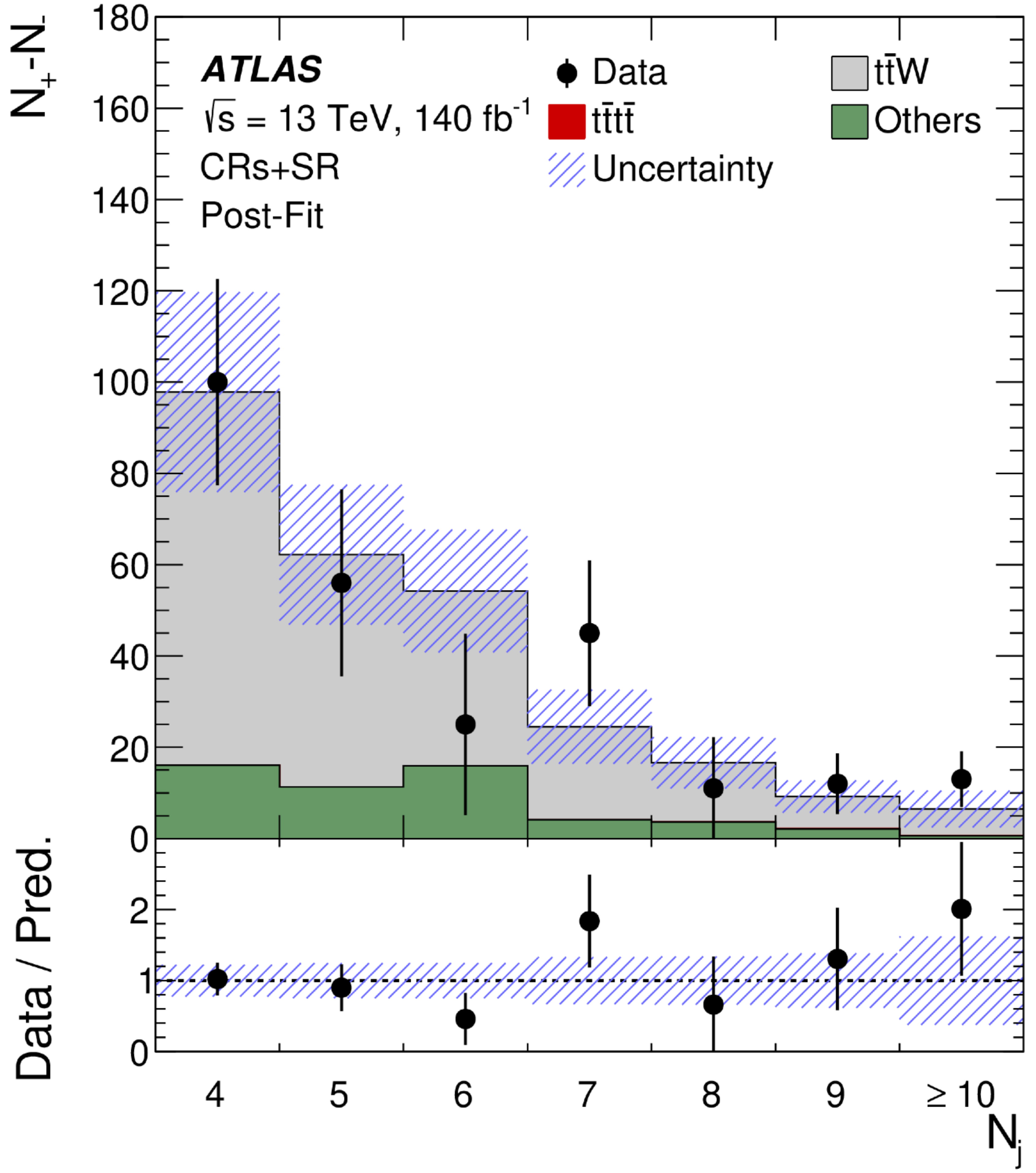
Path to the observation

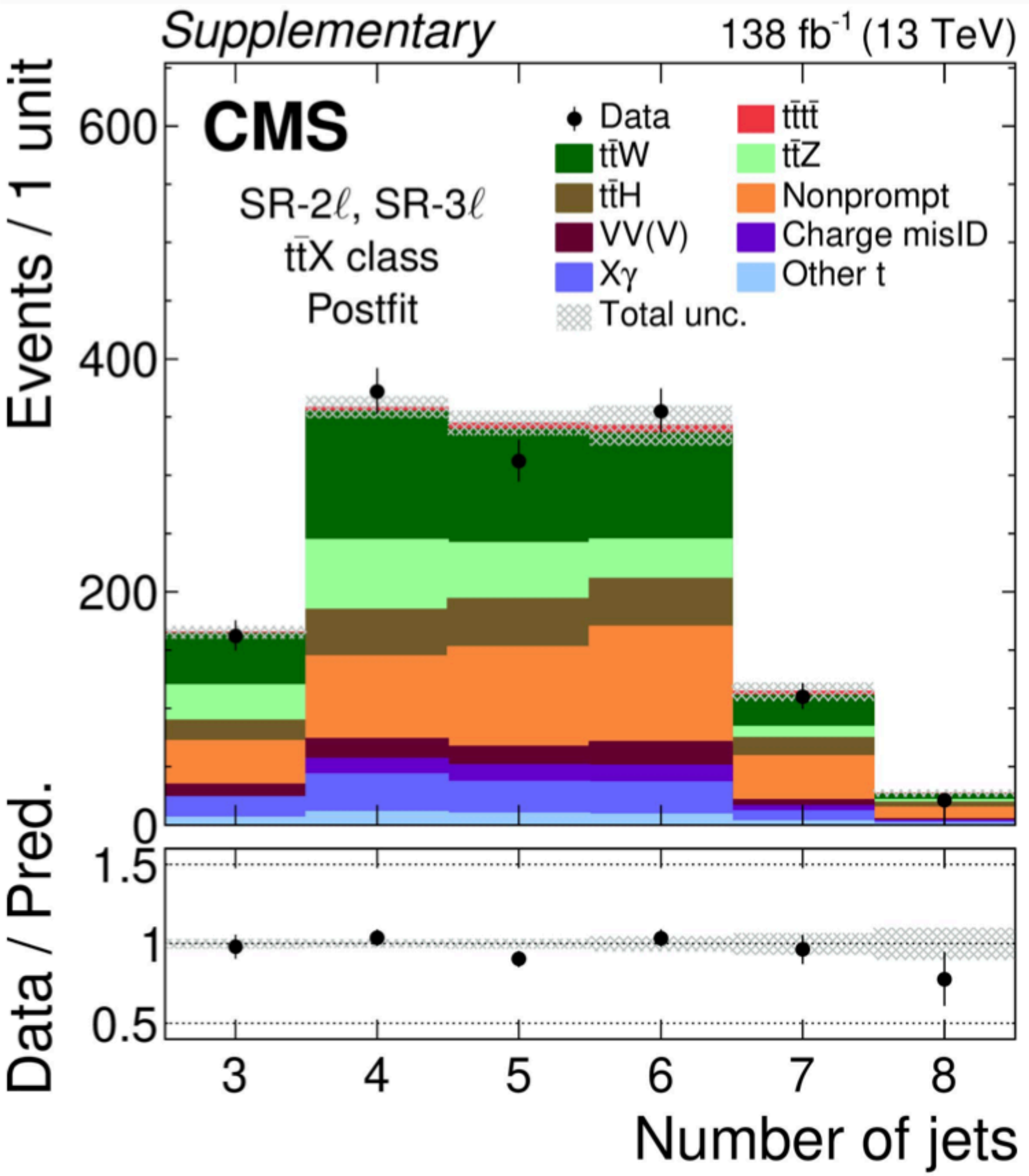
- Non-prompt/fake
    - CMS used classic data-driven method (loose-to-tight ratio)
    - ATLAS had a finer classification:
        - HFe, HFμ, material conversion, internal photon conversion
        - each with a dedicated CR and free-floating normalisation
- $t\bar{t}W$
    - ATLAS: NLO QCD+EW, data-driven N_{jets} distribution (JHEP 10 (2012) 162)

$$R_{(j+1)/j} = \frac{N_{j+1}}{N_j} = a_0 + \frac{a_1}{a_2 + j} \qquad (a_2 = 0)$$

    - CMS: NLO QCD MC, additional uncertainties based on JHEP 11 (2021) 029
        - free-floating normalisation

Path to the observation

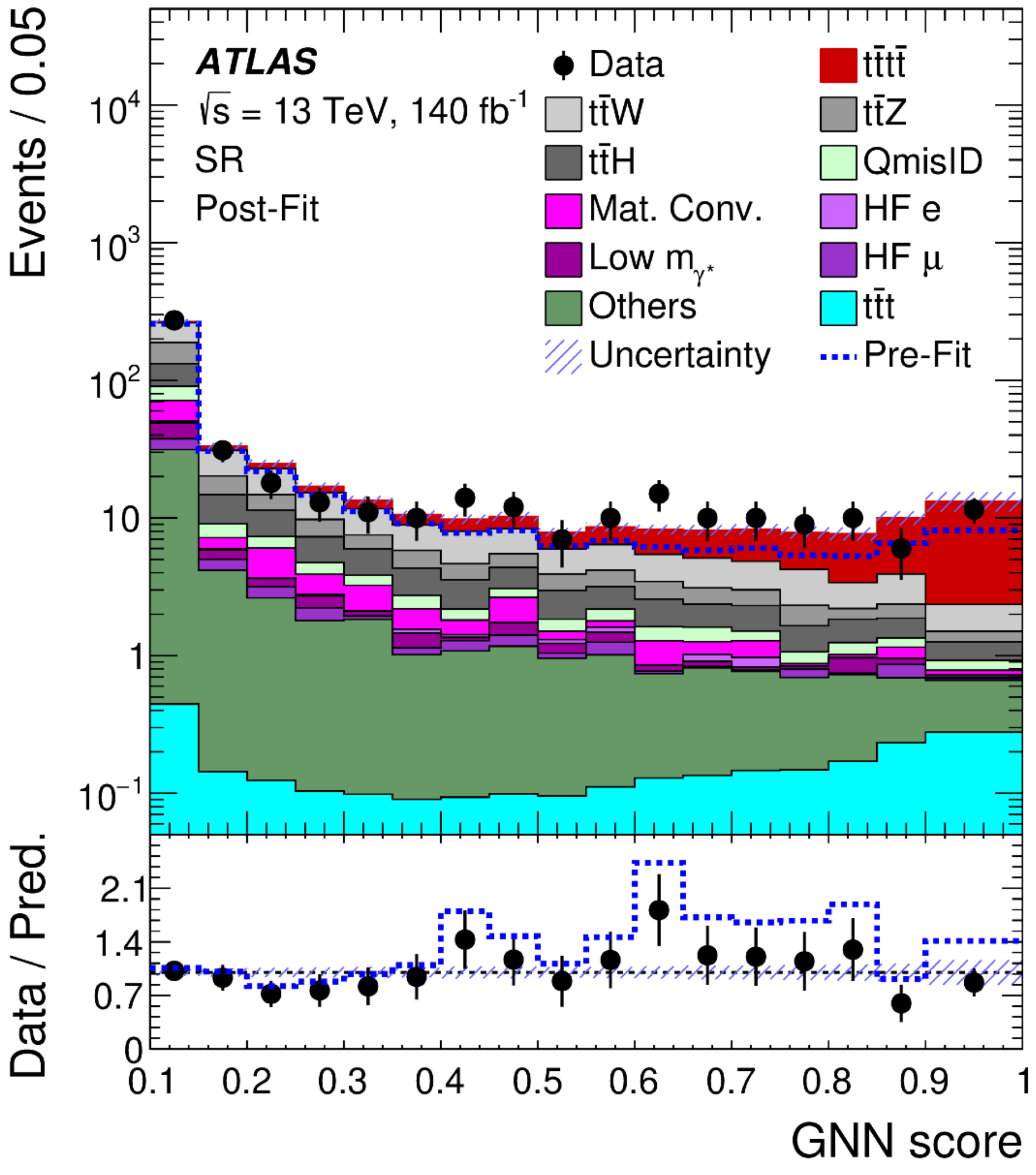




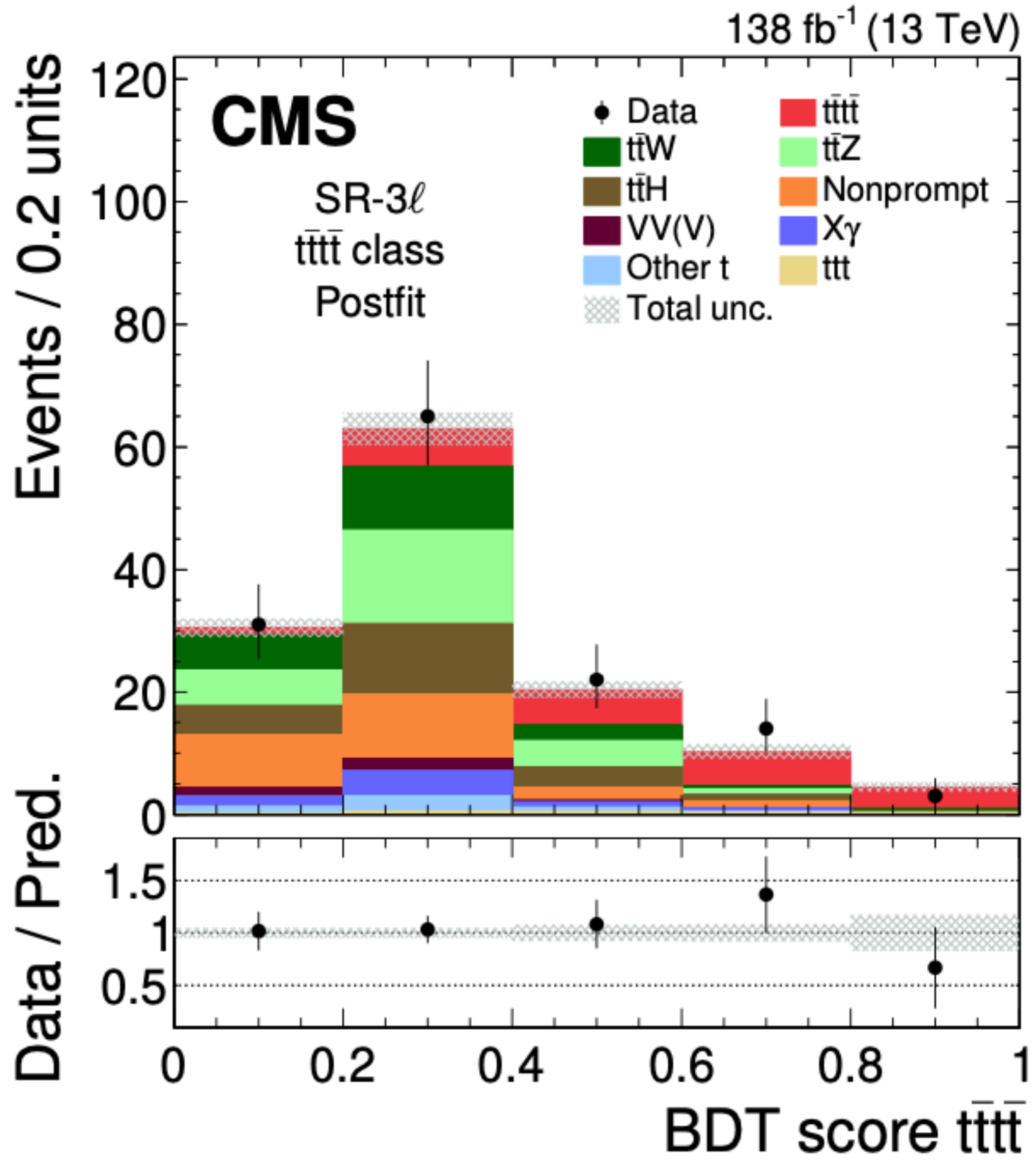
Path to the observation

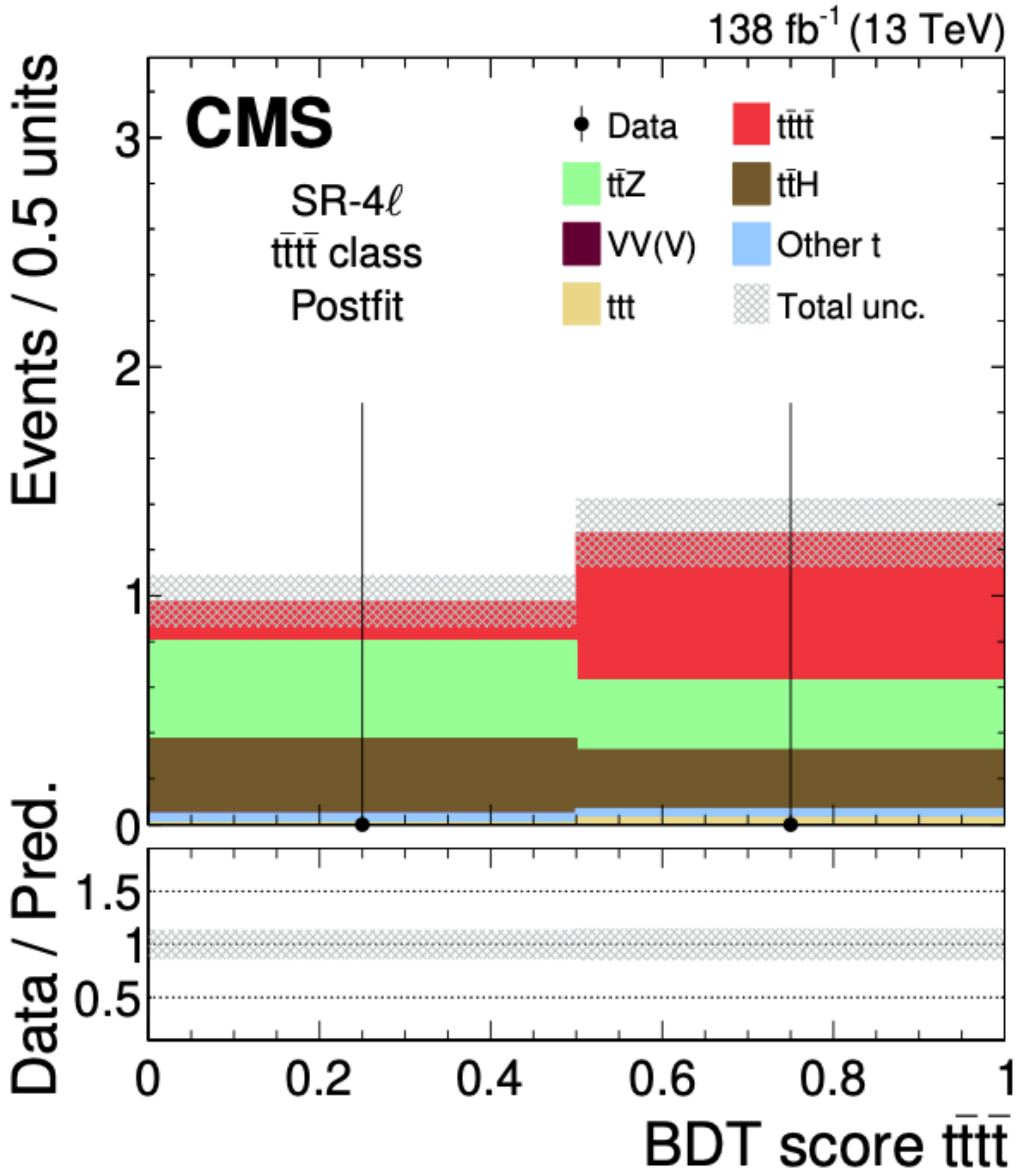
- Key improvement from signal-background discrimination strategy

- **ATLAS** use a single SR: ≥6 jets, ≥2 b-tagged jets, H_T > 500 GeV (scalar sum of lepton/jet p_T)
- Graph Neural Networks (GNN) for S-B separation
  - increased weights in training for ttW with ≥7 jets



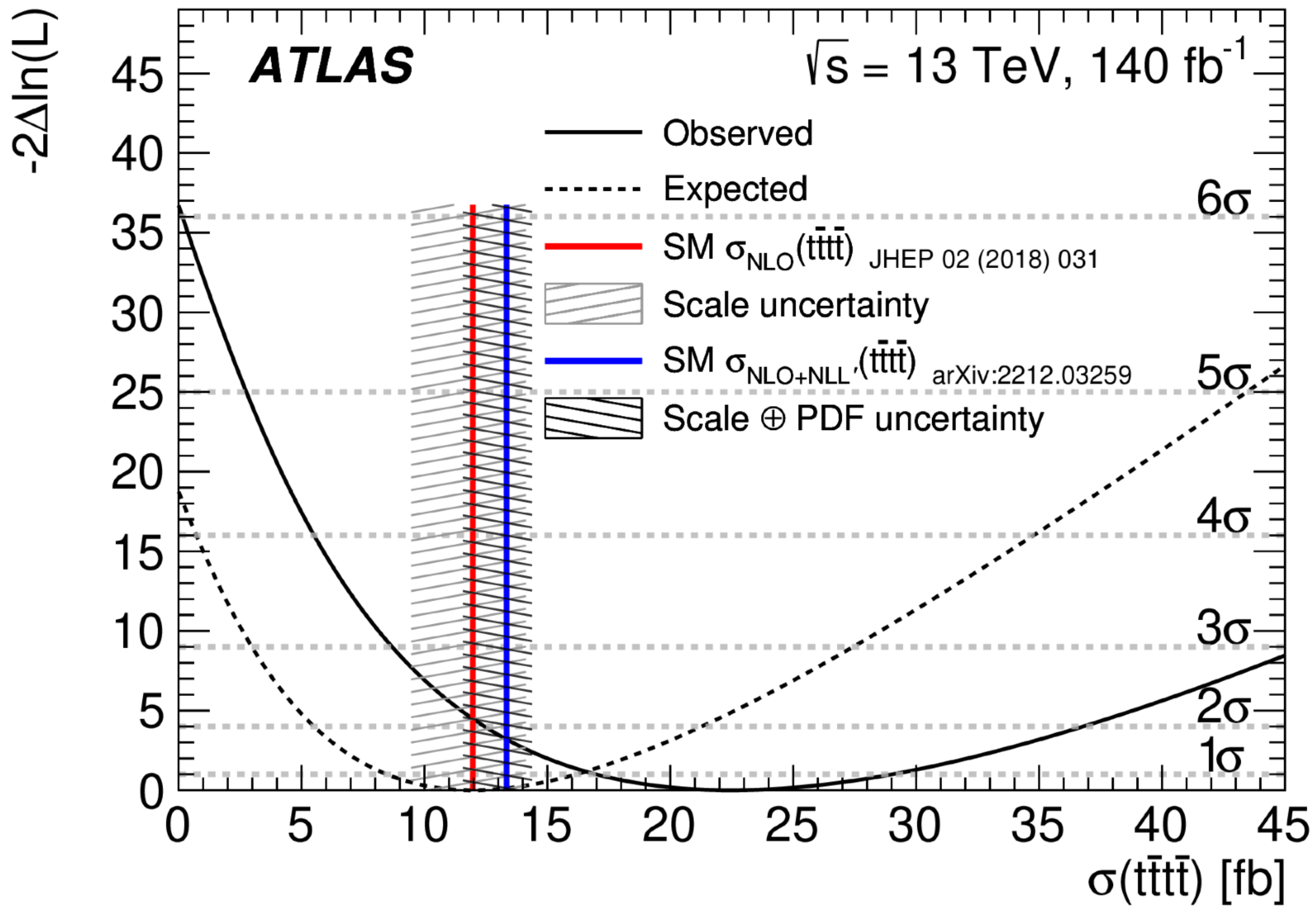
- **CMS** has a more complicated design of the SR
  - 2LSS, 3L and 4L, with different cuts on number of jets/b-jets and H_T
  - Multi-class BDTs to separating $t\bar{t}t\bar{t}$, $t\bar{t}X$ ($t\bar{t}W/Z/H$) and non-prompt+QmisID



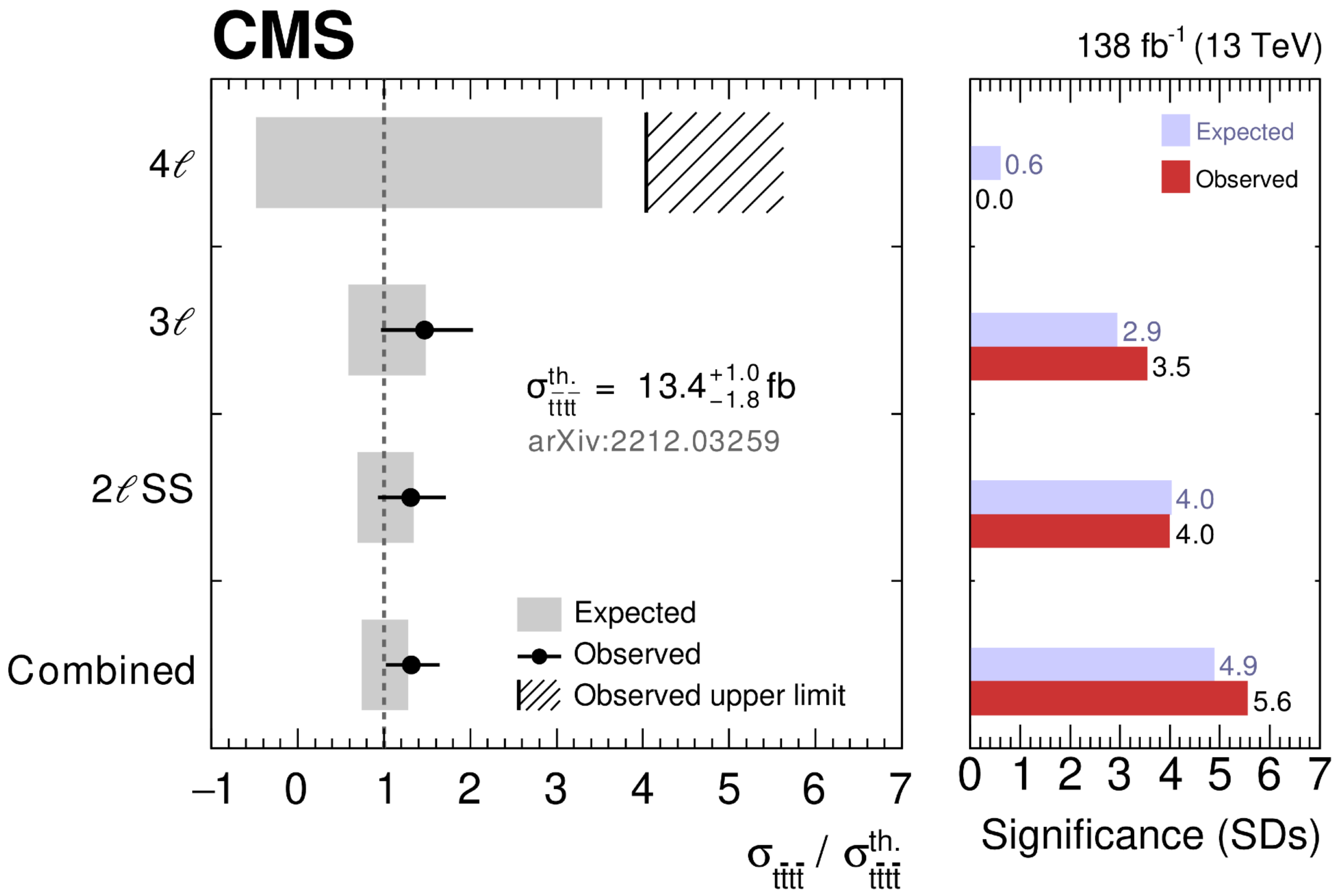


Path to the observation

$$\sigma_{t\bar{t}t\bar{t}} = 22.5^{+4.7}_{-4.3}(\text{stat})\,^{+4.6}_{-3.4}(\text{syst})\,\text{fb} = 22.5\,^{+6.6}_{-5.5}\,\text{fb}.$$



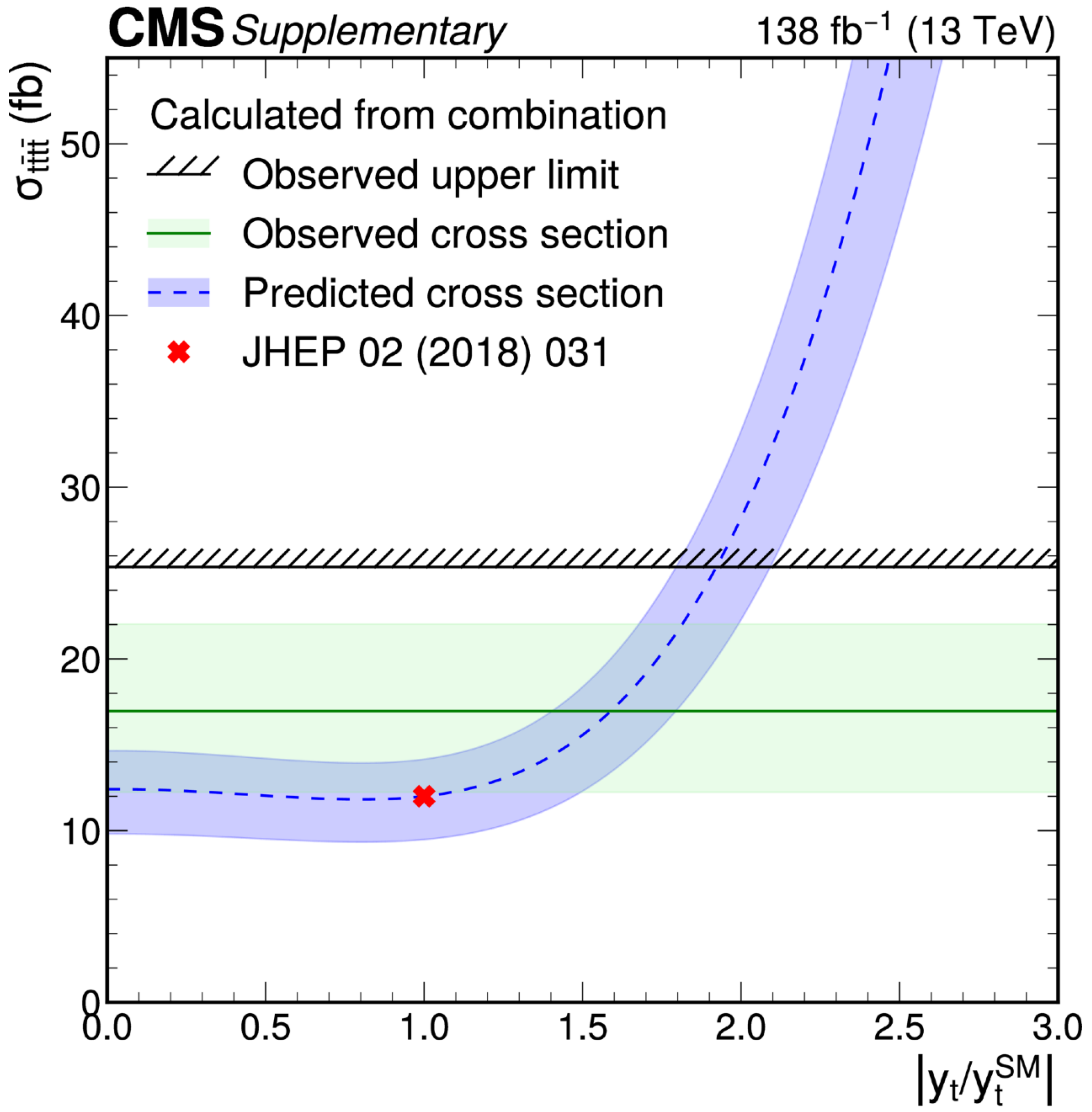
$$\sigma(t\bar{t}t\bar{t}) = 17.7\,^{+3.7}_{-3.5}\,(\text{stat})\,^{+2.3}_{-1.9}\,(\text{syst})\,\text{fb}$$



- ttt **production has an important role (back up slide)**

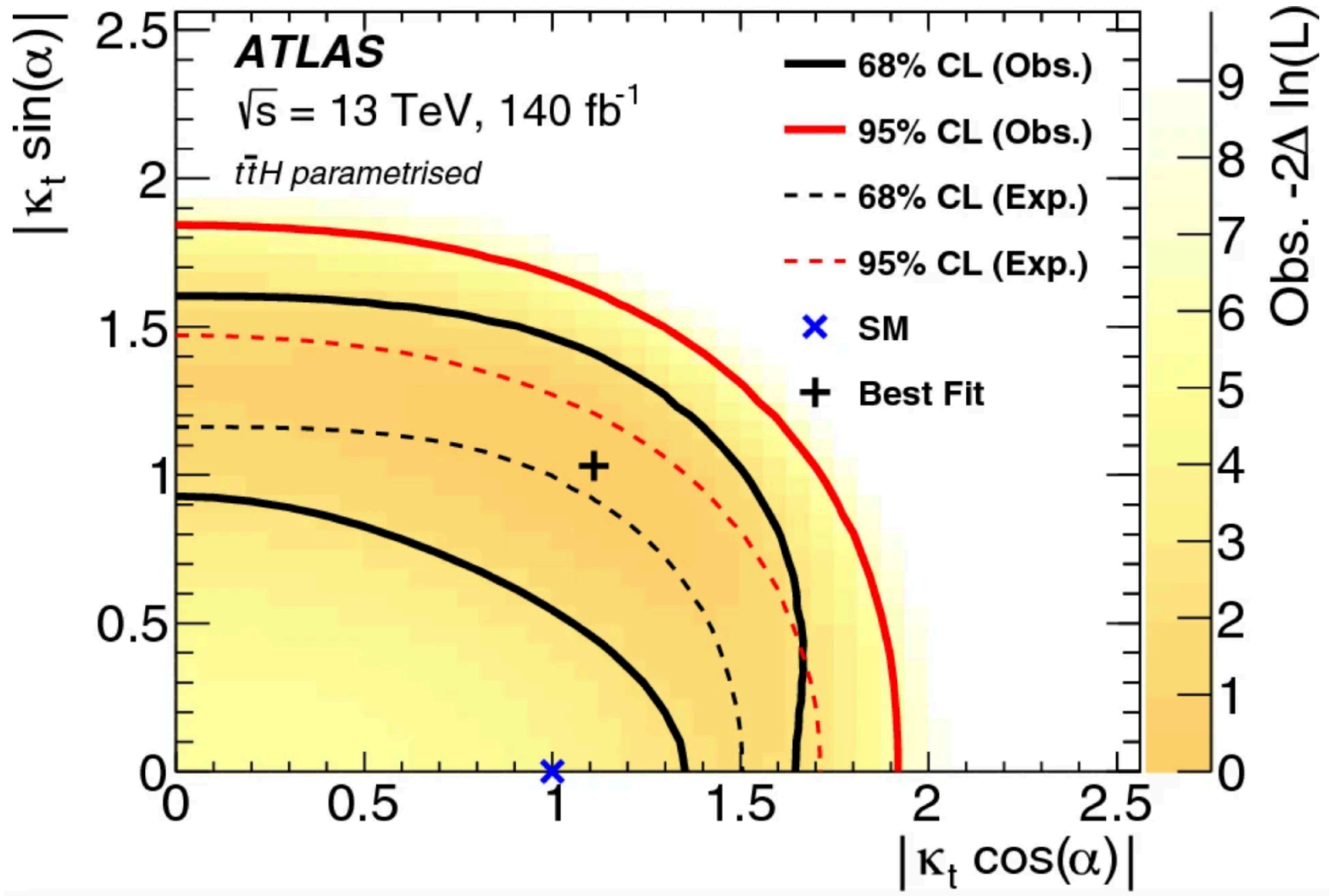
BSM Interpretation — Yukawa coupling

- **Top-Yukawa coupling κ_t and CP mixing**
  - ATLAS: using the observation results, observed (expected) 95% CL limit $|\kappa_t| < 1.9\ (1.6)$
  - CMS: using the all-had/1L/2LOS/2LSS/ML combination (best-fit μ=1.4)



- **CP mixing**
  - $\mathscr{L}_{t\bar{t}H} = -\kappa_t \phi \bar{\psi}_t (\cos\alpha + i\gamma_5 \sin\alpha)\psi_t$

EPJC 83 (2023) 496, Erratum: EPJC 84 (2024) 156



BSM Interpretation — EFT

- **heavy-heavy type four-fermion operators:**
  - 5 operators with different coupling structures
  - 4 degrees of freedoms

$$\mathcal{O}^1_{t\bar{t}} = (\bar{t}_R\gamma^\mu t_R)(\bar{t}_R\gamma_\mu t_R)$$
$$\mathcal{O}^1_{QQ} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{Q}_L\gamma_\mu Q_L)$$
$$\mathcal{O}^1_{Qt} = (\bar{Q}_L\gamma^\mu Q_L)(\bar{t}_R\gamma_\mu t_R)$$
$$\mathcal{O}^8_{Qt} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{t}_R\gamma_\mu T^A t_R)$$
$$\mathcal{O}^8_{QQ} = (\bar{Q}_L\gamma^\mu T^A Q_L)(\bar{Q}_L\gamma_\mu T^A Q_L)$$

t_R: right-handed weak isospin singlet
Q_L: left-handed weak isospin doublet

ATLAS observation results

Operators	Expected C_i/Λ^2 [TeV $^{-2}$]	Observed C_i/Λ^2 [TeV $^{-2}$]
O^1_{QQ}	[-2.5, 3.2]	[-4.0, 4.5]
O^1_{Qt}	[-2.6, 2.1]	[-3.8, 3.4]
O^1_{tt}	[-1.2, 1.4]	[-1.9, 2.1]
O^8_{Qt}	[-4.3, 5.1]	[-6.9, 7.6]

CMS 1L/2LOS channel + 2LSS/ML channel using 35.9 fb-1 Run 2 data (2018)

- best-fit μ = $1.4^{+1.2}_{-1.0}$

Operator	Expected C_k/Λ^2 (TeV^{-2})	Observed (TeV^{-2})
$\mathcal{O}^1_{tt}$	[−2.0, 1.9]	[−2.2, 2.1]
$\mathcal{O}^1_{QQ}$	[−2.0, 1.9]	[−2.2, 2.0]
$\mathcal{O}^1_{Qt}$	[−3.4, 3.3]	[−3.7, 3.5]
$\mathcal{O}^8_{Qt}$	[−7.4, 6.3]	[−8.0, 6.8]

BSM Interpretation — EFT

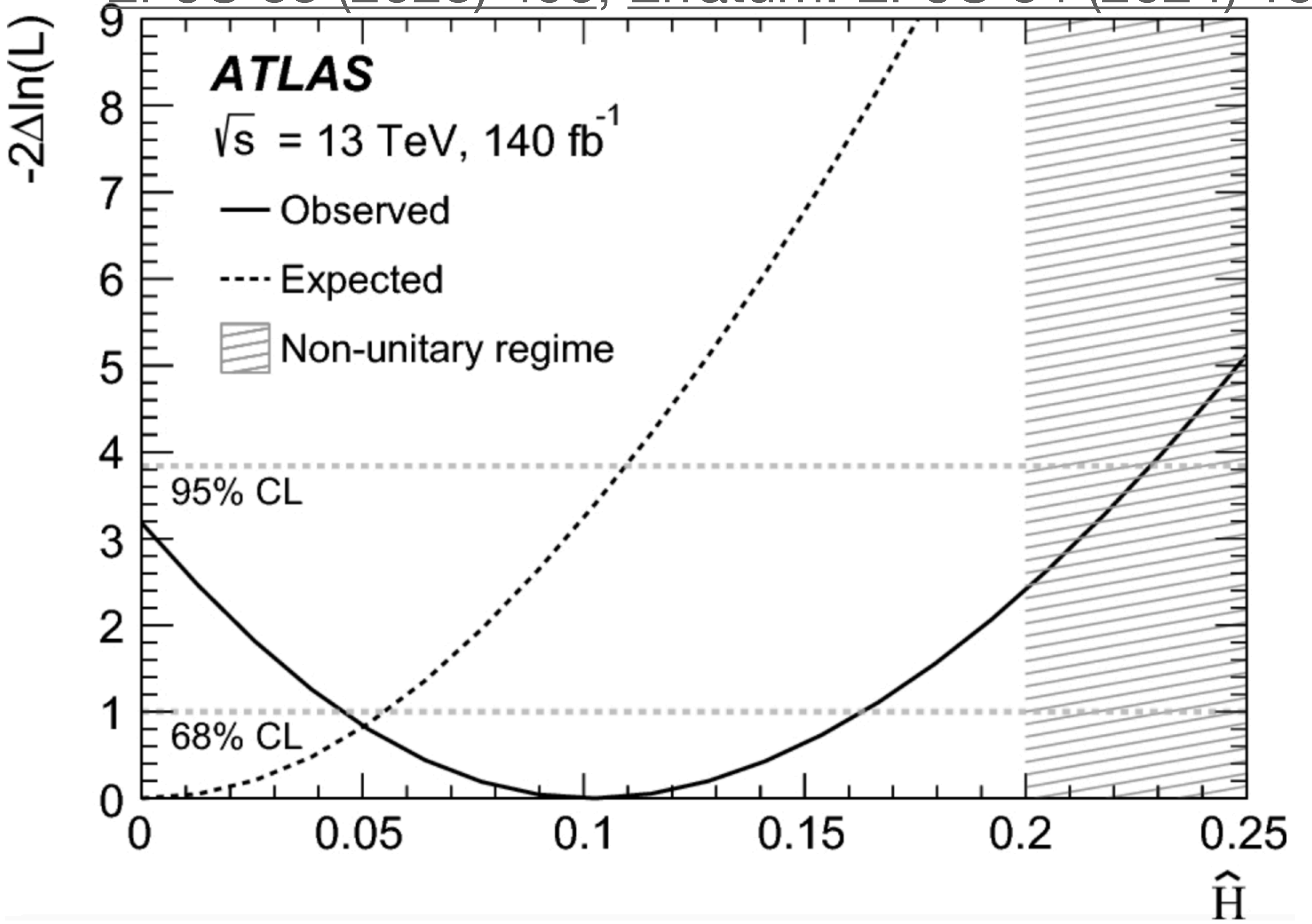
C. Englert, G. F. Giudice, A. Greljo, M. McCullough

- **Higgs oblique parameter** $\hat{H}$ modifies the propagation of the SM Higgs boson

$$\mathscr{L}_{\hat{H}} = \frac{\hat{H}}{m_h^2} |D^\mu D_\mu H|^2$$

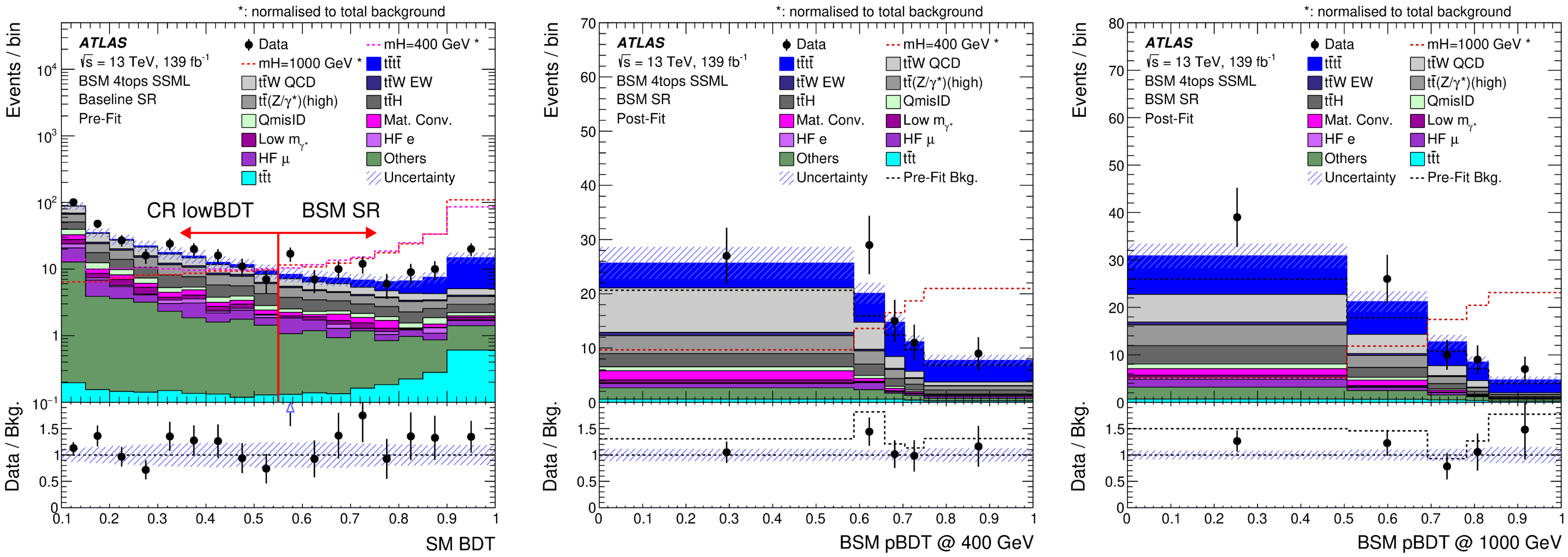
- Better sensitivity via $t\bar{t}t\bar{t}$ production than on-shell Higgs production in other channels
- 95% CL upper limit
  - CMS interpretation of the previous 2LSS/ML results (best-fit μ = 1.0)
    - $\hat{H}$ < 0.12
  - ATLAS interpretation of the observation result
    - $\hat{H}$ < 0.23 (0.11) observed (expected)

EPJC 83 (2023) 496, Erratum: EPJC 84 (2024) 156



Search for 2HDM $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$ JHEP 07 (2023) 203

- ATLAS 2LSS/ML channel: similar strategy as the observation analysis
- Additional BDT to separate BSM vs SM $t\bar{t}t\bar{t}$

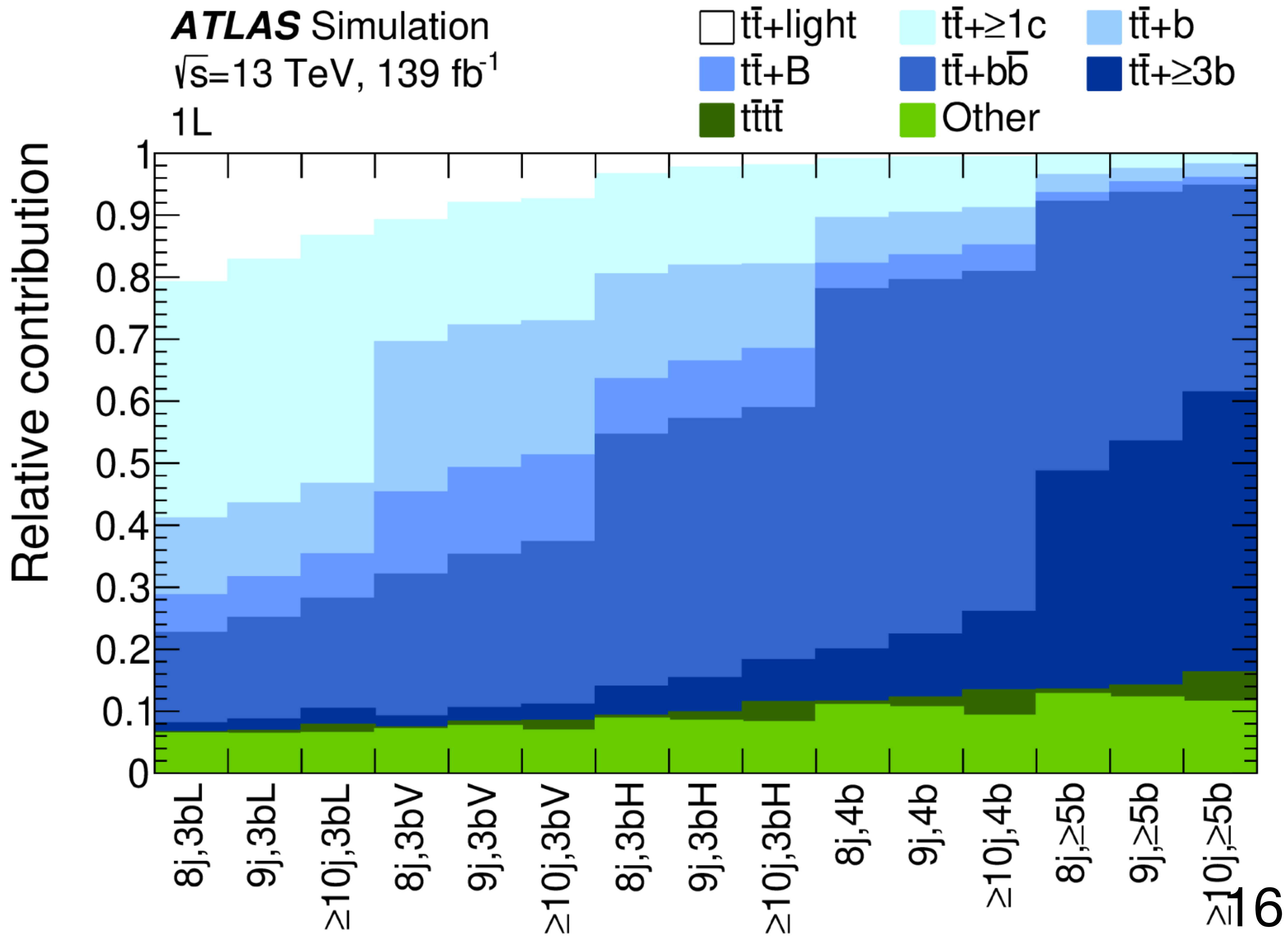


Search for 2HDM $t\bar{t}A/H \to t\bar{t}t\bar{t}$

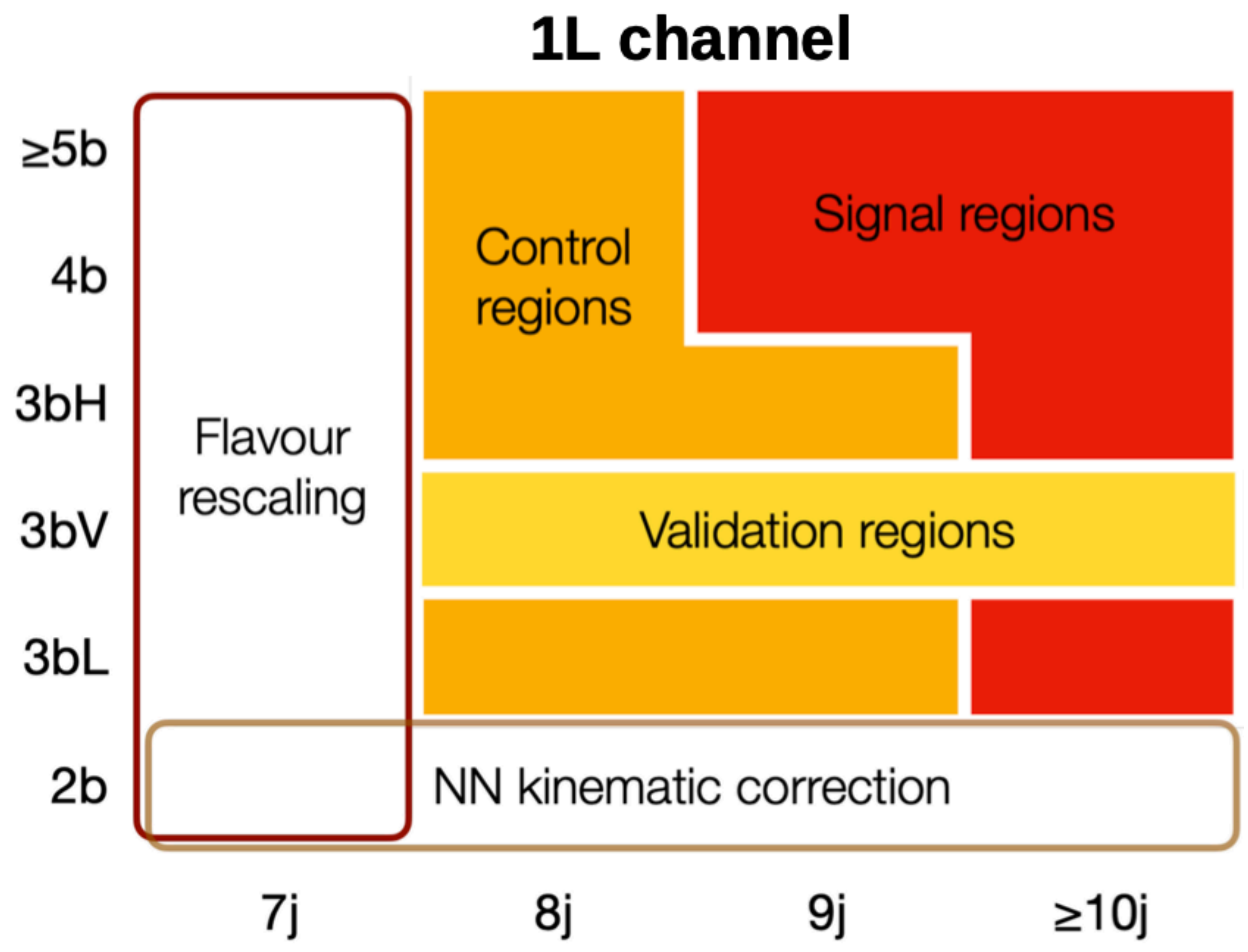
- **ATLAS 1L/2LOS channel (arXiv:2408.17164, submitted to EPJC)**
- Events categorised using number of jets and various b-tagging requirements
- The b-tagging requirements enhance separation between different $t\bar{t}$ subcategories: $t\bar{t}$+≥1b, $t\bar{t}$+≥1c and $t\bar{t}$+light
  - using particle-level jets matched to b/c hadrons
  - $t\bar{t}$+≥1b: $t\bar{t}$+b/B/bb/≥3b
    - according to number of jets matched to b-hadrons
    - b vs. B: a single vs. a pair of b-hadrons matched to a particle-level jet

3bL = Light-flavour enriched
3bH = Heavy-flavour enriched
3bV = Validation region

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	= 2	-
3bL	≤ 2	= 3	-
3bH	= 3	= 3	> 3
3bV	= 3	= 3	= 3
≥4b (2LOS)	-	≥ 4	-
4b (1L)	-	= 4	-
≥5b (1L)	-	≥ 5	-



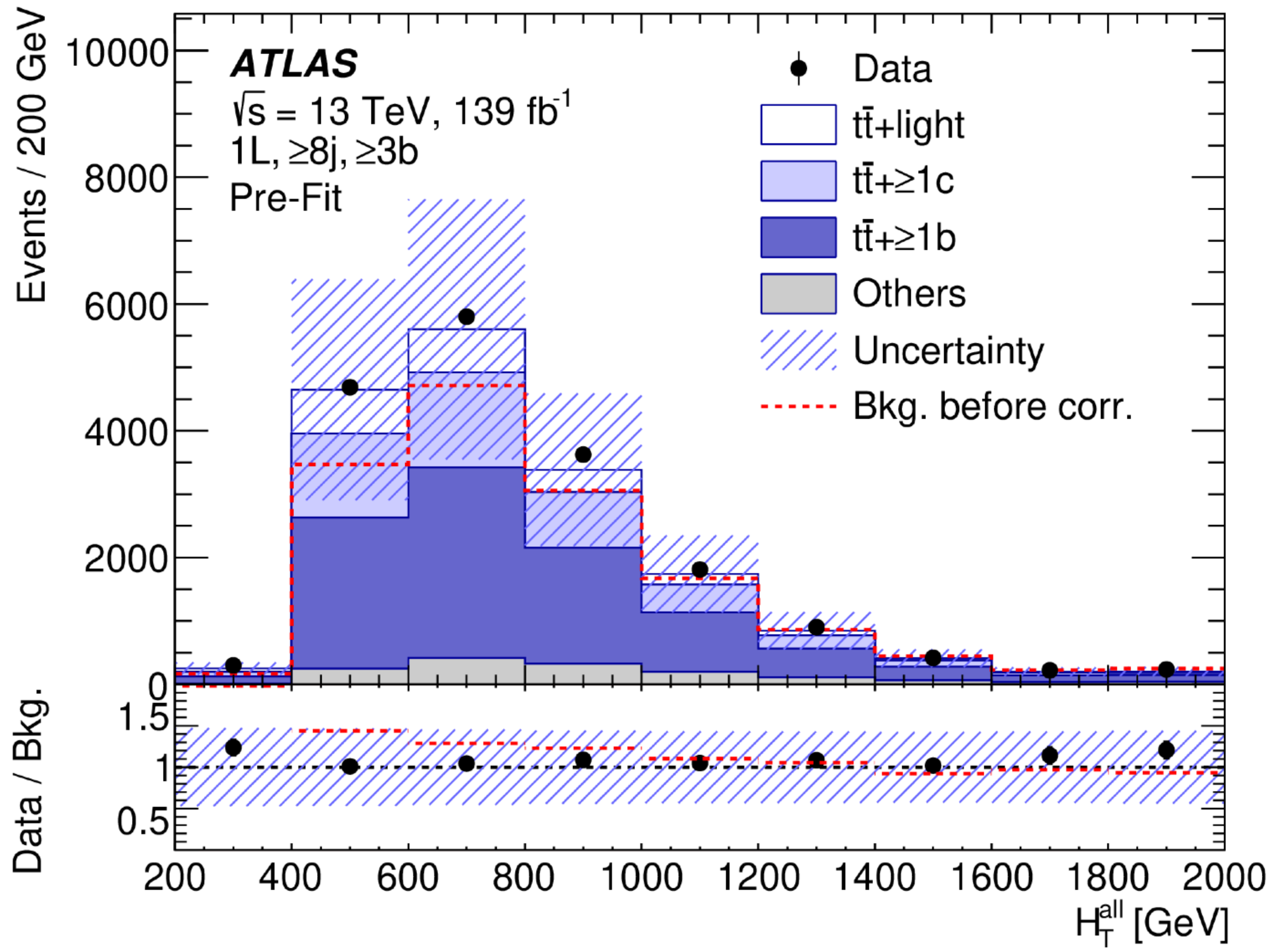
Search for 2HDM $t\bar{t}A/H \to t\bar{t}t\bar{t}$

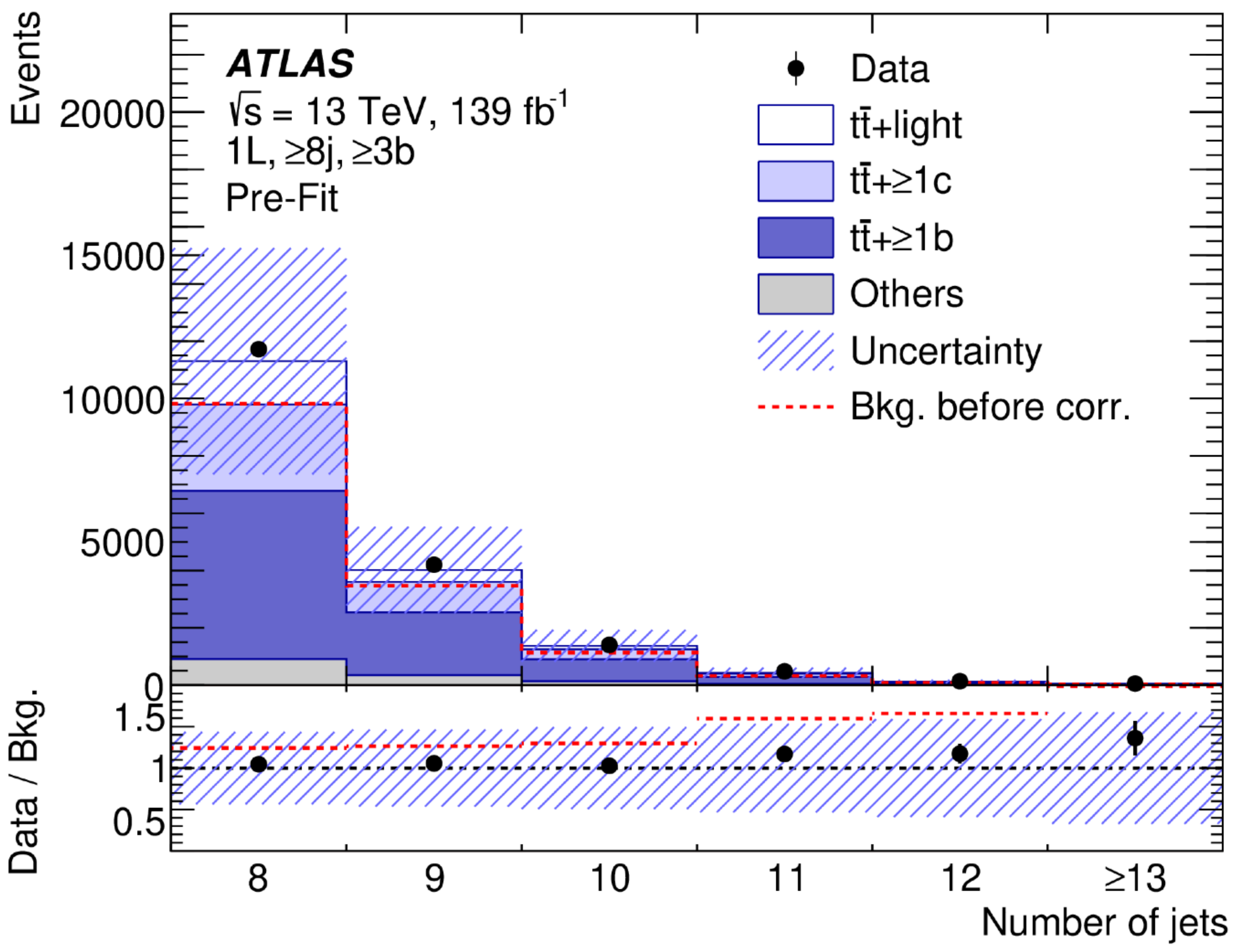


- Data-driven corrections on $t\bar{t}$+jets background
  - Flavour rescaling: correct normalisation of $t\bar{t}$+≥1b, $t\bar{t}$+≥1c and $t\bar{t}$+light
  - Multi-dimensional kinematic reweighting based a neural network (NN) trained as a binary classifier of data vs. $t\bar{t}$ simulation

$$O(\mathbf{x}) = P(\text{data}|\mathbf{x}) = \frac{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x})}{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x}) + \alpha_{\text{sim}} P_{\text{sim}}(\mathbf{x})}$$

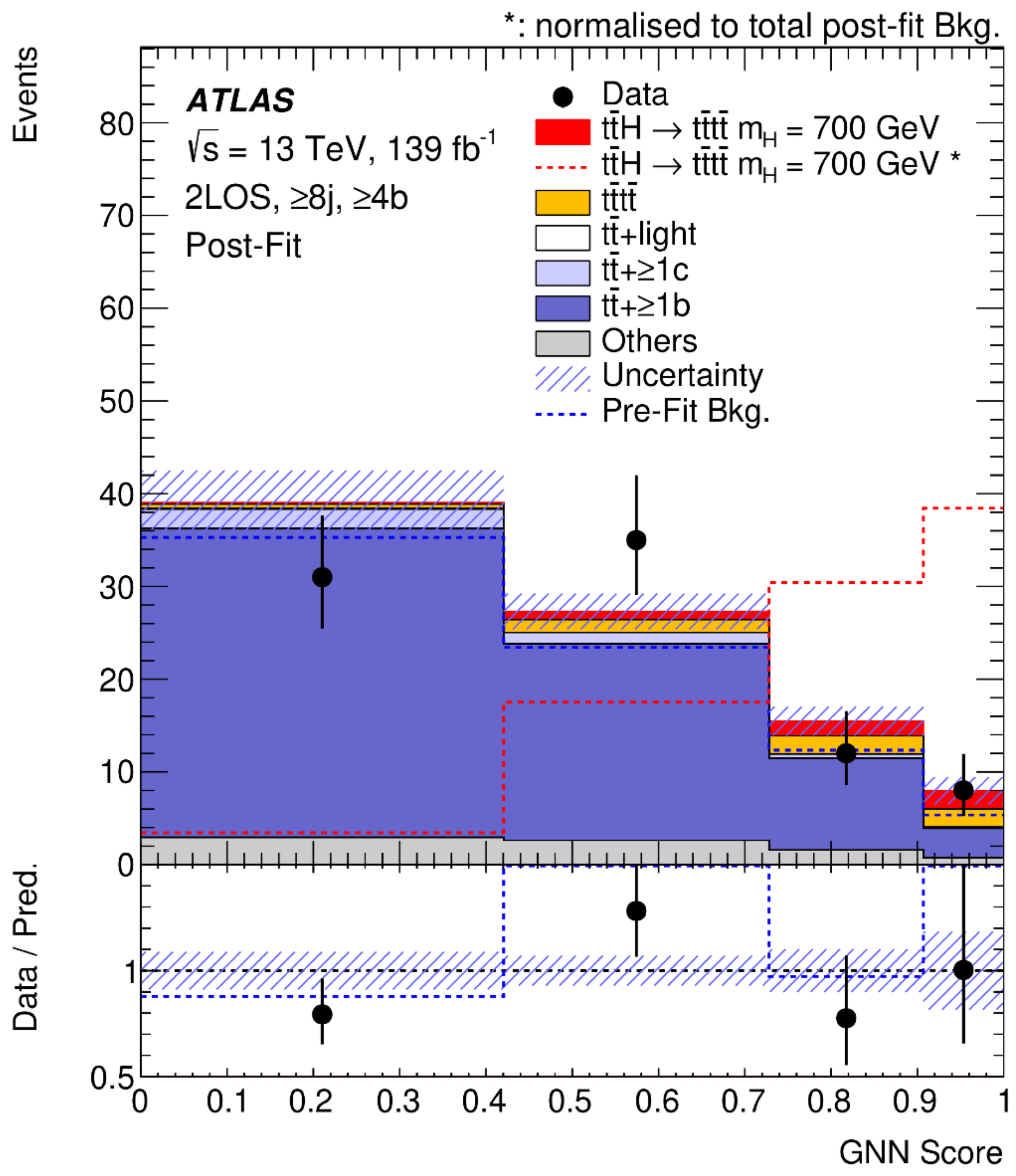
$$w(\mathbf{x}) = e^{O(\mathbf{x})}$$

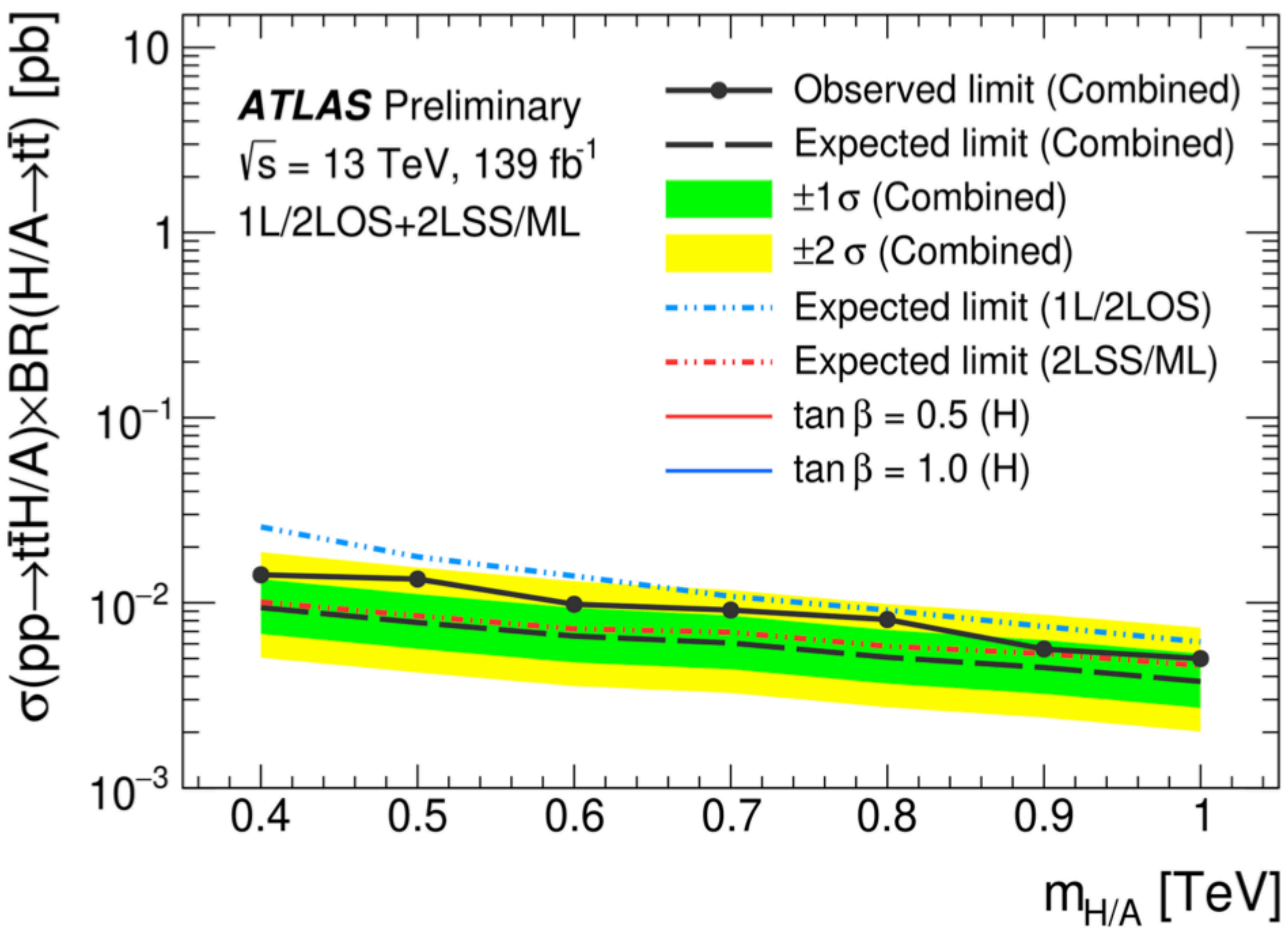




Search for 2HDM $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$

- GNN to optimise the signal-background discrimination
  - **A list of higher-level variables (sum of jet b-tag scores, H_T, …) included as global features**
    - helps with the validation of the background modelling
    - the training converge faster and less prone to training statistics
- **In final fit SM $t\bar{t}t\bar{t}$ cross-section is fixed to the prediction**
- Combined with the 2LSS/ML results
  - 2LSS/ML drives the sensitivity
  - 1L/2LOS introduces a larger improvement at high masses

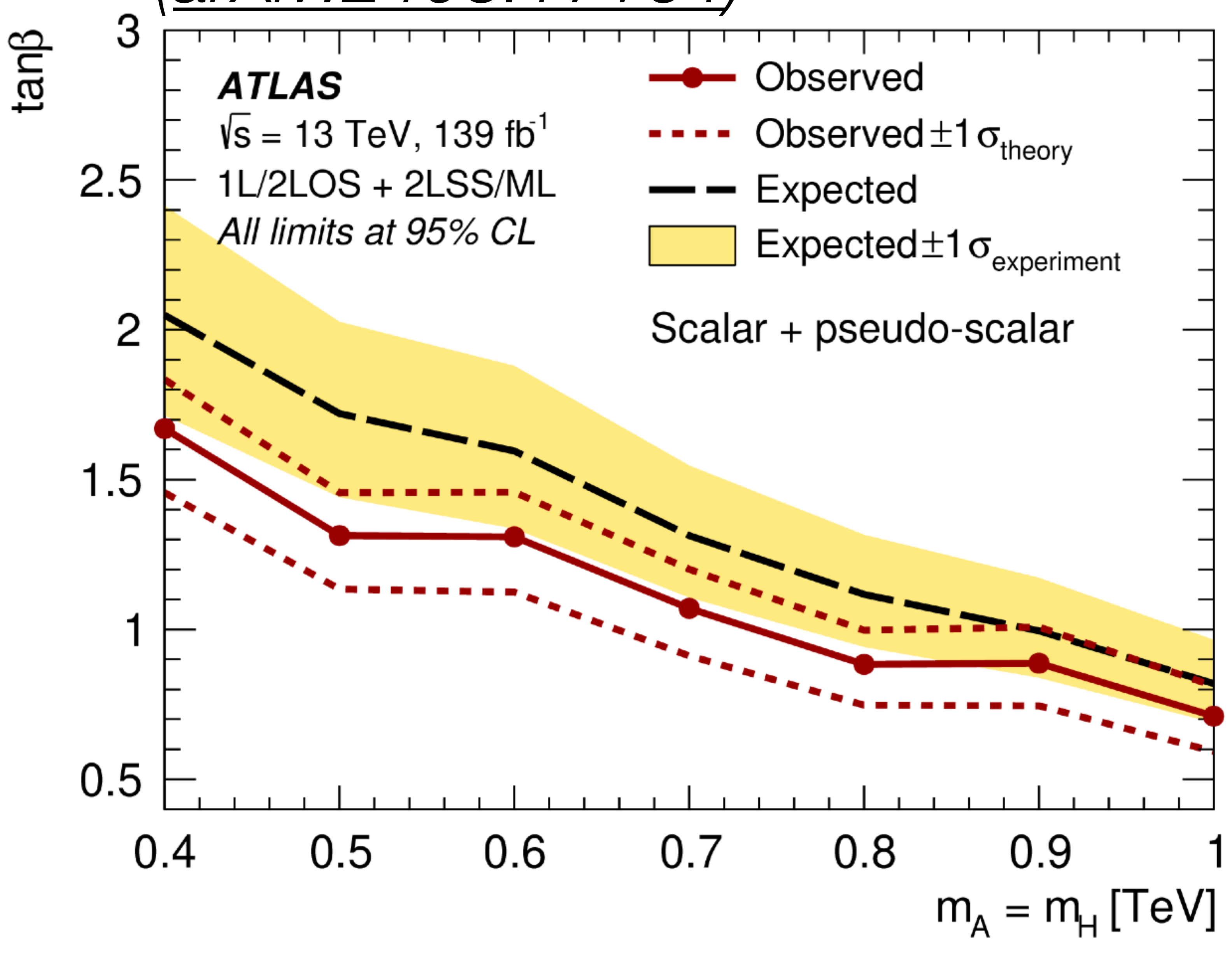




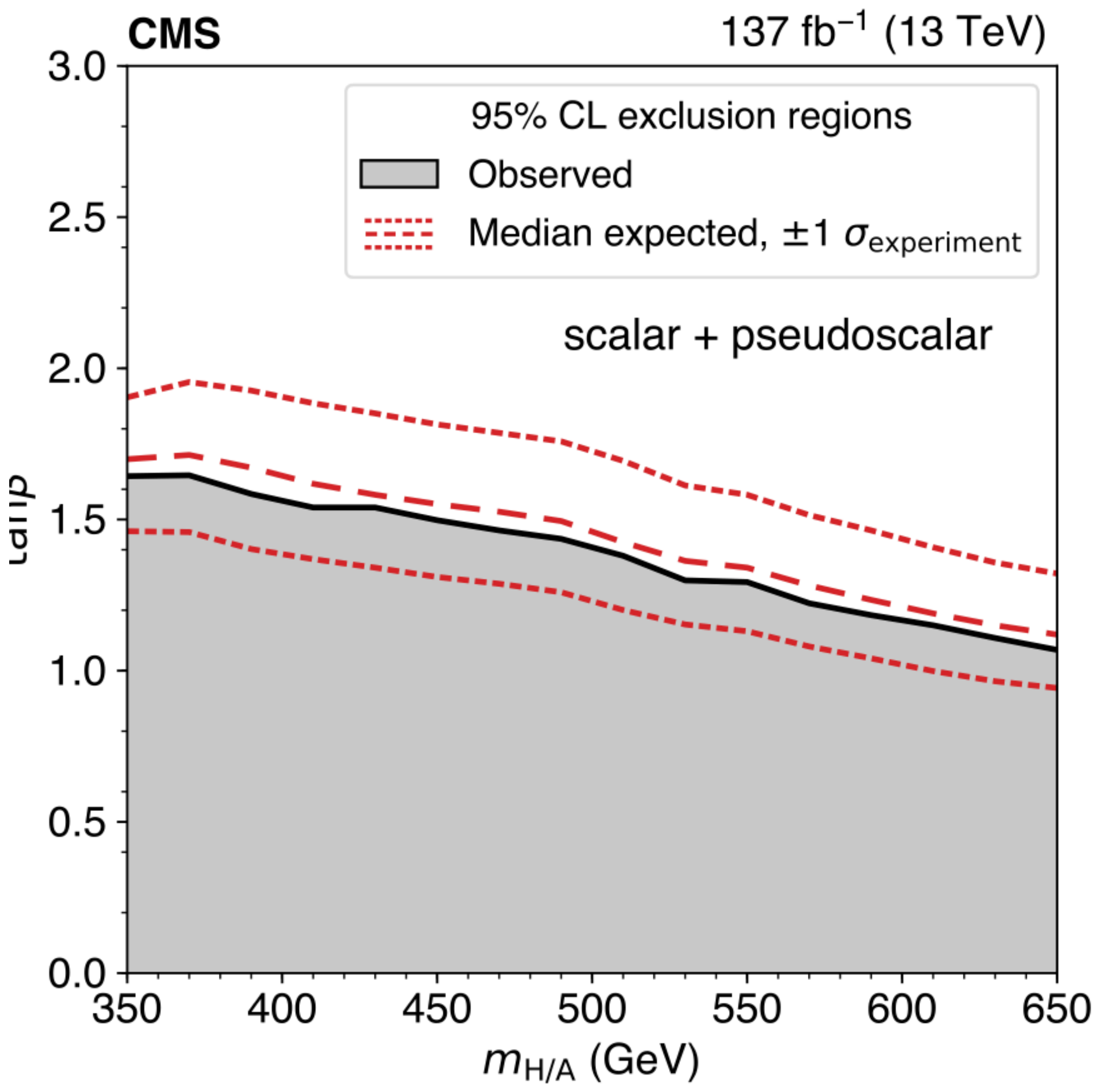
Search for 2HDM $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$

- More on 2HDM and scalar search by Eleanor

ATLAS - this analysis (arXiv:2408.17164)

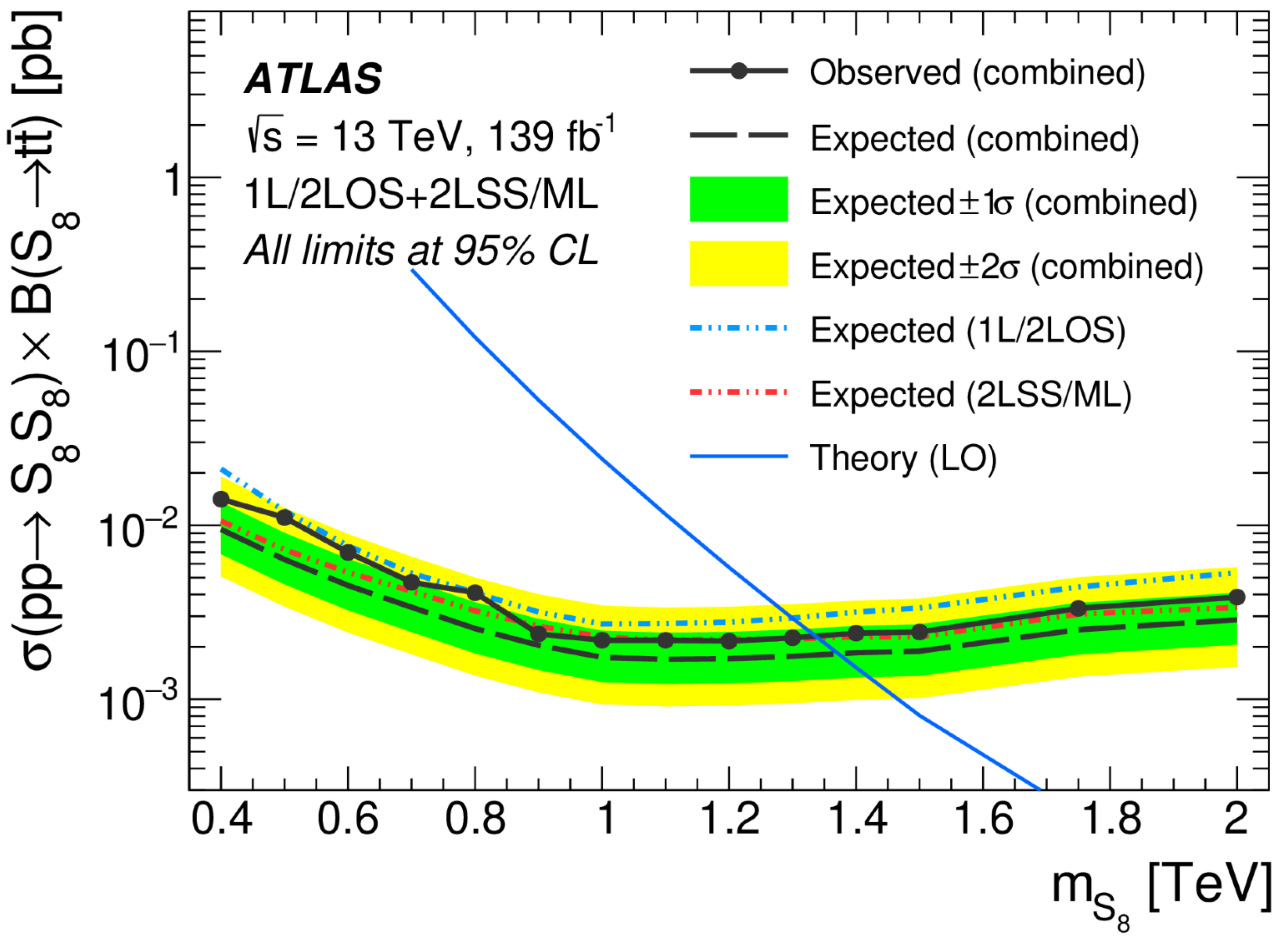


CMS previous 2LSS/ML result



ATLAS - this analysis (arXiv:2408.17164)

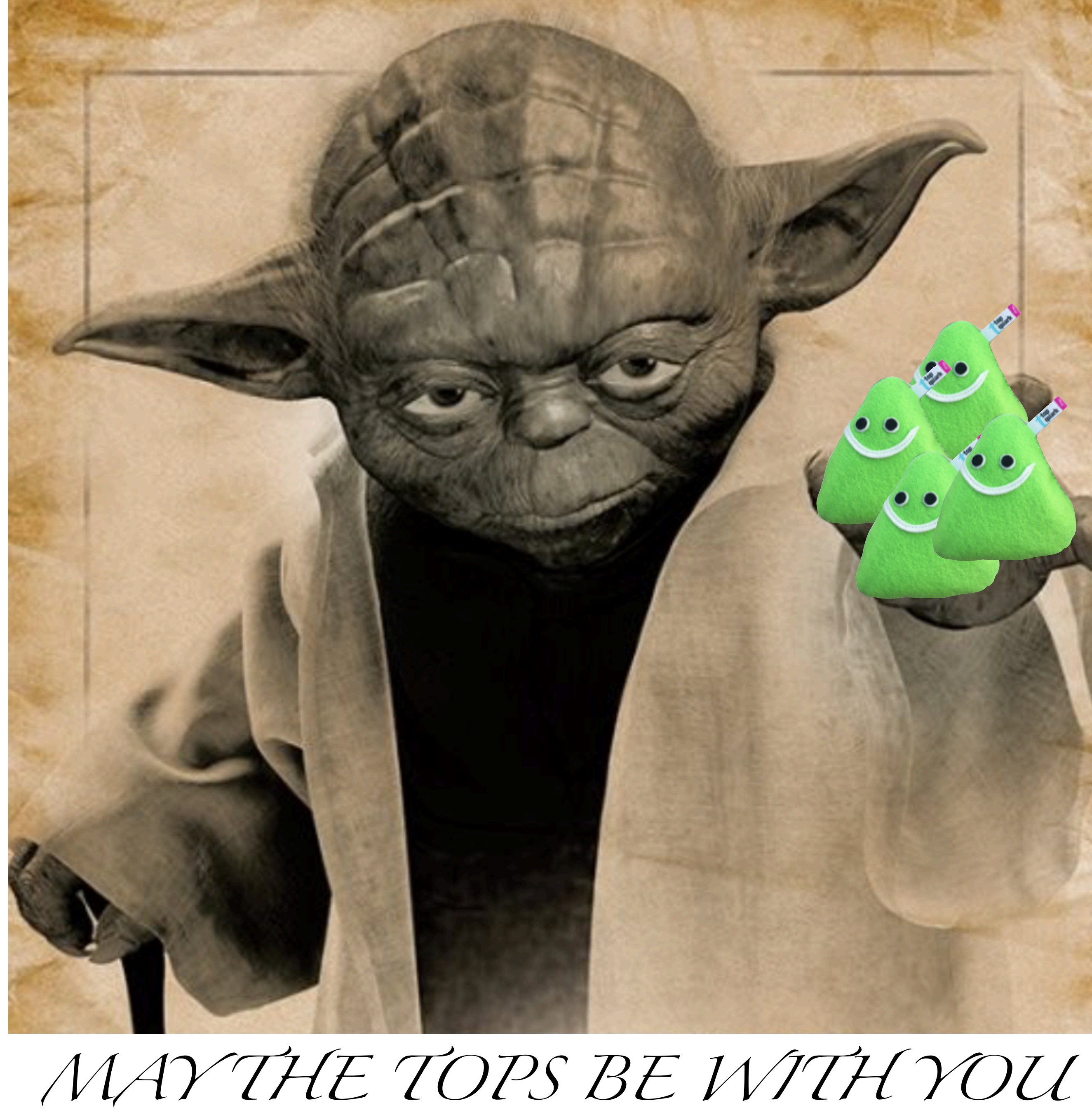
Sgluon pair production $S_8S_8 \rightarrow t\bar{t}t\bar{t}$

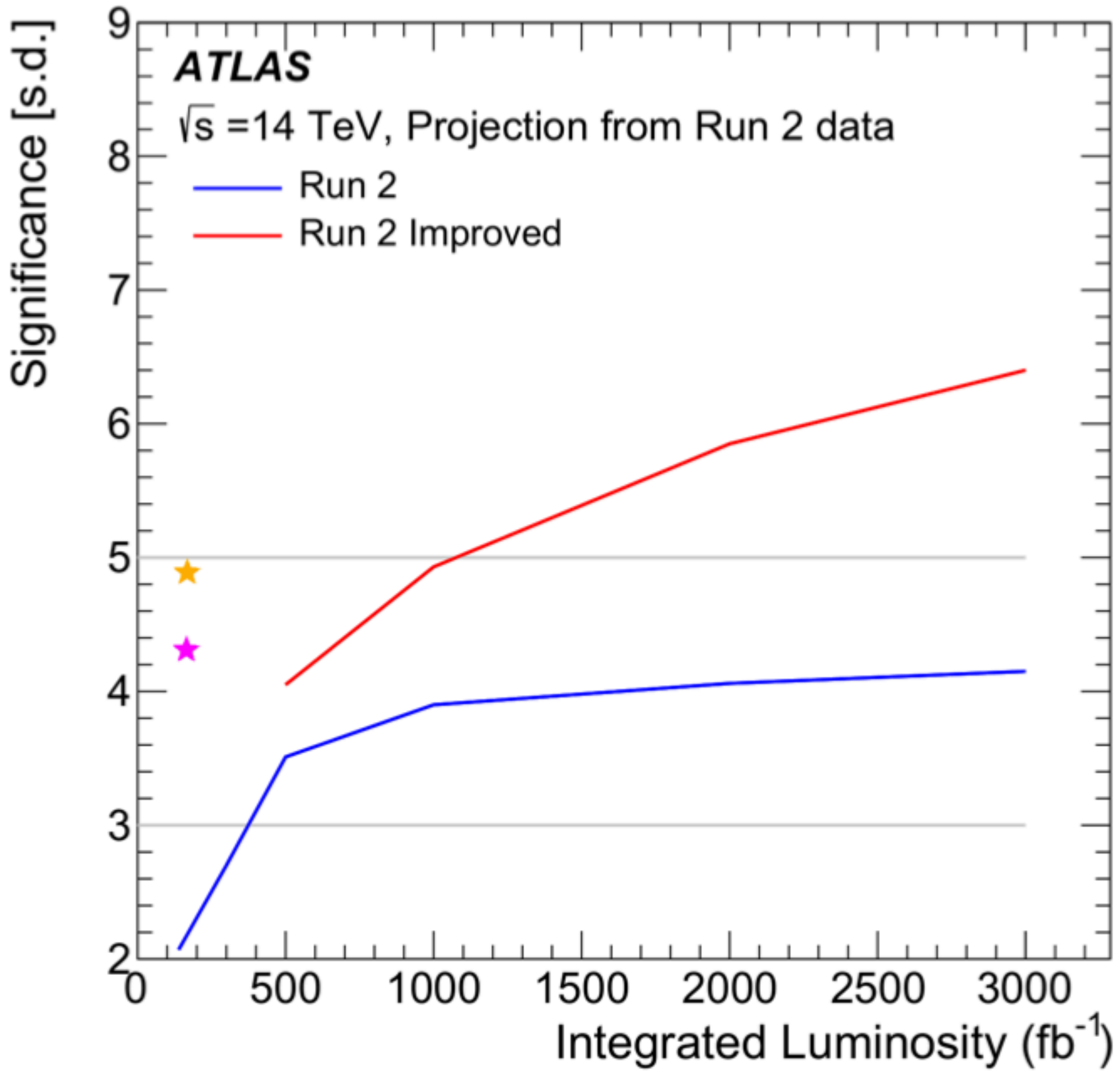


Summary

- $t\bar{t}t\bar{t}$ production observed by ATLAS and CMS experiments
  - both experiments outperformed the earlier projection
  - measured cross section slightly higher than the prediction
  - results can still benefit from more data
- Direct BSM searches and reinterpretation of the measurements
  - nothing significant so far - not the end of the story!

- Run 3 with √s=13.6 TeV — 20% larger $t\bar{t}t\bar{t}$ cross section
  - $15.82^{+1.5\%}_{-11.6\%}$ fb at 13.6 TeV (M. Beekveld, A. Kulesza, L. Valero)
  - independent data to check against what we saw in Run 2
  - much improved BSM search sensitivity when combining Run 2 + Run 3

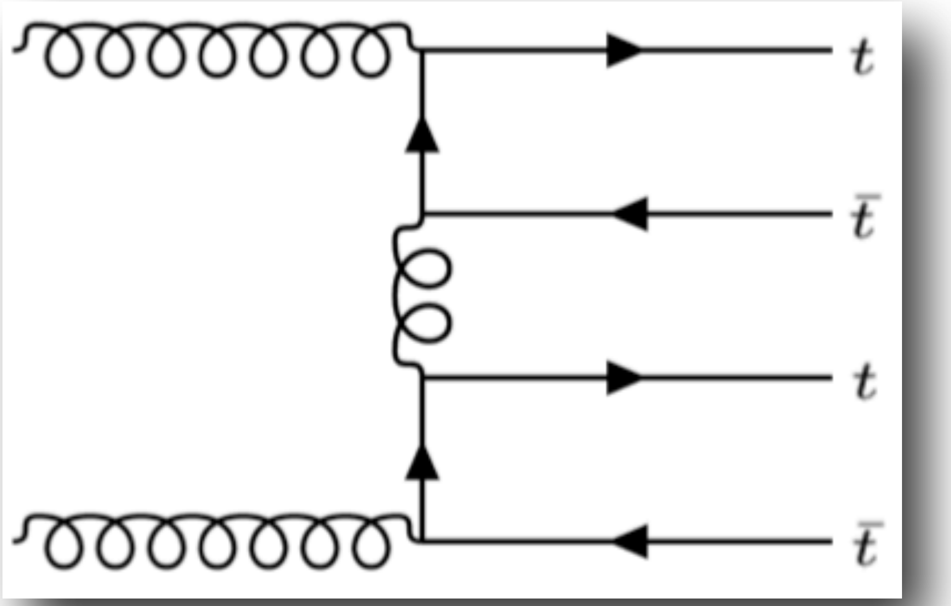




BACKUP

$t\bar{t}t\bar{t}$ production

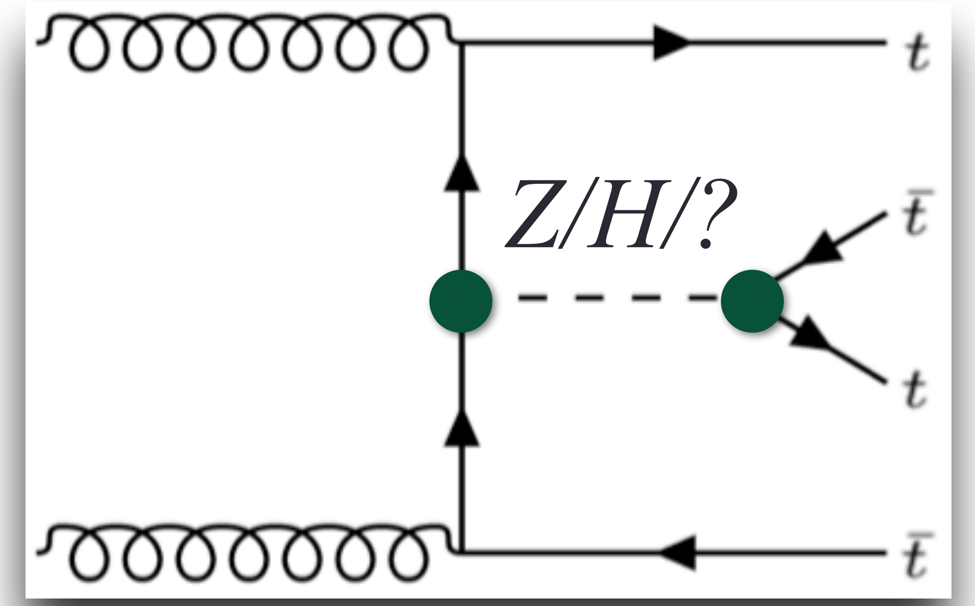
R. Frederix, D. Pagani, M. Zaro



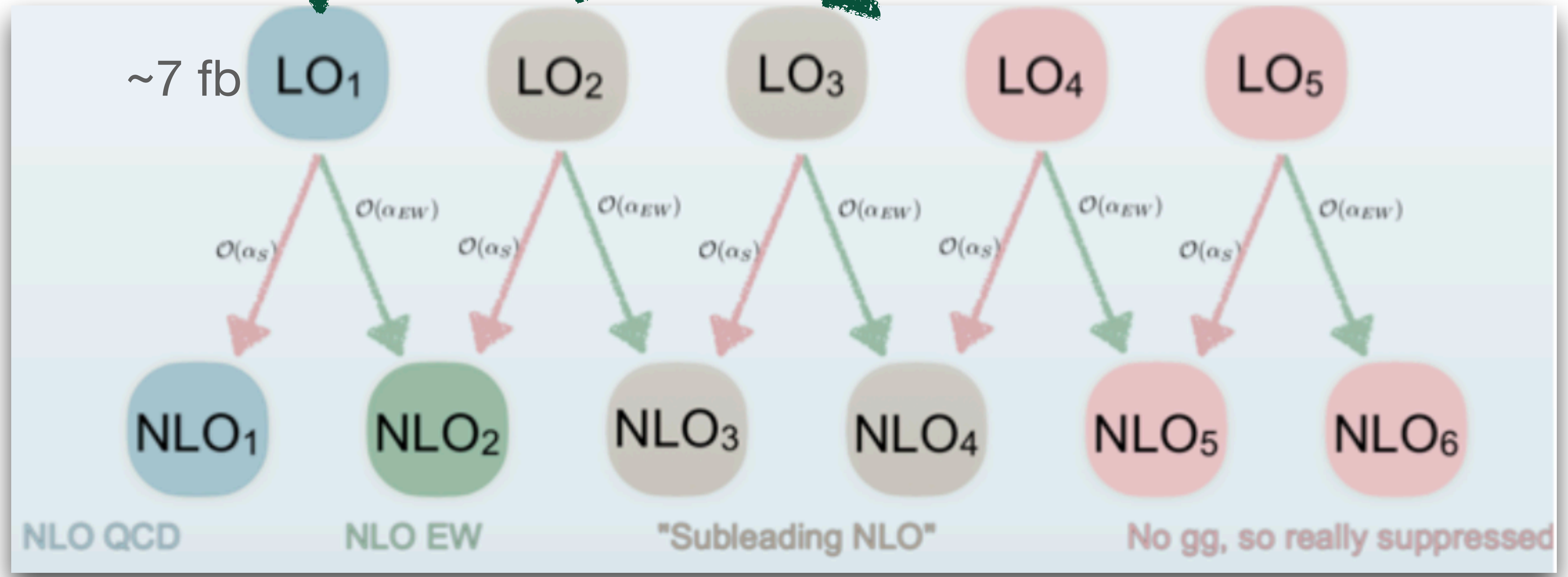
Leading: $\mathcal{O}(\alpha_S^4)$

Interference

Sub-leading: $\mathcal{O}(\alpha_S^3 y_t)$, $\mathcal{O}(\alpha_S^3 \alpha)$



Sub-leading: $\mathcal{O}(\alpha_S^2 y_t^2)$, $\mathcal{O}(\alpha_S^2 \alpha^2)$



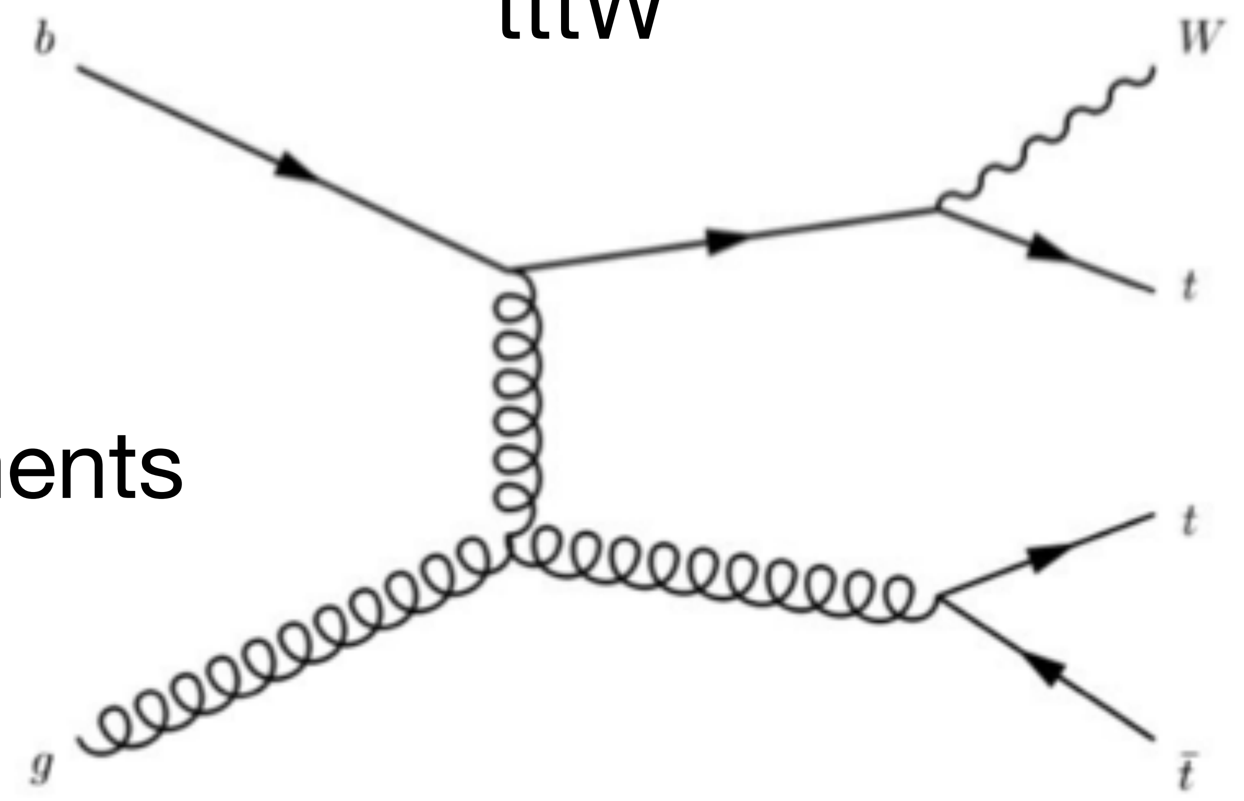
$\sigma_{\mathrm{(N)LO_i}}/\sigma_{\mathrm{LO_1}}$ [%]

δ[%]	$\mu = H_T/8$	$\mu = H_T/4$	$\mu = H_T/2$
LO_2	-26.0	-28.3	-30.5
LO_3	32.6	39.0	45.9
LO_4	0.2	0.3	0.4
LO_5	0.02	0.03	0.05
NLO_1	14.0	62.7	103.5
NLO_2	8.6	-3.3	-15.1
NLO_3	-10.3	1.8	16.1
NLO_4	2.3	2.8	3.6
NLO_5	0.12	0.16	0.19
NLO_6	< 0.01	< 0.01	< 0.01
$\mathrm{NLO}_2 + \mathrm{NLO}_3$	-1.7	-1.6	0.9

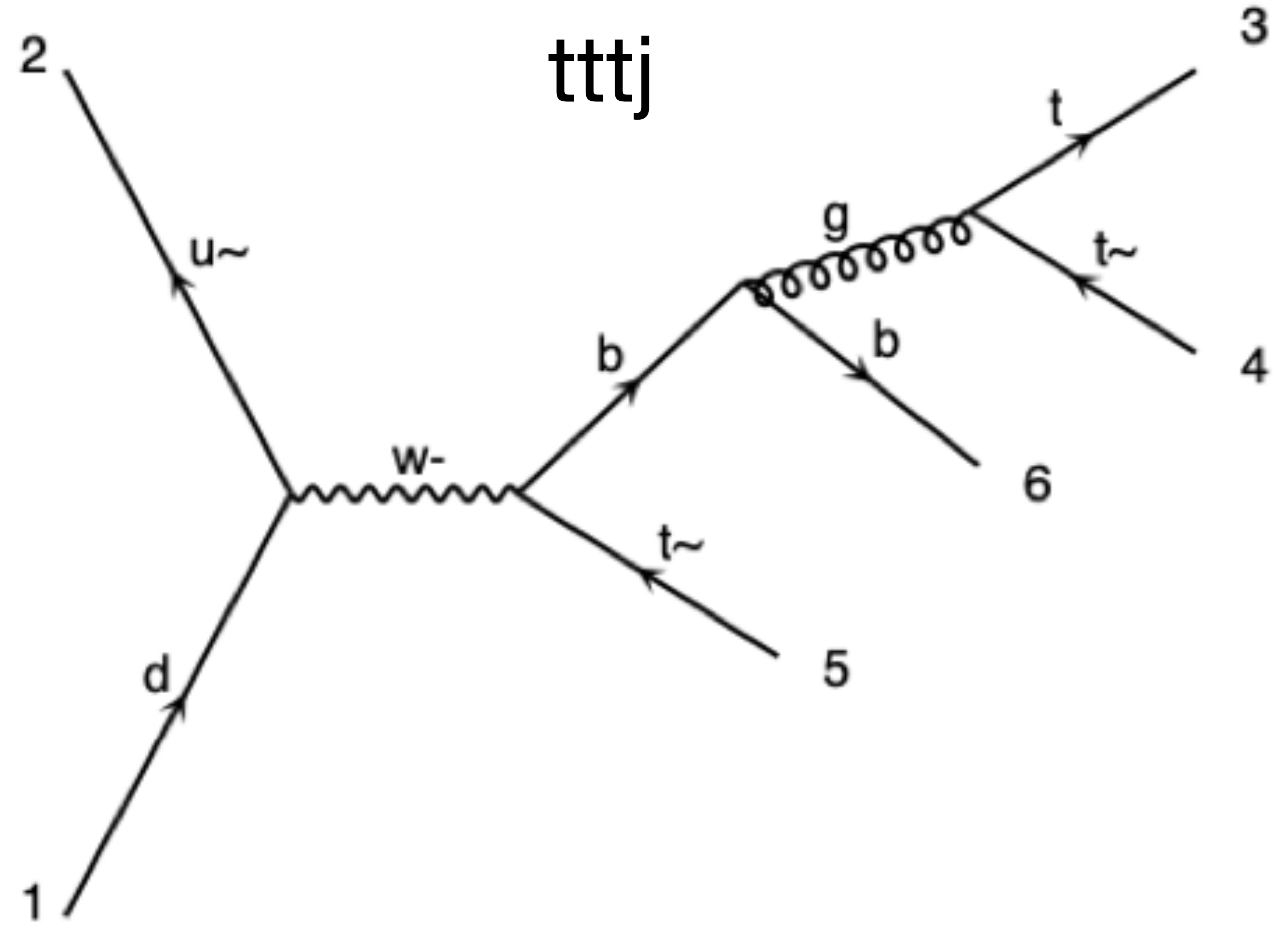
The role of ttt

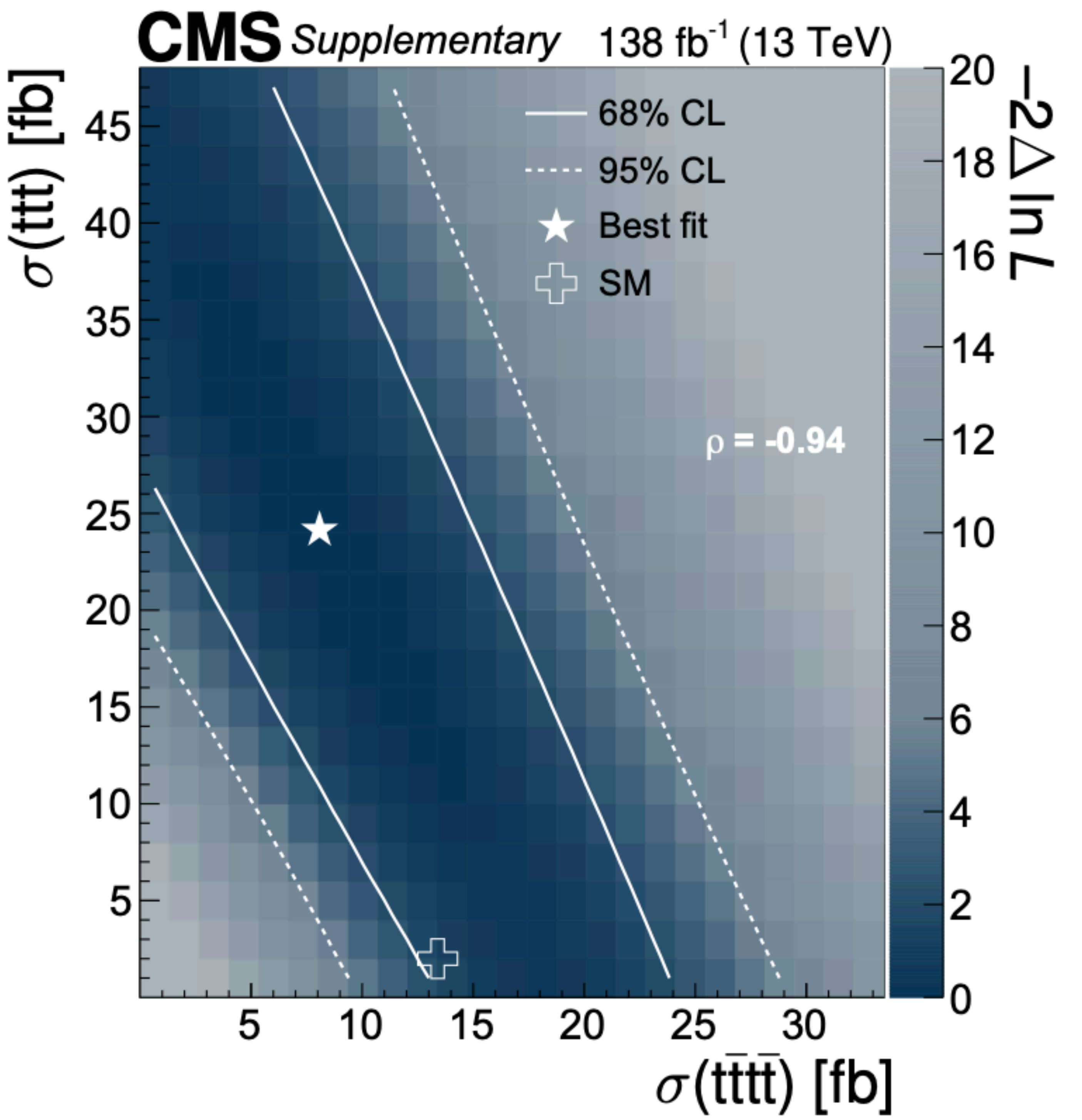
- Strong correlation with $t\bar{t}t\bar{t}$ seen by both experiments
  - tttW indistinguishable from $t\bar{t}t\bar{t}$
- NLO prediction from G. Durieux: 2 fb ±15%
  - higher order and EW correlations largely cancel (apart from NLO QCD)
- need better modelling and dedicated separation strategy in future analyses

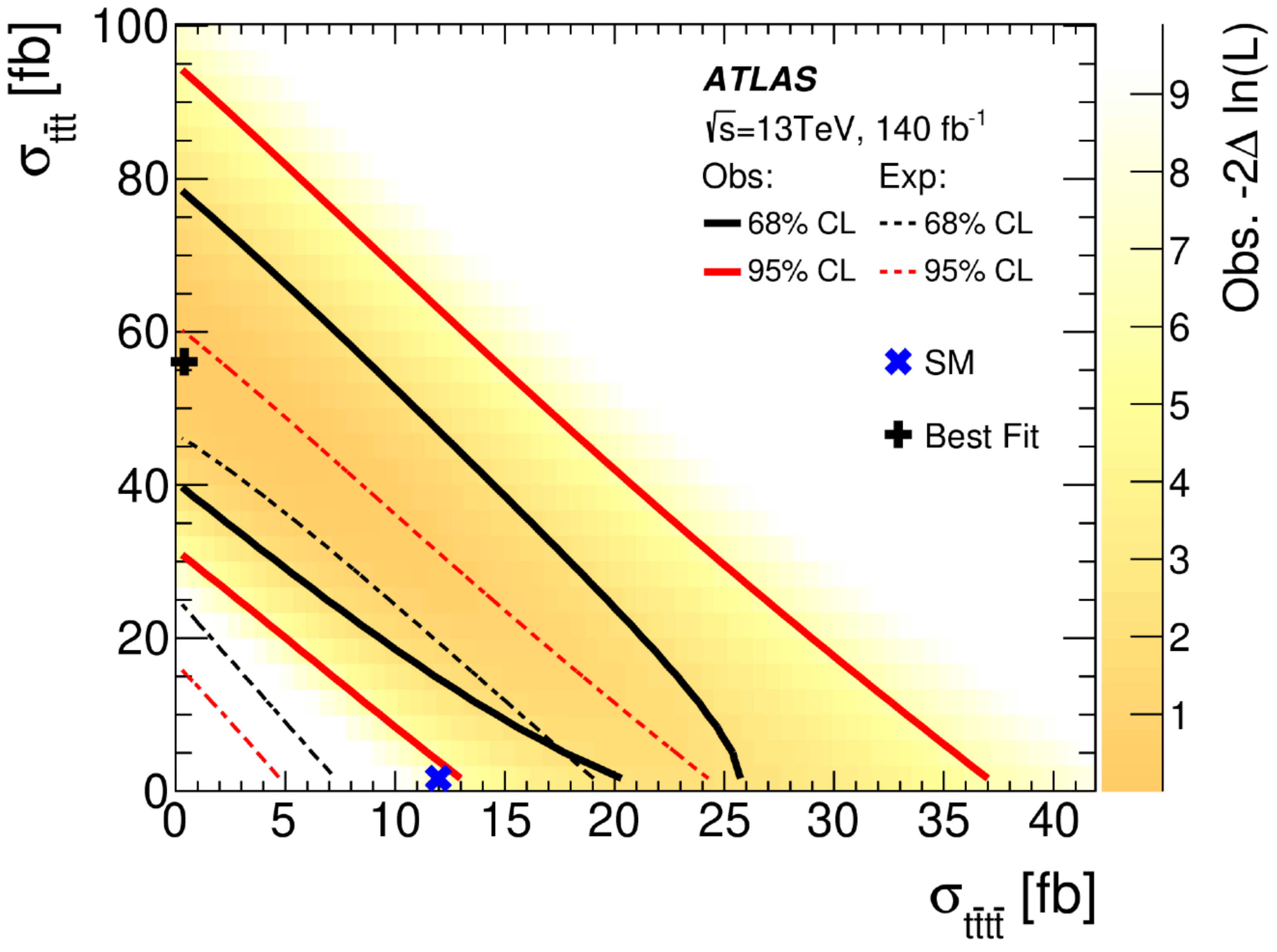
tttW



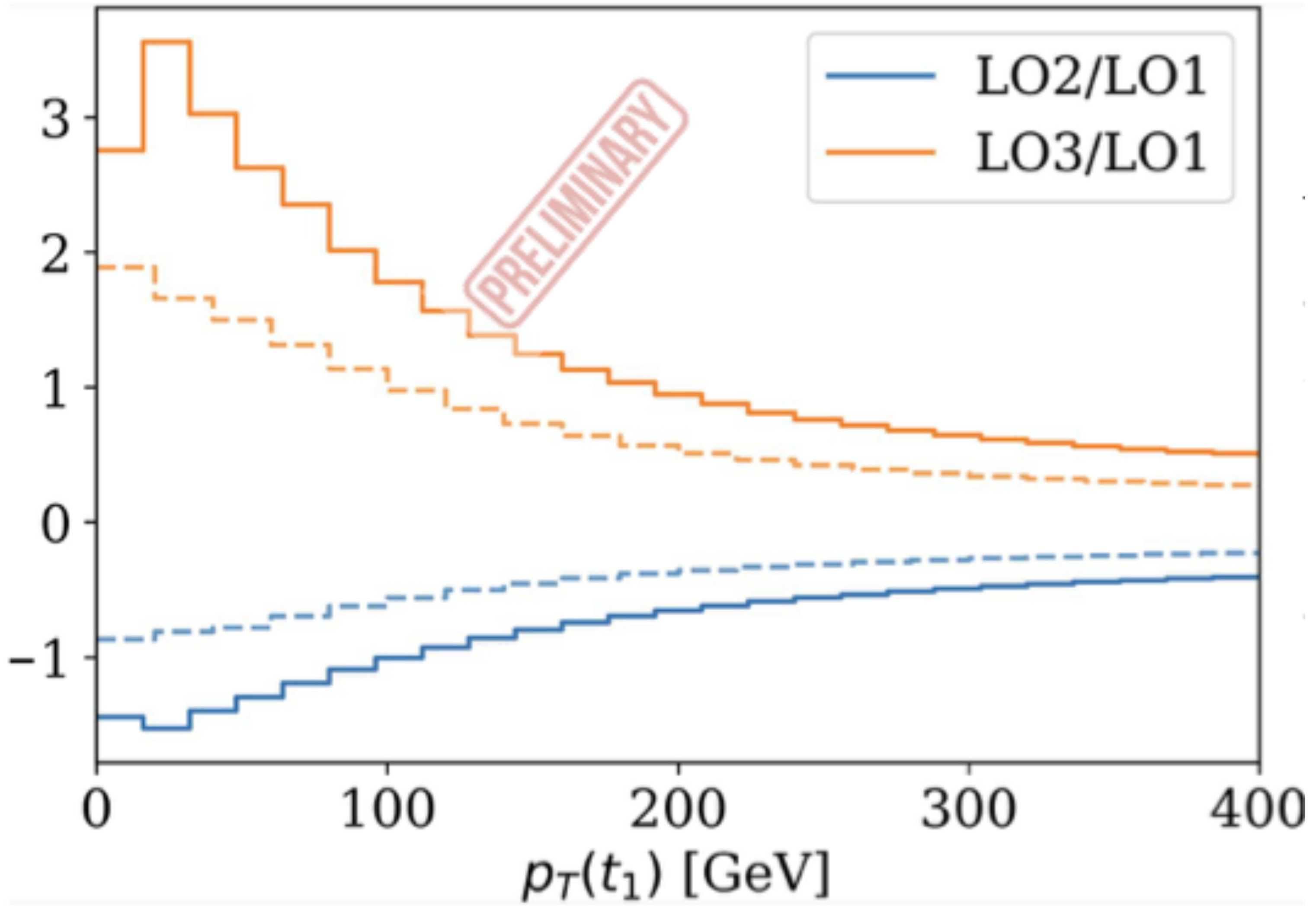
tttj





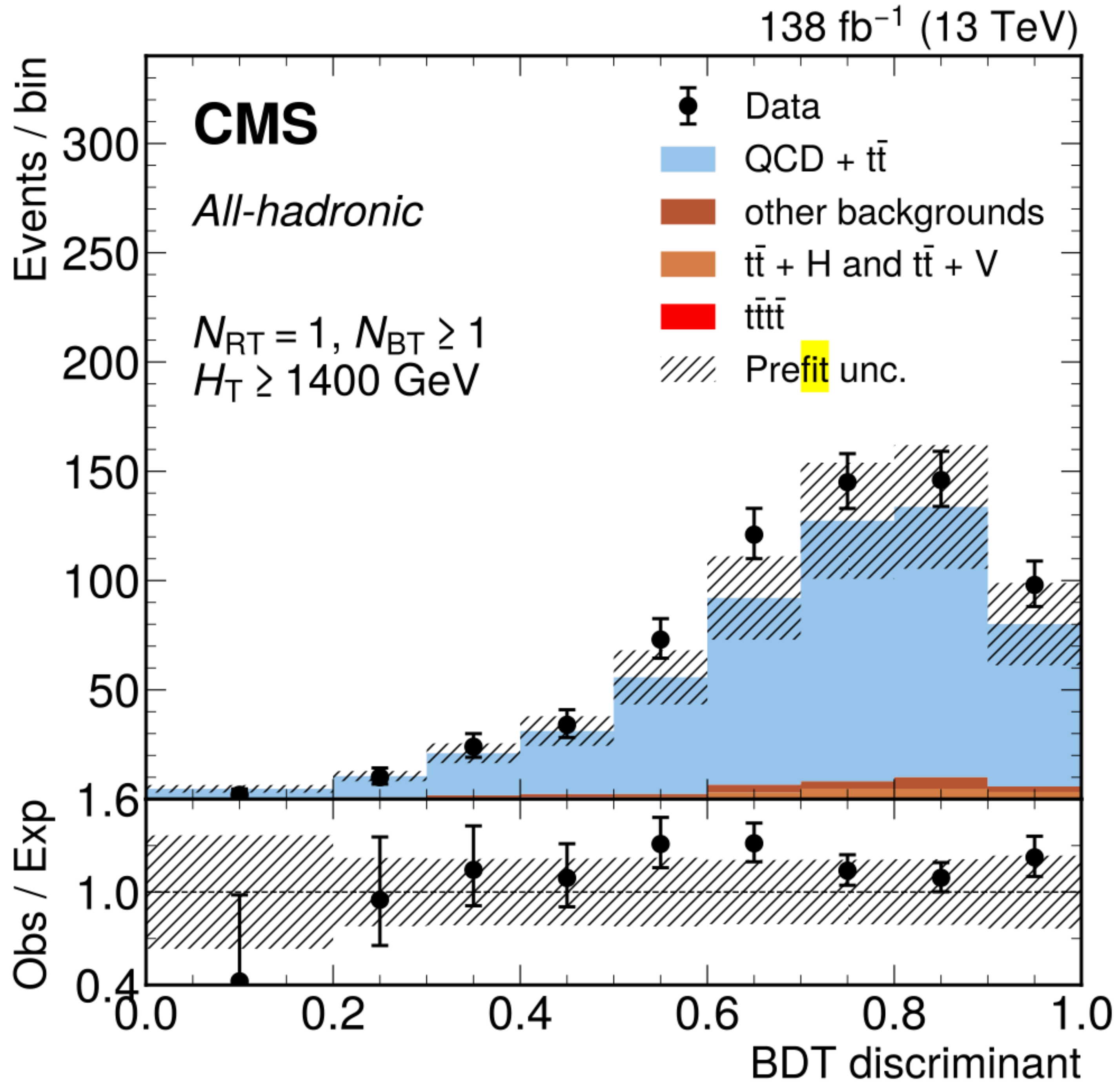


tttW only, H. Faham, G. Durieux, et al

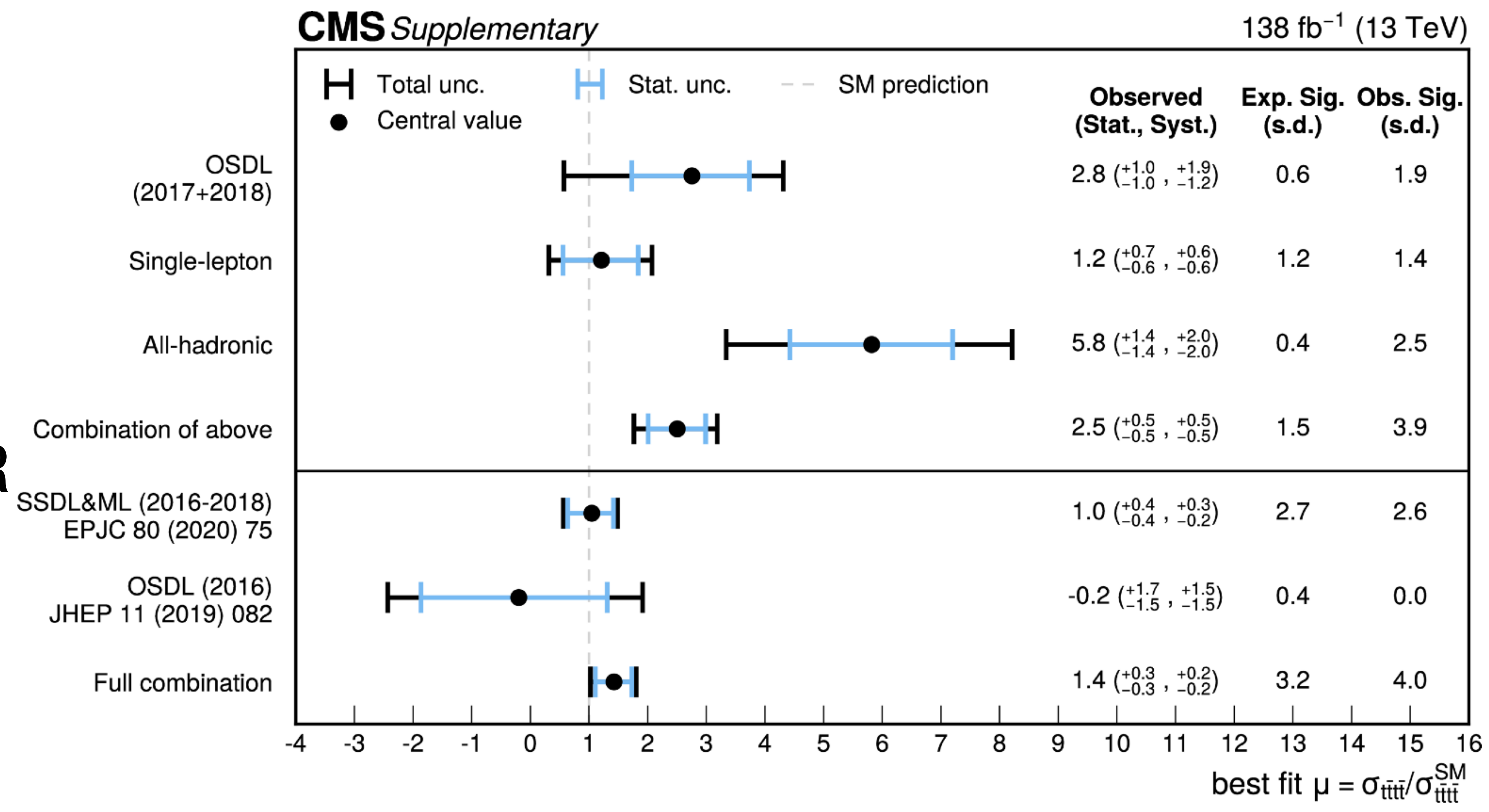


CMS: all-had/1L/2LOS channels

- 1L and 2LOS channels
  - SR/CR defined using number of leptons, jets and b-jets
    - 1L also uses the number of top candidates, identified using a BDT-based resolved top tagger
  - Background estimate relies on profile likelihood fit to CR+SR
  - S-B separation: 1L BDT; 2LOS H_T (scalar sum of jet p_T)

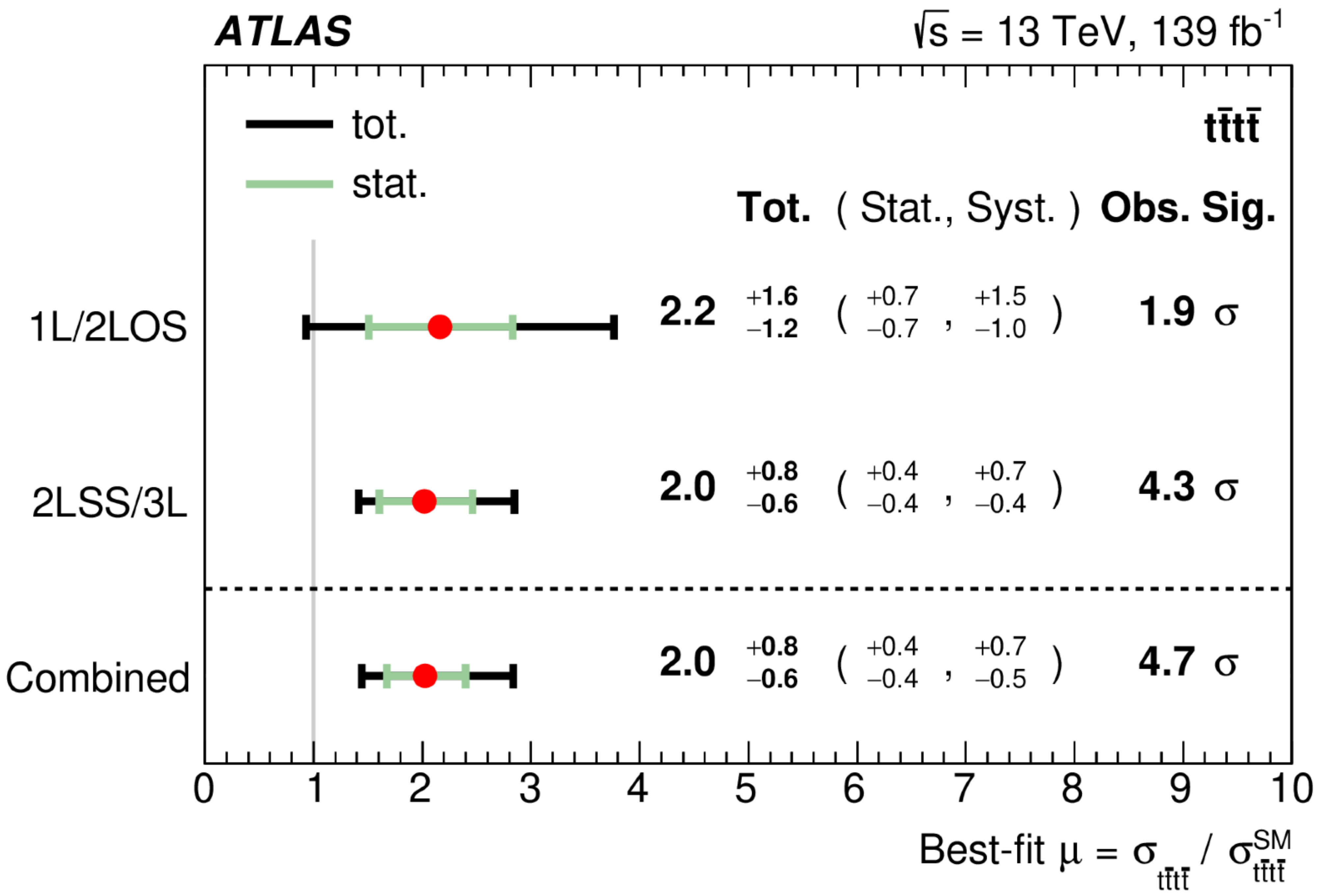


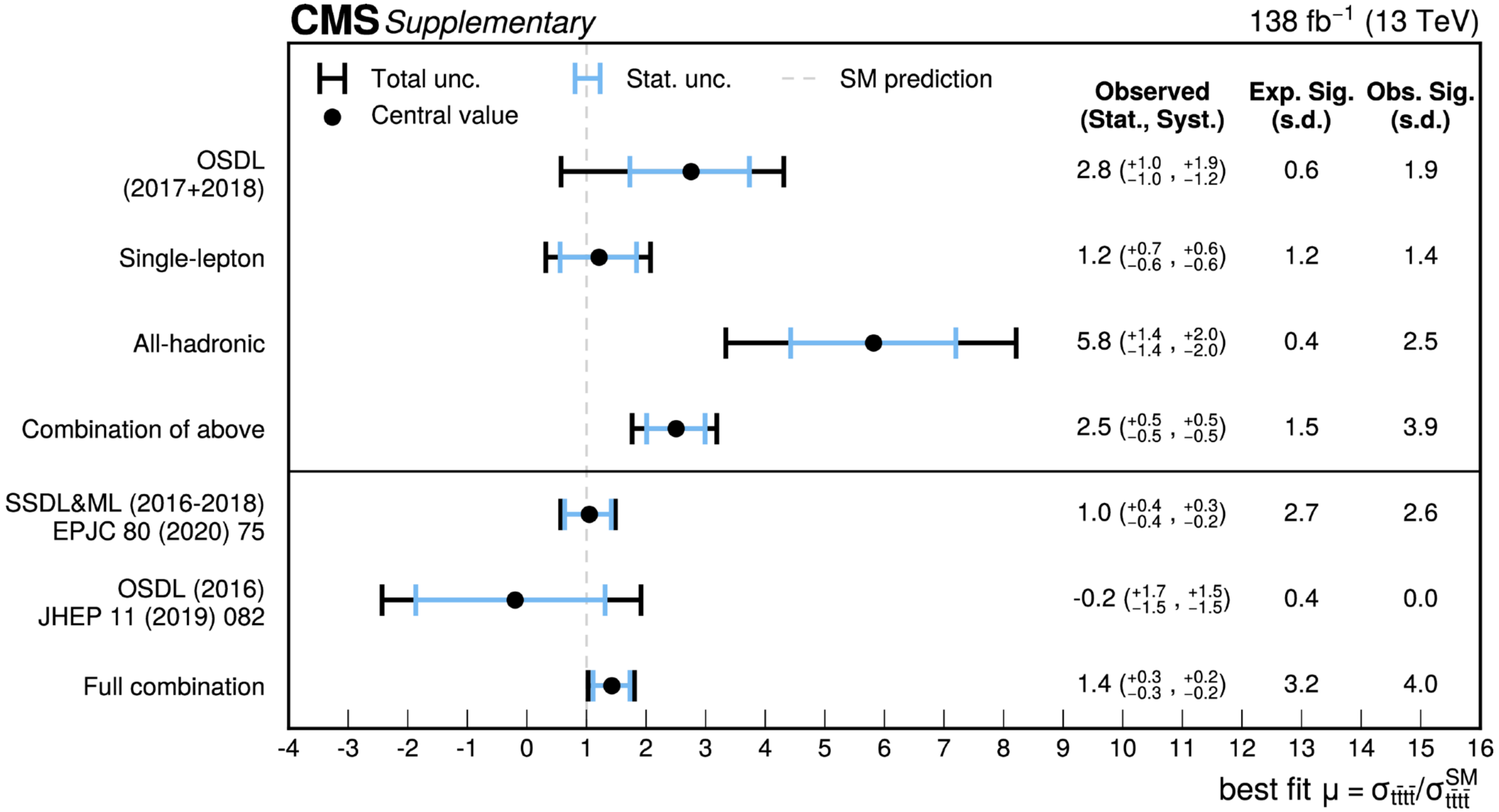
- All-had channel: first $t\bar{t}t\bar{t}$ analysis using this channel
  - SR/CR/VR defined using number of jets, b-jets
    - Each split by number of resolved/boosted top candidates and H_T
  - data-driven background estimate - extrapolated from CR to SR
    - ABCD method for normalisation
    - DDN trained to predict the shape
  - BDT used for S-B separation



All-had/1L/2LOS channel

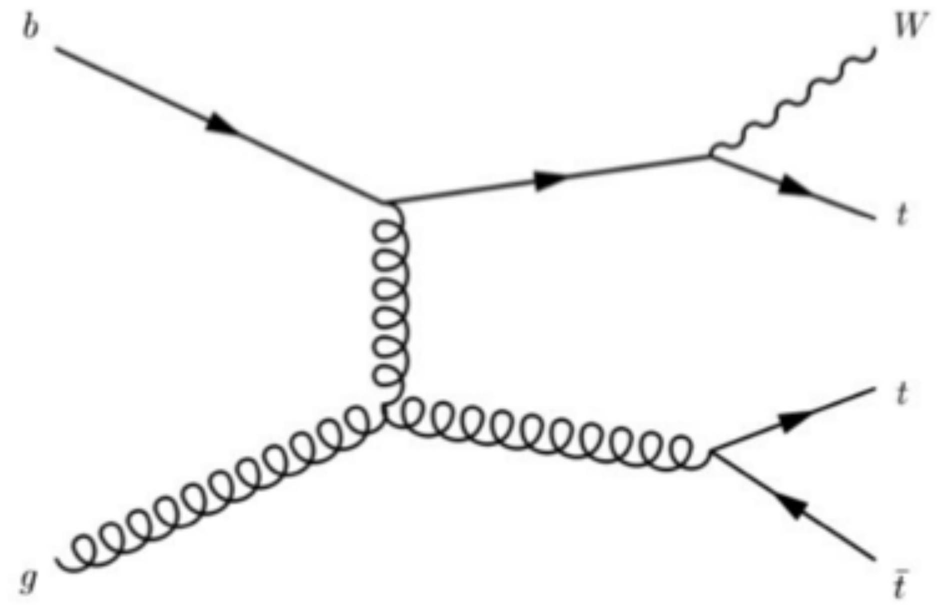
- Similar strategy used by ATLAS and CMS
  - categorise events according to number of leptons, jets, b-jets, and boosted top candidates
  - Boosted Decision Tree (BDT) for signal-background separation
- Compatible results from different channels and between ATLAS and CMS

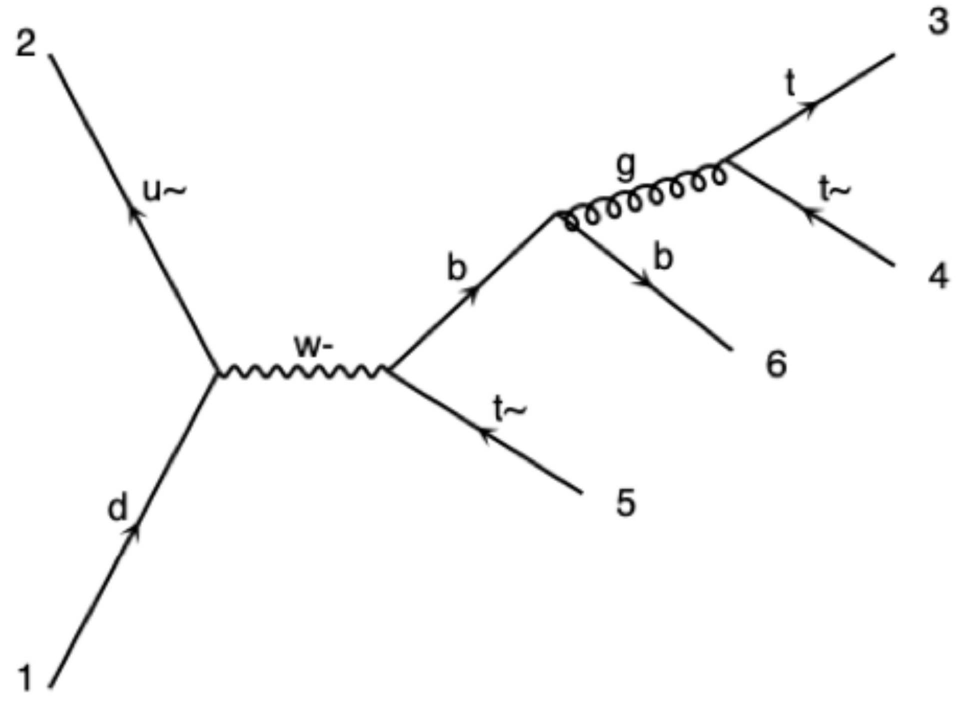




$t t t$ production

- An important background for $t\bar{t}t\bar{t}$ - potentially a signal very soon
  - two different groups of processes: tttW (dominant) and tttj (subleading)
- 4 vs 5 flavour scheme
- For tttW, interference with tttt already at LO when using 4FS; NLO when using 5FS
  - difficult to separate from $t\bar{t}t\bar{t}$
- NLO QCD prediction from Gauthier: 2 fb $^{+13\%}_{-12\%}$ (scales) ±5.9% (pdf)
- On-going studies for further improvement (Hesham El Faham, Gauthier, et al)
  - choice of the theorist HT/8 —> gives minimal scale variation
  - inclusion of NLO EW corrections





Gauthier

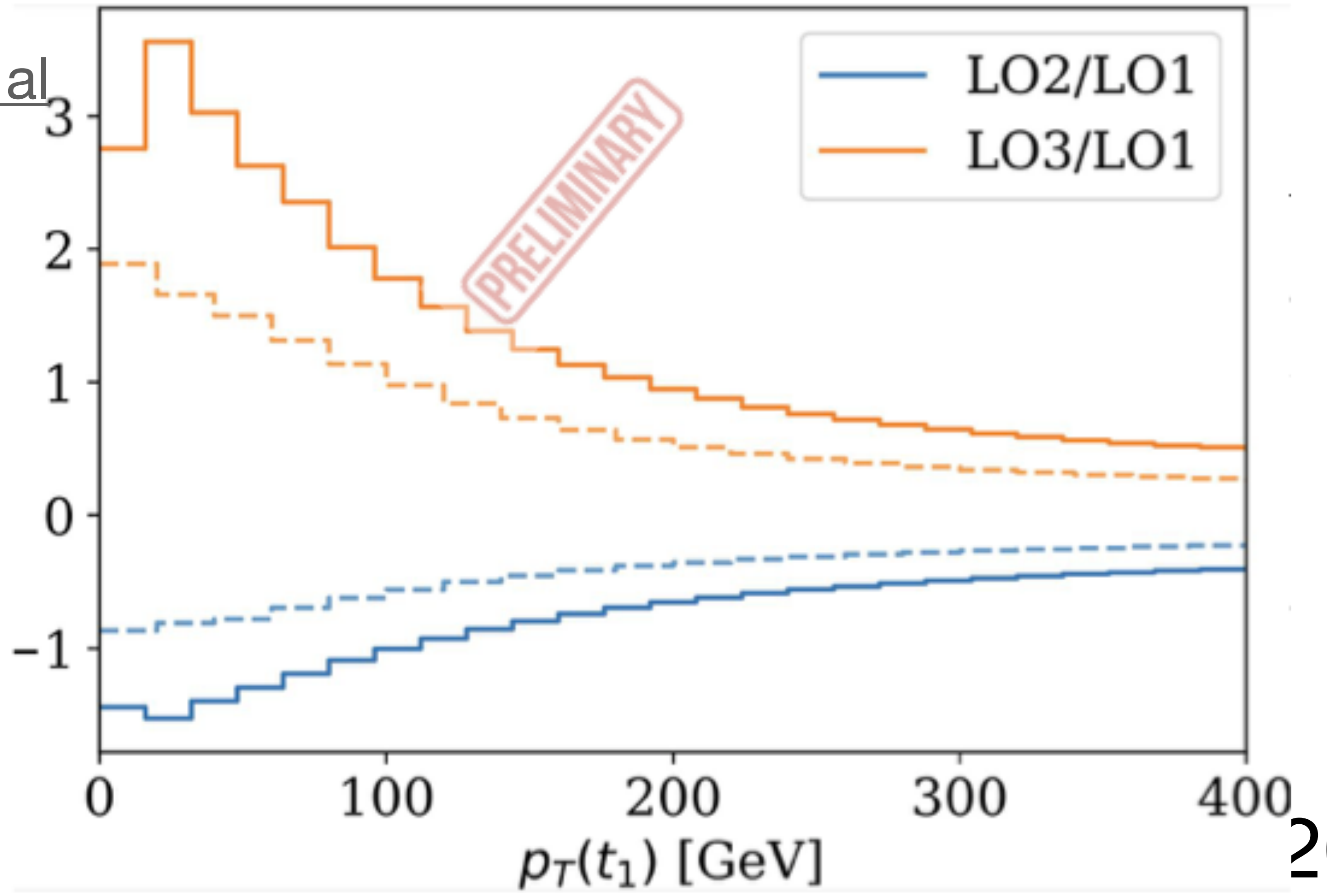
Cross section [fb]	NLO1 (+LO1)	LO1	LO2	LO3	LO QCD+EW	NLO QCD + LO EW
tttj+	0.2	0.11	-0.088	0.098	0.12	0.21
tttj-	0.44	0.24	-0.19	0.24	0.29	0.49
tttW+	0.52	0.29	-0.19	0.33	0.43	0.66
tttW-	0.52	0.29	-0.19	0.33	0.43	0.66
Total	1.68	0.93	-0.658	0.998	1.27	2.02

tttW only, Hesham El Faham, Gauthier, et al

LO	0.41 fb	-20%	+20%	(±0.3%)
LO1	0.27 fb	-30%	+40%	(±0.2%)
LO2	-0.18 fb	+30%	-20%	(±0.1%)
LO3	0.31 fb	-10%	+20%	(±0.2%)
LO4	0.013 fb	-9%	+8%	(±0.3%)
NLO	0.22 fb	-8%	+7%	(±1%)
NLO1	0.21 fb	-7%	+2%	(±0.8%)
NLO2	-0.053 fb	+30%	-60%	(±1%)
NLO3	0.057 fb	-60%	+50%	(±1%)
NLO4	0.0042 fb	-20%	+20%	(±7%)
NLO5	0.0017 fb	-4%	+5%	(±1%)

PRELIMINARY

tttW only, Hesham El Faham, Gauthier, et al

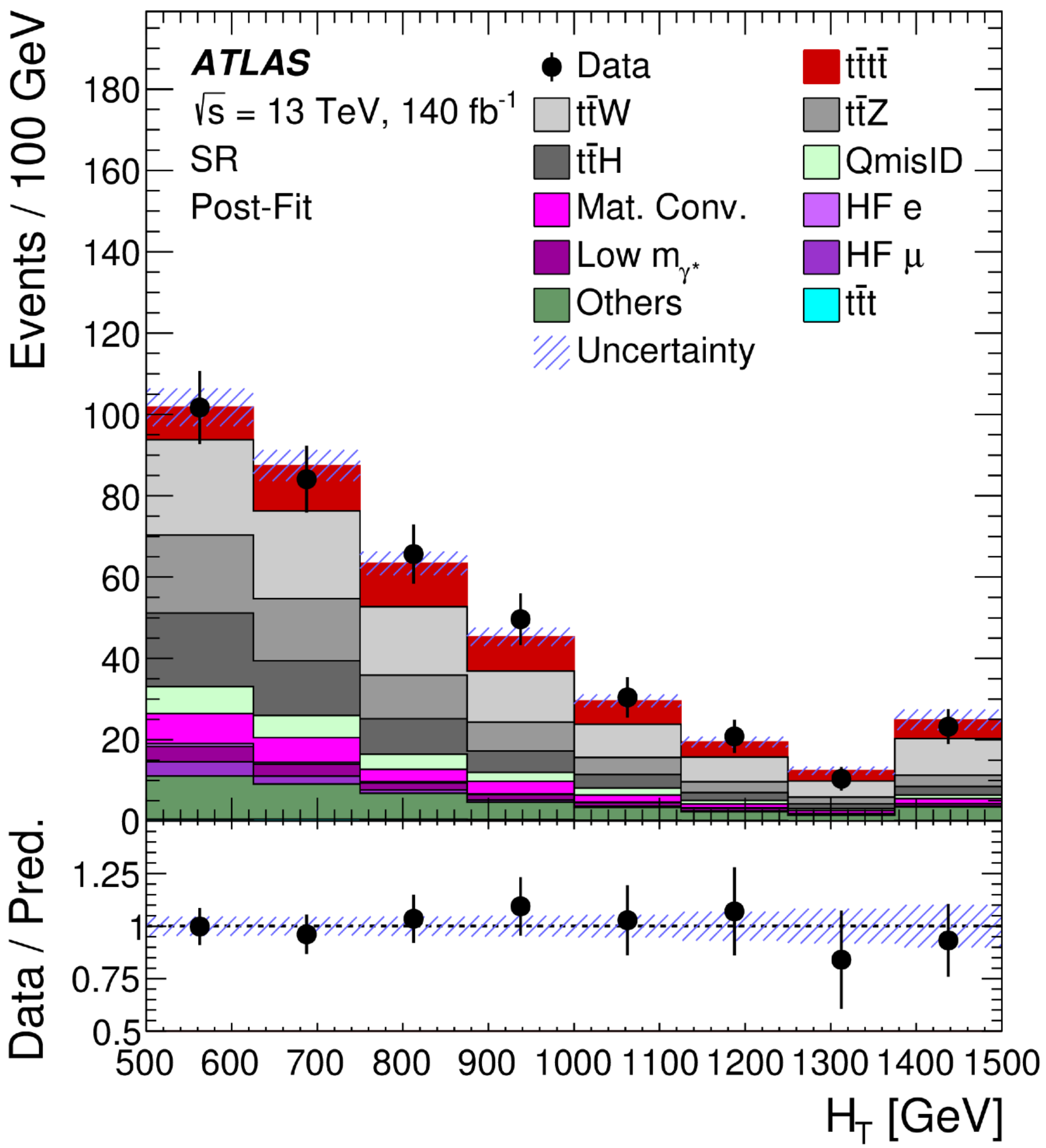


Observation of $t\bar{t}t\bar{t}$ production

EPJC 83 (2023) 496

- Using events in 2LSS/ML channel
  - requiring ≥2 SS leptons:
    - leading lepton $p_T > 28$ GeV
    - subleading leptons $p_T > 15$ GeV
  - jets $p_T > 20$ GeV
- Simple SR selection
  - ≥6 jets, ≥2 b-tagged jets (77% eff.), $H_T > 500$ GeV
  - Selected
    - 38 signal events (pre-fit)
    - 482 data events

* H_T: scalar sum of all leptons and jets p_T



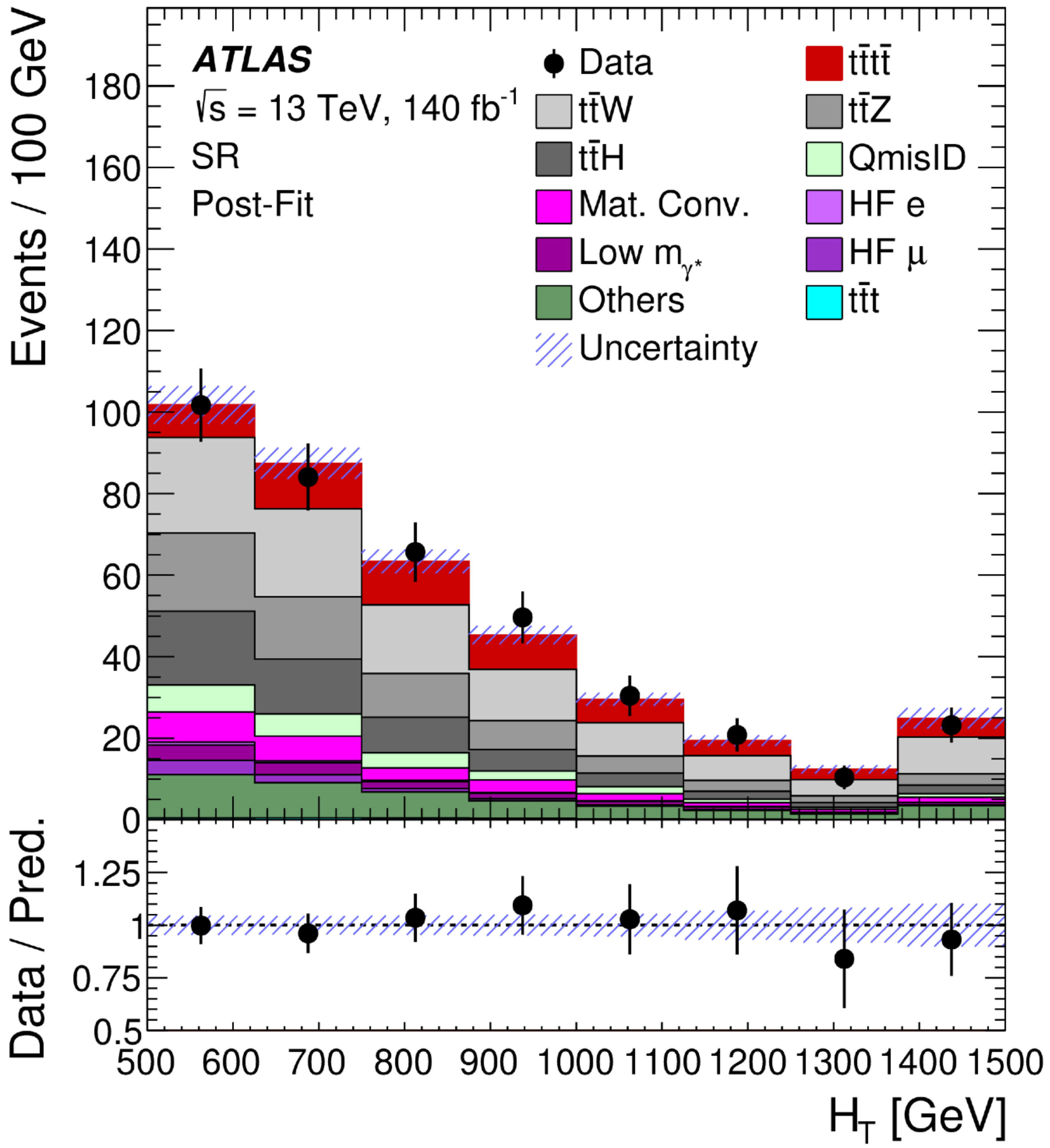
Background estimate

- Combining MC and data-driven techniques
- Reducible background - mainly from $t\bar{t}$ (~20%)
  - events with charge mis-identified leptons (QmisID)
    - data-driven QmisID rates using $Z \rightarrow ee$ events ~(p_{T}, η)
  - events with fake/non-prompt leptons
    - material conversion, low $m_{\gamma *}$, HFe, HFμ
    - using MC templates, with free floating normalisation, with dedicated CR for each
- Irreducible background (~60%)
  - $t\bar{t}W$: MC with data-driven N-jets (JHEP10(2012)162)

$$R_{(j+1)/j} = \frac{N_{j+1}}{N_j} = a_0 + \frac{a_1}{a_2 + j} \qquad (a_2 = 0)$$

  - fit the N-jets distributions separately in $t\bar{t}W^+$ and $t\bar{t}W^-$ regions
  - Other backgrounds from simulations
- Profile likelihood fit with all CRs and SR
  - determine background and signal simultaneously

	SR
$t\bar{t}W$	127 ± 35
$t\bar{t}Z$	79 ± 15
$t\bar{t}H$	68 ± 10
QmisID	27 ± 4
Mat. Conv.	30 ± 8
HF e	2.3 ± 2.4
HF μ	9 ± 4
Low m_{γ^*}	15 ± 5
Others	50 ± 10
$t\bar{t}t$	2.9 ± 0.9
Total bkg	412 ± 21
$t\bar{t}t\bar{t}$	69 ± 15
Total	480 ± 19
Data	482

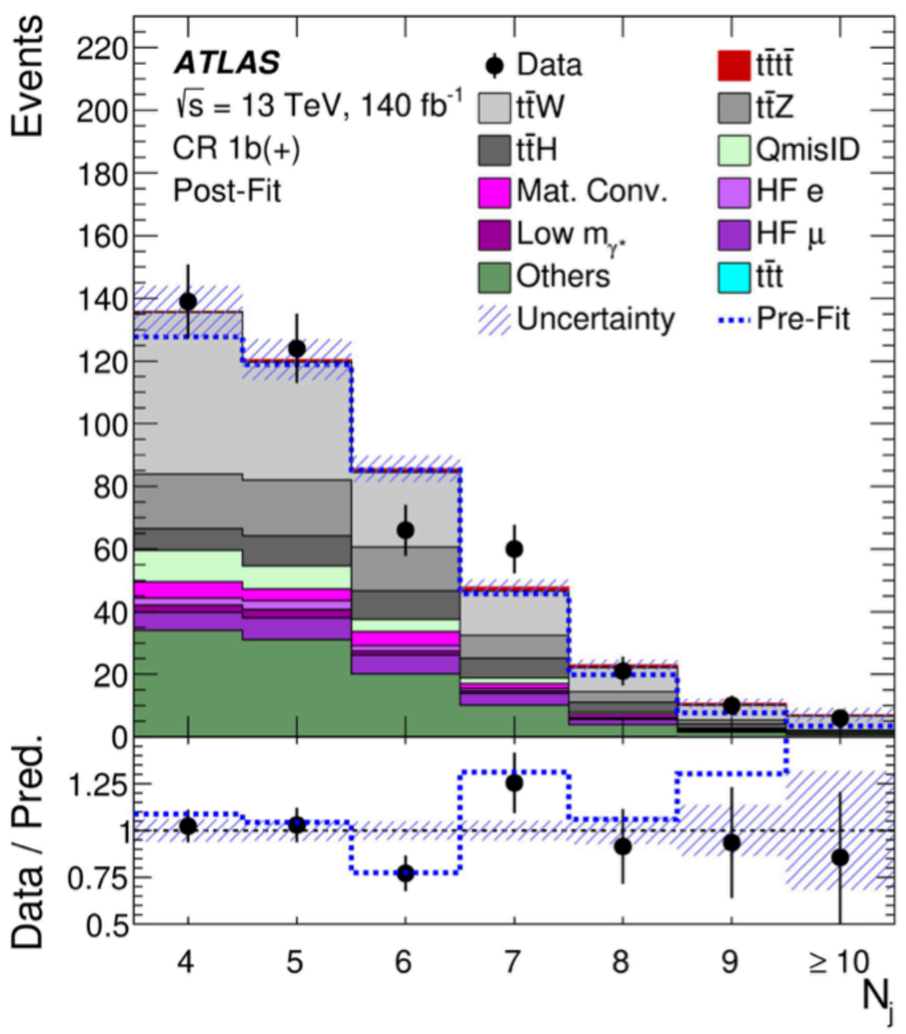


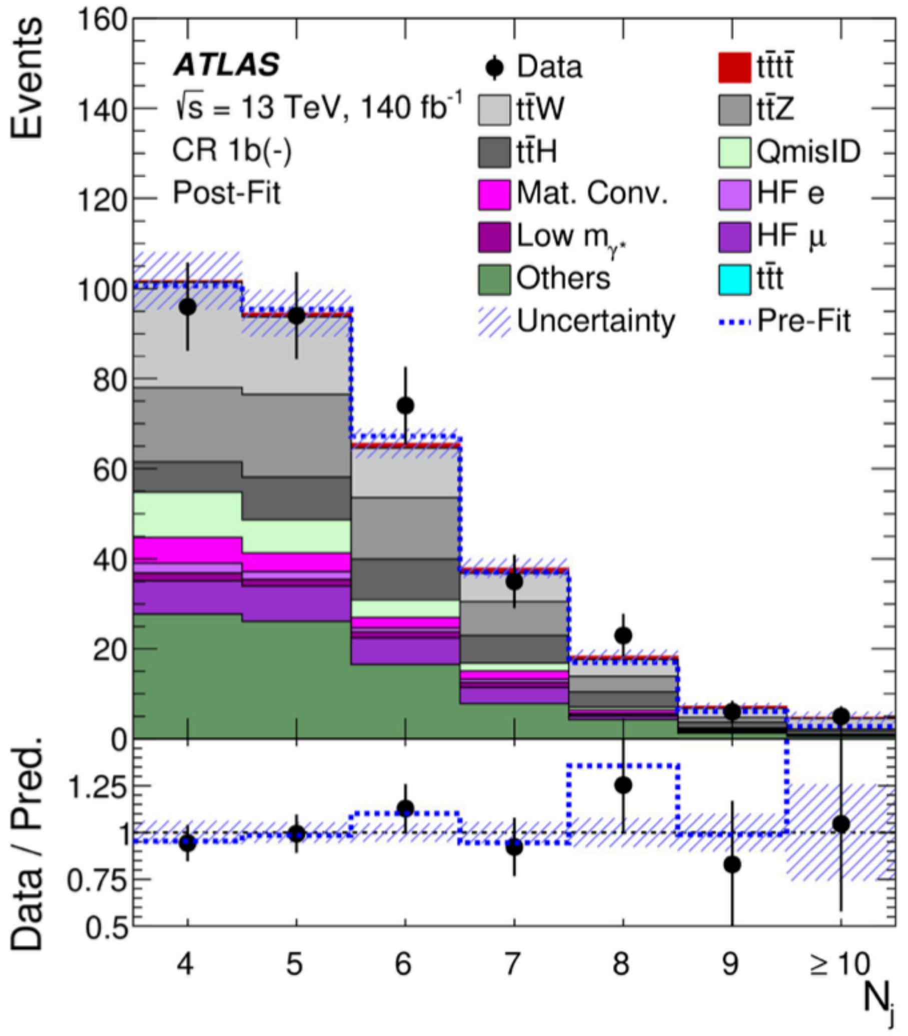
Path to the observation - ATLAS

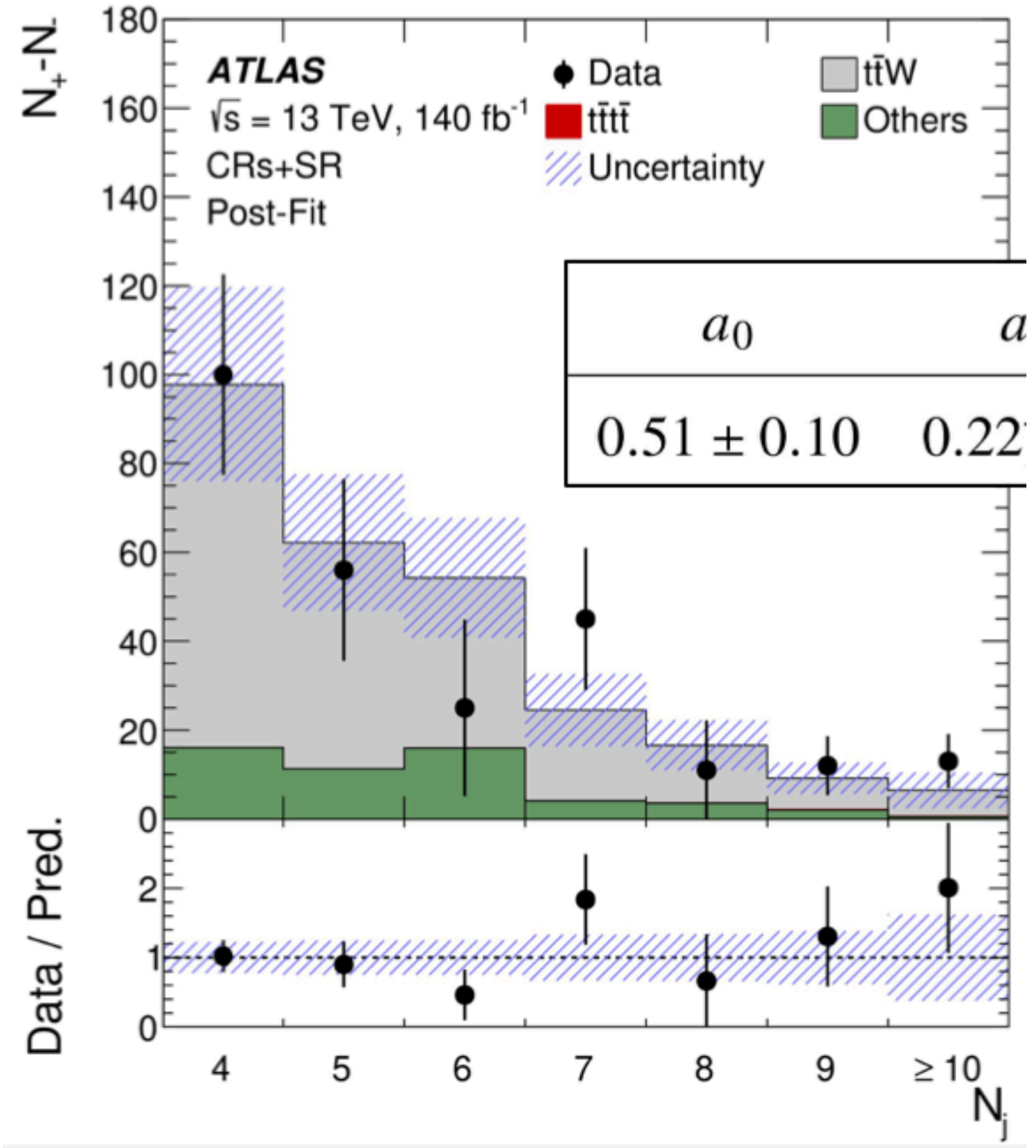
- Combining MC and data-driven techniques
- Reducible background
  - events with fake/non-prompt leptons
    - using shape from MC, with free floating normalisation in the profiling, with dedicated CR for each
  - QmisID: data-driven QmisID rates using Drell-Yan events, parametrised as (p_{T}, η)
- Irreducible background (~60%)
  - $t\bar{t}W$: MC includes NLO QCD + EW (t-W scattering) contributions
  - with data-driven N-jets (JHEP10(2012)162)

$$R_{(j+1)/j} = \frac{N_{j+1}}{N_j} = a_0 + \frac{a_1}{a_2 + j} \qquad (a_2 = 0)$$

  - fit the N-jets distributions separately in $t\bar{t}W^+$ and $t\bar{t}W^-$ regions
  - Other backgrounds from simulations

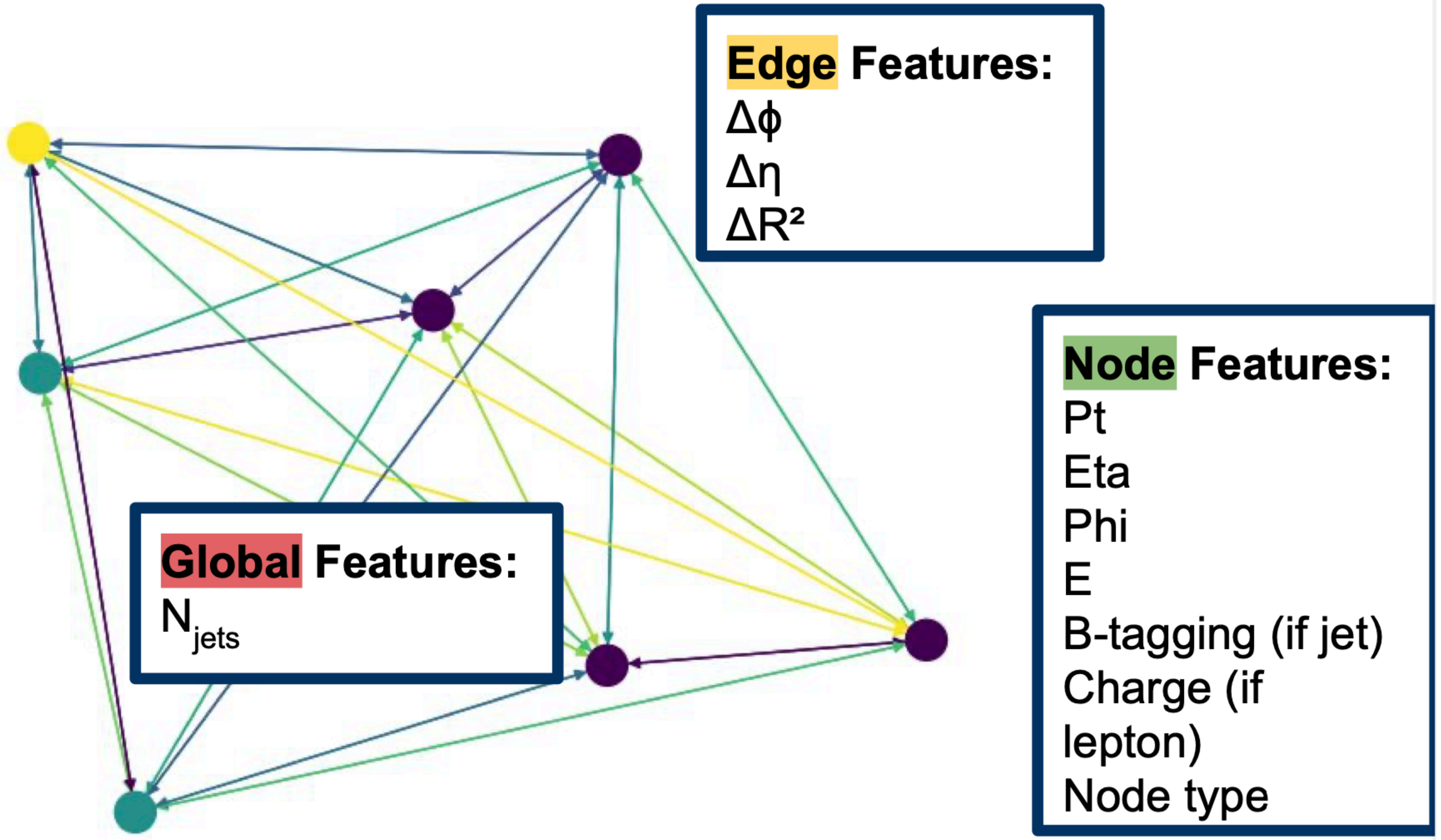




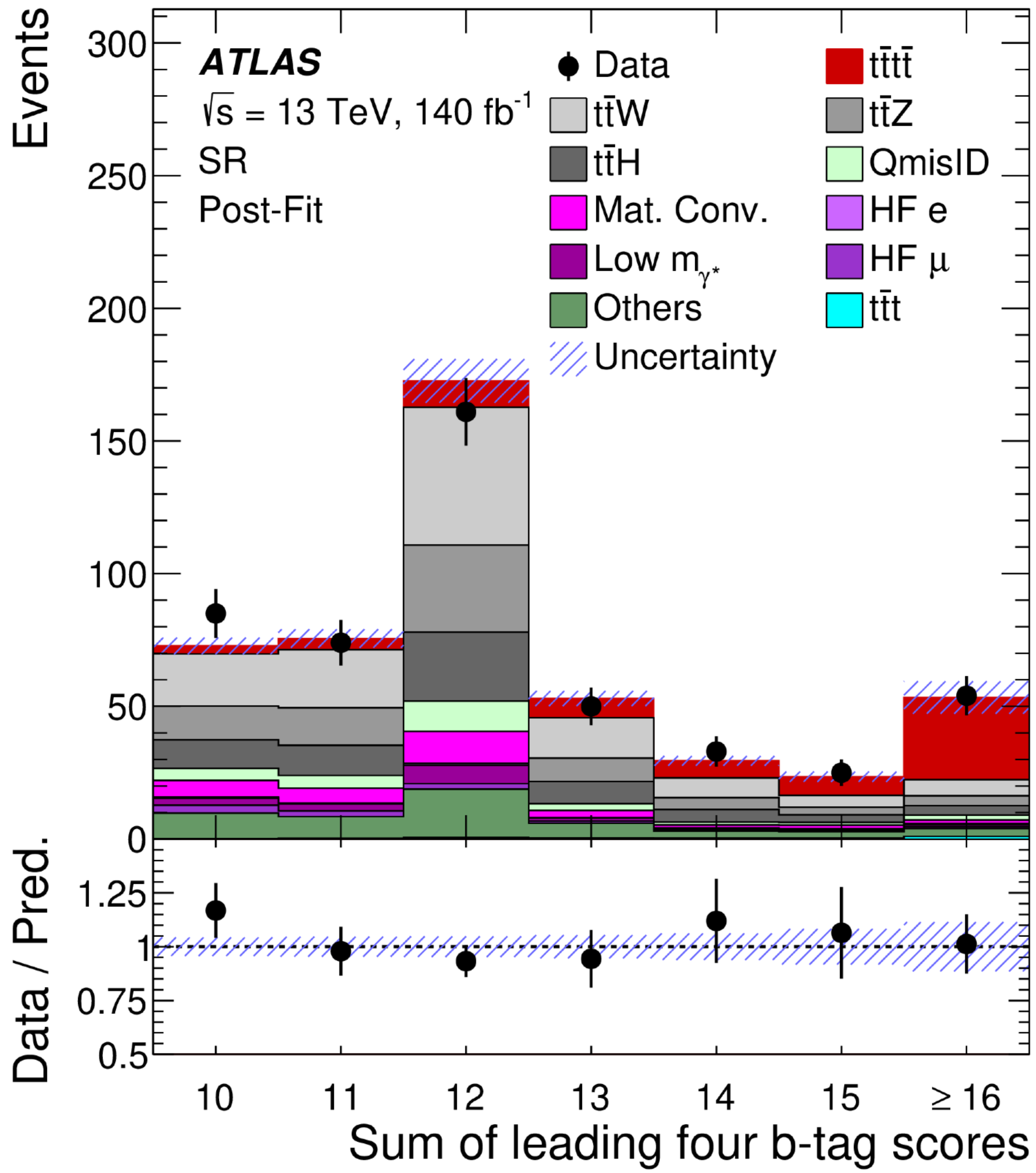


Graph neural networks

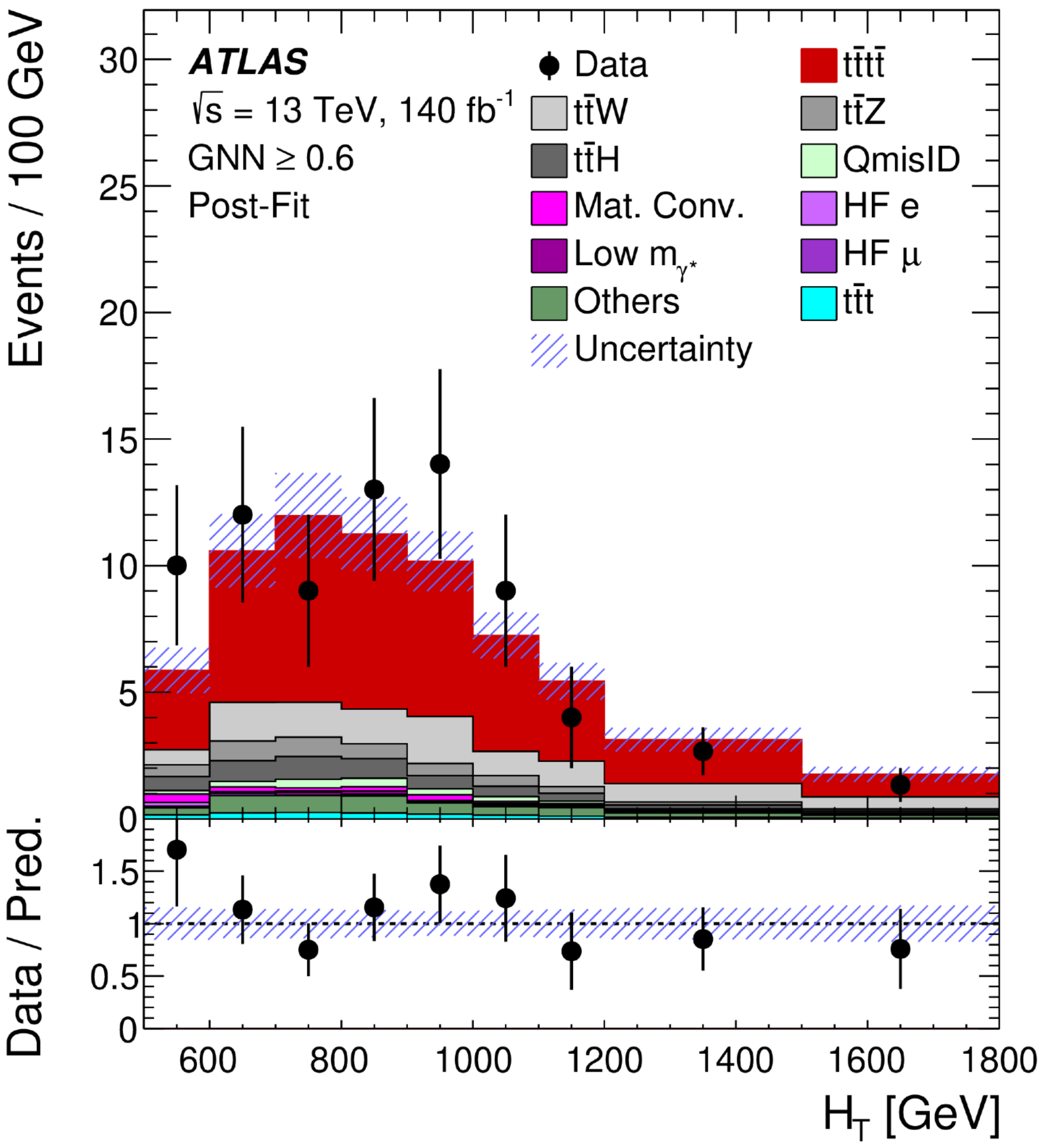
- Trained in the signal regions
  - increased weights assigned to $t\bar{t}W$ events with ≥7 jets

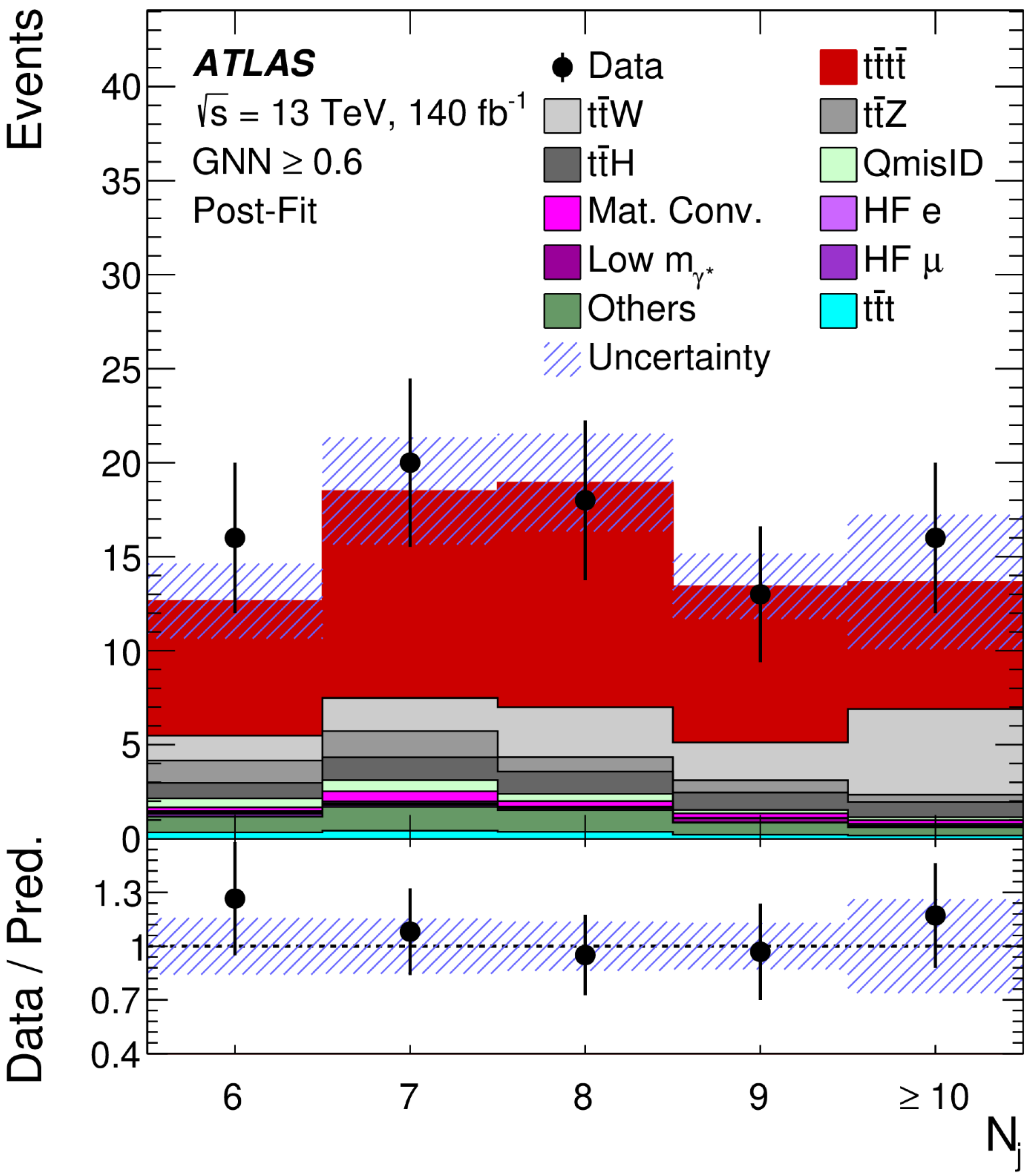


- most important input: pseudo-continuous b-tagging score



Results - SM $t\bar{t}t\bar{t}$ cross section





Systematics

- Stat. dominated measurement
  - $t\bar{t}W$ estimate also depend on stat.

- $t\bar{t}t\bar{t}$ modelling uncertainties
  - aMC@NLO+Pythia8 vs. Sherpa
  - aMC@NLO+Pythia8 vs +Herwig7
  - both aMC@NLO and Sherpa samples are LO QCD+EW with NLO QCD

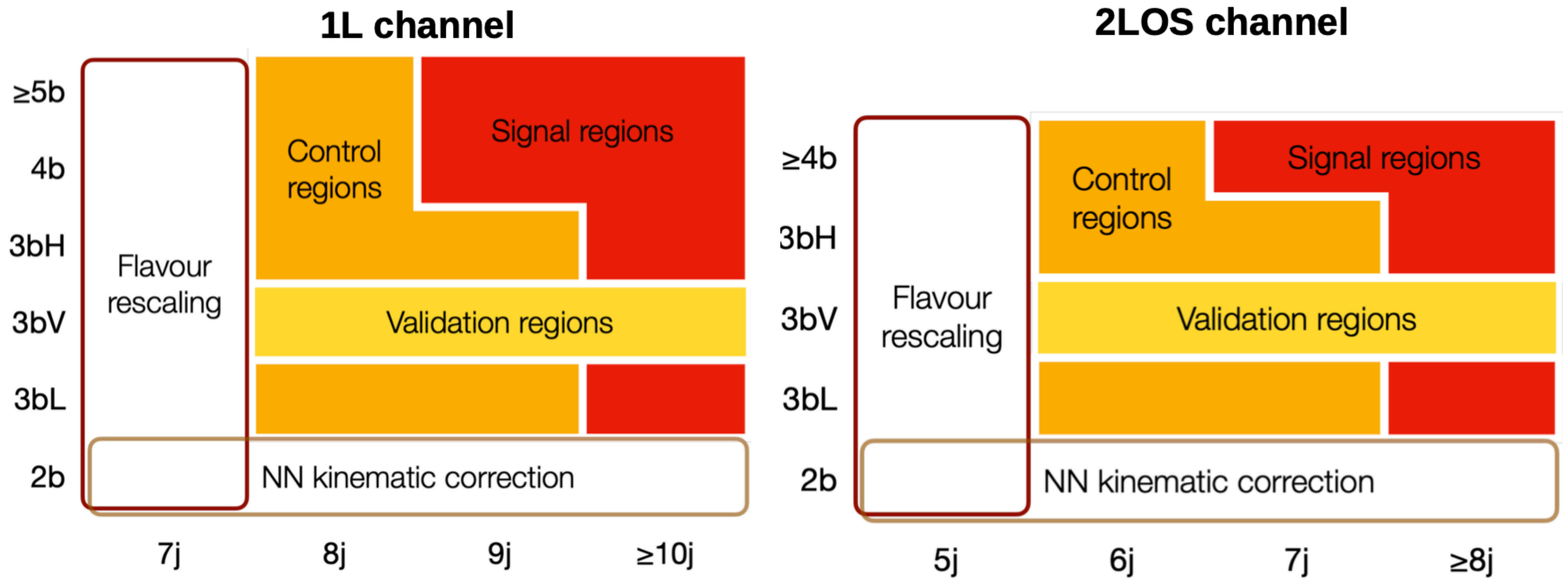
Uncertainty source	$\Delta\sigma$ [fb]		$\Delta\sigma/\sigma$[%]	
Signal modelling				
$t\bar{t}t\bar{t}$ generator choice	+3.7	−2.7	+17	−12
$t\bar{t}t\bar{t}$ parton shower model	+1.6	−1.0	+7	−4
Other $t\bar{t}t\bar{t}$ modelling	+0.8	−0.5	+4	−2
Background modelling				
$t\bar{t}H$+jets modelling	+0.9	−0.7	+4	−3
$t\bar{t}W$+jets modelling	+0.8	−0.8	+4	−3
$t\bar{t}Z$+jets modelling	+0.5	−0.4	+2	−2
Other background modelling	+0.5	−0.4	+2	−2
Non-prompt leptons modelling	+0.4	−0.3	+2	−2
$t\bar{t}t$ modelling	+0.3	−0.2	+1	−1
Charge misassignment	+0.1	−0.1	+0	−0
Instrumental				
Jet flavour tagging (b-jets)	+1.1	−0.8	+5	−4
Jet uncertainties	+1.1	−0.7	+5	−3
Jet flavour tagging (light-flavour jets)	+0.9	−0.6	+4	−3
Jet flavour tagging (c-jets)	+0.5	−0.4	+2	−2
Simulation sample size	+0.4	−0.3	+2	−1
Other experimental uncertainties	+0.4	−0.3	+2	−1
Luminosity	+0.2	−0.2	+1	−1
Total systematic uncertainty	+4.6	−3.4	+20	−16
Statistical				
Intrinsic statistical uncertainty	+4.2	−3.9	+19	−17
$t\bar{t}W$+jets normalisation and scaling factors	+1.2	−1.1	+6	−5
Non-prompt leptons normalisation (HF, Mat. Conv., Low m_{γ^*})	+0.4	−0.3	+2	−1
Total statistical uncertainty	+4.7	−4.3	+21	−19
Total uncertainty	+6.6	−5.5	+29	−25

Search for 2HDM $t\bar{t}A/H \rightarrow t\bar{t}t\bar{t}$

3bL = Light-flavour enriched
3bH = Heavy-flavour enriched
3bV = Validation region

Name	$N_b^{60\%}$	$N_b^{70\%}$	$N_b^{85\%}$
2b	-	= 2	-
3bL	≤ 2	= 3	-
3bH	= 3	= 3	> 3
3bV	= 3	= 3	= 3
≥4b (2LOS)	-	≥ 4	-
4b (1L)	-	= 4	-
≥5b (1L)	-	≥ 5	-

- **ATLAS 1L/2LOS channel (arXiv:2408.17164, submitted to EPJC)**
  - Events categorised using number of jets and various b-tagging requirements



Variable	Description
$\sum_{i\in[1,6]} \mathrm{pcb}_i$	Sum of the pcb scores of the six jets with the highest scores
H_{T}	p_{T} sum of all reconstructed leptons and jets
N_{jets}	Jet multiplicities
$H_{\mathrm{T}}^{\mathrm{ratio}}$	p_{T} sum of the four leading jets in p_{T} divided by the p_{T} sum of the remaining jets
$dR_{jj}^{\mathrm{avg.}}$	Average ΔR across all jet pairs
m_{T}^{W}	W-boson transverse mass calculated using the lepton four-momenta and $E_{\mathrm{T}}^{\mathrm{miss}}$ (1L only)
$\Delta R_{bb}^{\mathrm{min.}}$	Minimum ΔR between any pair of jets b-tagged at the 70% OP
$\Delta R_{\ell b}^{\mathrm{min.}}$	Minimum ΔR between any pair of lepton and jet b-tagged at the 70% OP
$m_{bbb}^{\mathrm{avg.}}$	Average invariant mass of all triplets of jets b-tagged at the 70% OP
$m_{jjj}^{\mathrm{avg.}}$	Average invariant mass of all jet-triplets with an angular separation of $\Delta R < 3$
$\sum d_{12}$	Sum of the first k_t splitting scale d_{12} over all large-R jets
$\sum d_{23}$	Sum of the second k_t splitting scale d_{12} over all large-R jets
$N_{\mathrm{LR\text{-}jets}}$	Number of large-R jets with a mass greater than 100 GeV
Centrality	$\sum_i p_{\mathrm{T}}^i / \sum_i E_i$ where the sums are performed over all reconstructed jets and leptons
$m_{\ell\ell}$	Invariant mass of the two leptons (2LOS only)

$$\mathcal{O}(\mathbf{x}) = P(\text{data}|\mathbf{x}) = \frac{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x})}{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x}) + \alpha_{\text{sim}} P_{\text{sim}}(\mathbf{x})}, \qquad w(\mathbf{x}) = \frac{\alpha_{\text{data}} P_{\text{data}}(\mathbf{x})}{\alpha_{\text{sim}} P_{\text{sim}}(\mathbf{x})} = \frac{\mathcal{O}(\mathbf{x})}{1 - \mathcal{O}(\mathbf{x})}.$$

- Exponential loss function to help with the training in low-stat regime

$$\mathcal{L} = P_{\text{data}} e^{-\frac{\mathcal{O}(\mathbf{x})}{2}} + P_{\text{sim}} e^{\frac{\mathcal{O}(\mathbf{x})}{2}}.$$

- after minimisation $\mathscr{L} = 0$
- resulting event weight

$$w(\mathbf{x}) = e^{\mathcal{O}(\mathbf{x})}.$$

Search for heavy resonances - H/A

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- Consider 2HDM signal in the alignment limit $\sin(\beta - \alpha) \sim 1$
  - 400 - 1000 GeV, with 100 GeV steps
  - mass width set to 5 - 30 GeV, consistent with $\tan\beta = 1$
- 95% CL upper limit on xsec x BR ~10 fb
- SM $t\bar{t}t\bar{t}$ normalised to 12 fb, with 20% uncertainty on xsec, plus other modelling uncertainties