Measurement of the CKM matrix element $|V_{cb}|$ in $t\bar{t}$ events with the ATLAS detector

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color meets flavor

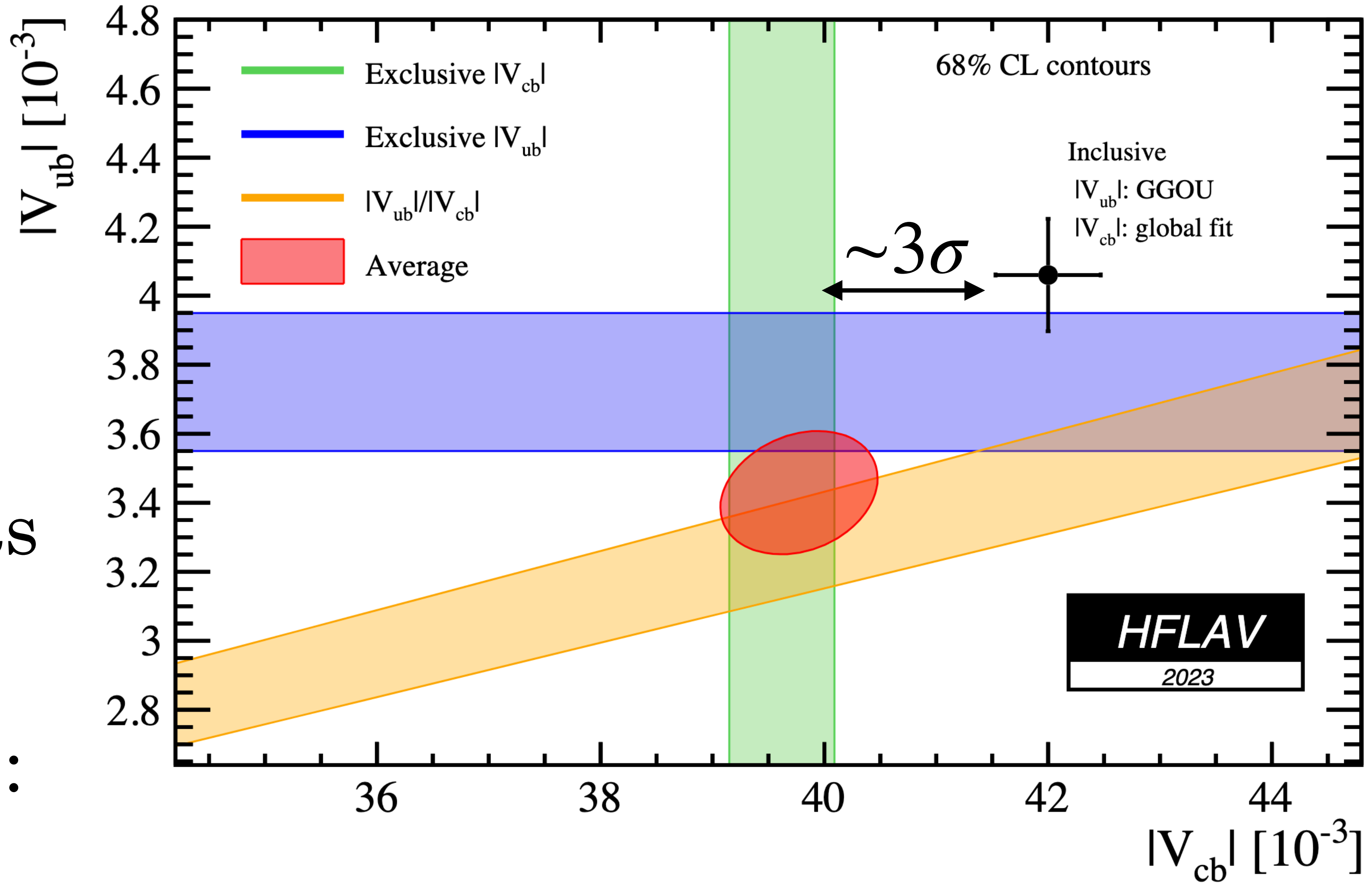
ATLAS EXPERIMENT

Motivation for a $|V_{cb}|$ measurement in ATLAS

- All $|V_{cb}|$ measurements so far are in B-hadron decays, most precise determinations from inclusive and exclusive decays

$$|V_{cb}|_{\text{world avg.}} = (41.1 \pm 1.2) \times 10^{-3}$$

- Currently around 3σ tension between inclusive and exclusive measurements



Physical Review D 113, 012008 (2026)

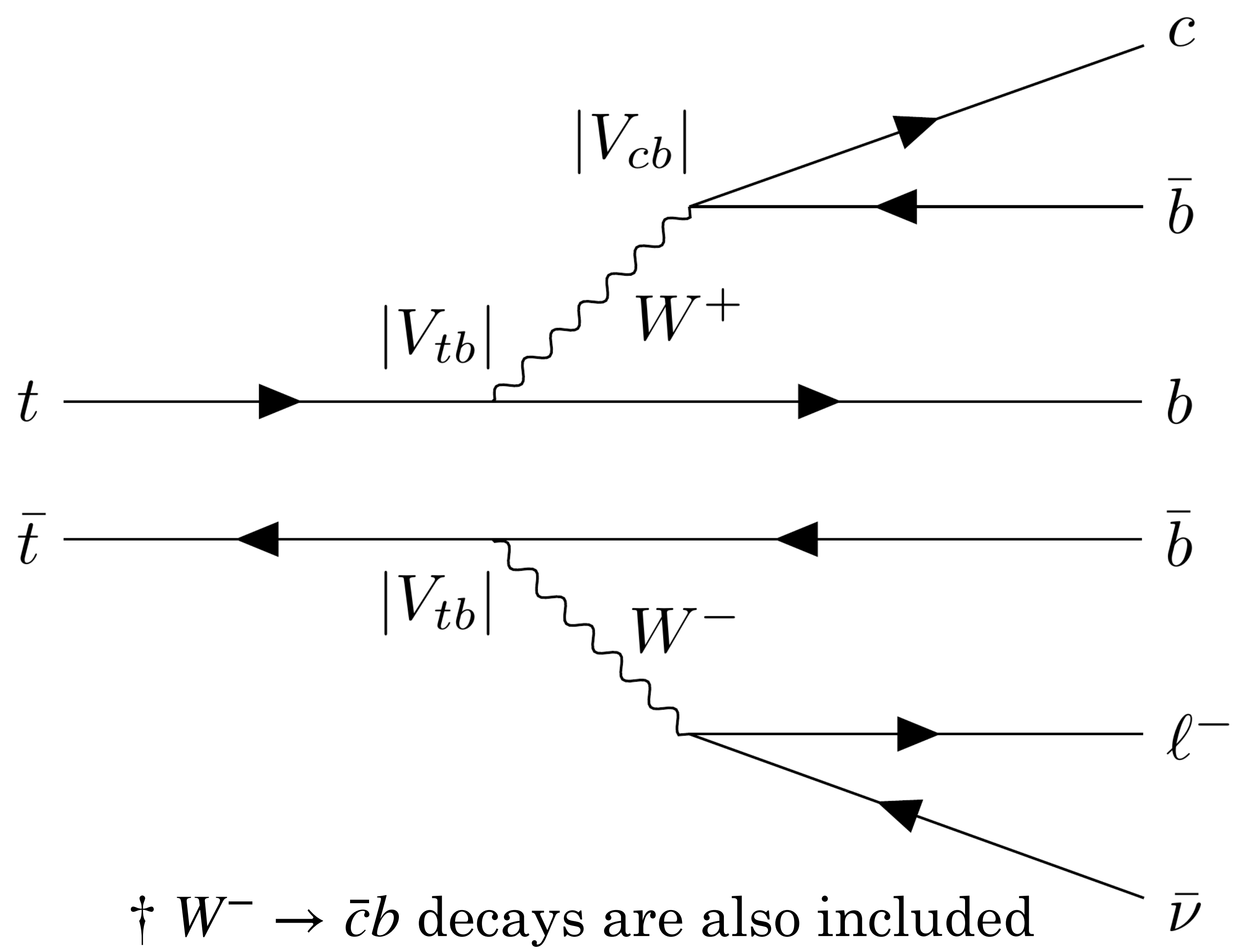
- In this analysis, $|V_{cb}|$ is extracted through the $W^+ \to c\bar{b}$ branching fraction†:

$$|V_{cb}|^2 = \frac{\mathrm{BF}(W^+ \to c\bar{b})}{\mathrm{BF}(W^+ \to c\bar{q})} = \frac{\mathrm{BF}(t\bar{t} \to b\, c\bar{b}, \bar{b}\, \ell^- \bar{\nu})}{\mathrm{BF}(t\bar{t} \to b\, c\bar{q}, b\, \ell^- \bar{\nu})}$$

- First measurement of $|V_{cb}|$ in on-shell W-boson decays

- No B-hadron form factor uncertainty

- Measurement complementary to previous $|V_{cb}|$ determinations, but difficult due to the small expected $W \to cb$ branching fraction: $\mathrm{BF}(W \to cb) \approx \dfrac{1}{1800}$



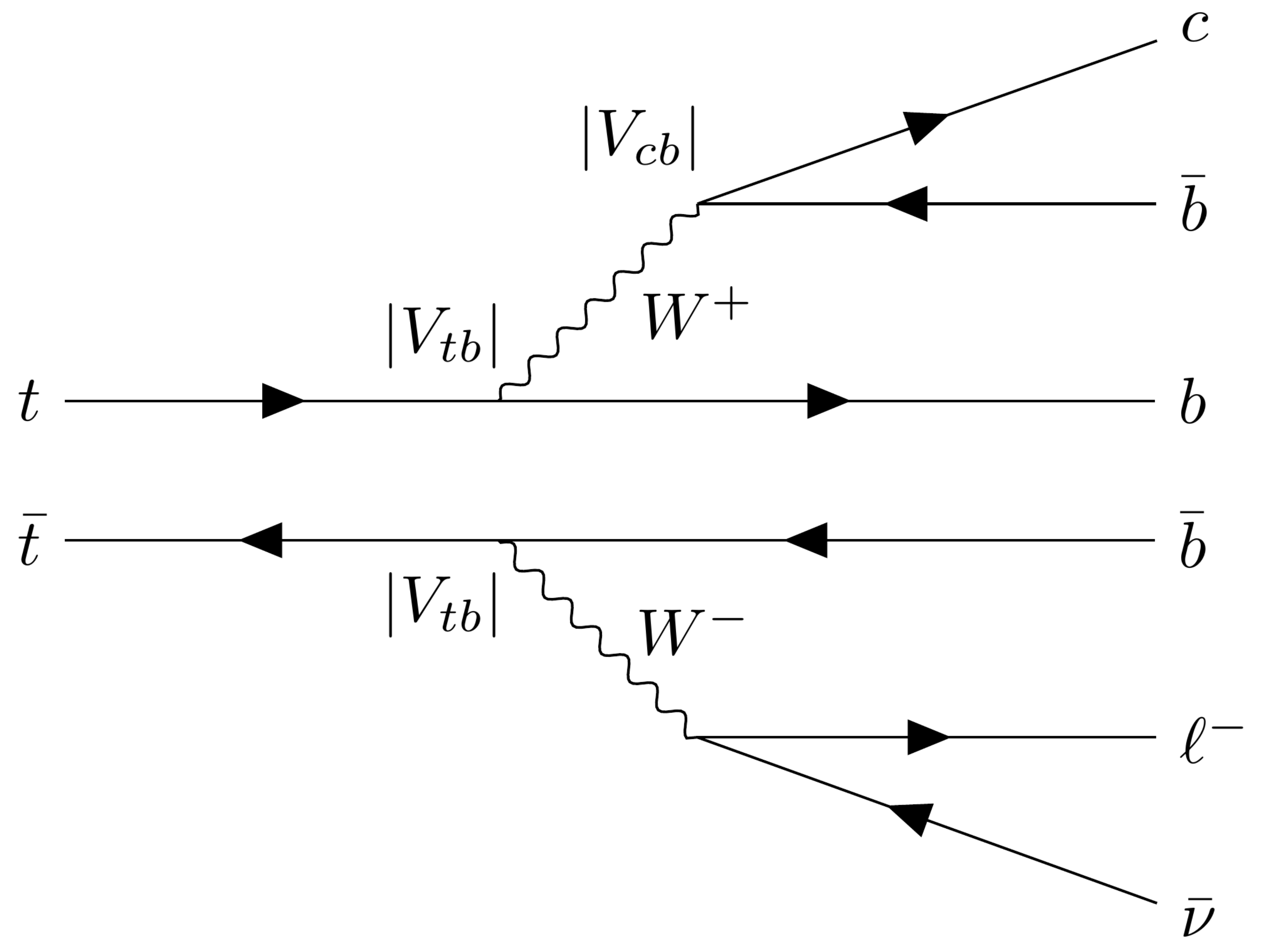
† $W^- \to \bar{c}b$ decays are also included

Overview of the analysis strategy

- The analysis targets $W \to cb$ decays in single lepton $t\bar{t}$ events

Event selection:

- Full Run 2 ATLAS dataset
- Trigger on single electron or muon above 27 GeV† and with $|\eta| < 2.5$
- Exactly 4 jets above 25 GeV and with $|\eta| < 2.5$
- At least 1 b-tagged and 2 b- or c-tagged jets



- A neural network (NN) classifier is used to reduce backgrounds

- Cannot use central ATLAS c-jet calibration since it uses a fixed $|V_{cb}|$
  $\Longrightarrow$ c-jet efficiency and mis-tag rates calibrated in-situ

$$|V_{cb}|^2 = \frac{\mathrm{BF}(W \to cb)}{\mathrm{BF}(W \to cq)} = \frac{\mathrm{BF}(t\bar{t} \to b\,cb, b\,\ell\nu)}{\mathrm{BF}(t\bar{t} \to b\,cq, b\,\ell\nu)}$$

- $|V_{cb}|$ extracted from the $W \to cb$ signal normalisation in a binned profile likelihood fit

† for 2015 simulation and data a 25 GeV cut is used

Flavour tagging working point definitions

- Need to find jets that originate from b- or c-quarks

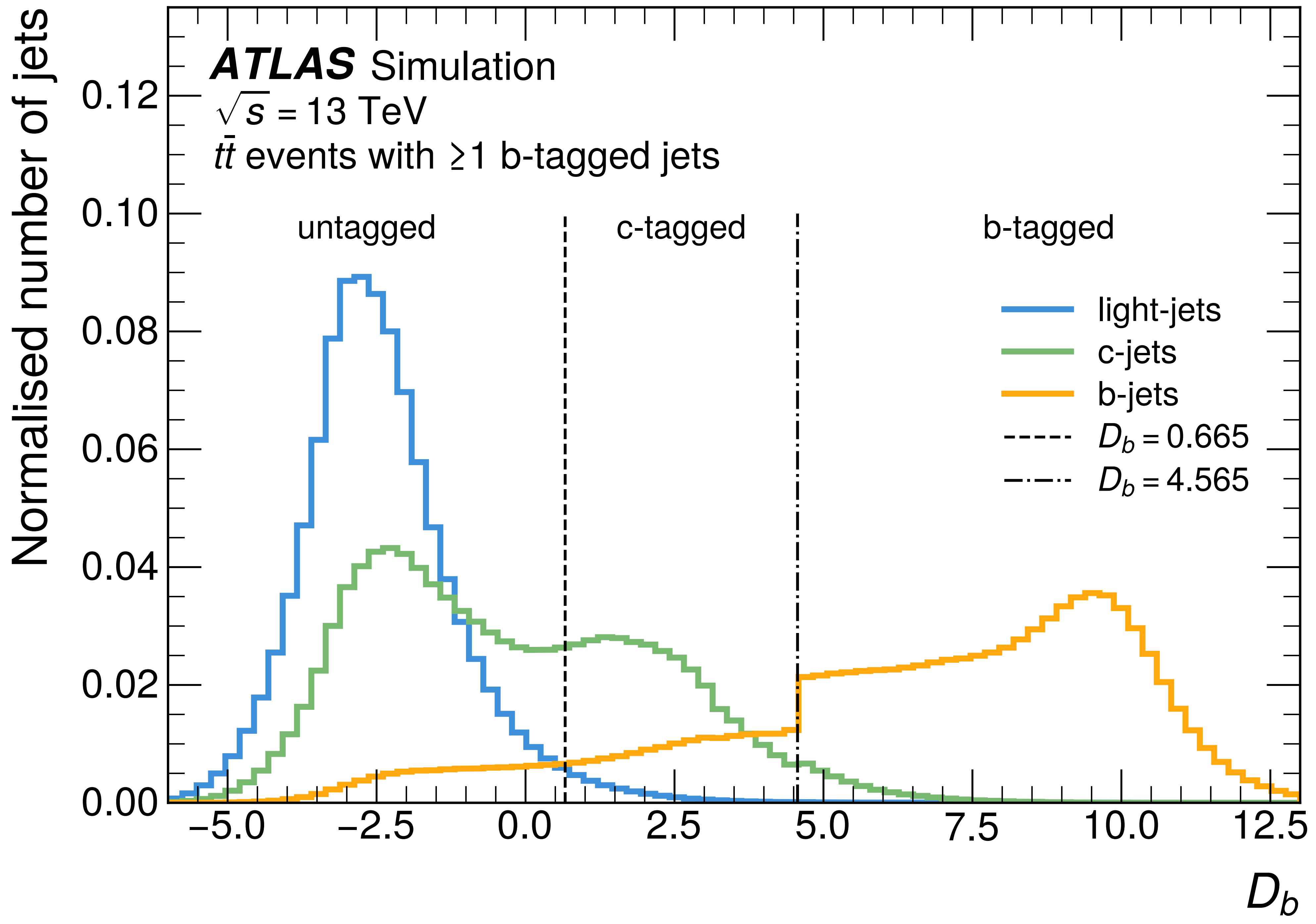
Jets tagged by DL1r algorithm:

- b-tagged jets: pass the 60% b-efficiency working point
- c-tagged jets: jets between the 60% — 85% b-efficiency working points, good proxy for c-tagging

- Analysis tagging categories defined by the number of b- and c-tagged jets:

  1b1c, 2b0c,
  1b2c, 2b1c, 3b0c
  1b3c, 2b2c, 3b1c

- Tagging category 3b1c is most sensitive to the signal



DL1r discriminant distribution for selected jets (each jet class normalised)

Simulated MC samples

Signal:

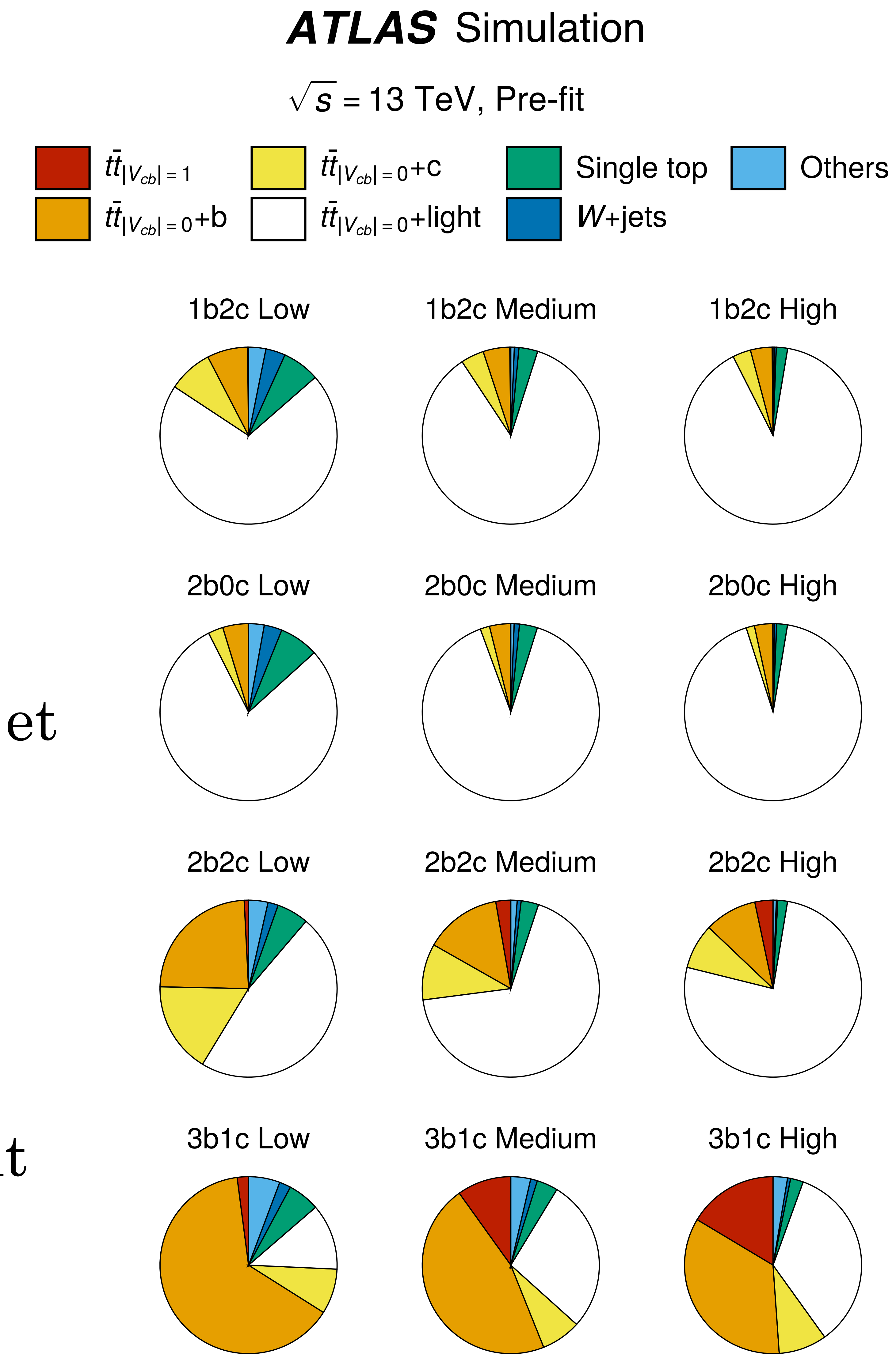
- $t\bar{t}_{|Vcb|=1}$, one W boson decays as $W \to cb$ while the other decays leptonically

Backgrounds:

- $t\bar{t}_{|Vcb|=0}$, only V_{ud}, V_{us}, V_{cd}, V_{cs} and V_{tb} are non-zero for this sample
- $t\bar{t}$ events split by HF content: $t\bar{t}$ + light/c/b
- Minor backgrounds: single top, V+jets, diboson and $t\bar{t} + H/V$ events, multi-jet

- 3b1c dominated by $t\bar{t}$ events, especially $t\bar{t} + b$

- Normalisations of $t\bar{t}$, $t\bar{t} + b$, $t\bar{t} + c$ and $t\bar{t}_{|Vcb|=1}$ events are free-floating in the fit



Neural network classifier

Goals:

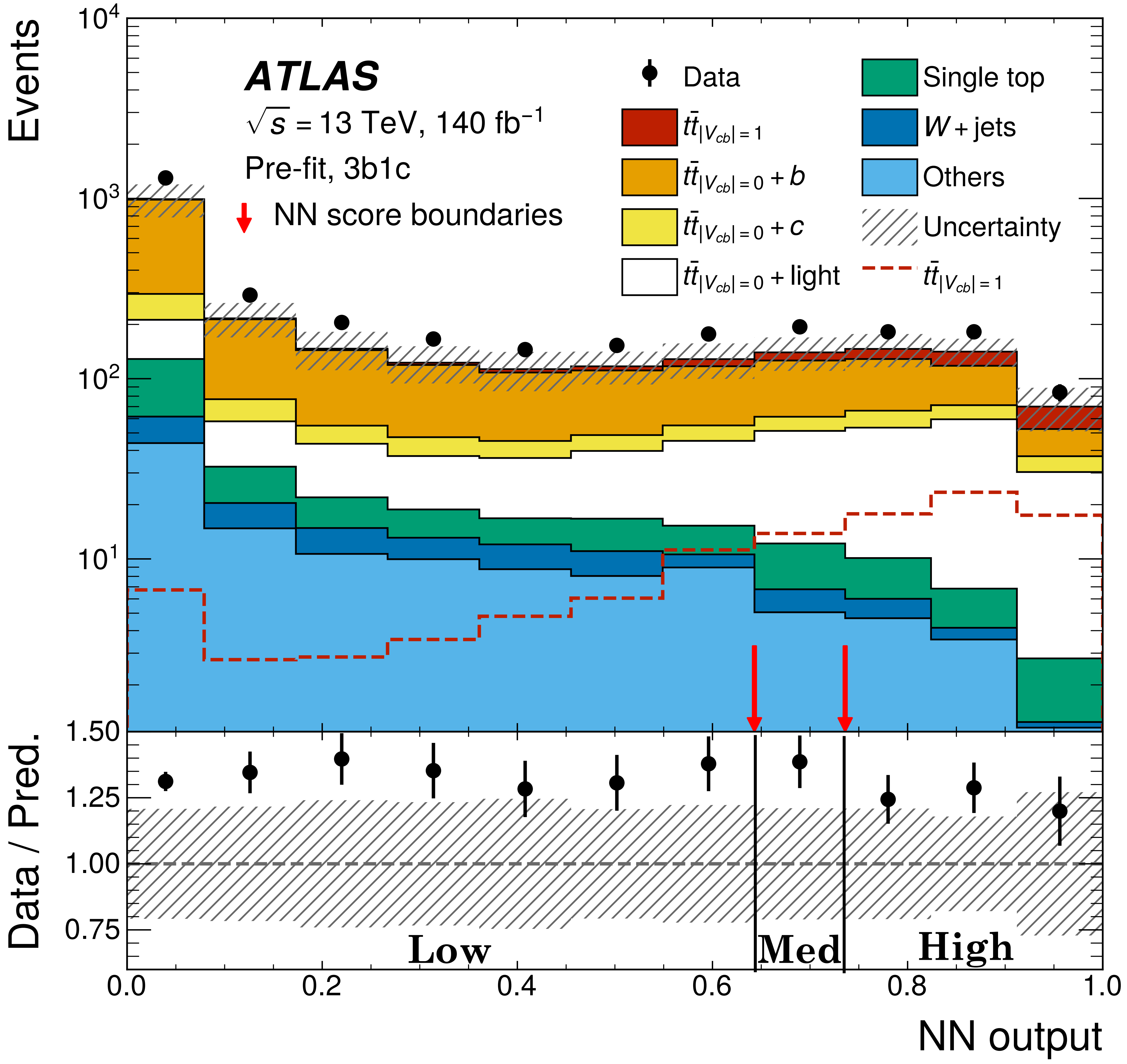
- Find events with all 4 jets from $t\bar{t}$ system, truth matched to partons (complete)
- Reject backgrounds (typically not complete)

Binary task neural network:

- Finds complete events
- Effectively separates complete $t\bar{t}$ events from $t\bar{t}$+HF and other backgrounds
- Events split into Low/Medium/High NN score (used for fit)
- Inputs used:

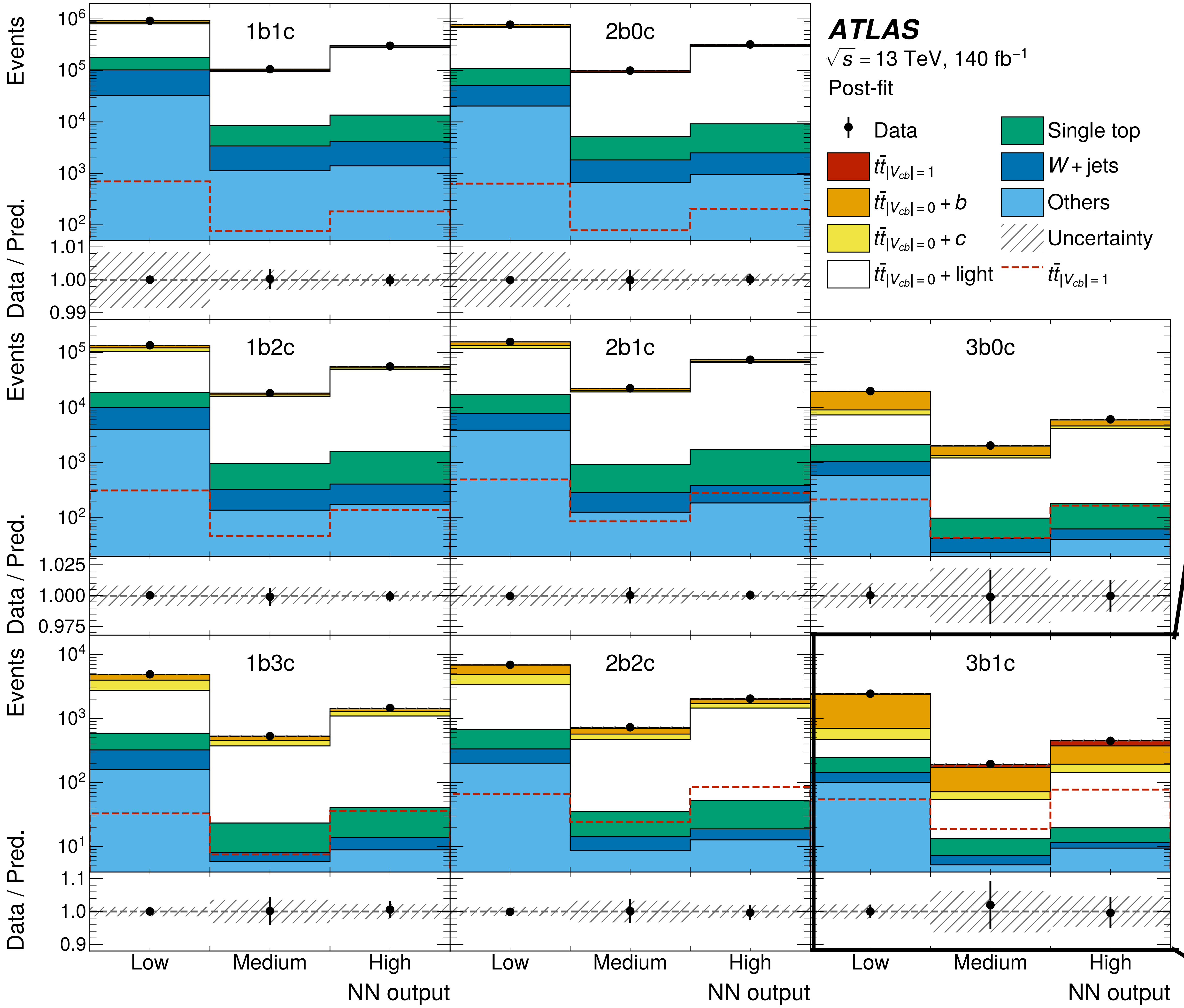
Neural network inputs:

1st jet p_T	$\Delta R(\ell, t_d^{\text{lep}})$
2nd jet p_T	$\Delta R(t_d^{\text{had.}}, t_d^{\text{lep.}})$
3rd jet p_T	$\Delta R(t_d^{\text{had.}}, W_{d1}^{\text{had.}})$
4th jet p_T	$\Delta R(t_d^{\text{had.}}, W_{d2}^{\text{had.}})$
Lepton p_T	$\Delta R(W_{d1}^{\text{had.}}, W_{d2}^{\text{had.}})$
Lepton E	$\Delta R(t, \bar{t})$
MET	t^{lep} mass
$\Delta R(\ell, \nu)$	W^{had} mass
$t\bar{t}$ mass	t^{had} mass

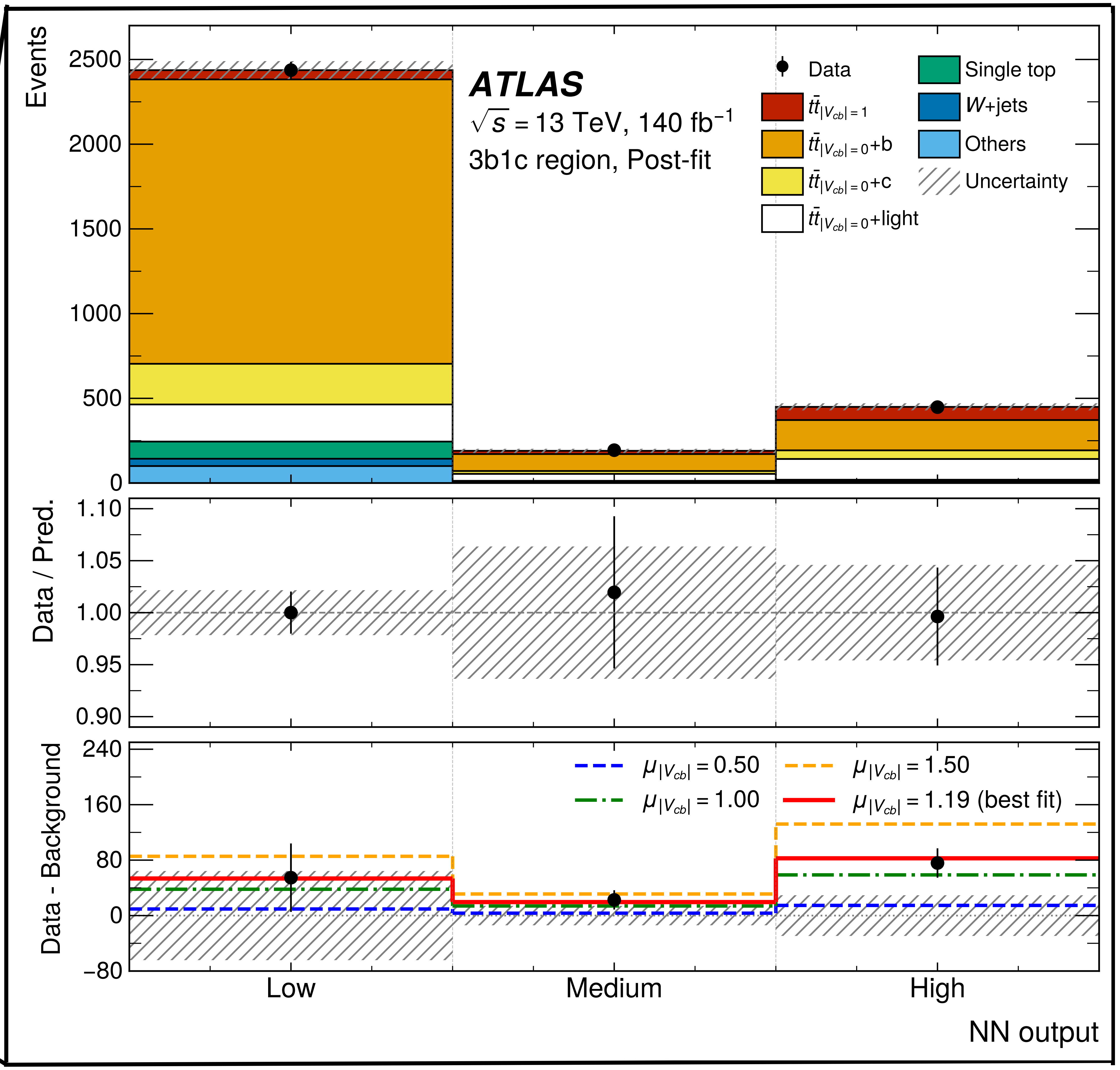


Pre-fit NN distribution in the region with 3 b-tagged and 1 c-tagged jet

Post-fit yields - all fit regions



Post-fit yield in all bins used in the fit

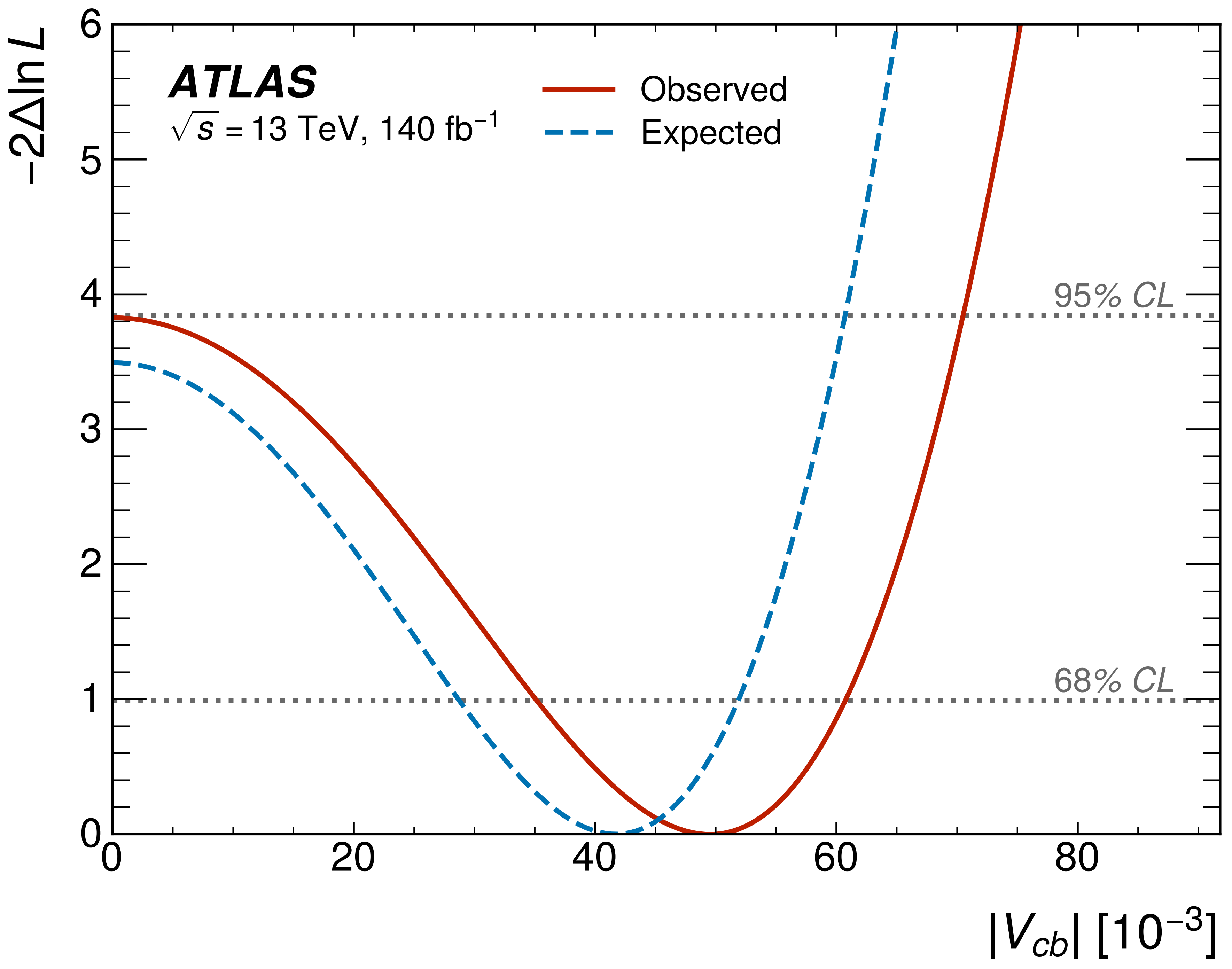


Post-fit yields in the 3b1c region

Results

Measured $|V_{cb}|$ value: $|V_{cb}| = \left(50^{+11}_{-14}\right) \times 10^{-3} = \left(50^{+7}_{-9}\,(\text{stat.})\,^{+9}_{-10}\,(\text{syst.})\right) \times 10^{-3}$

- Uncertainty in $|V_{cb}|$ balanced between stat. and syst. uncertainty, most impactful syst. uncertainty is $t\bar{t}$ modelling
- Measurement agrees well with results from B-hadron decays
- Background normalisations and charm tagging rates consistent with previous ATLAS measurements



Negative log likelihood scan of $|V_{cb}|$, both expected and observed

Uncertainty	Up/Down [10^{-3}]
Modelling of $t\bar{t}$	8/9
↪ PS and hadronisation	5/6
↪ Others	5/6
Jet flavour tagging calibration	2.9/3.1
↪ Light-jet	2.5/2.8
↪ b-jet	1.2/1.3
Simulation statistical uncertainty	2.6/2.7
Jet calibration	2.4
Modelling of non-$t\bar{t}$ processes	1.6
Others	0.8
Systematic uncertainty	9/10
Statistical uncertainty	7/9
Total uncertainty	11/14

Uncertainty breakdown in $|V_{cb}|$

Summary and outlook

- First first measurement of $|V_{cb}|$ in $t\bar{t}$ events:

$$|V_{cb}| = \left(50^{+11}_{-14}\right) \times 10^{-3} = \left(50^{+7}_{-9}\ (\text{stat.})\ ^{+9}_{-10}\ (\text{syst.})\right) \times 10^{-3},$$

compatible with the current world average of $|V_{cb}|_{\text{world avg.}} = (41.1 \pm 1.2) \times 10^{-3}$

- The systematic and statistical uncertainty are of similar size, with $t\bar{t}$ modelling being the main contribution to the systematic uncertainty

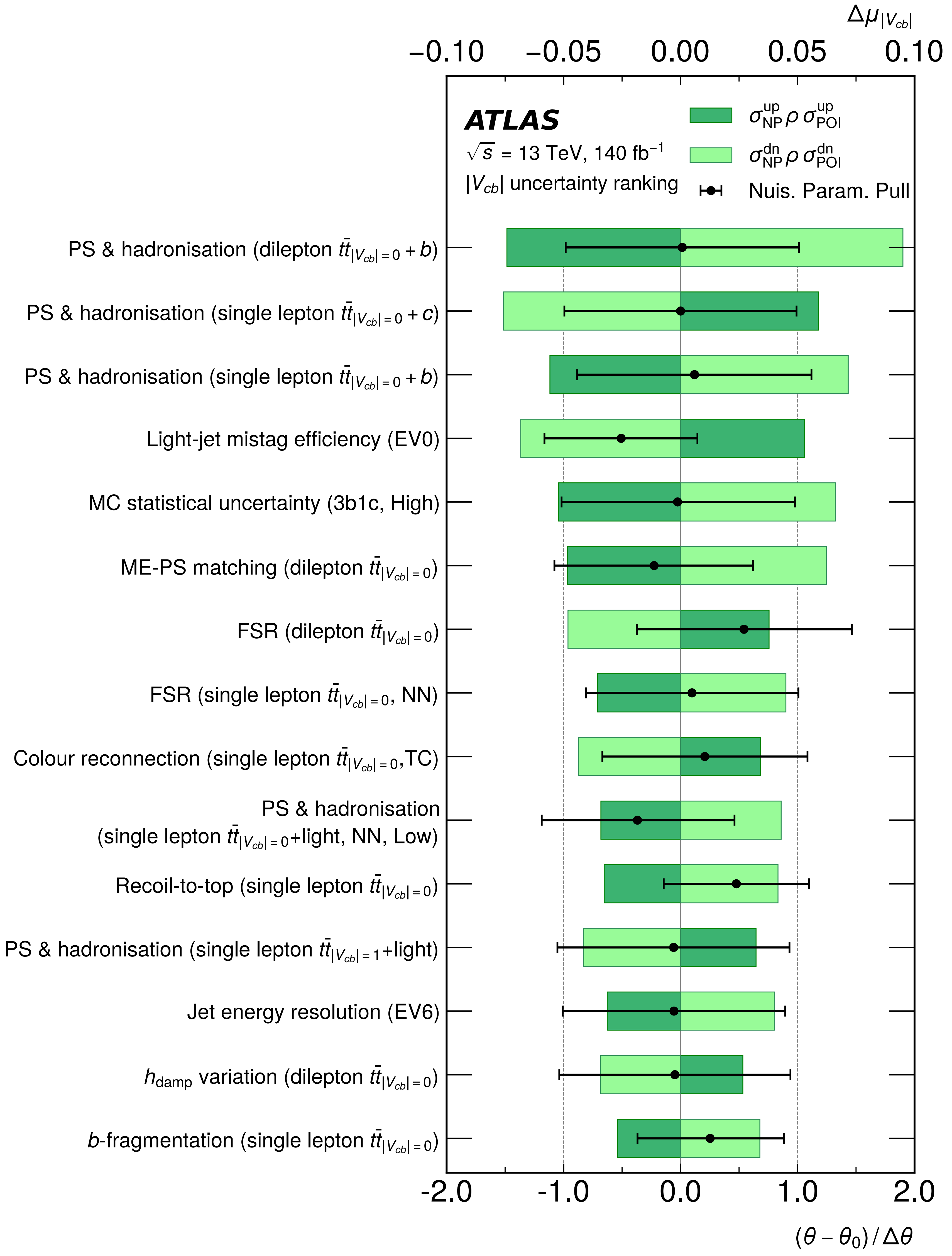
- This is the first measurement involving on-shell W bosons and is probing the weak scale, but the $|V_{cb}|$ uncertainty is not yet competitive with B-factory results

- Several things to look forward to: Run 3 data, improved flavour tagging (dedicated charm tagging), improved $t\bar{t}$ reconstruction and modelling, etc.

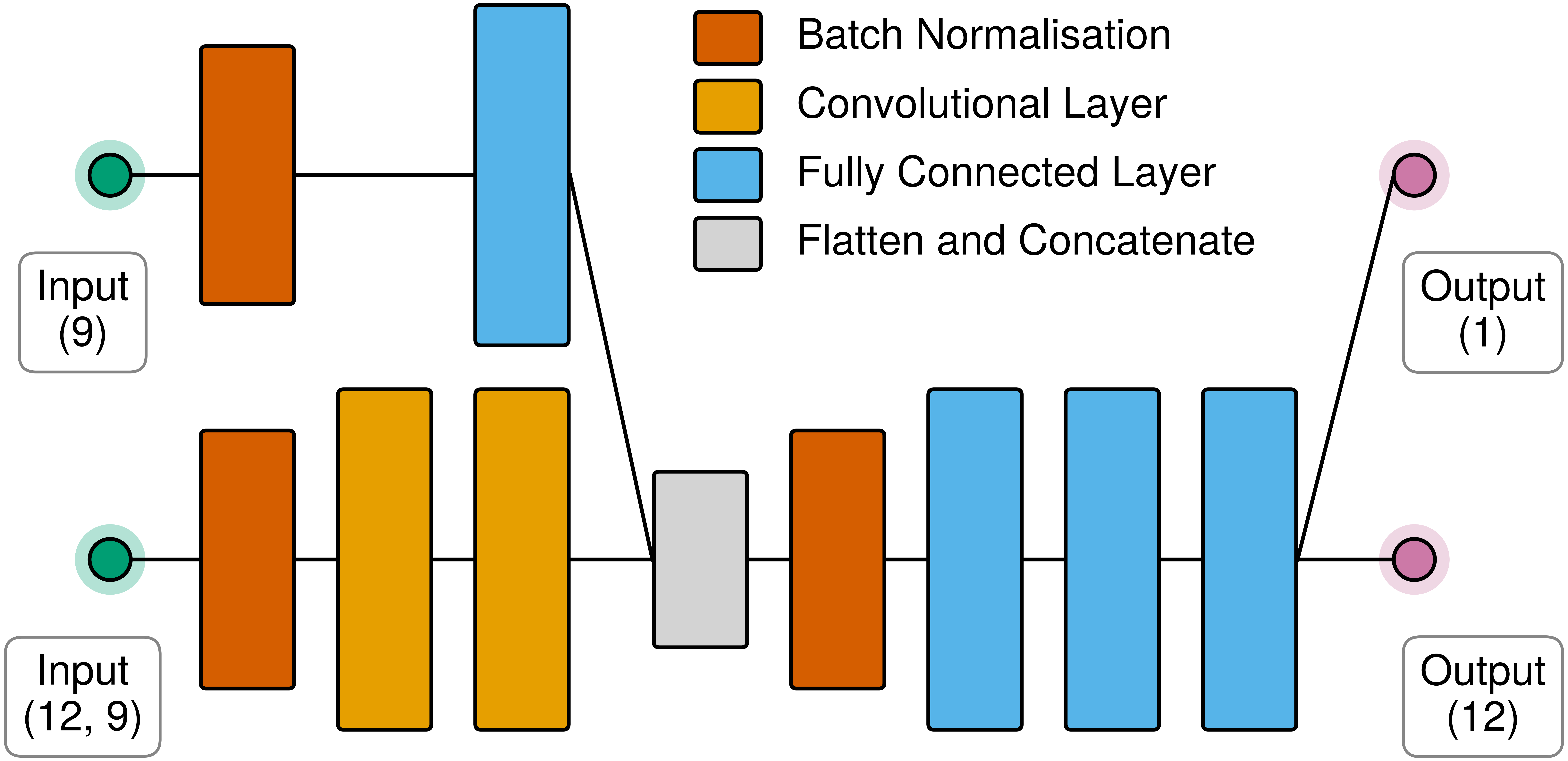
Backup slides

Ranking of the largest systematic uncertainties

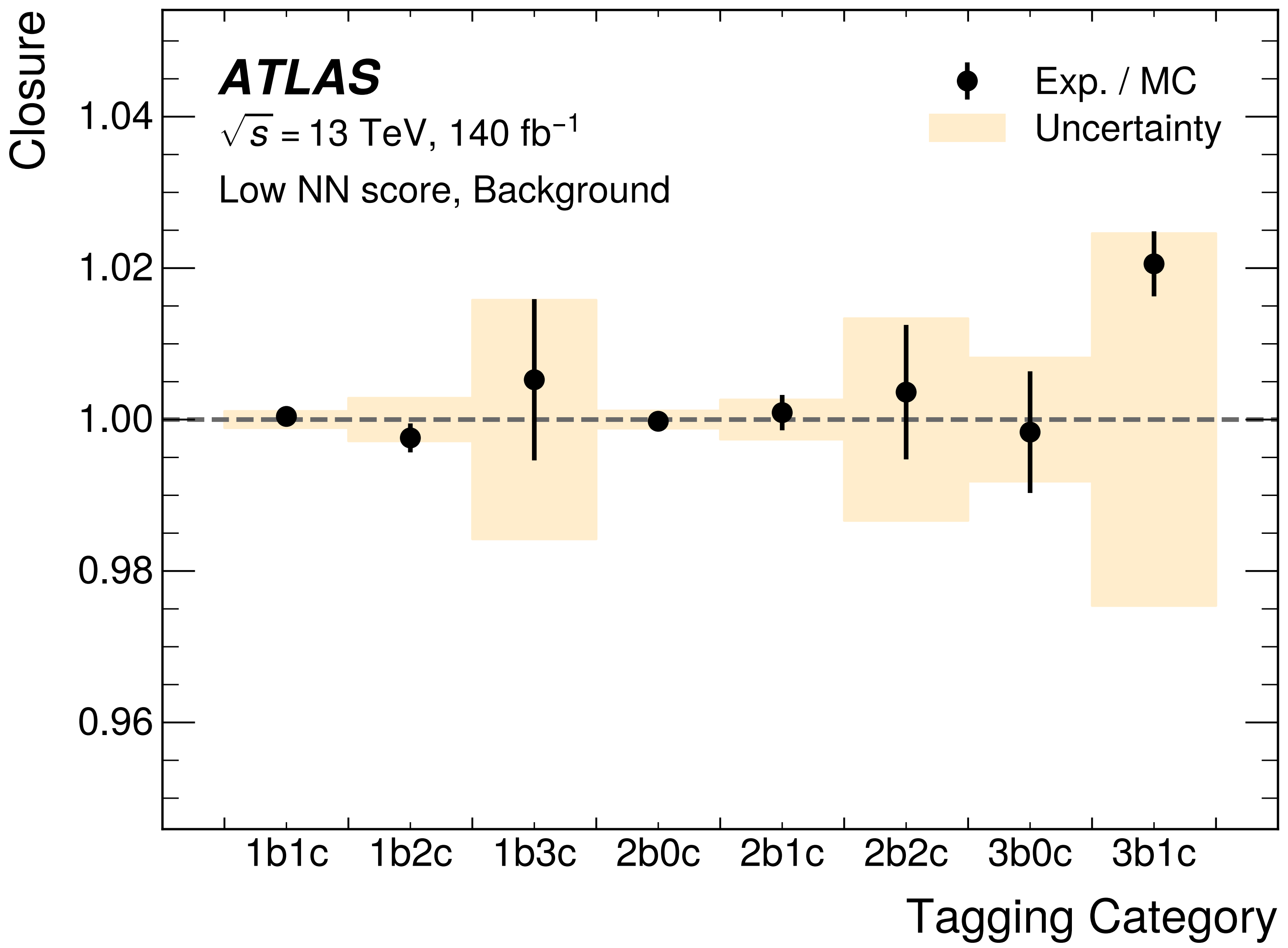
- Ranking of the impact in the $|V_{cb}|$ uncertainty for the systematic uncertainties, using the covariance method

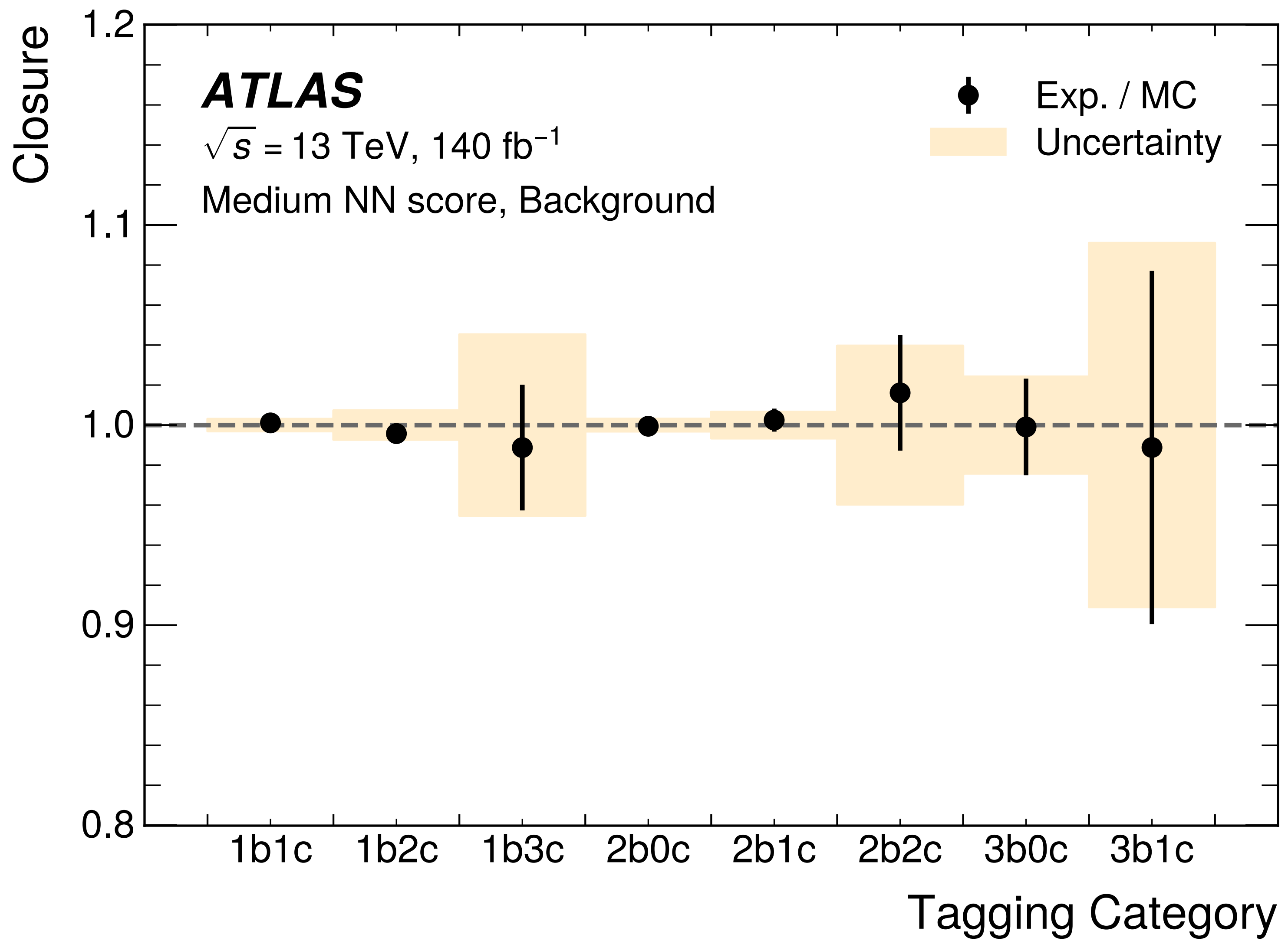


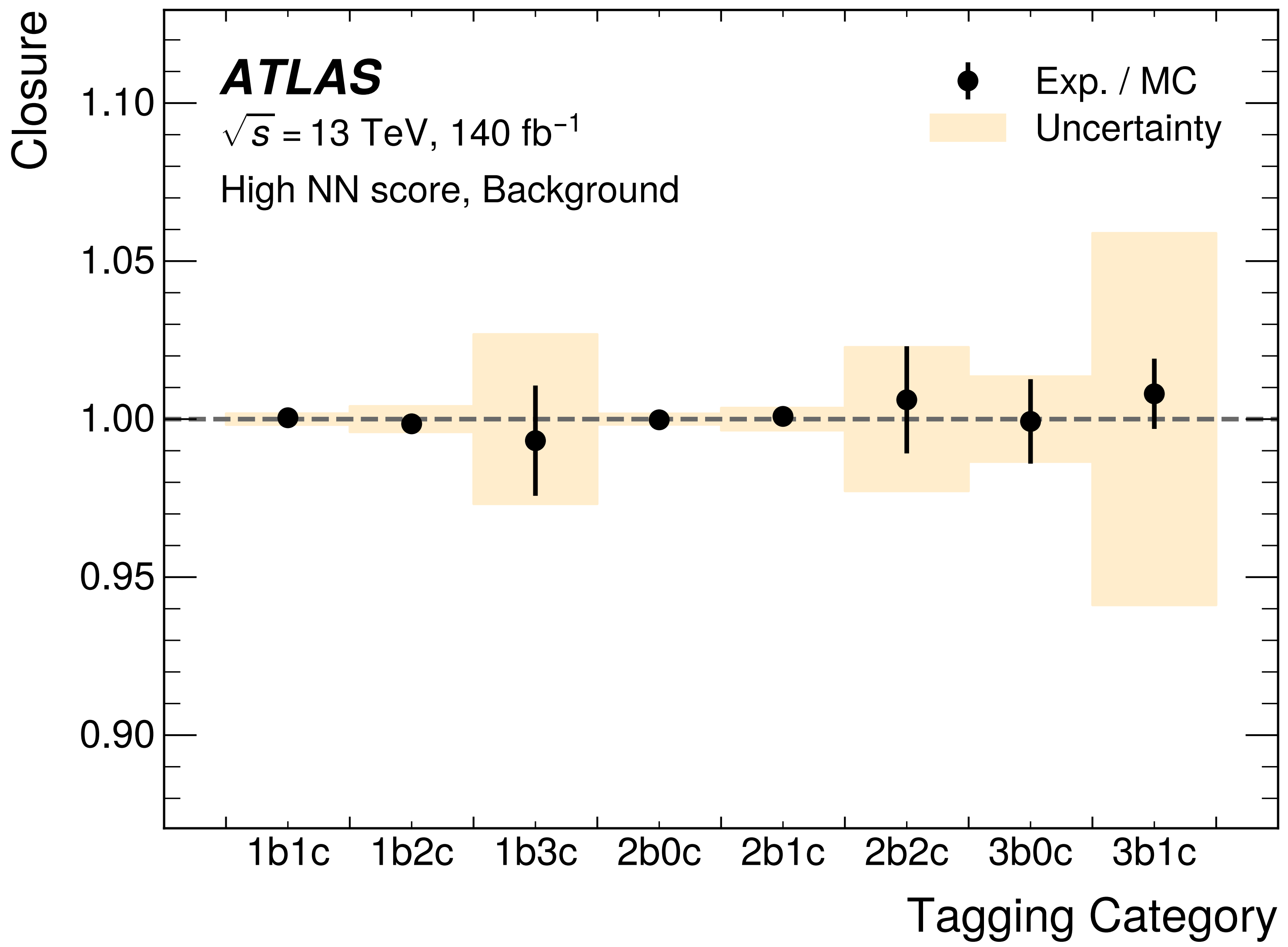
NN architecture

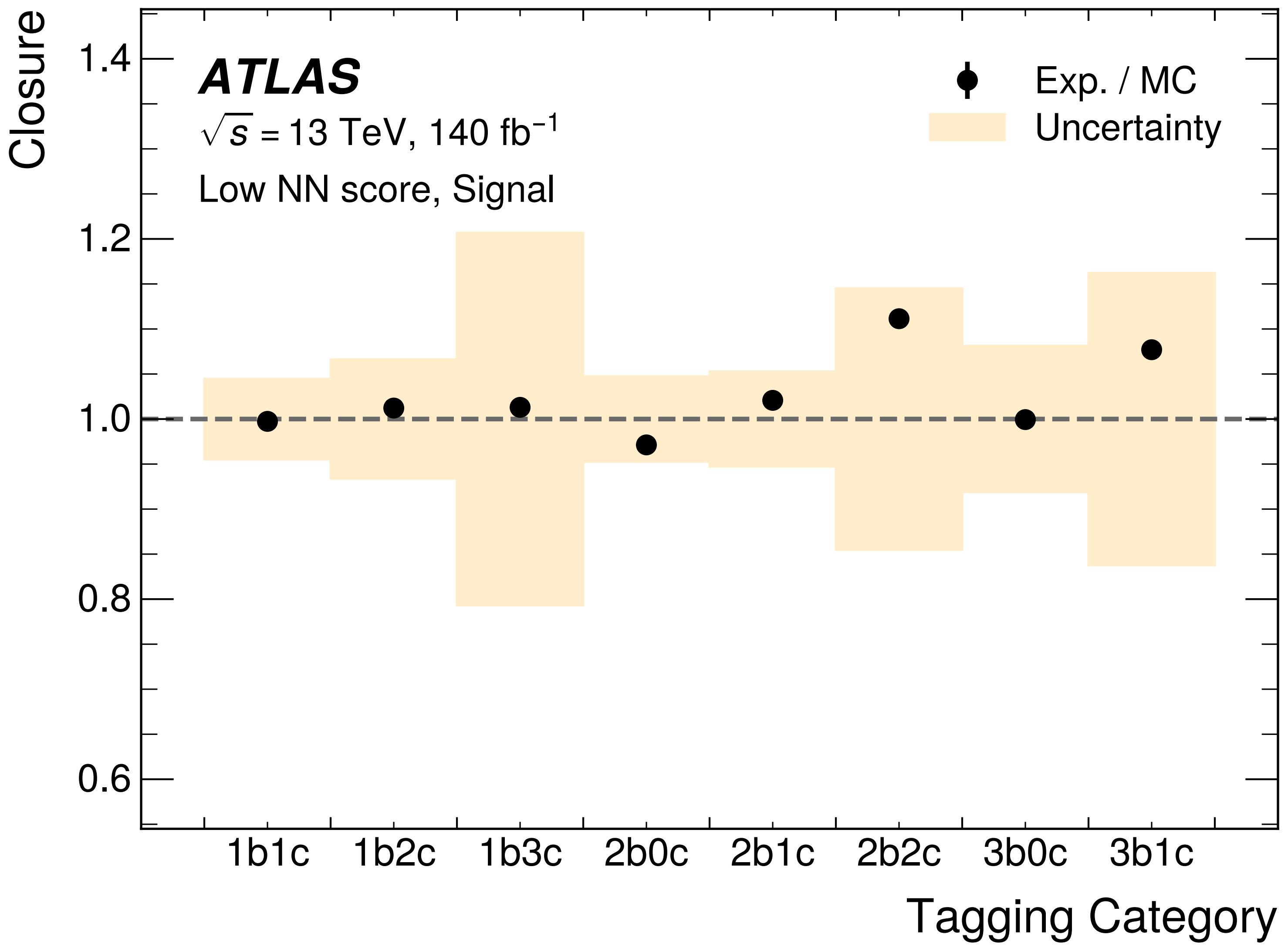


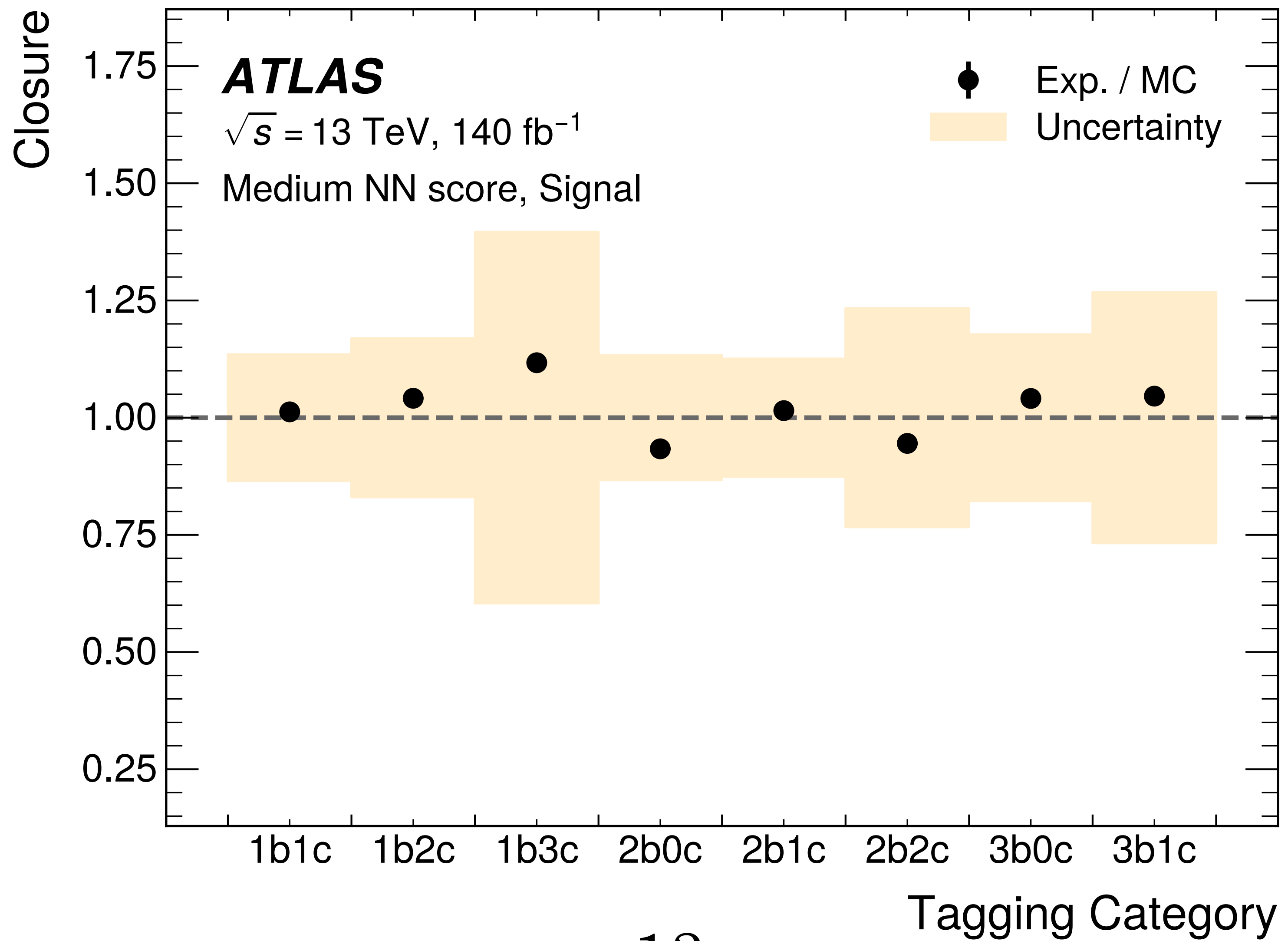
Charm-tagging closure plots (all within statistical uncertainty)

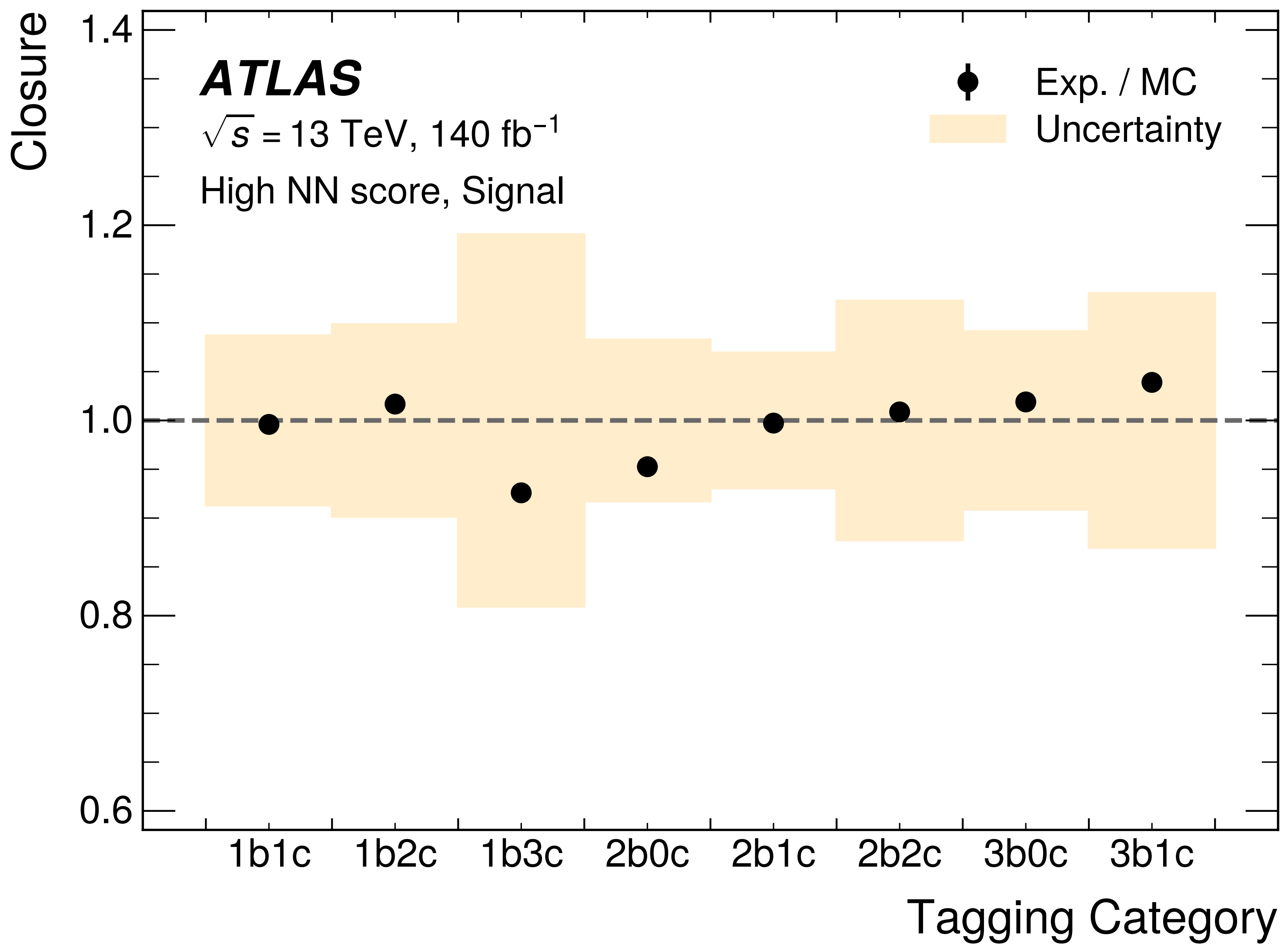




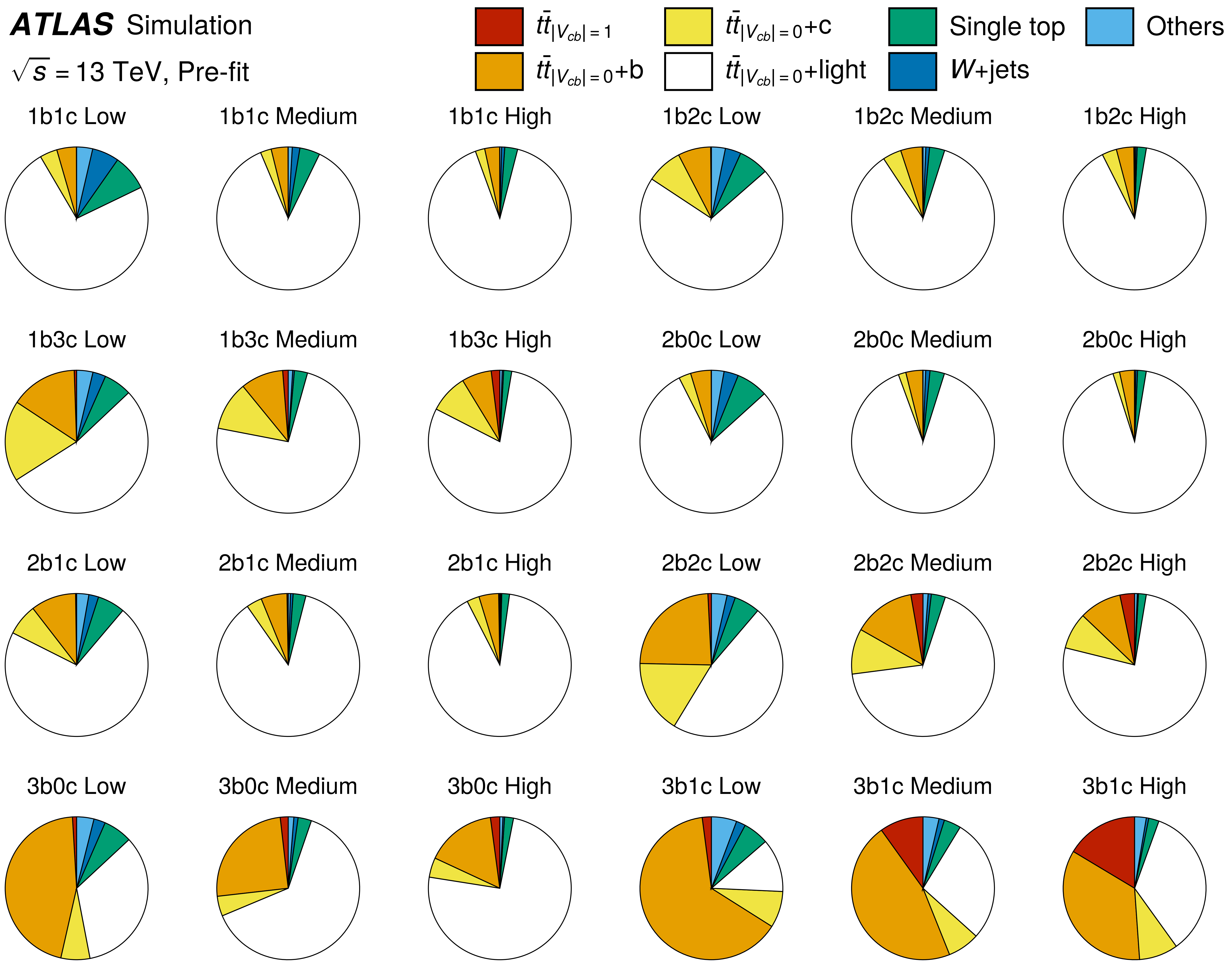








Pie charts over pre-fit yield in all analysis regions



In-situ charm jet calibration

- Charm jet efficiency ε_c and $c \to b$ mis-tag rate f_{cb} calibrated in two steps

$(\varepsilon_x \equiv f_{xx})$

- First, in MC, best fit tagging parameters found by minimising χ^2:

$$\chi^2 = \sum_{j=1}^{8} \left(\frac{N_j - N \cdot p_j(T)}{\Delta N_j} \right)^2, \quad T = \begin{pmatrix} \varepsilon_l & f_{lc} & f_{lb} \\ f_{cl} & \varepsilon_c & f_{cb} \\ f_{bl} & f_{bc} & \varepsilon_b \end{pmatrix}$$

Uses central calibration

Calibrated in-situ

Rows sum to 1 $\Longrightarrow$ 6 free parameters

N_j: Number of events in tagging category j, ΔN_j is the uncertainty

N: Total number of events

$p_j(T)$: Probability of an event ending up in region j given T and the true jet flavours of the event

- Kinematic efficiency dependence $\Longrightarrow$ efficiency fit separately in the Low, Medium and High NN regions

- Best fit parameters fixed, except for ε_c and f_{cb}, which are free floating in the fit to data

Results and uncertainty breakdown

- The best-fit value is $|V_{cb}| = \left(50^{+11}_{-14}\right) \times 10^{-3} = \left(50^{+7}_{-9}\ (\text{stat.})\ ^{+9}_{-10}\ (\text{syst.})\right)$

- Uncertainty in $|V_{cb}|$ balanced between stat. and syst. uncertainty, most impactful syst. uncertainty is $t\bar{t}$ modelling

- $t\bar{t}$+HF normalisations larger than predicted in MC, but agree with previous ATLAS measurements (Phys. Lett. B 860 (2025) 139177)

- Charm tagging rates consistent between NN bins, agree with central ATLAS calibrations (Eur. Phys. J. C 82 (2022) 95)

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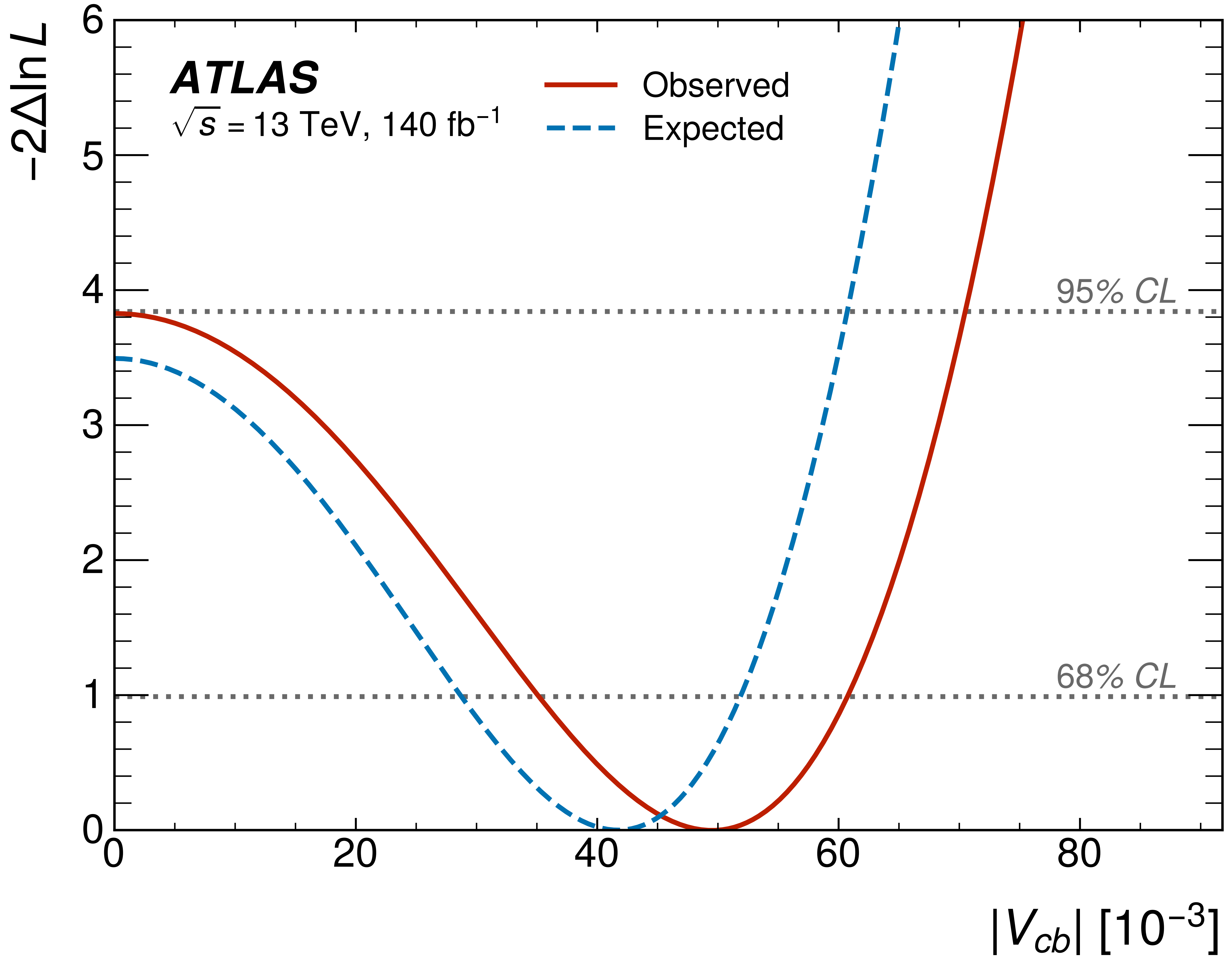
Uncertainty breakdown in $|V_{cb}|$

Parameter	Value	Parameter	Value		
			Low	Med	High
$\mu_{V_{cb}}$	$1.19^{+0.27}_{-0.35}$				
$\mu_{t\bar{t}}$	0.99 ± 0.03	ϵ_c	0.35 ± 0.02	0.34 ± 0.02	$0.33^{+0.02}_{-0.01}$
$\mu_{t\bar{t}+c}$	$1.60^{+0.64}_{-0.60}$	f_{cb} (10^{-3})	25 ± 6	26 ± 3	26 ± 2
$\mu_{t\bar{t}+b}$	$1.45^{+0.54}_{-0.34}$				

Post-fit values of all free parameters of the fit

Negative log likelihood scan



Charm jet efficiency and mistag rate scale factors