Measurement of CKM matrix element |Vcb| in $t\bar{t}$ decays with the ATLAS detector

arxiv:2603.16414 (accepted by JHEP)

Bowen Zhang
Warwick EPP Seminar - 18 June 2026

Outline

- **CKM matrix and new |Vcb| extraction**
- **Top-quark physics in ATLAS**
  - Some recent results
- **Measurement of |Vcb| using top-quark events with ATLAS**
  - Challenges
  - Analysis setup
  - Results
- **Conclusion and Outlook**

CKM

1963

UNITARY SYMMETRY AND LEPTONIC DECAYS

Nicola Cabibbo
CERN, Geneva, Switzerland
(Received 29 April 1963)

(3) J_μ has "unit length," i.e., $a^2+b^2=1$. We then rewrite J_μ as[4]

$$J_\mu = \cos\theta(j_\mu^{(0)}+g_\mu^{(0)}) + \sin\theta(j_\mu^{(1)}+g_\mu^{(1)}), \qquad (2)$$

where $\tan\theta = b/a$. Since J_μ, as well as the baryons and the pseudoscalar mesons, belongs to the octet representation of SU_3, we have relations (in which θ enters as a parameter) between processes with $\Delta S=0$ and processes with $\Delta S=1$.

To determine θ, let us compare the rates for $K^+\to\mu^++\nu$ and $\pi^+\to\mu^++\nu$; we find

$$\Gamma(K^+\to\mu\nu)/\Gamma(\pi^+\to\mu\nu) = \tan^2\theta M_K(1-M_\mu^2/M_K^2)^2/M_\pi(1-M_\mu^2/M_\pi^2)^2. \qquad (3)$$

From the experimental data, we then get[5,6]

$$\theta = 0.257. \qquad (4)$$

1973

Progress of Theoretical Physics, Vol. 49, No. 2, February 1973

***CP*-Violation in the Renormalizable Theory of Weak Interaction**

Makoto KOBAYASHI and Toshihide MASKAWA

Department of Physics, Kyoto University, Kyoto

(Received September 1, 1972)

Next we consider a 6-plet model, another interesting model of *CP*-violation. Suppose that 6-plet with charges $(Q, Q, Q, Q-1, Q-1, Q-1)$ is decomposed into $SU_{weak}(2)$ multiplets as $2+2+2$ and $1+1+1+1+1+1$ for left and right components, respectively. Just as the case of (A, C), we have a similar expression for the charged weak current with a 3×3 instead of 2×2 unitary matrix in Eq. (5). As was pointed out, in this case we cannot absorb all phases of matrix elements into the phase convention and can take, for example, the following expression:

$$\begin{pmatrix} \cos\theta_1 & -\sin\theta_1\cos\theta_3 & -\sin\theta_1\sin\theta_3 \\ \sin\theta_1\cos\theta_2 & \cos\theta_1\cos\theta_2\cos\theta_3-\sin\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\cos\theta_2\sin\theta_3+\sin\theta_2\cos\theta_3 e^{i\delta} \\ \sin\theta_1\sin\theta_2 & \cos\theta_1\sin\theta_2\cos\theta_3+\cos\theta_2\sin\theta_3 e^{i\delta} & \cos\theta_1\sin\theta_2\sin\theta_3-\cos\theta_2\cos\theta_3 e^{i\delta} \end{pmatrix}. \qquad (13)$$

Then, we have *CP*-violating effects through the interference among these different current components. An interesting feature of this model is that the *CP*-violating effects of lowest order appear only in $\Delta S\neq0$ non-leptonic processes and in the semi-leptonic decay of neutral strange mesons (we are not concerned with higher states with the new quantum number) and not in the other semi-leptonic, $\Delta S=0$ non-leptonic and pure-leptonic processes.

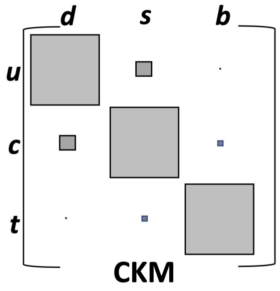
Toshihide Maskawa (益川 敏英)

Deciding to finish this work by writing a poor paper and thinking up an excuse, I got out of the bathtub. Probably this may have freed me from sticking to the four quark model. Suddenly, I recognized that it must work well in the six quark model. It was already clear from our many trials and calculations up until then that a complex phase could remain there.

CKM matrix

- Unitary complex matrix that governs quark mixing and CP violation in flavour-changing weak interaction in the Standard Model

$$V_{\mathrm{CKM}} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix} =$$

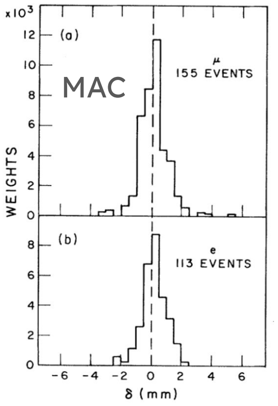


- Elements must be determined by experiments!

PDG 2025:

$$|V_{\mathrm{CKM}}| = \begin{pmatrix} 0.97435 \pm 0.00016 & 0.22501 \pm 0.00068 & 0.003732^{+0.000090}_{-0.000085} \\ 0.22487 \pm 0.00068 & 0.97349 \pm 0.00016 & 0.04183^{+0.00079}_{-0.00069} \\ 0.00858^{+0.00019}_{-0.00017} & 0.04111^{+0.00077}_{-0.00068} & 0.999118^{+0.000029}_{-0.000034} \end{pmatrix}$$

1983



$\tau_b = (1.8 \pm 0.6 \pm 0.4) \times 10^{-12}$ sec,

where the first error quoted is statistical and the second is systematic. This is the first non-zero result reported for τ_b.

$$\Gamma_b = \frac{1}{\tau_b} \propto \frac{|V_{cb}|^2 G_F^2 m_b^5}{192\pi^3}$$

Translate into |Vcb| ~ 0.04

CKM matrix

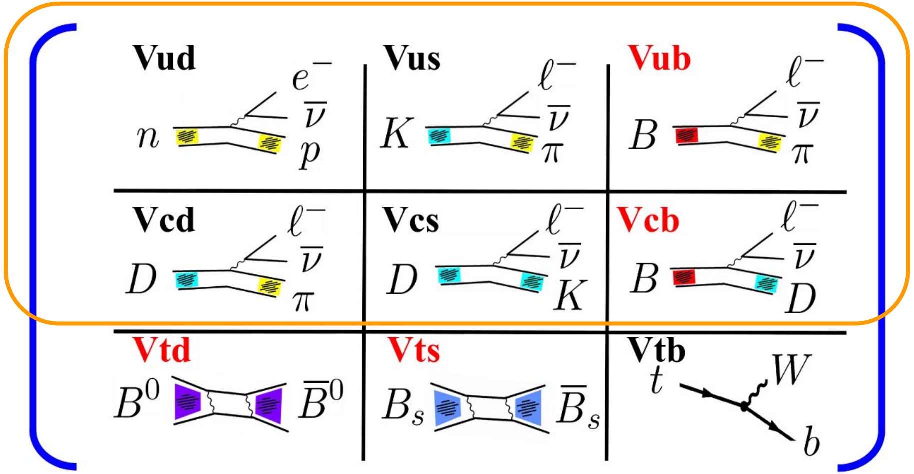


Image credit: Jolanta Brodzicka

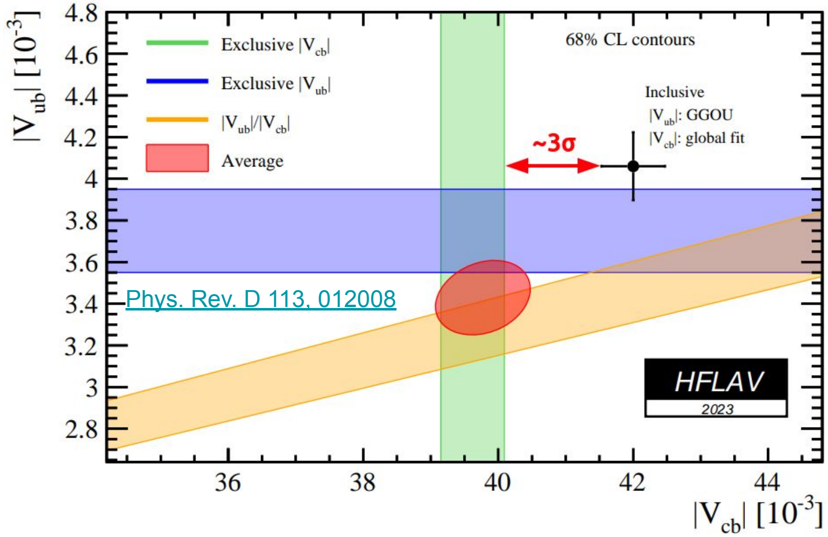
- Most precise measurements so far are made in semileptonic and leptonic decays of hadrons
- Limited by non-perturbative QCD knowledge (decay constants, form factors) which leads to inevitable theoretical uncertainty
- Can we measure them independent of hadrons?
- On-shell W decay! (e.g. LEP2 W->cs)
- What can be done with ATLAS and CMS?

Traditional |Vcb| measurements

- |Vcb| has so far (> 40 years) only been measured in semileptonic B-hadron decays (q ~ mb/2)
- Persistent 3σ tension between the inclusive and exclusive methods
- Both approaches depend closely on different theoretical inputs.

+ $|V_{cb}| = (42.2 \pm 0.5) \times 10^{-3}$ (inclusive)

■ $|V_{cb}| = (39.8 \pm 0.6) \times 10^{-3}$ (exclusive)



Phys. Rev. D 113, 012008

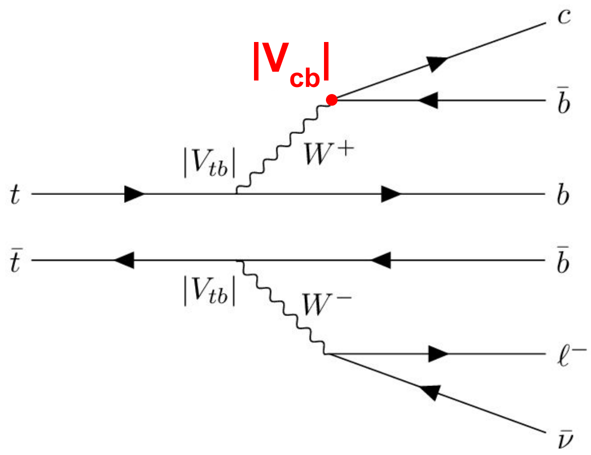
Decay Rate: **Γ** ∝ $|Vcb|^2$ **F**

- Inclusive: Decay rate is predicted using Heavy Quark Expansion (HQE). F contains HQE parameters that are extracted from data.
- Exclusive: Decay rate is measured in specific channels; The form factor F's shape is determined from data, whereas its normalisation relies on lattice calculation.
- (Both approaching 1% uncertainty..)

New |Vcb| measurement in on-shell W decays

- Proposal to measure |Vcb| in $t\bar{t}$ events: JHEP01(2019)191 [P. F. Harrison & V.E. Vladimirov]
- Offers an independent test to the tension in traditional low-energy extractions
  - Complementary approach, different source of uncertainties
- First measurement at weak scale (q ~ m_W) using on-shell W boson decays

Probes CKM suppressed t → bW → bcb



|Vcb| extracted from the ratio of W → cq BFs:

$$|V_{cb}|^2 = \frac{\mathcal{B}(W^+ \to c\bar{b})}{\mathcal{B}(W^+ \to c\bar{q})} = \frac{\mathcal{N}(t\bar{t} \to bc\bar{b}\ \bar{b}\ell^-\bar{\nu})}{\mathcal{N}(t\bar{t} \to bc\bar{q}\ \bar{b}\ell^-\bar{\nu})}$$ [*]

$\approx 1.7 \times 10^{-3}$

Additional physics potential:

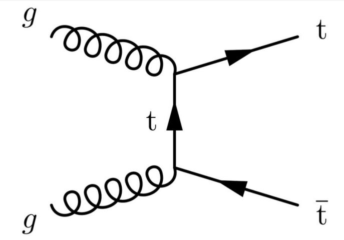
- ❏ Validation of energy scale dependence
- ❏ Any deviation from the world average could indicate new physics

[*] Ignore phase space difference of 0.25%

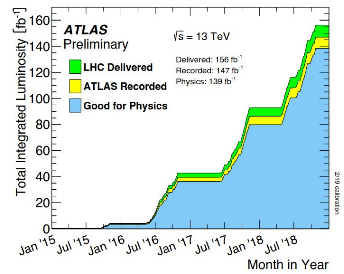
Top-quark physics in ATLAS

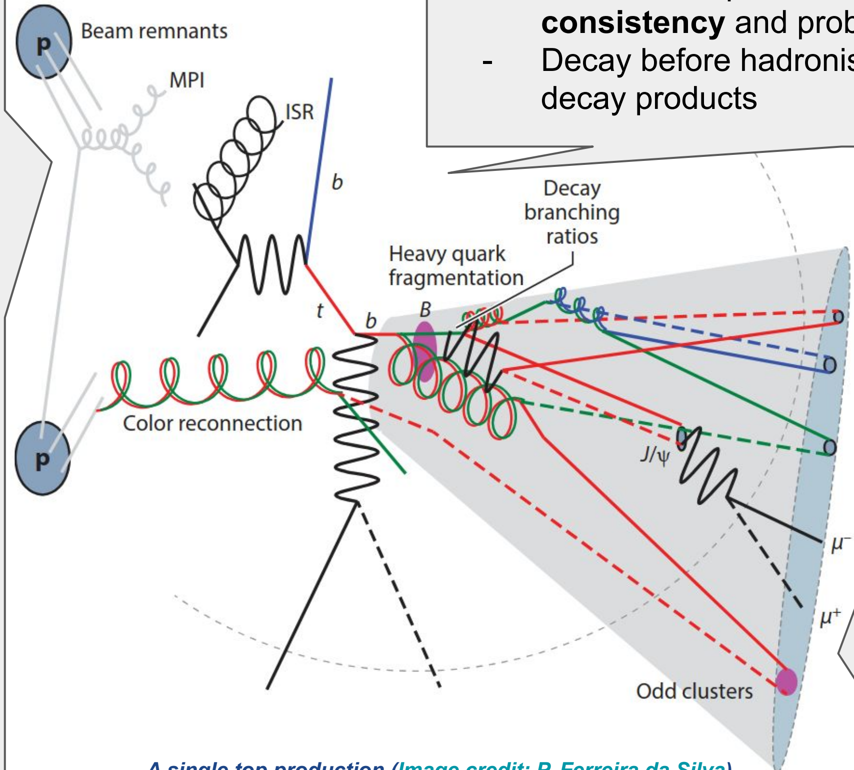
Production (QCD):

- Single production (|Vtx|)
- **Pair production: $t\bar{t}$**
- Associated production



About **100 million $t\bar{t}$** pairs produced in Run 2(3)





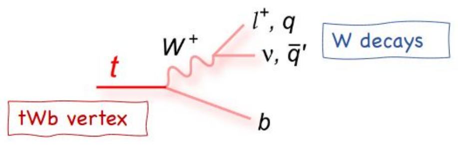
A single top production (Image credit: P. Ferreira da Silva)

Property:

- Heaviest known elementary particle: **m_t~172.5 GeV, y_t~1**
- Crucial in loop corrections of SM observables: test **SM consistency** and probe **BSM** phenomena
- Decay before hadronise: momentum and spin preserved in decay products

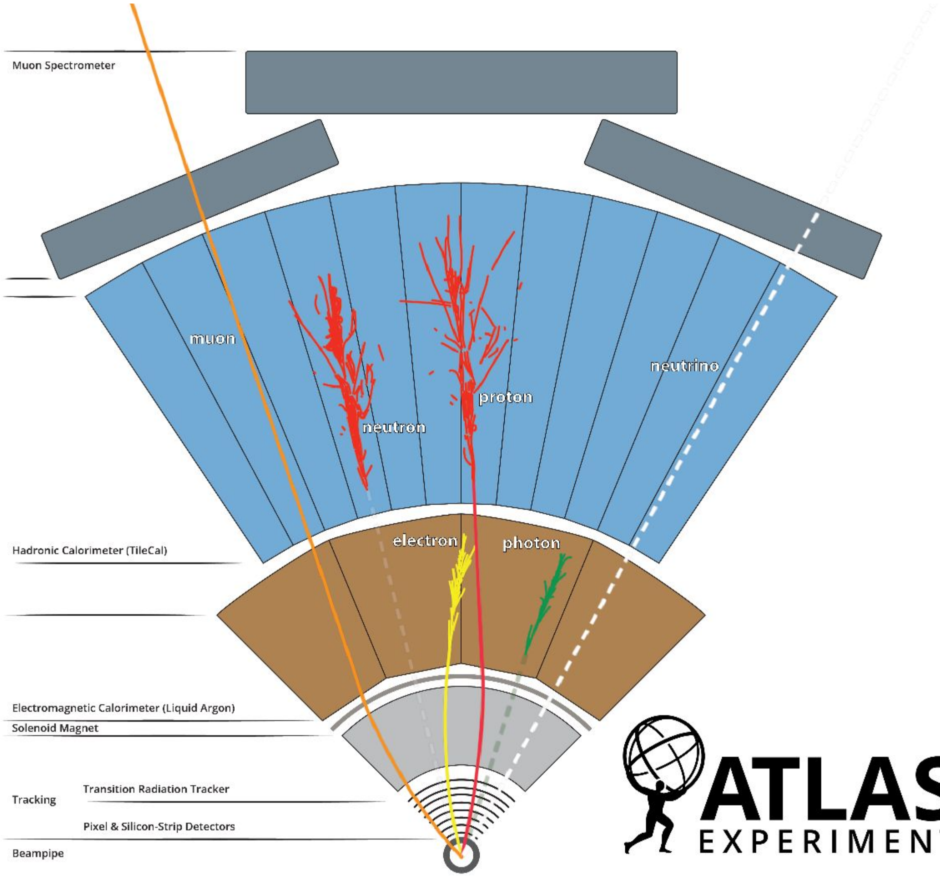
Decay:

- Exclusively decay to **Wb** (|Vtb|~1)



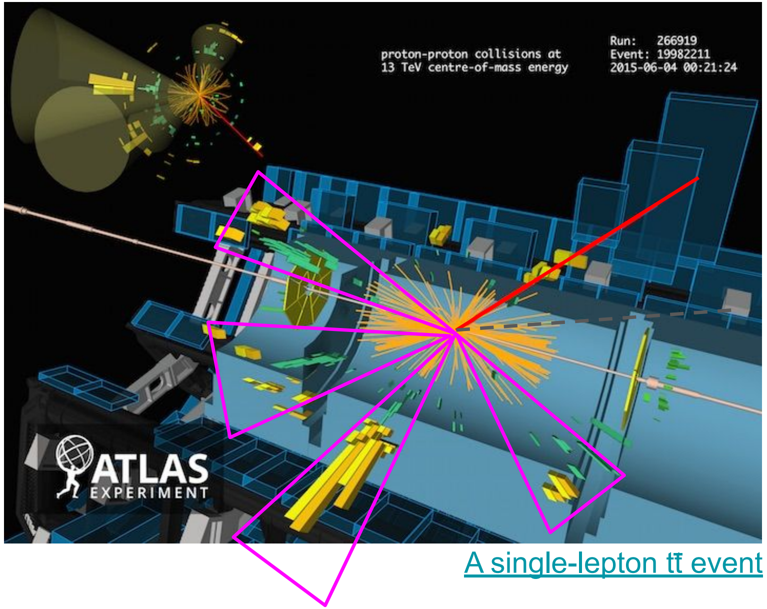
- **$t\bar{t}$ → 1L or 2L** often used (trigger on leptons) for low background levels
- W boson factory..
- Rare/BSM decays (FCNC, ..)

Top-quark analysis in ATLAS



About **40M** single-lepton **$t\bar{t}$** events with Run 2 data:

- Single lepton events with exactly 4 jets
- Neutrino appears as missing momentum



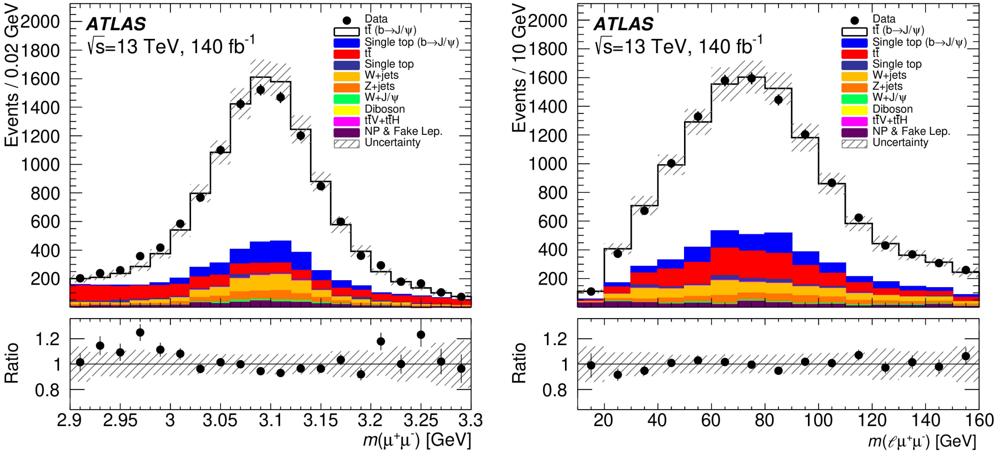
A single-lepton $t\bar{t}$ event

Mass measurement using J/ψ

JHEP 04 (2026) 099

Precision knowledge of m_t is crucial to test the internal consistency of the SM

- Historically limited by Jet Energy Scale (JES) and Resolution (JER) uncertainties
- This analysis uses a specific decay chain: $t \rightarrow (W \rightarrow \ell\nu)\ (b \rightarrow J/\psi + X \rightarrow \mu\mu + X)$ to avoid jet reconstruction and use fully lepton observables
- Main uncertainties are complementary to other analyses: Important for combination!
- Unbinned likelihood fit to $m(\ell\mu\mu)$ distribution using a template technique



Result:

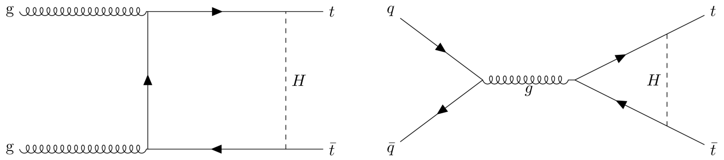
172.17 ± 0.80(stat) ± 0.81(syst) ± 1.07(recoil) GeV

JES+JER unc. drastically reduced (<0.1 GeV)

Dominant component is signal modelling

- Parton shower gluon-recoil scheme
- Parton shower and hadronisation model

Yukawa coupling using $t\bar{t}$



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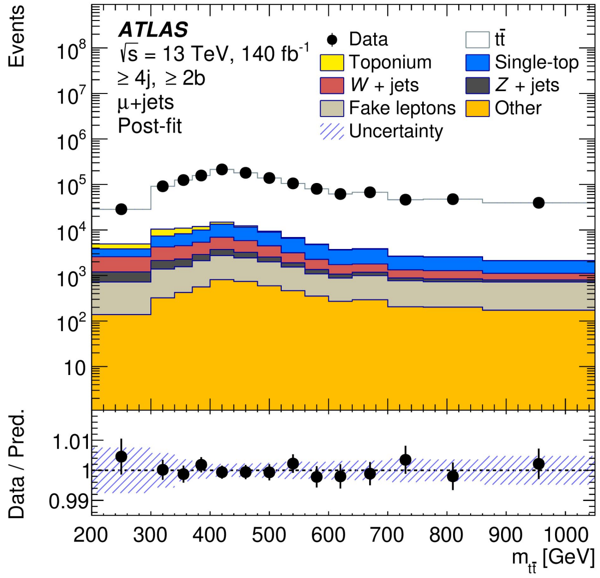
Uniquely large Yukawa coupling

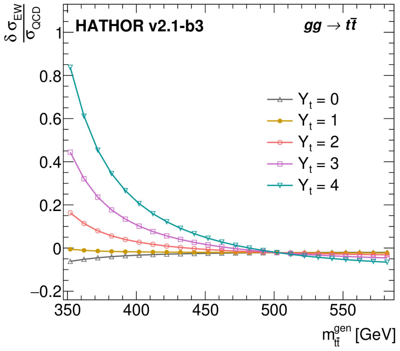
- Extract y_t via virtual EW correction to $t\bar{t}$ production cross section
- This correction is enhanced near $t\bar{t}$ production mass threshold and is proportional to **y_t^2**
- Highly complementary approach to direct $t\bar{t}H$ extractions

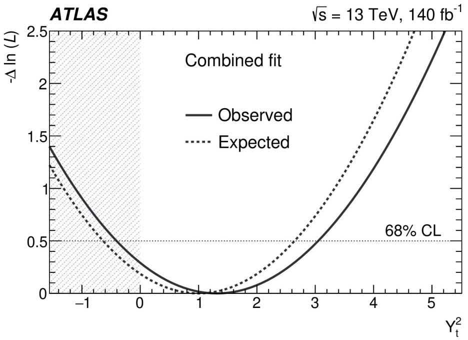


Result: $y_t^2 = 1.3 \pm 1.7$

Dominated by systematic uncertainty (±1.7 vs ±0.4 statistical):

- Signal modelling (±1.2, from QCD scales, parton shower and hadronisation, NNLO QCD reweighting)



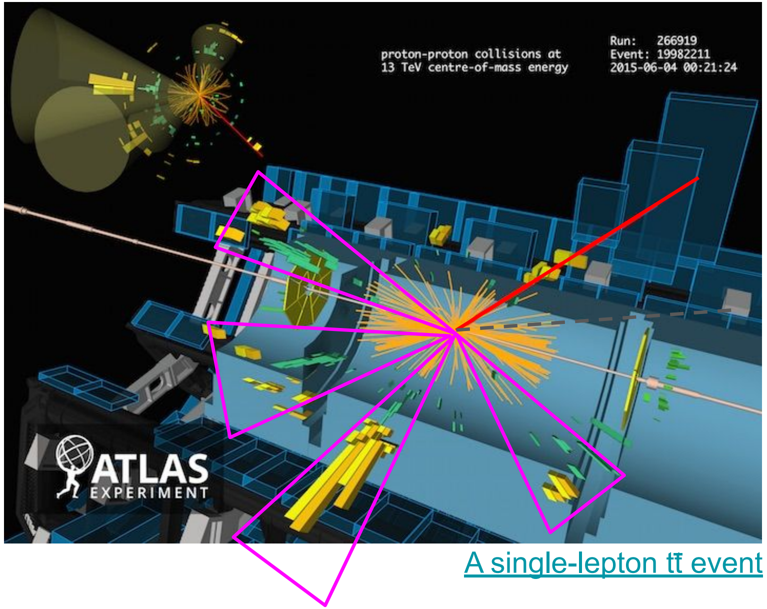


$t\bar{t}$ event in ATLAS detector

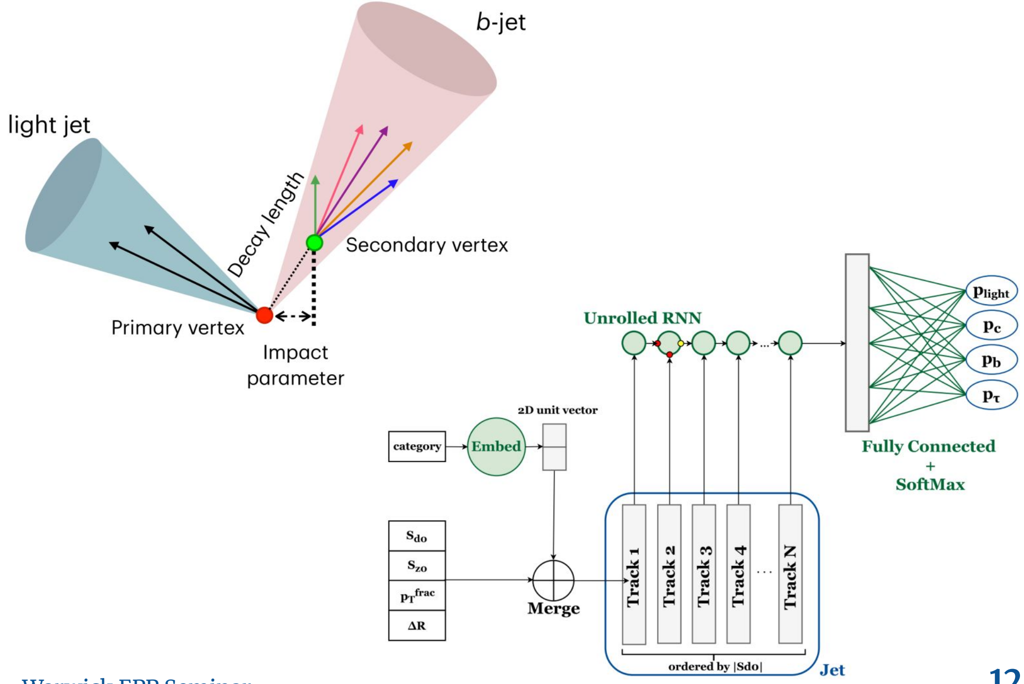
Full Run-2 pp dataset (140 fb-1, 2015-2018)

- ~100M $t\bar{t}$ events produced
- ~40M single-lepton events

- Jet flavours identified by flavour tagger (DL1r)
- Combine traditional IP- and vertex-based methods with Recurrent Neural Network (RNN) outputs in a high-level deep NN



A single-lepton $t\bar{t}$ event



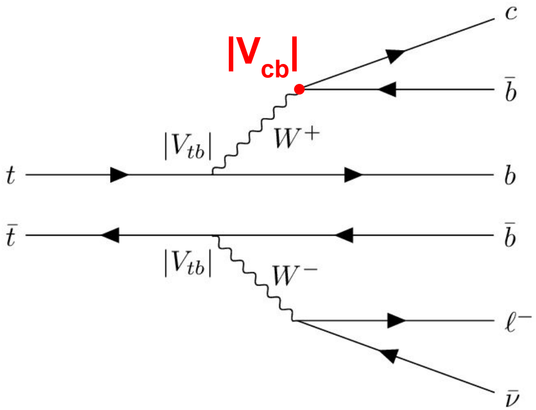
|Vcb| event in ATLAS detector

Full Run-2 pp dataset (140 fb-1, 2015-2018)

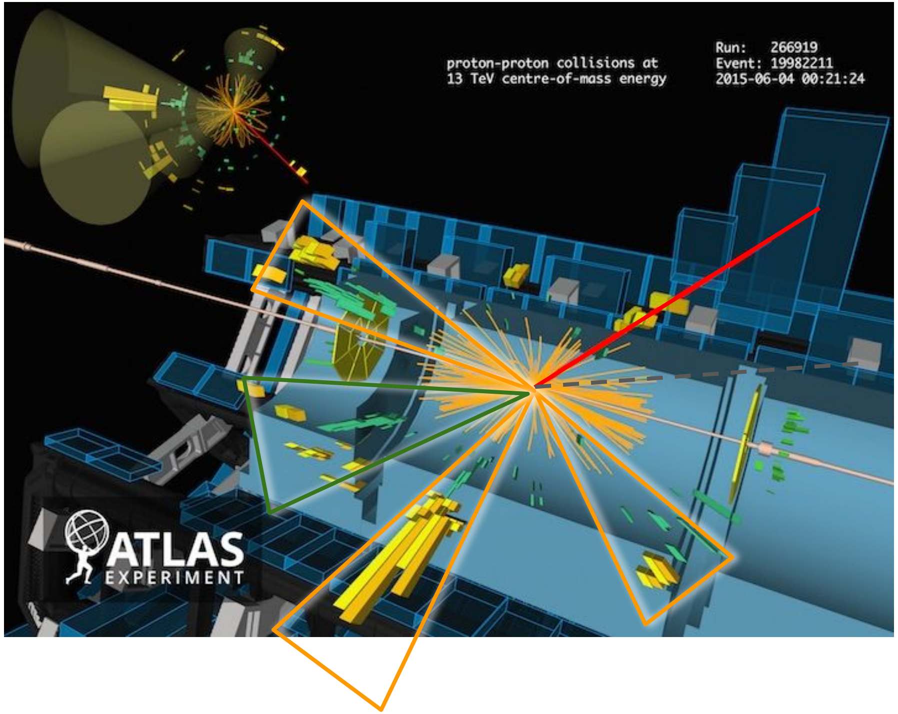
- ~100M tt̄ events produced
- ~40M single-lepton events
- **Only ~35K events expected with |Vcb|**

Event signature:

- Single lepton events with exactly 4 jets
- 3 b-tagged + 1 c-tagged jets -> **3b1c**



A single-lepton tt̄ event



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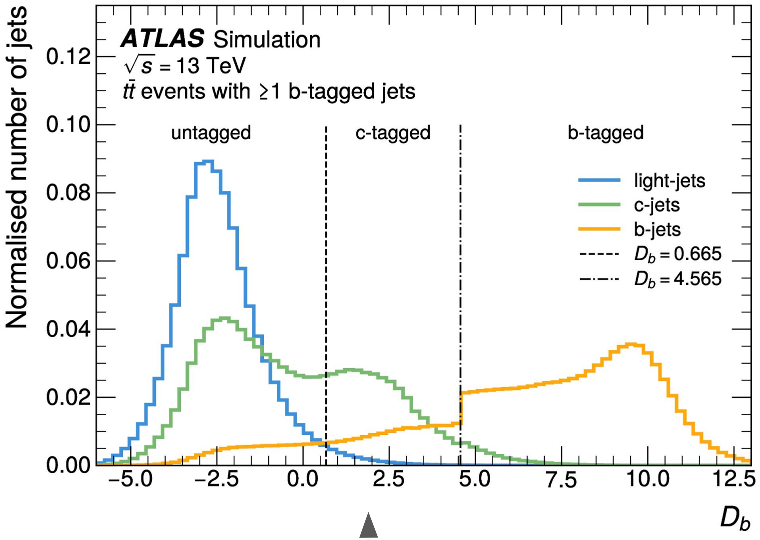

- Assign jet flavours using b-tagging working points in DL1r tagger
- Average tagging performance:

$$T = \begin{pmatrix} \varepsilon_l & f_{lc} & f_{lb} \\ f_{cl} & \varepsilon_c & f_{cb} \\ f_{bl} & f_{bc} & \varepsilon_b \end{pmatrix} = \begin{pmatrix} 97.5\% & 2.5\% & 0.04\% \\ 65.4\% & 32.1\% & 2.5\% \\ 15.0\% & 25.0\% & 60.0\% \end{pmatrix}$$

Calibrated in this analysis (ε_c, f_{cb})

- The standard c-jet tagging calibration assumes a fixed nominal value of |Vcb| and uses highly overlapped analysis region
- Using these scale factors will bias the |Vcb| extraction
- **Need to perform *in situ* calibration for c-jets**

Tagging rate f_{xy} represent the probability to tag a jet with true flavour x as y ($f_{xx} = \varepsilon_x$)

|Vcb| event in ATLAS detector

Full Run-2 pp dataset (140 fb-1, 2015-2018)

- ~100M $t\bar{t}$ events produced
- ~40M single-lepton events
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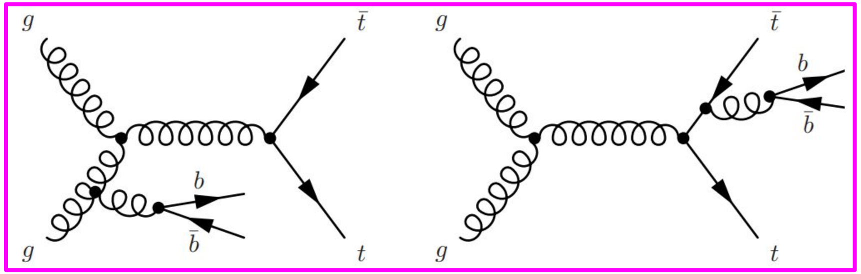
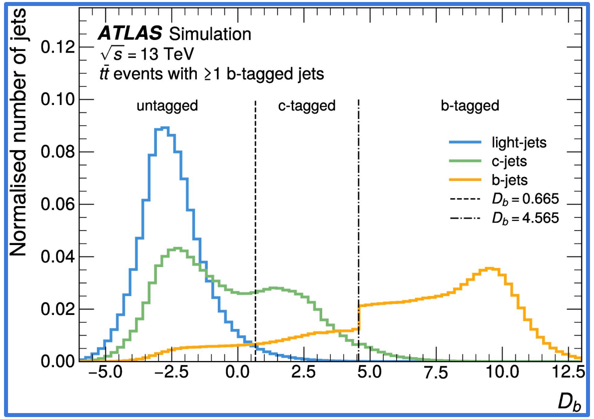


Event signature:

- Single lepton events with exactly 4 jets
- 3 b-tagged + 1 c-tagged jets -> **3b1c**

$t\bar{t}$ reconstruction challenges:

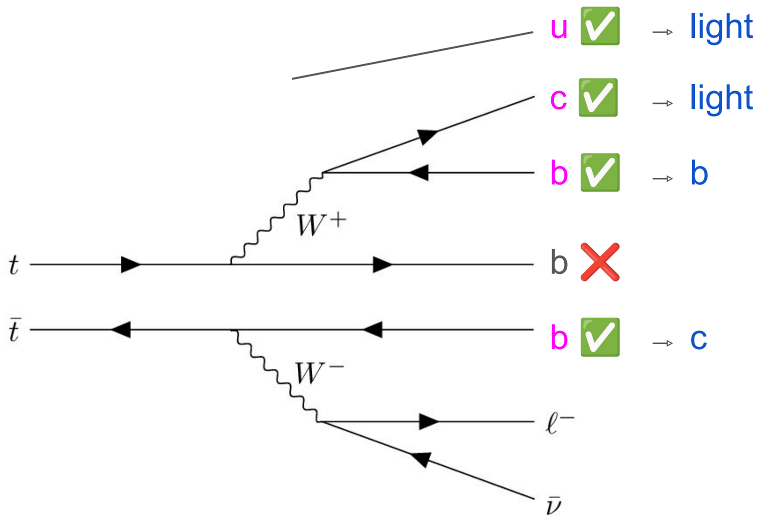
- Jet origins can be mis-assigned
- Jet flavours can be mis-tagged
- **Main background:** $t\bar{t}$ (without |Vcb|) events with mis-assigned and mis-tagged jets.



Jet assignment and flavour tagging

Events are sorted into Production Category based on truth flavours[*] of the jets (PC, denoted as *mbnc*) and Tagging Category based on the reconstructed flavours (TC, also denoted as *mbnc*)

- PC can be different from the generated process if a jet (e.g. from ISR) is mis-assigned as tt̄ decay product
- TC can be different from PC if a jet is mis-tagged with an incorrect flavour



Example (Signal): A 3b1c tt̄ (with |Vcb|) event is categorised into 2b1c PC and 1b1c TC

3b1c TC is expected to be the most signal-enriched region, however, |Vcb| events are distributed across other regions due to these effects

[*] In ATLAS flavour tagging, this is defined according to the match generator-level hadrons

Jet assignment and flavour tagging

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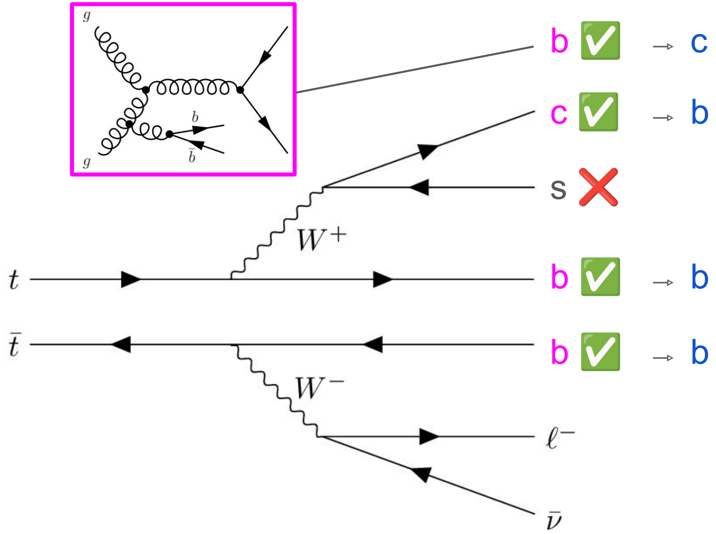


Example (Background): A 2b1c tt̄ (without |Vcb|) event is categorised into 3b1c PC and 3b1c TC

Results in background contamination in 3b1c TC:
- Mostly b/c-associated tt̄ production (tt̄ + HF)
- Modelling of these processes are challenging
- MC consistently underpredicts data
- **Normalisation must be extracted from data**

[*] In ATLAS flavour tagging, this is defined according to the match generator-level hadrons

Jet assignment Neural Network (NN)

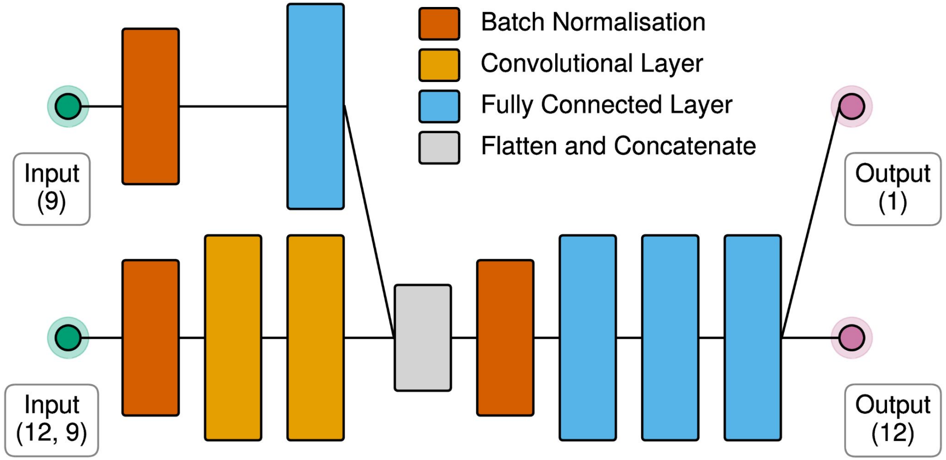
Binary classifier to suppress background from mis-assigned jets:

- Signal: $t\bar{t}$ events with all four jets truth-matched to the partons from the decay
- Background: not fully matched $t\bar{t}$ events and non-$t\bar{t}$ events

Notably, $t\bar{t}$+HF is selected as Bkg., allowing to constrain it using the low NN output score regions

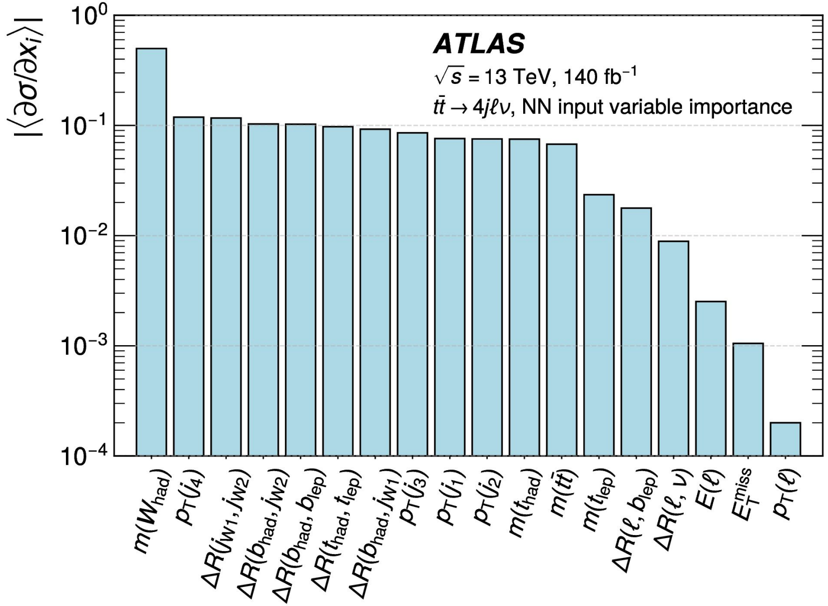
- Jet 0-3 pT (hardest to softest)
- Lepton energy and pT
- Missing transverse energy
- ΔR (lepton, neutrino)

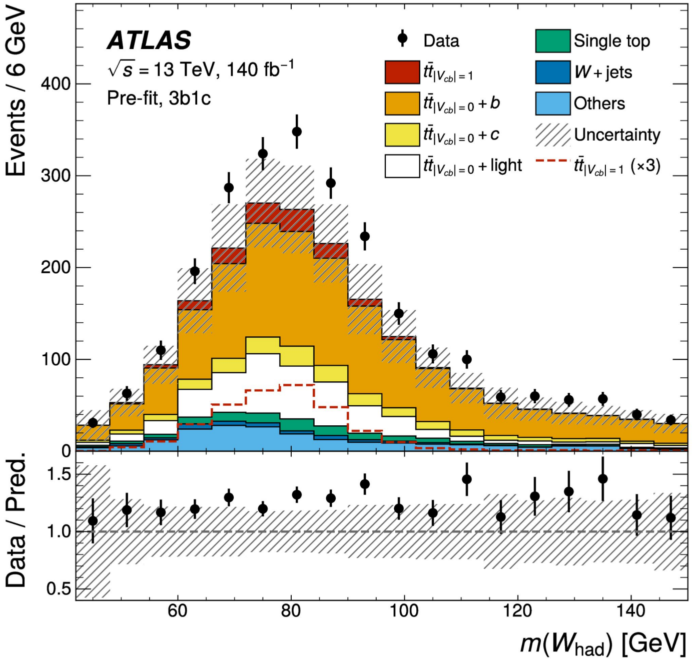
- 6 opening angles:
  - ΔR (lepton, b_{lep}), ΔR (b_{lep}, b_{had})
  - ΔR (b_{had}, W_{j0}), ΔR (b_{had}, W_{j1})
  - ΔR (W_{j0}, W_{j1}), ΔR (t_{had}, t_{lep})
- 3 masses: t_{lep}, t_{had}, W_{had}



Jet assignment Neural Network (NN)

Input variable ranking: hadronic W boson mass drives the discrimination, followed by several variables with comparable importance





Event Categorisation

- **Need to constrain overall $t\bar{t}$ normalisation**
  - cross section calculated at NNLO QCD
- **Need to constrain $t\bar{t}$ + b/c**
  - poorly modelled by MC
- **Need to calibration charm jet tagging (and mistagging) efficiencies**
  - can’t use standard calibration
- **Need to extract |Vcb|**

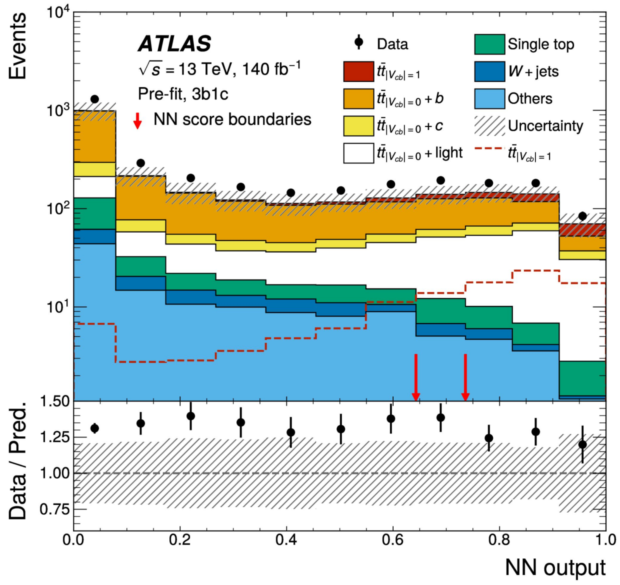
Event Categorisation

TCs defined by the number of b- and c-tagged jets:

- Signal TC (3b1c): maximises sensitivity for measuring |Vcb|
- Control TCs (2b0c, 2b1c, 3b0c, ..): calibrate c-jet tagging rates

NN bin edges optimised to minimise expected uncertainty of |Vcb|

- Three NN regions (NNRs): Low, Medium, High
- Low NNRs are used to constrain the $t\bar{t}$ + HF background
- Sensitivity saturates with more than 3 bins



Fit to the 24 regions (8 TCs x 3 NNRs):

	1b1c	1b2c	1b3c	2b0c	2b1c	2b2c	3b0c	3b1c
Low NNR								
Med NNR								
High NNR								

In situ c–jet tagging calibration

Calibrate c-jet efficiency ε_c and mis-tag rate f_{cb} in all top processes in bins of NN score

Two-step procedure:

- **Step 1:** Extract tagging rates from MC by minimising χ^2 fitted to event yields in each NNR

$$\chi^2 = \sum_j \left(\frac{N_j - N \cdot p_j(T)}{\Delta N_j} \right)^2$$

Nj (ΔNj): event yield (uncertainty) in the j-th TC
N : total event yield

The expected event fraction in TC j as a function of tagging rates

$$\begin{pmatrix} \varepsilon_l & f_{lc} & f_{lb} \\ f_{cl} & \varepsilon_c & f_{cb} \\ f_{bl} & f_{bc} & \varepsilon_b \end{pmatrix}$$

6 independent rates

$$p_j(T) = \sum_j^{\text{All PCs}} t_i \cdot P_{ij}(T)$$

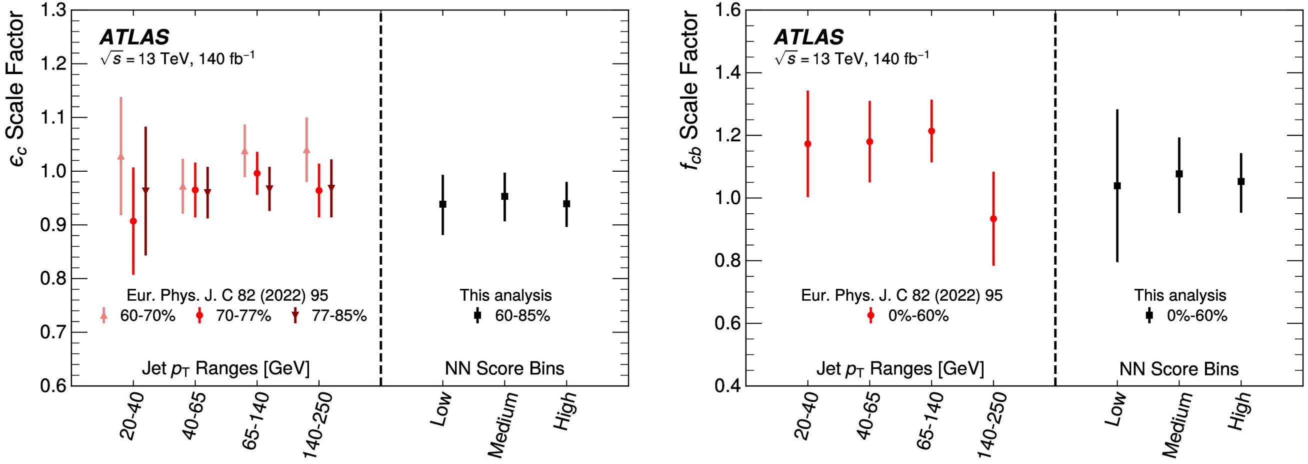
- Fraction of events in each PC (based on truth flavours)
- Transition probability from PC i to TC j:
- Example: 3b1c -> 3b1c: $\varepsilon_b^3 \varepsilon_c + 3\varepsilon_b^2 f_{bc} f_{cb}$

In situ c-jet tagging calibration

- **Step 2:** Tagging rates from Step 1 define the normalisation factors in the final fit

$$A_j = \frac{p_j(\varepsilon_c, f_{cb}, *)}{p_j(\varepsilon_c^{\mathrm{MC}}, f_{cb}^{\mathrm{MC}}, *)}$$

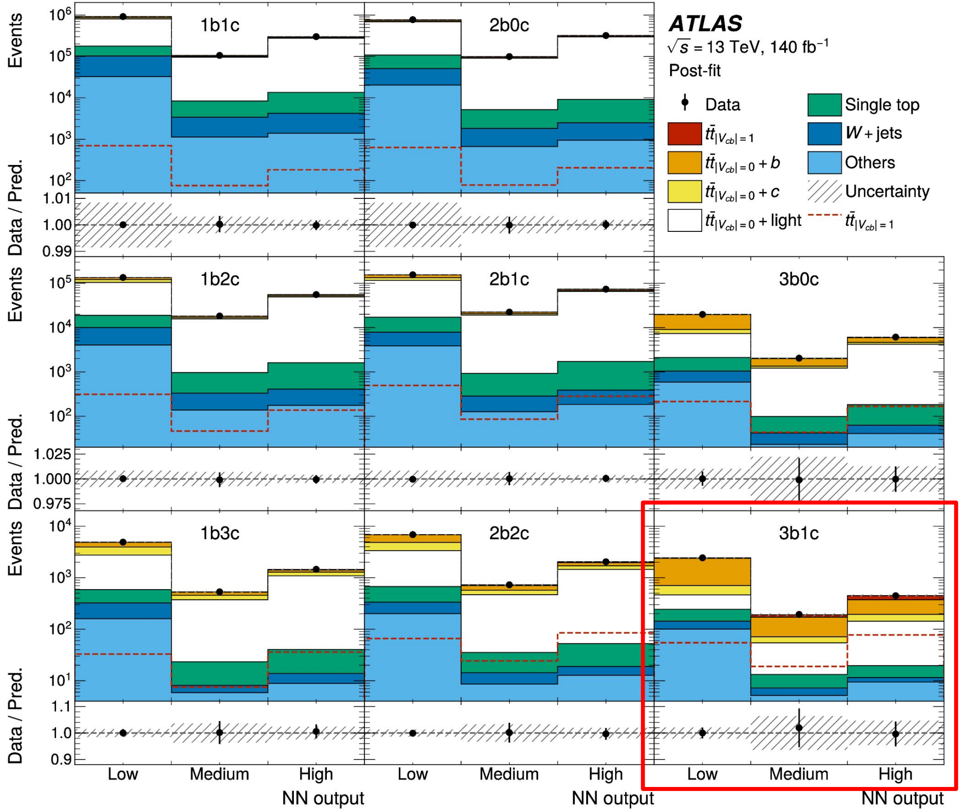
- (Scale factors of) c-jet efficiency ε_c and mis-tag rate f_{cb} float freely
- Other tagging rates (denoted as $*$) in T are fixed to their calibrated values except ε_c and f_{cb}



- **Compatible with values measured in the standard c-tagging calibration**

Fit results

- **Profile likelihood fit to 8 TCs x 3 NNRs**



Free Parameters are determined simultaneously

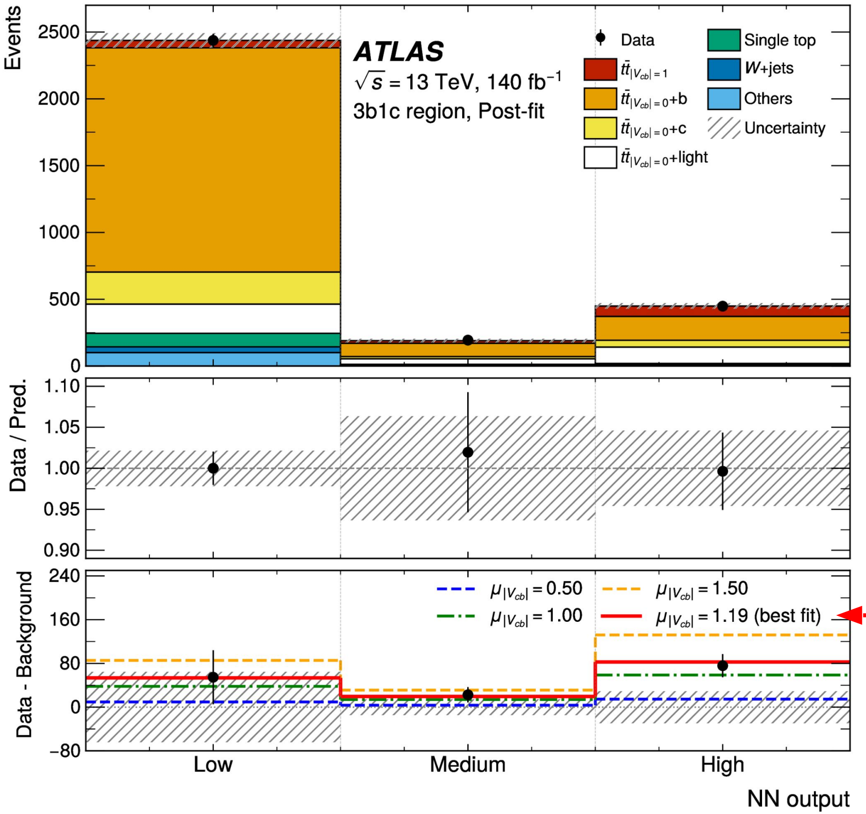
- c-jet tagging efficiency and c–to-b mis-tag rate scale factors (see last page)
- Scaling of |Vcb| (event yield scales with |Vcb|²)
- Normalisation of inclusive tt̄
- Normalisation of tt̄+c fraction
- Normalisation of tt̄+b fraction

Parameter	Value
$\mu_{\lvert V_{cb}\rvert}$	$1.19^{+0.27}_{-0.35}$
$\mu_{t\bar{t}}$	0.99 ± 0.03
$\mu_{t\bar{t}+c}$	$1.60^{+0.64}_{-0.60}$
$\mu_{t\bar{t}+b}$	$1.45^{+0.54}_{-0.34}$

Consistent with dedicated tt̄+HF measurements

Fit results

- **|Vcb| signal in 3b1c**



Free Parameters are determined simultaneously

- c-jet tagging efficiency and c–to-b mis-tag rate scale factors (see last page)
- Scaling of |Vcb| (event yield scales with |Vcb|²)
- Normalisation of inclusive tt̄
- Normalisation of tt̄+c fraction
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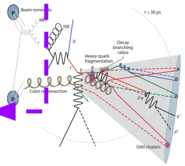
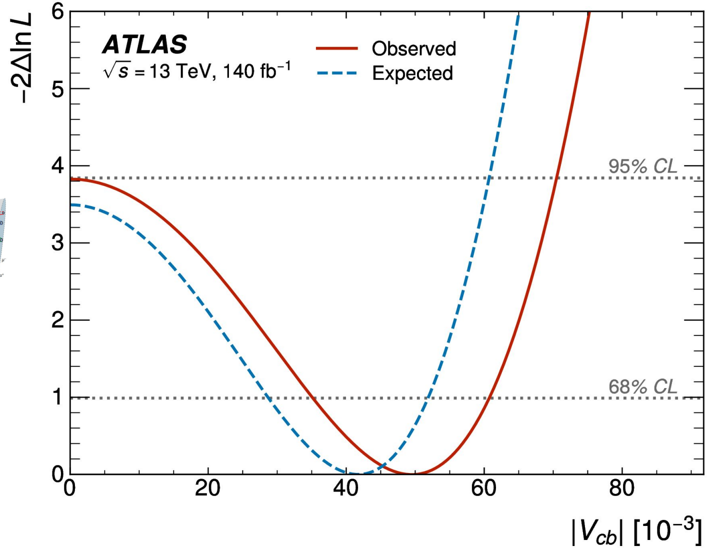
|Vcb| extraction and uncertainty

<u>|Vcb|:</u> (50^{+11}_{-14}) x 10^{-3} – Compared with world average: (41.1 ± 1.2) x 10^{-3}

- Balanced statistical and systematic uncertainties
- Systematic uncertainty dominated by $t\bar{t}$ modelling

Uncertainty in $\lvert V_{cb}\rvert$	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





Corresponds to:

<u>$|Vcb|^2$</u> = (2.5 ± 1.2) × 10^{-3}

<u>B(t → bc$\bar{b}$) in SM:</u> (8 ± 4) x 10^{-4}

Summary

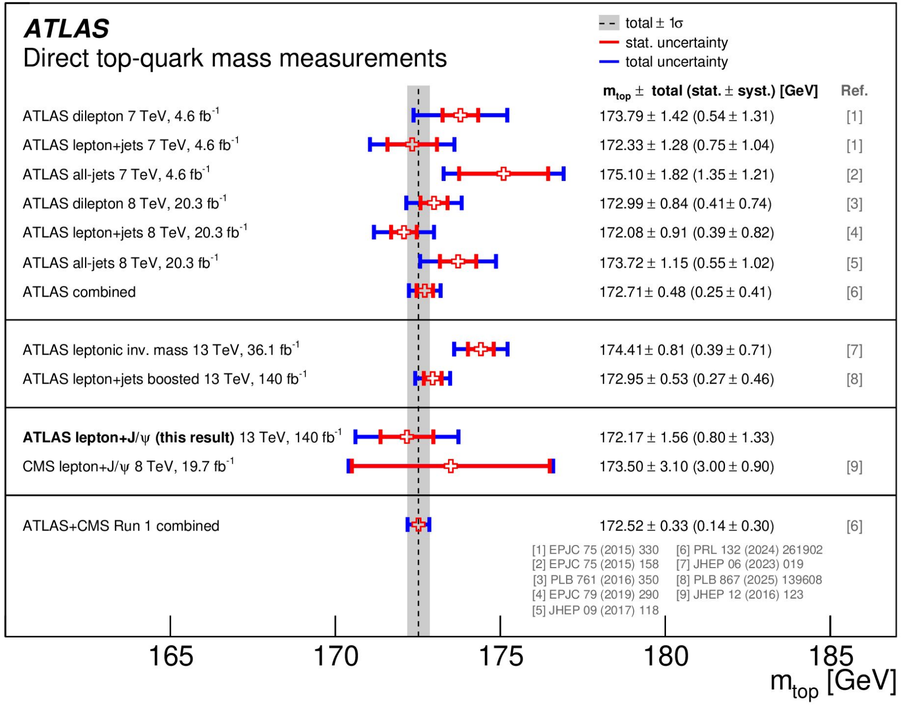
- First measurement of |Vcb| via on-shell W decays: **$|V_{cb}| = (50^{+11}_{-14}) \times 10^{-3}$**
- Within 3-generation SM: **$B(t \to bc\bar{b}) = (8 \pm 4) \times 10^{-4}$**
- Not yet enough to test the tension in traditional extractions, however, demonstrates the potential to measure CKM matrix elements at electroweak scale

Projections in different scenarios	Stat	Syst	Total
This paper (Run 2, L=140 fb^{-1})	+7 / -9	+9 / -10	+11 / -14
Only data and MC stat scale with Luminosity (Run 2+3, L=500 fb^{-1})	+4 / -5	+9 / -10	+9 / -11
+ Systematic uncertainties are halved* (Run 2+3, L=500 fb^{-1})	+4 / -5	+5 / -5	+6 / -7

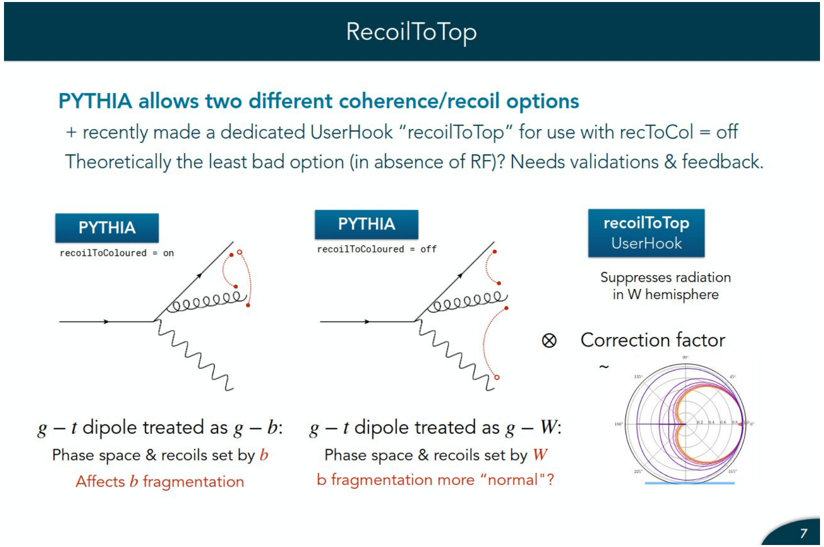
- Also profits from state-of-the-art flavour tagging algorithms and extended analysis categories

***** Maybe too optimistic**

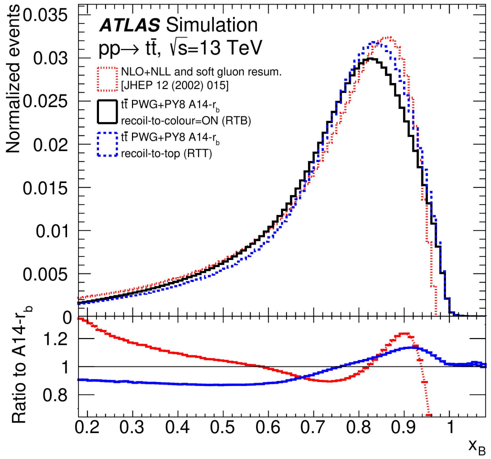
Backup



ATLAS
Direct top-quark mass measurements
total ± 1σ
stat. uncertainty
total uncertainty
m_top ± total (stat. ± syst.) [GeV]
Ref.
ATLAS dilepton 7 TeV, 4.6 fb-1 | 173.79 ± 1.42 (0.54 ± 1.31) | [1]
ATLAS lepton+jets 7 TeV, 4.6 fb-1 | 172.33 ± 1.28 (0.75 ± 1.04) | [1]
ATLAS all-jets 7 TeV, 4.6 fb-1 | 175.10 ± 1.82 (1.35 ± 1.21) | [2]
ATLAS dilepton 8 TeV, 20.3 fb-1 | 172.99 ± 0.84 (0.41 ± 0.74) | [3]
ATLAS lepton+jets 8 TeV, 20.3 fb-1 | 172.08 ± 0.91 (0.39 ± 0.82) | [4]
ATLAS all-jets 8 TeV, 20.3 fb-1 | 173.72 ± 1.15 (0.55 ± 1.02) | [5]
ATLAS combined | 172.71 ± 0.48 (0.25 ± 0.41) | [6]
ATLAS leptonic inv. mass 13 TeV, 36.1 fb-1 | 174.41 ± 0.81 (0.39 ± 0.71) | [7]
ATLAS lepton+jets boosted 13 TeV, 140 fb-1 | 172.95 ± 0.53 (0.27 ± 0.46) | [8]
ATLAS lepton+J/ψ (this result) 13 TeV, 140 fb-1 | 172.17 ± 1.56 (0.80 ± 1.33)
CMS lepton+J/ψ 8 TeV, 19.7 fb-1 | 173.50 ± 3.10 (3.00 ± 0.90) | [9]
ATLAS+CMS Run 1 combined | 172.52 ± 0.33 (0.14 ± 0.30) | [6]
[1] EPJC 75 (2015) 330
[2] EPJC 75 (2015) 158
[3] PLB 761 (2016) 350
[4] EPJC 79 (2019) 290
[5] JHEP 09 (2017) 118
[6] PRL 132 (2024) 261902
[7] JHEP 06 (2023) 019
[8] PLB 867 (2025) 139608
[9] JHEP 12 (2016) 123
165
170
175
180
185
m_top [GeV]



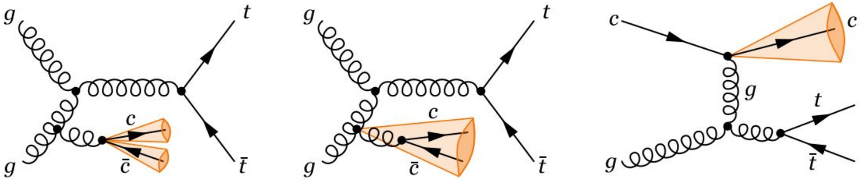
RecoilToTop
PYTHIA allows two different coherence/recoil options
+ recently made a dedicated UserHook "recoilToTop" for use with recToCol = off
Theoretically the least bad option (in absence of RF)? Needs validations & feedback.
PYTHIA
recoilToColoured = on
PYTHIA
recoilToColoured = off
recoilToTop UserHook
Suppresses radiation in W hemisphere
⊗ Correction factor
g − t dipole treated as g − b:
Phase space & recoils set by b
Affects b fragmentation
g − t dipole treated as g − W:
Phase space & recoils set by W
b fragmentation more "normal"?
7

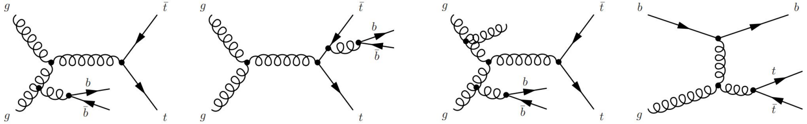


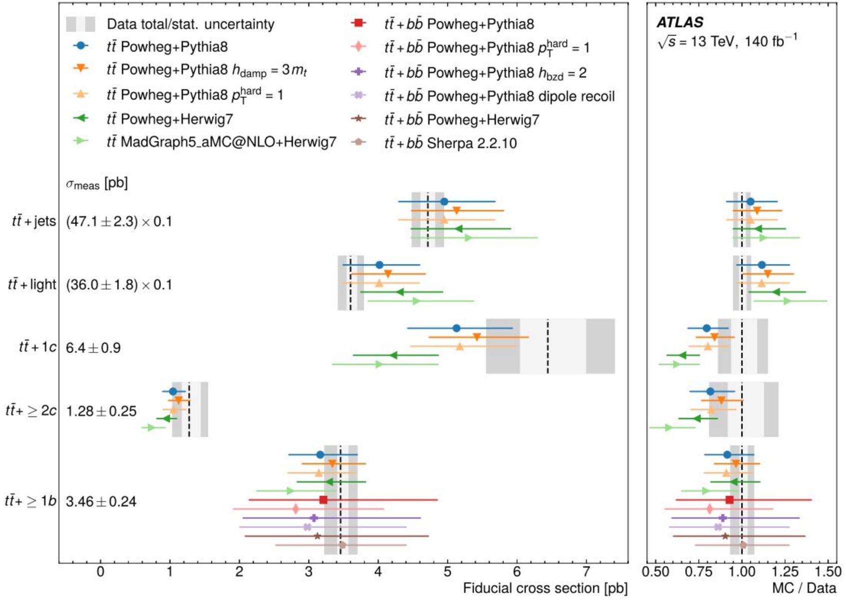
ATLAS Simulation
pp→ tt̄, √s=13 TeV
NLO+NLL and soft gluon resum. [JHEP 12 (2002) 015]
tt̄ PWG+PY8 A14-r_b recoil-to-colour=ON (RTB)
tt̄ PWG+PY8 A14-r_b recoil-to-top (RTT)
Normalized events
Ratio to A14-r_b
x_B

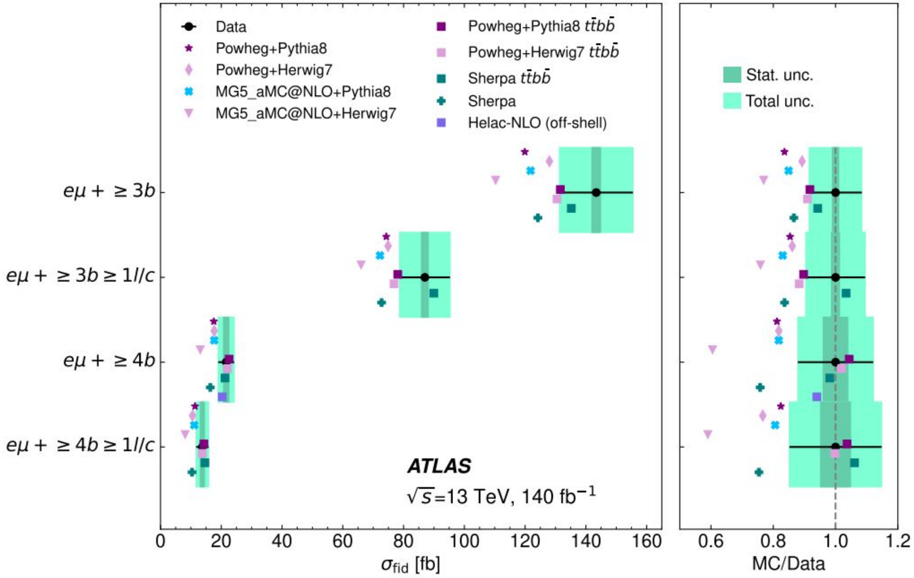
tt̄+c: Phys. Lett. B 860(2025)139177

tt̄+b: JHEP 01(2025)068

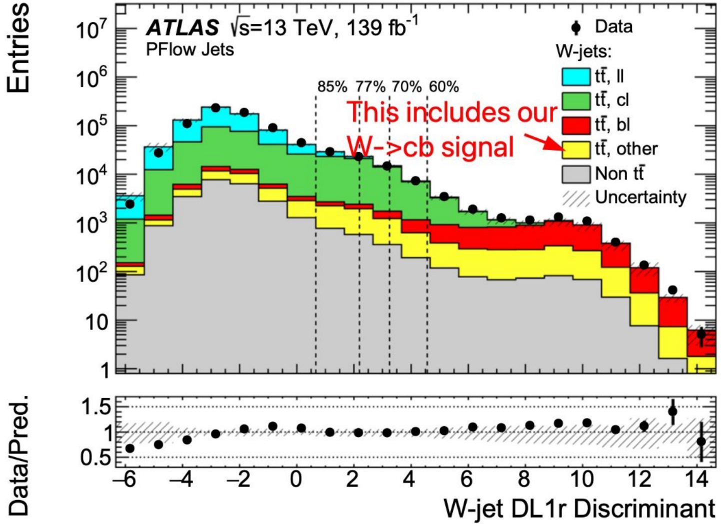


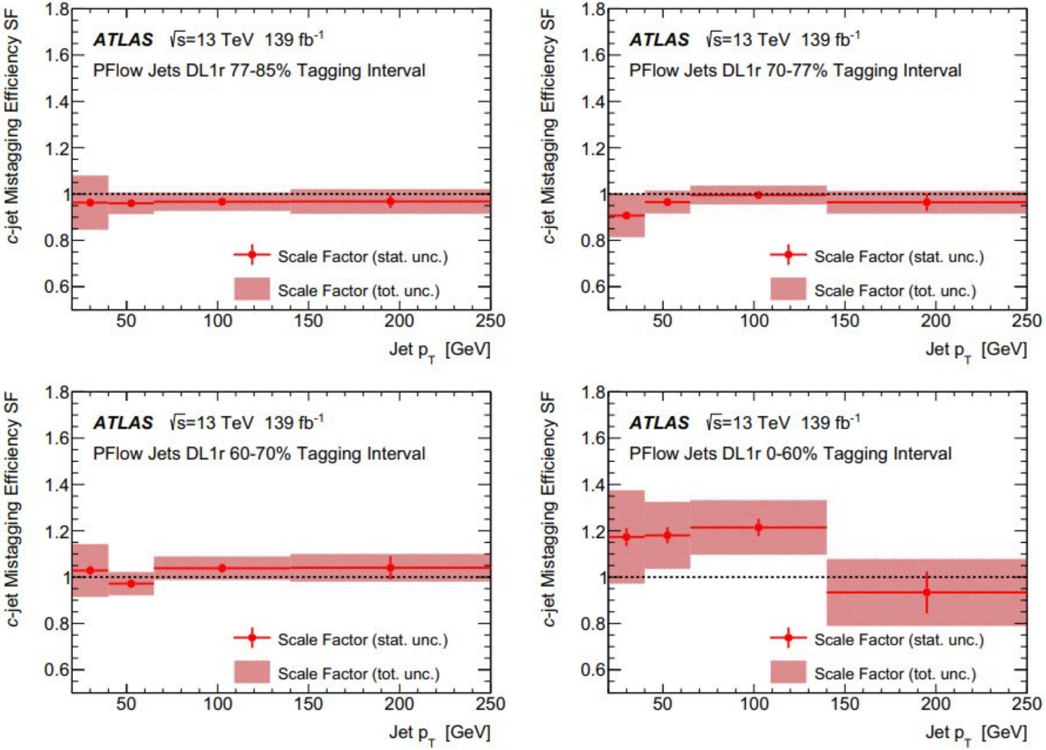


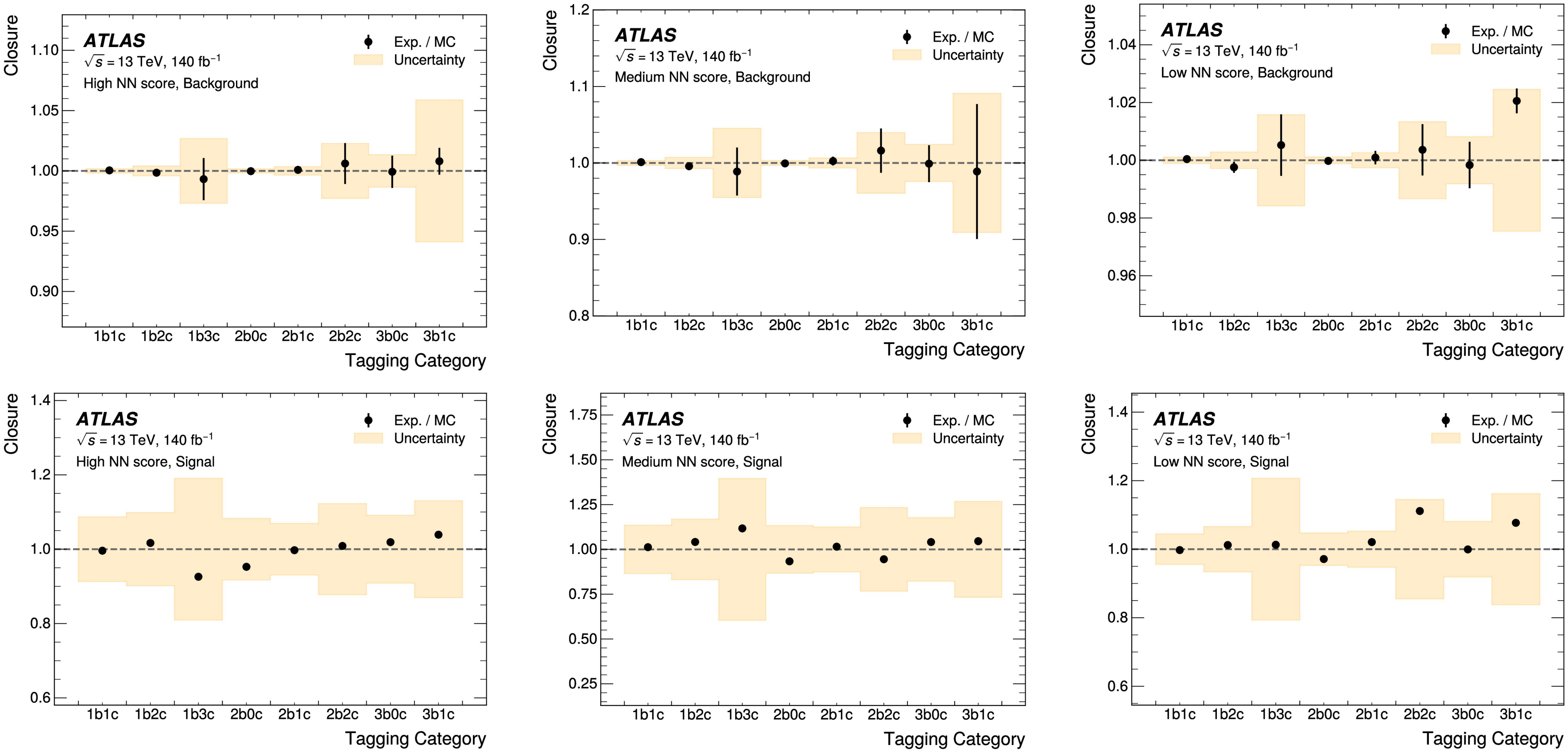




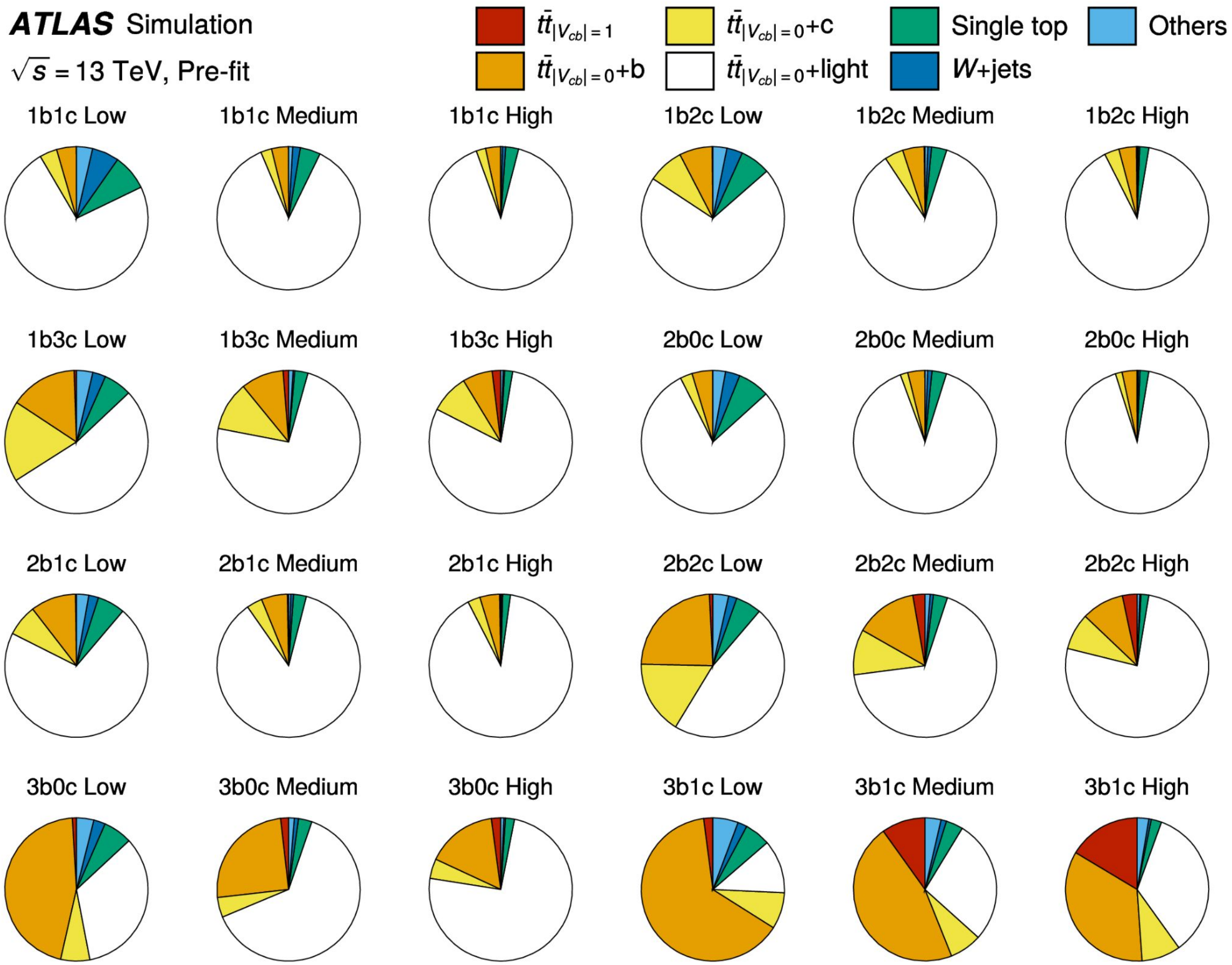
Standard c-jet tagging calibration: Eur. Phys. J. C (2022)

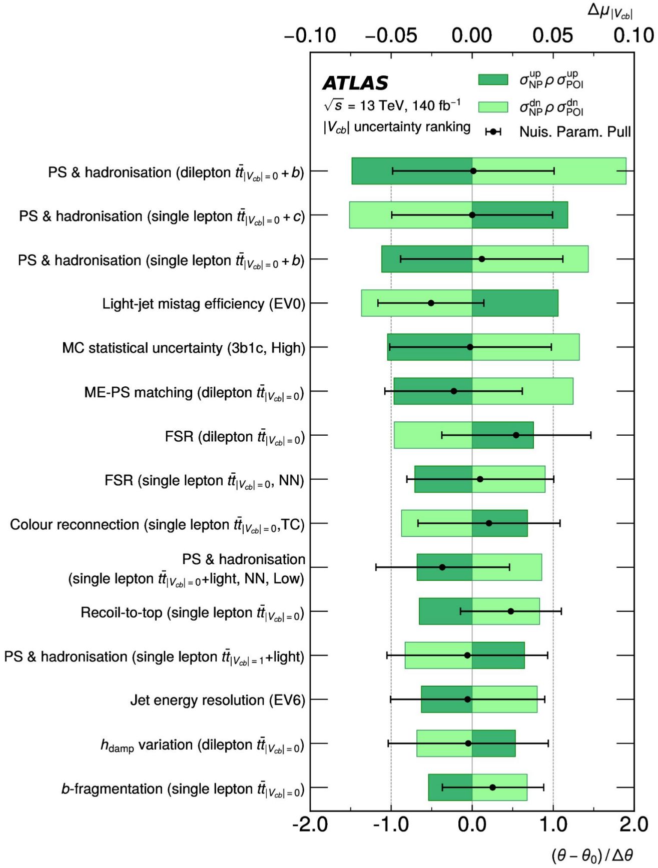




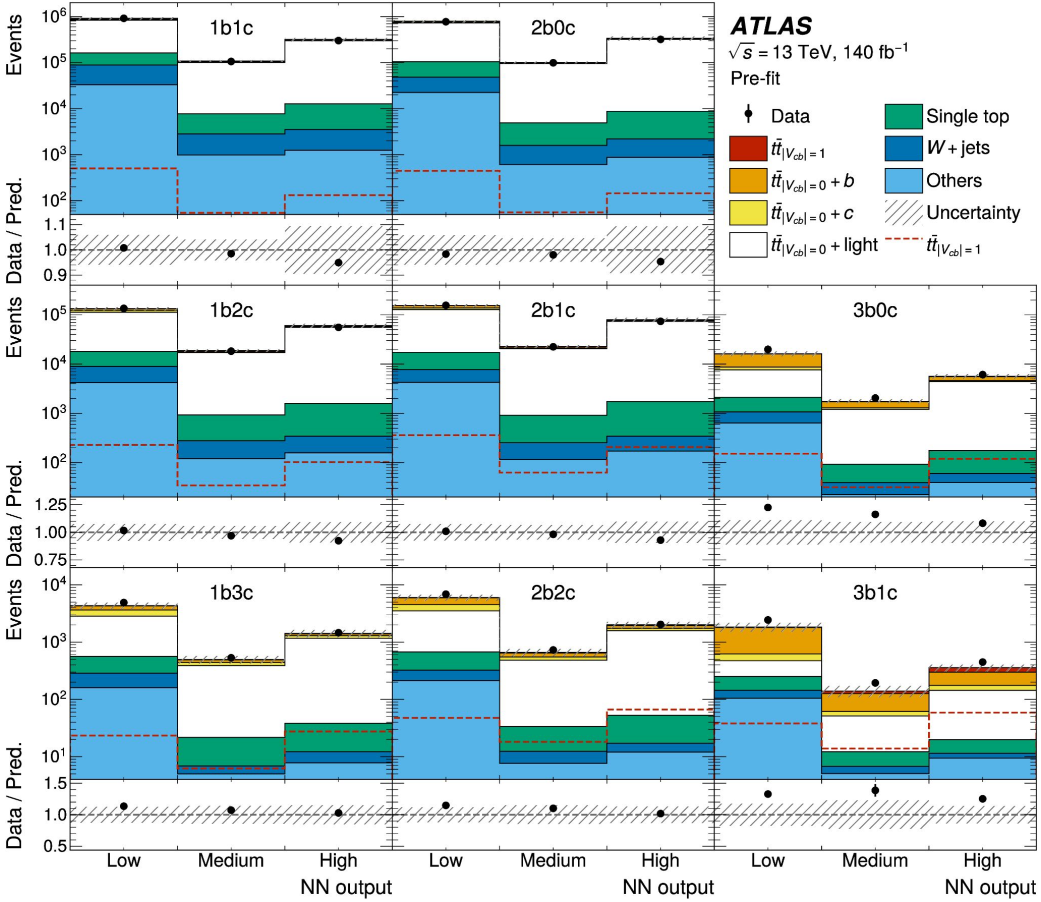


ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
High NN score, Background
Medium NN score, Background
Low NN score, Background
High NN score, Signal
Medium NN score, Signal
Low NN score, Signal
Exp. / MC
Uncertainty
Closure
Tagging Category
1b1c 1b2c 1b3c 2b0c 2b1c 2b2c 3b0c 3b1c


ATLAS Simulation
$\sqrt{s}$ = 13 TeV, Pre-fit
$t\bar{t}_{|V_{cb}|=1}$
$t\bar{t}_{|V_{cb}|=0}$+b
$t\bar{t}_{|V_{cb}|=0}$+c
$t\bar{t}_{|V_{cb}|=0}$+light
Single top
W+jets
Others
1b1c Low
1b1c Medium
1b1c High
1b2c Low
1b2c Medium
1b2c High
1b3c Low
1b3c Medium
1b3c High
2b0c Low
2b0c Medium
2b0c High
2b1c Low
2b1c Medium
2b1c High
2b2c Low
2b2c Medium
2b2c High
3b0c Low
3b0c Medium
3b0c High
3b1c Low
3b1c Medium
3b1c High

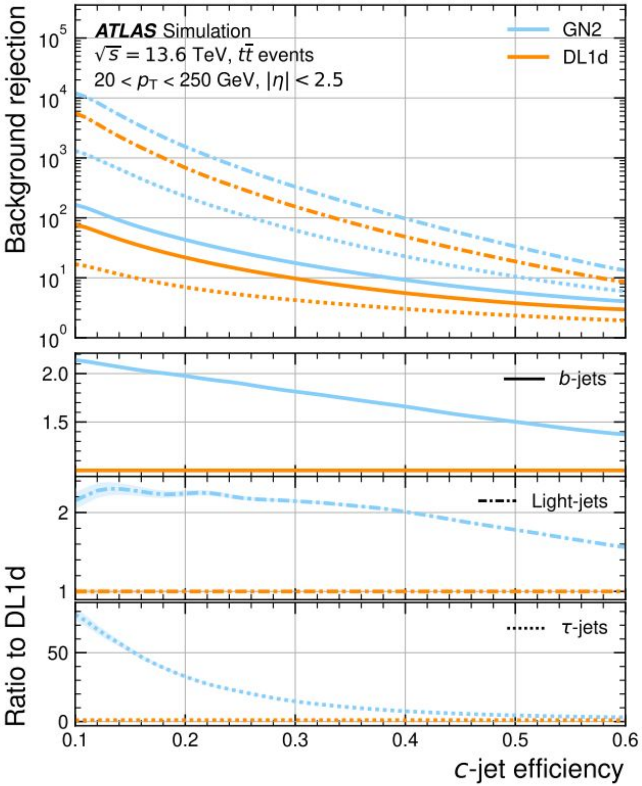


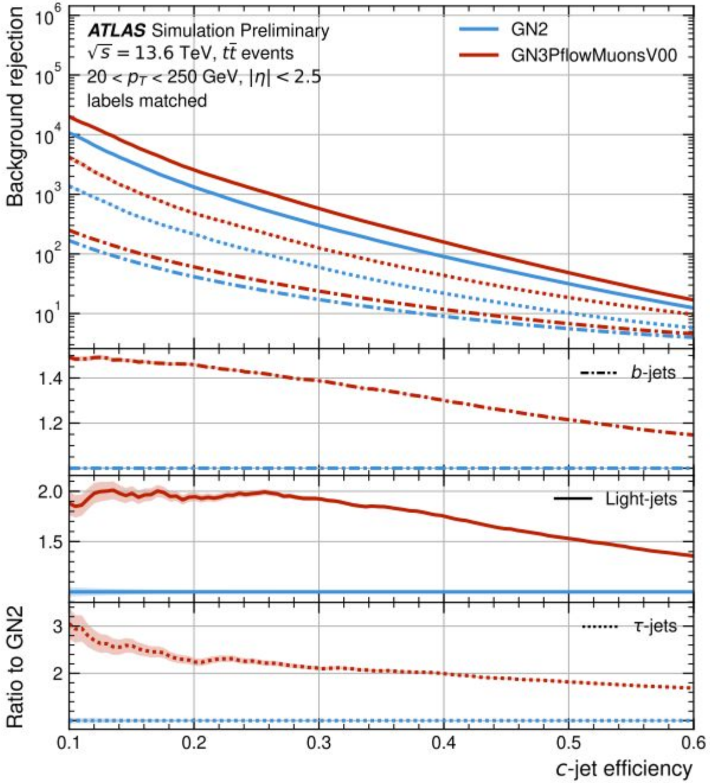
$\Delta\mu_{|V_{cb}|}$
−0.10 −0.05 0.00 0.05 0.10
ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
$|V_{cb}|$ uncertainty ranking
$\sigma_{NP}^{up}\rho\,\sigma_{POI}^{up}$
$\sigma_{NP}^{dn}\rho\,\sigma_{POI}^{dn}$
Nuis. Param. Pull
PS & hadronisation (dilepton $t\bar{t}_{|V_{cb}|=0}+b$)
PS & hadronisation (single lepton $t\bar{t}_{|V_{cb}|=0}+c$)
PS & hadronisation (single lepton $t\bar{t}_{|V_{cb}|=0}+b$)
Light-jet mistag efficiency (EV0)
MC statistical uncertainty (3b1c, High)
ME-PS matching (dilepton $t\bar{t}_{|V_{cb}|=0}$)
FSR (dilepton $t\bar{t}_{|V_{cb}|=0}$)
FSR (single lepton $t\bar{t}_{|V_{cb}|=0}$, NN)
Colour reconnection (single lepton $t\bar{t}_{|V_{cb}|=0}$,TC)
PS & hadronisation
(single lepton $t\bar{t}_{|V_{cb}|=0}$+light, NN, Low)
Recoil-to-top (single lepton $t\bar{t}_{|V_{cb}|=0}$)
PS & hadronisation (single lepton $t\bar{t}_{|V_{cb}|=1}$+light)
Jet energy resolution (EV6)
h_{damp} variation (dilepton $t\bar{t}_{|V_{cb}|=0}$)
b-fragmentation (single lepton $t\bar{t}_{|V_{cb}|=0}$)
-2.0 -1.0 0.0 1.0 2.0
$(\theta-\theta_0)/\Delta\theta$



ATLAS
$\sqrt{s}$ = 13 TeV, 140 fb^{-1}
Pre-fit
Data
$t\bar{t}_{|V_{cb}|=1}$
$t\bar{t}_{|V_{cb}|=0}+b$
$t\bar{t}_{|V_{cb}|=0}+c$
$t\bar{t}_{|V_{cb}|=0}$ + light
Single top
W + jets
Others
Uncertainty
$t\bar{t}_{|V_{cb}|=1}$
1b1c
2b0c
1b2c
2b1c
3b0c
1b3c
2b2c
3b1c
Events
Data / Pred.
Low
Medium
High
NN output

GN2: [Nature Commun. 17 (2026) 541] GN3: [ATL-PHYS-PUB-2026-001]





arxiv:2503.00118