Highlights on top quark physics with the ATLAS experiment at the LHC

Dominic Hirschbühl

BERGISCHE UNIVERSITÄT WUPPERTAL

FSP ATLAS
Erforschung von Universum und Materie

35th Recontres de Blois
24.10.2024

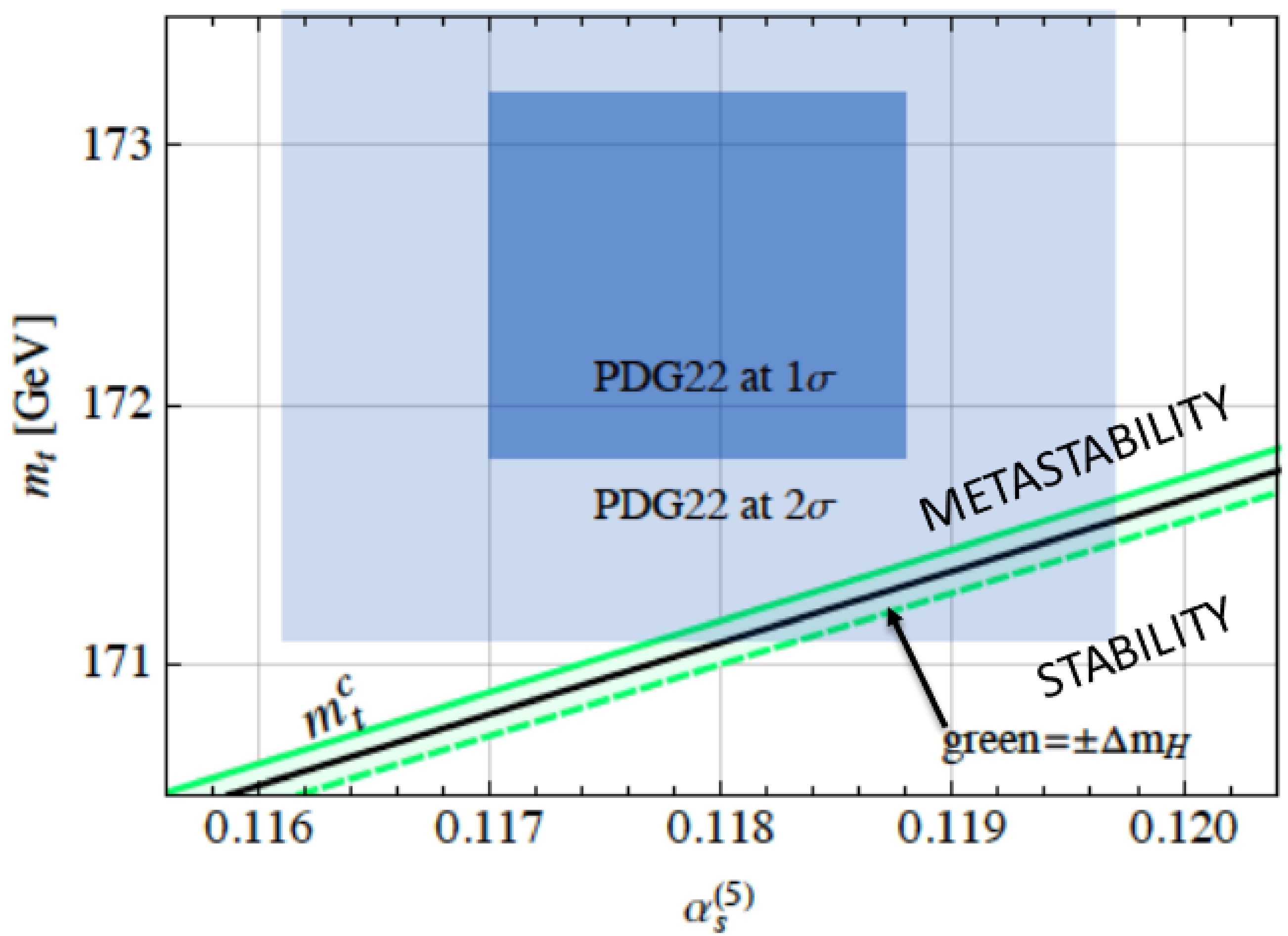
Introduction

By far the heaviest know elementary particle
- ~40x bottom quark mass
- Same mass scale as W, Z and Higgs Bosons
  → connection to EW Symmetry Breaking ?

Top Yukawa coupling is ~1 → coincidence?

It decays before it hadronises
- Can be studied as bare quark

Very high production rate at the LHC
- 0.2 – 0.8 nb production cross section
  @ LHC energies
- Produced more than 100M $t\bar{t}$ pairs
  in Run 2 and Run 3 each



Masina Quiros, arXiv:2403.02461

BERGISCHE UNIVERSITÄT WUPPERTAL

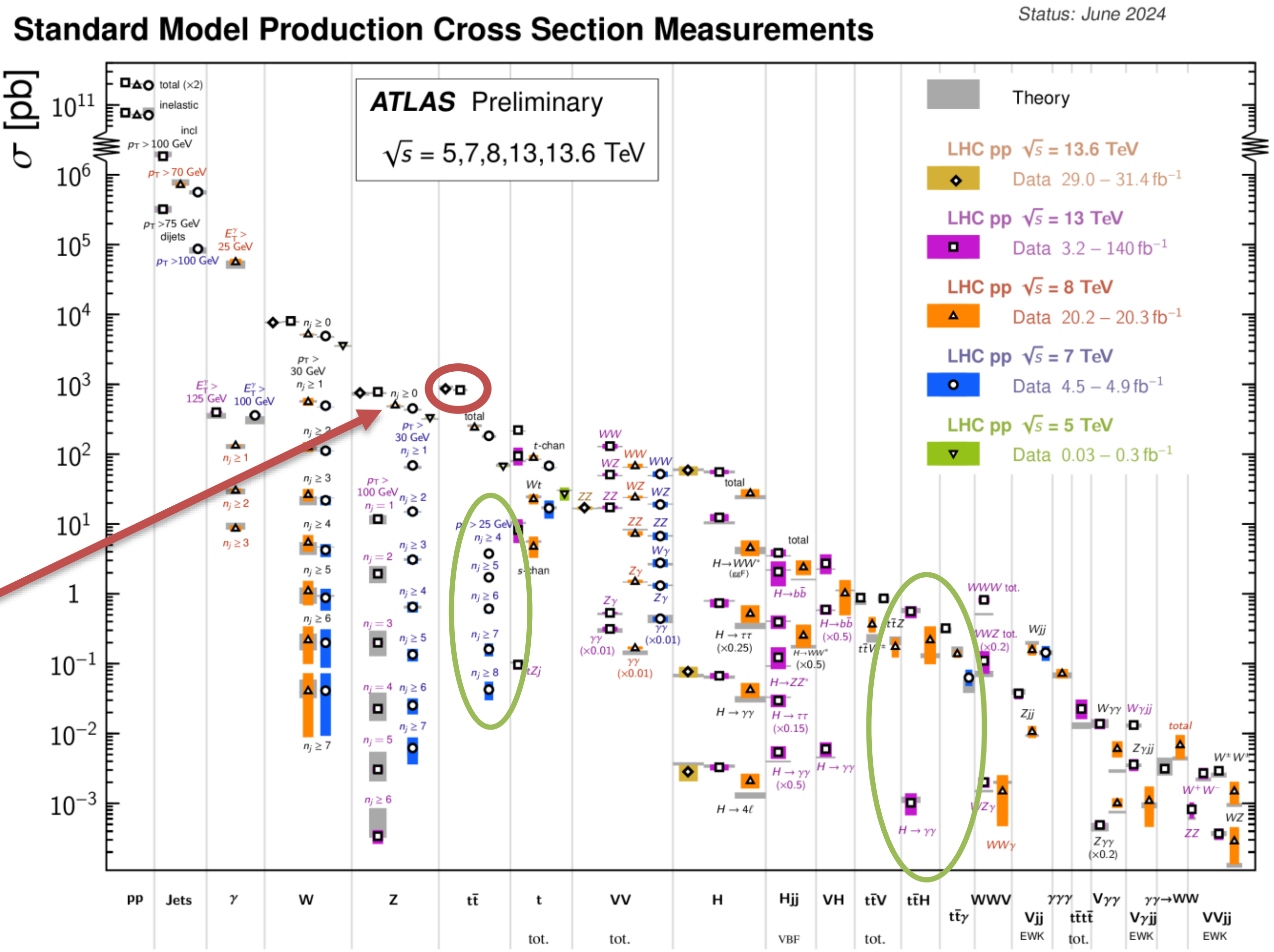
Introduction

By far the heaviest know elementary particle
- ~40x bottom quark mass
- Same mass scale as W, Z and Higgs Bosons
  → connection to EW Symmetry Breaking ?

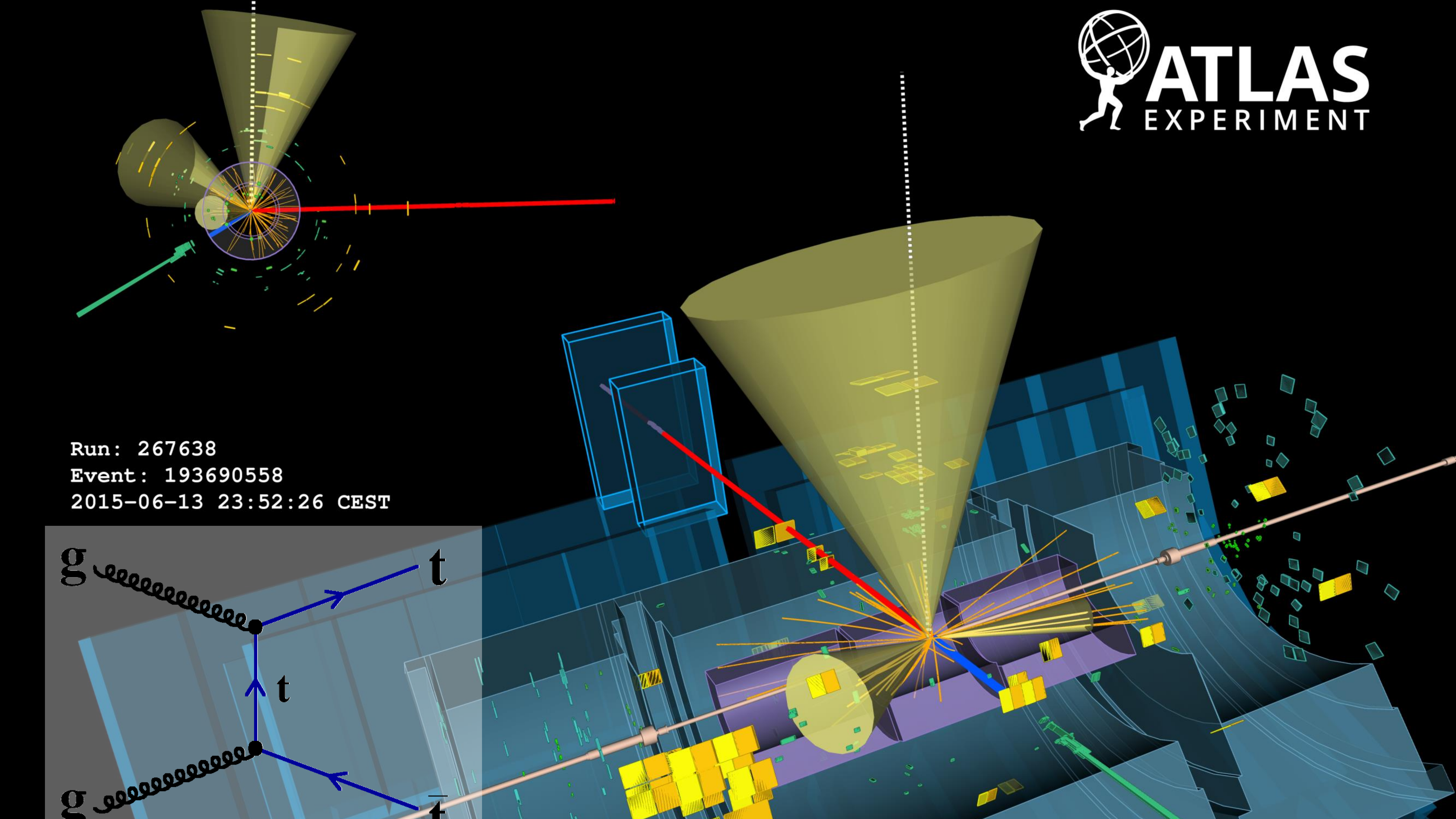
Top Yukawa coupling is ~1 → coincidence?

It decays before it hadronises
- Can be studied as bare quark

Very high production rate at the LHC
- 0.2 – 0.8 nb production cross section
  @ LHC energies
- Produced more than 100M $t\bar{t}$ pairs
  in Run 2 and Run 3(about 15 pairs/s)



→ Measurements of tt production in association of additional particles,
rare decays and rare production mechanism are now in reach (with high stats)

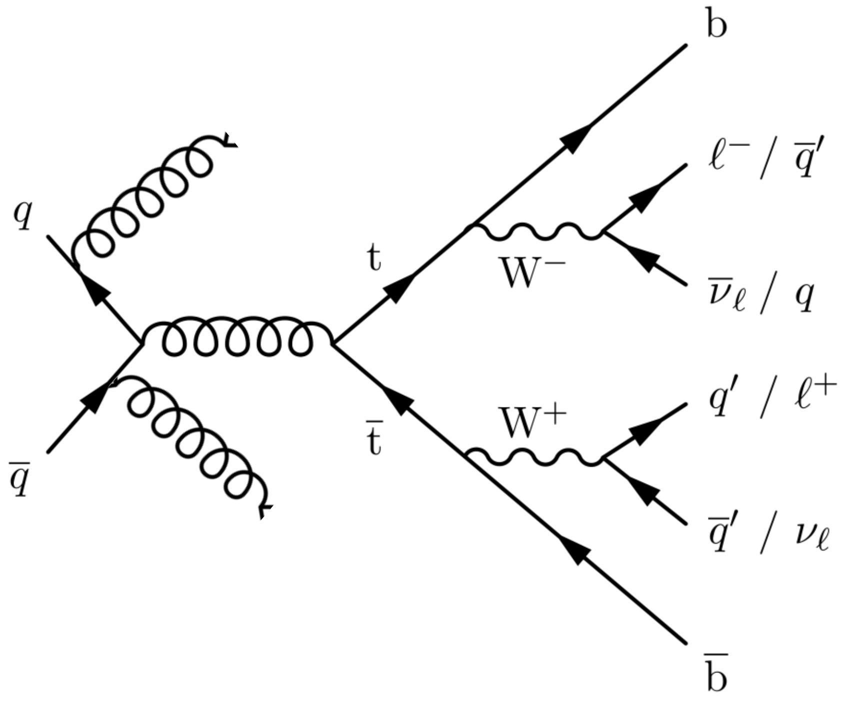

ATLAS
EXPERIMENT
Run: 267638
Event: 193690558
2015-06-13 23:52:26 CEST
g
g
t
t
t̄

Differential cross-sections in $t\bar{t}$ + jets

JHEP 08 (2024) 182
13 TeV / 140 fb^{-1}

- Already many distribution measured in the last years
- Here focus on dynamics and topology of the hardest and second-hardest QCD emissions using p_T and y of jets and their angular correlations and invariant masses

- Very good tests of pQCD theory via NLO and NNLO predictions and ME-PS matching algorithms

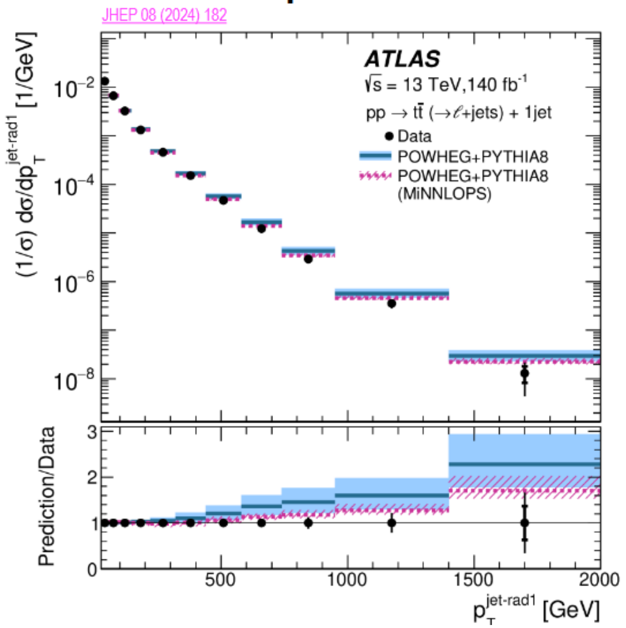


Analysis strategy:
- Lepton+jets channel
- Backgrounds taken from MC
- Fake lepton background using matrix method
- Unfolding using Bayesian unfolding

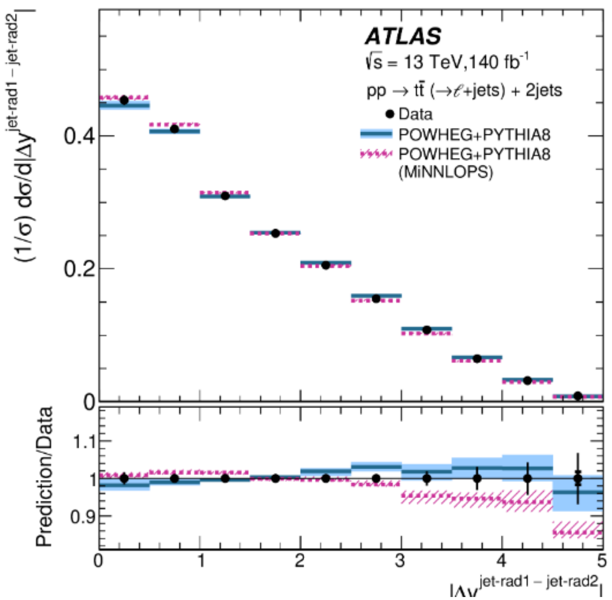
Differential cross-sections in $t\bar{t}$+jets

JHEP 08 (2024) 182
13 TeV / 140 fb^{-1}

$p_T^{\text{jet-rad1}}$



$|\Delta y^{\text{jet-rad1 - jet-rad2}}|$

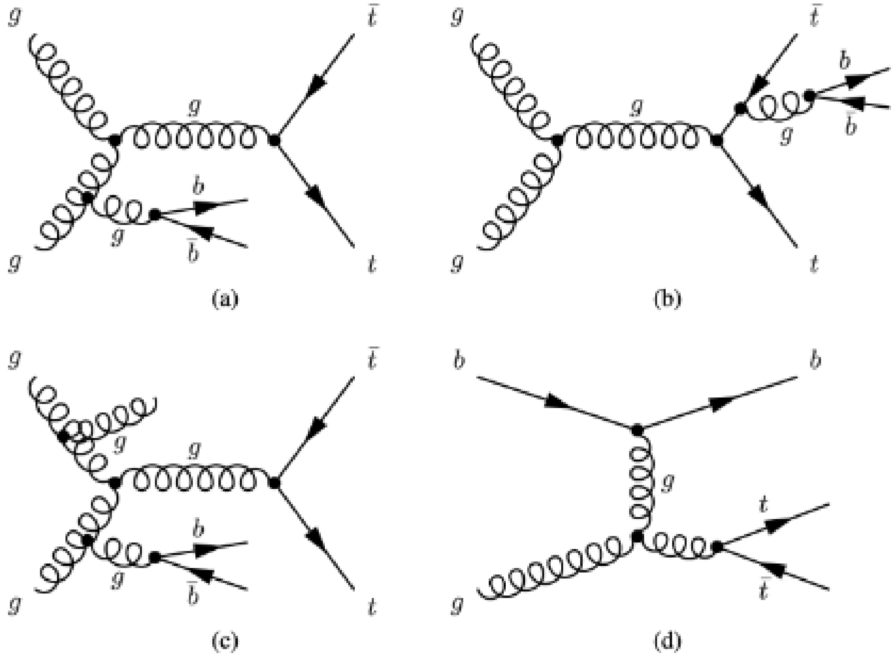


Prediction		Pwg+Py8		Pwg+Hw7		aMC@NLO+Hw7		Sherpa 2.2.12		Pwg+Py8 MiNNLOPS	
Observable	NDF	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value	χ^2	p-value
$p_T^{\text{jet-W1}}$	10	6.2	0.79	4.1	0.94	2.7	0.99	1.8	1.0	3.4	0.97
$\lvert y^{\text{jet-W1}}\rvert$	10	1.8	1.0	1.6	1.0	2.3	0.99	1.1	1.0	2.7	0.99
$p_T^{\text{jet-W2}}$	8	2.3	0.97	0.45	1.0	2.8	0.94	0.53	1.0	2.6	0.96
$\lvert y^{\text{jet-W2}}\rvert$	10	1.9	1.0	1.7	1.0	2.4	0.99	1.1	1.0	2.7	0.99
$\lvert\Delta y^{\text{jet-W1 – jet-W2}}\rvert$	10	1.6	1.0	2.7	0.99	4.3	0.93	0.90	1.0	6.0	0.81
$\lvert\Delta\phi^{\text{jet-W1 – jet-W2}}\rvert$	10	1.7	1.0	1.6	1.0	2.5	0.99	1.2	1.0	2.1	1.0
$p_T^{\text{jet-rad1}}$	11	7.7	0.74	7.1	0.79	3.3	0.99	2.6	1.0	6.4	0.85
$\lvert y^{\text{jet-rad1}}\rvert$	10	1.6	1.0	2.8	0.99	3.4	0.97	0.69	1.0	3.0	0.98
$\lvert\Delta\phi^{\text{toplep – jet-rad1}}\rvert$	7	1.4	0.99	2.2	0.95	2.9	0.89	0.81	1.0	2.3	0.94
$\lvert\Delta\phi^{\text{tophad – jet-rad1}}\rvert$	7	1.4	0.98	2.6	0.92	2.9	0.89	0.85	1.0	2.4	0.93
$\lvert\Delta\phi^{\text{jet-W1 – jet-rad1}}\rvert$	10	1.6	1.0	2.9	0.98	3.4	0.97	0.77	1.0	2.7	0.99
$m^{t\bar{t}\text{ – jet-rad1}}$	8	7.7	0.46	6.5	0.59	4.4	0.81	4.4	0.82	5.5	0.71
$p_T^{\text{jet-rad2}}$	9	3.2	0.96	4.0	0.91	37.0	< 0.01	1.7	1.0	11.0	0.28
$\lvert y^{\text{jet-rad2}}\rvert$	10	1.4	1.0	3.9	0.95	2.4	0.99	0.20	1.0	5.3	0.87
$\lvert\Delta y^{\text{jet-rad1 – jet-rad2}}\rvert$	10	1.6	1.0	4.0	0.95	4.0	0.95	0.13	1.0	5.4	0.86
$\lvert\Delta\phi^{\text{jet-rad1 – jet-rad2}}\rvert$	10	1.4	1.0	4.0	0.95	2.4	0.99	0.25	1.0	5.2	0.88
$\lvert\Delta\phi^{\text{toplep – jet-rad2}}\rvert$	7	1.3	0.99	3.2	0.86	2.0	0.96	0.46	1.0	4.1	0.77
$\lvert\Delta\phi^{\text{tophad – jet-rad2}}\rvert$	7	1.2	0.99	3.2	0.87	2.1	0.96	0.46	1.0	4.1	0.77
$\lvert\Delta\phi^{\text{jet-W1 – jet-rad2}}\rvert$	10	1.3	1.0	3.8	0.95	2.4	0.99	0.22	1.0	5.1	0.88
$m^{\text{jet-rad1 – jet-rad2}}$	9	6.2	0.72	6.7	0.66	2.6	0.98	4.2	0.90	8.8	0.45

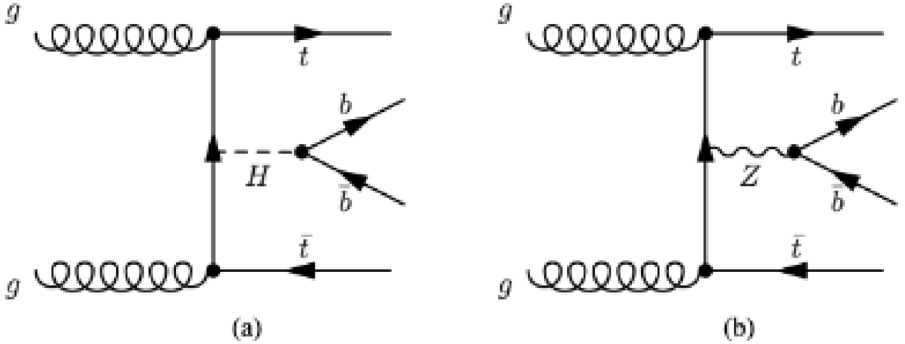
MiNNLOPS: improves leading jet pT, but doesn‘t improve in the rapidity separation to the 2nd leading jet
→ Most probably effect of matching

Measurement of production in association with additional b-jets

arXiv: 2407.13473
submitted to JHEP
13 TeV / 140 fb^{-1}



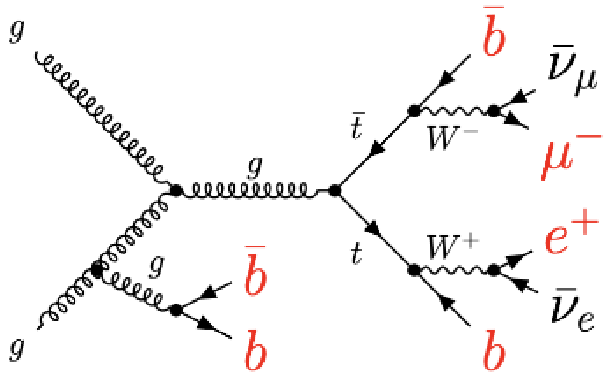
Examples of Feynman diagrams of QCD processes leading to $t\bar{t}b\bar{b}$ final state:

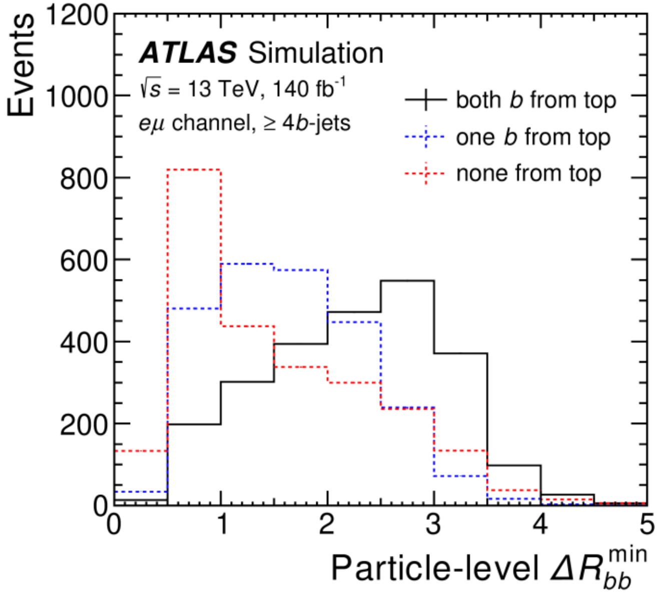


Examples of Feynman diagrams of electroweak processes leading to $t\bar{t}b\bar{b}$ final state:

- Non-trivial predictions due to very different scales involved starting from m_{top} down to momenta of soft additional radiations.
- Modelling of additional b-quark jets available at various state-of-the-art NLO ME+PS predictions.
- Important background for many processes: $ttH(bb)$, four tops and others

Measurement of production in association with additional b-jets





[arXiv: 2407.13473](https://arxiv.org/abs/2407.13473)
submitted to JHEP
13 TeV / 140 fb^{-1}

Analysis strategy:

- Dilepton channel
- Background corrections using semi-data-driven method:
  - Fake leptons (small background)
  - Miss-tagged $t\bar{t}$ + light jets and $t\bar{t}$ + c jets estimation
- Classification of events and b-jet assignment crucial

Fraction of events with correctly assigned *b*-jets:

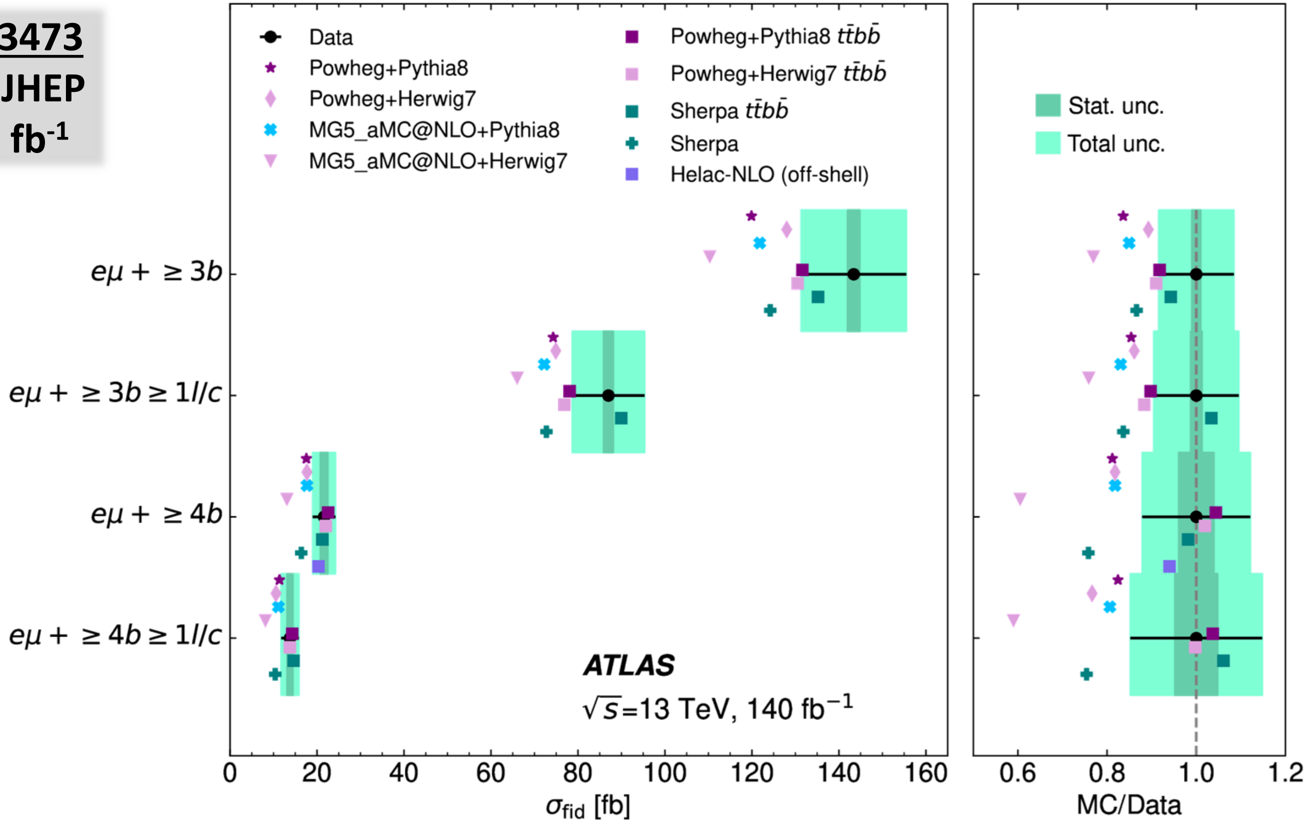
- By the algorithm: 53 % (56%) in $t\bar{t}$ events with at least 3 (4) *b*-jets.
- Selecting the leading p_T *b*-jets: 42 % (27%).

- Unfolding using Bayesian unfolding

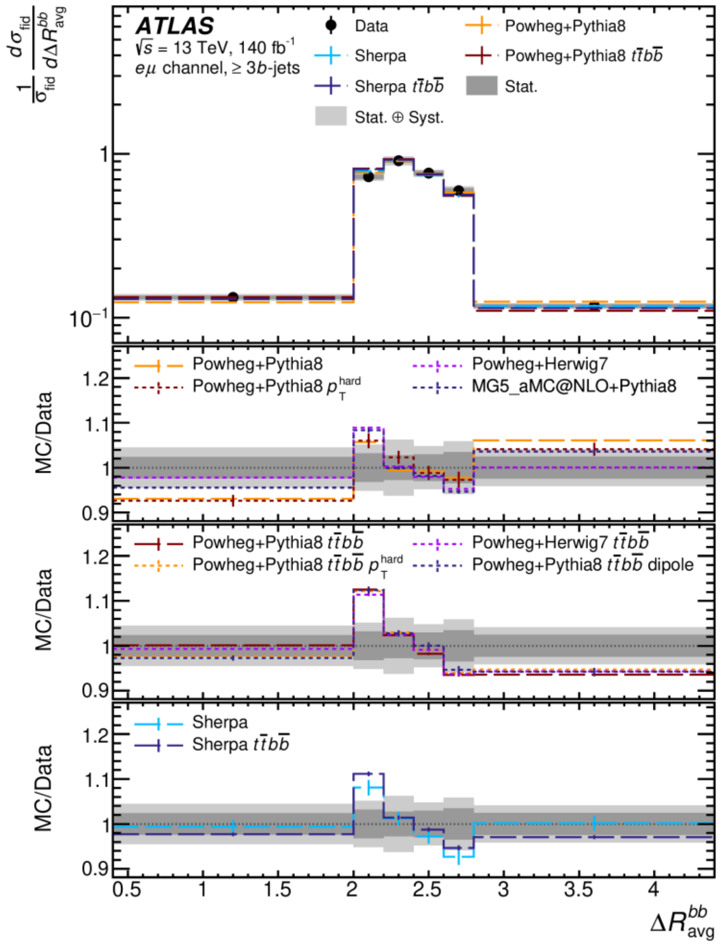
BERGISCHE UNIVERSITÄT WUPPERTAL

Measurement of $t\bar{t}$ production in association with additional b-jets

arXiv: 2407.13473
submitted to JHEP
13 TeV / 140 fb^{-1}



Example of a differential distribution

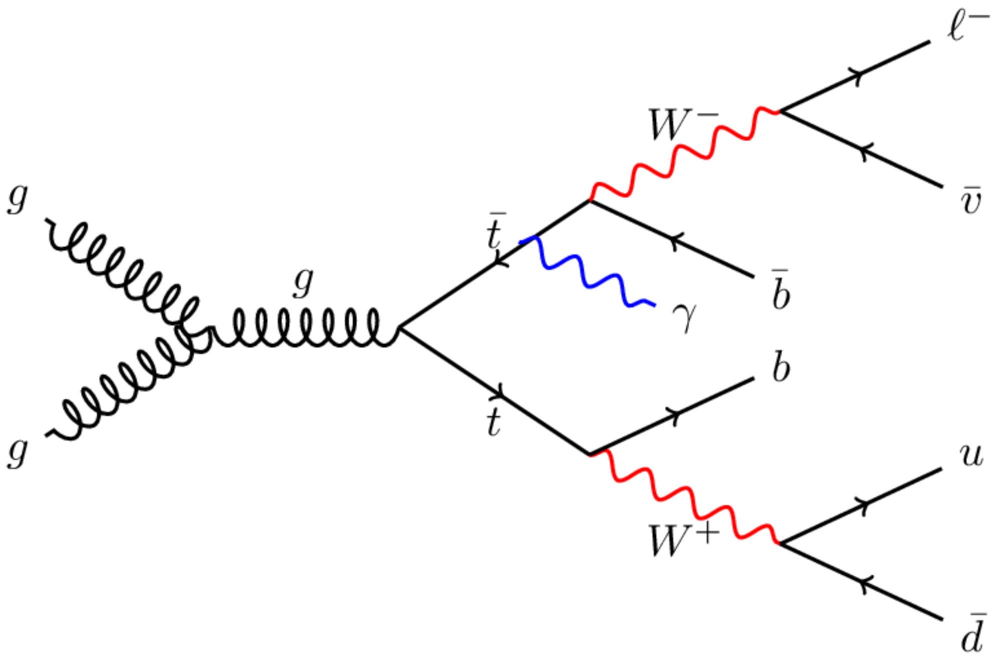


Overall 4FS generators predictions agree better with data than 5FS ones

A similar study is done using $t\bar{t} + c\bar{c}$ events: arXiv: 2409.11305 submitted to PLB

Cross-sections of $tt\gamma$ production

arXiv: 2403.09452
submitted to JHEP
13 TeV / 140 fb^{-1}



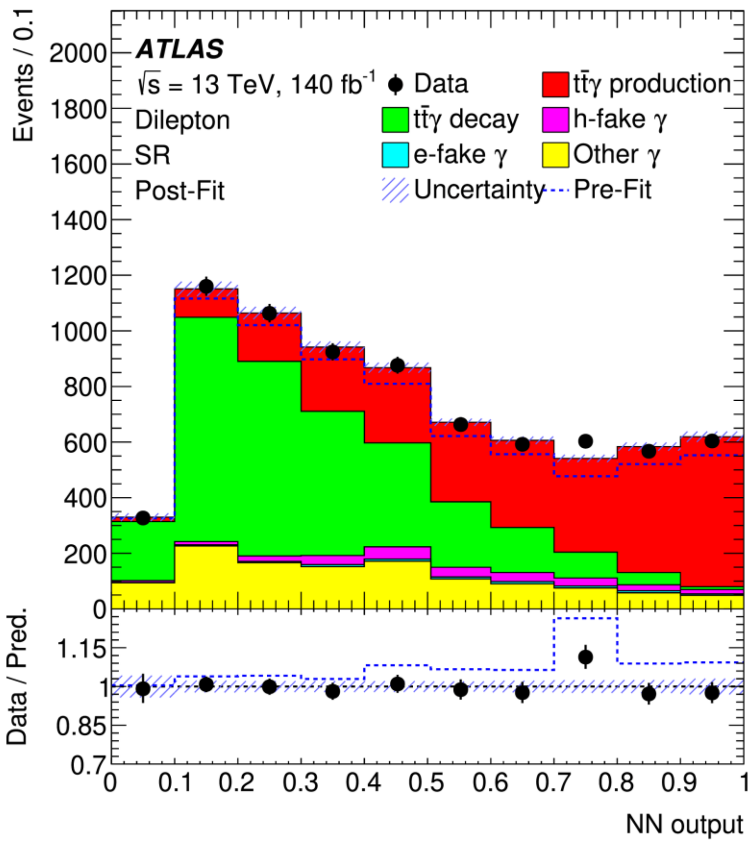
Analysis strategy:

- Dilepton and Lepton+jets channel with one additional photon
- Neural networks to enhance separation of $t\bar{t}\gamma$ production vs all backgrounds
- Profile-likelihood fit / profile likelihood unfolding

- Radiative production: probe structure of $t\gamma$ coupling
- Sensitive to new physics: top quark anomalous dipole moments, EFT interpretations (dim-6 operators - CtW, CtB)

Cross-sections of $tt\gamma$ production

arXiv: 2403.09452
submitted to JHEP
13 TeV / 140 fb^{-1}



Result:

$$\sigma_{t\bar{t}\gamma}(\text{lep}+\text{jets}) = 707^{+49}_{-46} = 707 \pm 6\,(stat)\ ^{+49}_{-46}(sys)\ \text{fb}$$

$$\sigma_{t\bar{t}\gamma}(\text{dilepton}) = 117.7^{+8.3}_{-7.9} = 117.7 \pm 1.7\,(stat)^{+8.1}_{-7.7}(sys)\ \text{fb}$$

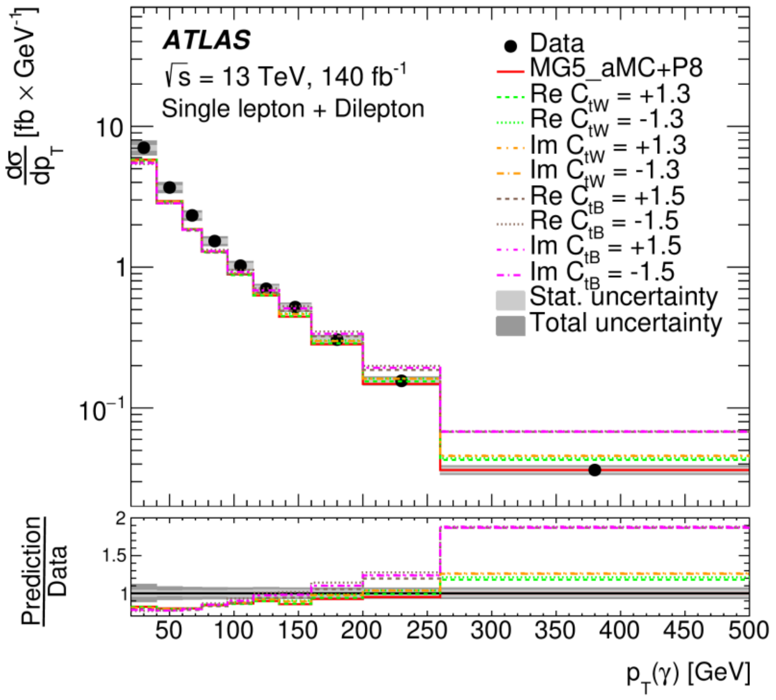
Source	$\Delta\sigma_{t\bar{t}\gamma\ \text{production}}/\sigma_{t\bar{t}\gamma\ \text{production}}$ (%) Single lepton	Dilepton	Combination
Statistical uncertainty	1.8	3.3	1.5
MC statistical uncertainties	1.5	1.5	1.0
Modelling uncertainties			
$t\bar{t}\gamma$ production PS uncertainty	2.4	3.7	0.9
Other $t\bar{t}\gamma$ production modelling	5.1	1.6	3.0
$t\bar{t}\gamma$ decay modelling	0.3	1.3	0.8
$t\bar{t}\gamma$ decay normalisation	2.4	3.1	2.1
Prompt photon background normalisation	1.5	2.0	2.0
Fake photon background estimate	0.8	1.5	1.6
Fake lepton background estimate	0.4	–	0.1
Other Background modelling	0.7	0.2	0.5
Experimental uncertainties			
Jet uncertainties	3.5	3.0	1.7
B-tagging uncertainties	2.6	2.1	1.0
Photon	0.5	1.5	0.8
Lepton	1.3	1.4	1.3
E_T^{miss}	0.3	0.4	0.4
Pile-up	0.3	0.7	0.5
Luminosity	0.8	1.0	0.8
Total systematic uncertainty	7.6	7.1	5.0
Total uncertainty	7.8	7.7	5.2

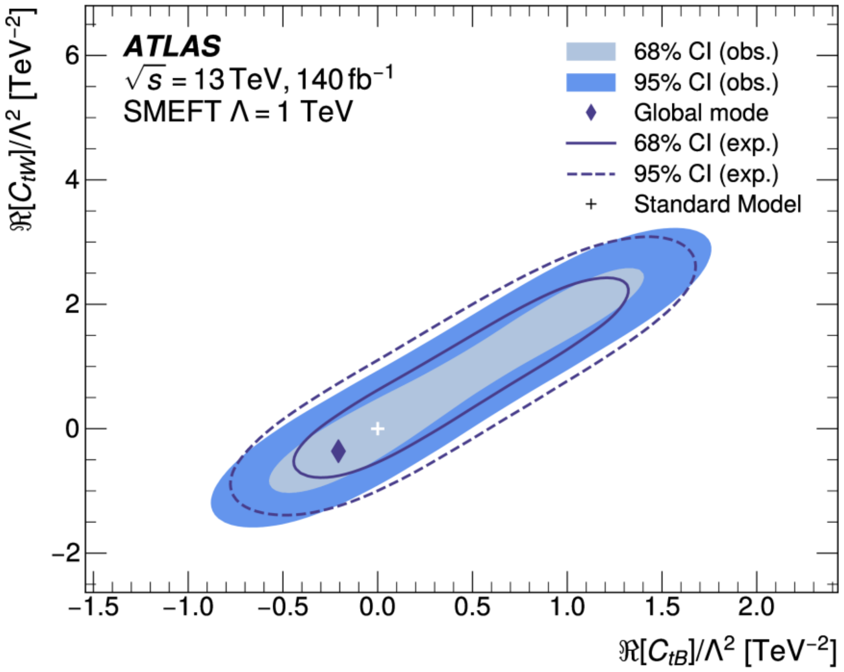
Cross-sections of $t\bar{t}\gamma$ production

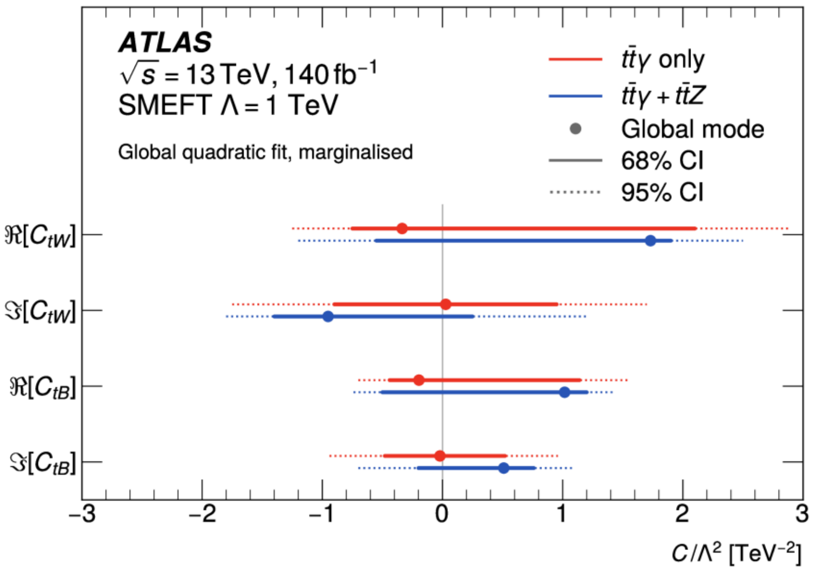
- EFT limits determined using photon p_T of $tt\gamma$ production
- Relevant dim-6 Wilson coefficients: C_{tB} and C_{tW}

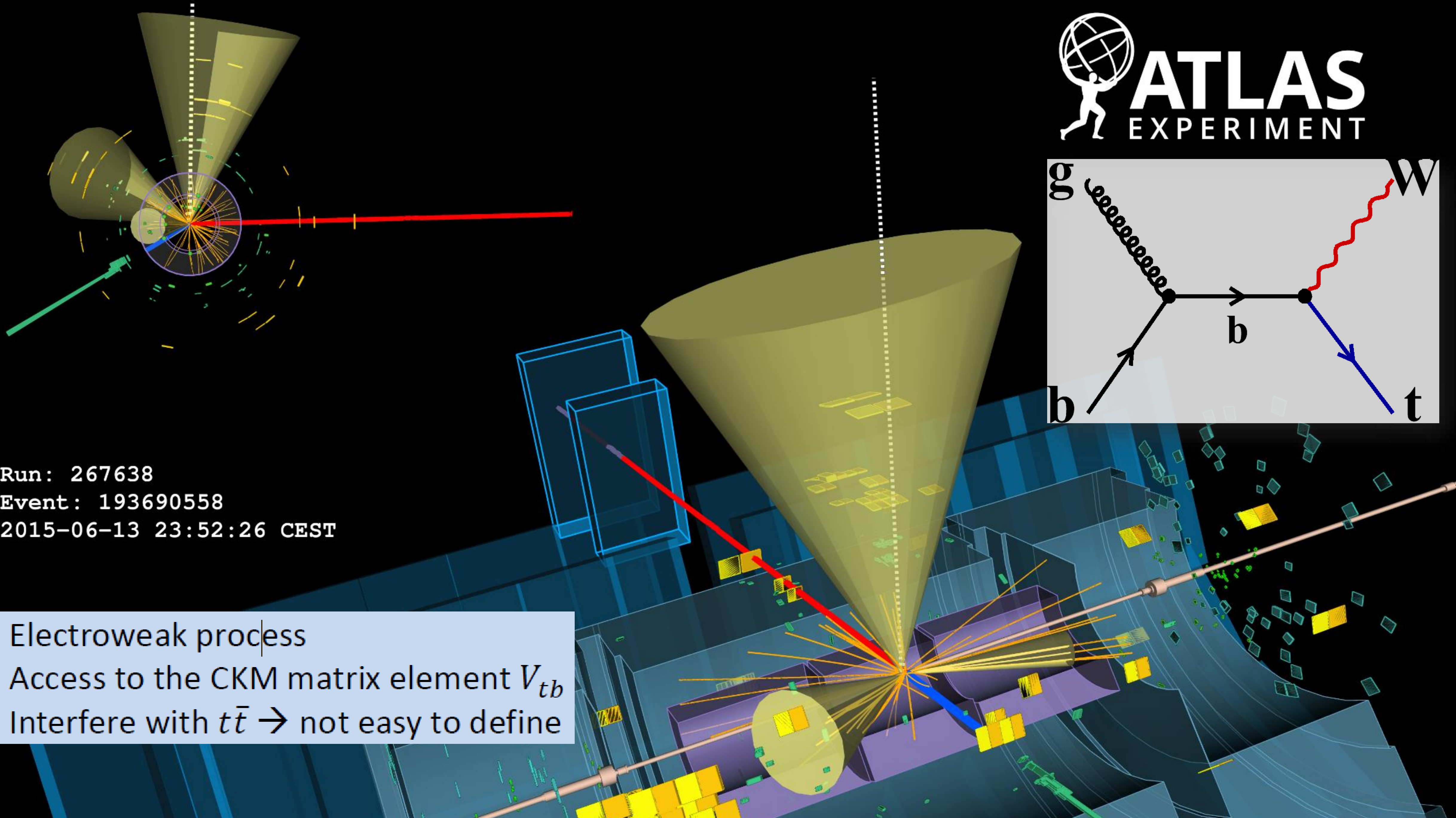
arXiv: 2403.09452
submitted to JHEP
13 TeV / 140 fb^{-1}

- Independent and simultaneous fits to all coefficients
- 2D marginalised confidence intervals from combined $tt\gamma$ production









Electroweak process

Access to the CKM matrix element V_{tb}

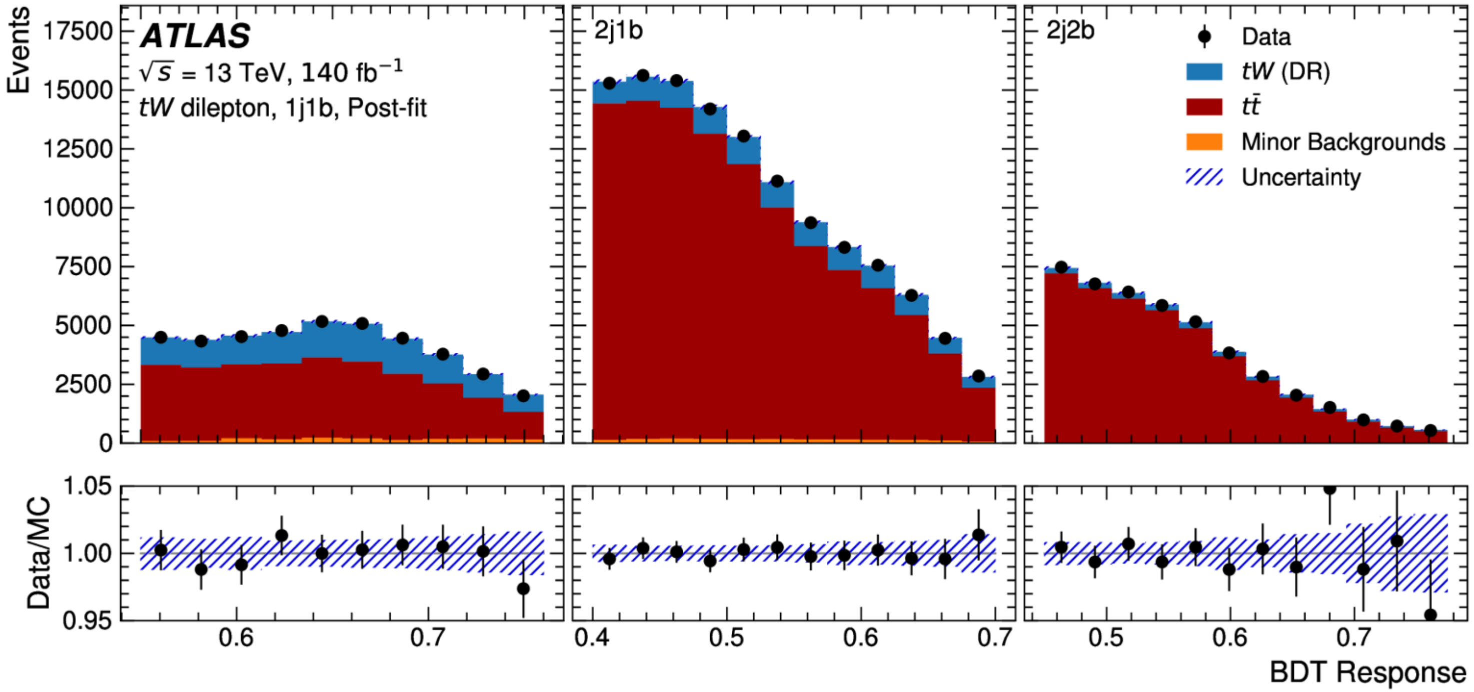
Interfere with $t\bar{t}$ → not easy to define

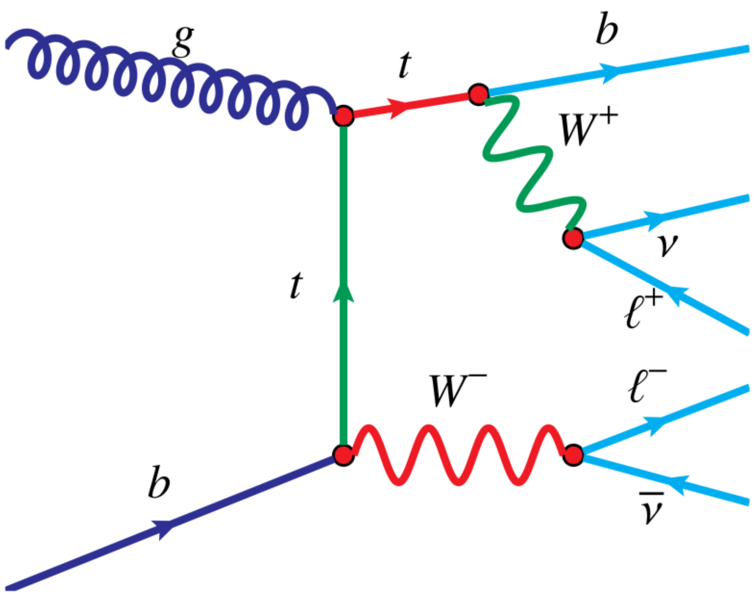
Measurement of tW production

Strategy:

- Event selection: 2 leptons, at least one b-jet
- Main backgrounds from MC: $t\bar{t}, W$+jets, Z+jets, and diboson
- Classify events into 3 signal regions: $1j1b$, $2j1b$, $2j2b$
- Boosted decision to separate signal from background
- Profile Likelihood Fit to extract cross section

arXiv: 2407.15594
Submitted to PRD
13 TeV / 140 fb^{-1}





BERGISCHE UNIVERSITÄT WUPPERTAL

Measurement of tW production

Uncertainty source	$\Delta\sigma_{tW}/\sigma_{tW}$ [%]
$t\bar{t}$ modeling	13.2
Jet energy scale	12.0
E_T^{miss} reconstruction and calibration	11.0
tW modeling	7.9
Jet energy resolution	7.0
Jet flavor tagging	3.7
Pileup	2.5
Lepton (e and μ) reconstruction and calibration	1.9
Other background modeling	0.9
Luminosity	0.8
PDF (tW and $t\bar{t}$)	0.6
MC statistical uncertainty	4.7
Total systematic uncertainty	19.2
Data statistical uncertainty	1.4
Total uncertainty	19.3

arXiv: 2407.15594
Submitted to PRD
13 TeV / 140 fb^{-1}

Result:

$\sigma_{tW} = 75 \pm 1\ (stat)\ ^{+15}_{-14}(sys) \pm 1\ (lumi)$ pb

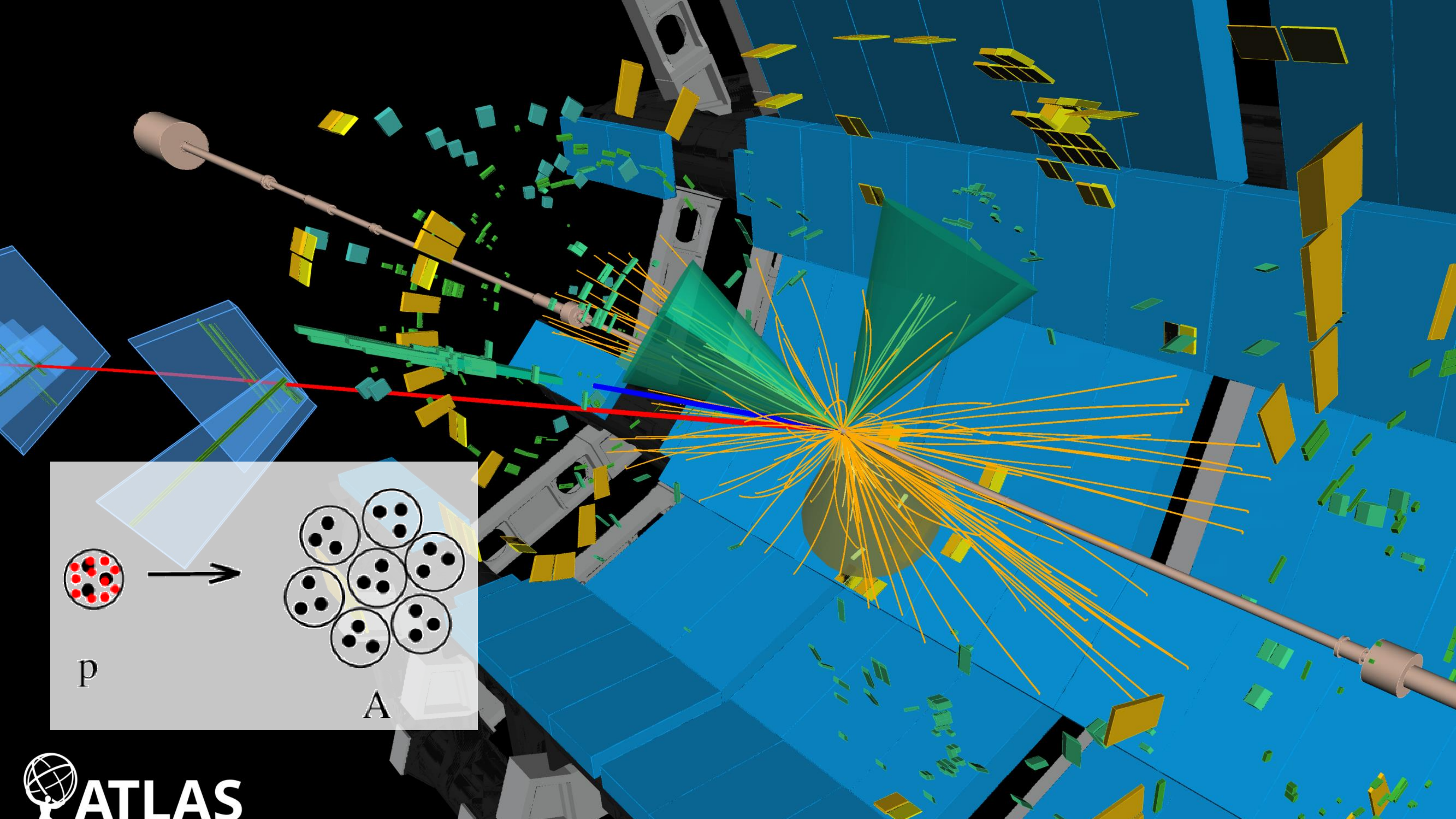
→ uncertainty of 20%

This result can converted into a limit on $|f_{LV}V_{tb}|$ using

$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{meas}}{\sigma_{theo}}}$$

f_{LV}: model-independent left-handed form factor

→ $|f_{LV}V_{tb}| = 0.97 \pm 0.10$


p
A
ATLAS

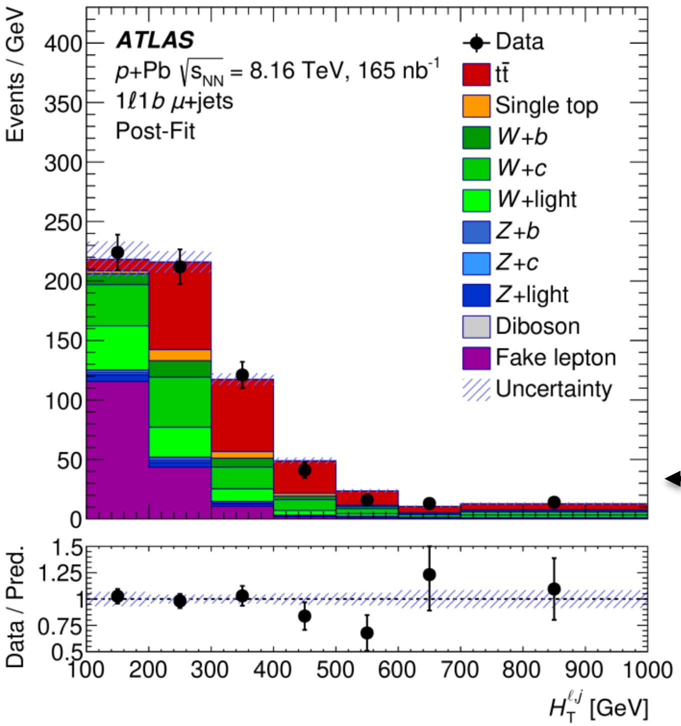
Observation of $t\bar{t}$ production in p+Pb collisions

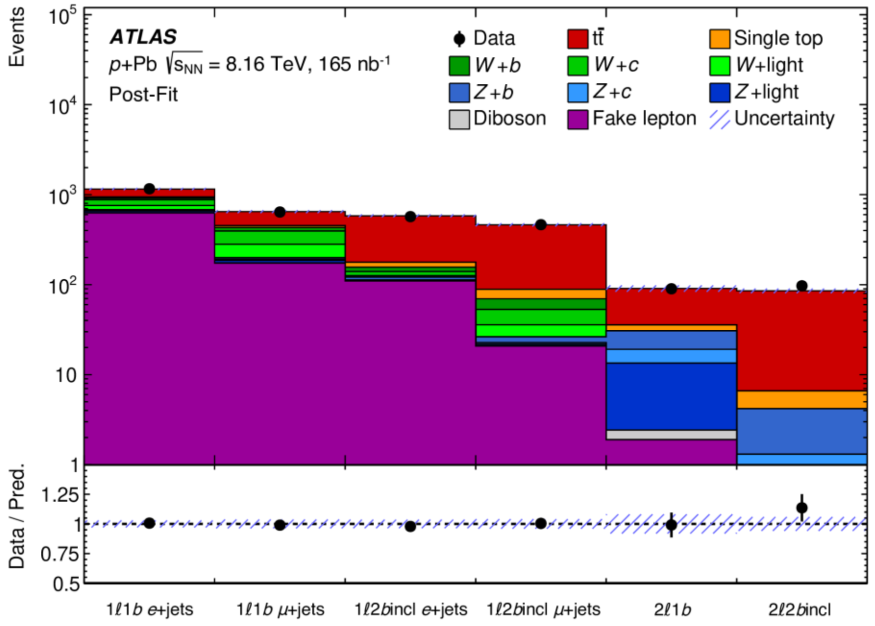
In $p + Pb$ collisions, measurements of top quarks access regions of nuclear PDFs that are not well-constrained by other measurements (e.g., gluon nPDFs)

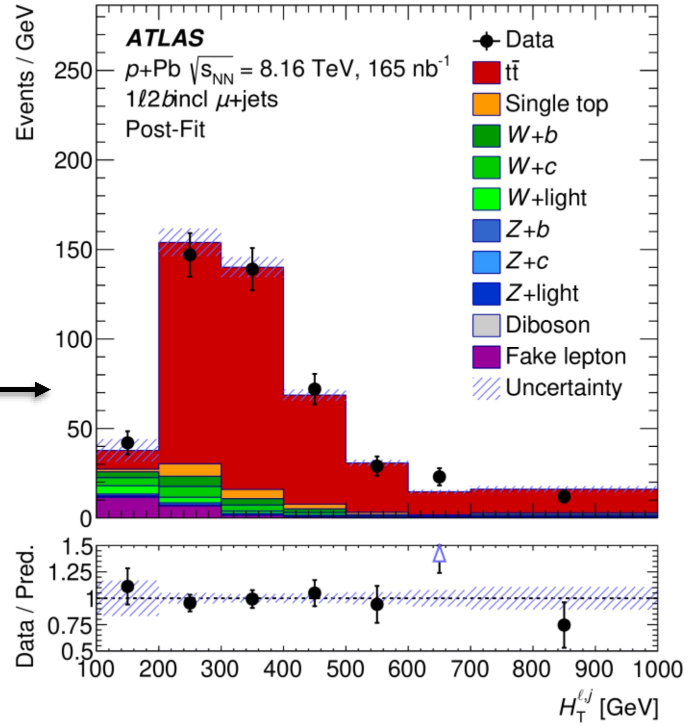
arXiv: 2405.05078
Submitted to JHEP
8.16 TeV / 165 nb^{-1}

Strategy:

- Lepton+jets and dilepton channel
- Fake lepton background is estimated from data all others are taken from simulations
- Simultaneous profile likelihood fit in 6 regions of H_T

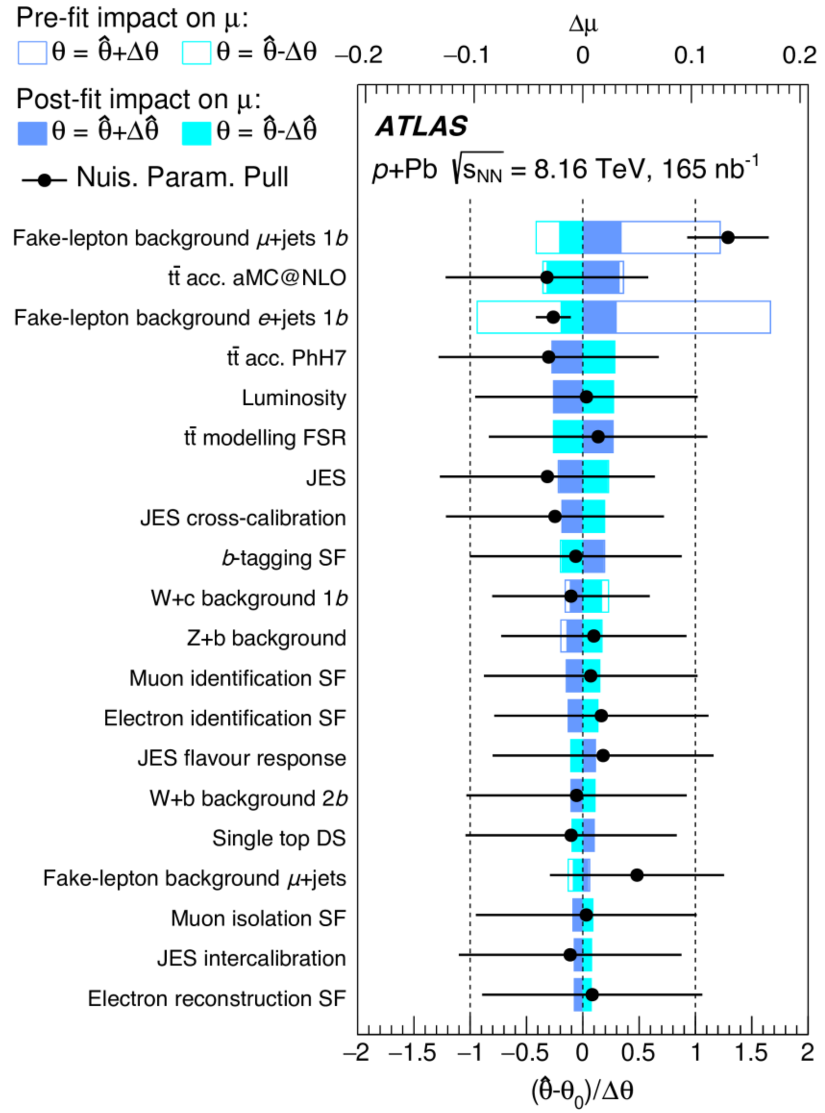


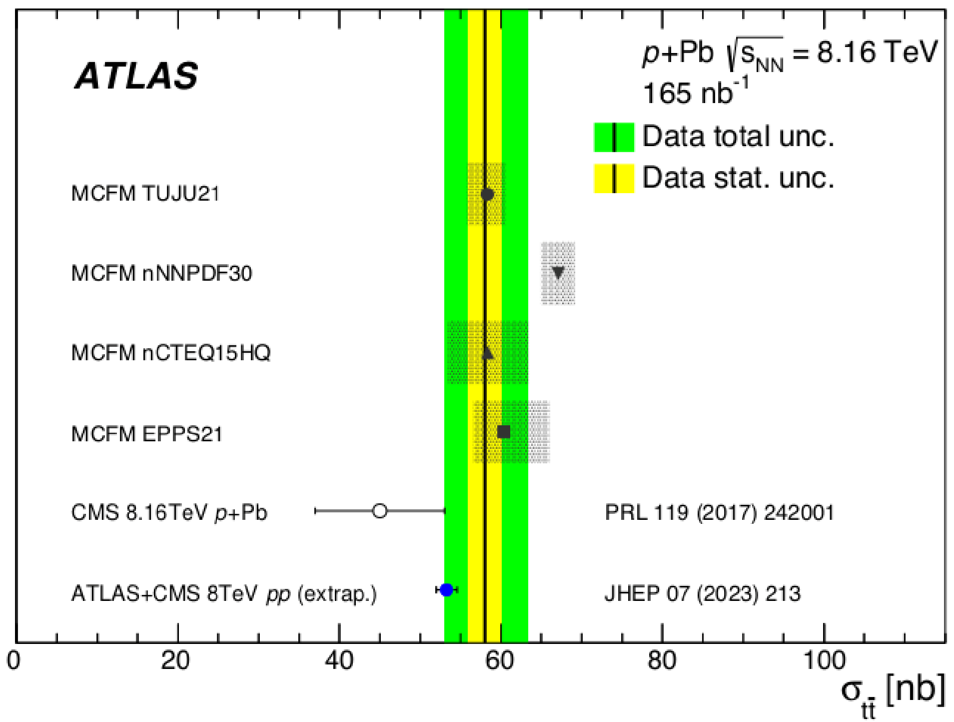




BERGISCHE UNIVERSITÄT WUPPERTAL

Observation of $t\bar{t}$ production in p+Pb collisions





Result:

$\sigma_{t\bar{t}} = 58.1 \pm 2.0\ (stat)\ ^{+4.8}_{-4.4}(sys)$ nb

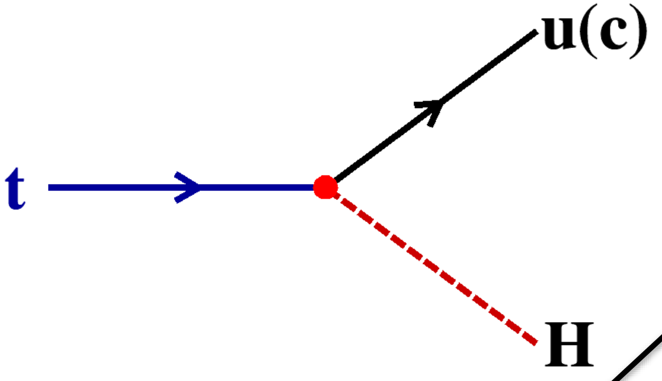
→ uncertainty of 9%

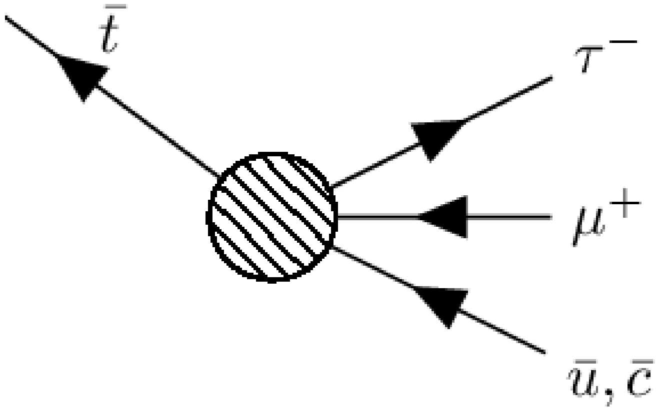
Nuclear modification factor:

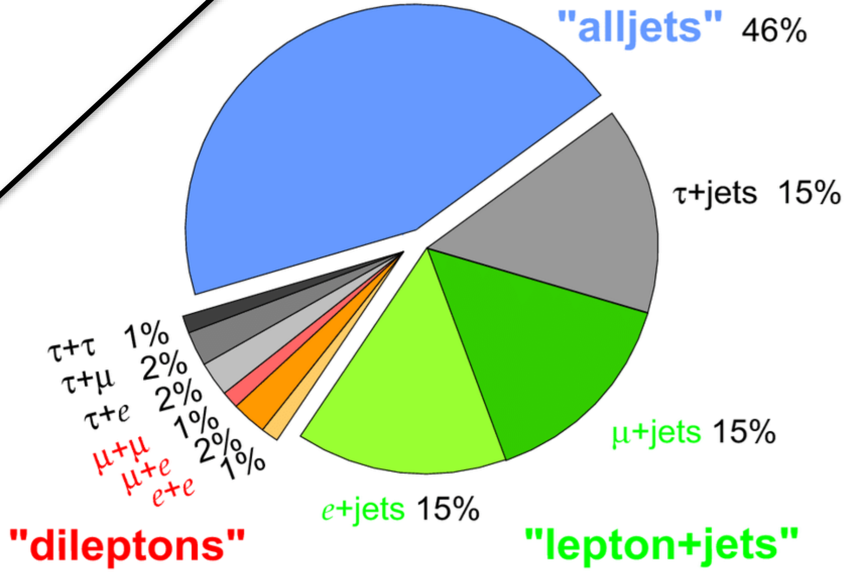
$$R_{pA} = \sigma_{t\bar{t}}^{p+Pb} = 1.090 \pm 0.039\ (stat)^{+0.094}_{-0.087}(syst)$$

arXiv: 2405.05078
Submitted to JHEP
8.16 TeV / 165 nb^{-1}

Hunt for new top-quark decays
(and new production modes)



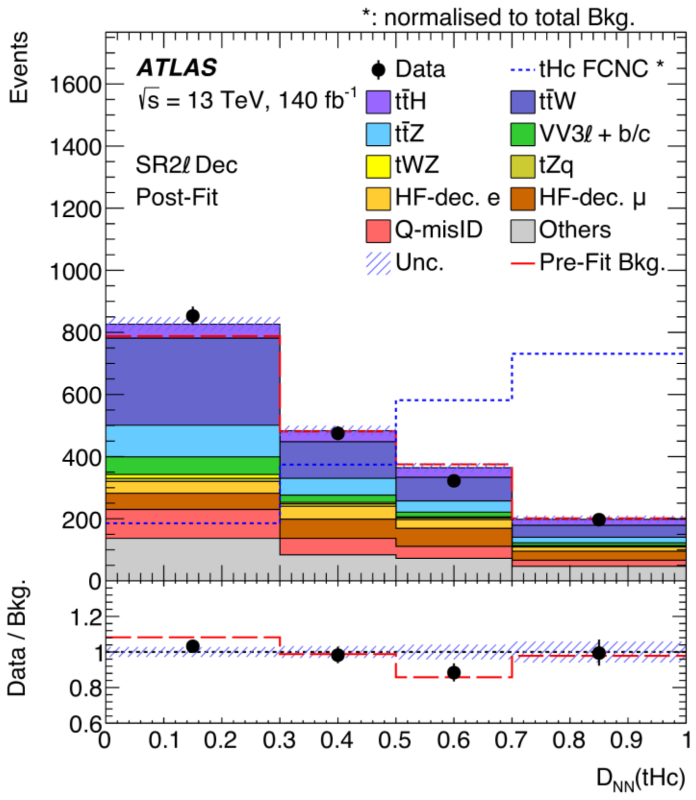


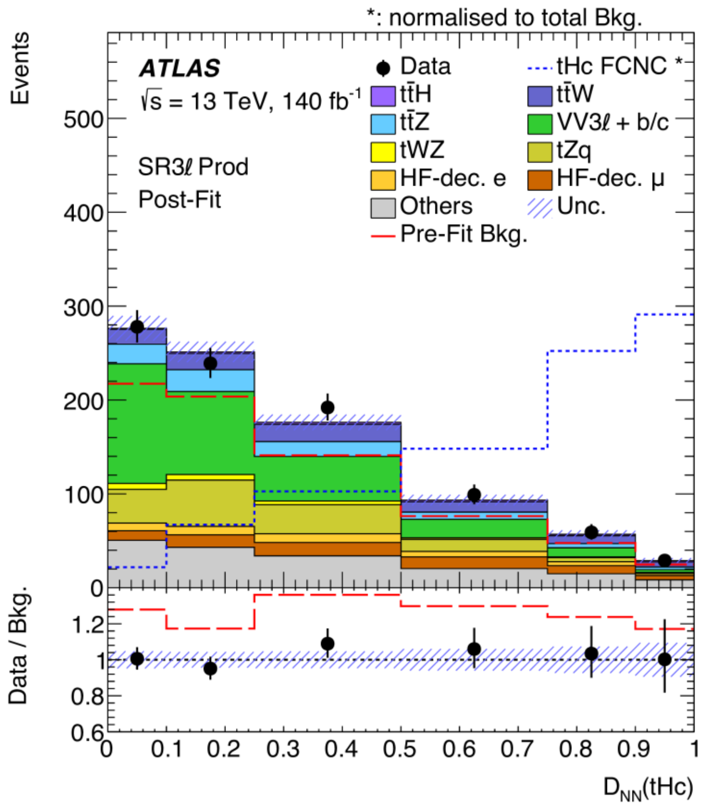


BERGISCHE UNIVERSITÄT WUPPERTAL

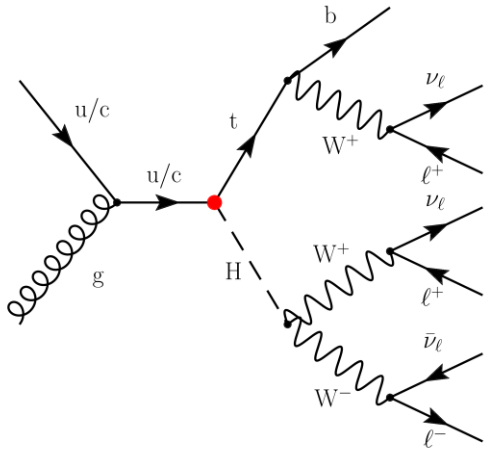
Search for flavour-changing neutral-current couplings

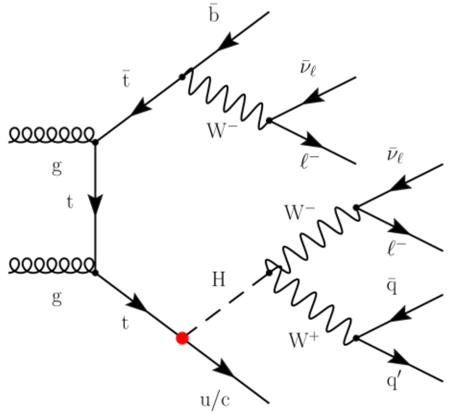
Strategy:
- Search with dilepton SS (e, μ) events and 3 leptons with ≥1 jets, ≥1 bjets events
- Neural networks to separate signal from background
- Simultaneous profile likelihood fit in 7 regions





Networks separated for production and decay

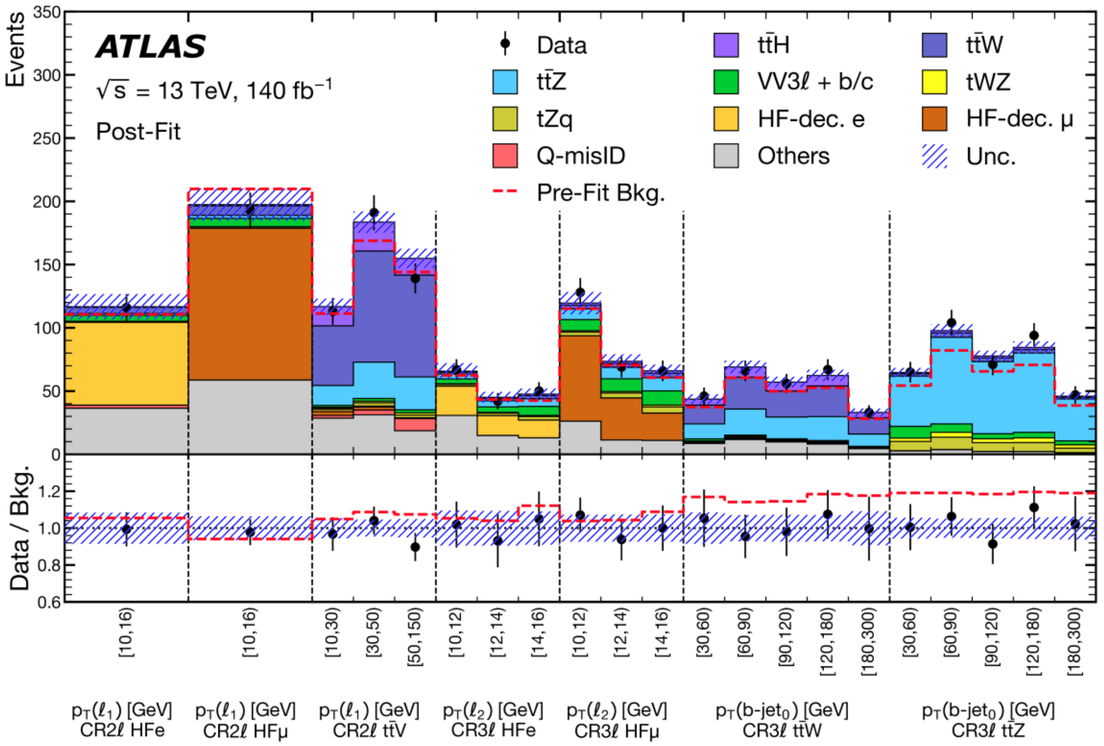


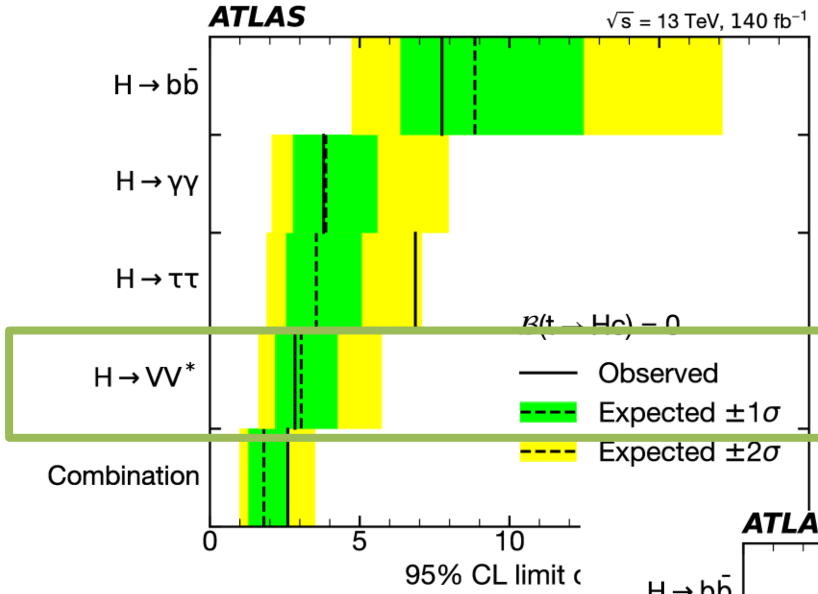


Eur. Phys. J. C 84 (2024) 757
13 TeV / 140 fb^{-1}

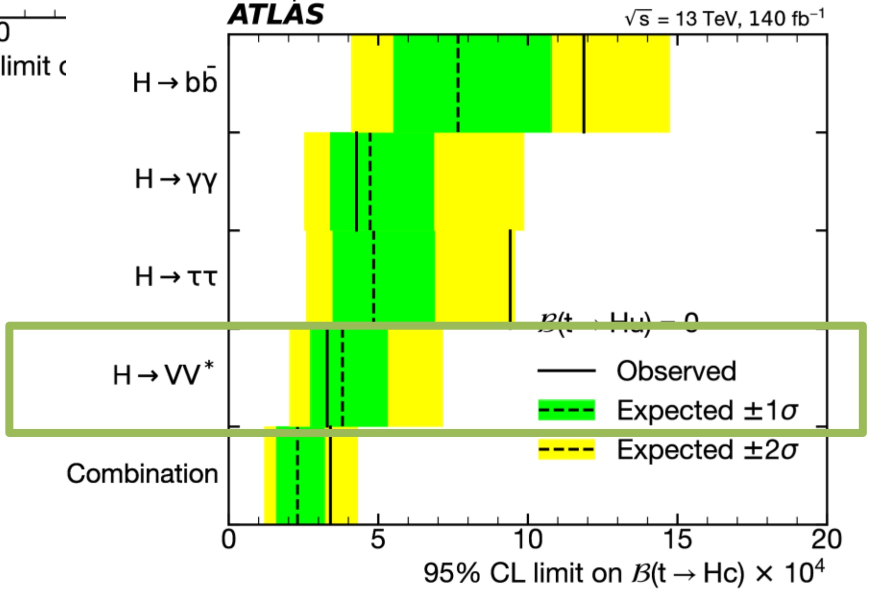
Search for flavour-changing neutral-current couplings

Eur. Phys. J. C 84 (2024) 757
13 TeV / 140 fb^{-1}





Combination dominated by multilepton analysis



$$Br(t \to uH) < 2.8 \cdot 10^{-4}\ (3.0 \cdot 10^{-4}),$$
$$Br(t \to cH) < 3.3 \cdot 10^{-4}\ (3.8 \cdot 10^{-4})$$

Search for lepton-flavour violating $\mu\tau qt$ interactions

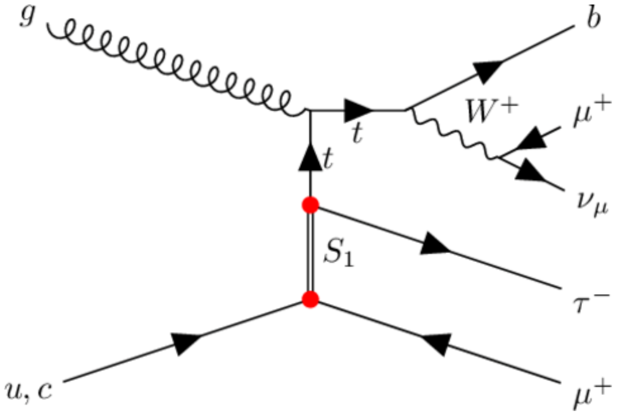
Phys. Rev. D 110 (2024) 012014
13 TeV / 140 fb^{-1}

- cLFV via neutrino oscillations is highly suppressed (BR~10^{-55})
- Some BSM processes (leptoquarks, SUSY, 2HDM) involve cLFV

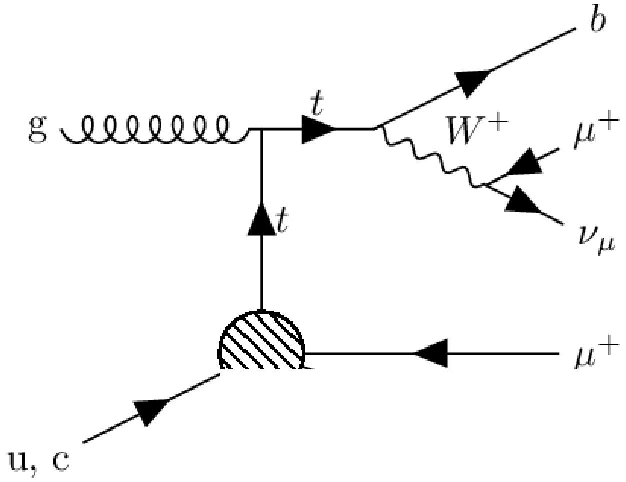
Strategy:

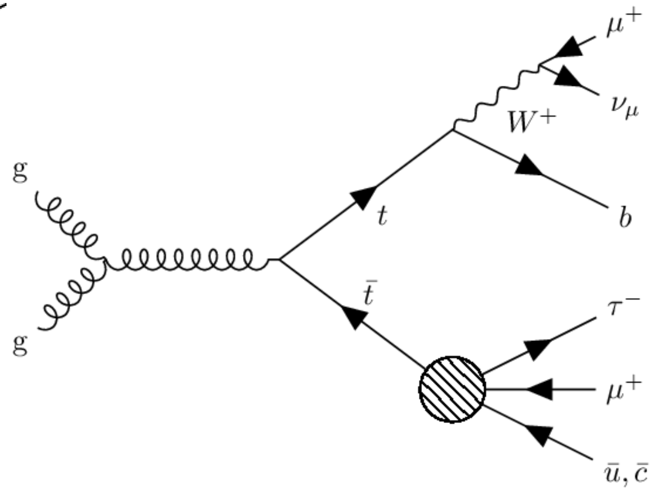
- Model independent EFT approach for $tq\ell\ell'$ operators
- Search for scalar leptoquark S_1

- Events with SS $\mu\mu$ and one hadronically decay τ are selected
- One SR and two CR for non-prompt leptons and fake τ contributions
- Profile likelihood fit to H_T distributions



scalar leptoquark S_1 model

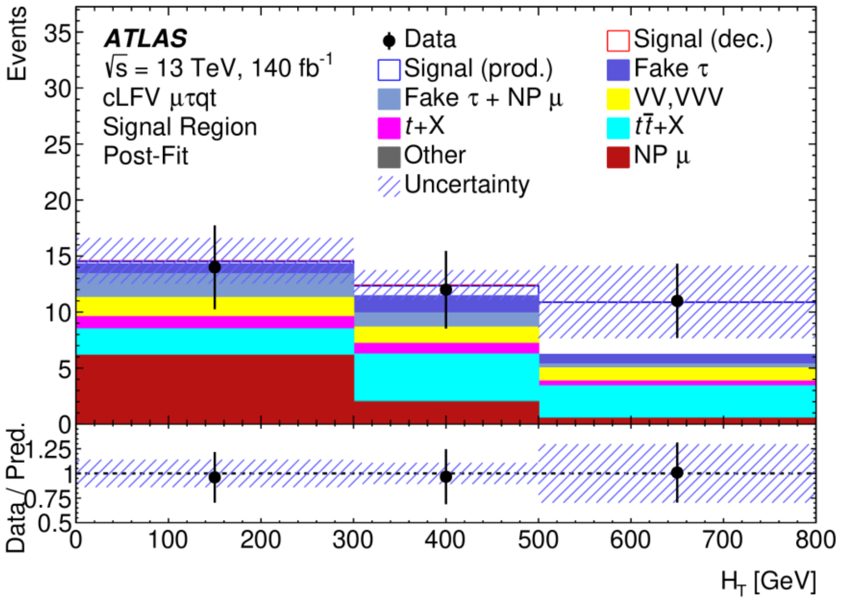


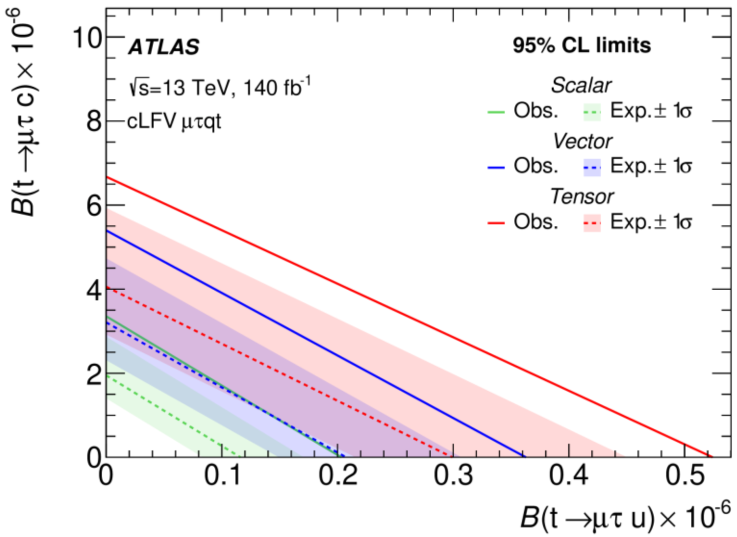


BERGISCHE UNIVERSITÄT WUPPERTAL

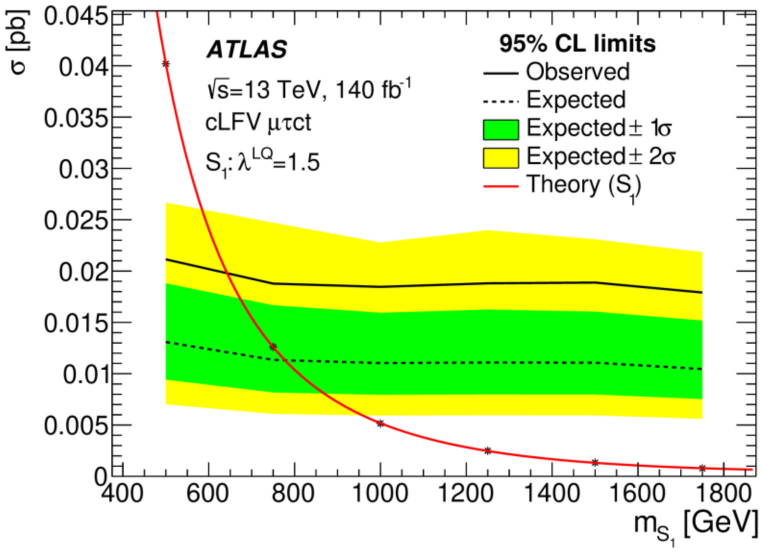
Search for lepton-flavour violating $\mu\tau qt$ interactions

Phys. Rev. D 110 (2024) 012014
13 TeV / 140 fb^{-1}





scalar leptoquark S_1 model



cLFV vertex		tμτq (q=u,c)
c/Λ^2 [GeV^{-2}]	u	0.10-0.44
	c	0.36-1.8
BR($t\to q\mu\tau$) [10^{-6}]	u	0.20-0.52
	c	3.4-6.7

7-41x better than previous indirect limits

Upper 95% CL limits on LQ coupling strengths from λ_{LQ} = 1.3 to λ_{LQ} = 3.7 for masses 0.5 to 2.0 TeV

Test of lepton flavour universality

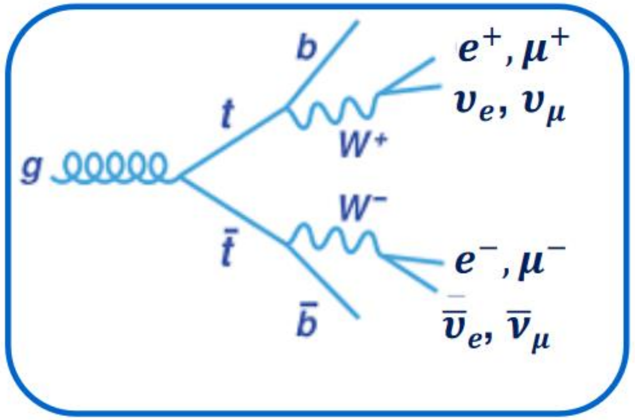
Lepton flavour universality (LFU) is a fundamental axiom of SM
→ Couplings of charged leptons e, μ, τ to W, Z are independent of the lepton mass

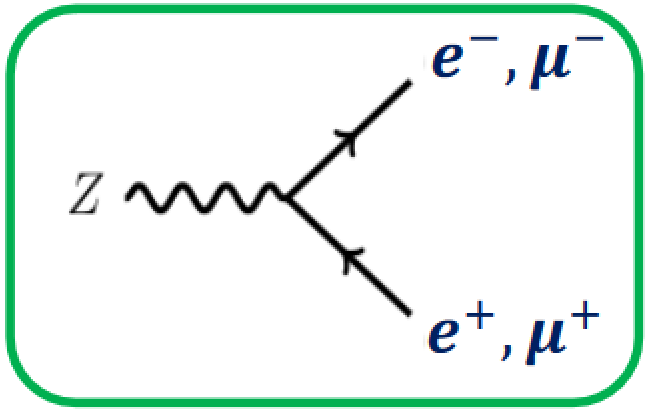
[Eur. Phys. J. C 84 (2024) 993](https://doi.org/10.1140/epjc/s10052-024-13305-z)
13 TeV / 140 fb^{-1}

Strategy

Measure ratio:

$$R_{WZ}^{\mu/e} = \frac{R_W^{\mu/e}}{\sqrt{R_Z^{\mu\mu/ee}}} = \frac{\mathcal{B}(W \to \mu\nu)}{\mathcal{B}(W \to e\nu)} \cdot \sqrt{\frac{\mathcal{B}(Z \to ee)}{\mathcal{B}(Z \to \mu\mu)}}$$



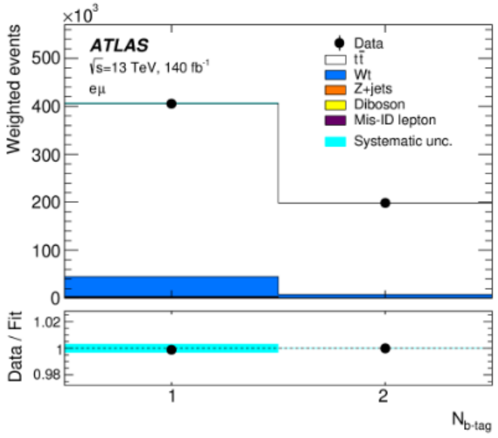


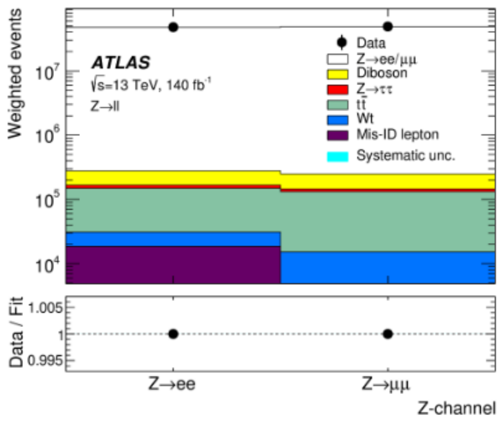
Simultaneous maximum likelihood fit to $t\bar{t}$ events ("b-tag counting method") and Z counts:

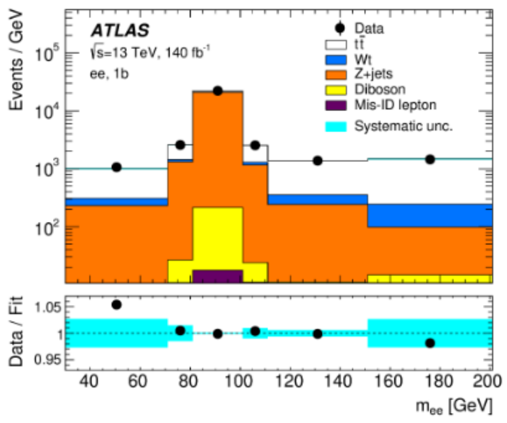
- Yields in $t\bar{t} \to e\mu$ $1b/2b$ and $Z \to ee/\mu\mu$ regions
- $m\ell\ell$ spectrum in $t\bar{t} \to ee/\mu\mu$ $1b/2b$ regions

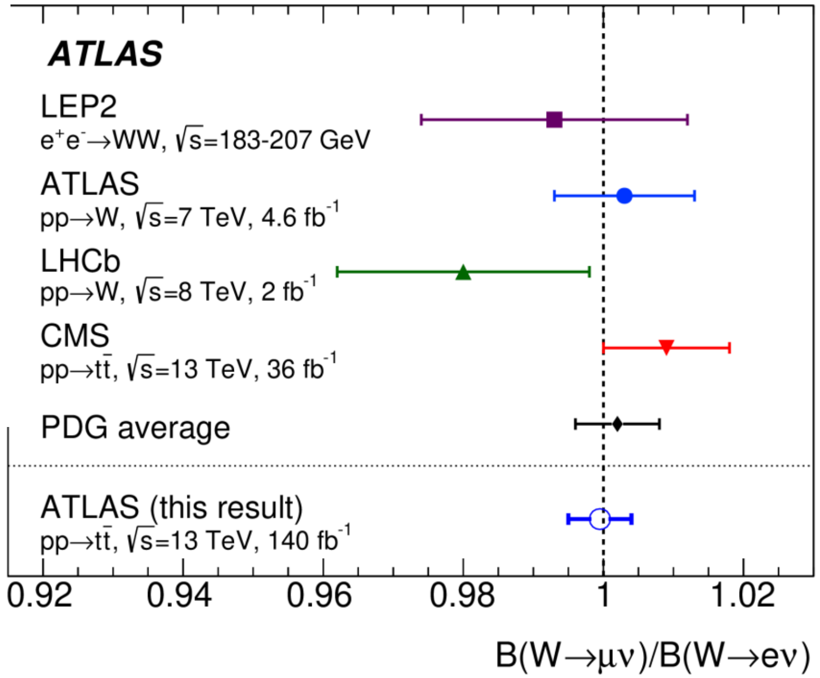
Parametrise fitted yields using deviations in BR

Test of lepton flavour universality









$$\mathcal{B}(W \to \mu\nu)/\mathcal{B}(W \to e\nu) = 0.9995 \pm 0.0045$$

- Most precise e/μ universality test (0.45%)
- Improves on the previous PDG average
- No evidence for LFU violation

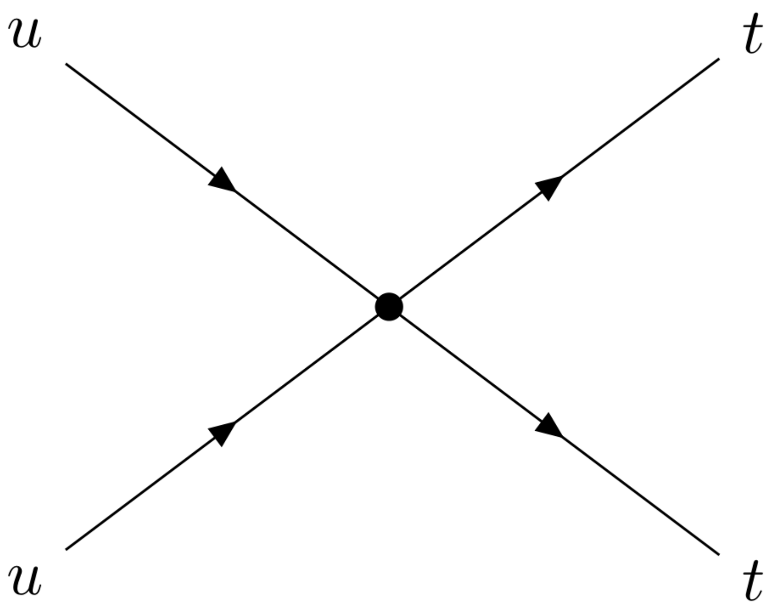
Measurement dominated by systematic uncertainties: PDF, modelling, lepton uncertainties

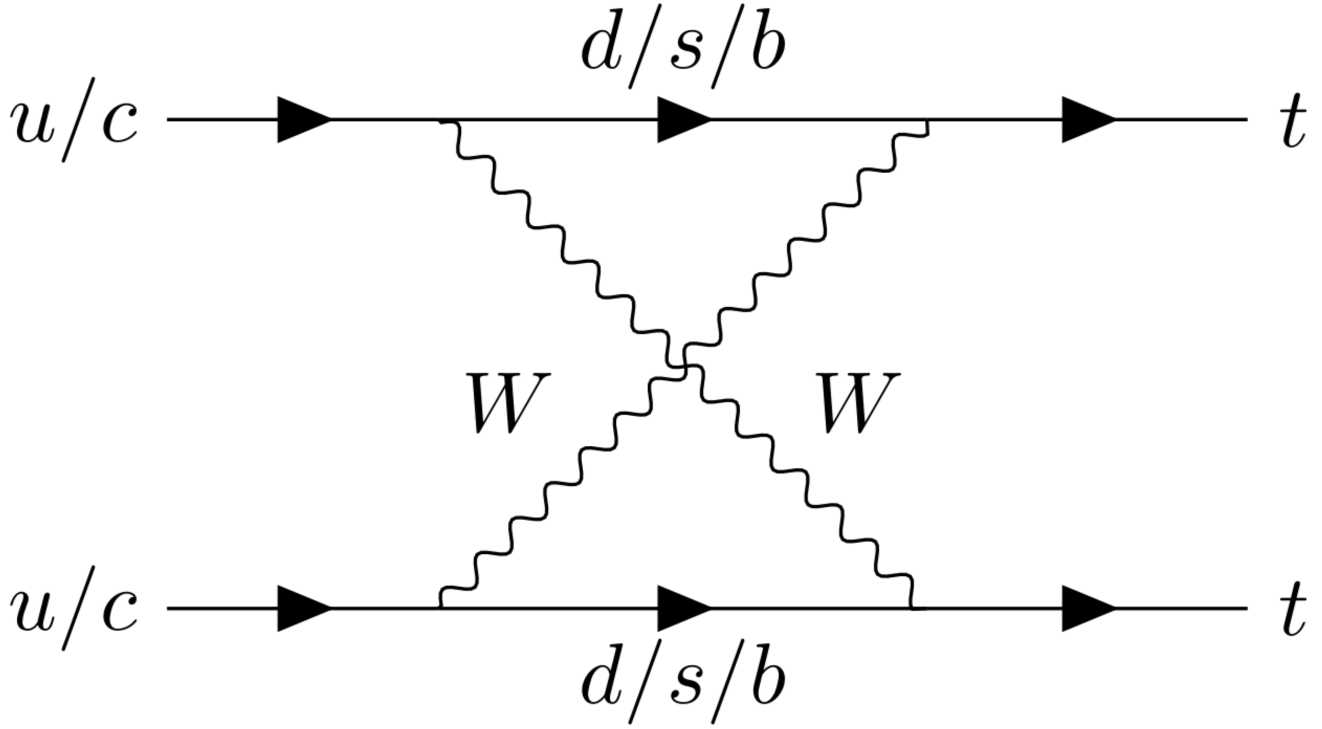
Eur. Phys. J. C 84 (2024) 993
13 TeV / 140 fb^{-1}

Search for same-charge top-quark pair production

Same-charge top-quark pair production is strongly suppressed in the SM

- Very clean signature in the dileptonic final state
- Observation would imply the existence of new underlying physics
- Signal modelling can be modelled via EFT operators $c_{tu}^{(1)}, c_{Qu}^{(1)}, c_{Qu}^{(8)}$



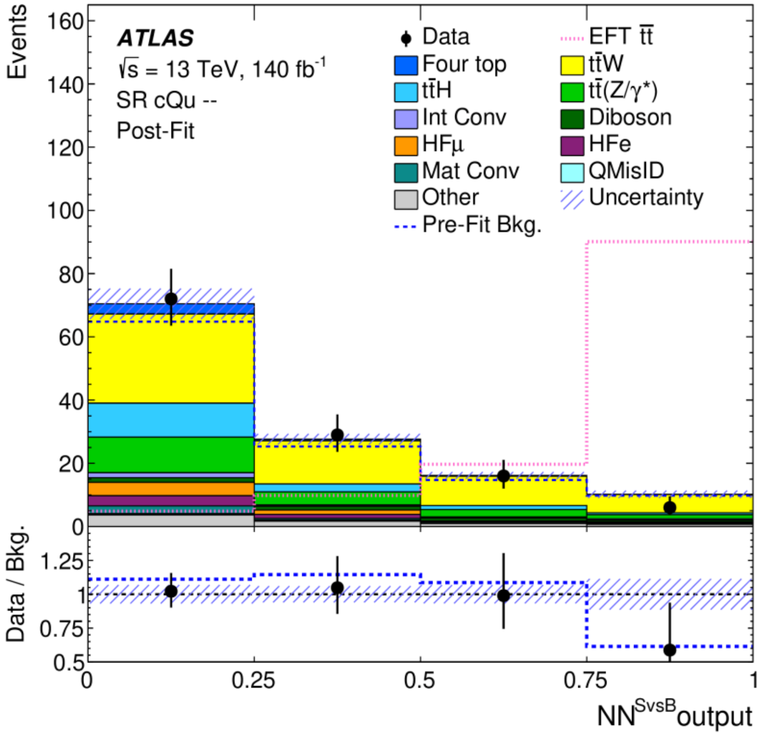


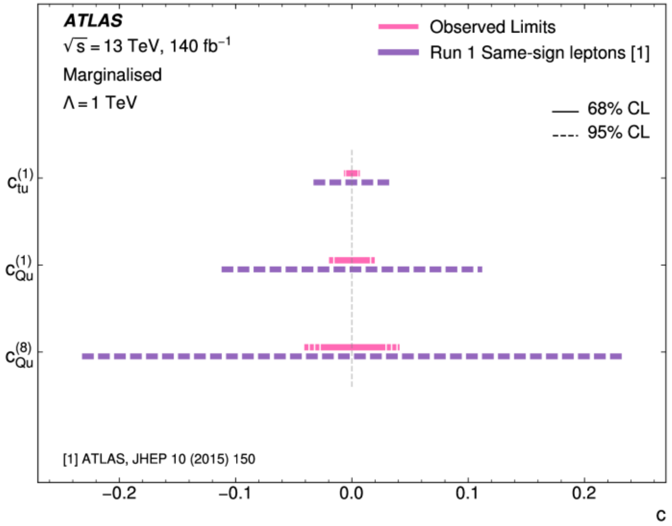
Search for same-charge top-quark pair production

arXiv: 2409.14982
submitted to JHEP
13 TeV / 140 fb^{-1}

Strategy:

- Neural networks used to split events in signal regions and validation regions
- SRs are split by charge and EFT operators
- Control regions used to constrain normalisation of the background processes
- Combined binned profile-likelihood fit over the SRs+CRs



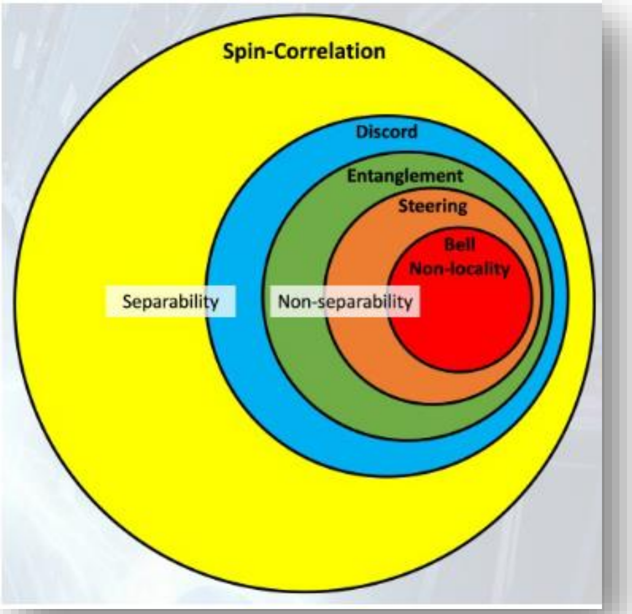


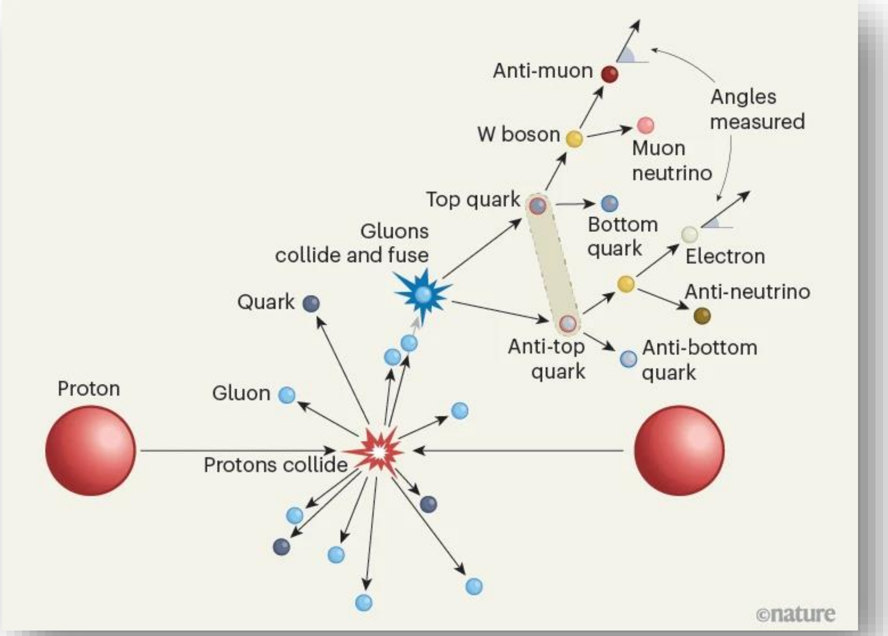
Uncertainties	Wilson Coefficient CIs at 95% CL ($\times 10^{-2}$) $c_{tu}^{(1)}$	$c_{Qu}^{(1)}$	$c_{Qu}^{(8)}$
Statistical uncertainty only	[-0.65, 0.65]	[-1.9, 1.9]	[-3.9, 3.9]
Statistical + modeling uncertainties	[-0.67, 0.67]	[-1.9, 1.9]	[-4.0, 4.0]
Total uncertainty	[-0.68, 0.68]	[-2.0, 2.0]	[-4.1, 4.1]

Improvement by a factor of 10!

Presicion limited by statistical uncertainties
Observed upper limits at 95% CL: $\sigma(pp \rightarrow tt, \bar{t}\bar{t}) < 1.6$ pb
Most stringent limits on $c_{tu}^{(1)}, c_{Qu}^{(1)}, c_{Qu}^{(8)}$

Quantum entanglement in top-quark pairs





Top quark decay products can be used to learn about top-quark spin or top-quark pair spin correlations

Entanglement: quantum state of one particle cannot be described independently from another particle

→ there are stronger correlations than classical system would exhibit

Typical example: a system of two fermions in a spin-singlet state

At the LHC initial state not controlled (no pure state)→ mixed state → described in general by density matrix (ρ)

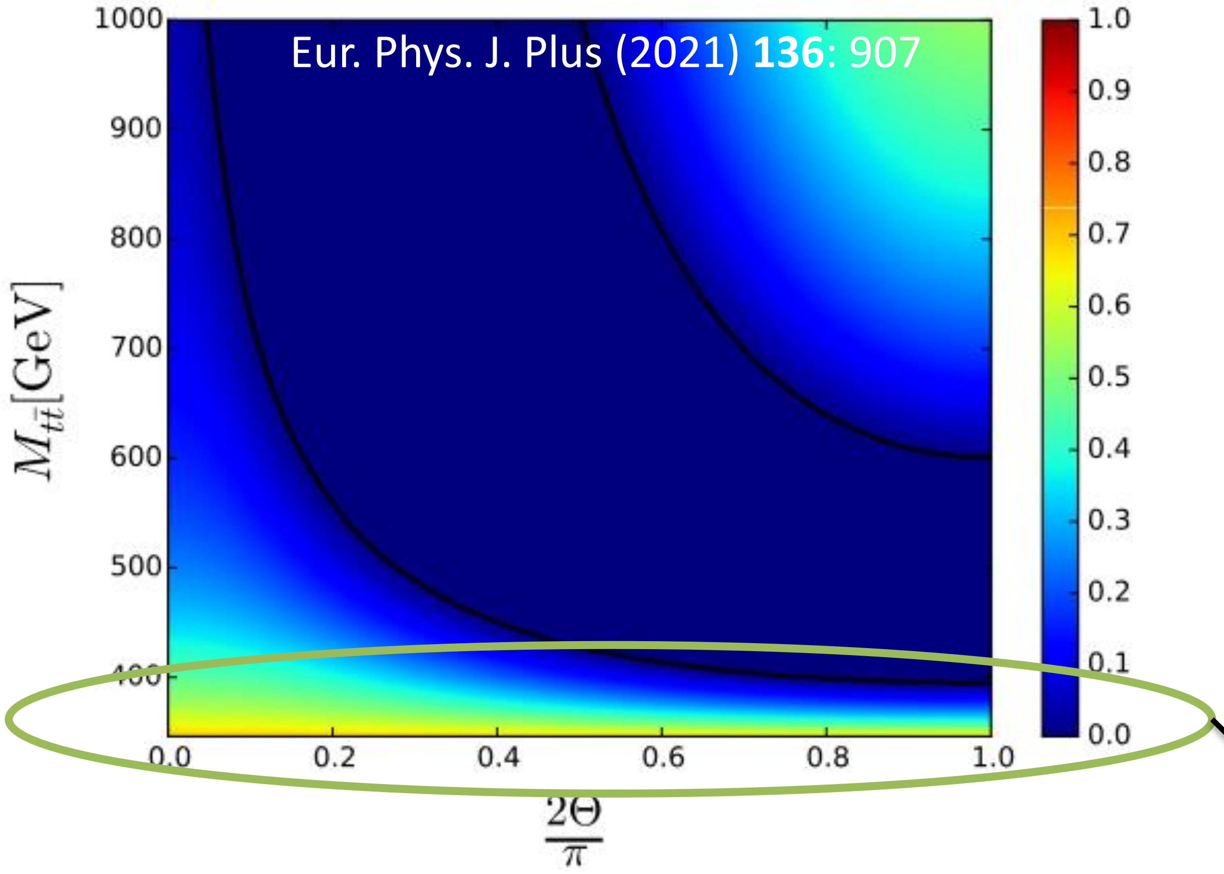
→ for two top quarks → spin density matrix

Entanglement can be characterized by their spin correlations magnitude

BERGISCHE UNIVERSITÄT WUPPERTAL

Quantum entanglement in top-quark pairs

A quantitative measure of the entanglement: concurrence $C[\rho]$ of the spin density matrix ρ :
→ Sufficient and necessary condition for entanglement: $C[\rho] > 0$



low $m(t\bar{t})$

Entanglement observable D:

$$\frac{1}{\sigma_{\ell\bar{\ell}}}\frac{d\sigma_{\ell\bar{\ell}}}{d\cos\varphi} = \frac{1}{2}(1 - D\cos\varphi), \;\; D = \frac{\mathrm{tr}[\mathbf{C}]}{3} \qquad D = -3\langle\cos\varphi\rangle$$

φ: angle between the two lepton directions measured in their parent top quark and antiquark rest frames

Entanglement condition:

$Tr[C] < -1$ → $D < -1/3$

Dominant contribution: gg fusion with tops in spin singlet state

Observation of quantum entanglement in top-quark pairs

Strategy:

Dilepton channel with $e\mu$ final state

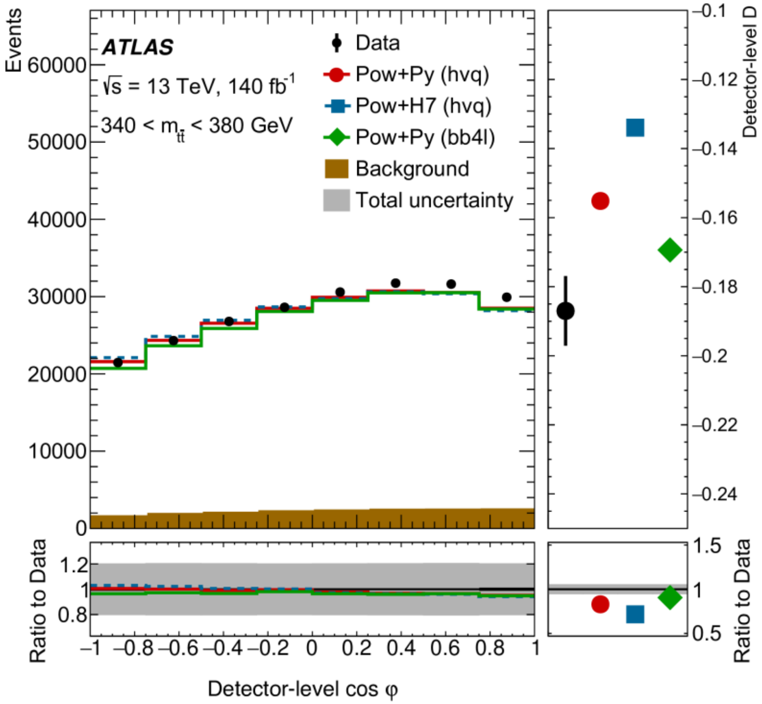
$\geq$ 2 jets and $\geq$ 1 b-tagged jet

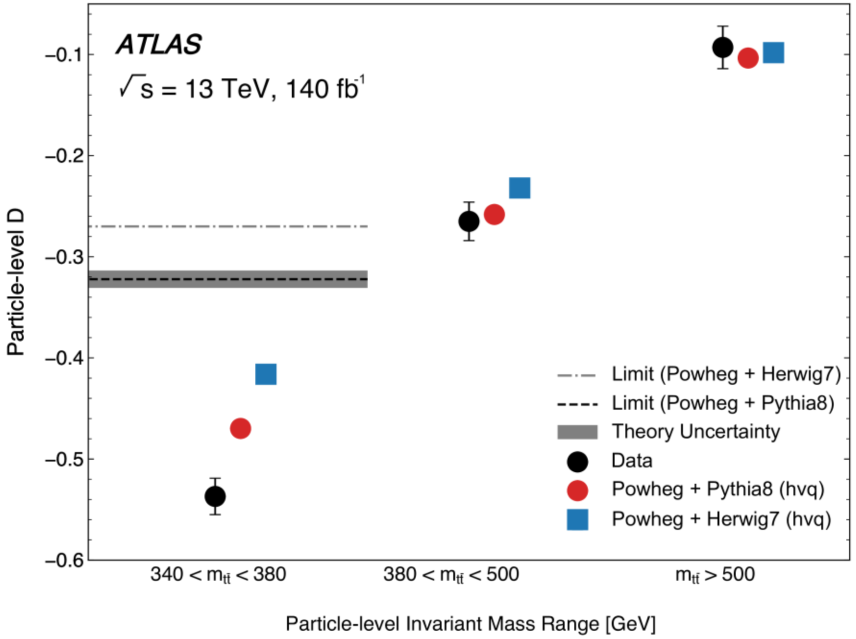
→ 90% signal purity

Correction of measured D to particle level D

Nature 633 (2024) 542

13 TeV / 140 fb^{-1}





$D = -0.537 \pm 0.002\ (stat) \pm 0.019\ (syst)$

$\gg 5\ \sigma$ below entanglement limit

→ Observation of entanglement

Dominant uncertainties: signal modelling

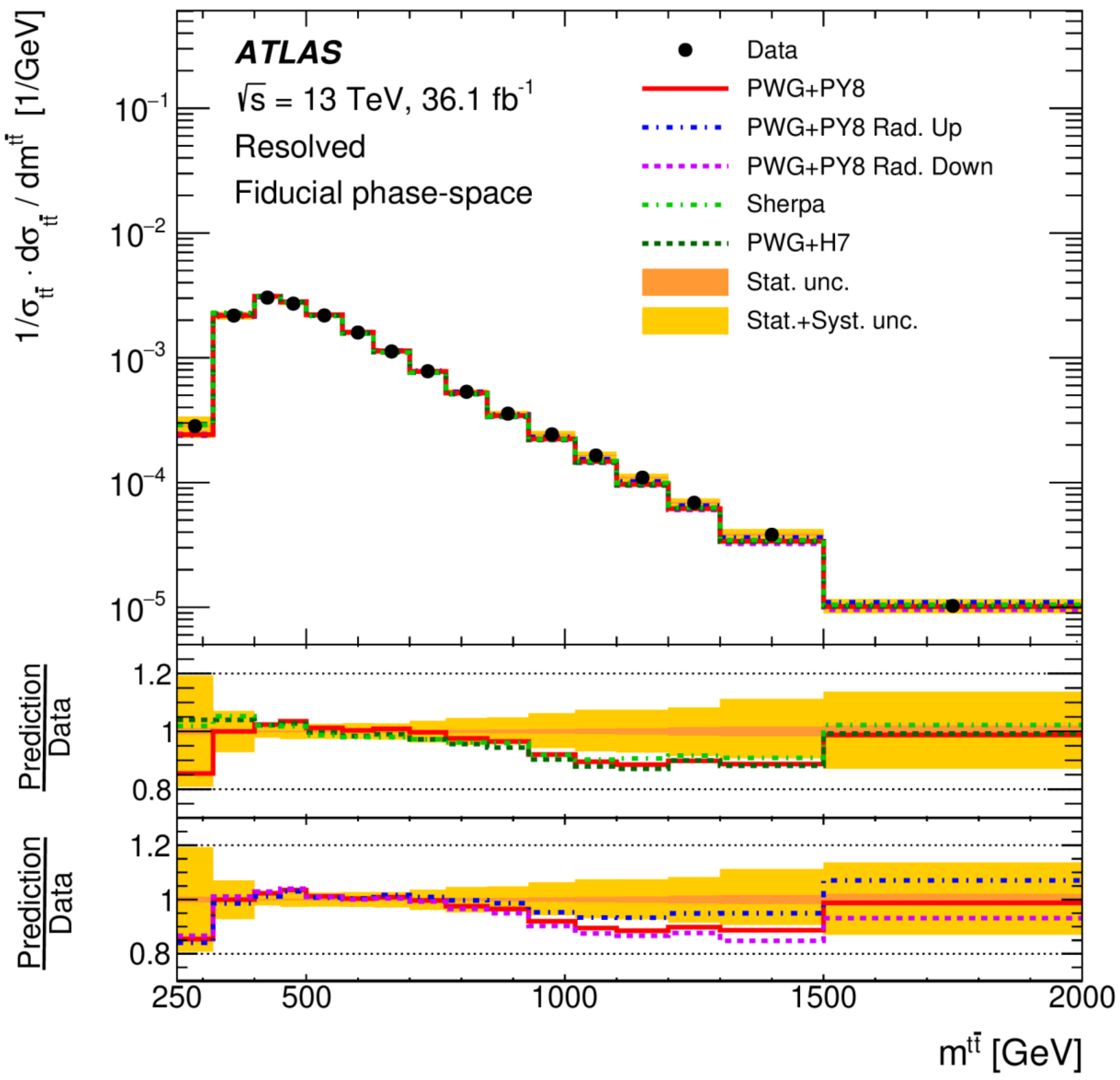
BERGISCHE UNIVERSITÄT WUPPERTAL

Conclusion

- Could only show a selection highlights from many many top-quark analyses
- Top-Quark processes are now also measured with high precision in association of heavy flavour quarks, photons, vector bosons
- Various searches for new physics either for model-independent searches using EFT or looking for specific model haven’t shown any hints yet
- Overview of all public top analyses can be found here: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/TopPublicResults

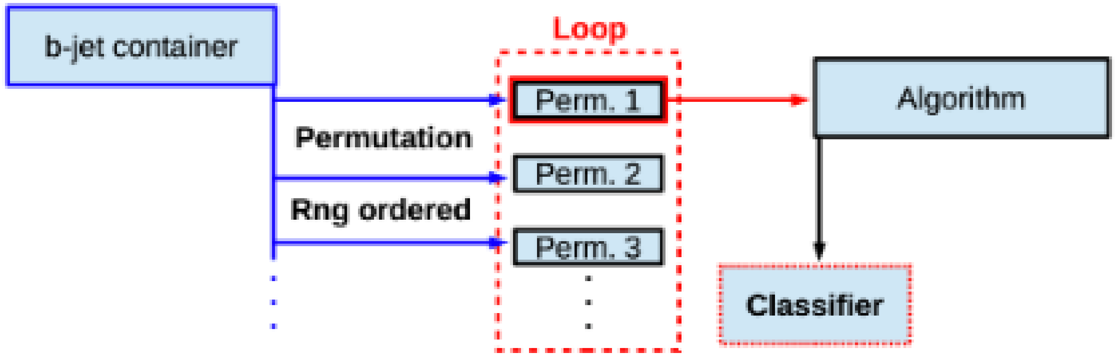
Backup

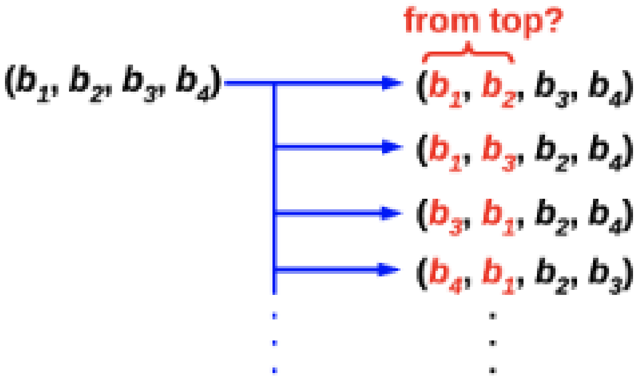
Invariant mass of top-quark pair



[Eur. Phys. J. C 79 (2019) 1028]

Conclusion





The permutation with the minimal $-\ln(w)$ is chosen, and the first two *b*-jets in the permutation are assigned to top quarks:

$$-\ln w = \begin{cases} \left(\Delta R_{\ell 1 b1} - \Delta R^{\min}_{\ell 1 b}\right)^2 + \left(\Delta R_{\ell 2 b2} - \Delta R^{\min}_{\ell 2 b}\right)^2 + \left(\max(\Delta R_{b1b3}, \Delta R_{b2b3}) - \Delta R^{\max}_{bb}\right)^2 & \text{if } N_{b\text{-jets}} = 3 \\ \left(\Delta R_{\ell 1 b1} - \Delta R^{\min}_{\ell 1 b}\right)^2 + \left(\Delta R_{\ell 2 b2} - \Delta R^{\min}_{\ell 2 b}\right)^2 + \left(\Delta R_{b3b4} - \Delta R^{\min}_{bb}\right)^2 & \text{if } N_{b\text{-jets}} \geq 4 \end{cases}$$

Fraction of events with correctly assigned *b*-jets:

- By the algorithm: $53\,\%$ (56%) in $t\bar{t}$ events with at least 3 (4) *b*-jets.
- Selecting the leading p_{T} *b*-jets: $42\,\%$ (27%).

Observation of $t\bar{t}$ production in p+Pb collisions

	$1\ell 1b$ e+jets	$1\ell 1b$ μ+jets	$1\ell 2b$incl e+jets	$1\ell 2b$incl μ+jets	$2\ell 1b$	$2\ell 2b$incl
$t\bar{t}$	214 ± 24	194 ± 21	405 ± 21	373 ± 19	55 ± 6	79 ± 5
t-channel	6.9 ± 1.0	6.4 ± 1.0	7.7 ± 0.9	7.1 ± 0.9	0 ± 0	0 ± 0
W+b	37 ± 19	37 ± 19	16 ± 8	17 ± 9	–	–
W+c	120 ± 40	110 ± 40	14 ± 7	17 ± 8	–	–
W+light	80 ± 40	80 ± 40	4.8 ± 3.1	9 ± 5	–	–
Z+b	16 ± 13	8 ± 7	8 ± 7	3.7 ± 3.0	12 ± 9	2.9 ± 2.4
Z+c	9 ± 14	5 ± 7	1.7 ± 2.6	0.9 ± 1.4	6 ± 9	0.4 ± 0.6
Z+light	28 ± 16	12 ± 7	1.2 ± 1.1	0.9 ± 0.5	11 ± 6	0.34 ± 0.25
Diboson	0.32 ± 0.16	0.29 ± 0.15	0.055 ± 0.029	0.039 ± 0.02	0.53 ± 0.27	0.049 ± 0.025
tW	17.1 ± 3.0	15.5 ± 2.7	13.6 ± 3.2	12.1 ± 2.9	5.1 ± 2	2.4 ± 1.2
Fake lepton	630 ± 50	170 ± 40	110 ± 19	21 ± 12	1.9 ± 1	0.51 ± 0.27
Total	1154 ± 34	648 ± 24	582 ± 21	462 ± 18	91 ± 7	85 ± 5
Data	1162	641	570	464	90	97