Single top quark and CKM measurements (ATLAS+CMS)

12th International Workshop on the CKM Unitarity Triangle (CKM2023)

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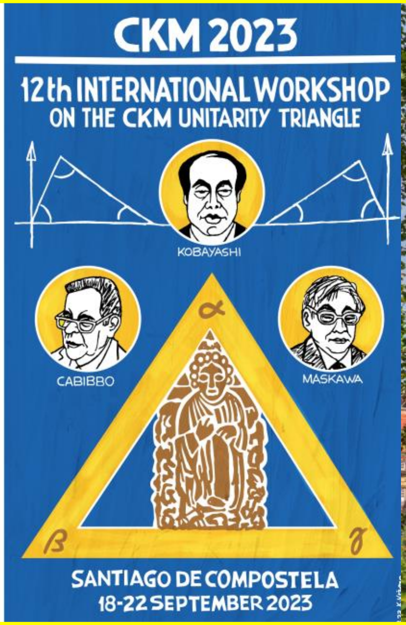
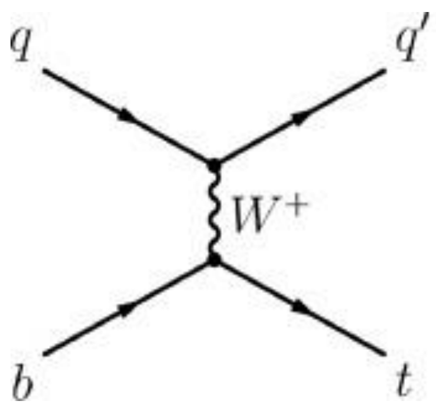
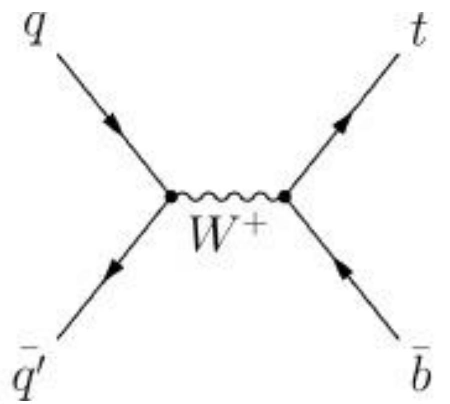
on behalf of ATLAS and CMS Collaborations



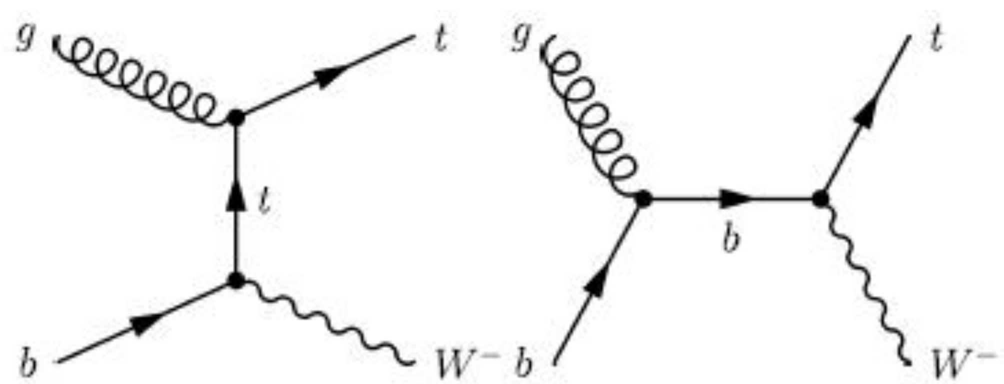
- Single top quarks are produced @ LHC via electroweak interaction
- The top quarks are polarised due to the tWb vertex
- Measurements of single top quark production allow studies of the unitarity of CKM matrix, tests of higher-order corrections from QCD, and constraints on PDFs



t-channel
σ ≃ 214 pb @13 TeV
(NNLO)



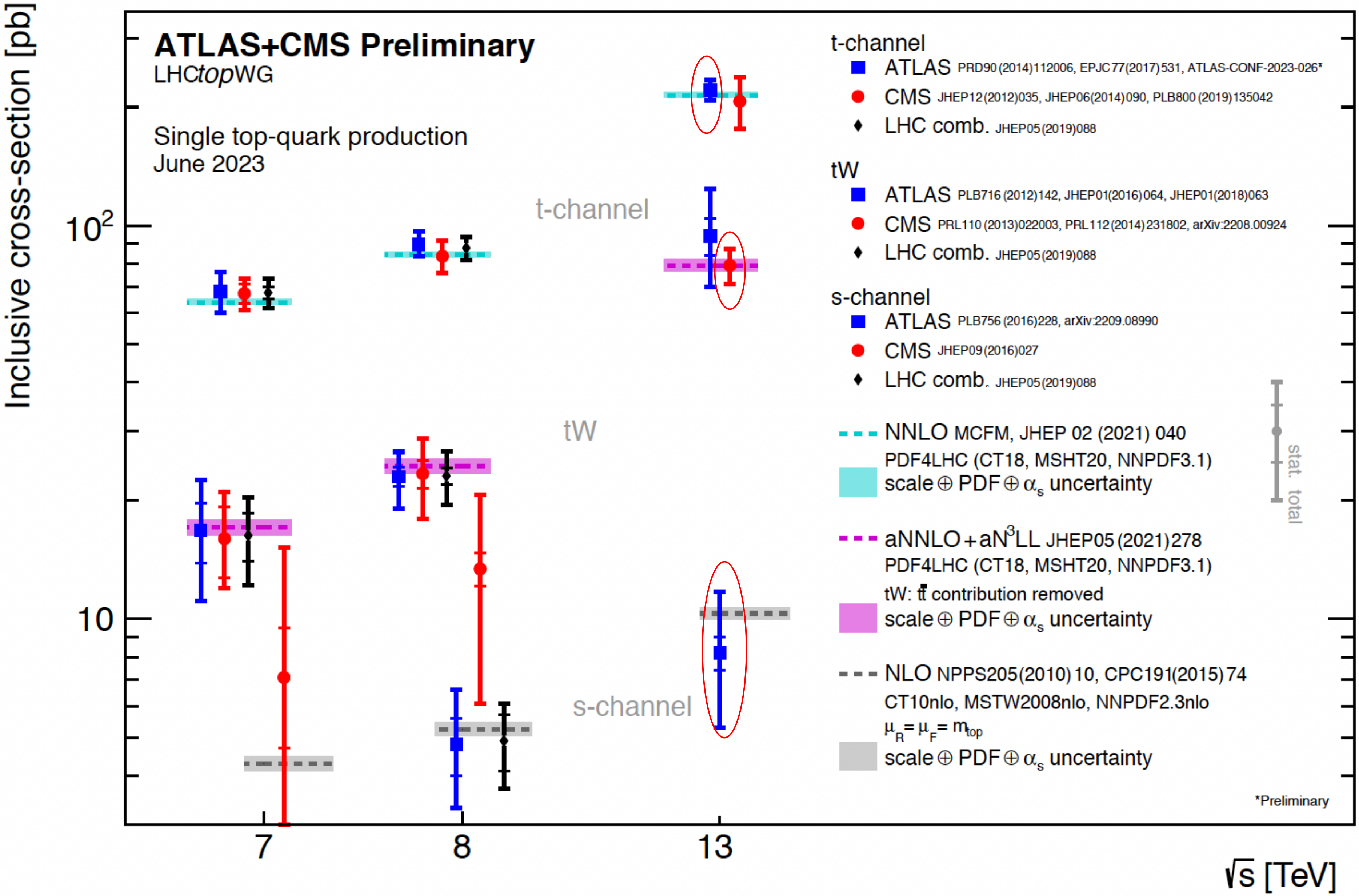
s-channel
σ ≃ 11 pb @13 TeV
(NNLO)



tW-channel
σ ≃ 79 pb @13 TeV
(NLO+NNLL)

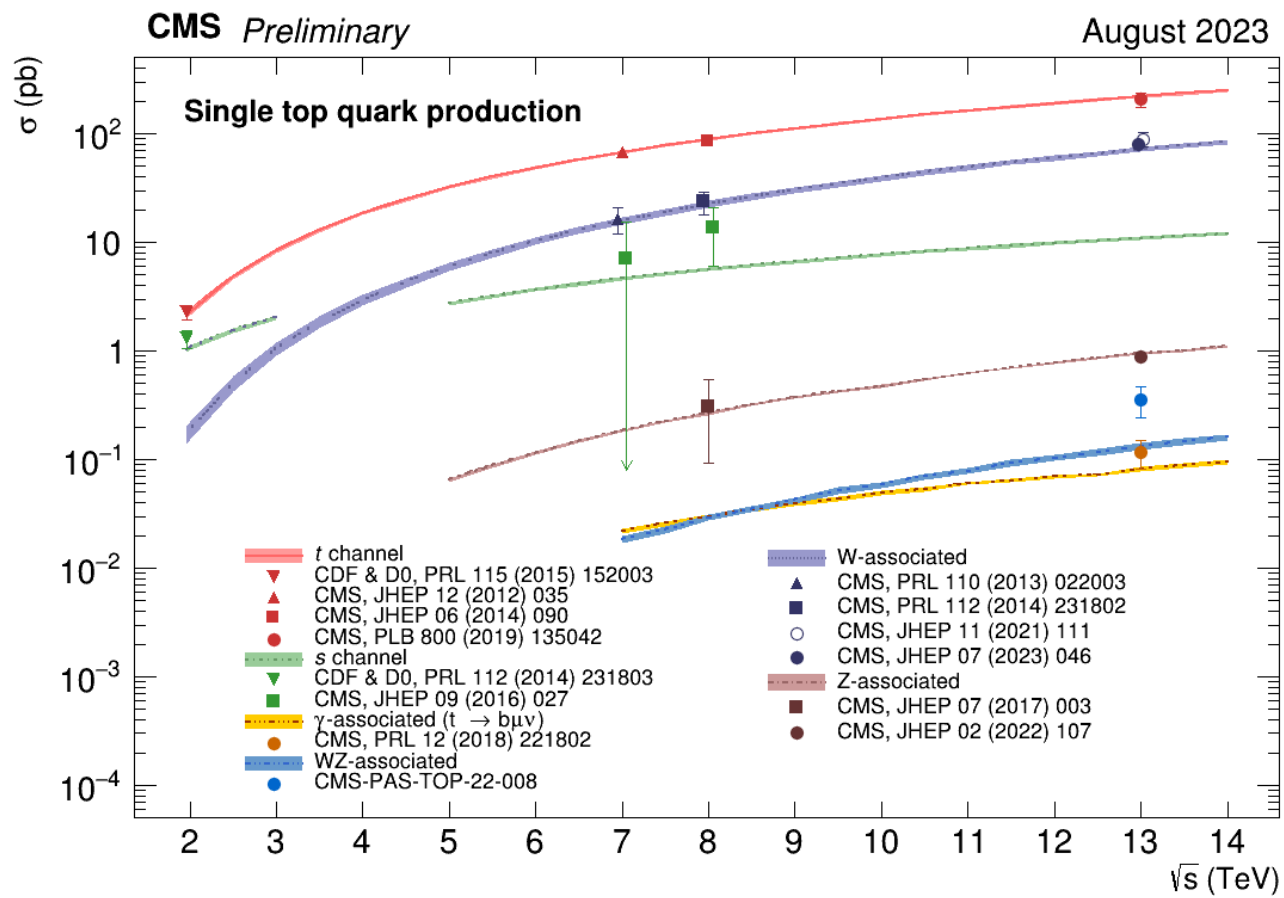
Latest single top quark cross-section measurements

[Summary plots]



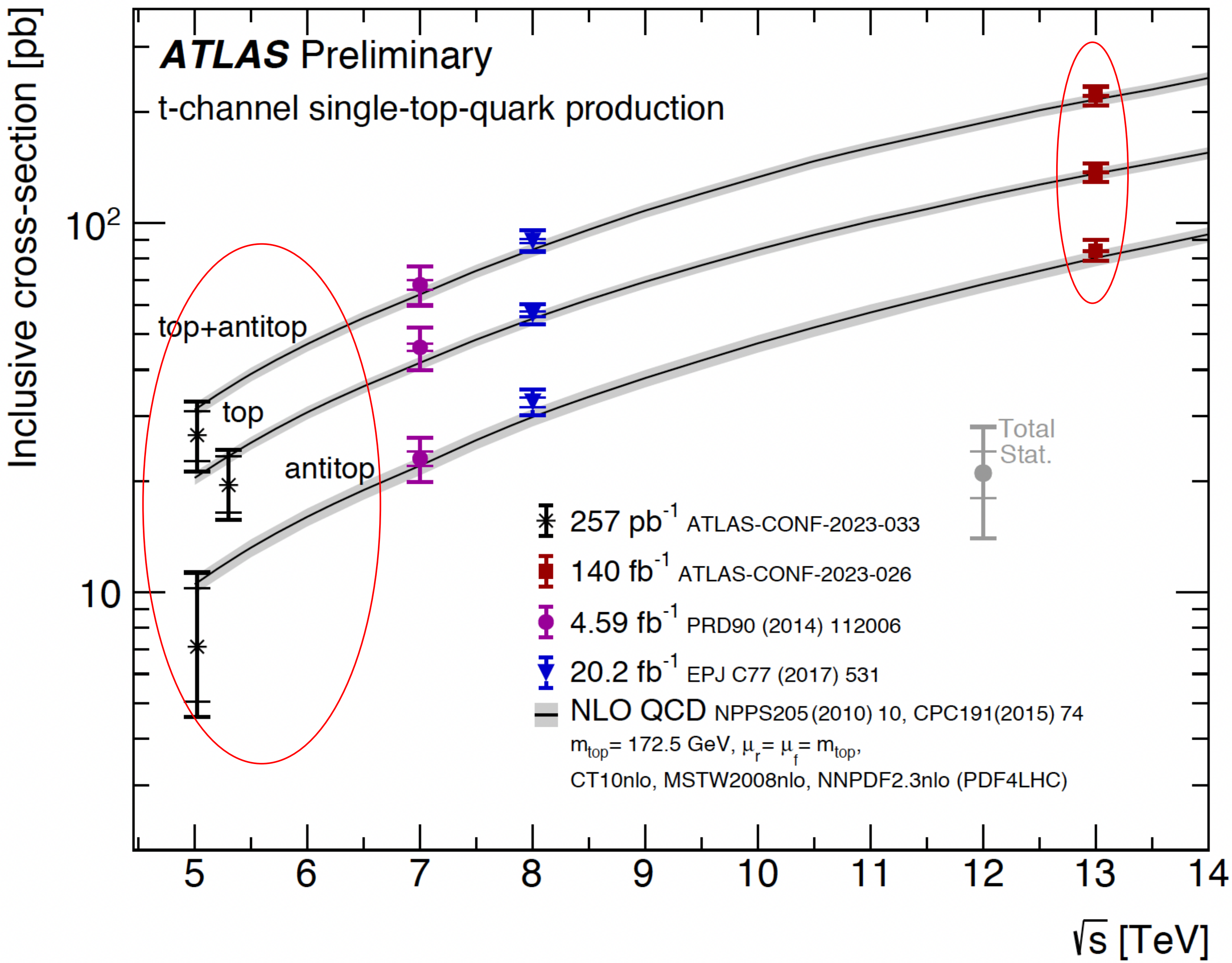
- t-channel inclusive cross-sections @ 5 and 13 TeV (ATLAS)
- tW differential cross-sections @ 13 TeV (CMS)
- Evidence of s-channel production @ 13 TeV (ATLAS)
- Observation of tγq process @ 13 TeV (ATLAS)
- tZq differential cross-sections @ 13 TeV (CMS)
- Evidence of tWZ production @ 13 TeV (CMS)
- Limits on tHq production

Summary plots



Latest t-channel cross-section measurements @ ATLAS

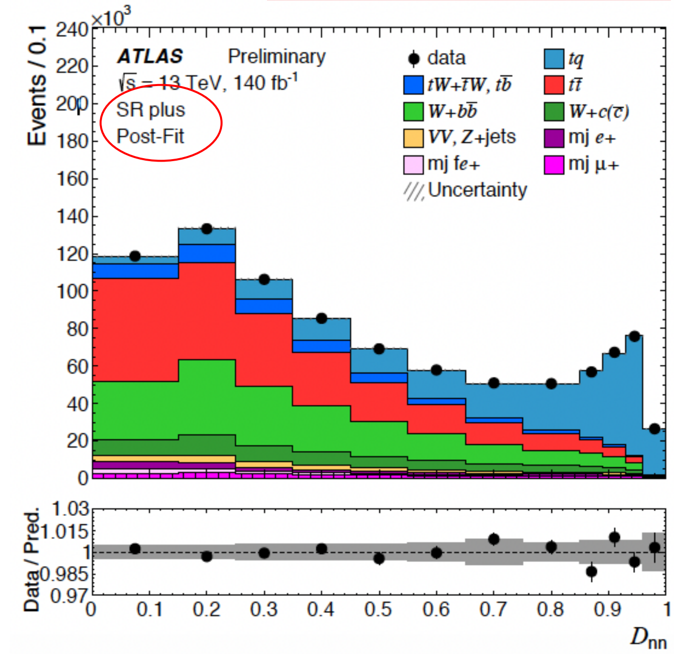
Summary plots



ATLAS-CONF-2023-026

- Recent ATLAS preliminary result, full Run-2 data (140 fb^{-1})
- Signal region: 1e/μ, 1b-jet, 1 forward jet
- Neural network to separate signal from backgrounds
- Cross-sections measured for top/antitop and its ratio:

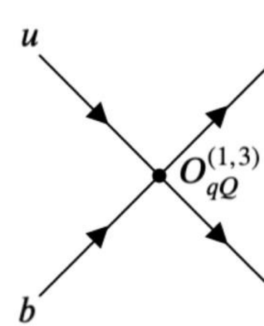
σ_{top} = 137 ± 8 pb
$\sigma_{antitop}$ = 84 $^{+6}_{-5}$ pb
σ = 221 ± 13 pb [6%]
R_t = 1.636 $^{+0.036}_{-0.034}$ [2%]

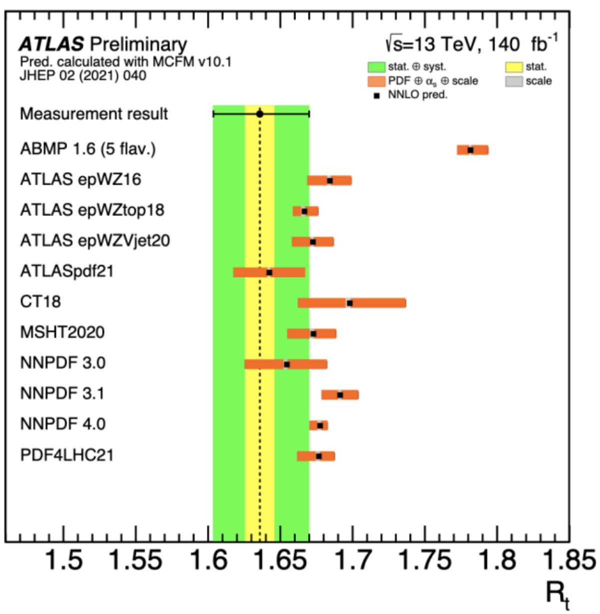


- Precision improved thanks to statistics, better detector calibration and advanced object reconstruction. Main unc: signal modelling

- The σ_{top} and $\sigma_{antitop}$ interpreted in an EFT approach:
  -0.25 < $O^{(1,3)}_{qQ}$ < 0.12 at 95%CL

$$O^{(1,3)}_{qQ} = (\bar{q}^i \gamma_\mu \tau^I q^j)(\bar{Q}\gamma^\mu \tau^I Q)$$





ATLAS-CONF-2023-026

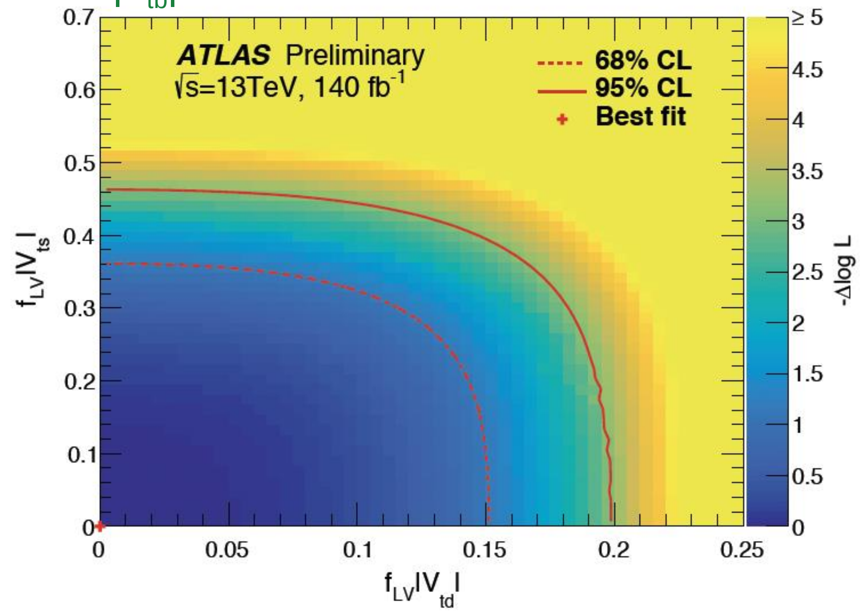
$$\frac{\sigma(tq+\bar{t}q)}{\sigma_{theo}} = f_{LV}^2|V_{tb}|^2$$

- Determination of V_{tb}:
  - $f_{LV}\cdot|V_{tb}| = 1.016 \pm 0.031$ $|V_{tb}| \gg |V_{td}|, |V_{ts}|$, LH coupling
  - $|V_{tb}| > 0.95$ (95% CL) asuming $|V_{tb}| \in [0,1]$ and $f_{LV}=1$

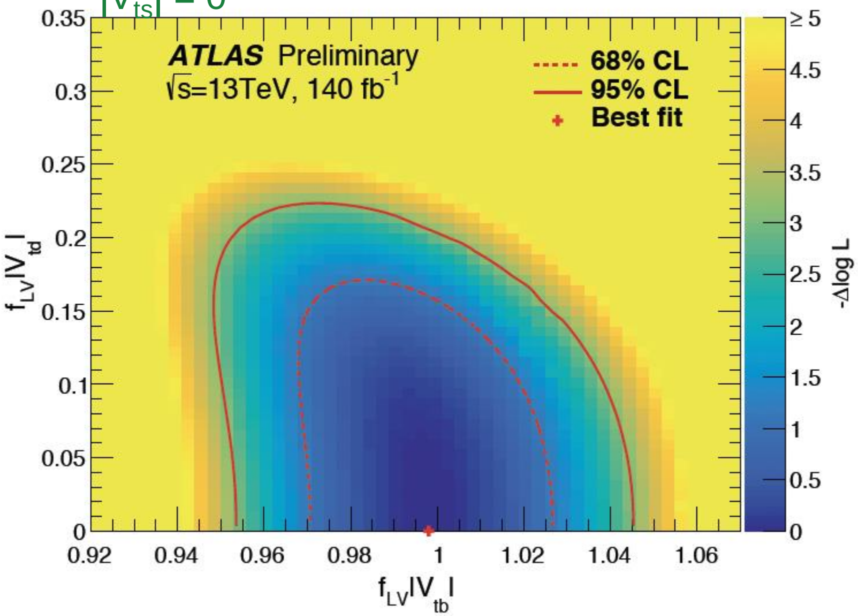
- Generalised CKM interpretation:
  - $f_{LV}\cdot|V_{tb}| \in [0.955, 1.045]$ at 95%CL
  - $f_{LV}\cdot|V_{td}| < 0.22$ and $f_{LV}\cdot|V_{ts}| < 0.54$

- All results in agreement with NNLO calculation

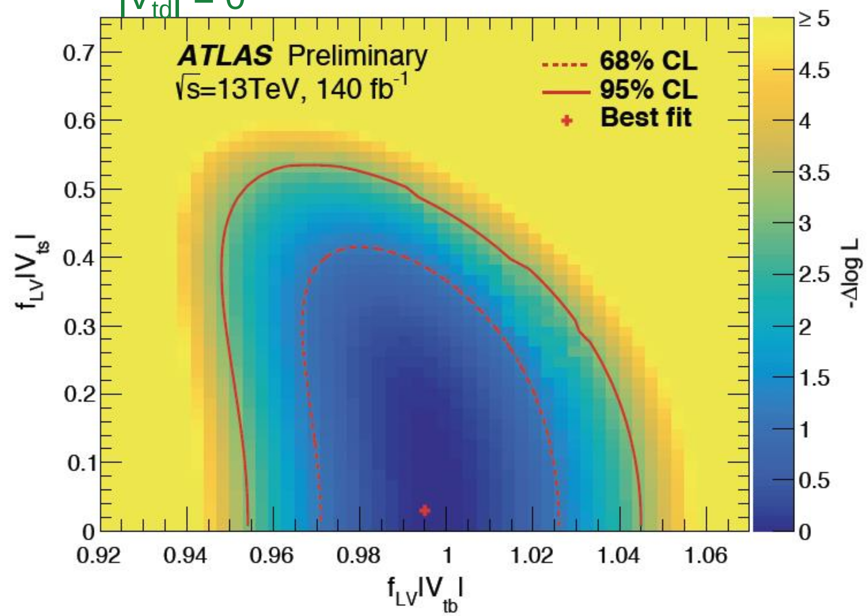
$|V_{tb}| = 1$



$|V_{ts}| = 0$

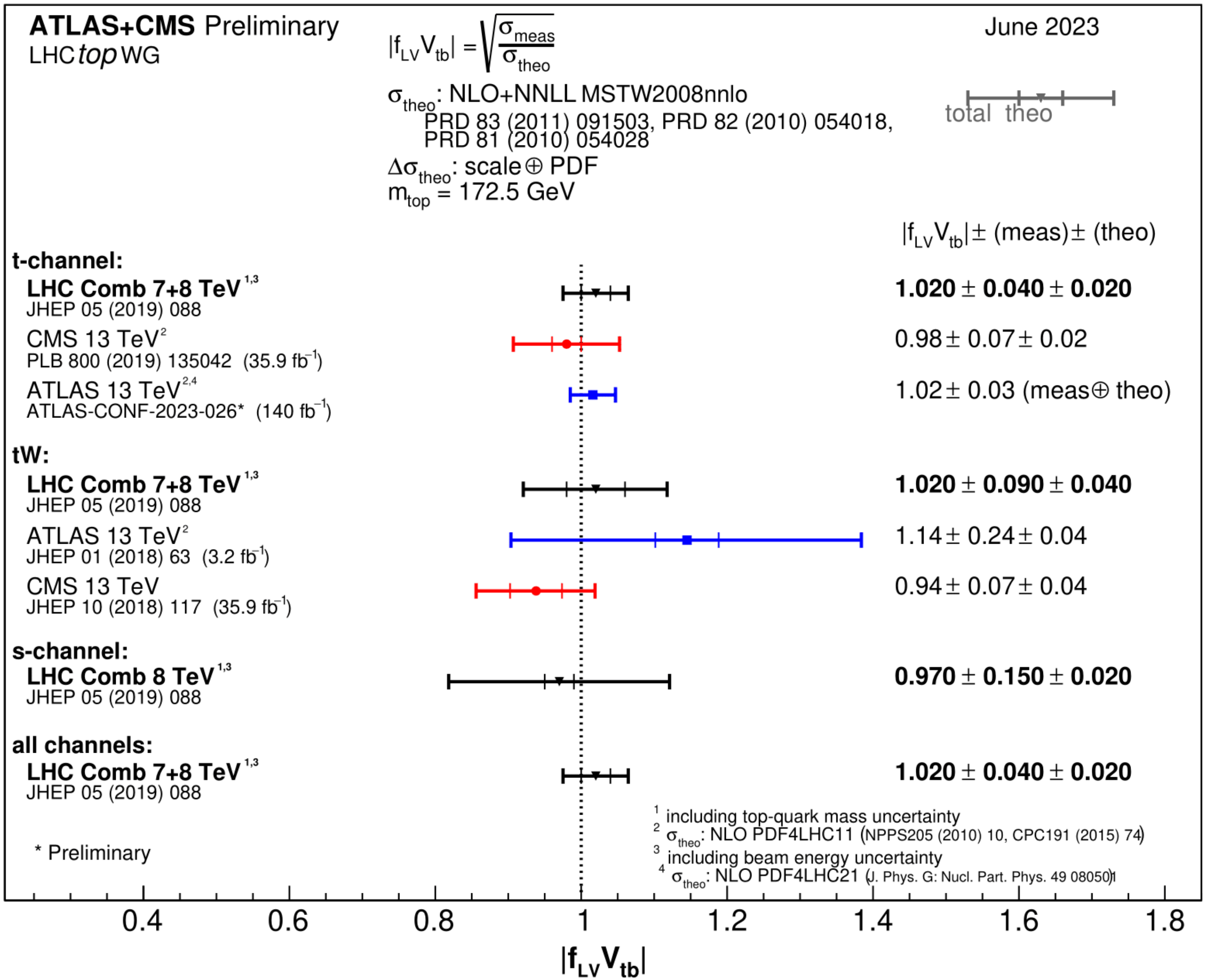


$|V_{td}| = 0$



Summary of V_{tb} measurements in ATLAS and CMS

Summary of ATLAS and CMS extractions of the CKM matrix element V_{tb} from single top quark measurements



Summary plots

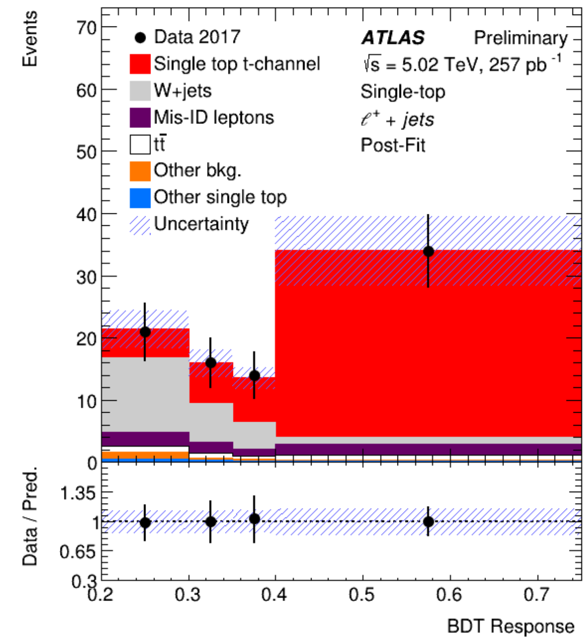
t-channel 5 TeV cross-section @ ATLAS

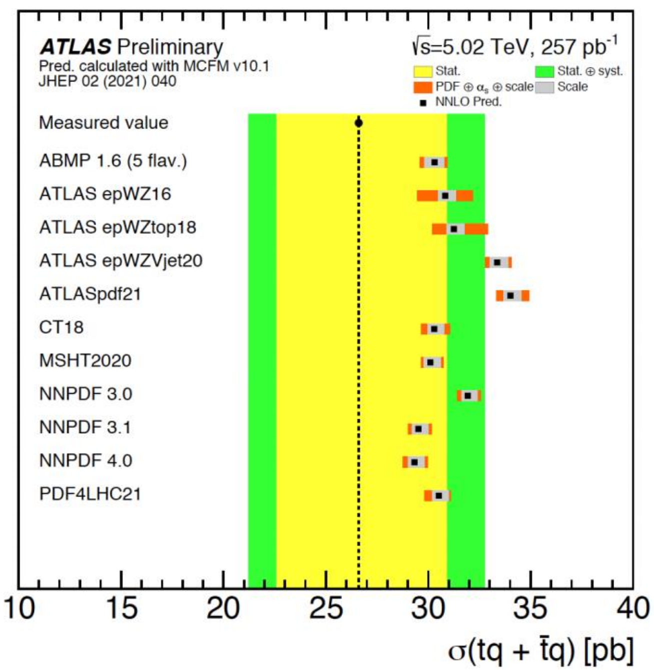
ATLAS-CONF-2023-033

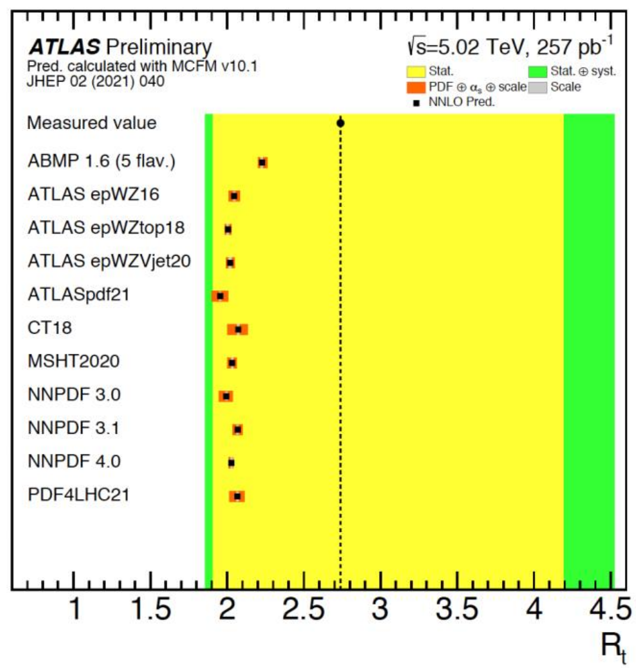
- Dataset: 257 pb^{-1} @ 5.02 TeV
- Similar strategy as for 13 TeV
- Cross-section measured:

$$\sigma_t = 19.5^{+3.8}_{-3.1}(stat)^{+2.9}_{-2.2}(syst)\mathrm{pb},\ \sigma_{\bar{t}} = 7.1^{+3.2}_{-2.1}(stat)^{+2.8}_{-1.5}(stat)\mathrm{pb},$$
$$\sigma_{t+\bar{t}} = 26.6^{+4.3}_{-4.0}(stat)^{+4.4}_{-3.6}(syst)\mathrm{pb},\ R_t = 2.74^{+1.44}_{-0.83}(stat)^{+1.04}_{-0.29}(syst)$$

- Significance: 6.1σ (6.4σ exp.)
- Extracted $f_{LV}\cdot|V_{tb}| = 0.94\ ^{+0.08}_{-0.07}(stat)\ ^{+0.08}_{-0.06}(syst)$ $|V_{tb}| \gg |V_{td}|, |V_{ts}|$
- All results in agreement with SM; limited by data statistics
- Additional probe for PDFs, at lower energies







tW 13 TeV inclusive cross-section (dilepton ch.) @ CMS

- tW observed with Run-1 data using dilepton decays - same strategy in Run-2 JHEP 07 (2023) 046
- tW process interferes with ttbar at NLO in QCD

  DR1 scheme is used

  difference with respect to DS → uncertainty

$$|\mathcal{A}_{tWb}|^2 = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 = \underbrace{\underbrace{|\mathcal{A}_{1t}|^2}_{\text{DR1}} + 2\text{Re}(\mathcal{A}_{1t}\mathcal{A}^*_{2t})}_{\text{DR2}} + |\mathcal{A}_{2t}|^2$$

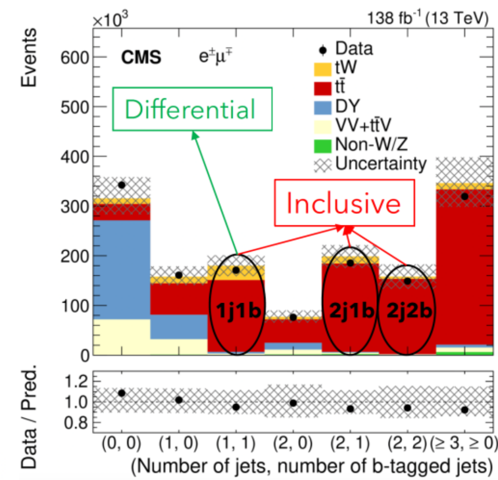
$$|\mathcal{A}_{tWb}|^2_{\text{DS}} = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 - \mathcal{C}_{2t}$$

Inclusive cross-section

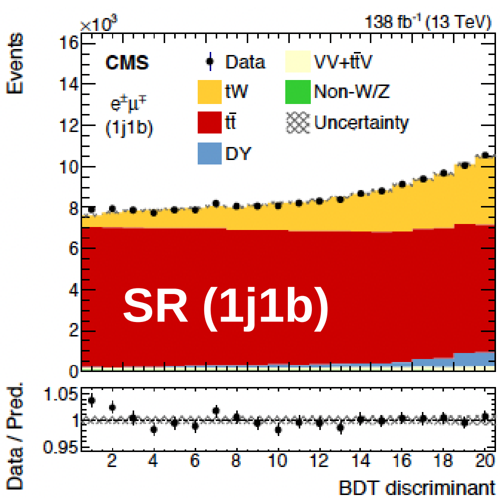
eμ, 1 or 2 jets, 1 b-tag → ~55k candidates

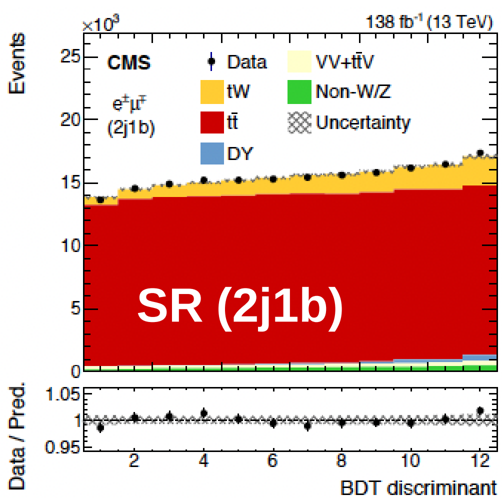
- Events classified into 3 categories (based on # jets and b-jets)
- MVA trained to separate tW from backgrounds (mainly ttbar)

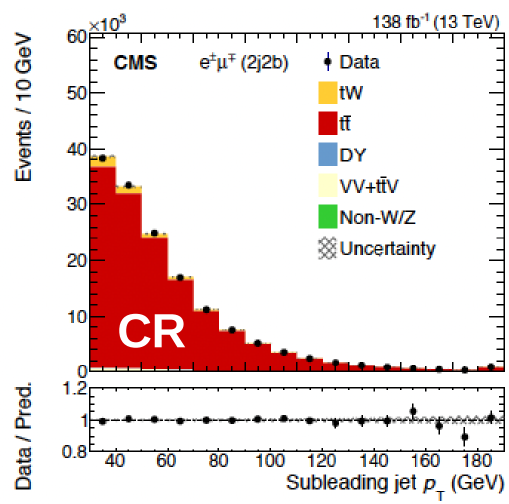
$\sigma = 79.2 \pm 0.9(\text{stat}) \,^{+7.7}_{-8.0}(\text{syst}) \pm 1.2(\text{lumi})$ pb [precision: ~10%]



- Main uncertainties: JES, normalisation of non-W/Z background, tW scale choice, and FSR modelling in ttbar and tW processes





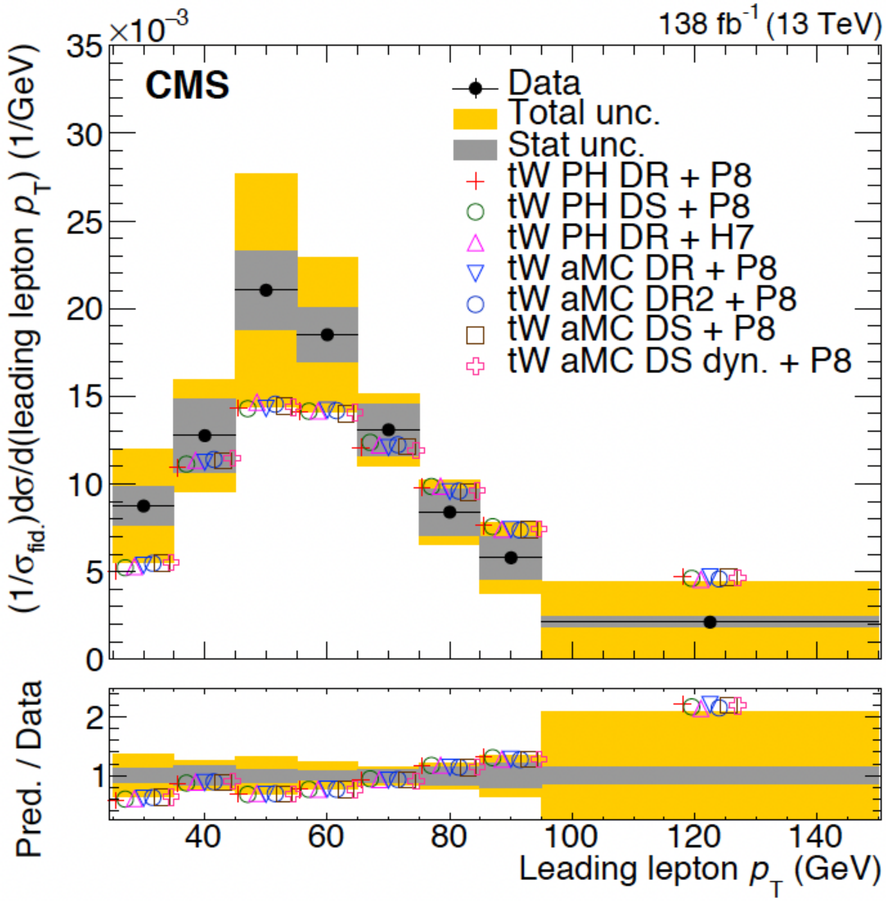


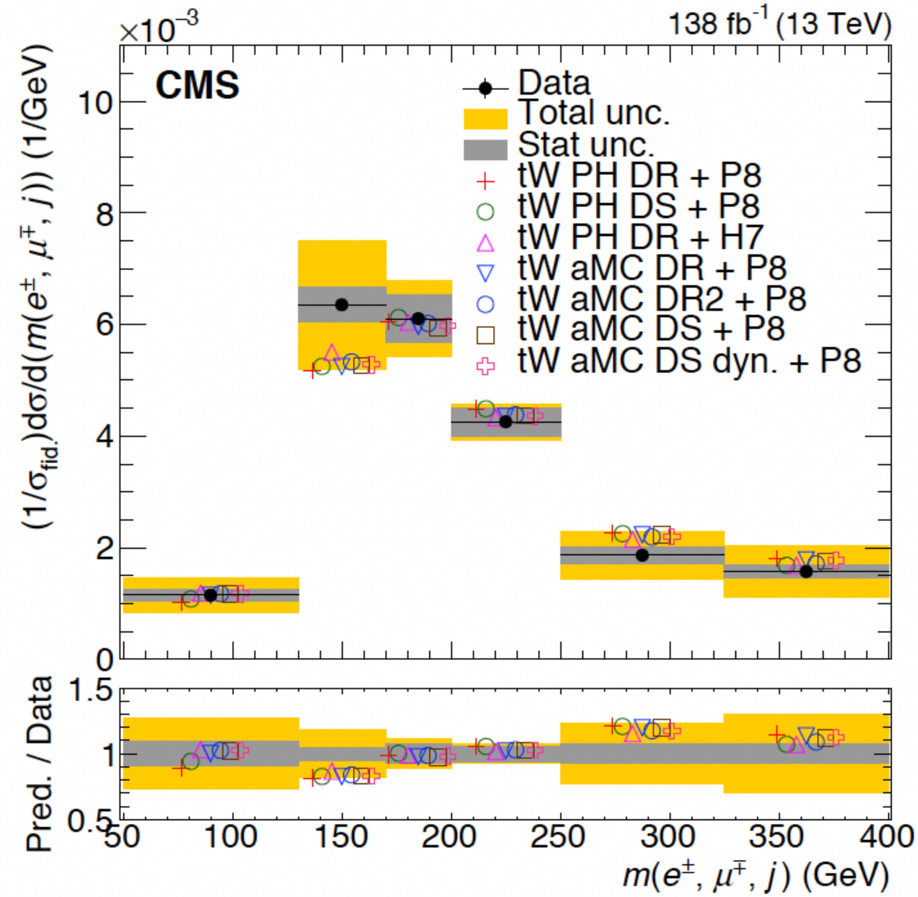
Normalised fiducial differential cross-sections JHEP 07 (2023) 046

SR: 1j1b + veto loose jets ($p_T \in$ [20-30] GeV)

Unfolding at particle level, using a maximum likelihood fit

- 6 variables: p_T(l1), p_T (j), Δϕ(e,μ), p_z(e,μ,j), m_T(e,μ,j,$E_{miss,T}$), m(e,μ, j) [precision: 10-50%]
- various MC models tested - none agree with all measured distributions

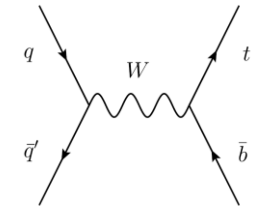




No significant difference between DR and DS overlap removal schemes

JHEP 06 (2023) 191

s-channel is the most challenging (qqbar process): S/B decreases with √s
- only observed at Tevatron (due to valence antiquarks)
- at LHC, only evidence in Run-1 (ATLAS, 8 TeV): limited by data statistics, JER and t-channel generator choice



New: First 13 TeV measurement with ~4k candidates

Main backgrounds: ttbar and W+jets (S/B~3%)

Baseline event selection & background estimation:

1 e/μ > 30GeV, $E_{miss,T}$ > 35GeV & $m_{T,W}$ > 30GeV

SR: 2j2b (jets p_T >30 GeV, b-tag eff 77%)

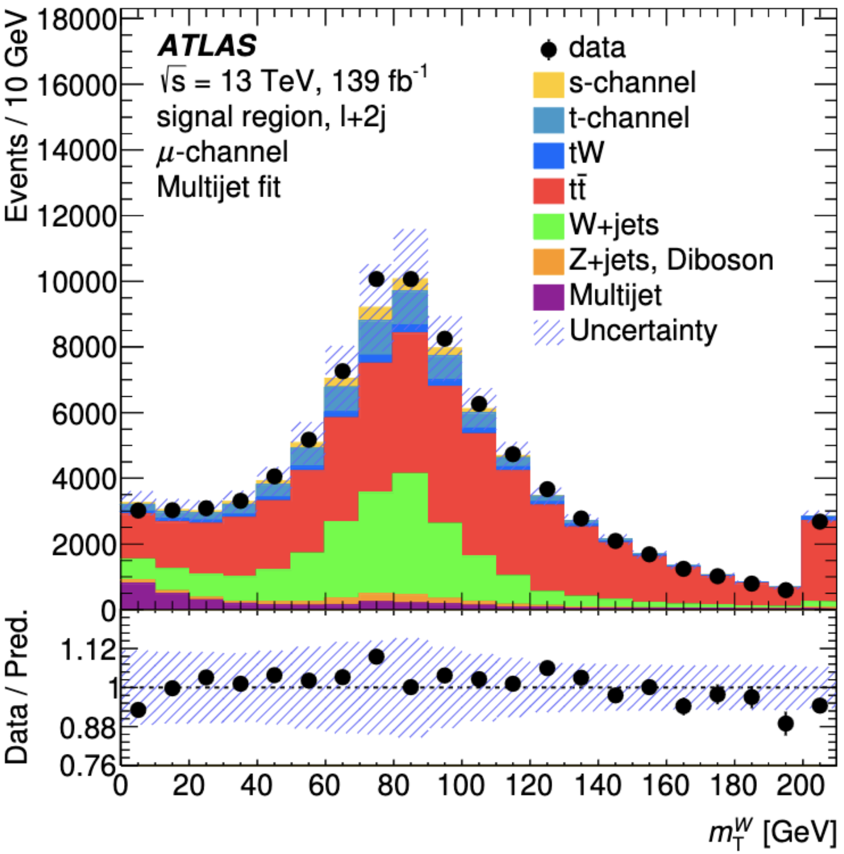
Veto events with additional looser jets and leptons

ttbar VRs: 3j2b, 4j2b

W+jets VR: 2j2b (with looser b-tagging WP)

Multijet production modelled by the jet-electron or anti-muon method; normalisation extracted from data

MC simulations for the rest of processes



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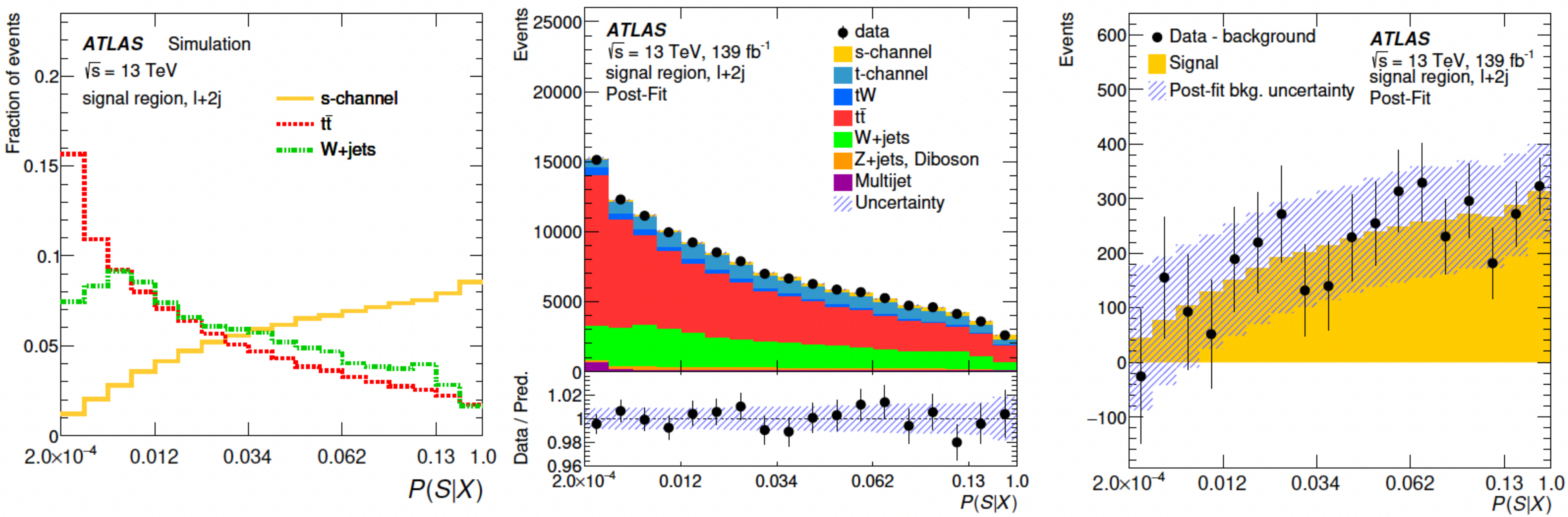
Strategy: discriminant based on matrix element calculations (at LO for S and B)
Good discrimination wrt. ttbar
Takes into account the detector resolution: transfer functions



Result:

σ = 8.2 ± 0.6(stat.) $^{+3.4}_{-2.8}$(syst.) pb [precision ~40%; stat: 8%]

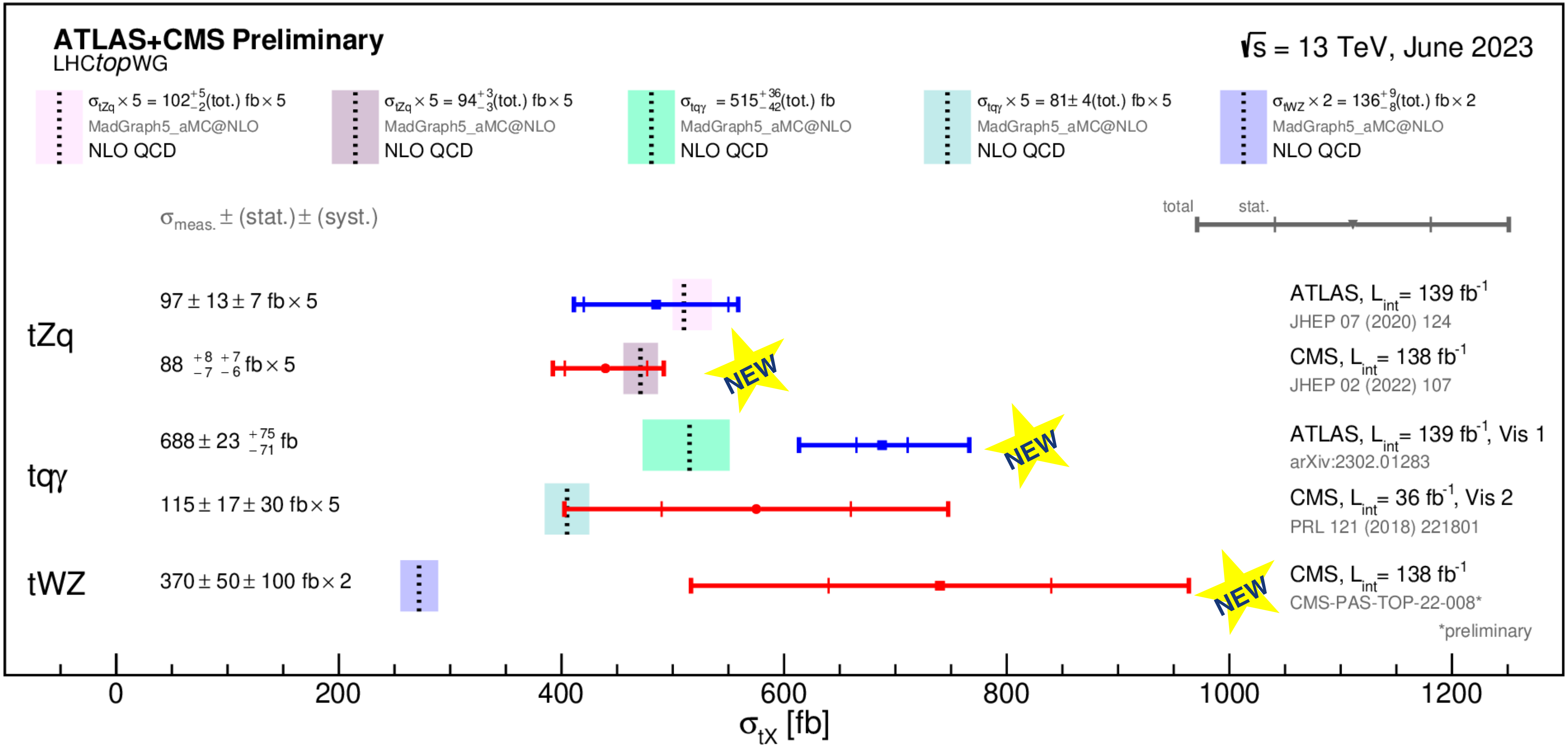
Compatible with SM NLO prediction: $\sigma_{pred.}$=10.32$^{+0.40}_{-0.36}$pb

Significance: 3.3σ (3.9σ exp.) - same sensitivity as with 8 TeV data

Result dominated by syst. unc.: ttbar norm., jet energy scale+resoluction and signal PS+Had.

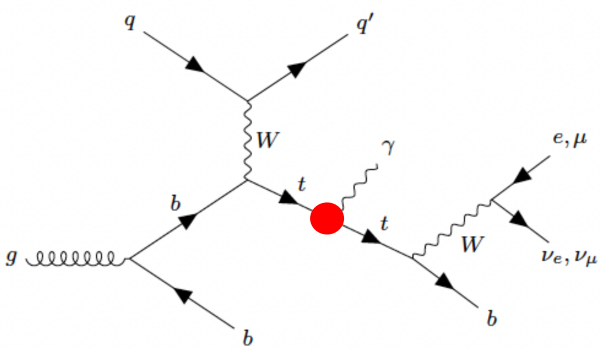
Associated production of single top quarks with bosons

Summary plots



arXiv:2302.01283
accepted by PRL

- Rare associated-production processes of the top quark crucial to constrain non resonant contributions from physics BSM, parameterised in the SMEFT framework



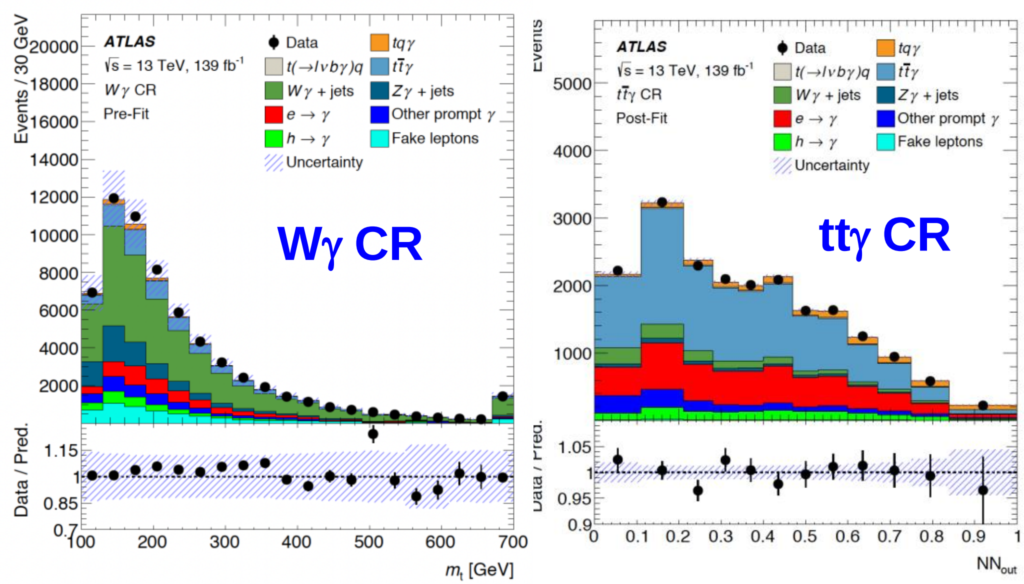
- Photons arising from ISR/FSR or via triple gauge couplings WWγ
    - Process sensitive to the top-photon coupling
    - Sensitivity to "anomalous gauge couplings"
    - Signature also sensitive to top-γ FCNC

- CMS reported evidence of this processs PhysRevLett.121.221802
- New ATLAS measurement has achieved the level of observation
    - Cross-sections are measured at parton and particle levels in a fiducial phase space

Event selection and strategy

1 γ (p_T >20 GeV), 1 e/μ, $E_{miss,T}$, cuts to suppress "soft" γ from parton shower or top decay, w/,w/o forward jets → 2 SRs

Neural networks trained in each SR
2 CRs to estimate normalisation of main bkgs., ttγ and Wγ (normalisation from data)



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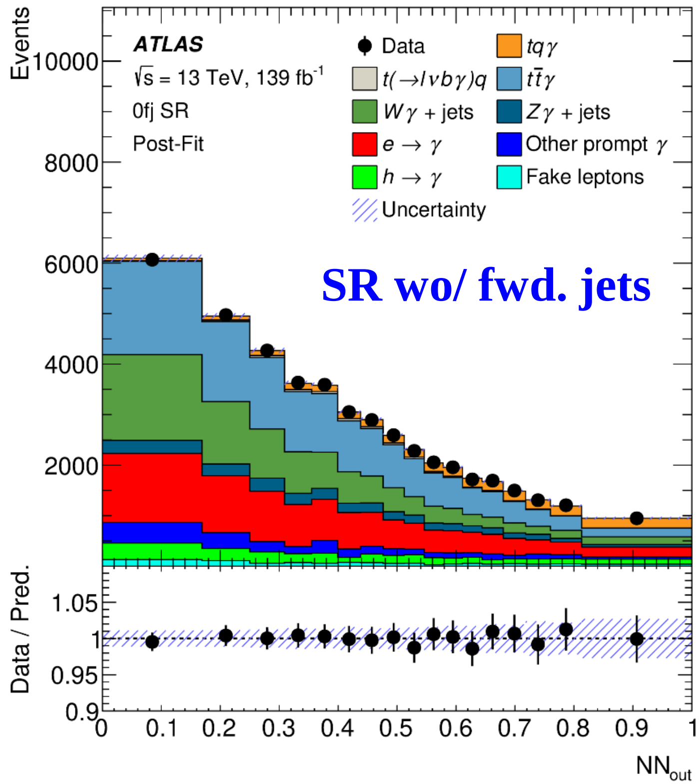
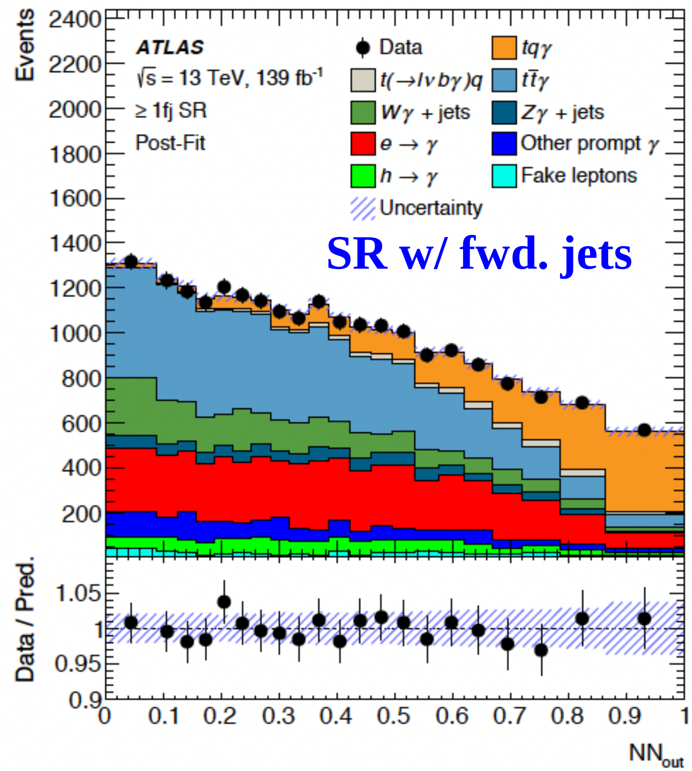




Cross-section measured in fiducial phase space at

parton level: $\sigma_{tq\gamma}\cdot BR(t\to l\nu b) = 688 \pm 23(stat.)^{+75}_{-71}$ (syst.) fb

particle level: $\sigma_{tq\gamma}\cdot BR(t\to l\nu b)+\sigma_{t(\to l\nu b\gamma)q} = 303 \pm 9(stat.)^{+33}_{-32}$ (syst.) fb

~40% higher than NLO SM prediction (compatible with SM within 2σ)

Significance: 9.3σ (6.8σ exp.)

Main syst. unc.: modelling of tqγ signal, limited MC stats. and modelling of *t(→lνbγ)* and ttbar

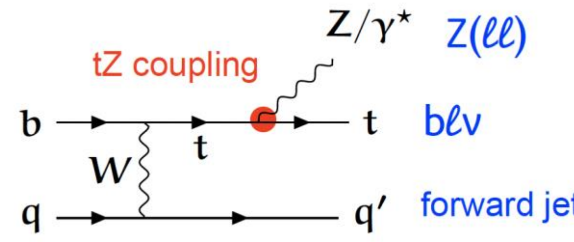
Consistent with previous CMS result

tZq 13 TeV differential cross-sections @ CMS

JHEP02(2022)107

- Also sensitive to BSM physics and SMEFT operators

- Z boson can arise from ISR/FSR or via triple gauge couplings WWZ
  - Process sensitive to the top-Z coupling
  - Sensitivity to "anomalous gauge couplings"
  - Signature also sensitive to top-Z FCNC



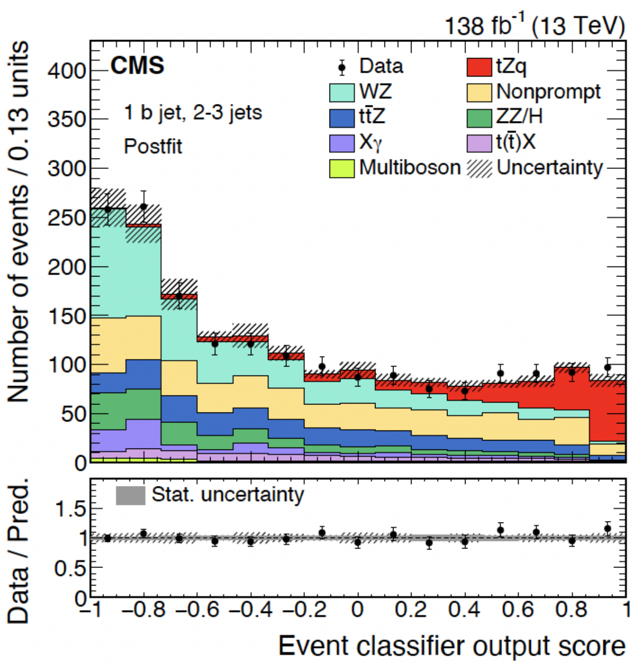
- Processes observed in CMS and ATLAS; inclusive XS reach 11-14% precision
- CMS has measured first parton and particle level differential XS and top/antitop XS ratio

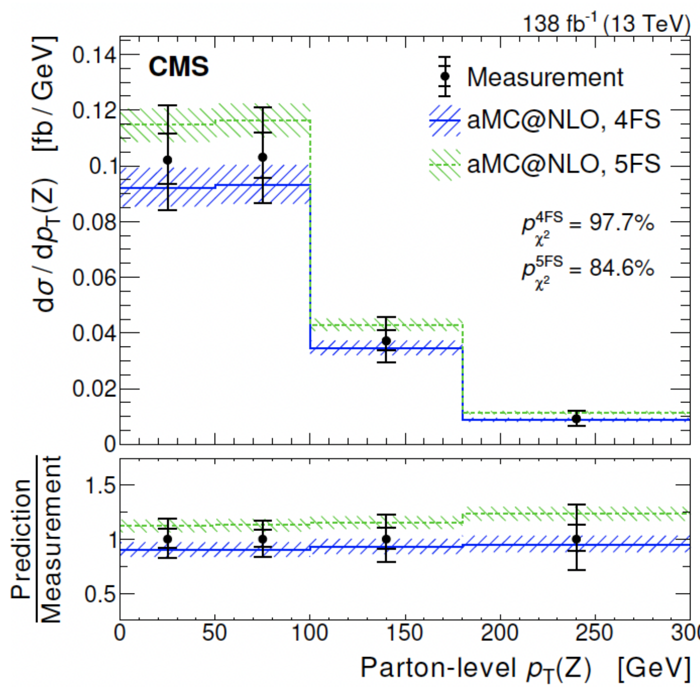
$$\sigma_{tZq(\ell_t^+)} = 62.2\ ^{+5.9}_{-5.7}\,(\text{stat})\ ^{+4.4}_{-3.7}\,(\text{syst})\ \text{fb}$$

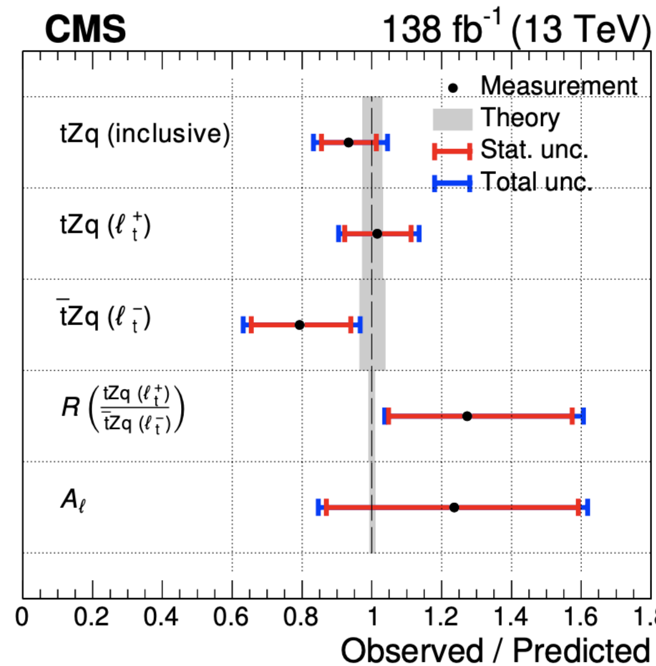
$$\sigma_{\bar{t}Zq(\ell_t^-)} = 26.1\ ^{+4.8}_{-4.6}\,(\text{stat})\ ^{+3.0}_{-2.8}\,(\text{syst})\ \text{fb}$$

$$R = 2.37\ ^{+0.56}_{-0.42}\,(\text{stat})\ ^{+0.27}_{-0.13}\,(\text{syst})$$

$$A_\ell = 0.54 \pm 0.16\,(\text{stat}) \pm 0.06\,(\text{syst})$$



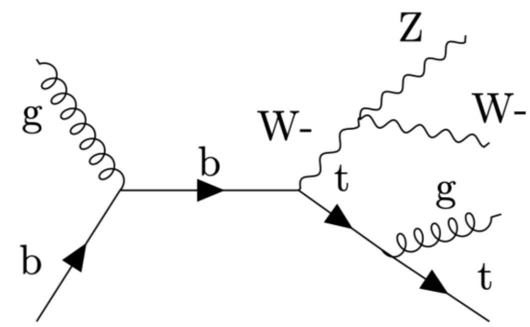




tWZ production at 13 TeV @ CMS

CMS-PAS-TOP-22-008

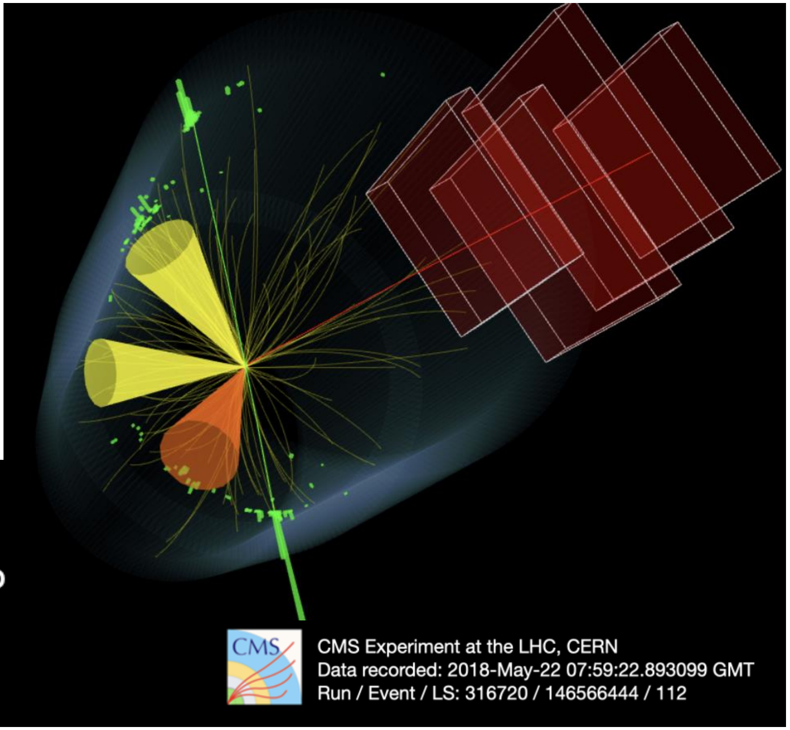
- This process probes bW→tZ scattering; enhances SMEFT sensitivity
- Very rare process (σ~136 fb)
- Treatment of ttZ bkg. is an experimental challenge (XS~5x higher)
- tWZ signal interferes at NLO with ttZ → theoretically also difficult
- First ever tWZ search (multilepton final state: 3 or 4l)
- Use binary and multiclass NNs for sig. vs. bkg. (tWZ, ttZ, other)



Based on top quark p_T → 2 regions in phase-space:

i) top quark is almost at rest: SM *tWZ* production
→ define several SRs: (3l,3j,1b), (3l,3j,>1b), (3l,2j) & (4l) and DNN used to distinguish tWZ from bkgs.

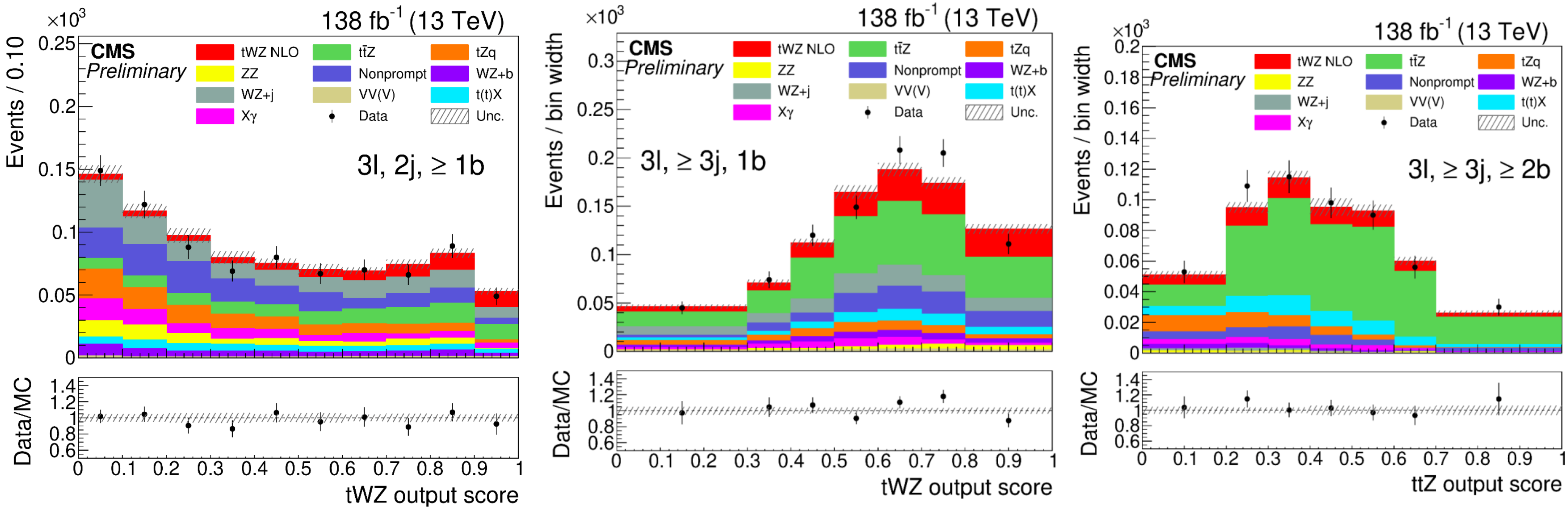
ii) top quark has a large p_T: enhanced sensitivity to BSM
→ 1 boosted SR (event counting)



This is a candidate event in which a top quark is produced in association with a W and a Z seen by the CMS detector. The Z boson decays to two electron (green lines) and the W decays to two jets (yellow cones). The top quark decays into a b quark, producing a b jet (orange cone), and a W boson, which decays into a muon (red lines) and a neutrino.

Evidence of tWZ production at 13 TeV @ CMS !

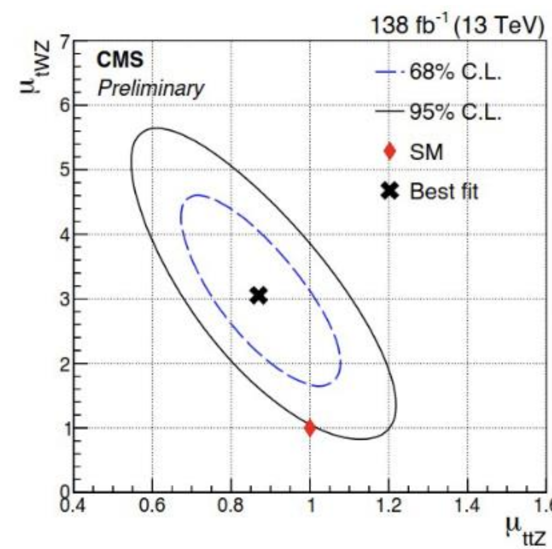
CMS-PAS-TOP-22-008



σ = 0.37 ±0.05(stat.) ±0.10 (syst.) fb

~2.1σ above the SM expectation

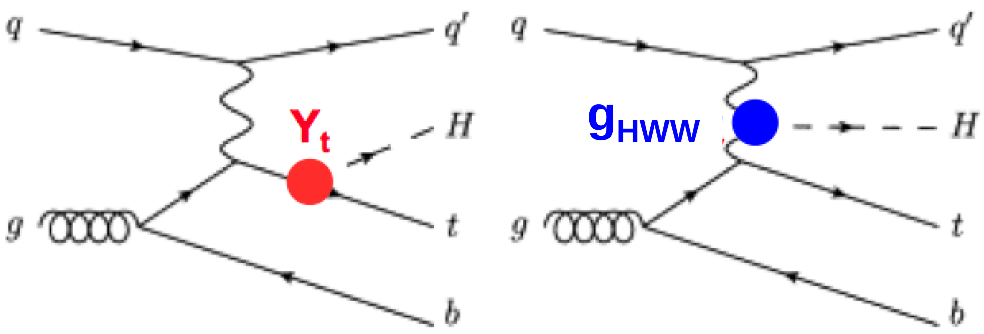
Significance: 3.5σ (1.4σ exp.) → **Evidence of tWZ production!**



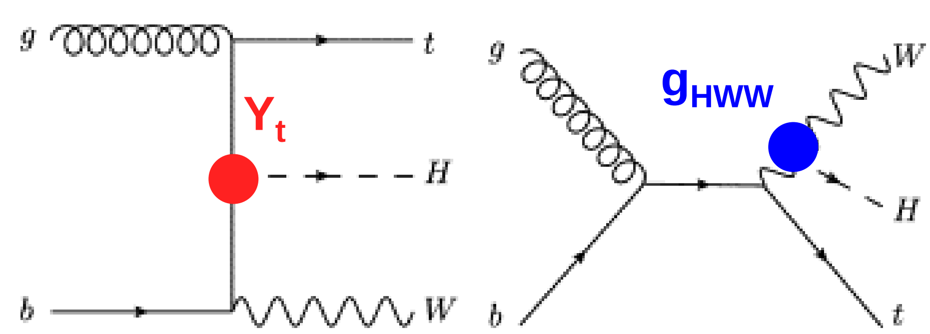
"The uncertainty associated with the ttZ normalization is found to have the dominant contribution to the systematic uncertainties. The reason of this behavior lies in the very similar nature of the tWZ and ttZ processes, observed as an anti-correlation feature in the statistical analysis."

Limits on tHq production cross-section

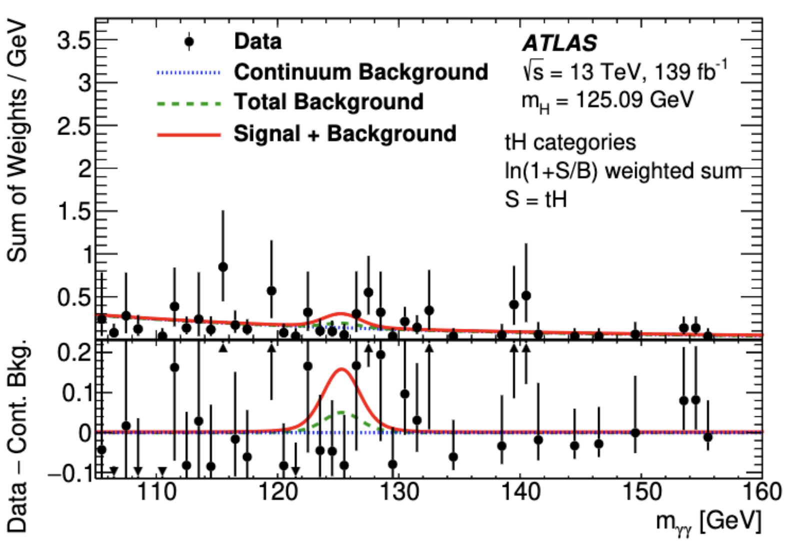
tHq ~70fb

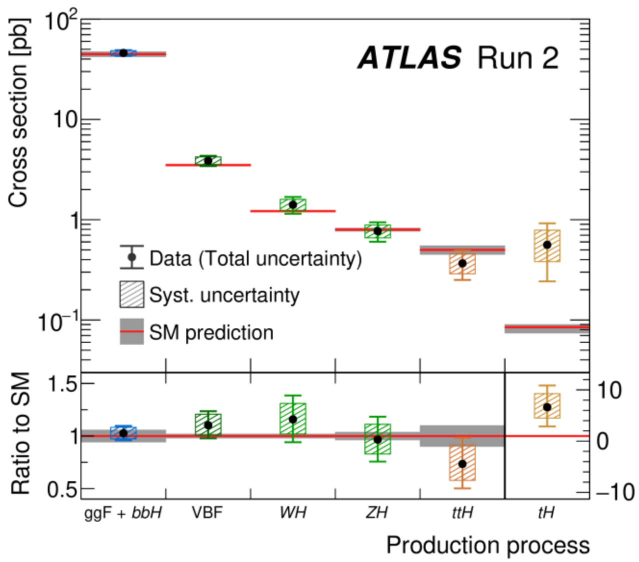


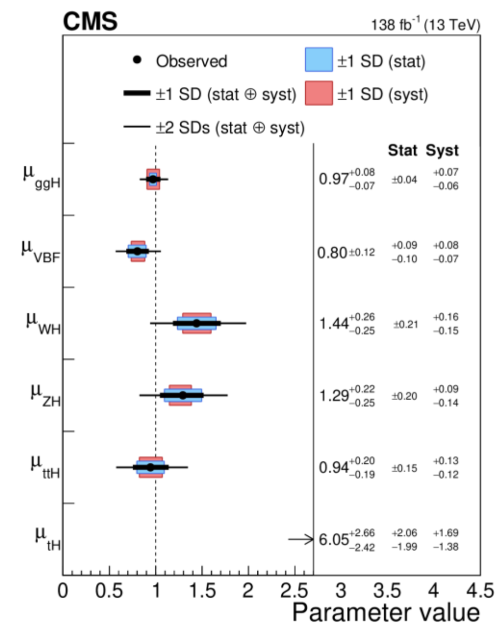
tHW ~16fb



- tH (tHq and tHW) is sensitive to both magnitude and sign of κ_t
- Suppressed in SM by destructive interference: $\kappa_t \cdot \kappa_V < 0$
- 15x increase in tH cross section assuming inverted coupling scenario
- Process not observed yet → upper limits in production cross-section







Summary

Latest measurements from single top processes presented:

- **t-channel:** used to measure the top quark CKM elements (also top quark polarisation vector and differential cross sections depending on angular observables)
- **tW channel:** measured in the dileptonic (differential and inclusive cross sections) and semileptonic (inclusive) decay modes
- **s-channel:** first 13 TeV measurement performed giving >3s significance

Associated production of single top quarks with vectors are rare processes, but on the path of precision regime:

- first observation of **tq**γ process and evidence of **tWZ** production.
- **tZq** process measured differentially in various observables, including top quark spin asymmetry

All these measurements open many possibilities for future interpretations and EFT fits.

THANKS FOR YOUR ATTENTION

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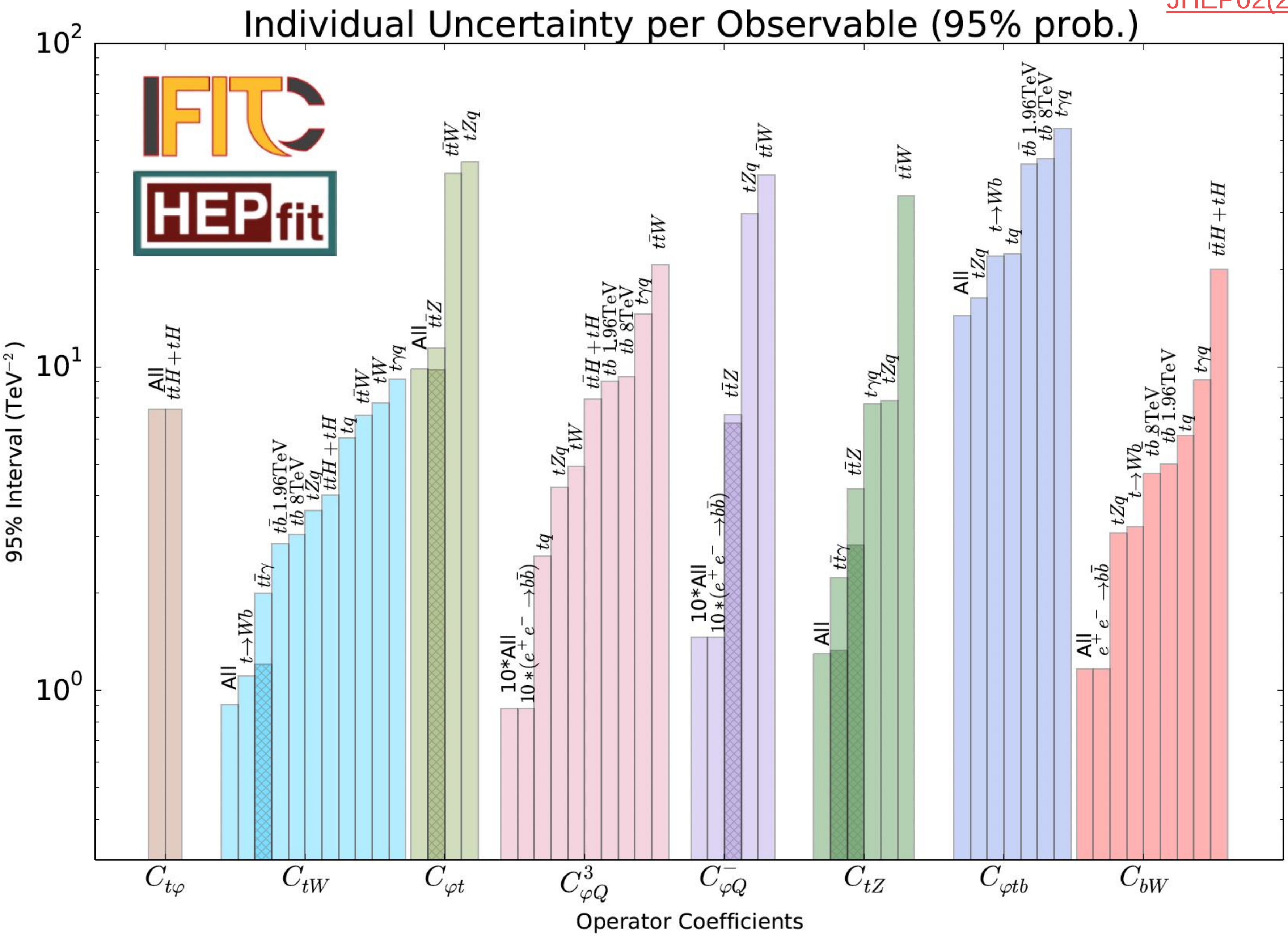
Summary: EFT importance of rare top quark processes

JHEP02(2022)032



BACK-UP

Earlier CMS paper, 2016 data 35.9fb^{-1}, dedicated BDTs - different scenarios:

- $|V_{tb}| > 0.95$ and $|V_{td}|^2 + |V_{ts}|^2 < 0.057$ (95% CL), $|V_{tb}|^2 + |V_{td}|^2 + |V_{ts}|^2 = 1$ (SM)
- $|V_{tb}| = 0.988 \pm 0.051$, $|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$, non-unitary CKM
- $|V_{tb}| = 0.988 \pm 0.024$, $|V_{td}|^2 + |V_{ts}|^2 = 0.06 \pm 0.06$, $\frac{\Gamma_t^{obs}}{\Gamma_t} = 0.99 \pm 0.42$, invis. decay

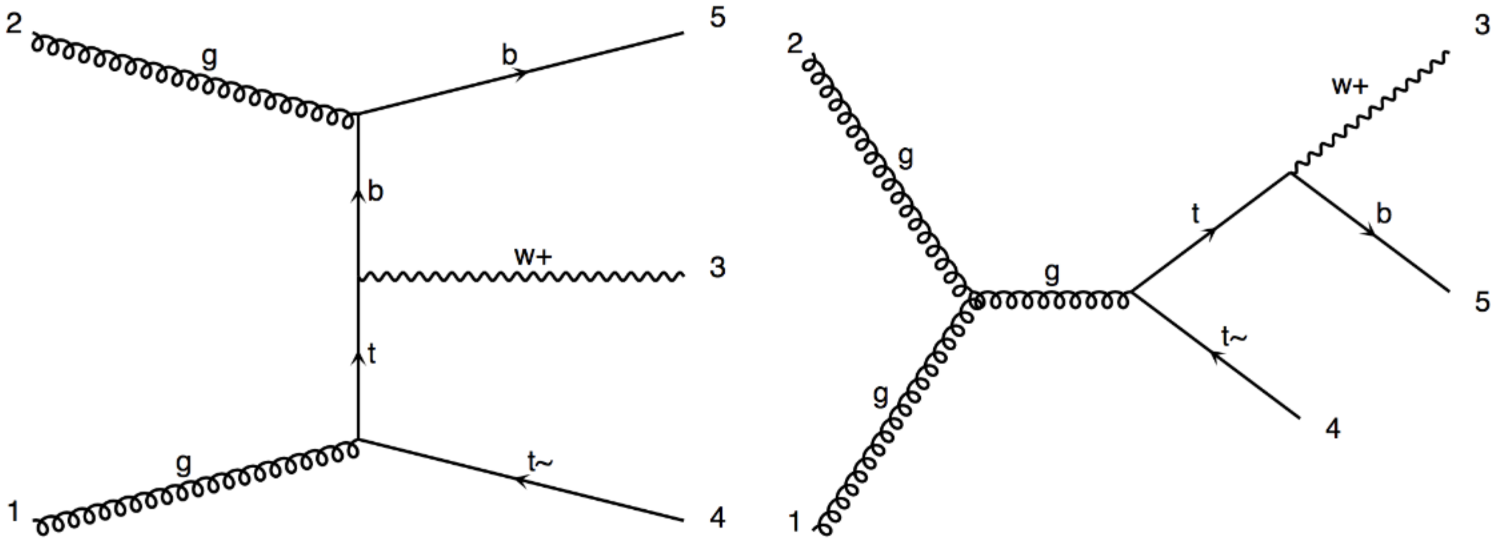
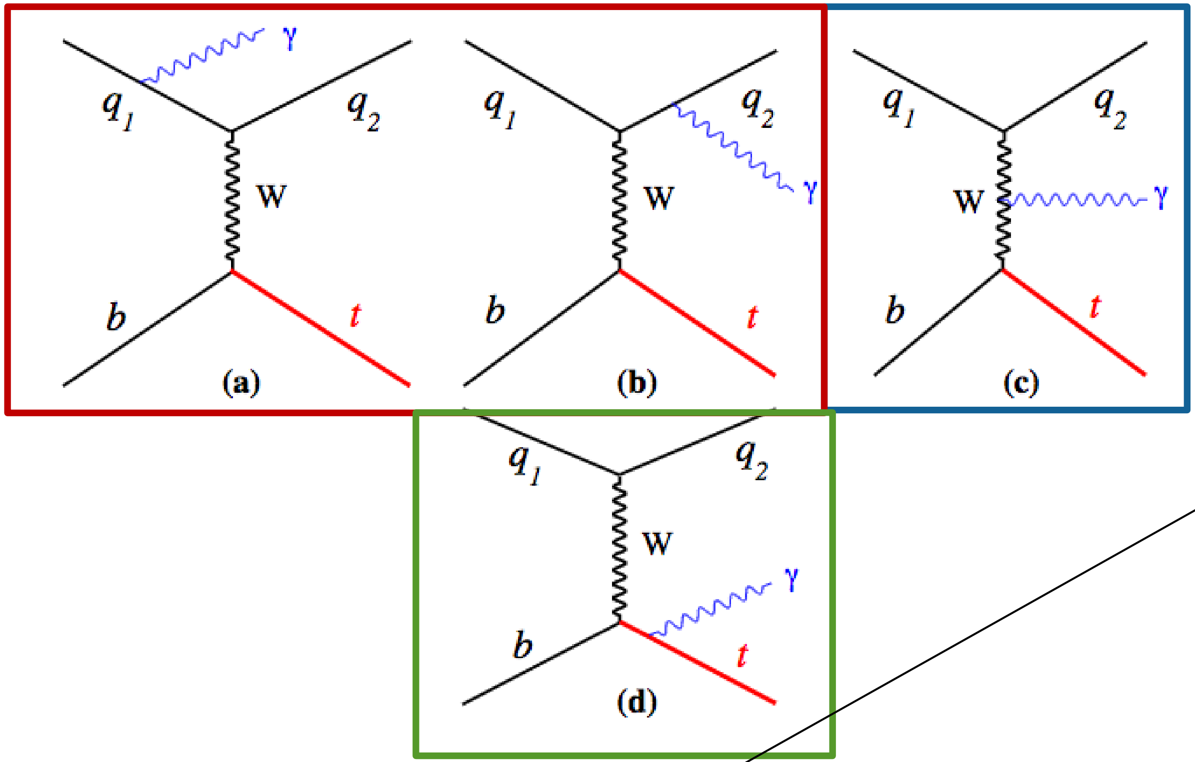


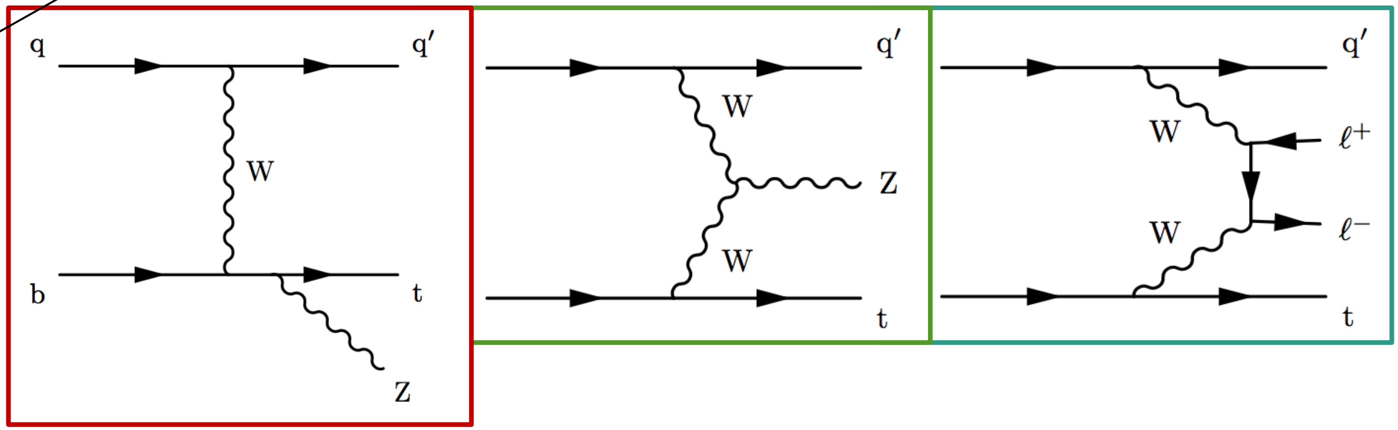
Figure 23: Diagrams generated [21] for Wt production at NLO in the five flavour scheme. A singly-resonant diagram is shown to the left and a doubly-resonant diagram, which overlaps with $t\bar{t}$ production at LO, is shown to the right.

$$|\mathcal{A}_{tWb}|^2 = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2$$

$$= \underbrace{\underbrace{|\mathcal{A}_{1t}|^2}_{\text{DR1}} + 2\text{Re}(\mathcal{A}_{1t}\mathcal{A}_{2t}^*)}_{\text{DR2}} + |\mathcal{A}_{2t}|^2$$

$$|\mathcal{A}_{tWb}|^2_{\text{DS}} = |\mathcal{A}_{1t} + \mathcal{A}_{2t}|^2 - \mathcal{C}_{2t}$$


γ
q1
q2
W
b
t
(a)
γ
q1
q2
W
b
t
(b)
γ
q1
q2
W
b
t
(c)
q1
q2
W
γ
b
t
(d)


q
q′
W
b
t
Z
q′
W
Z
W
t
q′
W
ℓ+
W
ℓ−
t

Summary: EFT importance of rare top quark processes

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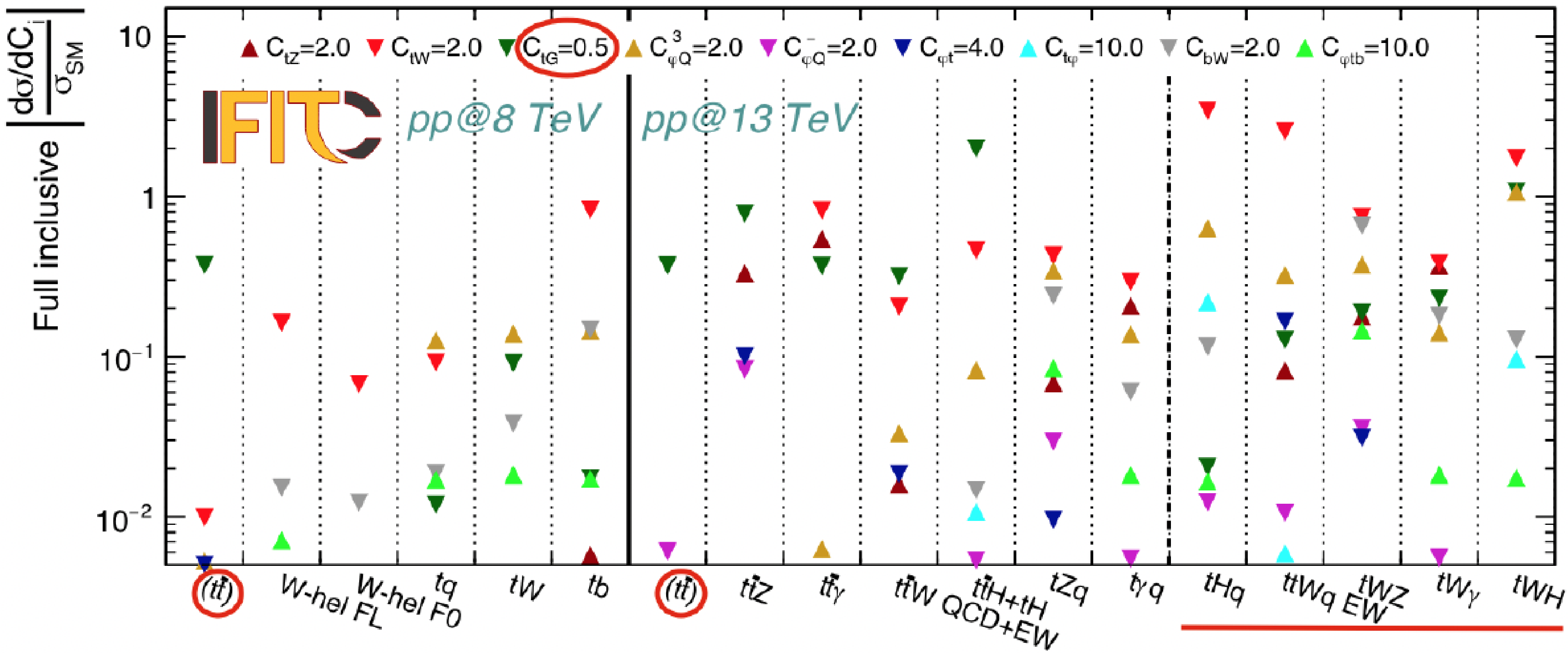
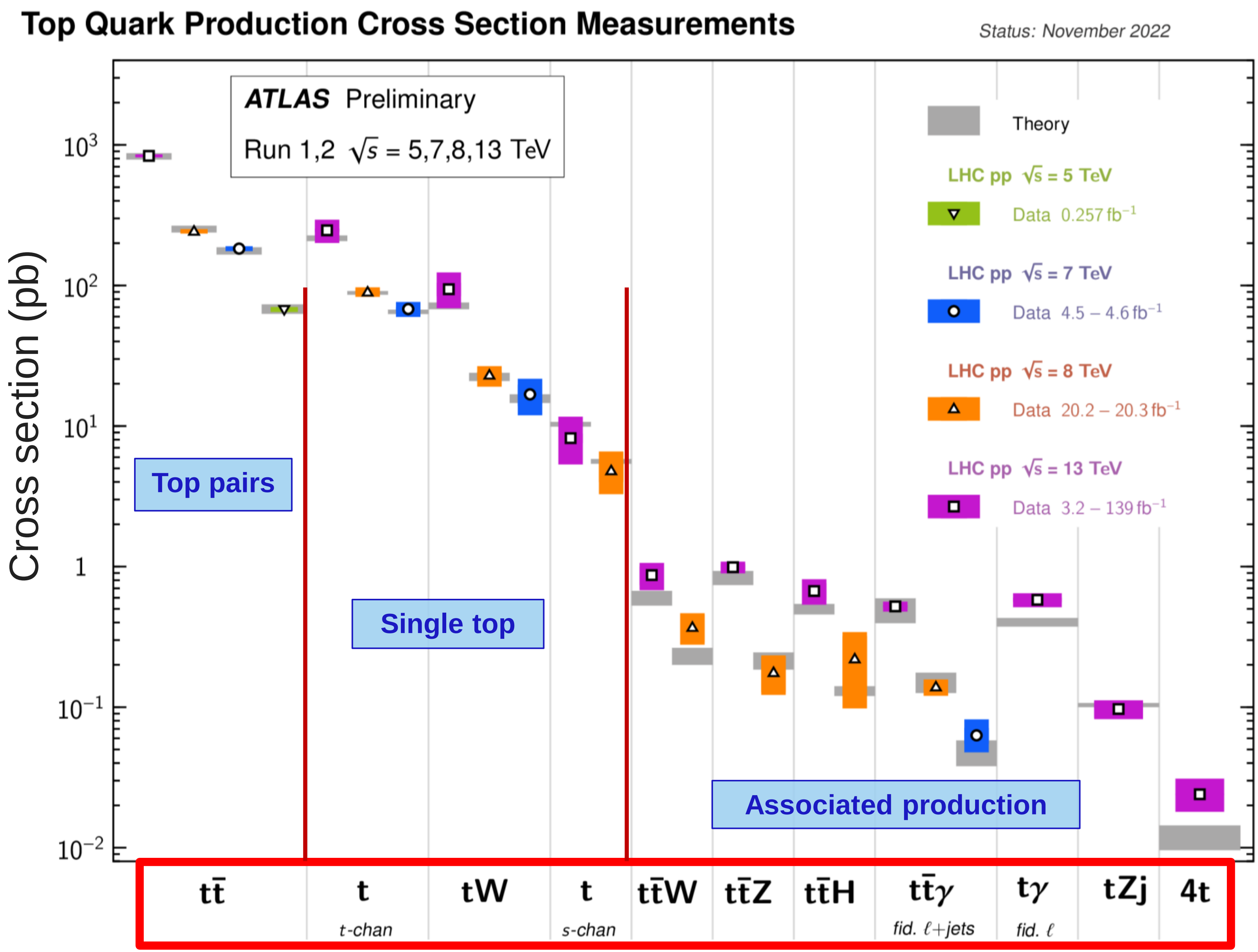


Reaching very rare processes as data increase



1 event every second

1 event every 100 s

So far, experimental results confirm the Standard Model

Increasing number of differential measurements and reaching very high precision.