Universität Siegen

Bundesministerium für Bildung und Forschung

Heisenberg-Programm

DFG Deutsche Forschungsgemeinschaft

Top-quark physics in ATLAS and CMS

Markus Cristinziani

on behalf of the ATLAS and CMS collaborations

Workshop on the Standard Model and Beyond
Corfu, August 27 – September 7, 2023

Plan

Overview of **most recent** top-quark results by ATLAS and CMS

Since Corfu 2022

- 12 new results by CMS (6 papers submitted, 6 preliminary results) [Link]
- 20 new results by ATLAS (13 papers submitted, 7 preliminary results) [Link]
- cannot cover them all in 25 minutes

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Focus on

- papers submitted in the last 6 months
- preliminary results in the last 4 months

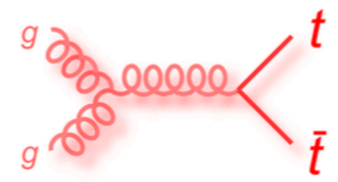
Covers many different aspects of the top programme at the LHC

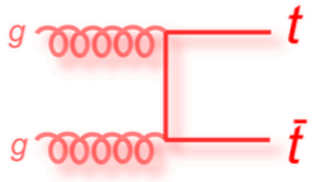
Top-quark production

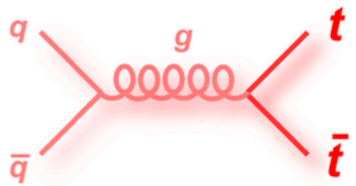
The top quark: the heaviest known fundamental particle, m_t ~ 172.5 GeV

Produced in pairs, singly, and with additional particles; sensitive to NP

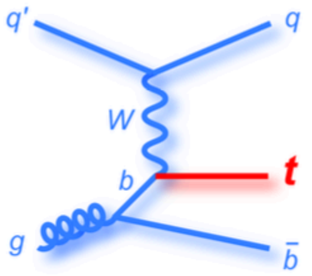
top-quark pair
$\sigma \simeq$ 834 pb @13 TeV
(NNLO+NNLL)

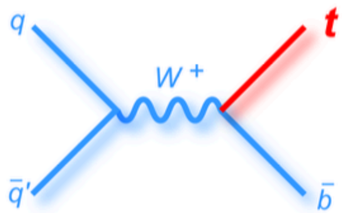


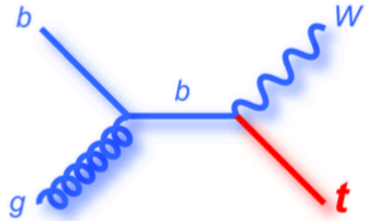




single-top







t-channel
$\sigma \simeq$ 214 pb @13 TeV
(NNLO)

s-channel
$\sigma \simeq$ 11 pb @13 TeV
(NNLO)

tW
$\sigma \simeq$ 79 pb @13 TeV
(NLO+NNLL)

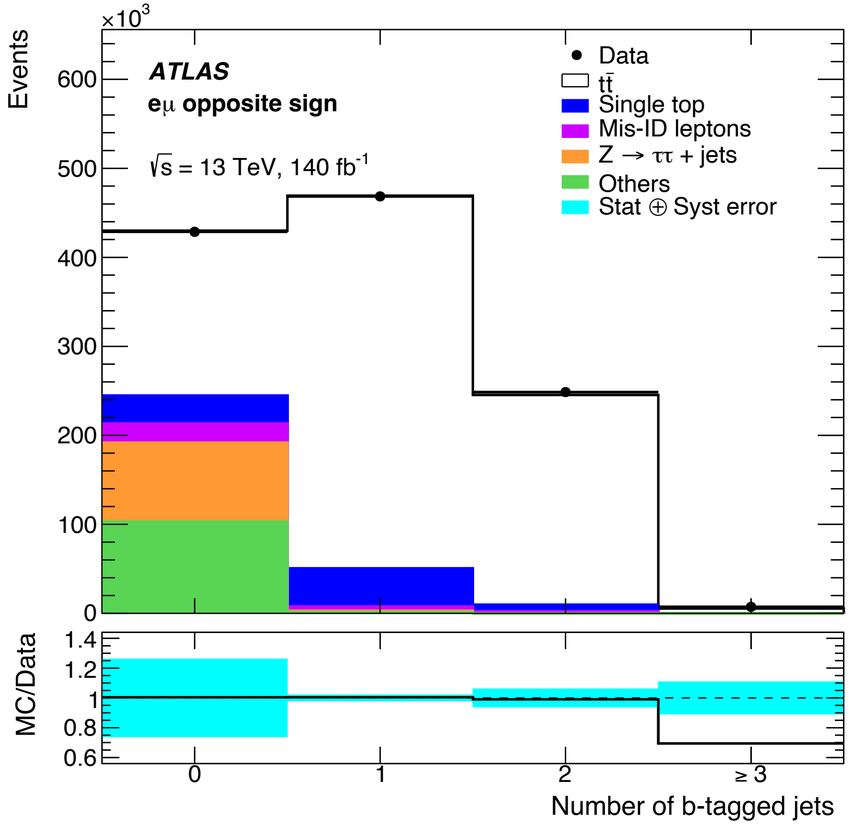
LHC as top factory: ~120M pairs in Run-2 (140 fb^{-1}) in each experiment

$t\bar{t}$ cross section in eμ channel

JHEP 07 (2023) 141

Analysis at 13 TeV collision energy

- inclusive and (double-)differential lepton distributions
- fiducial region and full phase space
- profits from latest luminosity measurement
- improved reconstruction



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Inclusive result

- $\sigma_{t\bar{t}} = 829 \pm 1_{(\text{stat.})} \pm 13_{(\text{syst.})} \pm 8_{(\text{lumi.})} \pm 2_{(\text{beam})}$ pb
- world-record 1.8% $t\bar{t}$ cross section uncertainty
- agrees with NNLO prediction

JHEP 07 (2023) 141

Source of uncertainty	$\Delta\sigma_{t\bar{t}}^{\text{fid}}/\sigma_{t\bar{t}}^{\text{fid}}$ [%]	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ [%]
Data statistics	0.15	0.15
MC statistics	0.04	0.04
Matrix element	0.12	0.16
h_{damp} variation	0.01	0.01
Parton shower	0.08	0.22
$t\bar{t}$ + heavy flavour	0.34	0.34
Top p_{T} reweighting	0.19	0.58
Parton distribution functions	0.04	0.43
Initial-state radiation	0.11	0.37
Final-state radiation	0.29	0.35
Electron energy scale	0.10	0.10
Electron efficiency	0.37	0.37
Electron isolation (in situ)	0.51	0.51
Muon momentum scale	0.13	0.13
Muon reconstruction efficiency	0.35	0.35
Muon isolation (in situ)	0.33	0.33
Lepton trigger efficiency	0.05	0.05
Vertex association efficiency	0.03	0.03
Jet energy scale & resolution	0.10	0.10
b-tagging efficiency	0.07	0.07
$t\bar{t}/Wt$ interference	0.37	0.37
Wt cross-section	0.52	0.52
Diboson background	0.34	0.34
$t\bar{t}V$ and $t\bar{t}H$	0.03	0.03
Z + jets background	0.05	0.05
Misidentified leptons	0.32	0.32
Beam energy	0.23	0.23
Luminosity	0.93	0.93
Total uncertainty	1.6	1.8

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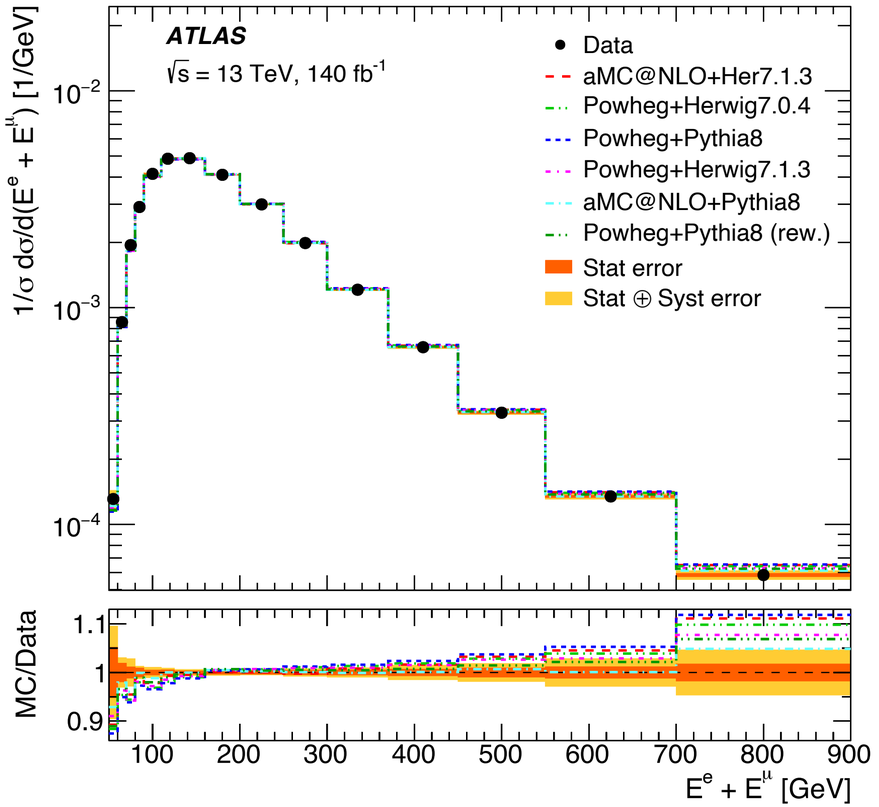
Differential results

- somewhat in tension with state-of-the-art simulation



Jet substructure in boosted $t\bar{t}$ events

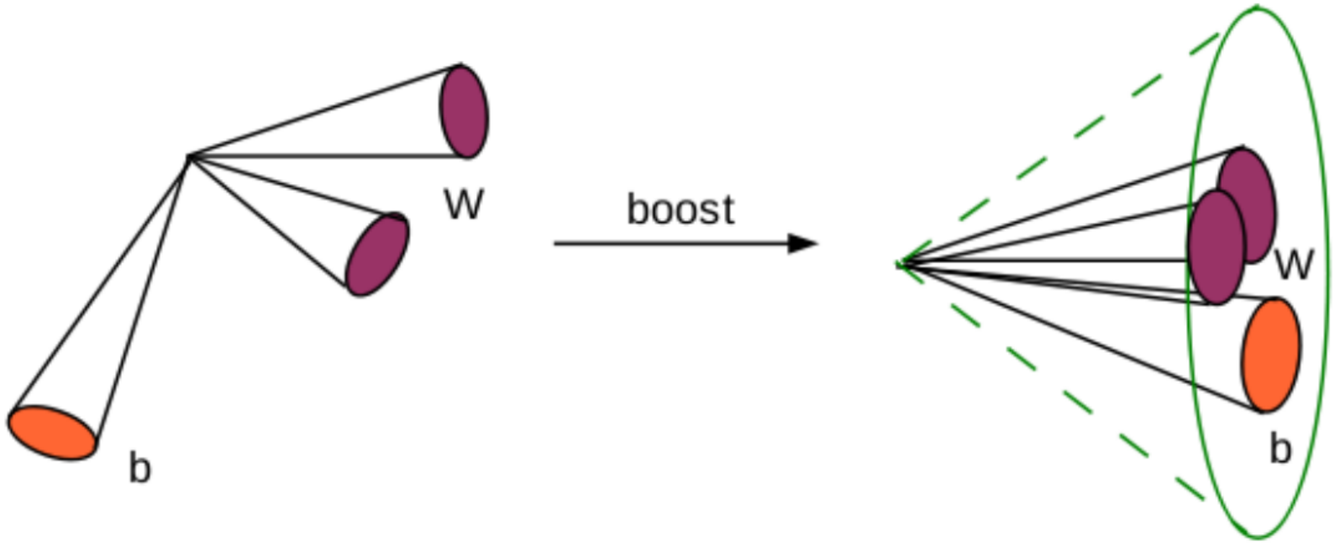
ATLAS-CONF-2023-027

Top-quark jet substructure

- anti-k_t R=1.0 jets in single lepton chan. and **fully hadronic** $t\bar{t}$ events
- p_T (top-jet) $\in$ (350,600) GeV

Differential cross section

- unfolded at particle level (IBU)
- using charged components of jet
  → 50% better resolution



Eight variables, 1D & 2D

- N-subjettiness τ_3, τ_{32}, τ_{21};
- norm. energy correlation f. ECF2, D_2, C_3;
- angularities LHA, $p_{\mathrm{T}}^{d,*}$
- predicted substructure is more 3-body-like

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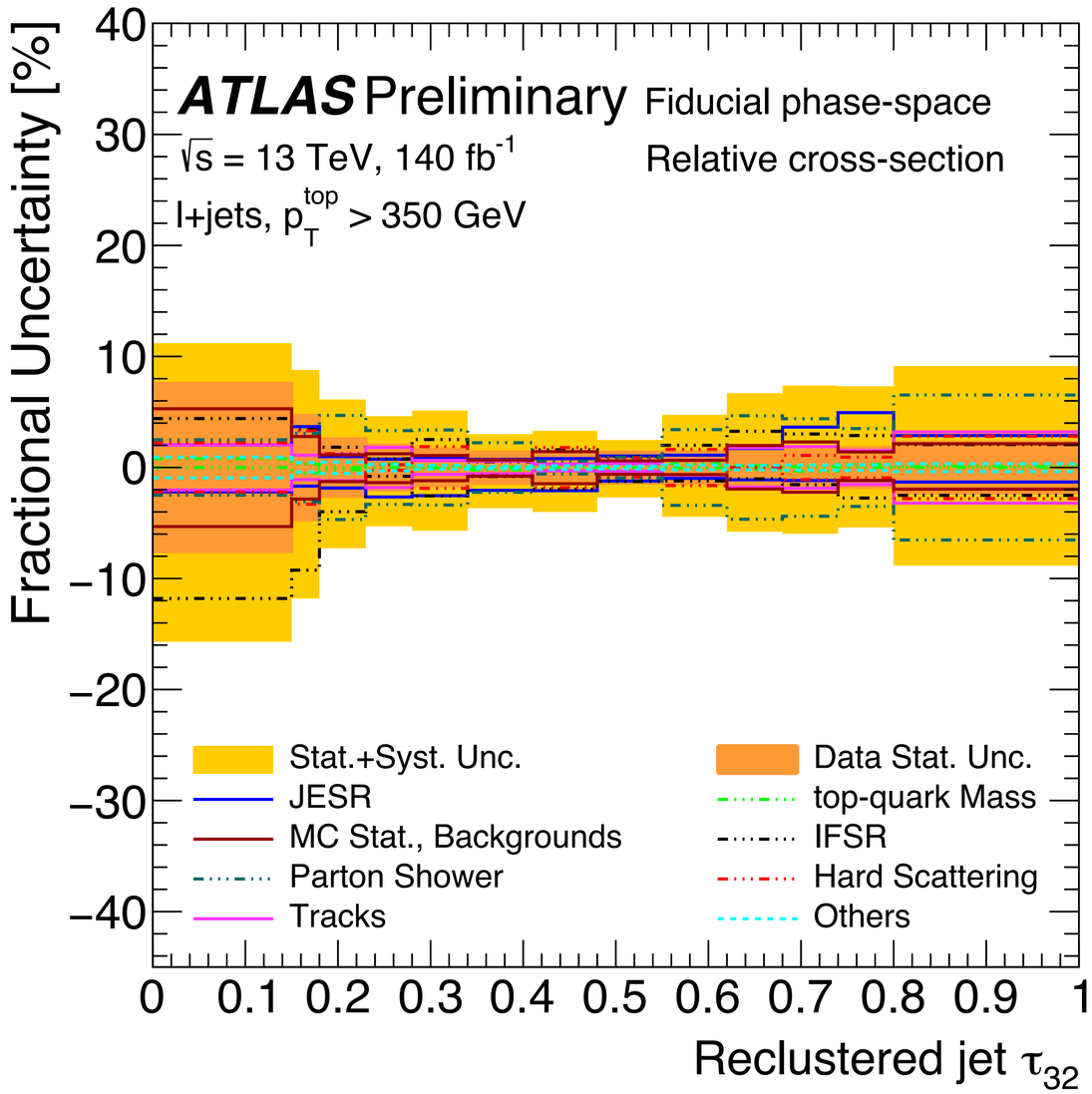

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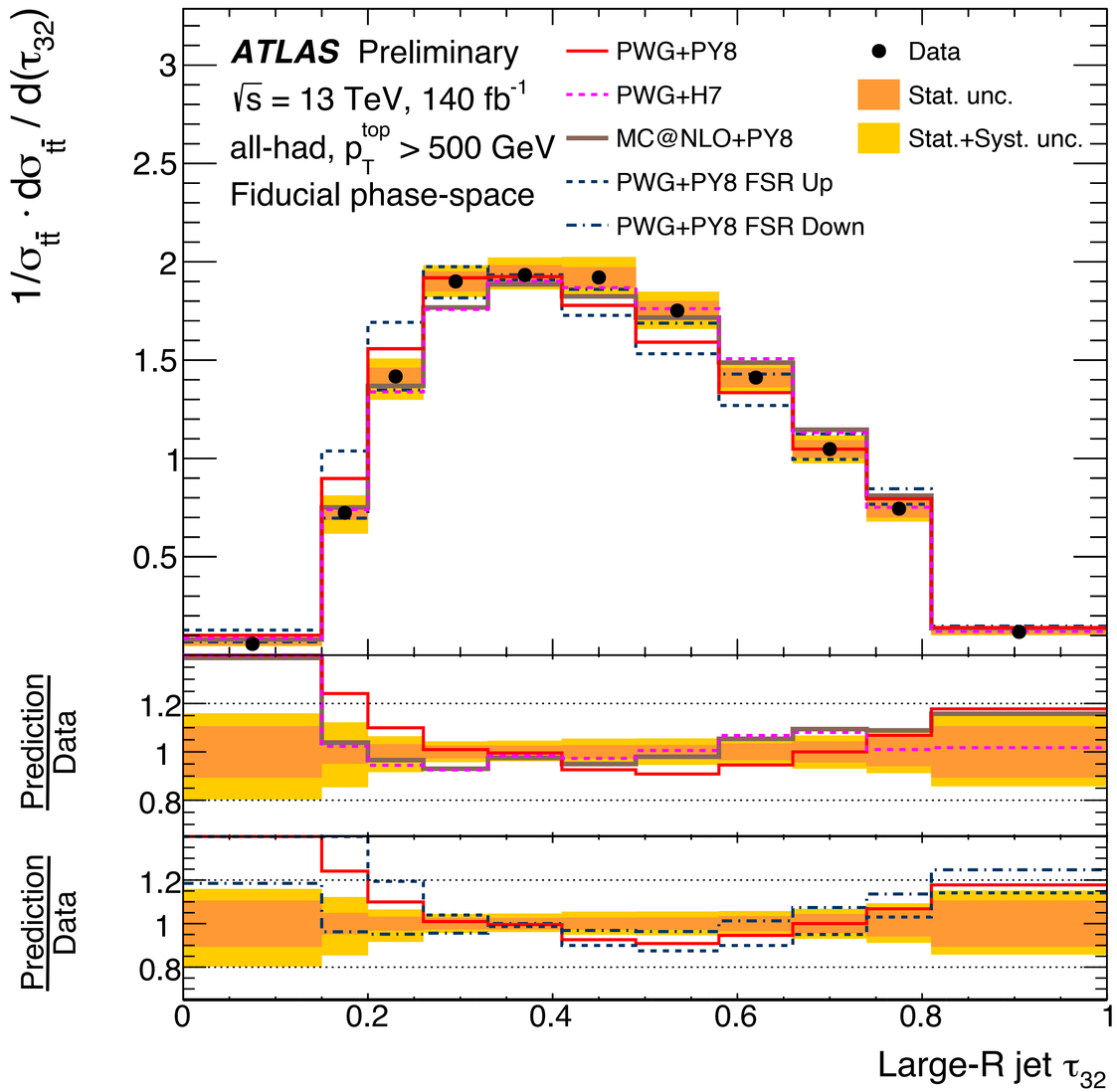

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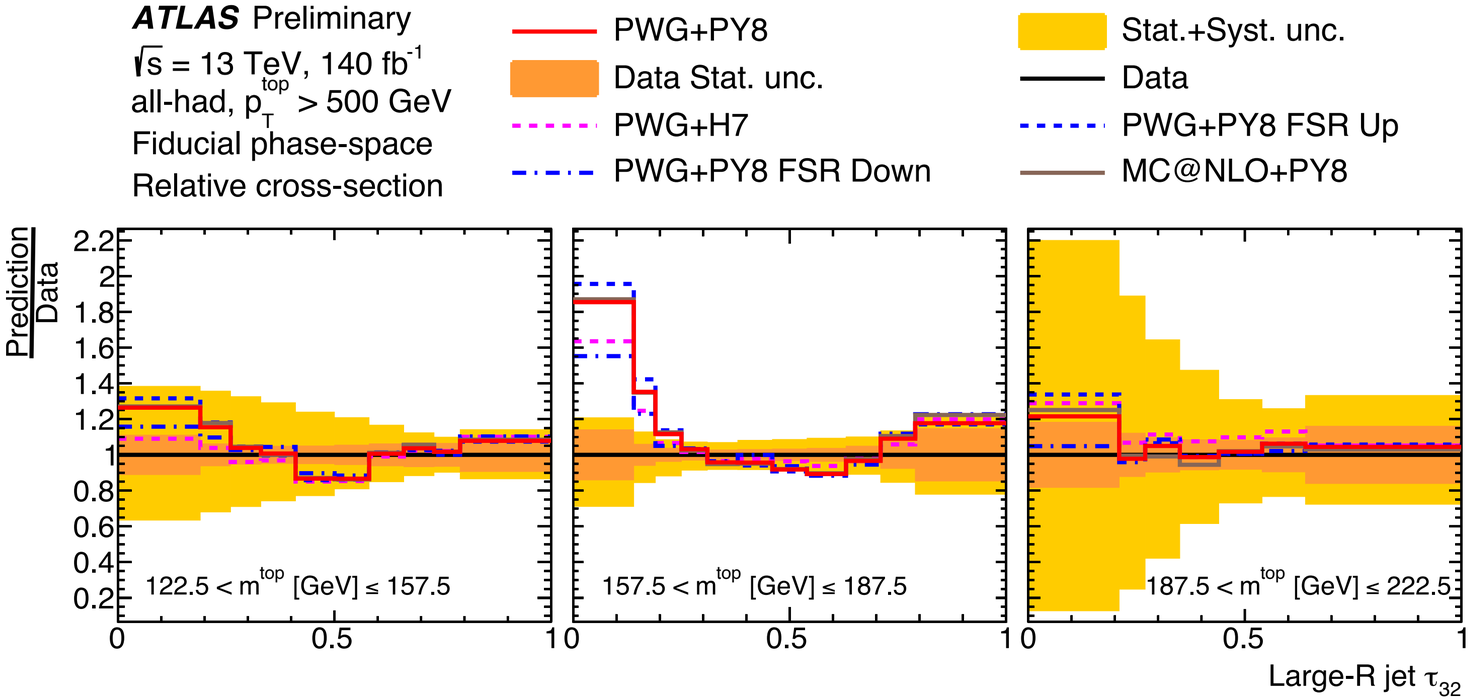

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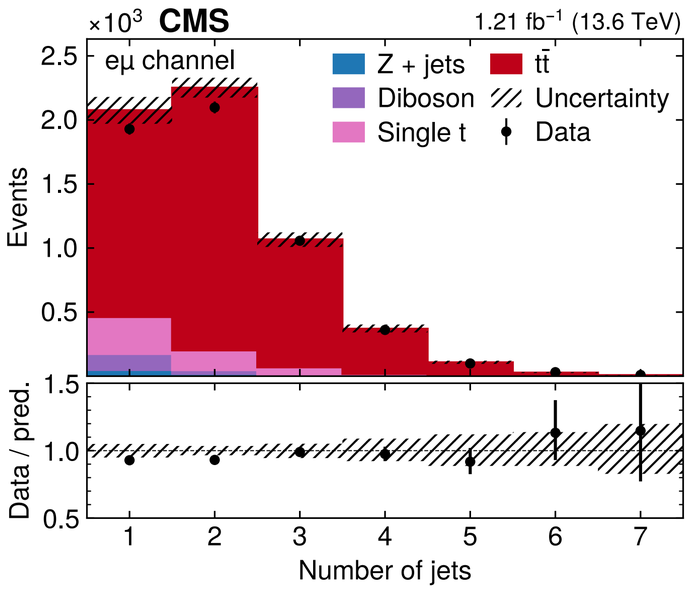
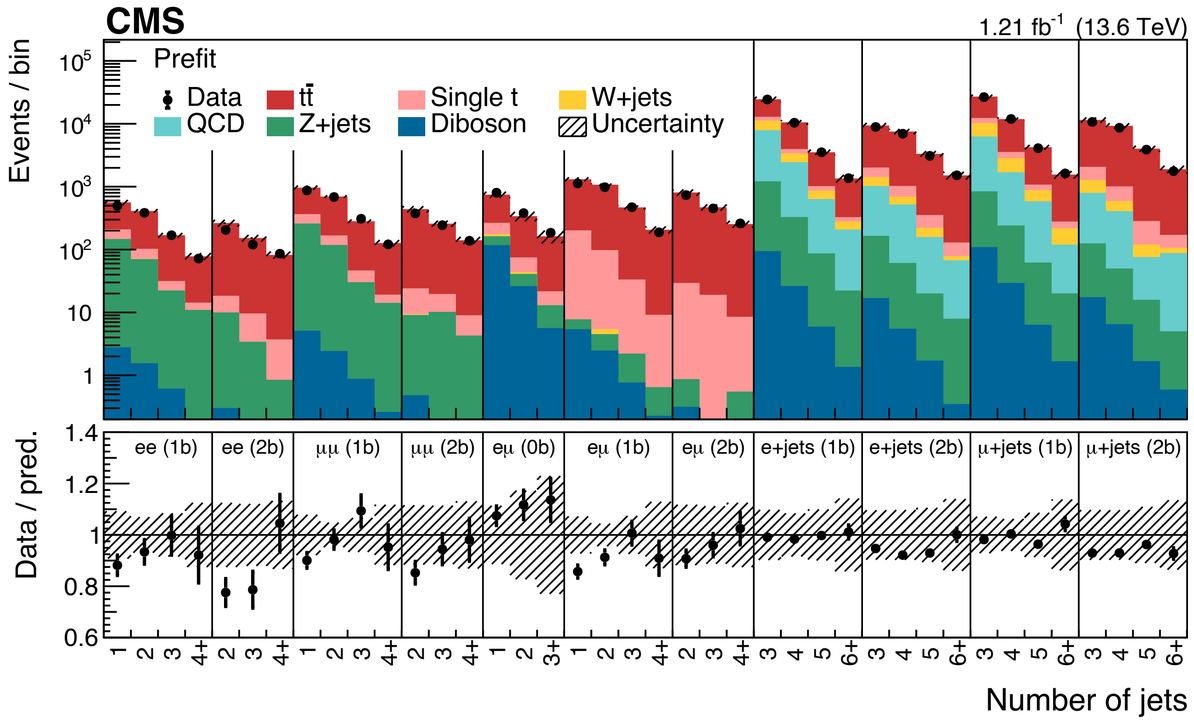
$t\bar{t}$ production at 13.6 TeV

arXiv:2303.10680

First $t\bar{t}$ measurement in Run-3 at new energy, 1.21 fb^{-1}

- single and dilepton channels
- $p_T(\ell)$>35 GeV; new jet calibration; data driven Z+jets & QCD multijet
- ML fit with cut&count cross-check in eμ channel





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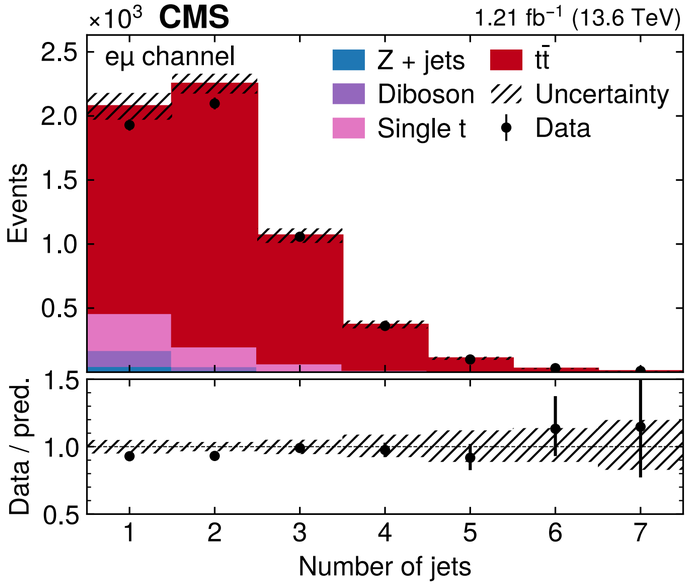

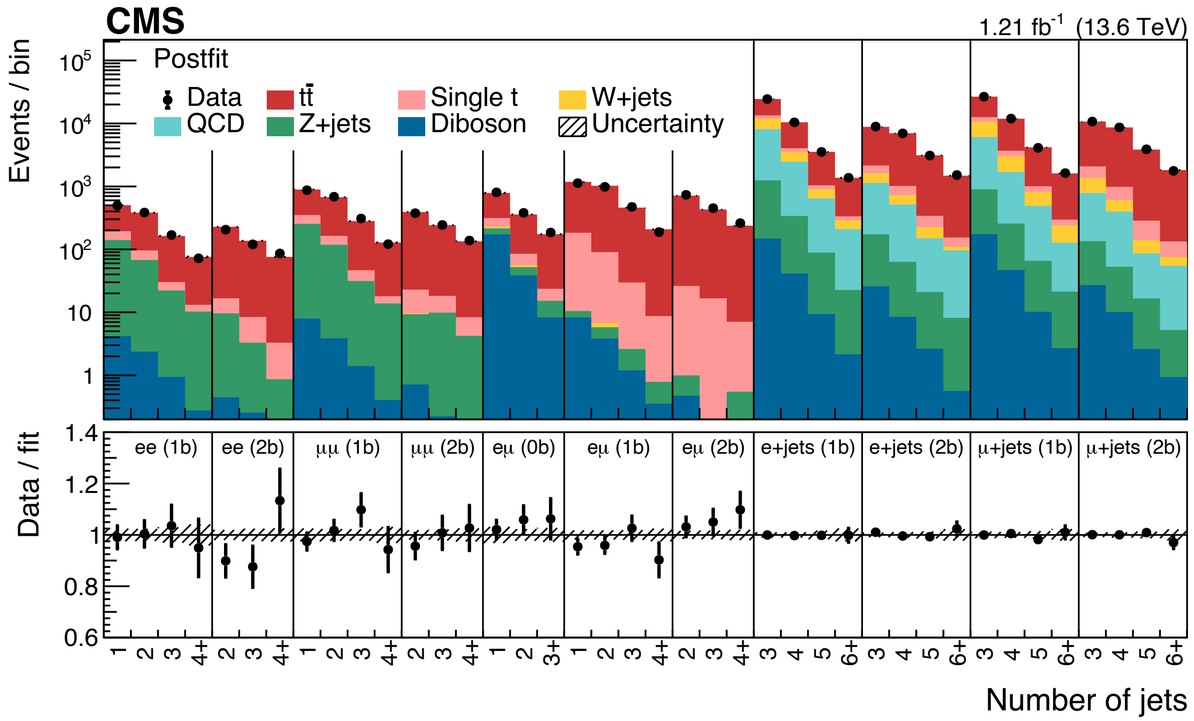

Source	Uncertainty (%)
Lepton ID efficiencies	1.6
Trigger efficiency	0.3
JES	0.7
b tagging efficiency	1.1
Pileup reweighting	0.5
ME scale, $t\bar{t}$	0.6
ME scale, backgrounds	0.1
ME/PS matching	0.1
PS scales	0.3
PDF and α_S	0.3
Single t background	1.0
Z+jets background	0.3
W+jets background	0.0
Diboson background	0.5
QCD multijet background	0.3
Statistical uncertainty	0.5
Combined uncertainty	2.6
Integrated luminosity	2.3

- $\sigma_{t\bar{t}} = 882 \pm 23\,(\text{stat.} + \text{syst.}) \pm 20\,(\text{lumi.})$ pb $\quad (921^{+29}_{-37}$ pb expected)

$t\bar{t}$ production at 13.6 TeV

arXiv:2308.09529

Measure $t\bar{t}$ and Z cross-section simultaneously, 29 fb^{-1}

- eμ channel for $t\bar{t}$
- ee and μμ for Z cross-section
- ratio cancels lumi dependence

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Strategy

- count b-tag multiplicity
- also extract b-tag efficiency

$$
\begin{aligned}
N_1 &= L\sigma_{t\bar{t}}\epsilon_{e\mu}2\epsilon_b\left(1 - C_b\epsilon_b\right) + N_1^{\text{bkg}}, \\
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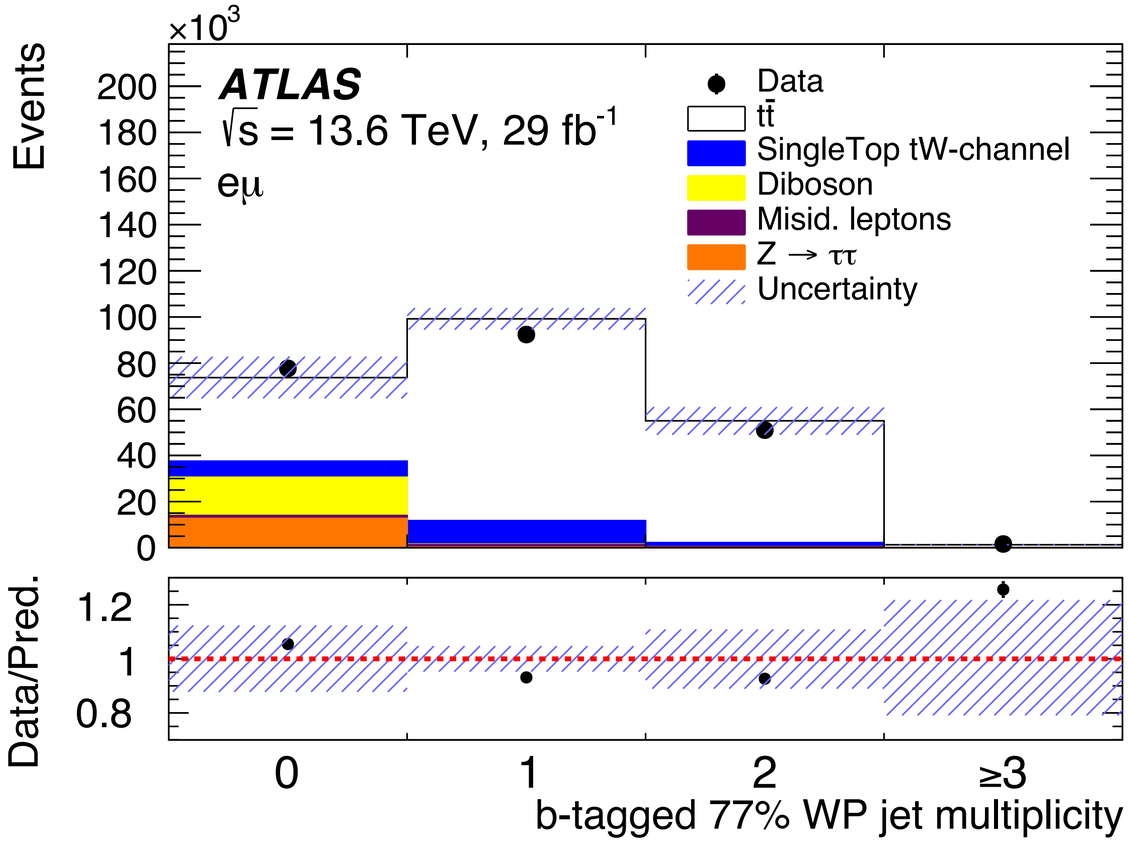

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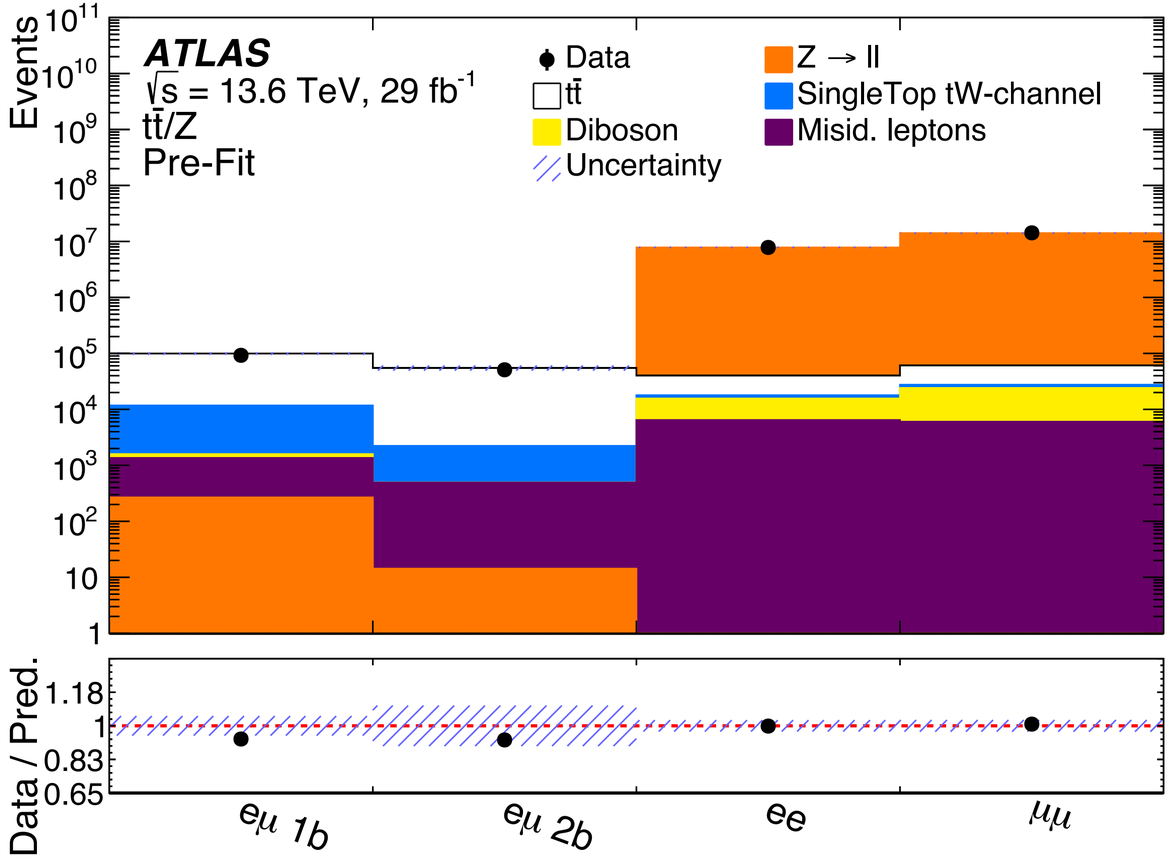

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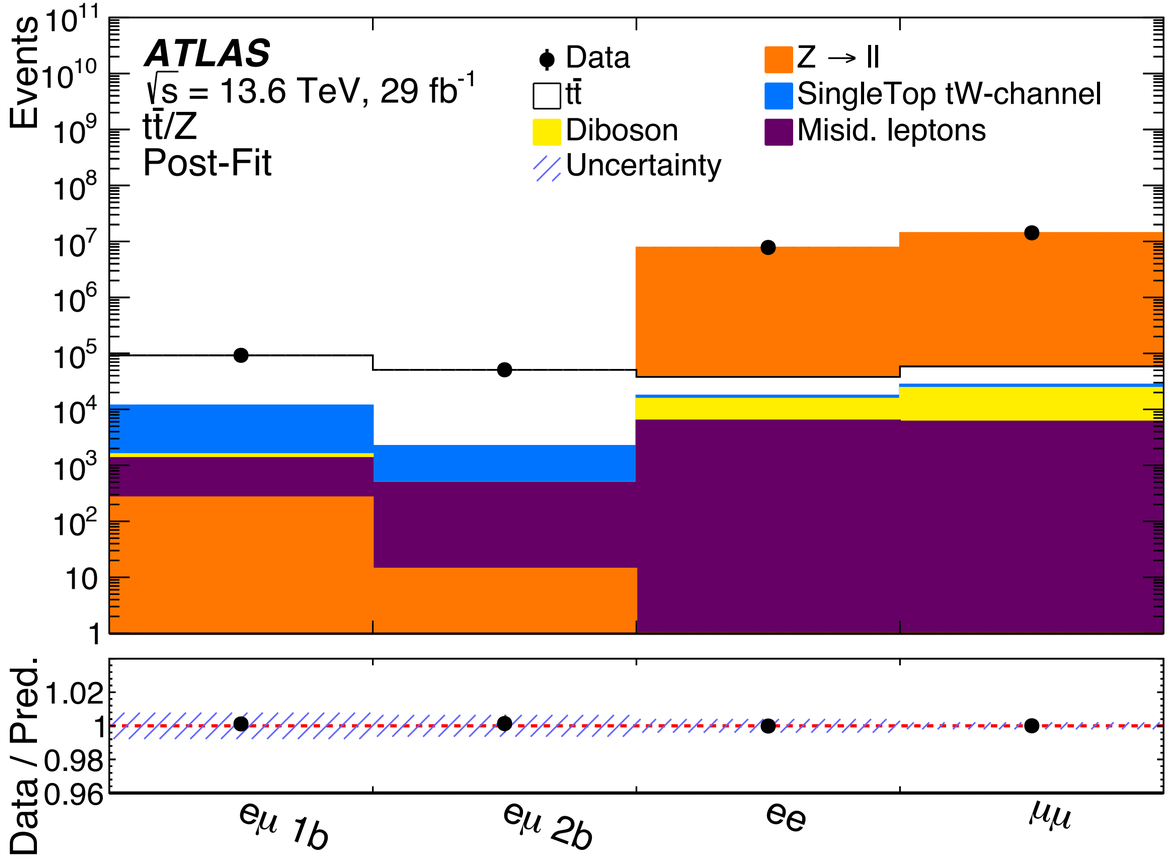

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	Category	**Uncertainty** [%]		
		$\sigma_{t\bar{t}}$	$\sigma^{\text{fid.}}_{Z\to\ell\ell}$	$R_{t\bar{t}/Z}$
$t\bar{t}$	$t\bar{t}$ parton shower/hadronisation	0.9	< 0.2	0.9
	$t\bar{t}$ scale variations	0.4	< 0.2	0.4
	$t\bar{t}$ normalisation	-	< 0.2	-
	Top quark p_{T} reweighting	0.6	< 0.2	0.6
Z	Z scale variations	< 0.2	0.4	0.3
Bkg.	Single top modelling	0.6	< 0.2	0.6
	Diboson modelling	< 0.2	< 0.2	0.2
	$t\bar{t}V$ modelling	< 0.2	< 0.2	< 0.2
	Fake and non-prompt leptons	0.6	< 0.2	0.6
Lept.	Electron reconstruction	1.2	1.0	0.4
	Muon reconstruction	1.4	1.4	0.3
	Lepton trigger	0.4	0.4	0.4
Jets/tagging	Jet reconstruction	0.4	-	0.4
	Flavour tagging	0.4	-	0.3
	PDFs	0.5	< 0.2	0.5
	Pileup	0.7	0.8	< 0.2
	Luminosity	2.3	2.2	0.3
	Systematic uncertainty	3.2	2.8	1.8
	Statistical uncertainty	0.3	0.02	0.3
	Total uncertainty	3.2	2.8	1.9

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arXiv:2308.09529

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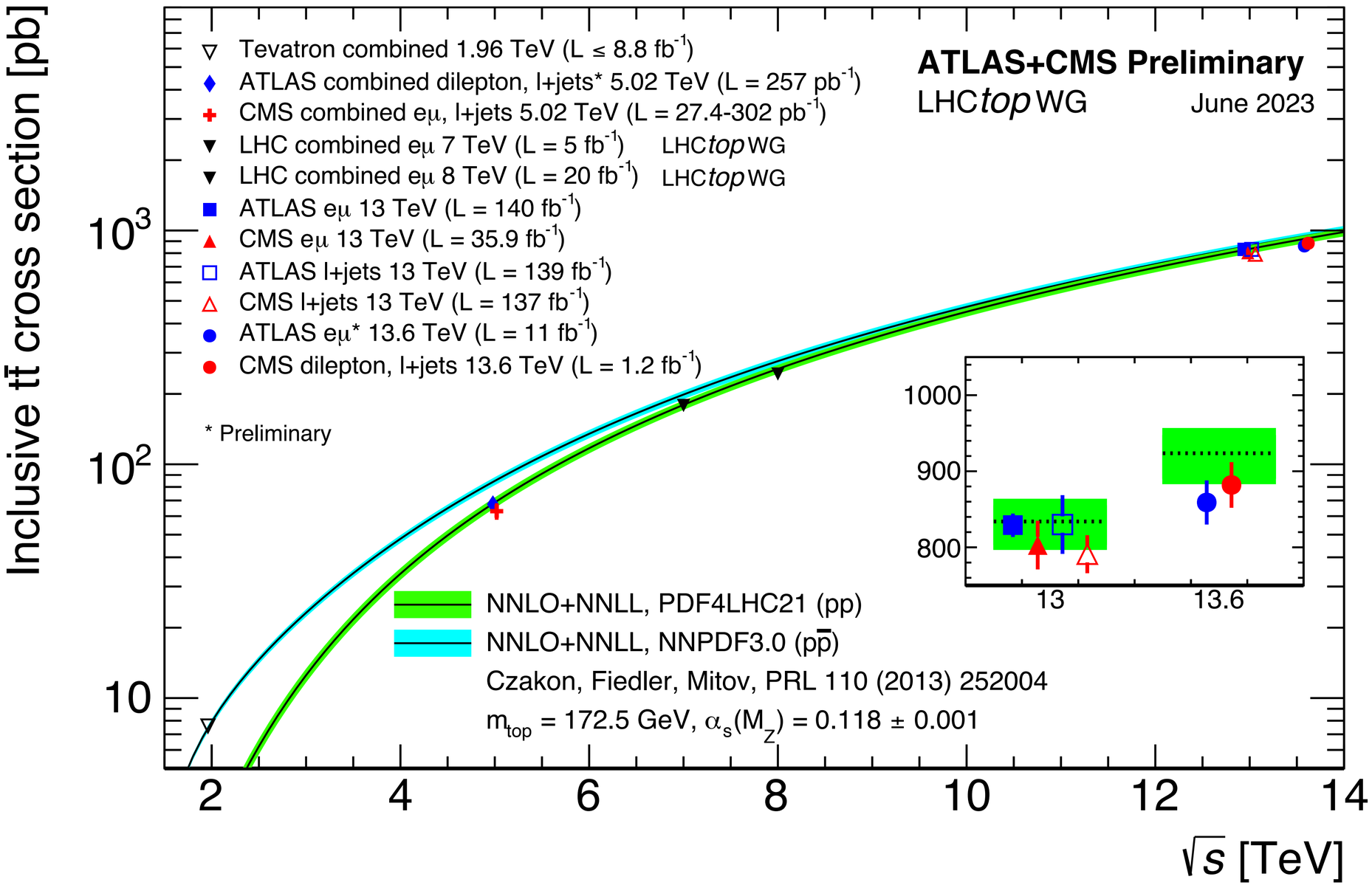
Results

- $\sigma_{t\bar{t}} = 850 \pm 3\,(\text{stat.}) \pm 18\,(\text{syst.}) \pm 20\,(\text{lumi.})$ pb
- $R_{t\bar{t}/Z} = 1.145 \pm 0.003\,(\text{stat.}) \pm 0.021\,(\text{syst.}) \pm 0.002\,(\text{lumi.})$

$pp \rightarrow t\bar{t}$ cross-section summary

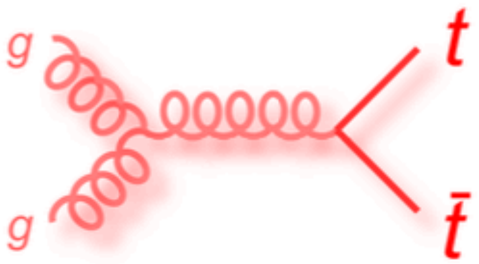


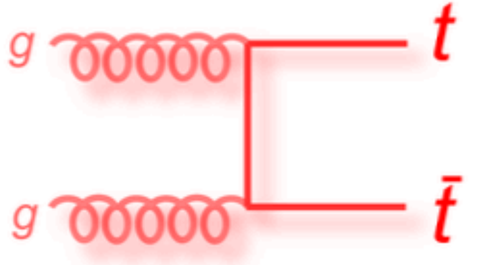
Single top production

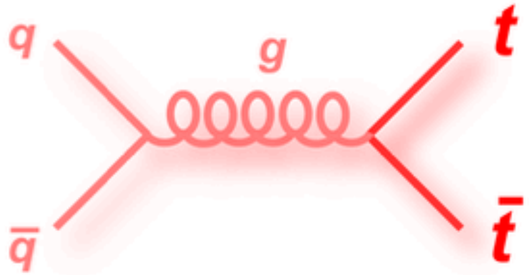
top-quark pair

$\sigma \simeq 834$ pb @13 TeV

(NNLO+NNLL)







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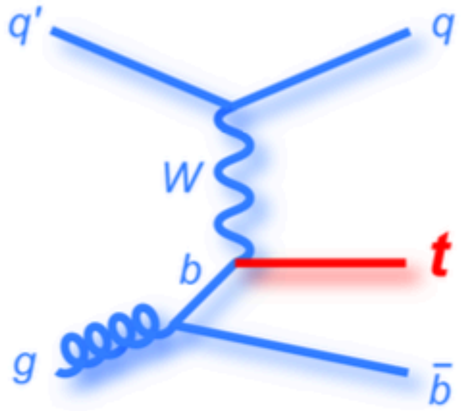
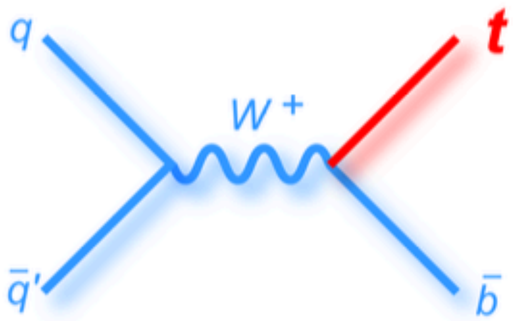
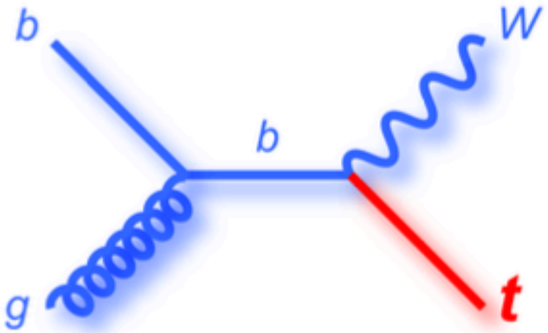






t-channel

$\sigma \simeq 214$ pb @13 TeV

(NNLO)

s-channel

$\sigma \simeq 11$ pb @13 TeV

(NNLO)

tW

$\sigma \simeq 79$ pb @13 TeV

(NLO+NNLL)

t-channel 13 TeV cross section

ATLAS-CONF-2023-026

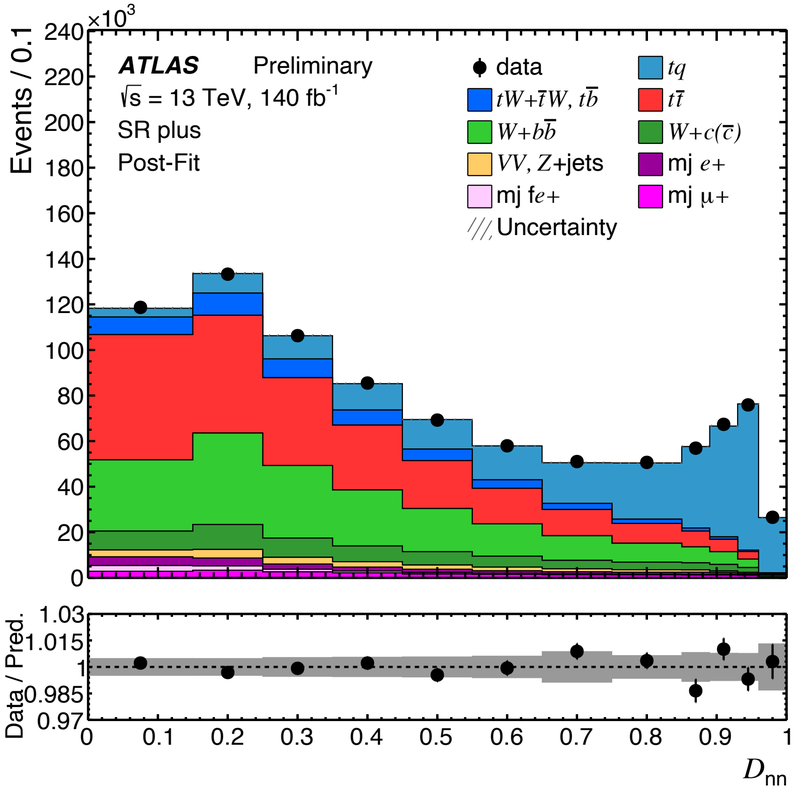
t-channel 13 TeV cross section

single top

ATLAS-CONF-2023-026

Typical signal region: 1e/μ, 1 b-jet, 1 forward jet

- NN to separate signal from background



t-channel 13 TeV cross section

single top

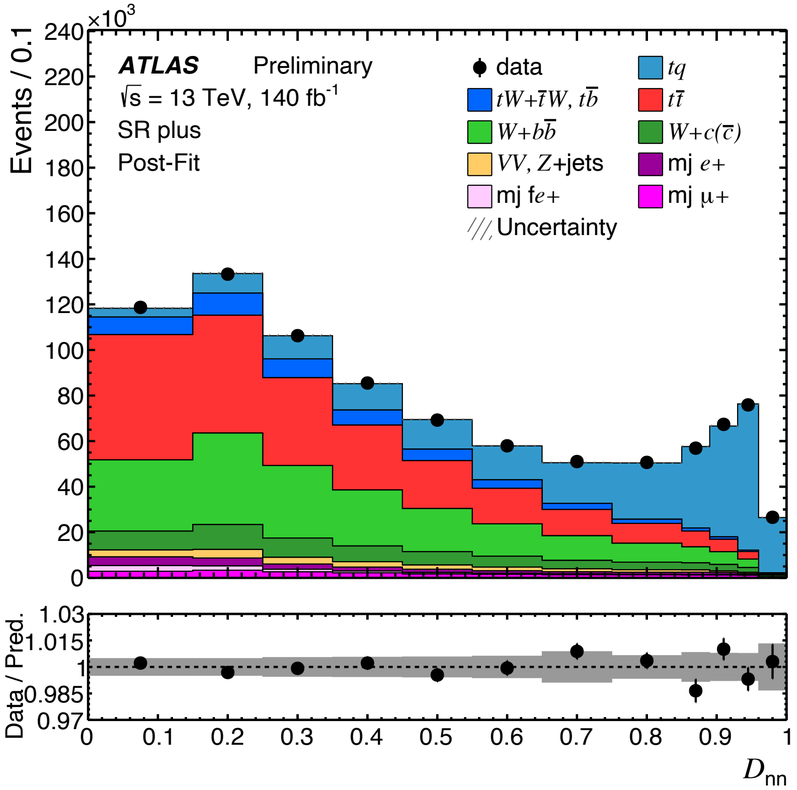
ATLAS-CONF-2023-026

Typical signal region: 1e/μ, 1 b-jet, 1 forward jet

- NN to separate signal from background

Preliminary result, full Run-2 dataset

- $\sigma_t = 137 \pm 8$ pb, $\sigma_{\bar{t}} = 84^{+6}_{-5}$ pb,
- $\sigma_{t+\bar{t}} = 221 \pm 13$ pb, $R_t = \sigma_t/\sigma_{\bar{t}} = 1.636^{+0.036}_{-0.034}$



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single top

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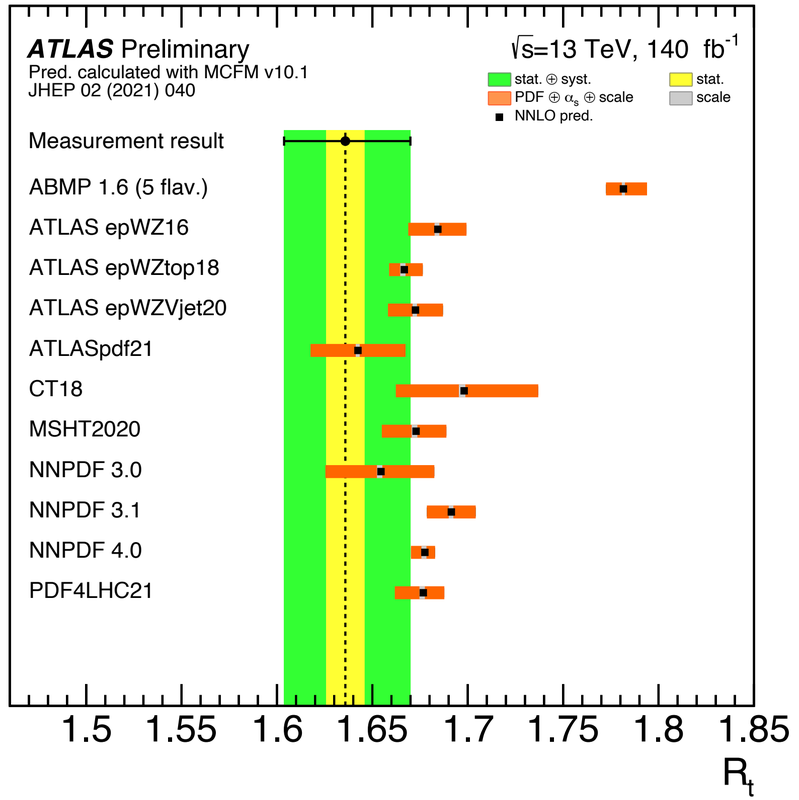
- sensitive to PDFs



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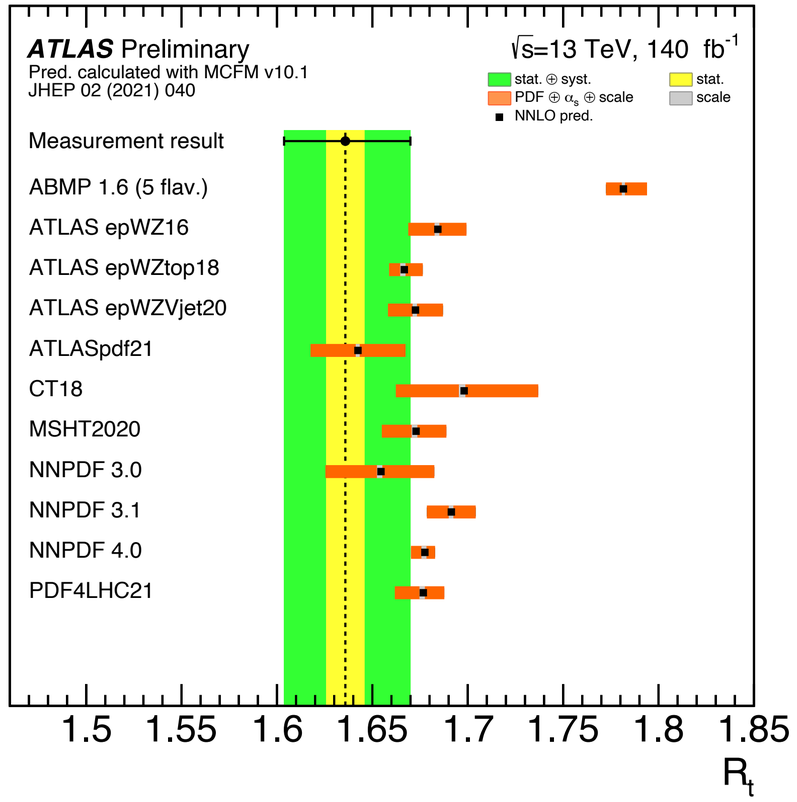
Wtq vertex in production and decay
→ σ and Γ sensitive to $|V_{tq}|$

- assuming $|V_{tb}| \gg |V_{td(s)}| \rightarrow f_{\mathrm{LV}} \cdot |V_{tb}| = 1.016 \pm 0.031$
- additionally $|V_{tb}| \in [0,1] \rightarrow |V_{tb}| > 0.95$ at 95% C.L.



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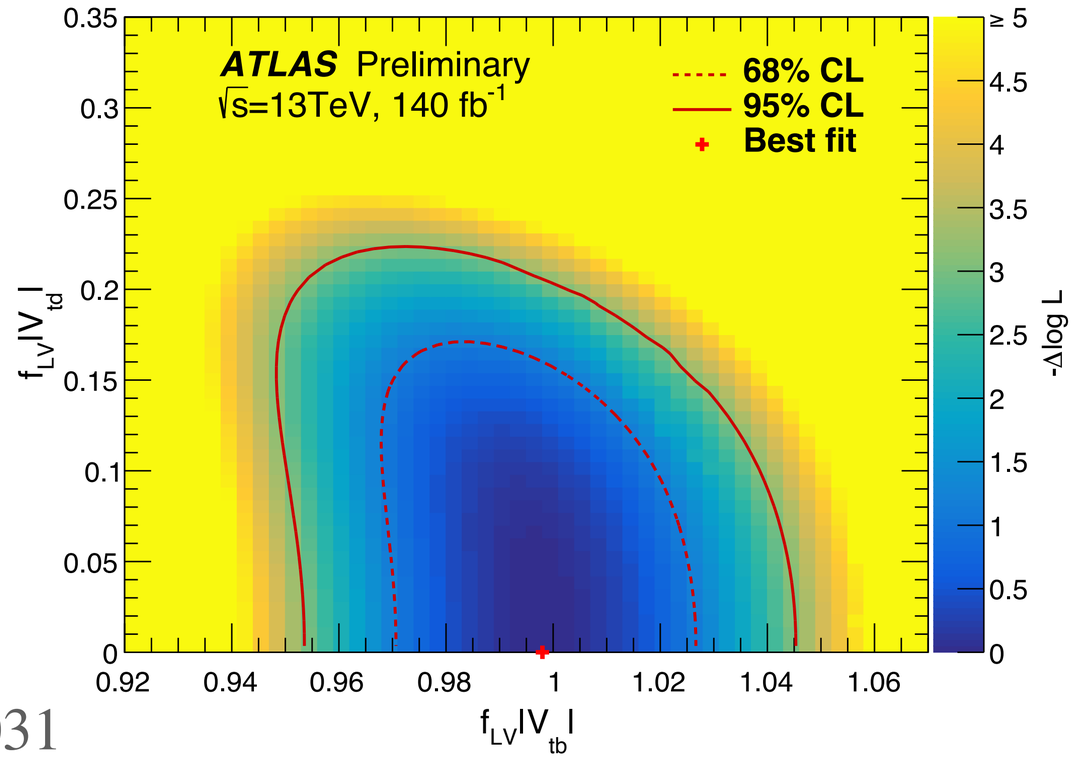
- 2D contours, relaxing constraints, three scenarios



$|V_{ts}| = 0$

t-channel 13 TeV cross section

single top

ATLAS-CONF-2023-026

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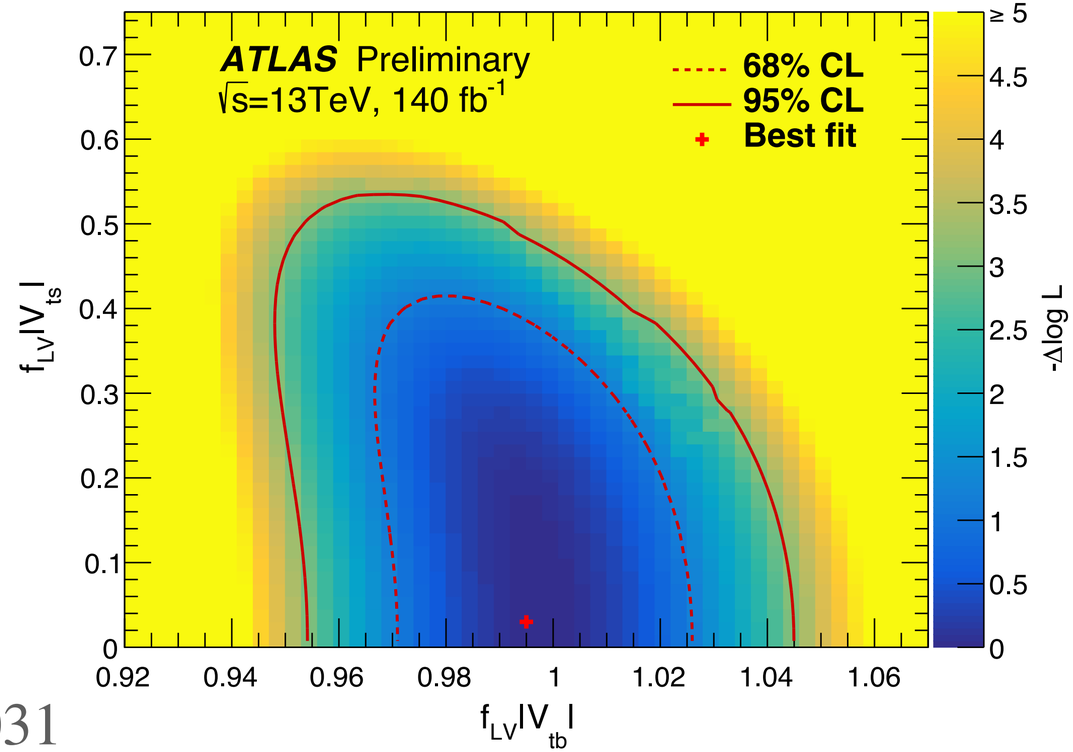

$|V_{td}| = 0$

t-channel 13 TeV cross section

single top

ATLAS-CONF-2023-026

Typical signal region: 1e/μ, 1 b-jet, 1 forward jet

- NN to separate signal from background

Preliminary result, full Run-2 dataset

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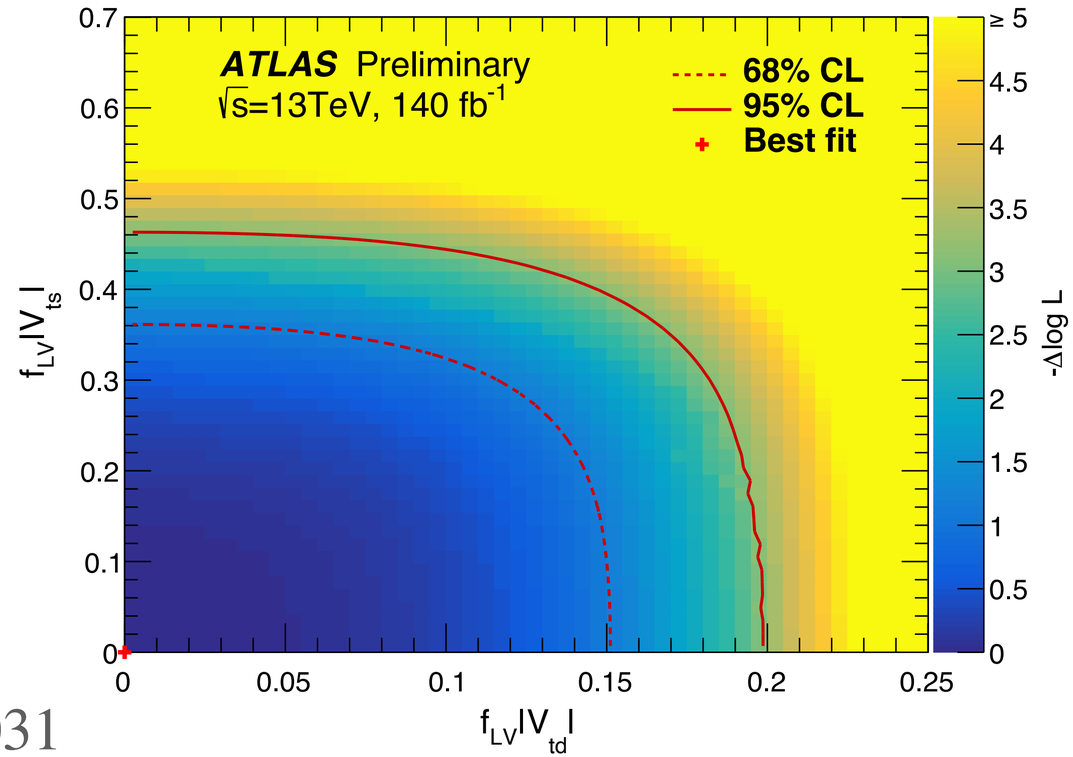


$|V_{tb}| = 1$

t-channel 5 TeV cross section

single top

ATLAS-CONF-2023-033

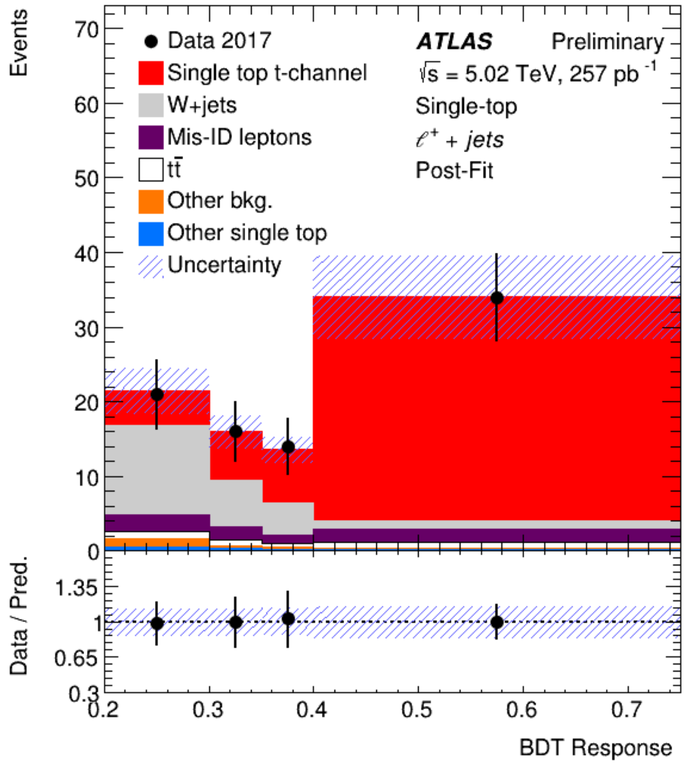
Preliminary result, 5 TeV pp collisions 257 pb^{-1}

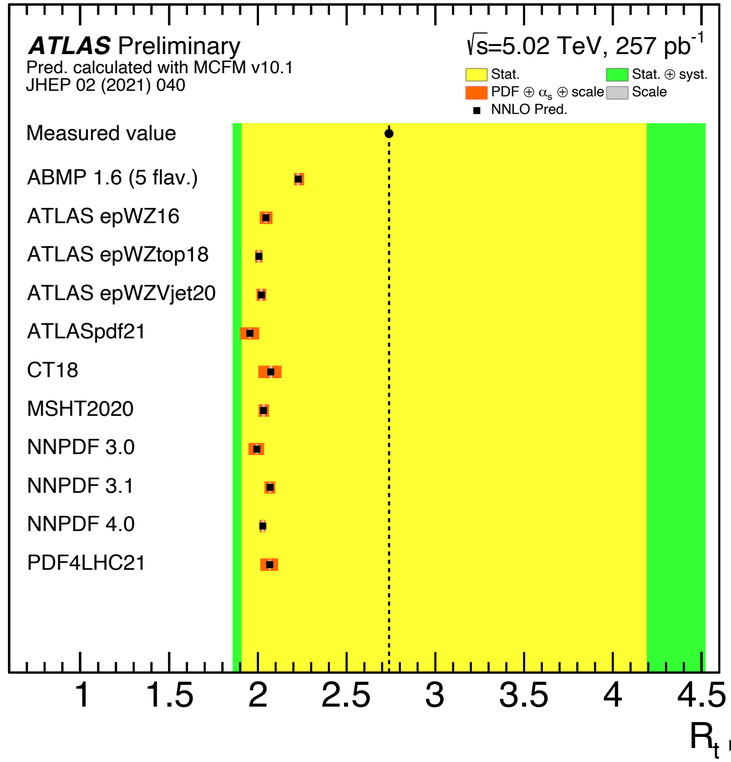
- similar analysis strategy as for 13 TeV collisions
- significance: 6.1σ (6.4σ expected)

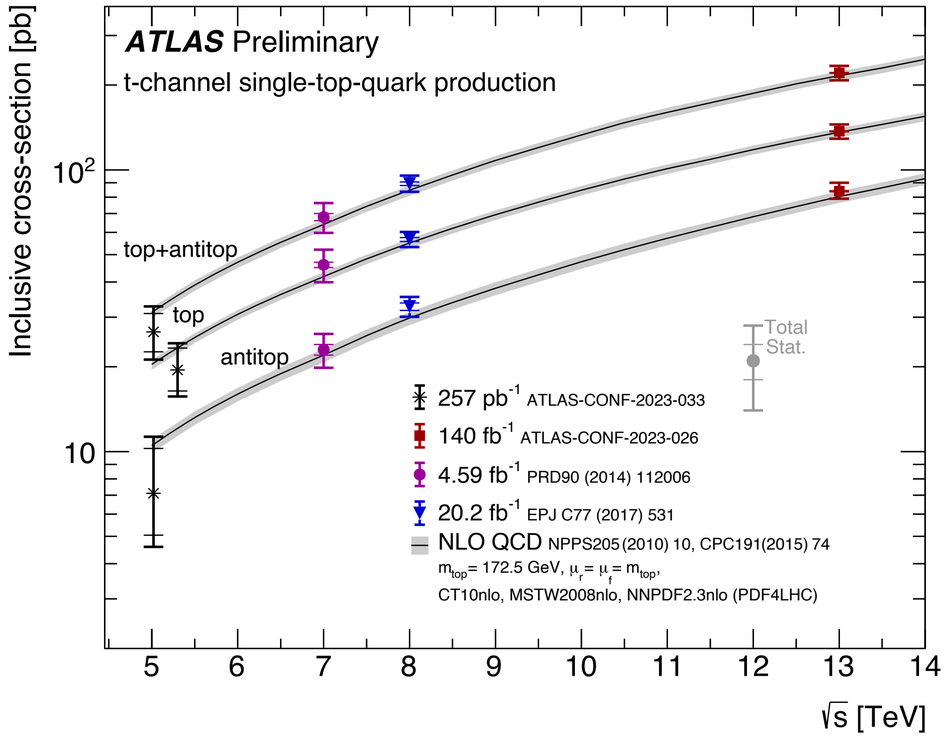
$$\sigma_t = 19.5^{+3.8}_{-3.1}(\text{stat.})^{+2.9}_{-2.2}(\text{syst.})\ \text{pb}$$
$$\sigma_{\bar{t}} = 7.1^{+3.2}_{-2.1}(\text{stat.})^{+2.8}_{-1.5}(\text{syst.})\ \text{pb}$$
$$\sigma_{t+\bar{t}} = 26.6^{+4.3}_{-4.0}(\text{stat.})^{+4.4}_{-3.6}(\text{syst.})\text{pb}$$
$$R_t = 2.74^{+1.44}_{-0.83}(\text{stat.})^{+1.04}_{-0.29}(\text{syst.})$$

Measurements compatible with SM predictions

Additional probe for PDFs, at lower energies

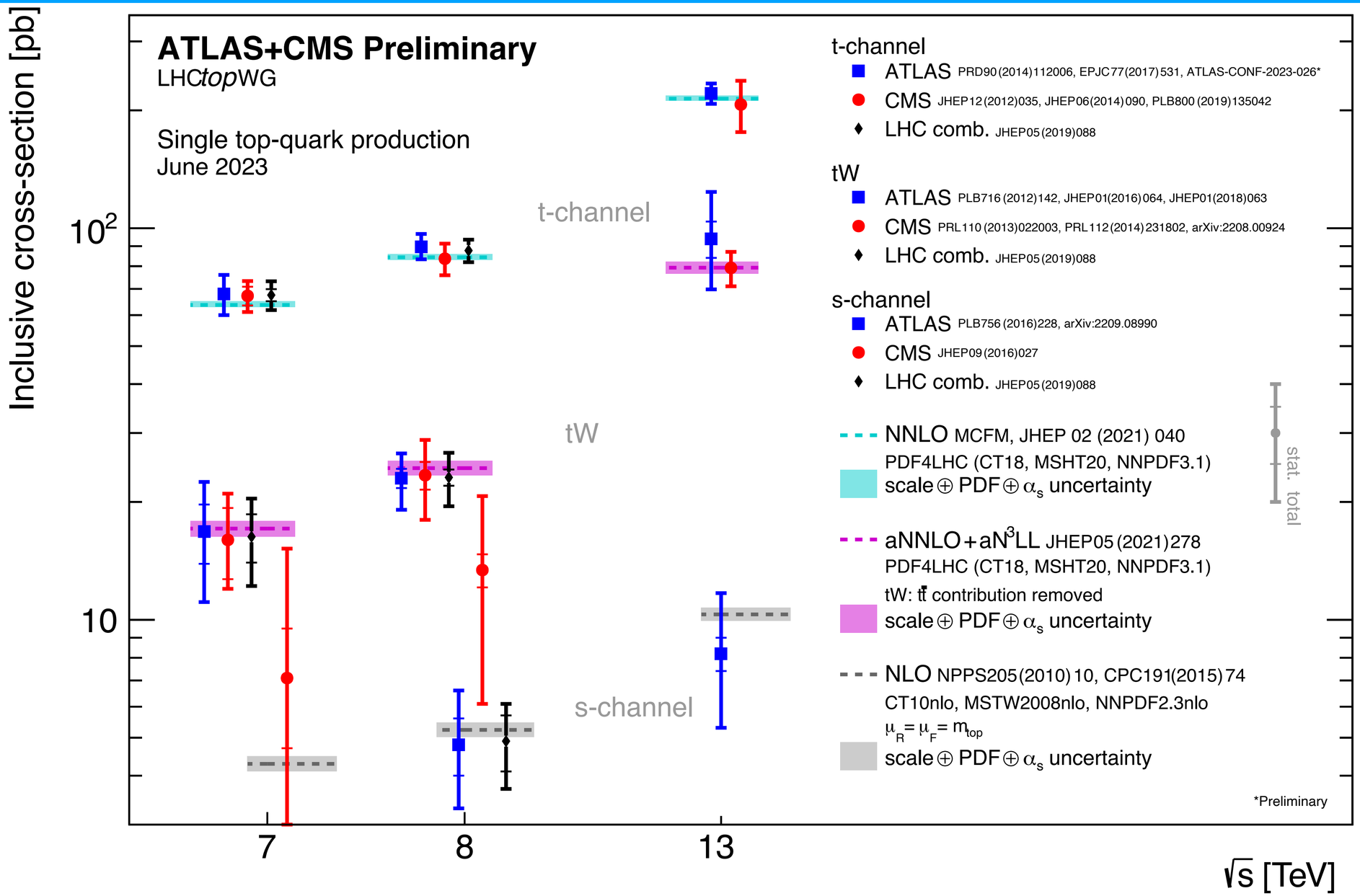






Single top pp cross-sections summary

single top



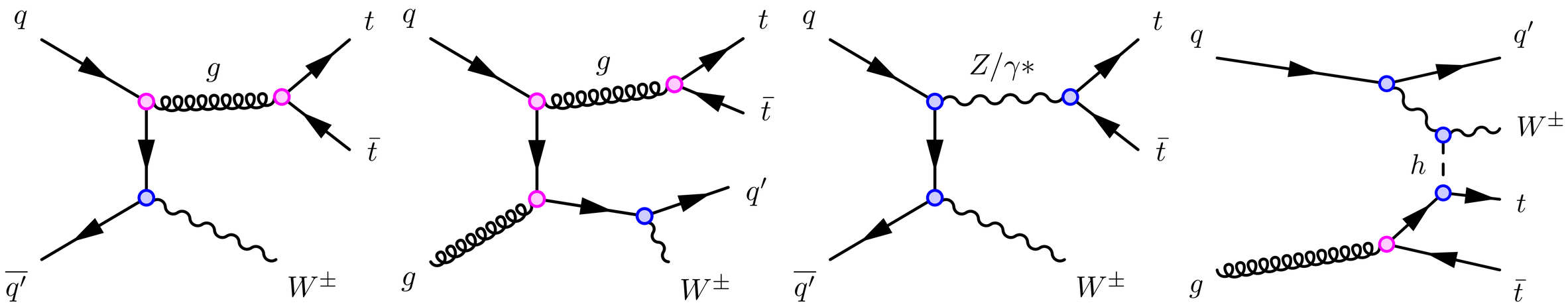
$t\bar{t}W$ inclusive and differential

ATLAS EXPERIMENT

top+X

ATLAS-CONF-2023-019

Rare process & important background for 4t, $t\bar{t}H$



Analysis strategy

- 2ℓSS and 3ℓ regions, jets and b-tags
- $t\bar{t}Z$ and WZ from control regions
- misidentified leptons from sidebands

$t\bar{t}W$ inclusive and differential

ATLAS-CONF-2023-019

$\sigma_{t\bar{t}W} = 890 \pm 80$ fb

- agrees with ref. prediction
  722^{+70}_{-78} (scale) $\pm$ 7 (PDF) fb
  (JHEP 11 (2021) 029)

$t\bar{t}W$ inclusive and differential

top+X

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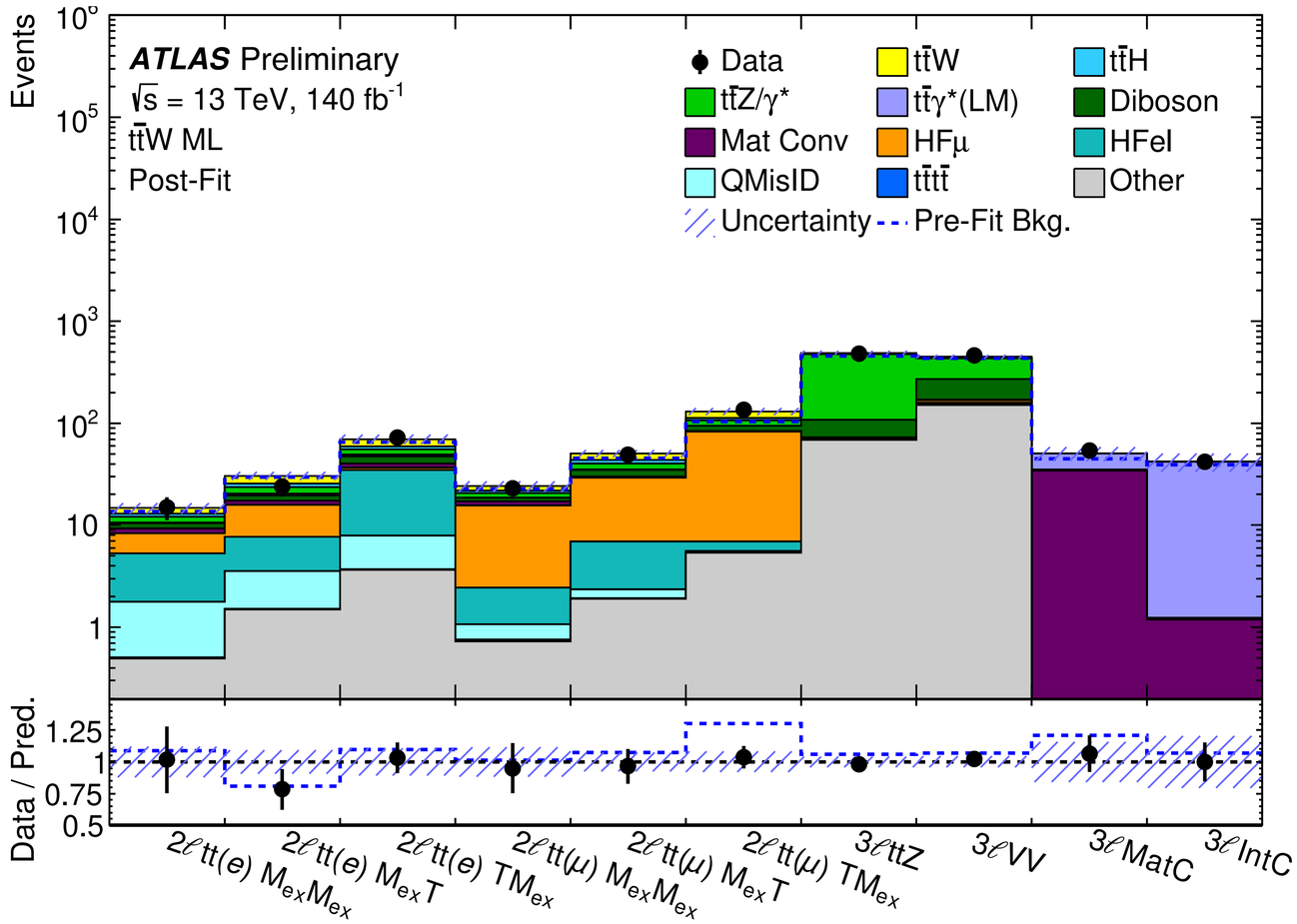

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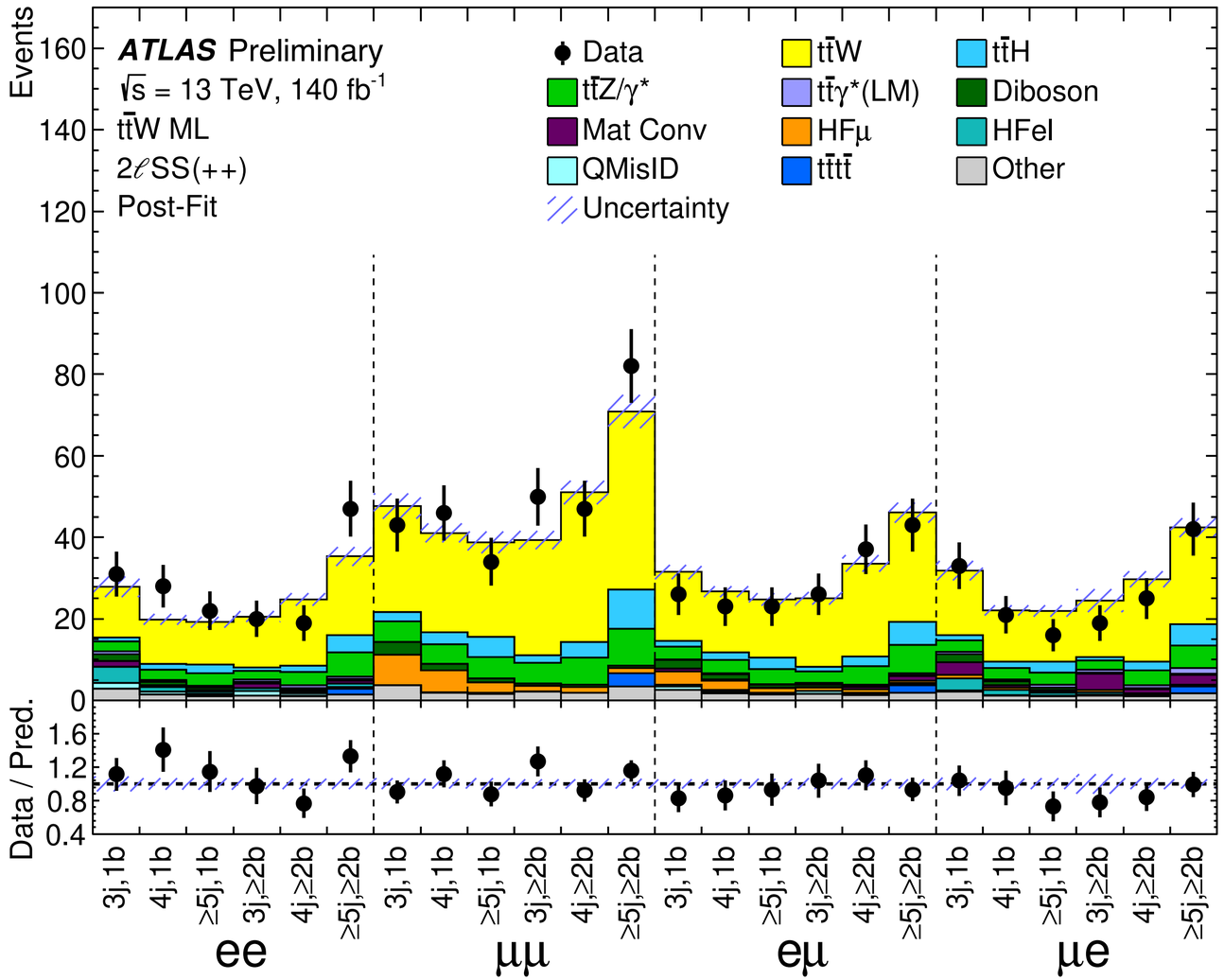

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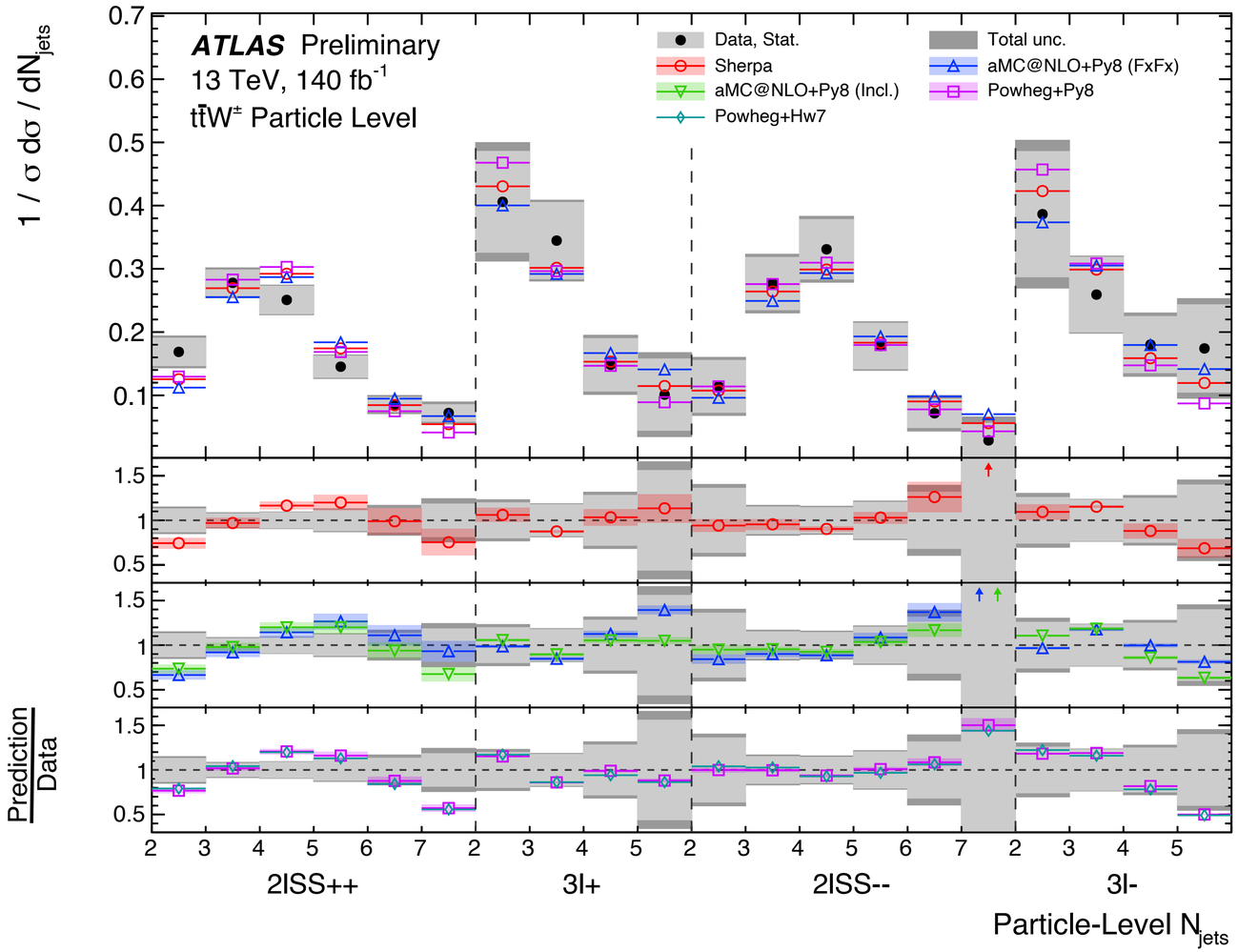
Unfolded to particle-level vs N_{jet}

Variable
N_{jets}
$H_{\text{T,jets}}$
$H_{\text{T,lep}}$
$\Delta R_{\text{lb, lead}}$
$\lvert\Delta\phi_{\text{ll, SS}}\rvert$
$\lvert\Delta\eta_{\text{ll, SS}}\rvert$
$M_{\text{jj, lead}}$

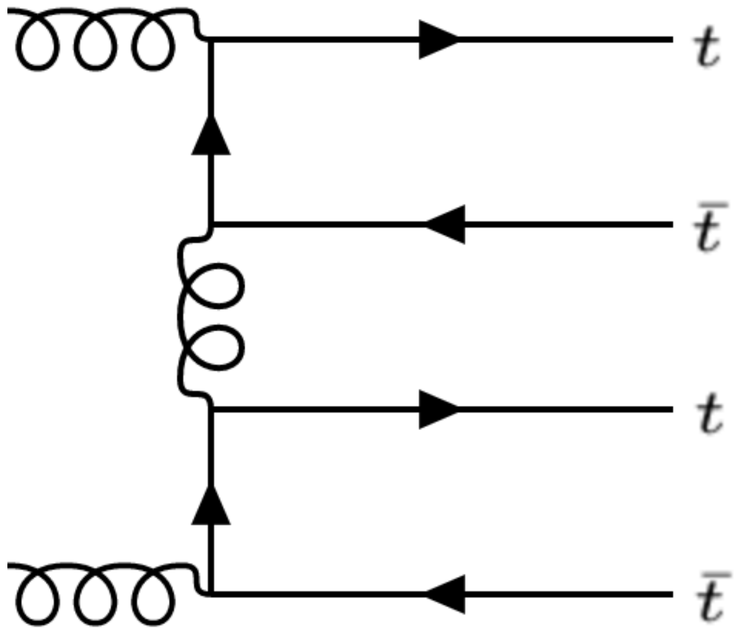
- agrees with simulations

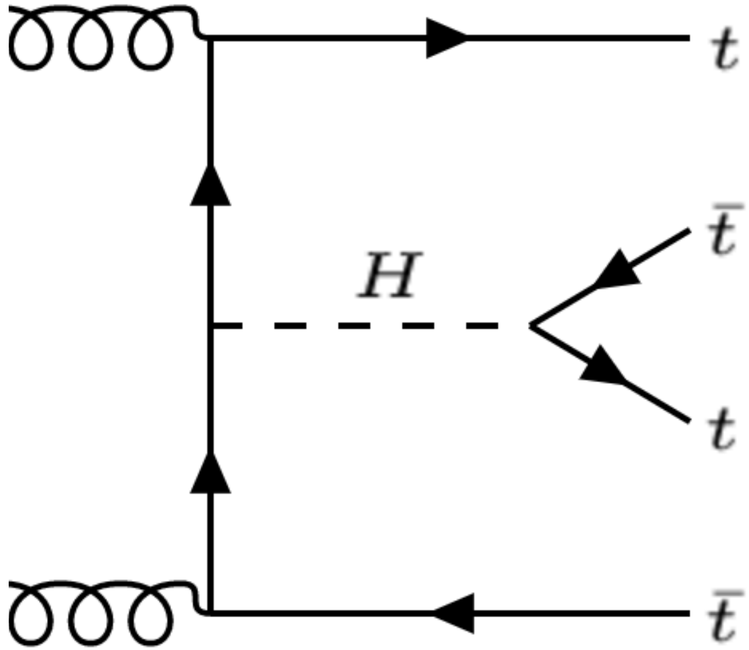


Four top-quark production

Very rare process sensitive to Higgs boson properties and BSM

- enhanced in BSM scenarios: gluino pairs, heavy bosons in 2HDM, 4-fermion interactions
- sensitive to top Yukawa coupling strengths, charge and CP properties





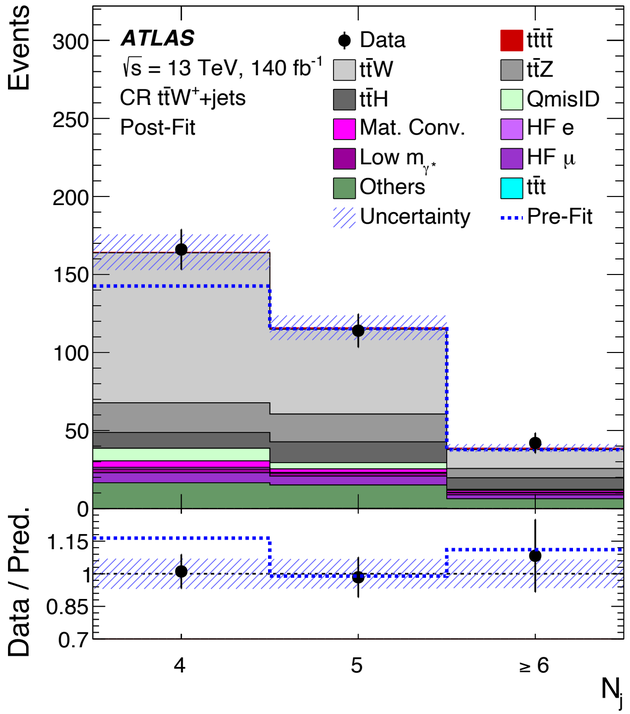
Four top-quark production

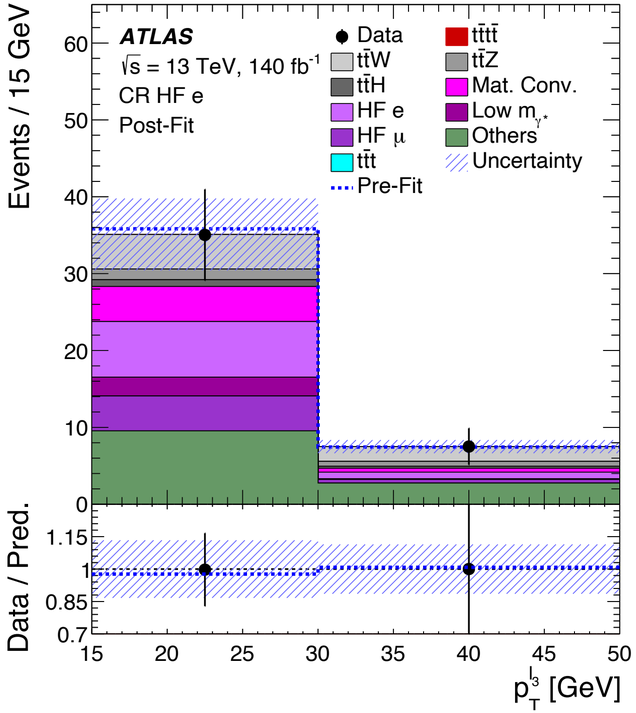
top+X

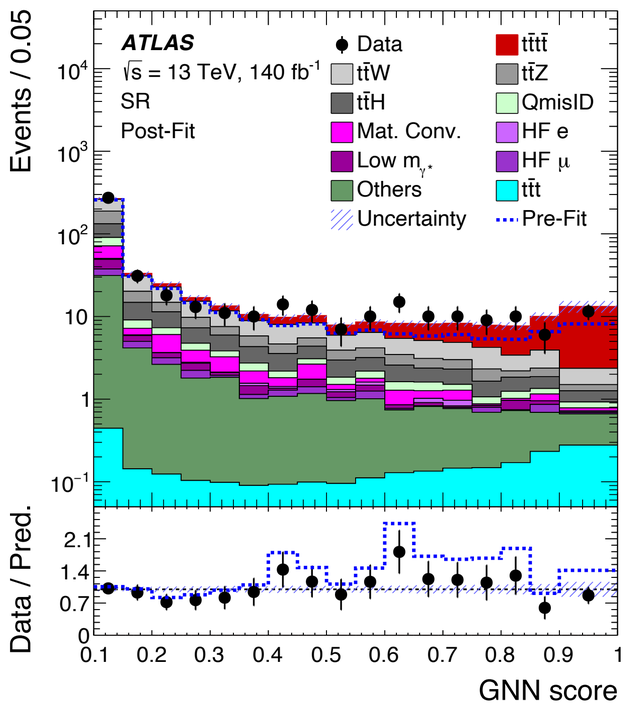
EPJC 83 (2023) 496

Observation combining several channels

- 2ℓSS and 3ℓ channels
- 8 control regions – $t\bar{t}W^+$ and $t\bar{t}W^-$ are determined independently
- non-prompt leptons determined from p_T (3rd lepton)
- employ Graph Neural Network, check distributions for GNN score > 0.6
- measure: $\sigma_{t\bar{t}t\bar{t}} = 22.5^{+6.6}_{-5.5}$ pb, 6.1σ significance







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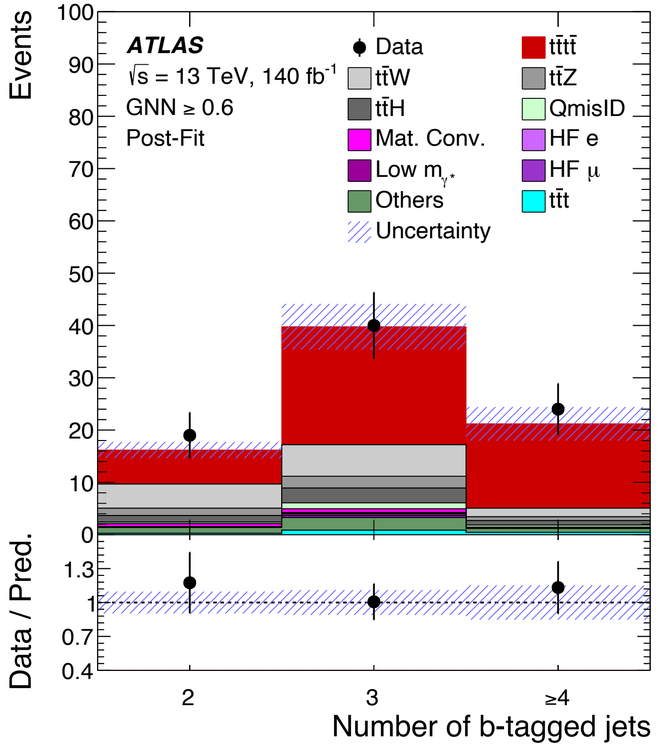

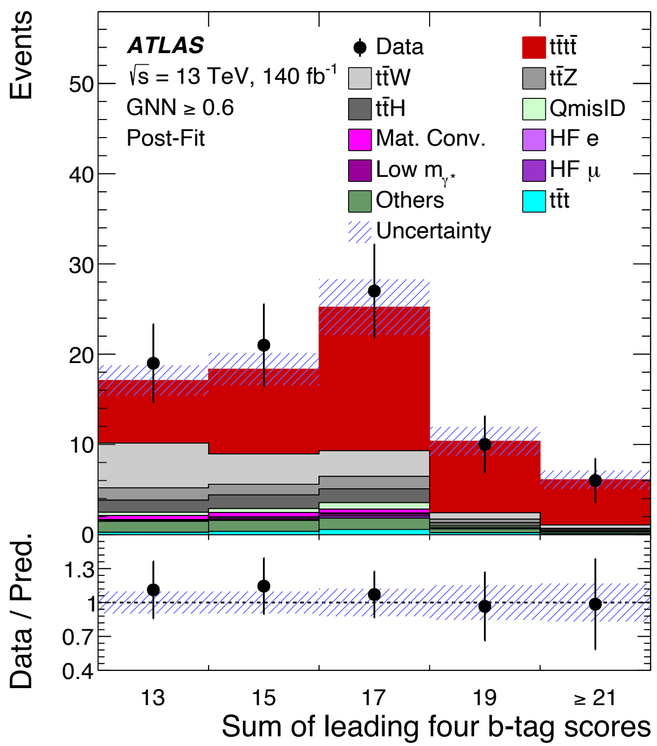

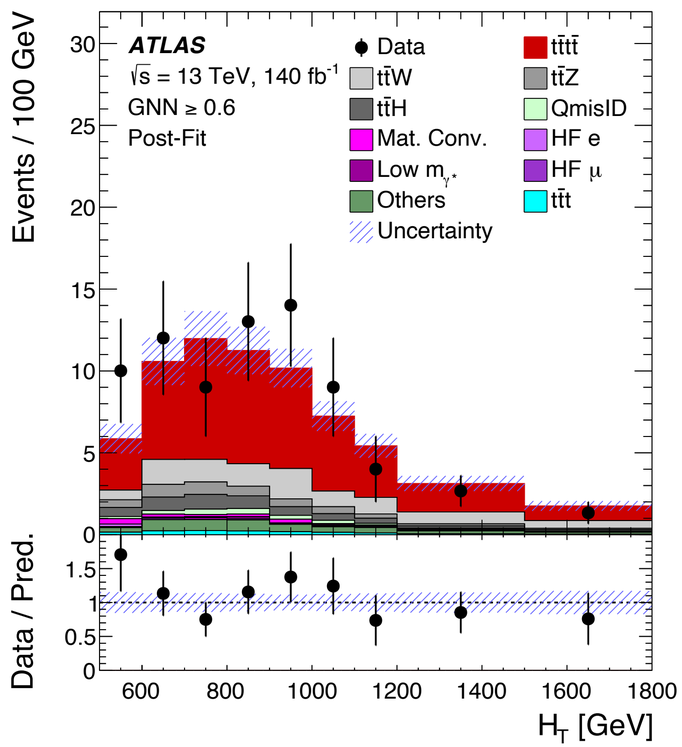

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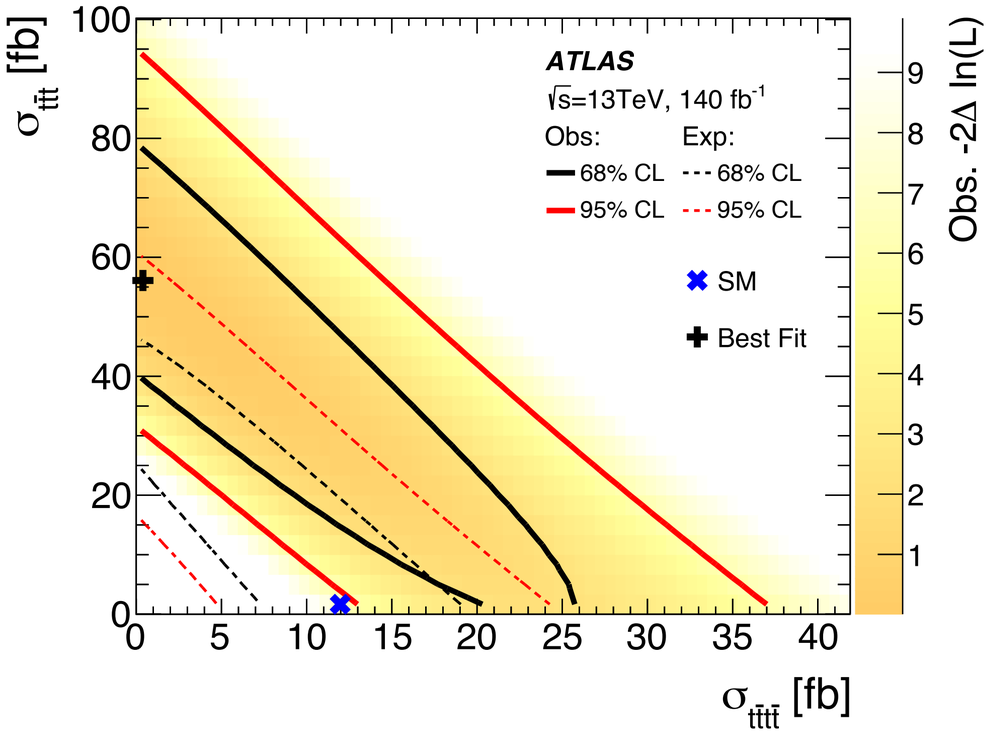

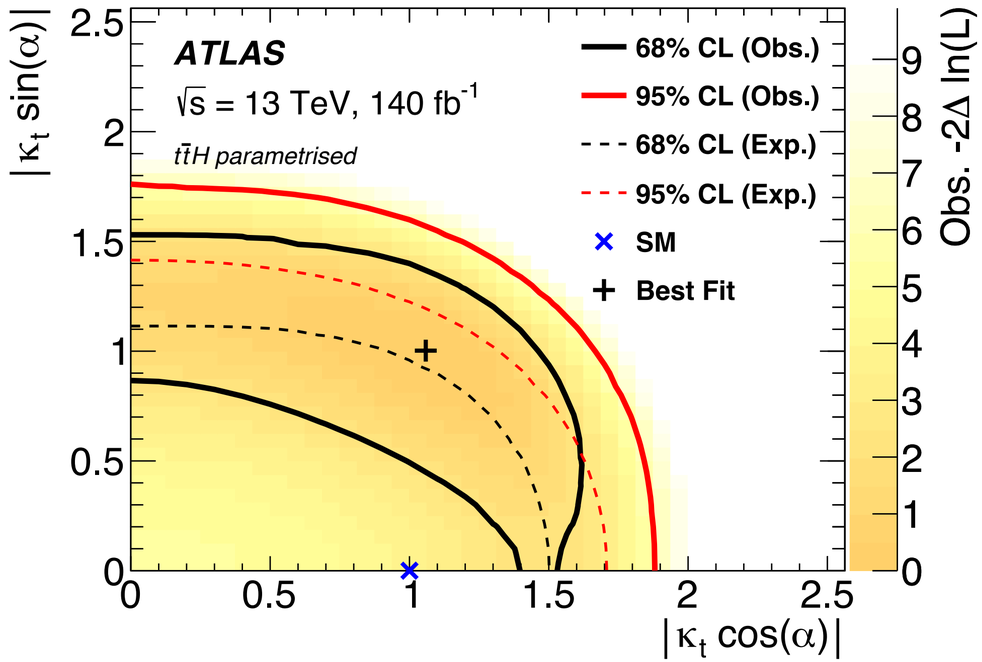

Four top-quark production

top+X

arXiv:2305.13439

Observation combining several channels

- 2ℓSS, 3ℓ and 4ℓ channels
- improvements in lepton id, b-tagging, MVA analysis: 2 BDTs with 34 variables
- expected significance 4.9σ (ATLAS 4.3σ)
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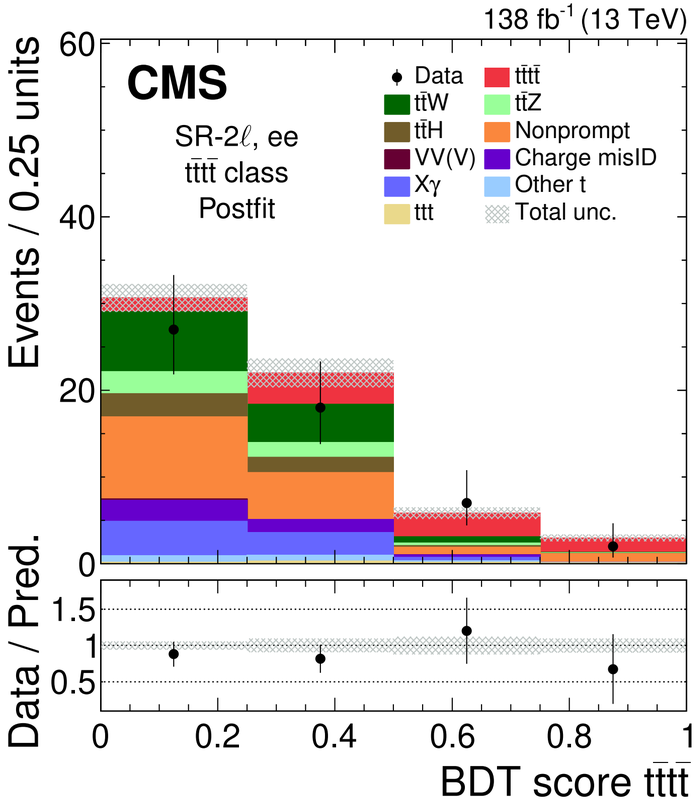

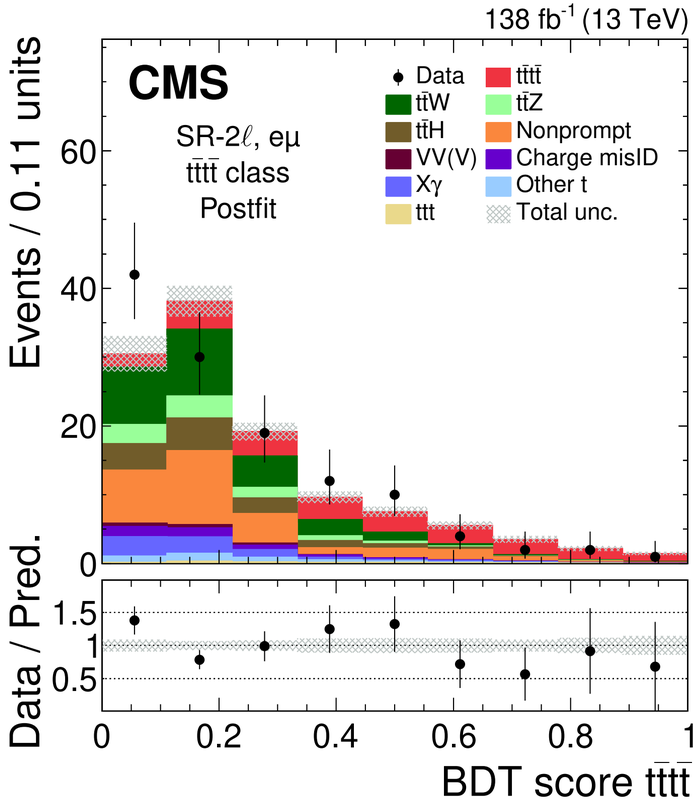

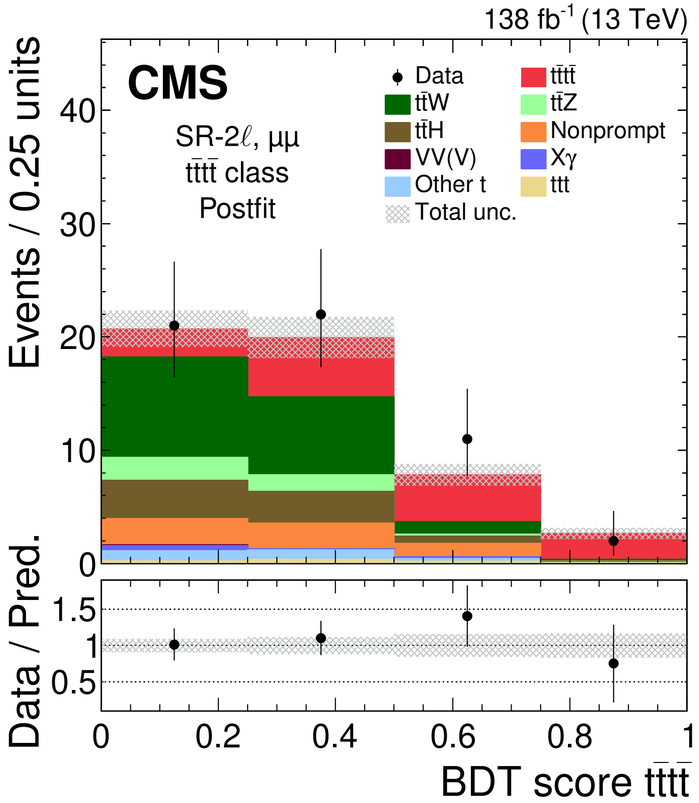

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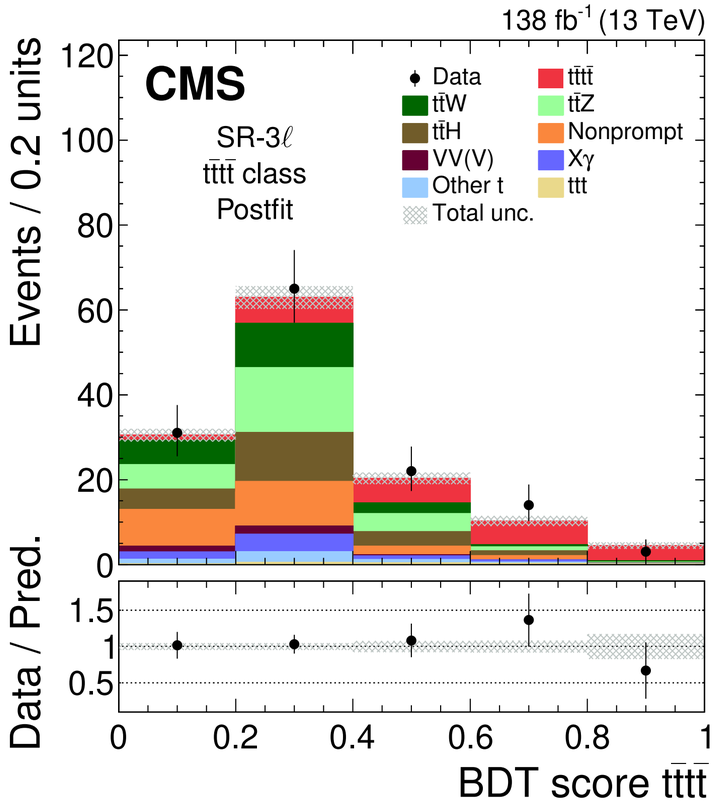

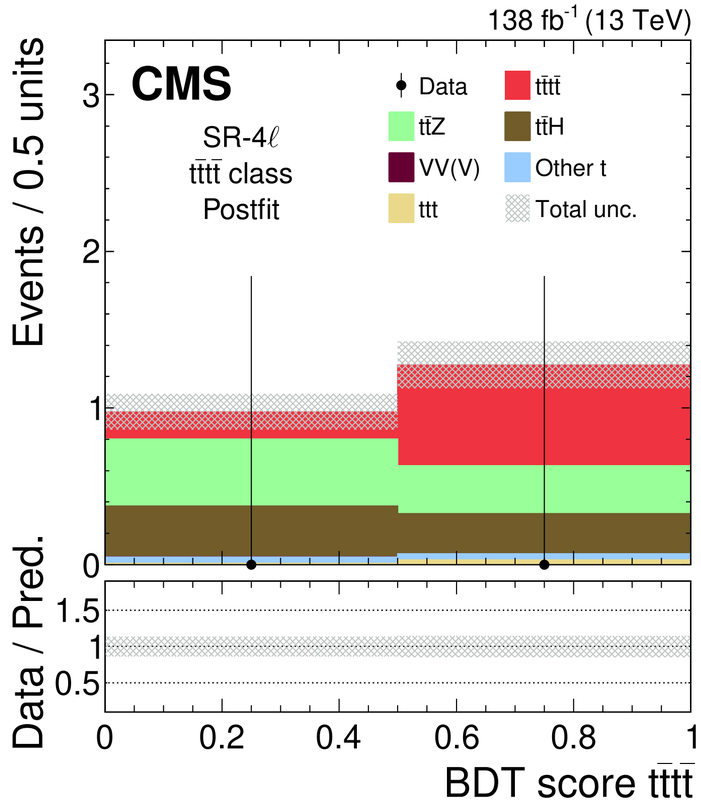

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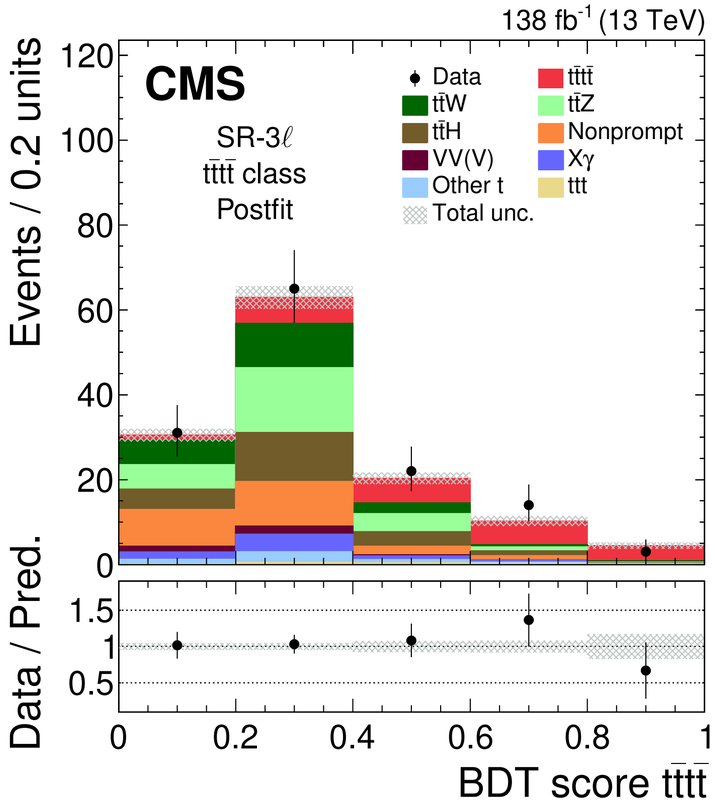
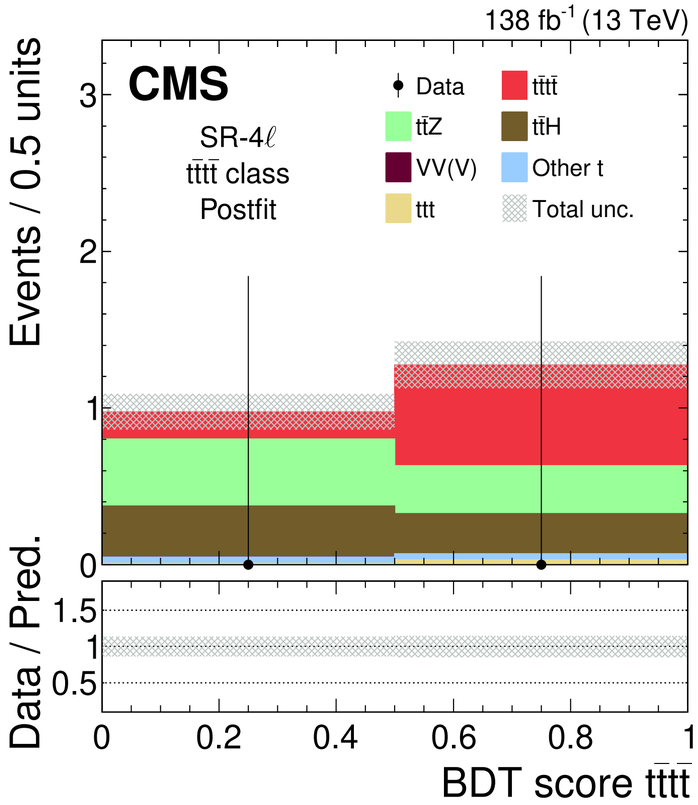
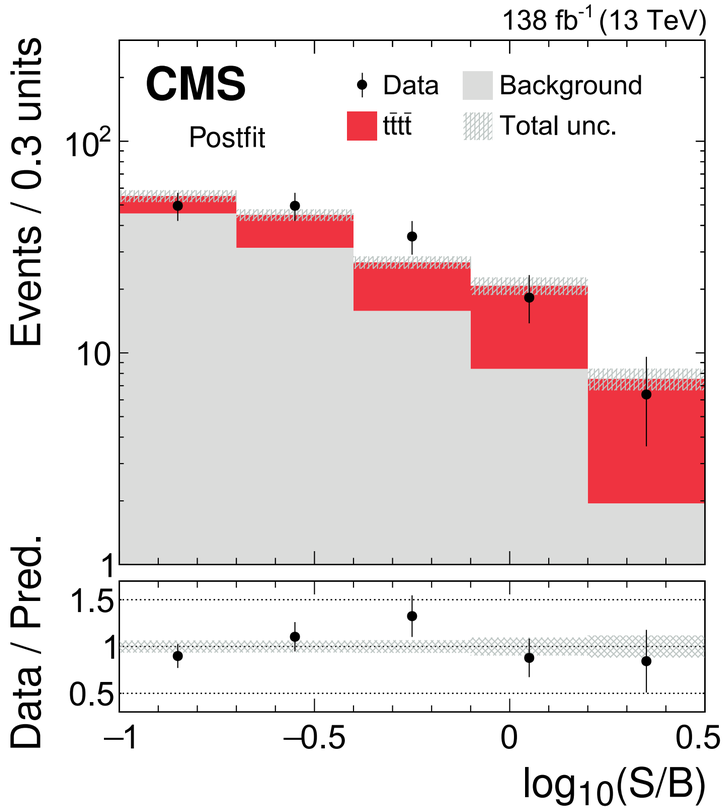






tWZ production

top+X

CMS-PAS-TOP-22-008

Rare process → test of SM

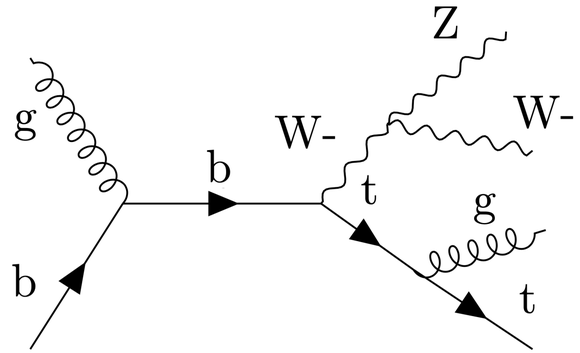
- multilepton channel

Analysis performed in 2 regions with different jet requirements

- top quark almost at rest
- top quark with large p_T

$t\bar{t}Z$ background

- large and interfering at NLO
- main systematics
- diagram removal vs. subtraction



tWZ production

top+X

CMS-PAS-TOP-22-008

Rare process → test of SM

- multilepton channel

Analysis performed in 2 regions with different jet requirements

- top quark almost at rest
- top quark with large p_T

$t\bar{t}Z$ background

- large and interfering at NLO
- main systematics
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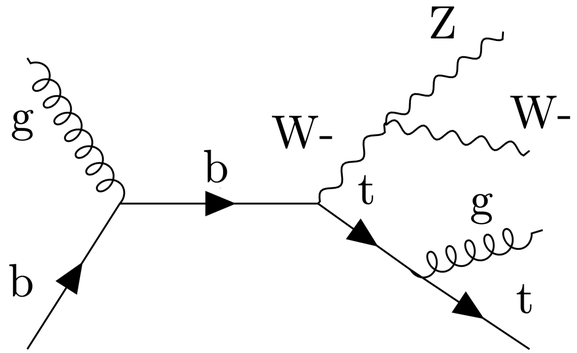

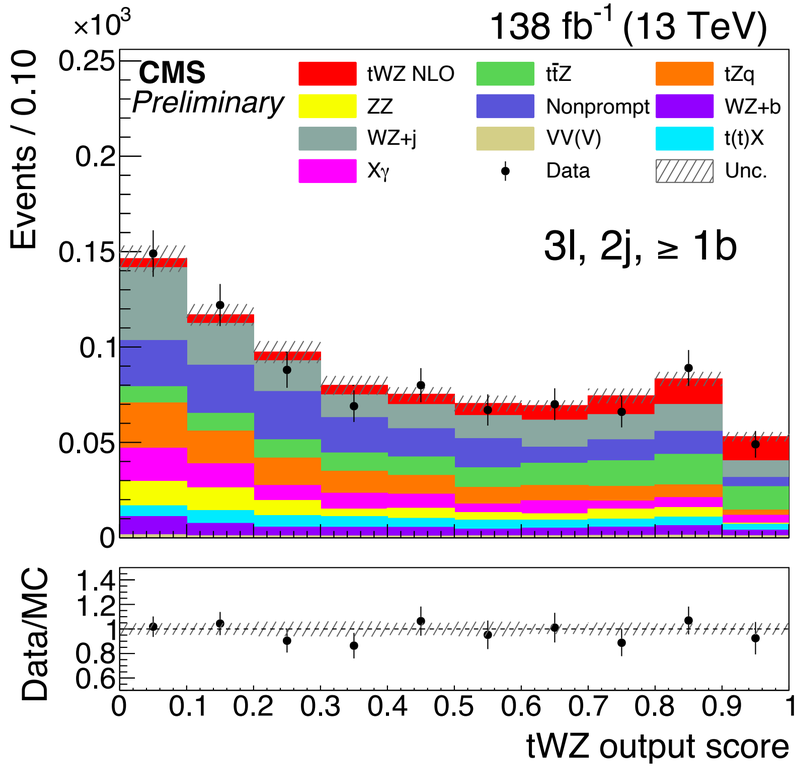

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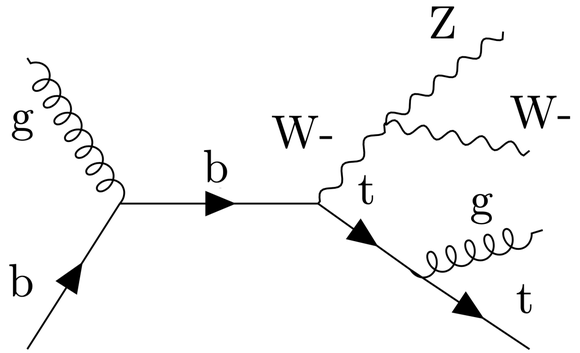

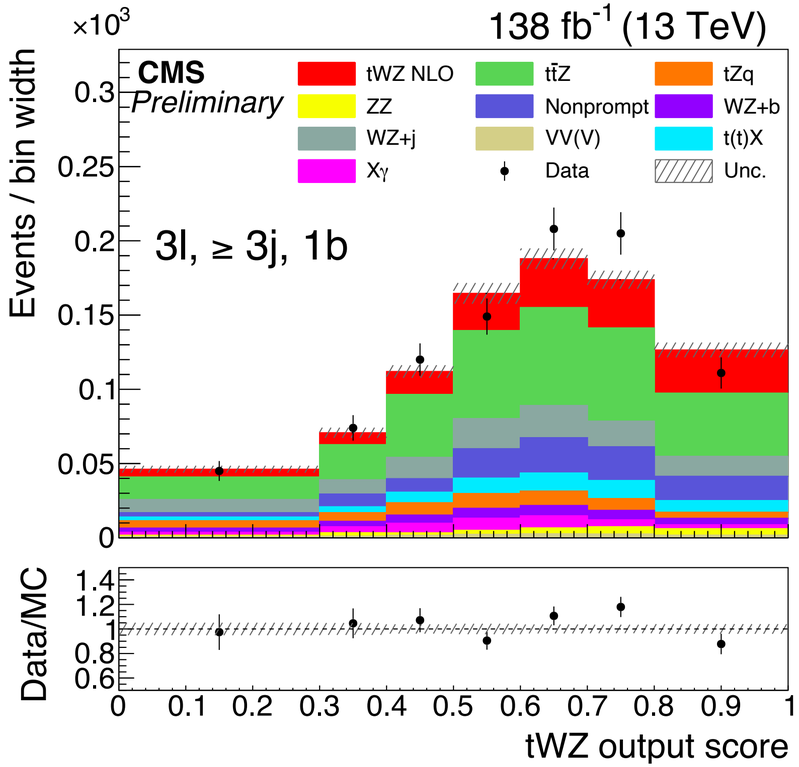

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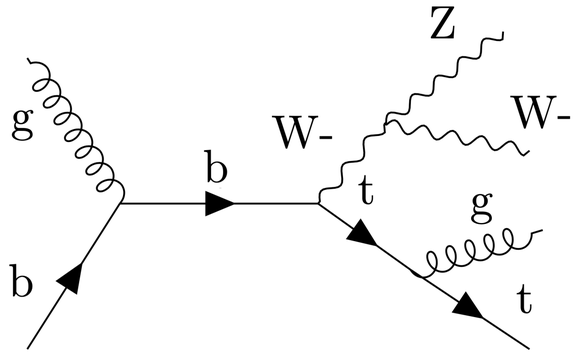

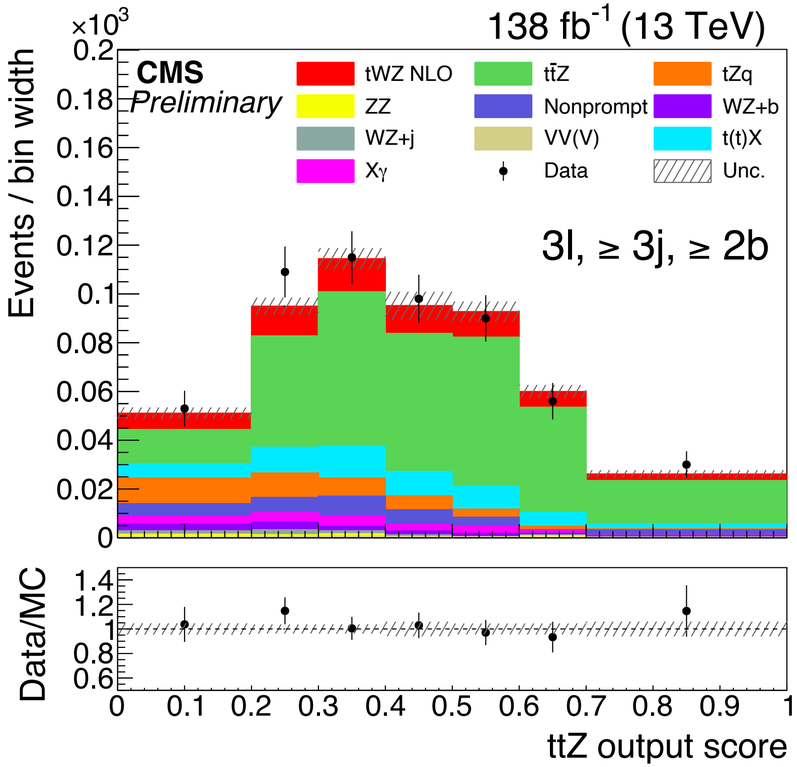

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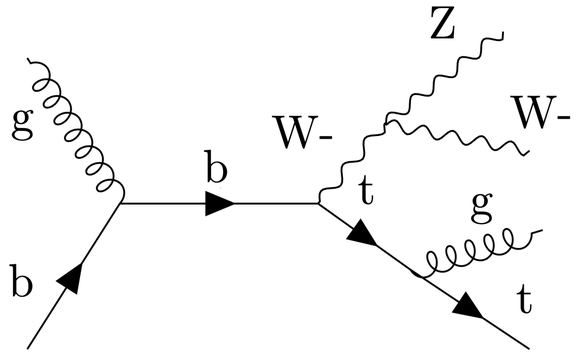
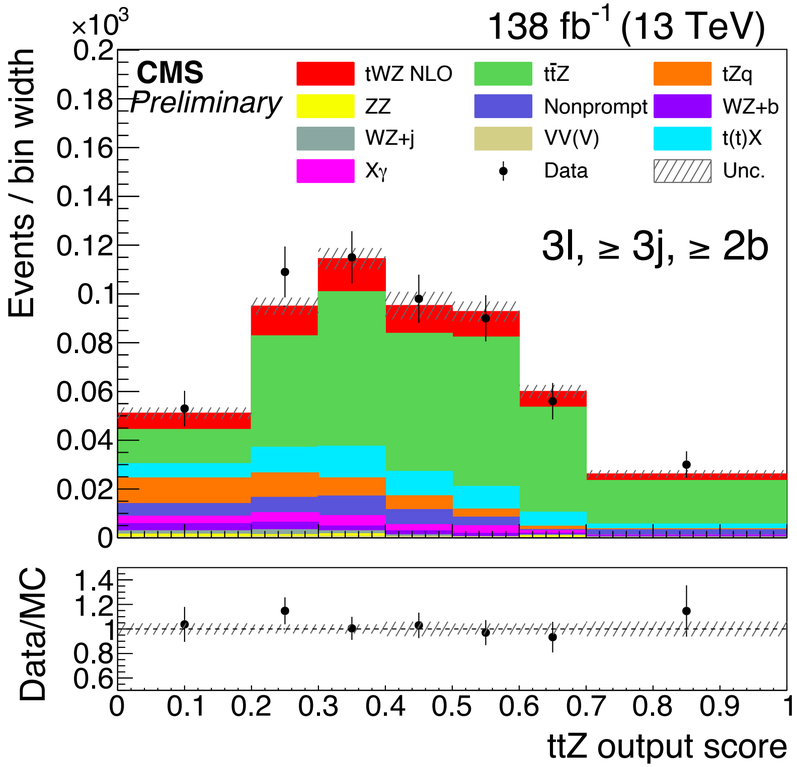
Evidence for tWZ production

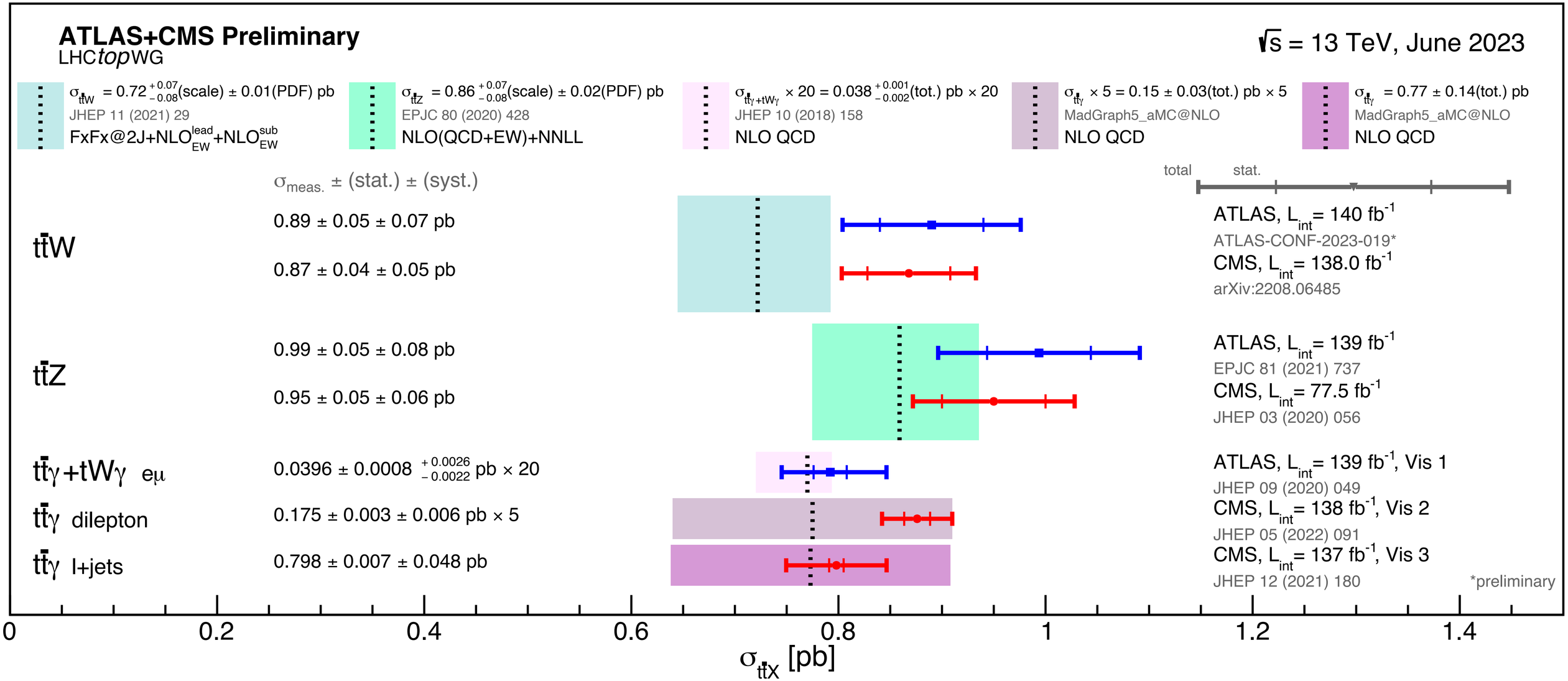
- 3.5σ measured (1.4σ expected),
- $\sigma_{tWZ} = 0.37 \pm 0.05\,(\text{stat.}) \pm 0.10\,(\text{syst.})$ pb
  $\mu = 2.7 \pm 0.8$





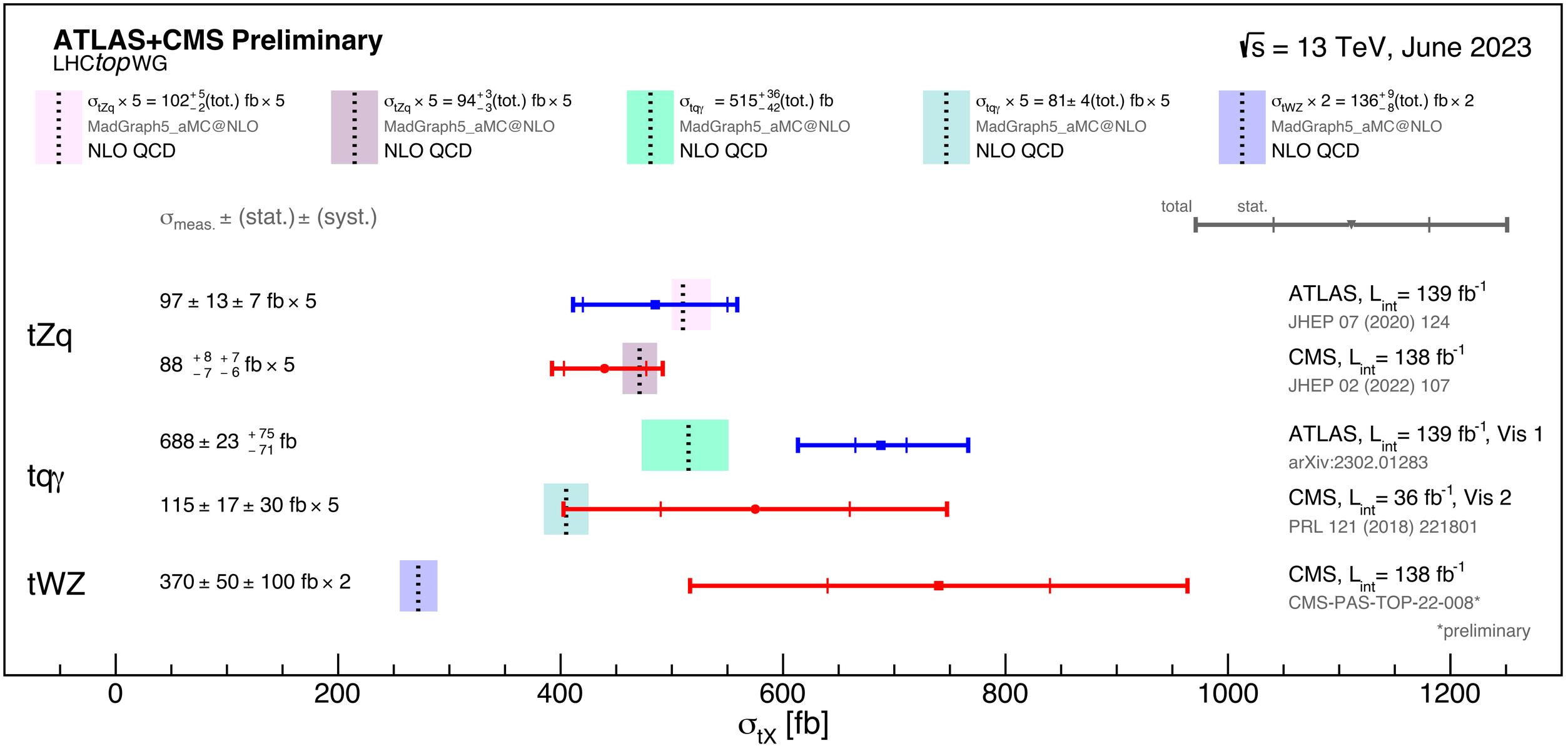
Top+X summary: $t\bar{t}$+X

top+X



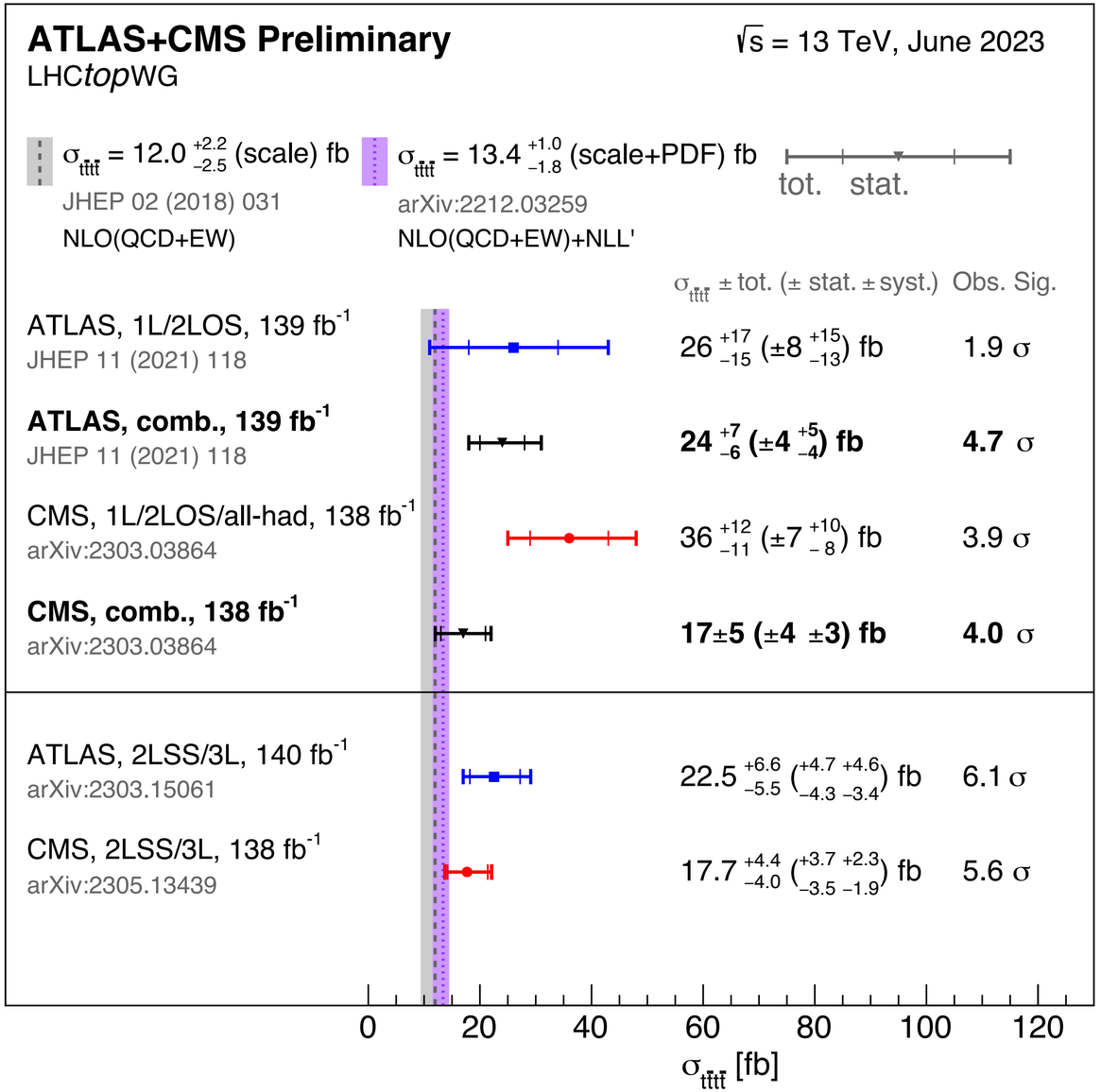
Top+X summary: t+X

top+X



Top+X summary: 4 top-quark observation

top+X



$t\bar{t}$+leptons EFT interpretation

searches

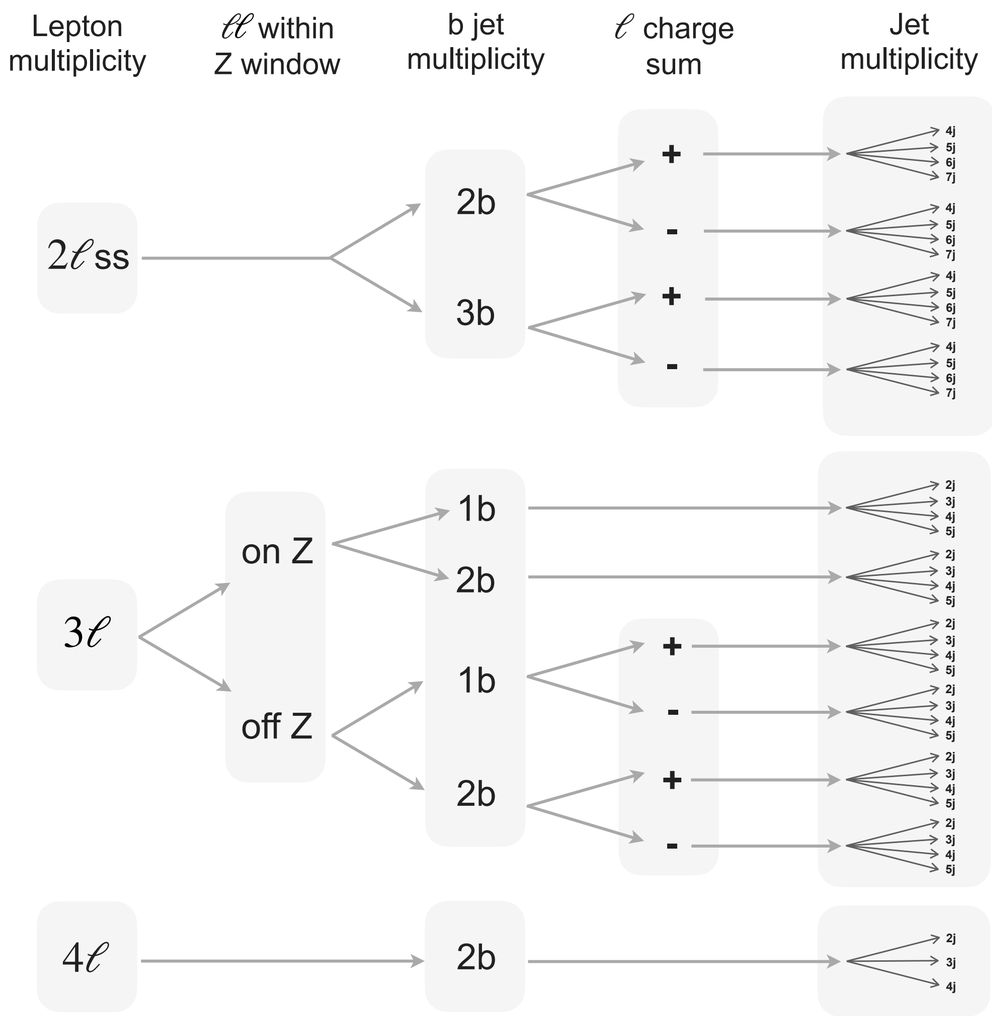
arXiv:2307.15761

Associated production of top quarks and leptons

- Event categories according to leptons and b-tags

EFT framework to search for new physics

$$\mathcal{L}_{\mathrm{EFT}} = \mathcal{L}_{\mathrm{SM}} + \sum_{d,i} \frac{c_i^d}{\Lambda^{d-4}} \mathcal{O}_i^d$$



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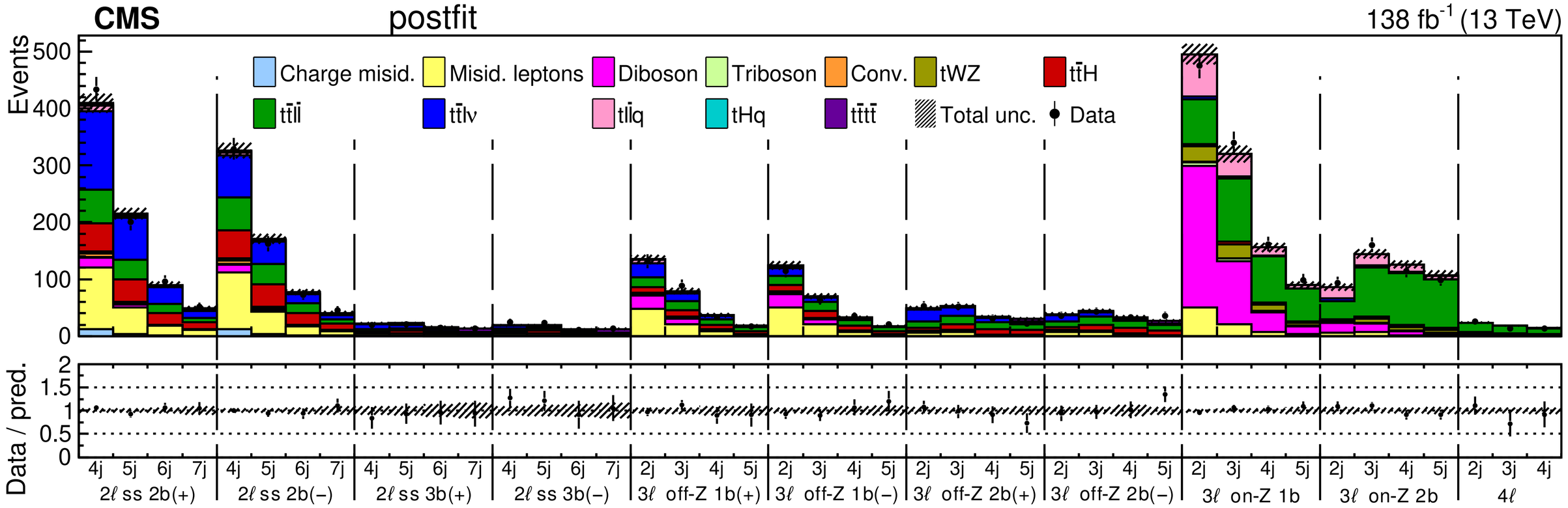
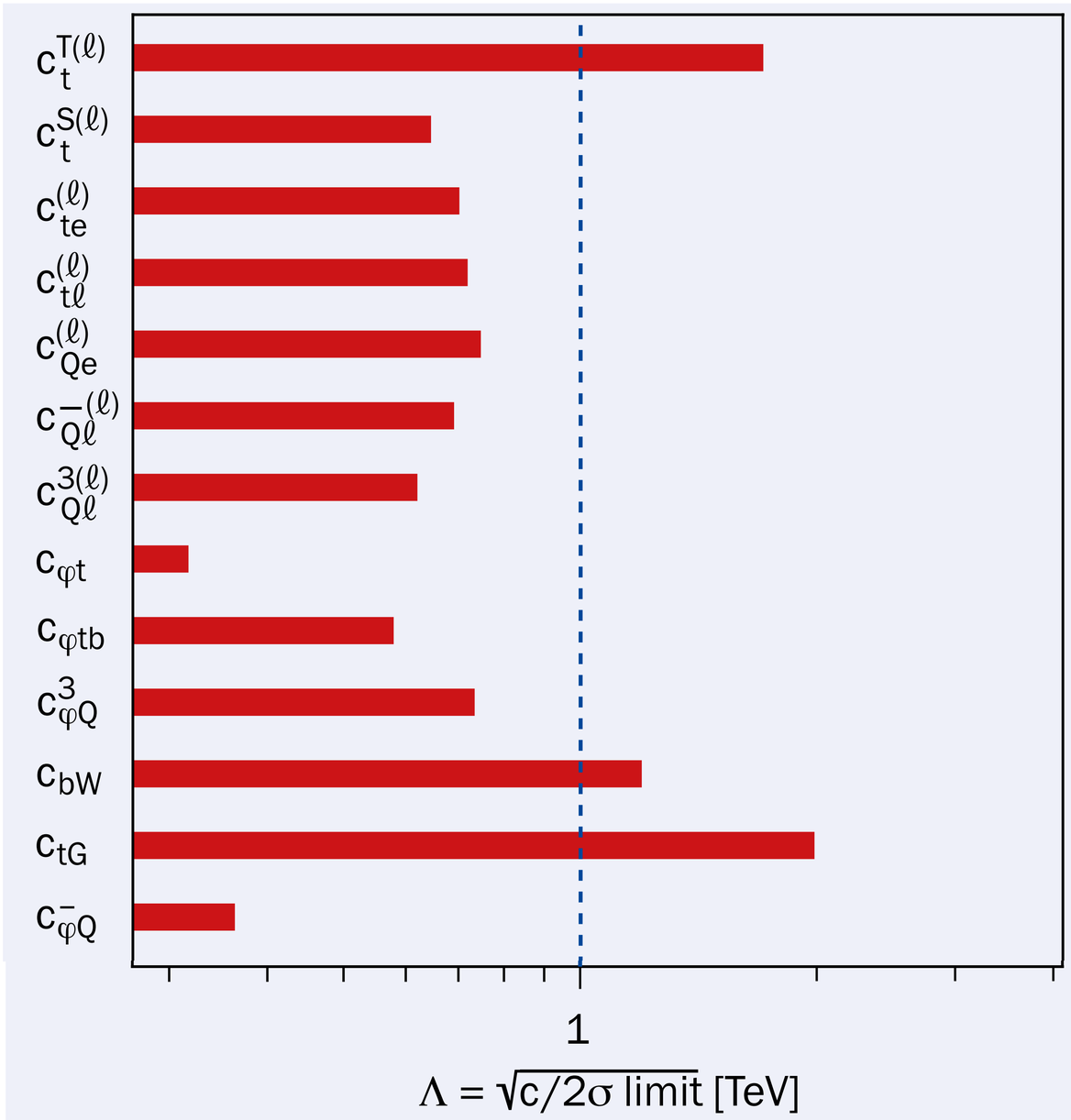
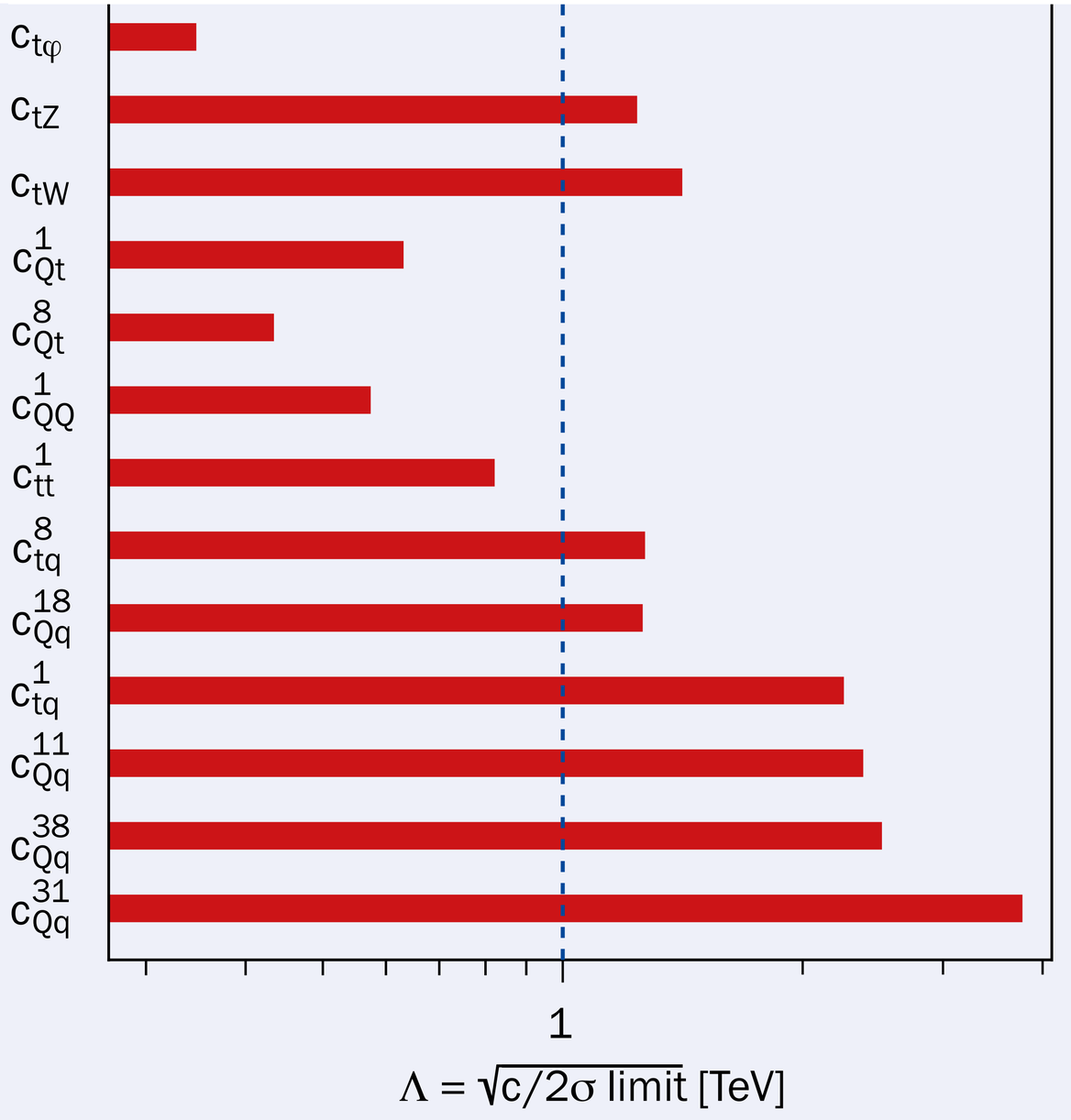


No significant deviation with respect to SM prediction found

$t\bar{t}$+leptons EFT interpretation

searches





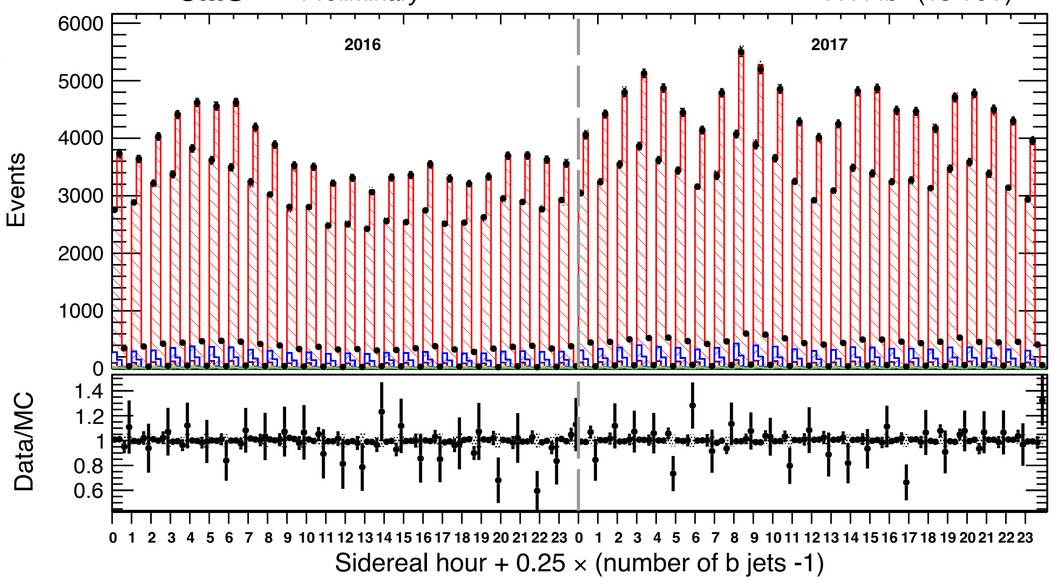
Lorentz invariance in tt̄ eμ events

searches

CMS-PAS-TOP-22-007

CMS preliminary result, 2016+2017 data

- differential tt̄ cross section vs. sidereal time
- probing of Lorentz invariance in tt̄ production, given LHC rotation in time



Using eμ channel – estimating tt̄ yield vs. sidereal time

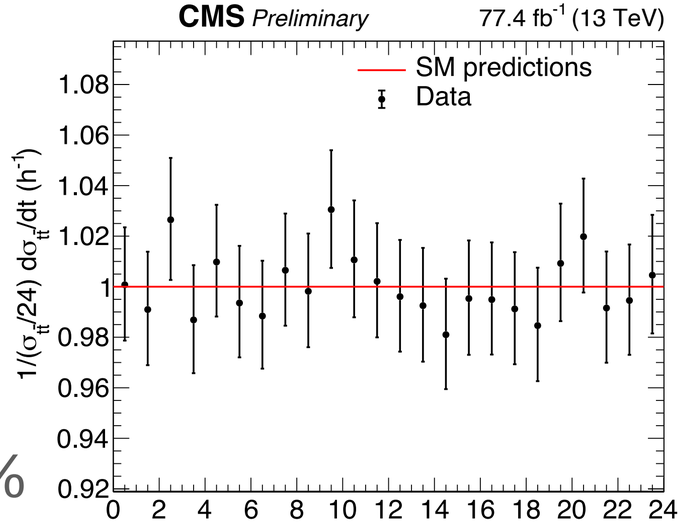
- expected variations due to changes in LHC conditions vs. time
- profile likelihood fit — no unfolding needed

No clear deviation of measurement wrt. SM

- limits set on Wilson coefficients which parametrise Lorentz-variant terms in SME Lagrangian

$$\mathscr{L}_{\mathrm{SME}} = \frac{1}{2} i\bar{\psi}(\gamma^{\nu} + c^{\mu\nu}\gamma_{\mu} + d^{\mu\nu}\gamma_5\gamma_{\mu})\overleftrightarrow{\partial_{\nu}}\psi - m_t\bar{\psi}\psi$$

- compatible with Lorentz invariance with a precision of 0.1–0.8%



Summary

Rich top-physics programme pursued at LHC

$t\bar{t}$ cross section

- uncertainty reduced to 1.8%; several energies; first Run-3 measurements
- detailed differential studies

Single top production

- extract V_{tb}; now also at 5 TeV

Top+X processes

- $t\bar{t}t\bar{t}$ observed by ATLAS and CMS
- $t\bar{t}W$; tWZ

Searches with top quarks

- Lorentz invariance violation
- EFT interpretation