CMS Top

ICNFP 2023: 12th International Conference on New Frontiers in Physics, 10-23 July

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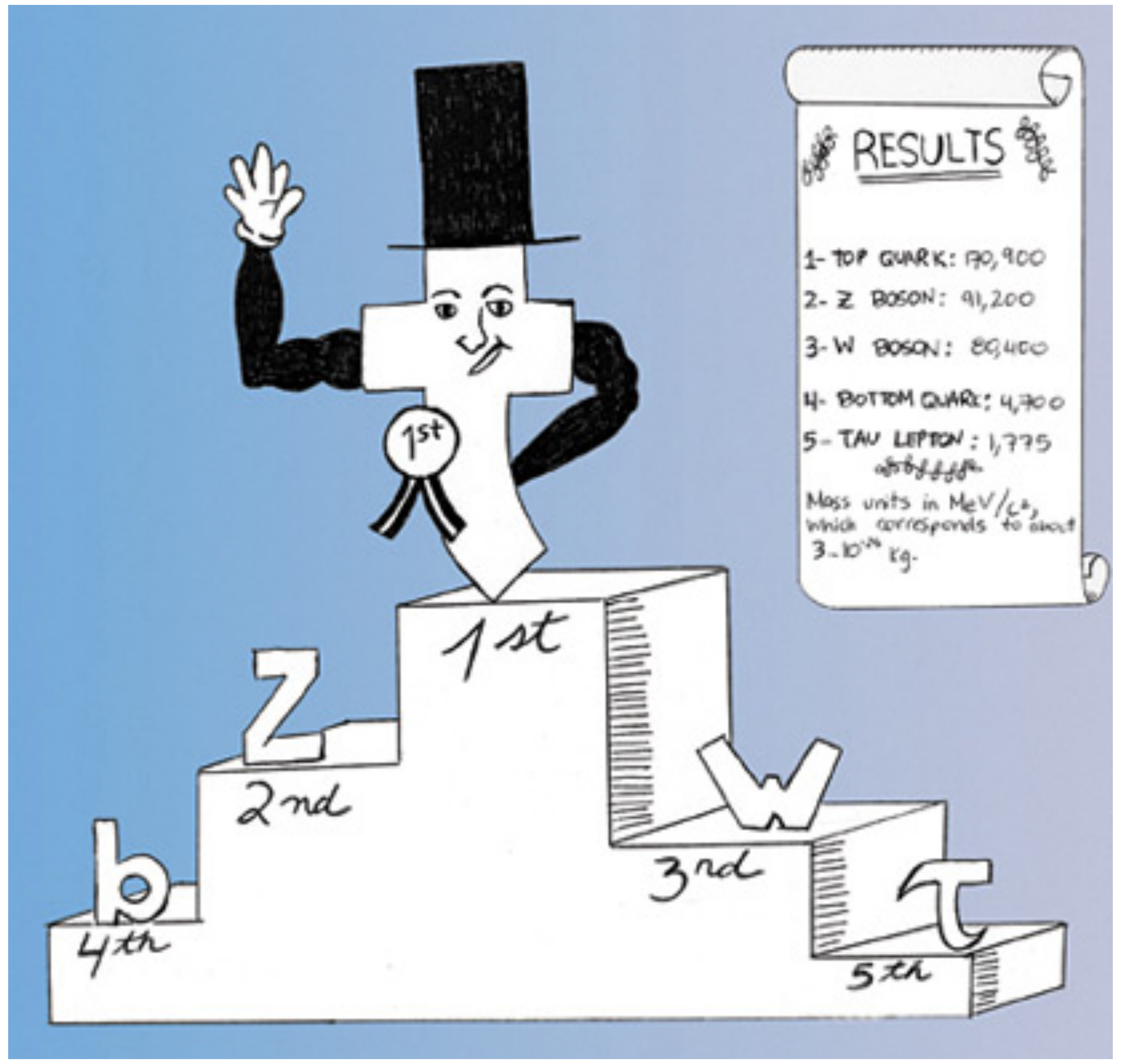
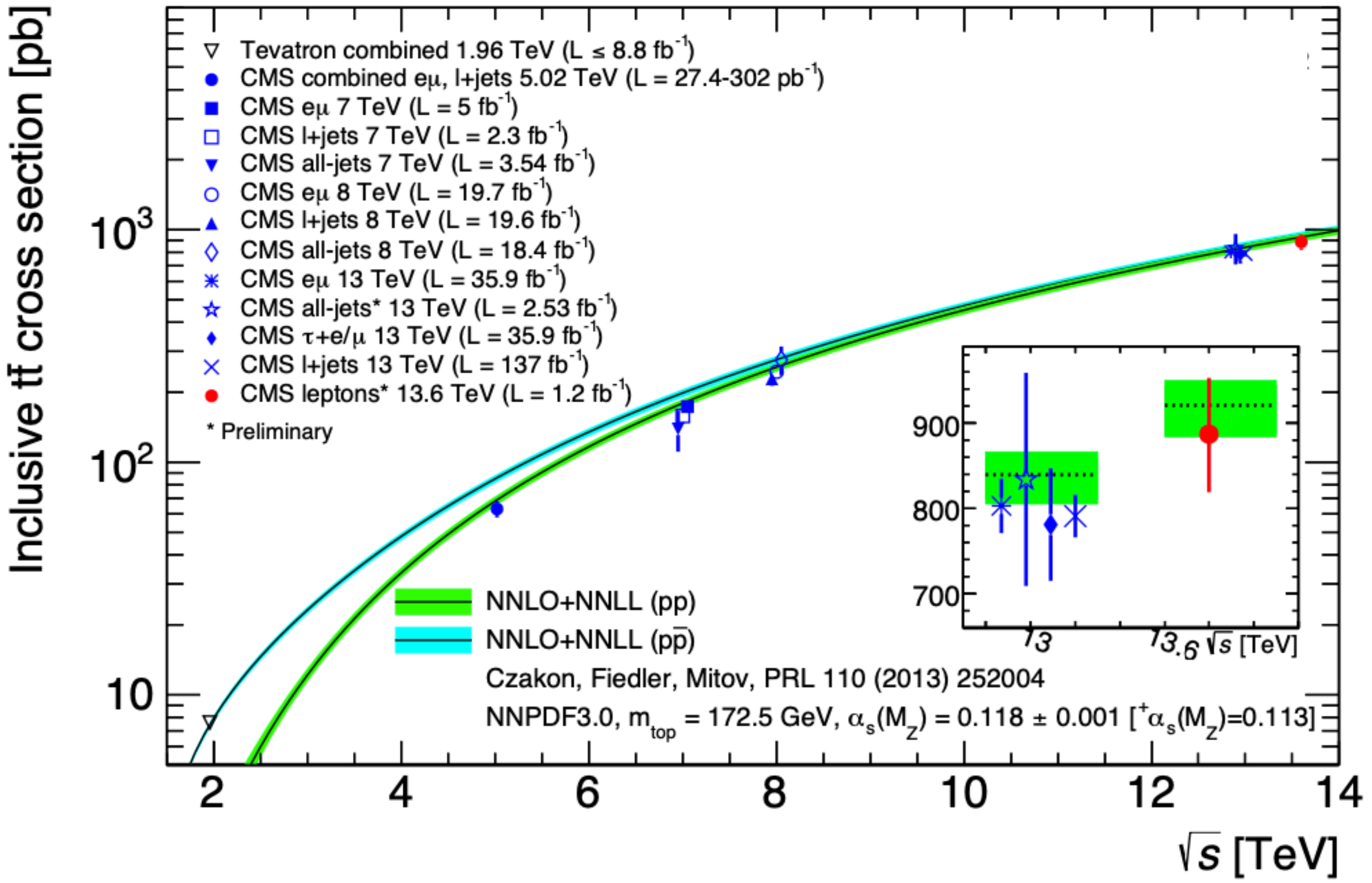
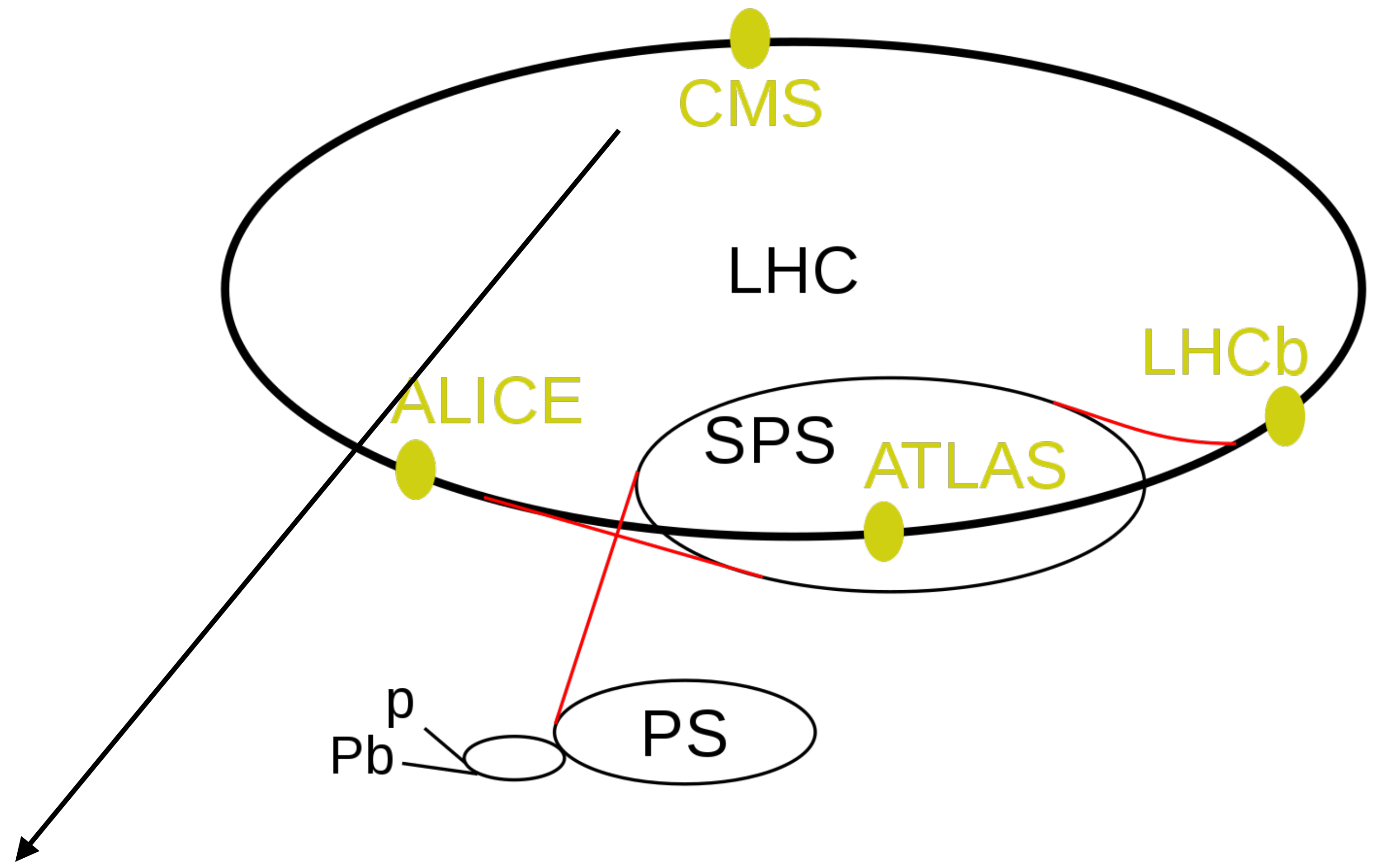
The top quark, a very unique particle

- **The top quark is the most massive elementary particle in the Standard Model**
  - **~173 GeV, which is equivalent to the mass of a gold atom. Why?**
- **Only coupling with the magnitude of order one in the Standard Model**
  - **Is there any connection to EW Symmetry Breaking ?**
- **Top decays before hadronization**
  - **Lifetime of ~5 * 10^-25 seconds. This allows study of bare quark properties**
- **With the enormous amount of top quark pairs produced in the LHC (over 120 M!!), we are entering to the era of high precision measurements in the top quark sector**





The CMS detector



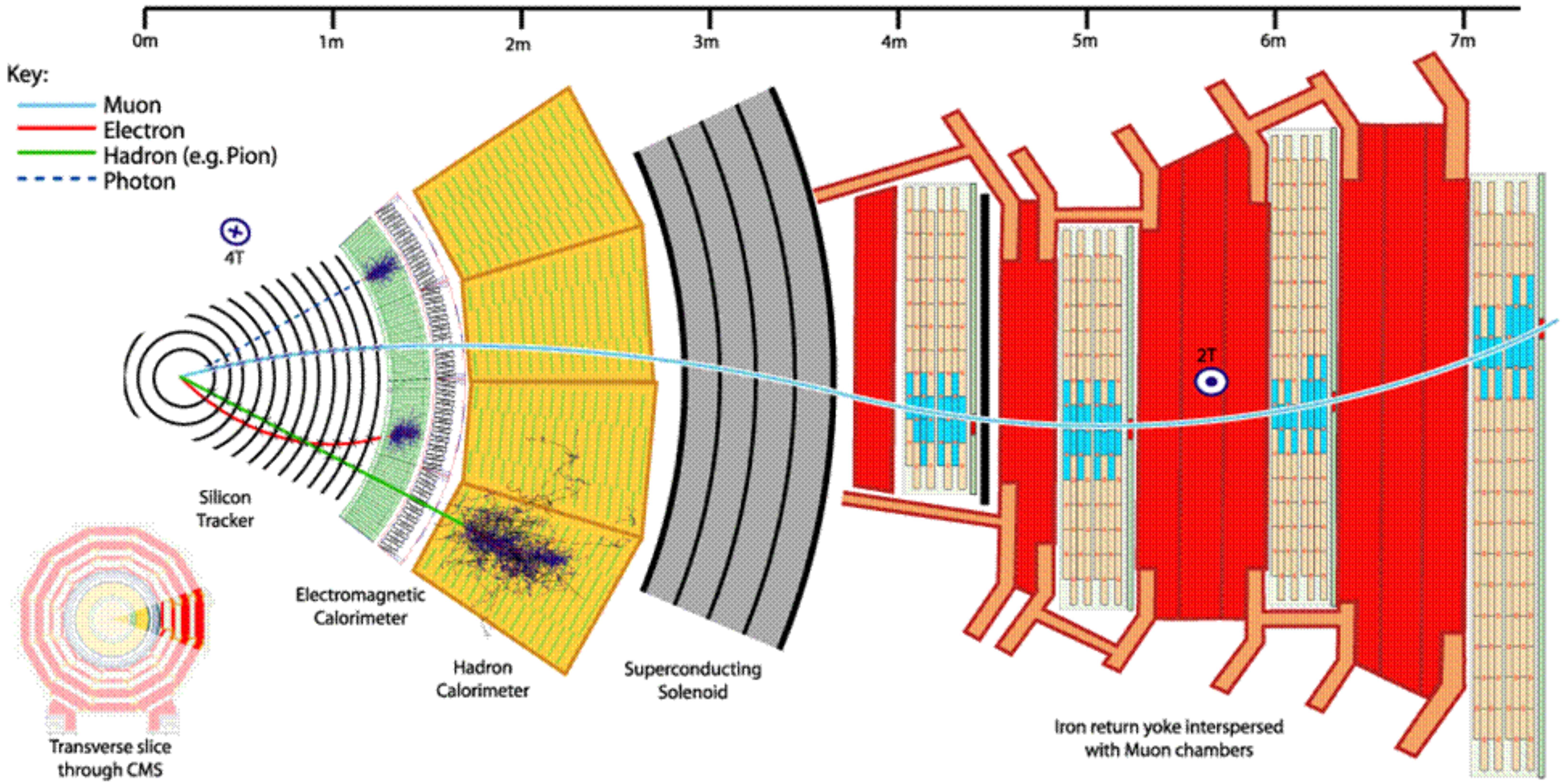
A general propuse detector that sits at one of these four collision points along the LHC ring: it is designed to observe any new physics phenomena that the LHC can reveal!

Cylindrical structure with different layers:

- **Tracker**
- **ECAL**
- **HCAL**
- **Solenoid Magnet**
- **Muon chambers**

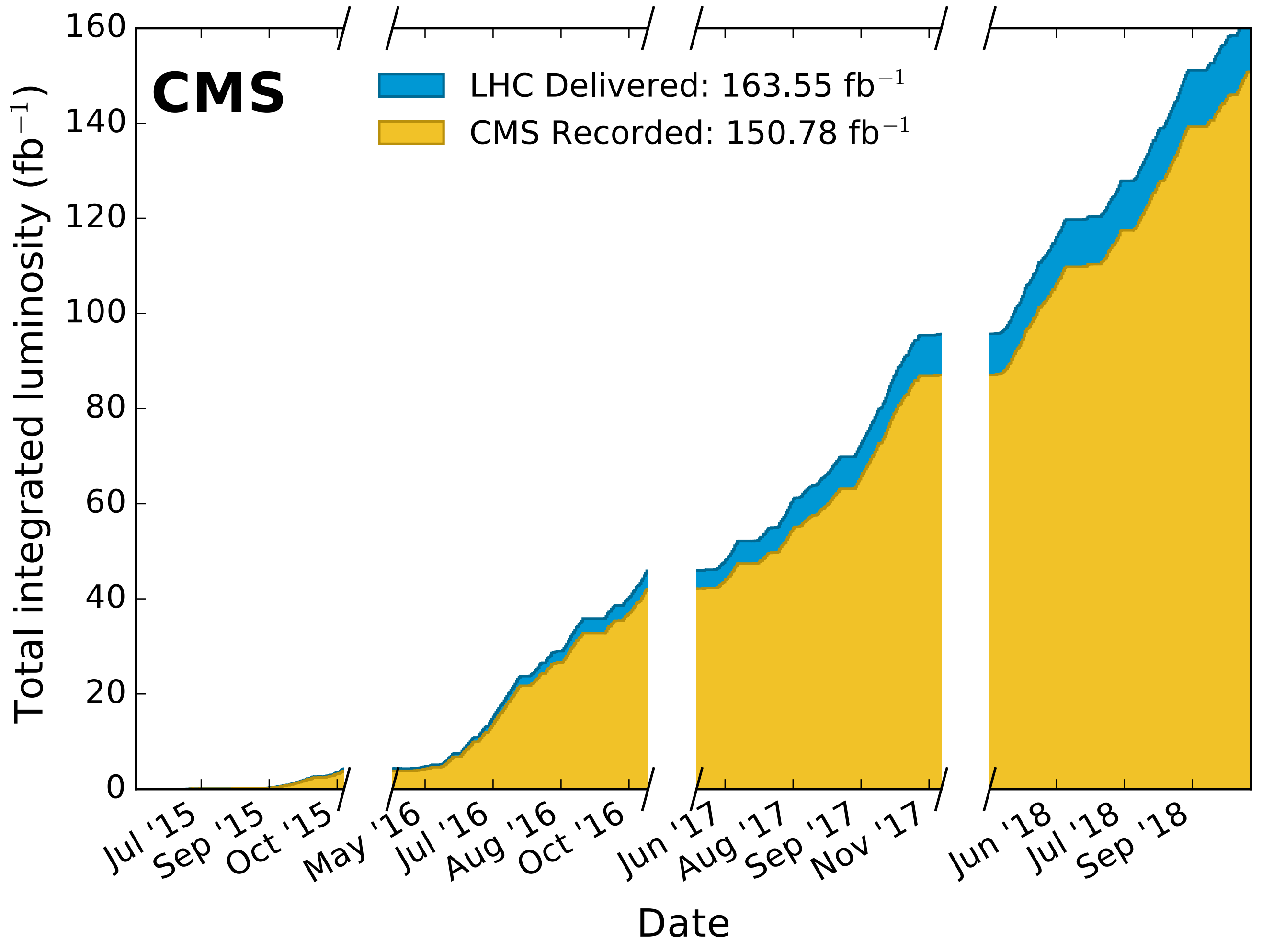
Two-level trigger

- **~40 MHz → ~1 kHz**

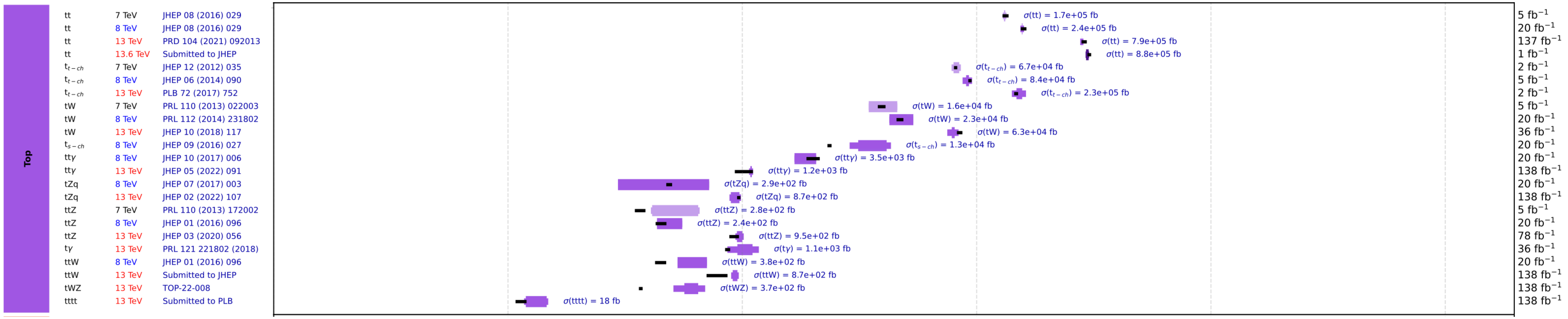


Overwiev Run 2

- CMS collected about 150fb-1 data
  - (~4% of all data to be collected by LHC)
- >1200 publications
  - 574 based on Run 1 data
- Most cited one
  "Observation of a New Boson at a Mass of 125 GeV.." in Phys.Lett.B from 2012 (>10k citations)



Summary of Top measured cross sections and exclusion limits at 95% CL



- Latest results have been beneficed from the “Ultra-legacy” reprocessing campaign
- Reprocess all Run 2 data and MC with latest, greatest reconstruction and calibrations!
- Amounts to 25 B MC + 35 B real data events!

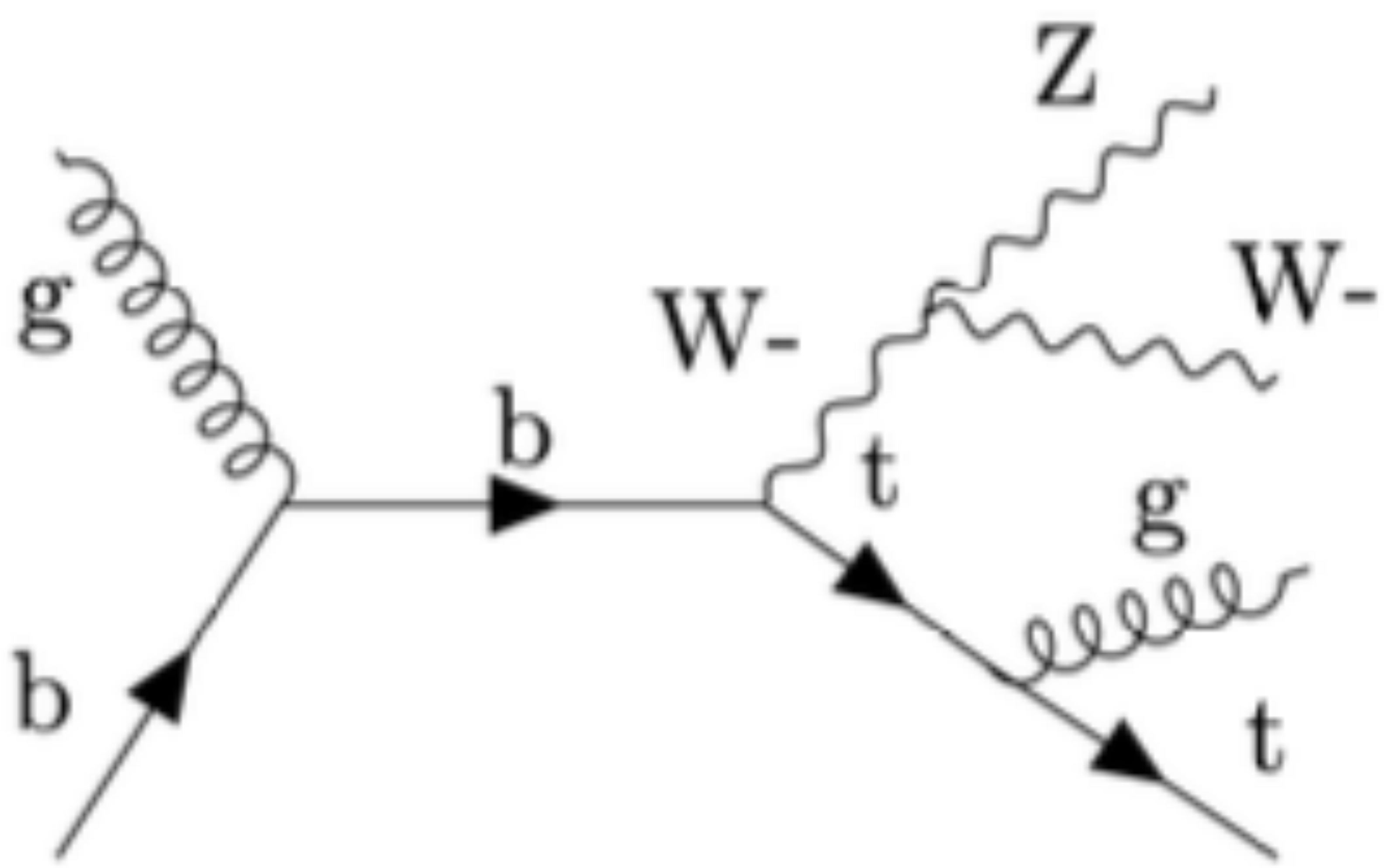
tWZ production

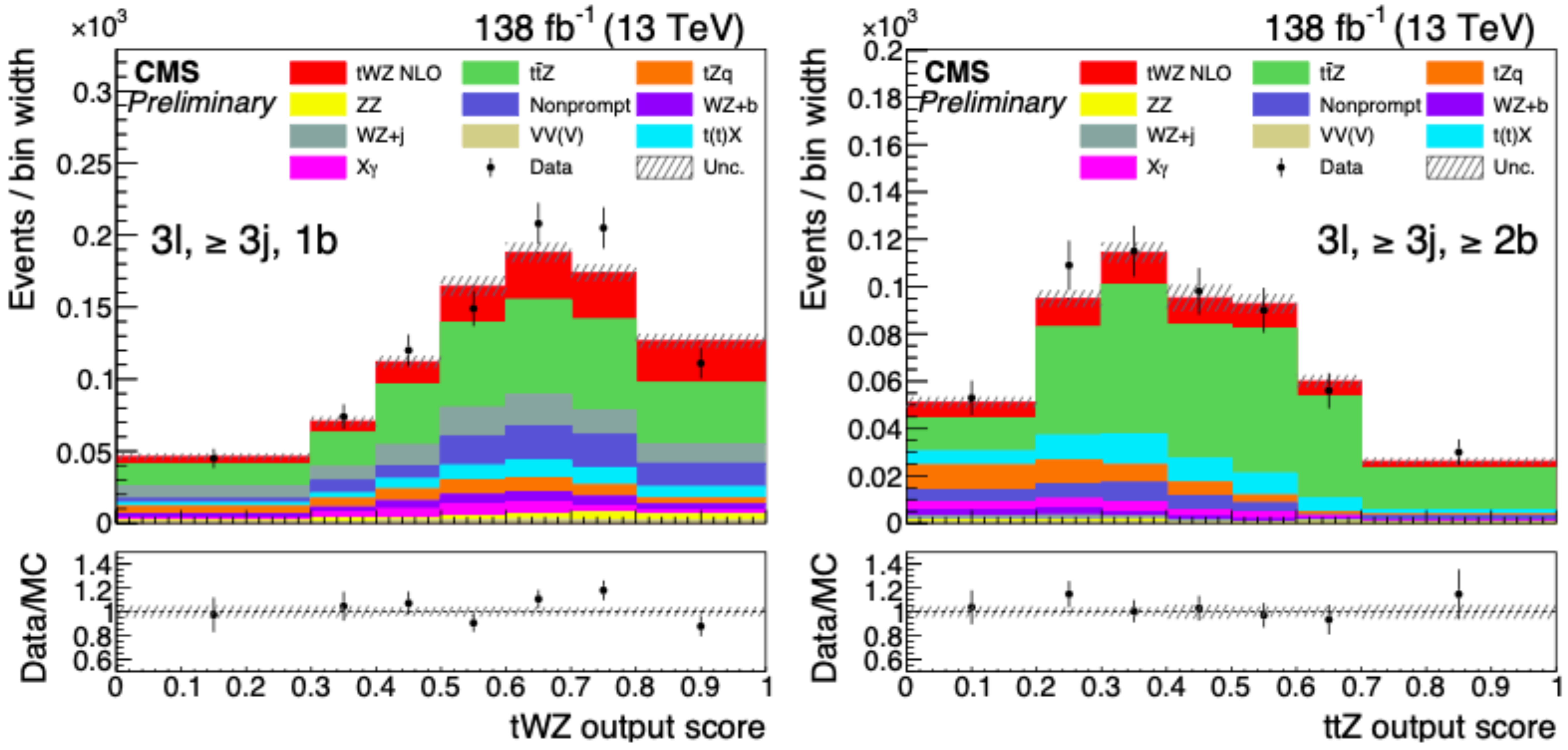
CMS-PAS-TOP-22-008

- **Extremely rare process: ~ 136 fb only**
  - **Depending on the decay of the W boson from the top quark, the final state consists of three or four leptons**
  - **Use of binary and multiclass NNs for background/signal discrimination.**
- **First evidence for the standard model production of a top quark in association with a W and a Z boson in multilepton final states:**

obs (exp) significance : 3.5 (1.4) s.d.

$$\sigma_{tWZ} = 0.37 \pm 0.05\ (\text{stat}) \pm 0.10\ (\text{syst})\ \text{pb}$$



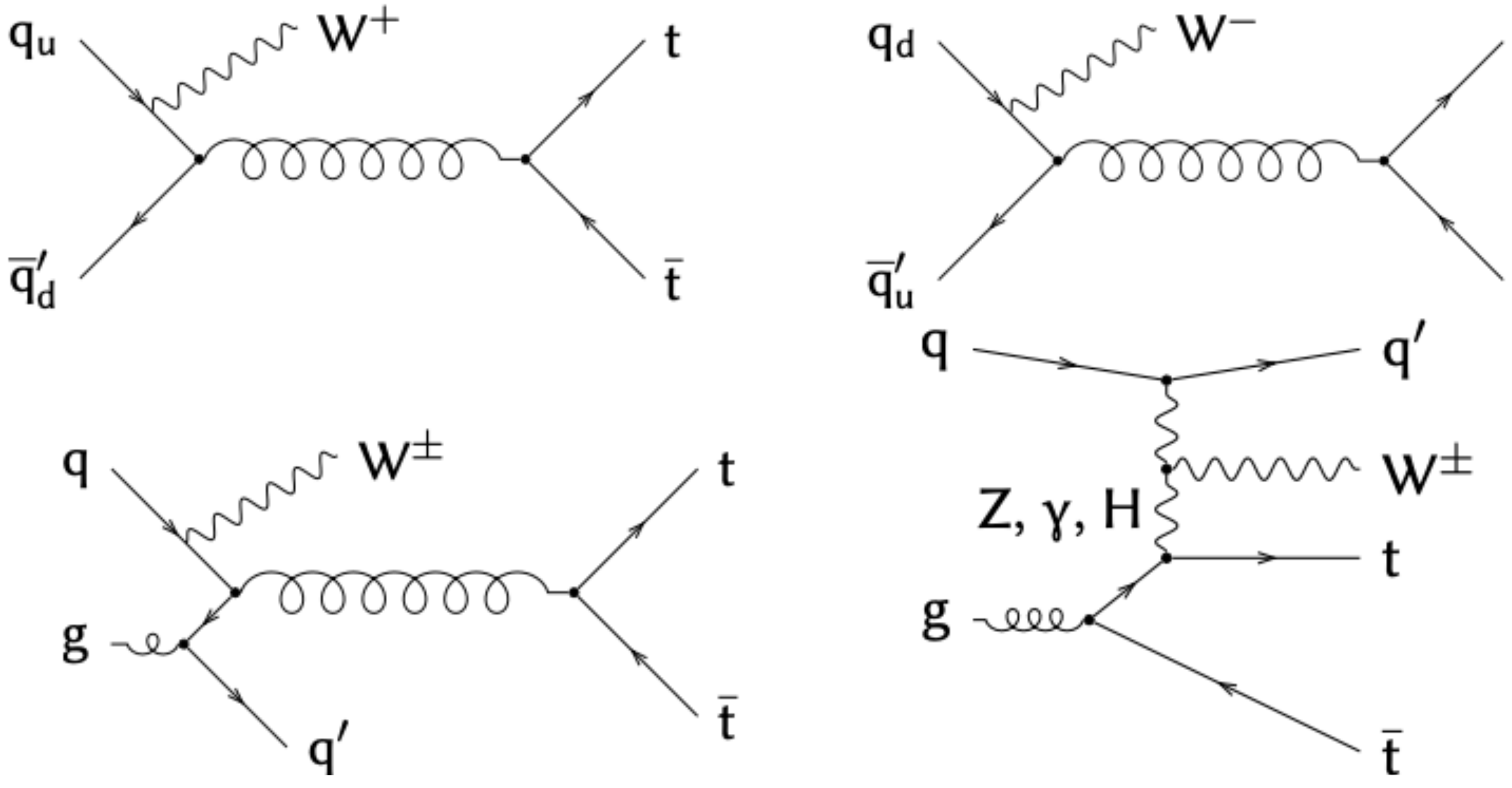


σ_{tWZ} = 0.37 ± 0.05 (stat) ± 0.10 (syst) pb

ttW cross section

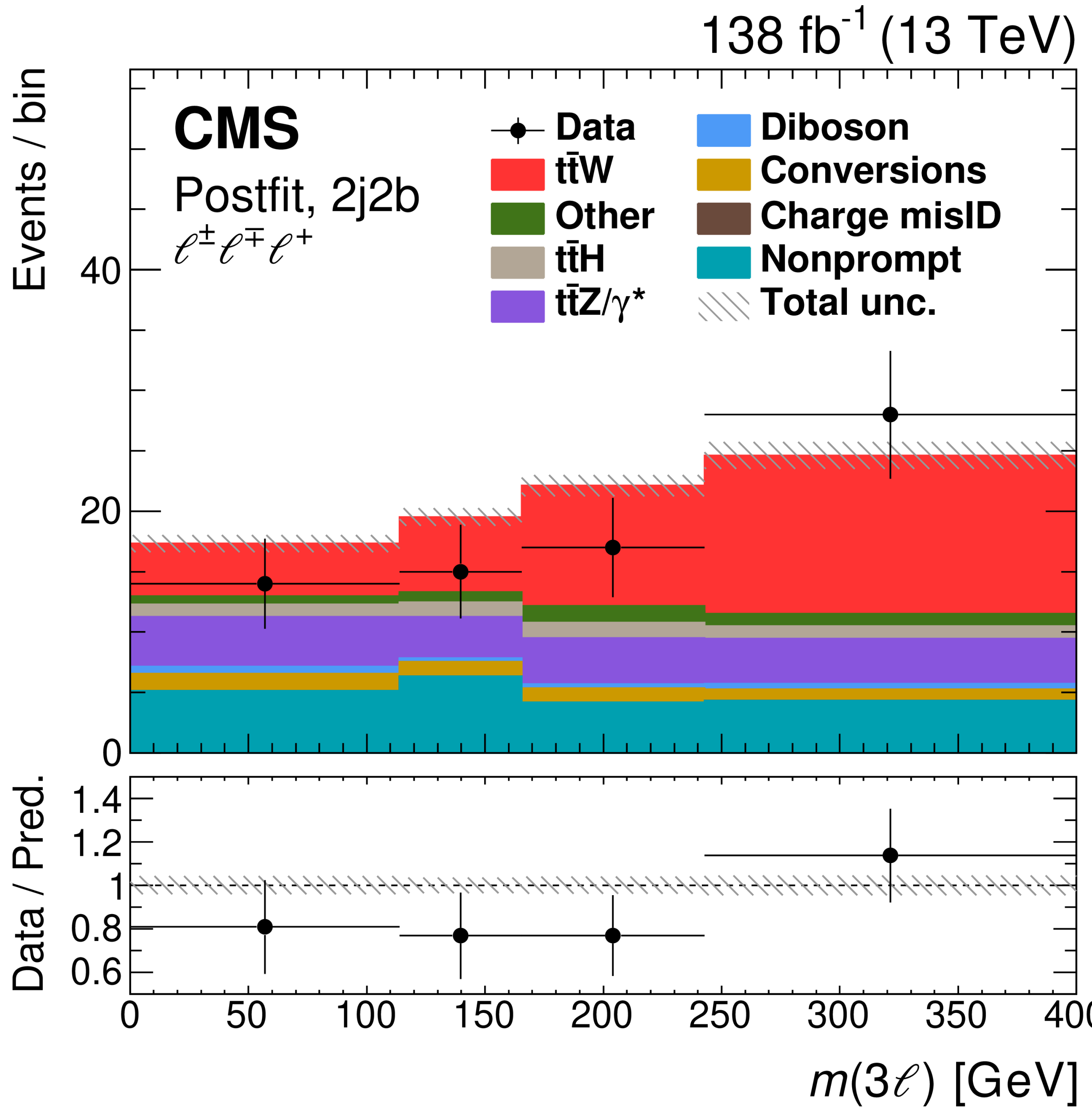
arXiv:2208.06485 (accepted in JHEP)

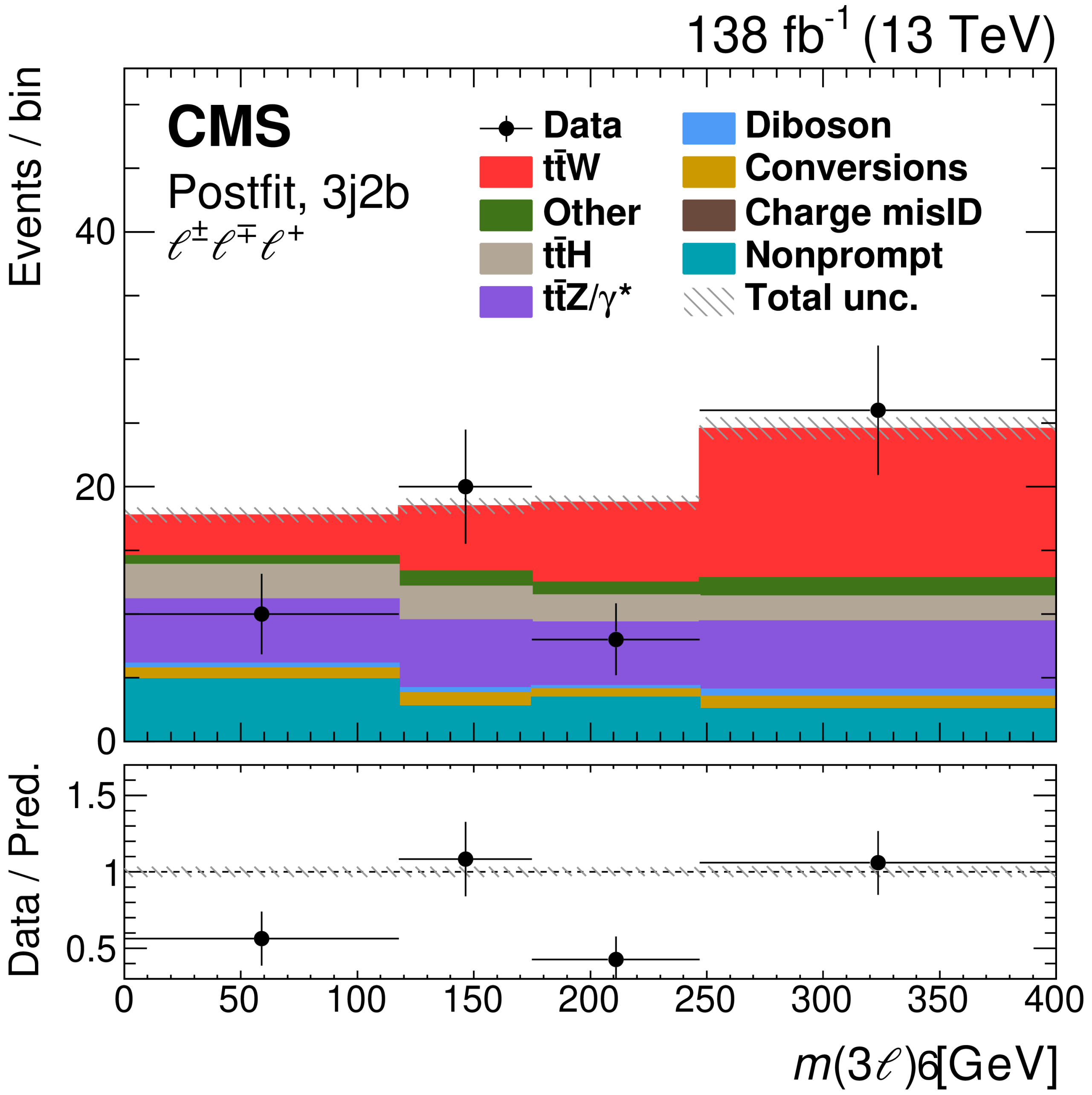
- The ttV processes of the weak interaction between a top quark and a W or a Z boson provide a direct measurement of the weak couplings of the top quark
- Important background for processes like ttH and tttt, a tension was observed between the measured and predicted production cross section
- The measurement targets the ttW signal process in which the W boson decays to a lepton (electron or muon) and a neutrino, and the final state of the tt system includes either lepton+jets or dileptons

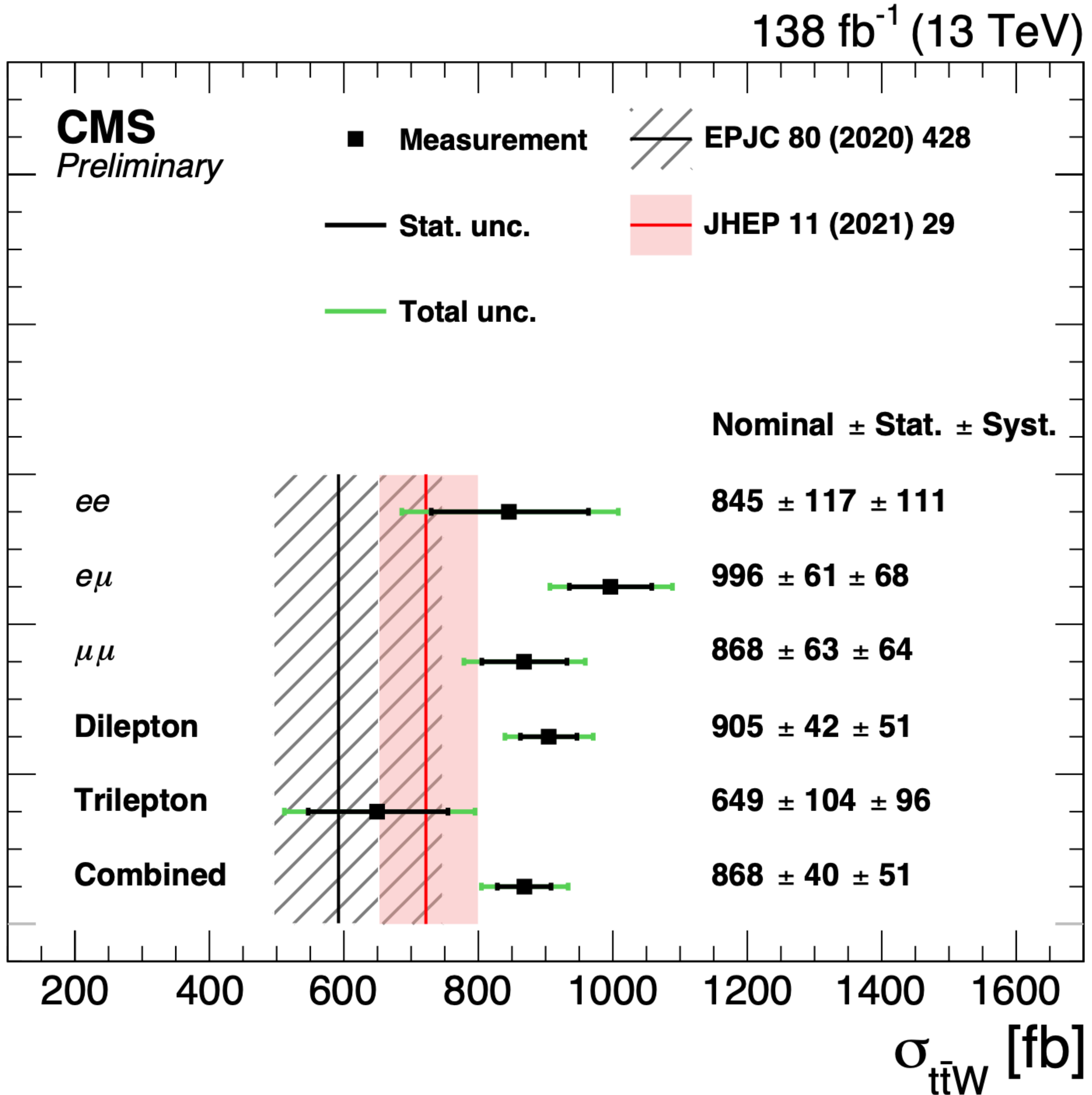


The measured cross section is:

- Associated production W^+: $553 \pm 30\ (\text{stat})^{+31}_{-30}\ (\text{syst})$ fb
- Associated production W^-: $343 \pm 26\ (\text{stat})^{+25}_{-25}\ (\text{syst})$ fb

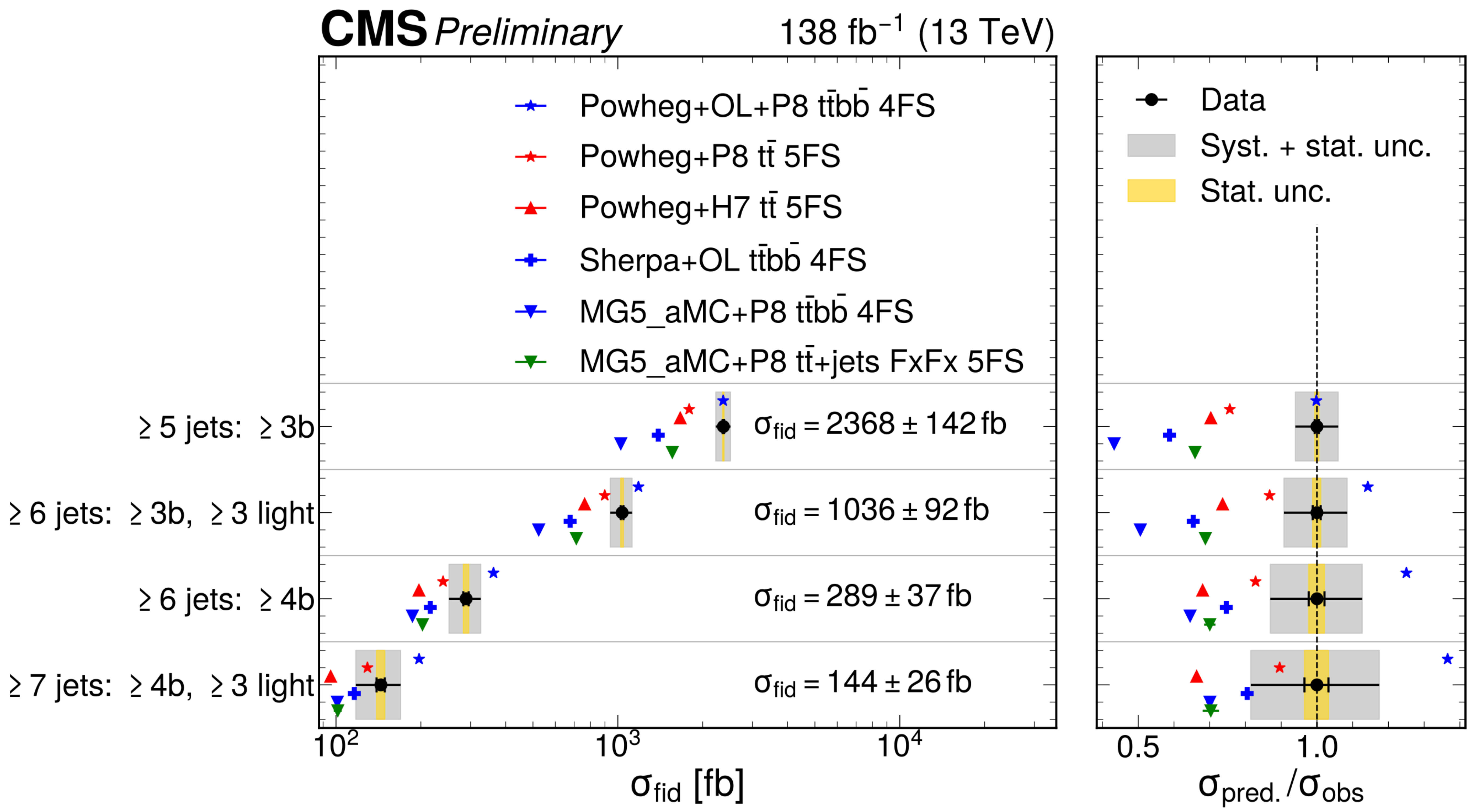






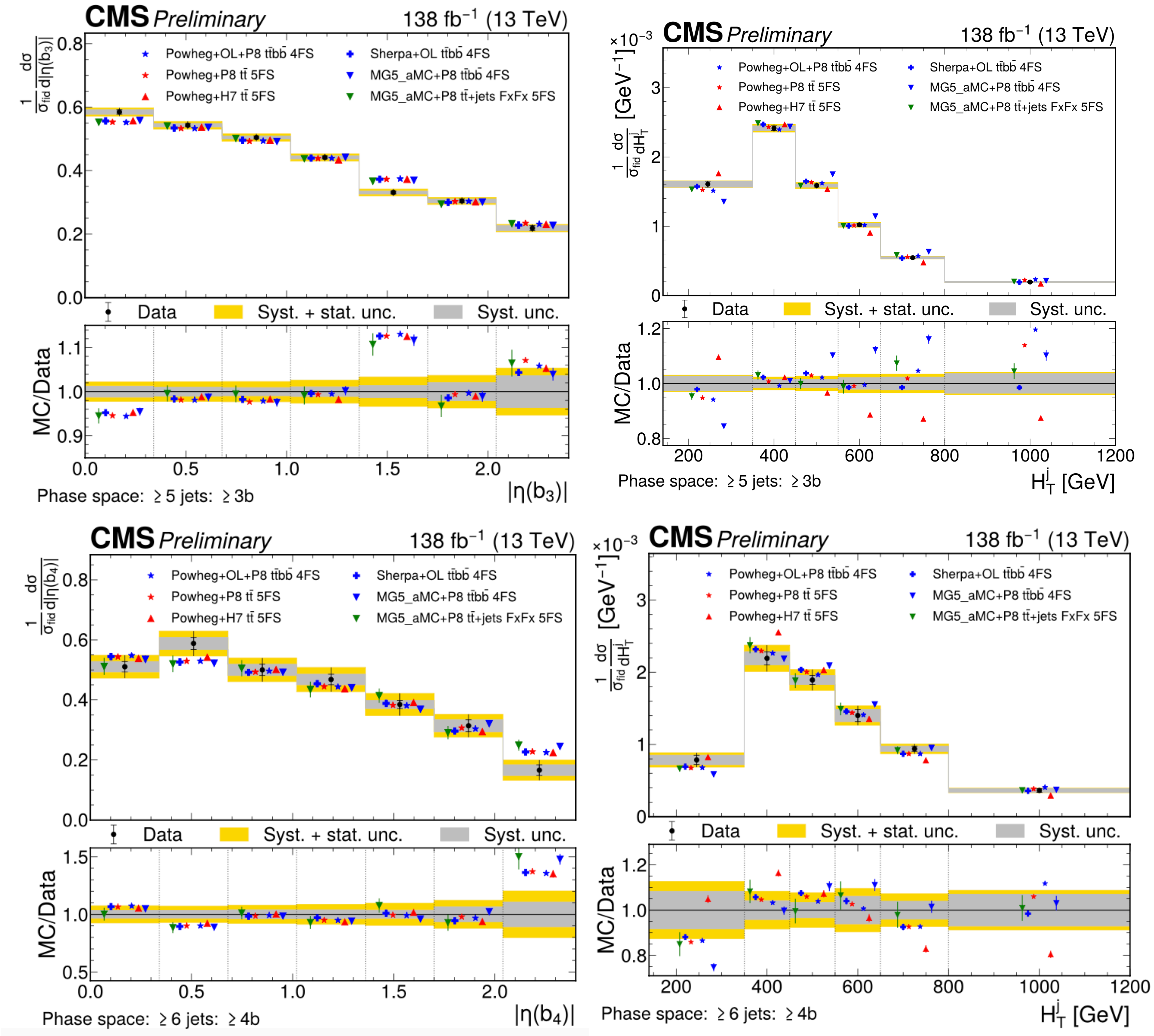
ttbb production (Inclusive and differential cross sections measurements) CMS-PAS-TOP-22-009

- **Rare SM process, irreducible ttH & tttt backgrounds**
- **Important test for perturbative QCD calculations**
- **The cross section are measured in the lepton + jets decay channel**
- **Inclusive σ higher than theor. predictions (consistent with previous measurements)**
- **The inclusive cross section measurements of the fiducial phase space regions are the most precise measurements of ttbb production so far**



ttbb production (continuation) CMS-PAS-TOP-22-009

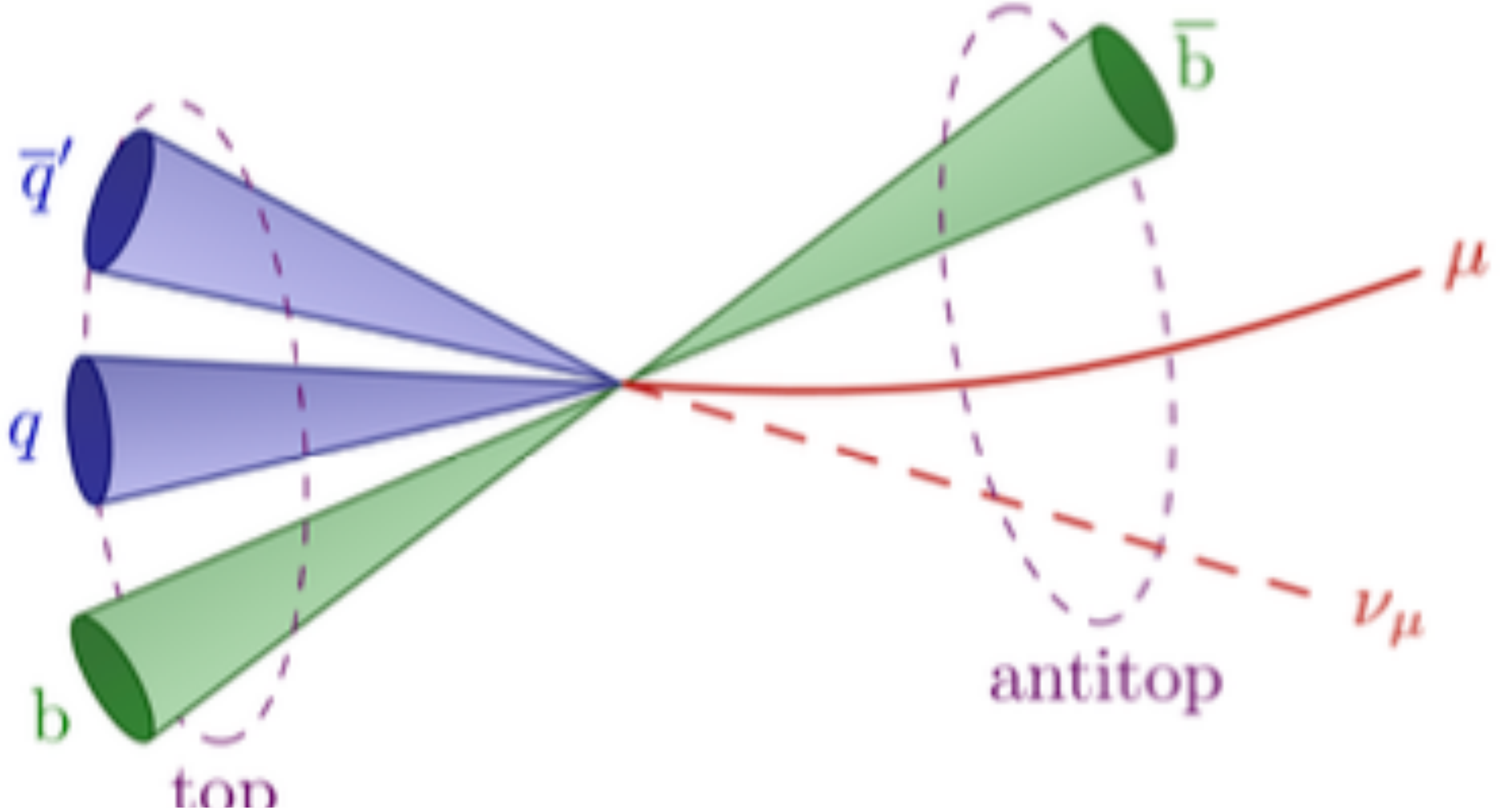
- **Differential cross section measured as function of 37 observables**
- **The results are compared to the predictions of several event generators: none of them simultaneously describe all measured distributions**
- **In the more inclusive phase space with five jets and three b jets, the agreement between data and predictions is generally poor, while in the phase space with six jets and four b jets, most predictions are compatible with the data**



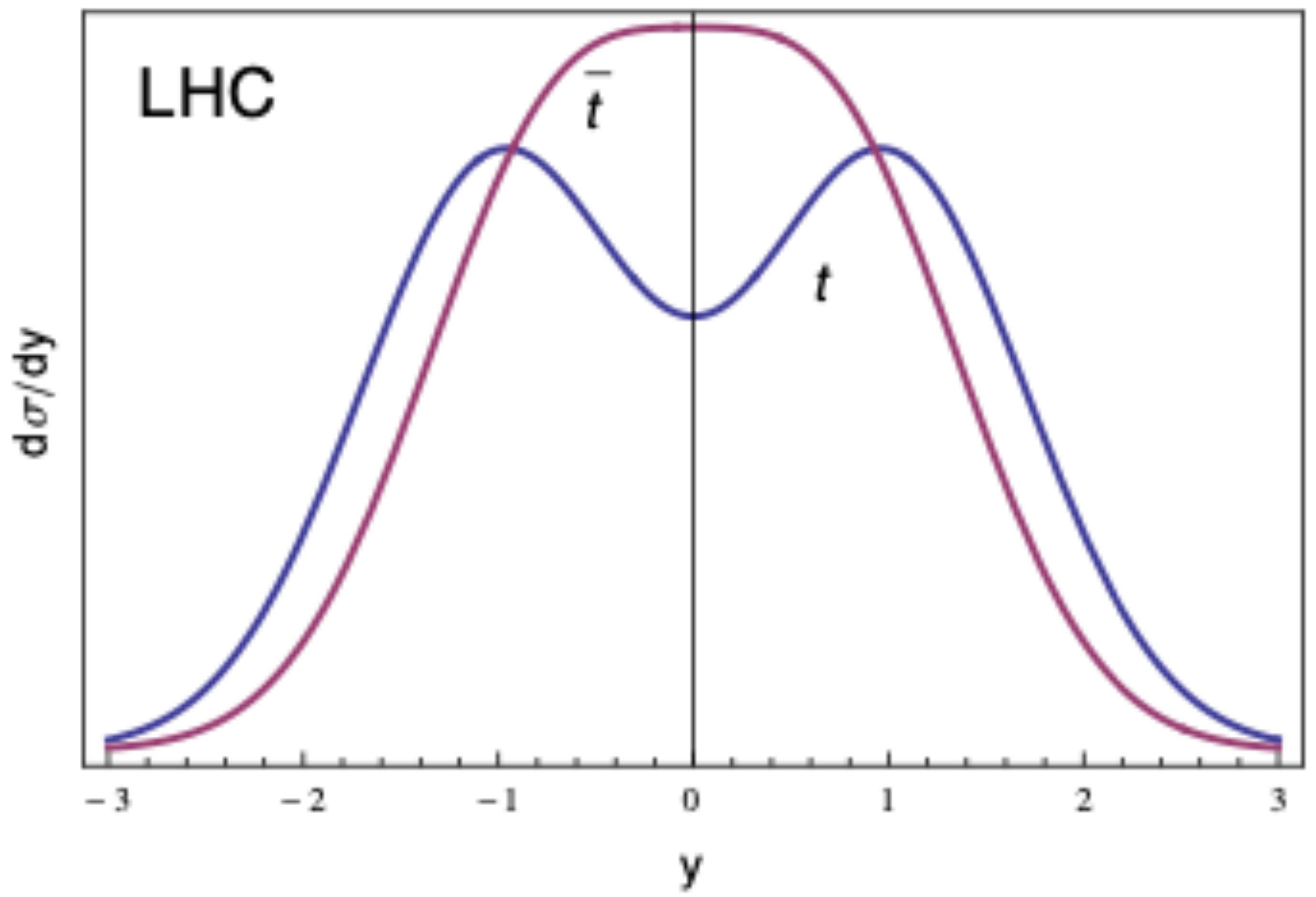
Boosting charge asymmetry!

arXiv:2208.02751 (accepted by PLB)

- **CMS measured A_C using lepton + jets events**
- **Selection is optimized for top quarks produced with large Lorentz boost, where is more likely to find top quark pairs initiated by quark-gluon or quark-quark interactions.**
- **Important for testing the standard model and searching for BSM physics**
- **Looking for non-isolating leptons, unlike previous LHC results.**
- **Measured for events with a t t̄ invariant mass larger than 750 GeV.**



arxiv:1207.0331



$$A_C = \frac{N(\Delta|y|>0) - N(\Delta|y|<0)}{N(\Delta|y|>0) + N(\Delta|y|<0)}$$

Boosting charge asymmetry!

arXiv:2208.02751 (accepted by PLB)

- Most precise charge asymmetry result from LHC ! (Error is dominated by the statistical component)
- Compared to theoretical prediction with NNLO QCD an NLO EW corrections
- Results are in very agreement with the SM prediction

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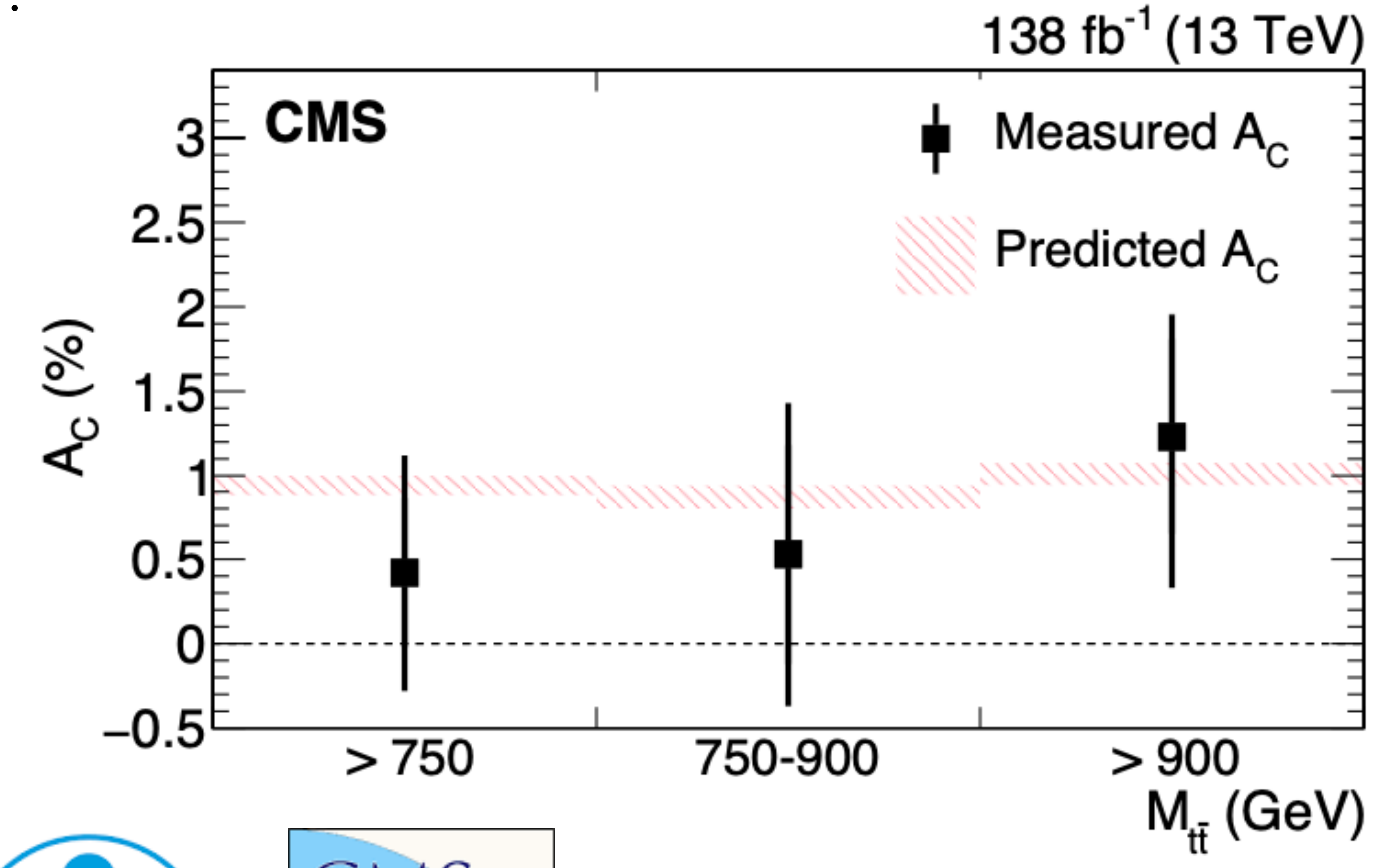
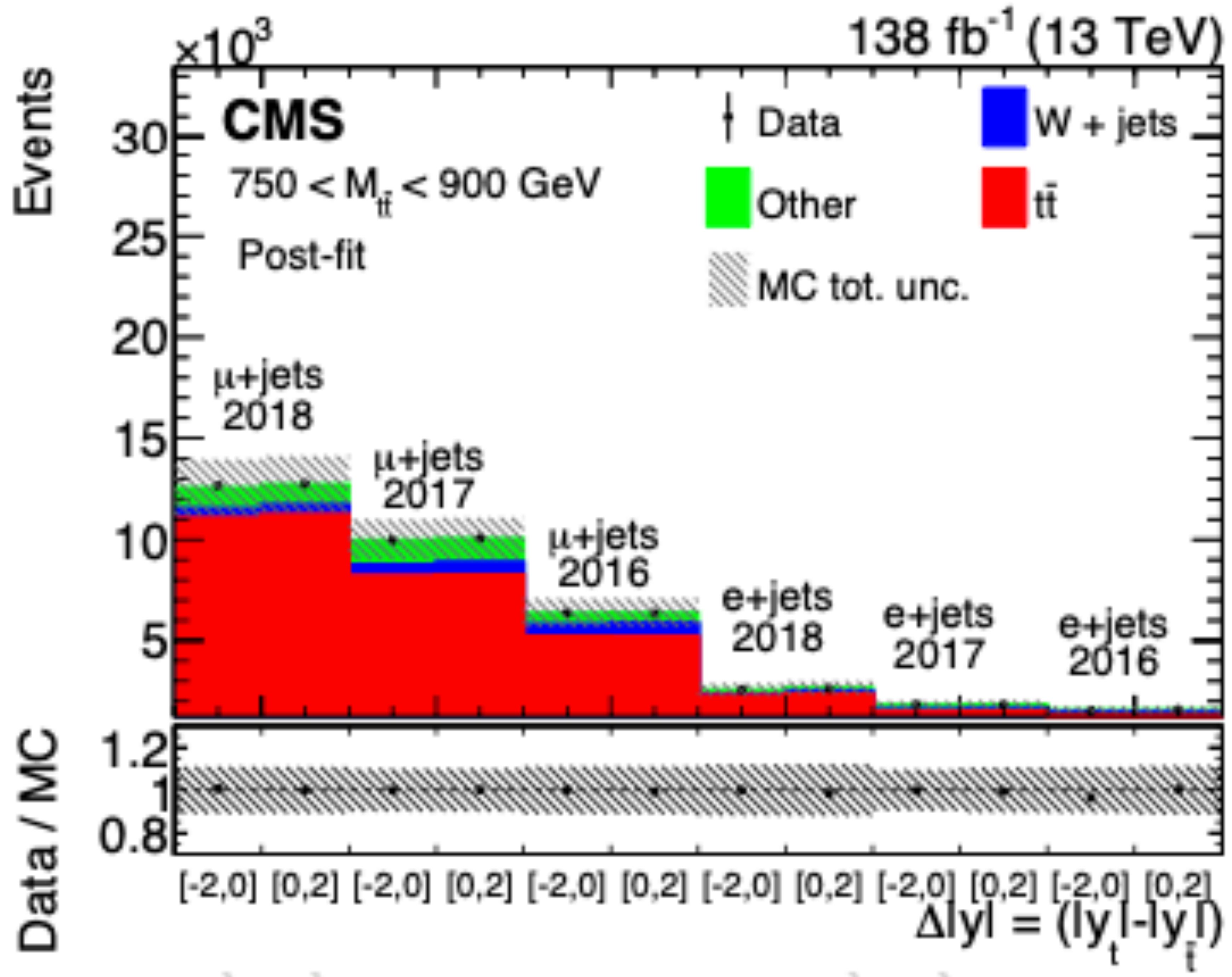
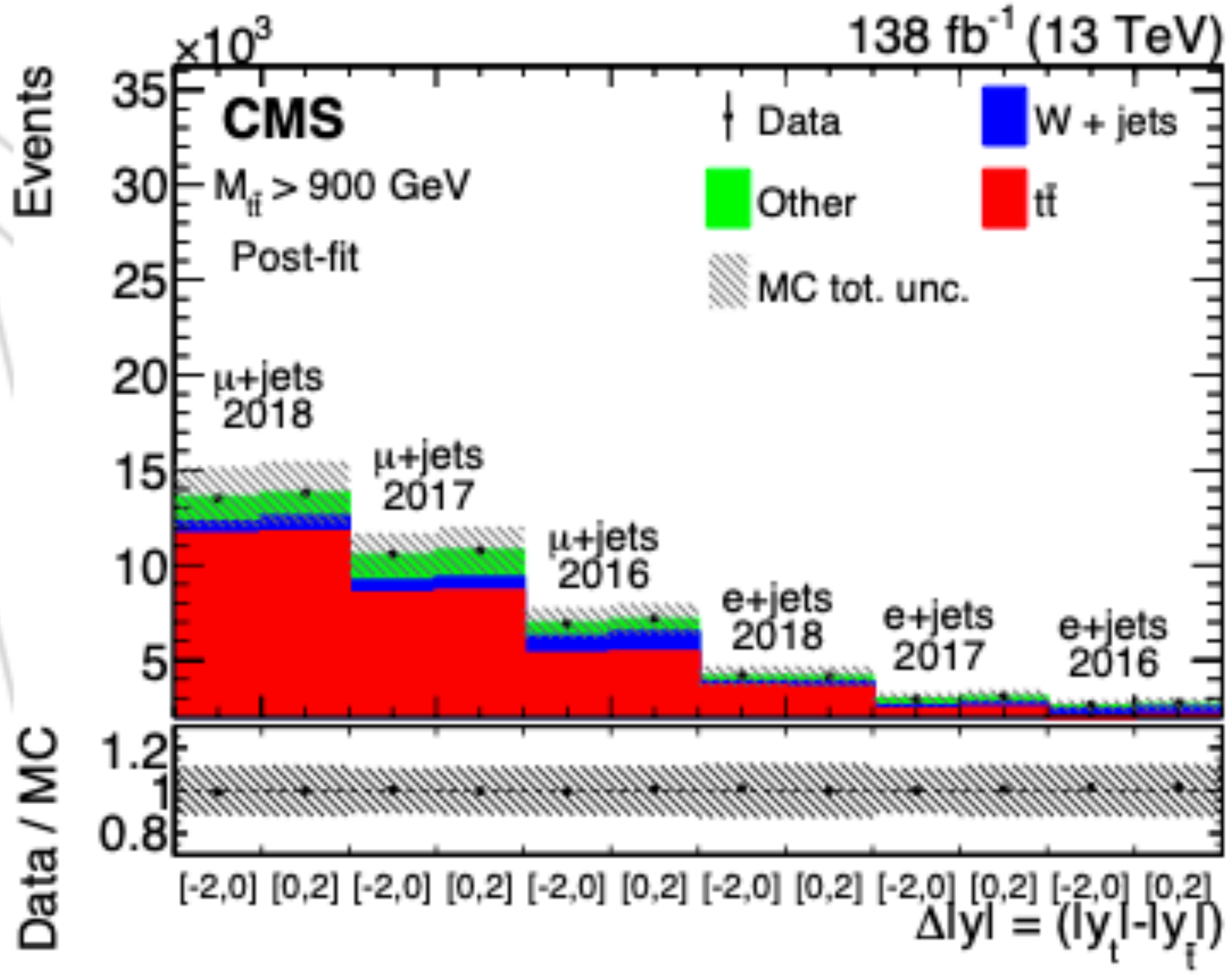


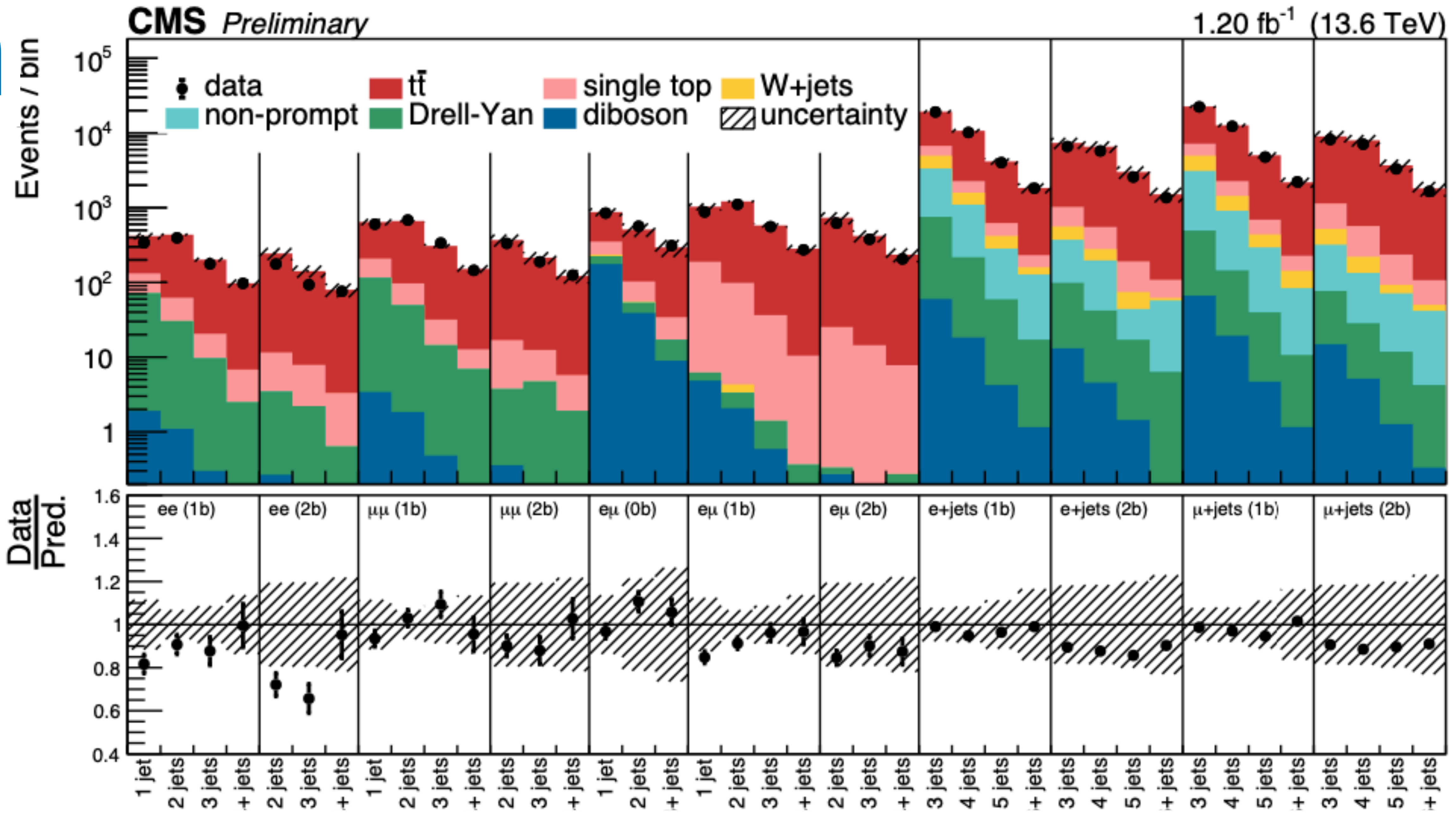


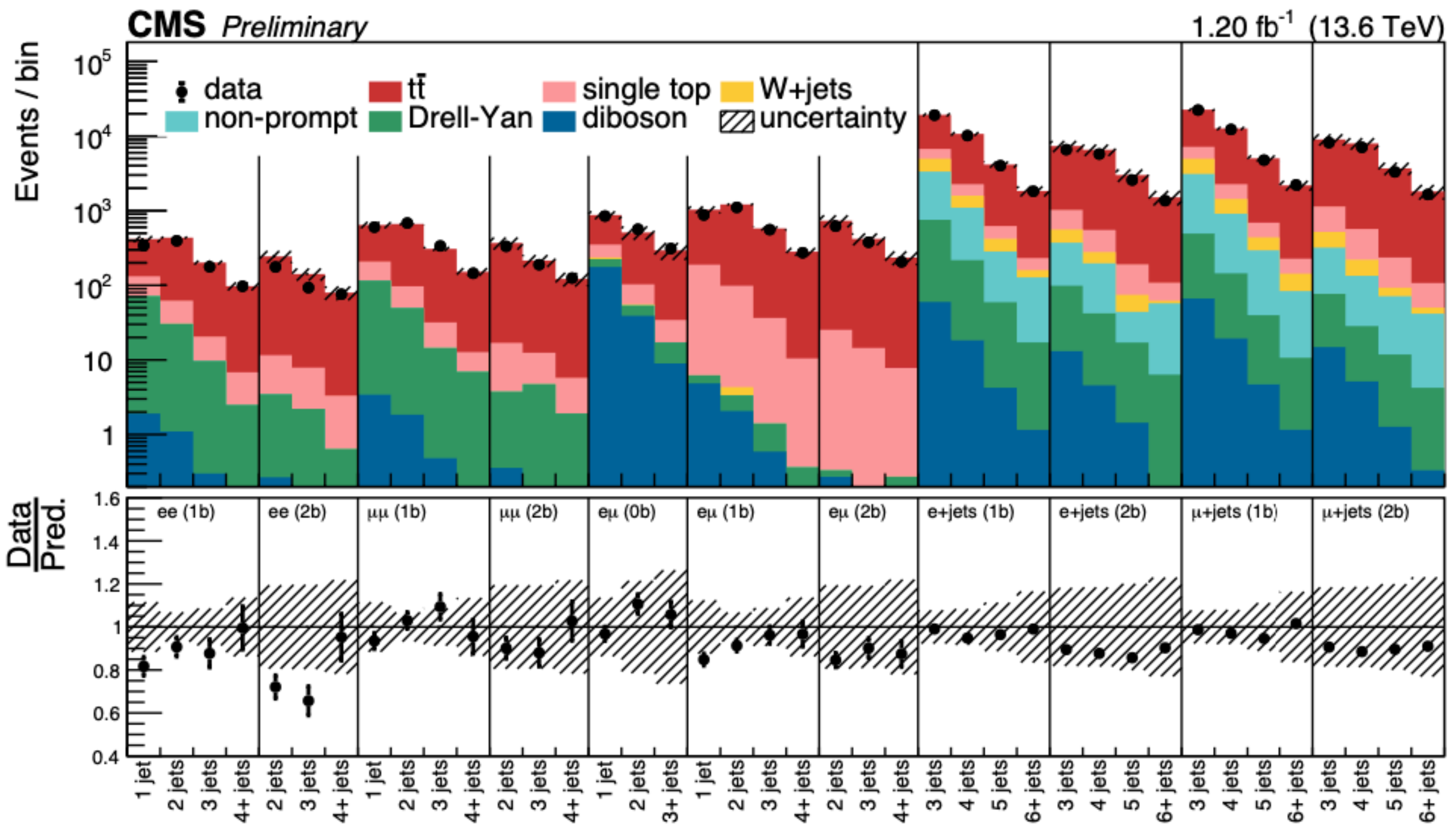


Inclusive $t\bar{t}$ cross section at 13.6 TeV

arXiv:2303.10680 (submitted to JHEP)

- **First measurement at CMS with new energy (Run-3 started in July 2022)**
- **1.21 fb-1 of luminosity**
- **2l and l+jets channels combined to calibrate in situ b-tagging, jets and lepton SFs**





profile likelihood fit in lepton and b-jet categories

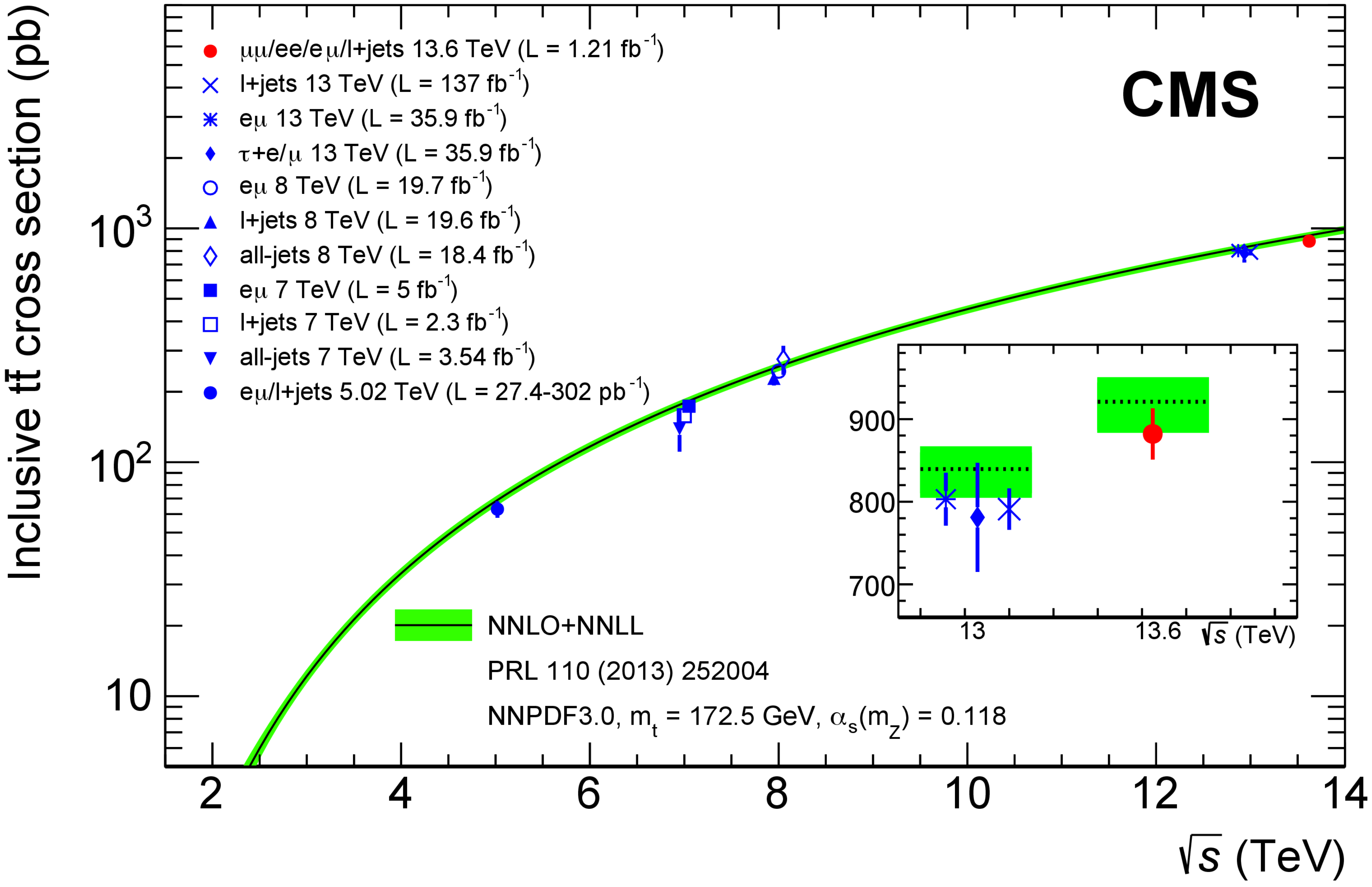
Inclusive $t\bar{t}$ cross section at 13.6 TeV

arXiv:2303.10680 (submitted to JHEP)

$\sigma(t\bar{t}) = 882 \pm 23$ (stat+syst) ± 20 (lumi) pb **[3.5%]**

theory: 921+29−37 (scale+PDF) pb

- **3.5% total uncertainty!**
- **Main uncertainties: luminosity, lepton and b-tag efficiencies**
- **In very good agreement with the SM prediction**



Summary

The CMS TOP program has been incredibly successful: multitude of exceptional results (only few of the latest ones were presented, you look at Backup slides):

- **More precise ttW cross section measurement**
- **First evidence of tWZ production**
- **Inclusive and differential measurements of the ttbb cross section**
- **Most precise charge asymmetry measurement date**
- **First Run 3 measurements: $t\bar{t}$ inclusive cross section measurement, essential measurement to test the functionality of the detectors in the new era**

OVERVIEW OF ALL CMS TOP RESULTS CAN BE FOUND HERE

Backup

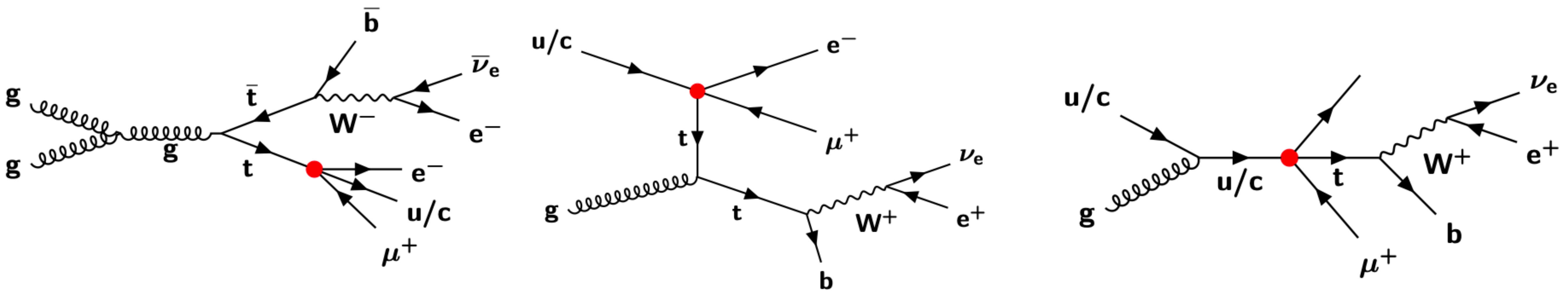
Search for charged lepton flavour violation

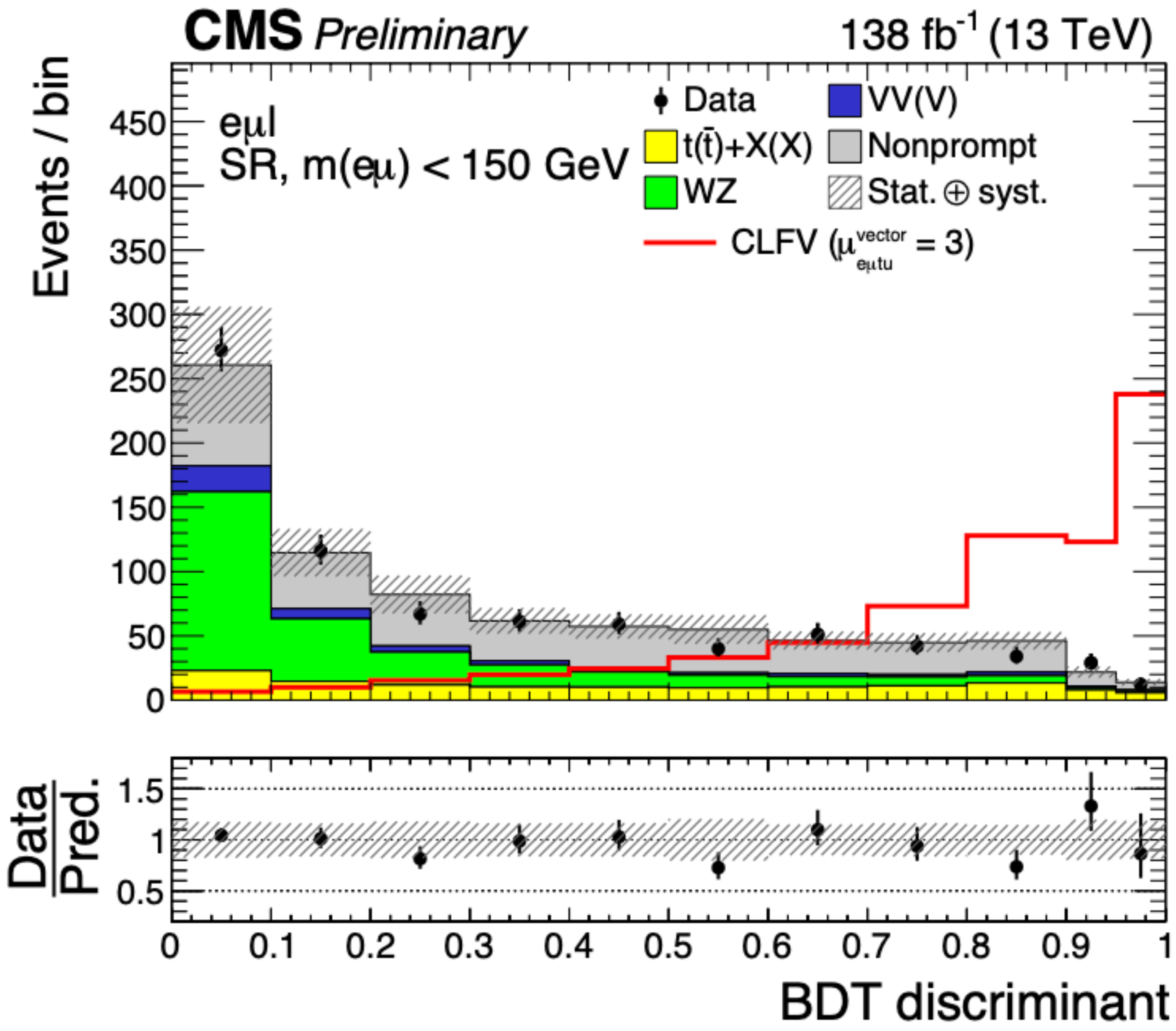
CMS-PAS-TOP-22-005

- **Lepton flavor is conserved in the standard model, However, the observation of neutrino oscillations indicates that lepton flavor violation ca also occur in the charged lepton sector**

- **Final states with exactly three charged leptons were considered:**
  - **two leptons originate from CLFV interactions**
  - **The third lepton originates from leptonically decaying top**

- **To separate a possible LFV signal from the SM background contributions in the signal region, BDTs were implemented. The most important input variables are:**
  - **invariant mass of the Z boson candidate**
  - **the number of b-tagged jets**
  - **invariant mass of the flavor-violating $e\mu$ pair**





Search for charged lepton flavour violation

CMS-PAS-TOP-22-005

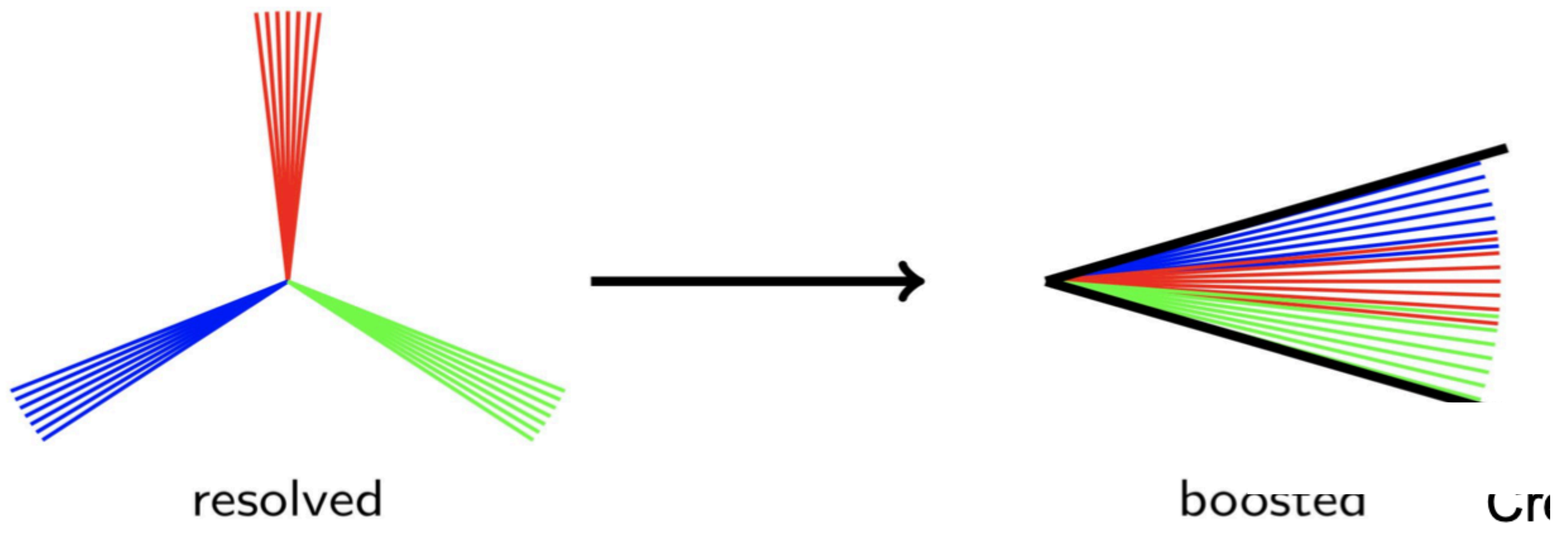
- No significant excess is observed over the prediction from the standard model.
- An effective field theory approach is used for parametrizing the charged lepton flavor violating interactions. The upper limits on the Wilson coefficients are then interpreted on upper limits on the branching ratios. Same strategy as in previous CMS analysis.
  - Upper limits are set on the branching ratios:

CLFV coupling	Interaction type	$C_{e\mu tq}/\Lambda^2$ (TeV^{-2}) Exp (68% range)	Obs	$\mathcal{B}(t \to e\mu q) \times 10^{-6}$ Exp (68% range)	Obs
eμtu	tensor	0.019 (0.015-0.023)	**0.020**	0.019 (0.013-0.029)	**0.023**
	vector	0.037 (0.031-0.046)	**0.041**	0.013 (0.009-0.020)	**0.016**
	scalar	0.077 (0.064-0.095)	**0.084**	0.007 (0.005-0.011)	**0.009**
eμtc	tensor	0.061 (0.050-0.074)	**0.068**	0.209 (0.143-0.311)	**0.258**
	vector	0.130 (0.108-0.159)	**0.144**	0.163 (0.111-0.243)	**0.199**
	scalar	0.269 (0.223-0.330)	**0.295**	0.087 (0.060-0.130)	**0.105**

Most stringent limits to date on this process!

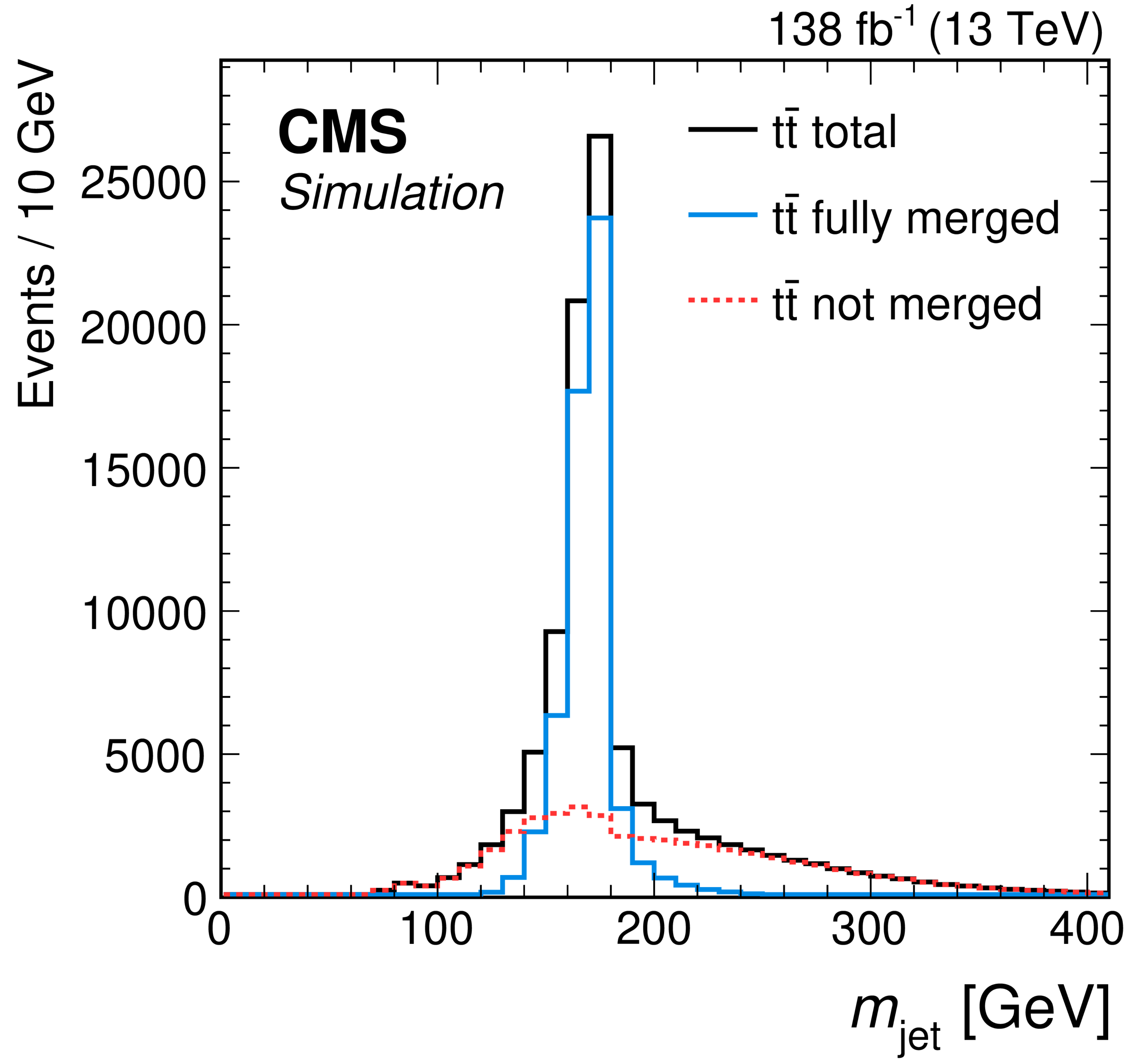
Top mass in boosted jets

Eur. Phys. J. C 83 (2023) 560



The top mass is a crucial parameter of the Standard Model. Why we should measured in boosted topologies?

- **Jet mass distribution is well defined in boosted topologies**
- **The peak position of the distribution in mjet is sensitive to m_t and allows for a precise measurement**



The problem -> larger uncertainty than resolved topology

Improved result using Full Run II data

Top mass in boosted jets

Eur. Phys. J. C 83 (2023) 560

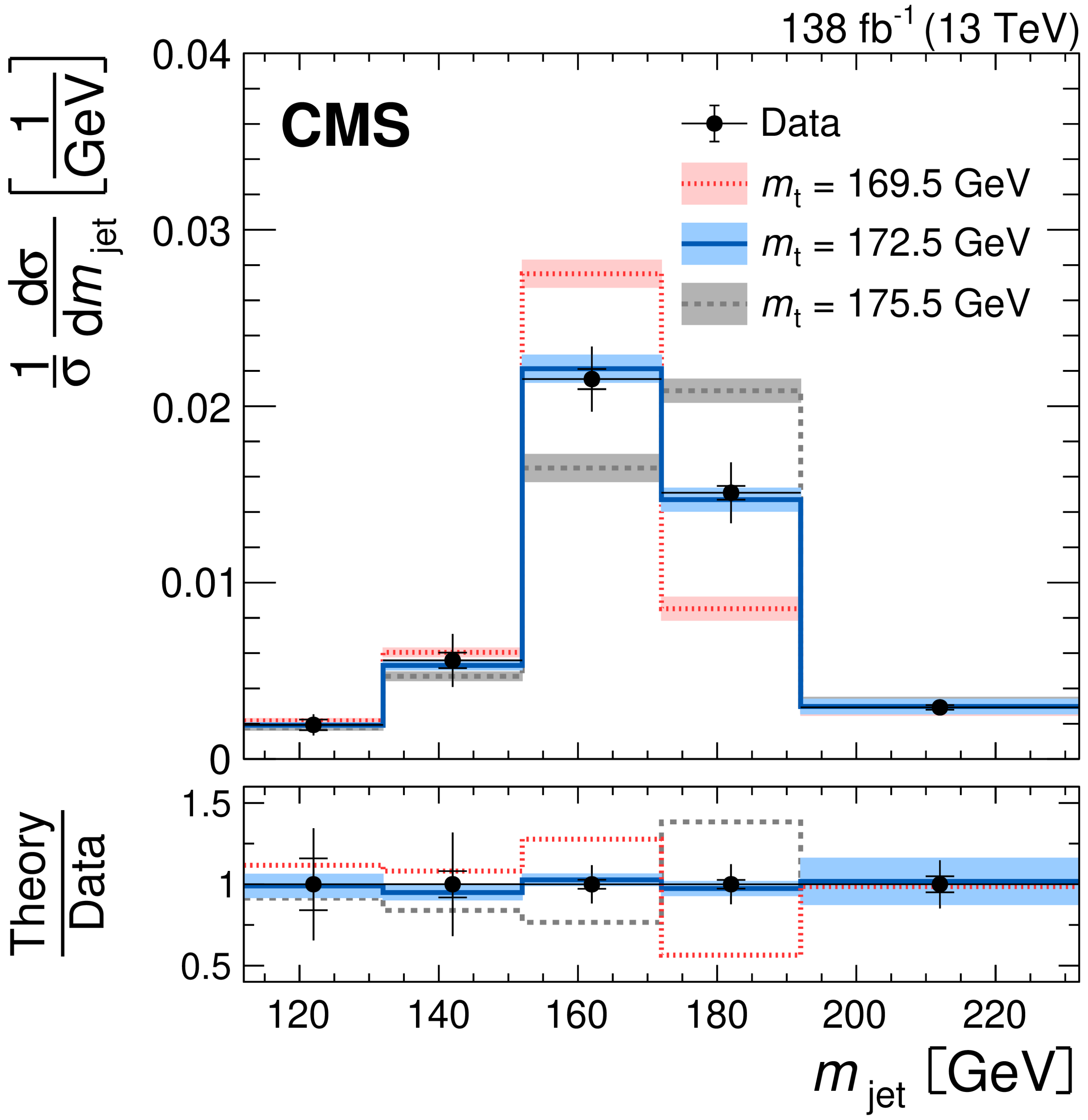
Top-jet candidate mass for jets with pT > 400 GeV in $|\eta|$ < 2.4

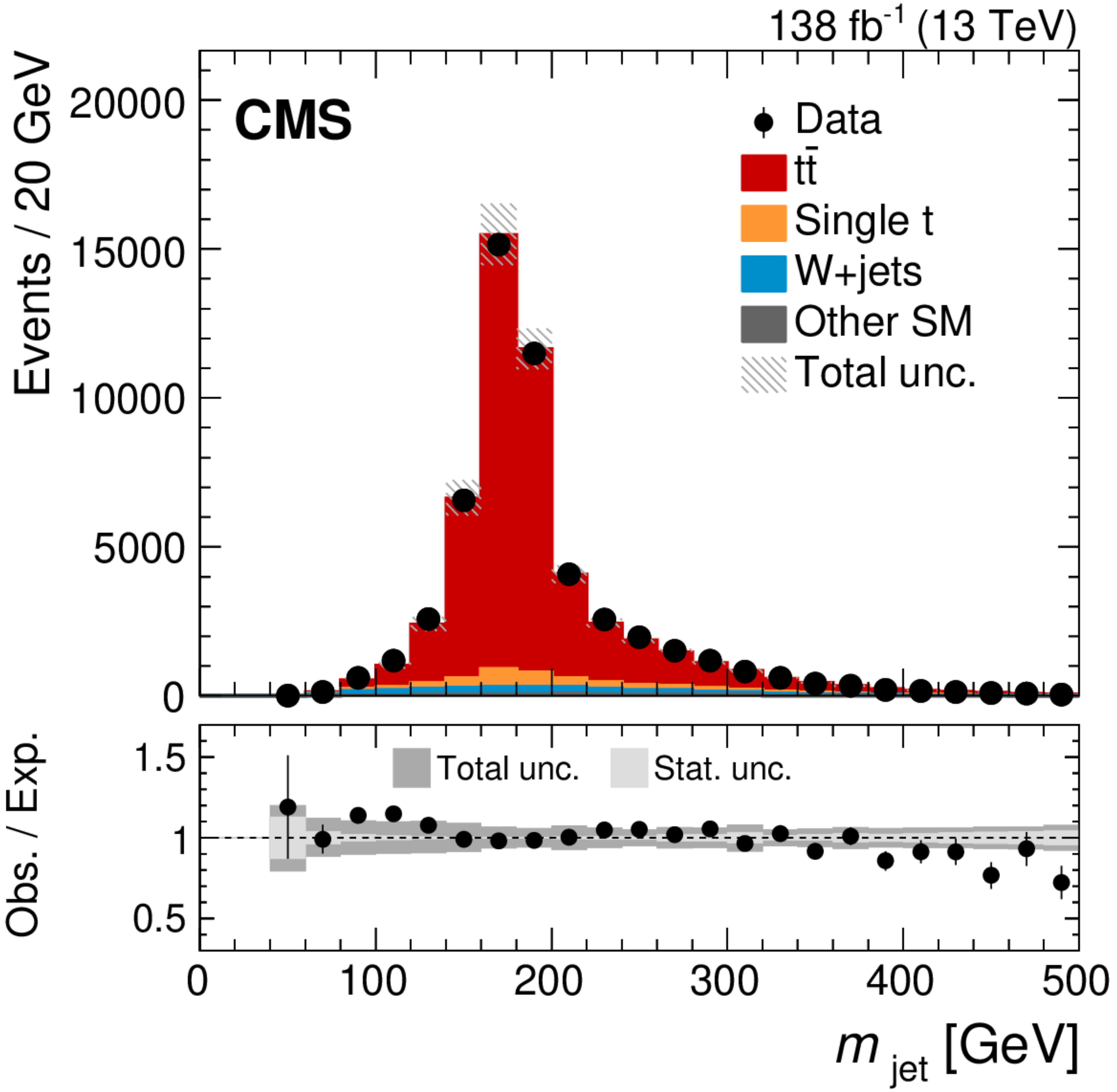
X cone jet clustering algorithm, with Nsub = 3, used for boosted top reconstruction

- **Jet axes found by minimizing the N-jettiness of the event**
- **Particles are clustered around these axes**

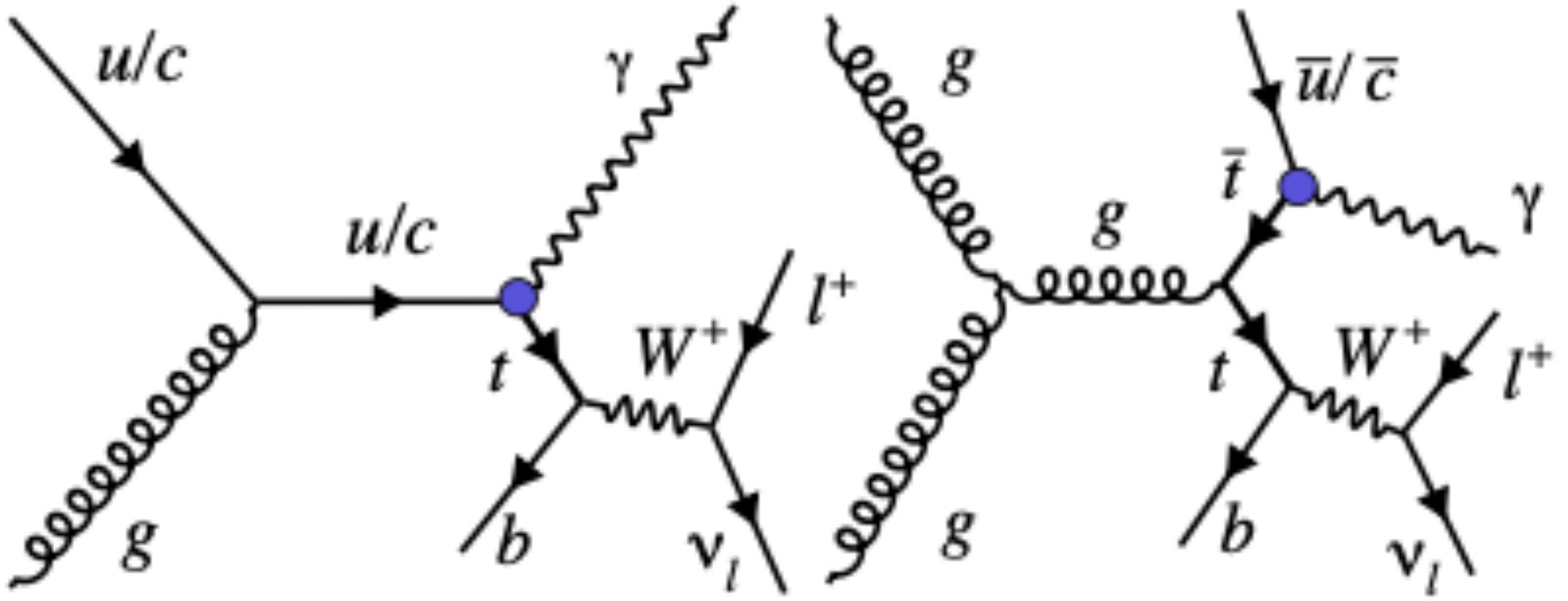
Very clean selection!, less than 4% is background
These developments lead to a significant increase in precision with respect to an earlier measurement

$m_t = 172.76 \pm 0.81$ GeV.



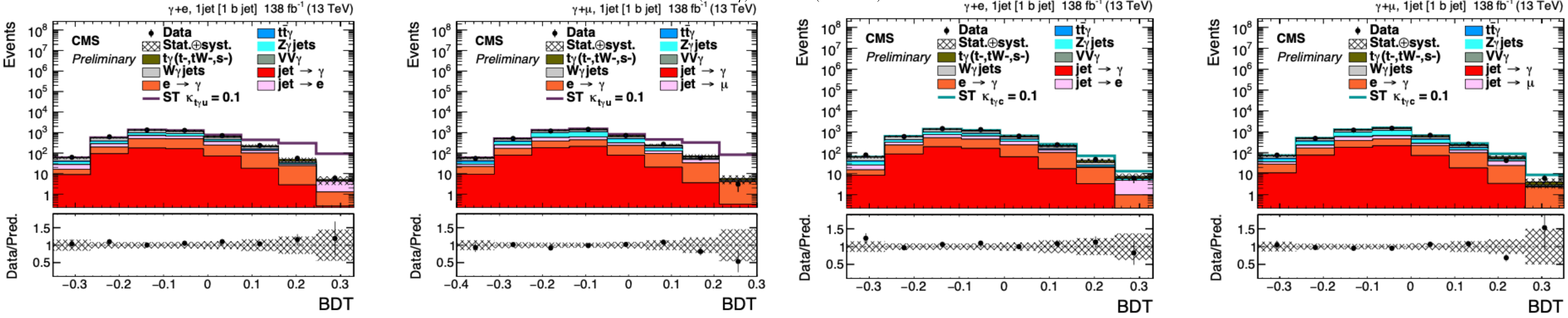


Search for FCNC tqgamma couplings CMS-PAS-TOP-21-013



- The predicted branching fraction for a top quark decaying into an up or a charm quark and a photon is of the order of 10^{-14}
- Within some SM extensions $B(t \to q + \gamma)$, with q = u, c, can be enhanced significantly

$B(t \to c+\gamma) < 1.51\times10^{-5}$ (1.54×10^{-5}) at 95%



No significant deviation is observed over the predicted standard model background.

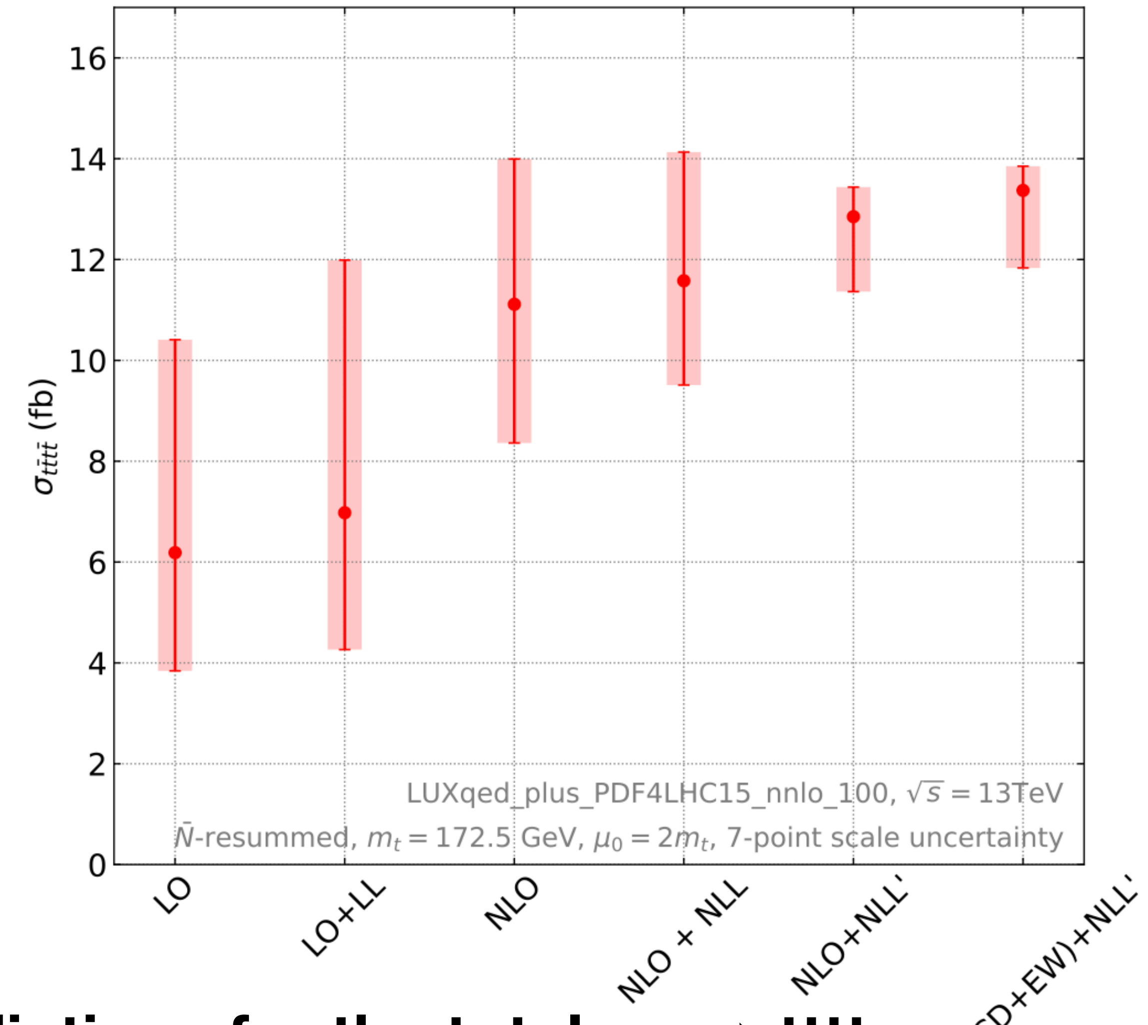
$B(t \to c+\gamma) < 1.51\times10{-5}$ $(1.54 \times 10{-5})$ at 95% and $B(t \to u+\gamma) < 0.95\times10^{-5}$ (1.20×10^{-5})

$t\bar{t}t\bar{t}$ observation

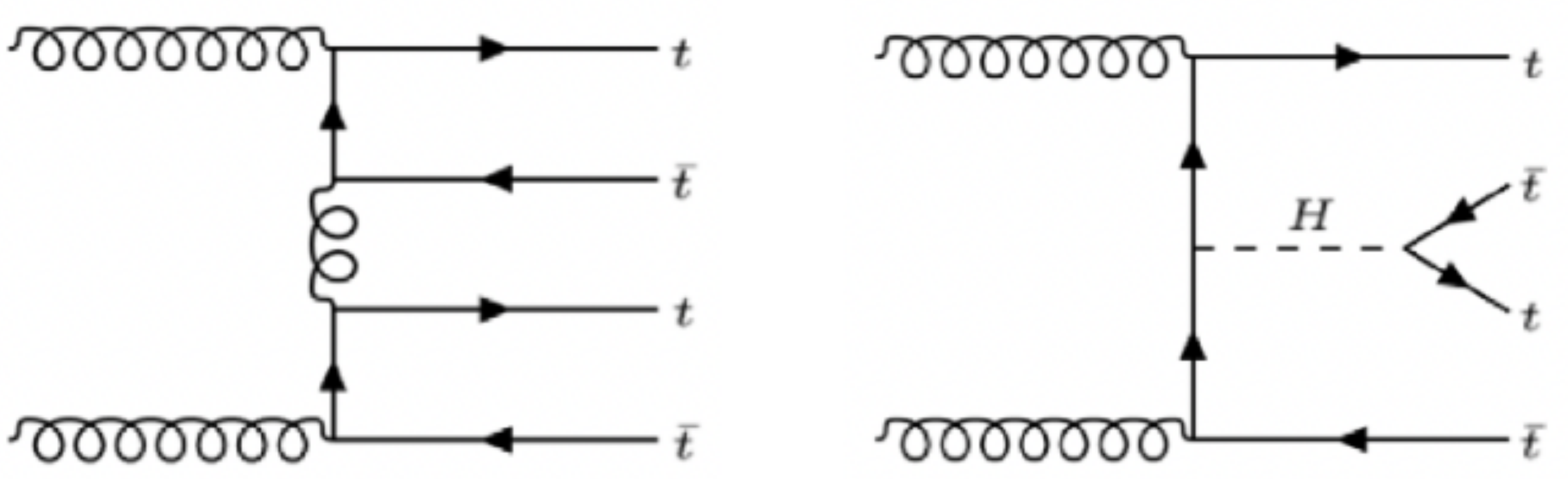
arXiv:2305.13439 (submitted to PLB)

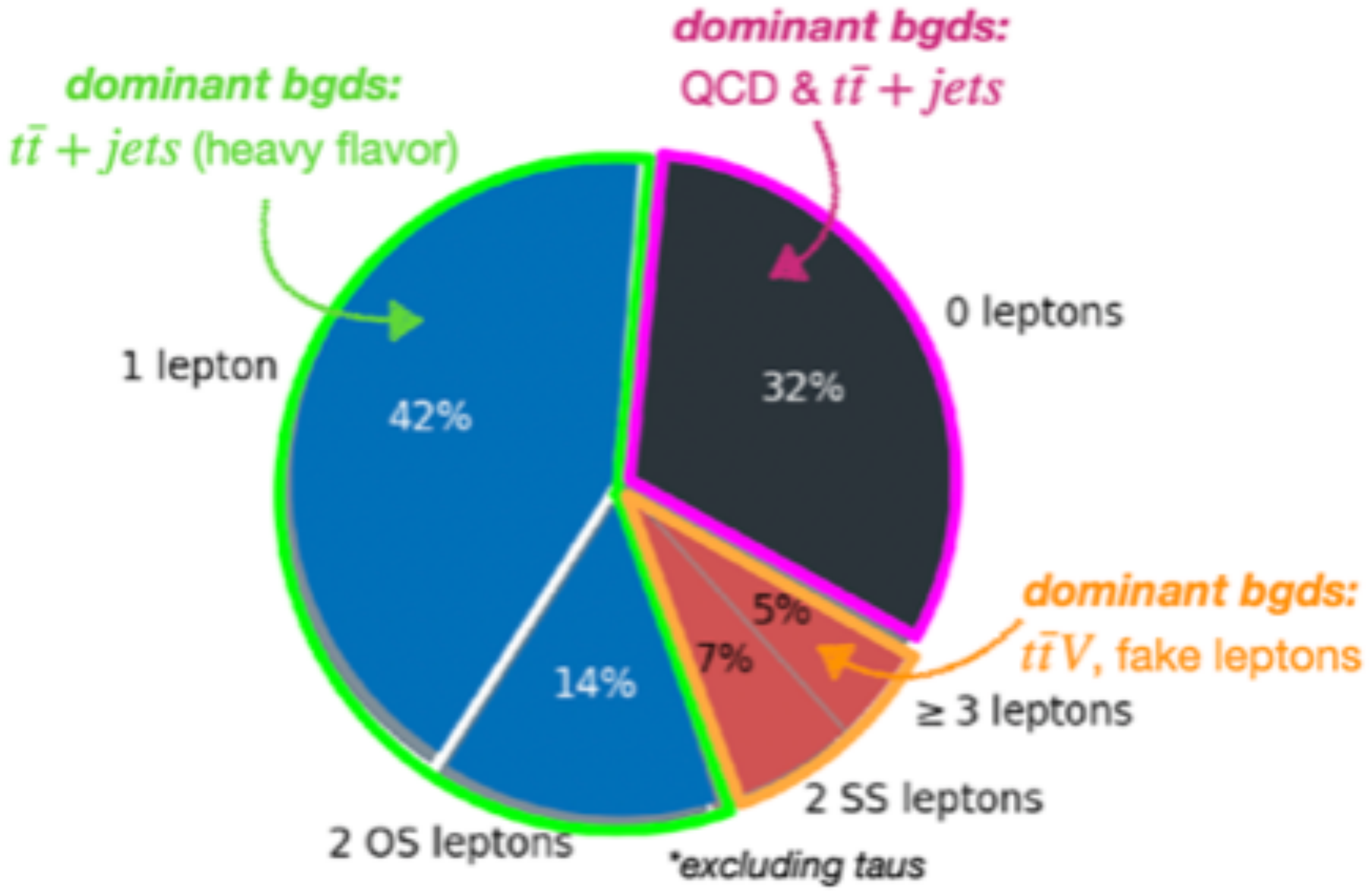
One of rarest Standard Model (SM) production processes currently accessible experimentally at the Large Hadron Collider (LHC

Receive significant contributions in various SM extensions, hence an accurate measurement can set strong constraints on new physics models



Predictions for the total pp → tttt cross section at $\sqrt{s}$ = 13 TeV for fixed-order calculations



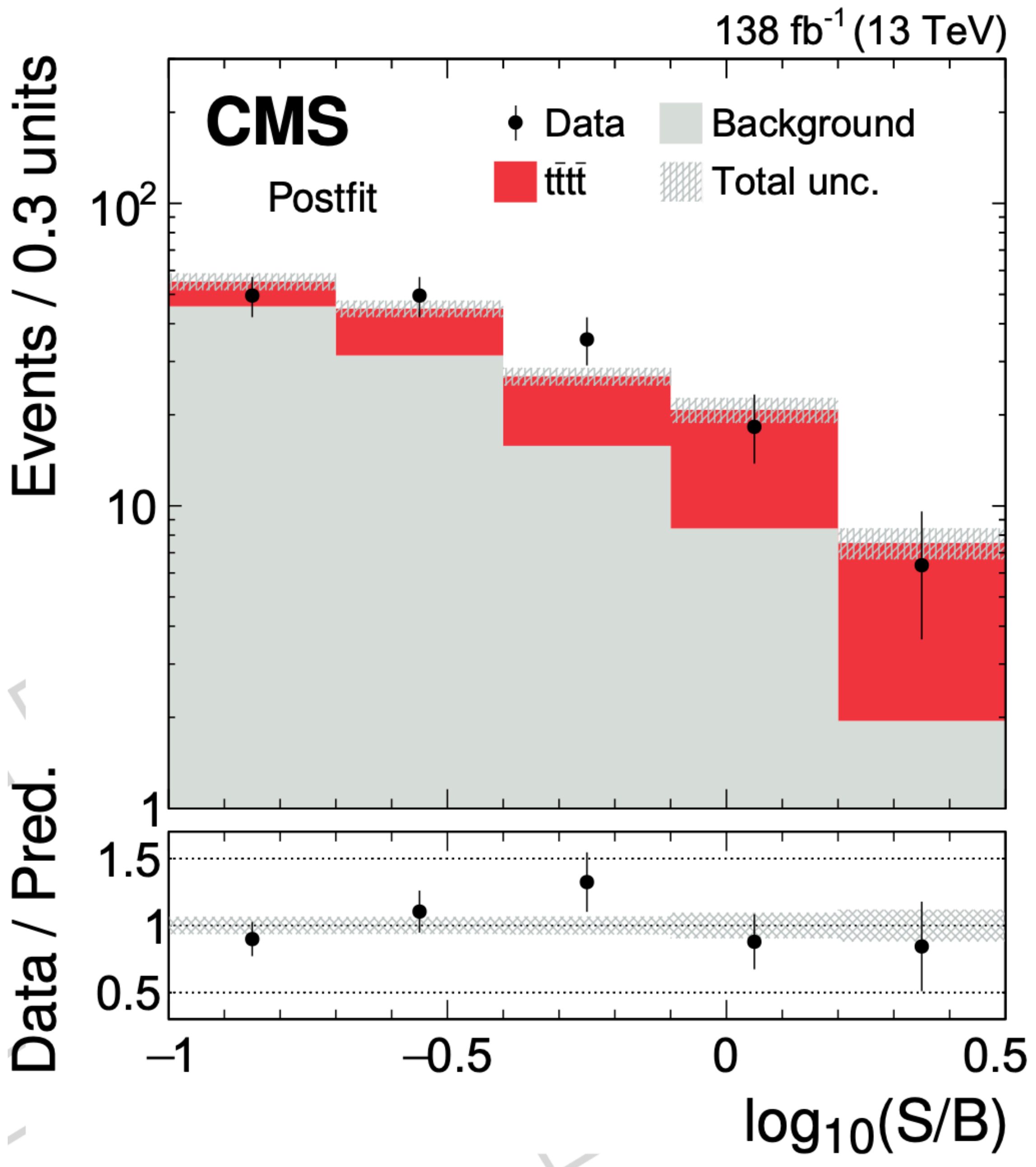


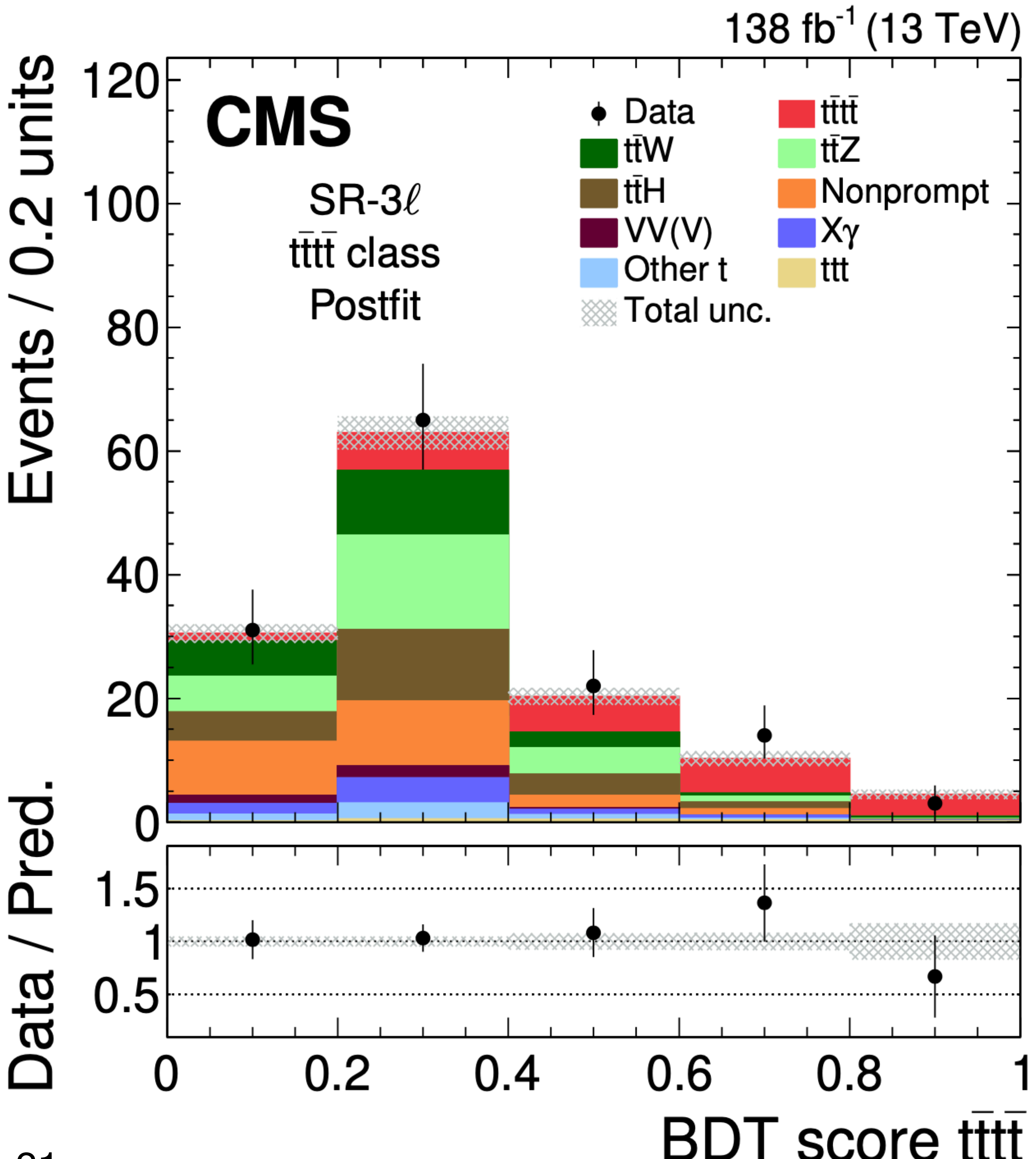
$t\bar{t}t\bar{t}$ observation

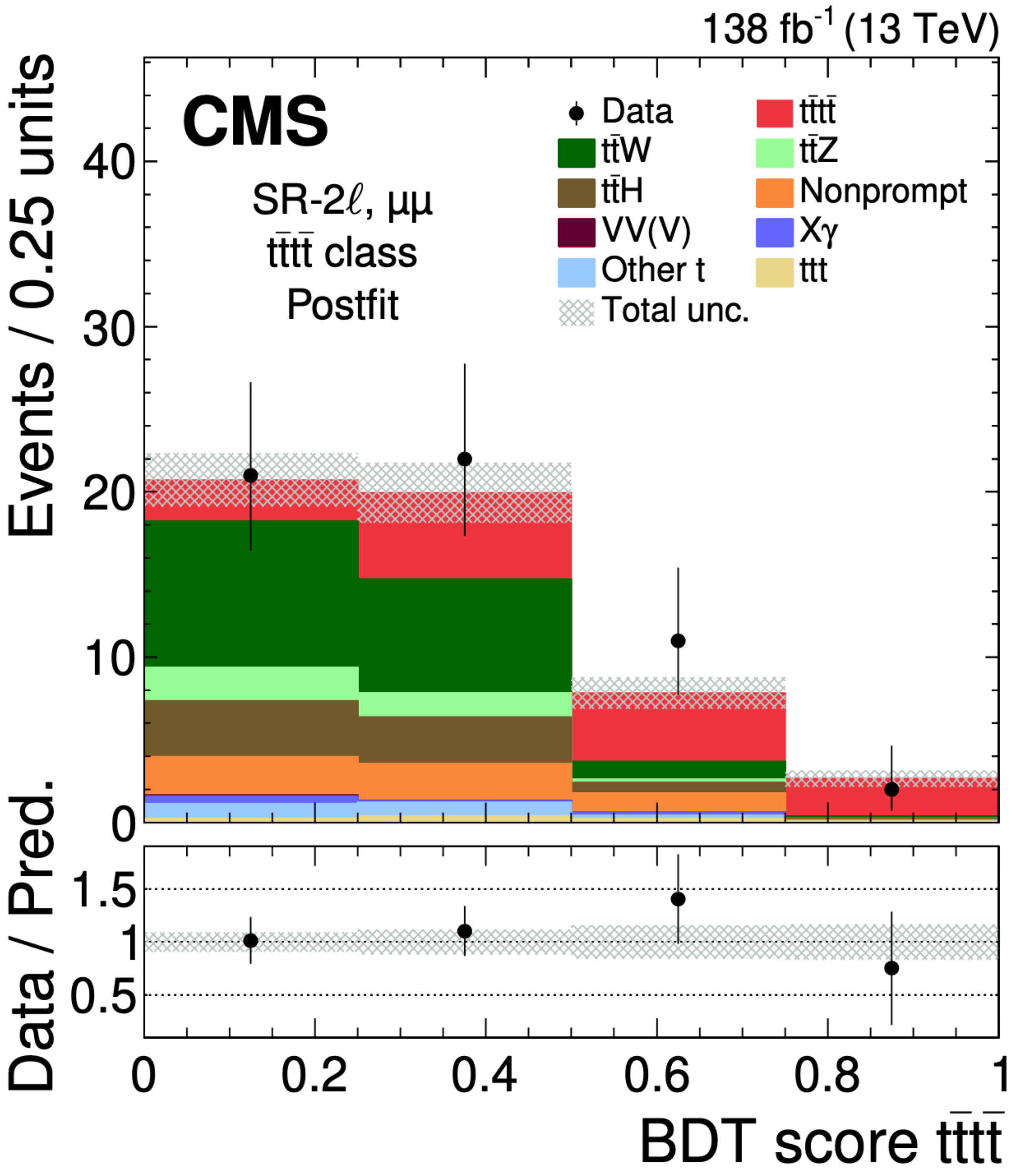
arXiv:2305.13439 (submitted to PLB)

- **CMS had already reported the evidence of $t\bar{t}t\bar{t}$ CMS-TOP-21-005**
- **What changed?**
  - **State-of-the-art machine learning techniques in the lepton identification**
  - **Improvement b-tagging**
  - **Separate multi-class BDTs for the discrimination between signal and background processes**
- **obs (exp) significance : 5.6 (4.9) s.d.**

$$\sigma(\mathrm{tttt}) = 17.7^{+3.7}_{-3.5}\,(\mathrm{stat})^{+2.3}_{-1.9}\,(\mathrm{syst})\ \mathrm{fb}$$







Probing EFT models using tt X

CMS-PAS-TOP-22-006

- **EFT interpretations are becoming more and more popular nowadays:**
  - **Flexible framework to describe the off-shell effects of new physics at a mass scale Λ**
- **This analysis focuses specifically on operators which couple the top quark to leptons, bosons, and other heavy quarks: 26 operators are study in total.**
- **In all cases, the data are found to be consistent with the SM expectations.**