Top quark cross section measurements in CMS

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on behalf of the CMS collaboration

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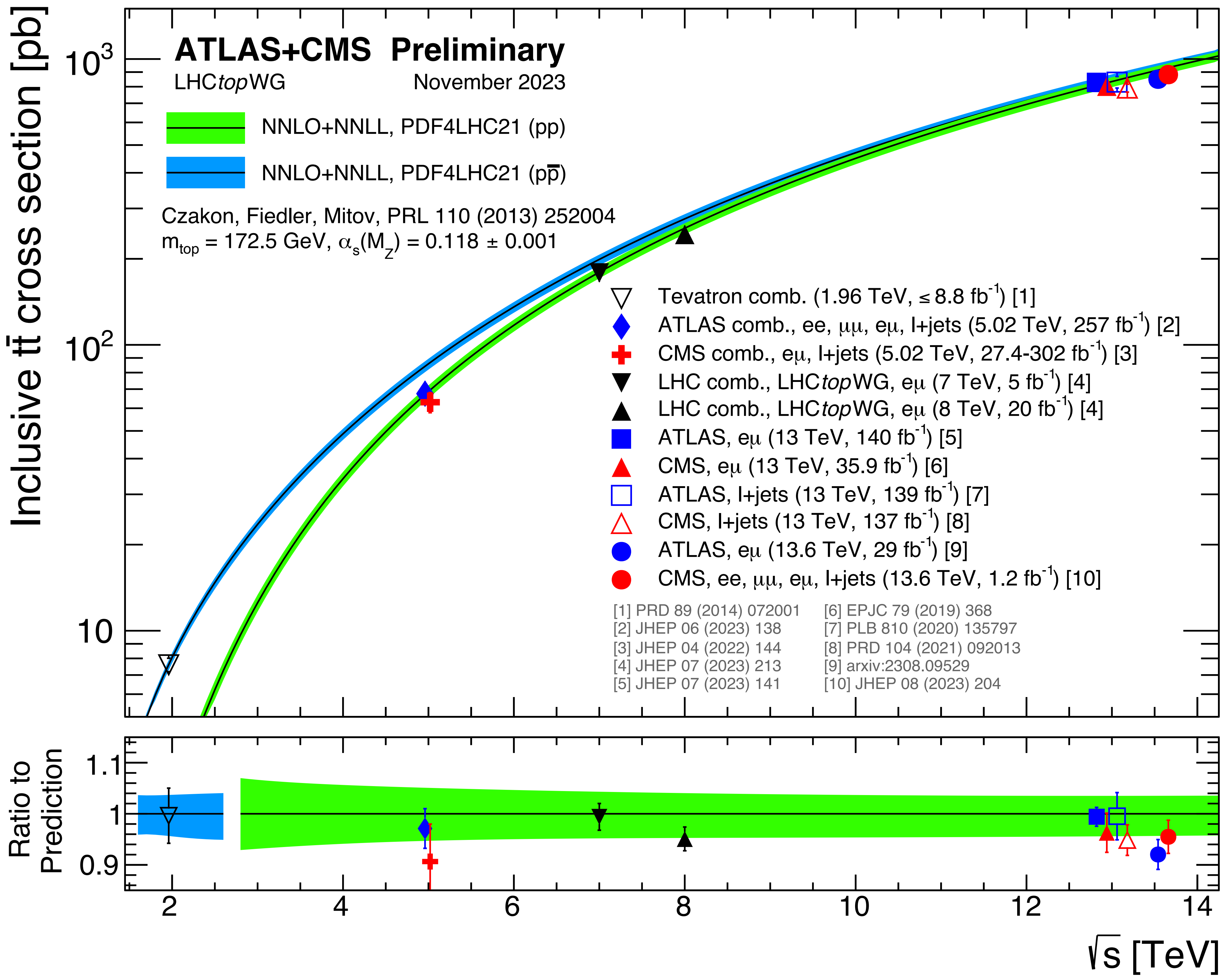
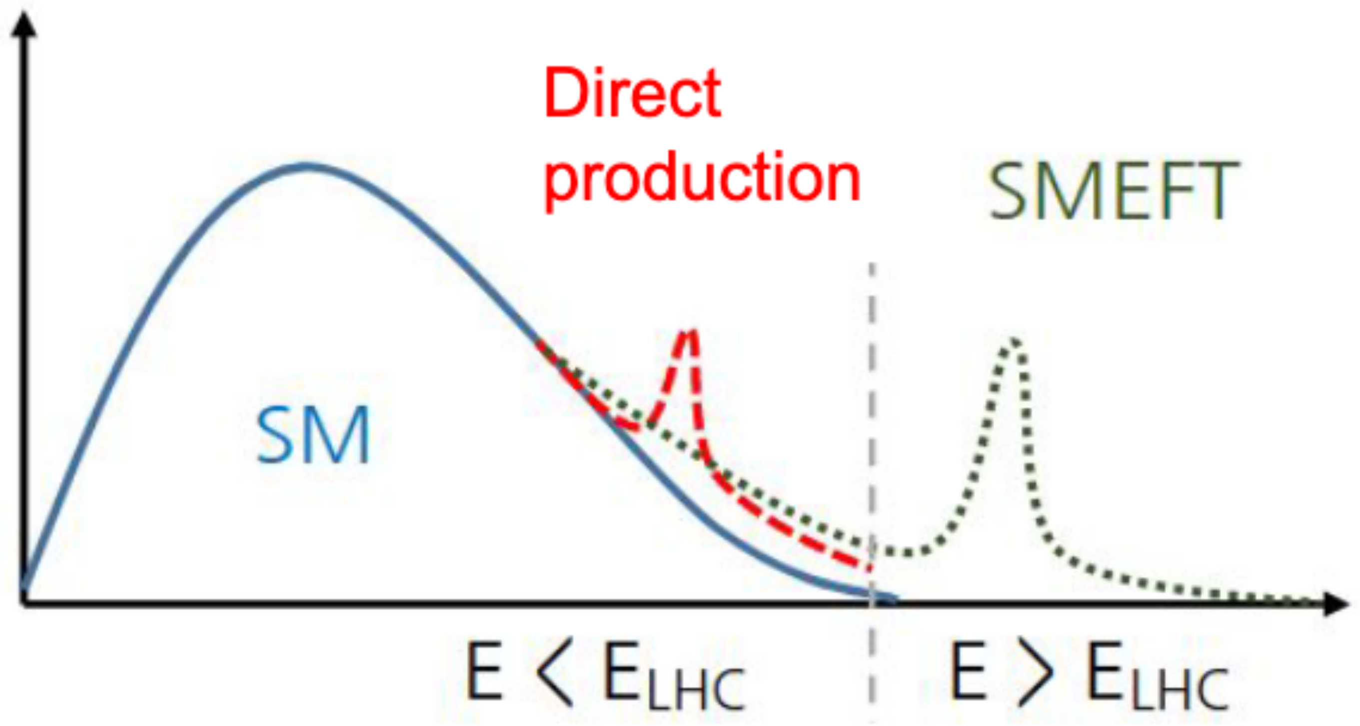
The top quark in the standard model (SM)

- Top quark is the most massive elementary particle
  - High relevance for EWK symmetry breaking (→BSM)
- High production rate at LHC
  - → High precision SM measurements, e.g. for $\sigma_{t\bar{t}}$
- Cross section measurements are a powerful probe of
  - → Perturbative calculations
  - → Modeling and Monte-Carlo (MC) generators
- And have a high importance as backgrounds for searches
  - → Portal to beyond-the SM (BSM) physics

[LHC Top WG]





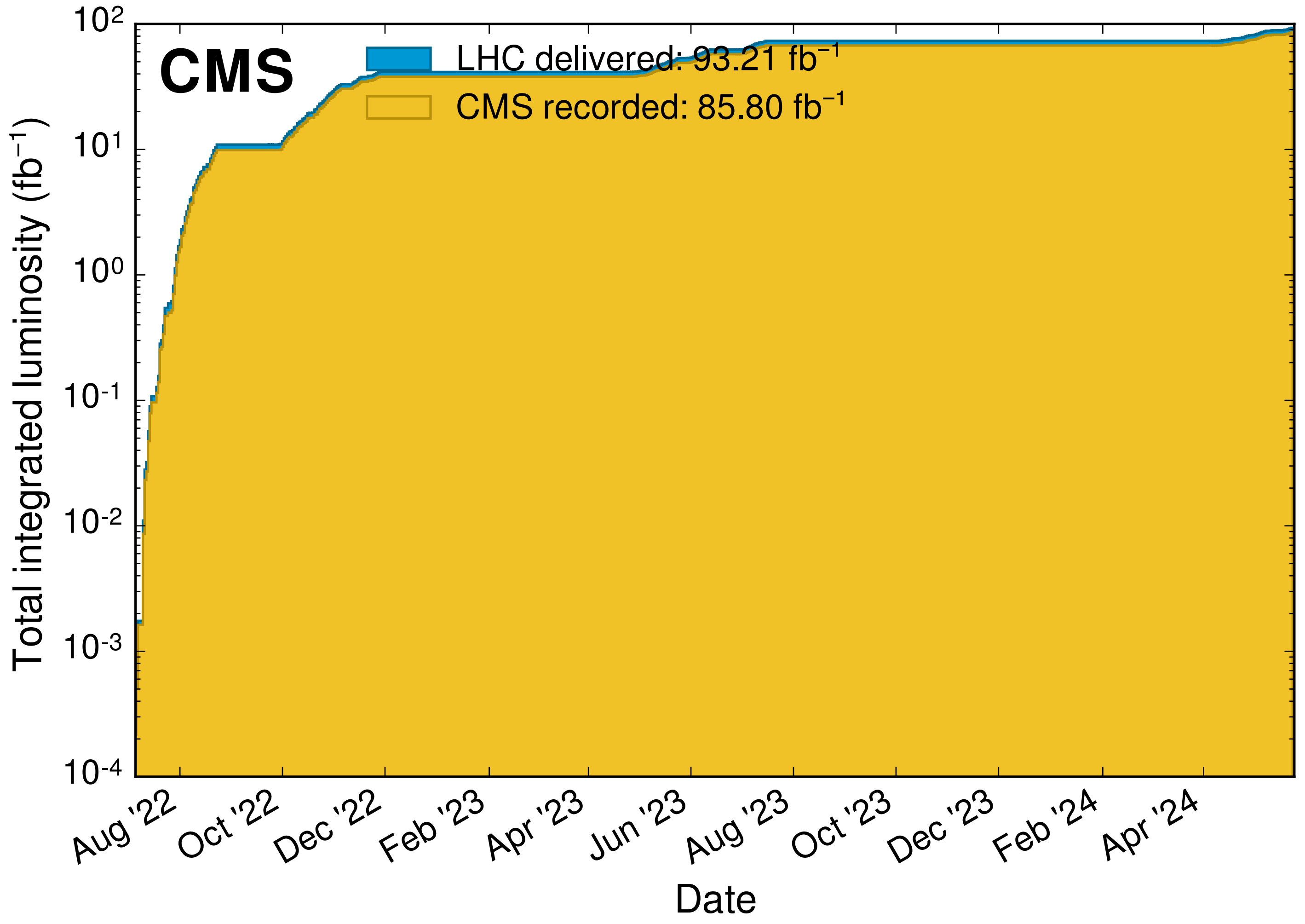
$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathscr{O}_i$$

- This is not yet-another “13 TeV” summary talk:
  - → LHC Run 3 is here!
  - → Looking into 13.6 TeV and 5.02 TeV pp data

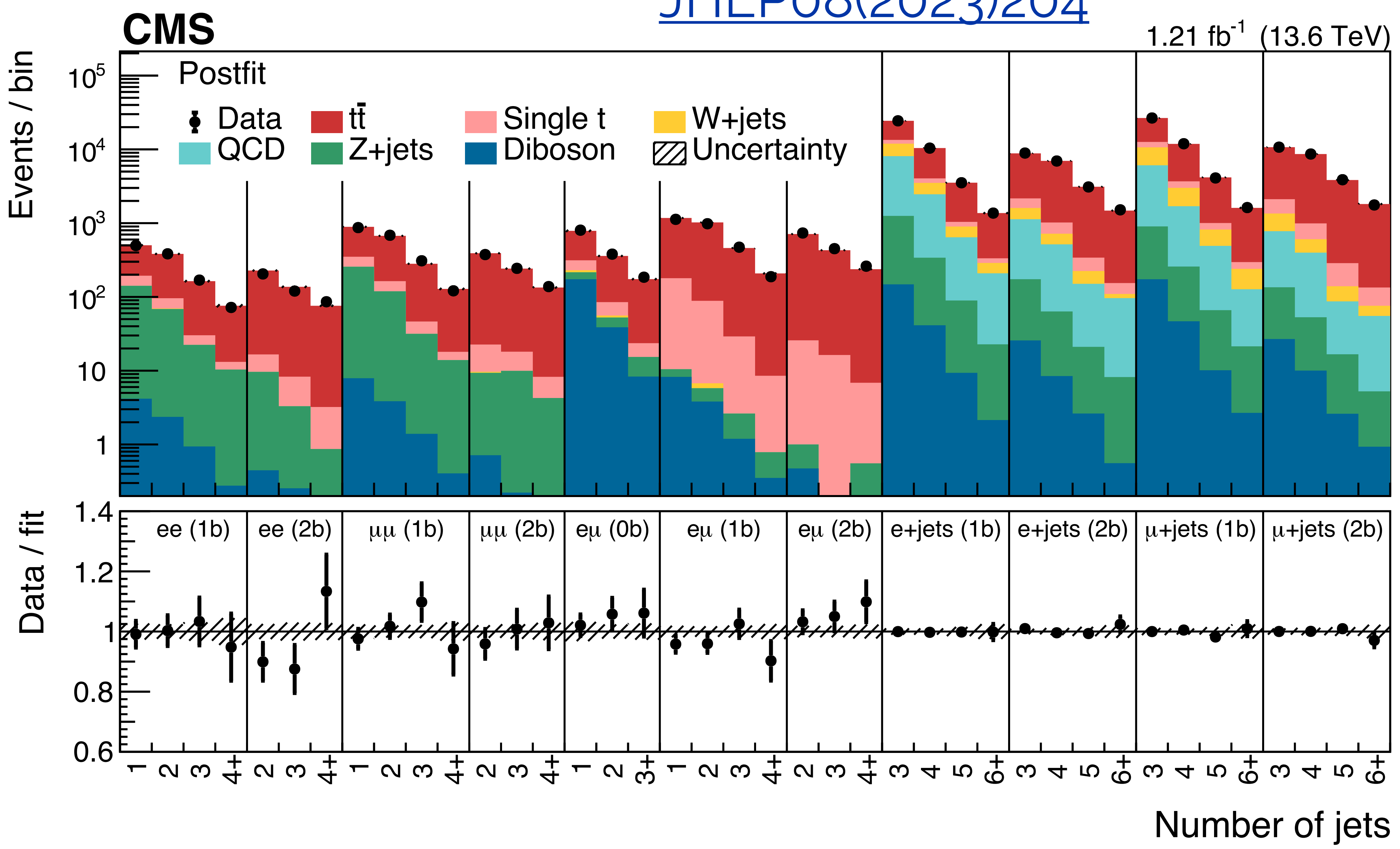
Measurements at 13.6 TeV

- (Early) LHC Run 3 measurements are important:
  - Testing new data and experimental calibrations
  - Validate agreement of theoretical predictions with measurements
    - Is the modeling of Monte-Carlo simulation still good?
    - Does the cross section evolve as expected with $\sqrt{s}$?
  - Important for SM physics but also searches!
    - E.g. $t\bar{t}$ and tW are important backgrounds

- CMS recorded ~85 fb^{-1} of Run 3 data
  - 34.7 fb^{-1} for 2022



JHEP08(2023)204



- Very first Run 3 measurement:
  - Small subset of data (1.2 fb^{-1})
  - Inclusive $t\bar{t}$ cross section
  - Lepton+jets + dilepton channels
  - In-situ efficiency constraints
  - σ_{tt} = 881 ± 23 (stat. + syst.) ± 20 (lumi) pb
    ~3.5% rel precision

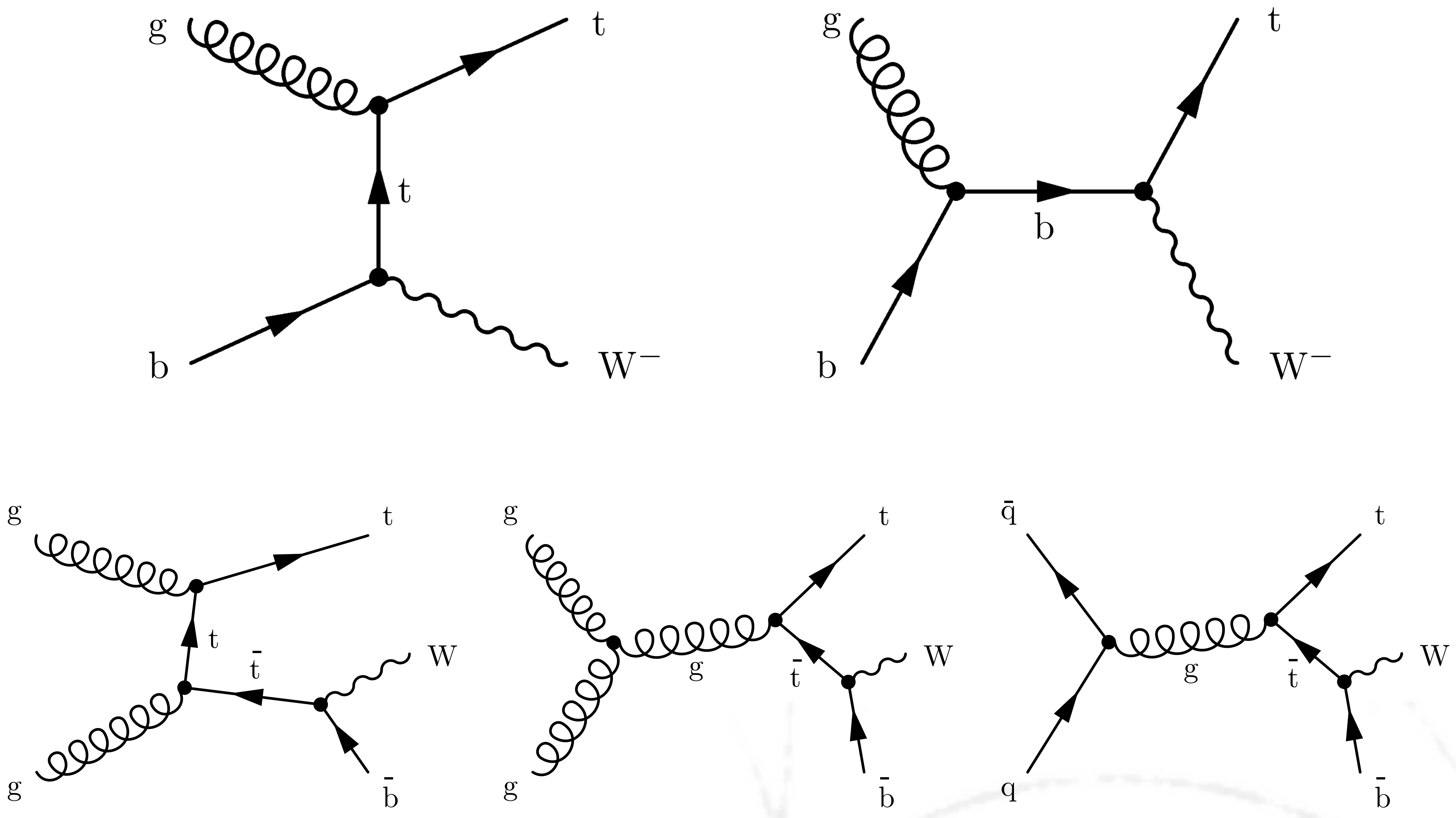
tW cross section at 13.6 TeV

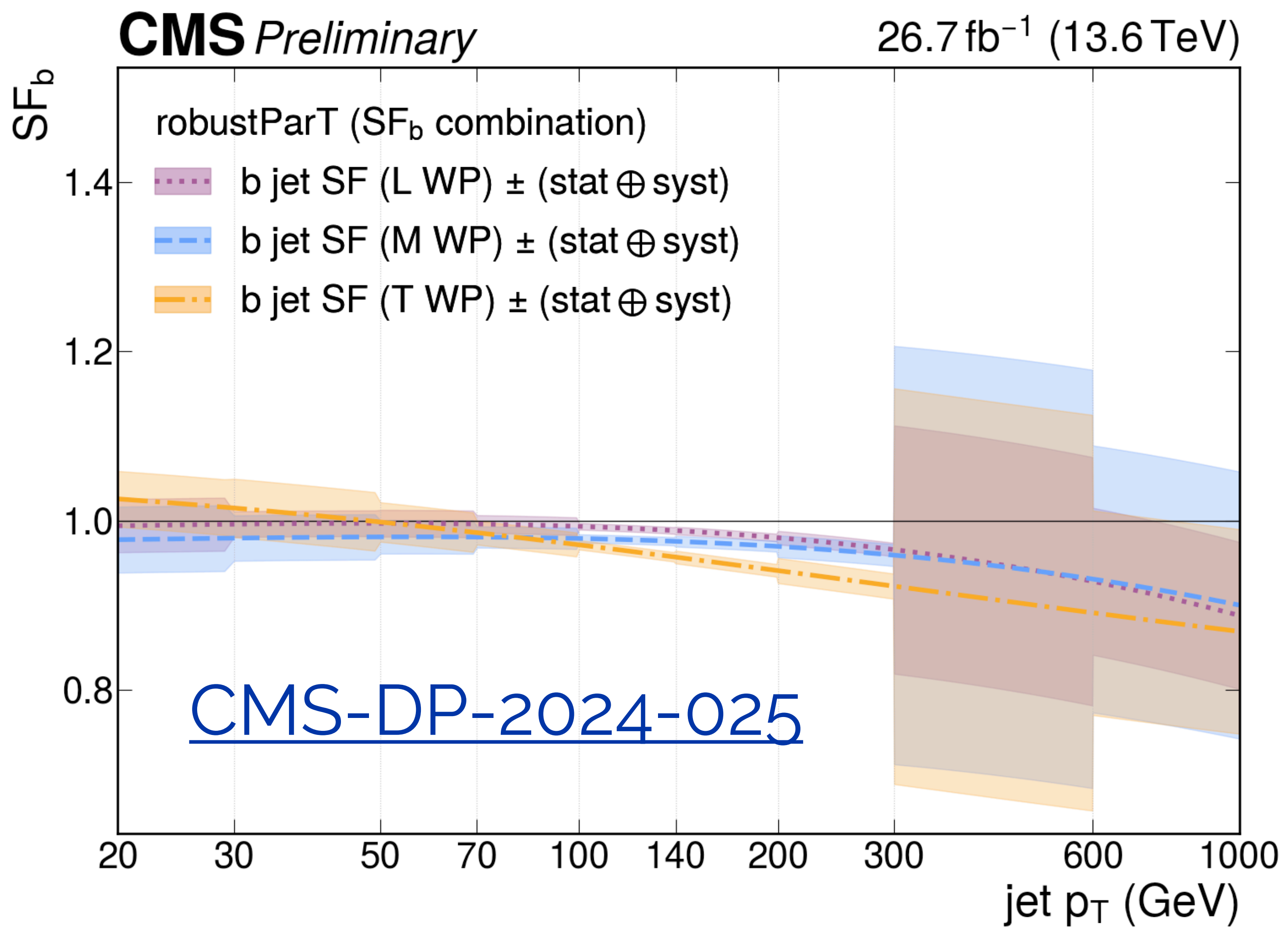
CMS-PAS-TOP-23-008

- **First single top measurement at Run 3**
  - Data collected in 2022, 34.7 fb^{-1}

- Based on previous measurements
  - Inclusive and differential with full Run 2 [JHEP 07 (2023) 046]
  - Inclusive. [CMS-PAS-TOP-19-003] and differential [JHEP 10 (2018) 117] partial Run 2

- Challenges:
  - $t\bar{t}$ is the dominant background
  - **NLO interference** between tW signal and background: Diagram removal (DR) and subtraction (DS)
    - Measurement performed using leptonic final state:
      - Two leptons (1 electron and 1 muon) - opposite charge
      - At least one jet
        - – b-jet identification using new Run 3 algorithm





CMS-DP-2024-025

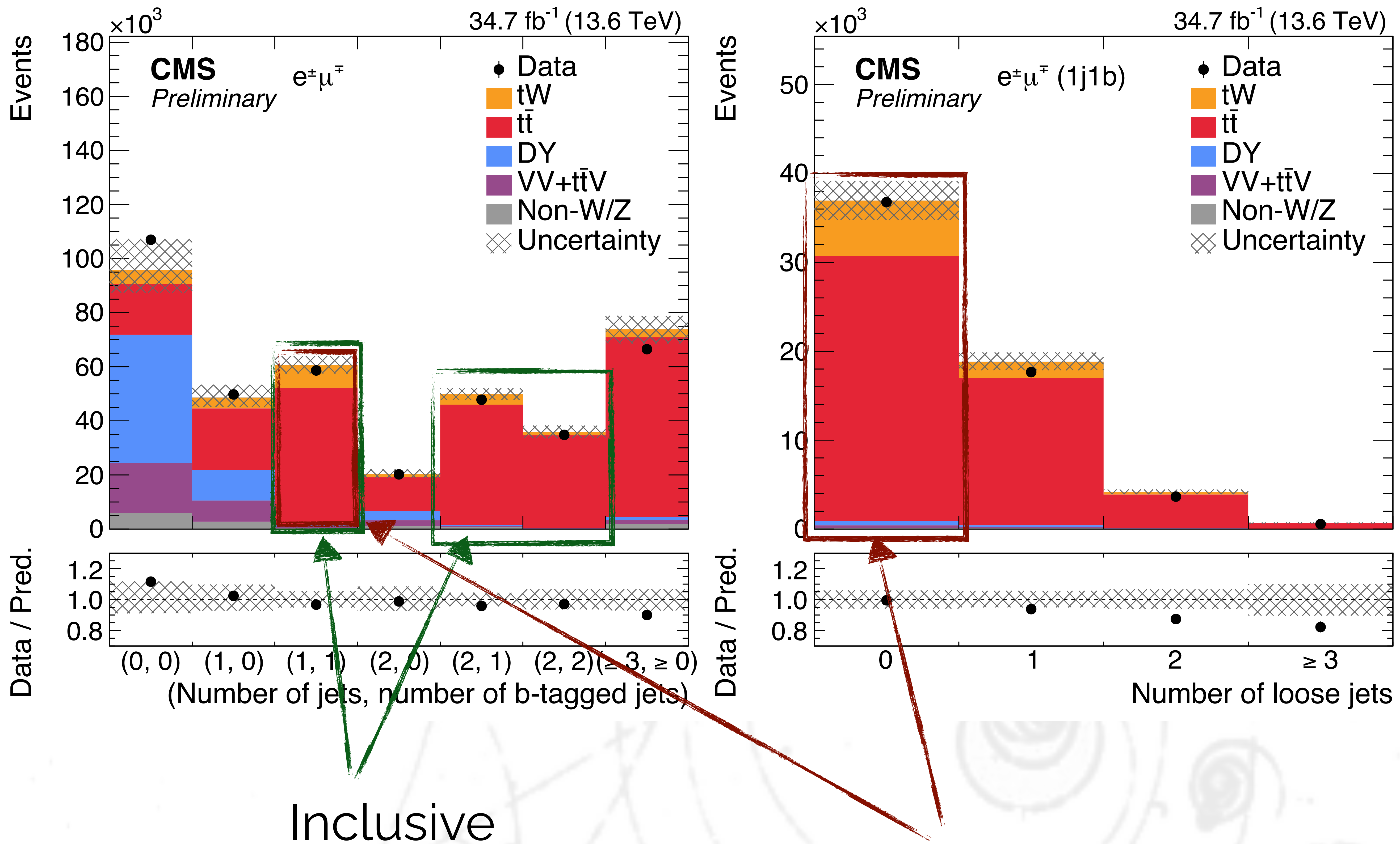
tW cross section at 13.6 TeV

CMS-PAS-TOP-23-008

Process	1j1b	2j1b	2j2b
tW	8 200 ± 300	3 710 ± 160	1 160 ± 70
$t\bar{t}$	48 900 ± 300	42 300 ± 200	33 350 ± 160
Drell–Yan	670 ± 60	320 ± 40	42 ± 7
$VV+t\bar{t}V$	460 ± 50	450 ± 70	190 ± 30
Non-W/Z	430 ± 90	1 050 ± 140	90 ± 20
Total	58 660 ± 160	47 800 ± 140	34 840 ± 130
Data	58 635	47 810	34 818

- Separate strategy for inclusive and differential measurements:
  - Inclusive measurement using likelihood fit in
    - **Signal regions (SR): 1j1b, 2j1b**
    - **And control region (CR): 2j2b**
  - Differential measurement in high-purity 1j1b SR plus no additional jet w/ p_T [20 GeV, 30 GeV]
    - Using TUnfold after background subtraction
    - For 6 observables:

Leading lepton p_T	$p_z(e, \mu, \text{jet})$
Jet p_T	$m(e, \mu, \text{jet})$
$\Delta\phi(e, \mu)$	$m_T(e, \mu, \text{jet}, p_T^{miss})$



Inclusive

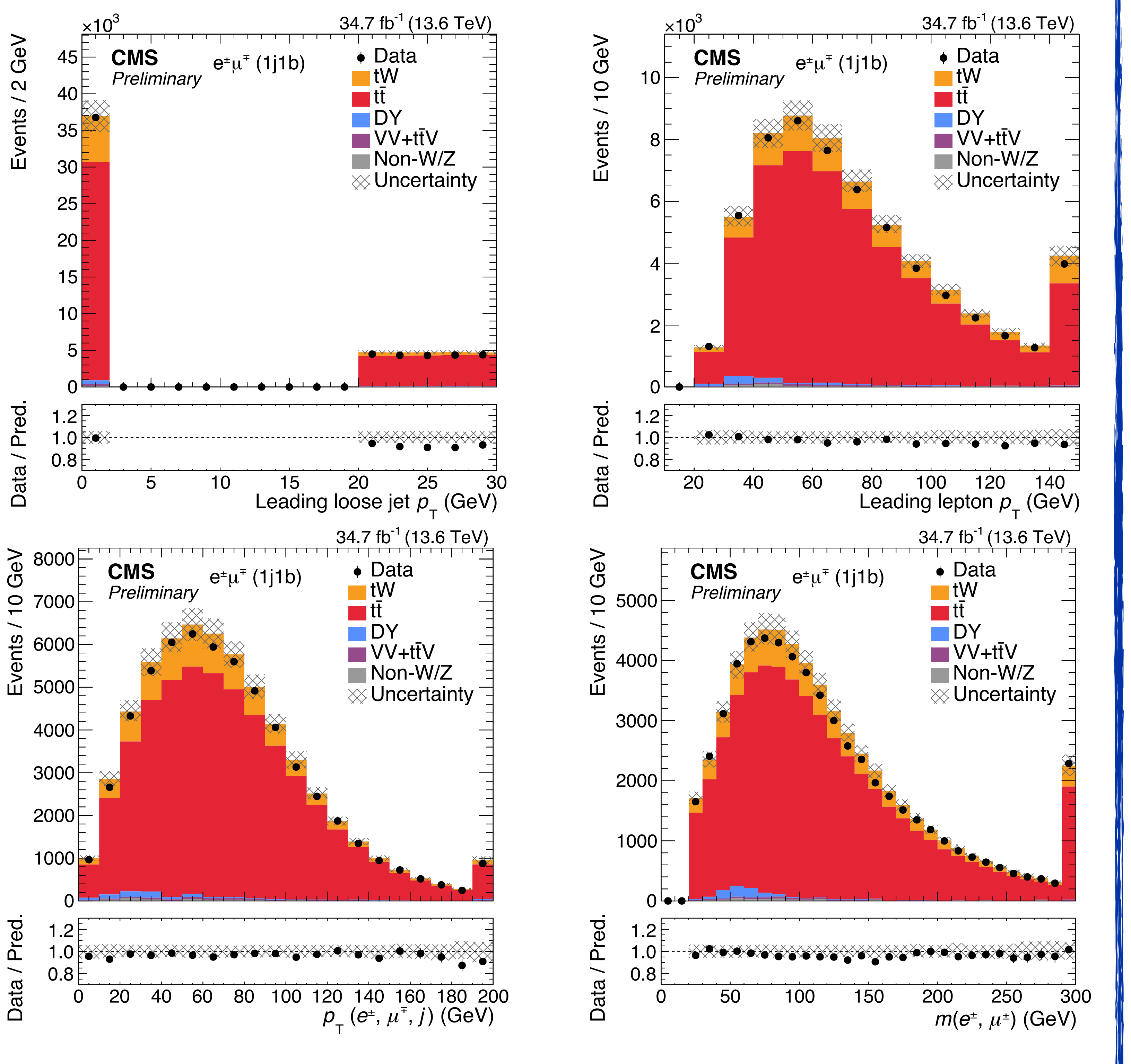
Differential

tW cross section at 13.6 TeV - Inclusive

CMS-PAS-TOP-23-008

- Exploit **multivariate analysis (MVA)** methods for signal vs. background discrimination
- Fit the subleading jet p_T to constrain JES

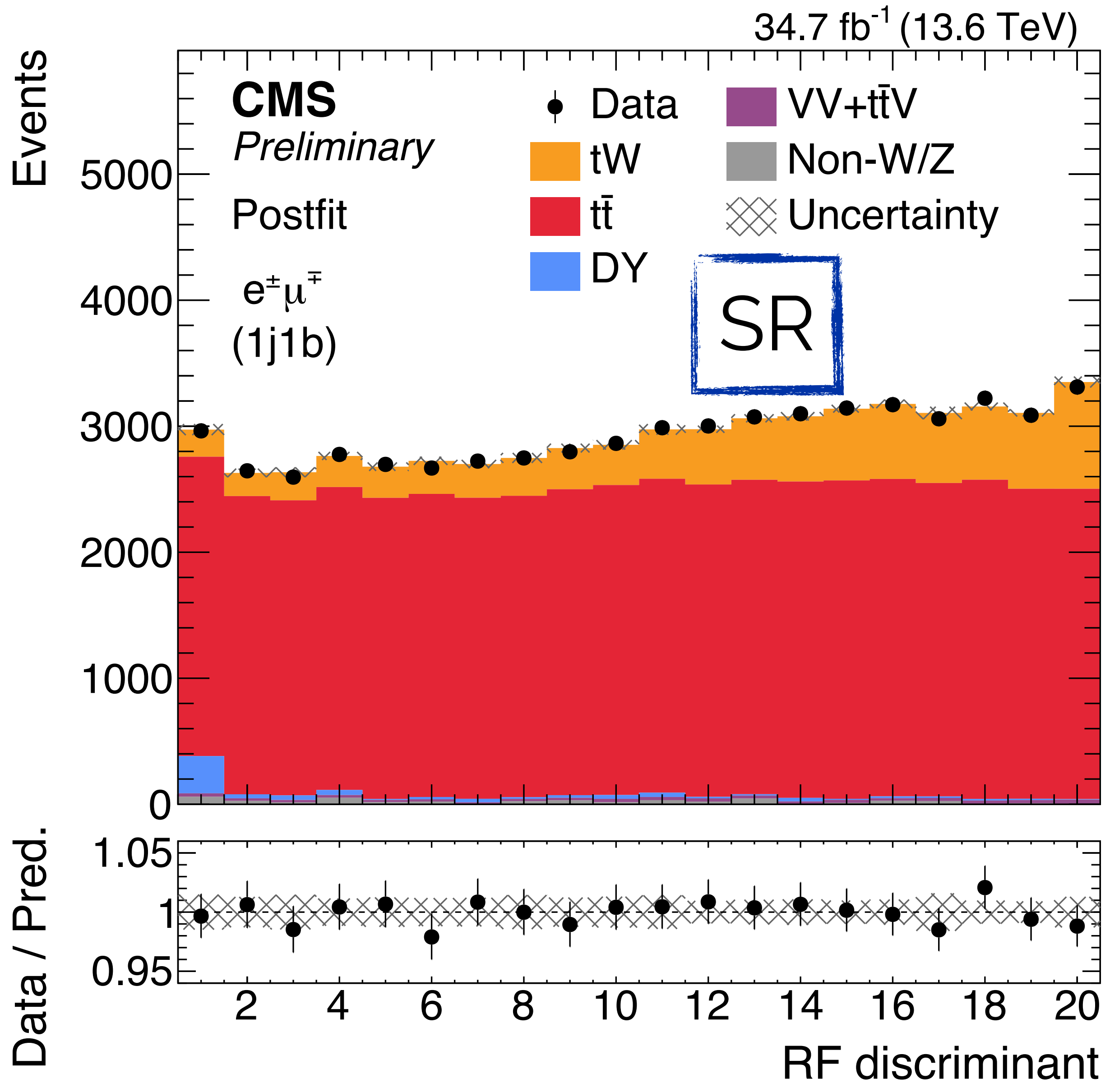
Four most important variables

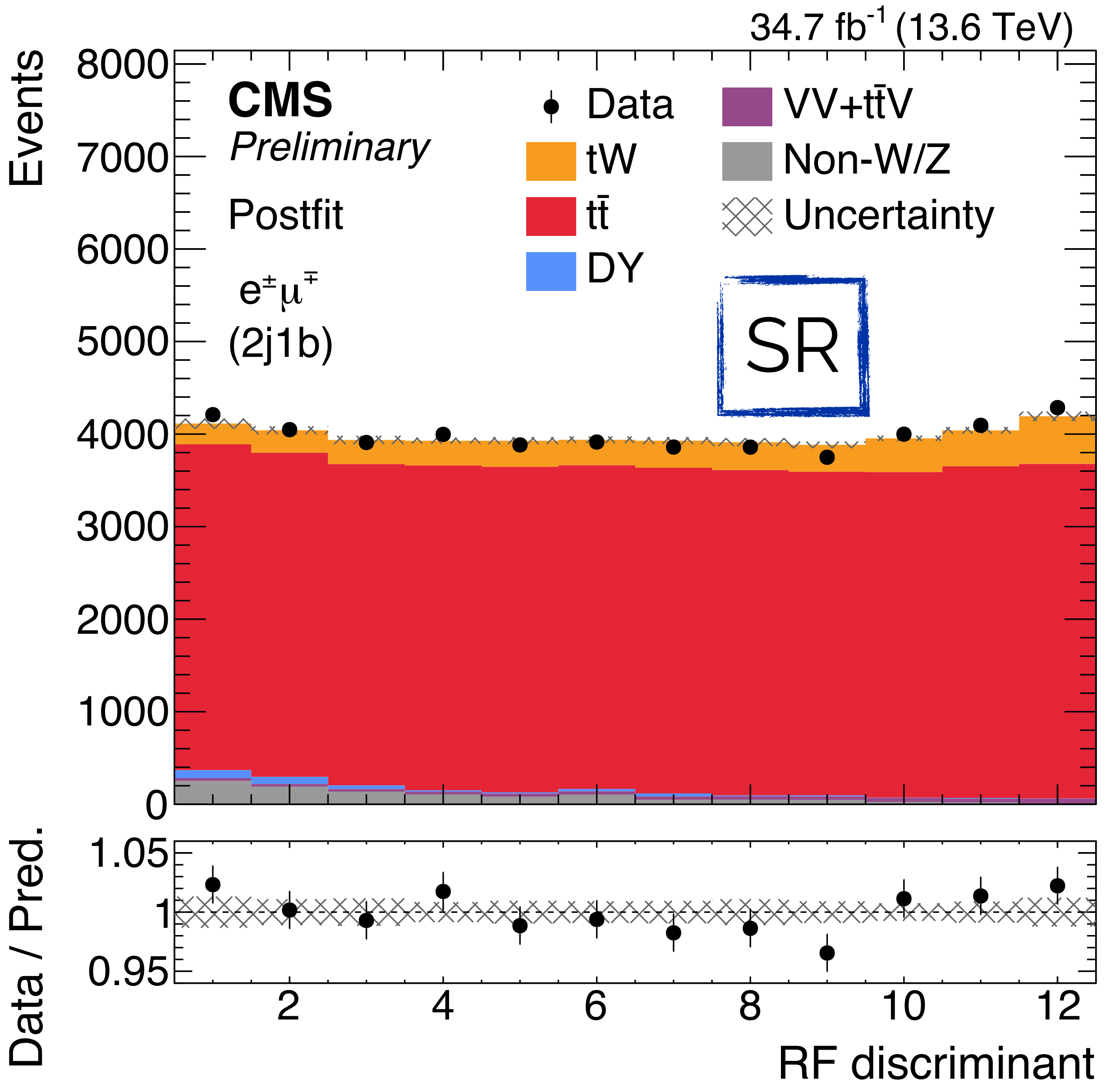


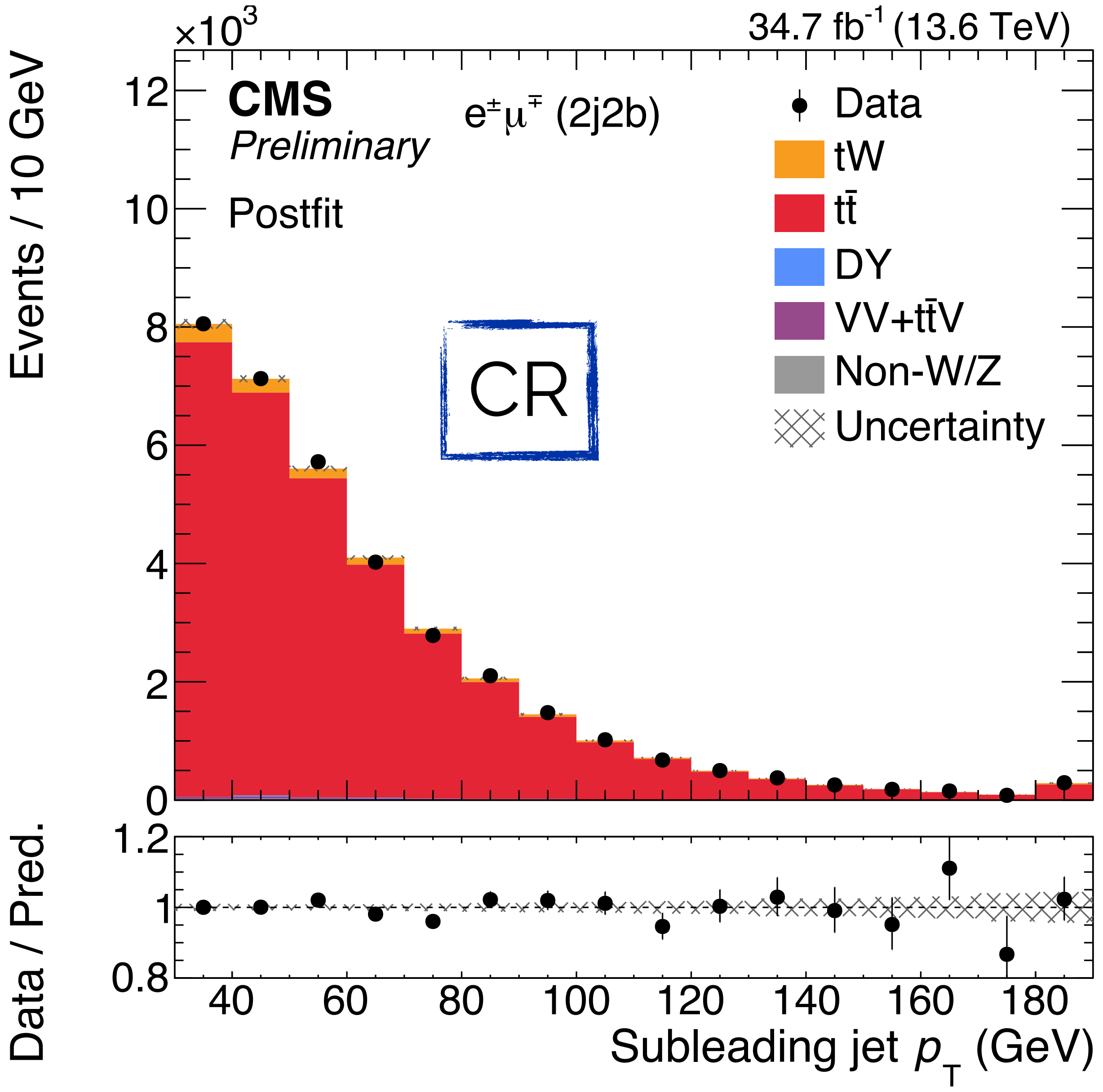
NB: Data / MC statistically tested

8 variables: kinematic variables such as p_T and m

MVAs: Random forest (RF) in 1j1b and 2j1b

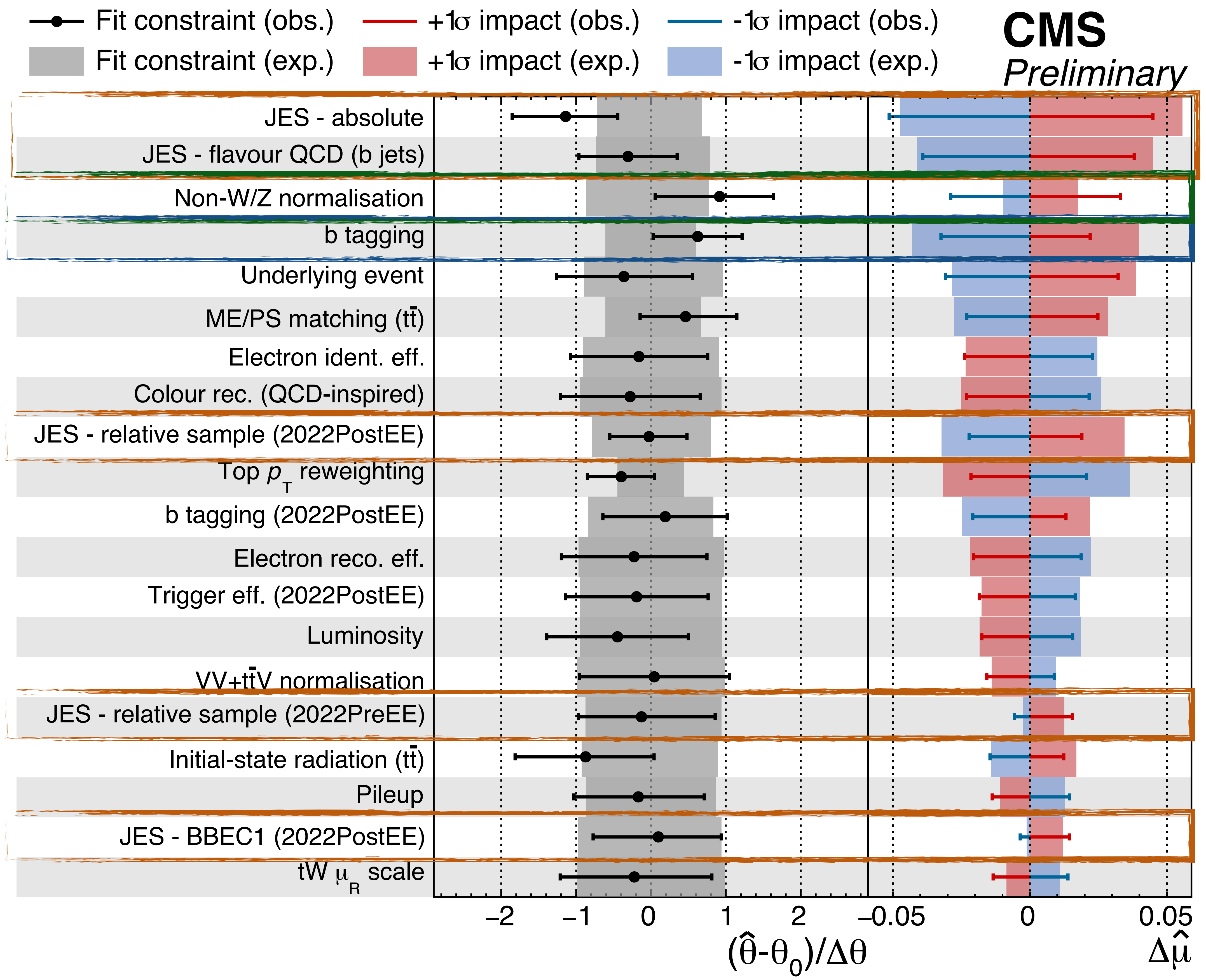


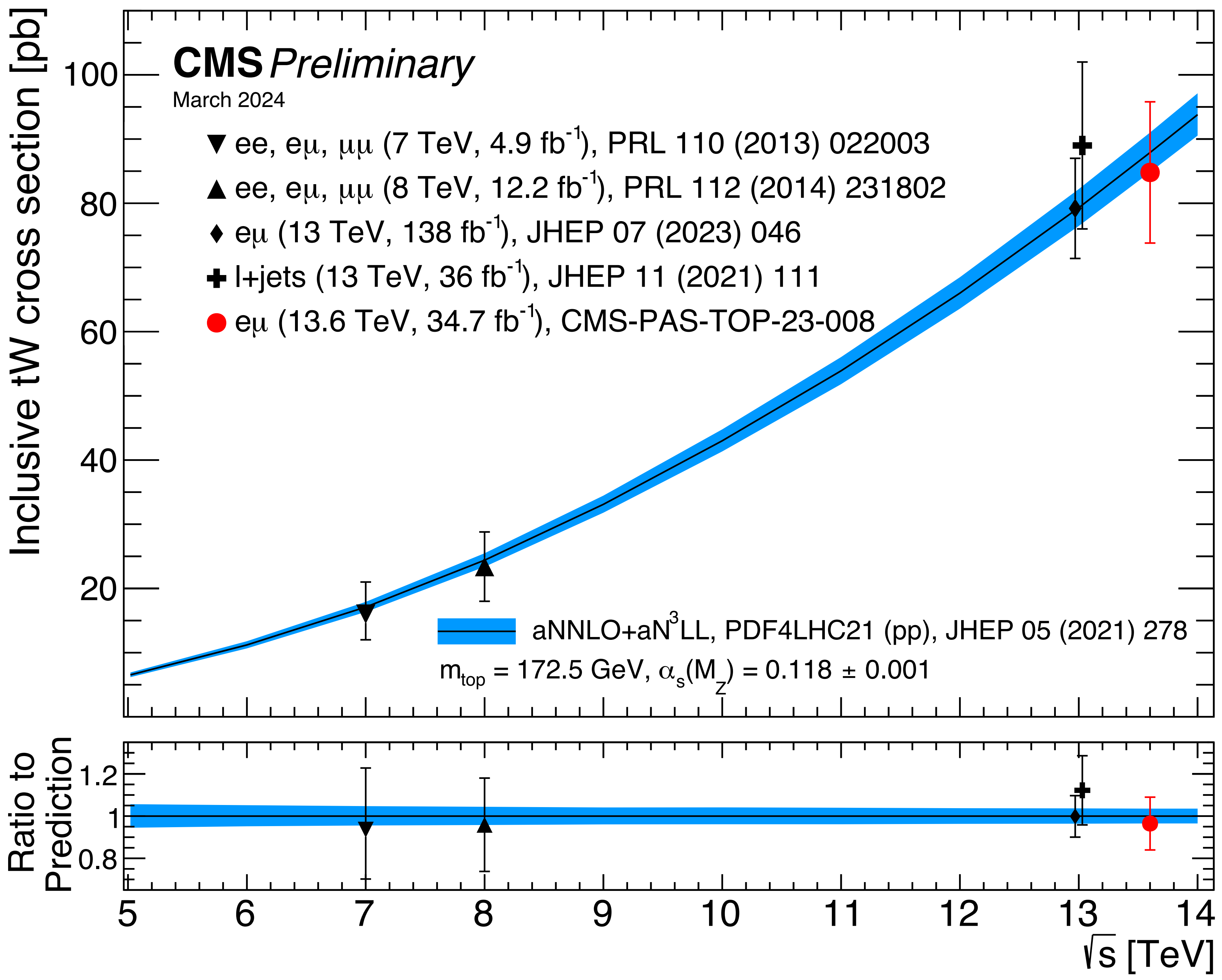




tW cross section at 13.6 TeV - Inclusive

CMS-PAS-TOP-23-008





Observation: 84.1 ± 2.1 (stat) $^{+9.8}_{-10.2}$ (syst) ± 3.3 (lum) pb

Prediction: 87.9 $^{+2.0}_{-1.9}$ (scale) ± 2.4 (PDF+α_S) pb

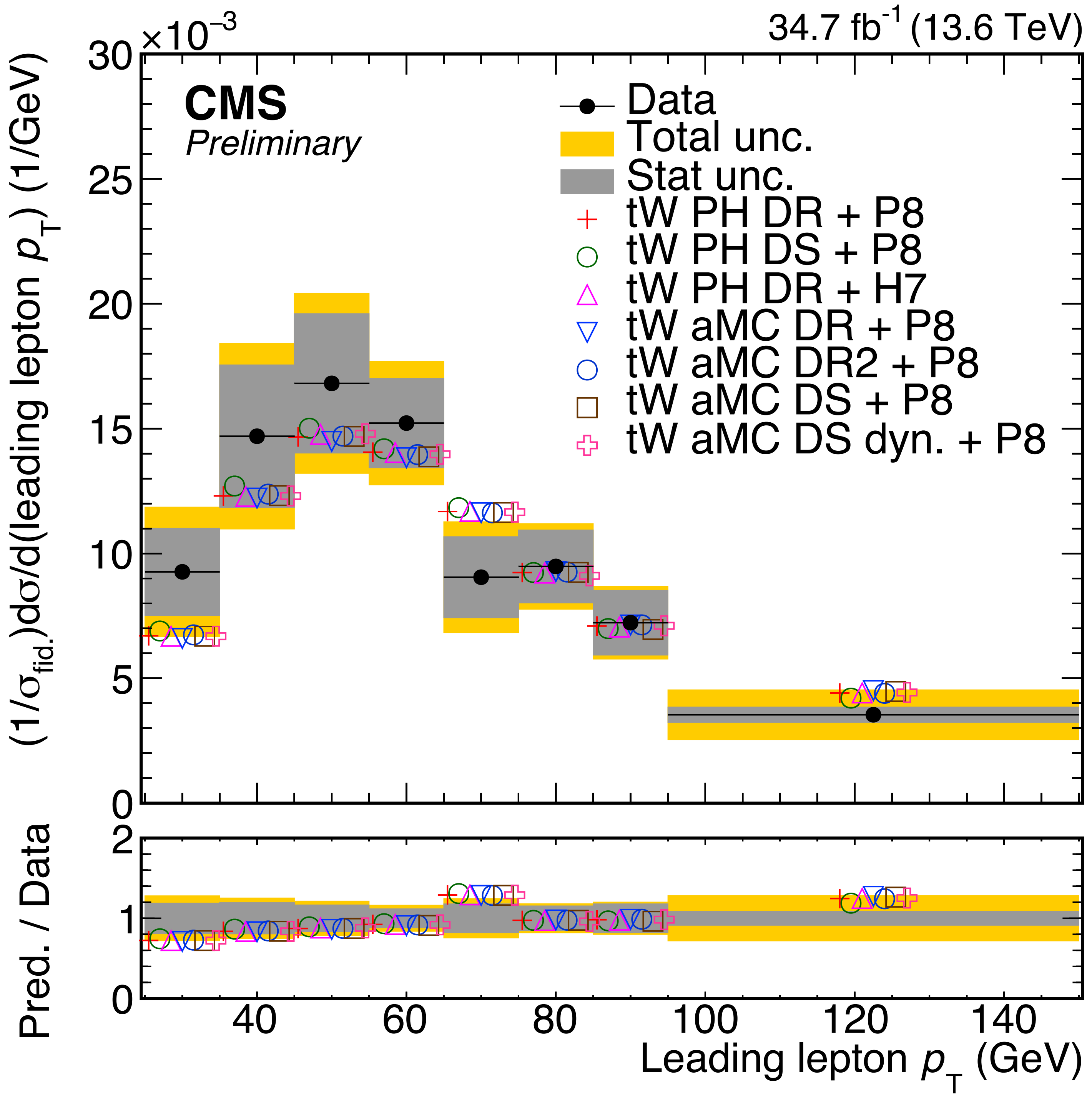
Kidonakis, Yamanaka @ aN^{3}LO

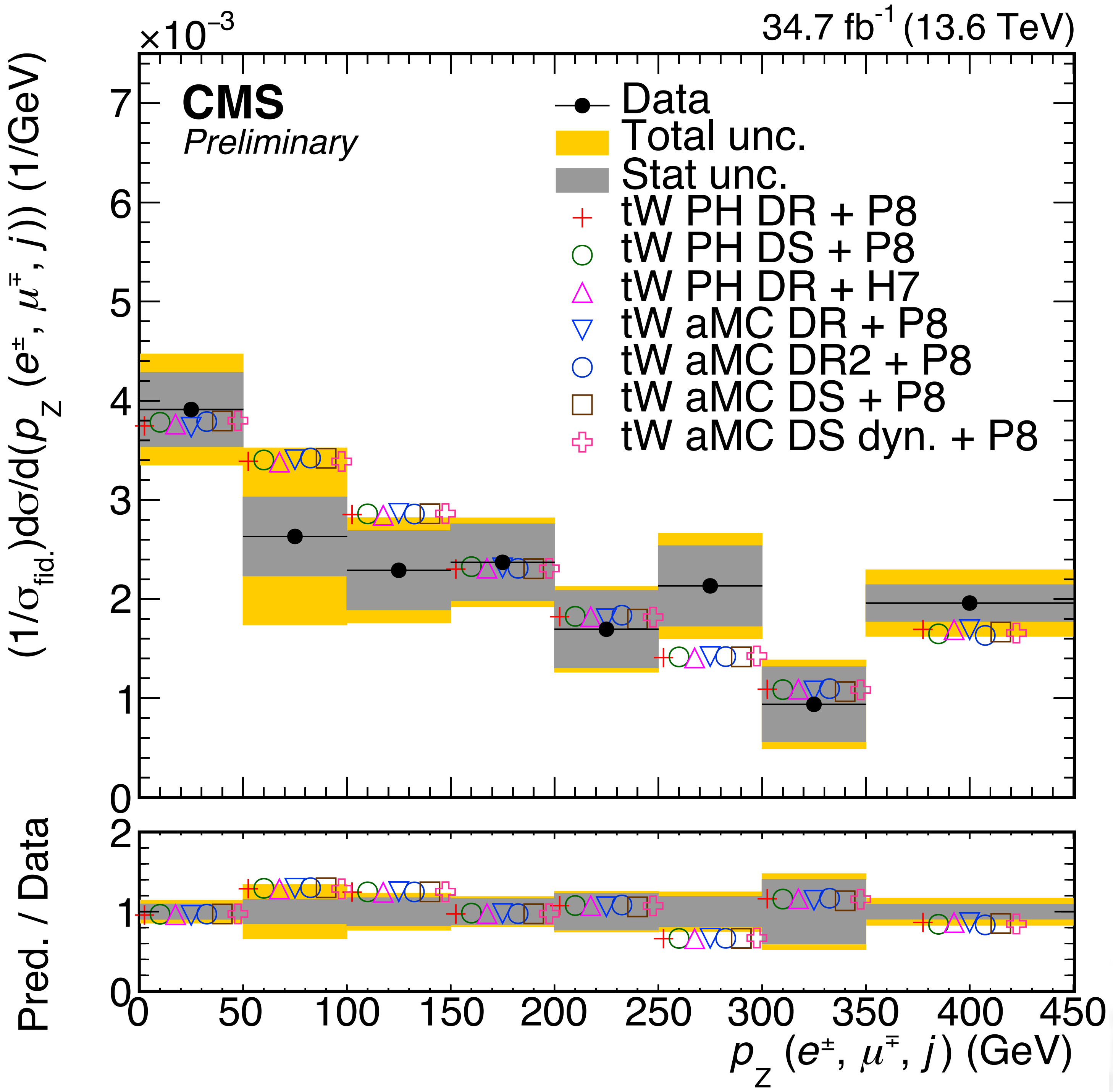
~13% rel. precision

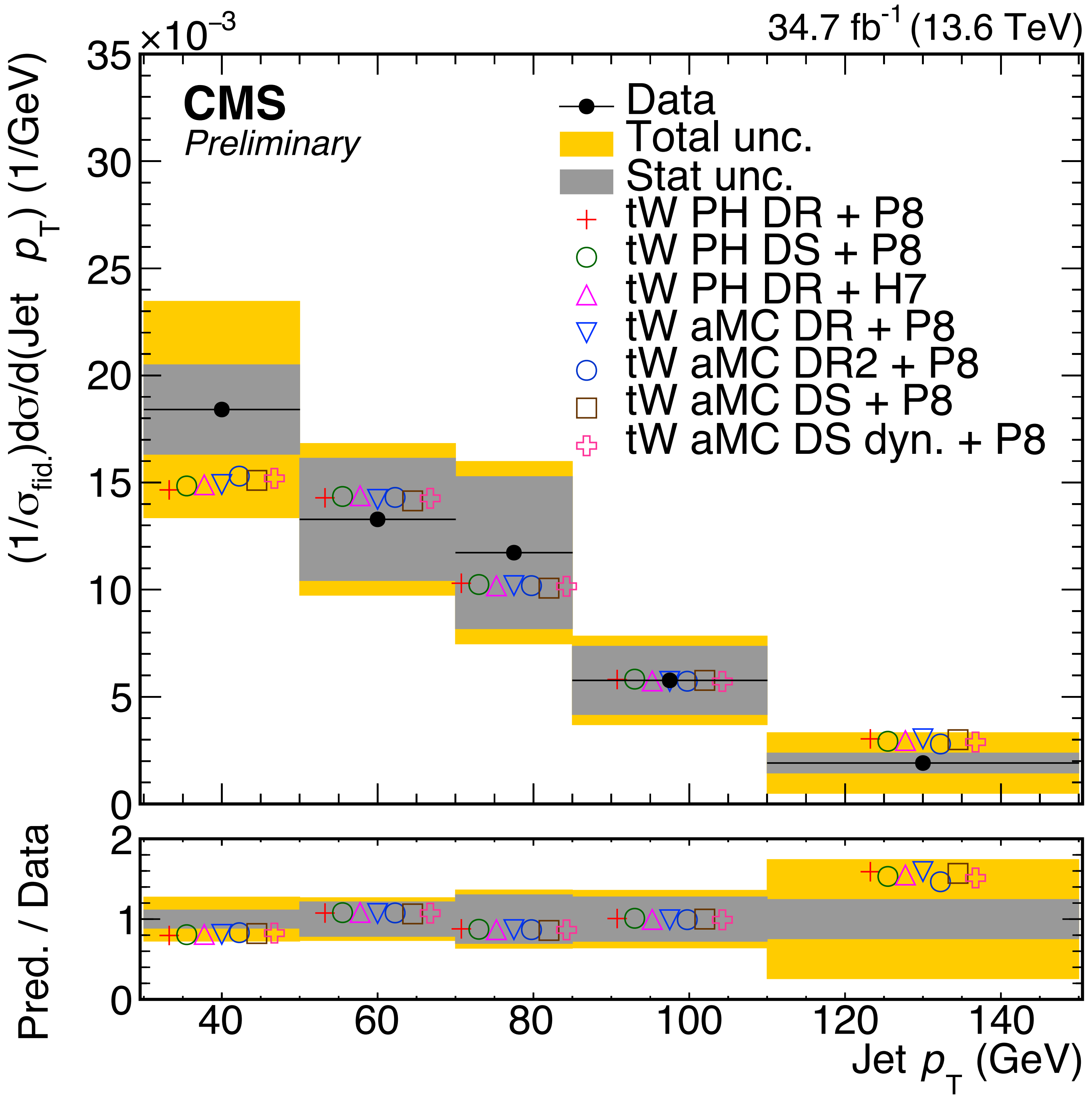
- Dominated by systematic uncertainties
  - JES and b-jet identification
  - Nonprompt background estimate

tW cross section at 13.6 TeV - Differential

CMS-PAS-TOP-23-008





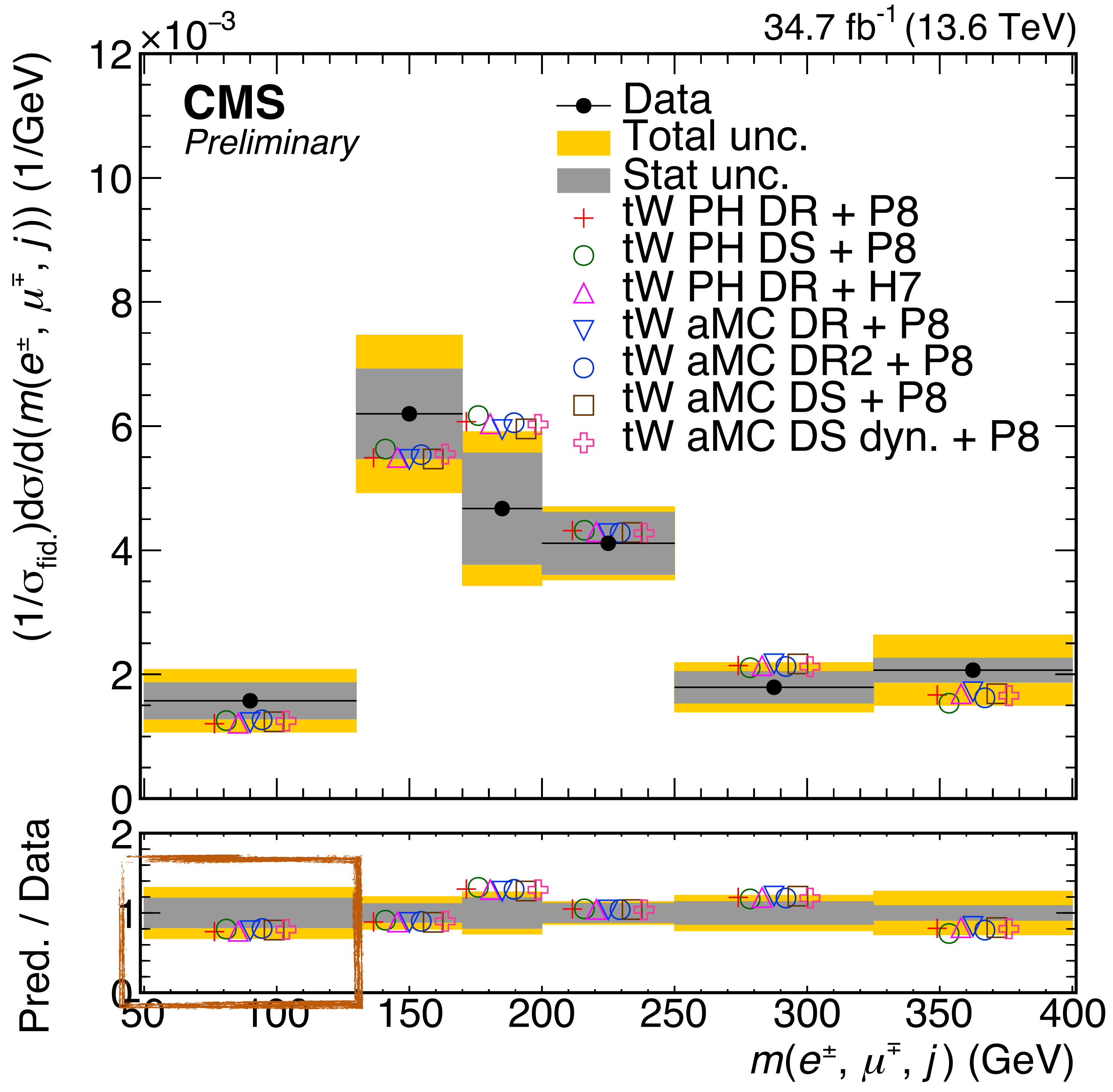


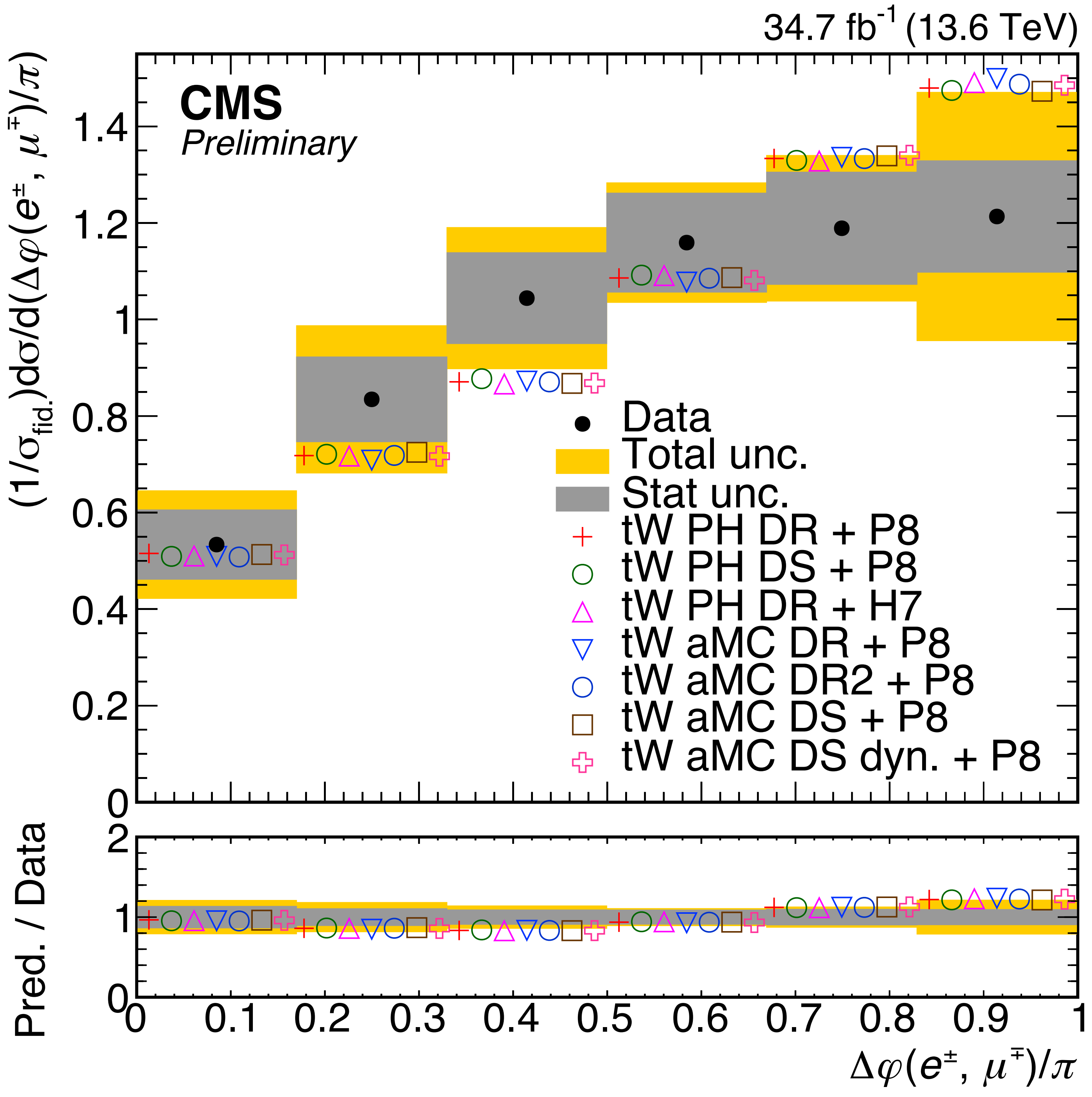
- Comparing unfolded data to:
  - Powheg (PH) interfaced with Herwig 7 (H7), Pythia 8 (P8)
  - aMC@NLO interfaced with P8
  - Comparing DR and DS schemes

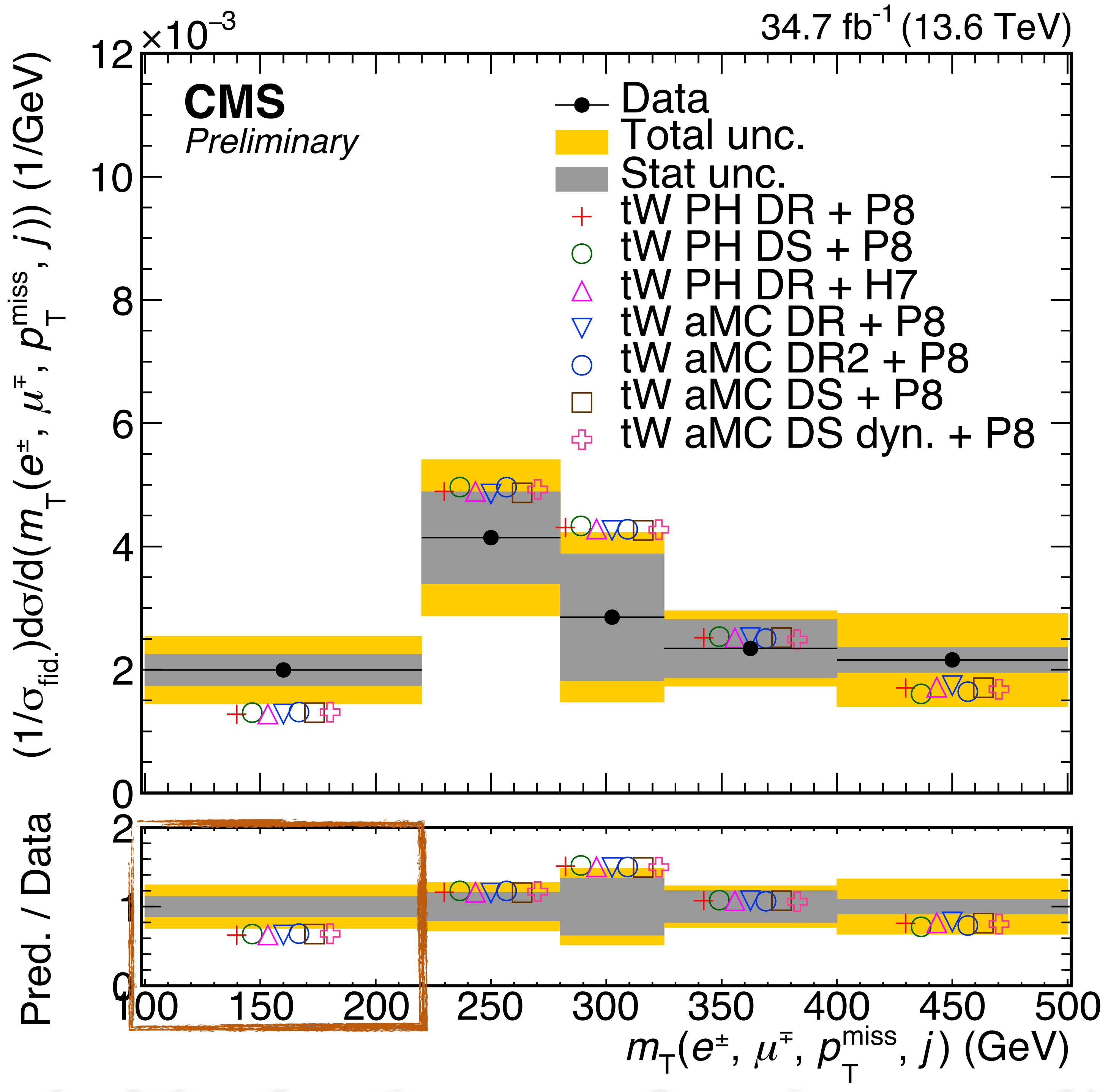
- Measurement statistically limited in many bins
- **Agreement for all predictions**
- p-value > 0.94 for shown observables

tW cross section at 13.6 TeV - Differential

CMS-PAS-TOP-23-008







- Comparing unfolded data to:
  - Powheg (PH) interfaced with Herwig 7 (H7), Pythia 8 (P8)
  - aMC@NLO interfaced with P8
  - Comparing DR and DS schemes

- Measurement statistically limited in many bins
- **Agreement for all predictions**
- p-value > 0.75 for shown observables

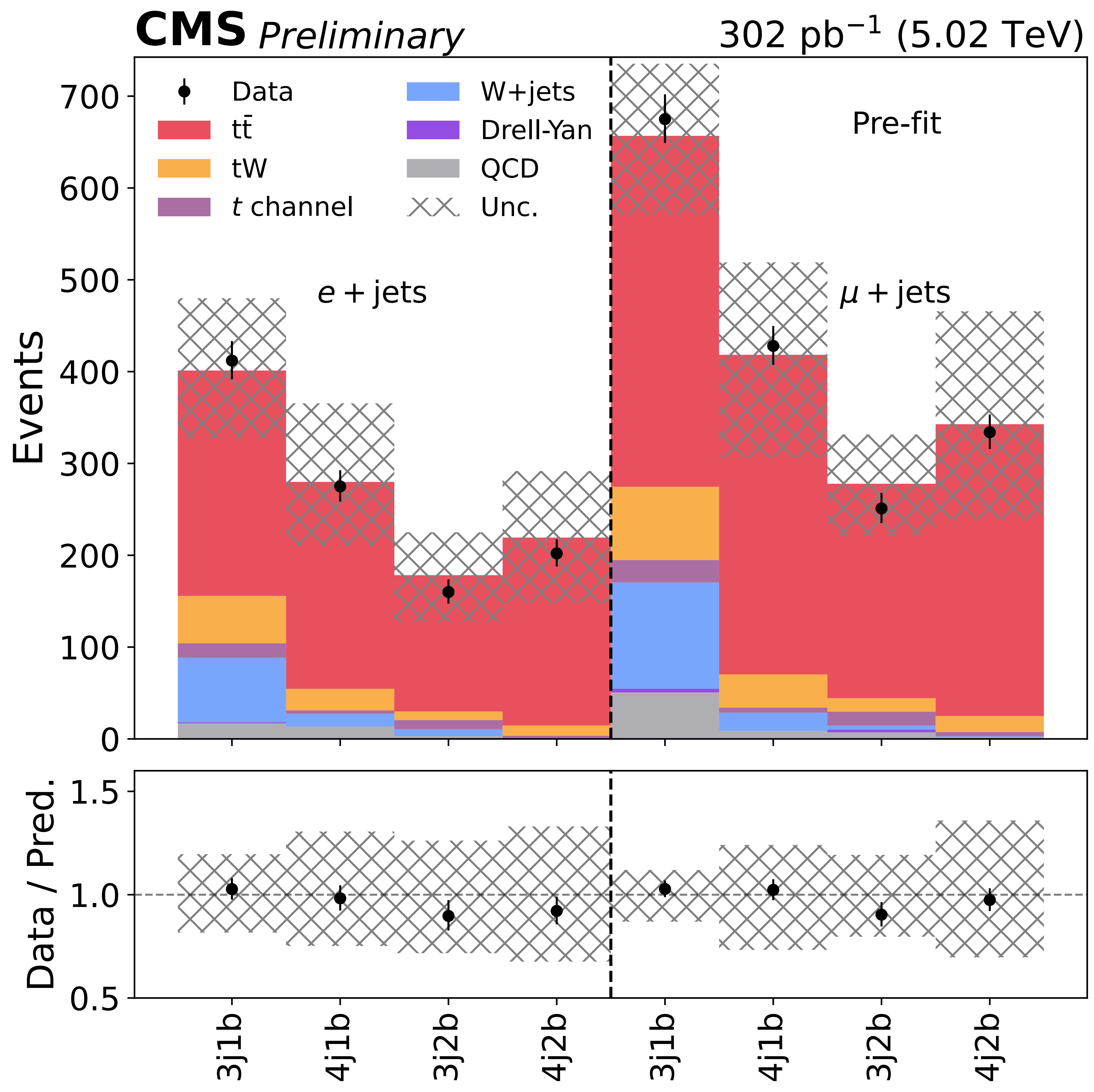
Top quark pair production at 5.02 TeV

PAS-TOP-23-005

- 5.02 TeV pp measurements important as **reference for PbPb analyses**, but also as SM standard candle
- Using 2017 data, 302 pb^{-1}
- Analysis extends existing measurement (dileptonic) with a lepton+jets measurement [JHEP 04 (2022) 144]
    - 1 lepton (electron or muon)
    - At least 3 jets
    - p_T^{miss} from neutrinos

    - Introducing several event categories
        - **90% purity** in 3j2b and 4j2b

- Profiting from low number of simultaneous bunch-crossing (**PU~2**)
    - But trade-off with low statistical power ~O(3000) events



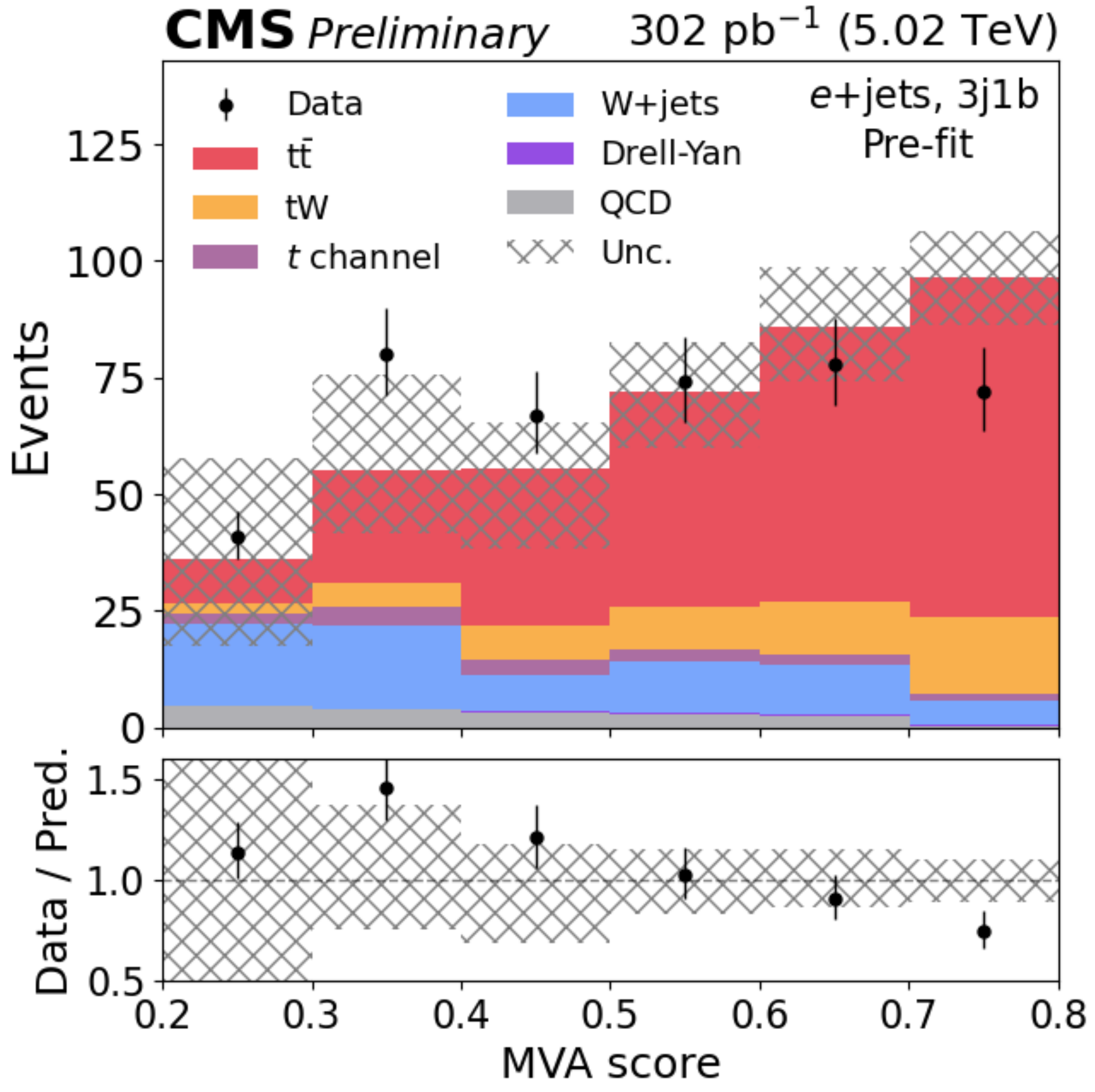
PAS-TOP-23-005

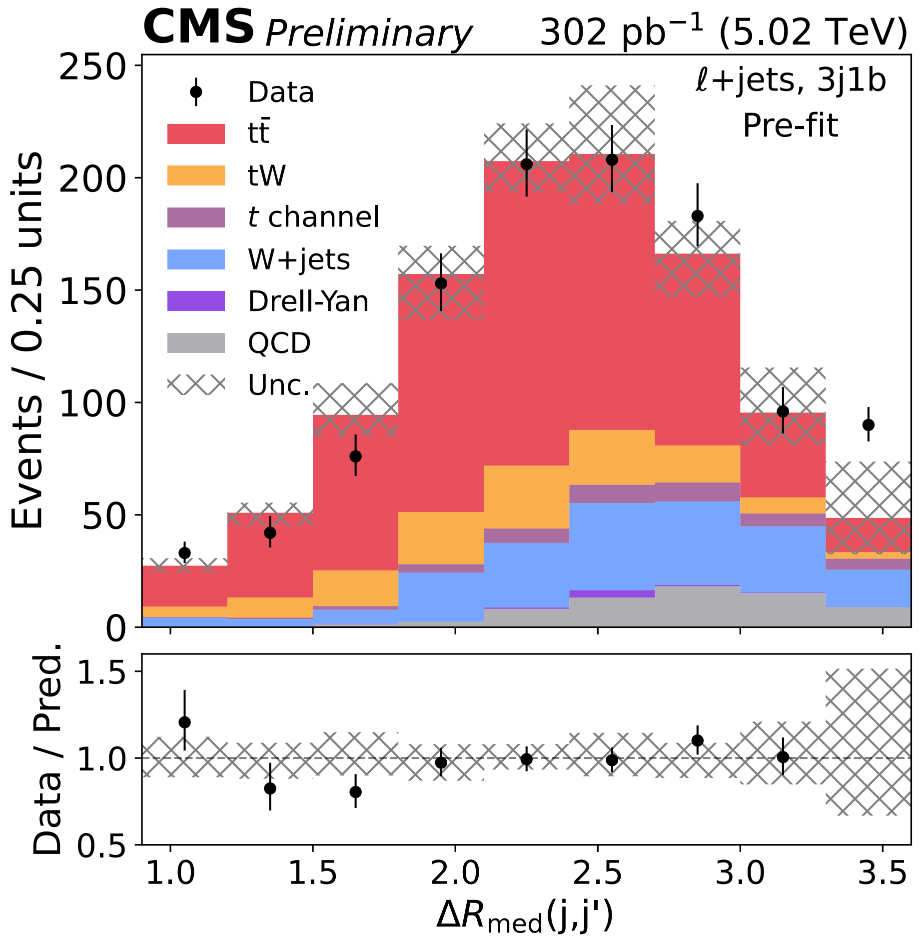
Top quark pair production at 5.02 TeV

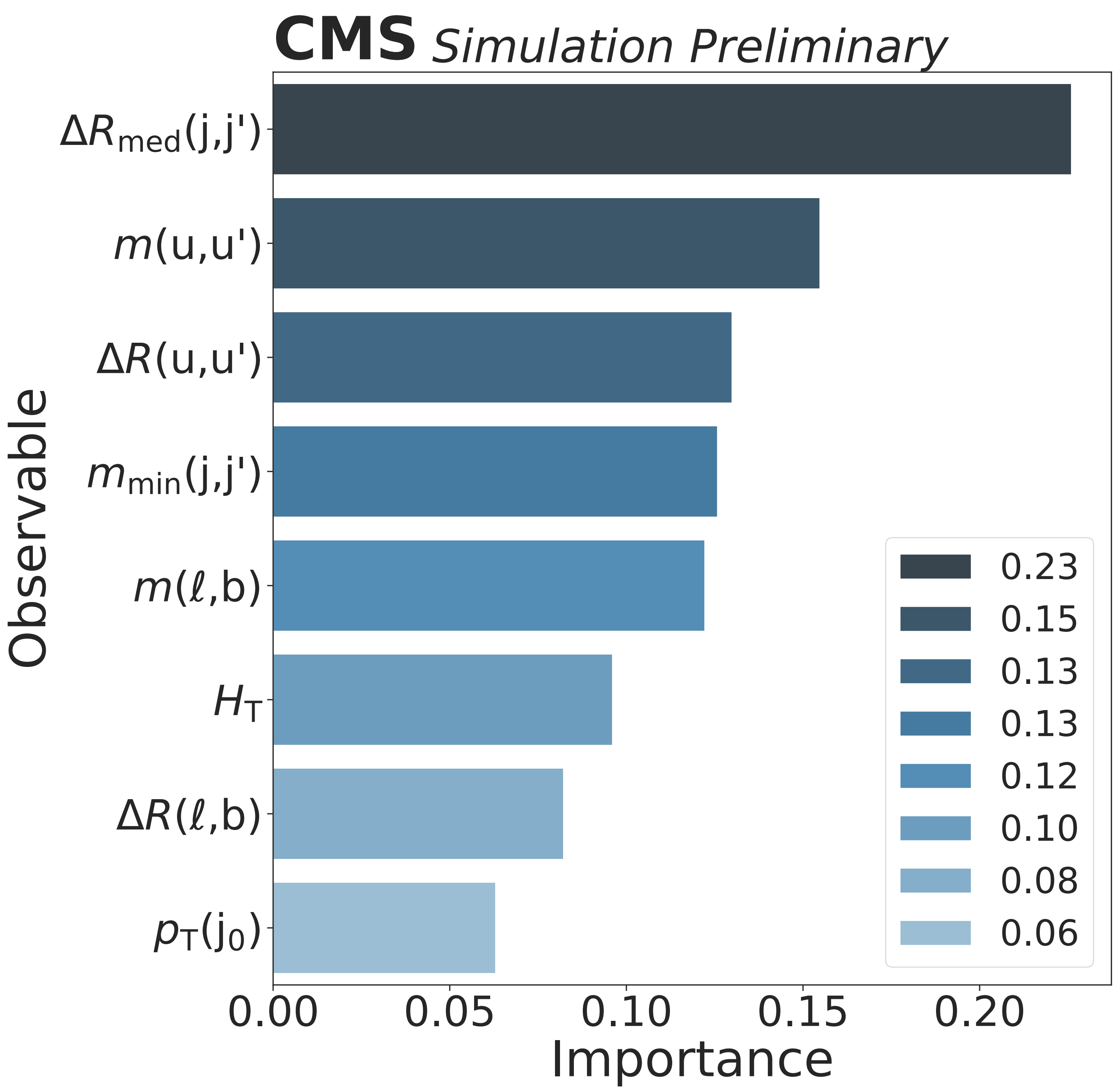
- To overcome the limitations:

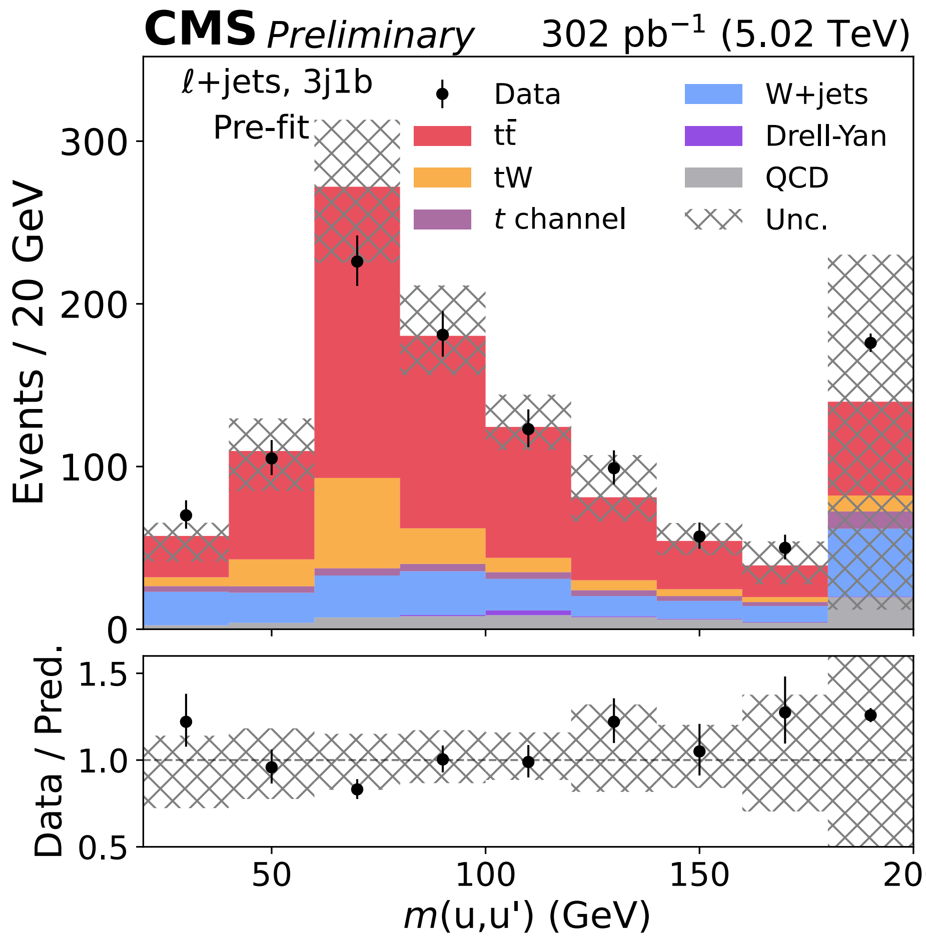
  → Use a MVA in form of a random forest! (only in 3j1b region)

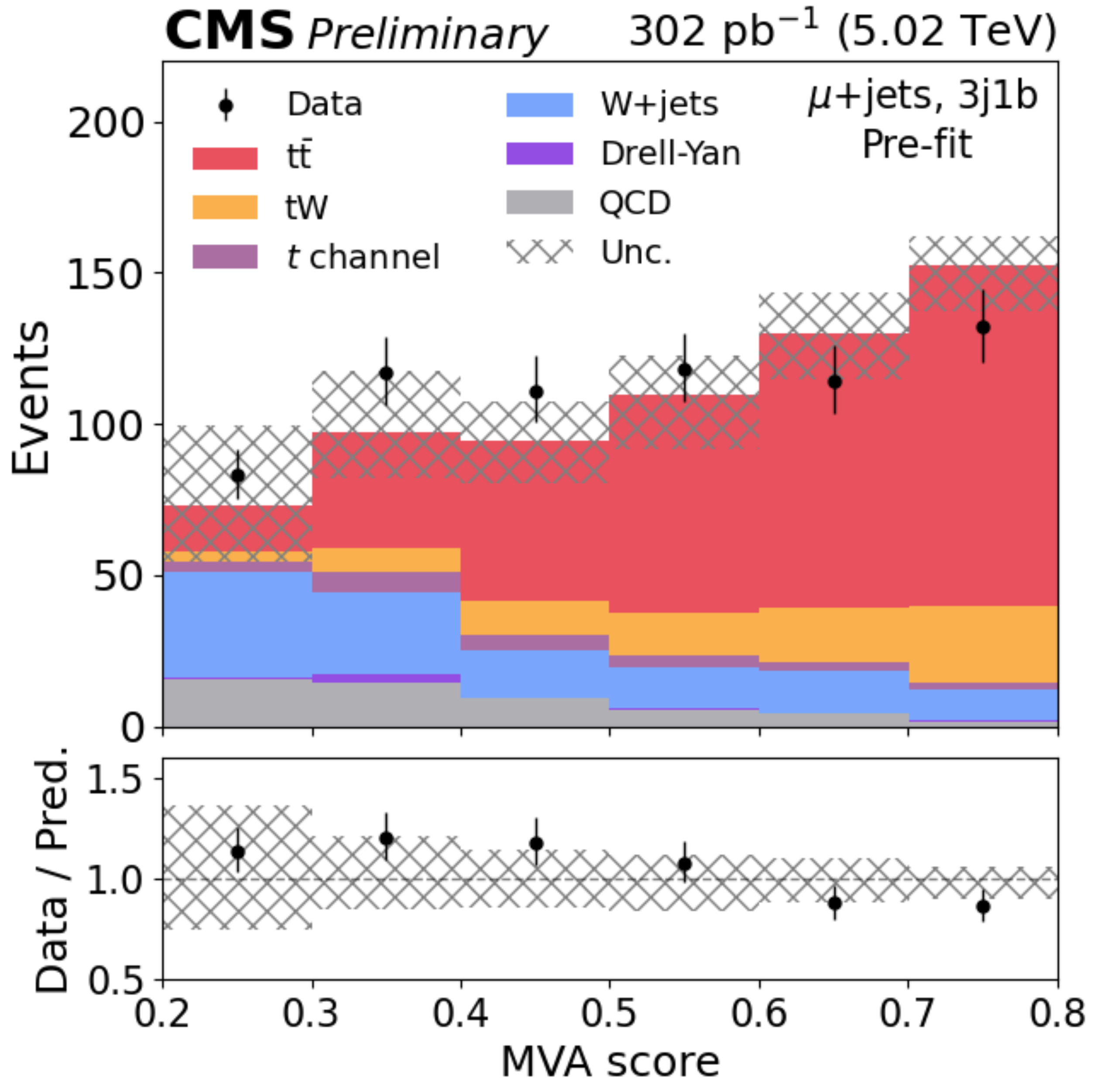
  - 8 input variables: kinematic and angular variables
    - Dedicated importance study performed







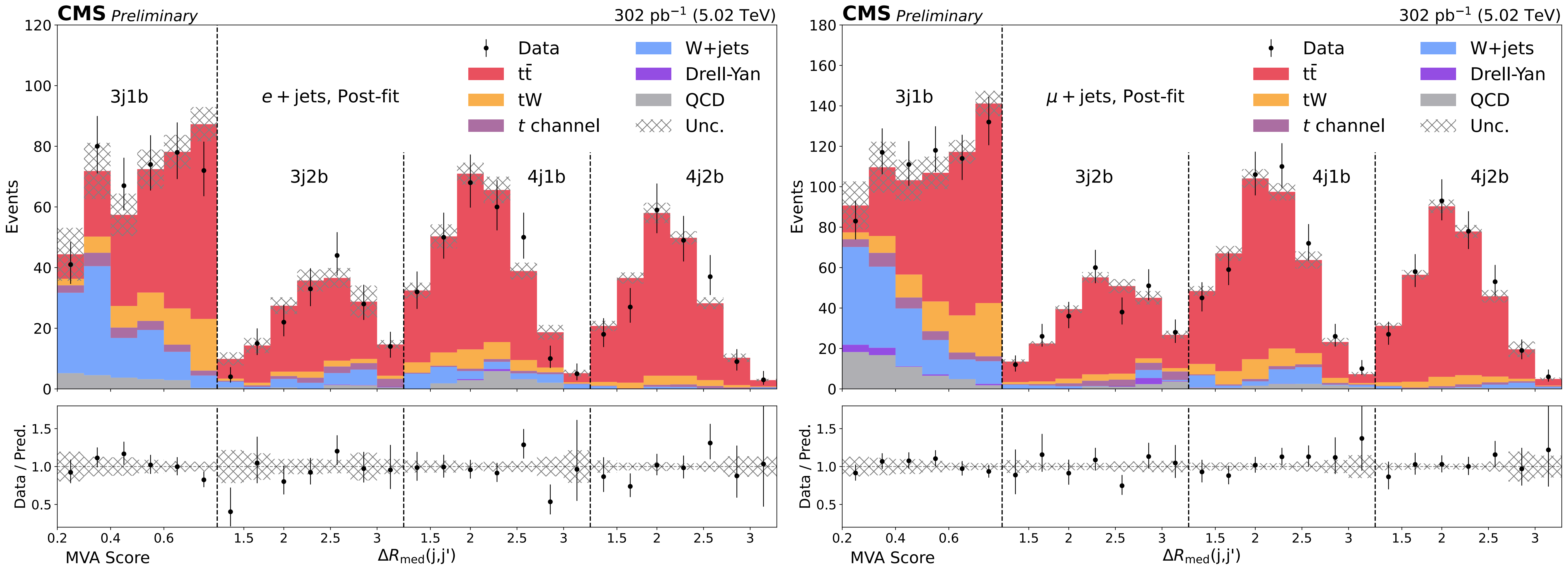




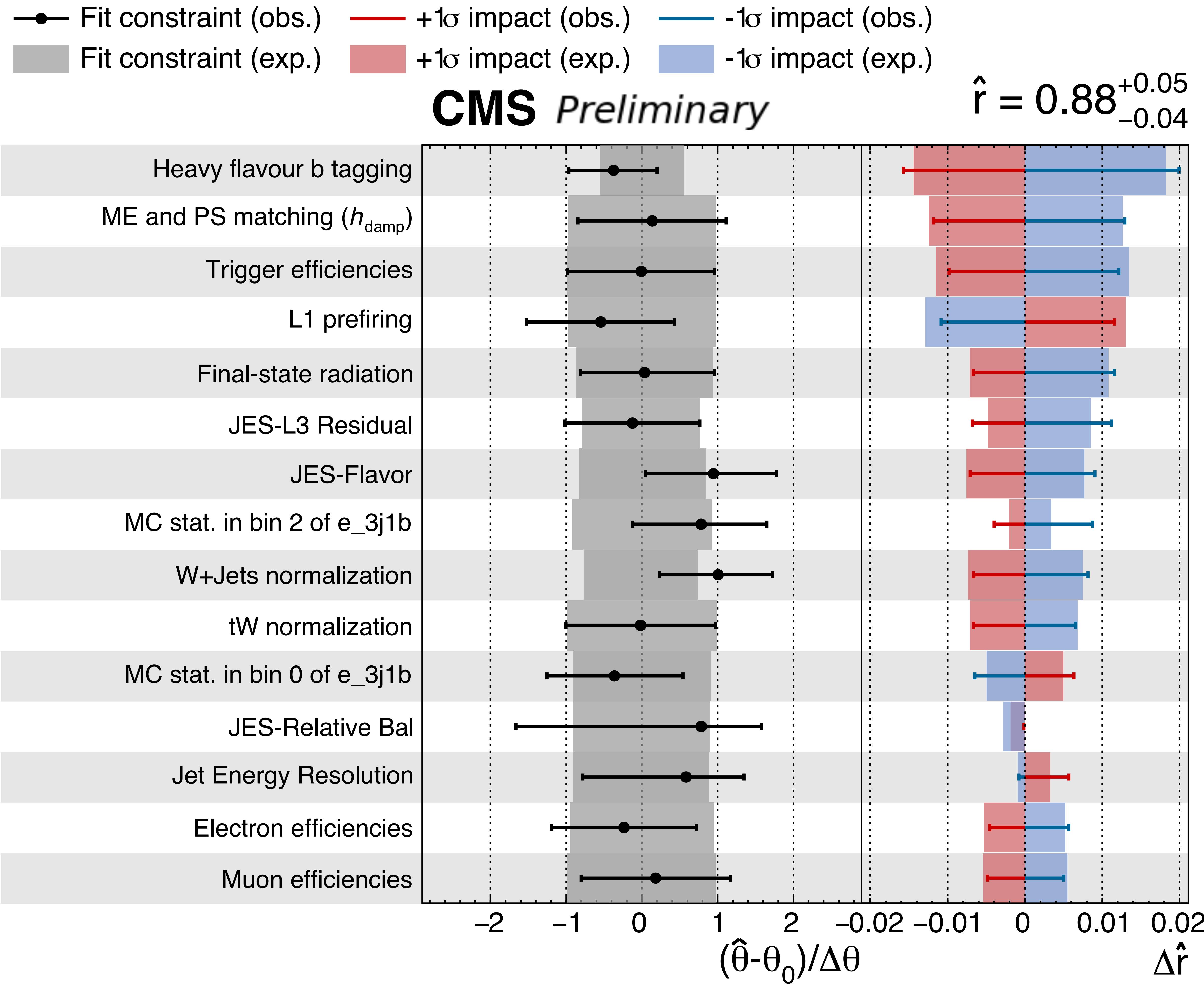
Top quark pair production at 5.02 TeV

PAS-TOP-23-005

- Fitting the MVA output and $\Delta R_{\text{med}}(j,j')$ in 2*27 bins
    - Categorised in lepton flavour, jet, and b-jet multiplicities
    - Sensitivity to object efficiencies and uncertainties
- **Total uncertainty ~ twice stat. uncertainty**
    - Modeling & object efficiencies of equal importance



Post-fit distributions



Luminosity uncertainty externalised

61.4 ± 1.6 (stat) $^{+2.7}_{-2.6}$ (syst) ± 1.2 (lum) pb

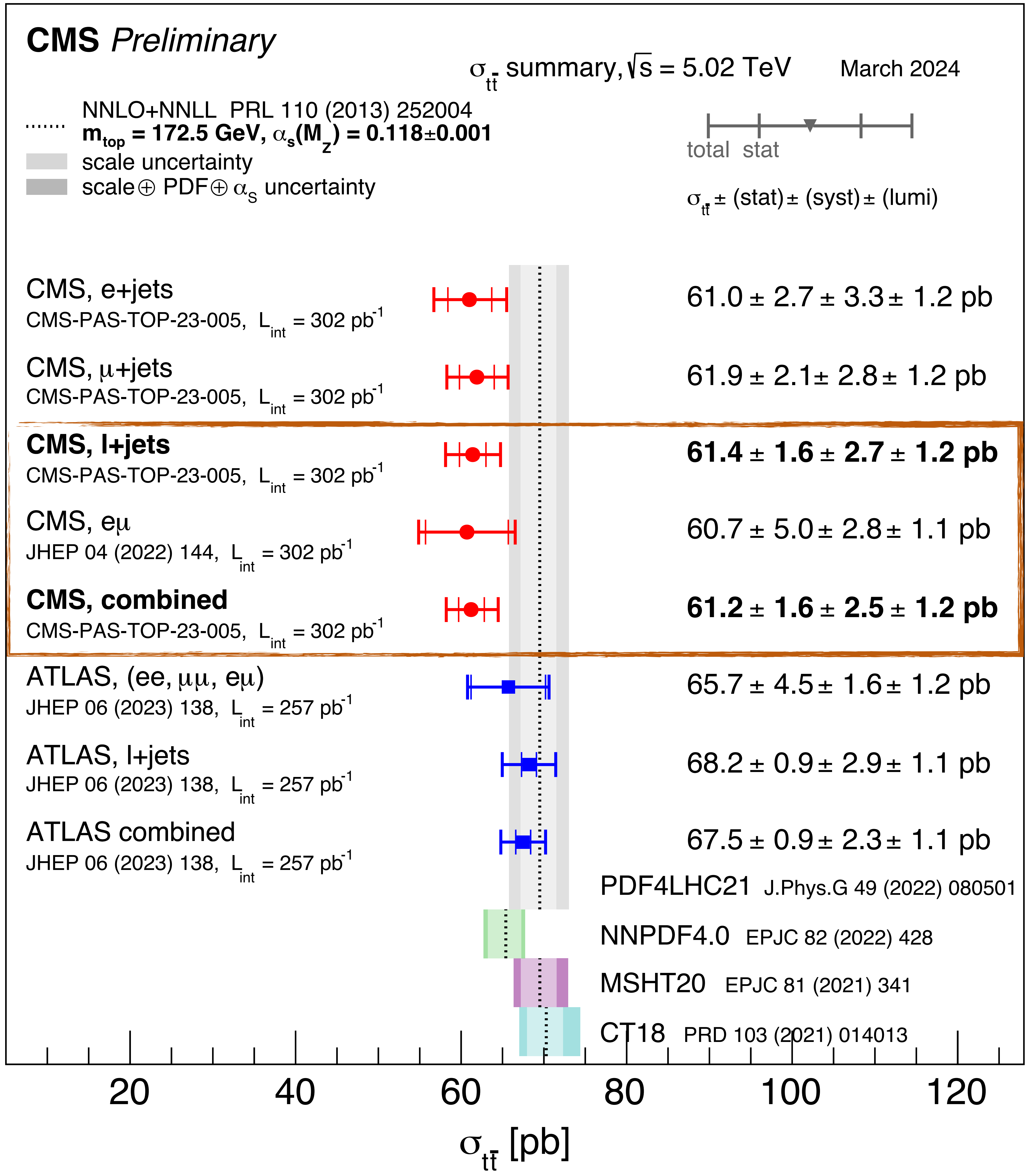
~5% rel. precision

Top quark pair production at 5.02 TeV

PAS-TOP-23-005

- **Combine** the result with a previous measurement in the **dileptonic channel**:
  - Using same data, do a combined fit
  - Largely dominated by l+jets result because of low statistical power in dilepton final states

- Improvement wrt. previous CMS measurements:
  - l+jets **13% → 5%** [CMS-PAS-TOP-16-023]
  - Dilepton + l+jets **8.4% → 5.1 %** [CMS-PAS-TOP-20-004]
- Systematic uncertainty compatible with ATLAS



$$\mathbf{61.2\ ^{+1.6}_{-1.5}\ (stat)\ ^{+2.6}_{-2.3}\ (syst) \pm 1.2\ (lum)\ pb}$$

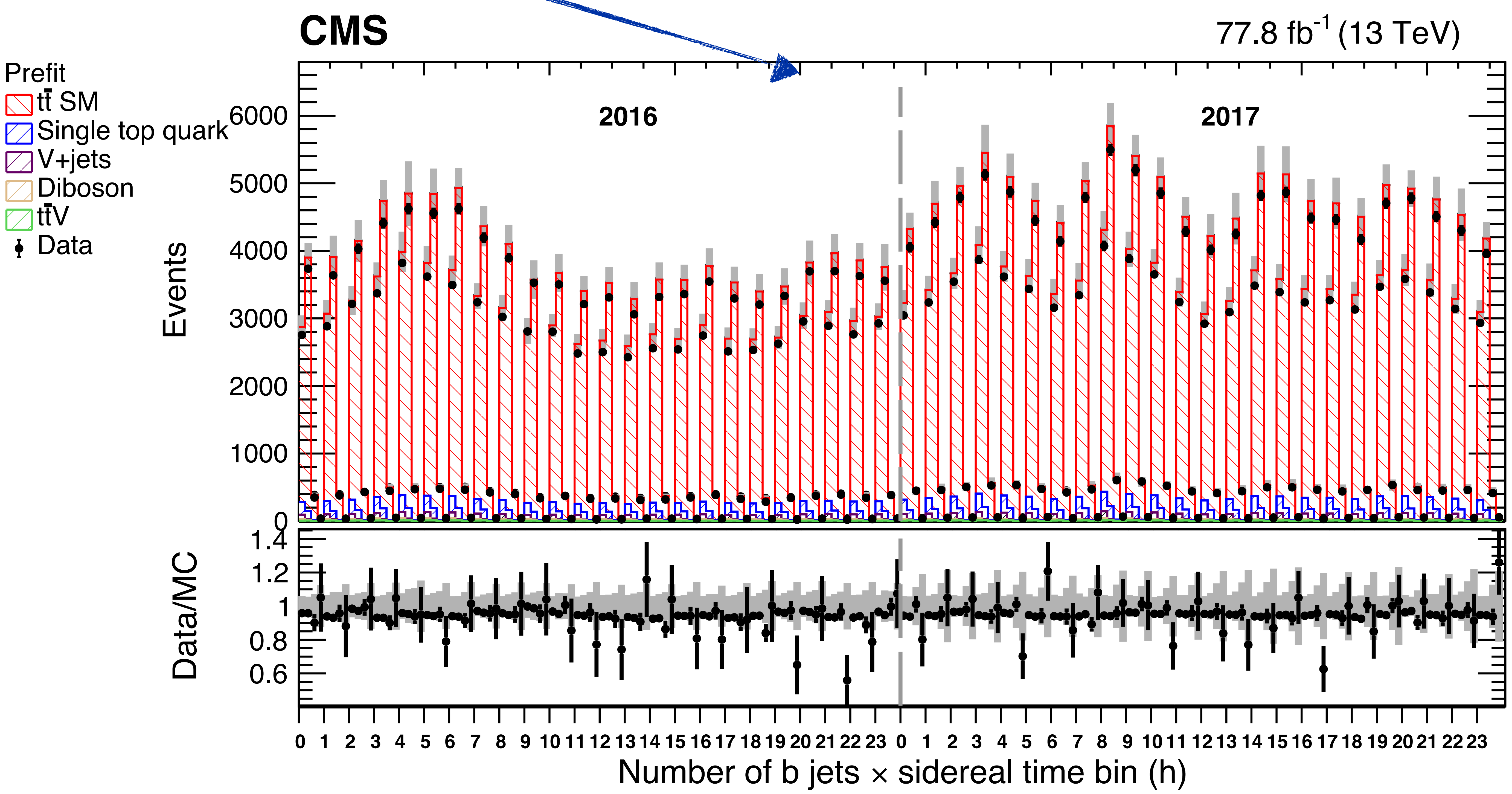
~5% rel. precision

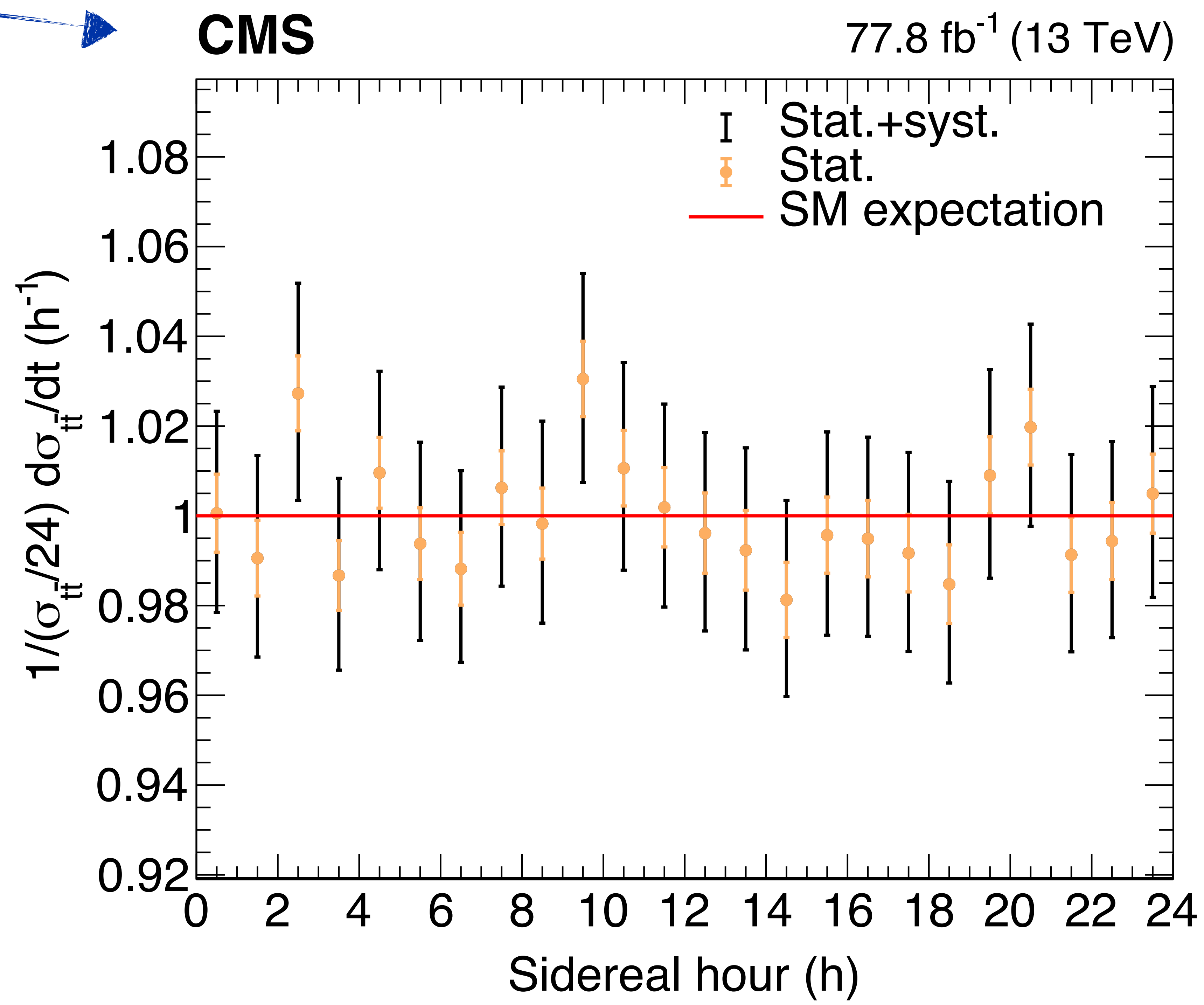
$t\bar{t}$ cross section as a function of time

Recently submitted to Phys. Lett. B:
arXiv:2405.14757

- **Search for Lorentz violation** in SM extension (SME) (EFT-framework)
- Reference frame is sun-centered frame → Measure as function sidereal time (ST)
  - **Cross section becomes modulated as function of ST**
- Challenge: Need to estimate systematics as function of ST (and correlation)
  - Great check of understanding of modeling! (Not time integrated)
- Likelihood fit to extract $\sigma_{t\bar{t}}$

EFT interpretation:
Most stringent to-date, factor 20-100 improvement!
No deviation found.



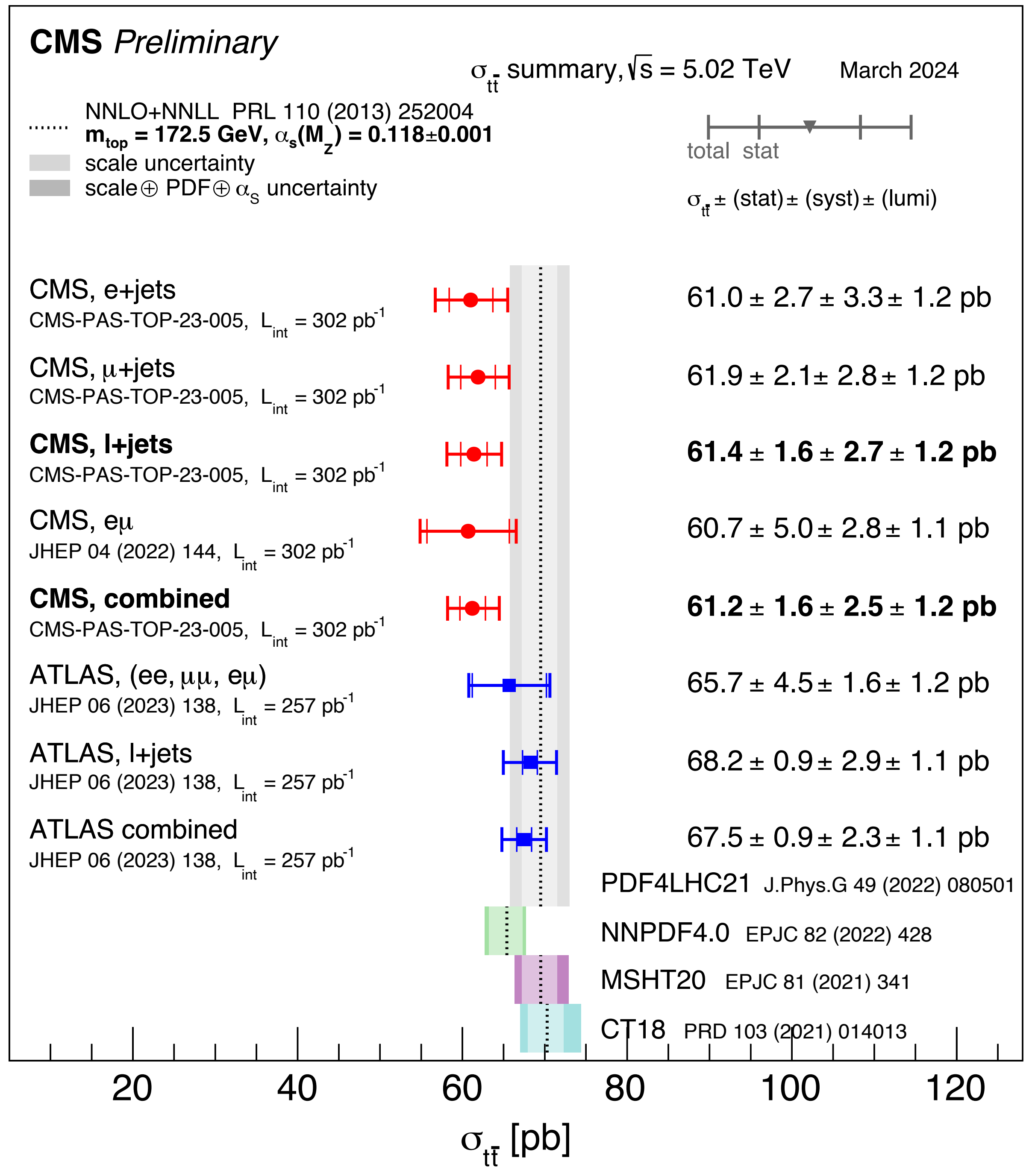


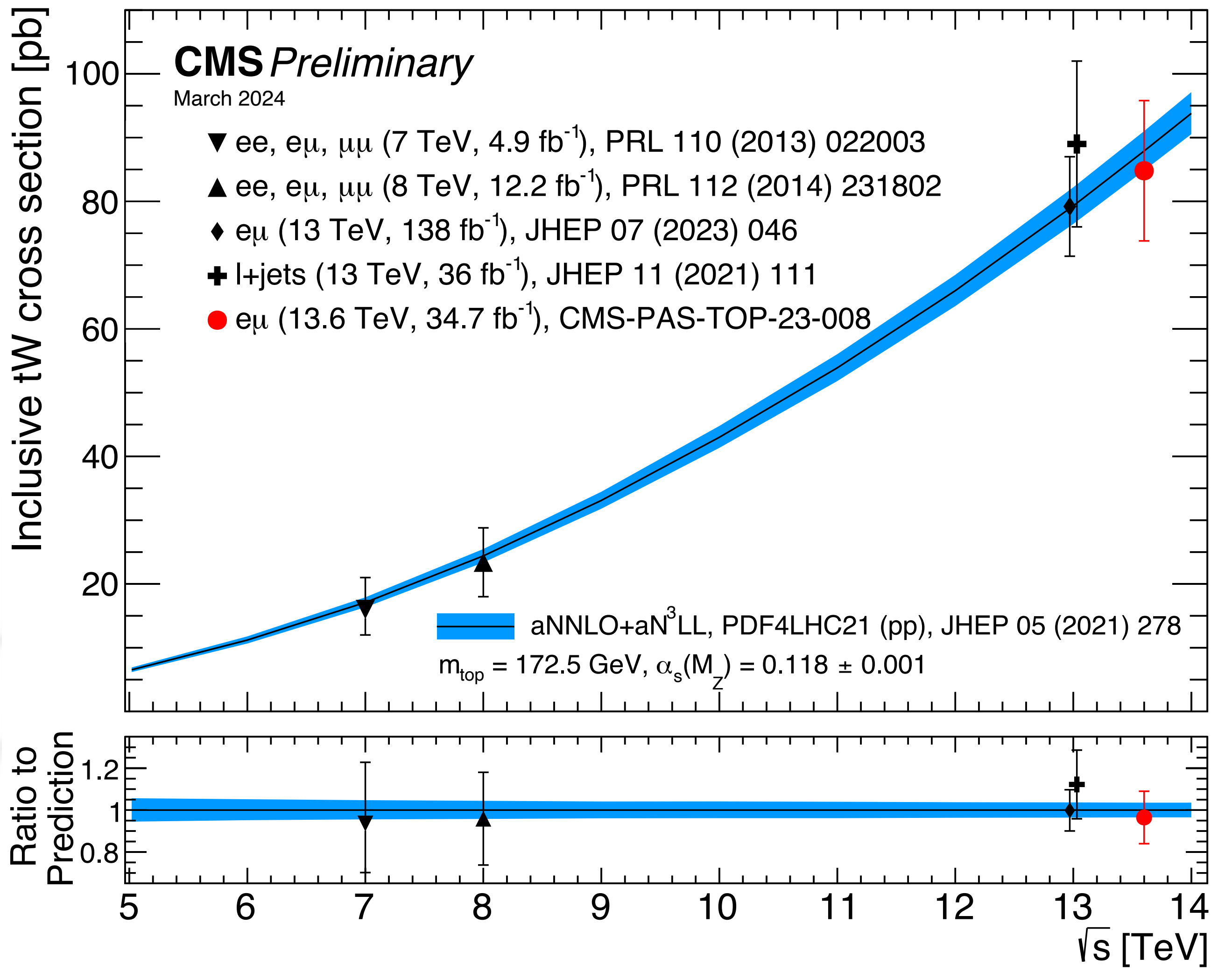
Summary

- Top quark cross section measurements are important tests of the standard model:
  - Confronting predictions and MC modeling
  - Standard candles and background for BSM searches

- New results at 13.6 and 5.02 TeV (tW and $t\bar{t}$)
- Time-dependent cross-section at 13 TeV

- Conclusions:
  - Combination of individual results and channels are useful!
  - Most results in good agreement with the SM
  - Available LHC Run 3 data will give rise to more opportunities





Backup

tW cross section at 13.6 TeV

Fiducial region

Observable	Requirement
Number of leptons	≥ 2
Leading lepton p_{T}	$>25\,\mathrm{GeV}$
Invariant mass of all dilepton pairs	$>20\,\mathrm{GeV}$
Number of jets	1
Number of loose jets	0
Number of b jets	1

p-values

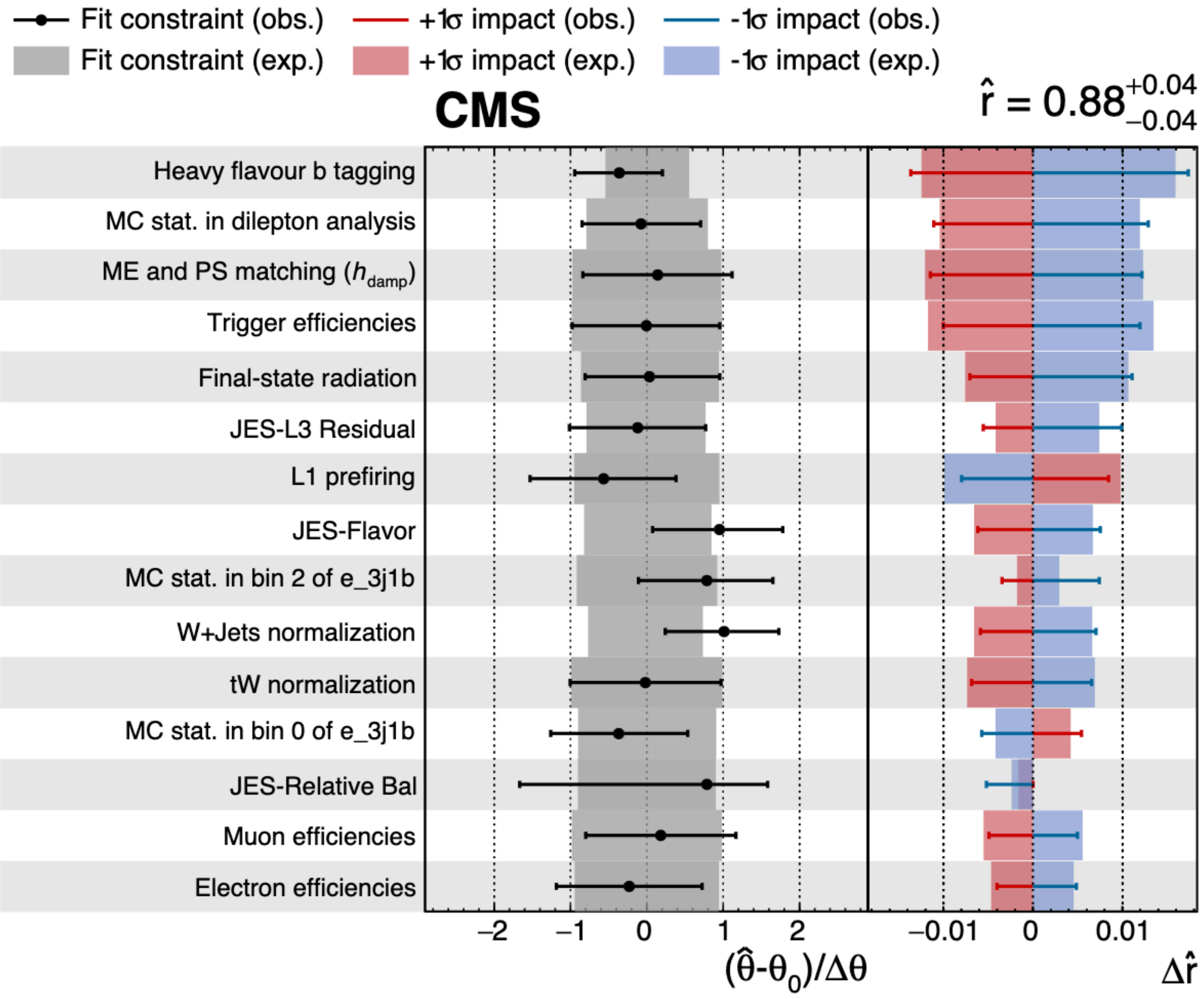
Variable	PH DR + P8	PH DS + P8	PH DR + H7
Leading lepton p_{T}	0.96	0.98	0.96
Jet p_{T}	0.96	0.97	0.97
$\Delta\varphi(\mathrm{e}^{\pm}, \mu^{\mp})/\pi$	0.94	0.94	0.93
$p_{\mathrm{z}}(\mathrm{e}^{\pm}, \mu^{\mp}, j)$	0.96	0.96	0.96
$m_{\mathrm{T}}(\mathrm{e}^{\pm}, \mu^{\mp}, j, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	0.78	0.75	0.79
$m(\mathrm{e}^{\pm}, \mu^{\mp}, j)$	0.95	0.93	0.95

Variable	aMC DR + P8	aMC DR2 + P8	aMC DS + P8	aMC DS dyn. + P8
Leading lepton p_{T}	0.94	0.96	0.95	0.96
Jet p_{T}	0.96	0.98	0.97	0.99
$\Delta\varphi(\mathrm{e}^{\pm}, \mu^{\mp})/\pi$	0.93	0.93	0.94	0.93
$p_{\mathrm{z}}(\mathrm{e}^{\pm}, \mu^{\mp}, j)$	0.96	0.96	0.96	0.96
$m_{\mathrm{T}}(\mathrm{e}^{\pm}, \mu^{\mp}, j, \vec{p}_{\mathrm{T}}^{\mathrm{miss}})$	0.80	0.77	0.80	0.79
$m(\mathrm{e}^{\pm}, \mu^{\mp}, j)$	0.96	0.95	0.96	0.96

Top quark pair production at 5.02 TeV

PAS-TOP-23-005

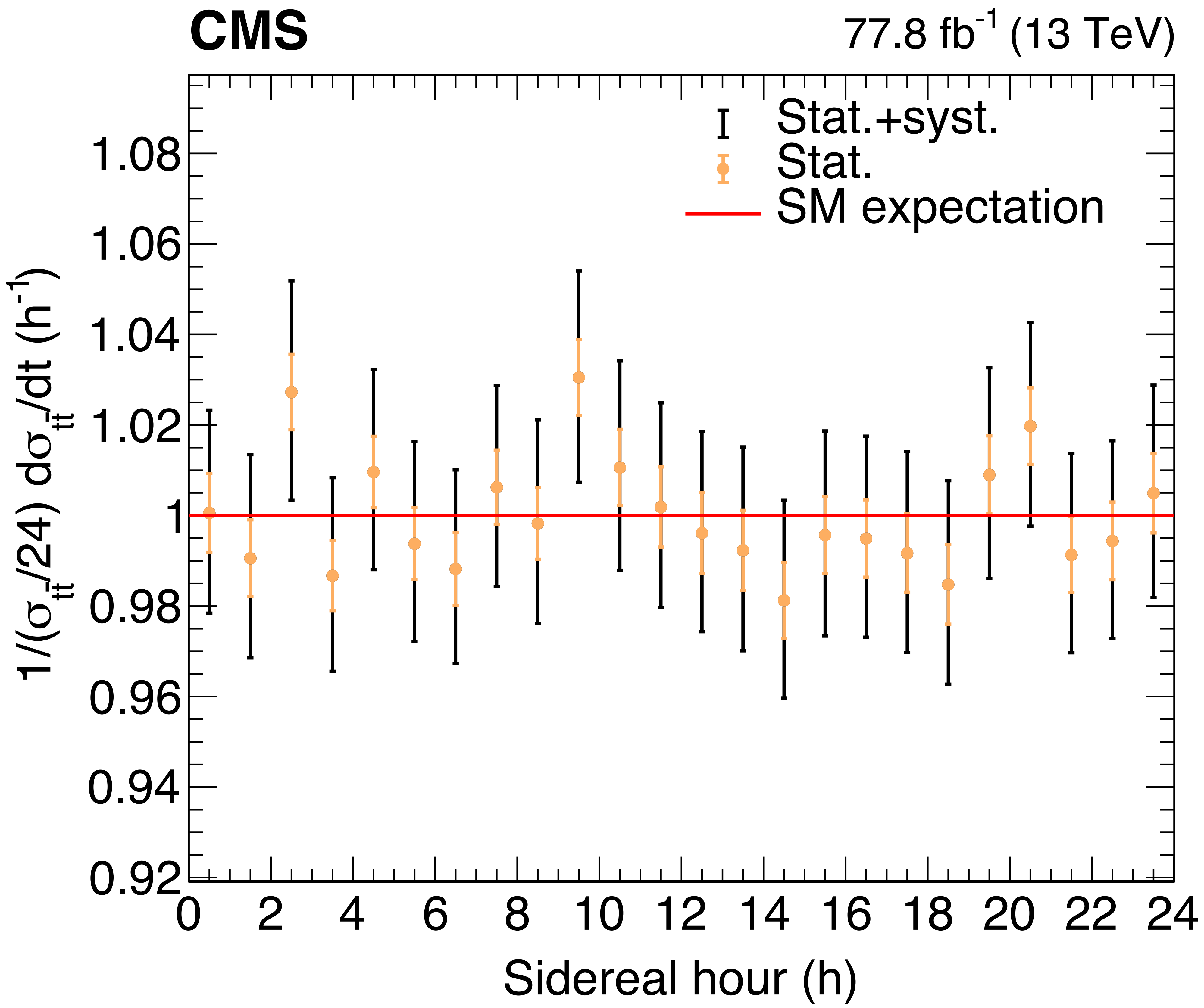
- **Combine** the result with a previous measurement in the **dileptonic channel**:
  - Using same data, do a combined fit
  - Largely dominated by l+jets result because of low statistical power in dilepton final states



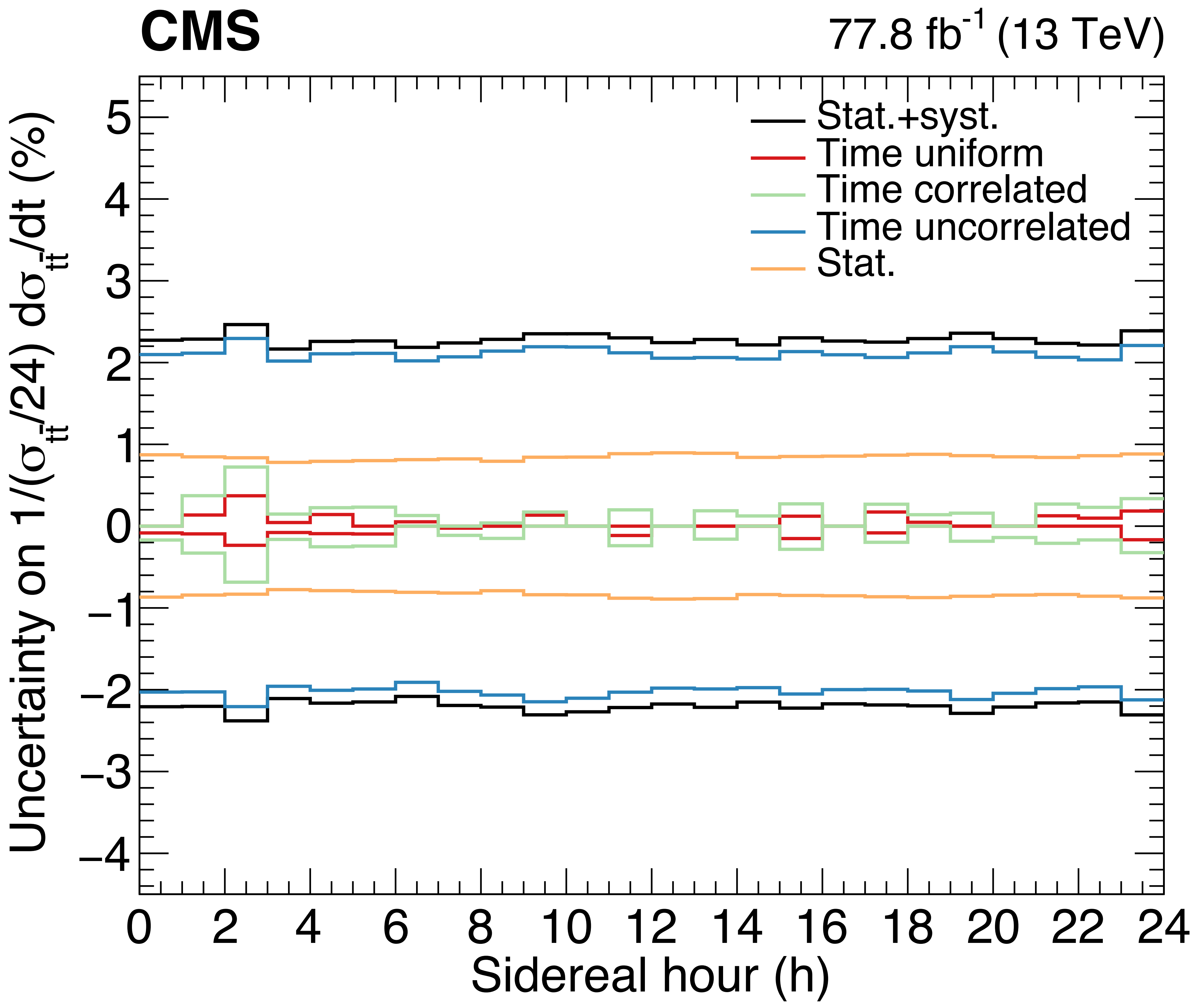
$61.2\ ^{+1.6}_{-1.5}$ (stat) $^{+2.6}_{-2.3}$ (syst) ± 1.2 (lum) pb

$t\bar{t}$ cross section as a function of time

Normalised diff. cross section

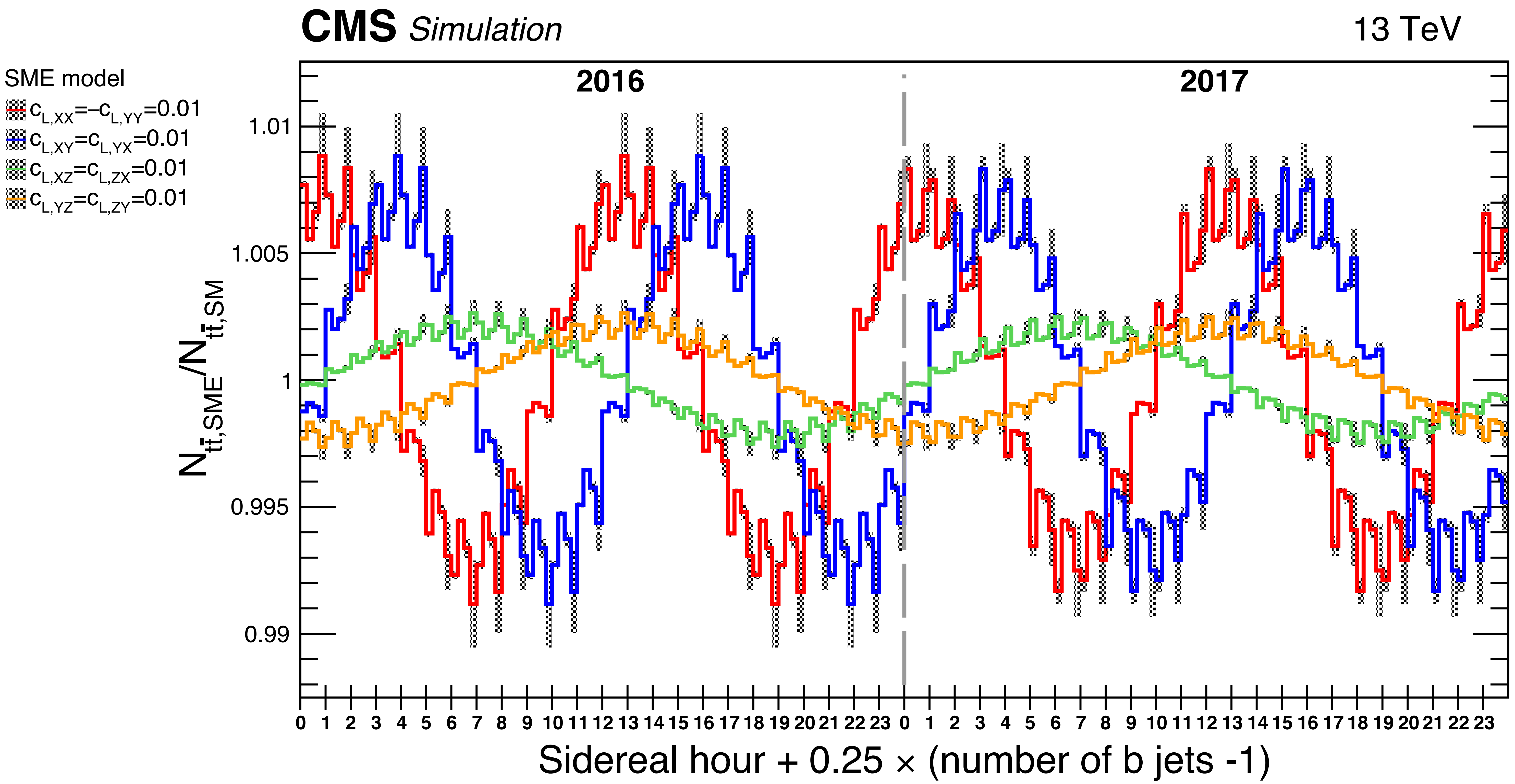


Uncertainties

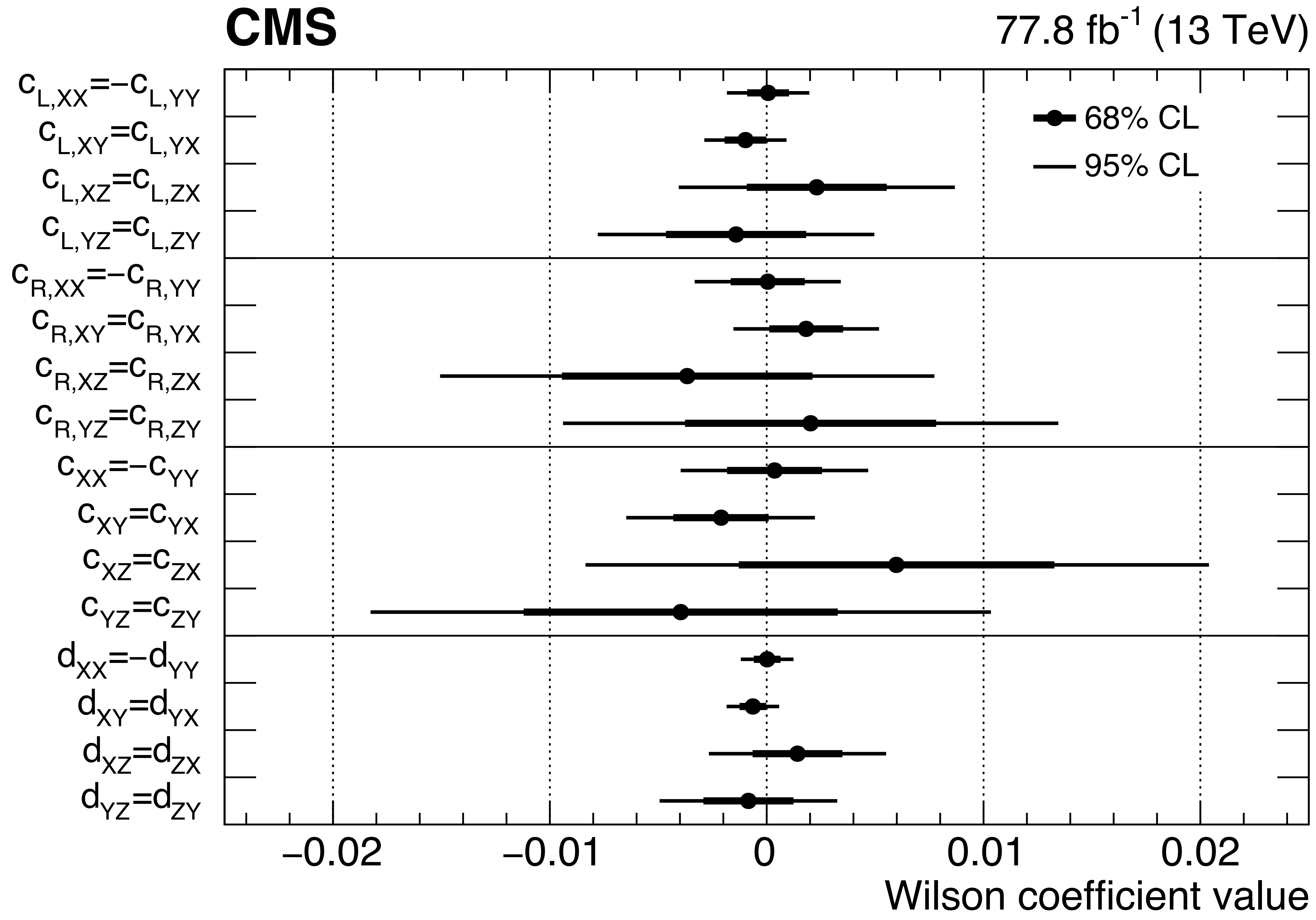


$t\bar{t}$ cross section as a function of time

SME extension fit

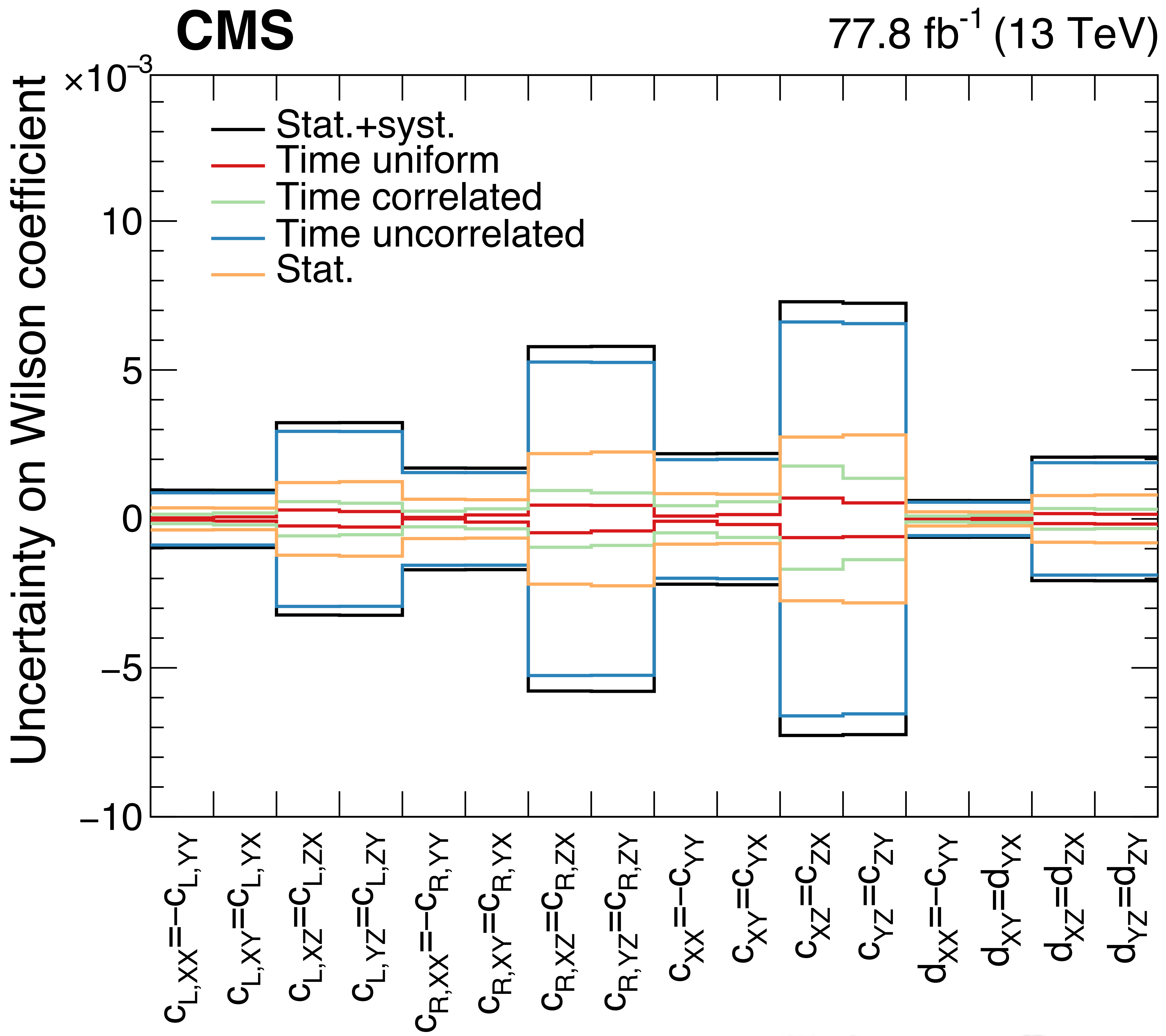


SME constraints



$t\bar{t}$ cross section as a function of time

SME uncertainties



$t\bar{t}$ cross section as a function of time

Event yields

Process	2016	2017
$t\bar{t}$ SM	$169\,500 \pm 6100$	$196\,000 \pm 7300$
$t\bar{t}V$	460 ± 60	540 ± 70
Single top quark	$8\,500 \pm 1600$	$9\,900 \pm 2000$
Diboson	700 ± 150	650 ± 130
V+jets	$2\,100 \pm 500$	$2\,300 \pm 600$
Total background	$11\,700 \pm 1700$	$13\,404 \pm 2000$
Total MC	$181\,000 \pm 6700$	$209\,000 \pm 8100$
Data	168 282	203 584

EFT results

Wilson coefficient $\times 10^3$	Others fixed to SM		Others floating	
	SM expected	Observed	SM expected	Observed
$c_{L,XX} = -c_{L,YY}$	$[-0.96; 0.96]$	$[-0.9; 1.03]$	$[-0.96; 0.96]$	$[-0.9; 1.03]$
$c_{L,XY} = c_{L,YX}$	$[-0.97; 0.97]$	$[-1.92; 0.0]$	$[-0.97; 0.97]$	$[-1.94; -0.02]$
$c_{L,XZ} = c_{L,ZX}$	$[-3.23; 3.23]$	$[-0.97; 5.49]$	$[-3.23; 3.23]$	$[-0.92; 5.54]$
$c_{L,YZ} = c_{L,ZY}$	$[-3.24; 3.24]$	$[-4.61; 1.85]$	$[-3.24; 3.24]$	$[-4.64; 1.82]$
$c_{R,XX} = -c_{R,YY}$	$[-1.7; 1.7]$	$[-1.65; 1.77]$	$[-1.7; 1.7]$	$[-1.66; 1.76]$
$c_{R,XY} = c_{R,YX}$	$[-1.71; 1.71]$	$[0.09; 3.5]$	$[-1.71; 1.71]$	$[0.12; 3.52]$
$c_{R,XZ} = c_{R,ZX}$	$[-5.78; 5.78]$	$[-9.36; 2.2]$	$[-5.78; 5.78]$	$[-9.45; 2.11]$
$c_{R,YZ} = c_{R,ZY}$	$[-5.8; 5.8]$	$[-3.82; 7.76]$	$[-5.8; 5.8]$	$[-3.77; 7.82]$
$c_{XX} = -c_{YY}$	$[-2.17; 2.17]$	$[-1.76; 2.62]$	$[-2.17; 2.17]$	$[-1.83; 2.55]$
$c_{XY} = c_{YX}$	$[-2.18; 2.18]$	$[-4.23; 0.17]$	$[-2.18; 2.18]$	$[-4.31; 0.09]$
$c_{XZ} = c_{ZX}$	$[-7.21; 7.21]$	$[-1.49; 13.07]$	$[-7.21; 7.21]$	$[-1.29; 13.27]$
$c_{YZ} = c_{ZY}$	$[-7.24; 7.24]$	$[-11.05; 3.38]$	$[-7.24; 7.24]$	$[-11.21; 3.28]$
$d_{XX} = -d_{YY}$	$[-0.61; 0.61]$	$[-0.6; 0.63]$	$[-0.61; 0.61]$	$[-0.59; 0.64]$
$d_{XY} = d_{YX}$	$[-0.62; 0.62]$	$[-1.24; -0.01]$	$[-0.62; 0.62]$	$[-1.25; -0.02]$
$d_{XZ} = d_{ZX}$	$[-2.07; 2.07]$	$[-0.68; 3.46]$	$[-2.08; 2.07]$	$[-0.65; 3.49]$
$d_{YZ} = d_{ZY}$	$[-2.08; 2.08]$	$[-2.9; 1.25]$	$[-2.08; 2.08]$	$[-2.92; 1.23]$

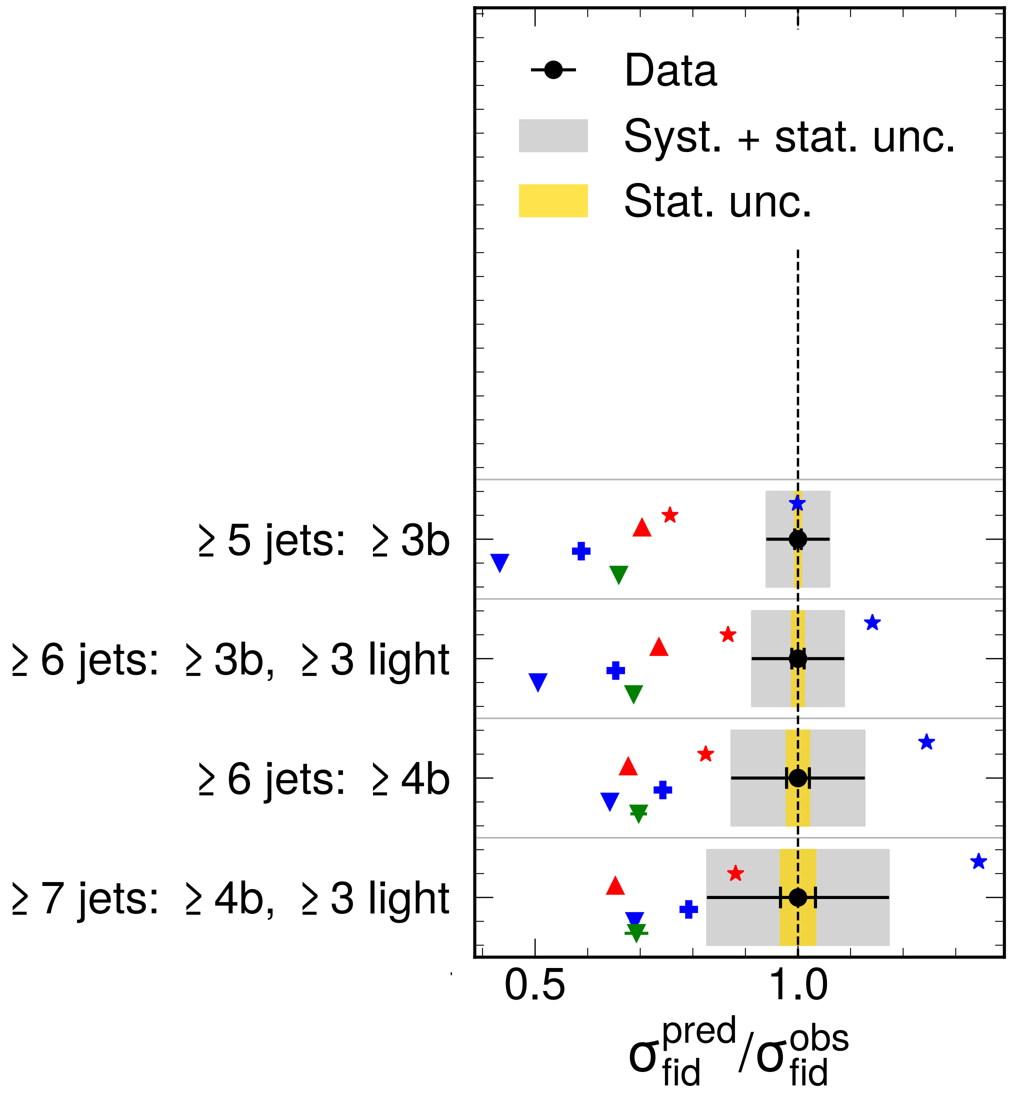
Uncertainty correlations

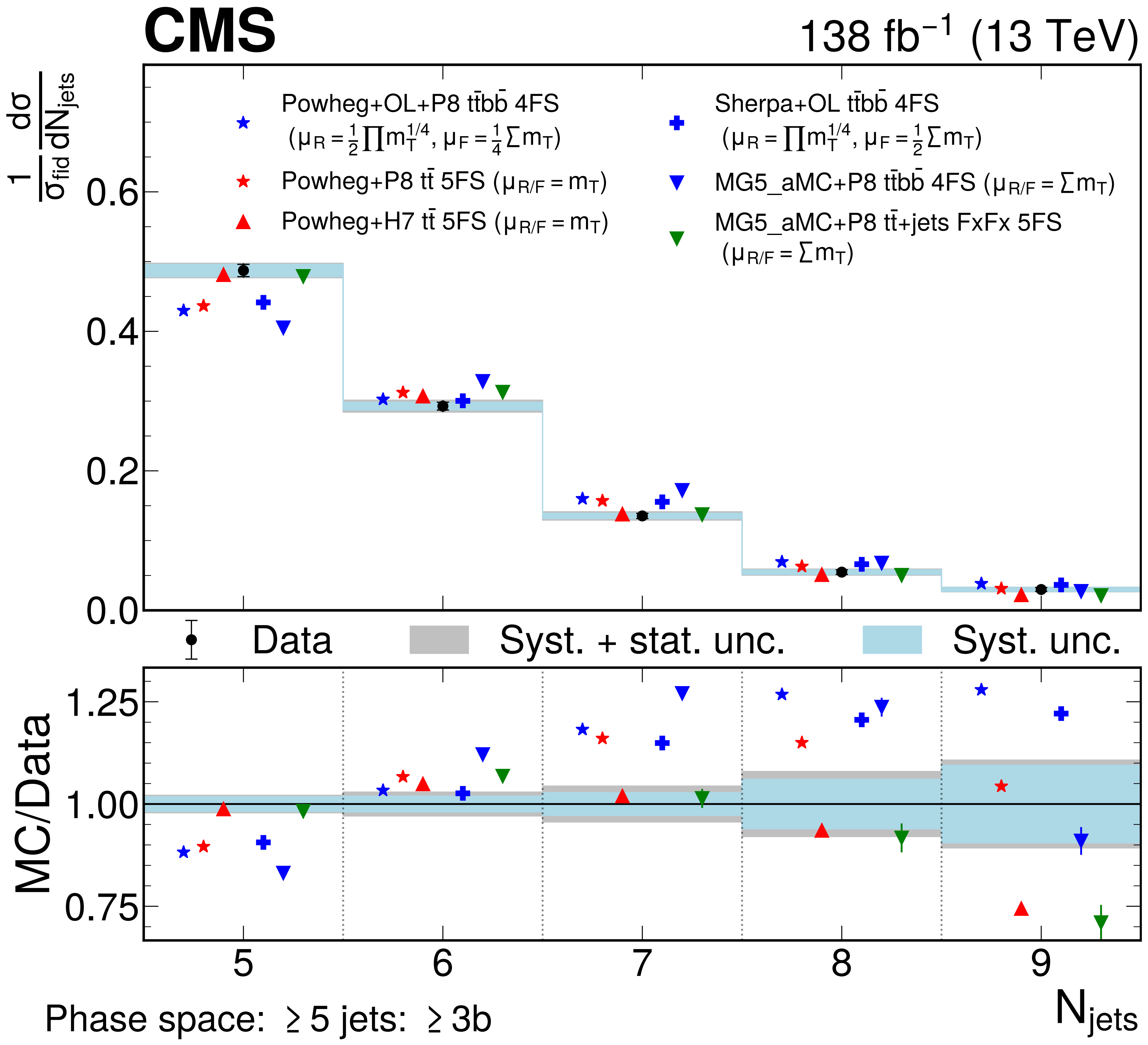
Systematic uncertainty source	Correlation 2016–2017	Correlation time bins	Magnitude
Flat luminosity, year-to-year correlated part	100%	100%	0.6–0.9%
Flat luminosity, year-to-year uncorrelated part	0%	100%	0.9–1.4%
Time-dependent luminosity stability	0%	100%	0.2–0.4%
Time-dependent luminosity linearity	0%	100%	0.2–0.4%
Time-dependent pileup reweighting	100%	100%	0.3–5%
Time-dependent trigger efficiency, syst. component	0%	100%	0.5–1%
Time-dependent trigger efficiency, stat. component	0%	0%	0.5%
L1 ECAL timing shift	100%	0%	0.5%
Electron reconstruction	100%	0%	0.4%
Electron identification	100%	0%	1.2–2.2%
Muon identification, syst. component	100%	0%	0.3%
Muon identification, stat. component	0%	0%	0.5%
Muon isolation, syst. component	100%	0%	<0.1%
Muon isolation, stat. component	0%	0%	0.2%
Phase-space extrapolation of lepton isolation	100%	100%	0.5–1%
Jet energy scale, year-to-year correlated part	100%	0%	0.8%
Jet energy scale, year-to-year uncorrelated part	0%	0%	1.4%
Parton flavor impact on jet energy scale	100%	100%	1.1%
b tagging	0%	0%	2–4%
Matrix element scale †	100%	100%	0.3–6%
PDF+α_S †	100%	100%	0.1–0.4%
Initial- & final-state radiation scale †	100%	100%	1–5%
Top quark p_T †	100%	100%	0.5–2.5%
Matrix element to parton shower matching †	100%	100%	0.7%
Underlying event tune †	100%	100%	0.2%
Color reconnection †	100%	100%	0.3%
Top quark mass †	100%	100%	0.5–3%
Single top quark cross section †	100%	100%	30%
$t\bar{t}V$ cross section †	100%	100%	20%
Diboson cross section †	100%	100%	30%
V+jets cross section †	100%	100%	30%
$t\bar{t}$ cross section *†	100%	100%	4%
Single top quark time modulation *	100%	100%	2%
MC statistical uncertainty	0%	100%	0.1–1%

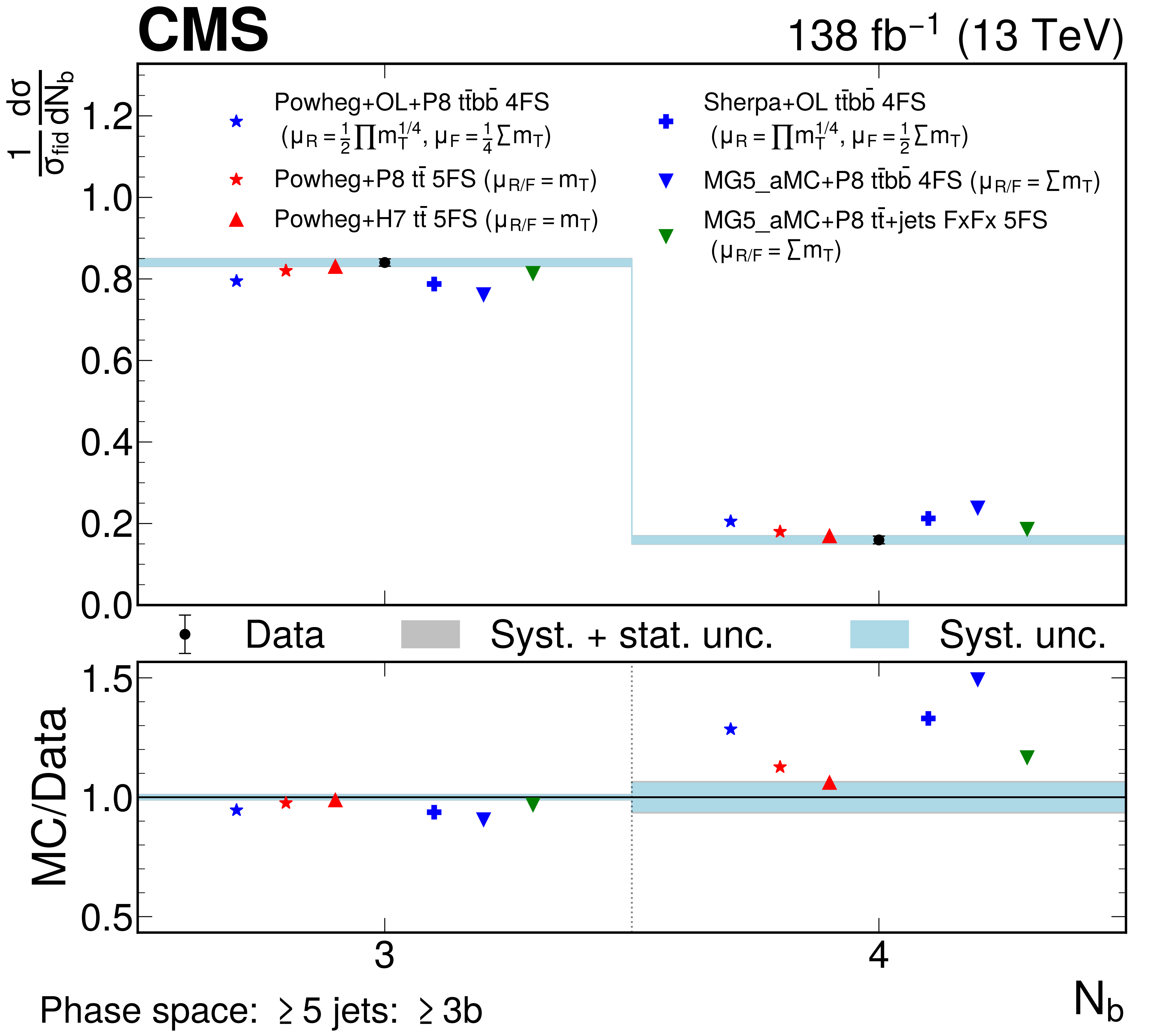
$t\bar{t}+b\bar{b}$ production at 13 TeV

Recently published:
JHEP 05 (2024) 042

- Important process for searches and SM measurements, eg. $t\bar{t}H(b\bar{b})/t\bar{t}t\bar{t}$
  - **Very challenging to model**
  - **important test of pQCD and PS**







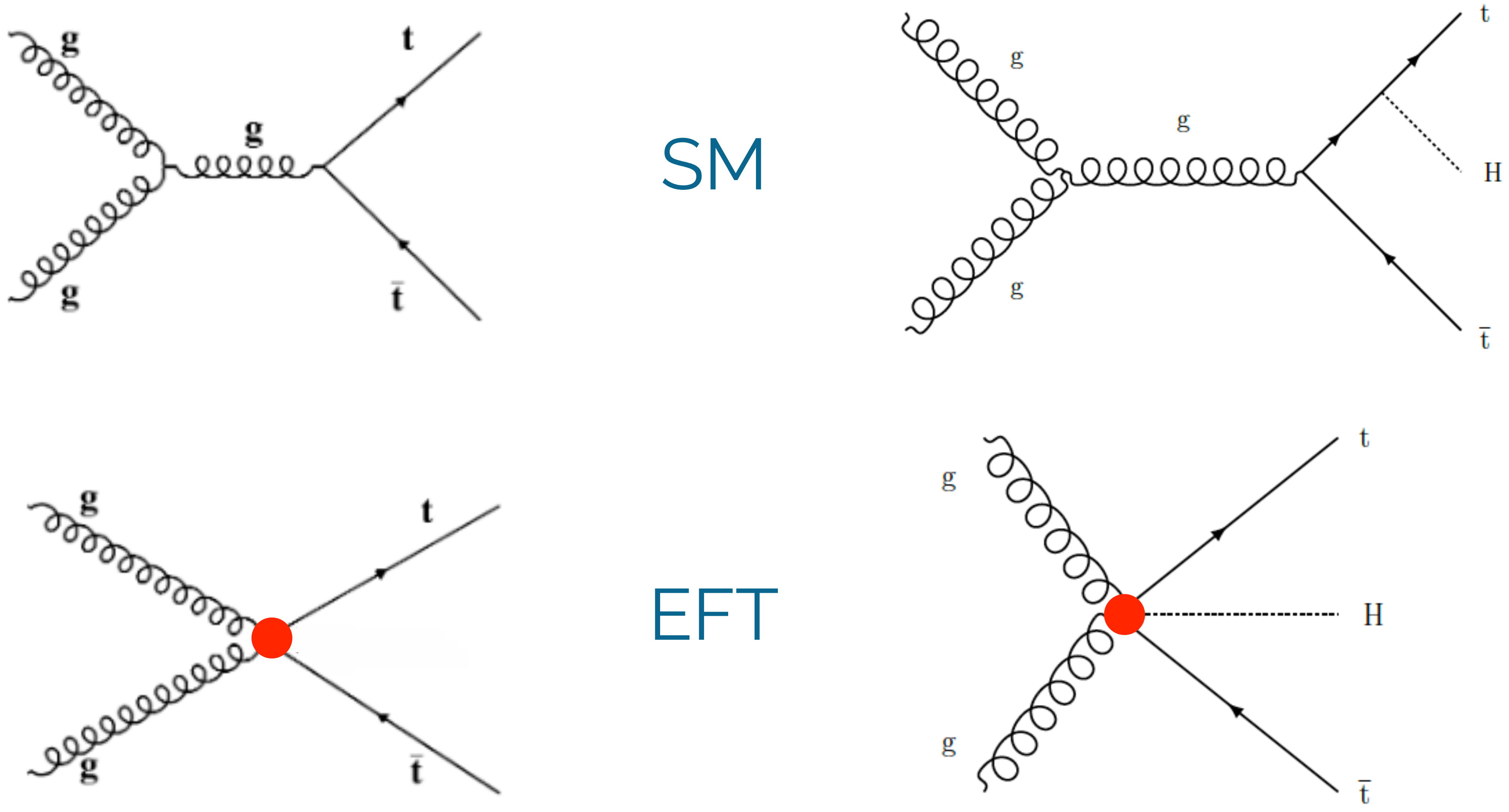
- No generator describes both the inclusive and differential cross sections
  - Generally 10-50% higher than prediction
- Dependence on shower and scale tuning

Most precise $t\bar{t}+b\bar{b}$ measurement!

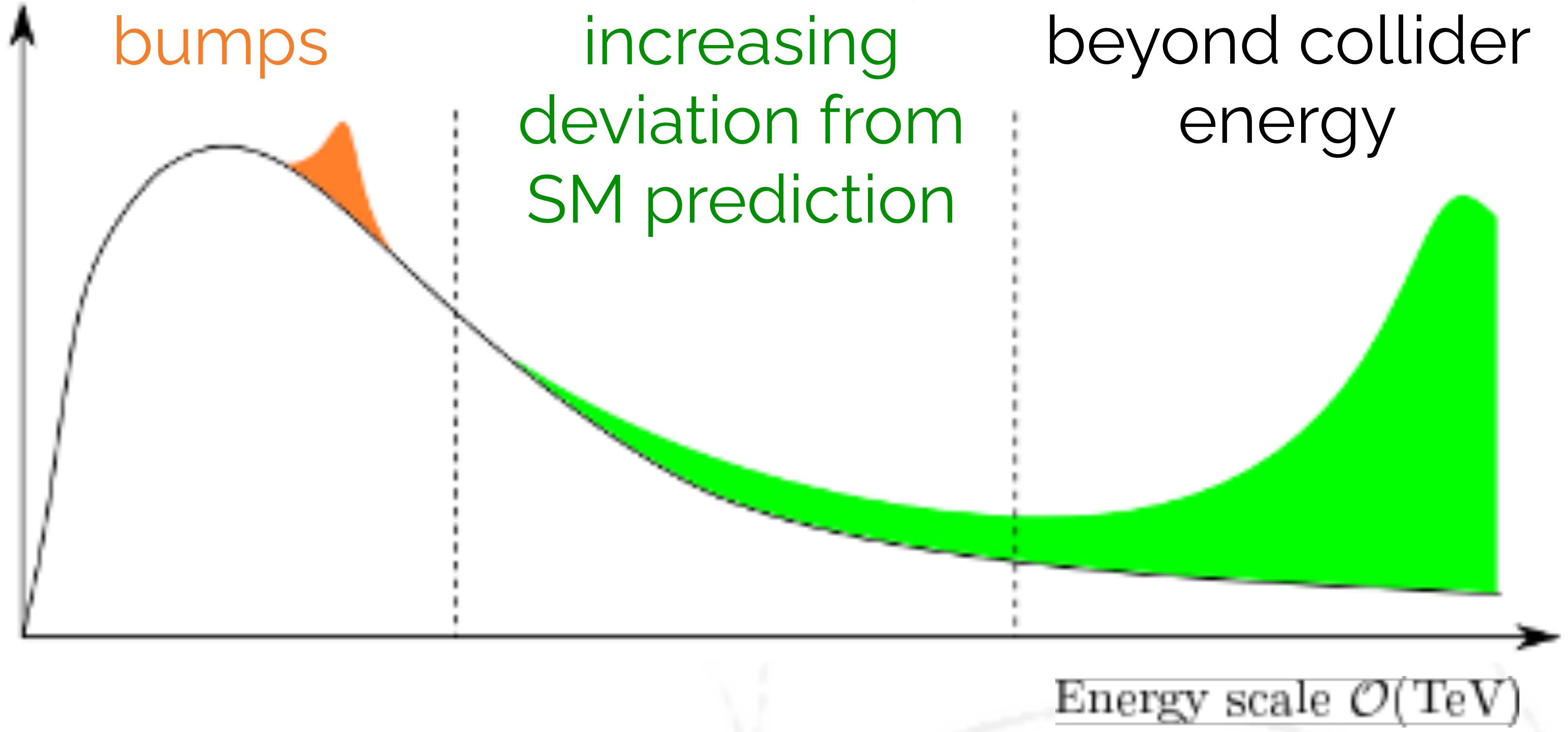
New physics via EFT

- Simplified description of the investigated system
- Robust within a limited region of validity
- Historical example: electroweak decay (Fermi)

- Standard Model effective field theory (SMEFT)
  - Dimension-6 operators parametrize new physics
  - 59 up to 2499 independent operators


SM

EFT


Direct search
resonance bumps

Indirect search
continuously increasing deviation from SM prediction

New physics manifesting beyond collider energy

Dimensionless Wilson coefficients

$$\mathscr{L}_{SMEFT} = \mathscr{L}_{SM} + \frac{1}{\Lambda^2}\sum_i c_i \mathcal{O}_i$$

New physics scale

Higher order EFT operators