Single and Double Top Quark Production at CMS

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(on behalf of the CMS Collaboration)

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Today's Menu

❖ $t\bar{t}$ production cross section with **5 TeV** data

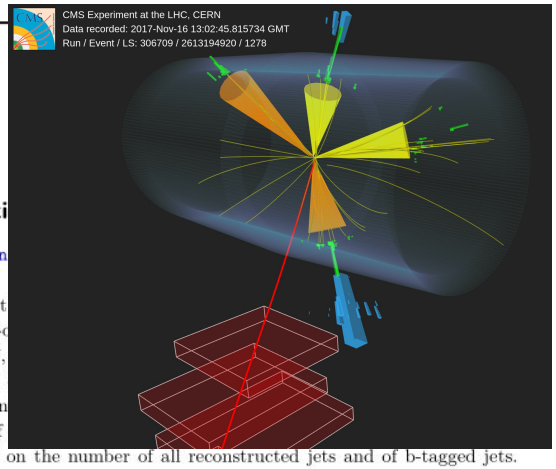
➢ *JHEP 04 (2025) 099*

JHEP

Published for SISSA by Springer

Received: *October 29, 2024*
Revised: *January 8, 2025*
Accepted: *February 20, 2025*
Published: *April 15, 2025*

Measurement of the inclusive $t\bar{t}$ cross section in final states with at least one lepton and additional jets with 302 pb^{-1} of pp collisions at $\sqrt{s} = 5.02$ TeV



The CMS collaborati

E-mail: cms-publication

Abstract: A measurement
proton collisions at a centre-
at the LHC in autumn 2017,
with respect to the default
302 pb^{-1}. The measuremen
multiple jets, at least one of
Events are classified based on the number of all reconstructed jets and of b-tagged jets. Multivariate analysis techniques are used to enhance the separation between the signal and backgrounds. The measured cross section is $62.5 \pm 1.6\,(\text{stat})^{+2.6}_{-2.5}\,(\text{syst}) \pm 1.2\,(\text{lumi})$ pb. A combination with the result in the dilepton channel based on the same data set yields $62.3 \pm 1.5\,(\text{stat}) \pm 2.4\,(\text{syst}) \pm 1.2\,(\text{lumi})$ pb, to be compared with the standard model p
of $69.5^{+3.5}_{-3.7}$ pb at next-to-next-to-leading order in perturbative quantum chromod

Keywords: Hadron-Hadron Scattering, Particle and Resonance Production, Top Physics

ArXiv ePrint: 2410.21631

JHEP04(2025)099

❖ **tW** production cross section with **Run 3** data

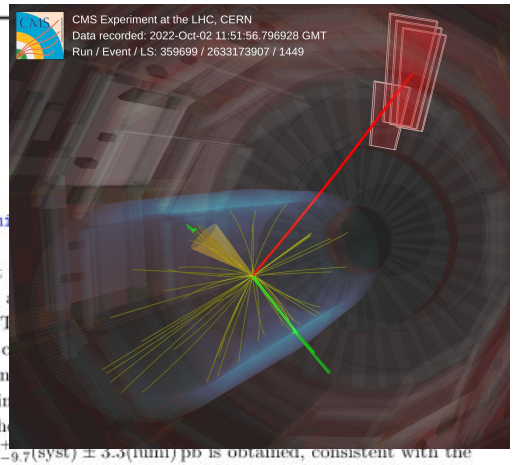
➢ *JHEP 01 (2025) 107*

JHEP

Published for SISSA by Springer

Received: *September 9, 2024*
Accepted: *December 9, 2024*
Published: *January 21, 2025*

Measurement of inclusive and differential cross sections of single top quark production in association with a W boson in proton-proton collisions at $\sqrt{s} = 13.6$ TeV



The CMS collaboration

E-mail: cms-publication-commi

Abstract: The first measurement
of single top quark production in
at a centre-of-mass energy of 13.6 T
detector at the LHC in 2022, and
analysed events contain one muon
measurement, multivariate discrimi
used to separate the signal from th
A cross section of $82.3 \pm 2.1(\text{stat})^{+}_{-9.7}(\text{syst}) \pm 3.3(\text{lumi})$ pb is obtained, consistent with the predictions of the standard model. A fiducial region is defined according to the detector acceptance to perform the differential measurements. The resulting differential distributions
ticle level and show good agreement with the predictions at next-to-leading
tive quantum chromodynamics.

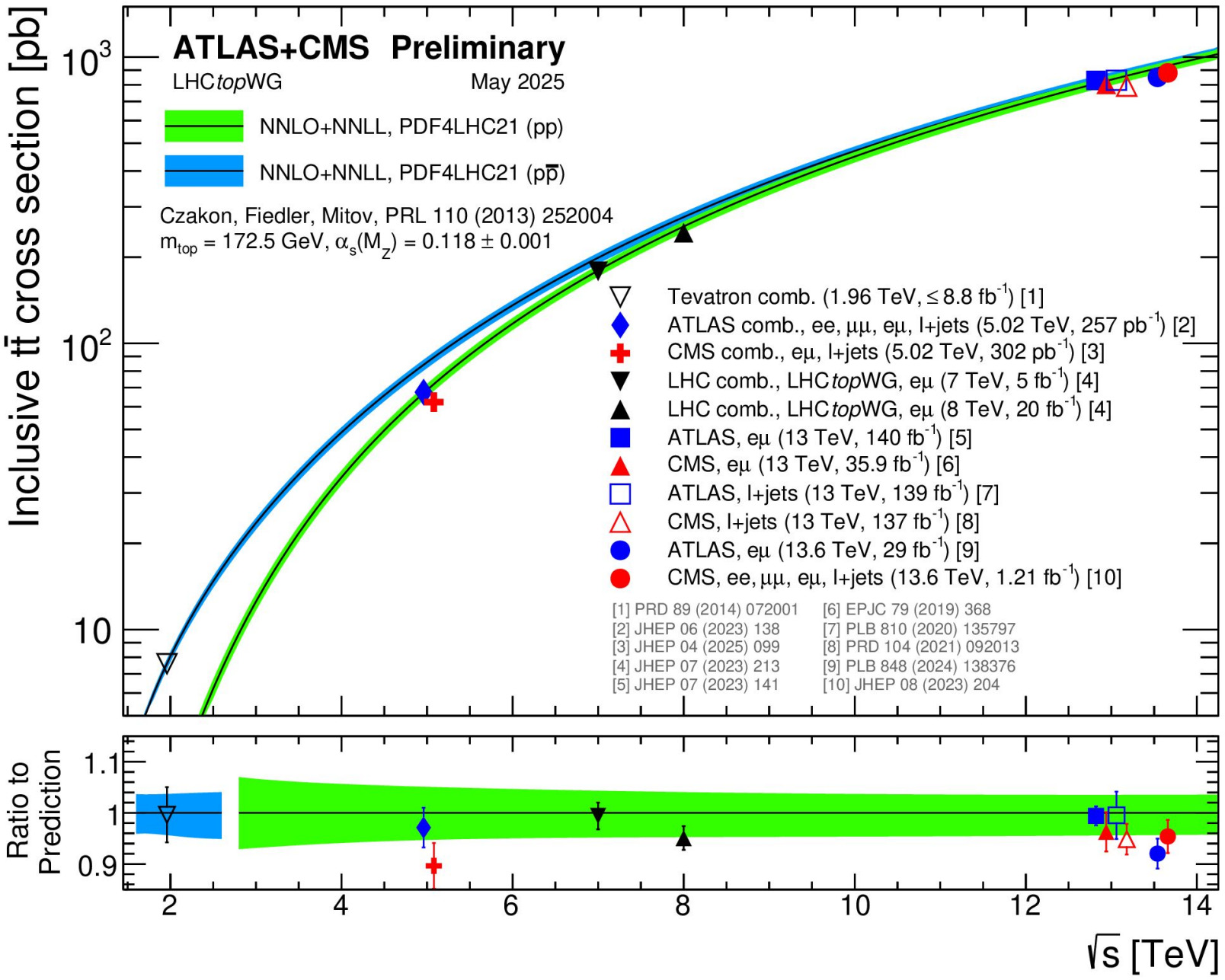
on-Hadron Scattering, Top Physics

ArXiv ePrint: 2409.06444

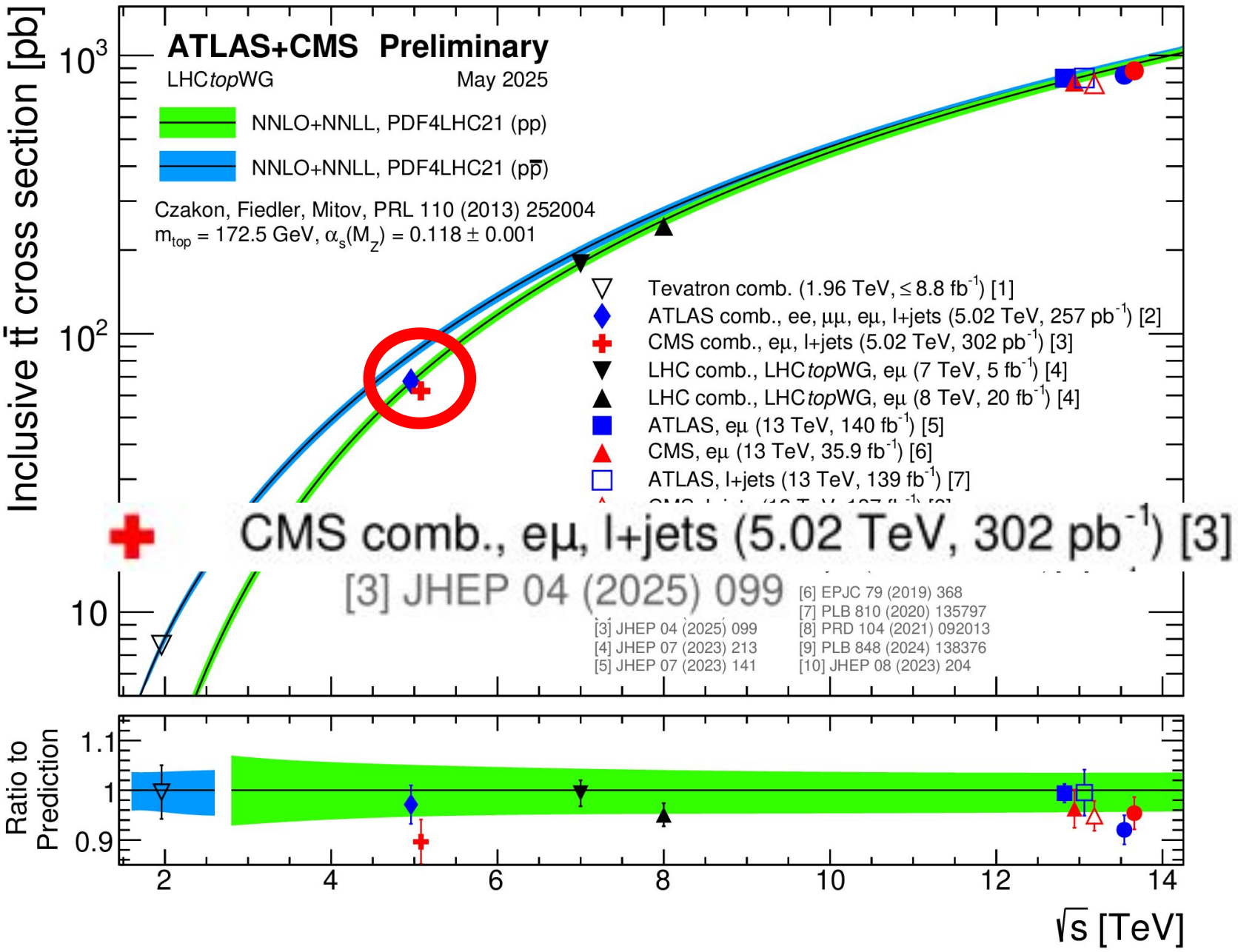
JHEP01(2025)107

… and a new result!

$t\bar{t}$ Production Cross Section

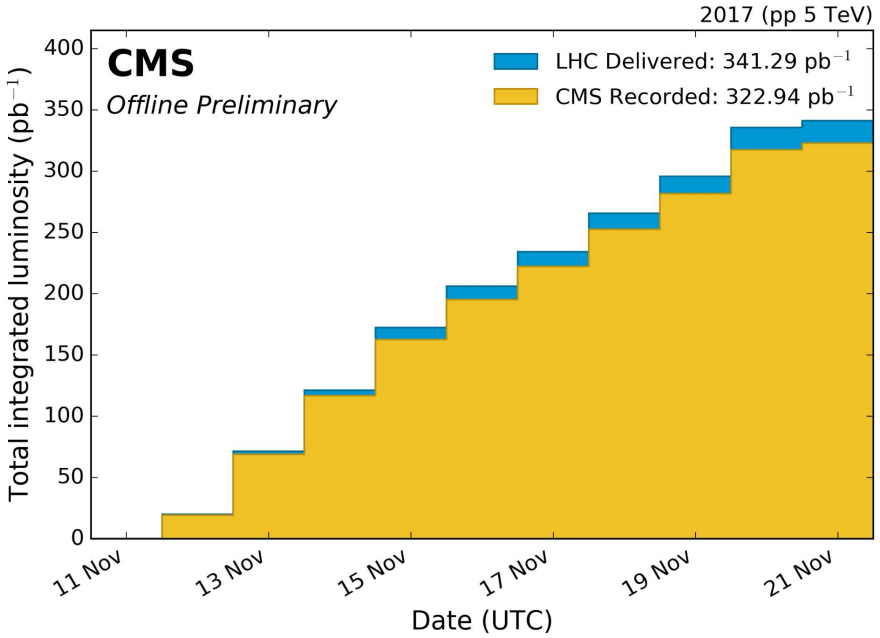


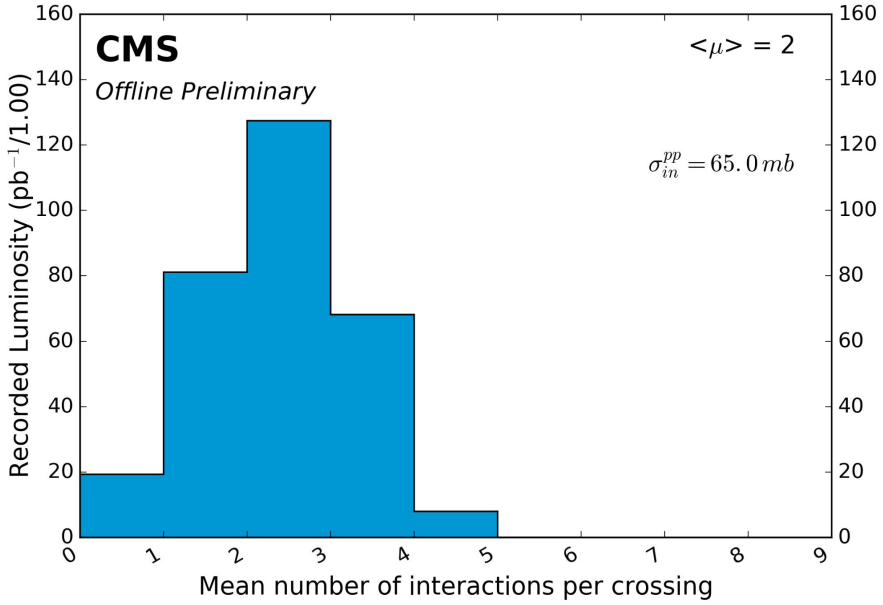
$t\bar{t}$ @5 TeV - JHEP 04 (2025) 099



5 TeV Run

- Data taken in **2017** (and 2015) intended to be used as calibration data for HI run





- **Low pileup** runs offer very good opportunities for measurements at the LHC
  - ➢ Clean environment allow for very precise measurements with low luminosity

- Data used already by CMS for top and diboson cross sections

PHYSICAL REVIEW LETTERS **127,** 191801 (2021)

Measurements of the Electroweak Diboson Production Cross Sections in Proton-Proton Collisions at $\sqrt{s} = 5.02$ TeV Using Leptonic Decays

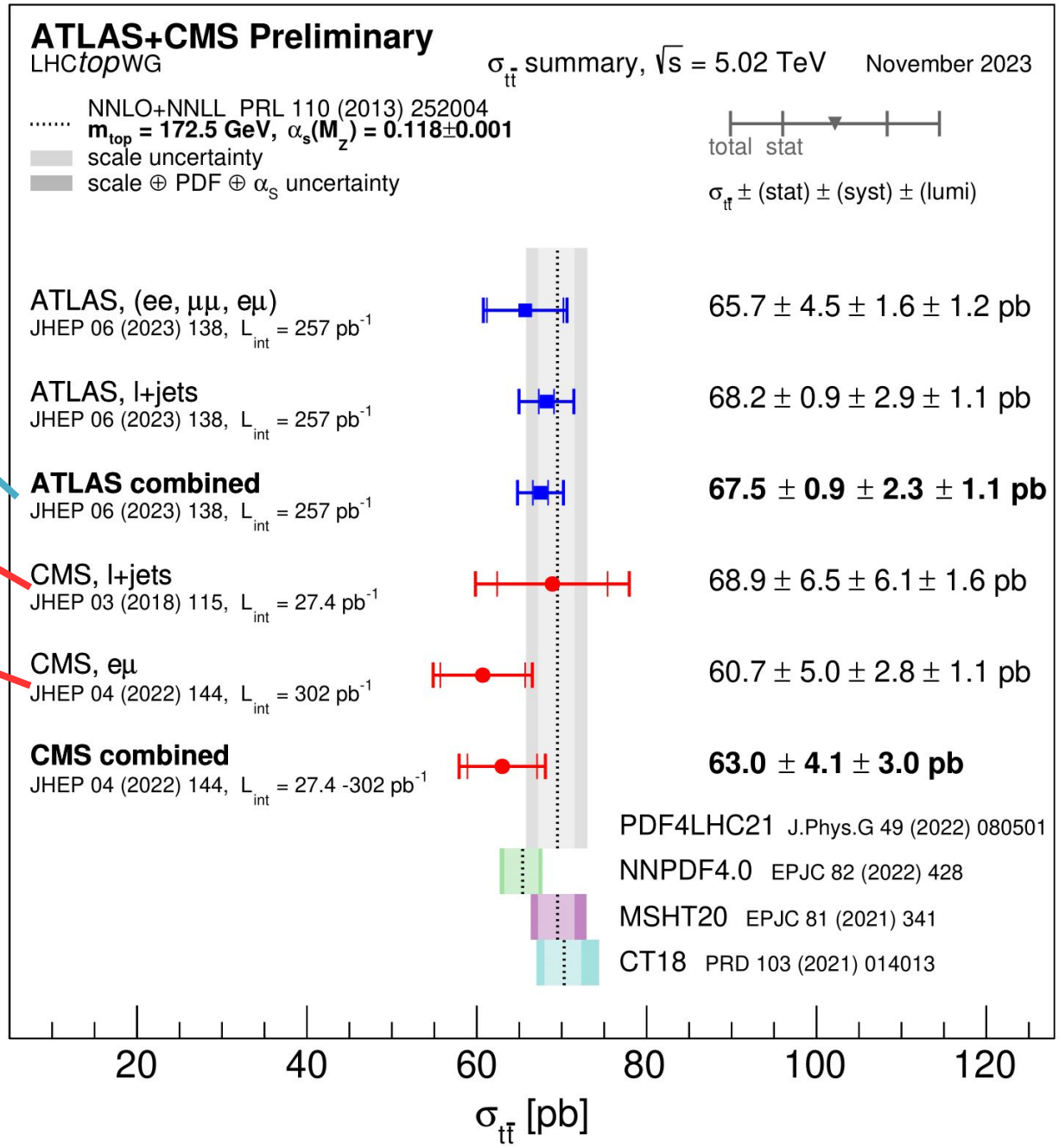
A. Tumasyan *et al.*[*]
(CMS Collaboration)

(Received 2 July 2021; accepted 22 September 2021; published 2 November 2021)

The first measurements of diboson production cross sections in proton-proton interactions at a center-of-mass energy of 5.02 TeV are reported. They are based on data collected with the CMS detector at the LHC, corresponding to an integrated luminosity of 302 pb^{-1}. Events with two, three, or four charged light leptons (electrons or muons) in the final state are analyzed. The WW, WZ, and ZZ total cross sections are measured as $\sigma_{WW} = 37.0^{+5.5}_{-5.2}(\text{stat})^{+2.7}_{-2.6}(\text{syst})$ pb, $\sigma_{WZ} = 6.4^{+2.5}_{-2.1}(\text{stat})^{+0.5}_{-0.3}(\text{syst})$ pb, and $\sigma_{ZZ} = 5.3^{+2.5}_{-2.1}(\text{stat})^{+0.5}_{-0.4}(\text{syst})$ pb. All measurements are in good agreement with theoretical calculations at combined next-to-next-to-leading order quantum chromodynamics and next-to-leading order electroweak accuracy.

DOI: 10.1103/PhysRevLett.127.191801

$t\bar{t}$ @5 TeV - State of the Art



Δ= 4%

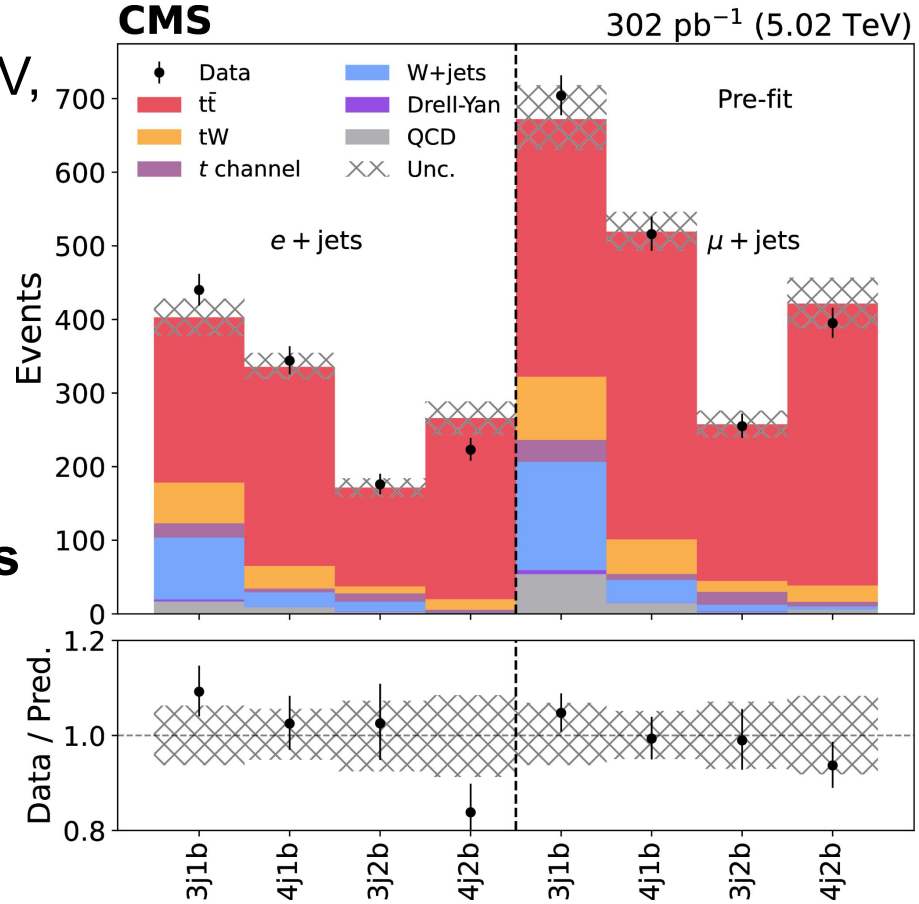
Δ= 12%

Δ= 8%

- The analysis shown here uses 2017 data and events with 1 lepton (and then combines with the existing 2 lepton result)

$t\bar{t}$ @5 TeV - Event Selection

- Exactly 1 lepton (electron or muon) (p_T > 20 GeV, $|\eta|$ < 2.4)
- At least 3 jets (p_T > 25 GeV, $|\eta|$ < 2.4)
- MET > 30 GeV
- Events are further categorized into **8 categories** depending on the number of jets and b-tagged jets, and the lepton flavour
  - All are signal-dominated
  - ℓ+3j2b and ℓ+4j2b are purest in signal (89% of total MC)
  - ℓ+3j1b provide the greatest contribution from tW and W+jets backgrounds (12% and 18% of total MC)



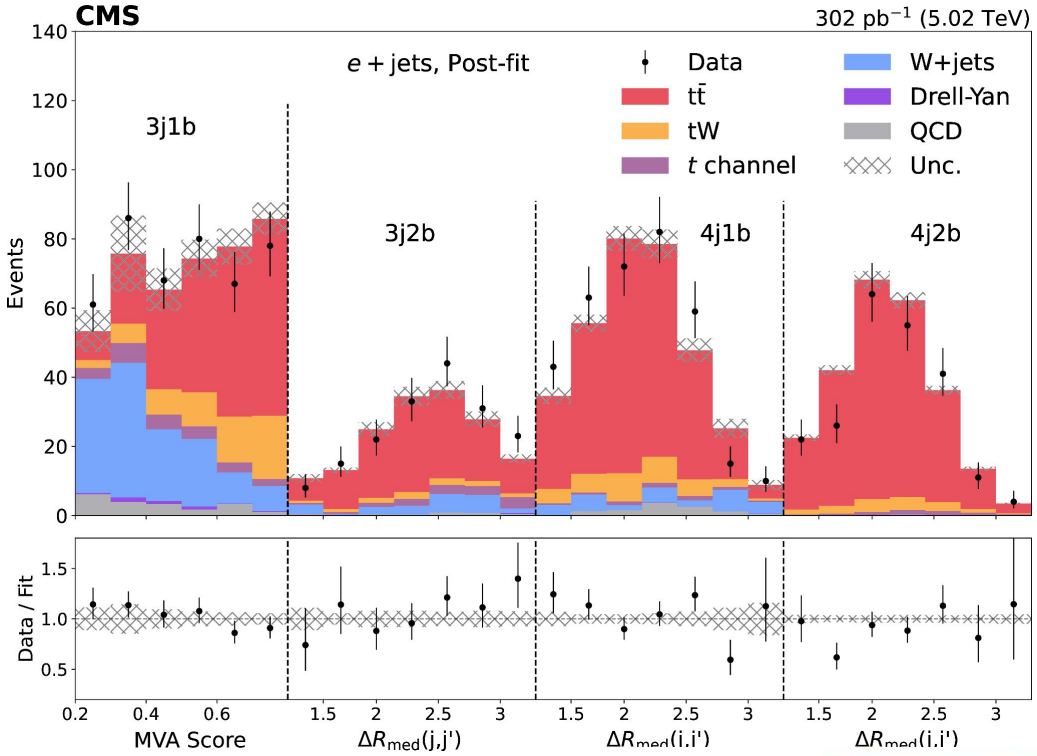
- 4 main backgrounds: Single top (tW + t-channel), W+jets, QCD multijets and DY

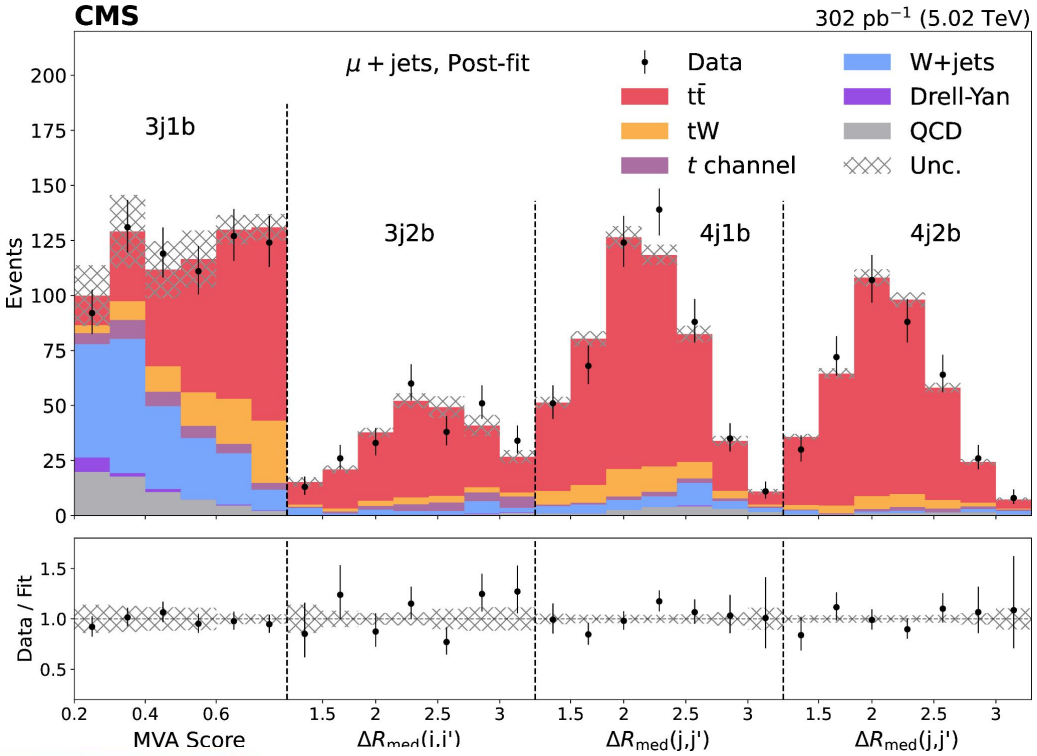
$t\bar{t}$ @5 TeV - Analysis Strategy

❖ A Maximum Likelihood fit is done simultaneously to these distributions

➢ median(ΔR(j, j')) + MVA Score (3j1b category)

➢ Final distribution of 27 bins x 2 (e/μ) = 54 bins



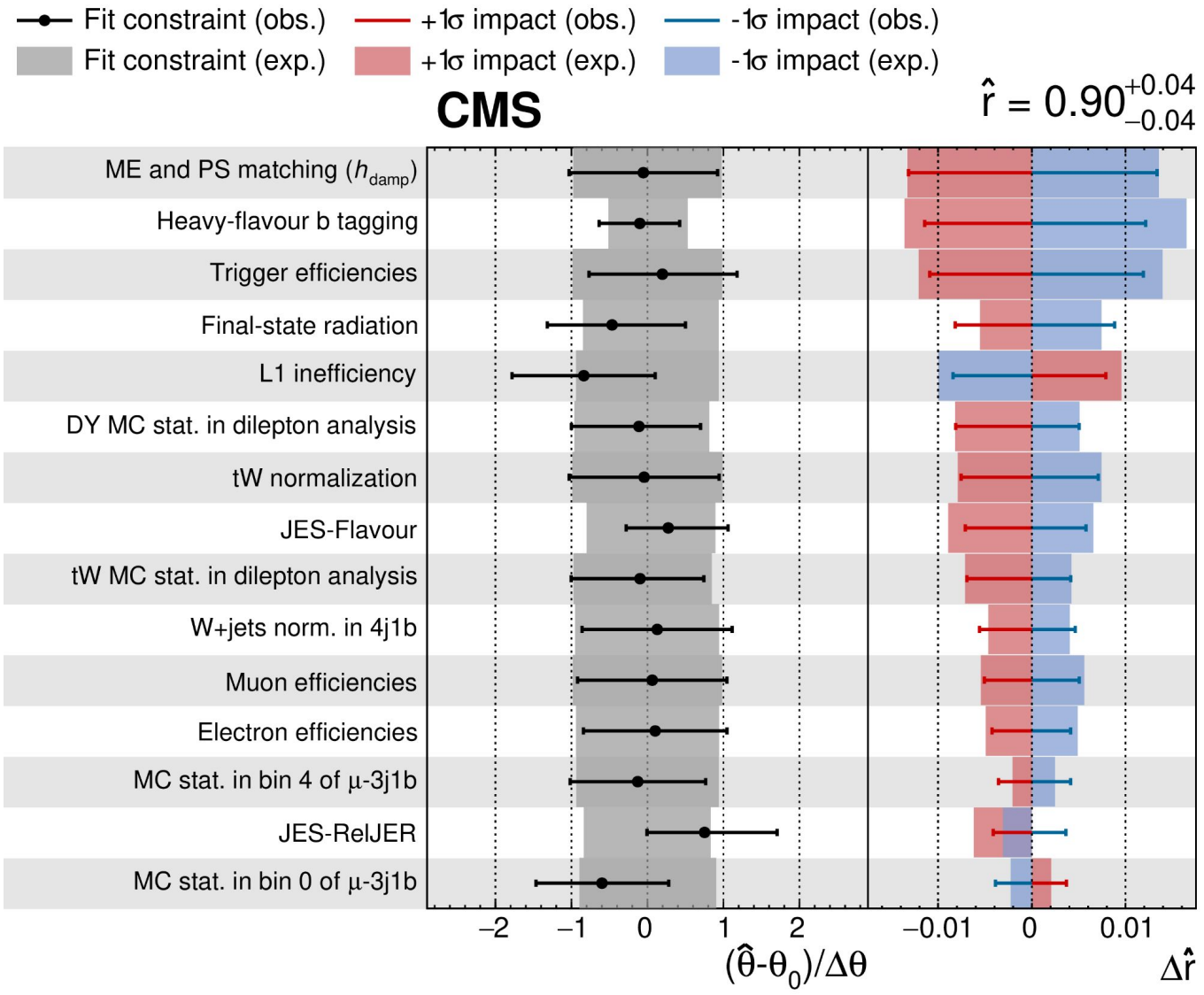


Δ= 5.5%

$$\sigma_{t\bar{t}} = 62.5 \pm 1.6\,(stat)^{+2.6}_{-2.5}(syst) \pm 1.2\,(lumi)\ pb$$

σ(SM) = $69.5\,^{+3.5}_{-3.7}$ pb

$t\bar{t}$ @5 TeV - Combination with $e\mu$

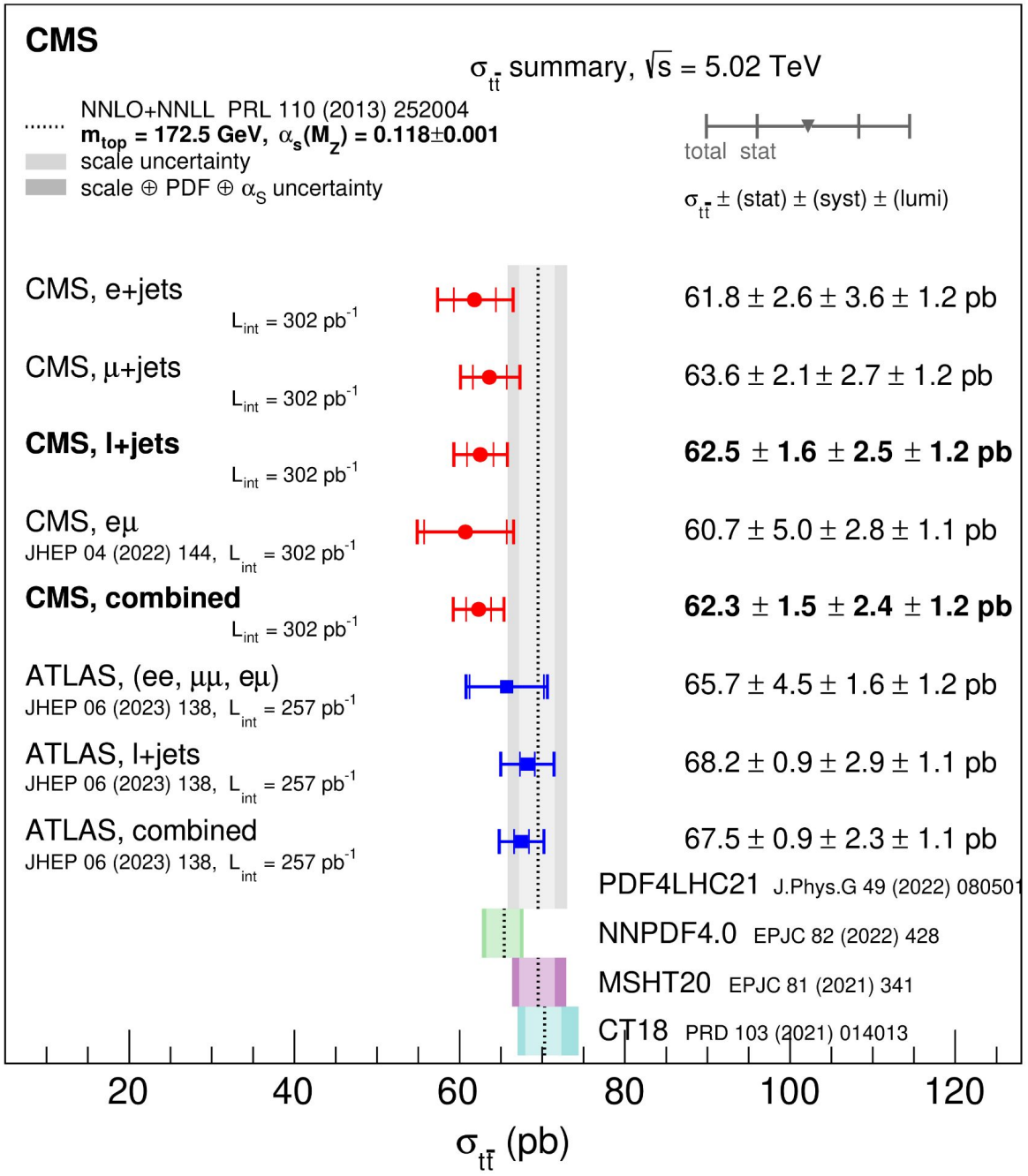


$$\sigma_{t\bar{t}} = 62.3 \pm 1.5\,(stat) \pm 2.4\,(syst) \pm 1.2\,(lumi)\ pb$$

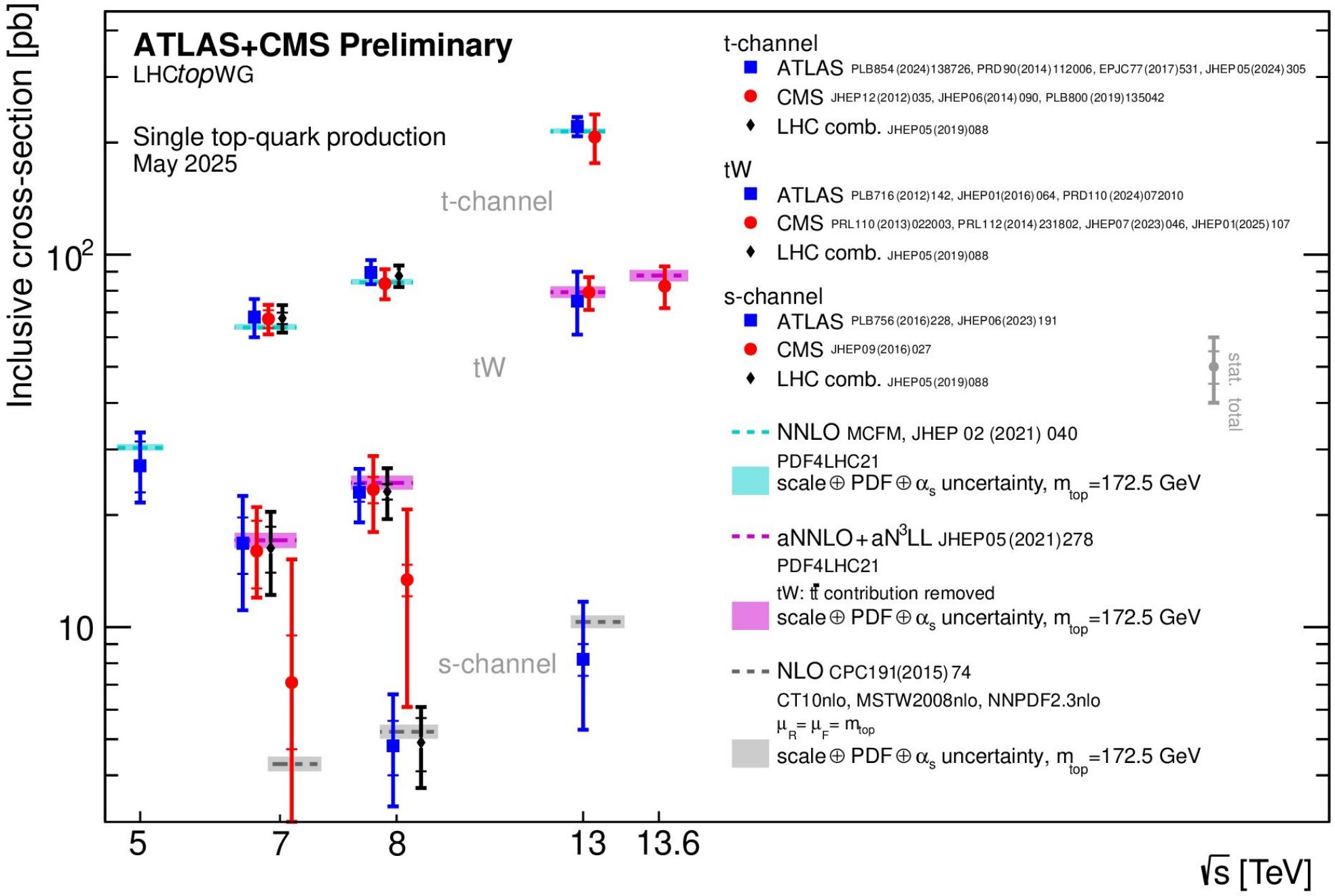
Δ= 4.9%

σ(SM) = $69.5\,^{+3.5}_{-3.7}$ pb

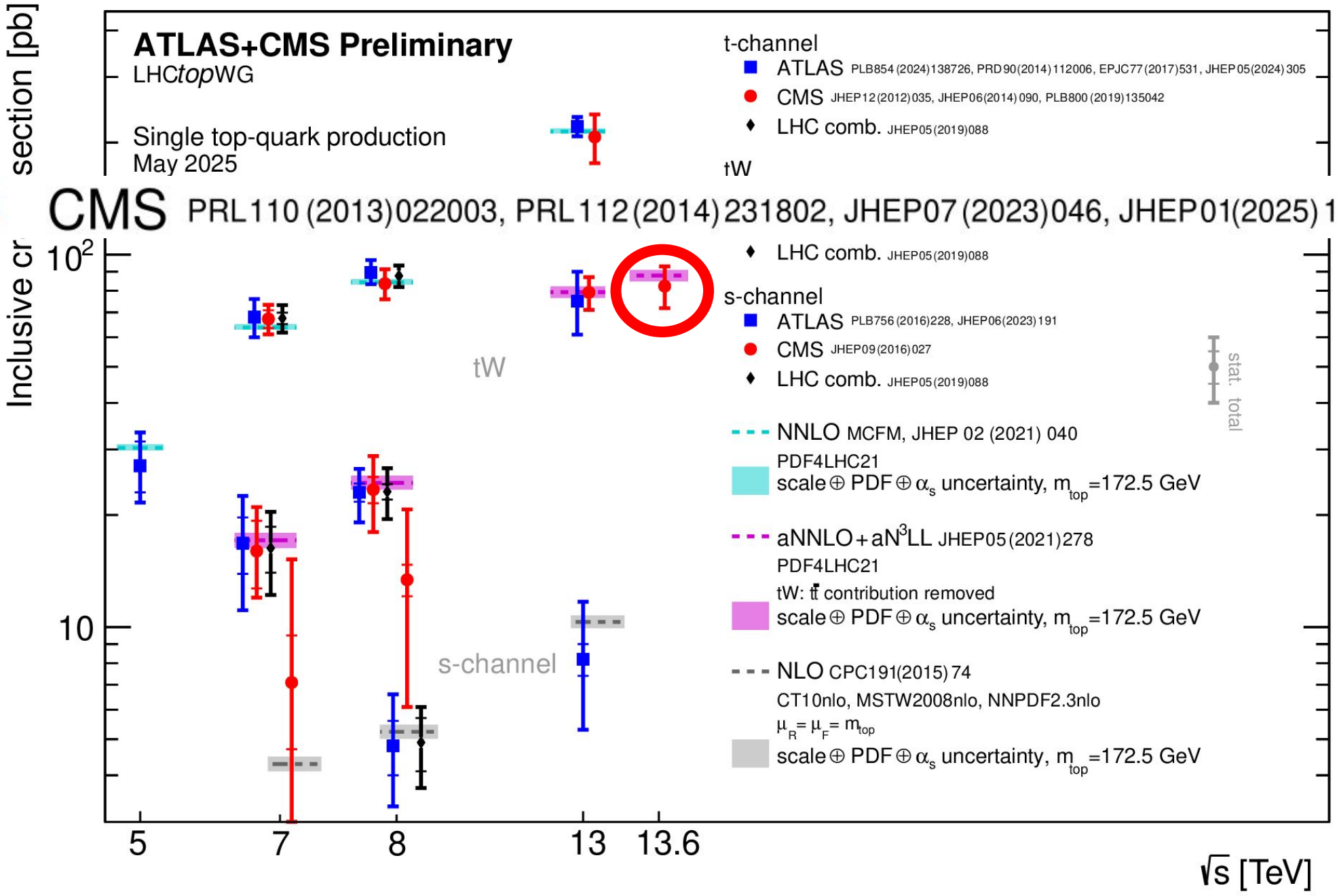
$t\bar{t}$ @5 TeV - Summary



Single Top Production Cross Section



tW @13.6 TeV - JHEP 01 (2025) 107

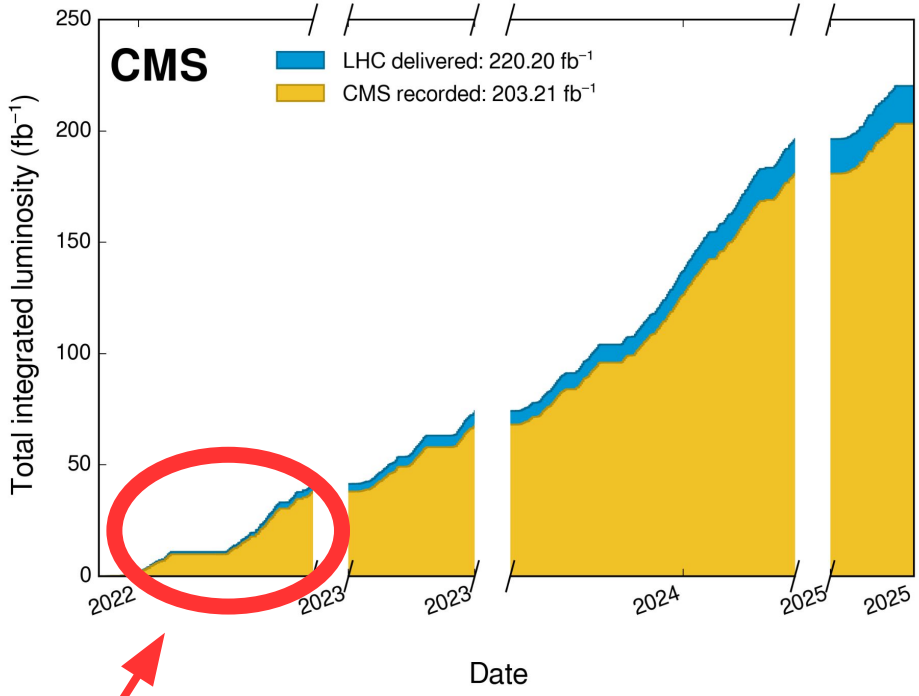


Run 3

❖ pp collisions @13.6 TeV

❖ With the new data we can extend further our knowledge of the SM

➢ First measurements are also important to test the performance of the CMS detector



❖ The analysis presented here uses the **2022 dataset**

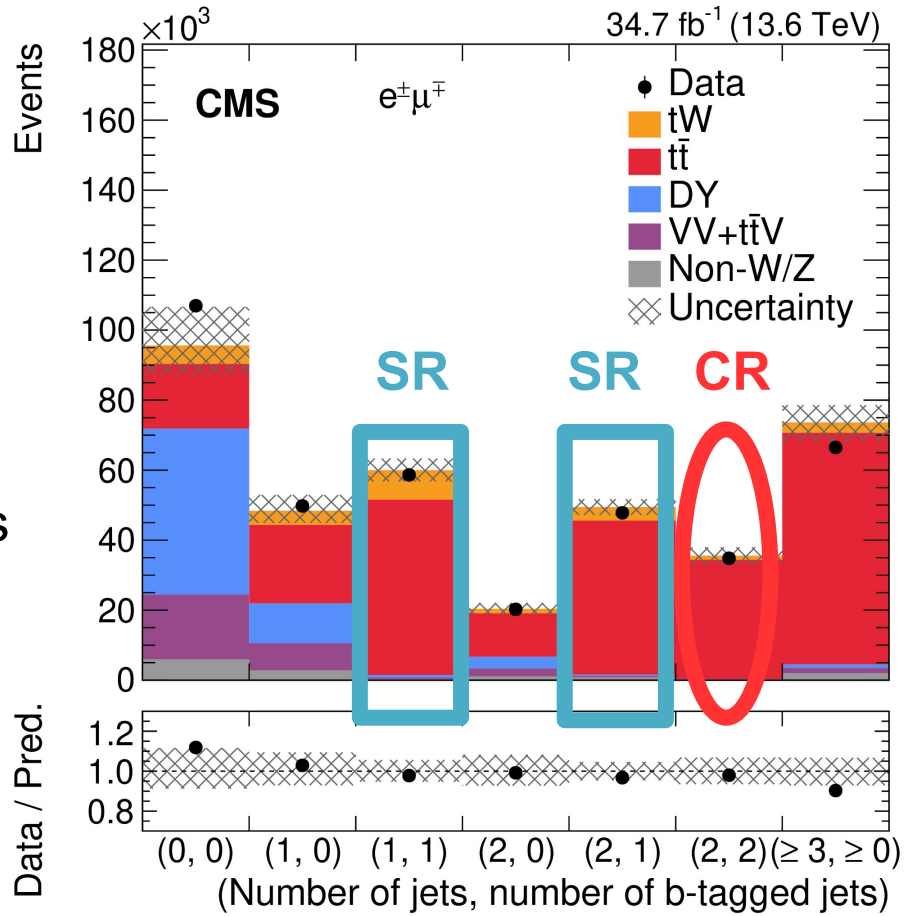
➢ Targets final state of tW $\rightarrow e^{\pm}\mu^{\mp}\, b$ jet + MET

➢ $t\bar{t}$ was measured at 13.6 TeV using a smaller dataset of 1.21 fb^{-1} (2022 data) [JHEP 08 (2023) 204]

tW @13.6 TeV - Analysis Strategy

- Events with 2 leptons of opposite flavor and opposite sign (p_T > 20 GeV, |η| < 2.4)

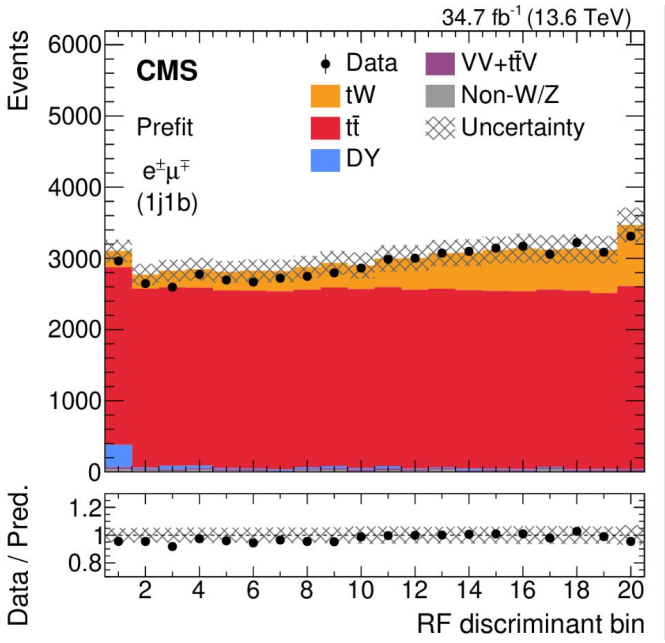
- Events are further categorized into 8 categories depending on the number of jets and b-tagged jets

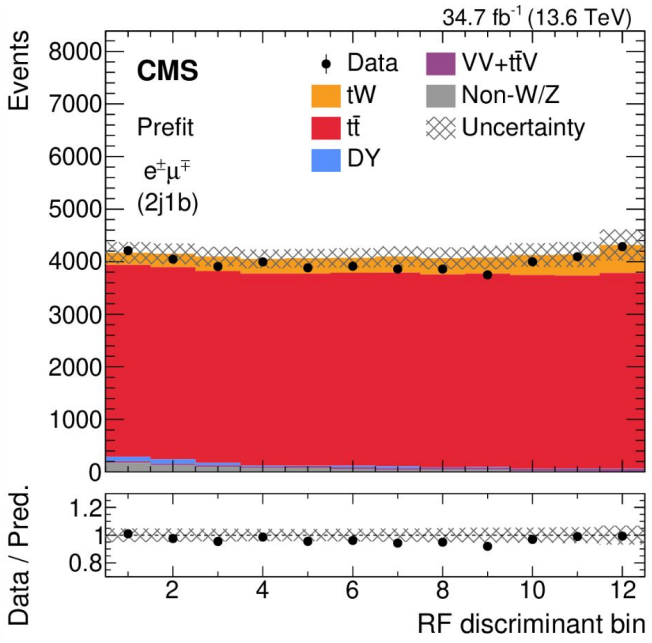


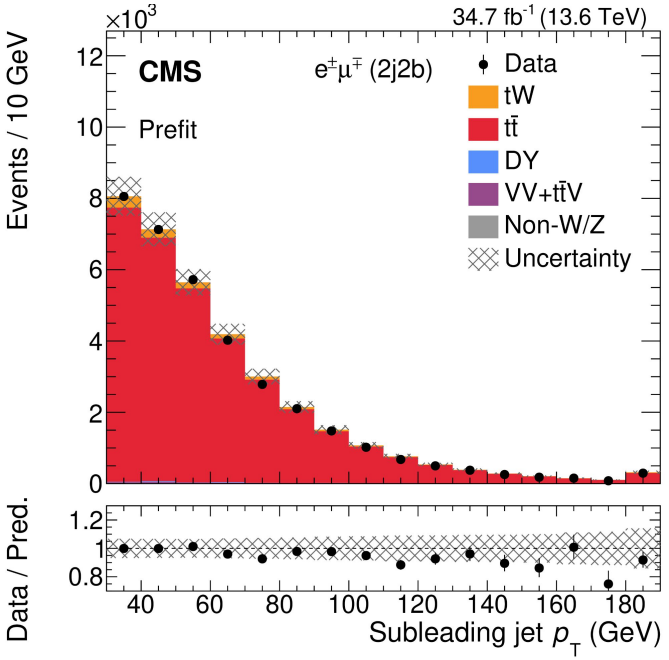
- A Maximum Likelihood fit is used to extract the inclusive cross section
  - 1j1b: Random Forest (RF) multiclassifier to discriminate **DY** vs **tt** vs **tW**
  - 2j1b: RF multiclassifier to discriminate tt semileptonic vs **tt** vs **tW**
  - 2j2b: subleading jet p_T

tW @13.6 TeV - Inclusive Measurement (I)

❖ A ML fit is performed using the two RF outputs and the subleading jet p_T







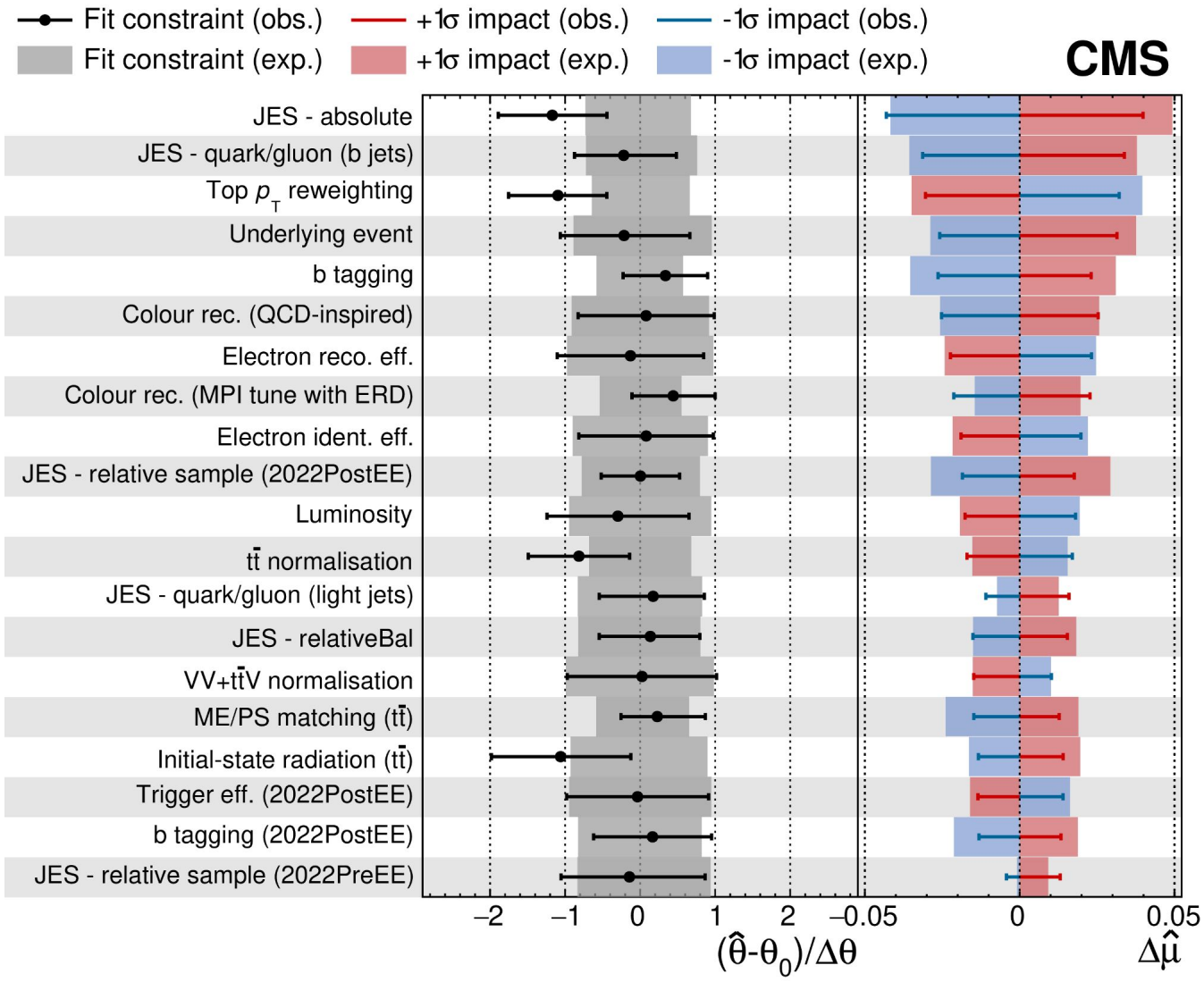
$$\sigma_{tW} = 82.3 \pm 2.1\,(\text{stat})\,^{+9.9}_{-9.7}\,(\text{syst}) \pm 3.3\,(\text{lumi})\,\text{pb}$$

aN^{3}LO

JHEP05 (2021) 278 ← $\sigma_{tW}^{SM} = 87.9^{+2.0}_{-1.9}(\text{scale}) \pm 2.4(\text{PDF} + \alpha_S)$ pb

❖ Measurement dominated by systematic uncertainties

tW @13.6 TeV - Inclusive Measurement (II)

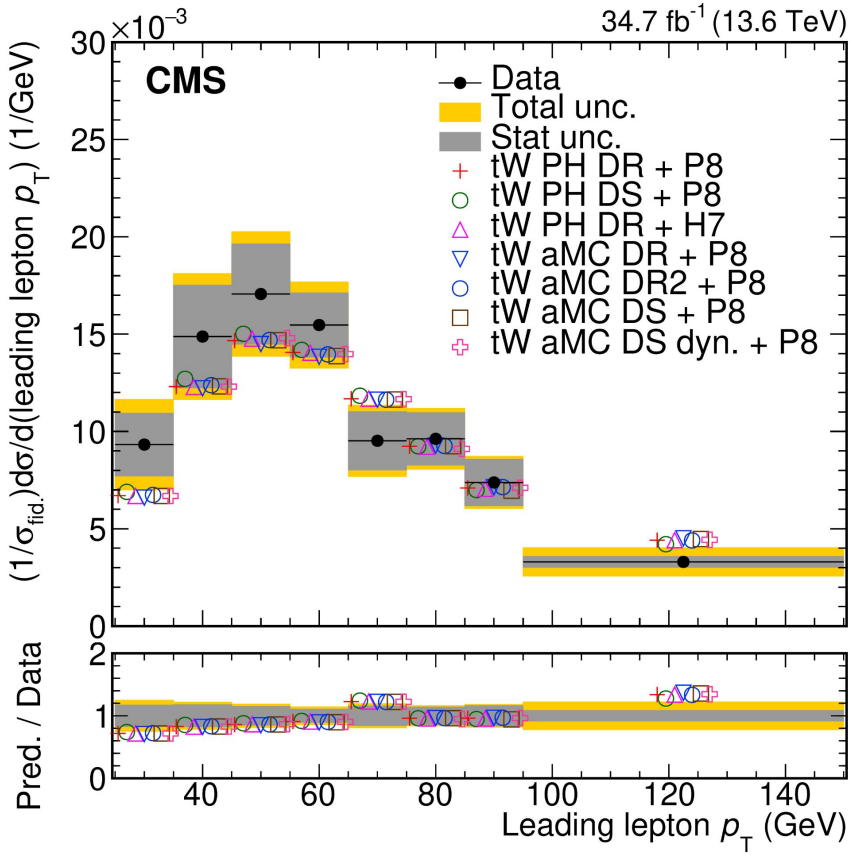


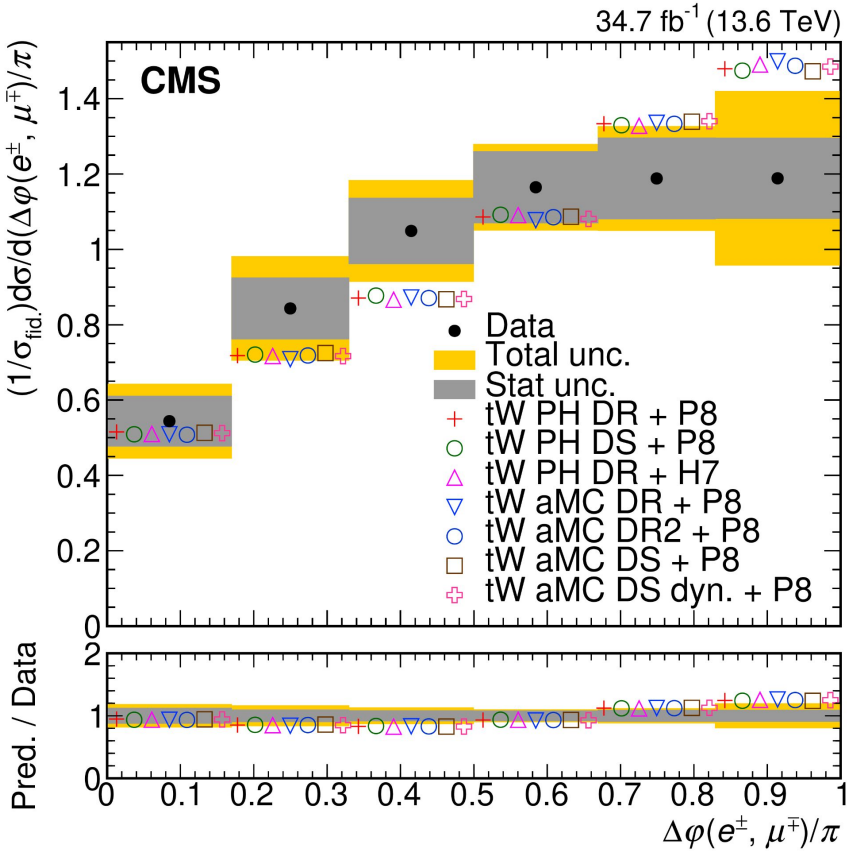
❖ The **leading uncs.** are the ones associated with the **energy of the jets** and b tagging

❖ But also, the modelling uncertainties: top p_T modelling and underlying event

tW @13.6 TeV - Differential Measurement

- Results are normalised to the fiducial cross section and bin width

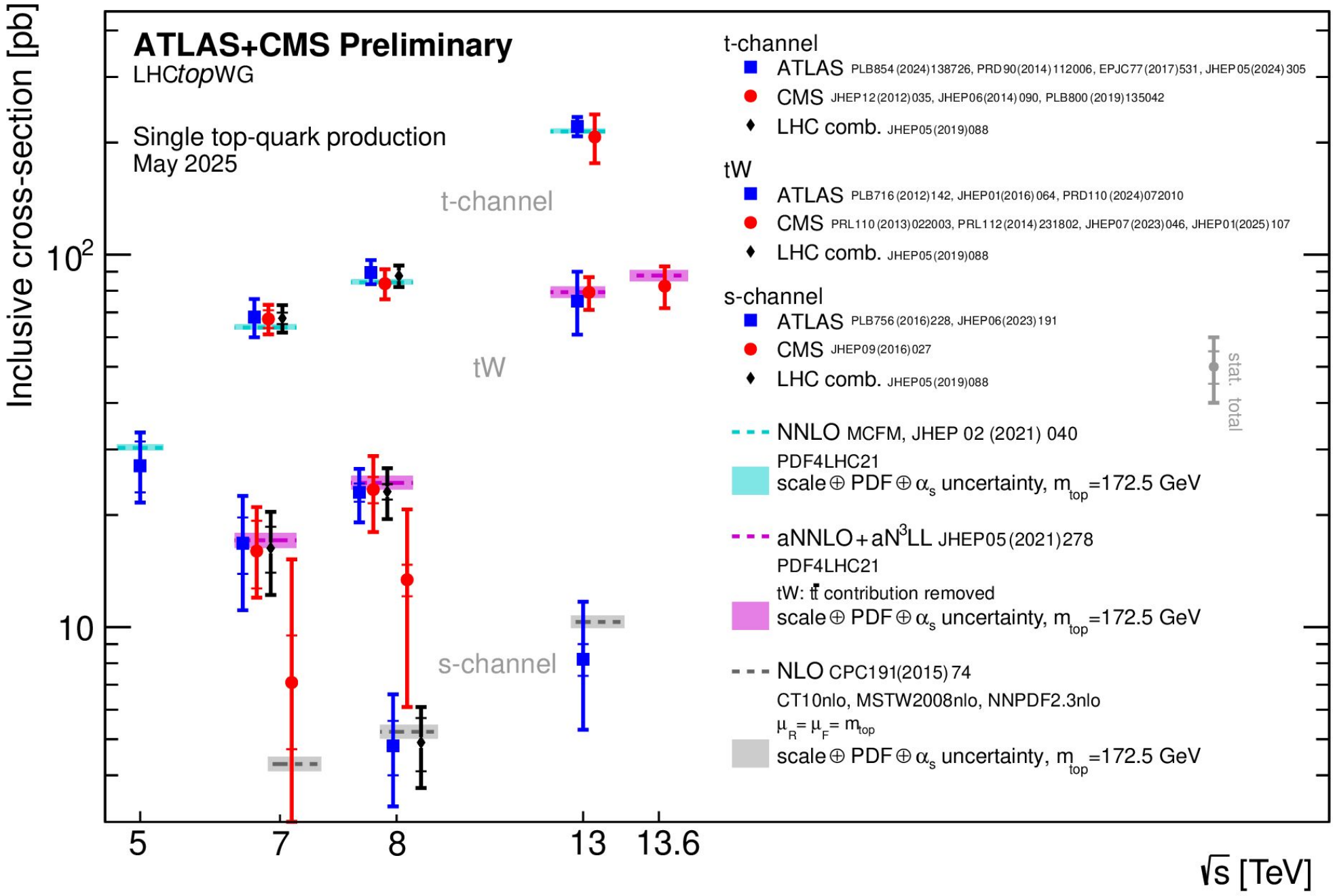




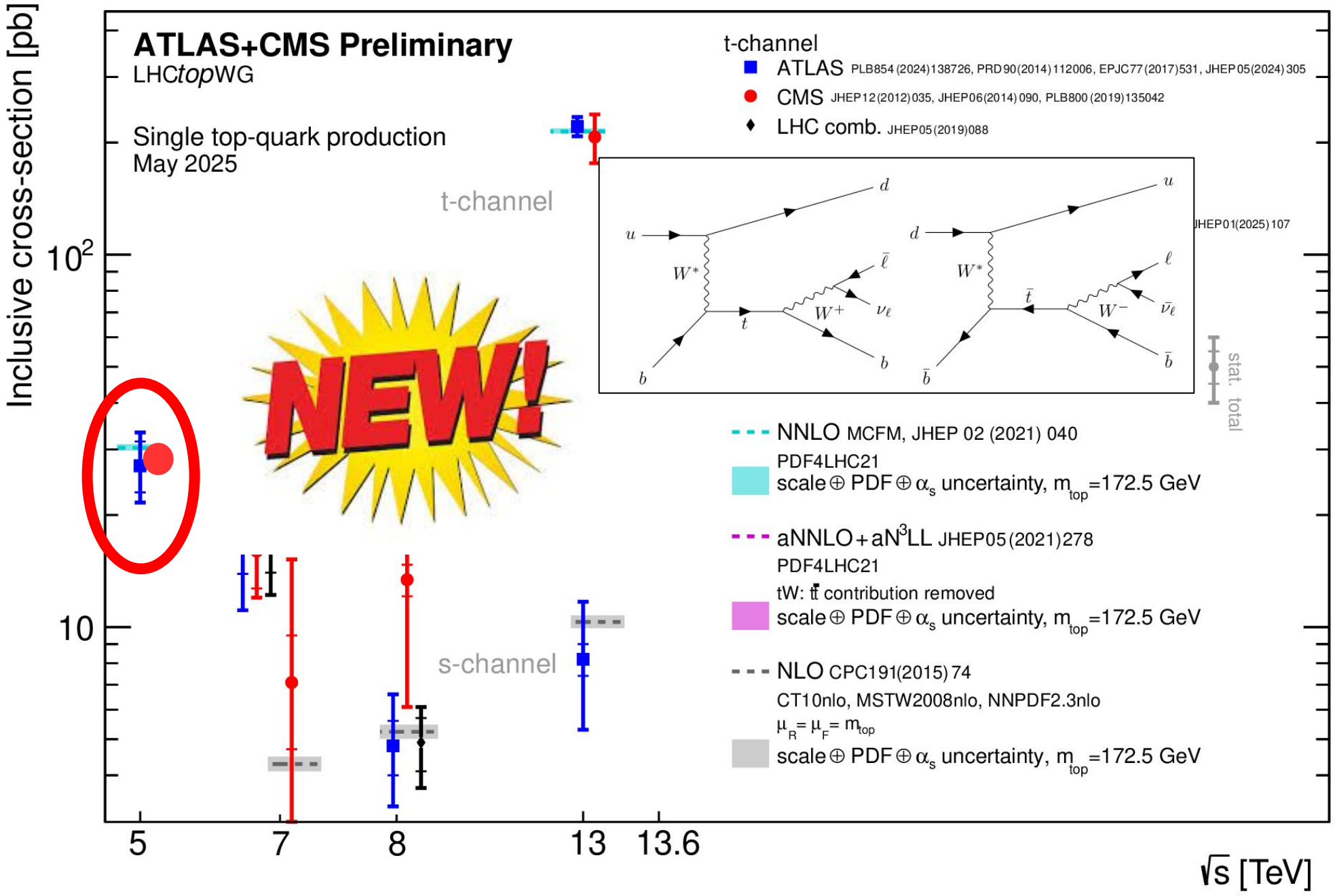
- Fair agreement between the measurements and the predictions from the different event generators

- **Limited sensitivity** to the different models

Single Top Production Cross Section

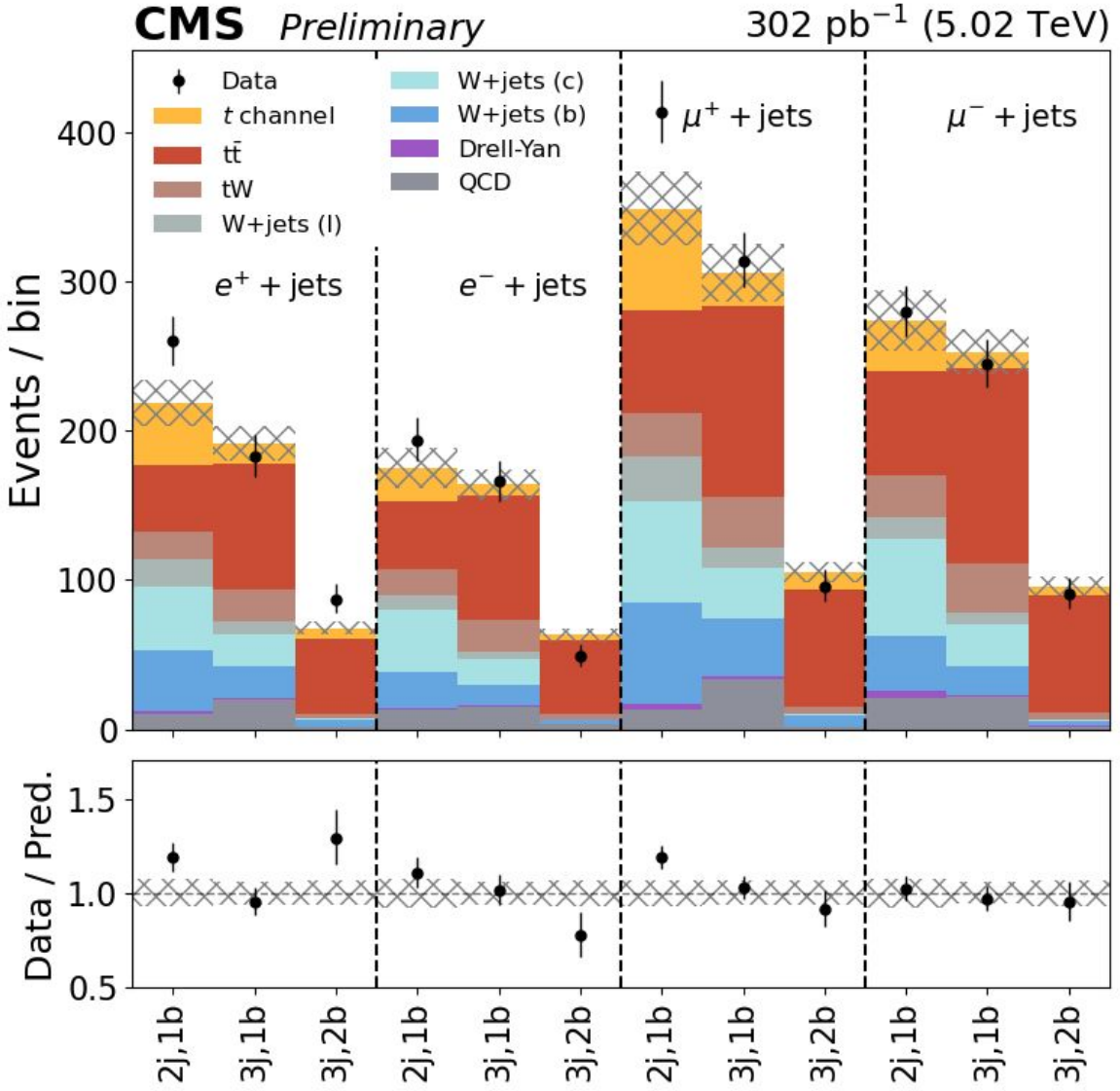


t-channel @5 TeV - CMS-PAS-TOP-24-011



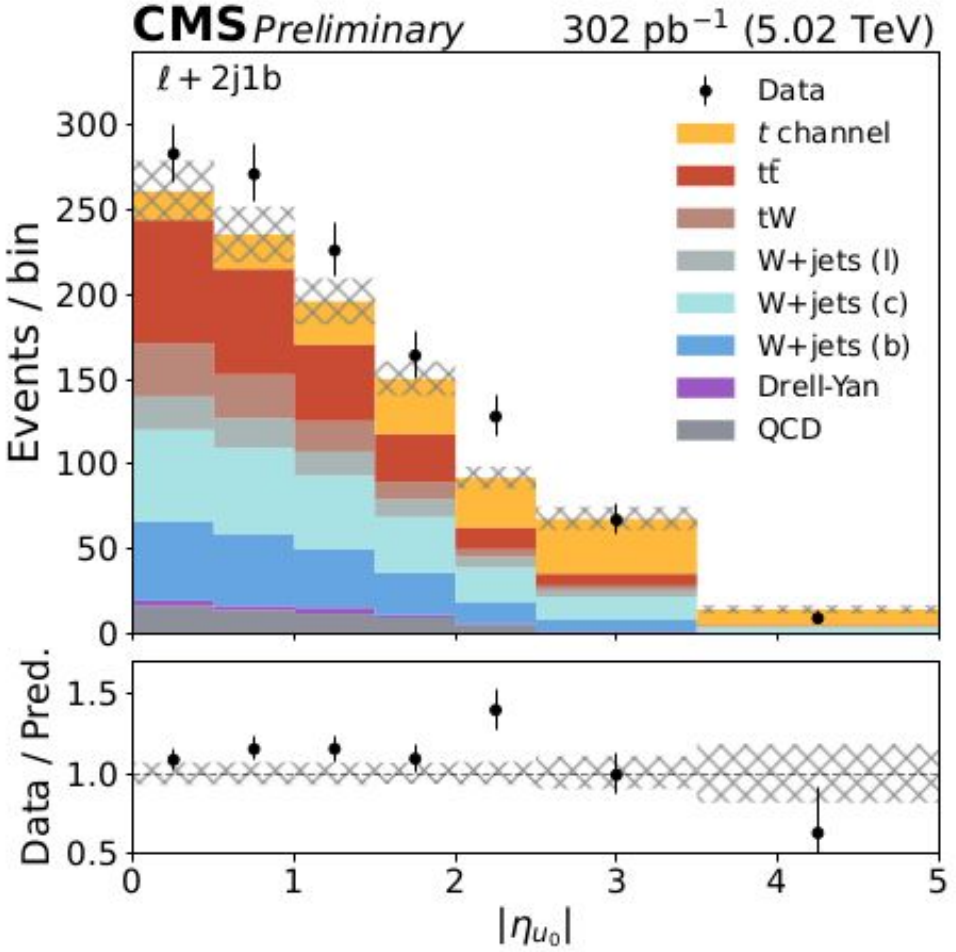
t-channel @5 TeV - Event Selection

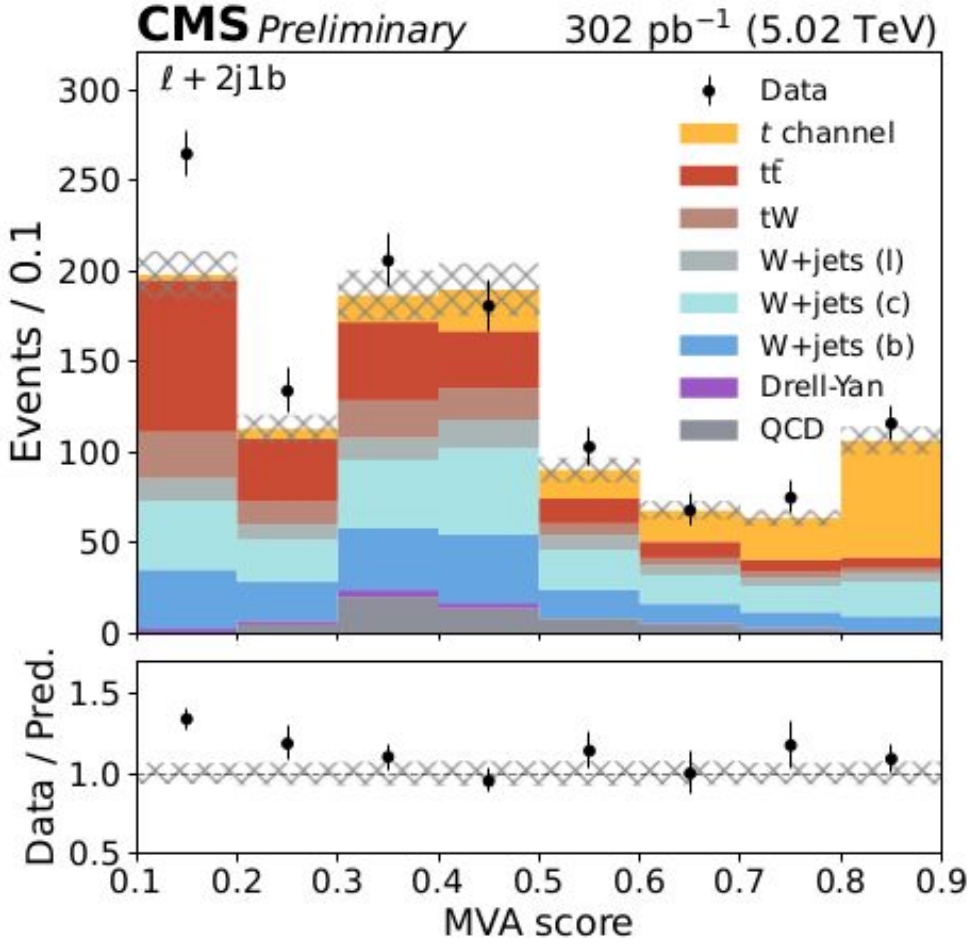
- Same objects as for $t\bar{t}$ but **larger jet |η| coverage** (up to 4.7)
- Same selection as for $t\bar{t}$ and: $m_T(W) > 50$ GeV and $H'_T > 170$ GeV (MET+jet p_T + ℓ p_T)
- Events are further categorized into **12 categories** depending on the number of jets and b-tagged jets, lepton flavour and lepton charge
- Maximum likelihood fits to extract the measurement
  - ➢ MVA score in 2j1b
  - ➢ |η| of the leading untagged jet in other categories



t-channel @5 TeV - MVA 2j1b

- RF trained with Sklearn to discriminate t-channel from $t\bar{t}$ and W+jets
- 13 input variables: $|\eta_{u0}|$, $|\Delta\eta(u_0, b_0)|$, $m_T(W)$, m_{top},…



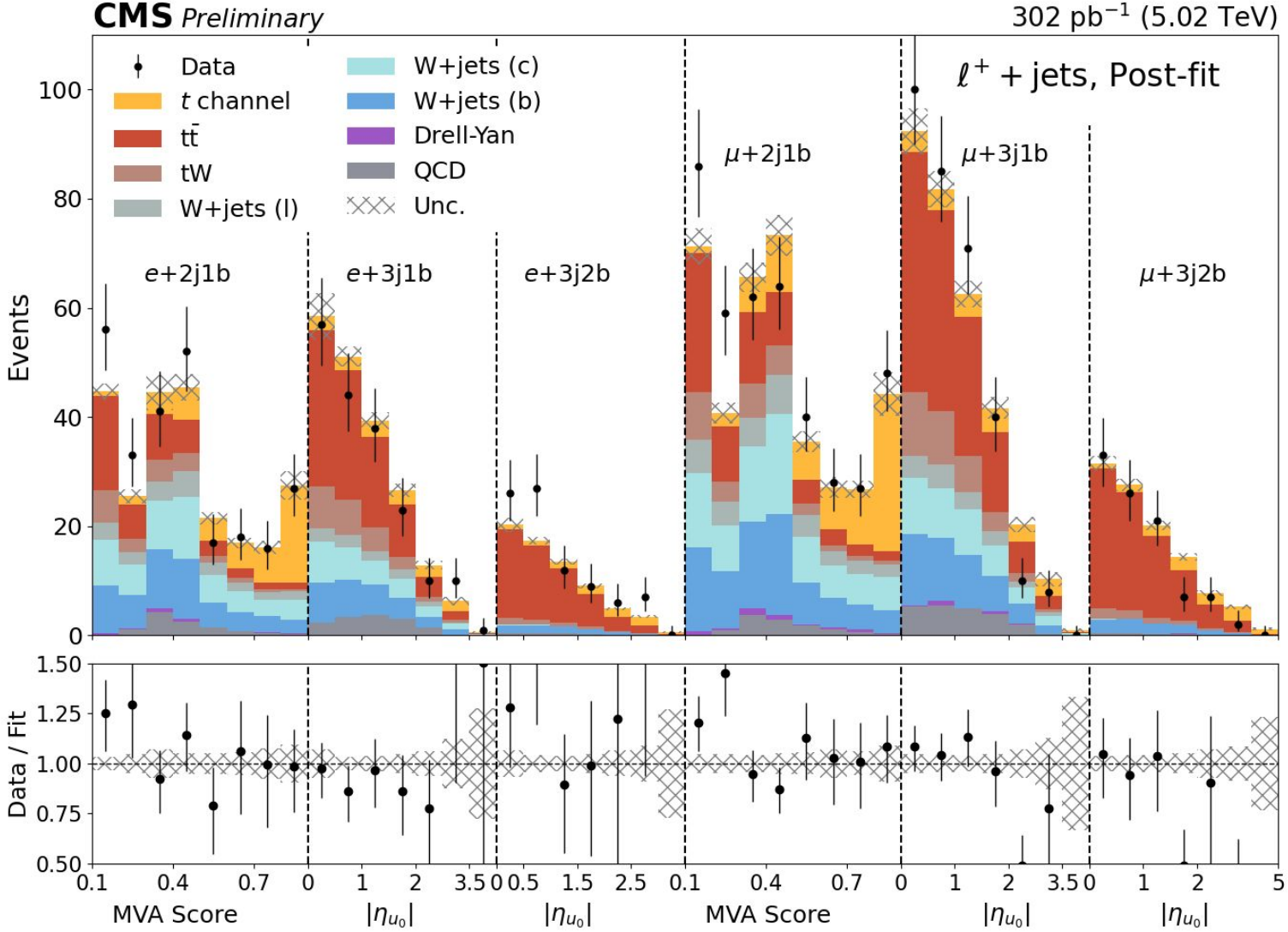


t-channel @5 TeV - Fit

❖ Fits to MVA score in 2j1b and |η| of the leading untagged jet in other categories

➢ one parameter of interest (POI) to measure $\sigma(tq + \bar{t}q)$

➢ two POIs to measure $\sigma(tq)$, $\sigma(\bar{t}q)$

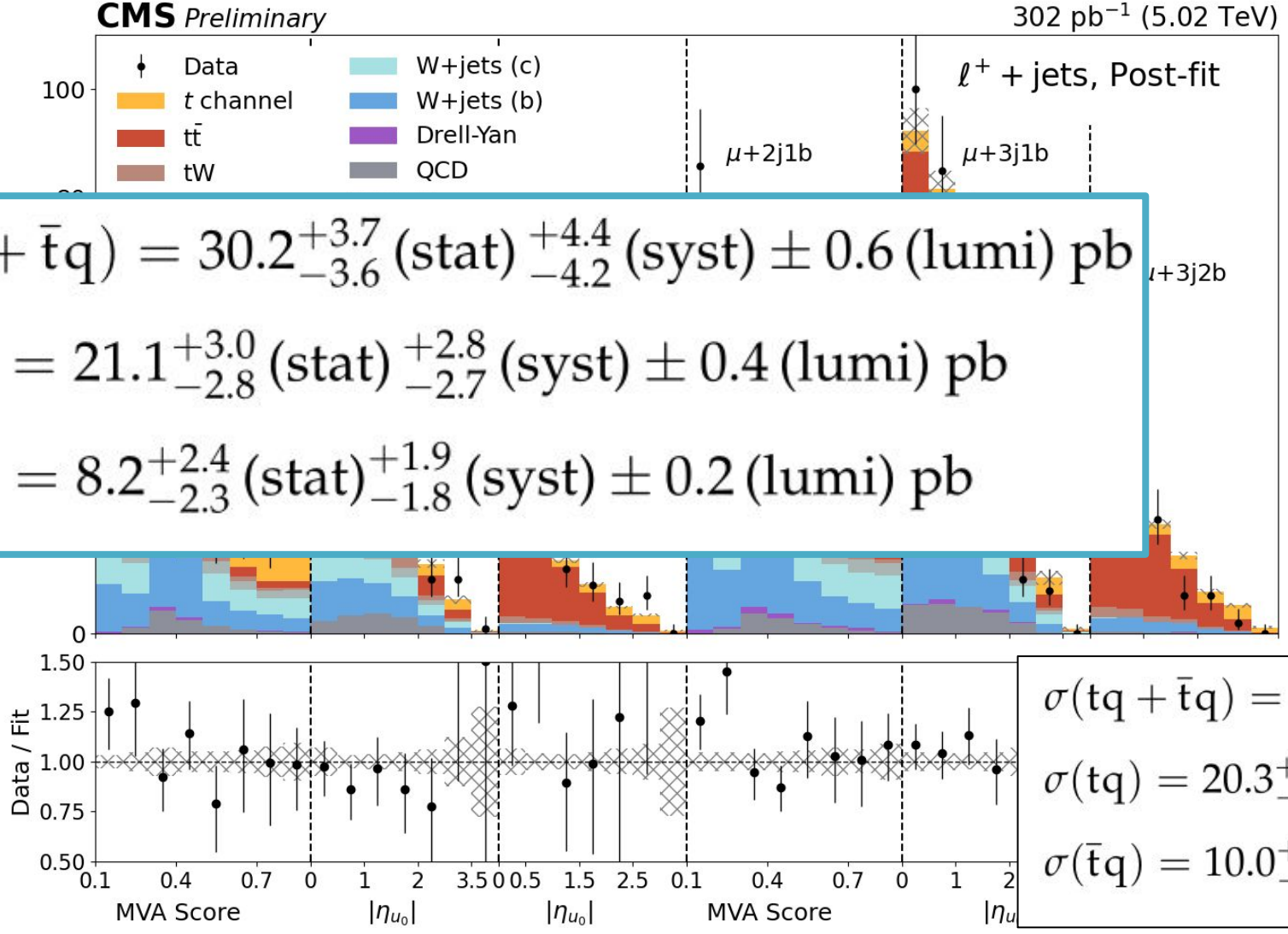


t-channel @5 TeV - Result

❖ Fits to MVA score in 2j1b and |η| of the leading untagged jet in other categories

➢ one parameter of interest (POI) to measure $\sigma(tq + \bar{t}q)$

➢ two POIs to measure $\sigma(tq)$, $\sigma(\bar{t}q)$



$$\sigma(tq + \bar{t}q) = 30.2^{+3.7}_{-3.6}\,(\text{stat})\,^{+4.4}_{-4.2}\,(\text{syst}) \pm 0.6\,(\text{lumi})\ \text{pb}$$

$$\sigma(tq) = 21.1^{+3.0}_{-2.8}\,(\text{stat})\,^{+2.8}_{-2.7}\,(\text{syst}) \pm 0.4\,(\text{lumi})\ \text{pb}$$

$$\sigma(\bar{t}q) = 8.2^{+2.4}_{-2.3}\,(\text{stat})^{+1.9}_{-1.8}\,(\text{syst}) \pm 0.2\,(\text{lumi})\ \text{pb}$$

$$\sigma(tq + \bar{t}q) = 30.3^{+0.7}_{-0.5}\ \text{pb}$$

$$\sigma(tq) = 20.3^{+0.5}_{-0.4}\ \text{pb}$$

$$\sigma(\bar{t}q) = 10.0^{+0.2}_{-0.3}\ \text{pb}$$

SM

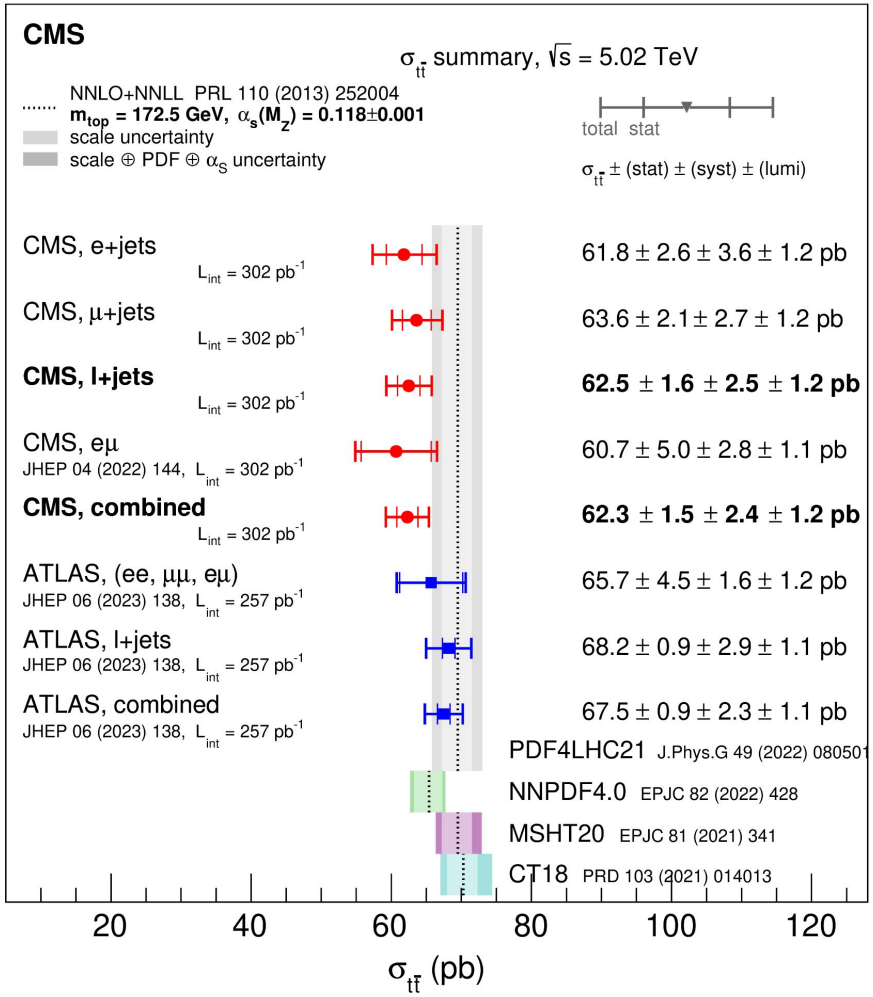
Summary (I)

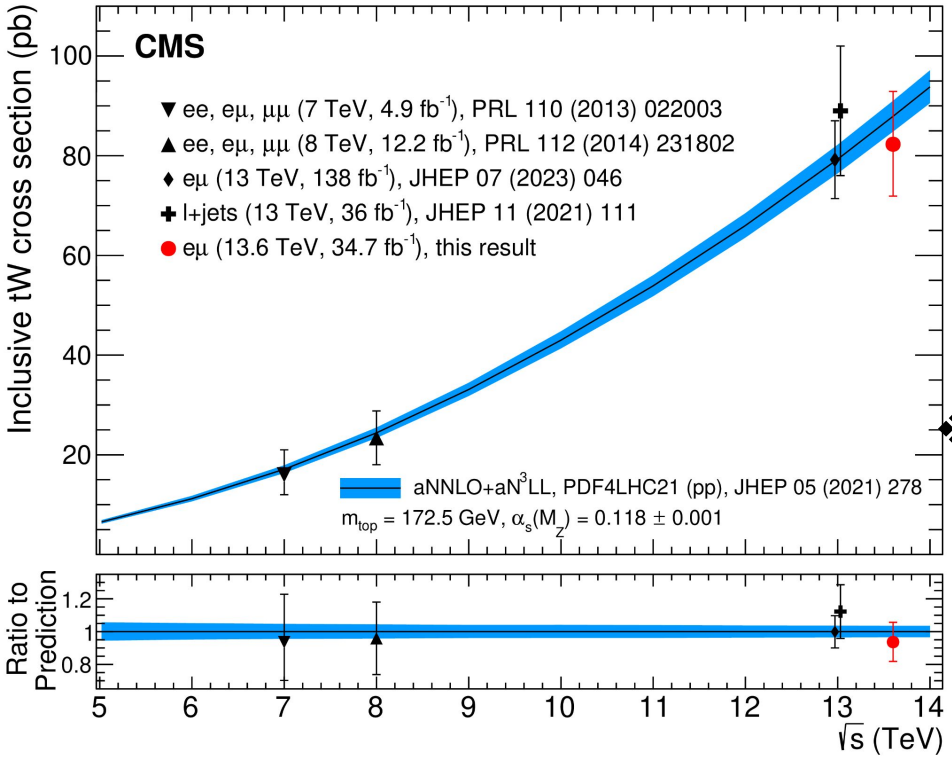
❖ **Most precise** CMS result for the $t\bar{t}$ inclusive cross cross section at 5 TeV

➢ **13% → 5.5%** wrt previous ℓ+jets result

➢ **8.4% → 4.9%** wrt previous combination

➢ Top quarks follows expectations at 5 TeV





❖ The **first** inclusive and differential cross section measurements of the tW process at 13.6 TeV

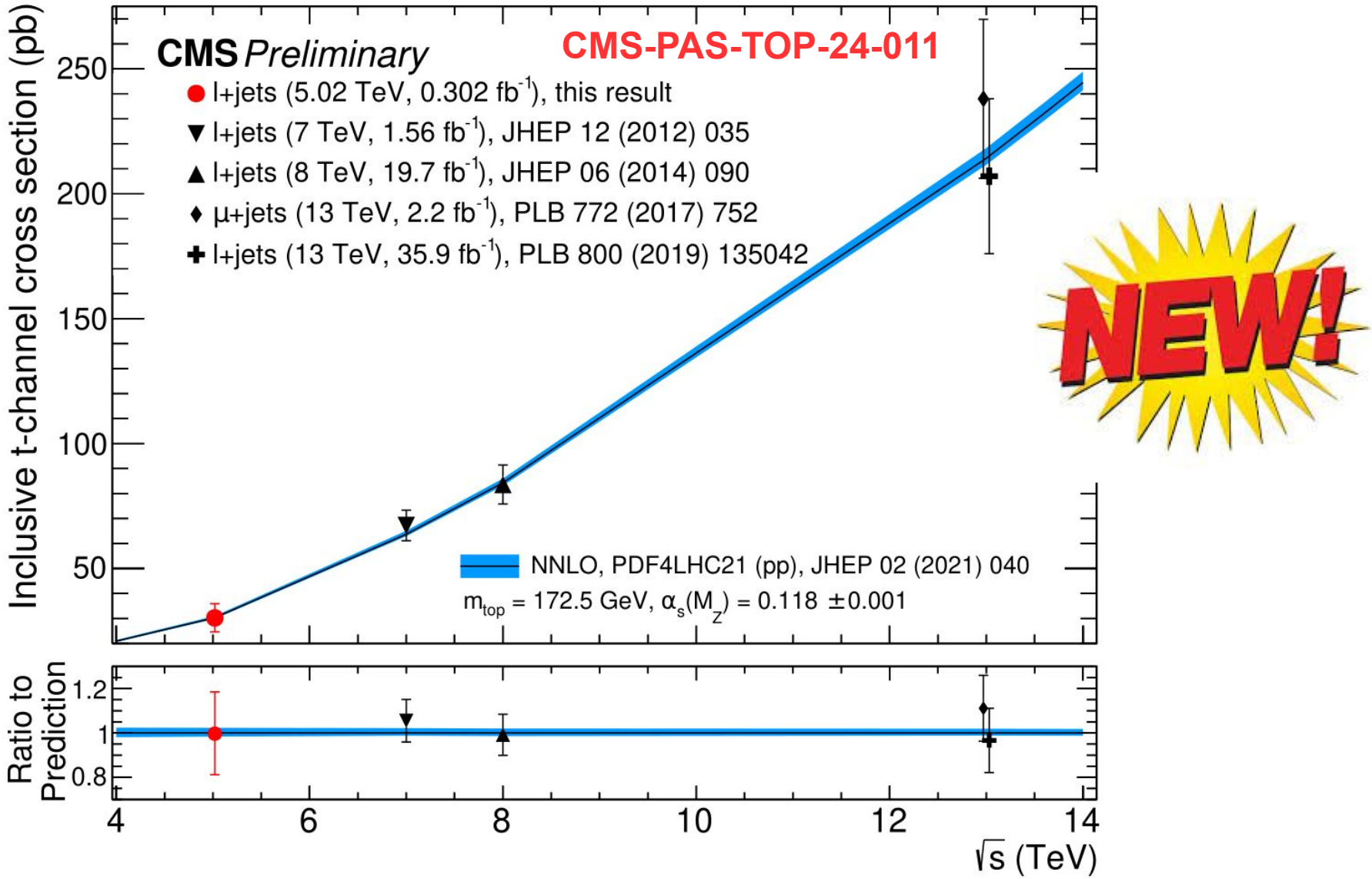
➢ Compatible with the SM prediction

➢ Not quite single at 13.6 TeV

Summary (II)

❖ **First** CMS result for the **single top t channel** inclusive cross cross section at **5 TeV**

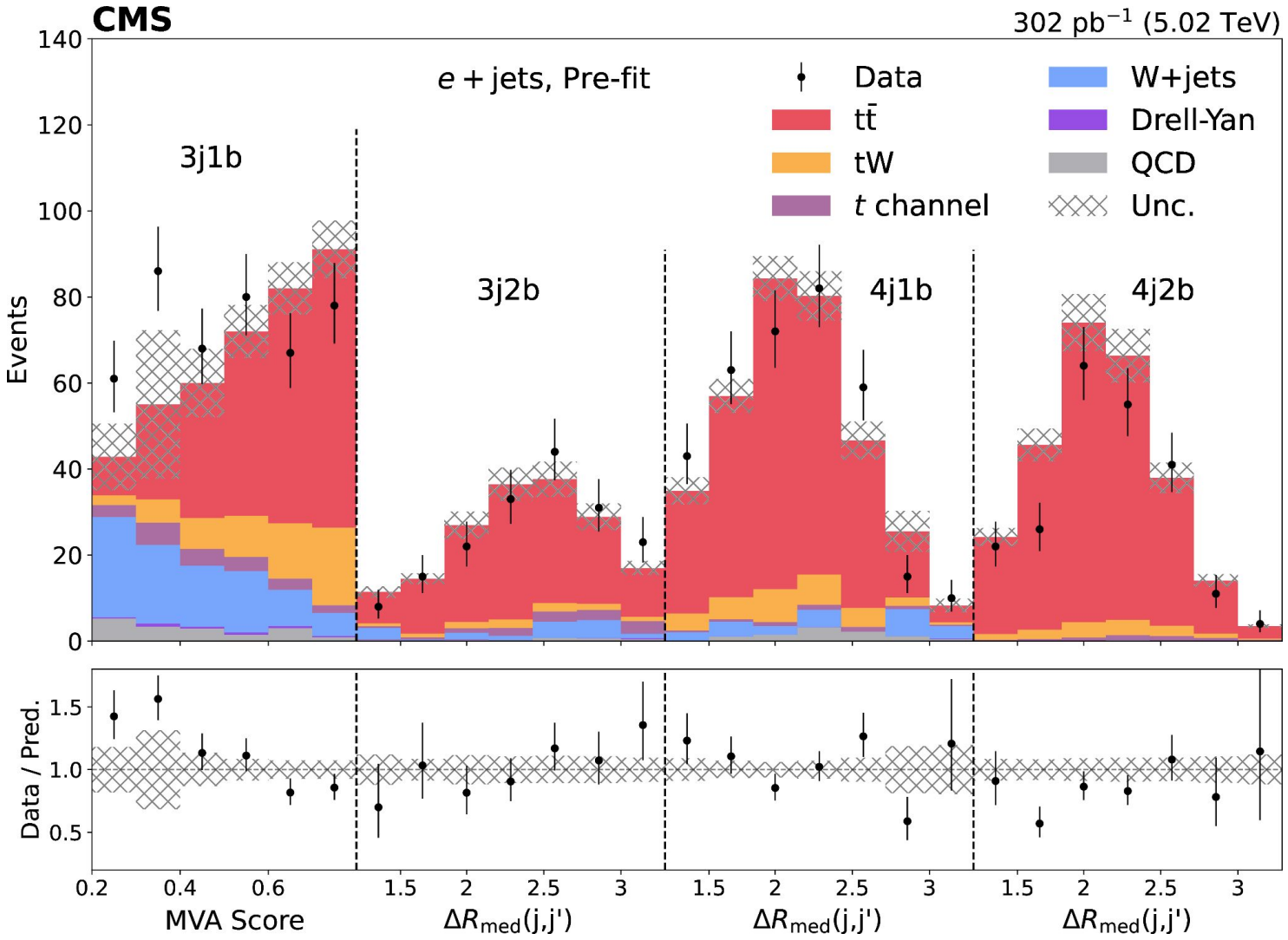
➢ Compatible with the SM prediction



Back-up Slides

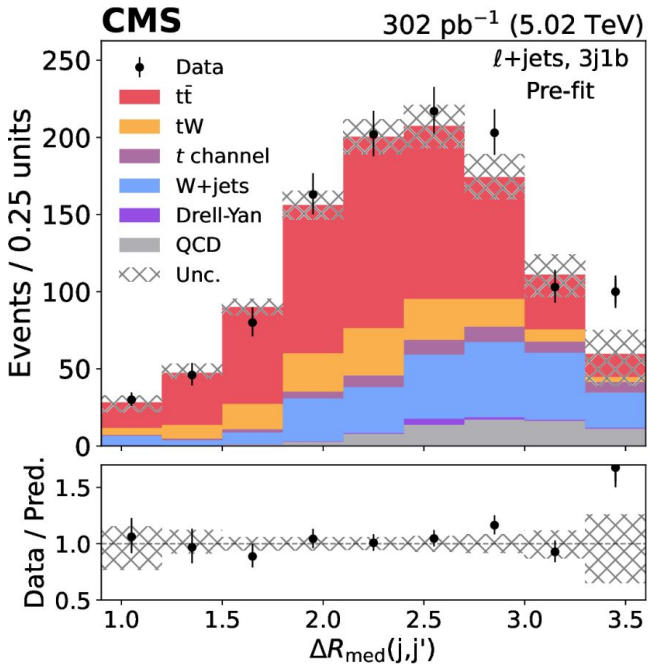
tt @5 TeV - Analysis Strategy

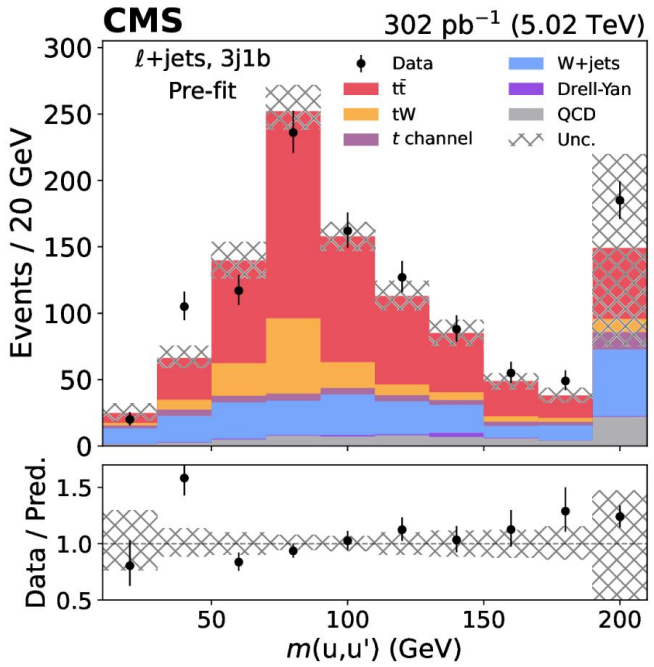
- Different observables were tested: m(j,j'), ΔR(j, j'), m(b,ℓ)
- **Median(ΔR(j, j'))** shape is used in the fits in every region expect the 3j1b category



tt @5 TeV - MVA for 3j1b

- In the 3j1b category, an MVA is trained to further separate tt from W+jets

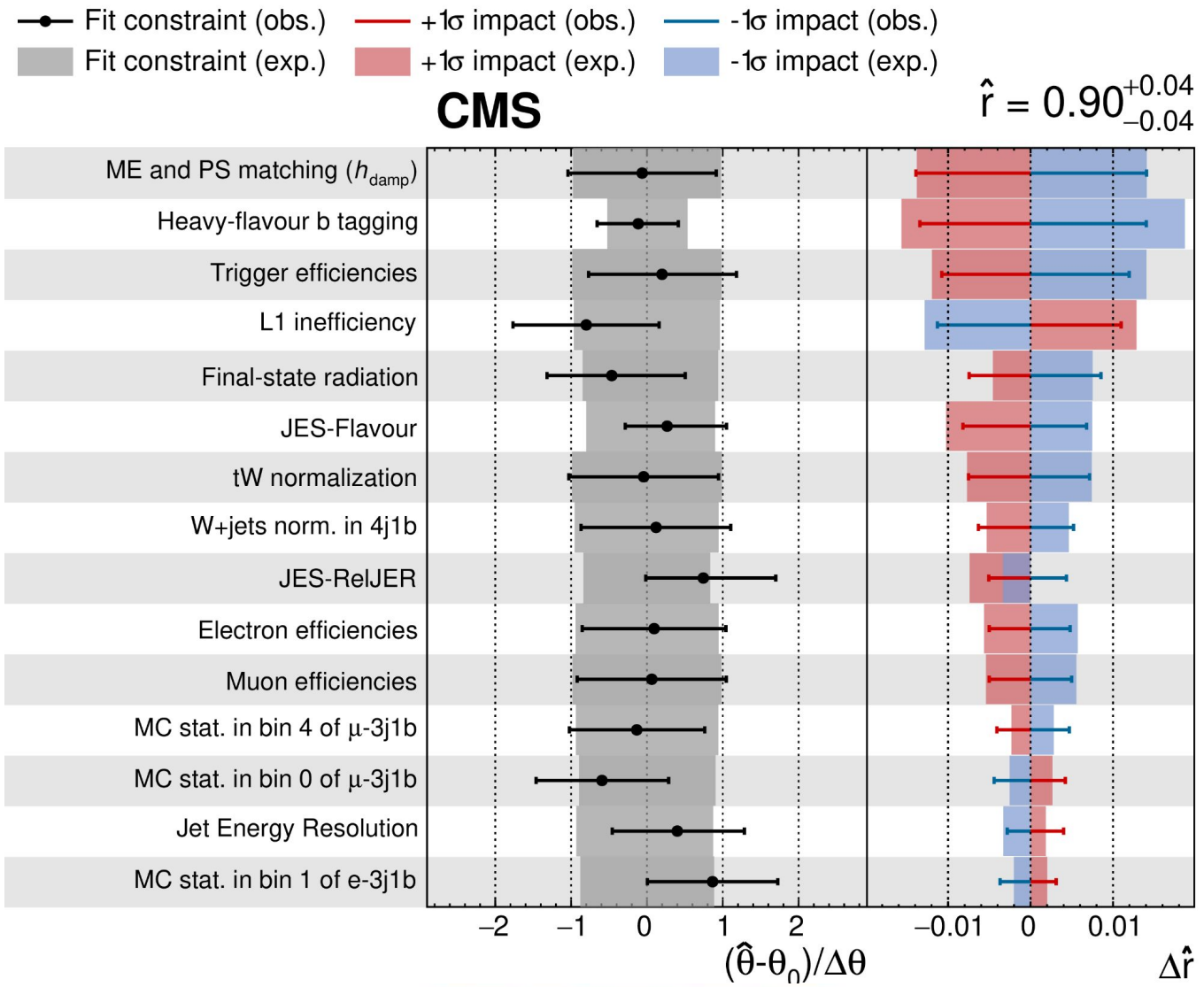




- Model: random forest trained with Sklearn. 500 trees with max depth 6
- Signal: tt sample. Background: W+jets sample
- 70% for train and 30% for test
- 8 input variables

Variable	Definition
$\Delta R_{\text{med}}(\text{j},\text{j}')$	Median ΔR between all possible combinations of two jets
$m(\text{u},\text{u}')$	Invariant mass of the two non-b-tagged jets
$\Delta R(\text{u},\text{u}')$	ΔR between the two non-b-tagged jets
$m_{\text{min}}(\text{j},\text{j}')$	Minimum invariant mass of all possible combinations of two jets
$m(\ell,\text{b})$	Invariant mass of the lepton and the b-tagged jet
H_{T}	Scalar p_{T} sum of all jets in the event
$\Delta R(\ell,\text{b})$	ΔR between the lepton and the b-tagged jet
$p_{\text{T}}(\text{j}_0)$	p_{T} of the leading jet

tt @5 TeV - Result ℓ+jets



Δ= 5.5%

$$\sigma_{t\bar{t}} = 62.5 \pm 1.6\,(stat)^{+2.6}_{-2.5}(syst) \pm 1.2\,(lumi)\ pb$$

σ(SM) = $69.5\,^{+3.5}_{-3.7}$ pb

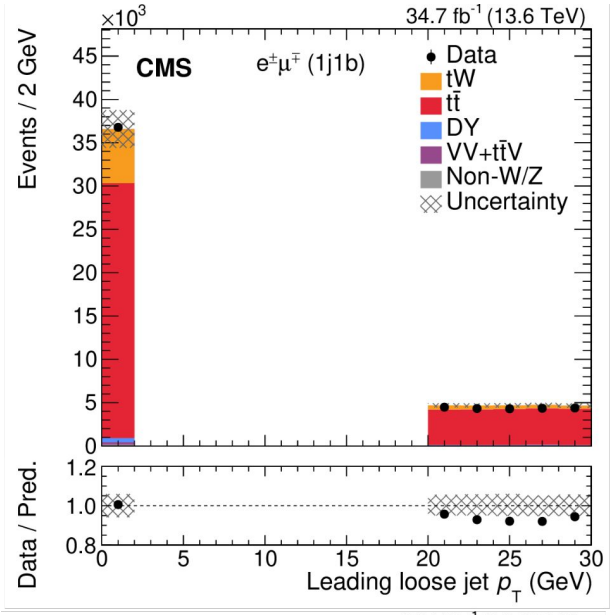
tW @13.6 TeV - MVA for 1j1b

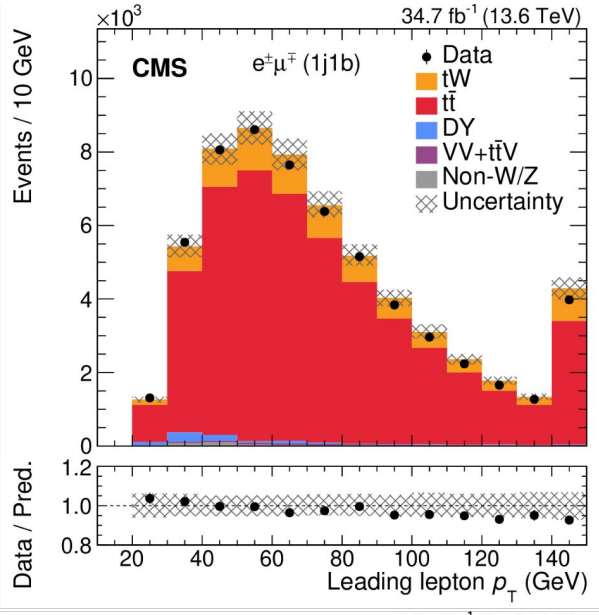
❖ 8 input variables are selected for each RF based on:

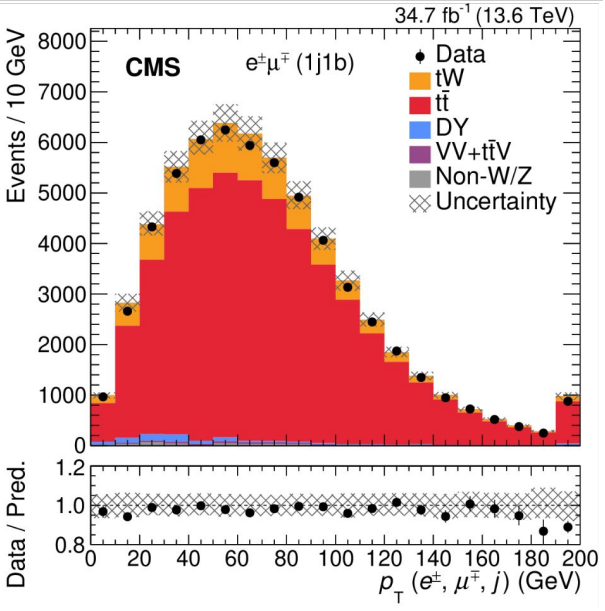
➢ Good discrimination power

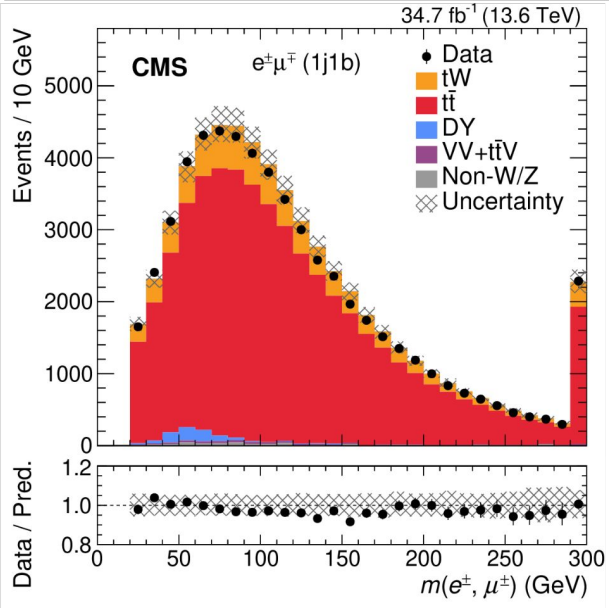
➢ Good modelling

Leading loose jet p_T
Leading lepton p_T
$p_T(e^{\pm}, \mu^{\mp}, j)$
$m(e^{\pm}, \mu^{\mp})$
$\Delta\varphi(e^{\pm}, \mu^{\mp})$
$m(e^{\pm}, \mu^{\mp}, j)$
$p_T(\ell_1, j)$
Jet p_T



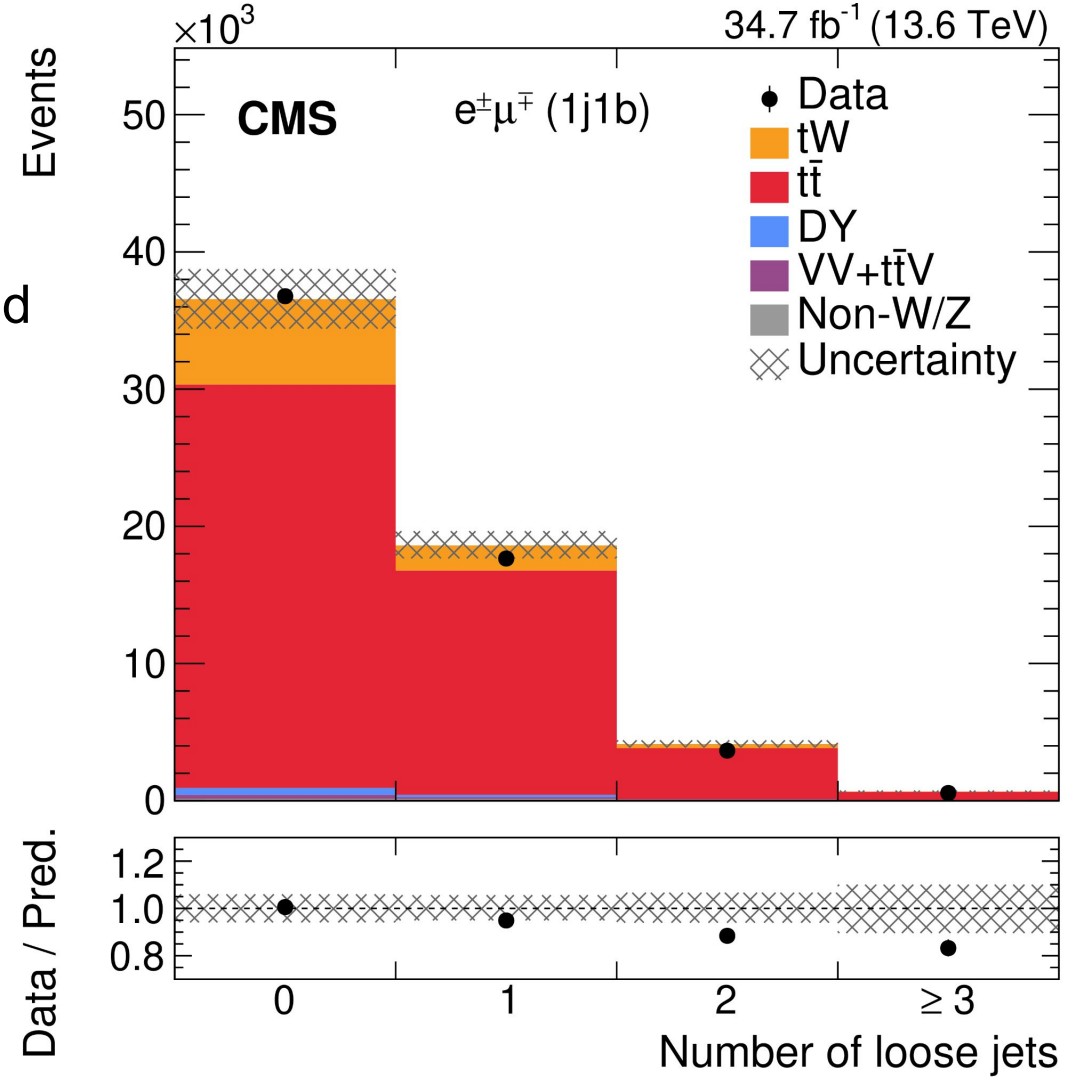






tW @13.6 TeV - Differential Measurement (I)

- Measurement performed in the 1j1b region vetoing events with low energy jets (loose jets)
- Signal estimated subtracting background from data
- Unfolding from detector level to particle level is performed using TUnfold [JINST 7 (2012) T10003]



t-channel @5 TeV - MVA 2j1b

Variable	Definition
$\lvert\eta_{u_0}\rvert$	The absolute value of η of the leading untagged jet
$\lvert\Delta\eta(u_0, b_0)\rvert$	The absolute value of the difference in η between the leading tagged and untagged jets
m_T^W	The transverse mass of ℓ and p_T^{miss}
m_{top}	The invariant mass of the reconstructed top quark
$\Delta R_{med}(j, j')$	The median ΔR between all possible combinations of two jets
$m(j, j')$	The minimum invariant mass of all possible combinations of two jets
$m(\ell, b)$	The invariant mass of the lepton and the b-tagged jet
$m(u, b)$	The invariant mass of the two most energetic b-tagged and non b-tagged jets
$H_T(j, \ell)$	The scalar sum of the p_T of all jets and the lepton in the event
H_T'	The scalar sum of the p_T of all jets, the lepton and p_T^{miss} in the event
$\lvert\Delta\eta(\ell, u)\rvert$	The absolute value of the difference in η between the lepton and the untagged jet
$\lvert\Delta\phi(W, ub)\rvert$	The absolute value of the difference in ϕ between the reconstructed W boson and the jet pair
$\lvert\Delta p_T(W, ub)\rvert$	The absolute value of the difference in p_T between the reconstructed W boson and the jet pair