Measurements of ttW in Run 3 at CMS

CPAN Days XVII – 20 November 2025

Miguel Obeso Menéndez on behalf of the CMS Collaboration

Universidad de Oviedo

ICTEA
Instituto Universitario de Ciencias
y Tecnologías Espaciales de Asturias

CMS
Compact Muon Solenoid

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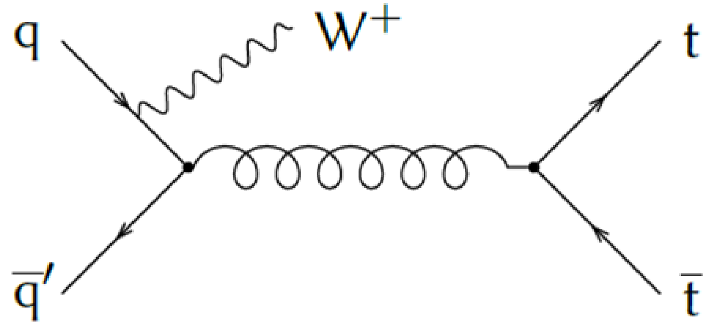
Ingenio 2010

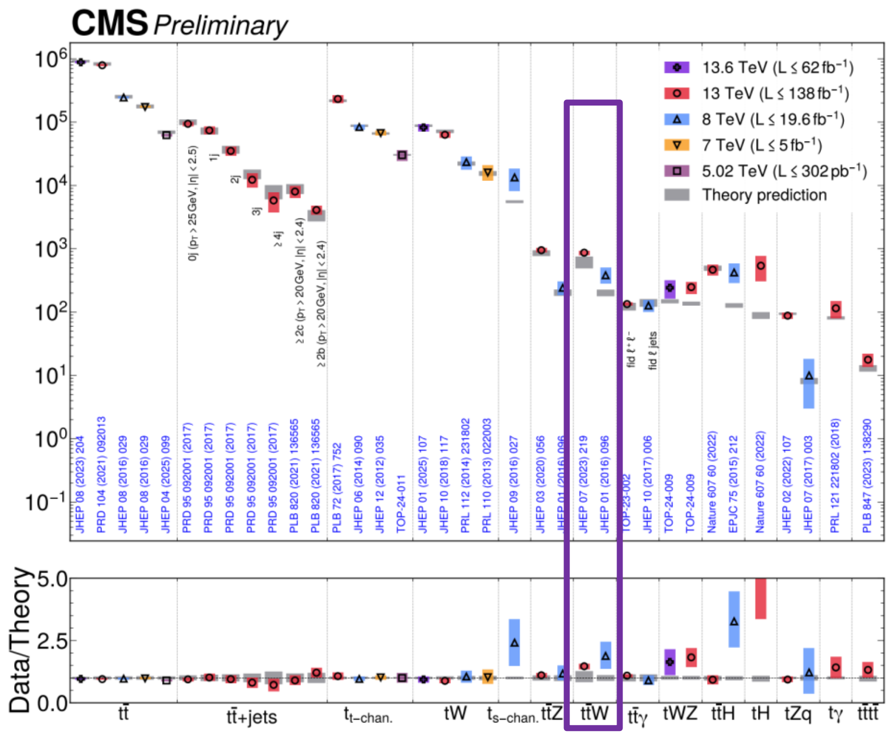
Motivation

- The production of top quarks pairs in association with bosons (ttZ, ttW, ttH…) provides an optimal window to study the nature of particle physics in proton-proton (pp) collisions.



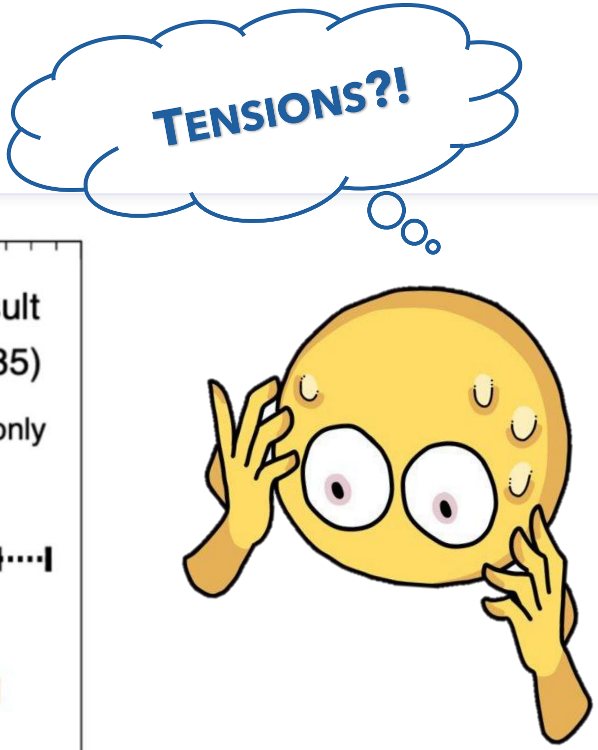
WHY HAS ATTRACTED THE INTEREST OF SCIENTIFIC COMMUNITY?

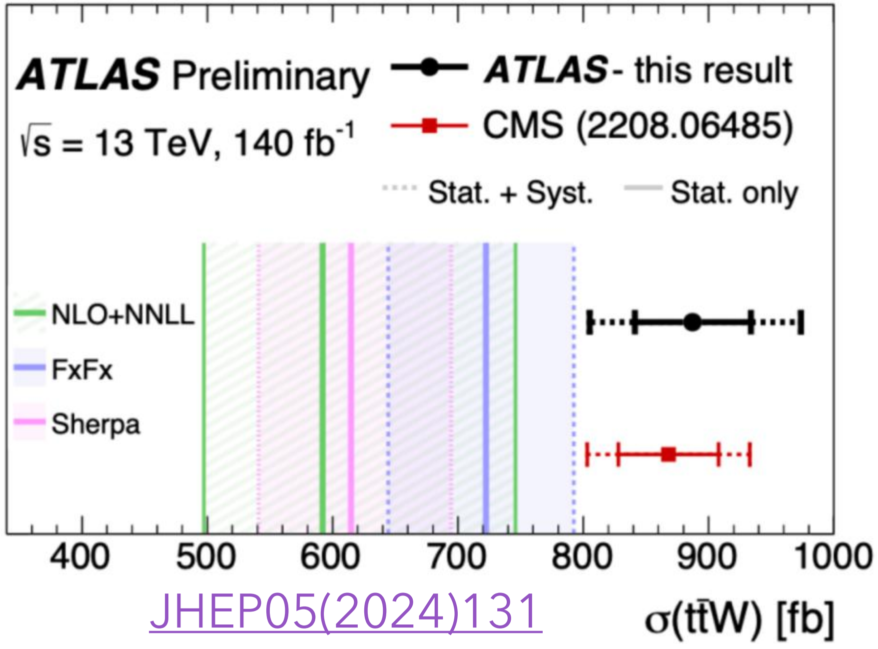
- The interest in the ttW process production can be found in…
  - Small cross section process.
  - Charge asymmetry properties in the initial state at LO and possible EFT interpretations.
  - Main background for different processes of interest (ttH, tttt…).



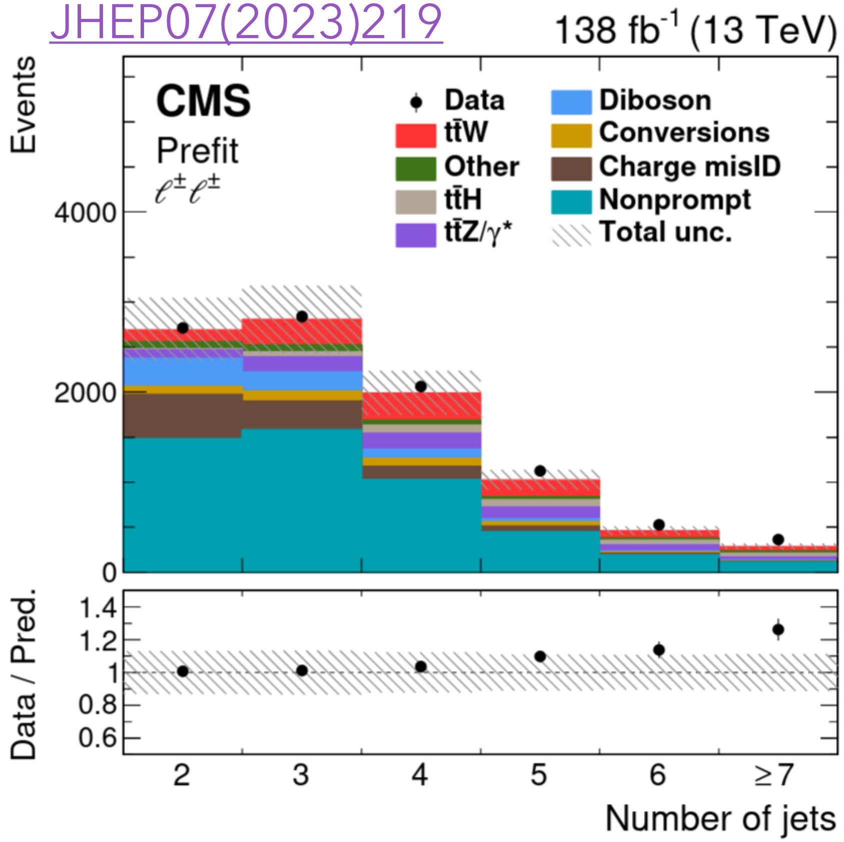
AND…

Run 2 results





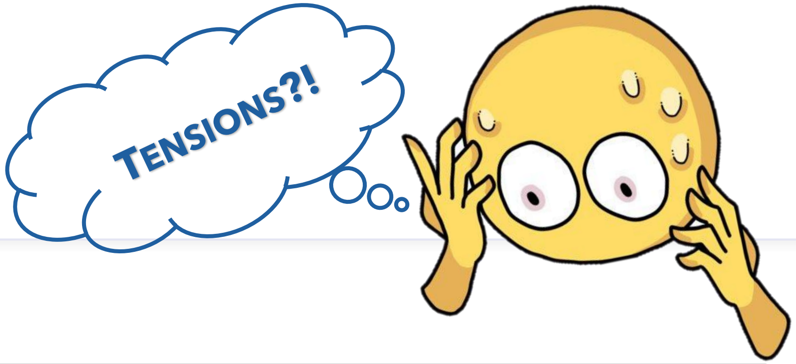
JHEP05(2024)131

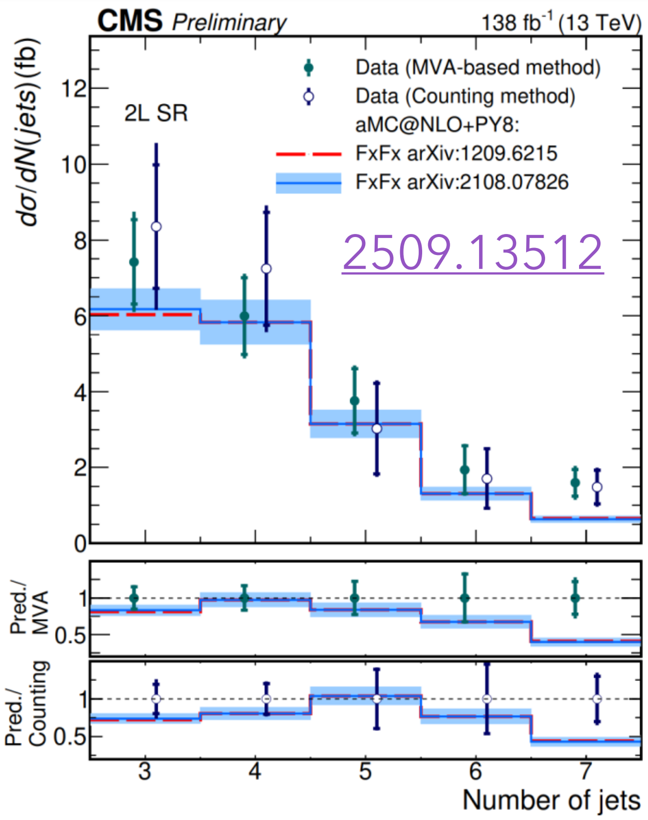


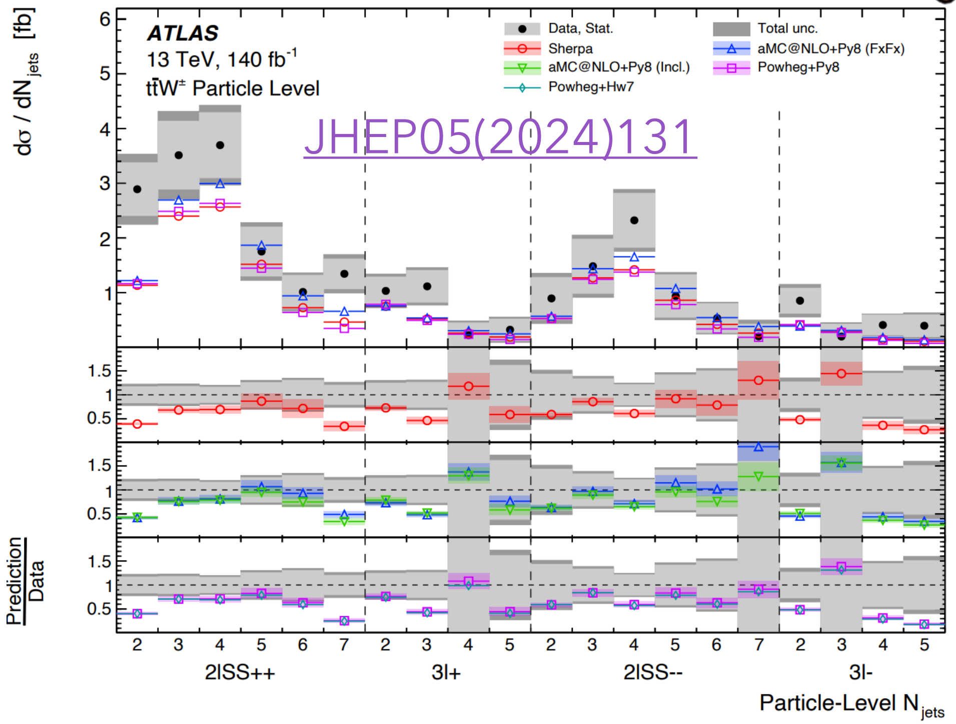
JHEP07(2023)219

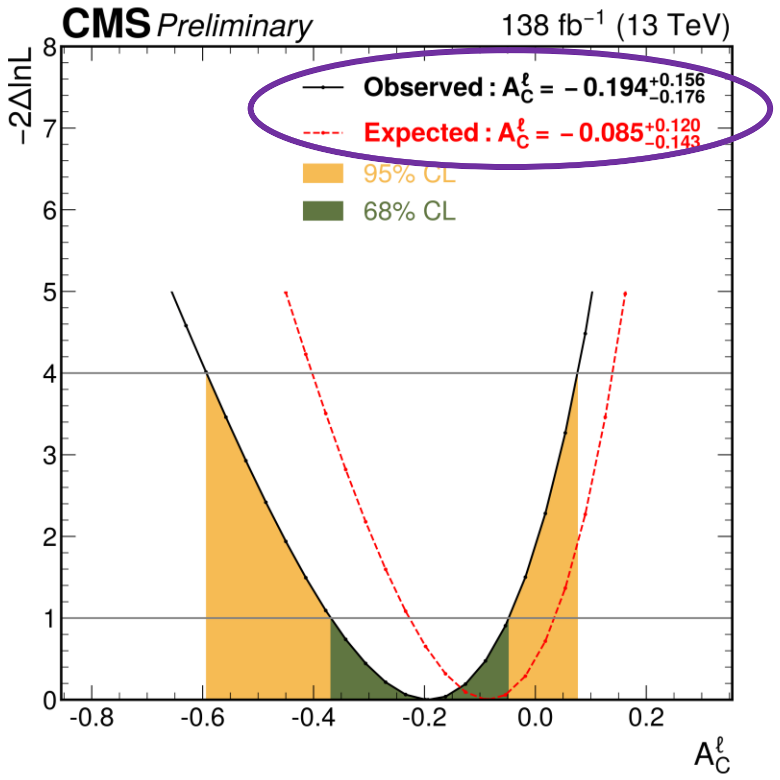
- ➢ Both Collaborations showing higher-than-expected values in several measurements with Run 2 data.
- ➢ Never studied before with Run 3 data!
- ➢ **Do we understand the problem? New physics? MC modeling?**

Run 2 results









- Also the differential measurements at 13 TeV from both Collaborations show higher-than-expected values.
- Flat excess, so no conclusive hints have been observed from differential measurements.

- Charge asymmetry measurements (CMS & ATLAS) are consistent with the Standard Model predictions.

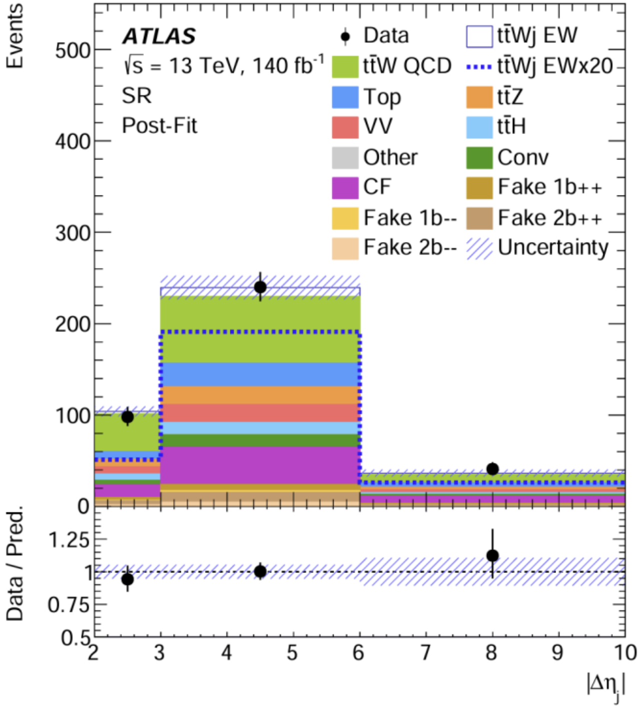
Summary of previous measurements

CMS measurements:

- Inclusive cross section + cross section ratio (13 TeV): JHEP07(2023)219
- Differential cross section + charge asymmetry (13 TeV): 2509.13512

ATLAS measurements:

- Inclusive + differential cross section + charge asymmetry (13 TeV): JHEP05(2024)131
- Search for electroweak ttWj production + EFT interpretation 13 TeV. 2509.19038 **QUITE NEW!!**



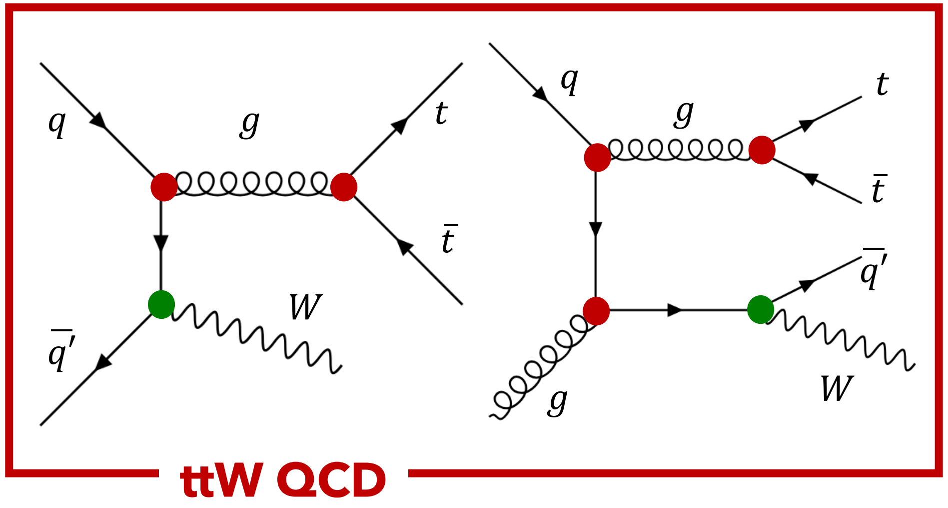
- THE QUESTION IS… WHAT HAVE WE LEARNED FROM THIS PROCESS WITH RUN 2 DATA?
- VERY PROMISING RUN 3 DATA WITH OUR CURRENT KNOWLEDGE FOR TTW!!!

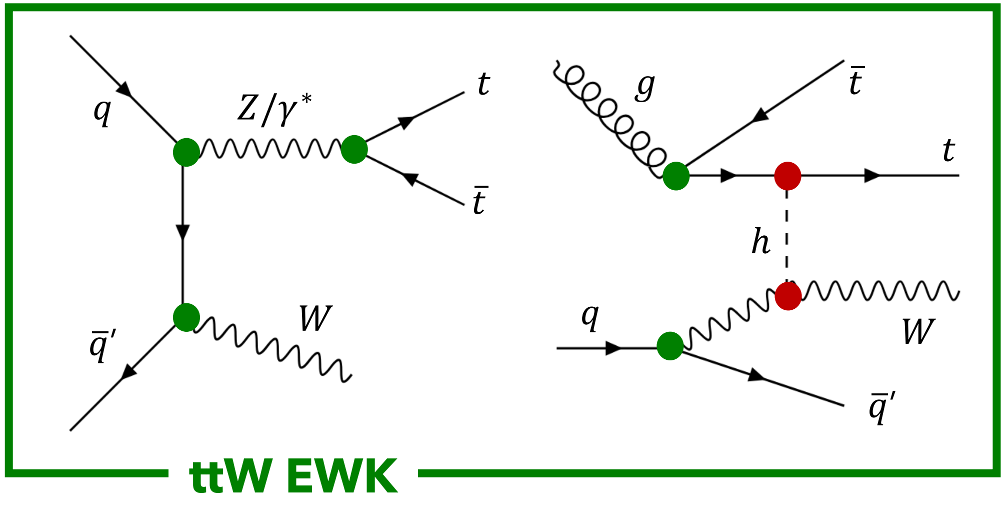
ttW MC challenge

"On improving NLO merging for ttW production"

Understanding the ttW anatomy is one of the most important challenges (2108.07826):

LO (50%-$\alpha_s^2\alpha$) + NLO(25%) + NNLO(12%) - Leading EW (3%) + Sublead EW (10%)



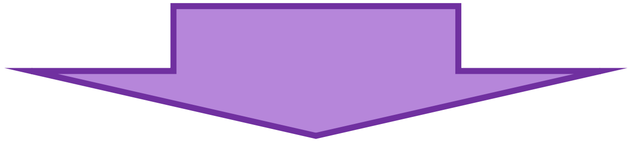


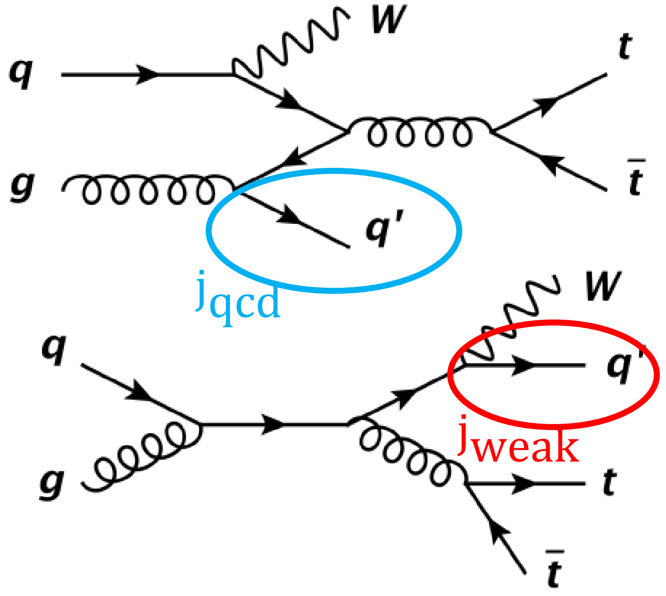
- The state-of-the-art of ttW modelling includes: LO and NLO (no NNLO).
- EW corrections are considered…
  - Leading EW: Fixed order in a normalization.
  - Sublead EW: Alternative sample using Madgraph5_aMC@NLO.
- Use of FxFx algorithm to consider the additional partons from real emission terms at NLO.

ttW MC challenge

- Use of FxFx algorithm to remove double countings when considering radiation at the ME when doing NLO MC.

- The new FxFx has only been tested at generator level in the differential measurement (2509.13512) with a consistent discrepancy with data of ~20%.



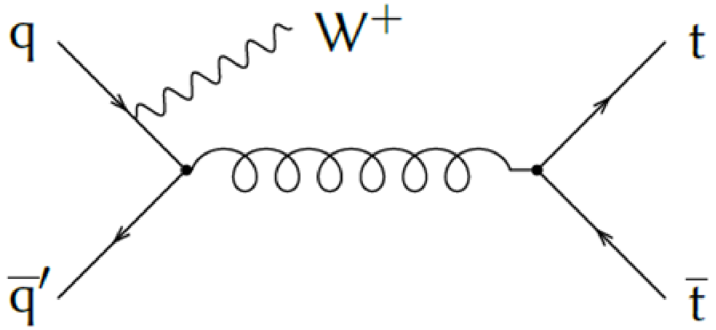


Run 3 data provides the perfect opportunity to test the new FxFx sample at detector level for the first time!

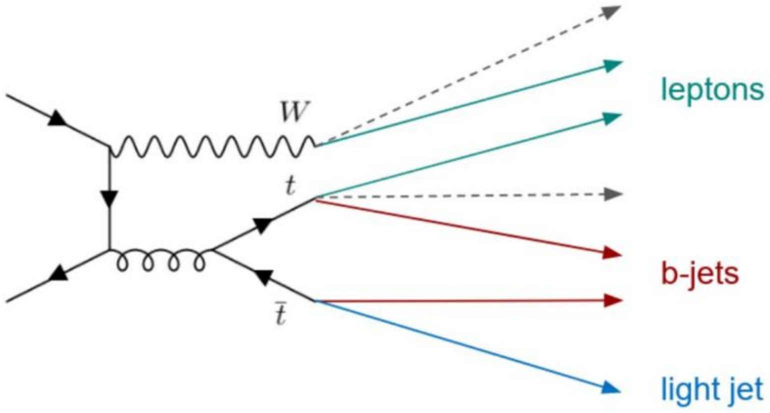
THE EFFORT HAS ALREADY BEGUN AND IS WELL ON TRACK!!!

Ongoing ttW Run 3 analysis…

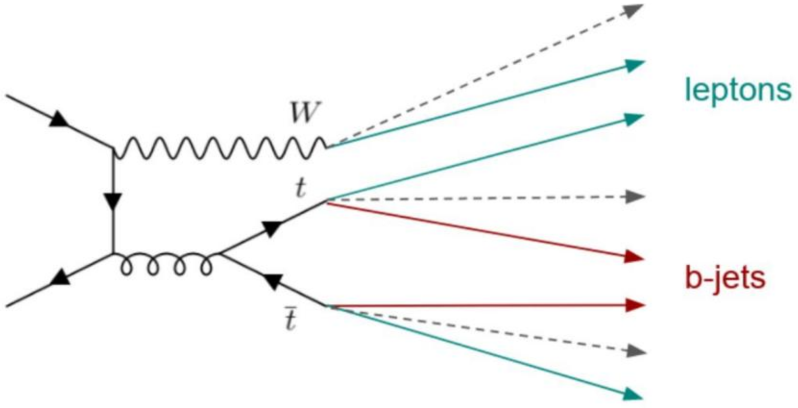
<u>GOAL:</u> Perform the first measurement of the ttW inclusive cross section in multileptonic final state at the energy regime of 13.6 TeV with similar precision as the Run 2 results.



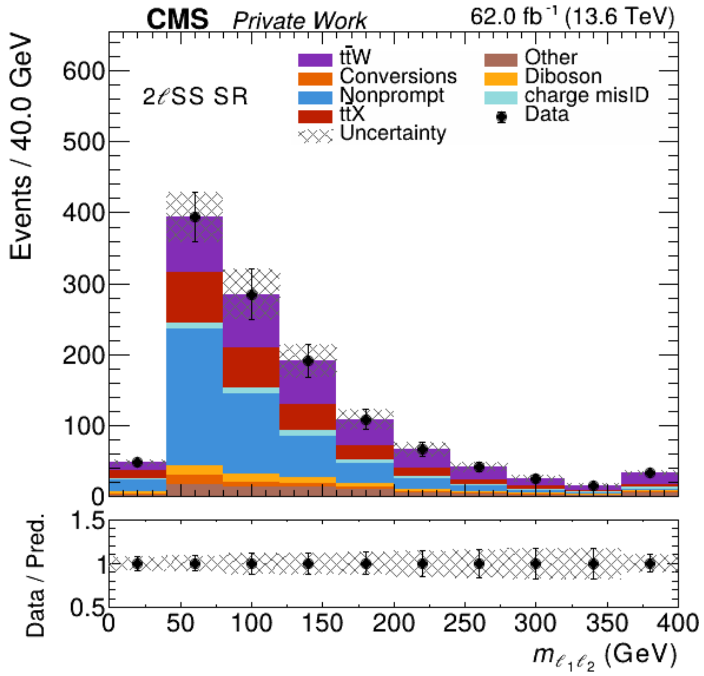
We target different multileptonic final states (electrons or muons).
Events with two leptons with the same electric charge (2lss) and three leptons (3l).



Two lepton same-sign

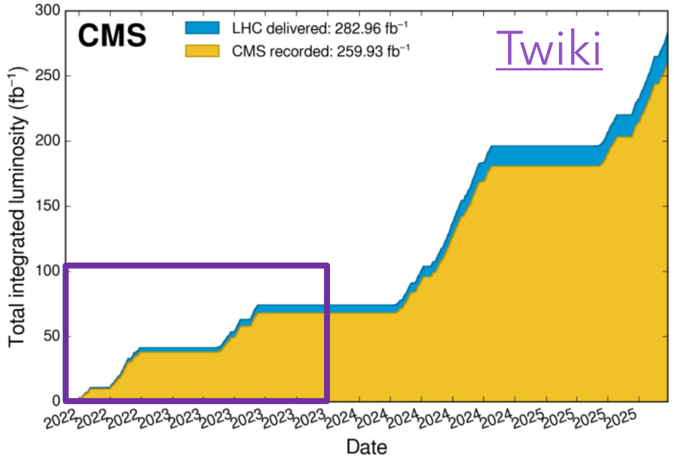


Three leptons



Data and object definition

- DATA: Use data from 2022 and 2023. Total luminosity for the analysis of 62.0 fb^{-1}.
- SIMULATION OF SIGNAL AND BACKGROUND: Signal and most of the backgrounds are defined by MC simulated samples. Nonprompt and chargemisID backgrounds are estimated by data-driven.



PHYSICAL OBJECTS IN THE ANALYSIS:

Light leptons: The core of the analysis. The selection is based on a multivariate analysis technique retrained for Run 3 (2024 JINST 19 P02031 & JHEP04(2025)115).

- Loose: Used for preselection of leptons.
- Fakeable: To study the effect of nonprompt leptons in final selection.
- Tight: Used for final selection of the analysis.

Jets: Using a algorithm that mitigates the effect of pileup interactions in the reconstruction of the jet momentum.
Selecting jets with p_T>25GeV with Tight ID criteria.
B-tag jets: Identified with an algorithm based on a DNN. We use two different WPs with a btagging efficiency of 91% and 80%.

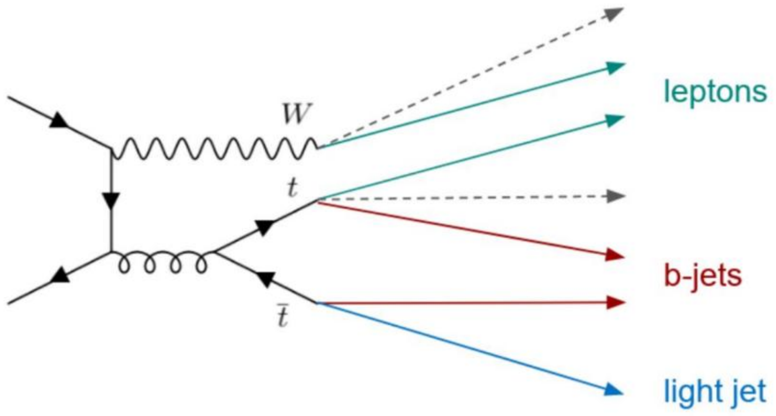
Ongoing ttW Run3 analysis…

Strategy of the analysis based on a categorization.

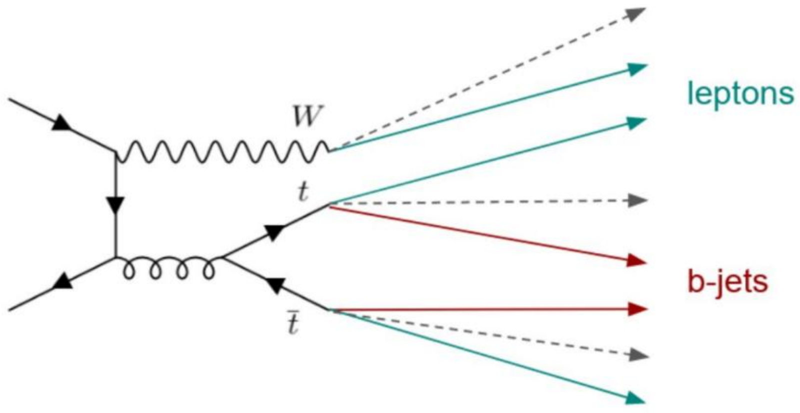
Defined in order to reduce the impact of different backgrounds:

Nonprompt contributions: Biggest background in the analysis (already reduce with tight lepton selection).

ttH prompt process: One of the main irreducible background with high impact in the analysis uncertainty in previous Run 2 measurements.



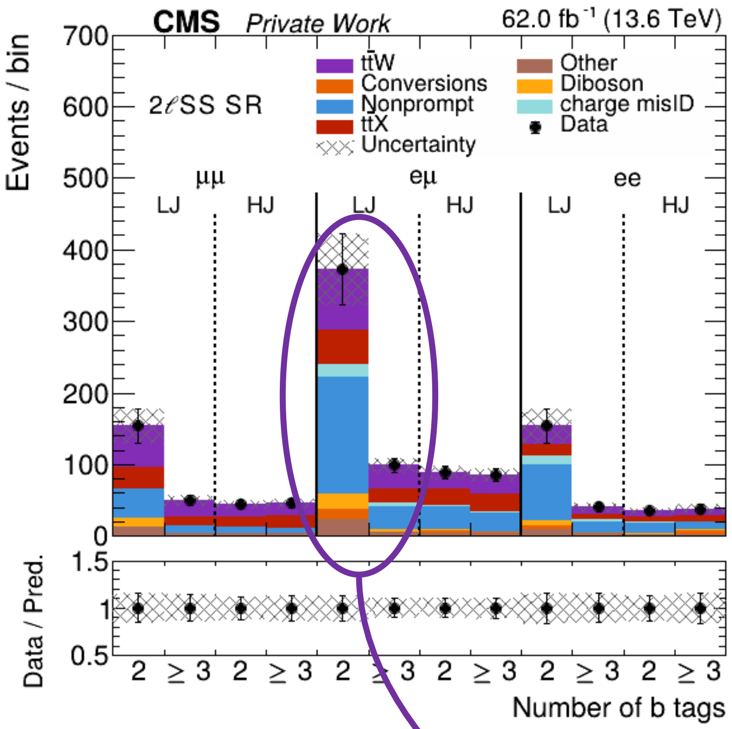
Two lepton same-sign



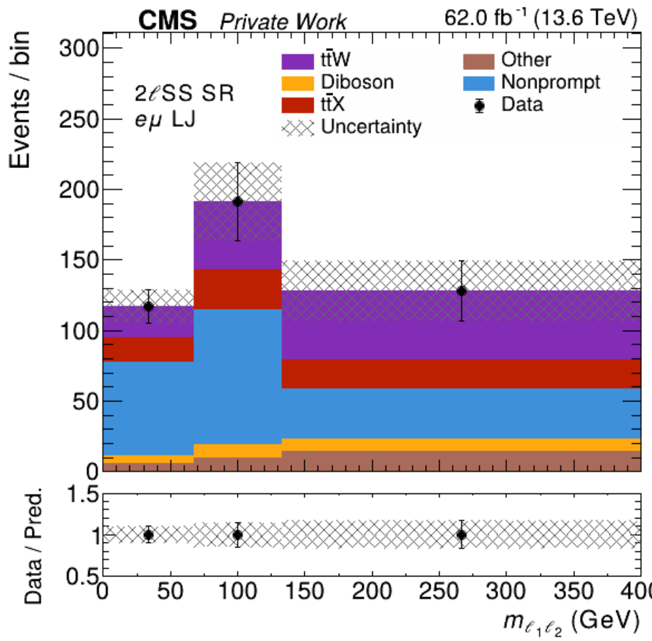
Three leptons

Two lepton same-sign signal region

Selection	$2\ell ss$	3ℓ
Number of tight leptons	$= 2$	$= 3$
Veto on additional (non tight) leptons	—	—
Lepton p_T (GeV)	25, 15	25, 15, 15
Charge requirement	$q_{\ell_1} = q_{\ell_2}$	$\sum_{\ell} q_\ell = \pm 1$
$\lvert m(\ell,\ell') - m_Z \rvert$ (OSSF)	> 10	> 10
$\lvert m(e_1,e_2) - m_Z \rvert$ (same-sign)	> 10	> 10
$m(\ell,\ell')$	> 30	> 30
Number of central jets	≥ 3	≥ 2
Number of b-tagged jets	2 loose	1 medium



We use the m_{ll} distributions in the different categories to extract the normalization of ttW.

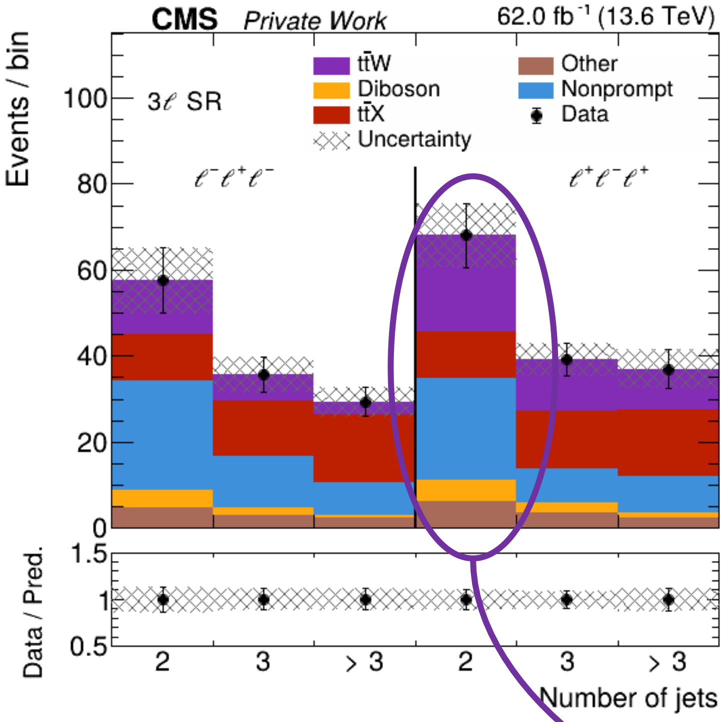


Split in twelve different categories based on:

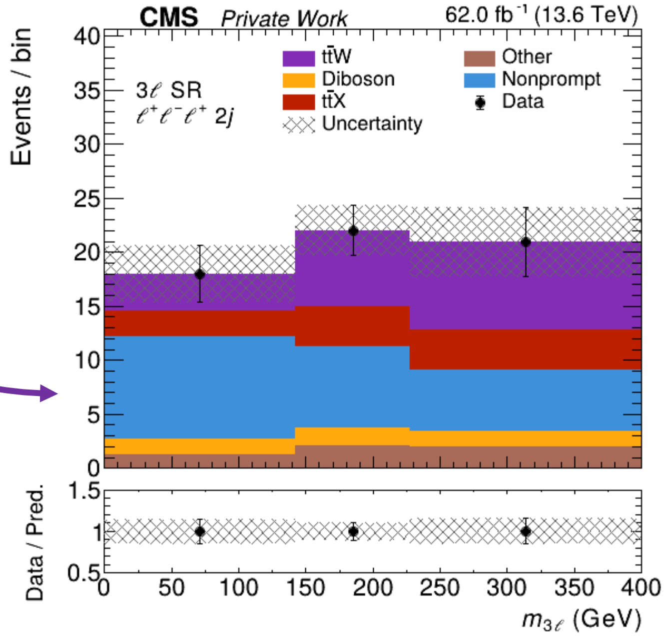
- Lepton flavor (ee, eμ and μμ).
- Jet multiplicity:
  - Low Jets (LJ): Njets= 3 or 4.
  - High Jets (HJ): Njets>4.
- Number of b-tag jets (Nbtags=2 or Nbtags>=3).

Three leptons signal region

Selection	2ℓss	3ℓ
Number of tight leptons	$= 2$	$= 3$
Veto on additional (non tight) leptons	—	—
Lepton p_T (GeV)	25, 15	25, 15, 15
Charge requirement	$q_{\ell_1} = q_{\ell_2}$	$\sum_\ell q_\ell = \pm 1$
$\lvert m(\ell,\ell') - m_Z \rvert$ (OSSF)	> 10	> 10
$\lvert m(e_1, e_2) - m_Z \rvert$ (same-sign)	> 10	> 10
$m(\ell,\ell')$	> 30	> 30
Number of central jets	≥ 3	≥ 2
Number of b-tagged jets	2 loose	1 medium



We use the m_{3l} distributions in the different categories to extract the normalization of ttW.

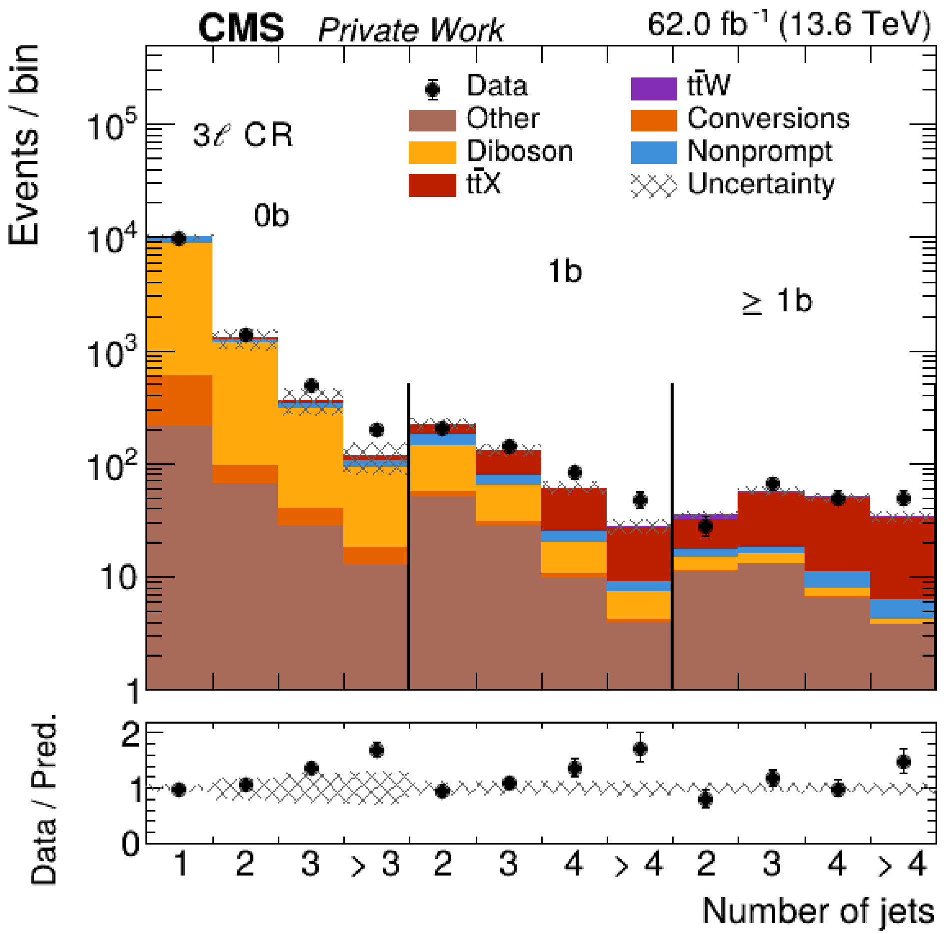


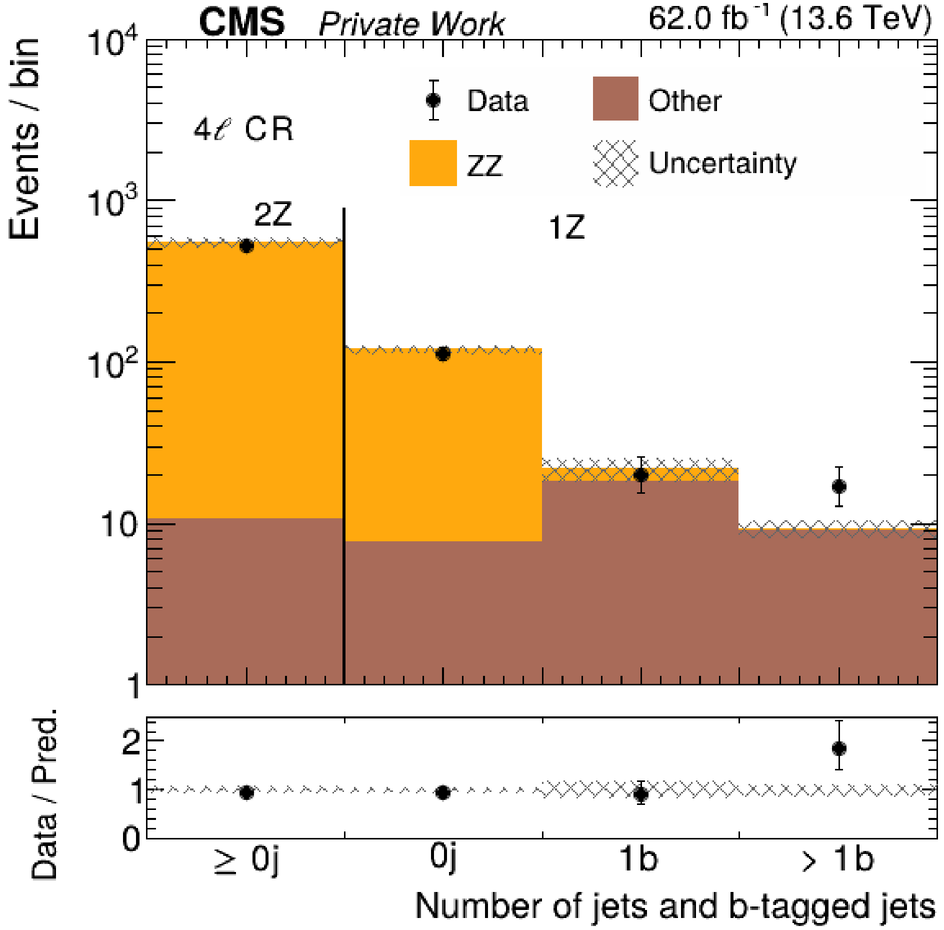
Less statistics than in 2lss region but less nonprompt contribution and more controlled backgrounds.
Split in six different categories based on:

- Total leptons charge (+1 or -1).
- Number of jets (2, 3 or >3).

Two control regions (3 leptons and 4 leptons)

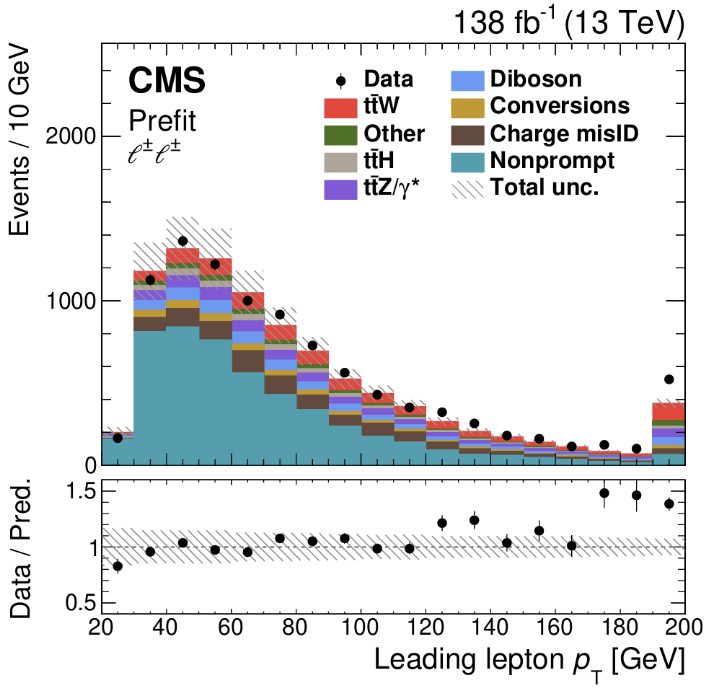
Also, 3-lepton and 4-lepton control regions are used to constrain the WZ+ttZ and ZZ background contributions, respectively.

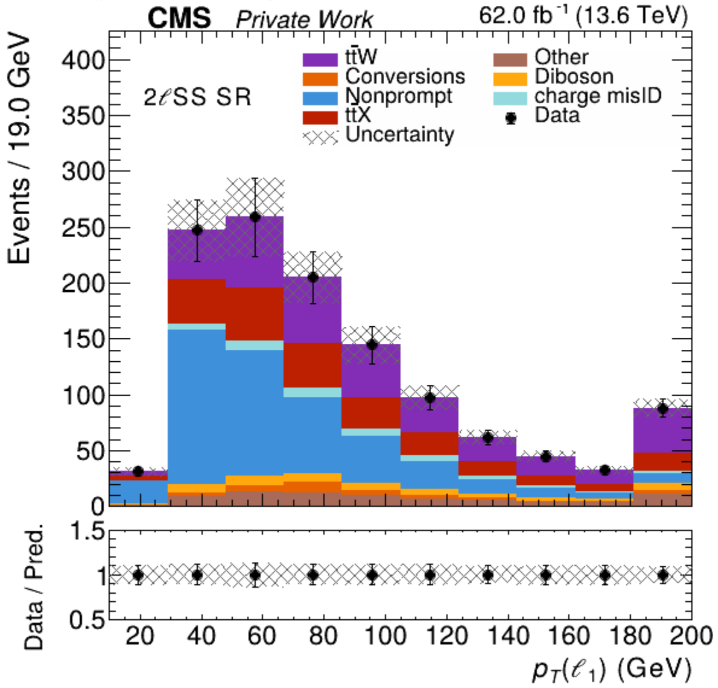




Preliminary results

- We perform a maximum likelihood fit to a total of 23 distributions:
  - Signal regions: In 2lss-SR mll distributions per category (12) and in 3l-SR m3l distributions per category (6).
  - Control regions: In 3l-CR Njets-Nbtags classifier distribution split per lepton flavor (4) and in 4l-CR number or reconstructed Z bosons and Njets/Btags classifier (1).





Main changes in the analysis strategy comparing with previous CMS ttW analysis:

- Tighter lepton working point reduce the nonprompt background.
- The impact of ttH normalization is lower than in previous analysis.

- This result is competitive in terms of uncertainties with the sensitivity obtained in Run 2 using 2018 data (similar luminosity).
- The strategy is defined and consistent to moving forward with the analysis!

Conclusions

- I have presented ttW process and its interesting properties in the study of high energy phyics in proton-proton collisions:
  - Measure of SM properties.
  - Its relevance as a background for other processes of interest such as: ttH or 4-tops.
  - Possible EFT interpretations.

- We cover the previous results performed by CMS and ATLAS and the tensions in all the previous measurements.

- Understanding the complex anatomy of this process is crucial to improve the modelling and understanding of the process.

- We use Run 3 to test the new FxFx sample at detector level for the first time.

- The analysis follows a categorization stratregy to extract the signal with all the ingredients in excellent shape to perform the first ttW cross section measurement with Run 3 data.

- Looking ahead to a future of possibilities: new measurements, alternative scales… with the goal of optimize ttW usage in CMS analysis and Run 3 is a great benchmark to improve it!

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Thank you for your attention!

MIGUEL OBESO MENÉNDEZ

miguel.obeso.menendez@cern.ch

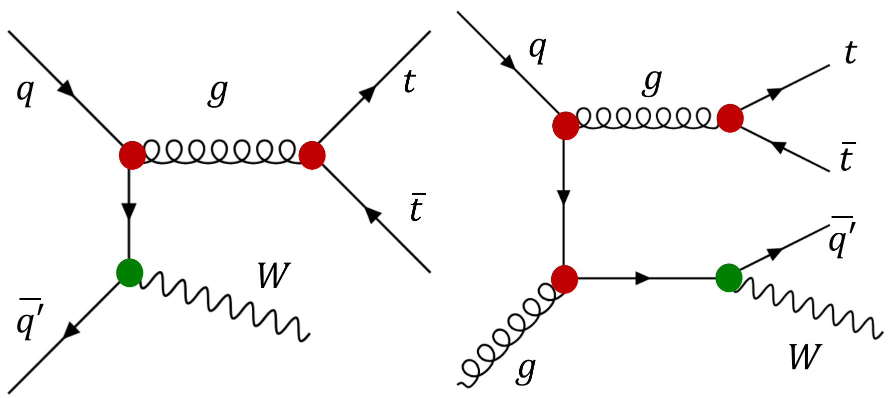
obesomiguel@uniovi.es

Backup

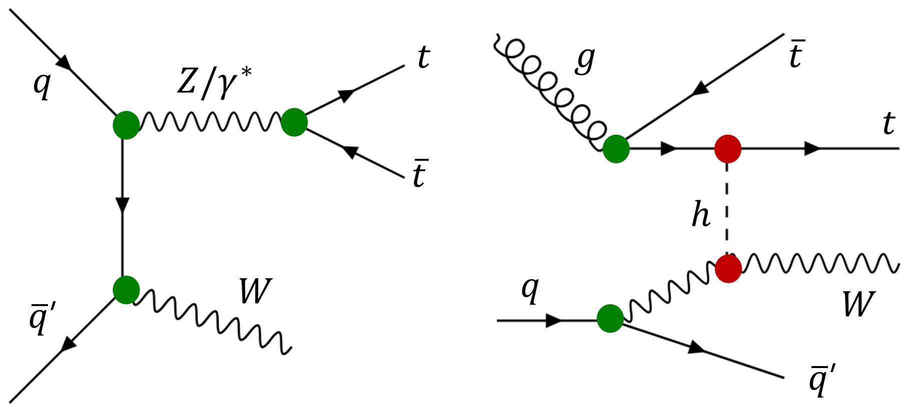
ttW MC challenge

$$
\begin{aligned}
\mathrm{LO_{QCD}} &= t\bar{t}W@\mathcal{O}(\alpha_S^2\alpha)\ , \\
\mathrm{NLO_{QCD}} &= t\bar{t}W@\mathcal{O}(\alpha_S^2\alpha, \alpha_S^3\alpha)\ , \\
\mathrm{NLO_{EW}^{lead}} &= t\bar{t}W@\mathcal{O}(\alpha_S^2\alpha^2)\ , \\
\mathrm{NLO_{EW}^{sub}} &= t\bar{t}W@\mathcal{O}(\alpha^3, \alpha_S\alpha^3)\ , \\
\mathrm{FxFx@1J} &= t\bar{t}W@\mathcal{O}(\alpha_S^2\alpha, \alpha_S^3\alpha) + t\bar{t}Wj@\mathcal{O}(\alpha_S^3\alpha, \alpha_S^4\alpha)\ , \\
\mathrm{FxFx@2J} &= t\bar{t}W@\mathcal{O}(\alpha_S^2\alpha, \alpha_S^3\alpha) + t\bar{t}Wj@\mathcal{O}(\alpha_S^3\alpha, \alpha_S^4\alpha) + t\bar{t}Wjj@\mathcal{O}(\alpha_S^4\alpha, \alpha_S^5\alpha)
\end{aligned}
$$

LO (50%-$\alpha_s^2\alpha$) + NLO(25%) + NNLO(12%) - Leading EW (3%) + Sublead EW (10%)



ttW QCD



ttW EWK

Object definition (Leptons)

- **Leptons:** Selection based on the ttH MVA retrained for both muons and electrons using Run 3 simulations (Same lepton definition as TOP-24-012).
- Using lepton categories:
  - Loose: Used for preselection of leptons.
  - Fakeable: To study the effect of non prompt leptons in final selection.
  - Tight: Used for final selection of the analysis.

Note: In the table p_T is in reality "p_T cone":

$$p_T^{l,cone} = \begin{cases} p_T^{l,reco}, & mvaTTH > WP \\ 0.9 \times p_T^{closest-jet}, & mvaTTH < WP \end{cases}$$

Electrons

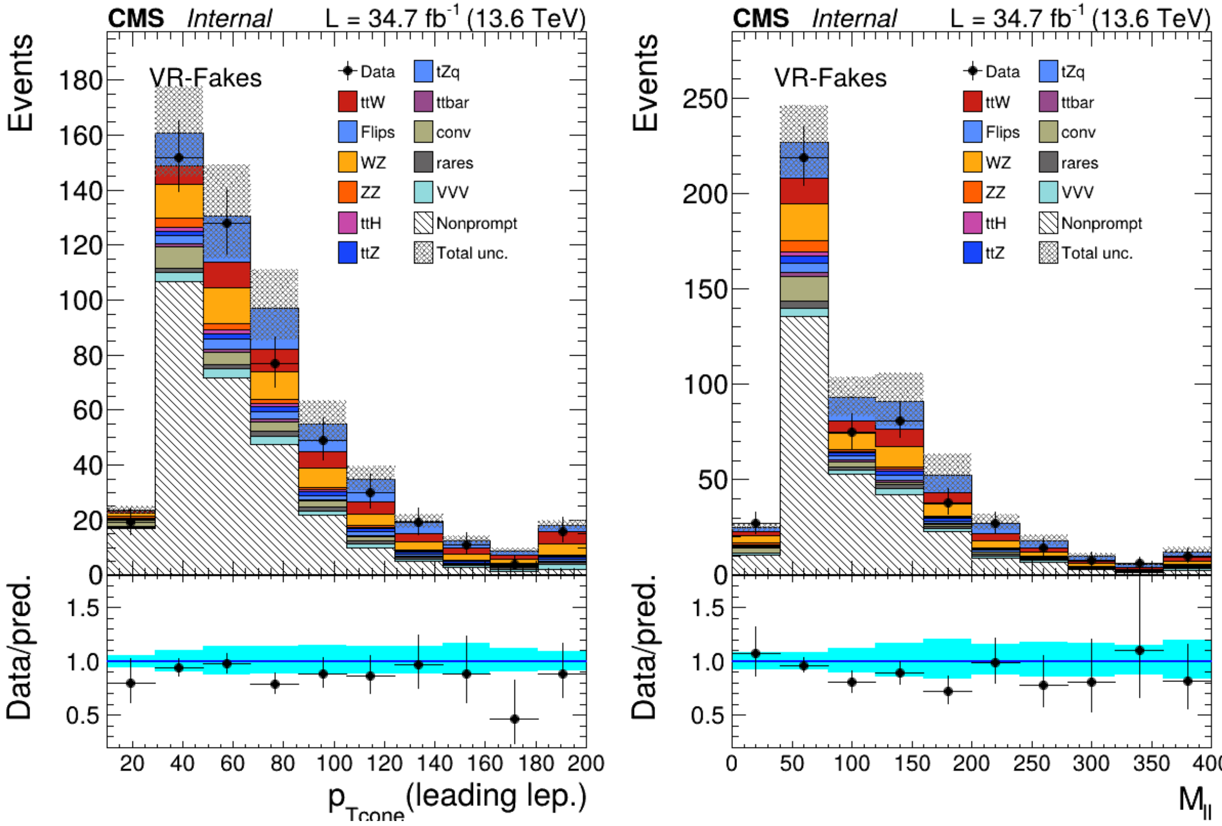
Observable	Loose	Fakeable	Tight
p_T	> 10 GeV	> 15 GeV	> 15 GeV
$\lvert\eta\rvert$	< 2.5	< 2.5	< 2.5
$\lvert d_{xy}\rvert$	< 0.05 cm	< 0.05 cm	< 0.05 cm
$\lvert d_z\rvert$	< 0.1 cm	< 0.1 cm	< 0.1 cm
d/σ_d	< 8	< 8	< 8
I_e	$< 0.4 \times p_T$	$< 0.4 \times p_T$	$< 0.4 \times p_T$
$\sigma_{i\eta i\eta}$	–	$<$ { 0.011 / 0.030 }[1]	$<$ { 0.011 / 0.030 }[1]
H/E	–	< 0.10	< 0.10
1/E - 1/p	–	> -0.04	> -0.04
Conversion rejection	–	✓	✓
Missing hits	≤ 1	$= 0$	$= 0$
Deep Jet of nearby jet	–	<WP-medium[2]	<WP-medium[2]
Jet relative isolation[3]	–	< 0.7 (–) †	–
Prompt-e MVA	–	< 0.90 (> 0.90)	> 0.90

Muons

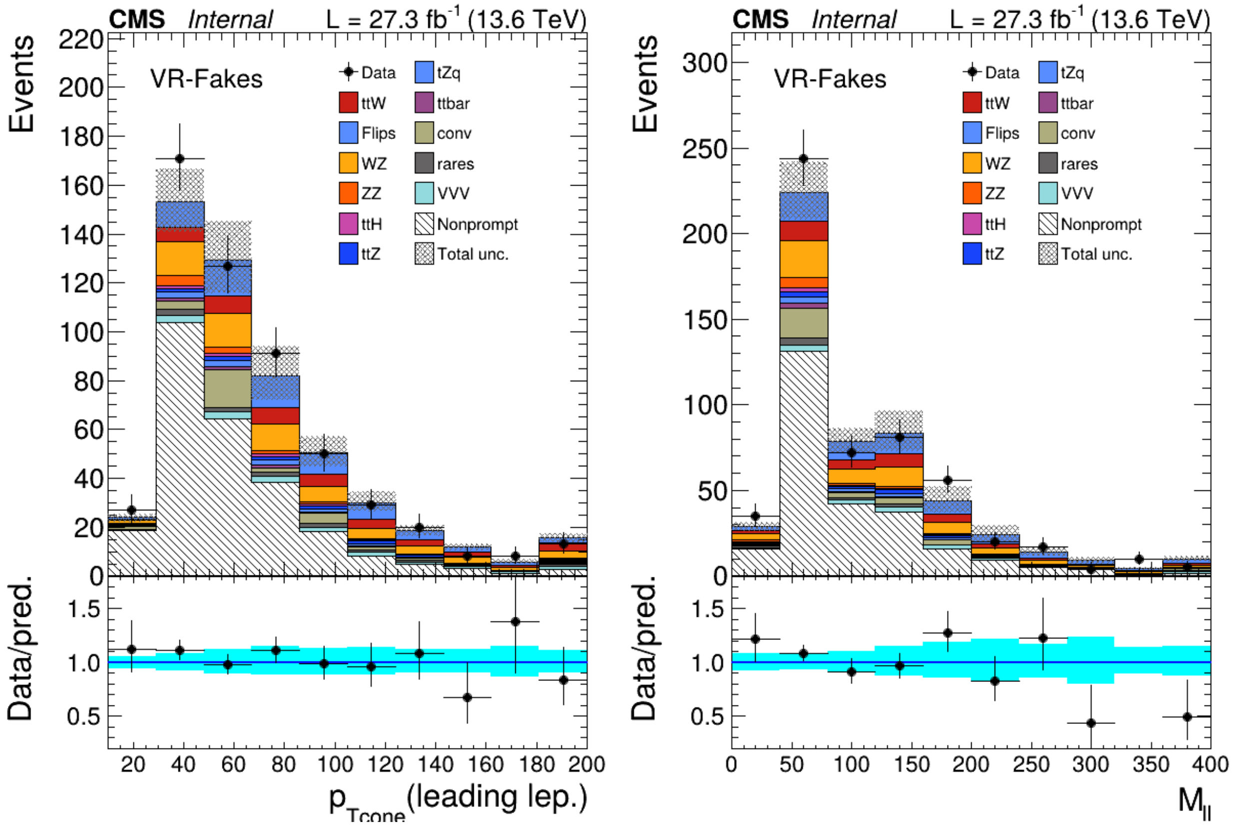
Observable	Loose	Fakeable	Tight
p_T	> 15 GeV	> 15 GeV	> 15 GeV
$\lvert\eta\rvert$	< 2.4	< 2.4	< 2.4
$\lvert d_{xy}\rvert$	< 0.05 cm	< 0.05 cm	< 0.05 cm
$\lvert d_z\rvert$	< 0.1 cm	< 0.1 cm	< 0.1 cm
d/σ_d	< 8	< 8	< 8
I_μ	$< 0.4 \times p_T$	$< 0.4 \times p_T$	$< 0.4 \times p_T$
PF muon	>WP-medium[1]	>WP-medium[1]	>WP-medium[1]
Deep Jet of nearby jet	–	<WP-interp. (<WP-medium)[2]	<WP-medium[2]
Jet relative isolation[3]	–	<0.5 (–) †	–
Prompt-μ MVA	–	< 0.64 (> 0.64)	> 0.64

Nonprompt estimation (Fakerates)

2022+2022EE

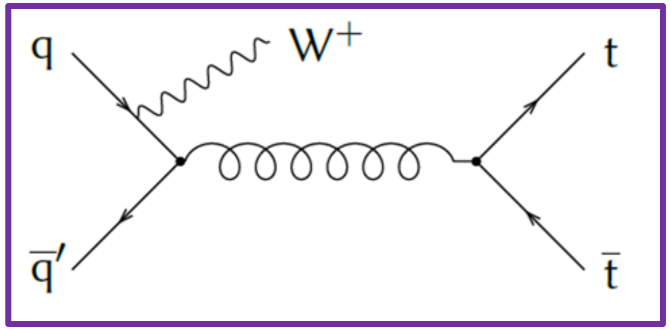


2023+2023BPix



Event selection

- Two different signal regions: Two lepton same-sign (SR-2lss) and three leptons (SR-3l).
- Studied the main background contributions regions.
  - 3 lepton CR (WZ/ttZ).
  - 4 lepton CR (ZZ).

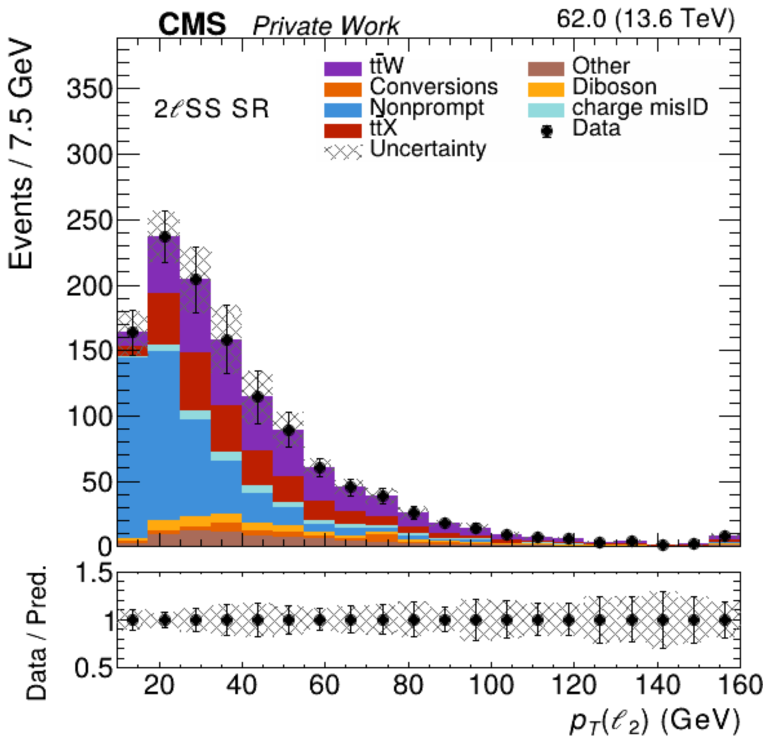


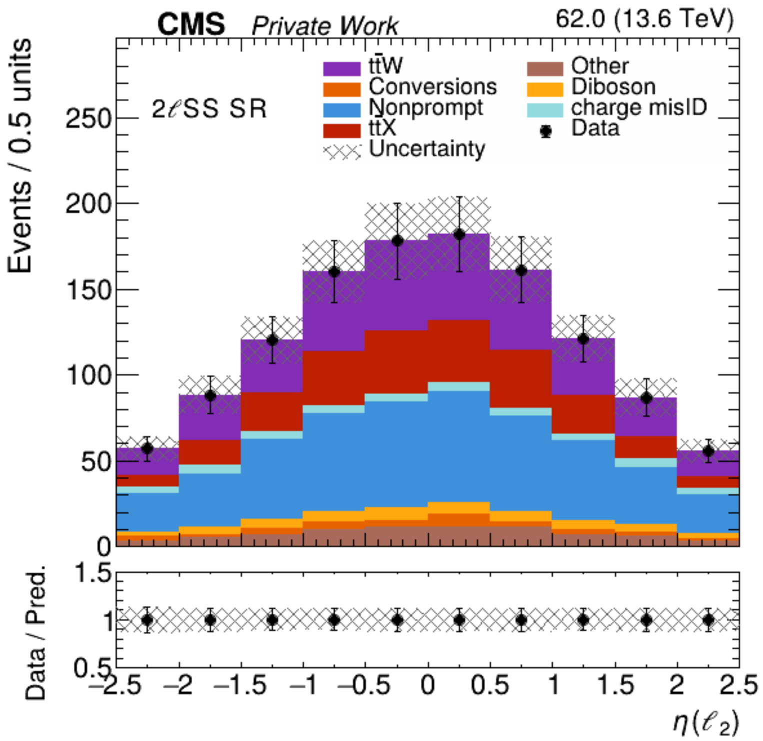
Region	N lep Tight (N_T^ℓ)	$\sum_{i=1}^{N_T^\ell} q_i$	lepton pt (GeV)	N Jets	N b-tags	$\|m_{ll} - Z_{mass}\|$
SR-2lss	2	± 2	>= 25; >= 15	>= 3	>= 2 (Loose)	> 10
SR-3l	3	± 1	>= 25; >= 15; >= 15	>= 2	>= 1 (Medium)	> 10
CR-3l	3	± 1	>= 25; >= 15; >= 15	>= 0	>= 0 (Loose)	< 10
CR-4l	4	X	>= 25; >= 15; >= 15; >= 10	>= 0	>= 0 (Loose)	< 10

- We also studied different validation regions in order to look for data/MC agreement (more details in backup):
  - For 3 leptons: For WZ and ttZ, with at least 2 jets with differents b-tags requirements.
  - For 2 leptons same-sign: a nonprompt validations region inverting the jets requirement of the SR and changing the b tags requirement.

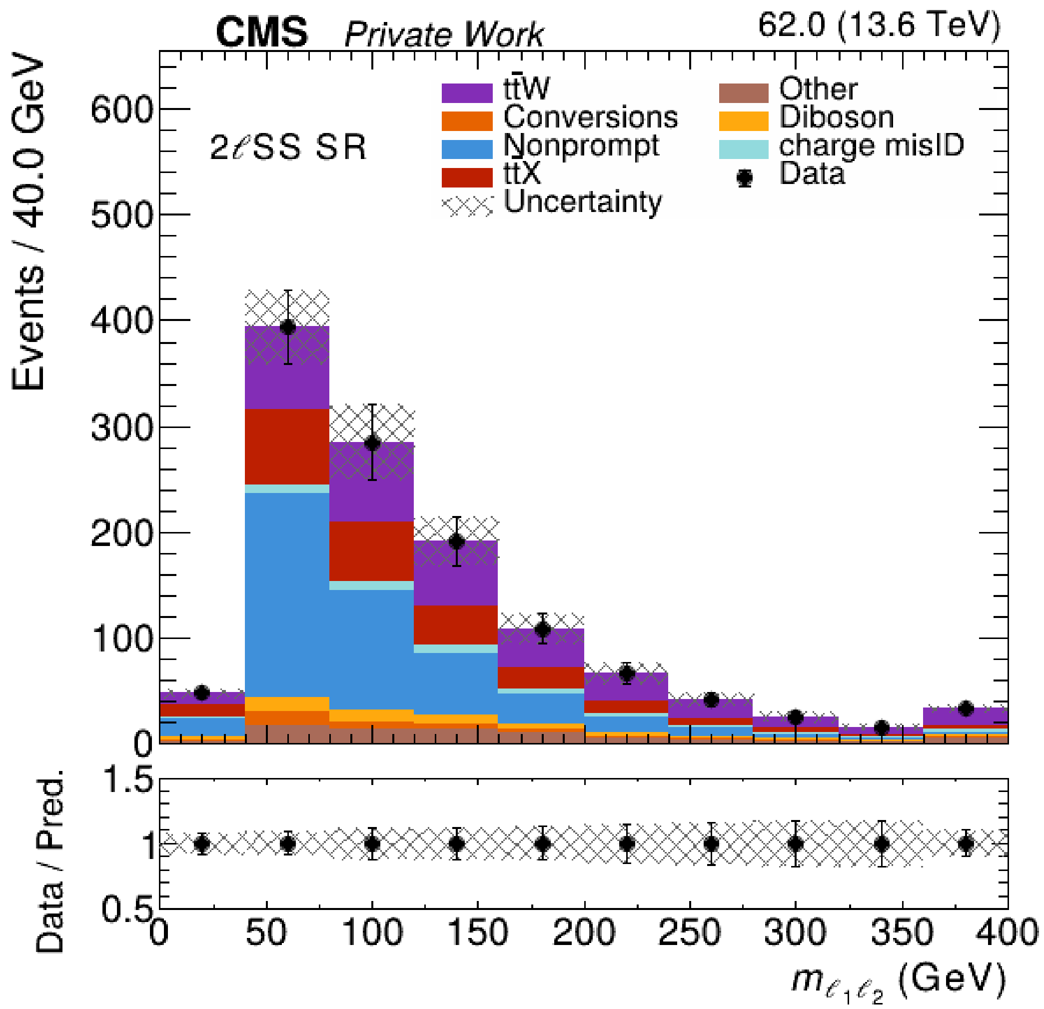
2 lepton same-sign signal region

Selection	2ℓss	3ℓ
Number of tight leptons	$=2$	$=3$
Veto on additional (non tight) leptons	—	—
Lepton p_{T} (GeV)	$25, 15$	$25, 15, 15$
Charge requirement	$q_{\ell_1} = q_{\ell_2}$	$\sum_{\ell} q_{\ell} = \pm 1$
$\lvert m(\ell,\ell') - m_{Z}\rvert$ (OSSF)	> 10	> 10
$\lvert m(e_1,e_2) - m_{Z}\rvert$ (same-sign)	> 10	> 10
$m(\ell,\ell')$	> 30	> 30
Number of central jets	≥ 3	≥ 2
Number of b-tagged jets	2 loose	1 medium



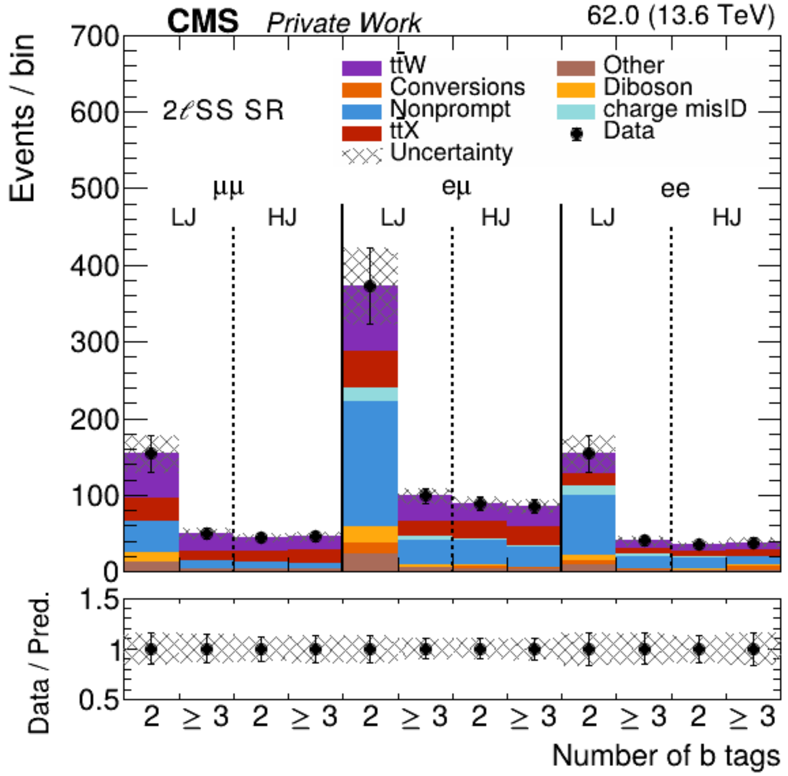


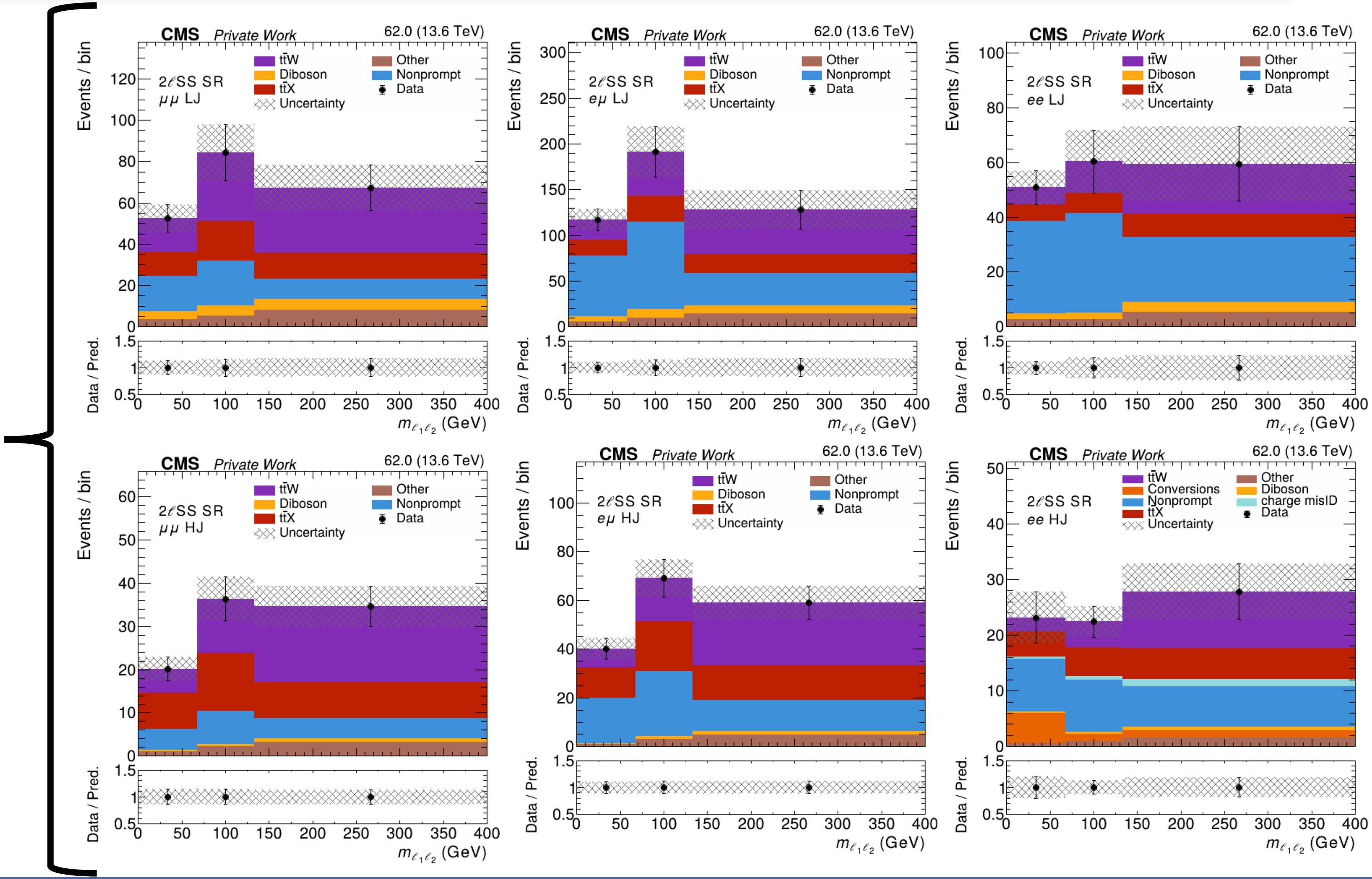
2 lepton same-sign signal region



Process	$\ell^-\ell^-$	$\ell^+\ell^+$	Total
ttX	112.10	111.67	223.77
Other	31.16	44.74	75.90
Conversions	15.63	18.19	33.82
Diboson	21.52	29.76	51.28
Nonprompt	219.12	222.82	441.94
Flips	22.26	21.68	43.94
Signal (ttW)	116.24	224.49	340.73
Background	421.79	449.86	870.65
Total	538.02	674.35	1211.38

2 lepton same-sign signal region

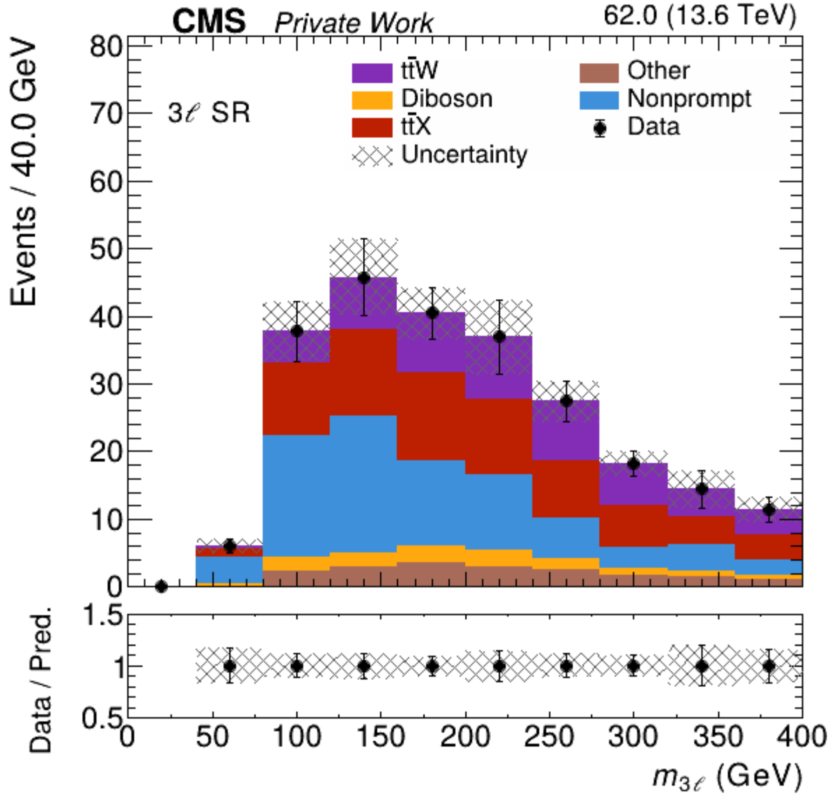




3 leptons signal region

Selection	2ℓss	3ℓ
Number of tight leptons	$= 2$	$= 3$
Veto on additional (non tight) leptons	—	—
Lepton p_T (GeV)	$25, 15$	$25, 15, 15$
Charge requirement	$q_{\ell_1} = q_{\ell_2}$	$\sum_{\ell} q_\ell = \pm 1$
$\lvert m(\ell,\ell') - m_Z \rvert$ (OSSF)	> 10	> 10
$\lvert m(e_1,e_2) - m_Z \rvert$ (same-sign)	> 10	> 10
$m(\ell,\ell')$	> 30	> 30
Number of central jets	≥ 3	≥ 2
Number of b-tagged jets	2 loose	1 medium

Proceso	$\ell^-\ell^+\ell^-$	$\ell^-\ell^+\ell^+$	Total
ttX	39.58	39.78	79.36
Other	9.96	12.33	22.29
Diboson	6.82	8.38	15.20
Nonprompt	44.71	39.86	84.57
Signal(ttW)	21.64	43.95	65.59
Background	101.07	100.35	201.42
Total	122.71	144.30	267.01



3 leptons signal region