



# First observation of tWZ production

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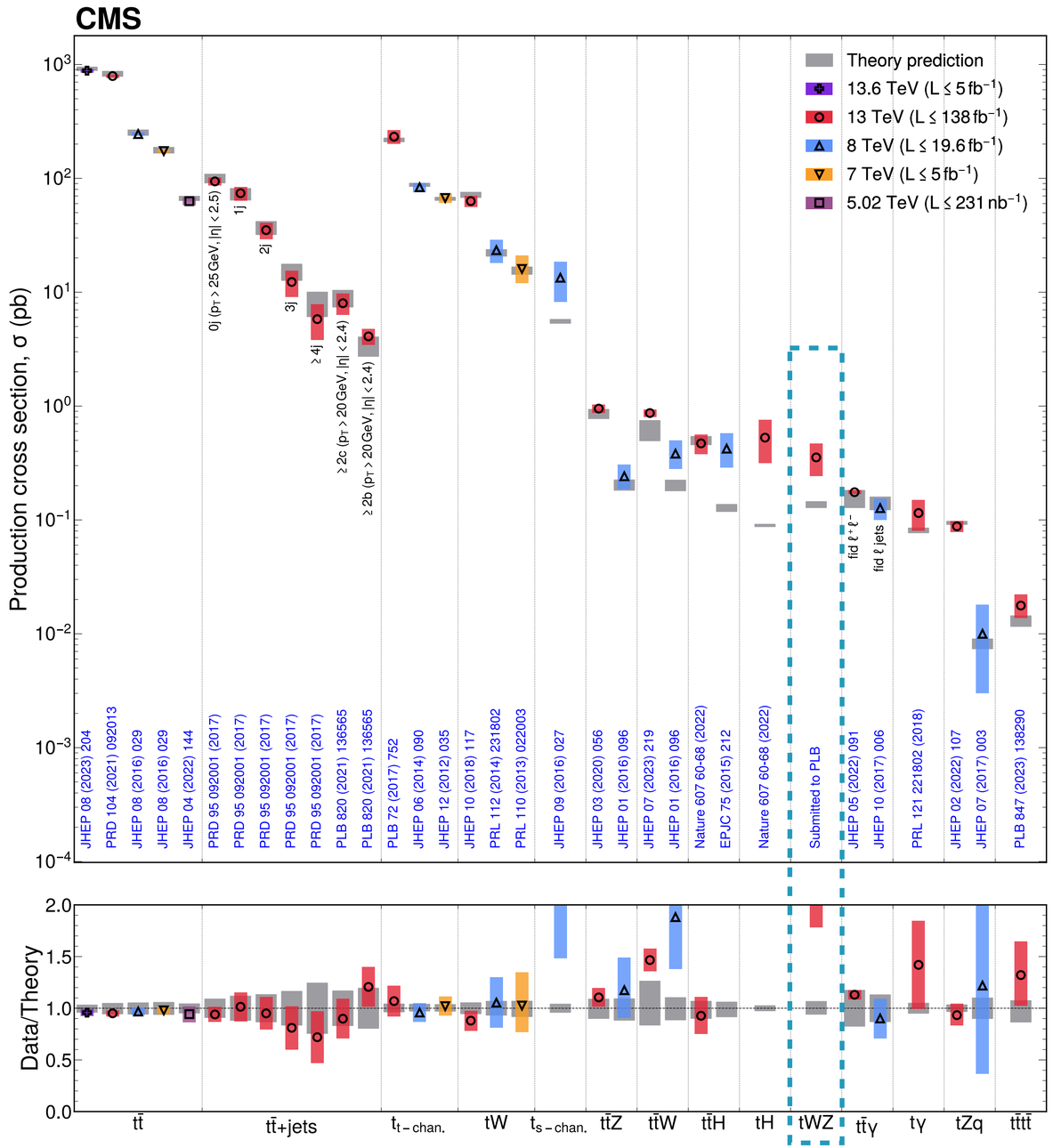
# INTRODUCTION

Top quark physics spans many orders of magnitude in cross section, with **EW boson-associated production** among the rarest processes.

The tWZ process has one of the **smallest cross section** of all top+V processes and it has **never been observed:**

- **Inclusive** cross section.
- Study of the **correlation with the ttZ** process.



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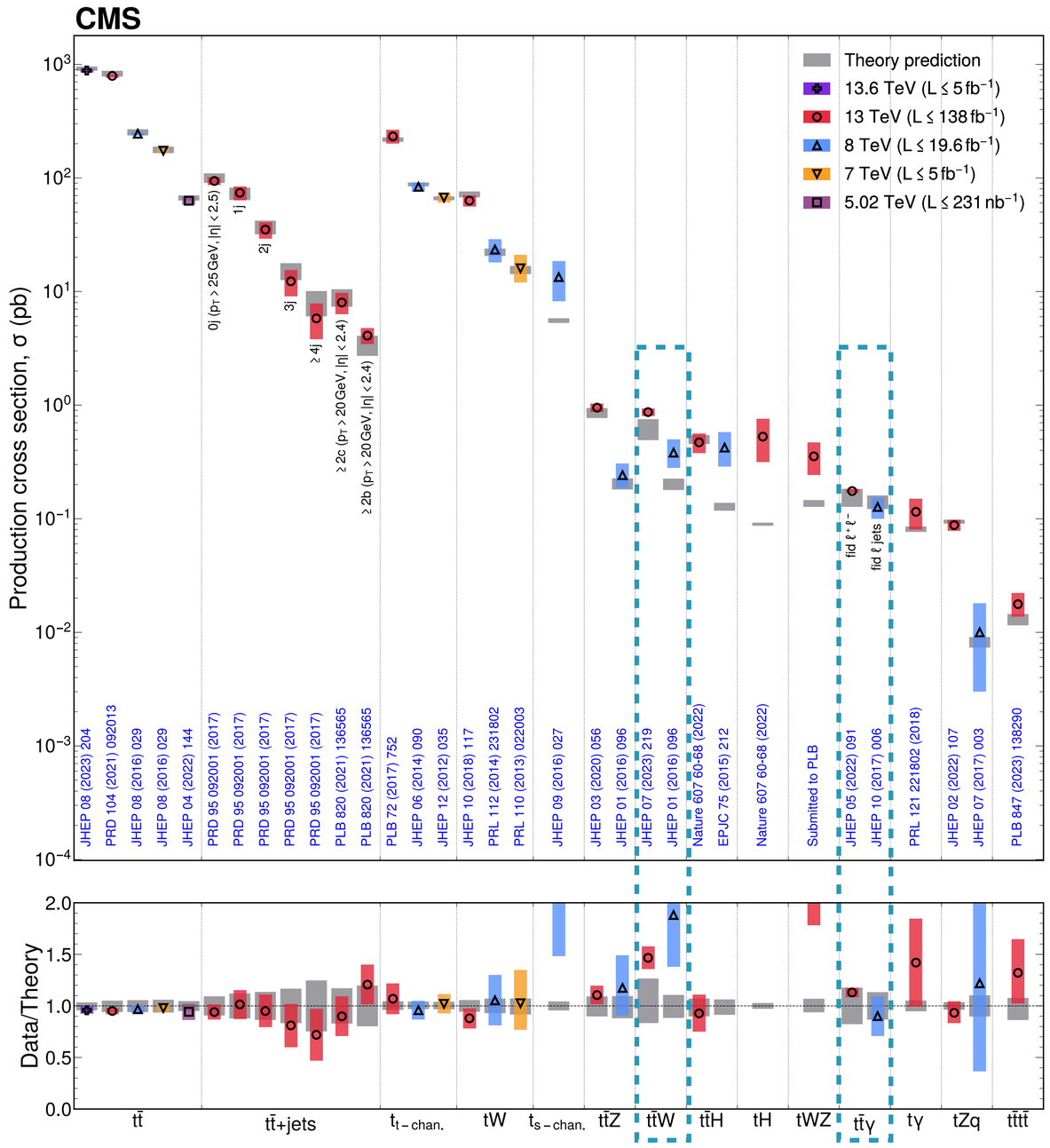
More about **top+V processes:**

- **ttW and ttγ** from Clara.



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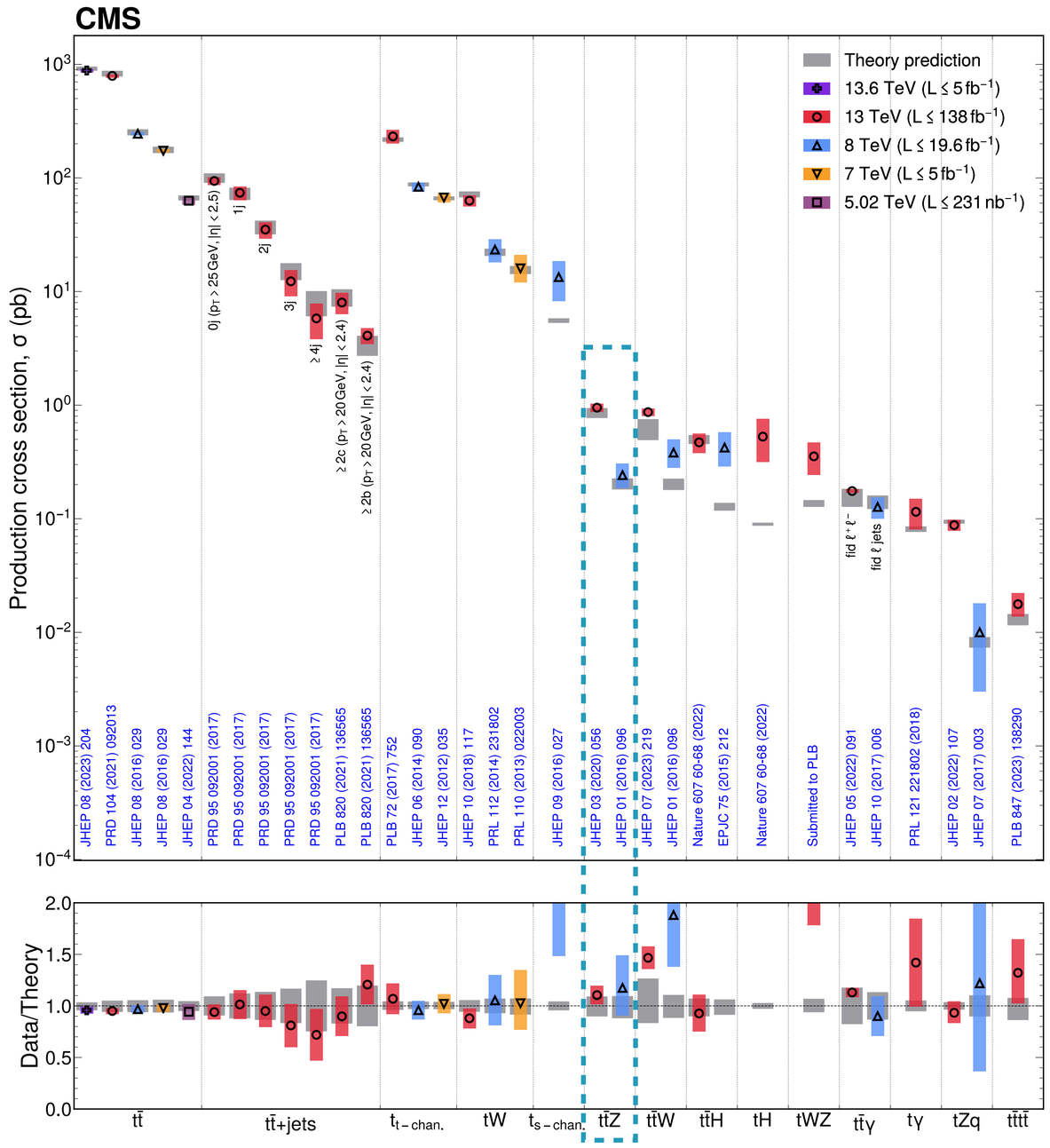
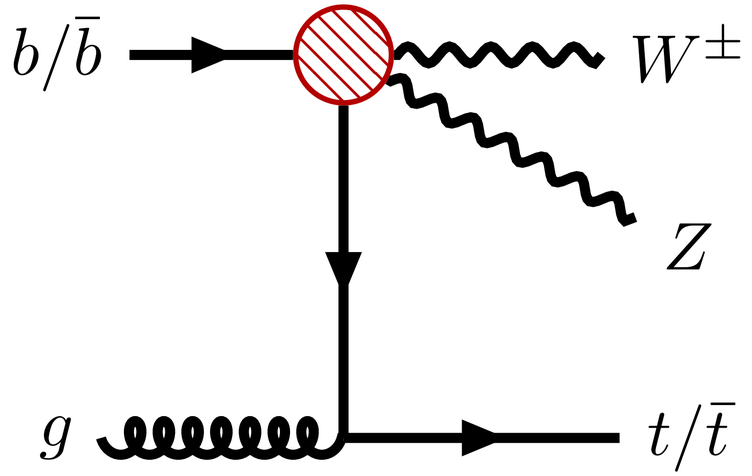
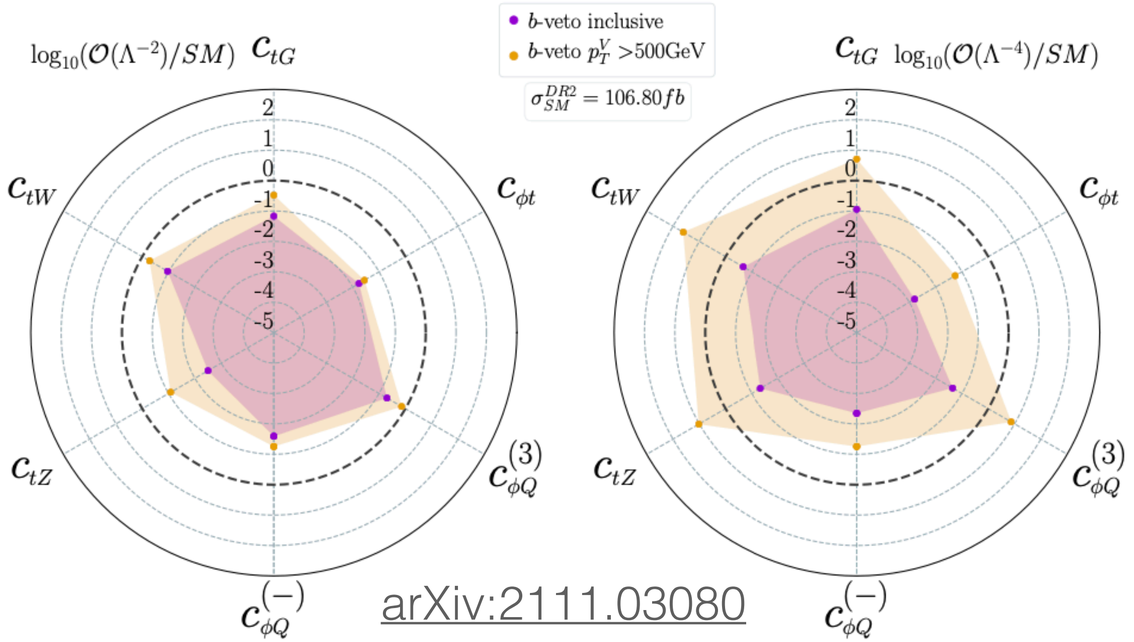
- **ttW and tt$\gamma$** from Clara.
- **EFT effects in ttZ** from Sergio.



# THE tWZ PROCESS

- tWZ has never been observed and previous measurements found **tensions with SM predictions**.
- **Small cross section** and **large backgrounds** contributions.
- Sensitive to **SMEFT operators** very loosely constrained.
- Possible new physics from **bW → tZ** vertices with energy growth for specific SMEFT operators.




arXiv:2111.03080

# OPERATIVE DEFINITION OF THE tWZ PROCESS

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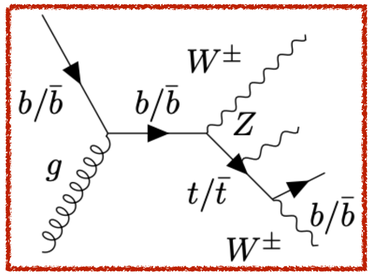
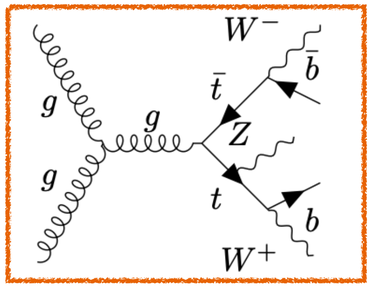
Overlap between tWZ and ttZ final state at NLO in QCD.




Overlap removal using the **diagram removal** (DR) or **diagram subtraction** (DS) schemes.

$$|\mathcal{M}_{tWZ}|^2 = |\mathcal{M}_{tWZ}^{non-res}|^2 + 2\mathcal{R}(\mathcal{M}_{tWZ}^{res}\mathcal{M}_{tWZ}^{non-res}) + |\mathcal{M}_{tWZ}^{res}|^2$$

$$|\mathcal{M}_{tWZ}|^2_{DR1} \equiv |\mathcal{M}_{tWZ}^{non-res}|^2$$

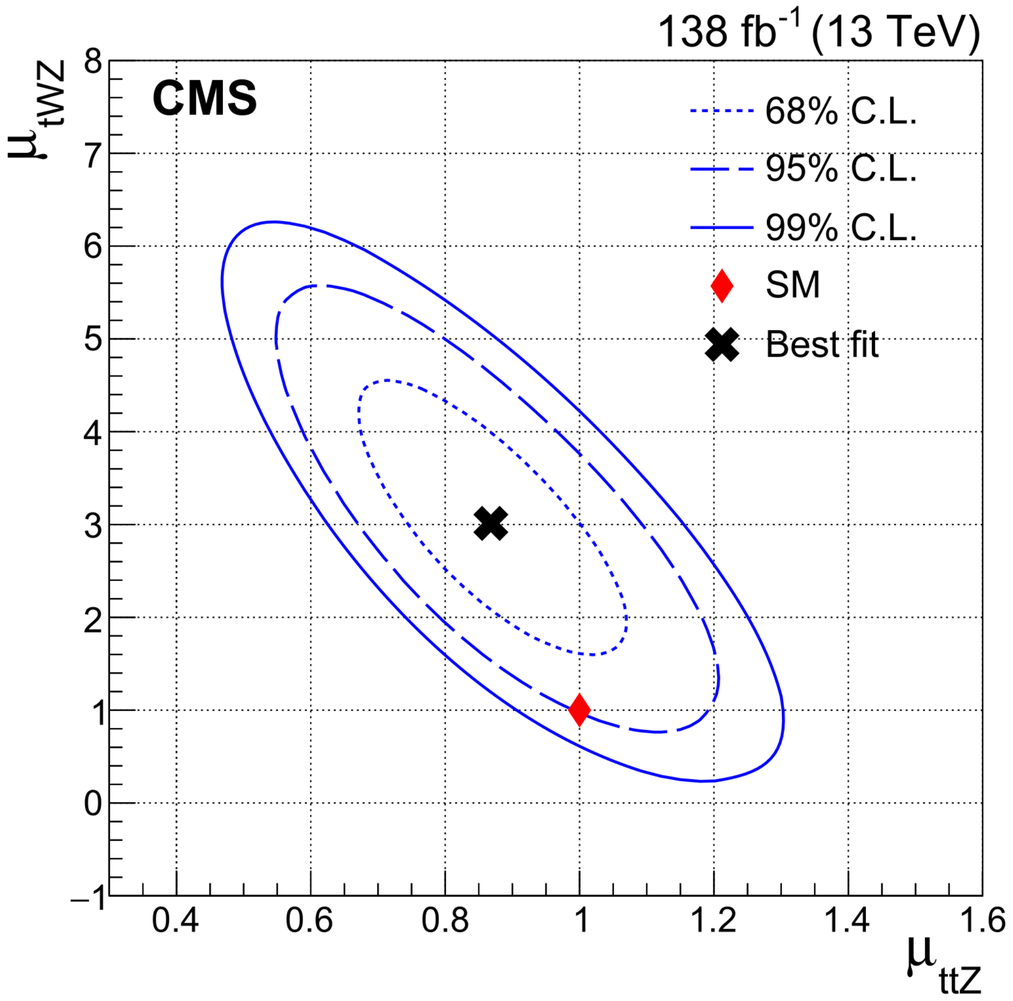
$$|\mathcal{M}_{tWZ}|^2_{DR2} \equiv |\mathcal{M}_{tWZ}^{non-res}|^2 + 2\mathcal{R}(\mathcal{M}_{tWZ}^{res}\mathcal{M}_{tWZ}^{non-res})$$

The **DR1** scheme is applied using the **MadSTR** tool.

# PREVIOUS RESULT

PLB 855 (2024) 138815

- **Full Run2** targeting multi-lepton final states.
- 3- and 4-leptons **signal regions.**
- **Control regions** to constrain the normalisation of WZ and ZZ.
- **DNN** to distinguish signal from background.
- **Fake leptons contribution** estimated with the fake factor method.




**Observed significance of 3.4 s.d. and expected significance of 1.4 s.d.**

$\mu$ = 2.6 ± 0.4 (stat) ± 0.7 (syst)

$\sigma_{tWZ}$ = 354 ± 54 (stat) ± 95 (syst) fb.

# ANALYSIS STRATEGY

Very **small cross section,** $\sigma_{tWZ}$=136 fb.

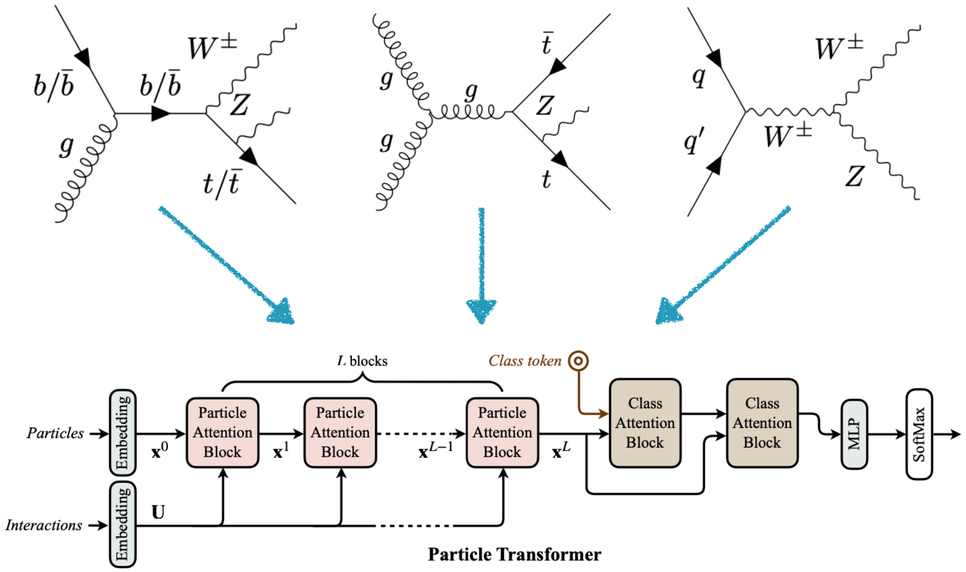
→ **Multi-lepton final states** and **b-tag information.**
→ Inclusion of **Run 3 data.**

**Main backgrounds:** ttZ, WZ, and tZq.

→ Cutting-edge **ML algorithms.**
→ CRs to constrain **normalisation uncertainties.**

Events from DY and tt plus **fake leptons.**

→ Estimated from data in the **maximum likelihood fit.**
→ CRs to constrain **fake lepton nuisance parameters.**




# REGIONS DEFINITION

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## Signal regions

### Three-lepton SR

- At least 2 jets
- At least 1 b-jet
- Exactly 3 leptons
- $|m(ll)-m(Z)| < 15$ GeV

### Four-lepton SR

- At least 1 jet
- At least 1 b-jet
- Exactly 4 leptons
- $|m(ll)-m(Z)| < 15$ GeV

## Control regions

### WZ CR

- At least 2 jets and 0 b-jet
- Exactly 3 leptons
- $|m(ll)-m(Z)| < 15$ GeV
- MET > 40 GeV

### ZZ CR

- At least 1 jet
- At least 1 b-jet
- Exactly 4 leptons
- $2x|m(ll)-m(Z)| < 15$ GeV

### DY CR

- 0 b-jet
- Exactly 3 leptons
- $|m(ll)-m(Z)| < 15$ GeV
- MET < 40 GeV

### tt CR

- At least 2 jet
- At least 1 b-jet
- Exactly 3 leptons
- $|m(ll)-m(Z)| > 15$ GeV

# THREE-LEPTON SR

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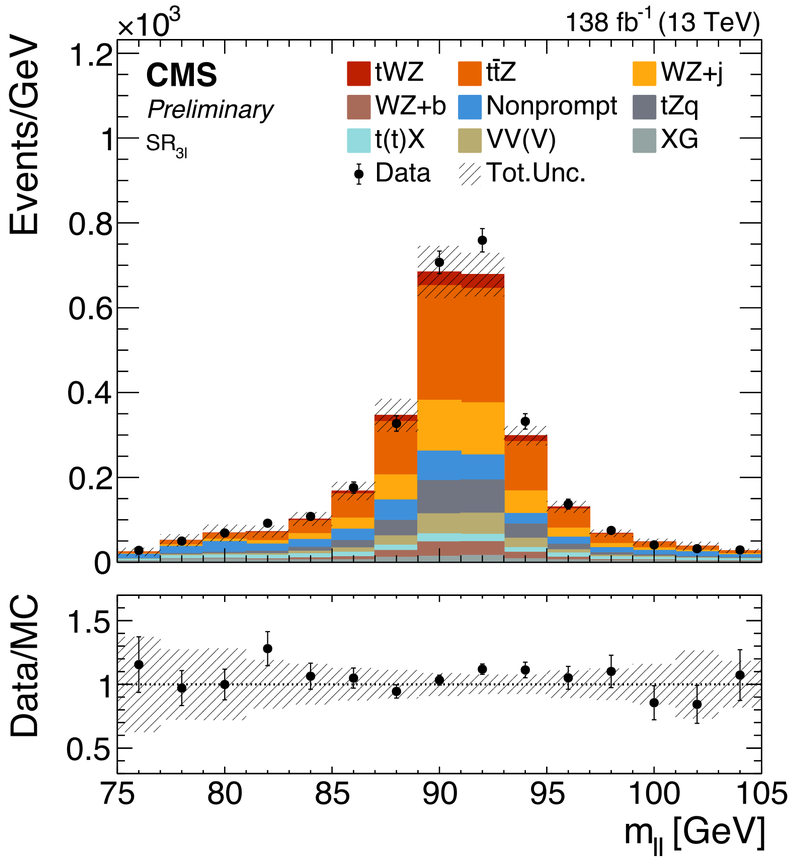
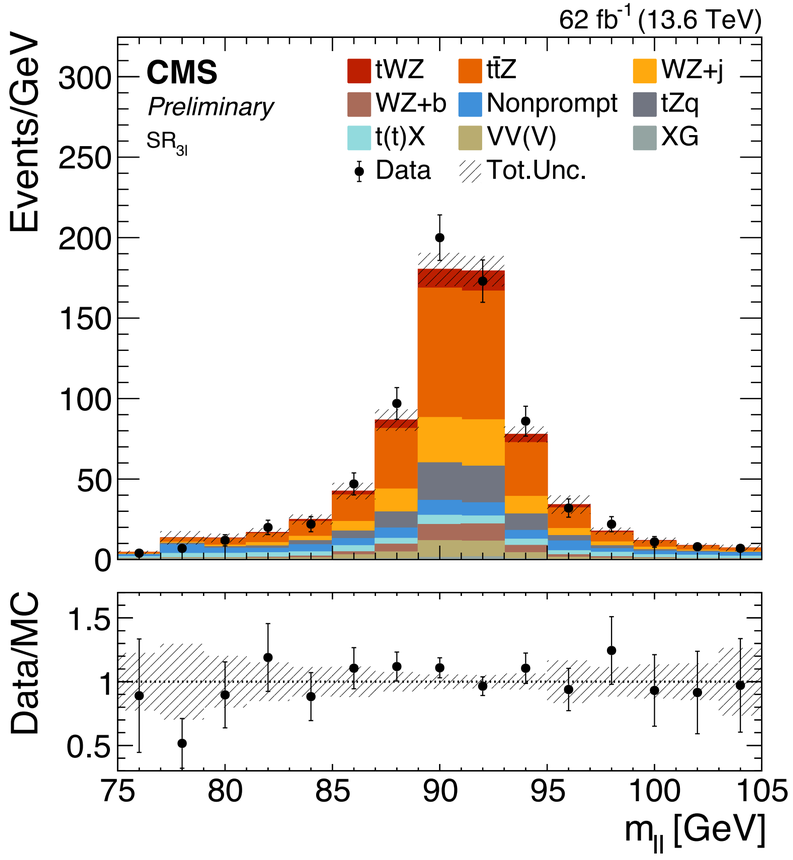
## Run 2




## Run 3




Good agreement in both data-taking periods.
The background is overwhelming, with the main contribution being **ttZ**.

# FAKE LEPTONS ESTIMATION

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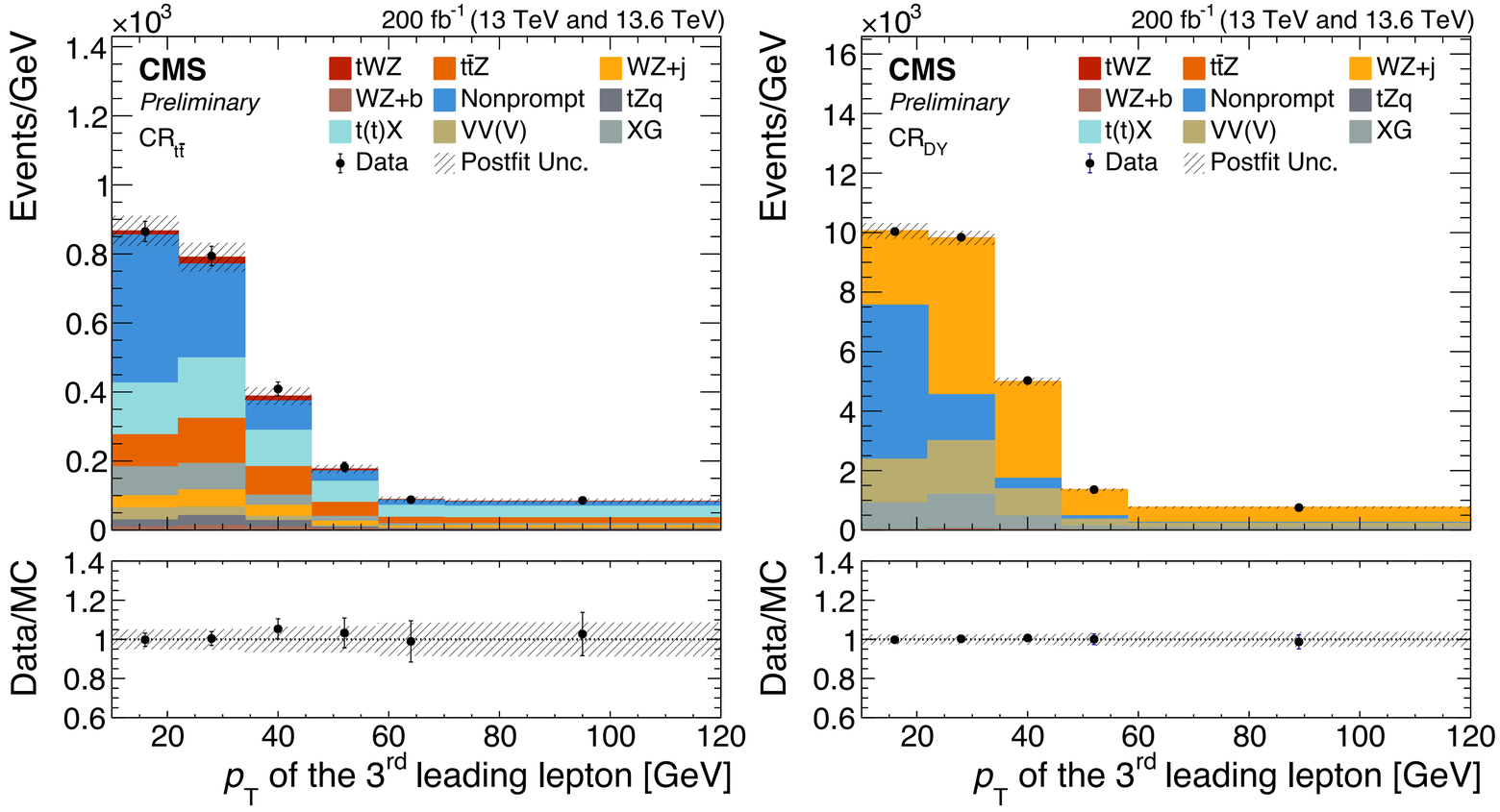
**Fake leptons** contribution measured **directly in the fit** to estimate this contribution from data.

Templates from **trailing lepton** $p_T$ for different fakes categories**:**

- **Fakes leptons from jets** measured using **unconstrained nuisance** parameters.
- **Fakes from photons** measured using **Gaussian constrained nuisance** parameters.



# WZ AND ZZ CONTROL REGIONS

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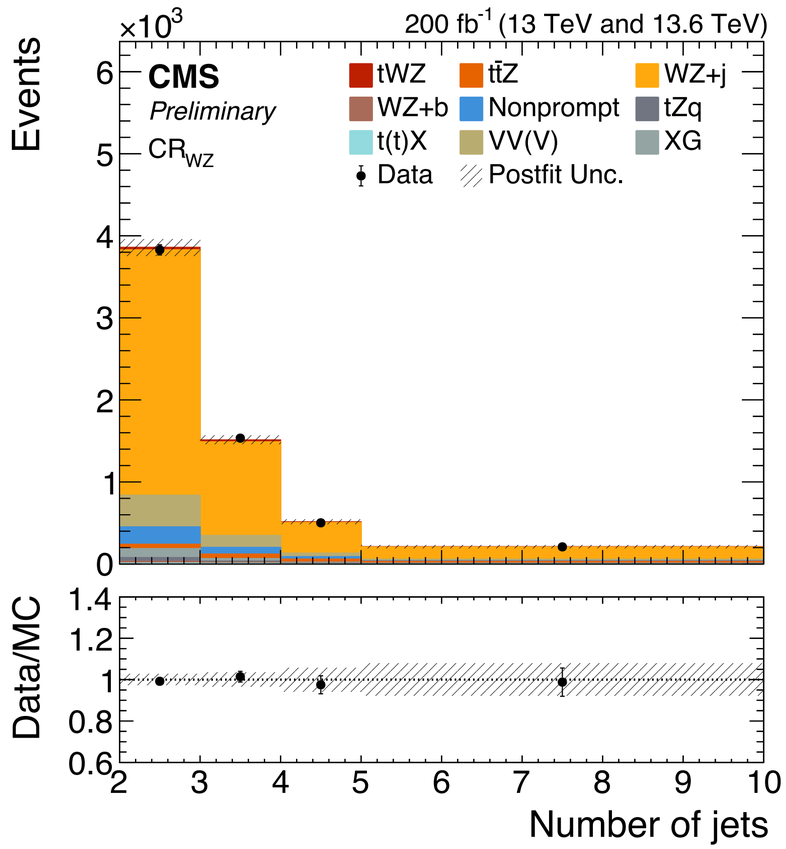
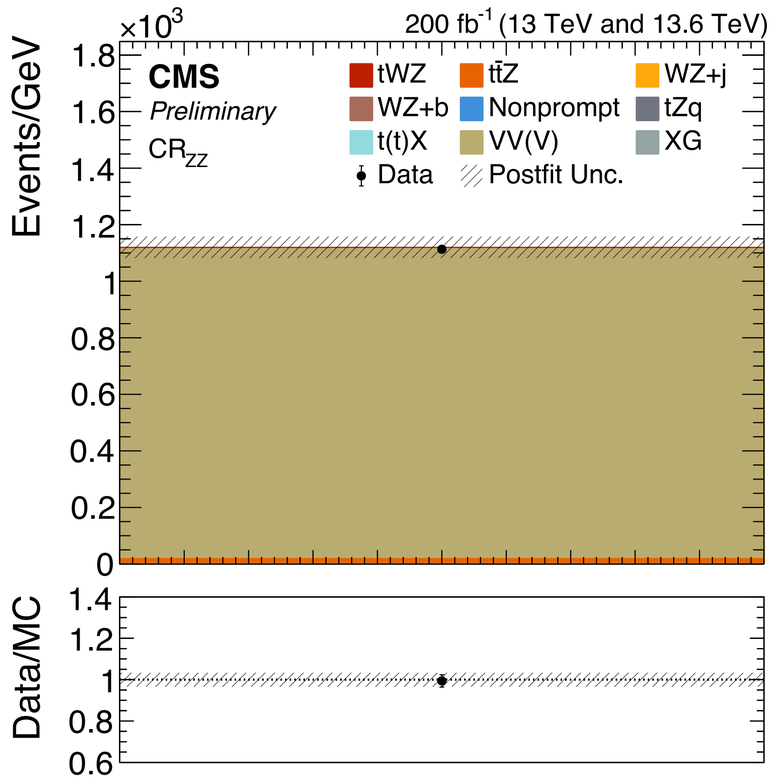
Number of jets:
constrain uncertainties on
additional jets description




Event yields:
constrain ZZ background
normalisation



# ML CLASSIFIER

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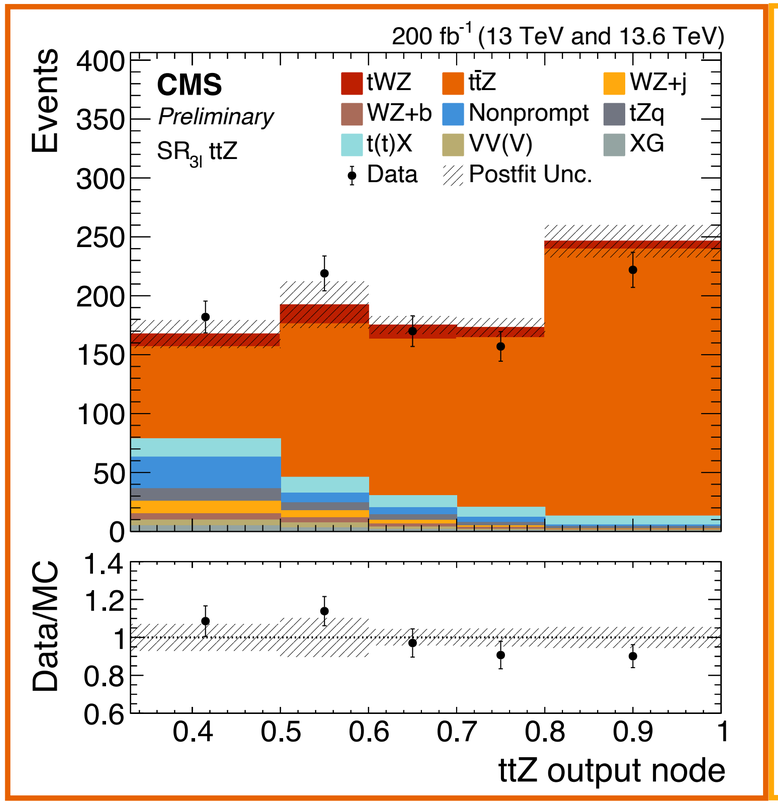
**Particle Transformer** algorithm to distinguish between signal and background.
**Dedicated algorithms** for the three- and four-lepton signal regions.

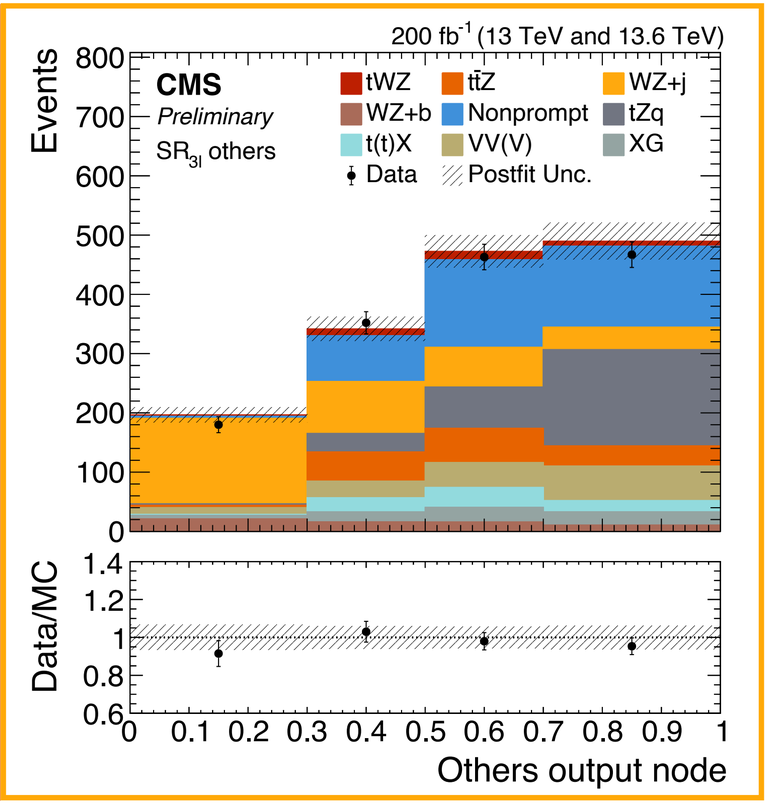
**Input variables:**

- 4-momentum of the **jets**.
- 4-momentum of **leptons and MET.**
- log($p_T$), log($E$), $\eta$, **b-tag**, and pdgID.

Three-lepton SR ML model has
**4 different output nodes:**

- tWZ
- ttZ
- WZ
- Minor backgrounds



# tWZ OUTPUT NODE

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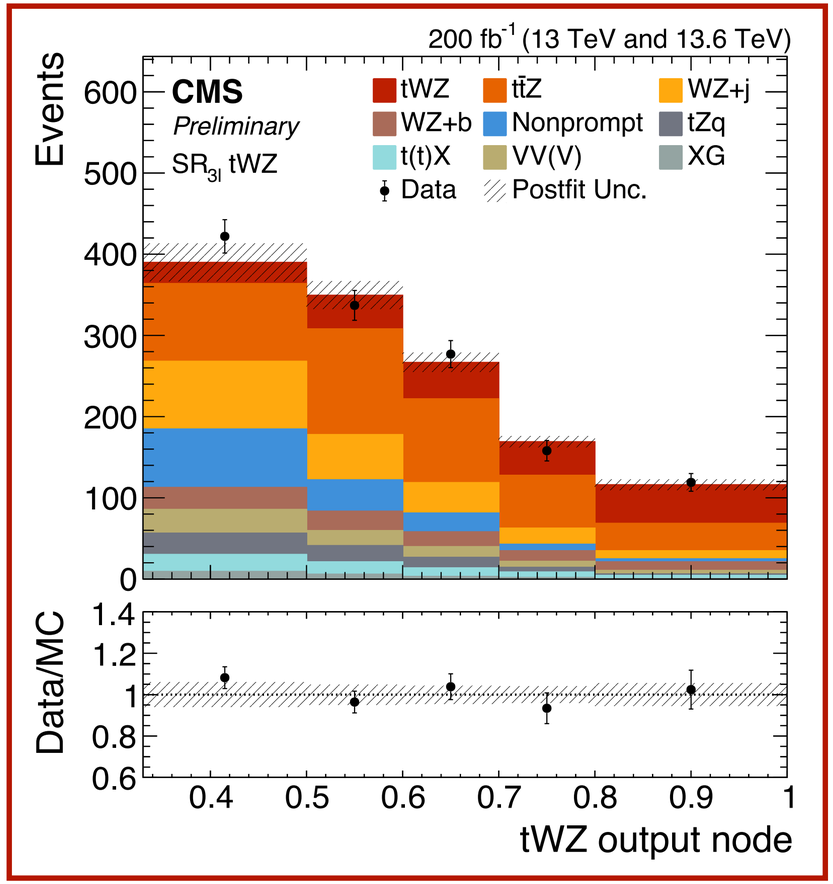


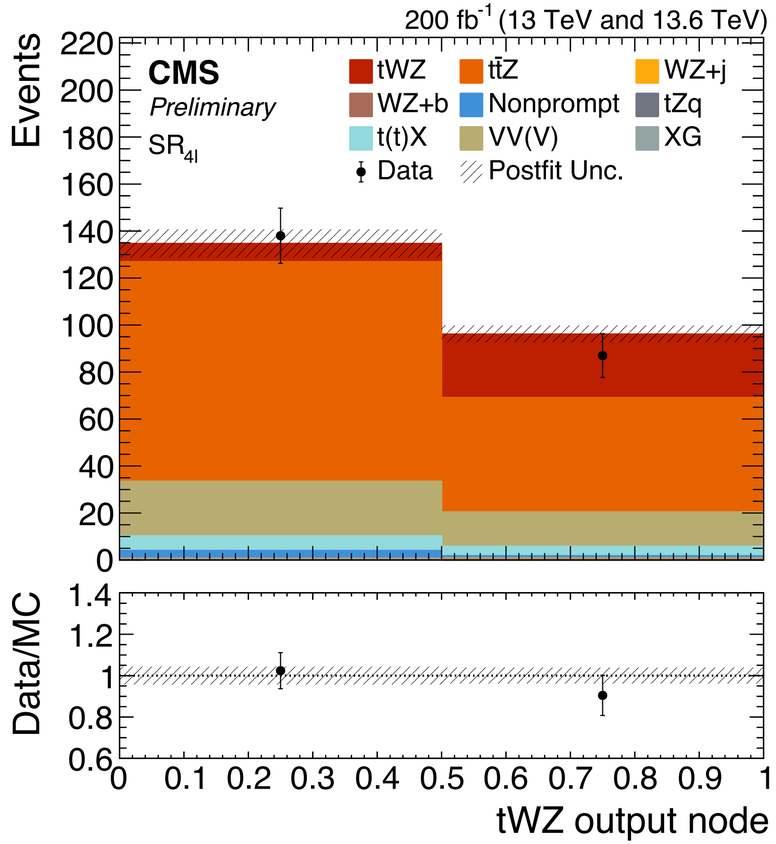


**Good data MC agreement** and very **significant separation** between signal and background, especially in the last bin of the three-lepton SR distribution.

# INCLUSIVE tWZ CROSS SECTION

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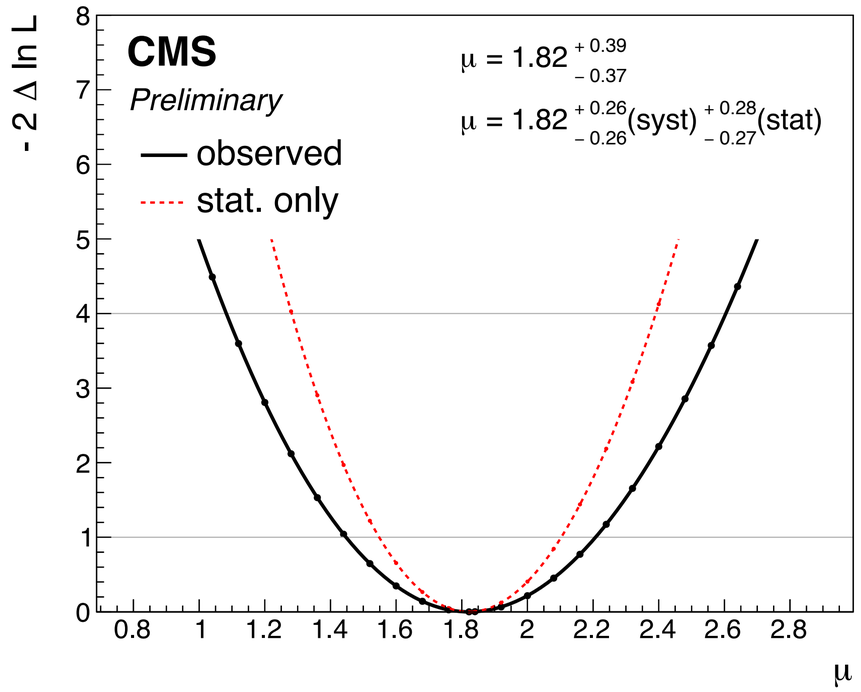
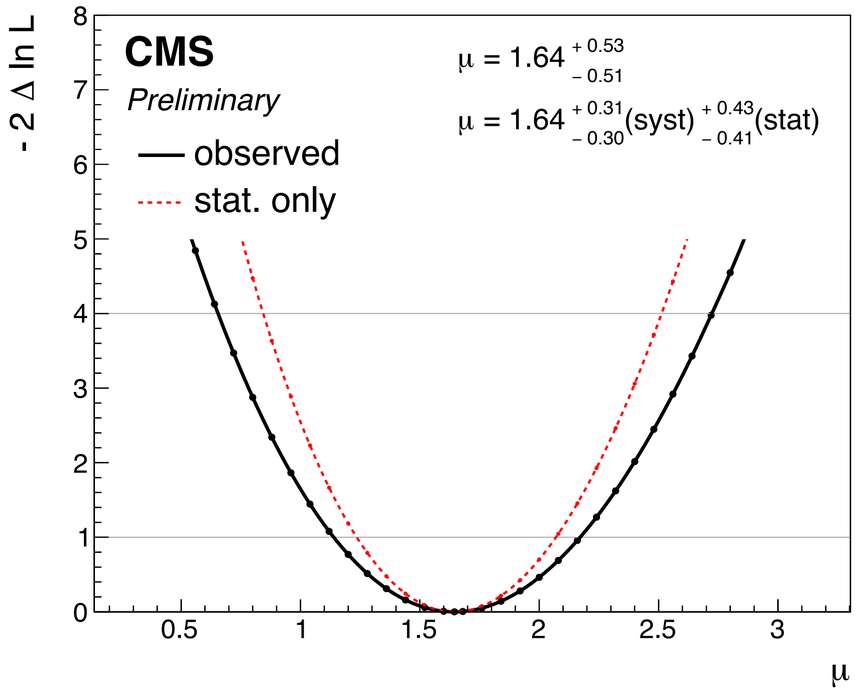
The inclusive **tWZ** cross section at $\sqrt{s}$ = 13 TeV is measured to be:

$$\sigma_{tWZ}(13\ \text{TeV}) = 248 \pm 38(\text{stat}) \pm 35(\text{syst})\ \text{fb}$$




The inclusive **tWZ** cross section at $\sqrt{s}$ = 13.6 TeV is measured to be:

$$\sigma_{tWZ}(13.6\ \text{TeV}) = 242 \pm 62(\text{stat}) \pm 46(\text{syst})\ \text{fb}$$



# Run 2 and Run 3 combined fit

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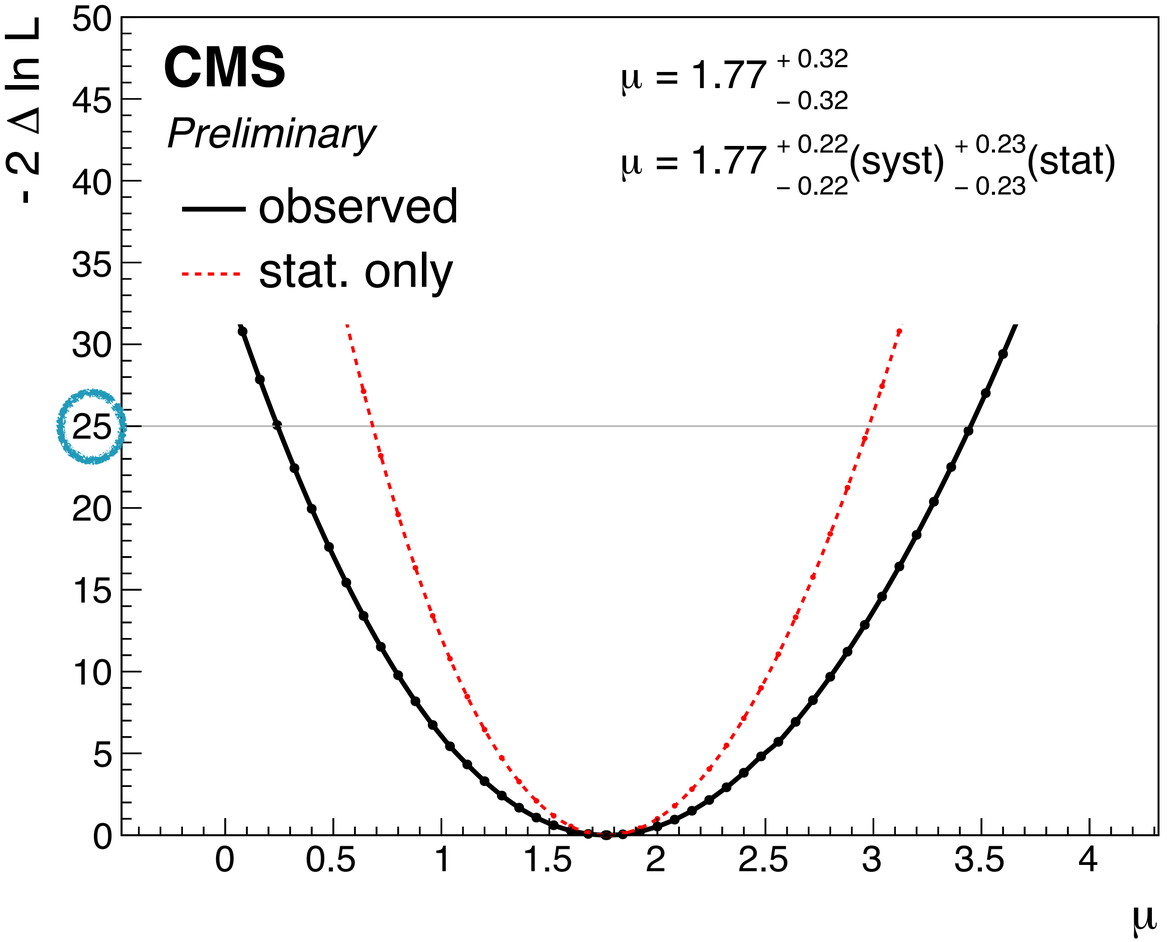
The signal strength of the **tWZ** process is also extracted in a Run 2 + Run 3 combined fit:

- $\mu = 1.77 \pm 0.23(\text{stat}) \pm 0.22(\text{syst})$
- Expected significance of 3.5 s.d.
- **Observed significance of 5.8 s.d.**




**This result marks the first observation of the tWZ process.**

# COMPATIBILITY ACROSS YEARS

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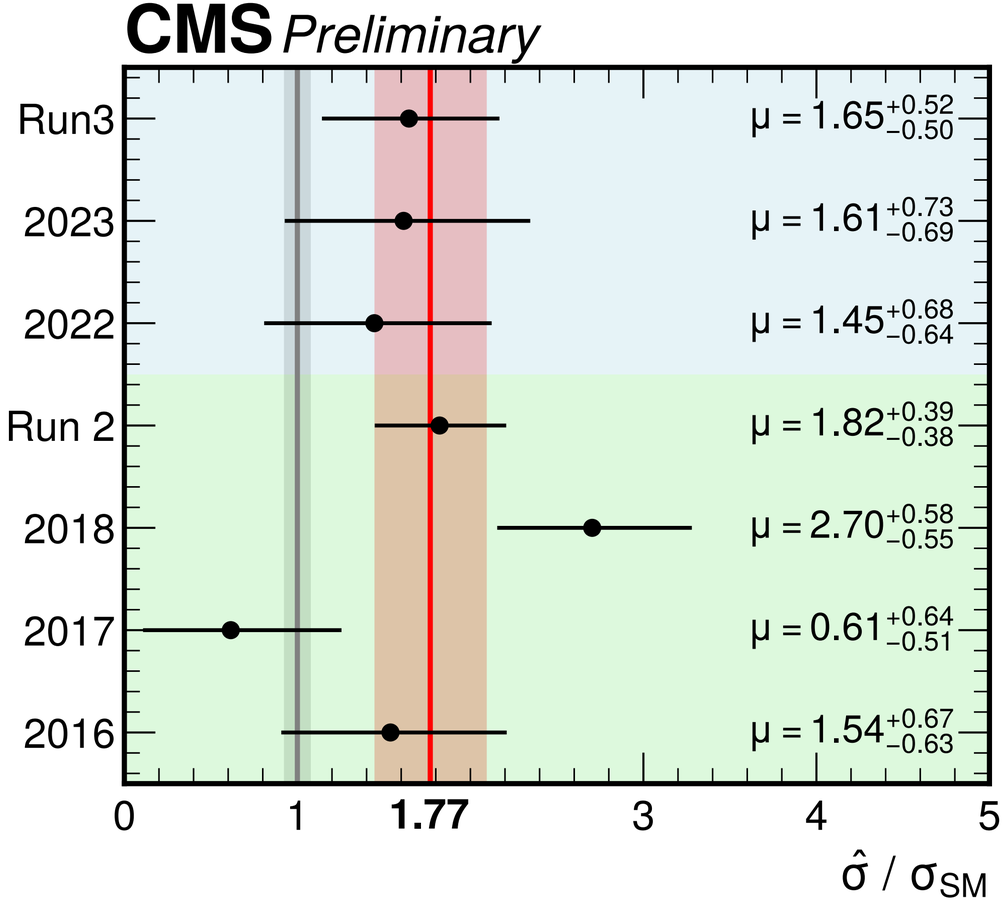
Good agreement between different data taking periods.

**~2 s.d. tension w.r.t. theory expectation.**



# COMPATIBILITY ACROSS CHANNELS

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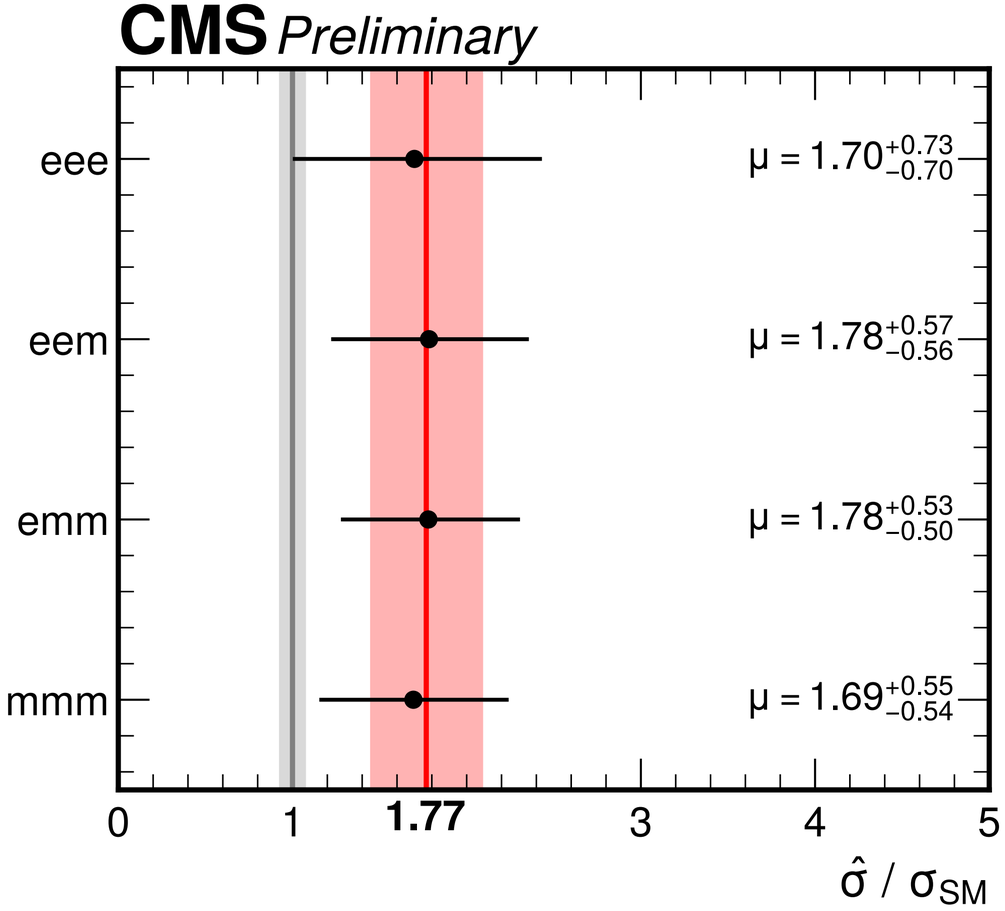
**Observed significance larger than 3 s.d.** for all the channels, except the eee one.



# SIMULTANEOUS MEASUREMENT OF tWZ AND ttZ

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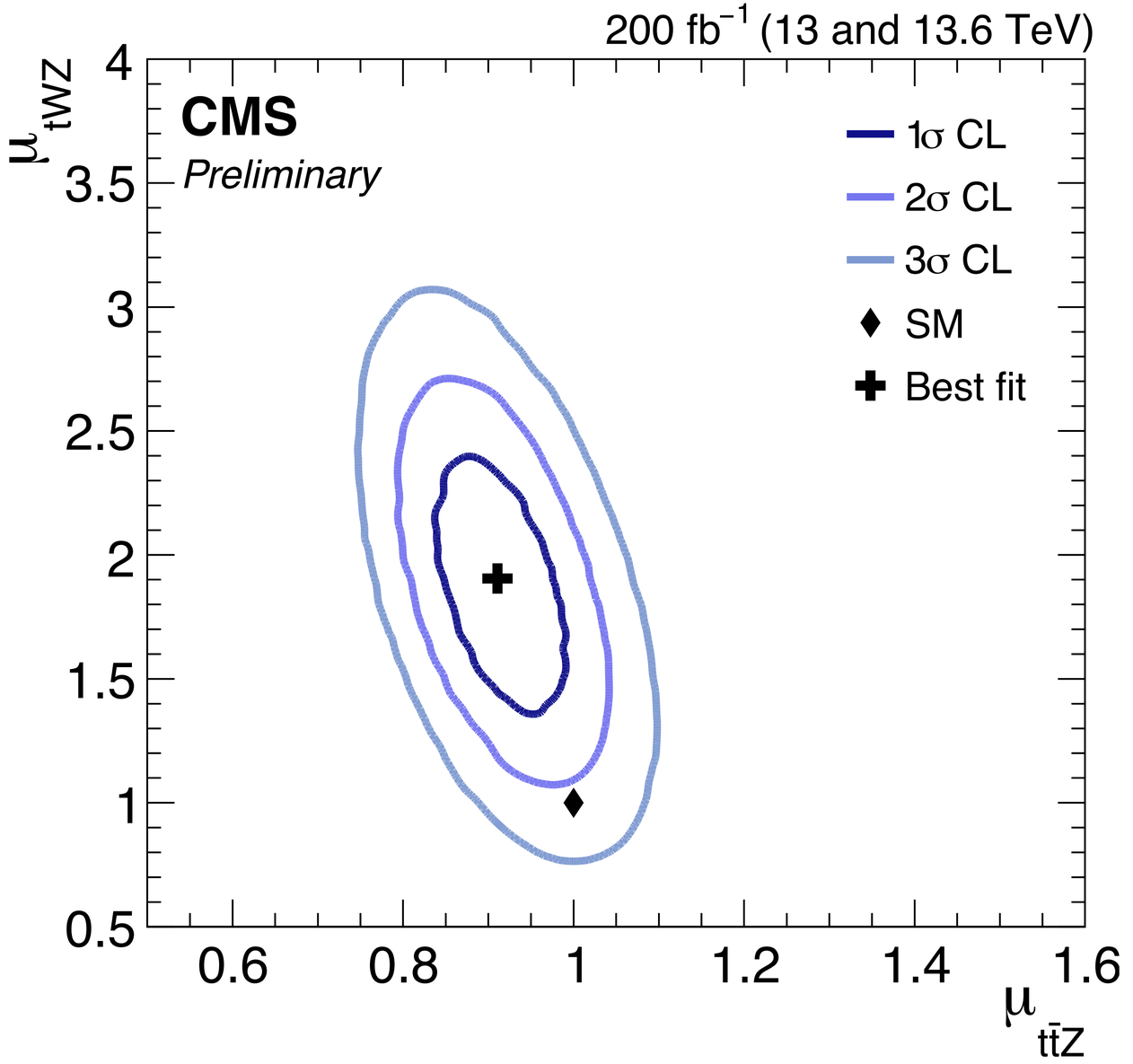
Simultaneous measurement of **tWZ** and **ttZ**:

$$\mu_{\mathrm{tWZ}} = 1.88 \pm 0.30\,(\mathrm{stat}) \pm 0.15\,(\mathrm{syst})$$

$$\mu_{\mathrm{ttZ}} = 0.91 \pm 0.04\,(\mathrm{stat}) \pm 0.03\,(\mathrm{syst})$$

Significant **reduction of the correlation** compared to the previous analysis (PLB 855 (2024) 138815).



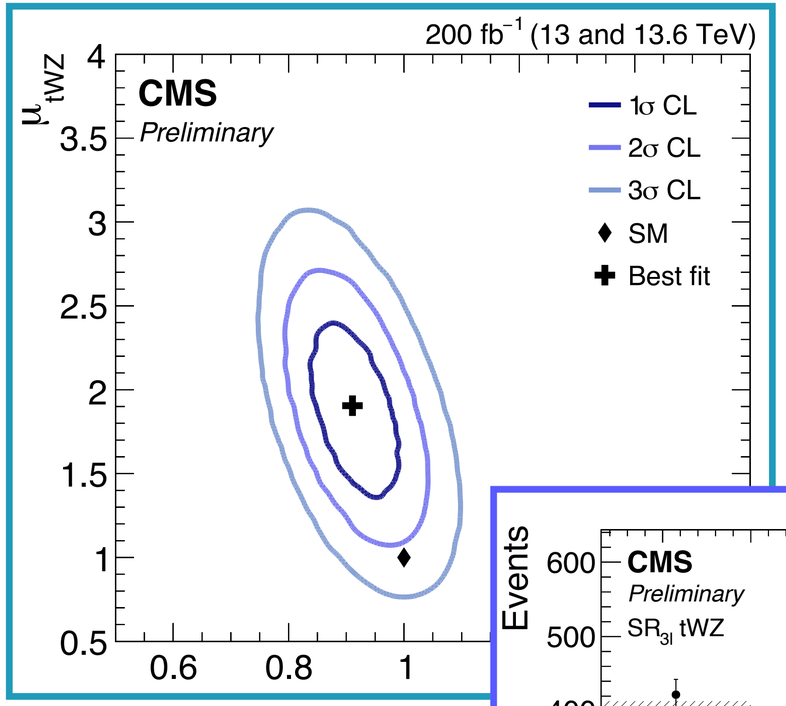
# CONCLUSIONS

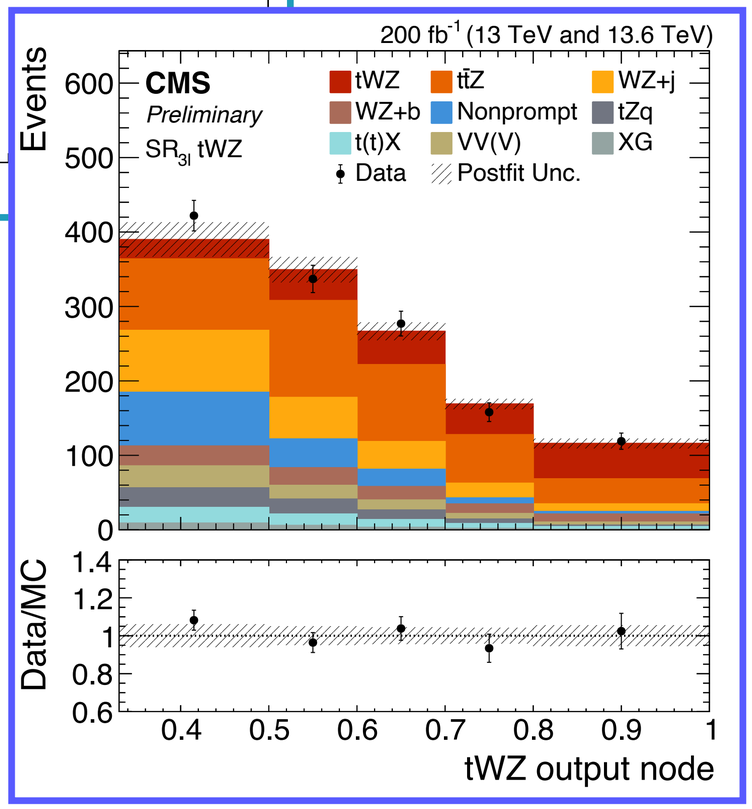
**More robust** modelling:

- Improved description of **WZ+jets.**
- New **fake leptons estimation.**

**Increased sensitivity** to tWZ:

- Refined **regions and objects definition.**
- Improved **ML performance.**




- **Expected significance doubled** for Run 2.
- Significant reduction of the **correlation between tWZ and ttZ.**
- tWZ signal strength measured with a **significance of 5.8 s.d.** marking the **observation of the tWZ process.**

# BACKUP

# OBJECTS SELECTION

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## Run 2

### 3(4) leptons

- $p_T$ > 25,15,10,(10) GeV
- $|\eta|$ < 2.5 (2.4)
- ID: $e$ tight, $\mu$ medium

### Jets

- $p_T$ > 25 GeV
- $|\eta|$ < 2.5
- ID: Tight
- B-tag: DeepJet medium

## Run 3

### 3(4) leptons

- $p_T$ > 25,15,15,(15) GeV
- $|\eta|$ < 2.5 (2.4)
- ID: $e$ tight, $\mu$ medium

### Jets

- $p_T$ > 25 GeV
- $|\eta|$ < 2.5
- ID: Tight
- B-tag: ParT medium

# ML MODEL

ParT paper

Github repository

Different ML models have been tested:

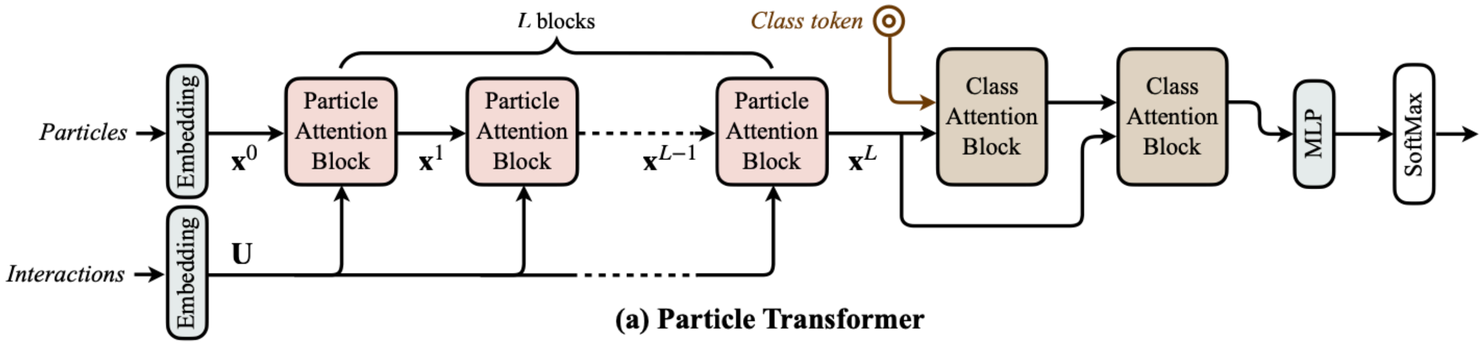
- Boosted decision trees.
- Fully connected feed forward NN.
- **Particle Transformer**.

Particles **variables** and **features**:

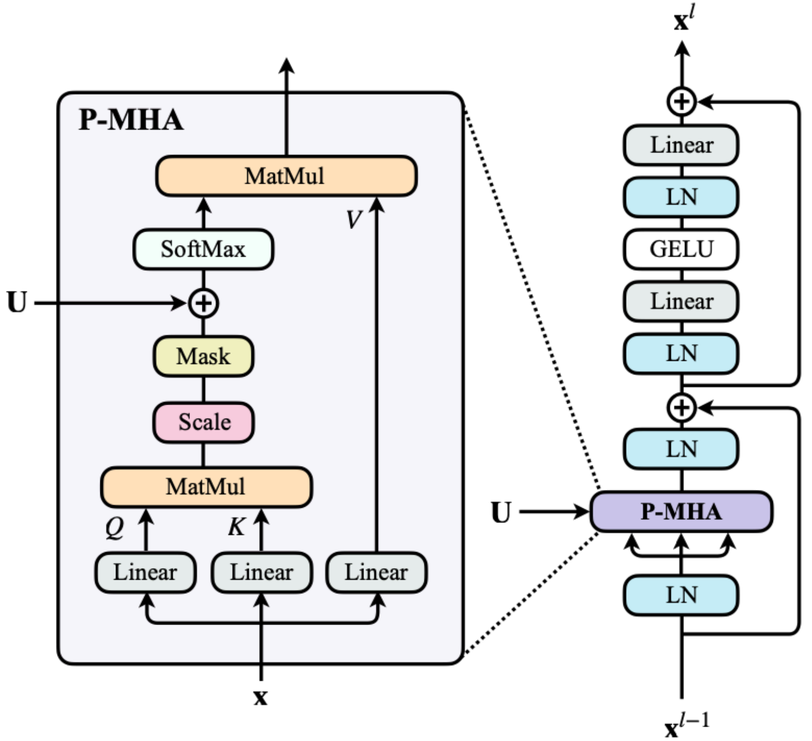
- 4-momentum of the first **6 jets**.
- 4-momentum of the **4/5 leptons**.
- log($p_T$), log($E$), $\eta$, b-tag, and pdgID.

**Interactions**:

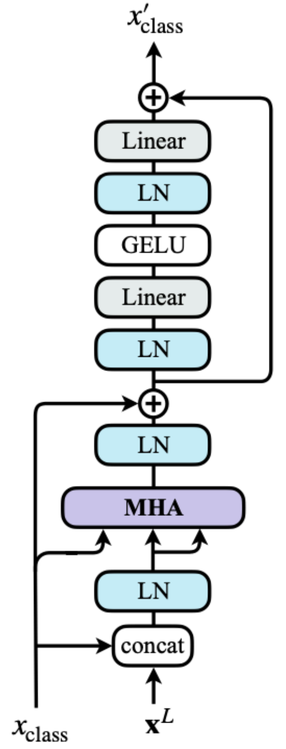
- $\Delta = \sqrt{(y_a - y_b)^2 + (\phi_a - \phi_b)^2}$
- $k_T = min(p_{T,a}, p_{T,b})\Delta$
- $z = min(p_{T,a}, p_{T,b})/(p_{T,a} + p_{T,b})$
- $m^2 = (E_a + E_b)^2 - ||\mathbf{p}_a + \mathbf{p}_b||^2$




(a) Particle Transformer




(b) Particle Attention Block




(c) Class Attention Block

# SYSTEMATIC UNCERTAINTIES (EXPERIMENTAL)

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Experimental uncertainties are uncorrelated between Run 2 and Run 3.

- Pileup
- B-tag ID corrections
- Lepton ID corrections
- Fake leptons

- Unclustered energy
- Jet corrections
- Trigger uncertainty
- Luminosity

# SYSTEMATIC UNCERTAINTIES (THEORETICAL)

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Theory and modelling uncertainties are correlated between Run 2 and Run 3.

- DR modeling
- Number of jets reweighting for WZ
- QCD scales
- PDF, 100 variations
- ISR and FSR
- DY: 10%
- ttZ: 7%
- ttX: 20%
- ttW: 25%
- VV(V): 10%
- ZZ+bjets: 20%
- tt: 5%
- tZq: 11%
- WZ: 10%
- WZ+b-jets: 20%
- XG: 10%