top 2024

17th International Workshop on Top Quark Physics

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Universidad de Oviedo

RECENT MEASUREMENTS OF TOP CROSS SECTIONS AT CMS

23/09/2024

Javier del Riego

(on behalf of the CMS Collaboration)

Universidad de Oviedo - Universitè Catholique de Louvain - University of Kansas

CERN

CMS
Compact Muon Solenoid

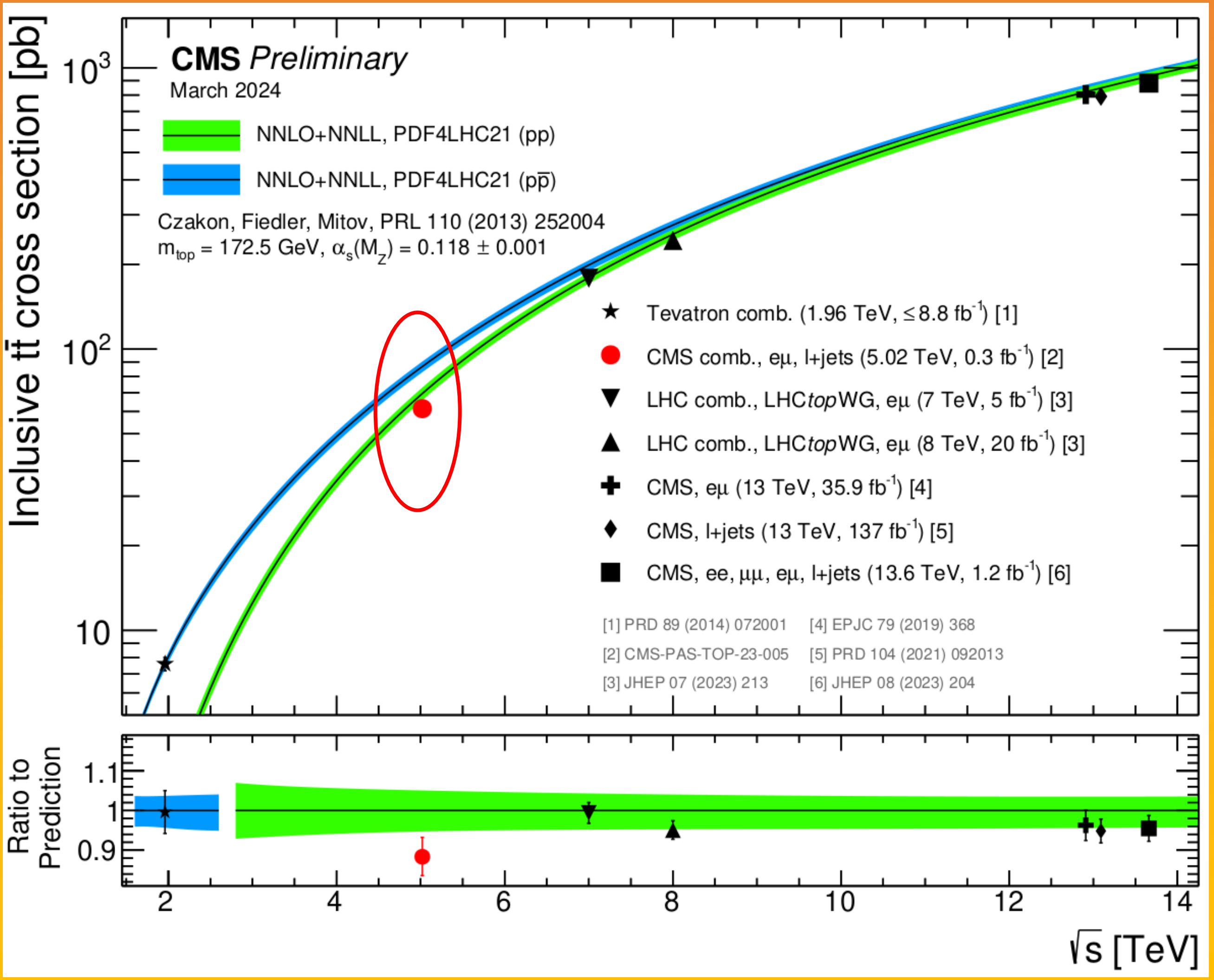
OVERVIEW

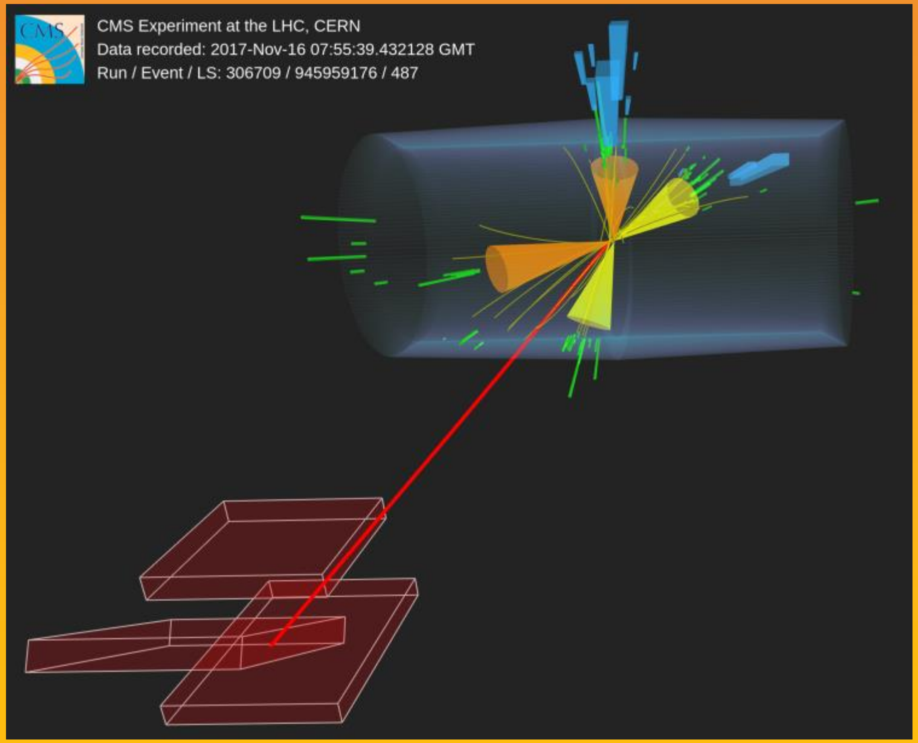
- **CMS Collaboration** has a comprehensive program of top quark pair and single production cross section measurements at all LHC energies.
- **This talk** presents two recent results made public in 2024.
- **More $t\bar{t}$** differential cross sections will be presented in Olaf's talk.

- $t\bar{t}$ @ $5.02\ TeV$ [CMS-PAS-TOP-23-005]
  - Interesting scenario: low pile-up (~2 int. per crossing)
  - Most precise CMS measurement of $t\bar{t}$ at that energy

- tW @ $13.6\ TeV$ [arxiv:2409.06444 (submitted to JHEP)]
  - First single-top LHC result from Run 3
  - Both inclusive and differential cross section measurements

$t\bar{t}$ @ $5.02\ TeV$





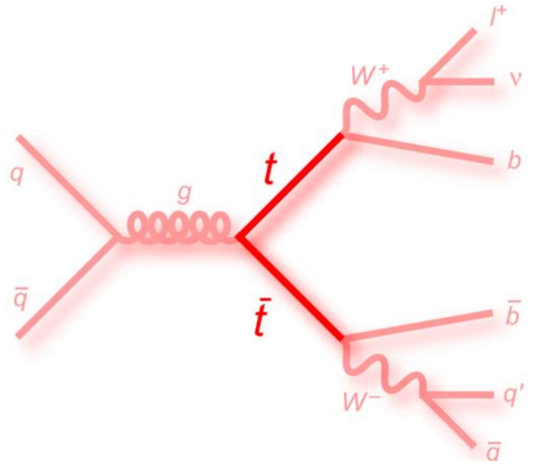
Motivation

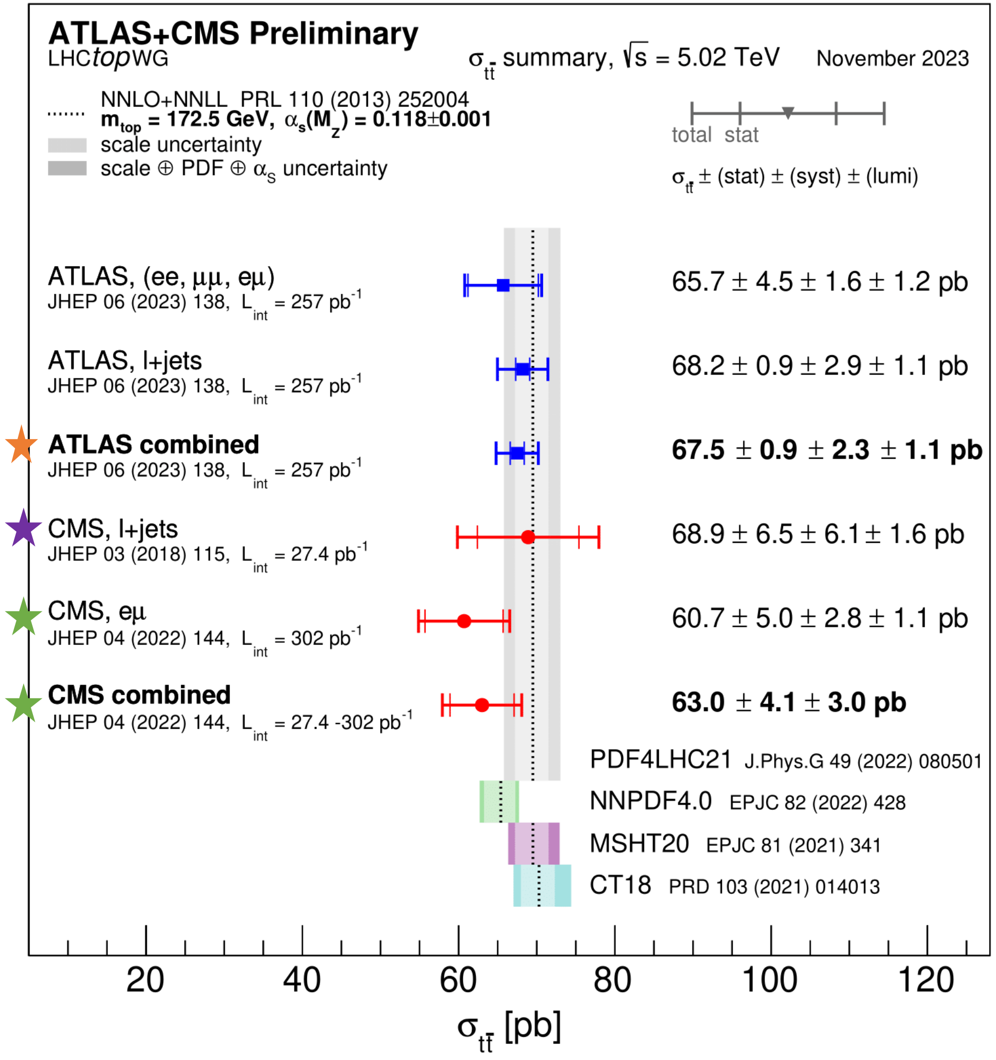
Goal: measure the $t\bar{t}$ **cross section at 5.02 TeV** in the semileptonic final state with the 2017 data 302 pb^{-1} .

➢ **Previous measurements** overview:

- JHEP 03 (2018) 115 : 27 pb^{-1} (2015 data). ★ Statistically dominated. Total uncertainty: 12%.
- JHEP 04 (2022) 144 : 302 pb^{-1}. Uncertainty still dominated by statistics. **Combined with ℓ+jets from 2015**. Total uncertainty: 8%. ★
- JHEP 06 (2023) 138 (ATLAS): Combination **dilepton+single lepton** using the 2017 dataset. Uncertainty: 4%. ★

➢ This analysis combines ℓ+jets with dilepton ★





Event Selection

- **Exactly 1 lepton (electron or muon)** (p_T > 20 GeV, $|\eta|$ < 2.4). Veto on sub-leading lepton of opposite flavour, p_T > 10 GeV.

- **At least 3 jets** (p_T > 25 GeV, $|\eta|$ < 2.4).

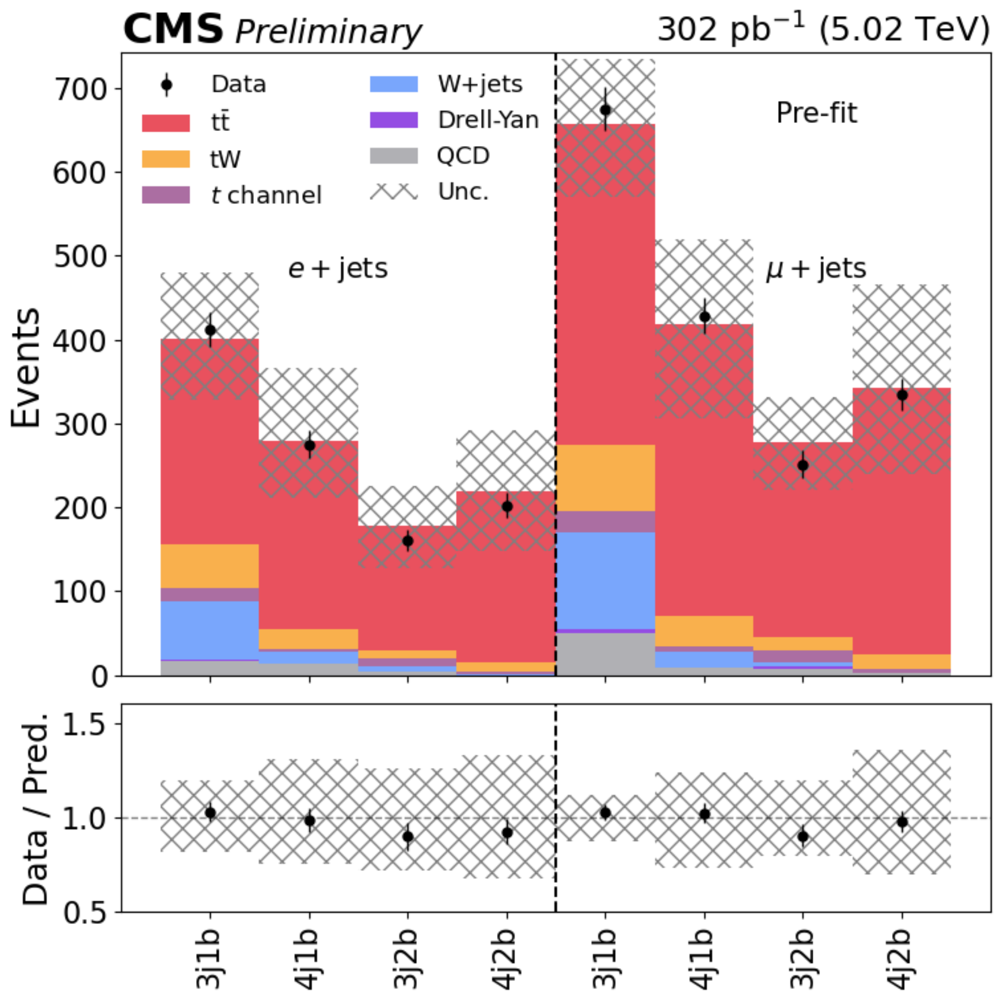
- **MET > 30 GeV.**

- Events are further categorized into **8 categories** depending on the **number of jets and b-tagged jets, and the lepton flavour** (electron or muon). Among those:

  - All are signal-dominated

  - $\ell + 3j \geq 2b$ and $\ell + 4j \geq 2b$ are purest in signal (89% of total MC)

  - $\ell + 3j1b$ provide the greatest contribution from tW and W+jets backgrounds (12% and 18% of total MC)



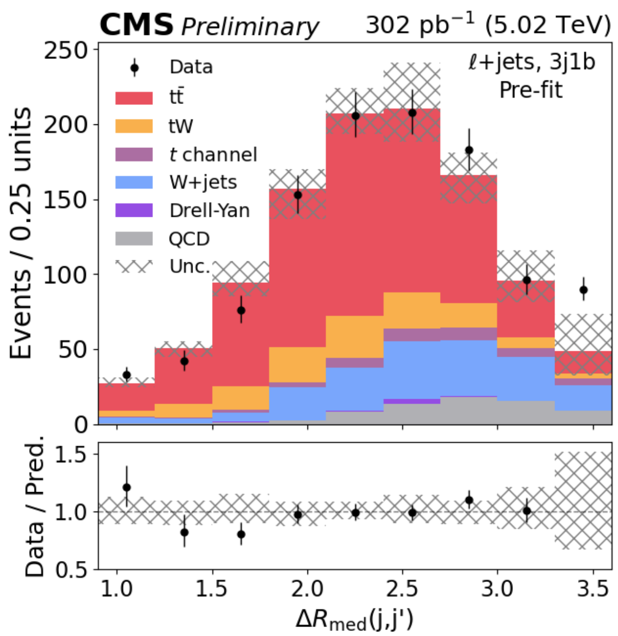
➢ **4 main backgrounds:** **Single top** (**tW + t-channel**), **W+jets**, **QCD multijets** (cut in **MET > 30GeV** to suppress it, estimated from data) and **Drell-Yan.**

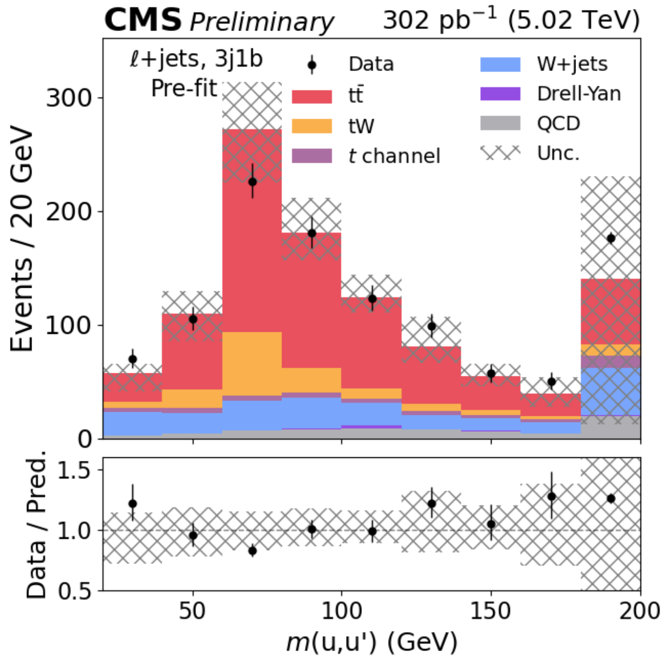
Analysis strategy

- Different observables were tested: m_T , m(j,j'), ΔR(j, j'), m(b,ℓ)…
- Finally, **median(ΔR(j, j'))** shape is used in the fits in every region expect the **3j1b category**, where an **MVA** is trained to further separate $t\bar{t}$ from W+jets.

ANALYSIS STRATEGY

- Different observables were tested: m_T , m(j,j'), ΔR(j, j'), m(b,ℓ)…
- Finally, **median(ΔR(j, j'))** shape is used in the fits in every region expect the **3j1b category**, where an **MVA** is trained to further separate $t\bar{t}$ from W+jets.
- **MVA details:**
  - Model: random forest trained with Sklearn. 500 trees with max depth 6.
  - Signal: $t\bar{t}$ sample. Background: W+jets sample.
  - Division of samples: 70% for train and 30% for test
  - 8 input variables: median ΔR(j, j'), m(u,u'), ΔR(u,u'), min m(j,j'), m(b,ℓ), H_T, ΔR(b,ℓ), $j_0 p_t$.





UNCERTAINTIES

- **Experimental**
  - Lepton efficiencies
  - Trigger efficiencies
  - B-tagging: light (udsg) and heavy (bc).
  - L1 Prefiring
  - JEC and JER (13 sources)
  - Unclustered energy.
  - Stat. unc. from limited size of the MC samples

Dedicated samples

- **$t\bar{t}$ modeling**
  - ISR/FSR: vary PS scales by 2, 0.5 factors
  - Underlying event: vary CP5 tuning → Normalization
  - ME/PS matching: vary h_{damp} of Powheg
  - ME scales: μ_F and μ_R scales by factors of 0.5 and 2
  - PDFs and α_S: 100+2 sources

ΔR/MVA shape

Nj/Nb shape

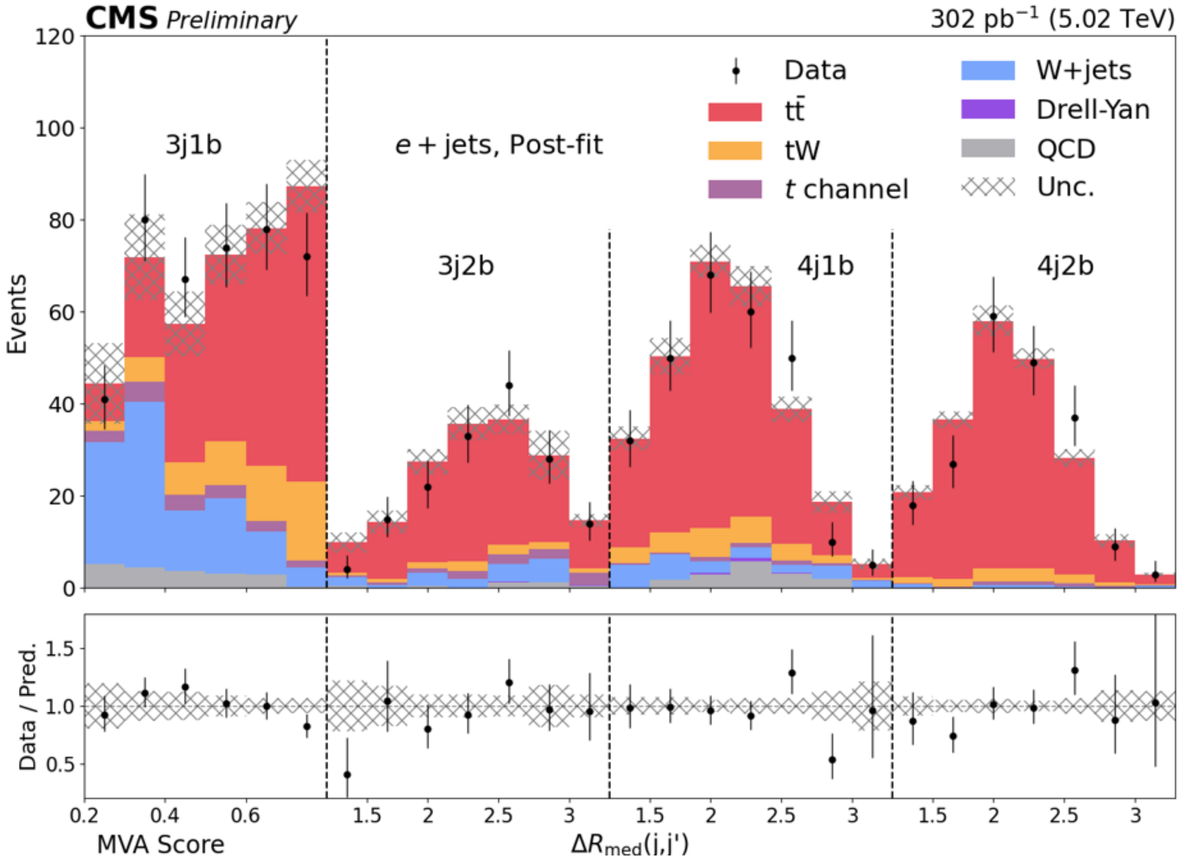
- **Normalization**
  - Background normalization -> QCD: stat+30% norm, DY: 30%, W+Jets: 20%, tW: 5.6%, t channel: 10%
  - Luminosity: 1.9%

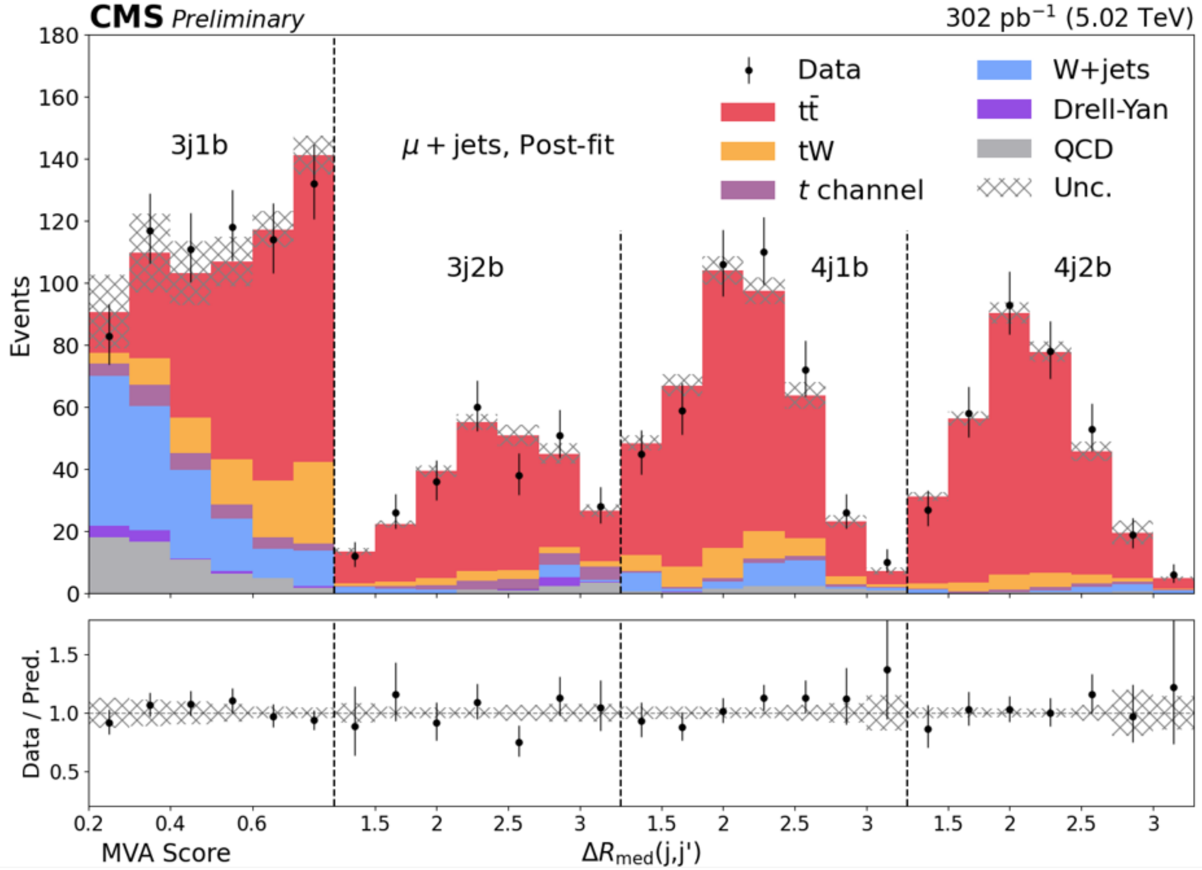
CROSS SECTION MEASUREMENT

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

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

- A maximum-likelihood fit is done simultaneously to the distributions.



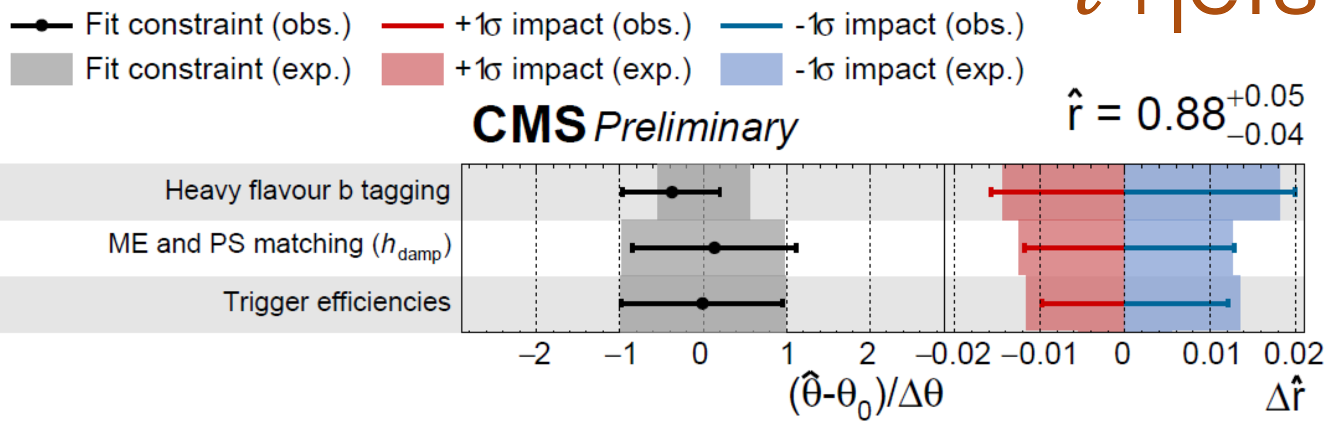


Postfit distributions

Observed Results

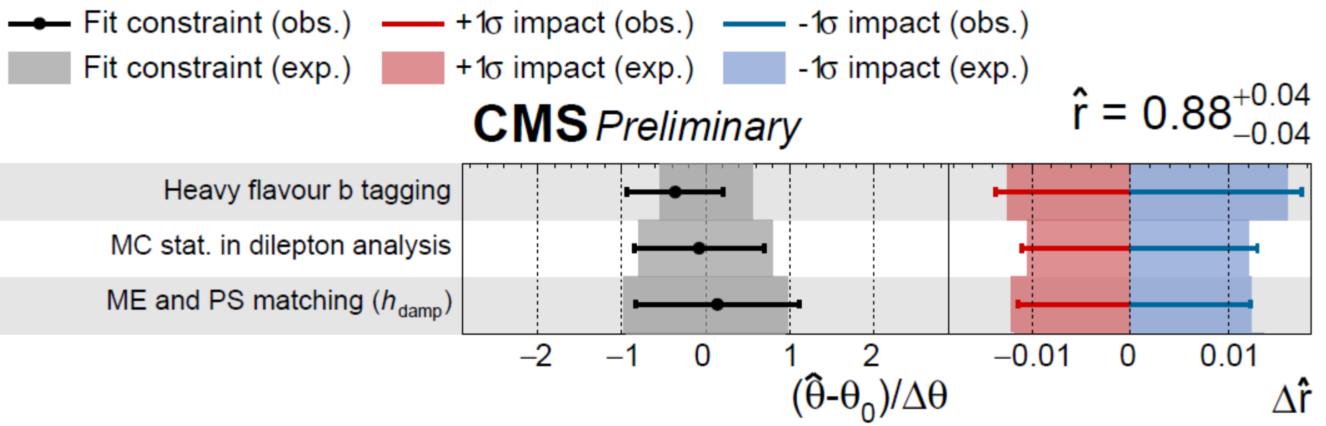
SM prediction: $\sigma^{SM}_{t\bar{t}} = 69.5^{+2.0}_{-2.3}\,(scales) \pm 2.9\,(PDFs + \alpha_S)\,pb$ LHCTopWG recomm.

ℓ+jets result



$\sigma_{t\bar{t}} = 61.4 \pm 1.6\,(stat)^{+2.7}_{-2.6}(syst) \pm 1.2\,(lumi)\,pb$

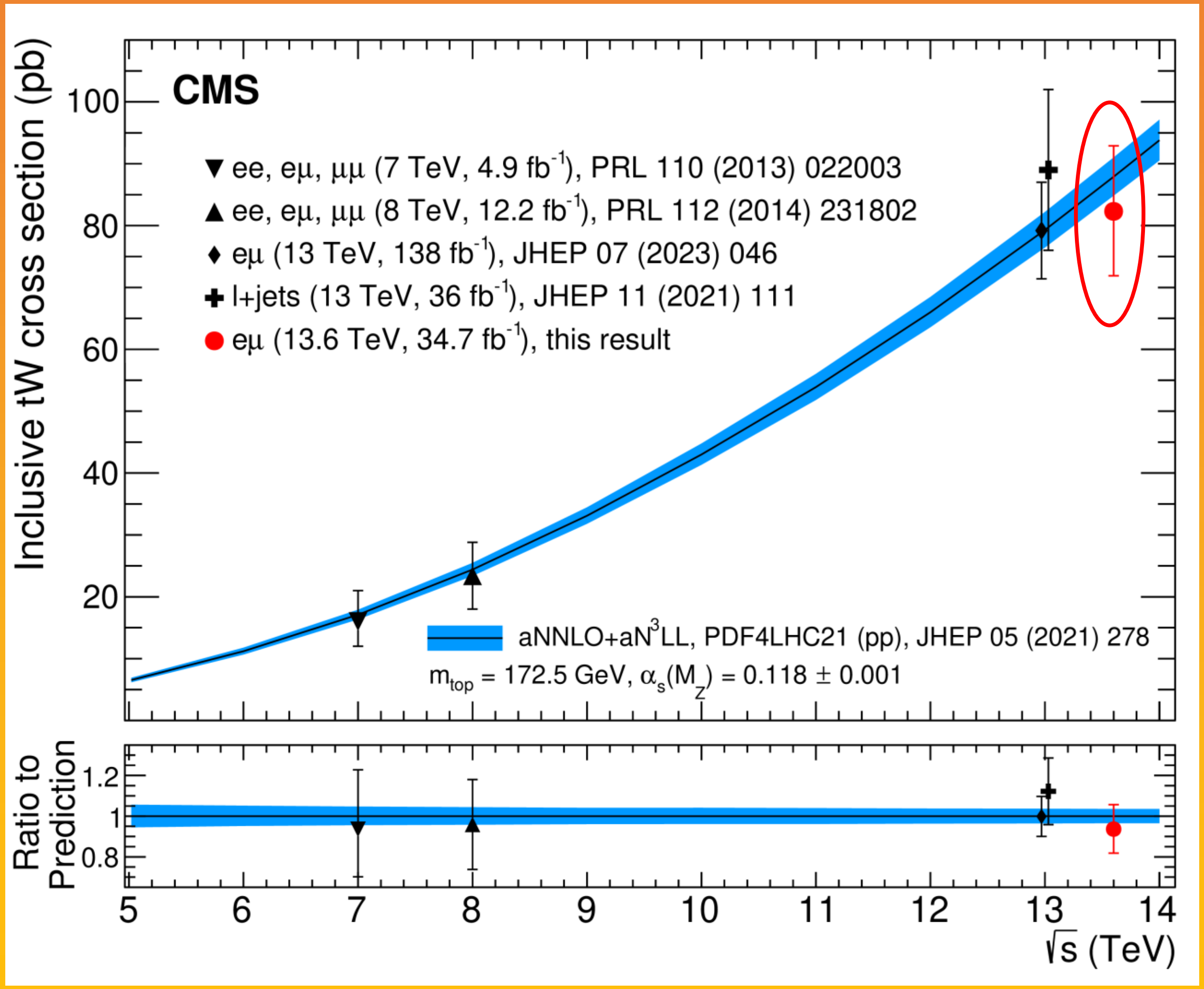
Comb. with dilep result



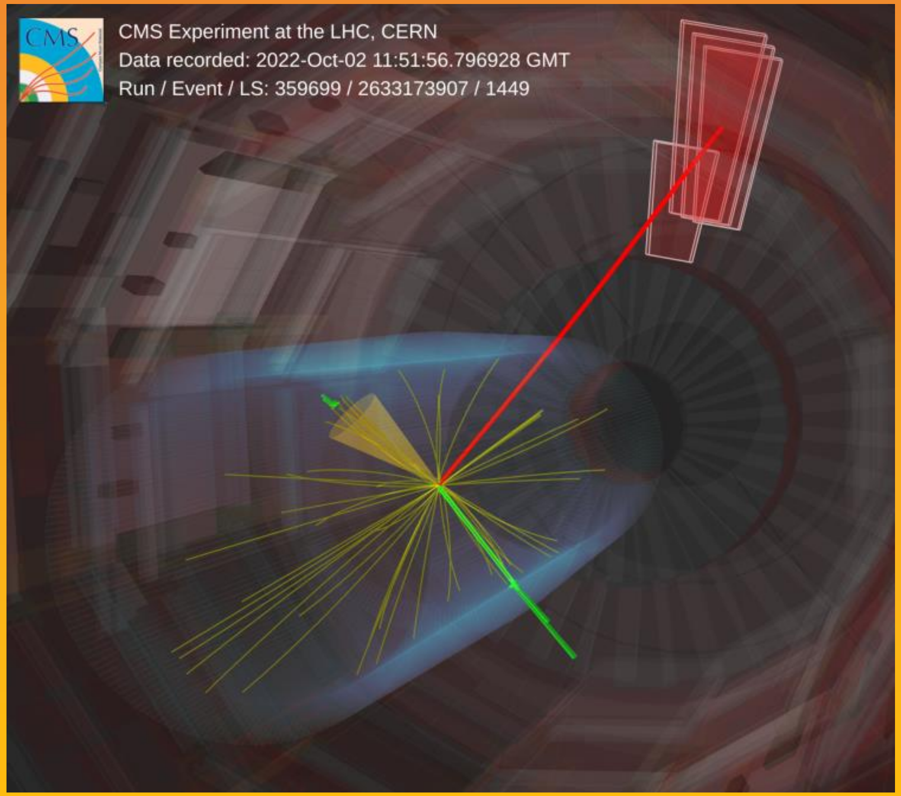
$\sigma_{t\bar{t}} = 61.2^{+1.6}_{-1.5}(stat)^{+2.6}_{-2.3}(syst) \pm 1.2\,(lumi)\,pb$

5.5% unc -> 5.1% unc

tW @ 13.6 TeV



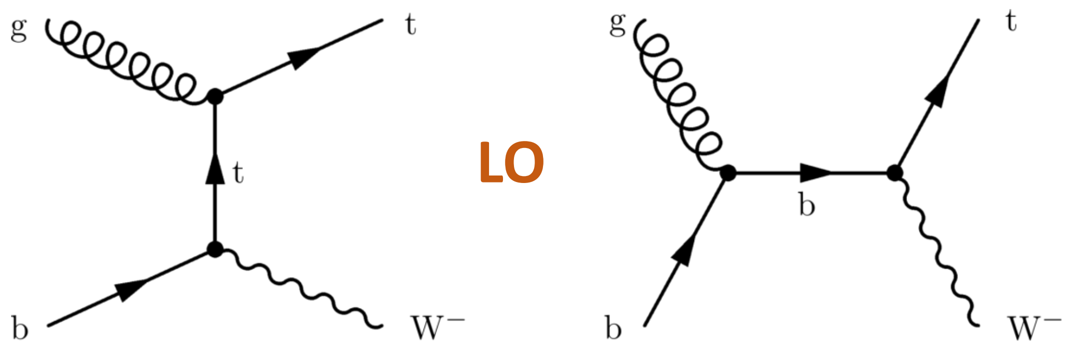
CMS
Inclusive tW cross section (pb)
▼ ee, eμ, μμ (7 TeV, 4.9 fb^{-1}), PRL 110 (2013) 022003
▲ ee, eμ, μμ (8 TeV, 12.2 fb^{-1}), PRL 112 (2014) 231802
♦ eμ (13 TeV, 138 fb^{-1}), JHEP 07 (2023) 046
✚ l+jets (13 TeV, 36 fb^{-1}), JHEP 11 (2021) 111
● eμ (13.6 TeV, 34.7 fb^{-1}), this result
aNNLO+aN^{3}LL, PDF4LHC21 (pp), JHEP 05 (2021) 278
m_{top} = 172.5 GeV, $\alpha_s(M_Z)$ = 0.118 ± 0.001
Ratio to Prediction
$\sqrt{s}$ (TeV)



CMS Experiment at the LHC, CERN
Data recorded: 2022-Oct-02 11:51:56.796928 GMT
Run / Event / LS: 359699 / 2633173907 / 1449

MOTIVATION

Goal: perform the first **inclusive and differential** cross section measurements **at 13.6 TeV** of the tW process using **Run 3** data (2022 data 34.7 fb^{-1}).

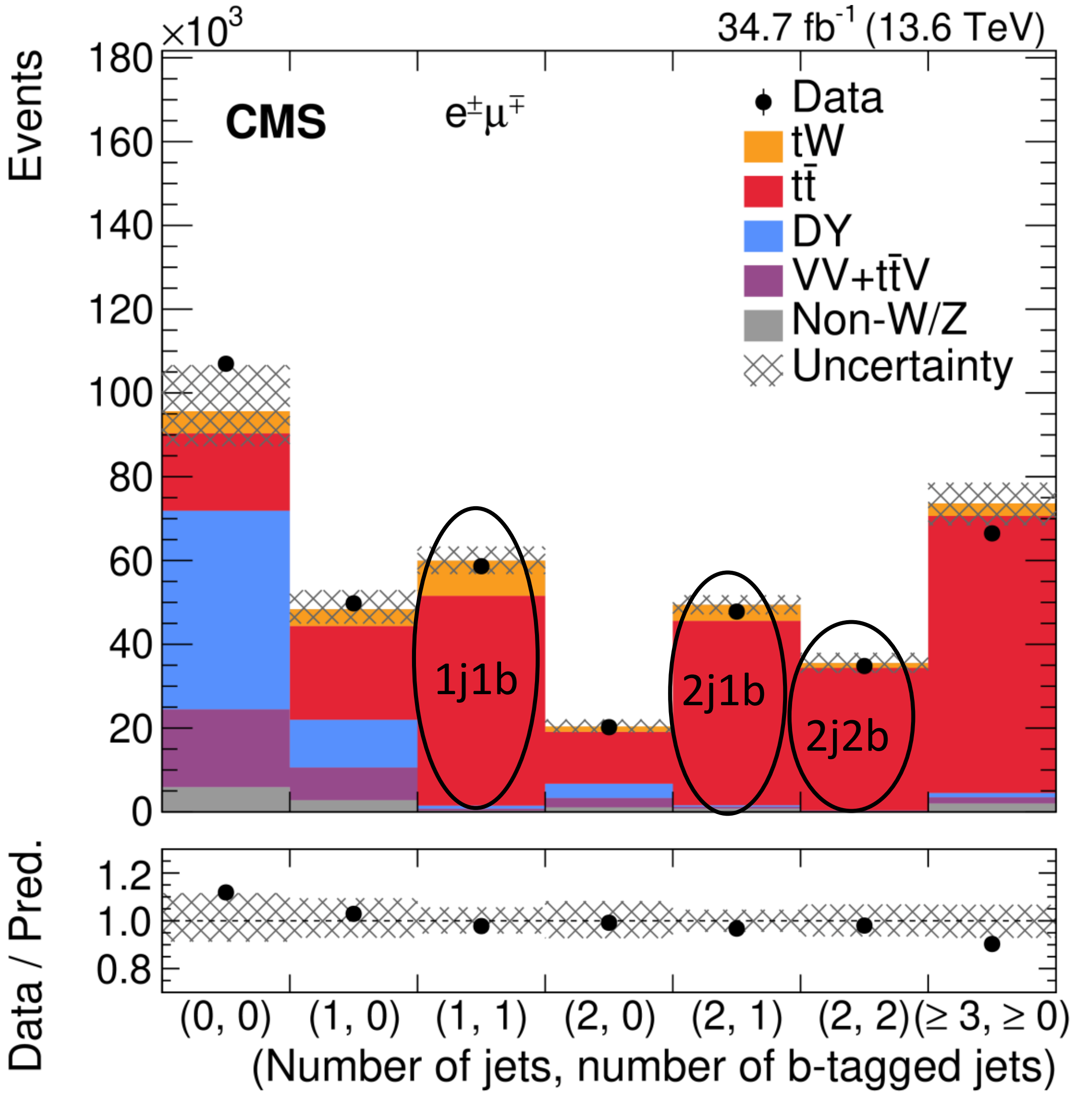


- **Other measurements** overview:
  - JHEP 07 (2023) 046: Inclusive and differential cross section measurements of tW using full Run 2.
  - CMS-PAS-TOP-19-003: Differential cross section measurements of tW using 2016 data.
  - JHEP 10 (2018) 117: Inclusive cross section measurement of tW using 2016 data
  - ArXiv 2407.15594: Inclusive cross section measurement of tW using full Run 2 (ATLAS).

- **Main challenge:** tW interferes with $t\bar{t}$ at NLO in QCD, and largely dominates the signal contribution. **Diagram Removal** (DR, for the nominal sample) and Diagram Substraction (DS, for differential measurements comparisons) schemes used to avoid double counting of diagrams.

Event Selection

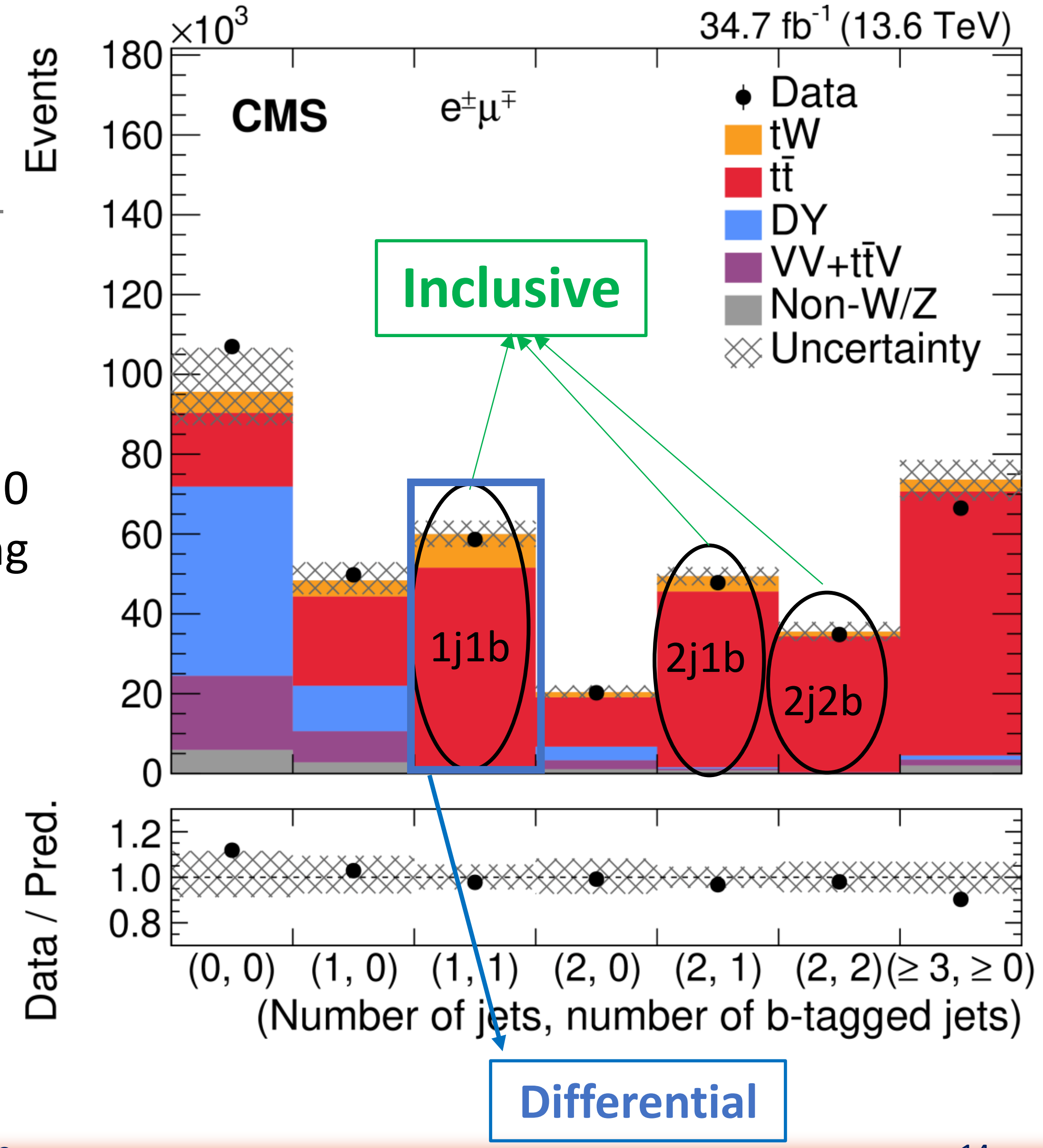
- **At least 2 leptons opposite charge and flavour ($e^{\pm}\mu^{\mp}$)** (p_T > 20 GeV, |η| < 2.4). Leading lepton p_T > 25 GeV.
- **Jets** (p_T > 30 GeV, |η| < 2.4).
- $m(\ell_1, \ell_2)$ **> 20 GeV.**
- **Categories** depending on the **number of jets and b-tagged jets.** Among those, used are **1j1b, 2j1b** (SRs) and **2j2b** ($t\bar{t}$ CR)



Analysis Strategy

- **Inclusive:** ML fit to 3 distributions:
  - **1j1b:** Random Forest MVA discriminating tW vs $t\bar{t}$ vs DY
  - **2j1b:** Random Forest MVA discriminating tW vs $t\bar{t}$ vs $Non-W/Z$ ($t\bar{t}$ semileptonic)
  - **2j2b:** subleading jet pT

- **Differential:** **1j1b** region, **veto** on low energy jets (pT< 30 GeV), signal extraction via **bkg substraction**, unfolding using **Tunfold.** Study of:
  - p_T of leading lepton
  - p_T of jet
  - $\Delta\phi(e,\mu)$
  - $p_z(e,\mu,jet)$
  - $m(e,\mu,jet)$
  - $m_T(e,\mu,jet,p_T^{miss})$

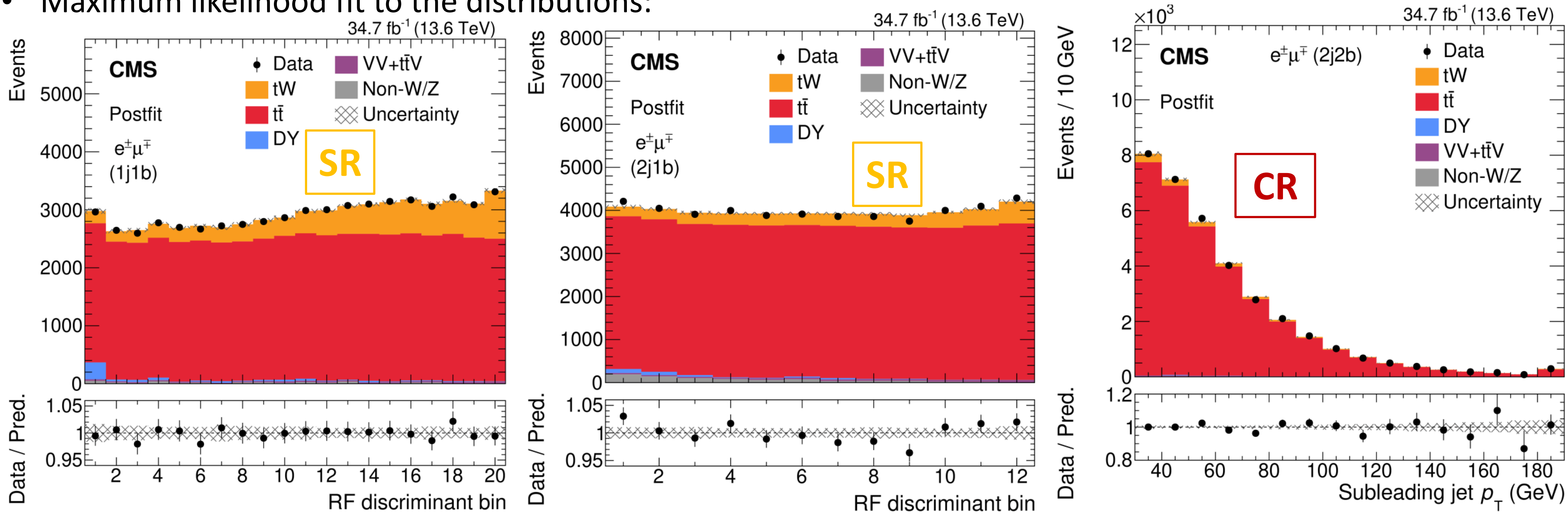


Inclusive Measurement

- For each RF, 8 kinematic observables are chosen in two independent trainings according to:
  - Discriminating power
  - Data/MC agreement (GoF test with p-value>5%)

- The most discriminating (1j1b) are: $p_T(loose\ j_0), p_T(\ell_0), p_T\left(e^{\pm}, \mu^{\mp}, j\right), m(e^{\pm}, \mu^{\mp})$.

- Maximum likelihood fit to the distributions:



UNCERTAINTIES I

➢ **Experimental** (shape)

- Lepton efficiencies
- Trigger efficiencies
- Electron scale and smearing: e momenta varied from e scale and smearing corrections
- B-tagging and mistagging
- JEC and JER: 20 groups of sources
- Unclustered energy: from calorimeters, into the momentum resolution of PF candidates
- Pile-up reweighting: ±4.6% variation in pp inelastic cross section

➢ **Normalization**

- Background normalization -> $t\bar{t}$: 3.5%, $VV + t\bar{t}V$: 15%, DY: 10%, Non-*W/Z* *(W+jets, $t\bar{t}$ semileptonic)*: 15%
- Luminosity: 1.4%

UNCERTAINTIES II

- **Modeling** (shape)
  - PDFs and α_S: 100+2 sources. 2 nuisances
  - Underlying Event: vary CP5 tuning. Dedicated samples
  - Color Reconnection: 3 models, nuisance per model
  - m_{top}: ±3 GeV varied samples, extrapolated to ±0.33 GeV
  - FSR: vary PS scales by 2, 0.5 factors

  → Correlated tW & $t\bar{t}$

  - ISR: vary PS scales by 2, 0.5 factors
  - ME scales: μ_F and μ_R scales by factors of 0.5 and 2

  → Uncorrelated tW & $t\bar{t}$

  - Top quark pT modeling: difference reweighted & unweighted
  - ME/PS matching: vary h_{damp} of Powheg. Dedicated samples

  → Only $t\bar{t}$

  - DS: Dedicated samples → Only tW

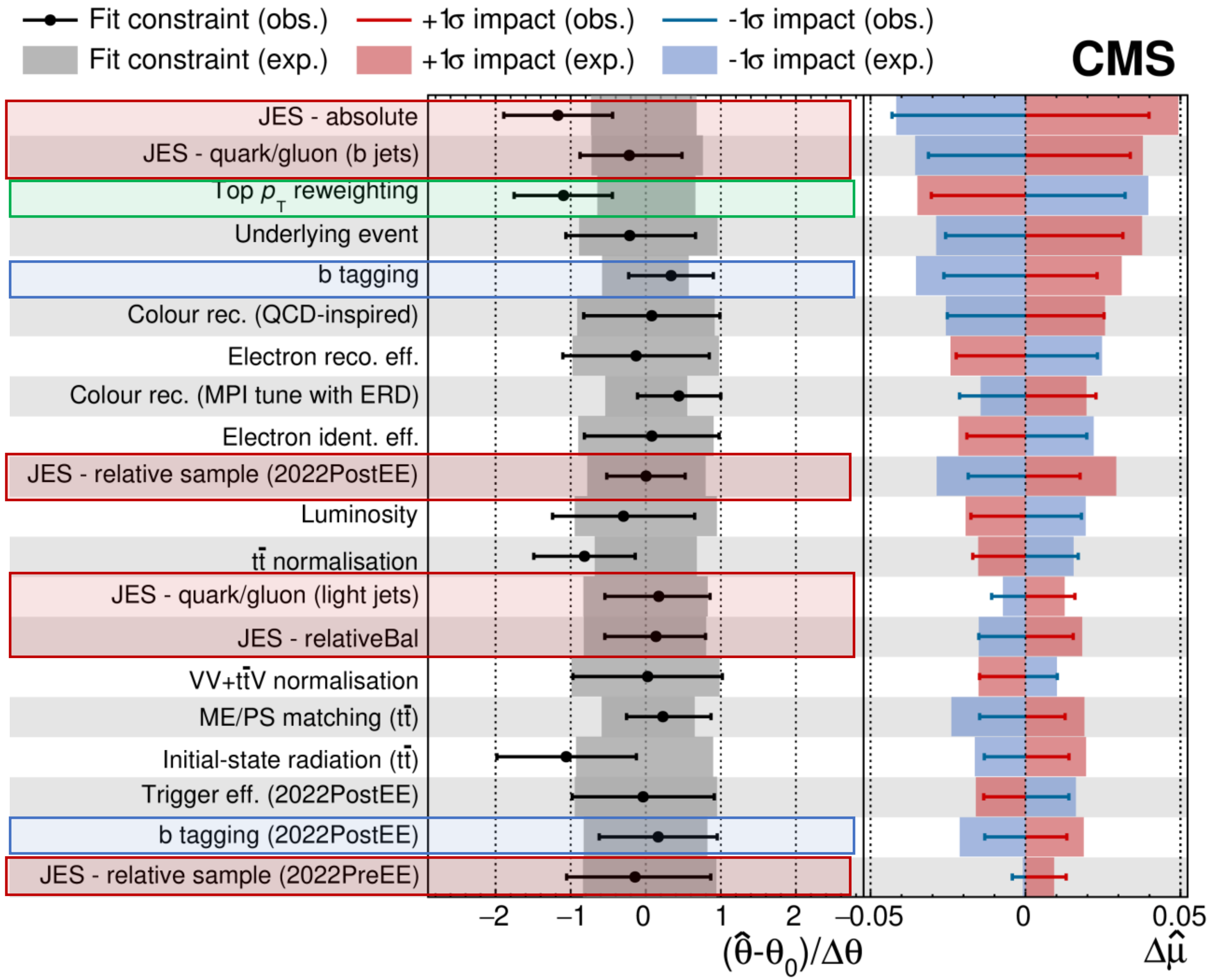
INCLUSIVE MEASUREMENT

$\sigma_{tW}^{SM} = 87.9^{+2.0}_{-1.9}(scale) \pm 2.4\ (PDFs + \alpha_S)\ pb$

aN^{3}LO, LHCTopWG Recomm.

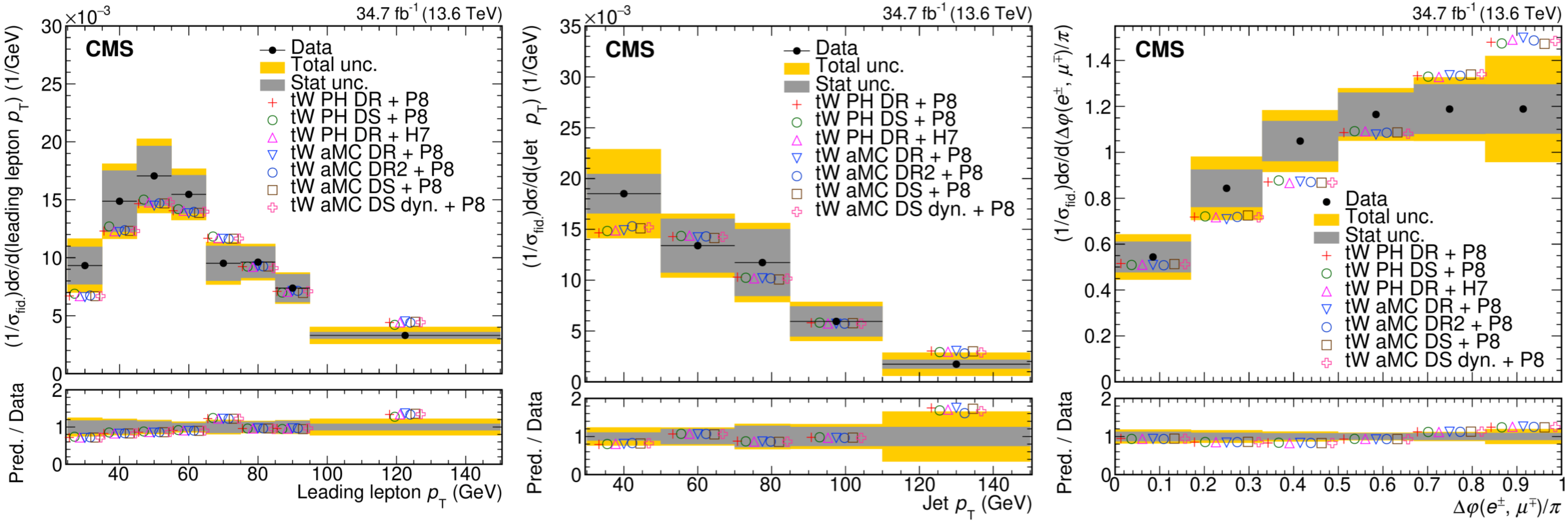
$\sigma_{tW}^{obs} = 82.3 \pm 2.1\ (stat)^{+9.9}_{-9.7}(syst) \pm 3.3\ (lumi)\ pb$

- Measurement dominated by **systematic** uncertainties.
- Main difference between tW and $t\bar{t}$ is the additional b jet in $t\bar{t}$, thus:
  - The leading uncertainties are the ones associated with energy of jets and b tagging.
  - In addition, Top pT reweighting. Accounting for mismodelling of pT spectrum in PowHeg sample. More in Olaf's talk.



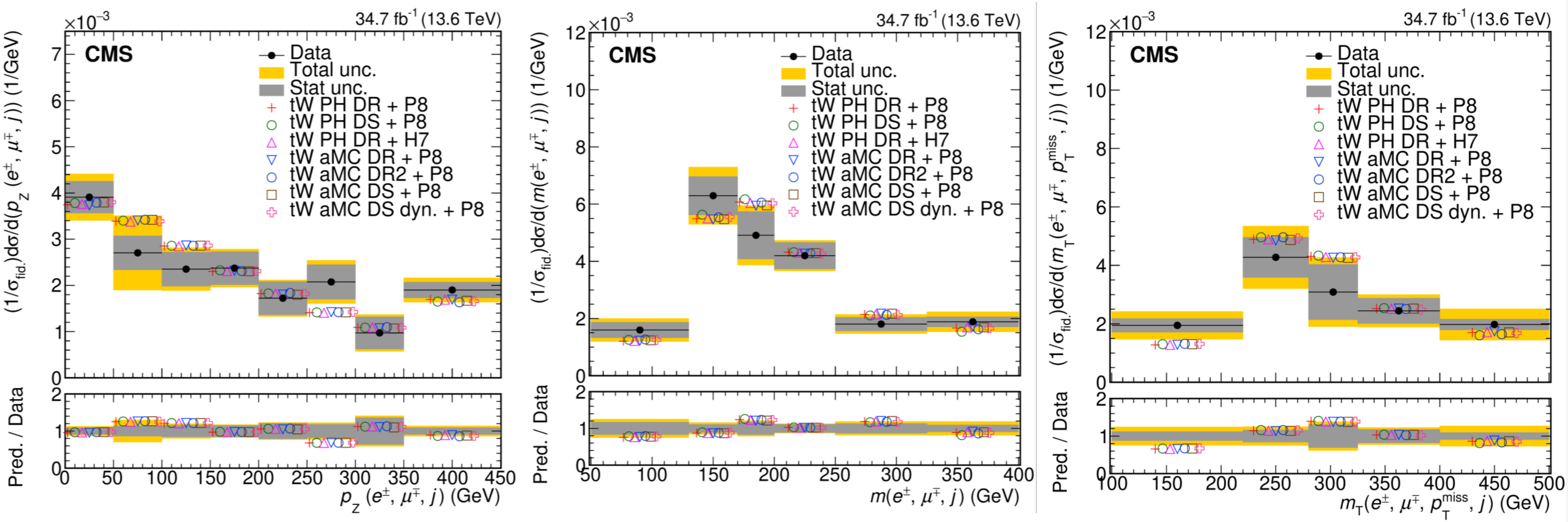
Differential Measurement

- Results normalized to the fiducial cross section and bin width
- Good agreement between measurements and predictions from different event generators:
  - POWHEG vs MADGRAPH5_aMC@NLO
  - PYTHIA8 vs HERWIG7
- Different schemes to treat the interference between tW and $t\bar{t}$



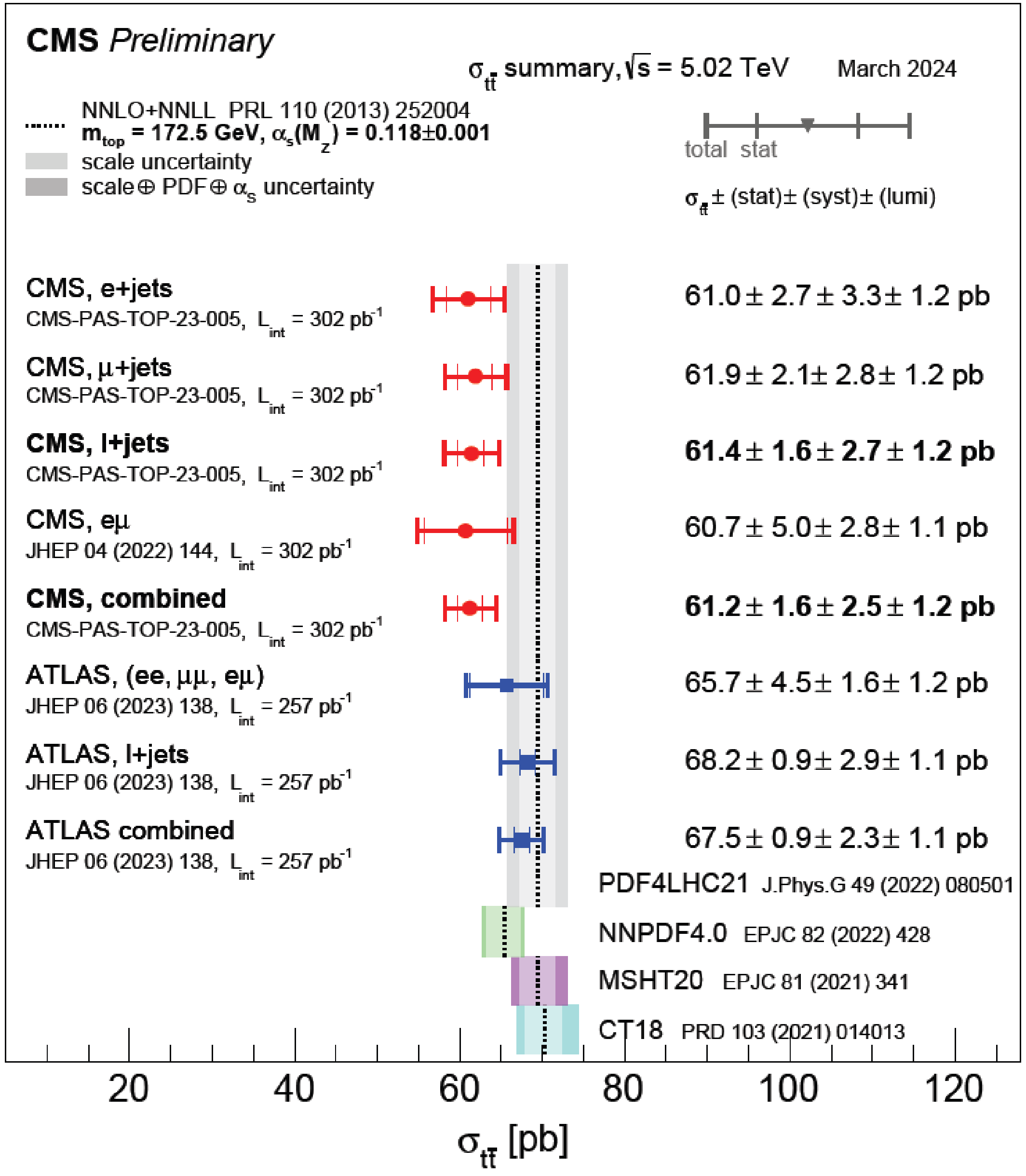
DIFFERENTIAL MEASUREMENT

- A χ^2 GoF test is performed for the differential distributions to compare observed result with different MC generators.
- Performed using the full covariance matrix as well as statistical uncertainties of the predictions.
- Compute p-values of the test, being almost all above 0.9-0.95.



SUMMARY

- Most precise CMS result for the $t\bar{t}$ inclusive cross section at 5.02 TeV! Means great improvement with respect to previous results:
  - previous ℓ+jets CMS result (JHEP 03 (2018) 115): **13% → 5.5%.**
  - previous dilepton & ℓ+jets CMS result (JHEP 04 (2022) 144): **8.4% → 5.1%.**
- Result consistent with SM prediction: →



- First inclusive and differential cross section measurements of the tW process at 13.6 TeV at LHC.
- Measured inclusive cross section of $\sigma_{tW}^{obs} = 82.3 \pm 2.1\ (stat)^{+9.9}_{-9.7}(syst) \pm 3.3\ (lumi)\ pb$ in agreement with SM prediction of $\sigma_{tW}^{SM} = 87.9^{+2.0}_{-1.9}(scale) \pm 2.4\ (PDFs + \alpha_S)\ pb$.
- Differential measurements also compatible with SM expectations with different generators and schemes.

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Thanks For Your Attention!

Any question?

Back up

SAMPLES/CORRECTIONS

Same as in TOP-20-004

- **DATA:**
  - **2017** data, for an integrated luminosity of **302 pb^{-1}**
  - Usage of **single-lepton** triggers
  - Mean number of pp interactions per bunch crossing ≈ **2 -> low PU.**

- **MC:**

Process	Generator + Parton Shower	Cross section, σ_{norm} (pb)	Order of σ_{norm} approximation
$t\bar{t}$	POWHEG + PYTHIA 8	69.5	NNLO+NNLL [28, 29]
t channel	POWHEG + PYTHIA 8	30.3	Approximate NNLO [37]
tW	POWHEG + PYTHIA 8	6.54	Approximate NNLO [38]
W+jets	MADGRAPH5_aMC@NLO + PYTHIA 8	21159	NNLO[QCD]+NLO[EW] [39]
Drell-Yan	MADGRAPH5_aMC@NLO + PYTHIA 8	3647	NNLO[QCD]+NLO[EW] [39]

- **Corrections:**

- **Lepton** (e and μ), **Trigger, B-tag SFs + JECs.**

QCD ESTIMATION

1) Define a control region: “non-iso”

We invert the lepton MVA and the isolation requirements to obtain a region enriched in QCD events.

Estimation of QCD in the CR as: $N^{non\text{-}iso}(QCD) = N^{non\text{-}iso}(obs) - N^{non\text{-}iso}(MC)$

2) Calculate the extrapolation factor using low-MET events: MET < 20 GeV

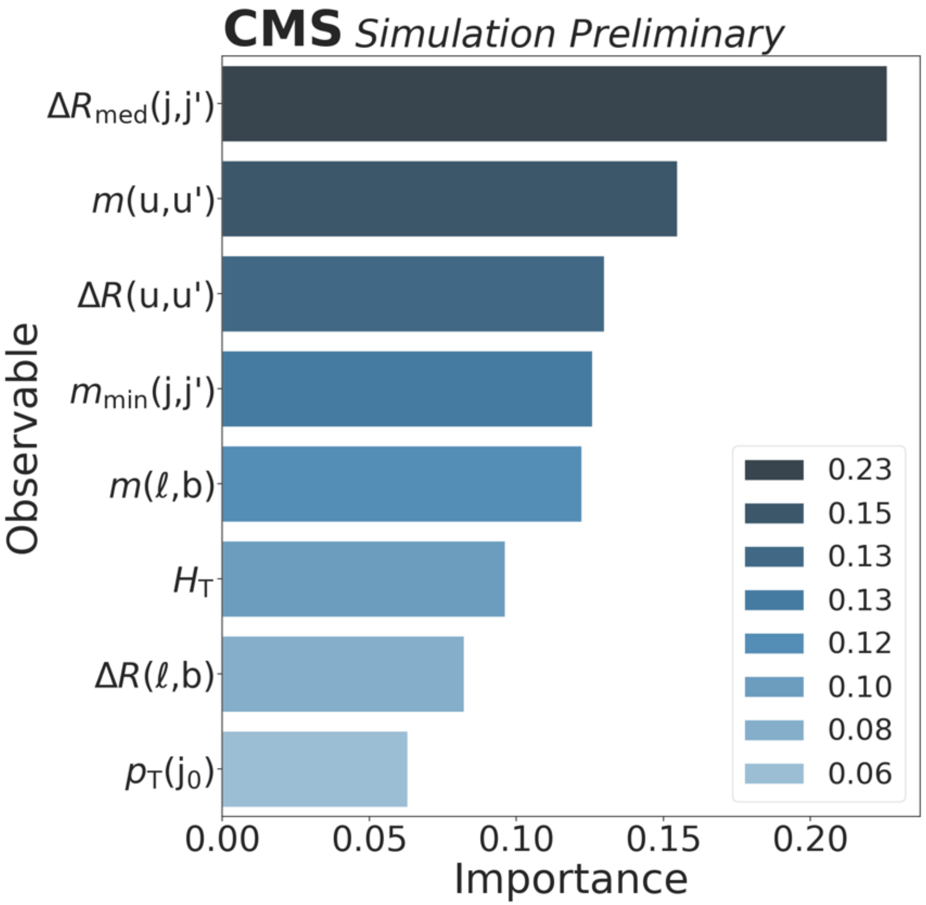
Assuming that the reconstruction of a QCD lepton does not depend on MET, we compute the extrapolation factor from the control region to our signal region using low-MET events.

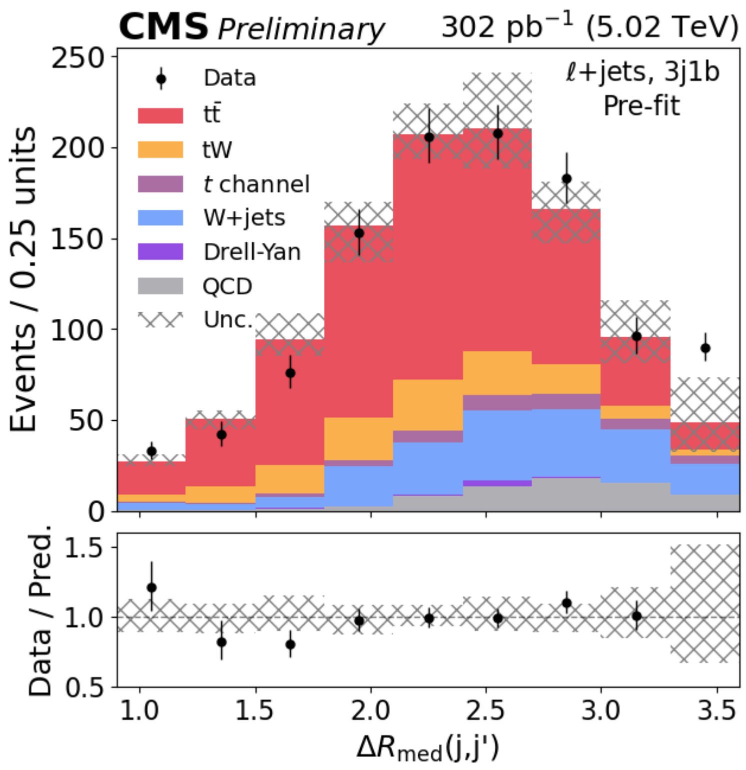
3) QCD estimation in the signal region:

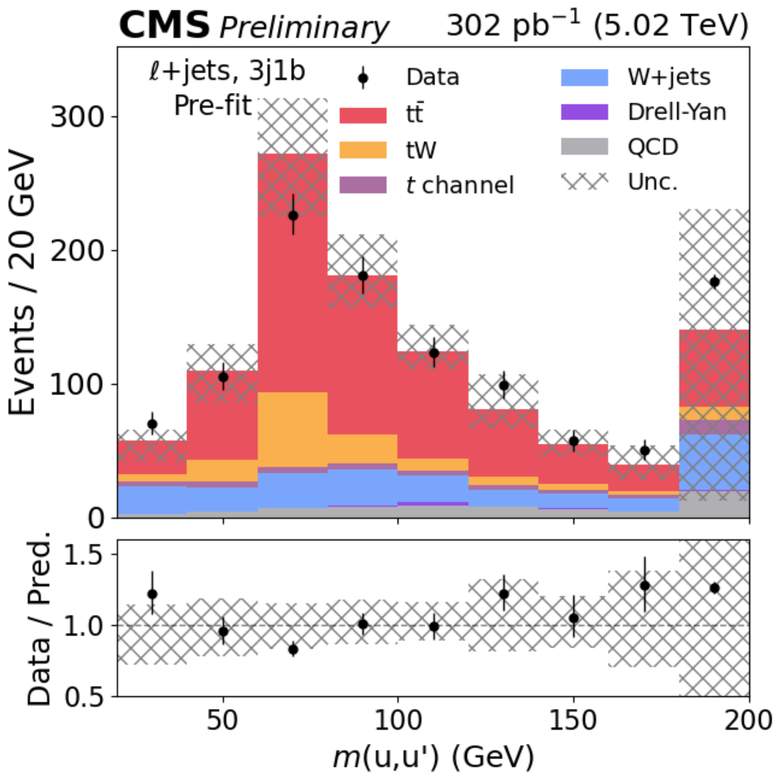
$$N^{SR}(QCD) = \left(N^{non-iso}(obs) - N^{non-iso}(MC)\right) \times \frac{N^{SR}_{\text{low } \not{E}_T}(obs) - N^{SR}_{\text{low } \not{E}_T}(MC)}{N^{non-iso}_{\text{low } \not{E}_T}(obs) - N^{non-iso}_{\text{low } \not{E}_T}(MC)}$$

ANALYSIS STRATEGY: MVA IN 3J1B

- The most important variables:

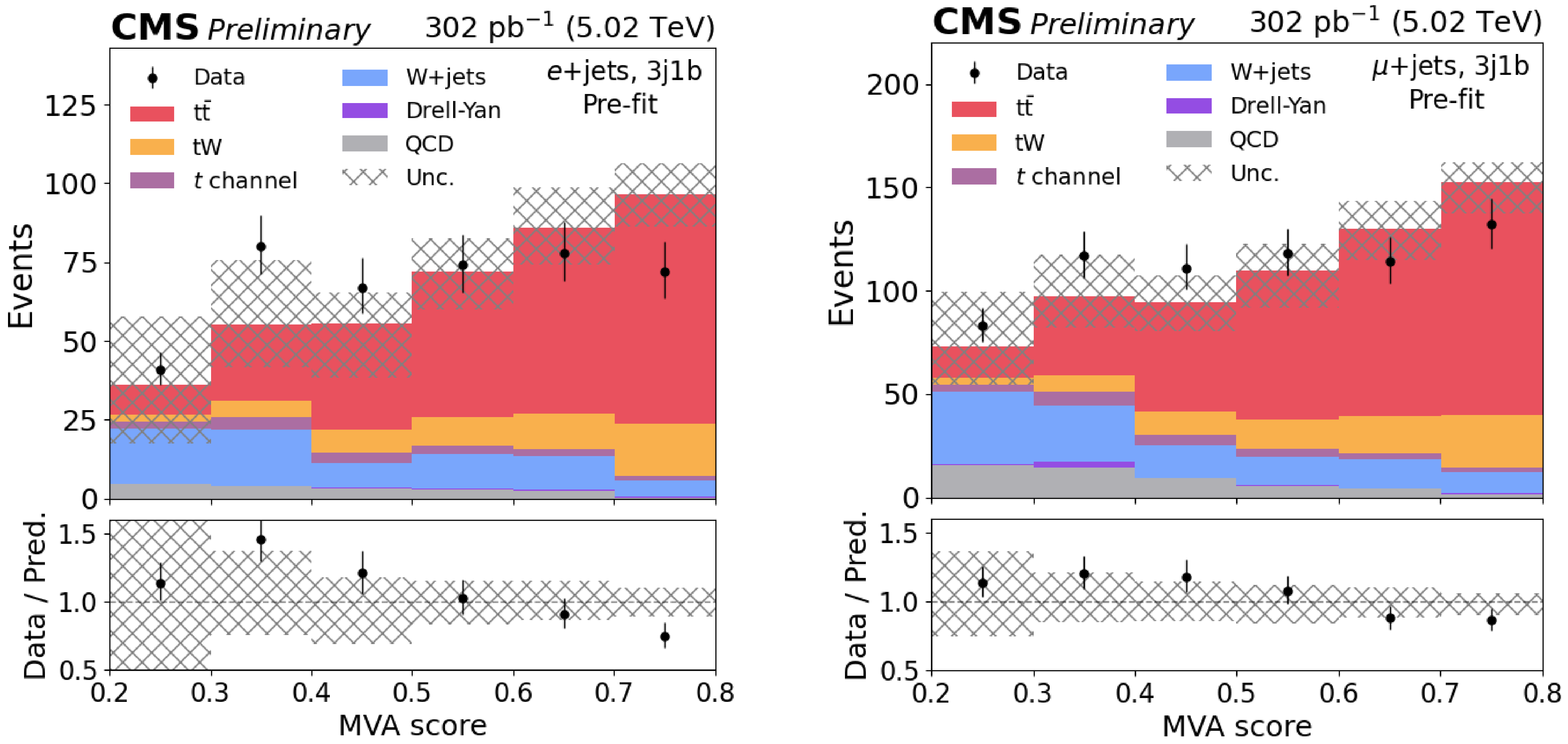






ANALYSIS STRATEGY: MVA IN 3J1B

➢ Obtaining the following discriminants:



Correlation scheme for final combination with dilepton result

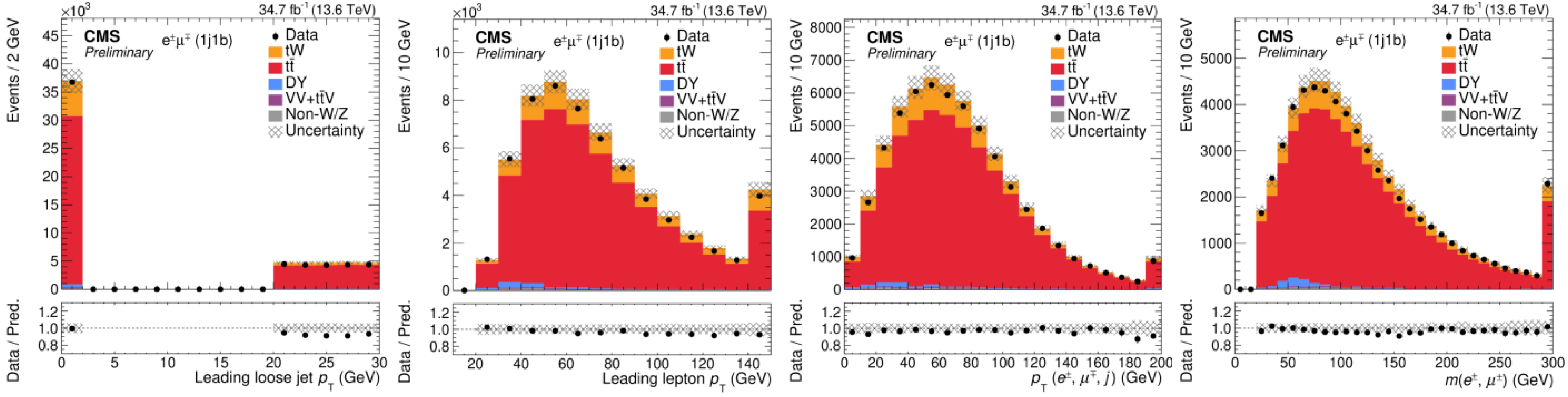
Source	Correlation with 2ℓ	
Electron efficiency	100%	
Muon efficiency	100%	
Trigger efficiency	100%	
b-tagging	0%	not included in dilep
JES	0%	in dilep 1 source, in ℓ+jets splitted
JER	100%	
Unclustered energy	0%	(not included in dilep)
L1 prefiring	100%	
Final-state radiation	100%	
Initial-state radiation	100%	
μ_R, μ_F scales	100%	
PDF$\oplus\alpha_S(m_Z)$	0%	in dilep 1 source, in ℓ+jets splitted
h_{damp}	100%	
Underlying event tune	100%	
tW	100%	
QCD	0%	not included in dilep
Drell–Yan	100%	
W+jets	100%	
t channel	0%	not included in dilep
Integrated luminosity	100%	

Summary of previous results

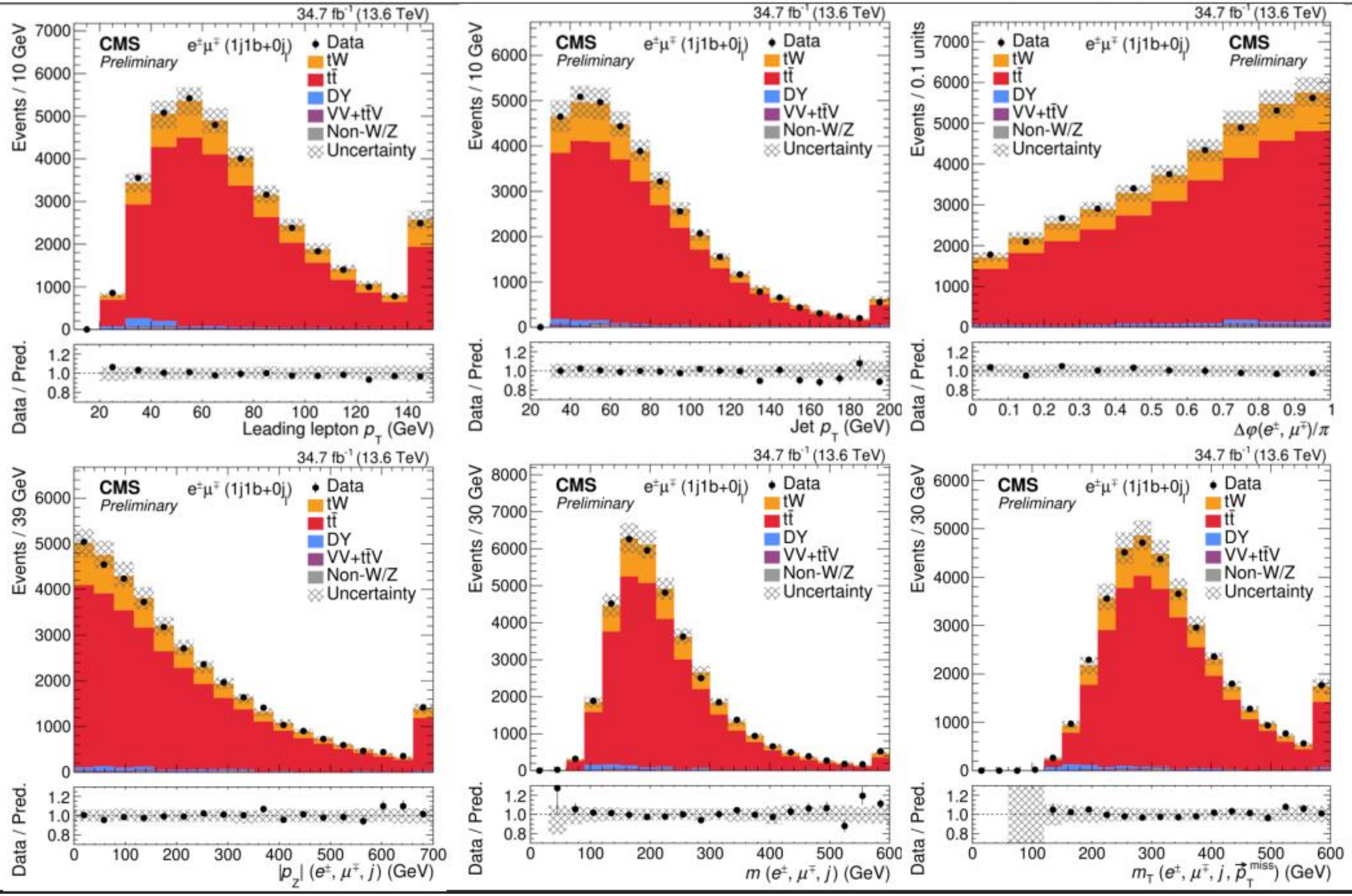
		Stat.	Syst.	Lumi	Total
Dilep 2015	CMS	24.7%	5.2%	2.6%	25%
Semilep 2015	CMS	9.4%	8.8%	2.3%	13.1%
Comb. dilep+semilep 2015	CMS	8.8%	8%	2.3%	12.1%
Semilep 2017	CMS	2.6%	4.4%	1.9%	5.5%
	ATLAS	1.3%	4.3%	1.6%	4.5%
Dilep 2017	CMS	8.2%	4.6%	1.9%	9.6%
	ATLAS	6.8%	2.5%	1.8%	7.5%
Comb. dilep 2017 + semilep 2015	CMS	6.5%	4.7%		8.4%
Comb. dilep + semilep 2017	CMS	2.4%	4.1%	1.9%	5.1%
	ATLAS	1.3%	3.4%	1.6%	3.9%

- The matrix element for the final state WWbb: $|\mathcal{M}_{WWb\bar{b}}|^2 = |\mathcal{M}_{\text{singly}}|^2 + |\mathcal{M}_{\text{doubly}}|^2 + 2Re\left(\mathcal{M}^*_{\text{singly}}\mathcal{M}_{\text{doubly}}\right)$
- Besides the nominal sample of tW generated with powheg-pythia8 with the **DR** method we consider (for the differential measurement comparisons):
  - Powheg DS-pythia8, Powheg DR-Herwig7, amcatnlo DR-pythia8, amcatnlo DR2-pythia8, amcatnlo DS-pythia8 and amcatnlo DS dyn.-pythia8.

- For the RF in the 1j1b region the **four most discriminating variables** are:



Differential measurements – data/MC comparison



Differential measurements – GOF test

- We perform a χ^2 GOF test for the differential distributions to compare the observed result with the different MC generators.
- Performed using the full covariance matrix as well as statistical uncertainties of the predictions.
- We tabulate the p-values of the test:

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
$\Delta\varphi(e^\pm, \mu^\mp)/\pi$	0.94	0.94	0.93
$p_z(e^\pm, \mu^\mp, j)$	0.96	0.96	0.96
$m_T(e^\pm, \mu^\mp, j, \vec{p}_T^{miss})$	0.78	0.75	0.79
$m(e^\pm, \mu^\mp, j)$	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
$\Delta\varphi(e^\pm, \mu^\mp)/\pi$	0.93	0.93	0.94	0.93
$p_z(e^\pm, \mu^\mp, j)$	0.96	0.96	0.96	0.96
$m_T(e^\pm, \mu^\mp, j, \vec{p}_T^{miss})$	0.80	0.77	0.80	0.79
$m(e^\pm, \mu^\mp, j)$	0.96	0.95	0.96	0.96