Universidad de Oviedo
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Interpreting the LHC Run 2 data and Beyond

Recent single top differential cross section measurements at CMS

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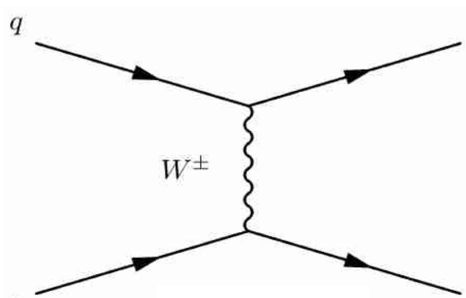
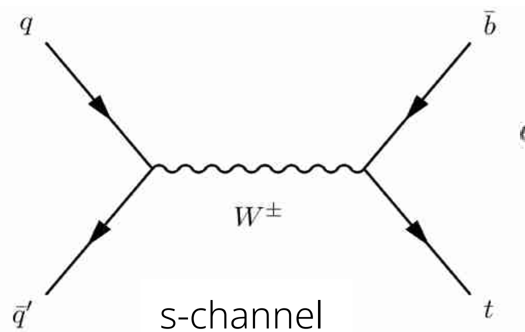
Top and single top physics

- The top quark is the most massive particle in the SM.
  - Highest Yukawa coupling to the Higgs boson.
  - Due to its large mass, decays almost always before hadronising.
- It has large interest at LHC physics due to:
  - Multiple links with BSM proposals (e.g. SUSY extensions such as stops).
  - Large presence of its production processes (above all pair production) due to their large cross section.

- Top quark processes are classified in pair production and **single top**:
  - Allow to probe and measure V_{tb}.



t-channel



s-channel

(13 TeV)

$$\sigma_{\text{s ch.}} = 10.32^{+0.29}_{-0.24}(\text{scale}) \pm 0.27(\text{PDF},\alpha_S)\,\text{pb}$$

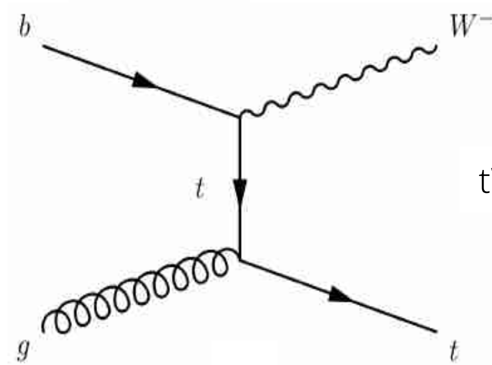
$$\sigma_{\text{t ch.}} = 217.0^{+6.6}_{-4.6}(\text{scale}) \pm 6.2(\text{PDF},\alpha_S)\,\text{pb}$$

(13 TeV)

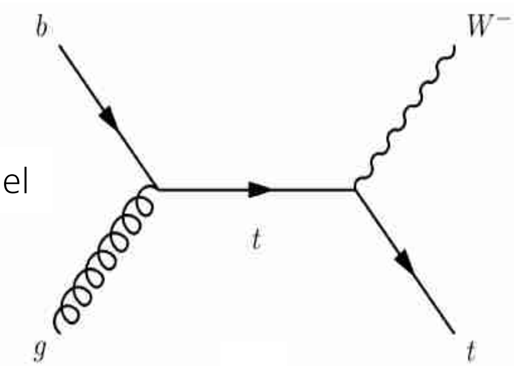
- M. Aliev et al., Comput.Phys.Commun.182:1034-1046,2011
- P. Kant et al., Comput.Phys.Commun. 191 (2015) 74-89
- N. Kidonakis, arXiv:1506.04072

(13 TeV)

$$\sigma_{tW} = 71.7 \pm 1.8(\text{scale}) \pm 3.4(\text{PDF},\alpha_S)\,\text{pb}$$



tW-channel



Previous (differential) measurements

- **7 TeV**
  - (ATLAS Collab.) *"Comprehensive measurements of* ***t-channel*** *single top-quark production cross sections at $\sqrt{s}$ = 7 TeV with the ATLAS detector". Phys. Rev. D. 90, 112006 (2014)*, arXiv:1406.7844.

- **8 TeV**
  - (CMS Collab.) *"Measurement of top quark polarisation in* ***t-channel*** *single top quark production". JHEP 04 (2016) 073*, arXiv:1511.02138.
  - (ATLAS Collab.) *"Fiducial, total and differential cross-section measurements of* ***t-channel*** *single top-quark production in pp collisions at 8 TeV using data collected by the ATLAS detector". Eur. Phys. J. C 77 (2017) 531*, arXiv:1702.02859.

- **13 TeV**
  - (ATLAS Collab.) *"Measurement of differential cross-sections of a single top quark produced* ***in association with a W boson*** *at $\sqrt{s}$ = 13 TeV with ATLAS". Eur. Phys. J. C 78 (2018) 186*, arXiv:1712.01602.

Last CMS measurement

- In the following slides: ***"Measurement of differential cross sections and charge ratios for t-channel single top quark production at 13 TeV"*** (CMS PAS TOP-17-023).

- **Data:** 36 fb^{-1} from 2016.
  - Trigger (summary): at least one isolated muon candidate p_T > 24 GeV and $|\eta| <$ 2.4 or one electron candidate p_T > 32 GeV and $|\eta| < 2.1$.

- **Simulation samples (t-chan., tW, ttbar, W+jets, DY):**
  - Generators: POWHEG v2 (t-ch., ttbar, tW), MG5_aMC@NLO (t-ch.,W+jets, DY).
  - Signal t-chan. samples are used for comparison with 4F & 5F variations.
  - Also used: PYTHIA v8.2 (PS), NNPDF3.0 (PDF), GEANT4 (detector sim.).

Object identification

- After the **Particle Flow** algorithm reconstructs and identifies the candidates from each event, other requirements are imposed over them (summary):

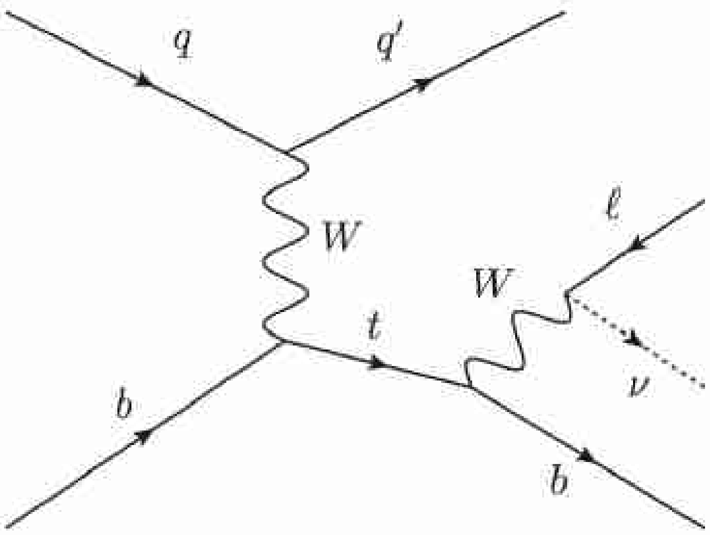
- **Muons**
  - $p_T > 26$ GeV.
  - $|\eta| < 2.4$.
  - Isolation.

- **Electrons**
  - $p_T > 35$ GeV.
  - $|\eta| < 1.479$.
  - Isolation.

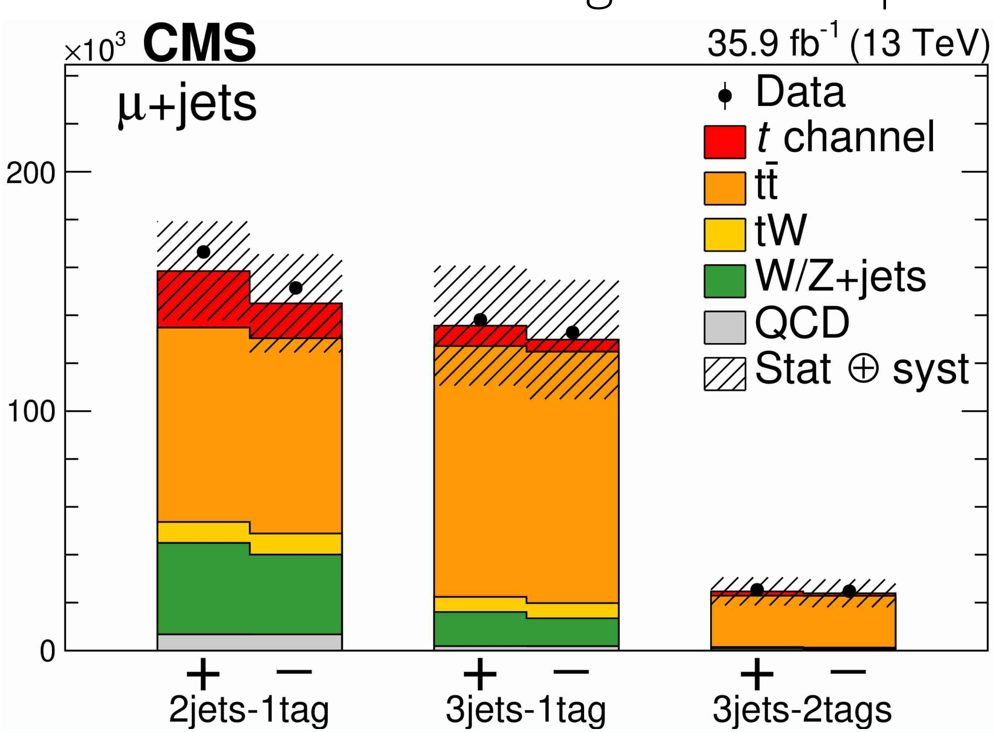
- **Jets**
  - $p_T > 40$ GeV (if $2.7 < |\eta| < 3.0$, $p_T > 50$ GeV).
  - $|\eta| < 4.7$.
  - Events are tagged as coming from a b quark using a MVA algorithm for those jets inside the acceptance of the CMS tracker ($|\eta| < 2.4$). Efficiency: ~50%. Misidentification rate: ~0.1%.

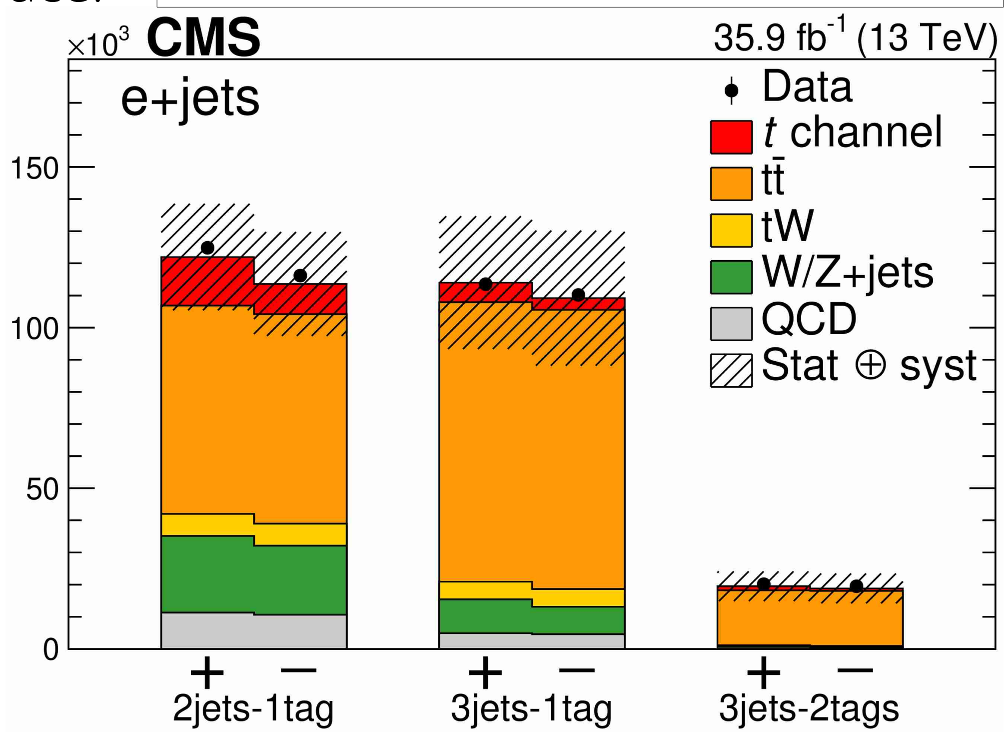
Event selection

- Events are chosen if they present:
  - a muon or an electron.
  - two or three jets.
  - no more muon (electron) candidates with $p_T >$ 10 (15) GeV and $|\eta| < 2.5$.
- Afterwards, the jet and the b-tagged jet multiplicity are used to define regions in the phase space:



- CMS-TOP-17-011, sub. to Phys. Lett. B, arXiv:1812.10514

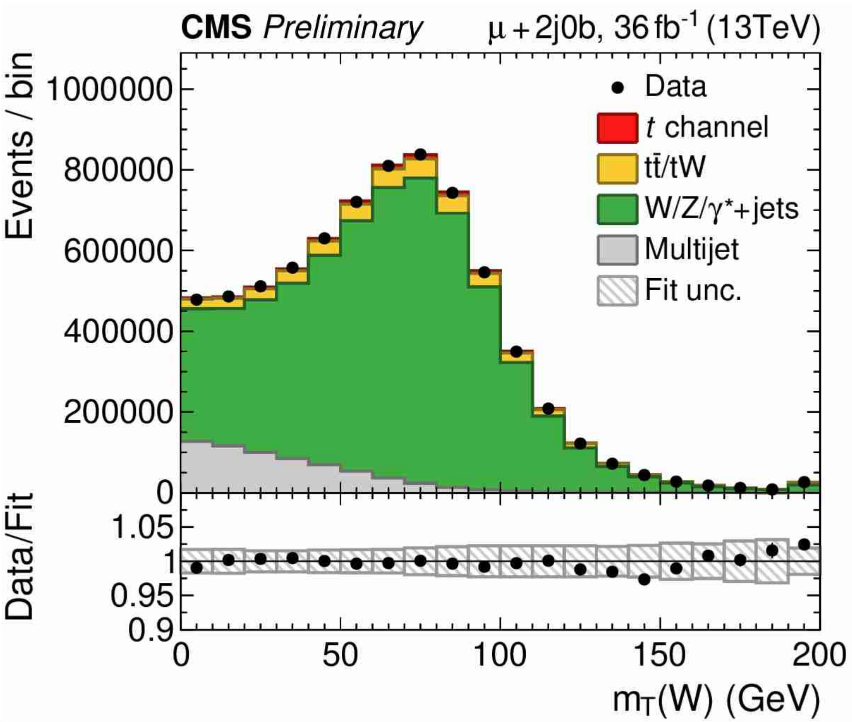


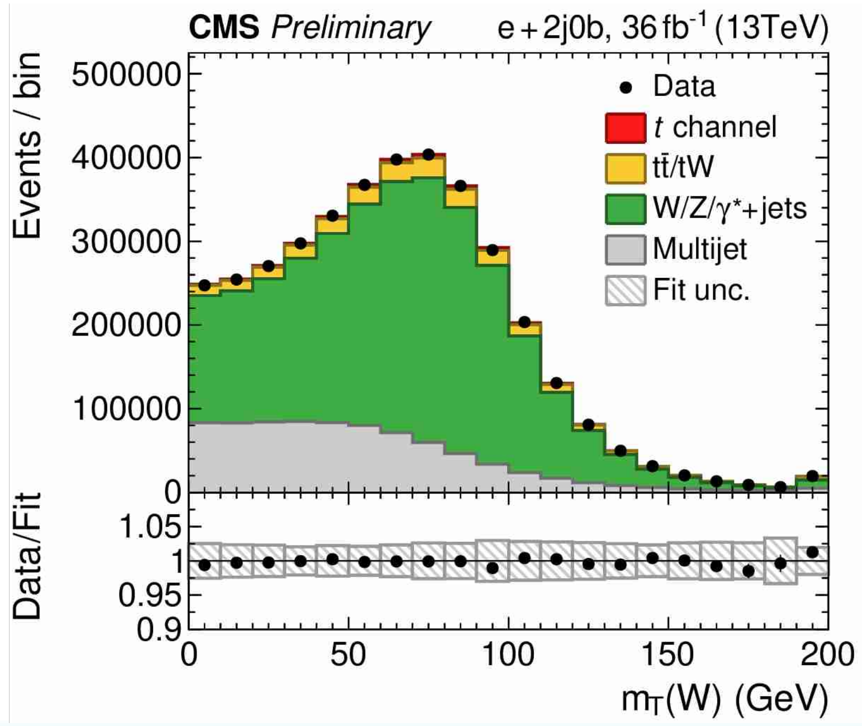


Multijet background estimation

- 2j1b, 3j2b regions are used to **estimate multijet background** normalisation. Shape is obtained through a ML fit done to a sideband region rich in multijet events (inverting isolation cuts).

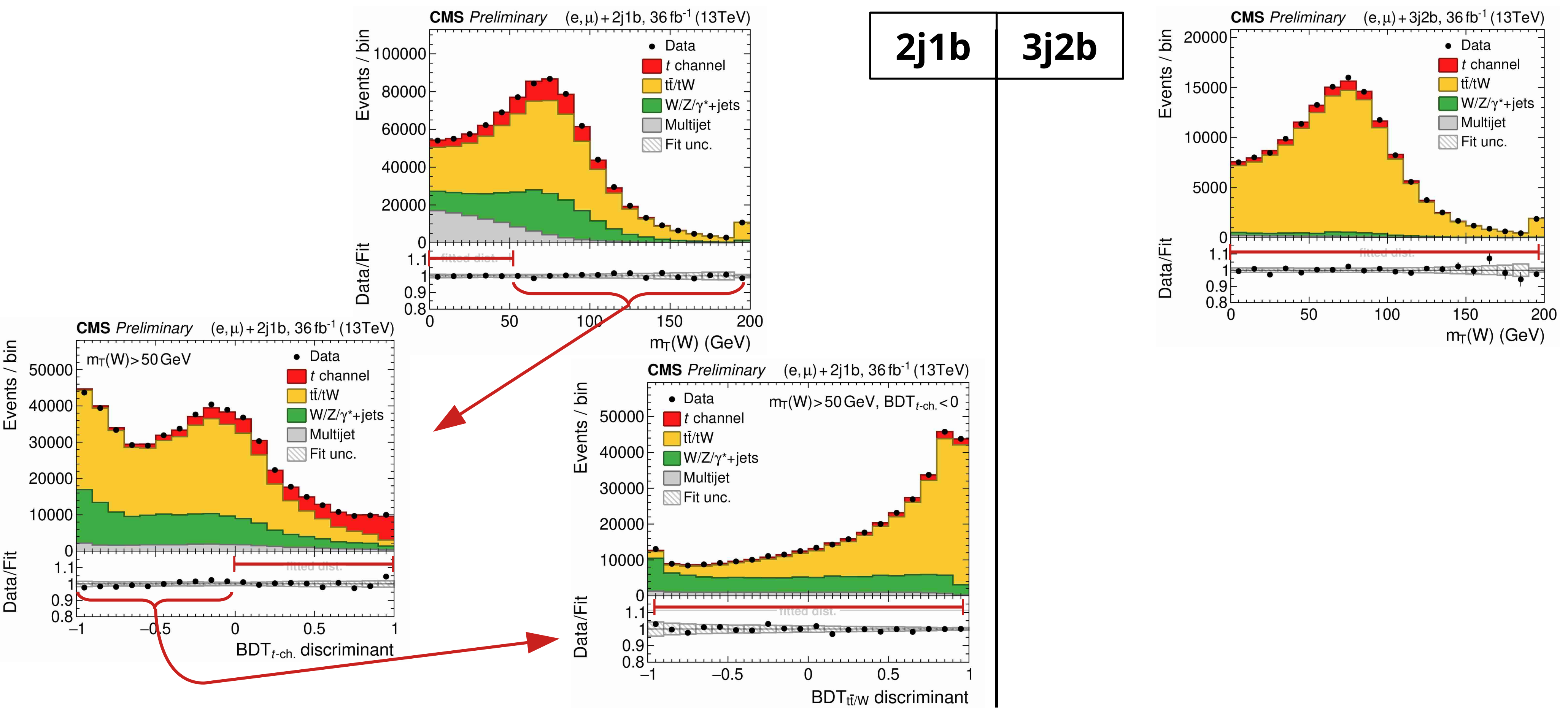
- Afterwards, the control region (2j0b) is used for validating the multijet normalisation and template:



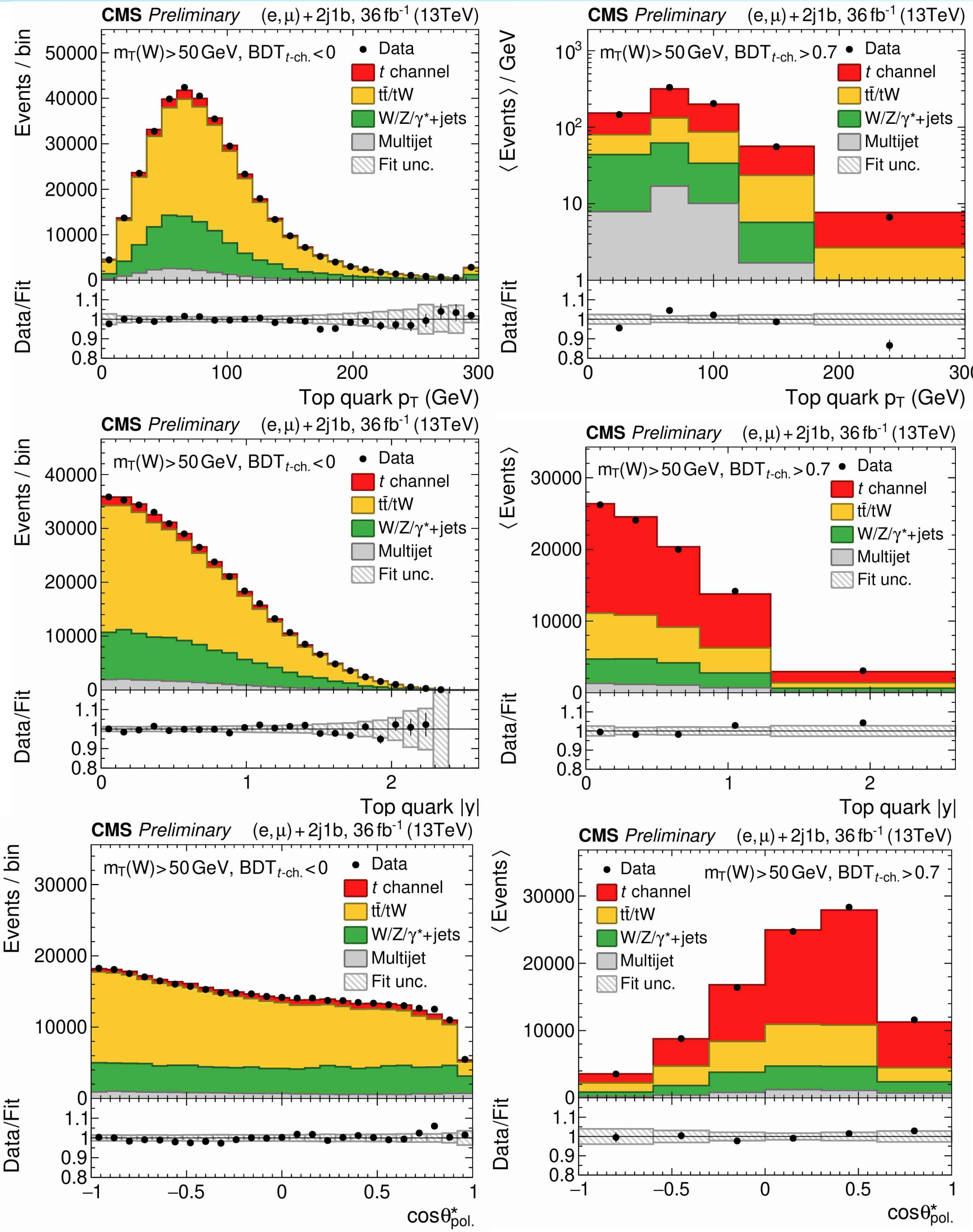


Signal extraction

- The amount of signal events is obtained by performing a **maximum likelihood fit** to a orthogonal combination of distributions:
  - The **m_T(W) distribution** in the **2j1b and 3j2b** regions.
  - The discriminant of a $BDT_{t\text{-ch.}}$ (t-chan. vs ttbar, W+jets, multijet) in the **2j1b** region.
  - The discriminant of a $BDT_{ttbar/W+jets}$ (ttbar vs W+jets) in the **2j1b** region.



Postfit results validation



- W boson 4-momentum reconstructed from the lepton 4-momentum and the p_T^{miss} of the event as the p_T of the neutrino. p_Z is calculated by imposing a W mass constraint.
- Top quark 4-momentum obtained from the reconstructed W boson 4-momentum and the b-tagged jet 4-momentum.
- The cosine of the top quark polarisation angle is defined as follows, using the momentum of the spectator quark and the lepton:

$$\cos\theta^{\star}_{\text{pol.}} = \frac{\vec{p}_{q'}^{\,(\text{top})} \cdot \vec{p}_{\ell}^{\,(\text{top})}}{|\vec{p}_{q'}^{\,(\text{top})}| \cdot |\vec{p}_{\ell}^{\,(\text{top})}|}$$

Unfolding

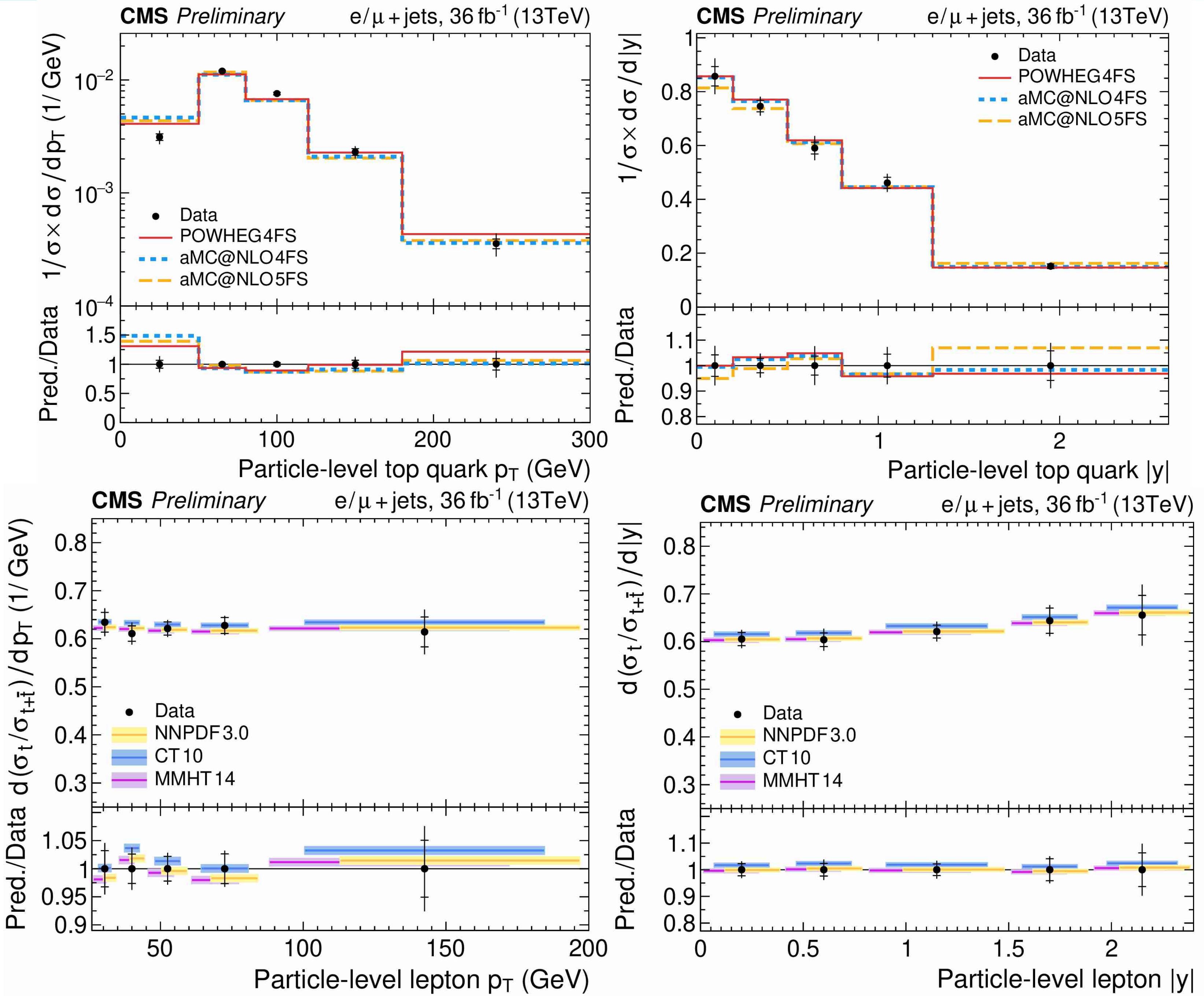
- Unfolding is performed to remove the detector effects and selection efficiencies and to obtain the differential cross section at **particle** and **parton** level from the post-fits results (at **detector** level).

- In addition to the differential cross section results, charge ratio (t / (t + tbar)) distributions are obtained.

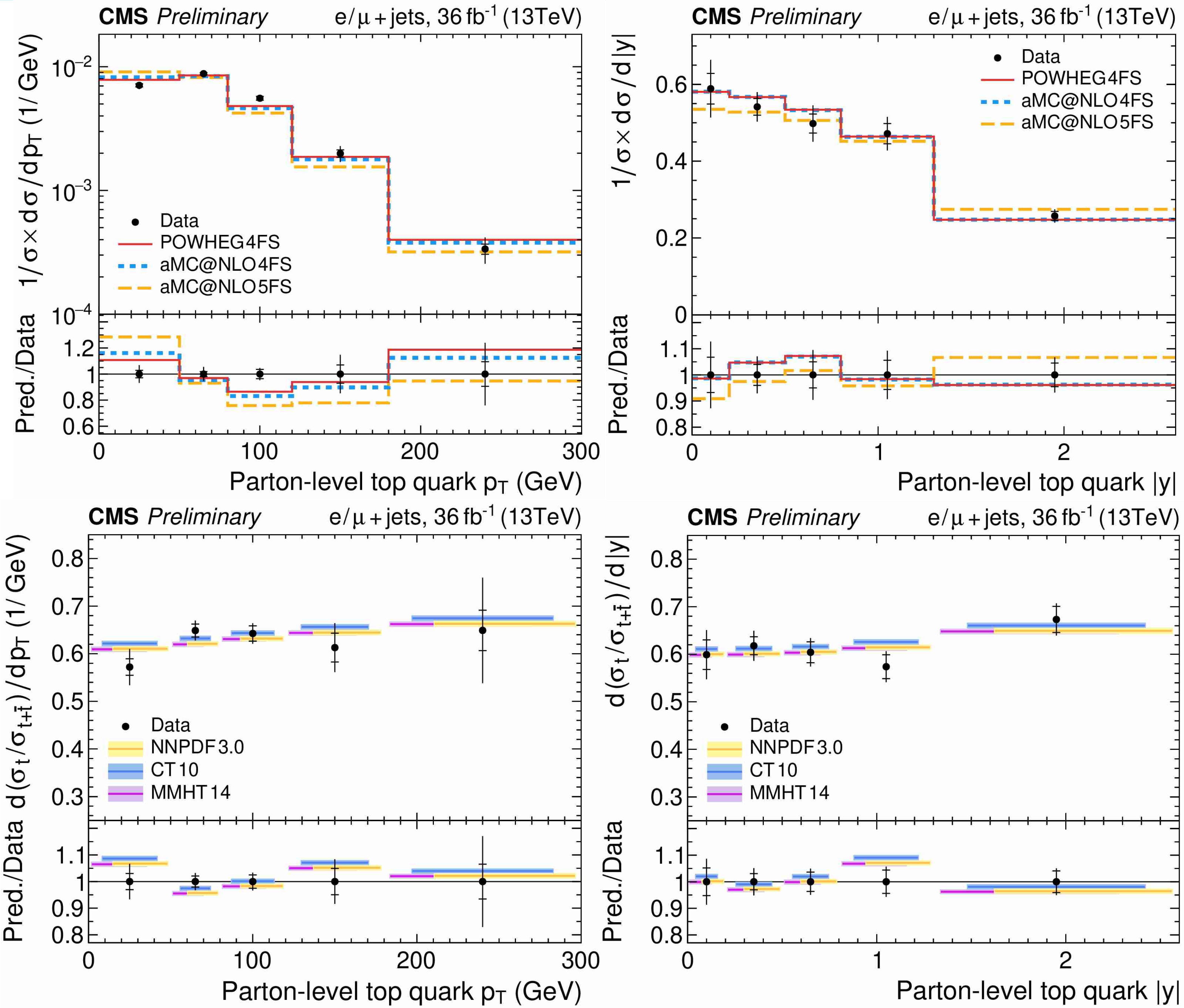
Uncertainties

- **Experimental uncertainties:** fitted in the ML fit during signal extraction (profiled).
  - Background normalisation.
  - Multijet shape estimation.
  - B-tagging and misidentification efficiency.
  - Jet energy scale and jet energy resolution.
  - Unclustered energy.
  - Pileup.
  - Lepton efficiencies.
- **Modelling uncertainties:** variated simulation samples by the uncertainty of each source are used to perform the entire analysis again. The maximum difference of each variation (up and down) is taken as the unc., which is added in quadrature to the final result.
  - Top quark p_T modelling.
  - Top quark mass.
  - PDF.
  - Renormalisation/factorisation scales.
  - Matrix element / Parton shower matching.
  - Parton shower initial and final state radiation.
  - Underlying event tune.

Results – Particle level



Results – Parton level



Results – Spin asymmetry

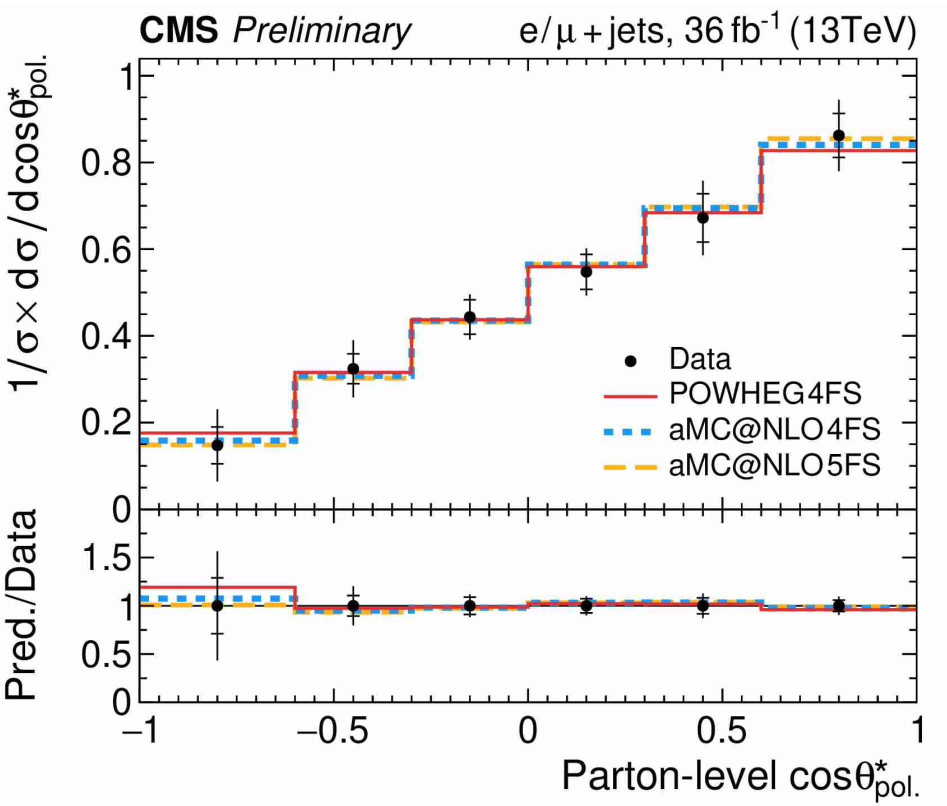
The cosine of the top quark polarisation angle can be related with its spin asymmetry at parton level as follows:

$$\frac{d\sigma}{\sigma \cdot d\cos\theta^{\star}_{\text{pol.}}} = \frac{1}{2}\left(1 + 2A_{\ell}\cos\theta^{\star}_{\text{pol.}}\right), \quad A_{\ell} = \frac{1}{2}P \cdot \alpha_{\ell}$$

Spin asymmetry

Top quark polarisation

Spin-analysing power of the lepton



Taking the differential cross section result of the cosine at parton level, a χ^2-based fit is done, obtaining the following results for the spin asymmetry:

$$A_e = 0.443 \pm 0.048\,(\text{stat+exp}) \pm 0.068\,(\text{syst}) = 0.443 \pm 0.083$$
$$A_\mu = 0.398 \pm 0.042\,(\text{stat+exp}) \pm 0.047\,(\text{syst}) = 0.398 \pm 0.063$$
$$A_{e+\mu} = 0.439 \pm 0.032\,(\text{stat+exp}) \pm 0.053\,(\text{syst}) = 0.439 \pm 0.062$$

Conclusions

- **Single top processes** are relevant for LHC physics, because they
  - appear as background in many analysis due to their relevant cross section.
  - contain the EW interaction of the top, being a portal to V_{tb}.
  - can be a way to BSM through their observables (cross section, spin asymmetry…), and some of them can only be obtained through differential measurements.
  - Thanks to large amount of data, differential measurements can be done.

- The **last CMS differential measurement**, before shown:
  - Measures the differential cross section of the t-ch. at particle and parton level with overall good agreement between MC and data, except from the top quark p_T.
  - The same can be said for the charge ratios measured.
  - The top quark spin asymmetry, sensible to the top quark polarisation, has been measured with a value of $A = 0.439 \pm 0.062$, in agreement with the 0.436 (with very small unc.) NLO prediction of POWHEG.

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CMS

Thanks for your attention

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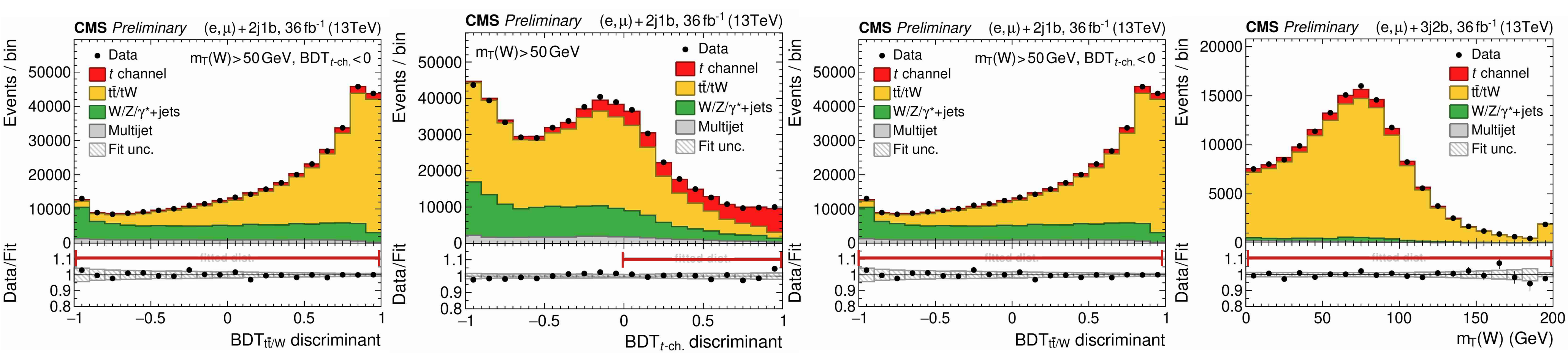
Bonus slides

Signal extraction (details)

- The amount of signal events is obtained by performing a **maximum likelihood fit** to a orthogonal combination of distributions:
  - The **m_T(W) distribution** in the **2j1b and 3j2b** regions.
  - The discriminant of a $BDT_{t\text{-ch.}}$ (t-chan. vs ttbar, W+jets, multijet) in the **2j1b** region.
  - The discriminant of a $BDT_{ttbar/W+jets}$ (ttbar vs W+jets) in the **2j1b** region.

- Ortogonality obtained in the 2j1b region by fitting:
  - m_T(W) distribution when m_T(W) < 50 GeV.
  - $BDT_{ttbar/W+jets}$ disc. distribution when m_T(W) > 50 GeV and $BDT_{t\text{-ch.}}$ < 0.
  - $BDT_{t\text{-ch.}}$ disc. distribution when m_T(W) > 50 GeV and $BDT_{t\text{-ch.}}$ > 0.



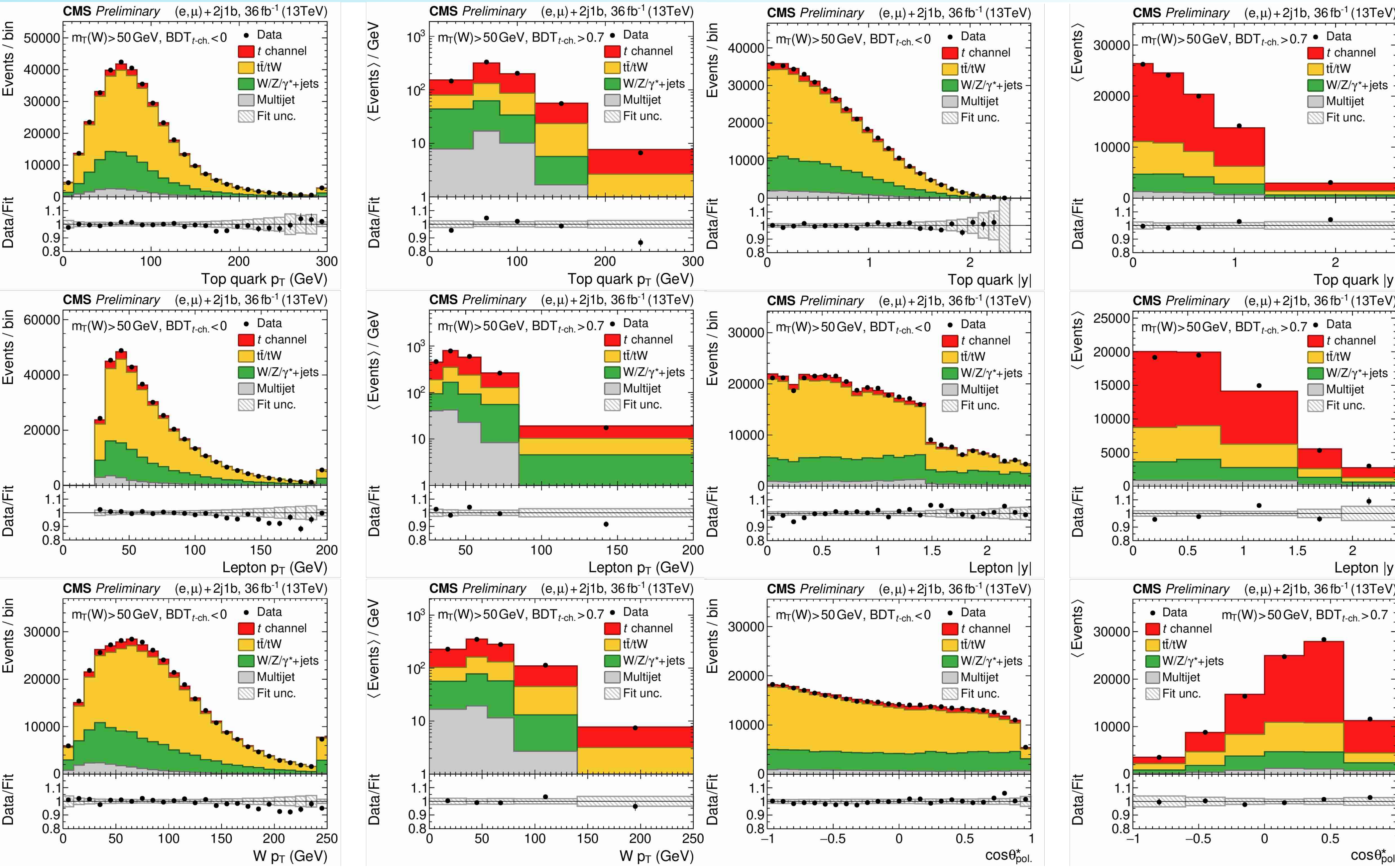
BDT construction (details)

- $BDT_{t\text{-}ch.}$ input variables.
  - $|\eta(j')|$.
  - $m_{l\nu b.}$
  - $m_T(W)$.
  - $\Delta R(b, j')$.
  - $|\Delta\eta(b, l)|$.

- $BDT_{ttbar/W+jets}$ input variables.
  - $m_{l\nu b}$.
  - p_T^{miss}.
  - $\Delta R(b, j')$.
  - $|\Delta\eta(b, l)|$.
  - $\cos\theta_W^*$.
  - Event shape, $C = 3(\lambda_1\lambda_2 + \lambda_1\lambda_3 + \lambda_2\lambda_3)$

$$S^{ab} = \frac{\sum_i^{\text{jets}, \ell, \vec{p}_T^{\text{miss}}} p_i^a \cdot p_i^b}{\sum_i^{\text{jets}, \ell, \vec{p}_T^{\text{miss}}} |\vec{p}_i|^2}$$

Postfit result validation (all)

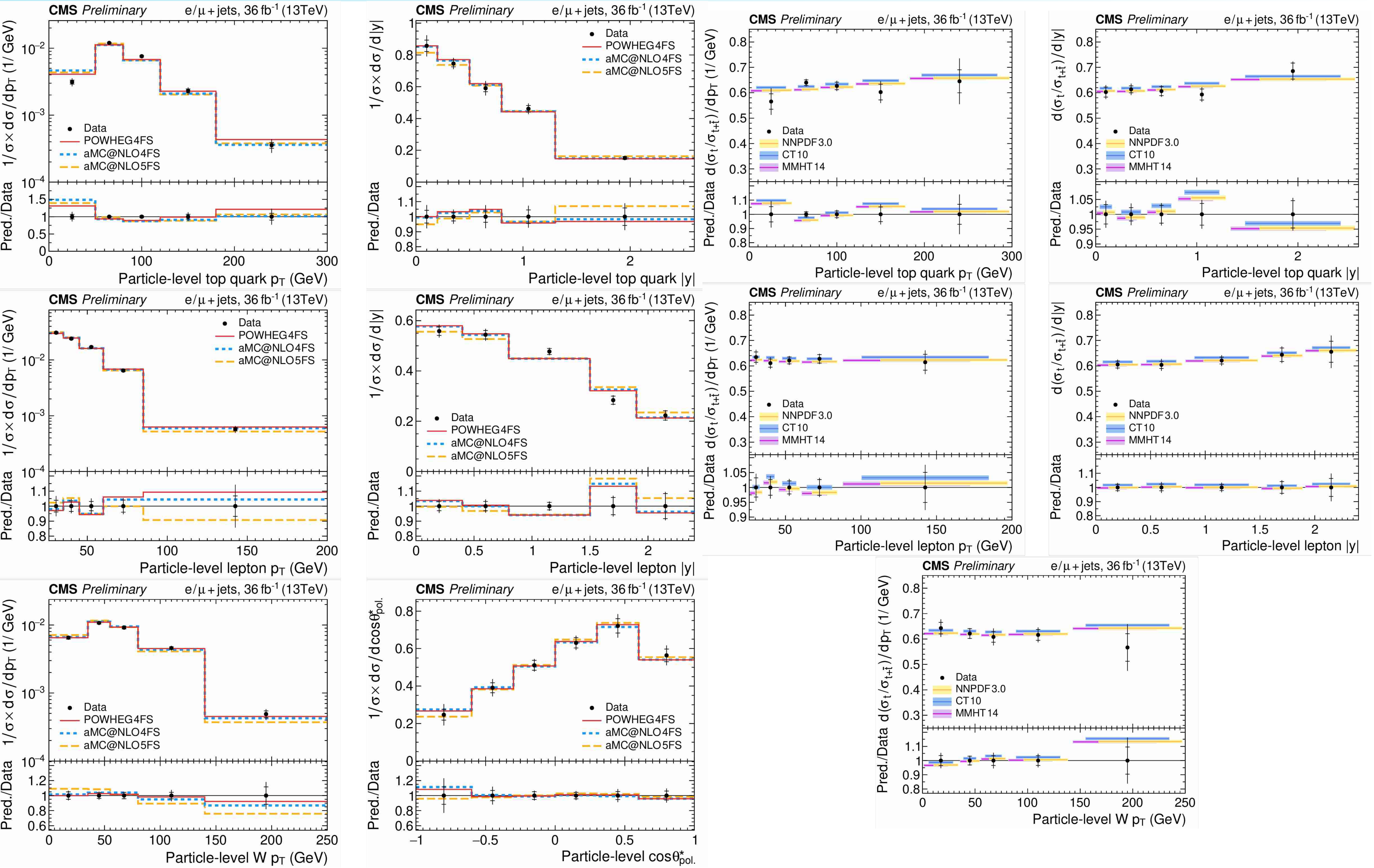


Postfit table results

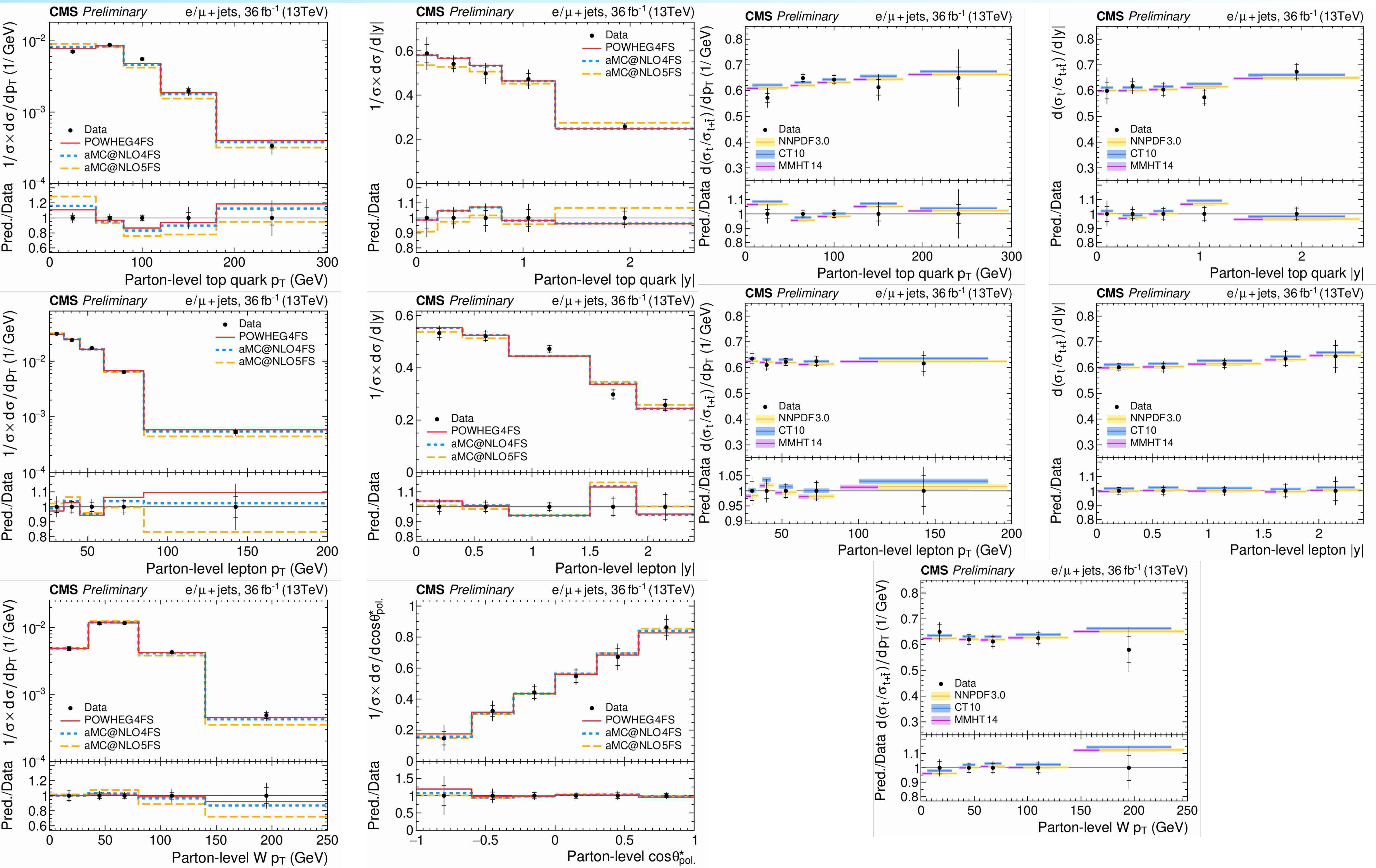
- Only directly postfit (i.e. profiled uncertainties) are shown.

Process	e^+	e^-	μ^+	μ^-
$W/Z/\gamma^*$+jets	$33\,400 \pm 3\,200$	$30\,700 \pm 2\,800$	$72\,000 \pm 6\,800$	$62\,800 \pm 5\,600$
$t\bar{t}/tW$	$84\,500 \pm 1\,400$	$84\,800 \pm 1\,500$	$142\,400 \pm 2\,400$	$143\,400 \pm 2\,500$
Multijet	$13\,500 \pm 1\,000$	$12\,700 \pm 1\,000$	$35\,150 \pm 550$	$35\,710 \pm 760$
t channel (top quark)	$17\,720 \pm 820$	27 ± 2	$34\,400 \pm 1500$	10 ± 3
t channel (top antiquark)	25 ± 3	$11\,460 \pm 880$	13 ± 2	$21\,600 \pm 1\,600$
Total	$149\,300 \pm 2\,400$	$139\,700 \pm 2\,200$	$284\,100 \pm 5\,800$	$263\,700 \pm 4\,600$
Data	148 400	138 700	283 300	260 000

Results – Particle level (all)



Results – Parton level (all)



Unfolding (details)

- Unfolding is performed to remove the detector effects and selection efficiencies and to obtain the differential cross section at **particle** and **parton** level from the post-fits results (at **detector** level).
  - **Parton** level: physical objects defined as generated in the final state of the process.
  - **Particle** level: physical objects defined as stable (τ > 30 ps) particles after hadronisation. Leptons are taken as dressed by all their emitted photons in a cone of $\Delta R = 0.1$. Jets are clustered from all non-prompt stable particles using anti-k_T alg. in a cone of $\Delta R = 0.4$.
- Technically, unfolding is implemented with the `TUnfold` algorithm and library (inside `ROOT`). In order to ease numerical problems…
  - …regularisation and area constraint terms are imposed.
  - …the binning of the distributions at detector, particle and parton levels are optimised so that the response matrices are as diagonal as possible.
- In addition to the differential cross section results, charge ratio (t / (t + tbar)) distributions are obtained.