Study of the top quark electroweak production, including associated productions with vector bosons at CMS

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for the CMS Collaboration

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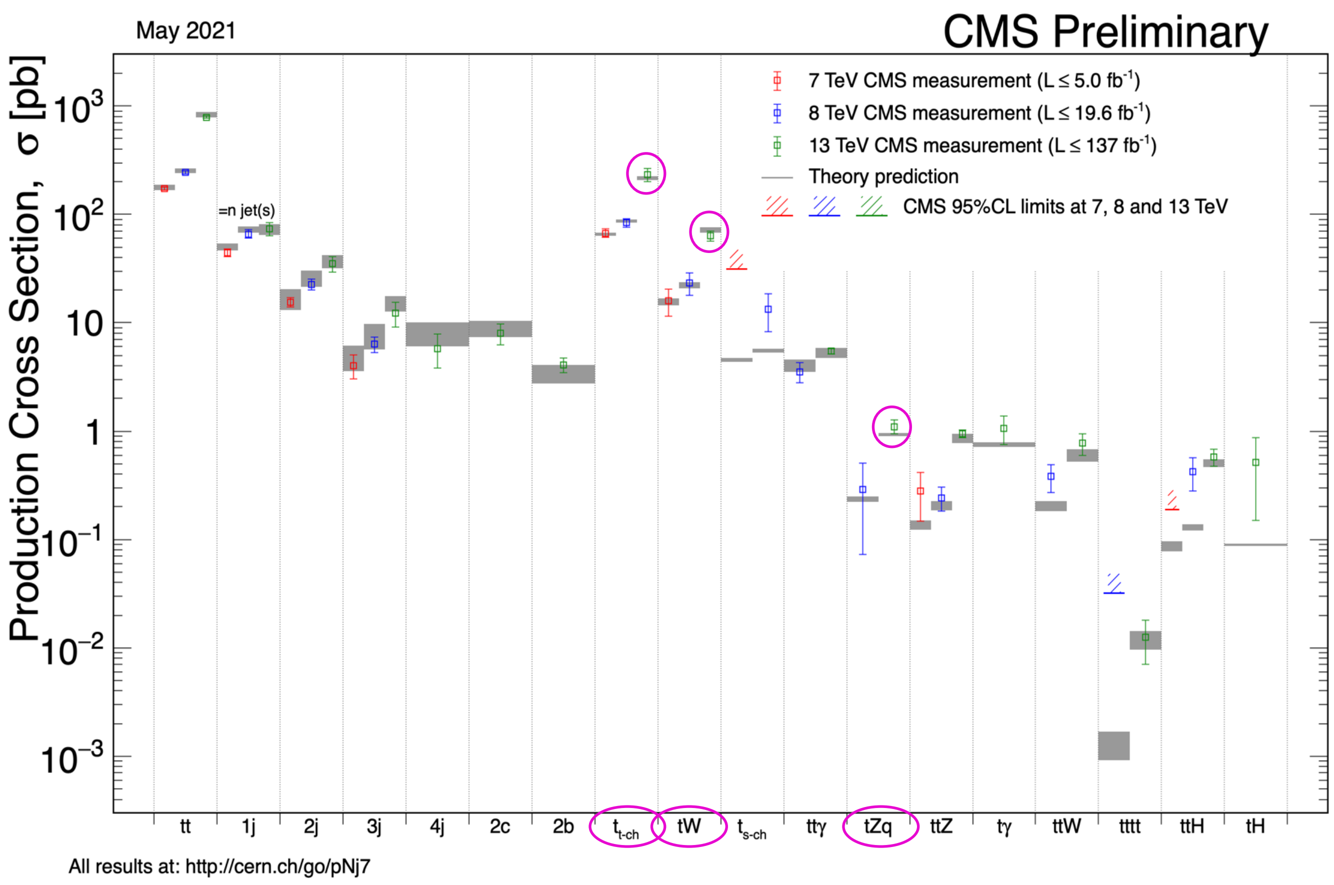
Introduction: single top production



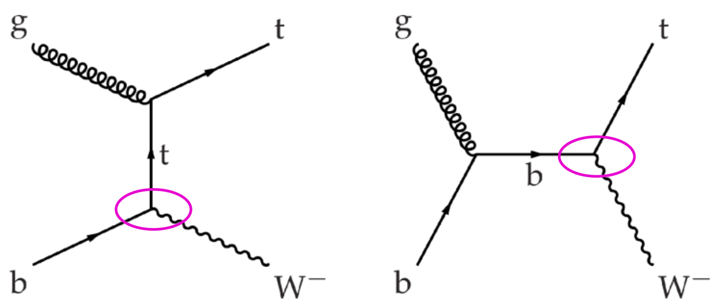
Will focus on single top results in these areas:

- first observation of tW in semileptonic channel.
- inclusive and differential tZq.
- differential t-channel single top.
- differential tW.

tW in semileptonic channel

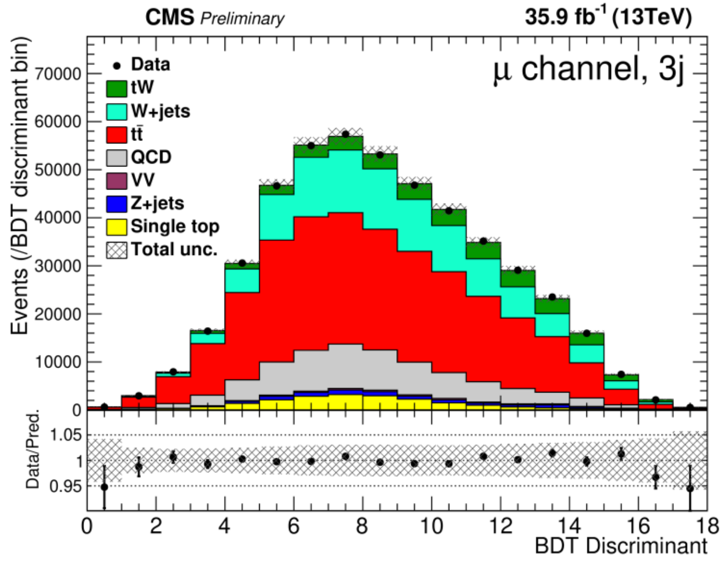
- Motivation:
  - tW process is sensitive to CKM element V_{tb} via Wtb vertex.
- History:
  - tW observed and measured by ATLAS and CMS (in dilepton channel!)
- New observation: tW in semileptonic channel.

reference: TOP-20-002



Analysis in a nutshell:

- Event selection:
  - 1 electron or muon
  - 1 b jet, 3 jets
- Control regions with 2 jets and 4 jets.
- Multijet QCD estimated from data in a sideband region.
- BDT to separate tW from $t\bar{t}$.



Fit strategy:

- binned simultaneous maximum likelihood fit to BDT discriminant output.
- systematic uncertainties as nuisance parameters in the fit.

Results:

- significance > 5 sigma → observation!
- signal strength: 1.24 ± 0.18.
- cross-section: 89 ± 4 (stat) ± 12 (syst) pb.

limiting sources of uncertainty:

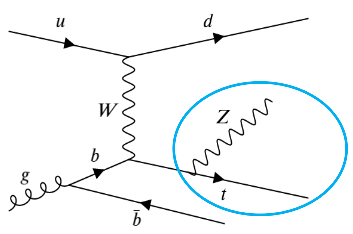
- nonprompt lepton background normalization.
- jet energy corrections.

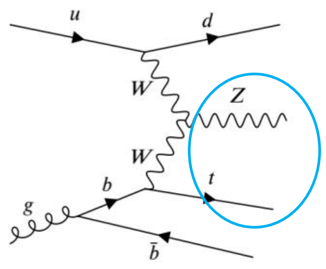
Inclusive and differential tZq

reference: TOP-20-010

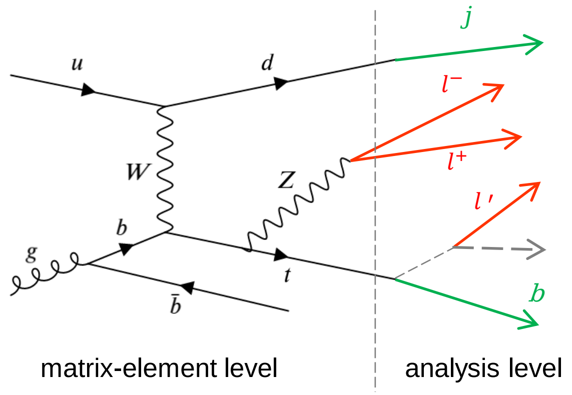
tZq is a probe for new physics:

- sensitive to: ttZ- and WWZ couplings,
  top quark polarization,
  proton PDFs via top quark-antiquark ratio.
- impacted by FCNC or more generally in the SMEFT phenomenology [1].





Earlier tZq measurements by CMS and ATLAS [2-4]: → precision: ±15%



- 3 leptons (electrons or muons)
  - selection based on new lepton MVA.
- ≥ 2 jets ($p_T > 25$ GeV, $|\eta| < 5$), ≥ 1 b-jet.

- Z boson candidate: OSSF lepton pair with $|m_Z - m_{ll}| < 15$ GeV.
- top quark candidate and accompanying b jet: reconstructed analytically.
- recoiling jet: leading non-b-tagged jet, tends to be forward.

- background from nonprompt leptons estimated from data and uncertainty constrained in dedicated nonprompt control region.

- multiclass NN or BDT to distinguish tZq from backgrounds.

[1]: *JHEP* **10** (2018) 5, doi [2]: *Phys. Lett. B* **779** (2018) 358, doi [3]: *Phys. Rev. Lett.* **122** (2019) 132003, doi [4]: *JHEP* **07** (2020) 124, doi

Inclusive and differential tZq

reference: TOP-20-010

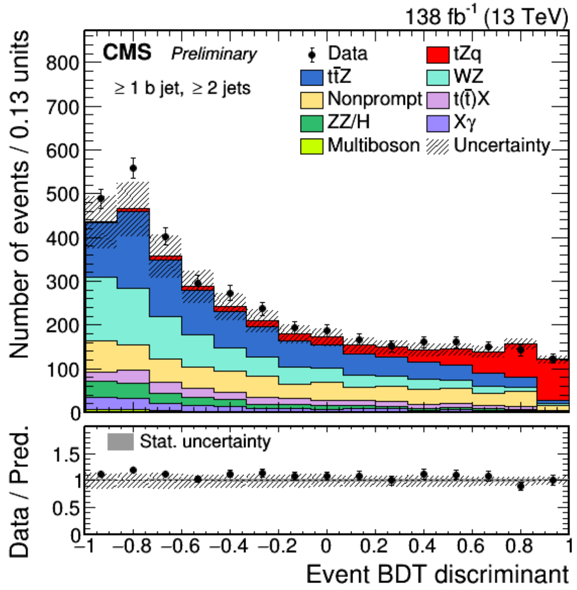
Inclusive tZq cross-section:

$$\sigma_{tZq} = 87.9^{+7.5}_{-7.3}\,(\text{stat.})^{+7.3}_{-6.0}\,(\text{syst.})\ \text{fb}$$

→ total uncertainty of **± 11%**

Improvement of about 30%
w.r.t. earlier measurements, due to

- larger data set.
- larger measurement region.
- improved lepton MVA.
- constraining nonprompt background (dominant in earlier measurements).

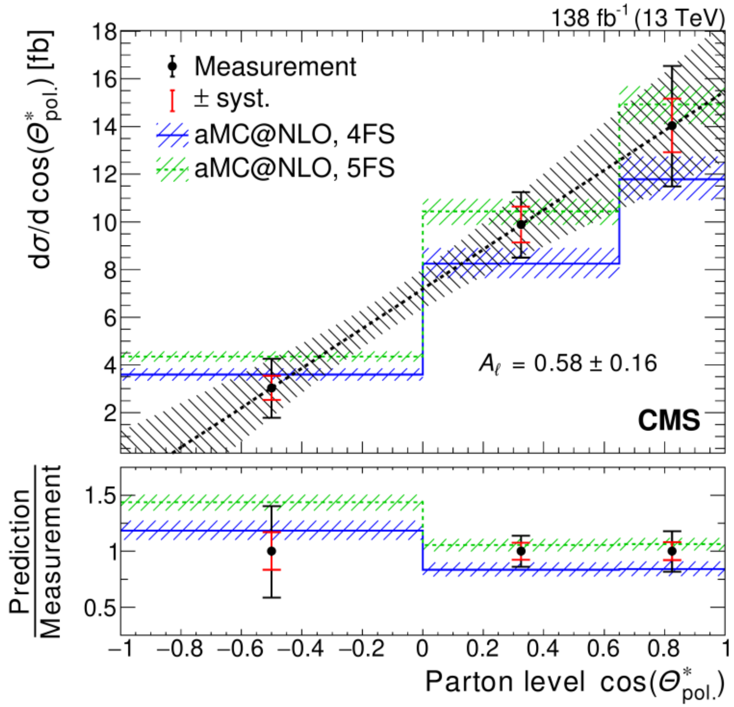


Spin asymmetry:

$$A_l = 0.58^{+0.15}_{-0.16}\,(\text{stat.}) \pm 0.06\,(\text{syst.})$$

compared to prediction:

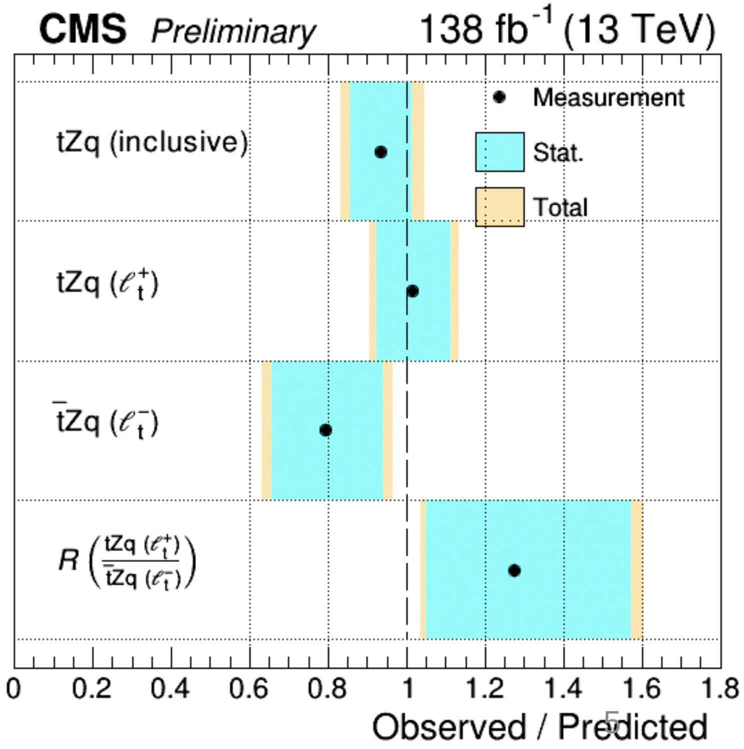
$$A_l^{4FS} = 0.437^{+0.004}_{-0.003}$$
$$A_l^{5FS} = 0.454^{+0.004}_{-0.005}$$



Partial tZq cross-sections:

$$\sigma_{tZq(l_t^+)} = 62.2^{+5.9}_{-5.7}\,(\text{stat})^{+4.4}_{-3.7}\,(\text{syst.})\ \text{fb}$$
$$\sigma_{tZq(l_t^-)} = 26.1^{+4.8}_{-4.6}\,(\text{stat})^{+3.0}_{-2.8}\,(\text{syst.})\ \text{fb}$$

$$R = 2.37^{+0.56}_{-0.42}\,(\text{stat})^{+0.27}_{-0.13}\,(\text{syst.})\ \text{fb}$$



Inclusive and differential tZq

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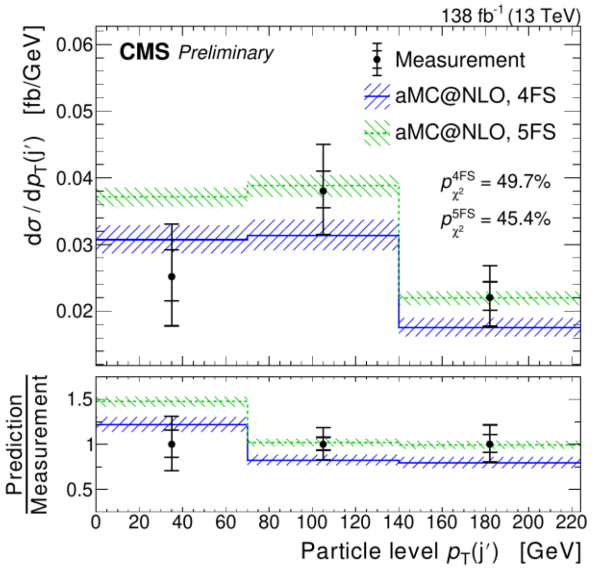
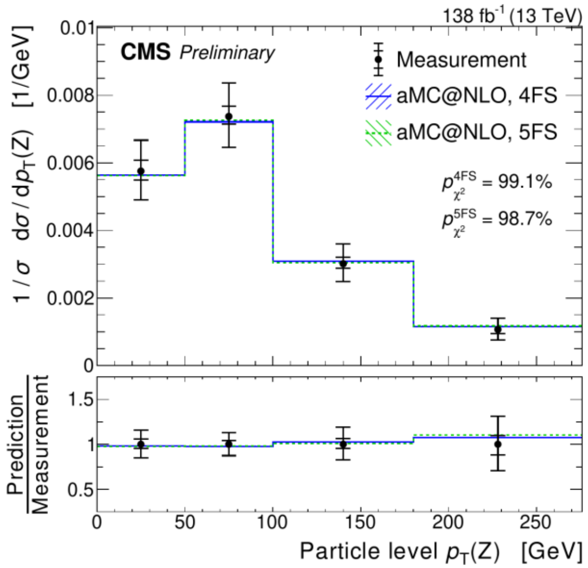
reference: TOP-20-010

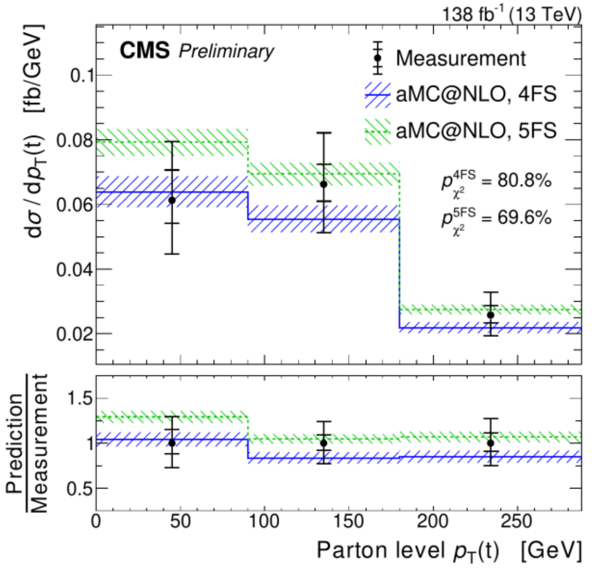
absolute | normalized

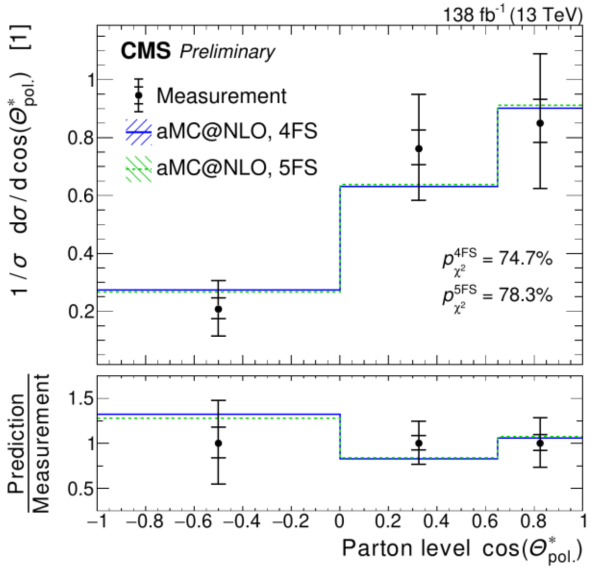
particle level





parton level

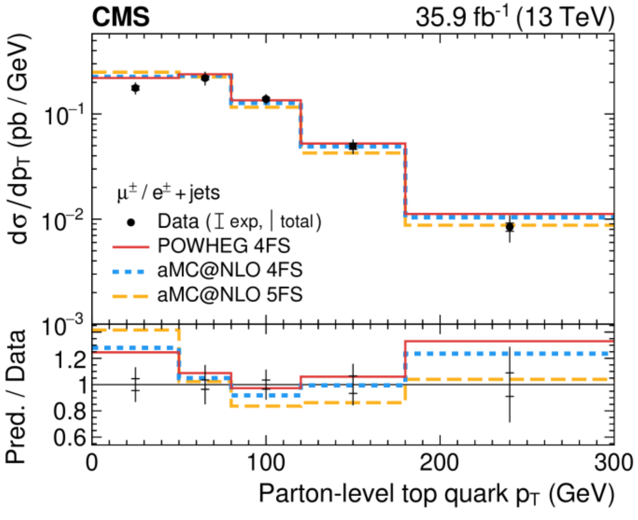


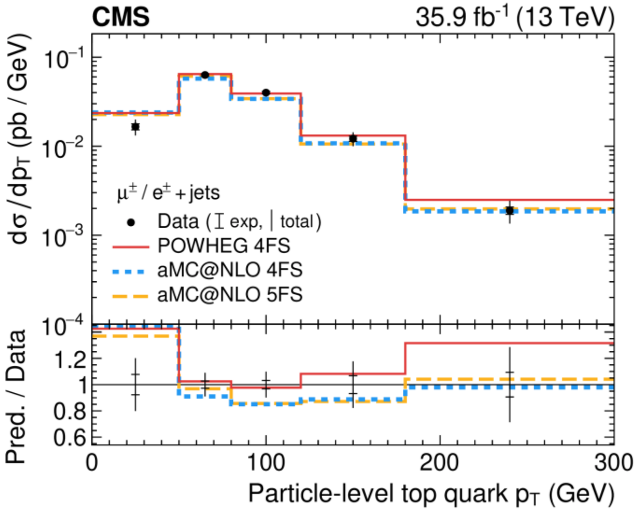


- In general, observe good agreement between measurement and prediction.
- Compared to both 4FS and 5FS prediction.
- Uncertainties down to 15% for purely leptonic observables, down to 25% for observables including jets.
- Other variables: see public note (see references) or backup!
- Note: see also related talk here.
- EFT interpretation: see TOP-21-001 and related talk here.

Differential measurements of t-channel single top

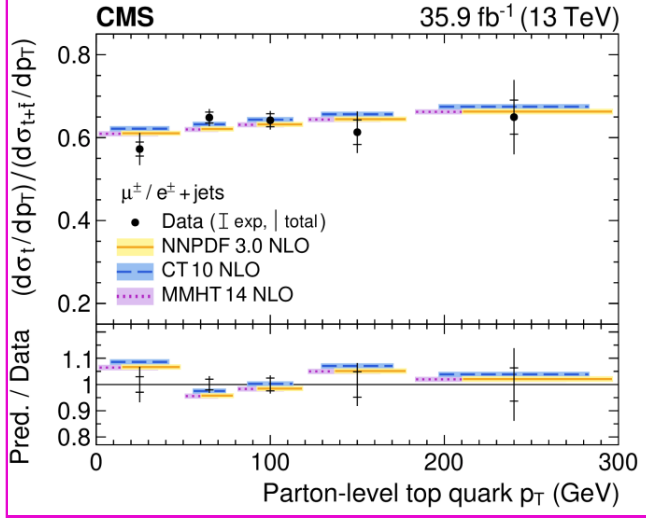
reference: TOP-17-023

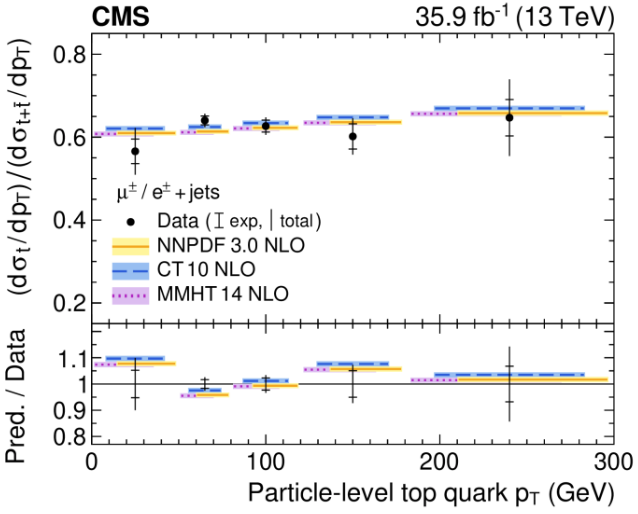




Analysis in a nutshell:

- 1 electron/muon., 2 jets, 1 b jet.
- top quark candidate reconstructed analytically.
- background from QCD multijet estimated from data.
- trained 2 BDT's:
  - signal vs. all backgrounds
  - $t\bar{t}$ vs. W+jets
- unfolding: χ^2 minimization (TUnfold implementation).
- comparison with both Powheg and Madgraph predictions, and both 4FS and 5FS (in Madgraph).





Results:

- differential cross-sections at parton and particle level, absolute and normalized.
- observables:
  - p_T and y of top quark and lepton
  - p_T of W boson
  - top quark polarization angle.
- differential $\sigma_t/\sigma_{t+\bar{t}}$ distributions for the same observables.
- spin asymmetry $A_l = 0.439 \pm 0.062$ (prediction: 0.436)
- no appreciable deviations from SM predictions.

Differential measurements of tW

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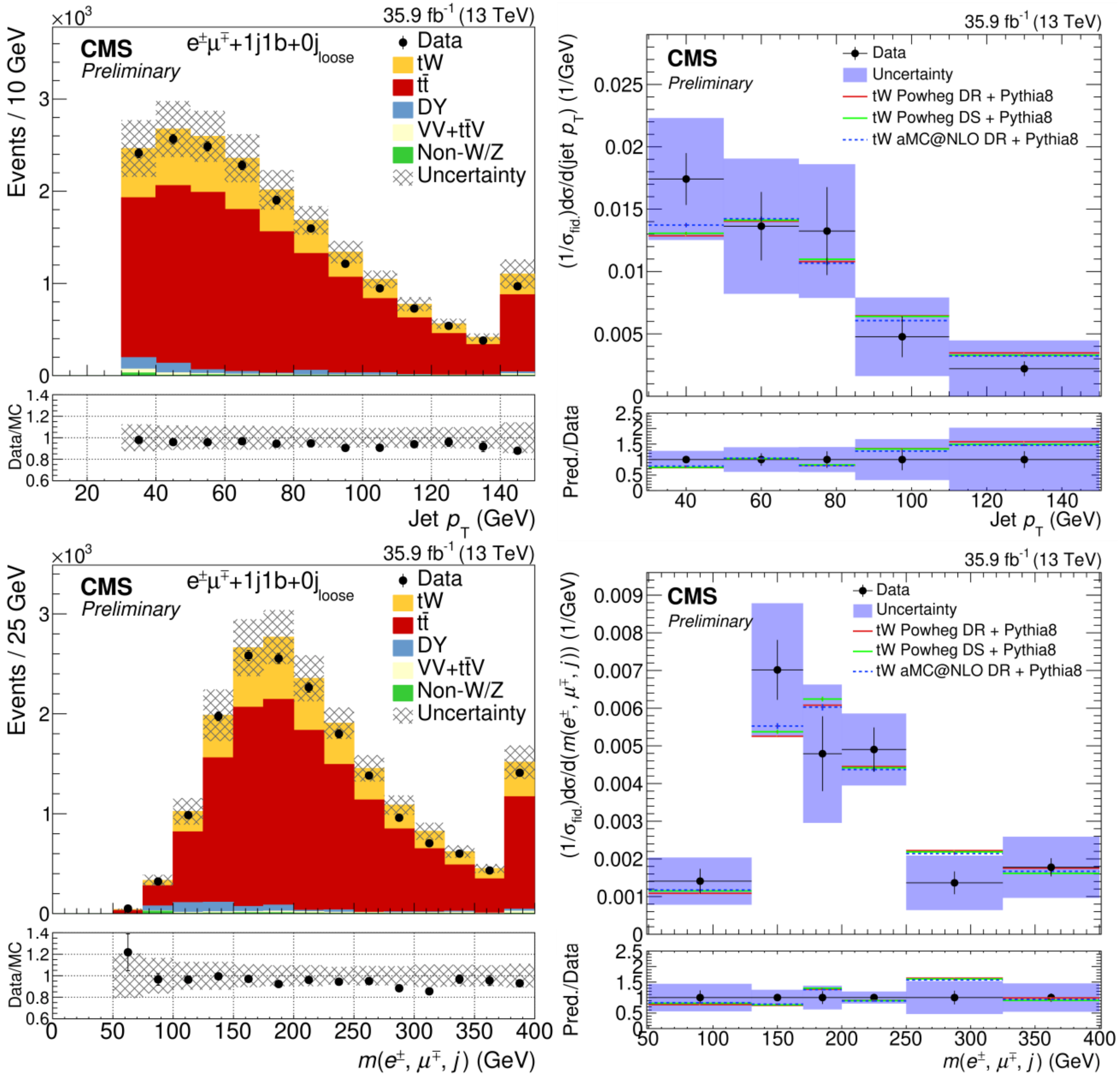


reference: TOP-19-003

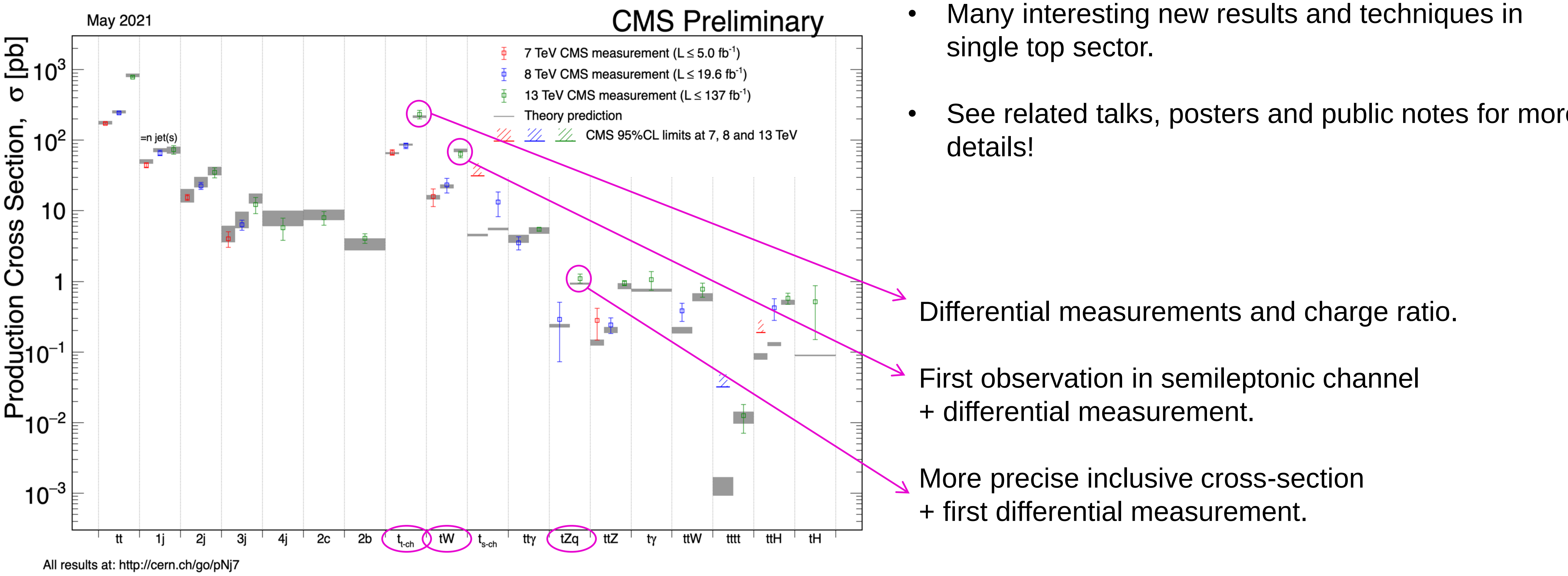
Analysis in a nutshell:

- ≥ 2 leptons, $e^{\pm}\mu^{\mp}$ final state, 1 b jet, 1 jet.
- main difficulty: overwhelming $t\bar{t}$ background.
- unfolding: $$N_i^{sig} = N_i - N_i^{bkg} = \sum_{j=1} R_{ij} N_j^{sig,\,unf}$$
  solved using χ^2 minimization (TUnfold implementation).
- comparison with both Powheg and Madgraph predictions, and both DR and DS scheme (in Powheg).

Results:

- normalized differential cross-sections at particle level.
- observables:
  - p_T of leading lepton and top quark
  - azimuthal angle between electron and muon
  - p_z of electron-muon-jet system.
  - invariant mass of electron-muon-jet system.
  - m_T of electron-muon-jet-p_T^{miss}-system
- no appreciable deviations from SM predictions.
- dominant systematic uncertainties: jet energy corrections (on the $t\bar{t}$ background).

Summary



- Many interesting new results and techniques in single top sector.
- See related talks, posters and public notes for more details!

Thank you for your attention!

Backup

single top (+ associated bosons) cross sections

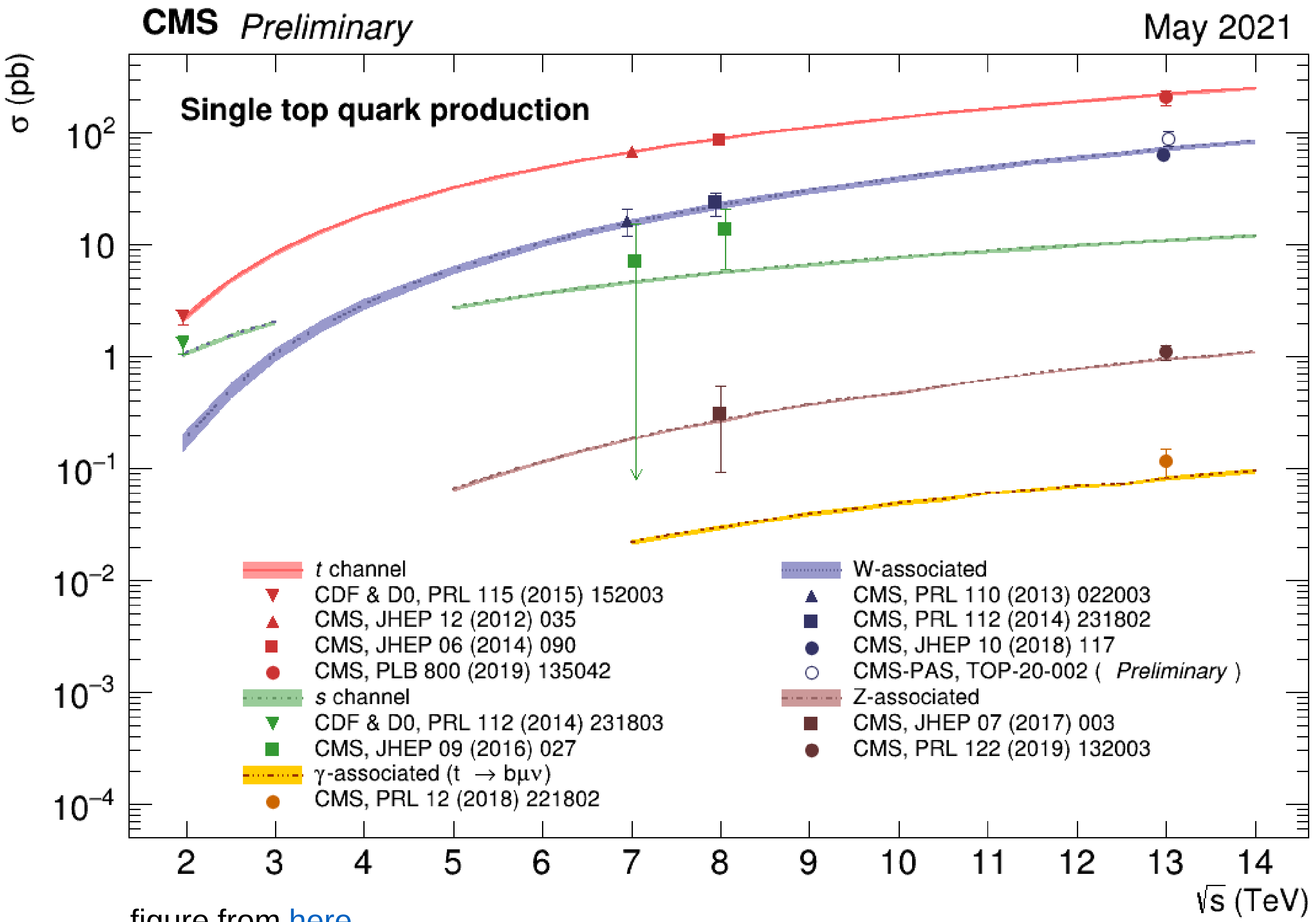


figure from here

top quark mass measurements

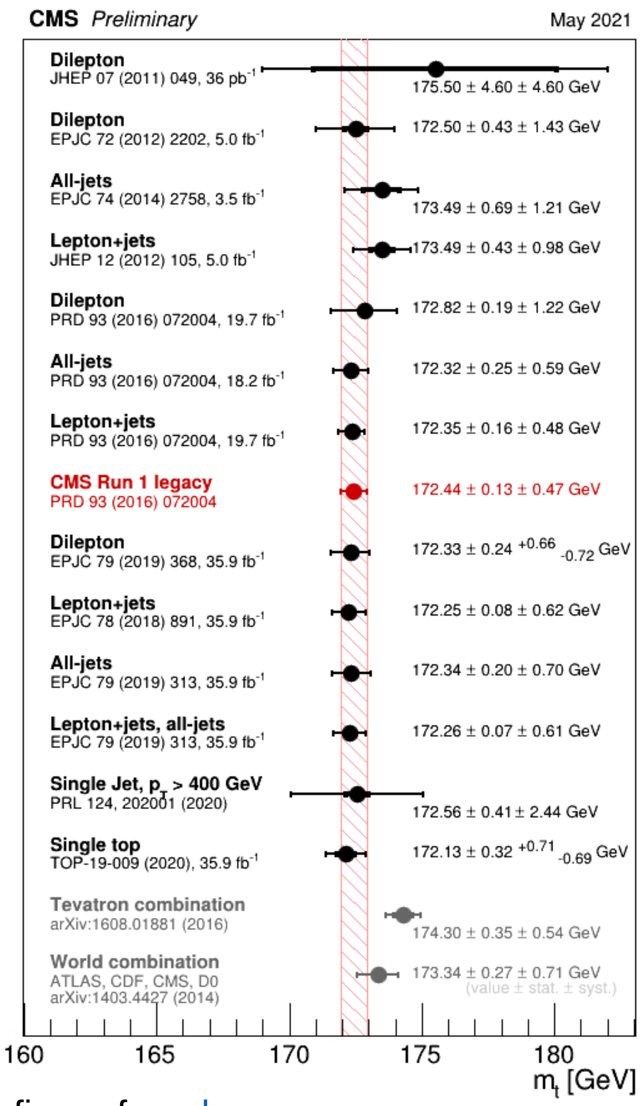


figure from [here]

observation of semileptonic tW (TOP-20-002)

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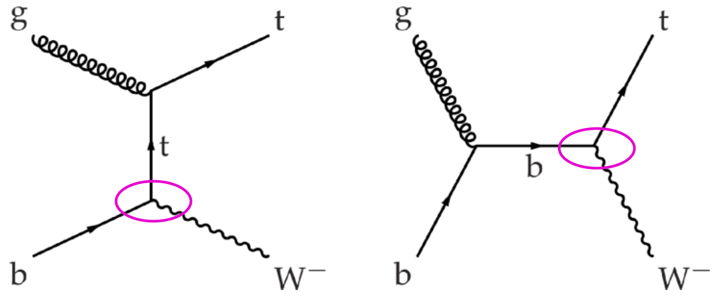
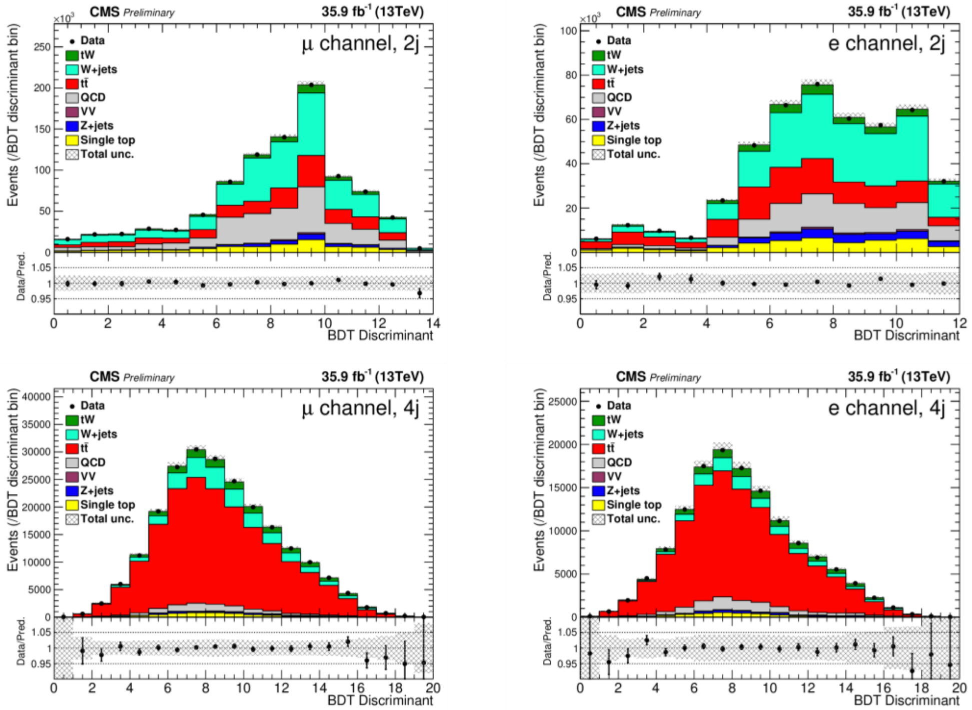
- Motivation:
  - tW process is sensitive to CKM element V_{tb} via Wtb vertex.
- History:
  - tW undiscovered at Tevatron.
  - evidence by ATLAS and CMS at 7 TeV.
  - observation by ATLAS and CMS at 8 TeV.
  - precisely measured at 13 TeV.

  } in dilepton channel.
- New observation at 13 TeV: tW in semileptonic channel.



Analysis in a nutshell:

- Event selection:
  - single electron or muon trigger
  - 1 electron or muon
  - 1 b jet
  - 3 jets
- Control regions with 2 jets and 4 jets.
- W+jets and multijet QCD estimated from data in a sideband region.
- BDT to separate tW from $t\bar{t}$.
- Note: interference with $t\bar{t}$ taken into account by removing doubly resonant diagrams from signal definition.



observation of semileptonic tW (TOP-20-002)

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BDT discriminant:

- trained to separate tW from dominant tt̄ background.
- input variables based on different number of b-jets in tW and tt̄

exactly one b-jet, and 2 non-b-jets coming from a W boson decay.

at least one b-jet must fail reconstruction or identification.

- trained separately for electron and muon channel, with same input variables and hyperparameters.

Fit strategy:

- binned maximum likelihood fit to BDT discriminant output.
- all SR and CR in electron and muon channel fitted simultaneously.
- systematic uncertainties as nuisance parameters in the fit.

Results:

- significance > 5 sigma.
- signal strength: 1.24 ± 0.18.
- cross-section: 89 ± 4 (stat) ± 12 (syst) pb.

limiting sources of uncertainty:

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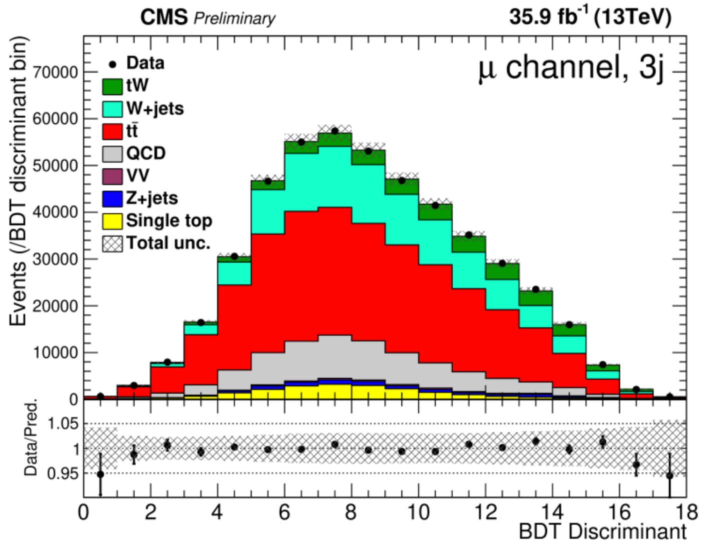
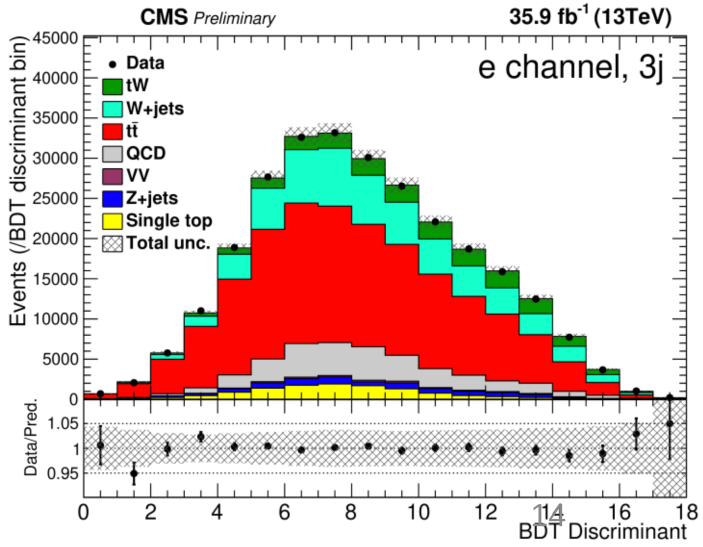
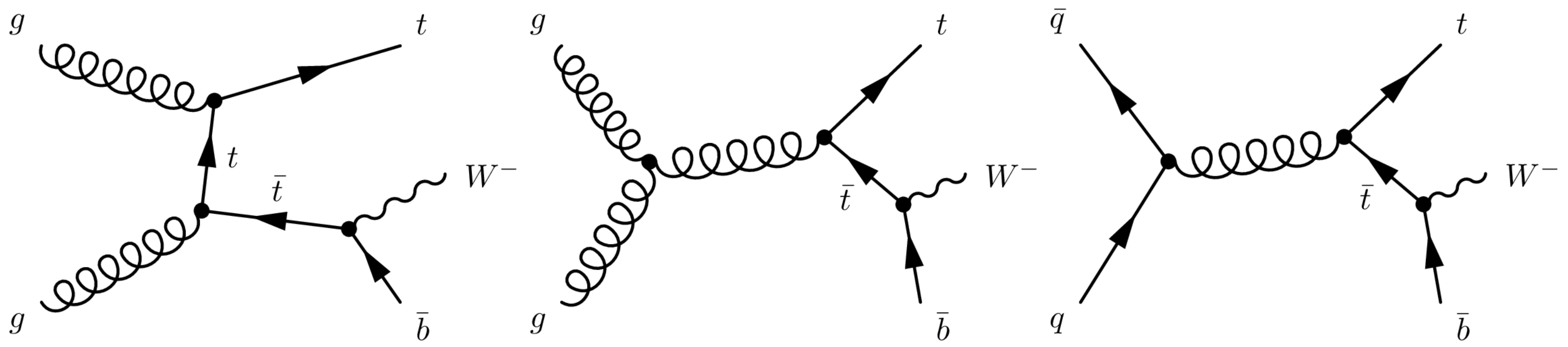




observation of semileptonic tW (TOP-20-002)



“Feynman diagrams for tW single top quark production at next-to-leading order that are removed from the signal definition in the DR scheme. The charge-conjugate modes are implicitly included.”

observation of semileptonic tW (TOP-20-002)

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Sample	Muon channel 3j	2j	4j
tW	26091 ± 62	29772 ± 66	10580 ± 40
$t\bar{t}$	272590 ± 360	196690 ± 300	184500 ± 300
W+jets	79800 ± 1200	332300 ± 3300	12000 ± 330
QCD multijet	67470 ± 320	275130 ± 700	10440 ± 140
Single top	15786 ± 55	54930 ± 100	4105 ± 28
Z+jets	7410 ± 500	26450 ± 970	2070 ± 240
VV	2850 ± 160	7450 ± 250	731 ± 81
Total prediction	472000 ± 2700	922700 ± 5700	224400 ± 1200
Data	472540	923880	223720

Sample	Electron channel 3j	2j	4j
tW	15725 ± 35	17453 ± 37	6578 ± 23
$t\bar{t}$	157780 ± 200	111030 ± 160	109259 ± 160
W+jets	63400 ± 850	191000 ± 1800	9610 ± 250
QCD multijet	15370 ± 180	85080 ± 410	5960 ± 100
Single top	8939 ± 30	30223 ± 54	2375 ± 15
Z+jets	7080 ± 300	23830 ± 590	1800 ± 140
VV	1645 ± 85	4010 ± 130	461 ± 44
Total prediction	269900 ± 1700	462600 ± 3200	136000 ± 740
Data	270330	462930	136190

“The total number of events passing event selection in each defined jet topology region for the analysis and their associated statistical uncertainties. The event yields are given for the tW signal and all major backgrounds for both the muon (upper) and electron (lower) channels. The estimations of QCD multijet and W+jets backgrounds include data-based estimates.”

observation of semileptonic tW (TOP-20-002)

"Descriptions of the variables used to train and evaluate the BDT, ranked in order of importance in the final result. The same variables are used in both muon and electron channels."

Variable Description
Mass of the reconstructed Wboson decaying hadronically
Invariant mass of the b-tagged jet and sub-leading non b-tagged jet
Angular separation between the two non b-tagged jets
Angular separation between the reconstructed leptonic Wboson and leading non b-tagged jet
Transverse momentum of the selected lepton
Energy of the two non b-tagged jets system
Angular separation between the b-tagged jet and the selected lepton
Transverse momentum of the system made of the three jets, lepton and $p_{\mathrm{T}}^{\mathrm{miss}}$

observation of semileptonic tW (TOP-20-002)

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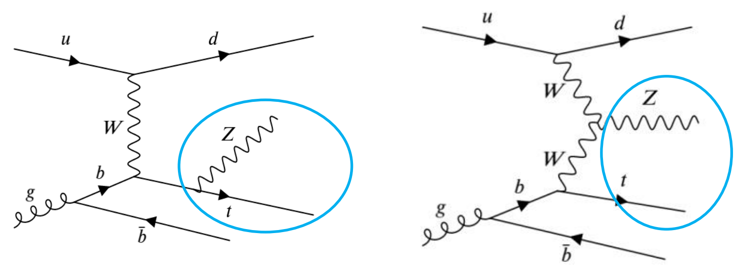
Source	Relative uncertainty (%)
QCD normalization	7
W+jets normalization	6
Z+jets normalization	3
Single top normalization	1
$t\bar{t}$ normalization	1
VV normalization	< 1
JES	6
b-tagging	4
Luminosity	3
LES	2
Trigger	1
JER	1
Mistag	< 1
Unclustered MET	< 1
Pileup	< 1
h_{damp}	4
DR/DS	3
MC tune	3
Colour reconnection	1
PDF	1
ME/PS matching	1
Final state radiation	< 1
Initial state radiation	< 1
Total systematic uncertainty	14
Statistical uncertainty	5
Total uncertainty	15

"Uncertainty in the signal strength from each source of systematic uncertainty for the combination of electron and muon channels. The table is divided between normalization, experimental and theoretical uncertainties. Uncertainties arising from the limited size of the MC samples are included in the statistical uncertainty."

Inclusive and differential tZq (TOP-20-010)

tZq is a probe for new physics:
- sensitive to ttZ- and WWZ couplings.
- sensitive to top quark polarization.
- sensitive to proton PDFs via top quark-antiquark ratio.
- impacted by FCNC or more generally in the SMEFT phenomenology [1].



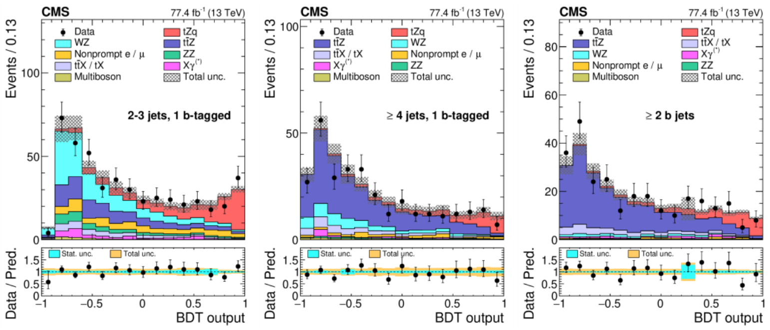
Earlier tZq measurements:

First evidence with 2016 data [2]

↓

First observation with 2016+2017 data [3]

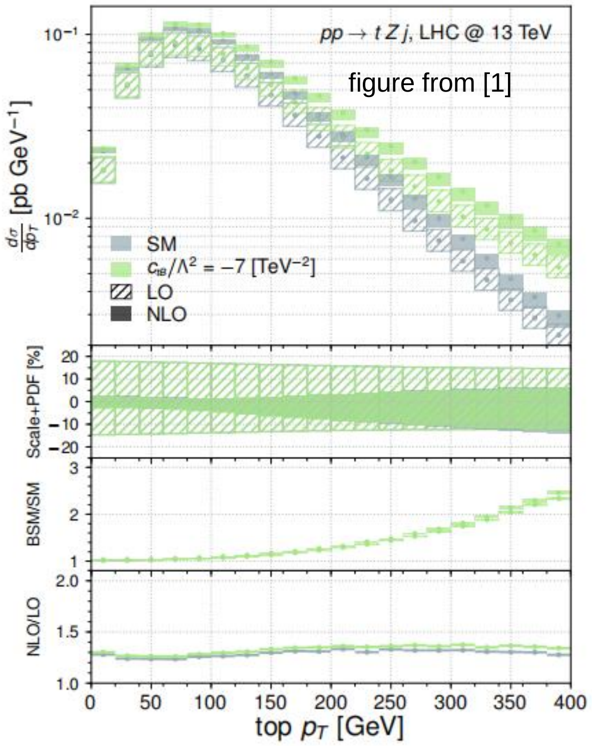
→ precision: ± 14-15%

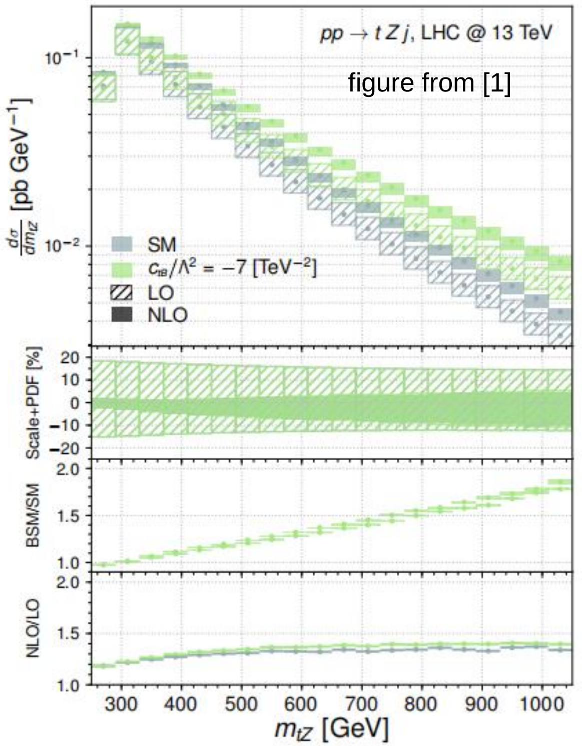


↓

Observation at ATLAS with full Run II dataset [4]

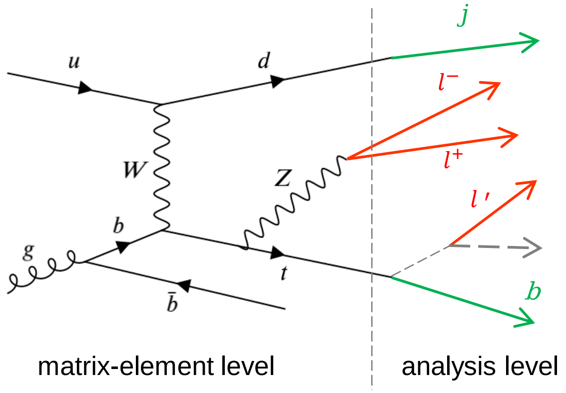
→ precision: ±15%

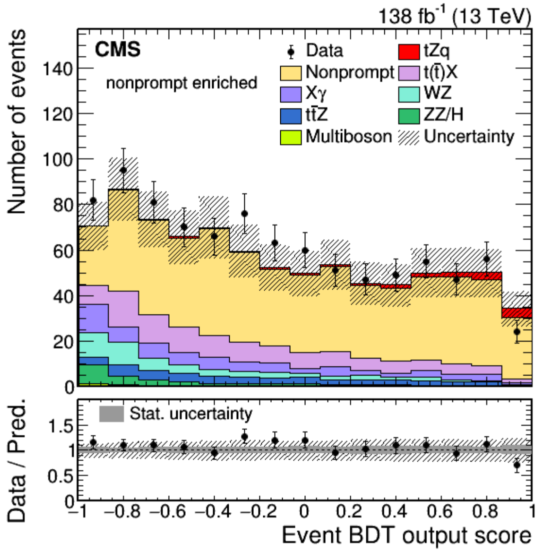




[1]: *JHEP* **10** (2018) 5, doi [2]: *Phys. Lett. B* **779** (2018) 358, doi [3]: *Phys. Rev. Lett.* **122** (2019) 132003, doi [4]: *JHEP* **07** (2020) 124, doi

Inclusive and differential tZq (TOP-20-010)





- 3 leptons (electrons or muons)
  - selection based on new lepton MVA.
- 1 OSSF pair compatible with Z boson mass within 15 GeV.
- ≥ 2 jets ($p_T > 25$ GeV, $|\eta| < 5$).
- < 4 central jets ($|\eta| < 2.4$ (2016) / < 2.5 (2017/2018)) (only in differential).
- ≥ 1 b-jet (medium deepFlavor working point, central).

- Z boson candidate:
  - OSSF lepton pair with $|m_Z - m_{ll}| < 15$ GeV.
- top quark candidate and accompanying b jet
  - reconstructed analytically using W boson and top quark mass constraints.
- recoiling jet
  - non b-tagged jet with highest p_T.
  - tends to be emitted in forward region of the detector.

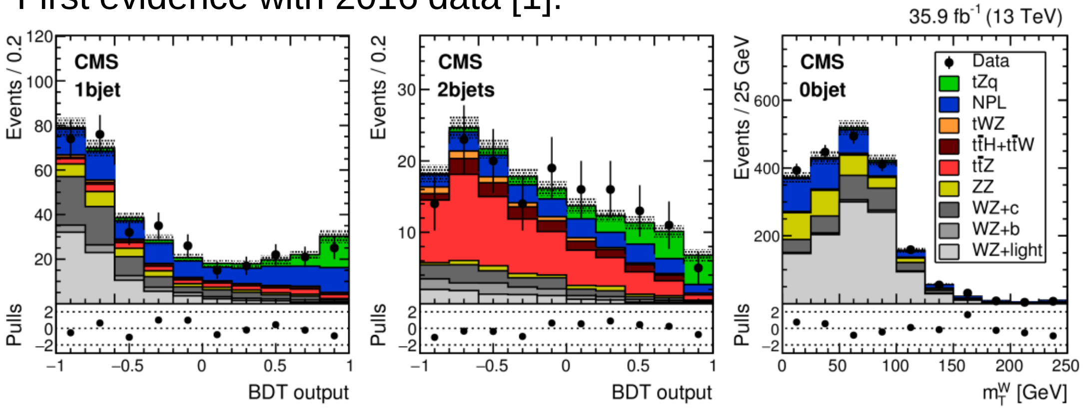
- background from nonprompt leptons estimated from data and uncertainty constrained in dedicated nonprompt control region.

- discriminating features based on presence of a hard forward jet, presence of at least one b-jet, charge asymmetry of the top quark etc.
- combined into MVA (multiclass NN or BDT) to distinguish tZq from WZ, ttZ and others.

Inclusive and differential tZq (TOP-20-010)

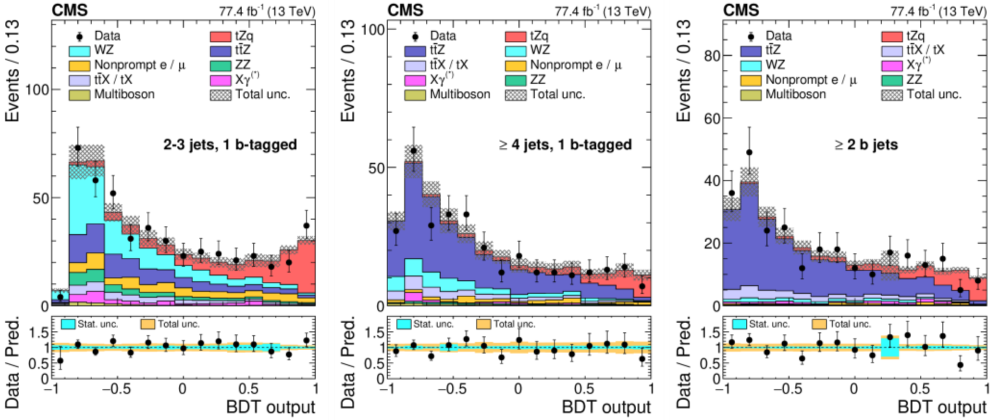
Standard model prediction:
$\sigma^{SM}_{tZq} = 94.2^{+1.9}_{-1.8}\ (\text{scale}) \pm 2.5\ (\text{PDF})$ fb [1]

First evidence with 2016 data [1]:



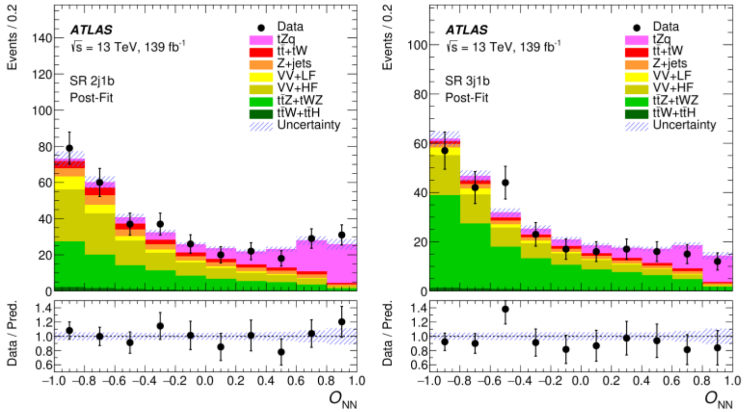
$\sigma_{tZq} = 123^{+33}_{-31}\ (\text{stat.})\ ^{+29}_{-23}\ (\text{syst.})$ fb
significance = 3.7 (obs.) / 3.1 (exp.)

First observation with 2016+2017 data [2]:



$\sigma_{tZq} = 111 \pm 13\ (\text{stat.})\ ^{+11}_{-9}\ (\text{syst.})$ fb (→ precision: ± 14-15%)
significance = 8.2 (obs.) / 7.7 (exp.)

Observation at ATLAS with full Run II dataset [3]:



$\sigma_{tZq} = 97 \pm 13\ (\text{stat.}) \pm 7\ (\text{syst.})$ fb (→ precision: ±15%)

Significance >> 5σ → observation has been established.
Next challenges: improve precision on σ_{tZq}.
perform first differential measurement.

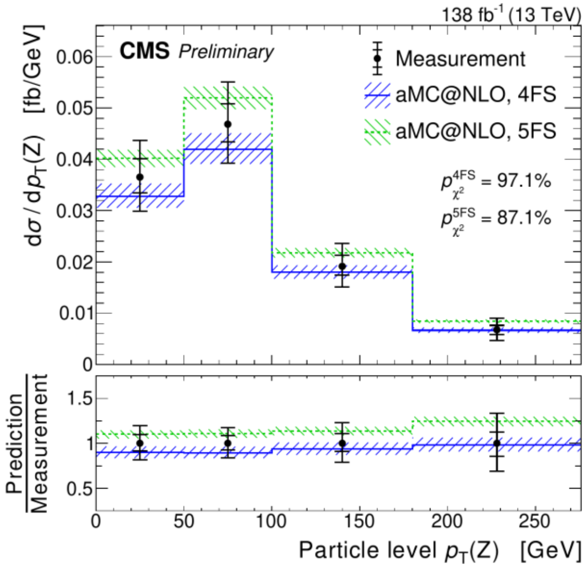
[1]: *Phys. Lett. B* **779** (2018) 358, doi
[2]: *Phys. Rev. Lett.* **122** (2019) 132003, doi
[3]: *JHEP* **07** (2020) 124, doi

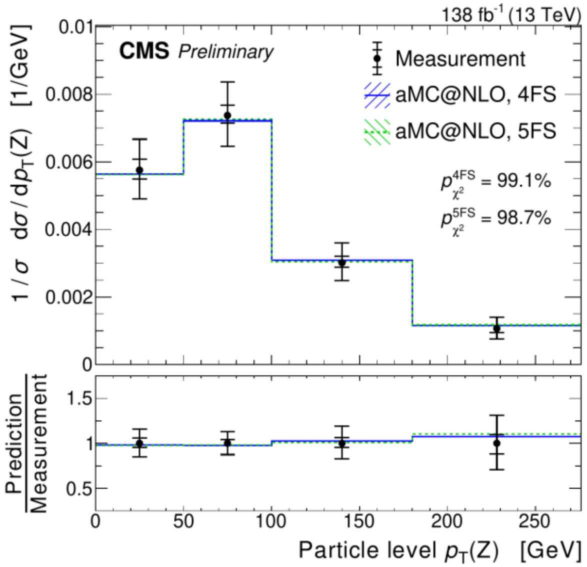
Inclusive and differential tZq (TOP-20-010)

absolute

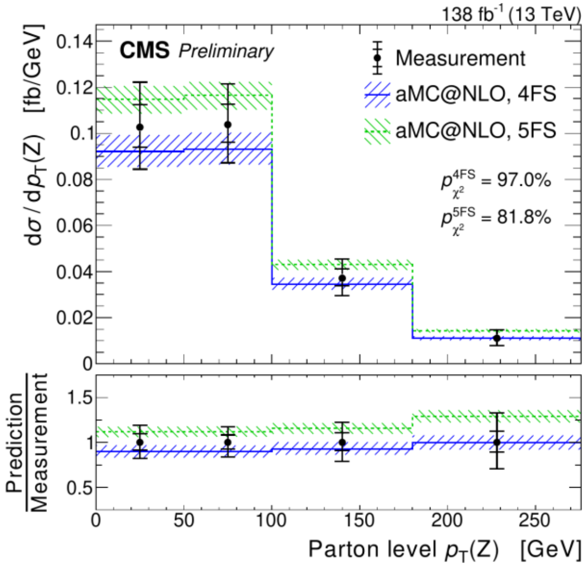
normalized

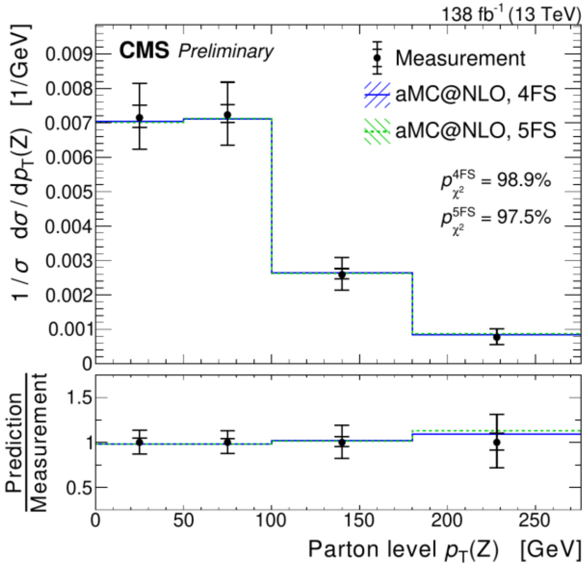
particle level





parton level





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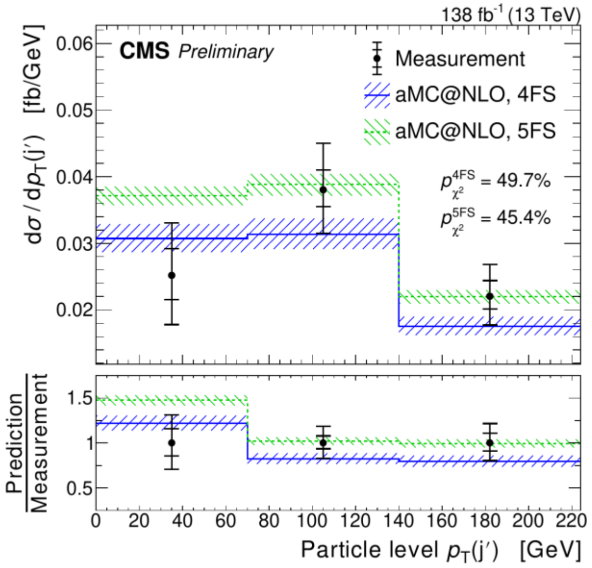
- Compared to both 4FS and 5FS prediction.
- Uncertainties down to 15% for purely leptonic observables, down to 25% for observables including jets.

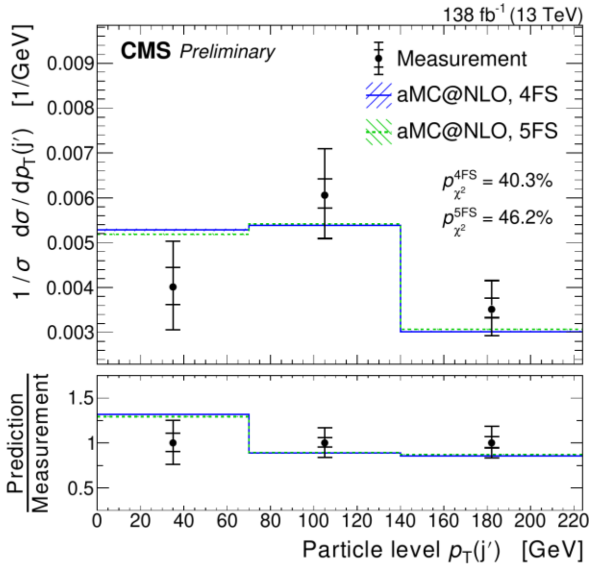
Inclusive and differential tZq (TOP-20-010)

absolute

normalized

particle level





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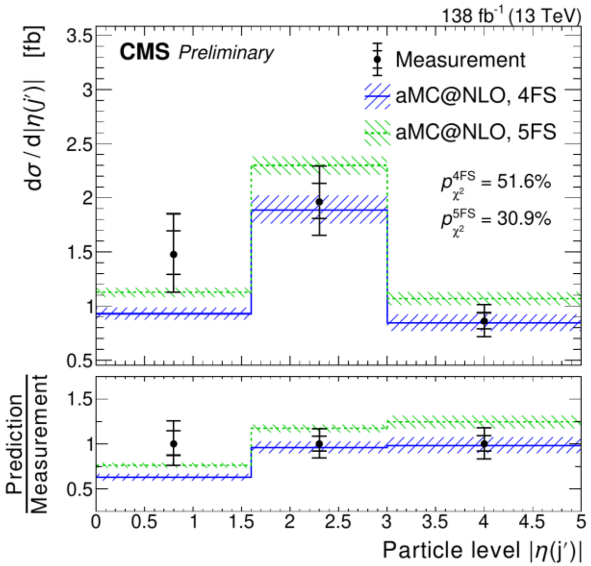

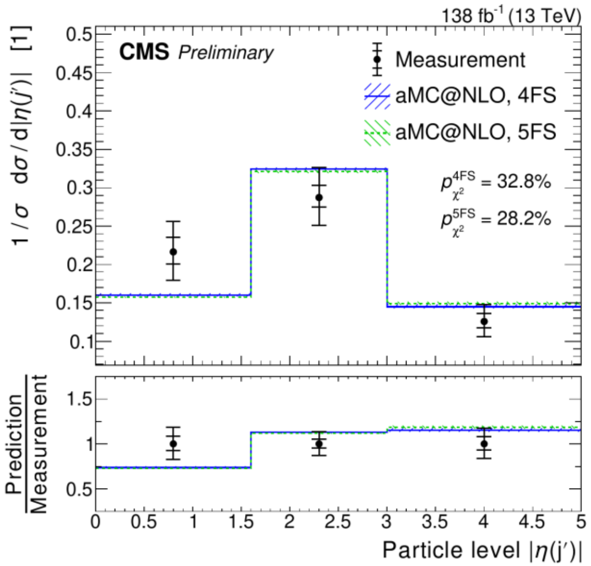

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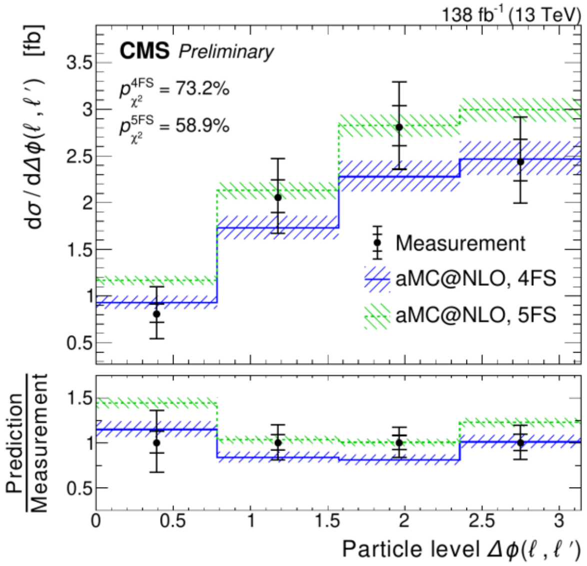
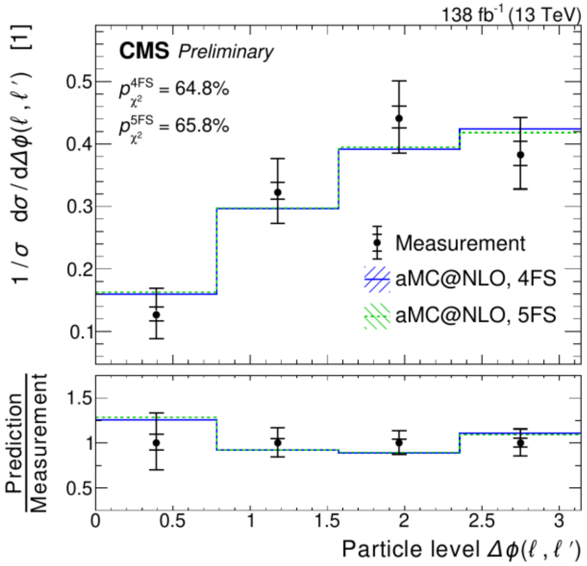
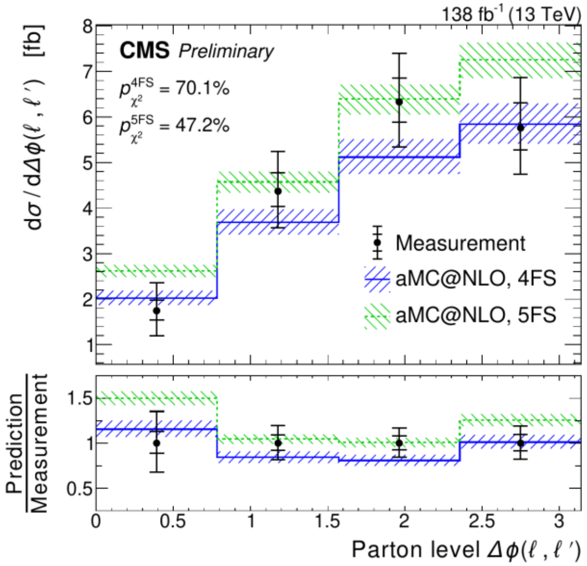
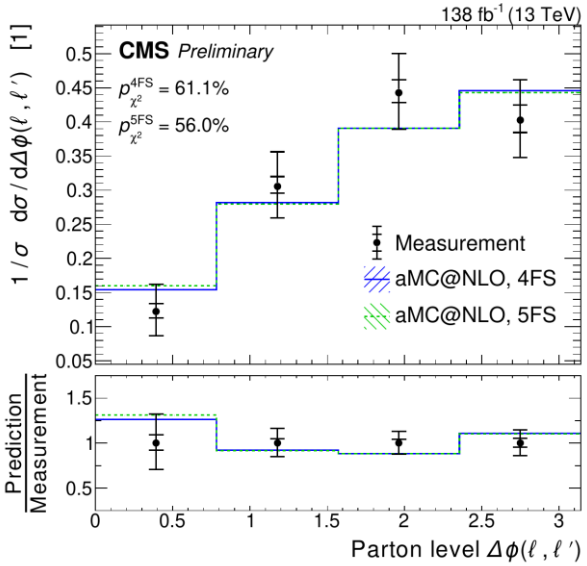




parton level





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absolute | normalized

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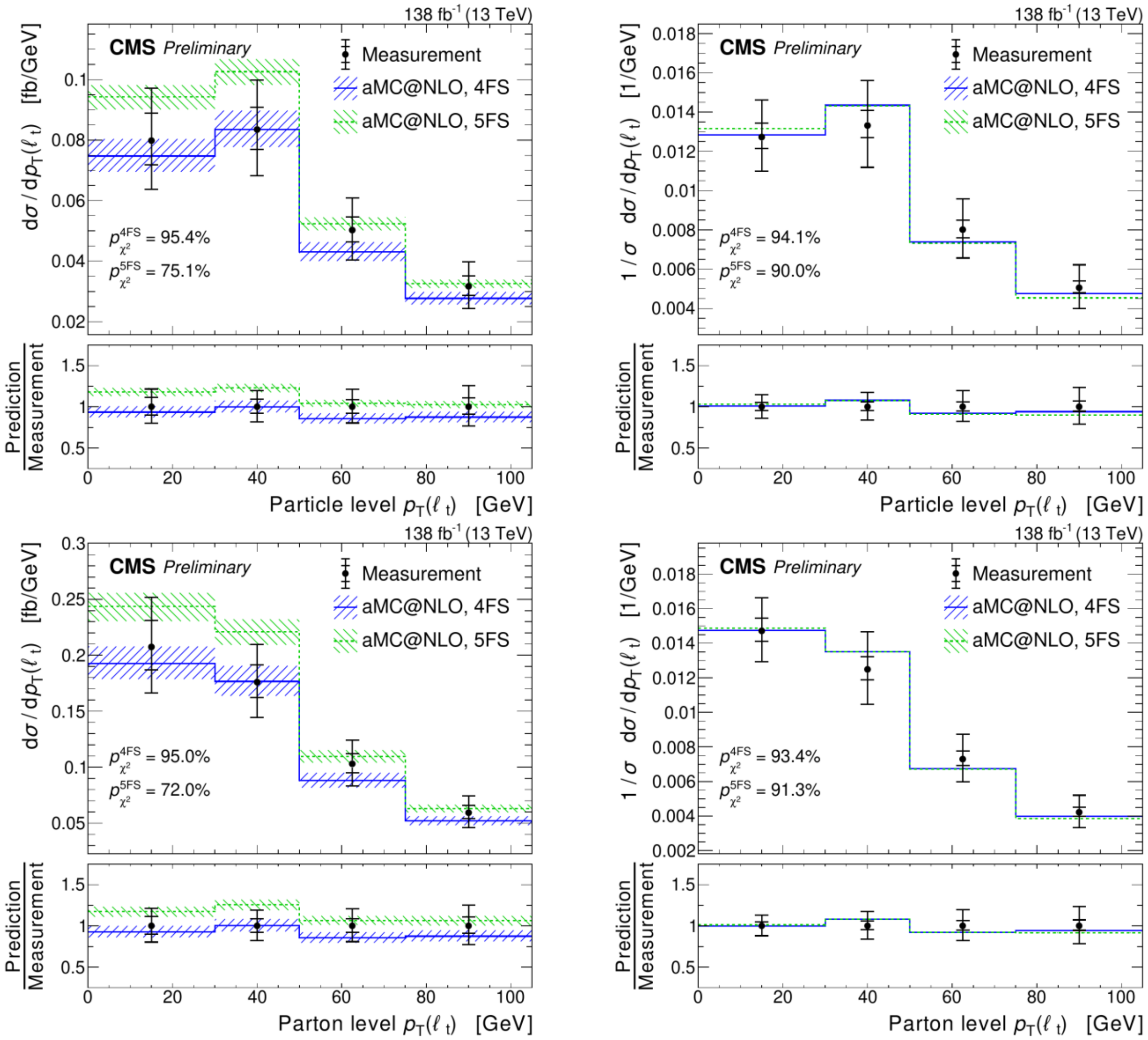

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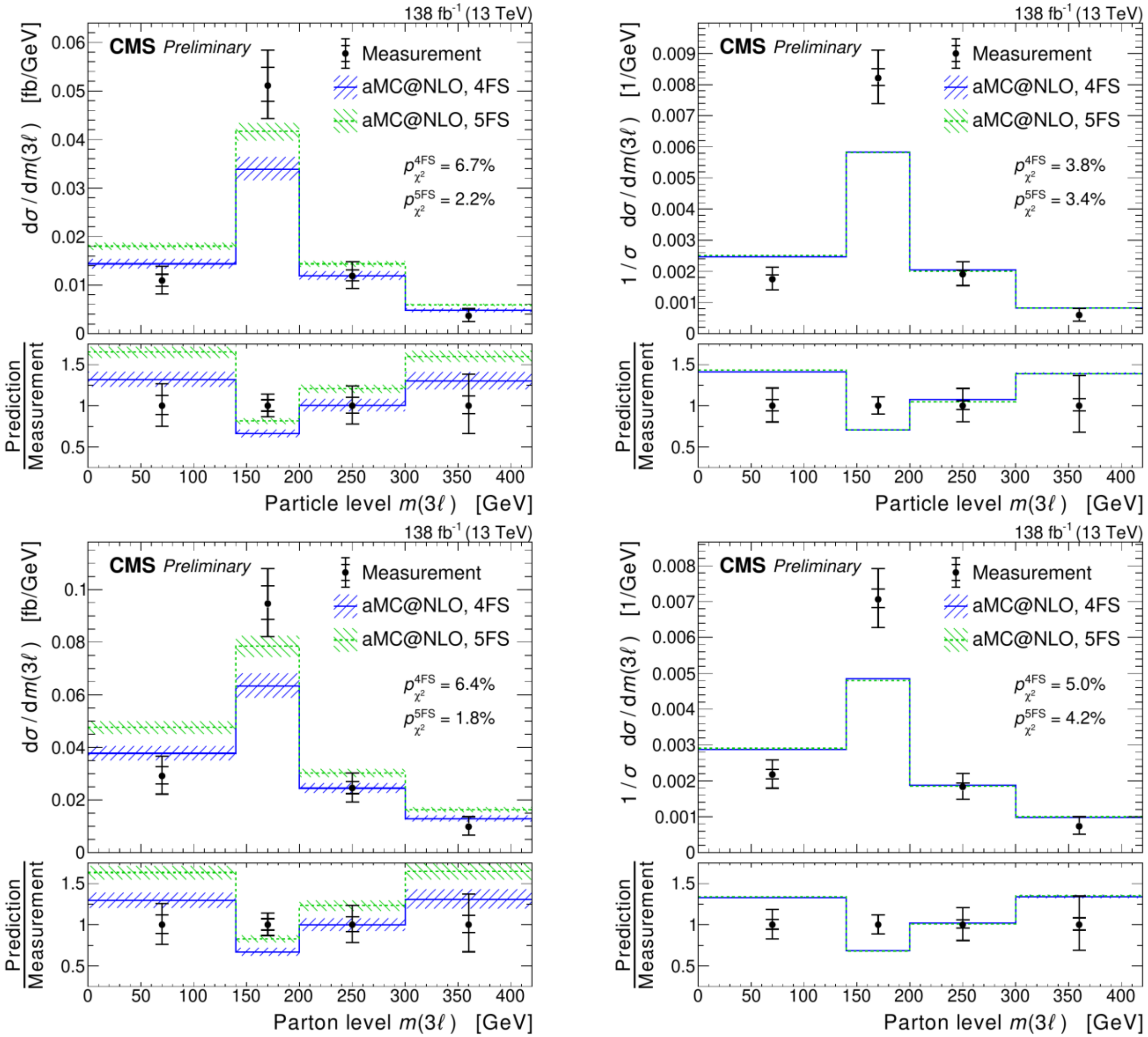

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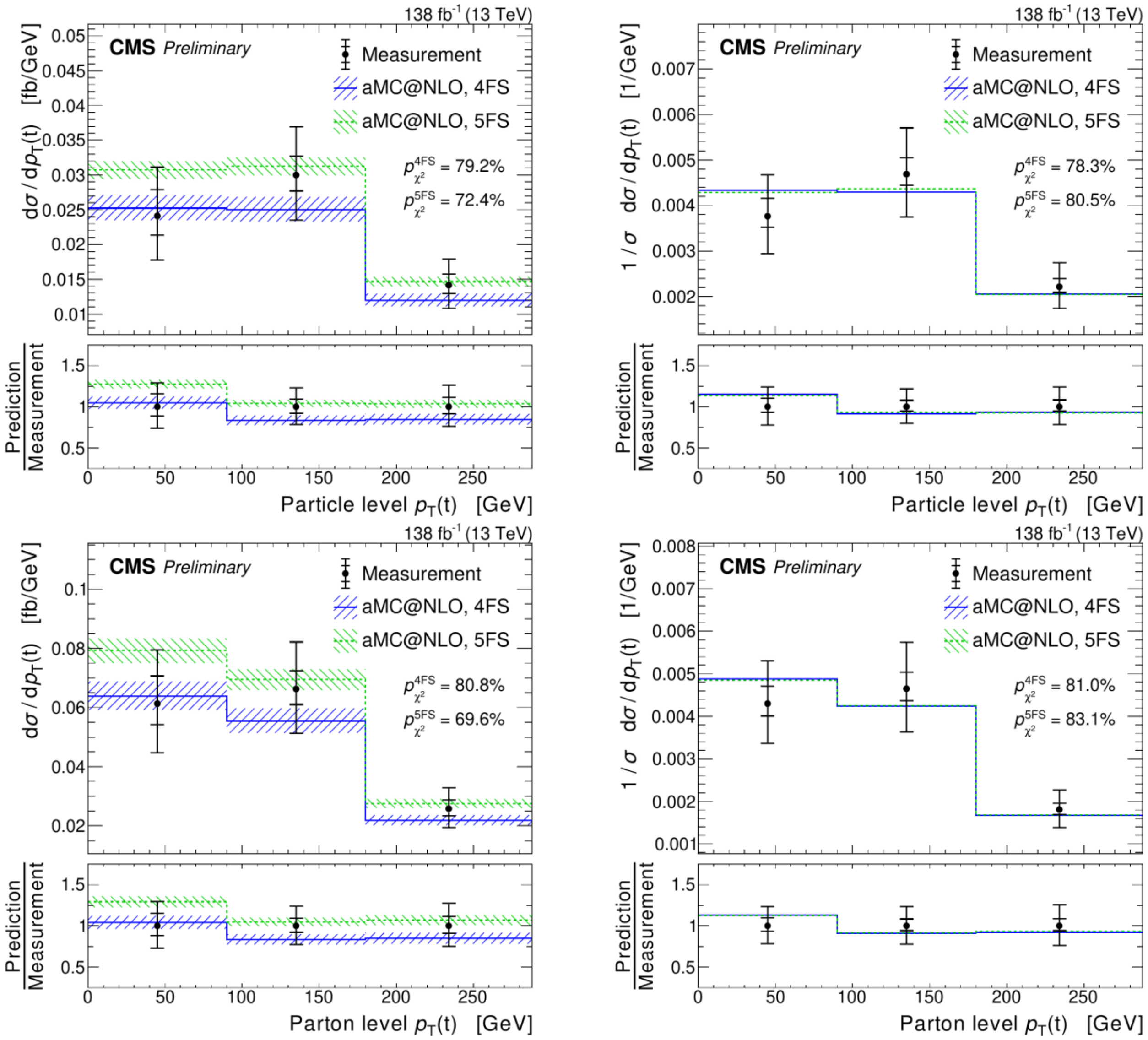

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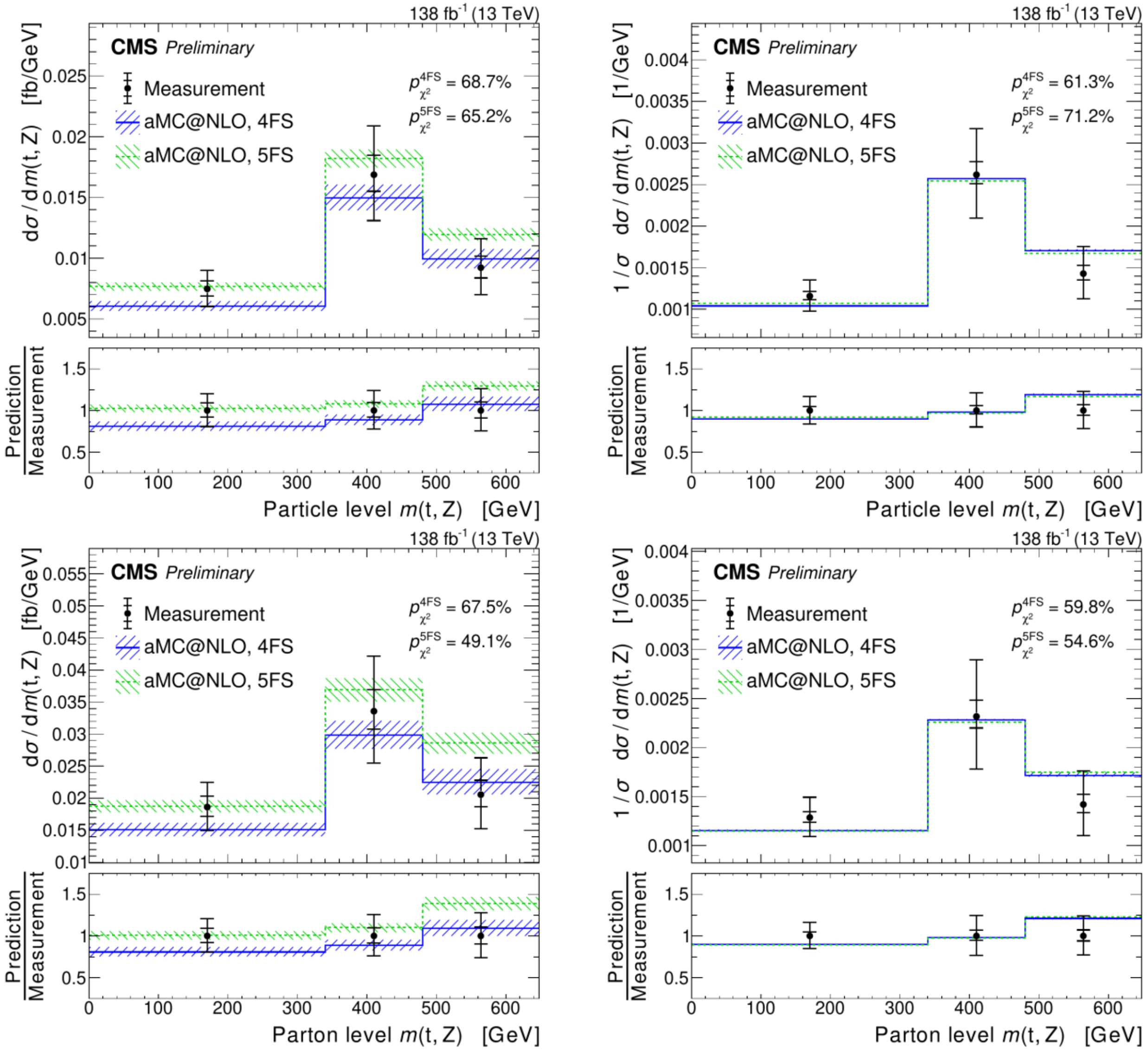
absolute normalized

particle level

parton level



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absolute | normalized

particle level

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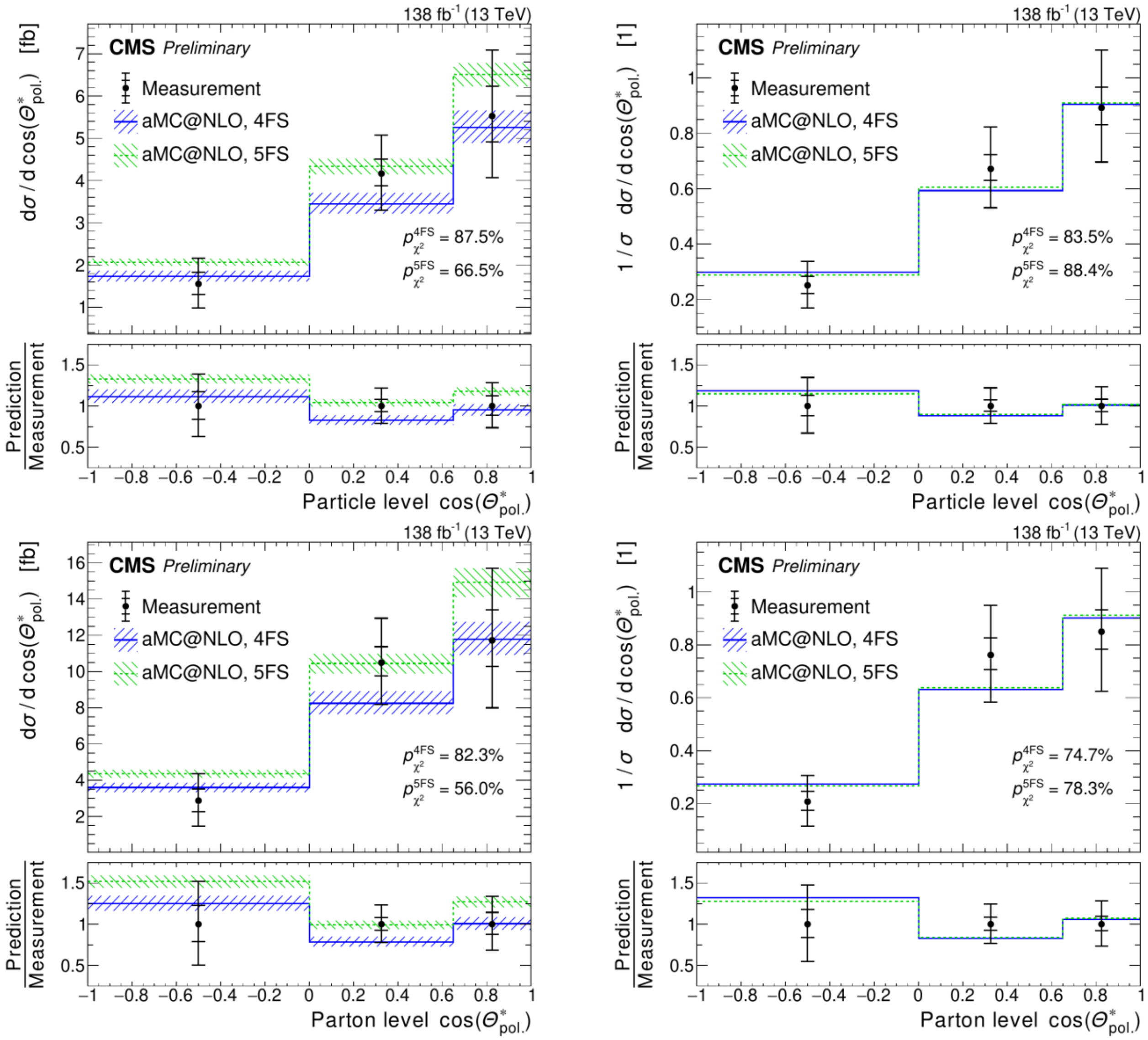

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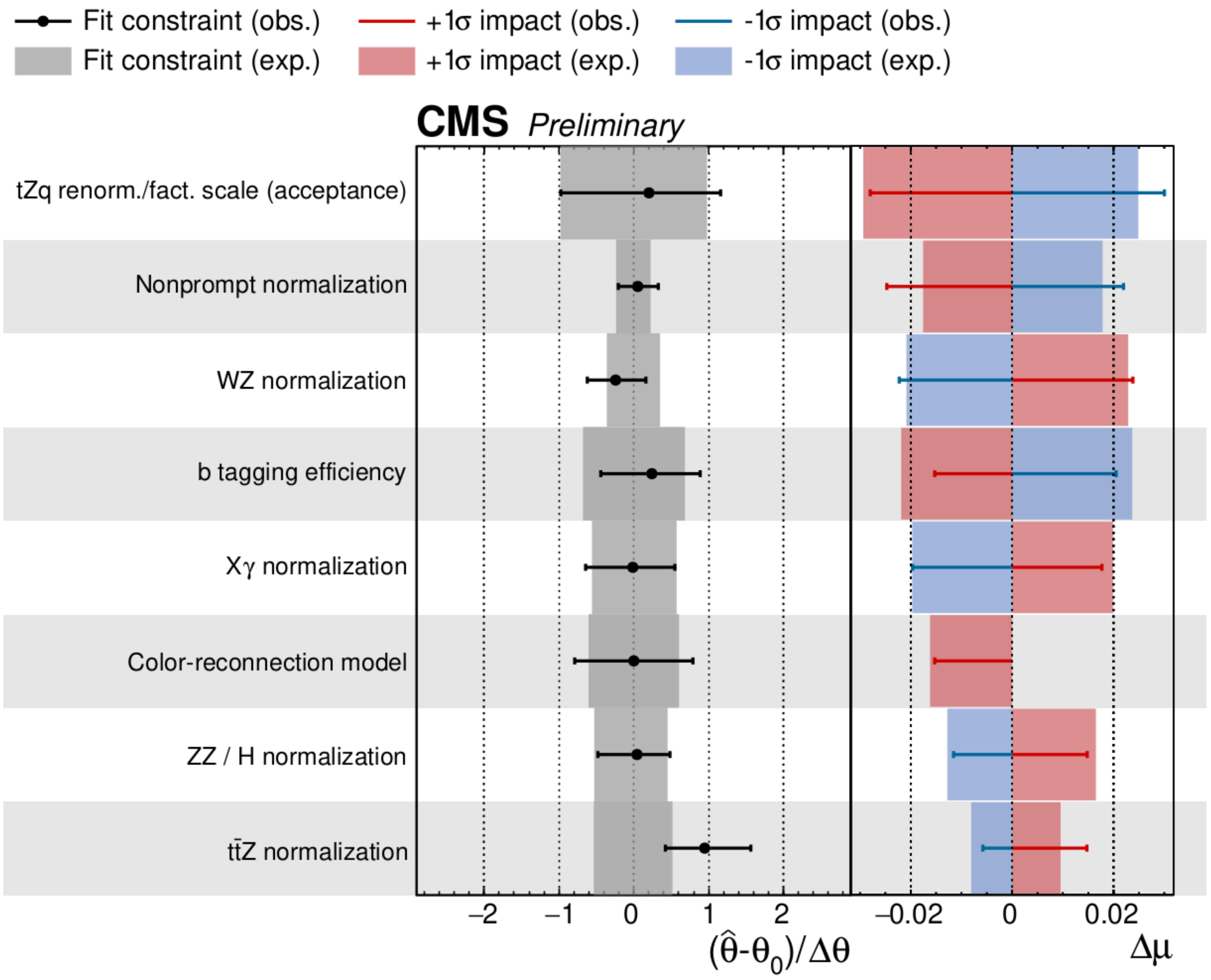
Inclusive and differential tZq (TOP-20-010)



"Summary of the dominant systematic uncertainties affecting the inclusive tZq cross section measurement. The left column lists the sources of systematic uncertainty, treated as nuisance parameters in the fit, in order of importance. In the middle column, the black points with the horizontal bars show for each source the difference between the observed best-fit value ($\hat{\theta}$) and the nominal value (θ_i), divided by the expected standard deviation ($\Delta\theta$). The right column plots the change in the tZq signal strength μ if a nuisance parameter is varied one standard deviation up (red), or down (blue). The gray, red and blue bands display the same quantity as their corresponding markers, but using a simulated data set where all nuisance parameters are set to their expected values."

EFT operators tZq/ttZ (TOP-21-001)

Introduction:

- Model-independent parametrization of physics beyond the standard model, in the form of additional operators added to the SM Lagrangian.
- Studied 5 operators that affect t-Z coupling:

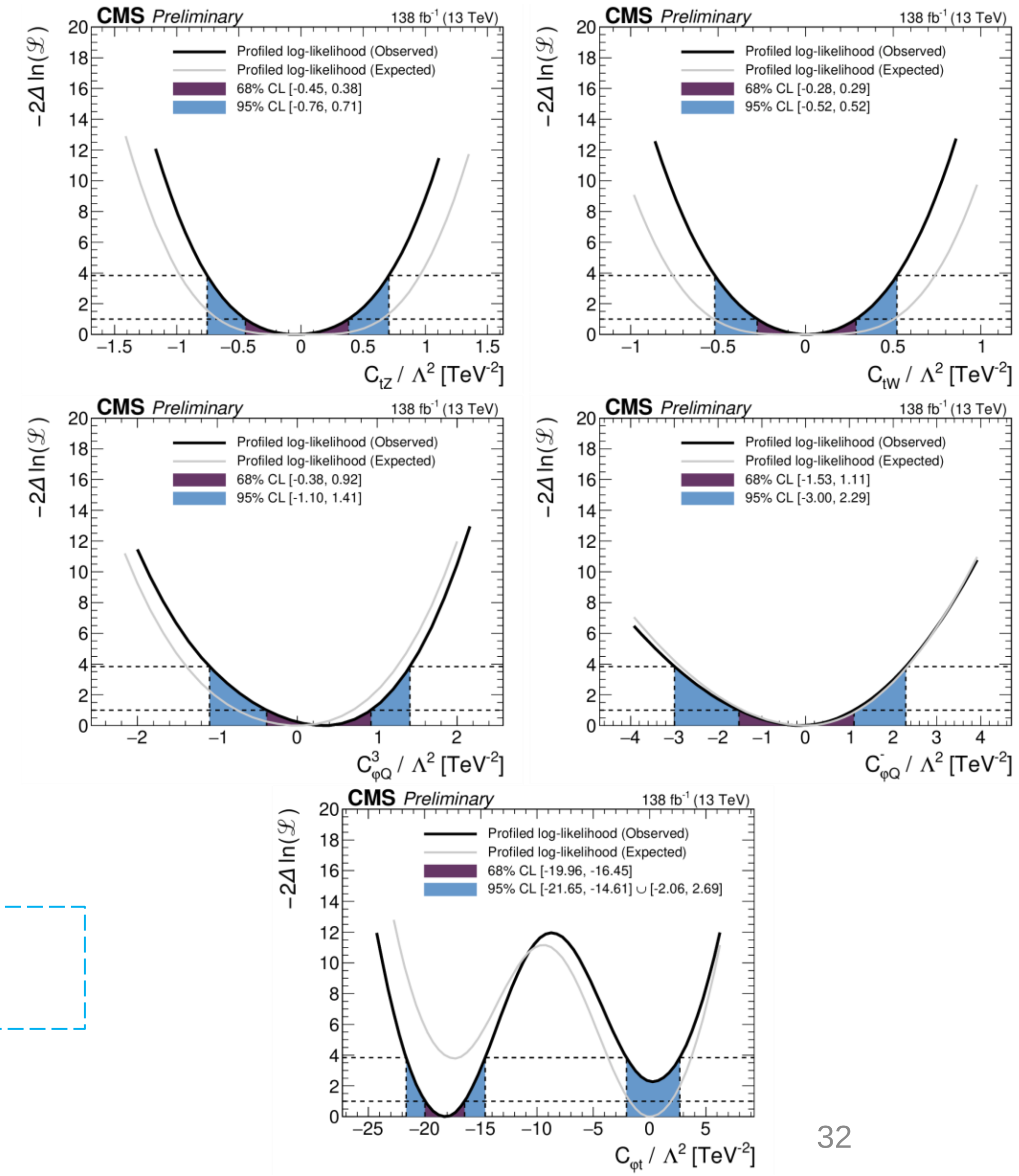
$$O_{tZ},\ O_{tW},\ O^{l}_{\varphi Q},\ O^{-}_{\varphi Q},\ O_{\varphi t}$$

Analysis in a nutshell:

- event selection targeted at ttZ, tZq and tW,
  similar to tZq analysis but including 4-lepton channel.
- parametrized reweighting of signal samples to access every relevant phase space point.
- innovative machine learning techniques:
  multiclass neural network to separate ttZ and tZq from backgrounds,
  binary neural networks to distinguish EFT.
- binned maximum likelihood fit with Wilson coefficients as POIs (1D scans, 2D scans, 5D fit).

Results:

SM values for all Wilson coefficients within 95% confidence interval.



EFT operators tZq/ttZ (TOP-21-001)

Source	c_{tZ}	c_{tW}	$c^{3}_{\varphi Q}$	$c^{-}_{\varphi Q}$	$c_{\varphi t}$
tZq normalization	<0.1	<0.1	1.2	0.1	0.8
$t\bar{t}Z$ normalization	0.6	<0.1	0.4	37.2	38
tWZ normalization	0.1	0.1	<0.1	0.7	2.1
Background normalizations	<0.1	<0.1	6.9	3.6	6.8
NPL background estimation	1.4	0.2	5.6	0.3	3.8
Jet energy scale	<0.1	<0.1	0.8	0.7	2.3
Jet energy resolution	<0.1	<0.1	<0.1	<0.1	1.4
p_{T}^{miss}	<0.1	<0.1	<0.1	<0.1	0.2
b tagging	<0.1	<0.1	0.9	2.0	0.3
Other (experimental)	<0.1	<0.1	1.6	0.8	0.6
Lepton identification and isolation	0.4	0.4	1.2	2.2	0.8
Theory	2.1	1.1	0.4	0.9	0.9

statistically limited

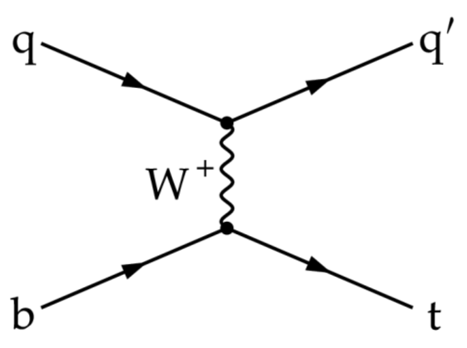
systematically limited

"Impacts from different groups of sources of systematic uncertainty on each individual WC. To estimate the impact of a given group, the corresponding sources of systematic uncertainty are excluded, the 1D fits to the data are repeated, and the reduction in the width of the confidence interval is quoted for each WC in %."

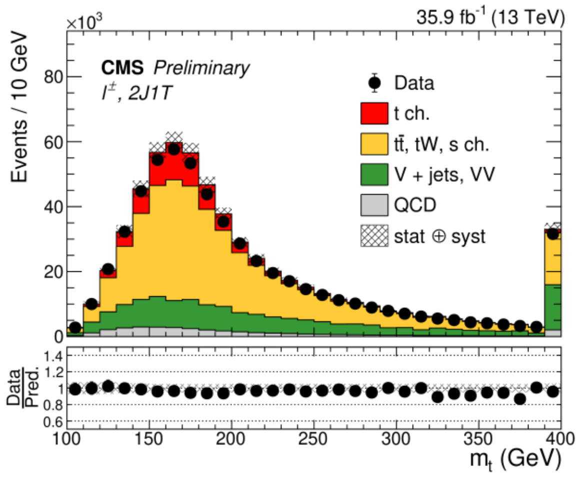
top quark mass (TOP-19-009)

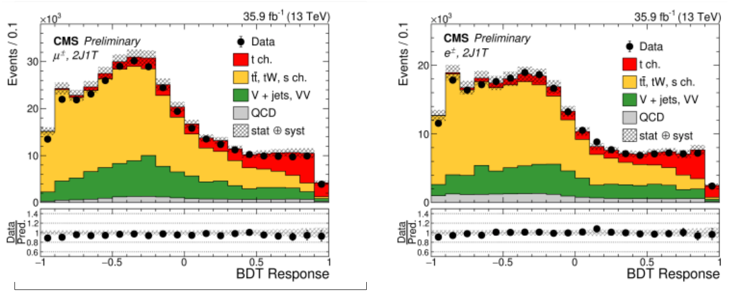
reference: TOP-19-009

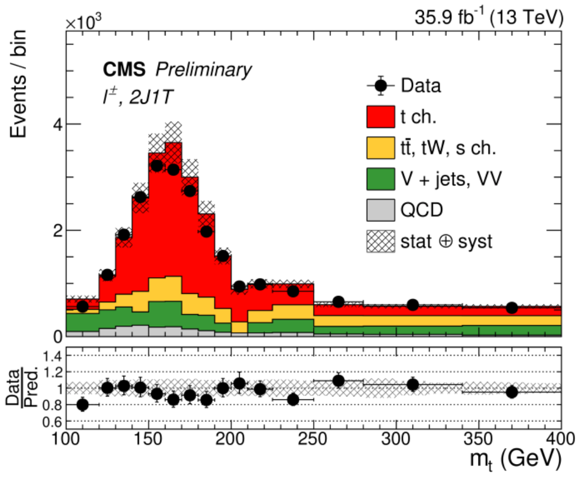
Motivation:
- top quark mass is important parameter of the standard model.
- most precisely measured in $t\bar{t}$ [1,2].
- measurement in t-channel single top provides complementary information (different phase space, different systematic effects).



Analysis in a nutshell:
- single lepton trigger, one isolated lepton with $p_T > 26/35$ GeV (muon/electron).
- two jets with $p_T > 40$ GeV and $|\eta| < 4.7$, of which one b-tagged jet.
- reconstructed transverse W boson mass $>$ 50 GeV.
- top quark mass reconstructed analytically from lepton, b-tagged jet and $\vec{p}_T^{\,miss}$.
- BDT to purify signal region.







[1] *The European Physical Journal C* **79** (2019) 290 doi

[2] *Phys. Rev. D* **93** (2016) 072004, doi

top quark mass (TOP-19-009)

reference: TOP-19-009

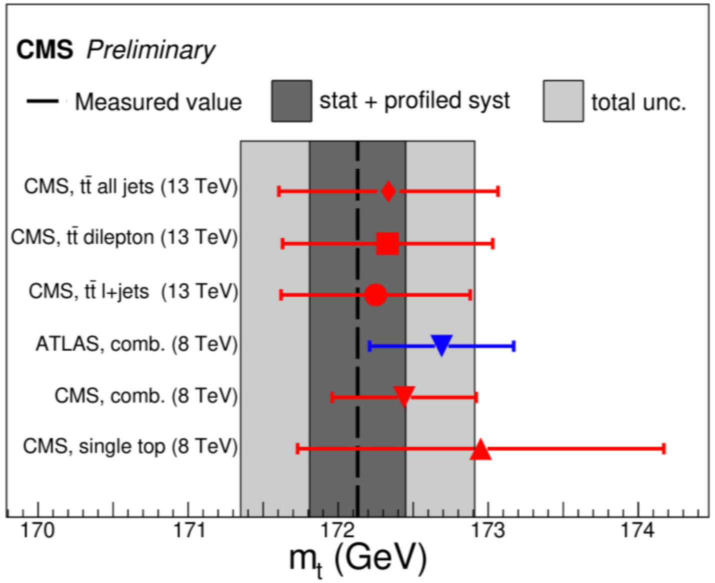
Top quark mass extraction:
- fit to logarithm of reconstructed top mass.
- template shapes fitted to MC simulation.
- normalizations + signal peak value left floating in the fit.

Results:

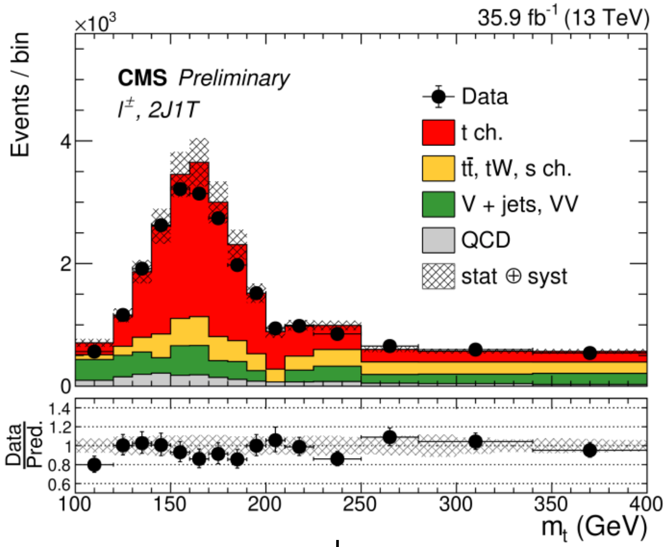
$$m_t = 172.13 \pm 0.32\ (\text{stat} + \text{prof})^{\mathtt{digor}}_{-\mathtt{igpi}}\ (\text{syst}) = 172.13^{\mathtt{digpo}}_{-\mathtt{igpp}}\ \text{GeV}$$

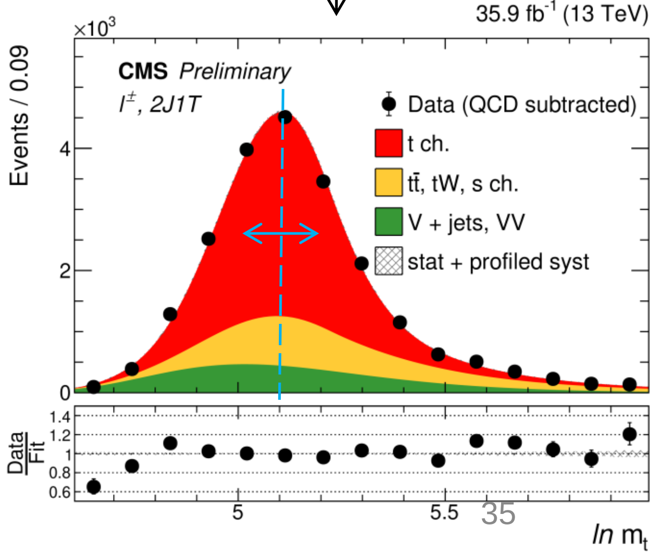
$$m_t = 172.62 \pm 0.37\ (\text{stat} + \text{prof})^{\mathtt{digrp}}_{-\mathtt{igon}}\ (\text{syst}) = 172.62^{\mathtt{djgim}}_{-\mathtt{igpn}}\ \text{GeV}$$

$$m_t = 171.79 \pm 0.58\ (\text{stat} + \text{prof})^{\mathtt{djglk}}_{-\mathtt{jglr}}\ (\text{syst}) = 171.79^{\mathtt{djgmm}}_{-\mathtt{jgnj}}\ \text{GeV}$$

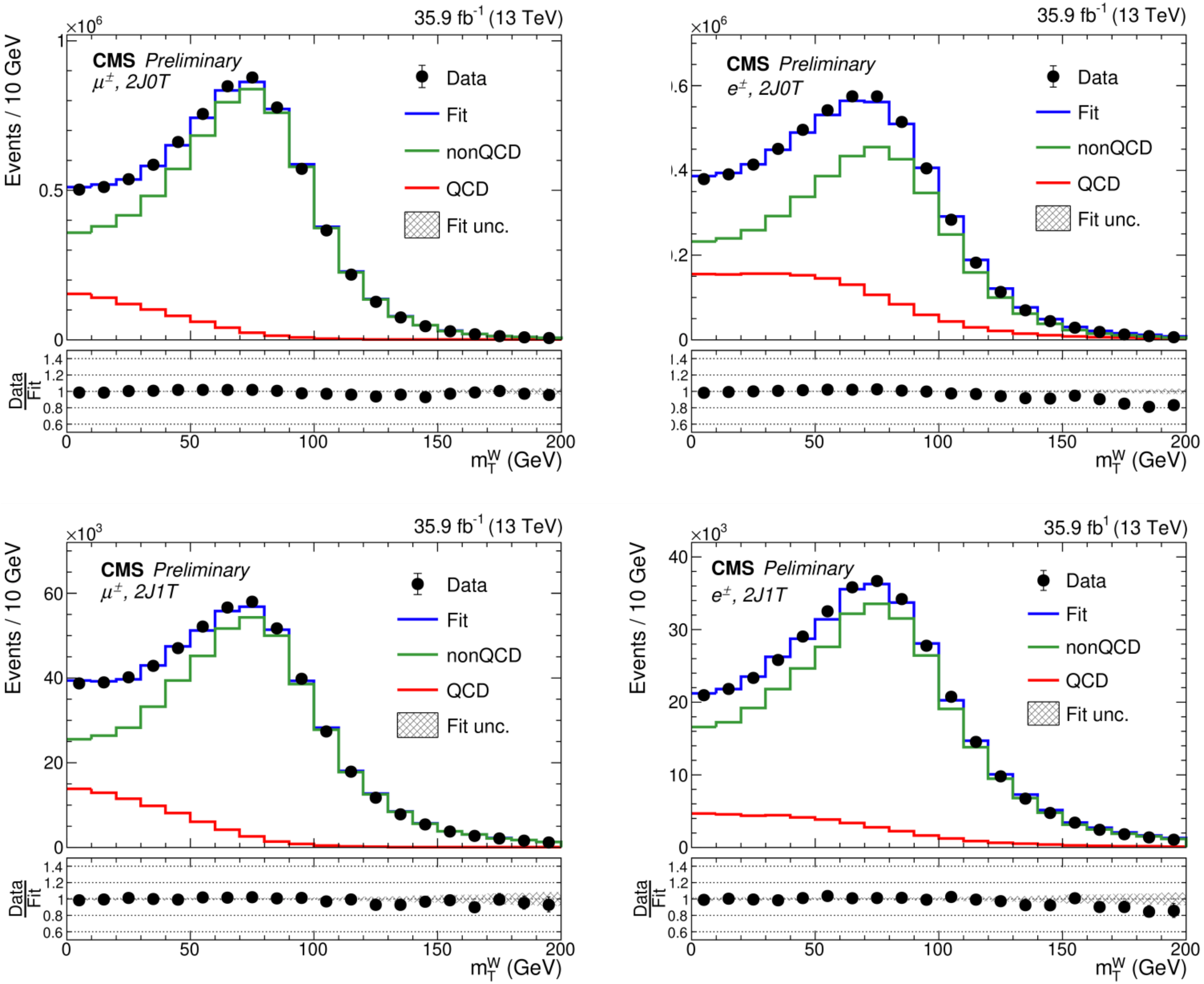


Dominating sources of systematic uncertainty:
- jet energy corrections
- signal modeling (mainly final-state radiation)





top quark mass (TOP-19-009)



nonprompt background estimation from data:

- define sideband to signal region by requiring muon and electron to fail tight identification requirements → enriched in QCD.
- derive QCD templates in this sideband by subtracting all non-QCD contributions (from MC simulation) from the data.
- calculate the normalization of these templates by fitting QCD template + non-QCD contributions (from MC simulation) to the data in the signal region, using transverse W boson mass.

figures:
“Figure 3: Postfit distributions of mtW for the muon (left) and electron (right) final state in the 2J0T (top) and 2J1T (bottom) event categories. The bands represent the postfit uncertainty on the mtW distribution predicted by the fit.”

top quark mass (TOP-19-009)

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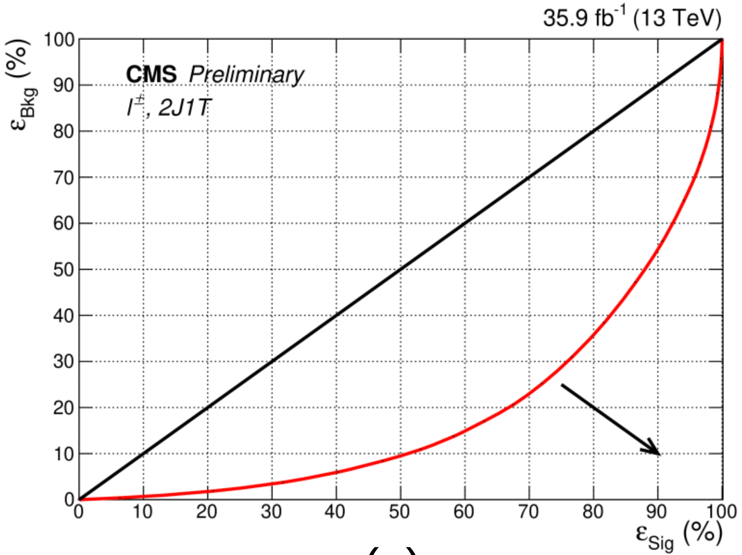
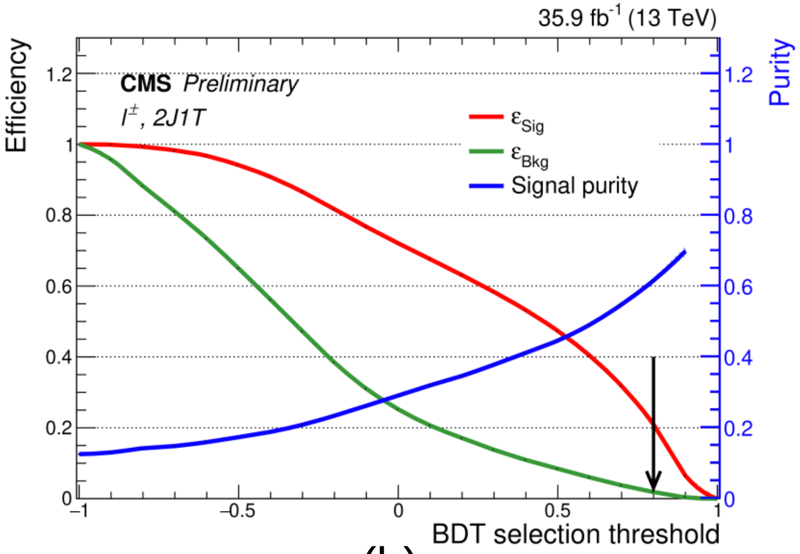
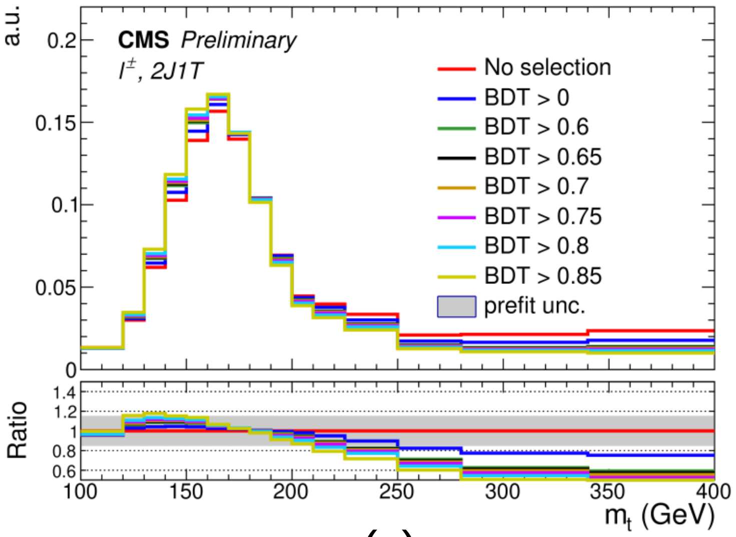


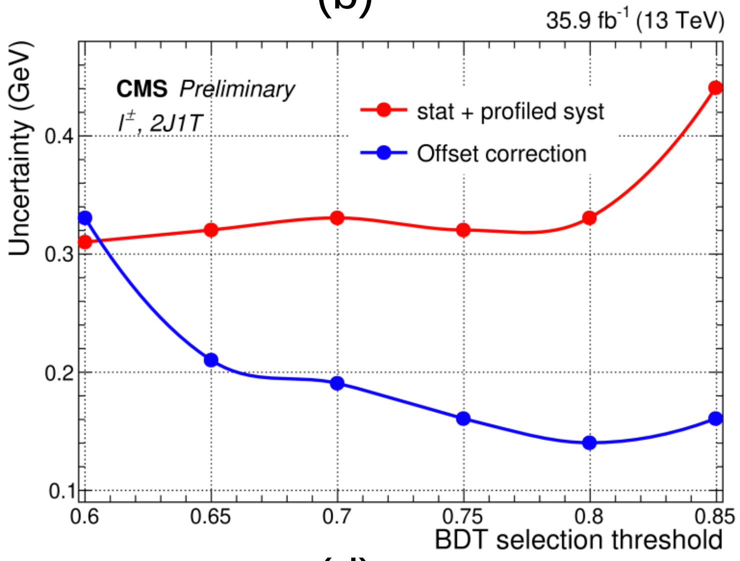
(a)



(b)



(c)



(d)

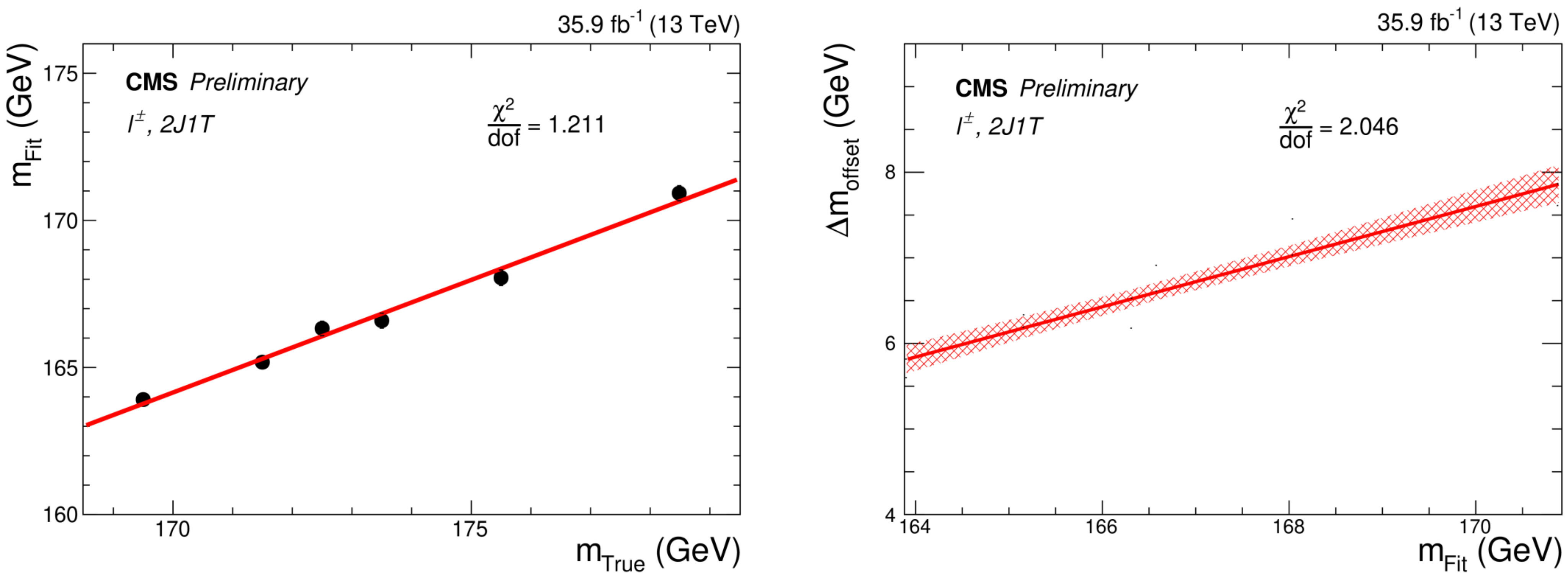
(a) ROC curve for the combined performance of the BDTs in muon and electron final states.

(b) Signal and background efficiencies + signal purity as a function of BDT selection threshold.

(c) Correlation study of BDT response to reconstructed top mass: comparison of normalized mt distribution without BDT cut (red) and after several BDT cuts (other colors).

(d) Uncertainties on the mass measurement as a function of BDT selection threshold (evaluated using pseudoexperiments with simulated events).

top quark mass (TOP-19-009)



"Test of the linearity of the fit output for different values of true mt (left) and resulting offset correction derived as a function of the postfit mass (right) for events in the 2J1T category [...]. The shaded regions indicate ± 1 standard deviations about the central values defined by the red line."

top quark mass (TOP-19-009)

Source		$\delta m_{\ell^\pm}$	δm_{ℓ^+}	δm_{ℓ^-}
Statistical + profiled systematic		±0.32	±0.37	±0.58
JES	Correlation Group Intercalibration	±0.09	±0.07	±0.12
	Correlation Group MPFInSitu	±0.02	±0.02	±0.01
	Correlation Group Uncorrelated	±0.39	±0.17	±0.83
	total (quadrature sum)	±0.40	±0.18	±0.84
JER		$< \pm0.01$	$< \pm0.01$	$< \pm0.01$
Unclustered energy		$< \pm0.01$	$< \pm0.01$	$< \pm0.01$
Muon efficiencies		$< \pm0.01$	$< \pm0.01$	$< \pm0.01$
Electron efficiencies		±0.01	±0.01	±0.01
Pileup		±0.14	±0.04	±0.34
b tagging		±0.20	±0.18	±0.22
QCD multijet background		±0.02	±0.01	±0.02
Offset correction		±0.11	±0.13	±0.20
Luminosity		$< \pm0.01$	$< \pm0.01$	±0.01
CR model and ERD		±0.24 (0.017)	±0.39 (0.027)	±0.68 (0.048)
Flavor-dependent JES	gluon	$+0.52$	$+0.75$	-0.03
	light quark (uds)	-0.18	$+0.18$	-0.23
	charm	$+0.01$	$+0.08$	$+0.11$
	bottom	-0.48	-0.29	-0.31
	total (linear sum)	-0.13	$+0.72$	-0.46
b quark hadronization model	b frag. Bowler-Lund	±0.03	±0.06	±0.08
	b frag. Peterson	$+0.14$	$+0.11$	$+0.19$
	semileptonic B decays	±0.18	±0.17	±0.19
	total (quadrature sum)	$^{+0.23}_{-0.18}$	$^{+0.21}_{-0.18}$	$^{+0.28}_{-0.21}$
Signal modeling	ISR	±0.01	±0.01	$< \pm0.01$
	FSR	±0.28	±0.31	±0.20
	μ_R/μ_F scale	±0.09	±0.13	±0.03
	PDF + α_S	±0.06	±0.06	±0.07
	total (quadrature sum)	±0.30	±0.34	±0.21
$t\bar{t}$ modeling	ISR	±0.11 (0.008)	±0.02 (0.001)	±0.22 (0.016)
	FSR	±0.10 (0.007)	±0.14 (0.010)	±0.40 (0.028)
	ME/PS matching scale	±0.10 (0.007)	±0.10 (0.006)	±0.10 (0.008)
	μ_R/μ_F scale	±0.03	±0.03	±0.01
	PDF + α_S	$< \pm0.01$	$< \pm0.01$	$< \pm0.01$
	Top p_T- reweighting	-0.04	-0.08	-0.04
	Underlying event	±0.07 (0.005)	±0.04 (0.003)	±0.17 (0.012)
	total (quadrature sum)	±0.20	$^{+0.18}_{-0.20}$	±0.50
Signal and background shape	signal shape	±0.05	±0.03	±0.04
	Top bkg. shape	±0.07	±0.04	±0.05
	EWK bkg. shape	±0.03	±0.01	±0.02
	total (quadrature sum)	±0.09	±0.05	±0.07
Total systematic		$^{+0.69}_{-0.71}$	$^{+0.97}_{-0.65}$	$^{+1.32}_{-1.39}$
Grand total		$^{+0.76}_{-0.77}$	$^{+1.04}_{-0.75}$	$^{+1.44}_{-1.51}$

“Summary of systematic uncertainties in GeV corresponding to final state lepton charge inclusive and exclusive cases as discussed in Section 7. With the exception of the flavor-dependent JES sources, the total systematic uncertainty is obtained from the sum in quadrature of the individual systematic source. The statistical uncertainties on the systematic shifts are quoted within parentheses whenever alternative simulated samples with systematic variations have been used. These statistical uncertainties are determined from 1000 pseudoexperiments in each case.”

differential t-channel single top (TOP-17-023)

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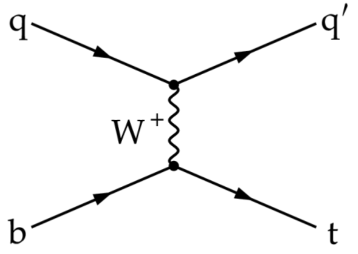
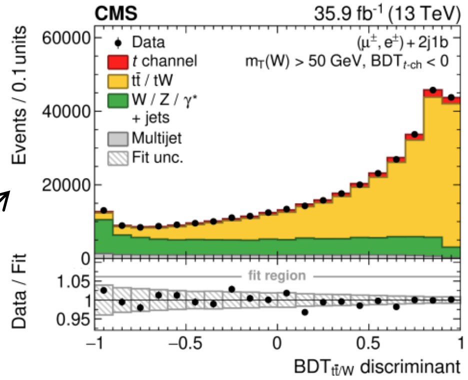
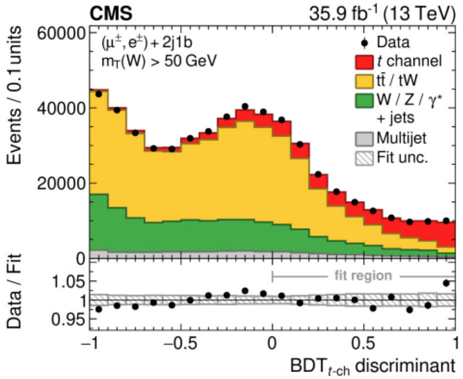
Analysis in a nutshell:
- single electron and single muon trigger.
- 1 electron/muon.
- 2 jets, 1 b jet.
- control regions with different number of (b-) jets.
- top quark candidate reconstructed analytically using W boson mass constraint.
- background from QCD multijet estimated from data.
- trained 2 BDT's:
  - signal vs. all backgrounds ($\mathrm{BDT}_{\mathrm{t-channel}}$)
  - $\mathrm{t\bar{t}}$ vs. W+jets ($\mathrm{BDT}_{\mathrm{t\bar{t}/W}}$)





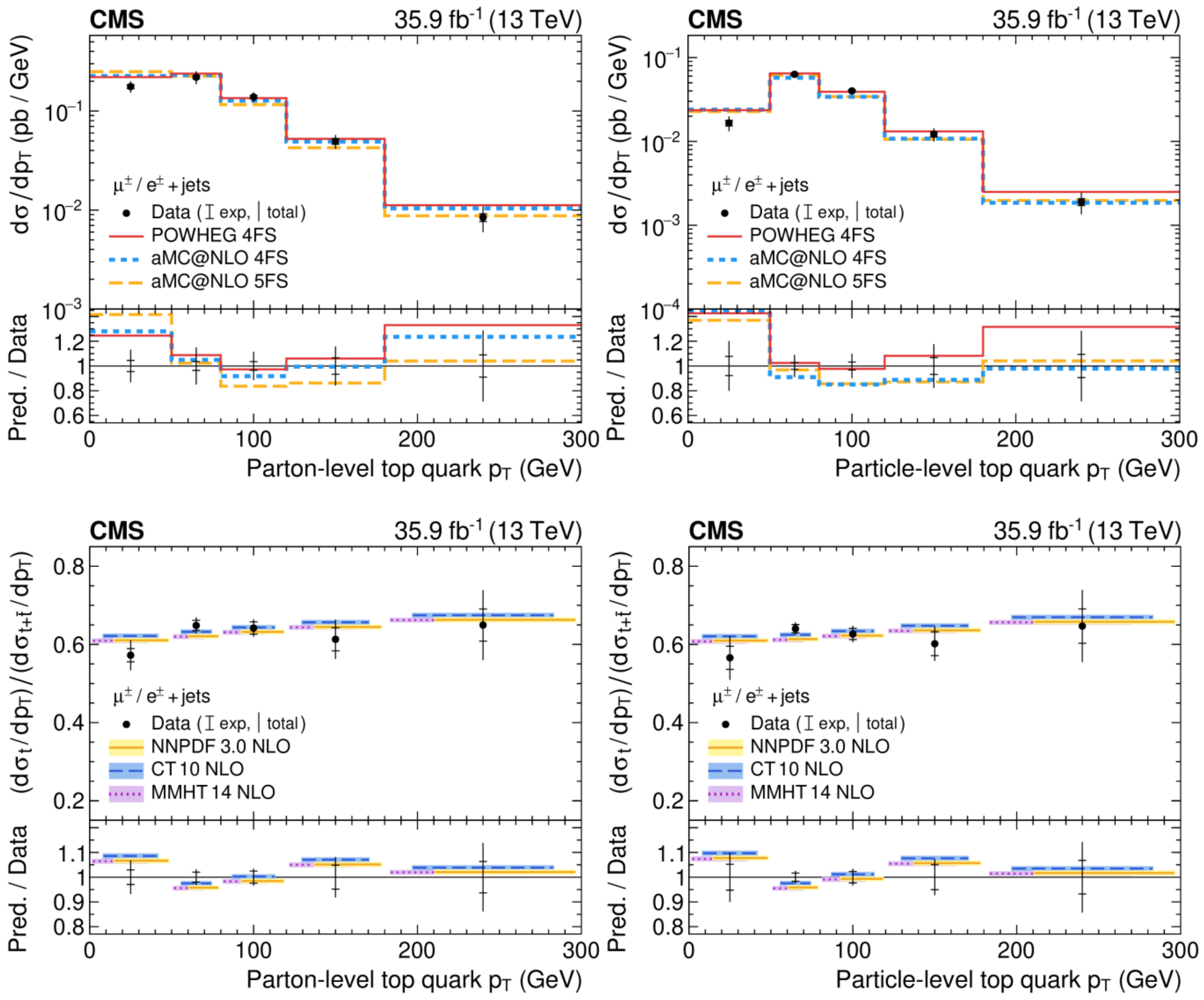


Fit procedure:
- signal region divided in 3 categories:
  - $\mathrm{m_T(W)} < 50$ GeV → fit $\mathrm{m_T(W)}$ distribution.
  - $\mathrm{m_T(W)} > 50$ GeV and $\mathrm{BDT}_{\mathrm{t-channel}} < 0$ → fit $\mathrm{BDT}_{\mathrm{t\bar{t}/W}}$ distribution.
  - $\mathrm{m_T(W)} > 50$ GeV and $\mathrm{BDT}_{\mathrm{t-channel}} > 0$ → fit $\mathrm{BDT}_{\mathrm{t-channel}}$ distribution.
- $\mathrm{m_T(W)}$ distribution in 3j2b control region included as well
- split per lepton charge and flavour → 16 distributions fitted simultaneously.
- for differential measurement: split per observable bin.

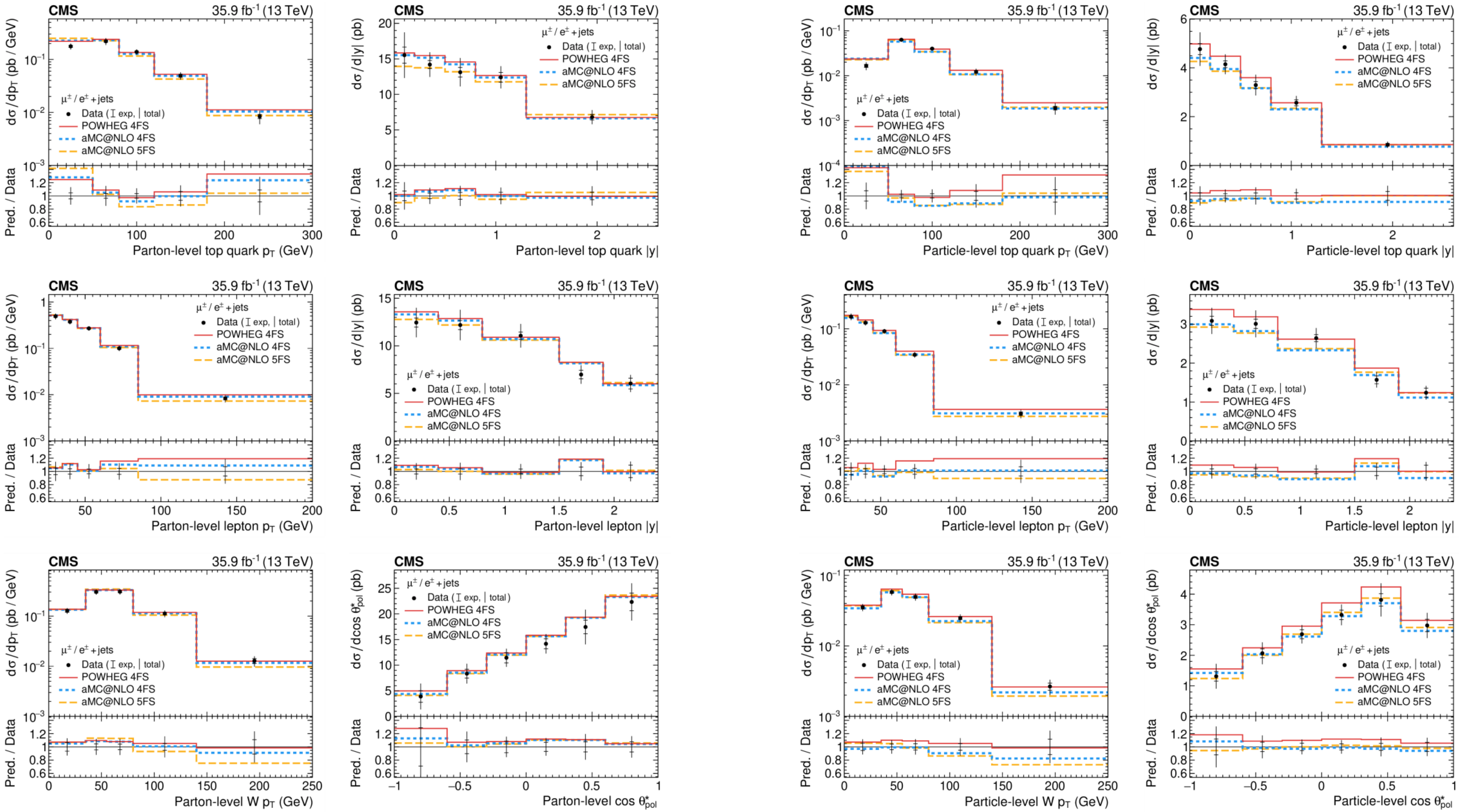
differential t-channel single top (TOP-17-023)

Results:

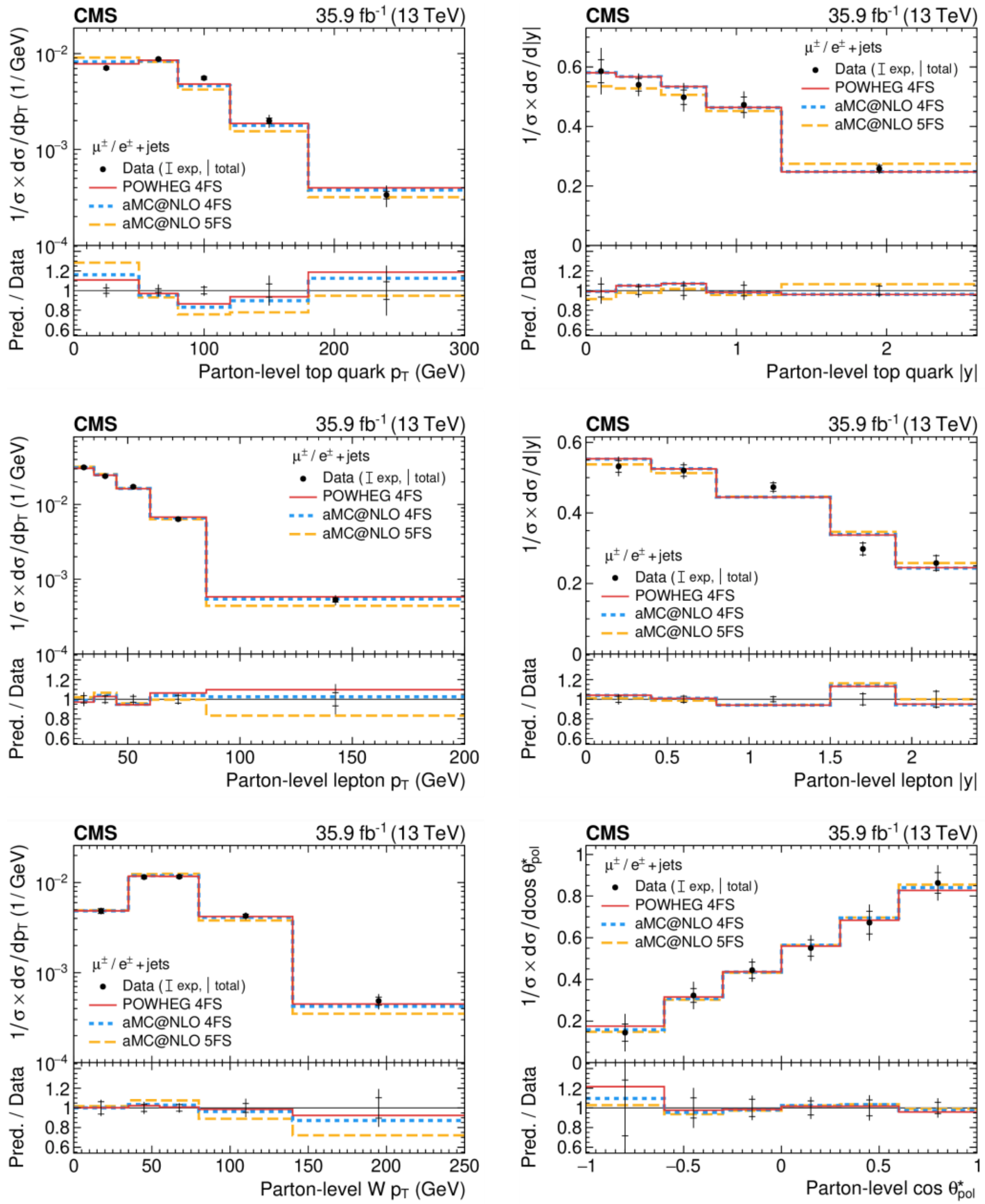
- differential cross-sections at parton and particle level, absolute and normalized.
- observables:
  - p_T and y of top quark
  - p_T and y of lepton
  - p_T of W boson
  - top quark polarization angle.
- differential $\sigma_t/\sigma_{t+\bar{t}}$ distributions for the same observables.
- no appreciable deviations from standard model predictions.

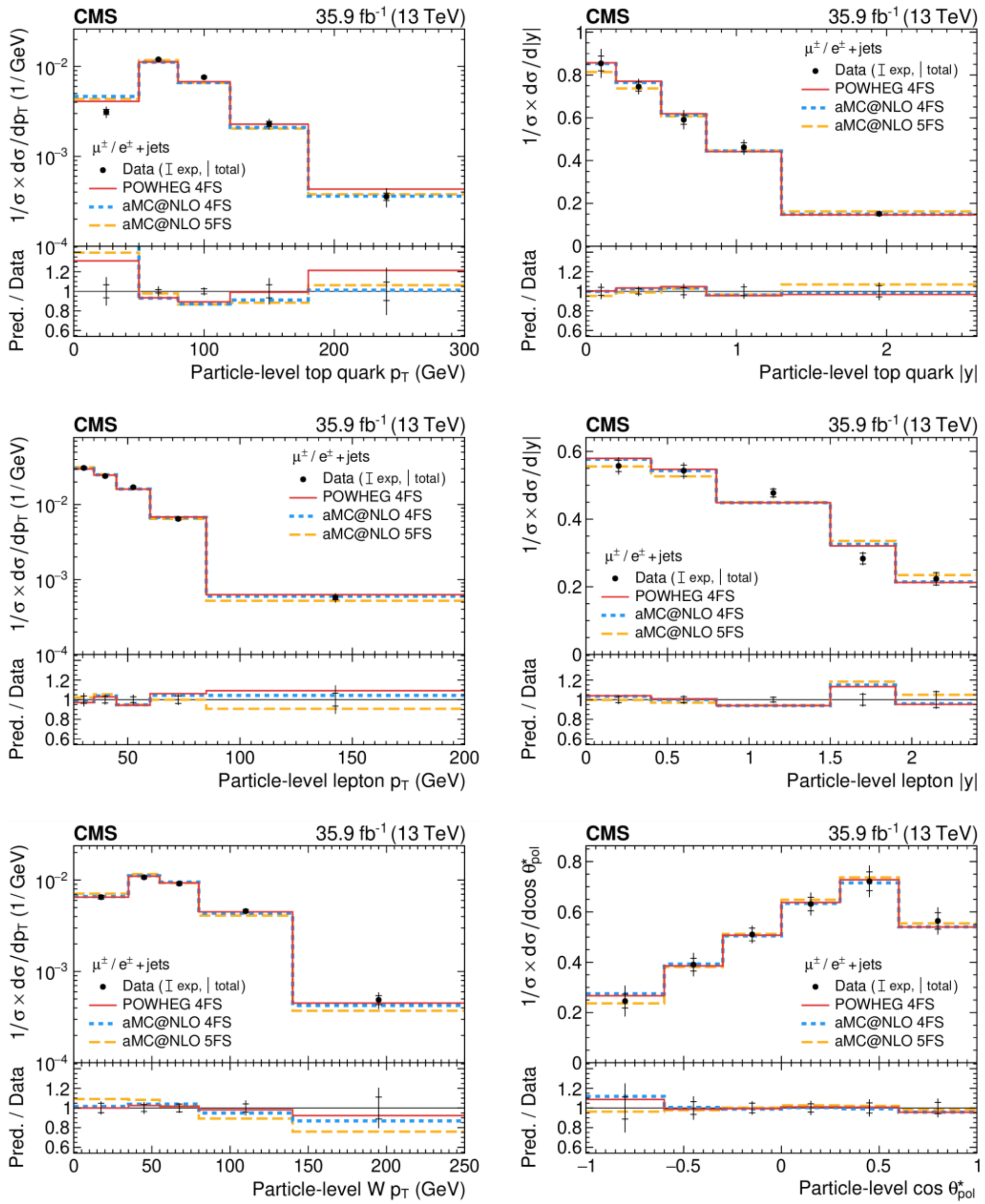


differential t-channel single top (TOP-17-023)



differential t-channel single top (TOP-17-023)





differential t-channel single top (TOP-17-023)

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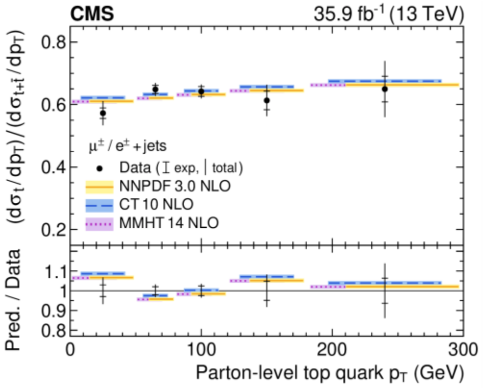
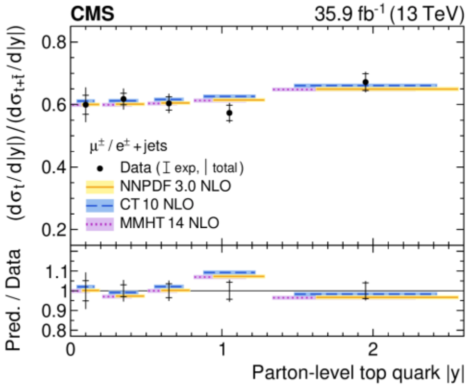
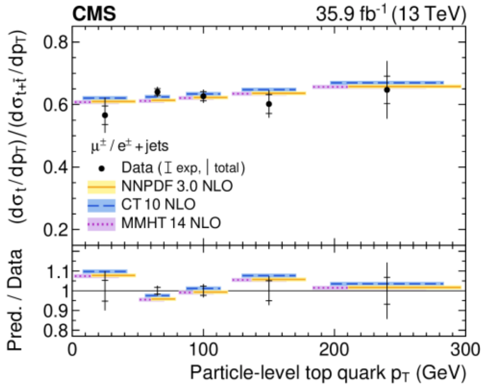
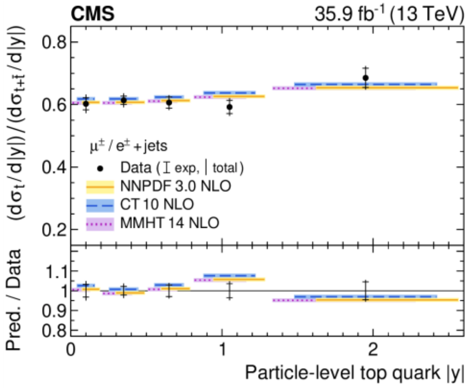
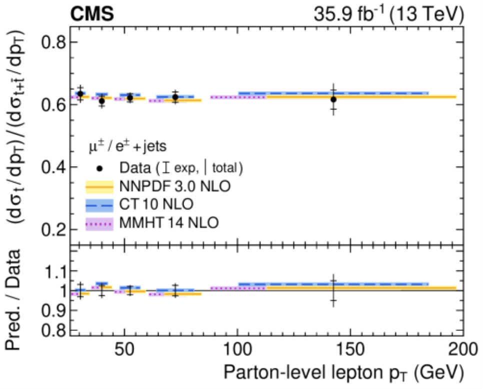
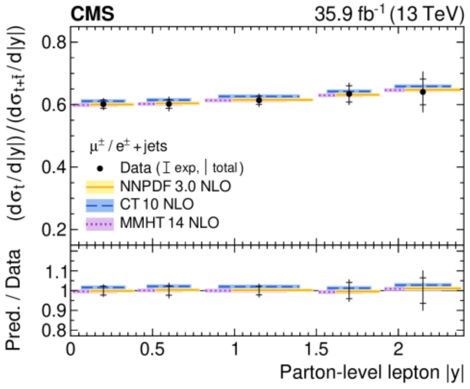


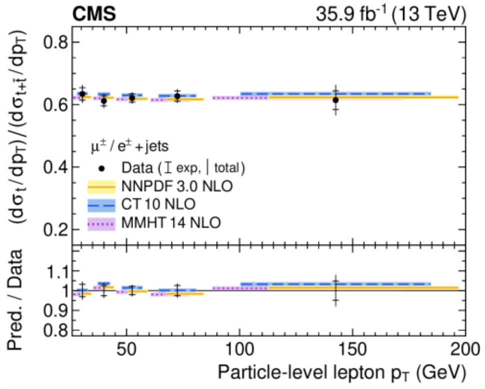


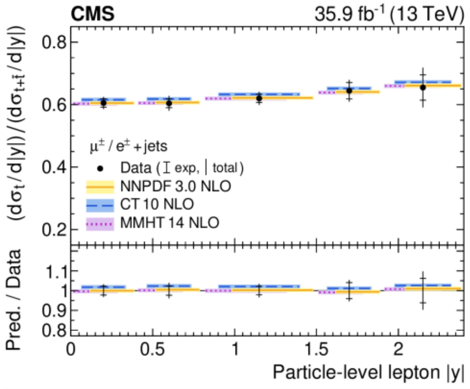


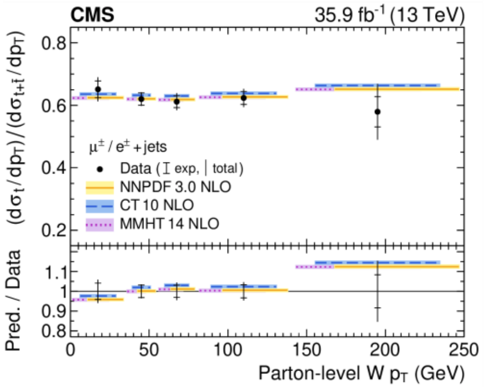


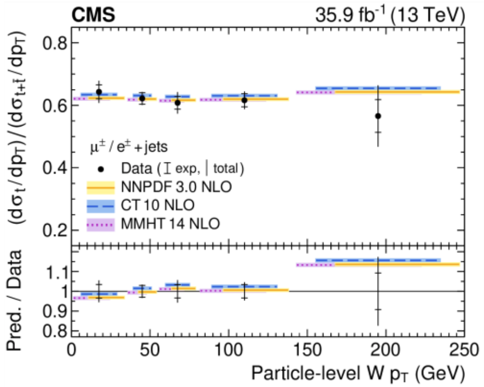




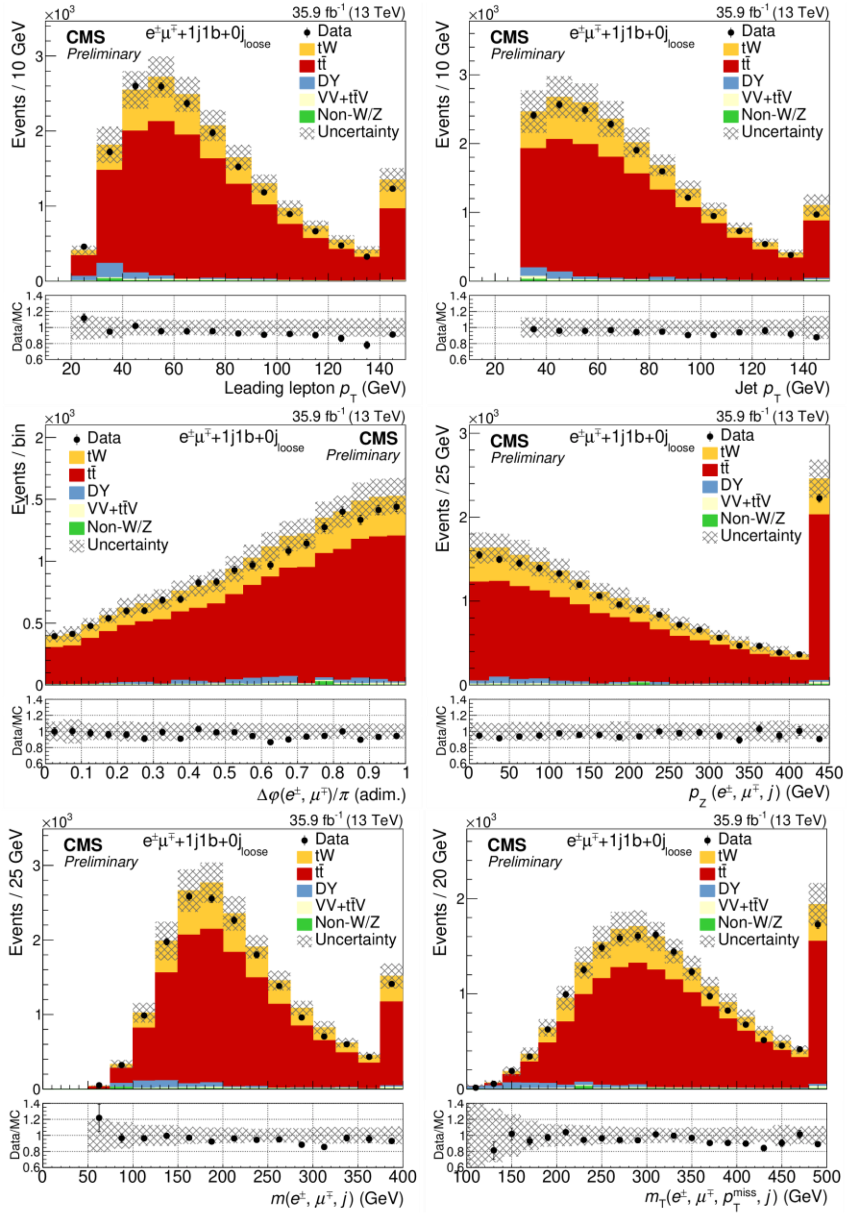




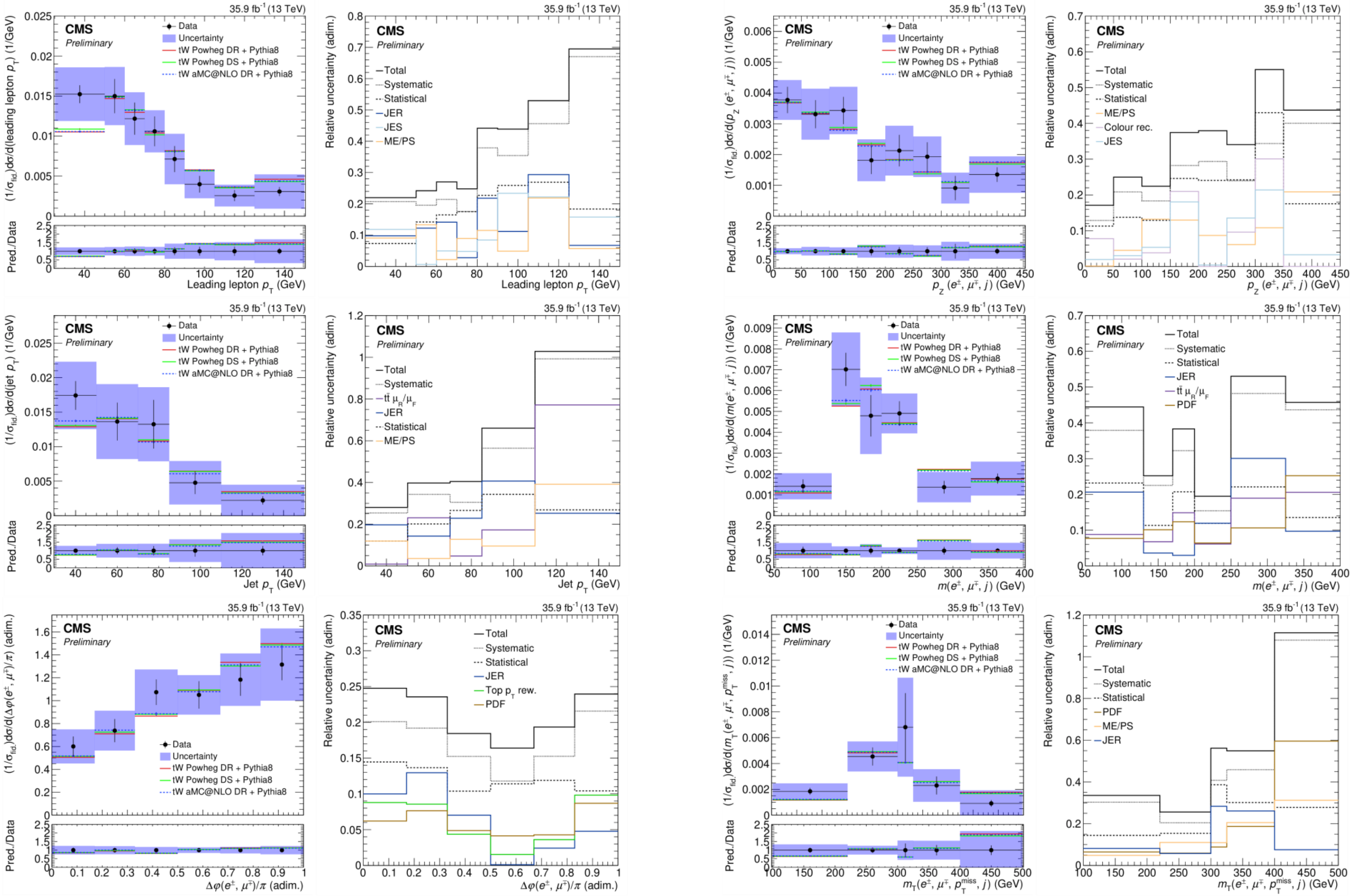




differential tW (TOP-19-003)



differential tW (TOP-19-003)



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Appendix: explicit searches for new physics involving single top quarks

References:

- "Search for flavor-changing neutral current interactions of the top quark and the Higgs boson in the diphoton decay channel in proton-proton collisions at $\sqrt{s}$ = 13 TeV", TOP-20-007
- "Search for charged lepton flavor violation in top quark production and decay in proton-proton collisions at $\sqrt{s}$ = 13 TeV", TOP-19-006

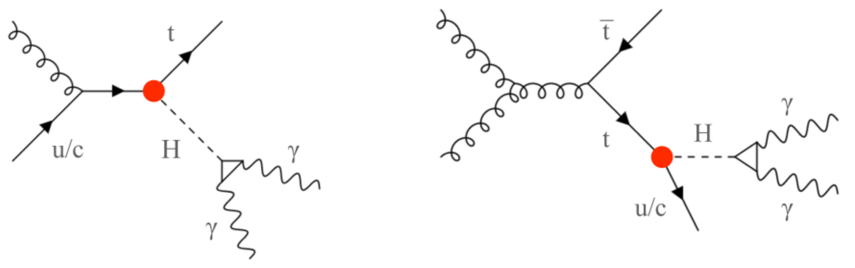
FCNC in t-H interactions (TOP-20-007)

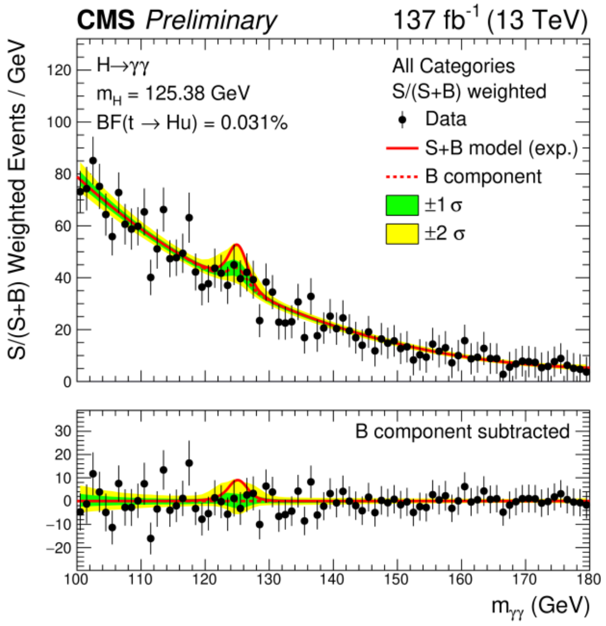
Motivation:
- FCNC forbidden at tree-level in SM, but enhanced in many BSM scenarios.
- strongest enhancement for Higgs boson as mediator.

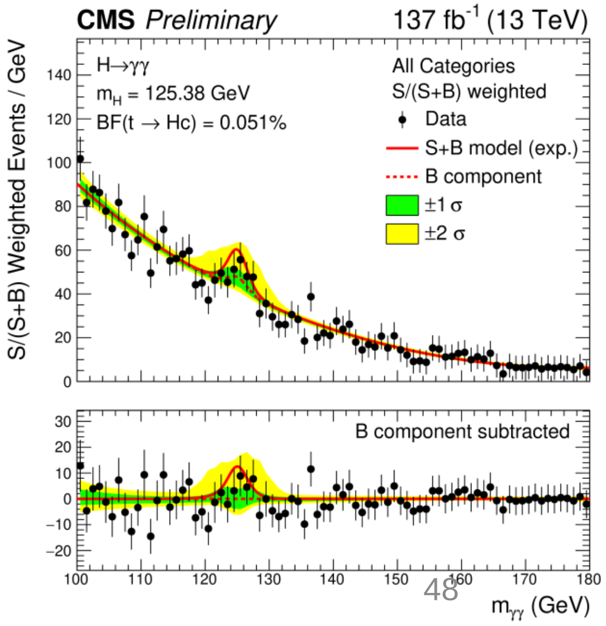
Analysis in a nutshell:
- signal samples with tHu or tHc vertex enabled.
- double-photon trigger.
- events with two photons satisfying BDT identification and 120 GeV < $m_{\gamma\gamma}$ < 130 GeV.
- leptonic channel: ≥ 1 jet, ≥ 1 isolated lepton.
- hadronic channel: ≥ 3 jet, ≥ 1 b-tagged jet, no isolated leptons.

Fit strategy:
- BDTs against resonant background (real higgs) and nonresonant background.
- 14 regions based on BDT output scores.
- simultaneous fit for 95% modified frequentist confidence limit.

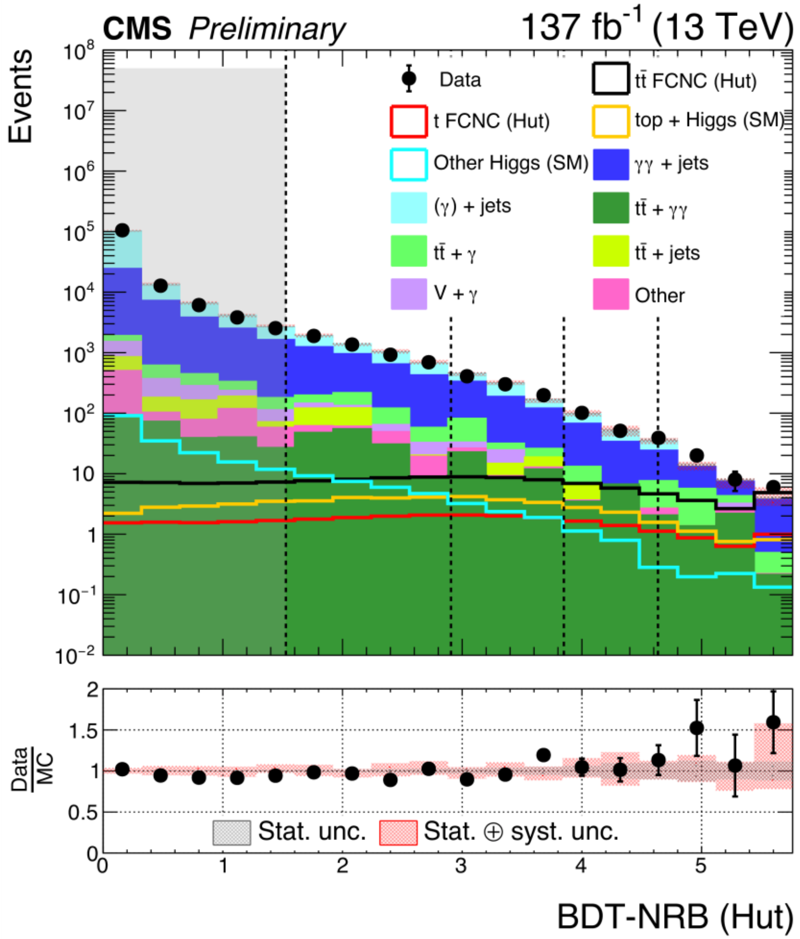
Results: no excess over background-only hypothesis,
$B(t \rightarrow Hu) < 1.9\text{x}10^{-4}$, $B(t \rightarrow Hc) < 7.3\text{x}10^{-4}$
(strongest limits up to now)

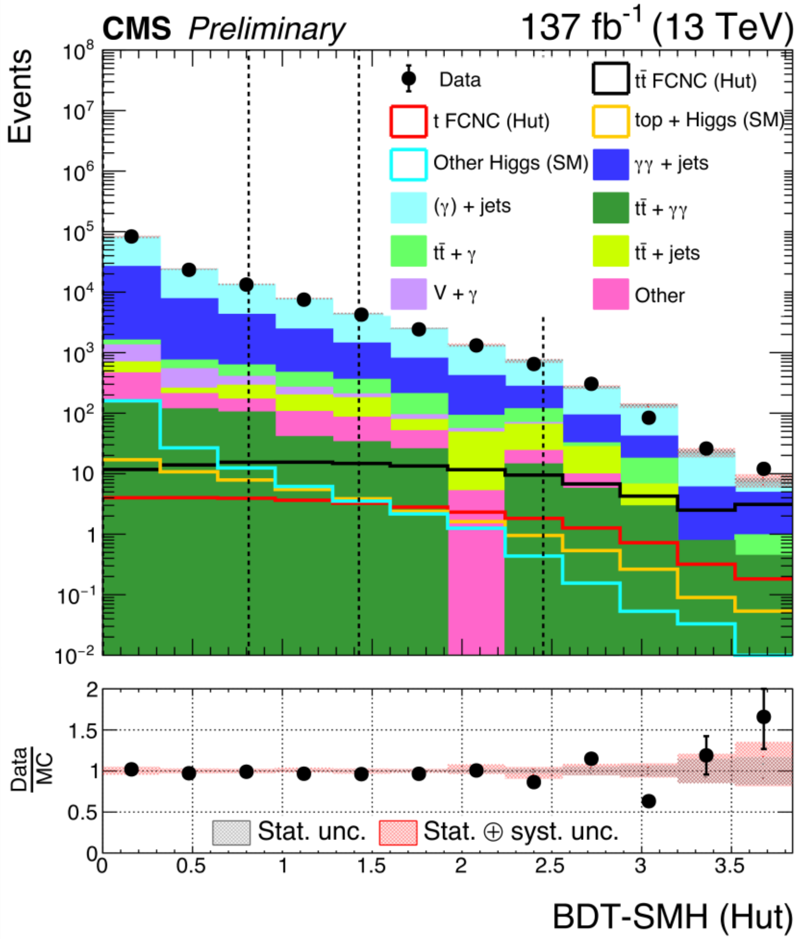






FCNC in t-H interactions (TOP-20-007)





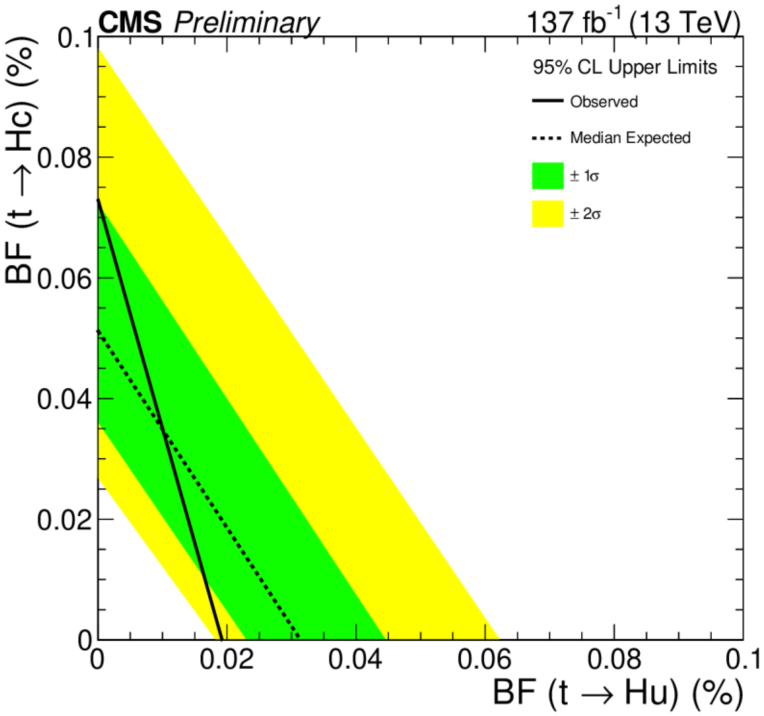
"Distributions of BDT-NRB (left) and BDT-SMH (right) output used for the event categorization targeting t → Hu FCNC interactions in the hadronic channel. The "Other" category includes contributions from ttZ, ttW, WW, WZ, ZZ, and t + γ + jets. Category boundaries are indicated with dotted lines. [...]"

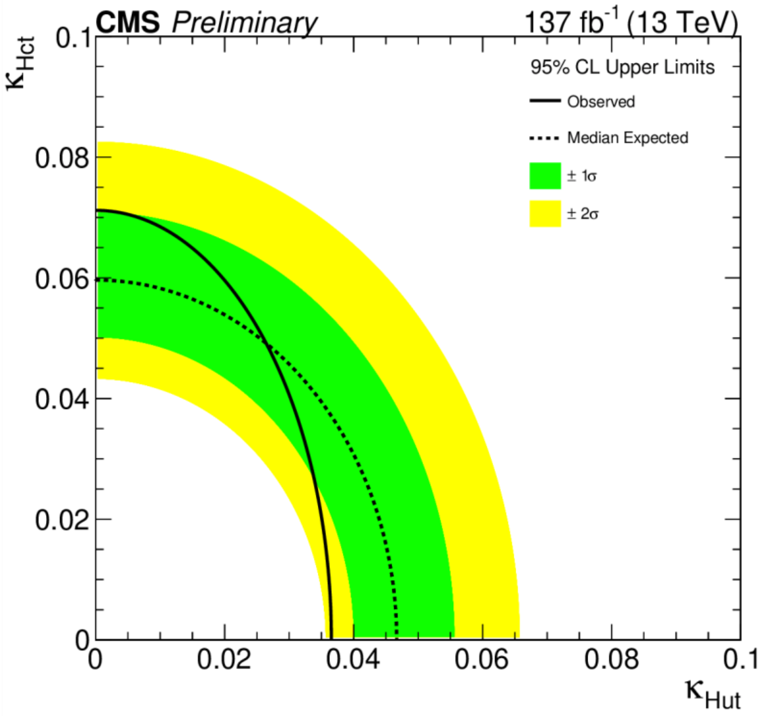
- separate BDT against nonresonant background (NRB) and standard-model-higgs (SMH).
- separate BDT in each channel (semileptonic vs. hadronic).
- separate BDT for each coupling (Hut vs. Hct).

→ 8 BDTs in total

- output scores for BDT-NRB and BDT-SMH are grouped into 7 categories.
- this gives 14 categories in total (semileptonic + hadronic).
- $m_{\gamma\gamma}$ distributions in 14 categories are fitted simultaneously.

FCNC in t-H interactions (TOP-20-007)





Limits on branching fractions:

$B(t \to Hu) < 1.9x10^{-4}$

$B(t \to Hc) < 7.3x10^{-4}$

Compare to earlier published results [1,2,3]:

$B(t \to Hu) < 1.2x10^{-3}$

$B(t \to Hc) < 1.1x10^{-3}$

Coupling is related to branching fraction by:

$$\kappa_{Hqt}^2 = \mathcal{B}(t \to Hq)\frac{\Gamma_t}{\Gamma_{Hqt}}$$

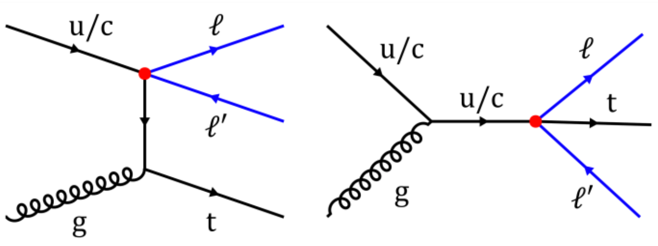
[1]: *JHEP* **10** (2017) 129, doi

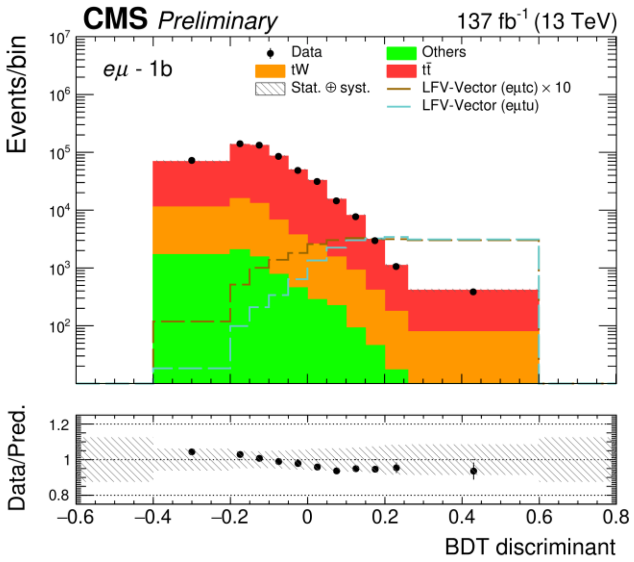
[2]: *Phys. Rev. D* ***98*** (2018) 032002, doi

[3]: *JHEP* **06** (2018) 102, doi

CLFV in top sector (TOP-19-006)

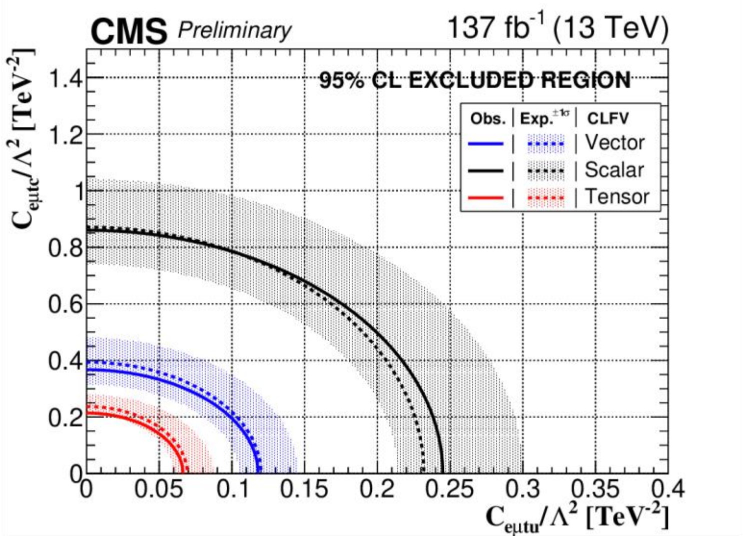
Motivation:
- CLFV allowed in SM via neutrino oscillations but heavily suppressed.
- Experimental hints of CLFV in B-sector → possibly also in top quark decays!

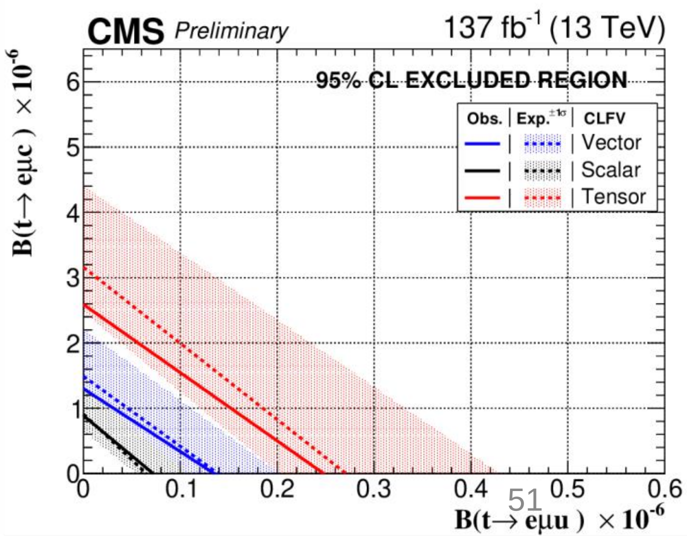




Analysis in a nutshell:
- combination of single e, single μ and $e\mu$ triggers.
- one electron and one muon with opposite charge.
- one b-tagged jet.
- BDT to separate signal from $t\bar{t}$ background.
- binned maximum likelihood fit on signal region + $t\bar{t}$ control region.

Results:
- no excess over background-only hypothesis.
- limits on branching fractions $B(t \rightarrow e\mu u)$ and $B(t \rightarrow e\mu c)$, most restrictive bounds to date.





CLFV in top sector (TOP-19-006)

In the Warsaw basis of EFT operators, the ones that give rise to CLFV in top quark processes are:

$$O_{\mathrm{lq}}^{(3)ijkl} = (\bar{\mathrm{l}}_i \gamma^\mu \tau^I \mathrm{l}_j)(\bar{\mathrm{q}}_k \gamma^\mu \tau^I \mathrm{q}_l),$$

$$O_{\mathrm{lq}}^{(1)ijkl} = (\bar{\mathrm{l}}_i \gamma^\mu \mathrm{l}_j)(\bar{\mathrm{q}}_k \gamma^\mu \mathrm{q}_l),$$

$$O_{\mathrm{lu}}^{ijkl} = (\bar{\mathrm{l}}_i \gamma^\mu \mathrm{l}_j)(\bar{\mathrm{u}}_k \gamma^\mu \mathrm{u}_l),$$

$$O_{\mathrm{eq}}^{ijkl} = (\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_j)(\bar{\mathrm{q}}_k \gamma^\mu \mathrm{q}_l),$$

$$O_{\mathrm{eu}}^{ijkl} = (\bar{\mathrm{e}}_i \gamma^\mu \mathrm{e}_j)(\bar{\mathrm{u}}_k \gamma^\mu \mathrm{u}_l),$$

$$O_{\mathrm{lequ}}^{(1)ijkl} = (\bar{\mathrm{l}}_i \mathrm{e}_j)\, \varepsilon\, (\bar{\mathrm{q}}_k \mathrm{u}_l),$$

$$O_{\mathrm{lequ}}^{(3)ijkl} = (\bar{\mathrm{l}}_i \sigma^{\mu\nu} \mathrm{e}_j)\, \varepsilon\, (\bar{\mathrm{q}}_k \sigma_{\mu\nu} \mathrm{u}_l),$$

simplified to:

$$O_{\mathrm{vector}} = O_{\mathrm{lq}} + O_{\mathrm{lu}} + O_{\mathrm{eq}} + O_{\mathrm{eu}},$$

$$O_{\mathrm{scalar}} = O_{\mathrm{lequ}}^{(1)},$$

$$O_{\mathrm{tensor}} = O_{\mathrm{lequ}}^{(3)}$$

CLFV in top sector (TOP-19-006)

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Source	$t\bar{t}$ (%)	CLFV signal Decay (%)	CLFV signal Production (%)
Trigger	1.2	1.2	2.9
Electron identification/isolation	1.6	1.6	3.9
Muon identification/isolation	0.6	0.6	0.7
Electron energy scale & resolution	<0.1	<0.1	<0.1
Muon momentum scale & resolution	<0.1	<0.1	<0.1
Jet energy scale & resolution	2.5	2.1	1.2
b tagging	3.1	3.9	4.5
Pileup	0.3	0.3	0.2
ME scale	0.9	0.8	0.7
ISR/FSR scale	1.5	2.9	1.9
PDF	0.8	0.8	0.9
UE tune	0.4	—	—
ME/PS matching	<0.1	—	—
Color reconnection	1.0	—	—
MC statistical	<0.1	<0.1	<0.1

"Summary of representative systematic uncertainties on the selection efficiency for the $t\bar{t}$ process and for the signal processes: single top quark production and top quark decays via vector eμtu CLFV interactions in the signal and $t\bar{t}$ control regions. "

CLFV in top sector (TOP-19-006)

Vertex	Int. type	Cross section [fb] Exp.	Cross section [fb] Obs.	$C_{e\mu tq}/\Lambda^2$ [TeV^{-2}] Exp.	$C_{e\mu tq}/\Lambda^2$ [TeV^{-2}] Obs.	$\mathcal{B} \times 10^{-6}$ Exp.	$\mathcal{B} \times 10^{-6}$ Obs.
$e\mu tu$	Vector	7.02	6.78	0.12	0.12	0.14	0.13
		[5.33,10.21]		[0.10,0.14]		[0.11,0.20]	
		(3.39,12.33)		(0.08,0.16)		(0.07,0.24)	
	Scalar	5.63	6.25	0.23	0.24	0.06	0.07
		[4.79,9.38]		[0.21,0.33]		[0.05,0.11]	
		(3.75,12.12)		(0.19,0.34)		(0.04,0.14)	
	Tensor	10.01	9.18	0.07	0.06	0.27	0.25
		[7.51,15.90]		[0.06,0.09]		[0.20,0.43]	
		(4.59,19.24)		(0.04,0.09)		(0.12,0.52)	
$e\mu tc$	Vector	11.21	9.73	0.39	0.37	1.49	1.31
		[7.21,16.63]		[0.32,0.48]		[0.96,2.21]	
		(4.33,21.61)		(0.24,0.55)		(0.58,2.89)	
	Scalar	9.11	8.88	0.87	0.86	0.91	0.89
		[6.58,13.10]		[0.74,1.04]		[0.65,1.31]	
		(3.54,17.41)		(0.54,1.21)		(0.35,1.74)	
	Tensor	21.02	17.22	0.24	0.21	3.16	2.59
		[16.52,29.21]		[0.21,0.28]		[2.48,4.41]	
		(10.51,42.02)		(0.17,0.33)		(1.58,6.32)	

"Expected/Observed upper limits on the signal cross sections (production + decay), CLFV Wilson coefficients, and top quark CLFV branching ratios are shown for all three years combined. For expected limits [−1σ,+1σ] and (−2σ,+2σ) ranges are shown."