Top quark cross sections and properties in CMS

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on behalf of the CMS Collaboration

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Introduction

Top quark inclusive cross section:

- Essential for probing SM through pQCD precision tests.
- Constrains proton PDFs, α_s, m_t and new physics scenarios.
- Main background in plenty of BSM searches.

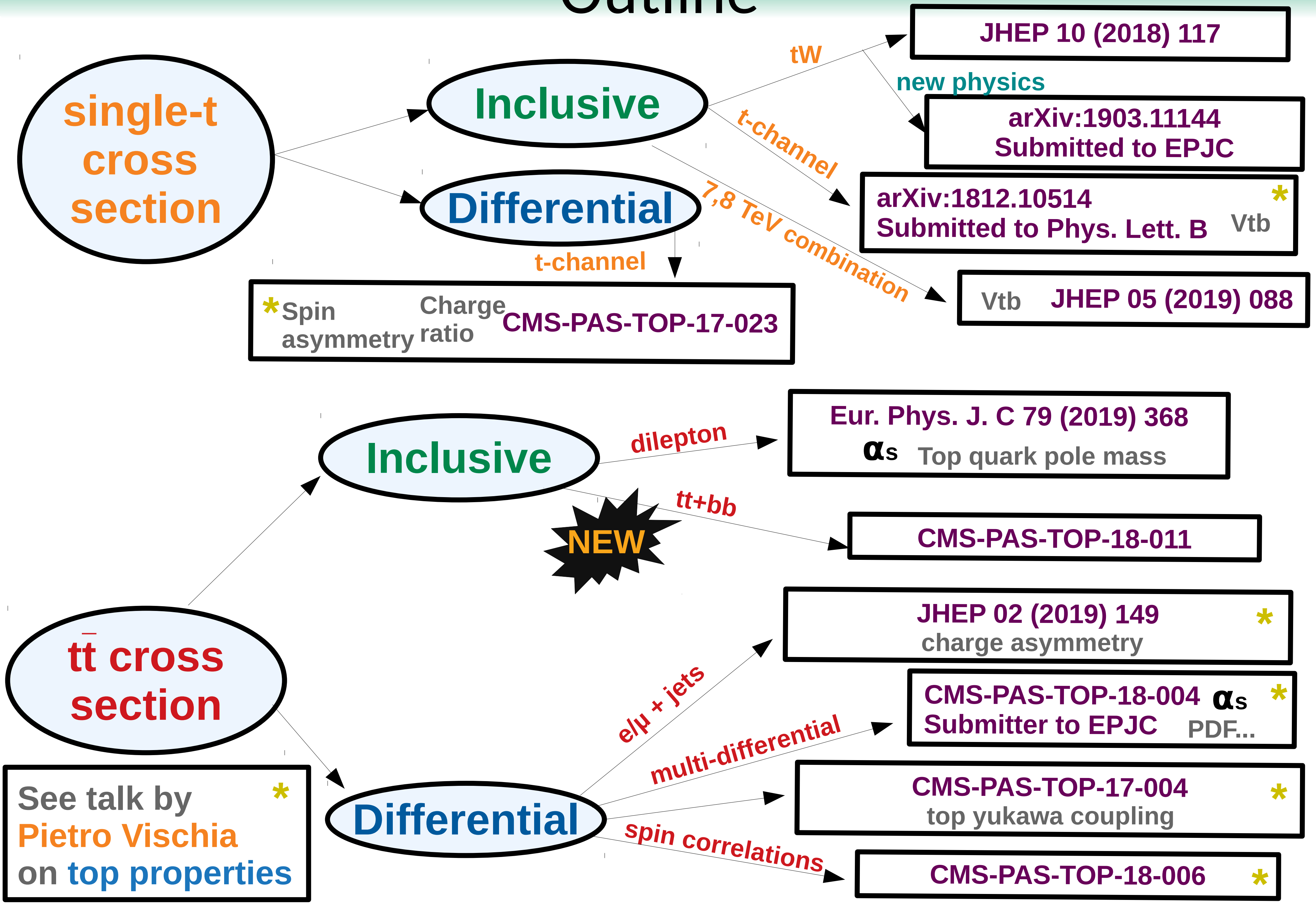
Differential cross sections:

- Unfolding at parton and particle level: direct comparison with theoretical predictions.
- Comparison between MC generators and setups and data for LO and NLO predictions.
- Studies of the modeling in different regions of the phase space: tune of parameters.
- Testing QCD, top Yukawa coupling, EFT physics, V_{tb}...

For all analysis (unless stated otherwise):

pp collisions, $\sqrt{s}$ = 13 TeV, 35.9 fb^{-1} (2016 dataset)

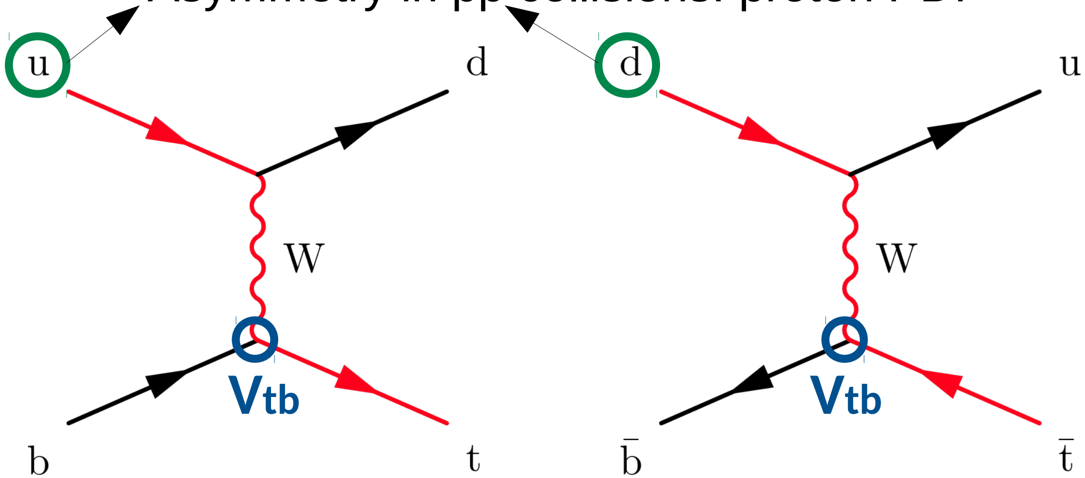
Outline

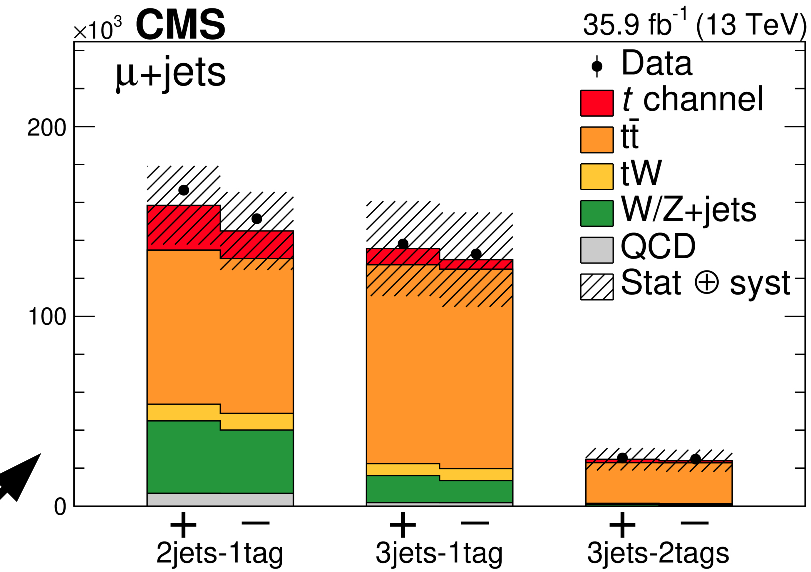

single-t cross section
Inclusive
Differential
tW
new physics
t-channel
7,8 TeV combination
t-channel
JHEP 10 (2018) 117
arXiv:1903.11144
Submitted to EPJC
arXiv:1812.10514
Submitted to Phys. Lett. B
Vtb
*
Vtb
JHEP 05 (2019) 088
*
Spin asymmetry
Charge ratio
CMS-PAS-TOP-17-023
$t\bar{t}$ cross section
Inclusive
Differential
dilepton
Eur. Phys. J. C 79 (2019) 368
α_s
Top quark pole mass
tt+bb
NEW
CMS-PAS-TOP-18-011
e/μ + jets
JHEP 02 (2019) 149
charge asymmetry
*
multi-differential
CMS-PAS-TOP-18-004
α_s
Submitter to EPJC
PDF...
*
CMS-PAS-TOP-17-004
top yukawa coupling
*
spin correlations
CMS-PAS-TOP-18-006
*
See talk by
Pietro Vischia
on top properties
*

t-channel inclusive cross section: e/μ + jets

arXiv:1812.10514

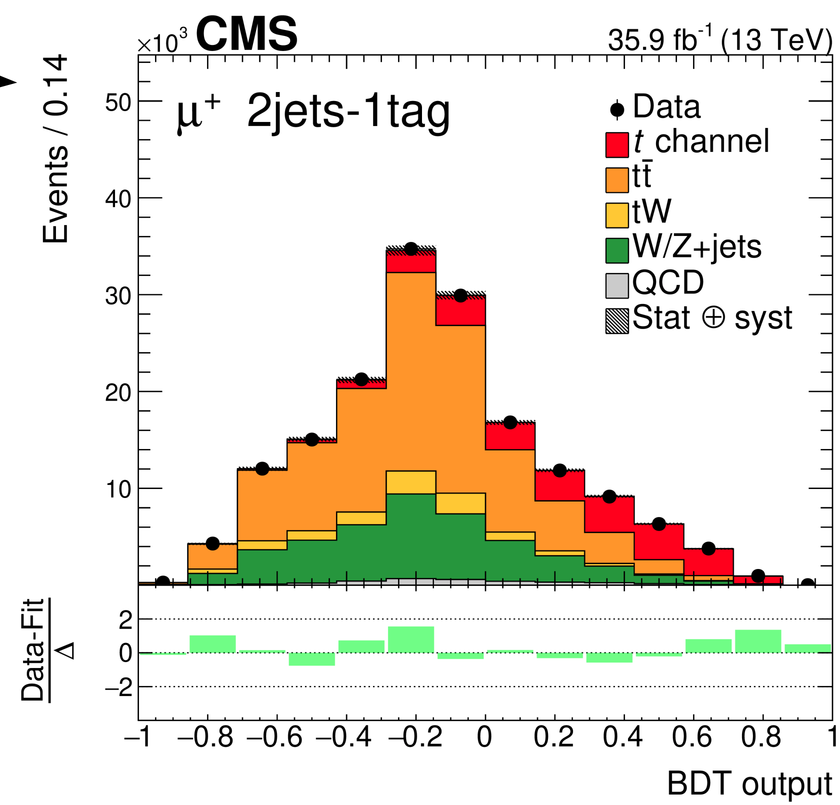
Asymmetry in pp collisions: proton PDF



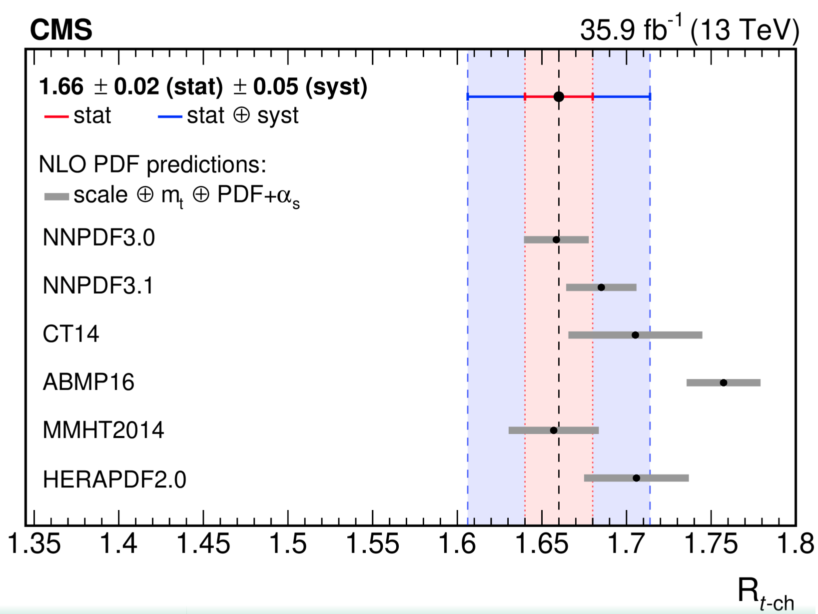


Classification in njets and nbtag categories.
BDT to separate signal from tt.

$$|f_{\mathrm{LV}} V_{tb}| = \sqrt{\frac{\sigma_{\mathrm{meas.}}}{\sigma_{\mathrm{theo.}\ (V_{tb}=1)}}}$$ **= 1.00±0.08 (exp)±0.02 (theo).**

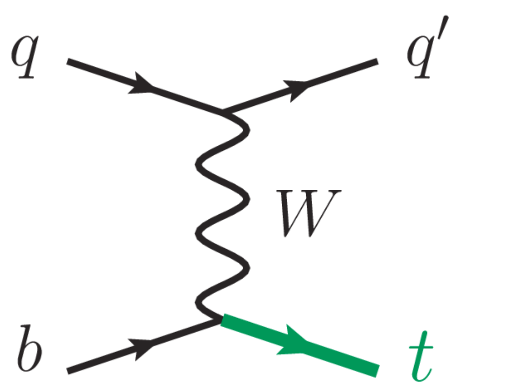


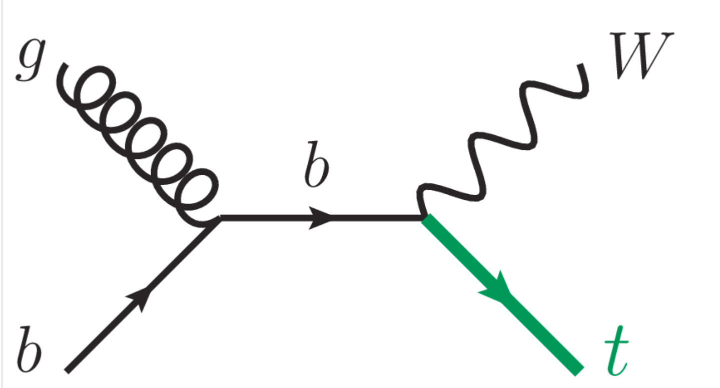
Ratio between cross sections for different PDF sets.

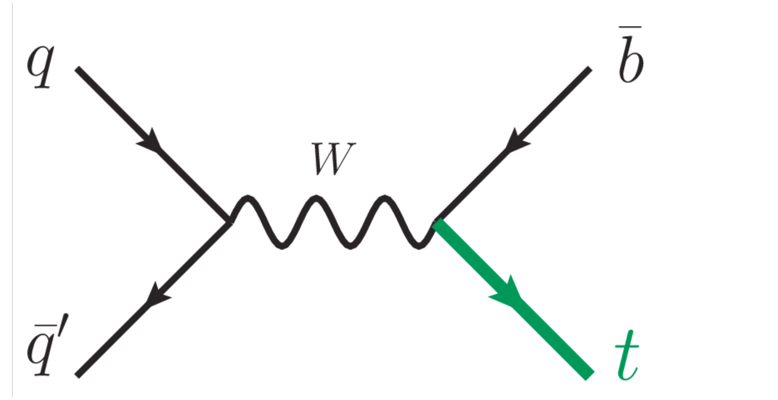


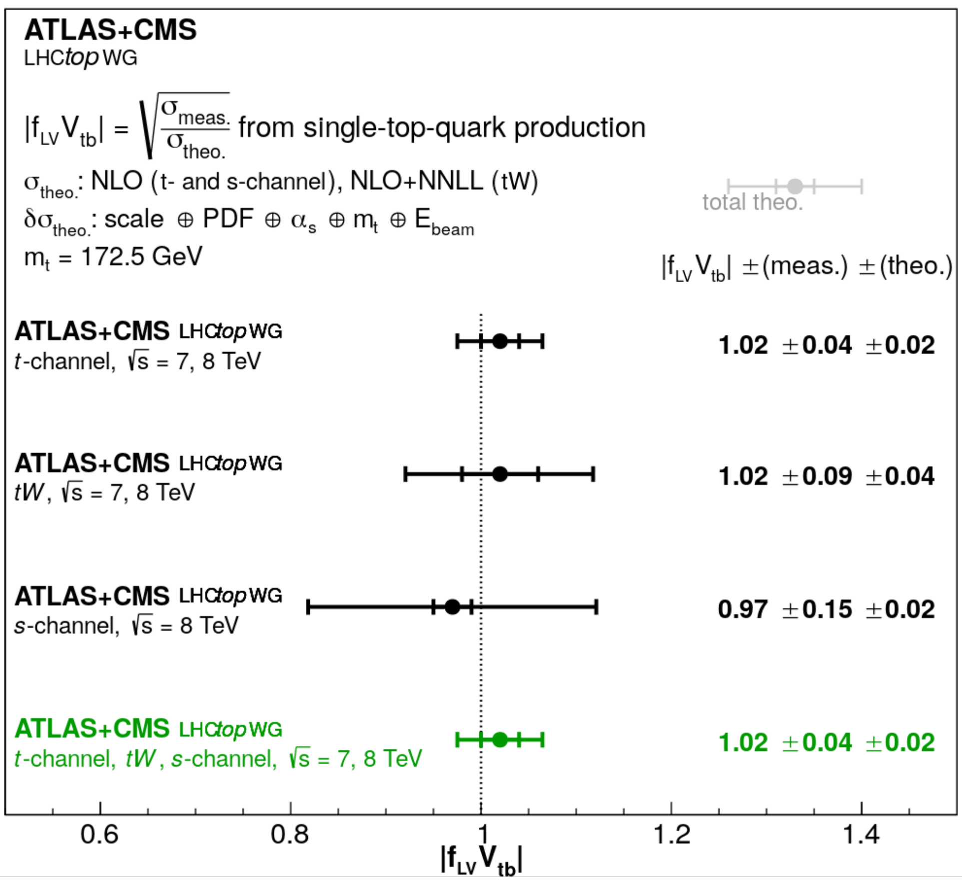
Single top combination (CMS+ATLAS) at 7 and 8 TeV

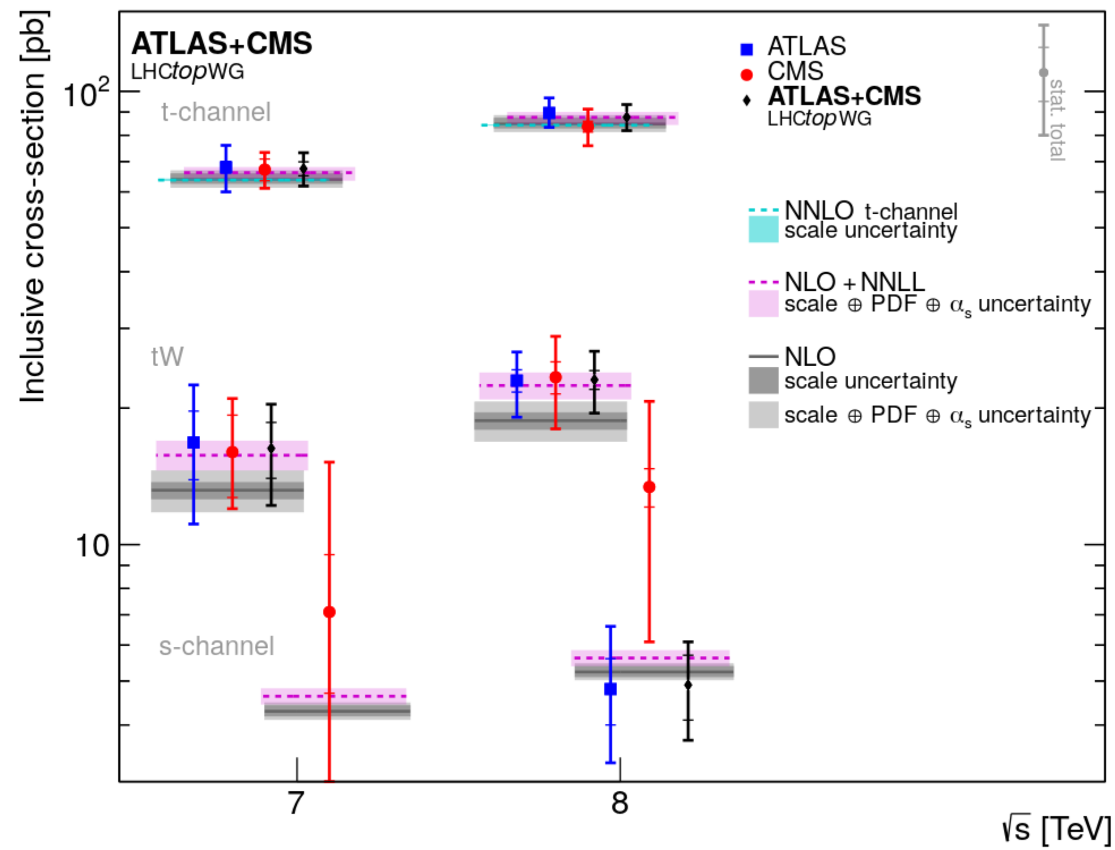
JHEP 05 (2019) 088











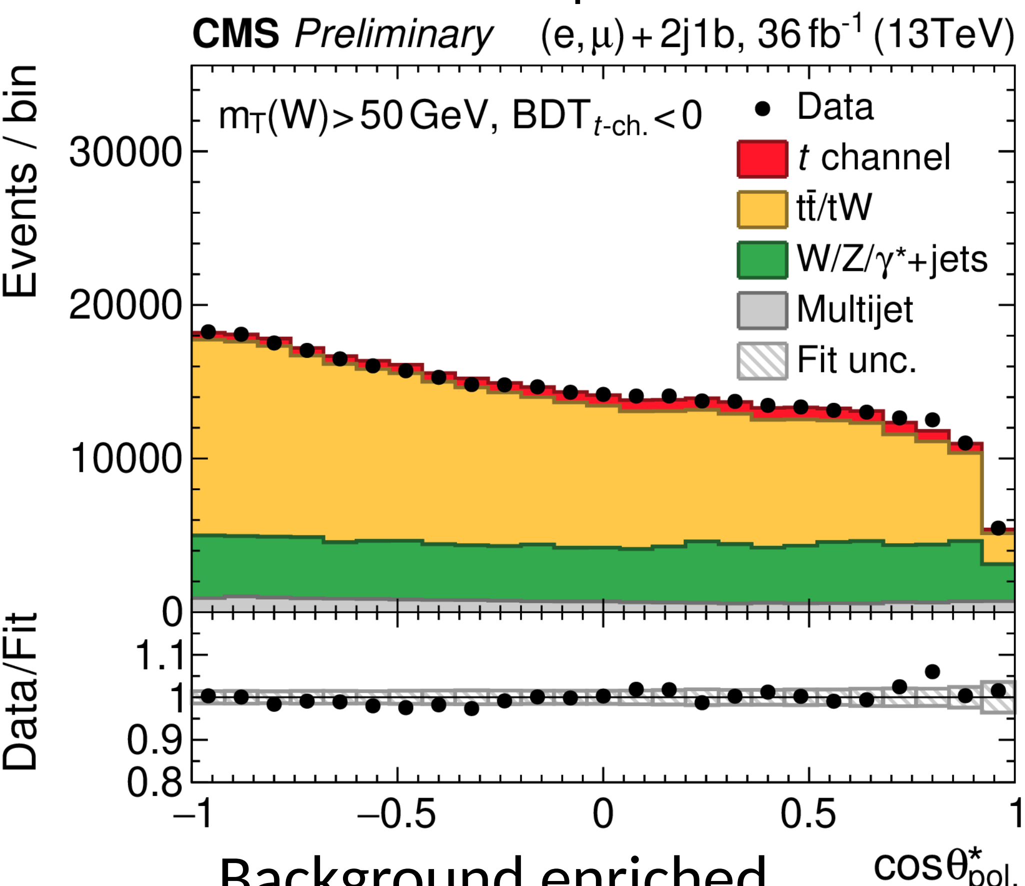
Dominant uncertainties: modeling, jets (jet energy scale, b-tagging).

t-channel differential cross section (1)

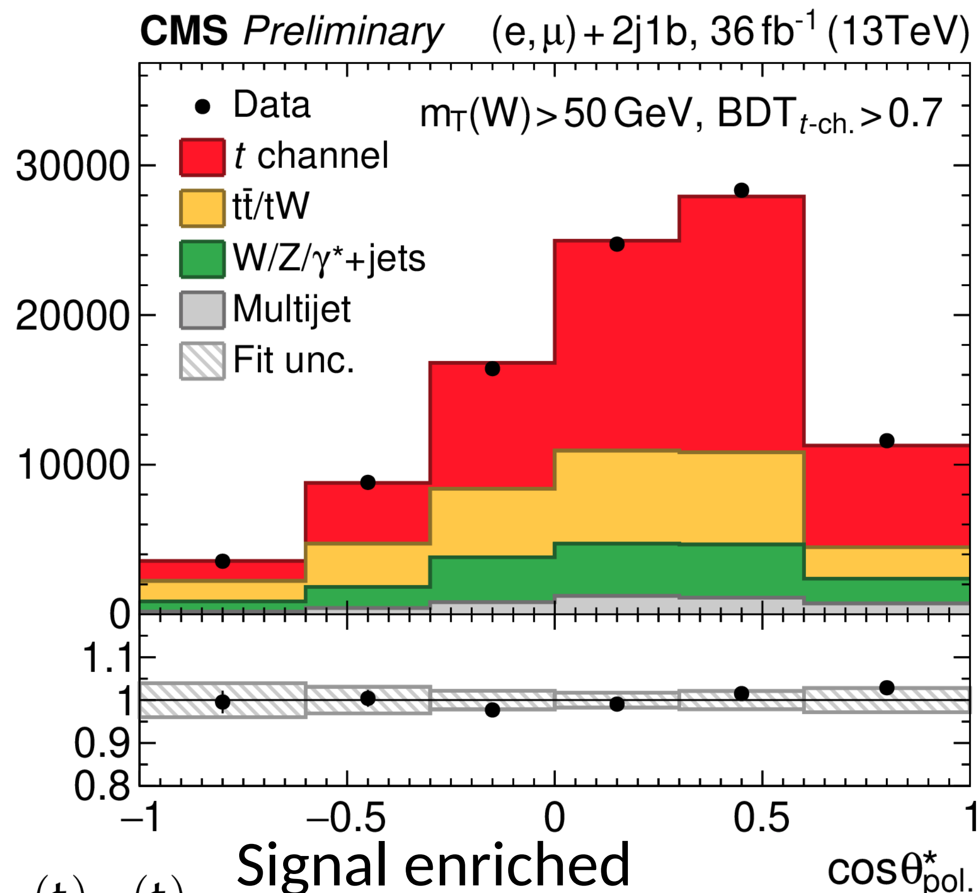
- 2j1b region → two BDT: training vs all background + training vs WJets and tt, and $m_T(W)$
- 3j2b region → $m_T(W)$ distribution

CMS-PAS-TOP-17-023

ML fit to **BDT** and **$m_T(W)$** distributions. Control distributions:



Background enriched



Signal enriched

$$\cos\theta^{\star}_{\text{pol.}} = \frac{\vec{p}^{\,(t)}_{q'}\,\vec{p}^{\,(t)}_{\ell}}{|\vec{p}^{\,(t)}_{q'}||\vec{p}^{\,(t)}_{\ell}|}$$

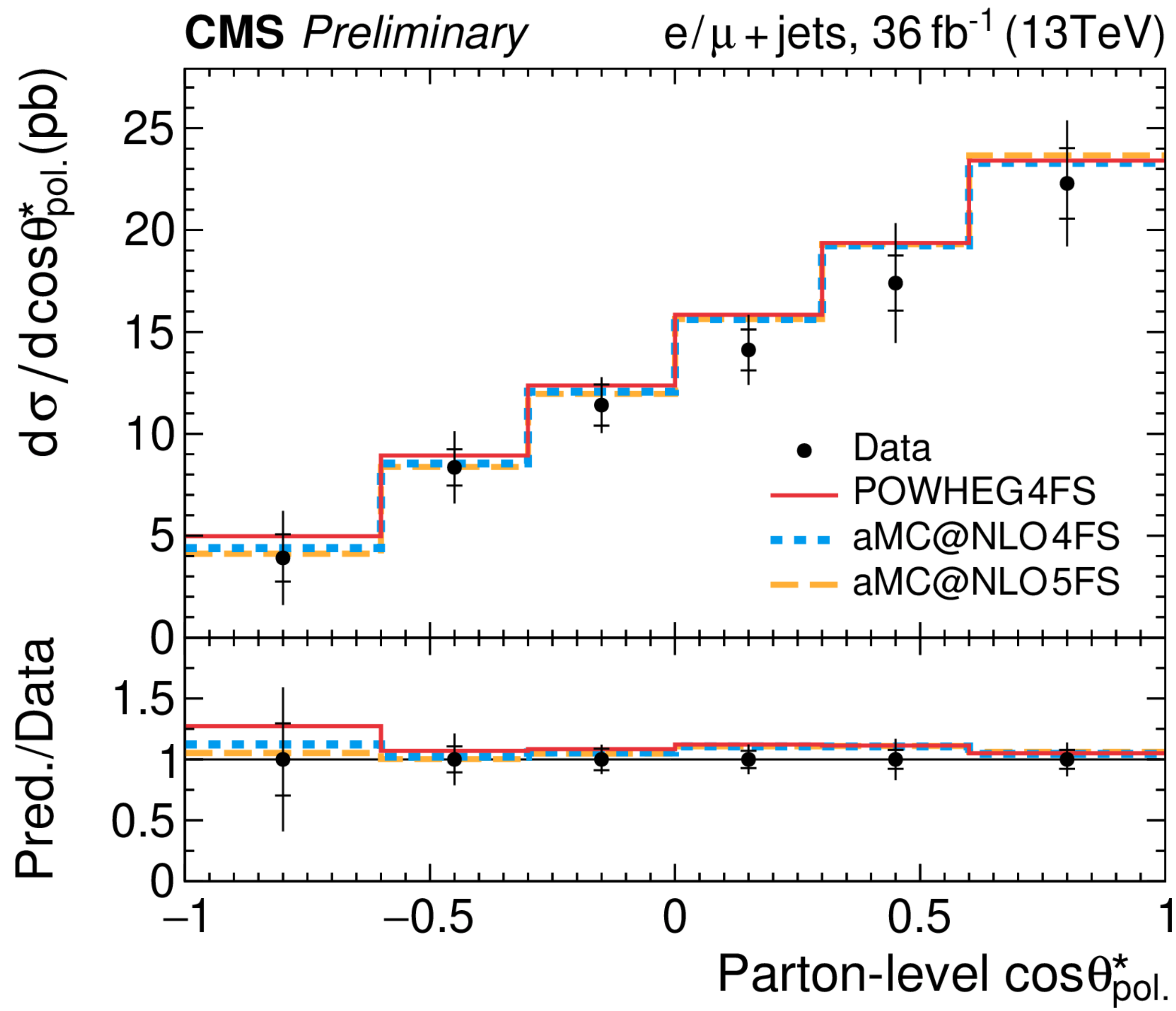
t-channel differential cross section (2)

CMS-PAS-TOP-17-023

The polarisation angle is measured from the $\cos\theta^*_{pol.}$ distribution.

SM value:
0.436

Measured value:
0.439 ± 0.062



$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta^\star_{\text{pol.}}} = \frac{1}{2}\left(1 + 2A_\ell \cos\theta^\star_{\text{pol.}}\right)$$

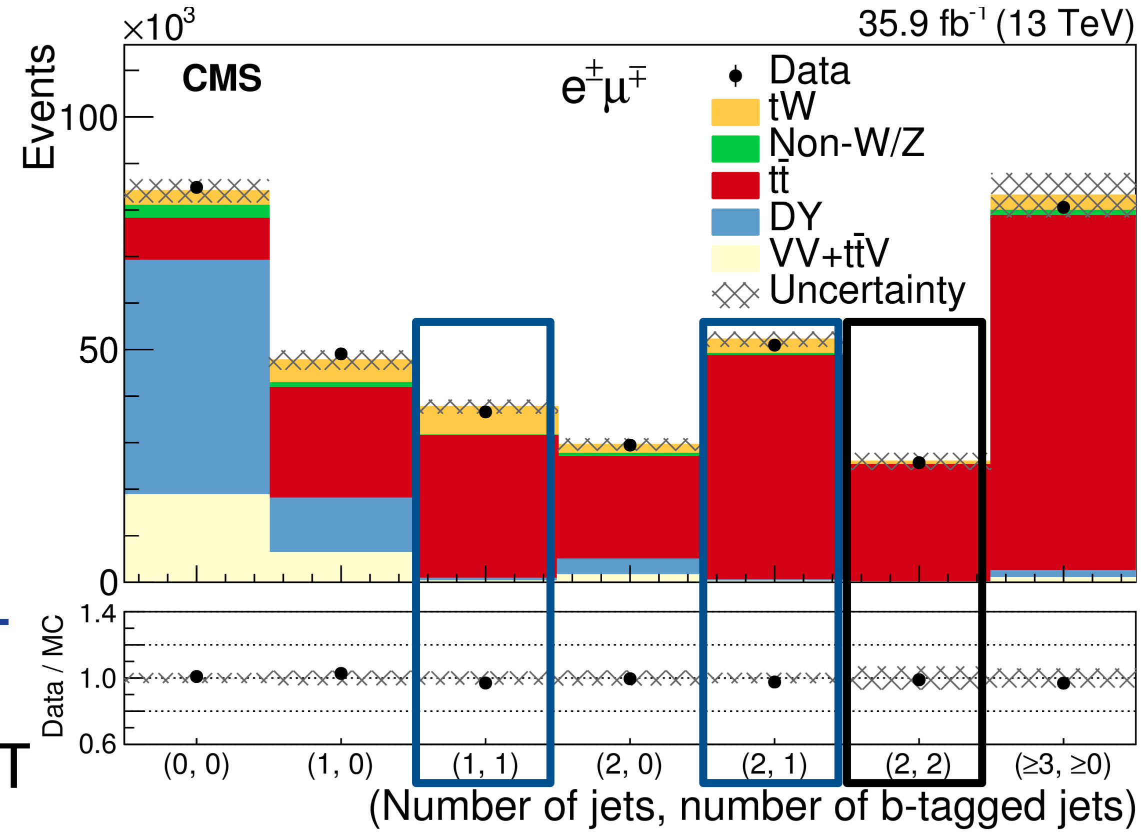
tW inclusive cross section

JHEP 10 (2018) 117

Inclusive cross section measurement using a BDT + subleading jet p_T in 2j2b.

63.1 ± 1.8 (stat) ± 6.4 (syst) ± 2.1 (lumi) pb

in agreement with the SM.



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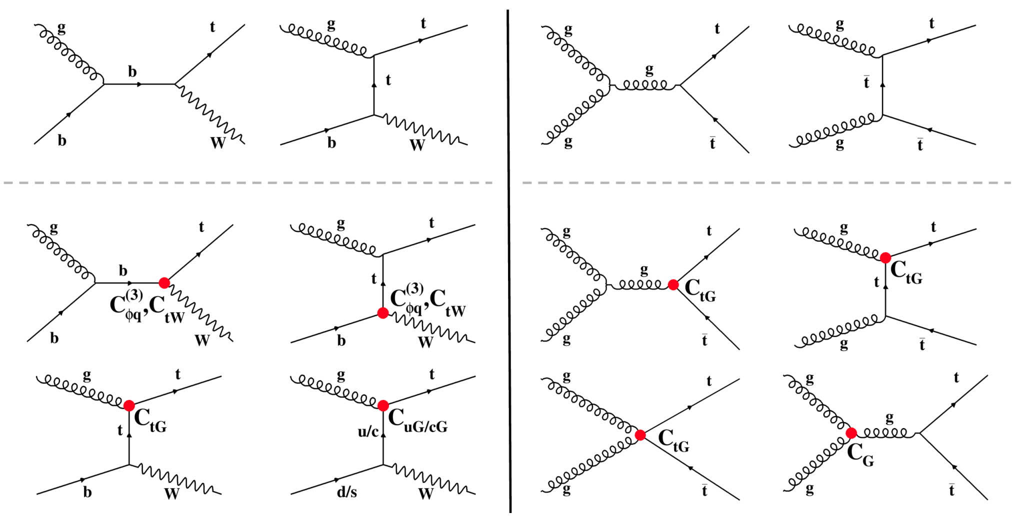
arXiv:1903.11144

Search for new physics using EFT in tW/tt dilepton final states.



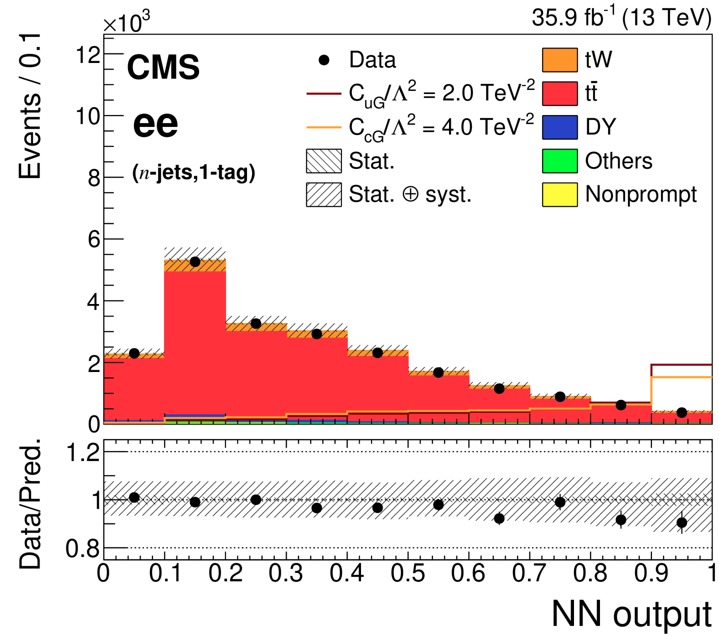
NN in different regions by flavour (ee, μμ, eμ) and jet/btag multiplicities:

- tt vs tW: $C(3)_{\Phi q}$, C_{tW} , C_{tG}
- tt+tW vs FCNC tW: C_{uG} , and C_{cG}

New physics from tW and $t\bar{t}$ cross section

arXiv:1903.11144

No significant deviation from SM.
First experimental constrain in C_G from top quark results.



	Effective coupling	Best fit	Observed [TeV^{-2}] [68% CI]	Observed [TeV^{-2}] [95% CI]	Expected [TeV^{-2}] Best fit	Expected [TeV^{-2}] [68% CI]	Expected [TeV^{-2}] [95% CI]
tW	C_G/Λ^2	-0.18	$[-0.73, 0.42]$	$[-1.01, 0.70]$	0.00	$[-0.82, 0.51]$	$[-1.07, 0.76]$
tt	$C^{(3)}_{\phi q}/\Lambda^2$	-1.52	$[-2.71, -0.33]$	$[-3.82, 0.63]$	0.00	$[-1.05, 0.88]$	$[-2.04, 1.63]$
tt+tW	C_{tW}/Λ^2	2.38	$[0.22, 4.57]$	$[-0.96, 5.74]$	0.00	$[-1.14, 5.93]$	$[-1.91, 6.70]$
	C_{tG}/Λ^2	-0.13	$[-0.27, 0.02]$	$[-0.41, 0.17]$	0.00	$[-0.15, 0.14]$	$[-0.30, 0.28]$
	C_{uG}/Λ^2	-0.017	$[-0.13, 0.13]$	$[-0.22, 0.22]$	0.00	$[-0.21, 0.21]$	$[-0.30, 0.30]$
tW	C_{cG}/Λ^2	-0.032	$[-0.26, 0.26]$	$[-0.46, 0.46]$	0.00	$[-0.46, 0.46]$	$[-0.65, 0.65]$

From FCNC results, limits on BR obtained at 95% CL:

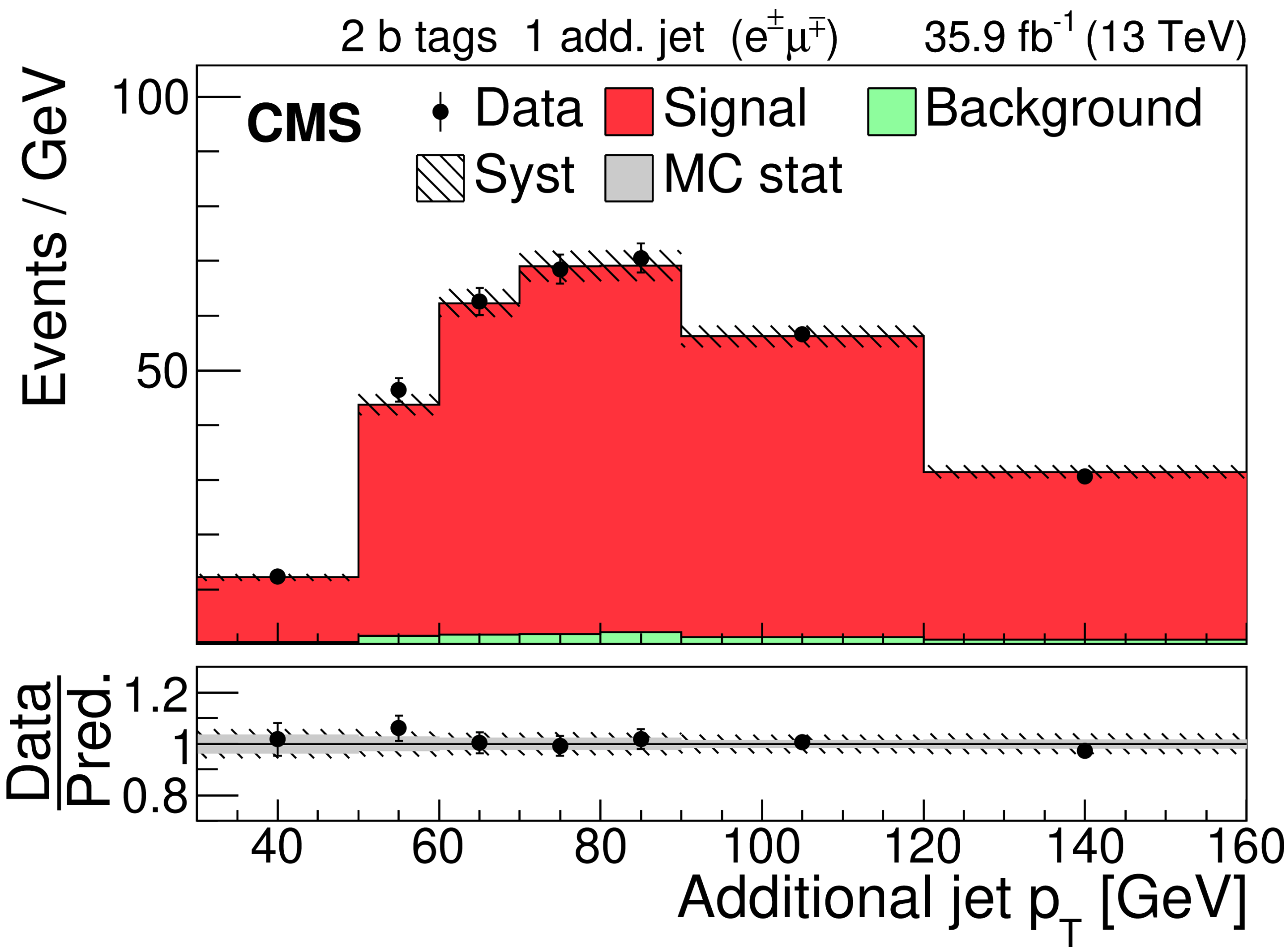
$BR(t \to cg) < 0.53\%$; $BR(t \to ug) < 0.12\%$

$t\bar{t}$ inclusive cross section

Cross section using dilepton events (ee, μμ, eμ), in jets and btag multiplicities.

Eur. Phys. J. C 79 (2019) 368

σ_{tt} = 803 ± 2 (stat) ± 25 (syst) ± 20 (lumi) pb



Template fit to different distributions. The values of the top quark pole mass and αs are also extracted.

Measurement of **σ_{tt}** cross checked with a cut-and-count approach in the eμ channel.

NNLO+NNLL prediction:

$\sigma_{tt} = 832^{+20}_{-29}$(scale)± 35 (PDF + α_s)pb

JHEP 01(2013)080

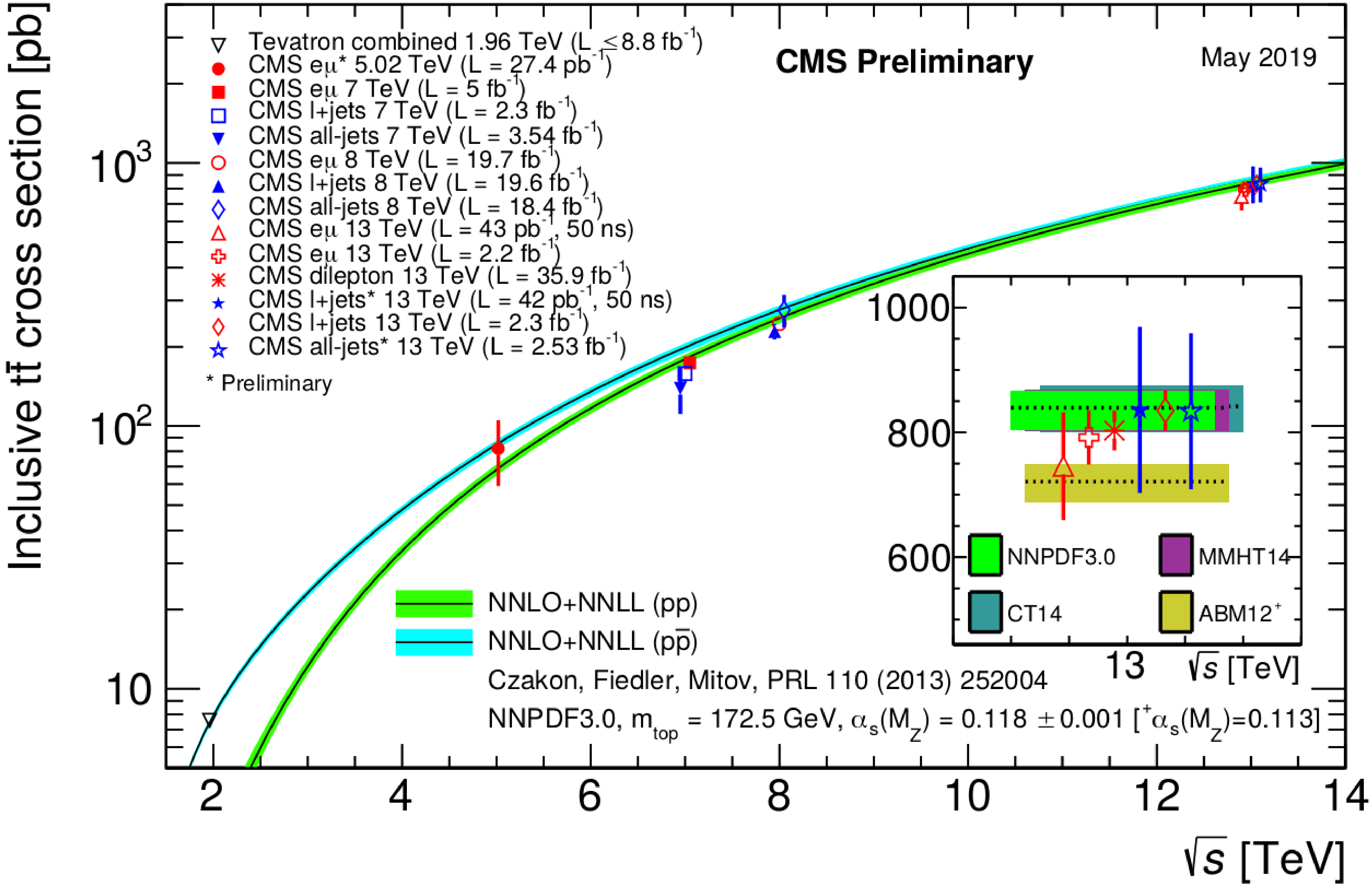
Precision beyond the theoretical predictions!

Example of post-fit distribution.

Constrain of m_t^{pole} and α_s.

Summary of $t\bar{t}$ inclusive cross section

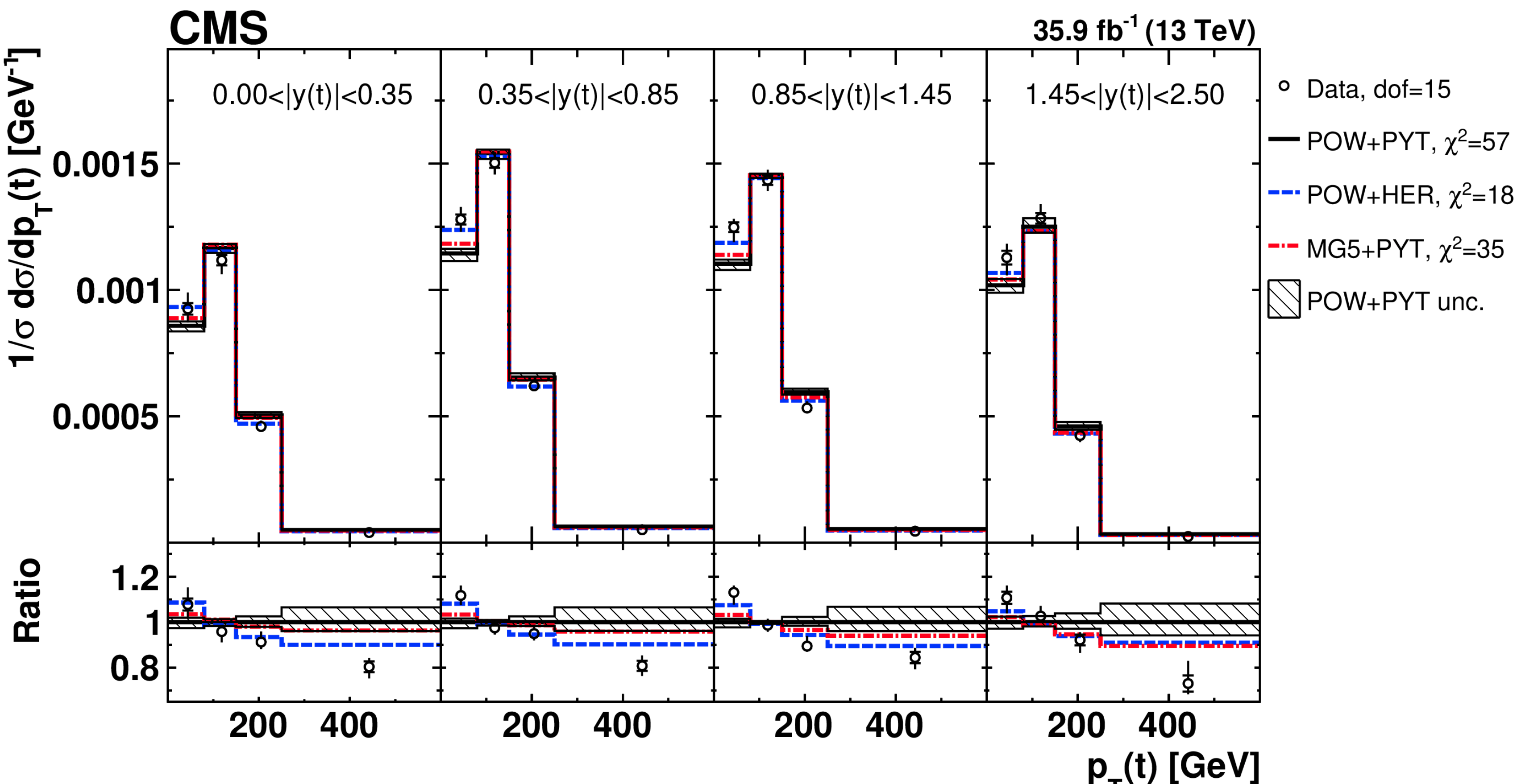
Results in agreement with the SM predictions at 5.02, 7, 8 and 13 TeV in pp collisions.



Multi-differential $t\bar{t}$ cross section

Double and triple differential cross section in the dilepton channel, as a function of kinematic variables of the top quark, at parton level.

arXiv:1904.05237

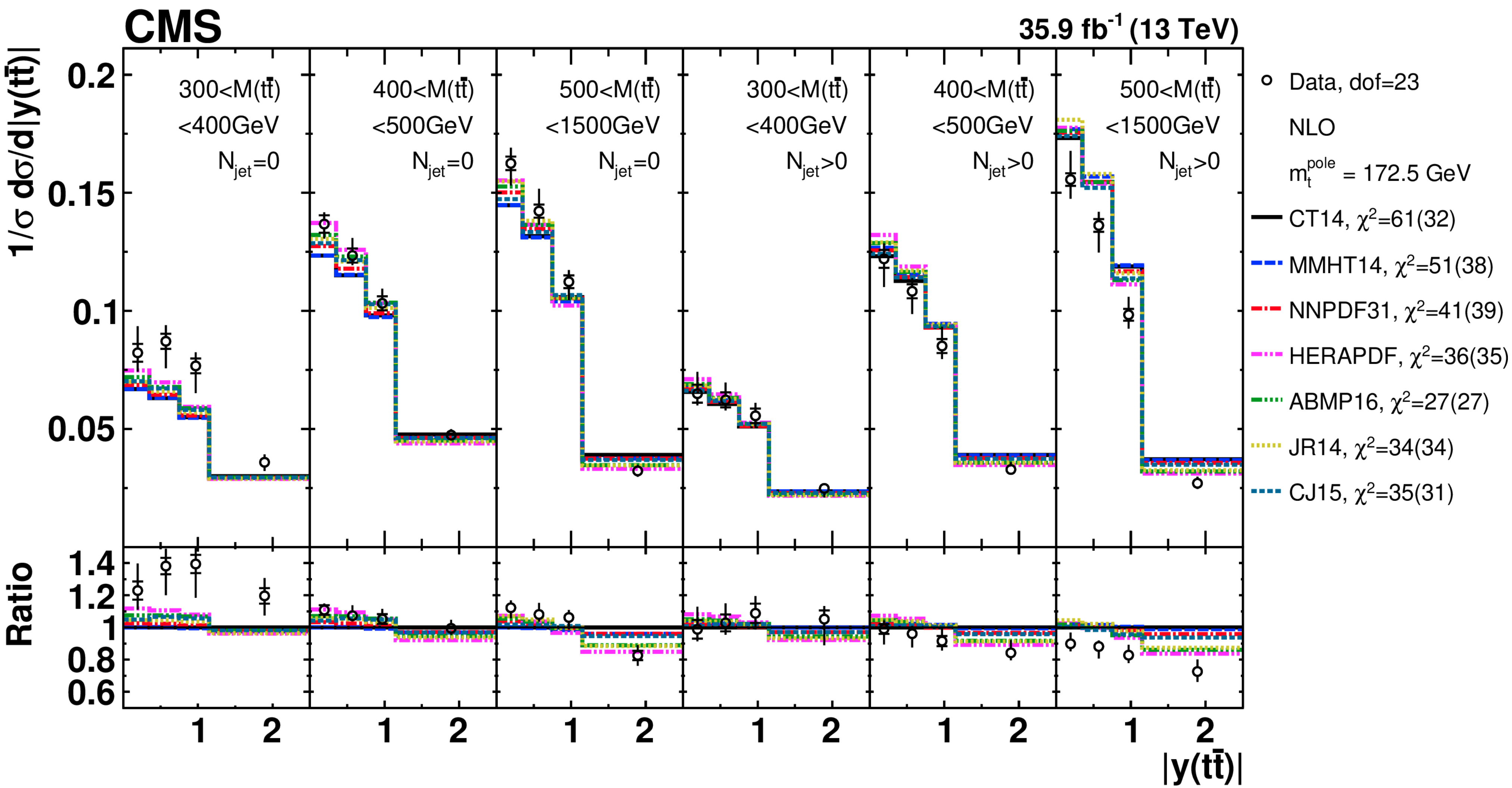


Comparison between different generators. **Powheg+Herwig** has the best description for **|y(t)|, p_T(t)**. Other distributions are better modeled by **Powheg+Pythia**.

Multi-differential $t\bar{t}$ cross section

arXiv:1904.05237

Furthermore, comparison between **different PDF sets**.



The differential cross sections are used to measure/constrain: top quark **pole mass**, **strong coupling constant**, **proton PDFs**.

$t\bar{t} + b\bar{b}$ inclusive cross section (1)

NEW

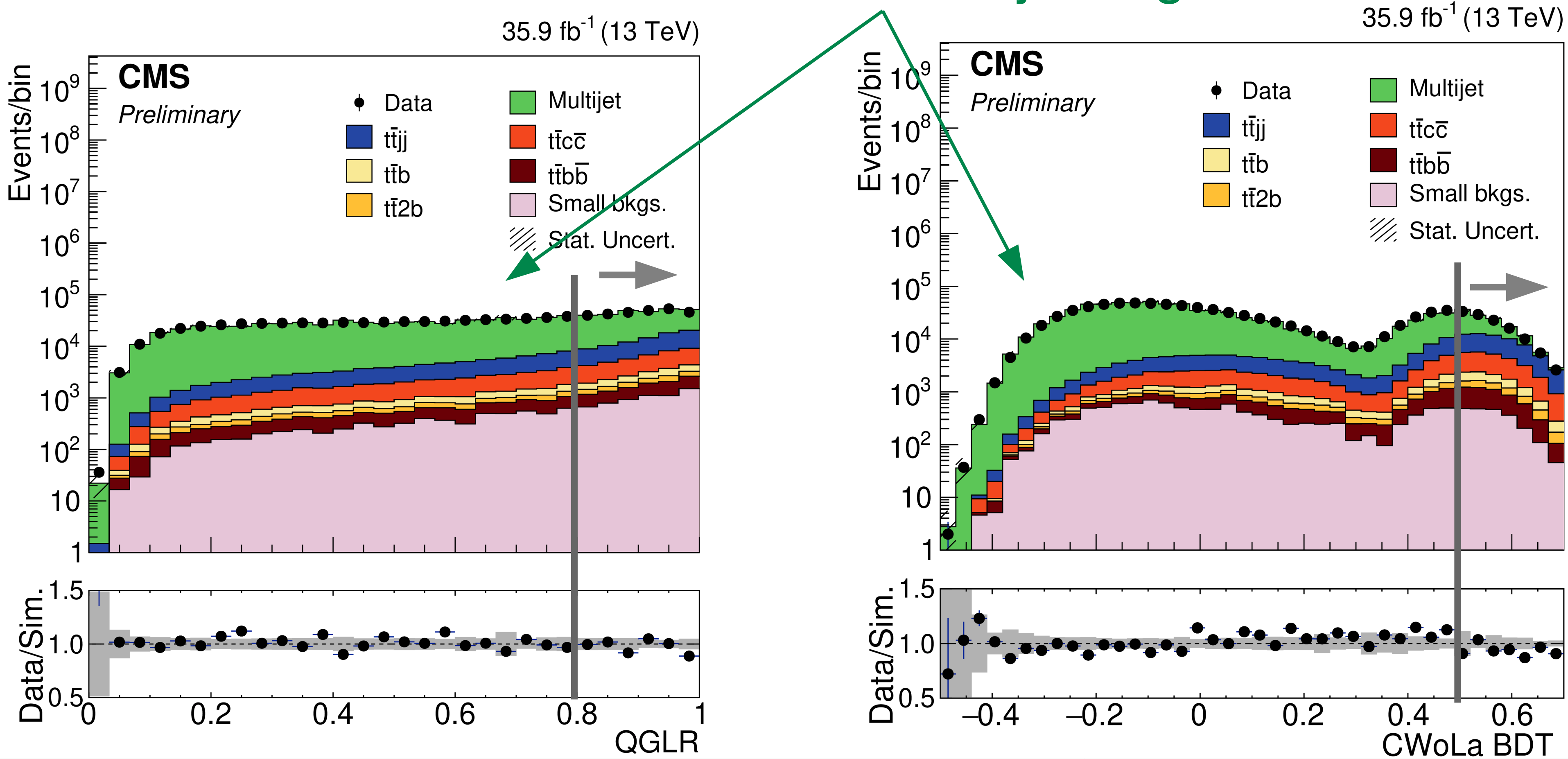
CMS-TOP-18-011

Measurement in the full-hadronic final state.

$t\bar{t}$ + two additional b-jets: signal region defined using a BDT and the quark-gluon likelyhood ratio (QGLR).

Classification Without Labels (CWoLa): weakly supervised approach, training data vs data in orthogonal regions.

Multijet bkg from low score

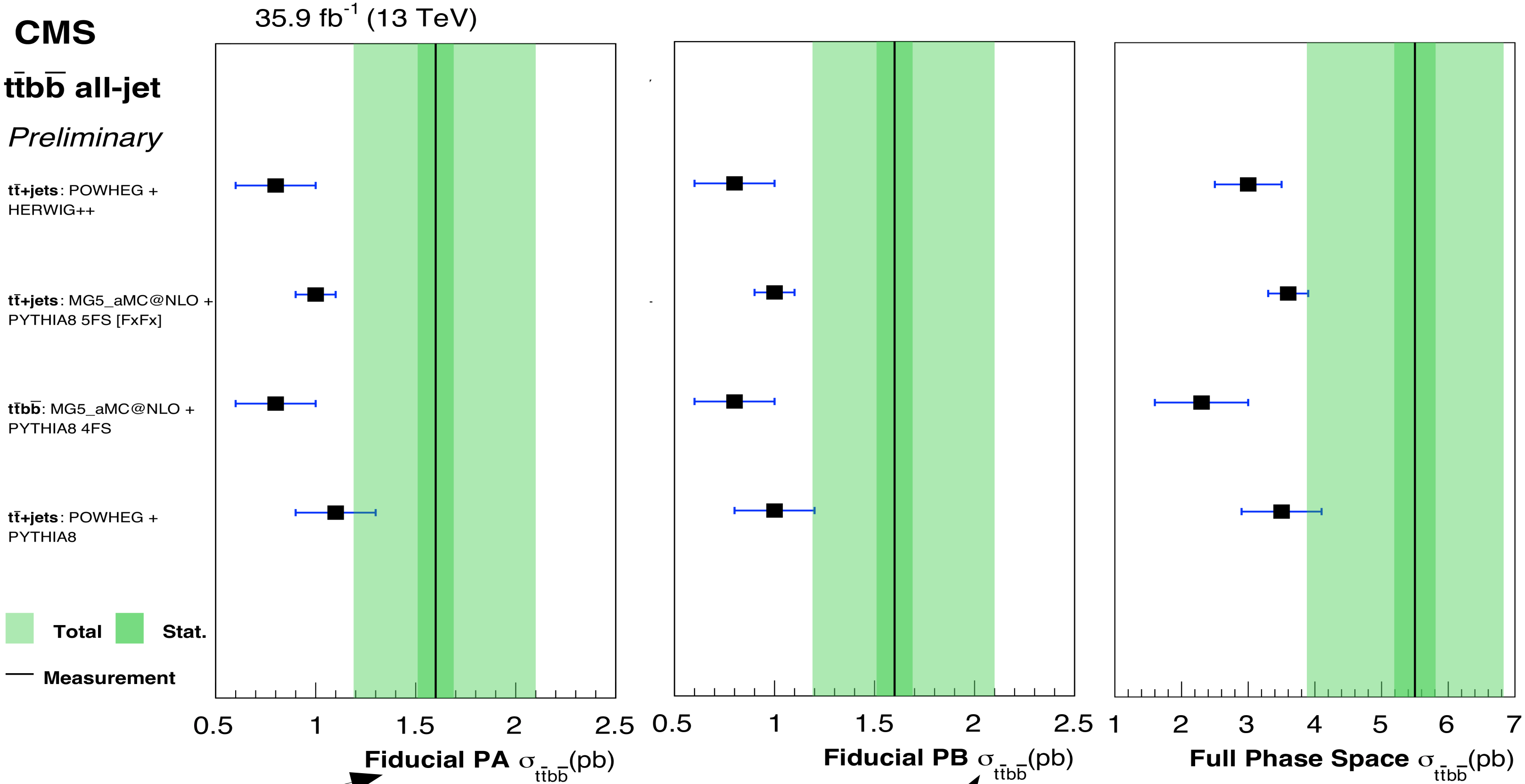


$t\bar{t}$ + $b\bar{b}$ inclusive cross section (2)

NEW

CMS-TOP-18-011

Signal extraction by fitting the **2D distribution of two largest b-tag output** of additional jets.



8 jets, 4 b jets

8 jets + 4 b jets, 2 b jets not coming from top quark decays.

Predictions are **lower** than the measured values.

Conclusions

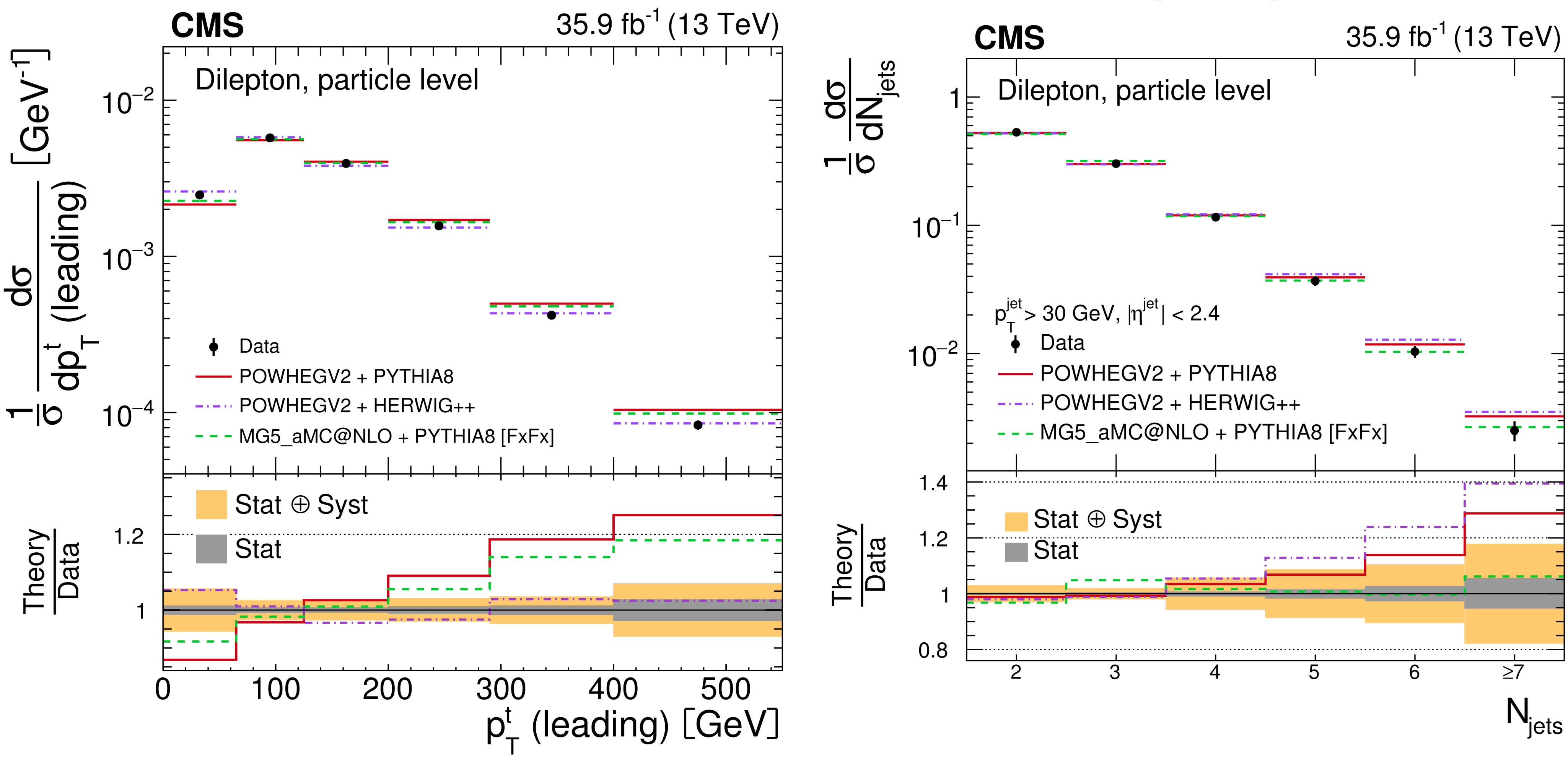
- New top-quark cross section results: (multi)differential and inclusive $t\bar{t}$ and single top cross sections and inclusive $t\bar{t}b\bar{b}$ cross section measurement.
- Comparison with different generators: none of them shows a good agreement with all the distributions.
- Several top properties and QCD parameters are extracted from these measurements: strong coupling constant, top quark Yukawa coupling, proton PDFs, angular and charge asymmetries…
- Cross sections used to probe EFT interpretations.

Thank you for your attention!!

BACK UP SLIDES

Differential $t\bar{t}$ cross section

Dilepton channel. The differential cross section is measured as a function of kinematic variables of top quark and tt system and their decay products. **JHEP 02 (2019) 149**



The **top quark chromomagnetic dipole moment** is constrained from the differential tt cross section as a function of **Δφ(l,l)**.

Single top inclusive cross section

Variable	Description
Light-quark jet $\|\eta\|$	Absolute value of the pseudorapidity of the light-quark jet
Top quark mass	Invariant mass of the top quark reconstructed from the lepton, the neutrino, and the b-tagged jet associated to the top quark decay
Dijet mass	Invariant mass of the light-quark jet and the b-tagged jet associated to the top quark decay
ΔR (lepton, b jet)	ΔR between the momentum vectors of the lepton and the b-tagged jet associated with the top quark decay
$\cos\theta^*$	Cosine of the angle between the lepton and the light-quark jet in the rest frame of the top quark
Jet p_T sum	Scalar sum of the transverse momenta of the light-quark jet and the b-tagged jet associated to the top quark decay
m_T^W	Transverse mass of the W boson
p_T^{miss}	Missing momentum in the transverse plane of the event
ΔR (light jet, b jet)	ΔR between the momentum vectors of the light-quark jet and the b-tagged jet associated to the top quark decay
Lepton $\|\eta\|$	Absolute value of the pseudorapidity of the selected lepton
W boson $\|\eta\|$	Absolute value of the pseudorapidity of the reconstructed W boson
Light-quark jet mass	Invariant mass of the light-quark jet

Single top inclusive cross section

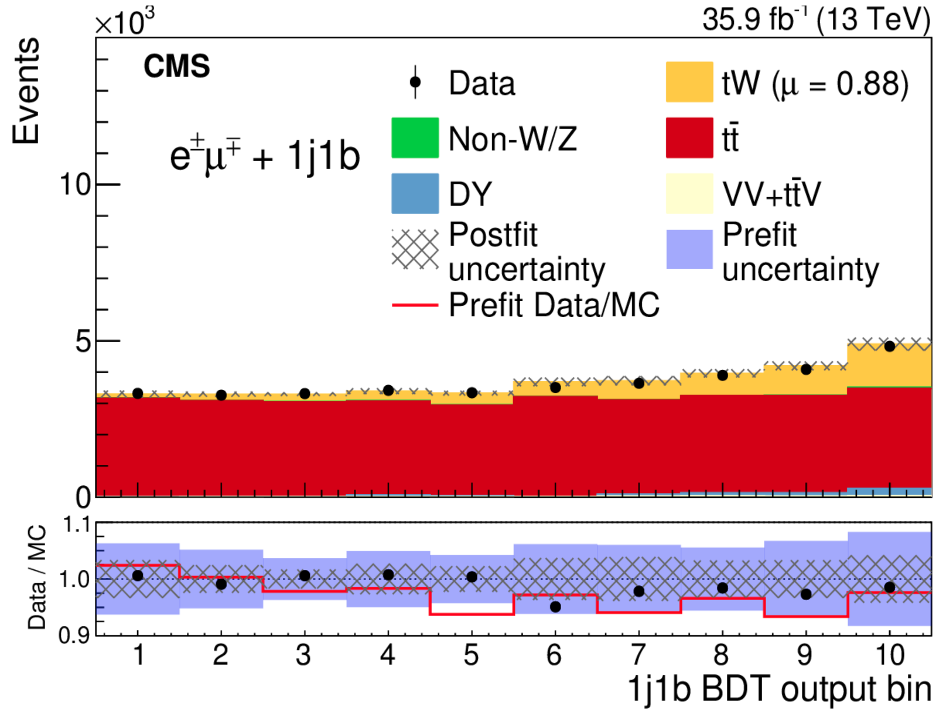
$$\begin{aligned}\sigma_{t\text{-ch},\mathrm{t}} &= 136 \pm 1\,(\mathrm{stat}) \pm 3\,(\mathrm{prof}) \pm 21\,(\mathrm{sig\text{-}mod}) \pm 4\,(\mathrm{lumi})\,\mathrm{pb}\\ &= 136 \pm 1\,(\mathrm{stat}) \pm 22\,(\mathrm{syst})\,\mathrm{pb}\\ &= 136 \pm 22\,\mathrm{pb},\\ \sigma_{t\text{-ch},\bar{\mathrm{t}}} &= 82 \pm 1\,(\mathrm{stat}) \pm 3\,(\mathrm{prof}) \pm 14\,(\mathrm{sig\text{-}mod}) \pm 2\,(\mathrm{lumi})\,\mathrm{pb}\\ &= 82 \pm 1\,(\mathrm{stat}) \pm 14\,(\mathrm{syst})\,\mathrm{pb}\\ &= 82 \pm 14\,\mathrm{pb}.\end{aligned}$$

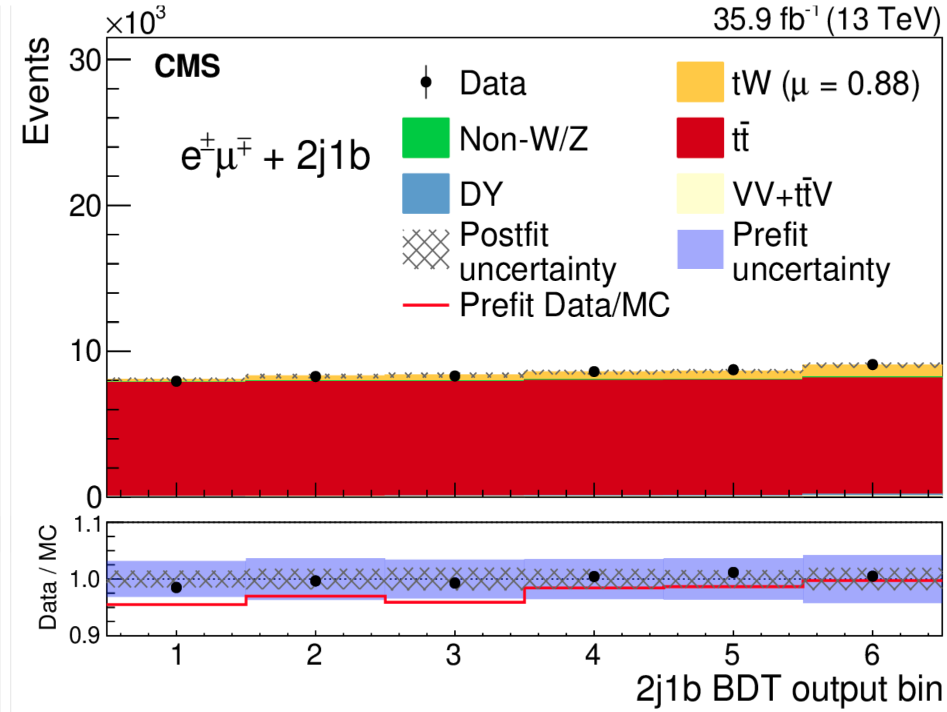
$$\begin{aligned}R_{t\text{-ch}} &= 1.66 \pm 0.02\,(\mathrm{stat}) \pm 0.03\,(\mathrm{prof}) \pm 0.04\,(\mathrm{sig\text{-}mod})\\ &= 1.66 \pm 0.02\,(\mathrm{stat}) \pm 0.05\,(\mathrm{syst})\\ &= 1.66 \pm 0.05.\end{aligned}$$

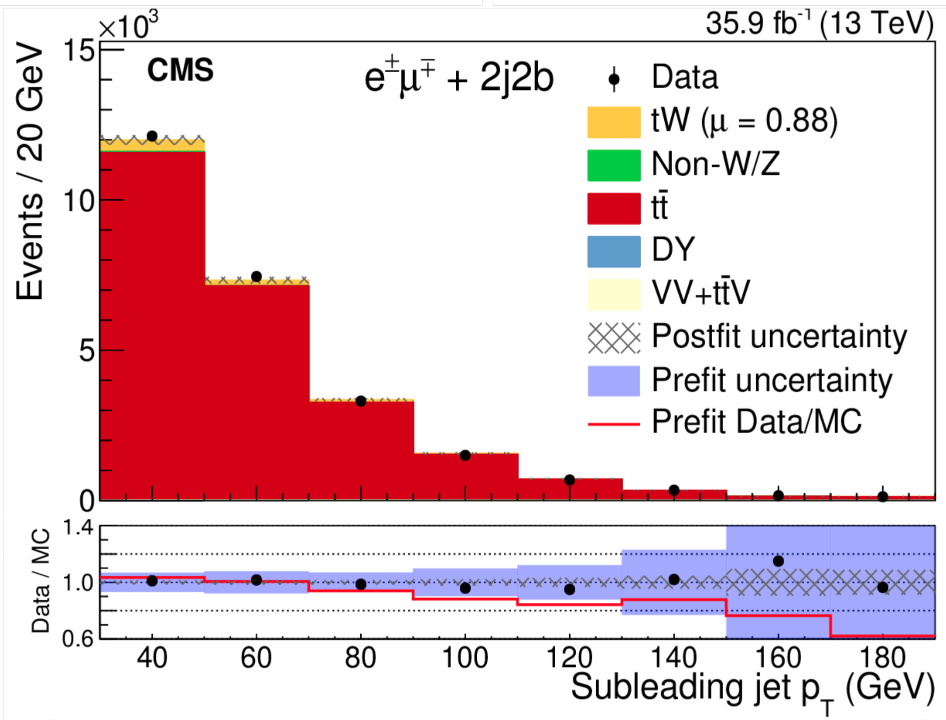
Single top inclusive cross section

	$\Delta R_{t\text{-ch}}/R_{t\text{-ch}}$	$\Delta\sigma/\sigma(\mathrm{t})$	$\Delta\sigma/\sigma(\bar{\mathrm{t}})$
Nonprofiled uncertainties			
μ_R/μ_F scale t channel	0.1	6.2	6.5
ME-PS scale matching t channel	0.5	2.9	2.3
PS scale t channel	0.6	12.9	13.3
PDF t channel	2.4	7.1	9.5
Luminosity	—	2.5	2.5
Profiled uncertainties			
JES	0.5	1.7	2.1
JER	0.2	0.1	0.3
Unclustered energy	0.2	0.1	0.3
b tagging	0.1	1.2	1.2
Muon and electron efficiencies	0.2	1.1	1.0
Pileup	0.4	0.9	1.2
QCD bkg. normalization	0.2	0.3	0.5
MC sample size	2.6	2.3	3.3
$\mathrm{t\bar{t}}$ bkg. model and normalization	0.6	1.1	1.5
Top quark p_T	< 0.1	0.5	0.5
tW bkg. normalization	0.1	0.4	0.5
W/Z+jets bkg. normalization	0.2	0.3	0.5
μ_R/μ_F scale $\mathrm{t\bar{t}}$, tW, W/Z+jets	0.8	0.3	0.5
PDF $\mathrm{t\bar{t}}$, W/Z+jets	0.6	0.2	0.7

tW inclusive cross section

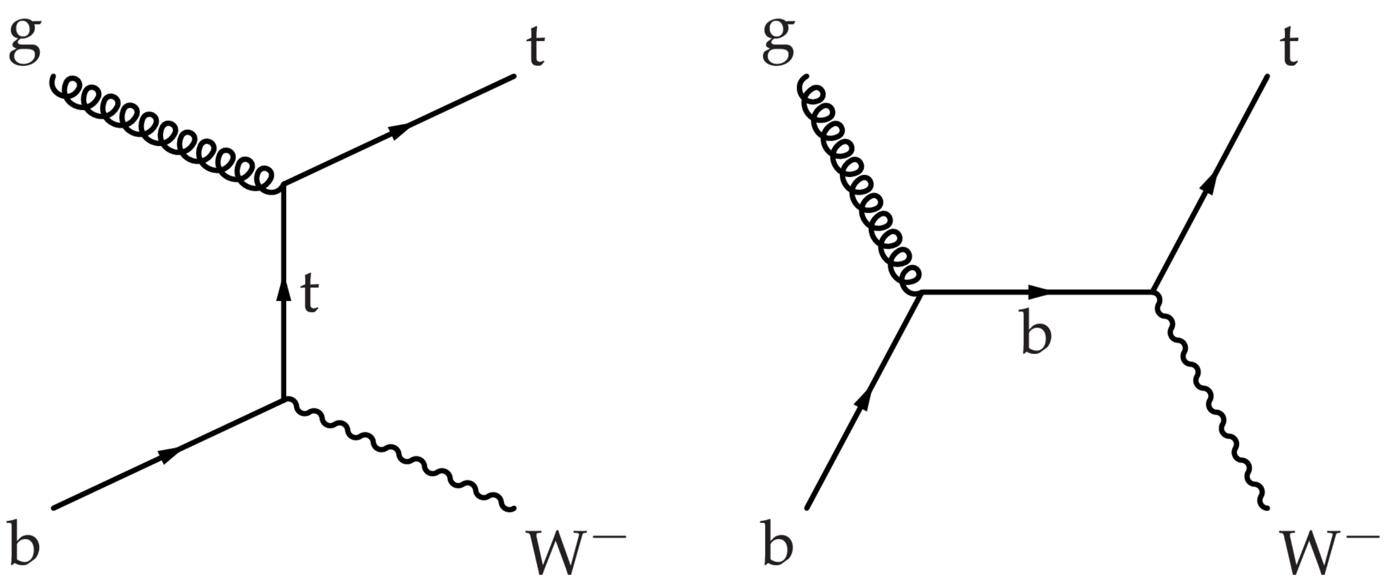






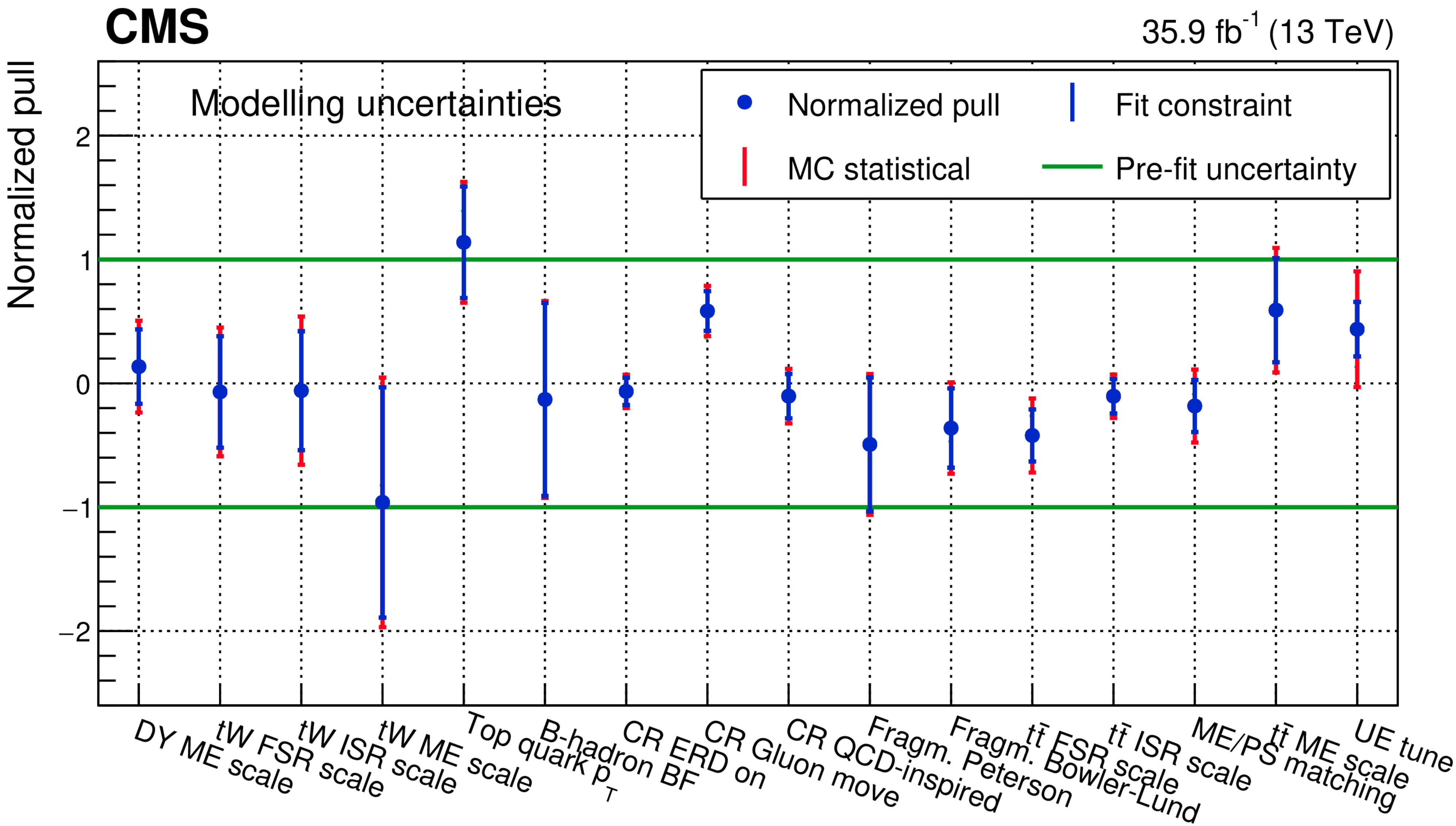
tW inclusive cross section

Source	Uncertainty (%)
Experimental	
Trigger efficiencies	2.7
Electron efficiencies	3.2
Muon efficiencies	3.1
JES	3.2
Jet energy resolution	1.8
b tagging efficiency	1.4
Mistag rate	0.2
Pileup	3.3
Modeling	
$t\bar{t}$ μ_R and μ_F scales	2.5
tW μ_R and μ_F scales	0.9
Underlying event	0.4
Matrix element/PS matching	1.8
Initial-state radiation	0.8
Final-state radiation	0.8
Color reconnection	2.0
B fragmentation	1.9
Semileptonic B decay	1.5
PDFs	1.5
DR-DS	1.3
Background normalization	
$t\bar{t}$	2.8
VV	0.4
Drell–Yan	1.1
Non-W/Z leptons	1.6
$t\bar{t}V$	0.1
MC finite sample size	1.6
Full phase space extrapolation	2.9
Total systematic (excluding integrated luminosity)	10.1
Integrated luminosity	3.3
Statistical	2.8
Total	11.1



	Prefit		Postfit	
Region	tW	$t\bar{t}$	tW	$t\bar{t}$
1j1b	6147 ± 442	30622 ± 1862	5440 ± 604	30592 ± 582
2j1b	3125 ± 294	48484 ± 1984	2888 ± 321	47436 ± 612
2j2b	725 ± 85	25052 ± 2411	719 ± 88	25114 ± 281

$t\bar{t}$ inclusive cross section



ttbb

Source	VPS (PA)	VPS (PB)
Simulated sample size	$+15/-11$	$+15/-11$
Quark-gluon likelihood	$+13/-8$	$+13/-8$
b tagging	±10	±10
JES & JER	$+5.1/-5.2$	$+5.0/-5.4$
Integrated luminosity	$+2.8/-2.2$	$+2.4/-2.2$
Trigger efficiency	$+2.6/-2.1$	$+2.5/-2.2$
Pileup	$+2.3/-2.0$	$+2.2/-1.9$
μ_R and μ_F scales	$+13/-9$	$+13/-9$
Parton shower scale	$+11/-8$	$+11/-8$
UE tune	$+9.0/-5.3$	$+9.0/-5.2$
Colour reconnection	±7.2	±7.1
Shower matching (h_{damp})	$+4.3/-2.8$	$+3.8/-2.7$
$\mathrm{t\bar{t}c\bar{c}}$ normalisation	$+3.2/-4.4$	$+2.9/-4.5$
Top quark p_T modelling	±2.5	±2.4
PDFs	$+2.2/-2.0$	$+2.2/-2.0$

	VPS (PA)	VPS (PB)	FPS
Measurement	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$1.6 \pm 0.1^{+0.5}_{-0.4}$	$5.5 \pm 0.3^{+1.6}_{-1.3}$
POWHEG ($\mathrm{t\bar{t}}$)	1.1 ± 0.2	1.0 ± 0.2	3.5 ± 0.6
POWHEG ($\mathrm{t\bar{t}}$) + HERWIG++	0.8 ± 0.2	0.8 ± 0.2	3.0 ± 0.5
MG5_aMC@NLO (4FS $\mathrm{t\bar{t}b\bar{b}}$)	0.8 ± 0.2	0.8 ± 0.2	2.3 ± 0.7
MG5_aMC@NLO (5FS $\mathrm{t\bar{t}}$+jets FxFx)	1.0 ± 0.1	1.0 ± 0.1	3.6 ± 0.3