Measurements of the single top quark production with CMS

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Introduction

- Single top quark production at the LHC ⇔ electro-weak production of top quarks.

- Important measurements for :
  - testing the SM predictions/calculations,
  - constraining PDFs, measuring $|V_{tb}|$,
  - searching for new physics.

- Measurements performed at 7, 8 and 13 TeV, for different channels :
  - t-channel, tW-channel, s-channel,
  - Other rare processes, tZq.

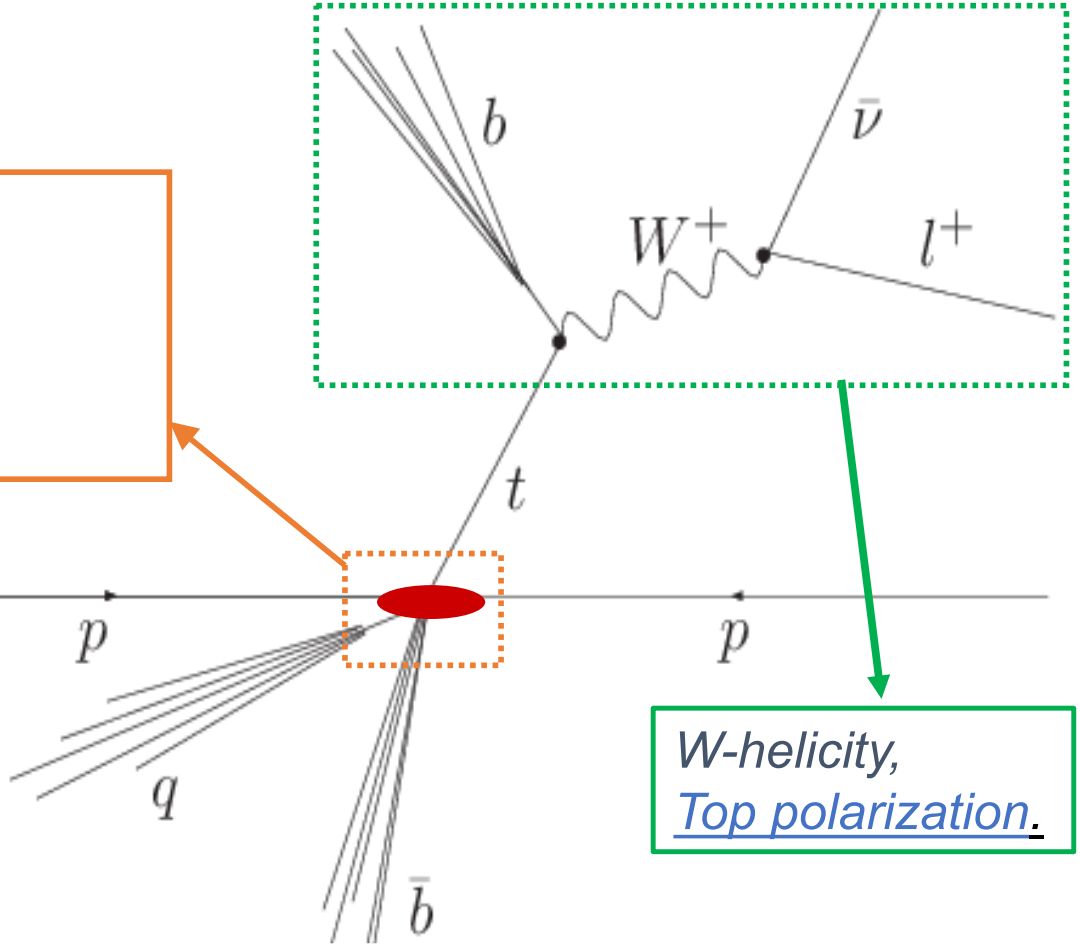
- Outline :
  - t-channel inclusive and differential cross sections, $|V_{tb}|$ and PDF constrains,
  - tW inclusive cross section,
  - Rare processes : s-channel, tZq channel.

Single top production and properties

Discussed in this talk

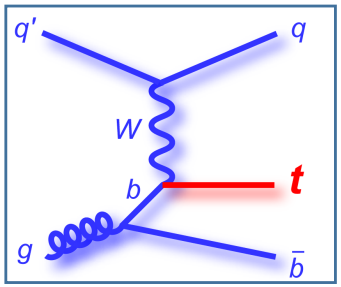
See talk of Andrea Castro

- *Cross-sections of t, s and tW channels,*
- *Measurement of |Vtb|,*
- *Anomalous couplings and FCNC/H,*
- *PDF,*
- *Top polarization.*

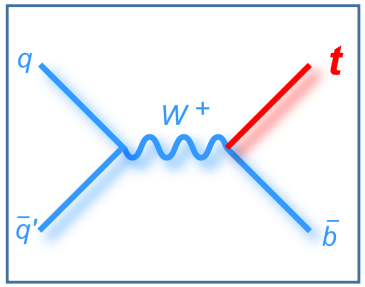


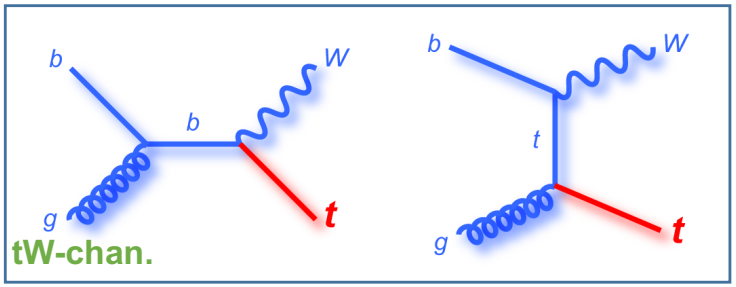
W-helicity,
Top polarization.

t-chan.



s-chan.

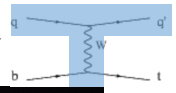




LHCTopWG

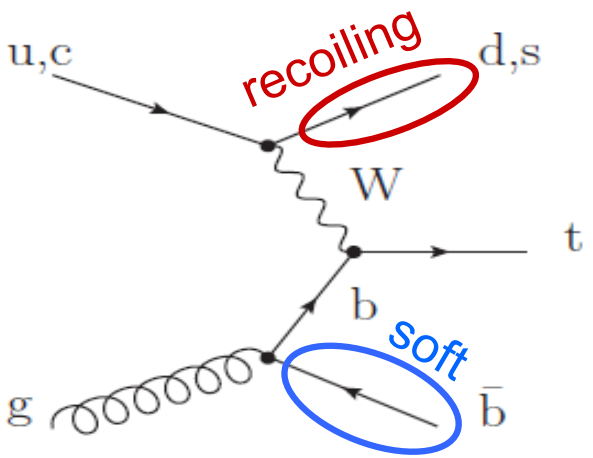
	8TeV	13 TeV	order
t-chan.	84^{+3}_{-3} pb	217^{+9}_{-8} pb ($213.7^{1.6}_{0.8}$pb)	NLO (NNLO)
tW-chan.	22^{+4}_{-4} pb	71^{+4}_{-4} pb	aNNLO
s-chan.	$5.2^{+0.22}_{-0.20}$ pb	10^{+4}_{-4} pb	NLO

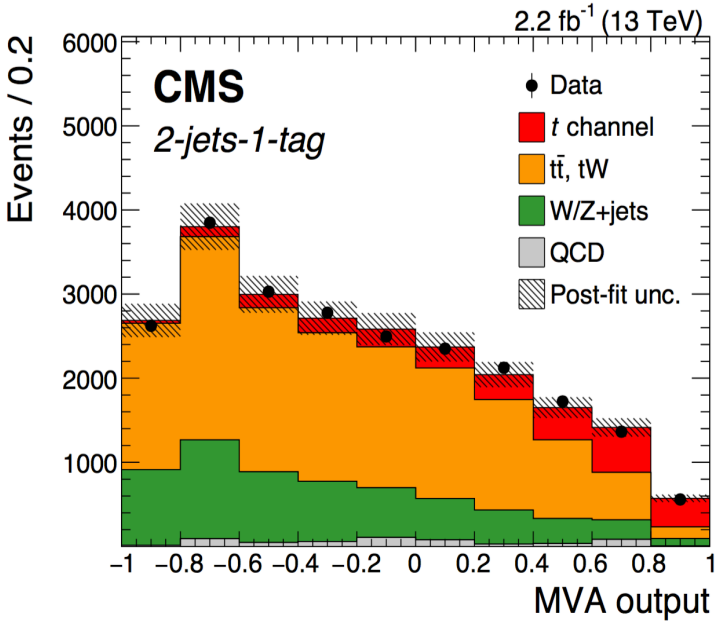
Measurement of the t-channel production

Mister 

t-channel cross section at 13 TeV

arXiv:1610.00678, acc. PLB





- Event selection :
  - single muon trigger, 1 isolated high p_T muon,
  - 2 high p_T jets (up to $|\eta|$ <4.5 for light jet, 2.4 for b-jet), b-tagging tight,
  - $m_T(W)$ >50 GeV.
- Multijet background : estimated from a fit of $m_T(W)$.
- Signal extraction: combined multivariate (NN) using 3 samples :
  - 2 jets, 1 tag (2J1T) => Signal Region,
  - 3J0T and 3J1T => $t\bar{t}$-enriched Control Regions,
  - 2J0T used to validate the W+jets background.
- Most discriminating variables: $|\eta(j')|$, m_t, dijet mass, $m_T(W)$. Dominant systematics: signal and $t\bar{t}$ modelling, JES.

$$\sigma^{\text{th}}_{t\text{-ch.},t+\bar{t}} = 238 \pm 13\,(\text{stat}) \pm 12\,(\text{exp}) \pm 26\,(\text{theo}) \pm 5\,(\text{lumi})\,\text{pb}$$
$$= 238 \pm 32\,\text{pb}.\ (\pm 13\%)$$

t-channel cross section at 13 TeV

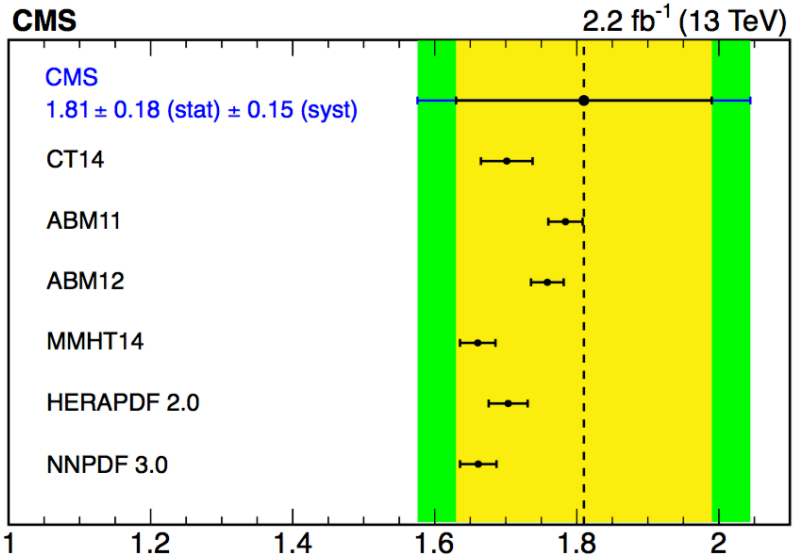
arXiv:1610.00678, acc. PLB

- Measurement if $|V_{tb}|$ from cross section.
- Assumes $|V_{tb}| \gg |V_{td}| \gg |V_{ts}|$.

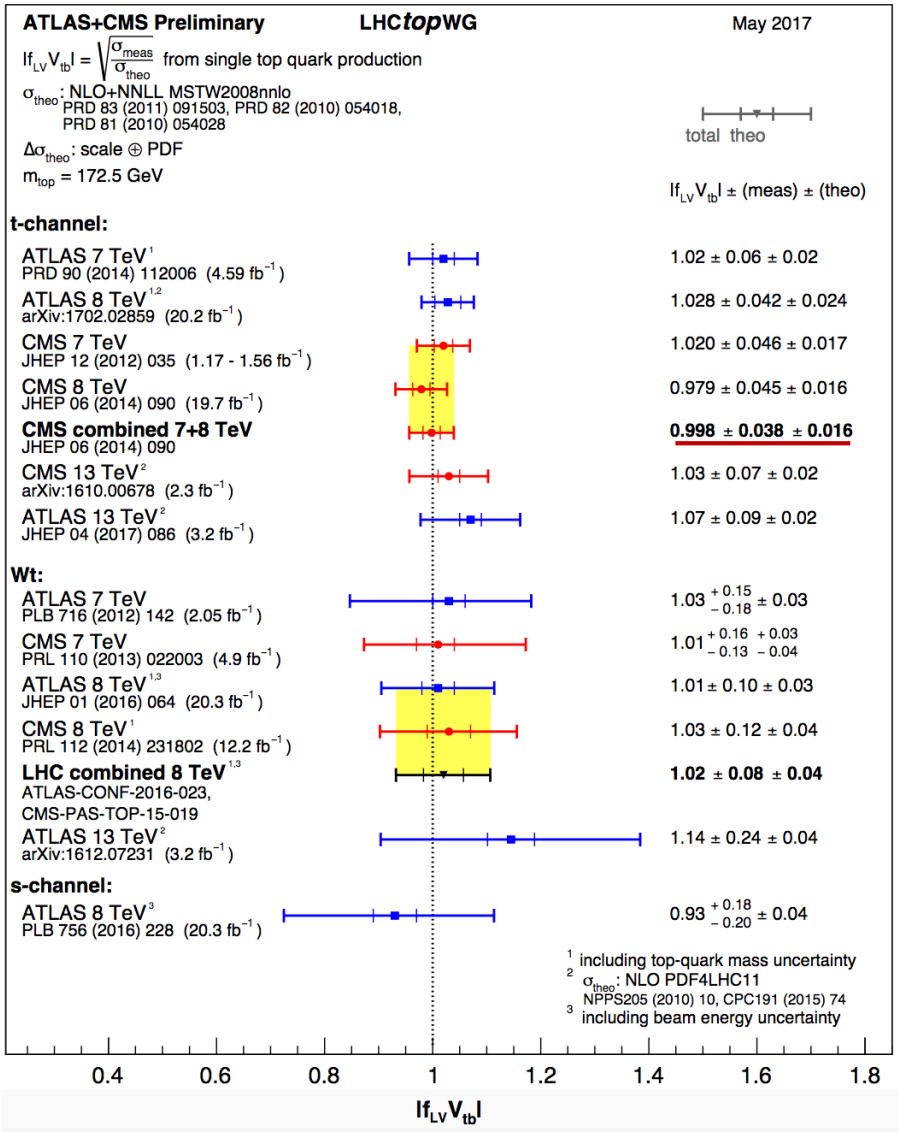
$$|f_{LV}V_{tb}| = \sqrt{\frac{\sigma_{t\text{-ch.},t+\bar{t}}}{\sigma^{th}_{t\text{-ch.},t+\bar{t}}}},$$

$$|f_{LV}V_{tb}| = 1.05 \pm 0.07\,(\text{exp}) \pm 0.02\,(\text{theo})$$

- Measurement of $t/\bar{t}$ cross section ratio.



$R_{t\text{-ch.}} = \sigma_{t\text{-ch.},t} / \sigma_{t\text{-ch.},\bar{t}}$



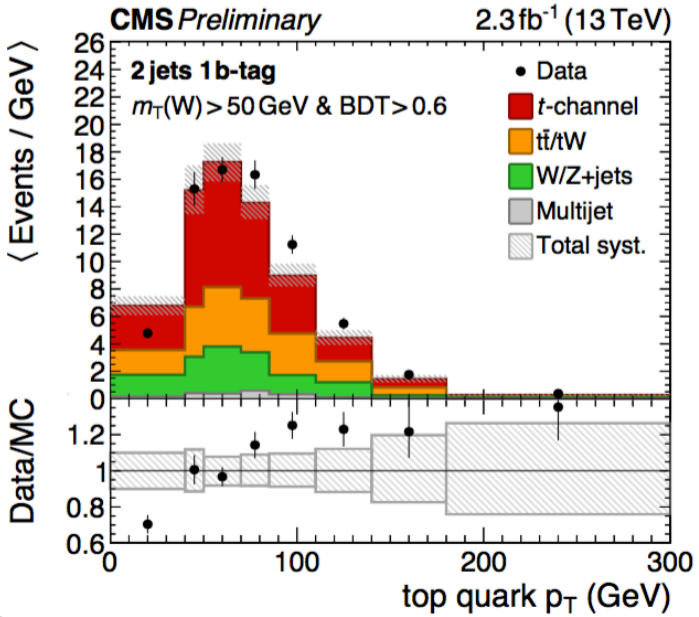
$$R_{t\text{-ch.}} = 1.81 \pm 0.18\,(\text{stat}) \pm 0.15\,(\text{syst}).$$

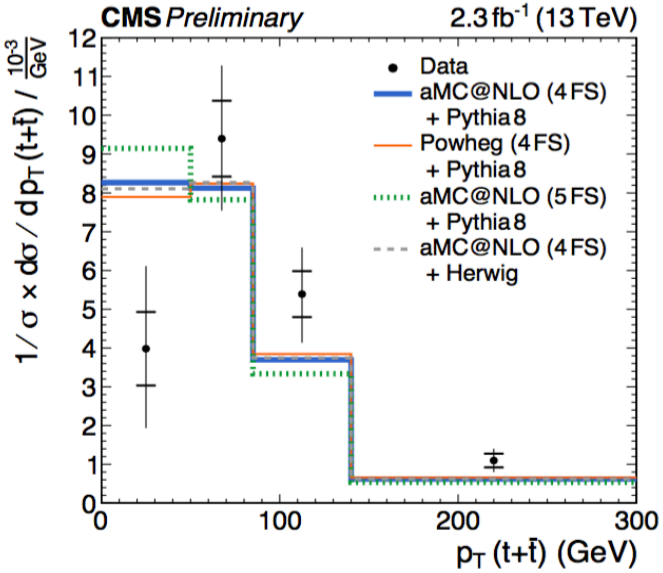
t-channel differential cross section at 13 TeV

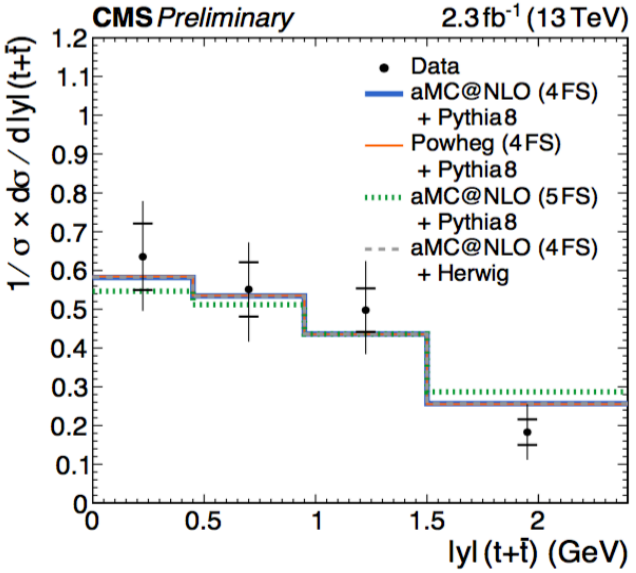
CMS-TOP-16-004

- Event Selection : similar to CMS-TOP-16-003.
- Top quark reconstructed from the muon, the b-jet and the MET + W mass constrain.

- Signal extraction:
  - similar to CMS-TOP-16-003,
  - Choice of BDT variables : avoid bias in the measurement,
  - in the 2J1T, fit of a BDT for $m_T(W)$>50 GeV, use $m_T(W)$ distribution otherwise.







- Distribution unfolded to parton level after background subtraction.

Top polarization in t-channel

JHEP 04 (2016) 073

- Measurement of the differential cross section as a function of $cos\theta^*$ (lepton in top rest frame and recoiling jet).

- Sensitive to the top-quark polarisation.

$$\frac{1}{\sigma}\frac{\mathrm{d}\sigma}{\mathrm{d}\cos\theta_X^*} = \frac{1}{2}(1 + P_t^{(\vec{s})}\alpha_X\cos\theta_X^*) = \left(\frac{1}{2} + A_X\cos\theta_X^*\right)$$

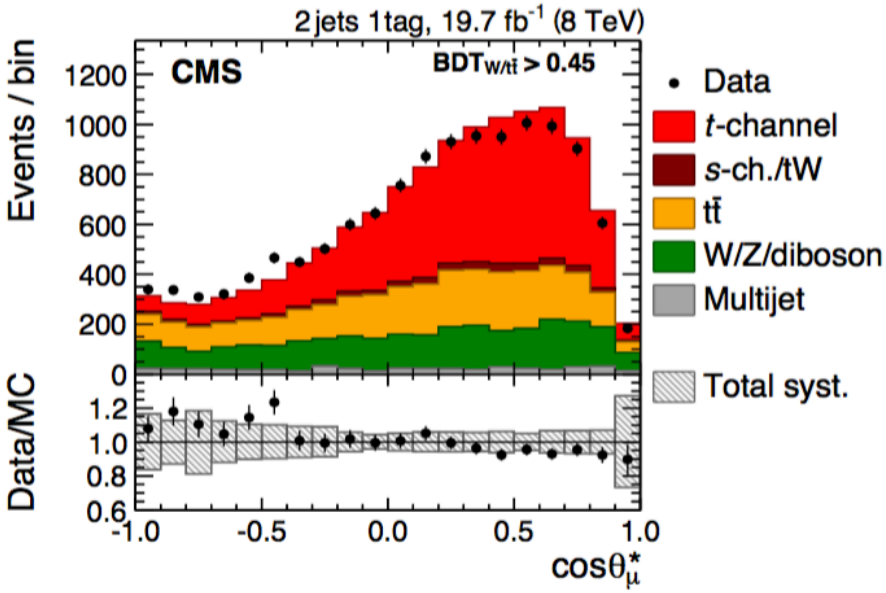
$$A_X \equiv \frac{1}{2}P_t\,\alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

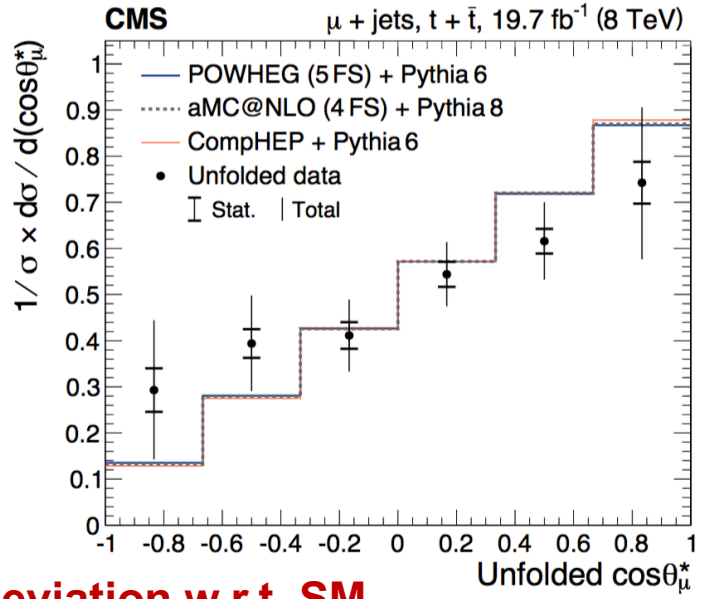
$$A_\mu(SM) = 0.44$$

- Event selection and signal extraction : similar to the t-channel inclusive cross section measurement.

- Differential cross section unfolded at parton level. Top quark spin asymmetries :

$$A_\mu(\mathrm{t}) = 0.29 \pm 0.03\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}) = 0.29 \pm 0.11,$$
$$A_\mu(\bar{\mathrm{t}}) = 0.21 \pm 0.05\,(\mathrm{stat}) \pm 0.13\,(\mathrm{syst}) = 0.21 \pm 0.14,$$
$$A_\mu(\mathrm{t}+\bar{\mathrm{t}}) = 0.26 \pm 0.03\,(\mathrm{stat}) \pm 0.10\,(\mathrm{syst}) = 0.26 \pm 0.11,$$





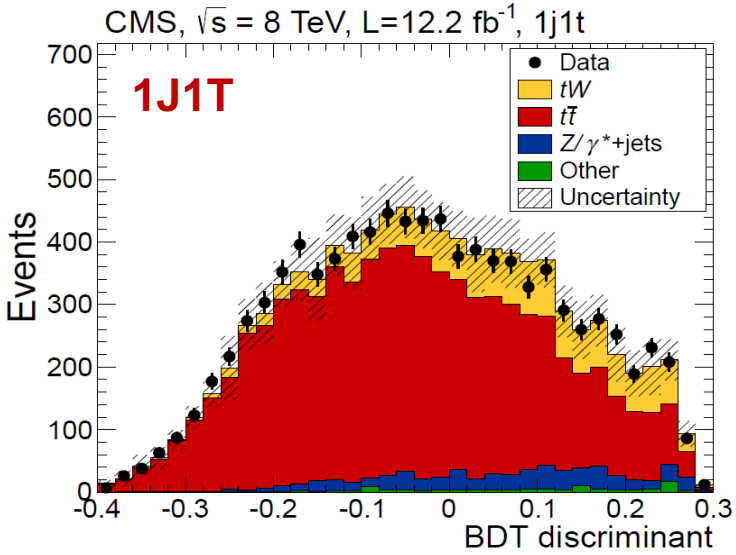
2σ deviation w.r.t. SM

Measurement of the tW- and s-channels production

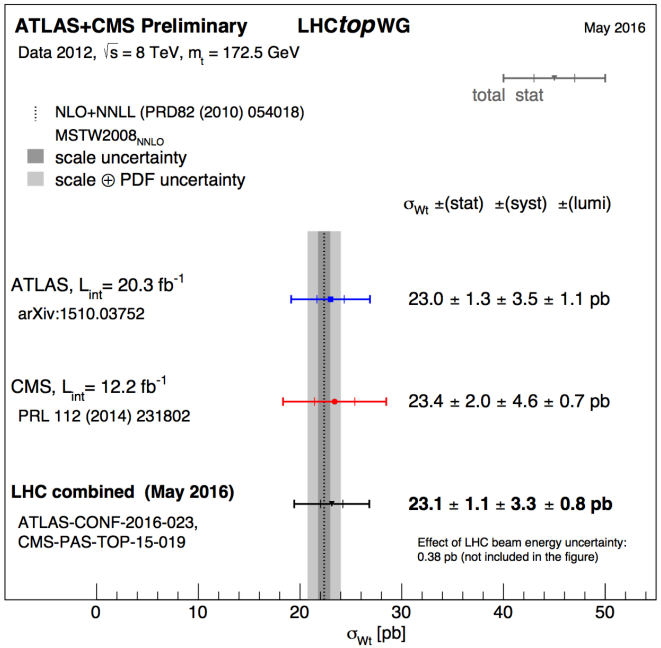
tW channel at 8 TeV

Phys. Rev. Lett. 112 (2014) 231802

- Signature (in dileptonic channel) : 2 leptons (e or μ), 1 b-tagged jet.
- Event selection :
  - dilepton triggers, 2 isolated leptons, ≥2 jets, ≥ 1 b-tagged jet,
  - Z mass veto and large MET only for ee and $\mu\mu$.
- Signal and control regions :
  - Signal : 1J1T,
  - Backgrounds and b-tag efficiency: 2J1T, 2J2T,
- Signal extraction : fit of a BDT discriminant. Most discriminating variables : (b-tag) multiplicities of loose jets.
- Dominant systematics : signal and $t\bar{t}$ modelling uncertainties.
- First Observation : 6.1σ, 23.4±5.4 pb. (±24%)
- Combination LHCtopWG : **~10%** improvement of the best measurement.

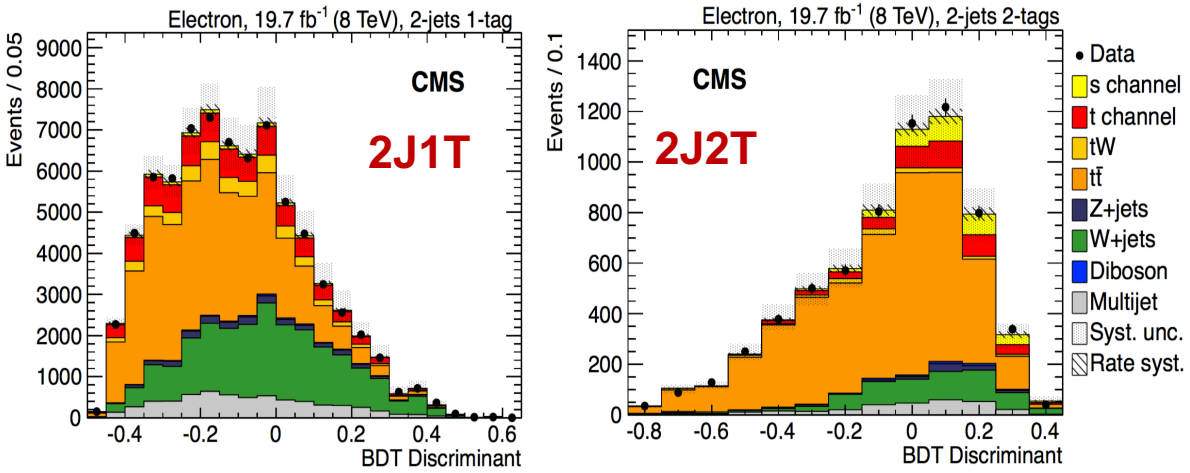


TOP-15-019



s-channel cross section at 7 and 8 TeV (CMS)

JHEP 09 (2016) 027



- Event selection: single lepton trigger, one high p_T lepton, at least one high p_T jets.
- Signal extraction : combined fit of a BDT discriminant : 2J2T(SR), 2J1T(Wjets), 3J2T(ttbar).
- Most discriminating variables : $m_T(W), \Delta R_{bb}, m_{lb2}, p_t^{bb}, \Delta\varphi_{lb1}$.

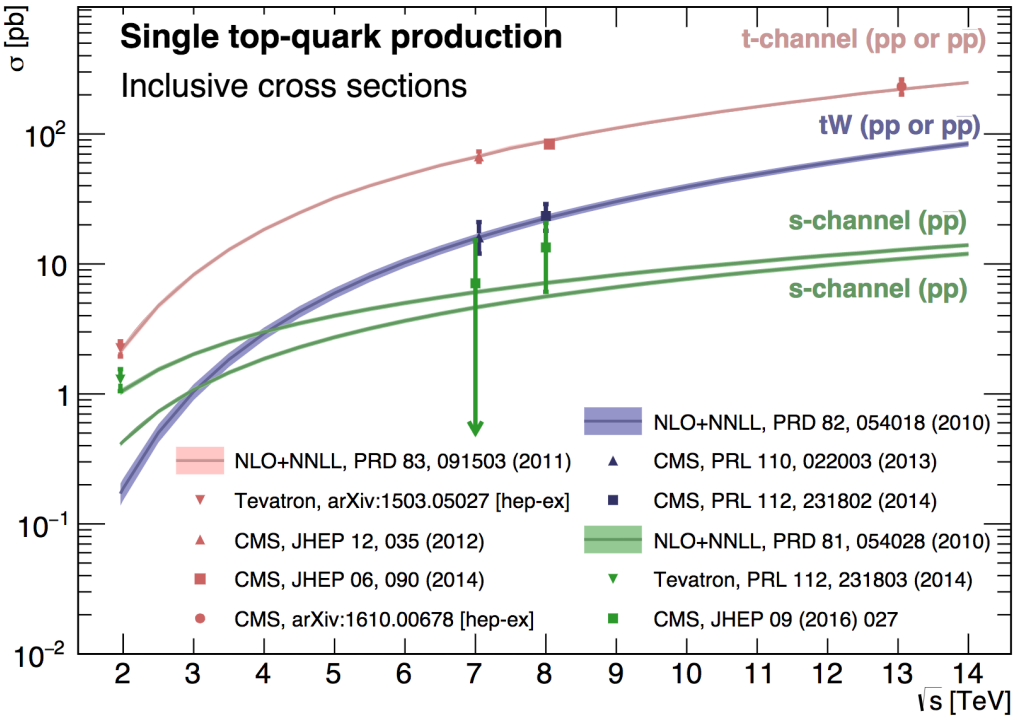
$\sigma_s = 7.1 \pm 8.1\,(\text{stat} + \text{syst})\,\text{pb}$, muon channel, 7 TeV;
$\sigma_s = 11.7 \pm 7.5\,(\text{stat} + \text{syst})\,\text{pb}$, muon channel, 8 TeV;
$\sigma_s = 16.8 \pm 9.1\,(\text{stat} + \text{syst})\,\text{pb}$, electron channel, 8 TeV;
$\sigma_s = 13.4 \pm 7.3\,(\text{stat} + \text{syst})\,\text{pb}$, combined, 8 TeV.

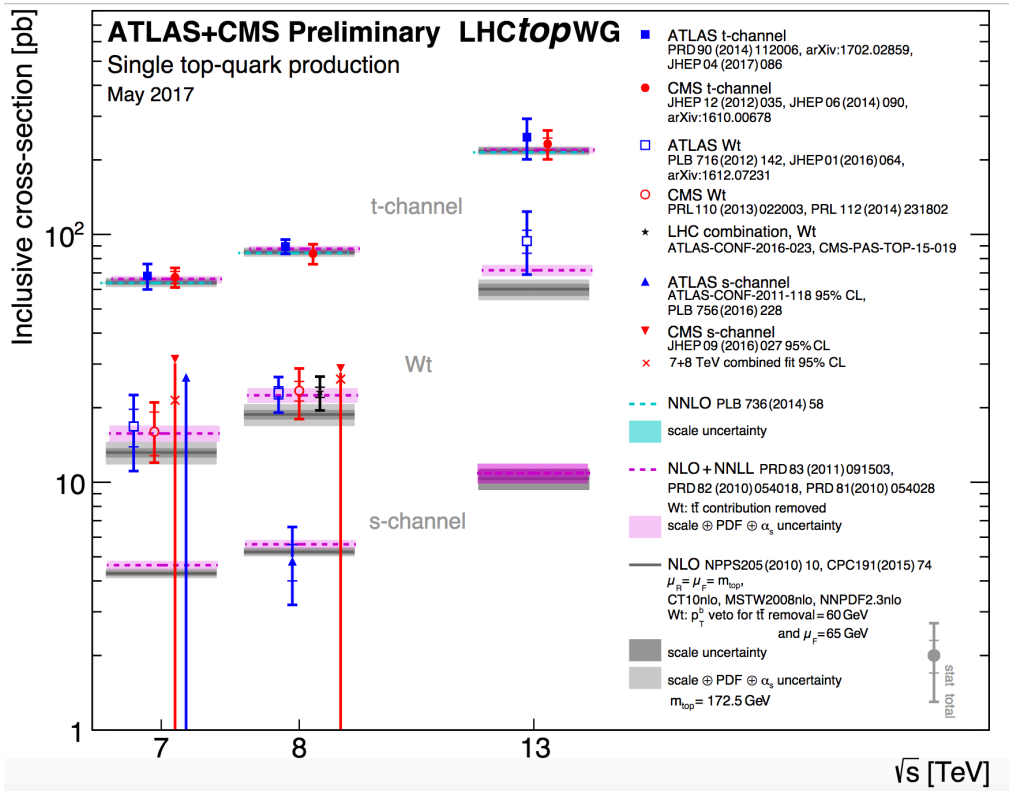
Significance : 2.5 (1.1) obs. (exp.)

Limited by stat. and signal and $t\bar{t}$ modelling.

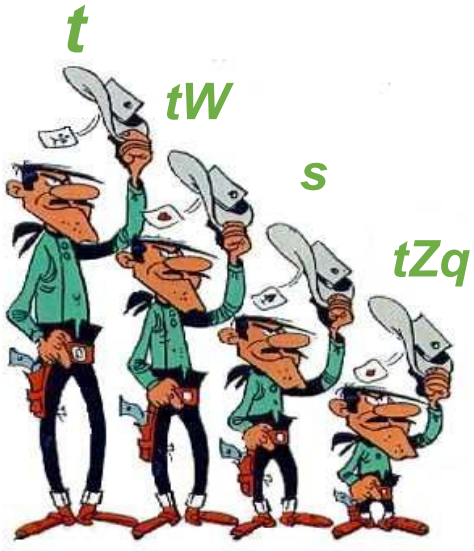
Channel	Observed UL	Expected UL—SM signal	Expected UL—no signal
μ, 7 TeV	31.4 pb	25.4 [19.0, 36.6] pb	20.2 pb
μ+e, 8 TeV	28.8 pb	20.5 [13.4, 26.7] pb	15.6 pb
7+8 TeV	4.7	3.1 [2.1, 4.0]	2.2

Summary of cross section measurements





Measurement of other rare single top processes

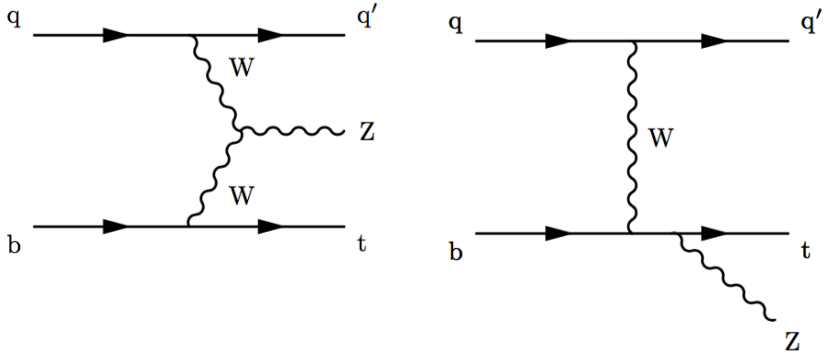


Search for tZq

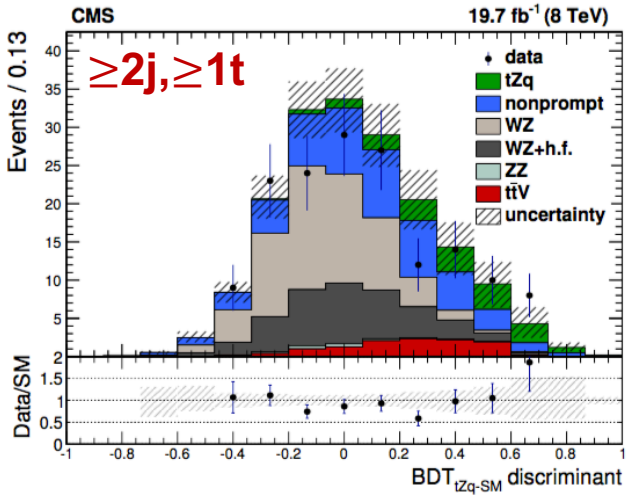
arXiv:1702.01404, acc. by JHEP

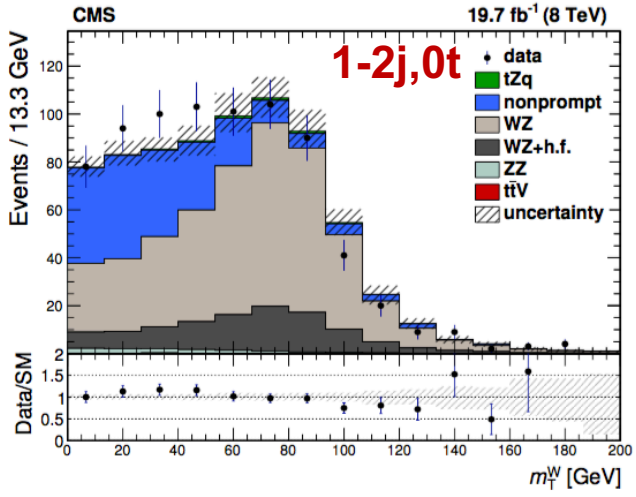
- Search for tZq (SM) at 8 TeV : sensitive to tZ-coupling, triple-boson coupling, backgrounds for searches.

- Event selection :
  - 3 leptons (e or μ), $p_T > 20$ GeV, $|\eta| < 2.5$,
  - 1 forward jet, $p_T > 30$ GeV, $|\eta| < 4.5$,
  - 1 loose b-tagged jet,
  - $m_T^W > 10$ GeV.



- Signal extracted from a BDT (2J1T), non-prompt leptons constrained using data (1-2J0T).
- Cross-checked with a Cut&count method : good agreement.





aMC@NLO : 8.2 fb

Channel	Cross section (fb)
eee	0^{+9}
eeμ	11^{+13}_{-10}
$\mu\mu$e	24^{+19}_{-16}
$\mu\mu\mu$	5^{+9}_{-5}
Combined fit	10^{+8}_{-7}

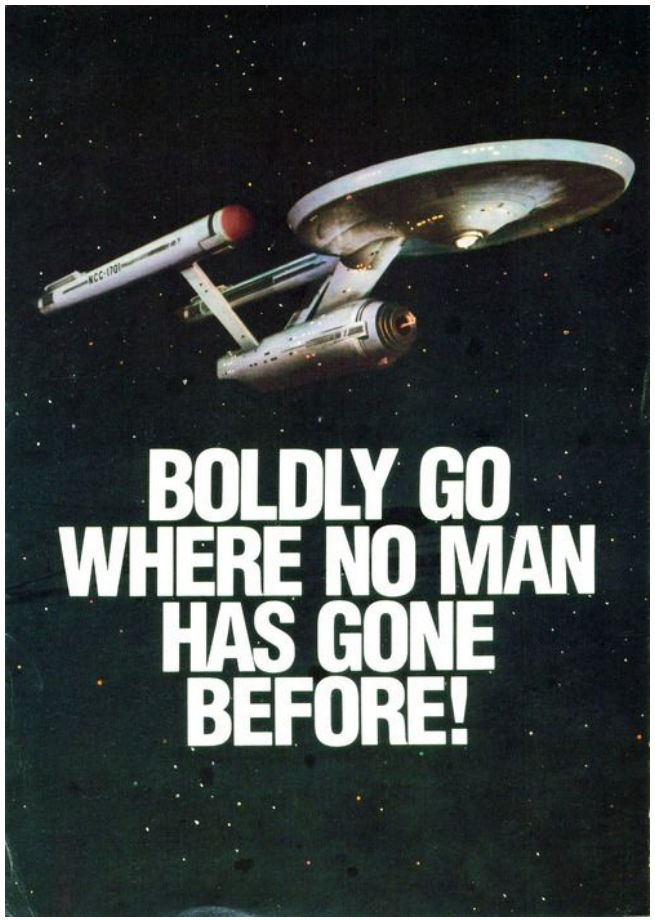
Sign = 2.4 (1.8 exp.)

FCNC re-interpretation : Andrea Castro

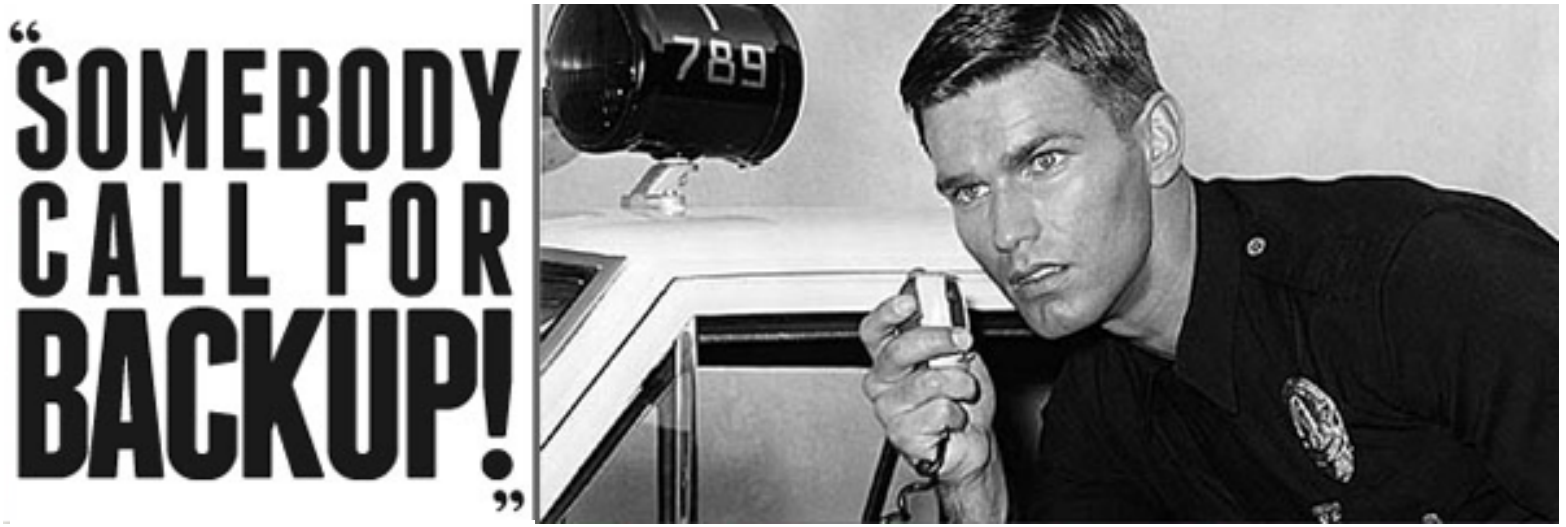
Conclusion

- Single top production intensively studied at CMS.
  - inclusive and differential cross sections for various channels and at various collision energies,
  - large statistics allows to probe more deeply single top processes,
  - start to be sensitive to rare processes.

- Higher luminosity will allow for more studies, many more results to come :
  - precision measurements,
  - more differential cross sections,
  - search for rare processes (tHq, tγq, tZq),
  - and search for new physics.



Backup



Systematic table t-channel

Uncertainty source	$\Delta\sigma_{t\text{-ch.},t+\bar{t}}/\sigma^{obs}_{t\text{-ch.},t+\bar{t}}$	$\Delta\sigma_{t\text{-ch.},t}/\sigma^{obs}_{t\text{-ch.},t}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma^{obs}_{t\text{-ch.},\bar{t}}$	$\Delta R_{t\text{-ch.}}/R_{t\text{-ch.}}$
MC samples size	±3.4%	±4.1%	±3.8%	±3.2%
JES	±4.1%	±4.7%	±3.5%	±2.1%
JER	±1.7%	±1.2%	±2.4%	±0.6%
b tagging efficiency	±1.9%	±2.0%	±1.8%	±1.4%
Mistag probability	±0.9%	±0.6%	±0.8%	±0.5%
Muon reco./trigger	±2.0%	±2.3%	±1.9%	±1.8%

Table 4: Relative impact of systematic uncertainties with respect to the observed cross sections as well as the top quark to top antiquark cross section ratio. Uncertainties are grouped and summed together with the method suggested in Ref. [45].

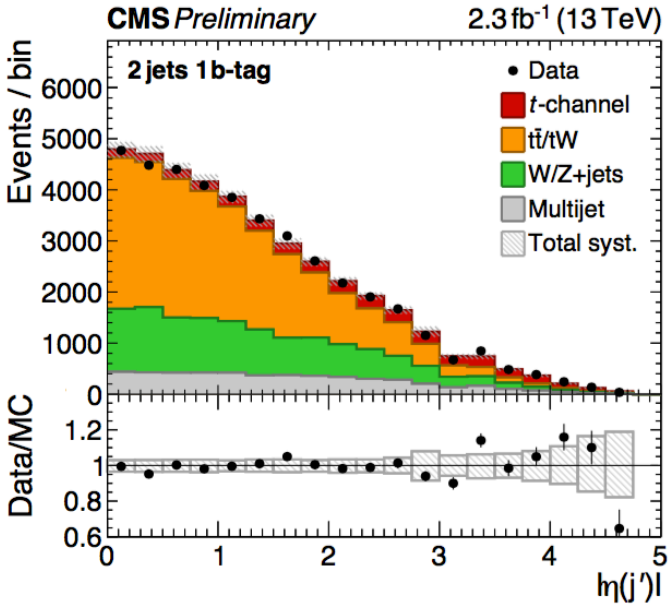
Uncertainty source	$\Delta\sigma_{t\text{-ch.},t+\bar{t}}/\sigma^{obs}_{t\text{-ch.},t+\bar{t}}$	$\Delta\sigma_{t\text{-ch.},t}/\sigma^{obs}_{t\text{-ch.},t}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma^{obs}_{t\text{-ch.},\bar{t}}$	$\Delta R_{t\text{-ch.}}/R_{t\text{-ch.}}$
Statistical uncert.	±5.5%	±5.3%	±11.5%	±9.7%
Profiled exp. uncert.	±5.2%	±5.7%	±4.9%	±3.3%
Total fit uncert.	±7.6%	±7.8%	±12.5%	±10.3%
Integrated luminosity	±2.7%	±2.7%	±2.7%	-
Signal modelling	±6.9%	±8.2%	±8.5%	±5.3%
$t\bar{t}$ modelling	±3.9%	±4.3%	±4.5%	±4.0%
W+jets modelling	−1.8/+2.1%	−1.6/+2.3%	−2.5/+2.3%	−1.7/+2.0%
μ_R/μ_F scale t-channel	−4.6/+6.1%	−5.7/+5.2%	−7.2/+5.1%	−0.7/+1.2%
μ_R/μ_F scale $t\bar{t}$	−3.5/+2.9%	−3.5/+4.1%	−4.7/+3.1%	−1.1/+1.0%
μ_R/μ_F scale tW	−0.3/+0.5%	−0.6/+0.8%	−1.1/+0.7%	−0.2/+0.1%
μ_R/μ_F scale W+jets	−2.9/+3.7%	−3.5/+3.0%	−4.9/+3.8%	−1.2/+0.9%
PDF uncert.	−1.5/+1.9%	−2.1/+1.6%	−1.8/+2.1%	−2.2/+2.5%
Top quark p_T modelling	±0.1%	±0.2%	±0.2%	±0.1%
Total theory uncert.	−10.7/+11.1%	−12.2/+12.1%	−13.6/+12.9%	±7.5%
Total uncert.	−13.4/+13.7%	±14.7%	−18.7/+18.2%	±12.7%

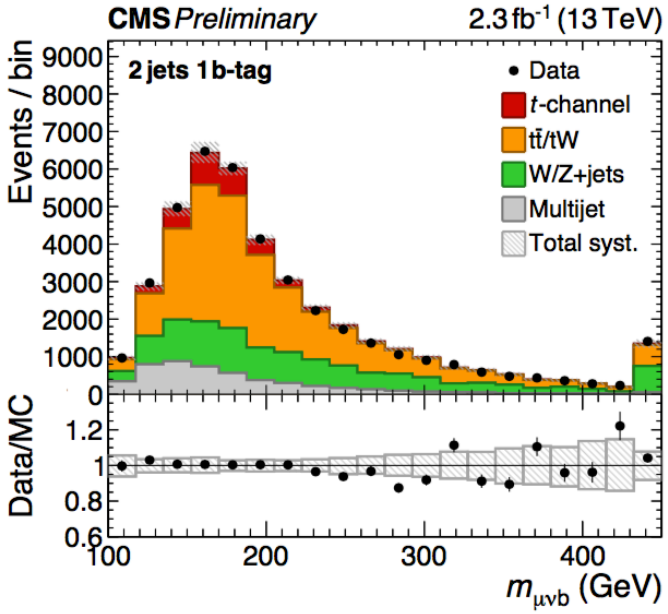
NN variable t-channel

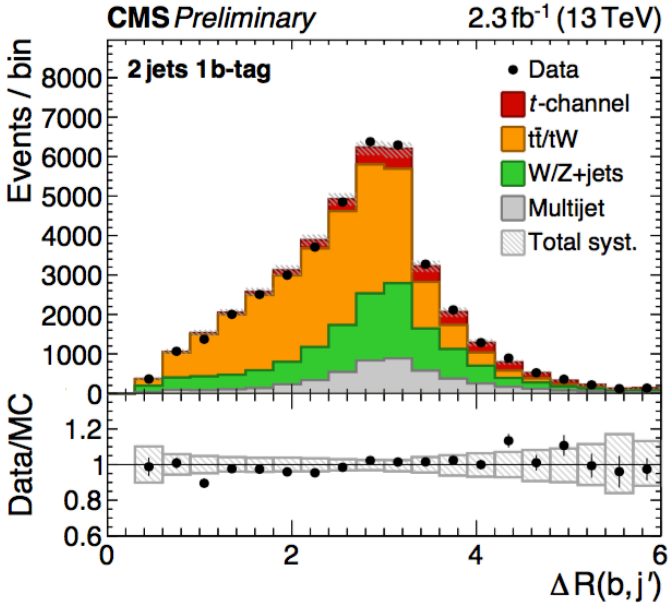
Table 2: Input variables used in the neural network ranked according to their importance.

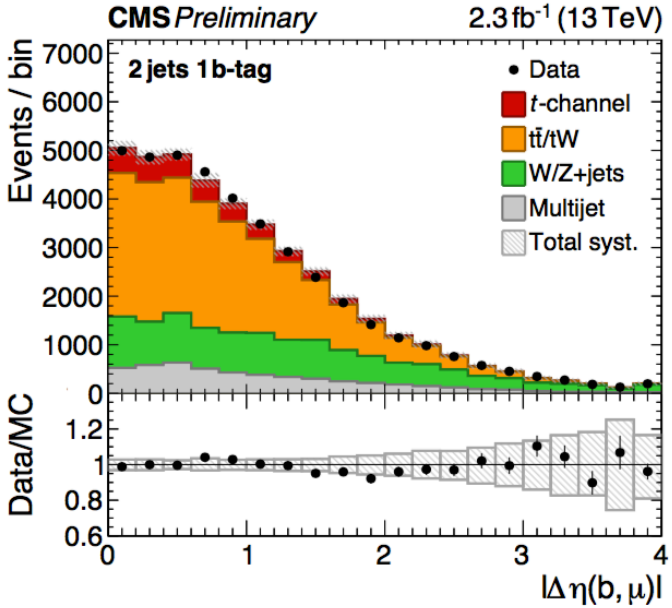
Rank	Variable	Description
1	Light quark $\lvert\eta\rvert$	Absolute value of the pseudorapidity of the light-quark jet
2	Top quark mass	Invariant mass of the top quark reconstructed from muon, neutrino, and b-tagged jet
3	Dijet mass	Invariant mass of the two selected jets
4	Transverse W boson mass	Transverse mass of the W boson
5	Jet p_{T} sum	Scalar sum of the transverse momenta of the two jets
6	$\cos\theta^*$	Cosine of the angle between the muon and the light-quark jet in the rest frame of the top quark
7	Hardest jet mass	Invariant mass of the jet with the largest transverse momentum
8	ΔR (light quark, b quark)	ΔR between the momentum vectors of the light-quark jet and the b-tagged jet.
9	Light quark p_{T}	Transverse momentum of the light-quark jet
10	Light quark mass	Invariant mass of the light-quark jet
11	W boson $\lvert\eta\rvert$	Absolute value of the pseudorapidity of the reconstructed W boson

Differential t-channel









Polarisation t-channel systematics

Table 3: List of systematic uncertainties and their induced shifts from the nominal measured asymmetry for the top quark ($\delta A_\mu(\mathrm{t})$), antiquark ($\delta A_\mu(\bar{\mathrm{t}})$), and their combination ($\delta A_\mu(\mathrm{t}+\bar{\mathrm{t}})$).

	$\delta A_\mu(\mathrm{t})/10^{-2}$	$\delta A_\mu(\bar{\mathrm{t}})/10^{-2}$	$\delta A_\mu(\mathrm{t}+\bar{\mathrm{t}})/10^{-2}$
Statistical	3.2	4.6	2.6
ML fit uncertainty	0.7	1.2	0.6
Diboson bkg. fraction	<0.1	<0.1	<0.1
Z/γ^*+jets bkg. fraction	<0.1	<0.1	<0.1
s-channel bkg. fraction	0.3	0.2	0.2
tW bkg. fraction	0.1	0.7	0.2
Multijet events shape	0.5	0.7	0.5
Multijet events yield	1.9	1.2	1.7
b tagging	0.7	1.2	0.9
Mistagging	<0.1	0.1	<0.1
Jet energy resolution	2.7	1.8	2.0
Jet energy scale	1.3	2.6	1.1
Unclustered $\not{E}_\mathrm{T}$	1.1	3.3	1.3
Pileup	0.3	0.2	0.2
Lepton identification	<0.1	<0.1	<0.1
Lepton isolation	<0.1	<0.1	<0.1
Muon trigger efficiency	<0.1	<0.1	<0.1
Top quark p_T reweighting	0.3	0.3	0.3
W+jets W boson p_T reweighting	0.1	0.1	0.1
W+jets heavy-flavour fraction	4.7	6.2	5.3
W+jets light-flavour fraction	<0.1	<0.1	0.1
W+jets $\cos\theta^*_\mu$ reweighting	2.9	3.4	3.1
Unfolding bias	2.5	4.2	3.1
Generator model	1.6	3.5	0.3
Top quark mass	1.9	2.9	1.8
PDF	0.9	1.6	1.2
t-channel renorm./fact. scales	0.2	0.2	0.2
$\mathrm{t\bar{t}}$ renorm./fact. scales	2.2	3.4	2.7
$\mathrm{t\bar{t}}$ ME/PS matching	2.2	0.5	1.6
W+jets renorm./fact. scales	3.7	4.6	4.0
W+jets ME/PS matching	3.8	3.0	3.4
Limited MC events	2.1	3.2	1.8
Total uncertainty	10.5	13.8	10.5

Polarisation t-channel BDT variables

QCD BDT

- the missing transverse energy, $\not{E}_{\mathrm{T}}$;
- the invariant mass of the top quark candidate, $m_{\mathrm{b}\mu\nu}$;
- the transverse mass of the W boson candidate, $m_{\mathrm{T}}(\mathrm{W}) = \sqrt{\left(p_{\mathrm{T}}^{\mu} + \not{E}_{\mathrm{T}}\right)^2 - \left(p_x^{\mu} + \not{p}_{\mathrm{T},x}\right)^2 - \left(p_y^{\mu} + \not{p}_{\mathrm{T},y}\right)^2}$;
- the transverse momentum of the untagged jet, $p_{\mathrm{T}}^{\mathrm{j}'}$;
- the event isotropy, defined as $(\mathcal{S}_{\max} - \mathcal{S}_{\min})/\mathcal{S}_{\max}$ with $\mathcal{S} \equiv \sum_i^{\mu,\mathrm{jets}} |\vec{n} \cdot \vec{p}_i|$, where the unit vector in the transverse r–ϕ plane, $\vec{n} = (\cos\phi, \sin\phi)$, can be chosen to either maximise or minimise $\mathcal{S}$.

QCD W/ttbar

- the invariant mass of the top quark candidate, $m_{\mathrm{b}\mu\nu}$;
- the absolute pseudorapidity of the untagged jet, $|\eta_{\mathrm{j}'}|$;
- the absolute pseudorapidity of the b-tagged jet, $|\eta_{\mathrm{b}}|$;
- the invariant mass of the b-tagged jet from the summed momenta of the clustered tracks, m_{b};
- the transverse momentum of the muon, p_{T}^{μ};
- the transverse momentum of the b-tagged jet, $p_{\mathrm{T}}^{\mathrm{b}}$;
- the transverse mass of the W boson candidate, $m_{\mathrm{T}}(\mathrm{W})$;
- the missing transverse energy, $\not{E}_{\mathrm{T}}$;
- the total invariant mass of the top quark candidate and the untagged jet system, $\hat{s}$;
- the transverse momentum of the hadronic final-state system, $H_{\mathrm{T}} = (\vec{p}_{\mathrm{b}} + \vec{p}_{\mathrm{j}'})_{\mathrm{T}}$.

Systematic table tW-channel

Systematic uncertainty	$\Delta\sigma$ (pb)	$\Delta\sigma/\sigma$	Notes
ME/PS matching thresholds	3.3	14%	Matching threshold 2× and 1/2× nominal 20 GeV value in $t\bar{t}$ simulation
Renormalization/factorization scale	2.9	12%	Scale value 2× and 1/2× nominal value of $m_t^2 + \sum p_T^2$ in $t\bar{t}$ and tW simulation
Top-quark mass	2.2	9%	m_t varied in tW and $t\bar{t}$ simulation by ± 2 GeV
Fit statistical	1.9	8%	Remaining uncertainty in fit when all other systematic uncertainties are removed
Jet energy scale	0.9	4%	Jet energy scale varied up/down
Luminosity	0.7	3%	2.6% uncertainty in the measured luminosity
Z+jets data/simulation scale factor	0.6	3%	Varying scale factors used for correcting Z+jets E_T^{miss} simulation
tW DR/DS scheme	0.5	2%	Difference between DR and DS scheme used for defining tW signal
$t\bar{t}$ cross section	0.4	2%	Uncertainty in the cross section of $t\bar{t}$ production
Lepton identification	0.4	2%	Uncertainty in scale factors for lepton efficiencies between data/simulation
PDF	0.4	2%	From choice of PDF
Jet energy resolution	0.2	1%	Energy resolution for jets varied up/down
b-tagging data/simulation scale factor	0.2	<1%	Variations in scale factors
$t\bar{t}$ spin correlations	0.1	<1%	Difference between $t\bar{t}$ simulation with/without spin correlations
Pileup	0.1	<1%	Varying effect of pileup
Top-quark p_T reweighting	0.1	<1%	Uncertainty due to differences in top quark p_T between data and $t\bar{t}$ simulation
E_T^{miss} modeling	0.1	<1%	Uncertainty in amount of unclustered E_T^{miss}
Lepton energy scale	0.1	<1%	Uncertainty in energy of leptons
Total	5.5	24%	

Systematic table s-channel

Table 4: Summary of the relative impact of the statistical and systematic uncertainties on the cross section measurement. Different prior uncertainties have been assigned to $t\bar{t}$, single top quark t channel and tW production, W+jets, Z +jets and diboson normalizations, see Section 7.

Source	Uncertainty (%)				
	μ, 7 TeV	μ, 8 TeV	e, 8 TeV	μ + e, 8 TeV	7+8 TeV
Statistical	34	15	14	10	11
$t\bar{t}$, single top quark normalization	29	15	14	12	14
W/Z+jets, diboson normalization	23	11	13	12	12
Multijet normalization	9	3	5	2	2
Lepton efficiency	14	1	2	1	3
Hadronic trigger	5	—	—	—	1
Luminosity	10	5	6	4	6
JER & JES	66	39	29	34	18
b tagging & mistag	34	15	14	14	16
Pileup	6	11	7	9	7
Unclustered $\not{E}_T$	5	8	2	6	5
μ_R, μ_F scales	54	34	31	30	28
Matching thresholds	43	11	12	7	17
PDF	12	8	7	7	9
Top quark p_T reweighting	3	5	7	6	6
Total uncertainty	115	64	54	55	47

Fiducial t-channel

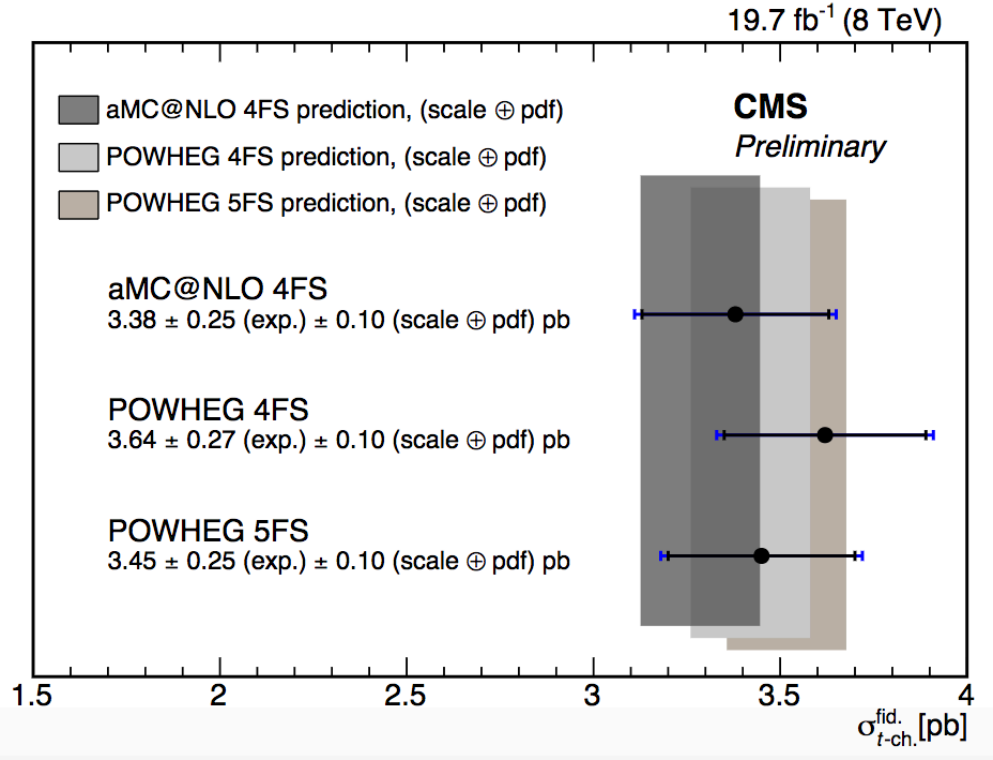
- Fiducial measurement : restrict acceptance to the visible phase-space.

- Motivations :
  - No extrapolation from the visible phase-space to the full phase space, rely less on MC,
  - Modelling uncertainties highly reduced.

- Main difficulty : definition of fiducial volume ⇔ selection at particle level.
- Particle level selection :
  - Stable particle =>$c\tau \geq 10$ mm,
  - Dressed leptons, jet clustered from stable particles,
  - B-jets determined from the “ghost-b-hadrons” method.

Object	Kinematic cuts at detector level	Cuts at particle level	number required
Tight Muon	$p_T > 26$, $\|\eta\| < 2.1$, $I_{rel} < 0.12$	$p_T > 30$, $\|\eta\| < 2.4$	exactly 1 (or 1 Ele)
Tight Electron	$E_T > 30$, $\|\eta\| < 2.4$, $I_{rel} < 0.1$	$p_T > 30$, $\|\eta\| < 2.4$	exactly 1 (or 1 Mu)
Veto Muon	$p_T > 10$, $\|\eta\| < 2.4$, $I_{rel} < 0.2$	-	0
Veto Electron	$E_T > 20$, $\|\eta\| < 2.4$, $I_{rel} < 0.15$	-	0
Jets	$p_T > 40$, $\|\eta\| < 4.7$	$p_T > 40$, $\|\eta\| < 5.0$	exactly 2
B-tagging	1 jet is tagged	$\|\eta\| < 2.4$, b-hadron	exactly 1
m_T (muons)	$m_T > 50$	-	-
$\not{E}_T$ (electrons)	$\not{E}_T > 45$	-	-

Fiducial t-channel



Model	$\sigma^{\text{fid}}_{t\text{-ch}}$	scale	PDF
aMC@NLO 4FS, muons + electrons	3.286	$^{+0.056}_{-0.100}$	$^{+0.017}_{-0.018}$
POWHEG 4FS, muons + electrons	3.420	$^{+0.056}_{-0.100}$	$^{+0.017}_{-0.018}$
POWHEG 5FS, muons + electrons	3.517	$^{+0.016}_{-0.031}$	$^{+0.018}_{-0.018}$

$$\sigma^{\text{fid,obs}}_{t\text{-ch (POWHEG4FS)}} = 3.64 \pm 0.27(\text{exp.})^{+0.06}_{-0.06}(\text{scale})^{+0.08}_{-0.08}(\text{PDF}) \pm 0.17(\text{NLO-subtr.})\,\text{pb}\,,$$

$$\sigma^{\text{fid,obs}}_{t\text{-ch (POWHEG5FS)}} = 3.45 \pm 0.25(\text{exp.})^{+0.08}_{-0.09}(\text{scale})^{+0.07}_{-0.07}(\text{PDF}) \pm 0.17(\text{NLO-subtr.})\,\text{pb}\,.$$

$$\sigma^{\text{fid,obs}}_{t\text{-ch (aMC@NLO4FS)}} = 3.38 \pm 0.25(\text{exp.})^{+0.06}_{-0.06}(\text{scale})^{+0.08}_{-0.08}(\text{PDF}) \pm 0.17(\text{NLO-subtr.})\,\text{pb}$$