Single top quark production with CMS

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for the CMS Collaboration

References for this talk:

- JHEP 12(2012)035
- arXiv:1403.7366
- arXiv:1401.2942
- CMS PAS TOP-12-020
- CMS PAS TOP-13-001
- CMS PAS TOP-13-009

Outline

- **The CMS Experiment at the LHC**

- **Single top inclusive production measurements:**
  - The high precision *t*-channel measurements
  - The tW channel observation
  - The search for the *s*-channel

- **Single-top events properties:**
  - The charge ratio measurements
  - The angular properties: W-helicity and top top polarisation

- **Summary**

The CMS detector

Compact Muon Solenoid

Total Weight:	14000 t
Overall diameter:	15 m
Length:	21 m
Magnetic field:	3.8 Tesla

Steel return yoke

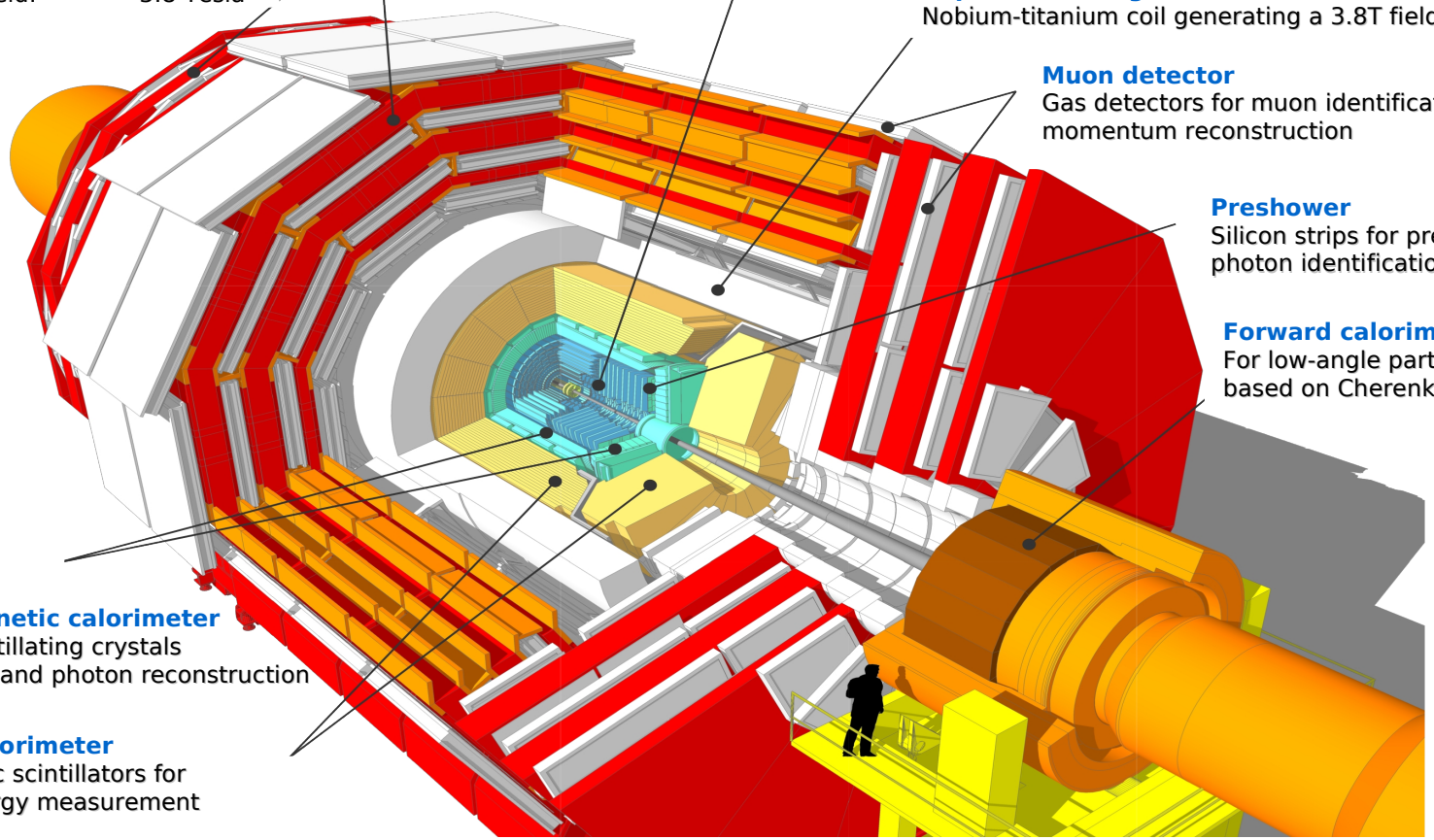
Inner tracking system
Silicon pixel and silicon strip detectors for
Charged particle tracks reconsrtruction

Superconducting solenoid
Nobium-titanium coil generating a 3.8T field

Muon detector
Gas detectors for muon identification and
momentum reconstruction

Preshower
Silicon strips for precise
photon identification

Forward calorimeter
For low-angle particle reconstruction
based on Cherenkov technology



Electomagnetic calorimeter
PbWO4 scintillating crystals
for electron and photon reconstruction

Hadron calorimeter
Brass/plastic scintillators for
hadron energy measurement

The single-top processes

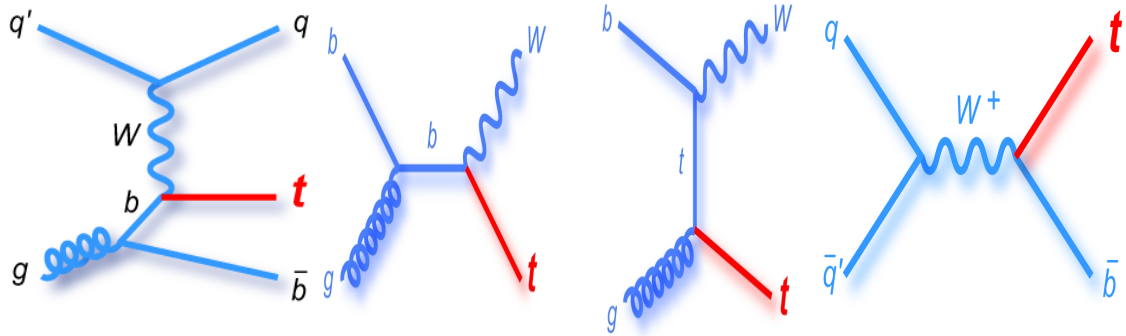
- **Single-top quark:**

- electroweak top-quark production via charged current processes

- All channels are sensitive to new physics

- All channels cross sections: proportional to $|V_{tb}|^2$

***t*-channel** **W associated (tW)** ***s*-channel**



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Tevatron: $p\bar{p}$ @1.96 TeV*	**2.08±0.12 pb**	**0.22±0.08 pb**	**1.046±0.058 pb**
LHC pp @7 TeV**	**64.6±2.1 pb**	**15.6±1.2 pb**	**4.59±0.19 pb**
LHC pp @8 TeV**	**87.1±2.8 pb**	**22.2±1.5 pb**	**5.55±0.22 pb**

* (N. KidonakisPhys. Rev. D 82, 054018 (2010) and arxiv:0909.0037

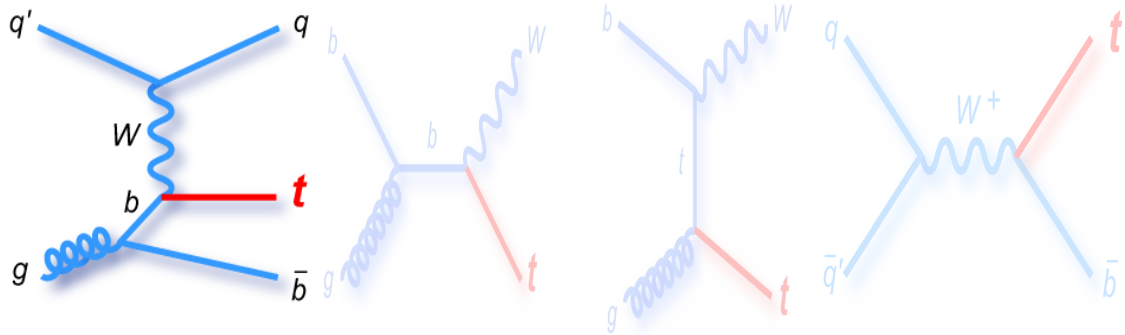
**(N. Kidonakis Phys. arXiv:1205.3453)

Inclusive measurements

The *t*-channel

- **Highest cross section** at LHC, with a factor ~30-40 gain w.r.t. the Tevatron
- **Final state:** a top quark, a light jet and a soft b-jet
- **Main backgrounds**: QCD, ttbar, W+jets

***t*-channel** | **W associated (tW)** | ***s*-channel**



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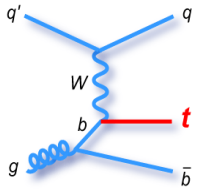
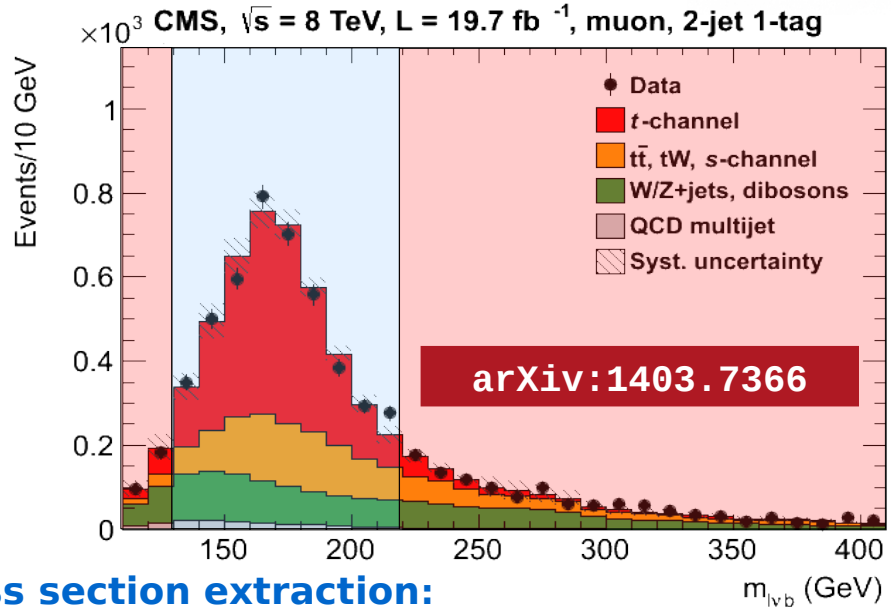


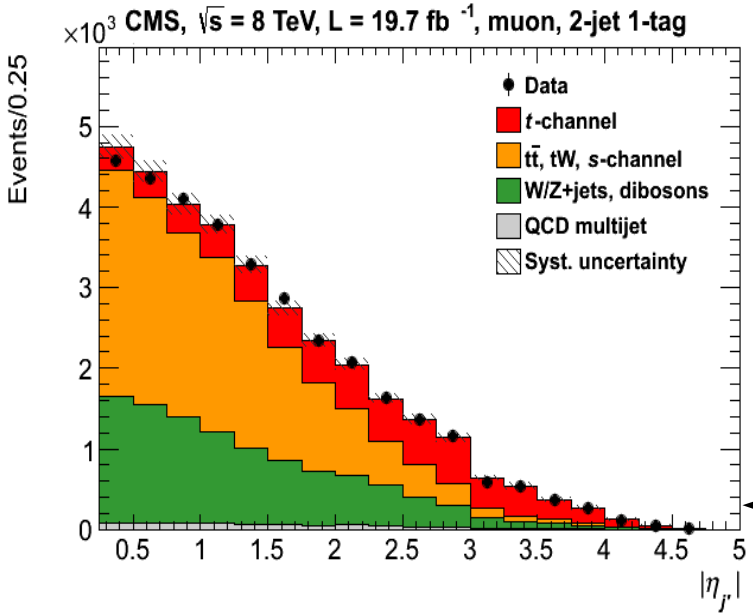
t-channel: 8 TeV cross section

- **Selection based on leptonic top decays:**

  - Considering t → Wb → lνb decay chain: 1 isolated lepton and missing energy in the final state

  - Selecting events with 2 jets, 1 of which b-tagged, coming from the top decay (the 2nd b is usually softer).



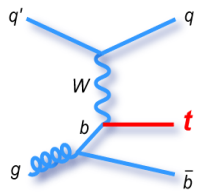


- **Cross section extraction:**

  - W transverse mass and $E_{T,miss}$ to extract the QCD multijet contribution.

  - Reconstruct top quark and use its mass to estimate W+jets.

  - Fit o the pseudorapidity of the recoil jet to derive the signal cross section

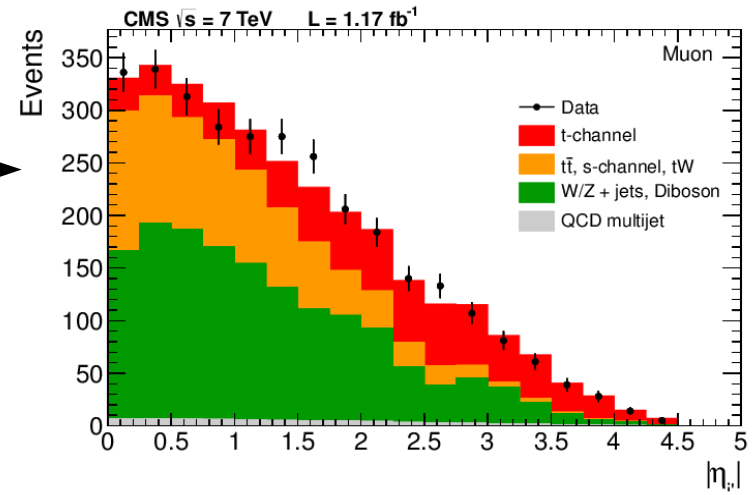


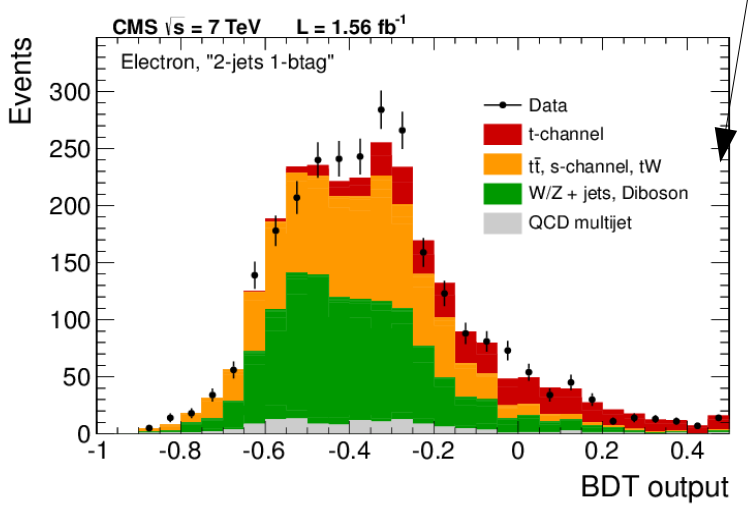
t-channel: 7 TeV cross section

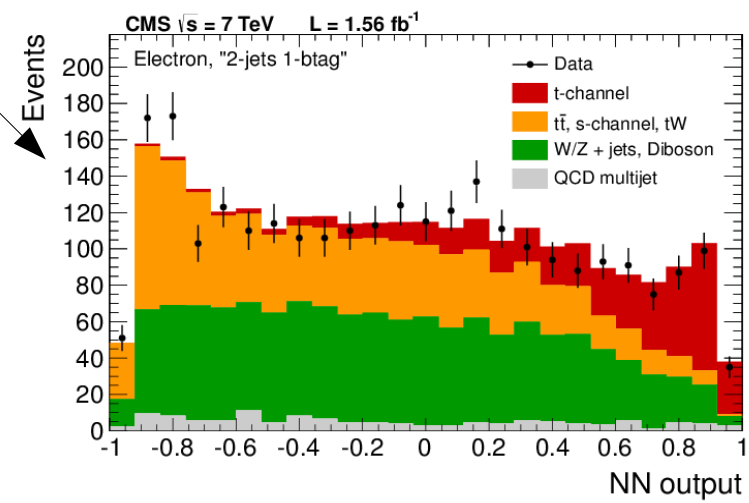
JHEP 12(2012)035

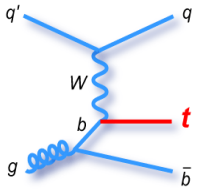
3 analyses in the leptonic top decay channel:

- **Analysis based on data-driven methods:**
  - Fit to pseudorapidity of the light jet $|\eta_{j'}|$ in the region with 2 jets and 1 b-tag (as for 8 TeV)
- **Multivariate analyses:**
  - Two analyses using a Neural Network (**NN**) and a Boosted Decision Trees (**BDT**) discriminant









t-channel cross section: results and $|V_{tb}|$ estimate

- **Cross section**

$\sigma_{(t\text{-ch.},7\text{ TeV})} = 67.2 \pm 6.1$ pb
$\sigma_{(t\text{-ch.},8\text{ TeV})} = 83.6 \pm 7.8$ pb

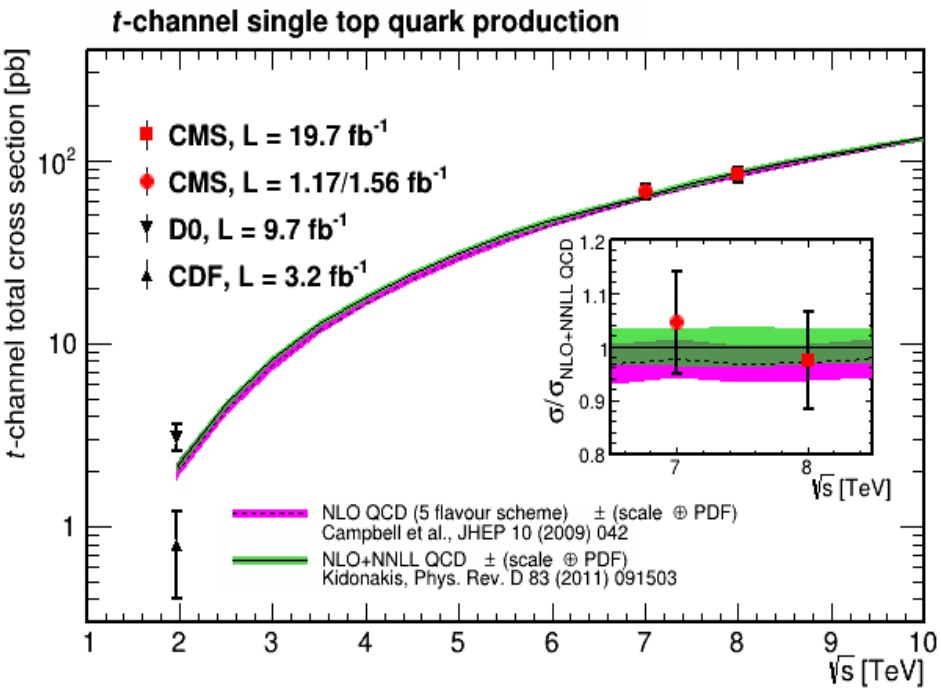
- Main uncertainties : signal modeling, high $|\eta|$ jet energy corrections

- **Cross section ratio:**

$R_{(8/7)} = \sigma_{(t\text{-ch.},8\text{ TeV})}/\sigma_{(t\text{-ch.},7\text{ TeV})} = 1.24 \pm 0.14$

- **$|V_{tb}|$ measurement:**

Assuming $|V_{td}|, |V_{ts}| << |V_{tb}| \rightarrow |V_{tb}| = \sqrt{(\sigma_{t\text{-ch.}}/\sigma_{t\text{-ch}})}$:



7 TeV: $|V_{tb}| = 1.020 \pm 0.046$ (exp.) ± 0.017 (theo.)

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8 TeV: $|V_{tb}| = 0.979 \pm 0.045$ (exp.) ± 0.016 (theo.)

arXiv:1403.7366

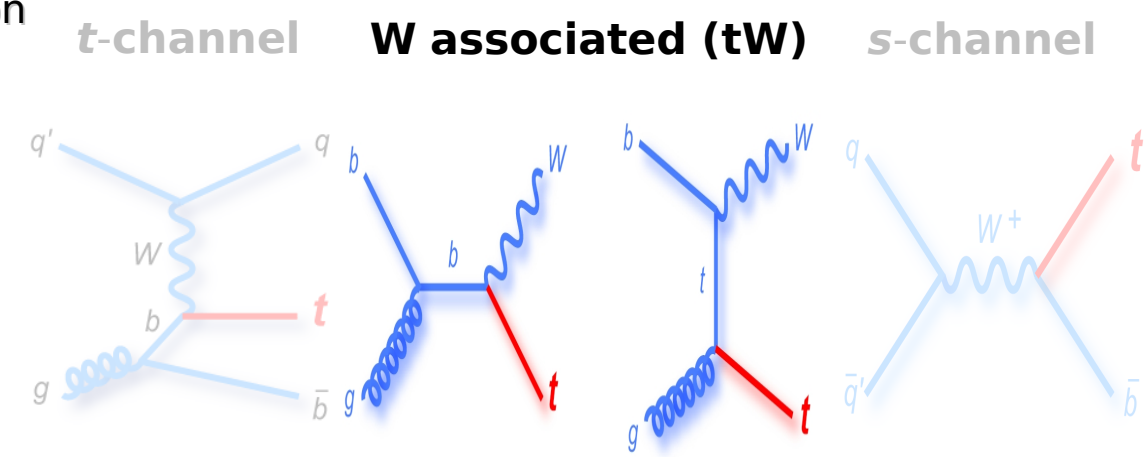
Combining the two yields: $|V_{tb}| = 0.998 \pm 0.038\,(\text{exp.}) \pm 0.016\,(\text{theo.})$

The W associated production (tW)

- **Huge gain at LHC wrt Tevatron:** factor ~100 increase in cross section

- **Final state:** a top quark and a W boson, with the respective decays.
  - Cleanest signature: where both t and W decay leptonically

- **ttbar is by far the main background,** followed by Z+jets in the dileptonic channels.



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* (N. KidonakisPhys. Rev. D 82, 054018 (2010) and arxiv:0909.0037

**(N. Kidonakis Phys. arXiv:1205.3453)

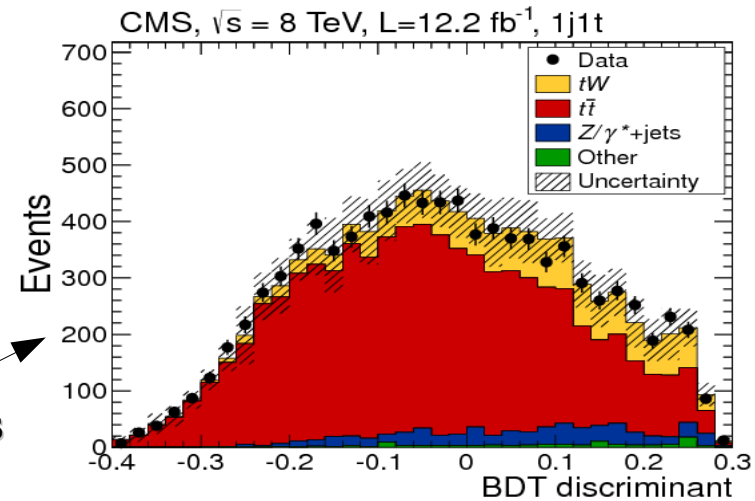
tW production: observation at 8 TeV

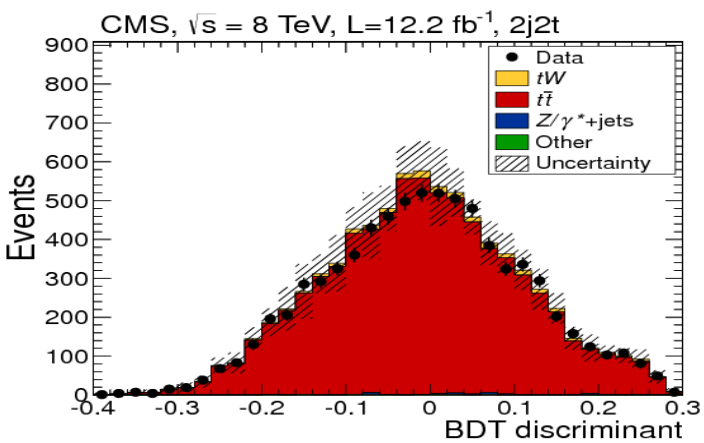
arXiv:1401.2942

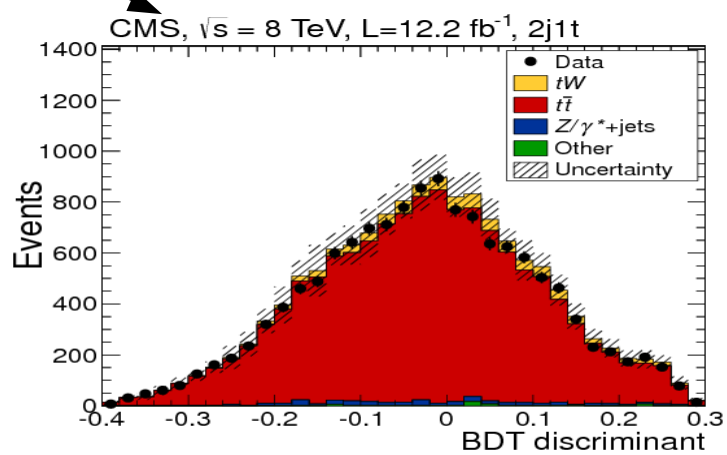
- **Observed for the first time at CMS!**
  - Channels where both t and W decay leptonically:
    2 opposite sign isolated leptons in the final state

- **Define a multivariate discriminant** using characteristic kinematic variables to distinguish signal from ttbar

- **Jet counting is used** to define a **signal enriched region** with 1-jet and 1 b-tag, and **two control regions** with 2-jets and 1 or 2 b-tags.







tW production: cross checks and results

- **The observed significance is 6.1 standard deviations**

- **The 8 TeV measured cross section is measured :**

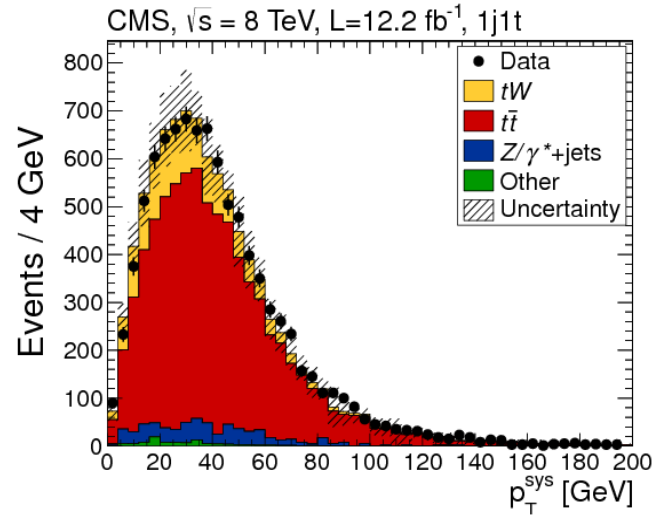
$\sigma_{(tW.,8\ TeV)} = 23.4 \pm 5.4$ pb

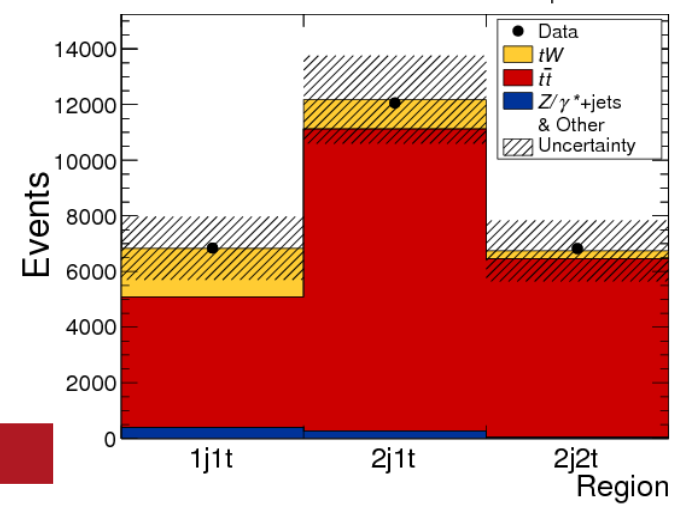
- Main uncertainites: modeling of the ttbar background, top mass

- **Extracting $|Vtb|^2$** from this channel yields:

$$|V_{tb}| = \sqrt{\sigma_{tW}/\sigma_{tW}^{th}} = 1.03 \pm 0.12\,(exp) \pm 0.04\,(th.)$$

- **Two cross-check analyses**, one based on the fit to the pt of the system composed by leptons, jets and $E_{T,miss}$, the other on event counting, provided consistent results

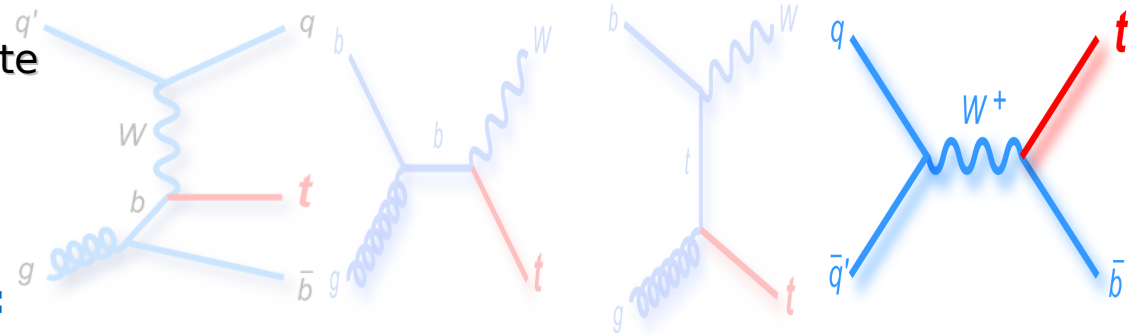




arXiv:1401.2942

The *s*-channel

- **The most rare of the three at LHC**, comparable with the *t*-channel at Tevatron (where it was recently observed)
- **1 top and 1 b-jet** in the final state
- **Overwhelming backgrounds:** tt, QCD, WJets and t-channel
- **Very sensitive to new physics:** new mediators, charged higgs...



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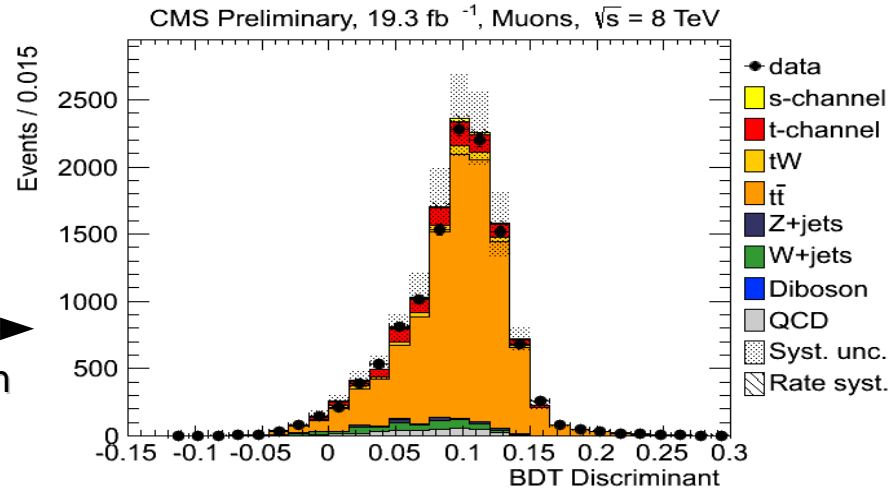
The s-channel search

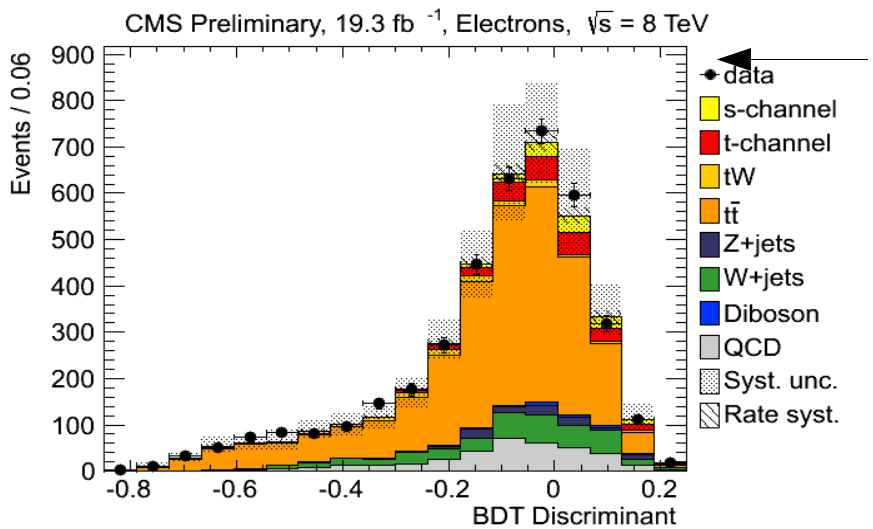
- **Selection based on leptonic top decays:**

- Requiring 1 lepton, 1 b-jet from top and $E_{T.miss}$ plus 1 b-jet

- Control regions for ttbar requiring 1 extra jet

- QCD control regions obtained with different isolation requirements on the lepton.





- **Fit to a multivariate discriminant** to get the signal yield

- **An upper limit** on the cross section is extracted:

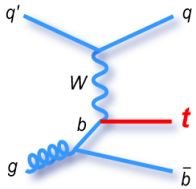
$$\sigma_{s\text{-ch.}} < 11.5 \quad (17.0, \quad 9.0)\ \text{pb} \quad @95\%\text{CL}$$

the 68% CL on $\sigma_{s\text{-ch}}$, yields: $\sigma_{s\text{-ch.}} = 6.2^{+8.0}_{-5.1}\ \text{pb}$

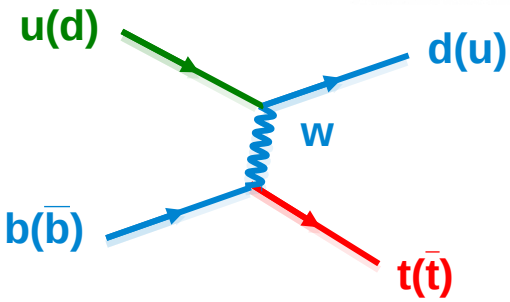
- the dominant uncertainties come from the modeling of the ttbar background

CMS-PAS-TOP-13-009

Properties and differential measurements



t-channel: charge asymmetry

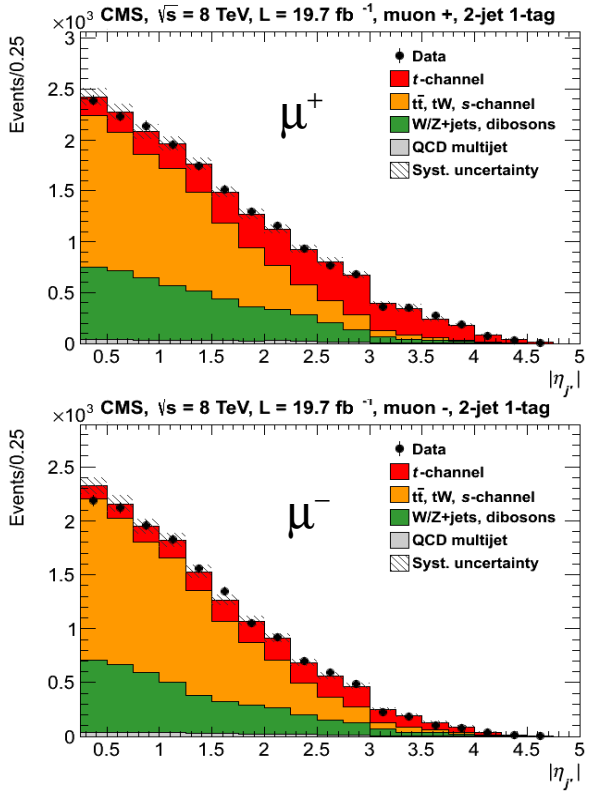


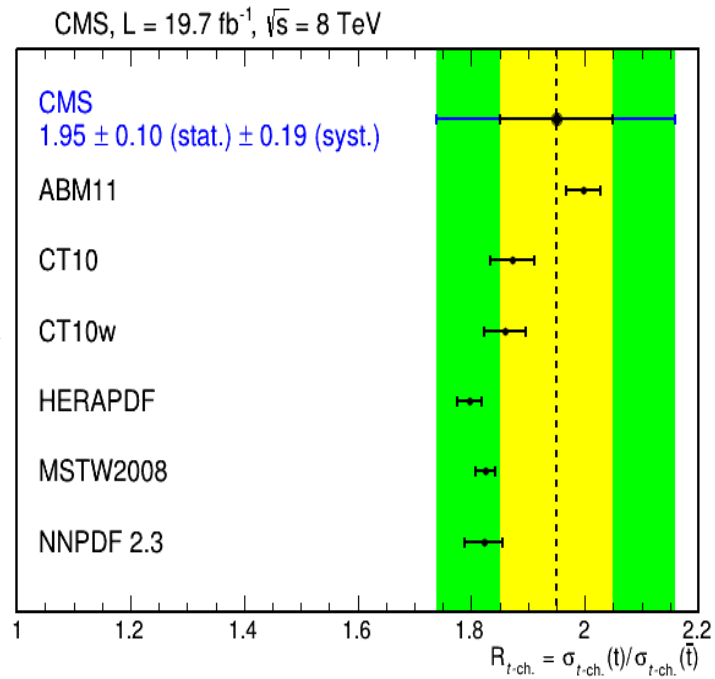
- **top quark charge:** inherited from the quark in the initial state
→ dependencyon proton parton distribution functions

- Fit to $|\eta_{j'}|$ performed on positively and negatively charged leptons
  - main uncertainties: signal modeling and PDF (acceptance)

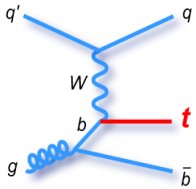
Ratio measured:

$$\frac{\sigma(\text{tops})}{\sigma(\text{anti-tops})}$$





arXiv:1403.7366



W-polarisation in single-top *t*-channel enriched events

- **W-helicity:** fraction of left (F_L), right (F_R) and longitudinally (F_0) polarized Ws is predicted by the SM and it's sensitive to anomalous tWb couplings

- **Reflects on the angular distribution** of the lepton and the W-boson in the W rest frame

$$\rho(\cos\theta_l^*) \equiv \frac{1}{\Gamma}\frac{d\Gamma}{d\cos\theta_l^*} = \frac{3}{8}(1-\cos\theta_l^*)^2 F_L + \frac{3}{8}(1+\cos\theta_l^*)^2 F_R + \frac{3}{4}\sin^2\theta_l^* F_0$$

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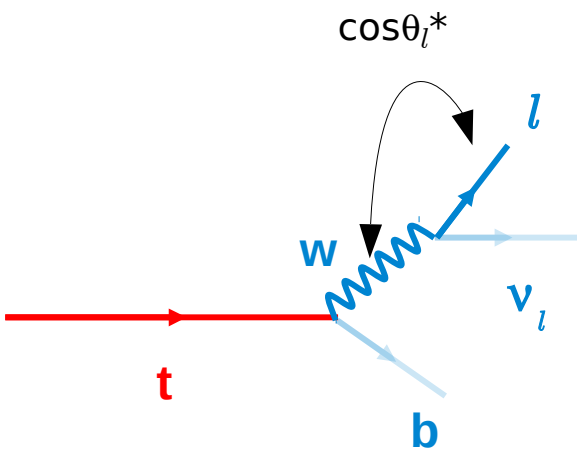
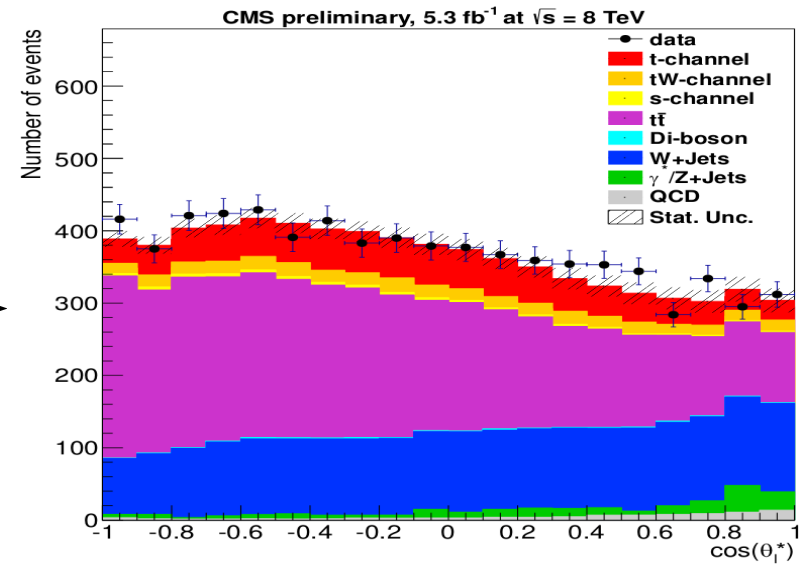
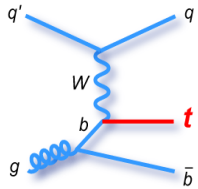






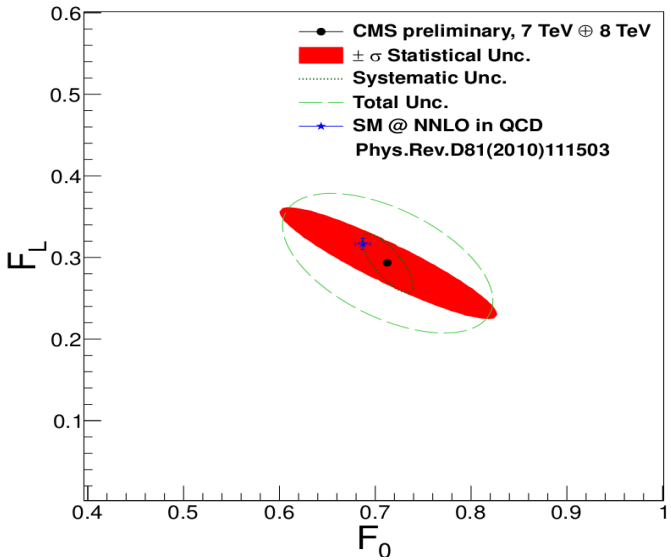
W-polarisation in the t-channel: 7 and 8 TeV

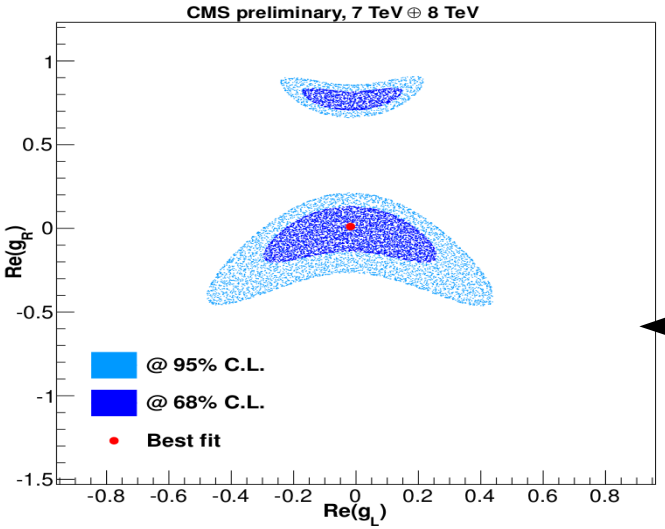
- **Fit to the cosθ_l*:**

  - same event selection as the cross section measurement

  - A point in the (F_L), (F_0) plane is obtained

  - Fit procedure mostly affected by W+Jets modeling and Jet and MET uncertainties





- **Constraints to anomalous couplings:**

  - Extracted limits on non SM tensor couplings (G_L,G_R) from the measurement of (F_L,F_0)

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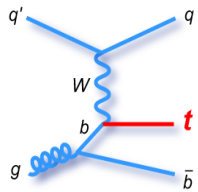

top-quark polarisation in *t*-channel events

- Top quark decay products distributions stems from the **V-A nature of the coupling:**

$$\frac{d\Gamma}{d\cos\theta_X} = \frac{\Gamma}{2}(1 + P_t \alpha_X \cos\theta_X) \equiv \Gamma(\frac{1}{2} + A_X \cos\theta_X)$$

- θ_X = angle between the top decay product X and the top spin axis
- A_X = spin asymmetry, depends on the top polarisation P_t

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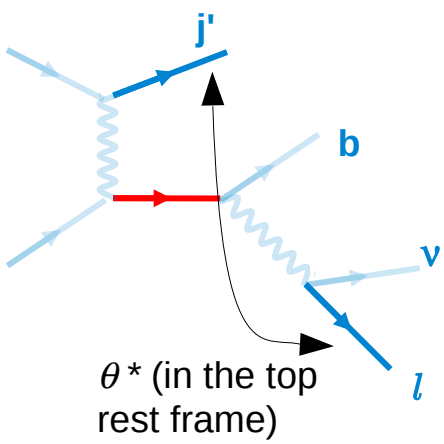
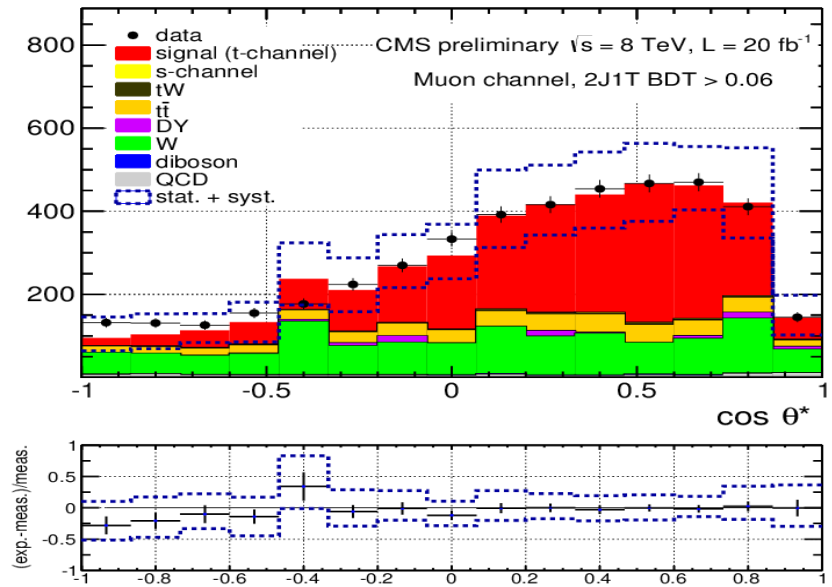
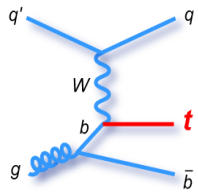
- **We measure:** θ^* in leptonic top decays:







top-quark polarisation in *t*-channel events

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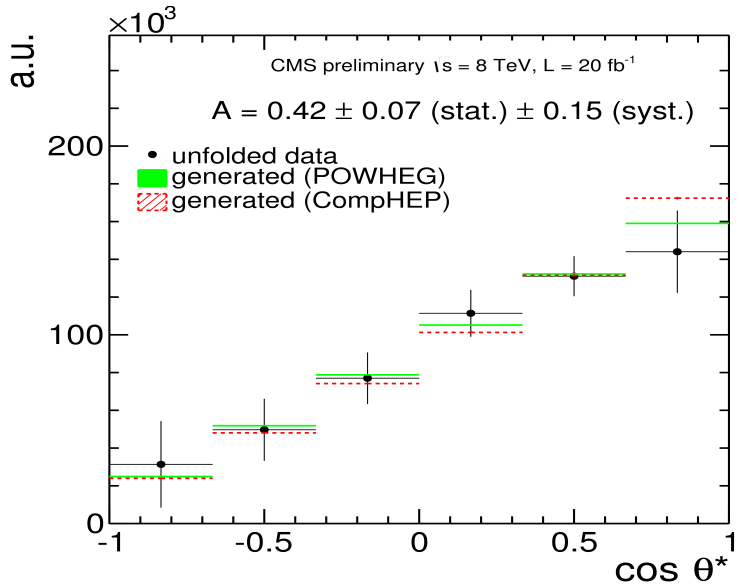
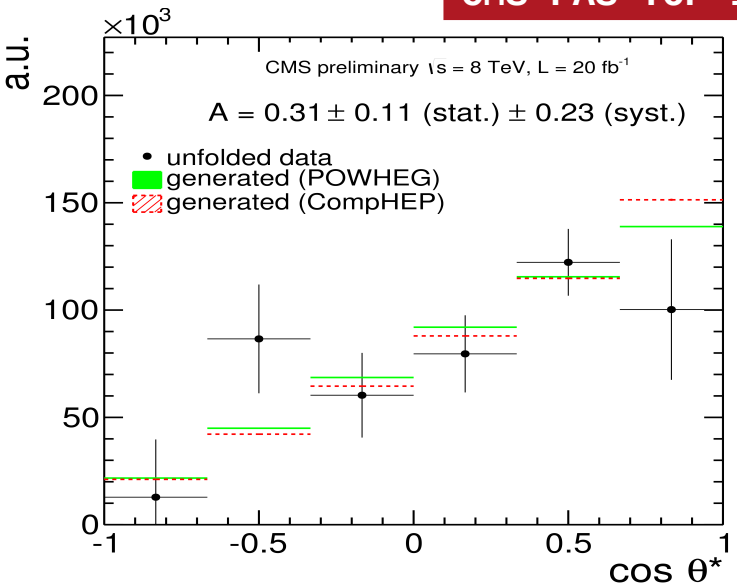




- **From the unfolded** cos θ* distribution A_l is obtained :

$$A_l = \frac{N(\cos\theta^*_{unfolded} > 0) - N(\cos\theta^*_{unfolded} < 0)}{N(\cos\theta^*_{unfolded} > 0) + N(\cos\theta^*_{unfolded} < 0)} = 0.41 \pm 0.06(stat.) \pm 0.16(syst.) = 0.41 \pm 0.17$$

- And the **top polarisation:**

$$P_t = 0.82 \pm 0.12(stat.) \pm 0.32(syst.)$$

- main systematics: jet energy scale and resolution, QCD multijet estimation.

Summary

- **An overview** of the single-top measurements performed by CMS has been presented.

- **Precision inclusive cross section measurements** performed both at 7 and 8 TeV for the *t*-channel single-top quark production were shown, and a combined measurement of the CKM matrix element $|V_{tb}|$ was performed.

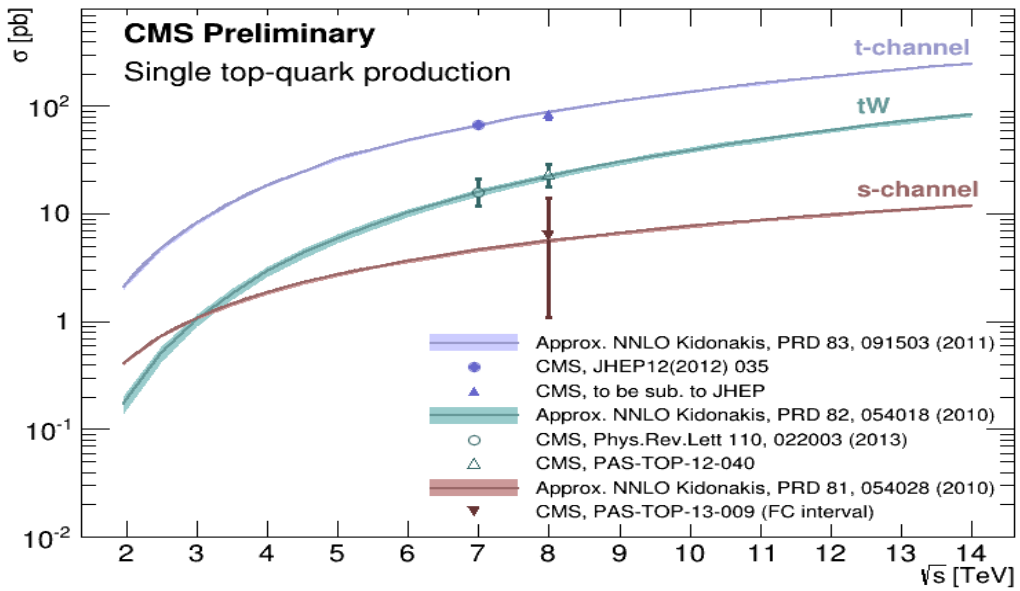
- **The first observation of the tW production mode** was reported. This important milestone paves the way for future properties studies in this production mode to complement the existing measurements in the *t*-channel.

Summary

- **The search for the *s*-channel** allowed to set upper limits to the SM cross section also at LHC.

- **Properties of single-top events in the *t*-channel,** like ratio of produced tops over antitops , the W-helicity fractions, and the top polarisation, were measured.

- **All measurements** display an overall agreement with the standard model prediction.



Thanks!

Backup

Systematics tables for the inclusive cross section measurements

		Uncertainty source	NN	BDT	$\lvert\eta_{j'}\rvert$
Marginalised (NN, BDT)	Experimental uncert.	Statistical	−6.1/+5.5%	−4.7/+5.4%	±8.5%
		Limited MC data	−1.7/+2.3%	±3.1%	±0.9%
		Jet energy scale	−0.3/+1.9%	±0.6%	−3.9/+4.1%
		Jet energy resolution	−0.3/+0.6%	±0.1%	−0.7/+1.2%
		b tagging	−2.7/+3.1%	±1.6%	±3.1%
		Muon trigger + reco.	−2.2/+2.3%	±1.9%	−1.5/+1.7%
		Electron trigger + reco.	−0.6/+0.7%	±1.2%	−0.8/+0.9%
		Hadronic trigger	−1.3/+1.2%	±1.5%	±3.0%
		Pileup	−1.0/+0.9%	±0.4%	−0.3/+0.2%
		$\not{E}_T$ modelling	−0.0/+0.2%	±0.2%	±0.5%
	Backg. rates	W+jets	−2.0/+3.0%	−3.5/+2.5%	±5.9%
		light flavour (u, d, s, g)	−0.2/+0.3%	±0.4%	n/a
		heavy flavour (b, c)	−1.9/+2.9%	−3.5/+2.5%	n/a
		$t\bar{t}$	−0.9/+0.8%	±1.0%	±3.3%
		QCD, muon	±0.8%	±1.7%	±0.9%
		QCD, electron	±0.4%	±0.8%	−0.4/+0.3%
		s-, tW ch., dibosons, Z+jets	±0.3%	±0.6%	±0.5%
	Total marginalised uncertainty		−7.7/+7.9%	−7.7/+7.8%	n/a
Not marginalised		Luminosity		±2.2%	
	Theor. uncert.	Scale, $t\bar{t}$	−3.3/+1.0%	±0.9%	−4.0/+2.1%
		Scale, W+jets	−2.8/+0.3%	−0.0/+3.4%	n/a
		Scale, t-, s-, tW channels	−0.4/+1.0%	±0.2%	−2.2/+2.3%
		Matching, $t\bar{t}$	±1.3%	±0.4%	±0.4%
		t-channel generator	±4.2%	±4.6%	±2.5%
		PDF	±1.3%	±1.3%	±2.5%
		Total theor. uncertainty	−6.3/+4.8%	−4.9/+5.9%	−5.6/+4.9%
Syst. + theor. + luminosity uncert.			−8.1/+7.8%	−8.1/+8.4%	±10.8%
Total (stat. + syst. + theor. + lum.)			−10.1/+9.5%	−9.4/+10.0%	±13.8%

7TeV t-channel cross section

JHEP 12(2012)035

8TeV t-channel cross section

arXiv:1403.7366

Uncertainty source	in pb	relative
Statistical	±5.7	±7.2 %
W+jets and $t\bar{t}$ modeling	±3.6	± 4.5 %
JES	− 6.2 / + 4.7	− 7.8 / + 5.8 %
JER	− 0.8 / + 0.3	− 1.0 / + 0.4 %
Unclustered $\not{E}_T$	− 0.8 / + 0.7	− 1.0 / + 0.9 %
Pileup	− 0.5 / + 0.3	− 0.6 / + 0.4 %
Muon trigger + reconstruction	− 4.1 / + 4.0	− 5.1 / + 5.1 %
Q^2	±2.5	±3.1 %
$t\bar{t}$, rate	− 1.5 / + 1.7	− 1.9 / + 2.1 %
QCD, rate	±0.7	±0.9 %
t−channel generator	±4.4	±5.5 %
Other backgrounds, rate	±0.5	±0.6 %
b-tagging	±3.7	±4.6 %
PDF	± 3.7	±4.6 %
Simulation statistics	±1.8	±2.2 %
Total systematics	±11.0	±13.7 %
Luminosity uncertainty	±4.0	±5.0 %
Total	±13.0	±16.3%

Systematics tables: tW

8TeV tW cross section

arXiv:1401.2942

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%	

Systematics: *t*-channel event properties measurements

8TeV: cross sction by charge and charge ratio

arXiv:1403.7366

Uncertainty source	$\sigma_{t\text{-ch.}}(t)$ (%)	$\sigma_{t\text{-ch.}}(\bar{t})$ (%)	$R_{t\text{-ch.}}$ (%)
Statistical uncertainty	± 2.7	± 4.9	± 5.1
JES, JER, MET, and pileup	± 4.2	± 5.2	± 1.1
b-tagging and mis-tag	± 2.6	± 2.6	± 0.2
Lepton reconstruction/trig.	± 0.5	± 0.5	±0.3
QCD multijet estimation	± 1.6	± 3.5	±1.9
W+jets, $t\bar{t}$ estimation	± 1.7	± 3.6	± 3.0
Other backgrounds ratio	± 0.1	± 0.2	± 0.6
Signal modeling	± 4.9	± 9.4	± 6.1
PDF uncertainty	± 2.5	± 4.8	± 6.2
Simulation sample size	± 0.6	± 1.1	± 1.2
Luminosity	± 2.6	± 2.6	—
Total systematic	± 8.2	± 13.4	± 9.6
Total uncertainty	± 8.7	± 14.2	± 10.9
Measured cross section or ratio	53.8 ± 4.7 pb	27.6 ± 3.9 pb	1.95 ± 0.21

7+8TeV: W polarisation

CMS-PAS-TOP-12-020

Systematic source	ΔF_L	ΔF_0
JES	0.007	0.007
JER	0.011	0.003
unclustered energy	0.018	0.010
pileup	0.002	0.002
b-flavored scale factor	0.003	0.001
non-b-flavored scale factor	0.001	0.002
single-top generator	0.005	0.009
Q^2 scale	0.006	0.008
m_{top}	0.001	0.001
PDF	0.003	0.003
$t\bar{t}$ normalization	0.003	0.002
QCD shape	0.003	0.003
W+jets shape	0.012	0.011
integrated luminosity	0.010	0.010
SM W-helicity reference	0.002	0.001
total systematic uncertainty	0.030	0.023

Top polarisation

CMS-PAS-TOP-13-001

Uncertainty source	δA_l^μ	δA_l^e
generator	0.025	0.009
Q^2 scale *t*-channel	0.024	0.055
Q^2 scale, $t\bar{t}$	0.015	0.005
Q^2 scale, W+jets	0.036	0.038
top quark mass	0.058	0.042
W+jets shape	0.016	0.007
W+jets flavour	0.005	0.008
top p_T, $t\bar{t}$	0.010	0.025
matching, $t\bar{t}$	0.028	0.052
matching, W+jets	0.025	0.038
PDF	0.013	0.014
JES	0.074	0.074
JER	0.016	0.179
unclustered $\not{E}_T$	0.013	0.006
lepton ID and isolation	0.001	0.002
lepton trigger	0.001	0.002
pileup	0.015	0.002
b tagging	0.007	0.009
mistagging	0.001	0.003
lepton weight	0.001	0.009
anti-isolation range of QCD	0.010	0.053
QCD fraction	0.092	0.028
background fractions	0.007	0.018
unfolding bias	0.002	0.003
total systematics	0.15	0.23
statistical	0.07	0.11
total	0.17	0.26