Measurement of *t*-channel single top quark production in pp collisions

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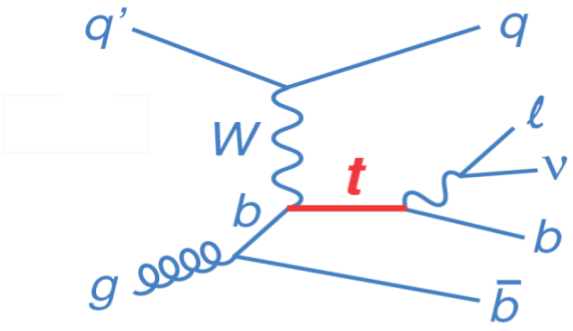
for the CMS Collaboration



References for this talk:

- JHEP 12(2012)035
- CMS PAS TOP-12-011
- CMS PAS TOP-12-038
- CMS PAS TOP-12-020

Outline

- **The CMS Experiment at the LHC**
- **Single-top *t*-channel in the standard model**
- **Inclusive cross section measurements**
  - 7TeV and 8TeV measurements
- ***t*-channel events properties**
  - Cross section as function of charge and charge ratio
  - W polarisation in t-channel events
- **Conclusion**

The CMS experiment at LHC

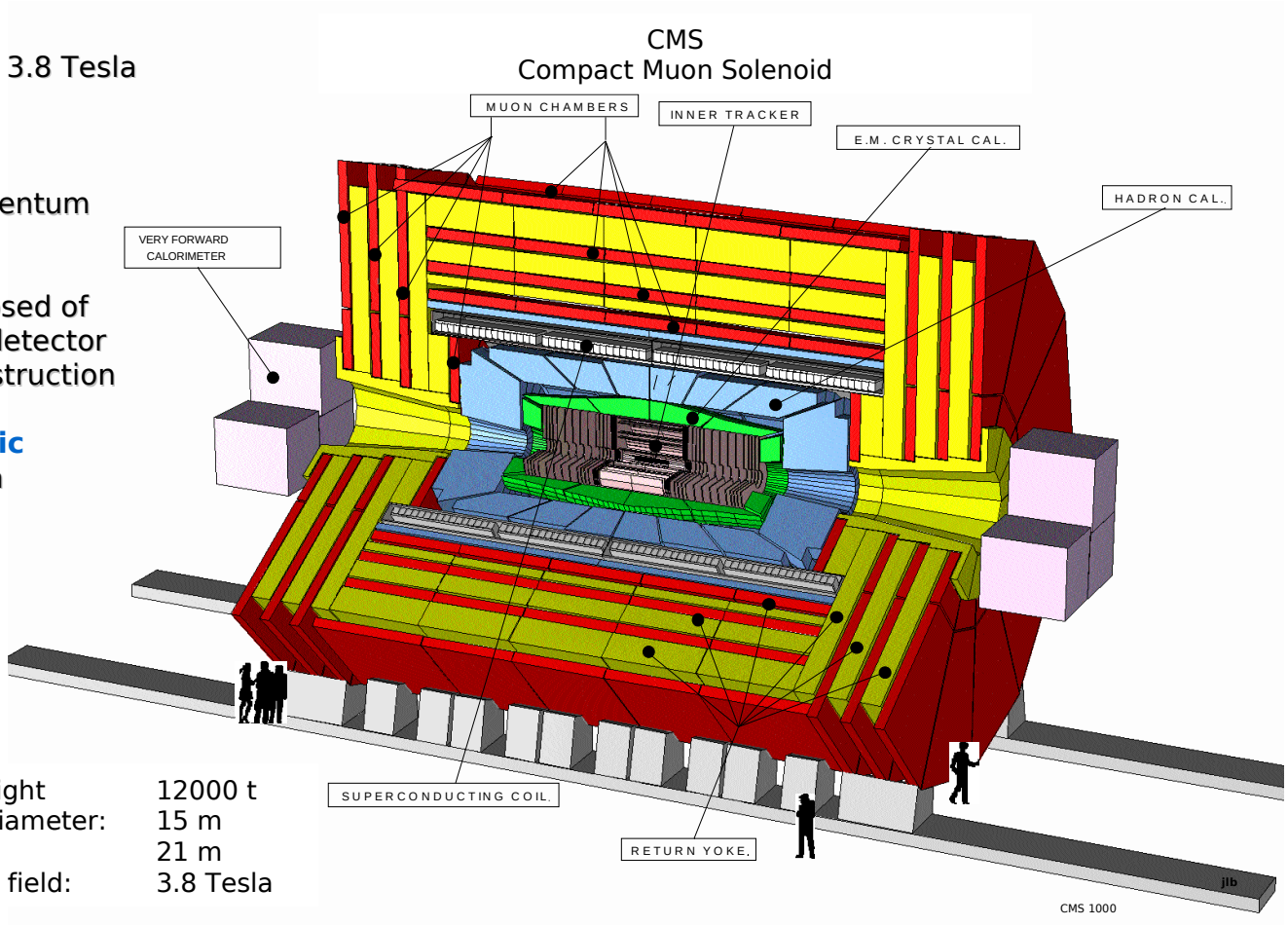
The CMS detector

- **Compact design** thanks to the 3.8 Tesla superconducting magnet

- **Muon detector**
For muon identification and momentum reconstruction

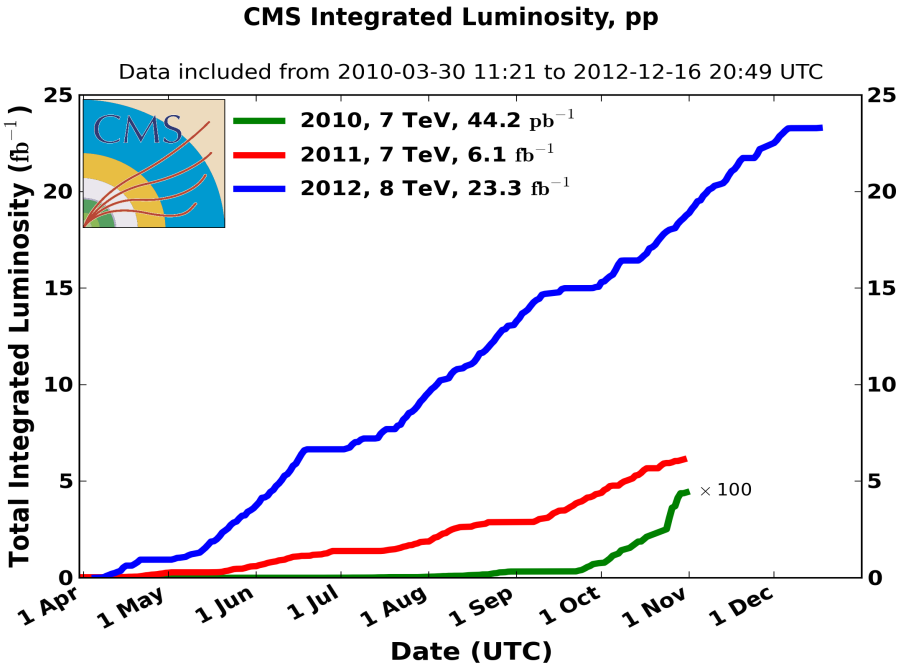
- **Inner tracking system** composed of a silicon pixel and a silicon strip detector for charged particle tracks reconstruction

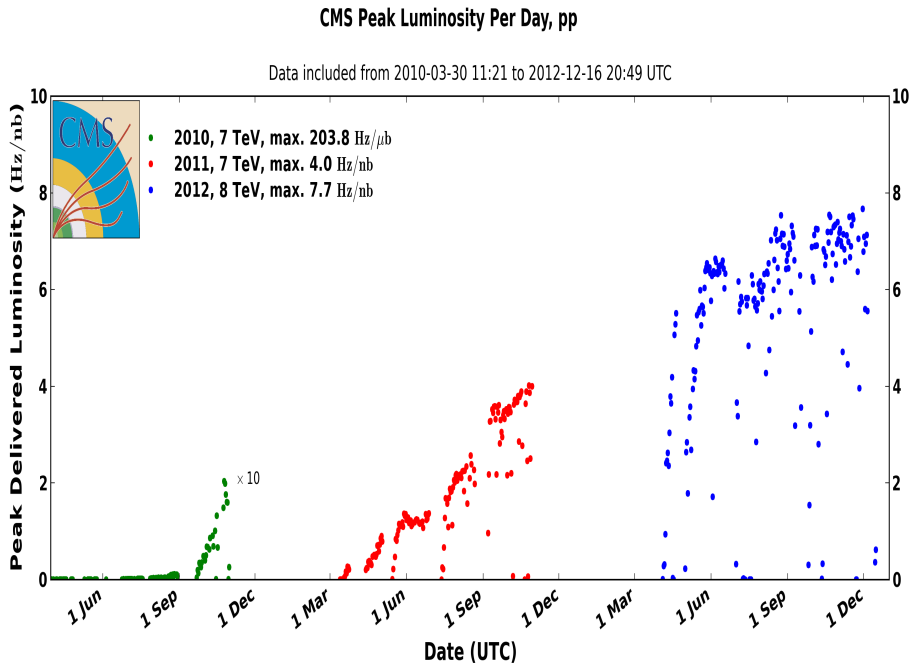
- **Electromagnetic and hadronic** calorimeters for electron, photon and jets reconstruction



Total Weight	12000 t
Overall diameter:	15 m
Length:	21 m
Magnetic field:	3.8 Tesla

CMS data taking during 2010-2012





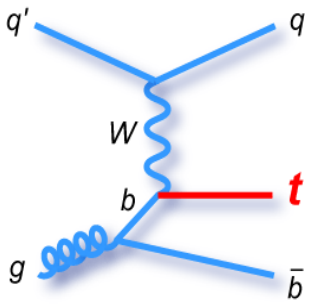
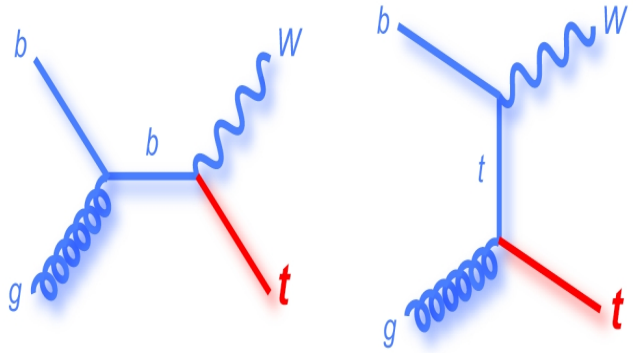
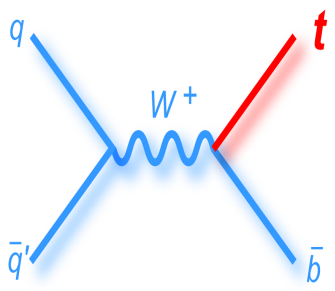
- **2011 data taking, proton-proton @ 7TeV :**
  - 6.1 fb^{-1} on tape
  - 4 nb^{-1}/s peak instantaneous luminosity
- **2012 data taking, pp @ 8TeV:**
  - 23.3 fb^{-1} on tape
  - 7.7 nb^{-1}/s peak instantaneous luminosity

Single-top in the standard model

The single-top processes

Electroweak top production

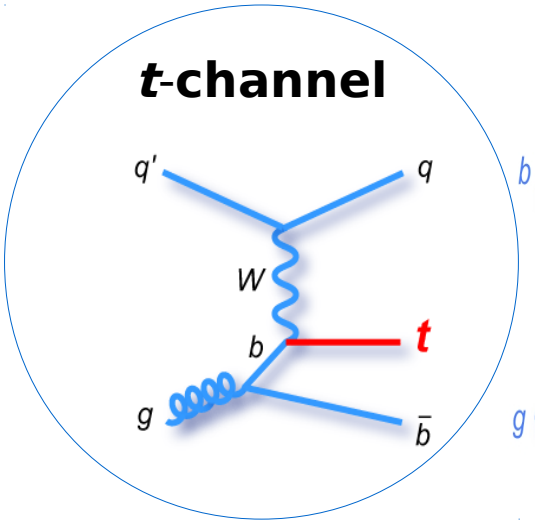
single-top

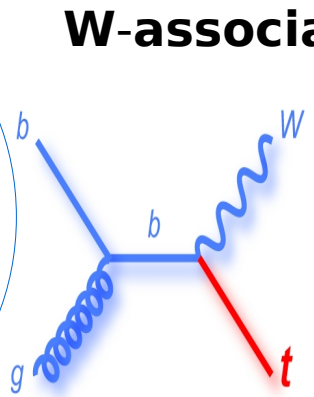
	***t*-channel**	**W-associated (tW)**	***s*-channel**
			
Tevatron: *pp* @1.96 TeV (N. KidonakisPhys. Rev. D 82, 054018 (2010) and arxiv:0909.0037	**2.08±0.12 pb**	**0.22±0.08 pb**	**1.046±0.058 pb**
LHC pp @7 TeV (N. Kidonakis Phys. arXiv:1205.3453)	**64.6±2.1 pb**	**15.6±1.2 pb**	**4.59±0.19 pb**
LHC pp @8 TeV (N. Kidonakis arXiv:1205.3453)	**87.1±2.8 pb**	**22.2±1.5 pb**	**5.55±0.22 pb**

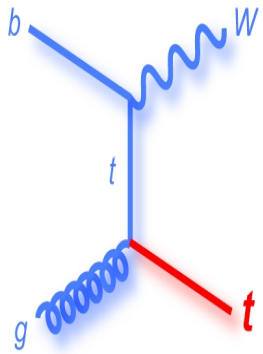
The single-top processes

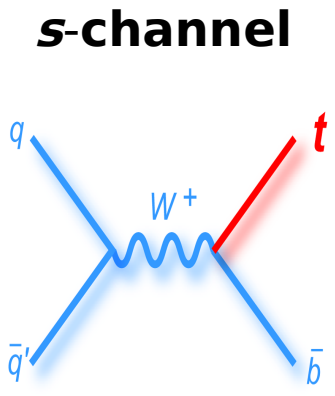
Electroweak top production

single-top









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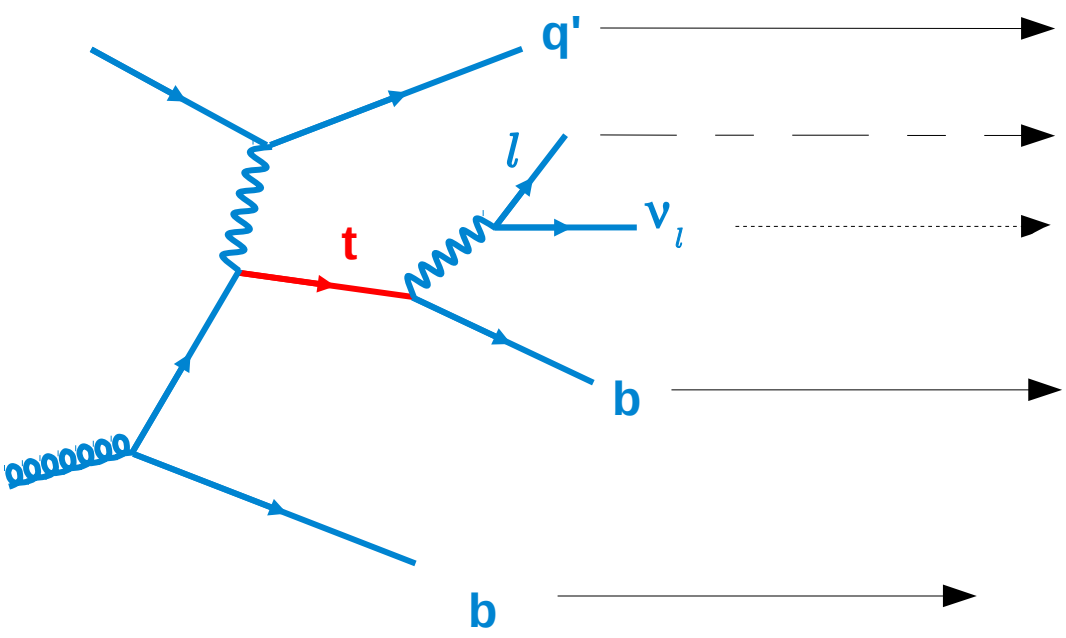
Single-top *t*-channel: leptonic events topology



Signature

"Light" jet j' with high pseudorapidity $|\eta_{j'}|$

μ or e

Missing energy

b-jet:
central, high p_T

2nd b-jet:
broad $|\eta|$, low p_T

Main backgrounds:

- $t\bar{t}$: both semileptonic and di-leptonic topologies
- $W(\rightarrow l\nu)$**+jets** : with contribution from W+(u,s,d,g) and W+(c,b)
- **Multijet QCD** → l + jets : reduced to extreme kinematic regions by selection cuts

Inclusive *t*-channel cross section measurements

t-channel event selection overview

	7 TeV	8 TeV
Trigger	Single muon/ Electron + 1 b-jet trigger	Single Muon/Single electron trigger
Exactly 1 lepton	Exactly 1 high p_T muon or electron in the trigger acceptance region, with isolation cuts for QCD rejection.	
Other leptons veto	Veto other muons or electrons wiht looser p_T and identification cuts	
Jet selection	2, 3, or 4 anti-kt jets with R = 0.5, depending on the analysis	Exactly 2 anti-kt jets with R = 0.5 and extra pile up rejection cuts
b-tagging	1 or 2 b-tagged jet amongst the selected jets	Exactly 1 b-jet
Missing energy/ transverse mass m_T	QCD rejection cuts on m_T for muons and missing energy for electrons	

- **Particle Flow algorithm** reconstructs each physics objects using information from all detectors

- **top quark candidate 4-momentum and the corresponding mass $m_{lb\nu}$** reconstructed for each event, from a b-jet ansatz, a lepton and the missing energy, imposing a constraint on the w mass.

t-channel cross section at 7TeV: 3 independent analyses

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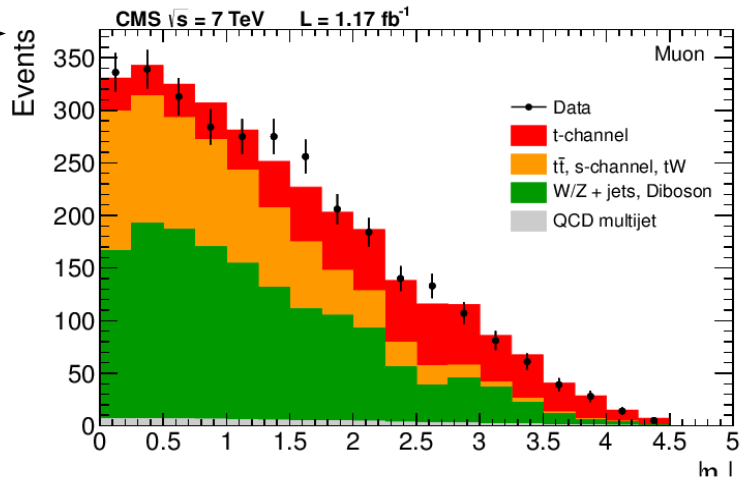
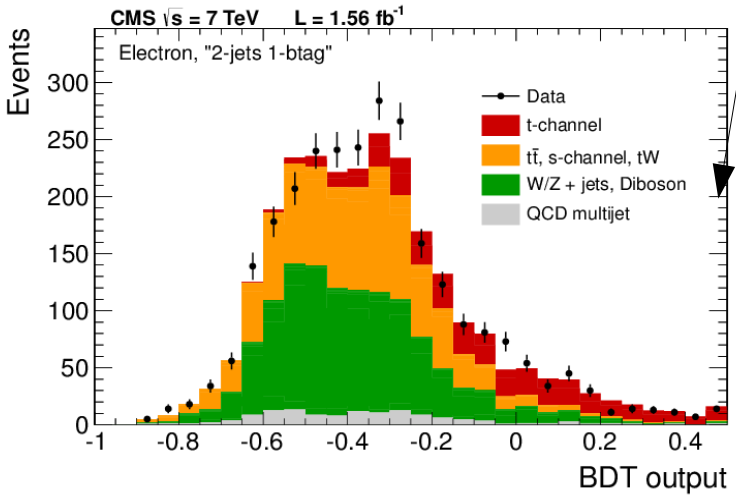
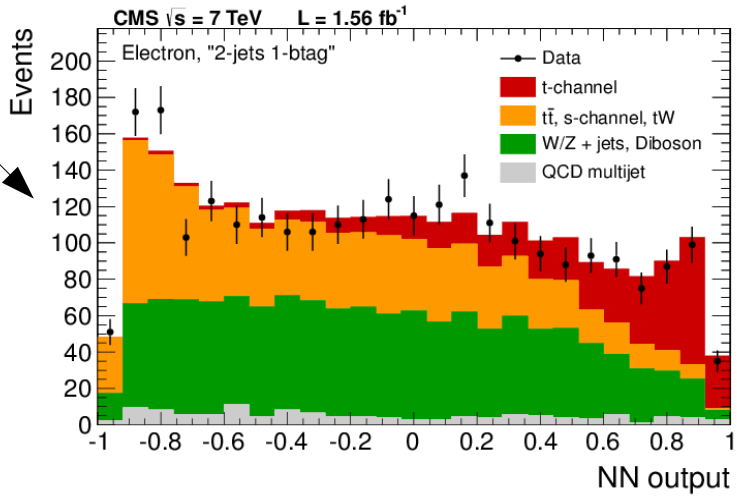
- **Robust analysis based on data-driven methods:**
  - Fit to pseudorapidity of the light jet $|\eta_{j'}|$ in the region with 2 jets and 1 b-tag

- **Multivariate analyses:**
  - Two analyses using a Neural Network (**NN**) and a Boosted Decision Trees (**BDT**) discriminant
  - Main backgrounds and systematics treated as nuisance parameters and marginalised over 6 events categories with 2-4 jets, and 1-2 b-tags







t-channel cross section at 7TeV: backgrounds estimation

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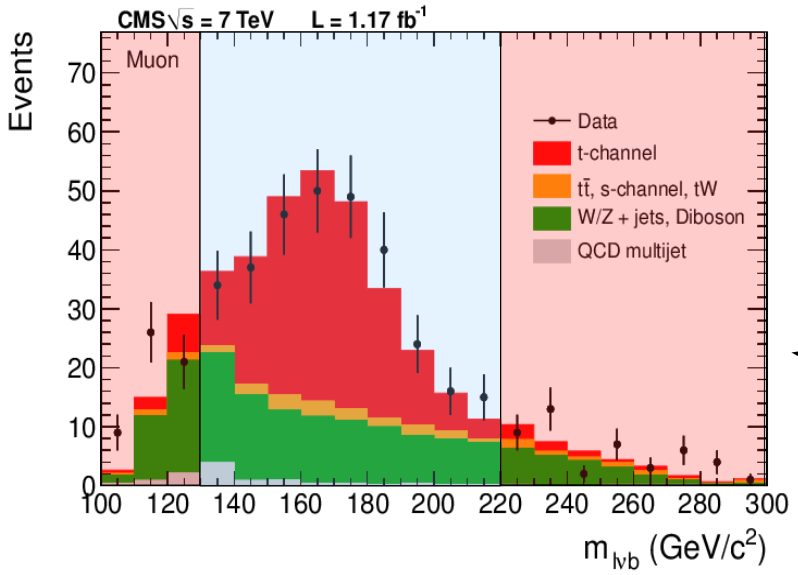
- **QCD treatment:**

- Fit to distribution of transverse mass m_T (Muon channel) or transverse missing energy $E_{T,miss}$ (Electron channel) to extract the qcd yield.

- Shape of the m_T, $E_{T,miss}$ extracted from qcd enriched sample.



- **W+jets treatment:**
  - Contributions from W+light and W+heavy flavours

- **NN,BDT** analyses: background yields treated as separate nuisance parameters and marginalized

- $|\eta_{j'}|$: extract W+jets shape for the fit from a sideband region in the reconstructed top quark mass m_{lbv}

t-channel cross section at 7TeV: combination and $|V_{tb}|$ extraction

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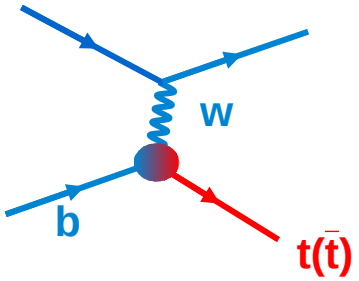
- **Combined measurement with BLUE:**

$\sigma_{(\text{t-channel,7 TeV})} = 67.2 \pm 3.7(\text{stat}) \pm 3.0(\text{syst}) \pm 3.5(\text{th.}) \pm 1.7\ (\text{lumi})$

- V_{tb} **estimation:**
  - **tWb vertex in production** → cross section depends on V_{tb}
  - assuming $|V_{td}|, |V_{ts}| << |V_{tb}|$ → $|V_{tb}| = \sqrt{(\sigma^{\text{obs.}}_{t\text{-ch.}}/\sigma^{\text{th.}}_{t\text{-ch}})}$:



$|V_{tb}| = 1.020 \pm 0.046\ (\text{meas.}) \pm 0.017\ (\text{theor.})$

- assuming $|V_{tb}| < 1$

$0.92 < |V_{tb}| \leq 1$ at 95% confidence level.

t-channel cross section at 8TeV:

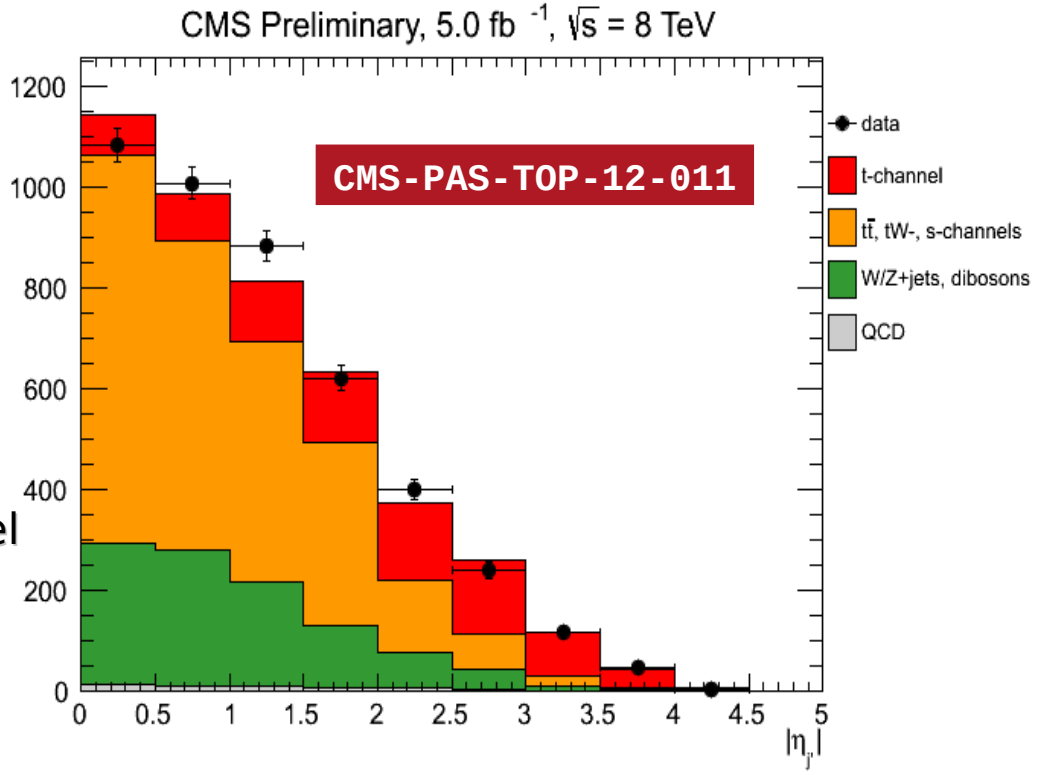
- **$|\eta_{j'}|$ analysis ported at 8 TeV:**

  - Same strategy for W+ jets and QCD as 7TeV

  - $t\bar{t}$ distribution modeled after data in a sample with 3-jets, 2 of which b-tagged

  - preliminary result in the muon channel

- **Fit results on 5.0 fb^{-1} :**



$\sigma_{(\text{t-channel,7 TeV})} = 80.4 \pm 5.7(\text{stat}) \pm 11.0(\text{syst+th.}) \pm 4.0\ (\text{lumi})$

Inclusive cross section overview

- **Cross section**

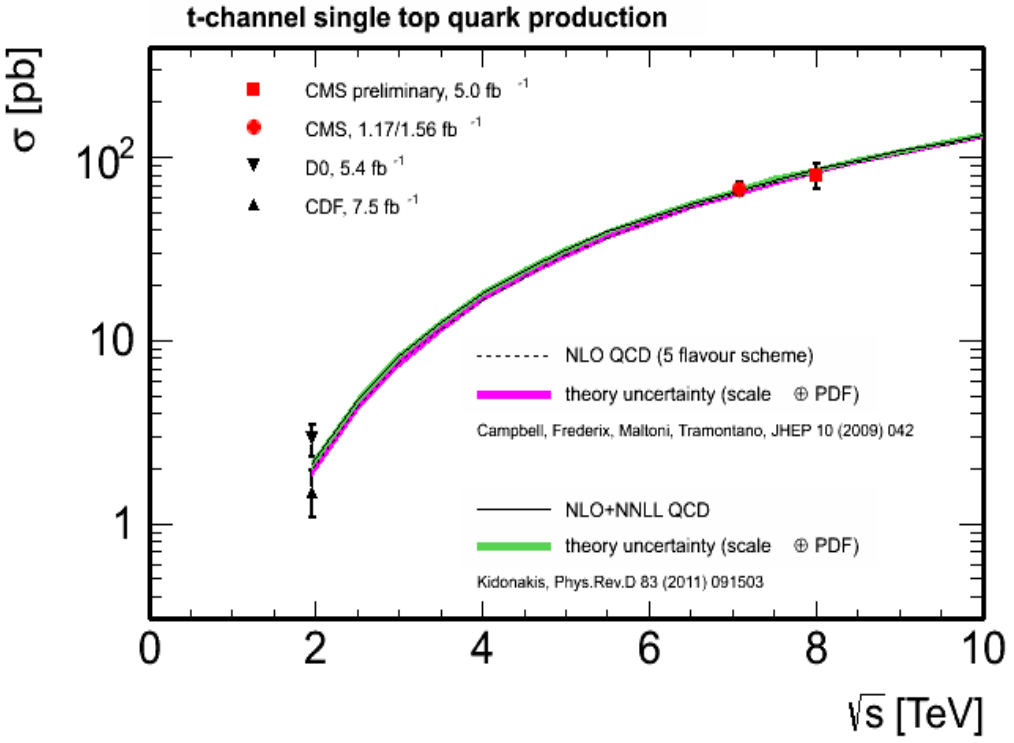
$\sigma_{(\text{t-ch.,7 TeV})} = 67.2 \pm 6.1$ pb (total)
$\sigma_{(\text{t-ch.,8 TeV})} = 80.4 \pm 13.0$ pb (total)

- **Cross section ratio:**

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

$= 1.14 \pm 0.12$ (stat) ± 0.14 (syst)

- Obtained only considering the $|\eta_{j'}|$ analysis for the 7 TeV part.



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

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

8 TeV: $|V_{tb}| = 0.96 \pm 0.08$ (exp.) ± 0.02 (theor.)

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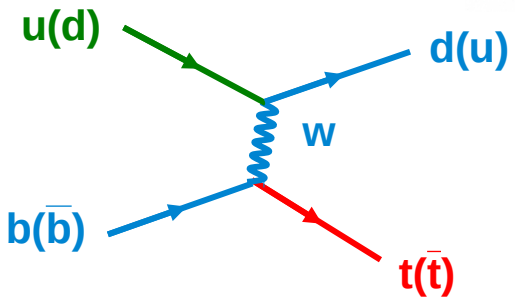
CMS-PAS-TOP-12-011

t-channel events properties

t-channel charge asymmetry

- *t*-channel **top quark charge:** inherited from the quark in the initial state

- **Valence u and d quarks** contribution generates difference in top-antitop cross sections → dependency on proton parton distribution functions



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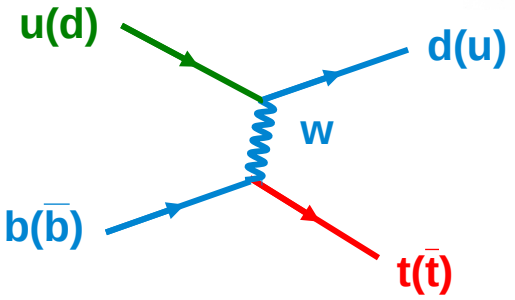

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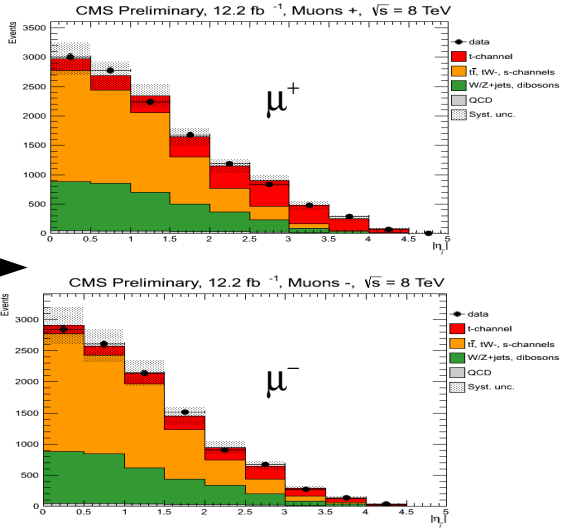
- $|\eta_{j'}|$ analysis: fit performed on positive and negative charge leptons simultaneously

Ratio measured:

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

CMS-PAS-TOP-12-038



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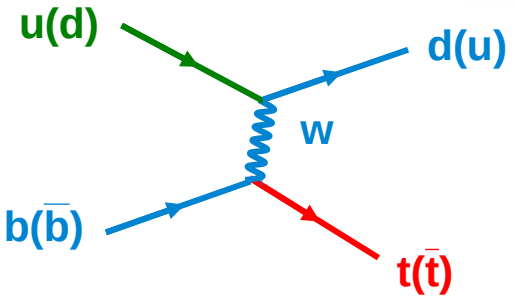

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Ratio measured:

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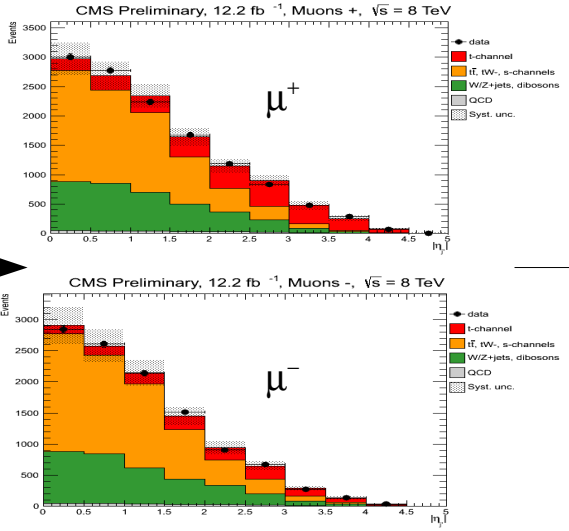
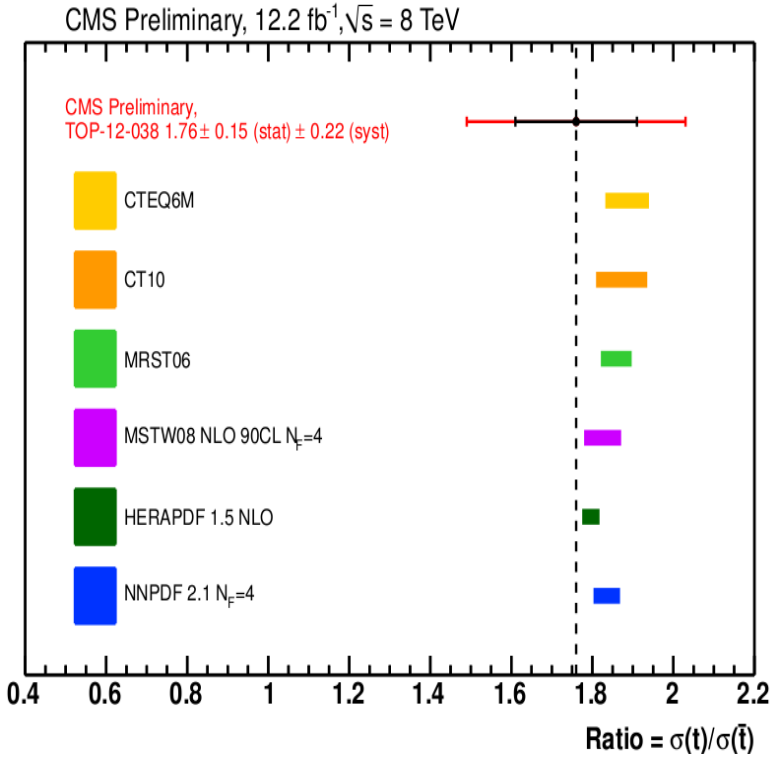


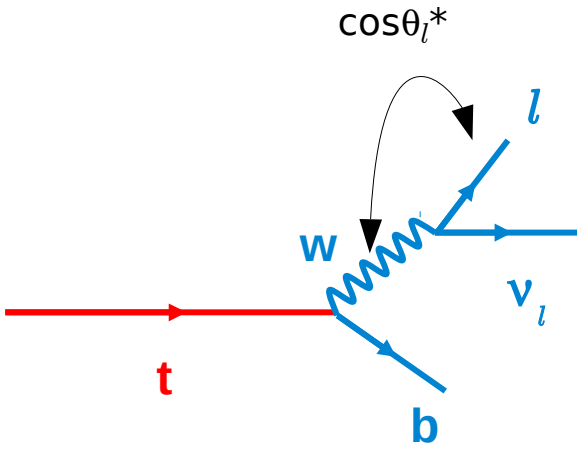


W-polarisation in single-top *t*-channel enriched events

- **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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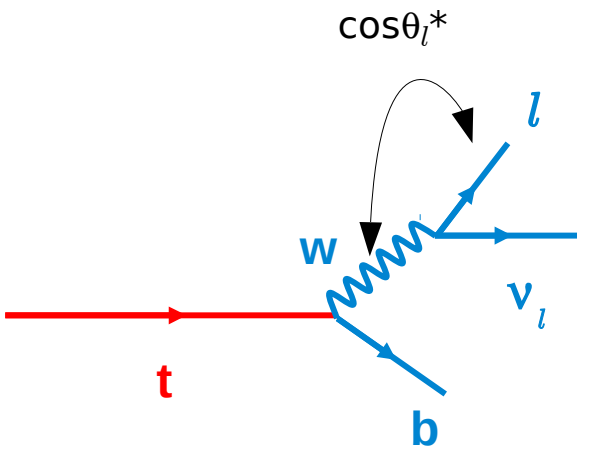
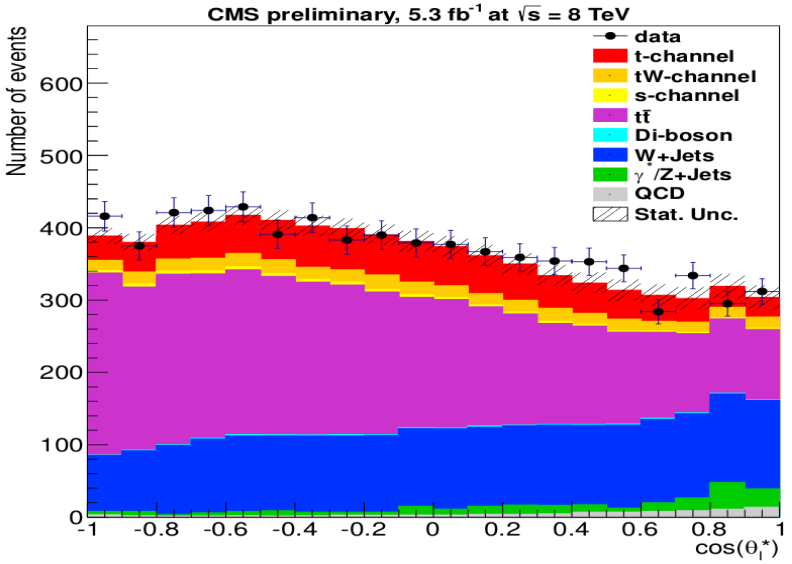


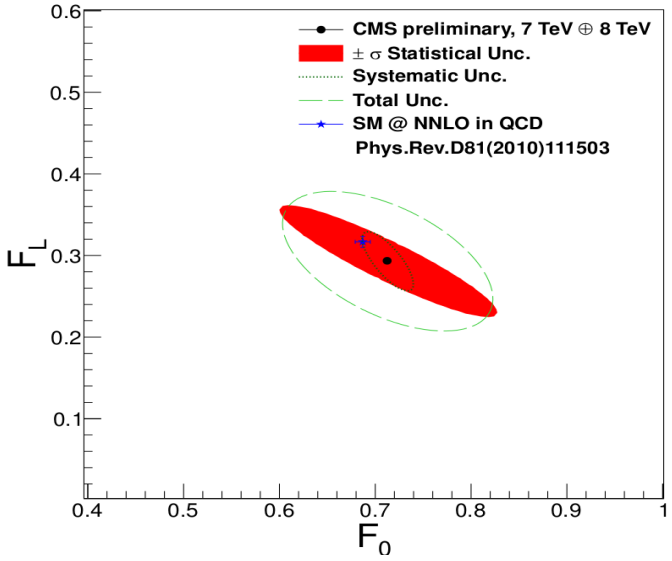


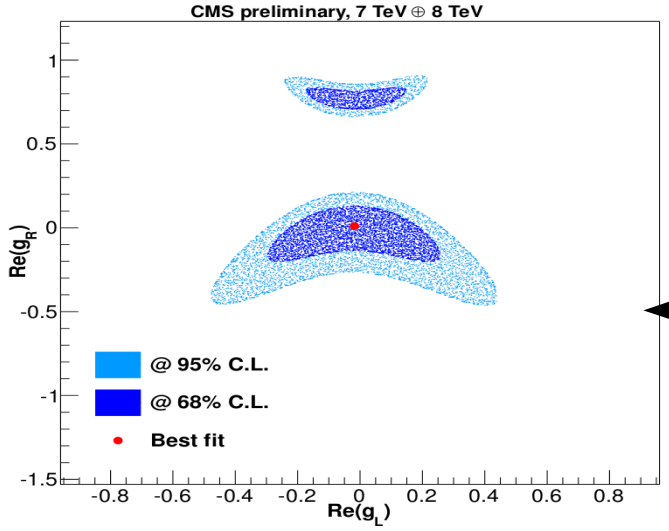
W-polarisation: 7 and 8 TeV measurement

- **Fit to the cosθ_l*:**

  - same event selection as the cross section measurement

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





- **Constraints to anomalous couplings:**

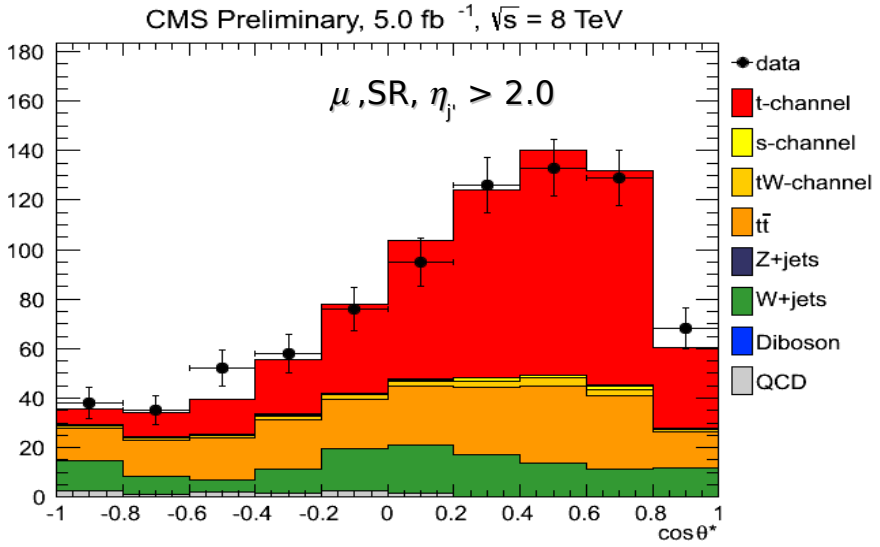
  - Extracted limits on non SM tensor couplings (G_L,G_R) from the measurement of (F_L,F_0)

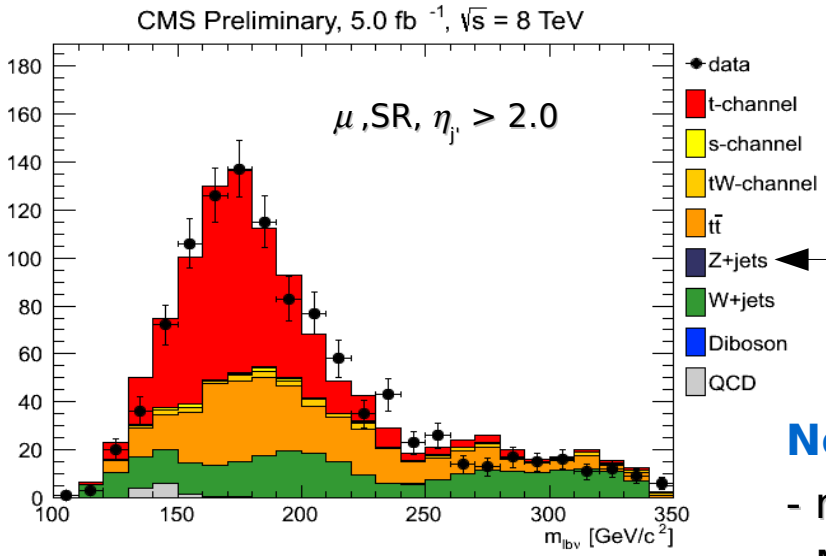
CMS-PAS-TOP-12-020

Top mass and polarisation: observables in data and MC

CMS-PAS-TOP-12-011

- **cosθ*:**
  - angle between the lepton and the recoil jet in the top rest frame
  - distribution stems from V-A nature of the coupling





- Reconstructed **top mass $m_{lb\nu}$**
  - Visible peak in t-channel enriched regions

Notes:
- no unfolding is applied to the MC distributions
- MC normalized to the measured cross section

Conclusions

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

- **Inclusive cross section measurements** performed both at 7 and 8 TeV were shown, and a measurement of the CKM matrix element $|V_{tb}|$ was extracted.

- **The top/antitop charge ratio** and the **W-helicity fractions** in single-top events were described as well, also showing respectively the agreement with different parton distribution functions sets, and the constraints put to tensor anomalous couplings scenarios.

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

Thanks!

Backup

Event selection: physics objects and Particle Flow

- **Particle Flow:** Algorithm which uses information from all the sub-detectors to reconstruct leptons, jets, missing energy

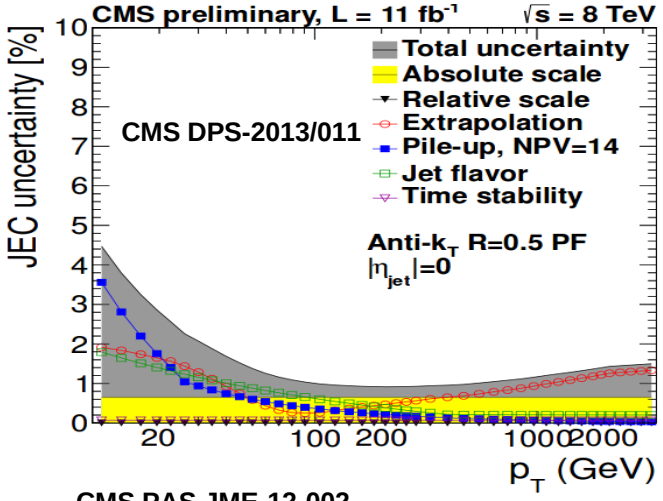
- **Jet Momentum resolution:** greatly benefits from the use of information from the tracking system

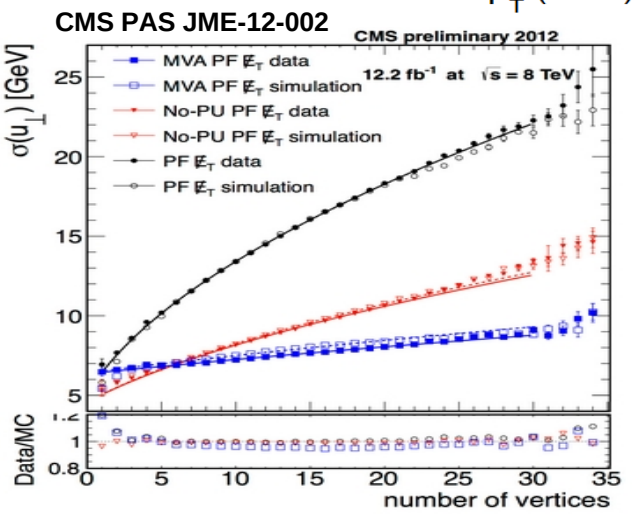
- **Missing energy resolution:** Increases due to intrinsicly inclusive nature of the Particle Flow algorithm

Plots from:

CMS DPS-2013/011

CMS PAS JME-12-002



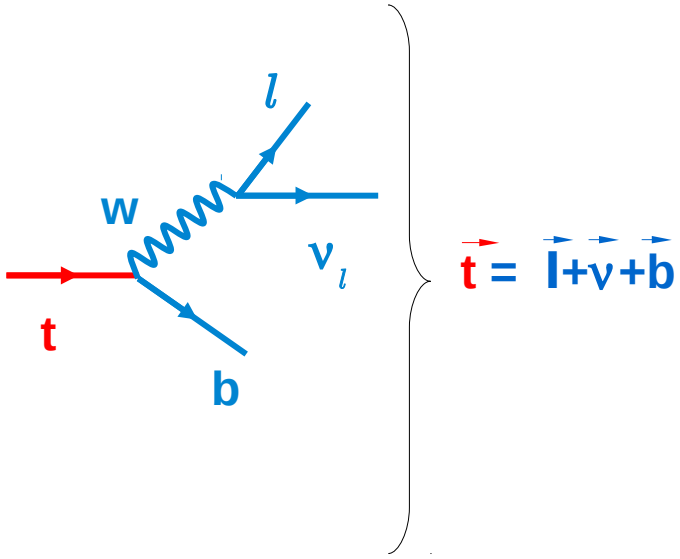


t-channel event selection details

	7 TeV	8 TeV
Trigger	Single muon/ Electron + 1 b-jet trigger	Single Muon/Single electron trigger
Exactly 1 lepton	1 Muon, pt > 20 GeV, |η|<2.1 or 1 Electron, pt > 30 GeV, |h|<2.5 Isolation cuts	1 Muon, pt > 26 GeV, |η|<2.1, or 1 Electron, pt > 30 GeV, |h|<2.5 Isolation cuts
Other leptons veto	Veto muons, pt > 10 GeV, |η|<2.5 Veto electrons, pt > 15 GeV, |η|<2.5	Veto muons, pt > 10 GeV, |η|<2.5 Veto electrons, pt > 20 GeV, |η|<2.5
Jet selection	2, 3, or 4 anti-kt jets with R = 0.5, p_T > 30,|η| < 4.5.	2 leading anti-kt jets with R = 0.5, p_T > 60 GeV, |η| < 4.5. Other jets p_T > 40 GeV
b-tagging	1 or 2 b-jets	Exactly 1 b-jet
Missing energy/ transverse mass m_T	Muons: m_T > 40 GeV Electrons: missing energy > 35 GeV	Muons: m_T > 50 GeV Electrons: missing energy > 45 GeV

- **jet b-tagging algorithm:** measures the impact parameter significance of the tracks associated to the Jet: the third highest value of the IP significance is taken as discriminator value for the jet. A tight threshold is applied on it in order to select b-jets

top quark 4-momentum reconstruction



Reconstructed taking 4 momenta of the lepton, the b-tagged jet and the MET:

1) take $(p_{x,\nu}, p_{y,\nu}) = (MET_x, MET_y)$

2) constrain the mass of the lν pair to the PDG value of m_W : **get 2nd order equation in $p_{z,\nu}$**

3)two real solutions:take the one with lowest $|p_{z,\nu}|$

4)two imaginary solutions: put discriminant to 0. In this case eq. 1) is not valid anymore, but **we can still impose 2.**

5)Chose $p_{x,\nu}, p_{y,\nu}$ with minimum distance from the MET in the p_x/p_y plane

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 cross section

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8TeV cross section

CMS-PAS-TOP-12-011

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: *t*-channel event properties measurements

8TeV: cross sction by charge and charge ratio

CMS-PAS-TOP-12-038

Uncertainty source	$\sigma_{t-ch,antitop}$ (%)	$\sigma_{t-ch,top}$ (%)	$R_{t-channel}$ (%)
stat. uncertainty	± 8.6	± 3.9	± 8.8
JES,JER, and MET	± 4.9	± 4.2	± 2.6
b-tagging and mis-tag	± 4.3	± 3.7	± 0.9
backgrounds ratio	± 0.6	± 0.5	± 1.1
lepton reconstruction/trig.	± 1.9	± 1.8	± 3.6
qcd extraction	± 6.4	± 3.4	± 0.9
W+Jets, $t\bar{t}$ extraction	± 5.9	± 2.4	± 6.8
signal modeling	± 11.4	± 15.4	± 5.4
pdf uncertainty	± 5.8	± 2.8	± 7.5
simulation statistics	± 1.1	± 0.6	± 1.1
luminosity	± 4.4	± 4.4	-
total systematics	± 17.4	± 17.8	± 12.6
total relative uncertainty	± 19.4	± 18.3	± 15.3
Scale factor w.r.t. SM ± uncertainty	0.92±0.18	0.88±0.16	0.96±0.15

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