Measurements of single top quark processes with CMS

DIS 2013 - Marseille

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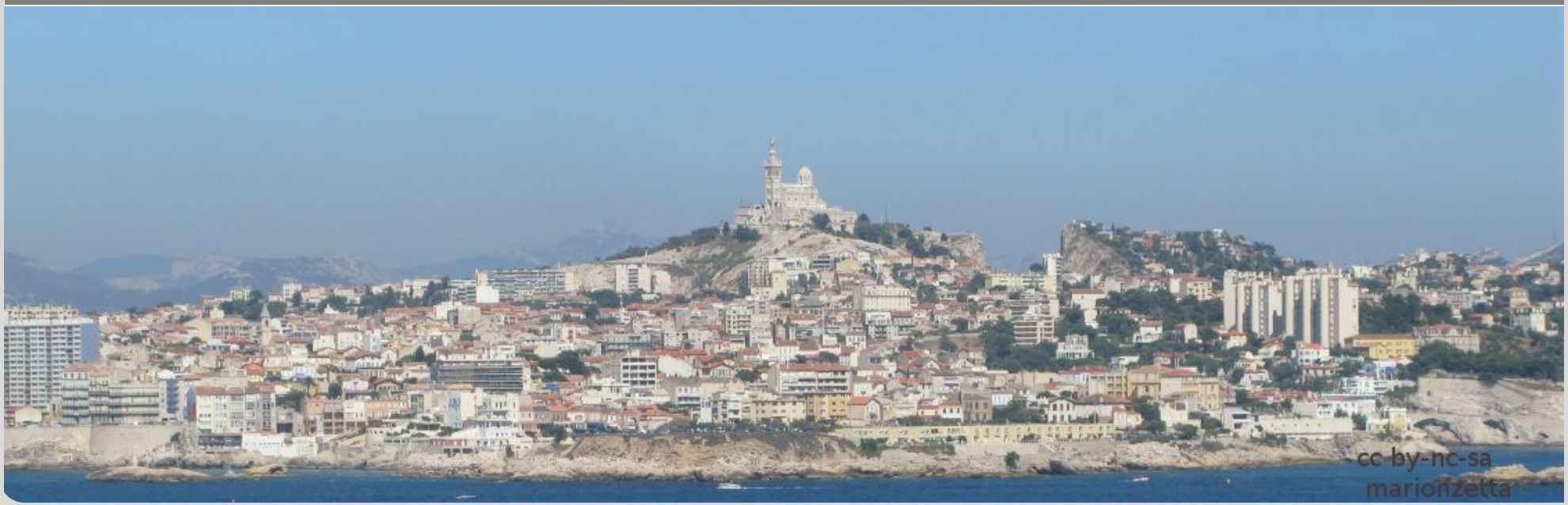
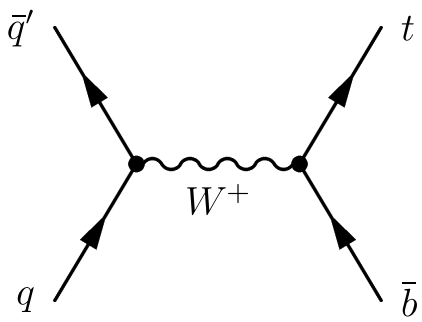
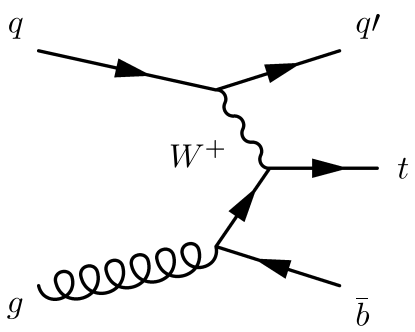
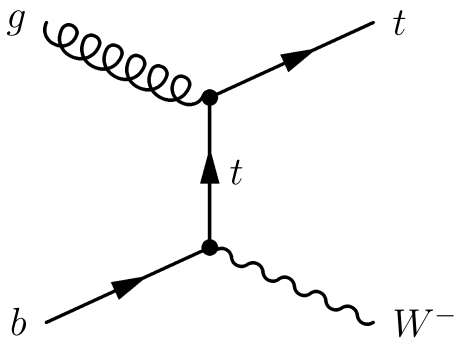


Single top quark production

Electroweak production of single top quarks:

Production	 *s*-channel	 **t-channel**	 associated *tW* production
Predicted σ [pb]			
$p\bar{p}$ $\sqrt{s} = 1.96$ TeV	1.05 ± 0.05	2.1 ± 0.1	0.25 ± 0.03
pp $\sqrt{s} = 7$ TeV	4.6 ± 0.2	$\mathbf{64.6^{+2.6}_{-1.9}}$	15.7 ± 1.2
pp $\sqrt{s} = 8$ TeV	5.6 ± 0.2	$\mathbf{87.2^{+3.4}_{-2.4}}$	22.2 ± 0.8
	PRD 81, 054028	PRD 83, 091503(R)	PRD 82, 054018 (Kidonakis)

Interesting properties:

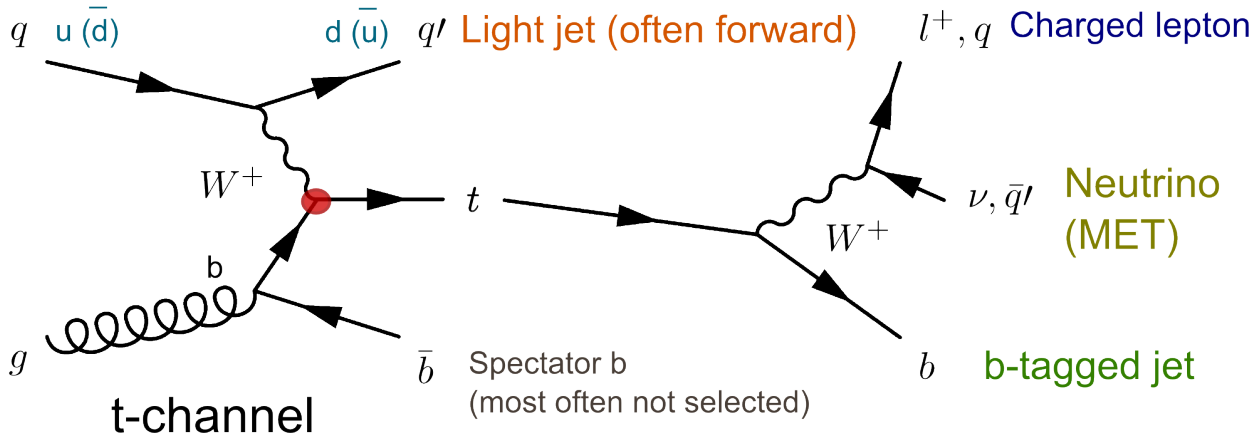
- Allows direct measurement of CKM matrix element $|V_{tb}|$
- *Wtb* vertex enables tests of V–A structure, anomalous couplings
- *t*-channel charge ratio sensitive to u(d) PDF, *t*-channel and tW production sensitive to *b* PDF
- Background for Higgs and searches for new physics (4th generation, FCNC, H^+, W'), SUSY

Outline

- Single top quark t-channel measurements
  - Cross section measurement (7 and 8 TeV)
  - Charge asymmetry $R_t = \frac{\sigma_t}{\sigma_{\bar{t}}}$ (8 TeV)
  - W helicity fractions (7 and 8 TeV)
- Associated tW production (7 TeV)
- Conclusion

Single top quark t-channel measurements (7 and 8 TeV)

Event selection for t-channel measurements



7 TeV selection:

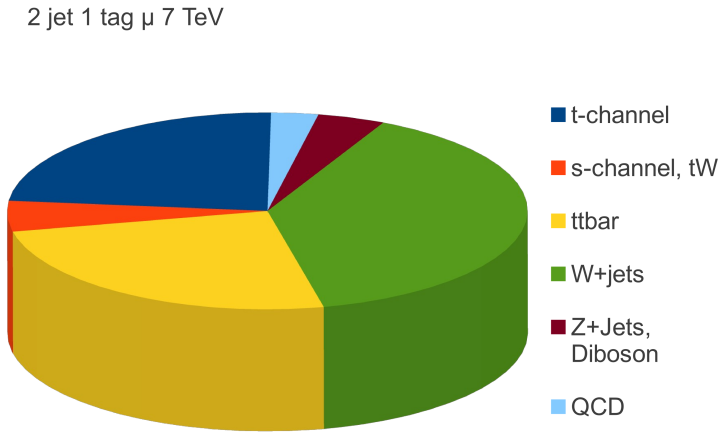
- Single lepton triggers (e+b-jet @ 7 TeV)
- 1 isolated charged lepton
- Veto events with other softer charged leptons
- $M_T(W)$ (E_T^{miss}) cut to suppress QCD multijet production
- 2 jets, can be forward $|\eta| < 4.5$
- 1 jet with b-tag (track counting algorithm, 0.1% mistag rate)

8 TeV selection:

- Increased p_T tresholds and additional cuts to reduce pile-up

Background processes

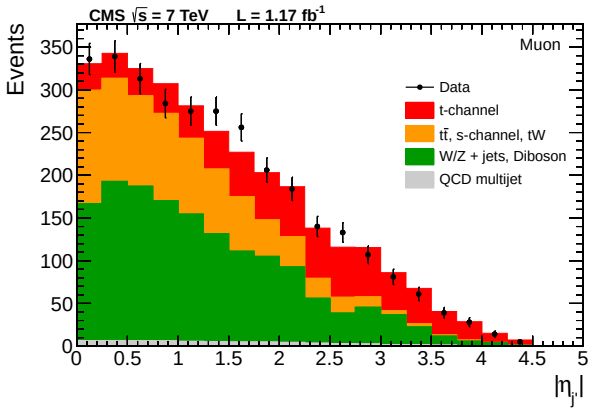
- Contribution from background processes after selection:
  - Single Top: s-channel, tW
  - Top quark pair production $t\bar{t}$
  - W+jets
  - Z+jets
  - Diboson (WW, WZ, ZZ)
  - QCD multijet

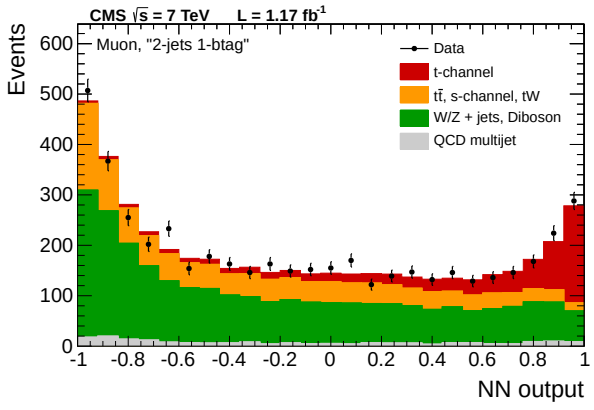


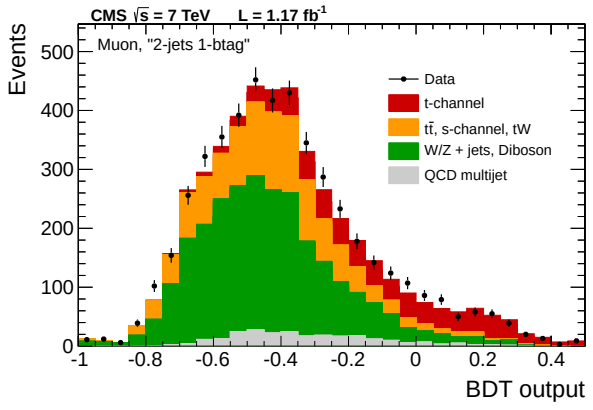
- Main backgrounds: W+jets and top quark pair production $t\bar{t}$
- QCD multijet background difficult to model and MC statistics very small after cuts
  $\rightarrow$ data driven estimation with fit to $M_T(W)$ (MET) in orthogonal data set

Cross section measurement (1.17/1.56 fb^{-1} at 7 TeV)

- Three different analyses: $|\eta_{j'}|$, NN, BDT







$|\eta_{j'}|$ analysis

- Robust template fit to $|\eta_{j'}|$
- Data driven W+jets estimation in top quark mass side band
- Signal region in top mass window $130 < M_{\ell\nu b} < 220$ GeV/c^2

Multivariate analyses

- Neural network and Boosted Decision Trees
- 6 analysis bins (up to 4 jets with $\geq$ 2 tags)
- Several well modeled input variables
- Bayesian method

- Correlation estimated with pseudo experiments, combination with BLUE

$$\sigma_{\text{t-ch.}} = 67.2 \pm 3.7\ (\text{stat.}) \pm 3.0\ (\text{syst.}) \pm 3.5\ (\text{theor.}) \pm 1.5\ (\text{lum.})\ \text{pb}$$

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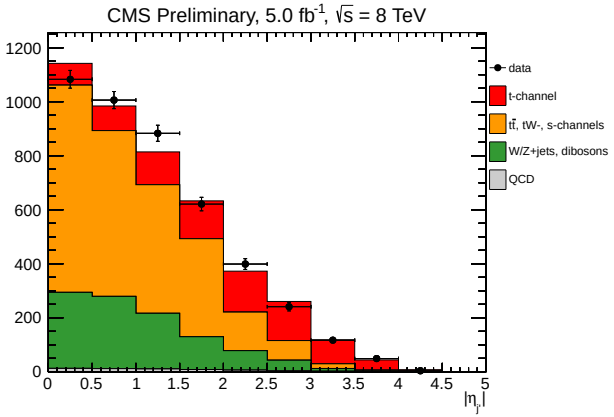
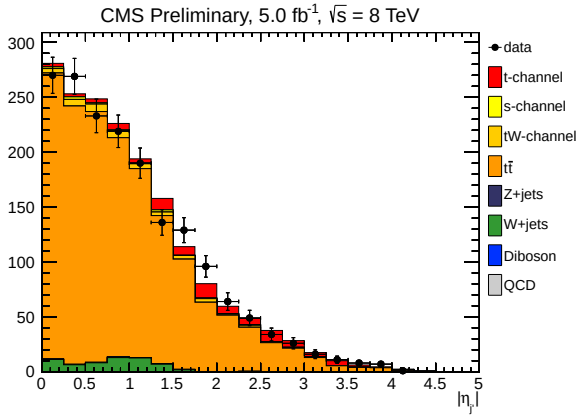
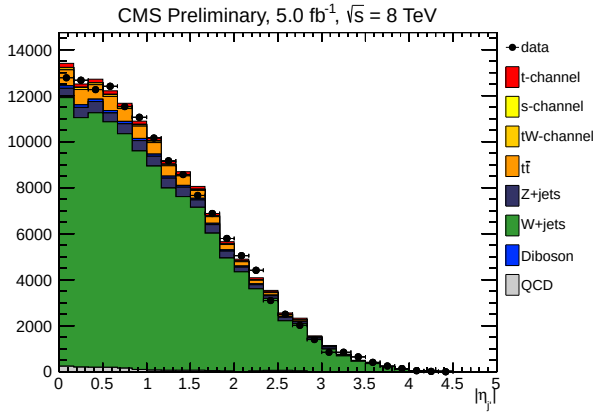
Cross section measurement (12.2/fb at 8 TeV)

- Template fit to $|\eta_{j'}|$ of recoil jet





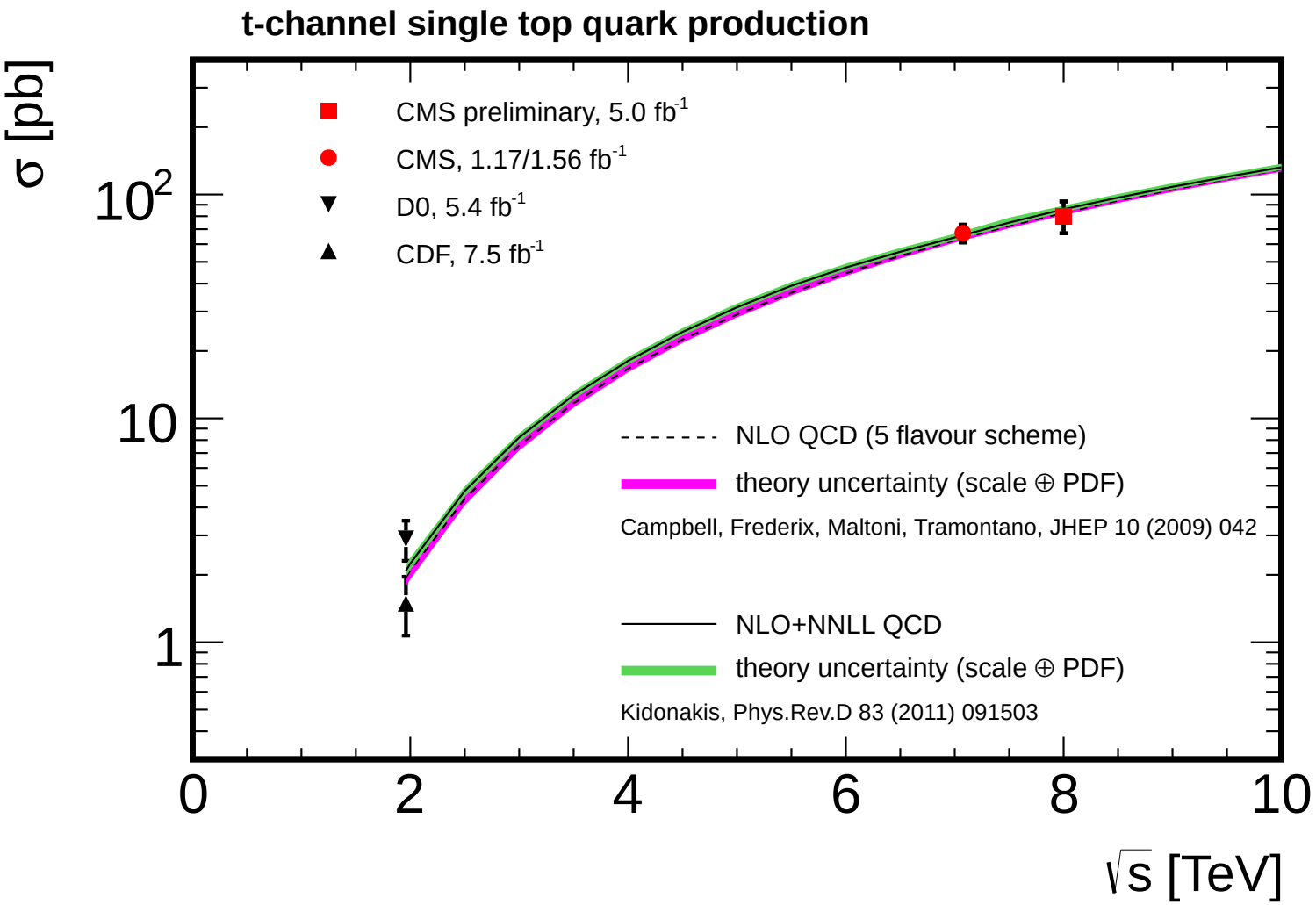


- Adapted p_T thresholds, additional cuts to suppress pile-up
- Different background composition at 8 TeV: More $t\bar{t}$, less W+jets
- $|\eta_{j'}|$ distribution for $t\bar{t}$ taken from 3 jet 2 tag region
- W+jets modeling checked in 2 jet 0 tag region

$$\sigma_{\text{t-ch.}} = 80.1 \pm 5.7(\text{stat.}) \pm 11.0(\text{syst.}) \pm 4.0(\text{lumi.})\ \text{pb}$$

CMS PAS TOP-12-011

Comparison with theory



- Good agreement with NNLO (approx.) theory prediction

Extraction of $|V_{tb}|$

- Assuming that $|V_{tb}|^2 \gg |V_{td}|^2 + |V_{ts}|^2$ and $|V_{tb}| = 1$ for $\sigma^{\text{th}}_{t\text{-ch.}}$
- $|V_{tb}|$ can be extracted from cross section measurement
  $|V_{\text{tb}}| = \sqrt{\frac{\sigma_{t\text{-ch.}}}{\sigma^{\text{th}}_{t\text{-ch.}}}}$

$$V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

$$|f_{L_V} V_{\text{tb}}| = 1.020 \pm 0.046\ (\text{exp.}) \pm 0.017\ (\text{theor.}) \qquad (7\ \text{TeV})$$
$$|f_{L_V} V_{\text{tb}}| = 0.96 \pm 0.08\ (\text{exp.}) \pm 0.02\ (\text{theor.}) \qquad (8\ \text{TeV})$$

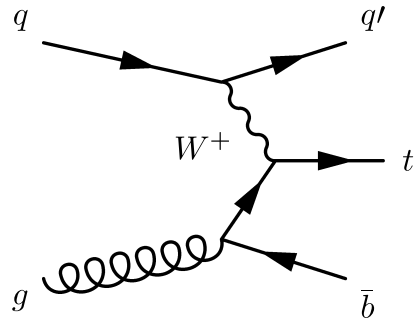
- f_{L_V} left-handed vector coupling,
  possible anomalous form factor from BSM contributions (e.g. vector-like quarks)

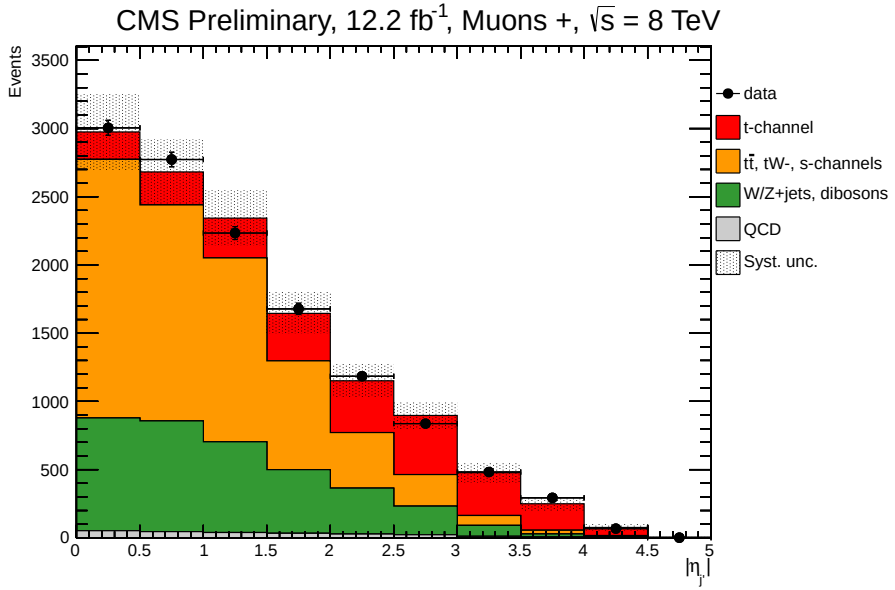
- Constraining $|V_{tb}|$ to the interval $[0, 1]$ and setting $f_{L_V} = 1$ yields:

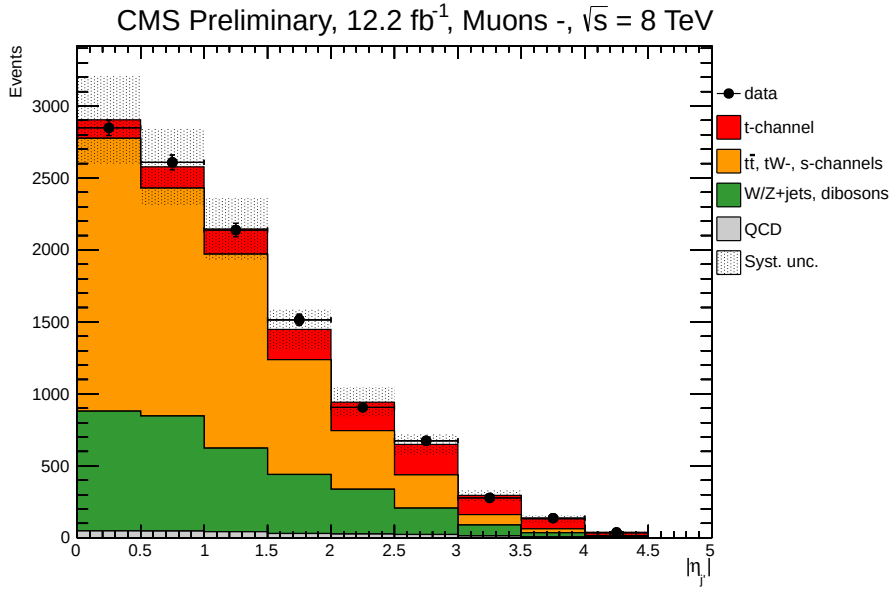
$$0.92 < |V_{tb}| \leq 1 @\ 95\%\ \text{CL}\ (7\ \text{TeV})$$
$$0.81 < |V_{tb}| \leq 1 @\ 95\%\ \text{CL}\ (8\ \text{TeV})$$

Charge asymmetry $R_t = \frac{\sigma_t}{\sigma_{\bar{t}}}$

- More top than anti-top quarks produced due to initial valence quark distribution
- Cross section ratio $R_t = \frac{\sigma_t}{\sigma_{\bar{t}}}$ depends on u(d) quark PDF, but also sensitive to new physics



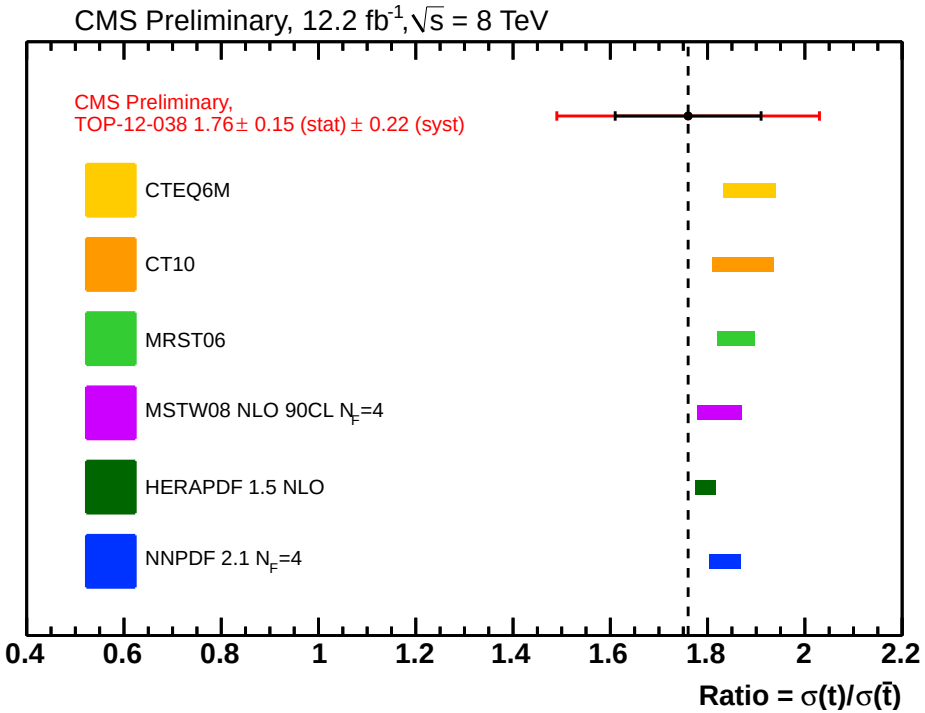




- Template fit to $|\eta_{j'}|$ separately for positive/negative charged leptons
- Systematic uncertainties estimated with pseudo experiments
  - Luminosity uncertainty cancels, JES/JER/MET uncertainty reduced due to ratio

Charge asymmetry results (12.2/fb 8 TeV)

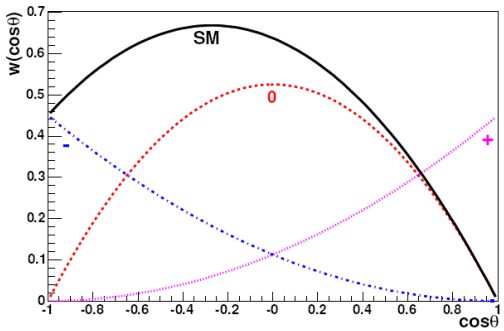
$$\sigma_{t\text{-ch.,top}} = 49.9 \pm 1.9(\text{stat.}) \pm 8.9(\text{syst.})\,\text{pb.}$$
$$\sigma_{t\text{-ch.,anti-top}} = 28.3 \pm 2.4(\text{stat.}) \pm 4.9(\text{syst.})\,\text{pb.}$$
$$R_{t\text{-ch.}} = 1.76 \pm 0.15(\text{stat.}) \pm 0.22(\text{syst.})$$



- Good agreement with SM prediction
- Ratio could be used for PDF fits (higher precision needed)

CMS PAS TOP-12-038

W helicity fractions



- W bosons from top quark decay polarized
- W helicity fractions measurable with $\cos\theta_l^*$ distribution:

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

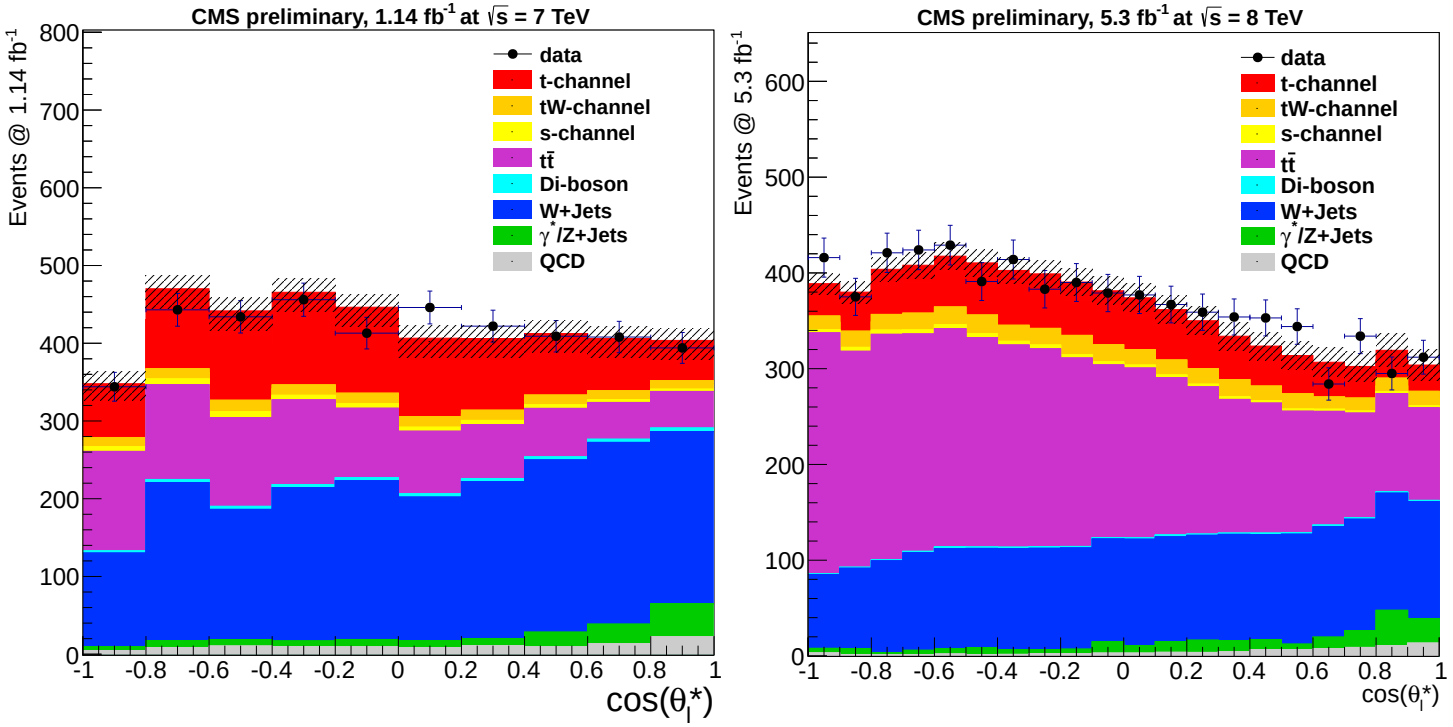
  - θ_l^*: Angle in top-quark rest frame between lepton 3-momentum in W boson rest frame and W boson 3-momentum
- SM prediction: $F_L \approx 0.30$, $F_R \approx 0$, $F_0 \approx 0.70$
- Helicity fractions can differ from SM by modifications of *Wtb* vertex through BSM contributions
- Lagrangian of *Wtb* vertex in effective field theory (dimension-6 operator):

$$\mathcal{L}_{Wtb}^{anom.} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^\mu(V_L P_L + V_R P_R)tW_\mu^- - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_\nu}{m_W}(g_L P_L + g_R P_R)tW_\mu^- + h.c,$$

  - SM: $V_L = V_{tb} \approx 1$, $V_R = g_L = g_R = 0$

W helicity measurement in single top event topology

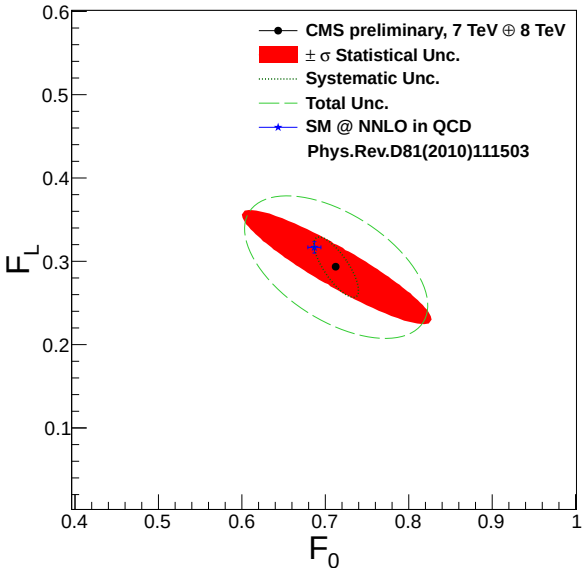
- Same selection as 7 and 8 TeV cross section measurements (μ only)
- *W*+jets shape data driven from control region (2 jets, 0 b-tags), QCD from data side band

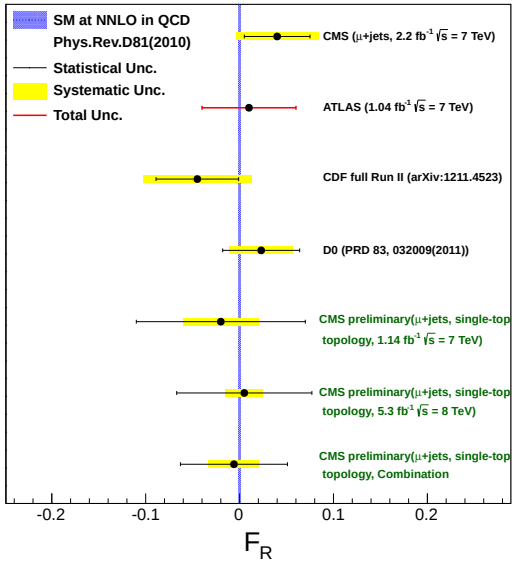


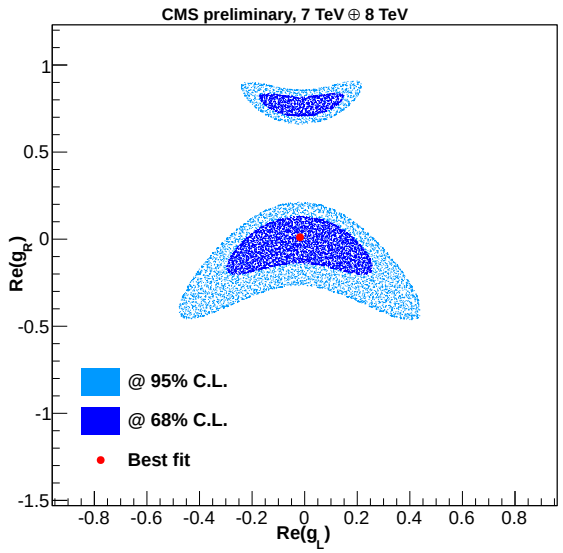
- Processes with *Wtb* vertex reweighted, measurement with likelihood fit
- Combination of 7 and 8 TeV results with combined likelihoods

W helicity results (1.17(1.56)/fb 7 TeV, 5.3/fb 8 TeV)

$$F_L = 0.293 \pm 0.069(\text{stat.}) \pm 0.030(\text{syst.})$$
$$F_0 = 0.713 \pm 0.114(\text{stat.}) \pm 0.023(\text{syst.})$$
$$F_R = -0.006 \pm 0.057(\text{stat.}) \pm 0.027(\text{syst.})$$







- Result consistent with SM V–A couplings and $t\bar{t}$ measurements (LHC combination)
- More data needed for tighter constraints

CMS PAS TOP-12-020

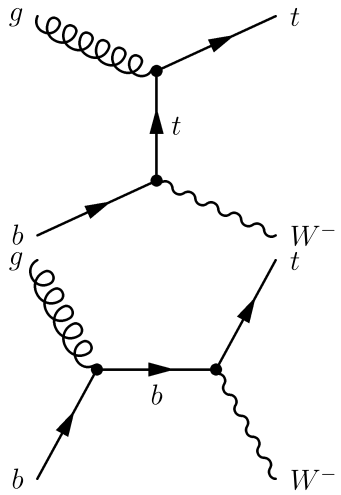
Associated tW production (7 TeV)

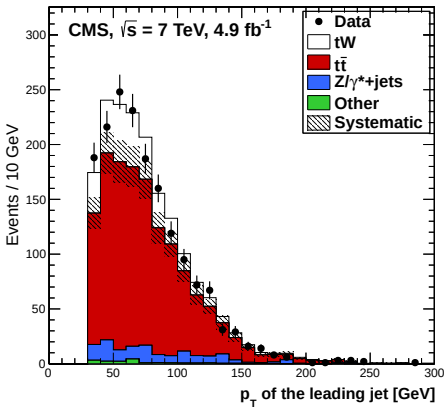
Associated production tW

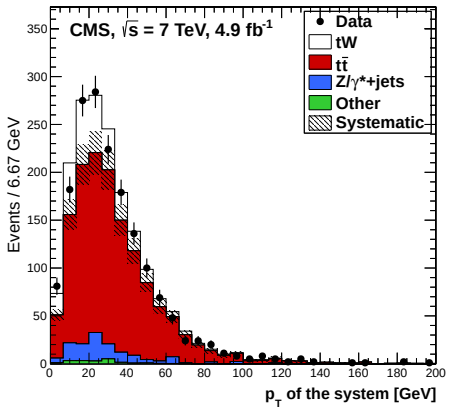
Selection:

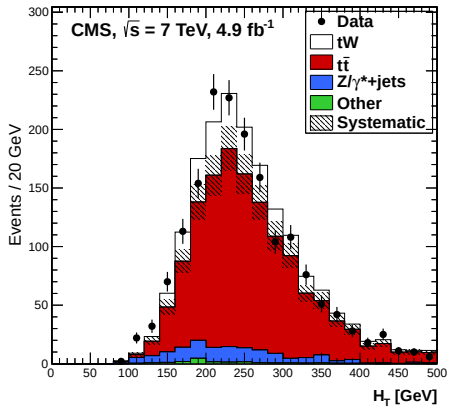
- 2 leptons (ee, $e\mu$, $\mu\mu$) with opposite charge
- Signal region: 1 b-tagged jet
- Background region: 2 jets, 1 or 2 b-tagged (constrain $t\bar{t}$)
- Veto events with dilepton mass in Z window

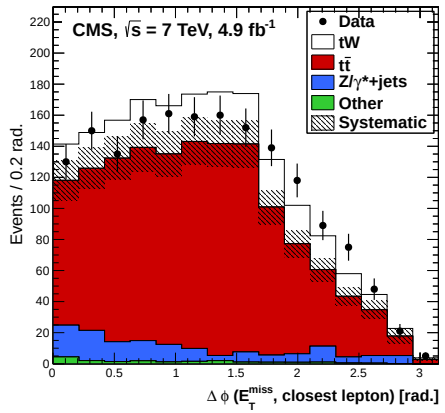
- Important backgrounds: $t\bar{t}$, Z/γ^*+jets
- Separation of $t\bar{t}$/tW with boosted decision tree:
  - jet p_T, system p_T, H_T, $\Delta\Phi(MET, \ell)$



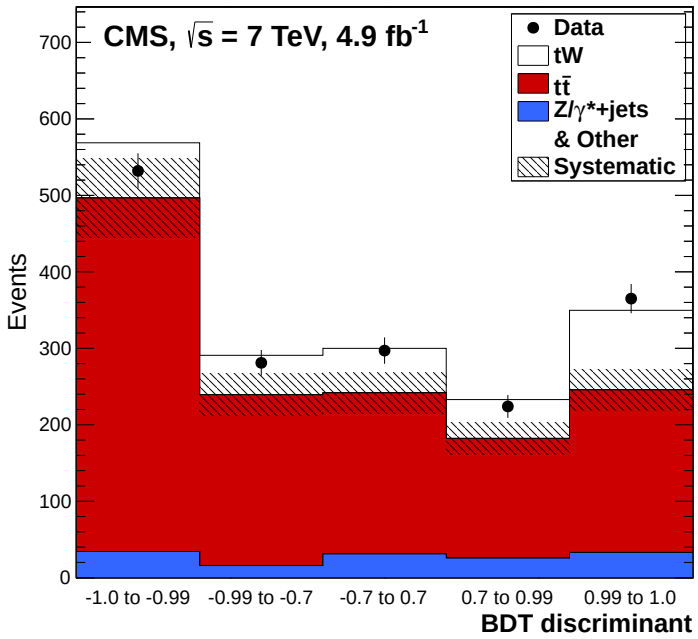








Evidence for associated production tW (4.9/fb 7 TeV)



- Simultaneous fit to BDT output in signal region and $t\bar{t}$ control region (ee, $e\mu$, $\mu\mu$)
- Observed significance: 4σ (Expected: $3.6^{+0.8}_{-0.9}\sigma$)
- Measured cross section: 16^{+5}_{-4} pb

$$|V_{tb}| = 1.01^{+0.16}_{-0.13}(\text{exp.})^{+0.03}_{-0.04}(th.) \text{ and } 0.78 \leq |V_{tb}| \leq 1.0$$

- Measurement consistent with SM prediction
- More data will enable first observation

Phys. Rev. Lett. 110 (2013) 022003

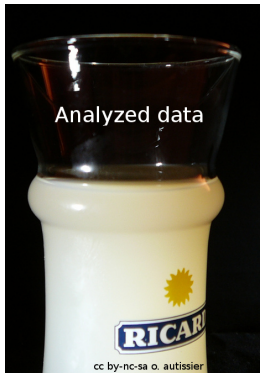
Conclusions and outlook

Conclusions:

- All single top quark measurements consistent with SM
- Precise direct measurement and limit on $|V_{tb}|$
- Charge asymmetry with higher precision can be used to constrain u(d) quark PDF
- Measured W helicity in single top event topology
- Evidence for associated single top quark production (tW) at 7 TeV

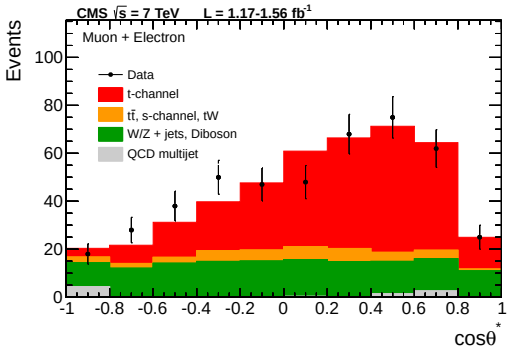
Outlook:

- More 8 TeV results underway
- Single top quark measurements are starting to enter precision regime
- More data allows higher precision and interesting property measurements



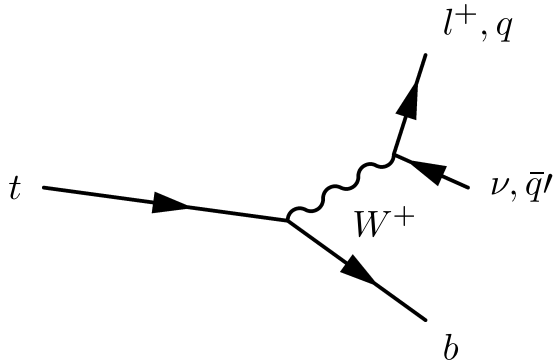
Backup

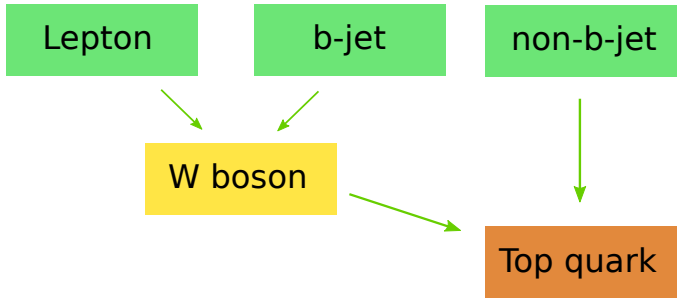
Top quark decay and reconstruction



- Top quark decays immediately due to high mass / large width ($t \to Wb$)
- $W \to \ell^{\pm}\nu$, BR $\approx 32\%$, here only e, μ
- Spin information passed to decay products

Top quark reconstruction in t-channel:





- Reconstructed from detector: jets, leptons, E_T^{miss}
- Top quark candidate reconstructed from W boson and b-tagged jet
- W boson from lepton and E_T^{miss} : $p_{z,\nu}$ from E_T^{miss} by constraint on W boson mass
  - Two real solutions: Choose the one with smallest $|p_{z,\nu}|$
  - Imaginary solution: Minimal variation of E_T^{miss} so that $M_T^W = M_W$
- Assign b-tagged jet to top quark decay

7 TeV t-channel cross section - Systematic uncertainties

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

8 TeV t-channel cross section - Event yield and systematic uncertainties

Process	SR	SB
$t\bar{t}$	2196 ± 17	1195 ± 13
W+jets	658 ± 75	867 ± 85
Z+jets	32 ± 16	41 ± 19
QCD	57 ± 24	33 ± 16
Diboson	10 ± 1	16 ± 1
tW-channel	195 ± 4	119 ± 3
s-channel	49 ± 2	19 ± 1
t-channel	915 ± 8	128 ± 3
Total MC	4112 ± 79	2418 ± 89
Data	4403	2618

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%

Charge asymmetry systematic uncertainties

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

W helicity systematic uncertainties

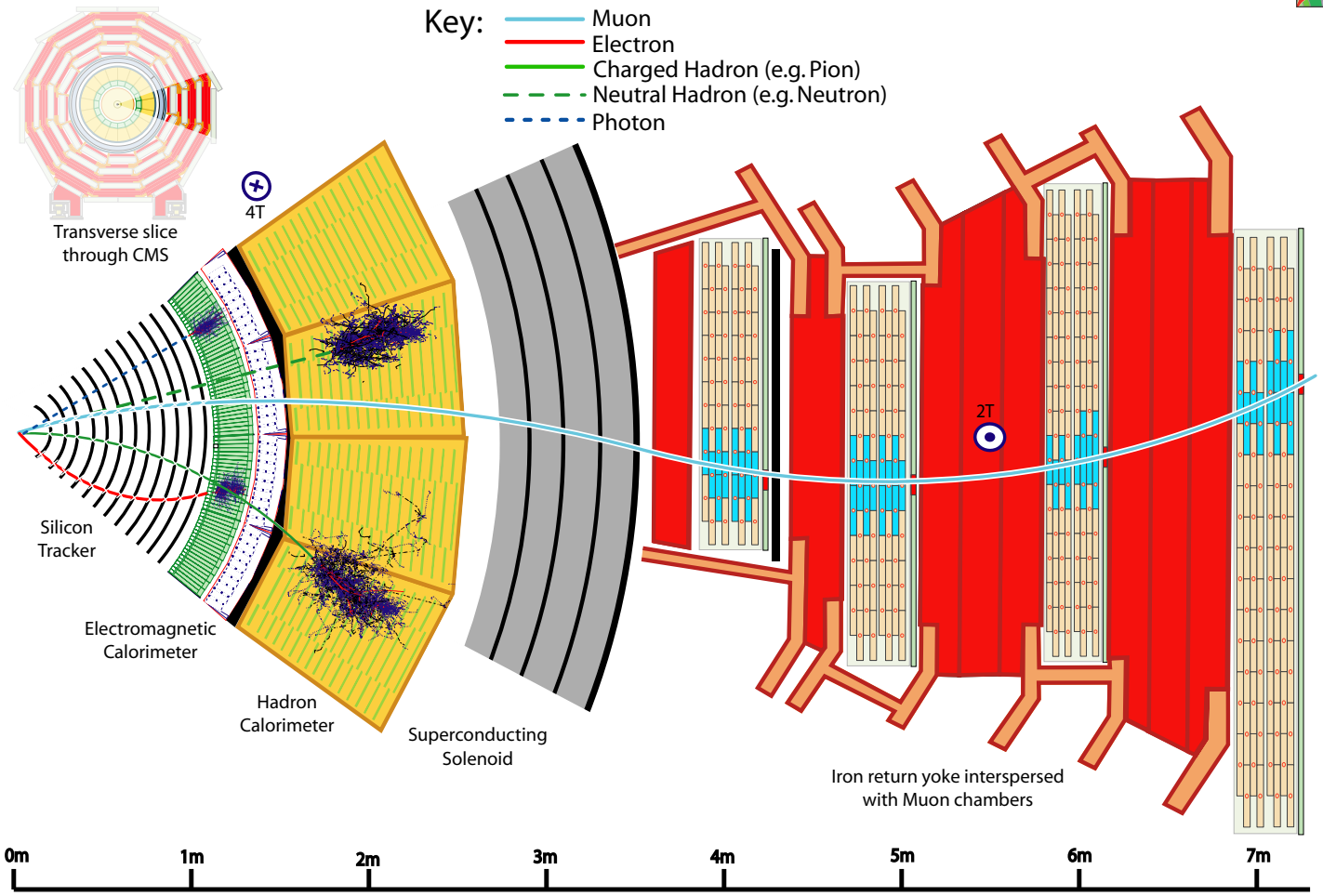
	$\sqrt{s} = 8\,\text{TeV}$		$\sqrt{s} = 7\,\text{TeV}$	
Systematic source	ΔF_L	ΔF_0	ΔF_L	ΔF_0
JES	0.006	0.006	0.020	0.020
JER	0.008	0.003	0.015	0.010
unclustered energy	0.013	0.003	0.015	0.015
pileup	0.002	0.003	0.004	0.000
b-flavored scale factor	0.004	0.006	0.009	0.009
non-b-flavored scale factor	0.004	0.007	0.002	0.001
single-top generator	0.008	0.014	0.004	0.004
Q^2 scale	0.009	0.012	0.040	0.007
m_{top}	0.005	0.006	0.010	0.010
PDF	0.005	0.005	0.000	0.000
$t\bar{t}$ normalization	0.002	0.003	0.008	0.008
QCD shape	0.002	0.002	0.004	0.004
W+jets shape	0.008	0.010	0.010	0.010
integrated luminosity	0.003	0.003	0.007	0.007
SM W-helicity reference	0.004	0.003	0.001	0.002
total systematic uncertainty (w/o generator)	0.022	0.021	0.054	0.035
total systematic uncertainty	0.024	0.026	0.054	0.035

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

Associated single top quark production - systematic uncertainties

Systematic Uncertainty	$\Delta\sigma$ (pb)	$\frac{\Delta\sigma}{\sigma}$
Luminosity	0.69	0.04
Pileup modeling	0.24	0.02
Electron trigger efficiency	0.35	0.02
Muon trigger efficiency	0.38	0.02
Electron identification	0.70	0.04
Muon identification	0.45	0.03
b-tagging	0.30	0.02
Jet Energy Scale	2.42	0.15
Jet Energy Resolution	0.58	0.04
$\mathrm{E_T^{miss}}$ modeling	0.40	0.05
tW Q^2	0.34	0.02
$t\bar{t}$ Q^2	0.29	0.02
ME/PS Matching Thresholds	1.62	0.10
tW DR/DS scheme	0.94	0.06
PDF uncertainties	0.34	0.02
$t\bar{t}$ cross section	0.96	0.06
$Z/\gamma^\star$ modeling	0.67	0.04
Statistical	3.33	0.21
Total	4.95	0.31

CMS detector



- Single top analyses need information from all detector subsystems to reconstruct (forward) jets, leptons, and missing transverse energy (E_T^{miss})