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

QCD@LHC2015 - London

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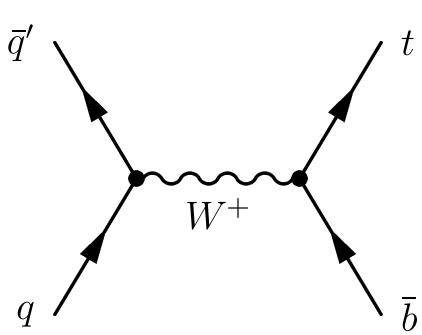
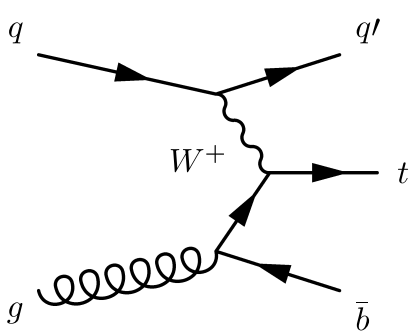
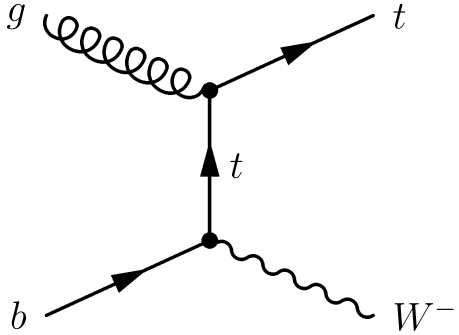
Single top quark production

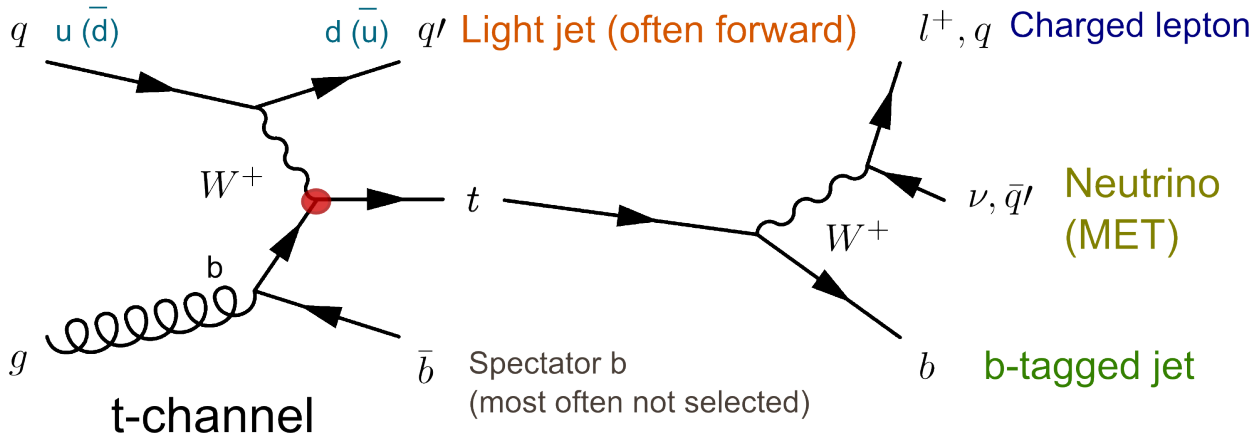
Electroweak production of single top quarks:

Production	 *s*-channel	 **t-channel**	 associated *tW* production
Predicted σ [pb]	PRD 81, 054028	PRD 83, 091503(R)	PRD 82, 054018 (Kidonakis)
$p\bar{p}$ $\sqrt{s} = 1.96$ 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
pp $\sqrt{s} = 13$ TeV	10	217	72

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

Event selection for t-channel measurements



7 TeV selection:

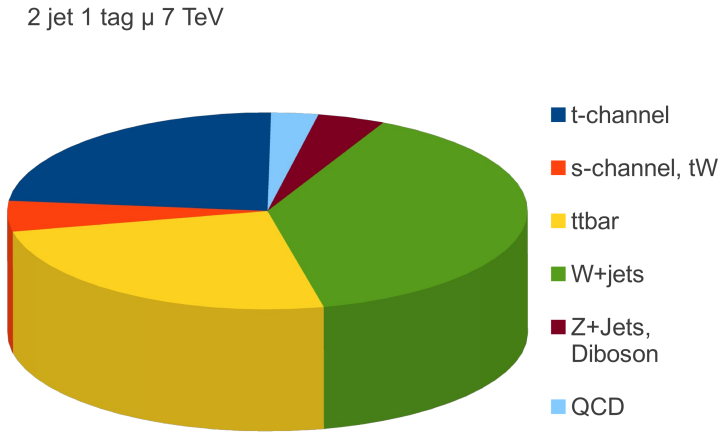
- Single lepton triggers (e+b-jet @ 7 TeV)
- 1 isolated charged lepton
- Veto events with other softer charged leptons
- $M_T(W)$ (E_T^{miss}) cut to suppress QCD multijet production
- 2 jets, can be forward $|\eta| < 4.5$
- 1 jet with b-tag (track counting algorithm, 0.1% mistag rate)

8 TeV selection:

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

Background processes

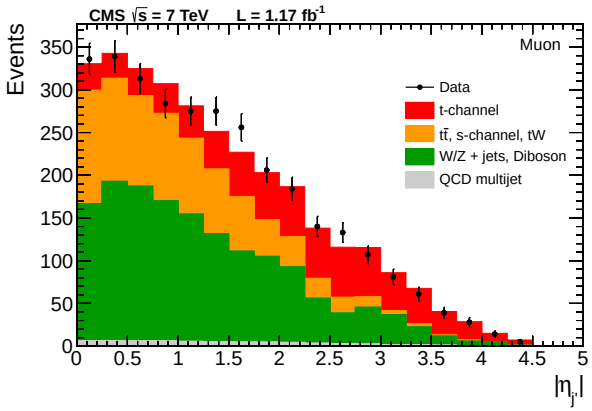
- Contribution from background processes after selection:
  - Single Top: *s*-channel, *tW*
  - Top quark pair production $t\bar{t}$
  - *W*+jets
  - *Z*+jets
  - Diboson (*WW*, *WZ*, *ZZ*)
  - QCD multijet

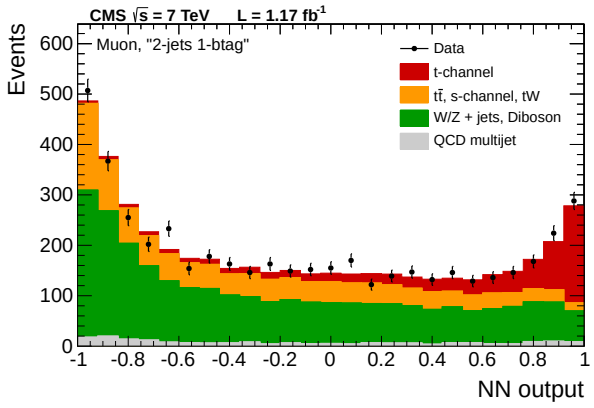


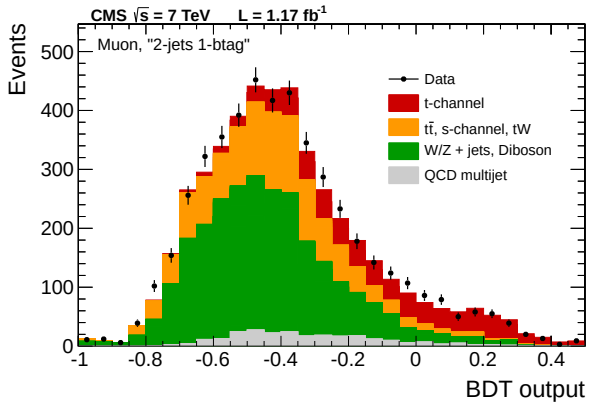
- Main backgrounds: *W*+jets and top quark pair production $t\bar{t}$
- QCD multijet background difficult to model and MC statistics very small after cuts
  $\rightarrow$ data driven estimation with fit to $M_T(W)$ (MET) in orthogonal data set

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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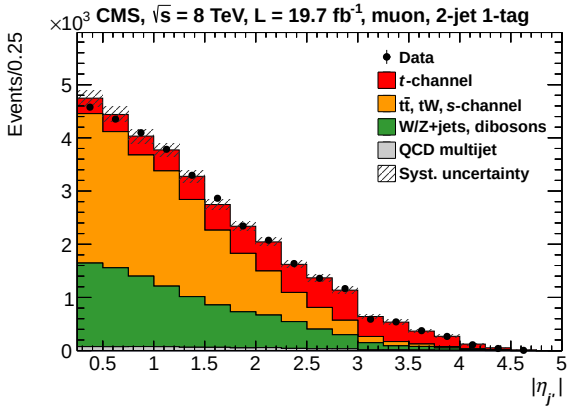
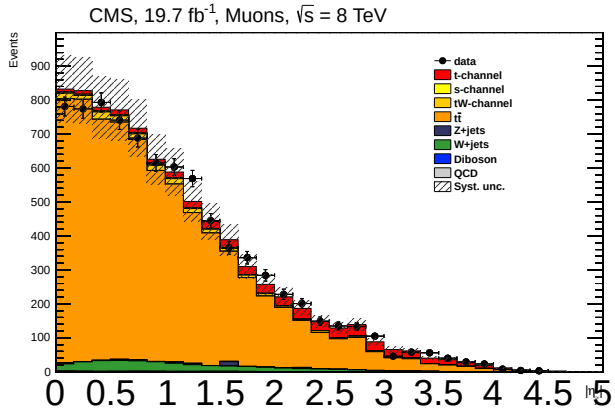
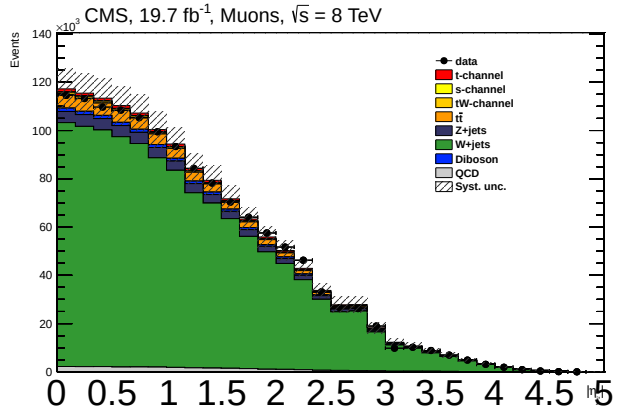
Cross section measurement (19.7/fb at 8 TeV)

- 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

$$\sigma_{\text{t-ch.}} = 83.6 \pm 2.3(\text{stat.}) \pm 7.4(\text{syst.})\ \text{pb}$$

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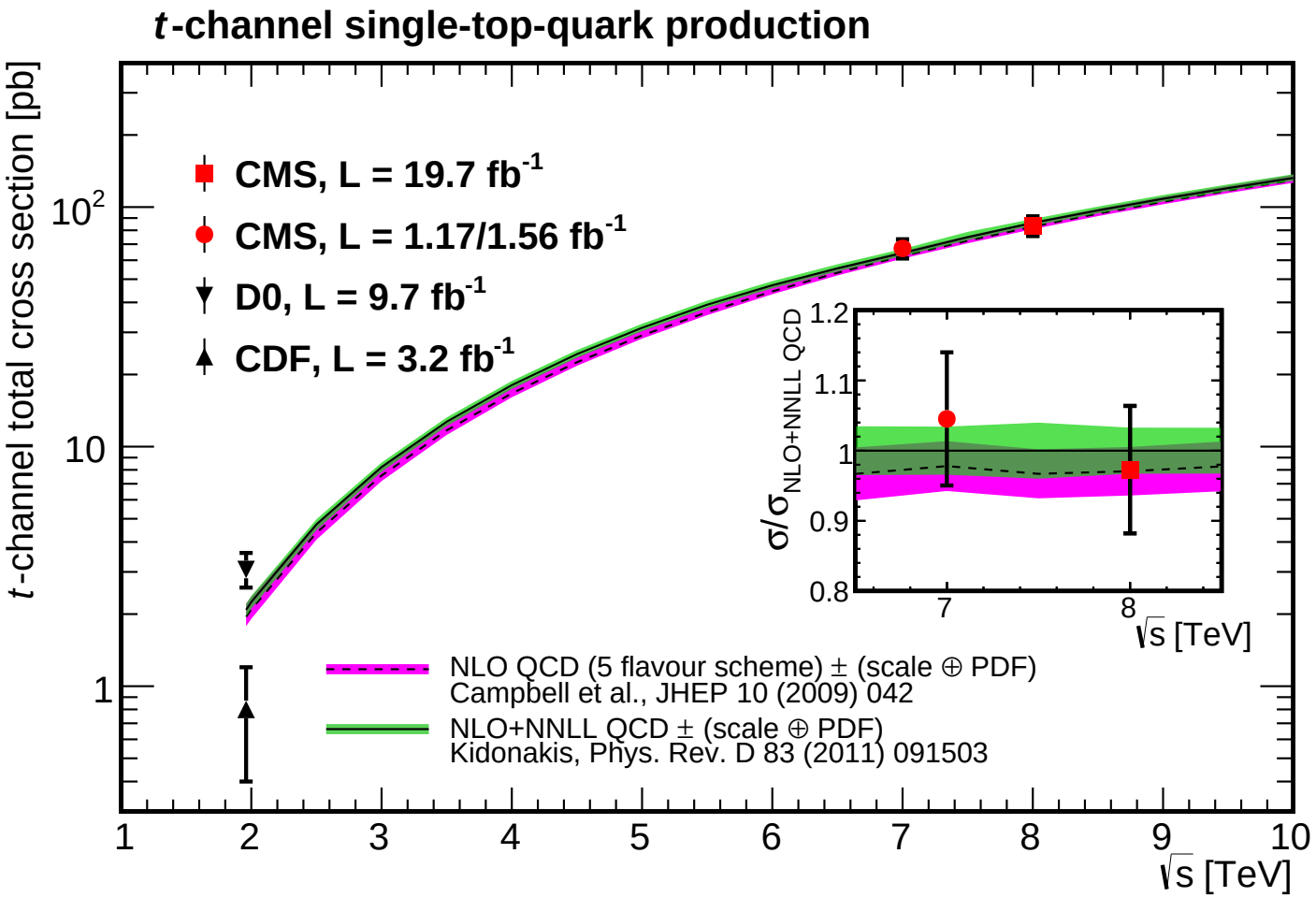
Comparison with theory



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

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

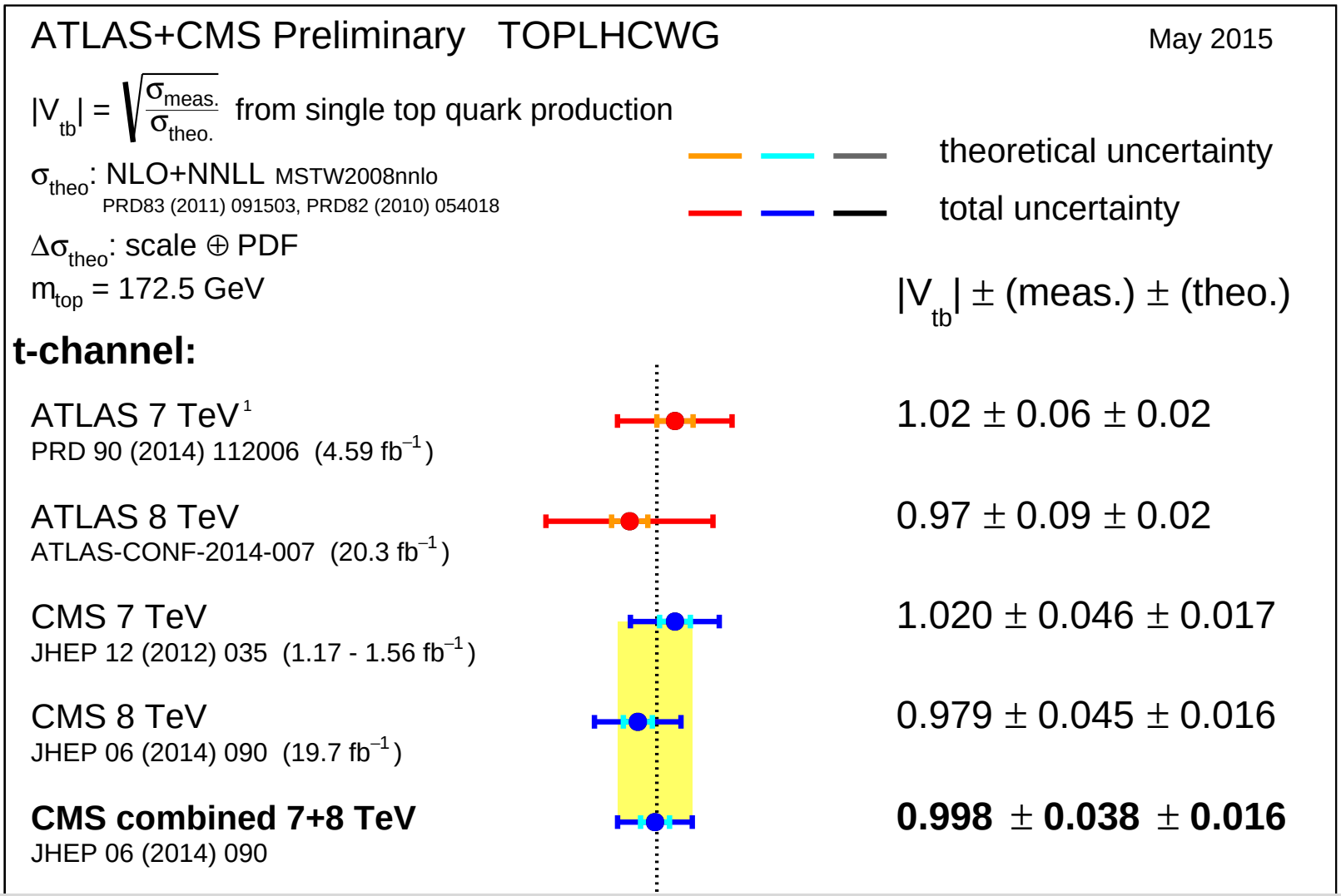
$$|f_{L_V} V_{\text{tb}}| = 1.020 \pm 0.046\ (\text{exp.}) \pm 0.017\ (\text{theor.}) \quad (7\ \text{TeV})$$
$$|f_{L_V} V_{\text{tb}}| = 0.979 \pm 0.045\ (\text{exp.}) \pm 0.016\ (\text{theor.}) \quad (8\ \text{TeV})$$
$$|f_{L_V} V_{\text{tb}}| = 0.998 \pm 0.038\ (\text{exp.}) \pm 0.016\ (\text{theor.}) \quad (7{+}8\ \text{TeV})$$

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

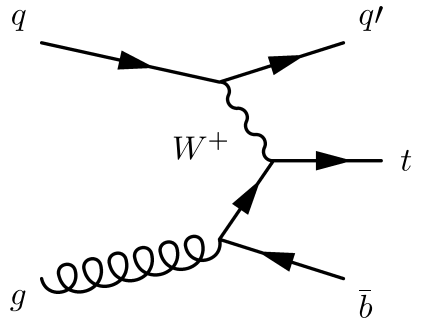
- Constraining $|V_{tb}|$ to the interval $[0, 1]$ and setting $f_{L_V} = 1$ yields:

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

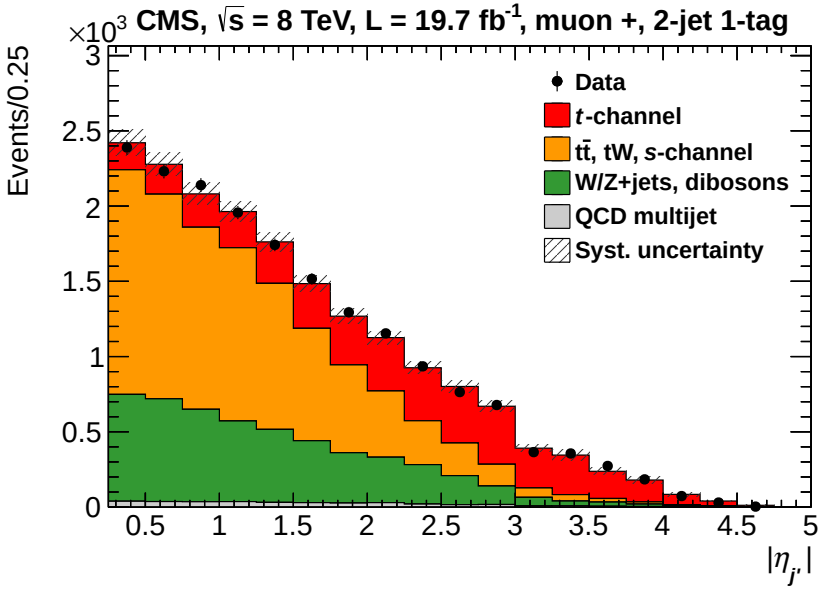
Overview of $|V_{tb}|$ measurements

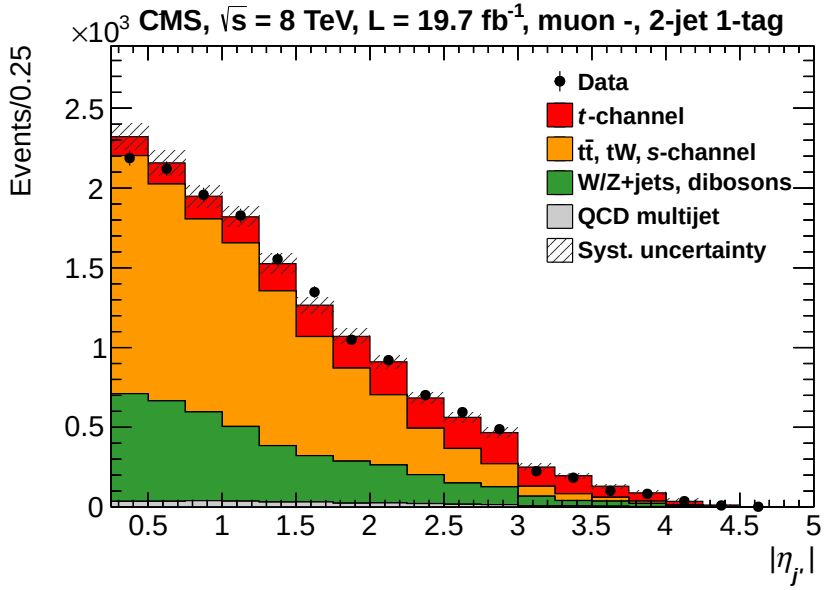


Charge ratio $R_t = \frac{\sigma_t}{\sigma_{\bar{t}}}$



- 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

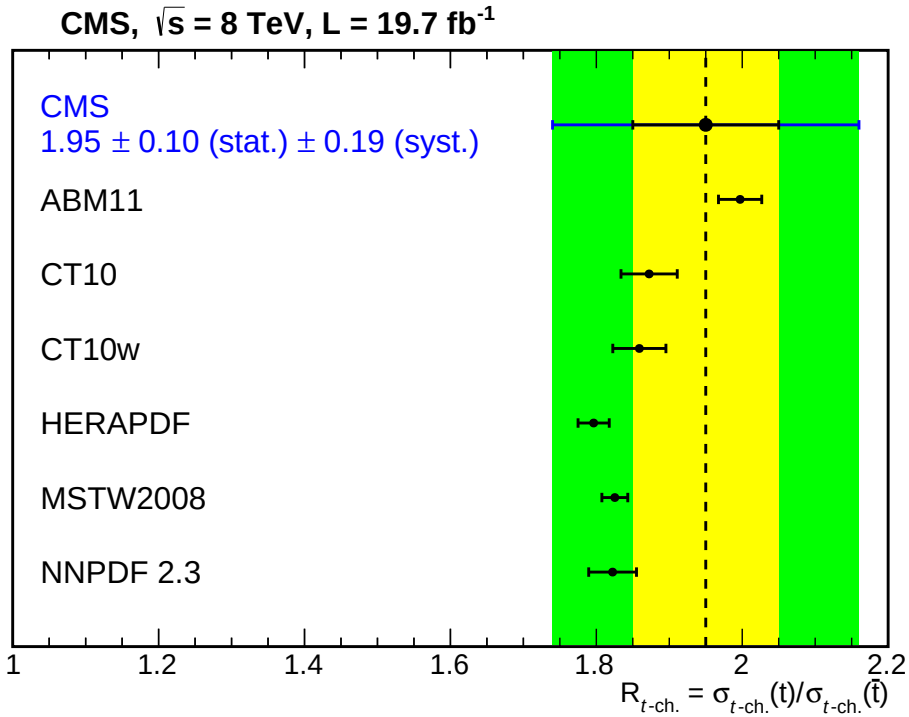




- Template fit to $|\eta_{j'}|$ separately for positive/negative charged leptons
- Systematic uncertainties estimated with pseudo experiments
  - Luminosity uncertainty cancels, JES/JER/MET uncertainty reduced due to ratio

Charge ratio results (19.7/fb 8 TeV)

$$\sigma_{t\text{-ch.,top}} = 53.8 \pm 1.5(\text{stat.}) \pm 4.4(\text{syst.})\,\text{pb.}$$
$$\sigma_{t\text{-ch.,anti-top}} = 27.6 \pm 1.3(\text{stat.}) \pm 3.7(\text{syst.})\,\text{pb.}$$
$$R_{t\text{-ch.}} = 1.95 \pm 0.10(\text{stat.}) \pm 0.19(\text{syst.})$$



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

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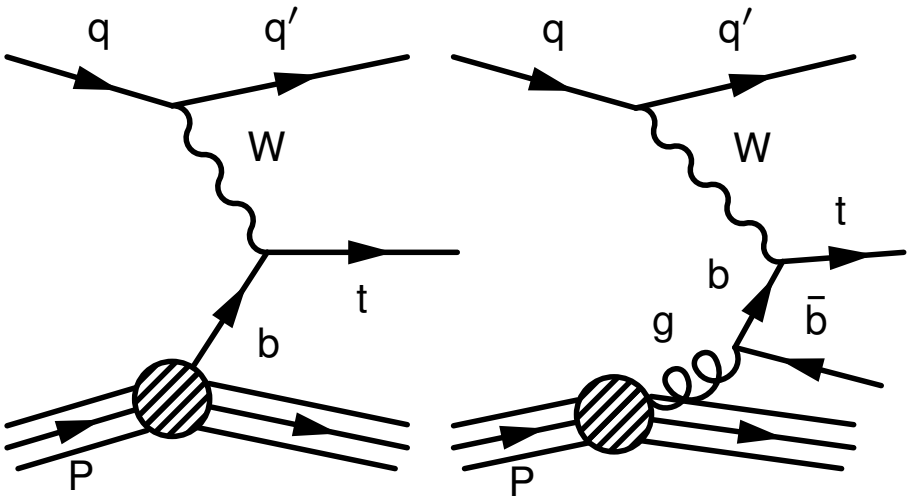
Motivation for differential cross section measurement

t-channel modeling

- Difficult to correctly model second b quark from gluon splitting
- NLO precision needed for correct kinematics

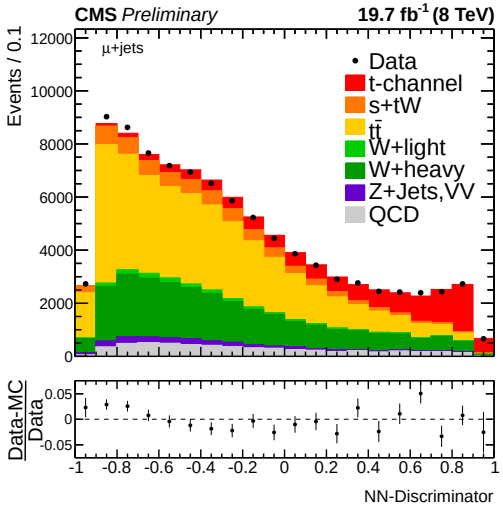


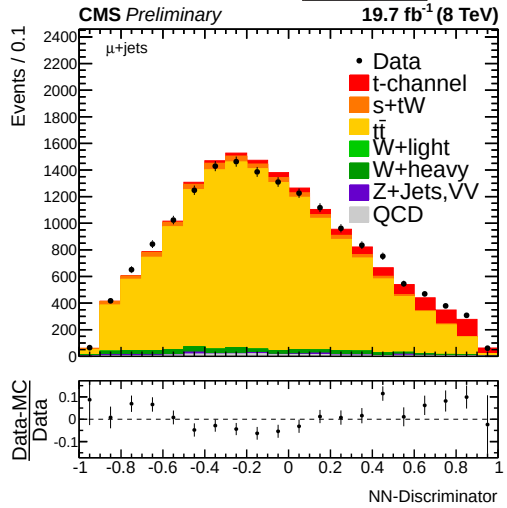
5FS 4FS

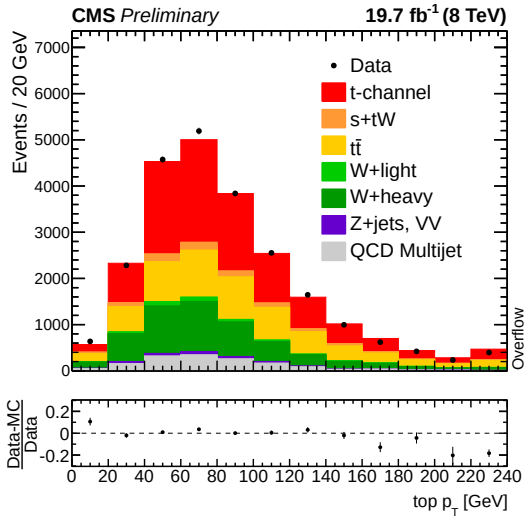
- 5FS:
  Born $2 \rightarrow 2$, second b only through NLO
- 4FS:
  Born $2 \rightarrow 3$, massive b quark in final state

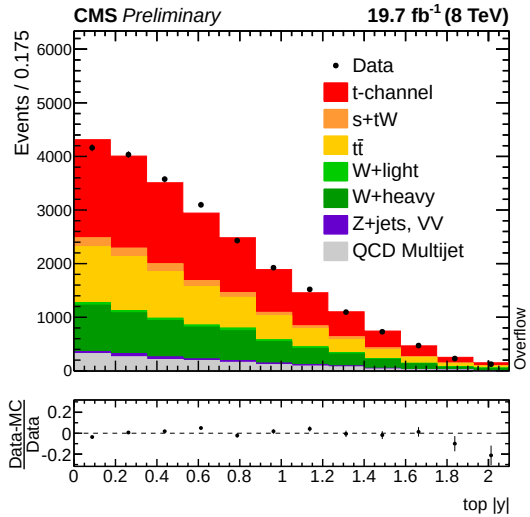
Differential cross section measurement at 8 TeV

- Train neural network uncorrelated to top p_T and $|y|$
- Validate and also fit in ttbar control region
- Cut on NN output for signal-enriched sample
- Subtract backgrounds, data-driven QCD estimation in sideband



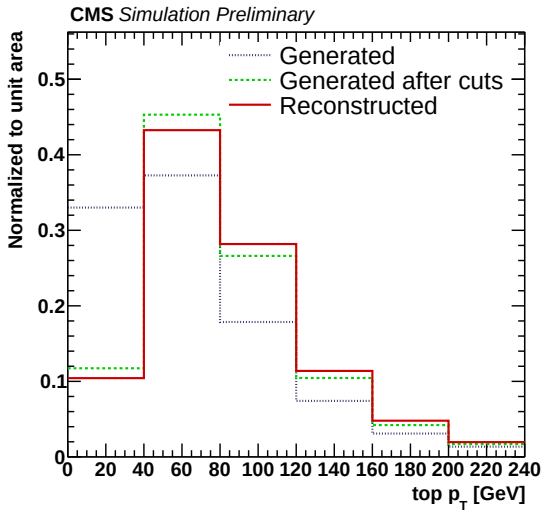


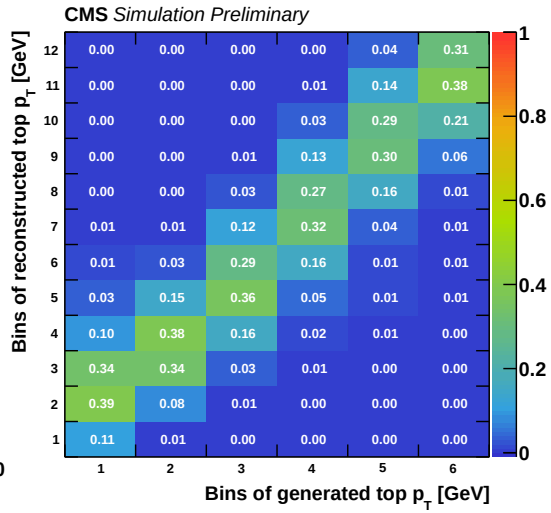


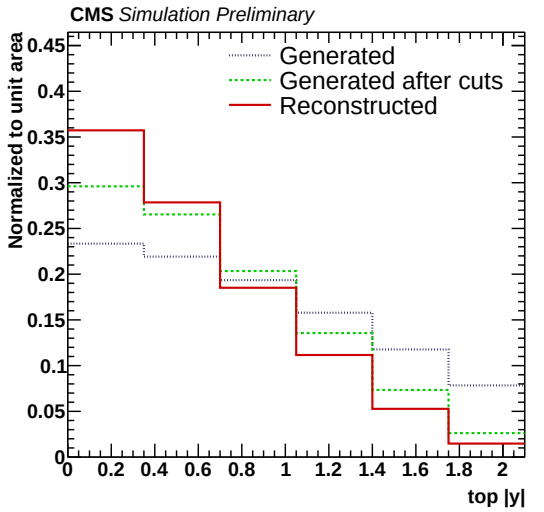


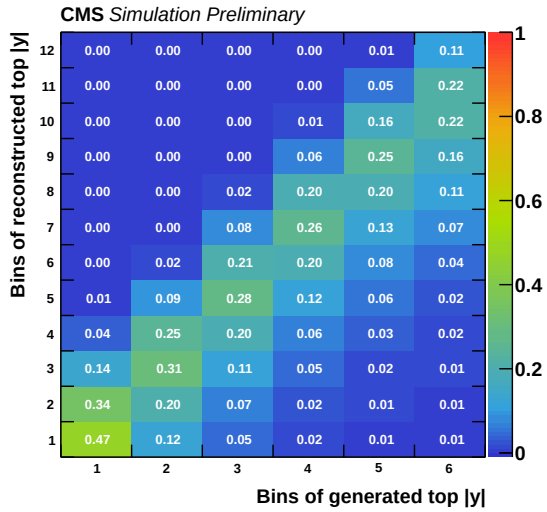
Unfolding

- Differences between generated and reconstructed distributions
- Correct detector and reconstruction effects with unfolding technique

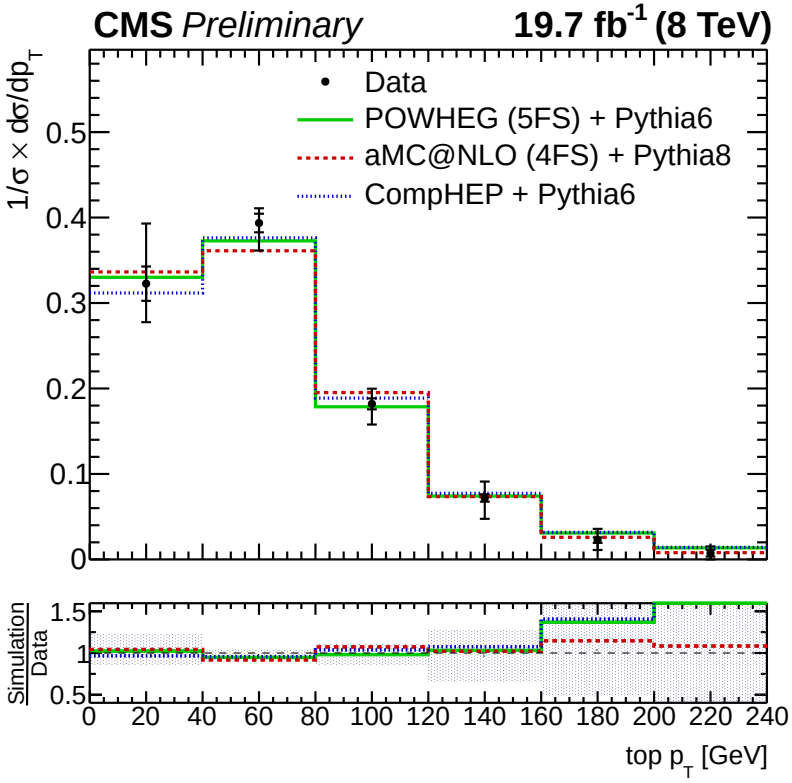


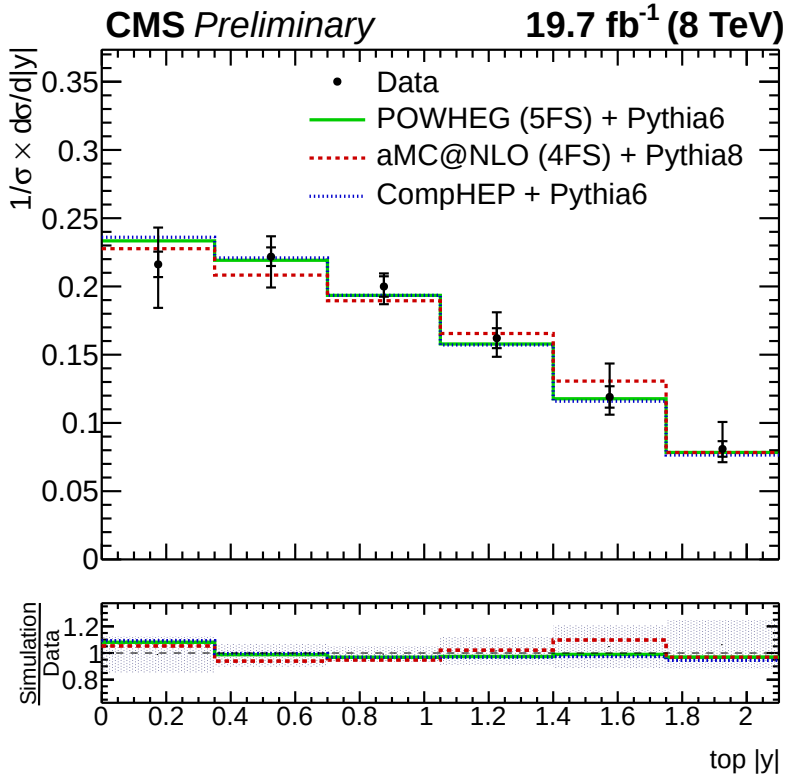






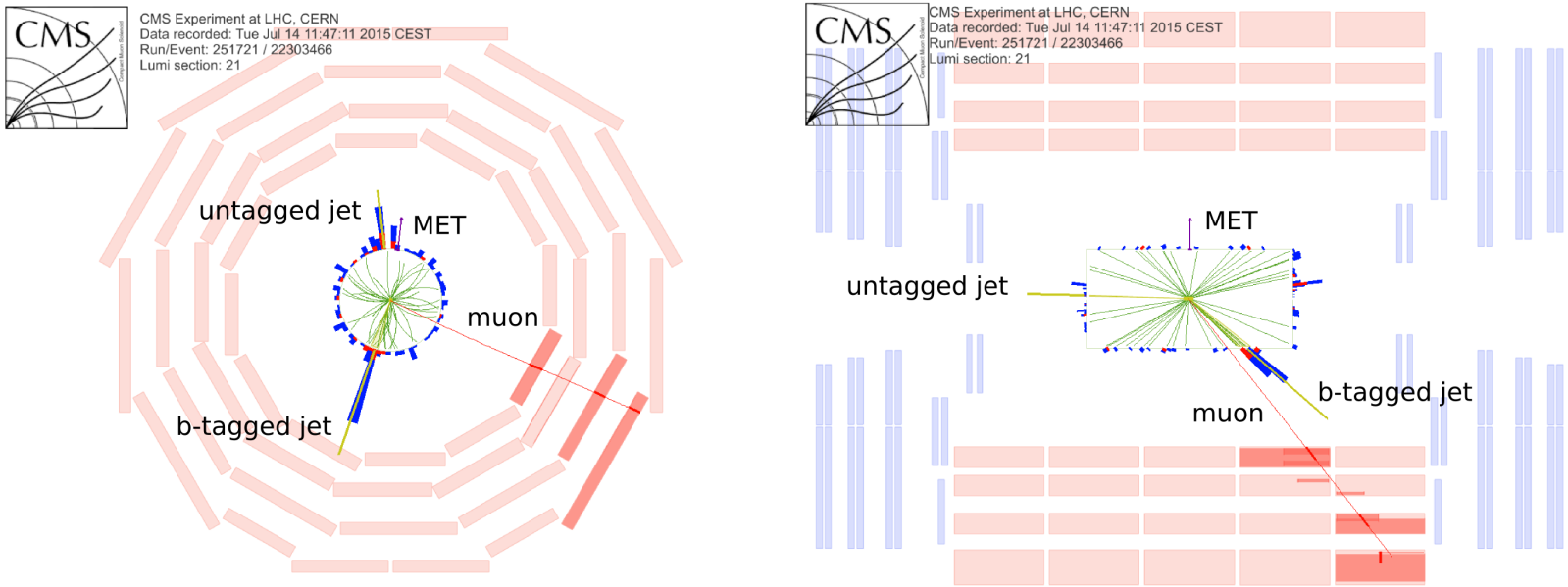
Differential cross section results





- Unfolded distributions of top p_T and $|y|$ agree well with different MC predictions
- More data in top p_T tail will allow to differentiate better
- Preliminary results published in **CMS PAS TOP-14-004**

Outlook on 13 TeV data



Single top quark *t*-channel candidate event with MET of 27 GeV, two jets, whereas one is b-tagged and the other very forward with $\eta = -4.3$. The reconstructed top quark mass is 177 GeV.

CMS DP-2015/019

Conclusions and outlook

Conclusions:

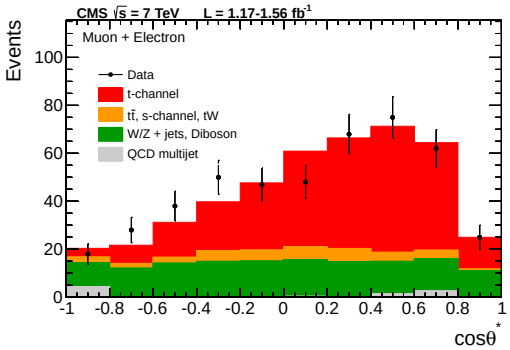
- All single top quark measurements consistent with SM
- Precise direct measurement and limit on $|V_{tb}|$
- Charge ratio with higher precision can be used to constrain u(d) quark PDF

Outlook:

- Single top quark measurements are starting to enter precision regime
- More data allows higher precision and interesting property measurements
- 13 TeV results in the pipeline for TOP2015

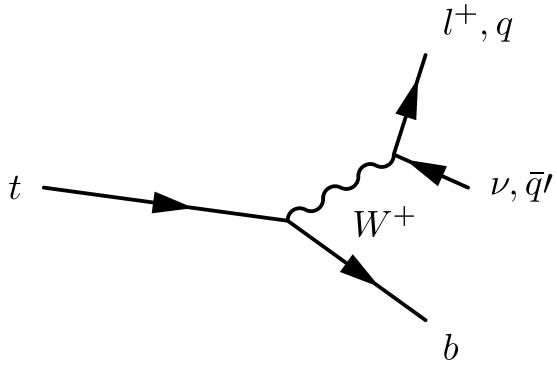
Backup

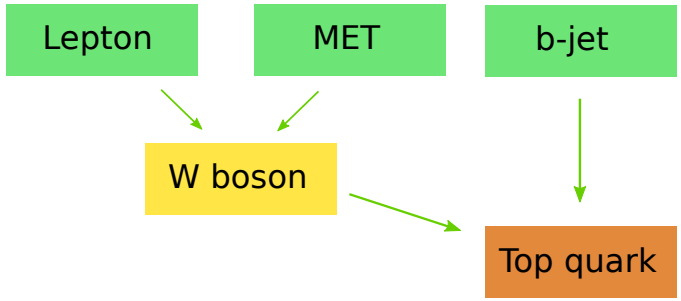
Top quark decay and reconstruction



- 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

Process	Muon		Electron	
	SR	SB	SR	SB
ttbar	17214 ± 49	8238 ± 35	11162 ± 38	8036 ± 33
WZjets	10760 ± 104	9442 ± 97	4821 ± 69	6512 ± 81
QCD	765 ± 5	271 ± 4	1050 ± 6	1350 ± 6
Diboson	179 ± 4	161 ± 4	95 ± 3	134 ± 3
tW	1914 ± 28	969 ± 20	1060 ± 28	858 ± 18
s-channel	343 ± 1	118 ± 1	180 ± 1	96 ± 1
t-channel	6792 ± 25	944 ± 9	3616 ± 17	753 ± 8
Total expected	37967 ± 121	20143 ± 106	21984 ± 85	17740 ± 90
Data	38202	20237	22597	17700

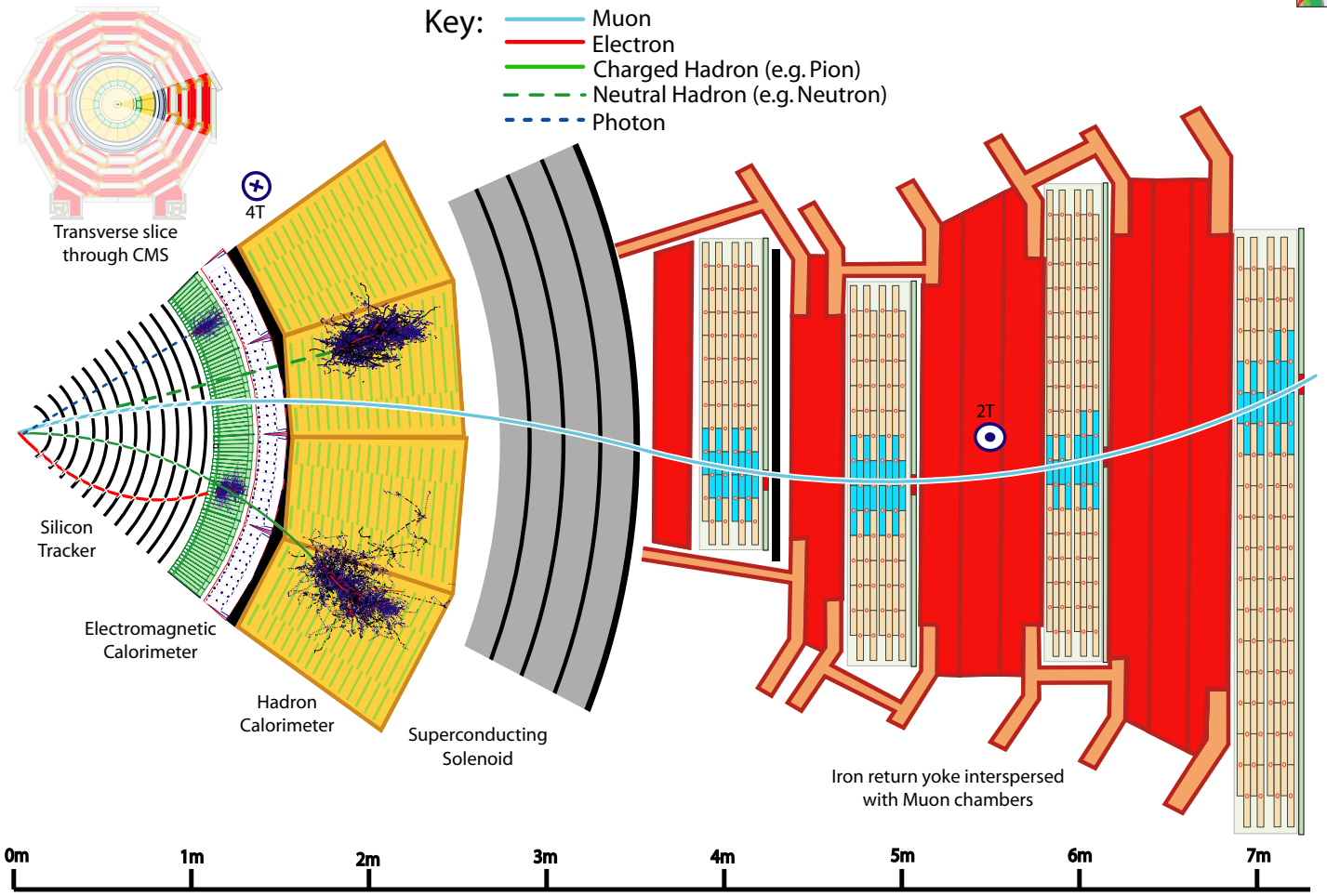
8 TeV t-channel cross section - Systematic uncertainties

Uncertainty source	$\sigma_{t-ch.}$ (%)
Statistical uncertainty	$\pm$ 2.7
JES, JER, MET, and pileup	$\pm$ 4.3
b-tagging and mis-tag	$\pm$ 2.5
Lepton reconstruction/trig.	$\pm$ 0.6
QCD estimation	$\pm$ 2.3
Wjets, ttbar estimation	$\pm$ 2.2
Other backgrounds ratio	$\pm$ 0.3
Signal modeling	$\pm$ 5.7
PDF uncertainty	$\pm$ 1.9
Simulation sample size	$\pm$ 0.7
Luminosity	$\pm$ 2.6
Total systematic	$\pm$ 8.9
Total uncertainty	$\pm$ 9.3
Measured cross section	83.6 $\pm$ 7.8pb

Charge ratio systematic uncertainties

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

CMS detector



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