# SM single top experimental overview at ATLAS and CMS.

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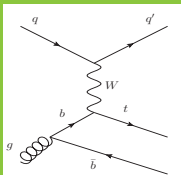
**top LHC-France**
**Lyon 7-8/04/2014**

# Top quark electroweak production at LHC

**t-channel**
$\sim 1/3\ \sigma_{t\bar{t}}$



- Observed at Tevatron (2009), then at LHC (2011).
- **Cross-section** and $|V_{tb}|$ measurements:
  - 7 TeV: Phys. Lett B 717 (2012) 330 (ATLAS); JHEP 12 (2012) 035 (CMS)
  - 8 TeV: ATLAS-CONF-2014-007; arXiv:1403.7366 (CMS-TOP-12-038)
  - LHC combination at 8 TeV: CMS-PAS-TOP-12-002 ; ATLAS-CONF-2013-098
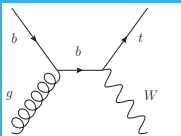    → **Contribution from LPC Clermont-Fd**
- **Charge ratio**: ATLAS-CONF-2012-056 @ 7 TeV; CMS-PAS-TOP-12-038 @ 8 TeV
- **Top polarisation**: CMS-PAS-TOP-13-001 @ 8 TeV; ATLAS - no public results yet
  → **Contribution from LPSC Grenoble**

**Wt channel**
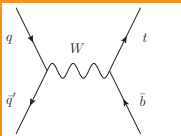$\sim 20\%\ \sigma_{singletop}$



- First evidence at LHC (2011).
- **Cross-section** and $|V_{tb}|$ measurements:
  → **Contribution from LPSC Grenoble**
  - 7 TeV: Phys. Lett B 716 (2012) 142 (ATLAS); Phys. Rev. Lett 110 (2013) 022003 (CMS).
  - 8 TeV: ATLAS-CONF-2013-100; arxiv:1401.2942 (CMS-TOP-12-040)

**s-channel**
$\sim \frac{1}{15}\ \sigma_{t-channel}$



- Challenge → smallest cross-section.
- Observation at Tevatron in 2014.
- Cross-section and $V_{tb}$ limits at LHC:
  - 7 TeV: ATLAS-CONF-2011-118;
  - 8 TeV: CMS-PAS-TOP-13-009; ATLAS - no public results yet.
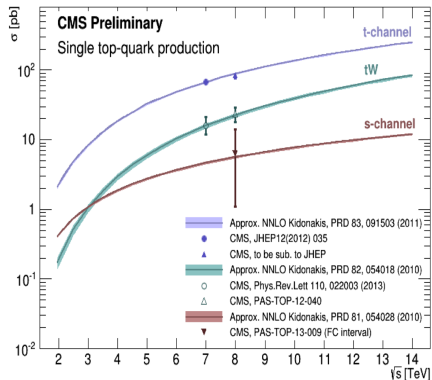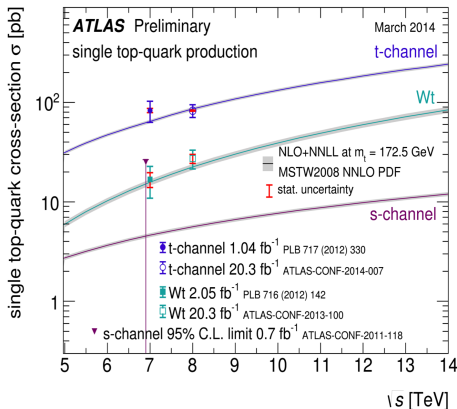    → **Contribution from LPSC Grenoble**

Approx. NNLO →

| $\sqrt{s}$ | $\sigma$ (t-channel) | $\sigma$ (Wt) | $\sigma$ (s-channel) |
|---|---|---|---|
| 7 TeV | $64.6 \pm 2.4$ pb | $15.7 \pm 1.1$ pb | $4.6 \pm 0.2$ pb |
| 8 TeV | $87.8 \pm 3.4$ pb | $22.4 \pm 1.5$ pb | $5.6 \pm 0.2$ pb |

# Single top quark production summary

Summary of measurements of the single top-quark cross-section compared to the corresponding theoretical expectation:
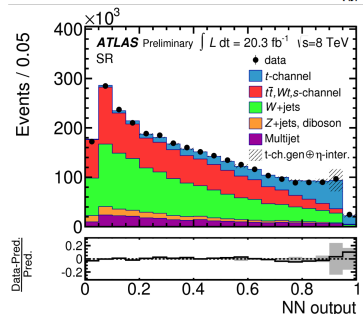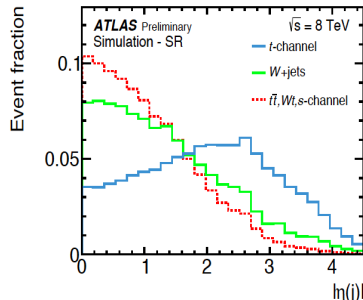


- All measurements are in agreement with approx. NNLO calculations
- Present here the LATEST cross-section results at 8 $\mathrm{TeV}$

# *t*-channel

# ATLAS; *t*-channel @ 8 TeV: analysis strategy

- Analysed data corresponding to 20.3 fb$^{-1}$ (ATLAS-CONF-2014-007)

- **Selection**:
  - Require exactly one isolated lepton ($e/\mu$) with $p_T > 25$ GeV
  - Two jets with $|\eta| < 4.5$ and $p_T > 30$ GeV and exactly one *b*-tagged jet
  - $E_T^{miss} > 30$ GeV, $m_T(W) > 50$ GeV

- Main **backgrounds**:
  - *W*+jets, top pairs derived using theoretical cross-sections.
  - multijet determined from data with a template fit to $E_T^{miss}$.

- **Analysis**:
  - For signal/background discrimination combine several kinematic variables into one discriminant by using a Neural Network (NN) technique.
  - Three kinematic regions are defined:
    - Signal region (SR) with 1 *b*-tag jet.
    - W-boson control region (W CR) with 1 *b*-tag jet with a less stringent btagging requirement.
    - $t\bar{t}$ control region ($t\bar{t}$ CR) with 2 *b*-tag jets.
  - 14 highest-ranking variables are chosen in the signal & control regions.

▶ The fiducial *t*-channel cross-section within detector acceptance is measured from the maximum likelihood fit to the NN output distributions:

$$\sigma_{fid} = 3.37 \pm 0.05 \text{ (stat.)} \pm 0.47 \text{ (syst.)} \pm 0.09 \text{ (lumi) pb (17\% syst.)}$$

▶ The *t*-channel cross-section is determined by extrapolation to the entire phase space using several generator assumptions :

$$\sigma = \frac{1}{\epsilon_{fid}} \cdot \sigma_{fid}, \text{ with } \epsilon_{fid} \text{ is the selection efficiency of the particle-level selection.}$$

$$\sigma_{t-channel} = 82.6 \pm 1.2 \text{ (stat.)} \pm 11.4 \text{ (syst.)} \pm 3.1 \text{ (PDF)} \pm 2.3 \text{ (lumi.) pb}$$
**(20% syst.)**
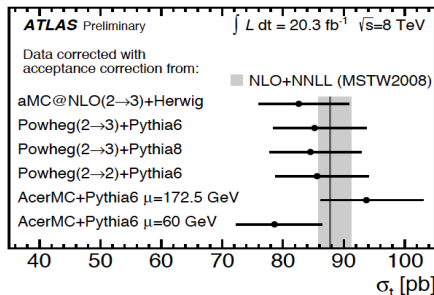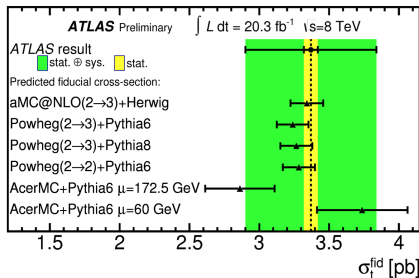


▶ Main systematics: Jet energy scale (7.9%) and *t*-channel generator (7.9%).

# CMS; t-channel @ 8 TeV: analysis strategy

- Analysed data corresponding to 19.7 $fb^{-1}$ (arXiv:1403.7366v1)

- **Selection**:
  - Require exactly one isolated lepton, $e/\mu$, with $p_T > 30$ GeV/$p_T > 26$ GeV
  - Jets with $|\eta| < 4.5$ and $E_T > 40$ GeV and exactly one $b$-tagged jet.

- Main **backgrounds**:
  - Mulijet, $W$+jets & top pairs.

- **Analysis**:
  - Used the $|\eta_{j'}|$ (pseudorapidity of the outgoing jet) to isolated the signal from background.
    - Signal events concentrated in forward regions of the $|\eta_{j'}|$ spectrum.
  - A top-quark candidate is reconstructed in several categories:
    - Enriched signal region (SR) with 2-jet, 1 $b$-tag jet.
    - 2-jet, 0 $b$-tag control region to estimate $W$+jets.
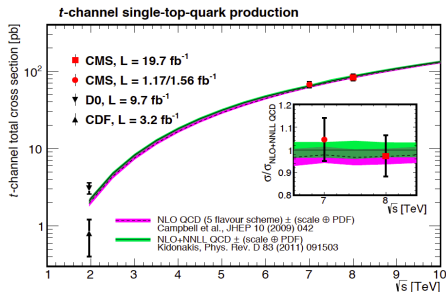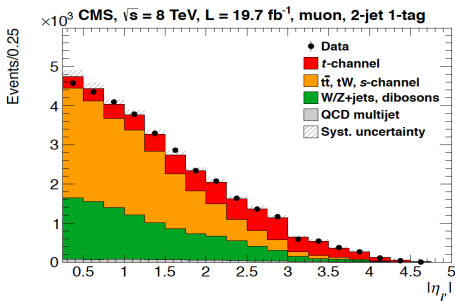    - 3-jet, 1 $b$-tag & 3-jet, 2 $b$-tag control regions to estimate $t\bar{t}$.
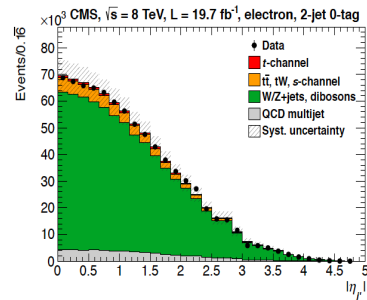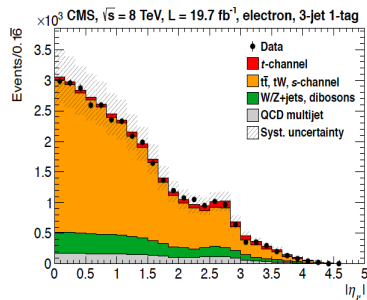
# CMS; t-channel @ 8 TeV: results

▶ A maximum-likelihood fit to the $|\eta_{j'}|$ is performed to extract the *t*-channel cross-section:

$$\sigma_{t-channel} = 83.6 \pm 2.3 \,(\text{stat.}) \pm 7.4 \,(\text{syst.}) \text{ pb (9\% syst.)}$$

▶ Ratio of *t*-channel production cross-sections at 8 & 7 TeV (JHEP 12 (2012) 035):

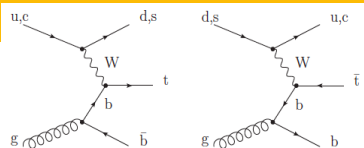$$R_{8/7} = 1.24 \pm 0.08 \,(\text{stat.}) \pm 0.12 \,(\text{syst.}) \text{ pb}$$



▶ Main systematics: *t*-channel generator ($\sim 6\%$) and Jet energy scale ($\sim 4\%$).

# CMS & ATLAS; Charge ratio

- Inside proton: 2 × $u$-quark density than $d$-quark.
- Measurements of $\sigma_t(t)$ & $\sigma_t(\bar{t})$ are sensitive to the PDFs of the $u$-quark & $d$-quark.



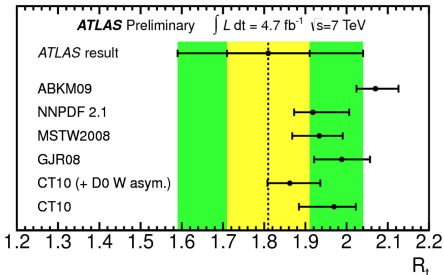## ATLAS at 7 TeV (ATLAS-CONF-2012-056)

- Binned max. likelihood fit to NN distribution in 2- & 3-jet bins.

$\sigma_t(t) = 53.2 \pm 1.7$ (stat.) $\pm 10.6$ (syst.) pb
$\sigma_t(t) = 29.5 \pm 1.5$ (stat.) $\pm 7.3$ (syst.) pb
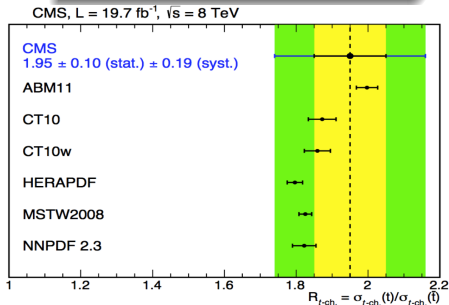
$R_t = 1.81 \pm 0.10$ (stat.)$^{+0.21}_{-0.20}$ (syst.)



## CMS at 8 TeV (arXiv:1403.7366v1)

- Binned max. likelihood fit to $|\eta_{j'}|$ distributions in 2-jet 1-tag bins.

$\sigma_t(t) = 53.8 \pm 1.5$ (stat.) $\pm 4.4$ (syst.) pb
$\sigma_t(t) = 27.6 \pm 1.3$ (stat.) $\pm 3.7$ (syst.) pb

$R_t = 1.95 \pm 0.10$ (stat.) $\pm 0.19$ (syst.)

# CMS; W boson/ top quark polarisation @ 8 TeV

- Analysed data corresponding to 20 fb$^{-1}$ (CMS-PAS-TOP-13-001)
- The $t$-channel data sample is large enough to study the differential cross-section distributions.

- **Motivation:**
  - To probe anomalous couplings in Wtb vertex.
  - The SM coupling $V_{tb} \sim 1$.

- **Analysis**:
  - Study single-top polarisation in the $t$-channel by the slope of the $cos\theta^*$.
    - $\theta^*$: angle between the lepton in $W$ rest frame and the untagged jet in the reconstructed top rest frame.
  - To remove detector effects $\rightarrow$ regularised unfolding of $cos\theta^*$ distribution, after selection based on BDT discriminant.

- **Results:**

$$A_l \equiv \frac{1}{2} \cdot P_t \cdot \alpha_l = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N\downarrow}$$

  - Top spin asymmetry:
  - $A_l = 0.41 \pm 0.06$ (stat.) $\pm 0.16$ (syst.).
  - Top polarization: $P_l = 0.82 \pm 0.12$ (stat.) $\pm 0.32$ (syst.)
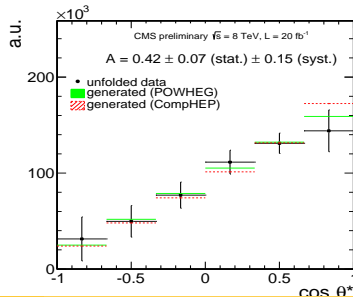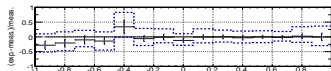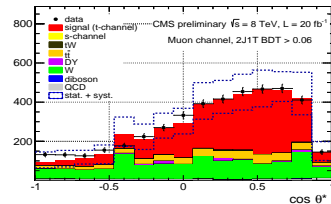
# *Wt* channel

# ATLAS; *Wt* channel @ 8 TeV: analysis strategy

- Analysed data corresponding to 20.3 fb$^{-1}$ (ATLAS-CONF-2012-100)

- **Selection**:
  - Require two opposite sign leptons (only $e\mu$) with $p_T > 25$ GeV
  - One or two central jets with $p_T > 30$ GeV and at least one $b$-tagged jet

- The main **background** is the top pair production simulated with POWHEG

- **Analysis**:
  - To separate the *Wt* signal from the large $t\bar{t}$ background a multivariate method called BDT is used.
  - 19 highest-ranking variables are chosen in the signal region (exactly 1 $b$-tag) and 20 for the control region (at least 1 $b$-tag)
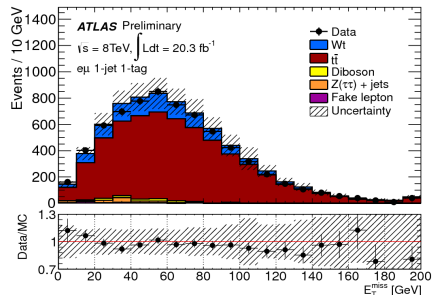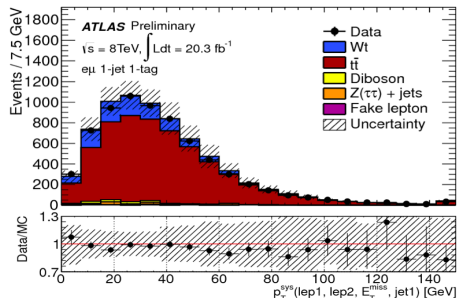
**1-jet signal region; $S/B \sim 0.16$; 80% top-pair**
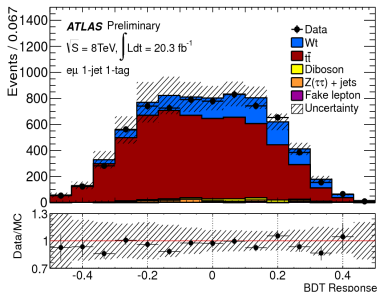


**2-jet control region; $S/B \sim 0.05$; 90% top-pair**
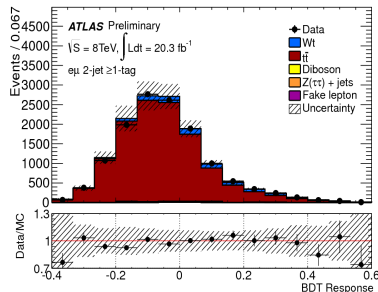


- The *Wt* cross-section is measured from a maximum likelihood fit to BDT classifier.
  - The 2-jets control region constrains the $t\bar{t}$ background uncertainties
  - The impact of systematic uncertainties is evaluated using ensembles of pseudo-experiments
    - Few systematics are profiled in the fit to data: *b*-tag, JES detector modelling component, $E_T^{miss}$ scale contributions

$\sigma_{Wt} = 27.2 \pm 2.8$ (stat.) $\pm 5.4$ (syst.) pb (19% syst. )
Significance: $4.2\sigma$ ($4.0\sigma$ exp.)

Consistent with SM expectation at 8 TeV:
$\sigma_{Wt} = 22.2 \pm 0.6 \pm 1.4$ pb

- Main **Systematics**: generator & PS modelling ($\sim 8$%), *b*-tagging ($\sim 9$%) and JES

# ATLAS; *Wt* channel @ 8 TeV: BG-subtracted BDT

- Subtracted the background prediction from the data to check the robustness of our analysis.

  - Data points follow the *Wt* signal prediction (blue distribution)
  - *Wt* signal is clearly visible
    - The systematic uncertainties affect the lower part of the 1-jet bin distribution



1-jet signal region
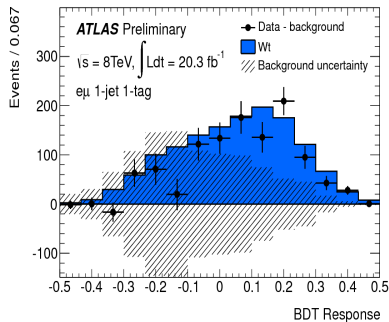
2-jet control region

# CMS; *Wt* channel @ 8 TeV: analysis strategy

- Analysed data corresponding to 12.2 fb$^{-1}$ (arXiv:1401.2942v1)

- **Selection**:
  - Require two opposite sign leptons (*ee*, $\mu\mu$, $e\mu$) with $p_T > 20$ GeV
  - One or two central loose jets with $p_T > 30$ GeV and at least one *b*-tagged jet.
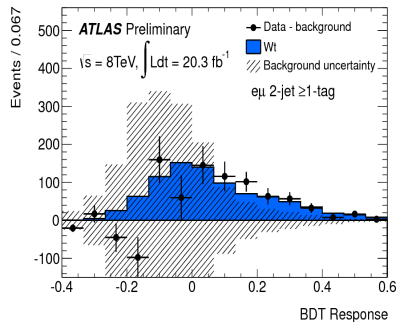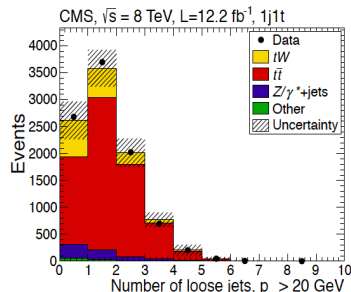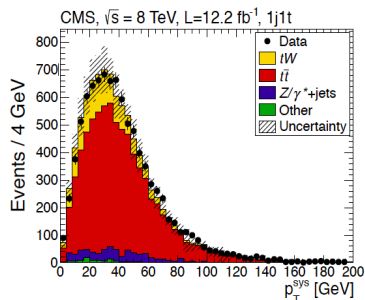  - For *ee* & $\mu\mu$: $m_{ll} < 81$ GeV or $m_{ll} > 101$ GeV and $E_T^{miss} > 50$ GeV.

- The main **background** is the top pair production simulated with MADGRAPH.

- **Analysis**:
  - To separate the *Wt* signal from the large $t\bar{t}$ background BDT is also used.
  - Three regions are defined:
    - Signal region with 1-jet b-tagged (1j1t).
    - Two control regions enriched in $t\bar{t}$: 2 jets with either one (2j1t) or both *b*-tagged (2j2t).
  - 13 highest-ranking variables are chosen as inputs to the training of the BDT.



CMS, $\sqrt{s}$ = 8 TeV, L=12.2 fb$^{-1}$, 1j1t

- Data
- *tW*
- $t\bar{t}$
- $Z/\gamma$*+jets
- Other
- Uncertainty

Events / 4 GeV

$p_T^{sys}$ [GeV]



CMS, $\sqrt{s}$ = 8 TeV, L=12.2 fb$^{-1}$, 1j1t

- Data
- *tW*
- $t\bar{t}$
- $Z/\gamma$*+jets
- Other
- Uncertainty

Events

Number of loose jets, $p_-$ > 20 GeV

# CMS; *Wt* channel @ 8 TeV: cross-section



1-jet signal region;
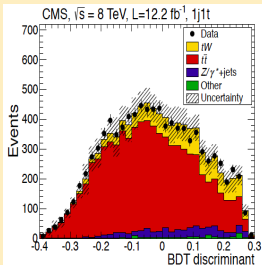
2-jet 1 b-tagged control region;
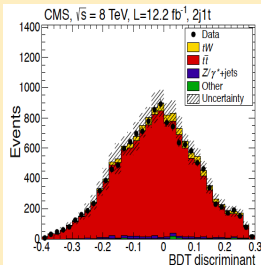
2-jet 2 b-tagged control region;
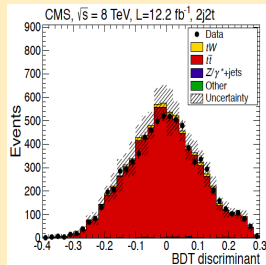
▸ The *Wt* cross-section is measured from a simultaneous binned likelihood fit to the rate and shape of the BDT distributions.

  ▸ The 2-jets control regions constrain the $t\bar{t}$ background uncertainties

$\sigma_{Wt} = 23.4 \pm 5.4$ pb (23% syst. )
Significance: $6.1\sigma$ ($5.4\sigma$ exp.)

OBSERVATION of the *Wt* channel
Consistent with SM expectation at 8 TeV:
$\sigma_{Wt} = 22.2 \pm 0.6 \pm 1.4$ pb

▸ Main **Systematics**:
ME/PS matching ($\sim 14\%$), renormalization/factorization scale ($\sim 12\%$) and JES

# *s*-channel

# CMS; *s*-channel @ 8 TeV

- Analysed data corresponding to 19.3 $\text{fb}^{-1}$ (CMS-PAS-TOP-13-009)
- **Selection**:
  - semileptonic channel.
- The main **background** is the top pair production simulated with MADGRAPH.
- **Analysis**:
  - BDT are used to separate *s*-channel signal from backgrounds.
  - Two regions are defined:
    - Signal region with 2-jet 2 b-tagged.
    - Control region enriched in $t\bar{t}$ with 3-jet 2 b-tagged
  - 10 highest-ranking variables are chosen as inputs to the training of the BDT.
- **Results**

Upper limit: $\sigma_{s-channel} < 11.5 = 2.1 \times \sigma^{SM}$, 95%CL
Assuming SM signal: $\sigma_{s-channel} = 6.2^{8.0}_{-5.1}$ pb (68% FC internal)
Sensitivity still very limited mainly by theory systematics: $0.9\sigma$ exp ($0.7\sigma$ obs).
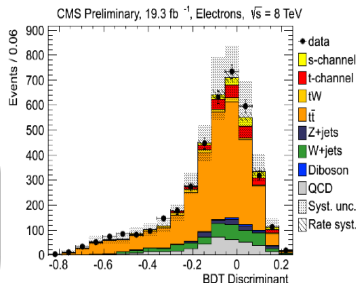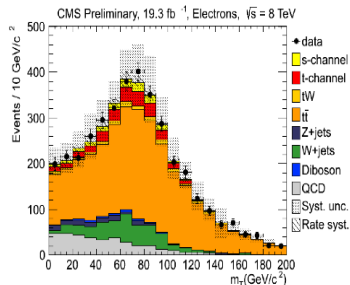
# ATLAS & CMS combination

▶ CMS & ATLAS starting to combine their results within the TOPLHCWG.

  ▶ Understand the different analysis strategies and systematic determination approaches.
  ▶ Blue method is used to extract the final result.
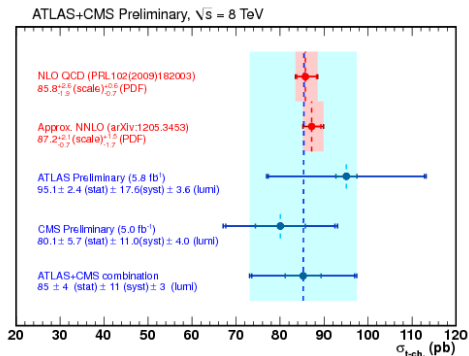  ▶ 1$^{st}$ single top combination: preliminary results at 8 TeV for the *t*-channel cross-section measurements (CMS-PAS-TOP-12-002 ; ATLAS-CONF-2013-098).
  ▶ Work in progress:
    ▸ *t*-channel cross-section measurements at 8 TeV with $\sim$ 20 fb$^{-1}$ luminosity.
    ▸ *Wt* cross-section measurements at 8 TeV.



ATLAS+CMS Preliminary, √s = 8 TeV

NLO QCD (PRL102(2009)182003)
85.8$^{+2.6}_{-1.9}$ (scale)$^{-0.6}_{-0.7}$ (PDF)

Approx. NNLO (arXiv:1205.3453)
87.2$^{+2.1}_{-0.7}$ (scale)$^{+1.5}_{-1.7}$ (PDF)

ATLAS Preliminary (5.8 fb$^1$)
95.1 ± 2.4 (stat) ± 17.6(syst) ± 3.6 (lumi)

CMS Preliminary (5.0 fb$^1$)
80.1 ± 5.7 (stat) ± 11.0(syst) ± 4.0 (lumi)

ATLAS+CMS combination
85 ± 4 (stat) ± 11 (syst) ± 3 (lumi)

$\sigma_{t\text{-ch.}}$ (pb)

# $|V_{tb}|$ measurements: $t$ & $Wt$ channel
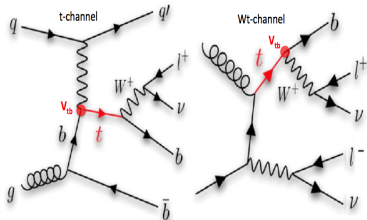
- Direct determination of the quark mixing matrix element $|V_{tb}|$:
  - Opportunity to test the unitarity of the CKM matrix.
  - Deviations from the SM are potentially sensitive to new physics.

- Measure of $|V_{tb}|$ assuming left-handed SM-like W-t-b coupling and $|V_{tb}| >> |V_{ts}|, |V_{td}|$:

$$|V_{tb} \cdot f|^2 = \frac{\sigma^{obs.}}{\sigma^{theory}}$$

with $f = 1$ in SM

- Independent of $N_{quark}$ generations or CKM unitarity



- Summary of the $|V_{tb}|$ measurements in the $t$-channel and $Wt$:

|  | ATLAS | | CMS | |
|---|---|---|---|---|
|  | $t$-channel | $Wt$ channel | $t$-channel | $Wt$ channel |
| 7 TeV | $1.13^{+0.14}_{-0.13}$ (11.9%) | $1.03^{+0.16}_{-0.19}$ (17.0%) | $1.02 \pm 0.05$ (4.8%) | $1.01^{+0.16}_{-0.14}$ (14.8%) |
| 8 TeV | $0.97^{+0.09}_{-0.10}$ (9.8%) | $1.10 \pm 0.12$ (11.2%) | $0.98 \pm 0.05$ (4.9%) | $1.03 \pm 0.13$ (12.3%) |

# Conclusions & Prospects

- We have learned a lot about the single top quark recently:
  - CMS & ATLAS experiments measured the cross-section and $|V_{tb}|$ for $t$-channel and $Wt$ channel with good precision.
  - CMS & ATLAS started to combine their results within the TOPLHCWG

- France labs involved in single top:
  - LPSC is strongly involved in several ATLAS single top analyses:
    - Top polarization using the $t$-channel @ 8 $\mathrm{TeV}$.
    - $Wt$ cross-section measurements @ 8 $\mathrm{TeV}$.
    - $s$-channel @ 8 $\mathrm{TeV}$
  - LPC is involved in the CMS & ATLAS combination.

- Challenges for future single top analyses at LHC:
  - Increase the precision by constraints of main systematics uncertainties: generator modelling, jet energy scale and $b$-tagging efficiency (in situ)
  - Effort on boosted top topologies

# BACKUP

Table 3: Selection cuts of the fiducial volume. Electrons and muons from $\tau$ contributes with about 3% to the acceptance.

| Object | Cut |
|---|---|
| Electrons | $p_T > 25$ GeV and $|\eta| < 2.5$ |
| Muons | $p_T > 25$ GeV and $|\eta| < 2.5$ |
| Jets | $p_T > 30$ GeV and $|\eta| < 4.5$ |
| | $p_T > 35$ GeV, if $2.75 < |\eta| < 3.5$ |
| Lepton ($\ell$), Jets ($j_i$) | $\Delta R(\ell, j_i) > 0.4$ |
| $E_T^{\text{miss}}$ | $E_T^{\text{miss}} > 30$ GeV |
| Transverse $W$-boson mass | $m_T(W) > 50$ GeV |
| Lepton ($\ell$), jet with the highest $p_T$ ($j_1$) | $p_T(\ell) > 40$ GeV $\left(1 - \frac{\pi - |\Delta\phi(j_1, \ell)|}{\pi - 1}\right)$ |