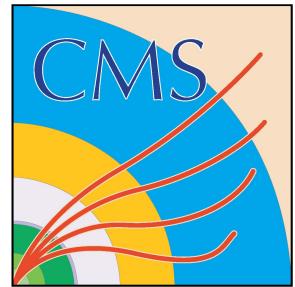


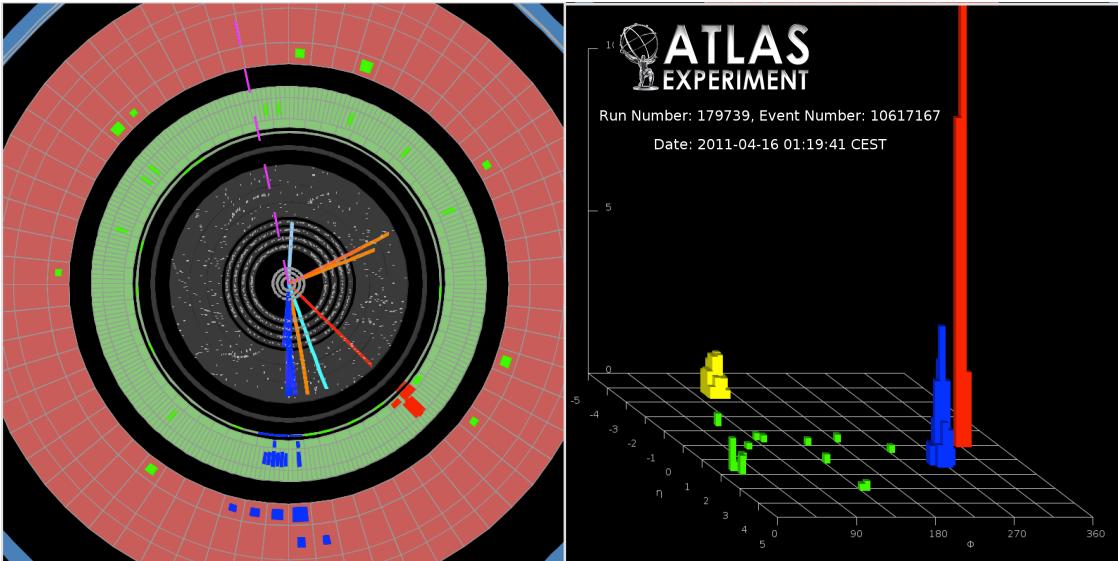


Single Top Results by ATLAS & CMS



Dr. Petra Haefner

Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)



Motivation

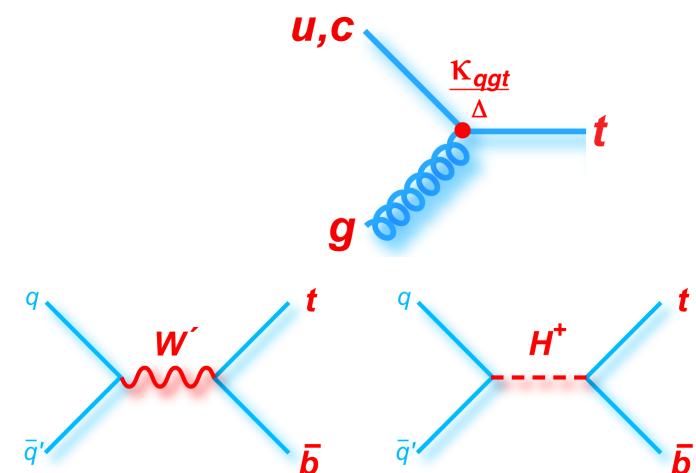
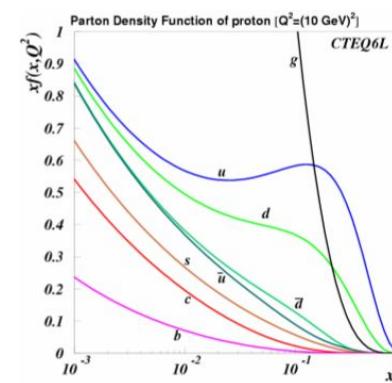
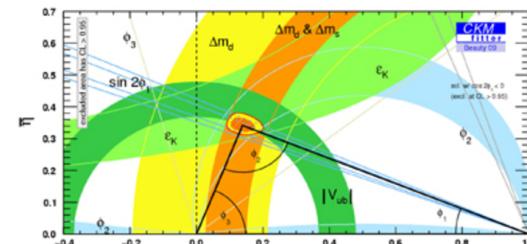
Electroweak production of top quark

- **Measurement of Standard Model (SM)**

- Establish different production channels
- Compare cross sections with SM
- Check unitarity of CKM matrix
- Test b-quark PDF

- **Search for New Phenomena**

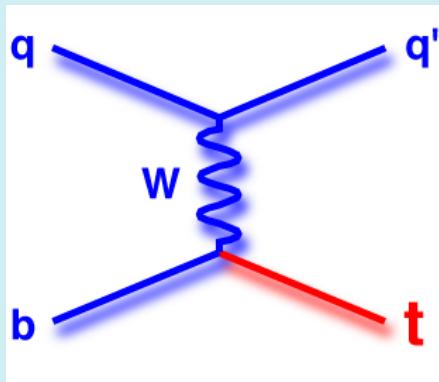
- FCNC
- W'
- H^+
- 4th generation
- ...



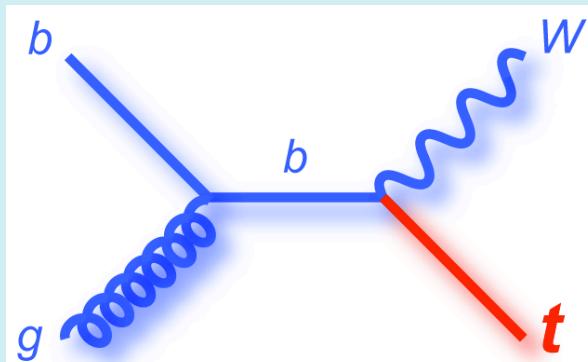
Overview of Channels

N. Kidonakis: arXiv 1103.2792, 1005.4451, 1001.5034

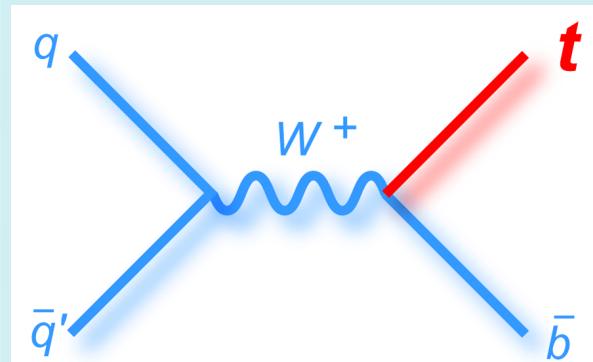
t-Channel



Wt-Channel



s-Channel



LHC cross sections* ($\sqrt{s} = 7 \text{ TeV}$)

$64.2 \pm 2.6 \text{ pb}$

$15.6 \pm 1.3 \text{ pb}$

$4.6 \pm 0.2 \text{ pb}$

Tevatron cross sections* ($\sqrt{s} = 1.96 \text{ TeV}$)

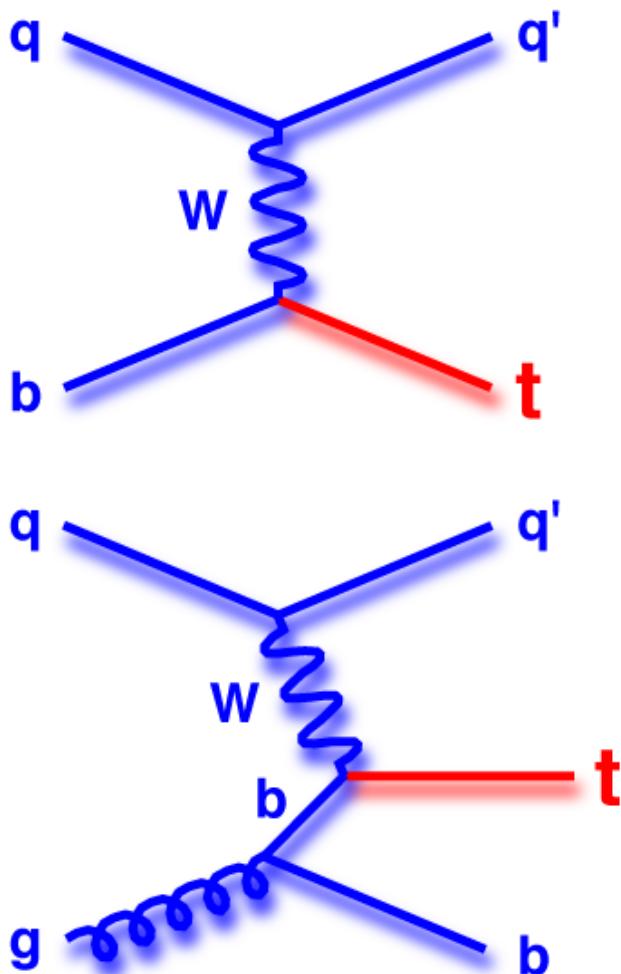
$2.1 \pm 0.1 \text{ pb}$

$0.25 \pm 0.03 \text{ pb}$

$1.05 \pm 0.05 \text{ pb}$

* NLO + NNLL resummation (NNLO approximation), $m_t = 173 \text{ GeV}$

t-Channel



- PRL 107 (2011) 091802
0.036 fb⁻¹



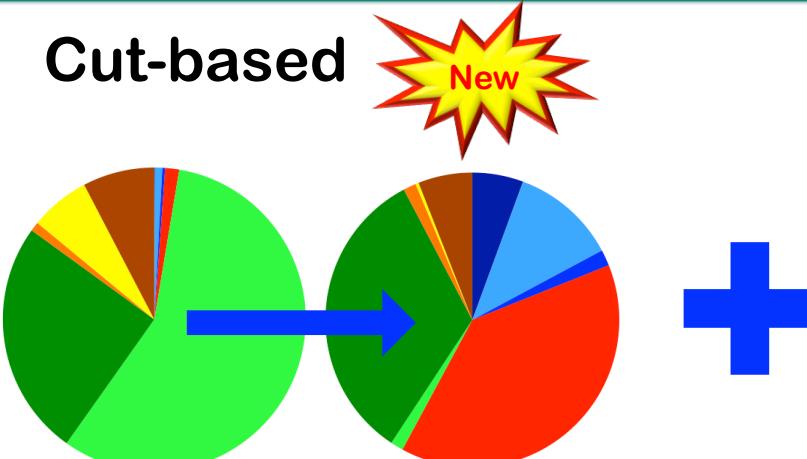
- ATLAS-CONF-2011-101
0.70 fb⁻¹
- ATLAS-CONF-2011-088
0.156 fb⁻¹
- ATLAS-CONF-2011-027
0.035 fb⁻¹

Measurement Strategies

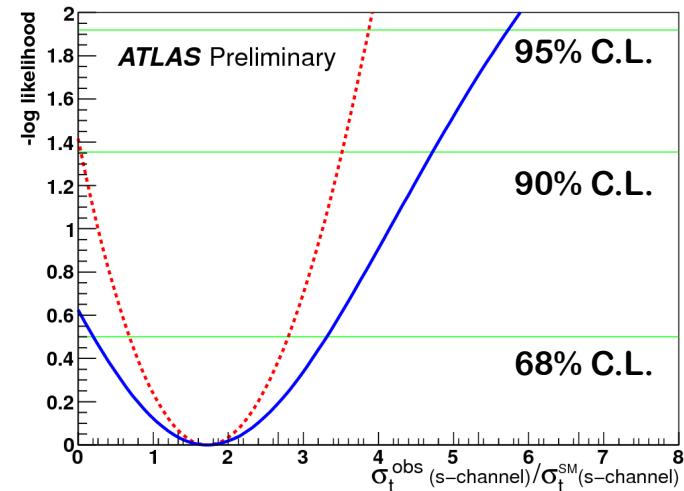
“Classical”

- s-channel
- t-channel
- Wt-channel
- ttbar
- W+light jets
- W+HF
- Diboson
- Z+jets
- QCD

Cut-based

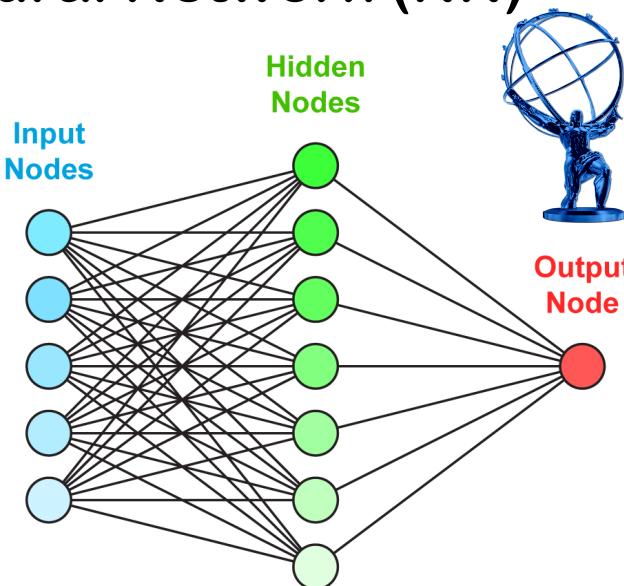


Likelihood Fit

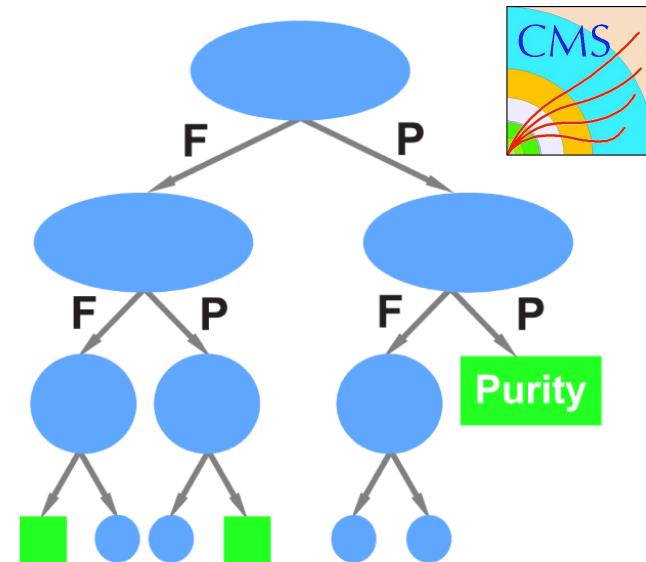


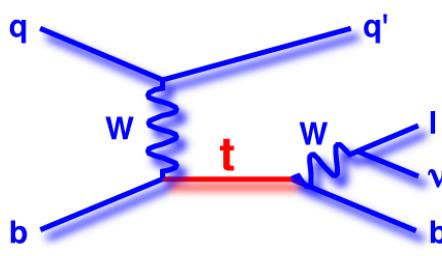
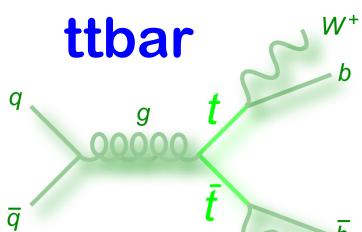
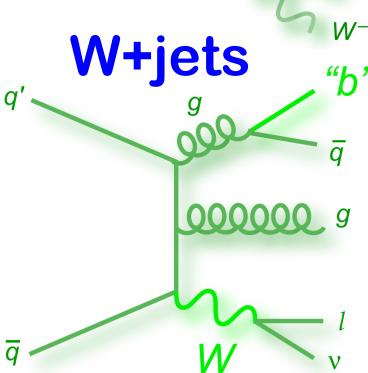
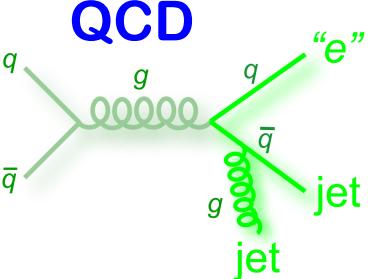
Neural Network (NN)

Multivariate
Techniques



Boosted Decision Trees (BDT)



t-channel**ttbar****W+jets****QCD**

- Anti- k_T jets, $\Delta R = 0.5$ ($= 0.4$), $N_{\text{jet}} = 2$ ($= 2-3$)
- 1 b-tag, IP significance (Secondary Vertex)
- 1 isolated lepton (e/μ)
- $E_T^{\text{miss}} > 25 \text{ GeV}$
- W boson: $M_T > 40^{\mu\nu}, 50^{\text{ev}} \text{ GeV}$ ($M_T^{\text{lv}} > 60 \text{ GeV} - E_T^{\text{miss}}$)

Normalized to theory prediction

Normalized to measured value (150 pb)

NN: simultaneous fit to NN output (shape: MC)

Cut: scale factors from 3 control regions (shape: MC)

HF: LO prediction scaled by factors of ttbar xs analysis

Light: BDT: scale to NNLO prediction

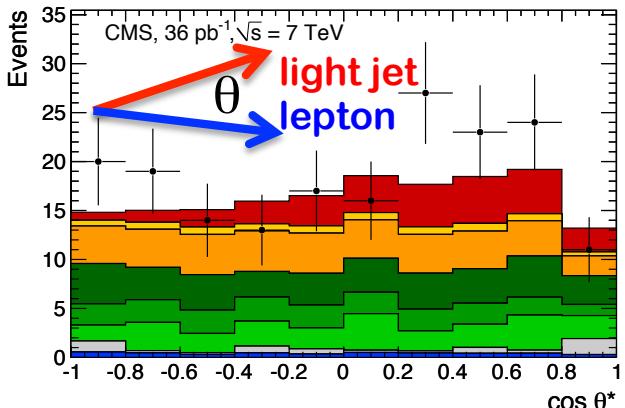
2D: norm.: fit to $M_T(W)$ in 2 control regions
shape: data-driven model

Likelihood fit to E_T^{miss} distribution

Shape from jet-e model / loose isolation μ sample

Likelihood fit to $M_T(W)$ distribution

Shape from orthogonal lepton isolation sample

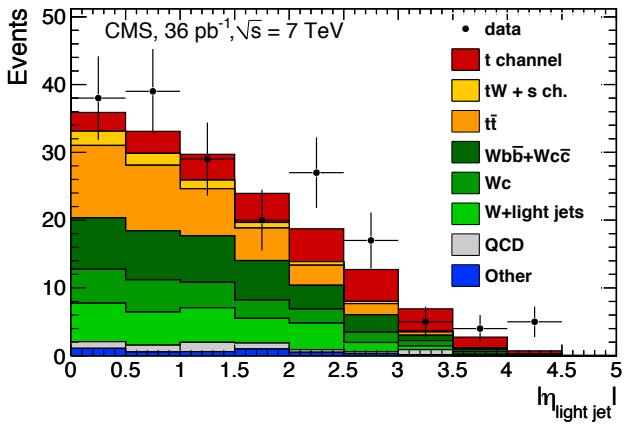


2D-Method

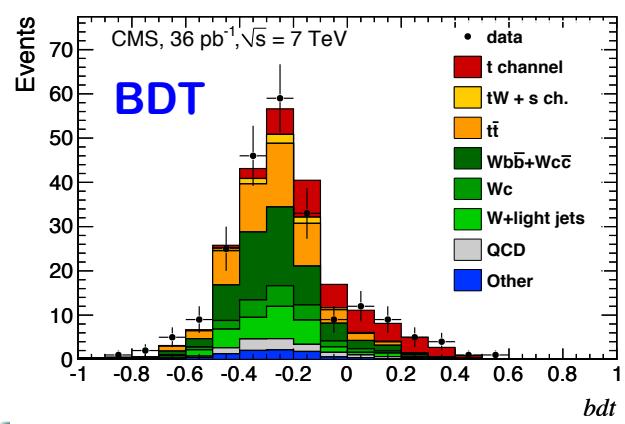


simple & robust
small model dependence

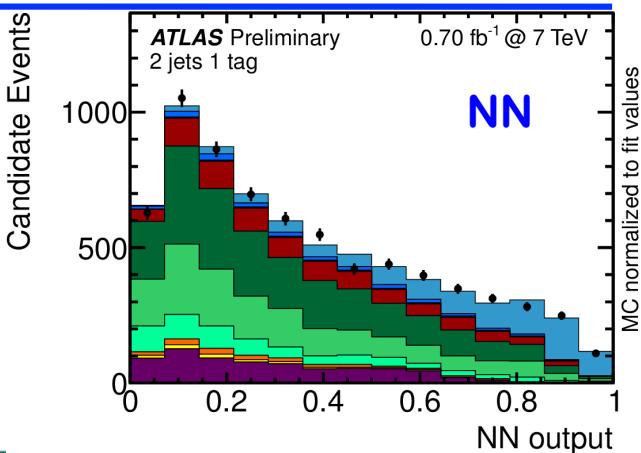
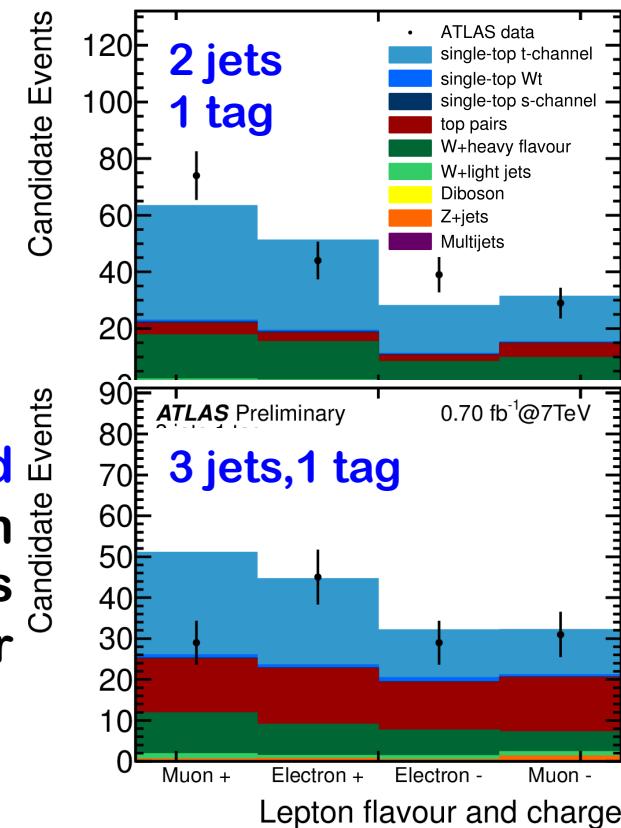
Max. Lhd. fit in 2 variables
Bkg free parameter



ATLAS EXPERIMENT Cut-based
Simultaneous fit to 8 lepton
flavour / charge samples
Bkg free parameter



Multivariate Approaches
High sensitivity
Exploits full kinematics
Fit full output distribution
Bkg: free parameter





0.036 fb⁻¹

| | |
|----------------------------------|-------------|
| $124 \pm 34^{+30}_{-34}$ pb (2D) | 3.7σ |
| $79 \pm 25^{+13}_{-15}$ pb (BDT) | 3.5σ |
| 84 ± 30 pb | 3.5σ |
| $ V_{tb} > 0.62$ (2D) | |
| $ V_{tb} > 0.68$ (BDT) | |



0.70 fb⁻¹

| | |
|---------------------------------|-------------|
| $90 \pm 9^{+31}_{-20}$ pb (cut) | 7.6σ |
| $105 \pm 7^{+36}_{-30}$ pb (NN) | |

0.156 fb⁻¹

| | |
|---------------------------|-------------|
| 97^{+54}_{-30} pb (cut) | |
| 76^{+41}_{-21} pb (NN) | 6.2σ |

0.035 fb⁻¹

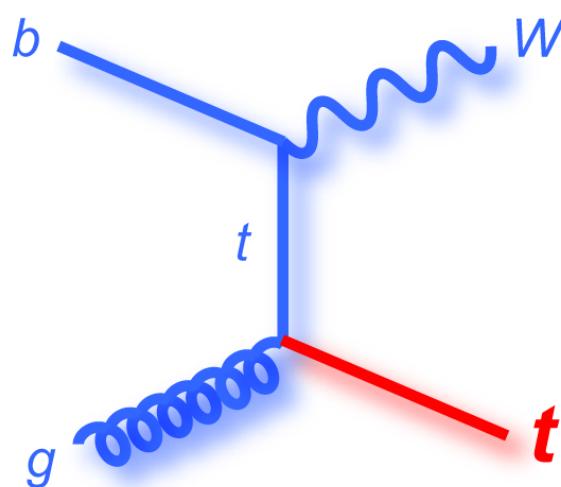
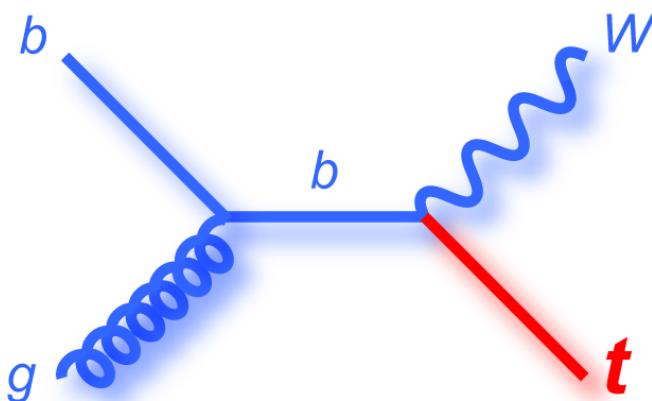
| | |
|--------------------------------|-------------|
| 53^{+46}_{-36} pb (cut) | 1.6σ |
| 76^{+64}_{-40} pb (Likelhd.) | |

Dominant Systematics

- b-tagging efficiency
- Signal model
- Factorization / renormalization W/Z+jets
- Jet energy scale
- Wc background

- b-tagging scale factor
- Jet η reweighting
- MC generator
- Parton shower
- Jet energy scale

Wt-Channel



- CMS PAS TOP-11-022
2.1 fb⁻¹

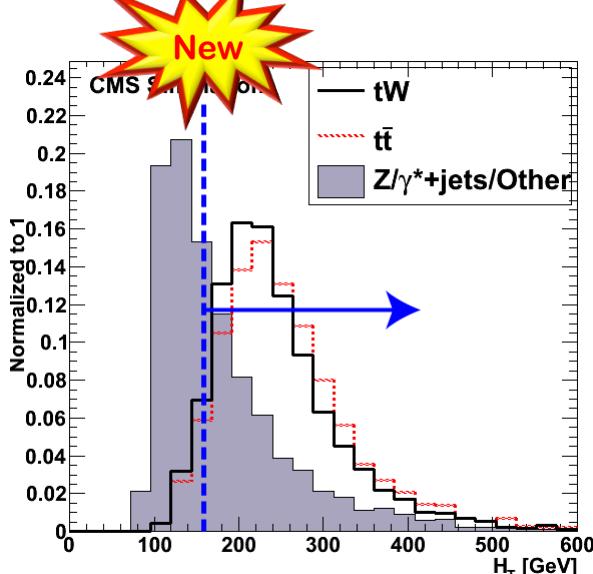
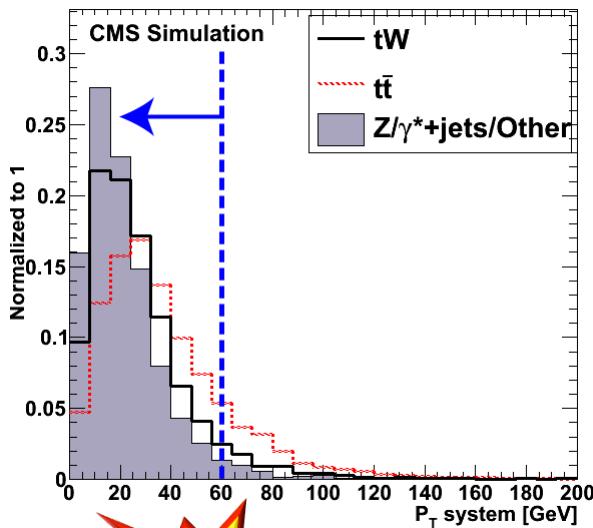


- ATLAS-CONF-2011-104
0.70 fb⁻¹
- ATLAS-CONF-2011-027
0.035 fb⁻¹

Event Selection

CMS PAS TOP-11-022

ATLAS-CONF-2011-104



Select dilepton signature only (ee, $\mu\mu$, e μ)

- 2 opposite-sign leptons

 $E_T^{\text{miss}} > 30 \text{ GeV}$

 $e\mu$: no E_T^{miss} cut,
 $H_T > 160 \text{ GeV}$

 $E_T^{\text{miss}} > 50 \text{ GeV}$

 Exactly 1 b-tagged jet

 Exactly 1 jet (no b-ID)

Background Veto Cuts

- Z-Window: $81 < M_{ee/\mu\mu} < 101 \text{ GeV}$

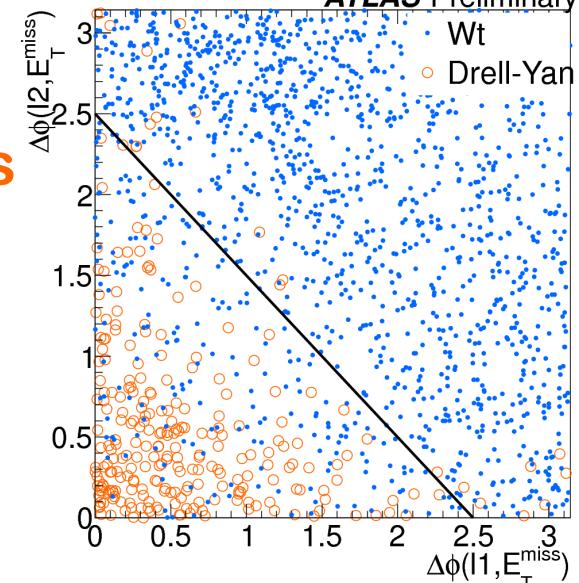
- Drell-Yan:

 triangle cut on $\Delta\phi(l, E_T^{\text{miss}})$

 reject $m_{ll} < 20 \text{ GeV}$

- ttbar:

 no bjet $> 20 \text{ GeV}$, $P_T^{\text{system}} < 60 \text{ GeV}$



CMS PAS TOP-11-022

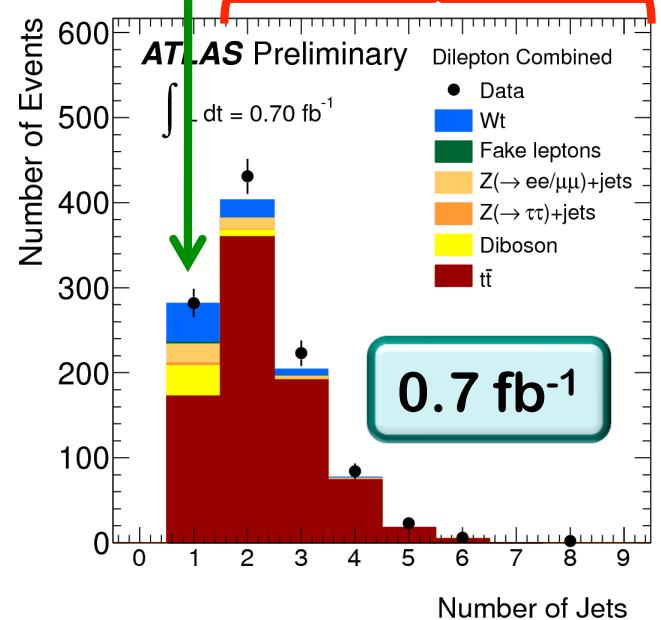
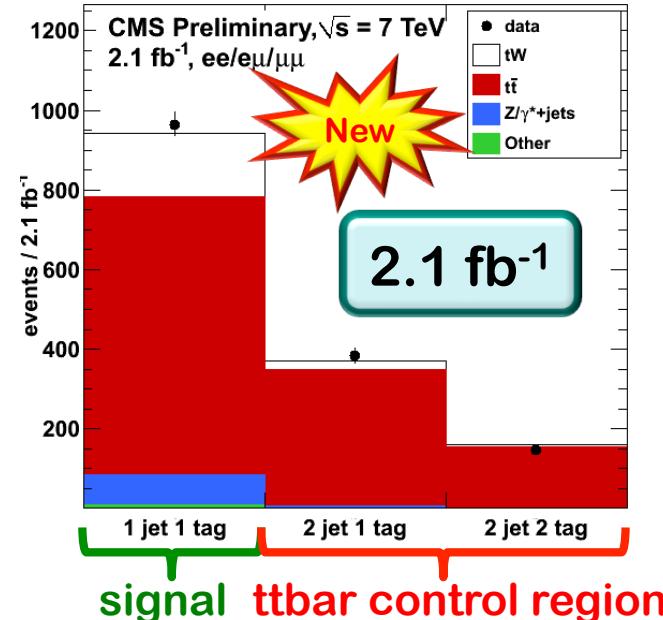
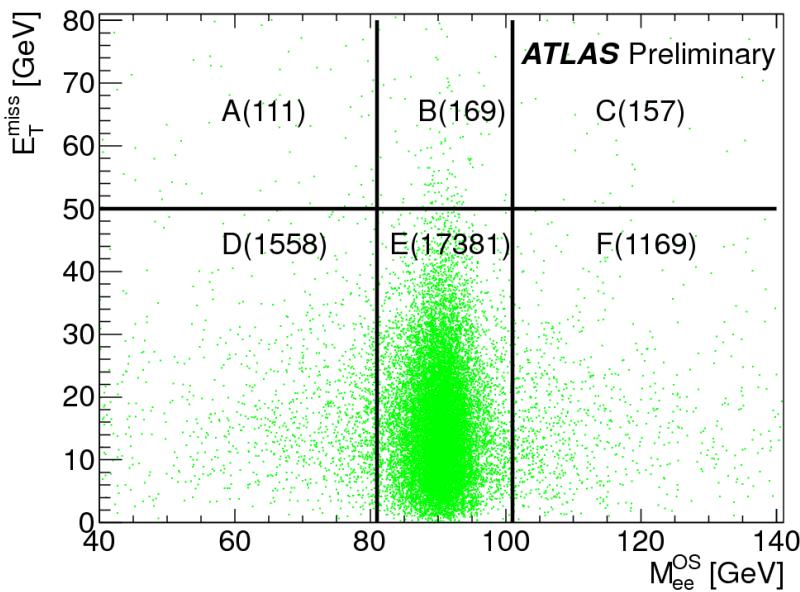
ATLAS-CONF-2011-104

Data-Driven Background Estimates Drell-Yan

- Estimate from Z-veto rejection region
- Estimate from ABCDEF method ($M_{||}$, E_T^{miss})

t \bar{t}

- Simultaneous fit (signal & 2 jets region)
- Estimate from sideband (≥ 2 jets region)



Wt-Channel Results



2.1 fb⁻¹



22^{+9}_{-7} pb (stat \oplus syst.)
 2.7σ obs.
 $(1.8 \pm 0.9)\sigma$ exp.



0.70 fb⁻¹

$14 \pm 5^{+10}_{-9}$ pb (1.2σ)
 $\sigma(Wt) < 39$ pb obs.
 $\sigma(Wt) < 41$ pb exp.

0.035 fb⁻¹

$\sigma(Wt) < 158$ pb obs.
 $\sigma(Wt) < 94$ pb exp.

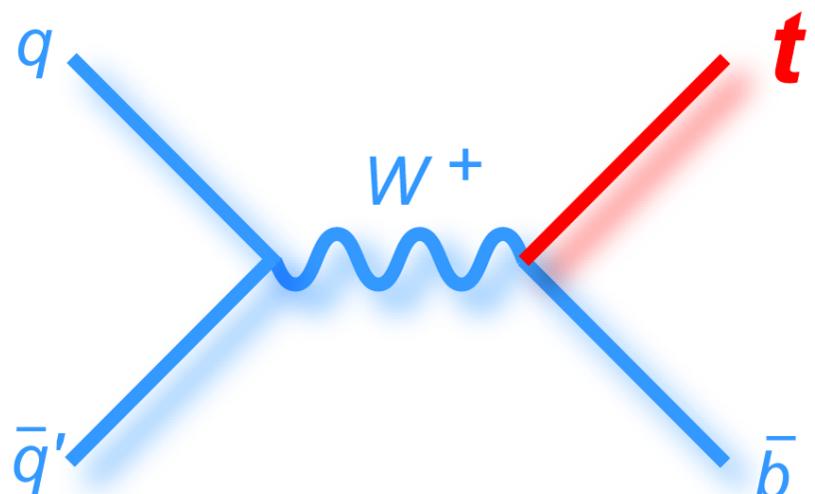
Dominant Systematics

- Jets (JES, res.)
- Factorization / Norm. Scale
- ISR / FSR
- b-tagging

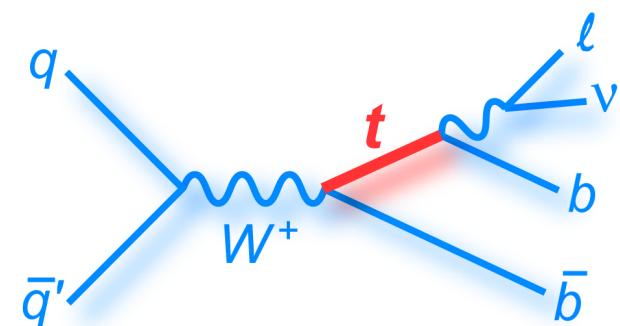
- Jets (JES, res., eff.)
- Generator

| Uncertainty | $\Delta\sigma/\sigma [\%]$ |
|-----------------|----------------------------|
| Statistics Data | +37 / -35 |
| Statistics MC | +11 / -5 |
| Systematics | +68 / -66 |
| Total | +77 / -75 |

s-Channel



- **ATLAS-CONF-2011-118**
0.70 fb⁻¹



Select leptonic W decays only (e, μ)

$p_T(\text{lep}, \text{jet}, E_T^{\text{miss}}) > 25 \text{ GeV}$

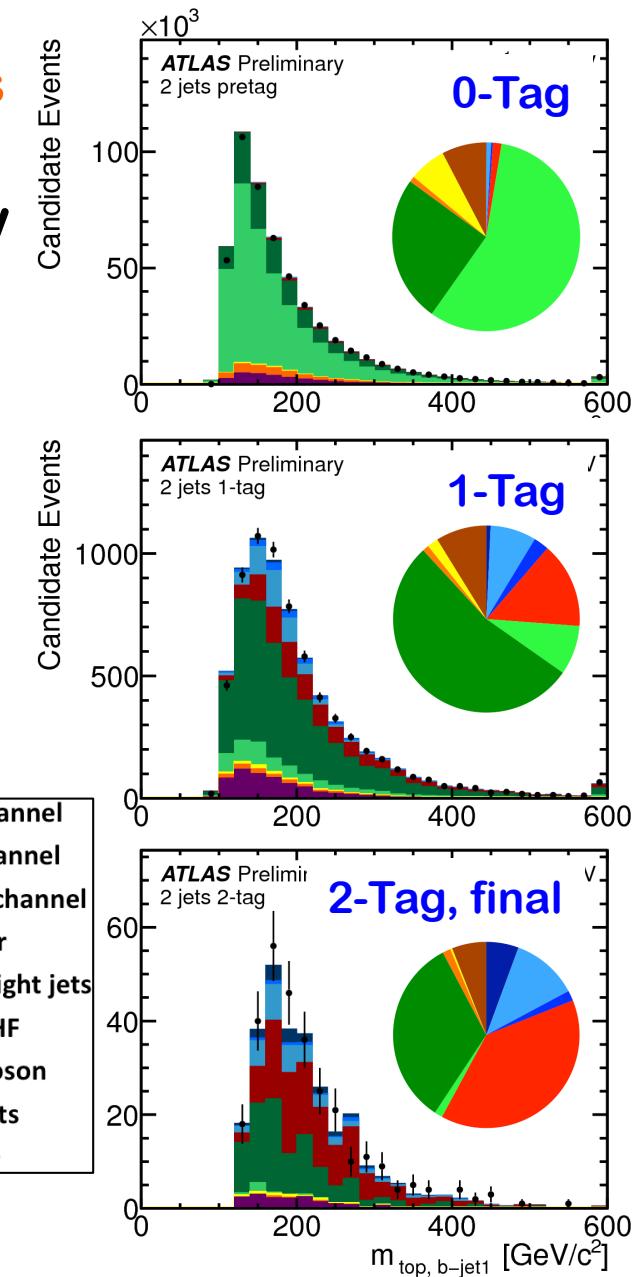
$m_T(W) > 60 \text{ GeV} - E_t^{\text{miss}}$

- Background Estimates

- QCD: data (E_T^{miss} , loose sample)
- $W+\text{jets}$: MC (shapes), data (norm., flavor)
- $t\bar{t}$, t-channel: theory predictions

- Final Selection

- 2 b-tagged jets (S/\sqrt{B} $0.26 \rightarrow 0.88$)
- $m_{\text{top,jet1}}, m_{\text{top,jet2}}$
- $p_T(\text{jet1,jet2})$
- $m_T(W)$
- $\Delta R(\text{jet1,lep}), \Delta R(\text{jet1,jet2})$
- 296 data events (285 ± 17 pred.), $S/\sqrt{B} = 0.98$



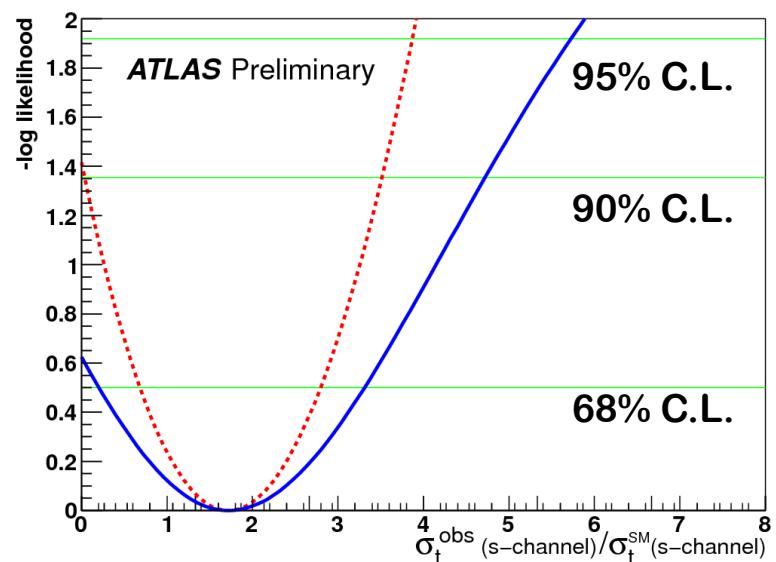
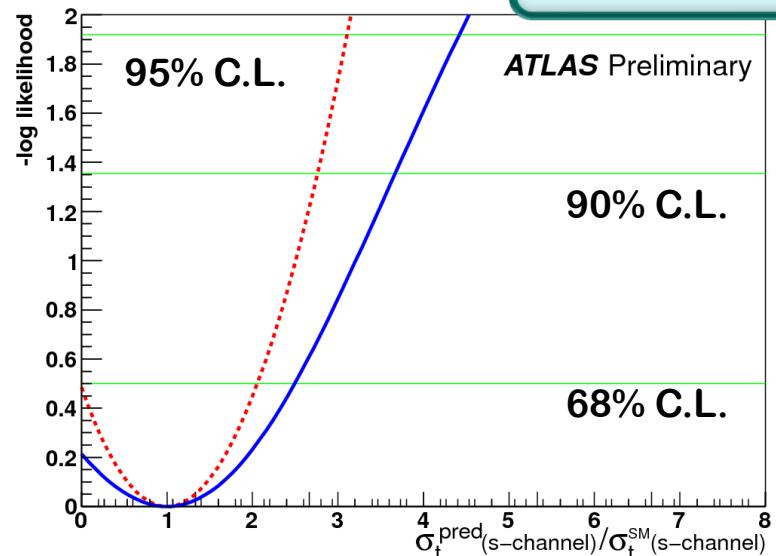
ATLAS-CONF-2011-118

| Uncertainty | $\Delta\sigma/\sigma [\%]$ |
|-----------------|----------------------------|
| Statistics Data | ± 100 |
| Statistics MC | ± 70 |
| Systematics | -110 / +90 |
| Total | -160 / +150 |

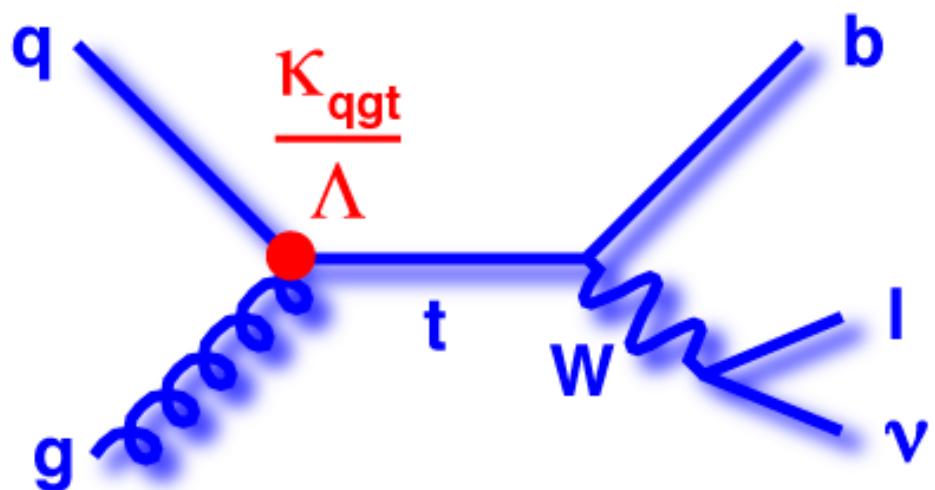
Dominant Systematics

- MC Generator
- Luminosity
- QCD normalization
- b-Identification

Expected limit $\sigma_t(s) < 20.5 \text{ pb}$
 Observed limit $\sigma_t(s) < 26.5 \text{ pb}$
 ~5 x SM cross section (4.6 pb)

 0.70 fb^{-1}


Flavour Changing Neutral Current



- ATLAS-CONF-2011-061
 0.035 fb^{-1}

ATLAS-CONF-2011-061

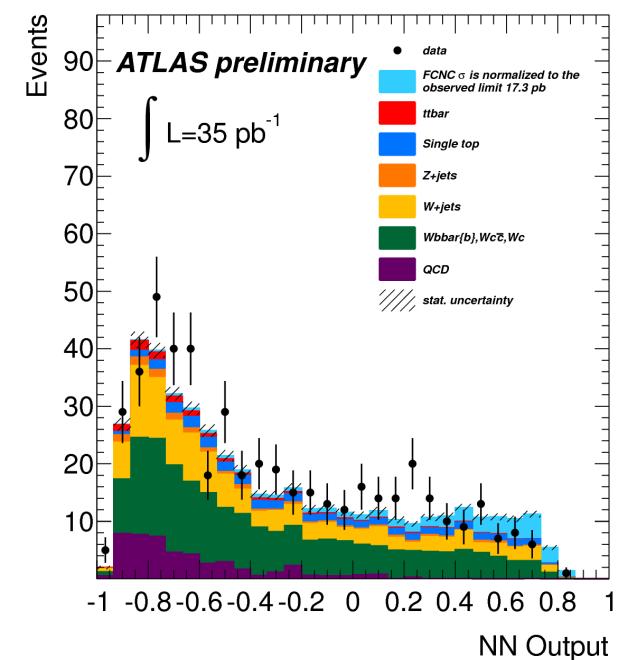
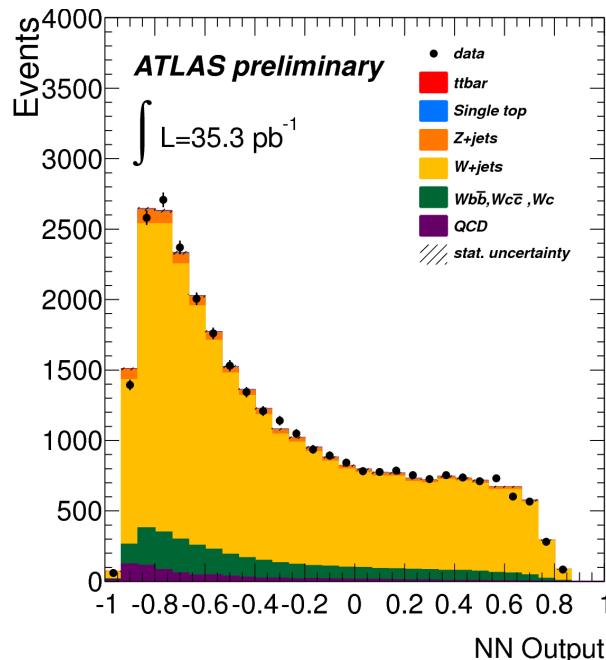
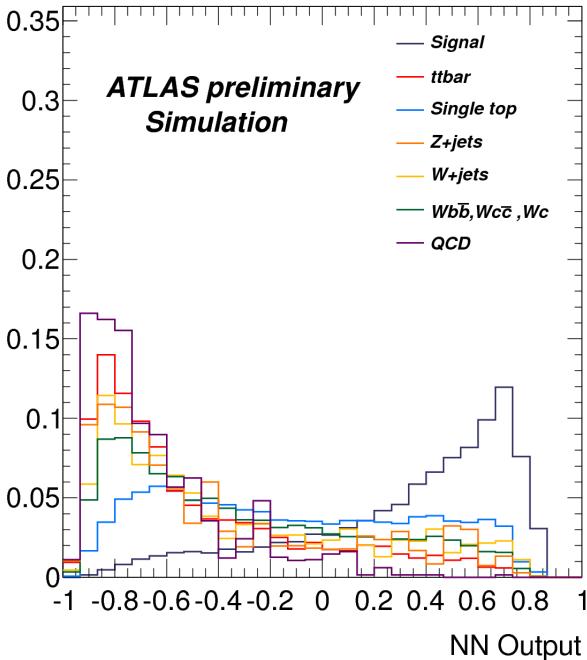
Event Selection

- Search for FCNC in single top production
- Highly suppressed in SM, enhanced BR in many BSM models
- Use NN to separate possible small signal from background

0.035 fb⁻¹

Event Selection

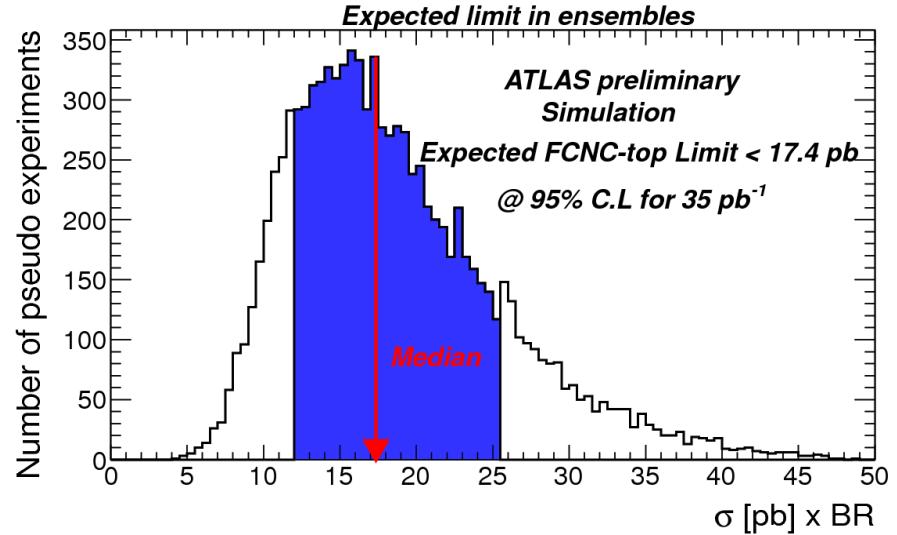
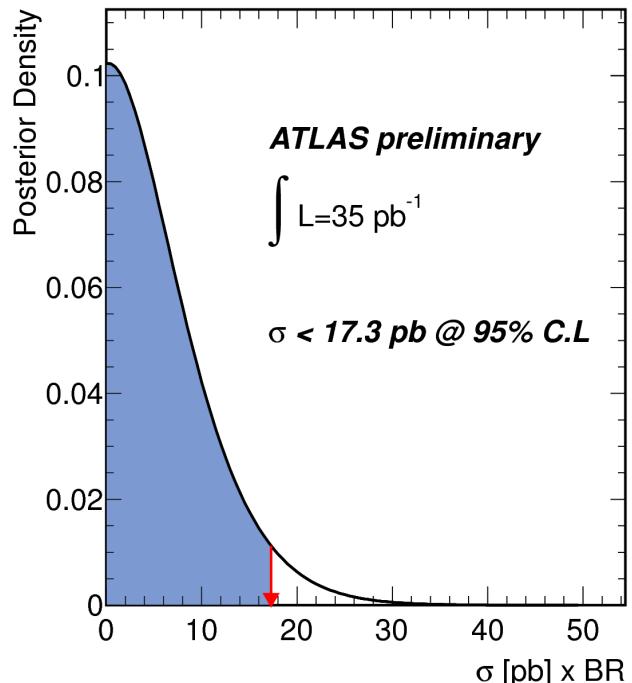
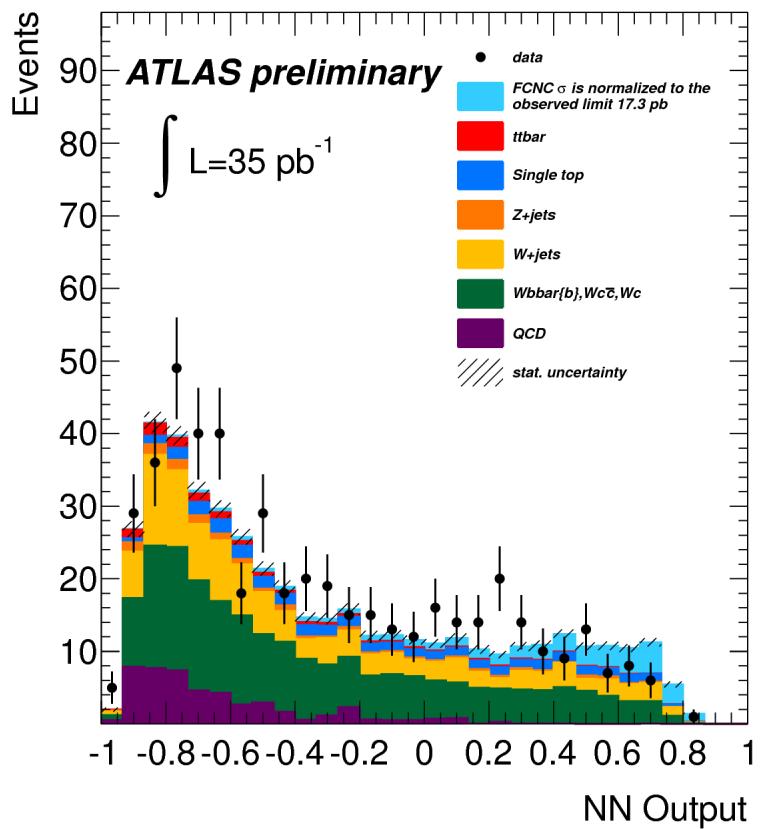
- Select leptonic W decays only (1 isolated e/μ, p_T > 25 GeV)
 - μ: E_T^{miss} > 20 GeV, M_T^W > (60 GeV – E_T^{miss})
 - e: E_T^{miss} > 35 GeV, M_T^W > 25 GeV
- Exactly 1 b-tagged jet, p_T > 25 GeV



No evidence for signal found

0.035 fb⁻¹

$\sigma(\text{FCNC}) < 17.3 \text{ pb}$ obs.
 $\sigma(\text{FCNC}) < 17.4 \text{ pb}$ exp.



Summary & Outlook

t-Channel

Established at LHC

$90 \pm 9^{+31}_{-20}$ pb (64 ± 3 pbSM)

 7.6 σ (0.7 fb⁻¹)

 3.5 σ (0.036 fb⁻¹)

Wt-Channel

1st time measured

22^{+9}_{-7} pb (16 ± 1 pbSM)

 2.7 σ (2.1 fb⁻¹)

 1.2 σ (0.7 fb⁻¹)

s-Channel

95% C.L. limit set

 <26.5 pb (0.7 fb⁻¹)

$\sim 5 \times \sigma_t(s)^{SM}$

Simple cut-based analyses possible!

FCNC in single top production

 < 17.3 pb (0.035 fb⁻¹) 95% C.L. limit set

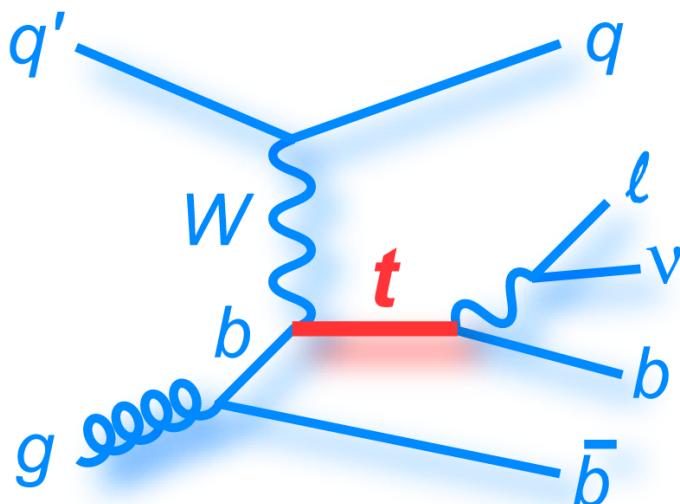
All results compatible with SM expectations

- Future Analyses: more new phenomena searches (W', H⁺,...)
 - Updates of presented analyses with full 2011 pp data set
- Stay tuned!

Backup

Jets: anti- k_T

- ΔR = 0.4, $p_T > 25 \text{ GeV}$, $|\eta| < 4.5$, $N_{\text{jet}} = 2\text{-}3$
- ΔR = 0.5, $p_T > 30 \text{ GeV}$, $|\eta| < 5.0$, $N_{\text{jet}} = 2$

**Lepton: 1 isolated e / μ**

- μ : $p_T > 25 \text{ GeV}$, $|\eta| < 2.5$
- μ : $p_T > 20 \text{ GeV}$, $|\eta| < 2.1$
- e : $p_T > 25 \text{ GeV}$, $|\eta| < 2.47$, $1.37 < |\eta| < 1.52$
- e : $p_T > 30 \text{ GeV}$, $|\eta| < 2.5$

$E_t^{\text{miss}} > 25 \text{ GeV}$

W Boson:

- $M_T^{\text{lv}} > (60 \text{ GeV} - E_t^{\text{miss}})$
- $M_T^{\mu\nu} > 40 \text{ GeV}$, $M_T^{\text{ev}} > 50 \text{ GeV}$

b-jets

- Sec. Vertex tagger**, b-ID eff. 50%, mis-ID eff. 0.37%, 1 tag
- IP significance tagger**, b-ID eff. 40%, mis-ID eff. 0.10%, 1 tag

t-Channel – Event Yields

| Process | 2D, μ channel | 2D, e channel | BDT, μ channel | BDT, e channel |
|-------------------------|------------------------------|------------------------------|------------------------------|------------------------------|
| single top, t channel | 17.6 ± 0.7 (\dagger) | 11.2 ± 0.4 (\dagger) | 17.6 ± 0.7 (\dagger) | 10.7 ± 0.5 (\dagger) |
| single top, s channel | 0.9 ± 0.3 | 0.6 ± 0.2 | 1.4 ± 0.5 | 1.0 ± 0.3 |
| single top, tW | 3.1 ± 0.9 | 2.4 ± 0.7 | 3.8 ± 1.1 | < 0.1 |
| WW | 0.29 ± 0.09 | 0.23 ± 0.07 | 0.32 ± 0.10 | 0.23 ± 0.07 |
| WZ | 0.24 ± 0.07 | 0.17 ± 0.05 | 0.33 ± 0.10 | 1.5 ± 0.4 |
| ZZ | 0.018 ± 0.005 | 0.011 ± 0.003 | 0.020 ± 0.006 | < 0.1 |
| W+ light partons | 18.2 ± 5.5 | 11.6 ± 2.3 | 8.4 ± 4.2 | 7.0 ± 3.5 |
| Z + X | 1.7 ± 0.5 | 1.6 ± 0.3 | 0.7 ± 0.2 | 0.05 ± 0.03 |
| QCD | 0.6 ± 0.3 | $2.6^{+3.4}_{-2.6}$ | 4.9 ± 2.5 | 5.3 ± 5.3 |
| VQQ | 20.4 ± 10.2 | 14.1 ± 7.1 | 17.6 ± 8.8 | 11.7 ± 5.8 |
| Wc | $12.9^{+12.9}_{-6.5}$ | $9.4^{+9.4}_{-4.7}$ | $9.2^{+9.2}_{-4.6}$ | $5.9^{+5.9}_{-2.9}$ |
| t <bar>t</bar> | 20.3 ± 3.6 | 15.6 ± 2.8 | 34.9 ± 4.9 | 22.9 ± 3.2 |
| Total background | 78.6 ± 15.2 | 58.4 ± 11.0 | 82.4 ± 13.1 | 55.9 ± 10.2 |
| Signal + background | 96.2 ± 15.3 | 69.6 ± 11.0 | 100.0 ± 13.2 | 66.6 ± 10.2 |
| Data | 112 | 72 | 139 | 82 |



| Channel | 2D analysis | BDT analysis |
|------------------------------|-------------------------------------|------------------------------------|
| μ | $104.1 \pm 42.3^{+24.8}_{-28.0}$ pb | $90.4 \pm 35.1^{+16.5}_{-19.7}$ pb |
| e | $154.2 \pm 56.0^{+40.6}_{-46.6}$ pb | $59.2 \pm 35.1^{+13.1}_{-13.7}$ pb |
| $\mu + e$ | $124.2 \pm 33.8^{+30.0}_{-33.9}$ pb | $78.7 \pm 25.4^{+13.2}_{-14.6}$ pb |
| combined: 83.6 ± 29.8 pb | | |

t-Channel – Event Yields

| | Cut-based 2-jet | | Cut-based 3-jet | |
|------------------------------|-----------------|----------------|-----------------|-----------------|
| | Lepton+ | Lepton- | Lepton+ | Lepton- |
| single-top <i>t</i> -channel | 51.8 ± 16.4 | 23.7 ± 6.5 | 33.0 ± 7.0 | 16.3 ± 4.8 |
| single-top <i>Wt</i> | 1.1 ± 0.5 | 0.6 ± 0.7 | 1.5 ± 0.6 | 1.5 ± 1.2 |
| single-top <i>s</i> -channel | 0.9 ± 0.2 | 0.6 ± 0.2 | 0.3 ± 0.1 | 0.3 ± 0.1 |
| top pairs | 7.1 ± 3.2 | 7.2 ± 2.9 | 26.8 ± 8.0 | 25.0 ± 7.6 |
| <i>W</i> +light jets | 3.7 ± 1.7 | 2.6 ± 1.2 | 2.1 ± 1.5 | 2.1 ± 1.4 |
| <i>Wc</i> +jets | 18.3 ± 3.8 | 11.7 ± 3.4 | 7.8 ± 3.0 | 6.5 ± 2.6 |
| <i>Wb</i> \bar{b} +jets | 7.7 ± 5.9 | 2.5 ± 2.5 | 6.2 ± 5.2 | 2.9 ± 2.4 |
| <i>Wc</i> \bar{c} +jets | 3.1 ± 2.4 | 1.3 ± 1.0 | 3.6 ± 2.8 | 1.7 ± 1.4 |
| Diboson | 0.1 ± 0.1 | 0.1 ± 0.1 | 0.2 ± 0.2 | 0.1 ± 0.1 |
| <i>Z</i> +jets | 0.2 ± 0.4 | 0.1 ± 0.2 | 1.0 ± 1.0 | 1.5 ± 1.3 |
| Multijets | < 0.1 | < 0.1 | < 0.1 | < 0.1 |
| TOTAL Expected | 94.1 ± 18.4 | 50.2 ± 8.5 | 82.6 ± 12.7 | 57.9 ± 10.1 |
| S/B | 1.23 | 0.89 | 0.67 | 0.39 |
| DATA | 118 | 68 | 74 | 60 |

| Source | yield after NN fit |
|--|--------------------|
| single-top <i>t</i> -channel | 900 ± 60 |
| single-top <i>s</i> -channel | 52 ± 5 |
| single-top <i>Wt</i> | 165 ± 16 |
| top pairs | 770 ± 64 |
| <i>W</i> +light jets | 545 ± 173 |
| <i>Wc</i> +jets | 1480 ± 400 |
| <i>Wb</i> \bar{b} / <i>c</i> \bar{c} +jets | 2130 ± 420 |
| Diboson | 79 ± 4 |
| <i>Z</i> +jets | 139 ± 78 |
| Multijets | 700 ± 250 |
| TOTAL Expexted | 6950 ± 880 |
| DATA | 6953 |

t-Channel - Systematics

| uncertainty | correlation | impact on | | | |
|---|-------------|-----------|-------|-------|-------|
| | | - | + | - | + |
| statistical only | 60 | 52 | | 39 | |
| shared shape/rate uncertainties: | | | | | |
| ISR/FSR for $t\bar{t}$ | 100 | -1.0 | +1.5 | < 0.2 | < 0.2 |
| Q^2 for $t\bar{t}$ | 100 | +3.5 | -3.5 | +0.3 | -0.4 |
| Q^2 for $V+jets$ | 100 | +5.7 | -12.0 | +2.6 | -4.5 |
| Jet energy scale | 100 | -8.8 | +3.6 | -5.1 | +1.2 |
| b tagging efficiency | 100 | -19.6 | +19.8 | -15.2 | +14.6 |
| MET (uncl. energy) | 100 | -5.7 | +3.7 | -3.9 | -0.5 |
| shared rate-only uncertainties: | | | | | |
| $t\bar{t}$ ($\pm 14\%$) | 100 | +2.0 | -1.9 | +0.5 | -0.6 |
| single top s ($\pm 30\%$) | 100 | -0.4 | +0.5 | -0.4 | +0.4 |
| single top tW ($\pm 30\%$) | 100 | +1.1 | -1.0 | < 0.2 | < 0.2 |
| $Wb\bar{b}, Wc\bar{c}$ ($\pm 50\%$) | 100 | -3.0 | +2.9 | +1.7 | -1.9 |
| Wc ($^{+100\%}_{-50\%}$) | 100 | -3.0 | +6.1 | -2.4 | +4.4 |
| Z+jets ($\pm 30\%$) | 100 | -0.6 | +0.7 | +0.4 | -0.2 |
| electron QCD (BDT: $\pm 100\%$, 2D: $^{+130\%}_{-100\%}$) | 50 | +2.9 | -3.7 | -1.7 | +1.7 |
| muon QCD (BDT: $\pm 50\%$, 2D: $\pm 50\%$) | 50 | < 0.2 | < 0.2 | -2.1 | +2.1 |
| signal model | 100 | -5.0 | +5.0 | -4.0 | +4.0 |
| BDT-only uncertainties: | | | | | |
| electron efficiency ($\pm 5\%$) | 0 | — | — | -1.4 | +1.4 |
| muon efficiency ($\pm 5\%$) | 0 | — | — | -3.6 | +3.5 |
| $V+jets$ ($\pm 50\%$) | 0 | — | — | -1.5 | < 0.2 |
| 2D-only uncertainties: | | | | | |
| muon W +light ($\pm 30\%$) | 0 | -1.4 | +1.4 | — | — |
| electron W +light ($\pm 20\%$) | 0 | -0.6 | +0.7 | — | — |
| W +light model uncertainties | 0 | -5.4 | +5.4 | — | — |



t-Channel - Systematics

| Source | $\Delta\sigma/\sigma [\%]$ | | | |
|--------------------------------------|----------------------------|----------|----------|-------------------|
| | 2-jet | 3-jet | combined | NN |
| Data statistics | ± 16 | ± 24 | ± 13 | ± 10 |
| MC statistics | ± 8 | ± 11 | ± 6 | ± 7 |
| Jet energy scale | +7/-5 | +10/-1 | +9/-1 | +32/-20 |
| Jet energy resolution | +6/-4 | +8/-7 | +6/-1 | ± 4 |
| Jet reconstruction | +2/-1 | ± 1 | ± 1 | +3/-2 |
| <i>b</i> -tagging scale factor | +17/-12 | +21/-14 | +18/-13 | ± 13 |
| Mis-tagging scale factor | ± 1 | ± 1 | ± 1 | ± 1 |
| Lepton efficiencies | +6/-5 | +11/-9 | +8/-6 | ± 5 |
| Lepton energy scale/resolution | ± 1 | ± 1 | +2/-1 | ± 5 |
| Generator | +10/-8 | +16/-12 | +11/-9 | ± 7 |
| Parton shower | +9/-7 | +14/-12 | +10/-9 | ± 6 |
| ISR/FSR | +19/-16 | ± 7 | ± 14 | ± 13 |
| PDF | +5/-4 | +6/-5 | ± 5 | ± 4 |
| <i>W+jets</i> shape modeling | ± 1 | ± 1 | ± 1 | ± 1 |
| Jet η reweighting | +12/-10 | +18/-14 | +13/-11 | +10/-6 ± 3 |
| Background normalization | | | | |
| QCD normalization | ± 4 | ± 8 | ± 4 | |
| <i>W+heavy flavour</i> normalization | ± 2 | ± 2 | ± 3 | |
| <i>W+light flavour</i> normalization | ± 1 | ± 1 | ± 1 | |
| Theory cross sections | ± 7 | ± 13 | ± 8 | |
| Luminosity | +6/-5 | +11/-8 | +7/-6 | ± 5 |
| All systematics | +42/-27 | +51/-37 | +41/-27 | +44/-34 |
| Total | +45/-31 | +57/-43 | +44/-30 | +45/-34 |

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Select dilepton signature only (ee, $\mu\mu$, e μ)

- Exactly 2 opposite-sign leptons

 $p_T^{e,\mu} > 20 \text{ GeV}$, $p_T^{\text{jet}} > 30 \text{ GeV}$, $E_T^{\text{miss}} > 30 \text{ GeV}$

 $p_T^{e,\mu} > 25 \text{ GeV}$, $p_T^{\text{jet}} > 30 \text{ GeV}$, $E_T^{\text{miss}} > 50 \text{ GeV}$

 Exactly 1 b-tagged jet

 Exactly 1 jet (no b-ID applied)

- Z-Veto: $81 < M_{ee/\mu\mu} < 101 \text{ GeV}$

 e μ : no E_T^{miss} cut, $H_T > 160 \text{ GeV}$

 Drell-Yan veto: reject $m_{||} < 20 \text{ GeV}$

 ttbar veto: no bjet $> 20 \text{ GeV}$, $P_T^{\text{system}} < 60 \text{ GeV}$

 QCD veto: triangle cut on $\Delta\phi(l, E_t^{\text{miss}})$

Wt-Channel



| process | <i>ee</i> channel | <i>eμ</i> channel | <i>μμ</i> channel |
|-----------------------------------|-------------------|-------------------|-------------------|
| Signal region (1jet, 1tag) | | | |
| tW | 24.7±0.9 | 88 ±2 | 39±1 |
| t̄t | 110±4 | 372±8 | 174±5 |
| Z/γ* (data-driven) | 20.7 ± 3.9 | 10 ± 2 | 45.7 ± 6.1 |
| other | 1.0 ±0.2 | 5 ±1 | 2.1 ±0.2 |
| all background | 132 ± 4 | 387 ± 9 | 222 ± 8 |
| data | 149 | 539 | 276 |
| Background region A (2jets, 1tag) | | | |
| t̄t | 53±3 | 169±5 | 81±4 |
| tW, Z/γ*, other | 5.1±0.8 | 11.0±0.6 | 9±1 |
| data | 76 | 208 | 100 |
| Background region B (2jets, 2tag) | | | |
| t̄t | 23 ±2 | 73±4 | 37±3 |
| tW, Z/γ*, other | 1.2±0.5 | 2.2±0.2 | 1.2±0.2 |
| data | 21 | 86 | 40 |

| Systematic uncertainty (<i>ee/eμ/μμ</i>) [%] | signal tW | t̄t | Z/γ* | other |
|--|----------------------------------|----------------------------------|------------|----------|
| Luminosity | 4.5 | 4.5 | - | 4.5 |
| Pile-up multiplicity | 0.48/0.55/0.73 | * | - | * |
| Trigger Efficiency | 1.5 | 1.5 | - | 1.5 |
| Muon reconstruction and identification | - /1/1 | - /1/1 | - | - /1/1 |
| Electron reconstruction and identification | 2/2/ - | 2/2/ - | - | 2/2/ - |
| JES | -2.5/-2.4/-0.6 +1.6/+0.1/+1.0 | -5.6/-6.0/-5.9 +4.4/+4.7/+2.3 | - | * |
| JER | 1.1/0.5/0.4 | 3.1/3.9/4.4 | - | * |
| B-tagging | -9.5/-9.8/-9.5 +10/+9.8/+10 | -8.5/-11/-9.1 +10/+10/+11 | - | * |
| Factorization/Normalization Scale (Q^2) | 7.7/6/10 | 7.7/11/12 | - | * |
| ME/PS matching thresholds | - | 5.7/0.7/2.3 | - | * |
| ISR/FSR | - | 8.9/7.3/7.3 | - | * |
| DR/DS scheme | 8.2/9.1/6.6 | - | - | * |
| E_T^{miss} modeling | 2.3/0.9/0.9 | * | - | * |
| PDF uncertainties | 4.5/4.5/4.5 | * | - | * |
| Background Normalization | - | 15/15/15 | 50/ 50/ 50 | * |
| Simulation statistics | 3.5/1.9/2.7 | - | - | 17/21/11 |

Wt-Channel



| | Wt | $t\bar{t}$ | WW, WZ, ZZ | $Z \rightarrow \tau\tau$ | Drell-Yan | Fakes | Source | $\Delta\sigma/\sigma [\%]$ |
|----------------------------------|-------------|--------------|-------------|--------------------------|------------|------------|-----------------------------------|----------------------------|
| Jet Energy Scale | -3.2% | +4.0% | + 8.9% | - | - | - | Data statistics | +37/-35 |
| | +1.1% | -4.0% | - 3.4% | - | - | - | MC statistics | +11/-5.4 |
| Jet Energy Resolution | $\pm 2.3\%$ | $\pm 9.0\%$ | $\mp 3.1\%$ | - | - | - | Lepton energy scale | +7.0/-5.4 |
| Jet Reconstruction | $\mp 1.7\%$ | $\pm 9.3\%$ | $\mp 2.8\%$ | - | - | - | Lepton energy resolution | +9.0/-8.9 |
| Lepton Scale Factor ($e\mu$) | $\pm 3.5\%$ | $\pm 3.7\%$ | $\pm 3.7\%$ | - | - | - | Lepton efficiencies | +5.3/-2.9 |
| Lepton Resolution ($e\mu$) | $\pm 2.0\%$ | - | $\pm 2.0\%$ | - | - | - | Jet energy scale | +34/-35 |
| Lepton Scale Factor (ee) | $\pm 4.7\%$ | $\pm 5.5\%$ | $\pm 6.9\%$ | - | - | - | Jet energy resolution | +29/-32 |
| Lepton Resolution (ee) | $\pm 2.0\%$ | - | $\pm 2.0\%$ | - | - | - | Jet reconstruction efficiency | +30/-33 |
| Lepton Scale Factor ($\mu\mu$) | $\pm 0.8\%$ | $\pm 0.6\%$ | $\pm 0.4\%$ | - | - | - | Top pair scaling factor | +23/-24 |
| Lepton Resolution ($\mu\mu$) | $\pm 2.0\%$ | - | $\pm 2.0\%$ | - | - | - | Drell-Yan background estimation | +2.7/-4.0 |
| PDF | +2.6% | +6.4% | +0.7% | - | - | - | Fake lepton background estimation | +4.2/-4.3 |
| | -1.4% | -6.3% | -0.7% | - | - | - | Generator | +16/-11 |
| ISR/FSR | $\mp 11\%$ | $\mp 5.0\%$ | $\mp 15\%$ | - | - | - | ISR/FSR | +6.0/-1.9 |
| MC Generator | $\pm 5.7\%$ | - | $\pm 10\%$ | - | - | - | PDF | +5.4/-2.8 |
| Pile up | $\pm 5.0\%$ | - | $\pm 5.0\%$ | - | - | - | Pileup | +10/-6.6 |
| Normalization to data | - | $\pm 19.8\%$ | - | $\pm 60\%$ | $\pm 20\%$ | $\pm 50\%$ | Background cross-sections | +6.9/-6.8 |
| Normalization to theory | - | - | $\pm 5.0\%$ | - | - | - | Luminosity | +9.2/-5.9 |
| Luminosity | - | - | $\pm 4.5\%$ | - | - | - | All systematics | +68/-66 |
| | | | | | | | Total | +77/-75 |

s-Channel

| Selection | Signal | Background | S/\sqrt{B} |
|--|--------|------------|--------------|
| Preselection Only | 104 | 153802 | 0.26 |
| Number of tagged jets=2 | 18 | 415 | 0.88 |
| $30 < m_{top,jet2} < 247 \text{ GeV}/c^2$ | 17 | 349 | 0.91 |
| $p_T(jet1, jet2) < 189 \text{ GeV}/c$ | 17 | 346 | 0.91 |
| $m_T(W) < 111 \text{ GeV}/c$ | 17 | 318 | 0.95 |
| $0.43 < \Delta R(b - jet1, lepton) < 3.6$ | 17 | 308 | 0.97 |
| $123 < m_{top,jet1} < 788 \text{ GeV}/c^2$ | 17 | 302 | 0.98 |
| $0.74 < \Delta R(b - jet1, b - jet2) < 4.68$ | 16 | 269 | 0.98 |

| Source | $\Delta\sigma/\sigma [\%]$ |
|-------------------------|----------------------------|
| cut-based | |
| Data statistics | ± 100 |
| MC statistics | ± 70 |
| b -tagging | -30/+20 |
| Jet and lepton modeling | -20/+10 |
| MC generator modeling | -60/+20 |
| Multijets normalization | ± 40 |
| Others | -10/+30 |
| Luminosity | ± 50 |
| All systematics | -110/+90 |
| Total uncertainty | -160/+150 |

| | Final Selection |
|------------------|-----------------|
| s -channel | 16 ± 6 |
| t -channel | 33 ± 13 |
| Wt | 5 ± 3 |
| $t\bar{t}$ | 111 ± 47 |
| $W+jets$ | 4 ± 5 |
| $Wc+jets$ | 10 ± 8 |
| $Wc\bar{c}+jets$ | 14 ± 12 |
| $Wb\bar{b}+jets$ | 70 ± 51 |
| $Z+jets$ | 1 ± 1 |
| Diboson | 4 ± 1 |
| Multijets | 17 ± 10 |
| TOTAL Exp | 285 ± 17 |
| S/\sqrt{B} | 0.98 |
| DATA | 296 |

FCNC Analysis

| Channel | e | μ | combined |
|-----------------------------------|------------------|------------------|------------------|
| Signal | 0.8 ± 0.0 | 1.2 ± 0.0 | 1.9 ± 0.0 |
| Single top | 12.9 ± 1.3 | 20.9 ± 2.1 | 33.9 ± 2.5 |
| $t\bar{t}$ | 5.1 ± 0.5 | 6.8 ± 0.7 | 12.0 ± 0.9 |
| $W+$ light jets | 37.7 ± 7.8 | 71.4 ± 14.5 | 109.1 ± 16.5 |
| $Wb\bar{b}/Wc\bar{c}+\text{jets}$ | 7.8 ± 1.6 | 16.8 ± 3.5 | 24.7 ± 3.8 |
| $W + c + \text{jets}$ | 52.6 ± 10.6 | 116.6 ± 23.4 | 169.2 ± 25.6 |
| $Z+\text{jets} + \text{diboson}$ | 1.9 ± 0.4 | 11.7 ± 2.5 | 13.5 ± 2.5 |
| QCD | 14.4 ± 7.2 | 33.1 ± 16.6 | 47.5 ± 18.0 |
| total background | 132.4 ± 15.1 | 277.5 ± 32.5 | 409.9 ± 35.8 |
| data | 150 | 340 | 490 |

| Source | (-1σ) | median | ($+1\sigma$) |
|--|----------------|--------|----------------|
| Cross section and QCD multijet uncertainties | 9.6 | 13.7 | 19.7 |
| Luminosity | 9.8 | 13.8 | 20.0 |
| Jet energy scale | 10.2 | 14.8 | 21.1 |
| Jet reco. efficiency | 9.5 | 13.7 | 19.7 |
| Jet energy resolution | 9.6 | 13.9 | 20.2 |
| b -tagging, mis-tagging | 9.6 | 13.9 | 19.5 |
| Electron trigger, eff. and ID | 9.8 | 13.9 | 20.0 |
| Electron energy scale | 9.9 | 14.3 | 20.0 |
| Electron energy resolution | 9.6 | 14.1 | 19.9 |
| Muon trigger, eff. and ID | 9.3 | 13.2 | 19.2 |
| Muon momentum resolution and energy scale | 9.7 | 13.9 | 19.6 |
| HF fraction | 9.6 | 14.2 | 20.5 |
| PDF | 9.5 | 13.3 | 19.4 |
| ISR | 11.1 | 15.7 | 22.9 |
| FSR | 9.5 | 13.3 | 19.4 |
| Pile-up | 9.7 | 13.9 | 19.7 |
| $W+\text{jets}$ shape | 9.5 | 13.7 | 19.8 |
| All systematics | 12.0 | 17.4 | 25.6 |



NN Variables

| Variable | Significance (σ) |
|-----------------------|---------------------------|
| $p_{T,W}$ | 66 |
| $\Delta R(\ell, b)$ | 29 |
| Lepton charge | 22 |
| m_t | 20 |
| $\Delta\phi(W, b)$ | 18 |
| η_b | 16 |
| W-boson helicity | 10 |
| $p_{T,b}$ | 9.3 |
| $p_{T,t}$ | 6.9 |
| η_ℓ | 6.6 |
| \cancel{E}_T | 3.8 |
| m_T^W | 4.3 |
| $\Delta\phi(\ell, b)$ | 4.2 |