Single top quark and V_{tb} measurements

Soureek Mitra
Tata Institute of Fundamental Research, Mumbai

Outline

- Introduction
- Cross - section and V_{tb} measurements

☛ t - channel

☛ tW - channel

☛ s - channel

- Probing the tWb vertex using t-channel single top events

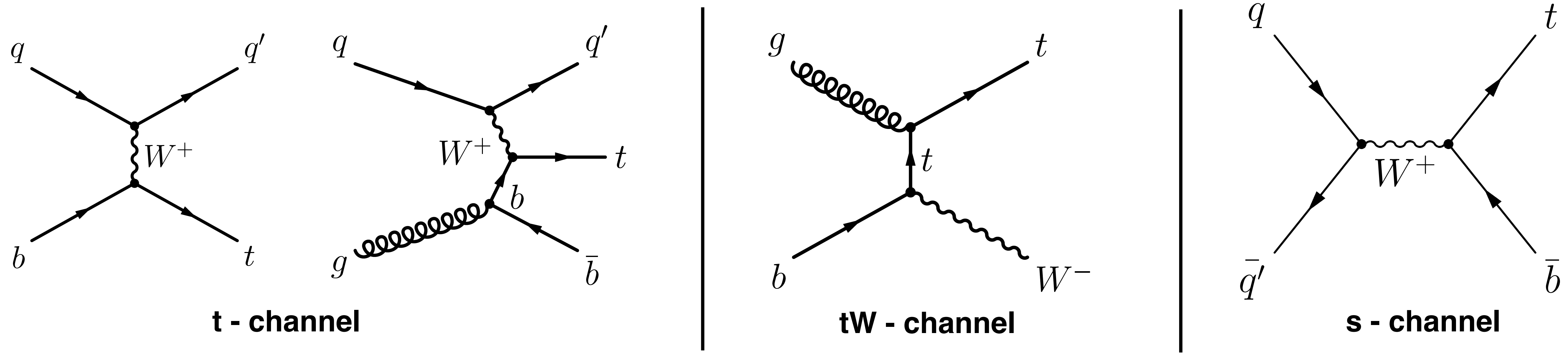
☛ top quark polarization

☛ Anomalous couplings

- Summary

Single top @ colliders

Single top quark production occurs via electroweak interactions:



- Discovered in 2009 @Tevatron (PRL 103 092002 , PRL 103 092002)
- It is one of the important electroweak processes for the following reasons:

➢ allows measurement of the CKM matrix element $|V_{tb}|$

➢ can reveal anomalies in the structure of tWb coupling

➢ allows study of top quark polarization and b-quark PDF

➢ sensitive to new physics via s-channel (new resonances like $H^{\pm}$, W′) and t-channel (FCNC processes)

- t-channel has the highest cross-section among the three production modes

➢ **$\sigma_{t\text{-}ch} \approx 1/3\ \sigma_{t\bar{t}}$**

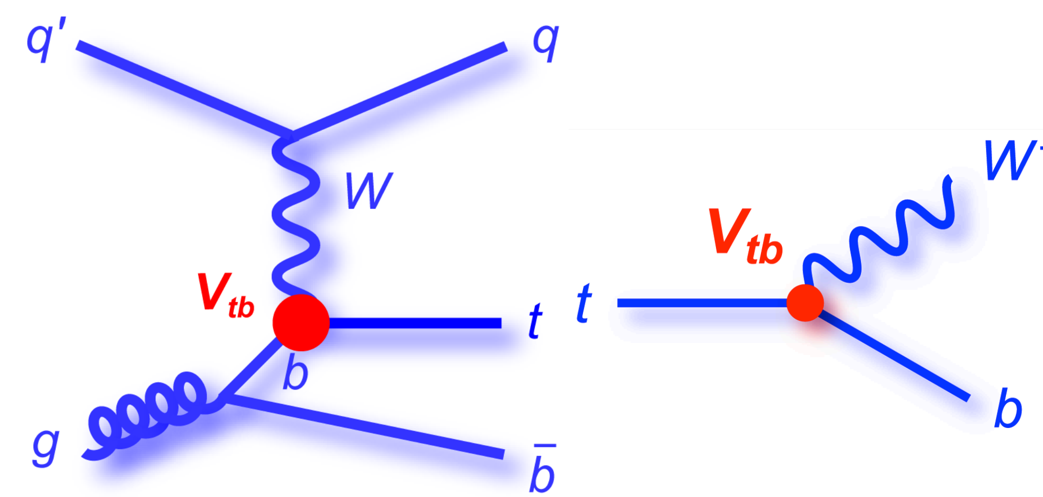
➢ already entered a precision regime at the LHC

V_{tb} using single top

- V_{tb} appears in production and decay of the top quark

$$\sigma \propto |V_{tb}|^2$$

$$|V_{tb}|^{meas.} = \sqrt{\frac{\sigma_{exp.}}{\sigma_{theory}}}$$



- σ_{theory} in SM ➛ $|V_{tb}| \approx 1$, $|V_{tb}| >> |V_{td}|, |V_{ts}|$

- Questions regarding CKM matrix:

➛ Is it a 3x3 matrix? Why not 4x4 or even larger?

➛ Is it unitary?

$|V_{td}|^2 + |V_{ts}|^2 + |V_{tb}|^2 = 1$?

Direct Measurements: see other talks

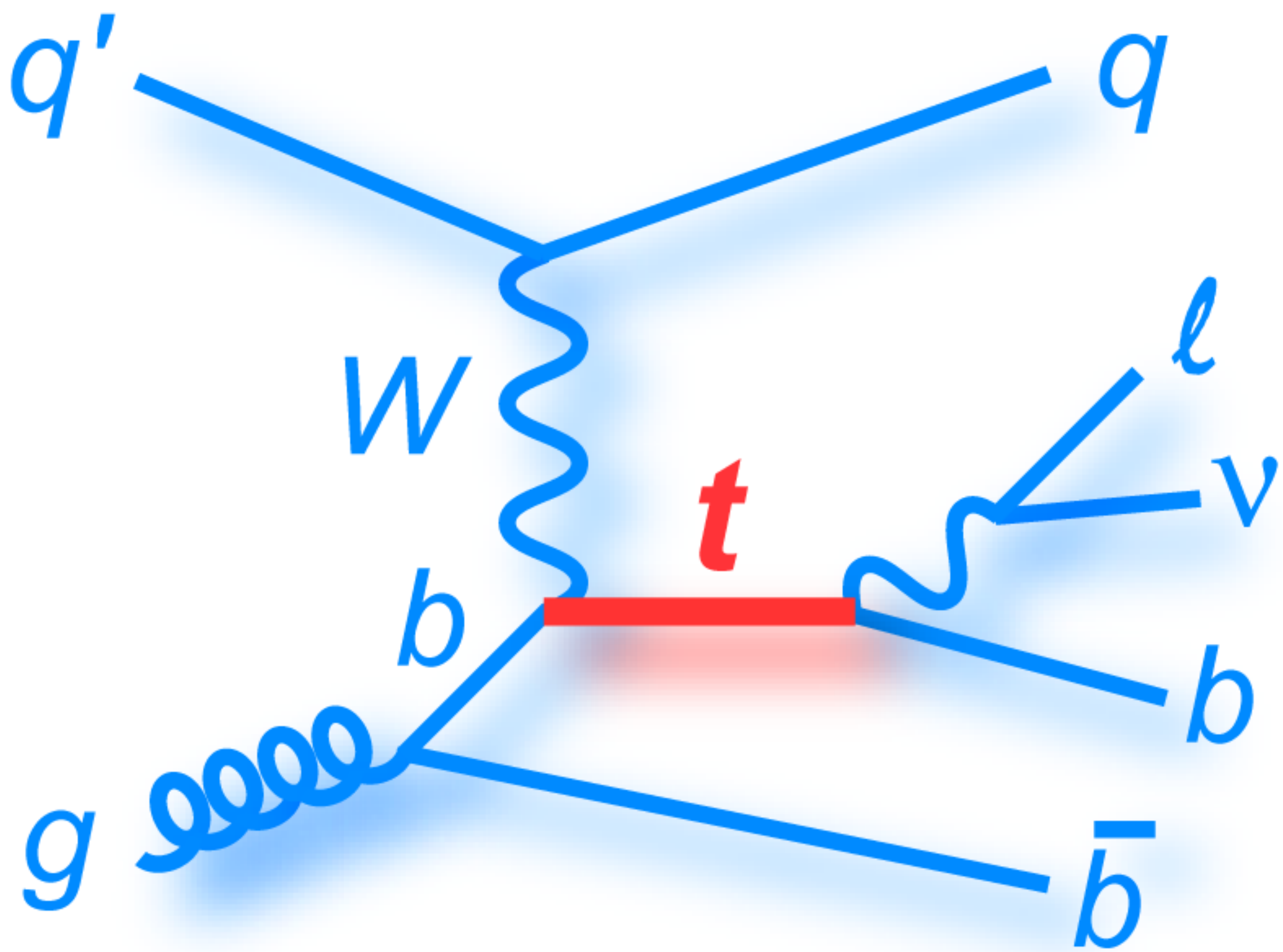
$$V_{CKM} = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

Ratio Constrained from Bs oscillations

Measured under certain assumptions

Cross-section and V_{tb} measurements

t - channel



→ Light flavor quark recoiling against top quark with high |η|

→ high p_T isolated lepton

→ Missing E_T

→ b-jet: high p_T, central

→ 2nd b-jet: low p_T, broad |η|, often escaping detector acceptance or selection criteria

Top reconstruction:

- Reconstruct W from $\mu\nu$

→ use m_W=80.4 GeV (PDG mass) constraint to resolve $p_{Z,\nu}$

- Add W candidate to b-jet to get top

Most abundant mode of production suitable for precise measurements

t-channel inclusive cross-section @13 TeV

- Analysis performed in electron and muon final state
- Typical 2J1T selection(2 jets, one of them b-tagged)
- Dominant backgrounds : $t\bar{t}$, W+Jets
- NN trained to discriminate t-channel from $t\bar{t}$ and W+Jets

➛ Input Variables: m_{top} , m_{jb}, m_T, light quark $|\eta|$ etc

- ML fit performed to NN discriminant in data to extract cross-section
- Dominant systematics: Parton shower modeling, b-tagging efficiency, JER

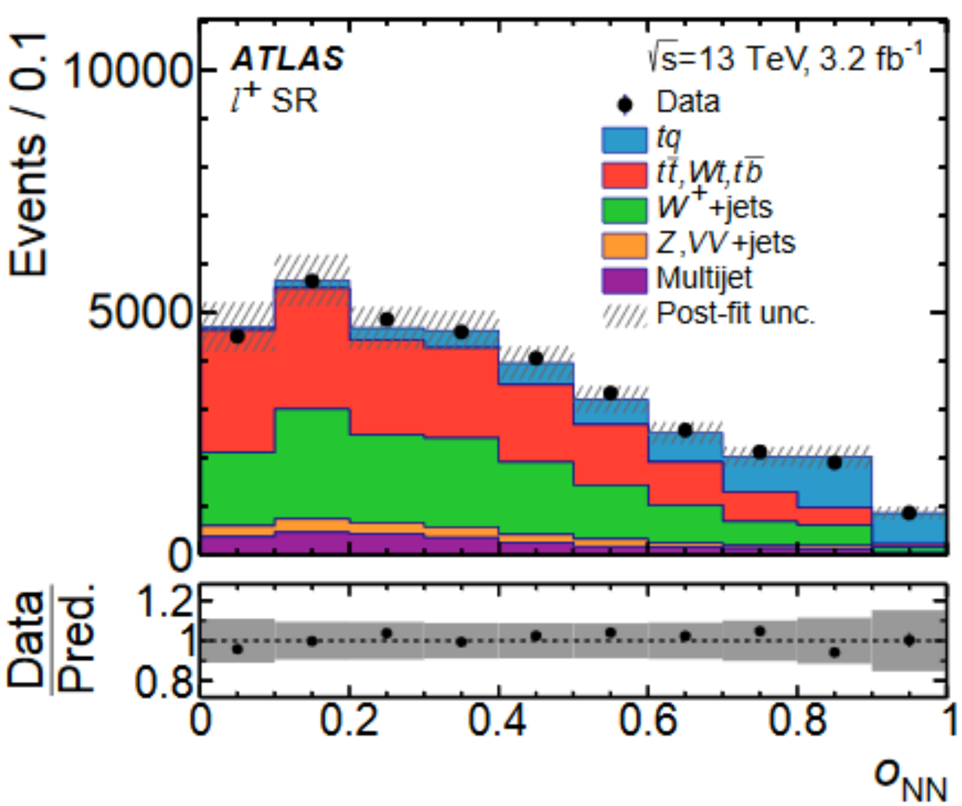
$\sigma(tq)$ = 156 ± 5 (stat) ± 27 (syst) ± 3 (lumi) pb

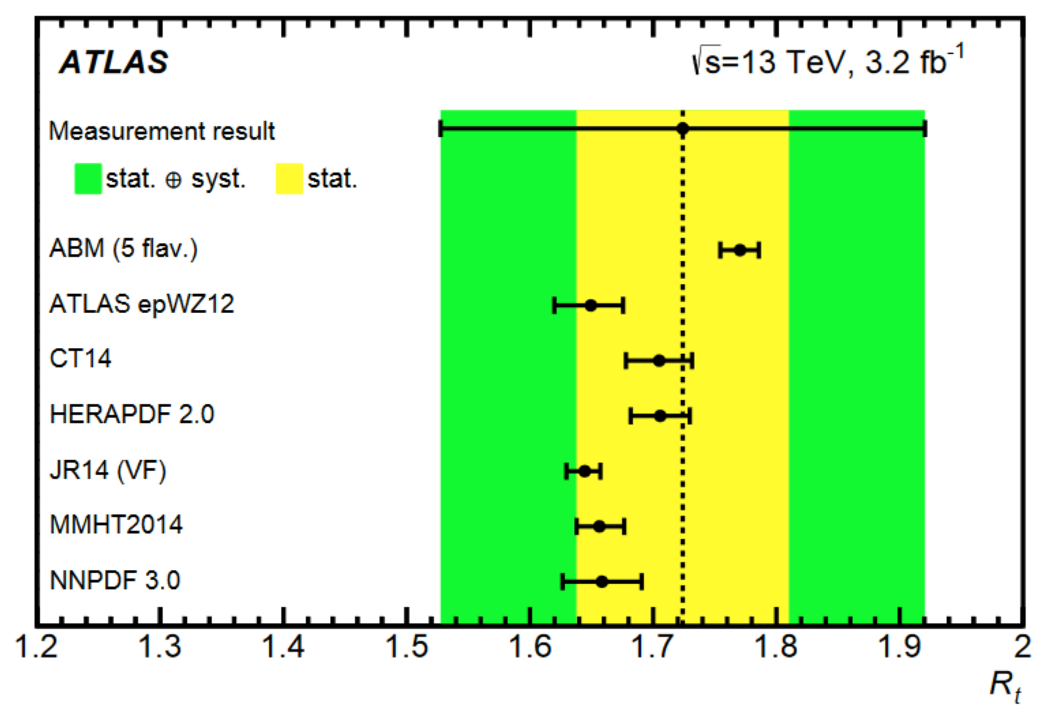
$\sigma(\bar{t}q)$ = 91 ± 4 (stat) ± 18 (syst) ± 2 (lumi) pb

$\sigma(tq + \bar{t}q)$ = 247 ± 6 (stat) ± 45 (syst) ± 5 (lumi) pb = 247 ± 46 pb

R_t = 1.72 ± 0.09 (stat) ± 0.18 (syst)

$|f_{LV} V_{tb}|$ = 1.07 ± 0.01 (stat) ± 0.09 (syst) ± 0.02 (theory) ± 0.01 (lumi)
= 1.07 ± 0.09





arXiv:1609.03920
Submitted to JHEP

t-channel inclusive cross-section @13 TeV

- Typical 2J1T selection
- Main Backgrounds: $t\bar{t}$, W+Jets, QCD multijet
- Data-driven QCD estimation from fit to m_T^W (inverting lepton isolation)
- MVA to discriminate t-channel signal against $t\bar{t}$ & W+Jets

➛Inputs variables: Light quark $|\eta|$, m_{top}, m_{jj}, m_T^W etc.

- $R_{t\text{-}ch}$ is extracted by floating it during fit to data
- Dominant uncertainties: Signal modeling, μ_R / μ_F scale, PDF

arXiv:1610.00678
Submitted to Phys.Letts.B

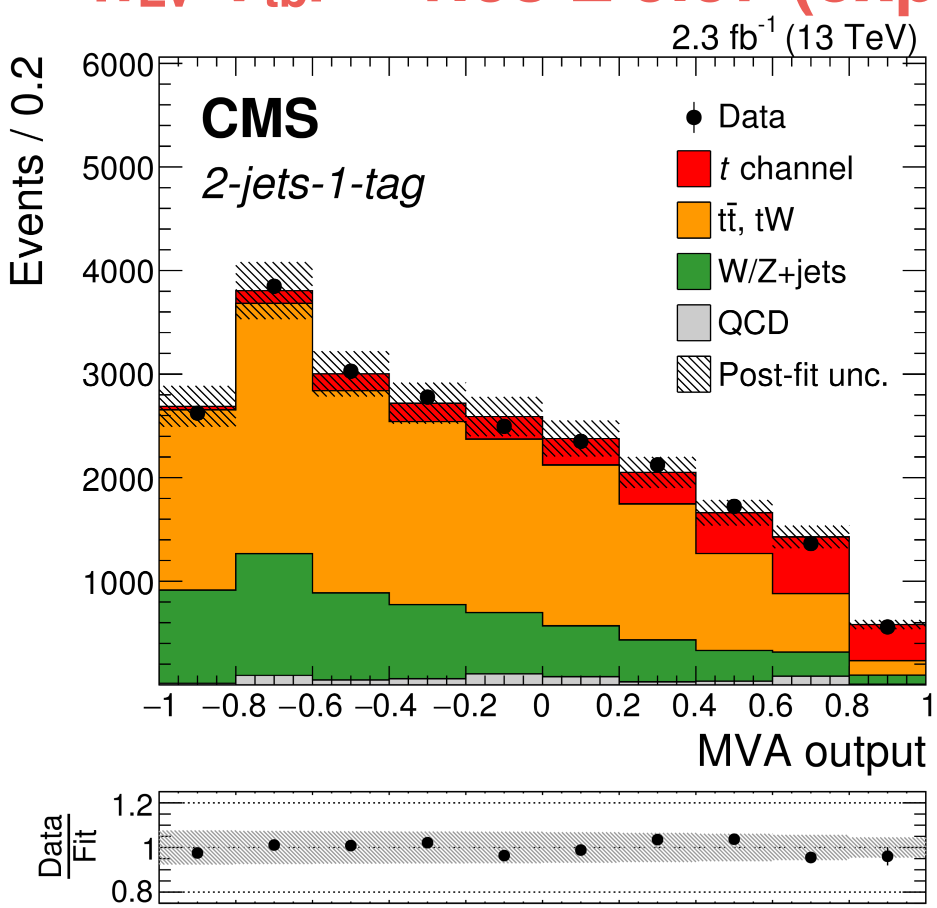
$\sigma_{t\text{-}ch,\, t}$ = 150 ± 8 (stat) ± 9 (exp) ± 18 (theo) ± 4(lumi) pb = 150 ± 22 pb

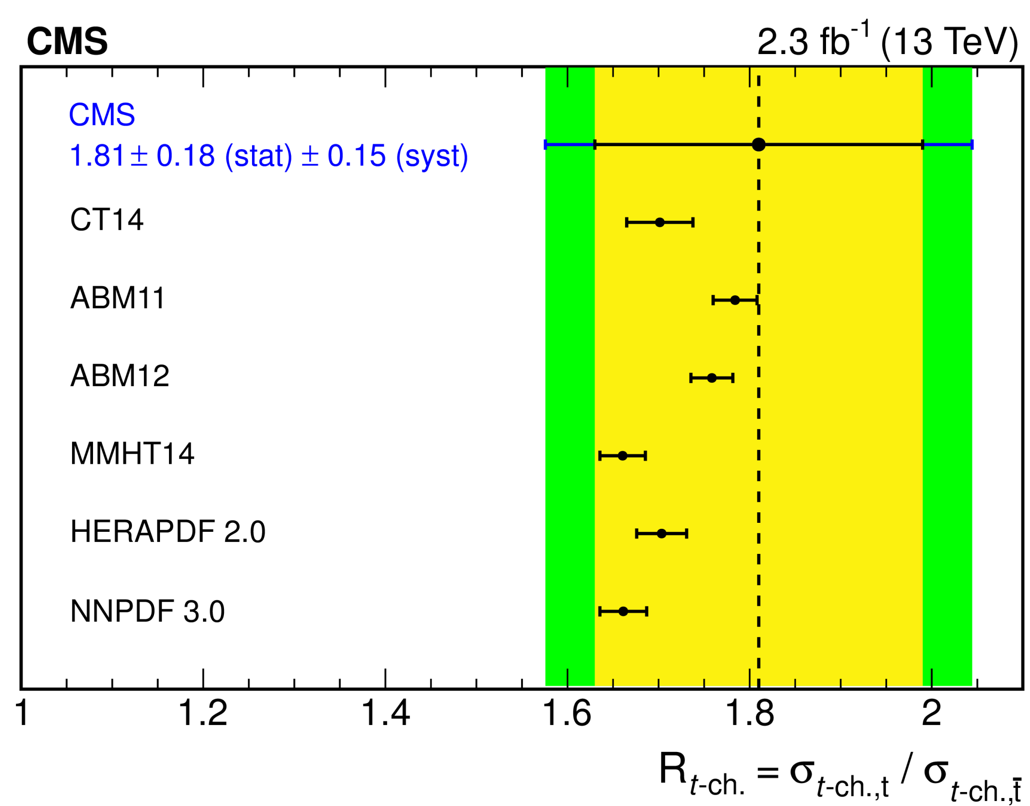
$R_{t\text{-}ch}$ = 1.81 ± 0.18(stat) ± 0.15 (syst)

$\sigma_{t\text{-}ch,\, \bar{t}}$ = 82 ± 10 (stat) ± 4 (exp) ± 11 (theo) ± 2 (lumi) pb = 82 ± 16 pb

$\sigma_{t\text{-}ch,\, t+\bar{t}}$ = 232 ± 13 (stat) ± 12 (exp) ± 26 (theo) ± 6 (lumi) pb = 232 ± 31 pb

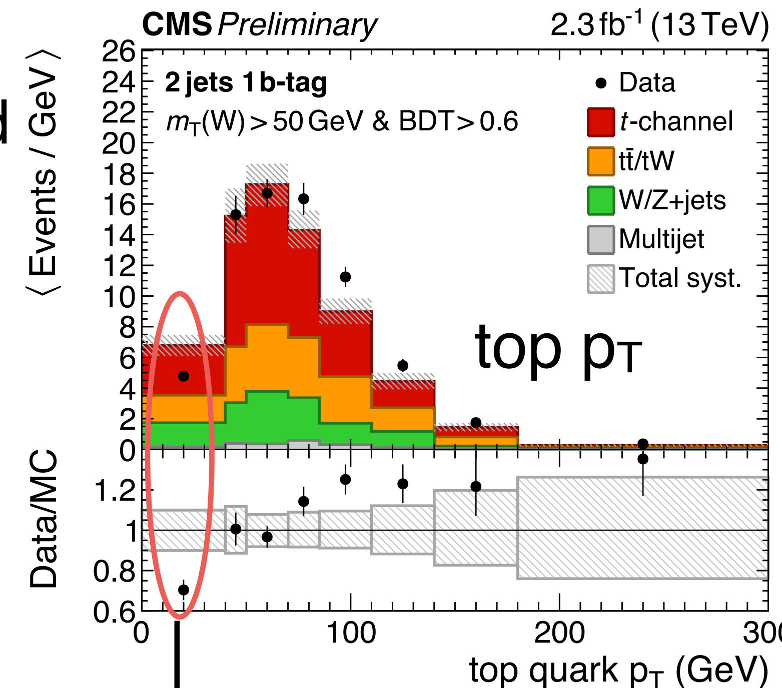
$|f_{LV} V_{tb}|$ = 1.03 ± 0.07 (exp) ± 0.02 (theo)

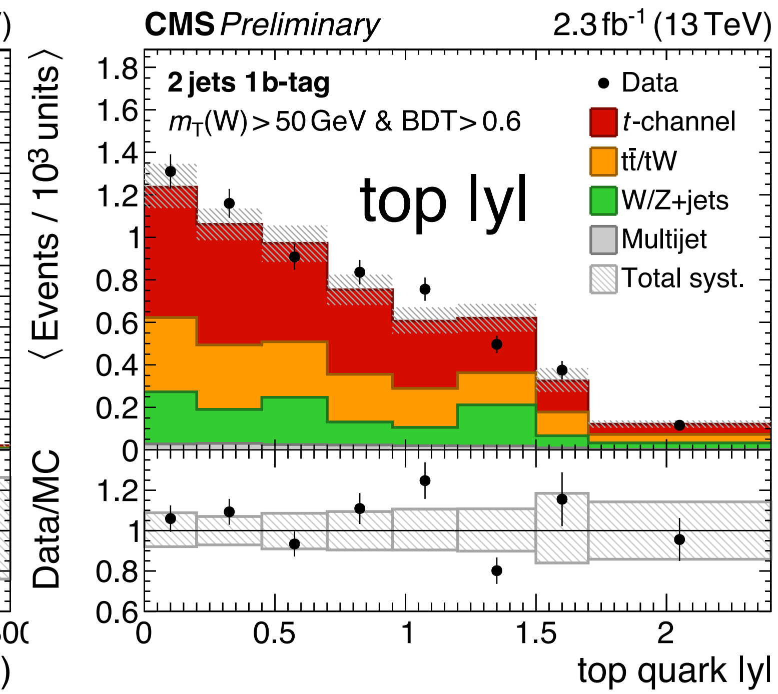




t-channel differential cross-section @13 TeV

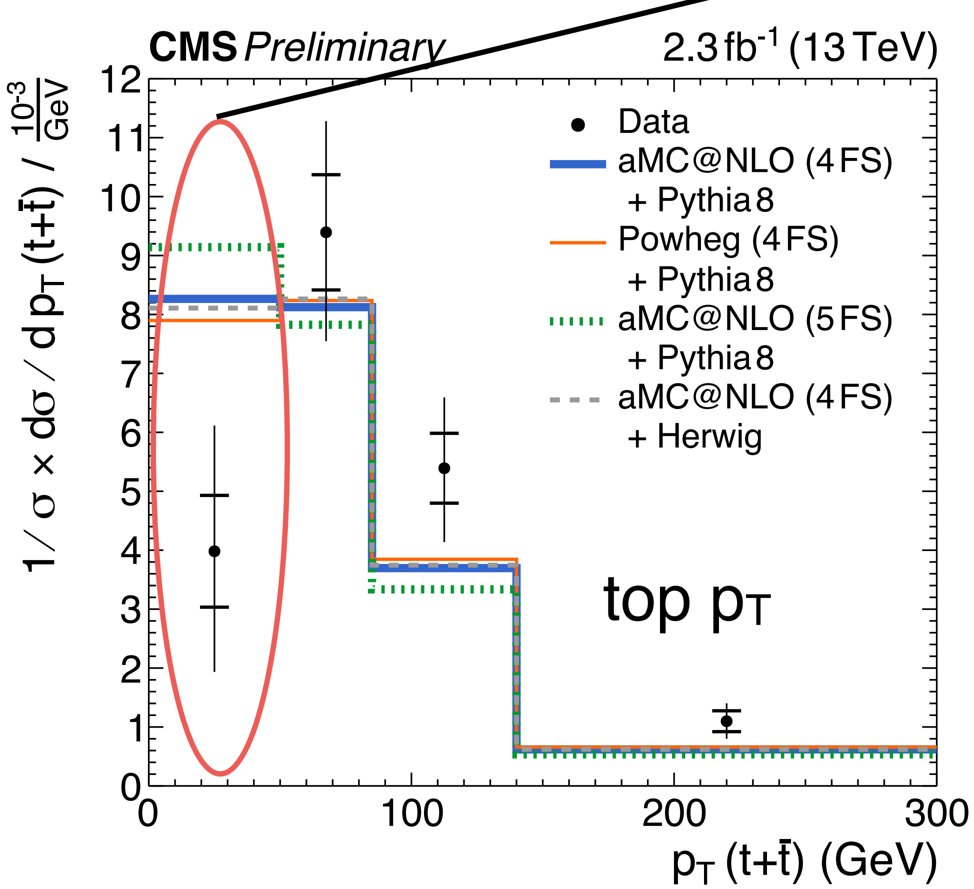
- 2J1T event selection
- BDT trained with variables uncorrelated to top p_T and |y|
- Cut on BDT output to obtain signal enriched sample
- Unfold background subtracted data to compare with MC prediction
- Dominant uncertainties: data statistics, μ_R / μ_F scale, top quark mass, JEC
- Harder p_T spectrum observed in data compared to prediction in signal enriched region

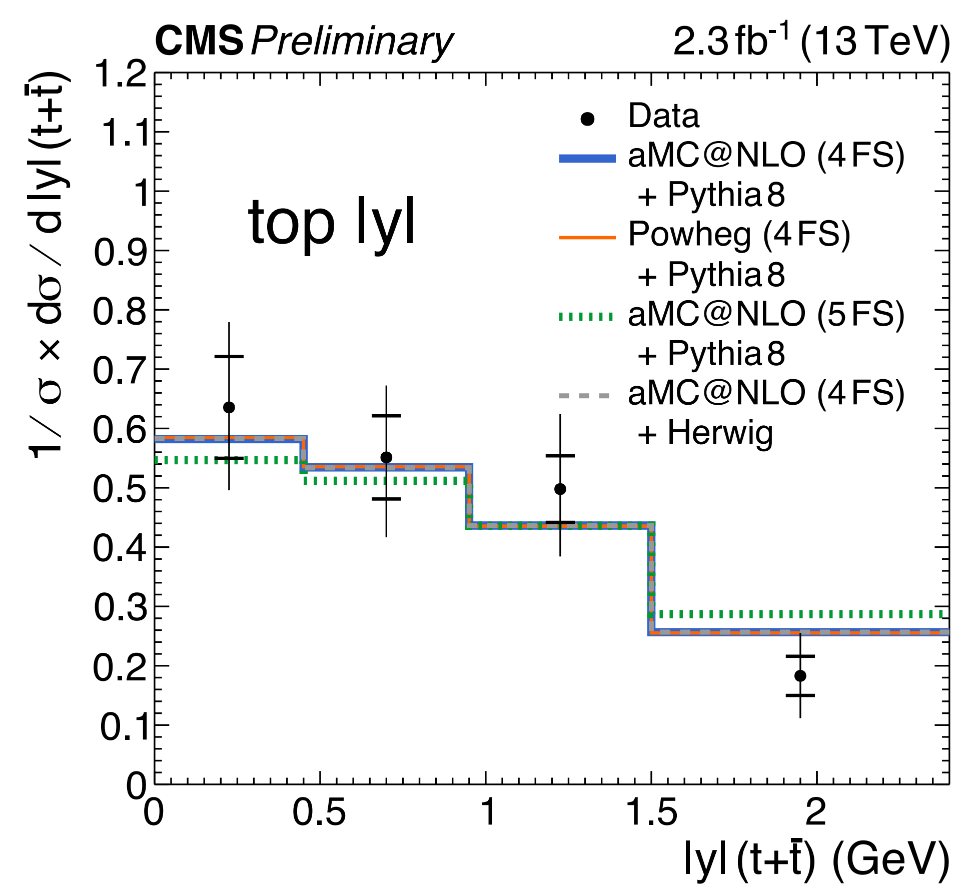




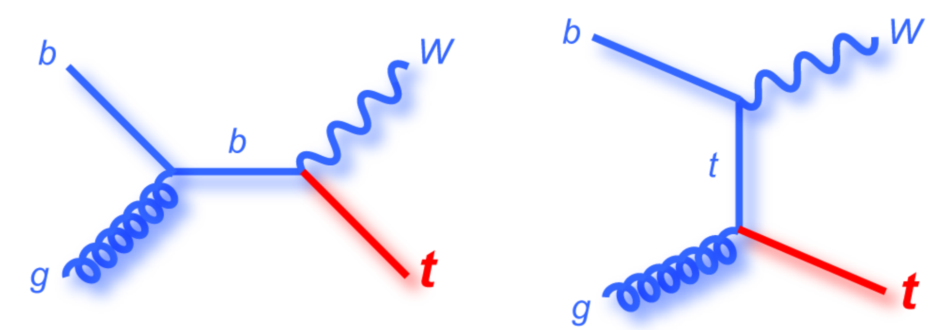
Due to low statistics in data and syst. effects

CMS-PAS-TOP-16-004





tW-channel@ 13 TeV

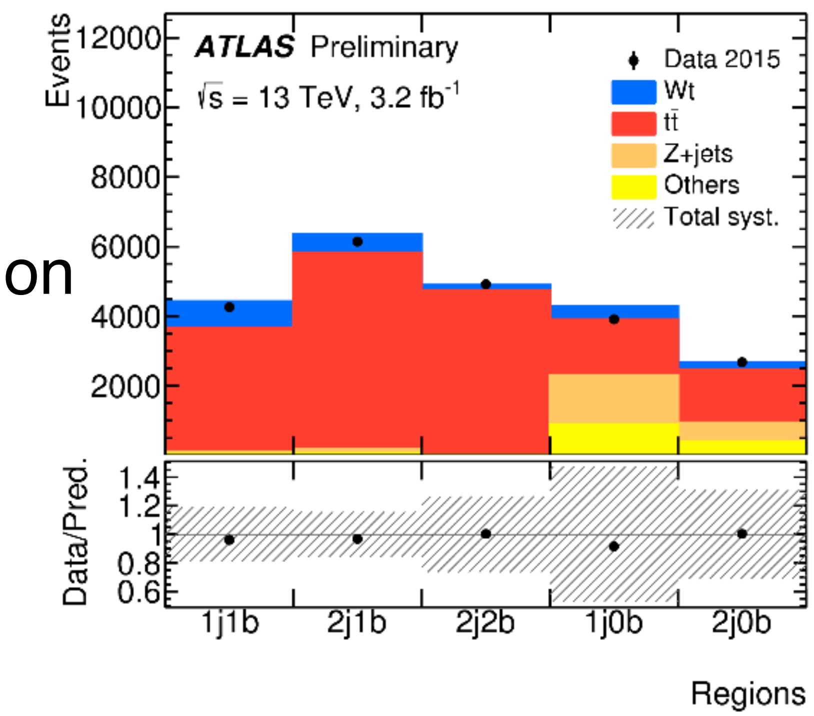


- Interference with $t\bar{t}$ at $\mathcal{O}(\alpha_s)$
- Dilepton (ee, eμ, μμ) final state
- Events categorized in bins of #of jets and # of b-tags
- Signal region: 1j1b (S/B ≈ 25%), 2j1b (S/B ≈ 10%)
- Dominant background: $t\bar{t}$
- 2 different BDTs trained in 1j1b and 2j1b region to discriminate signal from $t\bar{t}$ background
- $t\bar{t}$ normalization controlled by simultaneous fit in 2j2b region
- **Measurement:**

σ_{tW} = 94 ± 10 (stat) $^{+28}_{-23}$ (syst) pb

SM: σ(tW)= 71.1 ± 3.9 pb

=> 4.5σ Significance

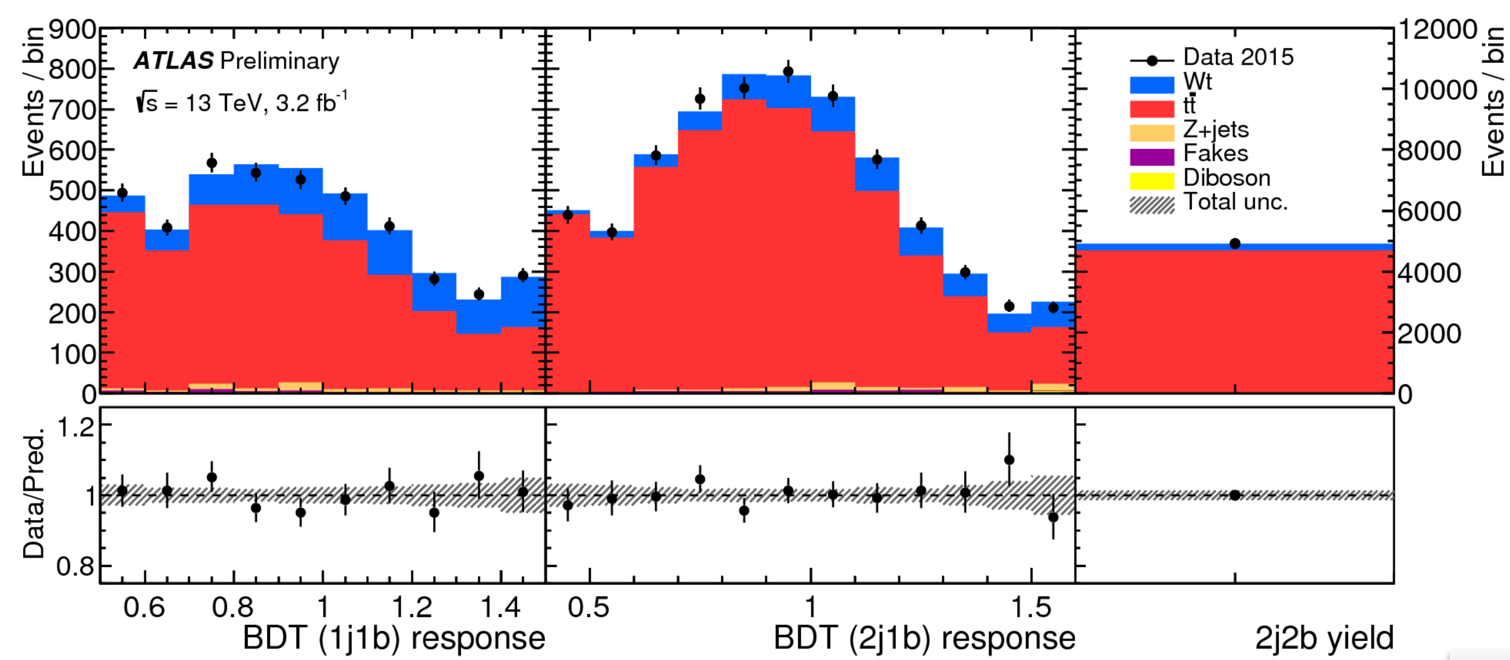


- **Dominant uncertainties:**

➛ JES (23%),

➛ NLO ME generator modeling (16%)

➛ Parton shower and hadronization modeling (20%)

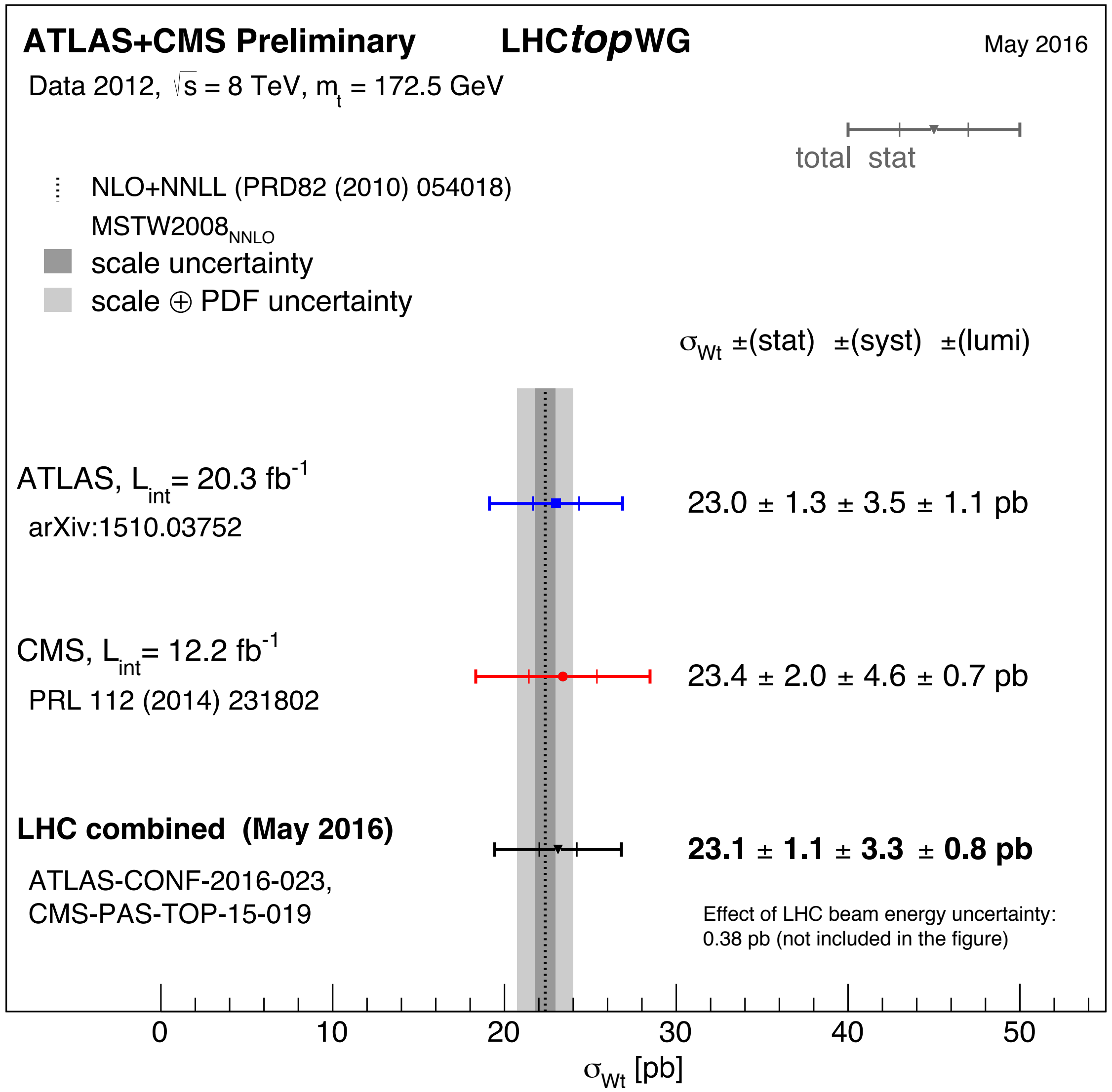


ATLAS-CONF-2016-065

tW-channel@ 8TeV

- Observation of tW -channel with significance > 5σ by both CMS and ATLAS at $\sqrt{s}$ = 8 TeV
➛ CMS: Phys. Rev. Lett. 112, 231802
➛ ATLAS: JHEP01(2016)064
- Cross-section measurements are combined

- Overall precision: 16 % (CMS: 23%, ATLAS:17%)
- Overall correlation: 40% (W_{CMS}=30%, W_{ATLAS}=70%)
- Dominant uncertainties: ISR/FSR and μ_R / μ_F scale (9.9%), Parton shower modeling and ME-PS matching threshold (5.4%) etc.



$$\sigma_{Wt} = 23.1 \pm 1.1(\text{stat}) \pm 3.3(\text{syst}) \pm 0.8(\text{lumi})\ \text{pb} = 23.1 \pm 3.6\ \text{pb}$$

$$|f_{LV} V_{tb}| = 1.02 \pm 0.09$$

CMS-PAS-TOP-15-019 **ATLAS-CONF-2016-023**

s-channel evidence @ 8TeV

- Lepton + 2 b-jet final state (2J2T)
- Dominant backgrounds : $t\bar{t}$, t-channel single top, W+bb
- Matrix-element-method to separate signal from backgrounds - approximate signal probability P(S|X)
- Profile likelihood fit of signal and background templates of P(S|X) to the data
- Test of B vs S+B hypothesis

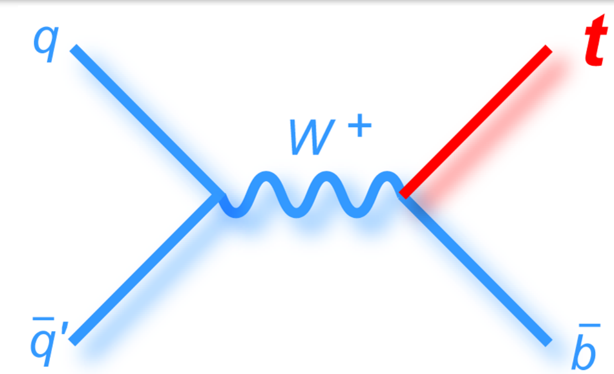
=> evidence with 3.2σ signal significance

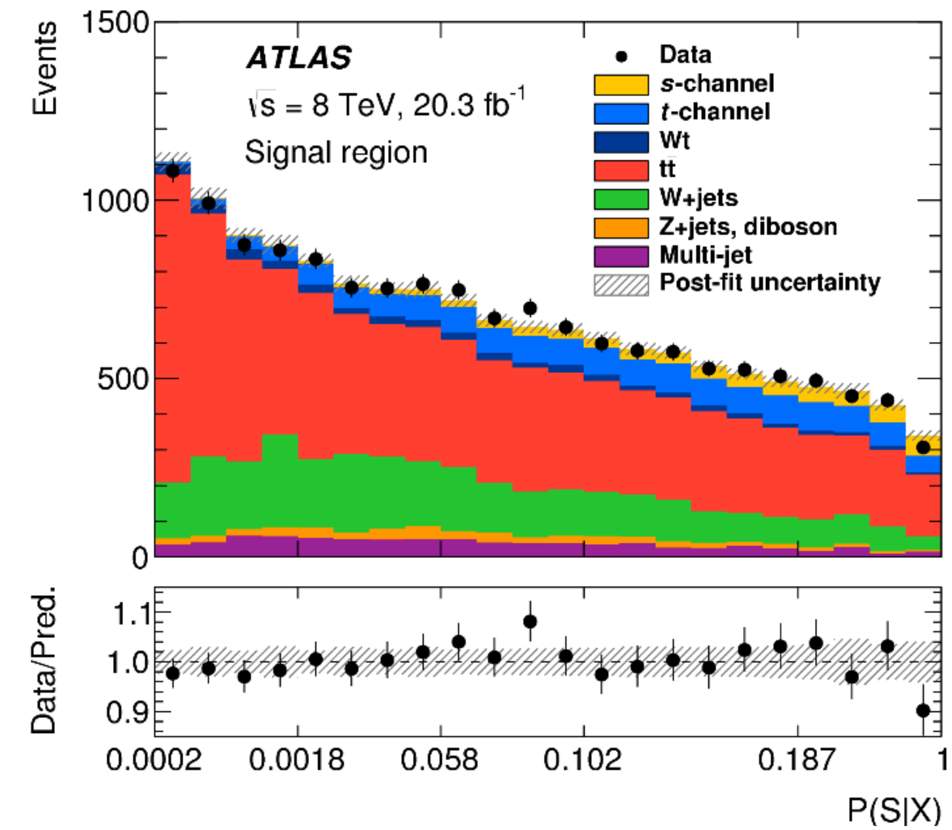
Measurement:

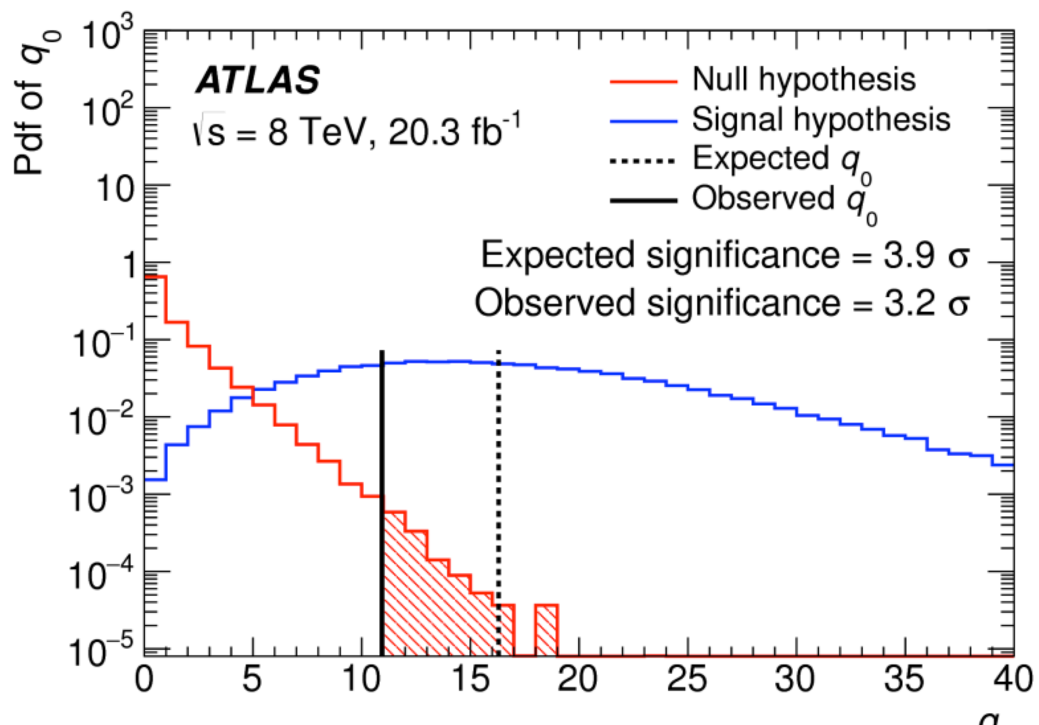
$\sigma = 4.8 \pm 0.8\ (\text{stat})\ ^{+1.6}_{-1.3}\ (\text{syst})\ \text{pb}$

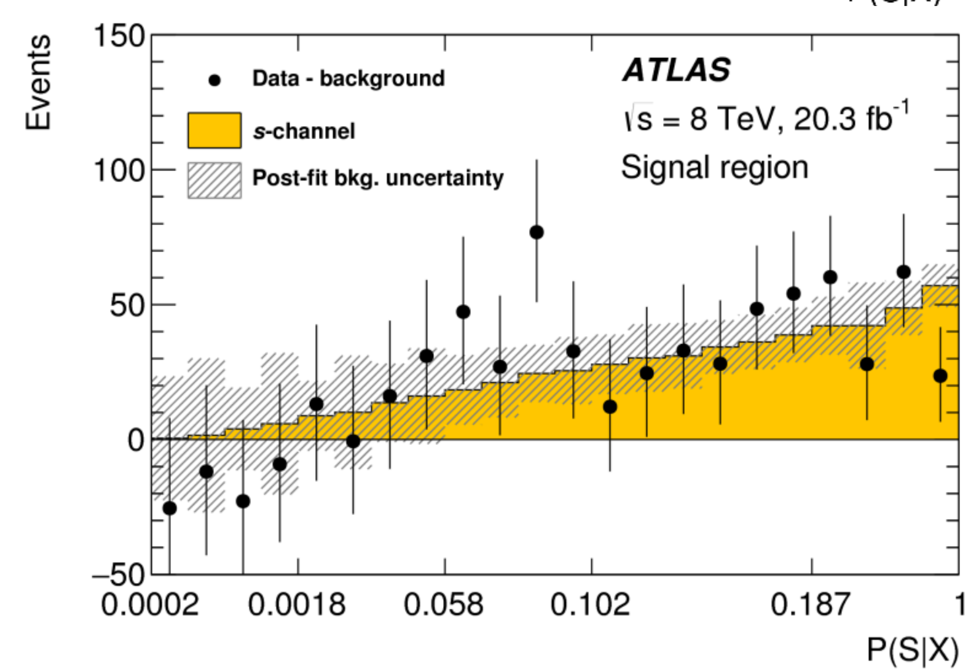
$\sigma_{SM} = 5.2 \pm 0.2\ \text{pb}$

➛ Precision limited by data statistics





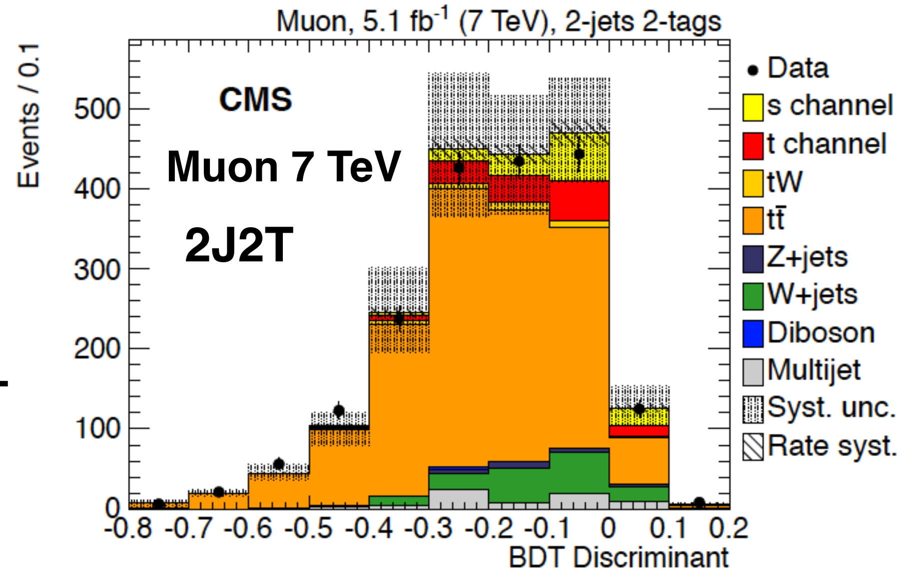


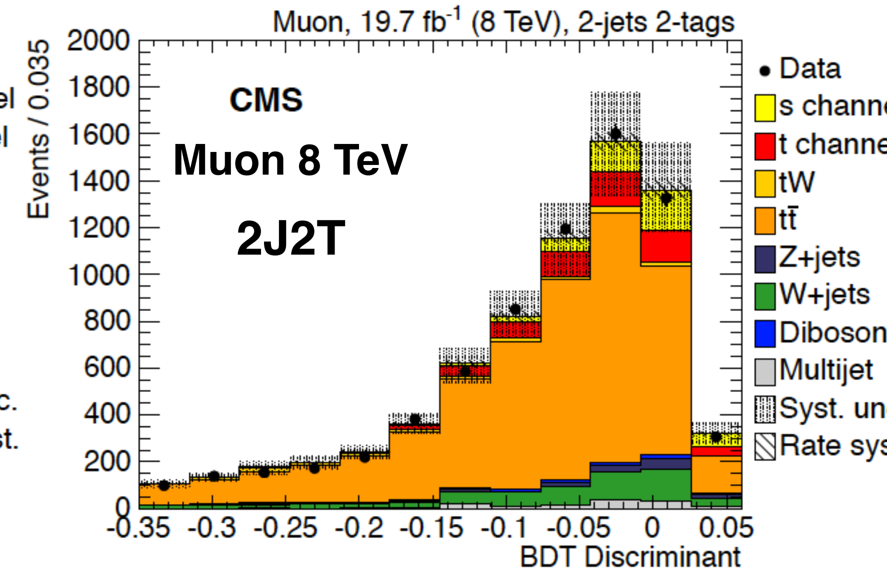


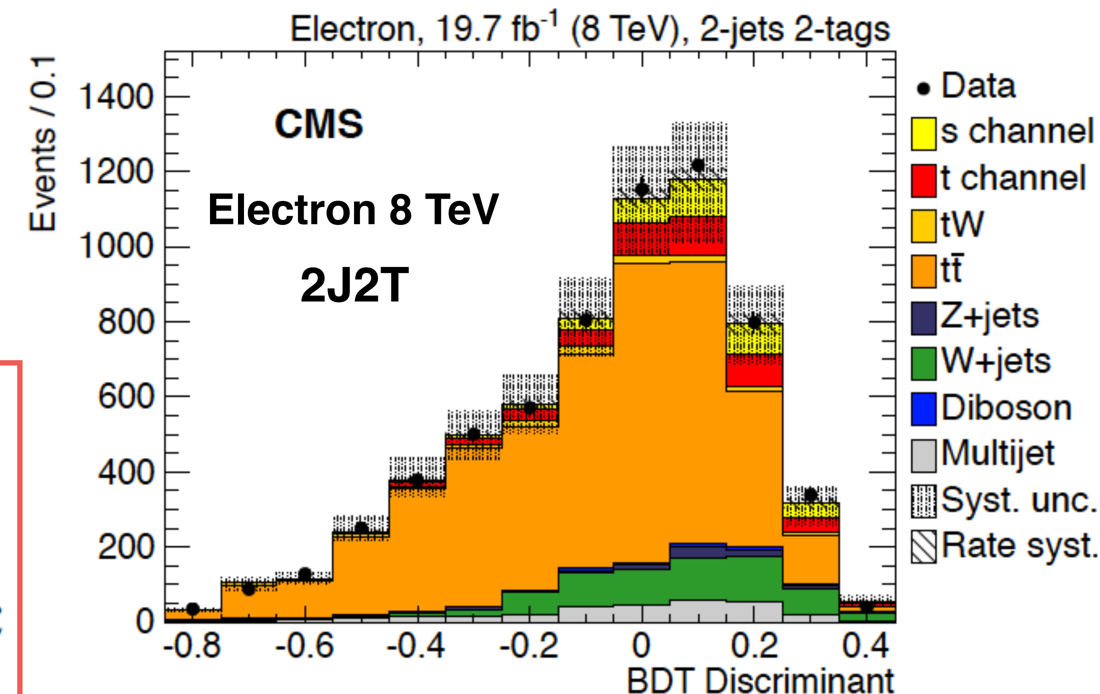
PLB 756 (2016) 228 -246

s - channel in CMS

- Lepton + 2 b-jet final state
- Tiny signal in comparison with backgrounds
- Dominant backgrounds : $t\bar{t}$, t-channel single top, W+bb
- BDTs trained in 2J2T and 3J2T
  - ☛ s-channel vs rest in 2J2T
  - ☛ $t\bar{t}$ vs rest in 3J2T
- Likelihood fit to BDTs
- Largest systematic uncertainties:
  - ☛ μ_R / μ_F scale, ME-PS
  - ☛ JES, JER, $\not{E}_T$





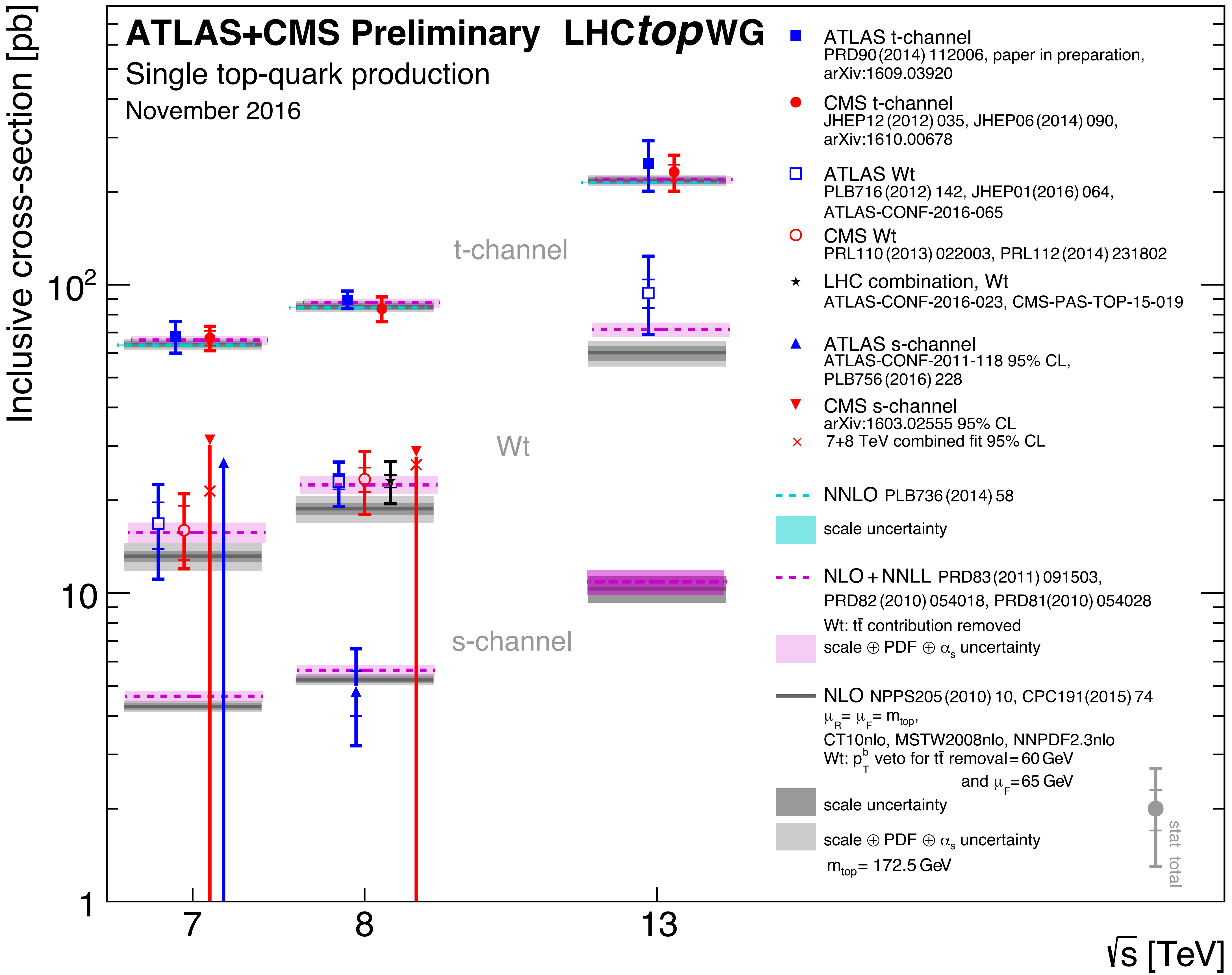


$$\sigma_s = 7.1 \pm 8.1\,(\text{stat} + \text{syst})\,\text{pb}, \quad \text{muon channel, 7 TeV;}$$
$$\sigma_s = 11.7 \pm 7.5\,(\text{stat} + \text{syst})\,\text{pb}, \quad \text{muon channel, 8 TeV;}$$
$$\sigma_s = 16.8 \pm 9.1\,(\text{stat} + \text{syst})\,\text{pb}, \quad \text{electron channel, 8 TeV;}$$
$$\sigma_s = 13.4 \pm 7.3\,(\text{stat} + \text{syst})\,\text{pb}, \quad \text{combined, 8 TeV.}$$

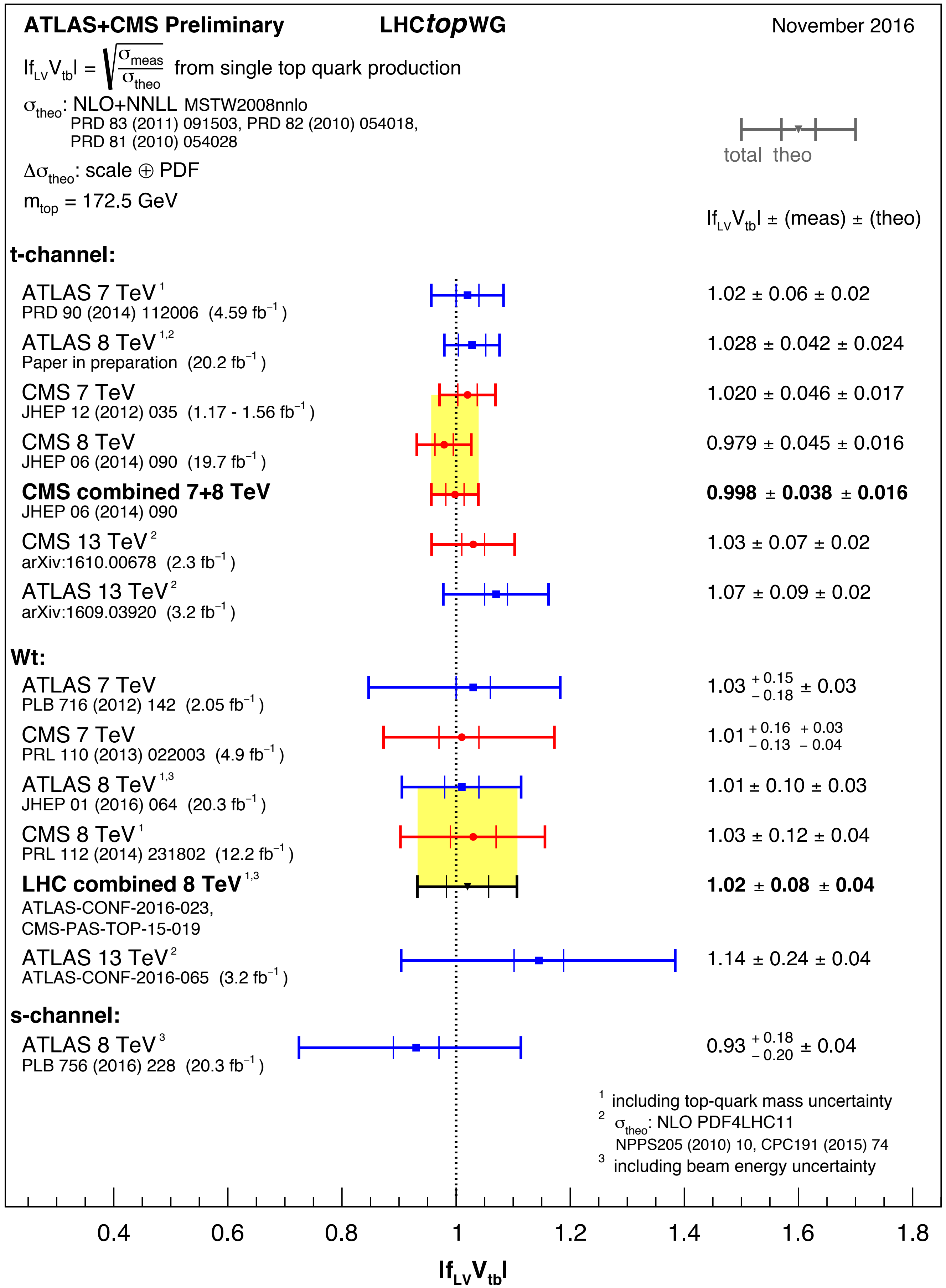
JHEP 09 (2016) 027

Channel	Observed UL	Expected UL—SM signal	Expected UL—no signal
μ, 7 TeV	31.4 pb	25.4 [19.0, 36.6] pb	20.2 pb
μ+e, 8 TeV	28.8 pb	20.5 [13.4, 26.7] pb	15.6 pb
7+8 TeV	4.7	3.1 [2.1, 4.0]	2.2

Summary of cross-section measurements



Summary of V_{tb} measurements

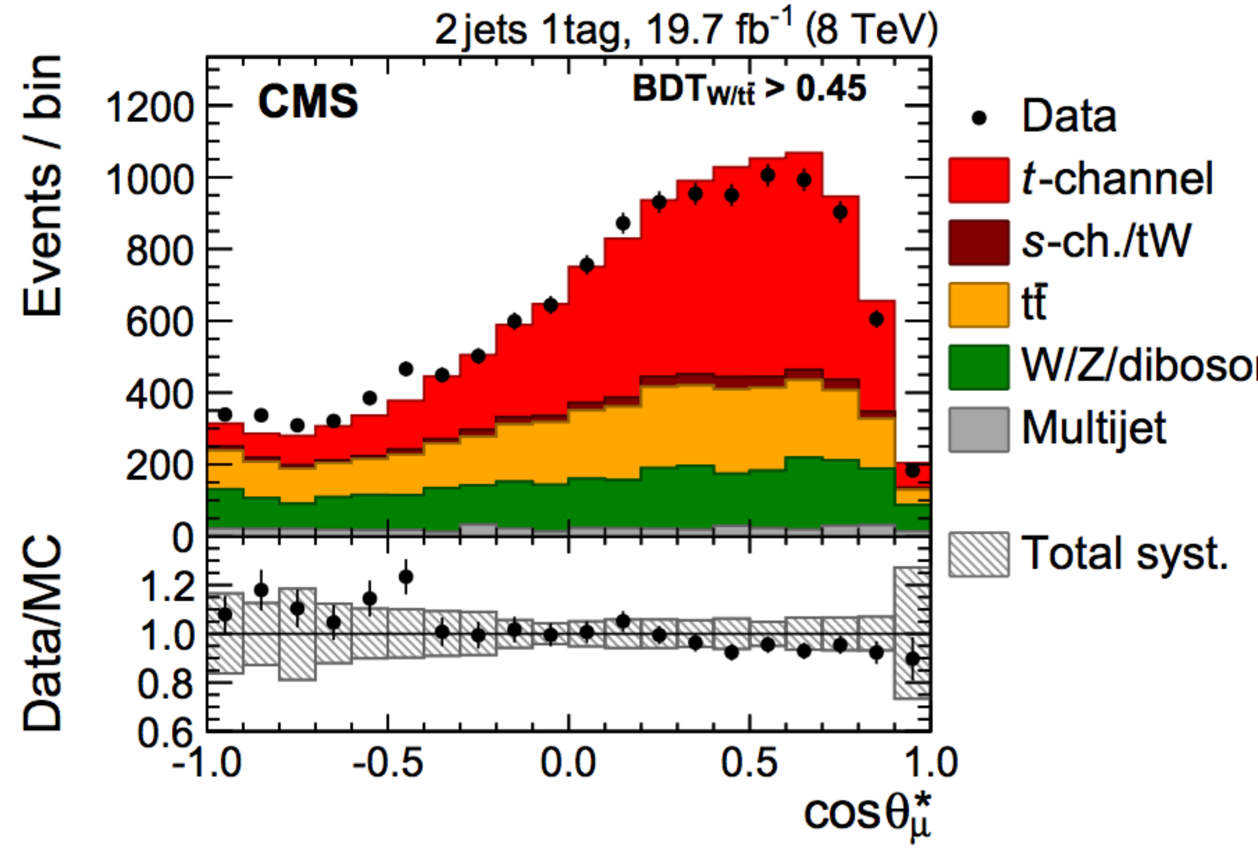


Probing the tWb vertex using t-channel single top events

Top polarization in t - channel

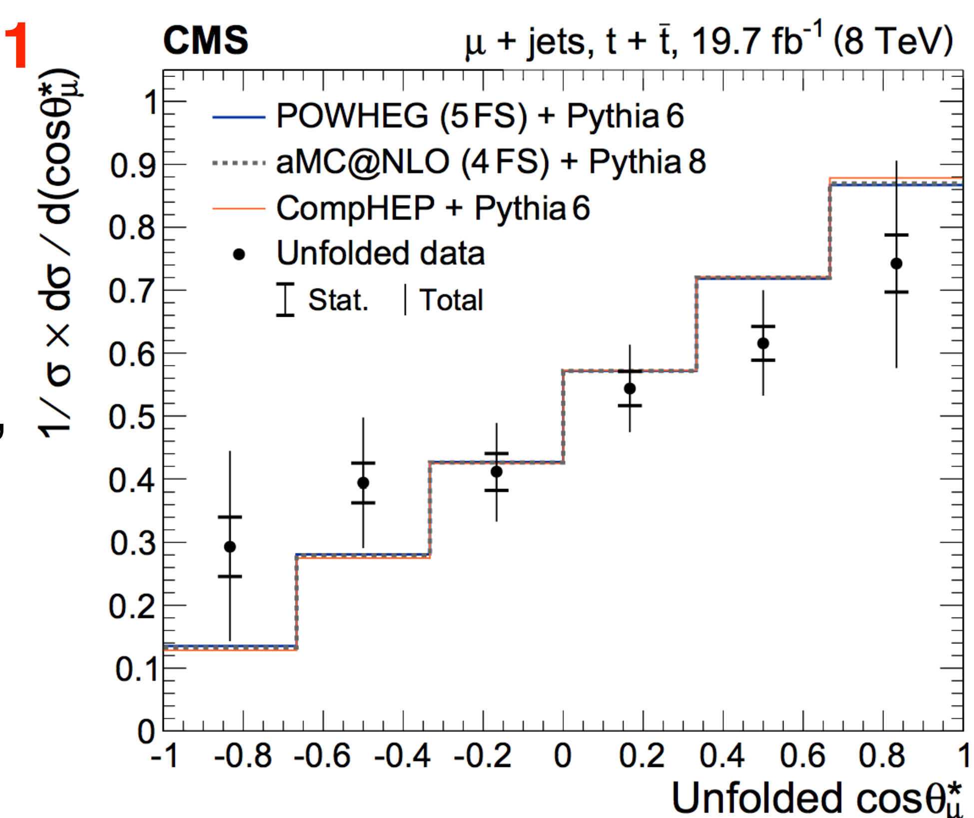
$$\frac{1}{\sigma}\frac{d\sigma}{d\cos\theta_X^*} = \frac{1}{2}(1 + P_t^{(\vec{s})}\alpha_X \cos\theta_X^*) = \left(\frac{1}{2} + A_X\cos\theta_X^*\right) \quad A_X \equiv \frac{1}{2}P_t\,\alpha_X = \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

- θ_X^* = Angle between muon and light quark in top rest frame
- P_t : Top polarization , $\alpha_X = 1$ in SM
- 2J1T event selection
- Fit BDT discriminant to determine signal and background normalization
- Cut on BDT output to select signal enriched region
- Unfolding to correct for detector effects



A_μ^{meas} = 0.26 ± 0.03 (stat.) ± 0.10 (syst) = 0.26 ± 0.11
A_μ^{SM} = 0.44
=> Measured value ~2σ away from SM prediction

- JES, JER, W+ heavy flavor jets modeling, Q^2 scale, PDF etc. are the main source of uncertainties



JHEP 04 (2016) 073

Anomalous couplings at 7 TeV

General structure of tWb vertex : **JHEP 04 (2016) 023**

$$\mathcal{L}_{\mathrm{tWb}}^{\mathrm{anom.}} = -\frac{g}{\sqrt{2}}\bar{\mathrm{b}}\gamma^{\mu}(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}})\mathrm{t}W^{-}{}_{\mu} - \frac{g}{\sqrt{2}}\bar{\mathrm{b}}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_{\mathrm{W}}}(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}})\mathrm{t}W^{-}{}_{\mu} + \mathrm{h.c.},$$

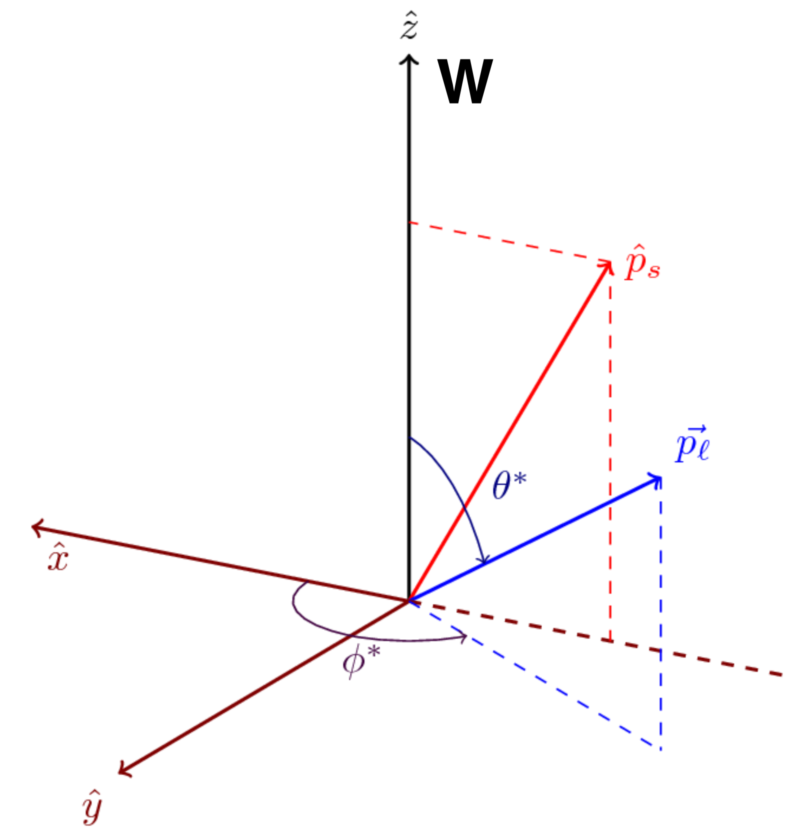
- SM predicts: $V_L = V_{tb}$, $V_R = g_L = g_R = 0$
- Measurement of angular distrbn. of $\ell^{\pm}$ using t-channel

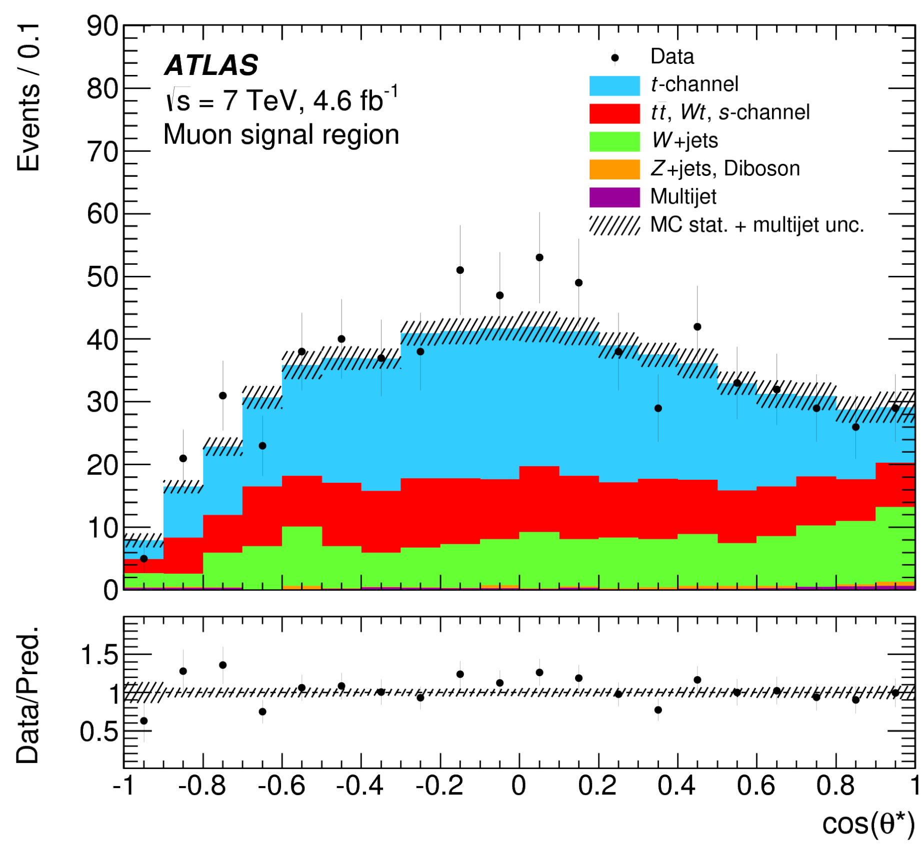
➛ constraint on coupling structure

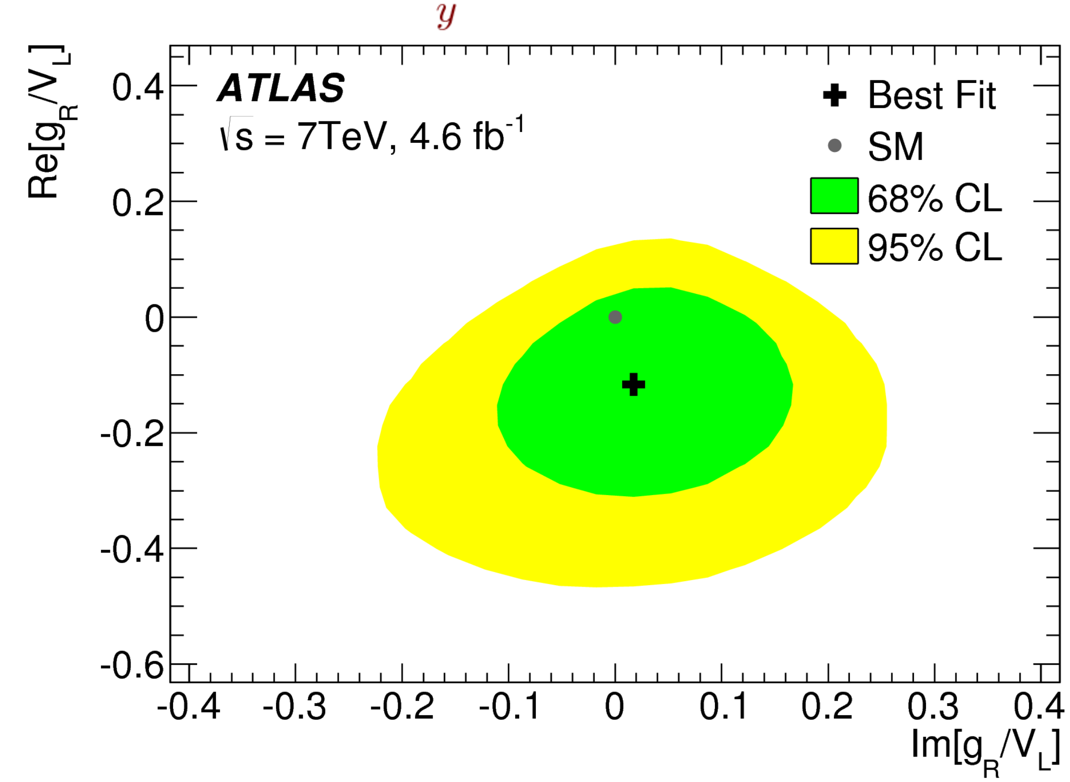
- Select a relatively pure sample of t-channel events
- Define prob. density of ($\cos\theta^*$, ϕ^*) and construct a likelihood
- Result from a 2-Dim fit:

  $Re[g_R/V_L] \in [-0.36,0.10]$, $Im[g_R/V_L] \in [-0.17,0.23]$

➛ consistent with SM

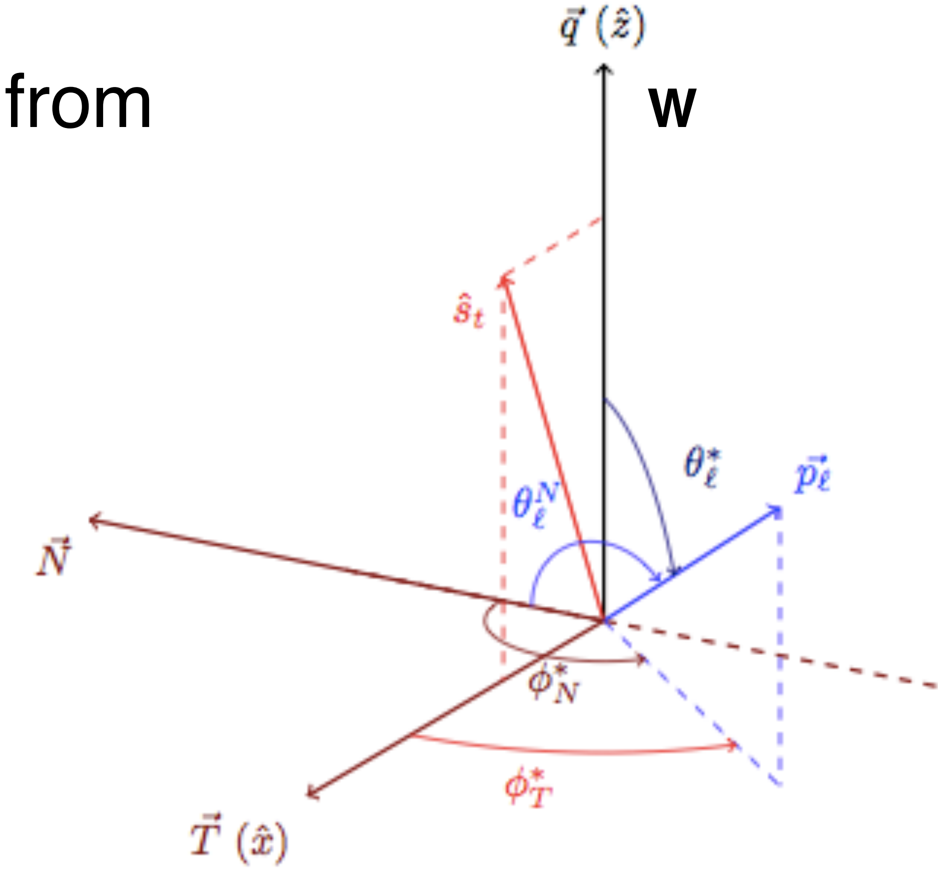






Anomalous couplings at 8 TeV

Top and W polarization observables can be extracted from asymmetries in different angular distributions



Asymmetry	Angular observable	Polarisation observable	SM prediction
$A_{\rm FB}^{\ell}$	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
$A_{\rm FB}^{tW}$	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P\,(F_{\rm R}+F_{\rm L})$	0.10
$A_{\rm FB}$	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}\,(F_{\rm R}-F_{\rm L})$	−0.23
$A_{\rm EC}$	$\cos\theta_\ell^*$	$\frac{3}{8}\sqrt{\frac{3}{2}}\langle T_0\rangle = \frac{3}{16}\,(1-3F_0)$	−0.20
$A_{\rm FB}^{T}$	$\cos\theta_\ell^T$	$\frac{3}{4}\langle S_1\rangle$	0.34
$A_{\rm FB}^{N}$	$\cos\theta_\ell^N$	$-\frac{3}{4}\langle S_2\rangle$	0
$A_{\rm FB}^{T,\phi}$	$\cos\theta_\ell^* \cos\phi_T^*$	$-\frac{2}{\pi}\langle A_1\rangle$	−0.14
$A_{\rm FB}^{N,\phi}$	$\cos\theta_\ell^* \cos\phi_N^*$	$\frac{2}{\pi}\langle A_2\rangle$	0

Asymmetries

$$A_{\rm FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)},$$

$$A_{\rm EC} = \frac{N(|\cos\theta| > \frac{1}{2}) - N(|\cos\theta| < \frac{1}{2})}{N(|\cos\theta| > \frac{1}{2}) + N(|\cos\theta| < \frac{1}{2})}$$

W boson rest frame:

$$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_\ell^*)d\phi_\ell^*} = \frac{3}{8\pi}\left\{\frac{2}{3} - \frac{1}{\sqrt{6}} <T_0> \left(1-3\cos^2\theta_\ell^*\right) + <S_3>\cos\theta_\ell^* \right.$$
$$+ <S_1>\cos\phi_\ell^*\sin\theta_\ell^* + <S_2>\sin\phi_\ell^*\sin\theta_\ell^*$$
$$\left. - <A_1>\cos\phi_\ell^*\sin 2\theta_\ell^* - <A_2>\sin\phi_\ell^*\sin 2\theta_\ell^* \right\}.$$

Top rest frame: $$\frac{1}{\Gamma}\frac{d\Gamma}{d(\cos\theta_X)} = \frac{1}{2}(1+\alpha_X P\cos\theta_X)$$

ATLAS-CONF-2016-097

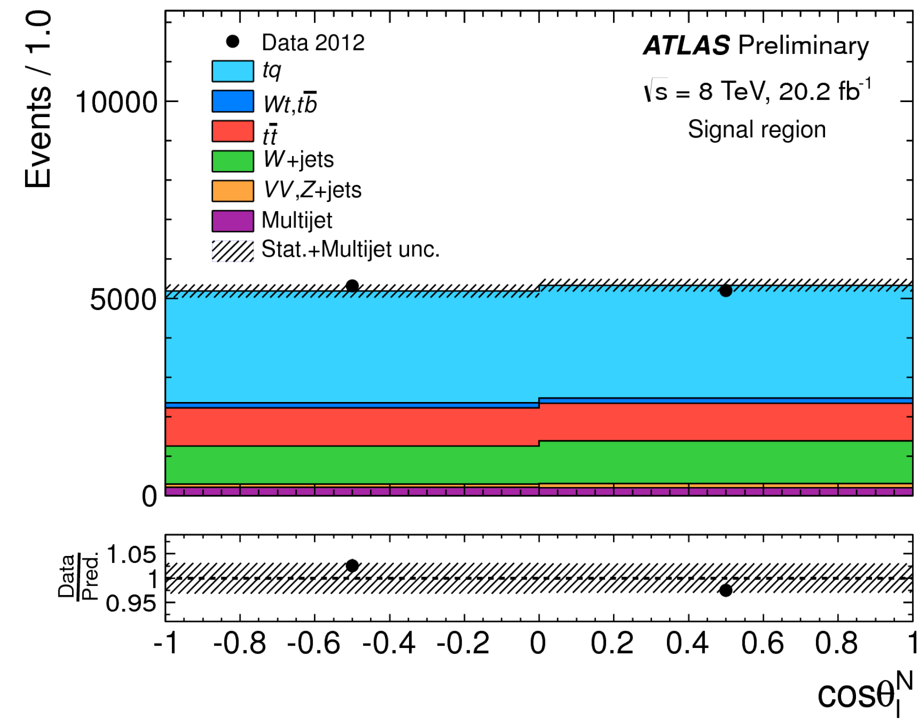
Anomalous couplings at 8 TeV

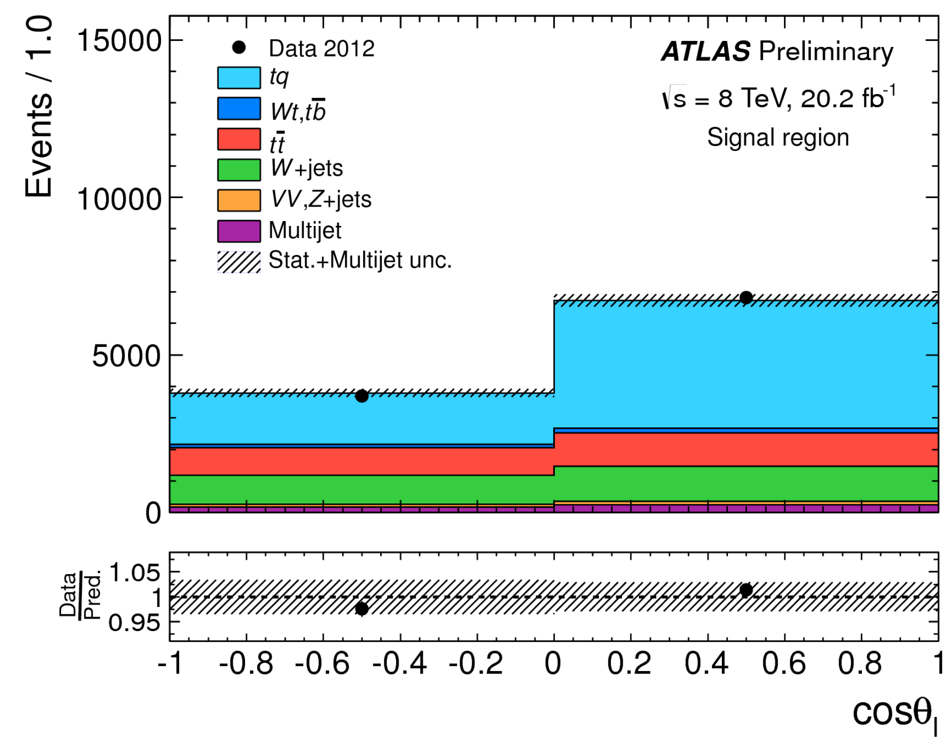
- Measured angular distributions are unfolded at parton level after background subtraction
- Angular asymmetries are extracted from unfolded distribution
- Dominant uncertainties: data statistics, signal and $t\bar{t}$ modeling , JES etc.

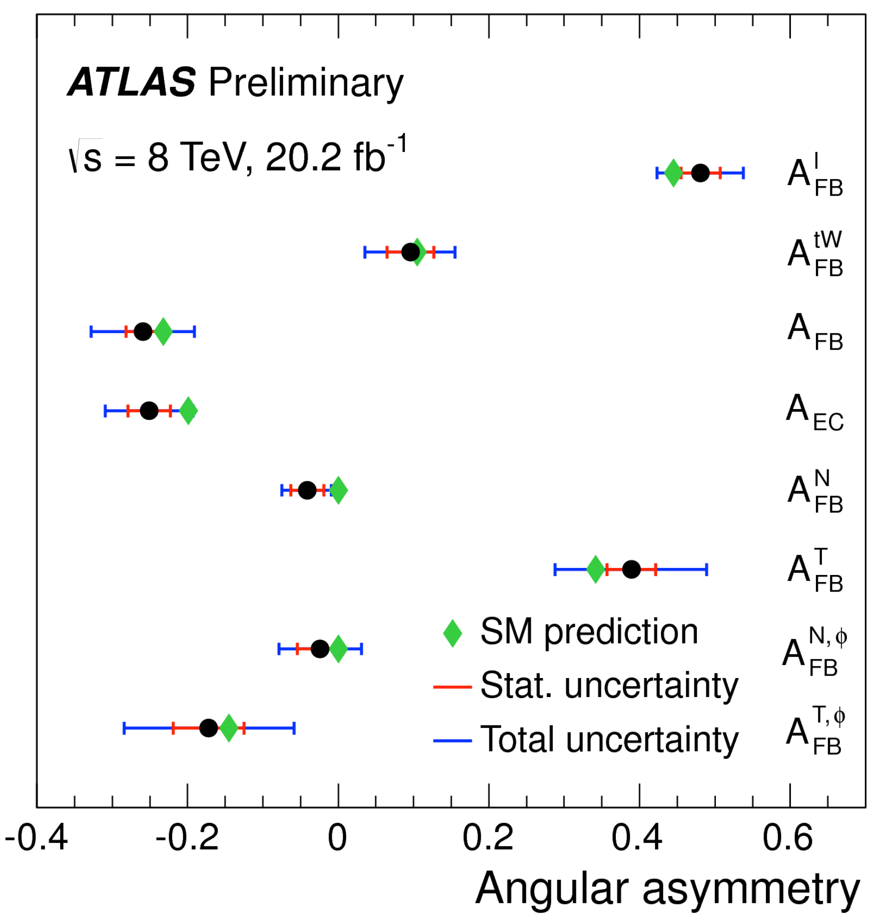
$\alpha_l P = 0.96 \pm 0.05\ (stat) \pm 0.10\ (syst)$

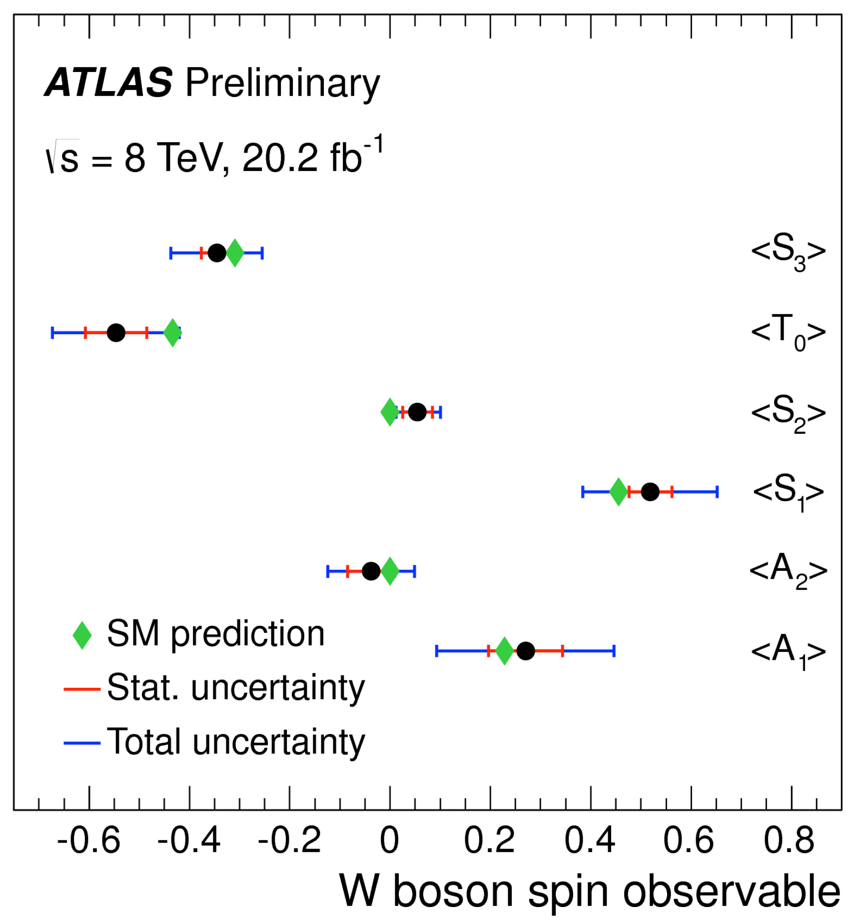
$P(F_R + F_L) = 0.26 \pm 0.08\ (stat) \pm 0.14\ (syst)$

$Im\ g_R \in [-0.17, 0.06]$









ATLAS-CONF-2016-097

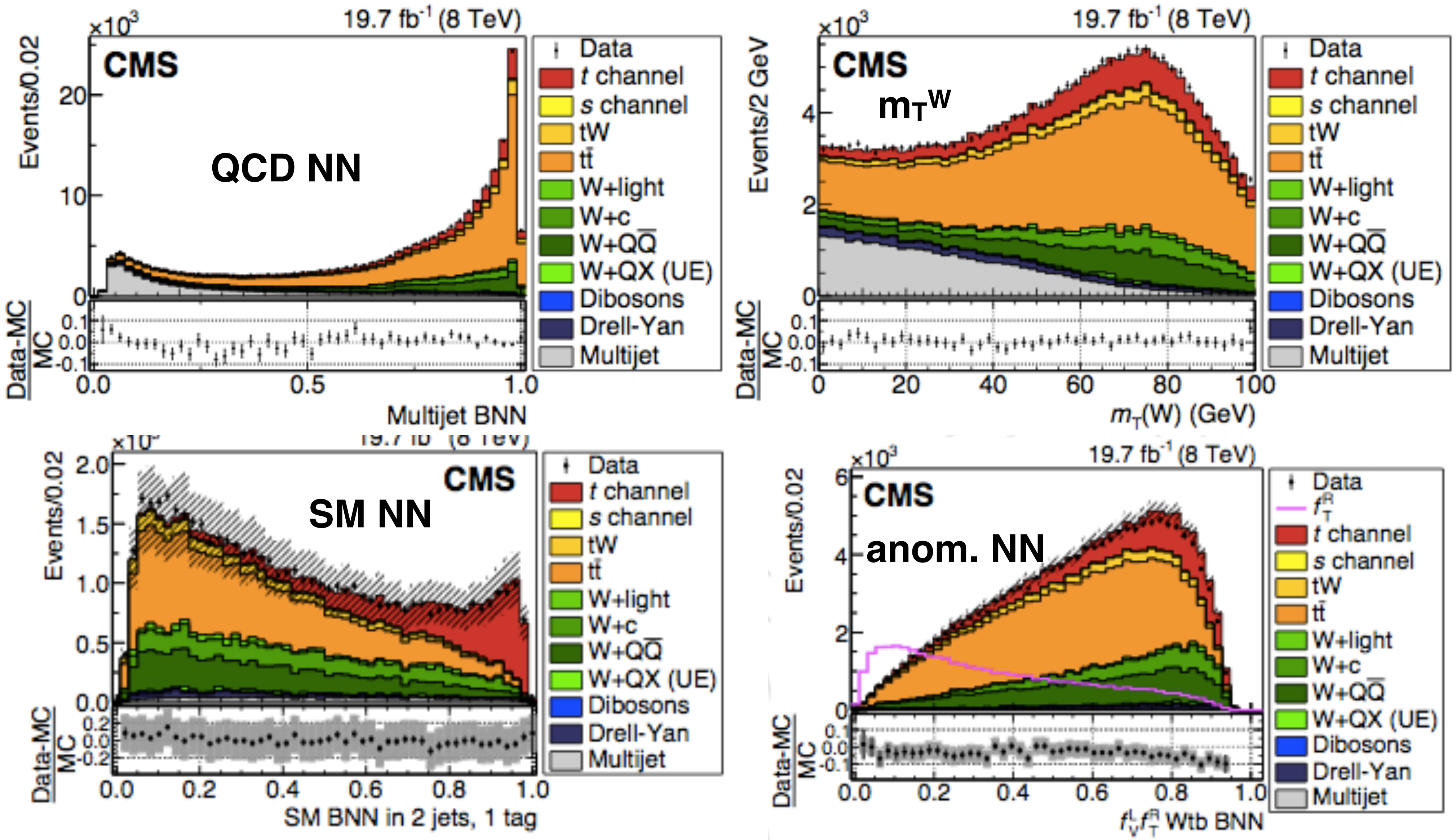
Anomalous couplings with Run-I data

$$\mathfrak{L} = \frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(f_V^L P_L + f_V^R P_R\right) tW_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{\sigma^{\mu\nu}\partial_{\nu}W_{\mu}^{-}}{M_W}\left(f_T^L P_L + f_T^R P_R\right) t + \text{h.c.},$$

SM => $f_V^L = V_{tb}$, $f_V^R = f_T^L = f_T^R = 0$

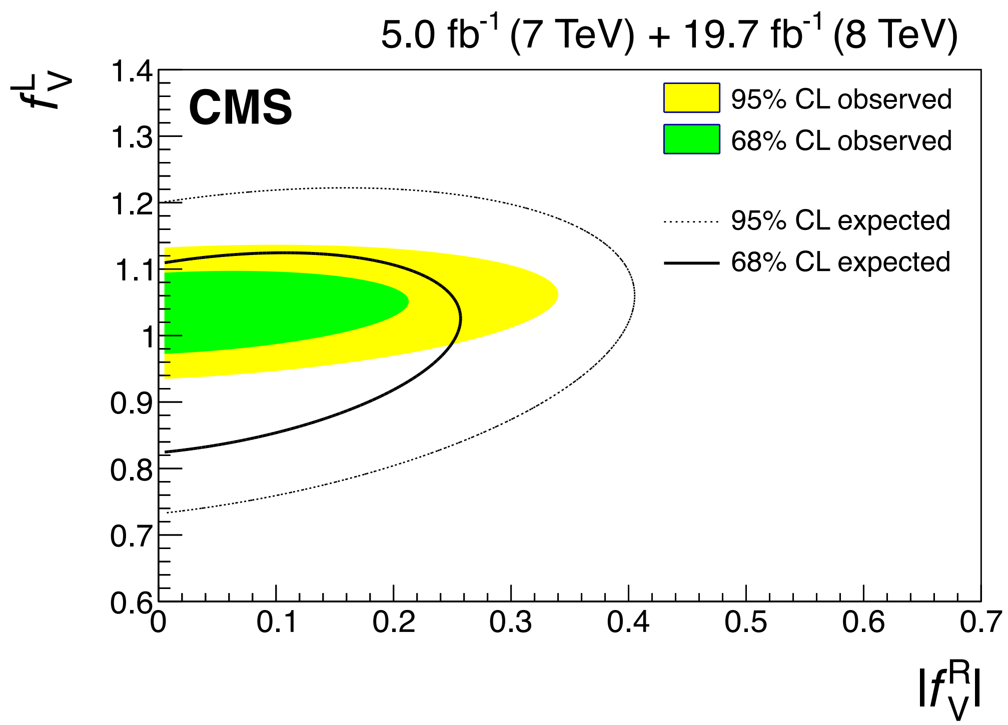
arXiv:1610.03545
Submitted to JHEP

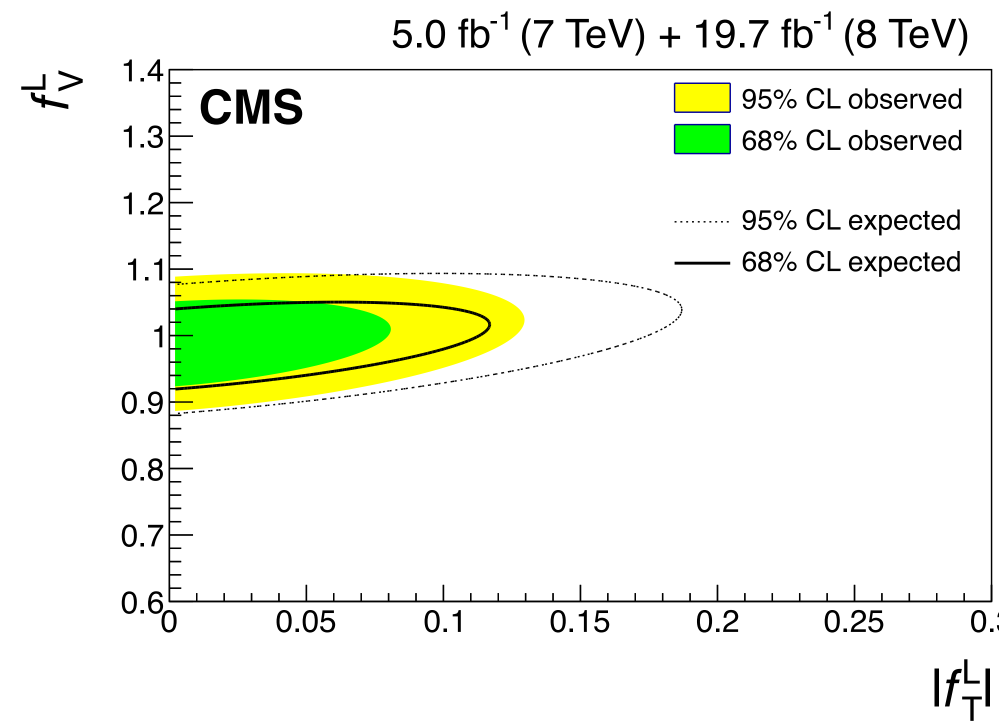
- Search in μ final state, 2J1T event selection
- QCD multijet events are rejected using dedicated NN
- 2 or 3 of four anomalous couplings are considered simultaneously in 2-D or 3-D scenarios
- Dedicated NNs for anomalous tWb couplings are used
- Limit extracted by simultaneous fit to SM NN and anomalous tWb NN

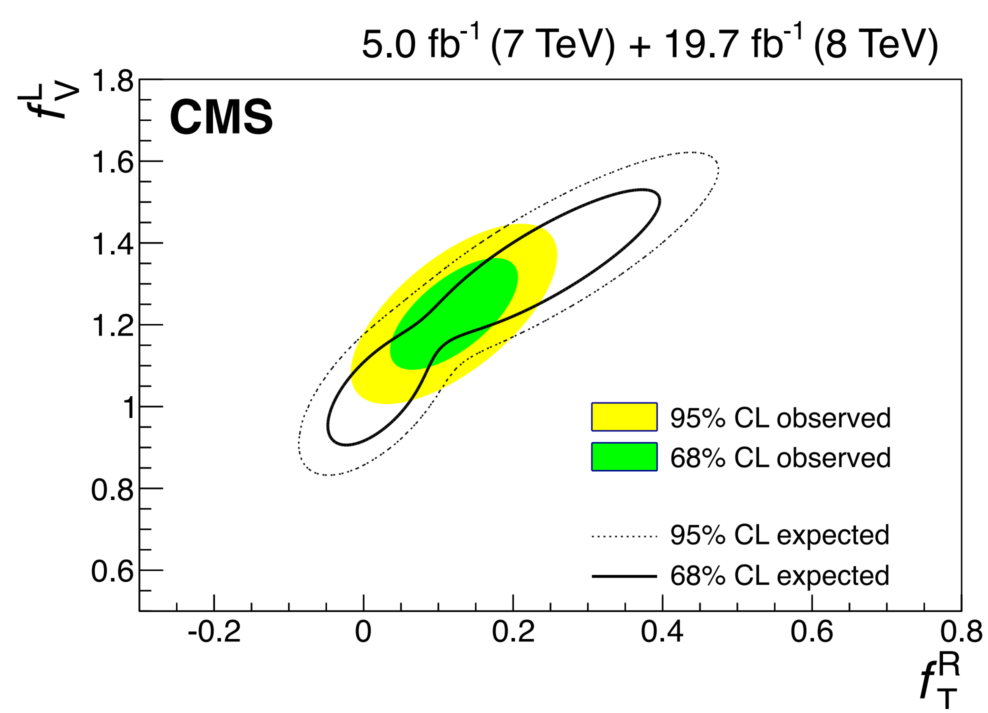


Anomalous couplings with Run-I data

$f_V^L > 0.98$, $|f_V^R| < 0.16$, $|f_T^L| < 0.057$
$-0.049 < |f_T^R| < 0.048$ (from 1-D fit)







from 2-D fit

arXiv:1610.03545
Submitted to JHEP

Summary

- Precise measurements of the t-channel cross -section at $\sqrt{s}$ = 13 TeV have been performed and results are in agreement with the SM within uncertainties

- $R_{t\text{-}ch}$ provides an extra handle to constrain u/d PDFs and allows study for b PDF

- Current measurements are mostly dominated by theory uncertainties

➢ Limiting factor for a more precise extraction of V_{tb}

➢ Need a better understanding of MC generators

- A precise tW - channel measurement is expected with Run-II data

- Push hard for s-channel observation at $\sqrt{s}$ = 13 TeV in order to look for new physics signature through this mode

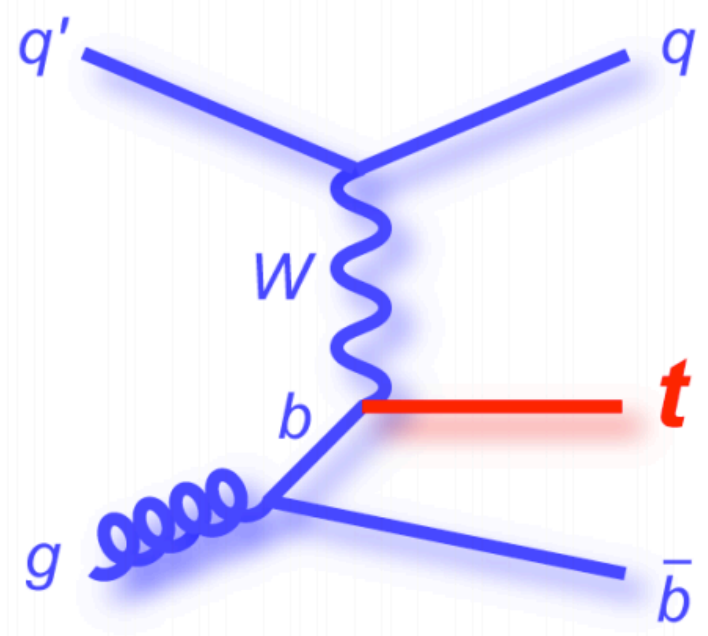
- LHC combination of single top cross-sections with Run-I data is ongoing

- More precision is required to improve limits on anomalous couplings at tWb vertex

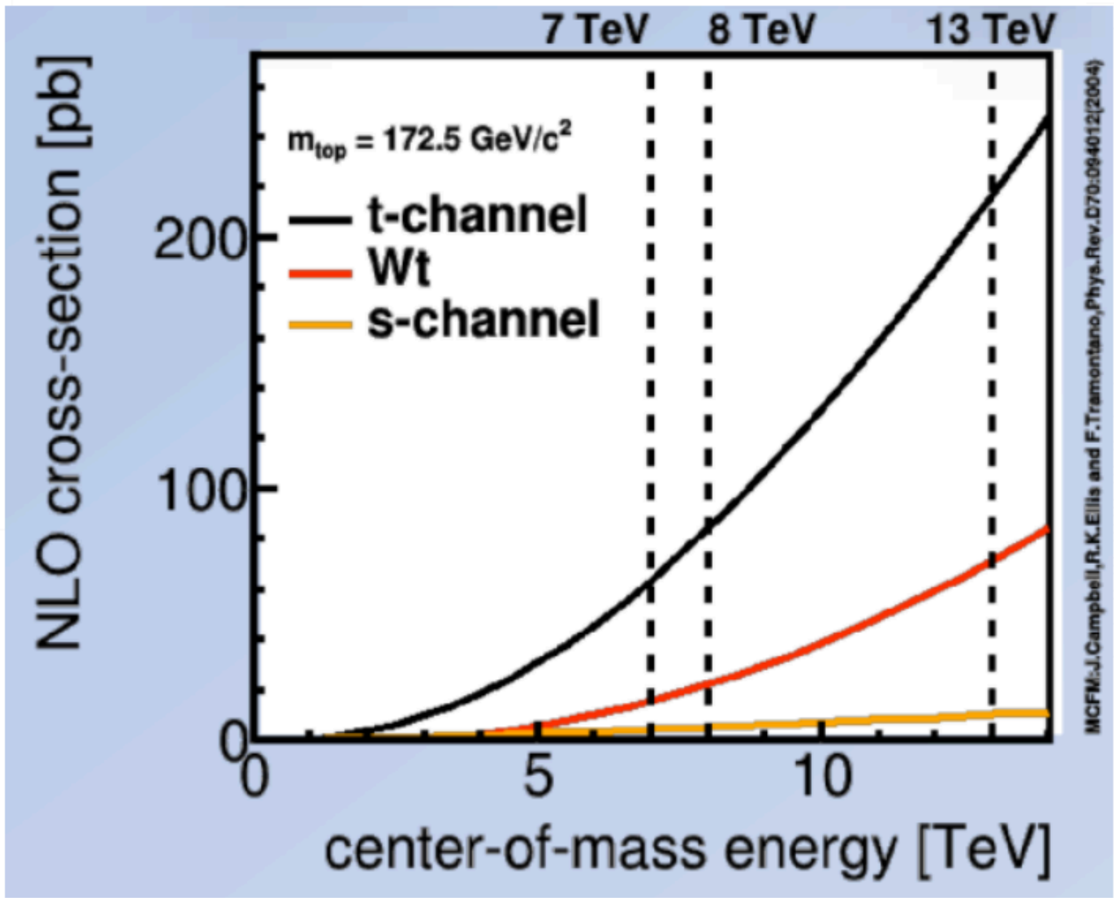
Back Up

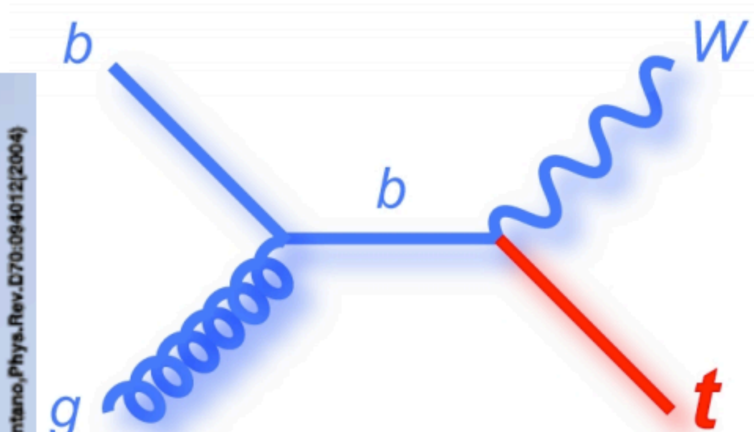
CKM Physics with Single Top

Single top quarks are produced via electroweak interaction:

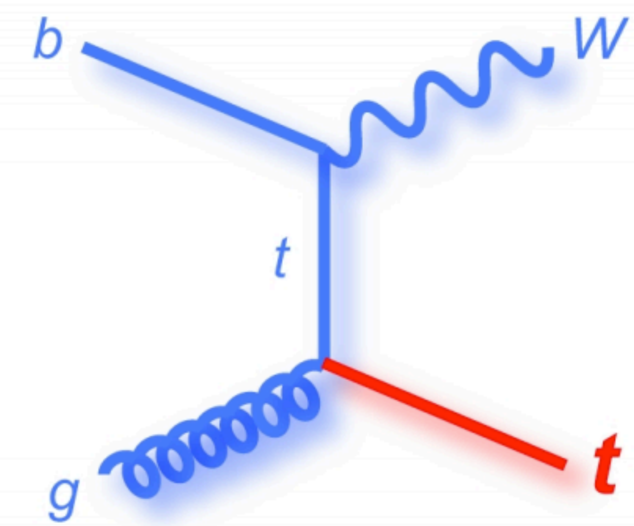


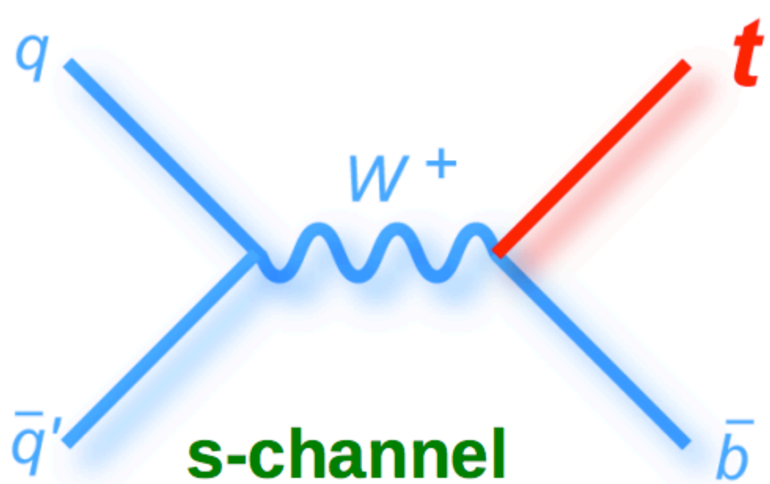
t-channel





tW-channel



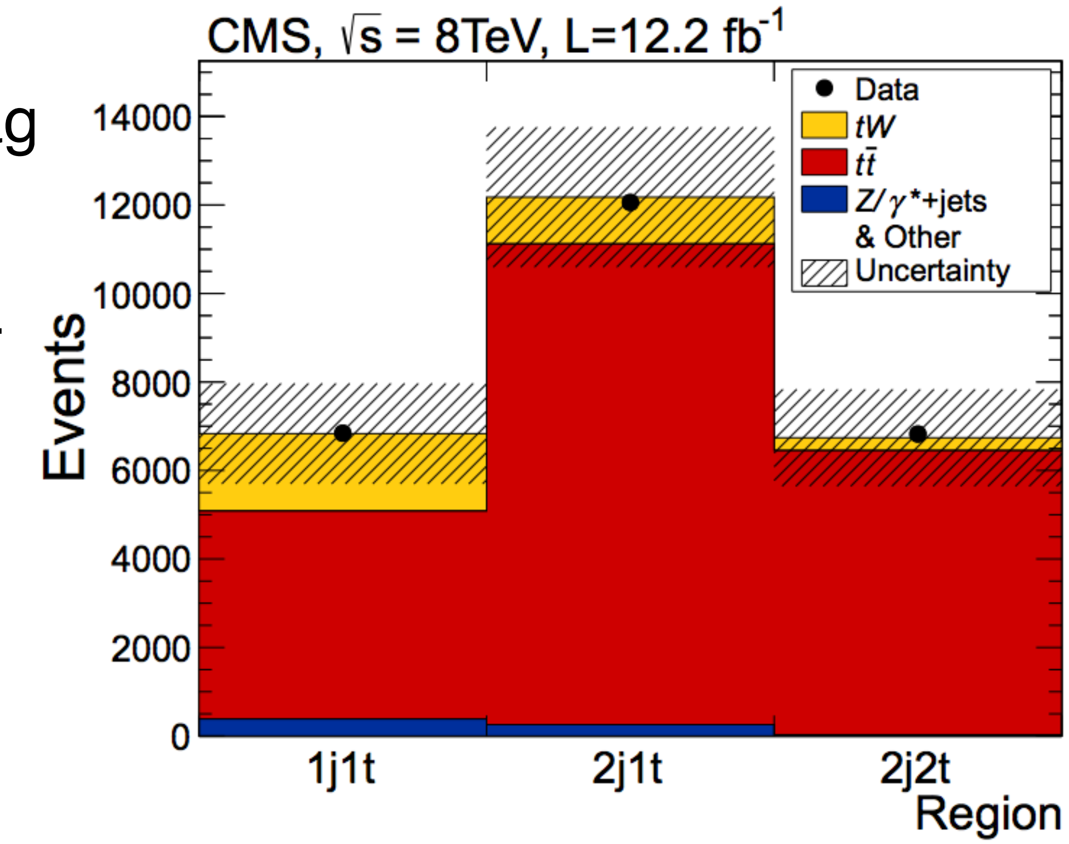


s-channel

Stolen from Jyotsna's talk yesterday 😛

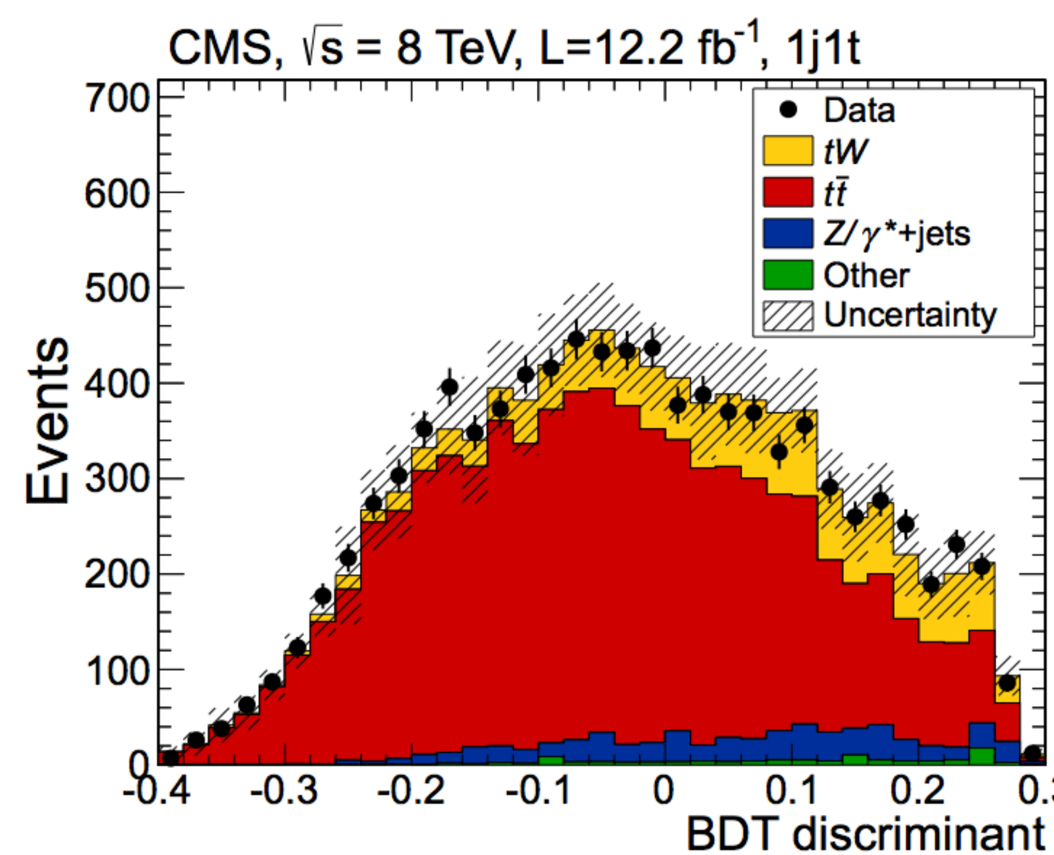
tW - channel observation @ 8TeV

- ee, eμ, μμ final state
- Events categorized in bins of #of jets and # of b-tag
- Signal region: 1J1T
- Dominant background: $t\bar{t}$
  ➛ controlled by simultaneous fit to 2J1T and 2J2T
- Fit BDT discriminant to extract cross-section
- **σ_{meas} = 23.4 ± 5.4 pb**
- **6.1σ** significance ➛ **First observation**
- **$|V_{tb}|$ = 1.03 ± 0.12 (exp.) ± 0.04 (th.)**



Largest systematic uncertainties

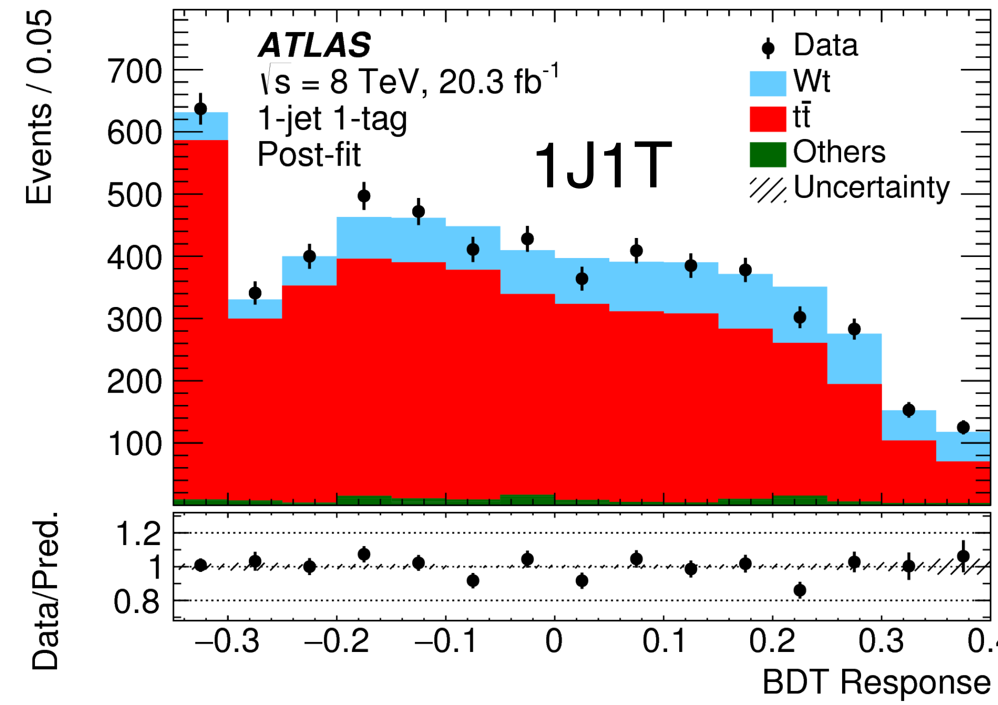
Systematic uncertainty	$\Delta\sigma/\sigma$
ME/PS matching thresholds	14%
Renormalization/factorization scale	12%
Top-quark mass	9%
Fit statistical	8%
Total	24%



PRL 112 (2014) 23180

tW-channel observation@ 8TeV

- Analysis performed with full 20.3 fb^{-1} data collected at $\sqrt{s}$ = 8 TeV
- ee, eμ, μμ final state explored
- Events categorized in bins of #of jets and # of b-tags
- Signal region: 1J1T
- Dominant background: $t\bar{t}$
  ➛ normalisation controlled by 2J1T, 2J2T events
- BDT used to discriminate signal and backgrounds
- Profile likelihood fit to BDT discriminant simultaneously in 1J1T, 2J1T and 2J2T region



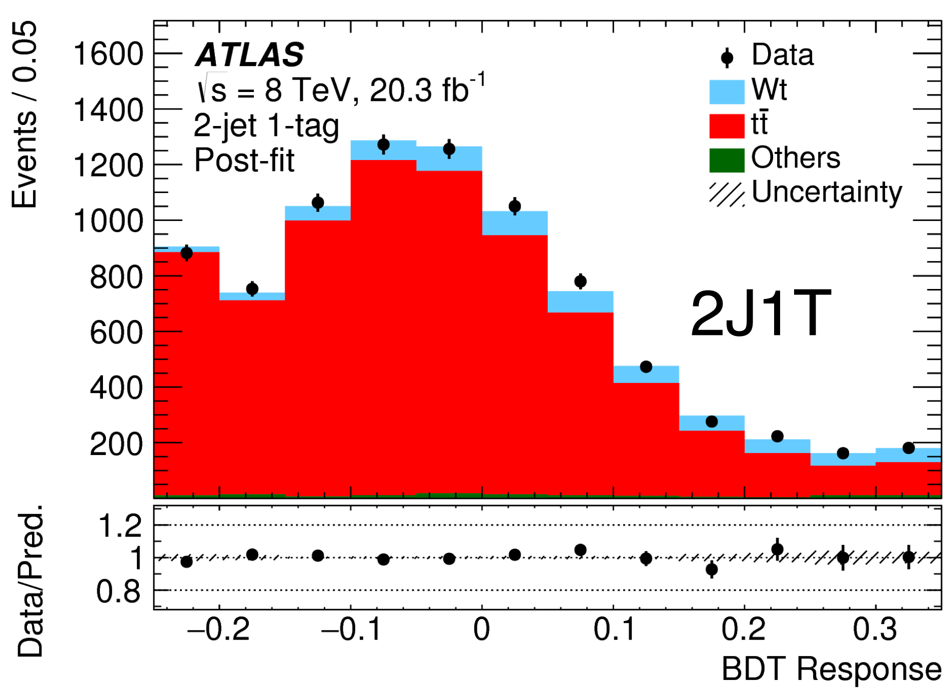
- **Measurement:**

σ_{tW} = 23.0 ± 1.3 (stat) $^{+3.2}_{-3.5}$ (syst.) ± 1.1 (lumi.) pb

$|f_{LV} V_{tb}|$ = 1.01 ± 0.1

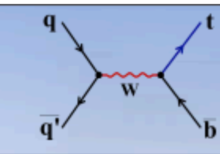
=> 7.7σ observed significance (6.9σ Expected)

Source	$\frac{\Delta\sigma_{Wt}}{\sigma_{Wt}}$ [%]
Statistics	5.8
QCD rad. modelling	+8.2/ -9.4
Jet reconstruction	+9.0/ -9.9
E_T^{miss}	5.5
others	< 5 each
Total	+16/ -17



JHEP01(2016)064

Matrix element method



Integration over part of the phase space Φ_4

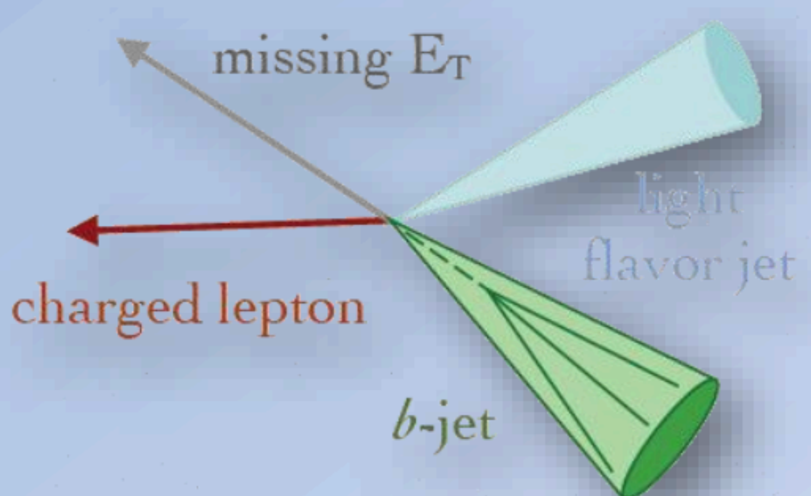
Parton distribution functions

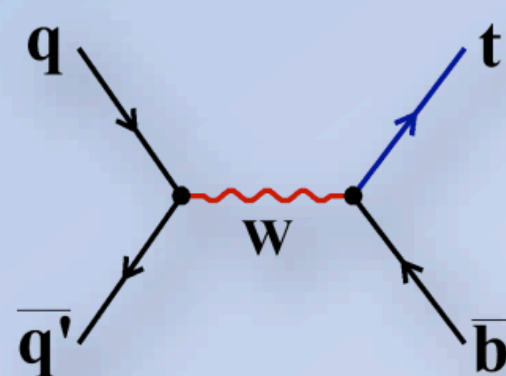
$$P(p_l^\mu, p_{j1}^\mu, p_{j2}^\mu) = \frac{1}{\sigma} \int d\rho_{j1} d\rho_{j2} dp_\nu^z \sum_{comb} \phi_4 \, |M(p_i^\mu)|^2 \, \frac{f(q_1) f(q_2)}{|q_1||q_2|} W_{jet}(E_{jet}, E_{part})$$

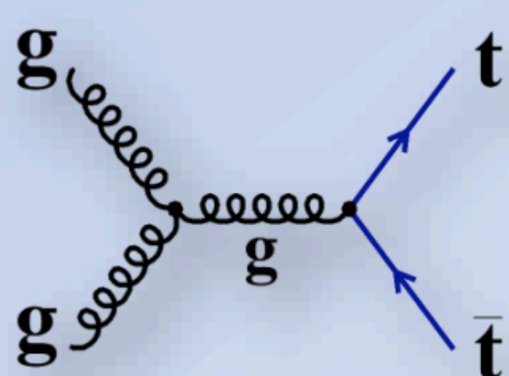
Input: lepton and jet-vectors

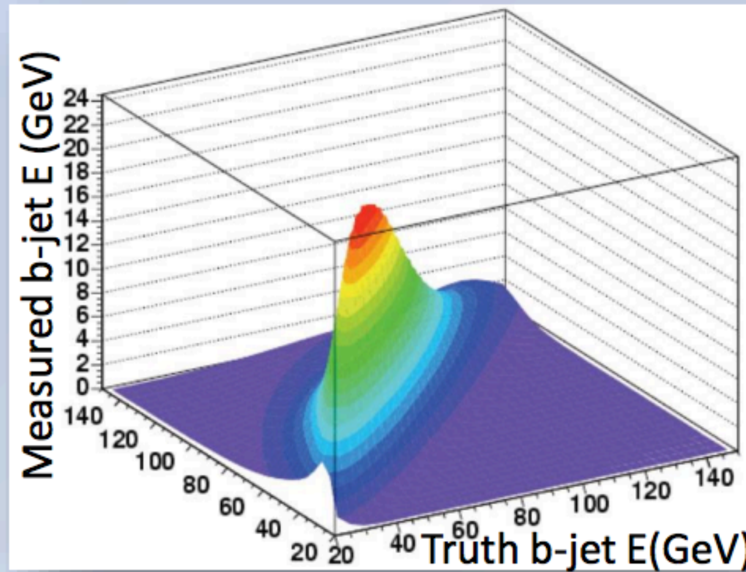
Leading order matrix elements

Probability of measuring a jet energy E_j if E_p was produced.









t-channel uncertainty table @ 13TeV

ATLAS EXPERIMENT

Source	$\frac{\Delta\sigma(tq)}{\sigma(tq)}$ [%]	$\frac{\Delta\sigma(\bar{t}q)}{\sigma(\bar{t}q)}$ [%]	$\frac{\Delta R_t}{R_t}$ [%]
Data statistics	$\pm$ 2.9	$\pm$ 4.1	$\pm$ 5.0
Monte Carlo statistics	$\pm$ 2.8	$\pm$ 4.2	$\pm$ 5.1
Reconstruction efficiency and calibration uncertainties			
Muon uncertainties	$\pm$ 0.8	$\pm$ 0.9	$\pm$ 1.0
Electron uncertainties	< 0.5	$\pm$ 0.5	$\pm$ 0.7
JES	$\pm$ 3.4	$\pm$ 4.1	$\pm$ 1.2
Jet energy resolution	$\pm$ 3.9	$\pm$ 3.1	$\pm$ 1.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ modelling	$\pm$ 0.9	$\pm$ 1.2	< 0.5
b-tagging efficiency	$\pm$ 7.0	$\pm$ 6.9	< 0.5
c-tagging efficiency	< 0.5	$\pm$ 0.5	$\pm$ 0.6
Light-jet tagging efficiency	< 0.5	< 0.5	< 0.5
Pile-up reweighting	$\pm$ 1.5	$\pm$ 2.2	$\pm$ 3.8
Monte Carlo generators			
tq parton shower generator	$\pm$ 13.0	$\pm$ 14.3	$\pm$ 1.9
tq NLO matching	$\pm$ 2.1	$\pm$ 0.7	$\pm$ 2.8
tq radiation	$\pm$ 3.7	$\pm$ 3.4	$\pm$ 3.7
$t\bar{t}$, Wt, $t\bar{b}+\bar{t}b$ parton shower generator	$\pm$ 3.2	$\pm$ 4.4	$\pm$ 1.2
$t\bar{t}$, Wt, $t\bar{b}+\bar{t}b$ NLO matching	$\pm$ 4.4	$\pm$ 8.6	$\pm$ 4.6
$t\bar{t}$, Wt, $t\bar{b}+\bar{t}b$ radiation	< 0.5	$\pm$ 1.1	$\pm$ 0.7
PDF	$\pm$ 0.6	$\pm$ 0.9	< 0.5
Background normalisation			
Multijet normalisation	$\pm$ 0.3	$\pm$ 2.0	$\pm$ 1.8
Other background normalisation	$\pm$ 0.4	$\pm$ 0.5	< 0.5
Luminosity	$\pm$ 2.1	$\pm$ 2.1	< 0.5
Total systematic uncertainty	$\pm$ 17.5	$\pm$ 20.0	$\pm$ 10.2
Total uncertainty	$\pm$ 17.8	$\pm$ 20.4	$\pm$ 11.4

t-channel uncertainty table @ 13TeV

Uncertainty source	$\Delta\sigma_{t\text{-ch.},t+\bar{t}}/\sigma^{obs}_{t\text{-ch.},t+\bar{t}}$	$\Delta\sigma_{t\text{-ch.},t}/\sigma^{obs}_{t\text{-ch.},t}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma^{obs}_{t\text{-ch.},\bar{t}}$	$\Delta R_{t\text{-ch.}}/R_{t\text{-ch.}}$
Statistical uncert.	±5.5%	±5.3%	±11.5%	±9.7%
Profiled exp. uncert.	±5.2%	±5.7%	±4.9%	±3.3%
Total fit uncert.	±7.6%	±7.8%	±12.5%	±10.3%
Integrated luminosity	±2.7%	±2.7%	±2.7%	-
Signal modelling	±6.9%	±8.2%	±8.5%	±5.3%
$t\bar{t}$ modelling	±3.9%	±4.3%	±4.5%	±4.0%
W+jets modelling	−1.8/+2.1%	−1.6/+2.3%	−2.5/+2.3%	−1.7/+2.0%
μ_R/μ_F scale t-channel	−4.6/+6.1%	−5.7/+5.2%	−7.2/+5.1%	−0.7/+1.2%
μ_R/μ_F scale $t\bar{t}$	−3.5/+2.9%	−3.5/+4.1%	−4.7/+3.1%	−1.1/+1.0%
μ_R/μ_F scale tW	−0.3/+0.5%	−0.6/+0.8%	−1.1/+0.7%	−0.2/+0.1%
μ_R/μ_F scale W+jets	−2.9/+3.7%	−3.5/+3.0%	−4.9/+3.8%	−1.2/+0.9%
PDF uncert.	−1.5/+1.9%	−2.1/+1.6%	−1.8/+2.1%	−2.2/+2.5%
Top quark p_T modelling	±0.1%	±0.2%	±0.2%	±0.1%
Total theory uncert.	−10.7/+11.1%	−12.2/+12.1%	−13.6/+12.9%	±7.5%
Total uncert.	−13.4/+13.7%	±14.7%	−18.7/+18.2%	±12.7%

Uncertainty source	$\Delta\sigma_{t\text{-ch.},t+\bar{t}}/\sigma^{obs}_{t\text{-ch.},t+\bar{t}}$	$\Delta\sigma_{t\text{-ch.},t}/\sigma^{obs}_{t\text{-ch.},t}$	$\Delta\sigma_{t\text{-ch.},\bar{t}}/\sigma^{obs}_{t\text{-ch.},\bar{t}}$	$\Delta R_{t\text{-ch.}}/R_{t\text{-ch.}}$
MC samples size	±3.4%	±4.1%	±3.8%	±3.2%
JES	±4.1%	±4.7%	±3.5%	±2.1%
JER	±1.7%	±1.2%	±2.4%	±0.6%
b tagging efficiency	±1.9%	±2.0%	±1.8%	±1.4%
Mistag probability	±0.9%	±0.6%	±0.8%	±0.5%
Muon reco./trigger	±2.0%	±2.3%	±1.9%	±1.8%

tW Uncertainties @13TeV

ATLAS EXPERIMENT

Source	$\Delta\sigma_{Wt}/\sigma_{Wt}$[%]
Luminosity	2.3
Lepton efficiency, energy scale and resolution	1.3
$E_{\mathrm{T}}^{\mathrm{miss}}$ soft terms	5.3
Jet energy scale	21
Jet energy resolution	8.6
b-tagging	4.3
NLO matrix element generator	18
Parton shower and hadronisation	7.1
Initial-/final-state radiation	6.4
Diagram removal/subtraction	5.3
Parton distribution function	2.7
Non-$t\bar{t}$ background normalisation	3.7
Total systematic uncertainty	30
Data statistics	10
Total uncertainty	31

Uncertainty table tW combination @ 8TeV

Source	Uncertainty (%)	Uncertainty (pb)
Data statistics	4.7	1.1
Simulation statistics	0.8	0.2
Luminosity	3.6	0.8
Theory modelling	11.8	2.7
Background normalization	2.2	0.5
Jets	6.2	1.4
Detector modelling	4.9	1.1
Total systematics (excl. lumi)	14.4	3.3
Total systematics (incl. lumi)	14.8	3.4
Total uncertainty	15.6	3.6

Theory modelling source	Uncertainty (%)	Uncertainty (pb)
ISR/FSR, Scale	9.9	2.3
Parton shower, ME/PS match. thr.	5.4	1.2
PDF	0.9	0.2
DR/DS	3.1	0.7
Other theory modelling	1.8	0.4
Total theory modelling	11.8	2.7

s-channel uncertainties @8TeV

ATLAS EXPERIMENT

Type	$\pm\Delta\sigma/\sigma$ [%]
Data statistics	16
MC statistics	12
Jet energy resolution	12
t-channel generator choice	11
b-tagging	8
s-channel generator scale	7
W+jets normalization	6
Luminosity	5
t-channel normalization	5
Jet energy scale	5
PDF	3
Lepton identification	2
Electron energy scale	1
$t\bar{t}$ generator choice	1
Lepton trigger	1
Charm tagging	1
Other	< 1
Total	34

CMS

Source	Uncertainty (%)				
	μ, 7 TeV	μ, 8 TeV	e, 8 TeV	μ + e, 8 TeV	7+8 TeV
Statistical	34	15	14	10	11
$t\bar{t}$, single top quark rate	29	15	14	12	14
W/Z+jets, diboson rate	23	11	13	12	12
Multijet rate	9	3	5	2	2
Lepton efficiency	14	1	2	1	3
Hadronic trigger	5	—	—	—	1
Luminosity	10	5	6	4	6
JER & JES	66	39	29	34	18
b tagging & mistag	34	15	14	14	16
Pileup	6	11	7	9	7
Unclustered $\not{E}_T$	5	8	2	6	5
μ_R, μ_F scales	54	34	31	30	28
Matching thresholds	43	11	12	7	17
PDF	12	8	7	7	9
Top quark p_T reweighting	3	5	7	6	6
Total uncertainty	115	64	54	55	47

Top polarization in t-channel@8 TeV: Uncertainty Table

	$\delta A_{\mu}(\mathrm{t})/10^{-2}$	$\delta A_{\mu}(\bar{\mathrm{t}})/10^{-2}$	$\delta A_{\mu}(\mathrm{t}+\bar{\mathrm{t}})/10^{-2}$
Statistical	3.2	4.6	2.6
ML fit uncertainty	0.7	1.2	0.6
Diboson bkg. fraction	<0.1	<0.1	<0.1
Z/γ^*+jets bkg. fraction	<0.1	<0.1	<0.1
s-channel bkg. fraction	0.3	0.2	0.2
tW bkg. fraction	0.1	0.7	0.2
Multijet events shape	0.5	0.7	0.5
Multijet events yield	1.9	1.2	1.7
b tagging	0.7	1.2	0.9
Mistagging	<0.1	0.1	<0.1
Jet energy resolution	2.7	1.8	2.0
Jet energy scale	1.3	2.6	1.1
Unclustered $\not{E}_{\mathrm{T}}$	1.1	3.3	1.3
Pileup	0.3	0.2	0.2
Lepton identification	<0.1	<0.1	<0.1
Lepton isolation	<0.1	<0.1	<0.1
Muon trigger efficiency	<0.1	<0.1	<0.1
Top quark p_{T} reweighting	0.3	0.3	0.3
W+jets W boson p_{T} reweighting	0.1	0.1	0.1
W+jets heavy-flavour fraction	4.7	6.2	5.3
W+jets light-flavour fraction	<0.1	<0.1	0.1
W+jets $\cos\theta^*_{\mu}$ reweighting	2.9	3.4	3.1
Unfolding bias	2.5	4.2	3.1
Generator model	1.6	3.5	0.3
Top quark mass	1.9	2.9	1.8
PDF	0.9	1.6	1.2
t-channel renorm./fact. scales	0.2	0.2	0.2
$\mathrm{t\bar{t}}$ renorm./fact. scales	2.2	3.4	2.7
$\mathrm{t\bar{t}}$ ME/PS matching	2.2	0.5	1.6
W+jets renorm./fact. scales	3.7	4.6	4.0
W+jets ME/PS matching	3.8	3.0	3.4
Limited MC events	2.1	3.2	1.8
Total uncertainty	10.5	13.8	10.5

Anomalous tWb coupling @7 TeV: Uncertainty Table

Source	$\sigma(f_1)$	$\sigma(\delta_-)/\pi$	$\rho(f_1, \delta_-)$
Data statistics	0.05	0.023	0.01
Jets	0.03	0.015	0.39
b-tagging	< 0.01	< 0.001	-0.70
Leptons	0.02	0.007	0.39
$E_{\mathrm{T}}^{\mathrm{miss}}$	0.01	0.004	-0.27
Generator	0.02	0.017	0.40
Parton shower	0.02	0.001	0.98
PDF variations	0.01	0.009	0.23
Cross-sections	< 0.01	< 0.001	1.00
W+jets shape	< 0.01	0.001	-0.59
Multijet normalisation	< 0.01	0.002	-1.00
Luminosity	< 0.01	< 0.001	-1.00
Model $l_{\max}$ variation	0.01	0.001	-0.70
MC statistics	0.02	0.011	0.14
Combined systematic	0.05	0.028	0.27
Total	0.07	0.036	0.15

ATLAS
EXPERIMENT

Anomalous tWb coupling @8 TeV: Uncertainty Table

Uncertainty source	$\Delta A^{\ell}_{\rm FB} * 10^2$	$\Delta A^{tW}_{\rm FB} * 10^2$	$\Delta A_{\rm FB} * 10^2$	$\Delta A_{\rm EC} * 10^2$
Statistical uncertainty	±2.6	±3.1	±2.3	±2.8
Simulation statistics	±1.8	±1.9	±1.4	±1.7
Luminosity	<0.1	<0.1	<0.1	<0.1
Background normalisation	±0.5	±0.5	±0.9	±0.6
$E_{\rm T}^{\rm miss}$reconstruction	$^{+0.9}_{-0.1}$	±0.8	±0.9	±0.6
Lepton reconstruction	$^{+0.7}_{-0.5}$	$^{+0.5}_{-1.3}$	$^{+1.2}_{-1.5}$	$^{+0.2}_{-0.4}$
Jet reconstruction	±0.9	±1.6	±1.2	±1.9
Jet energy scale	±1.8	±2.1	±3.4	±1.4
Jet flavour tagging	±0.9	±0.4	±0.6	±0.4
PDF	±0.1	<0.1	<0.1	±0.1
$t\bar{t}$ generator	±2.5	±1.4	±0.3	±1.1
$t\bar{t}$ parton shower	±0.1	±1.0	±2.5	±0.3
$t\bar{t}$ scales	±0.4	±0.3	±1.2	±0.2
Wt,s-channel generator	±0.8	±0.9	±0.4	±0.3
Wt,s-channel scales	±0.9	±0.3	±0.3	±0.3
t-channel NLO generator	±1.5	±1.1	±0.7	±2.7
t-channel LO-NLO generator	±1.3	±2.0	±2.8	±1.8
t-channel parton shower	±0.4	±0.5	±1.2	±0.4
t-channel scales	±1.0	±2.1	±0.5	±1.7
W+jets, multijet modelling	±1.9	±0.9	±2.2	±1.4
Systematic uncertainty	$^{+5.1}_{-5.2}$	$^{+5.1}_{-5.3}$	$^{+6.4}_{-6.5}$	±5.1

Uncertainty source	$\Delta A^{N}_{\rm FB} * 10^2$	$\Delta A^{T}_{\rm FB} * 10^2$	$\Delta A^{N,\phi}_{\rm FB} * 10^2$	$\Delta A^{T,\phi}_{\rm FB} * 10^2$
Statistical uncertainty	±2.2	±3.2	±3.0	±4.7
Simulation statistics	±1.3	±2.0	±1.8	±2.9
Luminosity	<0.1	<0.1	<0.1	<0.1
Background normalisation	±0.4	±1.1	±0.6	±0.9
$E_{\rm T}^{\rm miss}$reconstruction	$^{+0.1}_{-1.0}$	±0.9	$^{+0.5}_{-0.7}$	$^{+0.1}_{-1.3}$
Lepton reconstruction	$^{+0.1}_{-0.3}$	$^{+1.4}_{-1.6}$	$^{+0.8}_{-0.4}$	$^{+1.2}_{-1.0}$
Jet reconstruction	±0.3	$^{+3.1}_{-3.2}$	±1.3	±1.8
Jet energy scale	±0.5	±5.1	±0.8	±5.5
Jet flavour tagging	±0.2	±0.6	±0.2	±0.7
PDF	±0.1	<0.1	±0.1	±0.4
$t\bar{t}$ generator	±0.6	±4.1	±0.1	±1.2
$t\bar{t}$ parton shower	±0.9	±1.7	±0.4	±1.5
$t\bar{t}$ scales	±0.3	±0.7	±0.3	±1.2
Wt,s-channel generator	±0.3	±0.6	±0.4	±1.3
Wt,s-channel scales	±0.6	±0.5	±0.4	±0.9
t-channel NLO generator	±0.4	±3.8	±2.6	±5.4
t-channel LO-NLO generator	±0.4	±2.0	±1.6	±3.2
t-channel parton shower	±0.2	±0.9	±1.4	±1.2
t-channel scales	±0.9	±1.9	±1.4	±2.3
W+jets, multijet modelling	±0.7	±1.3	±0.6	±2.6
Systematic uncertainty	$^{+2.4}_{-2.6}$	$^{+9.5}_{-9.6}$	±4.6	$^{+10.3}_{-10.2}$

ATLAS EXPERIMENT