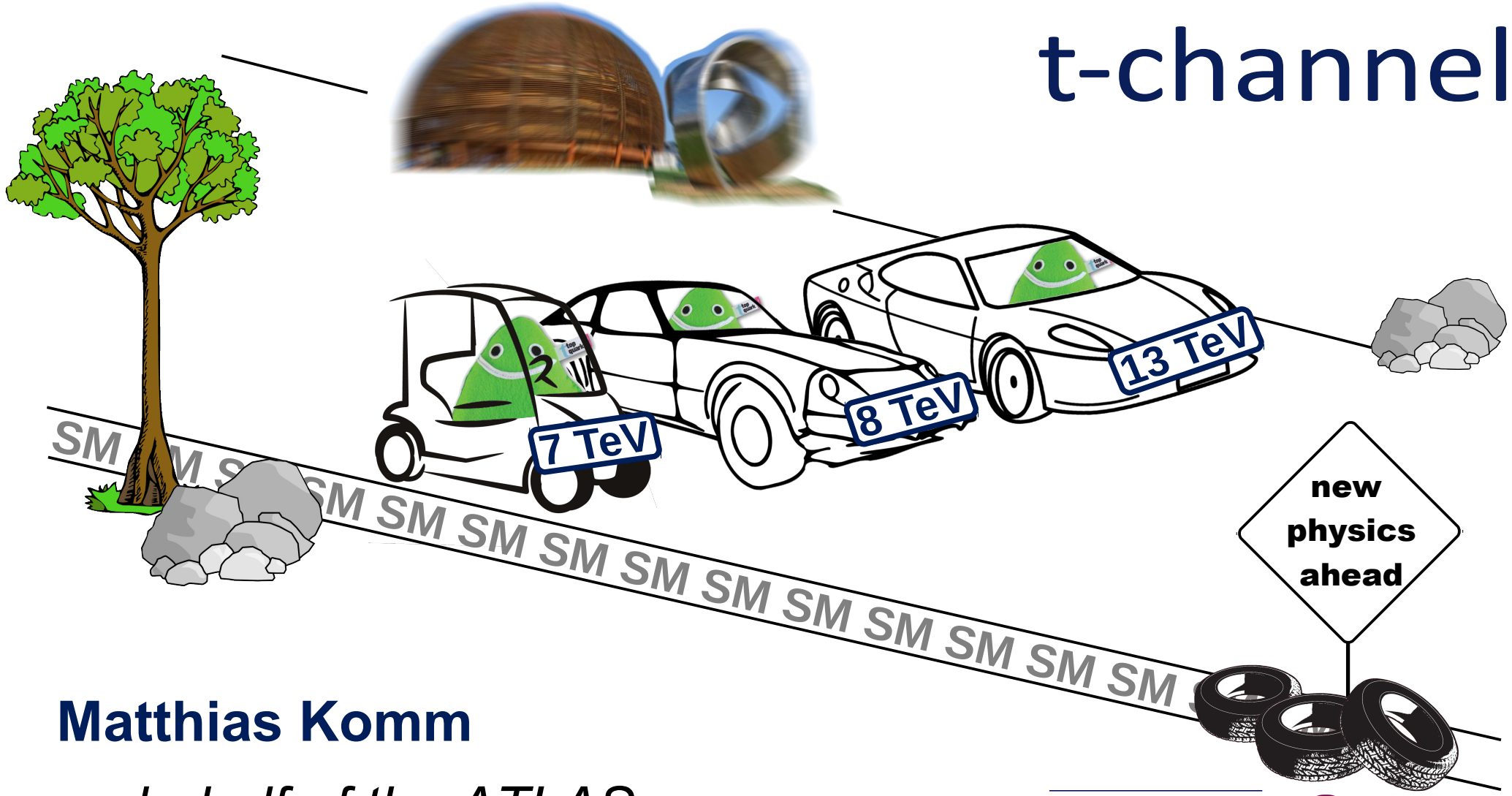
Single Top Quark Production t-channel



Matthias Komm

on behalf of the ATLAS & CMS collaborations

UCL Université catholique de Louvain

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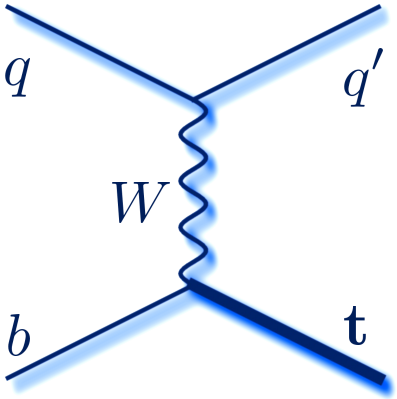
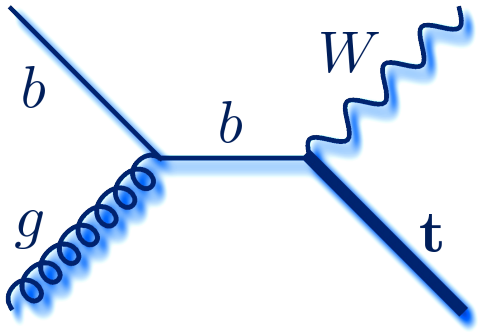
Introduction

Phys. Part. Nucl. 45, **2014** &
arXiv:1506.04072, **2015**

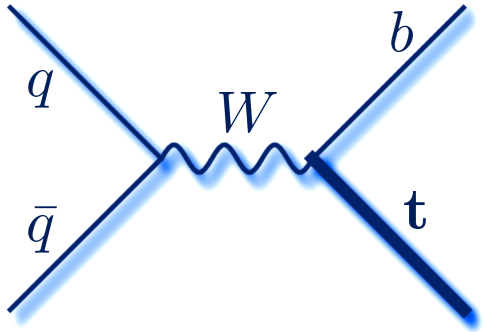
- single top quark production



t-channel



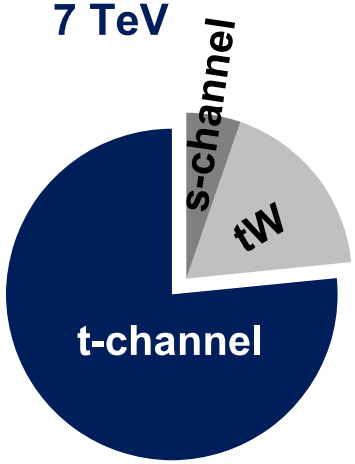
W associated producton (“tW”)



s-channel

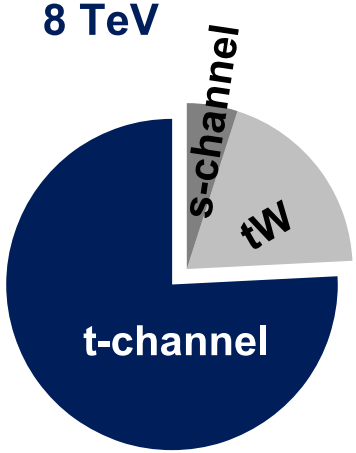
- single top at different energies (approx. NNLO, $m_t = 173\ \mathrm{GeV}$, 4FS, MSTW2008)

7 TeV



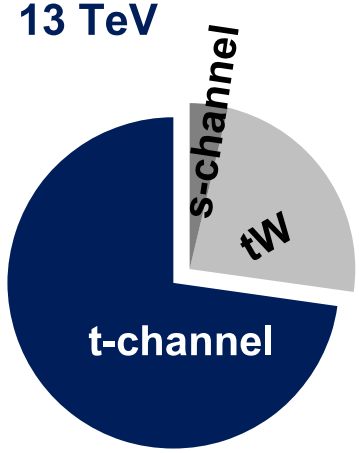
$$\sigma^{7\mathrm{TeV}}_{t\text{-ch.}} = 65.9^{+2.1}_{-0.7}(\mathrm{scale})\ ^{+1.5}_{-1.7}(\mathrm{PDF})\ \mathrm{pb}$$

8 TeV



$$\sigma^{8\mathrm{TeV}}_{t\text{-ch.}} = 86.5^{+2.8}_{-1.0}(\mathrm{scale})\ ^{+2.0}_{-2.2}(\mathrm{PDF})\ \mathrm{pb}$$

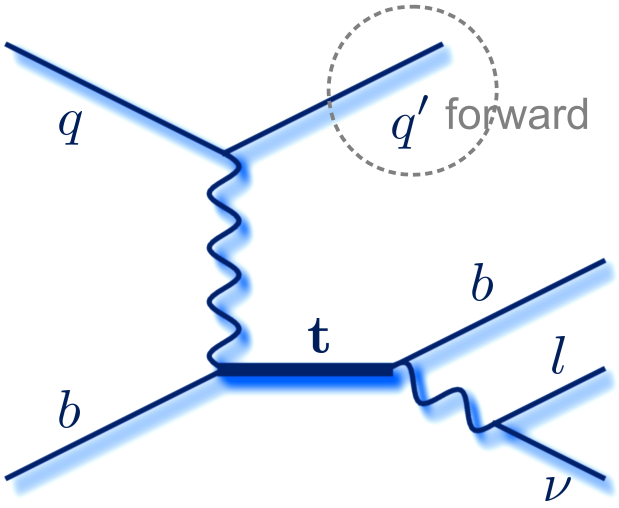
13 TeV



$$\sigma^{13\mathrm{TeV}}_{t\text{-ch.}} = 218^{+5}_{-5}(\mathrm{scale})\ \pm 5(\mathrm{PDF})\ \mathrm{pb}$$

Single Top t-channel Production

- Why are single tops interesting?



- … in the SM
  - direct measurement of CKM matrix element V_{tb}

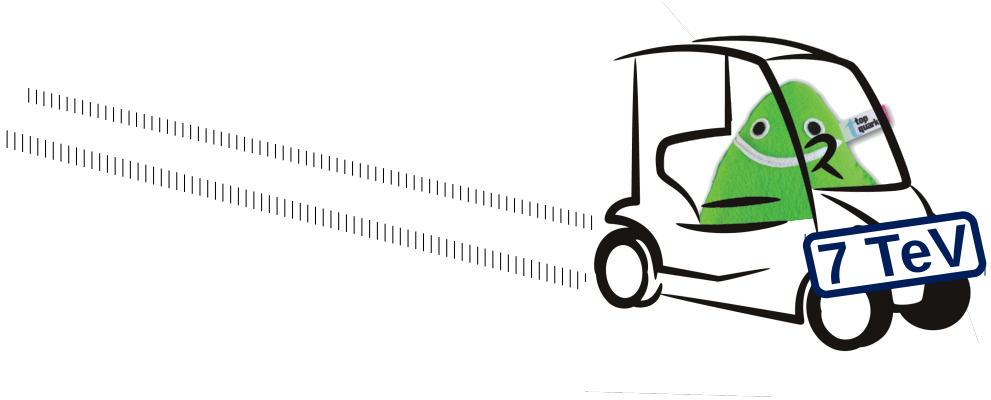
$$\begin{pmatrix} \mathrm{V}_{ud} & \mathrm{V}_{us} & \mathrm{V}_{ub} \\ \mathrm{V}_{cd} & \mathrm{V}_{cs} & \mathrm{V}_{cb} \\ \mathrm{V}_{td} & \mathrm{V}_{ts} & \mathrm{V}_{tb} \end{pmatrix}$$

  - test of EWK coupling structure

$$\mathcal{L}^{\mathrm{SM}}_{Wtb} \propto \bar{b}\left(\underbrace{\gamma_\mu}_{\mathrm{V}} - \underbrace{\gamma_\mu\gamma_5}_{\mathrm{A}}\right) t W^\mu + \mathrm{h.c.}$$

- … in searches for BSM
  - 4th generation of quarks, heavy bosons (W'), charged Higgs
  - FCNC
  - anomalous EWK couplings (corrections from higher energies)
  - dark matter associated production

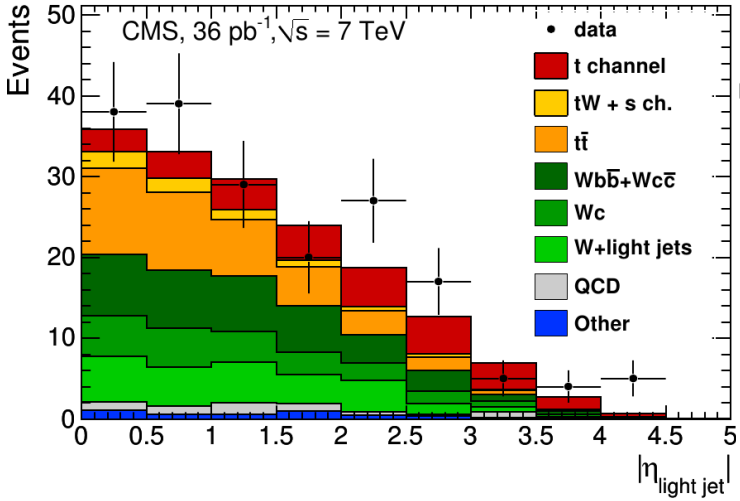
First Single Tops at LHC

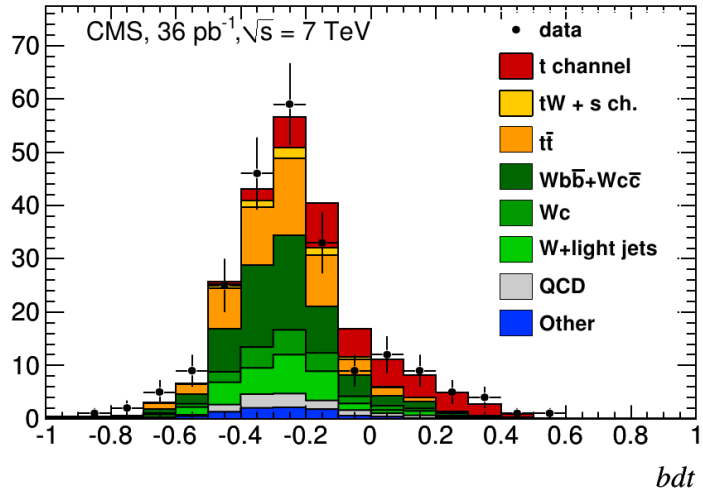


7 TeV: First Single Tops at LHC

Phys. Rev. Lett. 107:091802, **2011**
ATLAS-CONF-**2011**-027

- "early analysis" with only $36\ \mathrm{pb}^{-1}$ with CMS
  - **2D analysis**: binned likelihood fit to $\cos\theta_l^*$ & $|\eta_{j'}|$; **boosted decision tree** with Bayesian approach

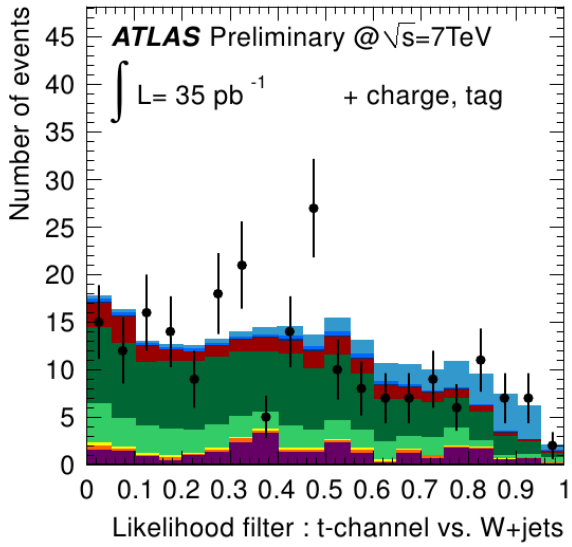


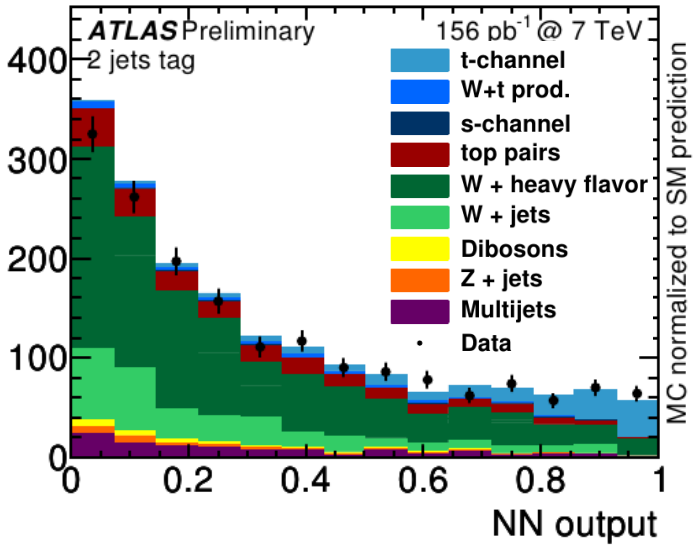


$$\sigma_{t\text{-ch.}}^{\text{comb.}} = 84\ \text{pb} \pm 26\%$$

- search ($35\ \mathrm{pb}^{-1}$) & observation ($156\ \mathrm{pb}^{-1}$) of single tops at ATLAS
  - cut analysis **likelihood-based** & binned fit to **neutral network**

$$\left[\sigma_{t\text{-ch.}}^{\text{SM}} = 66^{+3}_{-2}\ \text{pb}\right]$$





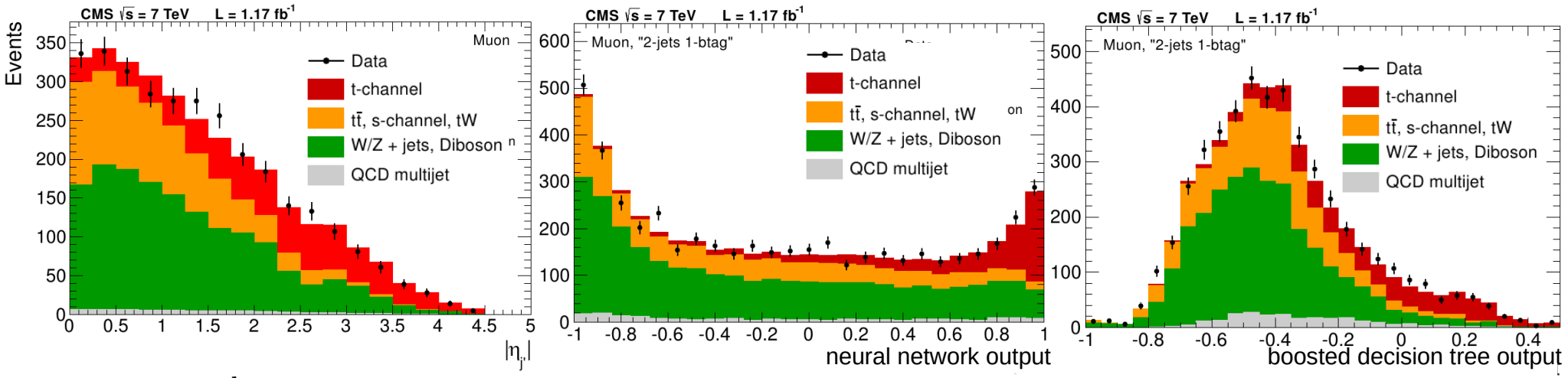
$$\sigma_{t\text{-ch.}}^{\text{cut}} = 97\ \text{pb}^{+56}_{-31}\%$$

$$\sigma_{t\text{-ch.}}^{\text{NN}} = 76\ \text{pb}^{+54}_{-28}\%$$

7 TeV: Advanced Analyses

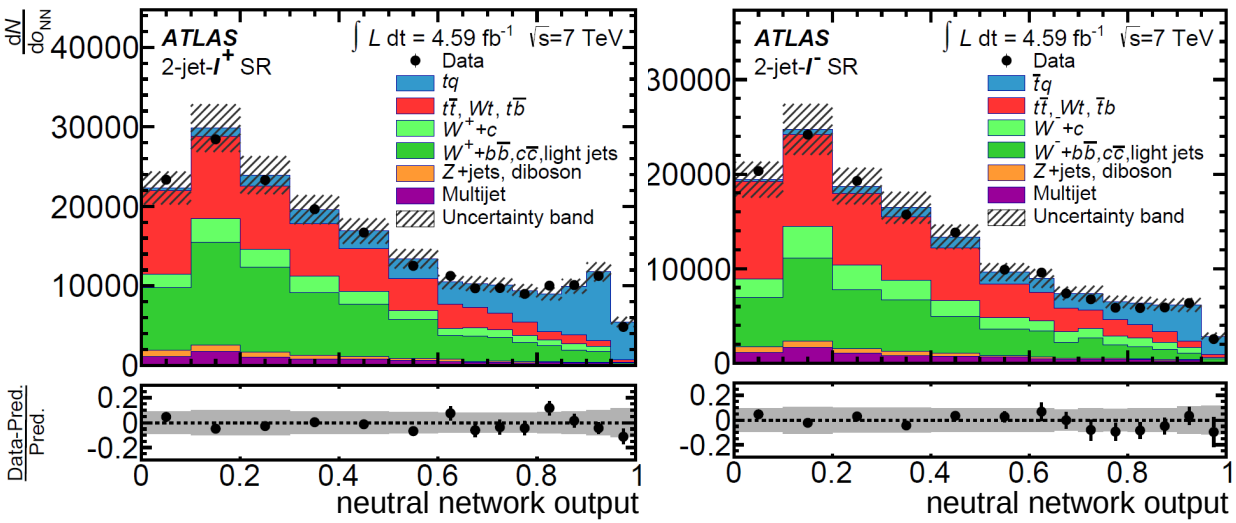
JHEP 12 (**2012**) 035
Phys. Rev. D. 90 112006 **2014**

- **CMS** : binned likelihood fit to untagged jet $|\eta_{j'}|$ & 2 complementary analyses with MVAs



$$\Rightarrow \sigma_{t\text{-ch.}}^{\text{comb}} = 67.2 \pm 3.7(\text{stat}) \pm 4.8(\text{syst}) \text{ pb} = 67.2 \text{ pb} \pm 9\%$$

- **ATLAS**: binned likelihood fit to MVA discriminator output distribution (lepton charge separated)



$$\Rightarrow \sigma_{t\text{-ch.}} = 68 \pm 2(\text{stat}) \pm 8(\text{syst}) \text{ pb}$$
$$= 68\text{pb} \pm 12\%$$

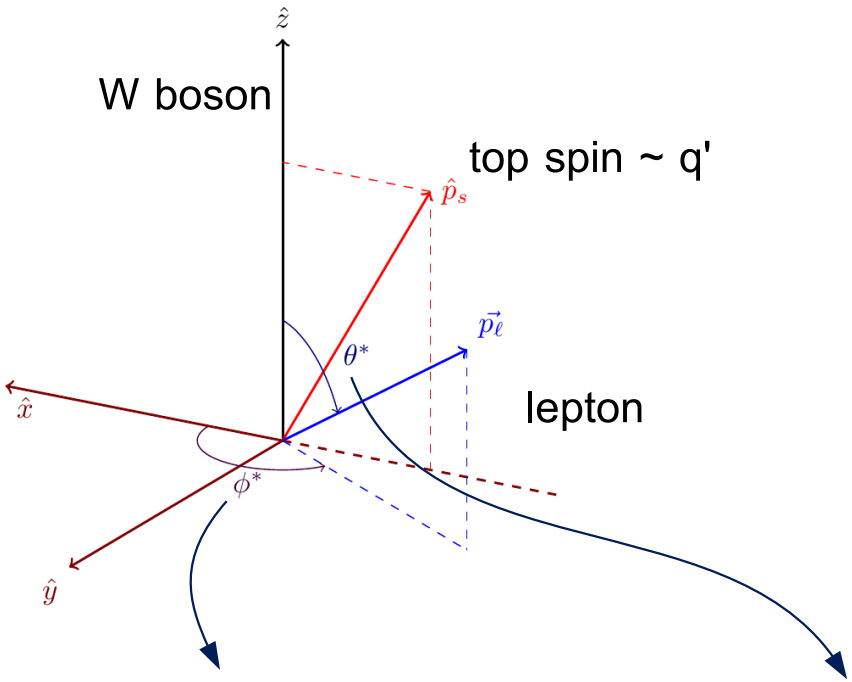
→ both results in agreement with prediction: $\sigma_{t\text{-ch.}}^{\text{SM}} = 66^{+3}_{-2}$ pb

7 TeV ATLAS: Wtb Couplings

paper in preparation

NEW

- define angles in **top rest frame**



- event selection like cross section measurement
  - 1 iso. $\mu/e\,(p_{\mathrm{T}} > 25\ \mathrm{GeV},\ |\eta| < 2.5)$
  - 2 jets $p_{\mathrm{T}} > 30\ \mathrm{GeV},\ |\eta| < 4.5$ (1 b-tagged)
- parametrization through **spherical expansion**

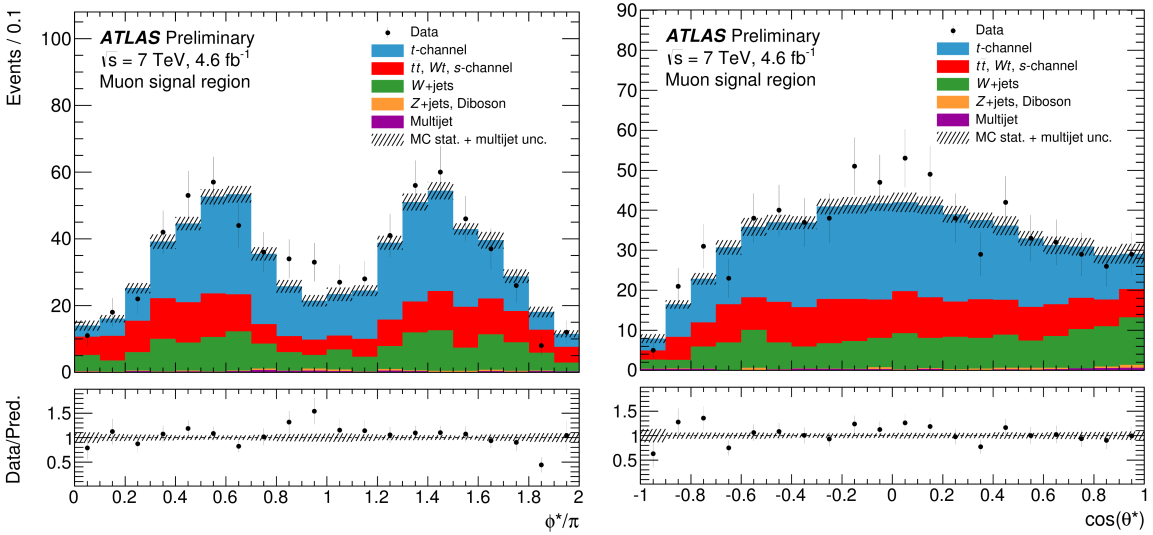
$$\rho(\theta^*, \phi^* | \vec{\alpha}, P) \approx \sum_{l=0}^{2} \sum_{m=-l}^{l} a_{l,m}(\vec{\alpha}, P) \cdot Y_l^m(\theta^*, \phi^*)$$

$\vec{\alpha} = (\underbrace{f_1, f_1^+, f_0^+}, \underbrace{\delta_+, \delta_-})$ & top polarization P

magnitude & rel. phase of **generalized helicity fractions**

→ depend on **anomalous Wtb couplings**

$$\mathcal{L}_{Wtb}^{\mathrm{eff.}} = -\frac{g}{\sqrt{2}} \bar{b} \gamma^\mu (\boxed{V_{\mathrm{L}} P_{\mathrm{L}}}^{\text{SM}} + V_{\mathrm{R}} P_{\mathrm{R}}) t W_\mu^- - \frac{g}{\sqrt{2}} \bar{b} \frac{i \sigma^{\mu\nu} q_\nu}{m_W} (g_{\mathrm{L}} P_{\mathrm{L}} + g_{\mathrm{R}} P_{\mathrm{R}}) t W_\mu^-$$



7 TeV ATLAS: Wtb Couplings (2)

paper in preparation

NEW

- novel measurement method
  - event-based probability through **analytical folding model**
    (comparable method: matrix element method)

signal yield

folding over true angles

$$\rho(\theta^*, \phi^* | \vec{\alpha}, P, f_s) = f_s \cdot \left(\sum_{l,m} \mathcal{E}_{l,m} \cdot \left(\mathcal{R}(\theta_t^*, \phi_t^*)_{l,m} \star p_t(\theta_t^*, \phi_t^* | \vec{\alpha}, P) \right) \cdot Y_m^l \right) + (1 - f_s)\mathrm{bkg.}$$

efficiency resolution

from PROTOS event generator

accounts also for $t\bar{t}$ background

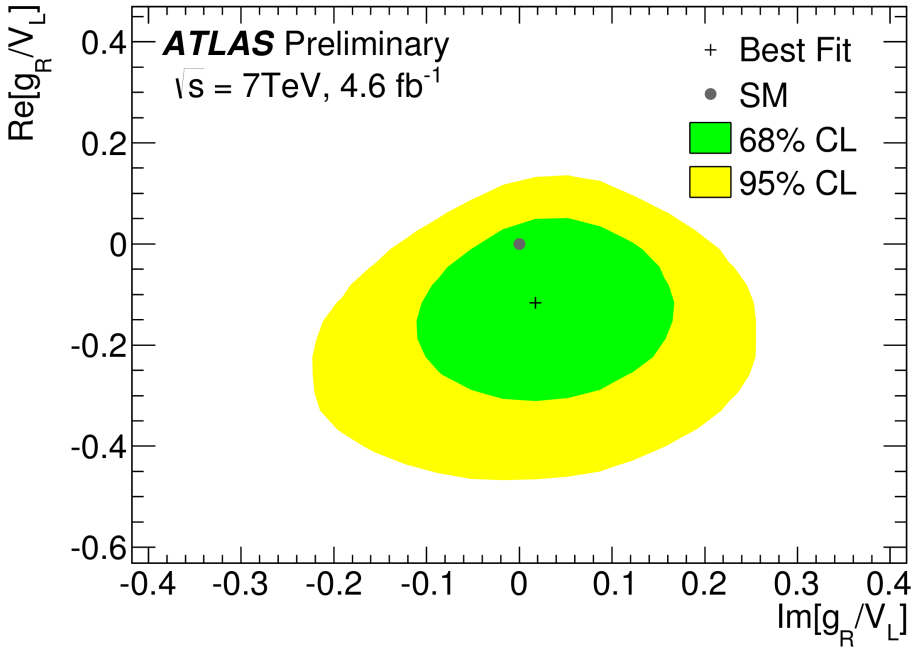
dependence on $\vec{\alpha}$

- **results** (assuming $V_R = g_L = 0$)

$$\mathrm{Re}\left(\frac{g_R}{V_L}\right) \in \left[-0.36,\ 0.10\right] \ @95\%\mathrm{CL}$$

$$\mathrm{Im}\left(\frac{g_R}{V_L}\right) \in \left[-0.17,\ 0.23\right] \ @95\%\mathrm{CL}$$

NEW! no previous limit

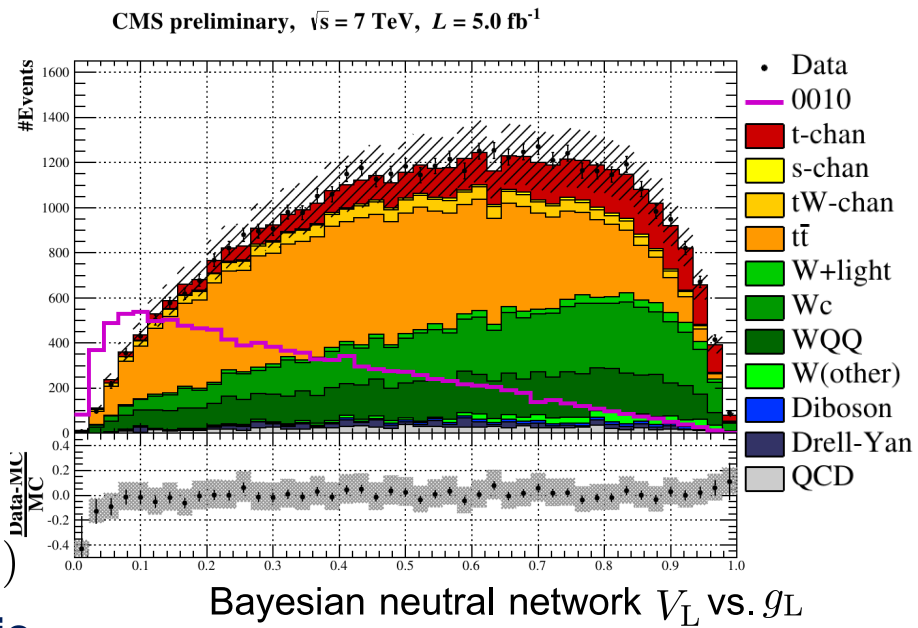


→ well in agreement with SM: $V_L = V_{tb},\ g_R = 0$

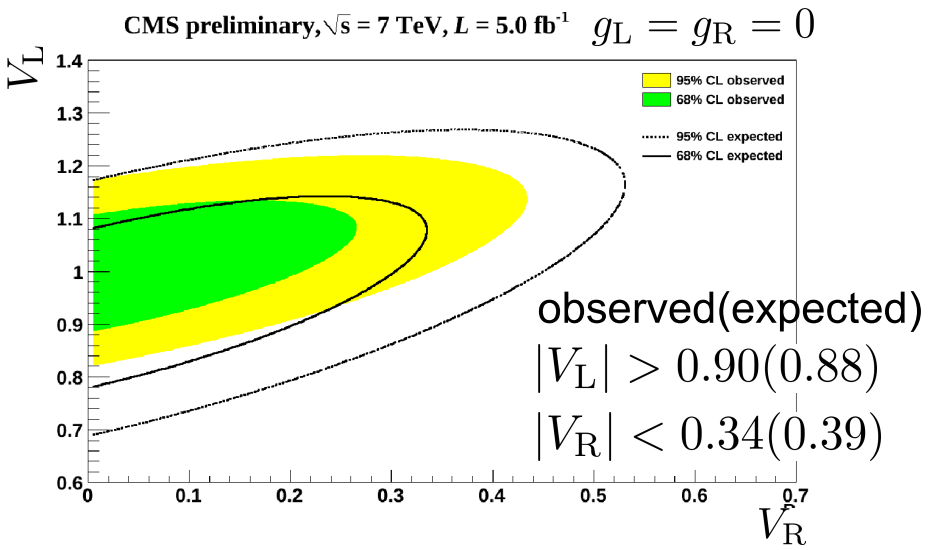
7 TeV CMS: Wtb Couplings

- event selection like cross section measurement
  - **1 iso. muon** $p_{\mathrm{T}} > 20\text{-}27\ \mathrm{GeV},\ |\eta| < 2.1$
  - **jets** $p_{\mathrm{T}} > 30\ \mathrm{GeV},\ |\eta| < 4.7$ **& b-tagging**

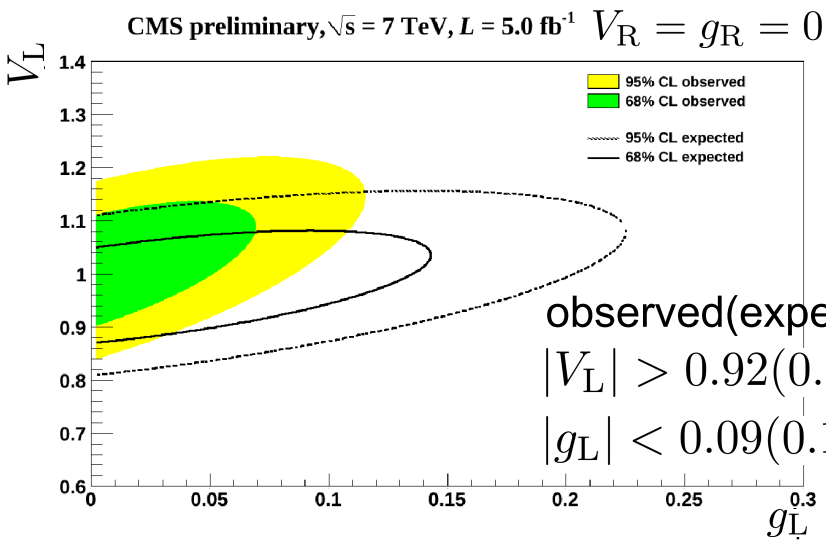
- measurement strategy
  - 2 **Bayesian neutral networks**
    (signal vs. background & SM vs. anom. couplings)
  - combine 3 special samples (CompHep)
    $\sigma(V_{\mathrm{L}}, V_{\mathrm{R}}) = m \cdot (1000) + n \cdot (\mathrm{artificial}) + k \cdot (0100)$
    → can be reweighted to **arbitrary coupling scenario**
  - infer limits through binned likelihood fit



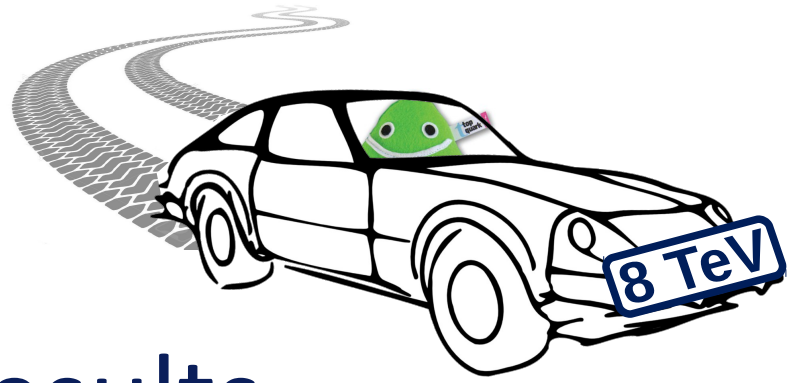
Bayesian neutral network V_{L} vs. g_{L}



observed(expected)
$|V_{\mathrm{L}}| > 0.90(0.88)$
$|V_{\mathrm{R}}| < 0.34(0.39)$



observed(expected)
$|V_{\mathrm{L}}| > 0.92(0.88)$
$|g_{\mathrm{L}}| < 0.09(0.16)$



8 TeV Results

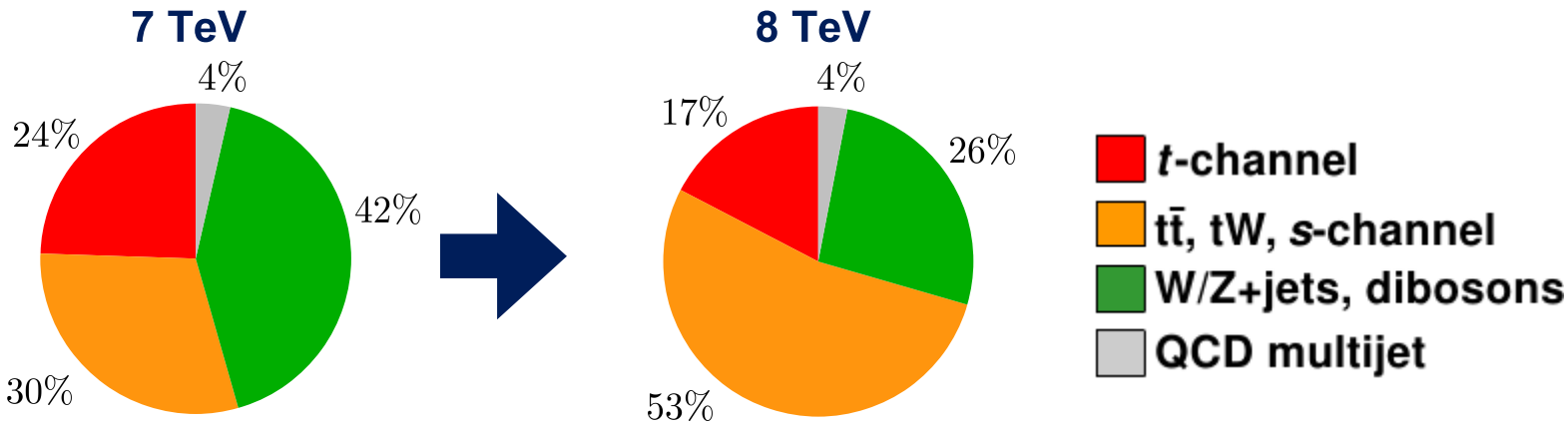
8 TeV: t-channel Cross Section

JHEP06 (**2014**) 090
ATLAS-CONF-**2014**-007

- event selection: ATLAS (CMS)
  - **1 isolated lepton**: muon $p_{\mathrm{T}} > 25(26)\ \mathrm{GeV}, |\eta| < 2.5(2.1)$
    or electron $p_{\mathrm{T}} > 25(30)\ \mathrm{GeV}, |\eta| < 2.47(2.5)$
  - **jets**: $p_{\mathrm{T}} > 30(40)\ \mathrm{GeV}, |\eta| < 4.5(4.5)$
  - **b-tagging**: MVA (3rd highest impact parameter significance Δ_{xy}/σ_{xy} of displaced tracks)

- analysis strategy
  - data-driven QCD multijet background estimation
  - solve neutrino p_z by imposing W mass constraint → reconstruct top quark
  - signal extraction: **binned likelihood fit**
    - CMS: $|\eta_{j'}|$ of **non-tagged jet** ⇒ inclusive cross section & $t/\bar{t}$ ratio
    - ATLAS: **neutral network** (NN) ⇒ fiducial cross section & inclusive total cross section

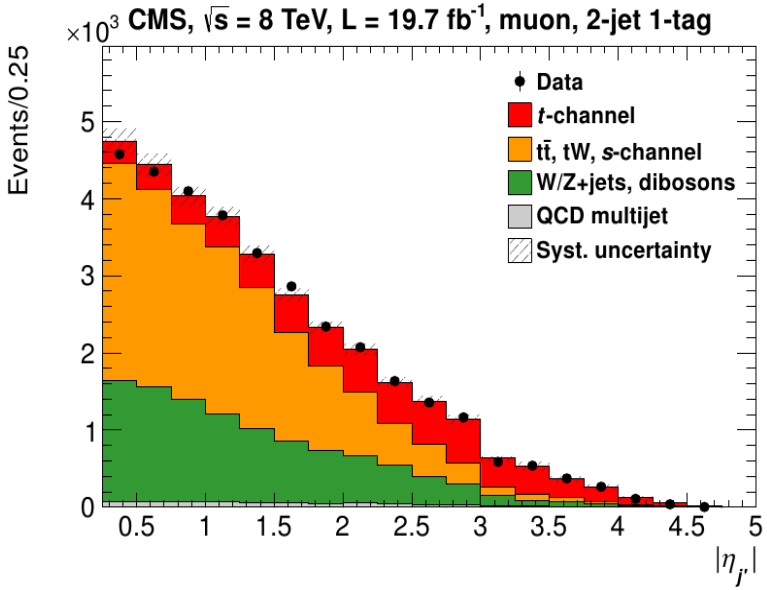
- background/signal (from CMS in top mass window)

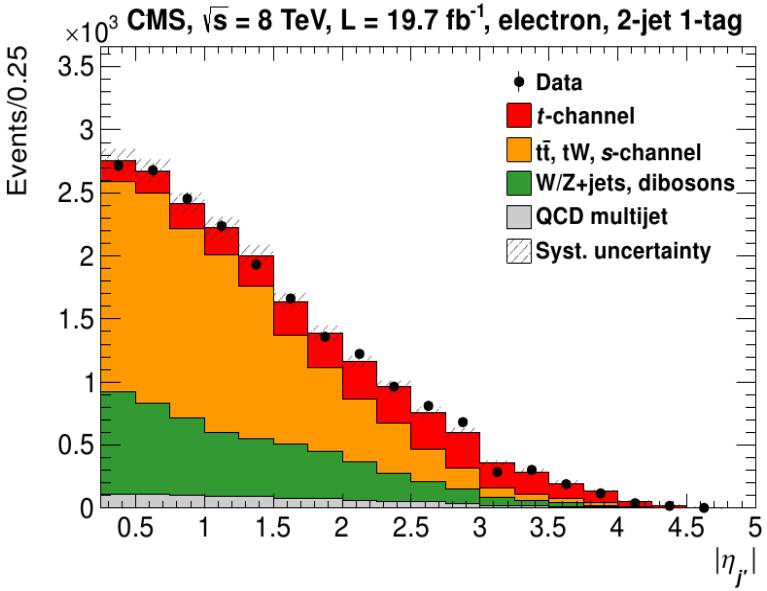


8 TeV CMS: Results

JHEP06 (**2014**) 090

- **pseudo rapidity of non-tagged jet**





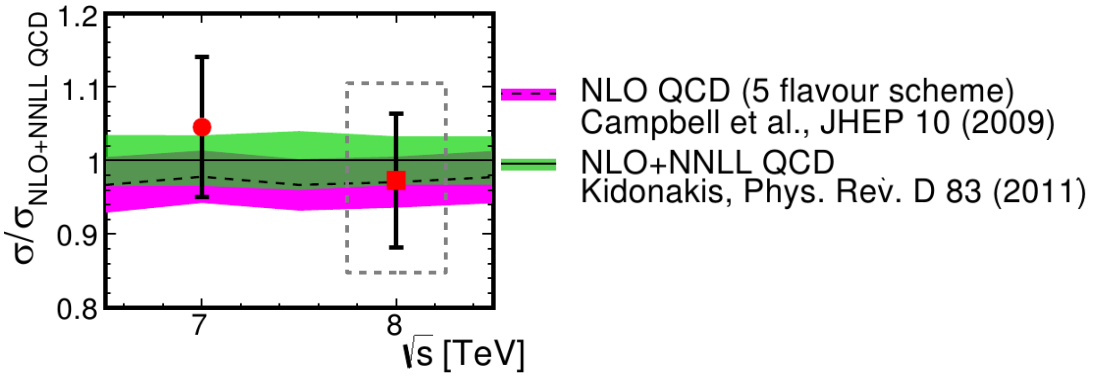
- **major uncertainties (>2%)**

Uncertainty source	$\sigma_{t\text{-ch.}}$ (%)
Statistical uncertainty	± 2.7
JES, JER, MET, and pileup	± 4.3
b-tagging and mis-tag	± 2.5
QCD multijet estimation	± 2.3
W+jets, tt̄ estimation	± 2.2
Signal modeling	± 5.7
PDF uncertainty	± 1.9
Luminosity	± 2.6

measured inclusive cross section

$$\sigma_{t\text{-ch}} = 83.6 \pm 2.3(\text{stat.}) \pm 7.4(\text{syst.}) \text{ pb}$$
$$= 83.6 \pm 7.8 \text{ pb}$$

comparison with theory



What's/Why Fiducial?

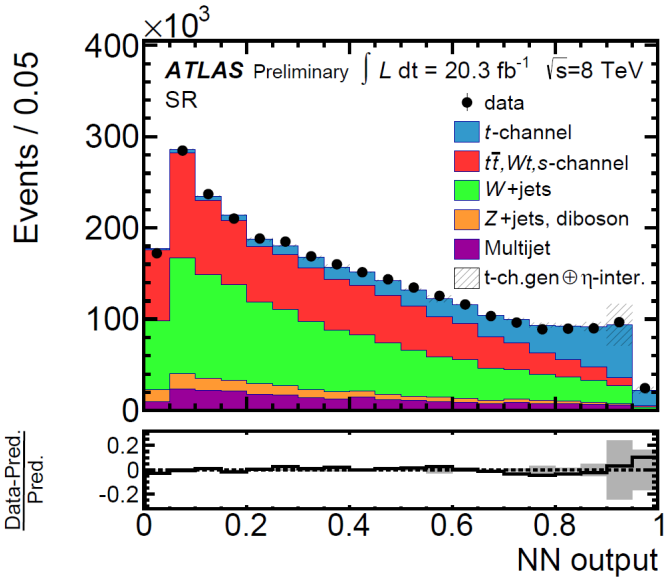
- measure $\sigma_{t\text{-ch}}$ only within **detector acceptance** ("fiducial region")
  - generator modeling can be verified against data
  - **no extrapolations** into "invisible" regions (e.g. $p_{\mathrm{T}} \to 0$, $|\eta| \to \infty$)
  - mostly only **experimental uncertainties** (theoretical uncertainties separated)
  - requires application of **selection at particle level** as well (close to acceptance)

- fiducial selection (ATLAS 8 TeV cross section measurement)
  - stable particles $\tau > 30$ ps
  - leptons (e/μ) from W boson decay (excl. leptons from hadron decays) & clustered with photons $\Delta R(l,\gamma) < 0.1$ → **"dressed" lepton**
  - jets (anti-k_{T}, $R = 0.4$) & b-tagging by **matching to B-hadrons**
  - missing transverse energy: $\not{E}_{\mathrm{T}} = \sum_i \vec{p}_i^{\,\nu}$

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

8 TeV ATLAS: Results

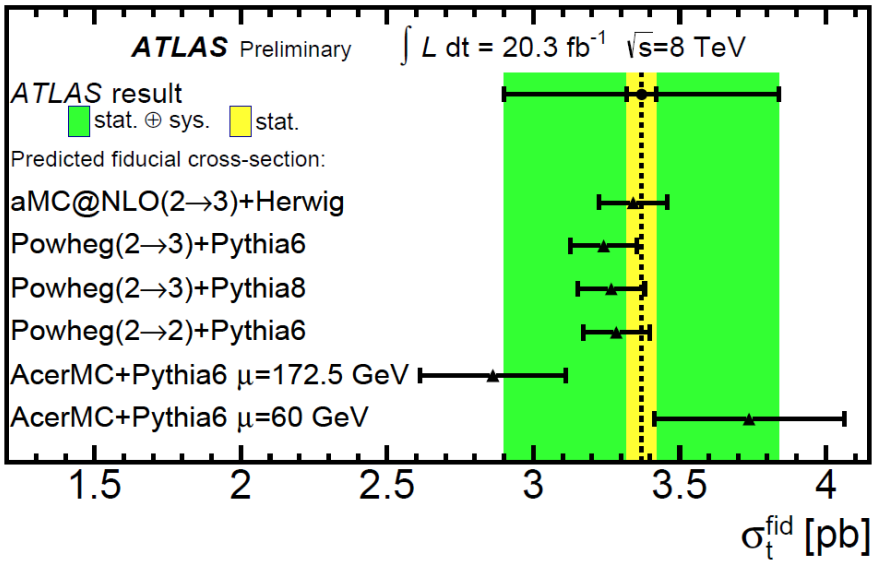
neutral network validation



major uncertainties (>2%)

Source	$\Delta\sigma_{\text{fid}}/\sigma_{\text{fid}}$ [%]
Data statistics	±1.5
Multijet normalisation	+2.3 -1.4
JES η intercalibration	±7.9
JES physics modelling	±3.0
Lepton uncertainties	±2.9
$E_{\text{T}}^{\text{miss}}$ modelling	±3.0
b-tagging efficiency	±3.5
t-channel generator	±7.9

fiducial cross section



$$\sigma_{t\text{-ch}}^{\text{fid.}} = 3.37 \pm 0.05(\text{stat}) \pm 0.47(\text{syst}) \pm 0.09(\text{lumi})\ \text{pb}$$

inclusive cross section

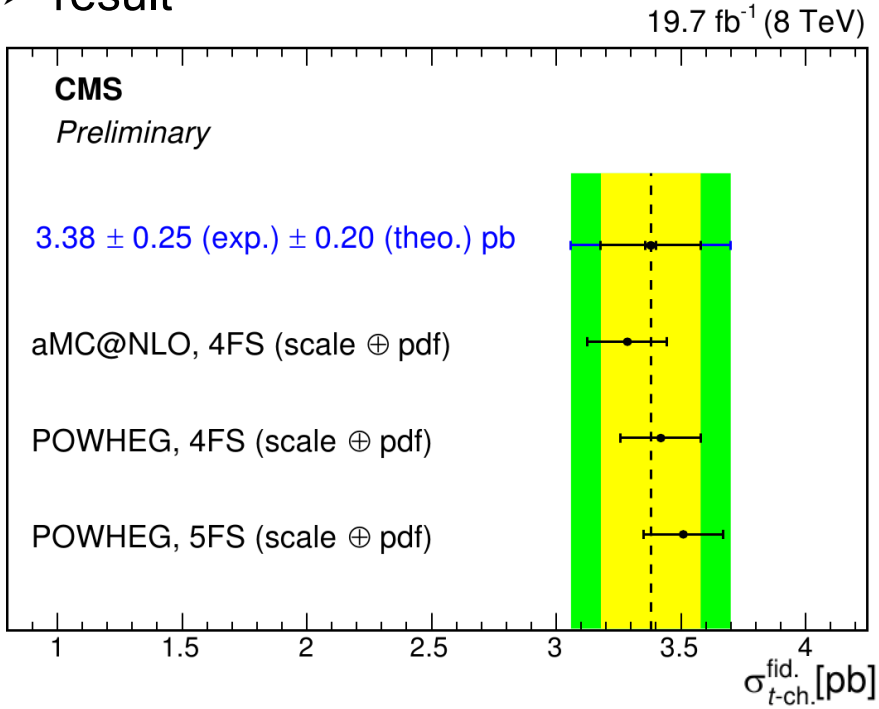
$$\sigma_{t\text{-ch}}^{\text{incl.}} = 82.6 \pm 1.2(\text{stat}) \pm 12.0(\text{syst})\ \text{pb} = 82.6 \pm 12.1\ \text{pb}$$

$$\left[\sigma_{t\text{-ch.}}^{\text{theo.}} = 87^{+3}_{-2}\ \text{pb}\right]$$

8 TeV CMS: Fiducial $\sigma_{t\text{-ch.}}$

CMS-PAS-TOP-**15**-007

- event selection same as inclusive 8 TeV cross section measurement
- fiducial selection on generator particles
  - consider particle $c \cdot \tau > 10$ mm as stable
  - 1 "dressed" e/μ (anti-k_{T}, $R = 0.1$) with $p_{\mathrm{T}} > 30$ GeV, $|\eta| < 2.4$
  - 2 jets (anti-k_{T}, $R = 0.5$) with $p_{\mathrm{T}} > 40$ GeV, $|\eta| < 5$
  - 1 b-jet using the **"ghost b-hadrons" method** ($p_{\mathrm{T}} > 40$ GeV, $|\eta| < 2.4$)
    - find non-resonant b-hadrons not decaying to other hardons
    - rescale momentum to very small value & allow them to be clustered into jets
- result



	stat+exp	scale	PDF	matching
fiducial	$\pm 7.4\%$	$\pm 1.8\%$	$\pm 2.4\%$	$\pm 5.0\%$
inclusive	$\pm 7.4\%$	$^{+0.2}_{-1.3}\%$	$\pm 2.2\%$	$\pm 0.8\%$

$$\sigma^{\text{fid.}}_{t\text{-ch}} = 3.38 \pm 0.32 \;\Rightarrow\; \sigma^{\text{incl.}}_{t\text{-ch}} = 87.2 \pm 6.9$$

$$\left[\sigma^{\text{theo.}}_{t\text{-ch.}} = 87^{+3}_{-2}\ \text{pb}\right]$$

8 TeV: Limits on CKM Element V_{tb}

JHEP06 (**2014**) 090
ATLAS-CONF-**2014**-007

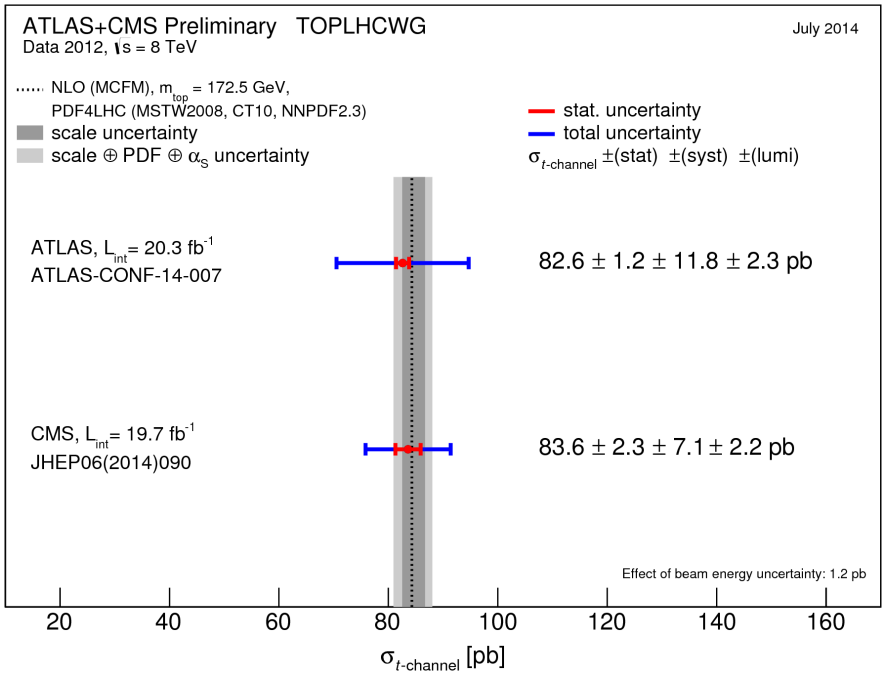
- calculation
  - assume $\mathcal{B}(t \to bW) = |V_{tb}|^2 / (\overbrace{|V_{td}|^2 + |V_{ts}|^2}^{\ll |V_{tb}|^2} + |V_{tb}|^2) \approx 100\%$
  - "strength" of top production vertex $\sigma(pp \to tq) \propto V_{tb}^2$

$$\Rightarrow |V_{tb} \cdot f_L| = \sqrt{\frac{\sigma_{measured}}{\sigma^{SM}_{theory}}}$$

(f_L = left-handed "form factor"; $f_L^{SM} \equiv 1$)

without assumptions on **number of quark** generation & **no unitarity** constraint

- results



ATLAS

$$|V_{tb}| = 0.97^{+0.06}_{-0.07}(\text{exp.}) \pm 0.06(\text{theo.})$$

$$|V_{tb}| > 0.78 \ @95\%\text{CL}$$

CMS

$$|V_{tb}| = 0.98 \pm 0.05(\text{exp.}) \pm 0.02(\text{theo.})$$

7+8 TeV t-channel combination

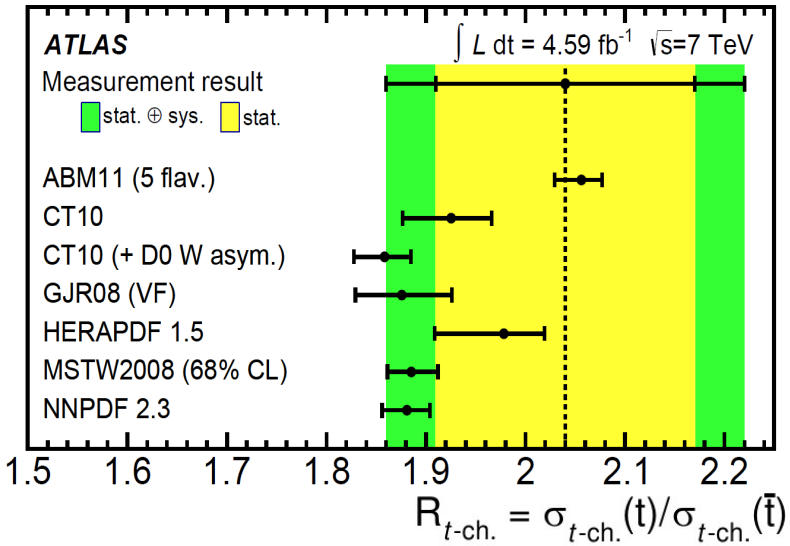
$$|V_{tb}| = 0.998 \pm 0.038(\text{exp.}) \pm 0.016(\text{theo.})$$

$$|V_{tb}| > 0.92 \ @95\%\text{CL}$$

Charge Ratio: $\sigma(t)/\sigma(\bar{t})$

JHEP06 (**2014**) 090
Phys. Rev. D. 90 112006 **2014**

ATLAS 7 TeV

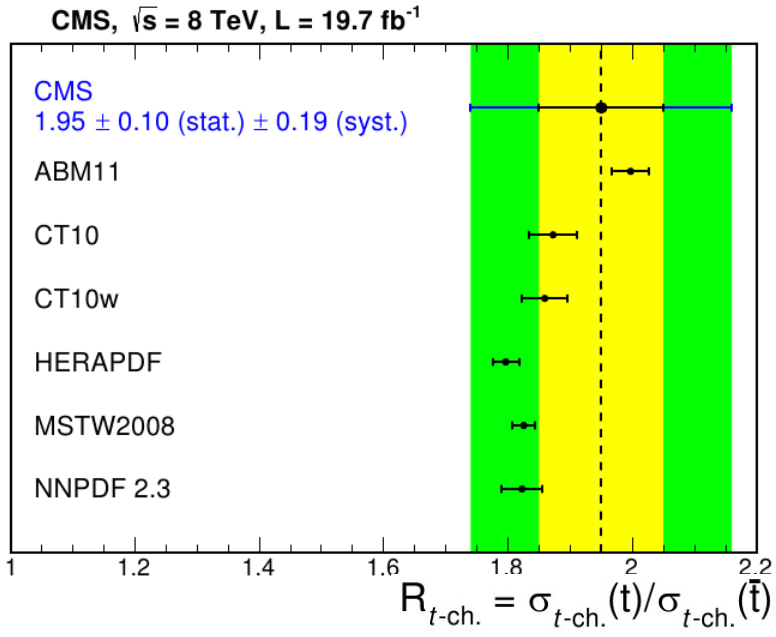


major uncertainties

Data statistical	±6.2
Monte Carlo statistical	±3.6
JES η intercalibration	±1.8
PDF	±2.5
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	±1.6

$$R(t/\bar{t}) = 2.04 \pm 0.18$$

CMS 8 TeV



major uncertainties

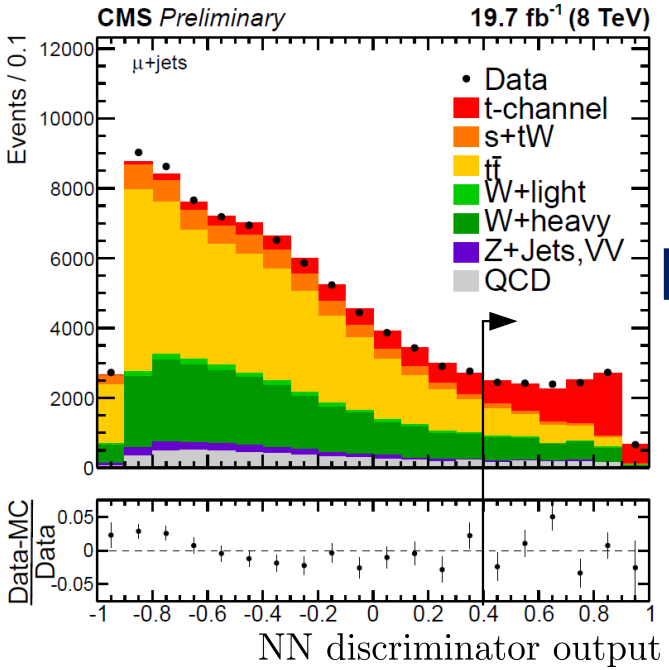
Statistical uncertainty	± 5.1
QCD multijet estimation	±1.9
W+jets, $t\bar{t}$ estimation	± 3.0
Signal modeling	± 6.1
PDF uncertainty	± 6.2

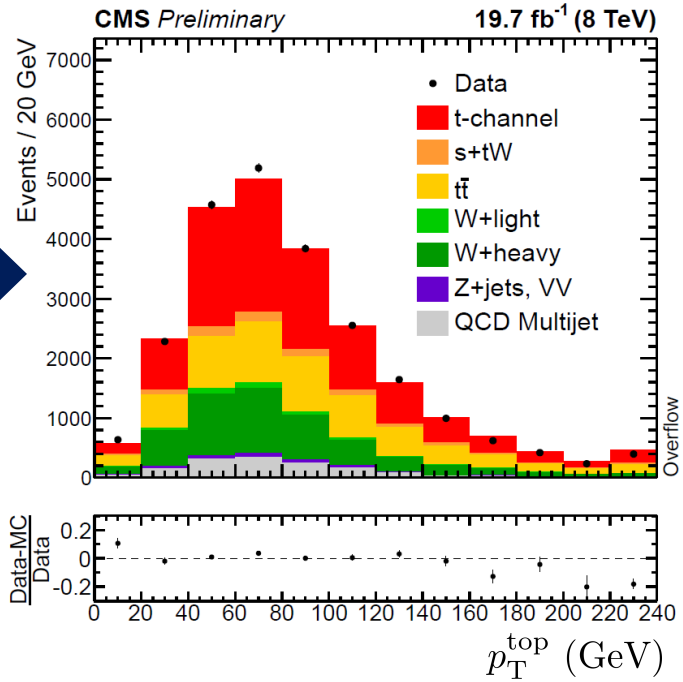
$$R(t/\bar{t}) = 1.95 \pm 0.21$$

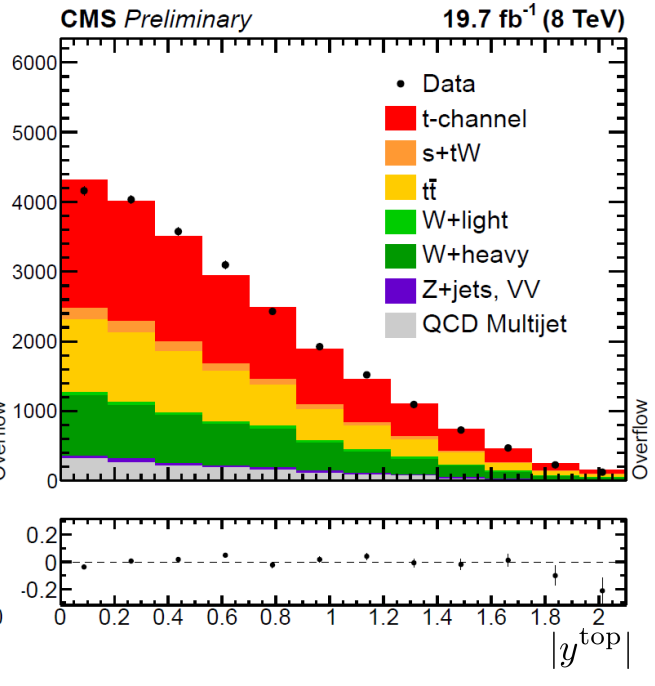
similar tension between data & PDF sets despite different $\sqrt{s}$

8 TeV CMS: Differential $\sigma_{t\text{-ch.}}$

- event selection similar to cross section measurement
- analysis strategy
  - train **neutral network**
  - **binned likelihood fit** to neural network (NN) output → signal/background yields
  - apply additional optimized selection on neutral network output
    (muon: $\mathrm{NN} > 0.3$, electron: $\mathrm{NN} > 0.4$)
  - unfold data in **single top enriched phase space** (after background subtraction)



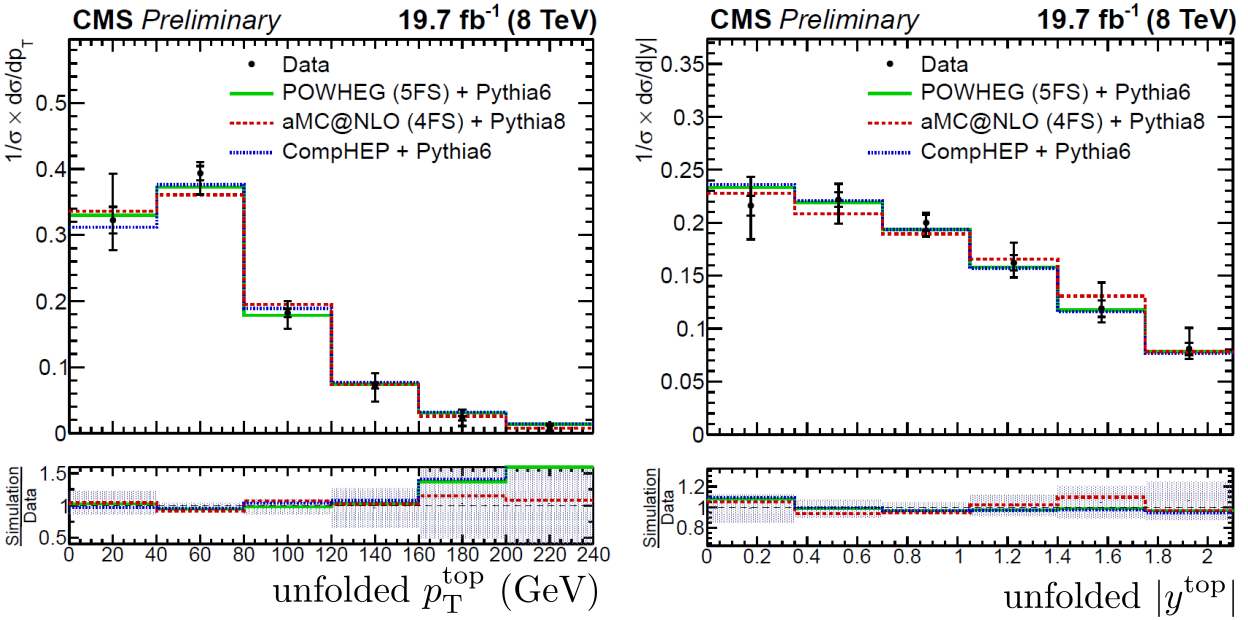




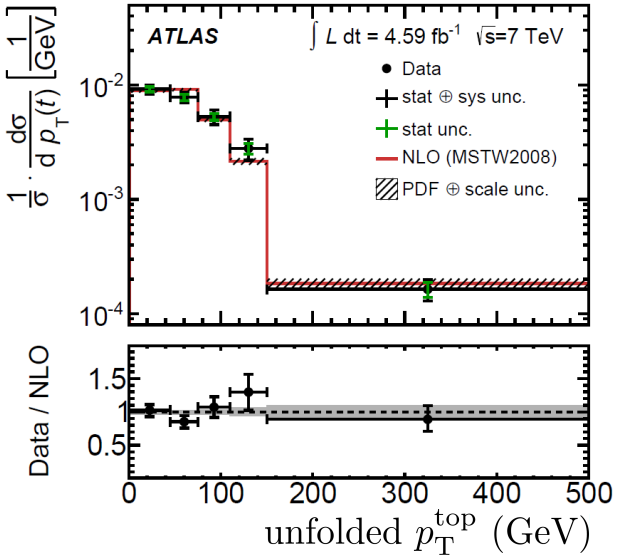
ATLAS/CMS: Differential $\sigma_{t\text{-ch.}}$

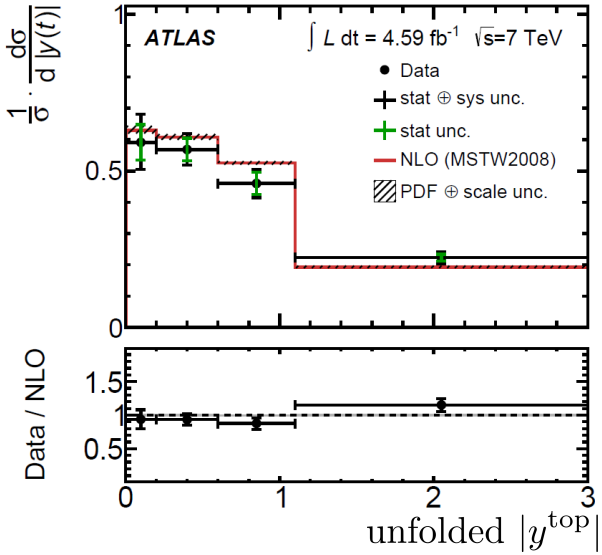
CMS-TOP-PAS-**14**-004
Phys. Rev. D. 90 112006 **2014**

CMS 8 TeV



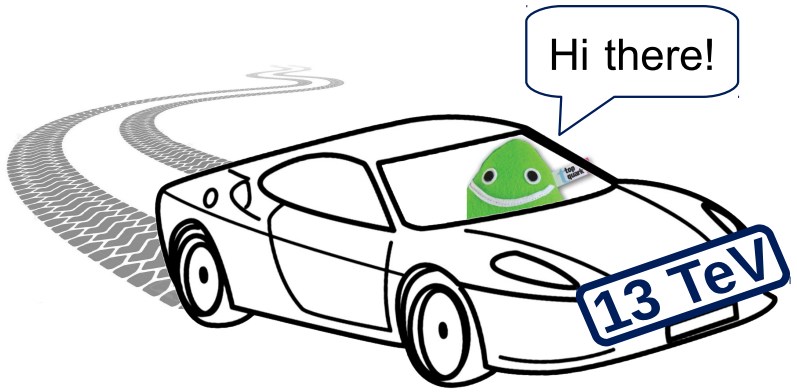
ATLAS 7 TeV (l^+-only)



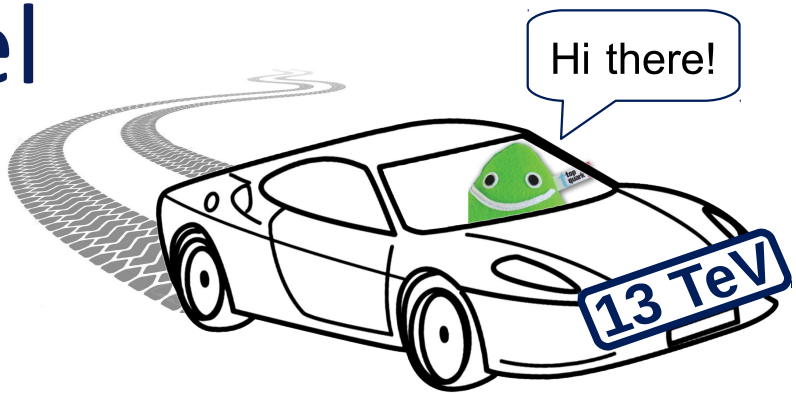


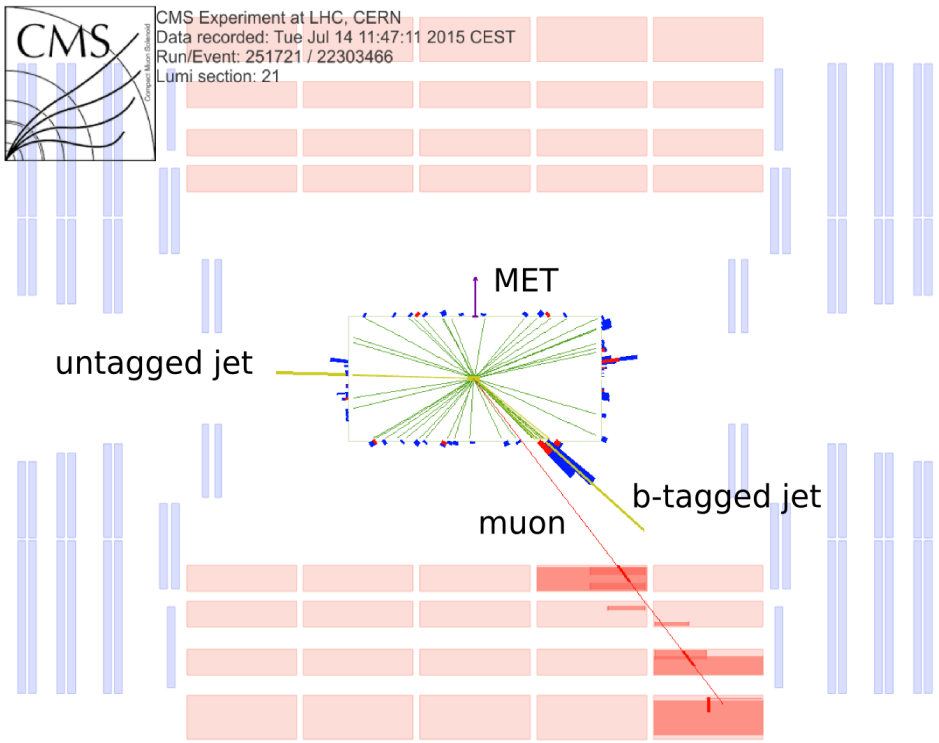
- unfolding
  - CMS: χ^2-minimization with penalty term for regularization
  - ATLAS: apply Bayes' theorem iteratively until result stabilizes
- result
  - first comparison of 4FS/5FS
  - data well in agreement with tested generators

Single Top at 13 TeV



13 TeV: Single Top t-channel





1 isolated muon, $\not{E}_{\mathrm{T}} = 27\ \mathrm{GeV}$,

2 jets: 1 passes b-tagging, other jet $\eta_{j'} = 4.3$,

reconstructed top candidate: $m = 177\ \mathrm{GeV}$

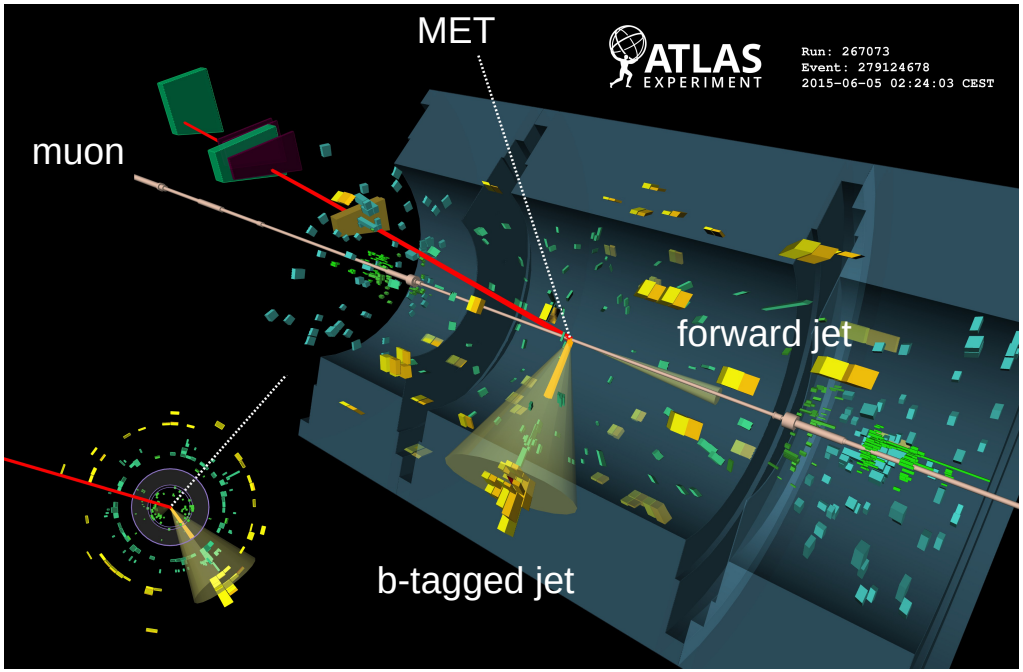
1 isolated muon $p_{\mathrm{T}} = 30\ \mathrm{GeV}$,

2 jets from calorimeters:

central jet passes b-tagging $p_{\mathrm{T}} = 50\ \mathrm{GeV}$,

forward jet $p_{\mathrm{T}} = 30\ \mathrm{GeV}$,

$\not{E}_{\mathrm{T}} = 40\ \mathrm{GeV}$



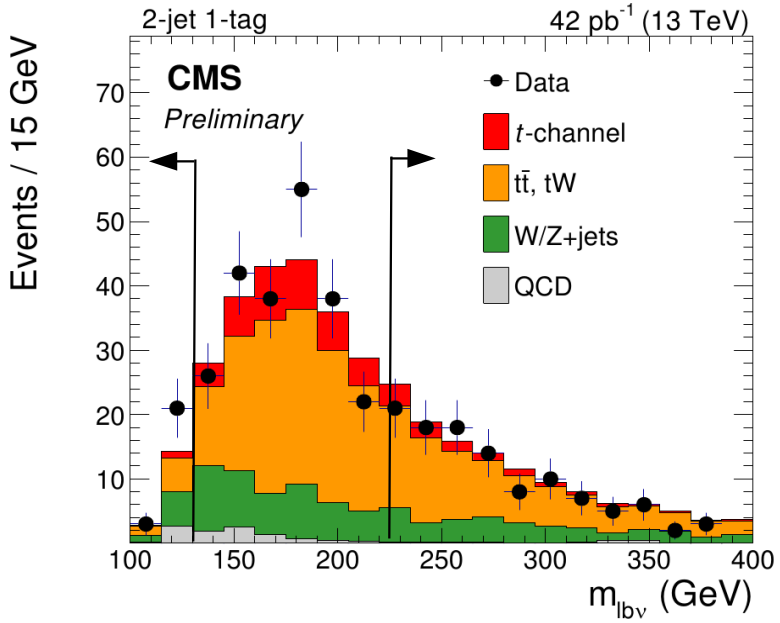
13 TeV CMS: *Early* $\sigma_{t\text{-ch.}}$

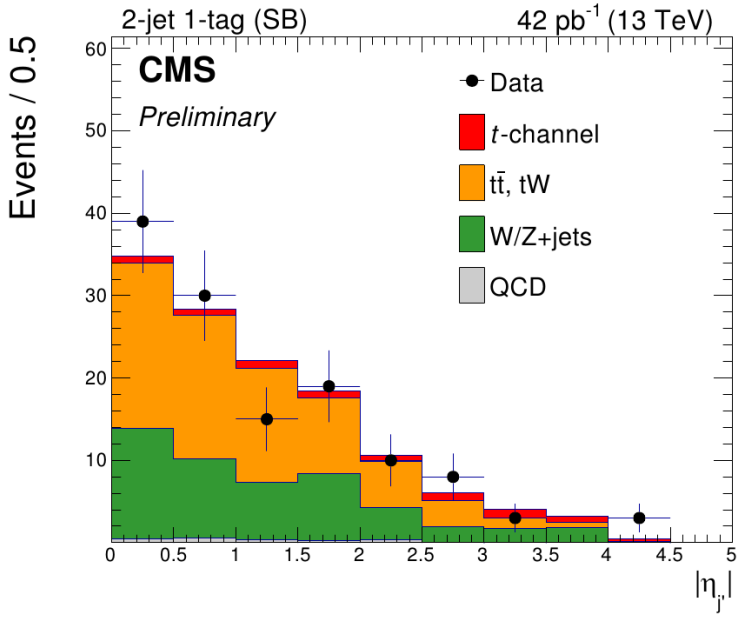
CMS-PAS-TOP-**15**-004

- follows strategy of 8 TeV inclusive cross section measurement
- event selection
  - 1 **single isolation muon**: $p_{\mathrm{T}} > 22\ \mathrm{GeV}, |\eta| < 2.1$
  - 2 jets: $p_{\mathrm{T}} > 40\ \mathrm{GeV}, |\eta| < 4.7$ & 1 jet b-tagged (MVA-based)
  - QCD multijet:
    - shape from data with **loosened lepton isolation**
    - yield from $m_{\mathrm{T}}(W)$**-fit** & rejection $m_{\mathrm{T}}(W) > 50\ \mathrm{GeV}$

    } *see also poster by G. Krintiras' !*

  - W+jets from simulation & validated outside top mass window ($130 < m_{l\nu b} < 225\ \mathrm{GeV}$)



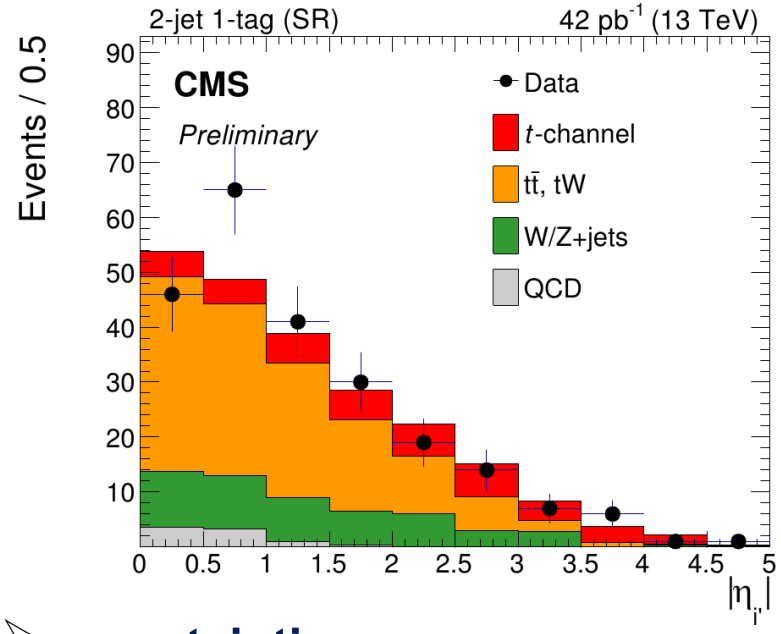


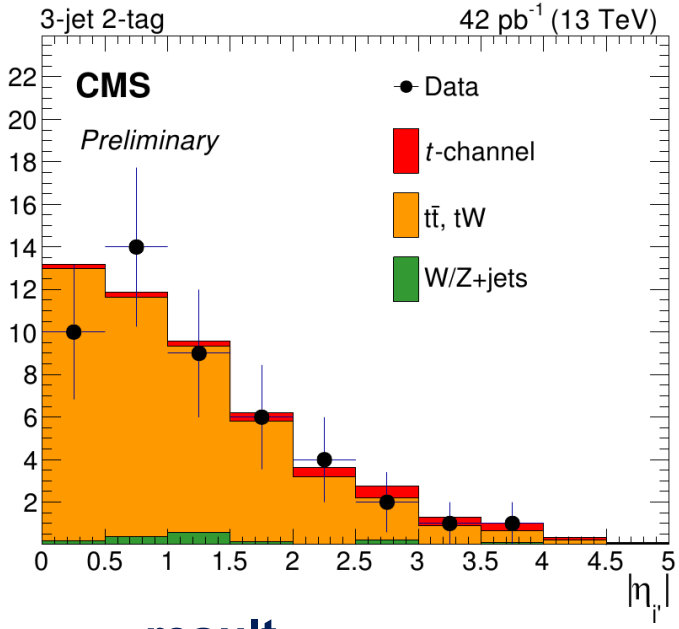
13 TeV CMS: *Early* $\sigma_{t\text{-ch.}}$ (2)

CMS-PAS-TOP-**15**-004

NEW

- binned likelihood fit to $|\eta_{j'}|$ in 2 jets (1 b-tag) & 3 jets (2 b-tags) region





uncertainties

Uncertainty source	$\Delta\sigma_{t-\text{ch}}/\sigma^{\text{obs}}_{t-\text{ch}}$
Statistical uncertainty	36%
JES	17%
JER	1.1%
b-tagging	5.6%
Muon trigger/reconstruction	3.4%
QCD extraction	1.1%
Signal generator	1.9%
Factorization and renormalization scales (Q^2)	3.3%
PDF	4.5%
MET	1.2%
Pileup	1.4%
Luminosity	12%

result

$$\sigma_{t\text{-ch}} = 274 \text{ pb} \pm 42\% \Rightarrow |V_{tb}| > 0.7 \text{ @95\%CL}$$

$$\left[\sigma^{\text{theo.}}_{t\text{-ch.}} = 218 \pm 7 \text{ pb}\right]$$

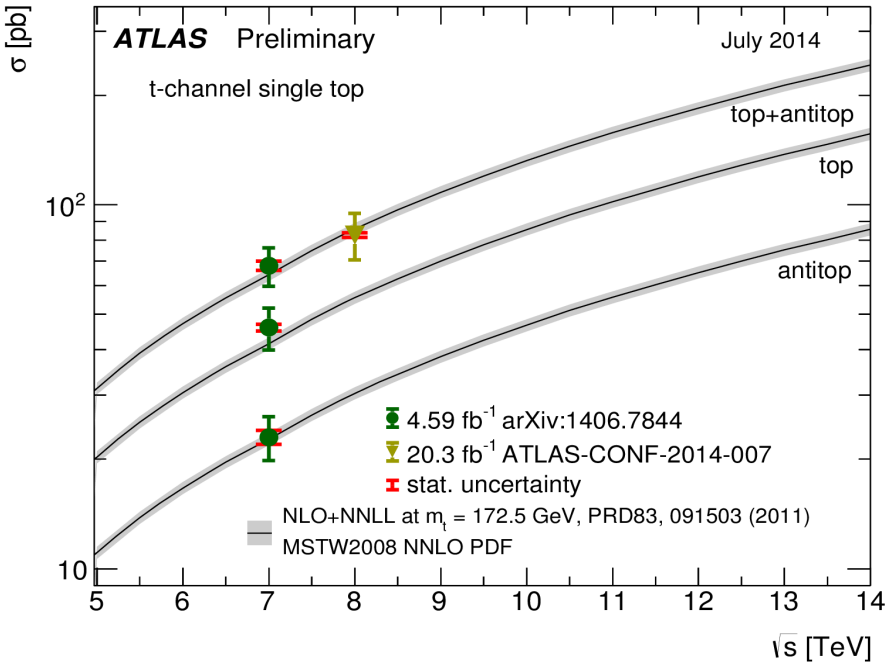
significance

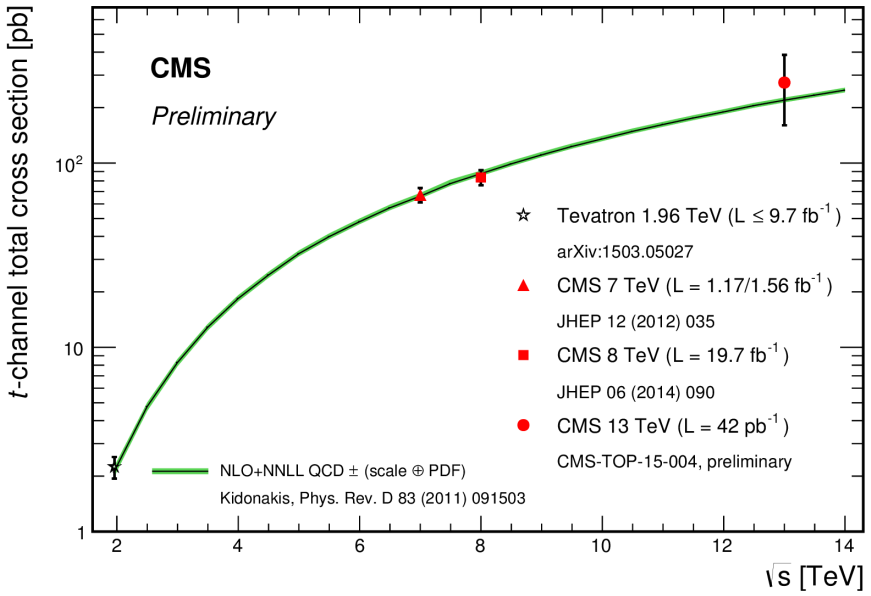
observed: 3.5 expected: 2.7

→ *more in N. Faltermann's talk (YSF)* ***this evening!***

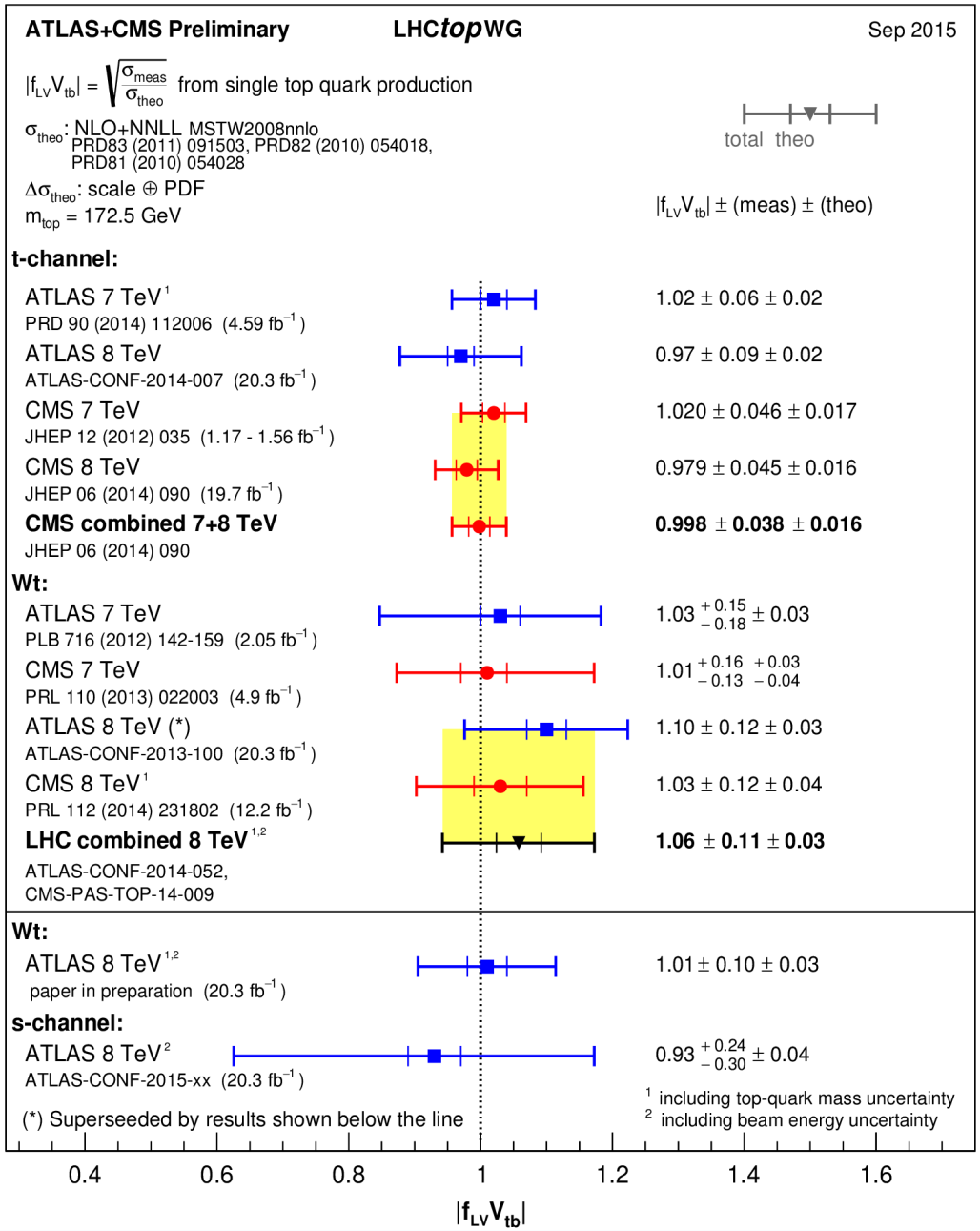
Conclusion: t-channel Production

measured cross section





CKM matrix element V_{tb}



Backup

Single Top Cross Sections

Phys. Part. Nucl. 45, **2014** & arXiv:1506.04072, **2015**

(approx. NNLO, $m_t = 173$ GeV, 4FS, MSTW2008)

LHC 7 TeV	$\sigma(t)$ (pb)	$\sigma(\bar{t})$ (pb)	$\sigma(t) + \sigma(\bar{t})$ (pb)
t-channel	$43.0^{+1.6}_{-0.2} \pm 0.8$	$22.9 \pm 0.5^{+0.7}_{-0.9}$	$65.9^{+2.1+1.5}_{-0.7-1.7}$
s-channel	$3.14 \pm 0.06^{+0.12}_{-0.10}$	$1.42 \pm 0.01^{+0.06}_{-0.07}$	$4.56 \pm 0.07^{+0.18}_{-0.17}$
tW	$7.8 \pm 0.2^{+0.5}_{-0.6}$	$7.8 \pm 0.2^{+0.5}_{-0.6}$	$15.6 \pm 0.4 \pm 1.1$

→ $R = 1.88$

- t-channel

LHC	t	$\bar{t}$	Total (pb)
8 TeV	$55.9^{+2.1}_{-0.3} \pm 1.1$	$30.6 \pm 0.7^{+0.9}_{-1.1}$	$86.5^{+2.8+2.0}_{-1.0-2.2}$
13 TeV	$136^{+3}_{-1} \pm 3$	$82^{+2}_{-1} \pm 2$	$218^{+5}_{-2} \pm 5$
14 TeV	$154^{+4}_{-1} \pm 3$	94^{+2+2}_{-1-3}	248^{+6+5}_{-2-6}

→ $R = 1.83$

→ $R = 1.66$

- tW

LHC	tW^-	$tW^- + \bar{t}W^+$ (pb)
8 TeV	$11.0 \pm 0.3 \pm 0.7$	$22.0 \pm 0.6 \pm 1.4$
13 TeV	$35.20 \pm 0.9^{+1.6}_{-1.7}$	$70.40 \pm 1.8^{+3.2}_{-3.4}$
14 TeV	$41.6 \pm 1.0^{+1.5}_{-2.3}$	$83.1 \pm 2.0^{+3.1}_{-4.6}$

- s-channel

LHC	t	$\bar{t}$	Total (pb)
8 TeV	$3.75 \pm 0.07 \pm 0.13$	$1.90 \pm 0.01 \pm 0.08$	$5.65 \pm 0.08 \pm 0.21$
13 TeV	$7.07 \pm 0.13^{+0.24}_{-0.22}$	$4.10 \pm 0.05^{+0.14}_{-0.16}$	$11.17 \pm 0.18 \pm 0.38$
14 TeV	$7.79 \pm 0.14^{+0.31}_{-0.24}$	$4.57 \pm 0.05^{+0.18}_{-0.17}$	$12.35 \pm 0.19^{+0.49}_{-0.41}$

7 TeV CMS: Uncertainties

JHEP 12 (**2012**) 035

		Uncertainty source	NN	BDT	$\lvert\eta_{j'}\rvert$
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	$-1.0/+0.9\%$	$\pm 0.4\%$	$-0.3/+0.2\%$
		$\not\!\!E_T$ modelling	$-0.0/+0.2\%$	$\pm 0.2\%$	$\pm 0.5\%$
	Backg. rates	W+jets	$-2.0/+3.0\%$	$-3.5/+2.5\%$	$\pm 5.9\%$
		light flavour (u, d, s, g)	$-0.2/+0.3\%$	$\pm 0.4\%$	n/a
		heavy flavour (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.)			$-10.1/+9.5\%$	$-9.4/+10.0\%$	$\pm 13.8\%$

7 TeV ATLAS: Uncertainties

Phys. Rev. D. 90 112006 **2014**

Source	$\Delta\sigma(tq)/\sigma(tq)$ [%]	$\Delta\sigma(\bar{t}q)/\sigma(\bar{t}q)$ [%]	$\Delta R_t/R_t$ [%]	$\Delta\sigma(tq+\bar{t}q)/\sigma(tq+\bar{t}q)$ [%]
Data statistical	±3.1	±5.4	±6.2	±2.7
Monte Carlo statistical	±1.9	±3.2	±3.6	±1.9
Multijet normalization	±1.1	±2.0	±1.6	±1.4
Other background normalization	±1.1	±2.8	±1.9	±1.6
JES detector	±1.6	±1.4	< 1	±1.4
JES statistical	< 1	< 1	< 1	< 1
JES physics modeling	< 1	< 1	< 1	< 1
JES η intercalibration	±6.9	±8.4	±1.8	±7.3
JES mixed detector and modeling	< 1	< 1	< 1	< 1
JES close-by jets	< 1	< 1	< 1	< 1
JES pile-up	< 1	< 1	< 1	< 1
JES flavor composition	±1.4	±1.4	±1.2	±1.6
JES flavor response	< 1	< 1	±1.0	< 1
b-JES	< 1	< 1	< 1	< 1
Jet energy resolution	±2.1	±1.6	±1.0	±1.9
Jet vertex fraction	< 1	< 1	< 1	< 1
b-tagging efficiency	±3.8	±4.1	< 1	±3.9
c-tagging efficiency	< 1	±1.4	< 1	< 1
Mistag efficiency	< 1	< 1	< 1	< 1
$b/\bar{b}$ acceptance	±1.0	< 1	< 1	−−
$E_{\mathrm{T}}^{\mathrm{miss}}$ modeling	±2.3	±3.4	±1.6	±2.6
Lepton uncertainties	±2.8	±3.0	±1.0	±2.8
PDF	±3.2	±5.8	±2.5	±3.2
W+jets shape variation	< 1	< 1	< 1	< 1
tq generator + parton shower	±1.9	±1.6	< 1	±1.9
tq scale variations	±2.6	±3.0	< 1	±2.6
$t\bar{t}$ generator + parton shower	< 1	±2.1	±1.6	< 1
$t\bar{t}$ ISR / FSR	< 1	< 1	±1.0	< 1
Luminosity	±1.8	±1.8	±0.5	±1.8
Total systematic	±12.0	±14.9	±6.1	±12.1
Total	±12.4	±15.9	±8.7	±12.4

7 TeV ATLAS: Wtb Couplings

paper in preparation

NEW

$$\mathcal{L}_{Wtb} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_{\mathrm{L}}P_{\mathrm{L}} + V_{\mathrm{R}}P_{\mathrm{R}}\right)tW^{-}_{\mu}$$
$$-\frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_{\mathrm{L}}P_{\mathrm{L}} + g_{\mathrm{R}}P_{\mathrm{R}}\right)tW^{-}_{\mu} + \mathrm{h.c.}$$

$$f_1 = \frac{2\left(|x_W V_{\mathrm{L}} - g_{\mathrm{R}}|^2 + |x_W V_{\mathrm{R}} - g_{\mathrm{L}}|^2\right) + O(x_b)}{2\left(|x_W V_{\mathrm{L}} - g_{\mathrm{R}}|^2 + |x_W V_{\mathrm{R}} - g_{\mathrm{L}}|^2\right) + |V_{\mathrm{L}} - x_W g_{\mathrm{R}}|^2 + |V_{\mathrm{R}} - x_W g_{\mathrm{L}}|^2 + O(x_b)}$$

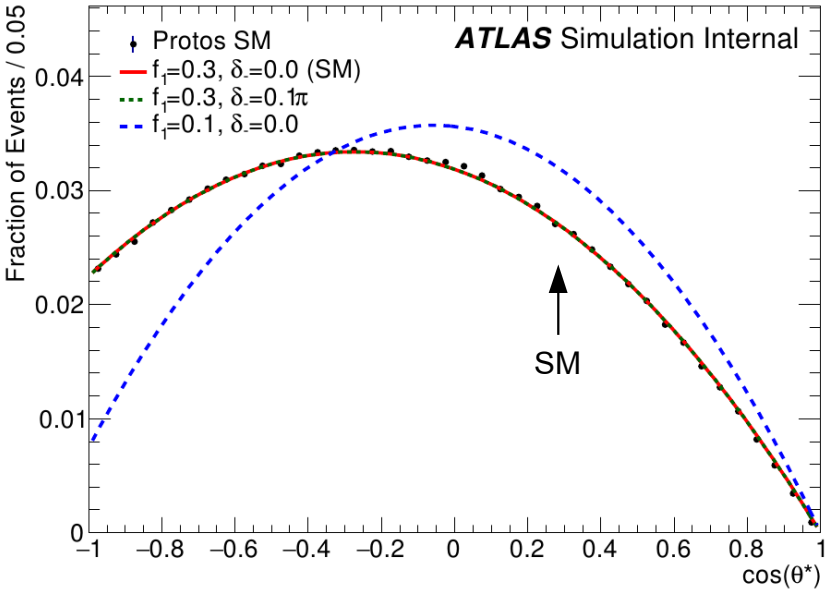
$$f_1^+ = \frac{|x_W V_{\mathrm{R}} - g_{\mathrm{L}}|^2 + O(x_b)}{|x_W V_{\mathrm{L}} - g_{\mathrm{R}}|^2 + |x_W V_{\mathrm{R}} - g_{\mathrm{L}}|^2 + O(x_b)}$$

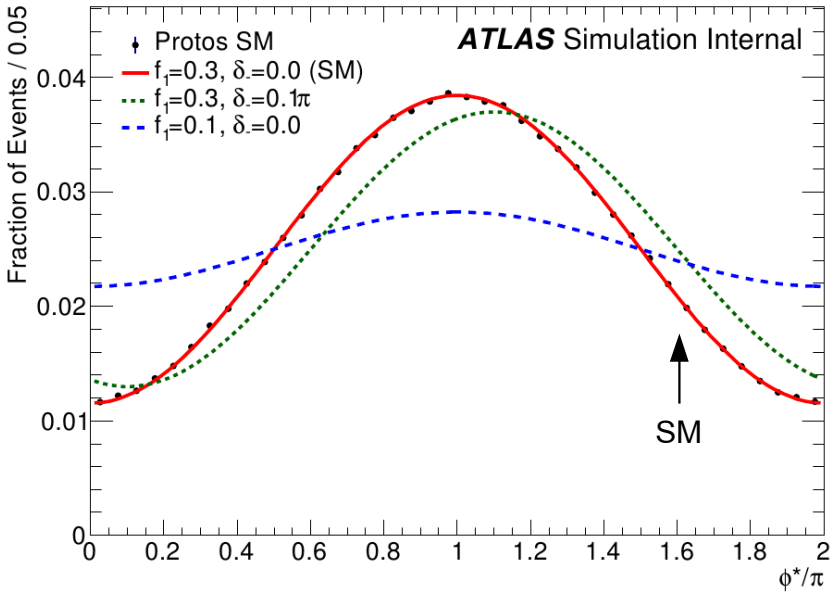
$$f_0^+ = \frac{|V_{\mathrm{R}} - x_W g_{\mathrm{L}}|^2 + O(x_b)}{|V_{\mathrm{R}} - x_W g_{\mathrm{L}}|^2 + |V_{\mathrm{L}} - x_W g_{\mathrm{R}}|^2 + O(x_b)}$$

$$\delta_+ = \arg\left((x_W V_{\mathrm{R}} - g_{\mathrm{L}})(V_{\mathrm{R}} - x_W g_{\mathrm{L}})^* + O(x_b)\right)$$

$$\delta_- = \arg\left((x_W V_{\mathrm{L}} - g_{\mathrm{R}})(V_{\mathrm{L}} - x_W g_{\mathrm{R}})^* + O(x_b)\right)$$

$$F_{\mathrm{R}} = f_1 f_1^+$$
$$F_{\mathrm{L}} = f_1(1 - f_1^+)$$





ATLAS Wtb: Analysis Method

paper in preparation

- efficiency

$$\epsilon(\theta^*_{\mathrm{T}}, \phi^*_{\mathrm{T}};\ \vec{\alpha}, P) = \sum_{l',m'}^{l^{\mathrm{eff}}_{\mathrm{max}}} e_{l',m'}(\vec{\alpha}, P) Y_{l'}^{m'}(\theta^*_{\mathrm{T}}, \phi^*_{\mathrm{T}})$$

- resolution

$$\mathcal{R}(\theta^*, \phi^* | \theta^*_{\mathrm{T}}, \phi^*_{\mathrm{T}};\ \vec{\alpha}, P) = \sum_{\lambda,\mu}^{l^{\mathrm{reco}}_{\mathrm{max}}} \sum_{L',M'}^{l^{\mathrm{true}}_{\mathrm{max}}} r_{\lambda,\mu,L',M'}(\vec{\alpha}, P) Y_{\lambda}^{\mu}(\theta^*, \phi^*) Y_{L'}^{M'}(\theta^*_{\mathrm{T}}, \phi^*_{\mathrm{T}})$$

- folding

$$\rho_{\mathrm{r}}(\theta^*, \phi^*;\ \vec{\alpha}, P) = \int \mathcal{R}(\theta^*, \phi^* | \theta^*_{\mathrm{T}}, \phi^*_{\mathrm{T}};\ \vec{\alpha}, P) \rho_s(\theta^*_{\mathrm{T}}, \phi^*_{\mathrm{T}};\ \vec{\alpha}, P) \mathrm{d}\Omega^*_{\mathrm{T}} = \sum_{\lambda,\mu} d_{\lambda,\mu}(\vec{\alpha}, P) Y_{\lambda}^{\mu}(\theta^*, \phi^*)$$

- final likelihood

$$\mathcal{L}(\vec{\alpha}) = \prod_{i=1}^{N} \exp\left(w_i \rho_{\mathrm{t}}(\theta^*_i, \phi^*_i |\ \vec{\alpha}, P, f_{\mathrm{s}})\right)$$

$$\rho_{\mathrm{t}}(\theta^*, \phi^*;\ \vec{\alpha}, P, f_{\mathrm{s}}) = \sum_{\lambda,\mu}^{\max\left(l^{\mathrm{reco}}_{\mathrm{max}}, l^{\mathrm{bkg}}_{\mathrm{max}}\right)} \mathcal{A}_{\lambda,\mu}(\vec{\alpha}, P) Y_{\lambda}^{\mu}(\theta^*, \phi^*)$$

$$\mathcal{A}_{\lambda,\mu}(\vec{\alpha}, P, f_{\mathrm{s}}) = f_s d_{\lambda,\mu}(\vec{\alpha}, P) + (1 - f_s) b_{\lambda,\mu}$$

Spherical Expansion

paper in preparation

$$\rho(\theta^*,\phi^*;\vec{\alpha},P) \equiv \frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\Omega^*} = \sum_{l=0}^{2}\sum_{m=-l}^{l} a_{l,m}(\vec{\alpha},P)Y_l^m(\theta^*,\phi^*), \text{ with}$$

$$a_{0,0} = \frac{1}{\sqrt{4\pi}}, \qquad a_{1,0} = \frac{\sqrt{3}}{\sqrt{4\pi}} f_1 \left(f_1^+ - \frac{1}{2}\right), \qquad a_{2,0} = \frac{1}{\sqrt{20\pi}}\left(\frac{3}{2}f_1 - 1\right),$$

$$a_{1,1} = -a_{1,-1}^* = P\frac{\sqrt{3\pi}}{16}\sqrt{f_1(1-f_1)}\left\{\sqrt{f_1^+ f_0^+}e^{i\delta_+} + \sqrt{(1-f_1^+)(1-f_0^+)}e^{-i\delta_-}\right\},$$

$$a_{2,1} = -a_{2,-1}^* = P\frac{\sqrt{3\pi}}{16\sqrt{5}}\sqrt{f_1(1-f_1)}\left\{\sqrt{f_1^+ f_0^+}e^{i\delta_+} - \sqrt{(1-f_1^+)(1-f_0^+)}e^{-i\delta_-}\right\},$$

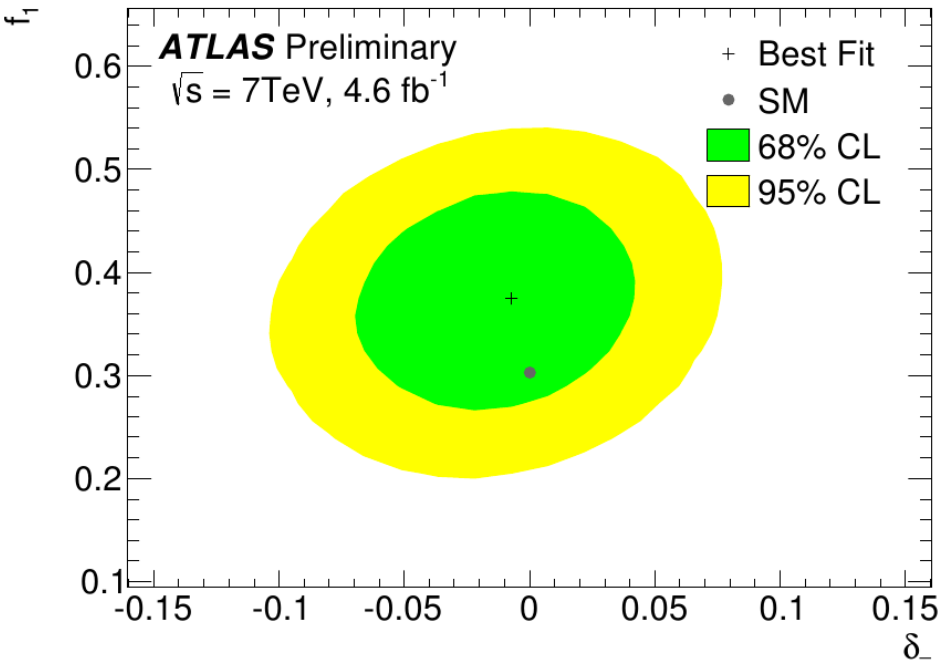
$$a_{2,2} = a_{2,-2} = 0.$$

ATLAS Wtb Couplings

paper in preparation

NEW

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-section	< 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



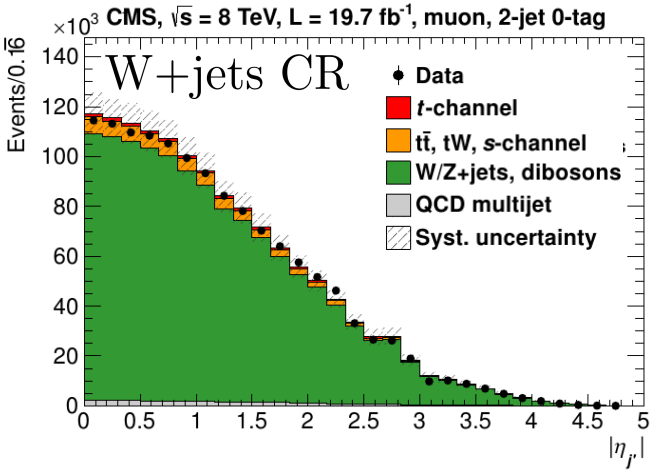
$$f_1 = 0.37 \pm 0.05\ (\mathrm{stat.}) \pm 0.05\ (\mathrm{syst.}),$$

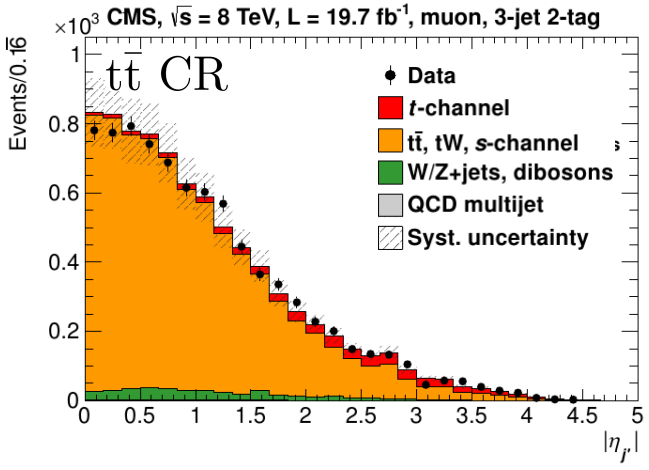
$$\delta_- = -0.014\pi \pm 0.023\pi\ (\mathrm{stat.}) \pm 0.028\pi\ (\mathrm{syst.}).$$

8 TeV CMS: Validation

JHEP06 (**2014**) 090

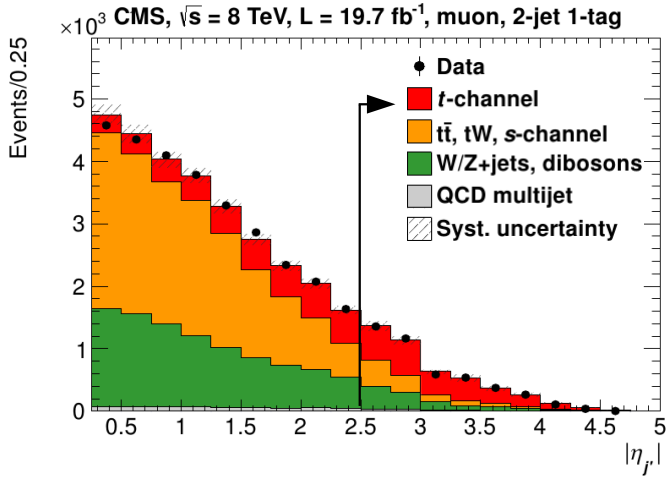
- validation of $|\eta_{j'}|$

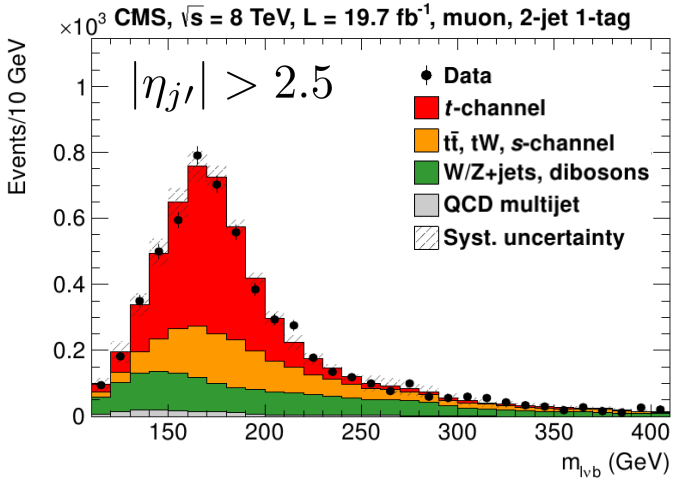




- QCD multijet shape: **loosened lepton isolation**
- QCD yield: $\not{E}_{\mathrm{T}}/m_{\mathrm{T}}(W)$-fit
- QCD rejection:
  electron: $\not{E}_{\mathrm{T}} > 45$ GeV
  muon: $m_{\mathrm{T}}(W) > 50$ GeV

- reconstructed top quark mass





- W+jet background shape from data in **top quark mass side band**
  ($m_{l\nu b} > 220$ GeV or $m_{l\nu b} < 130$ GeV)
  after subtracting all other contributions

8 TeV CMS: Uncertainties

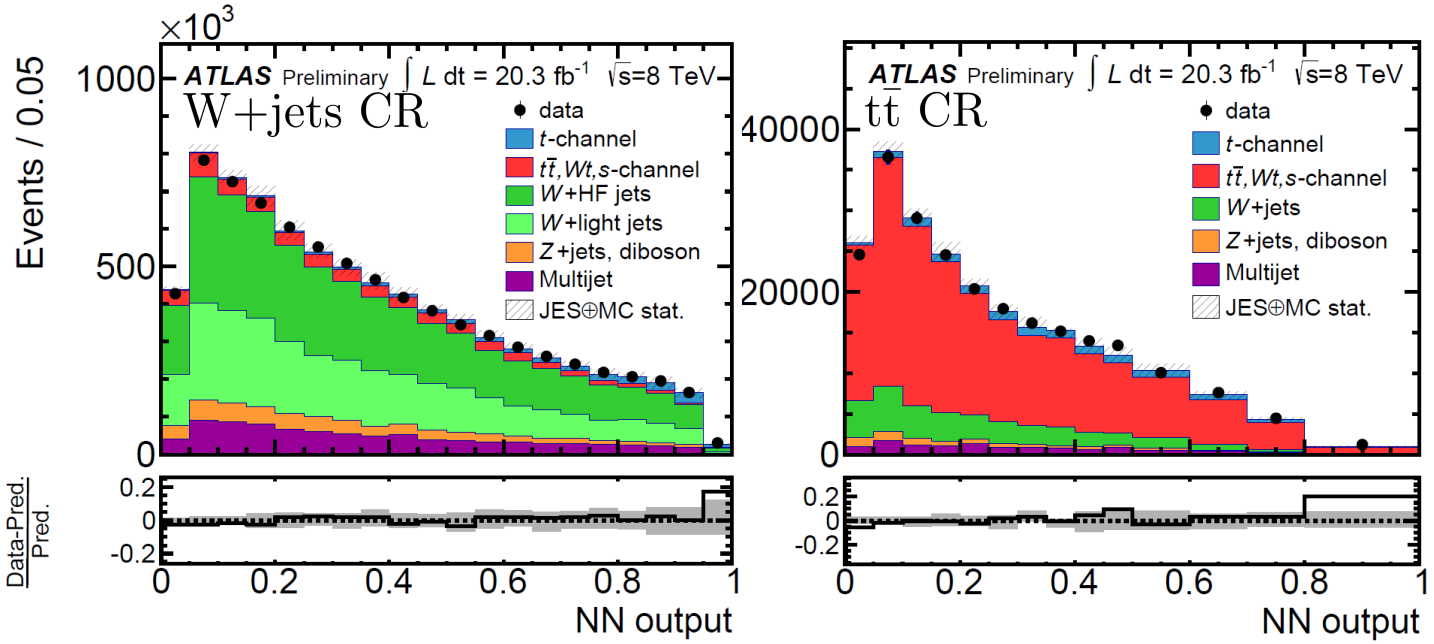
JHEP06 (**2014**) 090

Uncertainty source	$\sigma_{t\text{-ch.}}$ (%)
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 multijet estimation	$\pm$ 2.3
W+jets, $t\bar{t}$ 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 $\pm$ 7.8 pb

Uncertainty source	$\sigma_{t\text{-ch.}}(t)$ (%)	$\sigma_{t\text{-ch.}}(\bar{t})$ (%)	$R_{t\text{-ch.}}$ (%)
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 multijet estimation	$\pm$ 1.6	$\pm$ 3.5	$\pm$1.9
W+jets, $t\bar{t}$ 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 $\pm$ 4.7 pb	27.6 $\pm$ 3.9 pb	1.95 $\pm$ 0.21

8 TeV ATLAS: Validation

- validation of neutral network performance in control regions (CR)



- input variables

$$|\eta_{\mathrm{lj}}|,\ m_{\mathrm{top}},\ m_{\mathrm{jb}},\ m_{\mathrm{T}}(W),\ m_{\mathrm{lb}},\ \eta_W,\ \cos\theta^{\mathrm{top}}(l,j),\ H_{\mathrm{T}},\ \not{E}_{\mathrm{T}},\ \Delta R(t,l),\ p_{\mathrm{T}}^{W},\ \eta_{\mathrm{top}},\ \eta_b,\ p_{\mathrm{T}}^{\mathrm{top}}$$

- QCD multijet shape:
  - electron: "**lepton-jet**" method (select jets with similar properties as electrons from simulation)
  - muon: **inverted selections** (use data shape from multijet enriched region)
- QCD yield: $\not{E}_{\mathrm{T}}$ - fit
- QCD rejection: $m_{\mathrm{T}}(W) > 50\ \mathrm{GeV}$ & $\not{E}_{\mathrm{T}} > 30\ \mathrm{GeV}$

8 TeV ATLAS: Uncertainties

ATLAS-CONF-**2014**-007

Source	$\Delta\sigma_{\text{fid}}/\sigma_{\text{fid}}$ [%]
Data statistics	±1.5
MC statistics	±1.1
Multijet normalisation	+2.3 -1.4
Other background normalization	±0.8
JES η intercalibration	±7.9
JES physics modelling	±3.0
JES detector	< 0.5
JES statistical	< 0.5
JES mixed detector and modelling	< 0.5
JES single particle	< 0.5
JES pile-up	< 0.5
JES flavor composition	±0.8
JES flavor response	±0.5
b-JES	< 0.5
Lepton uncertainties	±2.9
$E_{\text{T}}^{\text{miss}}$ modelling	±3.0
b-tagging efficiency	±3.5
c-tagging efficiency	< 0.5
Mistag efficiency	< 0.5
Jet energy resolution	±1.7
Jet reconstruction eff.	< 0.5
Jet vertex fraction	< 0.5
t-channel generator	±7.9
W+jets generator	±1.4
PDF	±1.1
$t\bar{t}$,Wt and s-channel generator	< 0.5
ISR / FSR ($t\bar{t}$)	< 0.5
Total Systematic	±14
Total	±14

8 TeV CMS: Fiducial

CMS-PAS-TOP-**15**-007

NEW

$$\sigma_t^{\text{fid}}{}_{(\text{aMC@NLO})} = 3.38 \pm 0.25(\text{exp.})^{+0.06}_{-0.06}(\text{scale})^{+0.08}_{-0.08}(\text{PDF}) \pm 0.17(\text{NLO-subtr.})\,\text{pb}$$

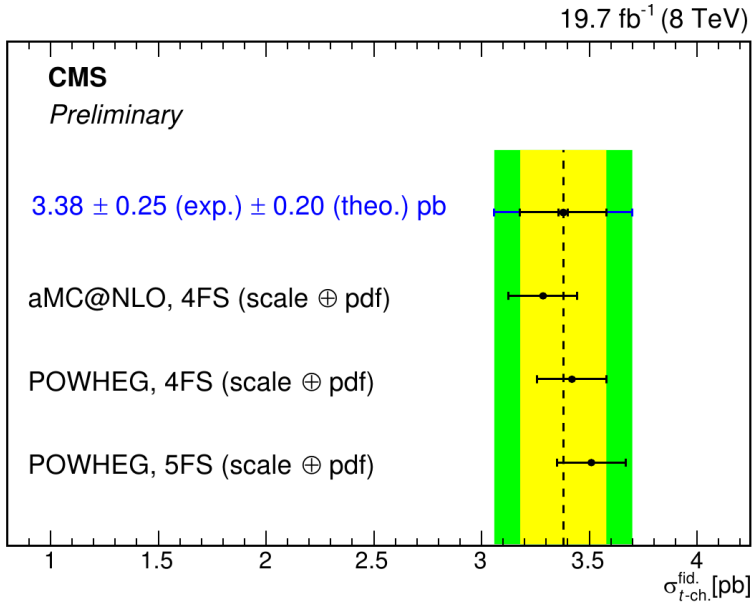
$$\sigma_t^{\text{fid}}{}_{(\text{POWHEG4FS})} = 3.64 \pm 0.27(\text{exp.})^{+0.06}_{-0.06}(\text{scale})^{+0.08}_{-0.08}(\text{PDF}) \pm 0.17(\text{NLO-subtr.})\,\text{pb}$$

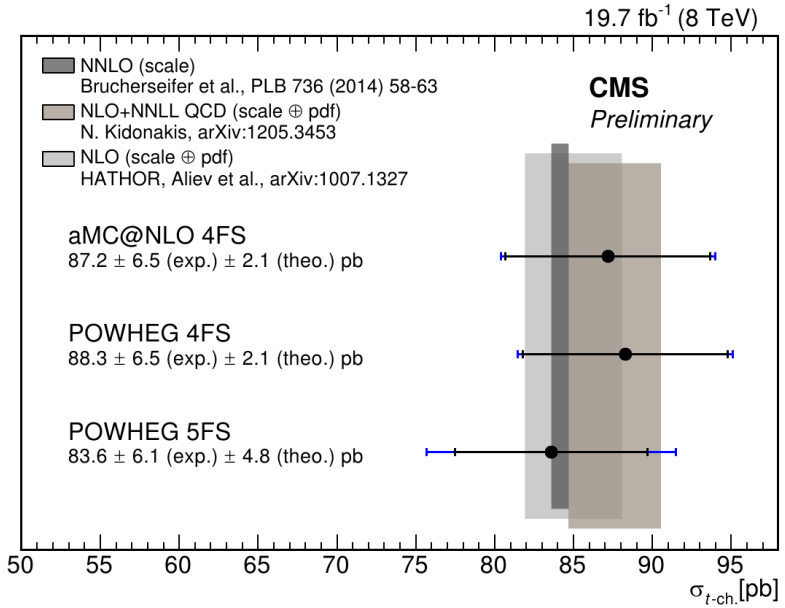
$$\sigma_t^{\text{fid}}{}_{(\text{POWHEG5FS})} = 3.45 \pm 0.25(\text{exp.}) \pm^{+0.08}_{-0.09}(\text{scale})^{+0.07}_{-0.07}(\text{PDF}) \pm 0.17(\text{NLO-subtr.})\,\text{pb}$$

$$\sigma_t^{\text{obs}}{}_{(\text{aMC@NLO})} = 87.2 \pm 6.5(\text{exp.})^{+0.2}_{-1.1}(\text{scale})^{1.9}_{-1.9}(\text{PDF}) \pm 0.7(\text{NLO-subtr.})\,\text{pb}$$

$$\sigma_t^{\text{obs}}{}_{(\text{POWHEG4FS})} = 88.3 \pm 6.5(\text{exp.})^{+0.2}_{-1.1}(\text{scale})^{1.9}_{-1.9}(\text{PDF}) \pm 0.7(\text{NLO-subtr.})\,\text{pb}$$

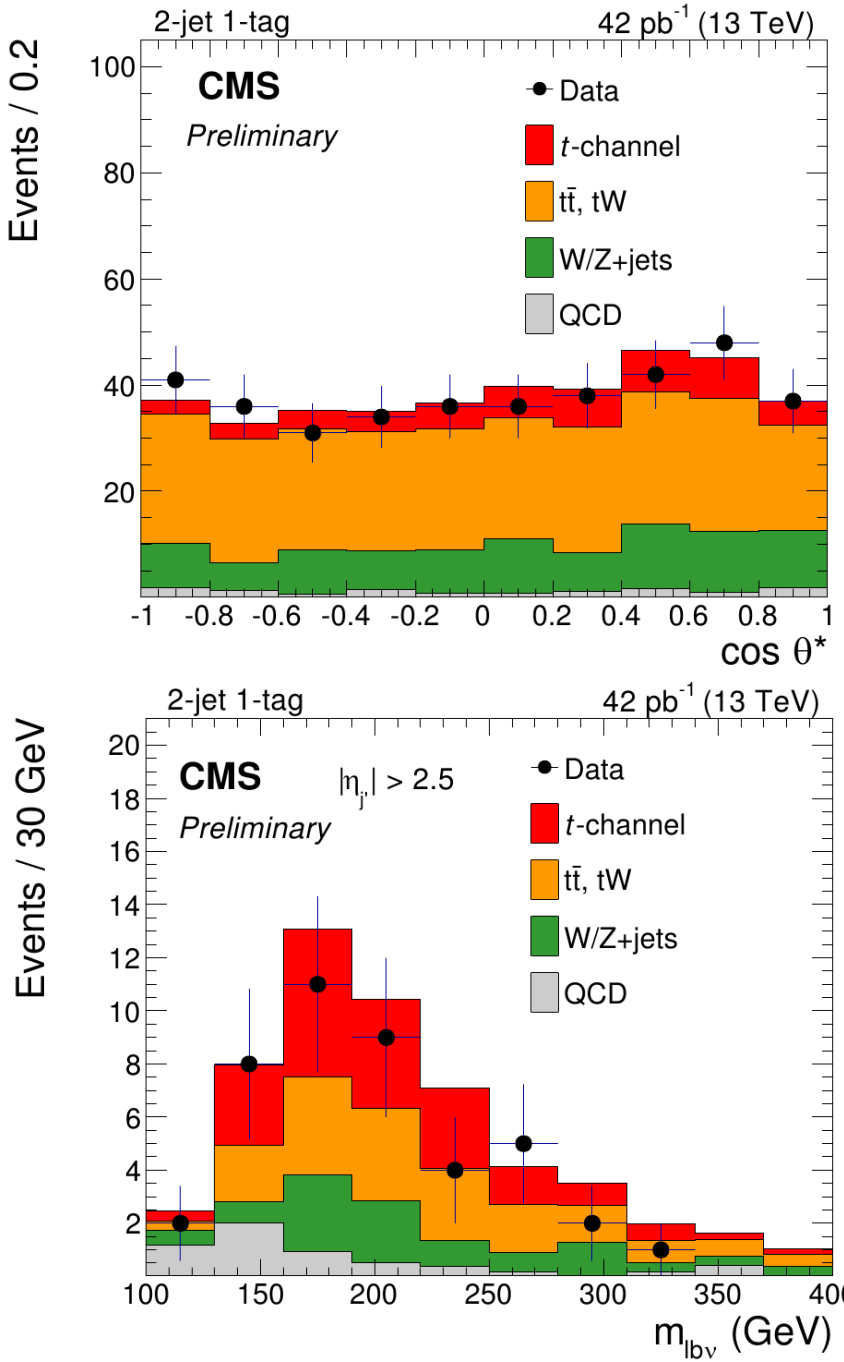
$$\sigma_t^{\text{obs}}{}_{(\text{POWHEG5FS})} = 83.6 \pm 6.1(\text{exp.})^{+1.7}_{-2.1}(\text{scale})^{+1.7}_{-1.7}(\text{PDF}) \pm 4.8(\text{NLO-subtr.})\,\text{pb}$$





CMS: 13 TeV

CMS-PAS-TOP-**15**-004



Uncertainty source	$\Delta\sigma_{t-\mathrm{ch}}/\sigma^{\mathrm{obs}}_{t-\mathrm{ch}}$
Statistical uncertainty	36%
JES	17%
JER	1.1%
b-tagging	5.6%
Muon trigger/reconstruction	3.4%
QCD extraction	1.1%
Signal generator	1.9%
Factorization and renormalization scales (Q^2)	3.3%
PDF	4.5%
MET	1.2%
Pileup	1.4%
Total systematic uncertainty	19%
Luminosity	12%
Total uncertainty	42%