Single-top-quark physics in ATLAS

5th CMS Single top workshop

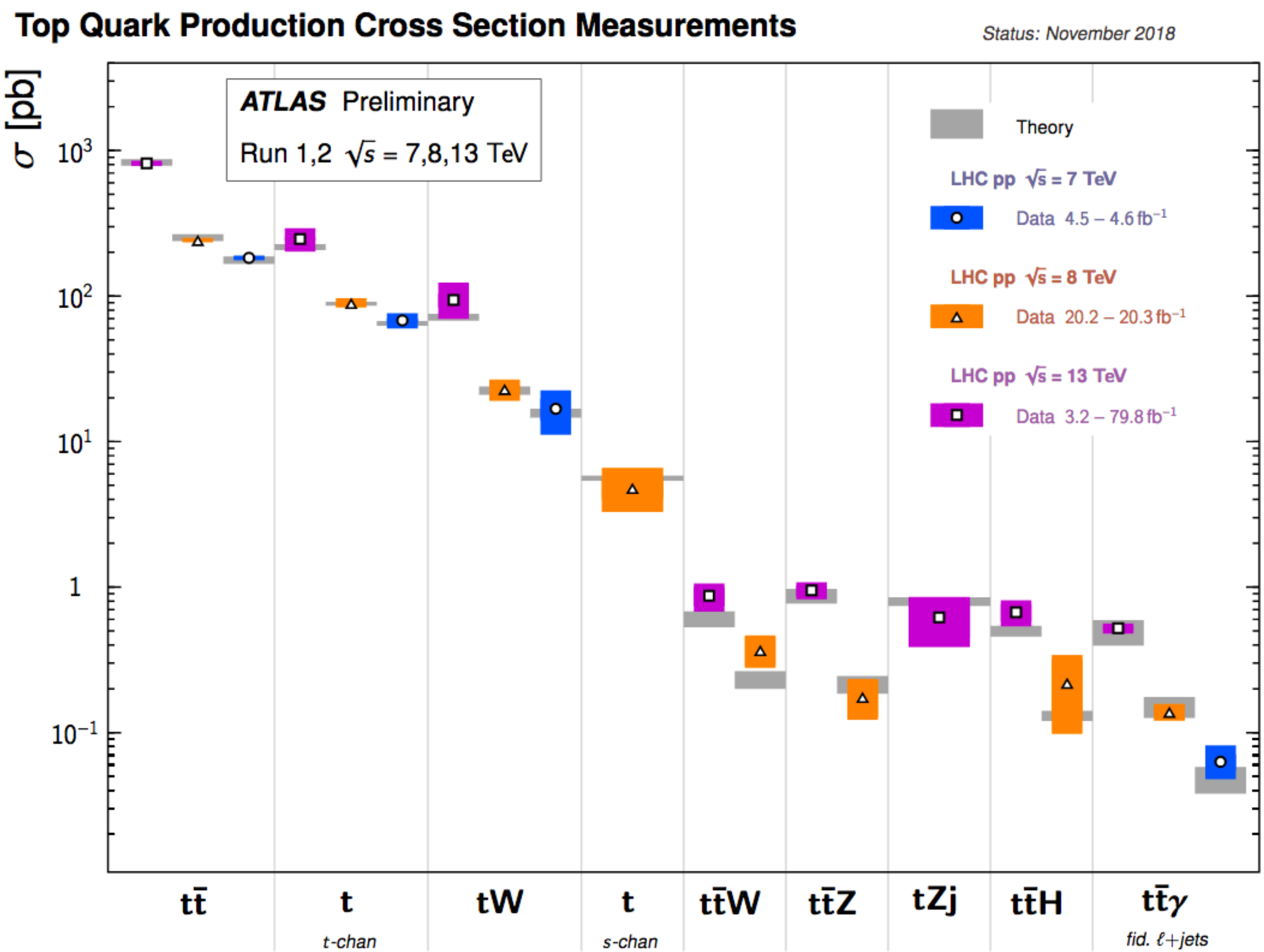
R.Moles-Valls on behalf of ATLAS Top group

Oviedo, 29th November 2018

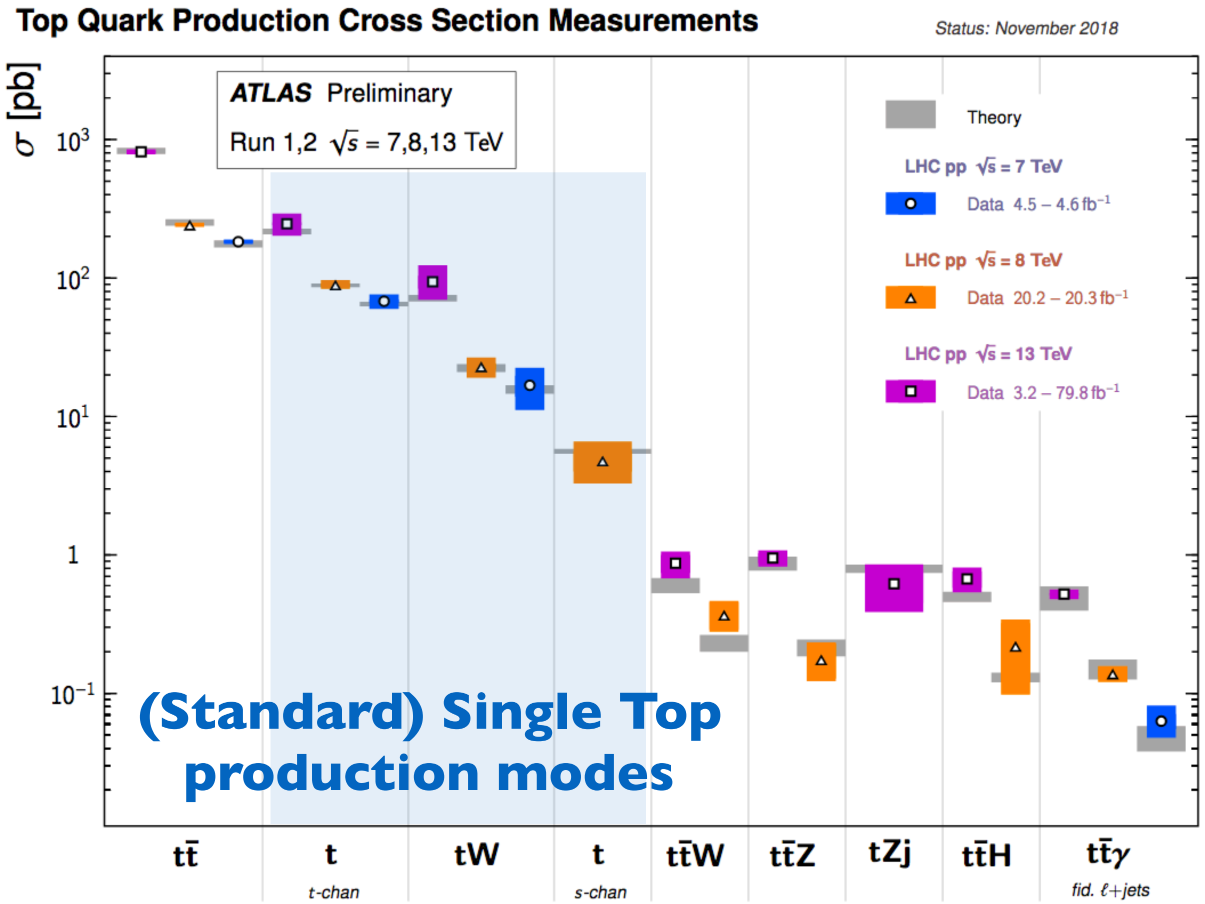
ATLAS EXPERIMENT

UNIVERSITÄT BONN

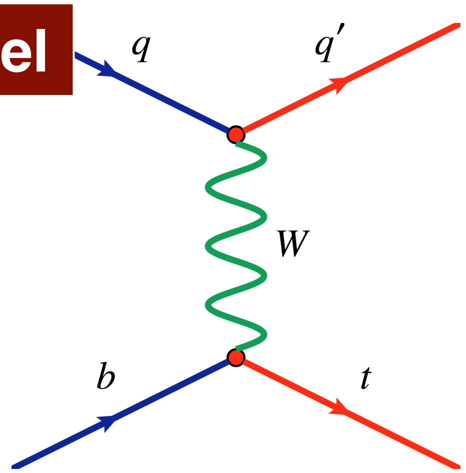
Top-quark physics



Single-top-quark production



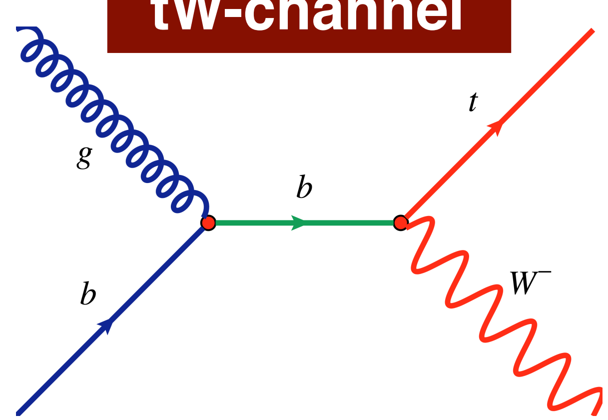
t-channel



$\sigma(8\text{TeV}) = 84.7^{+3.8}_{-3.2}\text{pb}$

$\sigma(13\text{TeV}) = 217.0^{+9.1}_{-7.7}\text{pb}$

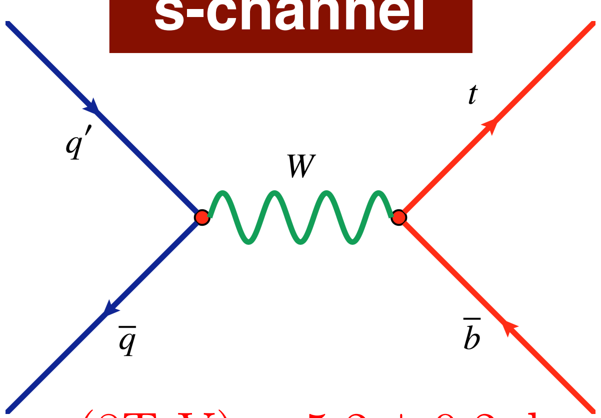
tW-channel



$\sigma(8\text{TeV}) = 22.4 \pm 1.5\text{pb}$

$\sigma(13\text{TeV}) = 71.7 \pm 3.8\text{pb}$

s-channel



$\sigma(8\text{TeV}) = 5.2 \pm 0.2\text{pb}$

$\sigma(13\text{TeV}) = 10.3 \pm 0.4\text{pb}$

Cross-sections from LHCTopWG (calculated @NLO)

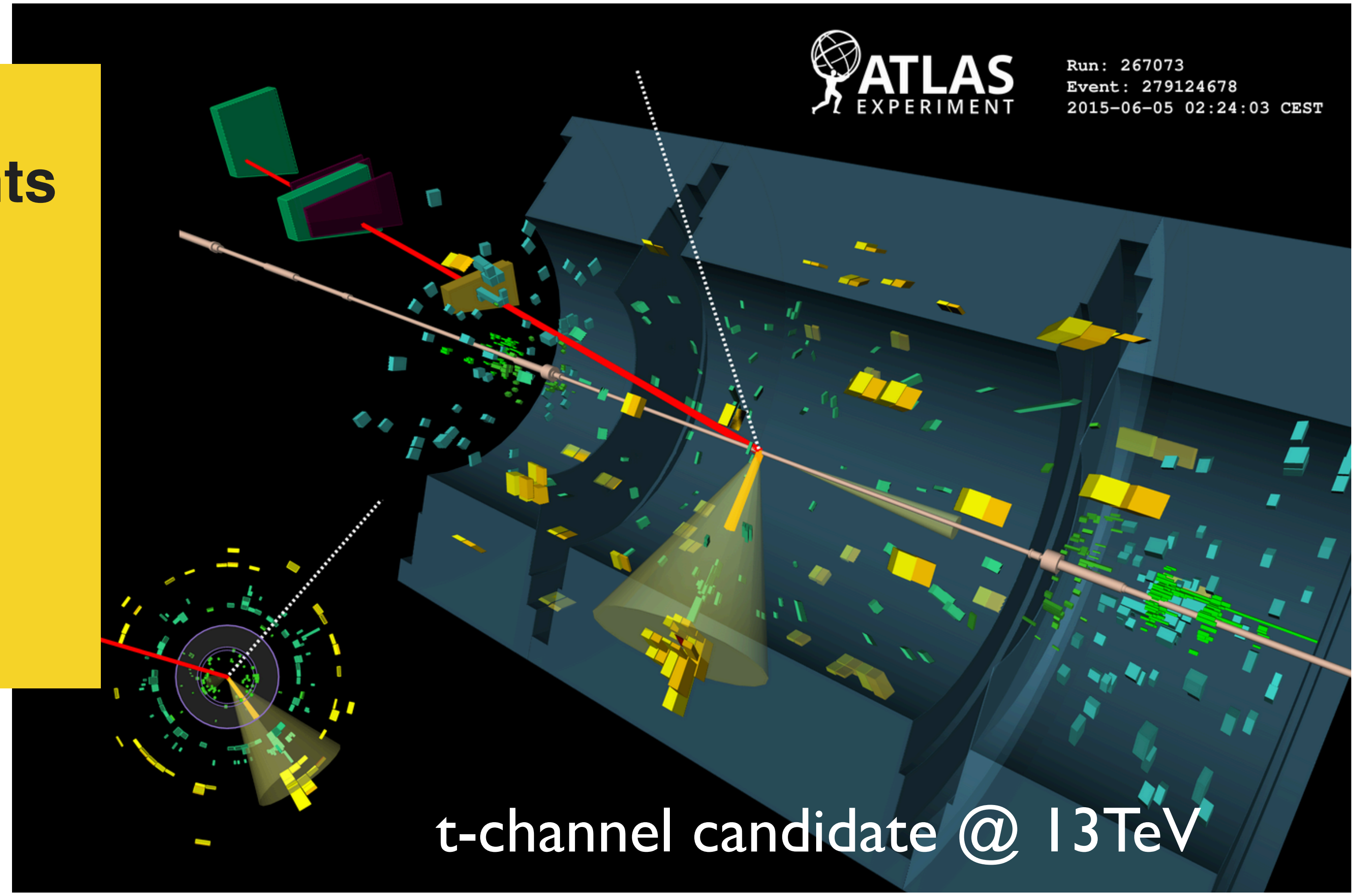
Single-top-quark production: t-channel

The single-top standard candle!

- Relatively large cross-section
- Good signal to background separation using MVA

Cross-section measurements

- Inclusive/fiducial/differential
- Constraint PDF (u/d-ratio)
- Tune MC generators
- Extraction of the $|V_{tb}|$
- *Wtb* anomalous couplings
- Top-quark mass

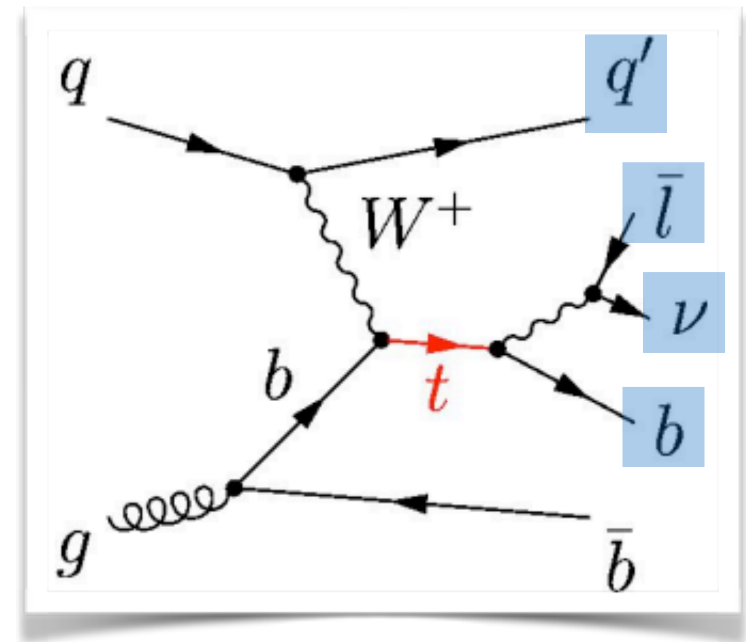


- Cross-section measurements @8TeV (EPJC77(2017)531) and @13TeV (JHEP04(2017)086)

Single-top-quark production: t-channel @8TeV

arXiv:1702.02859

- ***t*-channel signature (single lepton decay):**
  - One isolated **lepton**
  - Missing transverse momentum (**E_T^{miss}**)
  - Two high-p_T jets (one **forward** and one ***b*-tagged**)

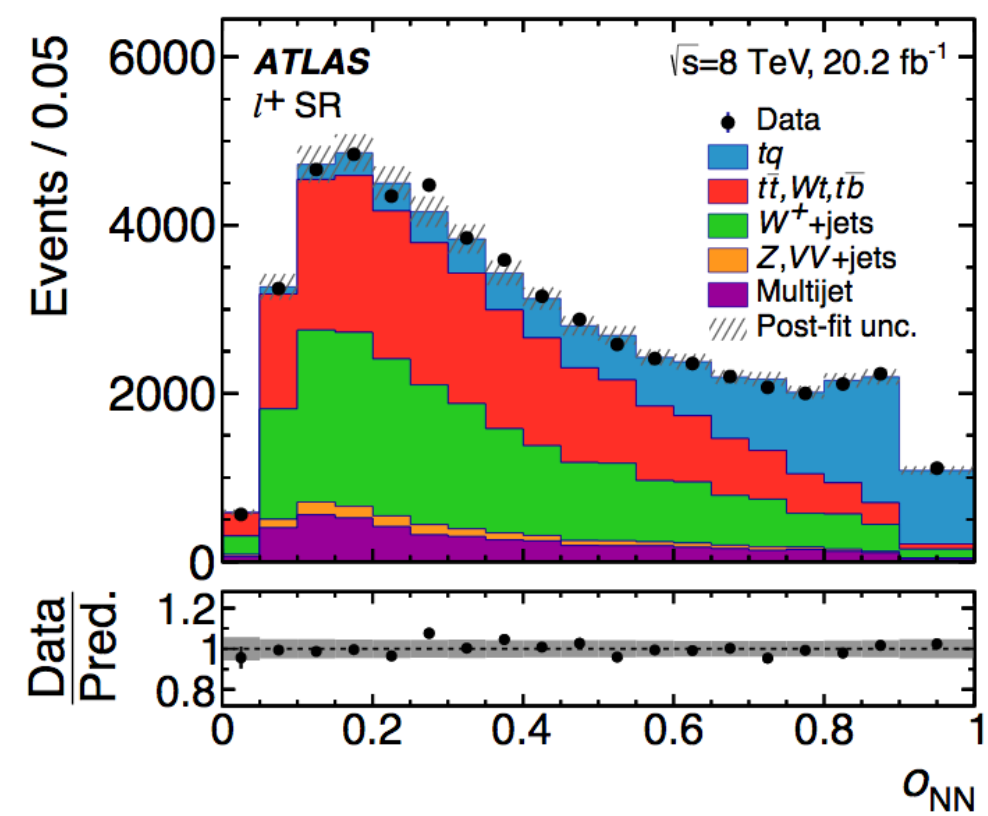


- **Strategy:**
  - Define three independent regions:
    - **SR (2j1b)**, **VR $t\bar{t}$ (3j2b)**, **VR W+jets**
  - NN to enhance S/B
    - Cross-section measured for ℓ^+ and ℓ^-
  - Maximum likelihood fit in SR

  - Measurement performed in a fiducial volume

(stable particles selected close to the final selection)

$$\sigma_{\text{fid}} = \frac{N_{\text{fid}}}{N_{\text{sel}}} \cdot \frac{\hat{\nu}}{L_{\text{int}}} .$$



Single-top-quark production: t-channel @8TeV

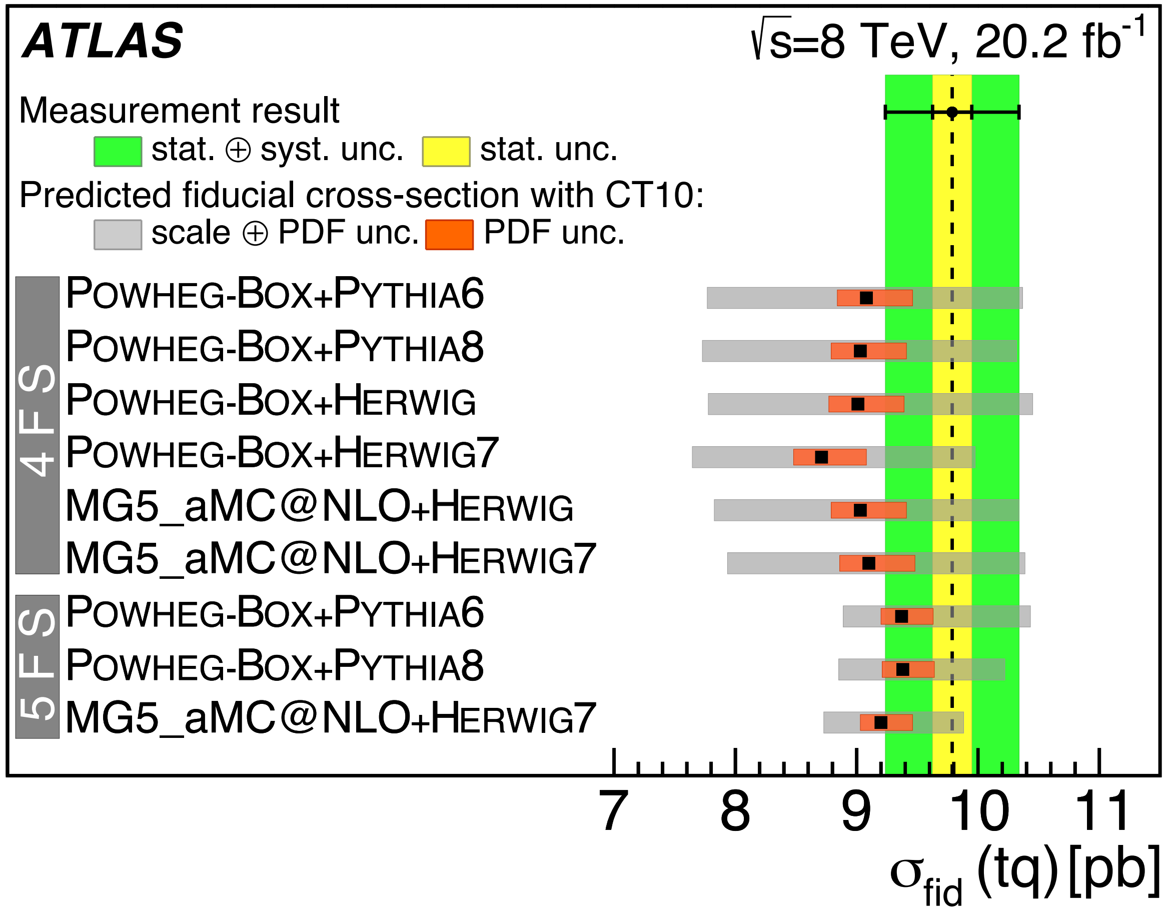
arXiv:1702.02859

Fiducial cross-section

- Fiducial cross-section reduces syst. uncertainties from PDF and MC generators

$$\sigma_{fid}(tq) = 9.78 \pm 0.57 \text{ pb } (5.8\%)$$
$$\sigma_{fid}(\bar{t}q) = 5.77 \pm 0.45 \text{ pb } (7.8\%)$$

- Dominant systematic: JES, NLO matching $t\bar{t}$ and lepton reconstruction efficiency

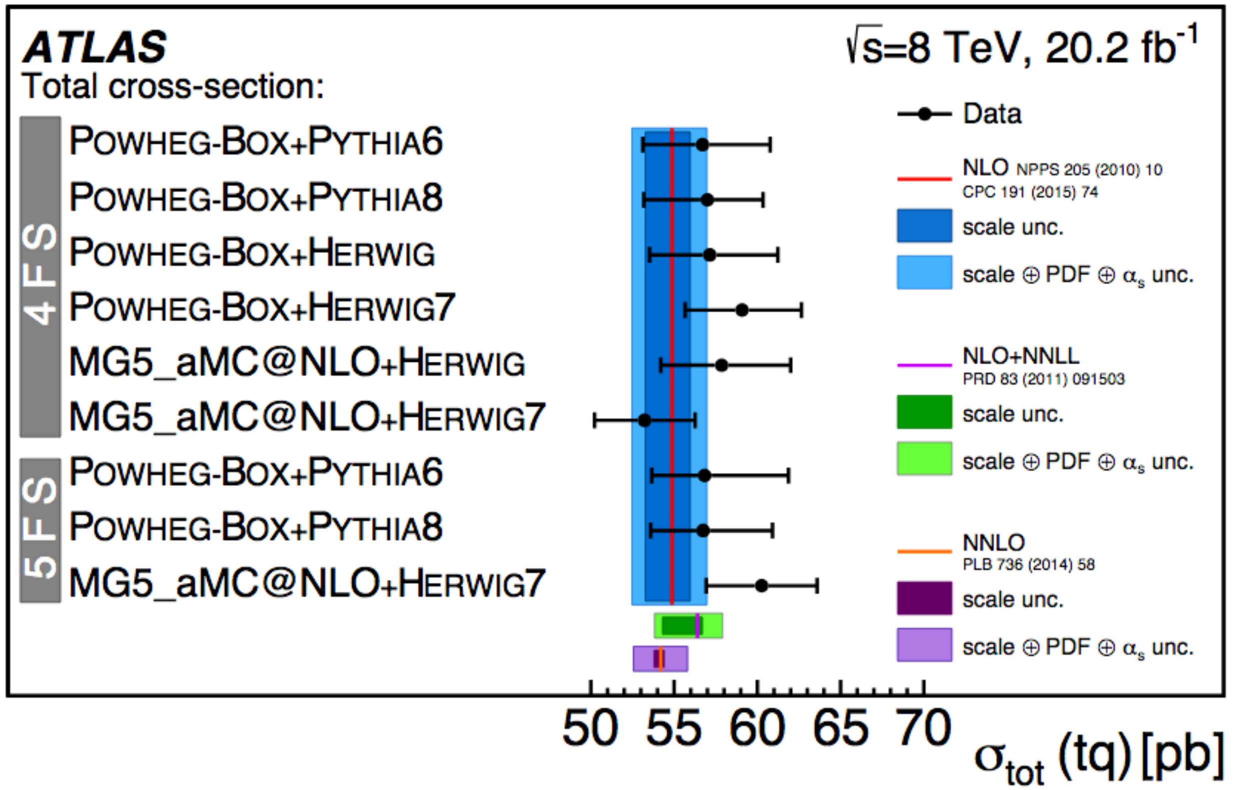


Inclusive cross-section

- Fiducial cross-section extrapolated to full phase space to get the full cross-section

$$\sigma_{\mathrm{tot}} = \frac{N_{\mathrm{tot}}}{N_{\mathrm{fid}}} . \sigma_{\mathrm{fid}}$$

$$\sigma_{tot}(tq) = 56.7^{+4.3}_{-3.8} \text{ pb } (^{+7.6}_{-6.7}\%)$$
$$\sigma_{tot}(\bar{t}q) = 32.9^{+3.0}_{-2.7} \text{ pb } (^{+9.1}_{-8.4}\%)$$

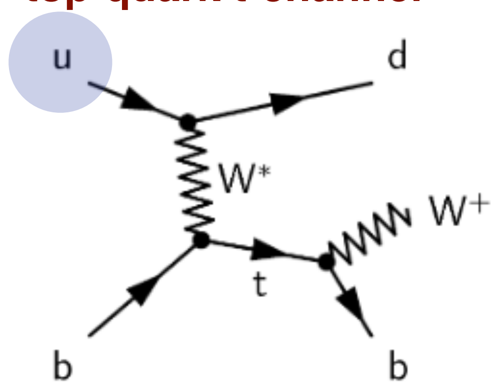


Single-top-quark production: t-channel @8&13TeV

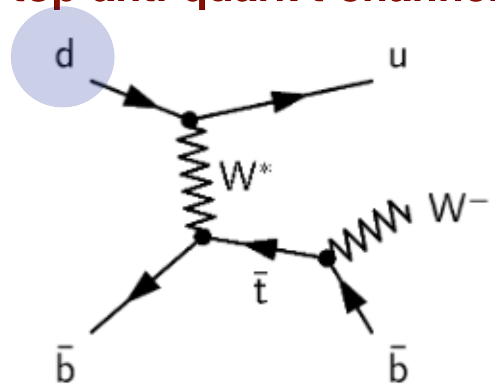
arXiv:1702.02859

Ratio Rt

top-quark t-channel

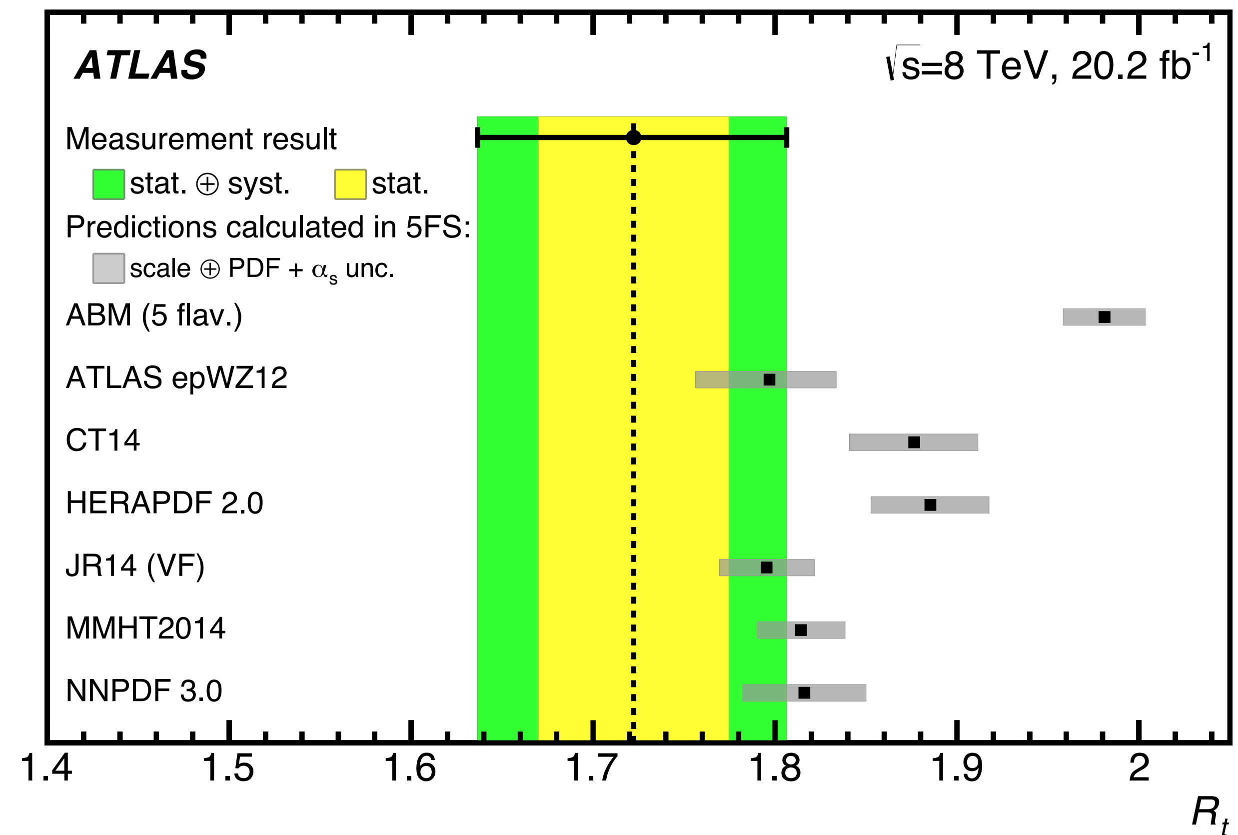


top-anti-quark t-channel



$$R_t = \frac{\sigma_{\text{tot}}(tq)}{\sigma_{\text{tot}}(\bar{t}q)}$$

$$R_t = 1.72 \pm 0.09$$



CKM matrix element V_{tb}

- Using the total cross-section

$$|f_{\rm LV} V_{tb}| = \sqrt{\frac{\sigma_{\rm meas.}}{\sigma_{\rm theo.}}},$$

f_{LV} form factor encapsulates effects from new physics

$$|f_{LV} \cdot V_{tb}| = 1.029 \pm 0.048$$

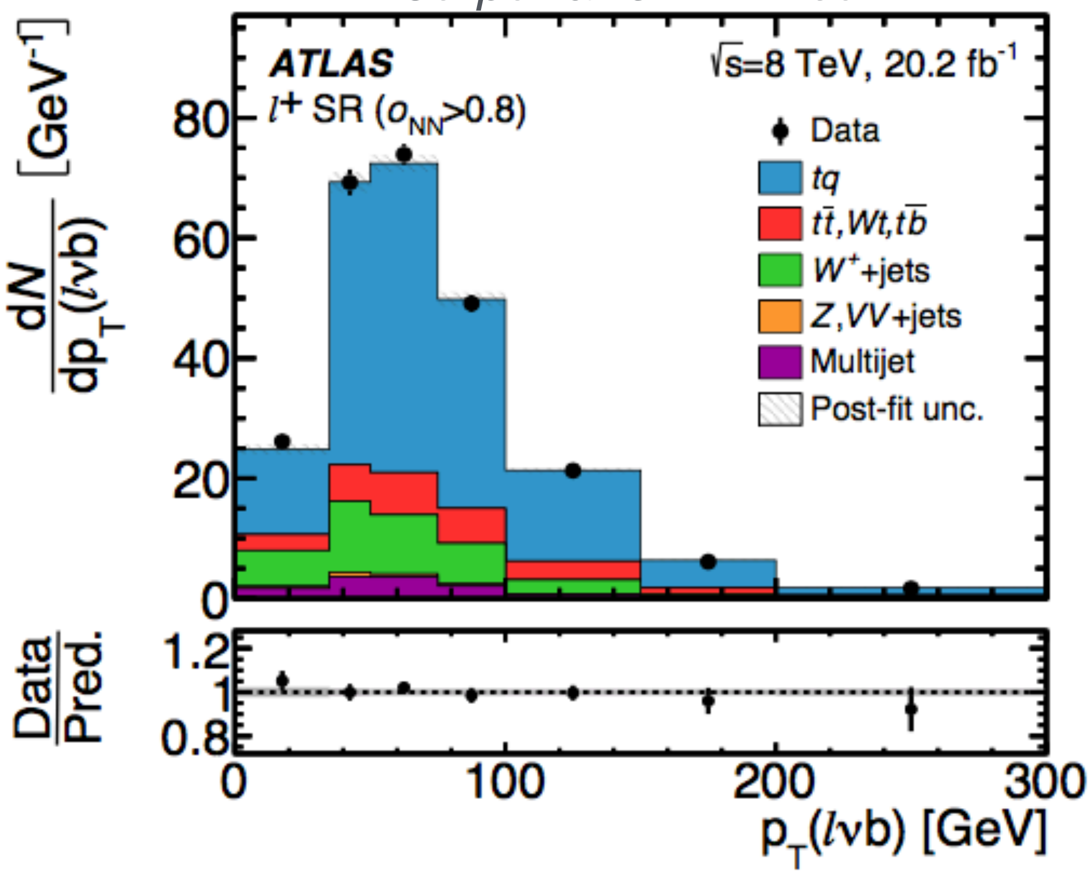
- Results @13TeV using 3.2fb^{-1} JHEP04(2017)086 (18-20% uncertainty)

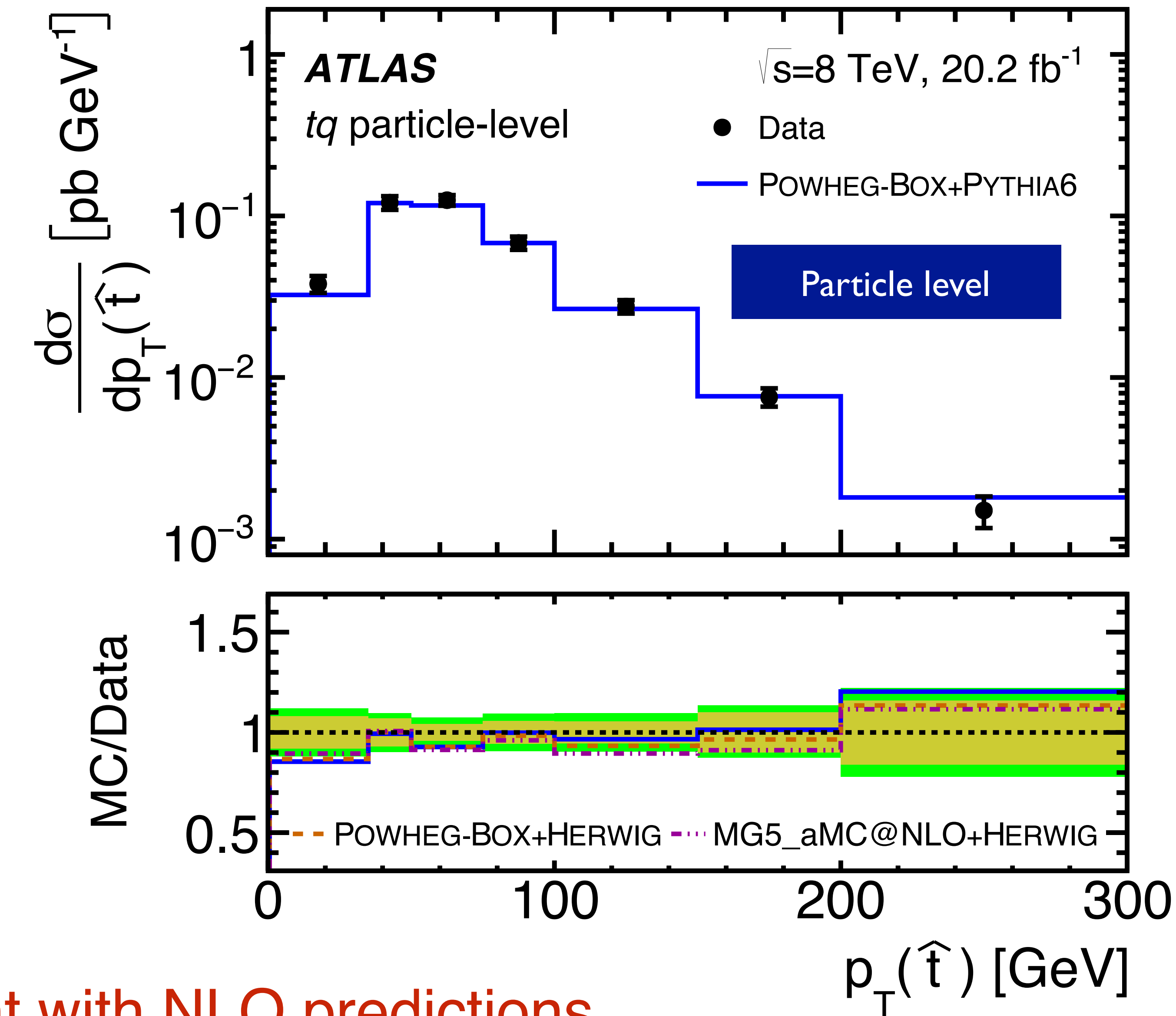
Single-top-quark production: t-channel @8TeV

arXiv:1702.02859

- Differential cross-section measured as a function of:
  - **p_T(t)** and |**y(t)**| for top and antitop at parton/particle level
  - **p_T(j)**, |**y(j)**| for the forward jet at particle level (NN without η_j used here)
- BDT cut for $NN_{output} > 0.8$

NN output after BDT cut





good agreement with NLO predictions

arXiv:1702.08309

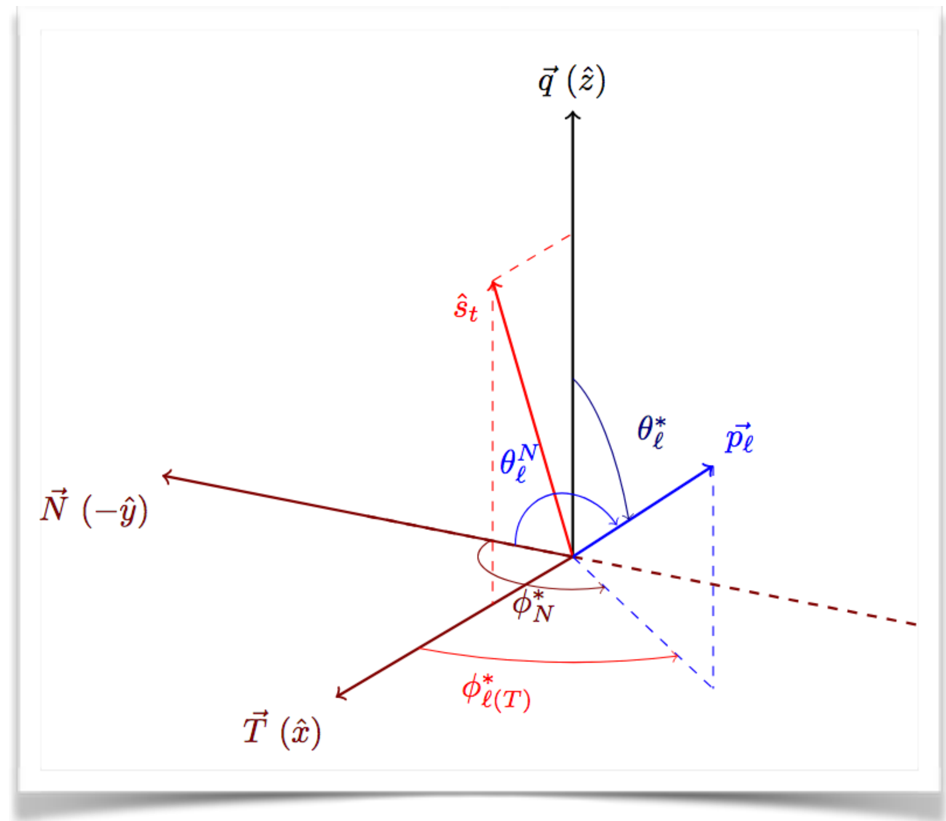
Single-top-quark: polarisation & anomalous couplings

- The SM predicts highly polarised tops in the direction of spectator quark
  P(t) = 0.91 and P(t̄) = -0.86 (NLO)

- Polarisation observables can be extracted from **angular asymmetries**

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

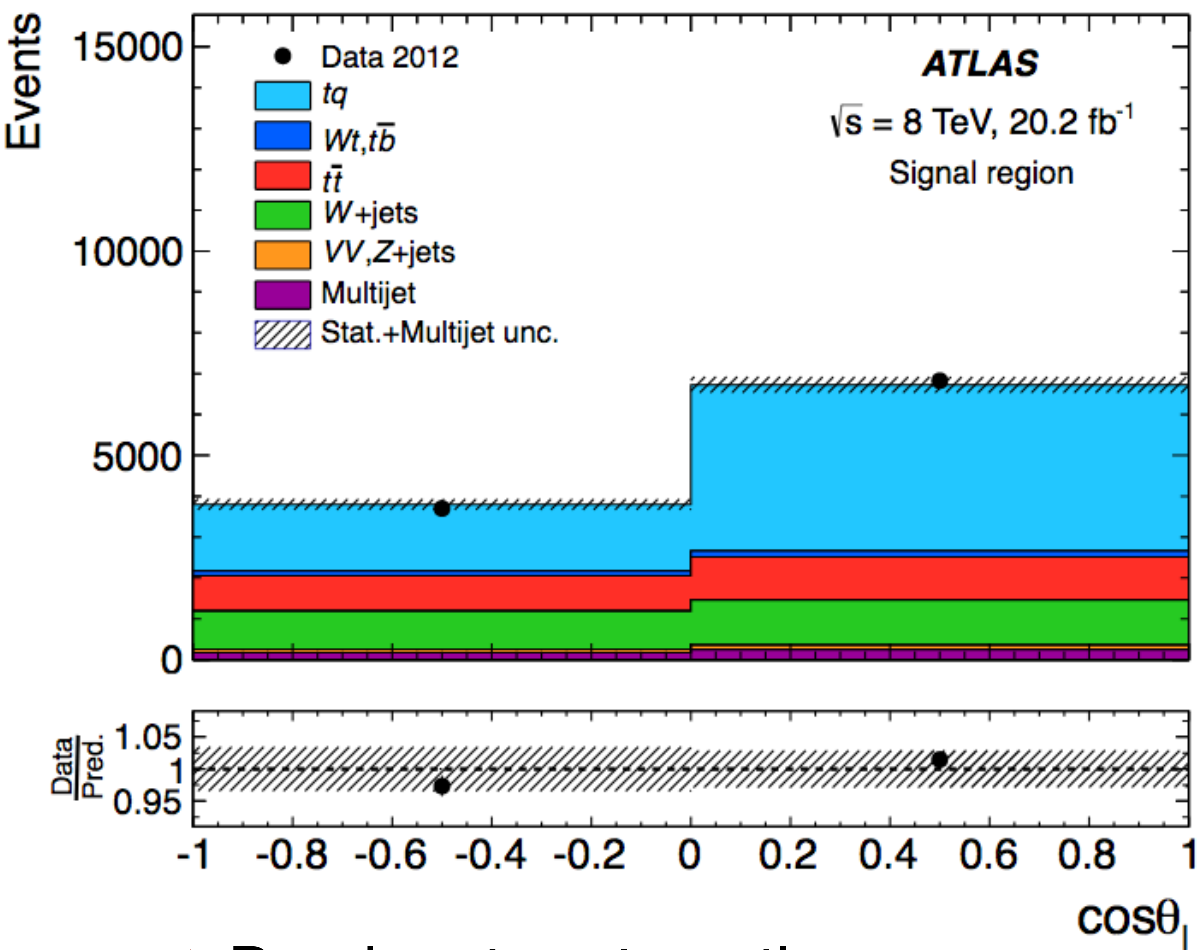
Asymmetry	Angular observable	Polarisation observable	SM prediction
A_{FB}^{ℓ}	$\cos\theta_\ell$	$\frac{1}{2}\alpha_\ell P$	0.45
A_{FB}^{tW}	$\cos\theta_W \cos\theta_\ell^*$	$\frac{3}{8}P\,(F_{\mathrm{R}} + F_{\mathrm{L}})$	0.10
A_{FB}	$\cos\theta_\ell^*$	$\frac{3}{4}\langle S_3\rangle = \frac{3}{4}\,(F_{\mathrm{R}}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

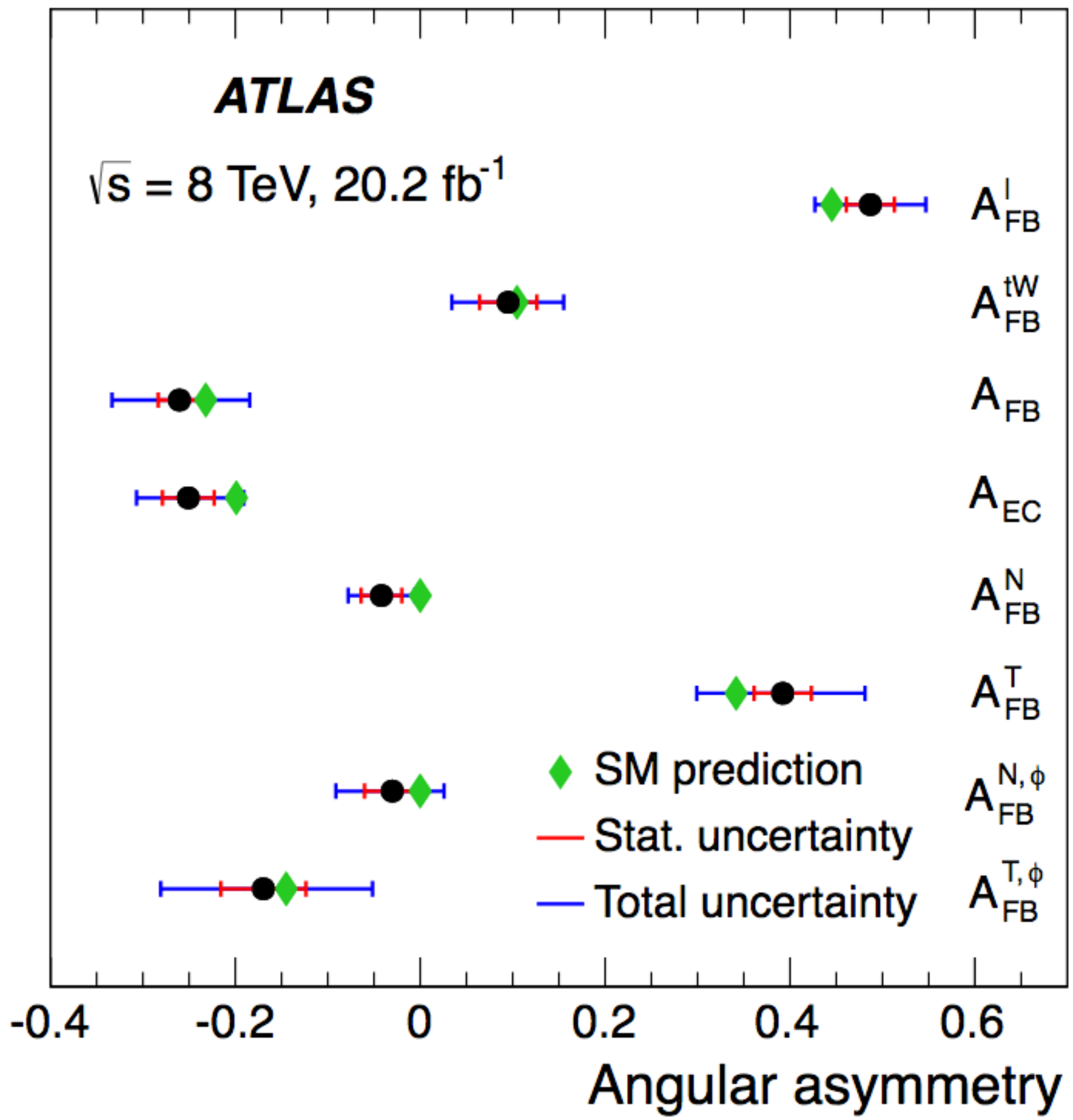


- **Strategy:**
  - Same three independent regions: **SR (2j1b)**, **CR tt̄ (3j2b)**, **CR W+jets**
  - Cut-based to enhance S/B
  - Maximum likelihood fit to get normalisation factors
  - Unfolded distributions @parton level

Single-top-quark: polarisation & anomalous couplings

arXiv:1702.08309





- Dominant systematic: tt̄ modelling, JES and MC statistics

$$A^l_{FB} = 0.49 \pm 0.03(\text{stat}) \pm 0.05(\text{syst})$$
$$\alpha_l P = 0.97 \pm 0.05(\text{stat}) \pm 0.11(\text{syst})$$

Single-top-quark: polarisation & anomalous couplings

JHEP12(2017)017

- New physics affecting the production or decay of the top quark can be parameterized with a set of effective couplings ($V_{L,R}$ and $g_{L,R}$):

$$\mathcal{L}_{\text{eff}} = -\frac{g}{\sqrt{2}}\bar{b}\gamma^{\mu}\left(V_L P_L + V_R P_R\right) t W_{\mu}^{-} - \frac{g}{\sqrt{2}}\bar{b}\frac{i\sigma^{\mu\nu}q_{\nu}}{m_W}\left(g_L P_L + g_R P_R\right) t W_{\mu}^{-} + \text{h.c.}$$

- Normalised triple-differential (θ, θ^*, ϕ^*) decay rate of top-quarks:

$$\begin{aligned}
\varrho(\theta,\theta^*,\phi^*;P) = \frac{1}{N}\frac{dN}{d\Omega d\Omega^*} &= \frac{1}{(4\pi)^2}\Bigg\{\frac{3}{4}\left|A_{1,\frac{1}{2}}\right|^2(1+P\cos\theta)(1+\cos\theta^*)^2 \\
&+ \frac{3}{4}\left|A_{-1,-\frac{1}{2}}\right|^2(1-P\cos\theta)(1-\cos\theta^*)^2 \\
&+ \frac{3}{2}\left(\left|A_{0,\frac{1}{2}}\right|^2(1-P\cos\theta)+\left|A_{0,-\frac{1}{2}}\right|^2(1+P\cos\theta)\right)\sin^2\theta^* \\
&- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1+\cos\theta^*)\,\mathrm{Re}\left[e^{i\phi^*}A_{1,\frac{1}{2}}A^*_{0,\frac{1}{2}}\right] \\
&- \frac{3\sqrt{2}}{2}P\sin\theta\sin\theta^*(1-\cos\theta^*)\,\mathrm{Re}\left[e^{-i\phi^*}A_{-1,-\frac{1}{2}}A^*_{0,-\frac{1}{2}}\right]\Bigg\} \\
&= \sum_{k=0}^{1}\sum_{l=0}^{2}\sum_{m=-k}^{k} a_{k,l,m}M^m_{k,l}(\theta,\theta^*,\phi^*),
\end{aligned}$$

Helicity amplitudes ($A_{\lambda b,\lambda W}$) from the $t \to Wb$ transition(dependence on anomalous couplings)

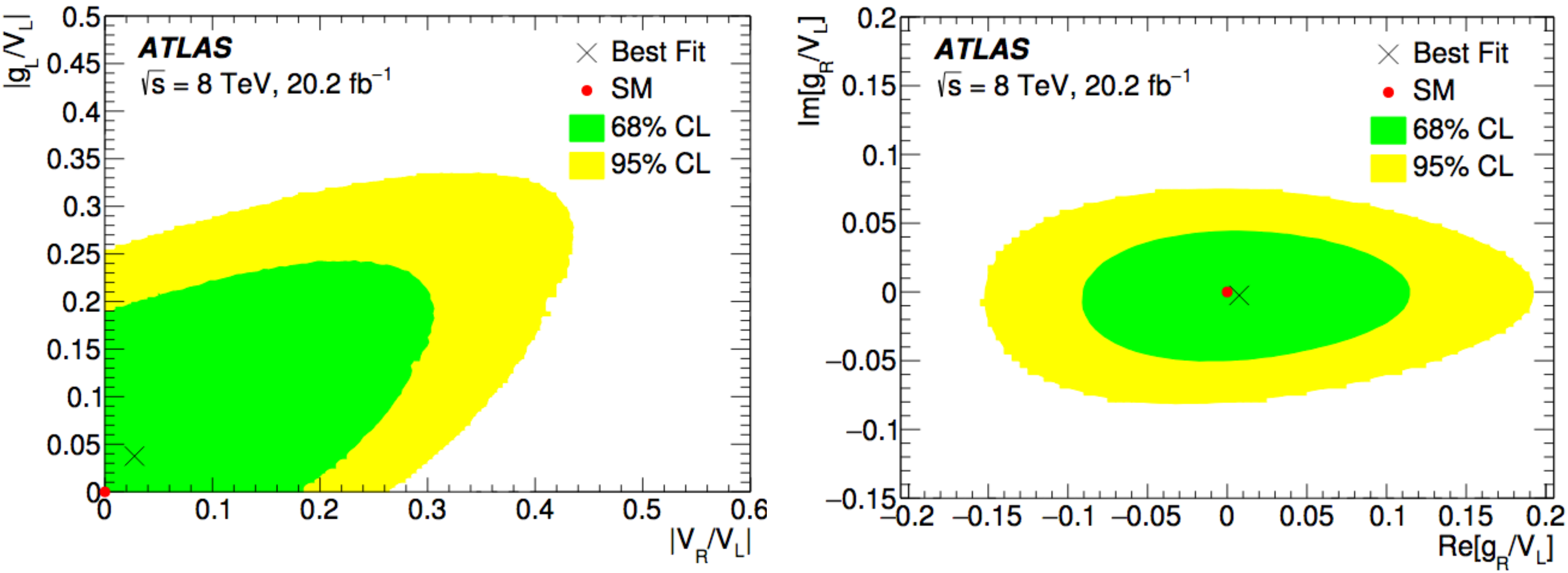
From the helicity amplitudes, five physics parameters can be constructed, representing three amplitude fractions and two phases. Observables:

$$\vec{\alpha} \equiv \left\{f_1, f_1^+, f_0^+, \delta_+, \delta_-, P\right\}$$

Single-top-quark: polarisation & anomalous couplings

JHEP12(2017)017

- The generalised helicity fractions, phases and polarisation are determined simultaneously, including all correlations
- Interpretation in terms of anomalous couplings V_L, V_R, g_R and g_L



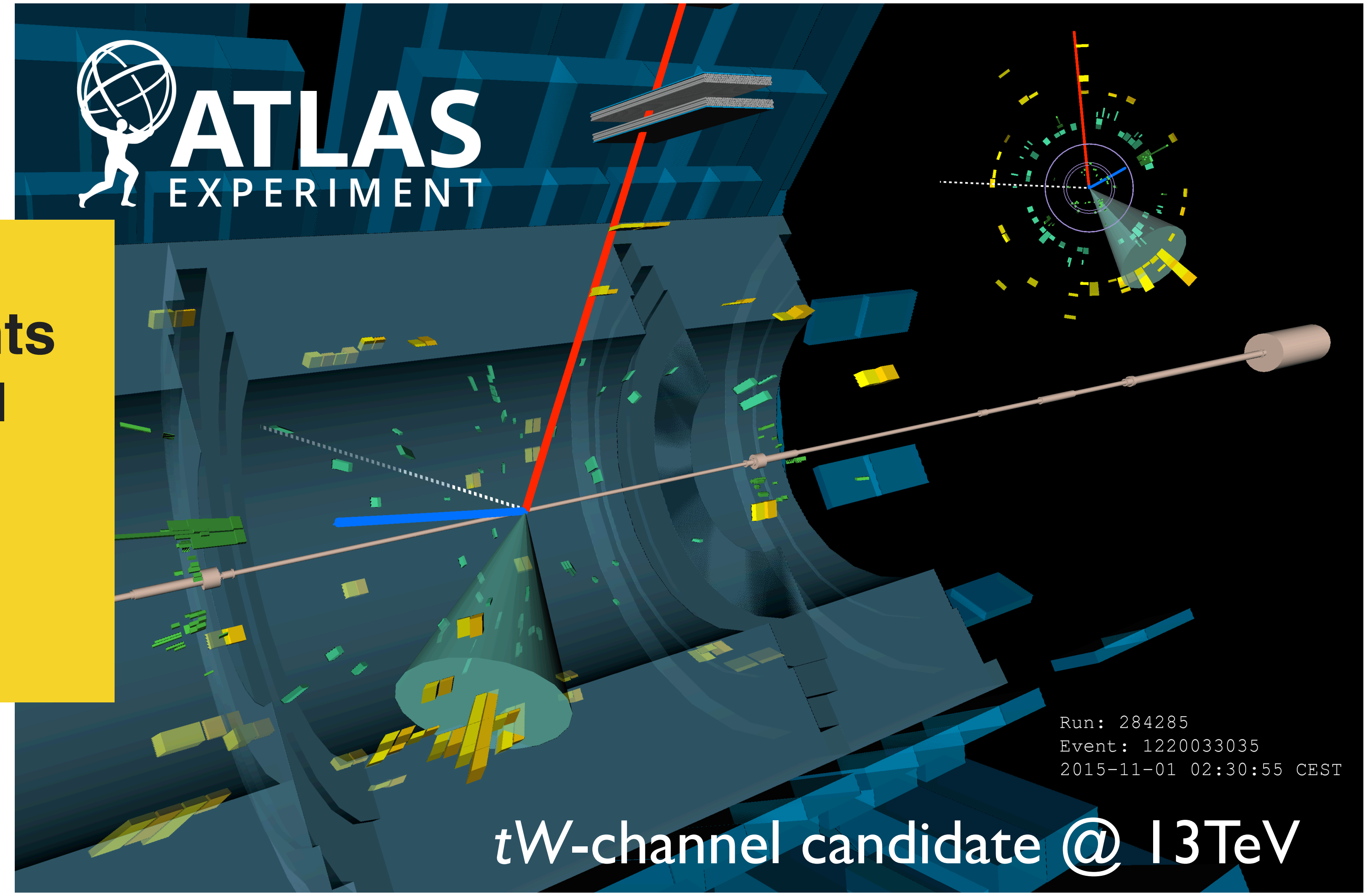
Single-top-quark production: tW associated production

Second largest cross-section

- Decent signal to background separation using MVA
- Suffering from $t\bar{t}$ huge background

Cross-section measurements

- Inclusive/fiducial/differential
- Extraction of the $|V_{tb}|$
- Tune MC generators
- Study tW-$t\bar{t}$ interference

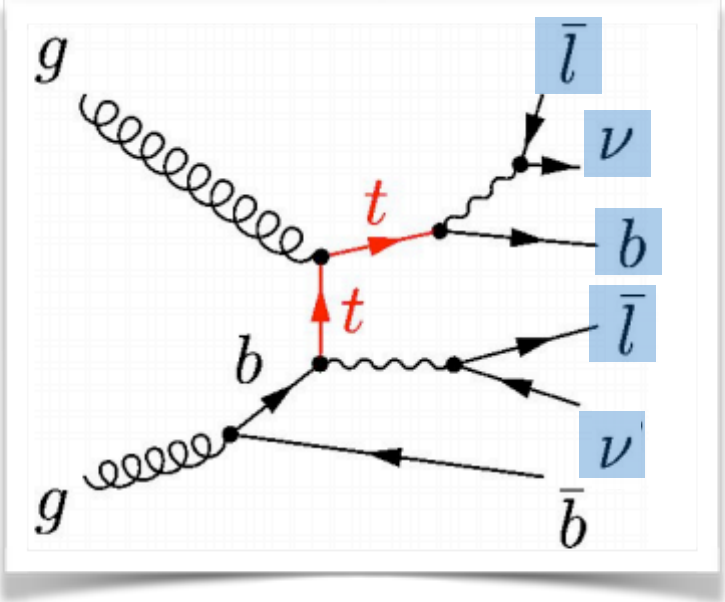


Cross-section measurements @8TeV (JHEP01(2016)064) and @13TeV (JHEP(2018)2018:63, EPJC78(2018)186, arXiv:1806.04667)

Single-top-quark production: tW @8TeV

JHEP01(2016)064

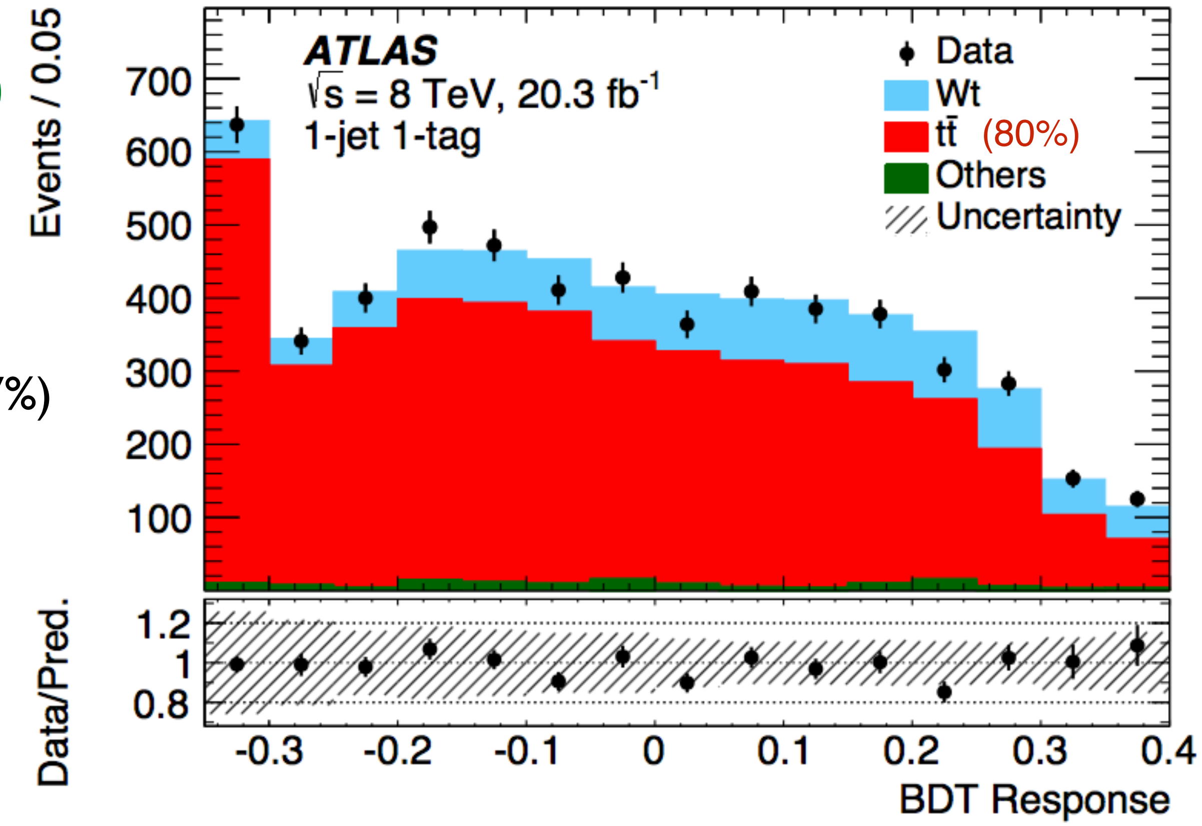
- *tW*-channel signature (dilepton decay):
  - Two opposite charged isolated **leptons** (*ee,μμ,eμ*)
  - Missing transverse momentum (**E_T^{miss}**)
  - One central high-p_T jet (***b*-tagged jet**)



- **Strategy:**
  - Define five independent regions:
    - **SR (1j1b)**, **CR $t\bar{t}$ (2j1-2b)**, **VR (1-2j0b)**
  - BDT to enhance S/B
  - Maximum likelihood fit in SR & CR

$$\sigma_{Wt} = 23.0 \pm 1.3(\mathrm{stat})^{+3.2}_{-3.5}(\mathrm{sys}) \pm 1.1(\mathrm{lumi})$$ (17%)

$$|V_{tb}| = 1.01 \pm 0.10$$



- Dominant syst. uncertainties:
  ISR/FSR, JES/JER, data statistics

Single-top-quark production: tW @13TeV

JHEP(2018)2018:63, EPJC78(2018)186

Inclusive (3.2fb^{-1})

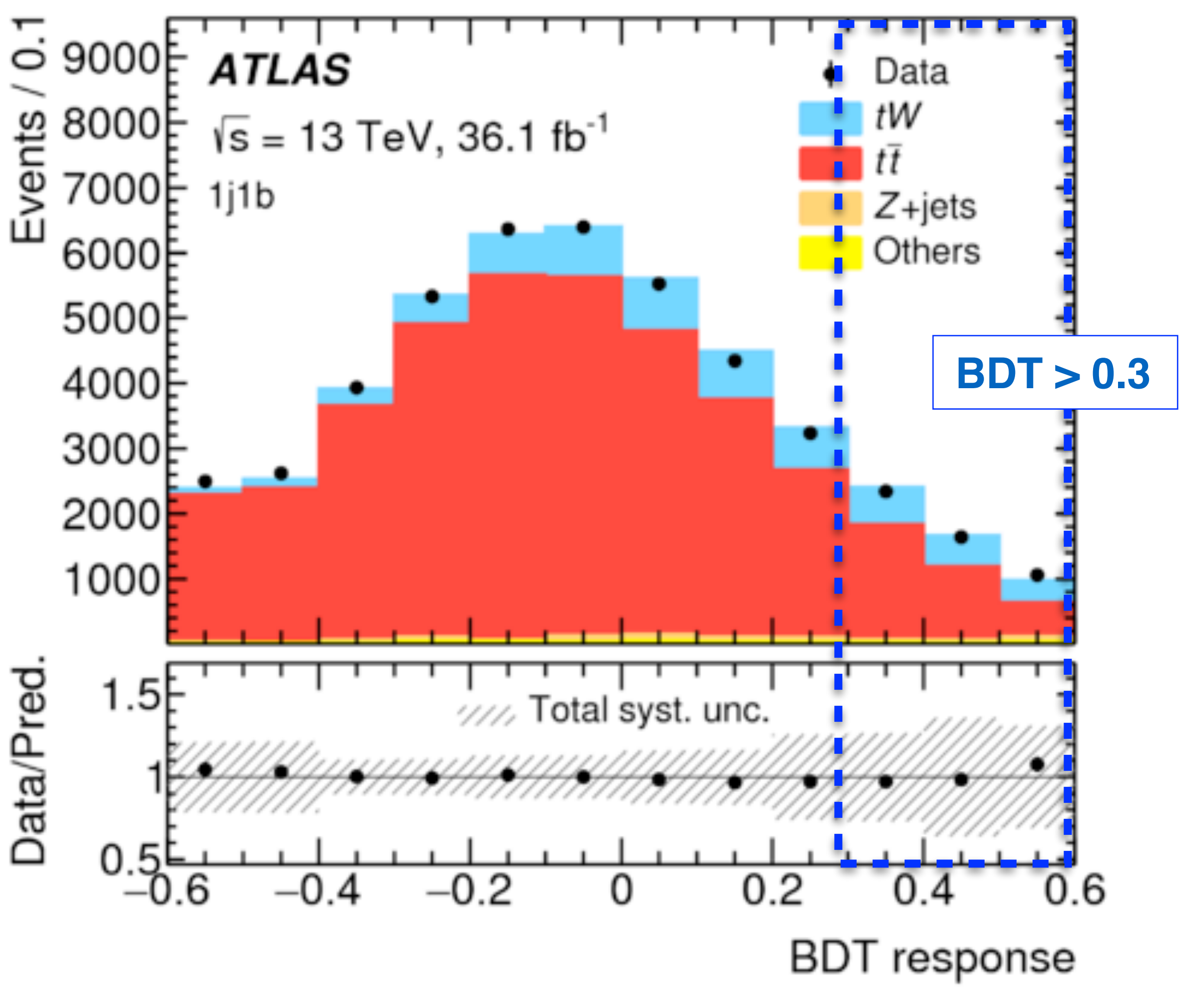
- Using similar strategy as @8TeV
- Dominant syst. uncertainties:
  JES(21%), JER (9%), ME (18%), PS(7%)

$$\sigma_{Wt} = 94 \pm 10(\mathrm{stat})^{+28}_{-22}(\mathrm{sys}) \pm 2(\mathrm{lumi})\mathrm{pb}$$

(relative uncertainty of 30%)

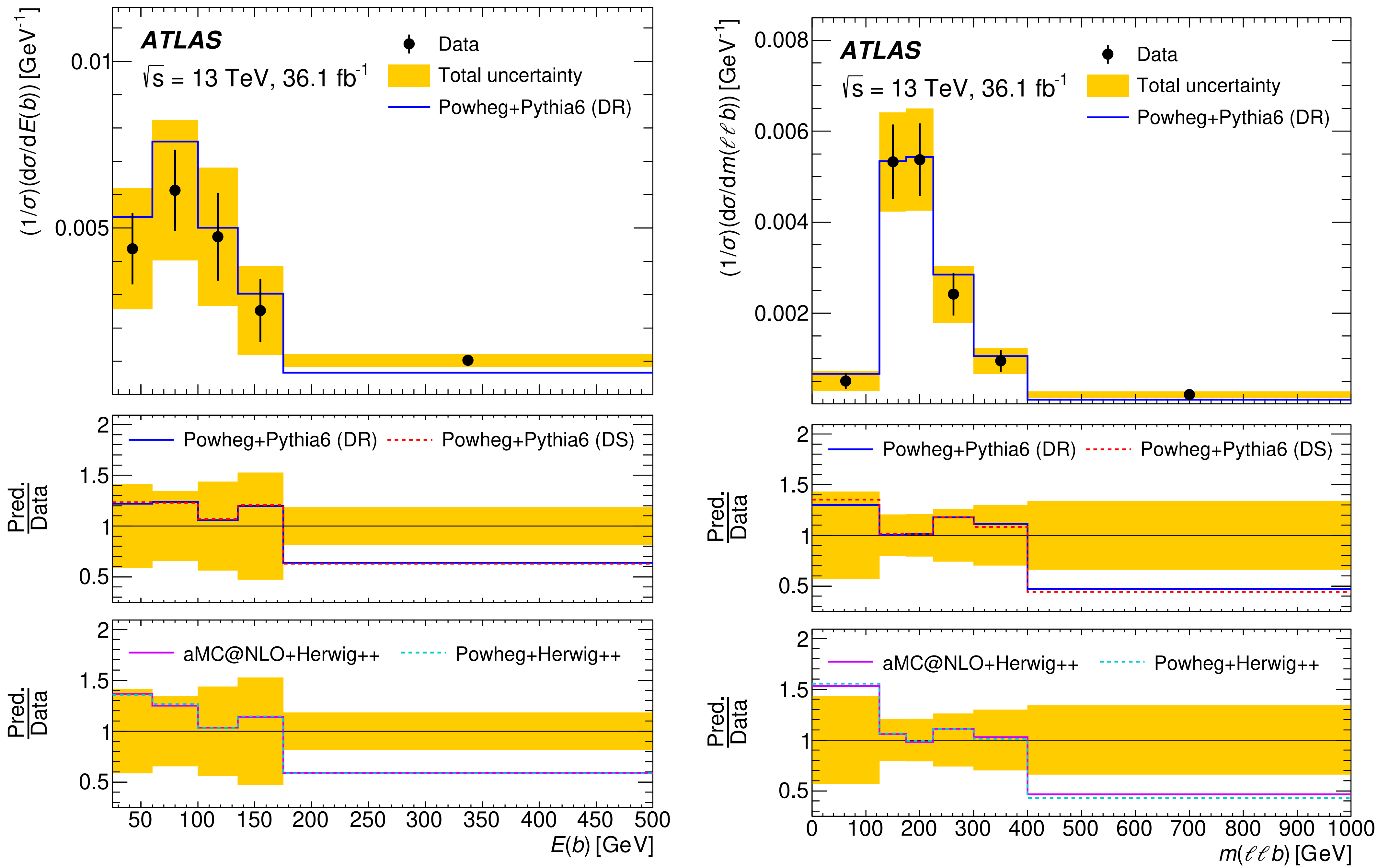
Differential (36fb^{-1})

- **Strategy:**
  - Defined **SR** as **1j1b** (S:B=1:5)
  - BDT to enhance S/B
    - $BDT_{output} > 0.3$ (S:B=1:2)
  - Unfolded distributions @particle level:
    - E(b), m(l_1b), m(l_2b)
    - E(llb), m(llb), m_T(llvvb)
  - Main uncertainties:
    - tW and $t\bar{t}$ modelling
    - statistics



Single-top-quark production: tW @13TeV

EPJC78(2018)186



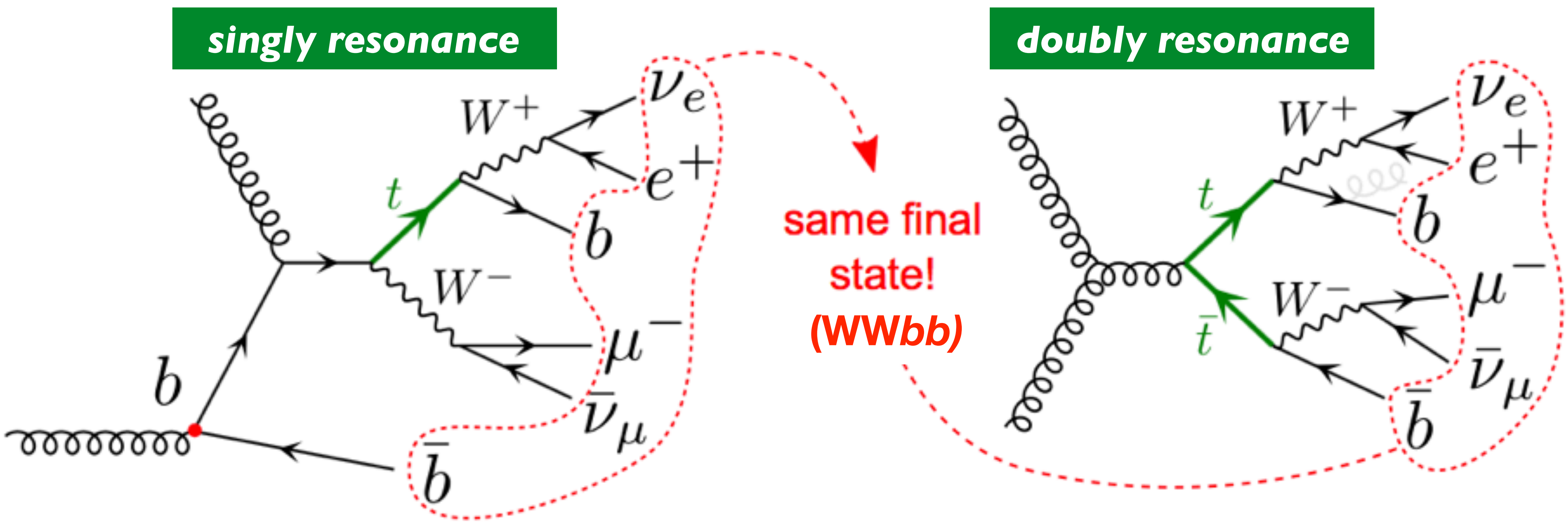
Overall good modelling

- Small differences in RadLo/RadHi, DR/DS.
- PW+HW++ disfavoured in some bins
- Negative on the slope of the ratio — MC tends to be softer than data

Single-top-quark production: tW-tt interference @13TeV

arXiv:1806.04667

- *tW* and top-quark pair processes interfere beyond LO:



$$|A_{tW}|^2 = |A_{t\bar{t}}|^2 + |A_{tWb}|^2 + 2Re\{A^*_{t\bar{t}} \cdot A_{tWb}\}$$

(NLO corrections to the LO tW amplitude) — tt @LO — tW@NLO — interference

What do we know about this interference?

Different approaches to handle it @NLO (DR,DS,DR2…)

Large impact on specific regions @high pT

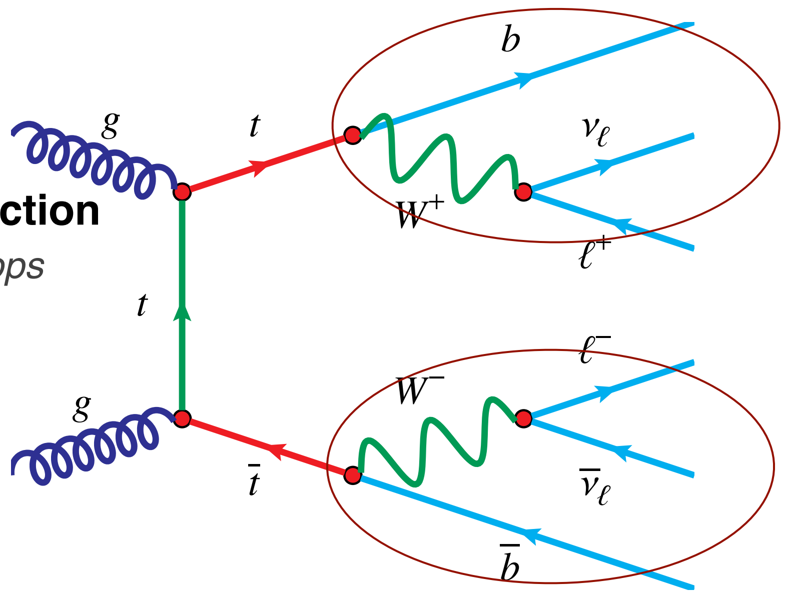
More information in C.Herwig talk this afternoon

Single-top-quark production: tW-tt interference @13TeV

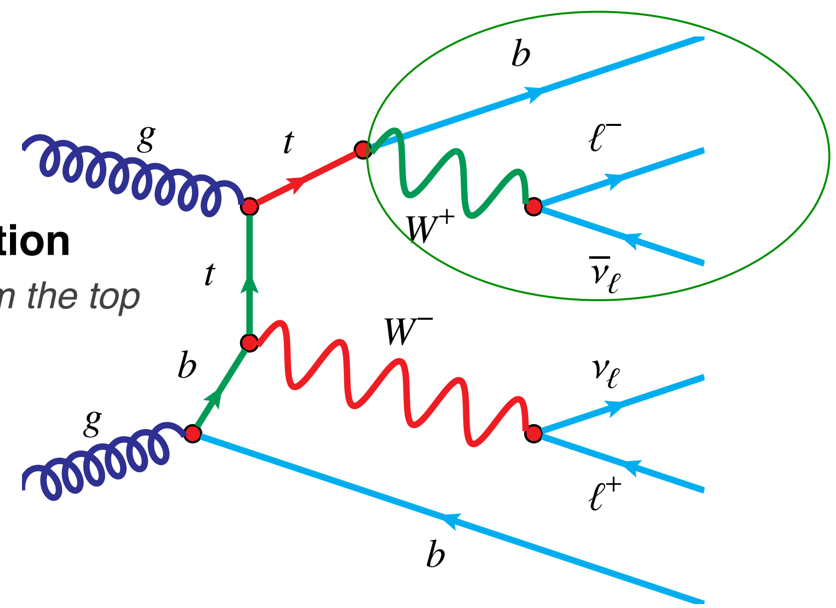
arXiv:1806.04667

- New approach to test interference models in place
  - Discriminant to exploit the differences between m(bW):
    - $t\bar{t}$ (doubly resonance) m(bW) ~ m_{top}
    - tWb (singly resonance) one pair is off from m_{top}

top-quark pair production
two *(b,l) pairs from the tops*

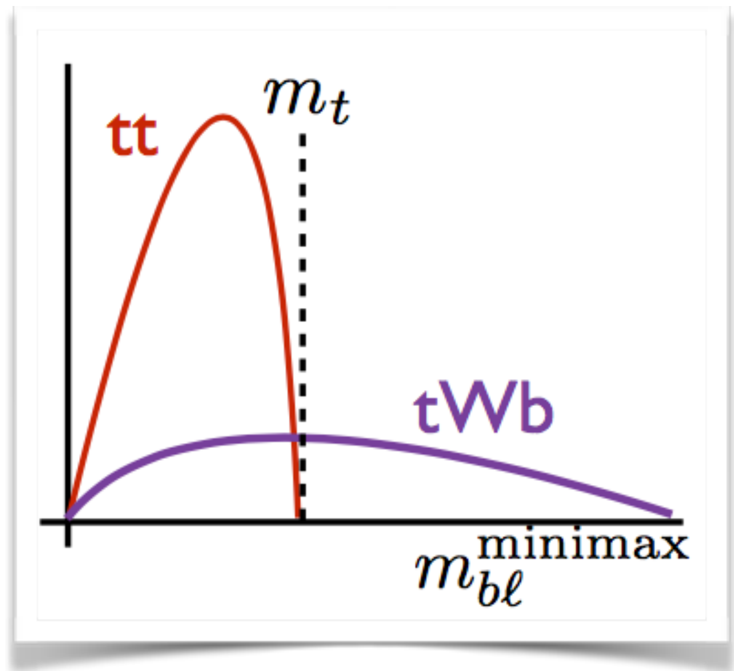


tW production
one *(b,l) pair from the top*



- **Discriminant:**
  - Signal: tWb+ $t\bar{t}$ in dilepton events
  - Lepton used as a proxy for the W: m(lW)

$\min\{\max\{m(b_1l_1),m(b_2l_2),\max\{m(b_1l_2),m(b_2l_1)\}$

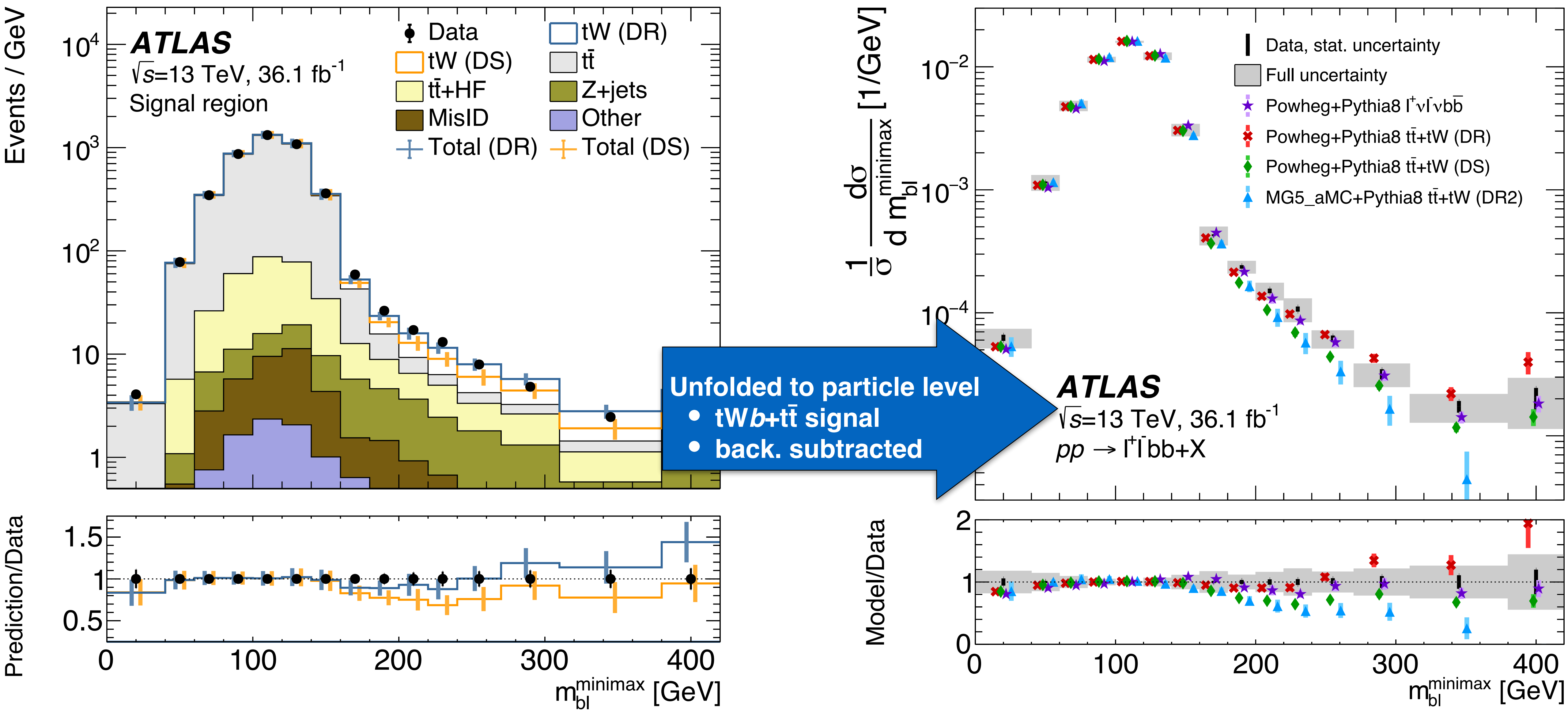


More information in C.Herwig talk this afternoon

Single-top-quark production: tW-tt interference @13TeV

arXiv:1806.04667

- Final discriminant at reconstructed level and unfolded @particle level
  - More tW events in the tail
  - Prediction for both tW interference schemes (**DR** and **DS**) shown



More information in C.Herwig talk this afternoon

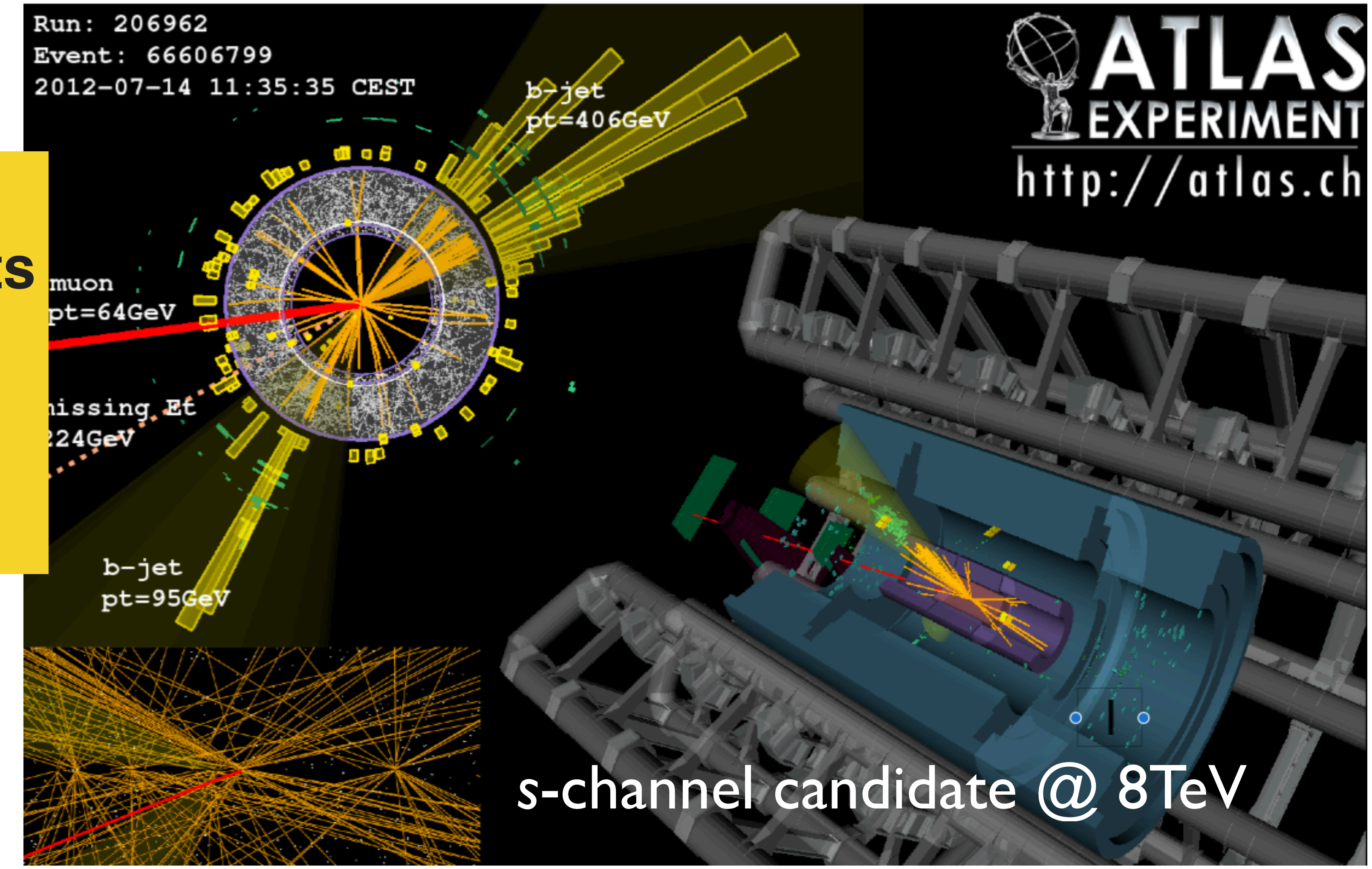
Single-top-quark production: s-channel

Challenging measurement @LHC

- A lot of effort to separate signal from backgrounds
- Backgrounds increase more than signal with higher √s

Cross-section measurements

- Inclusive
- Extraction of the $|V_{tb}|$
- Aiming for observation

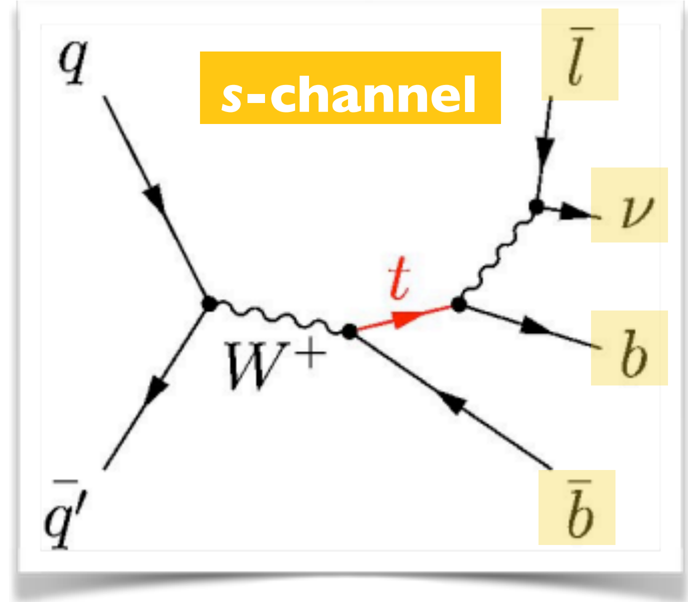


▷ Cross-section analysis @8TeV (PLB756(2016)228–246)

Single-top-quark production: s-channel @8TeV

Phys. Lett. B (2016) 228-246

- *s*-channel signature (single lepton decay):
  - Single isolated **lepton** (e, μ)
  - Missing transverse momentum (**E_T^{miss}**)
  - Two central high-p_T jets (two ***b*-tagged jets**)



- **Strategy:**
  - Define five independent regions:

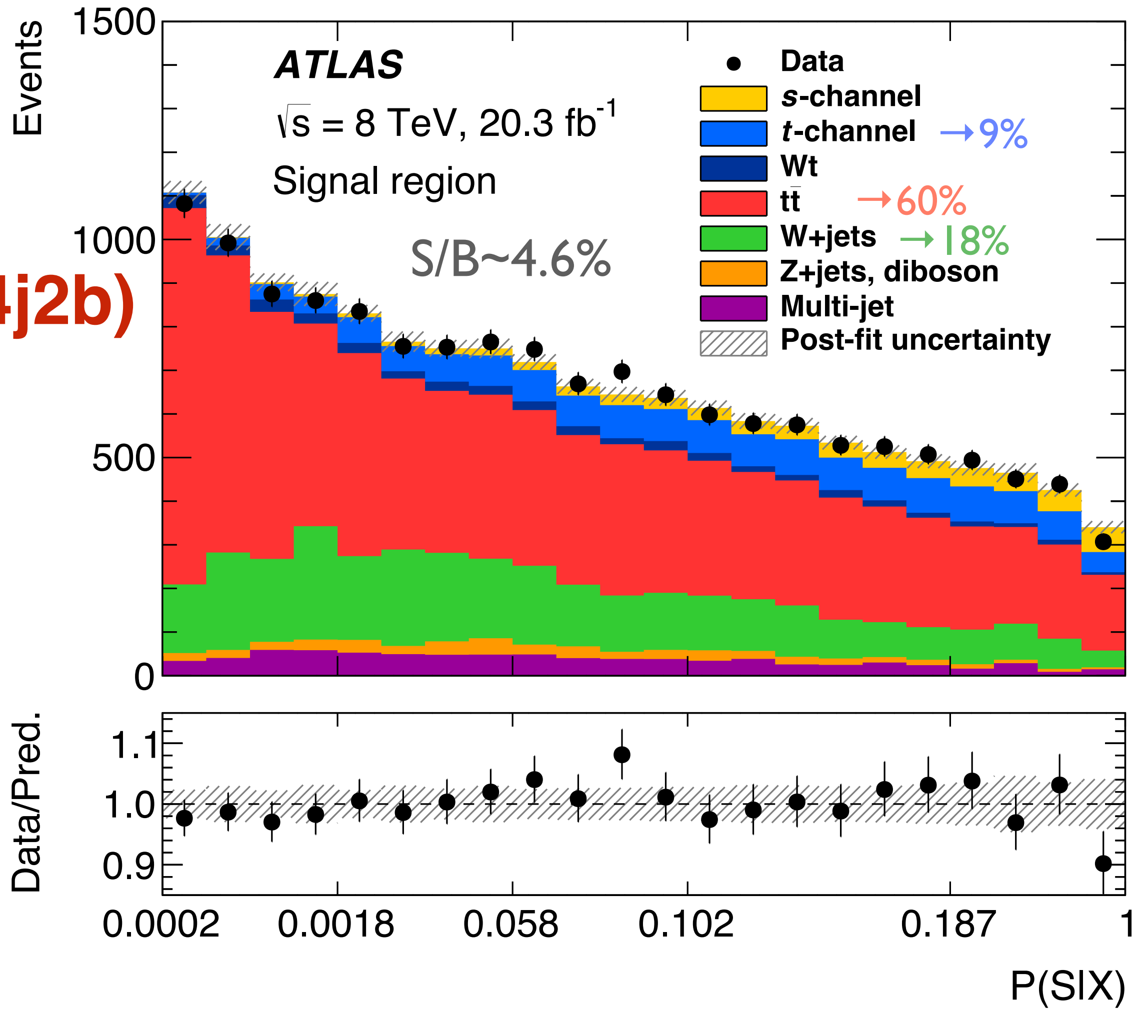
SR (2j2b), CR W+jets (2j2b(loose)), VR $t\bar{t}$ (4j2b)

  - ME to enhance S/B

$$P(S|X) = \frac{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i)}{\sum_i \alpha_{S_i} \mathcal{P}(X|S_i) + \sum_j \alpha_{B_j} \mathcal{P}(X|B_j)}.$$

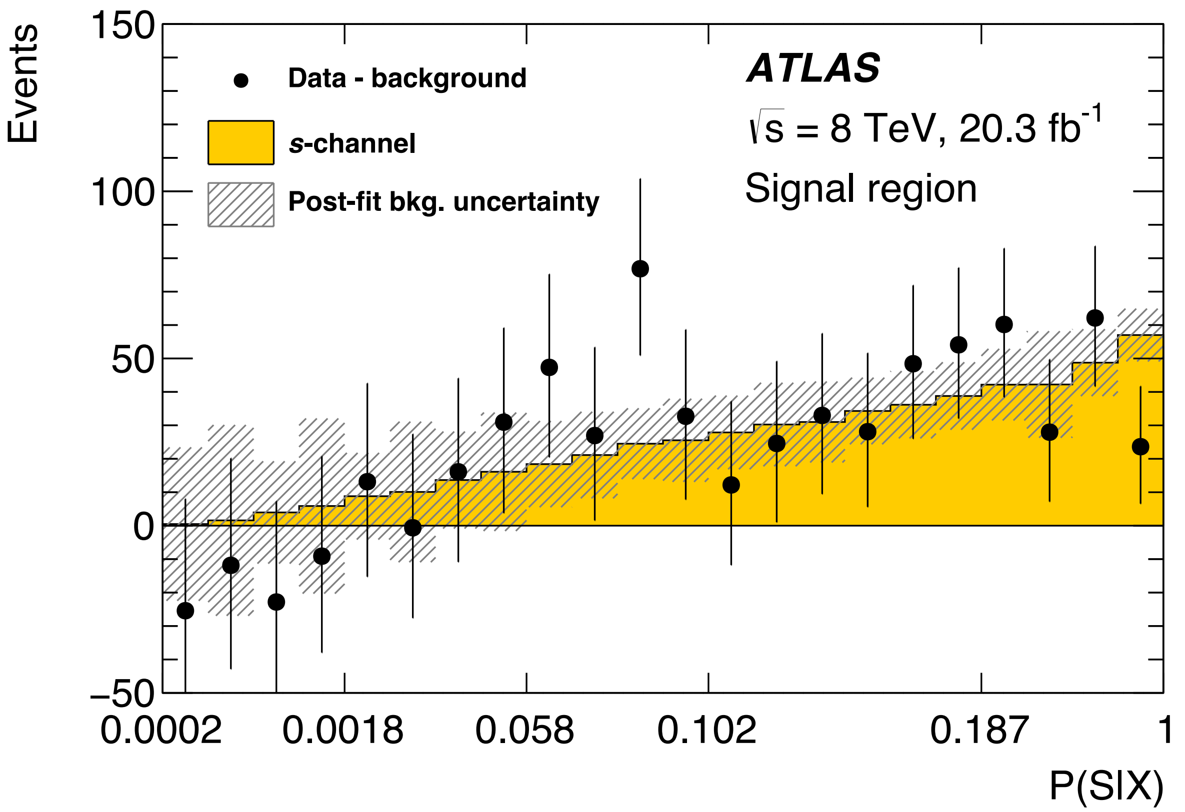
probability of measured event (X) to be a signal event S

  - Maximum likelihood fit in SR & CR



Single-top-quark production: s-channel @8TeV

Phys. Lett. B (2016) 228-246

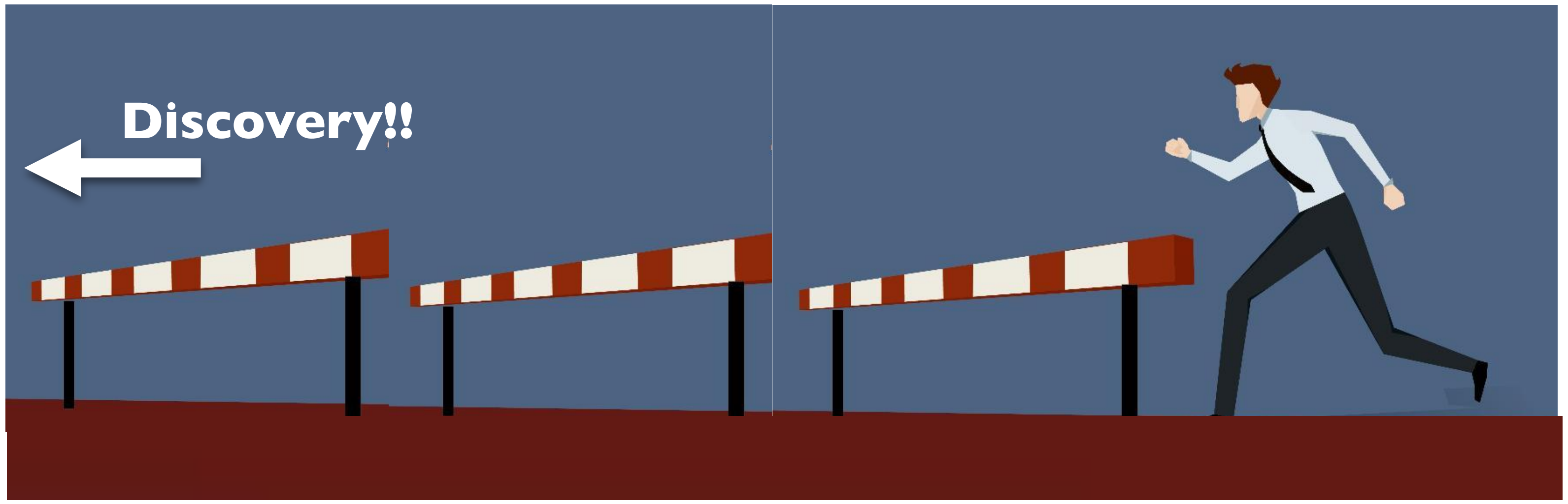


$$\sigma_s = 4.8 \pm 0.8(\text{stat})^{+1.6}_{-1.3}(\text{syst.})\ (37\%)$$

$$|\, f_{LV} V_{tb} \,| = 0.93^{+0.18}_{-0.20}$$

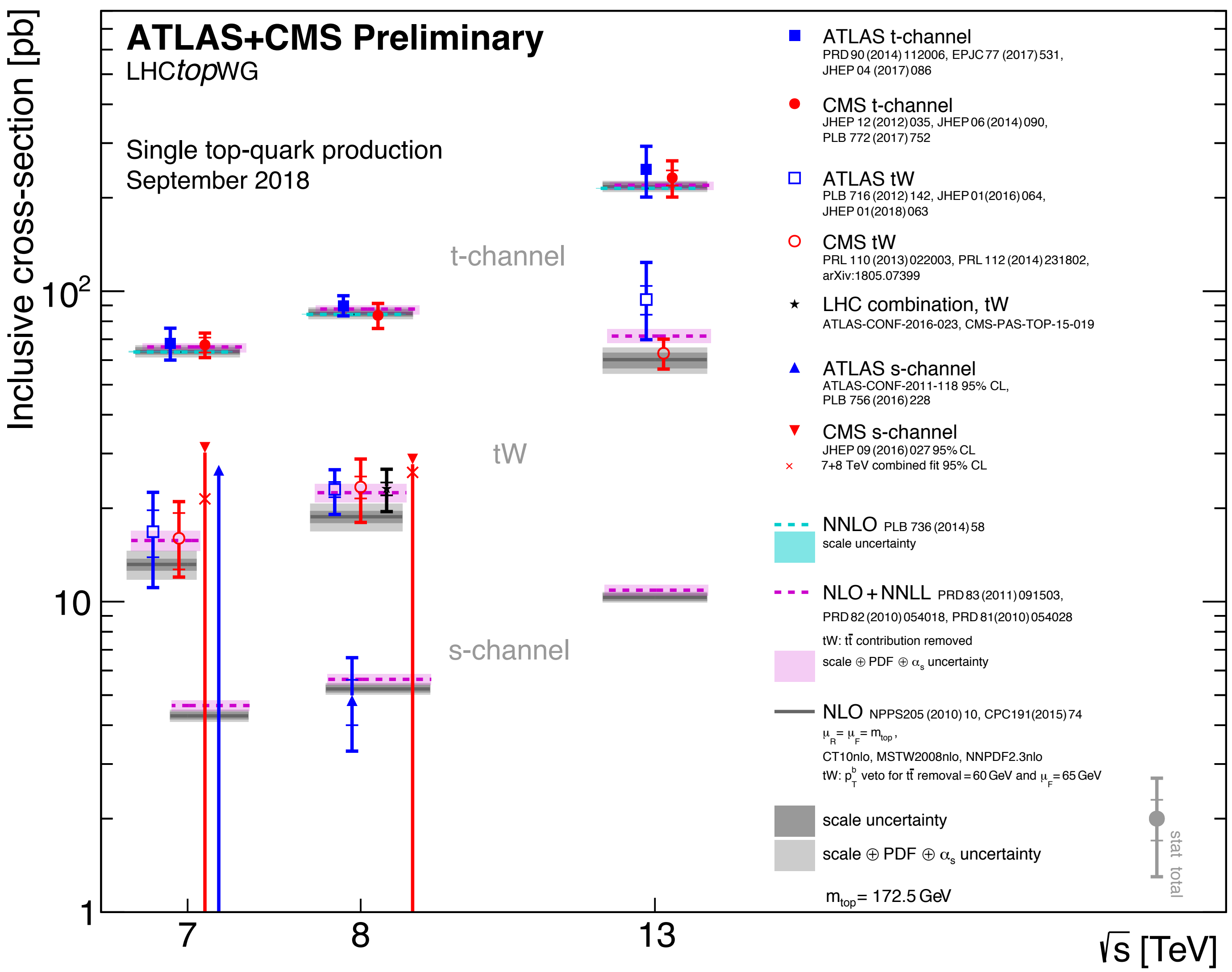
- Dominant systematics:
  - MC statistics (~12%)
  - JER (~12%)
  - *t*-channel generator (11%)

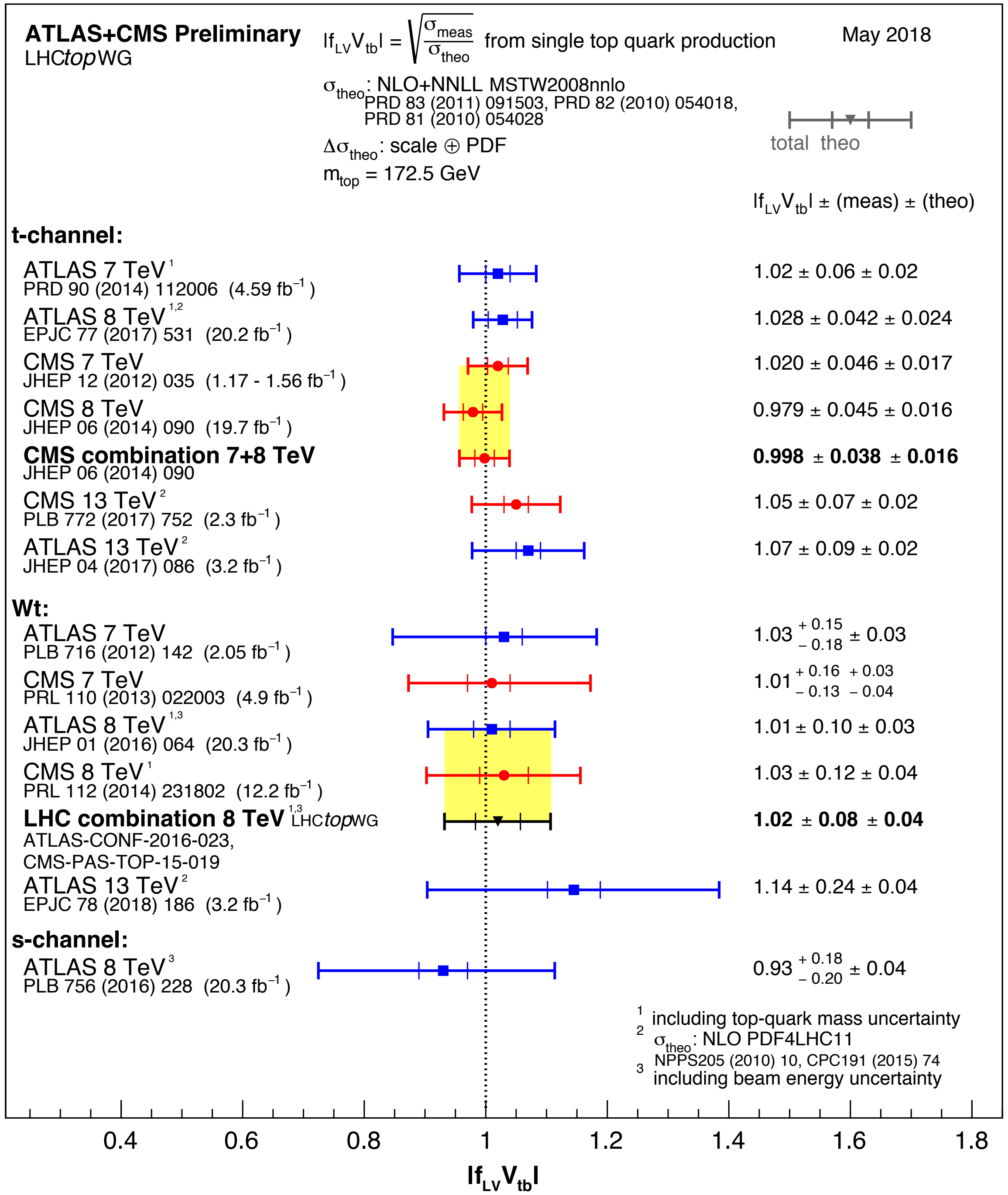
Evidence of s-channel! (observed significance of 3.2σ)



Cross-section summary and V_{tb} measurements

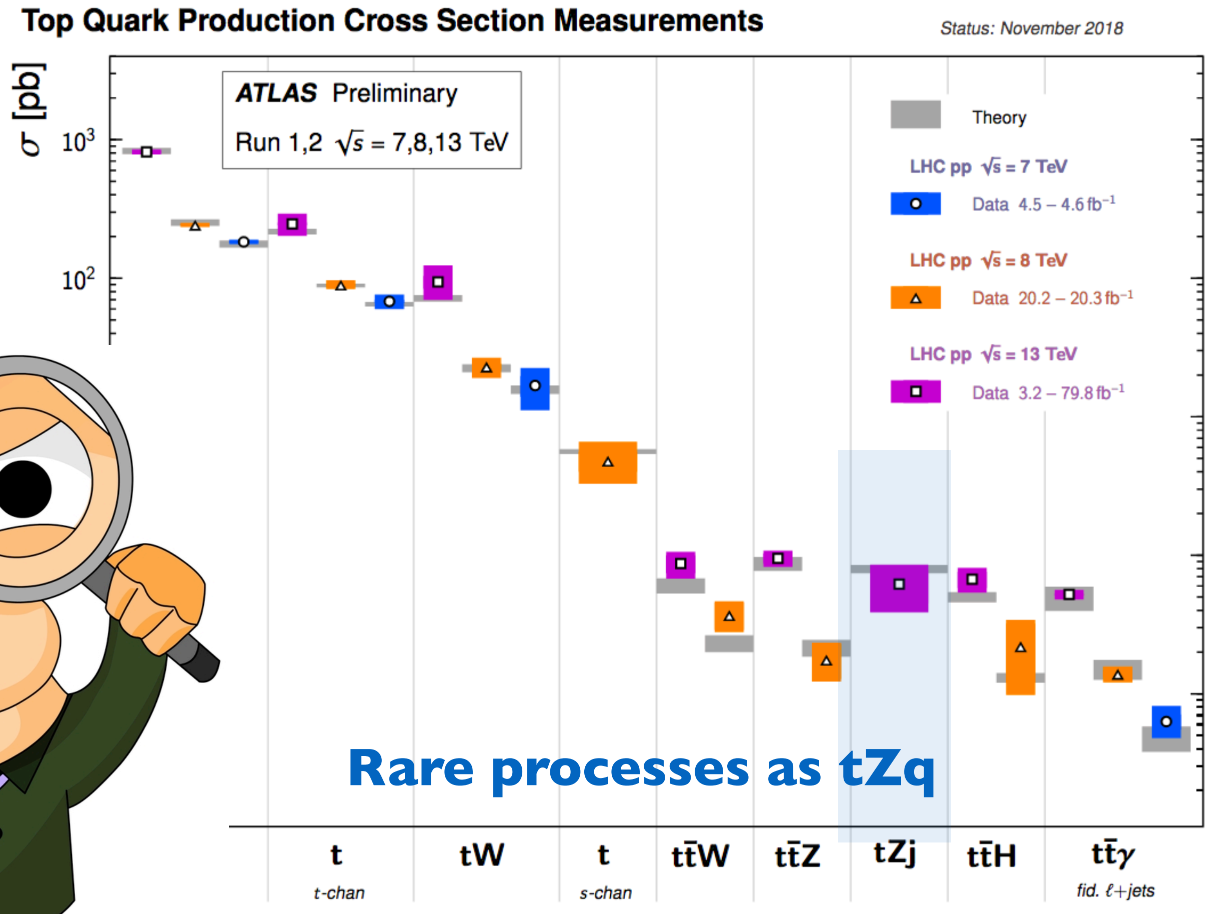
ATLAS+CMS combination ongoing





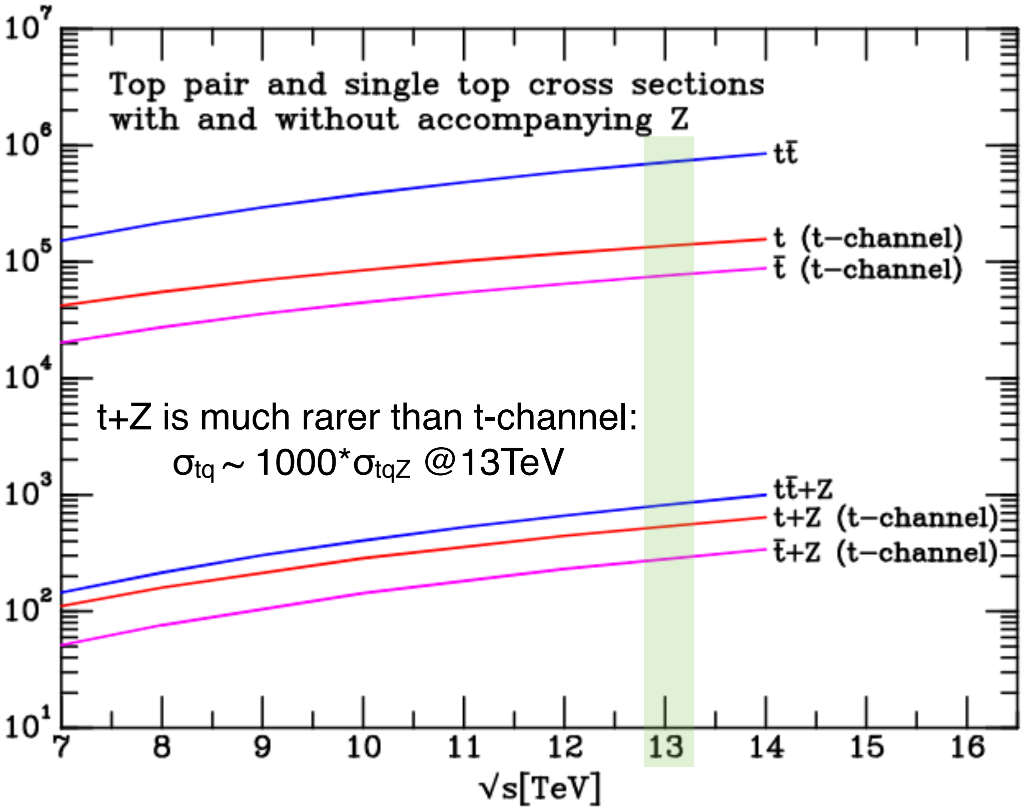
Cross-section and $|f_{LV}V_{tb}|$ results from all three single top-quark production processes are in agreement with the SM predictions

Single-top-quark production: rarer processes

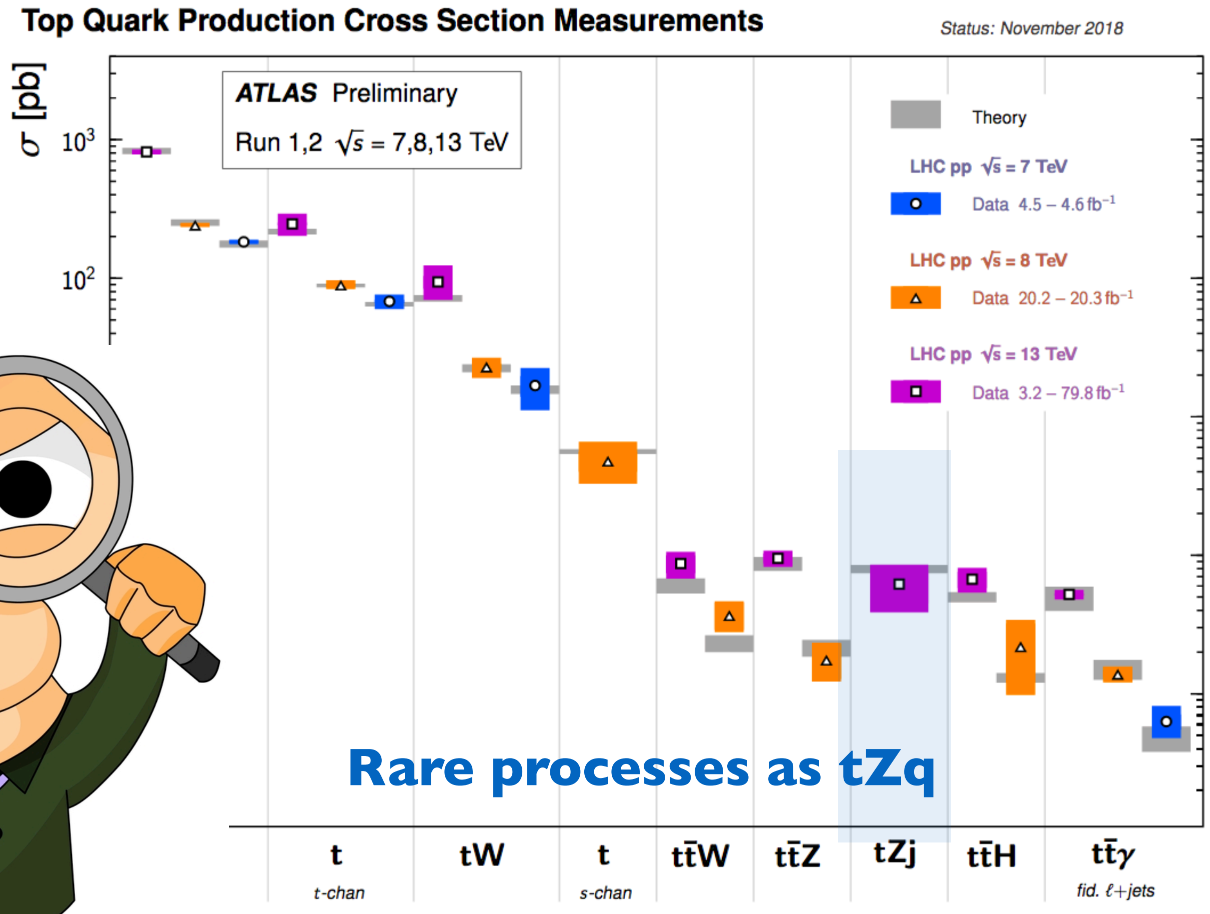


Cross-section measurements

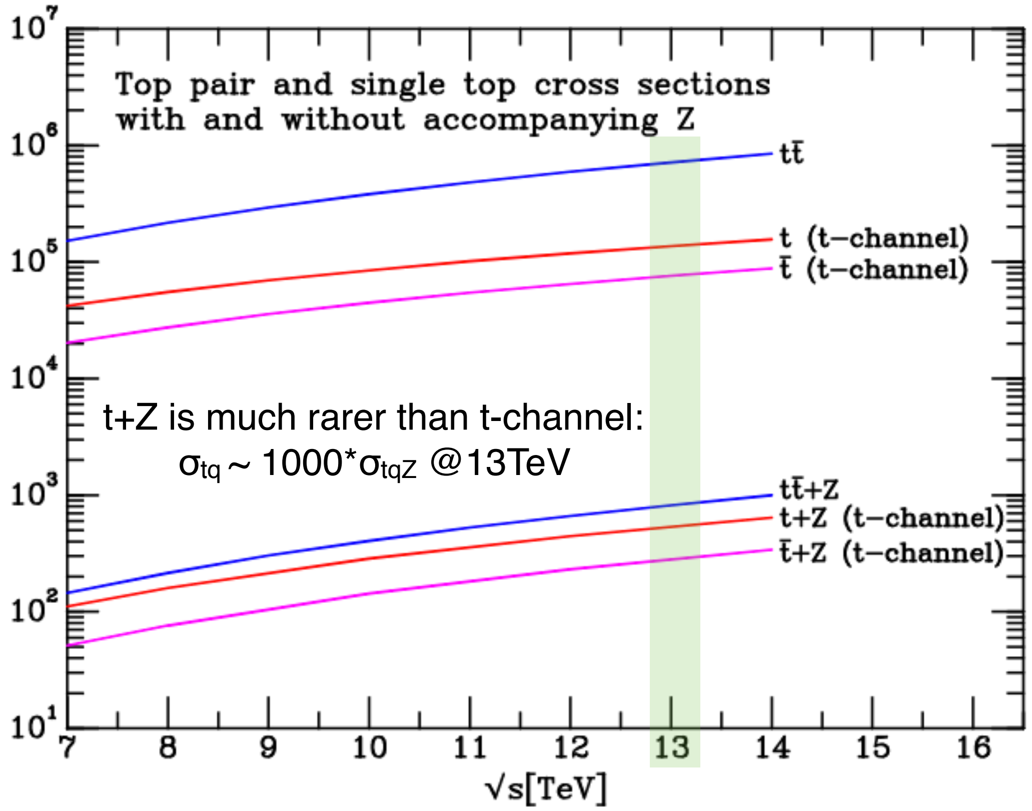
- Observation of these processes
- Inclusive/differential cross-section
- Study t+V coupling



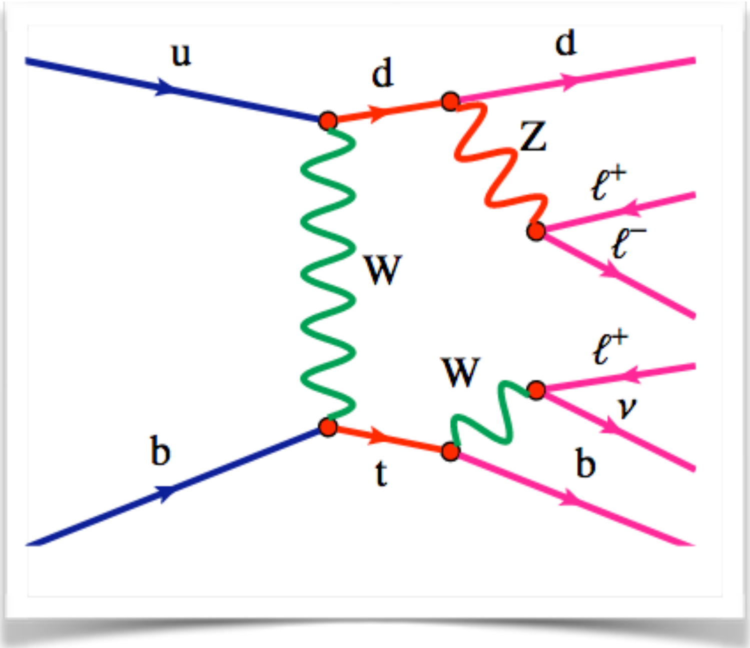
Single-top-quark production: rarer processes



to CMS for the observation!



Single-top-quark production: tZq

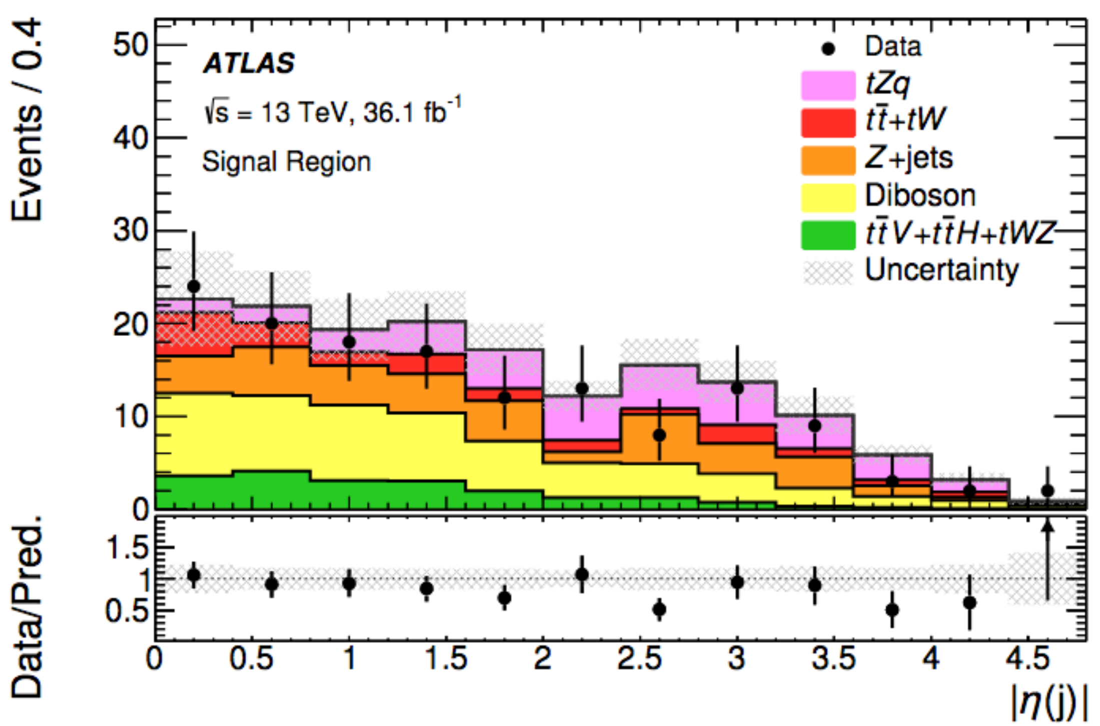


- *tZq* signature (multi-lepton channel):
  - Three isolated **lepton** (eee, eeμ, eμμ, μμμ)
  - Missing transverse energy (**E_T^{miss}**)
  - Two high-p_T jets (one **forward** and one ***b*-tagged**)

- **Strategy:**
  - Define 3 independent regions:
    - **SR (2j1b)**, **VR/CR DiBoson**, **VR/CR $t\bar{t}$**
  - NN to enhance S/B
  - Maximum likelihood fit in SR

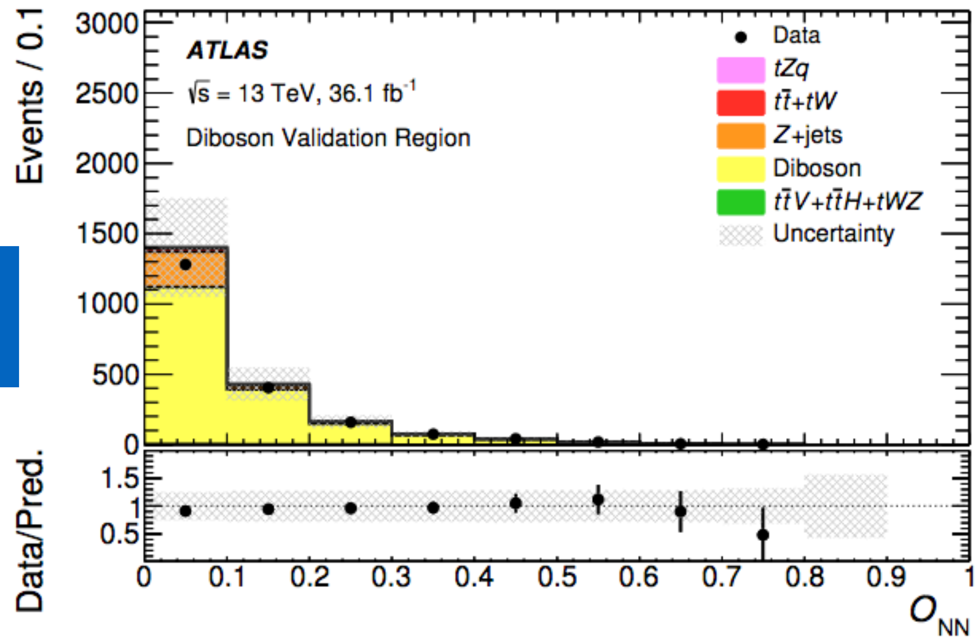
Table 1: Overview of the requirements applied for selecting events in the signal, validation and control regions.

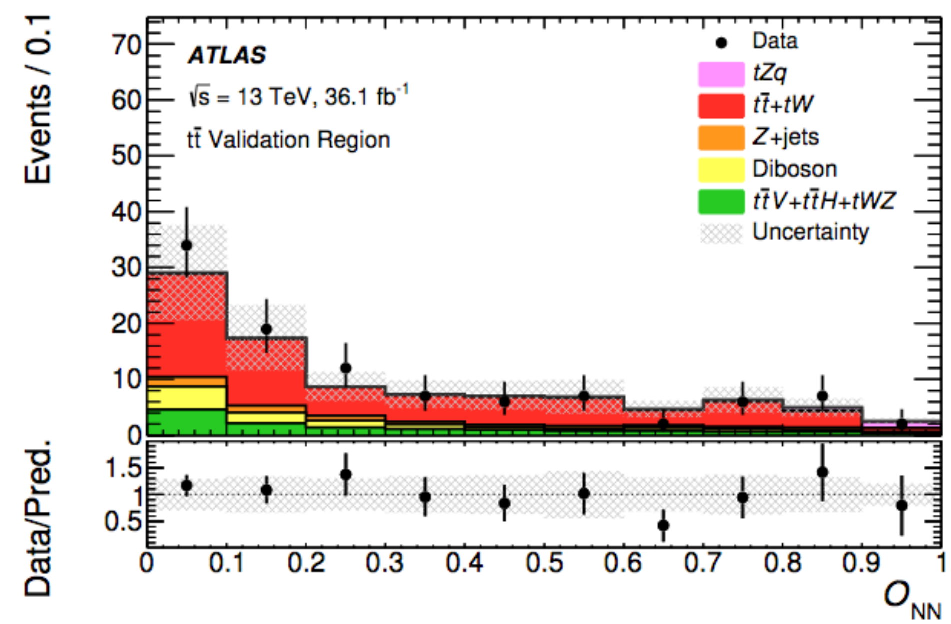
Common selections			
Exactly 3 leptons with $\lvert\eta\rvert < 2.5$ and $p_T > 15$ GeV $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 25$ GeV, $p_T(\ell_3) > 15$ GeV p_T(jet) > 30 GeV $m_T(\ell_W, \nu) > 20$ GeV			
SR	Diboson VR / CR	$t\bar{t}$ VR	$t\bar{t}$ CR
≥ 1 OSSF pair $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV 2 jets, $\lvert\eta\rvert < 4.5$ 1 *b*-jet, $\lvert\eta\rvert < 2.5$ —	≥ 1 OSSF pair $\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV 1 jet, $\lvert\eta\rvert < 4.5$ — VR/CR: $m_T(\ell_W, \nu) > 20/60$ GeV	≥ 1 OSSF pair $\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV 2 jets, $\lvert\eta\rvert < 4.5$ 1 *b*-jet, $\lvert\eta\rvert < 2.5$ —	≥ 1 OSDF pair No OSSF pair 2 jets, $\lvert\eta\rvert < 4.5$ 1 *b*-jet, $\lvert\eta\rvert < 2.5$ —



Single-top-quark production: tZq

Validation regions



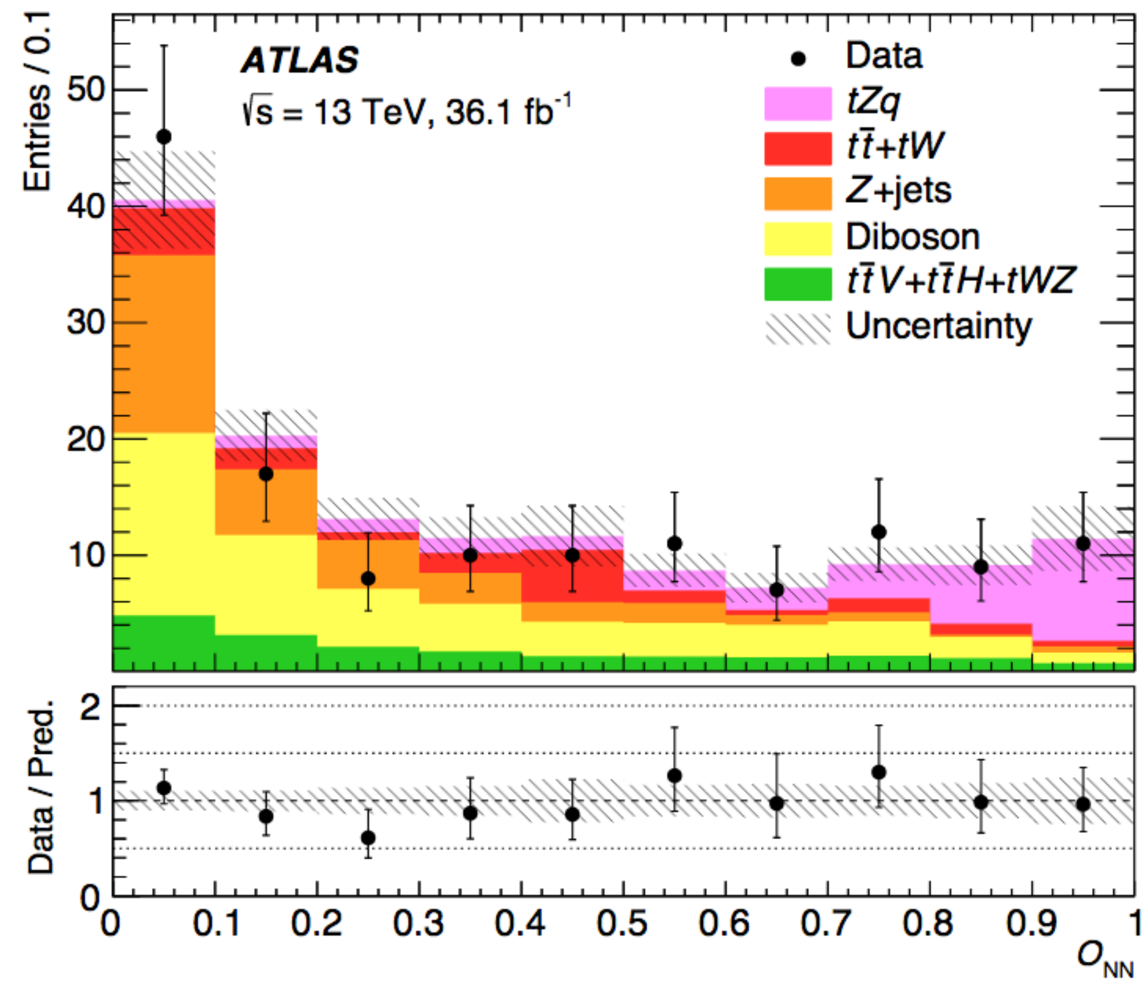


Obs. significance 4.2σ:

$$\sigma_{tZq} = 600 \pm 170(\text{stat.}) \pm 140(\text{syst.})\text{fb}$$

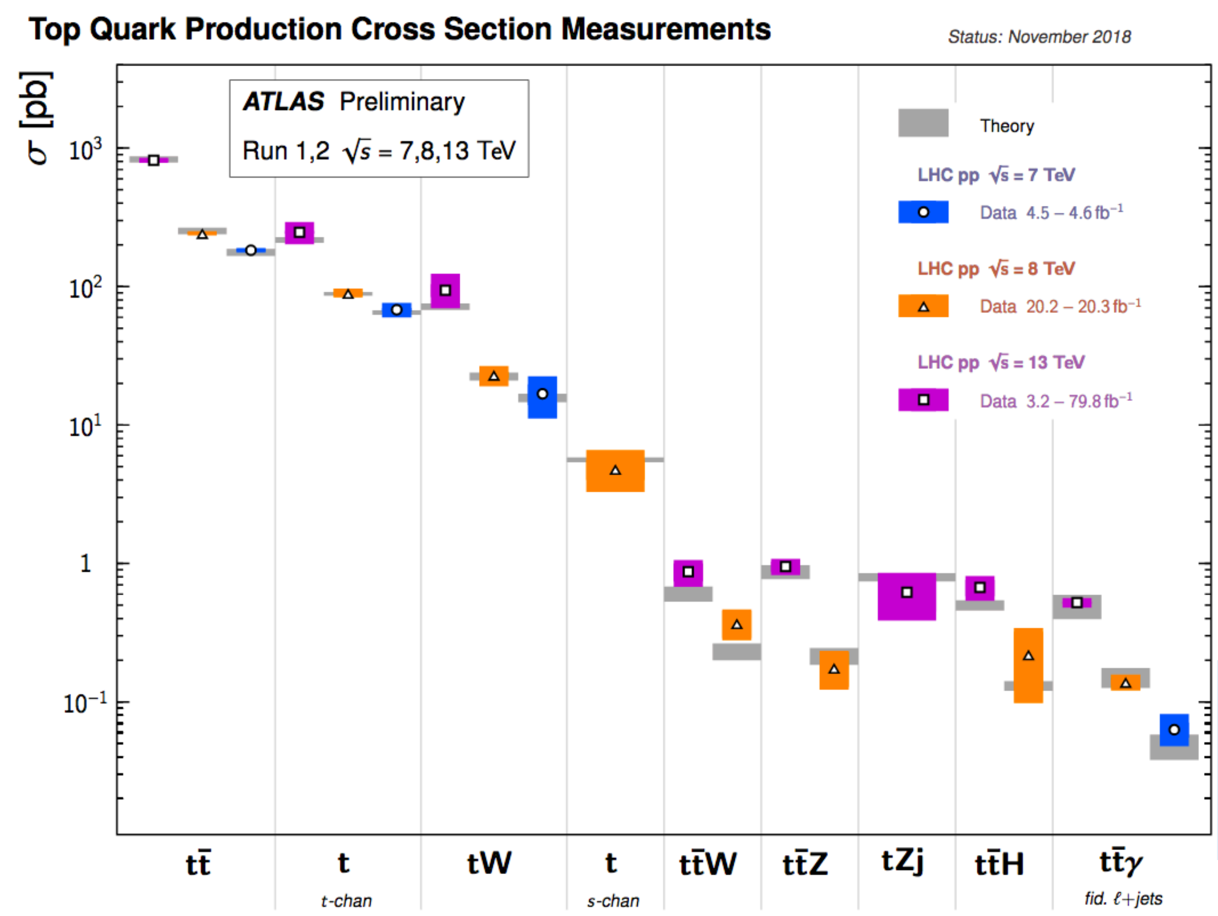
$$\sigma_{tZq} = 800\ \text{fb} + 6.1\% - 7.4\%(\text{theory})$$

Dominant systematics: tZq radiation

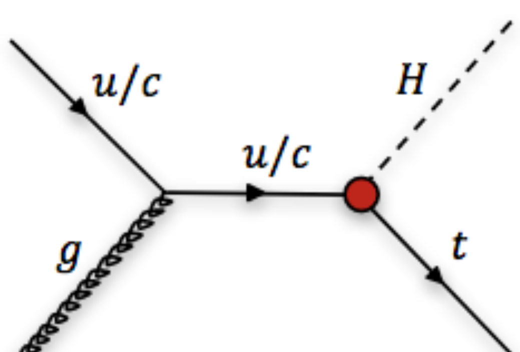


Single-top-quark production: FCNC

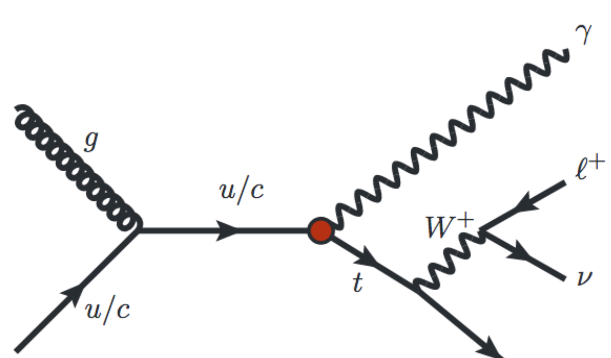
- An what else? FCNC



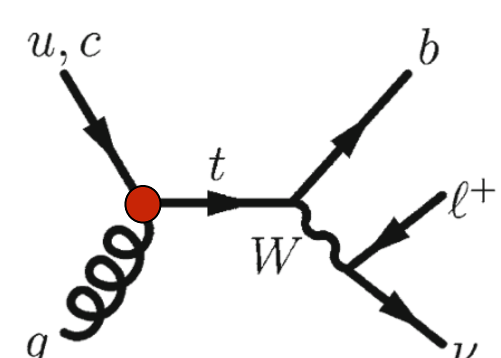
- FCNC can be studied in single-top processes



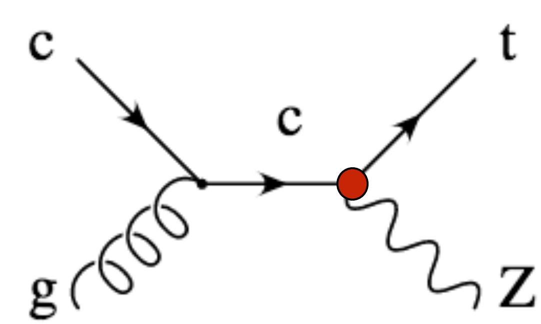
FCNC tH



FCNC tγ



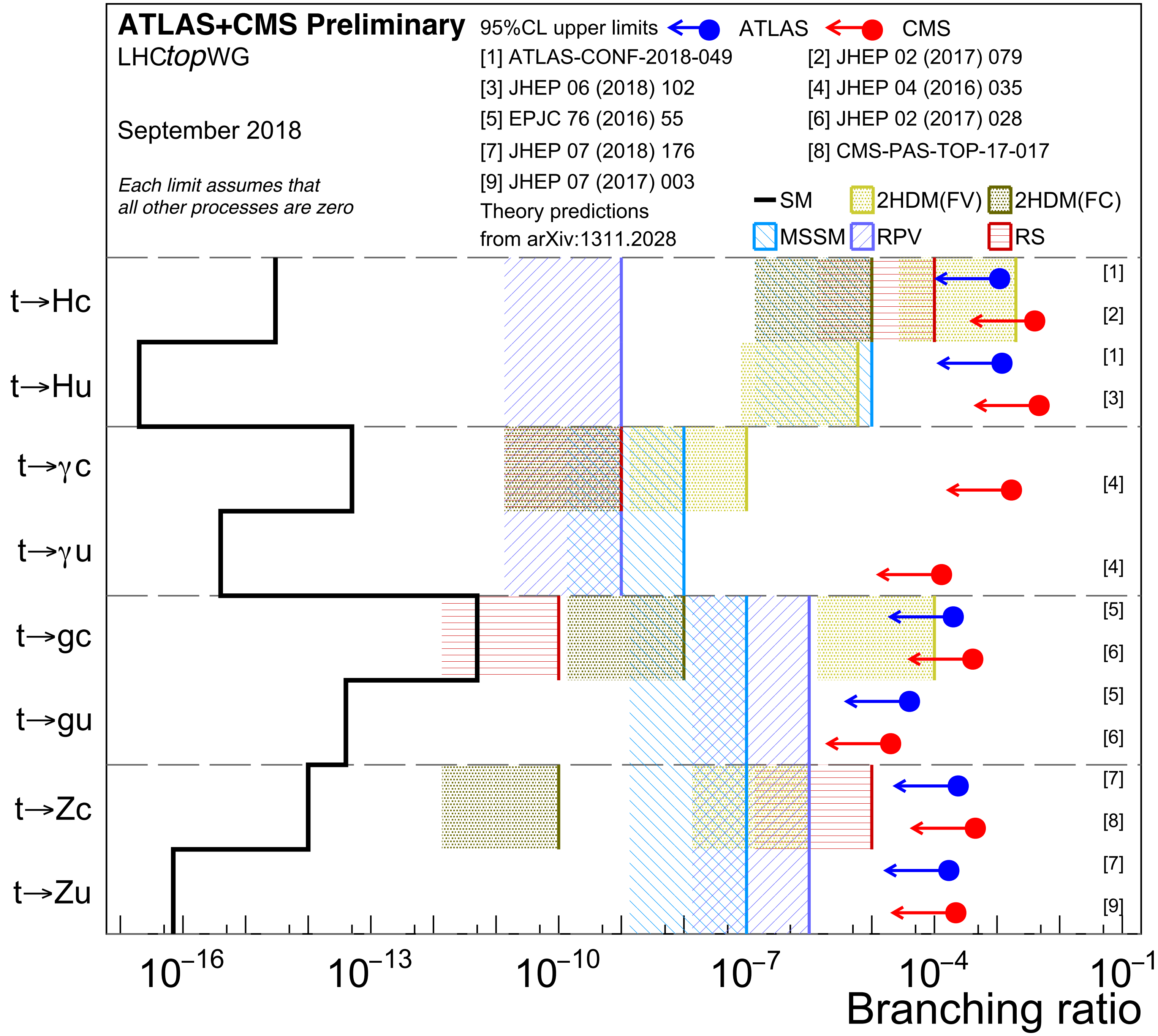
FCNC tg



FCNC tZ

- Searches @8TeV (EPJC76(2016)55)

Single-top-quark production: FCNC



- Run 2 analyses:
  - Improve the current limits and covered all processes
  - New analysis should combine signal in production and decay

Single-top-quark production: Limitations

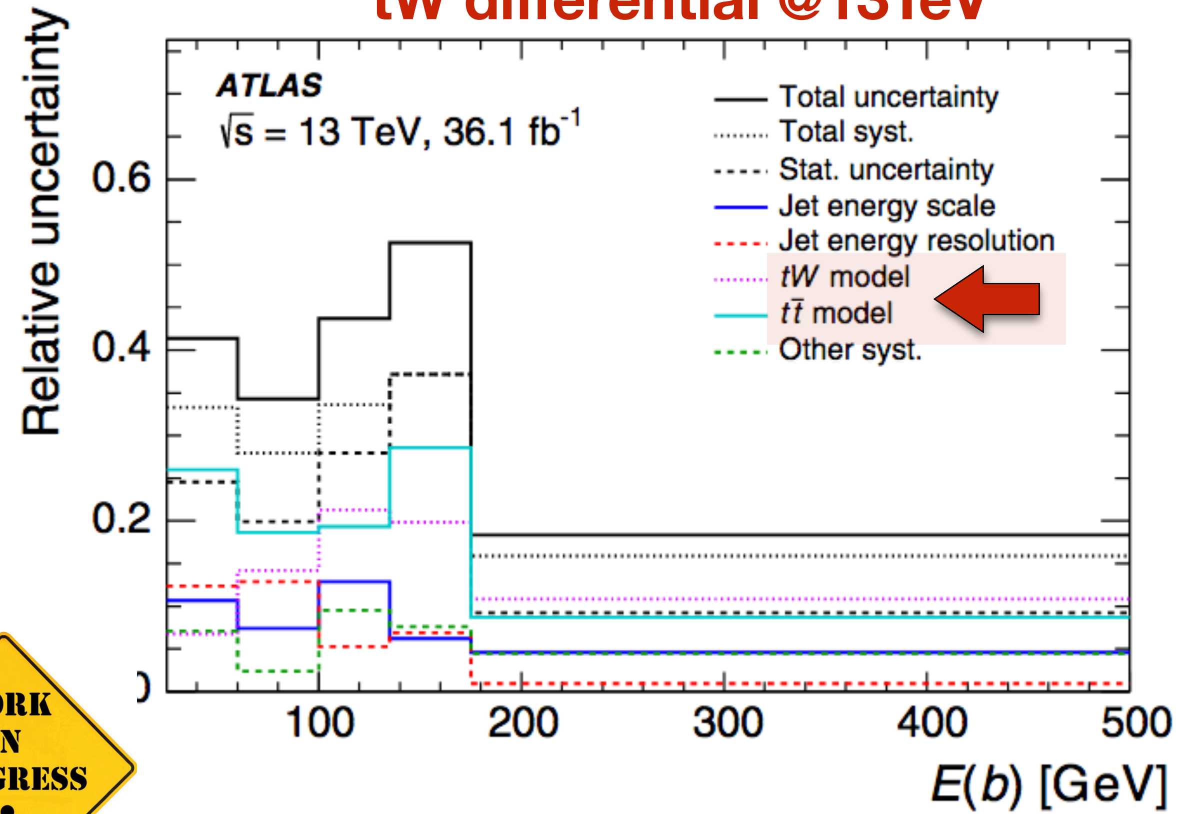
- Limitations of the current analyses:

t-channel fiducial @8TeV

Source	$\Delta\sigma_{\text{fid}}(tq)$ / $\sigma_{\text{fid}}(tq)$ [%]	$\Delta\sigma_{\text{fid}}(\bar{t}q)$ / $\sigma_{\text{fid}}(\bar{t}q)$ [%]
Data statistics	± 1.7	± 2.5
Monte Carlo statistics	± 1.0	± 1.4
Background normalisation	< 0.5	< 0.5
Background modelling	± 1.0	± 1.6
Lepton reconstruction	± 2.1	± 2.5
Jet reconstruction	± 1.2	± 1.5
Jet energy scale	± 3.1	± 3.6
Flavour tagging	± 1.5	± 1.8
$E_{\text{T}}^{\text{miss}}$ modelling	± 1.1	± 1.6
$b/\bar{b}$ tagging efficiency	± 0.9	± 0.9
PDF	± 1.3	± 2.2
tq ($\bar{t}q$) NLO matching	± 0.5	< 0.5
tq ($\bar{t}q$) parton shower	± 1.1	± 0.8
tq ($\bar{t}q$) scale variations	± 2.0	± 1.7
$t\bar{t}$ NLO matching	± 2.1	± 4.3
$t\bar{t}$ parton shower	± 0.8	± 2.5
$t\bar{t}$ scale variations	< 0.5	< 0.5
Luminosity	± 1.9	± 1.9
Total systematic	± 5.6	± 7.3
Total (stat. + syst.)	± 5.8	± 7.8

- $t\bar{t}$ and signal modelling
- MC statistics
- JES/JER
- background modelling

tW differential @13TeV



tW differential @13TeV

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

Present and future

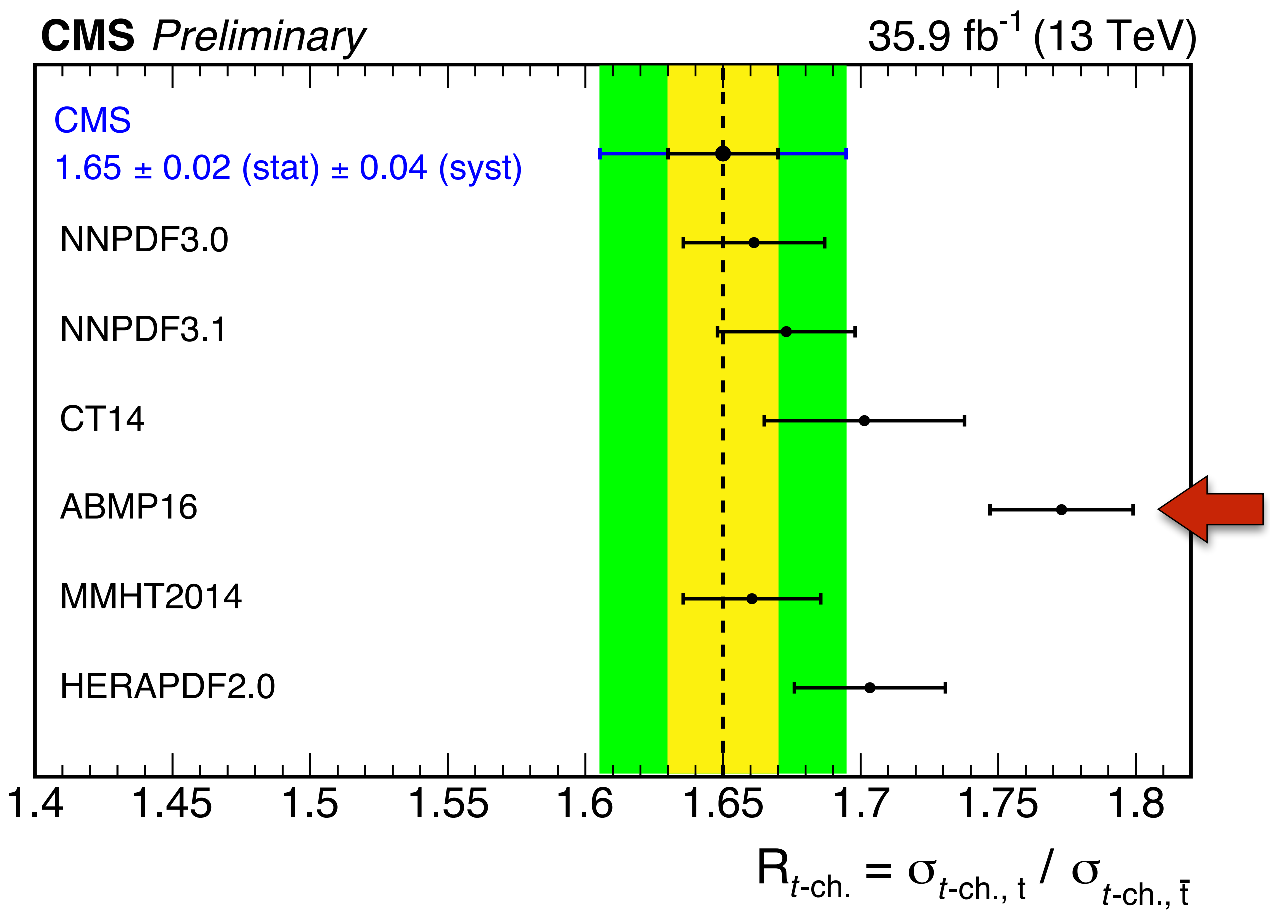
	tq	tW	tb	tZ	tγ	tWZ	tH	rarer processes
Total cross-section	👍	👍	👍	👍				
Fiducial cross-section	👍	👍						
Differential cross-section	👍	👍						
study interference processes	—	👍						
polarisation	👍							
move to higher pT regime?								

Increase complexity

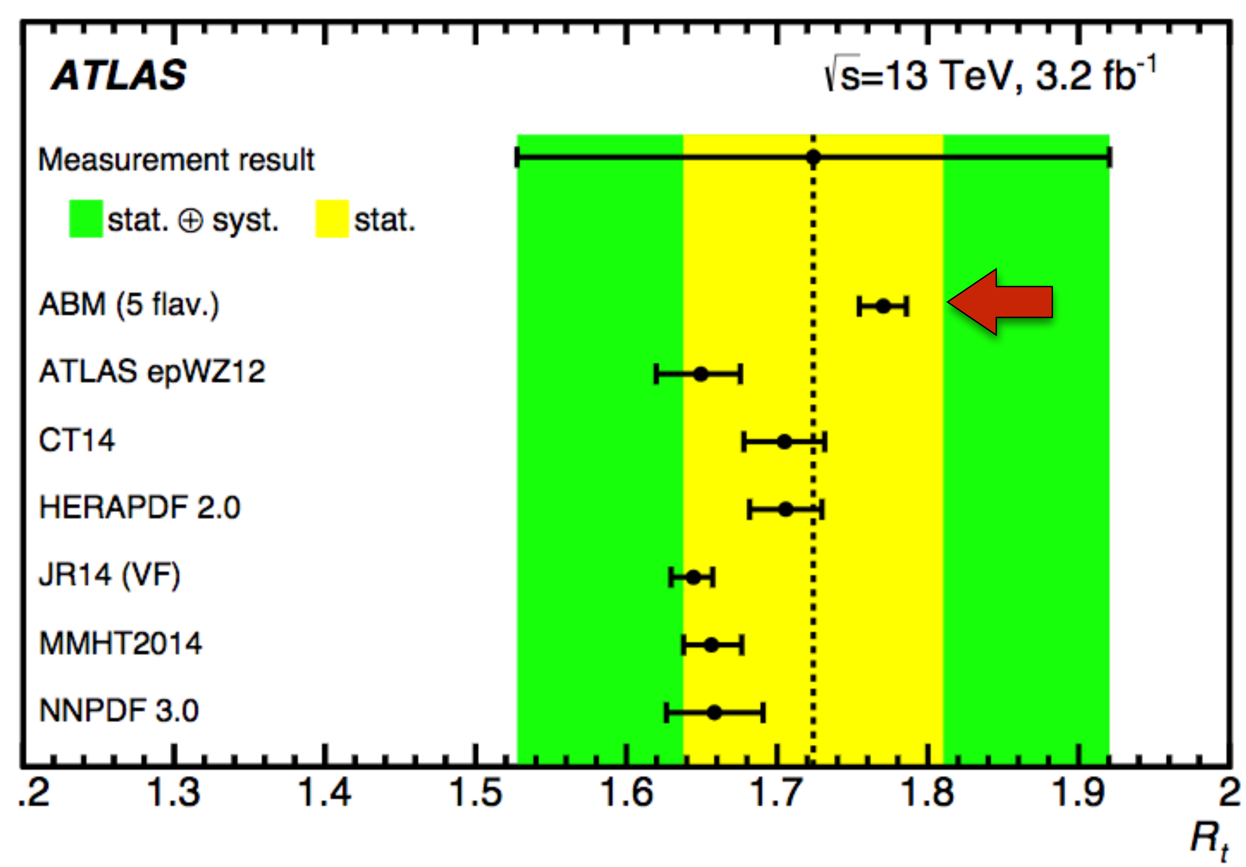
Thanks

Backup

CMS @ 13TeV



ATLAS @ 13TeV



Single-top-quark production: tChannel systematics

Source	$\Delta\sigma_{\text{fid}}(tq)$ / $\sigma_{\text{fid}}(tq)$ [%]	$\Delta\sigma_{\text{fid}}(\bar{t}q)$ / $\sigma_{\text{fid}}(\bar{t}q)$ [%]
Data statistics	± 1.7	± 2.5
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$t\bar{t}$ scale variations	< 0.5	< 0.5
Luminosity	± 1.9	± 1.9
Total systematic	± 5.6	± 7.3
Total (stat. + syst.)	± 5.8	± 7.8

Single-top-quark production: tChannel

from C.Escobar

Quadruple-differential (θ, ϕ, θ*, ϕ*) decay rate of (polarised) top quarks using single top quark events.

- Simultaneously constrain of the full space of generalised helicity fractions and phases + 3 top-quark polarisation components (transverse polarisation components introduced in PRD89 (2014) 114009).

$$
\begin{aligned}
\frac{1}{\Gamma}\frac{d\Gamma}{d\Omega d\Omega^*} = \frac{3}{64\pi^2}\frac{1}{\mathcal{N}} \Big\{ & \left[|a_{1\,\frac{1}{2}}|^2 (1+\lambda\cos\theta^*)^2 + 2|a_{0\,-\frac{1}{2}}|^2 \sin^2\theta^*\right] \left(1+\vec{P}\cdot\vec{u}_L\right) \\
& + \left[2|a_{0\,\frac{1}{2}}|^2 \sin^2\theta^* + |a_{-1\,-\frac{1}{2}}|^2 (1-\lambda\cos\theta^*)^2\right] \left(1-\vec{P}\cdot\vec{u}_L\right) \\
& + \lambda 2\sqrt{2}\left[\mathrm{Re}(a_{0\,\frac{1}{2}} a^*_{1\,\frac{1}{2}} e^{-i\phi^*})(1+\lambda\cos\theta^*)\right. \\
& \left. + \mathrm{Re}(a_{-1\,-\frac{1}{2}} a^*_{0\,-\frac{1}{2}} e^{-i\phi^*})(1-\lambda\cos\theta^*)\right] \sin\theta^* \vec{P}\cdot\vec{u}_T \\
& + \lambda 2\sqrt{2}\left[\mathrm{Im}(a_{0\,\frac{1}{2}} a^*_{1\,\frac{1}{2}} e^{-i\phi^*})(1+\lambda\cos\theta^*)\right. \\
& \left. + \mathrm{Im}(a_{-1\,-\frac{1}{2}} a^*_{0\,-\frac{1}{2}} e^{-i\phi^*})(1-\lambda\cos\theta^*)\right] \sin\theta^* \vec{P}\cdot\vec{u}_N \Big\} = \sum_{j_1 j_2 m' m} c^{j_1 j_2}_{m' m} M^{j_1 j_2}_{m' m}
\end{aligned}
$$

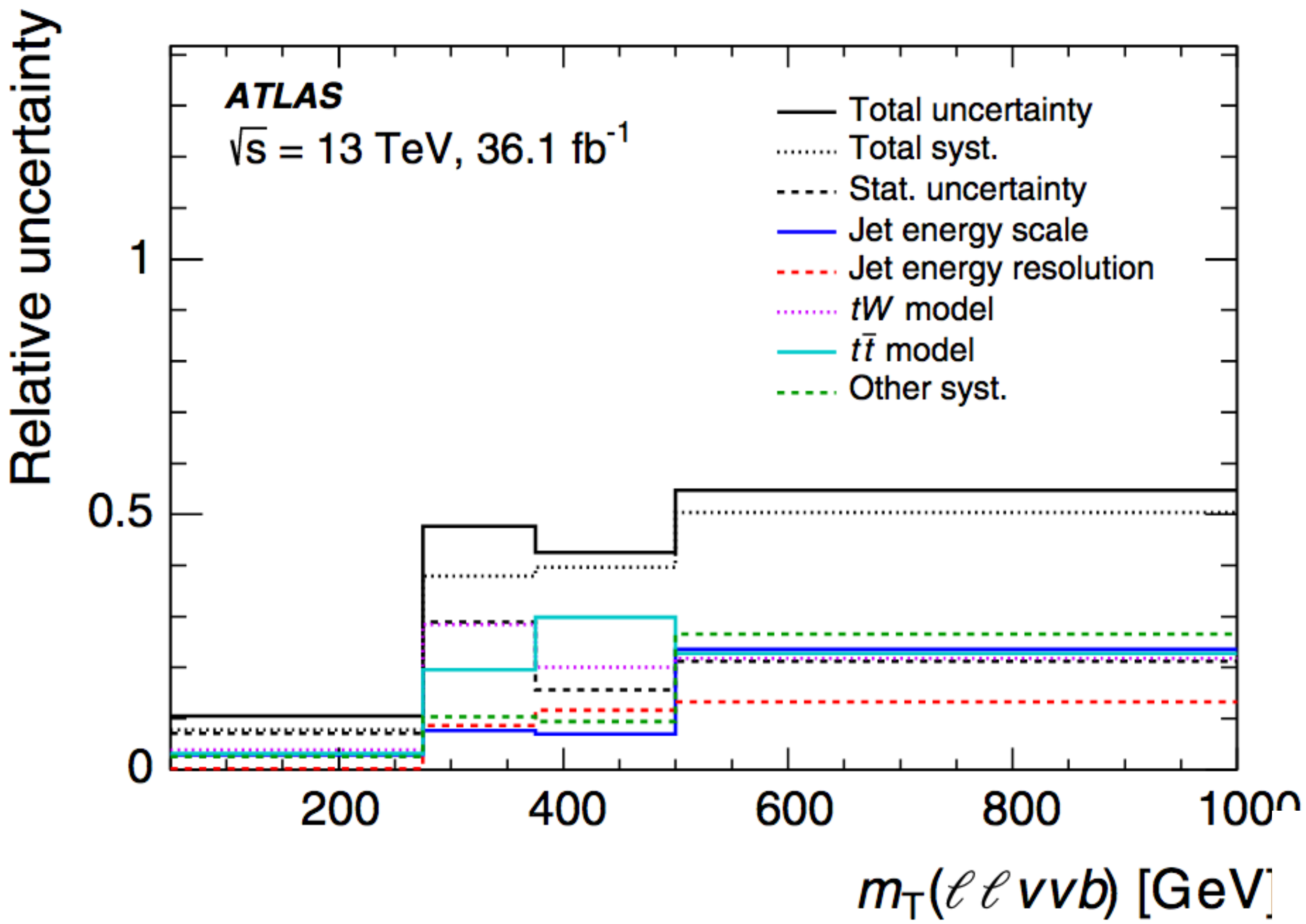
Finite series of orthonormal M-functions

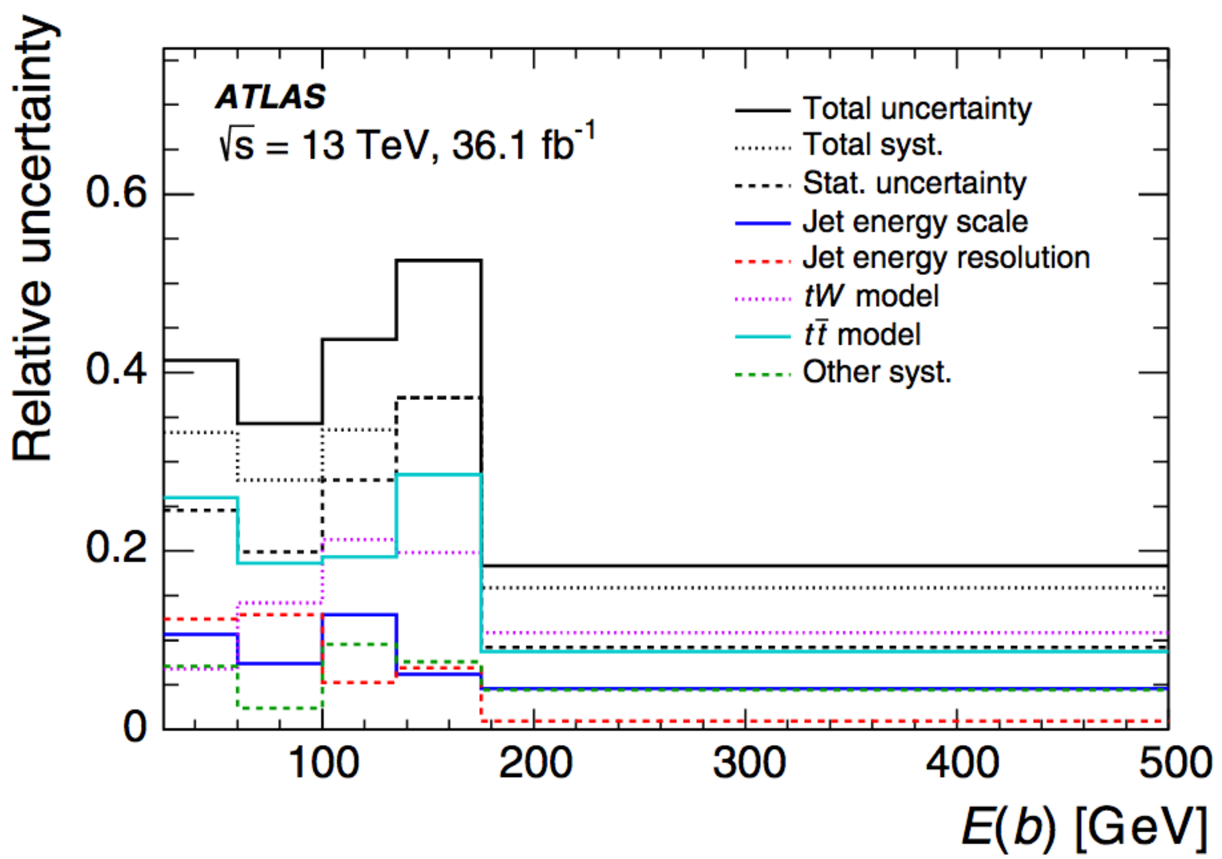
Where the M-functions are based on the Wigner *D* functions

Angular coefficients to be determined

- Angular coefficients related to various asymmetries and with *W* boson spin observables (PRD93 (2016) 011301) (as in JHEP 12 (2017) 017).
- Allows to produce MC samples with pure polarisation components.
- Interpretation in terms of either anomalous couplings or EFT with no assumptions on any parameter.

Single-top-quark production: tW systematics





Interference: tW and tt

- The NLO corrections to the LO *tW* amplitude:

$$|A_{tW}|^2 = |A_{t\bar{t}}|^2 + |A_{tWb}|^2 + 2Re\{A^*_{t\bar{t}} \cdot A_{tWb}\}$$

tt @LO — tW@NLO — interference

- **Different alternative used to handle the interference @NLO**
  - ➡ **Diagram Removal (DR):**
    - removes all tt diagram contributions (proportional to $|A_{tWb}|^2$)
    - neglect interference effects, not gauge invariant
  - ➡ **Diagram Subtraction (DS):**
    - removes resonant tt contributions, gauge invariant
    - includes interference
  - ➡ **Diagram Removal 2 (DR2):**
    - removes tt LO contribution (recent approach)
    - proportional to $|A_{tWb}|^2 + 2Re\{A^*_{tt}A_{tWb}\}$
  - ➡ **4lbb (lvlvbb):**
    - implemented in PowHeg, no narrow-width approximation
    - interference is automatically handled

Note: reference for every scheme will be added

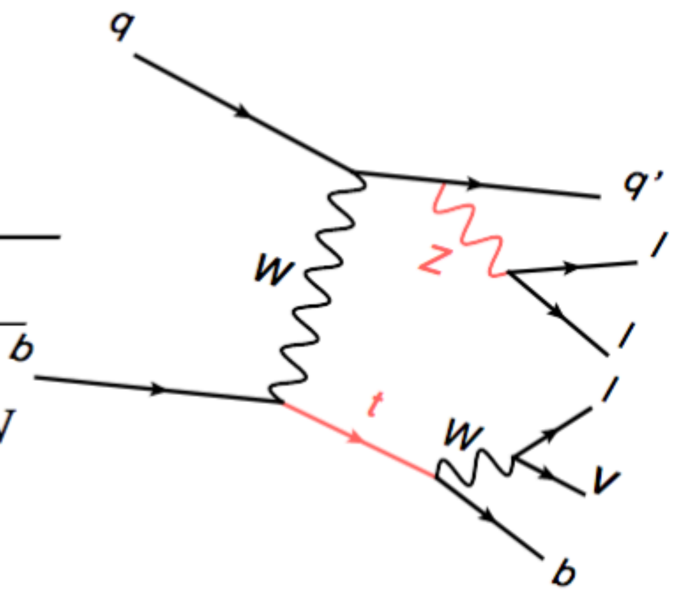
Single-top-quark production: s-channel systematics

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

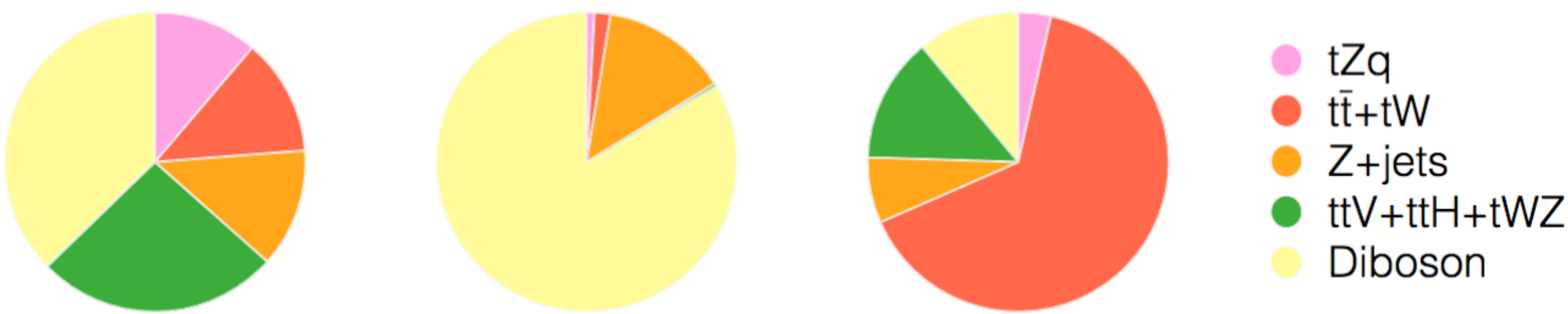
Table 2: Main statistical and systematic uncertainties contributing to the total uncertainty of the measured cross-section. The relative uncertainties reflect the influence of each systematic effect on the overall signal strength uncertainty. Apart from possible correlations between the systematic uncertainties, the total uncertainty contains several minor contributions which are all smaller than 1%.

from I.Cioara

Event Selection

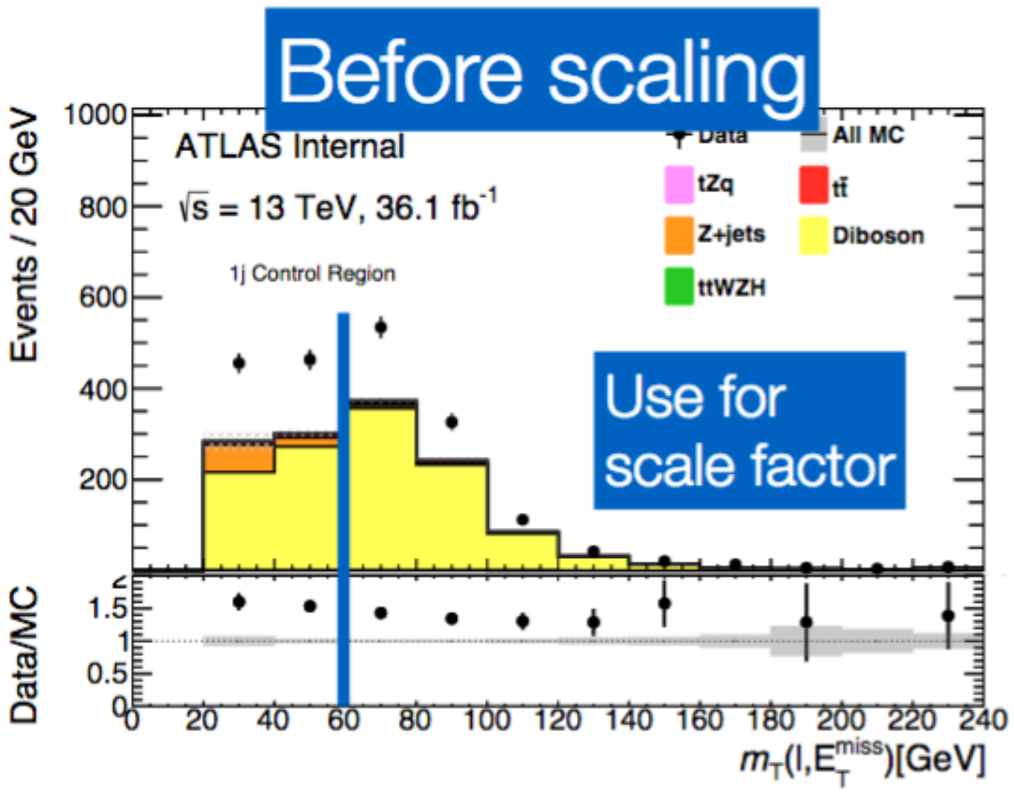


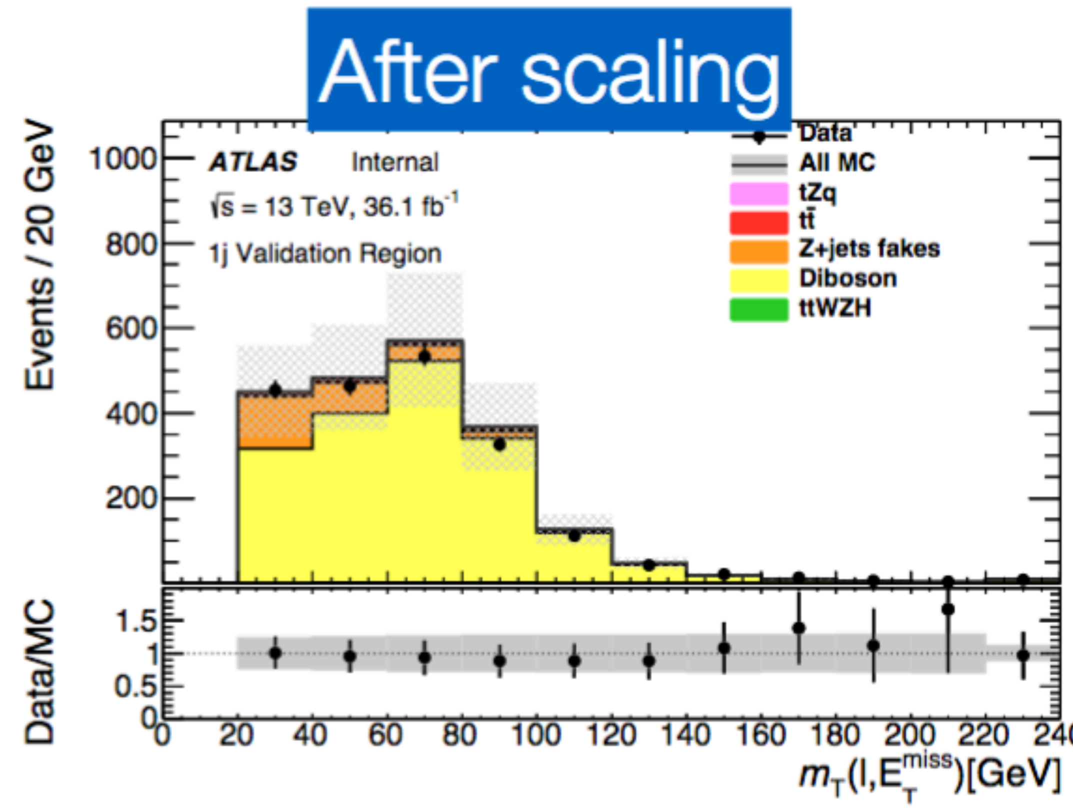
Common selections			
exactly 3 leptons with $\lvert\eta\rvert < 2.5$ and $p_T > 15$ GeV $p_T(\ell_1) > 28$ GeV, $p_T(\ell_2) > 25$ GeV, $p_T(\ell_3) > 15$ GeV $p_T(\text{jet}) > 30$ GeV $m_T(\ell_W, \nu) > 20$ GeV			
SR	**Diboson VR / CR**	**$t\bar{t}$ VR**	**$t\bar{t}$ CR**
≥ 1 OSSF Pair	≥ 1 OSSF Pair	≥ 1 OSSF Pair	≥ 1 OSOF Pair
$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert < 10$ GeV	$\lvert m_{\ell\ell} - m_Z\rvert > 10$ GeV	—
$= 2$ jets, $\lvert\eta\rvert < 4.5$	$= 1$ jet, $\lvert\eta\rvert < 4.5$	$= 2$ jets, $\lvert\eta\rvert < 4.5$	$= 2$ jets, $\lvert\eta\rvert < 4.5$
$= 1$ b-jet, $\lvert\eta\rvert < 2.5$	—	$= 1$ b-jet, $\lvert\eta\rvert < 2.5$	$= 1$ b-jet, $\lvert\eta\rvert < 2.5$
—	VR/CR: $m_T(\ell_W, \nu) > 20/60$ GeV	—	—



Diboson

- Use $m_T(W)$ distribution to determine scale factor





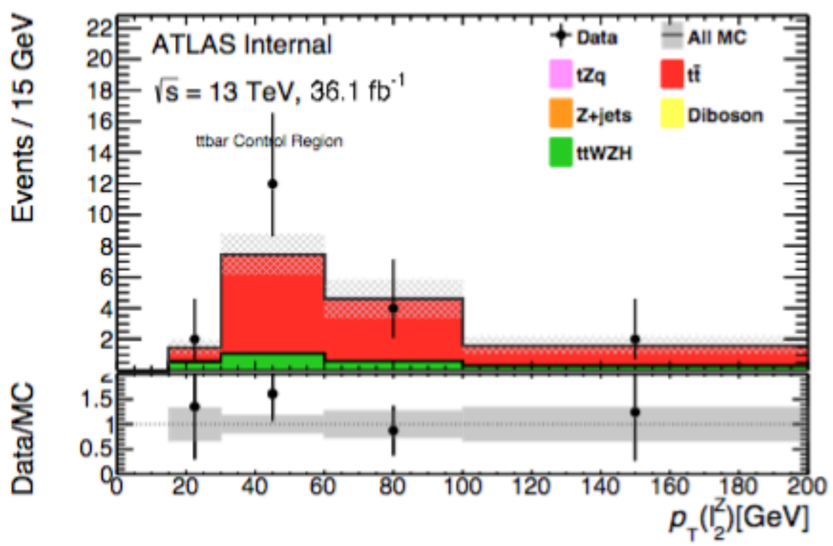
- Uncertainty on scale factor from:
  - variation of the requirement on $m_T(W)$
  - difference in SR between Sherpa and Powheg normalisations.

SF: 1.5 ± 0.4

from I.Cioara

Estimating the $t\bar{t}$ background

- Derive data/MC scale factor in a $t\bar{t}$ enriched region and apply it to the signal region



- $t\bar{t}$ fake leptons control region definition
  - 1 OSOF lepton pair (no OSSF pair allowed)
  - all other cuts identical to the SR
  - region is $t\bar{t}$ dominated (~80%) with no Z+jets contamination

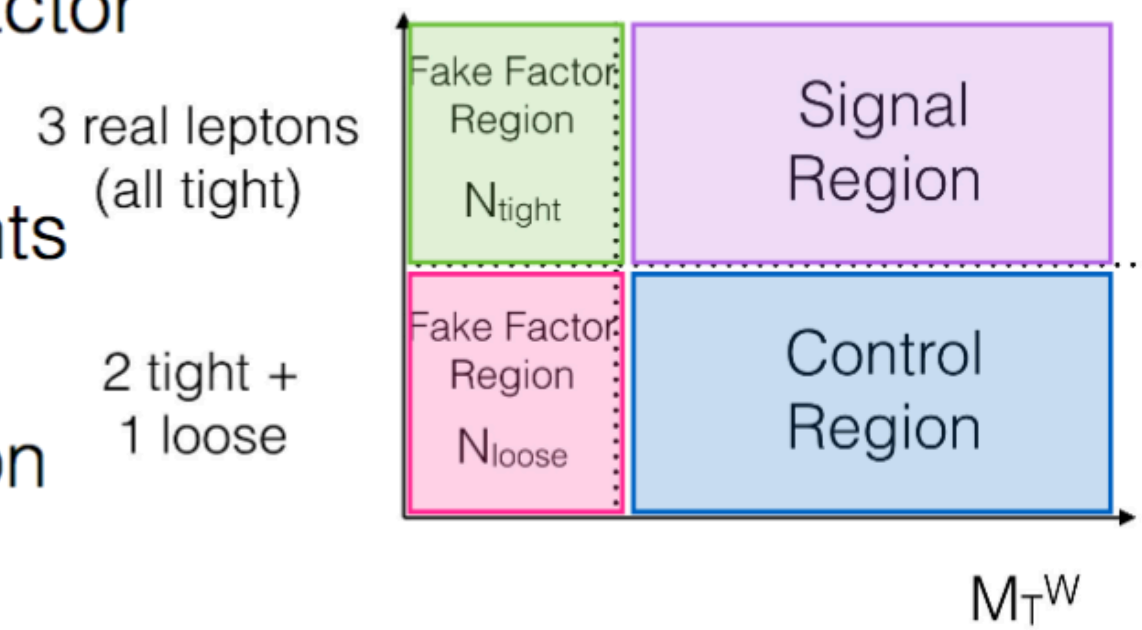
- Uncertainty on scale factor:
  - variation of the m_{ll} requirement
  - statistical uncertainty of the sample

$$SF_{\text{data/MC}} = \frac{N_{\text{data}} - N_{\text{MC}}^{\text{all-}t\bar{t}}}{N_{\text{MC}}^{t\bar{t}}}$$

SF: 1.21 ± 0.51

Z+jets fake background estimation

- data-driven method using fake factor method
- separate factors derived for events with a fake muon and electron
- contributions with three real lepton backgrounds subtracted



$$F = \frac{N^{FF}_{\mathrm{tight}}}{N^{FF}_{\mathrm{loose}}}$$

N^{FF}_{tight}: Number of events with 3 tight leptons in fake factor region

N^{FF}_{loose}: Number of events with exactly 1 loose-not-tight lepton in fake factor region

$$F \times N^{CR}_{\mathrm{loose}} = N^{SR}$$

N^{SR}: Number of *Z*+jets estimated events in the SR

N^{CR}_{loose}: Number of events with exactly1 loose-not-tight lepton in control region

Z+jets Estimation

- Fake factors are derived in bins of p_T of the lepton not associated to the *Z* boson
- Total number of *Z*+jets events: 36.9 ± 3.0
- Different sources of uncertainties investigated:
  - MC closure test
  - statistical uncertainties
  - change in diboson contribution
- Final assigned uncertainty, covering all these effects: 40%