# Single Top-Quark Production Cross-Section and Properties using the ATLAS detector at the LHC

**QCD@LHC 2016 | Zurich • August 22, 2016**

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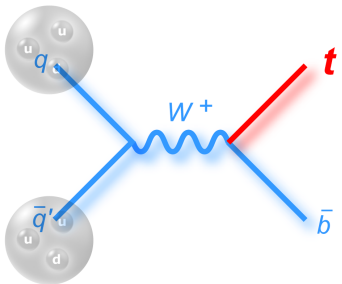
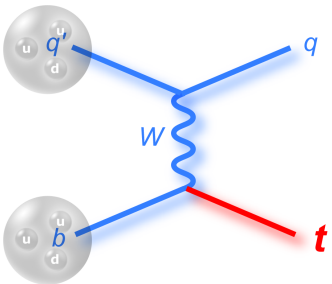
# Introduction



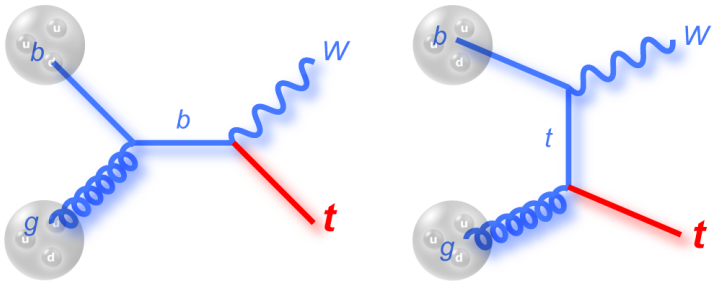
## Single top-quark production in LO: (exemplary)




*s*-channel



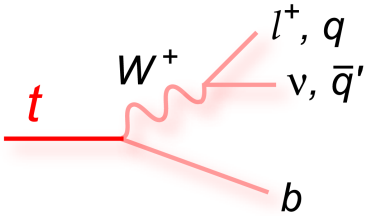

*t*-channel




associated Wt production

## Top quark decay:

- Almost all top quarks decay in b and W
- W decay either leptonically or hadronically ($\mathcal{BR} = 32\%; 68\%$)




## Sensitivity to new physics:

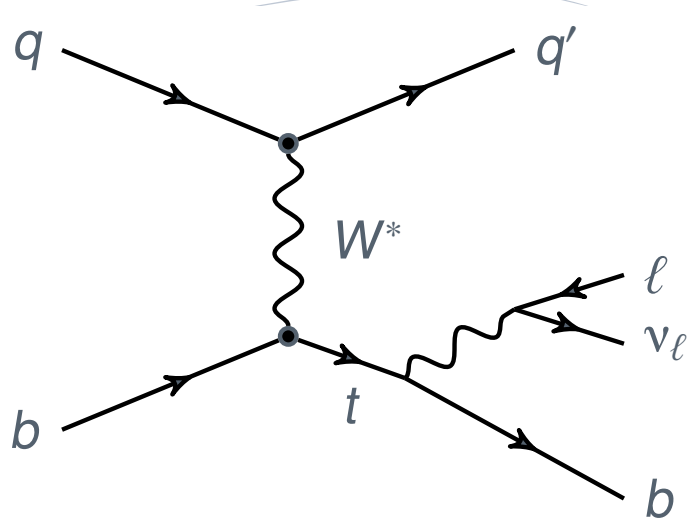
- Quark flavour mixing, $V_{tb}$
- Coupling structure at Wtb vertex
- New interactions (W′, b*, . . . ), FCNCs

## Signature:

- Isolated lepton(s) + b-jet(s) + $\not{E}_T$ + jets
- Dominant bkgs.: $t\bar{t}$ prod., W+jets, Z+jets, multi-jet
- Large bkg. rates ➔ difficult

# Part I

## $t$-channel inclusive cross-section measurement at $\sqrt{s} = 13\,\text{TeV}$



# t-Channel Production at 13 TeV

Analysis

ATLAS-CONF-2015-079



- $t$-channel is mode with highest rate
  - $t,\bar{t}$ cross-sections, $R_t$, $V_{tb}$
  - sensitive to b/u/d PDFs

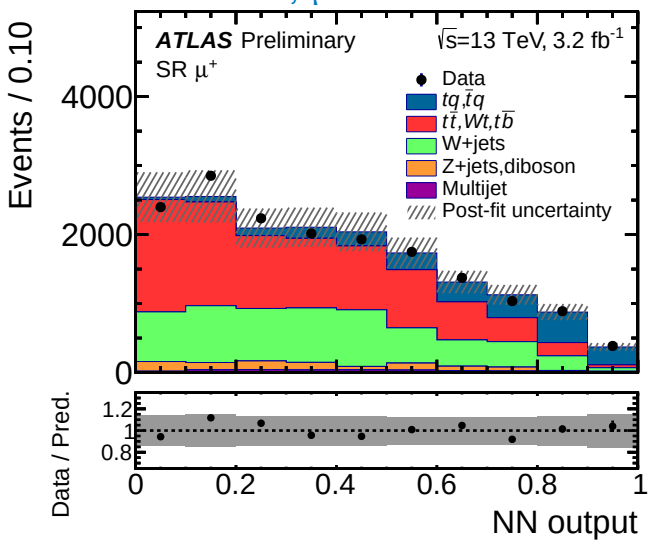
## Event selection:

- One isolated $\mu^+$ or $\mu^-$ ($p_T > 30$ GeV, $|\eta| < 2.5$)
- Two jets; at least one b-tagged ($p_T > 30$ GeV, $|\eta| < 3.5$, $|\eta_{\text{b-jet}}| < 2.5$)
- Missing transverse momentum ($E_T > 30$ GeV)
- No additional e or $\mu$ ➔ veto against $t\bar{t}$ bkg.

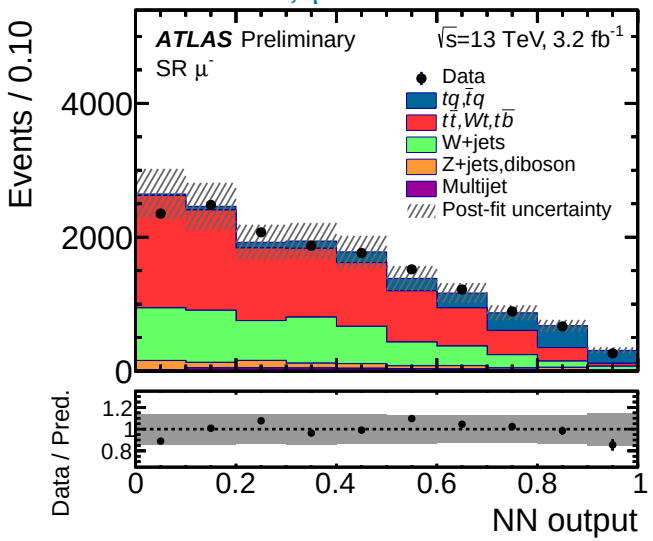
## Analysis method:

- Signal enrichment by Neural Network discriminant (Main NN input variables: $m(\ell\nu b)$, $m(jb)$, $M_T(W)$, $|\eta(j)|$, ...)
- Obtain signal strength by ML fit of signal and bkg. templates of the NN discriminant

NN discriminant, $\mu^+$




NN discriminant, $\mu^-$



# t-Channel Production at 13 TeV

Results

ATLAS-CONF-2015-079



## Cross-section measurement:

Top:

$$\sigma(tq) = 133 \pm 6(\text{stat.}) \pm 24(\text{syst.}) \pm 7(\text{lum.})\,\text{pb} = 133 \pm 25\,\text{pb} \qquad \frac{\Delta\sigma}{\sigma} = 19\%$$

$$\sigma(tq) = (0.98 \pm 0.05) \cdot \sigma^{\text{th}}(tq)\ @\text{NLO}$$

Antitop:

$$\sigma(\bar{t}q) = 96 \pm 5(\text{stat.}) \pm 23(\text{syst.}) \pm 5(\text{lum.})\,\text{pb} = 96 \pm 24\,\text{pb} \qquad \frac{\Delta\sigma}{\sigma} = 25\%$$

$$\sigma(\bar{t}q) = (1.18 \pm 0.06) \cdot \sigma^{\text{th}}(\bar{t}q)\ @\text{NLO}$$

Both:

$$\sigma(tq + \bar{t}q) = 229 \pm 48\,\text{pb} \qquad \frac{\Delta\sigma}{\sigma} = 21\%$$

| Uncertainty | $\frac{\Delta\sigma_s(tq)}{\sigma_s(tq)}$ [%] | $\frac{\Delta\sigma_s(\bar{t}q)}{\sigma_s(\bar{t}q)}$ [%] |
|---|---|---|
| Data statistics | 4.6 | 5.0 |
| MC statistics | 6.3 | 6.5 |
| *t*-channel generator | 11 | 15 |
| b-tagging | 7.1 | 7.5 |
| *t*-channel scale variations | 5.9 | 7.7 |
| Other | $<6$ each | $\leq 7$ each |
| **Total** | **19** | **25** |

← main unc.

## $V_{tb}$ measurement:

Assume $|V_{tb}| \gg |V_{ts}|, |V_{td}|$

$\Rightarrow |f_{LV} V_{tb}|^2 = \sigma^{obs}/\sigma^{th}$

- Unitarity **not** assumed

  $|f_{LV} V_{tb}| = 1.03 \pm 0.11$

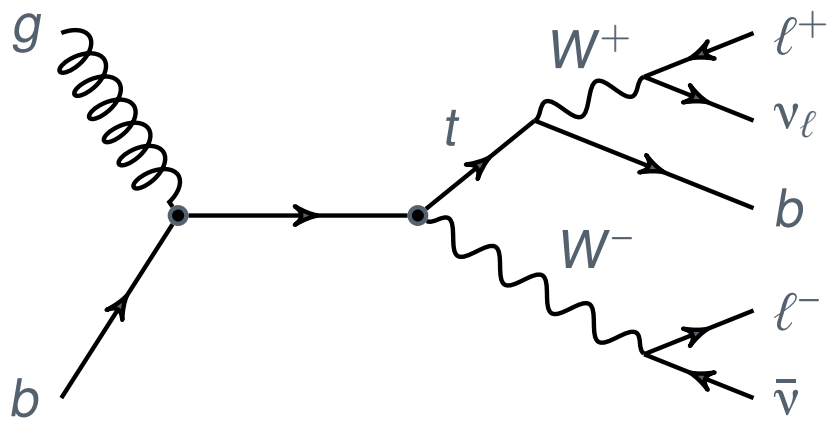
- Unitarity assumed; $f_{LV} = 1$

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

**→ Agreement with SM**

# Part II

## Associated Wt production at $\sqrt{s} = 13\,\text{TeV}$

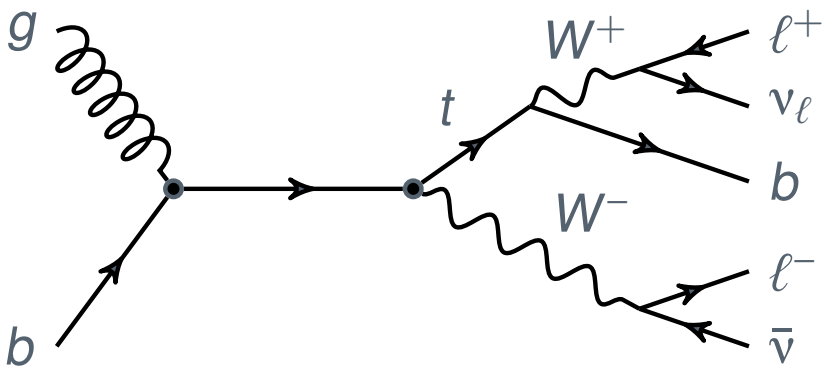


# Wt Production at 13 TeV

Inclusive cross-section measurement

ATLAS-CONF-2016-065



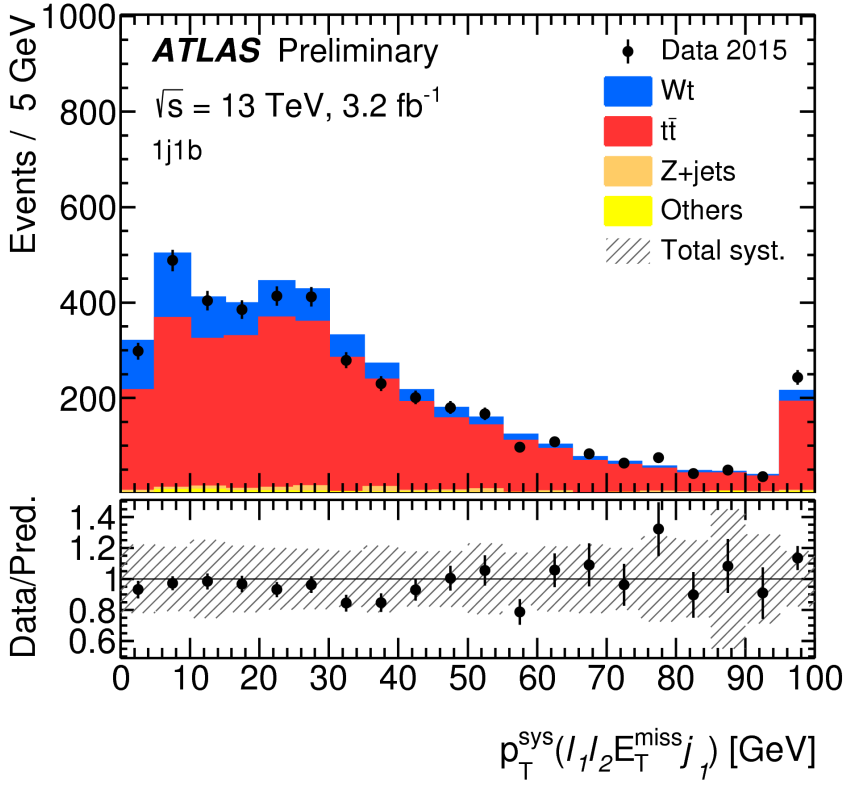



**Dilepton channel:**

- Two isolated leptons (e/μ)
- One or two jets; one or two b-tags
  - ⇒ 3 regions: 1j1b, 2j1b, 2j2b
- Missing transverse momentum
- Optimised cuts to reduce Z + jets background
- Multivariate analysis using Boosted Decision Trees (BDT)
- Profile ML fit of signal & bkg. templates

- Associated production of t and W
  - Interference with $t\bar{t}$ production (small within detector acceptance)

1 jet & 1 b-tag region

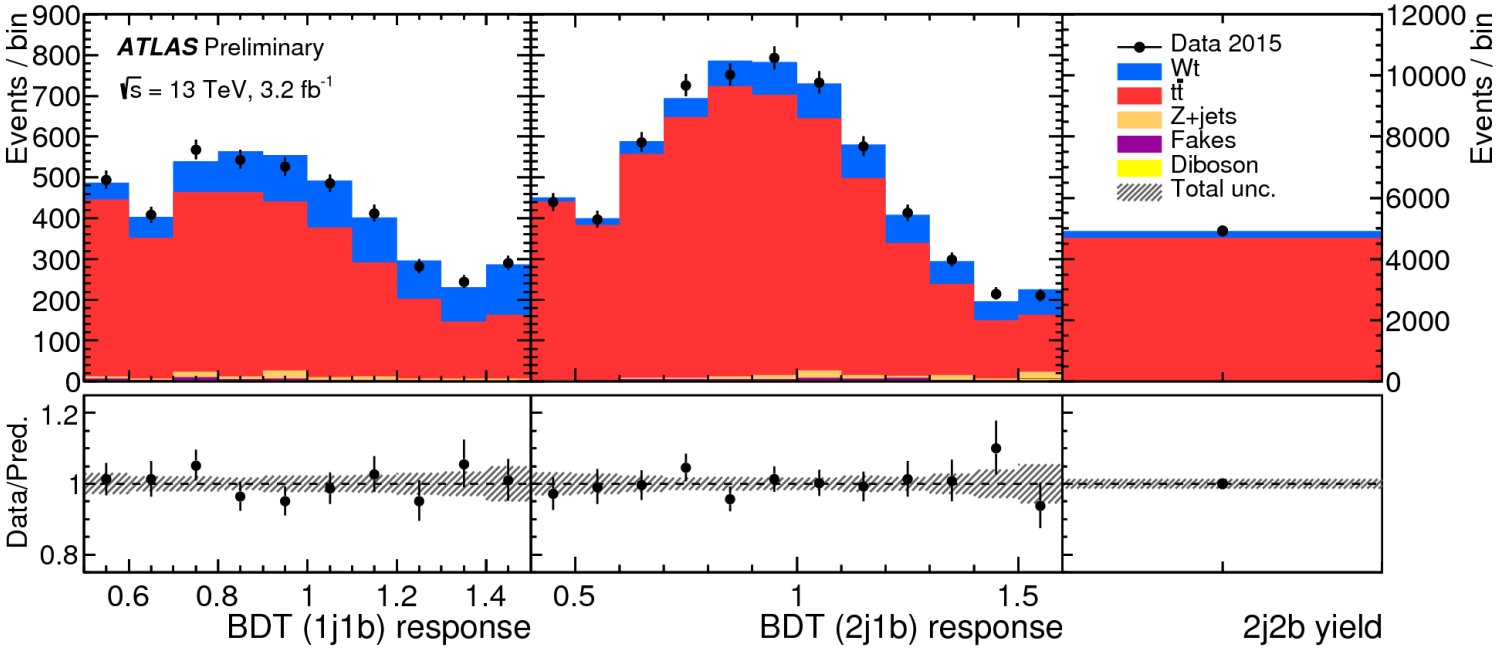


# Wt Production at 13 TeV

## Inclusive cross-section measurement

ATLAS-CONF-2016-065






## Results:

$$\sigma_{Wt} = 94 \pm 10(\text{stat.})^{+28}_{-23}(\text{syst.})\ \text{pb} \qquad \Delta\sigma/\sigma = ^{+32}_{-27}\ \%$$

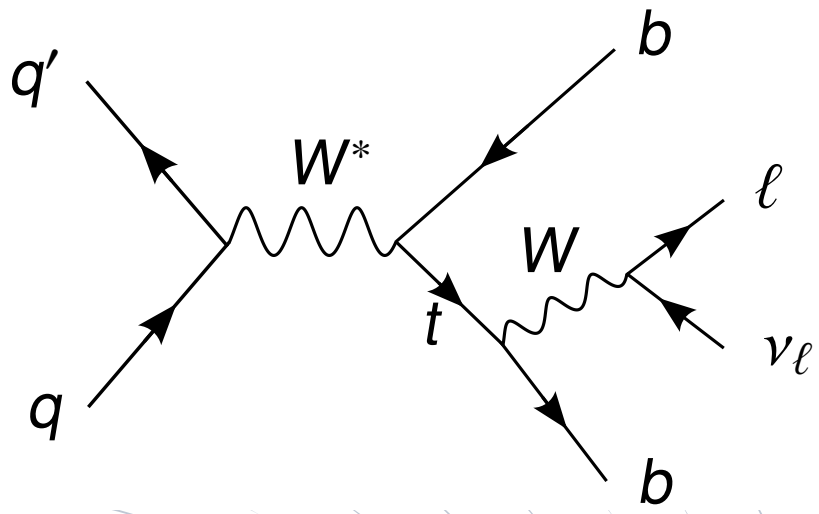
$$\sigma_{Wt} = 1.32^{+0.32}_{-0.27} \cdot \sigma^{\text{th}}_{Wt}(\text{NLO+NNLL})$$

Significance = 4.5 $\sigma$

| Uncertainty | $\Delta\sigma_{Wt}/\sigma_{Wt}$ [%] |
|---|---|
| Statistical | ±10 |
| Jet energy scale | ±21 |
| NLO ME generator | ±18 |
| Jet energy resolution | ±8.6 |
| Other | ≤ ±7 each |
| **Total** | ±31 |

# Part III

## Evidence for $s$-channel single top-quark production at $\sqrt{s} = 8$ TeV

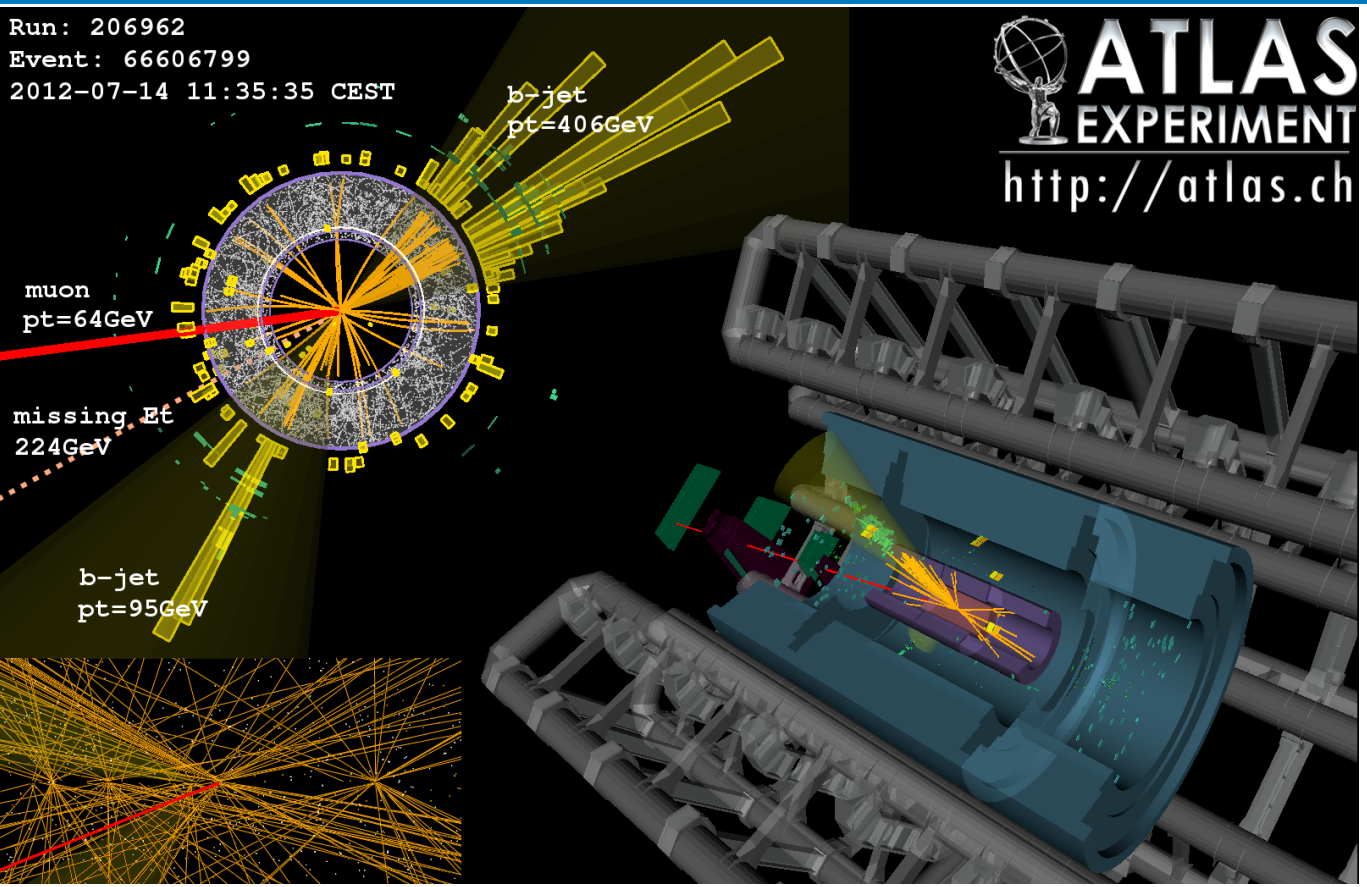


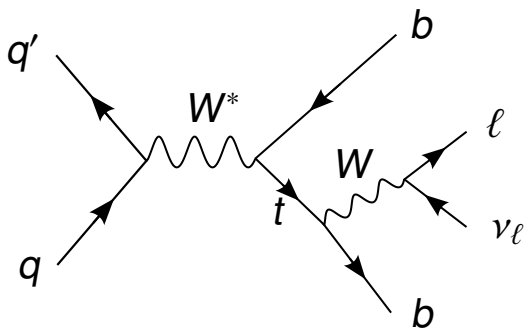
# s-Channel Production at 8 TeV

## Event selection

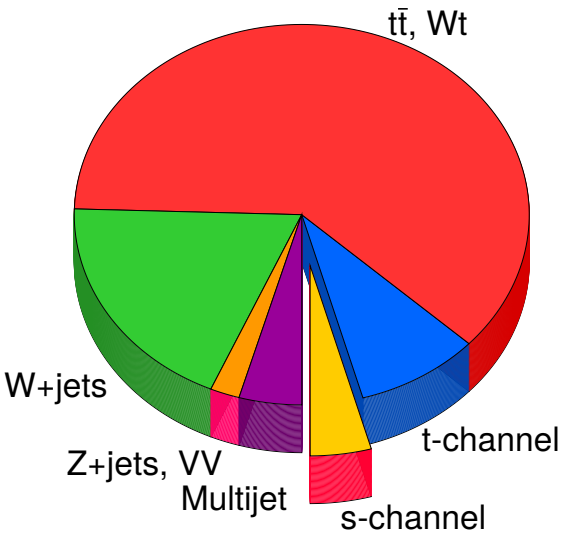
PLB 756 (2016)






s-channel production




- One isolated electron or muon ($p_T > 30$ GeV, $|\eta| < 2.5$)
- Two b-tagged jets ($p_{t,1} > 40$ GeV, $p_{t,2} > 30$ GeV, $|\eta| < 2.5$)
- Missing transverse momentum ($\not{E}_T > 35$ GeV)
- No additional e or μ ➔ veto against $t\bar{t}$ bkg.

#Events in the signal region:
$\Sigma = 14.000$ ($\mathcal{L} = 20.3\,\text{fb}^{-1}$)

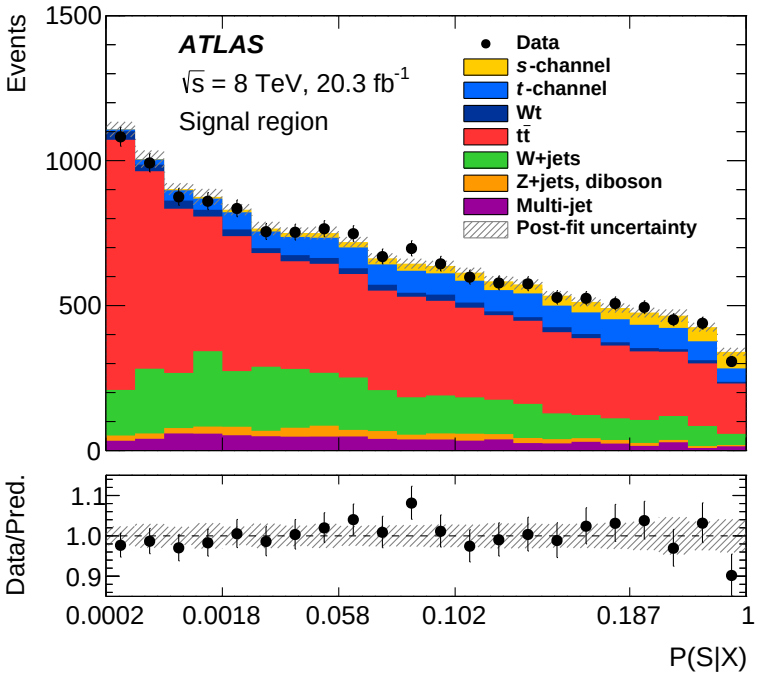
# s-Channel Production at 8 TeV

## Signal discriminant distribution

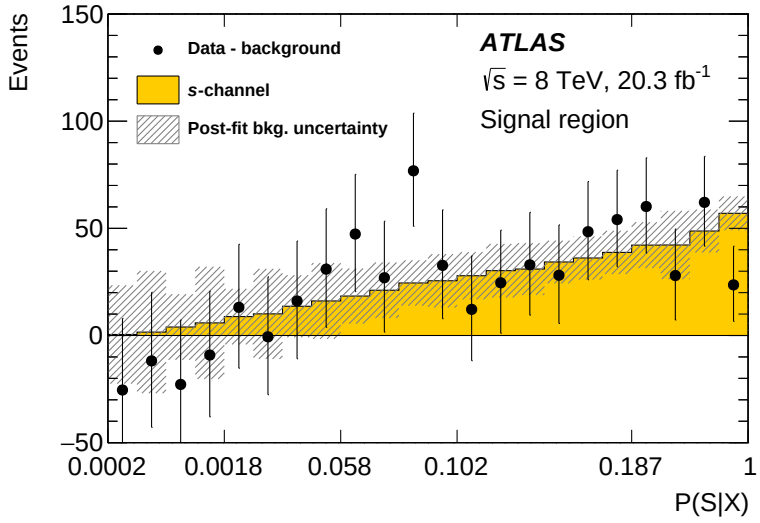
PLB 756 (2016)



- Use Matrix Element Method to separate signal from the main bkgs.
- Compute signal probability $P(S|X)$ for each selected event $X$




Discriminate *s*-channel against *t*-channel, $t\bar{t}$ (single-lepton | dilepton) and W+jets




➔ Clear separation between signal and bkg. processes

➔ Allows *s*-channel cross-section measurement

- Profile likelihood fit of signal and bkg. templates of the $P(S|X)$ discriminant to extract the signal strength

# s-Channel Production at 8 TeV

Results

PLB 756 (2016)



## Cross-section measurement:

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

$\Delta\sigma/\sigma = 34\%$, $\sigma_s = 0.86^{+0.31}_{-0.28} \cdot \sigma_s^{\text{th}}(\text{NLO+NNLL})$

- Observed significance $3.2\sigma$

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

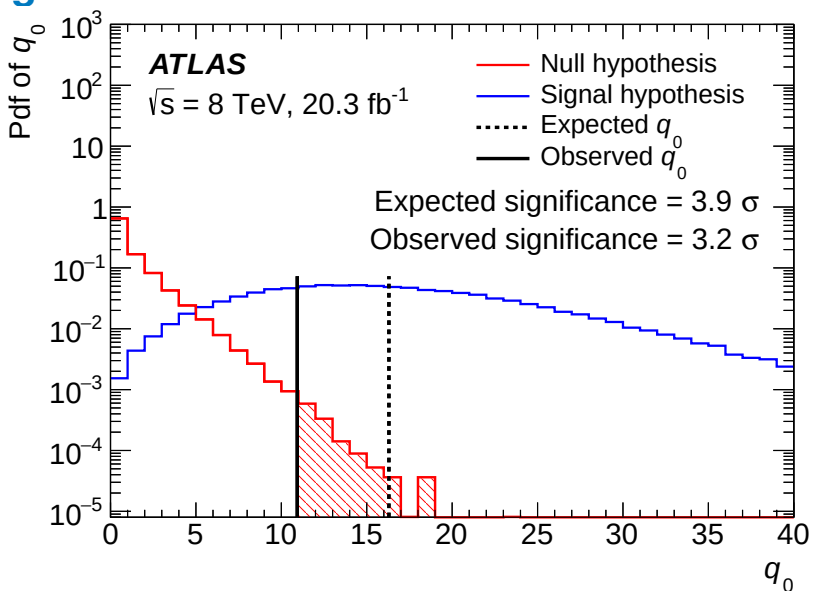
$|V_{\text{tb}}| > 0.5$ @95% CL

| Uncertainty | $\Delta\sigma_s/\sigma_s$ [%] |
|---|---|
| Data statistics | 16 |
| MC statistics | 12 |
| Jet energy resolution | 12 |
| $t$-channel generator | 11 |
| Other | $<10$ each |
| **Total** | **34** |

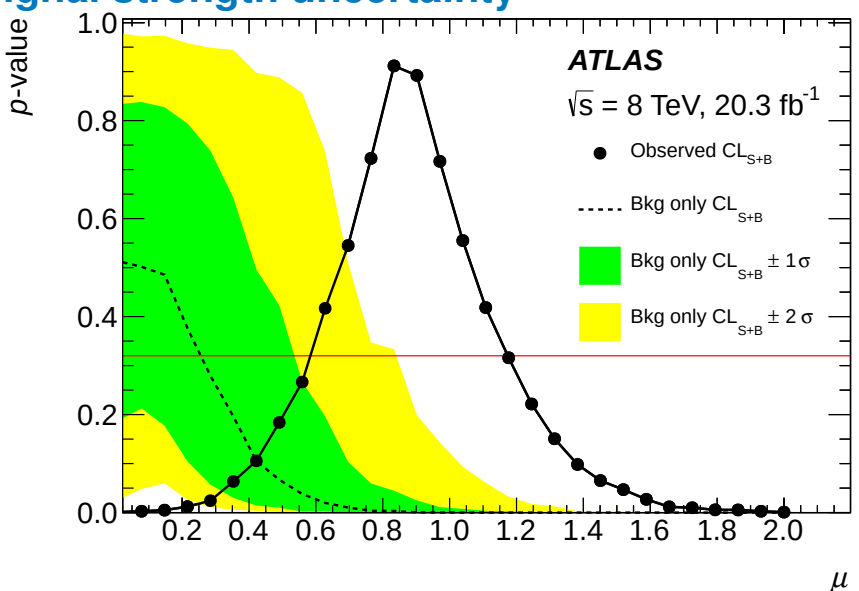
statistically limited

First evidence for single top $s$-channel production at the LHC

### Significance determination

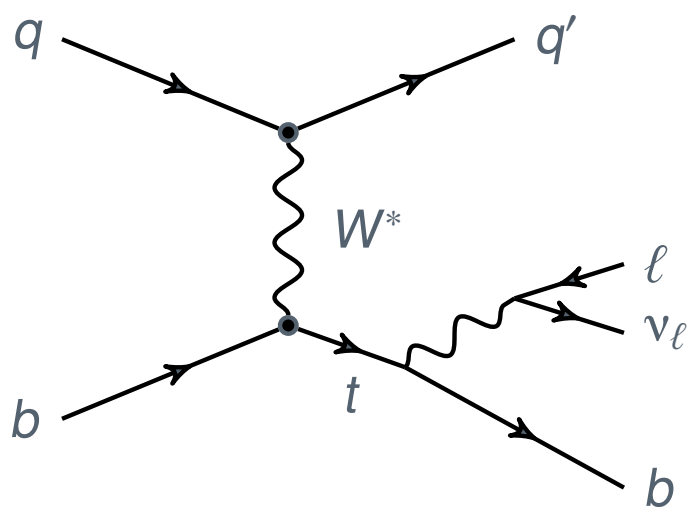



### Signal strength uncertainty



# Part IV

## Search for anomalous Wtb couplings in $t$-channel events at $\sqrt{s} = 7$ TeV



# Search for Anomalous Wtb Couplings

Analysis

JHEP 04 (2016) 023



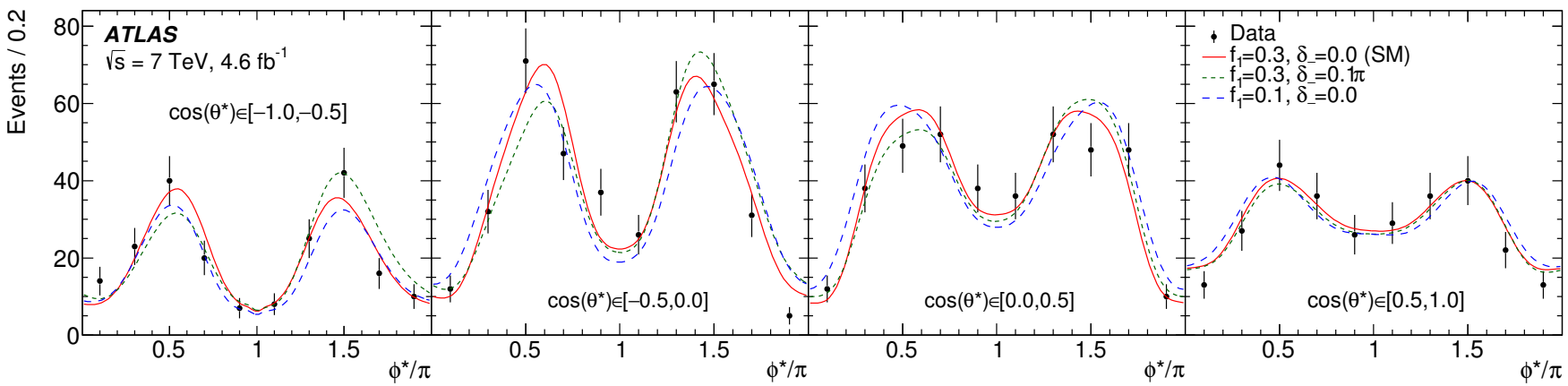
- Select a rather pure $t$-channel sample (signal enrichment of $\approx 50\%$)
- Make use of the generalized structure of the Wtb vertex

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

(Anomalous couplings in the SM: $V_L = V_{tb}$, $V_R = g_L = g_R = 0$)

- Construct 2-dim. decay angle distribution $\rho(\theta^*, \phi^*)$ for the charged lepton from the Wtb decay (in convenient basis)
- Fold detector effects analytically into $\rho(\theta^*, \phi^*)$ (use spherical harmonics)
- $\rho(\theta^*, \phi^*)$ depends on $f_1$ and $\delta_-$

  $f_1$ = fraction of transv. polarized decaying Ws
  $\delta_-$ = phase between ampl. for long. and transv. polarized Ws
  } related to $V_L$ and $g_R$



# Search for Anomalous Wtb Couplings

Results

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- Determine $f_1$ and $\delta_-$ from unbinned ML fit of all selected events to 2-dim. angular distribution $\rho(\theta^*, \phi^*)$
- Express $f_1$, $\delta_-$ into terms of anomalous couplings $V_L$ and $g_R$

## Measurement:

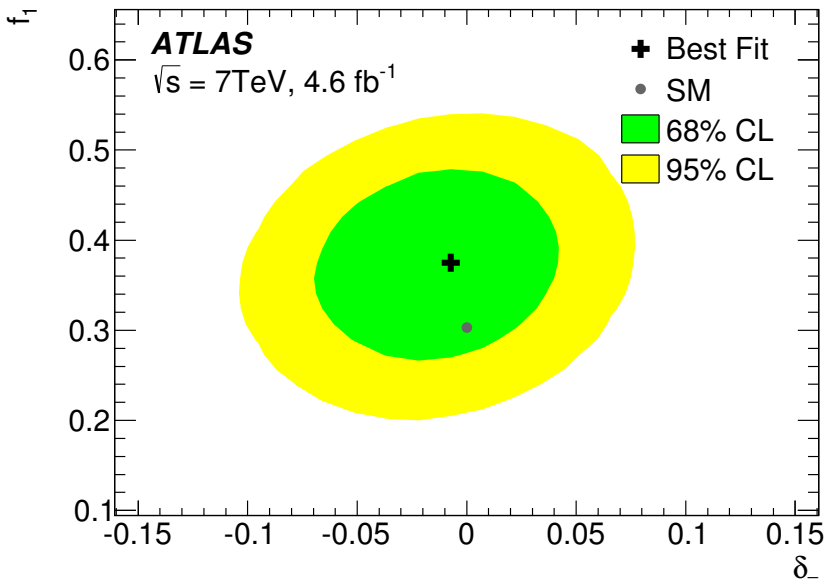
$f_1 = 0.37 \pm 0.05(\text{stat.}) \pm 0.05(\text{syst.})$

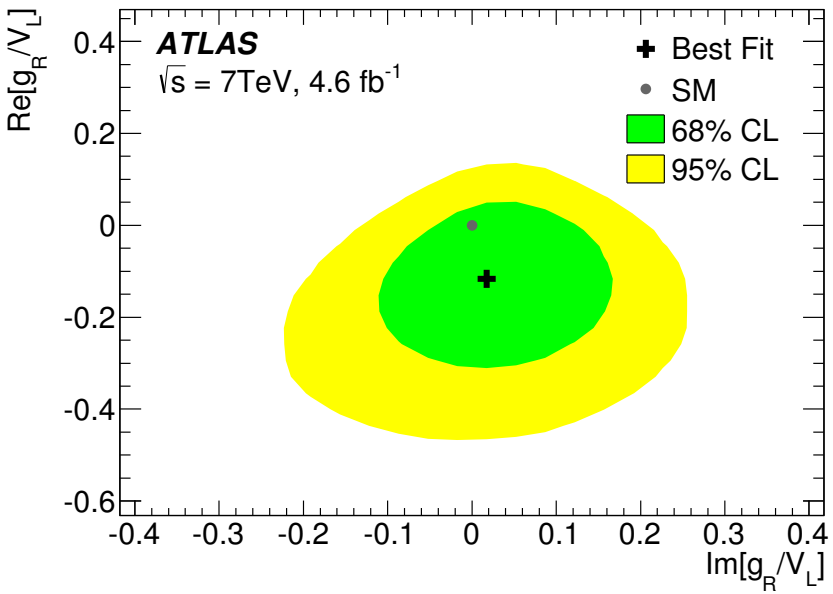
$\delta_- = -0.014\pi \pm 0.023\pi(\text{stat.}) \pm 0.028\pi(\text{syst.})$

## At 95% CL:

$\text{Re}\,[g_R/V_L] \in [-0.36, 0.10]$

$\text{Im}\,[g_R/V_L] \in [-0.17, 0.23]$




- First simultaneous measurement of $\text{Re}\,[g_R/V_L]$ and $\text{Im}\,[g_R/V_L]$

  No need to assume $V_L = 1$ and $\text{Im}[g_R] = 0$ as in other analyses (eg. W helicity fract. in $t\bar{t}$)

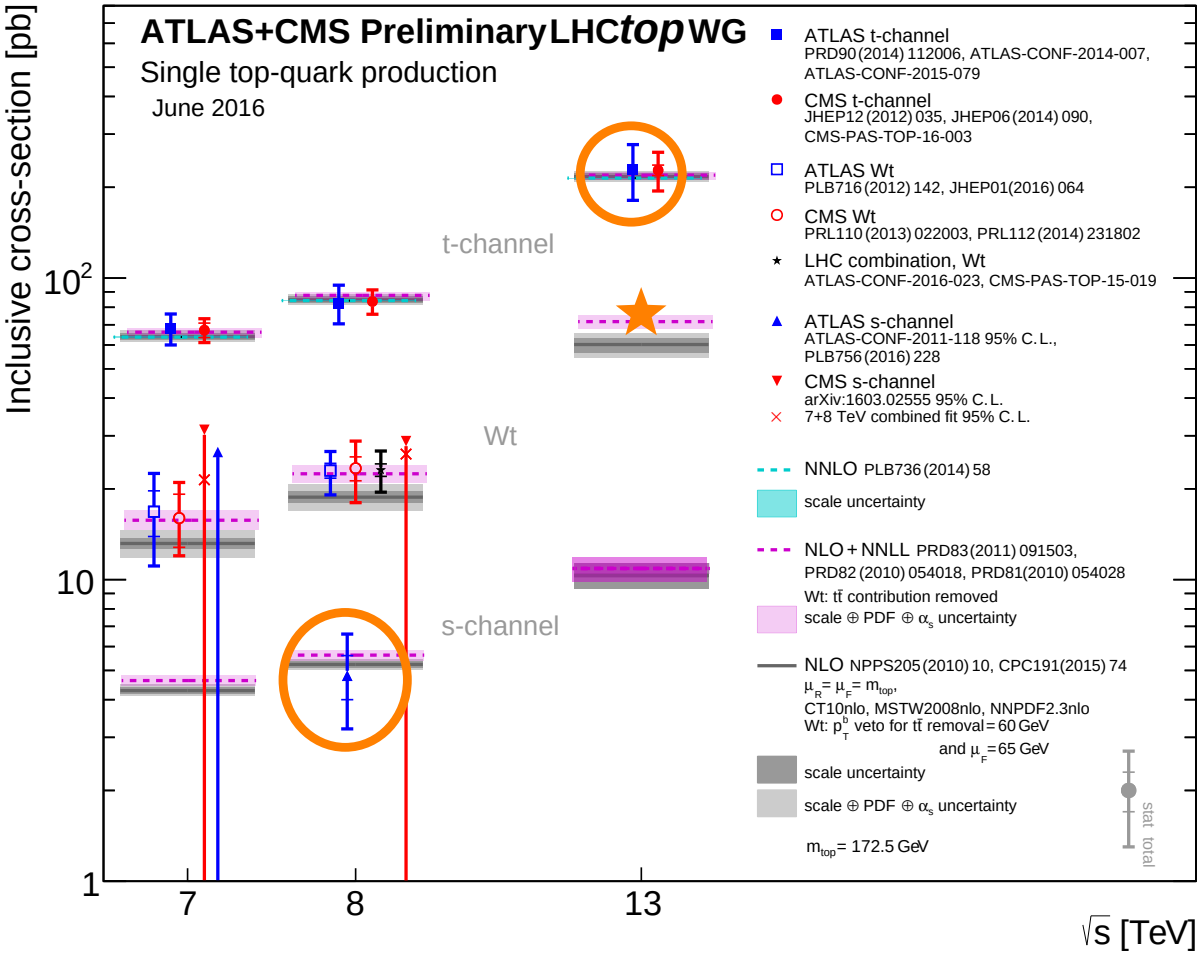
# Summary



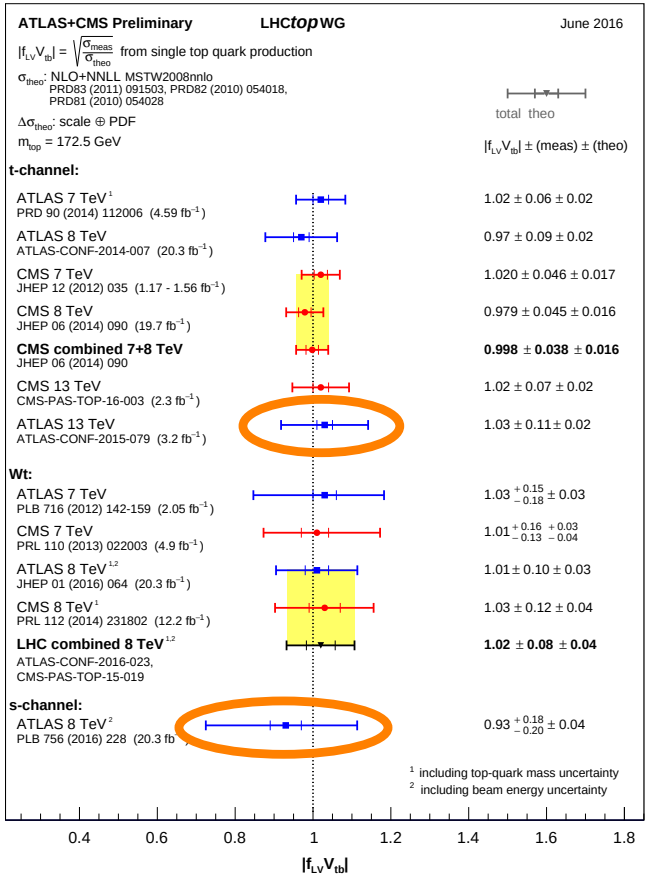
- First Evidence for the *s*-channel at the LHC
  - Statistically limited ( $\sqrt{s}=8$ TeV , $\mathcal{L}=20.3\,\text{fb}^{-1}$ )
  - Analysis will benefit from Run-II data
- First results for Run-II data at $\sqrt{s}=13$ TeV
  - Presented cross-section measurements for single-top *t*-channel production and assoc. Wt production
  - Main uncertainties: modelling, jet energy scale
- Search for anomalous couplings at $\sqrt{s}=7$ TeV
  - Analysis of double differential angular decay rates
- Everything is in agreement with the Standard Model

# Summary






## $V_{tb}$ measurements



# Part VI

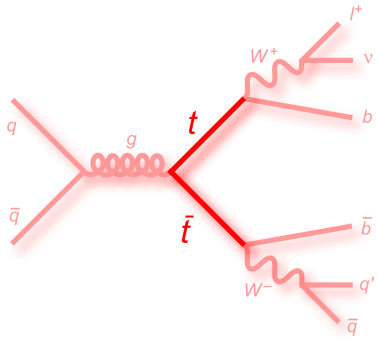
# Appendix

# Background Processes

## Single-Top production

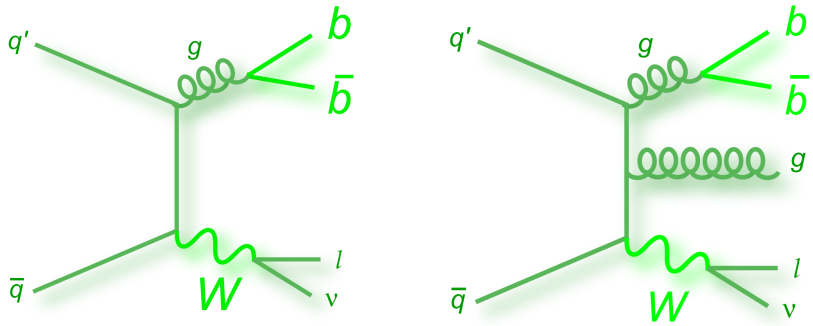


### Top-quark pair production:



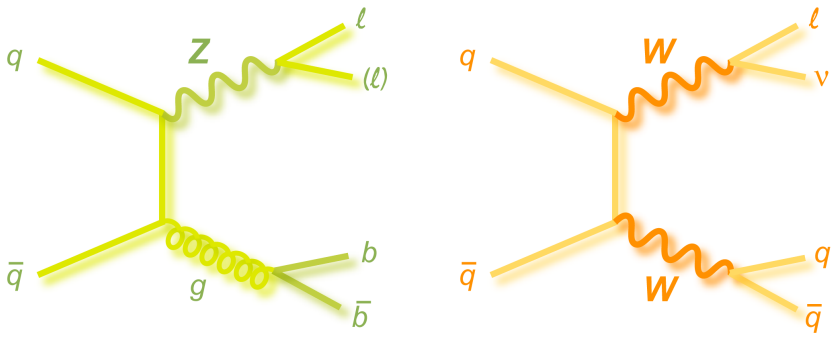

- Shape and normalization from MC simulation

### W+jets:



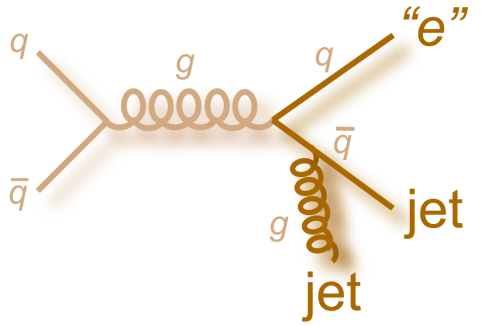

- Shape from MC simulation; normalization from dedicated control regions

### Z+jets & WW/WZ/ZZ production:




- Shape and normalization from MC simulation

### Multi-jet ("lepton fakes"):

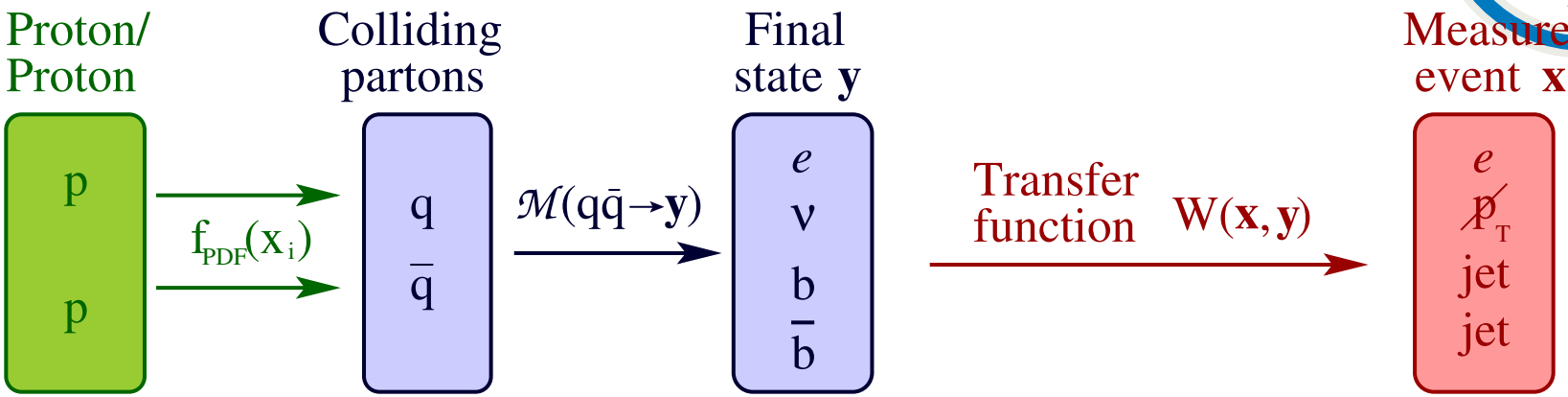



- Normalization from real data; shape (sometimes) from simulation

# The Matrix Element Method

## Computation of event likelihoods






$$\mathcal{P}(\mathbf{X}|H) = \frac{1}{\sigma\epsilon} \sum_{p \in \{\text{perms}\}} \int dx_1 dx_2 \sum_{i,j} f_i(x_1) f_j(x_2) \cdot \int d\mathbf{y} \underbrace{\frac{\|\mathcal{M}^H_{i,j}(\mathbf{y})\|^2}{2x_1 x_2 s}}_{= d\sigma_{ij}/d\mathbf{y}} \cdot W_p(\mathbf{x}|\mathbf{y})$$

- Compute likelihood $\mathcal{P}$ for each measured event $\mathbf{X}$ to be of a certain process type $H$
- Three building blocks needed
  - Hard scattering cross-section $d\sigma_{ij}/d\mathbf{y}$
  - Transfer functions $W_p(\mathbf{x}|\mathbf{y})$
  - Phase space integration $\int d\mathbf{y}$

# Single-Top $s$-Channel Production

## ME discriminant



- Build ME discriminant for each selected event

  Discriminate $s$-channel against $t$-channel, $t\bar{t}$, W+$b\bar{b}$, W+c + jet, W+*jets* light-flavour
- Signal probability for given event X:

  (Bayes' theorem)

$$P(S|X) = \frac{\sum_S P(S)\mathcal{P}(X|S)}{\sum_S P(S)\mathcal{P}(X|S) + \sum_B P(B)\mathcal{P}(X|B)}$$

- Process likelihoods, $\mathcal{P}(X|H)$:
  - $s$-channel, 2 outgoing partons
  - $s$-channel, 3 outgoing partons
  - $t$-channel (2→3)
  - $t\bar{t}$, single lepton | di-lepton
  - W + 2 outgoing light partons
  - W + $b\bar{b}$
  - W + c + 1 outgoing parton
- P(H): *a priori* probabilities given by relative MC event yields
- Signal shape differs from background shapes

➔ signal extraction: template fit of ME discriminant distributions

# Part VII

# Associated Wt production at $\sqrt{s} = 13\,\text{TeV}$

- Summary of event selection criteria used in the analysis

| | | |
|---|---|---|
| At least one jet with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$ | | |
| Exactly two leptons of opposite charge with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ | | |
| At least one lepton with $p_{\mathrm{T}} > 25\,\mathrm{GeV}$, veto if third lepton with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ | | |
| At least one lepton matched to the trigger object | | |
| Different flavour | $E_{\mathrm{T}}^{\mathrm{miss}} > 50\,\mathrm{GeV}$, | if $m_{\ell\ell} < 80\,\mathrm{GeV}$ |
| | $E_{\mathrm{T}}^{\mathrm{miss}} > 20\,\mathrm{GeV}$, | if $m_{\ell\ell} > 80\,\mathrm{GeV}$ |
| Same flavour | $E_{\mathrm{T}}^{\mathrm{miss}} > 40\,\mathrm{GeV}$, | always |
| | veto, | if $m_{\ell\ell} < 40\,\mathrm{GeV}$ |
| | $4E_{\mathrm{T}}^{\mathrm{miss}} > 5m_{\ell\ell}$, | if $40\,\mathrm{GeV} < m_{\ell\ell} < 81\,\mathrm{GeV}$ |
| | veto, | if $81\,\mathrm{GeV} < m_{\ell\ell} < 101\,\mathrm{GeV}$ |
| | $2m_{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}} > 300\,\mathrm{GeV}$, | if $m_{\ell\ell} > 101\,\mathrm{GeV}$ |

# Part VIII

# Associated Wt production at $\sqrt{s} = 8\,\text{TeV}$

# Wt Production at 8 TeV

Inclusive cross-section measurement

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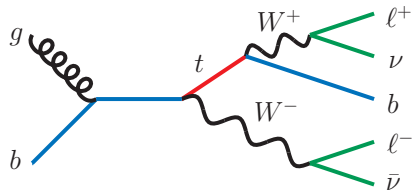
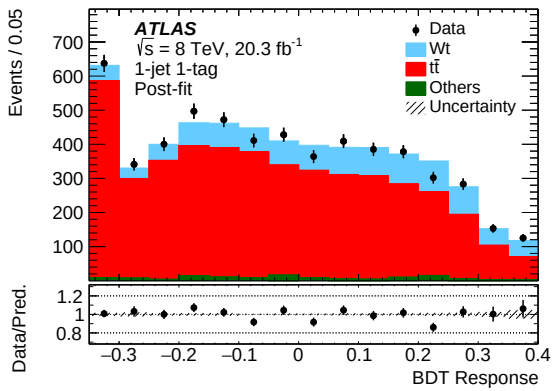
- Associated production of t and W
  - Interference with $t\bar{t}$ production (small within detector acceptance)
- Full 2012 dataset: $\sqrt{s} = 8\,\text{TeV}$, $\mathcal{L} = 20.3\,\text{fb}^{-1}$




## Dilepton channel:

- Two isolated leptons (e/μ)
- One or two jets; one or two b-tags
- Missing transverse momentum
- Multivariate analysis using Boosted Decision Trees
- Profile ML fit of signal & bkg. templates

1 jet & 1 b-tag region




## Results:

significance $= 7.7\sigma$

$$\sigma_{Wt} = 23.0 \pm 1.3(\text{stat.})^{+3.2}_{-3.5}(\text{syst.}) \pm 1.1(\text{lum.})\,\text{pb}$$

$\Delta\sigma/\sigma = ^{+16}_{-17}\,\%$ $\quad \sigma_{Wt} = 1.03^{+0.16}_{-0.17} \cdot \sigma^{\text{th}}_{Wt}(\text{NLO+NNLL})$

$|f_{LV} V_{tb}| = 1.01 \pm 0.10$ $\quad |V_{tb}| > 0.80$ @95% CL

| Uncertainty | $\Delta\sigma_{Wt}/\sigma_{Wt}$ [%] |
|---|---|
| Statistical | ±5.8 |
| ISR/FSR modelling | +8.2/− 9.4 |
| Jet reconstruction | +9.0/− 9.9 |
| $\not{E}_T$ reconstruction | ±5.5 |
| Other | < ±5 each |
| **Total** | +16/− 17 |

# Wt Production at 8 TeV

## Fiducial cross-section measurement

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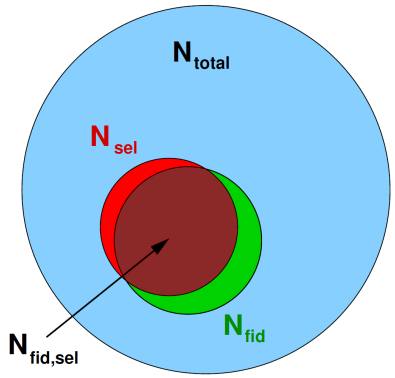
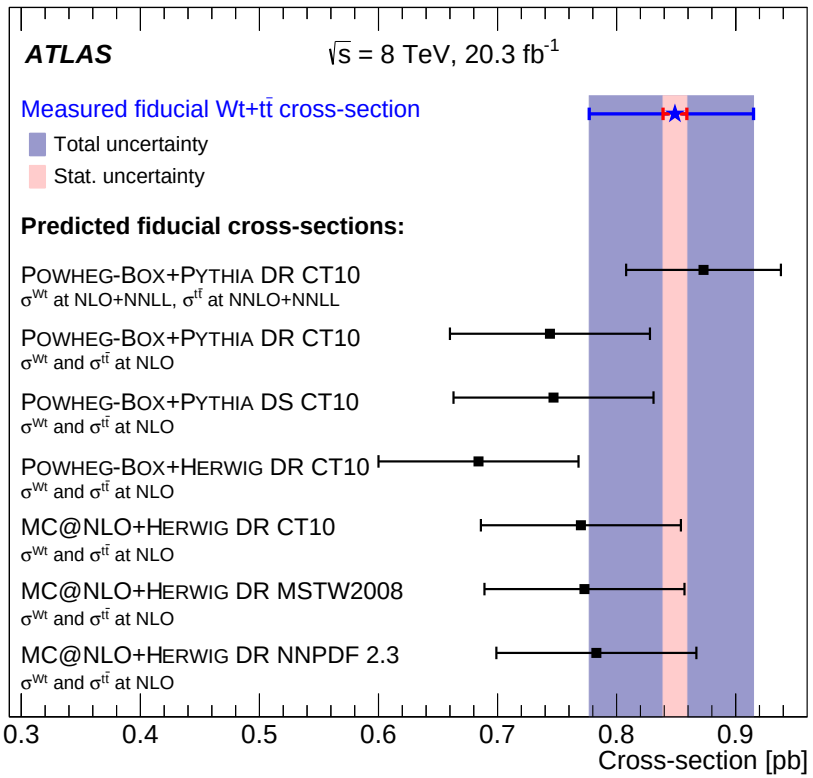
- Define fiducial volume similar to signal region

$$\sigma_{\text{inc}} = \frac{1}{\alpha_{\text{fid}}} \cdot \underbrace{\frac{N_{\text{fid}}}{N_{\text{sel}}} \cdot \frac{\hat{\nu}_{\text{sig}}}{\mathcal{L}}}_{\sigma_{\text{fid}}}$$

  ➔ Cancellation of several uncertainties
  ➔ No extrapolation to full phase-space needed
  ➔ Less sensitive to modelling uncertainties

- Fiducial selection at particle level
- Here: signal consists of Wt and $t\bar{t}$ contributions
- Exactly two leptons ($p_T > 25$ GeV, $|\eta| < 2.5$)
- Use 1 jet & 1 b-tag region only
  ($p_T > 20$ GeV, $|\eta| < 2.5$, $\not{E}_T > 20$ GeV)




## Result:

$$\sigma^{\text{fid}}_{\text{Wt}+t\bar{t}} = 0.85 \pm 0.01(\text{stat.})^{+0.06}_{-0.07}(\text{syst.}) \pm 0.03(\text{lum.})\ \text{pb}$$

$$\Delta\sigma_{\text{Wt}+t\bar{t}}/\sigma_{\text{Wt}+t\bar{t}} = 8.5\%$$

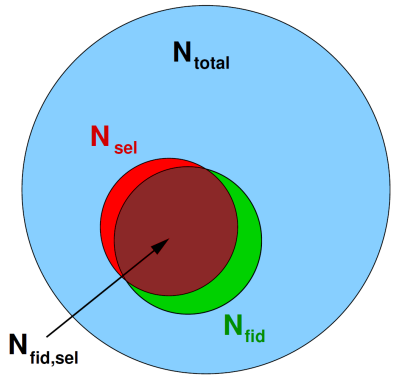
# Wt Production at 8 TeV

## Fiducial selection



- Define fiducial volume similar to signal region

$$\sigma_{\text{inc}} = \frac{1}{\alpha_{\text{fid}}} \cdot \underbrace{\frac{N_{\text{fid}}}{N_{\text{sel}}} \cdot \frac{\hat{\nu}_{\text{sig}}}{\mathcal{L}}}_{\sigma_{\text{fid}}}$$




### Object selection at particle level:

- Stable particles ($\tau > 0.3 \cdot 10^{-10}$ s)
- Electrons and muons from W decays (directly or via τ decays)
  - $p_{\text{T}} > 25$ GeV, $|\eta| < 2.5$
  - Correct for photons inside $\Delta R = 0.1$
- Particle jets using anti-$k_T$ with $R = 0.4$
  - $p_{\text{T}} > 20$ GeV, $|\eta| < 2.5$
  - Exclude ν, leptons from W decays and pile-up from clustering
  - Include underlying event particles
  - Jet ↔ lepton overlap removal
- Compute $\not{E}_{\text{T}}$ from ν of W decay

### Fiducial event selection:

- Exactly 2 leptons
- Exactly 1 b-jet
- $\not{E}_{\text{T}} > 20$ GeV

### At detector level:

| | in-fid. | out-fid. |
|---|---|---|
| Wt | 25% | 10% |
| $t\bar{t}$ | 75% | 90% |