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ATLAS

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$t\bar{t}$ cross-section measurements in ATLAS

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on behalf of the ATLAS Collaboration

top 2016
OLOMOUC, CZECH REPUBLIC
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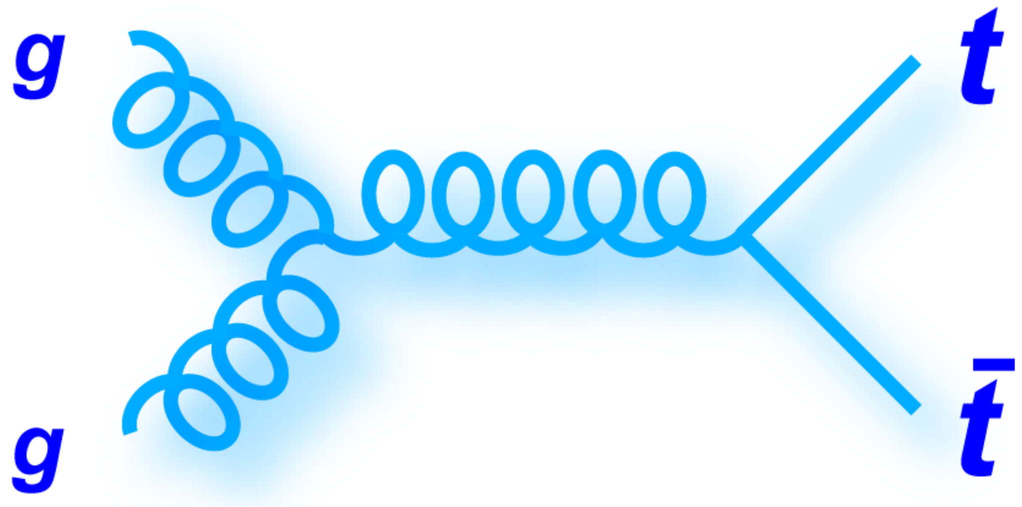
19 - 23 September 2016

Introduction



- Measurement of the ttbar cross-section is important:
    - Test the SM QCD predictions
    - Constrain new physics
    - Improve modelling and parameters in MC generator
        - Of particular interest for searches like *ttH*
    - Sensitive to PDF
        - Especially high x gluon

Outline

13 TeV analyses	
• dilepton *eμ* + *b*-tagged jets - published on PLB	Phys. Lett. B761 (2016) 136
• dilepton same flavour (ee/μμ channels) • lepton+jets channel	ATLAS-CONF-2015-049

8 TeV analyses	
• dilepton *eμ* + *b*-tagged jets - published on EPJC	Eur.Phys.J. C74 (2014) 3109
• lepton+jets channel (fit-based) - published on PRD	Phys. Rev. D 91, 112013 (2015)

$e\mu$ + *b*-tagged jets @ 13 TeV

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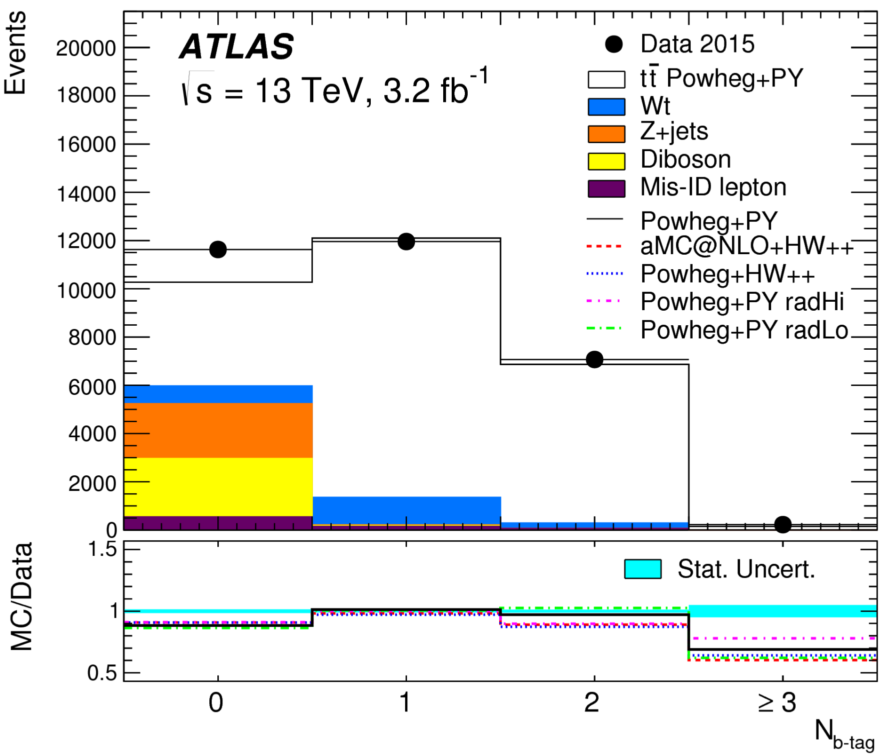

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- Extract the x-sec from the following equations

$$N_1 = L\sigma_{t\bar{t}}\,\epsilon_{e\mu} 2\epsilon_b(1 - C_b\epsilon_b) + N_1^{\rm bkg}$$
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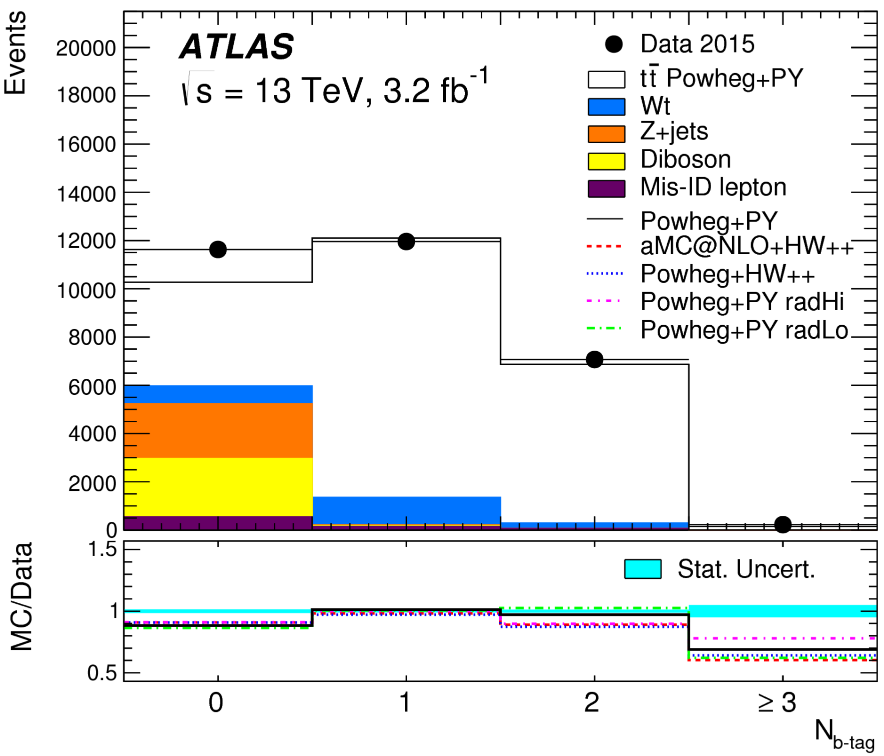

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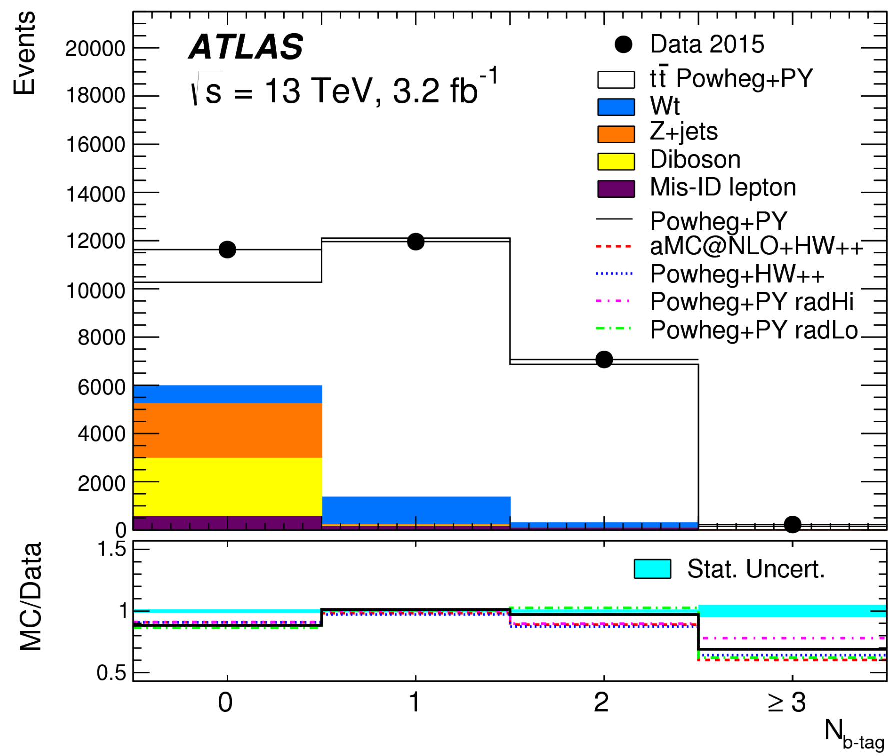

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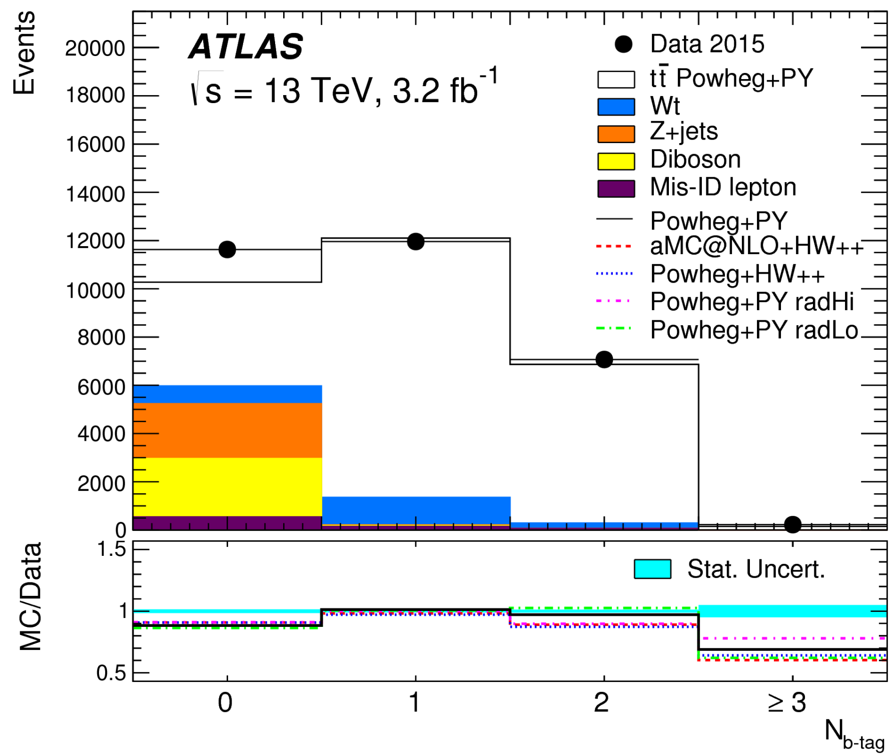

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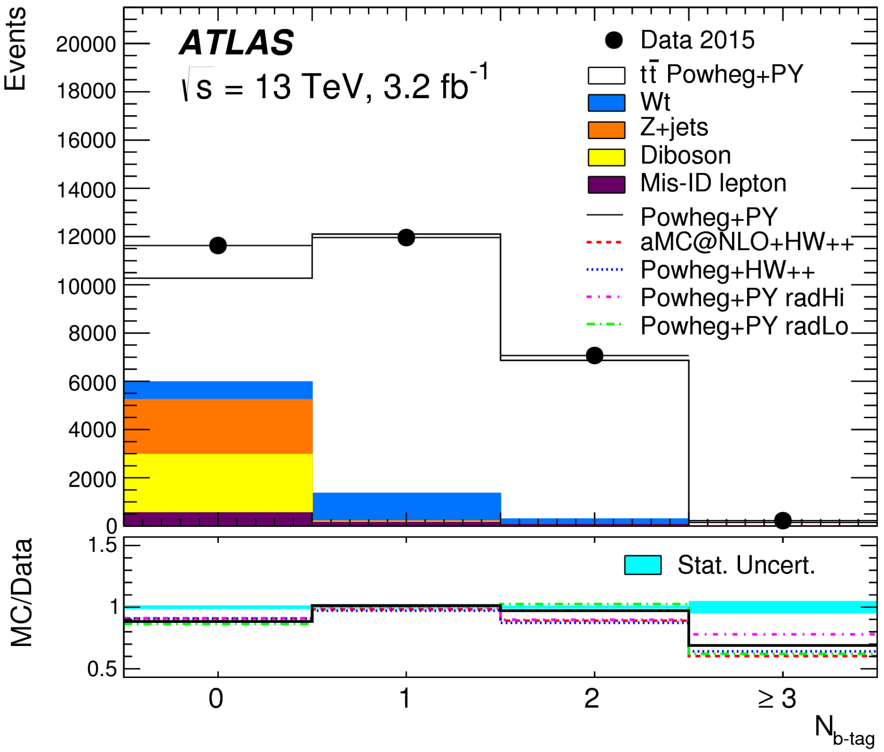

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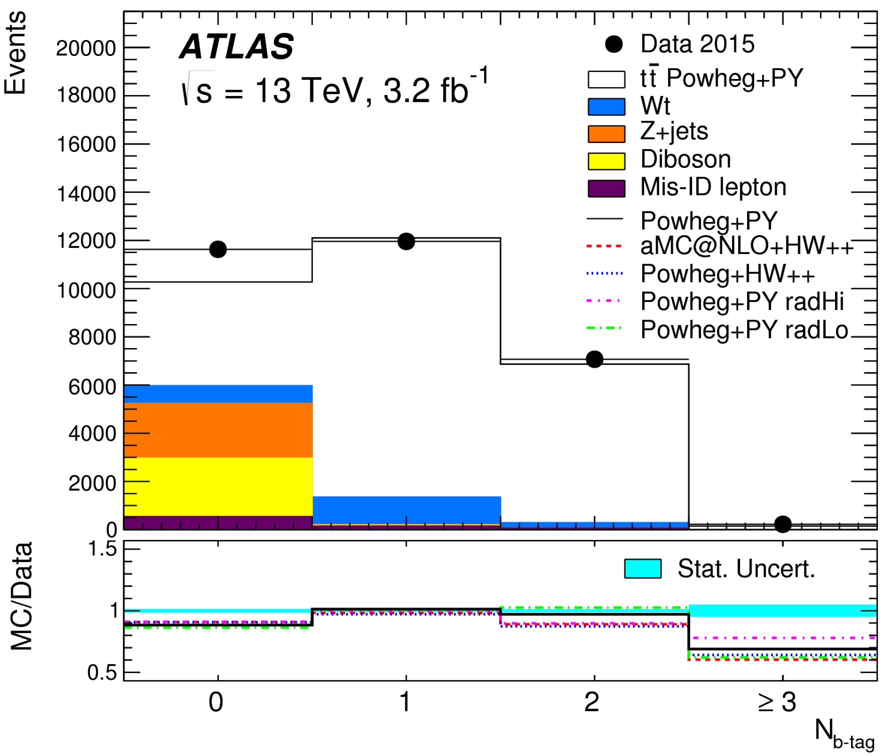

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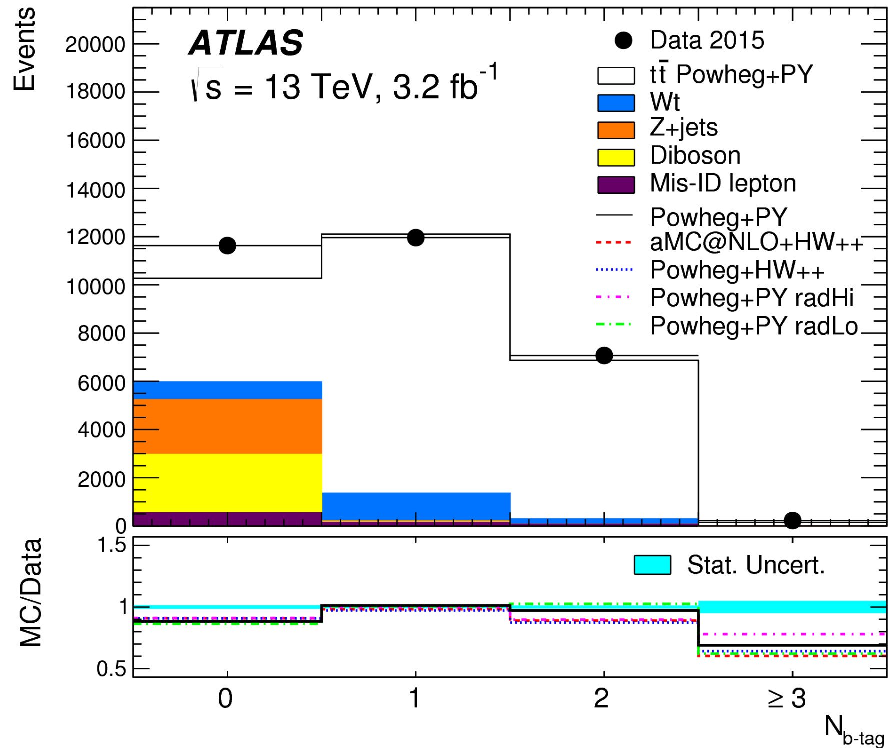

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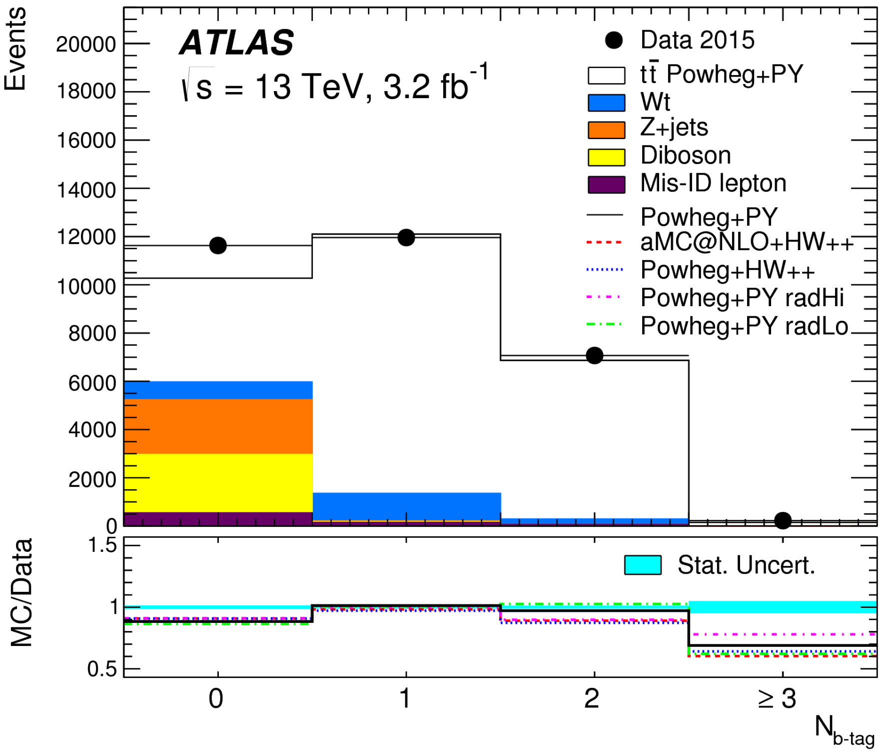

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- Input:
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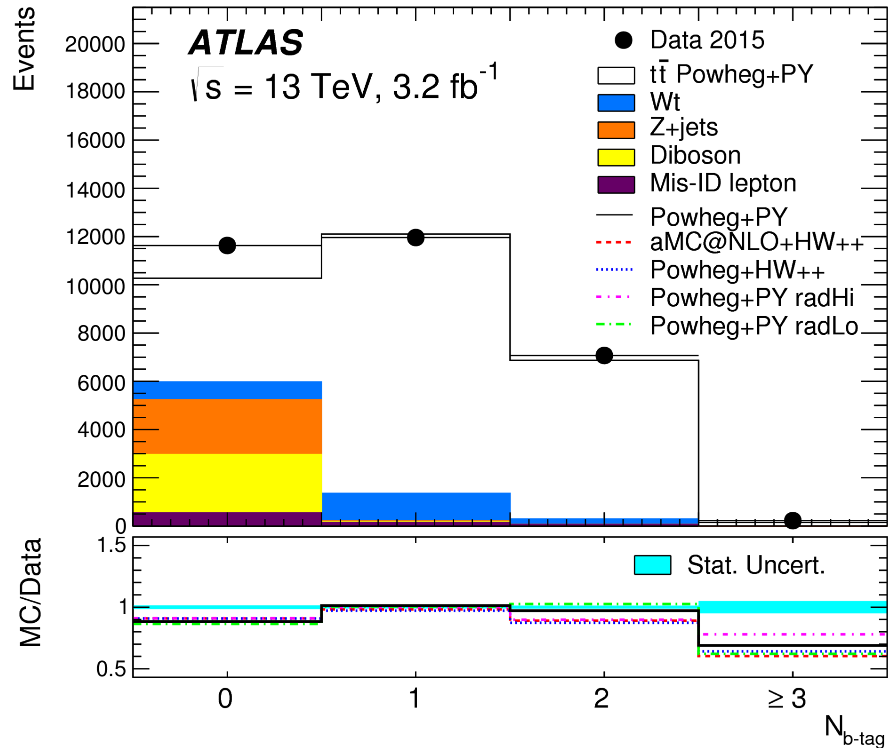

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  - N_1^{bkg}, N_2^{bkg} – from combined simulation + data-based methods
  - N_1, N_2, L

Background estimate – $e\mu$ + b-tagged jets @ 13 TeV

Event counts	N_1	N_2
Data	11958	7069
Single top	1140 ± 100	221 ± 68
Diboson	34 ± 11	1 ± 0
$Z(\rightarrow \tau\tau \rightarrow e\mu)$+jets	37 ± 18	2 ± 1
Misidentified leptons	164 ± 65	116 ± 55
Total background	1370 ± 120	340 ± 88

- Purity: ~90% / 95%
- *Wt* single top
- Diboson

} from simulation

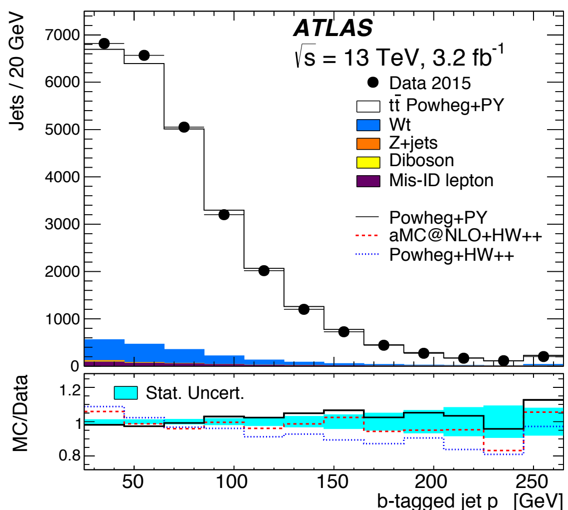
- *Z*+jets: *Z*+HF has large theoretical uncertainties - scale simulation according to data-driven study. Sale factors obtained from *Z->ee* and *Z->μμ* events.
- Fake leptons: estimated using SS data events and OS/SS ratio from simulation

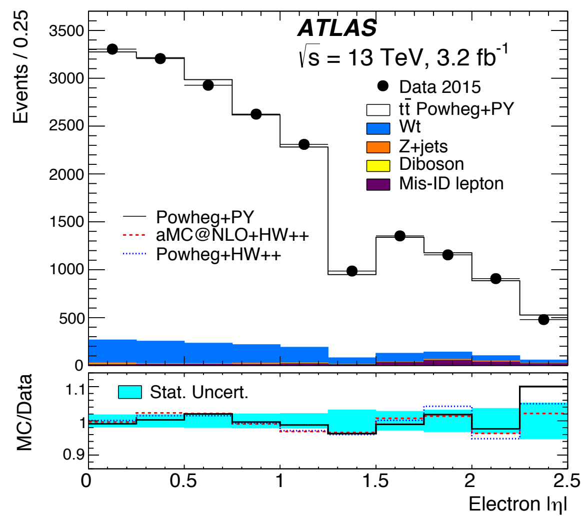
$$N_j^{\text{fake}} = R_j(N_j^{\text{d,SS}} - N_j^{\text{prompt,SS}})$$

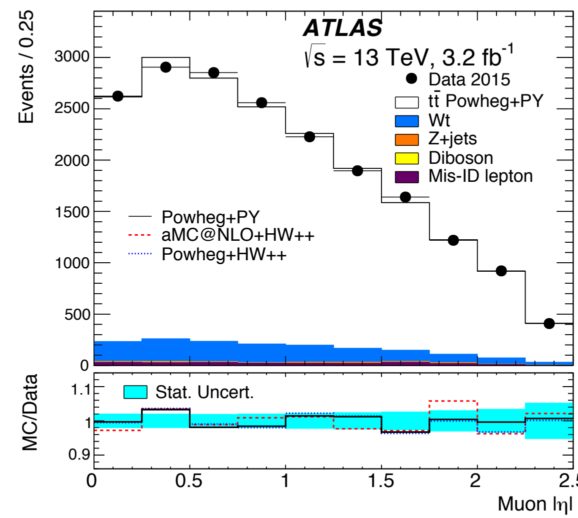
$$R_j = \frac{N_j^{\text{fake,OS}}}{N_j^{\text{fake,SS}}}$$

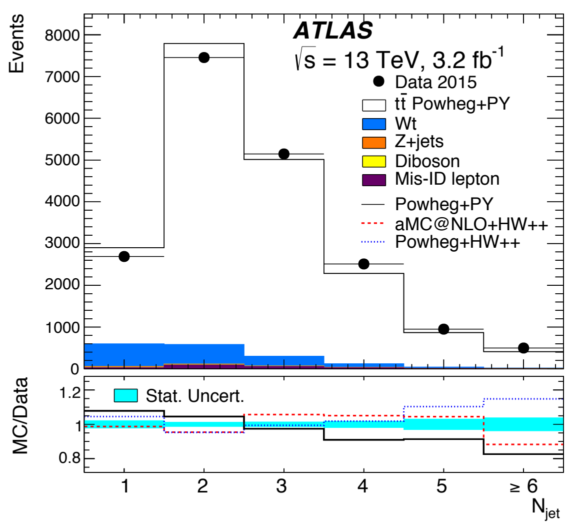
Kinematics – *eμ* + *b*-tagged jets @ 13 TeV

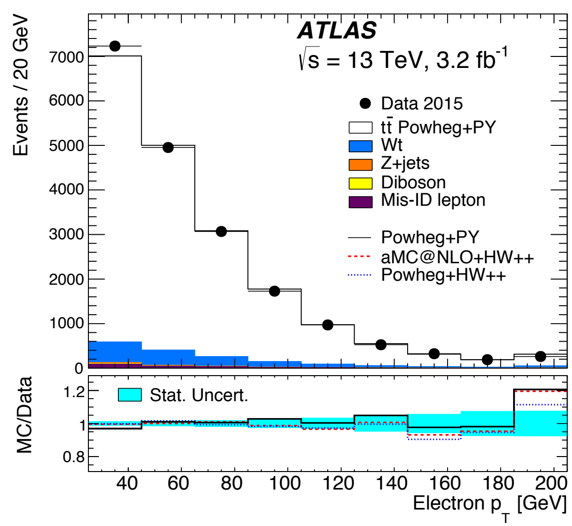
- Events with ≥ 1 *b*-tagged jets

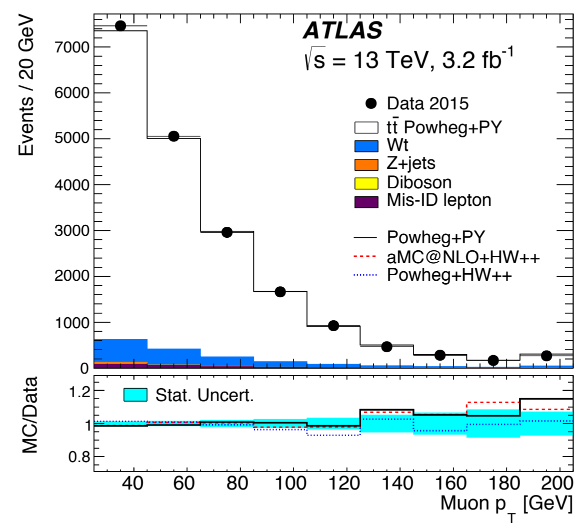












Results – $e\mu$ + b-tagged jets @ 13 TeV

- σ_{tt} = 818 ± 8 (stat) ± 27 (syst) ± 19 (lumi) ± 12 (beam) pb
- Total uncertainty: 4.4%
  - syst.: 3.3%
  - lumi.: 2.3%
- Leading analysis systematics:
  - ttbar hadronisation modelling:
    - 2.8%
    - Pythia6 vs. Herwig++
- ε_b = 0.559 ± 0.004 (stat) ± 0.003 (syst) - consistent with simulation: 0.549

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- σ_{tt}^{fid} = 11.32 ± 0.10 (stat) ± 0.29 (syst) ± 0.26 (lumi) ± 0.17 (beam) pb
- Much less susceptible to modelling uncertainties compared to the inclusive measurement
- Total uncertainty: 3.9%
    - syst.: 2.5%
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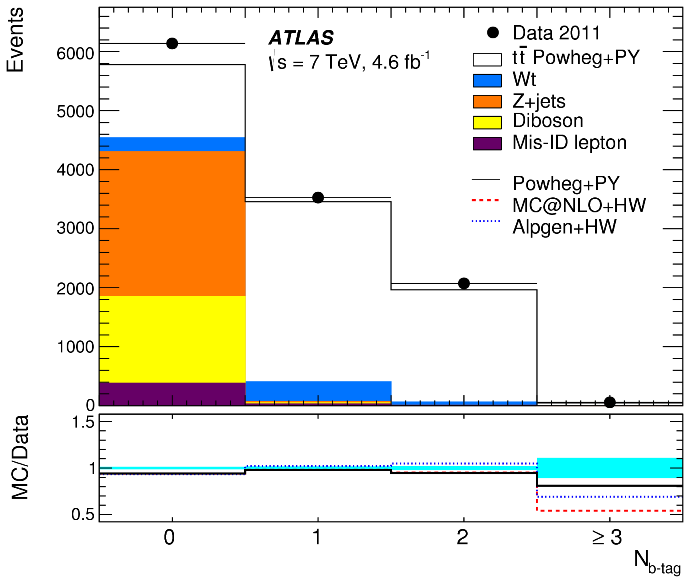
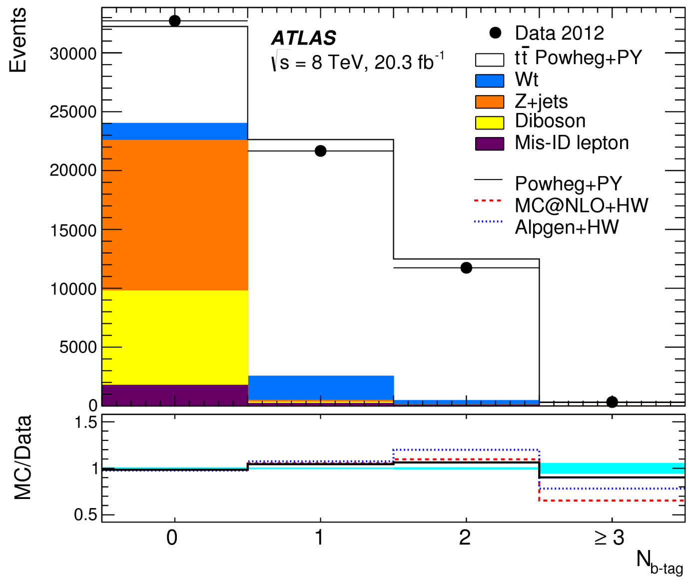
eμ + *b*-tagged jets @ 7 & 8 TeV

- Use the same analysis strategy and similar selection





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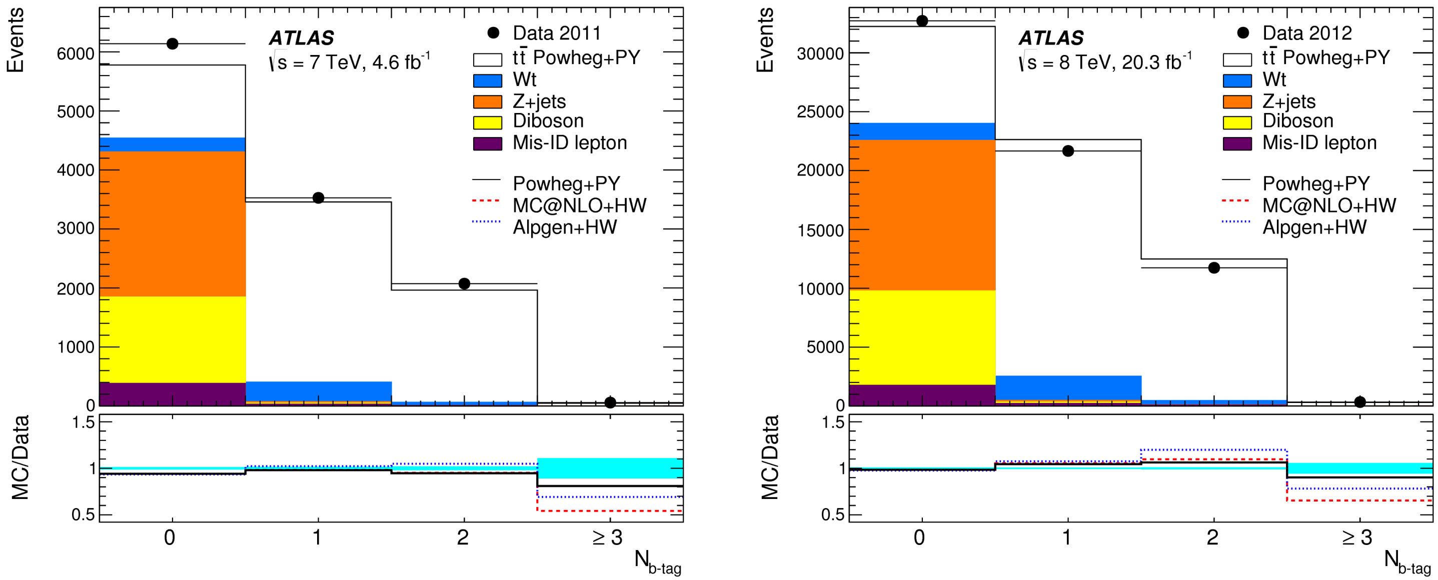

- Inclusive cross-section:
  - 7 TeV: σ_{tt} = 182.9 ± 3.1 (stat) ± 4.2 (syst) ± 3.6 (lumi) ± 3.3 (beam) pb
    - Analysis syst.: 2.3%
    - Total: 3.9%
  - 8 TeV: σ_{tt} = 242.4 ± 1.7 (stat) ± 5.5 (syst) ± 7.5 (lumi) ± 4.2 (beam) pb
    - Analysis syst.: 2.3%
    - Total: 4.3%
- ε_b: 0.557 ± 0.009 (7 TeV) and 0.540 ± 0.006 (8 TeV) - consistent with simulation

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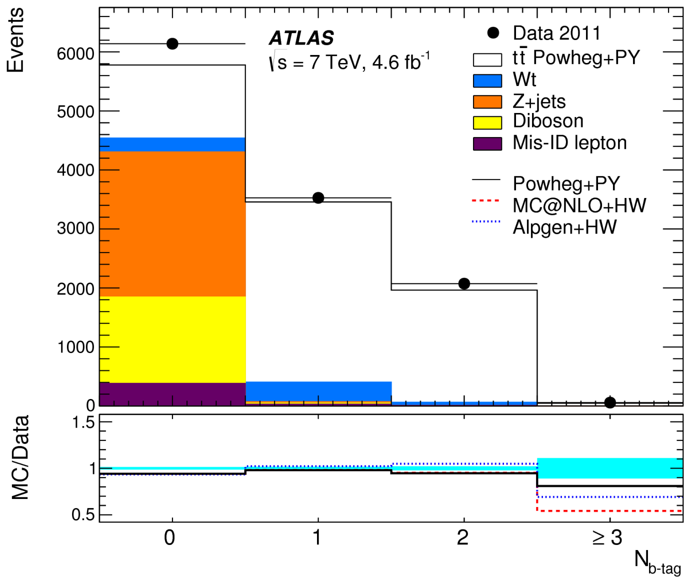

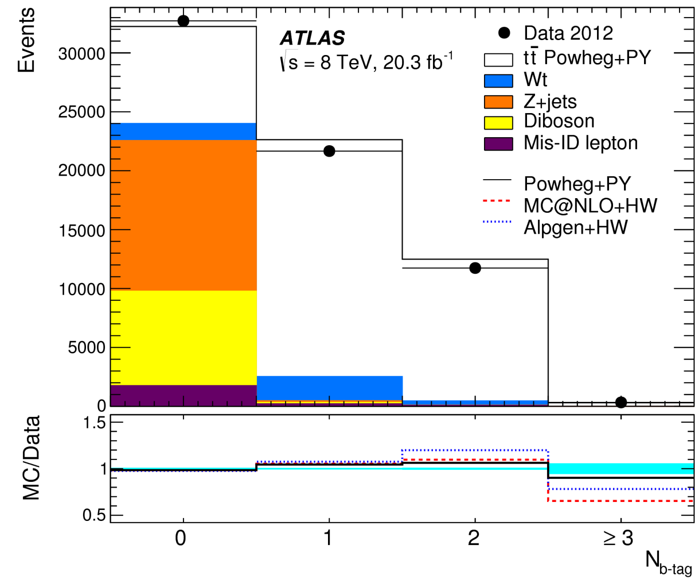

- Fiducial cross-section measured in different fiducial regions

central value + stat.+ syst. + lumi. + beam

p_T^ℓ (GeV)	$\lvert\eta^\ell\rvert$	$W \to \tau \to \ell$	$\sqrt{s} = 7$ TeV (pb)	$\sqrt{s} = 8$ TeV (pb)
>25	<2.5	Yes	$2.615 \pm 0.044 \pm 0.056 \pm 0.052 \pm 0.047$	$3.448 \pm 0.025 \pm 0.069 \pm 0.107 \pm 0.059$
>25	<2.5	No	$2.305 \pm 0.039 \pm 0.049 \pm 0.046 \pm 0.041$	$3.036 \pm 0.022 \pm 0.061 \pm 0.094 \pm 0.052$
>30	<2.4	Yes	$2.029 \pm 0.034 \pm 0.043 \pm 0.040 \pm 0.036$	$2.662 \pm 0.019 \pm 0.054 \pm 0.083 \pm 0.046$
>30	<2.4	No	$1.817 \pm 0.031 \pm 0.039 \pm 0.036 \pm 0.033$	$2.380 \pm 0.017 \pm 0.048 \pm 0.074 \pm 0.041$

- systematic uncertainties reduced in PDF and QCD scale choice

Dominant uncertainties - *eμ* + *b*-tagged jets

	7 TeV [%]	8 TeV [%]	13 TeV [%]
Inclusive cross-section			
Data stat.	1.7	0.7	0.9
Luminosity	2.0	3.1	2.3
Beam energy	1.8	1.7	1.5
ttbar modelling	1.4	1.2	0.8
ttbar hadronisation	-	-	2.8
PDF	1.0	1.1	0.5
Analysis total	2.3	2.3	3.3
Total	3.9	4.3	4.4
Fiducial cross-section			
ttbar modelling	1.6	1.3	0.6
ttbar hadronisation	-	-	1.9
PDF	0.4	0.3	0.1
Analysis total	2.1	2.0	2.5
Total	3.8	4.1	3.9

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Ratio to *Z* cross-section: σ_{tt}/σ_Z @ 13 TeV

- Allows for cancellation of uncertainties, e.g. luminosity and lepton related uncertainties
- Ratio defined as $R_{t\bar{t}/Z} = \dfrac{\sigma_{t\bar{t}}}{0.5\left(\sigma_{Z\to ee} + \sigma_{Z\to\mu\mu}\right)}$
- Results using 78 pb^{-1} for σ_{tt} and 85 pb^{-1} for σ_Z

$$R_{t\bar{t}/Z} = 0.445 \pm 0.027\ (\text{stat}) \pm 0.028\ (\text{syst})$$

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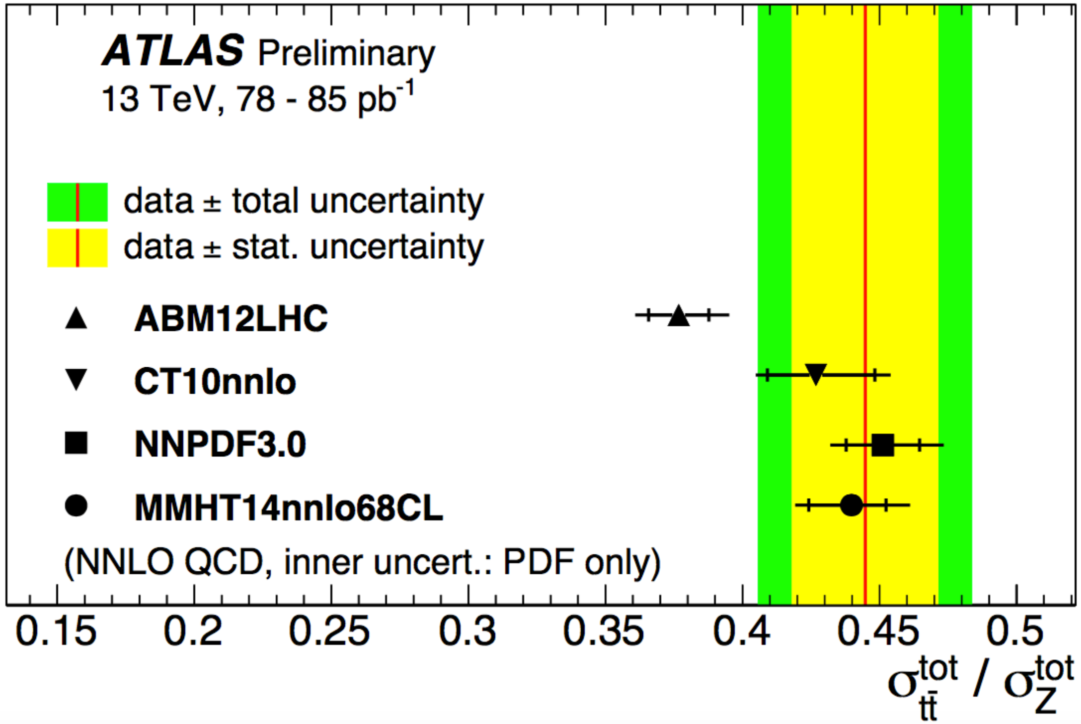
- Compare to $e\mu$ σ_{tt} result
  - Luminosity: 10.0% → 1.0%
  - Total: 13.7% → 8.8%
- Updated result exploiting new 3.2 fb^{-1} ttbar measurement should allow significant improvement in precision



Dilepton channel same flavour (*ee*/*μμ*) @ 13 TeV

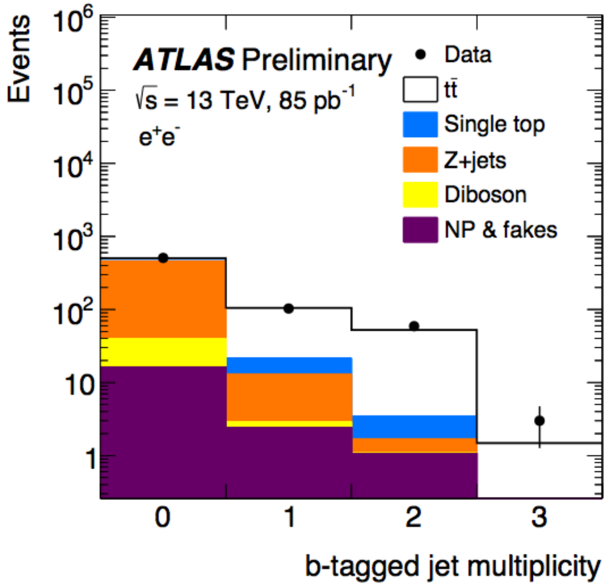
- Using 85 pb^{-1} of early Run 2 data
- Same strategy as the *eμ* analysis

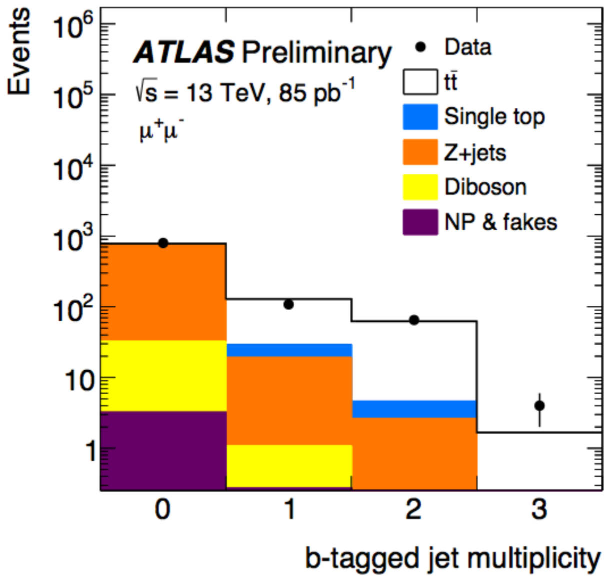
$$
\begin{aligned}
N_1^{ee} &= L\sigma_{t\bar{t}}\,\epsilon_{\rm presel}^{ee} 2\epsilon_b^{ee}(1 - C_b^{ee}\epsilon_b^{ee}) + N_1^{\rm bkg,\mathit{ee}} \\
N_2^{ee} &= L\sigma_{t\bar{t}}\,\epsilon_{\rm presel}^{ee} C_b^{ee}\epsilon_b^{ee}\epsilon_b^{ee} + N_2^{\rm bkg,\mathit{ee}} \\
N_1^{\mu\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{\rm presel}^{\mu\mu} 2\epsilon_b^{\mu\mu}(1 - C_b^{\mu\mu}\epsilon_b^{\mu\mu}) + N_1^{\rm bkg,\mu\mu} \\
N_2^{\mu\mu} &= L\sigma_{t\bar{t}}\,\epsilon_{\rm presel}^{\mu\mu} C_b^{\mu\mu}\epsilon_b^{\mu\mu}\epsilon_b^{\mu\mu} + N_2^{\rm bkg,\mu\mu}\,,
\end{aligned}
$$

- Pre-selection
  - 2 same-flavour leptons, OS
  - E_T^{miss} > 30 GeV
  - $|M_{ll} - M_Z| > 10$ GeV
- Extract σ_{tt}, ε_b^{ee} and $\varepsilon_b^{\mu\mu}$ simultaneously using a maximum likelihood fit
- Results

ee	824 ± 88 (stat) ± 91 (syst) ± 82 (lumi) pb
μμ	683 ± 74 (stat) ± 76 (syst) ± 68 (lumi) pb
ee and *μμ* combined	749 ± 57 (stat) ± 79 (syst) ± 74 (lumi) pb

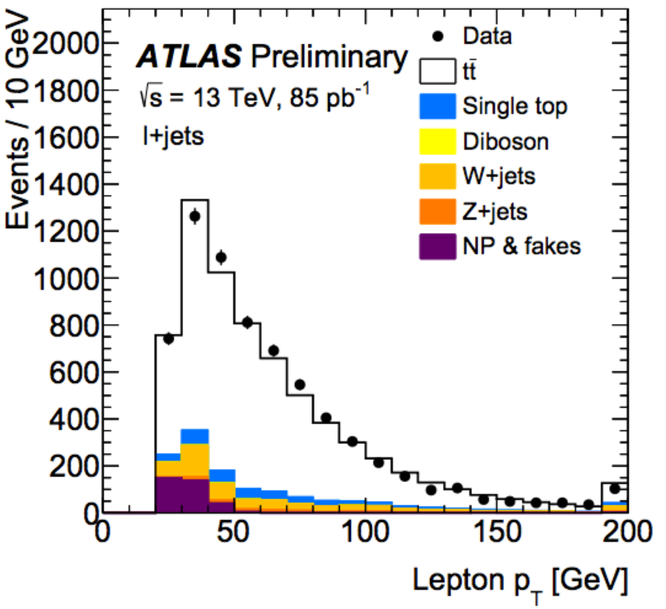
  - Total: 16%
  - Stat.: 7.6%
  - Syst.: 11% (ttbar hadronisation 7.9%)

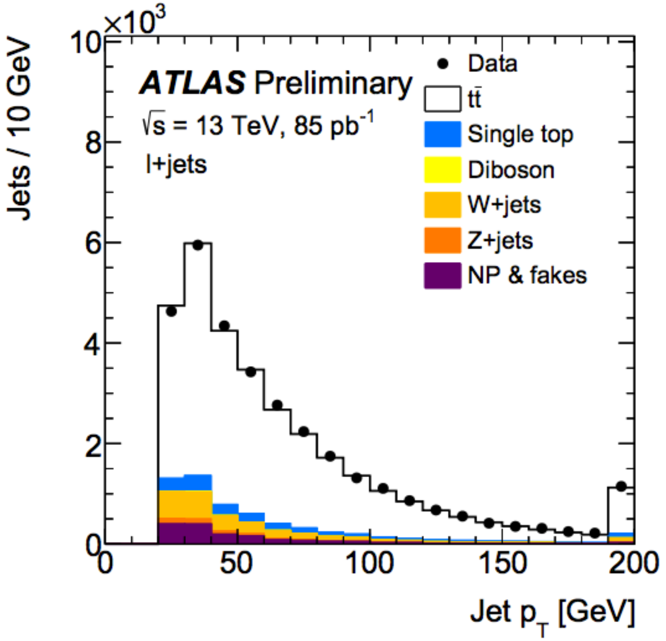




lepton+jets channel @ 13 TeV

- Using 85 pb^{-1} of early Run 2 data
- Event selection
  - 1 *e* or *μ*
  - ≥ 4 jets; ≥ 1 *b*-tag
  - *e*+jets: E_T^{miss} > 40 GeV or m_T^W > 50 GeV; *μ*+jets: E_T^{miss} + m_T^W > 60 GeV
- Extract cross-section $$\sigma_{t\bar{t}}^{\ell j} := \frac{N_{\text{Obs}}^{\ell j} - N_{\text{Bgr}}^{\ell j}}{\varepsilon_{\ell j} \cdot \mathcal{L}_{\text{Int}}}$$
- Result: 817 ± 13 (stat) ± 103 (syst) ± 88 (lumi) pb
  - total: 17%
  - stat.: 1.5%
  - syst.: 13%
    - ttbar hadronisation: 4.1%
    - JES: 10%
    - *b*-tagging: 4.1%





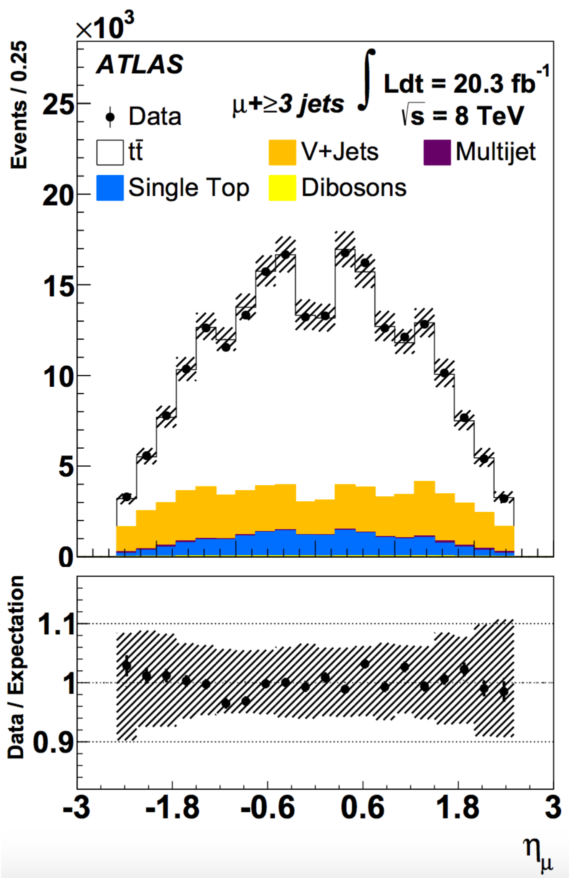
lepton+jets channel @ 8 TeV

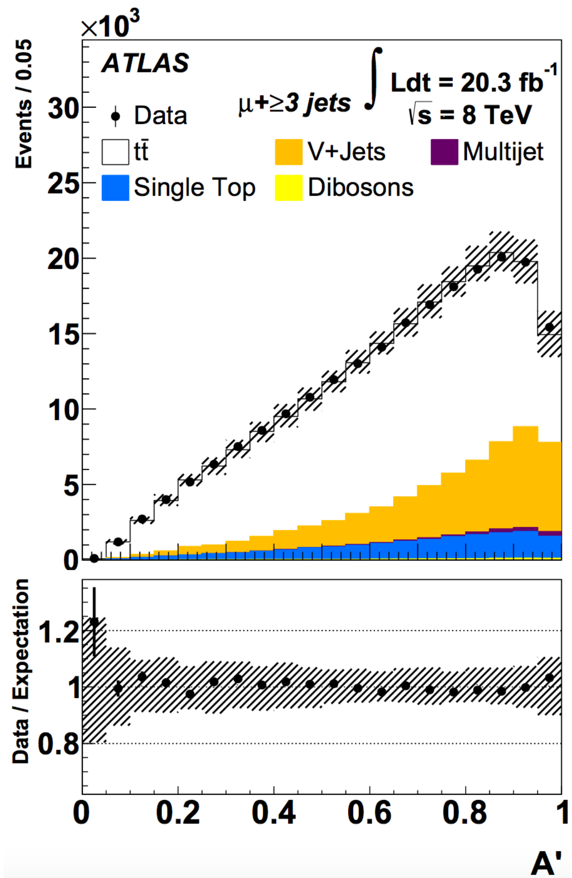
- Event selection:
  - e/μ + ≥ 3 jets; ≥ 1 *b*-tagged jet
  - E_T^{miss} > 30 GeV
  - m_T^W > 30 GeV

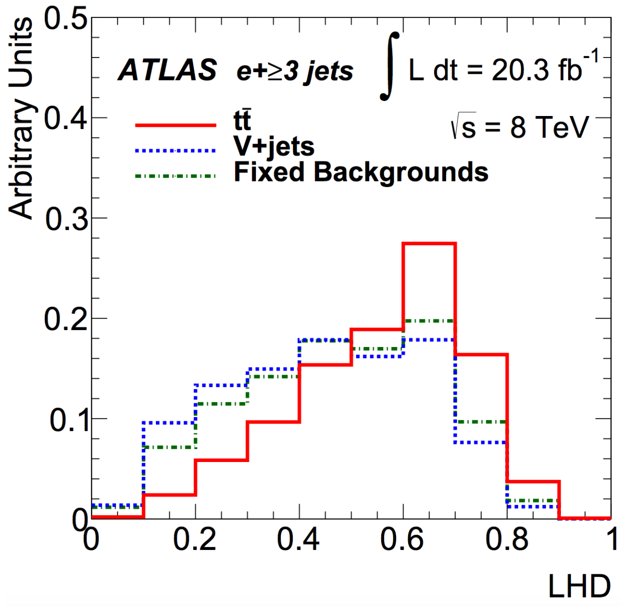
- Analysis strategy
  - Determine the number of events using a template fit to a likelihood discriminant $D_i = \frac{L_i^s}{L_i^s + L_i^b}$
  - Likelihood function constructed as product of PDFs of two kinematic variables
    - Lepton η
    - Transformed Aplanarity $\mathcal{A}' = \exp(-8\mathcal{A})$
      - $\mathcal{A}$ = 3/2 x smallest eigenvalue of the momentum tensor $M_{ij} = \sum_{k=1}^{N_{\text{objects}}} p_{ik} p_{jk} / \sum_{k=1}^{N_{\text{objects}}} p_k^2$
  - Fit *e*+jets and *μ*+jets channels separately
    - different templates due to different *e* and *μ* efficiencies as a function of *η*
  - extract cross-section $\sigma_{t\bar{t}} = \frac{N_{t\bar{t}}}{\varepsilon_{t\bar{t}} \times \mathcal{B} \times \mathcal{L}}$

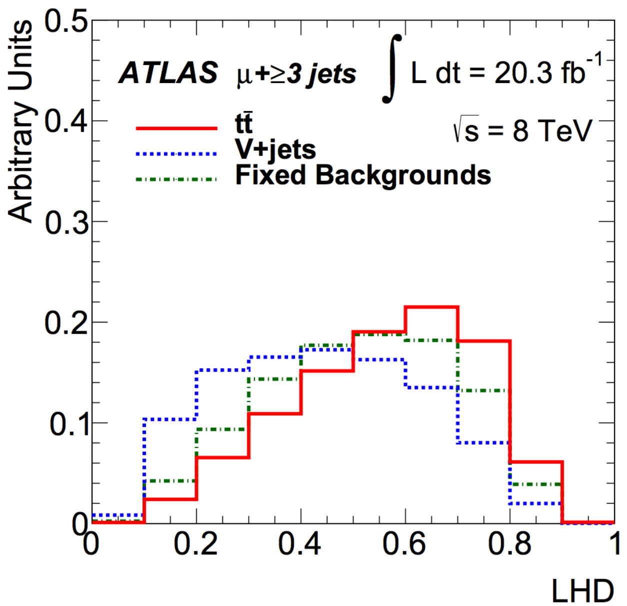
$$\sigma_{t\bar{t}}^{\text{fid}} = \frac{N_{t\bar{t}}^{\text{fid}}}{\varepsilon_{t\bar{t}}^{\text{fid}} \times \mathcal{L}}$$

Discriminant variables

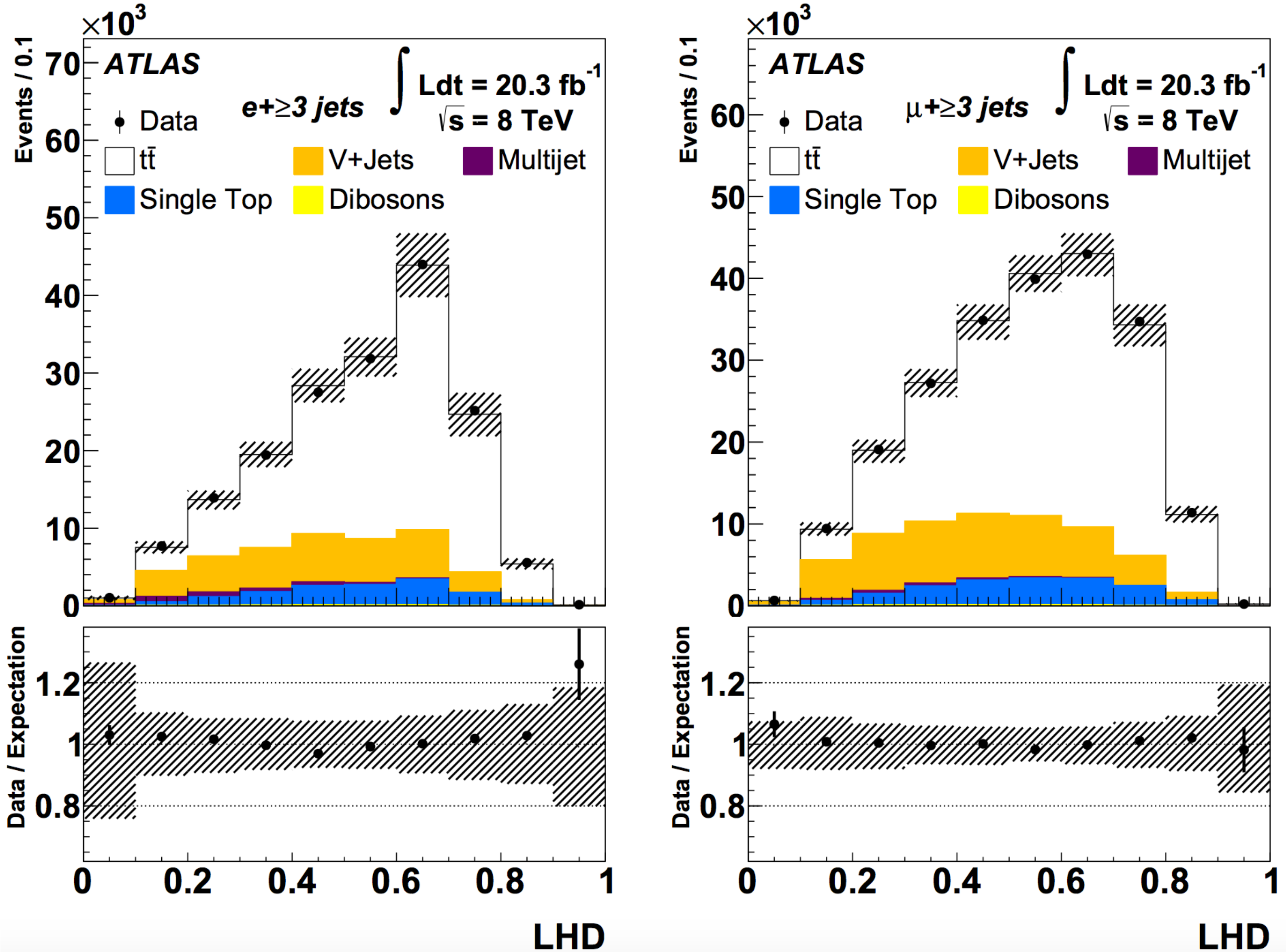








Likelihood discriminant



Results

- Inclusive cross-section

$$e\text{+jets} : \sigma_{t\bar{t}} = 256 \pm 2(\text{stat.}) \ \pm 25(\text{syst.}) \ \pm 7(\text{lumi.}) \ \pm 4(\text{beam}) \text{ pb},$$
$$\mu\text{+jets} : \sigma_{t\bar{t}} = 260 \pm 1(\text{stat.}) \ {}^{+22}_{-23}(\text{syst.}) \ \pm 8(\text{lumi.}) \ \pm 4(\text{beam}) \text{ pb},$$
$$\ell\text{+jets} : \sigma_{t\bar{t}} = 258 \pm 1(\text{stat.}) \ {}^{+22}_{-23}(\text{syst.}) \ \pm 8(\text{lumi.}) \ \pm 4(\text{beam}) \text{ pb},$$

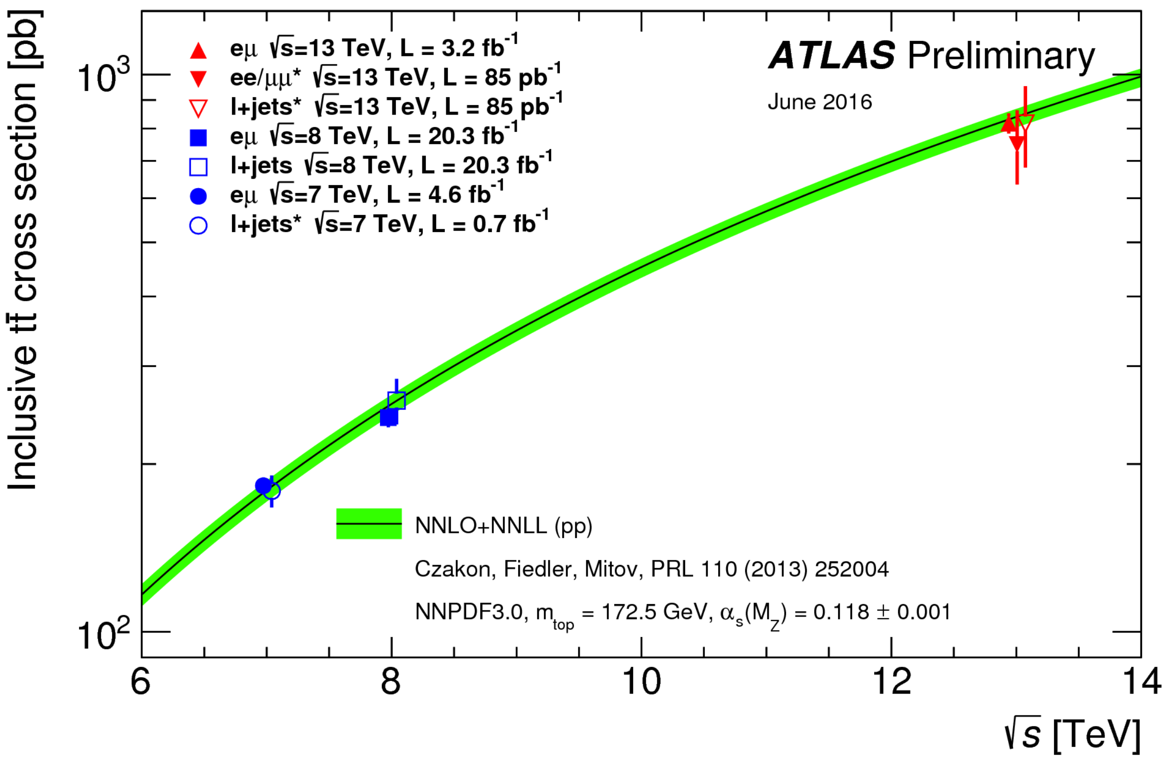
- Fiducial cross-section

$$e\text{+jets} : \sigma^{\text{fid}}_{t\bar{t}} = 11.3 \pm 0.1(\text{stat.}) \ \pm 1.0(\text{syst.}) \ \pm 0.3(\text{lumi.}) \ \pm 0.2(\text{beam}) \text{ pb},$$
$$\mu\text{+jets} : \sigma^{\text{fid}}_{t\bar{t}} = 11.5 \pm 0.1(\text{stat.}) \ \pm 1.0(\text{syst.}) \ \pm 0.3(\text{lumi.}) \ \pm 0.2(\text{beam}) \text{ pb},$$
$$\ell\text{+jets} : \sigma^{\text{fid}}_{t\bar{t}} = 22.8 \pm 0.1(\text{stat.}) \ {}^{+1.9}_{-2.0}(\text{syst.}) \ \pm 0.7(\text{lumi.}) \ \pm 0.4(\text{beam}) \text{ pb},$$

- Leading systematic uncertainties

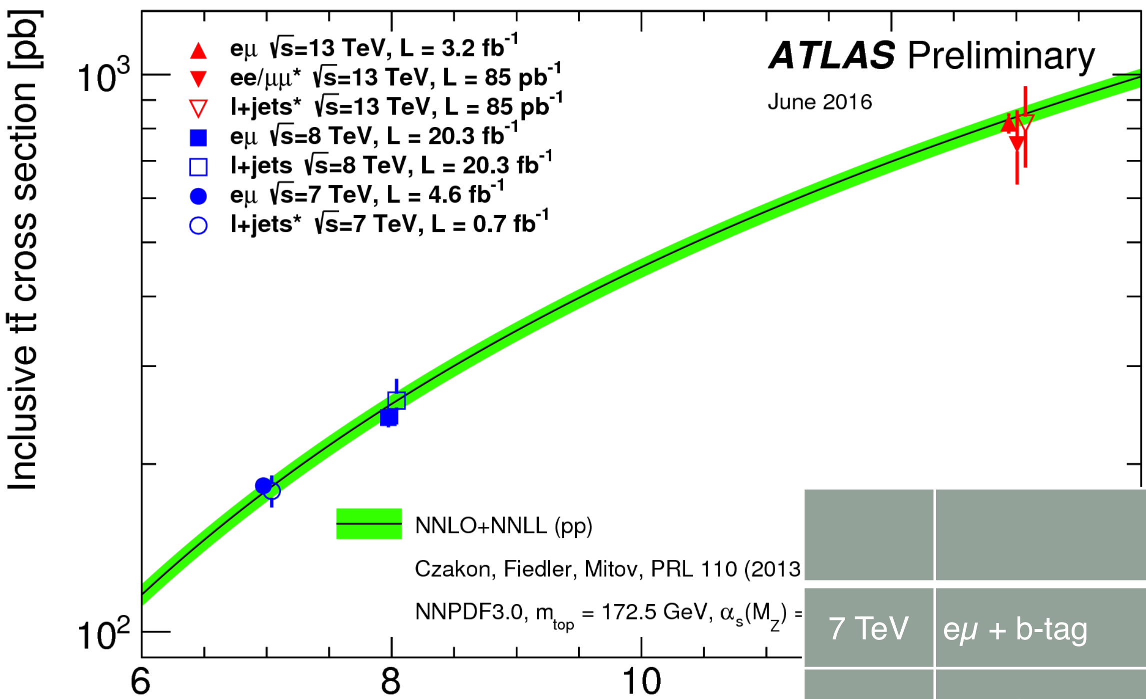
	σ_{tt} [%]	σ_{tt}^{fid} [%]
MC generator	2.7	2.8
PS and fragmentation	2.3	2.9
ISR & FSR	3.0	0.3
PDF	5.9	5.9
Total systematic uncert.	+8.6 -8.9	+8.3 -8.6

Summary of results at different √s



- Good agreement with SM prediction at different √s

Summary of results at different √s



- Good agreement with SM prediction at different √s

- Comparable uncertainties with theoretical uncertainties with NNLO+NNLL precision

		Measured	NNLO+NNLL (PDF, α_s, QCD scale)
7 TeV	$e\mu$ + b-tag	3.9%	$^{+5.3}_{-5.7}\%$
8 TeV	$e\mu$ + b-tag	4.3%	$^{+5.7}_{-6.1}\%$
	l+jets	$^{+9.2}_{-9.6}\%$	
13 TeV	$e\mu$ + b-tag	4.4%	$^{+4.8}_{-5.5}\%$
	dilepton ee/$\mu\mu$	16%	
	l+jets	$^{+17}_{-14}\%$	

Summary

- Inclusive cross-section has been measured by the ATLAS experiment at $\sqrt{s}$ = 7, 8 and 13 TeV
- Measurements in good agreement with NNLO+NNLL predictions
- Comparable experiment uncertainties with theoretical uncertainties
- Fiducial cross-section also measured
  - allowing for reduction of PDF and modelling uncertainties

- Accumulating data @ 13 TeV allow for more detailed measurements
  - key to understanding physics at the new energy regime
  - improving QCD predictions, MC modelling and PDFs

BACKUP

In-situ measurement of lepton isolation efficiency

- Reduce uncertainty on ttbar hadronisation
  - Measure in-situ lepton isolation inefficiency in $e\mu$ + 1 or 2 b-tagged jets events
    - Define probe lepton: remove isolation requirement
    - Fraction of prompt probe leptons that fail the isolation cut in a sample with j b-tagged jets

$$\zeta_j = \frac{M_j^{\mathrm{d,prompt}}}{N_j^{\mathrm{d,prompt}}} = \frac{M_j^{\mathrm{d}} - M_j^{\mathrm{d,fake}}}{N_j^{\mathrm{d}} - N_j^{\mathrm{d,fake}}} \quad (\zeta = 1 - \epsilon_{\mathrm{isol}})$$

  - Isolation efficiency correction and uncertainties
    $\delta\epsilon_{\mathrm{isol}}/\epsilon_{\mathrm{isol}} = -\Delta\zeta/\epsilon_{\mathrm{isol}}$
  - Measure ttbar hadronisation uncertainty without isolation cut
    - decouple hadronisation and isolation uncertainties