Tests of Quantum Chromodynamics with the ATLAS experiment

Term Paper "Physics at the LHC"

Alena Lösle

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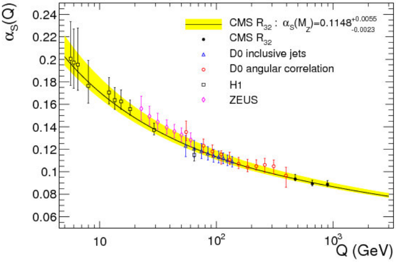
Outline

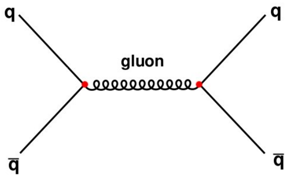
1. Introduction
2. Jet reconstruction at ATLAS
3. Inclusive jet and dijet cross section measurements
4. W/Z production cross section measurements
5. Production of W+jets
6. Cross section measurements of $t\bar{t}$ production
7. Conclusion and outlook

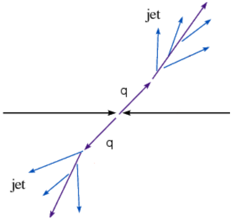
1.1. Quantum Chromodynamics

- gauge theory of strong interaction described by $SU(3)_C$ symmetry
- couples to colour charge
  $\rightarrow$ quarks, gluons
- running coupling constant: α_s is energy dependent

$\rightarrow$ confinement: no unbound quarks
$\rightarrow$ hadronization: formation of particle jets

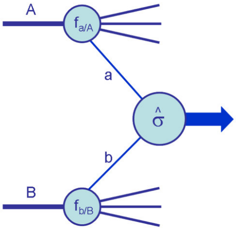






1.2. Calculation of cross sections

cross section for AB $\rightarrow$ X:
$\sigma_{AB} = \int dx_a dx_b f_{a/A}(x_a, \mu_F^2) f_{b/B}(x_b, \mu_F^2) \hat{\sigma}_{ab}$

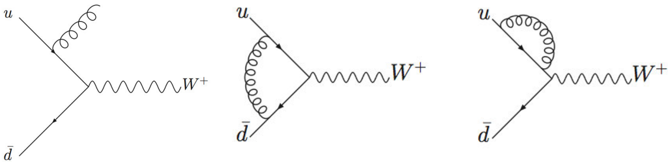


for large momentum scale Q^2:
calculate $\hat{\sigma}_{ab}$ in pertubation series (pQCD):
$\hat{\sigma}_{ab} = [\hat{\sigma}_0 + \alpha_s(\mu_R)\hat{\sigma}_1 + ...]$

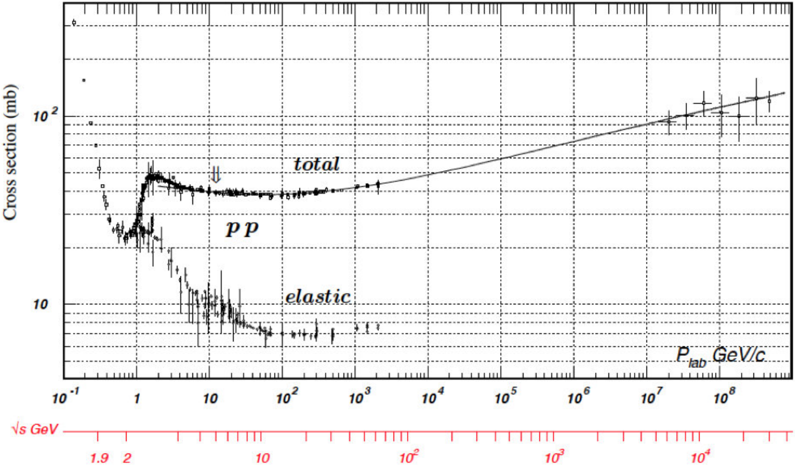
μ_F: factorization scale
μ_R: renormalization scale

Natural choice for Drell-Yan process:
$\mu_F = \mu_R = M_Z$

example for real and virtuell corrections at NLO:



1.3. phenomenology of proton-proton collisions



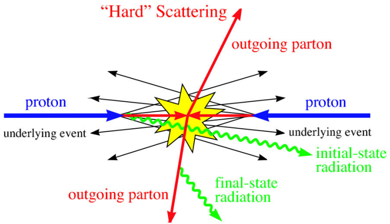
1.3. phenomenology of proton-proton collisions

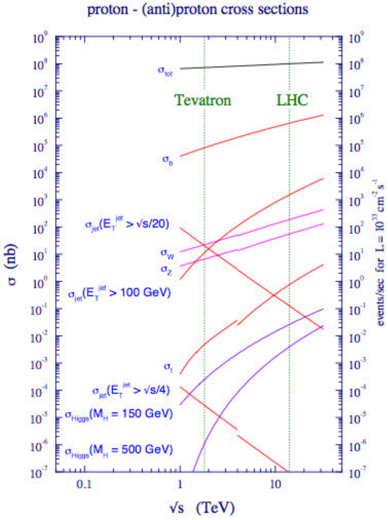
hard scattering processes:

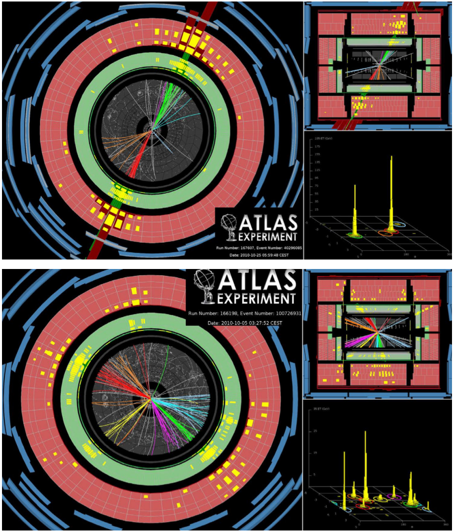
- high momentum transfer between partons
$\rightarrow$ cross section can be calculated in pQCD

- fragmentation of the remaining proton
$\rightarrow$ underlying event

- cross section depends on parton distribution functions (PDFs)
$\rightarrow$ cannot be described from first principles
$\rightarrow$ fit to experimental data







quarks and gluons itselfs are not oberved in the detector
$\rightarrow$ jets: collimated spray of energetic hadrons

jet signature in the detector:

- inner detector: particle tracks originating from one primary vertex
- energy deposition in em and hadronic calorimeter
- momentum measurement of muons in muon chamber

energy deposition in calorimeter cells are input for jet reconstruction

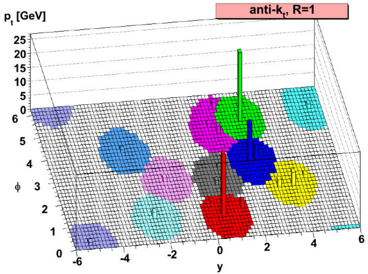
2.1. The anti-k_T algorithm

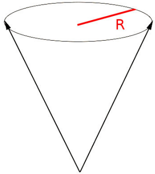
requirement: jet definition should be insensitive to collinear and soft gluon radiation
(infrared safety)

→ anti-k_T algorithm: define jet cone with radius R$=\sqrt{\eta^2 + \Phi^2}$

define distance $d_{ij} = min\left(\frac{1}{k^2_{T,i}}, \frac{1}{k^2_{T,j}}\right)\frac{\Delta R^2_{i,j}}{R^2}$ and $d_{iB} = \frac{1}{k^2_{T,i}}$

- start with energy deposition i and calculate all d_{ij} and d_{iB}
- find minimum distance
  - if min $= d_{i,j}$: recombine deposition i - j and start again
  - otherwise: deposition i is jet, back to first step
- stop algorithm when no energy depositions remain





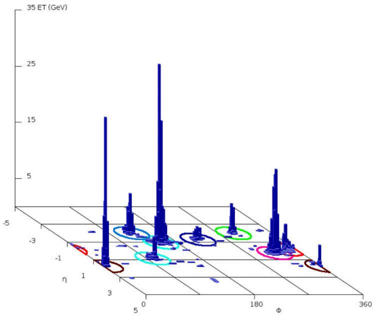
dominant hard scattering process at LHC:
$\rightarrow$ tests of QCD, bkg estimation

measurements of double diff. cross section:

inclusive jet: all jets are considered, $\frac{d^2\sigma}{dp_T\,dy}$

dijet: only two leading jets are considered

$$\frac{d^2\sigma}{dMdy^*} \text{ with } y^* = \frac{|y_1 - y_2|}{2}$$



jet reconstruction:

- anti-$k_T$algorithm with R=0.4, R=0.6
- correction for additional energy (pile-up)
- jet energy scale correction factor (JES): correct for different calorimeter response

3.1. Inclusive jet cross section measurements

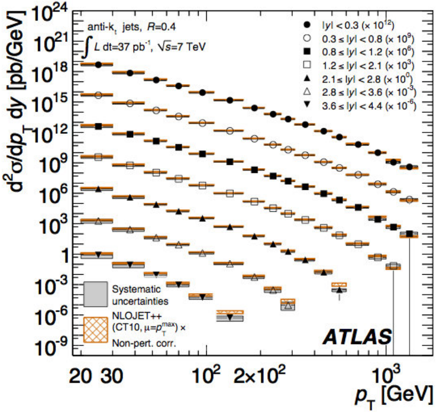
event selection:

- $p_T^{jet} > 20\,\text{GeV}$, y<4.4
- jets must pass quality selection criteria

unfolding:

signal events are corrected back to particle level taking into account detector acceptance and reconstruction efficiency

theoretical predicitions:
fixed-order NLO pQCD calculations with corrections for non-perturbative effects (hadronization, underlying event),
no electroweak corrections applied



3.2. Dijet cross section measurements

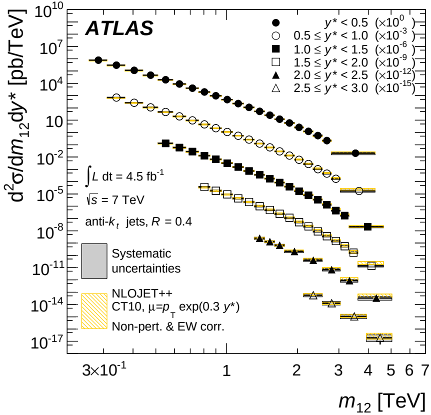
double differential cross section as a function of dijet mass M is sensitiv to new resonance
$\rightarrow$ beyond SM processes

event selection:

leading (subleading) jets within y $<$ 3.0 with $p_T^{lead} > 100$ GeV and $p_T^{sub} > 50$ GeV

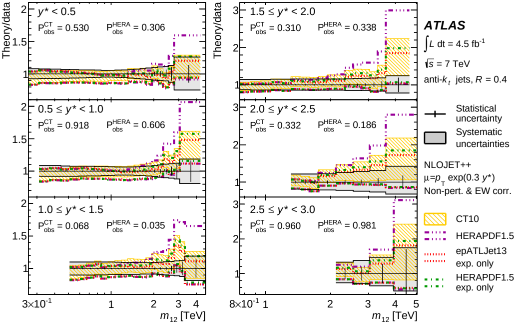
theory predicitions:

fixed-order NLO QCD predicitions corrected for non-perturbative and electroweak effects



3.2. Dijet cross section measurements

Ratio of the NLO QCD predictions to the measurements of the dijet double-differential cross sections:



dominant exp. syst. uncertainties:

jet energy scale (JES) ($\sim 30 - 60\%$)
jet energy resolution (JER) ($\sim$15% for inclusive, $\sim$ 8% for dijet)

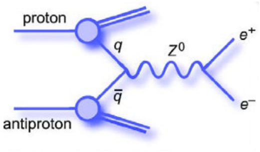
dominant theory uncertainties:

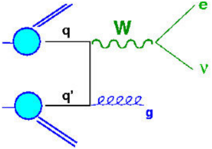
scale variation (missing higher order terms, PDFs)

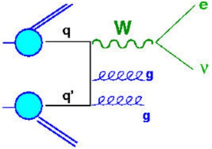
comparison of measurements and theory by using a χ^2-teststatistics
$\rightarrow$ no major deviation observed

4. W/Z production cross section measurements

W/Z-boson production at hadron colliders:







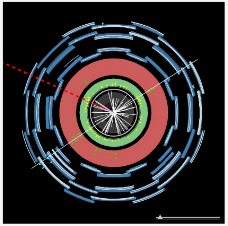
QCD effects contribute only at NLO and beyond

theoretical predictions: NNLO QCD calculations

signal channels: Z→ll, W→ lν

neutrino only accessible over missing transverse energy: $E_T^{miss}|_{x,y} = -\sum_i E^i_{x,y}$

$\rightarrow (E_T^{miss})^2 = (E_x^{miss})^2 + (E_y^{miss})^2$



4. W/Z production cross section meausurements

event selection W $\rightarrow l\nu$

one tight electron/muon, isolated

no additional medium lepton

$E_T^{miss} > 25$ GeV

$m_T > 40$ GeV

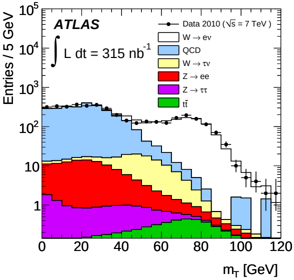
event selection Z $\rightarrow ll$

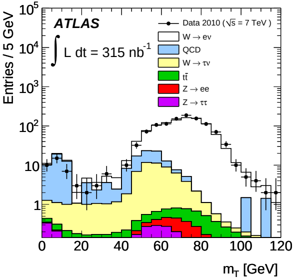
two medium electrons/muons, isolated

no additional medium lepton

opposite charge, same flavor leptons

$66 < m_{ll} < 116$ GeV





4. W/Z production cross section meausurements

comparison of measurements with theoretical predicitions:

$$\sigma^{tot}_{W/Z} \cdot BR(W/Z \to l\nu/ll) = \frac{N^{sig}_{W/Z}}{C_{W/Z} \cdot L_{W/Z} \cdot A_{W/Z}}$$

$N^{sig}_{W/Z}$: number of bkg-substracted signal events passing selection

$C_{W/Z}$: efficiency for triggering, reconstruction and identification

$L_{W/Z}$: intergrated luminosity

$A_{W/Z}$: detector acceptance

	$\sigma^{tot}_{W(\pm)} \cdot \mathrm{BR}(W \to e\nu)$ [nb]	$\sigma^{tot}_{W(\pm)} \cdot \mathrm{BR}(W \to \mu\nu)$ [nb]
W^+	$6.27 \pm 0.26(\mathrm{stat}) \pm 0.48(\mathrm{syst}) \pm 0.69(\mathrm{lumi})$	$5.71 \pm 0.23(\mathrm{stat}) \pm 0.30(\mathrm{syst}) \pm 0.63(\mathrm{lumi})$
W^-	$4.23 \pm 0.22(\mathrm{stat}) \pm 0.33(\mathrm{syst}) \pm 0.47(\mathrm{lumi})$	$3.86 \pm 0.20(\mathrm{stat}) \pm 0.20(\mathrm{syst}) \pm 0.42(\mathrm{lumi})$
W	$10.51 \pm 0.34(\mathrm{stat}) \pm 0.81(\mathrm{syst}) \pm 1.16(\mathrm{lumi})$	$9.58 \pm 0.30(\mathrm{stat}) \pm 0.50(\mathrm{syst}) \pm 1.05(\mathrm{lumi})$
	$\sigma^{tot}_{Z/\gamma^*} \cdot \mathrm{BR}(Z/\gamma^* \to ee)$ [nb], $66 < m_{ee} < 116$ GeV	$\sigma^{tot}_{Z/\gamma^*} \cdot \mathrm{BR}(Z/\gamma^* \to \mu\mu)$ [nb], $66 < m_{\mu\mu} < 116$ GeV
Z/γ^*	$0.75 \pm 0.09(\mathrm{stat}) \pm 0.08(\mathrm{syst}) \pm 0.08(\mathrm{lumi})$	$0.87 \pm 0.08(\mathrm{stat}) \pm 0.06(\mathrm{syst}) \pm 0.10(\mathrm{lumi})$

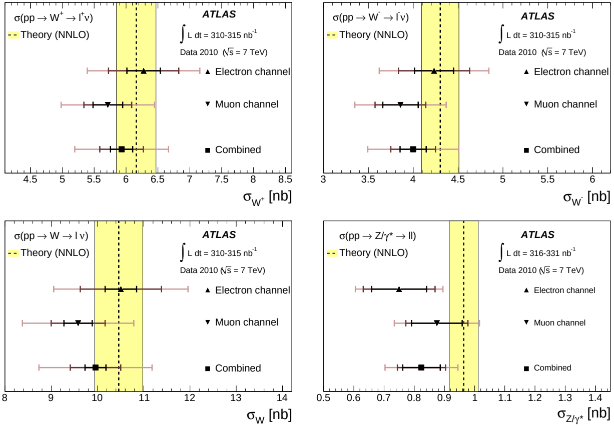
4. W/Z production cross section meausurements

systematic uncertainties for electron-channel on total cross section results mainly dominated by $C_{W/Z}$ uncertainties:

Parameter	$\delta C_W / C_W (\%)$	$\delta C_Z / C_Z (\%)$
Trigger efficiency	<0.2	<0.2
Material effects, reconstruction and identification	5.6	8.8
Energy scale and resolution	3.3	1.9
E_T^{miss} scale and resolution	2.0	-
Problematic regions in the calorimeter	1.4	2.7
Pile-up	0.5	0.2
Charge misidentification	0.5	0.5
FSR modelling	0.3	0.3
Theoretical uncertainty (PDFs)	0.3	0.3
Total uncertainty	7.0	9.4

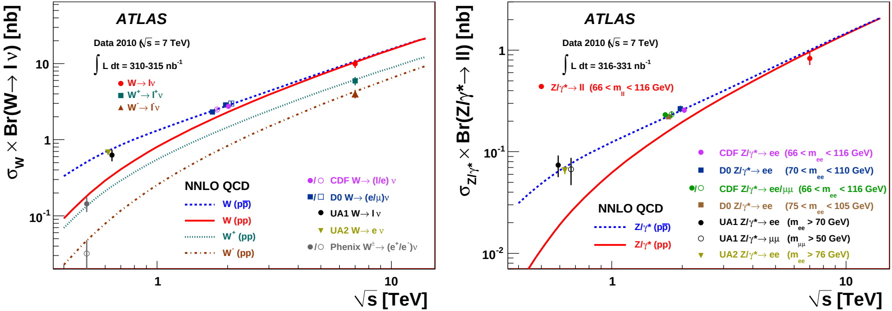
4. W/Z production cross section meausurements

Comparison of measurements with NNLO pQCD predictions:
Error bars represent statistical, statistical plus systematic and total uncertainty



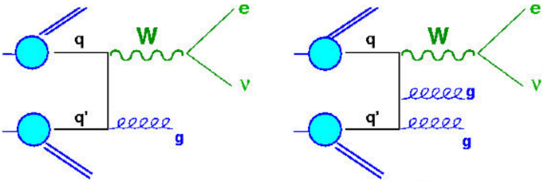
4. W/Z production cross section meausurements

Comparison of the combined electron and muon measurements and previous results to theoretical cross section predicitions



5. W+jets cross section measurements

measuring the W - production cross section as a function of inclusive jet multiplicity N_{jet}
$\rightarrow$ test of pQCD, extract informations about PDFs



Jet selection:

- anti-$k_T$algorithm with R=0.4
- $p_T^{jet} > 30$ GeV
- $|\ y\ | < 4.4$ and ΔR(l,jet) > 0.5
- reject jets with JVF < 0.75

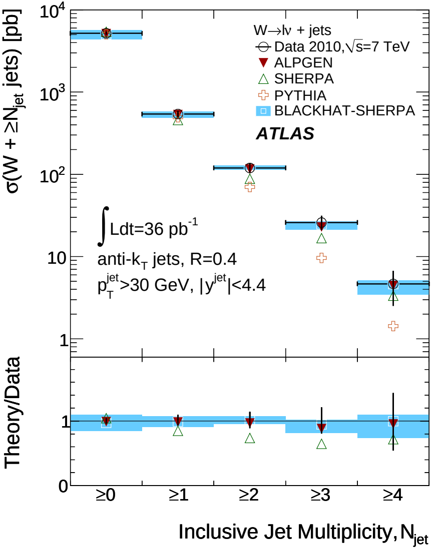
JVF= $\frac{\sum p_T \text{jet tracks from prim. vertex}}{\sum p_T \text{jet tracks from all vertices}}$

event selection W $\rightarrow$ e/$\mu\,\nu$:

same as in previous W-analysis

- $E_T^{miss} > 25$ GeV
- $m_T(W) > 40$ GeV

5.W+jets cross section measurements



theoretical predictions:

NLO QCD calculations corrected for non-perturbative effects

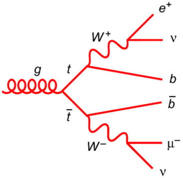
dominant syst. uncertainties:

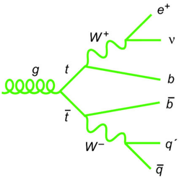
JES, JER ($\sim$ 10%)
electron identification ($\sim$ 8%)
muon momentum resolution ($\sim$ 6%)
luminosity ($\sim$ 4%)

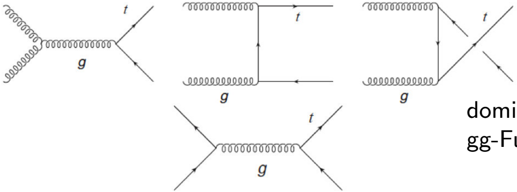
6. $t\bar{t}$ cross section measurements

short recap on top quarks:

- heaviest known particle with $m_t = 173\text{GeV}$
- production of top pair via QCD
- predominant decay channel $t \to \text{Wb}$
- identify b-jets by b-tagging at 70% efficiency







dominant $t\bar{t}$-production process at LHC:
gg-Fusion (95 % at $\sqrt{s} = 14\,TeV$)

single lepton channel:

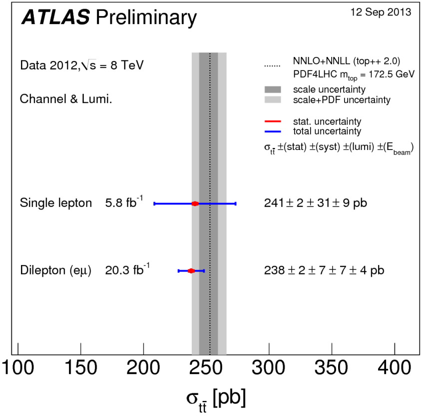
- jet reconstruction with R=0.4
- 3 jets with $p_T > 25$ GeV, $|\eta| < 2.5$
- one of these tagged as a b-jet
- JVF > 0.5
- tight electron/muon requirements

dilepton channel:

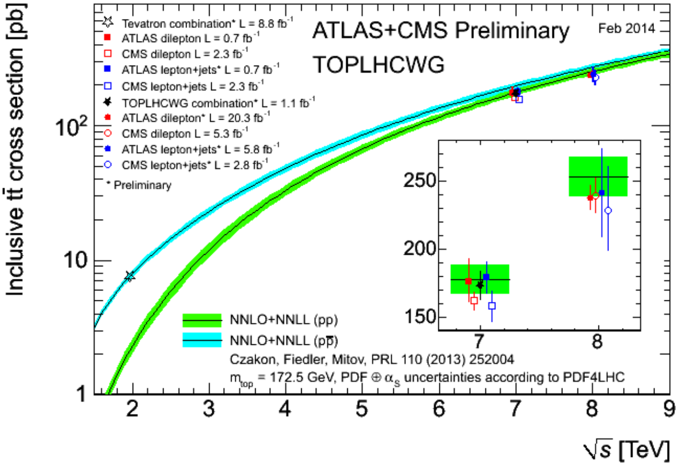
- jet reconstruction with R=0.4
- $p_T^j > 25$ GeV, $|\eta| < 2.5$
- one jet tagged as a b-jet
- medium electron/muon requirements
- opposite charge leptons, different flavor

main syst. uncertainties:

e,μ identification/isolation
JES, JER, b-tagging, integrated luminosity



Comparison of the inclusive $t\bar{t}$ cross section measurements and previous results to theoretical predicitions:



7. Conclusion and outlook

- cross section measurements presented for inclusive+dijet, W/Z production, W+jets and $t\bar{t}$ production are consistent with (N)NLO QCD predicitions

  $\rightarrow$ test of perturbative QCD

  $\rightarrow$ measurements provide also information on PDFs

- results are dominated by systematic uncertainties

  $\rightarrow$ jet energy scale and resolution uncertainties, luminosity uncertainty

- experiments need to reduce uncertainties on jet reconstruction

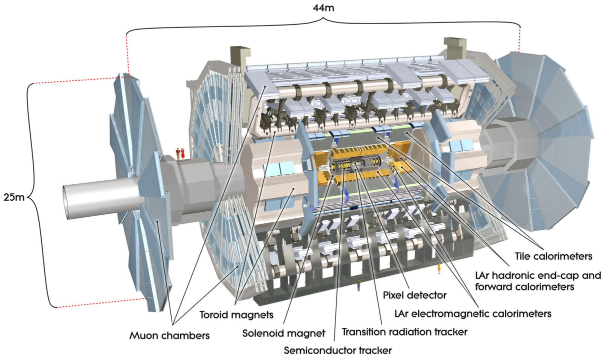
- further theoretical calculations desirable
  (NNLO pQCD for inclusive and dijet cross sections)

8. Literature

- G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **86** (2012) 014022 [arXiv:1112.6297 [hep-ex]].
- G. Aad *et al.* [ATLAS Collaboration], arXiv:1312.3524 [hep-ex].
- G. Aad *et al.* [ATLAS Collaboration], JHEP **1012** (2010) 060 [arXiv:1010.2130 [hep-ex]].
- G. Aad *et al.* [ATLAS Collaboration], Phys. Rev. D **85** (2012) 092002 [arXiv:1201.1276 [hep-ex]].
- [ATLAS Collaboration], ATLAS-CONF-2012-131.
- ATLAS Collaboration], ATLAS-CONF-2013-097.

9. Appendix

The ATLAS detector:



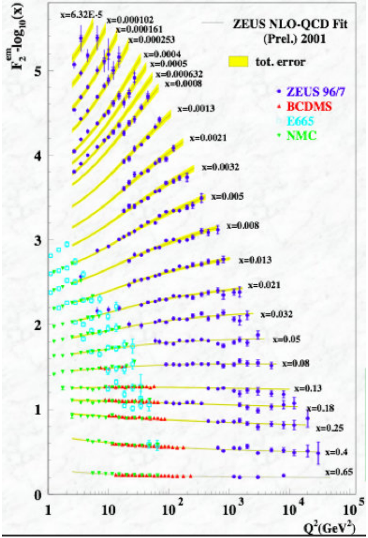
inner detector: silicon pixel and microstrip detectors, TRT detector surrounded by **EM calorimeter**: consists

LAr+Pb absorber

hadronic calorimeter: Fe+scintillator with LAr/Cu and LAr/W moduls

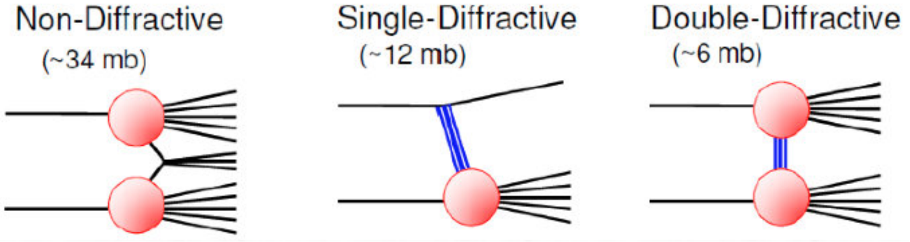
muon chamber

1. Determination of PDFs in DIS



9. Appendix

1. Contributions to total inelastic xsection:



9. Appendix

1. Jet reconstruction: Definition of jet algorithm

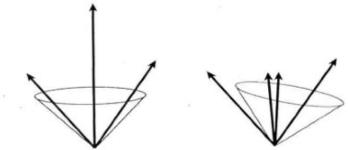


Figure 4.3: *Collinear safety violation. The splitting of one tower into two can change the jet properties.*

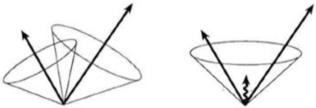
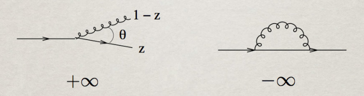
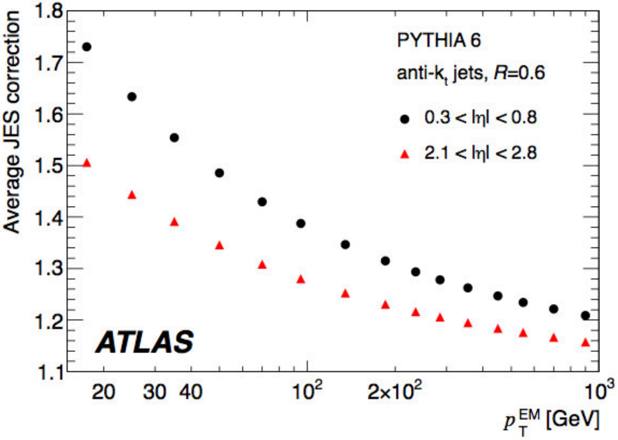


Figure 4.2: *Infrared safety violation: the radiation of a soft gluon can change the jet properties.*



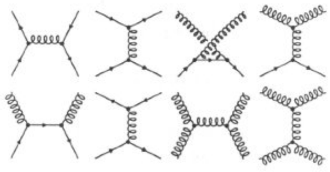
2. Jet energy correction factor



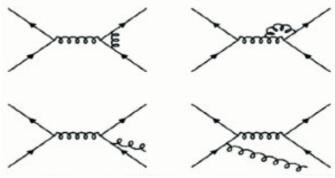
9. Appendix

3.1. Jet production mechanism at hadron colliders:

Often many diagrams contribute:

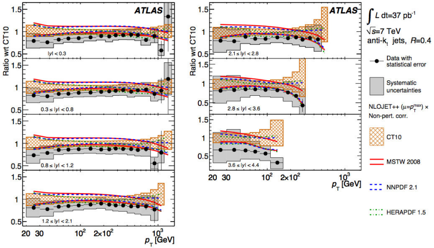


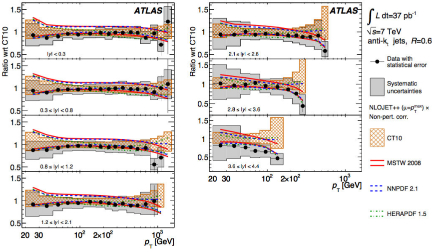
Higher order corrections important:



3.1. Inclusive jet cross section measurements

ratio of inclusive double-differential cross section to theoretical predicitions





no major deviation observed over the full momentum range

9. Appendix

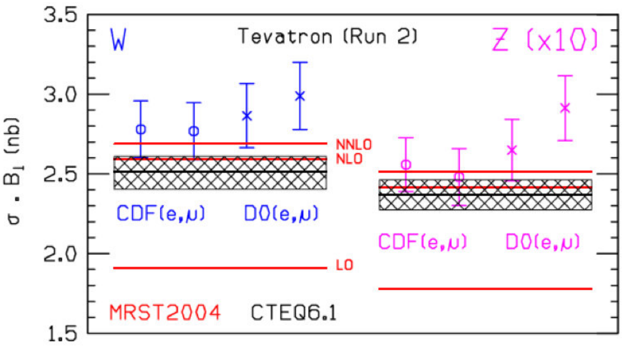
3.3. Systematic uncertainties inclusive and dijet dominant systematic uncertainties on inclusive jet cross section measurements:

p_T [GeV]	$\|y\|$	JES	JER	Trigger	Jet Rec.
20–30	2.1–2.8	$^{+35\%}_{-30\%}$	17%	1%	2%
20–30	3.6–4.4	$^{+65\%}_{-50\%}$	13%	1%	2%
80–110	< 0.3	10%	1%	1%	1%

dominant systematic uncertainties on dijet cross section measurements:

m_{12} [TeV]	y^*	JES	JER	Trigger	Jet Rec.
0.37–0.44	2.0–2.5	$^{+46\%}_{-27\%}$	7%	1%	2%
2.55–3.04	4.0–4.4	$^{+110\%}_{-50\%}$	8%	2%	2%
0.21–0.26	< 0.5	10%	1%	1%	2%

4. W/Z production NNLO predicitons



4. W/Z production cross section systematic uncertainties

	W^+				W^-				W			
Electron channel												
	value	stat	syst	lumi	value	stat	syst	lumi	value	stat	syst	lumi
N_W^{sig}	604.2	25.2	7.6	2.0	403.2	20.8	7.5	1.5	1007.5	32.7	10.8	3.5
L_W [nb^{-1}]	315	-	-	35	315	-	-	35	315	-	-	35
C_W	0.656	-	0.046	-	0.662	-	0.046	-	0.659	-	0.046	-
A_W	0.466	-	0.014	-	0.457	-	0.014	-	0.462	-	0.014	-
Muon channel												
	value	stat	syst	lumi	value	stat	syst	lumi	value	stat	syst	lumi
N_W^{sig}	655.6	26.6	6.2	4.7	425.0	21.7	5.4	3.9	1080.6	34.4	11.2	8.5
L_W [nb^{-1}]	310	-	-	34	310	-	-	34	310	-	-	34
C_W	0.765	-	0.031	-	0.748	-	0.030	-	0.758	-	0.030	-
A_W	0.484	-	0.015	-	0.475	-	0.014	-	0.480	-	0.014	-

main bkg contributions:

- $W \to \tau\nu$: leptonic τ decay
- $Z \to ll$: $z \to \mu\mu$ with one missing muon contributes to W-analysis
- $Z \to \tau\tau$: single or double leptonic tau decay
- $t\bar{t}$ production
- QCD processes: semileptonic decays of heavy quarks, hadrons misidentified als electrons and electrons from conversions

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4. W/Z production cross section systematic uncertainties on Cw in muon channel:

Parameter	$\delta C_W/C_W(\%)$	$\delta C_Z/C_Z(\%)$
Trigger efficiency	1.9	0.7
Reconstruction efficiency	2.5	5.0
Momentum scale	1.2	0.5
Momentum resolution	0.2	0.5
E_T^{miss} scale and resolution	2.0	-
Isolation efficiency	1.0	2.0
Theoretical uncertainty (PDFs)	0.3	0.3
Total uncertainty	4.0	5.5

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W/Z production cross section meausurements, fiducial cross section:

$$\sigma^{fid}_{W/Z} \cdot BR(W/Z \to l\nu/ll) = \sigma^{tot}_{W/Z} \cdot BR(W/Z \to l\nu/ll) \cdot A_{W/Z}$$

$A_{W/Z}$: detector acceptance for considered W/Z-boson decay

	$\sigma^{tot}_{W(\pm)} \cdot \mathrm{BR}(W \to e\nu)$ [nb]	$\sigma^{tot}_{W(\pm)} \cdot \mathrm{BR}(W \to \mu\nu)$ [nb]
W^+	$6.27 \pm 0.26(\mathrm{stat}) \pm 0.48(\mathrm{syst}) \pm 0.69(\mathrm{lumi})$	$5.71 \pm 0.23(\mathrm{stat}) \pm 0.30(\mathrm{syst}) \pm 0.63(\mathrm{lumi})$
W^-	$4.23 \pm 0.22(\mathrm{stat}) \pm 0.33(\mathrm{syst}) \pm 0.47(\mathrm{lumi})$	$3.86 \pm 0.20(\mathrm{stat}) \pm 0.20(\mathrm{syst}) \pm 0.42(\mathrm{lumi})$
W	$10.51 \pm 0.34(\mathrm{stat}) \pm 0.81(\mathrm{syst}) \pm 1.16(\mathrm{lumi})$	$9.58 \pm 0.30(\mathrm{stat}) \pm 0.50(\mathrm{syst}) \pm 1.05(\mathrm{lumi})$
	$\sigma^{tot}_{Z/\gamma^*} \cdot \mathrm{BR}(Z/\gamma^* \to ee)$ [nb], $66 < m_{ee} < 116$ GeV	$\sigma^{tot}_{Z/\gamma^*} \cdot \mathrm{BR}(Z/\gamma^* \to \mu\mu)$ [nb], $66 < m_{\mu\mu} < 116$ GeV
Z/γ^*	$0.75 \pm 0.09(\mathrm{stat}) \pm 0.08(\mathrm{syst}) \pm 0.08(\mathrm{lumi})$	$0.87 \pm 0.08(\mathrm{stat}) \pm 0.06(\mathrm{syst}) \pm 0.10(\mathrm{lumi})$

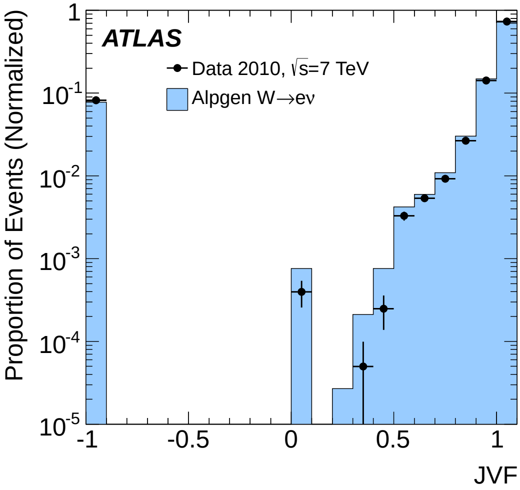
	$\sigma^{fid}_{W(\pm)} \cdot \mathrm{BR}(W \to e\nu)$ [nb]	$\sigma^{fid}_{W(\pm)} \cdot \mathrm{BR}(W \to \mu\nu)$ [nb]
W^+	$2.92 \pm 0.12(\mathrm{stat}) \pm 0.21(\mathrm{syst}) \pm 0.32(\mathrm{lumi})$	$2.77 \pm 0.11(\mathrm{stat}) \pm 0.12(\mathrm{syst}) \pm 0.30(\mathrm{lumi})$
W^-	$1.93 \pm 0.10(\mathrm{stat}) \pm 0.14(\mathrm{syst}) \pm 0.21(\mathrm{lumi})$	$1.83 \pm 0.09(\mathrm{stat}) \pm 0.08(\mathrm{syst}) \pm 0.20(\mathrm{lumi})$
W	$4.85 \pm 0.16(\mathrm{stat}) \pm 0.34(\mathrm{syst}) \pm 0.53(\mathrm{lumi})$	$4.60 \pm 0.15(\mathrm{stat}) \pm 0.20(\mathrm{syst}) \pm 0.51(\mathrm{lumi})$
	$\sigma^{fid}_{Z/\gamma^*} \cdot \mathrm{BR}(Z/\gamma^* \to ee)$ [nb], $66 < m_{ee} < 116$ GeV	$\sigma^{fid}_{Z/\gamma^*} \cdot \mathrm{BR}(Z/\gamma^* \to \mu\mu)$ [nb], $66 < m_{\mu\mu} < 116$ GeV
Z/γ^*	$0.33 \pm 0.04(\mathrm{stat}) \pm 0.03(\mathrm{syst}) \pm 0.04(\mathrm{lumi})$	$0.43 \pm 0.04(\mathrm{stat}) \pm 0.02(\mathrm{syst}) \pm 0.05(\mathrm{lumi})$

4. W/Z production cross section meausurements

all systemativ uncertainties on total cross section results mainly dominated by $C_{W/Z}$ uncertainties:

	W^+				W^-				W			
Electron channel												
	value	stat	syst	lumi	value	stat	syst	lumi	value	stat	syst	lumi
N_W^{sig}	604.2	25.2	7.6	2.0	403.2	20.8	7.5	1.5	1007.5	32.7	10.8	3.5
L_W [nb^{-1}]	315	-	-	35	315	-	-	35	315	-	-	35
C_W	0.656	-	0.046	-	0.662	-	0.046	-	0.659	-	0.046	-
A_W	0.466	-	0.014	-	0.457	-	0.014	-	0.462	-	0.014	-
Muon channel												
	value	stat	syst	lumi	value	stat	syst	lumi	value	stat	syst	lumi
N_W^{sig}	655.6	26.6	6.2	4.7	425.0	21.7	5.4	3.9	1080.6	34.4	11.2	8.5
L_W [nb^{-1}]	310	-	-	34	310	-	-	34	310	-	-	34
C_W	0.765	-	0.031	-	0.748	-	0.030	-	0.758	-	0.030	-
A_W	0.484	-	0.015	-	0.475	-	0.014	-	0.480	-	0.014	-

4. W+jets cross section measurements
JVF distribution:



5. W+jets cross section measurements systematic uncertainties for electron and muon final states:

$W \to e\nu$ channel			
		Cross Section Uncertainty (%)	
Effect	Range	$N_{\rm jet} \geq 1$	$N_{\rm jet} \geq 4$
Jet and cluster energy scales	2.5–14% (dependent on jet η and $p_{\rm T}$)	+9.0, −6.6	+37, −35
Jet energy resolution	~10% on each jet (dependent on jet η and $p_{\rm T}$)	±1.6	±6
Electron trigger	±0.5%	+0.6, −0.5	±1
Electron reconstruction	±1.5%	+1.7, −1.6	±4
Electron identification	±2–8% (dependent on electron η and $p_{\rm T}$)	+4.3, −4.0	+10, −9
Electron energy scale	±0.3–1.6% (dependent on η and $p_{\rm T}$)	±0.6	+1, −3
Electron energy resolution	< 0.6% of the energy	±0.0	<1
Pile–up removal requirement	~ 1.5% in lowest jet $p_{\rm T}$ bin	±1.1	±3
Multijet QCD background shape	from template variation	±0.7	±11
Unfolding	ALPGEN vs. SHERPA	±1.5	±6
Luminosity	±3.4%	+3.8, −3.6	+9, −8
NNLO cross section for W/Z	±5%	±0.2	<1
NLO cross section for $t\bar{t}$	$^{+7}_{-10}$%	±0.3	±10
Simulated $t\bar{t}$ shape	from samples with more or less ISR	±0.1	+12, −21

$W \to \mu\nu$ channel			
		Cross Section Uncertainty (%)	
Effect	Range	$N_{\rm jet} \geq 1$	$N_{\rm jet} \geq 4$
Jet and cluster energy scales	2.5–14% (dependent on jet η and $p_{\rm T}$)	+8.2, −6.2	+33, −26
Jet energy resolution	10% on each jet (dependent on jet η and $p_{\rm T}$)	±1.5	±5
Muon trigger	±0.7% (±0.6%) in barrel (endcap)	±0.6	±1
Muon reconstruction and identification	±1.1%	±1.1	±2
Muon momentum scale	±0.4%	+0.2, −0.3	<1
Muon momentum resolution	±6%	±0.1	<1
Pile–up removal requirement	~ 1.5% in lowest jet $p_{\rm T}$ bin	±1.0	±3
Multijet QCD background shape	from template variation	+0.8	−20
Unfolding	ALPGEN vs. SHERPA	±0.2	<1
Luminosity	±3.4%	+3.7, −3.5	±7
NNLO cross section for W/Z	±5%	±0.4	<1
NLO cross section for $t\bar{t}$	$^{+7}_{-10}$%	+0.4, −0.3	+10, −7
Simulated $t\bar{t}$ shape	from samples with more or less ISR	<0.1	+13, −15

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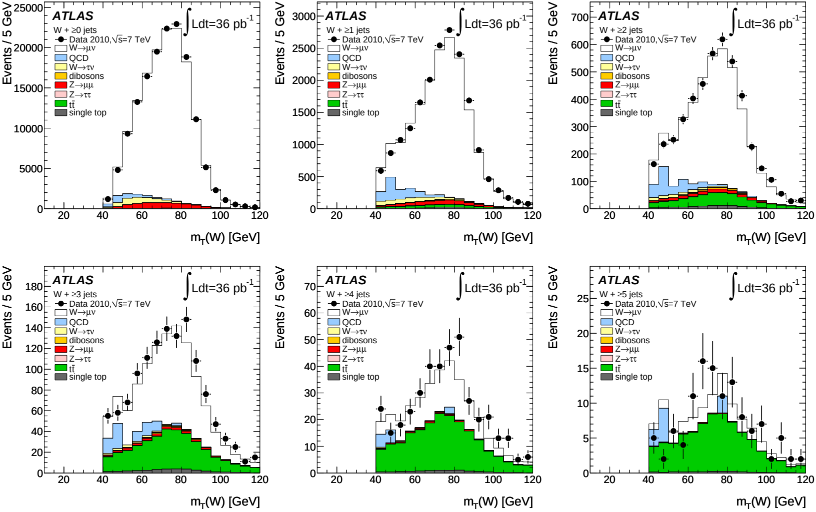
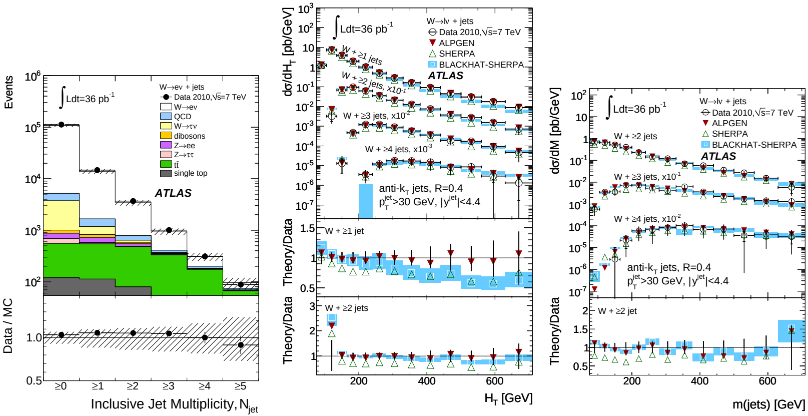
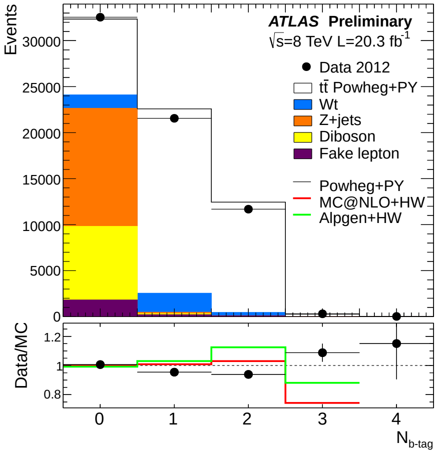
5. W+jets cross section measurements transv. mass distributions for different jet multiplicities:

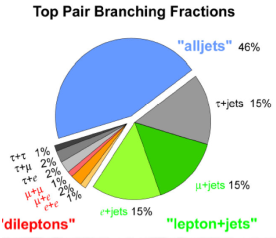


5. W+jets cross section measurements



6. $t\bar{t}$ cross section measurements
distribution of the number of b-tagged jets:





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6. $t\bar{t}$ cross section measurements

systematic uncertainties dilepton:

Uncertainty	$\Delta\epsilon_{e\mu}/\epsilon_{e\mu}$ (%)	$\Delta C_b/C_b$ (%)	$\Delta\sigma_{t\bar{t}}/\sigma_{t\bar{t}}$ (%)	$\Delta\sigma_{t\bar{t}}$ (pb)	$\Delta\epsilon_b/\epsilon_b$ (%)
Data statistics	-	-	0.72	1.7	0.57
$t\bar{t}$ modelling	0.91	-0.61	1.52	3.6	0.61
Initial/final state radiation	-0.76	0.26	1.23	2.9	0.37
Parton density functions	1.08	-	1.09	2.6	0.06
QCD scale choices	0.30	-	0.30	0.7	0.00
Single-top modelling	-	-	0.38	0.9	0.56
Single-top/$t\bar{t}$ interference	-	-	0.15	0.4	0.25
Single-top Wt cross-section	-	-	0.70	1.7	0.24
Diboson modelling	-	-	0.42	1.0	0.19
Diboson cross-sections	-	-	0.03	0.1	0.01
Z+jets extrapolation	-	-	0.05	0.1	0.02
Electron energy scale/resolution	0.43	0.01	0.48	1.1	0.03
Electron identification/isolation	1.28	0.00	1.42	3.4	0.05
Muon momentum scale/resolution	0.01	0.01	0.05	0.1	0.02
Muon identification/isolation	0.50	0.00	0.52	1.2	0.01
Lepton trigger	0.15	0.00	0.16	0.4	0.01
Jet energy scale	0.46	0.07	0.49	1.2	0.11
Jet energy resolution	-0.44	0.04	0.59	1.4	0.08
Jet reconstruction/vertex fraction	0.02	0.01	0.04	0.1	0.01
b-tagging	-	0.13	0.42	1.0	0.09
Pileup modelling	-0.30	0.05	0.28	0.7	0.05
Misidentified leptons	-	-	0.38	0.9	0.12
Total systematic	2.29	0.69	3.12	7.4	1.02
Integrated luminosity	-	-	3.11	7.4	0.11
LHC beam energy	-	-	1.70	4.0	0.00
Total uncertainty	2.29	0.69	4.77	11.3	1.17

systematic uncertainties single lepton:

Source	$e+\geq 3$ jets	$\mu+\geq 3jets$	combined
Jet/MET reconstruction, calibration	6.7, -6.3	5.4, -4.6	5.9, -5.2
Lepton trigger, identification and reconstruction	2.4, -2.7	4.7, -4.2	2.7, -2.8
Background normalization and composition	1.9, -2.2	1.6, -1.5	1.8, -1.9
b-tagging efficiency	1.7, -1.3	1.9, -1.1	1.8, -1.2
MC modelling of the signal	±12	±11	±11
Total	±14	±13	±13