W/Z and top at the LHC

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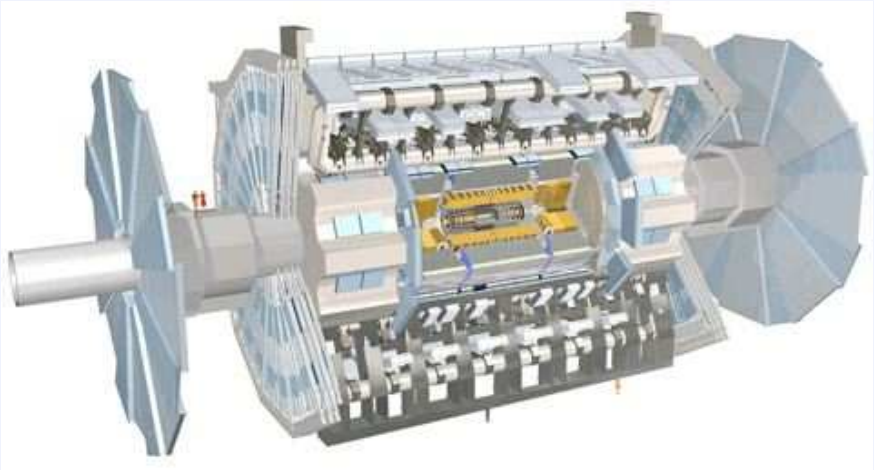
LHC experiments have been built for discovery

- New physics = measurement − standard model physics (background)
  - Need re-discovery of the standard model particles at the first stage of the experiment
- W/Z and top are the heavy particles in the standard model
  - Measurements of these particles are good exercise for discovery
    - yesterday's signal is today's control sample and tomorrow's background, in other word, bridge to New Physics
  - Let's start with W/Z and top as today's signal
- K. Hanagaki: Higgs searches at the LHC
- A. Ishikawa: BSM physics at the LHC

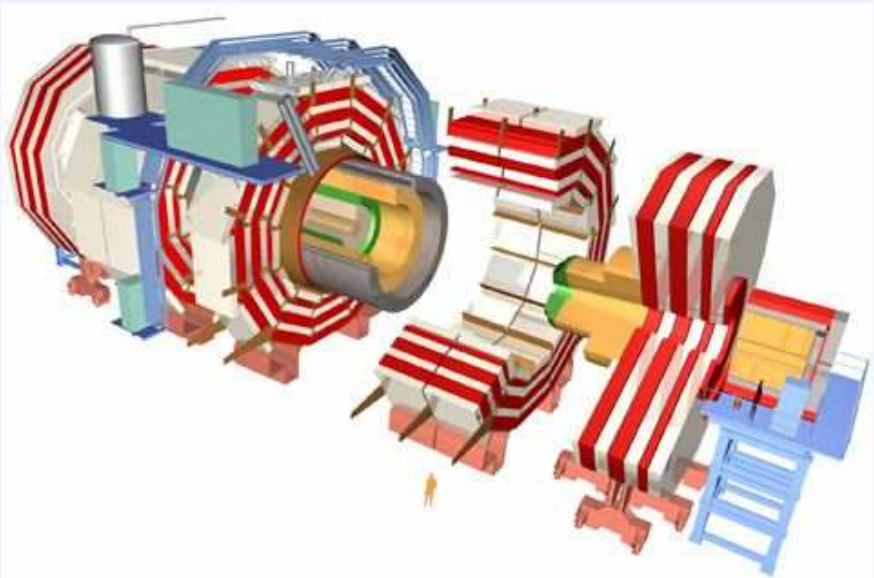
- ATLAS/CMS detectors
- W/Z at LHC
  - $W \rightarrow l\nu$: E_T^{miss}, M_T
  - $Z \rightarrow ll$: invariant mass
  - $W \rightarrow l\nu$, $Z \rightarrow ll$: cross sections
  - W/Z to τ
  - W/Z distributions with full 2010 data
  - W/Z + jets
- top at LHC
  - top control plots
  - top cross sections
- summary

ATLAS detector overview



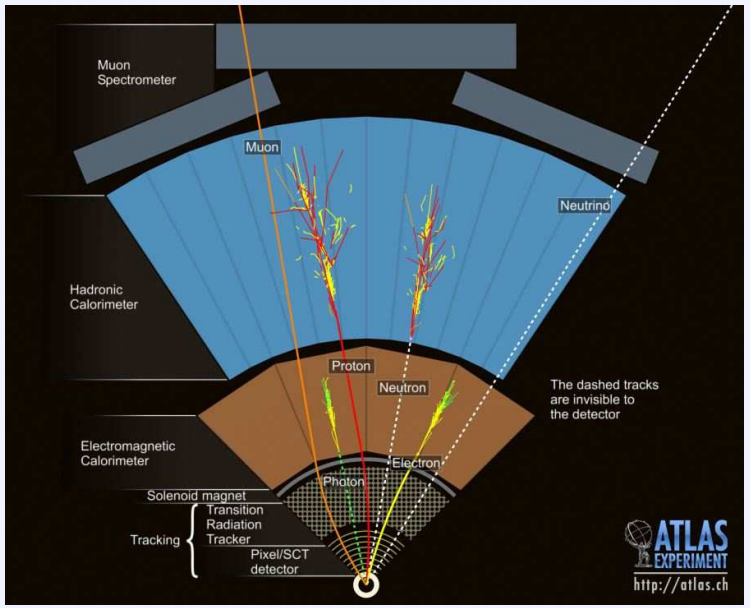
- length: ∼45 m
- diameter: ∼22 m
- weight: ∼7,000 tons
- 2 T solenoid and air-core toroids

CMS detector overview

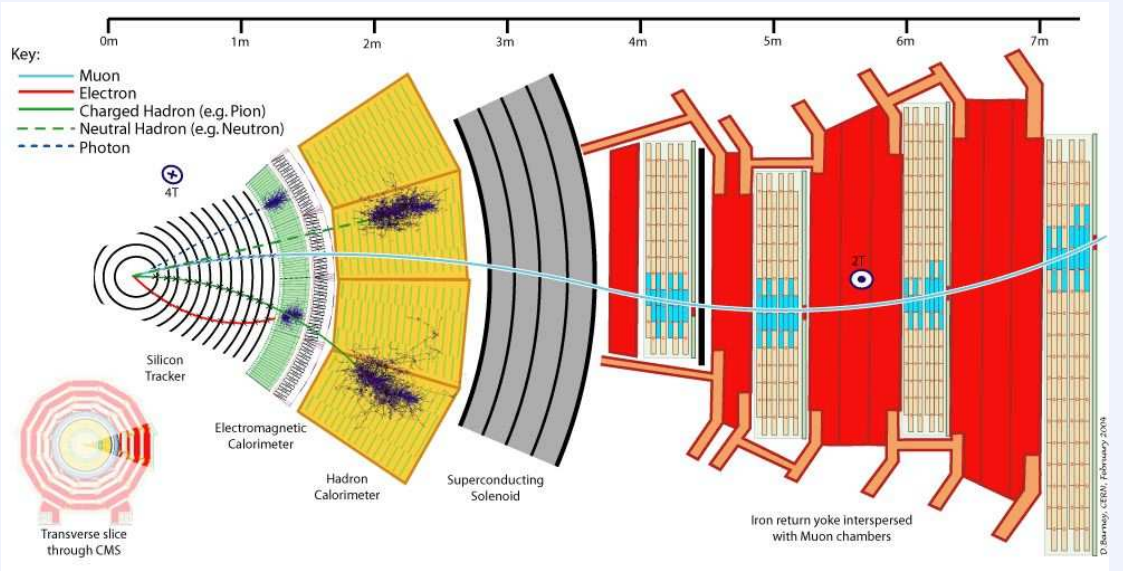


- length: 21.6 m
- diameter: 15 m
- weight: 12,500 tons
- 3.8 T solenoid and iron return york

ATLAS detector layout



CMS detector layout



- Tracker
  - silicon tracker (pixel + strip), transition radiation tracker
- Calorimeter
  - EM: lead/LAr, HAD: steel/scintillator, copper/LAr
- Muon system
  - drift tube, cathod strip chamber, thin-gap chamber, resistive plate chamber

- Tracker
  - silicon tracker (pixel + strip)
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  - EM: lead tangsten crystal, HAD: brass/steel and scintillator
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W/Z at LHC

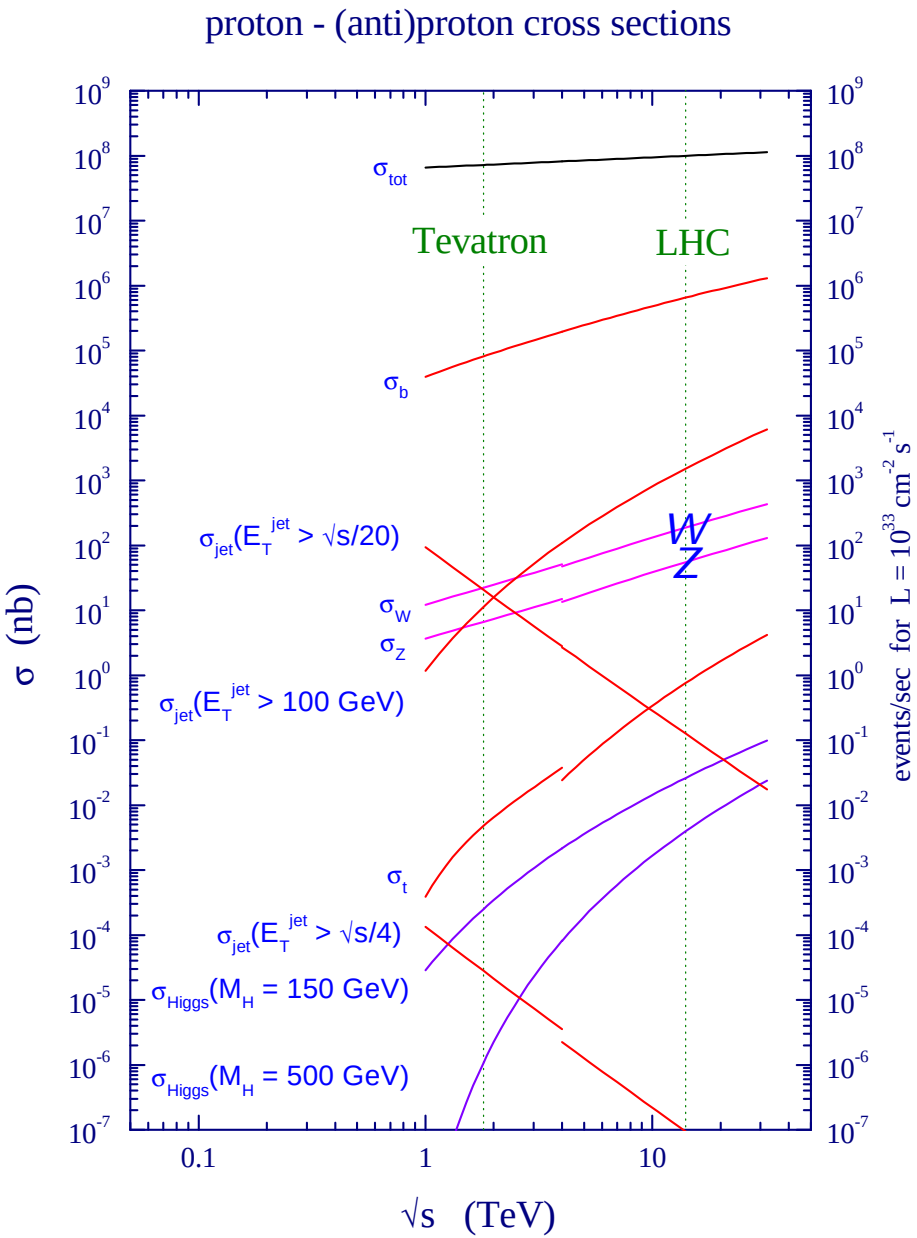
W/Z are important for:

- detector performance study with high-p_T objects
  - lepton identification
  - E_T^{miss}
- test of the SM at 7 TeV

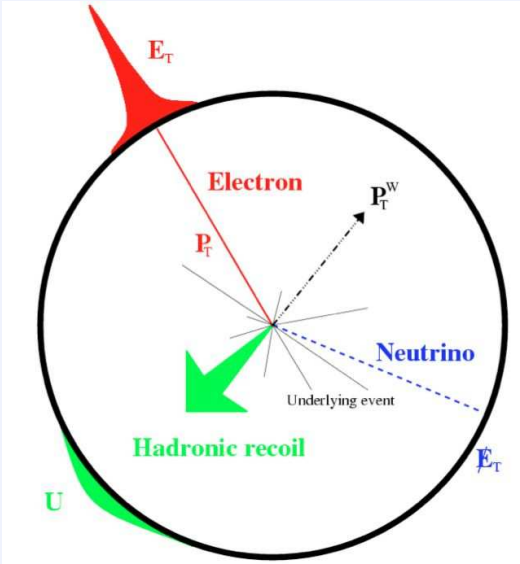
  cross section known at NNLO

$\sigma^{NNLO}_{W\to l\nu}$	10.5 ± 0.5 nb
$\sigma^{NNLO}_{Z/\gamma^*\to ll}$	1.0 ± 0.1 nb

- background study for new physics searches

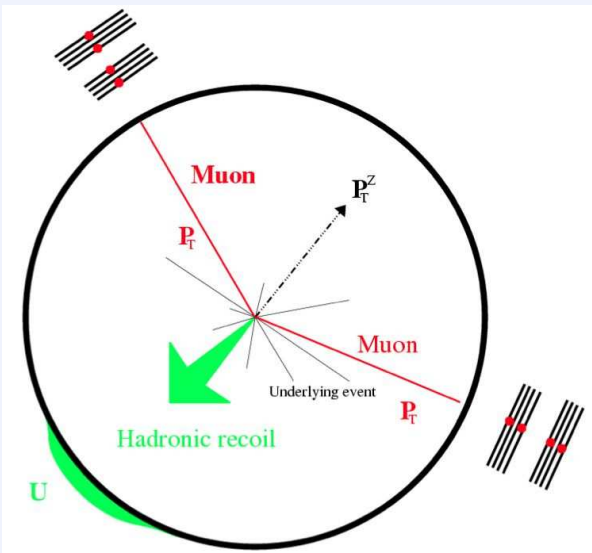


$W \to l\nu$ event topology



- high-p_T lepton
  - cluster of energy deposit in electro-magnetic calorimeter
  - track in muon spectrometer
- E_T^{miss}
- characterised by transverse mass
  $M_T = \sqrt{2E_{T\nu}E_{Tl} - 2p_{T\nu} \cdot p_{Tl}}$

$Z \to ll$ event topology



- two high-p_T leptons
  - cluster of energy deposit in electro-magnetic calorimeter
  - track in muon spectrometer
- characterised by invariant mass of di-lepton

- ATLAS/CMS detectors
- W/Z at LHC
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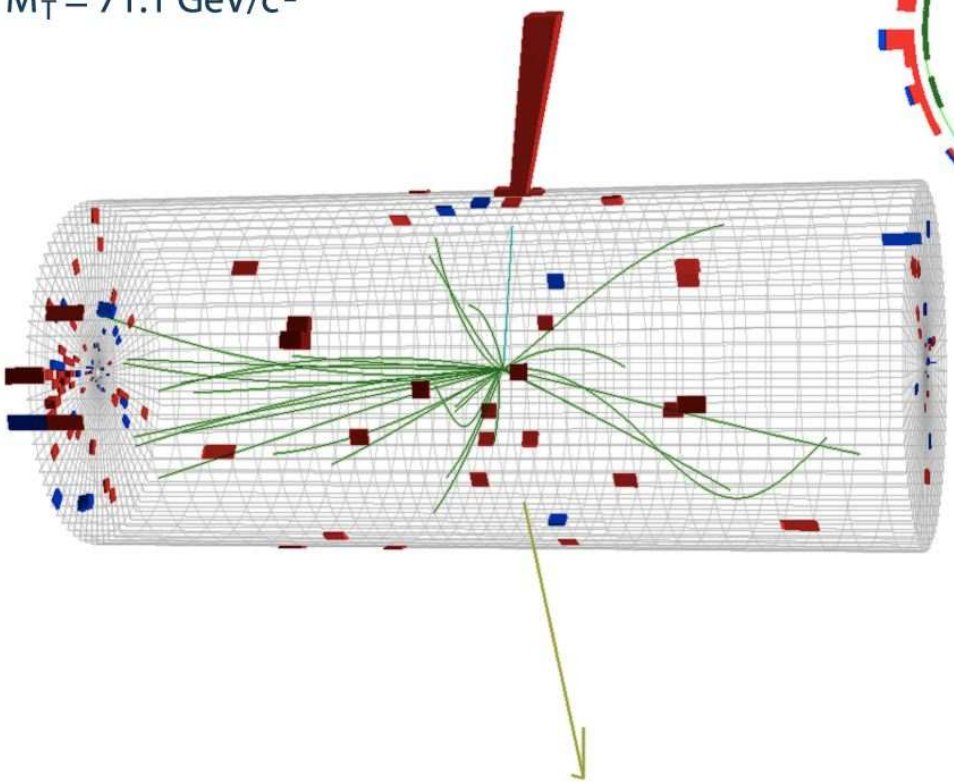
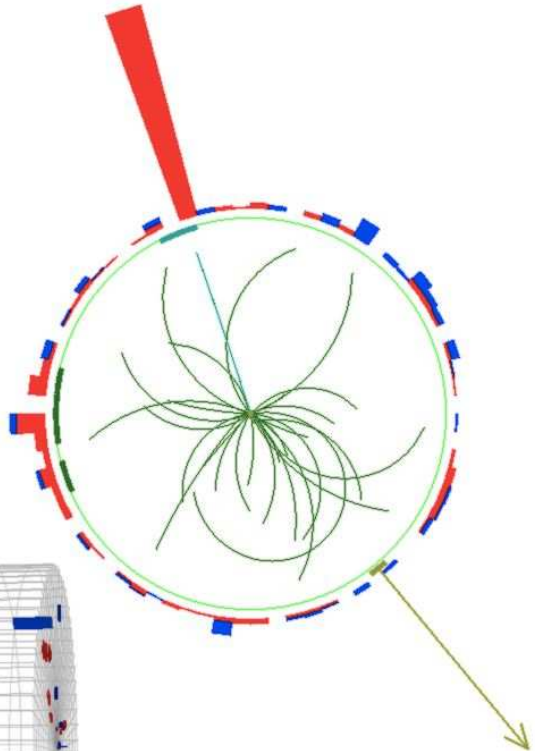
$W \to e\nu$ candidate

CMS

CMS Experiment at LHC, CERN
Run 133874, Event 21466935
Lumi section: 301
Sat Apr 24 2010, 05:19:21 CEST

Electron $p_T = 35.6$ GeV/c
$ME_T = 36.9$ GeV
$M_T = 71.1$ GeV/c^2

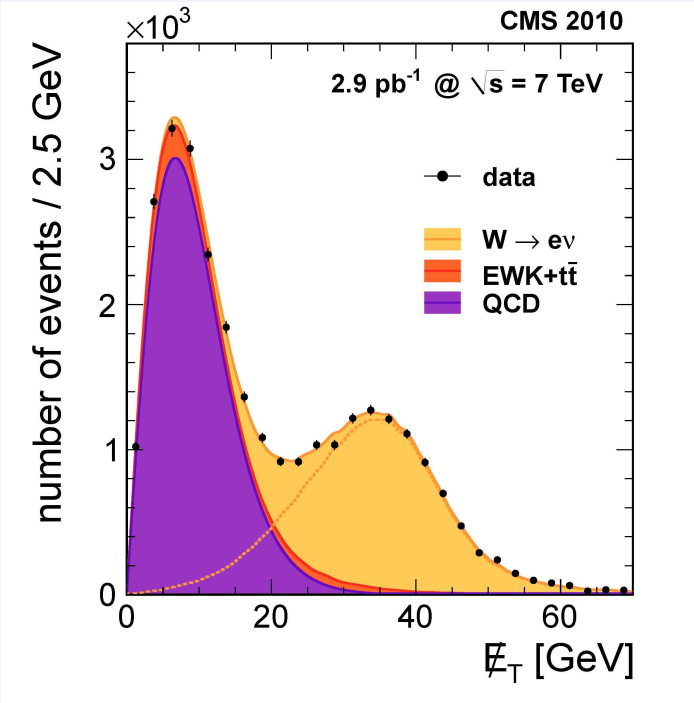




$W \rightarrow l\nu$

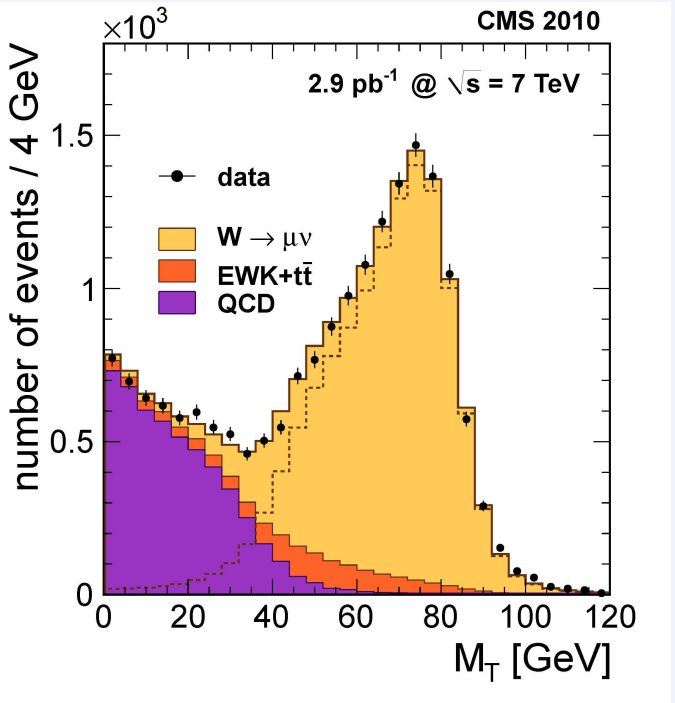
CMS: 2.9 pb^{-1}

electron channel



- $p_T > 20$ GeV, $|\eta| < 1.44$ or $1.57 < |\eta| < 2.5$
- unbinned likelihood fit:
  - QCD background modelled with a modified Rayleigh distribution
- fit distribution describes data well

muon channel

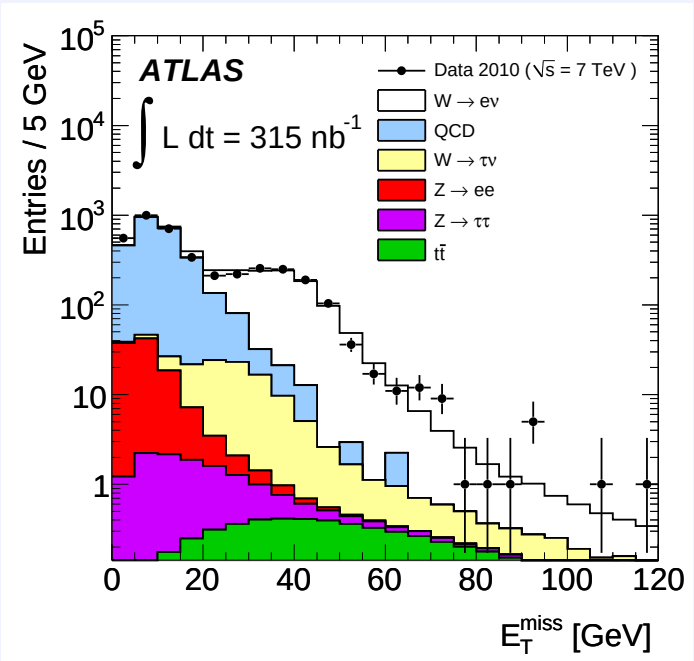


- $p_T > 20$ GeV, $|\eta| < 2.1$
- binned likelihood fit:
  - QCD background shape from data
- fit distribution describes data well

$W \to l\nu$

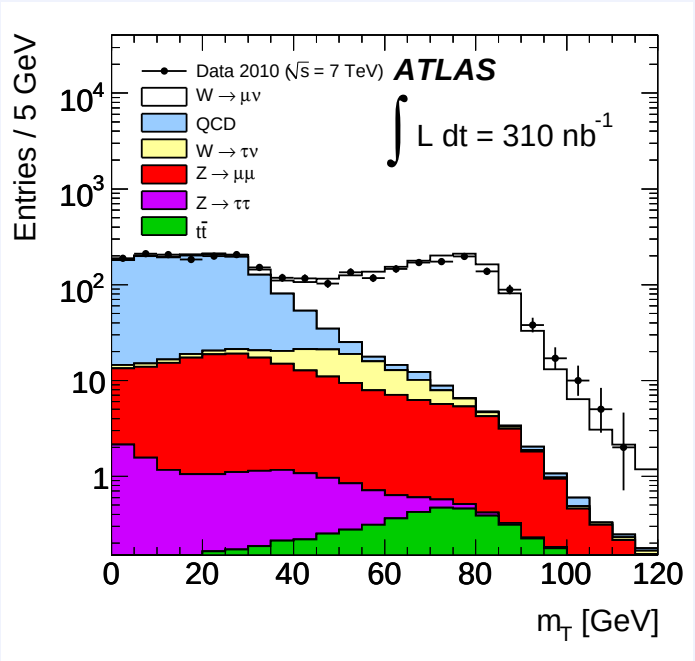
ATLAS: 0.3 pb^{-1}

electron channel



- $p_T > 20$ GeV, $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$
- W MC populates in high-E_T^{miss}

muon channel



- $p_T > 20$ GeV, $|\eta| < 2.4$
- W MC gives Jacobian peak in M_T distribution

- without $E_T^{\text{miss}} > 25$ GeV and $M_T > 40$ GeV cuts

- ATLAS/CMS detectors
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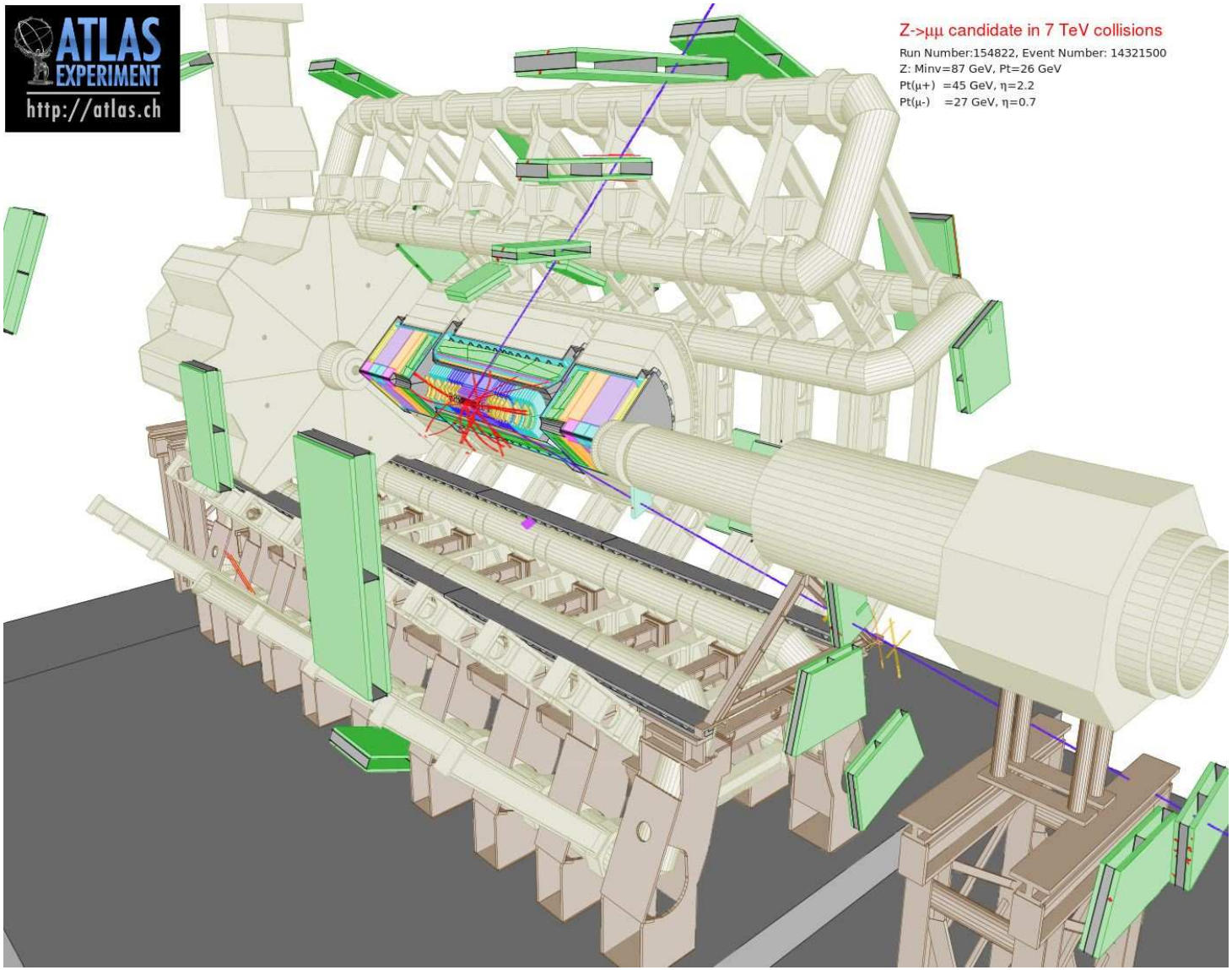
$Z \to \mu\mu$ candidate

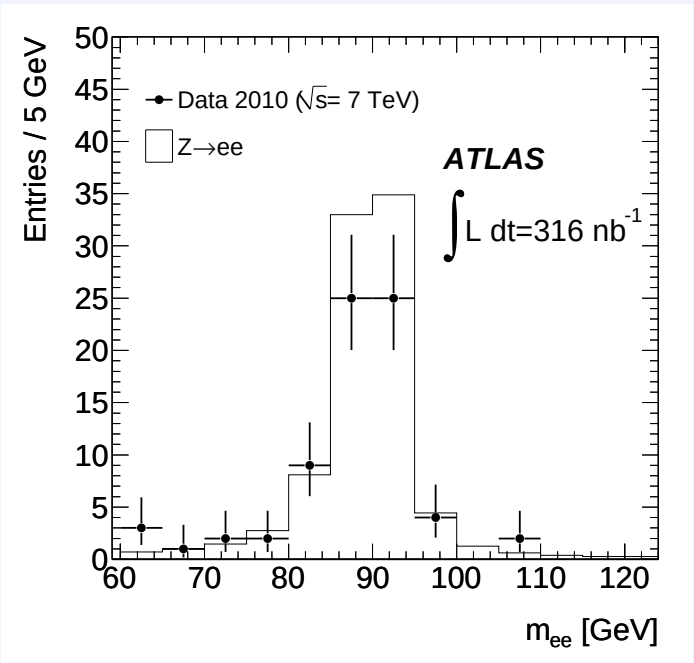
ATLAS



$Z \longrightarrow ll$

ATLAS: 0.3 pb^{-1}

electron channel



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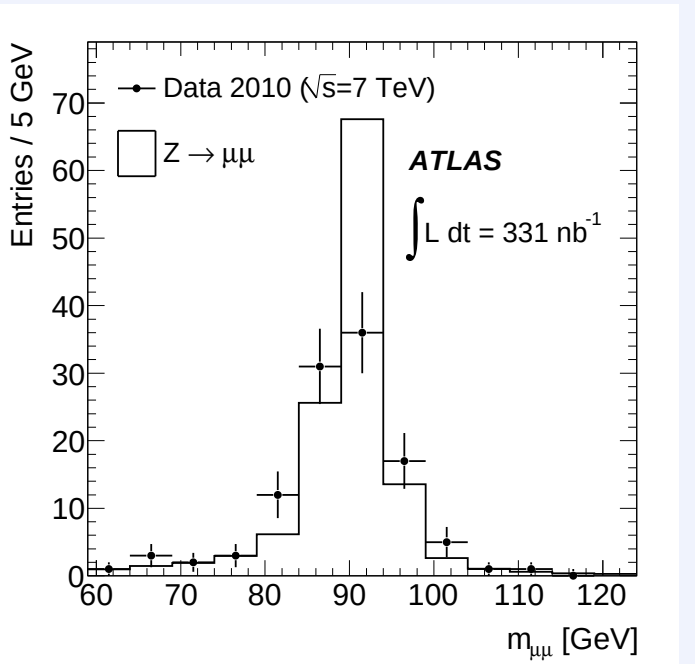
muon channel



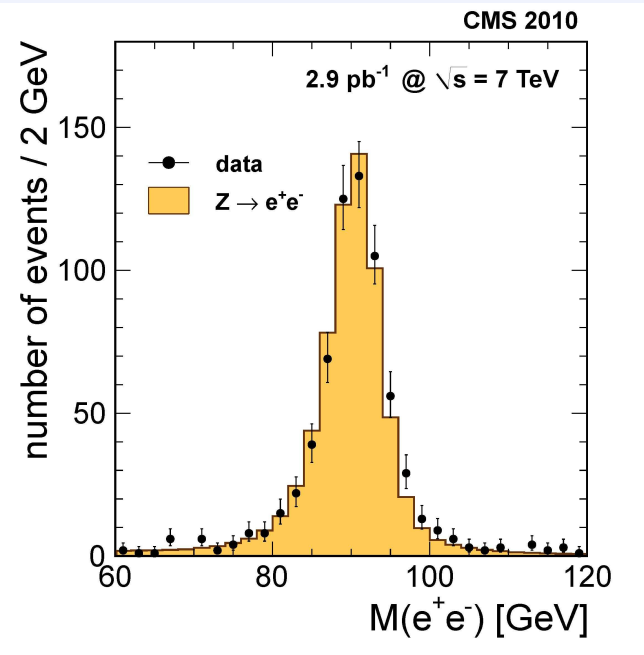
- $p_T > 20$ GeV, $|\eta| < 2.4$
- worse resolution in data taken into account in the systematics

- backgrounds are negligible and not shown

$Z \longrightarrow ll$

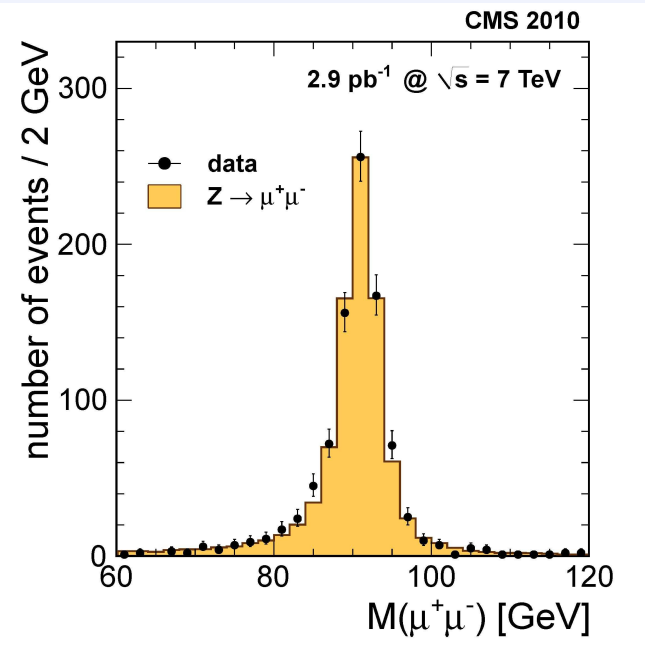
CMS: 2.9 pb^{-1}

electron channel



- $p_T > 20$ GeV, $|\eta| < 1.44$ or $1.57 < |\eta| < 2.5$

muon channel



- $p_T > 20$ GeV,
- $|\eta| < 2.1$

- backgrounds are negligible and not shown

- ATLAS/CMS detectors
- W/Z at LHC
  - $W \to l\nu$: E_T^{miss}, M_T
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W/Z cross sections

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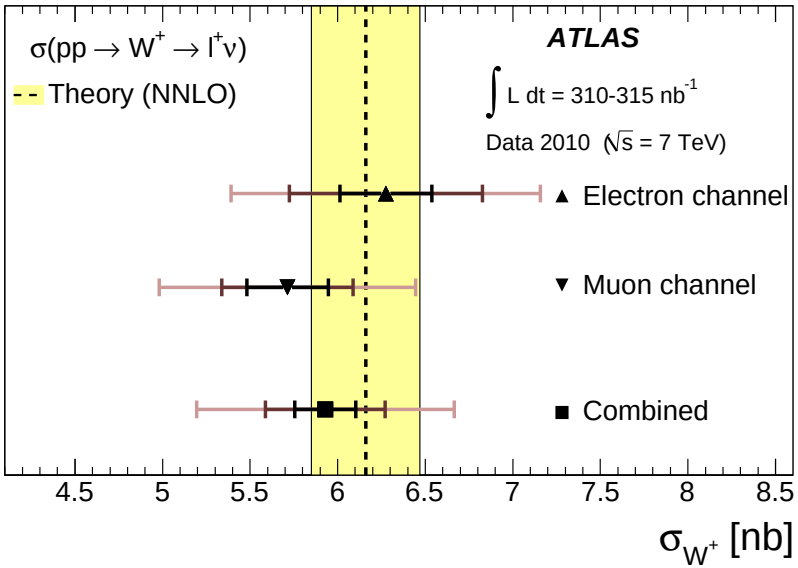
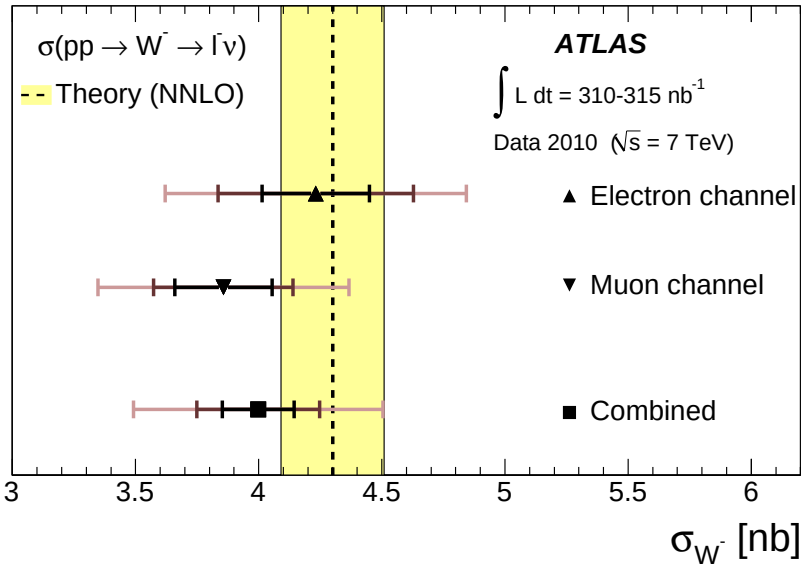
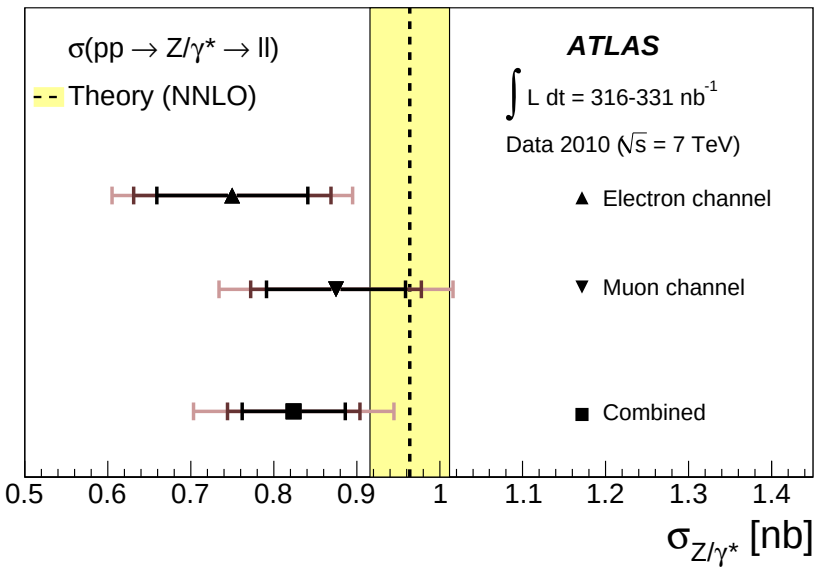






- measured cross sections agrees with the prediction within errors (stat. + syst. + lumi.) (Theory: FEWZ with MSTW 08 NNLO PDF)
- expected asymmetry between W^+ and W^- confirmed

W/Z cross sections: systematics

ATLAS: 0.3 pb^{-1}

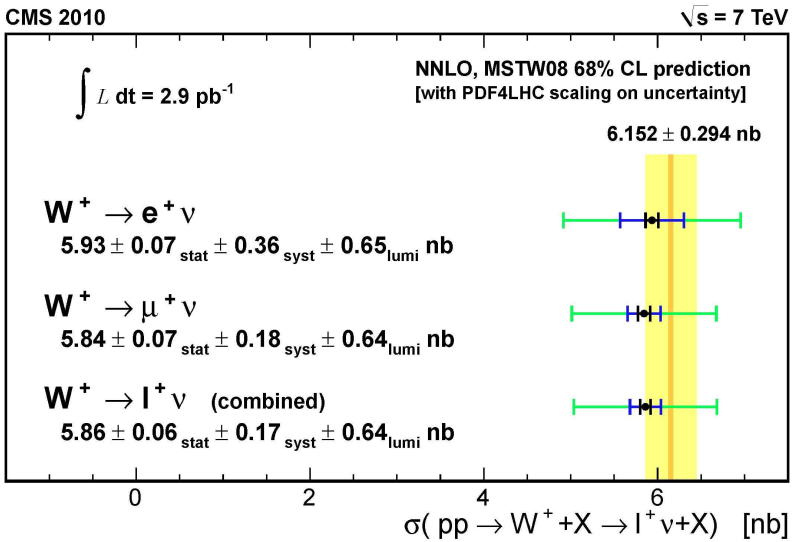
	$W \to e\nu$	$Z \to ee$
trigger eff.	< 0.2	< 0.2
material/reco./id	5.6	8.8
E scale/res.	3.3	1.9
E_T^{miss} scale/res.	2.0	-
problematic calo. region	1.4	2.7
pile-up	0.5	0.2
charge mis-id	0.5	0.5
FSR modelling	0.3	0.3
PDF	0.3	0.3
total	7.0	9.4

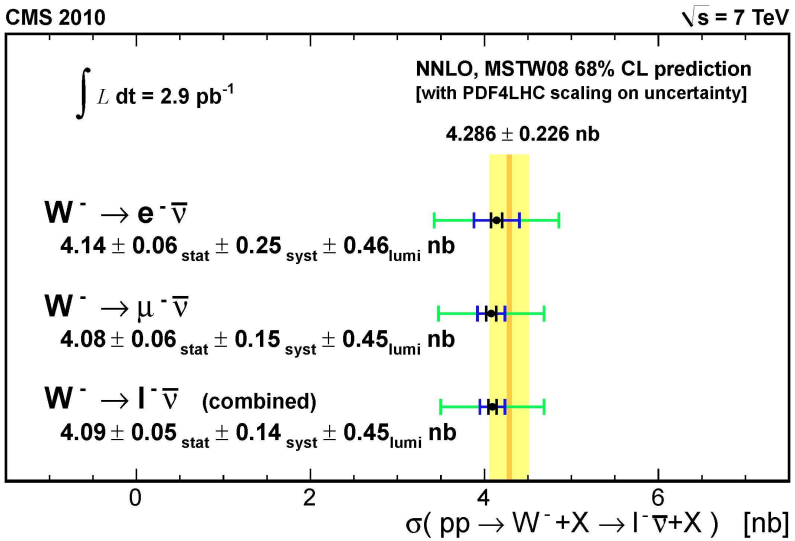
	$W \to \mu\nu$	$Z \to \mu\mu$
trigger eff.	1.9	0.7
reco eff.	2.5	5.0
momentum scale	1.2	0.5
momentum resolution	0.2	0.5
E_T^{miss} scale/res.	2.0	-
isolation eff.	1.0	2.0
PDF	0.3	0.3
total	4.0	5.5

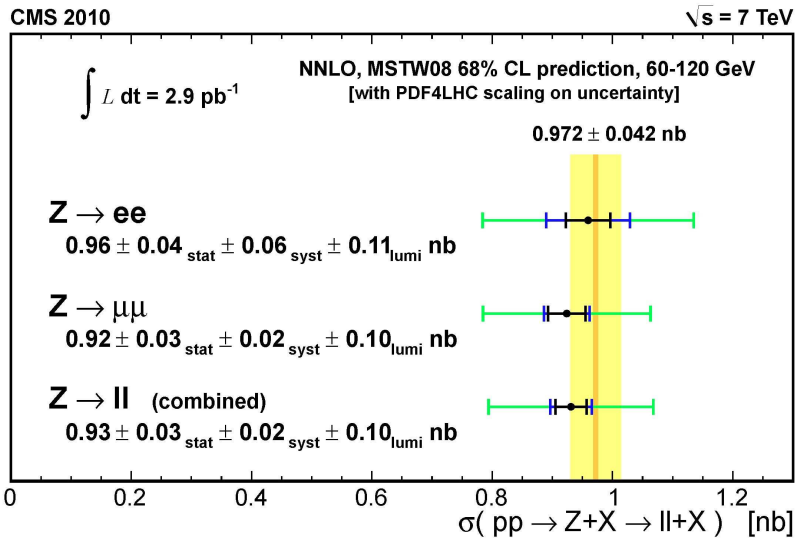
- electron have larger uncertainties due to higher sensitivity to the material effects in the inner detector.

W/Z cross sections

CMS: 2.9 pb^{-1}







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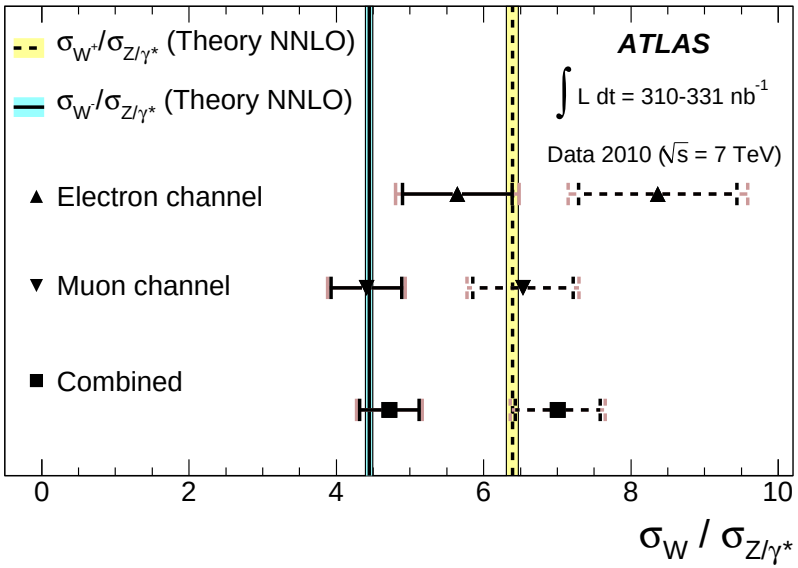
W/Z cross sections: systematics

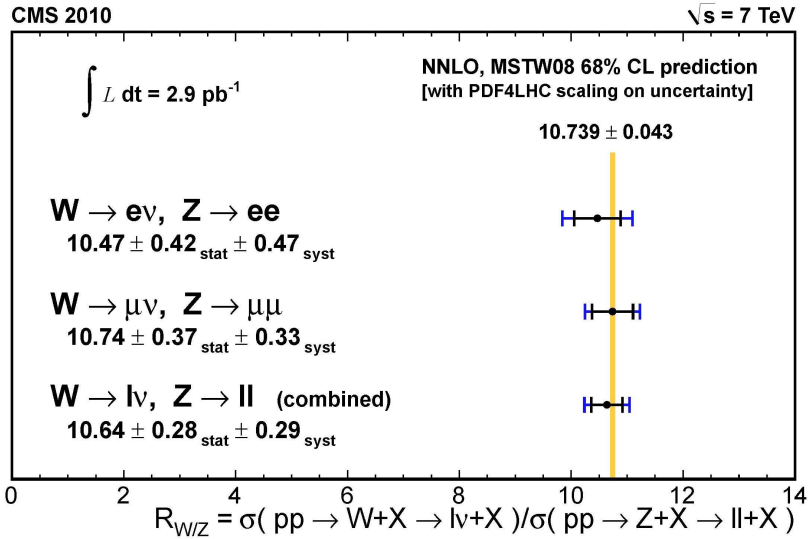
CMS: 2.9 pb^{-1}

	$W \to e\nu$	$Z \to ee$		$W \to \mu\nu$	$Z \to \mu\mu$
reco. & id. eff.	3.9	5.9	reco. & id. eff.	1.5	0.5
momentum scale/res.	2.0	0.6	momentum scale/res.	0.3	0.2
E_T^{miss} scale/res.	1.8	-	E_T^{miss} scale/res.	0.4	-
bg subtraction & modelling	1.3	0.1	bg subtraction & modelling	2.0	0.2
PDF	0.8	1.1	PDF	1.1	1.2
ISR/FSR/norm. & fact. scale	1.3	1.3	ISR/FSR/norm. & fact. scale	1.4	1.6
total	5.1	6.2	total	3.1	2.3

W/Z cross section ratio

ATLAS: 0.3 pb^{-1}, CMS: 2.9 pb^{-1}

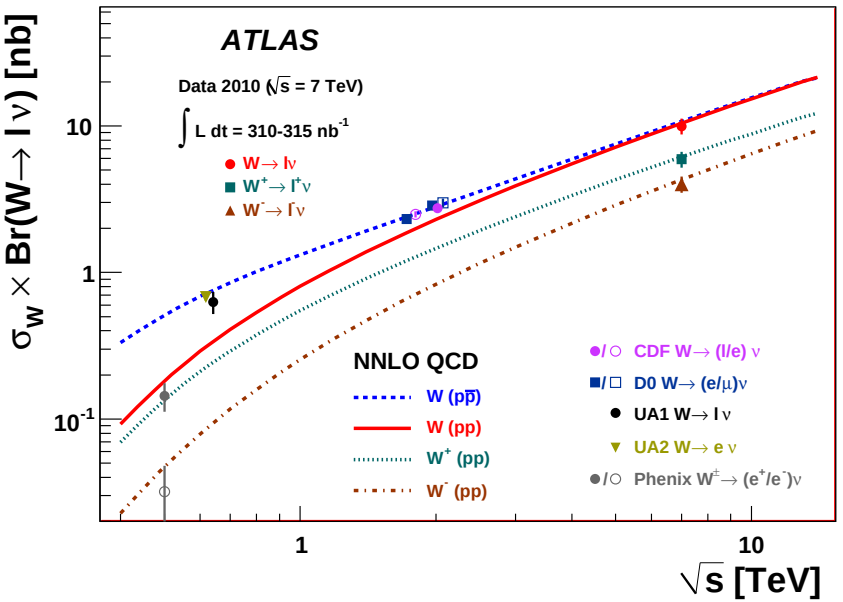


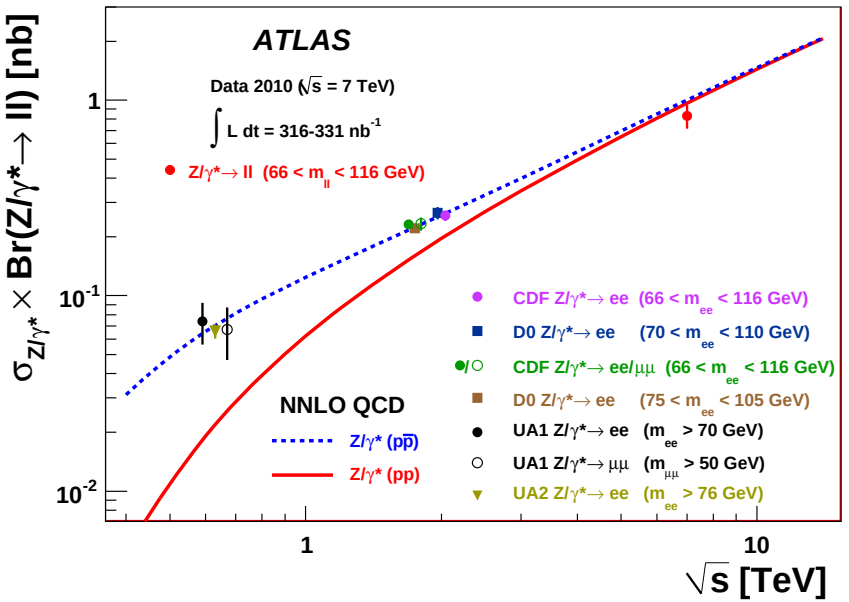


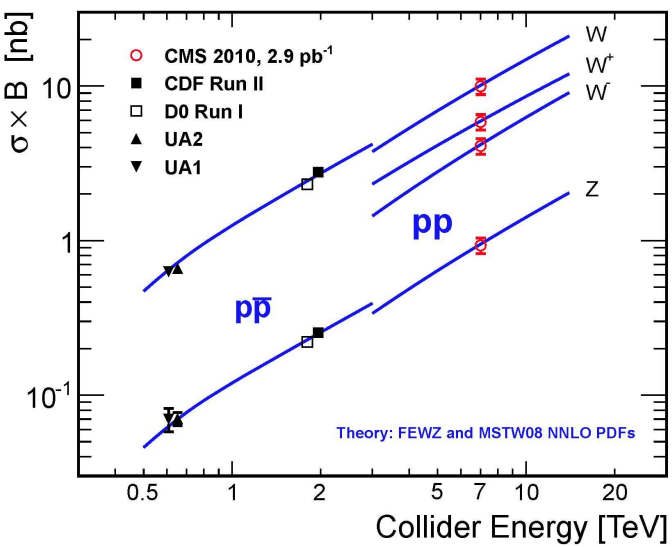
- Theory: FEWZ with the MSTW 08 NNLO PDF
- uncertainty on luminosity cancels out
- measured ratio are consistent with the predictions
  - ATLAS electron channel slightly higher than prediction due to slightly low observed $Z \longrightarrow ee$ cross section

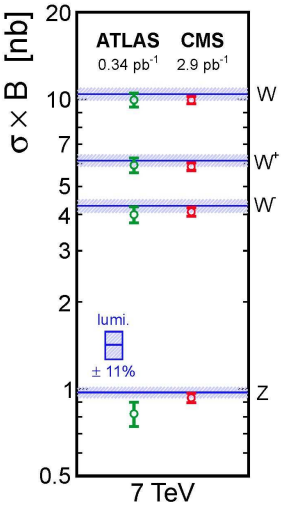
W/Z cross sections

ATLAS: 0.3 pb^{-1}, CMS: 2.9 pb^{-1}









- theoretical predictions are in good agreement with all measurements
- energy dependence of the W and Z production cross sections is well described

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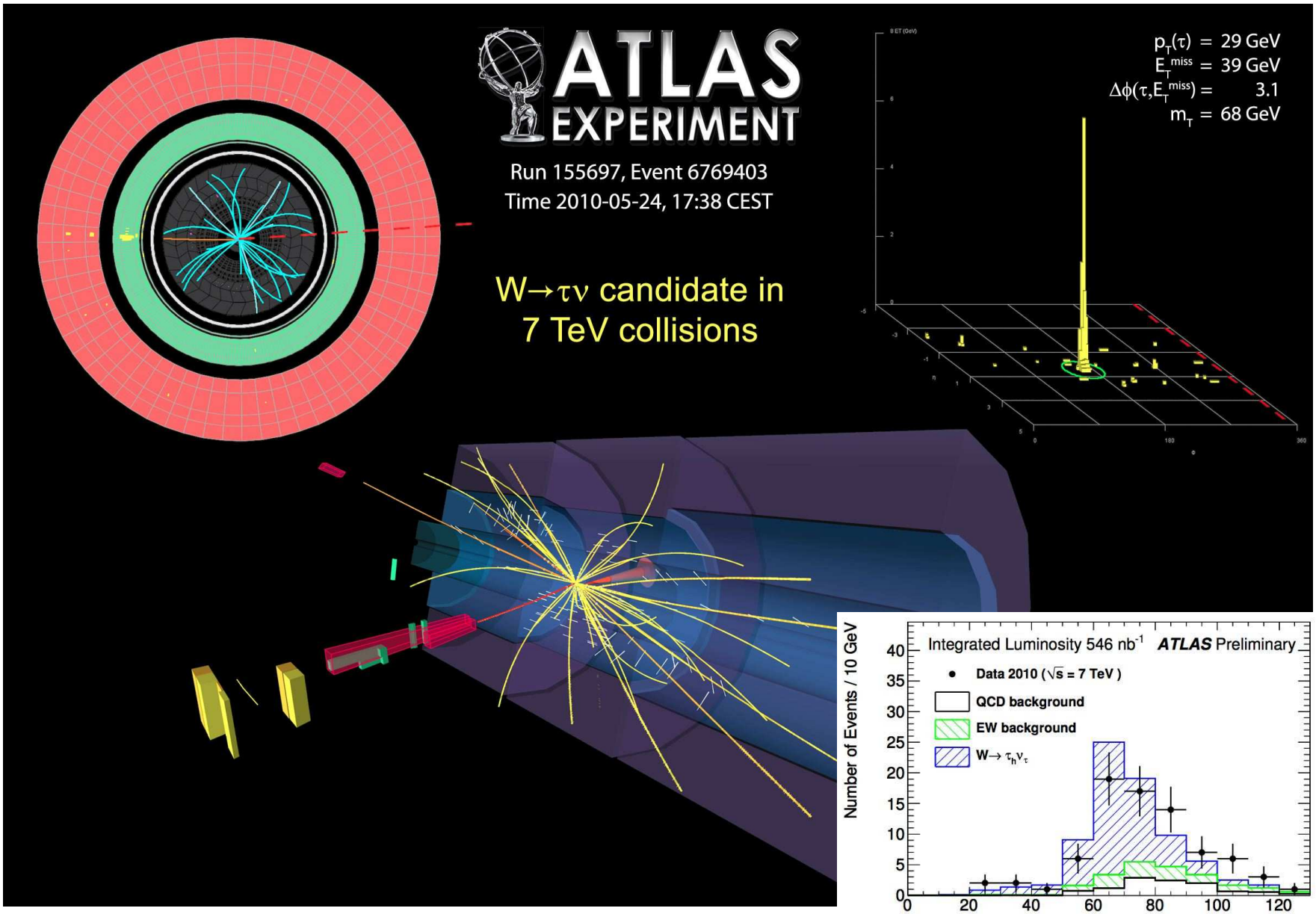
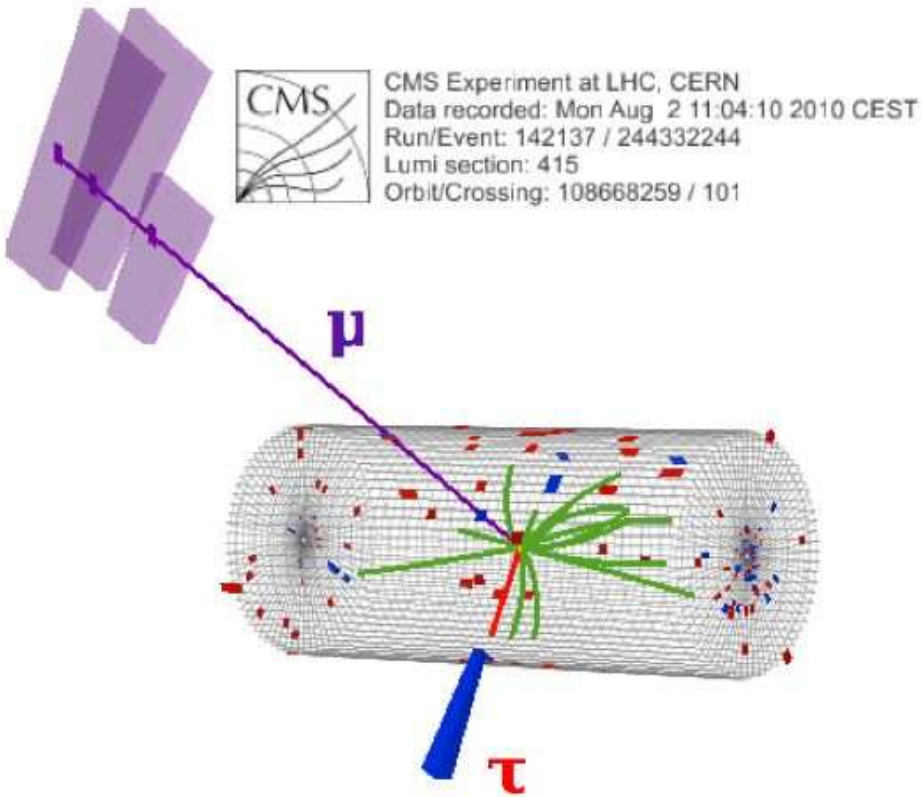
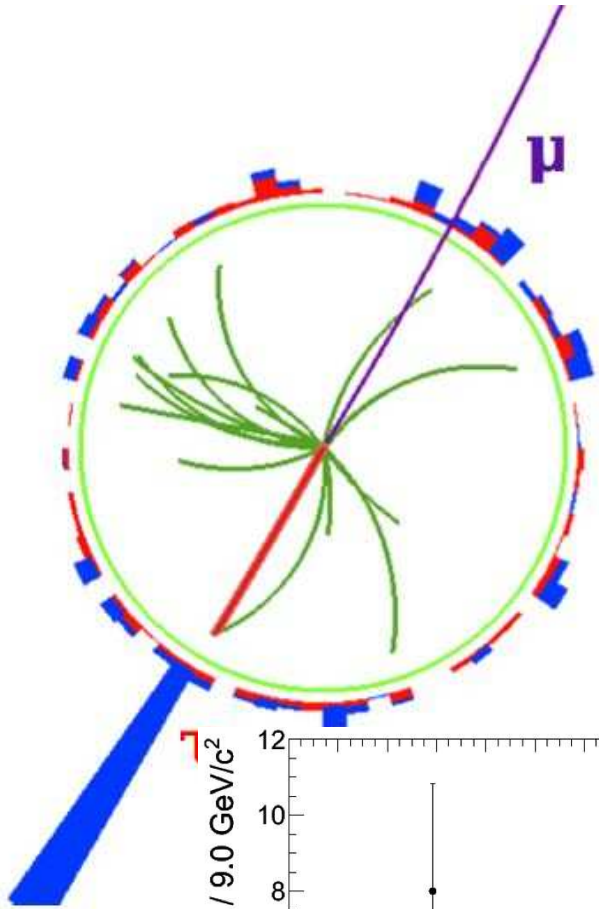
W/Z to τ

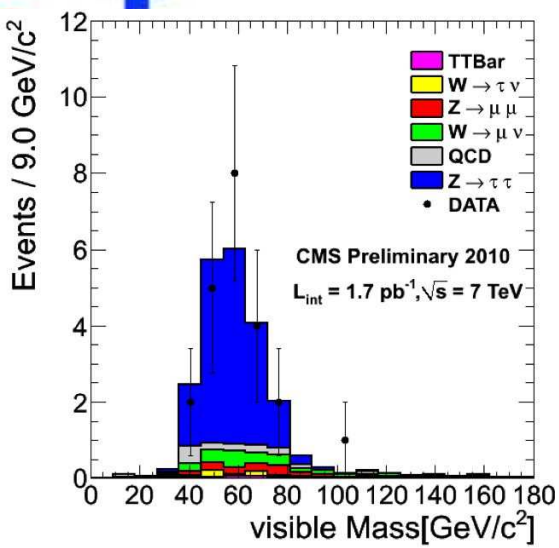

ATLAS
EXPERIMENT
Run 155697, Event 6769403
Time 2010-05-24, 17:38 CEST
W→τν candidate in
7 TeV collisions
$p_T(\tau)$ = 29 GeV
E_T^{miss} = 39 GeV
$\Delta\phi(\tau, E_T^{miss})$ = 3.1
m_T = 68 GeV
Integrated Luminosity 546 nb^{-1} ATLAS Preliminary
Data 2010 ($\sqrt{s}$ = 7 TeV)
QCD background
EW background
W→ $\tau_h\nu_\tau$
Number of Events / 10 GeV
m_T [GeV]

W/Z to τ





visible mass = 73 GeV
$p_T(\tau)$ = 36.8 GeV



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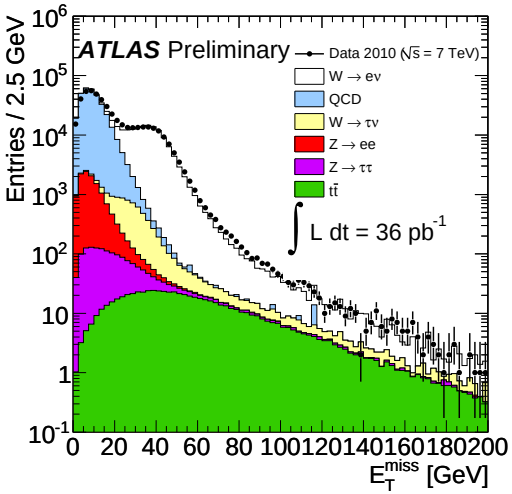
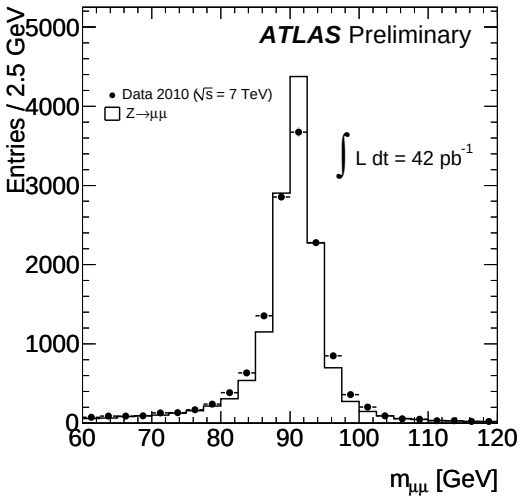
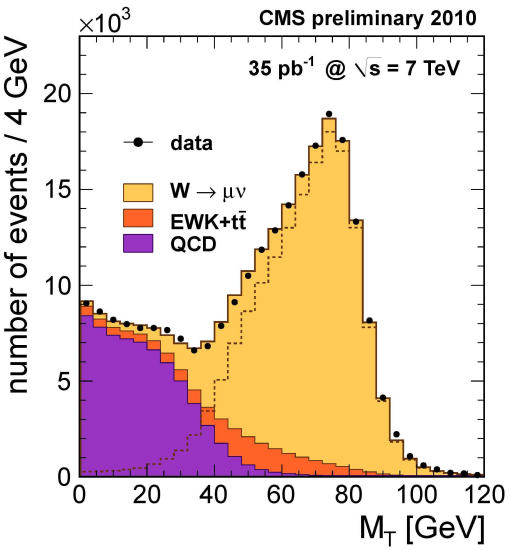
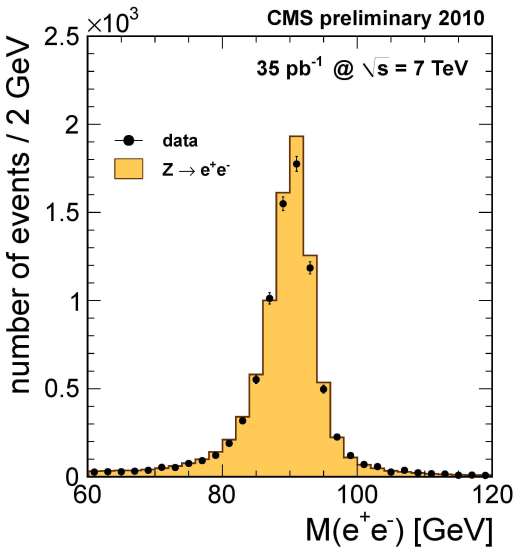
W/Z distributions with full 2010 data







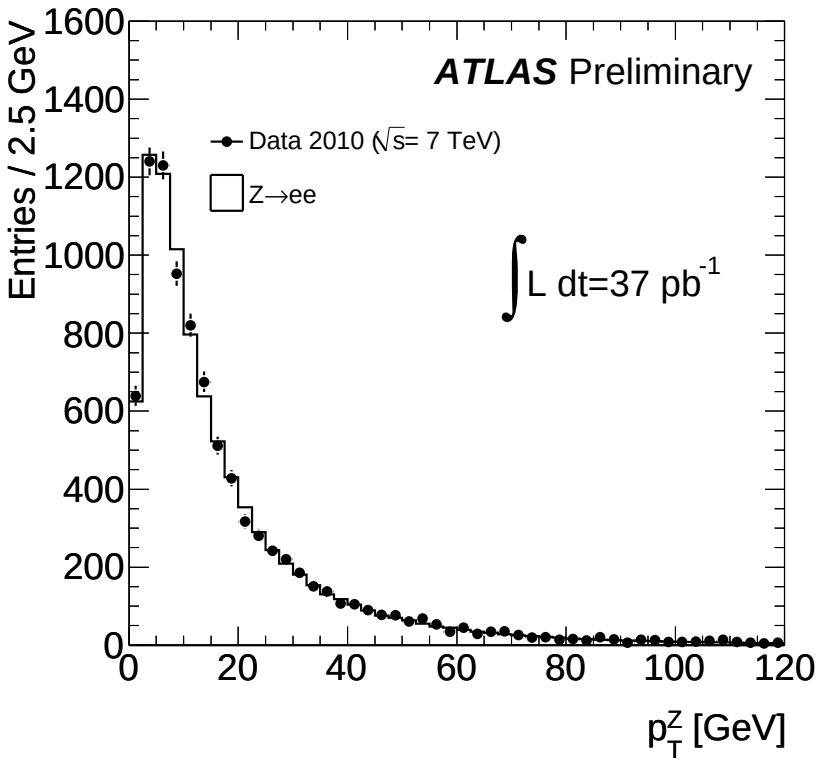


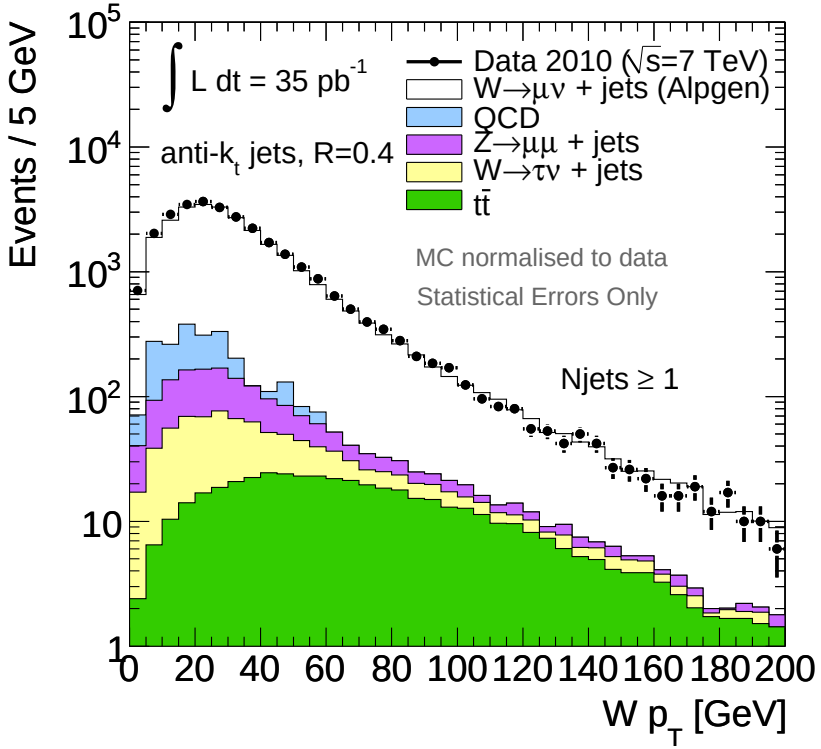
- good agreement between data and MC
- ATLAS m_Z distribution closer to prediction with improved understanding of detector alignment

	W candidates
CMS	305 k
ATLAS	250 k
	Z candidates
CMS	20 k
ATLAS	23 k

- good control sample for understanding the detectors

W/Z distributions with full 2010 data





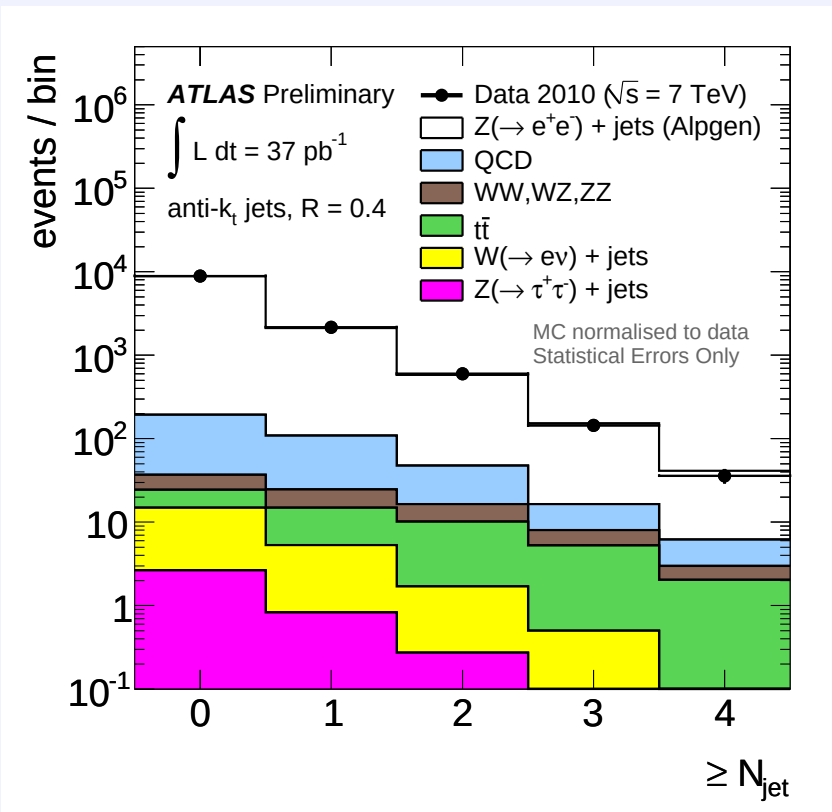
- differential distributions are important for
  - test of QCD
  - constraining PDF
  - M_W measurement

- ATLAS/CMS detectors
- W/Z at LHC
  - $W \to l\nu$: E_T^{miss}, M_T
  - $Z \to ll$: invariant mass
  - $W \to l\nu$, $Z \to ll$: cross sections
  - W/Z to τ
  - W/Z distributions with full 2010 data
  - **W/Z + jets**
- top at LHC
  - top control plots
  - top cross sections
- summary

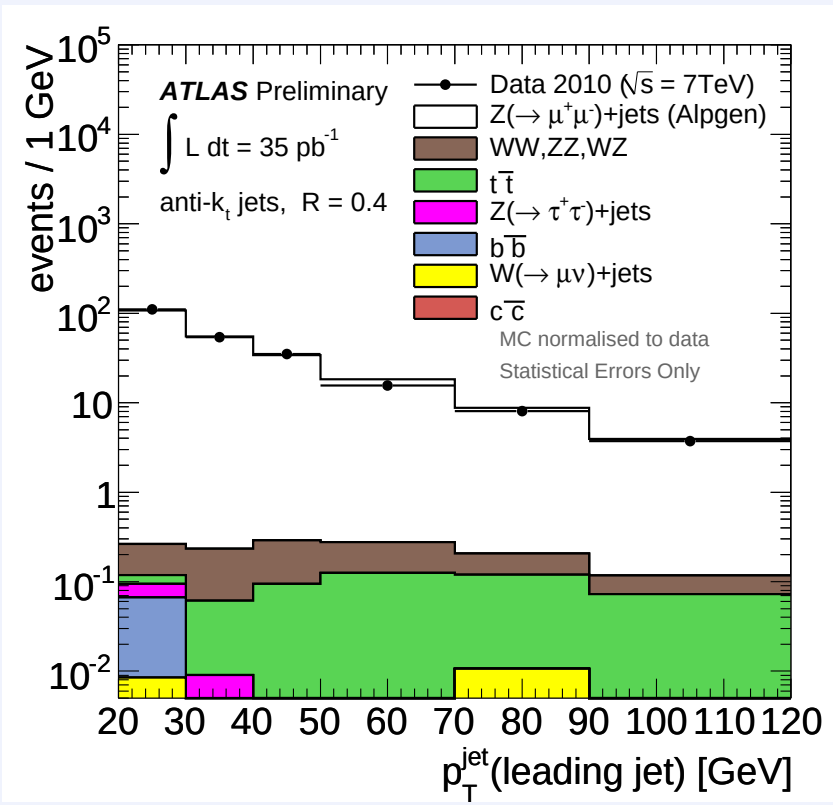
Z + jets
detector-level distributions

- anti-k_T: $R = 0.4$, $|\eta| < 2.8$, $p_T > 20$ GeV
- jet multiplicity and p_T of leading jets
- predictions normalised to data
- ME + PS simulation (Alpgen + Herwig) describes data well

electron channel



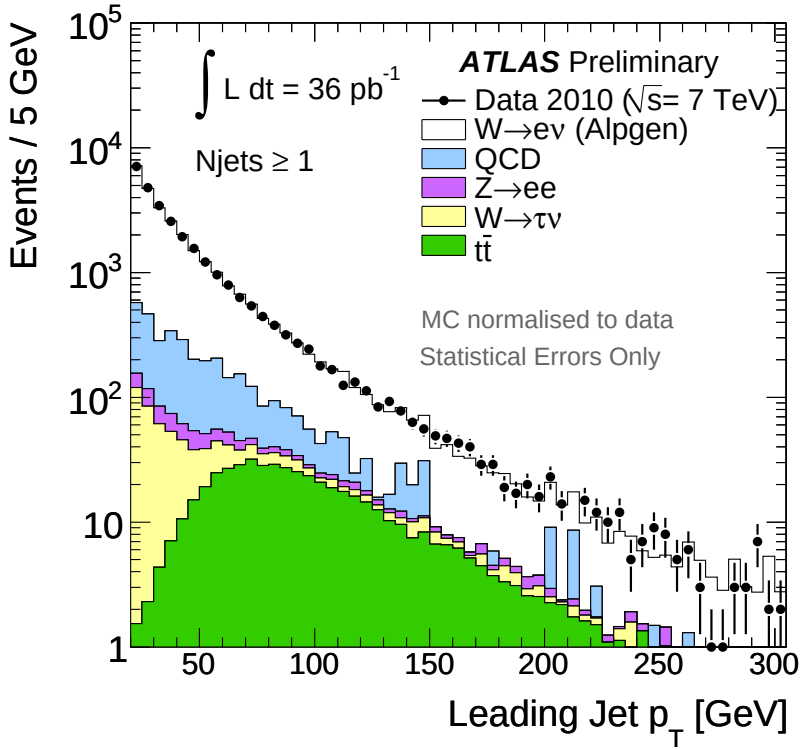
muon channel



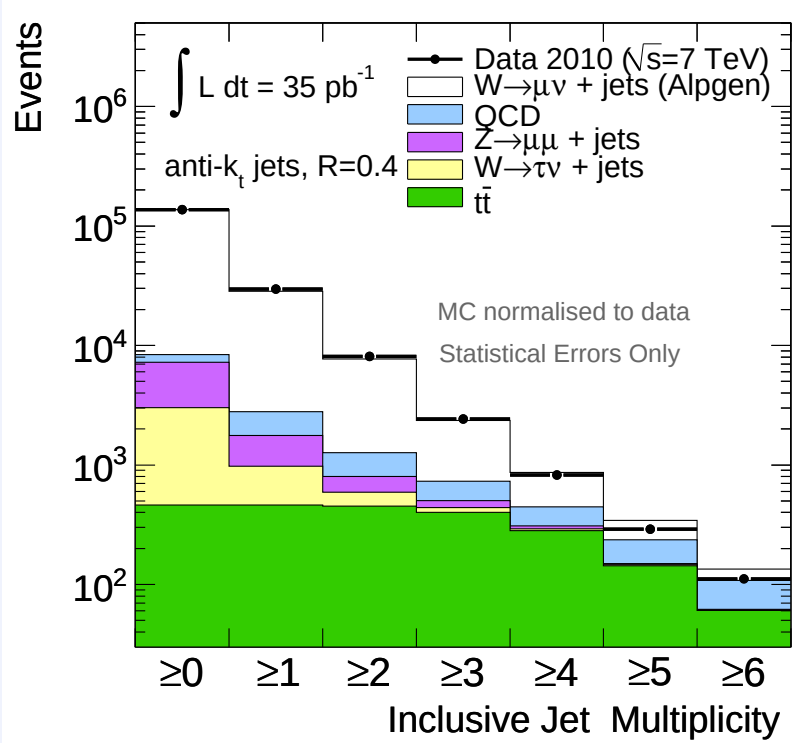
W + jets
detector-level distributions

- anti-k_T: $R = 0.4$, $|\eta| < 2.8$, $p_T > 20$ GeV
- p_T of leading jets and jet mutiplicity
- predictions normalised to data
- ME + PS simulation (Alpgen + Herwig) describes data well

electron channel



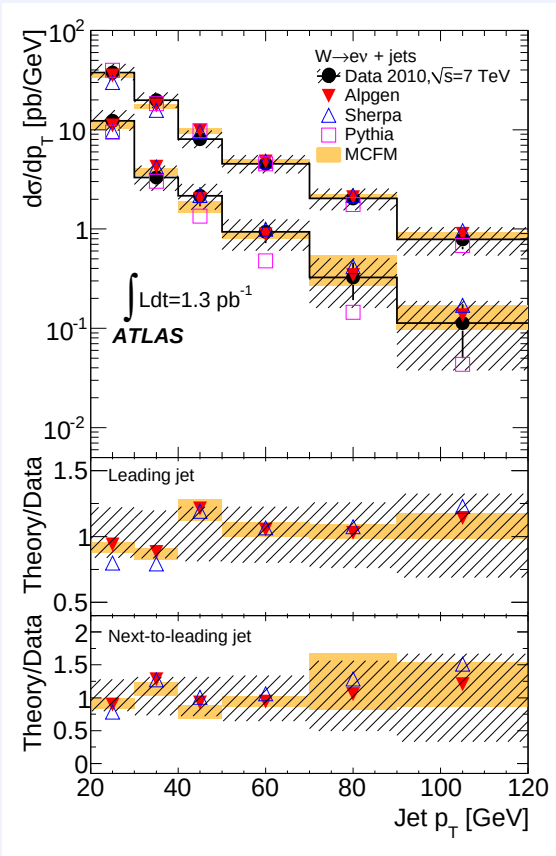
muon channel



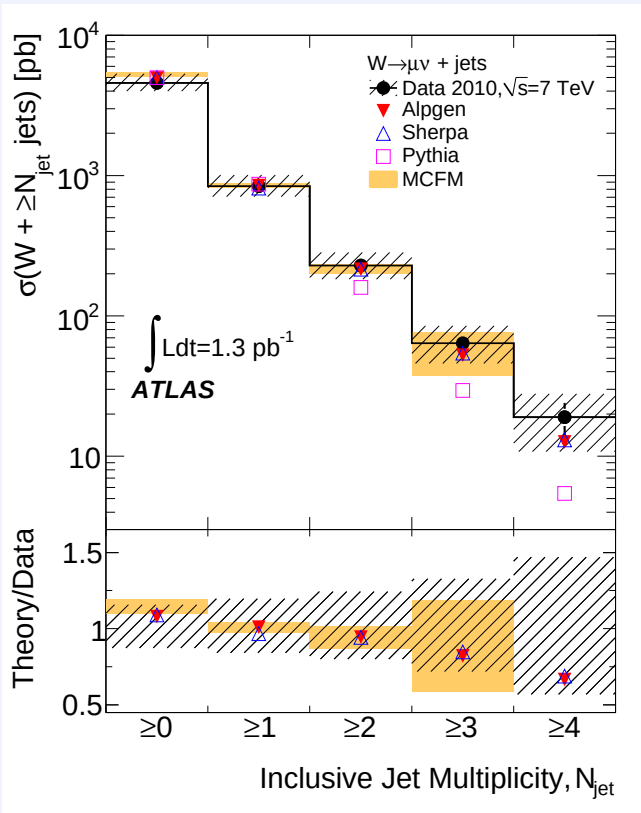
W + jets
cross sections

- Good agreement between the measured cross sections in terms of two leading jets in event and NLO predictions from MCFM
- Good agreement between the measured cross sections in terms of jet multiplicity and NLO ($\leq$ 2 jets) and LO (jet = 3) predictions from MCFM
- JES is the dominant systematics

electron channel



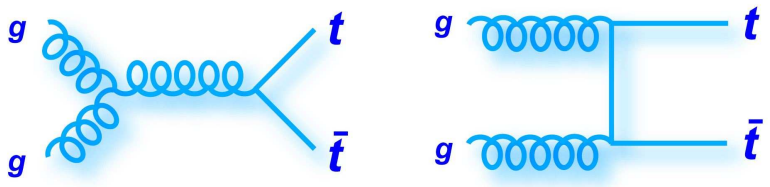
muon channel



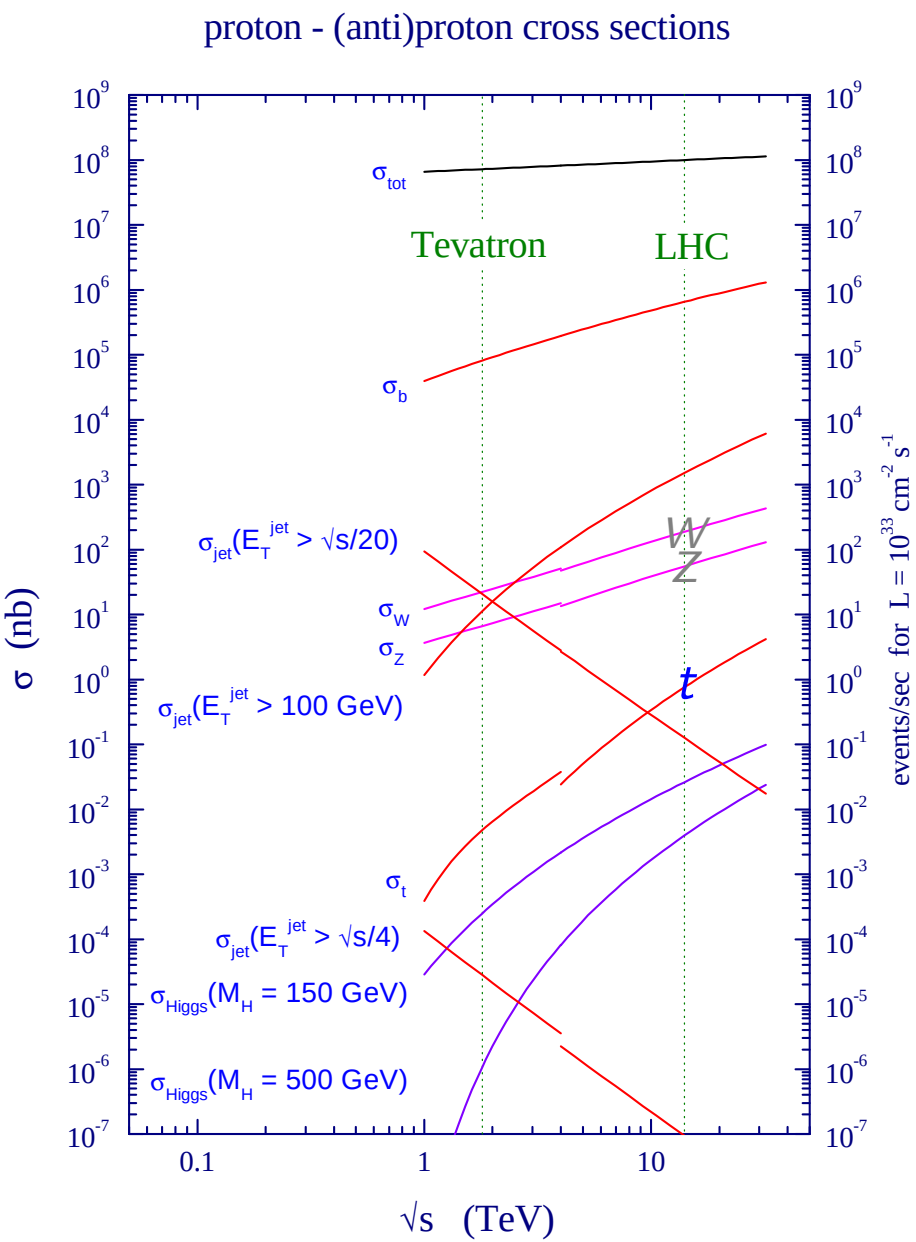
- ATLAS/CMS detectors
- W/Z at LHC
  - $W \rightarrow l\nu$: E_T^{miss}, M_T
  - $Z \rightarrow ll$: invariant mass
  - $W \rightarrow l\nu$, $Z \rightarrow ll$: cross sections
  - W/Z to τ
  - W/Z distributions with full 2010 data
  - W/Z + jets
- top at LHC
  - top control plots
  - top cross sections
- summary

top at LHC

- top quark
  - The heaviest known elementary particle, $m_t = 173.3 \pm 1.1$ GeV
  - $\tau_t = 5{\cdot}10^{-25}$ s $\ll \tau_{\text{hadr.}}$. no bound states
  - $V_{tb} \sim 0.999$. almost always $t \longrightarrow bW$
- main production modes are gluon fusion (85%)



- remaining mode is $q\bar{q}$ annihilation
- $\sigma_{t\bar{t}}(\text{theory}) = 164^{+11.4}_{-15.7}$ pb assuming $m_t = 172.5$ GeV
  20 * $\sigma_{t\bar{t}}$ (Tevatron)

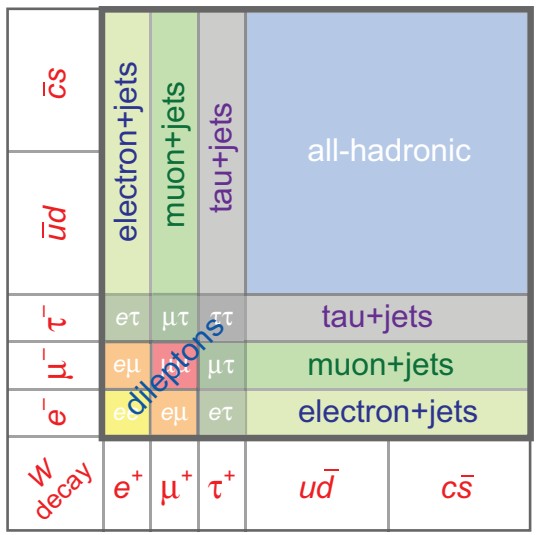


top at LHC

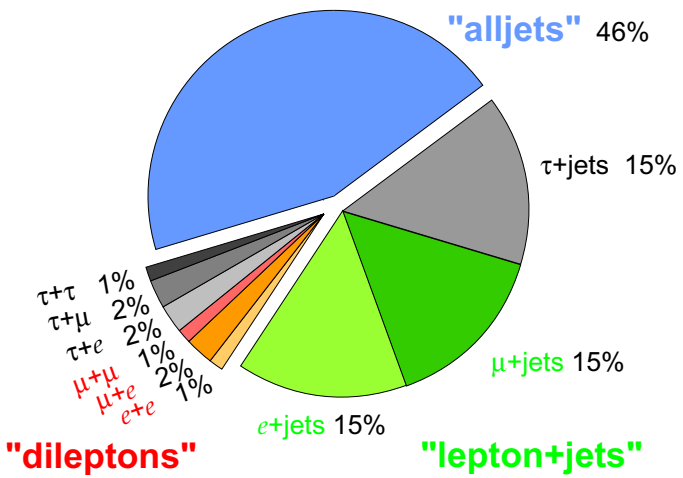
- at early stage
  - re-discovery of top
    - first cross-section measurement
  - detector performance
    - leptons, jets, E_T^{miss}
- decay modes[a]
  - di-lepton (6.5%)
    - $l^+l^-\nu\nu bb$
  - lepton + jets (38%)
    - $l\nu qqbb$
  - all hadronic (55.5%)
    - $qqqqbb$
  - additional jets come from ISR/FSR

[a] include tau decays

Top Pair Decay Channels

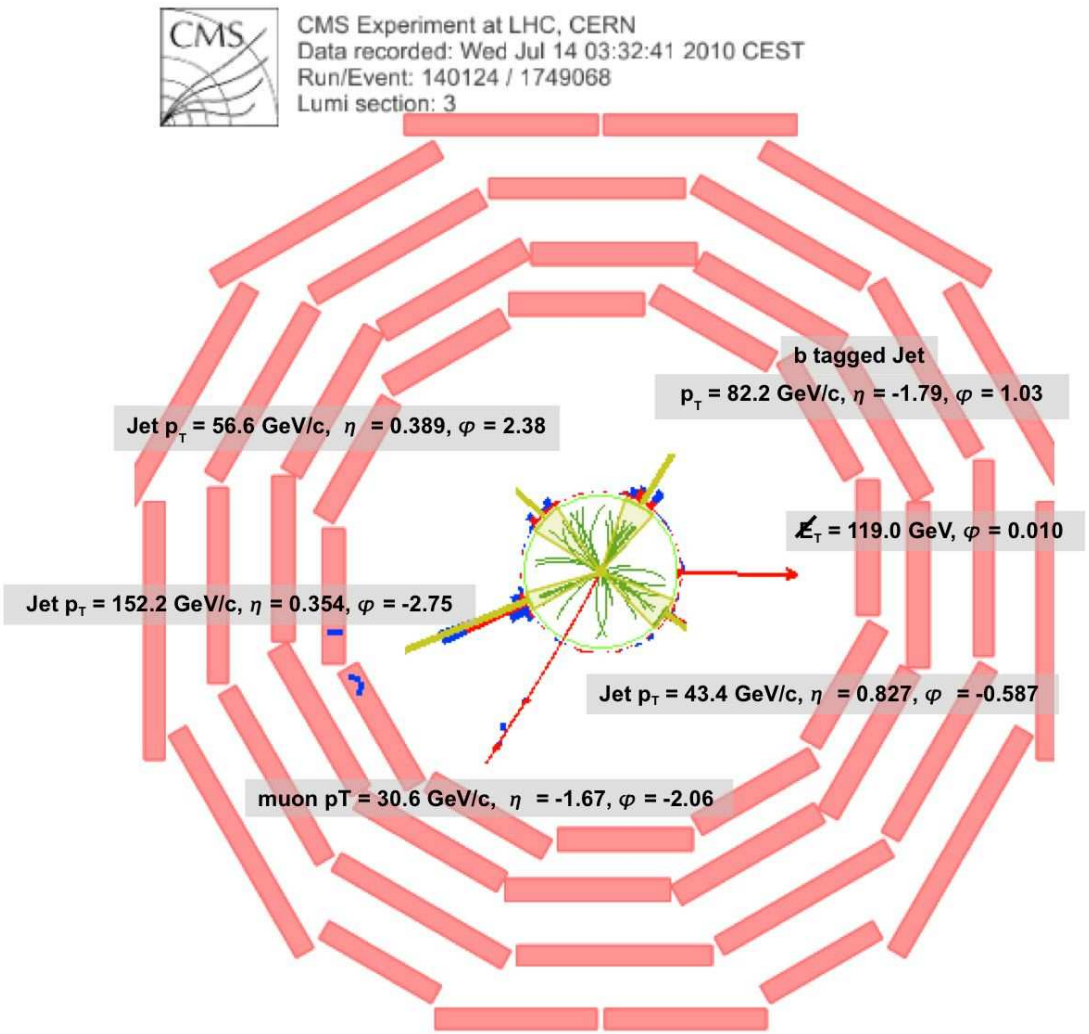


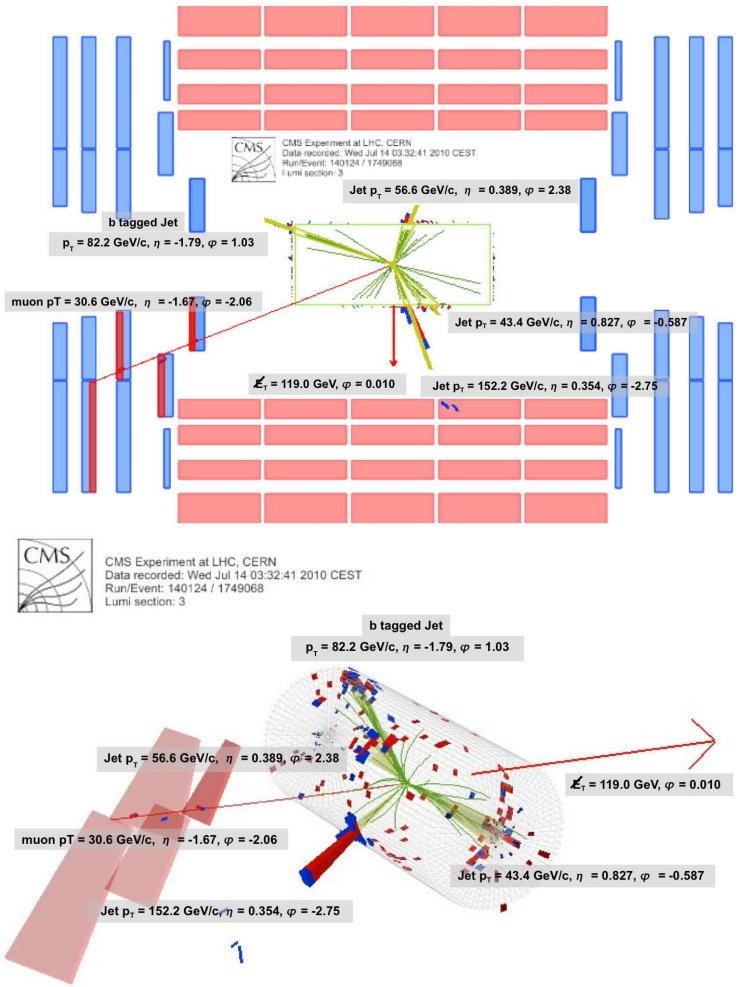
Top Pair Branching Fractions



$t\bar{t} \longrightarrow$ lepton + jets candidate

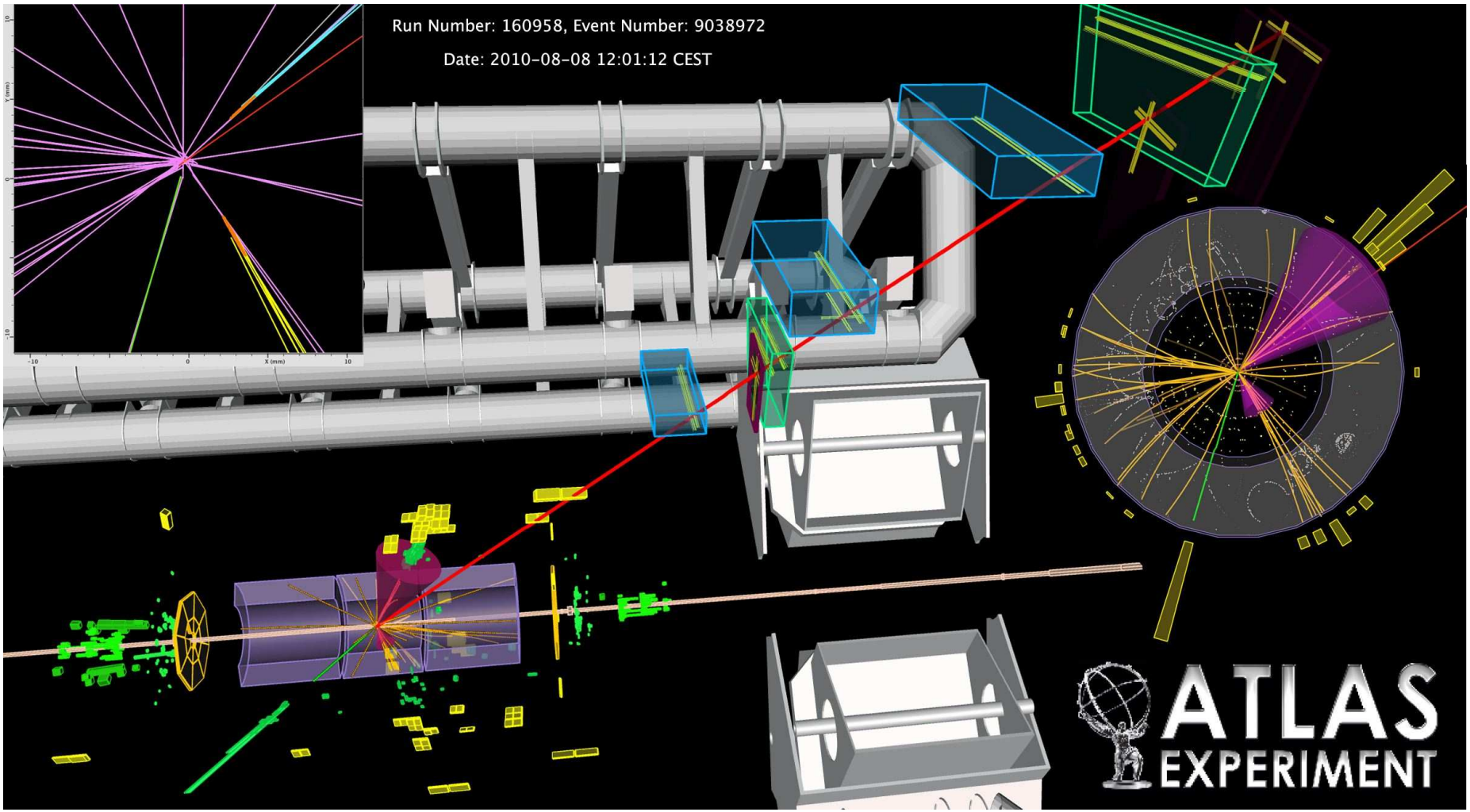
μ + 4 jets





$t\bar{t} \longrightarrow$ di-lepton candidate

$e - \mu$ with two b-tagged jets

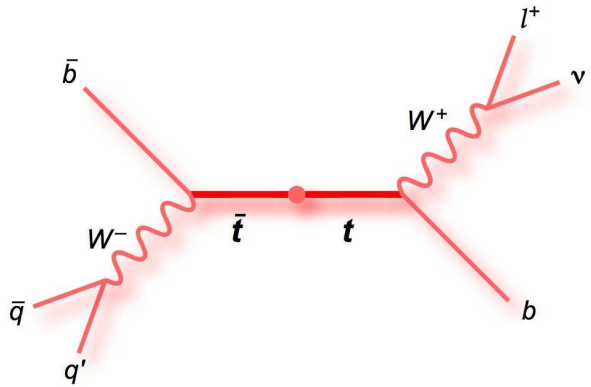


$p_T(\mu) = 51$ GeV, $p_T(e) = 66$ GeV, $p_T(b\text{-tag jets}) = 175, 45$ GeV, $E_T^{\text{miss}} = 113$ GeV.

Event selection for σ_{tt} measurement

ATLAS analysis

- lepton
  - electron or muon
  - $p_T > 20$ GeV, $|\eta| < 2.5$, isolated
- jet
  - anti-k_T: $R = 0.4$, $|\eta| < 2.4$



lepton + jets

- one lepton
- ≥ 4 jets with $p_T > 25$ GeV
- ≥ 1 jet(s) with b-tag at 50% efficiency working point
- $E_T^{\text{miss}} > 20$ GeV
- $E_T^{\text{miss}} + m_T(W) > 60$ GeV

di-lepton

- two leptons with opposite charge
- ≥ 2 jets with $p_T > 20$ GeV, no b-tag
- ee: $|M_{ee} - M_Z| > 5$ GeV, $E_T^{\text{miss}} > 40$ GeV
- $\mu\mu$: $|M_{\mu\mu} - M_Z| > 10$ GeV, $E_T^{\text{miss}} > 30$ GeV
- $e\mu$: $H_T{}^a > 150$ GeV

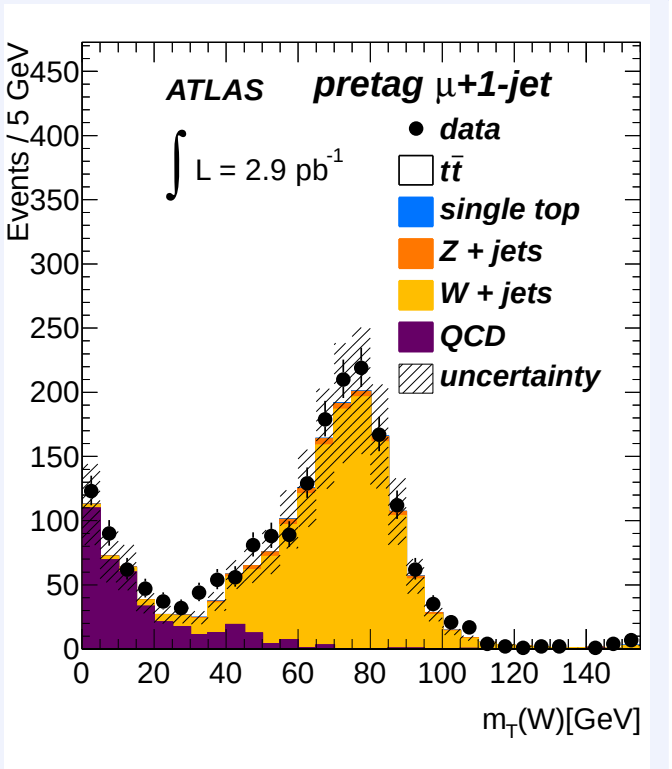
[a] scaler sum of p_T of leptons and selected jets

- CMS uses similar analysis

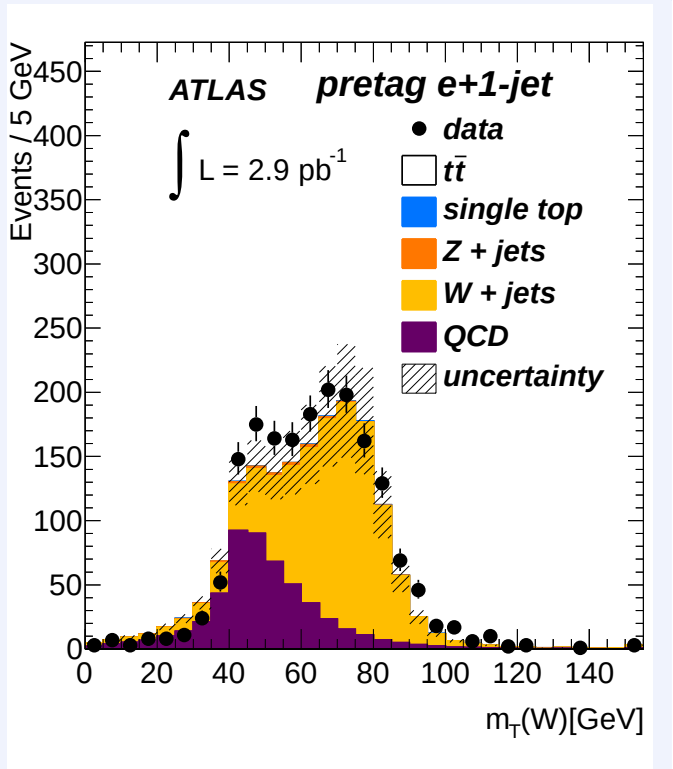
$t\bar{t} \rightarrow$ lepton + jets: control plots

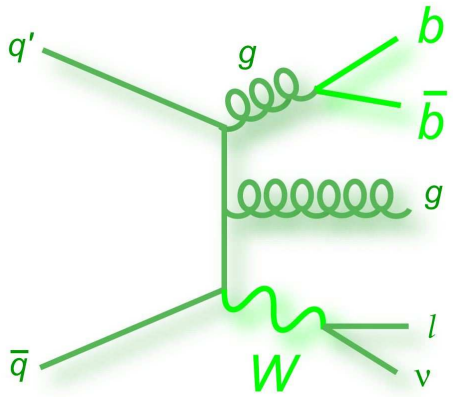
ATLAS: 2.9 pb^{-1}

μ + jets



e + jets





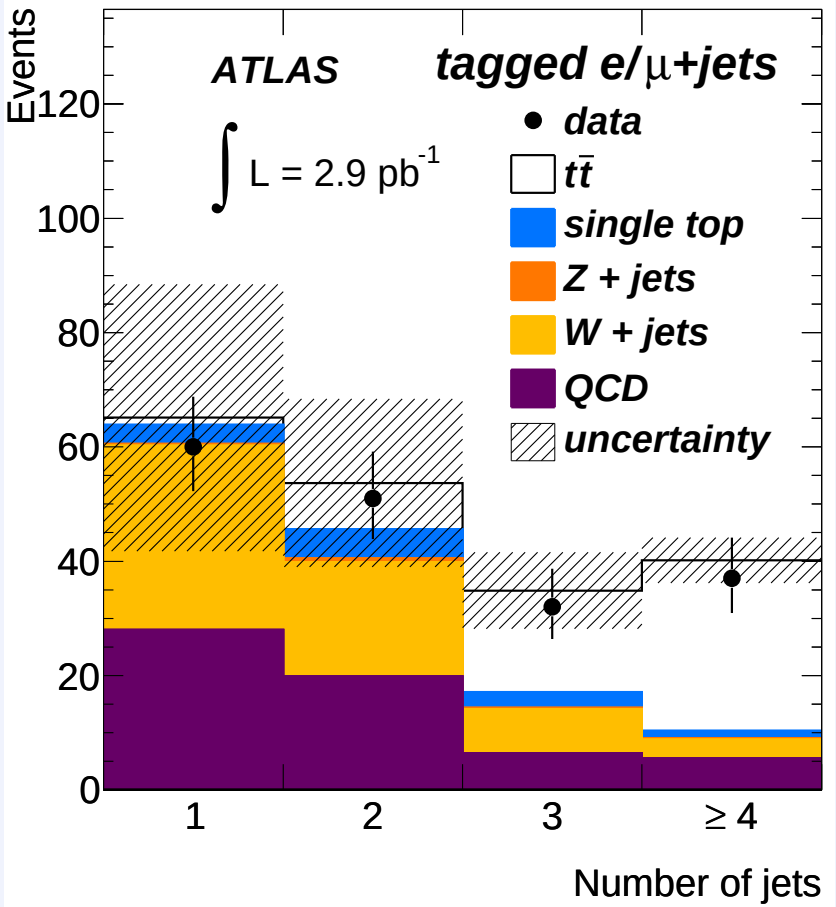
- dominant background

- μ channel without E_T^{miss}, M_T cut
- QCD multi-jet estimation is data driven
- Acceptable agreement between data and prediction

$t\bar{t} \rightarrow$ lepton + jets

ATLAS: 2.9 pb^{-1}

ATLAS



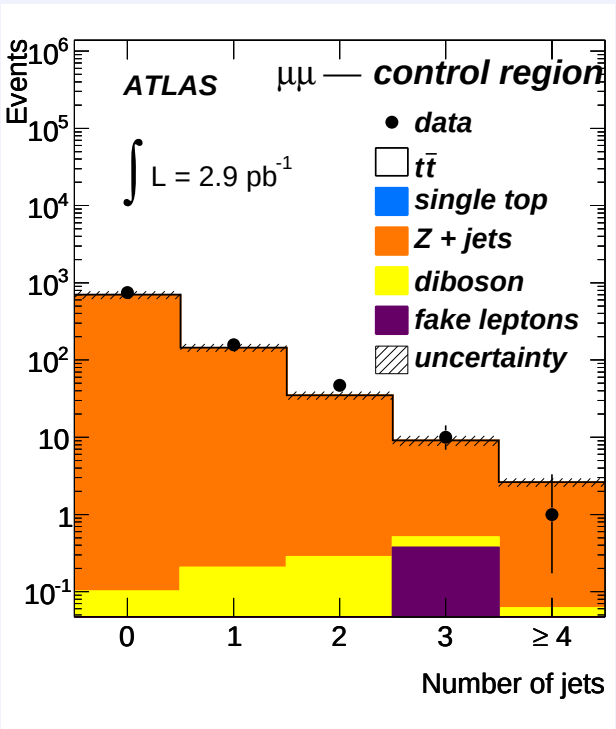
- clear excess of top like events with ≥ 4 jets

	e+jets	μ+jets
QCD (DD)	4.8±3.1	0.8±0.5
W+jets (DD)	1.9±1.1	3.2±1.7
Z+jets (MC)	0.2±0.1	0.1±0.1
single t (MC)	0.7±0.2	0.7±0.2
total BG	7.2±3.4	3.3±1.7
$t\bar{t}$ (MC)	14.9±3.5	15.0±3.4
Data	17	20

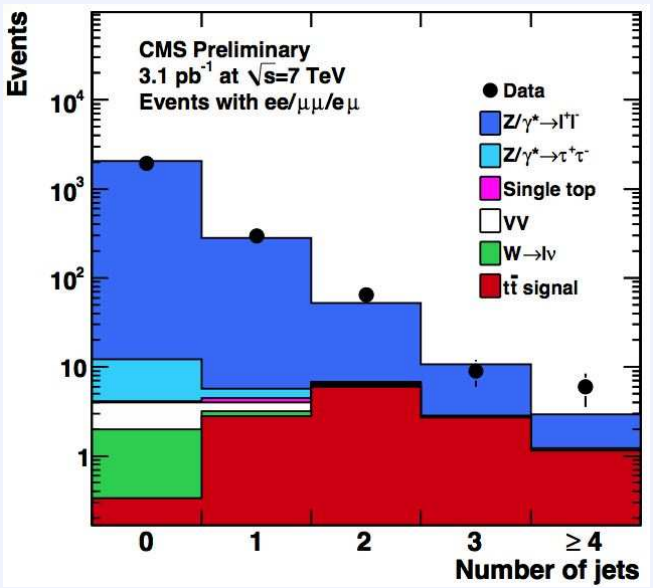
$t\bar{t} \longrightarrow$ di-lepton: control plots

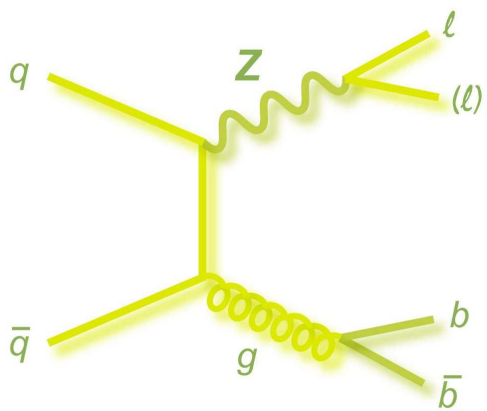
ATLAS: 2.9 pb^{-1}, CMS: 3.1 pb^{-1}

ATLAS



CMS





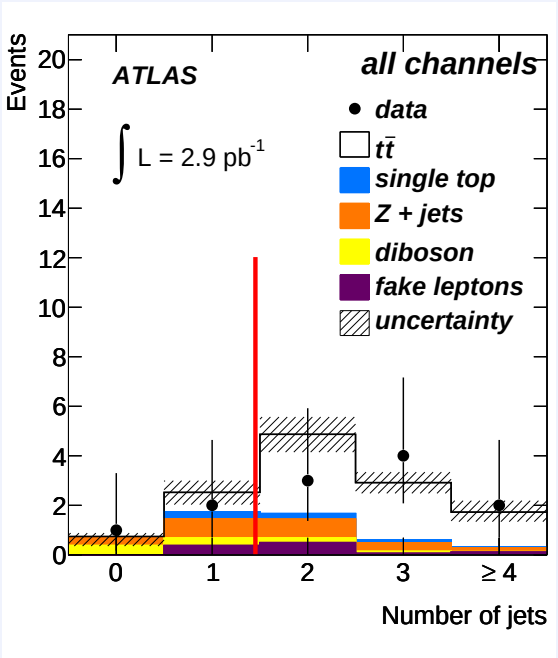
- dominant background

- Good agreement between data and prediction

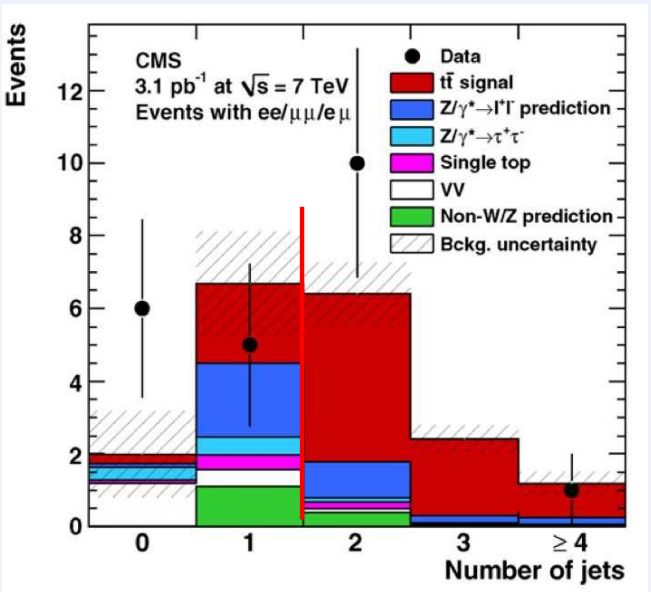
$t\bar{t} \rightarrow$ di-lepton

ATLAS: 2.9 pb^{-1}, CMS: 3.1 pb^{-1}

ATLAS



CMS



ATLAS	ee	$\mu\mu$	$e\mu$
Z+jets (DD)	0.25±0.18	0.67±0.38	-
$Z \rightarrow \tau\tau$+jets (MC)	0.07±0.04	0.14±0.07	0.13±0.06
non-Z leptons (DD)	0.16±0.18	-0.08±0.07	0.47±0.28
single t (MC)	0.08±0.02	0.07±0.03	0.22±0.04
dibosons (MC)	0.04±0.02	0.07±0.03	0.15±0.05
total BG	0.60±0.27	0.88±0.40	0.97±0.30
$t\bar{t}$ (MC)	1.19±0.19	1.87±0.26	3.85±0.51
Data	2	3	4

CMS	
Z+jets (DD)	1.4±0.5
$Z \rightarrow \tau\tau$+jets (MC)	0.18±0.09
non-WZ (DD)	0.1±0.5
single t (MC)	0.25±0.13
dibosons (MC)	0.13±0.07
total BG	2.1±1.0
$t\bar{t}$ (MC)	7.7±1.5
Data	11

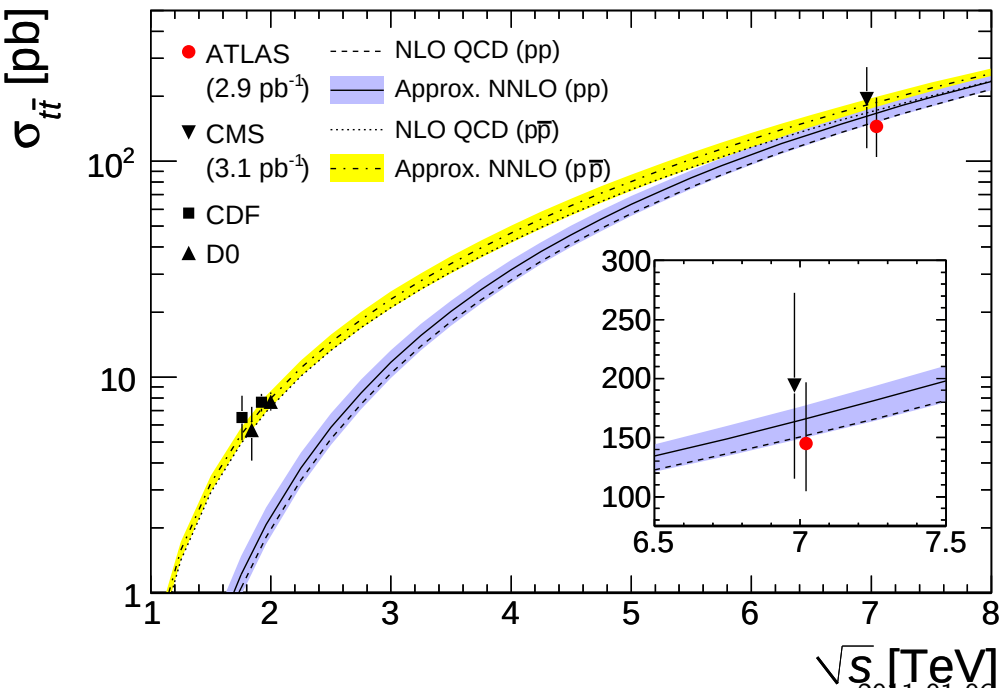
$t\bar{t}$ cross-sections

ATLAS

lepton + jets	di-lepton	combined	approx. NNLO
$142 \pm 34\ ^{+50}_{-31}$	$151\ ^{+78}_{-62}\ ^{+37}_{-24}$	$145 \pm 31\ ^{+42}_{-27}$	$164^{+11.4}_{-15.7}$

CMS

di-lepton	NLO
$194 \pm 72 \pm 24$	$158\ ^{+23}_{-24}$



- dominant systematics are due to statistical uncertainties in data-driven measurements, jet energy reconstruction
- measured cross sections agree with theoretical predictions within errors

Summary & Outlook

- W/Z cross sections measured and the results are in good agreement with NNLO predictions
- Measurements are being updated with full statistics of 2010
- Differential measurements in preparation
- Cross section measurements of $W \to \tau\nu$ and $Z \to \tau\tau$ underway

- Top cross section measured and the results are in good agreement with theoretical predictions
- Measurements are being updated with full statistics of 2010

- Re-discovery of W/Z and top have been performed
- Understanding of detectors and backgrounds continues for discovery
- This year will be an exciting year