Measurement of the $Z \rightarrow \tau^+\tau^-$ cross section in proton-proton collisions with the ATLAS experiment

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Introduction

Motivation for $Z \rightarrow \tau\tau$ analysis:

→ cross section measurement of SM process, confirm the ATLAS measurement of $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$,

→ background for new particle searches in τ final states,

→ unbiased source of τ leptons for calibration and efficiency measurements.

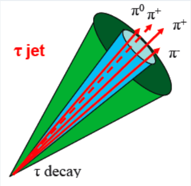
Topic of the talk: update (40 times more luminosity) of the analysis published in Phys. Rev. **D84**, 112006 (2011) by the ATLAS Collaboration

Final state depends on the decay modes of the τ leptons:

- τ leptonic decay: $\rightarrow l\nu_l\nu_\tau$ (35 %)
- τ hadronic decay: $\rightarrow had\ \nu_\tau$ (65 %), mainly 1 or 3 charged pions.

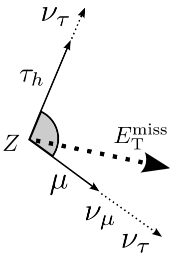
The challenge: Distinguish hadronic τ decays from QCD jets.

- Hadrons from τ decays are collimated along the τ direction.
- Low track multiplicity (1 or 3) corresponding to the charge pions produced .
- Algorithms developed to identify hadronic τs.



Analysis of the $Z \to \tau\tau$ decays

Analysis of the semi-leptonic final state: 1 hadronic τ and 1 electron (muon).



Dataset
$\gamma^*/Z \to \tau\tau$ ($m_{\tau\tau} > 10$ GeV)
$\gamma^*/Z \to ee$ ($m_{ee} > 10$ GeV)
$\gamma^*/Z \to \mu\mu$ ($m_{\mu\mu} > 10$ GeV)
$W \to e\nu$
$W \to \mu\nu$
$W \to \tau\nu$
$t\bar{t}$
Dibosons (WW, WZ and ZZ)
Multijet

- Electroweak processes and $t\bar{t}$ are estimated by the Monte Carlo simulation, multi-jet background estimated from data.
- Normalization factors calculated for W and Z backgrounds.
- Multijet contribution is the main background, suppressed by the specific cuts.

In this talk, main emphasis is given to:

- ✓ Measurement of the efficiency scale factors for the selected muons with the $Z \to \mu\mu$ tag-and-probe method,
- ✓ Background estimation from data.

Event selection (1)

✓ Events are selected with different triggers:

Trigger	$\tau_\mu\tau_h$	channel: muon with $p_T > 15$ GeV plus isolation cuts
	$\tau_e\tau_h$	channel: electron with $p_T > 15$ GeV and τ with $p_T > 16$ GeV

✓ Object selection

	Electrons	Muons	Hadronic τs
p_T min (GeV)	17	17	20($\tau_\mu\tau_h$ chan), 25($\tau_e\tau_h$ chan)
	Identification and quality cuts		

✓ Isolation cuts on selected leptons to reduce the Multijet background.

Reconstruction-isolation-trigger efficiency scale factors applied to isolated leptons.

Event selection (2)

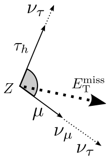
Additional selection to reduce the residual background:

1) Opposite sign of the electric charge: the lepton and the hadronic τ are required to have opposite charge.

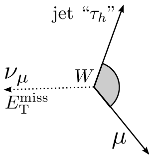
2) Di-lepton veto: events with > 1 leptons are removed.

3) W suppression cuts: based on the angular distance between the lepton (hadronic τ) and transverse missing energy.

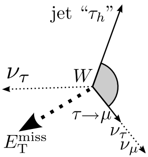
$Z \to \tau\tau \to \mu\tau_h$



$W \to \mu\nu$



$W \to \tau\nu \to \mu\nu\nu\nu$



Two variables are defined:

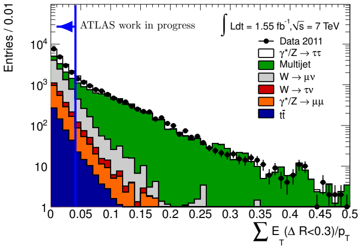
$$\sum \cos \Delta\phi = \cos\left(\phi(\ell) - \phi(E_T^{miss})\right) + \cos\left(\phi(\tau_h) - \phi(E_T^{miss})\right) .$$

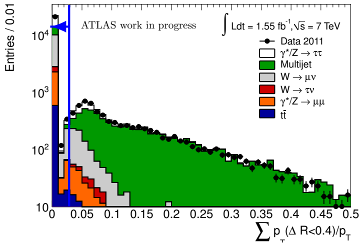
$$m_T(\ell, E_T^{miss}) = \sqrt{2\, p_T(\ell) \cdot E_T^{miss} \cdot (1 - \cos \Delta\phi(\ell, E_T^{miss}))} .$$

4) Further selection of the hadronic τ: cut on the charge and numbers of tracks.

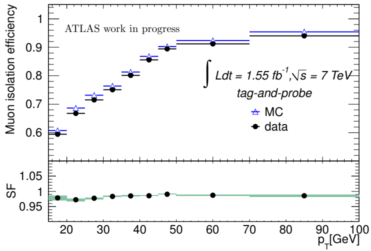
Muon isolation efficiency

- The isolation of muons relies on both calorimeter ($\sum_i E_T(\Delta R)$) and tracking variables ($\sum_i p_T(\Delta R)$).





- Efficiency measured with muons from $Z \to \mu\mu$ decays.
- The muon isolation efficiency is defined as the fraction of reconstructed muons that satisfy the isolation cuts.
- Efficiency scale factors are derived (ϵ_{data} / ϵ_{MC}).

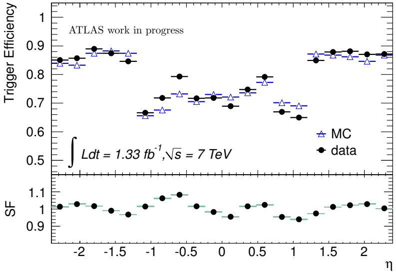


Muon trigger efficiency

- Isolated single muon triggers used for the $Z \rightarrow \tau\tau$ analysis, with p_T threshold at 15 GeV.

The muon trigger efficiency is measured with muons from $Z \rightarrow \mu\mu$ decays and is defined as the fraction of reconstructed and isolated muons that fired the trigger.

Efficiency as a function of the muon η

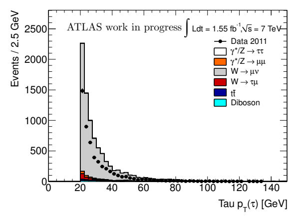


- Efficiency scale factors applied to the triggered muon in the $Z \rightarrow \tau\tau$ analysis.

Estimation of the W/Z + jet background

- The number of W/Z simulated events is overestimated, after the τ identification cuts on the hadronic τ candidates.
- Data and simulation compared in background enriched control regions.
- The number of simulated events is normalized to the number of events in data.

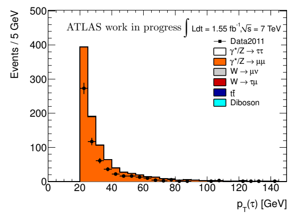
W control region: pass the dilepton veto and τ cleaning but fails both W suppression cuts.



Normalization factors:

$$k_W = \begin{cases} 0.44 \pm 0.02 \text{ (stat.)} & \tau_e\tau_h \text{ channel} \\ 0.54 \pm 0.01 \text{ (stat.)} & \tau_\mu\tau_h \text{ channel} \end{cases}$$

Z control region: two electrons (muons) with an invariant mass close to the Z mass.



Normalization factors:

$$k_Z = \begin{cases} 0.39 \pm 0.05 \text{ (stat.)} & \tau_e\tau_h \text{ channel} \\ 0.57 \pm 0.04 \text{ (stat.)} & \tau_\mu\tau_h \text{ channel} \end{cases}$$

Estimation of the multijet background

- Data-driven technique for the multijet estimation
- Define 4 different control regions: opposite sign and same sign refer to the charges of the electron (muon) and hadronic τ.

non-isolated lepton	C	D
isolated lepton	A signal region	B
	opposite sign	same sign

- The number of multi-jet events in the signal region is calculated from the ratio of multi-jet events in region C and D:

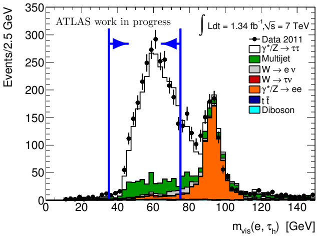
$$N^{A}_{\mathrm{Multi-jet}} = \frac{N^{C}_{\mathrm{Multi-jet}}}{N^{D}_{\mathrm{Multi-jet}}} N^{B}_{\mathrm{Multi-jet}} = R_{\mathrm{OSSS}} N^{B}_{\mathrm{Multi-jet}}$$

$$R_{\mathrm{OSSS}} = \begin{cases} 1.06 \pm 0.03\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{iso\ sys.}) \pm 0.04\ (\mathrm{cutflow\ sys.}) & \tau_{\mathrm{e}}\tau_{\mathrm{h}}\ \mathrm{channel}\,, \\ 1.13 \pm 0.04\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{iso\ sys.}) & \tau_{\mu}\tau_{\mathrm{h}}\ \mathrm{channel}\,. \end{cases}$$

Cross section measurement (1)

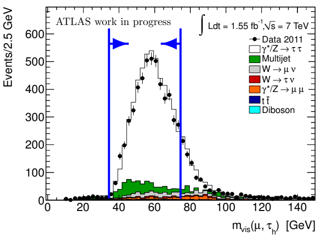
Event counting in the Visible Mass (i.e. the invariant mass between the lepton and the hadronic τ) range: $35 < M_{\text{vis}} < 75$ GeV.

Electron channel



Data 2011	2600(51)
$Z/\gamma^* \rightarrow \tau\tau$	2029(25)
$W \rightarrow e\nu$	45(5)
$W \rightarrow \tau\nu$	18(2)
$Z/\gamma^* \rightarrow ee$	64(4)
$t\bar{t}$	17(1)
Dibosons	6(1)
Multi-jets	300(21)

Muon channel



Data 2011	5184(72)
$Z/\gamma^* \rightarrow \tau\tau$	4544(49)
$W \rightarrow \mu\nu$	186(13)
$W \rightarrow \tau\nu$	49(5)
$Z/\gamma^* \rightarrow \mu\mu$	81(7)
$t\bar{t}$	31(1)
Diboson	15(2)
Multi-jet	432(30)

Cross section measurement (2)

$$\sigma(Z \to \tau\tau) \times BR(\tau \to l\nu\nu) \times BR(\tau \to \tau_{\mathrm{had}}\nu) = \frac{N_{\mathrm{obs}} - N_{\mathrm{bkg}}}{A_Z \cdot C_Z \cdot \mathcal{L}}$$

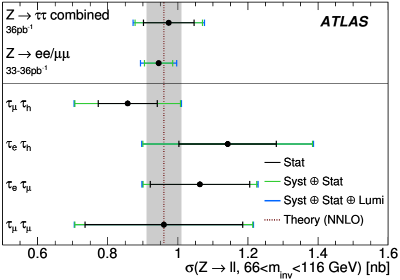
$$\mathrm{BR}(\tau \to \mu\,\nu\,\nu) \times \mathrm{BR}(\tau \to \tau_{had}\,\nu) = 0.2250 \pm 0.0009,$$
$$\mathrm{BR}(\tau \to e\,\nu\,\nu) \times \mathrm{BR}(\tau \to \tau_{had}\,\nu) = 0.2313 \pm 0.0009.$$

	$\tau_\mu\tau_{\mathrm{h}}$	$\tau_e\tau_{\mathrm{h}}$
N_{obs} number of data events	5184 ± 72(stat.)	2600 ± 51(stat.)
N_{bkg} number of background events	793 ± 34(stat.)	449 ± 22(stat.)
A_Z acceptance	0.0976 ± 0.0002(stat.)	0.0687 ± 0.0002(stat.)
C_Z signal efficiency	0.1417 ± 0.0016(stat.)	0.1009 ± 0.0013(stat.)
$\mathcal{L}$ integrated luminosity	1547.1 pb^{-1}	1343.7 pb^{-1}

Results in agreement with theoretical prediction ($\sigma_{\mathrm{theory}} = 960 \pm 50$ pb) and $Z \to \mu\mu/ee$ cross sections measured by ATLAS.

Conclusion

- Full analysis with 2011 data performed: good agreement between data and simulation means good understanding of detector performance in the reconstruction and identification of electrons, muons and hadronic τ leptons.
- Cross section measurement in the semi-leptonic channels is calculated with systematic uncertainties.
- Results from the semileptonic final state are combined with the dileptonic final state, the result of the combination (see F. Seifert's talk) is compatible with the theoretical prediction and the ATLAS measurements of Z$\rightarrow \mu\mu$ and Z$\rightarrow ee$ decays.
- Published results of the $Z \rightarrow \tau\tau$ cross section (lower integrated luminosity):



Data and Monte Carlo samples (2)

Collision data are collected during 2011 with a centre-of-mass energy of 7 TeV. Data are divided to different data taking periods with different data taking conditions. In particular difference in the pile-up environment is expected since the distance between bunches and their dimension vary in each data taking period. Table 1 shows the integrated luminosity of each period used for the analysis. The total luminosity is 1.34 fb^{-1} and 1.55 fb^{-1} for the electron and muon channel respectively.

run period	run number	$\int \mathcal{L}dt$ (pb^{-1}), $\tau_e\tau_\mathrm{h}$	$\int \mathcal{L}dt$ (pb^{-1}), $\tau_\mu\tau_\mathrm{h}$
period B	178044 - 178109	-	11
period D	179725 - 180481	-	150
period E	180614 - 180776	-	42
period F	182013 - 182519	123	123
period G	182726 - 183462	464	464
period H	183544 - 184169	240	240
period I	185353 -186493	305	305
period J	186516 - 186755	212	212
total		1344	1547

Table: Integrated luminosity relative to the different data taking periods analysed.

Muon selection

Preselection Muons are reconstructed with the STACO algorithm with *Loose* identification requirements. Muons are preselected if their $p_T > 6$ GeV and $|\eta| < 2.7$. Few cuts are applied at preselection: the contribution of fake hadronic τ leptons is indeed reduced by the overlap removal procedure, that selects hadronic τ candidates whose distance from the preselected objects is less that $\Delta R < 0.4$.

Selection Muon that passed the preselection criteria are selected for the analysis. Further cuts are applied to reduce the contribution of fake muons, mainly from pion decays. The muon selection requires $p_T > 17$ GeV within $|\eta| < 2.4$ to deal with the trigger p_T-threshold and acceptance. The trigger efficiency curve of the selected muon trigger reaches the plateau at ~ 17 GeV. The longitudinal distance from the primary vertex is required to be less than 10 mm. Inner detector quality criteria are applied.

Electron selection

Preselection Identification cuts are applied to reconstructed electrons to reduce the background from photon and jet misidentification. Electrons for the analysis are identified with a medium selection based on cuts on both calorimeter and Inner Detector variables. Electrons are preselected with $E_T > 15$ GeV and $|\eta| < 2.47$, excluding the region between end-cap and barrel ($|\eta| = 1.37$-1.52). In addition, electrons are not counted if they lie in clusters affected by detector problems (check with Object Quality Map).

Selection In addition to the preselection requirements, electrons are selected if their $E_T > 17$ GeV. Selected electrons are identified as tight. The increase of the electron transverse energy is due to the threshold of the electron trigger.

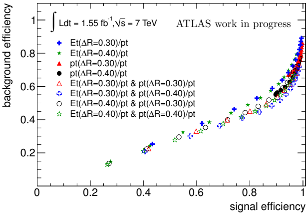
Hadronic τ selection

Preselection Hadronic τ candidates are preselected if their $p_T > 20$ GeV and $|\eta| < 2.47$, excluding the crack region at $|\eta| = 1.37$-1.52. The transverse energy of the hadronic τ candidates is raised to 25 GeV in the $\tau_e\tau_h$ channel, where the τ trigger turn-on curve is not well modelled by the simulation close to the p_T threshold. A small part of the hadronic τ candidates is removed at $|\eta| < 0.03$, due to high fakerate from electrons in the small crack region of the TRT.

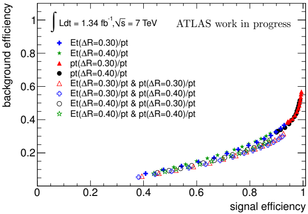
Selection Hadronic τ candidates are selected if they fulfill the preselection requirements and do not overlap with electrons and muons. A Boosted Decision Tree of medium tightness is applied to both 1-prong and multi-prong candidates, to reduce the fakerate from jets. A tight electron veto is applied to reduce the number of electrons misidentified as hadronic τ candidates.

Lepton isolation (2)

Muon channel



Electron channel

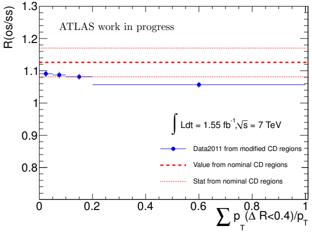


Estimation of the multijet background (2)

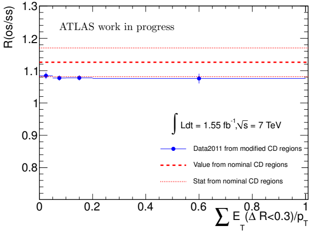
The method applied for the multi-jet background estimation from data relies on the fact that the R_{OSSS} does not depend on the lepton isolation.
Two sources of systematics are considered:

- Dependence on the isolation cut.

Muon channel, **pt_in_cone** in $\Delta R = 0.40$



Muon channel, **Et_in_cone** in $\Delta R = 0.30$



- The estimation is calculated at the different steps of the cut flow. No dependence is found in the $\tau_\mu \tau_\mathrm{h}$ channel.

$$R_{\mathrm{OSSS}} = \begin{cases} 1.06 \pm 0.03\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{iso\ sys.}) \pm 0.04\ (\mathrm{cutflow\ sys.}) & \tau_\mathrm{e}\tau_\mathrm{h}\ \mathrm{channel}\,, \\ 1.13 \pm 0.04\ (\mathrm{stat.}) \pm 0.02\ (\mathrm{iso\ sys.}) & \tau_\mu\tau_\mathrm{h}\ \mathrm{channel}\,. \end{cases}$$