Z and W Physics with Taus at the LHC

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on behalf of the LHCb Collaboration
including results from ATLAS and CMS

Massachusetts Institute of Technology

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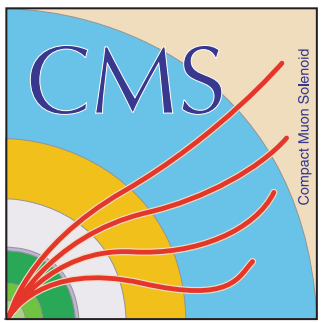
@2014



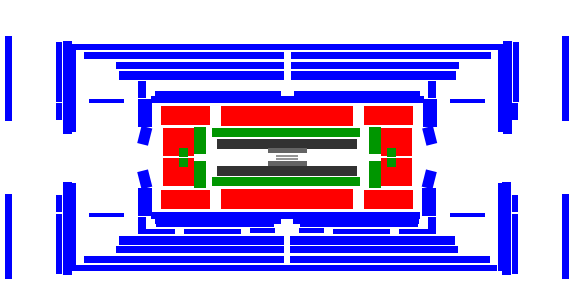
Analyses

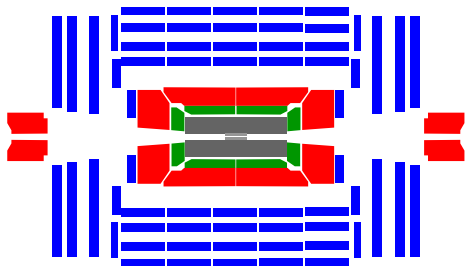
	Analysis		$\mathcal{L}$		Data	Documentation
ATLAS	$Z \to$	$\tau_\mu\tau_\mu$	36	pb^{-1}	2010	Phys.Rev. D84 (2011) 112006
		$\tau_\mu\tau_e$	4.6	fb^{-1}	2011	CERN-PH-EP-2014-119*
		$\tau_\mu\tau_h$	1.55	fb^{-1}	2011	ATLAS-CONF-2012-006
		$\tau_e\tau_h$	1.34	fb^{-1}		
	$W \to \tau\nu$	(σ)	34	pb^{-1}	2010	Phys.Lett. B706 (2012) 276-294
		$(\mathcal{P}_\tau)$	24	pb^{-1}	2010	Eur.Phys.J. C72 (2012) 2062
CMS	$Z \to$	$\tau_\mu\tau_\mu$				
		$\tau_\mu\tau_e$	36	pb^{-1}	2010	JHEP 08 (2011) 117
		$\tau_\mu\tau_h$				
		$\tau_e\tau_h$				
	$W \to \tau\nu$		32	pb^{-1}	2010	CMS-PAS-EWK-11-019
LHCb	$Z \to$	$\tau_\mu\tau_\mu$	1.03	fb^{-1}		
		$\tau_\mu\tau_e$	1.03	fb^{-1}	2011	JHEP 01 (2013) 111
		$\tau_\mu\tau_h$	1.03	fb^{-1}		
		$\tau_e\tau_h$	0.96	fb^{-1}		

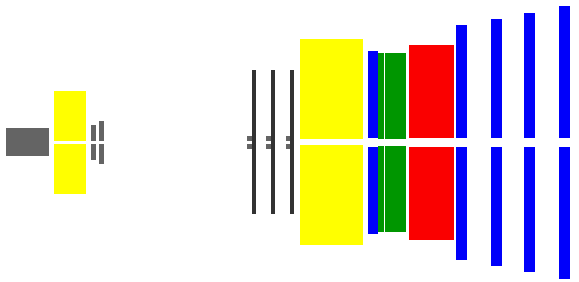
* combined SM fit, extrapolated to dedicated fiducial region

Detectors

pixel | silicon strip | ECAL | Cherenkov
drift tube | HCAL | muon







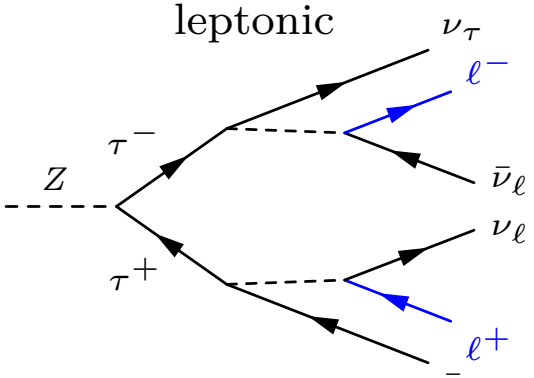
ATLAS	CMS	LHCb
full detector ($\tau\tau$)	full detector ($\tau\tau$)	forward arm
missing energy	*missing energy*	*no missing energy*
pixel, strip, drift	pixel, strip	vertex, strip, drift ($\tau\tau$)
$\sigma_{\mathrm{IP}_T} \approx 22$, $\sigma_{\mathrm{IP}_z} \approx 112$ μm	$\sigma_{\mathrm{IP}_T} \approx 18$, $\sigma_{\mathrm{IP}_z} \approx 35$ μm	$\sigma_{\mathrm{IP}} \approx 14\,\mu$m
liquid argon ($\tau_\mu\tau_e$)	lead tungstate ($\tau_\mu\tau_e$)	polystyrene
$\frac{\sigma_E}{E} \approx \frac{10\%}{\sqrt{E}} \oplus 0.2\%^\dagger$	$\frac{\sigma_E}{E} \approx \frac{3\%}{\sqrt{E}} \oplus 0.5\%$	$\frac{\sigma_E}{E} \approx \frac{10\%}{\sqrt{E}} \oplus 1\%$

† all mass, momentum, and energy units unless explicitly labeled are given in GeV with $c = 1$

$Z \to \tau\tau$ Cross Section

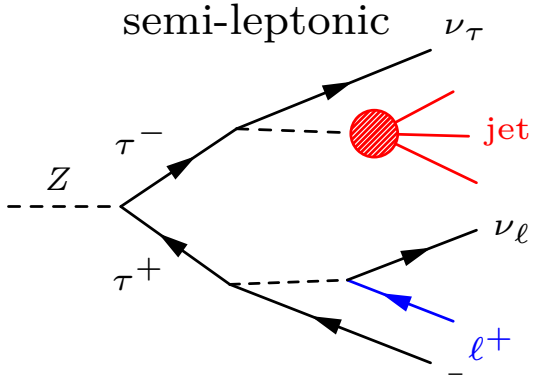
Signals and Backgrounds

leptonic



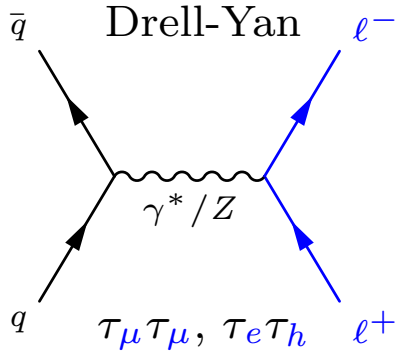
$\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$

semi-leptonic



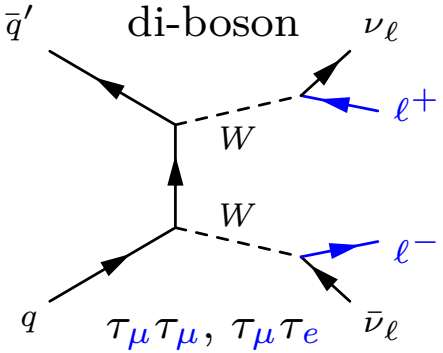
$\tau_\mu\tau_h$, $\tau_e\tau_h$

Drell-Yan



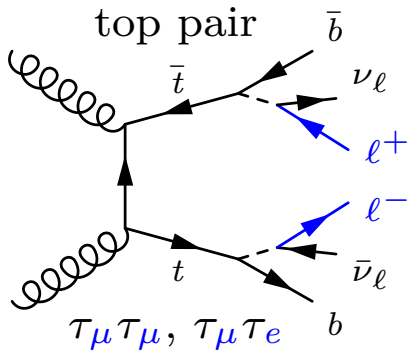
$\tau_\mu\tau_\mu$, $\tau_e\tau_h$

di-boson



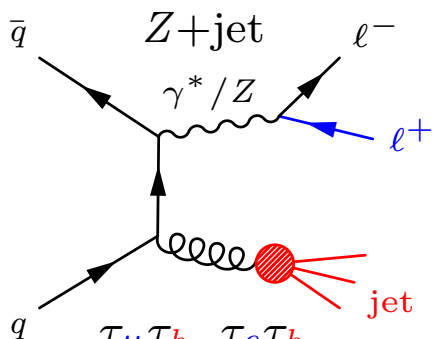
$\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$

top pair



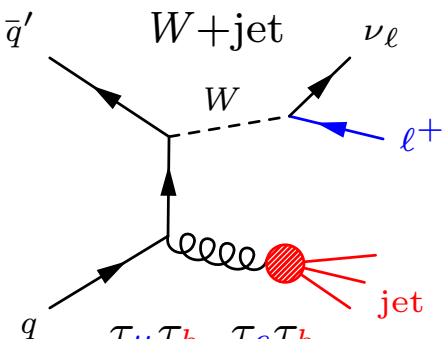
$\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$

Z+jet



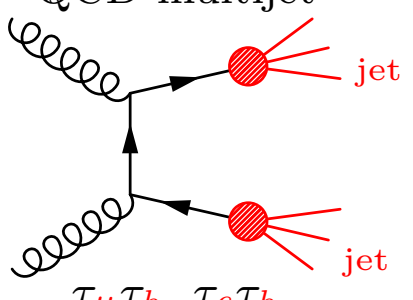
$\tau_\mu\tau_h$, $\tau_e\tau_h$

W+jet



$\tau_\mu\tau_h$, $\tau_e\tau_h$

QCD multijet



$\tau_\mu\tau_h$, $\tau_e\tau_h$

Particle Selection

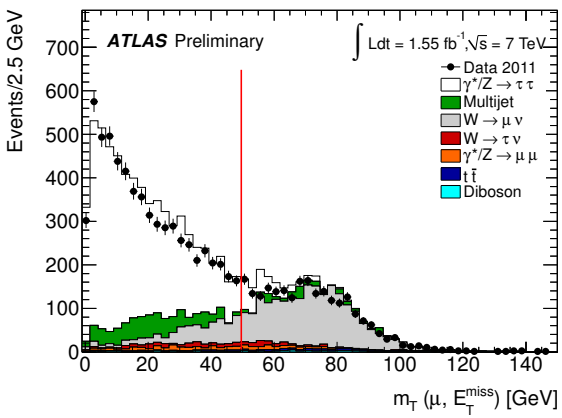
	ATLAS	CMS	LHCb
triggers	muon $p_T > 10 - 15; 18$ $\tau_\mu\tau_\mu$, $\tau_\mu\tau_h$; $\tau_\mu\tau_e$ electron/hadrons $E_T > 20 - 22; 15/16$ $\tau_\mu\tau_e$; $\tau_e\tau_h$	muon $p_T > 9 - 15$ $\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$, $\tau_\mu\tau_h$ electron $E_T > 12$ $\tau_e\tau_h$	muon $p_T > 15$ $\tau_\mu\tau_\mu$, $\tau_\mu\tau_e$, $\tau_\mu\tau_h$ electron $p_T > 10$ $\tau_\mu\tau_e$, $\tau_e\tau_h$
muon	track + muon system isolated $p_T > 17, 20, 15/10\,\tau_\mu\tau_\mu$ $\lvert\eta\rvert < 2.4, 2.5\,\tau_\mu\tau_e$	track + muon system isolated $p_T > 15, 19/10\,\tau_\mu\tau_\mu$ $\lvert\eta\rvert < 2.1$	track + muon system isolated $p_T > 20, 20/5\,\tau_\mu\tau_\mu$ $2.0 < \eta < 4.5$
electron	track + ECAL isolated $E_T > 17, 25\,\tau_\mu\tau_e$ $\lvert\eta\rvert < 2.47$	track + ECAL isolated $E_T > 15$ $\lvert\eta\rvert < 2.4, 2.1\,\tau_e\tau_h$	track + ECAL isolated $p_T > 20, 5\,\tau_\mu\tau_e$ $2.0 < \eta < 4.5$
hadrons‡	one or three-pronged anti-k_T $p_T > 20, 25\,\tau_e\tau_h$ $\lvert\eta\rvert < 2.47$	one or three-pronged anti-k_T $p_T > 20$ $\lvert\eta\rvert < 2.3$	one-pronged isolated $p_T > 5$ $2.25 < \eta < 3.75$

‡ see *Tau Trg/Rec/ID ATLAS* (Limbach 09 : 00) and *Tau Trg/Rec/ID CMS* (Veelken 09 : 20)

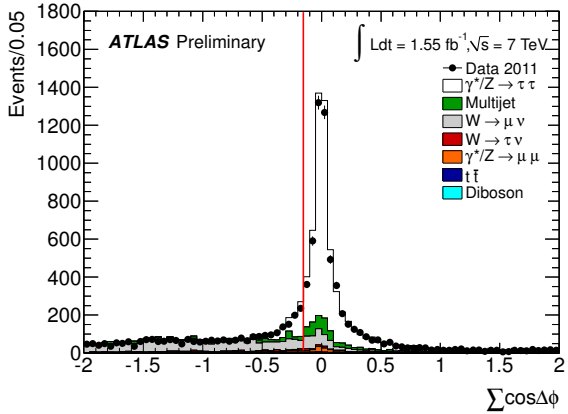
Event Selection

	ATLAS			CMS				LHCb			
M_{vis}	$\tau_\mu\tau_\mu$		$\tau_\mu\tau_h$	$\tau_e\tau_h$	$\tau_\mu\tau_\mu$				$\tau_\mu\tau_\mu$	$\tau_\mu\tau_e$	$\tau_\mu\tau_h$	$\tau_e\tau_h$
M_T			$\tau_\mu\tau_h$	$\tau_e\tau_h$		$\tau_\mu\tau_e$	$\tau_\mu\tau_h$	$\tau_e\tau_h$				
ϕ_τ $\phi_{\not{E}_T}$			$\tau_\mu\tau_h$	$\tau_e\tau_h$	$\tau_\mu\tau_\mu$							
$\Delta\phi$	$\tau_\mu\tau_\mu$				$\tau_\mu\tau_\mu$				$\tau_\mu\tau_\mu$	$\tau_\mu\tau_e$	$\tau_\mu\tau_h$	$\tau_e\tau_h$
A_{p_T}	$\tau_\mu\tau_\mu$				$\tau_\mu\tau_\mu$				$\tau_\mu\tau_\mu$			
IP	$\tau_\mu\tau_\mu$				$\tau_\mu\tau_\mu$				$\tau_\mu\tau_\mu$		$\tau_\mu\tau_h$	$\tau_e\tau_h$

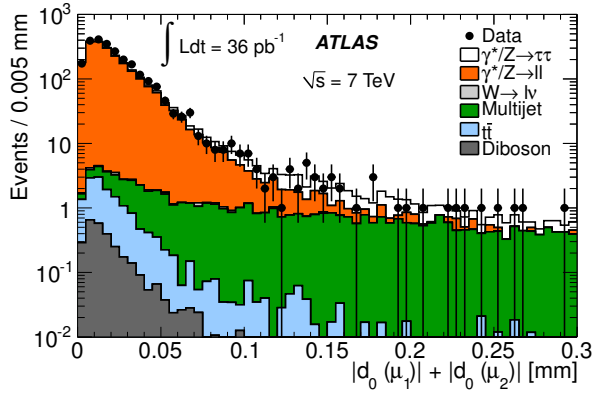
m_T: $\tau_\mu\tau_h$



ϕ_τ, $\phi_{\not{E}_T}$: $\tau_\mu\tau_h$



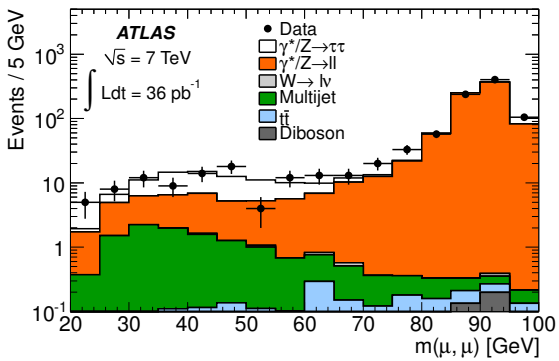
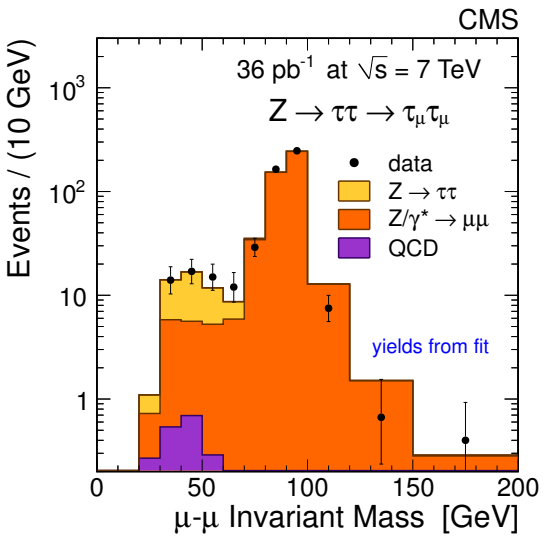
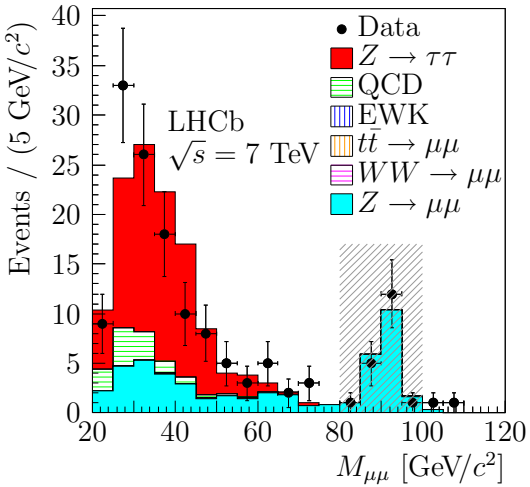
IP: $\tau_\mu\tau_\mu$



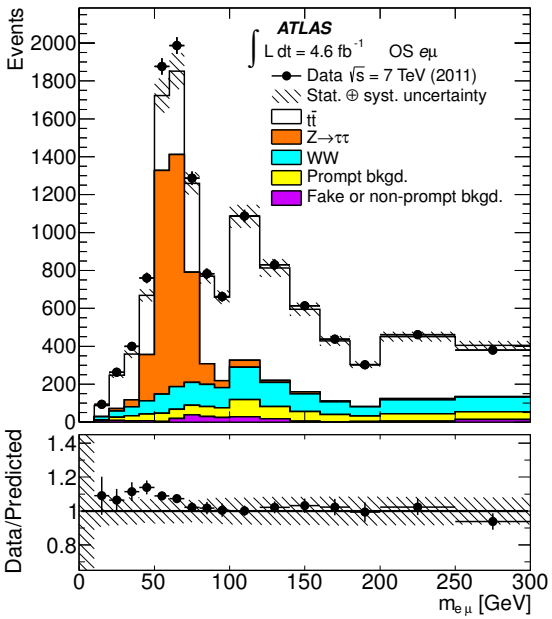
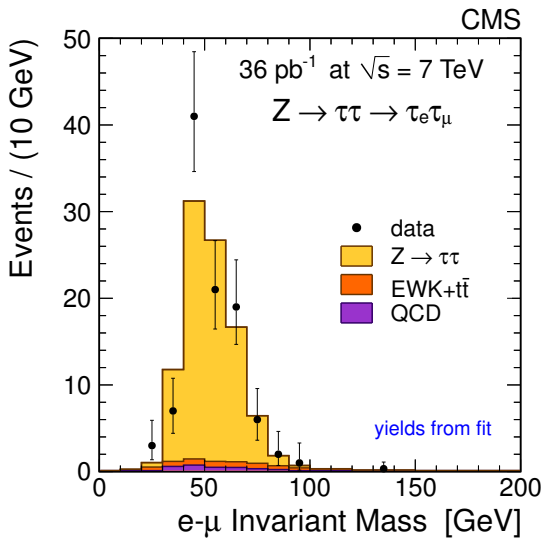
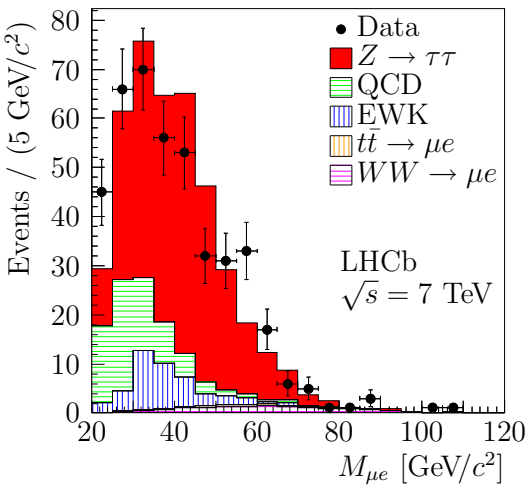
Background Estimation

		ATLAS	CMS	LHCb
Drell-Yan	*norm*	data M_{vis}	data IP	data M_{vis}
	temp	MC	data IP	data IP
di-boson	*norm*	MC	data M_T	MC
	temp	MC	MC	MC
top pair	*norm*	MC	data M_T	MC
	temp	MC	MC	MC
W+jet	*norm*	MC/data M_T, ϕ	data M_T	data OS/SS
	temp	MC	MC	MC
Z+jet	*norm*	data M_{vis}	data IP	data OS/SS
	temp	MC	data IP	MC
QCD multijet	*norm*	data OS/SS	data OS/SS	data OS/SS
	temp	data SS	data SS	data SS

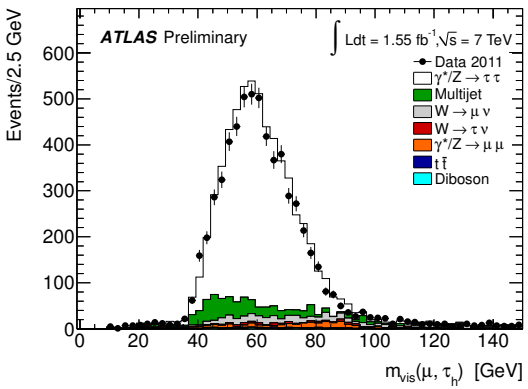
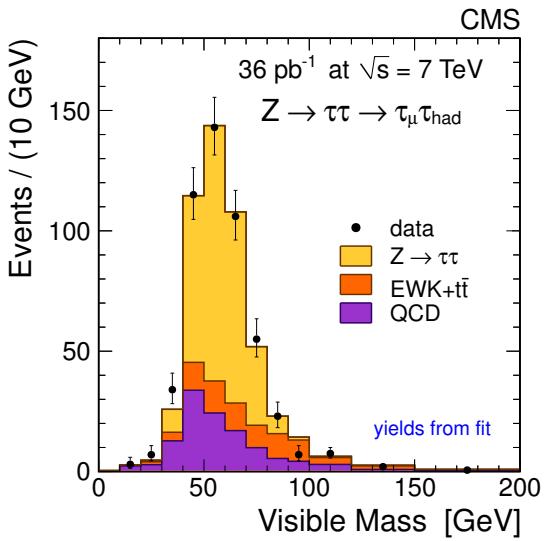
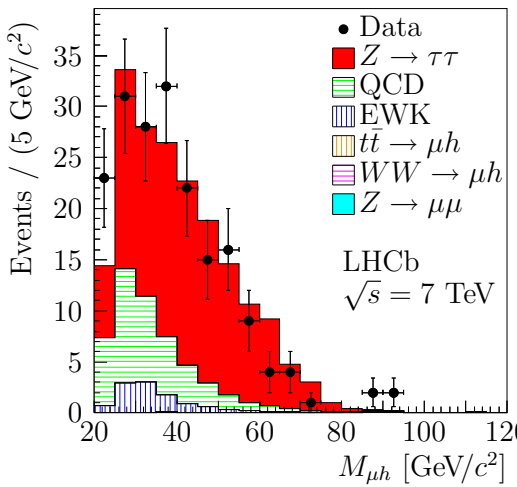
$\tau_\mu\tau_\mu$ Final State Results

ATLAS (36 pb^{-1})	CMS (36 pb^{-1})	LHCb (1.03 fb^{-1})
		
observed: 90 background: 47 signal: 43	observed: 58 background: 23 signal: 35	observed: 124 background: 42 signal: 82
primary background: 40% $\gamma^*/Z \to \mu\mu$	primary background: 34% $\gamma^*/Z \to \mu\mu$	primary background: 24% $\gamma^*/Z \to \mu\mu$
primary systematic: 9% *muon efficiency*	primary systematic: 2% *muon acceptance*	primary systematic: 8% $\gamma^*/Z \to \mu\mu$ *background*

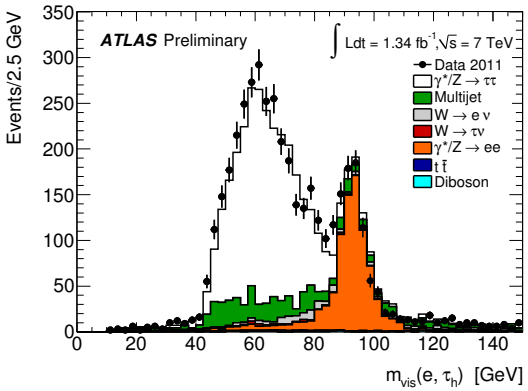
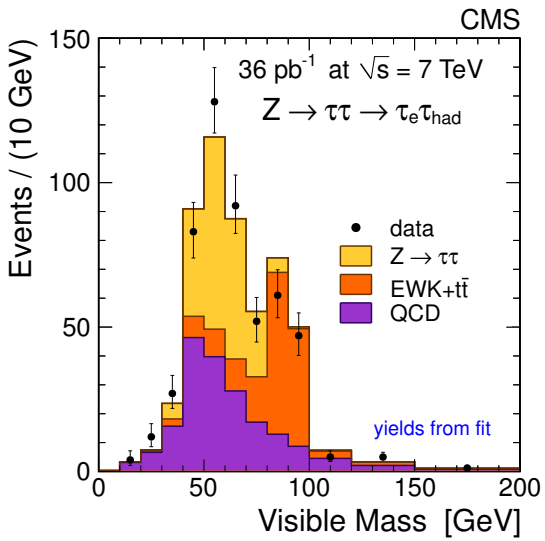
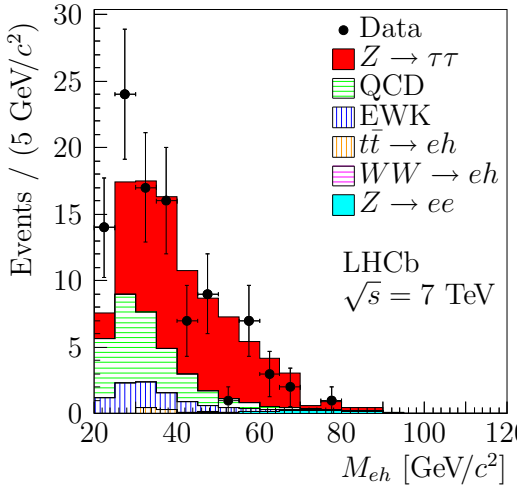
$\tau_\mu\tau_e$ Final State Results

ATLAS (4.6 fb^{-1})	CMS (36 pb^{-1})	LHCb (1.03 fb^{-1})
		
observed: 12224 background: 8384 signal: 3840	observed: 101 background: 14 signal: 87	observed: 421 background: 130 signal: 291
primary background: 49% *top pair*	primary background: 7% *top pair*	primary background: 10% *W+ jets*
primary systematic: 3% *$Z \to \tau\tau$ modeling*	primary systematic: 2% *electron acceptance*	primary systematic: 4% *electron efficiency*

$\tau_\mu\tau_h$ Final State Results

ATLAS (1.55 fb^{-1})	CMS (36 pb^{-1})	LHCb (1.03 fb^{-1})
		
observed: 5184	observed: 517	observed: 189
background: 793	background: 228	background: 53
signal: 4391	signal: 289	signal: 136
primary background: 8%	primary background: 26%	primary background: 22%
QCD multijet	*QCD multijet*	*QCD multijet*
primary systematic: 8%	primary systematic: 23%	primary systematic: 2%
energy scale	*hadronic efficiency*	*IP selection efficiency*

$\tau_e\tau_h$ Final State Results

ATLAS (1.34 fb^{-1})	CMS (36 pb^{-1})	LHCb (0.96 fb^{-1})
		
observed: 2600	observed: 540	observed: 101
background: 449	background: 346	background: 37
signal: 2151	signal: 194	signal: 66
primary background: 11% *QCD multijet*	primary background: 34% *QCD multijet*	primary background: 24% *QCD multijet*
primary systematic: 9% *energy scale*	primary systematic: 23% *hadronic efficiency*	primary systematic: 4% *electron efficiency*

ATLAS Cross Sections

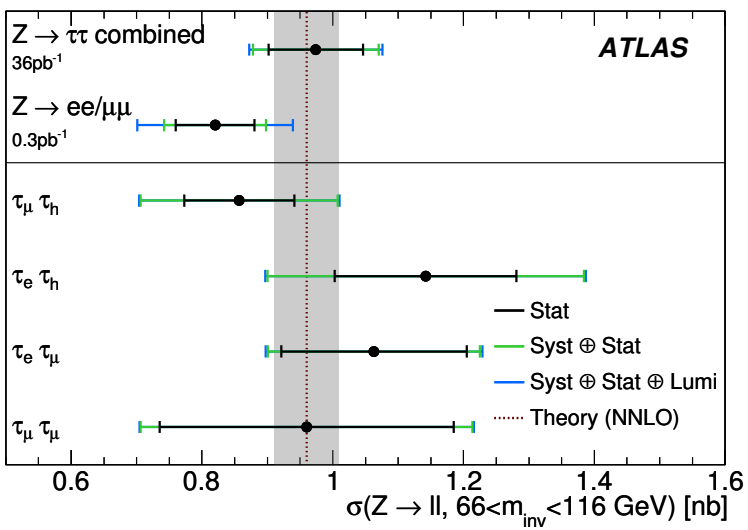
$$\sigma_{pp\to Z\to\tau\tau}\left(\sqrt{s} = 7 \text{ TeV}, 66 < M_{\tau\tau} < 116 \text{ GeV}\right)$$

theory using FEWZ + MSTW08 @ NNLO

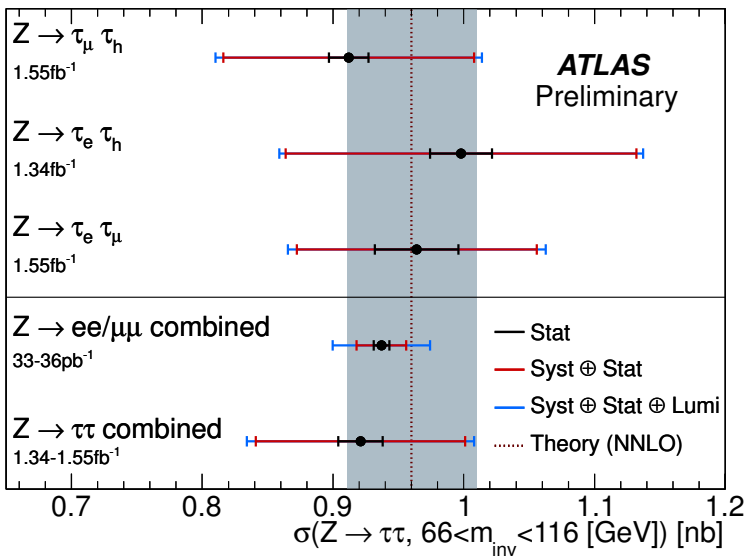
$\sigma \pm$ statistical $\pm$ systematic $\pm$ luminosity [nb]

theory	0.96 ± 0.05	combined	$0.92 \pm 0.02 \pm 0.08 \pm 0.03$
$\tau_\mu\tau_\mu$	$0.96 \pm 0.22 \pm 0.12 \pm 0.03$	$\tau_\mu\tau_e$	$1.06 \pm 0.02 \pm 0.07 \pm 0.02$
$\tau_\mu\tau_h$	$0.91 \pm 0.01 \pm 0.09 \pm 0.03$	$\tau_e\tau_h$	$1.00 \pm 0.02 \pm 0.13 \pm 0.04$

2010



2011



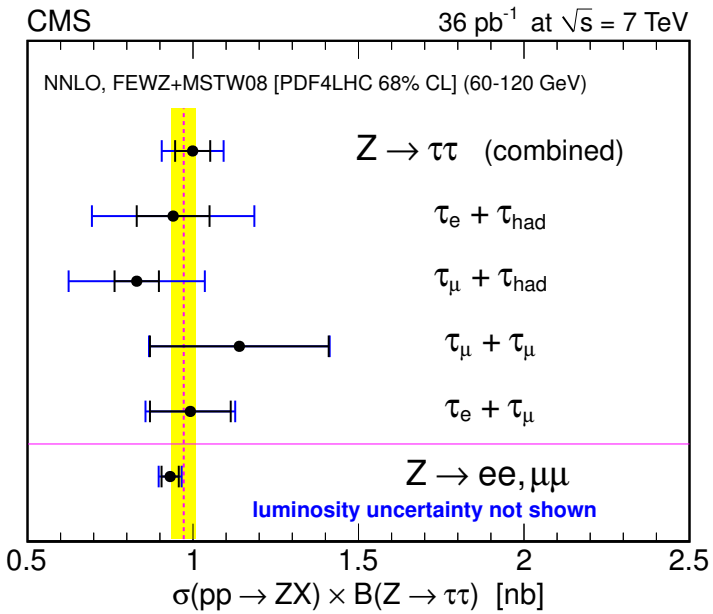
CMS Cross Sections

$$\sigma_{pp\to Z\to\tau\tau}\left(\sqrt{s} = 7 \text{ TeV}, 60 < M_{\tau\tau} < 120 \text{ GeV}\right)$$

theory using FEWZ + MSTW08 @ NNLO

$\sigma \pm$ statistical $\pm$ systematic $\pm$ luminosity [nb]

theory	0.97 ± 0.04	combined	$1.00 \pm 0.05 \pm 0.08 \pm 0.04$
$\tau_\mu\tau_\mu$	$1.14 \pm 0.27 \pm 0.04 \pm 0.05$	$\tau_\mu\tau_e$	$0.99 \pm 0.12 \pm 0.06 \pm 0.04$
$\tau_\mu\tau_h$	$0.83 \pm 0.07 \pm 0.19 \pm 0.03$	$\tau_e\tau_h$	$0.94 \pm 0.11 \pm 0.22 \pm 0.04$



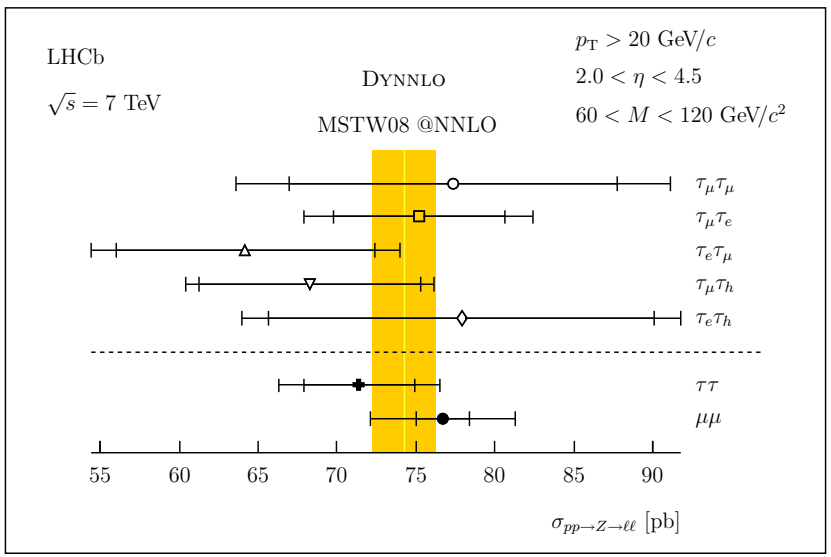
LHCb Cross Sections

$$\sigma_{pp\to Z\to\tau\tau}\left(\sqrt{s} = 7 \text{ TeV}, 60 < M_{\tau\tau} < 120 \text{ GeV}, 2.0 < \eta^{\tau} < 4.5, p_T^{\tau} > 20 \text{ GeV}\right)$$

theory using DYNNLO + MSTW08 @ NNLO

$\sigma \pm$ statistical $\pm$ systematic $\pm$ luminosity [pb]

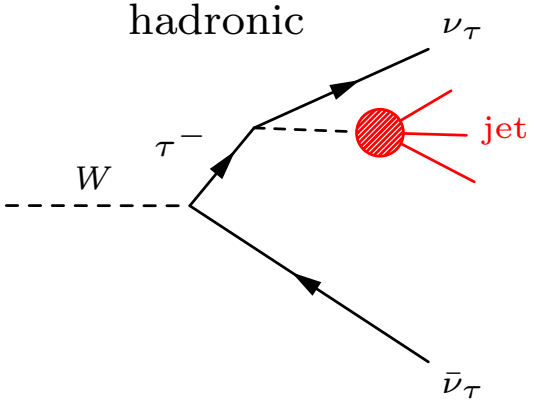
theory	74.3 ± 2.1	combined	$71.4 \pm 3.5 \pm 2.8 \pm 2.5$
$\tau_\mu\tau_\mu$	$77.4 \pm 10.4 \pm 8.6 \pm 2.7$	$\tau_\mu\tau_e$	$75.2 \pm 5.4 \pm 4.1 \pm 2.6$
		$\tau_e\tau_\mu$	$64.2 \pm 8.2 \pm 4.9 \pm 2.2$
$\tau_\mu\tau_h$	$68.3 \pm 7.0 \pm 2.6 \pm 2.4$	$\tau_e\tau_h$	$77.9 \pm 12.2 \pm 6.1 \pm 2.7$



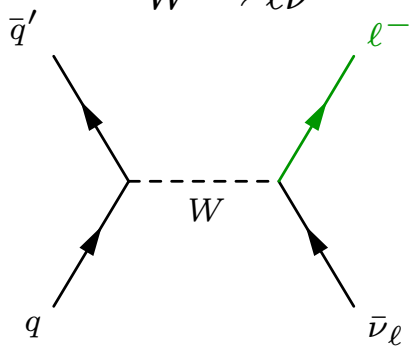
$W \to \tau\nu$ Cross Section

Signal and Backgrounds

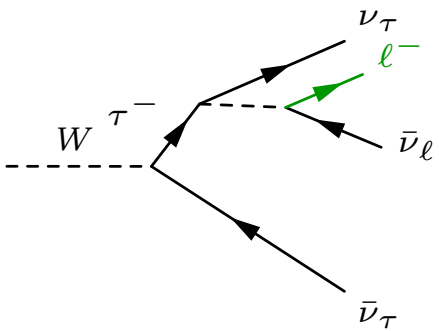
hadronic



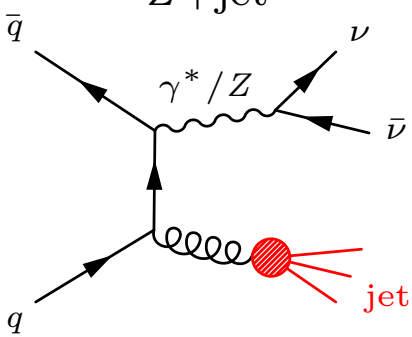
$W \to \ell\nu$



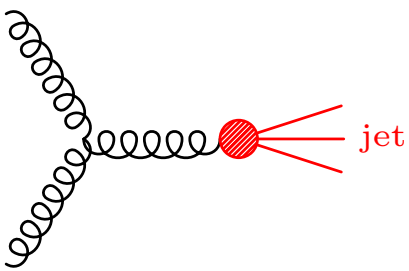
$W \to \tau\nu$



Z+jet

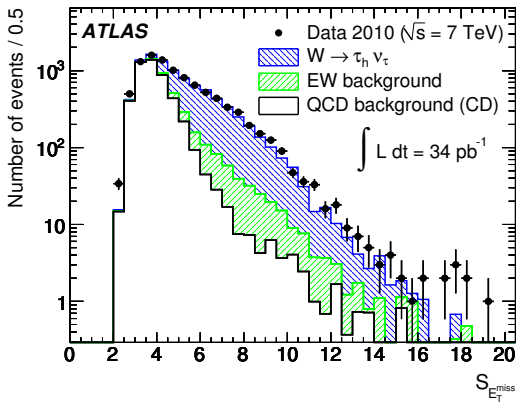


QCD jet

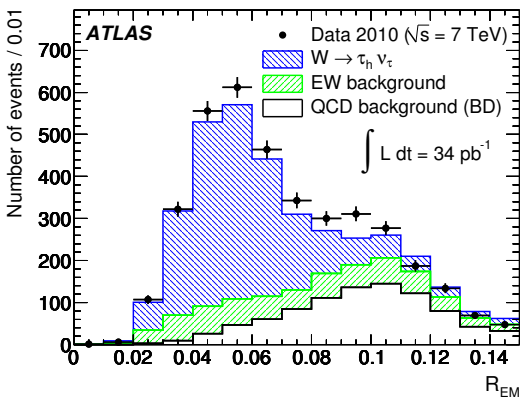


Particle and Event Selection

ATLAS	CMS
trigger	trigger
τ_h $p_T > 12, \not{E}_T > 20$ τ_h $p_T > 16, \not{E}_T > 22$	τ_h $p_T > 20, \not{E}_T > 25$
τ_h selection (BDT)	τ_h selection (cuts)
$20 < p_T < 60, \lvert\eta\rvert < 2.5$ lead track p_T over ECAL collimated impact parameter	$p_T > 30, \lvert\eta\rvert < 2.3$ lead track p_T isolated no muon hits
event selection	event selection
no high p_T leptons $\not{E}_T > 30$ $\Delta\phi(\tau, \not{E}_T)$ $\not{E}_T$ significance	no high p_T leptons $\not{E}_T > 30$ transverse mass tau p_T over jets p_T (R_{HT})



$\not{E}_T$ significance



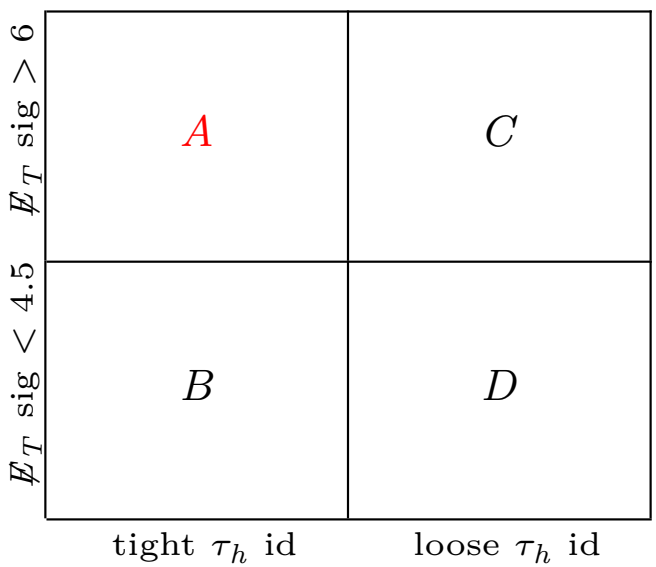
collimation

Background Estimation

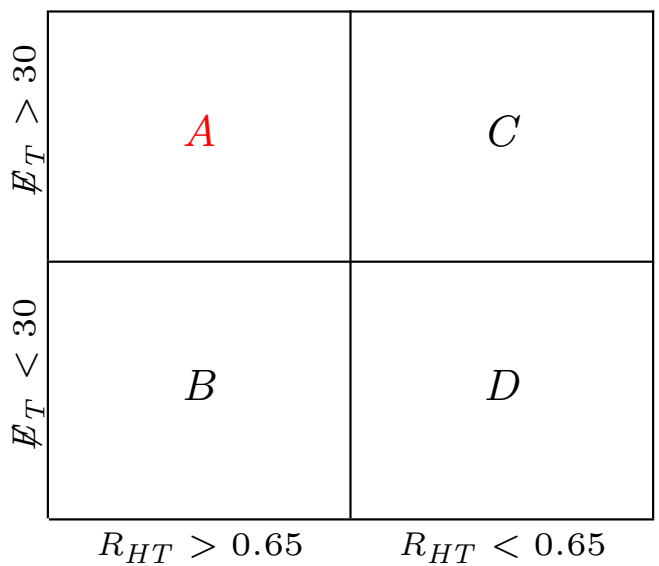
		ATLAS	CMS
$W \to \ell\nu$ Z+*jet*	*norm* *temp*	MC embedded MC	MC MC
QCD jet	*norm* *temp*	data *ABCD* data *ABCD*	data *ABCD*, $\not\!\!E_T$ topology data *ABCD*

$$N_A = N_B \left(\frac{N_C}{N_D}\right)$$

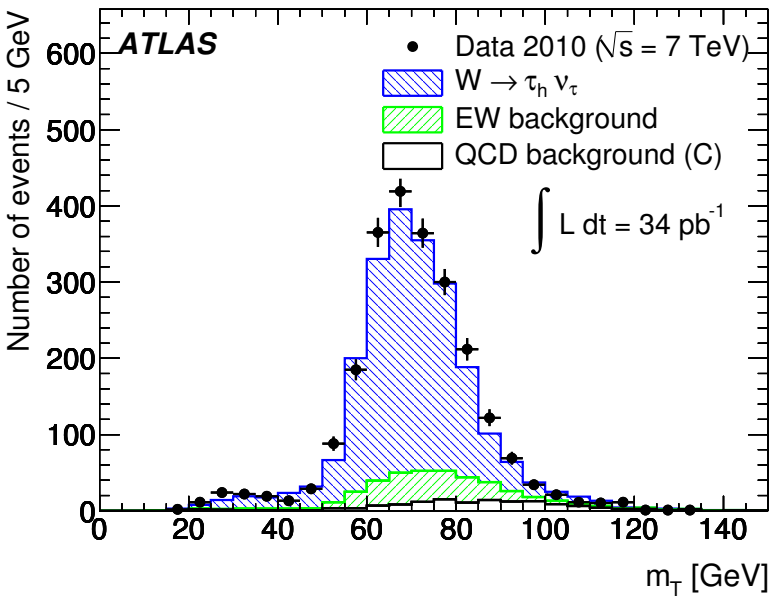
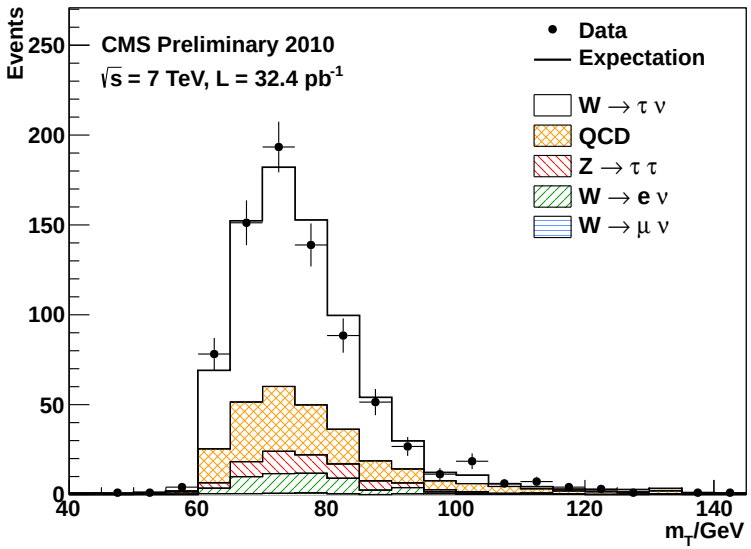
ATLAS



CMS



Results

ATLAS (34 pb^{-1})	CMS (32 pb^{-1})
	
observed: 2335 background: 411 signal: 1924	observed: 793 background: 297 signal: 496
primary background: 12% *electroweak*	primary background: 24% *QCD jet*
primary systematic: 10% *hadronic efficiency*	primary systematic: 16% *energy scale*

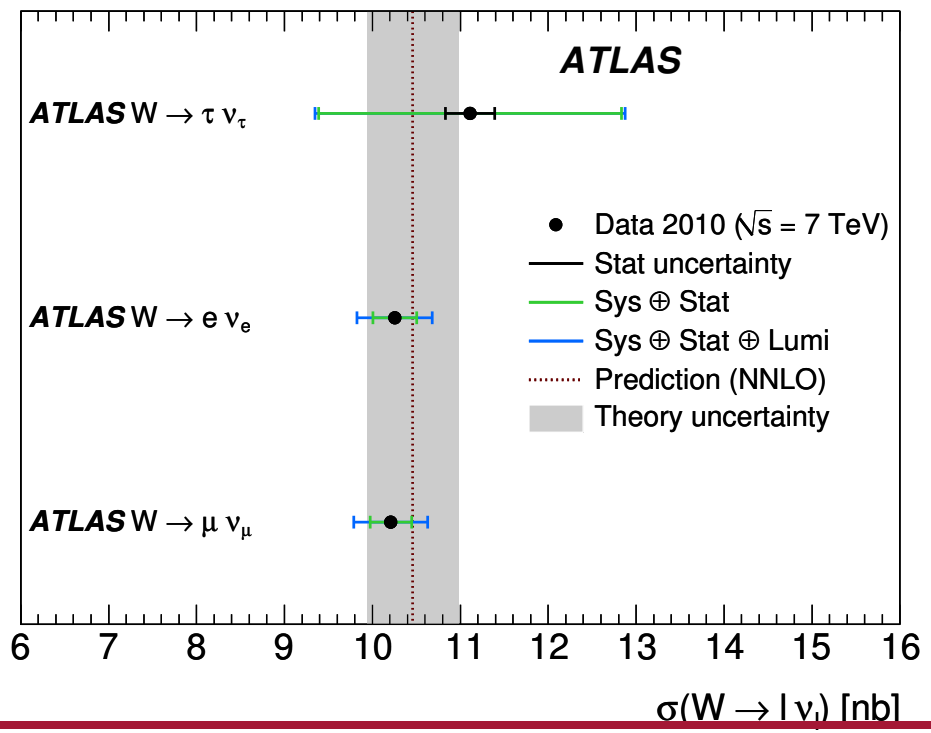
ATLAS Cross Sections

$$\sigma_{pp\to W\to\tau\nu}\left(\sqrt{s} = 7 \text{ TeV}\right)$$

theory using FEWZ + MSTW08 @ NNLO

$\sigma \pm$ statistical $\pm$ systematic $\pm$ luminosity [nb]

theory	10.5 ± 0.5	$W \to \tau_h\nu$ fiducial	$0.70 \pm 0.02 \pm 0.11 \pm 0.02$
observed	$11.1 \pm 0.3 \pm 1.7 \pm 0.4$	$W \to \tau_h\nu$ total	$7.2 \pm 0.2 \pm 1.1 \pm 0.2$



CMS Cross Sections

$$\sigma_{pp\to W\to\tau\nu}\left(\sqrt{s} = 7 \text{ TeV}\right)$$

theory using FEWZ + MSTW08 @ NNLO

$\sigma \pm$ statistical $\pm$ systematic $\pm$ luminosity [nb]

	theory	observed
$W^{\pm} \to \tau^{\pm}\nu$	10.44 ± 0.52	$8.96 \pm 0.51 \pm 2.32 \pm 0.36$
$W^{+} \to \tau^{+}\nu$	6.15 ± 0.29	$5.26 \pm 0.39 \pm 1.36 \pm 0.21$
$W^{-} \to \tau^{-}\nu$	4.29 ± 0.23	$3.40 \pm 0.33 \pm 0.93 \pm 0.14$

$W \to \tau\nu$ Polarization

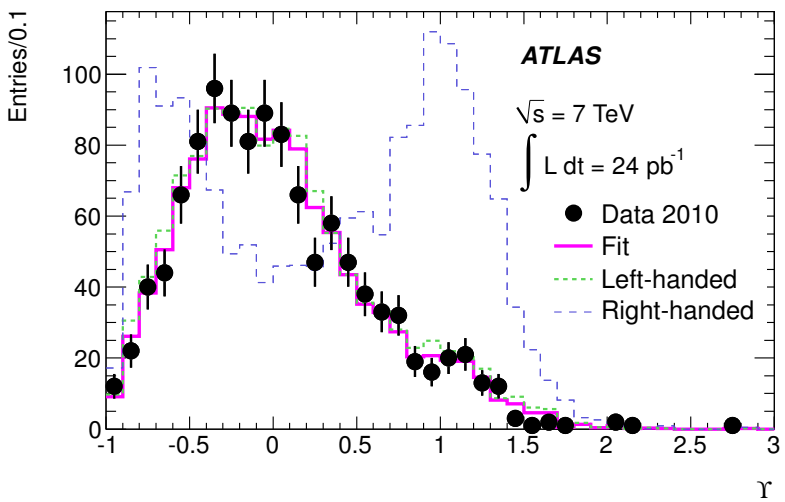
Analysis

- analysis similar to ATLAS cross section measurement
- only uses single prong decays
  - sensitive with $\tau \to \rho\nu$ decay
  - approximately 50% of decays
- angle between ρ and $\pi^{\pm}$:

$$\cos\psi = \frac{m_\rho}{\sqrt{m_\rho^2 - 4m_\pi^2}} \frac{E_{\pi^\pm} - E_{\pi^0}}{|\vec{p}_{\pi^\pm} + \vec{p}_{\pi^0}|}$$

- charged asymmetry:

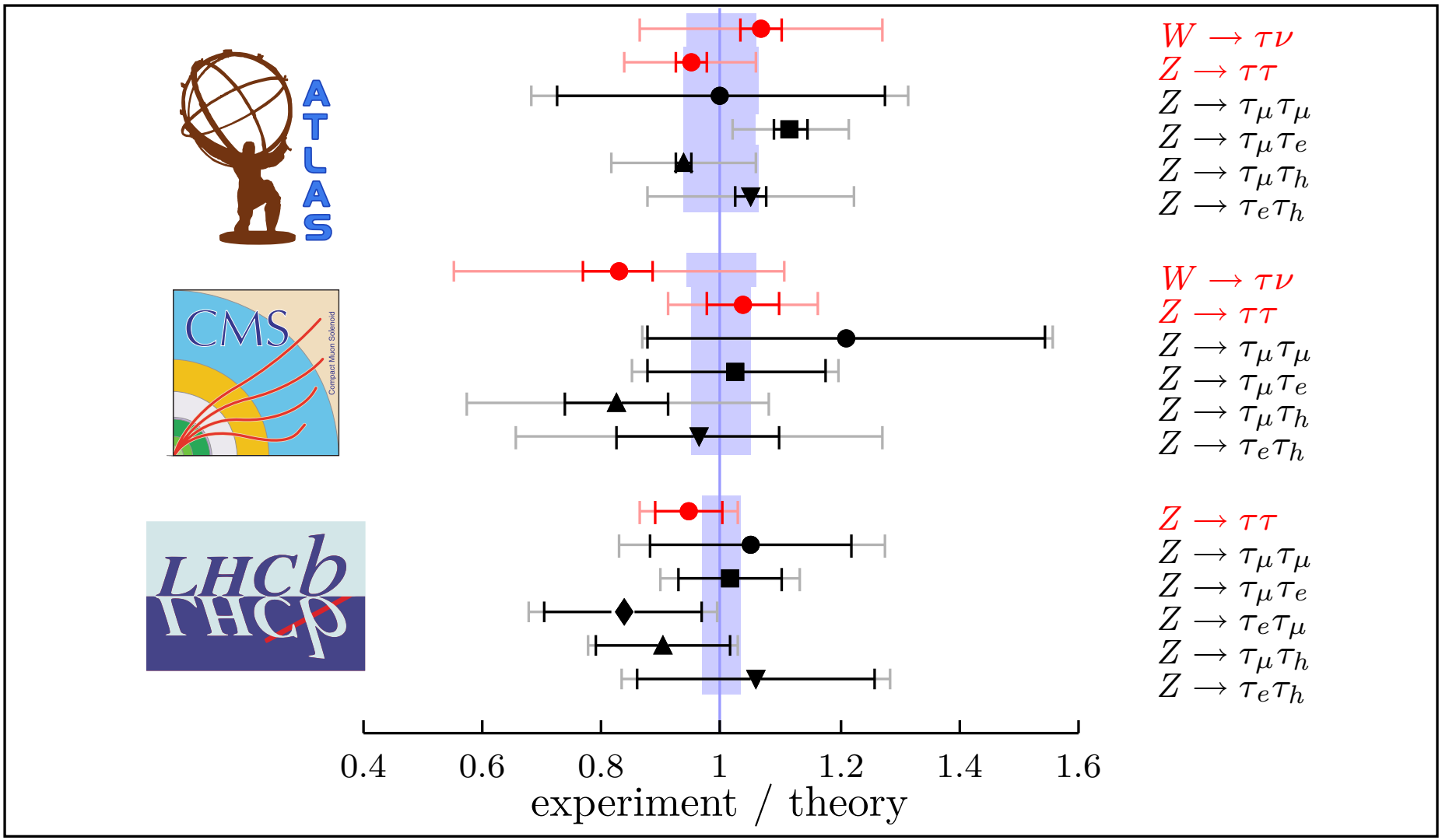
$$\Upsilon = \frac{2p_T^{\text{trk}}}{p_T^{\text{vis}}} - 1 \approx \frac{E_T^{\pi^\pm} - E_T^{\pi^0}}{p_T^{\text{vis}}}$$



$$\mathcal{P}_\tau = -1.06 \pm 0.04\,(\text{stat}) \pm 0.07\,(\text{syst})$$

primary background: 13% *QCD jet*
primary uncertainty: 6% *energy scale*

Summary


ATLAS
CMS
Compact Muon Solenoid
LHCb
$W \to \tau\nu$
$Z \to \tau\tau$
$Z \to \tau_\mu\tau_\mu$
$Z \to \tau_\mu\tau_e$
$Z \to \tau_\mu\tau_h$
$Z \to \tau_e\tau_h$
$W \to \tau\nu$
$Z \to \tau\tau$
$Z \to \tau_\mu\tau_\mu$
$Z \to \tau_\mu\tau_e$
$Z \to \tau_\mu\tau_h$
$Z \to \tau_e\tau_h$
$Z \to \tau\tau$
$Z \to \tau_\mu\tau_\mu$
$Z \to \tau_\mu\tau_e$
$Z \to \tau_e\tau_\mu$
$Z \to \tau_\mu\tau_h$
$Z \to \tau_e\tau_h$
0.4
0.6
0.8
1
1.2
1.4
1.6
experiment / theory

Remarks

- $Z \to \tau\tau$ analyses from ATLAS, CMS, and LHCb
- $W \to \tau\nu$ analysis from ATLAS and CMS
- all results look consistent with SM
- important channels for Higgs and BSM
- looking forward to Run II data
- thanks to the ATLAS, CMS, LHCb, and LHC teams for all of their hard work!

Variables

$$M_{\text{vis}} \equiv \sqrt{p(\ell/h + \ell/h)^2}$$

$$M_T \equiv \sqrt{2p_T(\mu)\not{E}_T + (1 - \cos\Delta\phi(\mu, \not{E}_T))}$$

$$\phi_\tau \quad \phi_{\not{E}_T} \equiv \begin{cases} \cos\left(\phi(\ell) - \phi(\not{E}_T)\right) + \cos\left(\phi(h) - \phi(\not{E}_T)\right) & \text{ATLAS} \\ \Delta\phi(\mu^+, \not{E}_T) & \text{CMS} \end{cases}$$

$$A_{p_T} \equiv \begin{cases} p_T(\mu_1) - p_T(\mu_2) & \text{ATLAS} \\ \frac{p_T(\mu_1+\mu_2)}{|p(\mu_1)|+|p(\mu_2)|} & \text{CMS} \\ \frac{|p_T(\mu_1)-p_T(\mu_2)|}{p_T(\mu_1)+p_T(\mu_2)} & \text{LHCb} \end{cases}$$