

Standard Model W^+W^- cross section measurement with the ATLAS detector and extension for exclusive W^+W^- -production

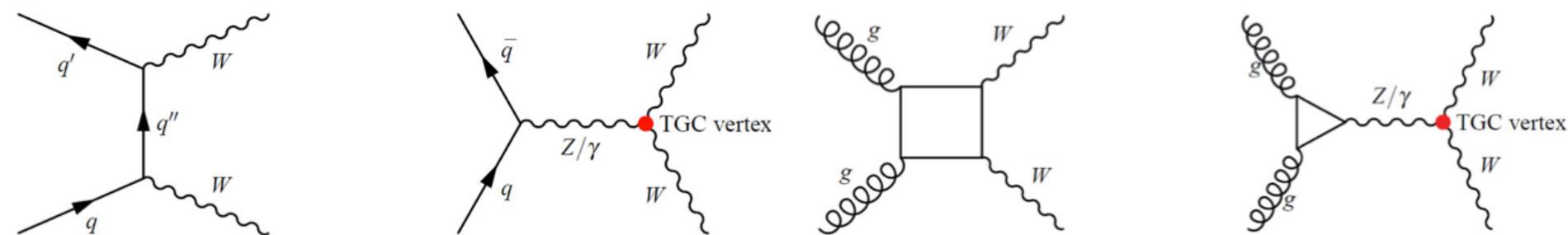
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Standard model W^+W^- production

- Measurement of the **WW cross section** in purely leptonic channels (di-lepton: e, μ)
- Important test of the electroweak sector of the Standard model
- Background to Higgs searches
- Sensitive to anomalous TGC that could cause deviations in the production x-section
- Theoretical prediction from NLO: $\bar{q}q \rightarrow WW$ production $\sigma_{NLO} = 44.7 \pm 2.8 \text{ pb}$



Gluon fusion: $gg \rightarrow WW$ contributes additional $\sim 3\%$

Analysis characteristics:

- Signal signature includes three final states $e^+e^-E_T^{\text{miss}}$, $\mu^+\mu^-E_T^{\text{miss}}$ and $e^\pm\mu^\mp E_T^{\text{miss}}$
- Di-lepton decay channels allow signal extraction from large background
- Isolated high p_T di-lepton final states are considered: ee, e μ , $\mu\mu$
- Tau decay cascade $W \rightarrow \tau + X \rightarrow e/\mu + X$ is included
- Expected backgrounds: Drell-Yan, ttbar, single top, $W+jets$, other di-bosons etc.
- Contributions from $H \rightarrow WW$ not included ($\sim 3\%$ increase for 126 GeV)

Background characteristics & samples

Standard model processes producing $I^+I^-E_T^{\text{miss}}$ signature are:

- **Drell-Yan:** $Z/\gamma^* \rightarrow l\bar{l}$ in association with jets,
where apparent E_T^{miss} arises from mismeasurement of the two leptons or pileup
- **Top:** $t\bar{t}\text{bar}$ and Wt where b-jets are not reconstructed or identified
- **$WZ \rightarrow ll\nu\nu$:** where one final state lepton is not detected
- **$ZZ \rightarrow ll\nu\nu$:** where di-lepton invariant mass is not near the Z-mass
- **$W+\text{jets}$:** W production in association with jets, where jet is misidentified as lepton
- **$W+\gamma^*$:** where the photon converts into electrons
- **QCD:** multi-jet production where two jets are reconstructed as leptons due to misidentification (found to be negligible)

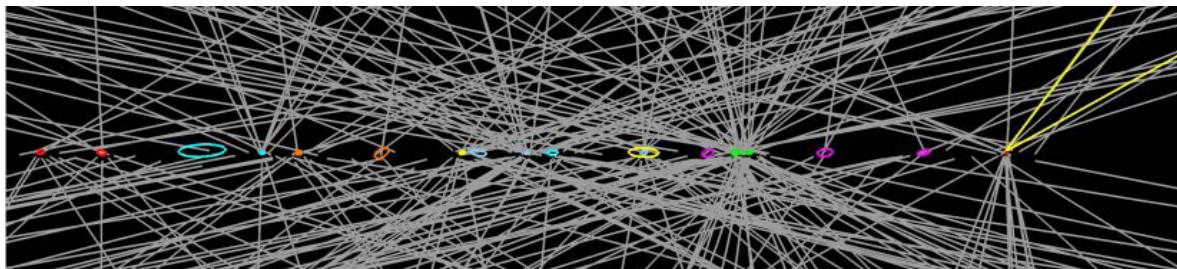
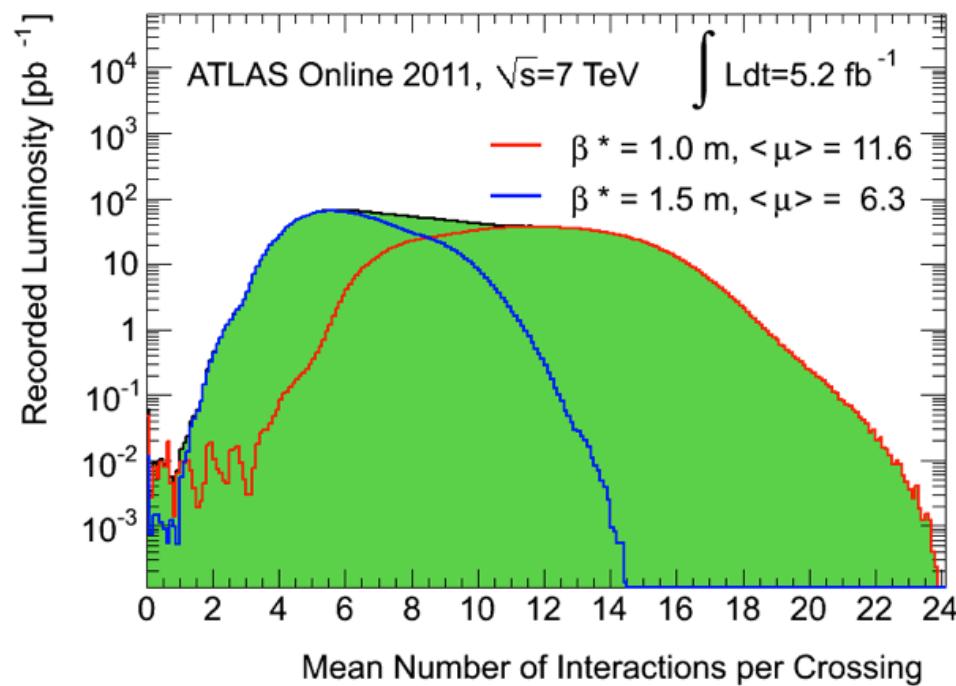
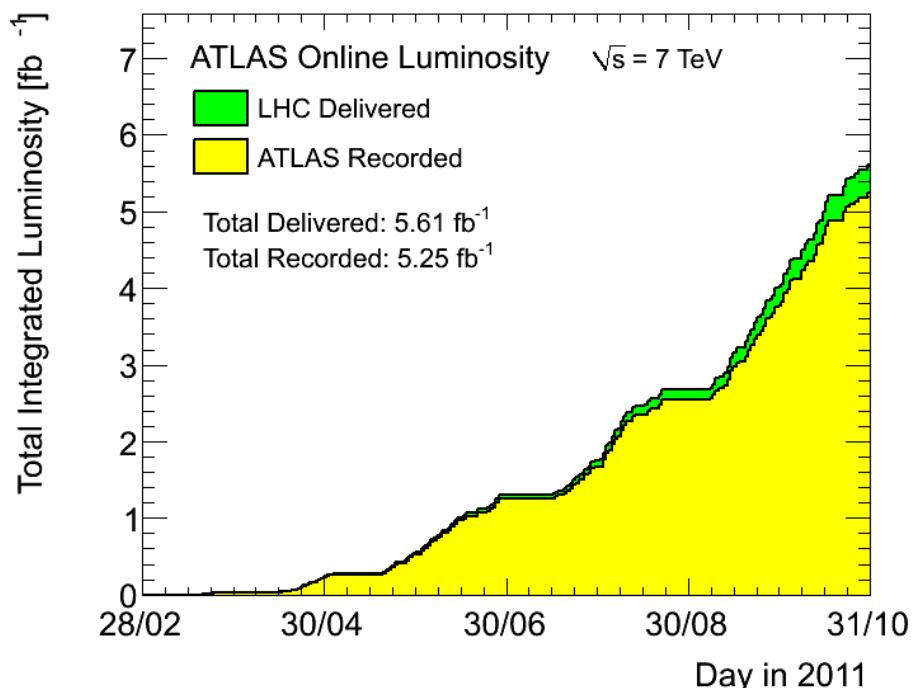
Generator summary:

- Signal: $qq \rightarrow WW$ – MC@NLO, $gg \rightarrow WW$ – gg2ww,
- $V+X$: $W+X$ Np0-5 – Alpgen, $Z+X$ Np0-5 – Alpgen, Zbb Np0-3 – Alpgen, $Wc/cc/bb$ Np0-4 - Alpgen
- Dibosons: WZ , ZZ – Herwig, $W\gamma$ Np0-5 – Alpgen, $W\gamma^*$ – MadGraph
- Top: $t\bar{t}\text{bar}$ – MC@NLO, Wt – AcerMC, **Single top** – AcerMC
- QCD: bb/cc - PythiaB

Data sets full 2011 data set

5.61 fb^{-1} delivered by LHC, 5.3 fb^{-1} recorded by ATLAS, $\sim 4.6 \text{ fb}^{-1}$ after DQ requirements

High number of proton-proton interactions per bunch crossing
→ challenging analyses in particular for final states with jets and missing E_T



Primary vertex selection:

- Max sum(p_T)
- At least 3 tracks with $p_T > 400 \text{ MeV}$ to reduce cosmics

SM W⁺W⁻ object selection

Optimization driven by increased number of interactions per crossing (pileup)

Muon definition:

- STACO Combined, $p_T > 20 \text{ GeV}$, $|\eta| < 2.4$, tight requirements: pixel hits, b-layer hits etc.
- Calo isolation: cluster $\Sigma E_T(\text{cone } dR=0.3) < 14\%$, track isolation $\Sigma p_T(\text{cone } dR=0.3) < 15\%$ to suppress hadronic jets mistakenly reconstructed as leptons

Electron definition:

- $E_T > 20 \text{ GeV}$, $|\eta| < 2.47$, LAr crack region removal $1.37 < |\eta| < 2.47$
- **Tight++ quality** – shower shape, detection of transition radiation, track matching to calorimeter cluster
- Calo isolation: cluster $\Sigma E_T(\text{cone } dR=0.3) < 14\%$, track isolation $\Sigma p_T(\text{cone } dR=0.3) < 13\%$ to suppress hadronic jets mistakenly reconstructed as leptons

- Energy leakage and pileup corrections inside the isolation cone applied to both e and μ calo isolations
- z_0 , d_0 significance to ensure compatibility with primary vertex
- **Overlap removal**: e and μ are required to be separated by $dR > 0.1$, electron discarded

Jet definition:

- AntiKt4TopoEM jet: $p_T > 25 \text{ GeV}$, $R = 0.4$, $|\eta| < 4.5$
- **Overlap removal**: Lepton/jet separation required: $dR > 0.3$, jet discarded

MET definition:

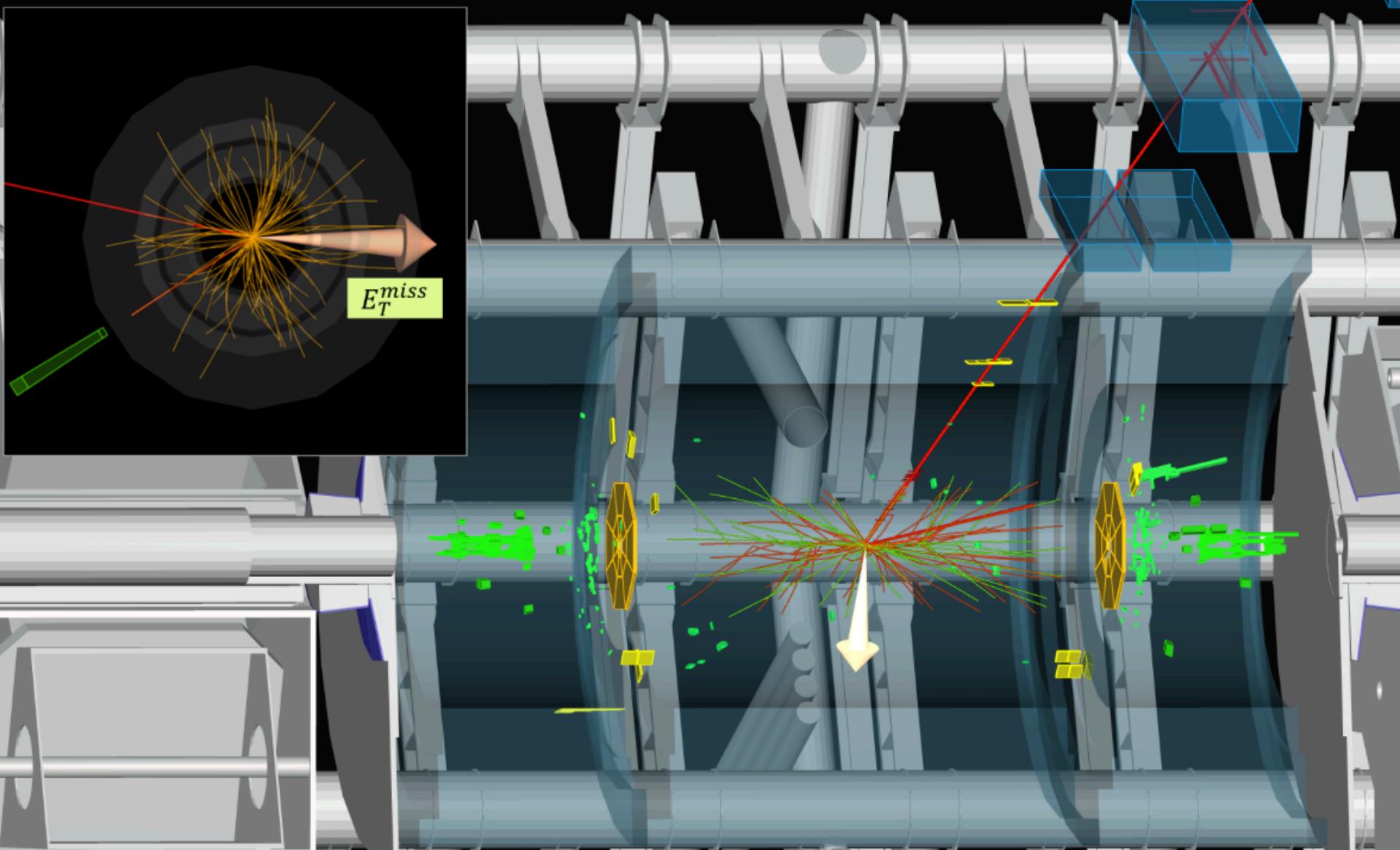
- Sum E_T of calibrated topological clusters stored in **MET_RefFinal** (includes ECAL, HCAL, Inner detector, Muons), $|\eta| < 4.9$



WW → eνμν Candidate

Run 167576 Event 120642801

Time 2010-10-24 13:06:00 EDT



Event selection (I)

Pre-selection criteria:

- **Datasets:** SMWZ D3PD ntuples
- **Duplicates removal:** removal of overlaps between combined electron/muon D3PD datasets
- **Data quality:** official Good-Run-List
- **Primary vertex selection:** at least 3 good tracks with $p_T > 400$ MeV to reduce cosmics
- **Trigger selection:** single lepton trigger with period dependent thresholds (unprescaled)
- **Di-lepton selection:** Exactly two oppositely charged leptons (e or μ),
leading/trailing lepton $pT > 25$ GeV / $pT > 20$ GeV
for all channels
- **Trigger matching:** at least one of the two leptons
has to be geometrically matched to the lepton
reconstructed by trigger algorithm.
(the matching lepton is required to have $pT > 25$ GeV,
to avoid effects of the turn-on curve)
- **Pileup reweighting:** PileupReweighting-00-02-03 applied to MC
- **Event cleaning:** reject LArErrors > 1 events, reject events with jets in LAr hole

Channel	Period	Trigger
μ	D-I	mu18_MG
μ	J-M	mu18_MG_medium
e	D-J	e20_medium
e	K	e22_medium
e	L-M	e22vh_medium1

Event selection (II)

ee and $\mu\mu$ at pre-selection: dominant contribution (>99%) from Drell-Yan

WW signal only contributes ~0.065%

e μ at pre-selection: WW signal already 10.4%, major background contributions
ttbar/single-top (50.3%), $Z \rightarrow \tau\tau$ (35.4%) and QCD + W+jet (2.7%)

Analysis cuts to reject backgrounds:

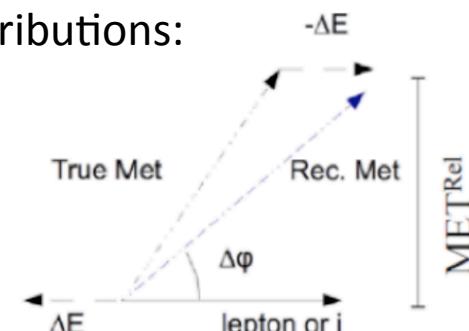
1. Invariant mass $m_{ll} > 15$ GeV if same flavor (ee, $\mu\mu$), else > 10 GeV to reject di-jet events
2. Z mass veto $|m_{ll} - m_Z| > 15$ GeV, only if same flavor ($M_Z = 91.1876$ GeV) to reject $Z \rightarrow ll$
3. Modified missing E_T to effectively remove Drell-Yan and QCD contributions:

$$E_{T, \text{Rel}}^{\text{miss}} = \begin{cases} E_T^{\text{miss}} \times \sin(\Delta\phi_{\ell,j}) & \text{if } \Delta\phi_{\ell,j} < \pi/2 \\ E_T^{\text{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \end{cases} \quad (\text{azimuthal angle})$$

Designed to reject events where the apparent E_T^{miss} arises from mismeasurement

E_T^{miss} projection > 45 GeV for ee/ $\mu\mu$ and > 25 GeV for e μ .

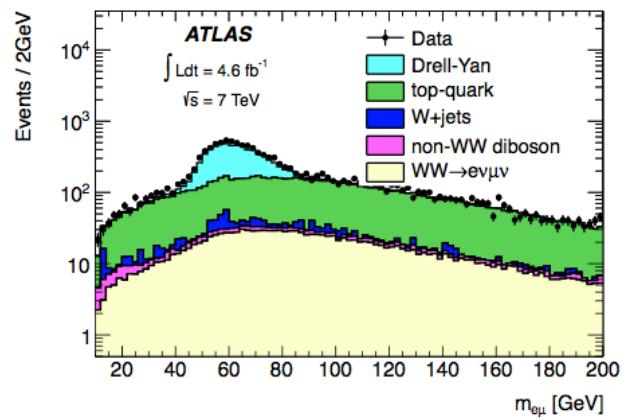
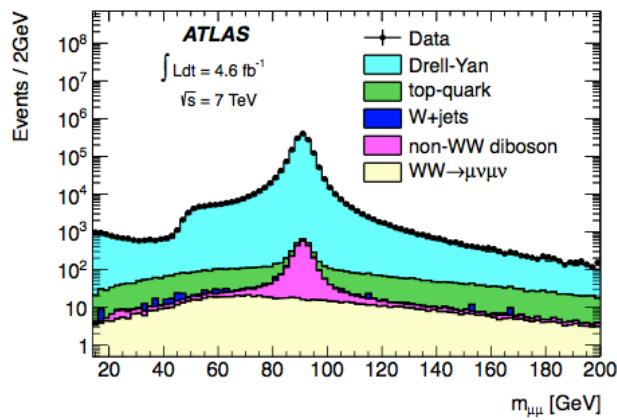
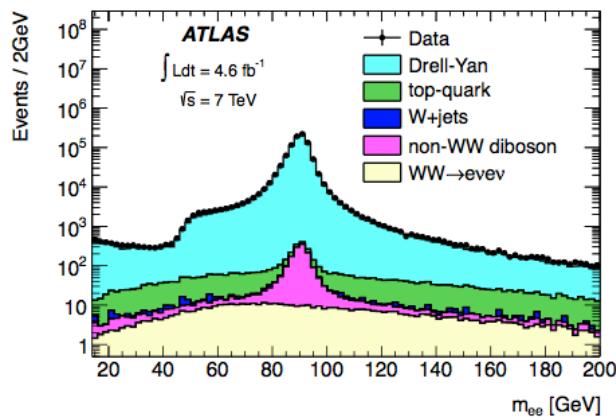
(less strict in e μ because the Drell-Yan background is inherently smaller)



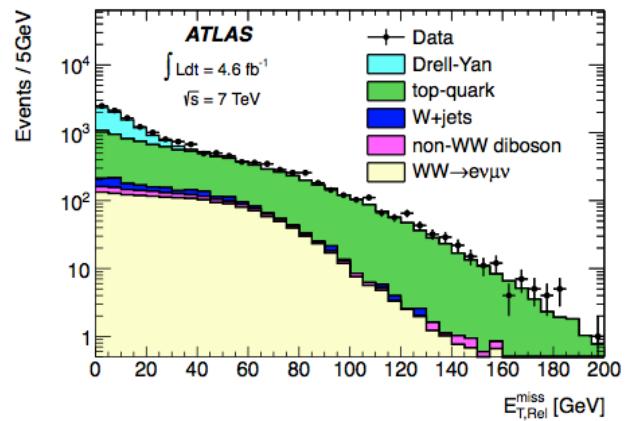
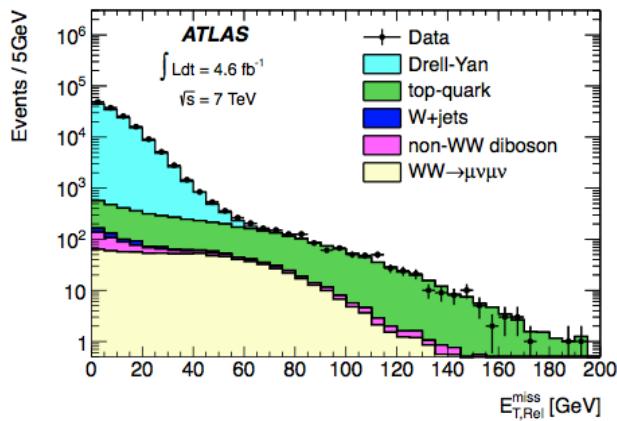
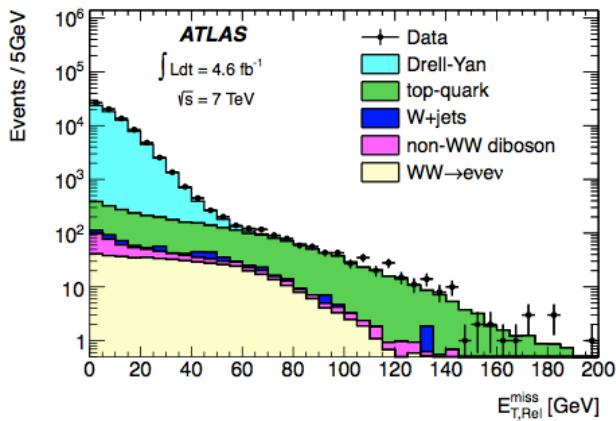
4. Number of good jets (jet $p_T > 25$ GeV, $|\eta| < 4.5$) equals zero to remove top contribution
5. $p_{Tll} > 30$ GeV for all channels to further reduces Drell-Yan contribution

Kinematic distributions

Invariant mass at preselection level (i.e. before the first cut):



Missing E_T projection before the $E_{T,\text{Rel}}$ cut:

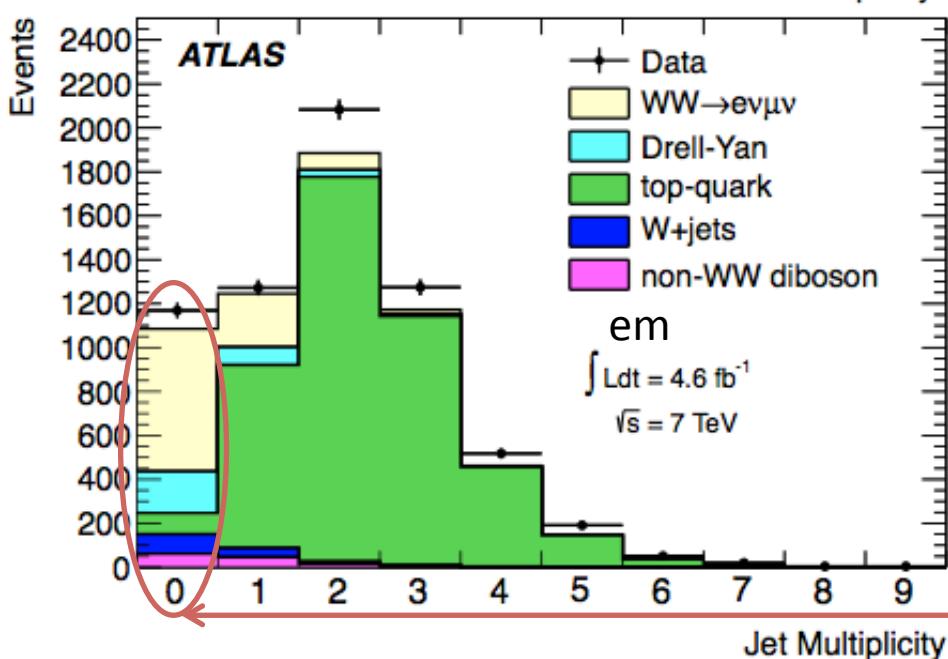
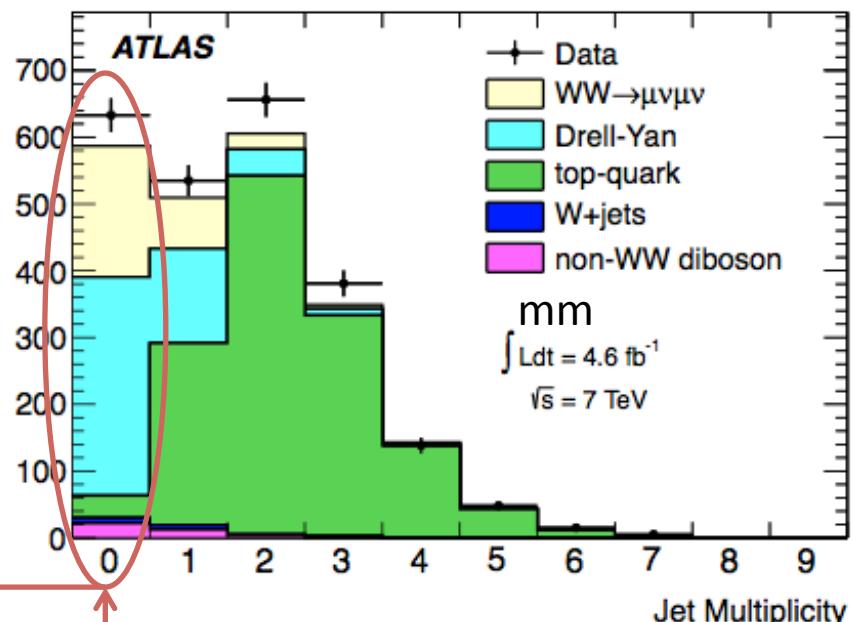
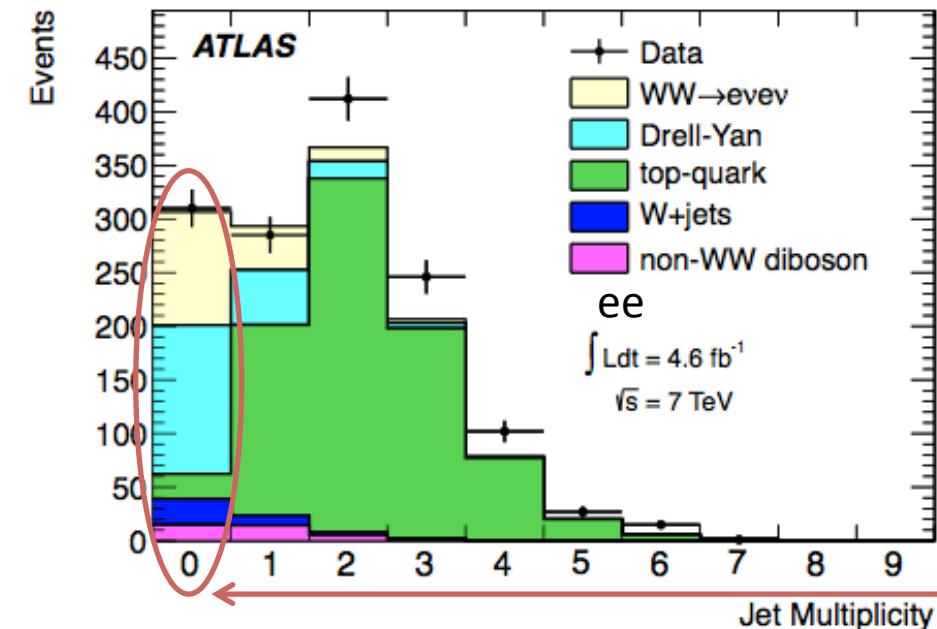


ee

mm

em

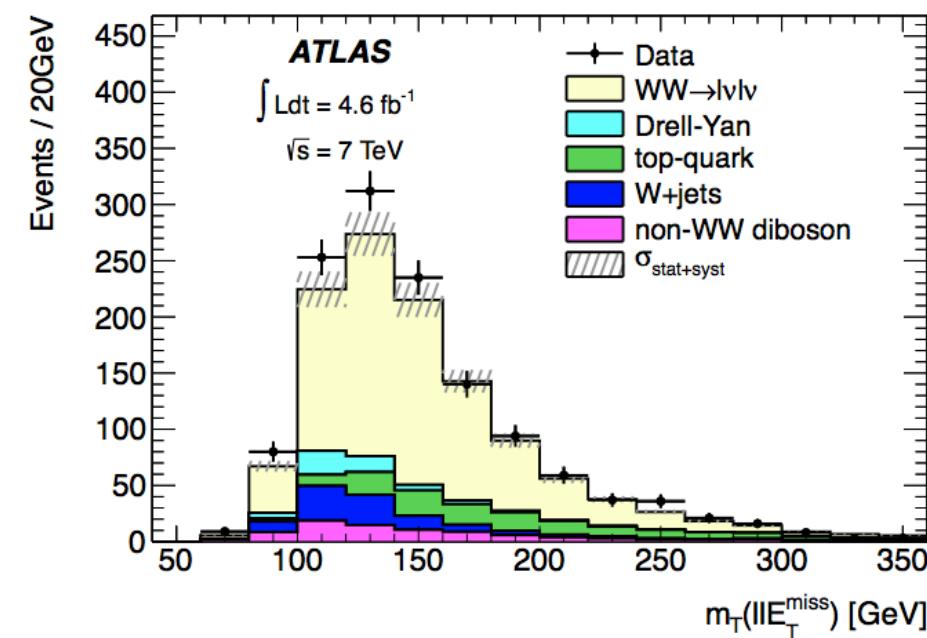
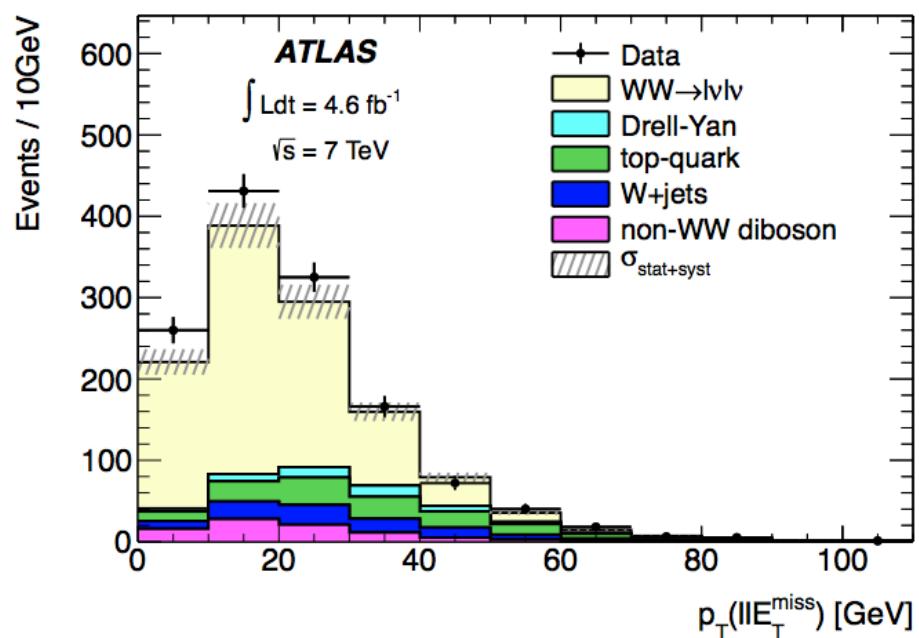
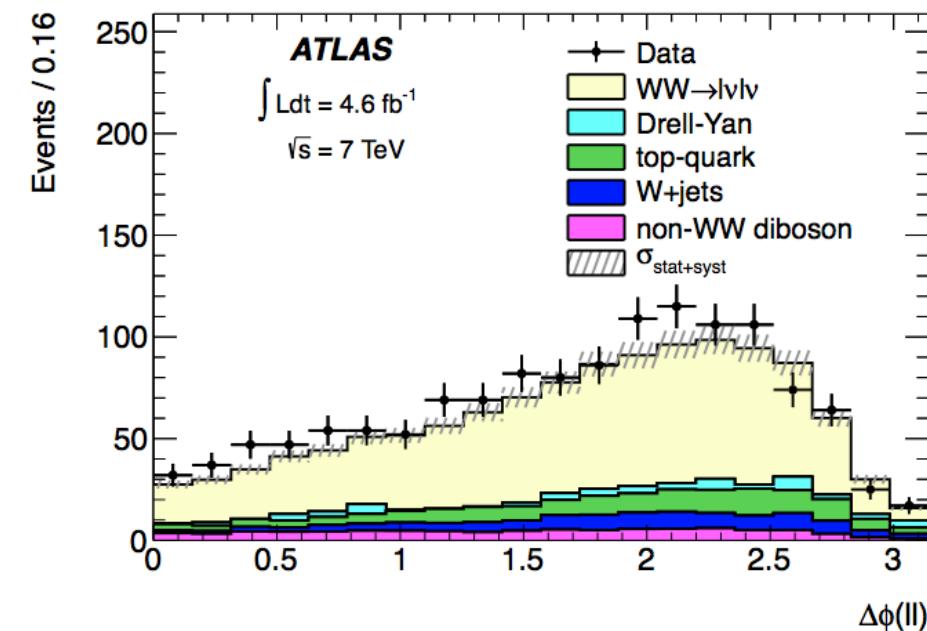
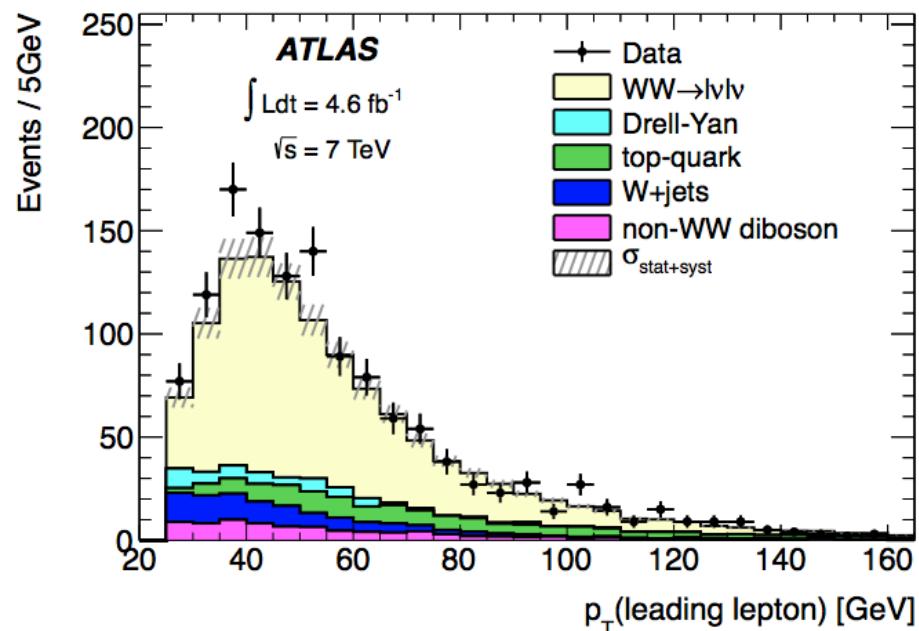
Jet multiplicity just before “jet veto” cut



WW signal region

zero-jet analysis

Kinematic distributions at final selection



Inclusive channel

Systematic uncertainties

Sources	$e^+e^-E_T^{\text{miss}}$	$\mu^+\mu^-E_T^{\text{miss}}$	$e^\pm\mu^\mp E_T^{\text{miss}}$	Combined
Luminosity	1.8%	1.8%	1.8%	1.8%
<i>A_{WW}</i> uncertainties				
PDF	0.85%	0.93%	0.88%	0.88%
Scale (μ_R , μ_F)	0.48%	0.48%	0.63%	0.41%
Jet veto	5.60%	5.60%	5.60%	5.60%
$\Delta A_{WW}/A_{WW}$	5.68%	5.69%	5.70%	5.69%
<i>C_{WW}</i> uncertainties				
Trigger	0.1%	0.6%	0.3%	0.4%
Electron Scale	0.8%	$\leq 0.1\%$	0.4%	0.3%
Electron Resolution	0.2%	$\leq 0.1\%$	$\leq 0.1\%$	$\leq 0.1\%$
Muon Scale	$\leq 0.1\%$	0.5%	0.2%	0.2%
ID Muon Resolution	$\leq 0.1\%$	0.1%	$\leq 0.1\%$	$\leq 0.1\%$
MS Muon Resolution	$\leq 0.1\%$	0.1%	$\leq 0.1\%$	$\leq 0.1\%$
Electron recon. SF	1.6%	$\leq 0.1\%$	0.8%	0.7%
Electron ID SF	2.3%	$\leq 0.1\%$	1.1%	1.0%
Muon ID SF	$\leq 0.1\%$	0.5%	0.3%	0.3%
Electron IsoIP	0.7%	$\leq 0.1\%$	0.3%	0.3%
Muon IsoIP	$\leq 0.1\%$	0.4%	0.2%	0.2%
Scale Soft Terms	0.4%	0.2%	0.4%	0.2%
Reso Soft Terms	0.3%	0.1%	$\leq 0.1\%$	$\leq 0.1\%$
JES & JER	0.6%	0.5%	0.5%	0.5%
Jet veto scale factor	2.8%	2.8%	2.7%	2.8%
PDF and Scale	0.7%	0.7%	0.3%	0.3%
$\Delta C_{WW}/C_{WW}$	4.2%	3.1%	3.2%	3.2%
<i>A_{WW}C_{WW}</i> uncertainties				
Jet veto scale factor	3.7%	3.6%	3.6%	3.6%
$\Delta C_{WW}A_{WW}/C_{WW}A_{WW}$	4.9%	4.0%	4.1%	4.0%
$\sigma(WW)$ theoretic uncertainty	6.2%	6.2%	6.2%	6.2%
Full WW signal estimation uncertainty	8.1%	7.6%	7.6%	7.6%

Total cross section:

$$\sigma_{WW} = \frac{N_{\text{data}} - N_{\text{bkg}}}{C_{WW} A_{WW} \text{ Br } \mathcal{L}}$$

- Many systematic uncertainties on the signal
- Jet veto efficiency determined from data
- Data driven estimate of the ttbar, Drell-Yan, W+Jets
- MC driven estimate of diboson background

Combined performance groups packages:

MissingETUtility-00-02-10
 PileupReweighting-00-02-03
 JetResolution-00-00-09
 JetUncertainties-00-03-05
 ApplyJetCalibration-00-01-07
 ApplyJetResolutionSmearing-00-00-03
 JetTagAlgorithms-00-00-01
 CalibrationDataInterface-00-01-02-branch
 MuonEfficiencyCorrections-01-01-00
 MuonMomentumCorrections-00-05-00
 MuonIsolationCorrection-01-01
 TrigMuonEfficiency-00-01-01
 egammaAnalysisUtils-00-02-70
 IsoIPSF-00-01-01
 IsolationScaleFactors-00-00

Summary of SM W^+W^- @ 7TeV analysis

$pp \rightarrow WW$ cross section measured on 2011 data using 4.6 fb^{-1} using di-lepton channels:

- 1325 candidates observed
- Estimated 369 ± 61 background events in all channels
- Statistical uncertainty 3.9%, systematic uncertainty 7.6% → overall ~9%
- Measured cross section compatible with the Standard model NLO prediction

$$\sigma_{pp \rightarrow WW + X} = 51.9 \pm 2.0 \text{ (stat)} \pm 3.9 \text{ (syst)} \pm 2.0 \text{ (lumi)}$$

$$\text{Theoretical } \sigma_{\text{NLO}} = 44.7 \pm 2.8$$

	ee	$\mu\mu$	$e\mu$	Combined
Data	174	330	821	1325
WW	$100 \pm 2 \pm 9$	$186 \pm 2 \pm 15$	$538 \pm 3 \pm 45$	$824 \pm 4 \pm 69$
Top	$22 \pm 12 \pm 3$	$32 \pm 14 \pm 5$	$87 \pm 23 \pm 13$	$141 \pm 30 \pm 22$
$W+jets$	$21 \pm 1 \pm 11$	$7 \pm 1 \pm 3$	$70 \pm 2 \pm 31$	$98 \pm 2 \pm 43$
Drell-Yan	$12 \pm 3 \pm 3$	$34 \pm 6 \pm 10$	$5 \pm 2 \pm 1$	$51 \pm 7 \pm 12$
Other dibosons	$13 \pm 1 \pm 2$	$21 \pm 1 \pm 2$	$44 \pm 2 \pm 6$	$78 \pm 2 \pm 10$
Total background	$68 \pm 12 \pm 13$	$94 \pm 15 \pm 13$	$206 \pm 24 \pm 35$	$369 \pm 31 \pm 53$
Total expected	$169 \pm 12 \pm 16$	$280 \pm 16 \pm 20$	$744 \pm 24 \pm 57$	$1192 \pm 31 \pm 87$

Standard model W⁺W⁻ cross section measurements

Prior to this analyses two other measurements were performed:

2010 7TeV

- 34 pb⁻¹
- ~ 8 WW events observed (1ee, 2mm, 5em)
- 3 σ evidence for the WW process
- background of 1.7 ± 0.6 events.

Documents:

[Internal note](#)

2011 7TeV

- 1.02 fb⁻¹
- 325 WW candidate events observed (59 ee, 64 mm, 202 em)
- $83.6 \pm 5.5 \pm 6.2$ background events

Documents:

Documents:

[Internal note](#), [Paper](#)

$$34 \text{ pb}^{-1}: \sigma_{\text{pp} \rightarrow \text{WW}+X} = 41.2 + 20.5 / -16.2 \text{ (stat)} \pm 4.9 \text{ (syst)}$$

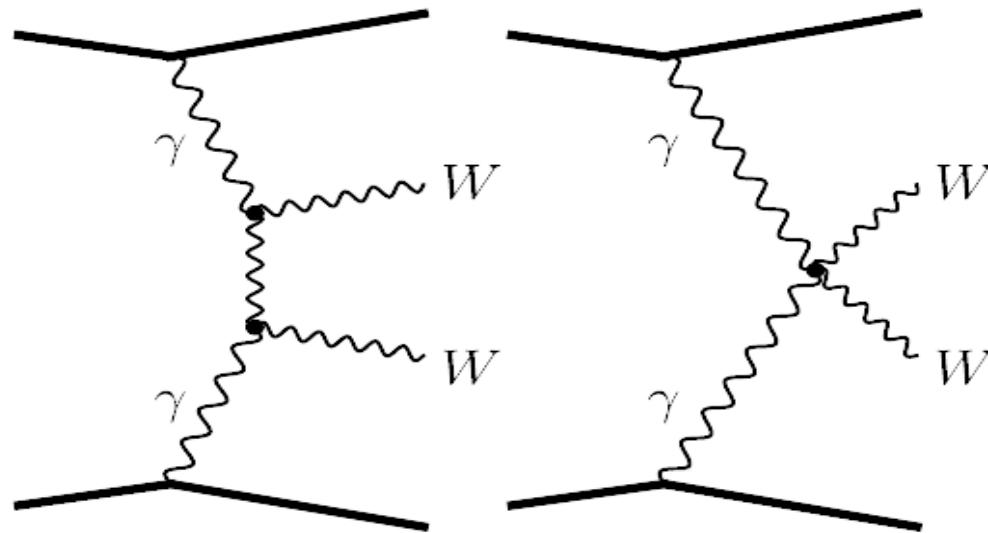
$$1.02 \text{ fb}^{-1}: \sigma_{\text{pp} \rightarrow \text{WW}+X} = 54.4 \pm 4.0 \text{ (stat)} \pm 3.9 \text{ (syst)} \pm 2.0 \text{ (lumi)}$$

$$4.6 \text{ fb}^{-1}: \sigma_{\text{pp} \rightarrow \text{WW}+X} = 51.9 \pm 2.0 \text{ (stat)} \pm 3.9 \text{ (syst)} \pm 2.0 \text{ (lumi)}$$

$$\text{Theoretical } \sigma_{\text{NLO}} = 44.7 \pm 2.8$$

Anomalous quartic gauge coupling

- Possible extension of the previous analysis:
Take SM W^+W^- candidates and request that the event contains exactly two W bosons and nothing else, i.e. exclusive
- Test of electroweak symmetry that can be performed on $\gamma\gamma WW$, $\gamma\gamma ZZ$, $\gamma\gamma\gamma\gamma$ channels
- Studies show that ATLAS can measure anomalous quartic coupling very precisely:
 $\gamma\gamma \rightarrow WW$ up to $a_0^W/\Lambda^2 \sim 10^{-6}$
- Realistically, can this measurement be done at $\langle\mu\rangle = 23, 46$?
- No full simulation + no pileup modelling performed yet



$$\begin{aligned}\mathcal{L}_{\text{eff}}^{\text{BSM}} = & - \frac{e^2}{8} \frac{a_0^W}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_{\alpha}^{-} - \frac{e^2}{16} \frac{a_C^W}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_{\beta}^{-} + W^{-\alpha} W_{\beta}^{+}) \\ & - \frac{e^2}{16 \cos^2 \theta_W} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^{\alpha} Z_{\alpha} - \frac{e^2}{16 \cos^2 \theta_W} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^{\alpha} Z_{\beta}\end{aligned}$$

Strategy for exclusive W^+W^- analysis with AFP

- Exclusive WW signal:
 - **QED WW SM with quartic gauge coupling (semi-leptonic decays)**
- Backgrounds:
 - Non-diffractive:
 - **Dibosons (WW, WZ, ZZ)**
 - **Drell-Yan**
 - **W/Z+jet**
 - **ttbar**
 - **single top**
 - Diffractive:
 - **QED dileptons**
 - **Single-diffractive WW**
 - **Double-pomeron exchange WW**
 - **Double-pomeron exchange dilep.**

- Generators: FPMC, Herwig++, Pythia

- **Given estimates with AFP tagged protons:**

Estimates at 14 TeV,
pileup: $\langle\mu\rangle = 24$ ($\langle\mu\rangle = 46$)

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Couplings	OPAL limits $[{\rm GeV}^{-2}]$	Sensitivity @ $\mathcal{L} = 30$ (200) ${\rm fb}^{-1}$ 5σ	Sensitivity @ $\mathcal{L} = 30$ (200) ${\rm fb}^{-1}$ 95% CL
a_0^W/Λ^2	$[-0.020, 0.020]$	$5.4 \cdot 10^{-6}$ ($2.7 \cdot 10^{-6}$)	$2.6 \cdot 10^{-6}$ ($1.4 \cdot 10^{-6}$)
a_C^W/Λ^2	$[-0.052, 0.037]$	$2.0 \cdot 10^{-5}$ ($9.6 \cdot 10^{-6}$)	$9.4 \cdot 10^{-6}$ ($5.2 \cdot 10^{-6}$)
a_0^Z/Λ^2	$[-0.007, 0.023]$	$1.4 \cdot 10^{-5}$ ($5.5 \cdot 10^{-6}$)	$6.4 \cdot 10^{-6}$ ($2.5 \cdot 10^{-6}$)
a_C^Z/Λ^2	$[-0.029, 0.029]$	$5.2 \cdot 10^{-5}$ ($2.0 \cdot 10^{-5}$)	$2.4 \cdot 10^{-5}$ ($9.2 \cdot 10^{-6}$)

Event selection for exclusive W^+W^- with AFP

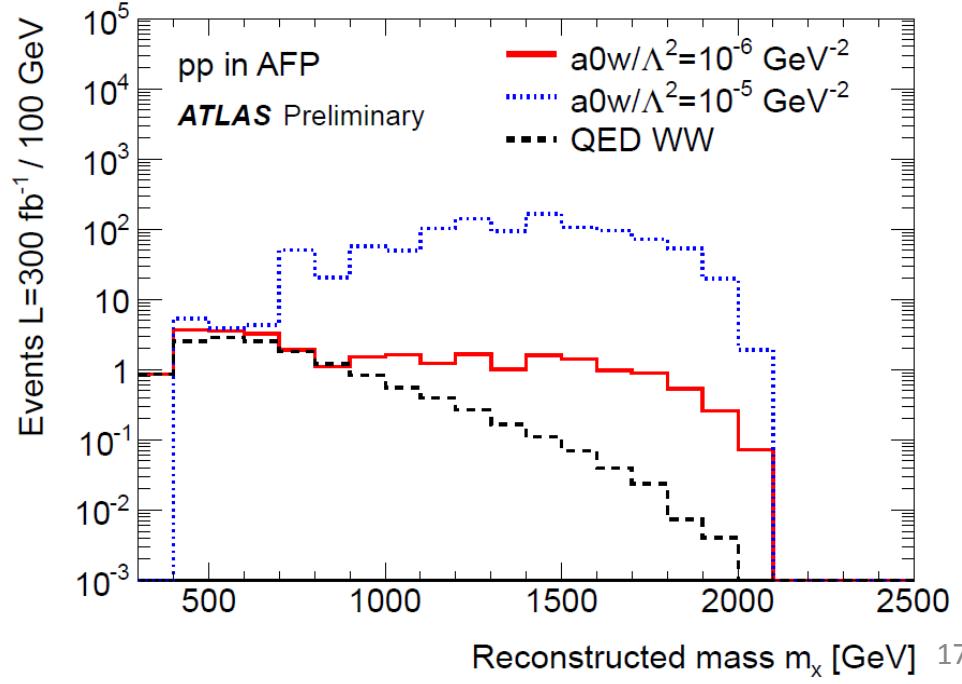
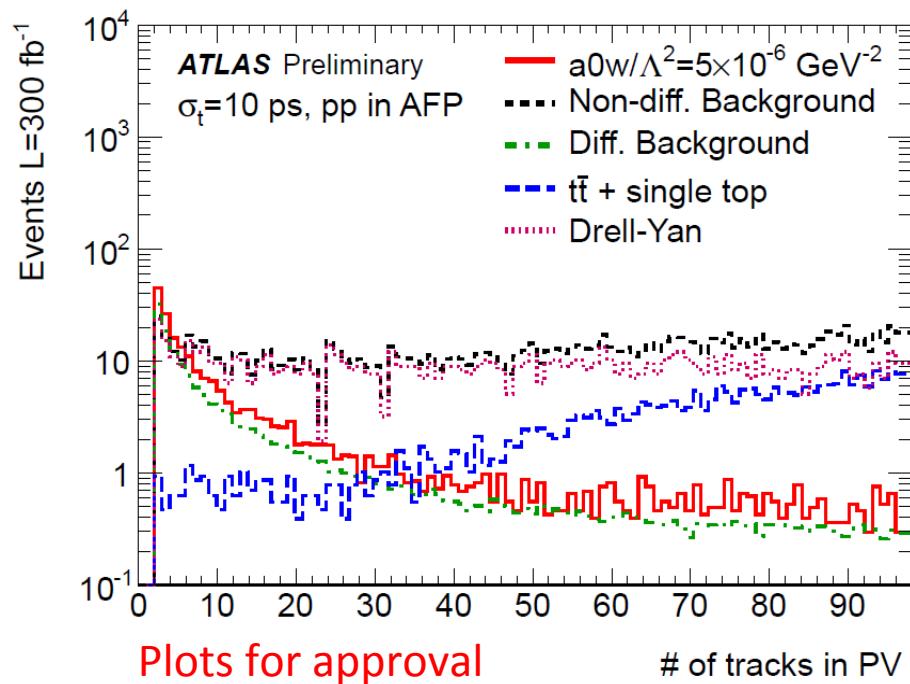
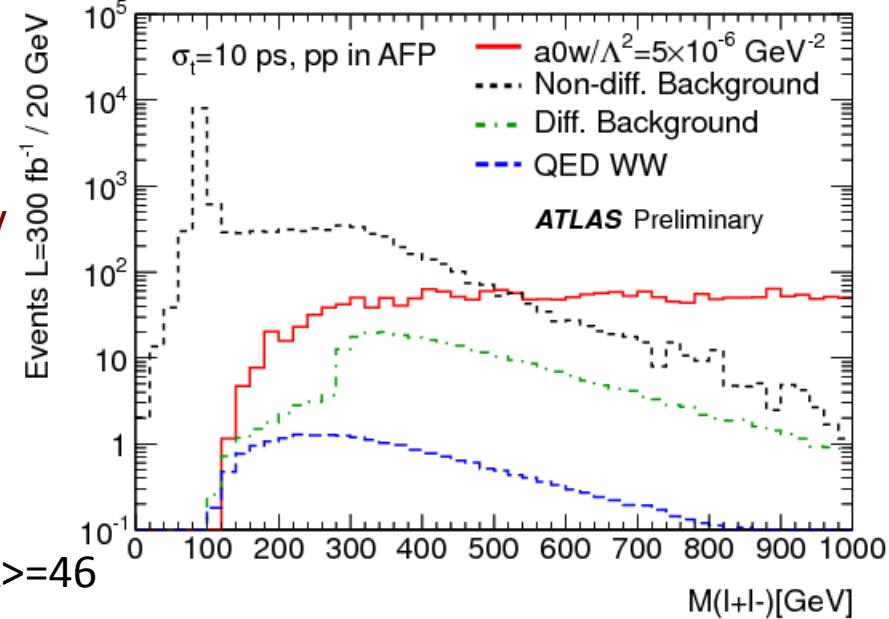
AFP acceptance $0.02 < \xi < 0.15$:

protons tracked through magnetic field of LHC,
detector at 206, 214m @ 1.5 mm from the beam

1. $p_T(\text{lead lep}) > 150 \text{ GeV}, p_T(\text{sub-lead lep}) > 20 \text{ GeV}$
2. $M_{\parallel} > 300 \text{ GeV}$
3. $n_{\text{tracks}} \leq 3$
4. $\Delta\phi_{\parallel} < 3.1 \text{ rad}$
5. $m_x > 800 \text{ GeV}$

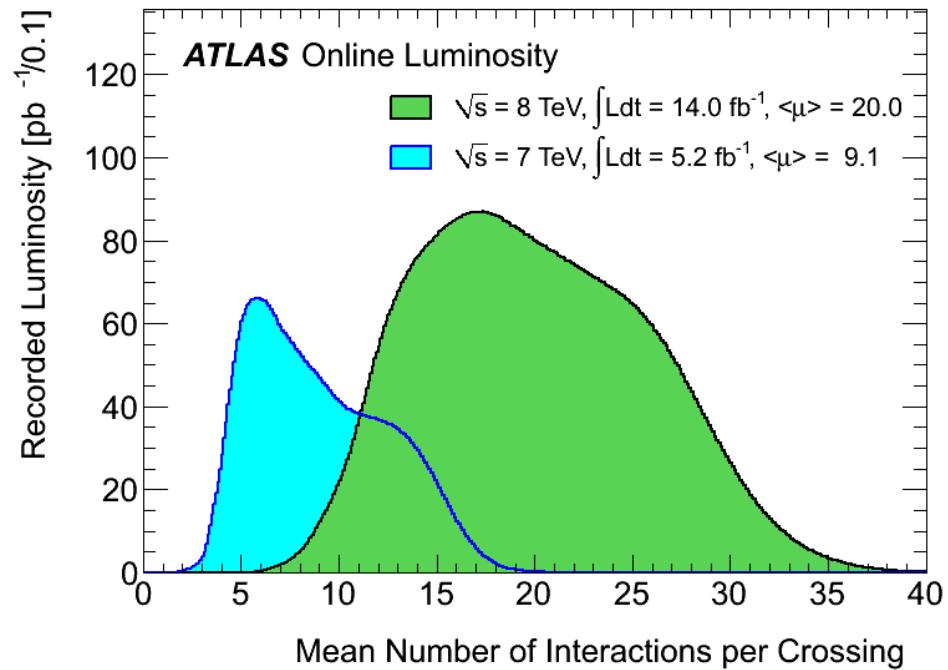
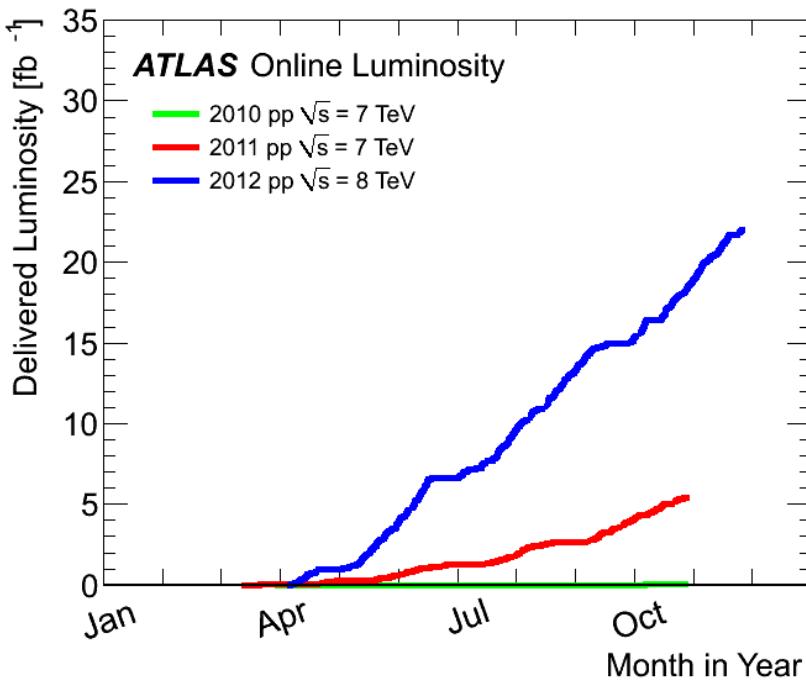
Analysis for high pile-up $\langle\mu\rangle=23$

Increase lepton threshold $p_T(\text{lead lep}) > 300 \text{ GeV} \langle\mu\rangle=46$



Summary

- Continue working on $W^+W^- \rightarrow llvv$ @ 8 TeV: meetings just started, aims for Moriond 2013
- Then perform exclusive cuts on SM W^+W^- candidates requesting:
 - high p_T of the leading lepton (~ 150 GeV)
 - small number of tracks fitted to the WW vertex (less than 3)
- The key difference to previous slides: **no AFP!**



=> Re-optimize object and event selection, new triggers, estimate backgrounds, unfolding ...

More on object selection

Electron Selection

Reconstructed Electron Candidate

Geometrical Acceptance: $|\eta| < 2.47$, outside crack region $1.37 \leq |\eta| \leq 1.52$

Object Quality: Outside regions w/LAr readout problems

Kinematic Acceptance: $E_T > 20\text{GeV}$

Identification Criteria: Tight++

Calorimeter Isolation Requirement: $\sum_{\Delta R < 0.3} E_T(i) < 0.14 \times E_T(e)$

Track Isolation Requirement: $\sum_{\Delta R < 0.3} p_T(i) < 0.13 \times E_T(e)$

Transverse Impact parameter requirement: $\frac{d_0}{\sigma_{d_0}} < 10$

Longitudinal Impact parameter requirement: $|z_0| < 1\text{mm}$

Muon Selection

Reconstructed combined staco muon

Kinematic Acceptance: $p_T > 20\text{ GeV}$

nBLayerHits > 0 if BLayerHits are expected

nPixHits + nPixelDeadSensors > 1

nSCTHits + nSCTDeadSensors ≥ 6

nPixHoles + nSCTHoles < 3

$(\text{nTRTOutliers} + \text{nTRTHits}) \geq 6$ and $\text{nTRTOutliers}/(\text{nTRTOutliers} + \text{nTRTHits}) < 0.9$ for $|\eta| < 1.9$;
 $\text{nTRTOutliers}/(\text{nTRTOutliers} + \text{nTRTHits}) < 0.9$ for $|\eta| > 1.9$ and $(\text{nTRTOutliers} + \text{nTRTHits}) \geq 6$

Geometrical Acceptance: $|\eta| < 2.4$

Longitudinal Impact parameter requirement: $|z_0(\mu)| < 1\text{ mm}$

Transverse Impact parameter requirement: $\frac{d_0}{\sigma_{d_0}} < 3$

Track Isolation Requirement: $\sum_{\Delta R < 0.3} p_T(i) < 0.15 \times p_T(\mu)$

Calorimeter Isolation Requirement: $\sum_{\Delta R < 0.3} E_T(i) < 0.14 \times p_T(\mu)$