

Measurements of Exclusive Dilepton Production at 7 and 8 TeV with the ATLAS Detector

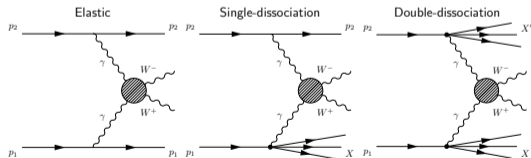
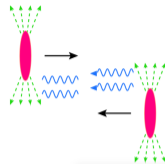
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On behalf of the ATLAS Collaboration

[Low-x Meeting 2016](#)

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- Initial state photons are emitted from high energy proton beams
 - pp collision can be considered as a $\gamma\gamma$ collision
 - protons deflected at small angles
 - better known initial conditions and simpler final states
- Exclusive production of a final state X via the reaction $pp \rightarrow ppX$
 - Elastic: $pp \rightarrow pp(\gamma\gamma) \rightarrow pp\ell\ell$ where both protons remain intact
 - Single-dissociation: $pp \rightarrow pX'(\gamma\gamma) \rightarrow pX'\ell\ell$ where one proton dissociate
 - Double-dissociation: $pp \rightarrow X'X''(\gamma\gamma) \rightarrow X'X''\ell\ell$ where both protons dissociate



- Use [Equivalent Photon Approximation \(EPA\)](#) to calculate the pp cross section
 - Significant corrections needed due to hadronic interactions between elastic scattered protons

- Exclusive $\gamma\gamma$ production computed in QED with small uncertainty
 - Possible to use $pp(\gamma\gamma) \rightarrow pp\mu^+\mu^-$ for luminosity measurement at the LHC
- Exclusive $\ell^+\ell^-$
 - Standard candle for photon physics
 - Non-negligible background to Drell-Yan (DY) reactions
- Exclusive W^+W^-
 - Test of SM quartic gauge couplings of $W^+W^- \gamma\gamma$
 - Probe anomalous quartic gauge couplings (aQGCs)
- Exclusive Higgs
 - Low systematics due to the clean production environment
 - Potentially used for Higgs properties studies

- Exclusive: Large rapidity gaps between protons and $\ell^+\ell^- / W^+W^- / \text{Higgs}$
 - Clean signature with back-to-back leptons and no other activity in the central detectors
 - Absence of tracks in detector near those from $\ell^+\ell^- / W^+W^- / \text{Higgs}$
- Inclusive: Extra particles from additional parton emission, ISR, FSR, etc
 - Presence of tracks from same vertex in detector
- Pileup: additional interactions coming from a different proton-proton collision
- Underlying event: additional interactions from the same proton collision

- Exclusive l^+l^-

- Elastic - **Signal**: Herwig++ (EPA)
- Single dissociation: LPAIR (Brase and Suri-Yennie structure function)
- Double dissociation: Pythia8 (NNPDF2.3QED PDF)

- Exclusive W^+W^-

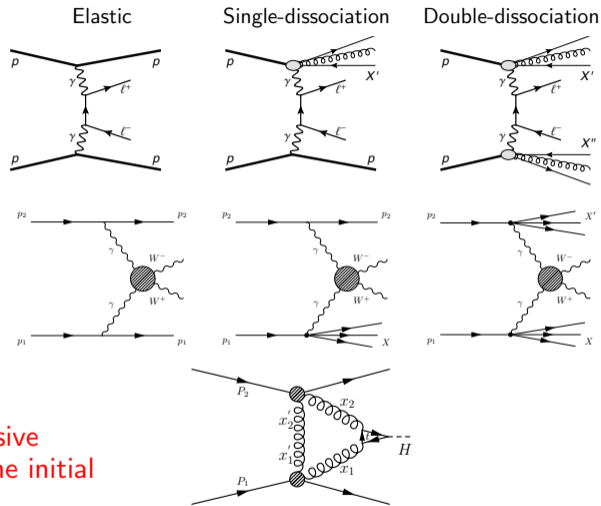
- Elastic - **Signal**: Herwig++ generator
- $\gamma\gamma \rightarrow W^+W^-$ with aQGC: FPMC

- Exclusive Higgs

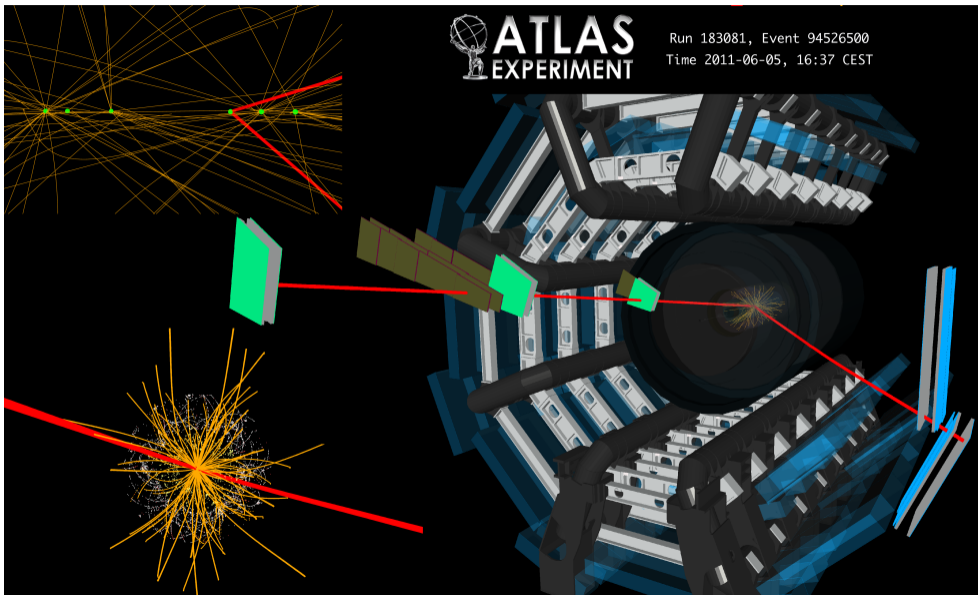
- $pp \rightarrow pggp \rightarrow pHp$: FPMC

- **No available generator that supports exclusive W^+W^- and Higgs when one or both of the initial protons dissociate**

- Necessary to estimate it using data-driven methods



Measurement of exclusive $\gamma\gamma \rightarrow l^+l^-$ production at 7 TeV



Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Event Selection

- [Physics Letters B 749 \(2015\)](#)

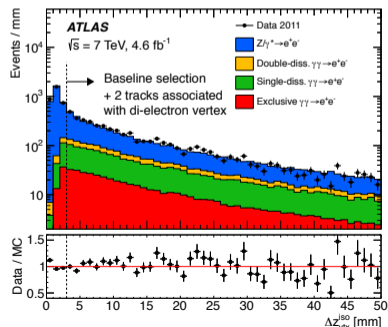
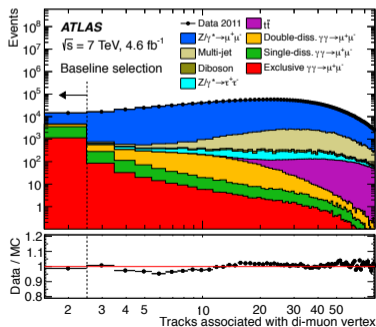
- Data: 4.6 fb^{-1} at 7 TeV

- Isolated e^+e^- or $\mu^+\mu^-$ candidates

- Exactly 2 tracks ($p_T > 400 \text{ MeV}$) associated with the dilepton vertex

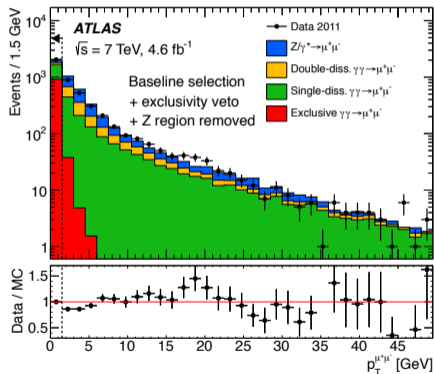
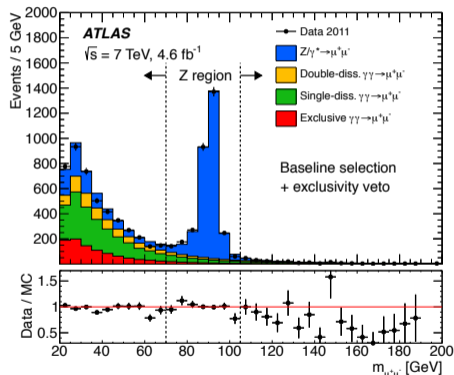
- Distance between dilepton vertex and closest vertex: $\Delta z_{vtx}^{iso} > 3 \text{ mm}$ to reject DY

Variable	Electron Channel	Muon Channel
p_T^ℓ	$> 12 \text{ GeV}$	$> 10 \text{ GeV}$
$ \eta^\ell $	< 2.4	< 2.4
$m_{\ell^+\ell^-}$	$> 24 \text{ GeV}$	$> 20 \text{ GeV}$



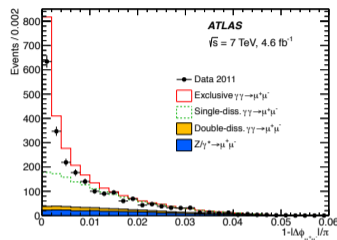
Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Event Selection

- Remove Z-region dominated by DY
- p_T of the dilepton system $p_T^{\ell\ell} < 1.5$ GeV: low virtuality of incoming photons



Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Yields

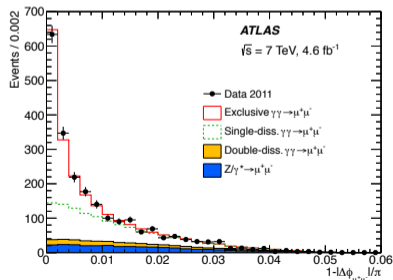
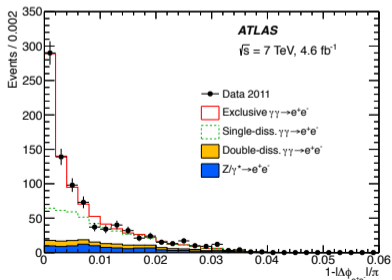
- Observed 869/2124 while expected 1030/2630 in $e^+e^- / \mu^+\mu^-$ channels
 - Number of selected events in data 20% lower than expectation
 - due to proton absorptive corrections not included in MC
 - Proton has a finite size, the impact parameter dependence is non-negligible [arXiv:1410.2983](https://arxiv.org/abs/1410.2983)



Selection	$\gamma\gamma \rightarrow \ell^+\ell^-$			Z/γ^*	Multi-	Z/γ^*	Di-	Total	Data	
	Signal	S-diss.	D-diss.	$\rightarrow \ell^+\ell^-$	jet	$\rightarrow \tau^+\tau^-$				
Electron channel ($\ell = e$)										
Preselection	898	2096	2070	1 460 000	83 000	3760	4610	1950	1 560 000	1 572 271
Exclusivity veto	661	1480	470	3140	0	9	0	5	5780	5410
Z region removed	569	1276	380	600	0	8	0	3	2840	2586
$p_T^{\ell^+\ell^-} < 1.5$ GeV	438	414	80	100	0	2	0	0	1030	869
Muon channel ($\ell = \mu$)										
Preselection	1774	3964	4390	2 300 000	98 000	7610	6710	2870	2 420 000	2 422 745
Exclusivity veto	1313	2892	860	3960	3	8	0	6	9040	7940
Z region removed	1215	2618	760	1160	3	8	0	3	5760	4729
$p_T^{\ell^+\ell^-} < 1.5$ GeV	1174	1085	160	210	0	3	0	0	2630	2124

Exclusive $\gamma\gamma \rightarrow l^+l^-$: Signal extraction

- Binned maximum-likelihood fit of signal (exclusive) and background (single dissociation) to the measured dilepton acoplanarity distribution
- DY and double dissociation fixed
- Both exclusive and single dissociation requires scaling down:
 - $R_{\gamma\gamma \rightarrow e^+e^-}^{excl.} = 0.863 \pm 0.070$, $R_{\gamma\gamma \rightarrow e^+e^-}^{s-diss} = 0.759 \pm 0.080$
 - $R_{\gamma\gamma \rightarrow \mu^+\mu^-}^{excl.} = 0.791 \pm 0.041$, $R_{\gamma\gamma \rightarrow \mu^+\mu^-}^{s-diss} = 0.762 \pm 0.049$



Exclusive $\gamma\gamma \rightarrow l^+l^-$: Results

- Cross section extracted by measuring suppression factor $R_{\gamma\gamma \rightarrow l^+l^-}^{excl.}$ applied to prediction:

$$\sigma_{\gamma\gamma \rightarrow l^+l^-}^{excl.} = R_{\gamma\gamma \rightarrow l^+l^-}^{excl.} \times \sigma_{\gamma\gamma \rightarrow l^+l^-}^{pred.}$$

- The fiducial cross sections:

- $\sigma_{\gamma\gamma \rightarrow e^+e^-}^{excl.} = 0.428 \pm 0.035 (stat.) \pm 0.018 (syst.) pb$

- $\sigma_{\gamma\gamma \rightarrow \mu^+\mu^-}^{excl.} = 0.628 \pm 0.032 (stat.) \pm 0.021 (syst.) pb$

- The measurement is statistically limited:

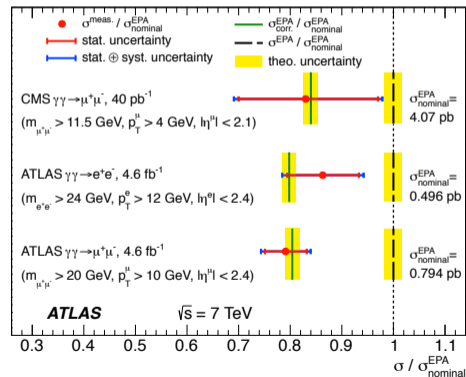
- Statistical = 8.2% for e^+e^- and 5.1% for $\mu^+\mu^-$

- Systematic = 4.3% for e^+e^- and 3.3% for $\mu^+\mu^-$

- The theory predictions with absorptive corrections (20% effect):

- $\sigma_{\gamma\gamma \rightarrow e^+e^-}^{EPA,corr.} = 0.398 \pm 0.007 pb$

- $\sigma_{\gamma\gamma \rightarrow \mu^+\mu^-}^{EPA,corr.} = 0.638 \pm 0.011 pb$

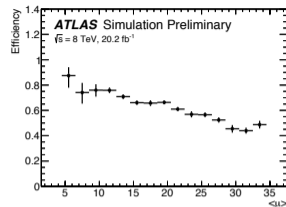


- Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs production at 8 TeV

Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: Event Selection

- Define dilepton vertex z_0^{av} as $e^\pm\mu^\mp$ average z_0 position
- Exclusivity selection: No additional tracks in $\Delta z_0^{iso} = |z_0^{track} - z_0^{av}| = \pm 1$ mm
- Optimal $\Delta z_0^{iso} = 1$ mm, $\epsilon = 58 \pm 6\%$
- Rest of the selection:

Variable	Excl W^+W^-	Excl Higgs
p_T^{lep}	$> 25, 20$ GeV	$> 25, 15$ GeV
$m_{e\mu}$	> 20 GeV	> 10 GeV
$p_T^{e\mu}$	> 30 GeV	> 30 GeV
Δz_0^{iso}	1mm	1mm
$p_T^{e\mu}$ (aQGC)	> 120 GeV	-
$m_{e\mu}$	-	< 55 GeV
$\Delta\phi_{e\mu}$	-	< 1.8
m_T	-	< 140 GeV



Variable	7 TeV	8 TeV
Avg. pileup	7	21
Vertex	$ z_0^{track} - z_0^{PV} $	$ z_0^{track} - z_0^{av} $
Δz_0	3 mm	1 mm

- Higgs selection has a lower p_T and mass because one W is offshell
- Additional selection in Higgs meant to reduce W^+W^-

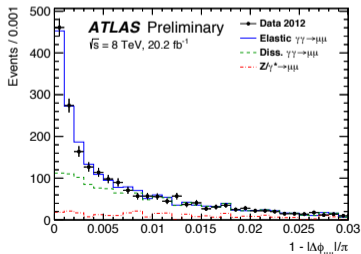
Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: Exclusivity validation

- Validated in a $\gamma\gamma \rightarrow \mu^+\mu^-$ selection

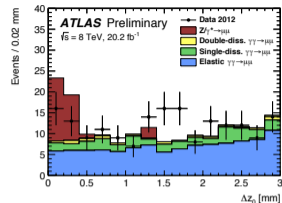
- f_{EL} = ratio of observed elastic $\gamma\gamma \rightarrow \mu^+\mu^-$ to prediction
- Extracted from template fits in acoplanarity ($1 - |\Delta\phi_{\mu\mu}|/\pi$)
- Vary $p_T^{\mu\mu}$ and Δz_0^{iso} to evaluate systematic uncert. (total 14%)
- Systematic error due to pileup at the 10% level

$$f_{EL} = 0.76 \pm 0.04(stat.) \pm 0.10(sys.)$$

Exclusive $\mu^+\mu^-$ at 8 TeV

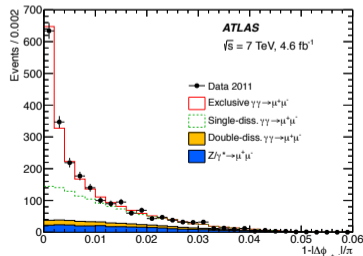


compatible with $R_{\gamma\gamma \rightarrow \mu^+\mu^-}^{excl.} = 0.791 \pm 0.041$ [Slide10](#)



pileup: extra track flat for exclusive

Exclusive $\mu^+\mu^-$ at 7 TeV

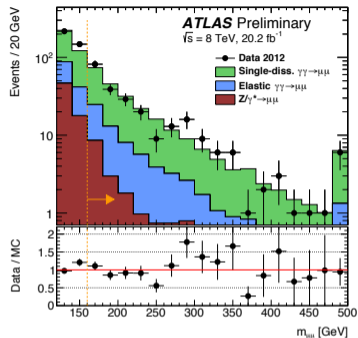


Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: SD and DD estimation

- Exclusive production of W^+W^- and $\ell^+\ell^-$ are similar
- Since there is no simulation for SD and DD $\gamma\gamma \rightarrow W^+W^-$, a correction factor f_γ is extracted from data
- Same $\gamma\gamma \rightarrow \mu^+\mu^-$ selection is applied except for $m_{\mu\mu} > 160$ GeV and no $p_T^{\mu\mu}$ cut

$$f_\gamma = \frac{N_{Data} - N_{Background}^{POWHEG}}{N_{ELASTIC}^{HERWIG++}} = 3.30 \pm 0.22(stat.) \pm 0.06(syst.)$$

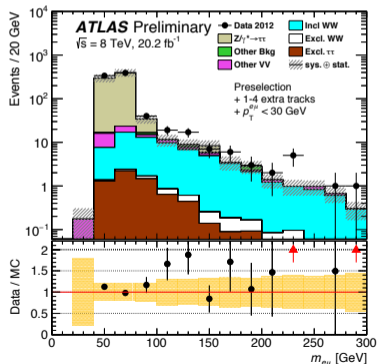
- Exclusive $\gamma\gamma \rightarrow W^+W^-$ estimate is scaled by f_γ
- The systematic uncertainty is obtained by varying DY contribution by 20%
- The total uncertainty is 7% dominated by the statistical uncertainty



Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: Track multiplicity

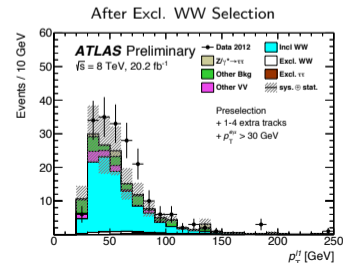
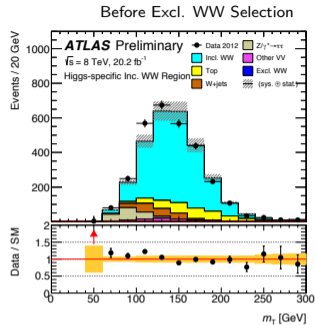
- Underlying event emits additional tracks from the lepton vertex
- Necessary to validate modeling of underlying event in simulation
- Extract scale factors $\frac{\epsilon_{Data}}{\epsilon_{MC}}$ from Z peak data region since it is DY dominated with no exclusive dileptons
- Same [\$\gamma\gamma \rightarrow \mu^+\mu^-\$ selection](#) with $80 \text{ GeV} < m_{\mu\mu} < 100 \text{ GeV}$ and no $p_T^{\mu\mu}$ cut

- Data/MC scale factors are stable within $\pm 20\%$ over a wide $m_{\mu\mu}$ range
- Scale factors are validated in a $Z \rightarrow \tau\tau$ control region with $N_{trk} = 1 - 4$ and an $e\mu$ selection



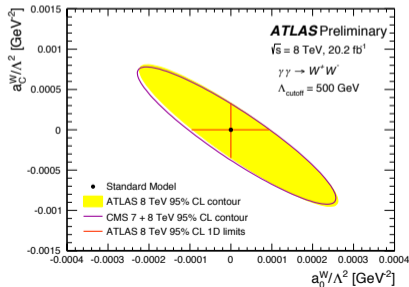
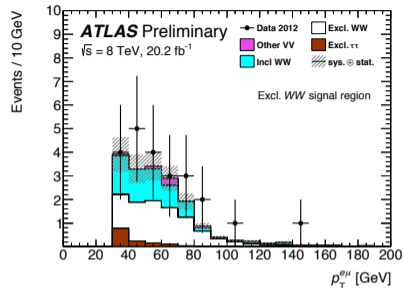
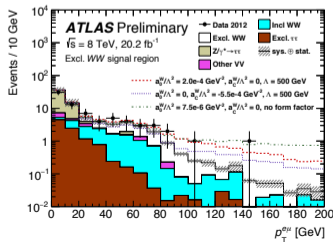
Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: Inclusive W^+W^- + Other

- Powheg+Pythia8 known to **underestimate** W^+W^- yields
 - Extract a scale factor from data
 - Use the **Higgs selection** (slide13) with $55 \text{ GeV} < m_{\ell\ell} < 100 \text{ GeV}$, $\Delta\phi_{\ell\ell} < 2.6$ and 0 jets
 - Uncertainties dominated by statistics (5%)
- Estimate inclusive W^+W^- + (DY, W +jets, Top) from data
- Used as a constraint in excl. Higgs and aQGC
- Use the **excl. W^+W^- selection** (slide13) with 1 to 4 extra tracks
- Estimate bracketed by
 - Upper bound: Data prediction - (Excl. + other VV)
 - Lower bound: Predicted W^+W^- from Powheg+Pythia8
- Extrapolate to the 0 track bin by:
$$N_0^{Est.} = N_{1-4}^{Est.} \times \frac{N_{WW,0}^{Pred.}}{N_{WW,1-4}^{Pred.}}$$

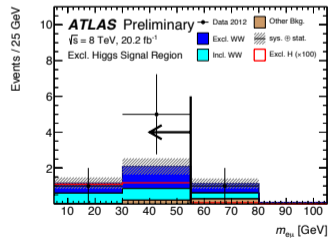
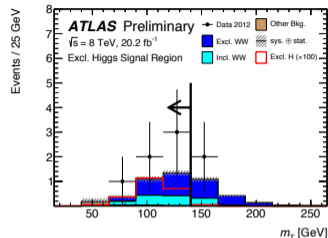


Exclusive $\gamma\gamma \rightarrow W^+W^-$: Results

- Exclusive W^+W^- event yields: Data=23, Background = 8.3 ± 2.6 , Signal = 9.3 ± 1.2
- Observed signal exceeds predicted signal by 50 % leading to a measurement significance of 3σ
- aQGC event yields ($p_T^{e\mu} > 120$ GeV): Data=1, Background = 0.37 ± 0.13 , SM Signal = 0.37 ± 0.04



- Exclusive and inclusive W^+W^- are the dominant background
- Use the result from exclusive W^+W^- to predict its contribution
- Exclusive Higgs event yields: Data=6, Background = 3.0 ± 0.8 , Signal = 0.023 ± 0.003
- Observed and expected limits are in agreement
- Upper limit $400 \times \sigma_H^{predicted}$ (which predicts just the elastic process)



- Studies of **exclusive dilepton production** processes have been conducted by ATLAS
- Cross section of the exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$ production has been measured
- Observation is consistent with the suppression (20%) expected due to proton absorption contributions
- **No simulation available** for SD and DD exclusive W^+W^- production requiring data driven estimates
- Track-based technique for selecting exclusive processes was developed and validated
- **Evidence** of SM exclusive W^+W^- production was found to be at the level of 3σ
- No evidence for an excess in the kinematic region targetting aQGC
- **Limits on exclusive Higgs** total production cross section set to $400 \times \sigma_H^{predicted}$
 - $\sigma_H^{predicted}$ for elastic process only

- Backup

Equivalent Photon Approximation (EPA)

- Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$

$$\sigma_{pp(\gamma\gamma)\rightarrow\ell^+\ell^-}^{EPA} = \int \int P(x_1) P(x_2) \sigma_{\gamma\gamma\rightarrow\ell^+\ell^-}(m_{\ell^+\ell^-}^2) dx_1 dx_2$$

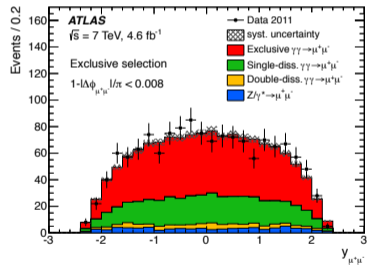
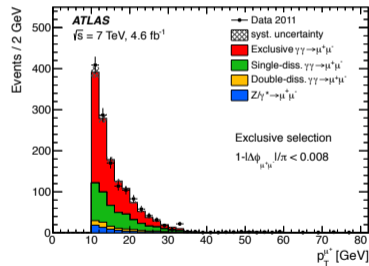
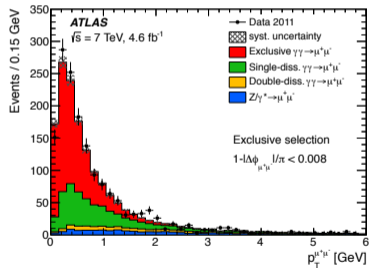
- Exclusive $\gamma\gamma \rightarrow W^+W^-$

$$\sigma_{pp(\gamma\gamma)\rightarrow W^+W^-}^{EPA} = \int \int P(x_1) P(x_2) \sigma_{\gamma\gamma\rightarrow W^+W^-}(m_{\gamma\gamma}^2) dx_1 dx_2$$

- $P(x_1)$, $P(x_2)$ are the equivalent photon spectra for the protons
- x_1 and x_2 are the fractions of the proton energy carried away by the emitted photons
- $m_{\ell^+\ell^-}$ is the invariant mass of the two leptons
- $m_{\gamma\gamma}$ is the two photons center-of-mass energy

Exclusive $\gamma\gamma \rightarrow \ell^+\ell^-$: Control distributions

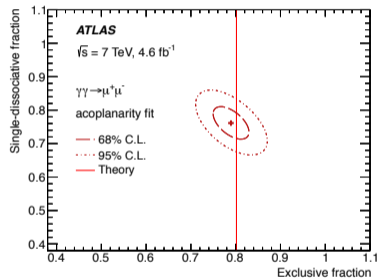
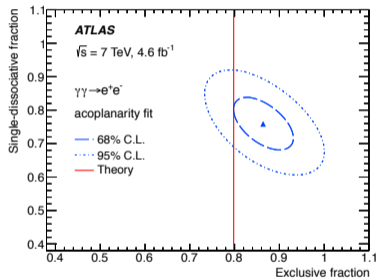
- Apply scaling factors to MC, use acoplanarity < 0.008 instead of $p_T^{\ell\ell} < 1.5$ GeV
- Good modeling of data seen in both channels



Exclusive $\gamma\gamma \rightarrow l^+l^-$: Breakdown of systematic uncertainties

Source of uncertainty	Uncertainty [%]	
	$\gamma\gamma \rightarrow e^+e^-$	$\gamma\gamma \rightarrow \mu^+\mu^-$
Electron reconstruction and identification efficiency	1.9	-
Electron energy scale and resolution	1.4	-
Electron trigger efficiency	0.7	-
Muon reconstruction efficiency	-	0.2
Muon momentum scale and resolution	-	0.5
Muon trigger efficiency	-	0.6
Backgrounds	2.3	2.0
Template shapes	1.0	0.9
Pile-up description	0.5	0.5
Vertex isolation efficiency	1.2	1.2
LHC beam effects	0.5	0.5
QED FSR in DY e^+e^-	0.8	-
Luminosity	1.8	1.8
Total systematic uncertainty	4.3	3.3
Data statistical uncertainty	8.2	5.1

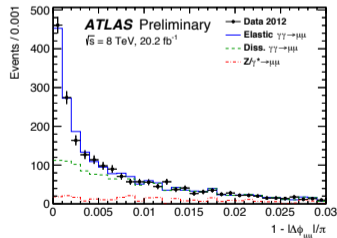
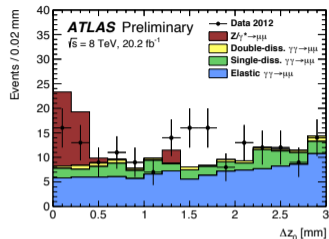
Exclusive $\gamma\gamma \rightarrow l^+l^-$: Fit results



- 2 μ with $p_T^\mu > 20$ GeV
- $45 \text{ GeV} < m_{\mu\mu} < 75 \text{ GeV}$ or $m_{\mu\mu} > 105 \text{ GeV}$
- $p_T^{\mu\mu} < 3 \text{ GeV}$ and $\Delta z_0^{iso} = 1.0 \text{ mm}$

Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: pileup

- Effect of pileup on exclusivity selection must be quantified
- Evaluate a factor: $f = \frac{Data}{Elastic+SD+DD}$ in nominal exclusivity vs. pileup-prone exclusivity regions
- Nominal exclusivity:
 - Require acoplanarity < 0.0015 and $p_T^{\mu\mu} < 3$ GeV to enhance elastic events with $\Delta z_0^{iso} = 1$ mm
 - $f = 0.73 \pm 0.03(stat.) \pm 0.01(syst.)$
- Pileup-prone exclusivity:
 - Similar but ask for exactly one track in $\Delta z_0^{iso} = 3$ mm expected to be from pileup
 - Extra track distribution in Δz_0^{iso} is flat for exclusive events
 - $f = 0.70 \pm 0.06(stat.) \pm 0.03(syst.)$
- 2 scale factors compatible at 10%: assign a systematic error of 10%



Exclusive $\gamma\gamma \rightarrow W^+W^-$ and Higgs: Selection

Variable	Excl W^+W^-	Excl Higgs
ρ_T^{lep}	> 25, 20 GeV	> 25, 15 GeV
$m_{e\mu}$	> 20 GeV	> 10 GeV
$\rho_T^{e\mu}$	> 30 GeV	> 30 GeV
Δz_0^{iso}	1mm	1mm
$\rho_T^{e\mu}$ (aQGC)	> 120 GeV	-
$m_{e\mu}$	-	< 55 GeV
$\Delta\phi_{e\mu}$	-	< 1.8
m_T	-	< 140 GeV