Observation of Photon-Induced W Boson Pair Production

Photon-induced processes, Durham

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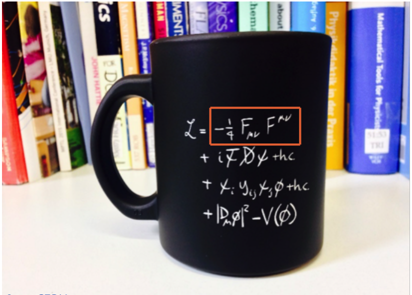
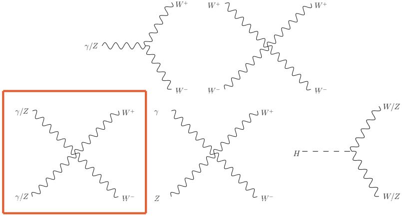
The Standard Model

- The Standard Model describes the fundamental constituents of matter and their interactions
  - strong and electroweak (EW) interaction
  - Rich variety of interactions derived from a rather simple set of symmetries
- Self-interactions of electroweak gauge bosons
  - Quantum corrections at EW mass scale
  - Large effects at highest energies



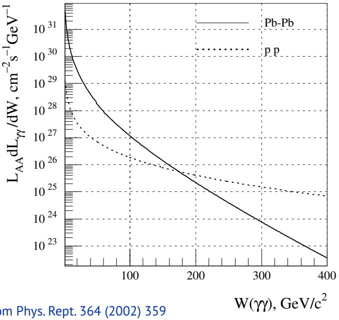
from CERN



$SU(3)_C$	$\times$	$SU(2)_L$	$\times$	$U(1)_Y$
colour red, green, blue		weak isospin $I_3 = 0, \pm\frac{1}{2}$		weak hypercharge Y
8 gluons		W^1, W^2, W^3		B
				$\rightarrow W^+, W^-, Z, \gamma$

Production of W^+W^- from photons uniquely sensitive to $\gamma\gamma WW$ coupling

Photon-induced Processes



from Phys. Rept. 364 (2002) 359
(with outdated LHC design parameters)

Lead–lead vs proton–proton:

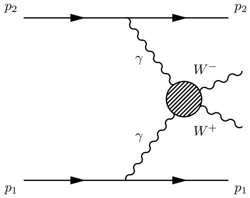
- Photon luminosity scales with $\sim Z^4$
- Maximum photon energy $\sim \gamma/R$ (uncertainty principle)

→ Use *pp* data to produce particles at electroweak mass scales or higher

Signal predictions:

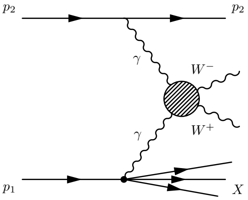
- This analysis was (almost) entirely relying on elastic $\gamma\gamma \to WW$ simulation

elastic



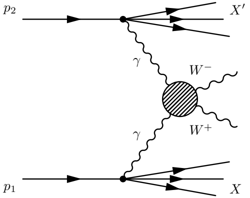
16%

semi-dissociative



81%

double-dissociative

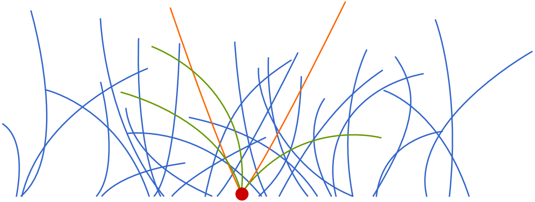


3%

Analysis in a Nutshell

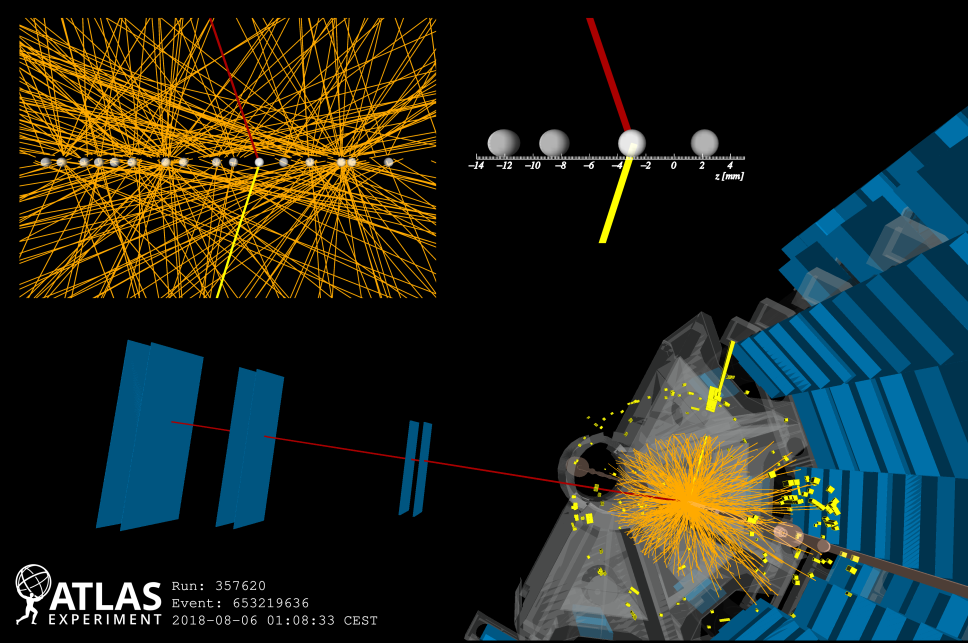
Experimental Signature:

- exactly one electron and muon with opposite electric charge
- $p_{\mathrm{T}}(ll) > 30$ GeV, $m_{\ell\ell} > 20$ GeV
- no charged particles associated with the primary interaction vertex



Experimental Challenges:

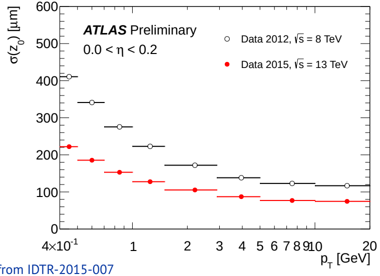
- In a typical ATLAS event we have a primary interaction vertex, and particles from the hard interaction, the proton fragmentation and additional *pp* interactions
- The analysis requires detailed understanding of:
  - vertex reconstruction
  - modelling of signal
  - the pileup density and multiplicity
  - underlying event of background processes



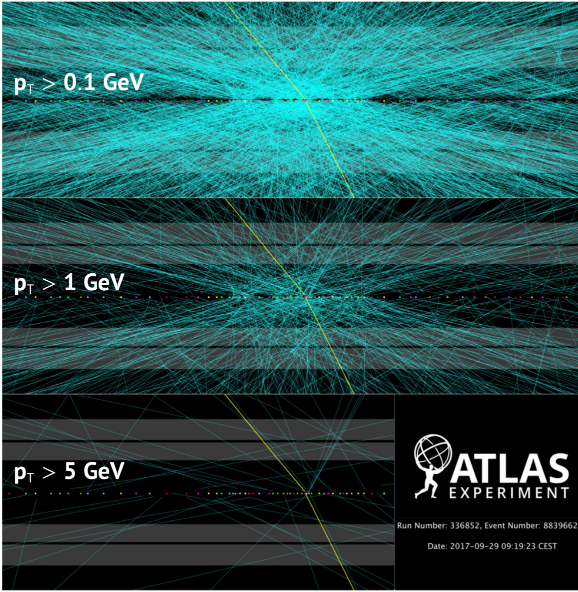
−14 −12 −10 −8 −6 −4 −2 0 2 4
z [mm]
ATLAS
EXPERIMENT
Run: 357620
Event: 653219636
2018-08-06 01:08:33 CEST

Track Selection

- Tracks are the largest consumer of CPU in ATLAS reconstruction, and of disk space
- Only tracks with $p_T > 500$ MeV are available for analysis
- Tracks for analysis are selected with $d_0 < 1$ mm and $z_0 < 1$ mm



from IDTR-2015-007



Vertex Reconstruction

- Usually, the interaction vertices are reconstructed from charged-particle tracks in the inner detector
- The vertex with the largest $\sum p_{\mathrm{T}}^2$ is chosen as the primary vertex

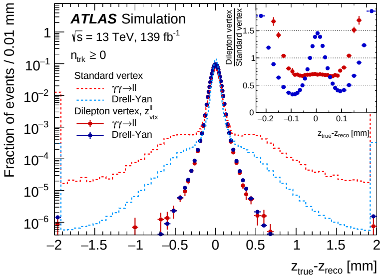
→ Not optimal for photon-induced processes

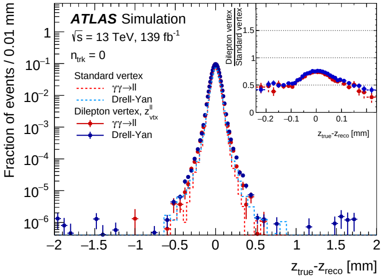
- Instead, leptons are used to reconstruct the interaction vertex:

$$z_{\mathrm{vtx}}^{\ell\ell} = \frac{z_{\ell_1} \sin^2 \theta_{\ell_1} + z_{\ell_2} \sin^2 \theta_{\ell_2}}{\sin^2 \theta_{\ell_1} + \sin^2 \theta_{\ell_2}}$$

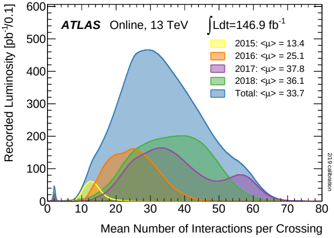
where $\sin^{-1} \theta_\ell$ parametrises the uncertainty of the measured z_ℓ position

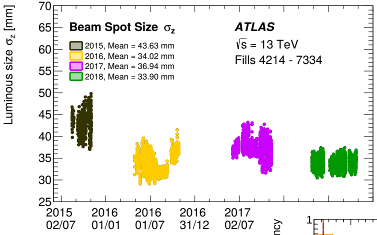
- This vertex is *unbiased* by close-by pileup tracks
- and *more efficient* than the usual $\sum p_{\mathrm{T}}^2$ criterion

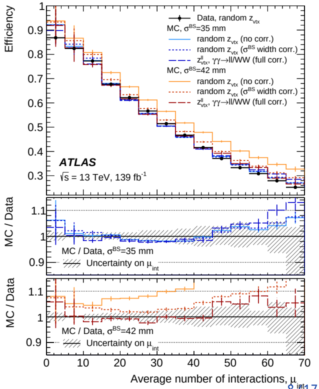




Pileup Challenge







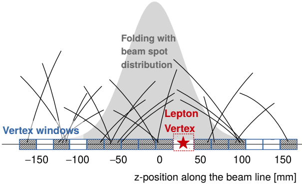
- Between 2015 and 2018 ATLAS recorded 139 fb^{-1} of *pp* collision data
  - With an average of 33.7 collisions per bunch crossing
  - With varying beam conditions
- A pileup vertex in the vicinity of the $\gamma\gamma \to WW$ vertex causes the event to be dropped
- Measurement relies on the correct description of the multiplicity and density of pileup tracks

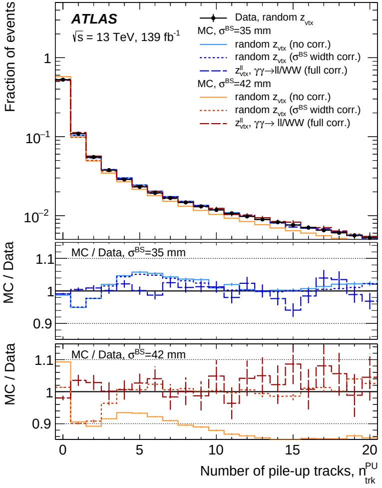
Pileup Modelling

- The probability of finding a pileup track within 1 mm of the vertex is 47.4%

→ Large source of efficiency loss

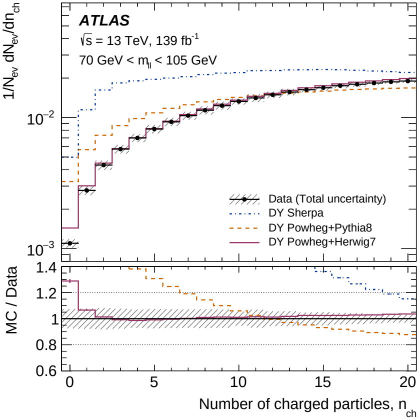
- Measured from several *z*-positions in Drell-Yan events, weighted with beam-spot distribution

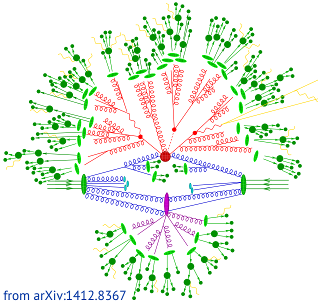




- Small differences between data and simulation are used as a correction, after correcting the beam-spot size

- An accurate estimation of the backgrounds relies on the modelling of the underlying event
- Dominated by low-p_T, non-perturbative physics

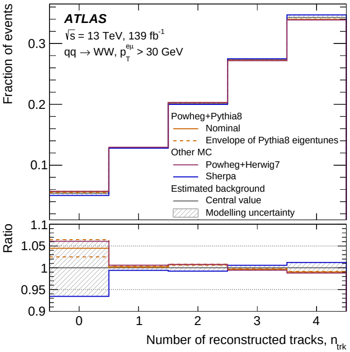


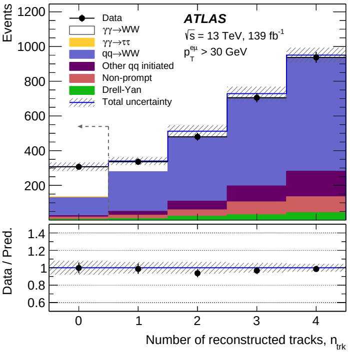


from arXiv:1412.8367

- The number of charged particles is measured in Drell-Yan events
- Double differentially in n_{ch} and $p_T(ll)$
- Separately for every parton shower models used in the analysis

Modelling of $qq \rightarrow WW$ Production





- Underlying event corrections derived in Drell-Yan events are used to correct $qq \rightarrow VV$ events, as a function of n_{ch} and $p_{\text{T}}(VV)$
- Pythia8 eigentune vars., Herwig7 and Sherpa parton-shower models agree within 1% … except for $n_{\text{tracks}} = 0$

Differences are the largest source of uncertainty in the measurement

(with the $qq \rightarrow VV$ yield estimated from the average and envelope of the highest and lowest number)

Signal Modelling

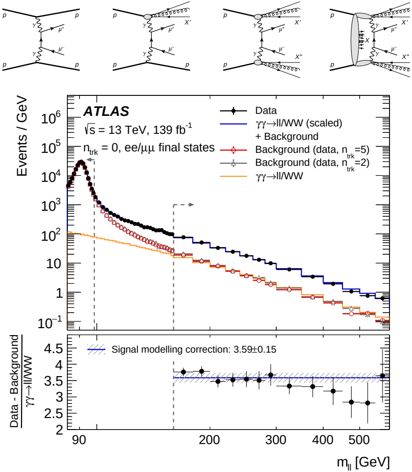
- No complete simulation of $\gamma\gamma \to WW$ available (at least not at the time :-))
- In particular, no rescattering of the proton

$\rightarrow$ Measure missing components in $\gamma\gamma \to \ell\ell$

- Using elastic contributions for signal predictions, only

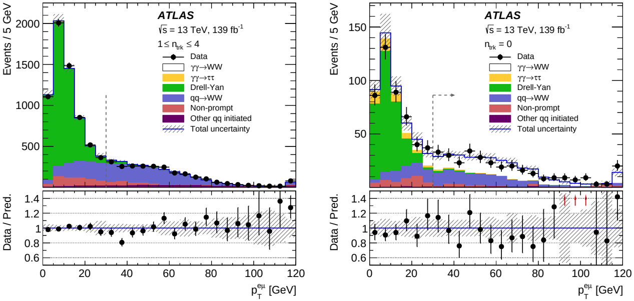
$$\beta_{\gamma\gamma\to\ell\ell} = \frac{N_{\text{data}} - N_{\text{bkg}}}{N^{\text{elastic}}_{\gamma\gamma\to\ell\ell}} = 3.59 \pm 0.15 \text{ (stat.+syst.)}$$

- Applicability to $\gamma\gamma \to WW$ ensured with $m_{\ell\ell} > 160$ GeV $\sim 2 \cdot m_W$ (and a generous uncertainty)



This approach assumes that the fraction of elastic and dissociative components are the same in $\gamma\gamma \to \ell\ell$ and $\gamma\gamma \to WW$ events, for a given $m_{\gamma\gamma}$

The Observation



$$\beta_{WW} = 1.21^{+0.19}_{-0.23}$$
$$\beta_{\text{Drell-Yan}} = 1.16^{+0.10}_{-0.12}$$
$$\beta_{\gamma\gamma\to\ell\ell} = 3.59 \pm 0.15$$
$$\mu_{\gamma\gamma\to WW} = 1.33$$
$$\pm 0.14\ (\text{stat.})\ ^{+0.22}_{-0.17}\ (\text{syst.})$$

- Signal extracted in a profile likelihood fit, using
  - four bins with $p_T(ll) < 30$ GeV or $p_T(ll) > 30$ GeV, and $1 \leq n_{\text{tracks}} \leq 4$ or $n_{\text{tracks}} = 0$
  - one bin for the signal modelling correction, $n_{\text{tracks}} = 0$ and $m_{\ell\ell} > 160$ GeV
  - four free parameters, the normalisations of $\gamma\gamma \to WW$, $\gamma\gamma \to \ell\ell$, Drell-Yan and $qq \to WW$
- 307 candidate events are selected in data where 127 are expected from background

The background-only hypothesis is rejected with 8.4σ (6.7σ expected)

Fiducial Cross Section

- The fiducial cross section ($n_{\text{ch}} = 0$ + kinematic requirements) is measured to be

$$\sigma_{\text{meas.}} = 3.13 \pm 0.31 \text{ (stat.)} \pm 0.28 \text{ (syst.) fb}$$

Source of uncertainty	Impact [%]
Experimental	
Track reconstruction	1.1
Electron energy scale and resolution, and efficiency	0.4
Muon momentum scale and resolution, and efficiency	0.5
Misidentified leptons	1.5
Background, statistical	6.7
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other backgrounds	1.7
Luminosity	1.7
Total	8.9

- Largest sources of uncertainty
  - Stat. uncertainties in the backgrounds
  - Background modelling
  - Signal modelling (dissociative contributions)
- Compared to our "expectation"

$$\sigma_{\text{elastic}} \cdot \beta_{\gamma\gamma\to\ell\ell} = 2.34 \pm 0.27 \text{ fb}$$

- A standalone prediction from Madgraph with MMHT2015qed PDF

$$\sigma_{\text{theo.}} = 4.3 \pm 1.0 \text{ (scale)} \pm 0.12 \text{ (PDF) fb}$$

- This value needs to be corrected for rescattering effects ranging between 0.65 and 0.82

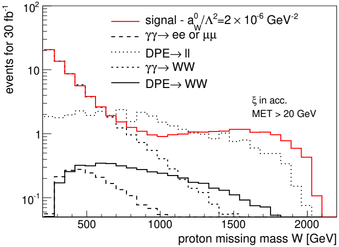
Where AFP Comes In

- Forward proton tagging allows reconstruction of the *WW* system in $\gamma\gamma \to WW$ events

$$W = \sqrt{s\xi_1\xi_2} = m_{WW}$$

- With acceptance of 300 GeV $< W <$ 1.5 TeV of double-tagged events

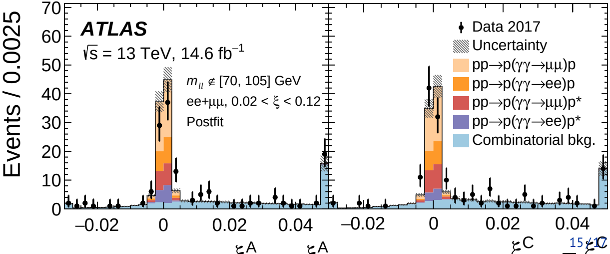
→ Increased sensitivity in EFT interpretations



from Phys. Rev. D 81, 074003 (2010)

- Dedicated background estimation techniques allow reduction of dominant source of systematic uncertainty

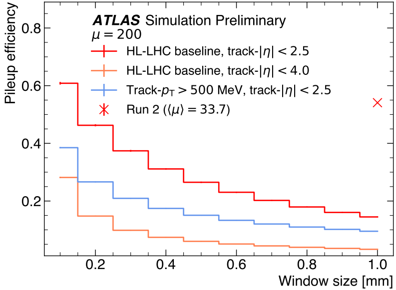
- Demonstrated in PRL 125 (2020) 261801

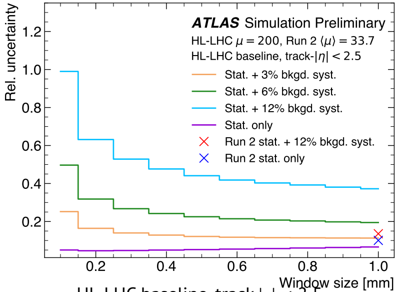


Prospects for Run-4

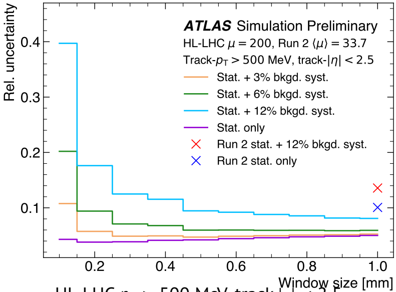
- Prospect study for HL-LHC in ATL-PHYS-PUB-2021-026
- Comparing the (expected) track reconstruction with ITk with a run-2 like low-p_T option

	Run 2 ID	ITk (HL-LHC baseline)		
	$\|\eta\| < 2.5$	$\|\eta\| < 2.0$	$2.0 < \|\eta\| < 2.6$	$2.6 < \|\eta\| < 4.0$
Min. p_T [MeV]	500	900	400	400
Min. number of Si hits	7	9	8	7





HL-LHC baseline, track-$|\eta| < 2.5$



HL-LHC $p_T > 500$ MeV, track-$|\eta| < 2.5$

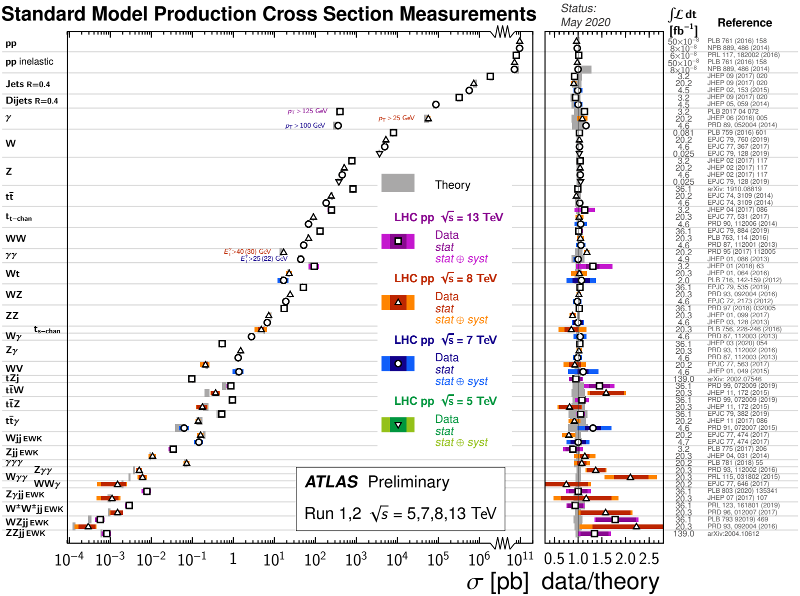
Summary

- The production of two W bosons from two photons has been observed
- As it proceeds through quartic gauge couplings, it confirms a longstanding Standard Model prediction

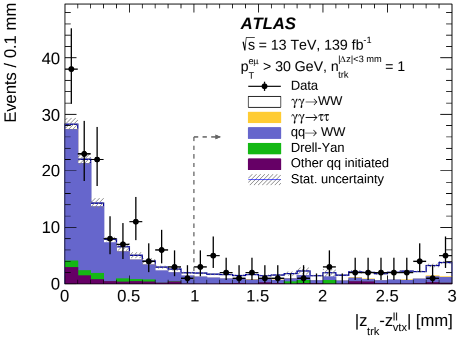
- Progress in experimental techniques allow use of high pileup pp data
- Use of AFP would allow to reconstruct the WW system and improve on background uncertainties

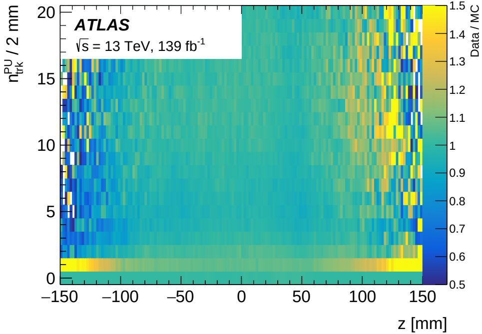
- Measurement published in Phys. Lett. B 816 (2021) 136190

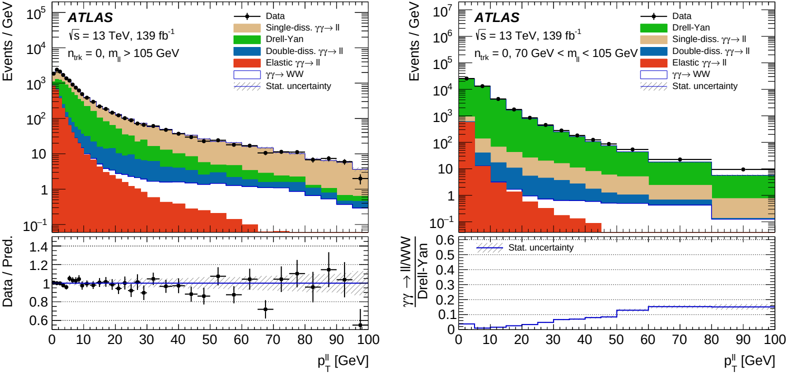
Backup


Standard Model Production Cross Section Measurements
Status: May 2020
∫ℒ dt [fb⁻¹]
Reference
pp
pp inelastic
Jets R=0.4
Dijets R=0.4
γ
W
Z
tt̄
t_t−chan
WW
γγ
Wt
WZ
ZZ
t_s−chan
Wγ
Zγ
WV
tZj
tt̄W
tt̄Z
tt̄γ
Wjj EWK
Zjj EWK
γγγ
Zγγ
Wγγ
WWγ
Zγjj EWK
W±W±jj EWK
WZjj EWK
ZZjj EWK
p_T > 125 GeV
p_T > 100 GeV
p_T > 25 GeV
Theory
LHC pp √s = 13 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 8 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 7 TeV
Data
stat
stat ⊕ syst
LHC pp √s = 5 TeV
Data
stat
stat ⊕ syst
ATLAS Preliminary
Run 1,2 √s = 5,7,8,13 TeV
10⁻⁴ 10⁻³ 10⁻² 10⁻¹ 1 10¹ 10² 10³ 10⁴ 10⁵ 10⁶ 10¹¹
σ [pb]
0.5 1.0 1.5 2.0 2.5
data/theory

	Signal region		Control regions	
n_{trk}	$n_{\mathrm{trk}} = 0$		$1 \leq n_{\mathrm{trk}} \leq 4$	
$p_{\mathrm{T}}^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \to WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \to \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell–Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \to WW$ (incl. gg and VBS)	101 ± 17	55 ± 10	1700 ± 270	970 ± 150
Non-prompt	14 ± 14	36 ± 35	220 ± 220	500 ± 400
Other backgrounds	7.1 ± 1.7	1.9 ± 0.4	311 ± 76	81 ± 15
Total	305 ± 18	459 ± 19	2460 ± 60	6320 ± 130
Data	307	449	2458	6332


ATLAS
√s = 13 TeV, 139 fb-1
p_T^eμ > 30 GeV, n_trk^|Δz|<3 mm = 1
Data
γγ→WW
γγ→ττ
qq→ WW
Drell-Yan
Other qq initiated
Stat. uncertainty
Events / 0.1 mm
|z_trk-z_vtx^ll| [mm]
0
10
20
30
40
0.5
1
1.5
2
2.5
3


ATLAS
√s = 13 TeV, 139 fb-1
n_trk^PU / 2 mm
z [mm]
Data / MC
–150
–100
–50
0
50
100
150
0
5
10
15
20
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5


ATLAS
√s = 13 TeV, 139 fb-1
n_trk = 0, m_ll > 105 GeV
Data
Single-diss. γγ→ ll
Drell-Yan
Double-diss. γγ→ ll
Elastic γγ→ ll
γγ→ WW
Stat. uncertainty
Events / GeV
Data / Pred.
p_T^ll [GeV]
ATLAS
√s = 13 TeV, 139 fb-1
n_trk = 0, 70 GeV < m_ll < 105 GeV
Data
Drell-Yan
Single-diss. γγ→ ll
Double-diss. γγ→ ll
Elastic γγ→ ll
γγ→ WW
Stat. uncertainty
Events / GeV
γγ → ll/WW / Drell-Yan
Stat. uncertainty
p_T^ll [GeV]