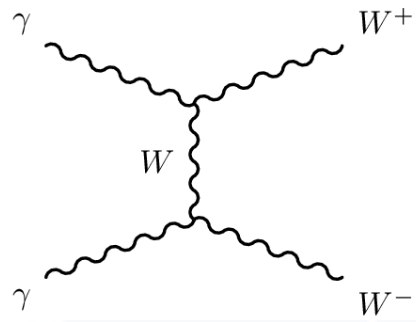
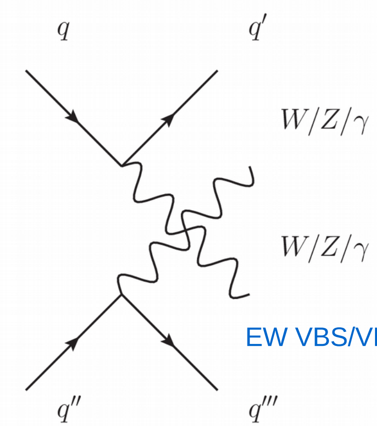
VBS/VBF measurements with photons with ATLAS and CMS

Ben Smart,
on behalf of the ATLAS and CMS collaborations



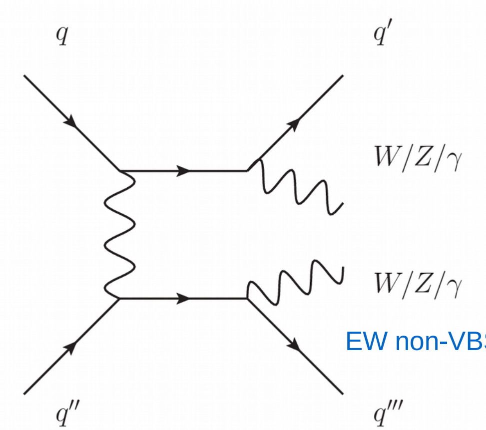
- One of the main goals of ATLAS and CMS has been to study **EW symmetry breaking**
  - VBF/VBS provide excellent tools to probe this:
    - Unitarity in WW scattering provided motivation for the Higgs boson
    - Allow precision measurements of the SM, and **setting of limits on anomalous quartic couplings**



EW VBS/VBF

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{SM} + \sum_i \frac{C_{6i}}{\Lambda^2}\mathcal{O}_{6i} + \sum_j \frac{C_{8j}}{\Lambda^4}\mathcal{O}_{8j} + \ldots ,$$

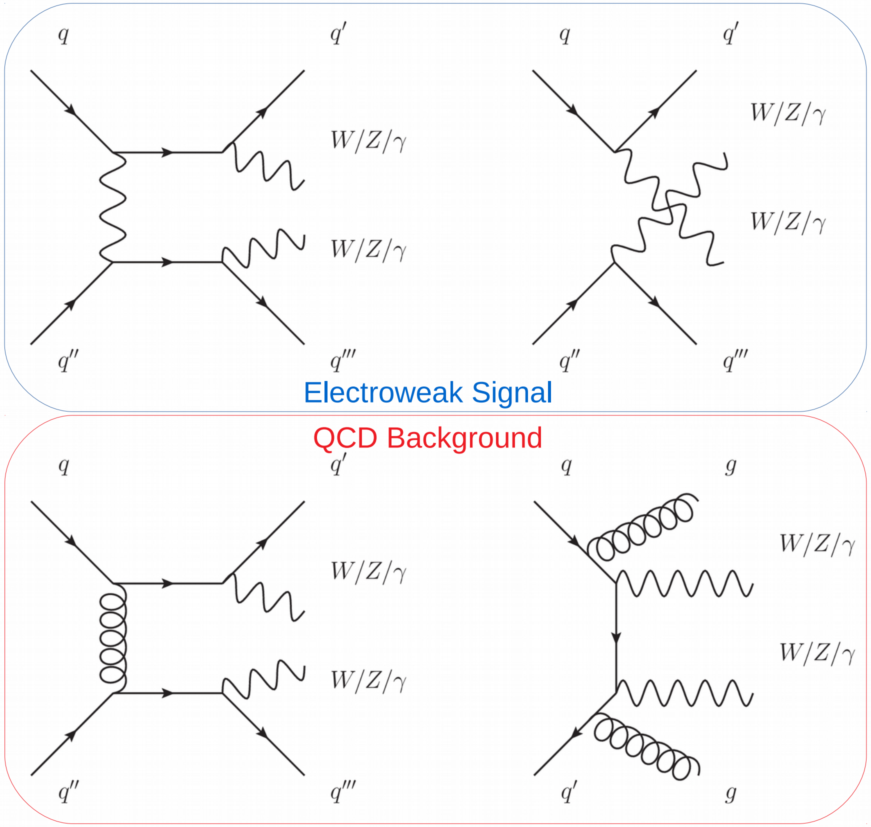
$$\mathcal{L}_{aQGC} = \sum_{i=0}^{2} \frac{f_{S_i}}{\Lambda^4} O_{S_i} + \sum_{j=0}^{7} \frac{f_{M_j}}{\Lambda^4} O_{M_j} + \sum_{k=0}^{9} \frac{f_{T_k}}{\Lambda^4} O_{T_k} ,$$



EW non-VBS/VBF

- Can also study photon-photon scattering that can leave protons intact

- VBS/VBF are **rare processes**
  - **Large QCD background**
  - Typically look for **two well-separated jets**, as well as products of gauge boson interactions
    - **Semi/leptonic decay modes** of W/Z help
    - **Photon in final state** allows for cleaner signal identification and reduction in backgrounds
  - **Complex final state topologies** are well suited to machine learning and multivariate analysis techniques



- There are many analyses we could look at:

Date	Analysis	Link (Clickable)
March 2021	$Z\gamma$+dijet at 13 TeV (full Run2 dataset)	https://cds.cern.ch/record/2759297
December 2020	$W\gamma$+dijet at 13 TeV	Phys. Lett. B 811 (2020) 135988
October 2020	Observation of photon-induced W pair production	Phys. Lett. B 816 (2021) 136190
August 2020	Photon-photon scattering in Pb+Pb collisions	JHEP 03 (2021) 243
February 2020	$Z\gamma$+dijet at 13 TeV	JHEP 06 (2020) 076
October 2019	$Z\gamma$+dijet at 13 TeV	Phys. Lett. B 803 (2020) 135341
May 2017	$Z\gamma$+dijet at 8 TeV	JHEP 07 (2017) 107
February 2017	$Z\gamma$+dijet at 8 TeV	Phys. Lett. B 770 (2017) 380
December 2016	$W\gamma$+dijet at 8 TeV	JHEP 06 (2017) 106

- Today I will discuss the following:

Date	Analysis	Link (Clickable)
March 2021	$Z\gamma$+dijet at 13 TeV (full Run2 dataset)	https://cds.cern.ch/record/2759297
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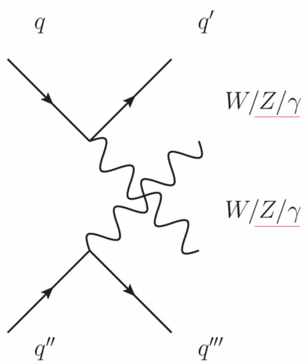
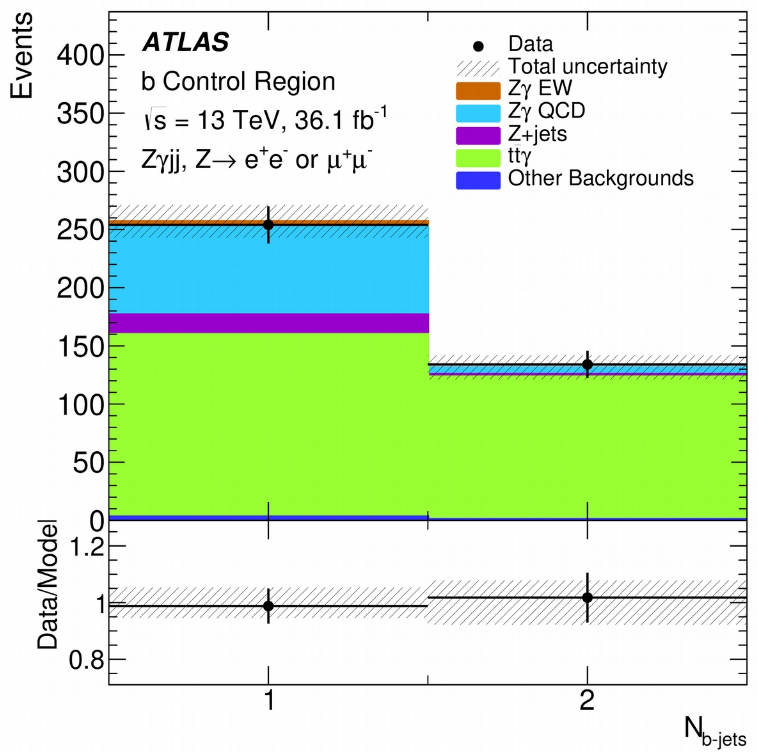
$Z\gamma$ + dijet at $\sqrt{s}$ = 13 TeV

Phys. Lett. B 803 (2020) 135341

- Targeting electroweak $Z\gamma$, in association with two jets, in 36.1 fb^{-1} of data.
  - Two well-separated jets ($|\Delta\eta_{jj}| > 1.0$)
  - e^+e^- or $\mu^+\mu^-$ from Z decay.
  - Zero b-tagged jets in signal region.
  - At least one b-tagged jet in control region.
  - BDT used to separate EW $Z\gamma jj$ from backgrounds.



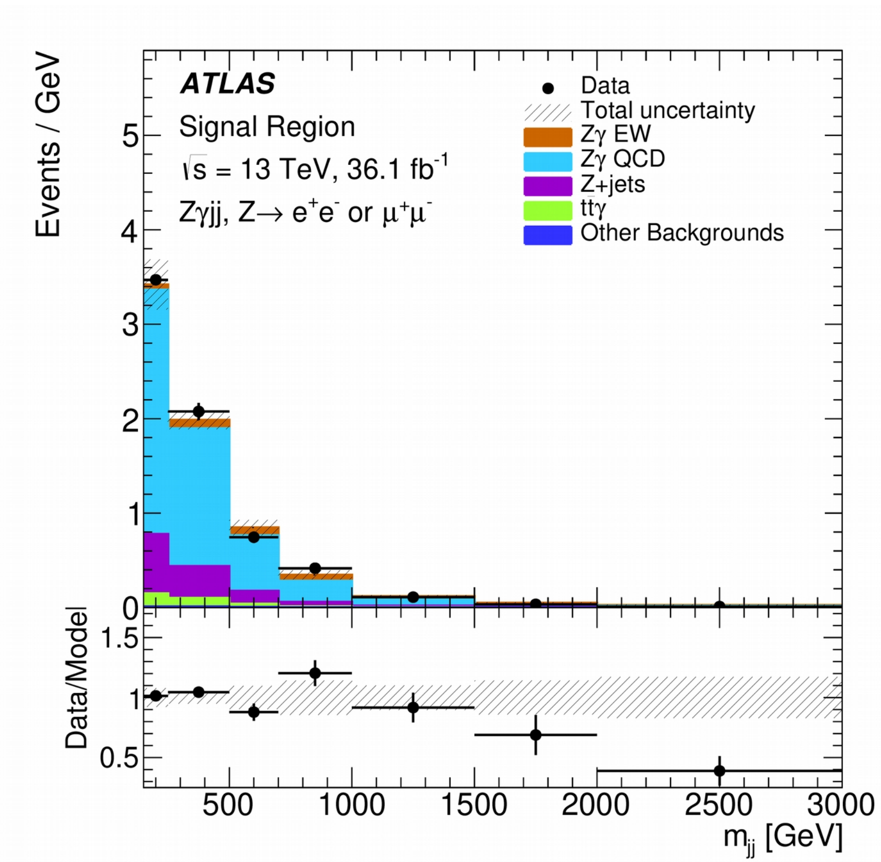
Source	Uncertainty [%]
Statistical	$^{+19}_{-18}$
$Z\gamma jj$–EW theory modelling	$^{+10}_{-6}$
$Z\gamma jj$–QCD theory modelling	±6
$t\bar{t}+\gamma$ theory modelling	±2
$Z\gamma jj$–EW and $Z\gamma jj$–QCD interference	$^{+3}_{-2}$
Jets	±8
Pile-up	±5
Electrons	±1
Muons	$^{+3}_{-2}$
Photons	±1
Electrons/photons energy scale	±1
b-tagging	±2
MC statistical uncertainties	±8
Other backgrounds normalisation (including Z+jets)	$^{+9}_{-8}$
Luminosity	±2
Total uncertainty	±26

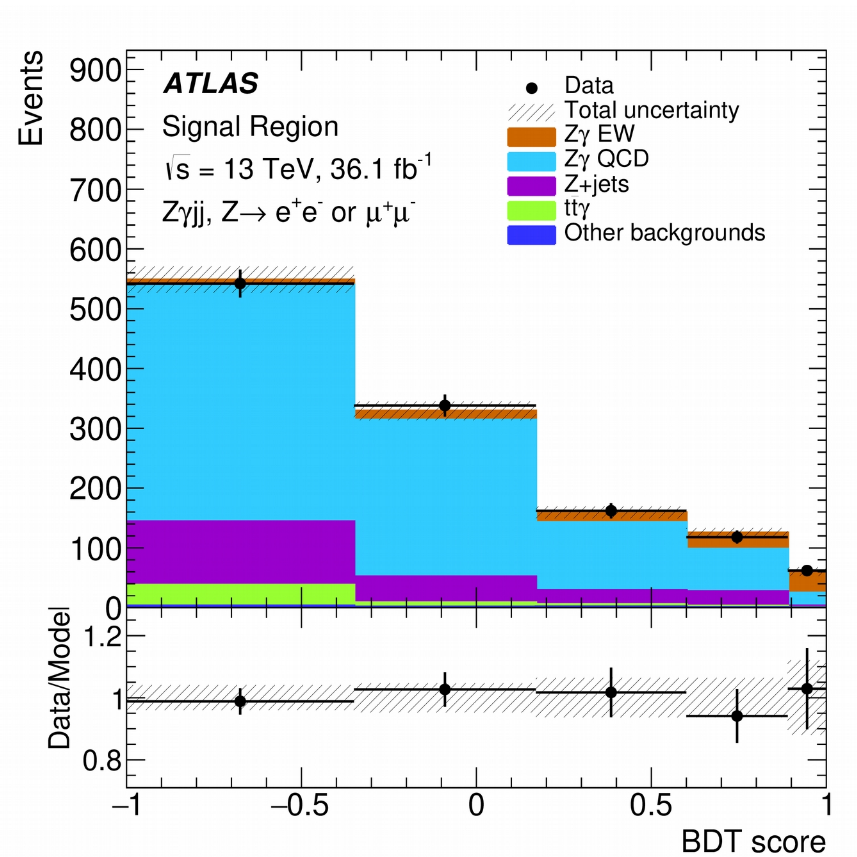


Phys. Lett. B 803 (2020) 135341

- Evidence of EW Zγjj at 4.1σ (expected and observed).

  cross section: $\sigma_{Z\gamma jj\text{-}EW} = 7.8 \pm 2.0$ fb





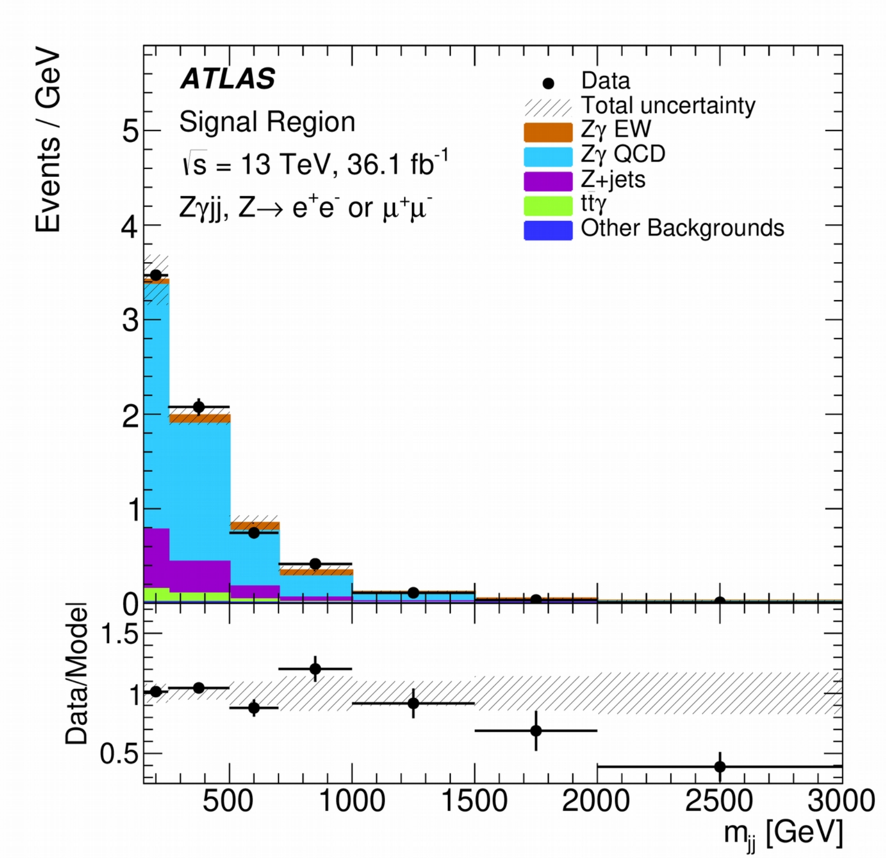
- Improvement on previous (√s = 8TeV, 20.2 fb^{-1}) analysis which gave significance on EW Zγjj of 2.0σ measured, (1.8σ expected).

$Z\gamma$ + dijet at $\sqrt{s}$ = 13 TeV

Phys. Lett. B 803 (2020) 135341

- Evidence of EW $Z\gamma jj$ at 4.1σ (expected and observed).

  cross section: $\sigma_{Z\gamma jj\text{-}EW} = 7.8 \pm 2.0$ fb



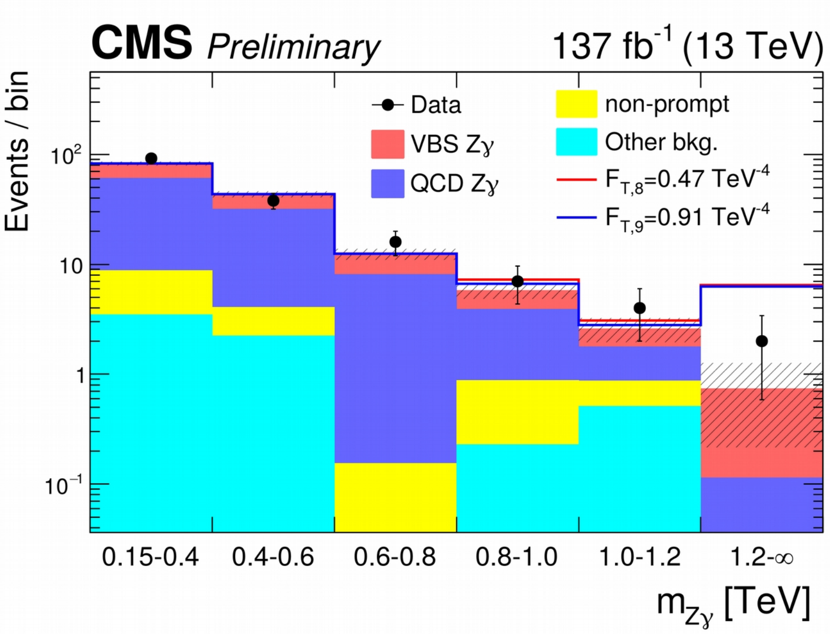
	SR		*b*-CR	
Data	1222		388	
Total expected	1222	±35	389	±19
$Z\gamma jj$–EW (signal)	104	±26	5	± 1
$Z\gamma jj$–QCD	864	±60	82	± 9
Z+jets	200	±40	19	± 4
$t\bar{t}+\gamma$	48	±10	280	±21
Other backgrounds	7	± 1	4	± 1

- Improvement on previous ($\sqrt{s}$ = 8TeV, 20.2 fb^{-1}) analysis which gave significance on EW $Z\gamma jj$ of 2.0σ measured, (1.8σ expected).

https://cds.cern.ch/record/2759297

- **First observation** of electroweak $Z\gamma$, in association with two jets, in 137 fb^{-1} of data.
  - e^+e^- or $\mu^+\mu^-$ from Z decay.
  - For likelihood fit, signal and control regions are binned in barrel/endcap (based on γ in ECAL), and e/μ channel.
    - Signal region is further binned in m_{jj} and $|\Delta\eta_{jj}|$.

Common selection	$p_T^{\ell 1,\ell 2} > 25\,\mathrm{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.5$ for electron channel $p_T^{\ell 1,\ell 2} > 20\,\mathrm{GeV}$, $\lvert\eta^{\ell 1,\ell 2}\rvert < 2.4$ for muon channel $p_T^{\gamma} > 20\,\mathrm{GeV}$, $\lvert\eta^{\gamma}\rvert < 1.444$ or $1.566 < \lvert\eta^{\gamma}\rvert < 2.500$ $p_T^{j1,j2} > 30\,\mathrm{GeV}$, $\lvert\eta^{j1,j2}\rvert < 4.7$ $70 < m_{\ell\ell} < 110\,\mathrm{GeV}$, $m_{Z\gamma} > 100\,\mathrm{GeV}$ $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{j\ell} > 0.5$, $\Delta R_{\ell\gamma} > 0.7$
Control region	Common selection, $150 < m_{jj} < 500\,\mathrm{GeV}$
EW signal region	Common selection, $m_{jj} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$, $\eta^* < 2.4$, $\Delta\phi_{Z\gamma,jj} > 1.9$
Fiducial volume	Common selection, $m_{jj} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$
aQGC search region	Common selection, $m_{jj} > 500\,\mathrm{GeV}$, $\lvert\Delta\eta_{jj}\rvert > 2.5$, $p_T^{\gamma} > 120\,\mathrm{GeV}$



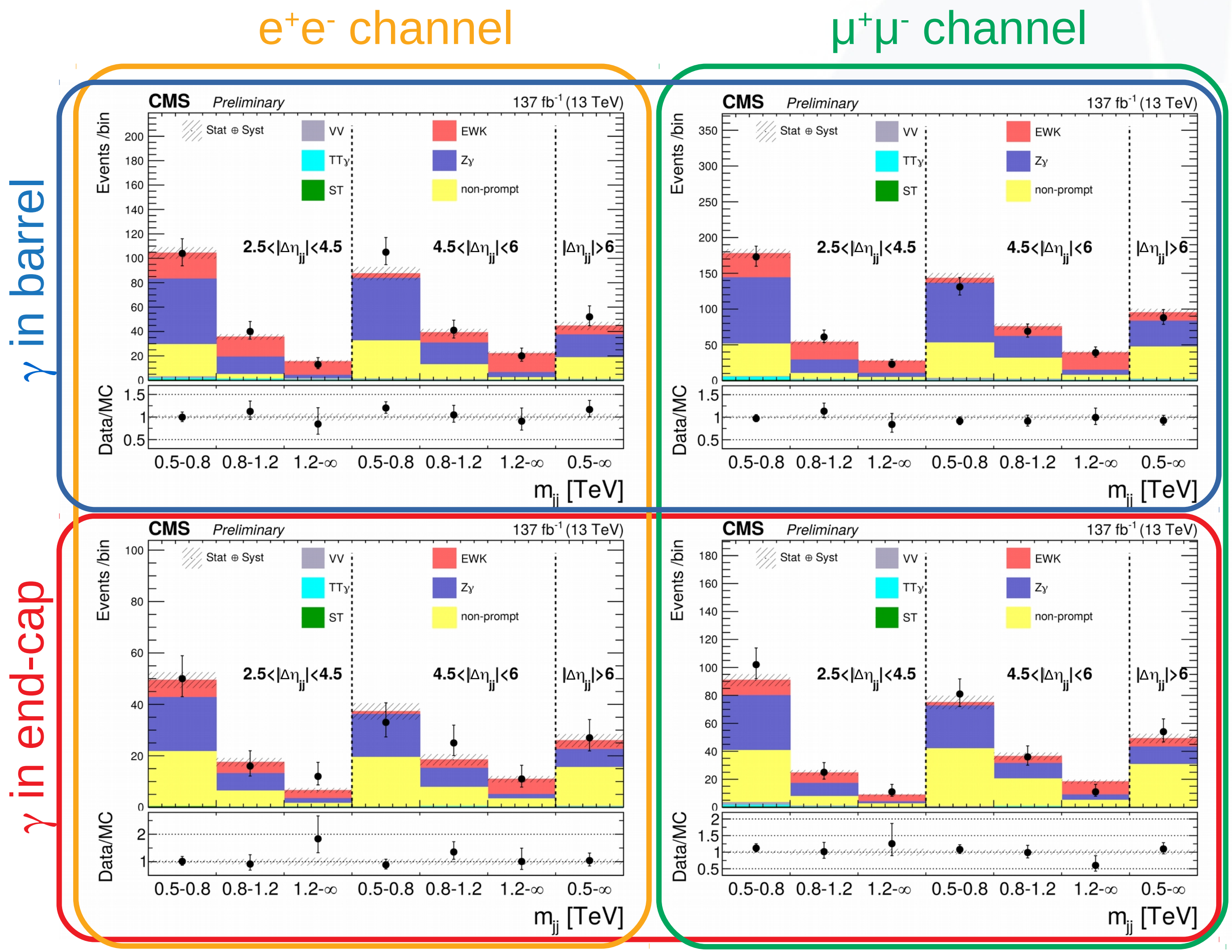
$Z\gamma$ + dijet at $\sqrt{s}$ = 13 TeV

https://cds.cern.ch/record/2759297

- EW $Z\gamma jj$ observed with significance of 9.4σ (8.4σ expected).

  cross section: $\sigma_{Z\gamma jj\text{-}EW} = 5.21 \pm 0.52\ (\text{stat}) \pm 0.56\ (\text{syst})$ fb

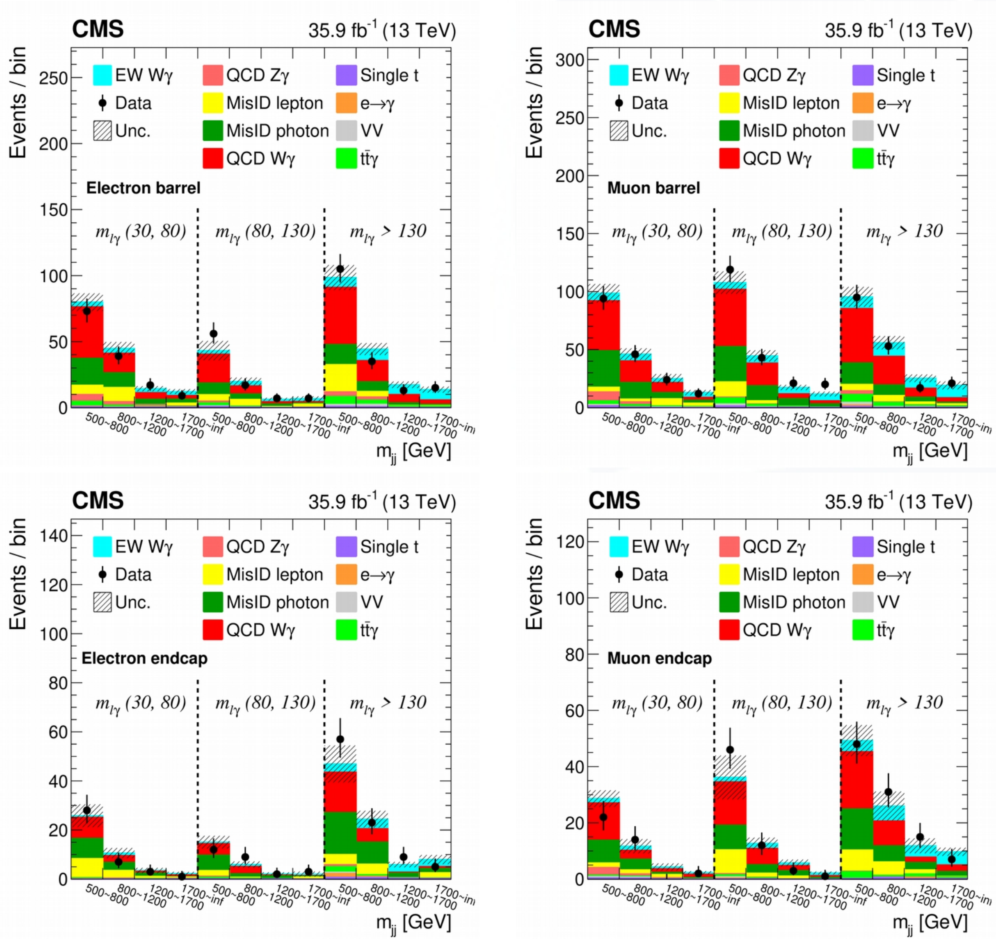
Systematic uncertainty	impact [%]
MC Statistical uncertainties	+4.6 -4.5
Theoretical uncertainties	+5.5 -4.7
Jet energy correction	+7.8 -6.7
Luminosity	+1.4 -1.2
PU	+4.8 -4.1
Non-prompt photons estimation	+2.0 -1.7
Uncertainties related with μ	+1.7 -1.3
Uncertainties related with eγ	+4.5 -3.6
L1 prefiring	+3.4 -2.8
PU jet ID	+3.7 -3.5
Total systematic uncertainty	+14 -12



- Limits set on dimension-8 aQGCs.
- Best limit to-date on $\mathbf{F_{T9}}$ ±0.91 (±0.72) TeV^{-4} observed (expected).

Phys. Lett. B 811 (2020) 135988

- **First observation** of electroweak Wγ, in association with two jets, in 35.9 fb^{-1} of √s = 13 TeV and 19.7 fb^{-1} of √s = 8 TeV data.
  - e or μ, and p_T^{miss}, from $W \rightarrow l\nu$ decay.
  - For likelihood fit, signal and control regions are binned in barrel/endcap (based on γ in ECAL), e/μ channel, and in both m_{jj} and $m_{l\gamma}$.
  - Control region:
    $200 < m_{jj} < 400$ GeV.
  - Signal region:
    $m_{jj} > 500$ GeV
    $|\Delta\eta_{jj}| > 2.5$
    $m_{W\gamma} > 100$ GeV
    $|y_{W\gamma} - ((y_{j1}+y_{j2})/2)| < 1.2$
    $|\phi_{W\gamma} - \phi_{jj}| > 2$ Rad
    - Latter two cuts above aim at Wγ balanced with dijet system, reducing additional QCD.
  - $Z \rightarrow e^+e^-$ peak also suppressed with $|m_{l\gamma} - 91| > 10$ GeV.



Phys. Lett. B 811 (2020) 135988

- Results combined with previous √s = 8 TeV results.
  - Observed (expected) significance is 5.3σ (4.8σ)
- EW cross section, using only √s = 13 TeV data:

$$\sigma_{W\gamma jj\text{-}EW} = 20.4 \pm 0.4\ (\text{lumi}) \pm 2.8\ (\text{stat}) \pm 3.5\ (\text{syst})\ \text{fb} = 20.4 \pm 4.5\ \text{fb}$$

- Limits set on aQGCs.
- Best limits to-date set on $\mathbf{F}_{M2\text{-}5}$ and $\mathbf{F}_{T6\text{-}7}$

Parameters	Obs. limit	Exp. limit	$\mathcal{U}_{\text{bound}}$
$f_{M,0}/\Lambda^4$	$[-8.1, 8.0]$	$[-7.7, 7.6]$	1.0
$f_{M,1}/\Lambda^4$	$[-12, 12]$	$[-11, 11]$	1.2
$f_{M,2}/\Lambda^4$	$[-2.8, 2.8]$	$[-2.7, 2.7]$	1.3
$f_{M,3}/\Lambda^4$	$[-4.4, 4.4]$	$[-4.0, 4.1]$	1.5
$f_{M,4}/\Lambda^4$	$[-5.0, 5.0]$	$[-4.7, 4.7]$	1.5
$f_{M,5}/\Lambda^4$	$[-8.3, 8.3]$	$[-7.9, 7.7]$	1.8
$f_{M,6}/\Lambda^4$	$[-16, 16]$	$[-15, 15]$	1.0
$f_{M,7}/\Lambda^4$	$[-21, 20]$	$[-19, 19]$	1.3
$f_{T,0}/\Lambda^4$	$[-0.6, 0.6]$	$[-0.6, 0.6]$	1.4
$f_{T,1}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.5
$f_{T,2}/\Lambda^4$	$[-1.0, 1.2]$	$[-1.0, 1.2]$	1.5
$f_{T,5}/\Lambda^4$	$[-0.5, 0.5]$	$[-0.4, 0.4]$	1.8
$f_{T,6}/\Lambda^4$	$[-0.4, 0.4]$	$[-0.3, 0.4]$	1.7
$f_{T,7}/\Lambda^4$	$[-0.9, 0.9]$	$[-0.8, 0.9]$	1.8

Source	EW Wγjj	QCD Wγjj	VV	$t\bar{t}\gamma$	QCD Zγ	Single t	MisID photon	MisID lepton	Double misID	$e \to \gamma$
JES	0.9–6.9	11–28	6.4–38	3.7–16	12–78	3.3–18	—	—	—	11–28
JER	0.7–2.2	0.7–4.1	6.9–21	1.3–4.9	6.5–15	2.9–7.1	—	—	—	0.7–4.1
Integrated luminosity	2.5	2.5	2.5	2.5	2.5	2.5	—	—	—	2.5
MisID photon	—	—	—	—	—	—	12–22	—	12–22	—
MisID lepton	—	—	—	—	—	—	—	30	30	—
μ_R/μ_F scales	1.5–11	6.1–20	—	—	—	—	—	—	—	—
PDF	3.2–5.6	1–2	—	—	—	—	—	—	—	—
Interference	1.8–2.8	—	—	—	—	—	—	—	—	—
Cross section for $t\bar{t}\gamma$	—	—	—	10	—	—	—	—	—	—
Cross section for VV	—	—	10	—	—	—	—	—	—	—
Modeling of pileup	0–0.6	0.3–1.4	4.8–13	2.6–3.9	6.2–19	1.0–3.9	—	—	—	0.3–1.4
Statistical uncertainty	7–11	6–36	45–100	13–56	16–100	17–55	7–36	43–72	30–100	54–100
L1 mistiming	1.7–2.4	0.8–1.6	0.5–1.6	1.4–2.5	0.6–3.6	1.0–2.1	—	—	—	1.1–2.8
Muon ID/Iso	0.3	0.3	0.3	0.3	0.3	0.3	—	—	—	0.3
Muon trigger	0.3	0.2	0.2	0.2	0.1	0.1	—	—	—	0.2
Electron reconstruction	0.5	0.6	0.5	0.6	0.6	0.5	—	—	—	0.5
Electron ID/Iso	1.3	1.3	1.3	1.3	1.3	1.3	—	—	—	1.3
Electron trigger	2.5	2.5	2.5	2.5	2.5	2.5	—	—	—	2.5
Photon ID	1.2	1.2	1.1	1.2	1.3	1.2	—	—	—	1.2

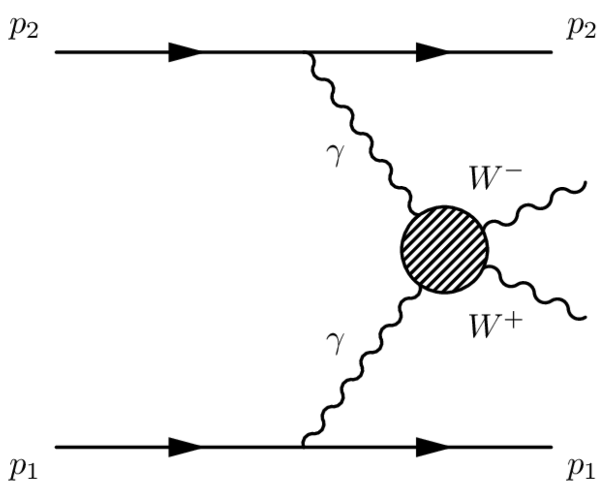
% Uncertainties. Ranges correspond to different m_{jj} and $m_{l\gamma}$ bins, with uncertainties generally increasing with increasing m_{jj} and $m_{l\gamma}$.

Observation of Photon-Induced W Pair Production

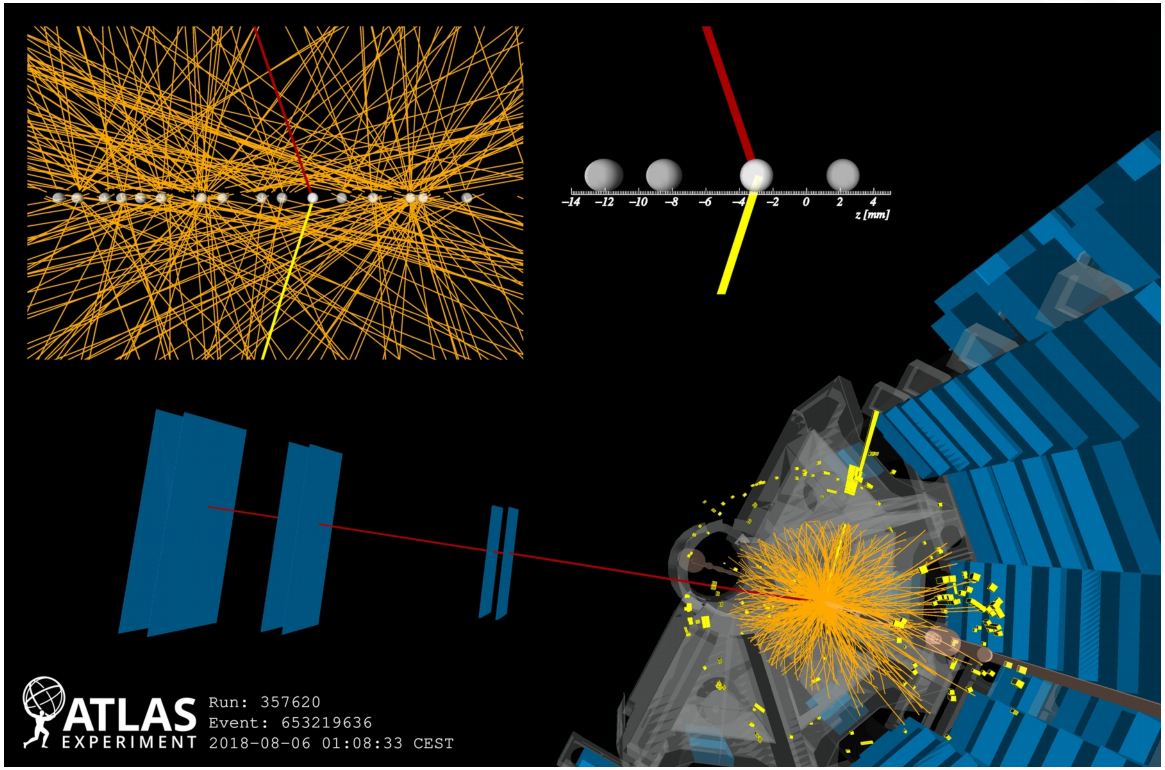
Phys. Lett. B 816 (2021) 136190

- $\gamma\gamma \rightarrow$ WW can leave initial protons intact.
- Search uses 139 fb^{-1} of $\sqrt{s}$ = 13 TeV data, looking for:
  $e^{\pm}\mu^{\mp}$ from the decay $W^{+}W^{-} \rightarrow e^{\pm}\nu\mu^{\mp}\nu$, with zero additional tracks.
- $\gamma\gamma \rightarrow$ WW observed with **8.4 σ**

  cross section: $\sigma_{\gamma\gamma \rightarrow WW \rightarrow e\nu\mu\nu}$ = 3.13 ± 0.31 (stat) ± 0.28 (syst) fb
- In agreement with SM prediction.

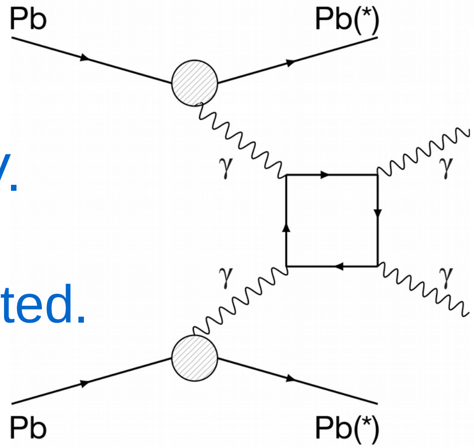


See Christophe Royon's talk for more information!



Photon-Photon Scattering in Pb+Pb Collisions

- Study uses 2.2 nb^{-1} of Pb+Pb data collected in 2015 and 2018 at $\sqrt{s_{NN}}$ = 5.02 TeV.
  - Events containing only two photons selected.
- Data/theory ratio after all corrections is ~1.5±0.3, (dependent on generator choice).
  - Within 2σ of SM.
- Results used to set limits on axion-like particles (ALPs).
- Result give most stringent limits to date on ALP production for ALP masses in the range 6-100 GeV.



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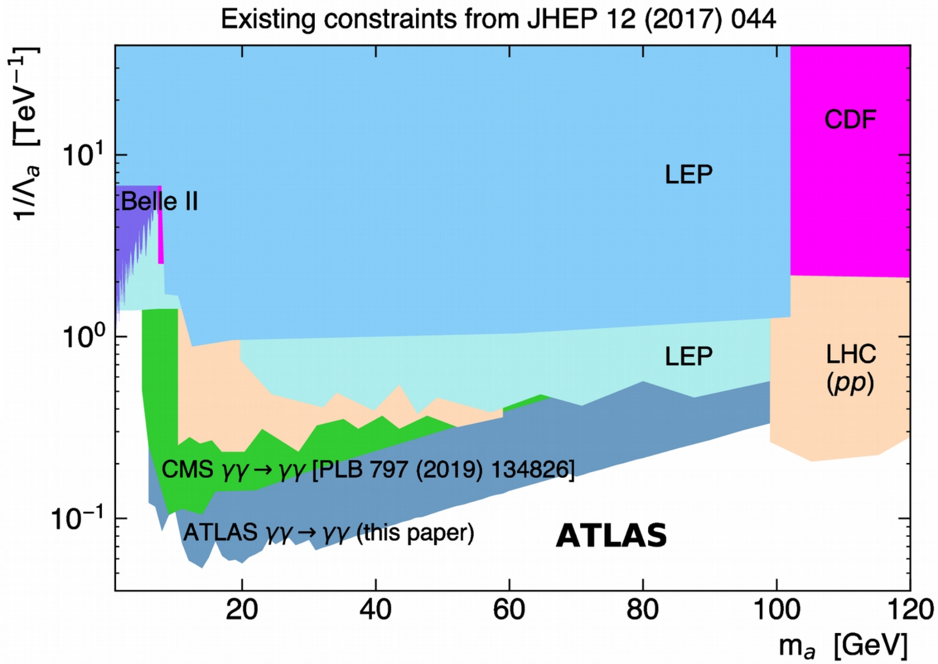
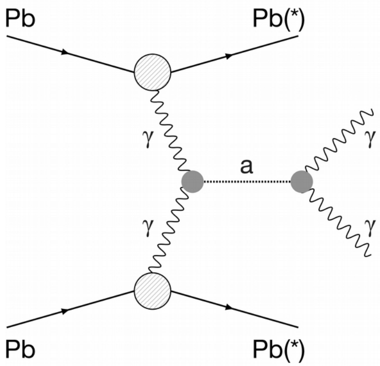
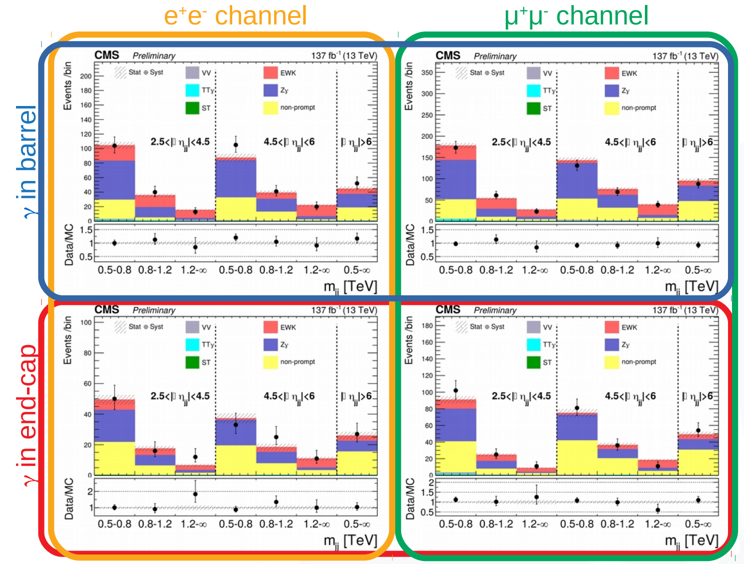


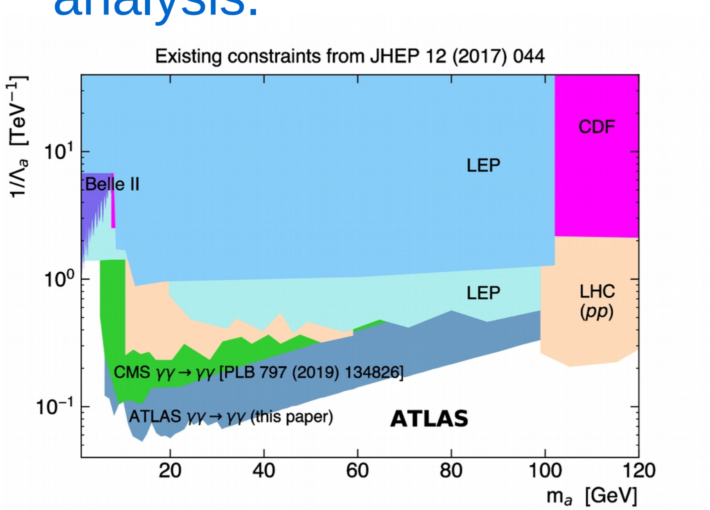


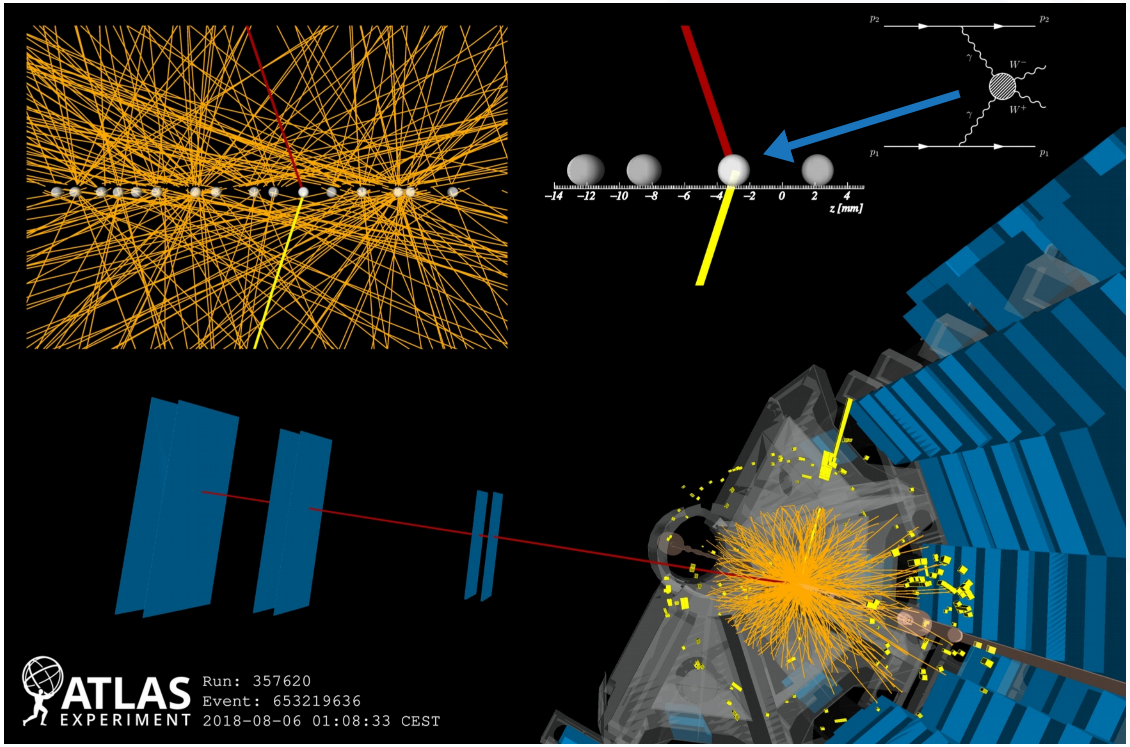
See Christophe Royon's talk for more information!

Summary

- VBS/VBF provides excellent tools for probing the nature of electroweak symmetry breaking.
- **First observations** of EW $Z\gamma jj$, EW $W\gamma jj$, and photon-photon scattering producing W pairs.
- **Strongest limits to-date set** on:
  - Anomalous quartic gauge couplings from EW $Z\gamma jj$ and EW $W\gamma jj$ analyses.
  - Axion-like particle production from Pb+Pb photon-scattering analysis.





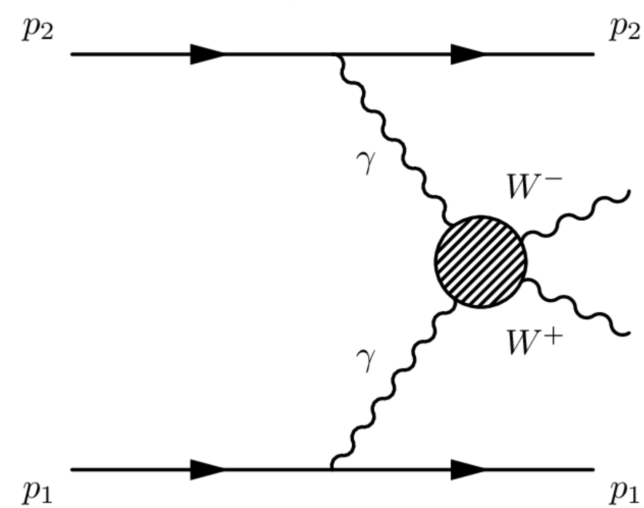


Backup

Observation of Photon-Induced W Pair Production

Phys. Lett. B 816 (2021) 136190

- Photon-photon interactions producing a W-pair can leave initial protons intact.
- Search uses 139 fb^{-1} of $\sqrt{s}$ = 13 TeV data, looking for:
  - One electron and one muon, corresponding to the decay $W^+W^- \rightarrow e^{\pm}\nu\mu^{\pm}\nu$
  - Electron and muon must be opposite sign.
  - Zero additional tracks.



- MC requires accurate modelling of track density around eμ vertex.
  - MC reweighted by data/MC ratios in $Z \rightarrow ll$ and $\gamma\gamma \rightarrow ll$.

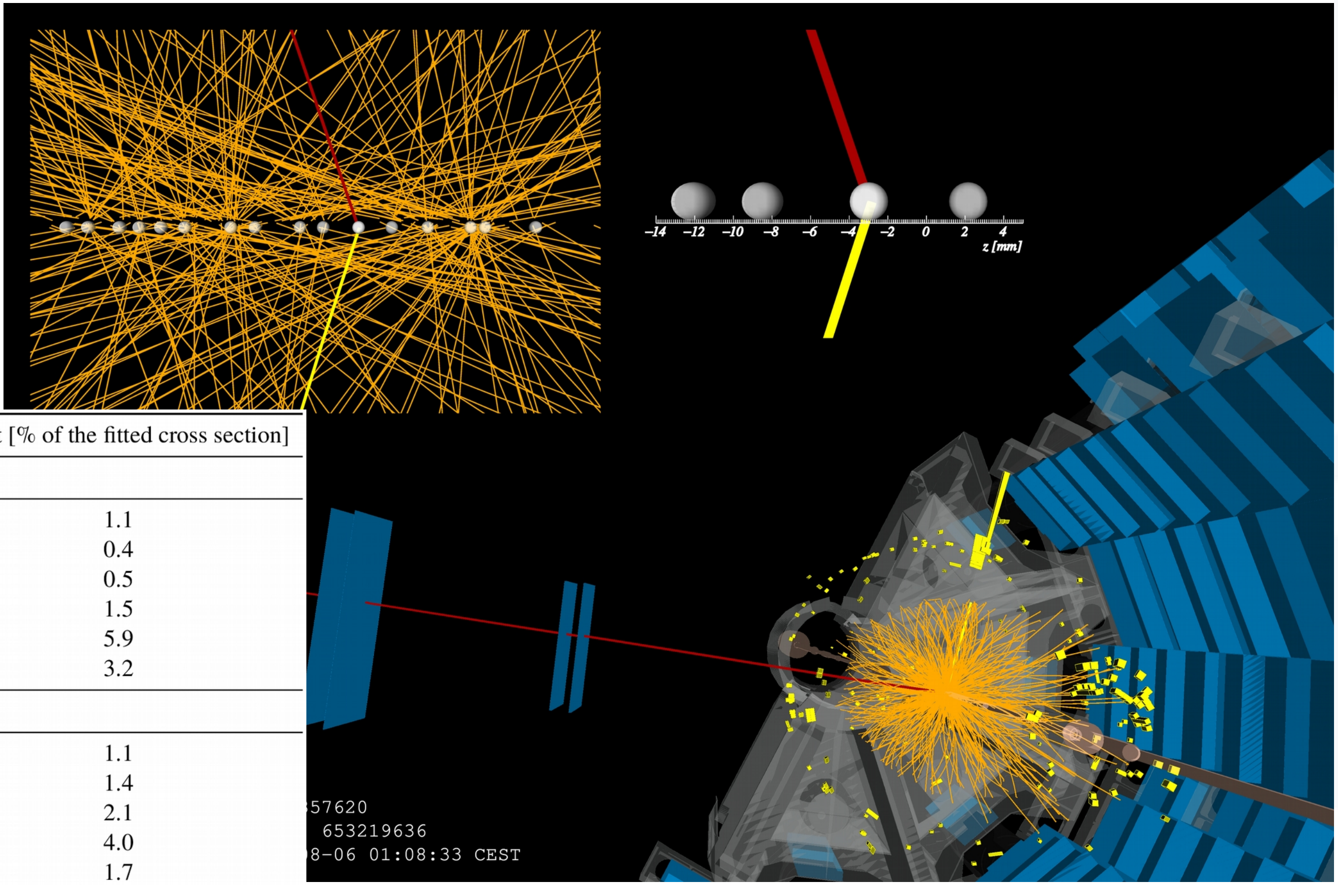
	Signal region		Control regions	
n_{trk}	$n_{trk} = 0$		$1 \leq n_{trk} \leq 4$	
$p_T^{e\mu}$	> 30 GeV	< 30 GeV	> 30 GeV	< 30 GeV
$\gamma\gamma \rightarrow WW$	174 ± 20	45 ± 6	95 ± 19	24 ± 5
$\gamma\gamma \rightarrow \ell\ell$	5.5 ± 0.3	39.6 ± 1.9	5.6 ± 1.2	32 ± 7
Drell–Yan	4.5 ± 0.9	280 ± 40	106 ± 19	4700 ± 400
$qq \rightarrow WW$ (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

Phys. Lett. B 816 (2021) 136190

- $\gamma\gamma \rightarrow$ WW observed with **8.4 σ**

  cross section: $\sigma_{\gamma\gamma \rightarrow WW \rightarrow e\nu\mu\nu}$ = 3.13 ± 0.31 (stat) ± 0.28 (syst) fb

- In agreement with SM prediction.



Source of uncertainty	Impact [% of the fitted cross section]
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, systematic	1.5
Misidentified leptons, statistical	5.9
Other background, statistical	3.2
Modelling	
Pile-up modelling	1.1
Underlying-event modelling	1.4
Signal modelling	2.1
WW modelling	4.0
Other background modelling	1.7
Luminosity	1.7
Total	8.9

Photon-Photon Scattering in Pb+Pb Collisions

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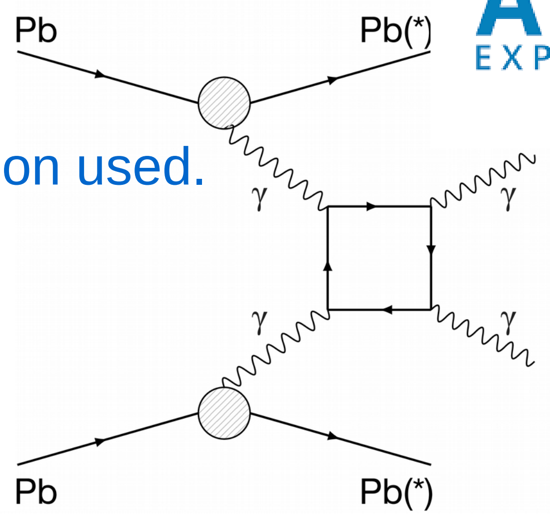
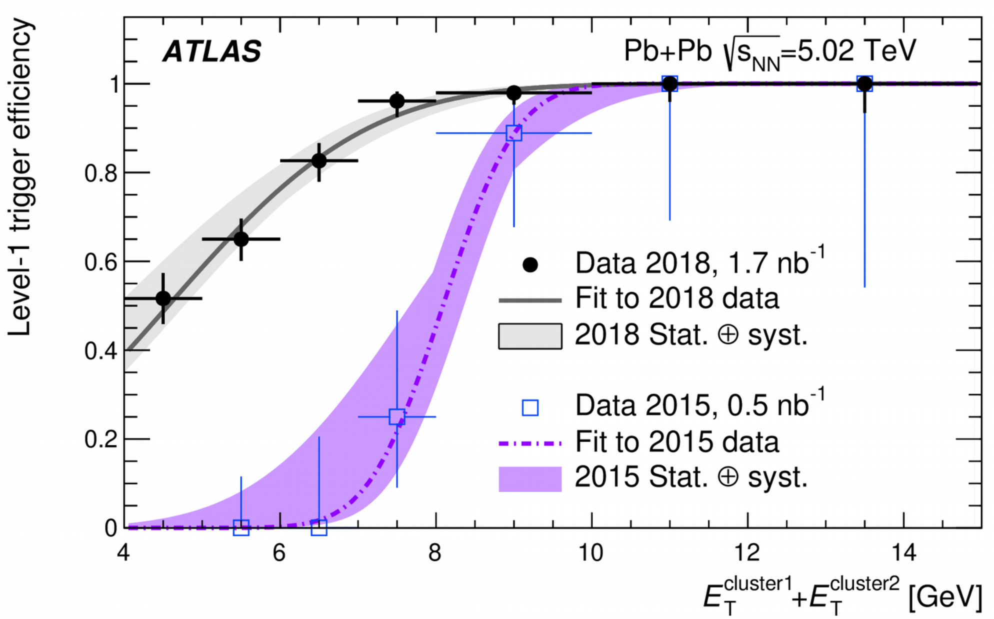
- Study uses 2.2 nb^{-1} of Pb+Pb data collected in 2015 and 2018 at $\sqrt{s_{NN}}$ = 5.02 TeV.
- Events containing only two photons selected.
- Custom triggers and low-ET object reconstruction used.
  - Calibrated with $\gamma\gamma \rightarrow ee$ and $\gamma\gamma \rightarrow ee\gamma$ events.



Source of uncertainty	Detector correction (C)
	0.263 ± 0.021
Trigger efficiency	5%
Photon reco. efficiency	4%
Photon PID efficiency	2%
Photon energy scale	1%
Photon energy resolution	2%
Photon angular resolution	2%
Alternative signal MC	1%
Signal MC statistics	1%
Total	8%



Photon-Photon Scattering in Pb+Pb Collisions

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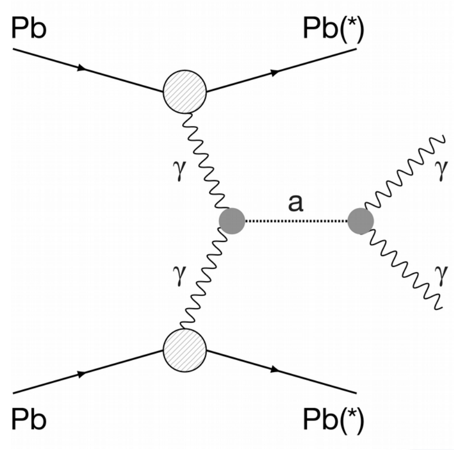
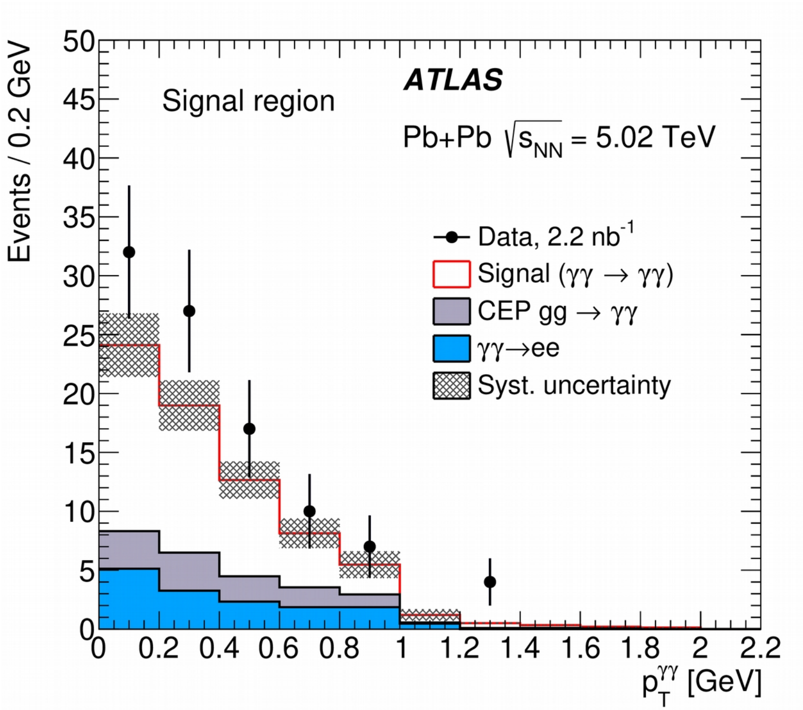


- Data/theory ratio after all corrections is ~1.5±0.3, (dependent on generator choice).
  - Within 2σ of SM.
- Results used to set limits on axion-like particles (ALPs).
- Result give most stringent limits to date on ALP production for ALP masses in the range 6-100 GeV.



Existing constraints from JHEP 12 (2017) 044