

# Diboson production involving photons and aQGCs. ATLAS and CMS

Narei Lorenzo Martinez on behalf of ATLAS and CMS collaborations

# Introduction

- ❖ **Dibosons productions with photon(s) in final state:  $Z\gamma$ ,  $W\gamma$ ,  $\gamma\gamma$**

- ❖ Inclusive production
- ❖ Production in association with EW production of 2 jets -> access to aQGCs
- ❖ Exclusive production (heavy-ions collisions)

- ❖ **Why interesting ?**

- ❖ Major background for several exotic/Higgs analyses
- ❖ Test pQCD at NLO or NNLO
- ❖ Access to neutral QGCs (direct coupling Z to photon)

VVjj final state	ZZ	$Z\gamma$ $\gamma\gamma$	$W^+W^-$ $WZ$	$W^\pm W^\pm$	$W\gamma$
$f_{S,0}, f_{S,1}$	✓		✓	✓	
$f_{M,0}, f_{M,1}, f_{M,6}, f_{M,7}$	✓	✓	✓	✓	✓
$f_{M,2}, f_{M,3}, f_{M,4}, f_{M,5}$	✓	✓	✓		✓
$f_{T,0}, f_{T,1}, f_{T,2}$	✓	✓	✓	✓	✓
$f_{T,5}, f_{T,6}, f_{T,7}$	✓	✓	✓		✓
$f_{T,8}, f_{T,9}$	✓	✓			

- ❖ **What has been done so far, and what will be covered in this talk ?**

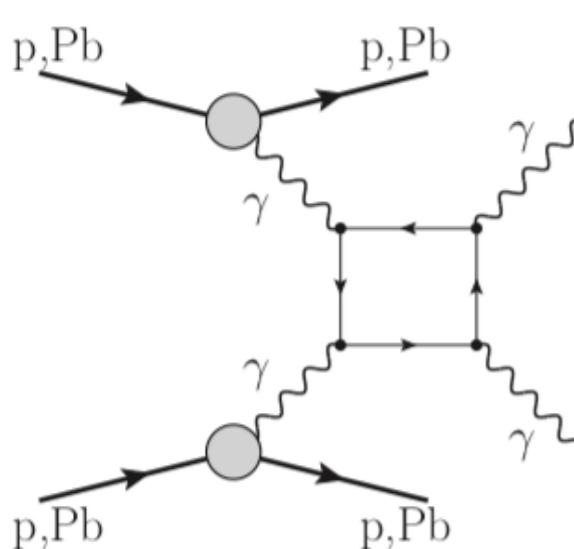
	ATLAS	CMS	
$W\gamma$	7 TeV	7 TeV	
$Z(l+l-) \gamma$	7, 8, <b>13 TeV</b>	7, 8 TeV	
$Z(vv)\gamma$	8, 13 TeV	7, 8 TeV	
$\gamma\gamma$	7, 8 TeV	7 TeV	
EW $W\gamma+2j$	-	8 TeV	
EW $Z\gamma+2j$	8 TeV, <b>13 TeV</b>	8 TeV, <b>13 TeV</b>	
$\gamma\gamma \rightarrow \gamma\gamma$	HI collisions: 2015, <b>2018</b>	HI collisions: 2015	

**Most recent results  
covered in this talk**

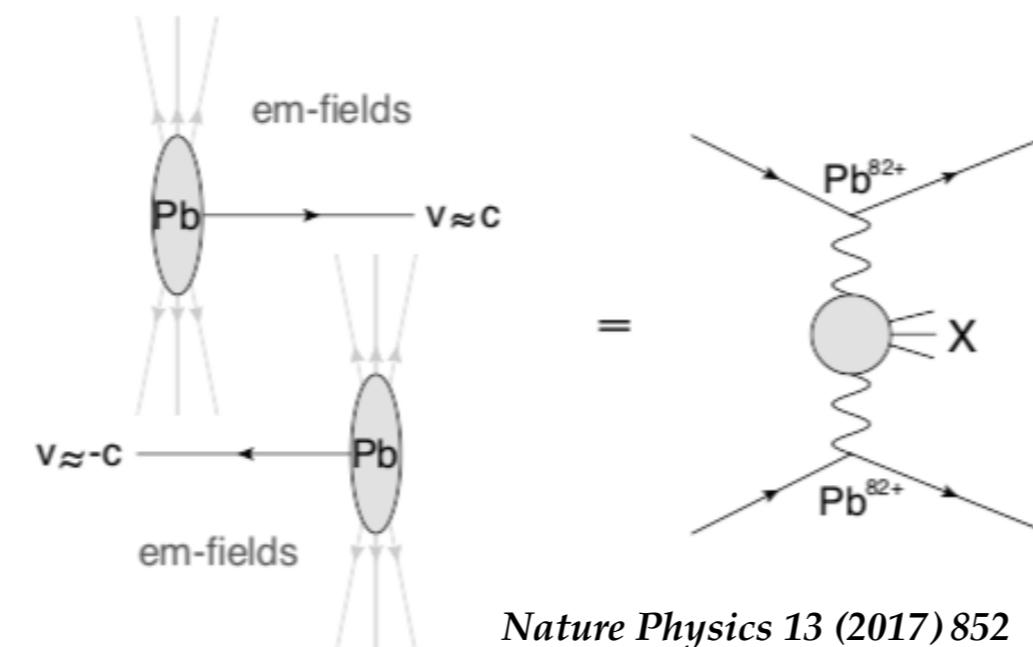
- 1)  $\gamma\gamma \rightarrow \gamma\gamma$  ATLAS
- 2)  $Z(l+l-) \gamma$  ATLAS
- 3) EW  $Z\gamma+2j$  CMS
- 4) EW  $Z\gamma+2j$  ATLAS

# Light-by-light scattering - Introduction

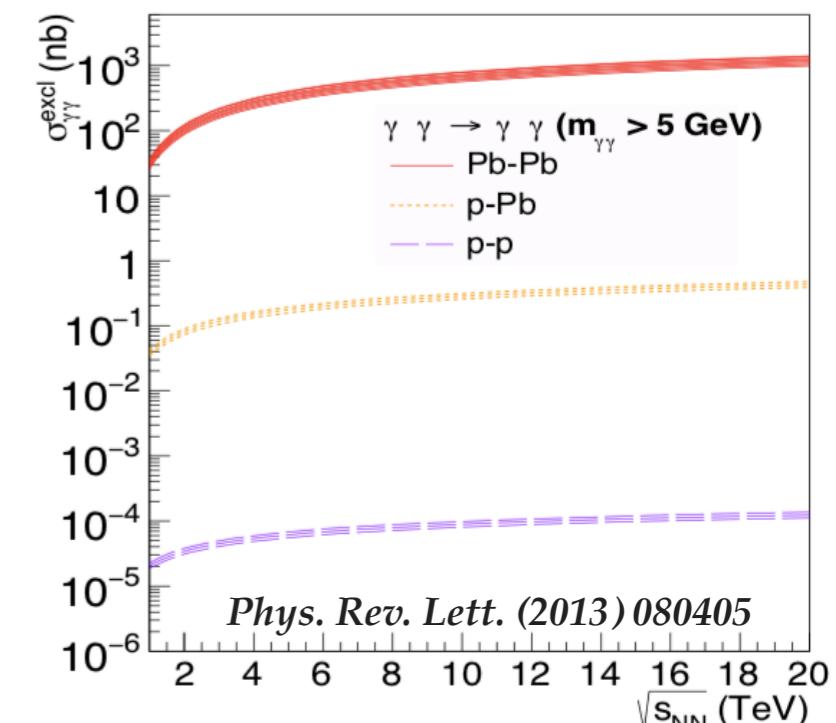
- ❖  $\gamma\gamma \rightarrow \gamma\gamma$ : purely quantum mechanical process, forbidden in classical theory of electrodynamics
- ❖ Sensitive to new physics
- ❖ Can be detected in PbPb collisions in Ultra Peripheral Collisions (impact parameters larger than  $2R_{\text{ions}}$ ) -> **EM interaction much more important than strong interaction**
- ❖ EM fields produced by colliding Pb nuclei = **beam of quasi-real photons** with small virtuality.
- ❖ **Photon flux scales with square of the number of protons** -> XS enhanced in Pb-Pb compared to p-p
- ❖ **Clean topology**: diphoton final-state measured in central detector, and incoming hadrons survive and are scattered at very low angles -> **no additional activity in central detector**



*Phys. Rev. Lett. (2013) 080405*

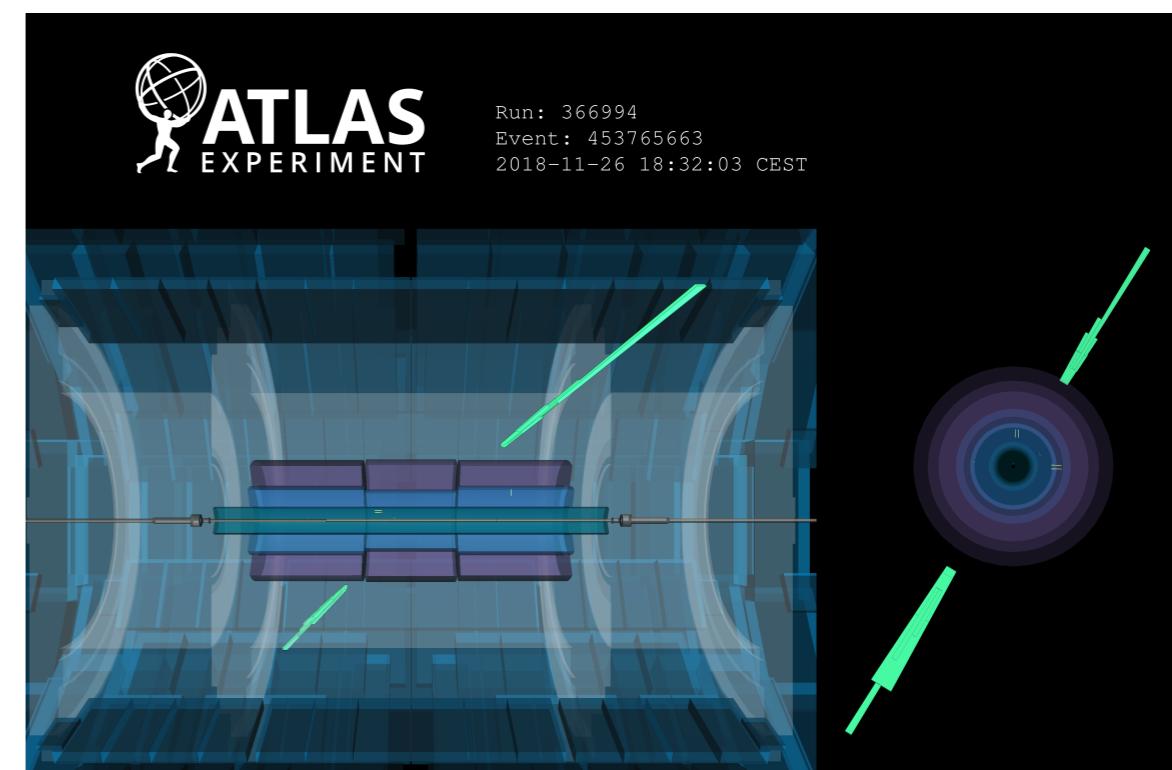
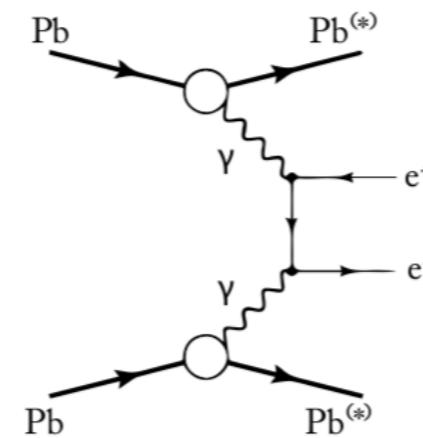
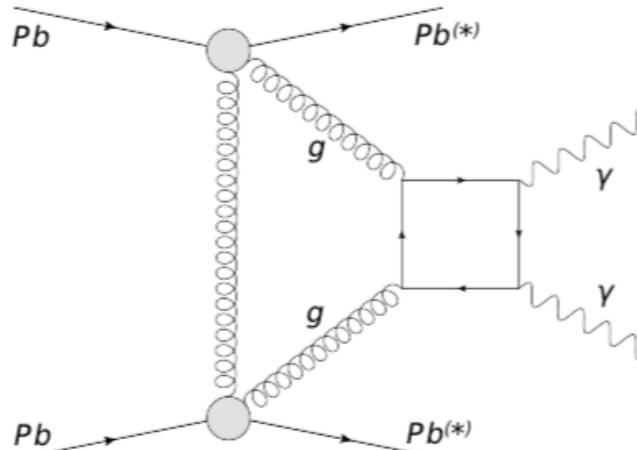


*Nature Physics 13 (2017) 852*



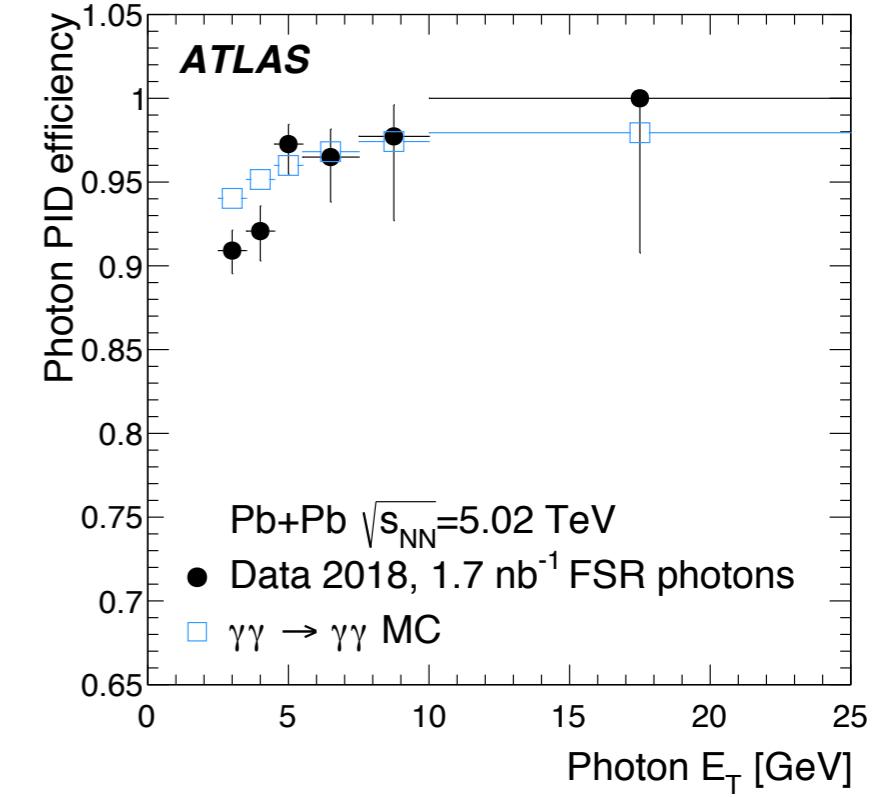
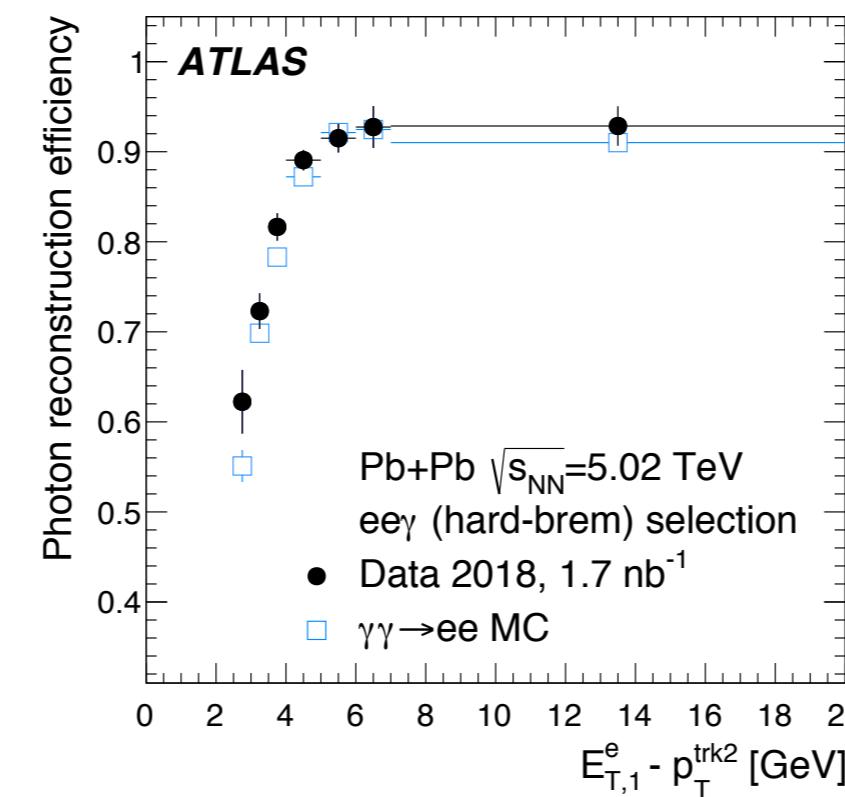
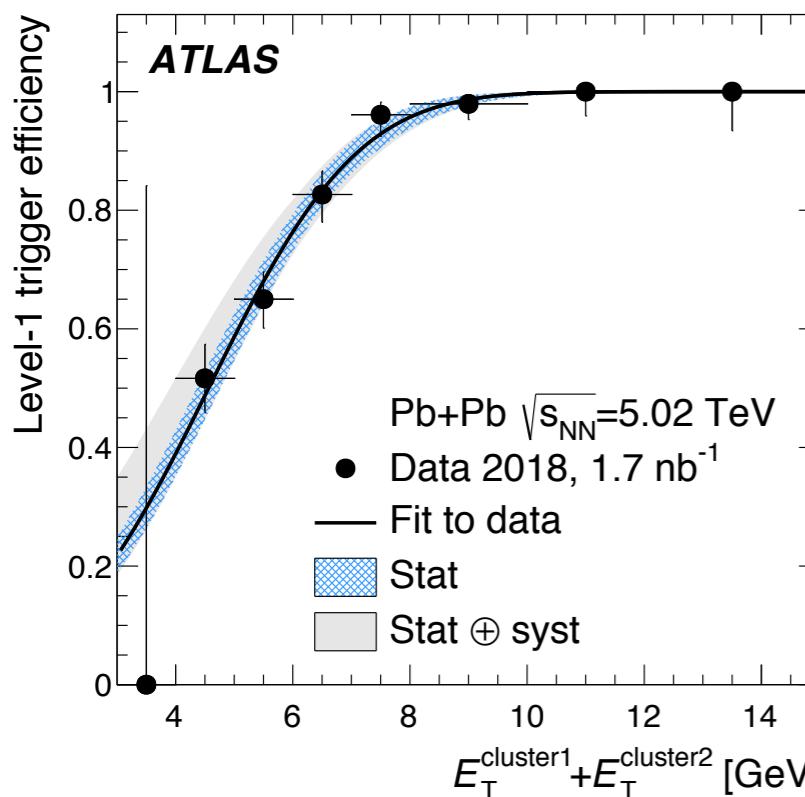
# Observation of light-by-light scattering by ATLAS

- ❖ PbPb collisions,  $\sqrt{s}=5.02$  TeV ,  $1.73 \text{ nb}^{-1}$ , Nov.2018
- ❖ Dedicated trigger: moderate activity in calo and little add. activity in detector. 99.1% efficient
  - ❖ Level-1: 1 or 2 EM clusters
  - ❖ HLT: total FCal  $E_T$  consistent with noise (FCal veto) and number of hits in ID<15
- ❖ Signal simulation: SuperChic 3.0 MC.
  - ❖ Theory uncertainties mainly due to limited knowledge of the nuclear form factors and initial photon fluxes -> 10% in fiducial phase space. Higher-order corrections: 1-3%
- ❖ Final state clean, but some backgrounds expected:
  - ❖ central exclusive production CEP (via a quark loop)
  - ❖  $\gamma\gamma \rightarrow ee$  (e misidentified as photons)
  - ❖ fake photons (from cosmic ray muons)



# Signal events selection

- ❖  $E_T\gamma > 3 \text{ GeV}$ ,  $|\eta| < 2.37$ , exclude crack, photon good ID required,  $m_{\gamma\gamma} > 6 \text{ GeV}$ .
  - ❖ To reduce CEP bkg:  $A\phi = (1 - |\Delta\phi_{\gamma\gamma}|/\pi) < 0.01$  (reduced acoplanarity): 86% efficiency for the signal.
    - ❖  $A\phi$  broader for CEP (gluons recoil against the Pb nucleus, which then dissociates) than for  $\gamma\gamma \rightarrow \gamma\gamma$ .
  - ❖ To reduce  $\gamma\gamma \rightarrow ee$ : remove events that have tracks with  $p_T > 100 \text{ MeV}$  and  $>= 6$  hits in ID + require no pixel tracks matched to a photon candidate within  $\Delta\eta < 0.5$ 
    - ❖ reduce bkg by factor of  $10^4$  while keeping 93% efficiency for signal
  - ❖ To reduce other fake bkg (cosmic rays muons):  $p_T\gamma\gamma < 1$  (2) GeV for  $m_{\gamma\gamma} < (>) 12 \text{ GeV}$
- ❖  $\gamma\gamma \rightarrow ee$  events also used to calibrate data
  - ❖ Trigger efficiency: 60% at 5 GeV, 100% at 10 GeV
  - ❖ Photon reco efficiency goes from 60% at  $\sim 3$  GeV to 90% at 6 GeV



# Backgrounds

---

- ❖ **CEP: SuperChic 3.0 MC but large theory uncertainty (~100%) -> normalisation taken from CR in data.**
  - ❖ CR = inversion of  $A\phi$  cut ( $>0.01$ ).
  - ❖ Alternative SuperChip MC sample with no absorptive effects (no secondary particle) to estimate MC modelling of  $A\phi$
- ❖  **$\gamma\gamma \rightarrow ee$ , estimate from data-driven method (checks with Starlight 2.0)**
  - ❖ 2 CRs defined: 2 photons + 1 or 2 associated pixels tracks -> extrapolation to SR
- ❖ **Cosmic ray muons: estimated from data-driven method**
  - ❖ CR: at least 1 track in muon spectrometer
  - ❖ After  $p_T^{\gamma\gamma}$  cut, bkg negligible
- ❖ **Other backgrounds:**
  - ❖ **Two-photon production of quark–antiquark pairs:** Herwig ++ 2.7.1 -> negligible.
  - ❖  **$\gamma\gamma \rightarrow ee\gamma\gamma$ :** MadGraph5\_aMC@NLO + PbPb photon flux from Starlight -> negligible

$\gamma\gamma \rightarrow \gamma\gamma$	$30 \pm 4$ (syst)
CEP	$4 \pm 1$ (stat)
$\gamma\gamma \rightarrow ee$	$7 \pm 1$ (stat) $\pm 3$ (syst)
Data	59

*Event yield in signal region*

# Sensitivity and cross-section

- ❖ Sensitivity calculated in region  $A\phi < 0.005$

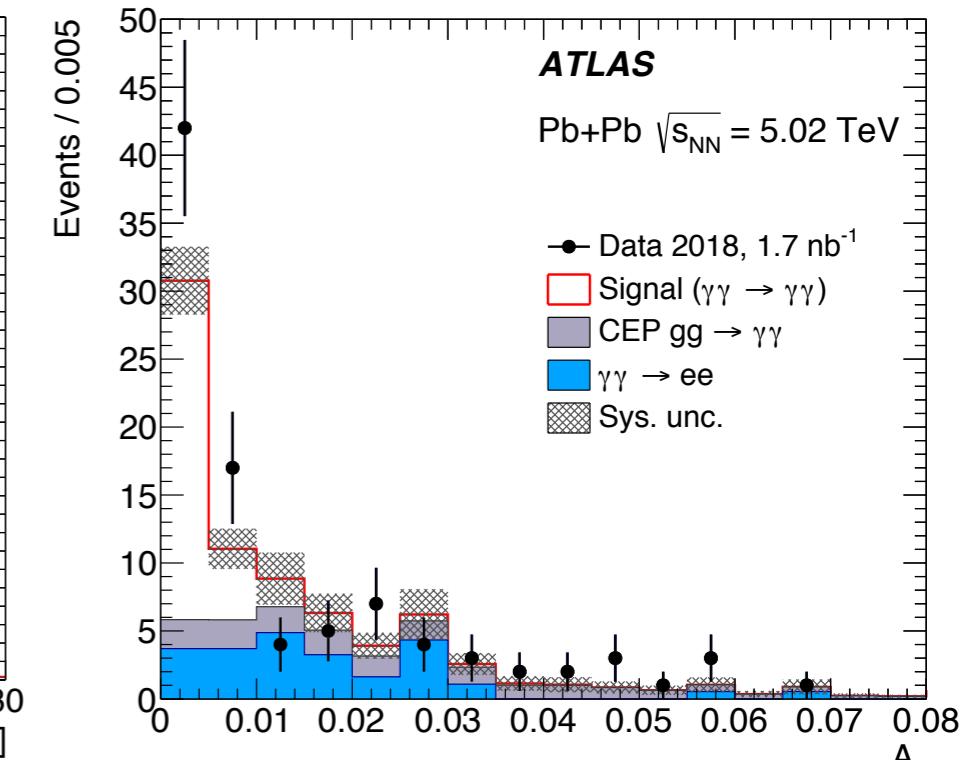
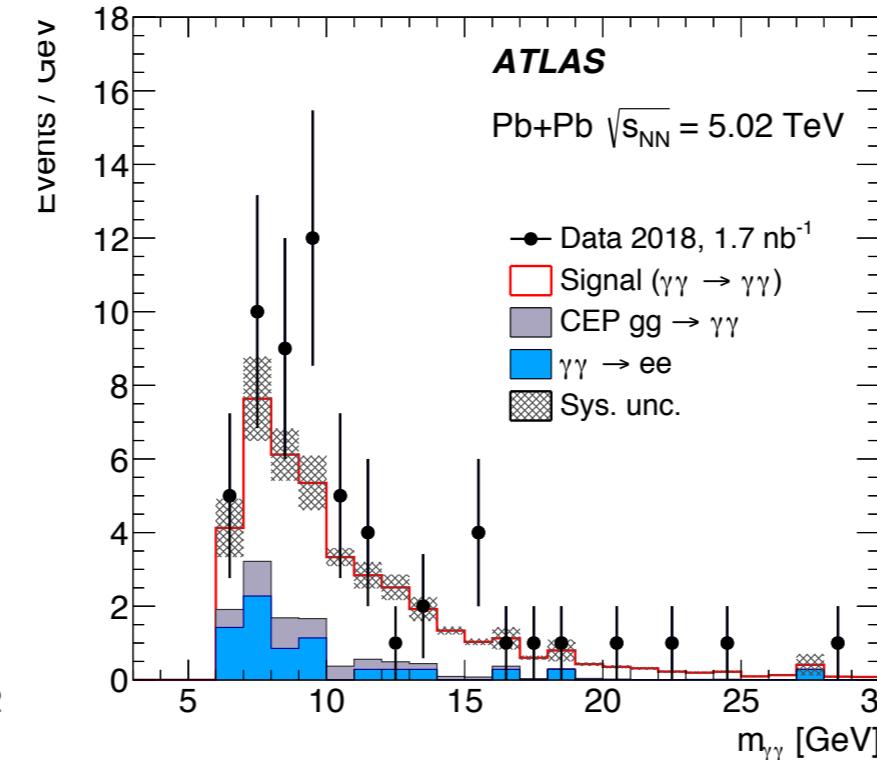
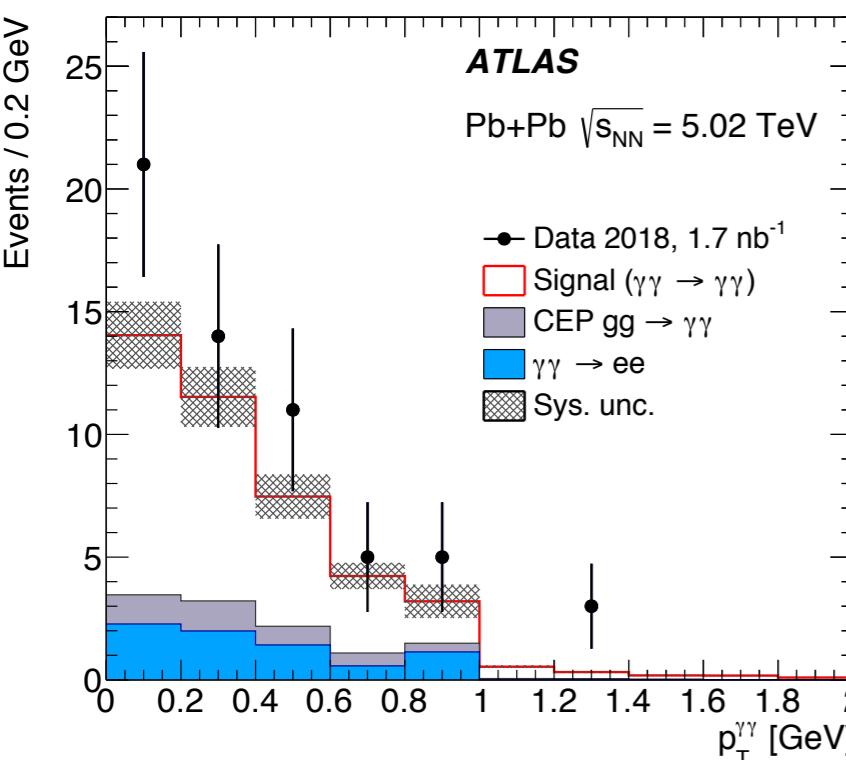
- ❖ 42 events observed,  $25 \pm 3$  (syst.) signal and  $6 \pm 1$  (stat.)  $\pm 2$  (syst.) bkg
- ❖  $8.2 (6.2) \sigma$  observed (expected)

- ❖ Cross-section  $\gamma\gamma \rightarrow \gamma\gamma$  measured in fiducial region close to SR selection

- ❖  $\sigma_{\text{fid}} = (N_{\text{data}} - N_{\text{bkg}}) / CxL$ .
- ❖ Overall uncertainty dominated by unc. on photon reco efficiency (4%), and trigger efficiency (2%)

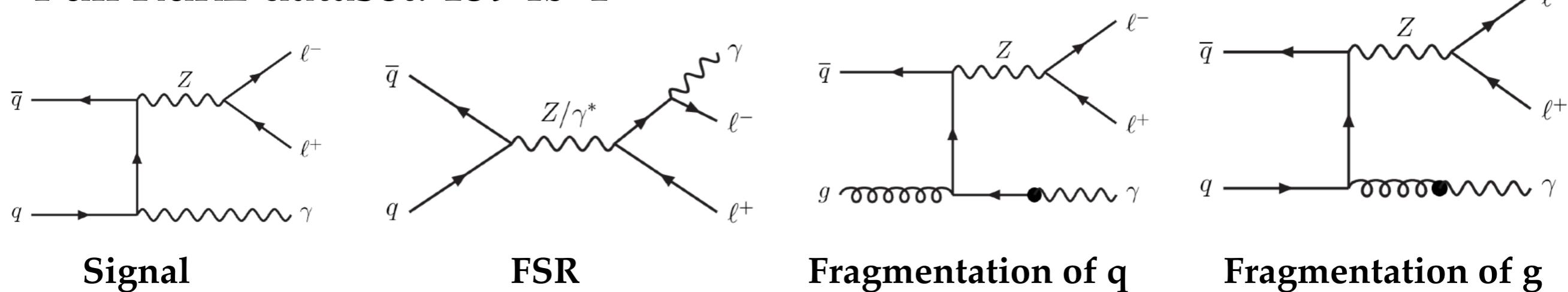
- ❖  $\sigma_{\text{fid}} = 78 \pm 13$  (stat)  $\pm 7$  (syst)  $\pm 3$  (lumi) nb =  $78 \pm 15$  nb

- ❖ prediction:  $50 \pm 5$  nb from SuperChic 3.0 MC



# Z $\gamma$ inclusive ATLAS @ 13 TeV

- Measurement of differential cross-section, Z(l+l-) $\gamma$ ,
- Full Run2 dataset: 139 fb-1



- Signal and main backgrounds MC samples used:

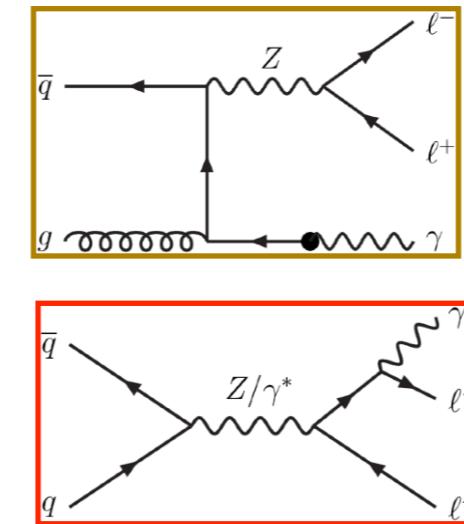
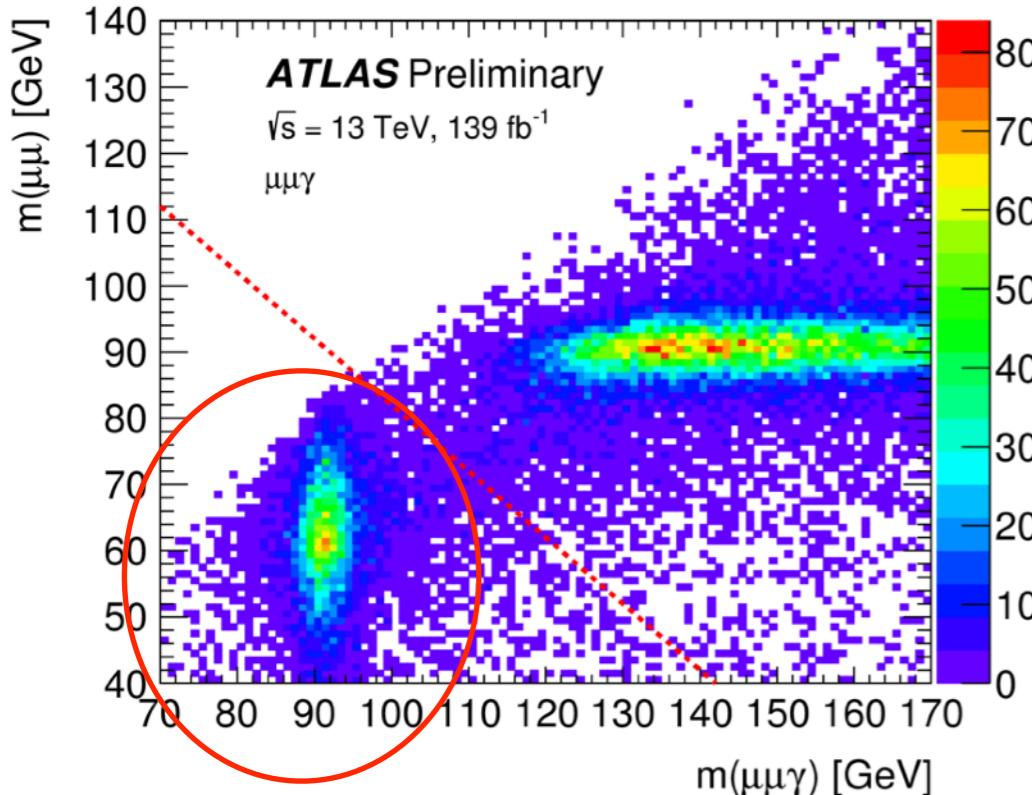
Process	Generator	Order	PDF Set	PS/UE/MPI
$Z\gamma$	SHERPA 2.2.4	LO	NNPDF3.0 NNLO	SHERPA 2.2.4
$Z\gamma$	MADGRAPH5_aMC@NLO 2.3.3	NLO	NNPDF3.0 NLO	PYTHIA 8.212
$Z + \text{jets}$	POWHEG-BOX	NLO	CT10 NLO	PYTHIA 8.186
$t\bar{t}\gamma$	MADGRAPH5_aMC@NLO 2.3.3	LO	NNPDF2.3 LO	PYTHIA 8.212
$WZ, ZZ$	SHERPA 2.2.2	NLO	NNPDF3.0 NNLO	SHERPA 2.2.2
$WW\gamma$	SHERPA 2.2.5	NLO	NNPDF3.0 NNLO	SHERPA 2.2.5
$\tau\tau\gamma$	SHERPA 2.2.4	LO	NNPDF3.0 NNLO	SHERPA 2.2.4
$H \rightarrow Z\gamma$	POWHEG-BOX	NLO	PDF4LHC15 NNLO	PYTHIA 8.186

Main bkg, DD  
method used

# Selection

- **Lowest unprescaled single lepton trigger** : 24 GeV (e), 20 GeV (muon) in 2015, 26 GeV for e /  $\mu$  + tighter iso / ID . Trigger efficiency 99%

	Photons	Electrons	Muons
Kinematics:	$E_T > 30 \text{ GeV}$ $ \eta  < 2.37$ excl. $1.37 <  \eta  < 1.52$	$p_T > 30, 25 \text{ GeV}$ $ \eta  < 2.47$ excl. $1.37 <  \eta  < 1.52$	$p_T > 30, 25 \text{ GeV}$ $ \eta  < 2.5$
Identification:	Tight [53]	Medium [54]	Medium [52]
Isolation:	FixedCutLoose [53] $\Delta R(\ell, \gamma) > 0.4$	FCLoose [54] $\Delta R(\mu, e) > 0.2$	FCLoose_FixedRad [52]
Event selection:		$m(\ell\ell) > 40 \text{ GeV}$ , $m(\ell\ell) + m(\ell\ell\gamma) > 182 \text{ GeV}$	



*Isolation reduce fragmentation diagrams*

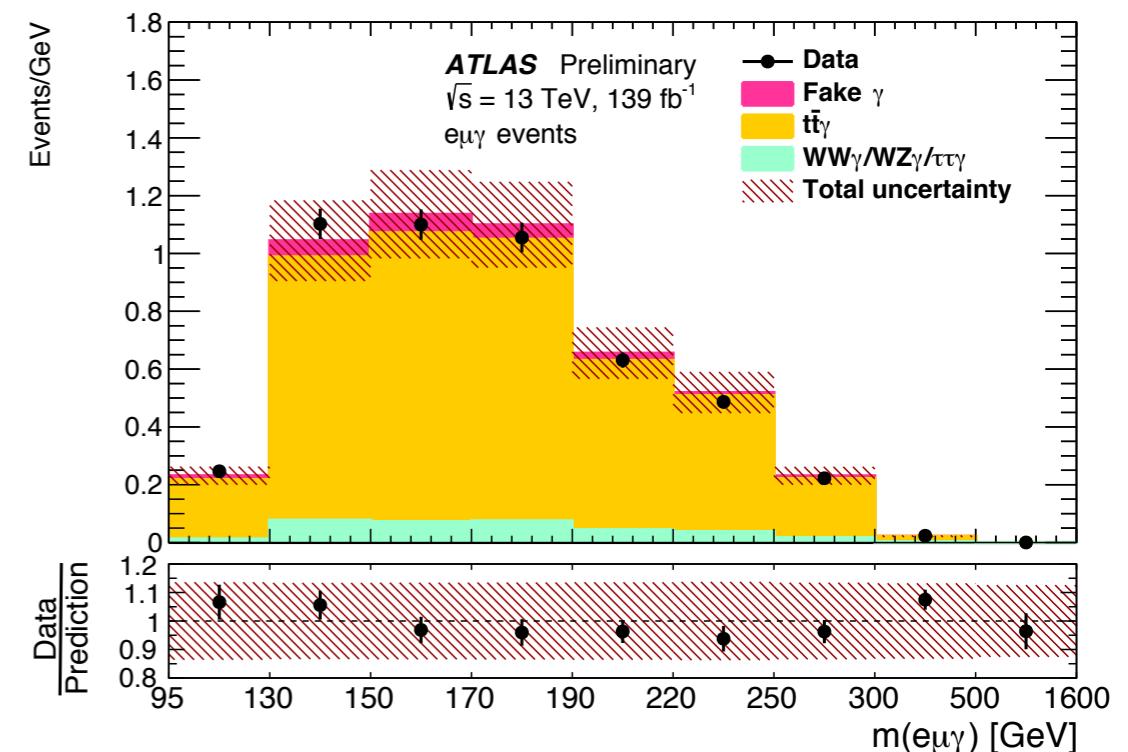
*mll+mllgamma cut reduce FSR diagrams*

- **Total of 41343 ee $\gamma$  events and 54413  $\mu\mu\gamma$  events**

# Main backgrounds

---

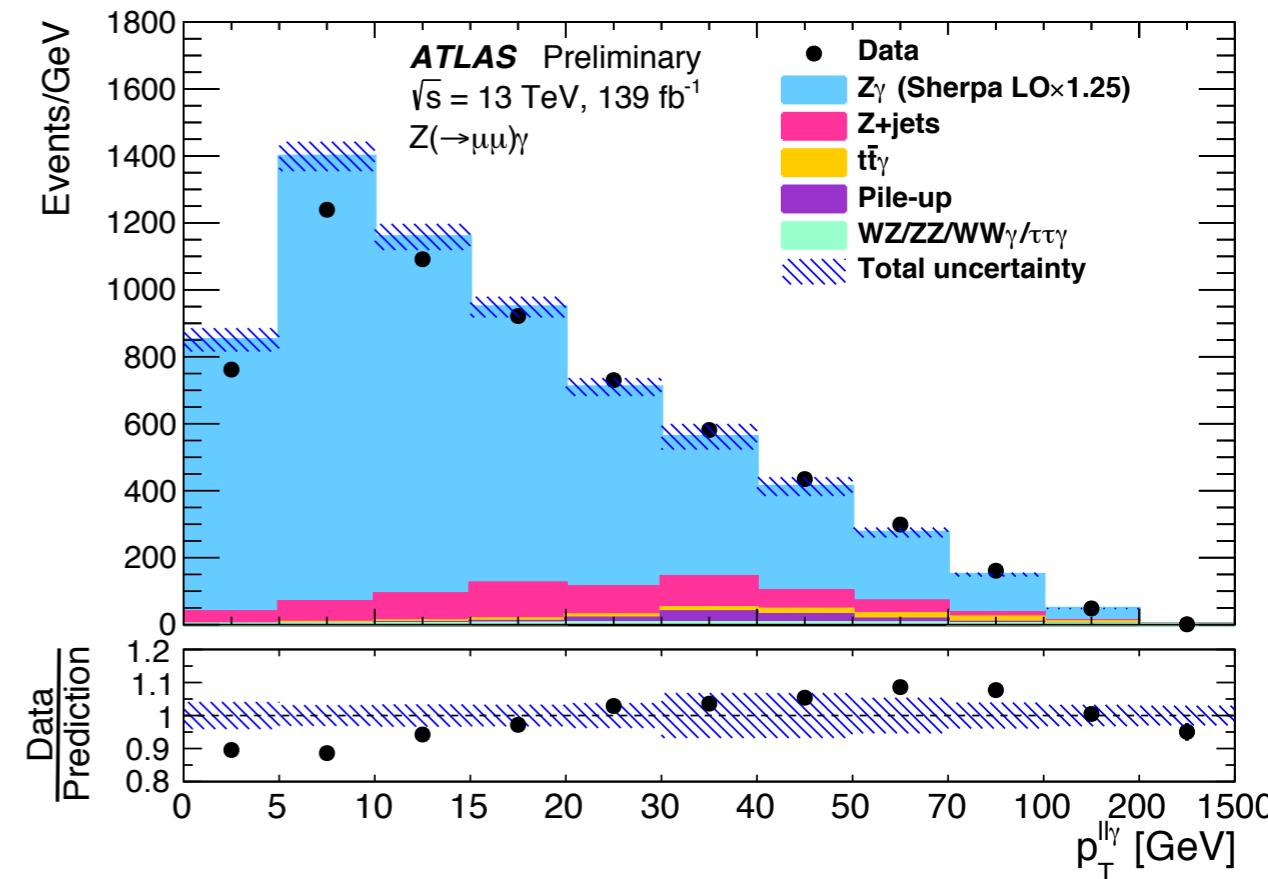
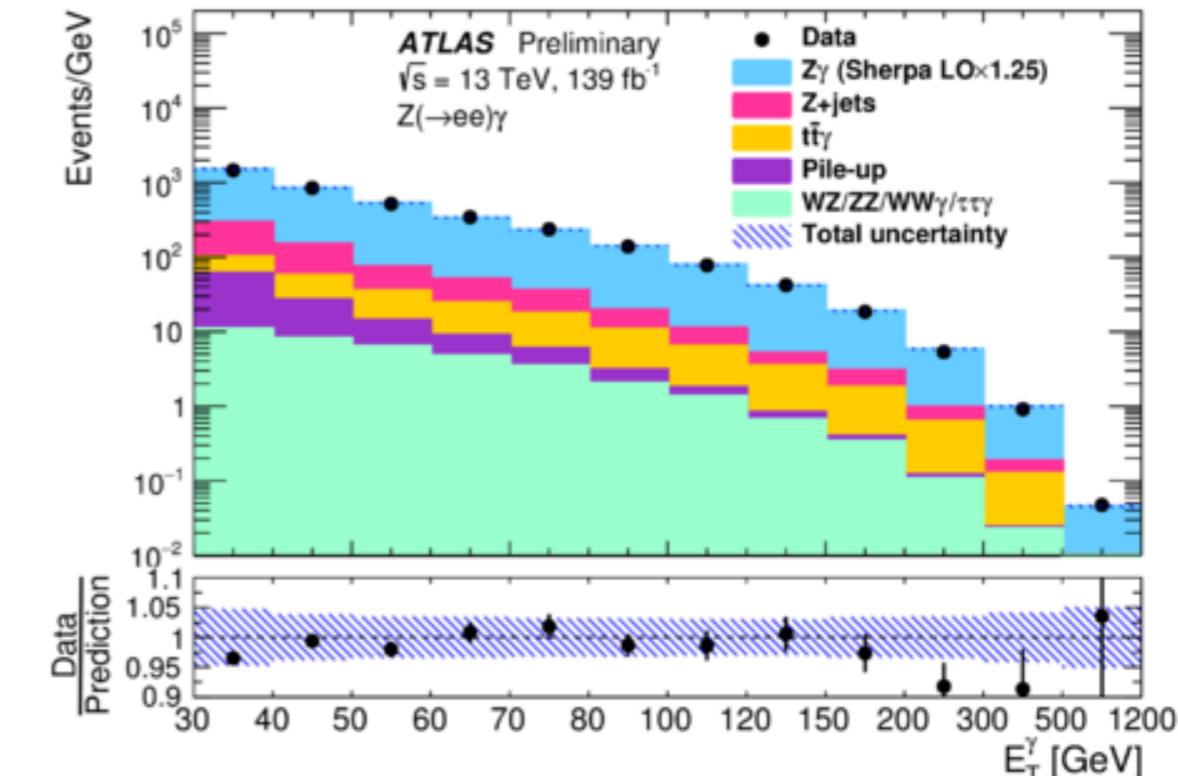
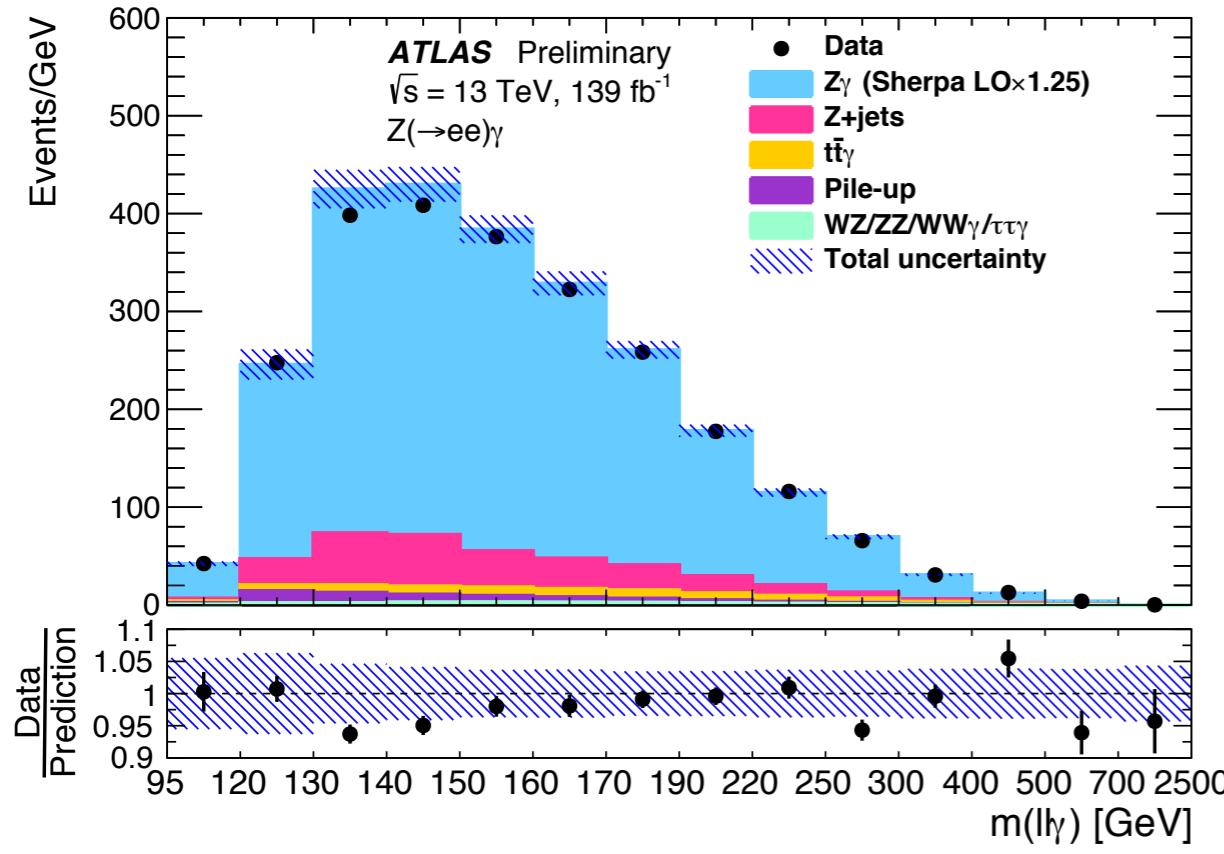
- ❖ **Z+jet: shape and norm estimated using a 2D sideband method, based on isolation and ID of photon**
  - ❖ Contribution from  $Z\gamma$  and other non(Z+jet) events subtracted from MC
  - ❖ **Correlation ID/Iso :**  $R = 1.33 +/- 0.06$  (MC stat)
  - ❖ **R value consistent in bins of  $E_T\gamma$  and  $\eta$  within 20% -> assigned as systematic**
- ❖ **Pileup background**
  - ❖ Lepton pair combined with a photon from a different pp interaction
  - ❖ **Fraction of bkg in SR estimated using longitudinal separation  $\Delta Z = Z_\gamma - Z_{\text{vertex}}$** 
    - ❖ broader for pileup bkg than for signal or other bkg in same pp interaction. Use of pixels converted photons
  - ❖  $\text{Fraction}_{\text{PU}} = 2.1 +/- 2.1\%$  (conservative unc.)
- ❖ **Other backgrounds:**
  - ❖  $t\bar{t}\gamma$  (23% of total bkg), norm factor of 1.44 (NLO), relative unc. of 15%
    - ❖ **e $\mu\gamma$  sample dominated at 90% by ttbar $\gamma$  events**
  - ❖ WZ (4%), WW $\gamma$  (<2%), conservative unc. of 30%



# Event yield and control distributions

	$e^+e^-\gamma$	$\mu^+\mu^-\gamma$
$N_{\text{obs}}$	41343	54413
$N_{Z + \text{jets}}$	$4130 \pm 440$	$5470 \pm 580$
$N_{\text{PU}}$	$870 \pm 870$	$1140 \pm 1140$
$N_{t\bar{t}\gamma}$	$1650 \pm 250$	$1980 \pm 300$
$N_{WZ}$	$254 \pm 76$	$199 \pm 60$
$N_{ZZ}$	$64 \pm 19$	$102 \pm 31$
$N_{WW\gamma}$	$92 \pm 28$	$112 \pm 34$
$N_{\tau\tau\gamma}$	$46 \pm 15$	$39 \pm 12$
$N_{\text{obs}} - N_{\text{bkg}}$	$34240 \pm 1000$	$45370 \pm 1300$

Normalisation factor of 1.25 applied to signal (Sherpa LO)



# Cross-section

- ❖ **Fiducial phase space:**

- ❖ similar to signal region
- ❖ Photon isolation at particle level

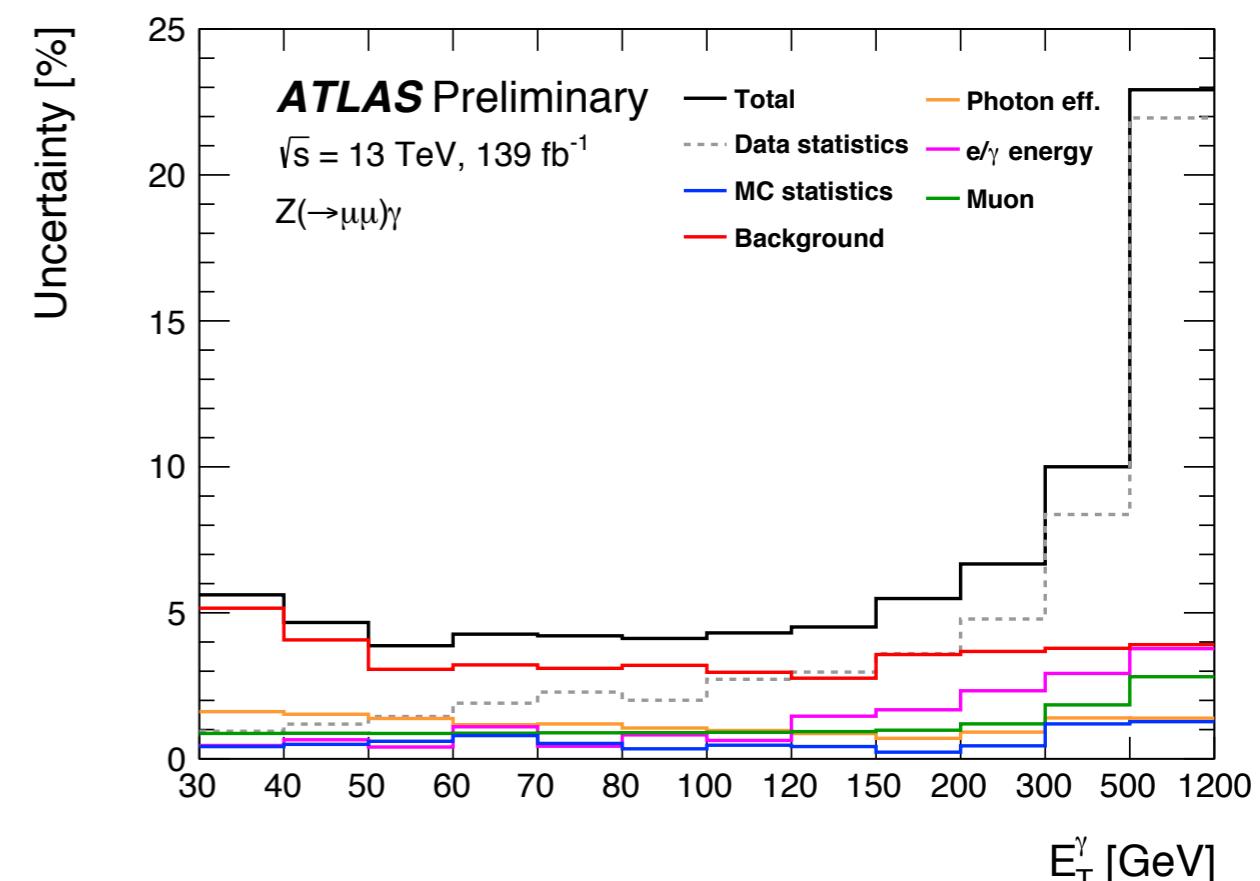
- ❖ **Differential XS for 4 variables:  $E_T^\gamma$ ,  $\eta_\gamma$ ,  $m_{ll\gamma}$ ,  $p_T^{ll\gamma}$ ,**

- ❖ Electron/muon channels combined using a  $\chi^2$  minimisation method
- ❖ Unfolding: iterative Bayesian method, 2 iterations
- ❖ Stat uncertainty and MC stat shape obtained by generating pseudo-exp.

- ❖ **Uncertainties on XS:**

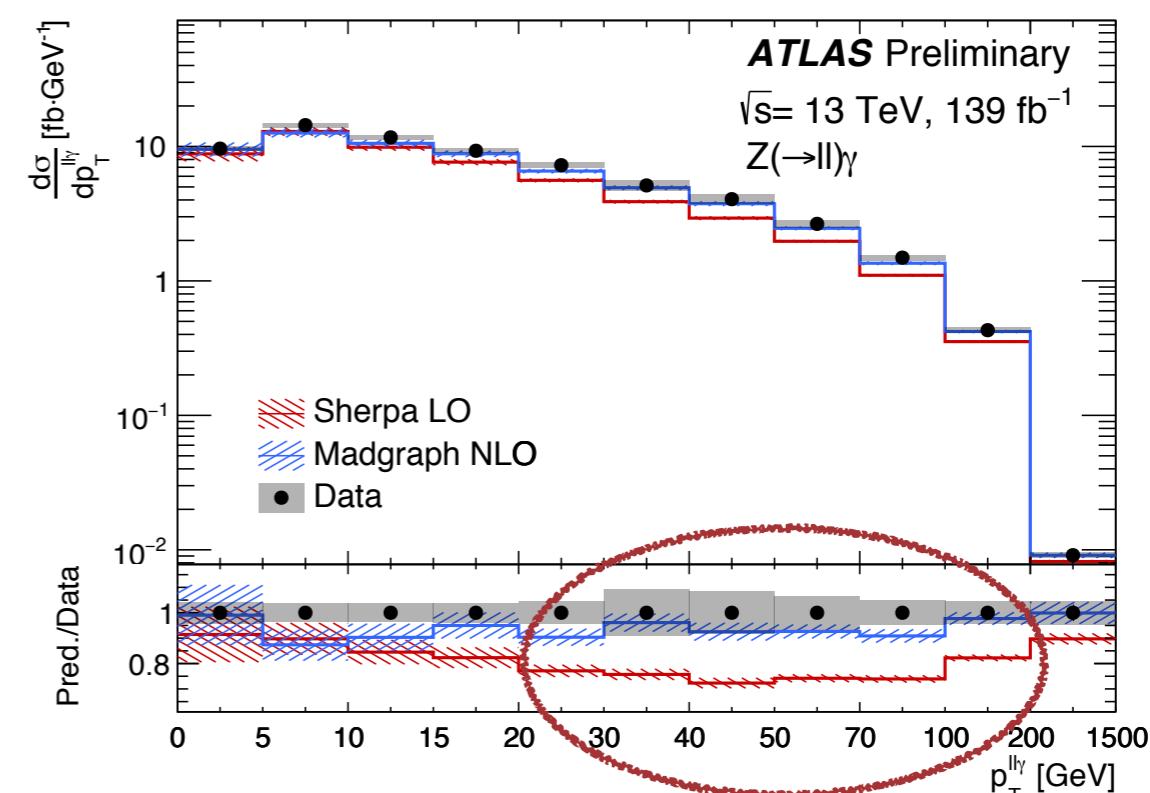
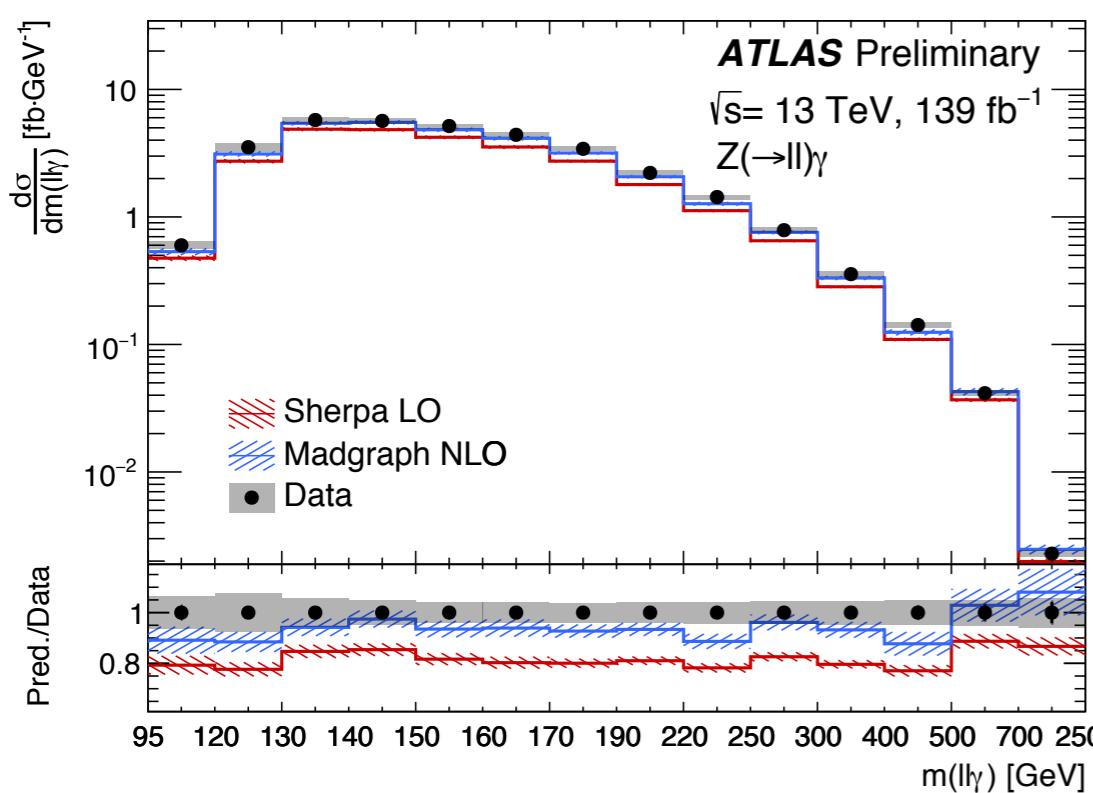
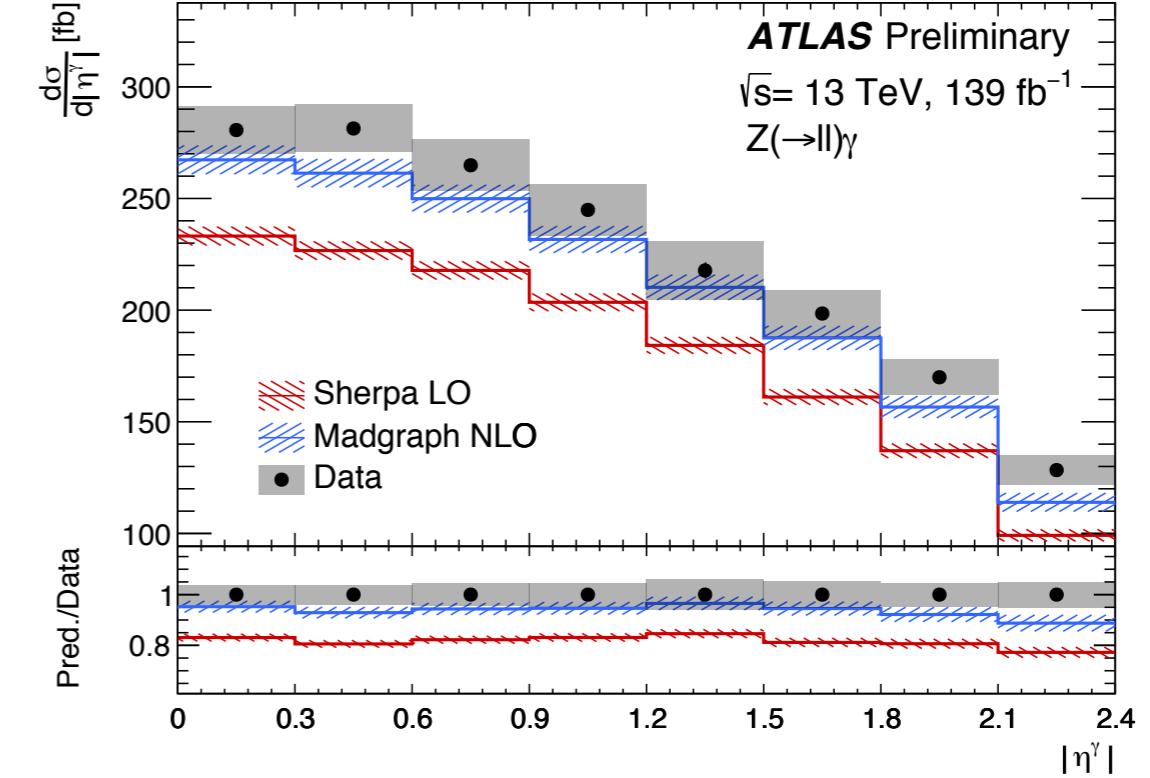
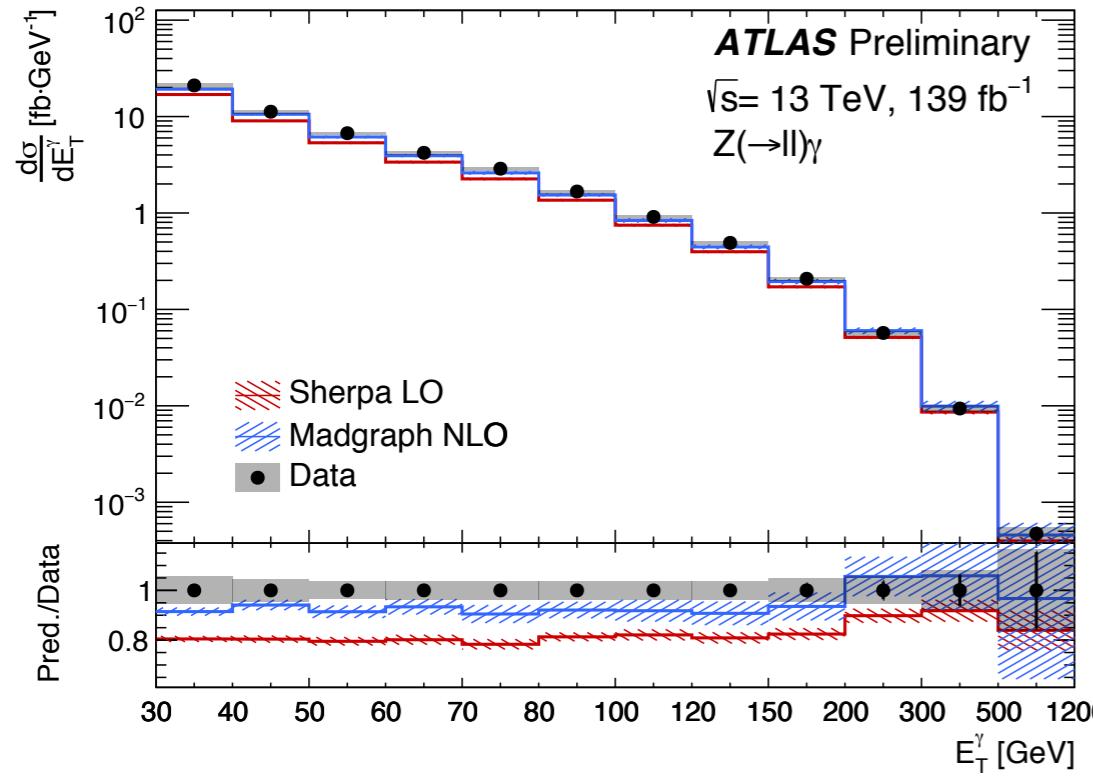
- ❖ response matrix (trigger, reco and particle ID and iso efficiencies, energy and momentum scales and resolution)
- ❖ **background -> main one**
- ❖ Luminosity

Photons	Electrons/Muons
$E_T^\gamma > 30 \text{ GeV}$	$p_T^\ell > 30, 25 \text{ GeV}$
$ \eta^\gamma  < 2.37$	$ \eta^\ell  < 2.47$
$E_T^{\text{cone}0.2}/E_T^\gamma < 0.07$	dressed leptons
$\Delta R(\ell, \gamma) > 0.4$	
	Event selection
	$m(\ell\ell) > 40 \text{ GeV}$
	$m(\ell\ell) + m(\ell\ell\gamma) > 182 \text{ GeV}$



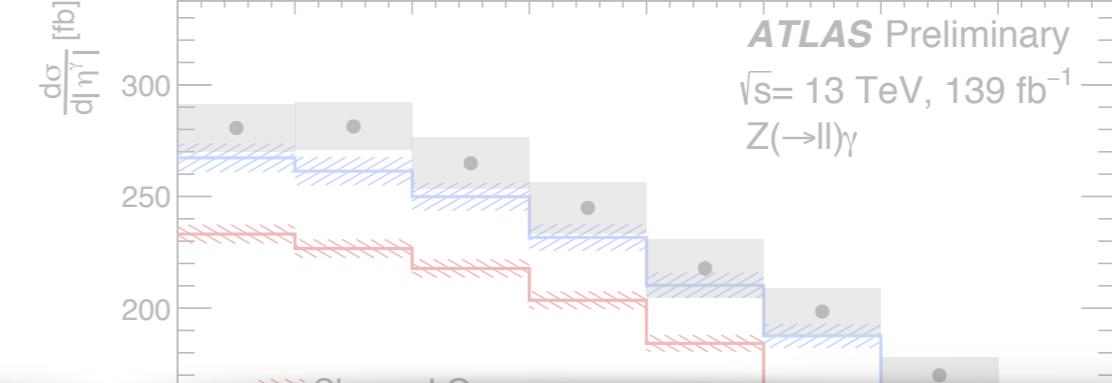
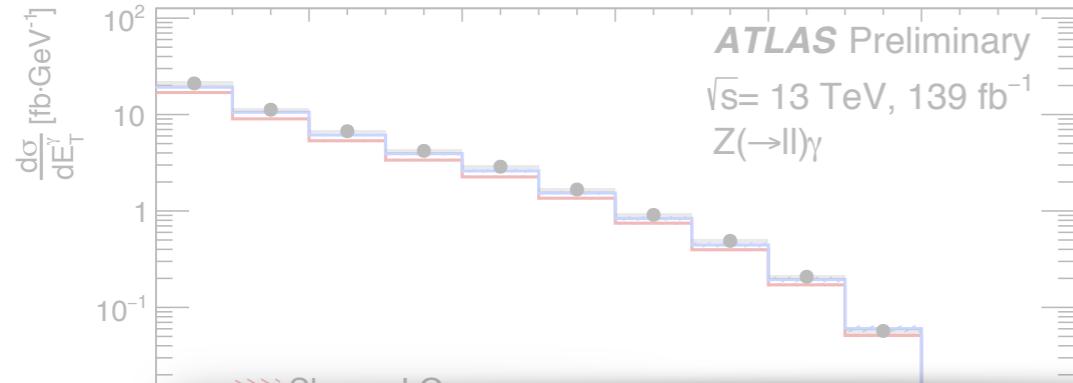
# Results: comparison with Sherpa (LO) and MadGraph (NLO)

**Small contribution from EW Z $\gamma$ +2j considered in signal, using MadGraph 2.3.3**

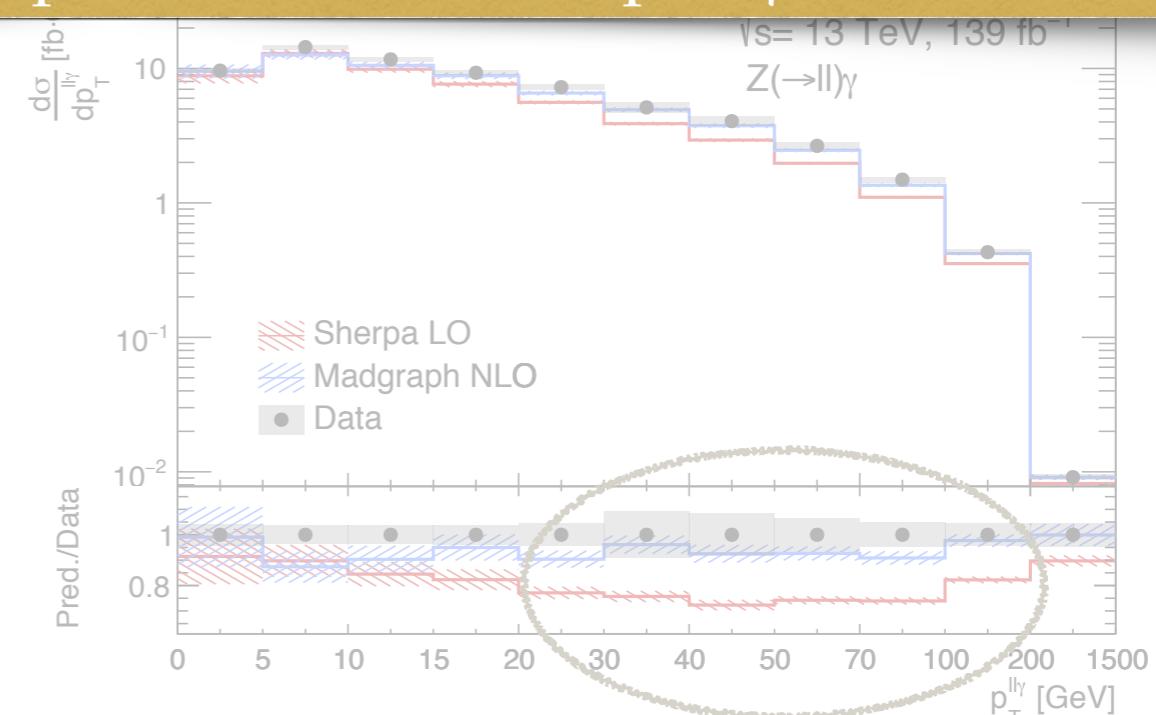
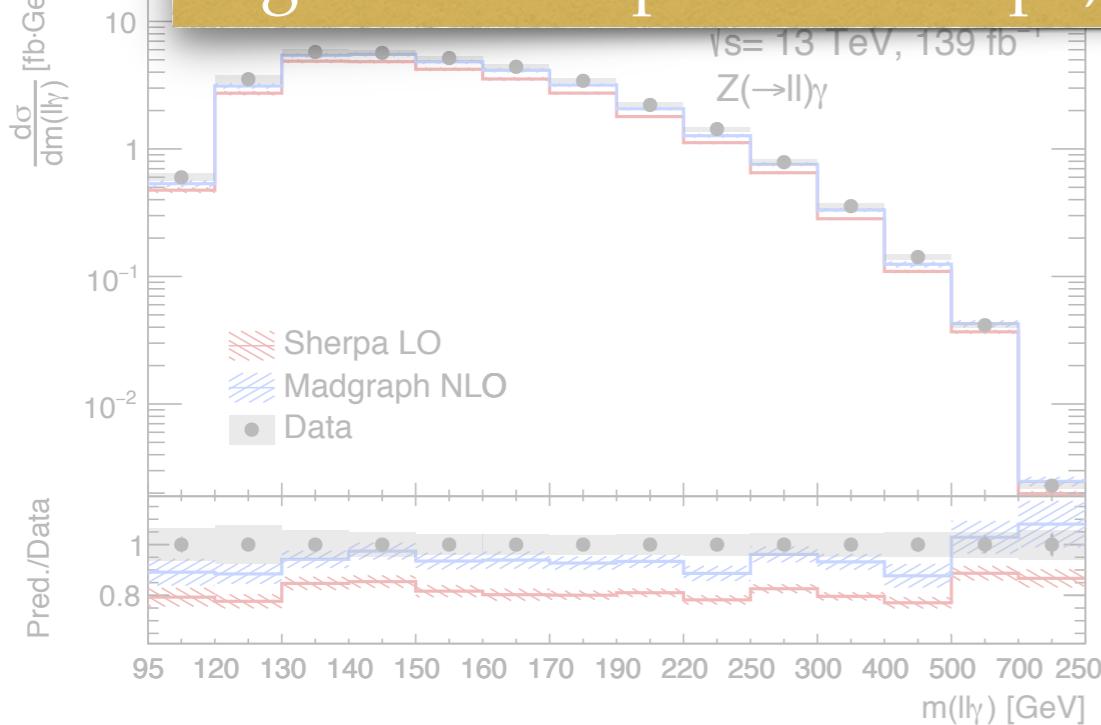


# Results: comparison with Sherpa (LO) and MadGraph (NLO)

**Small contribution from EW Z $\gamma$ +2j considered in signal, using MadGraph 2.3.3**

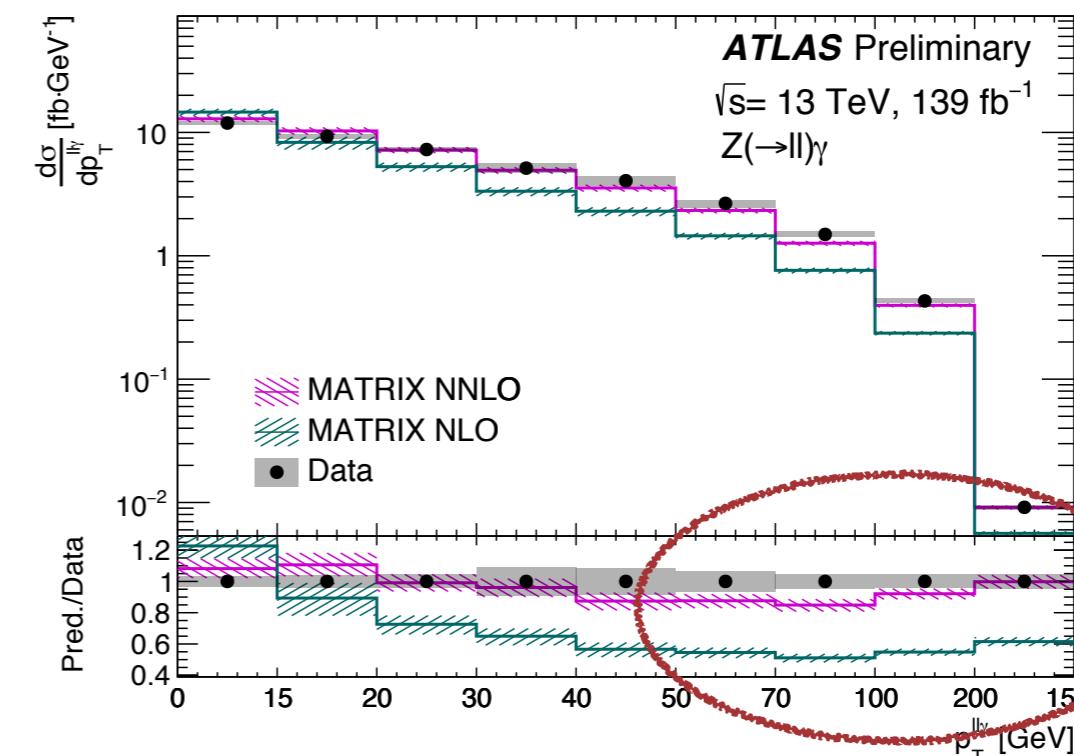
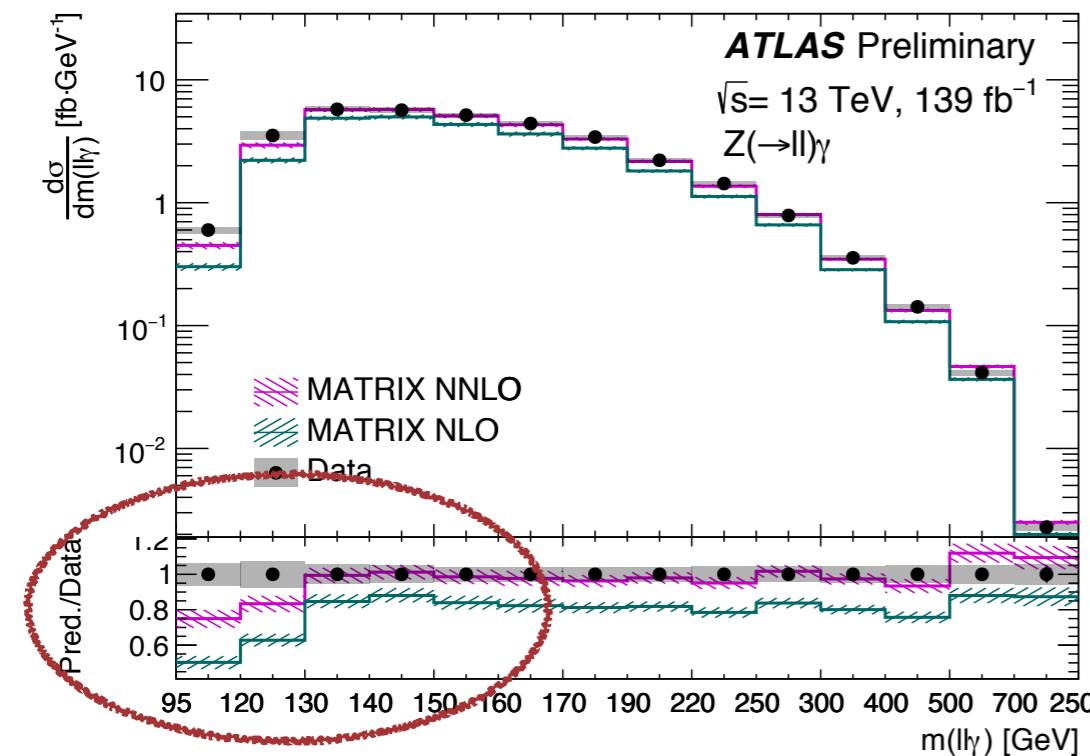
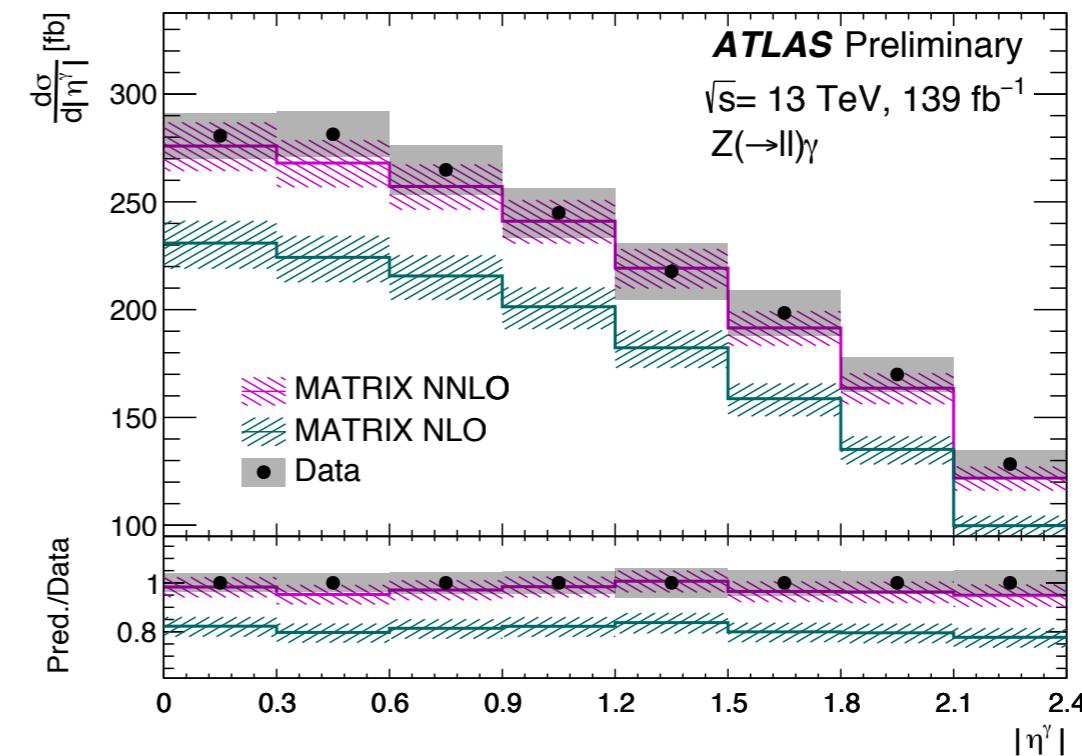
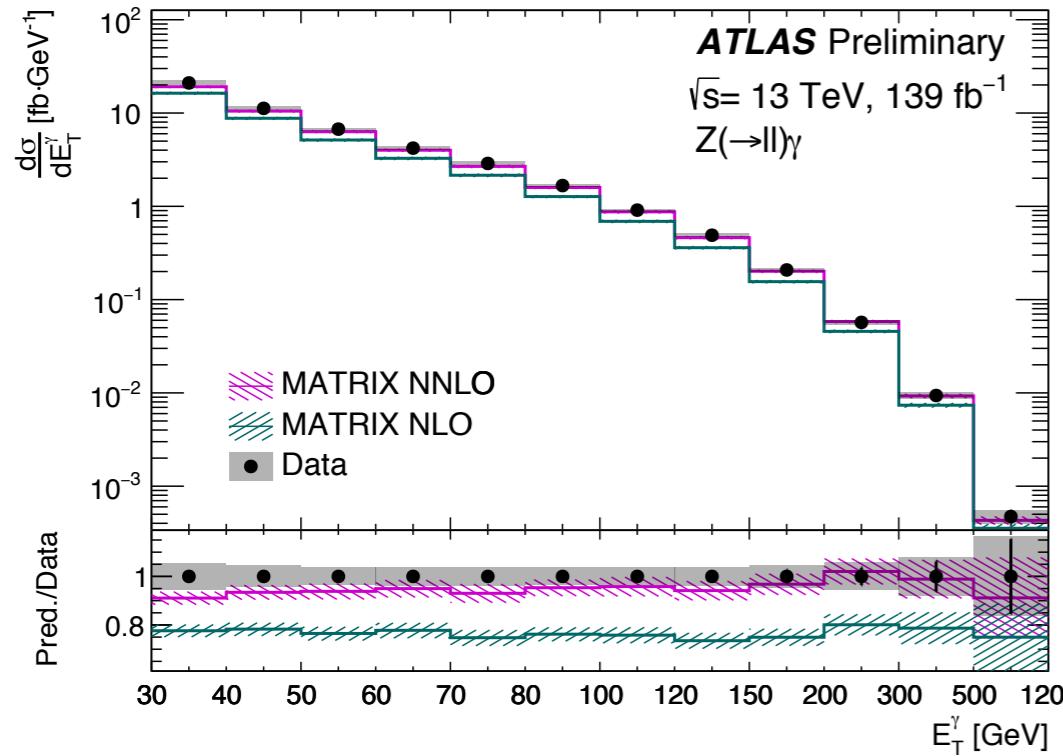


- ✿ For  $E\gamma$ , **overall relative precision of 5%** (20% in the highest bin)
- ✿ MadGraph (NLO) reproduces normalisation and shape well (only slight underestimation of overall norm)
- ✿ Prediction from Sherpa (LO) underestimate XS by 20-30%, generally good description of shape, except of intermediate  $pT ll\gamma$



# Results: comparison with Parton-level Matrix (NLO and NNLO)

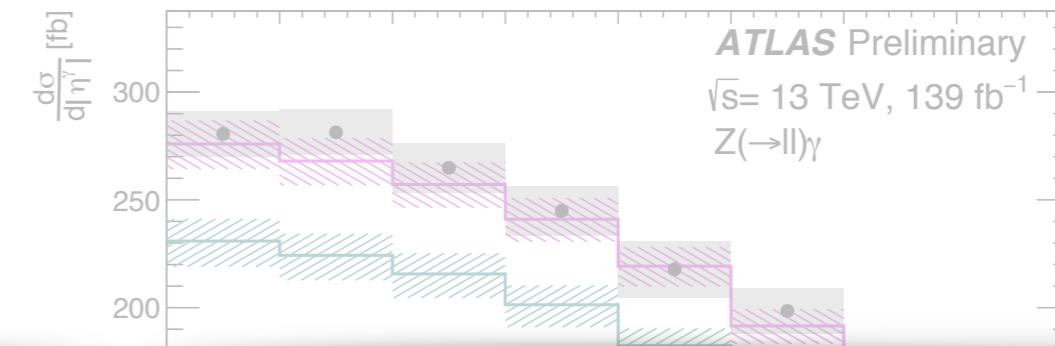
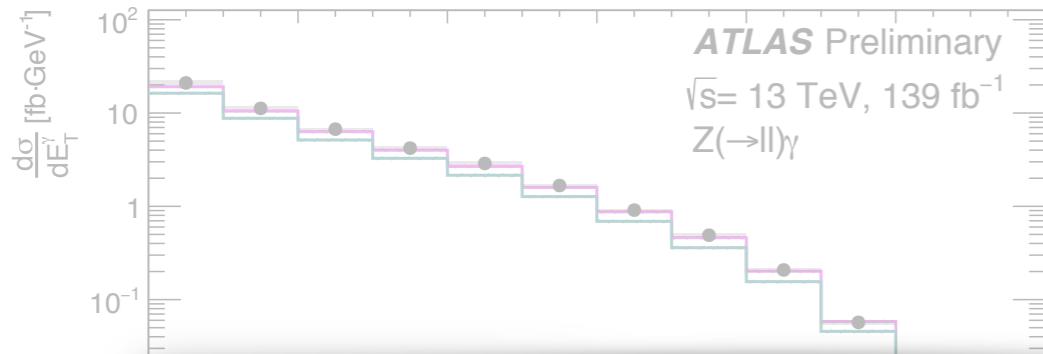
**Small contribution from EW Z $\gamma$ +2j considered in signal, using MadGraph 2.3.3**



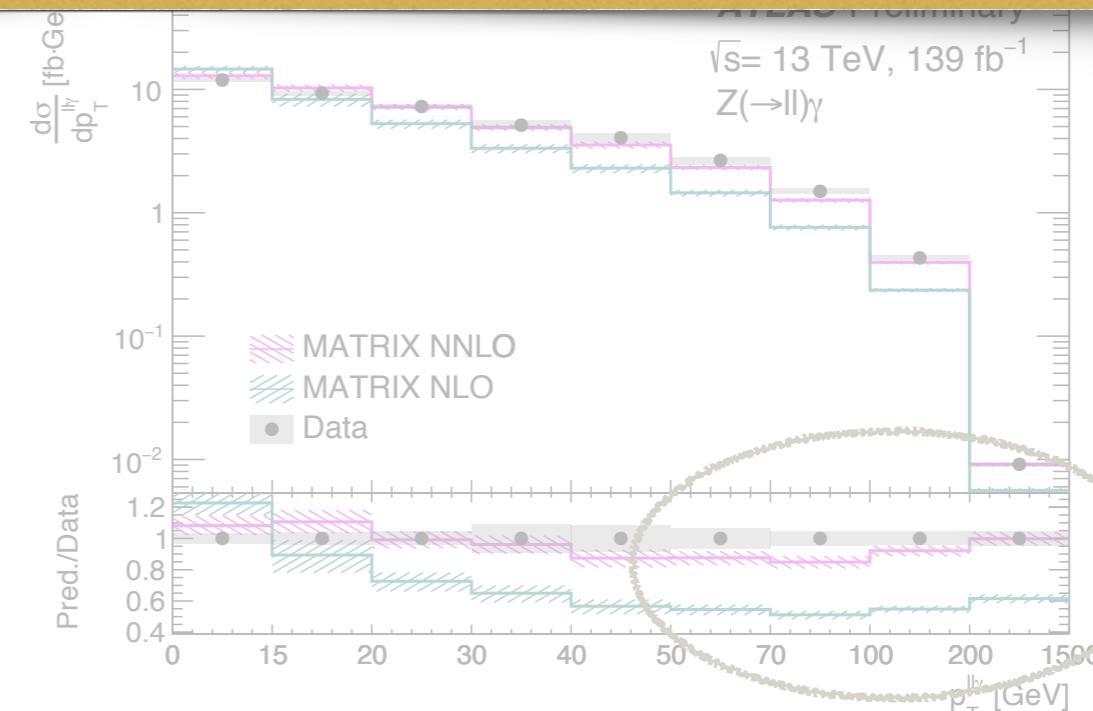
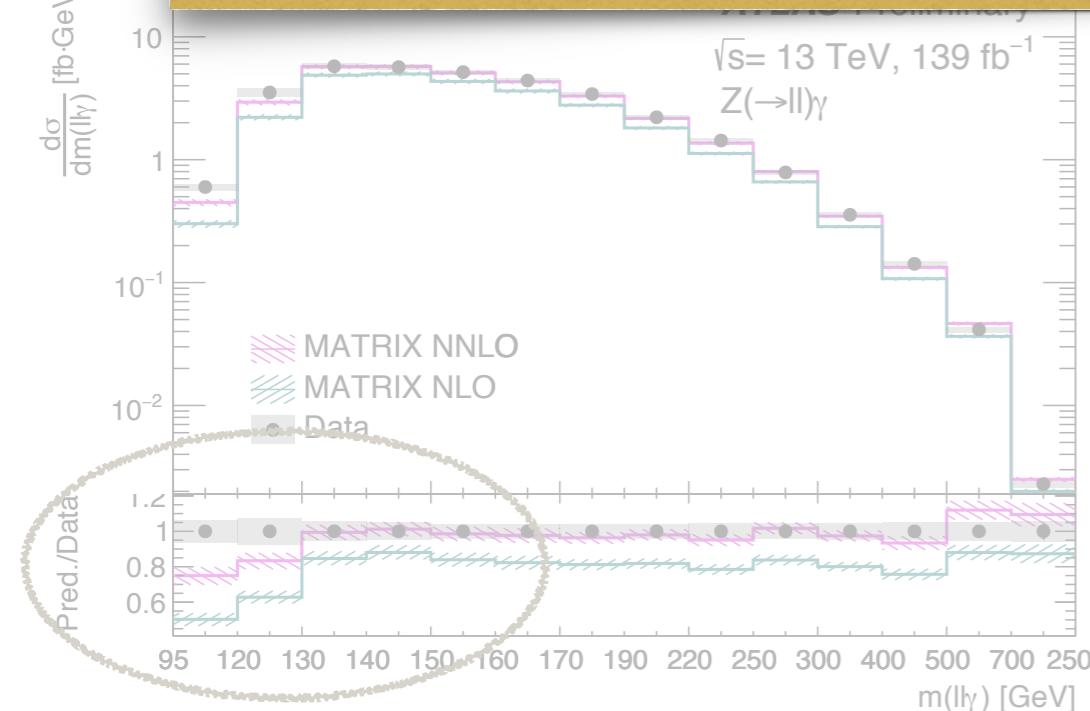
**Parton-to-particule correction factor extracted from Sherpa LO: 0.80 to 0.98, depending on the bin**

# Results: comparison with Parton-level Matrix (NLO and NNLO)

Small contribution from EW Z $\gamma$ +2j considered in signal, using MadGraph 2.3.3



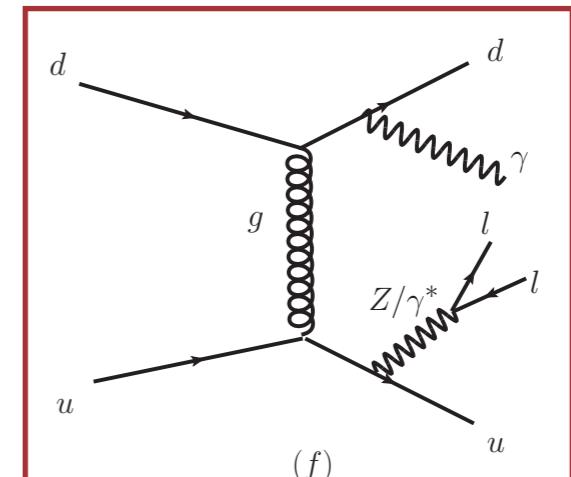
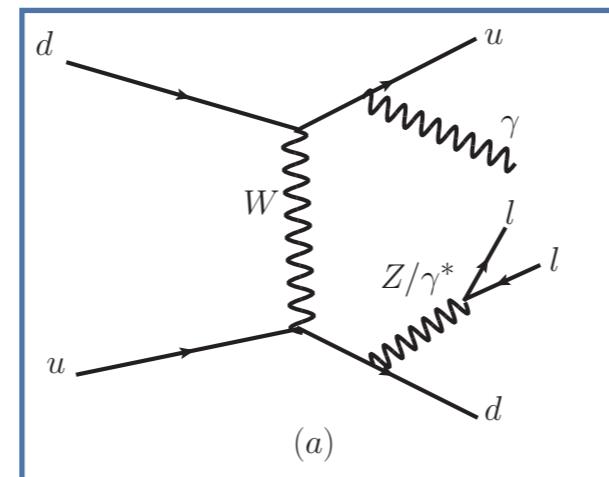
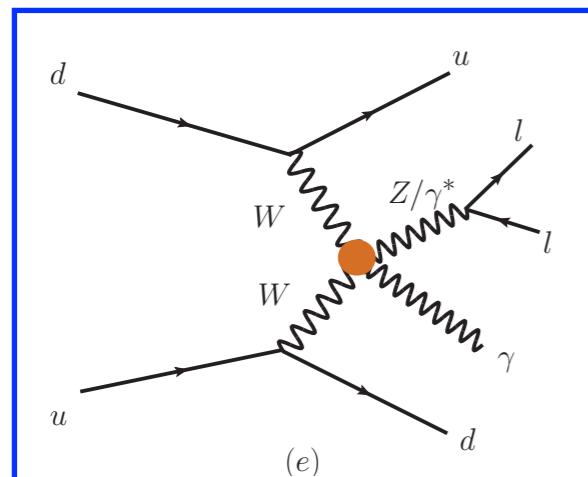
- NNLO Matrix reproduces well data (except  $m_{ll\gamma} < 130$  GeV)
- NLO Matrix underestimates XS by ~20%
- NLO Matrix does not describe well the shape for low  $m_{ll\gamma}$  and high  $pT_{ll\gamma}$  -> due to large resummation effects (fixed order calculation).



Parton-to-particule correction factor factored from Herpa LO: 0.80 to 0.98, depending on the bin

# Electroweak $Z\gamma+2j$ with ATLAS and CMS

- ✿ Electroweak  $Z\gamma+2j$  production not yet observed.
  - ✿ Strong evidence reported by both ATLAS and CMS with 13 TeV data
  - ✿ 2015+2016 data,  $36.1 \text{ fb}^{-1}$  (ATLAS), 2016 data,  $35.9 \text{ fb}^{-1}$  (CMS)
- ✿ Interesting channel to probe **neutral aQGCs** (XS larger than ZZ), sensitive to  $\text{WWZ}\gamma$  vertex
- ✿ **Signal is a mix of VBS and non-VBS diagrams**
- ✿ **Channel difficult due to very large irreducible background: QCD production of  $Z\gamma+2j$**



# Selection CMS

---

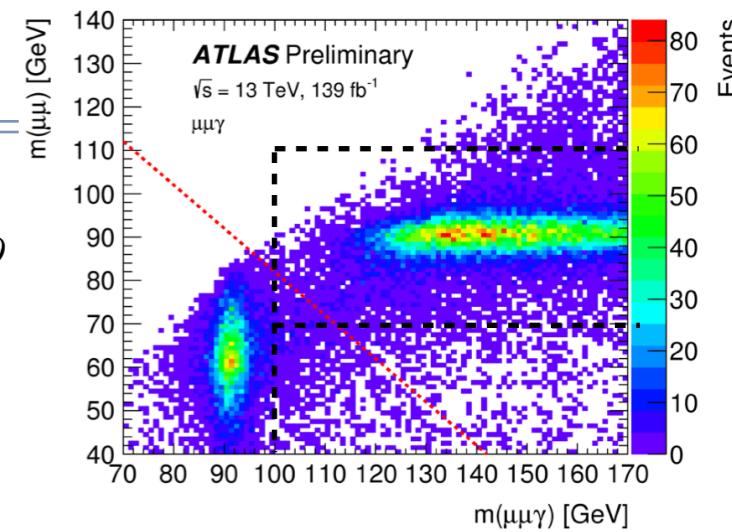
- ❖ **Dimuon trigger (17, 8 GeV) or single (25 GeV) or di-electron trigger (23, 12 GeV)**
- ❖ Loss of efficiency for VBS  $Z\gamma$  due to Partial mistiming of signals in the forward region of the ECAL endcaps ( $2.5 < |\eta| < 3$ ):
  - ❖ 8% for  $m_{jj} > 500$  GeV, 15% for  $m_{jj} > 2$  TeV

Common selection	$p_T^{l1,l2} > 25$ (20) GeV, $ \eta^{l1,l2}  < 2.5$ (2.4), electron (muon), $p_T^\gamma > 20$ GeV, $ \eta^\gamma  < 1.4442$ or $1.566 <  \eta^\gamma  < 2.5$ , $p_T^{j1,j2} > 30$ GeV, $ \eta^{j1,j2}  < 4.7$ , $70 < m_{ll} < 110$ GeV, $\Delta R_{jj}, \Delta R_{j\gamma}, \Delta R_{jl} > 0.5, \Delta R_{l\gamma} > 0.7$ ,
Control region	$150 < m_{jj} < 400$ GeV, $m_{Z\gamma} > 100$ GeV, Common selection
EW signal region	$500 \text{ GeV} < m_{jj}, \Delta\eta_{jj} > 2.5, m_{Z\gamma} > 100 \text{ GeV}$ , zepp < 2.4, $\Delta\Phi_{Z\gamma,jj} > 1.9$ , Common selection
Fiducial region	$500 \text{ GeV} < m_{jj}, \Delta\eta_{jj} > 2.5$ , Common selection
aQGC search region	$p_T^\gamma > 100$ GeV, $500 \text{ GeV} < m_{jj}, \Delta\eta_{jj} > 2.5$ , Common selection

# Selection ATLAS

- ❖ Single + di-lepton triggers -> efficiency close to 100%

$\ell^+\ell^-\gamma jj$ preselection	
Lepton	$p_T^\ell > 20 \text{ GeV}$ $ \eta_\ell  < 2.47(2.5)$ for $e(\mu)$ remove $e$ if $\Delta R(e, \mu) < 0.1$
Boson	$N_\ell \geq 2$ $m_{\ell^+\ell^-} > 40 \text{ GeV}$ $m_{\ell^+\ell^-} + m_{\ell^+\ell^-\gamma} > 182 \text{ GeV}$
Photon	$E_T^\gamma > 15 \text{ GeV}$ $ \eta_\gamma  < 2.37$ (excl. $1.37 <  \eta_\gamma  < 1.52$ ) remove $\gamma$ if $\Delta R(\ell, \gamma) < 0.4$
$b$ -jet	$N_\gamma \geq 1$ $p_T^{jet} > 25 \text{ GeV},  \eta_{jet}  < 2.5$
Jet	$p_T^{jet} > 50 \text{ GeV},  \eta_{jet}  < 4.5$ $N_{\text{jets}} \geq 2$ remove jets if $\Delta R(\ell, jet) < 0.3$ OR $\Delta R(\gamma, jet) < 0.4$
$b$ -CR	$\Delta\eta_{jj} > 1.0$ $M_{jj} > 150 \text{ GeV}$
Signal Region	$\ell^+\ell^-\gamma jj$ preselection $\zeta(Z\gamma) < 5$ Nb-jet>1
	$\ell^+\ell^-\gamma jj$ preselection $\zeta(Z\gamma) < 5$ Nb-jet=0



$$\zeta(\ell\ell\gamma) = \left| \frac{y_{\ell\ell\gamma} - (y_{j1} + y_{j2})/2}{(y_{j1} - y_{j2})} \right|$$

## Differences in selection w.r.t CMS:

- ❖ Lower photon and lepton pT threshold
- ❖ Different boson cuts and removal of FSR photons
- ❖ Larger jet pT cut for ATLAS (50 vs 30 GeV)
- ❖ Lower  $\Delta\eta$  cut for ATLAS (1 vs 2.5)
- ❖ Lower dijet mass in SR (150 vs 500 GeV)

# Signal and background simulation

	ATLAS	CMS
Signal	<b>MadGraph5_aMC@NLO 2.3.3 (LO)</b>	<b>MadGraph5_aMC@NLO 2.4.2 (LO)</b>
QCD	<b>Sherpa 2.2.2</b> 0 and 1 jet @ NLO, up to 3 partons at LO	<b>MadGraph5_aMC@NLO 2.6.0</b> 0 and 1 jet @ NLO
Z+jet	<b>Sherpa 2.2.1</b> (up to 2 jets @NLO, 4 jets @LO)	-
ttbar $\gamma$	<b>MadGraph5_aMC@NLO</b> 2.3.3+Pythia 8.212	<b>MadGraph5_aMC@NLO + Pythia</b>
WZ, WW, ZZ	<b>Sherpa 2.2.1</b>	Pythia 8
Single top, Wt	<b>Powheg+Pythia 6.4</b>	<b>Powheg 2.0</b>
Interference	<b>MadGraph5 (LO)</b>	<b>MadGraph5_aMC@NLO</b>
aQGC	-	<b>MadGraph5_aMC@NLO (LO)</b>

# Background estimation - CMS

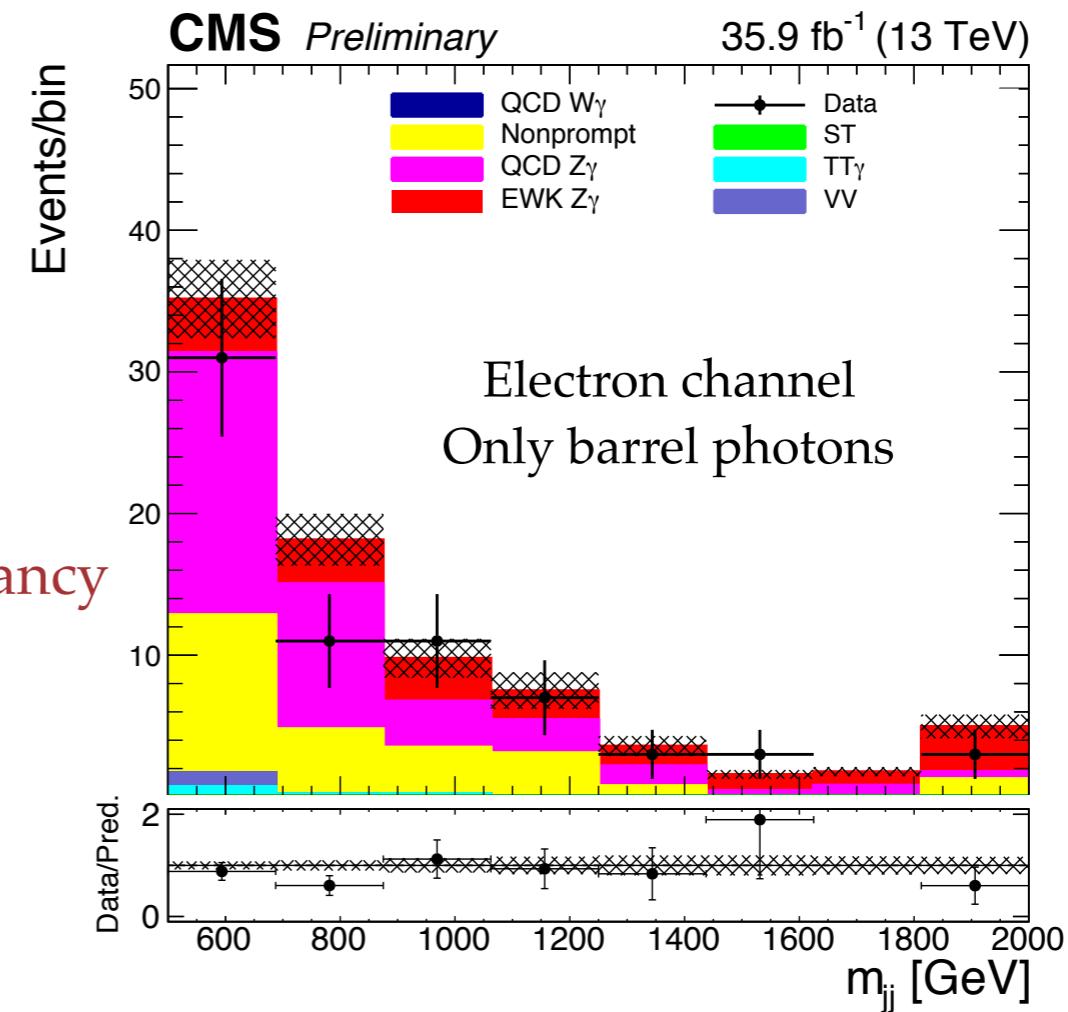
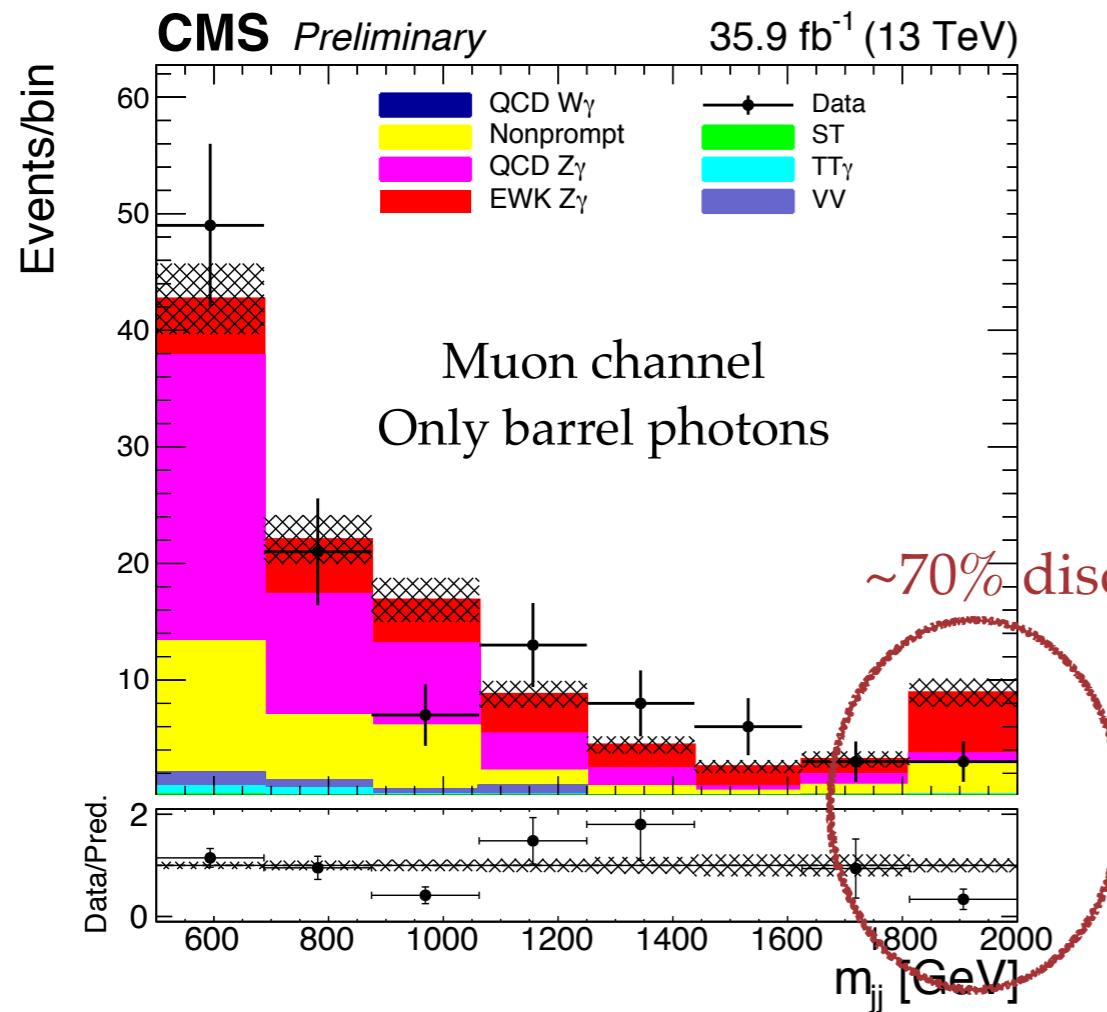
## 1. QCD Z $\gamma$ +2j QCD shape and normalisation taken from MC simulation

- ❖ Simultaneous fit in CR and SR to constrain uncertainty

## 2. Z+jet (non prompt photon): data-driven sideband estimate

- ❖ Dominant uncertainties due to choice of isolation variable sideband, and non-closure b/w simu/obs

## 3. Other backgrounds: **single top**, **ttbar $\gamma$** , **diboson**, all taken from MC



# Background estimation ATLAS

## 1. QCD $Z\gamma+2j$

- ❖ Normalisation estimated from data (pre-correction 0.91), and then fitted in SR

## 2. Z+jet: DD estimate of shape and normalisation

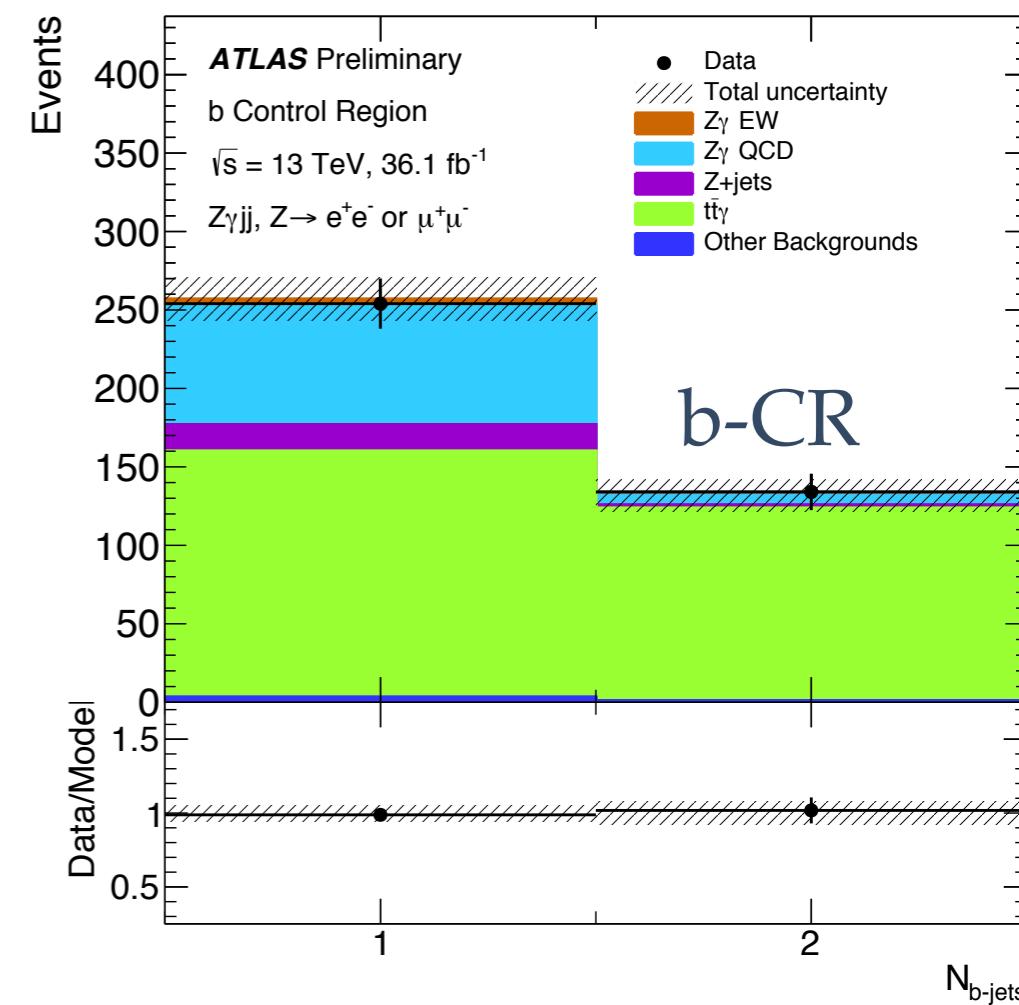
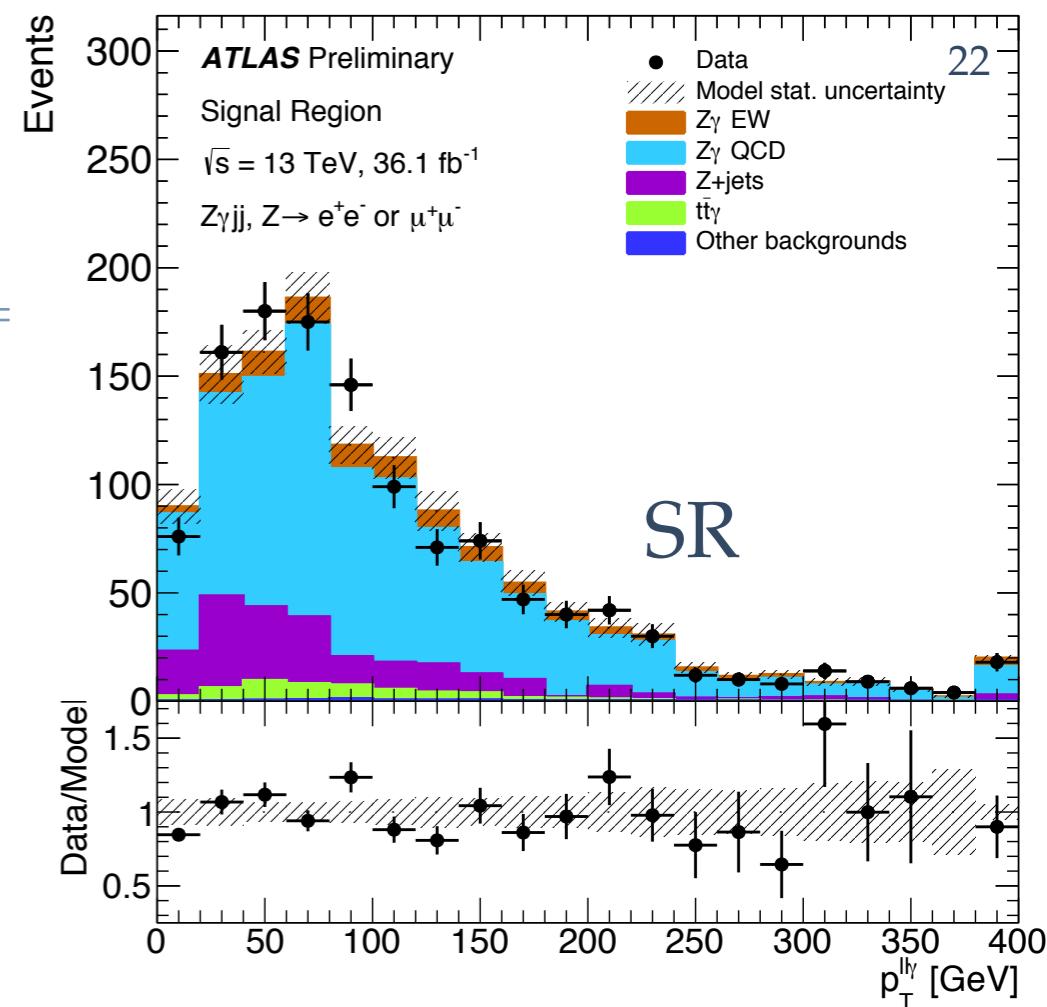
- ❖ 2D sideband method (photon ID, isolation), in region close to SR except: jet pT  $> 30$  GeV,  $m_{jj} < 150$  GeV
- ❖ Extrapolation to SR using ratio Z+jet/Z $\gamma$

## 3. ttbar $\gamma$ :

- ❖ Pre-correction factor from data: 1.41 + fit in a CR
- ❖ Dedicated CR (b-CR):  $>= 1$  b-jet  $\rightarrow \sim 70\%$  purity, 25% Z $\gamma$  QCD.

## 4. Smaller backgrounds: WZ, Wt

- ❖ From MC (less than 0.5% in SR)



# Systematic uncertainties - CMS

## Uncertainty on signal yield

Source of systematic uncertainty	Relative uncertainty [%]	
QCD $Z\gamma$ scale	5 - 25	→ Constrained by low $m_{jj}$ CR
EW $Z\gamma$ scale	2 - 14	
JES	1 - 31	
JER	1 - 13	
Interference	4 - 8	
Nonprompt photon	9 - 37	
Integrated luminosity	2.5	

- ✿ Lepton trigger, reconstruction, selection efficiency (measured with T&P technique) = 3%
- ✿ Finite size of simulated and data samples (Poisson stat): 5-100% depending on sample (EW, QCD, non-prompt photons)
- ✿ Theory unc:
  - ✿ PDF: 3-11% with increasing  $m_{jj}$  and  $\Delta\eta$  for EW, 1-3% for QCD
  - ✿ For signal fiducial XS, theoretical uncertainties associated with signal are not considered
- ✿ All systematic correlated for e/mu channels except for trigger and lepton ID

# Systematic uncertainties - ATLAS

---

## 1. Theory uncertainties:

- ❖ PDF,  $\alpha_s$ : 2%
- ❖ QCD-scale: +30-20% on QCD  $Z\gamma$ , ttbar $\gamma$ , 5% for EW  $Z\gamma$  (norm); shape 2-4%
- ❖ PS, UE, ME:
  - ❖ Signal & ttbar $\gamma$  (Herwig 7): 5% at large BDT score
  - ❖ QCD (diff. b/w Sherpa 2.2.2 & MadGraph5): 5-20% at low-high BDT

## 2. Largest experimental uncertainties: JES/JER (8% norm, 2-18% shape for QCD, 4% EW) and pileup uncertainty

## 3. Background uncertainty also large:

- ❖ 20% on Z+jet yield (from the method and limited stat)
- ❖ 20% on other backgrounds

## 4. MC stat: 5-13% QCD, 2% EW

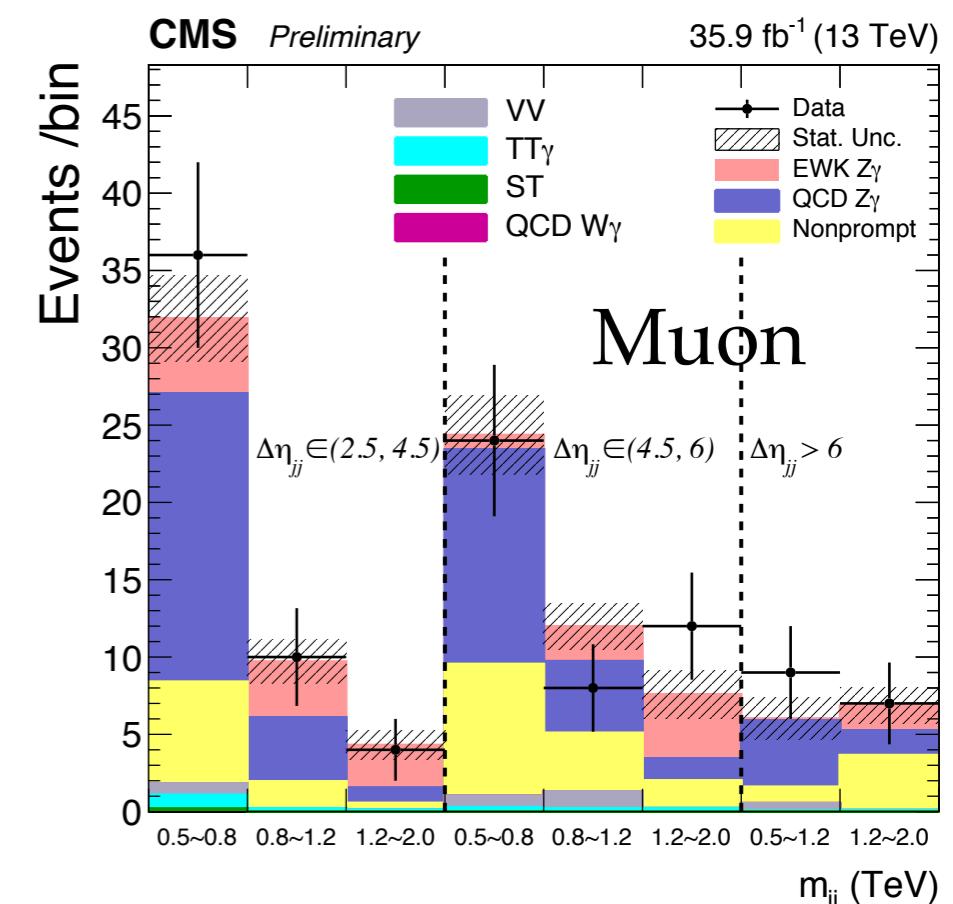
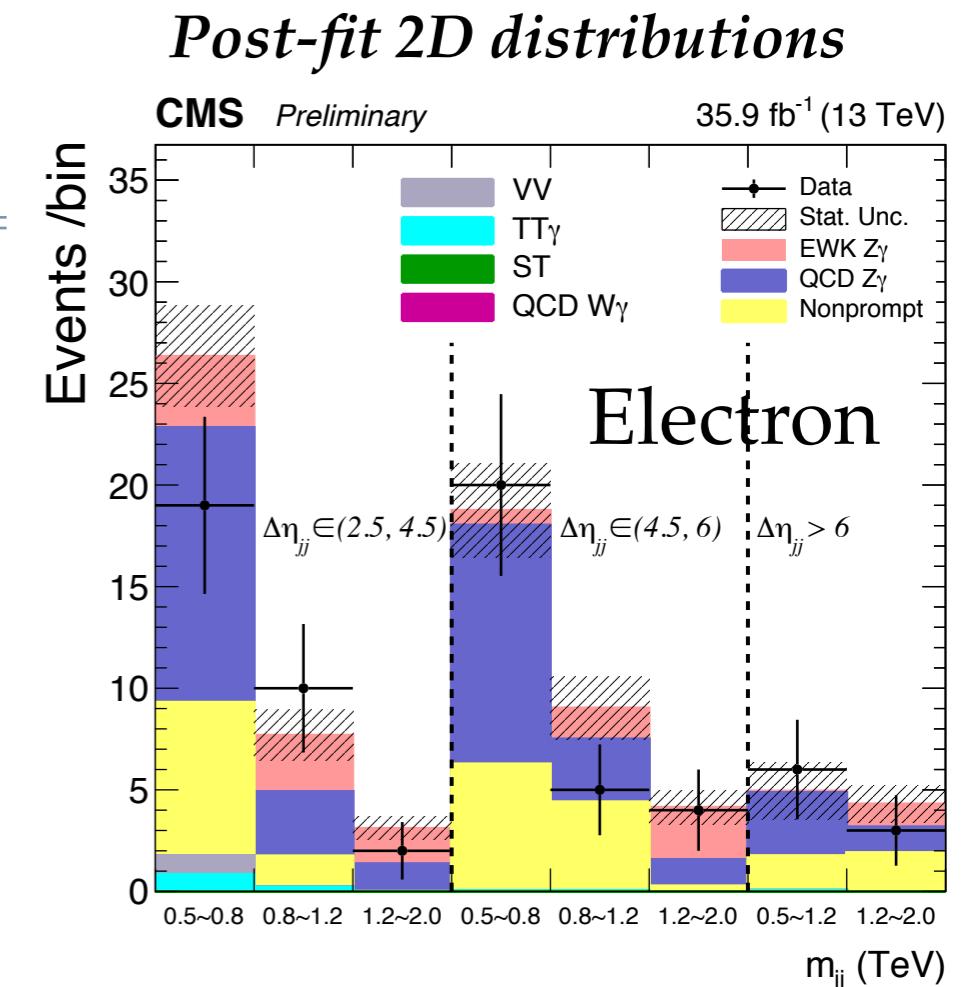
## Effect of uncertainties on EW fiducial cross-section

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	+6 -4
Electrons	±1
Muons	+3 -2
Photons	±1
Electrons/photons scale	±1
$b$ -tagging	±2
MC statistics	±8
Other backgrounds normalisation (including Z+jets)	+9 -8
Luminosity	±2
Total uncertainty	+27 -25

# Signal significance - CMS

	muon channel	electron channel
Nonprompt photon	$47.6 \pm 4.5$	$39.3 \pm 4.0$
Other background	$7.4 \pm 1.4$	$2.7 \pm 0.8$
QCD $Z\gamma jj$	$62.9 \pm 3.1$	$49.6 \pm 2.7$
EW $Z\gamma jj$	$36.5 \pm 0.7$	$25.4 \pm 0.6$
Total background	$117.9 \pm 5.6$	$91.6 \pm 4.8$
Data	$172 \pm 13$	$113 \pm 11$

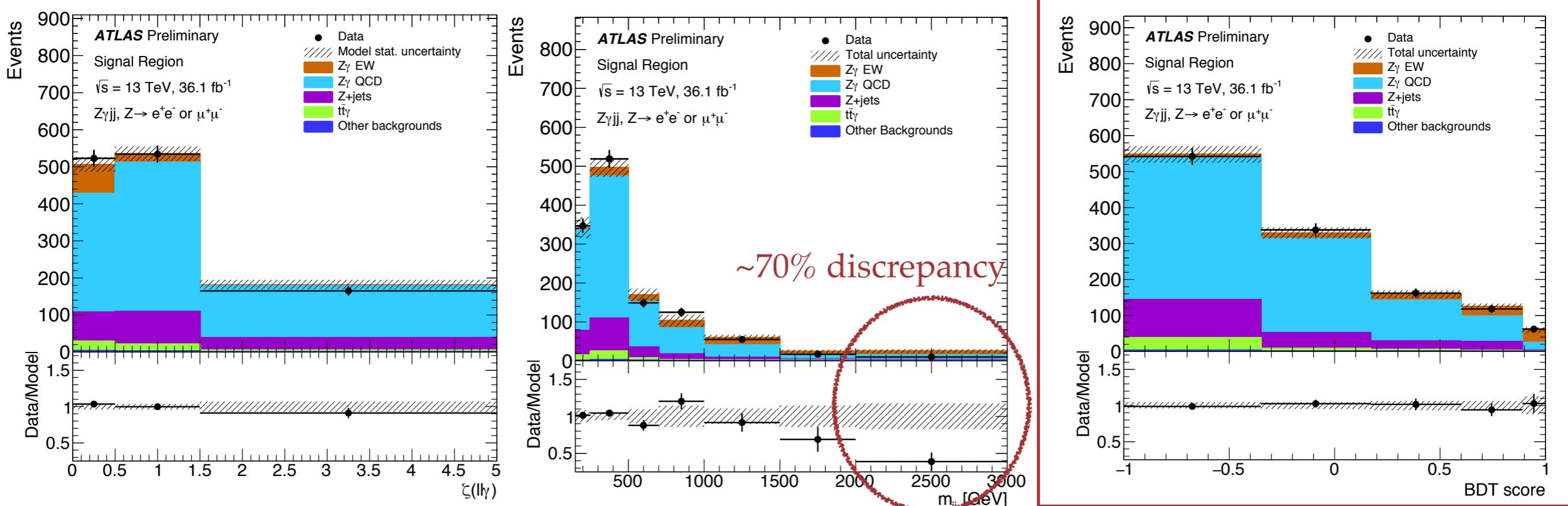
- Statistical analysis of event yields in 2D  $m_{jj}$ - $\Delta\eta$  grid
- 4 categories in signal region
  - barrel/endcap photon x ( $e, \mu$ )
- Simultaneous fit to SR/CR to constraint  $Z\gamma+2j$  QCD
- Significance: **3.9 (5.2)  $\sigma$  observed (exp.) with 2016 data**
- Significance: **4.7 (5.5)  $\sigma$  observed (exp.) with 2016+2012 (8TeV) data**
  - Theory uncertainties correlated, exp. syst uncorrelated b/w 2 datasets



# Signal extraction - ATLAS

- ✿ **BDT used to separate EW signal from background**
  - ✿ 13 kinematic variables used as input -> all variables well modelled by MC except for high  $m_{jj}$
  
- ✿ **Maximum likelihood fit, muon and electron channels combined**
  - ✿ Simultaneous fit of SR and b-CR
  - ✿ 3 normalisation fitted:  $\mu_{QCD}$ ,  $\mu_{t\bar{t}bary}$ ,  $\mu_{EW} \rightarrow$ POI
  
- ✿ **Cross-check with cut-based analysis, using 2 CRs (additional QCD-CR with  $m_{jj} < 500$  GeV with discriminant variable being  $Z\gamma$  centrality)**

Variable used in the BDT	
$m_{jj}$	
$\Delta\eta(j1, j2)$	
$\zeta(Z\gamma)$	
$m_{Z\gamma}$	
$Z\gamma$	
$p_T$	
$m_Z$	
$p_T^Z$	
$p_T^{j1}$	
$p_T^{j2}$	
$\eta^{j1}$	
$\eta^{j2}$	
$\min\Delta R(\gamma, j)$	
$\Delta\phi(Z\gamma, jj)$	
$\Delta R(Z\gamma, jj)$	



# Fit results - ATLAS

---

- ❖ Yield obtained after the fit

	SR		$b$ -CR	
Data	1222			388
Total predicted	1222	$\pm 35$	389	$\pm 19$
$Z\gamma jj$ -EW (signal)	104	$\pm 26$	5	$\pm 0$
$Z\gamma jj$ -QCD	864	$\pm 60$	82	$\pm 9$
$Z + \text{jets}$	200	$\pm 40$	19	$\pm 4$
$t\bar{t} + \gamma$	48	$\pm 10$	280	$\pm 21$
Other backgrounds	7	$\pm 1$	4	$\pm 1$

- ❖ Signal strength and norm. factors (including pre-corrections):

- ❖  $\mu_{Z\gamma jj-EW} = 1.00 \pm 0.19 \text{ (stat.)} \pm 0.13 \text{ (syst.)} {}^{+0.13}_{-0.10} \text{ (mod.)} = 1.00 \pm 0.26$
- ❖  $\mu_{t\bar{t}+\gamma} = 1.49 \pm 0.28$
- ❖  $\mu_{Z\gamma jj-QCD} = 0.78 \pm 0.23$

- ❖ Significance: 4.1 (3.8)  $\sigma$

- ❖ Cross-check with cut-based analysis gives compatible results and sensitivity of 2.9 (2.7)  $\sigma$  observed (expected)

# Fiducial cross-section, ATLAS and CMS

---

- Obtained by multiplying signal-strength to predicted cross-section in PS

	Cross-section [fb]
CMS	$\sigma_{Z\gamma-EW}^{fid,obs} = 3.2 \pm 1.0 \text{ (stat)} \pm 0.6 \text{ (syst)} \pm 0.07 \text{ (lumi)} = 3.2 \pm 1.2$
	$\sigma_{Z\gamma-EW}^{fid,MadGraph} = 4.97 \pm 0.14 \text{ (PDF + } \alpha_S) \pm 0.25 \text{ (scale)}$
ATLAS	$\sigma_{Z\gamma-EW}^{fid,obs} = 7.8^{+1.5}_{-1.4} \text{ (stat)}^{+0.9}_{-1.0} \text{ (sys)}^{+1.0}_{-0.8} \text{ (mod)} = 7.8^{+2.0}_{-1.9}$
	$\sigma_{Z\gamma-EW}^{fid,MadGraph} = 7.75 \pm 0.03 \text{ (stat)} \pm 0.20 \text{ (PDF + } \alpha_S) \pm 0.40 \text{ (scale)}$
	$\sigma_{Z\gamma-EW}^{fid,Sherpa} = 8.94 \pm 0.08 \text{ (stat)} \pm 0.20 \text{ (PDF + } \alpha_S) \pm 0.50 \text{ (scale)}$

- Combined EW+QCD  $Z\gamma jj$  cross-section also measured: same method and phase spaces, except for CRs which are excluded

	Cross-section [fb]
CMS	$\sigma_{Z\gamma jj}^{fid,obs} = 15.1 \pm 1.2 \text{ (stat)} \pm 2.1 \text{ (sys)} \pm 0.4 \text{ (lumi)} = 15.1 \pm 2.4$
	$\sigma_{Z\gamma jj}^{fid,MadGraph} = -$
ATLAS	$\sigma_{Z\gamma jj}^{fid,obs} = 71 \pm 2 \text{ (stat)}^{+9}_{-7} \text{ (sys)}^{+21}_{-17} \text{ (mod)} = 71^{+23}_{-19}$
	$\sigma_{Z\gamma jj}^{fid,MadGraph+Sherpa} = 88.4 \pm 2.4 \text{ (stat)} \pm 2.3 \text{ (PDF + } \alpha_S) \pm^{29.4}_{-19.1} \text{ (scale)}$

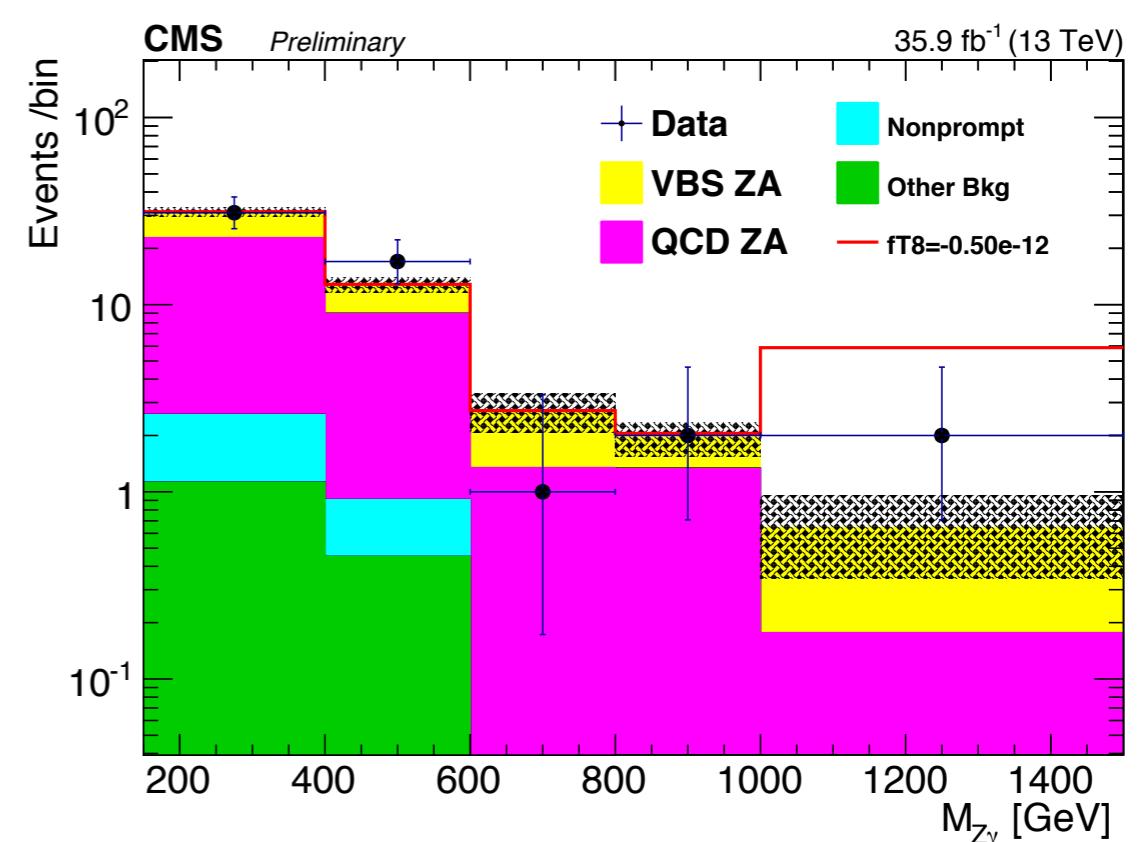
- Corresponding signal strengths:

	$\mu = \sigma^{fid,obs} / \sigma^{fid,pred.}$
CMS	$Z\gamma\text{-EW} = 0.64^{+0.23}_{-0.21}$
	$Z\gamma \text{ total} = 0.96^{+0.15}_{-0.13}$
ATLAS	$Z\gamma\text{-EW} = 1.00 \pm 0.19 \text{ (stat)} \pm 0.13 \text{ (sys)}^{+0.13}_{-0.10} \text{ (mod)} = 1.00 \pm 0.26$
	$Z\gamma \text{ total} = \sim 0.8 \text{ (not provided)}$

# Limit on aQGC - CMS

- ❖ Presence of nonzero aQGCs would enhance the production rate of events at high  $mZ\gamma$ .
  - ❖ aQGC region: add a cut on photon pT ( $>100$  GeV)
  - ❖ Relevant operators:  $L_{M0}-L_{M7}$  and  $L_{T0}-L_{T9}$
- ❖ Use a MC that includes effects of non-zero aQGC +SM EW  $Z\gamma jj$  process + interferences
- ❖ Likelihood on 10 bins (5  $mZ\gamma$  bins muons and electrons)
  - ❖ Operators varied one by one
- ❖ Unitarity bound: VBFNLO framework      Obtain most stringent limits on FT8 and FT9

Observed Limits ( $\text{TeV}^{-4}$ )	Expected Limits ( $\text{TeV}^{-4}$ )	Unitarity Bound
$-19.3 < F_{M,0}/\Lambda^4 < 20.2$	$-15.0 < F_{M,0}/\Lambda^4 < 15.1$	1.0
$-47.8 < F_{M,1}/\Lambda^4 < 46.9$	$-30.1 < F_{M,1}/\Lambda^4 < 30.0$	1.2
$-8.16 < F_{M,2}/\Lambda^4 < 8.04$	$-6.09 < F_{M,2}/\Lambda^4 < 6.06$	1.3
$-20.9 < F_{M,3}/\Lambda^4 < 21.1$	$-13.2 < F_{M,3}/\Lambda^4 < 13.3$	1.5
$-15.2 < F_{M,4}/\Lambda^4 < 15.8$	$-11.7 < F_{M,4}/\Lambda^4 < 11.7$	1.5
$-24.9 < F_{M,5}/\Lambda^4 < 24.4$	$-19.1 < F_{M,5}/\Lambda^4 < 18.2$	1.8
$-38.6 < F_{M,6}/\Lambda^4 < 40.5$	$-30.0 < F_{M,6}/\Lambda^4 < 30.1$	1.0
$-60.8 < F_{M,7}/\Lambda^4 < 62.6$	$-46.1 < F_{M,7}/\Lambda^4 < 46.3$	1.3
$-0.74 < F_{T,0}/\Lambda^4 < 0.69$	$-0.56 < F_{T,0}/\Lambda^4 < 0.51$	1.4
$-1.16 < F_{T,1}/\Lambda^4 < 1.15$	$-0.73 < F_{T,1}/\Lambda^4 < 0.72$	1.5
$-1.96 < F_{T,2}/\Lambda^4 < 1.85$	$-1.48 < F_{T,2}/\Lambda^4 < 1.37$	1.5
$-0.70 < F_{T,5}/\Lambda^4 < 0.74$	$-0.51 < F_{T,5}/\Lambda^4 < 0.57$	1.8
$-1.64 < F_{T,6}/\Lambda^4 < 1.67$	$-1.23 < F_{T,6}/\Lambda^4 < 1.26$	1.7
$-2.59 < F_{T,7}/\Lambda^4 < 2.80$	$-1.91 < F_{T,7}/\Lambda^4 < 2.12$	1.8
$-0.47 < F_{T,8}/\Lambda^4 < 0.47$	$-0.36 < F_{T,8}/\Lambda^4 < 0.36$	1.6
$-1.26 < F_{T,9}/\Lambda^4 < 1.27$	$-0.95 < F_{T,9}/\Lambda^4 < 0.95$	1.5



# Conclusion

---

- ✿ **Z $\gamma$  diboson production measured with more and more precision**
  - ✿ Precise differential cross-section for the inclusive productions, able to test pQCD
  - ✿ Strong evidence of EW production of Z $\gamma$ +2j for both ATLAS and CMS
  - ✿ Expect an observation of the EW production with full Run2 dataset
- ✿ **Ligh-by-light scattering observed for the first time in heavy-ions collisions by ATLAS**
  - ✿ Precise cross-section measurement thanks to good purity of signal