Study of Z→llγ decays at √s = 8 TeV in the ATLAS experiment at the CERN LHC

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https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/CONFNOTES/ATLAS-CONF-2022-046/

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Introduction

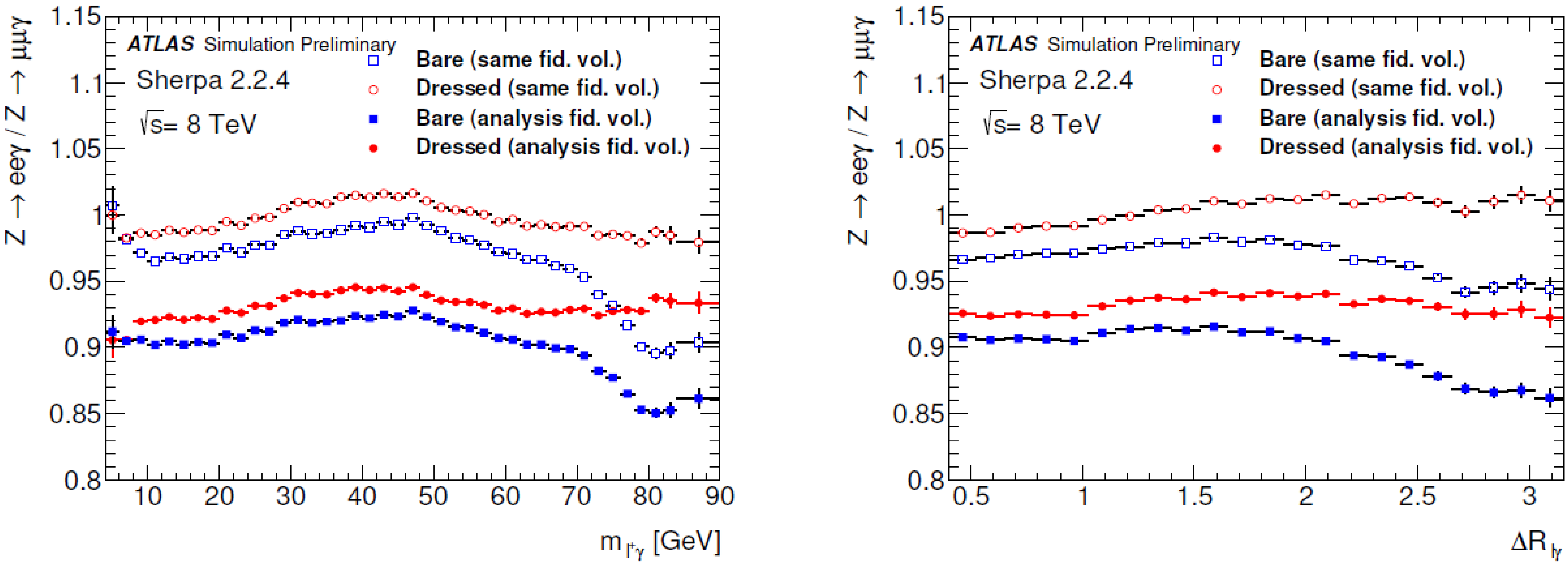
- QED state of the art predictions for llγ final states dominated by FSR has order of magnitude smaller uncertainty in principle than QCD.

    Therefore need to remove any QCD modeling uncertainties in MC by reweighting as precisely as possible to data.

    This is achieved mostly by reweighting of $pT_{ll\gamma}$ to data and other distributions such as $Y_{ll\gamma}$ and $\cos\theta_{CS}$ and φ_{CS} have smaller impact.

- Expected differences between electrons and muons or between data and MC are small, few % at most, so normalized distributions most sensitive to details of QED FSR are measured : $m_{l\gamma}$, $dR_{l\gamma}$, pT_{γ}. Future measurements might reach better sensitivity if performed in the llγ rest frame.

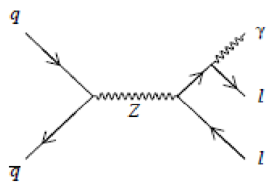
- Performing such tests with high precision using Z decays will eventually help with QED component of systematic uncertainty in W mass measurements.



At high orders electrons and muons radiate differently, the difference is large for “bare” particles.

Motivation

Z→ll vertex function V(Q) is expressed by formula:



$$\langle f\bar{f}|J_Z^{\mu}|0\rangle = V_f(q^2)\bar{u}_f\gamma_\mu\left[\frac{I_{3f}(1-\gamma_5)}{2} - \hat{k}_f(q^2)\hat{s}^2 Q_f\right]v_f,$$

[A. Sirlin, A.Ferroglia. Rev.Mod.Phys., V85 (2013): eq. (59) p.273]

The most general vector boson - fermion - antifermion coupling

$$V_\mu\left(Q^2\right) = (2\pi)^4\, i\,\frac{ig^3}{16\pi^2}\left[F_V\gamma_\mu + F_A\gamma_\mu\gamma_5 + F_M\sigma_{\mu\nu}Q_\nu + F_S Q_\mu + F_P\gamma_5 Q_\mu + F_E\gamma_5\left(p_1 - p_2\right)_\mu\right]$$

[D. Bardin, G. Passarino. The Standard Model in the Making, Oxford, UK; Clarendon 1999, p. 233]

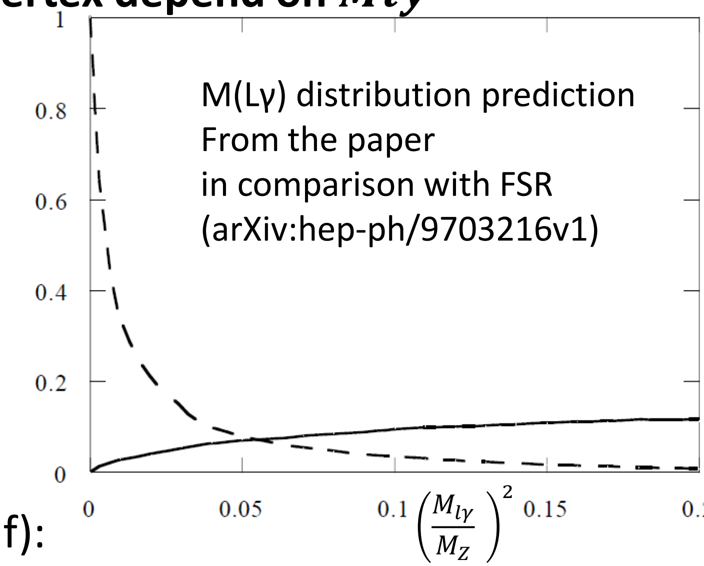
Here Q_μ is four-momentum of Z

V(Q) can be sensitive to effects of New Physics

Vertex depend on Mly

D.Bruss, O.Nachtmann, P.Overmann,
CP Violation in radiative Z Decays
arXiv:hep-ph/9703216v1

Photon emitted from the vertex but without
CP-violation with Lagrangian
(B. Grzadkowski , M. Iskrzyński , M. Misiak
and J. Rosiek1 http://arxiv.org/pdf/1008.4884v2.pdf):



Data and MC samples used

- Data 2012, 8 TeV, pp collisions 20.2 fb^{-1}
- Powheg+Pythia8+Photos MC
- Sherpa v.1.4 (Run I) MC (1 photon from ME tree level, M(2l) > 40 GeV)
- Sherpa v.1.4 (Run I 2l2γ) MC (2 photon from ME tree level)

For comparisons at truth level:

- **Sherpa v.2.2.4 (YFS QED FSR NLO)**
- **KKMChh (LO QCD)**

a) KKMChh and Photos are based on the initial KKMC developed for LEP. Powheg+Photos has only FSR (including ME corrections bringing it close to NNLO QED, KKMC+Herwig has ISR and FSR including photon resummation for both plus IFI, the first complete calculation of such processes at the LHC.
b) Sherpa is based on YFS resummation, very similar to Photos.
A special Sherpa 1.4 MEγ and MEγγ versions were used to predict exact tree-level Z to llγ, llγγ final states. Sherpa 1.4 and 2.2 are identical for QED treatment.

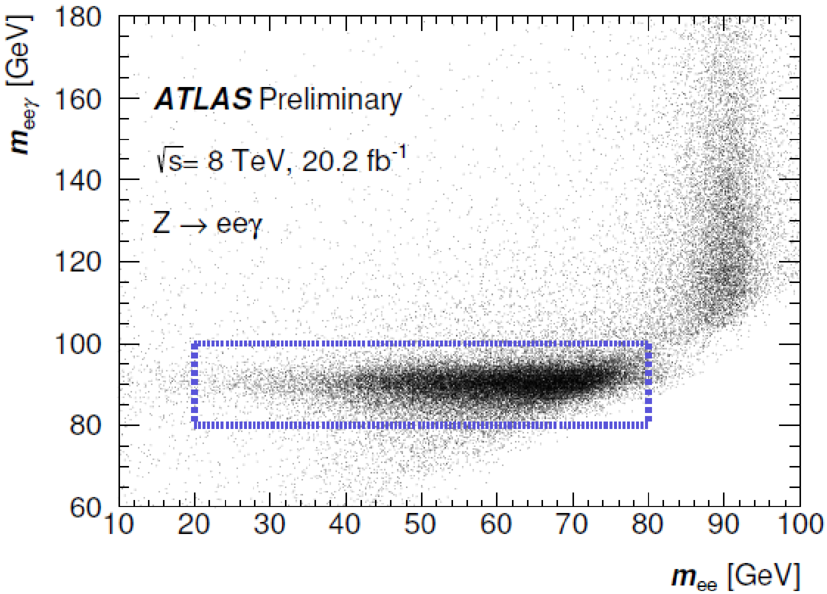
Selections

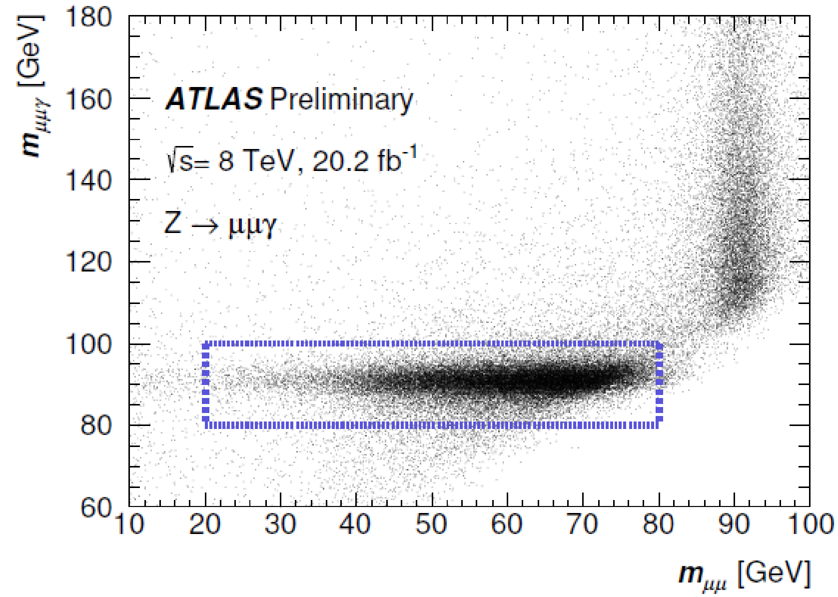
	Z->eeγ	Z->μμγ
Triggers	EF_2e12Tvh_loose EF_mu24i_tight EF_mu36_tight	EF_2mu13 EF_mu18_mu8_EFFS EF_mu24i_tight EF_mu36_tight
Photon selection	Photon with highest P_t; $P_t(\gamma) > 15$ GeV $\lvert\eta(\gamma)\rvert < 2.37$ excluding $1.37 < \lvert\eta(\gamma)\rvert < 1.52$; pass tight ID $\Delta R(\gamma, l) > 0.4$ (0.3); topoEtcone40(γ) < 4 GeV	
Lepton selection	$P_t(e)>10$ GeV*; Loose e; $\lvert\eta(e)\rvert < 2.47$; topoEtcone40(e)/$E_t$ < 0.3	$P_t(\mu)>10$ GeV; $\lvert\eta(\mu)\rvert < 2.37$; topoEtcone40($\mu$)/$E_t$ < 0.2
Invariant mass	At least 1 photon +2 e with opposite sign $\mathrm{Max}(P_{t1},P_{t2})>25$ GeV **20** GeV < M(ee) < 80 GeV; 80 GeV < M(eeγ) < 100 GeV;	At least 1 photon +2 μ with opposite sign $\mathrm{Max}(P_{t1},P_{t2})>25$ GeV **20** GeV< M(μμ) < 80 GeV; 80 GeV < M(μμγ) < 100 GeV;

* $P_t(e) > 13$ GeV for electrons triggered with EF_2e12Tvh_loose (18 events in data and 208 events in MC with P_t<13 GeV)

Event selection: $m_{ll\gamma}$ vs m_{ll} for $Z \to 2l\gamma$ process

For the analysis we take only $Z \to 2l\gamma$ blue region of the plots

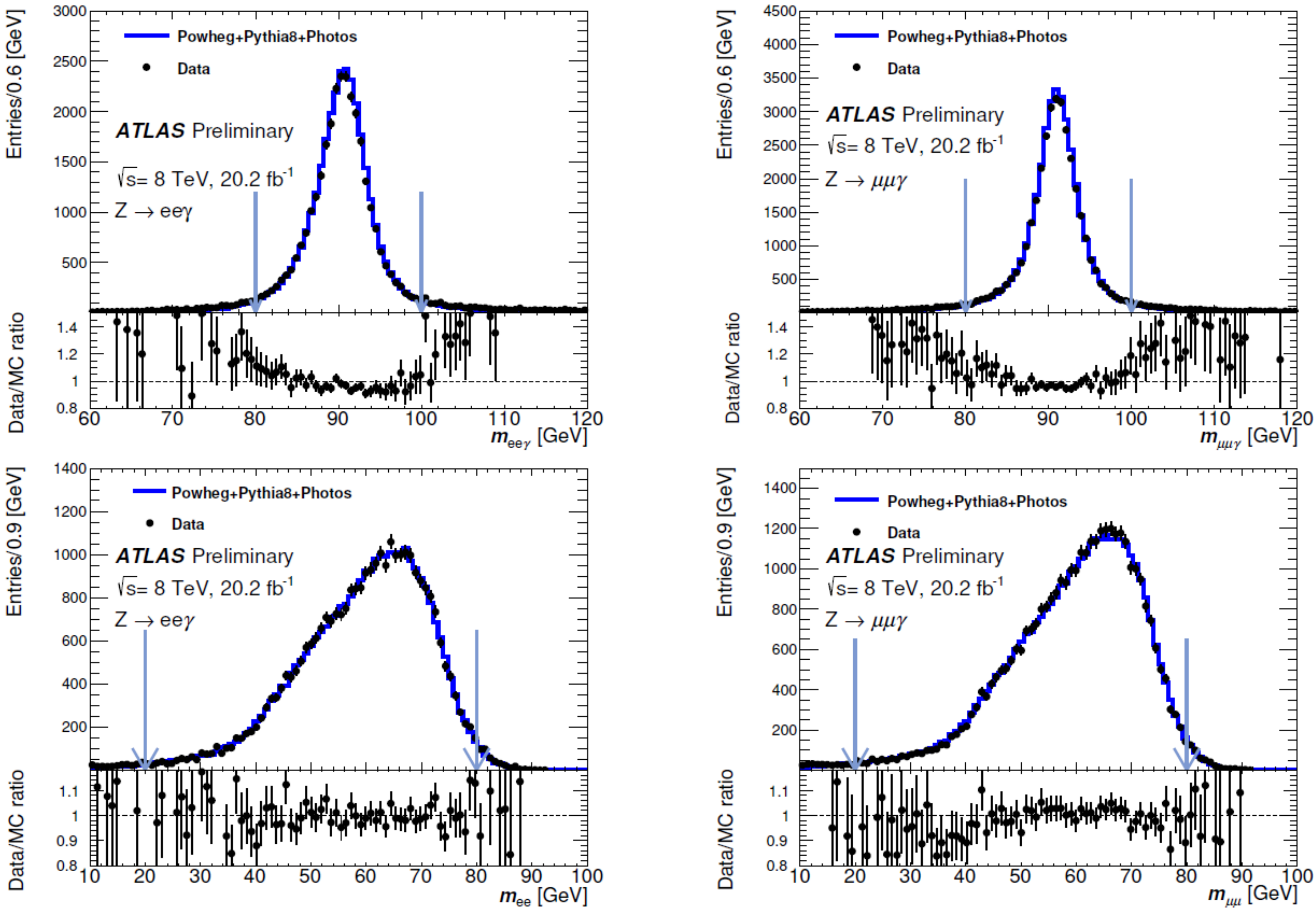




Channel	$Z \to ee\gamma$	$Z \to \mu\mu\gamma$
Data	30571	34948
Prompt background	360 ± 43	290 ± 48
Fake γ background	450 ± 91	500 ± 93
Total background	810 ± 92	790 ± 105
Total expected $Z \to ll\gamma$ signal	28990	34530

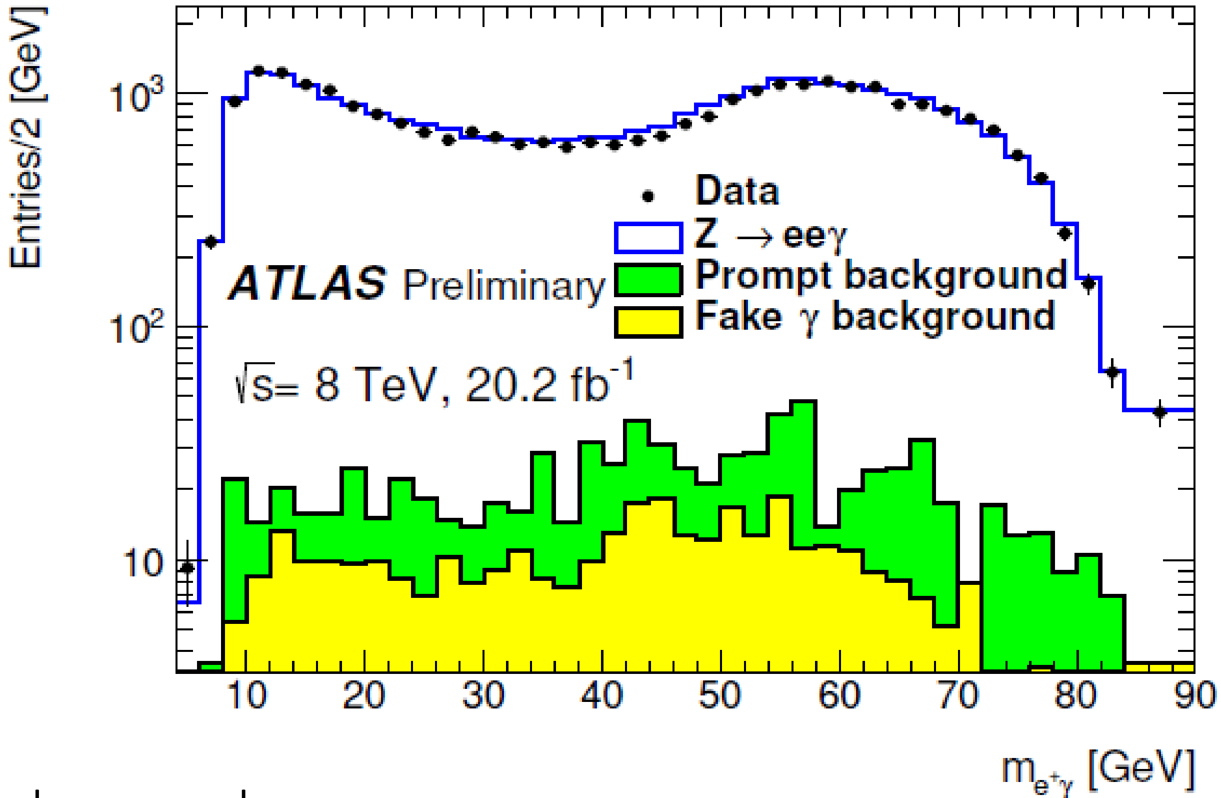
Event selections:

Invariant mass of 2l and 2lγ



Good description by the MC

Backgrounds estimation



Two methods were used:

1) Fit of m(llγ) in each bin of m(lγ) distribution.

2) ABCD method (loose not isolated photons)

Both are in agreement.

Fit of $M_{ll\gamma}$ from 60 to 120 GeV using MC-based shape for all backgrounds including fake photons.

Normalization of prompt photon backgrounds from MC.

Normalization of fake photon background (from Z+jets and ttbar) taken from fit to data outside pole region (with ratio of Z to ttbar fixed by MC cross sections).

Channel	$Z \rightarrow ee\gamma$	$Z \rightarrow \mu\mu\gamma$
Data	30571	34948
Prompt background	360 ± 40	290 ± 50
Fake γ background	450 ± 90	500 ± 90
Total background	810 ± 100	790 ± 100
$Z \rightarrow ll\gamma$ expected signal	28990 ± 990	34530 ± 1100

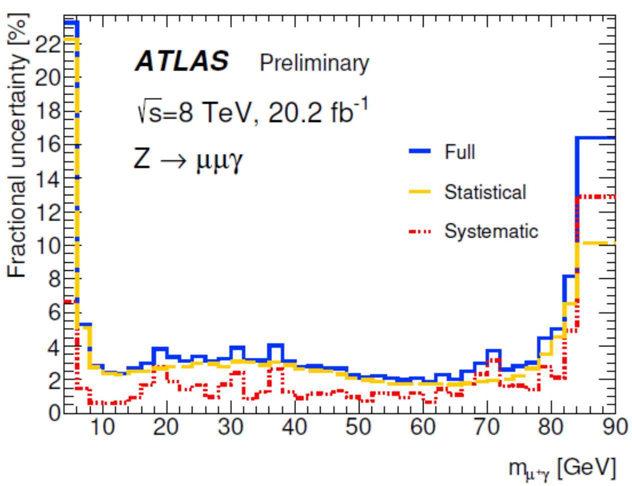
Systematic uncertainties

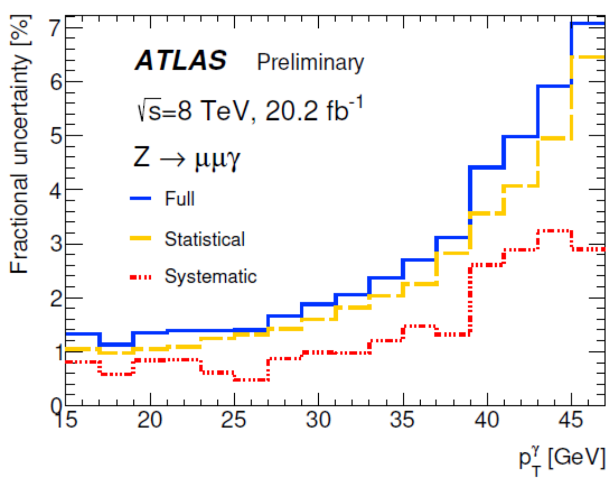
- the main measurement is that of normalized differential distributions sensitive to QED FSR. Since these are shape measurements, many sources of experimental uncertainties are greatly reduced (compared to integrated fiducial cross section measurements that are also produced by the analysis).

Table 2: Breakdown of systematic uncertainties in the normalised differential fiducial cross sections

Uncertainty source	$Z \to ee\gamma$ channel	$Z \to \mu\mu\gamma$ channel
Experimental		
Energy/momentum scale and resolution	0.2%	0.2%
Efficiency	0.3%	0.3%
Background subtraction	0.3%	0.3%
Theory related		
PDF	< 0.1%	< 0.1%
QCD scale variations	0.1 %	0.1%
QCD modeling	0.3%	0.3%
Total	0.6%	0.6 %

$$F(Q/M_Z) = \frac{N_{MC}}{N_{exp}} \frac{\frac{\partial N_{exp}}{\partial(Q/M_Z)}}{\frac{\partial N_{MC}}{\partial Q/M_Z}}$$



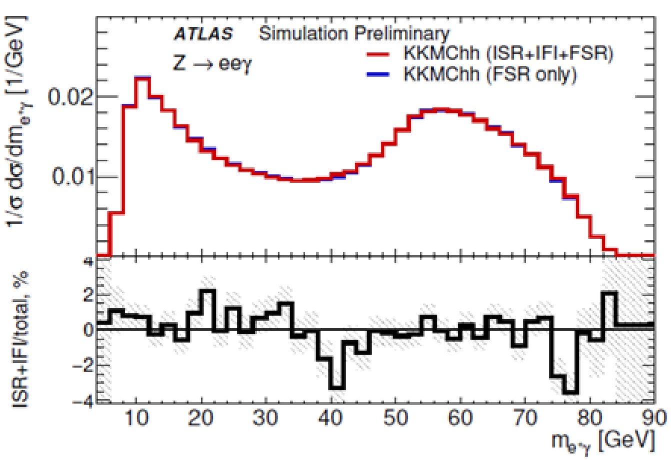


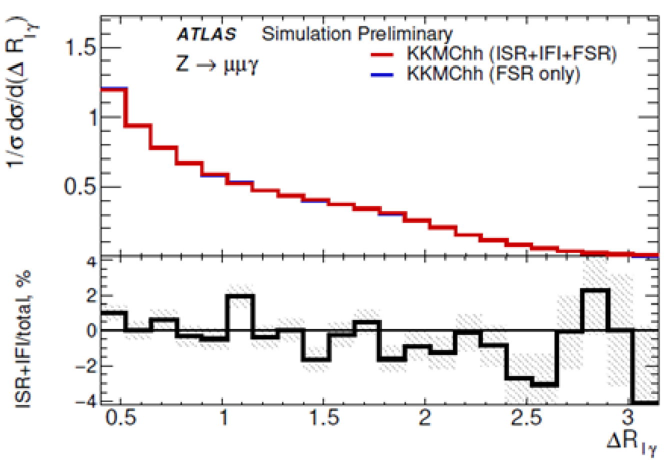
Theory uncertainties on predictions

a) for FSR itself, theory uncertainty estimated for Photos from variations of higher order corrections is ~ 0.2%

b) Sherpa theory uncertainty is estimated for full llγ predicted rate (this includes QED ISR and FSR but not IFI) as 2%. Certainly too conservative, needs further discussion with authors.

c) KKMChh includes full QED prediction and separates out QED ISR and IFI. Uncertainties are the same as for Photos since, as shown later, contributions from ISR and IFI are almost negligible within the fiducial selections of this analysis.





Unfolding for Z→2lγ process

- $m_{l\gamma}$, ΔR, p_t^{γ} are variables of interest
- EWUnfolding tool implements Bayesian unfolding with 3 iterations
- Powheg+Photos is used as baseline MC for unfolding.

Fiducial volume

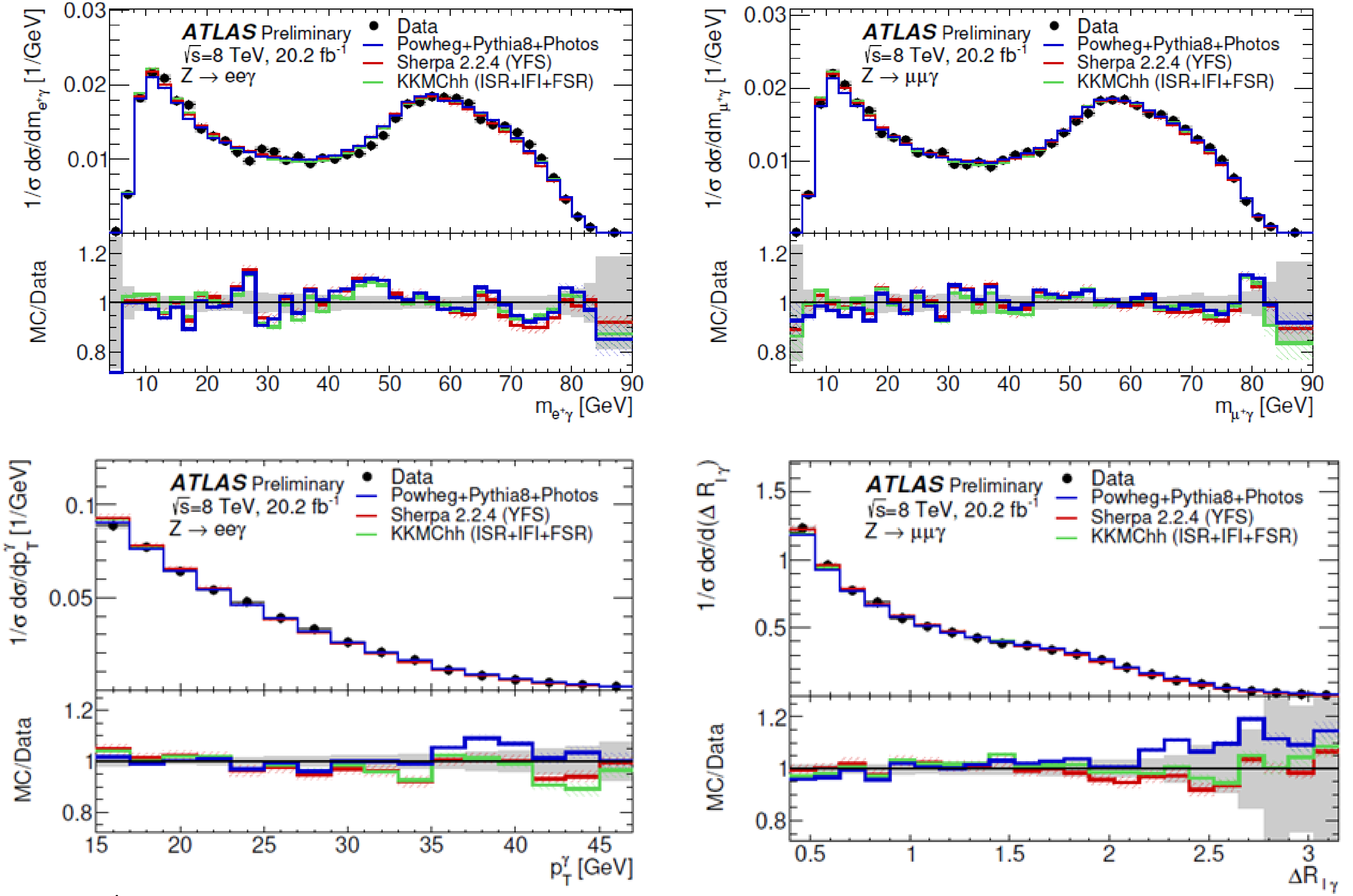
Photon with $p_{\mathrm{T}} > 15$ GeV
$\lvert\eta_\gamma\rvert < 2.37$ excluding $1.37 < \lvert\eta_\gamma\rvert < 1.52$
Leptons with $p_{\mathrm{T}} > 25, 10$ GeV
$\lvert\eta_\mu\rvert < 2.7$
$\lvert\eta_e\rvert < 2.47$
At least one photon + one pair of same-flavour opposite-sign leptons
$\Delta R_{l\gamma} > 0.4$
$20 < m_{ll} < 80$ GeV
$80 < m_{ll\gamma} < 100$ GeV

Prompt leptons and photons

For bare and dressed leptons

Dressing: the photons with ΔR<0.1 were absorbed by the leptons.

The unfolded data in comparison with different MC



Powheg/Photos and KKMChh should be almost identical since they are based both on initial Photos some years ago. But it seems that KKMChh agrees more closely with Sherpa than with Powheg/Photos.

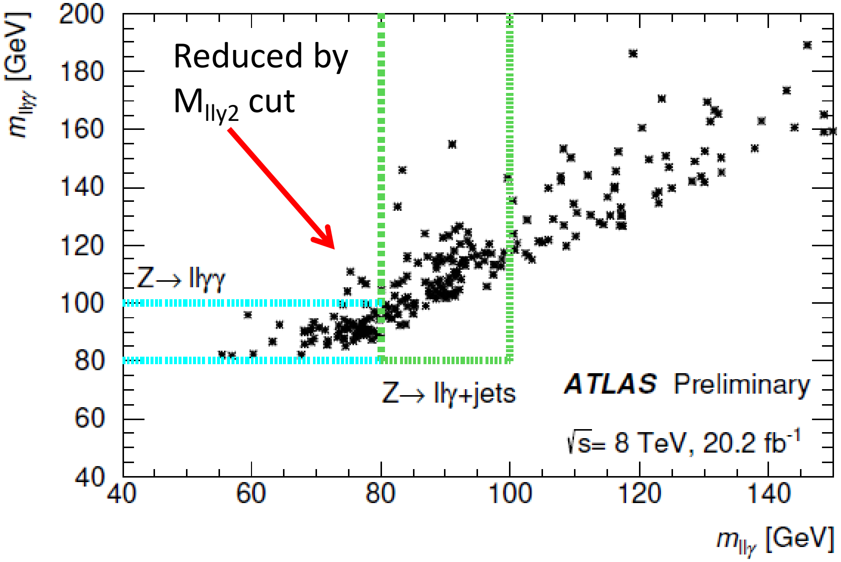
Selections $Z \to 2l2\gamma$

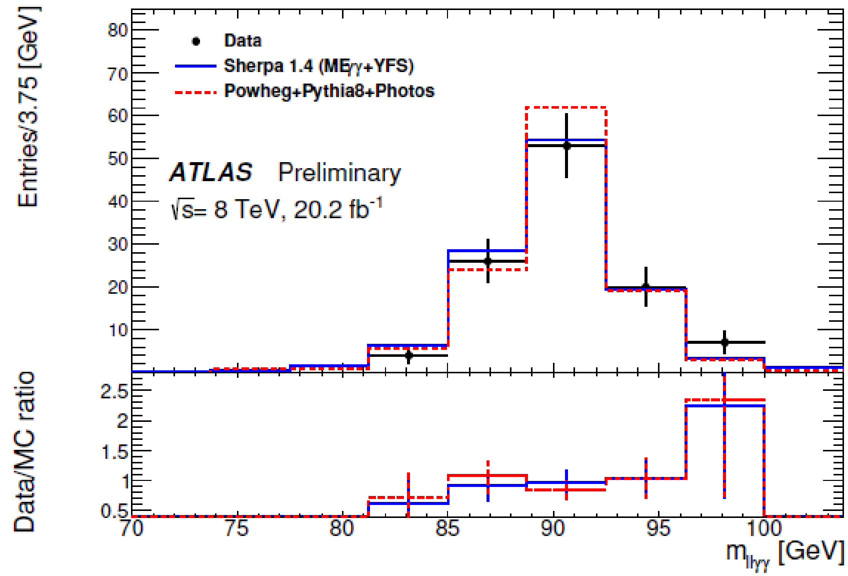
	Z->eeγ	**Z->μμγ**
Triggers	EF_2e12Tvh_loose EF_mu24i_tight EF_mu36_tight	EF_2mu13 EF_mu18_mu8_EFFS EF_mu24i_tight EF_mu36_tight
Photon selection	Photon with highest P_t; $P_t(\gamma) > 15$ GeV Second photon $P_t(\gamma) > 10$ GeV $\|\eta(\gamma)\| < 2.37$ excluding $1.37 < \|\eta(\gamma)\| < 1.52$; pass tight ID $\Delta R(\gamma, l) > 0.4$ (0.3); topoEtcone40(γ) < 4 GeV	
Lepton selection	$P_t(e)$>15 GeV; Loose e; $\|\eta(e)\| < 2.47$; topoEtcone40(e)/E_t < 0.3	$P_t(\mu)$>15 GeV; $\|\eta(\mu)\| < 2.37$; topoEtcone40(μ)/E_t < 0.2
Invariant mass	At least 2 photon +2 e with opposite sign Max(P_{t1},P_{t2})>25 GeV M(eeγ) < 80 GeV;	At least 2 photon +2 μ with opposite sign Max(P_{t1},P_{t2})>25 GeV M(μμγ) < 80 GeV;

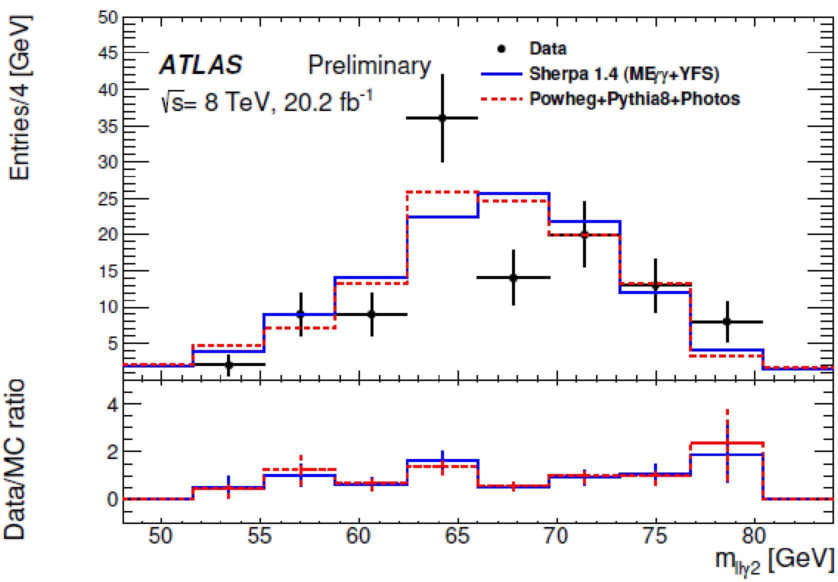
The difference with 2lγ selections:
- PTγ2 > 10 GeV
- m_llγ < 80 GeV for both photons
- no m_llγγ cut

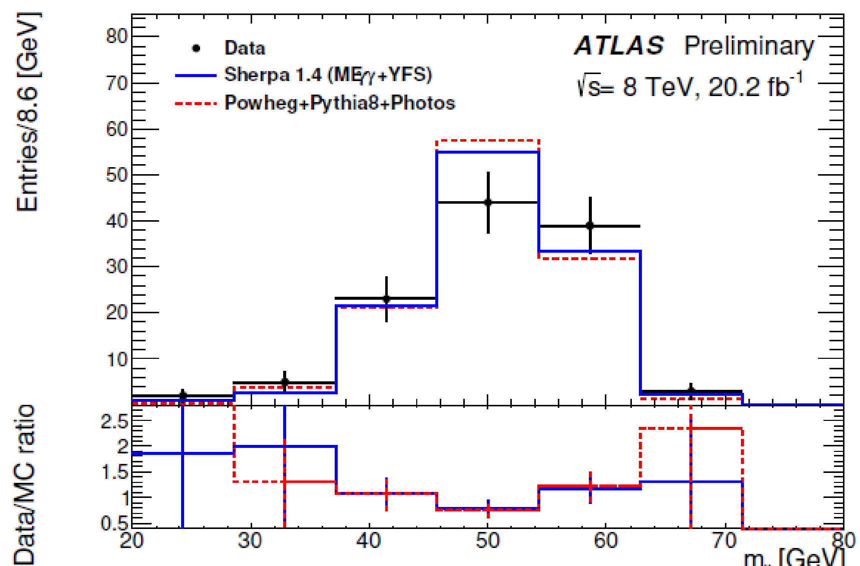
Selections $Z \to 2l2\gamma$

116 events $ee2\gamma+\mu\mu2\gamma$









There is no $M_{ll\gamma\gamma}$ cut and no background is seen at top right plot.
The background at top left plot is reduced by $M_{ll\gamma 2}$ < 80 GeV cut.

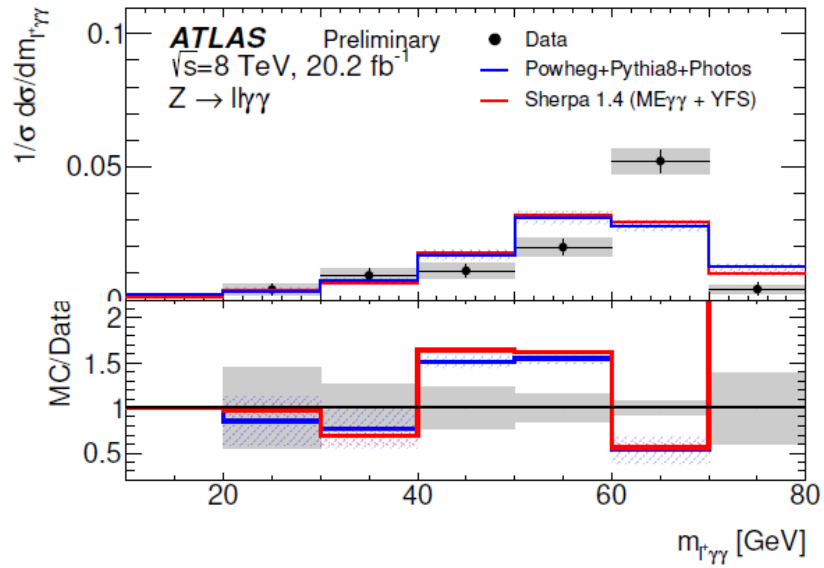
Unfolding

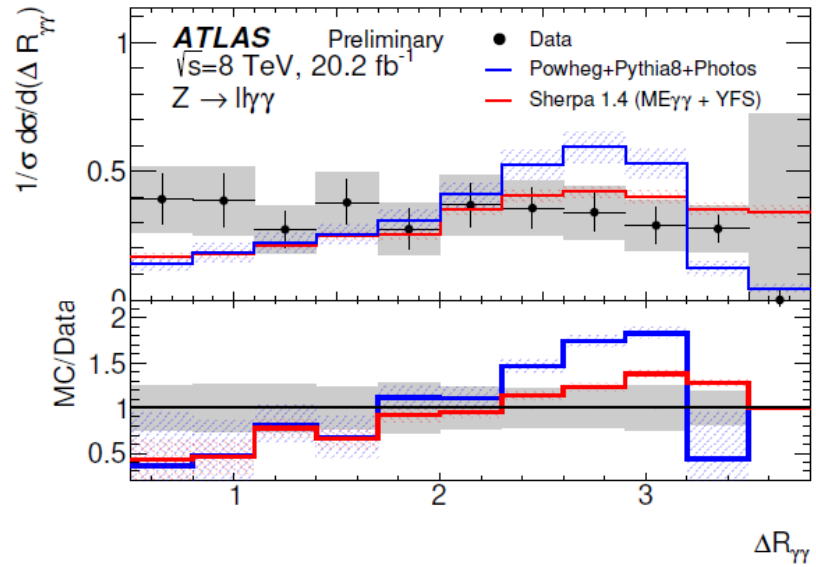
- $m_{l+\gamma\gamma}$, $m_{l-\gamma\gamma}$, ΔR (l, γ_1), $p_T(\gamma_1)$, ΔR(l, γ_2), $p_T(\gamma_2)$, $\Delta R(\gamma_1, \gamma_2)$ are variables of interest
- EWUnfolding tool implements Bayesian unfolding with 1 iteration
- No Background was found
- Sherpa 2l2γ MC at LO is used as baseline MC for unfolding.
- 2μγ and 2eγ channels are combined

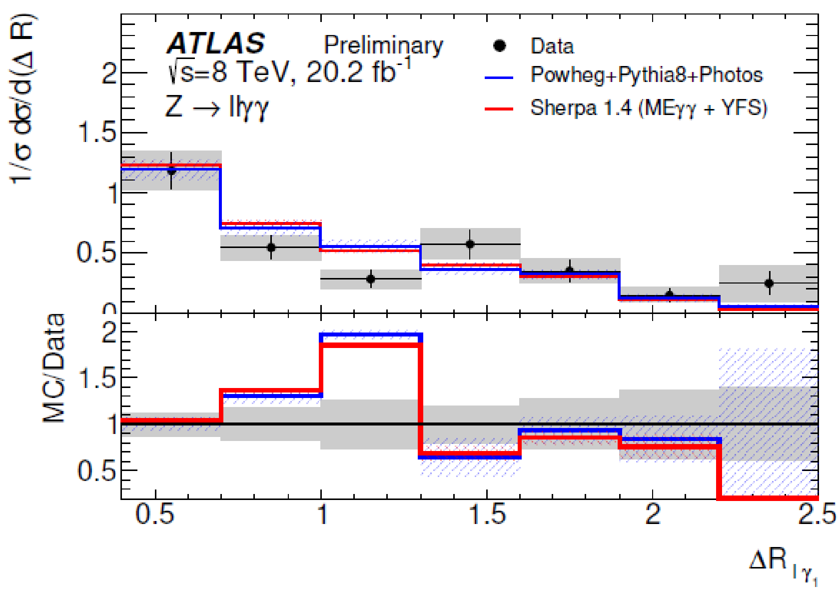
Table 20: Fiducial volume, cuts at truth level

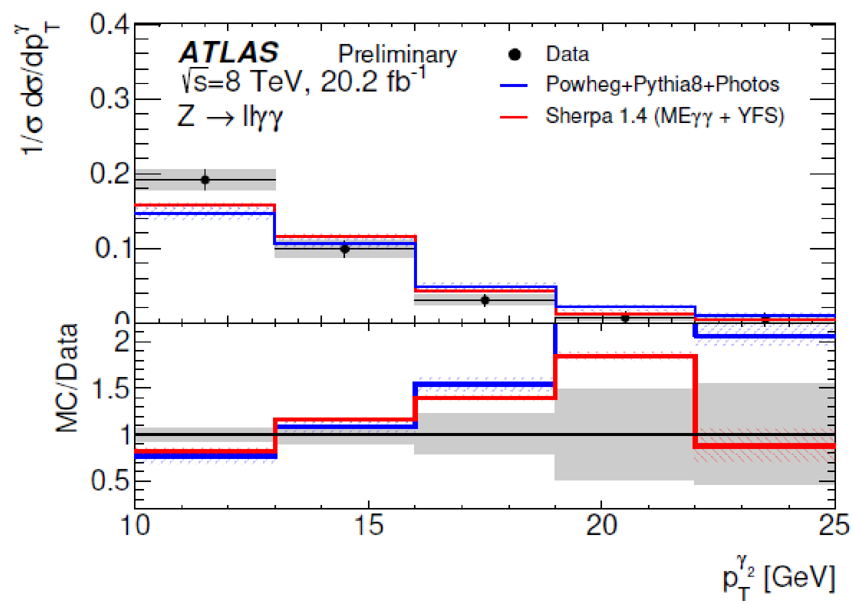
Photon with the highest $P_t(\gamma_1) > 15\ GeV$;
Second photon $P_t(\gamma_2) > 10\ GeV$;
Leptons with the highest $P_t(l) > 15\ GeV$
At least 2 photon + 2l same flavor with opposite sign
$\delta R(\gamma_1, l) > 0.4$
$\delta R(\gamma_2, l) > 0.4$
$max(P_{t_1}, P_{t_2}) > 25\ GeV$
$M(ll\gamma) < 80\ GeV$

The unfolded data for Z →2l2γ









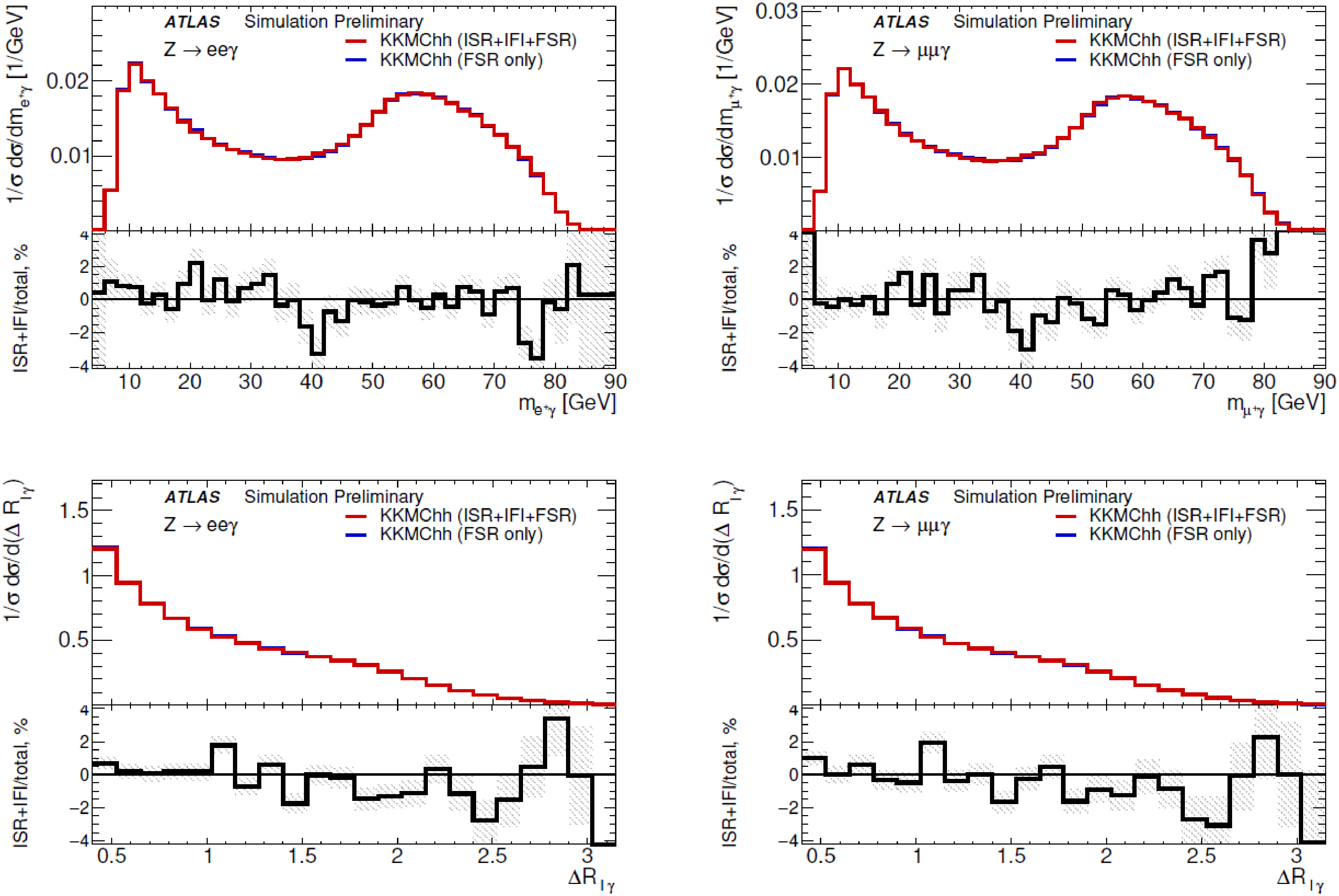
This is the first observation of the Z→2L2γ process

Summary

1. Differential distributions of the $m_{l\gamma}$, ΔR, p_t^{γ} are measured with high precision. The overall accuracy of the measurements is at the 1-2% percent level over a large fraction of the overall phase space, with an average overall systematic uncertainty of 0.6% for the chosen observables, $m_{l\gamma}$, ΔR, p_t^{γ}.
2. The results are found to be in agreement with state-of-the-art predictions with PowHeg+Pythia8+PHOTOS, Sherpa 2.2.4 and KKMChh.
3. Some small hints of deviations from state-of-the-art predictions are present in phase space corners: $20<m_{ll}<45$ GeV, $m_{l\gamma}$~80 GeV, $\Delta R_{l\gamma}$~2.5.
4. First observation of the process $Z\rightarrow 2l2\gamma$. 116 events are observed for both e and μ channels. Data is described by LO MC rather well with respect to statistics. $dR_{\gamma\gamma}$ distribution reveals some Data\MC difference.
5. Future measurements using full run-2 dataset should reach accuracy required to observe e/mu difference expected for bare leptons at the edge of the phase space. They will also shed light on whether the state of the art predictions shown here are sufficiently accurate to describe the data, in particular for events with more than one hard photon in the final state.

Thanks for your attention

Backup


ATLAS Simulation Preliminary
Z → eeγ
KKMChh (ISR+IFI+FSR)
KKMChh (FSR only)
1/σ dσ/dm_{e⁺γ} [1/GeV]
ISR+IFI/total, %
m_{e⁺γ} [GeV]
ATLAS Simulation Preliminary
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KKMChh (ISR+IFI+FSR)
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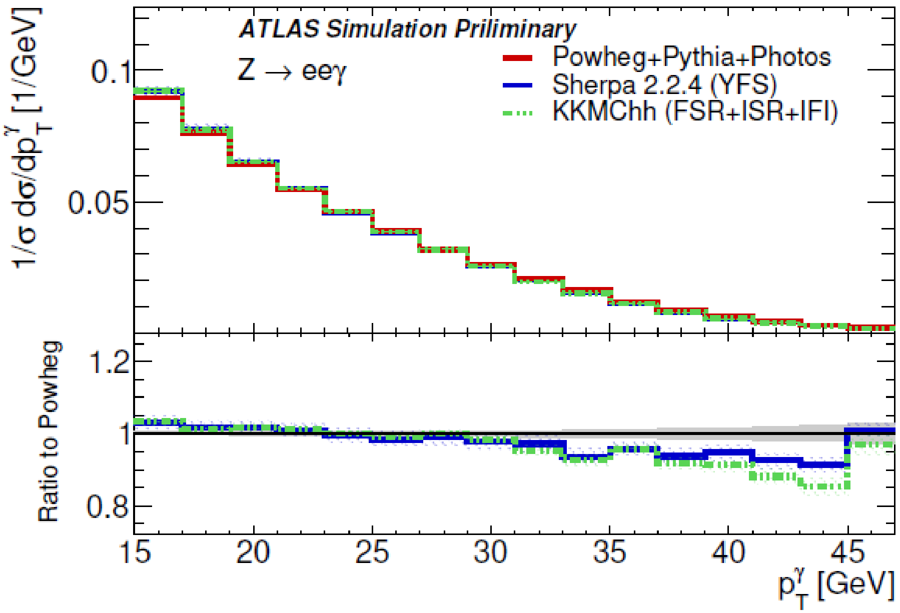
ATLAS Simulation Priliminary
Z → eeγ
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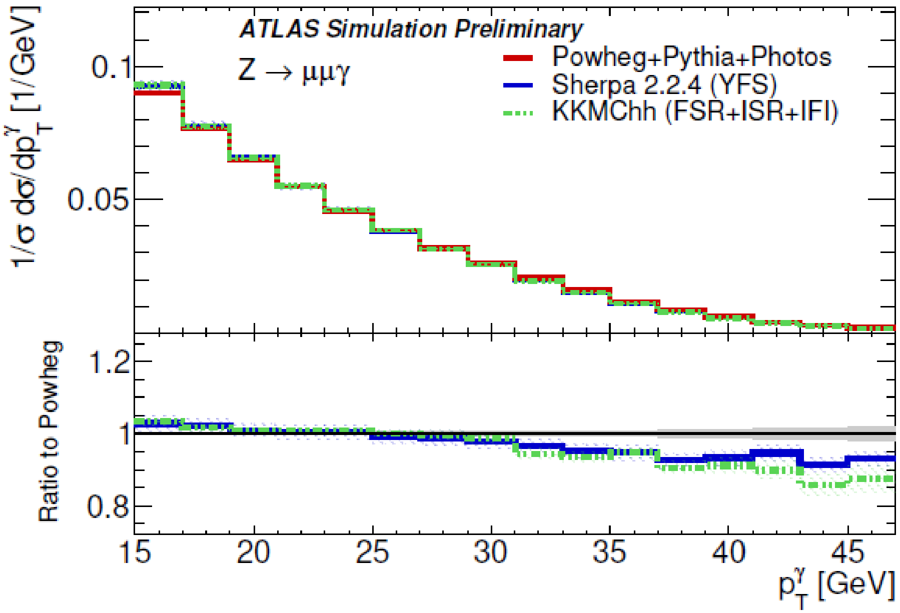
1/σ dσ/dp$_T^γ$ [1/GeV]
Ratio to Powheg
p$_T^γ$ [GeV]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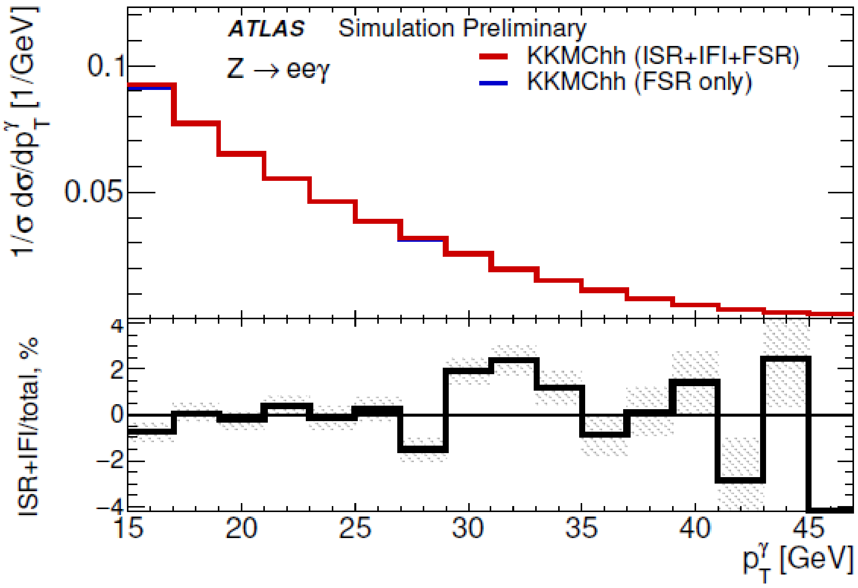
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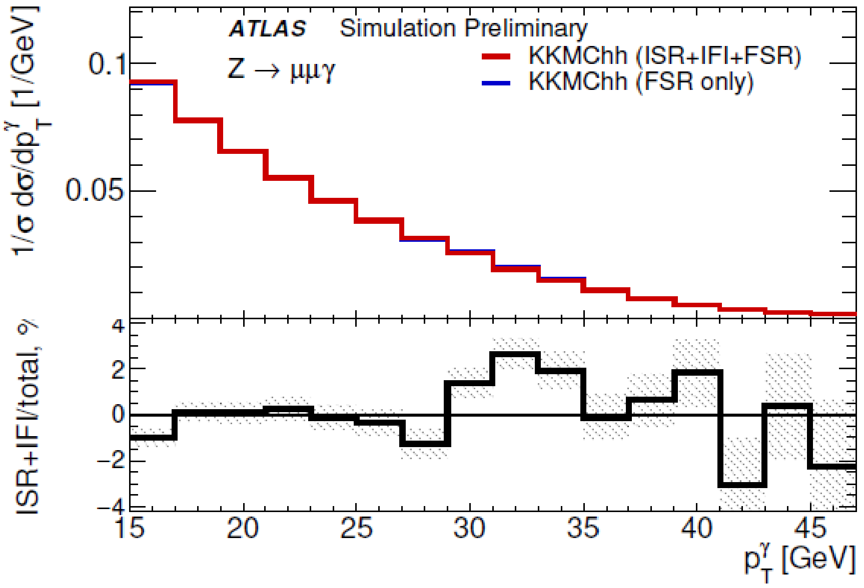
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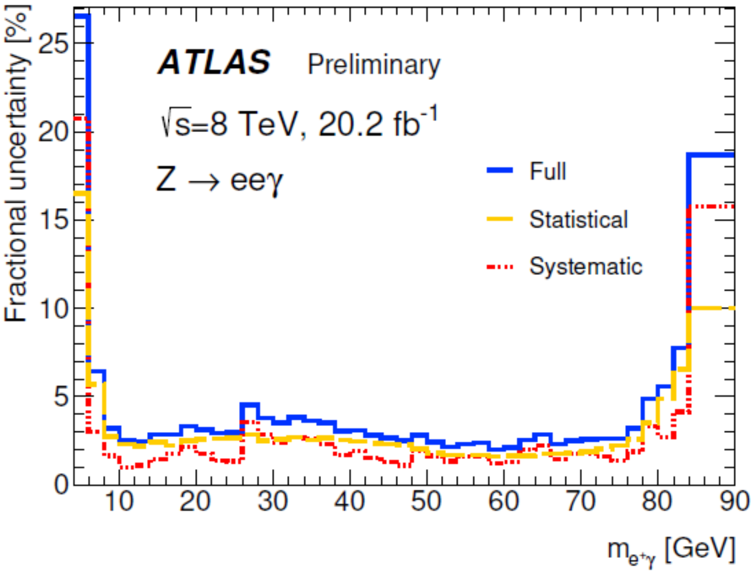
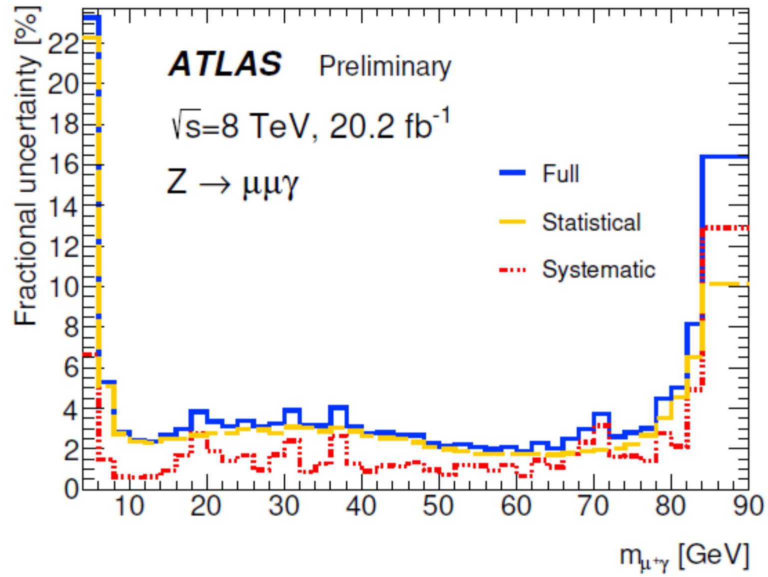
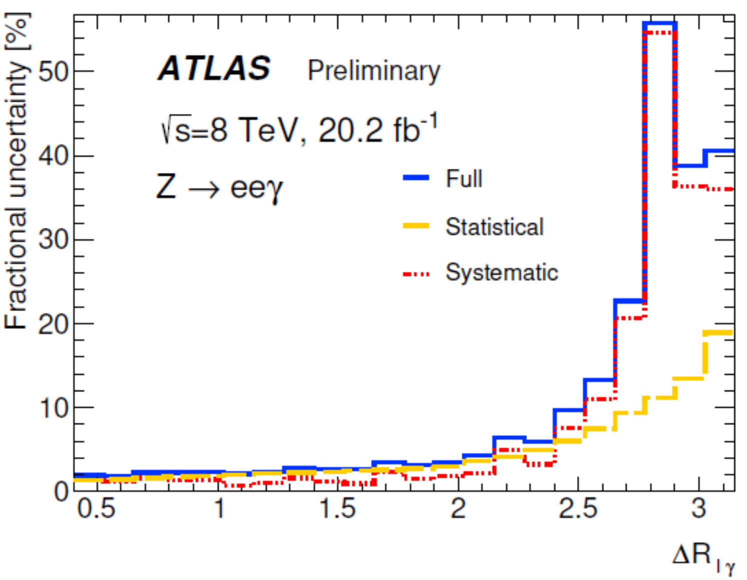
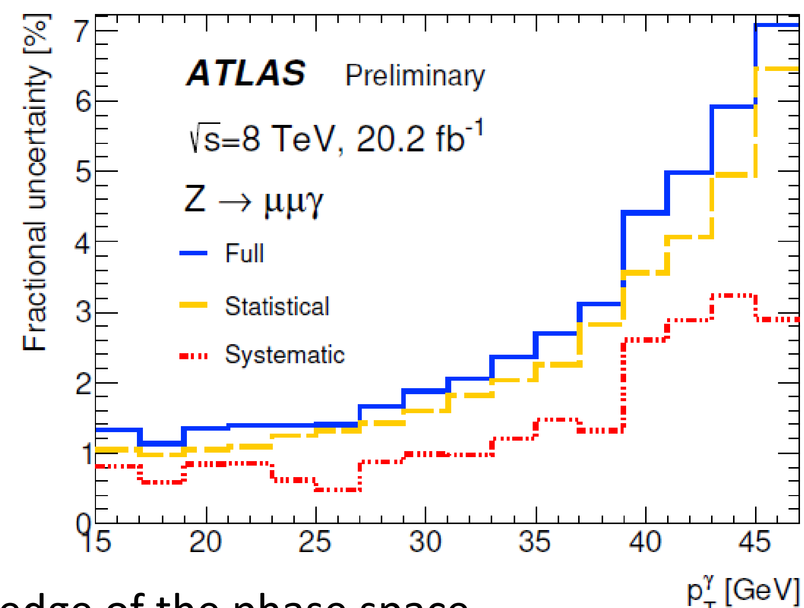
Systematic uncertainties

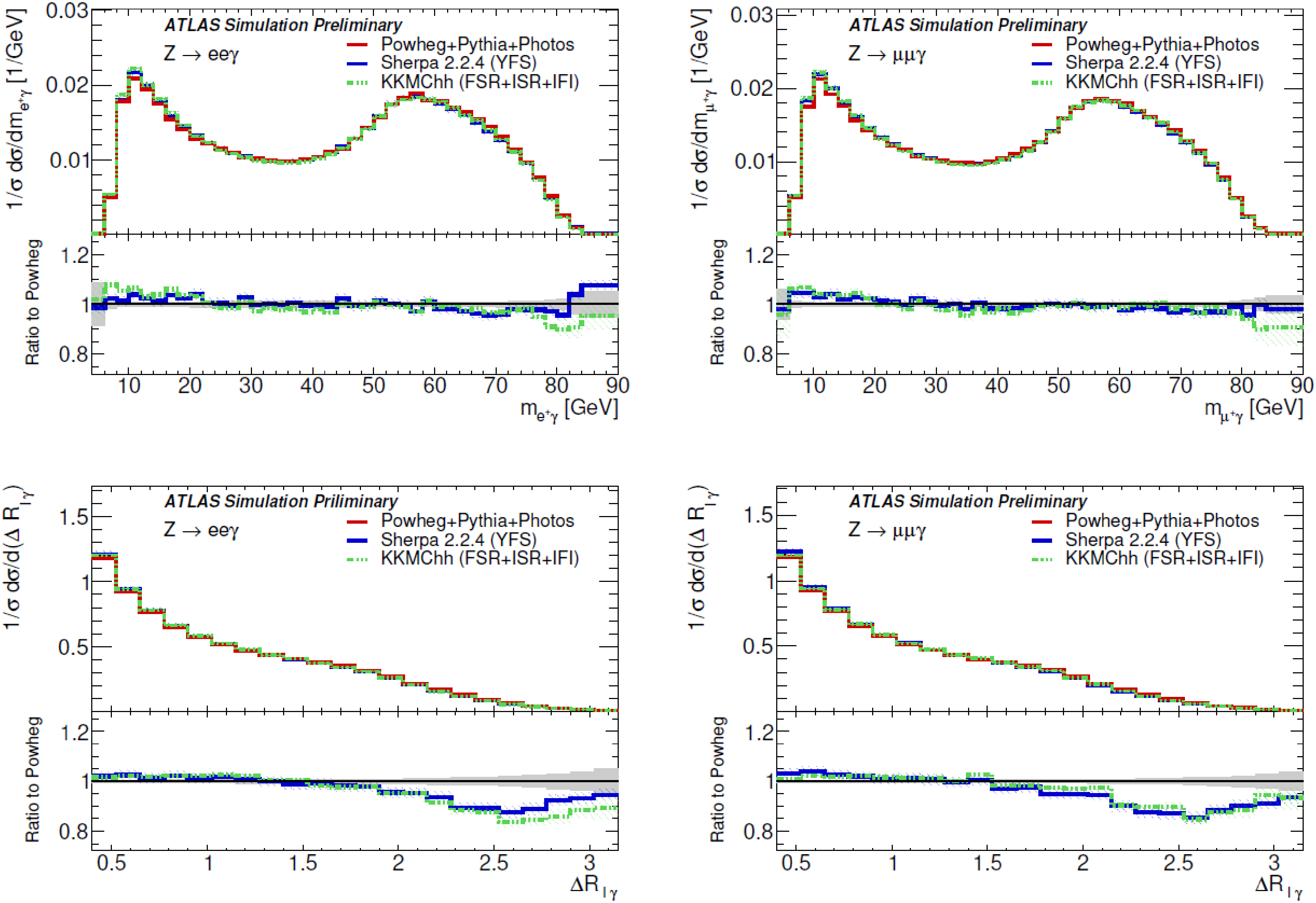








MC statistical uncertainty dominates at the edge of the phase space



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KKMChh (FSR+ISR+IFI)
1/σ dσ/d(Δ R_{lγ})
Ratio to Powheg
ΔR_{lγ}

Integrated fiducial cross sections

Table 4: Uncertainties in the fiducial cross-section measurements

Uncertainty	$Z \to ee\gamma$	$Z \to \mu\mu\gamma$
Statistical	0.7%	0.7%
Experimental systematic	3.5%	2.3%
Luminosity	1.9%	1.9%
QCD theory	0.3%	0.3%
Total	4.1%	3.1 %

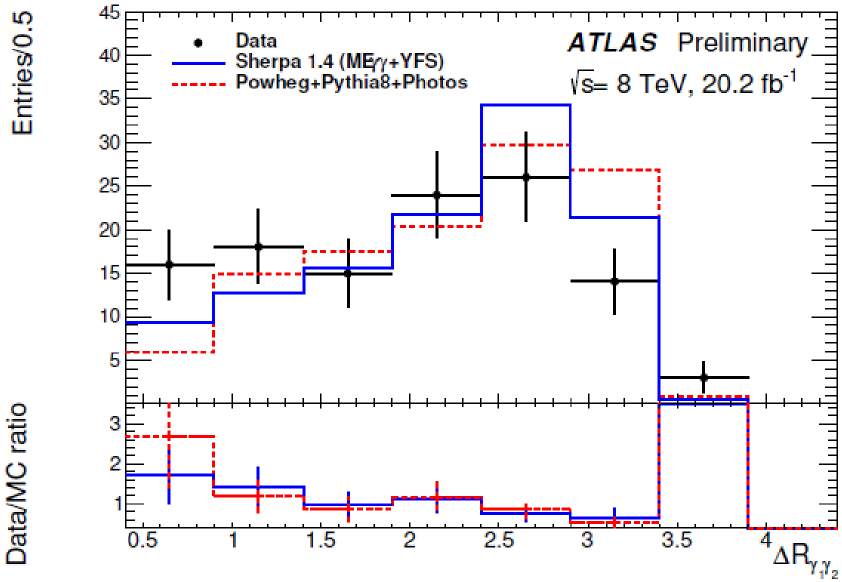
Table 5: Integrated fiducial cross sections (pb)

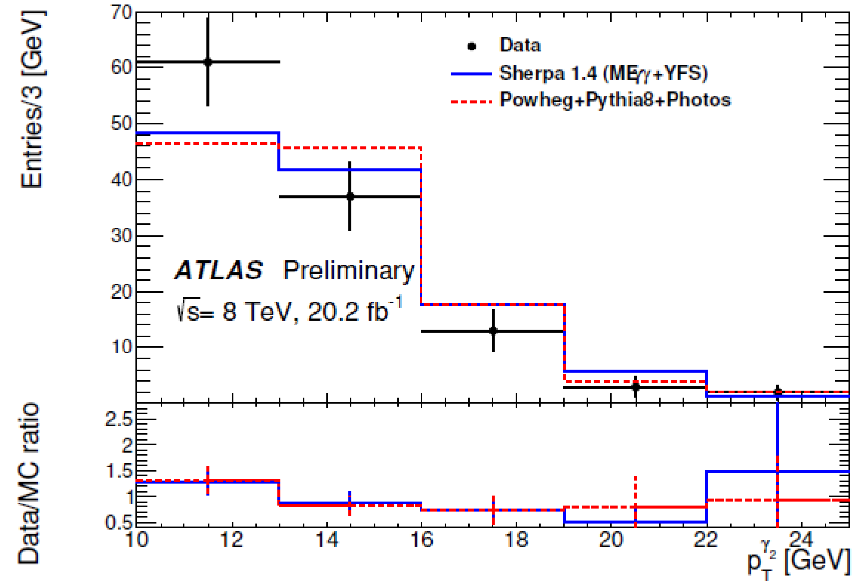
Process	Measurement	Prediction
$Z \to ee\gamma$ ($m_{ll} > 20$ GeV)	3.15 ± 0.02 (stat) ± 0.11 (syst) ± 0.06 (lumi)	3.07 ± 0.1
$Z \to \mu\mu\gamma$ ($m_{ll} > 20$ GeV)	3.21 ± 0.02 (stat) ± 0.07 (syst) ± 0.07 (lumi)	3.24 ± 0.1
$Z \to ee\gamma$ ($m_{ll} > 45$ GeV)	2.83 ± 0.02 (stat) ± 0.10 (syst) ± 0.06 (lumi)	2.73 ± 0.1
$Z \to \mu\mu\gamma$ ($m_{ll} > 45$ GeV)	2.89 ± 0.02 (stat) ± 0.06 (syst) ± 0.06 (lumi)	2.88 ± 0.1
$Z \to ee\gamma$ ($20 < m_{ll} < 45$ GeV)	0.328 ± 0.005 (stat) ± 0.011 (syst) ± 0.006 (lumi)	0.335 ± 0.01
$Z \to \mu\mu\gamma$ ($20 < m_{ll} < 45$ GeV)	0.322 ± 0.005 (stat) ± 0.006 (syst) ± 0.006 (lumi)	0.355 ± 0.01

Theory uncertainty on integrated cross section is dominated by QCD scale variations and PDFs and is taken from DYNNLO to be ~ 2-3%

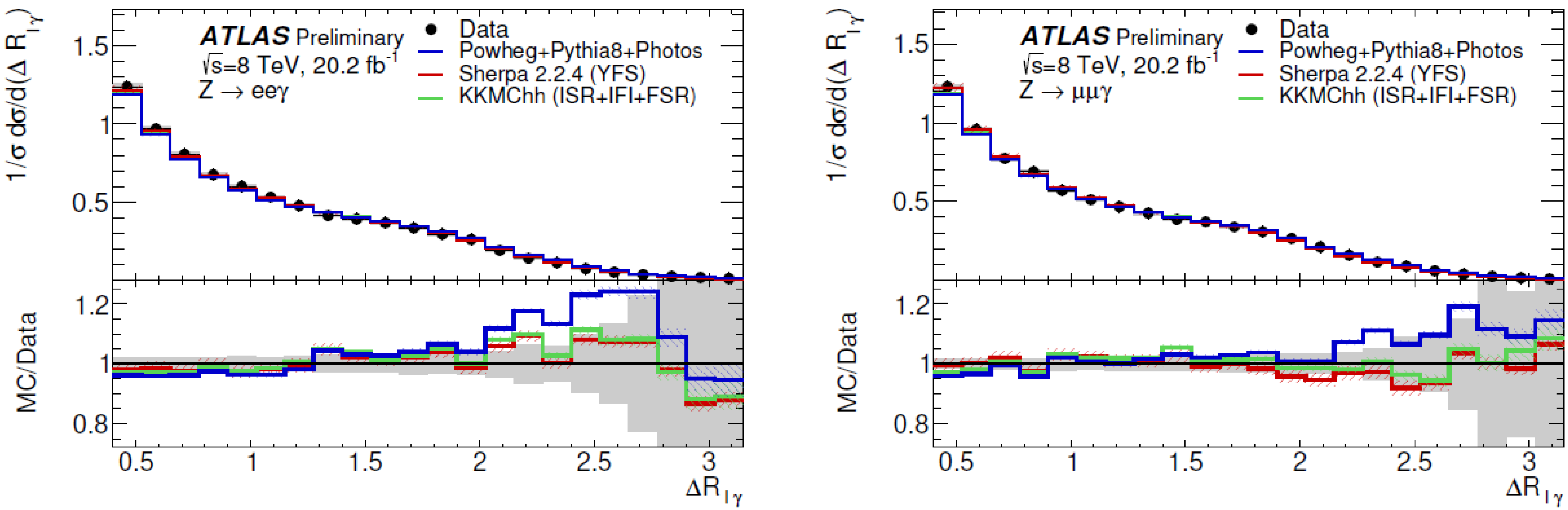
Data to MC comparison p_T^{γ}, $\Delta R_{\gamma\gamma}$

Given low stats, electrons and muons are combined yielding at total of 116 events





The unfolded data in comparison with different MC



Powheg/Photos and KKMChh should be almost identical since they are based both on initial Photos some years ago. But it seems that KKMChh agrees more closely with Sherpa than with Powheg/Photos.