Electron and Photon energy calibration with $J/\psi \rightarrow ee$ and $Z \rightarrow ll\gamma$ events in 13 TeV ATLAS data

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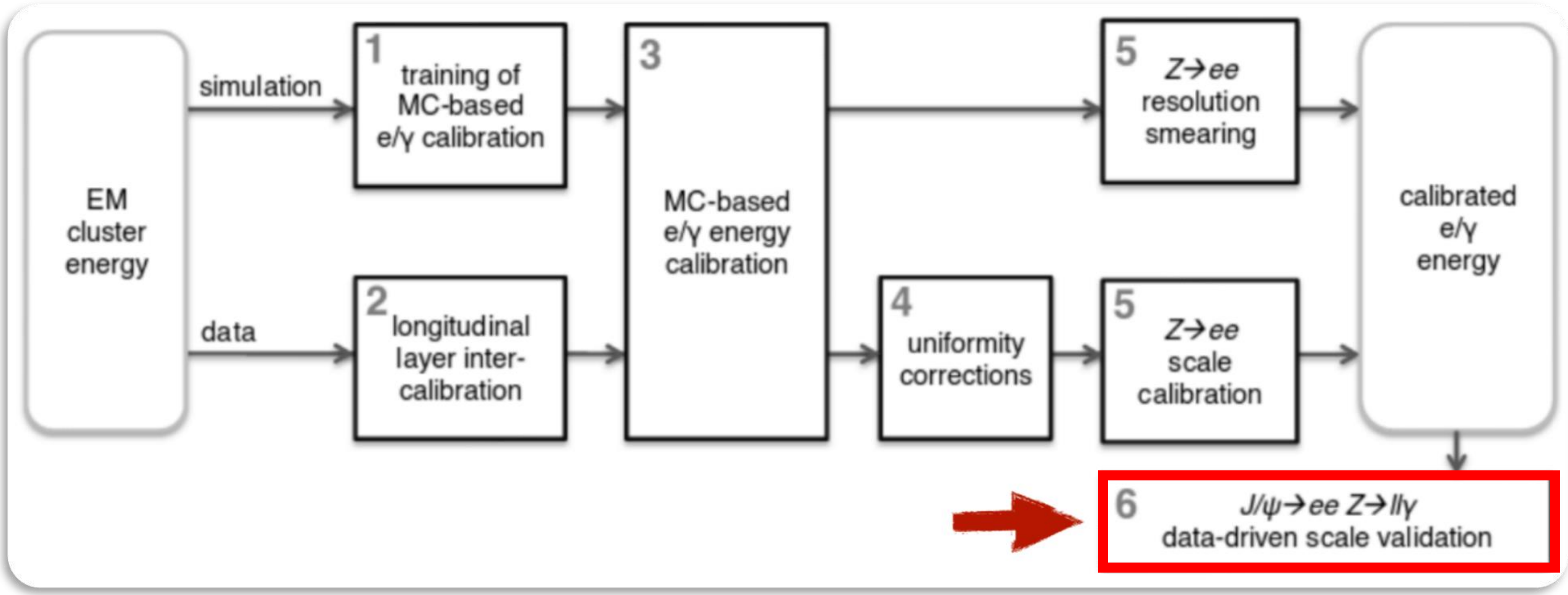
Motivation

- The standard calibration of photon is extracted from $Z \rightarrow ee$ events. The nominal $Z \rightarrow ee$ calibration is applied to all the electrons and photons in ATLAS.
- **Validate** the electron energy calibration at low pT with $J/\psi \rightarrow ee$ events.
- **Validate** the photons energy calibration with Radiative Z decays ($Z \rightarrow ll\gamma$ events).



Electron calibration with $J/\psi \rightarrow ee$

Introduction

- Obtain electron energy scale correction from the invariant mass of reconstructed pure and high statistics $J/\psi \to ee$ events.
- **Validate** the nominal electron energy calibration. (All the nominal $Z \to ee$ based calibration have been applied prior.)
- The residual miscalibration of electron energy can be parametrized:

$$E_{reco}^{Data}(\eta) = E_{reco}^{MC}(\eta)\big(1 + \alpha(\eta)\big)$$

Neglecting second-order terms

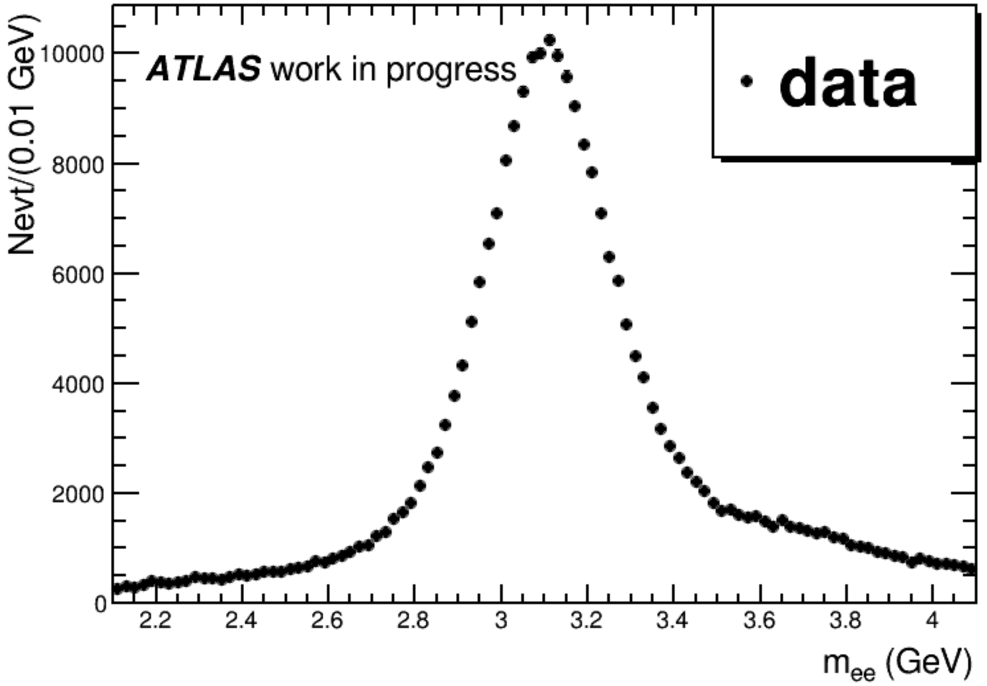
$$m_{ee}^{Data}(\eta_i, \eta_j) \cong m_{ee}^{MC}(\eta_i, \eta_j)\left(1 + \frac{\alpha_i + \alpha_j}{2}\right)$$

- The Procedure to get α:
  - Estimate the fraction of prompt J/ψ in data then merge prompt and non-prompt MC.
  - Divide the sample in (η_i, η_j) bins depending on the η value of the two selected electrons.
  - Fitting m_{ee} on MC to evaluate the J/ψ peak position and shape in each (η_i, η_j) bin.
  - Then do simultaneous fit on data for all (η_i, η_j) bins to get all α together.

Object and Event selection

- Both data and MC events are required to contain two electrons after the following criteria

- $5 < E_T < 30$ GeV for leading electron
- $5 < E_T < 15$ GeV for sub leading electron
- electron pseudorapidity $|\eta| < 2.40$
- the primary vertex was located at the region $|z| < 150$ mm
- fixed cut loose isolation
- likelihood-based tight identification, to suppress fake electron candidates from misidentified hadronic jets.
- only 2 good electrons are selected with opposite charge, so there is one candidate in the event.
- the invariant mass of reconstructed dielectron in $[1, 5]$ GeV for the spectrum.

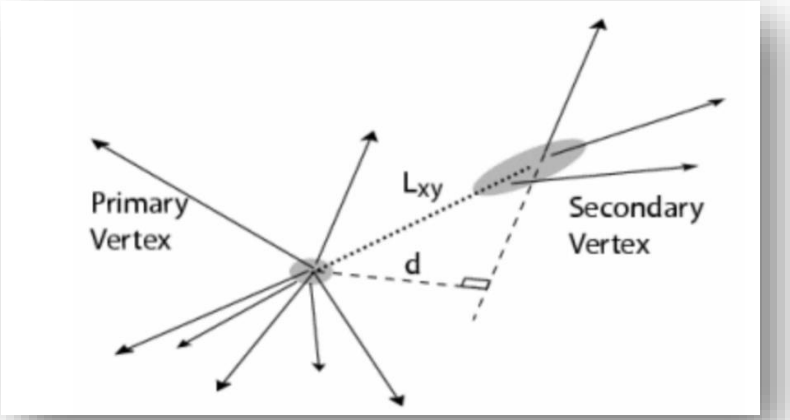


The Pseudo-proper time fit

- J/ψ candidates produced in pp collisions at the LHC can be:
  - prompt, when they are a direct product of the pp collision.
  - non-prompt, when they originate from the decay of a hadron.
- The fraction of prompt J/ψ in data is estimated by fitting the pseudo proper time (τ) distribution. The total PDF of τ:

$$f(\tau) = f_P \cdot h_P(\tau) \otimes R(\tau) + (1 - f_P) \cdot h_B(\tau) \otimes R(\tau)$$

- Here, $h_P(\tau)$ is the model for prompt (delta) and $h_B(\tau)$ is the model for non-prompt (exponential decay). $R(\tau)$ is the sum of resolution gaussians.

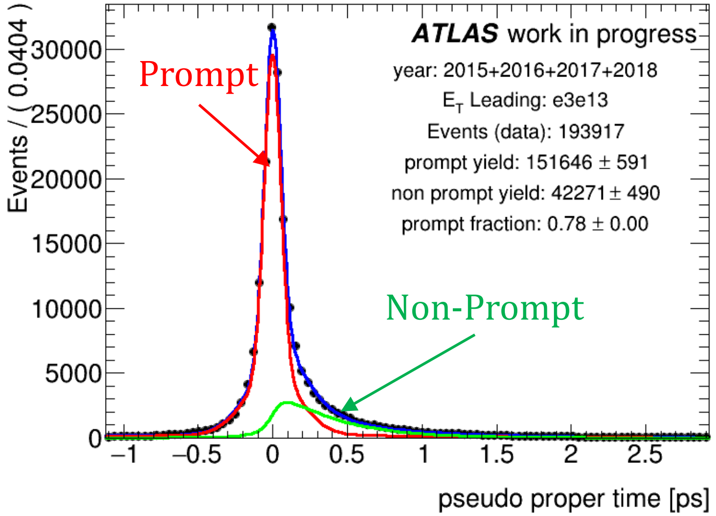


$$\tau = \frac{L_{xy} m^{J/\psi}}{p_T^{J/\psi}}$$

L_{xy}: decay length in the xy plane

The Prompt Fraction based on full Run2 data

Leading E_T (GeV)	PromptFraction
[5,7]	80.73% ± 2.77%
[7,9]	79.15% ± 1.95%
[9,14]	76.99% ± 0.44%
[14,30]	78.20% ± 0.21%

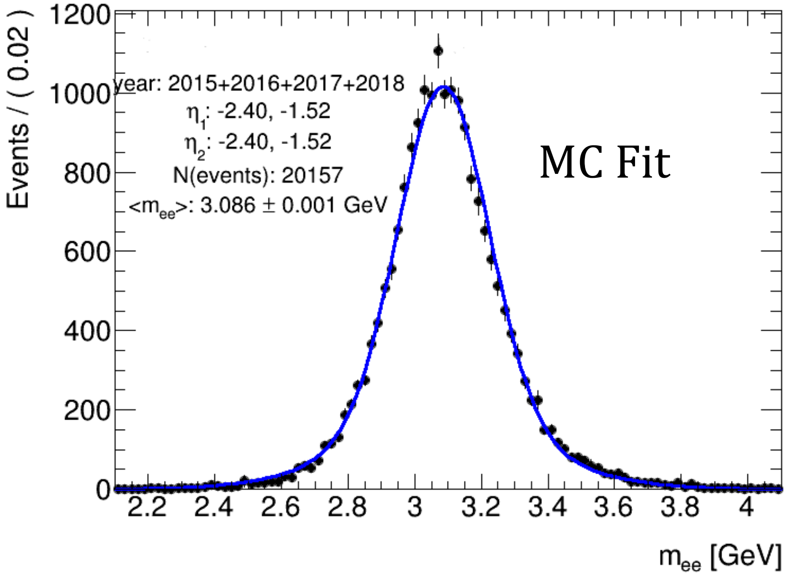


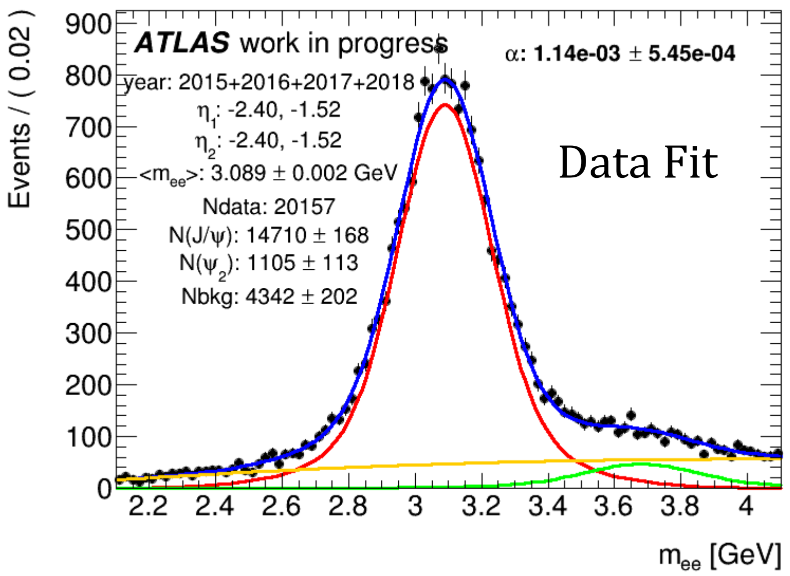
The invariant mass fit

- Divide the sample in (η_i, η_j) categories: $[0.0, \pm 0.4, \pm 0.8, \pm 1.1, \pm 1.37, \pm 1.52, \pm 2.40]$
- Fitting MC m_{ee} spectrum separately for each category with Double Sided Crystal Ball (DSCB) function to evaluate the J/ψ peak position and peak shape in each (η_i, η_j) bin.
- Perfrom simultaneous fit on data in all (η_i, η_j) bins to get all α together:

$$f(m_{ee}^{reco}) = DSCB(J/\psi) + DSCB(\psi(2S)) + ChebPol(2)$$

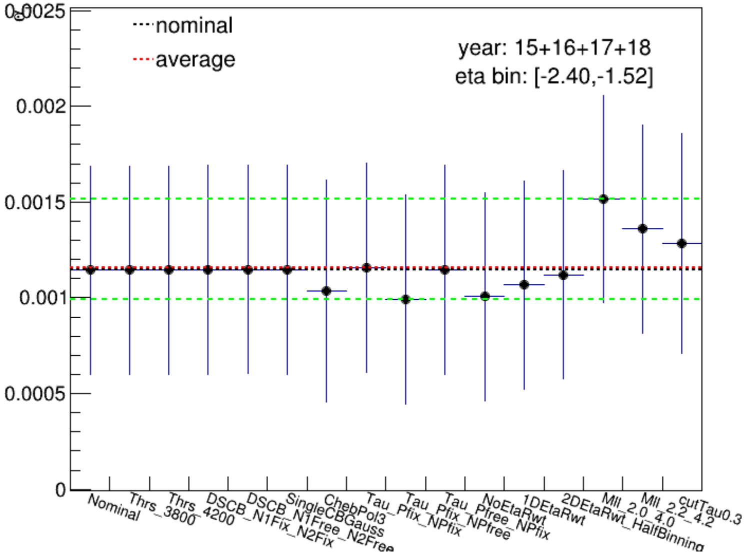
  - Description for J/ψ: fix the peak shape from MC sample, but float the peak position by introduce the energy scale variations of α_i and α_j.
  - Description of $\psi(2S)$: simply shift the J/ψ globe mass shape with the PDG value. (Float $N_{\psi(2S)}$)
  - Background contribution: Polynominal function.



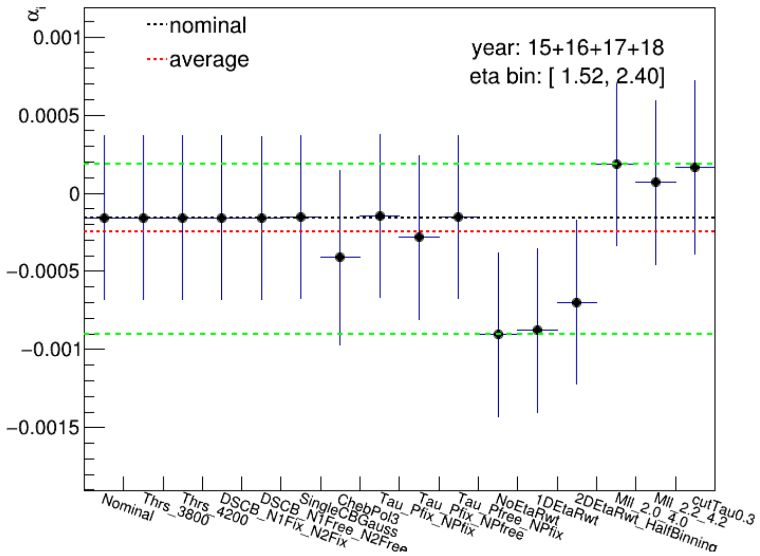


Systematic uncertainty

➢ The nine systematic sources are considered. The difference between the nominal value and the maximum and minimum variation (highlighted by green dashed line) is taken as systematic uncertainty on the α.



$-2.4 < \eta < -1.52$

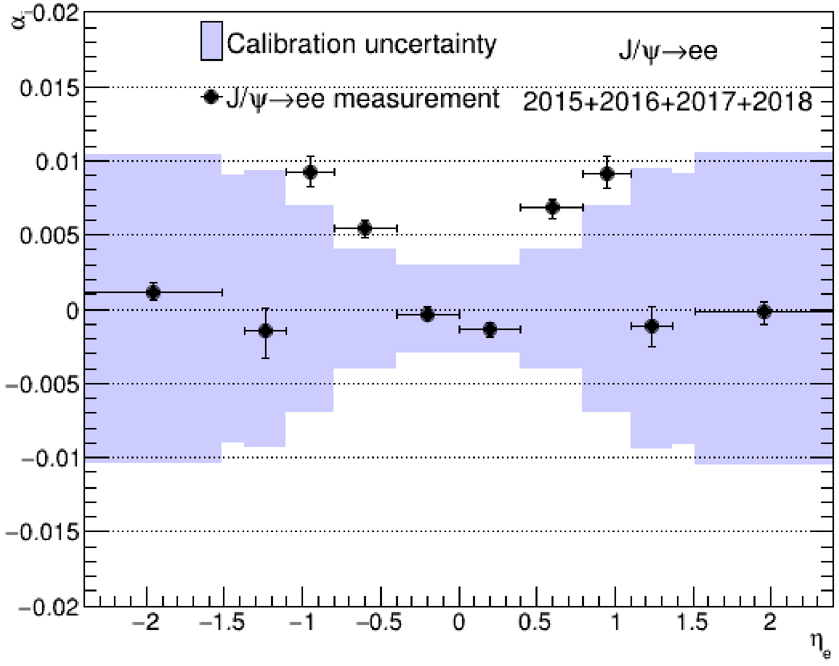


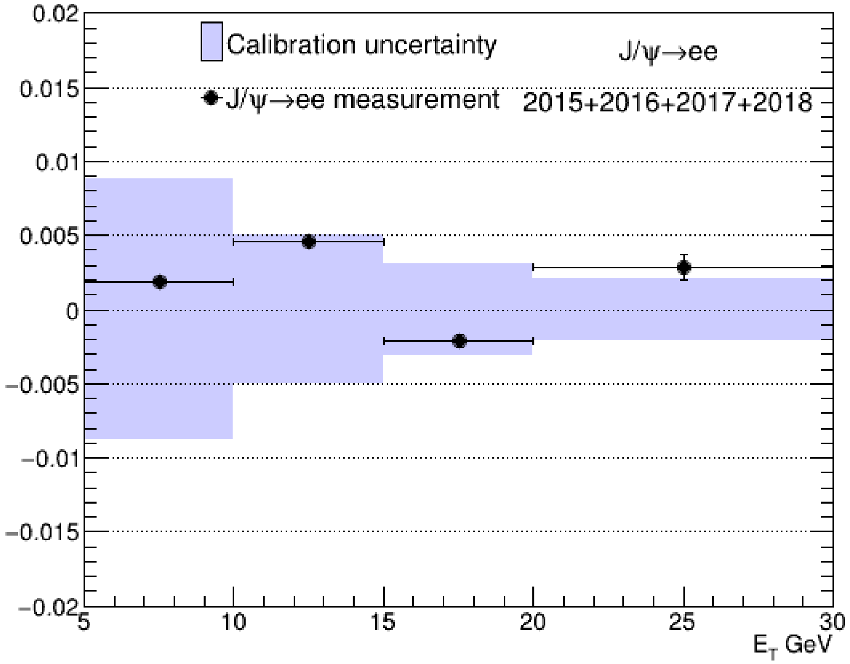
$1.52 < \eta < 2.40$

- The dots and blue error bars represent central values and statistical uncertainties in varied case.
- The black dashed line highlights the nominal α value, while the red dashed line refers to the arithmetic mean of α from all the variations in this η bin.

Results

- Obtained the Energy scales as a function of the electron η or E_T extracted from J/ψ events, and compared them with the systematic uncertainties extrapolated from the $Z \rightarrow ee$ calibration.
  - The error bars on the black dots represent the total uncertainty specific to the $J/\psi \rightarrow ee$ analysis.
  - The violet band represents $Z \rightarrow ee$ calibration uncertainty.
  - Good agreement between α and $Z \rightarrow ee$ calibration uncertainy.





Photon calibration with $Z \rightarrow ll\gamma$

Introduction

- The standard calibration of photon is extracted from $Z \rightarrow ee$ events.
- Since the inconsistence between the behaviour of electron and photon, the validation of photon energy scale is required to ensure that the extraction is resonable in photon energy calibration.
- To investigate that, the measurement of photon energy scale is performed on radiative Z decays: $Z \rightarrow ee\gamma$ and $Z \rightarrow \mu\mu\gamma$.
- Get the scale with Template fit
  - In the template fit method, the photon pT is multiplied a factor (1+α).
  - The χ^2 between MC templates and data is computed at each α point:

$$\chi^2 = \sum_{i=1}^{N_{bin}} \frac{(Data_{i-bin} - MC_{i-bin})^2}{(\delta Data_{i-bin})^2 + (\delta MC_{i-bin})^2}$$

  - The distribution of χ^2 is treated as a function of α and fitted with $\chi^2(\alpha) = \frac{(\alpha-\mu)^2}{\sigma^2} + \chi^2_{min}$
  - The best estimator of PES is the μ while the uncertainty will be σ.

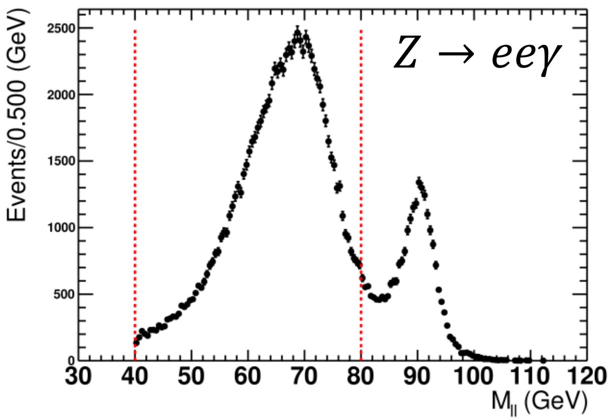
Object and Event selection criteria

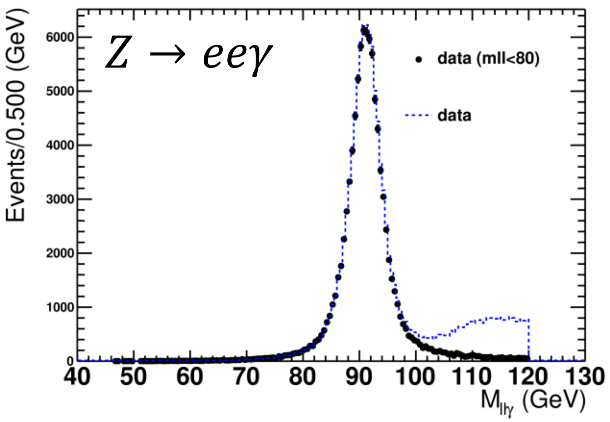
- The object selection criteria of photon, electron and muon.

	Electron	Muon	Photon
Acceptance	$p_t > 18GeV$ $\lvert\eta\rvert < 1.37, 1.52 < \lvert\eta\rvert < 2.47$ $d_0/\sigma_{d_0} < 10$ $\lvert Z_{PV}\rvert < 10mm$	$p_t > 15GeV$ $\lvert\eta\rvert < 2.5$ $d_0/\sigma_{d_0} < 10$ $\lvert Z_{PV}\rvert < 10mm$	$E_t > 10GeV$ $\lvert\eta\rvert < 1.37, 1.52 < \lvert\eta\rvert < 2.47$
ID	LHMedium	Medium	Tight
Isolation	FCLoose	FCLoose	FixedCutLoose

- The event selection criteria of $Z \to ll\gamma$

	$Z \to ll\gamma$
N_l	At least 2 leptons
N_γ	At least 1 photon
FSR cut	$40 < m_{ll\gamma} < 120GeV$
ISR cut	$40 < m_{ll} < 80GeV$
$\Delta R_{l,\gamma}$	$\Delta R_{l,\gamma} > 0.4$



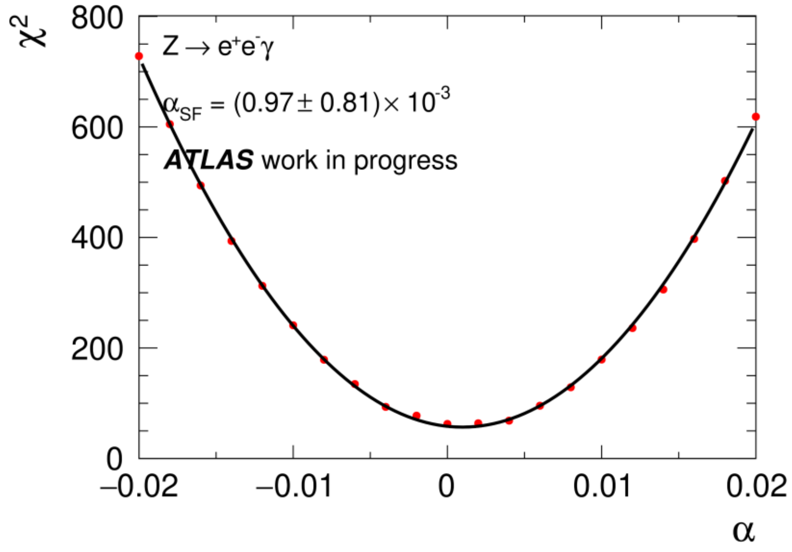


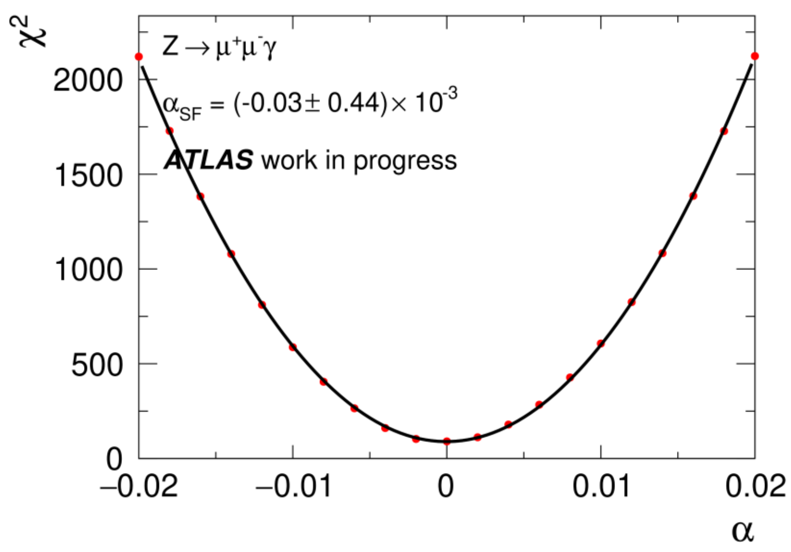
Inclusive photon energy scale factor

- Calculate the $\chi^2(\alpha)$ between data and each MC template (applied the PES α).

$$\chi^2(\alpha) = \sum_{i=1}^{N_{bin}} \frac{(Data_{i-bin} - MC_{i-bin})^2}{(\delta Data_{i-bin})^2 + (\delta MC_{i-bin})^2}$$

- Fit the χ^2 distribution with parabola formula $\chi^2(\alpha) = \frac{(\alpha-\mu)^2}{\sigma^2} + \chi^2_{min}$, where the μ is best estimator of PES and the σ is the uncertainty of PES.
  - The fit results are show in the table.

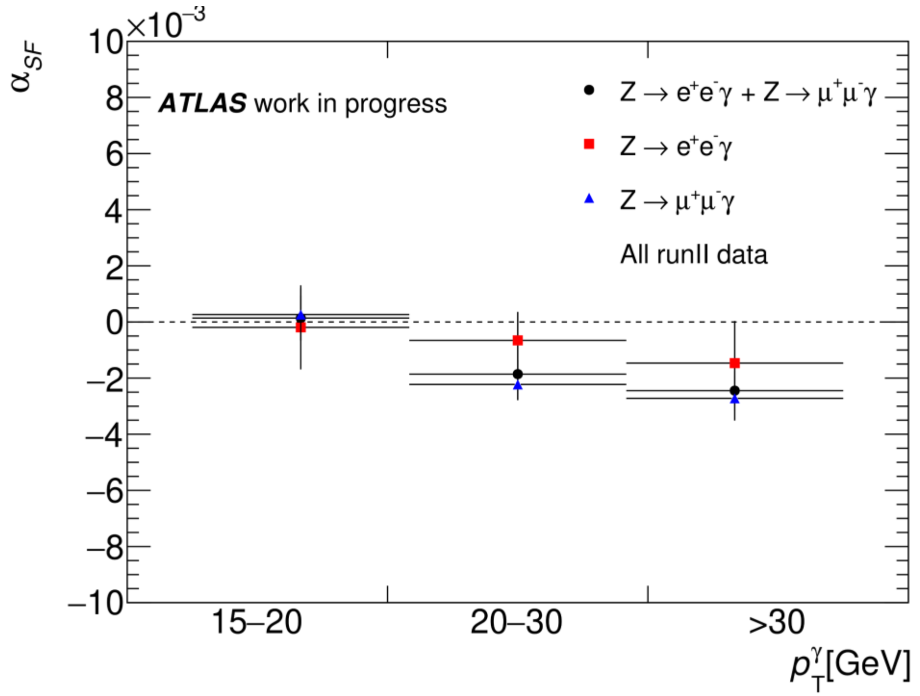


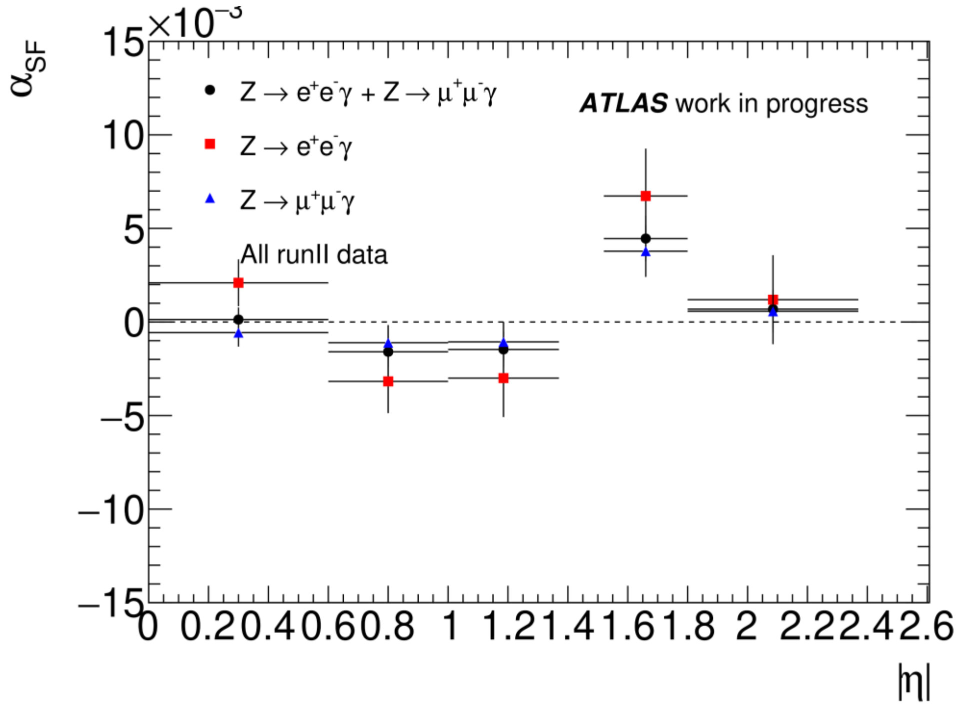


channel	$\alpha_{SF}(\times 10^{-3})$
$Z \rightarrow ee\gamma$	$(+0.97 \pm 0.81) \times 10^{-3}$
$Z \rightarrow \mu\mu\gamma$	$(-0.03 \pm 0.44) \times 10^{-3}$

Differential photon energy scale factor

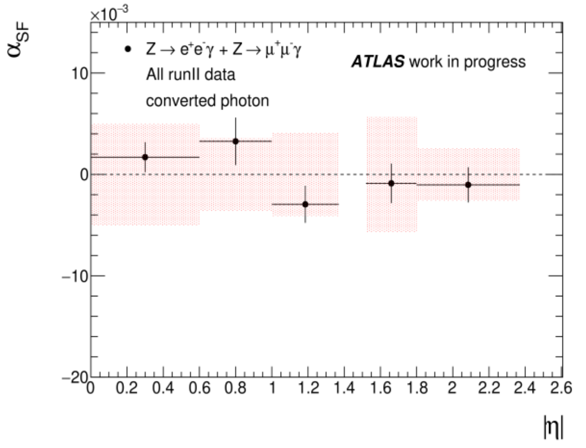
- Split the sample into different photon pT or η categories
  - Photon pT binning: (15,20), (20,30) and (30,$+\infty$)
  - Photon $|\eta|$ binning: (0.00,0.60),(0.60,1.00),(1.00,1.37),(1.37,1.52),(1.52,1.80) and (1.80,2.37)

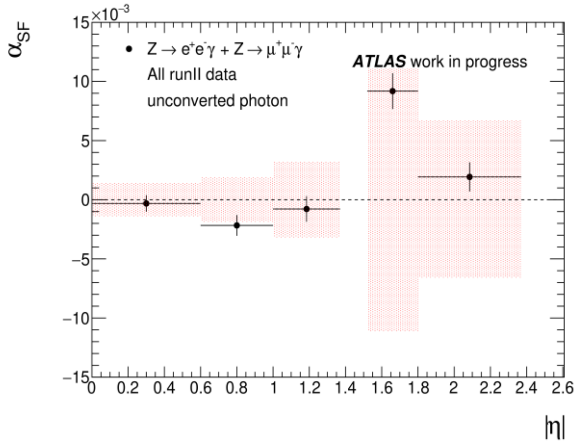


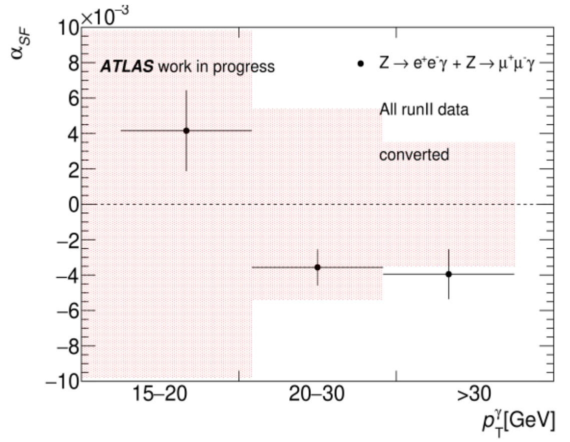


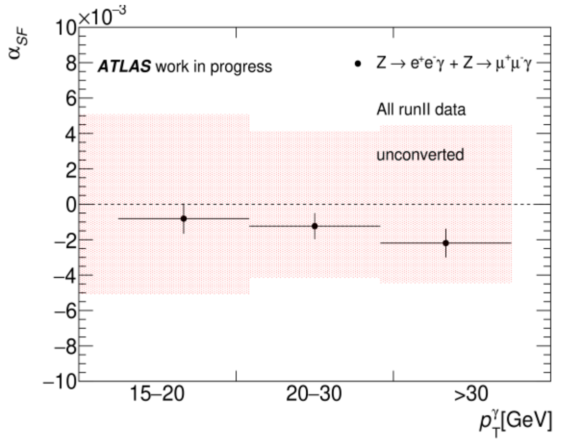
Differential photon energy scale factor

- Since photons can convert into an electron pair, it is necessary to check the difference between converted and unconverted photons in photon energy scale.
- Split the sample according to photon conversion status
- The PES distribution of converted/unconverted photon pT (or η)
  - Combined $Z \rightarrow ee\gamma$ and $Z \rightarrow \mu\mu\gamma$ channel
  - The Error bands represent the Zee systematic uncertainty









Summary

- Performed the validation of electron and photons energy calibration with $J/\psi \rightarrow ee$ and $Z \rightarrow ll\gamma$ events and compared the residual energy scale corrections with standard calibration uncertainty which extracted from $Z \rightarrow ee$ events.

- Electrons
  - The distribution of α as function of η (or pT) are shown with total uncertainties.
  - The highest disagreement of the residual energy scale corrections vs η is found to be ~0.9%.
  - The extracted residual energy scale corrections are compatible with the extrapolated systematic uncertainties from $Z \rightarrow ee$ nominal scales.

- Photons
  - Corrections to the photon energy is estimated to be $(+0.97 \pm 0.81) \times 10^{-3}$ in the $Z \rightarrow ee\gamma$ channel and $(-0.03 \pm 0.44) \times 10^{-3}$ in $Z \rightarrow \mu\mu\gamma$ channel.
  - There is the good agreement between PES and the Zee systematic uncertainty in each η (or pT) categories for converted and unconverted photons.

Thanks!

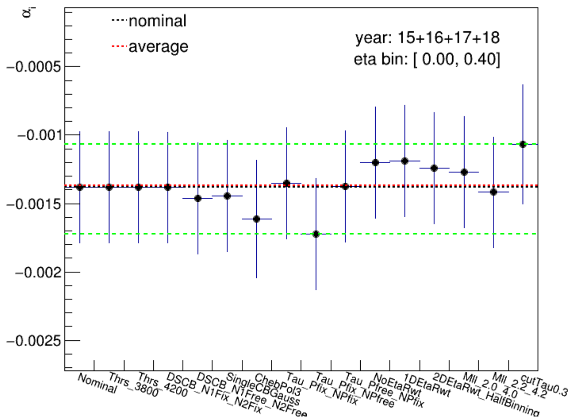
Systematic uncertainty source for $J/\psi \rightarrow ee$

The systematic unertainties from these source are shown in following:

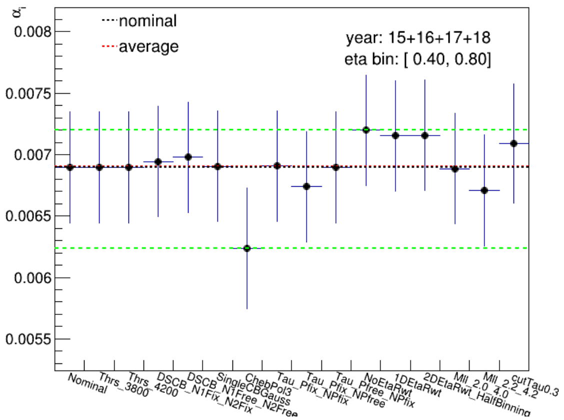
- Fit range of m_{ee}. The nominal fit range is (2.1,4.1)GeV. We may change the lower or upprt limit to study the impacts
  - change the range to (2.0,4.0)GeV
  - change the range to (2.2,4.2)GeV
- The threshold on the minimum numbers of events per categroy. The nominal values are 4000.
  - change the threshold to 3900
  - change the threshold to 4100
- The parameters (N) of the tails of the DSCB function. In the nominal case, N1 is fixed and N2 is float.
  - both of N1 and N2 are free
  - both of N1 and N2 are fixed
- Signal function form. In default, we use DSCB functions as signal pdf.
  - change to SingleCBGauss (CB+gaussian)
- Background function form. In default, ChebPol2 is used.
  - change the bkg function to ChebPol1 to study the difference
- η reweight. 2D η reweight was performed in nominal case.
  - NO η reweight performed
  - 1D η reweight peformed
- The number of eta bins for the 2D η reweighting. It is 96 in nominal case.
  - change the number of eta bins to 48
- The mean of the gaussians used for the pseudo proper time fit, kept both free for the prompt and non prompt PDF in nominal case.
  - PromptFree_NonPromptFix
  - PromptFix_NonPromptFree
  - PromptFix_NonPromptFix
- The pseudo proper time fit range. Nominal $\boldsymbol{\tau}$ range: [-1.12,2.92]
  - tighter $\boldsymbol{\tau}$ range: [-1.12,0.3]

Systematic uncertainty in different eta bins

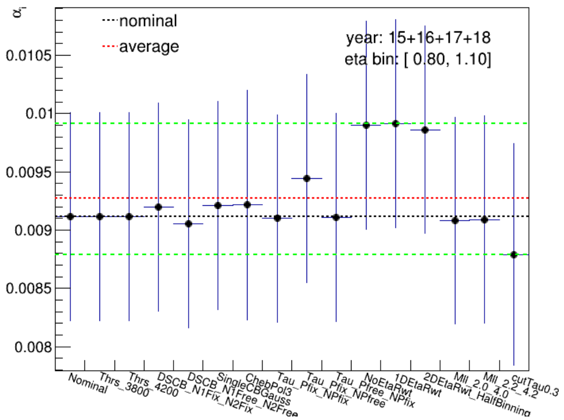
- Plots of systematic uncertainty of α in other 8 eta bins are shown in this page.



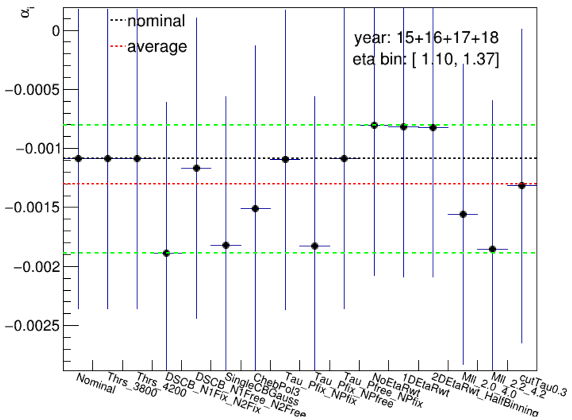
$0 < \eta < 0.40$



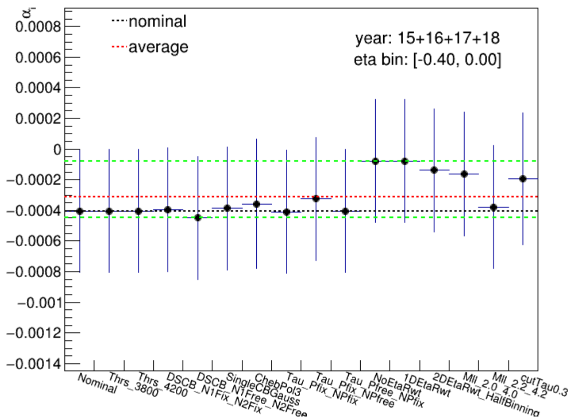
$0.40 < \eta < 0.80$



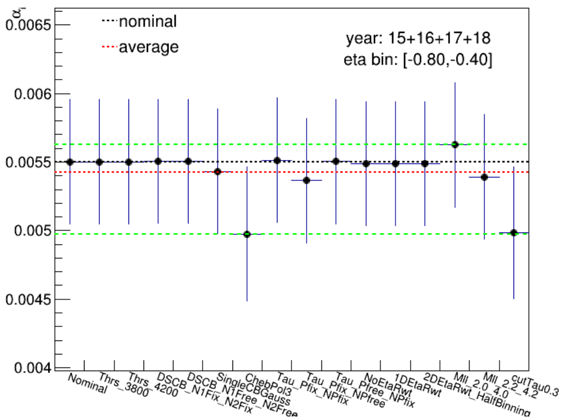
$0.80 < \eta < 1.10$



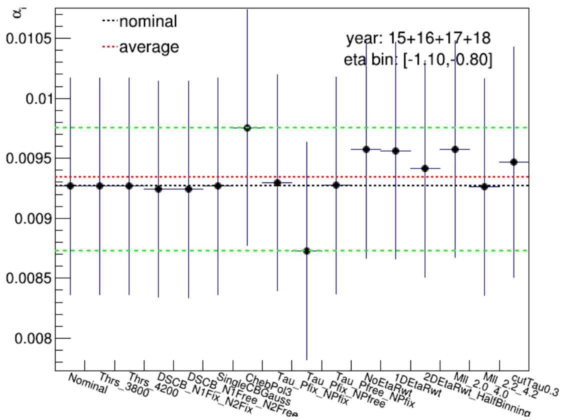
$1.10 < \eta < 1.37$



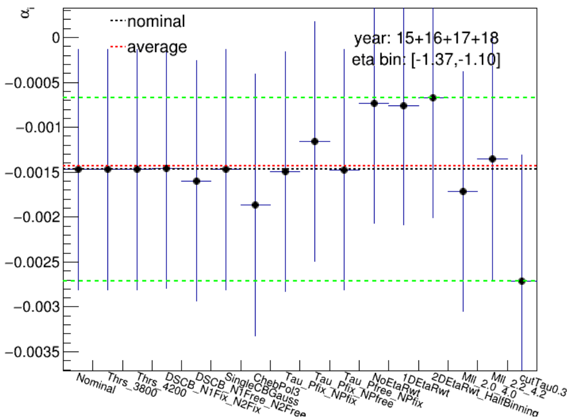
$-0.40 < \eta < 0$



$-0.80 < \eta < -0.40$



$-1.10 < \eta < -0.80$



$-1.37 < \eta < -1.10$

Data and MC samples

- Sample list:

data2015	data15_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM2.grp15_v01_p5232
data2016	data16_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM2.grp16_v01_p5232
data2017	data17_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM2.grp17_v01_p5232
data2018	data18_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM2.grp18_v01_p5232
MC16a	mc16_13TeV.423200.Pythia8B_A14_CTEQ6L1_Jpsie3e3.deriv.DAOD_EGAM2.e3869_s3126_r9364_p4078 mc16_13TeV.423201.Pythia8B_A14_CTEQ6L1_Jpsie3e8.deriv.DAOD_EGAM2.e3869_s3126_r9364_p4078 mc16_13TeV.423202.Pythia8B_A14_CTEQ6L1_Jpsie3e13.deriv.DAOD_EGAM2.e3955_s3126_r9364_p4078
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MC16d	mc16_13TeV.423200.Pythia8B_A14_CTEQ6L1_Jpsie3e3.merge.DAOD_EGAM2.e3869_s3126_r10201_p4078 mc16_13TeV.423201.Pythia8B_A14_CTEQ6L1_Jpsie3e8.merge.DAOD_EGAM2.e3869_s3126_r10201_p4078 mc16_13TeV.423202.Pythia8B_A14_CTEQ6L1_Jpsie3e13.merge.DAOD_EGAM2. e3955_s3126_r10201_p4078
	mc16_13TeV.423210.Pythia8B_A14_CTEQ6L1_bb_Jpsie3e3.merge.DAOD_EGAM2. e4364_s3126_r10201_p4078 mc16_13TeV.423211.Pythia8B_A14_CTEQ6L1_bb_Jpsie3e8.merge.DAOD_EGAM2. e4364_s3126_r10201_p4078 mc16_13TeV.423212.Pythia8B_A14_CTEQ6L1_bb_Jpsie3e13.merge.DAOD_EGAM2. e4364_s3126_r10201_p4078
MC16e	mc16_13TeV.423200.Pythia8B_A14_CTEQ6L1_Jpsie3e3.deriv.DAOD_EGAM2.e3869_e5984_s3126_r10724_r10726_p3654 mc16_13TeV.423201.Pythia8B_A14_CTEQ6L1_Jpsie3e8.deriv.DAOD_EGAM2.e3869_e5984_s3126_r10724_r10726_p3654 mc16_13TeV.423202.Pythia8B_A14_CTEQ6L1_Jpsie3e13.deriv.DAOD_EGAM2.e3955_e5984_s3126_r10724_r10726_p3654
	mc16_13TeV.423210.Pythia8B_A14_CTEQ6L1_bb_Jpsie3e3.deriv.DAOD_EGAM2.e4364_e5984_s3126_r10724_r10726_p3654 mc16_13TeV.423211.Pythia8B_A14_CTEQ6L1_bb_Jpsie3e8.deriv.DAOD_EGAM2.e4364_e5984_s3126_r10724_r10726_p3654 mc16_13TeV.423212.Pythia8B_A14_CTEQ6L1_bb_Jpsie3e13.deriv.DAOD_EGAM2.e4364_e5984_s3126_r10724_r10726_p3654

GRL and Trigger

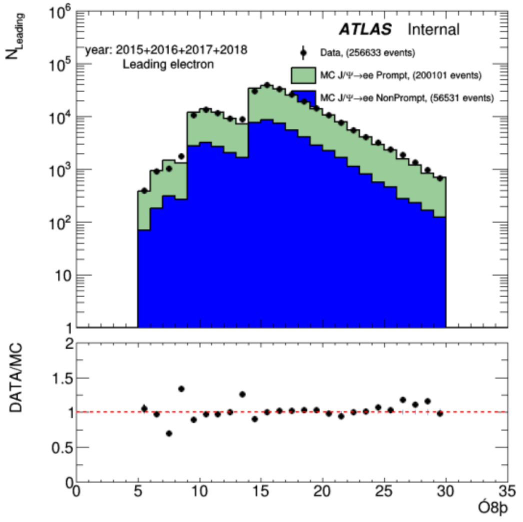
- GRL
- Trigger

Year	Good Run List
2015	data15_13TeV.periodAllYear_DetStatus-v89-pro21-02_Unknown_PHYS_StandardGRL_All_Good_25ns.xml
2016	data16_13TeV.periodAllYear_DetStatus-v89-pro21-01_DQDefects-00-02-04_PHYS_StandardGRL_All_Good_25ns_ignore_TOROID_STATUS.xml
2017	data17_13TeV.periodAllYear_DetStatus-v99-pro22-01_Unknown_PHYS_StandardGRL_All_Good_25ns_Triggerno17e33prim.xml
2018	data18_13TeV.periodAllYear_DetStatus-v105-pro22-13_Unknown_PHYS_StandardGRL_All_Good_25ns_Triggerno17e33prim.xml

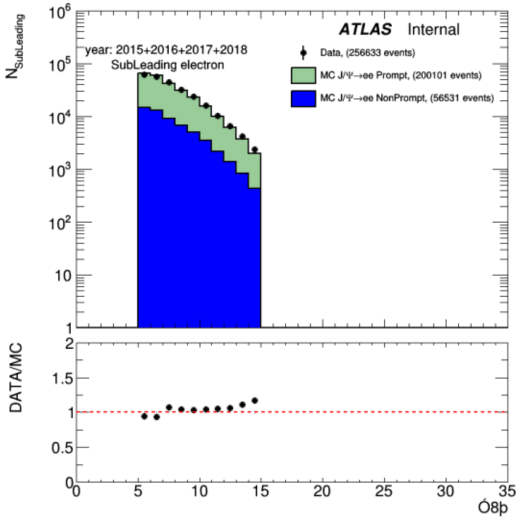
year	triggers
2015-2016	HLT_e5_lhtight_nod0_e4_etcut_Jpsiee HLT_e9_lhtight_nod0_e4_etcut_Jpsiee HLT_e14_lhtight_nod0_e4_etcut_Jpsiee
2017-2018	HLT_e5_lhtight_nod0_e4_etcut_Jpsiee HLT_e9_lhtight_nod0_e4_etcut_Jpsiee HLT_e14_lhtight_nod0_e4_etcut_Jpsiee HLT_e5_lhtight_nod0_e4_etcut HLT_e5_lhtight_e4_etcut HLT_e5_lhtight_e4_etcut_Jpsiee HLT_e9_lhtight_e4_etcut_Jpsiee HLT_e9_etcut_e5_lhtight_Jpsiee HLT_e9_etcut_e5_lhtight_nod0_Jpsiee HLT_e14_lhtight_e4_etcut_Jpsiee HLT_e14_etcut_e5_lhtight_nod0_Jpsiee HLT_e14_etcut_e5_lhtight_Jpsiee HLT_e5_lhtight_nod0_e4_etcut_Jpsiee_L1RD0_FILLED HLT_e9_lhtight_nod0_e4_etcut_Jpsiee_L1JPSI-1M5-EM7 HLT_e14_lhtight_nod0_e4_etcut_Jpsiee_L1JPSI-1M5-EM12 HLT_e5_lhtight_nod0_e9_etcut_Jpsiee_L1JPSI-1M5-EM7 HLT_e5_lhtight_nod0_e14_etcut_Jpsiee_L1JPSI-1M5-EM12 HLT_e5_lhtight_nod0_e4_etcut_Jpsiee_L1RD0_FILLED HLT_e9_lhtight_nod0_e4_etcut_Jpsiee_L1JPSI-1M5-EM7 HLT_e14_lhtight_nod0_e4_etcut_Jpsiee_L1JPSI-1M5-EM12 HLT_e5_lhtight_nod0_e9_etcut_Jpsiee_L1JPSI-1M5-EM7 HLT_e5_lhtight_nod0_e14_etcut_Jpsiee_L1JPSI-1M5-EM12

Kinematic distributions

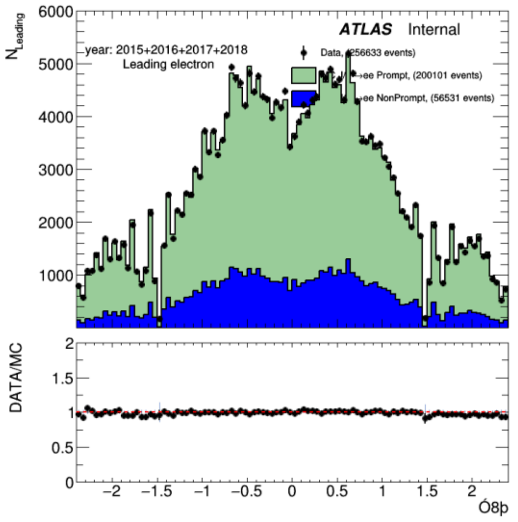
- Kinematic distributions for leading and subleading electrons in data and MC simulation after the η reweighting.
  - (a) Leading and (b) subleading electron ET distributions showing prompt and non prompt contributions to the simulation.
  - (c) Leading and (d) subleading electron pseudorapidity distributions.
  - Good agreement between data and MC.



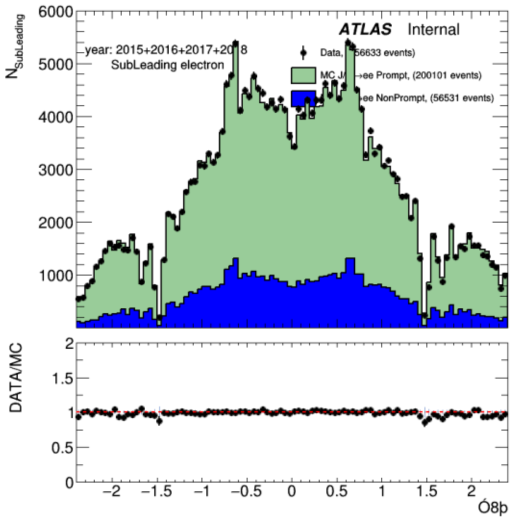
(a)



(b)



(c)



(d)

Prompt Fraction

J/ψ candidates produced in pp collisions at the LHC can be either:

- ***prompt***, when they are a direct product of the proton-proton collision.
- ***non-prompt***, when they originate from the decay of a hadron.

$$\tau = \frac{L_{xy} m^{J/\psi}}{p_{\mathrm{T}}^{J/\psi}}$$

L_{xy} is the decay length in the xy plane

The fraction of prompt and non prompt J/ψ in data can be quantified by studying their pseudo proper time (τ) distribution.

f_P is the fraction of prompt component, $P_P(\tau)$ describes prompt J/ψ, $P_B(\tau)$ describes non-prompt J/ψ coming from B-hadrons, the total PDF of τ can be written as:

$$f(\tau) = f_P \cdot P_P(\tau) + (1 - f_P) \cdot P_B(\tau)$$

The PDF for promptly produced J/ψ can be modelled as a Dirac's delta function peaked at zero convoluted with a resolution function. The decay probability for a B-hadron at truth-level is an exponential distribution, so the PDF for non promptly produced J/ψ will be an exponential decay convoluted with the same resolution function. Defining $R(\tau' - \tau, \delta_\tau)$ the resolution function, represented as the sum of three gaussians, $P_P(\tau)$ and $P_B(\tau)$ can be written as:

$$P_P(\tau) = R(\tau' - \tau, \delta_\tau) \otimes \delta(\tau') = \Sigma_{i=1}^{3} c_i G(\mu_i, \sigma_i)$$

$$P_B(\tau) = R(\tau' - \tau, \delta_\tau) \otimes E(\tau') = \Sigma_{i=1}^{3} c_i G(\mu_i, \sigma_i) \otimes E(\tau')$$

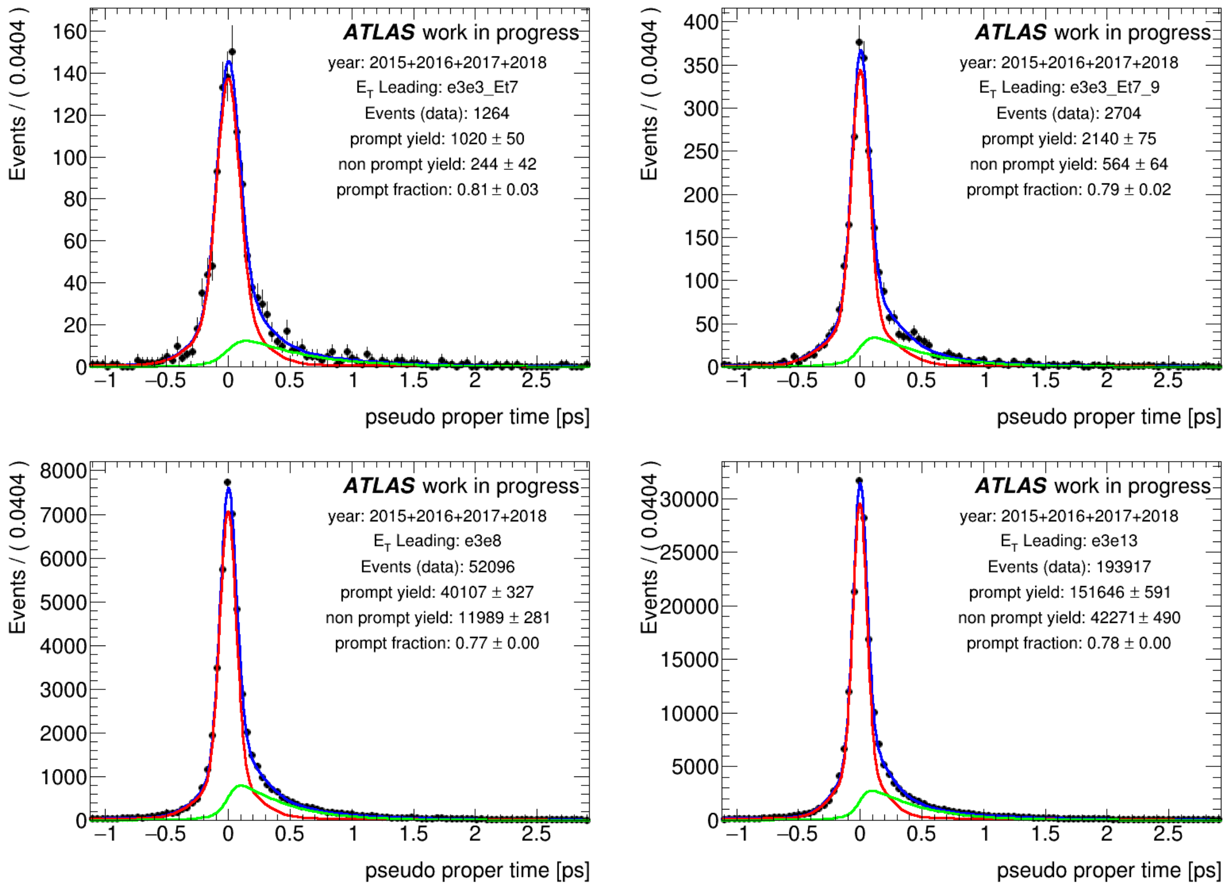
Prompt Fraction

- The fraction of prompt and non prompt J/ψ in data can be quantified by studying their pseudo proper time (τ) distribution. The total PDF of τ can be written as:

$$f(\tau) = f_P \cdot \{f_1 G(m, s_1) + f_2 G(m, s_2) + (1 - f_1 - f_2) \cdot G(m, s_3)\} + (1 - f_P) \cdot \{f_1 G(m, s_1) + f_2 G(m, s_2) + (1 - f_1 - f_2) \cdot G(m, s_3)\} \otimes E(\tau')$$

Prompt Fraction of full Run2 data

Leading E_T (GeV)	PromptFraction
[5,7]	$80.73\% \pm 2.77\%$
[7,9]	$79.15\% \pm 1.95\%$
[9,14]	$76.99\% \pm 0.44\%$
[14,30]	$78.20\% \pm 0.21\%$



Fit model

- The fit stragety is using signal + backgroud PDF to construct total PDF in each (η_i, η_j) bin. The total PDF can be written as:
  - $f(m_{ee}^{reco}) = DSCB(J/\psi) + DSCB(\psi(2S)) + ChebPol(2)$
  - Description for J/ψ: fix the peak shape from MC sample, but float the peak position by introduce the energy scale variations of α_i and α_j.
  - Description of $\psi(2S)$: simply shift the J/ψ globe mass shape with the PDG value. (Float $N_{\psi(2S)}$)
  - Residual background contribution: Polynominal function.

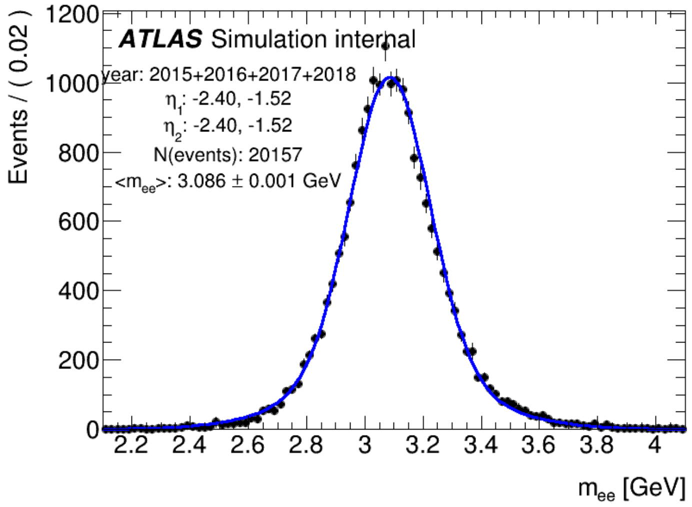


Figure 1: MC Fit

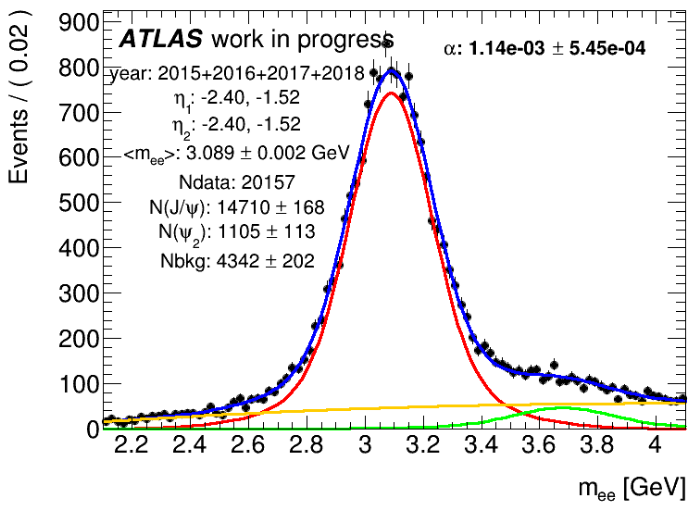
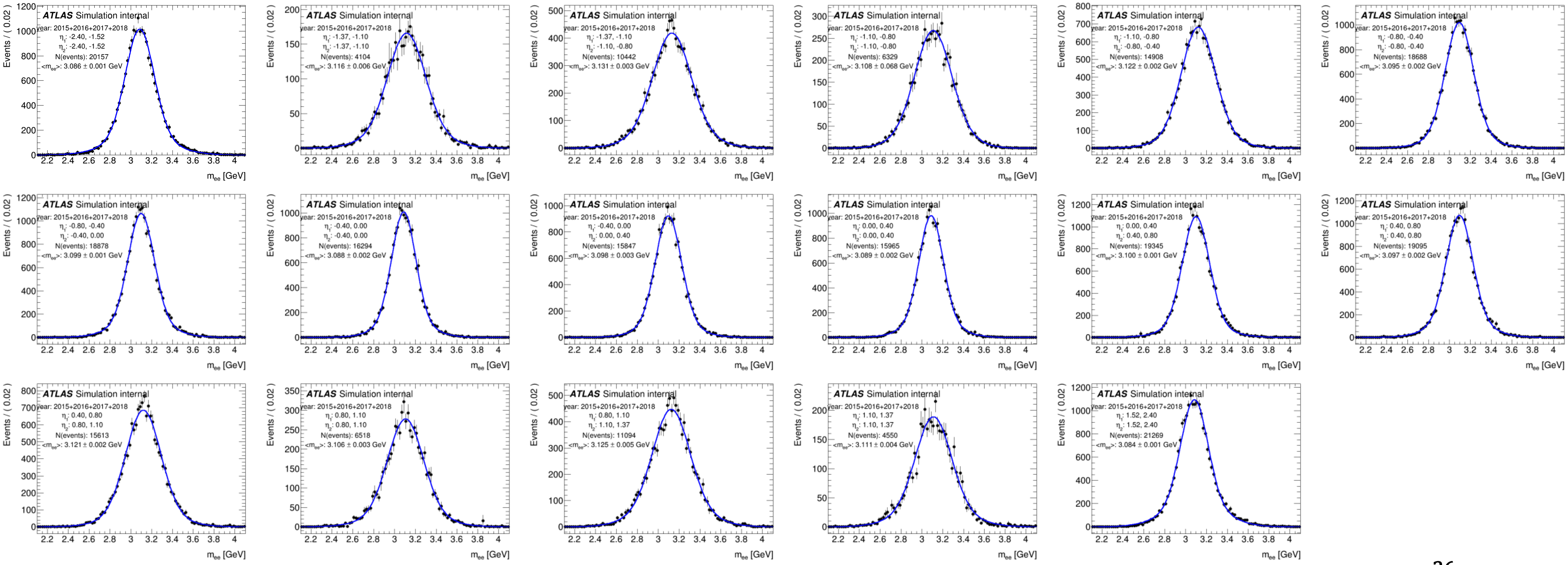


Figure 2: Data Fit

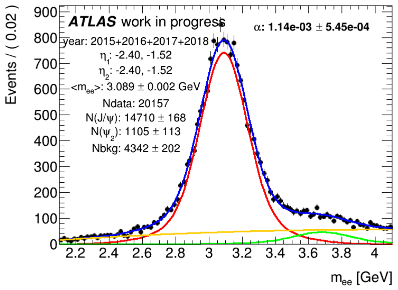
Mass fit

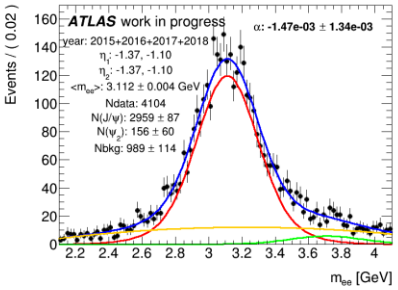
- Since we get the fraction for prompt and non-prompt samples, we can merge the prompt MC and nonprompt MC samples then perform mass fit.
- The result of mass fit in different η bins are shown in following plots.

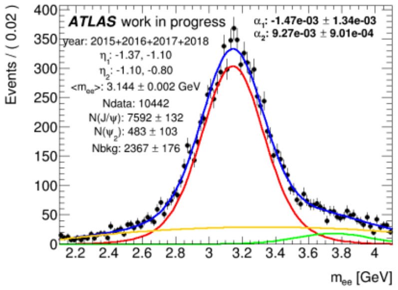


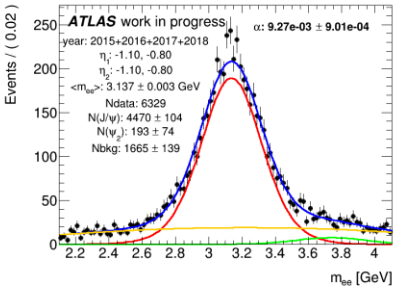
Mass fit

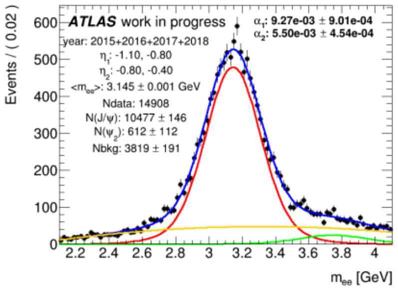
- Fix the peak shape from MC sample and then Perform simultaneous fit to data.
- The result of mass fit in different η bins are shown in following plots.

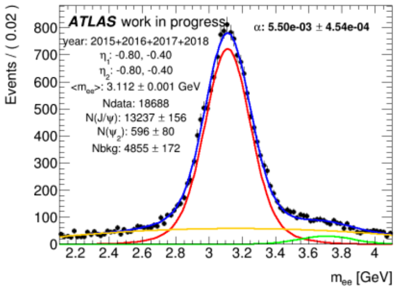


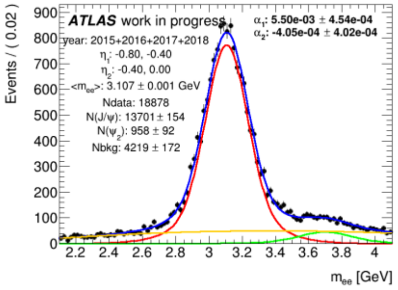


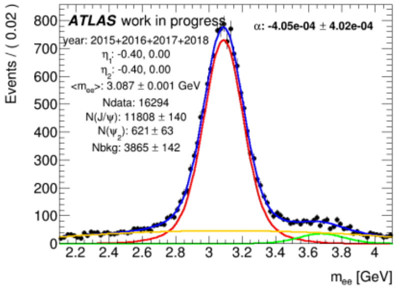


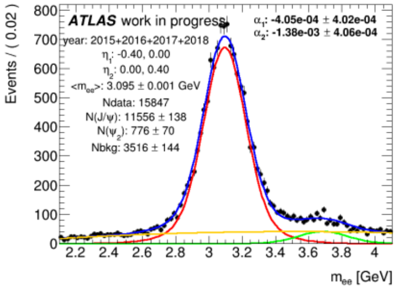


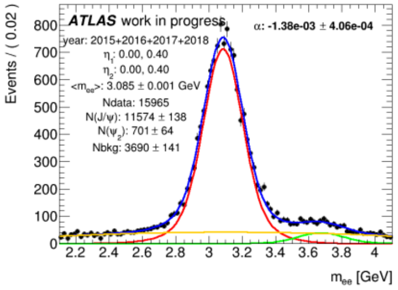


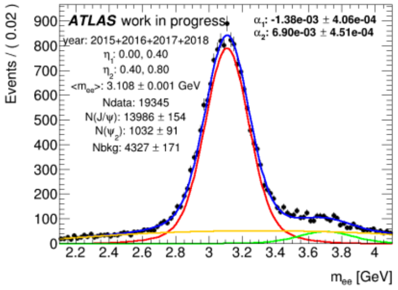


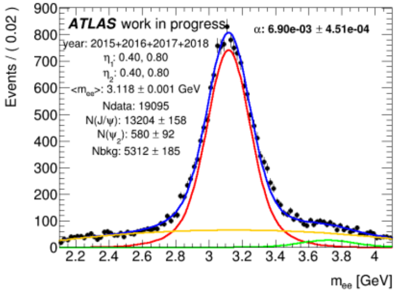


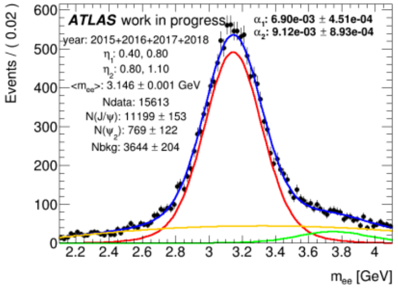


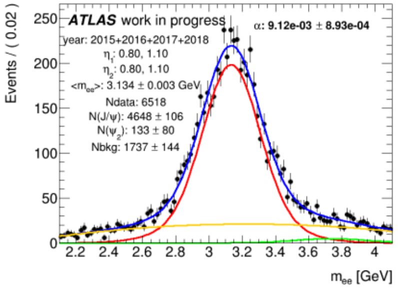


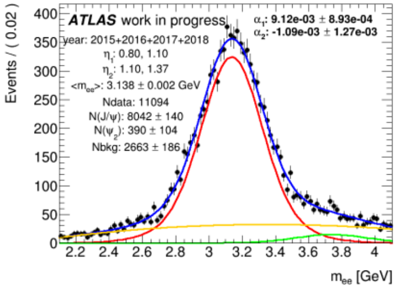


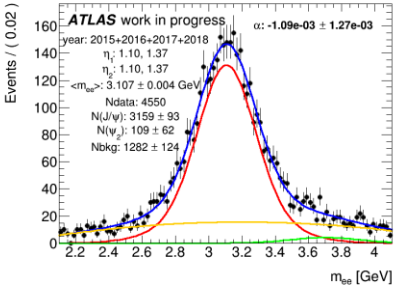


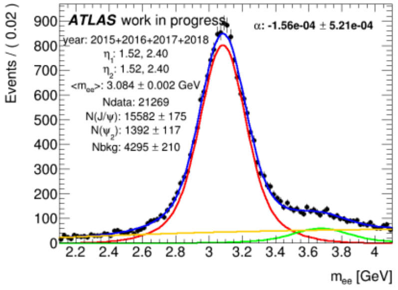












Cross check about scale result difference

- Two definitions are used to evaluate the difference between current scal result and previous result.
- The first definition is $\frac{1+\alpha^{new}}{1+\alpha^{old}}$; The second definition is $1+\alpha^{diff}$.
- The α^{diff} can be parametrized by replacing the m_{reco}^{MC} with $m_{reco}^{Old\ Data}$ in following formula:

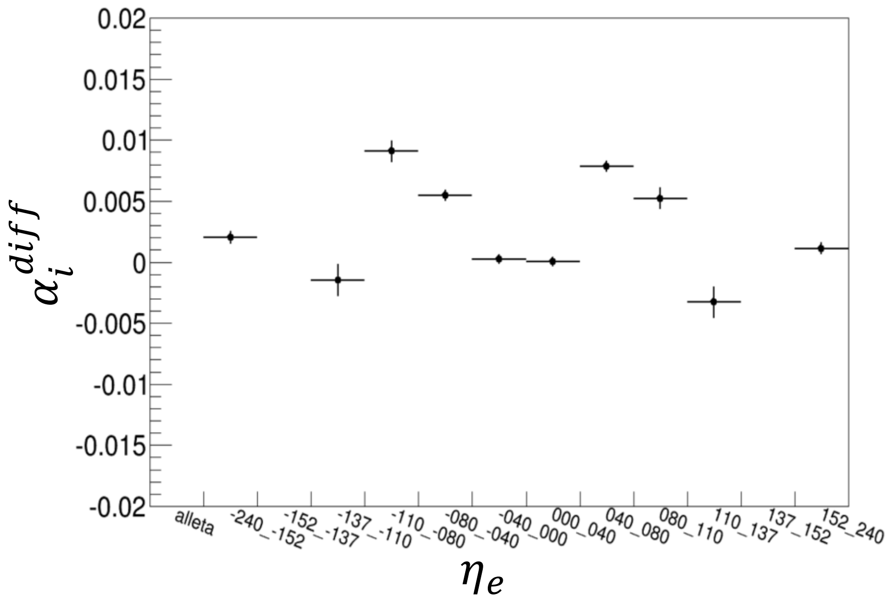
$$m_{reco}^{Data}(\eta) \cong \boxed{m_{reco}^{MC}(\eta)}\left(1+\frac{\alpha_i+\alpha_j}{2}\right)$$

$$m_{reco}^{New\ Data}(\eta) \cong m_{reco}^{Old\ Data}(\eta)\left(1+\frac{\alpha_i^{diff}+\alpha_j^{diff}}{2}\right)$$

where $m_{reco}^{Old\ Data}$ is extracted from the simultaneous fit on old data. Then, the α^{diff} can be obtained by the simultaneous fit on new data.

Cross check about scale result difference

- The distribution of α^{diff} vs η_e ; the values of $\frac{1+\alpha^{new}}{1+\alpha^{old}}$ are summarized in the table.
- The comparison of the two evaluations ($\frac{1+\alpha^{new}}{1+\alpha^{old}}$ and $1+\alpha^{diff}$) of difference between current scale result and previous result.
- The second column of the table shows the value obtained directly from calibration tool comparing the old and new model .



a_1: (0.20 +/- 0.05)%
a_3: (-0.15 +/- 0.13)%
a_4: (0.91 +/- 0.09)%
a_5: (0.54 +/- 0.05)%
a_6: (0.02 +/- 0.04)%
a_7: (0.00 +/- 0.04)%
a_8: (0.78 +/- 0.05)%
a_9: (0.52 +/- 0.09)%
a_10: (-0.33 +/- 0.13)%
a_12: (0.11 +/- 0.05)%

from the calibration tool comparing the old and new model

provided by Stefano

Eta bin		$\frac{1+\alpha^{new}}{1+\alpha^{old}}$	$1+\alpha^{diff}$
[-2.47, -1.52]	1.0024	1.0024	1.0020
[-1.52, -1.37]	1.0016	1.0000	1.0000
[-1.37, -1.1]	0.9994	0.9966	0.9985
[-1.1, -0.8]	1.0005	1.0022	1.0091
[-0.8, -0.4]	1.0056	1.0070	1.0054
[-0.4, 0]	1.0027	1.0005	1.0002
[0, 0.4]	1.0027	1.0005	1.0000
[0.4, 0.8]	1.0056	1.0067	1.0078
[0.8, 1.1]	1.0007	1.0019	1.0052
[1.1, 1.37]	0.9998	0.9977	0.9967
[1.37, 1.52]	1.0020	1.0000	1.0000
[1.52, 2.47]	1.0025	1.0022	1.0011

Scale result with systematic uncertainty

- In the tables, the complete results of α as function of η regions is shown with statistical and systematic uncertainties.

new result

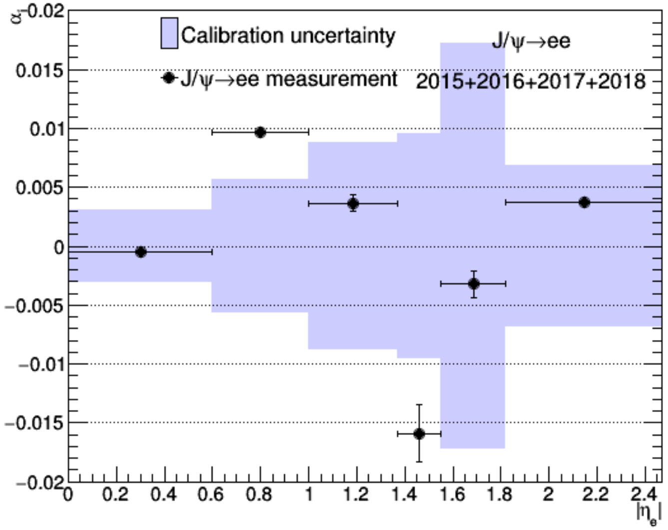
Eta bin	Energy scale correction (10^{-3})
	year:2015+2016+2017+2018
$-2.40 < \eta < -1.52$	$\alpha = 1.14^{+0.54}_{-0.54}(stat.)^{+0.37}_{-0.15}(syst.) = 1.14^{+0.66}_{-0.57}(tot.)$
$-1.37 < \eta < -1.10$	$\alpha = -1.47^{+1.35}_{-1.35}(stat.)^{+0.80}_{-1.24}(syst.) = -1.47^{+1.56}_{-1.83}(tot.)$
$-1.10 < \eta < -0.80$	$\alpha = 9.27^{+0.90}_{-0.90}(stat.)^{+0.49}_{-0.54}(syst.) = 9.27^{+1.02}_{-1.05}(tot.)$
$-0.80 < \eta < -0.40$	$\alpha = 5.50^{+0.45}_{-0.45}(stat.)^{+0.12}_{-0.53}(syst.) = 5.50^{+0.47}_{-0.69}(tot.)$
$-0.40 < \eta < 0$	$\alpha = -0.40^{+0.40}_{-0.40}(stat.)^{+0.33}_{-0.04}(syst.) = -0.40^{+0.52}_{-0.40}(tot.)$
$0 < \eta < 0.40$	$\alpha = -1.38^{+0.41}_{-0.41}(stat.)^{+0.31}_{-0.35}(syst.) = -1.38^{+0.51}_{-0.53}(tot.)$
$0.40 < \eta < 0.80$	$\alpha = 6.90^{+0.45}_{-0.45}(stat.)^{+0.30}_{-0.66}(syst.) = 6.90^{+0.54}_{-0.80}(tot.)$
$0.80 < \eta < 1.10$	$\alpha = 9.12^{+0.89}_{-0.89}(stat.)^{+0.80}_{-0.33}(syst.) = 9.12^{+1.20}_{-0.95}(tot.)$
$1.10 < \eta < 1.37$	$\alpha = -1.09^{+1.26}_{-1.26}(stat.)^{+0.28}_{-0.80}(syst.) = -1.09^{+1.30}_{-1.50}(tot.)$
$1.52 < \eta < 2.40$	$\alpha = -0.16^{+0.52}_{-0.52}(stat.)^{+0.34}_{-0.75}(syst.) = -0.16^{+0.63}_{-0.91}(tot.)$

old result

Eta bin	Energy scale correction (10^{-3})
	year:2015+2016+2017+2018
$-2.40 < \eta < -1.52$	$\alpha = -1.24^{+0.55}_{-0.55}(stat.)^{+0.11}_{-0.32}(syst.) = -1.24^{+0.56}_{-0.64}(tot.)$
$-1.37 < \eta < -1.10$	$\alpha = 1.30^{+1.34}_{-1.34}(stat.)^{+1.50}_{-0.63}(syst.) = 1.30^{+2.01}_{-1.48}(tot.)$
$-1.10 < \eta < -0.80$	$\alpha = 7.04^{+0.89}_{-0.89}(stat.)^{+0.46}_{-1.02}(syst.) = 7.04^{+1.01}_{-1.35}(tot.)$
$-0.80 < \eta < -0.40$	$\alpha = -1.16^{+0.45}_{-0.45}(stat.)^{+0.00}_{-0.70}(syst.) = -1.16^{+0.45}_{-0.83}(tot.)$
$-0.40 < \eta < 0$	$\alpha = -0.71^{+0.40}_{-0.40}(stat.)^{+0.02}_{-0.46}(syst.) = -0.71^{+0.40}_{-0.61}(tot.)$
$0 < \eta < 0.40$	$\alpha = -1.85^{+0.41}_{-0.41}(stat.)^{+0.14}_{-0.39}(syst.) = -1.85^{+0.43}_{-0.57}(tot.)$
$0.40 < \eta < 0.80$	$\alpha = -0.09^{+0.45}_{-0.45}(stat.)^{+0.51}_{-0.17}(syst.) = -0.09^{+0.68}_{-0.48}(tot.)$
$0.80 < \eta < 1.10$	$\alpha = 6.97^{+0.90}_{-0.90}(stat.)^{+0.84}_{-0.65}(syst.) = 6.97^{+1.23}_{-1.11}(tot.)$
$1.10 < \eta < 1.37$	$\alpha = 1.63^{+1.26}_{-1.26}(stat.)^{+0.38}_{-1.15}(syst.) = 1.63^{+1.31}_{-1.97}(tot.)$
$1.52 < \eta < 2.40$	$\alpha = -1.89^{+0.53}_{-0.53}(stat.)^{+0.00}_{-1.04}(syst.) = -1.89^{+0.53}_{-1.17}(tot.)$

Scale Results with other eta binning

- In order to easily perform comparison, the eta binning used in the linearity measurement have been used in $J/\psi \rightarrow ee$.
  - |eta|=0,0.6,1.0,1.37,1.55,1.82,2.47
- Based on above eta binning, the energy scale factors have been obtained and shown in the following plot and table with statistical uncertainty.
  - The events in the crack region were not rejected in this result.
  - The violet band represents the systematic uncertainty from $Z \rightarrow ee$ calibration (from Linghua)
  - The black error bars represent statistical uncertainties from $J/\psi \rightarrow ee$. (Estimate syst. uncertainty in next)



Eta bin	Energy scale correction	Calibration uncertainty
$0 < \|\eta\| < 0.60$	(0.02 +/- 0.02)%	0.30%
$0.60 < \|\eta\| < 1.00$	(0.97 +/- 0.04)%	0.57%
$1.00 < \|\eta\| < 1.37$	(0.37 +/- 0.07)%	0.89%
$1.37 < \|\eta\| < 1.55$	(-1.59 +/- 0.24)%	0.96%
$1.55 < \|\eta\| < 1.82$	(-0.32 +/- 0.11)%	1.73%
$1.80 < \|\eta\| < 2.47$	(0.37 +/- 0.04)%	0.68%

Pseudo proper time fit

For every fit we assumed the same resolution for prompt and non prompt gaussians, this was implemented using the same sigma parameter in both gaussians. For mean parameter, We investigated all the possible combinations of fixed/free parameter to fit pseudo proper time in different leading E_T range.

Option	Prompt		Non Prompt	
	mean	sigma	mean	σ
Both Free	free	free	free	= prompt
PromptFree - NonPromptFix	free	free	fix(0)	= prompt
PromptFix - NonPromptFree	fix(0)	free	free	= prompt
BothFix	fix(0)	free	fix(0)	= prompt

For example: if option is Both Free,

$$f(\tau) = f_P \cdot \Sigma_{i=1}^{3} f_i G(m, \sigma_i) + (1 - f_P) \cdot \Sigma_{i=1}^{3} f_i^{(B)} G(m, \sigma_i) \otimes E(\tau')$$

if option is PromptFree - NonPromptFix,

$$f(\tau) = f_P \cdot \Sigma_{i=1}^{3} f_i G(m, \sigma_i) + (1 - f_P) \cdot \Sigma_{i=1}^{3} f_i G(0, \sigma_i) \otimes E(\tau')$$

Data and MC Samples

- Derivations:
  - EGAM3: $Z \to ee\gamma$
  - EGAM4: $Z \to \mu\mu\gamma$
- Datasets:
  - Data: 2015+2016+2017+2018 pp collision data at 13 TeV.
  - MC: MC16a, MC16d, MC16e

Channle	name
$Z \to ee\gamma$	data15_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM3.grp15_v01_p5232
	data16_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM3.grp16_v01_p5232
	data17_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM3.grp17_v01_p5232
	data18_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM3.grp18_v01_p5232
$Z \to \mu\mu\gamma$	data15_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM4.grp15_v01_p5232
	data16_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM4.grp16_v01_p5232
	data17_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM4.grp17_v01_p5232
	data18_13TeV.periodAllYear.physics_Main.PhysCont.DAOD_EGAM4.grp18_v01_p5232

channel	DSID	pTy (GeV)
$Z \to ee\gamma$	366140	7-15
	366141	15-35
	366142	35-70
	366143	70-140
	366144	140_E_CMS
$Z \to \mu\mu\gamma$	366145	7-15
	366146	15-35
	366147	35-70
	366148	70-140
	366149	140_E_CMS

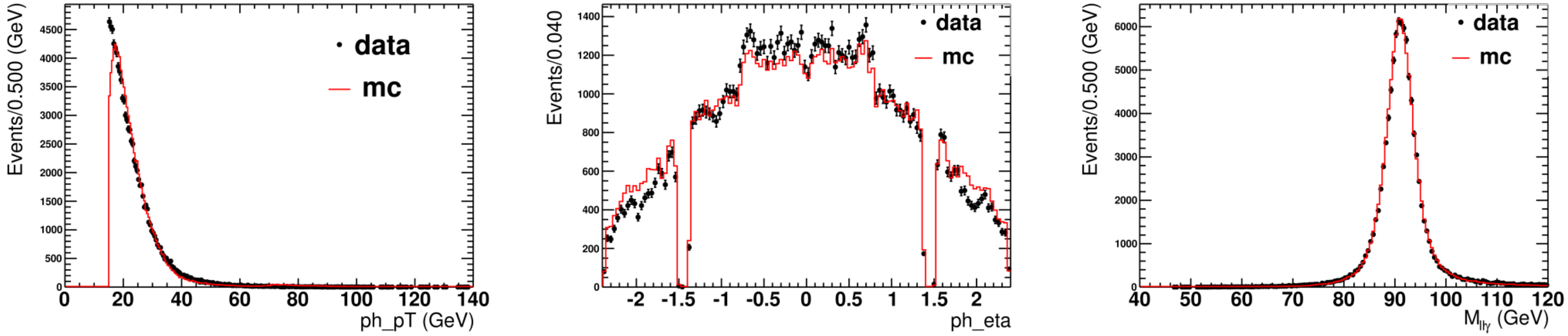
Trigger requirements for $Z \rightarrow ll\gamma$

- The triggers I used are shown as below

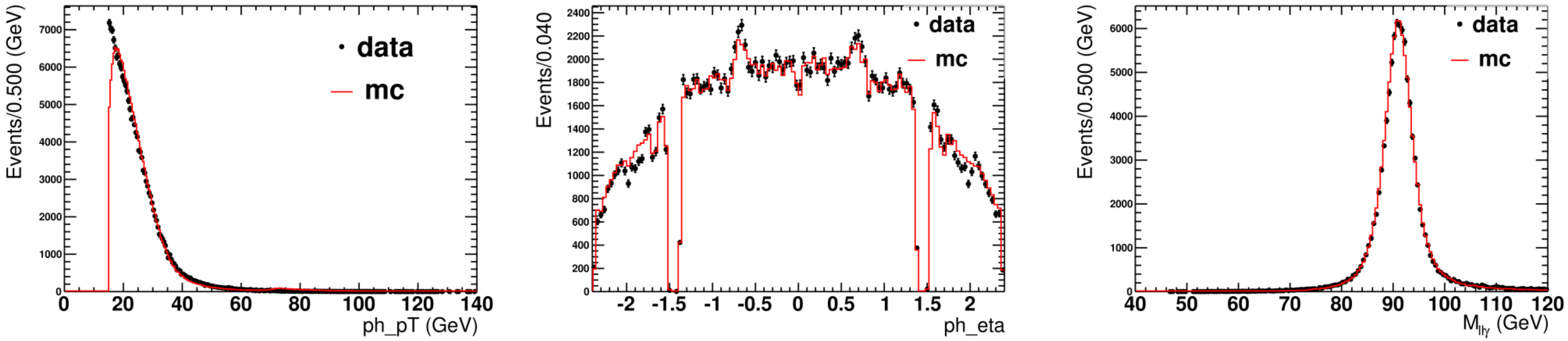
Year	Triggers of electron	Triggers of muon
2015	HLT_e24_lhmedium_L1EM18VH	HLT_mu20_iloose_L1MU15_OR_HLT_mu50
	HLT_e24_lhmedium_iloose_L1EM18VH	HLT_mu20_iloose_L1MU15
	HLT_e24_lhmedium_iloose_L1EM20VH	HLT_mu50
	HLT_e24_lhmedium_L1EM20VH	HLT_mu60_0eta105_msonly
	HLT_e60_lhmedium	HLT_2mu10
	HLT_e120_lhloose	
	HLT_2e12_lhloose_L12EM10VH	
2016	HLT_e24_lhtight_nod0_ivarloose	HLT_mu26_ivarmedium_OR_HLT_mu50
	HLT_e26_lhtight_nod0_ivarloose	HLT_mu26_ivarmedium
	HLT_e60_lhmedium_nod0	HLT_mu50
	HLT_e140_lhloose_nod0	HLT_mu60_0eta105_msonly
	HLT_2e15_lhvloose_nod0_L12EM13VH	HLT_2mu14
	HLT_2e17_lhvloose_nod0	HLT_mu20_mu8noL1
		HLT_2mu14_nomucomb
2017	HLT_e26_lhtight_nod0_ivarloose	HLT_mu26_imedium
	HLT_e60_lhmedium_nod0	HLT_mu26_ivarmedium_OR_HLT_mu50
	HLT_e140_lhloose_nod0	HLT_mu26_ivarmedium
	HLT_2e24_lhvloose_nod0	HLT_mu50_0eta105_msonly
		HLT_2mu14
		HLT_mu50
		HLT_mu22_mu8noL1
2018	HLT_e26_lhtight_nod0_ivarloose	HLT_mu26_imedium
	HLT_e26_lhtight_nod0	HLT_mu26_ivarmedium_OR_HLT_mu50
	HLT_e60_lhmedium_nod0	HLT_mu26_ivarmedium
	HLT_e140_lhloose_nod0	HLT_mu50 , HLT_2mu14
	HLT_2e17_lhvloose_nod0_L12EM15VHI	HLT_mu50_0eta105_msonly
	HLT_2e24_lhvloose_nod0	HLT_mu22_mu8noL1

Comparison between data and MC

- The photon pt, eta and mlly comparison plots between data and MC
  - $Z \to ee\gamma$ channel

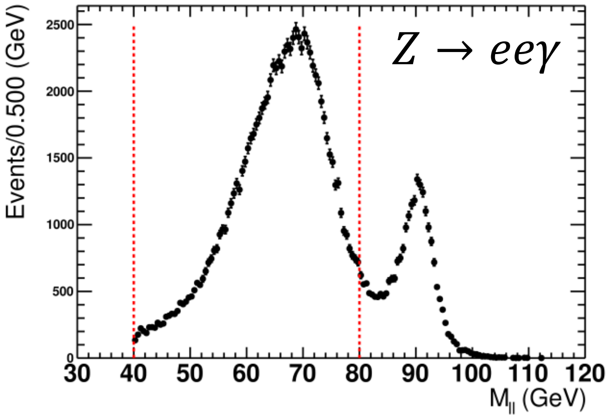


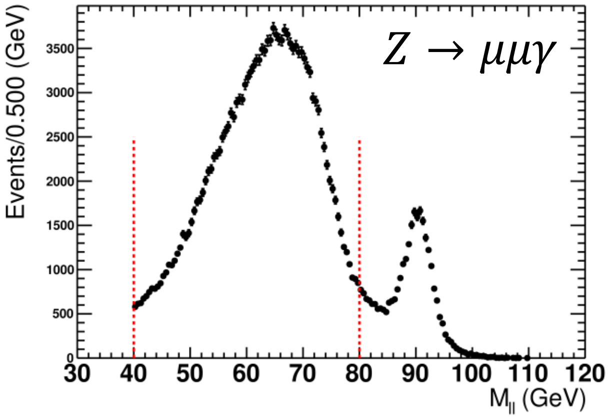
  - $Z \to \mu\mu\gamma$ channel



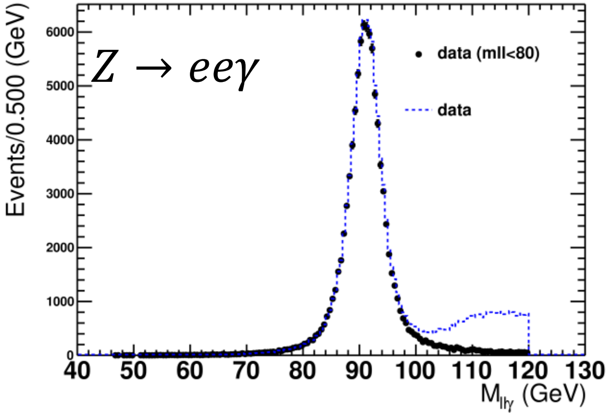
Selection result

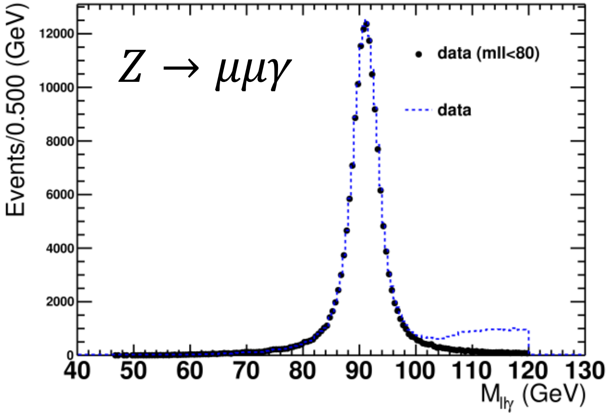
- The m_{ll} distribution of full Run2 data. (left: $ee\gamma$ channel; right: $\mu\mu\gamma$ channel)





- Even $40 < m_{ll} < 80$ GeV is required, there maybe are some events from ISR. The $m_{ll\gamma}$ distribution after $40 < m_{ll} < 80$ GeV.

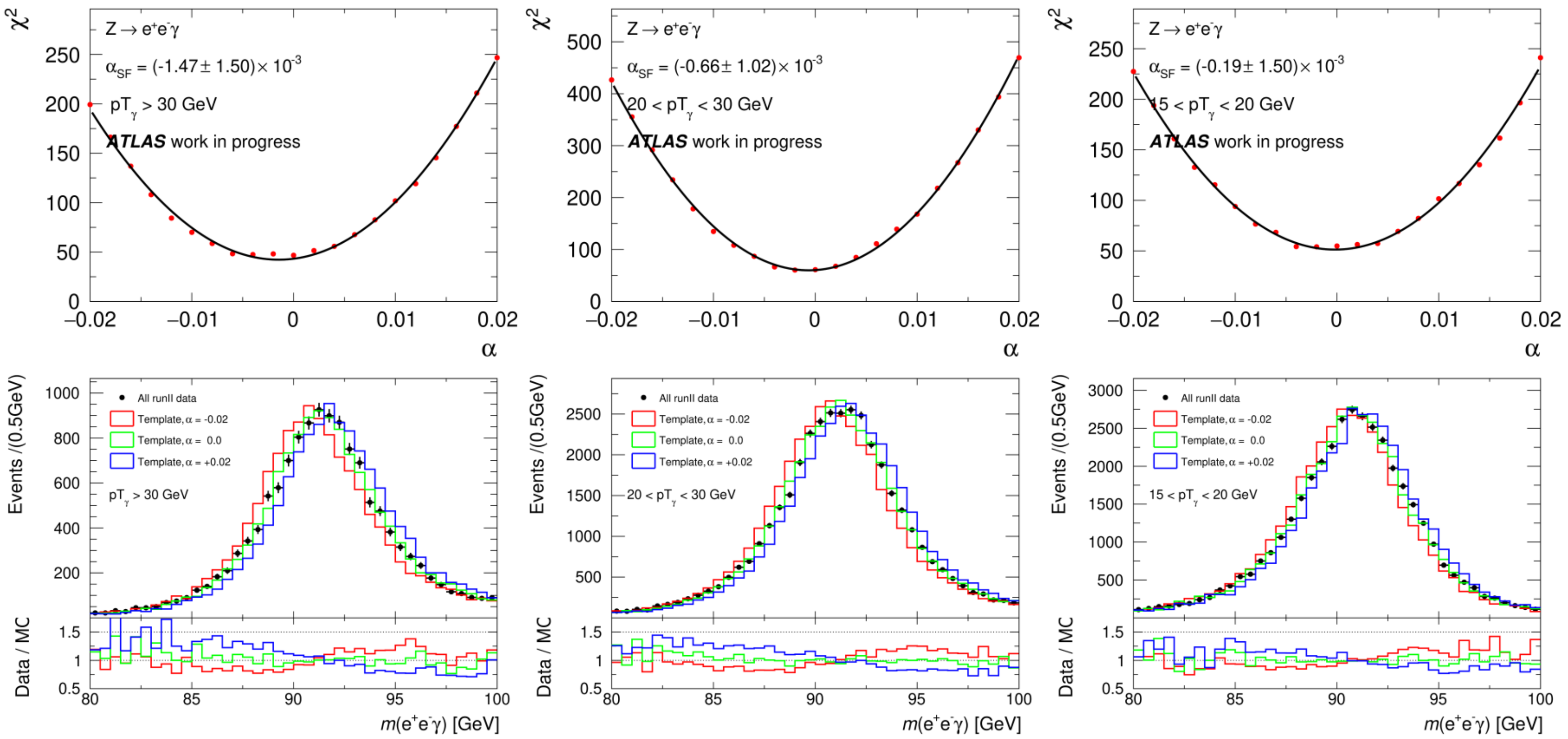




Differential photon energy scale factor

- Differential PES corresponding to photon p_T
  - (15,20), (20,30) and (30,$\sqrt{s}$)
  - chi2 scan plots and mlly distributions

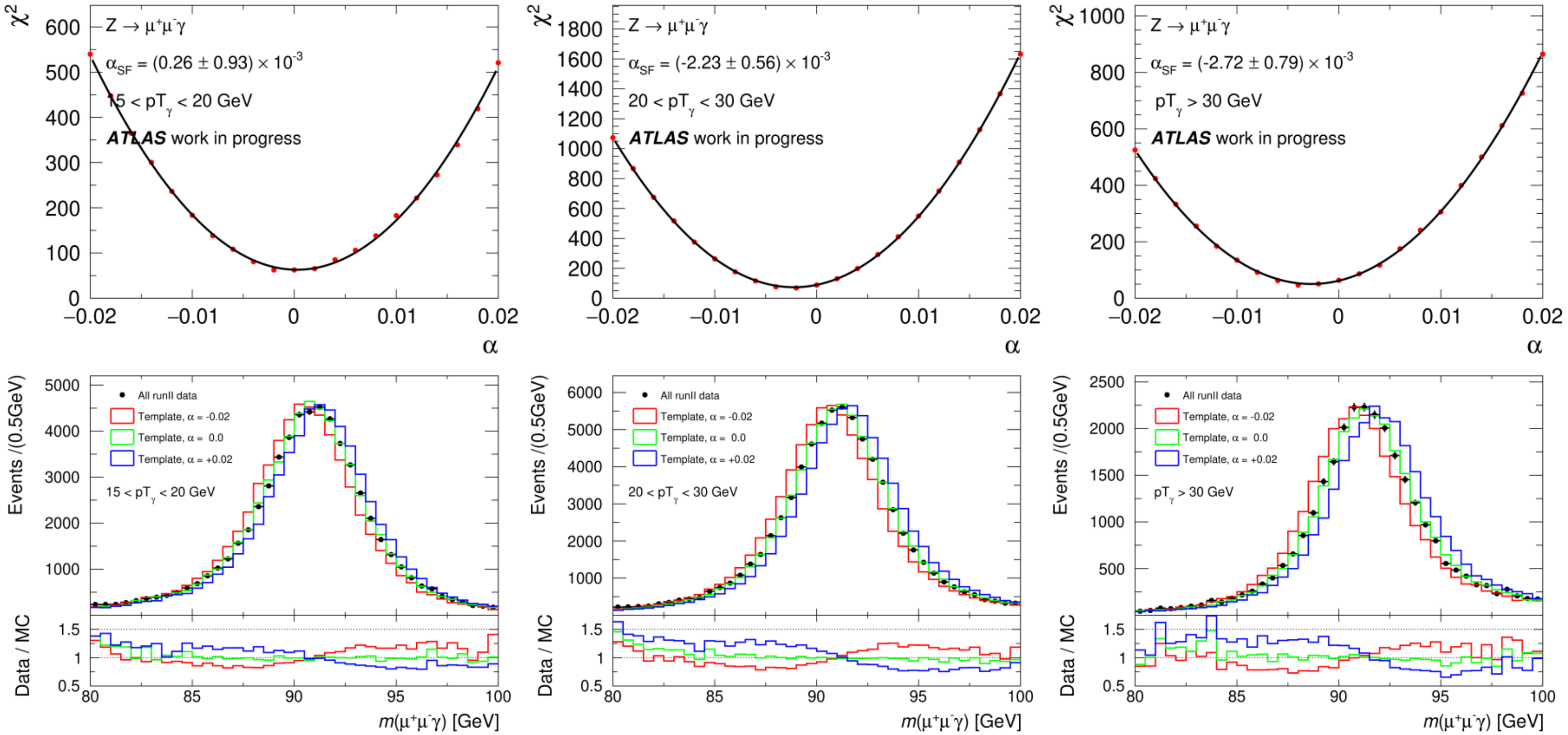
$Z \rightarrow ee\gamma$ channel



Differential photon energy scale factor

- Differential PES corresponding to photon p_T
  - (15,20), (20,30) and (30,$\sqrt{s}$)
  - chi2 scan plots and mllγ distributions

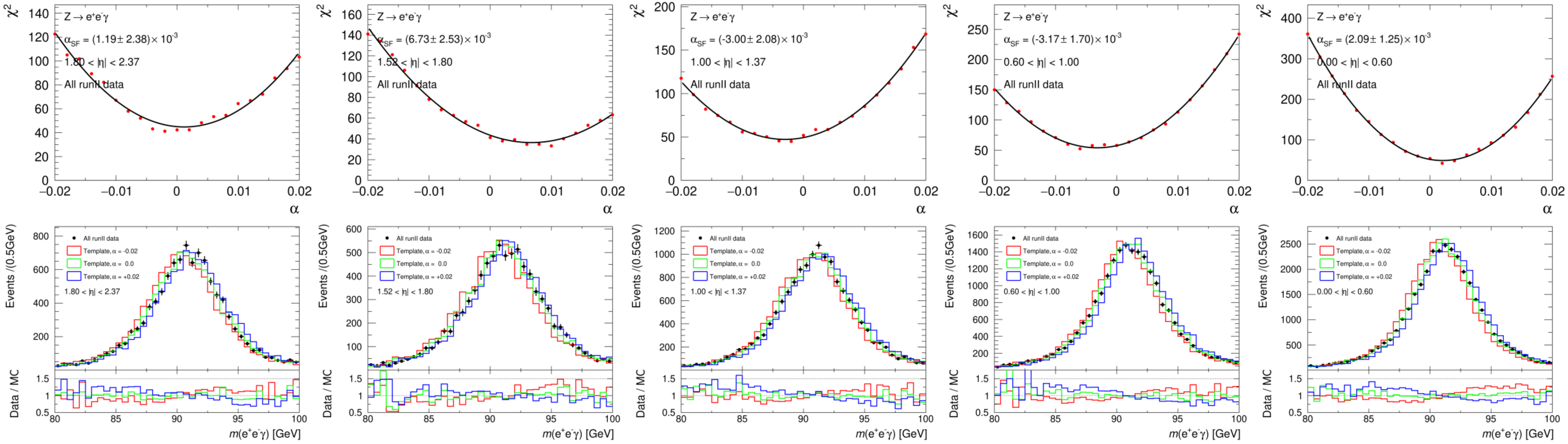
$Z \rightarrow \mu\mu\gamma$ channel



Differential photon energy scale factor

- Differential PES corresponding to photon η
  - (0.00,0.60),(0.60,1.00),(1.00,1.37),(1.37,1.52),(1.52,1.80) and (1.80,2.37)
  - chi2 scan plots and mlly distributions

$Z \rightarrow ee\gamma$ channel



Differential photon energy scale factor

$Z \to \mu\mu\gamma$ channel

- Differential PES corresponding to photon η
  - (0.00,0.60),(0.60,1.00),(1.00,1.37),(1.37,1.52),(1.52,1.80) and (1.80,2.37)
  - chi2 scan plots and mlly distributions