Inclusive $W^{\pm}(\rightarrow l^{\pm}\nu)\gamma$ Differential Cross Section Measurement with Full Run-2 Data

Joint APP, HEPP and NP Conference

10/04/2024

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Motivation

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- **CP violating operators affecting the Higgs/multiboson interactions** can be probed via Effective Field Theory:

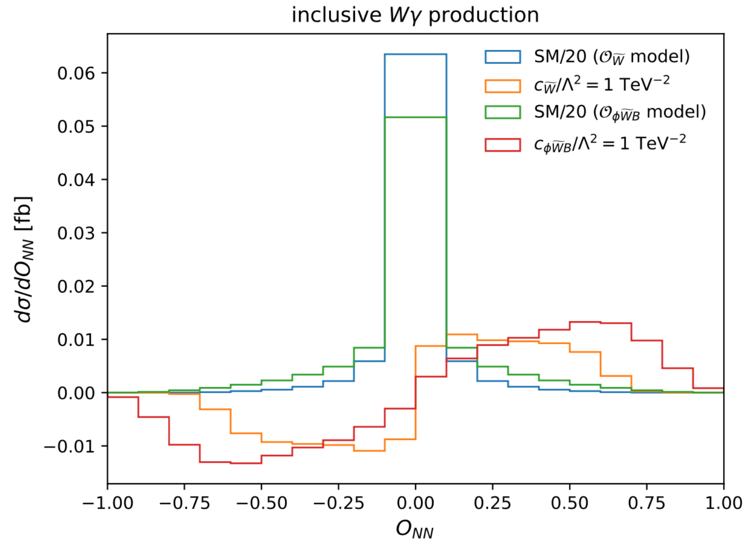
$$\mathcal{L} = \mathcal{L}_{SM} + \sum_i \frac{c_i^{(6)}}{\Lambda^2}\mathcal{O}_i^{(6)}$$

c_i/Λ^2 the Wilson coefficients, Λ the scale of new physics

$$\widetilde{\mathcal{O}}_{\widetilde{W}} = \varepsilon_{ijk}\widetilde{W}^i_{\mu\nu}W^{j\,\nu\rho}W^{k\,\mu}_{\rho}\,,$$
$$\widetilde{\mathcal{O}}_{\Phi\widetilde{B}} = \Phi^\dagger\Phi B^{\mu\nu}\widetilde{B}_{\mu\nu}\,,$$
$$\widetilde{\mathcal{O}}_{\Phi\widetilde{W}} = \Phi^\dagger\Phi W^{i\,\mu\nu}\widetilde{W}^i_{\mu\nu}\,,$$
$$\widetilde{\mathcal{O}}_{\Phi\widetilde{W}B} = \Phi^\dagger\sigma^i\widetilde{W}^{i\,\mu\nu}B_{\mu\nu}\,.$$

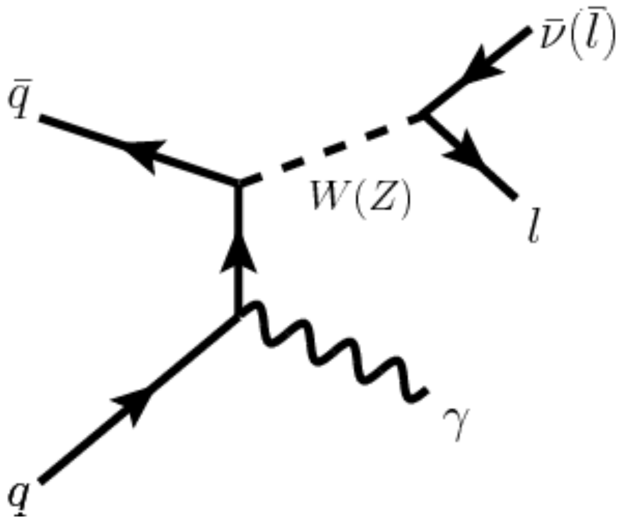
- Beyond-the-SM amplitude is then given by: $|\mathcal{M}_{\mathrm{BSM}}|^2 = |\mathcal{M}_{\mathrm{SM}}|^2 + 2\mathrm{Re}\{\mathcal{M}_{\mathrm{SM}}\mathcal{M}^*_{\mathrm{d6}}\} + |\mathcal{M}_{\mathrm{d6}}|^2$
- **Interference term leads to asymmetries in CP-odd observables**

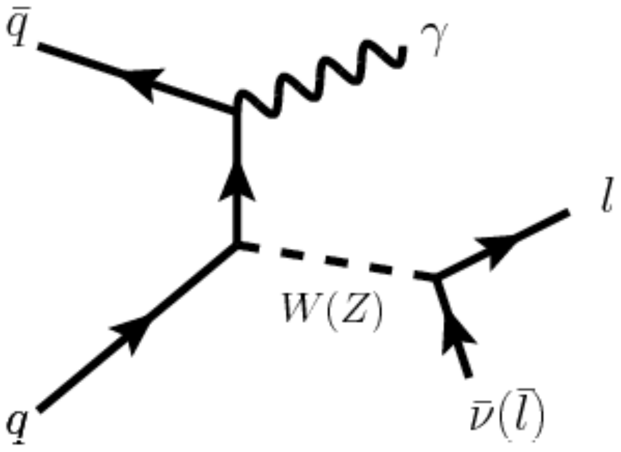
- **Inclusive $W\gamma$ production** particularly sensitive to $\mathcal{O}_{\phi\widetilde{W}B}$ and $\mathcal{O}_{\widetilde{W}}$
- Differential cross-section as function of NN-constructed CP-odd observable (2209.05143, Phys. Lett. B 832 (2022) 137246):
- Predicted factor of **10 (2) improvement** in sensitivity to $\mathcal{O}_{\phi\widetilde{W}B}$ ($\mathcal{O}_{\widetilde{W}}$) compared to any other known measurement (including in Higgs final states)



Motivation

- ATLAS has **no Run 2 measurement of inclusive $W\gamma$** production cross-section
  - Latest ATLAS result using 2011 data at $\sqrt{s}$ = 7 TeV: Phys. Rev. D 87 (2013) 112003
  - CMS with 7 TeV and 13 TeV measurements: Phys. Rev. D 89 (2014) 092005, Phys. Rev. Lett. 126, 252002
- **Very important to measure this fundamental process of the SM!**





Event Selection

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Variable Definition

Event Selection

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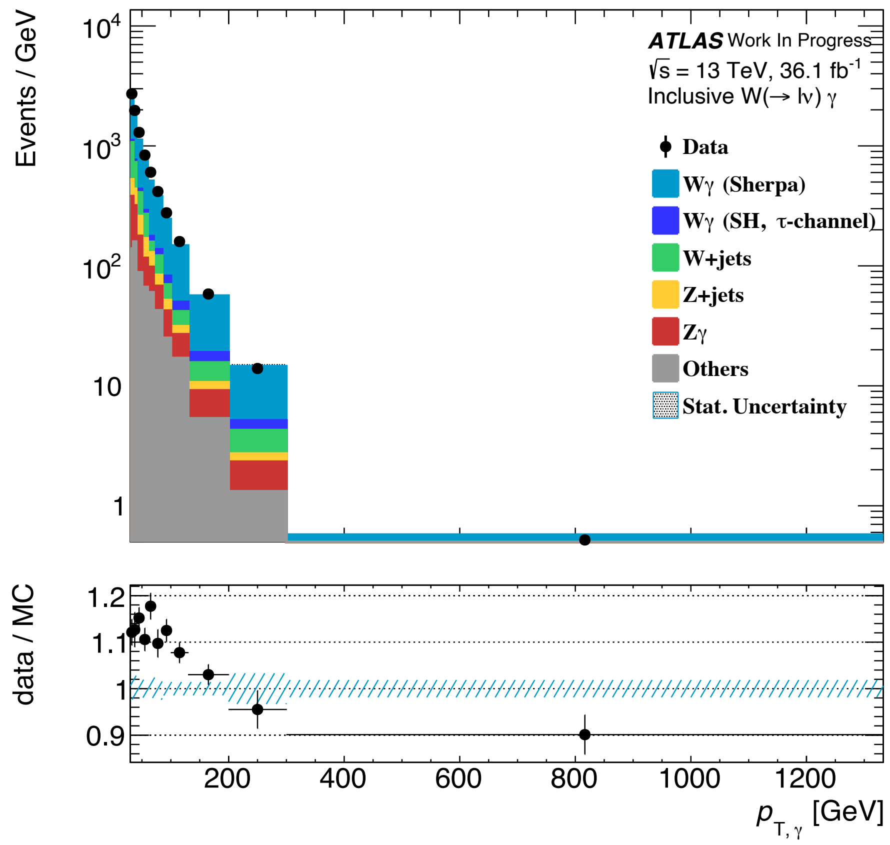
- At least one photon
- Only one lepton (electron or muon) in the event
- No b–tagged jets (*Veto top-related events*)
- MET > 40 GeV
- Lepton:
  - $p_T > 30$ GeV, $|\eta| < 2.47$ (electron)
  - $p_T > 30$ GeV, $|\eta| < 2.5$ (muon)
  - Impact Parameter: $d_0/\sigma_{d_0} < 5$, $z_0 \times \sin\theta < 0.5$ mm
- Photon:
  - $p_T > 30$ GeV, $|\eta| < 2.37$
- $m_{l\gamma} < 80\ or\ m_{l\gamma} > 100$ GeV (*Veto Z-jets event*)
- $\Delta R_{l\gamma} > 0.8$

Background treatment

- **Discrepancy** between MC and data is due to the MC cannot describe the background with faking photon/lepton well.

- **Background** consists of two types of contributions:
  - **Prompt** backgrounds
    - $Z\gamma$, $tX\gamma$
    - Contributions **obtained from MC**
  - **Fake** backgrounds
    - **Jet faking photons**: in W+jets, Z+jets, $t\bar{t}$, single-top
    - **Jet faking leptons:** in γ+jets
    - **Electron faking photons**: in Z+jets, $t\bar{t}$, diboson
    - **Photons from pile-up** interactions
    - Estimates **obtained via data-driven methods**



Background Estimation: Jet Faking Photon

Photon Isolation Variable

- In this analysis, we select photon with:

$$E_{T,cone40} < 0.022\, p_{T,\gamma} + 2.45\ [\mathrm{GeV}]$$

where $E_{T,cone40}$ is the sum of transverse energy within the photon cone of $\Delta R < 0.4$

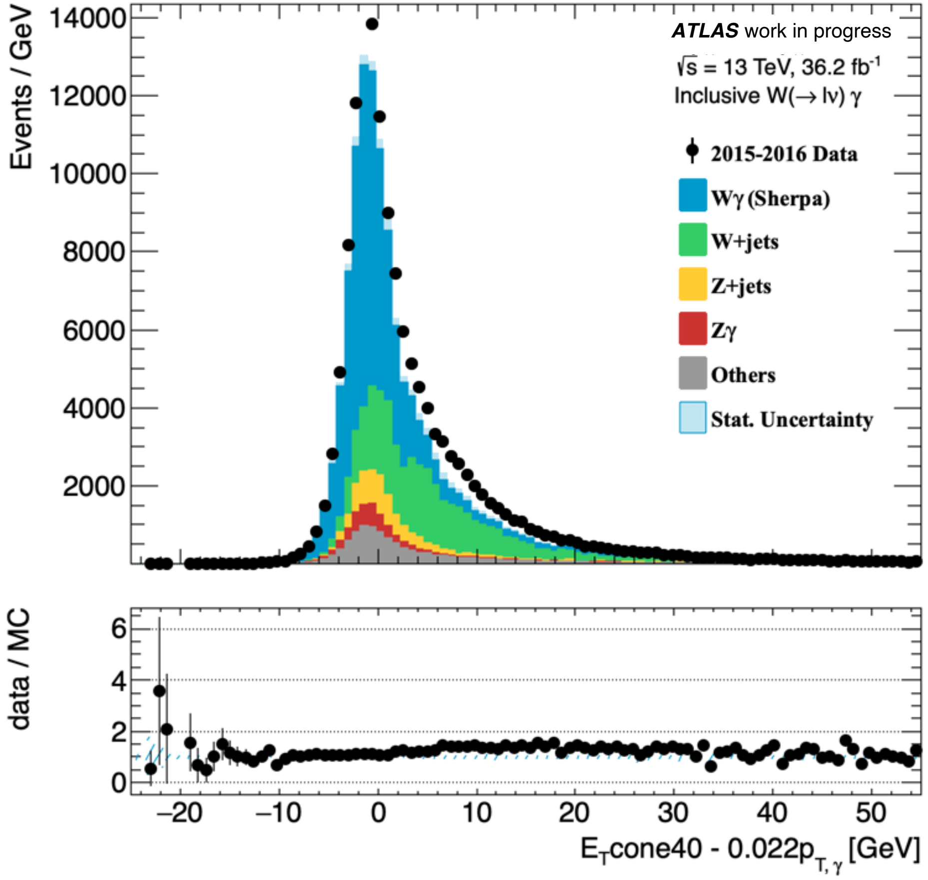
- We define photon isolation variable:

$$E_{iso} = E_{T,cone40} - 0.022\, p_{T,\gamma}$$

- Photon in signal region is photon with:

$$E_{iso} < 2.45\ \mathrm{GeV}$$

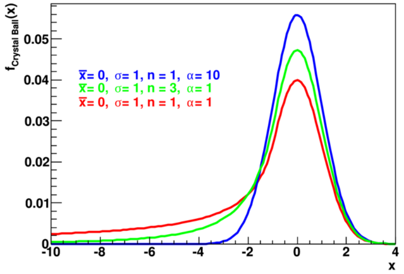
- We use the full E_{iso} range to estimate the fake photon yields by its side band.



E_{iso} of tight ID photon

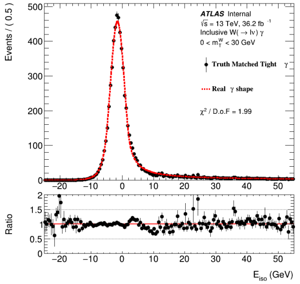
$j \rightarrow \gamma$ Background Estimation workflow

In the1st bin of $m_{T,W}$, we want to measure:



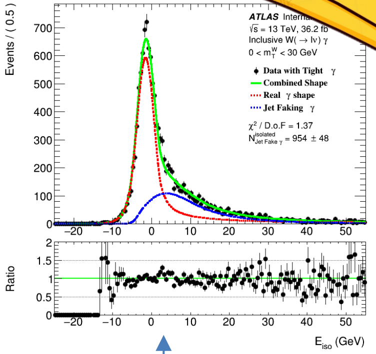
Crystal ball (CB)

Fit to → Truth-Matched tight (ID) photon MC sample =



Signal shape

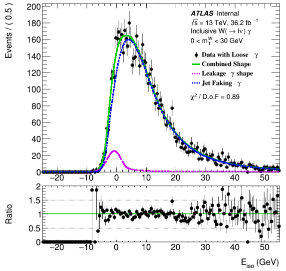
Fit to → Multi-Gaus Constraint



tight (ID) photo data

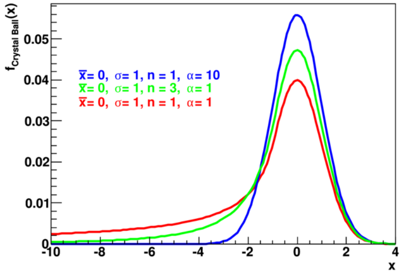
Fit to Multi-Gaus Constraint

In this analysis, photon with tight Identification (ID) is selected as signal.



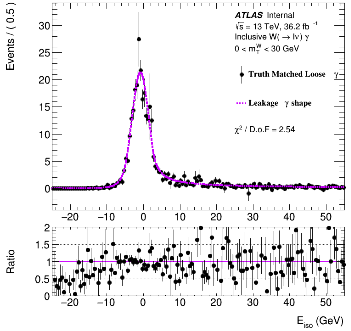
Resulting background shape

=



Crystal ball (CB)

Fit to → Truth-Matched loose but not tight (ID) photon MC sample =



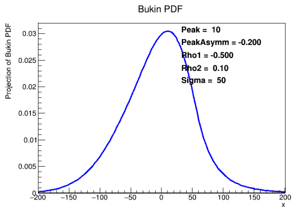
Leakage shape

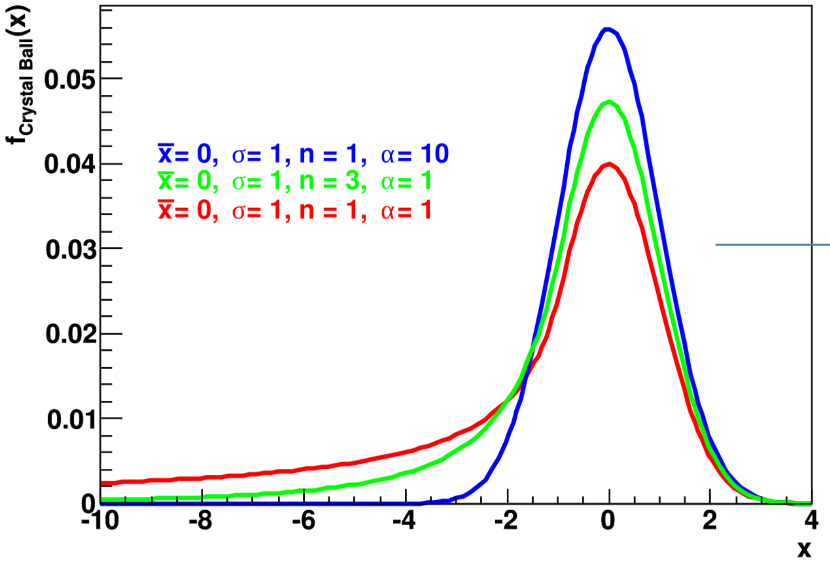
Fit to → Multi-Gaus Constraint → Loose'4 but not tight (ID) photon data

Loose ID region is used to extract background shape

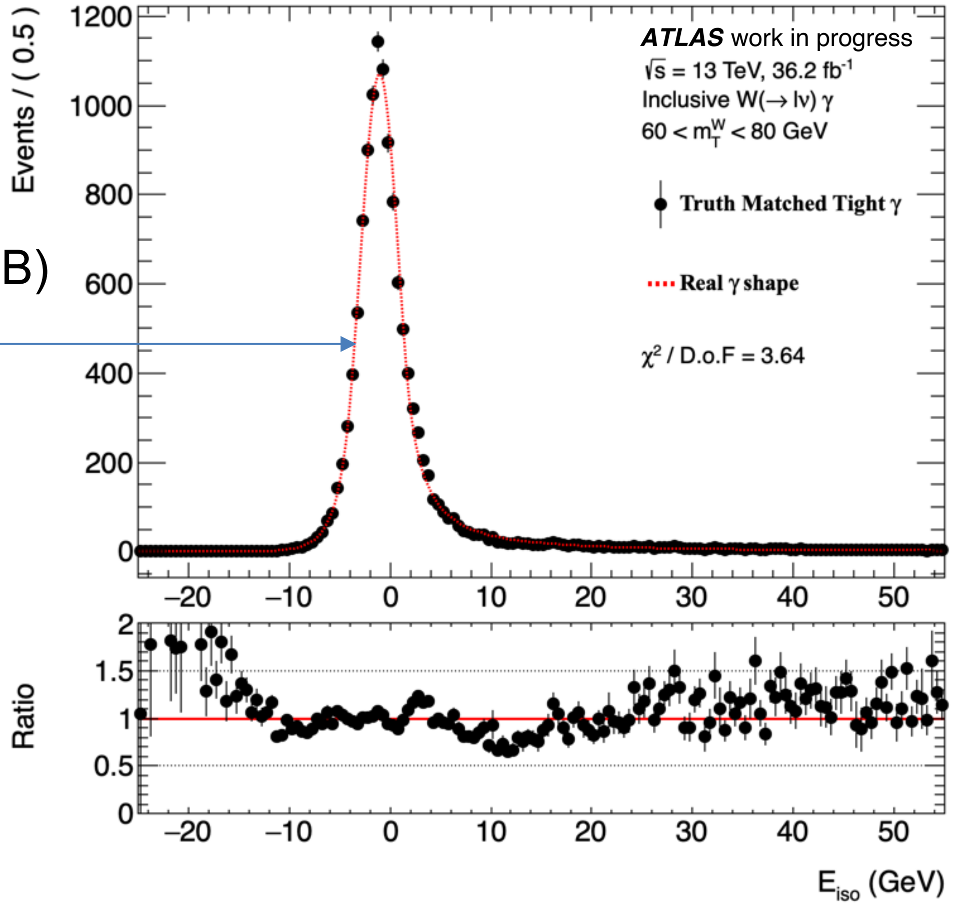
Fit to

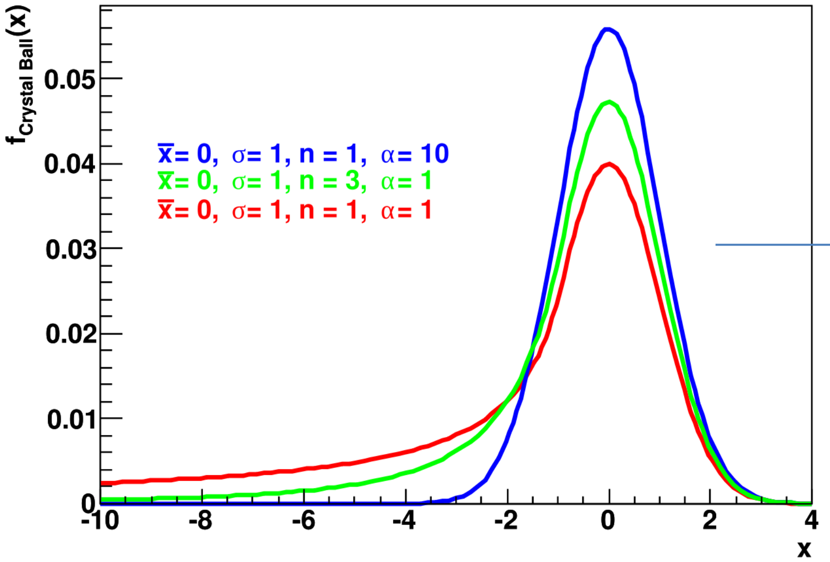
Bukin Function (Background shape)





Crystal ball (CB)





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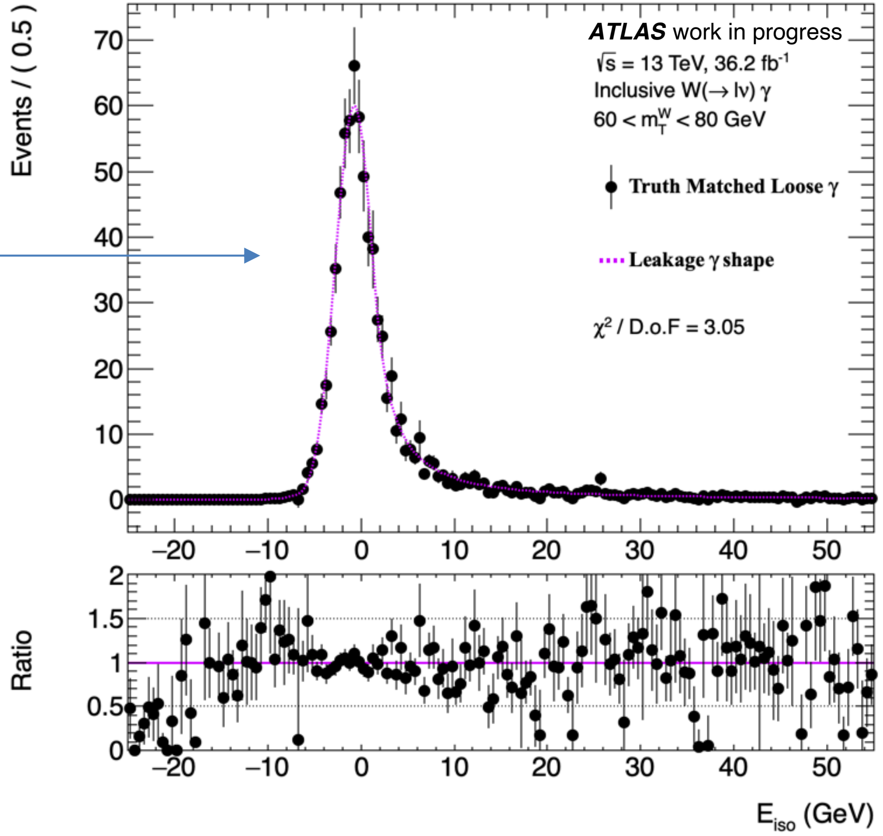

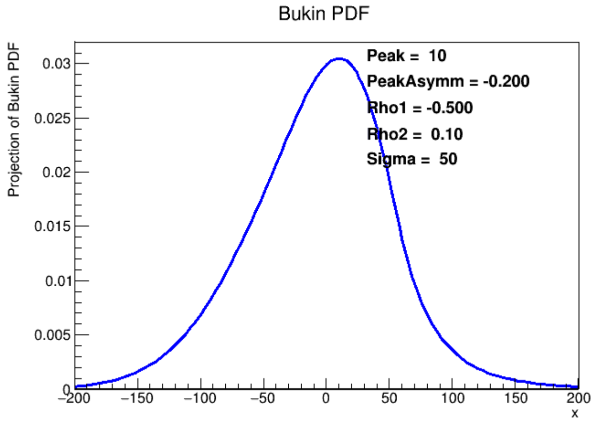

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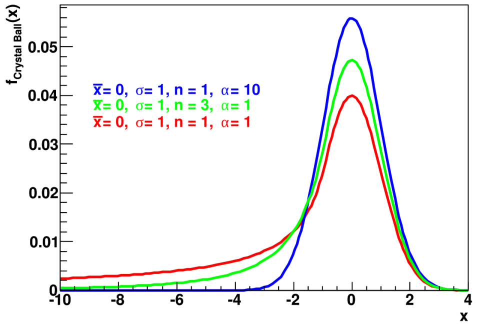
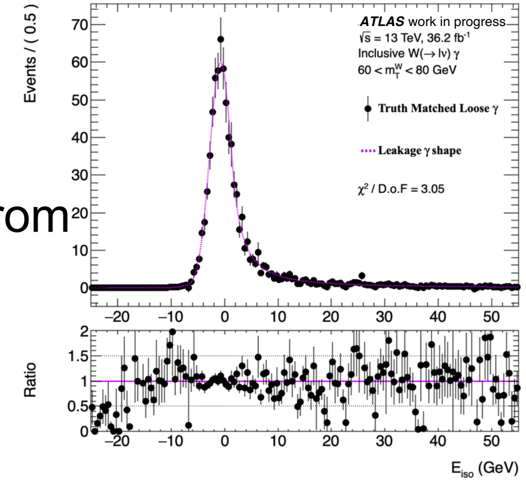
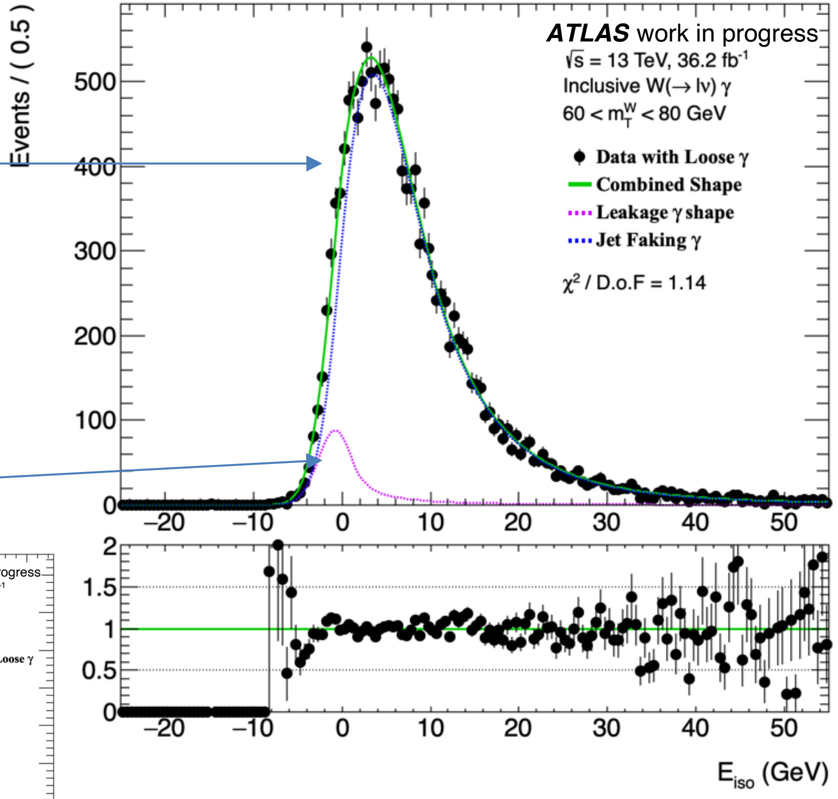


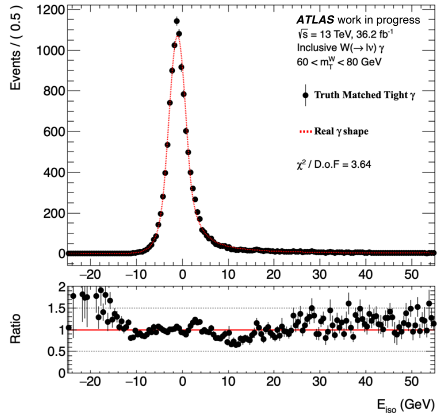
Crystal ball (CB)

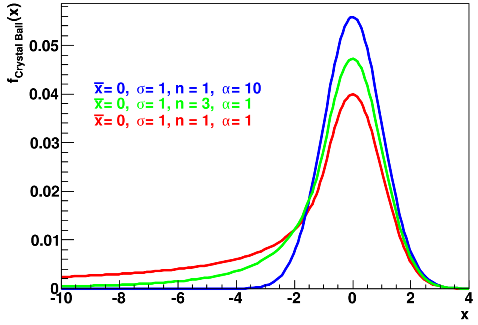
Via fit constraints from



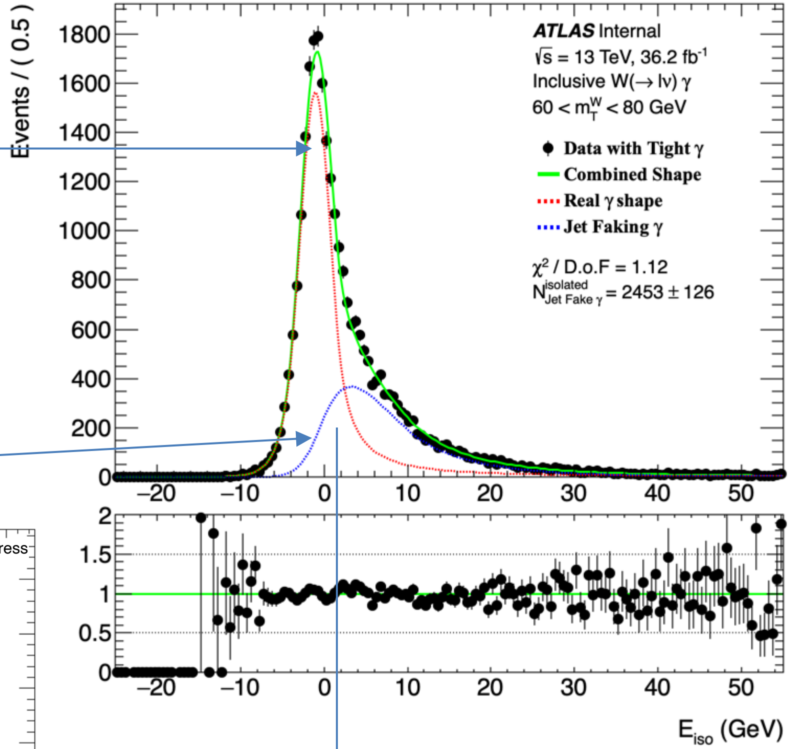


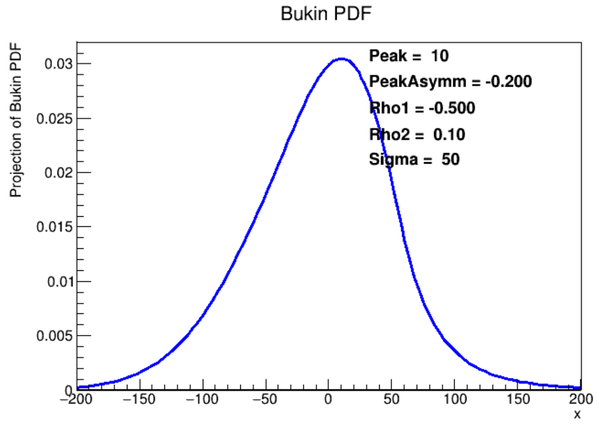
Via fit constraints from





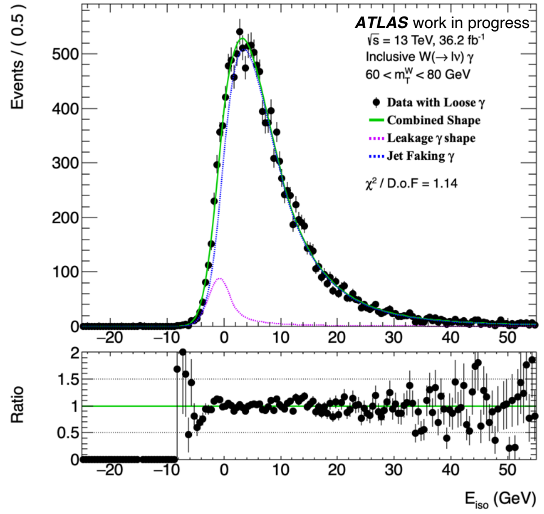
Crystal ball (CB)





bukin

Via fit constraints from



Calculate the integral of background PDF in range [-25, 2.45] GeV, obtaining the yields of jet-faking photon.

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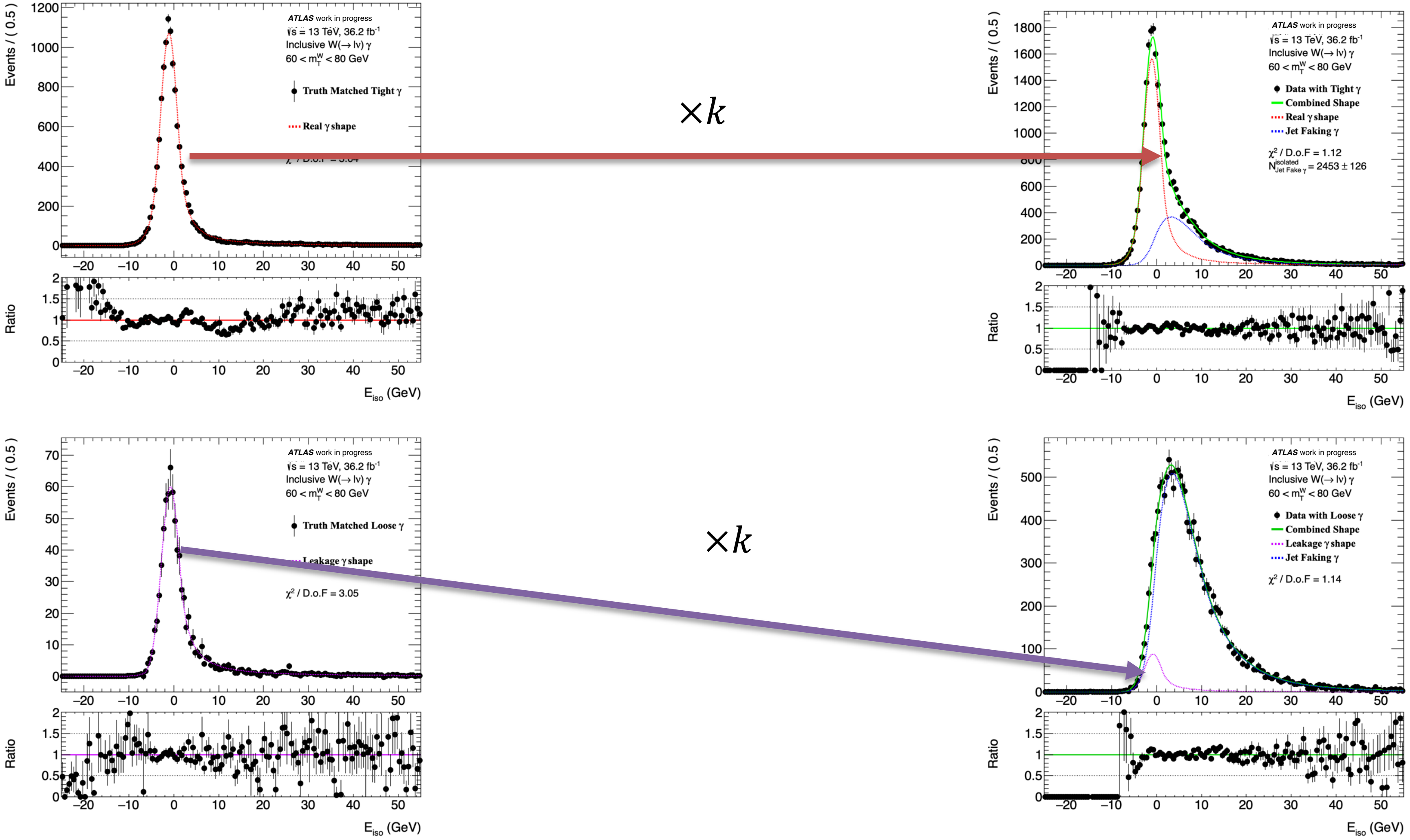
For the fit stability

- A basic assumption: the MC should have same scale factor to data in both loose and tight ID region

$$k = \frac{N^{sig}_{fit,data}}{N^{sig}_{MC}} = \frac{N^{leakage}_{fit,data}}{N^{leakage}_{MC}}$$



Background Estimation: Electron Faking Photon

“Pseudo” Fake Rate

- The simplest fake rate for electron fake photon:

$$\rho = \frac{N_\gamma^{Reco}}{N_e^{Truth}}$$

- However, in data, truth-level event can’t be measured, hence we need to use reco-level event, let us define a “pseudo” fake rate:

$$F_{e\to\gamma} = \frac{N_\gamma^{Reco}}{N_e^{Reco}} = \frac{N_e^{Truth}\rho\epsilon_\gamma}{N_e^{Truth}(1-\rho)\epsilon_e} = \frac{\rho\epsilon_\gamma}{(1-\rho)\epsilon_e}$$

Here ϵ_γ is the photon (electron) reconstruction efficiency.

- And this pseudo fake rate will be applied via $SF = \frac{F_{e\to\gamma}^{data}}{F_{e\to\gamma}^{MC}}$. This will be applied to the MC event with a photon from a faking electron.

Control Region Definition

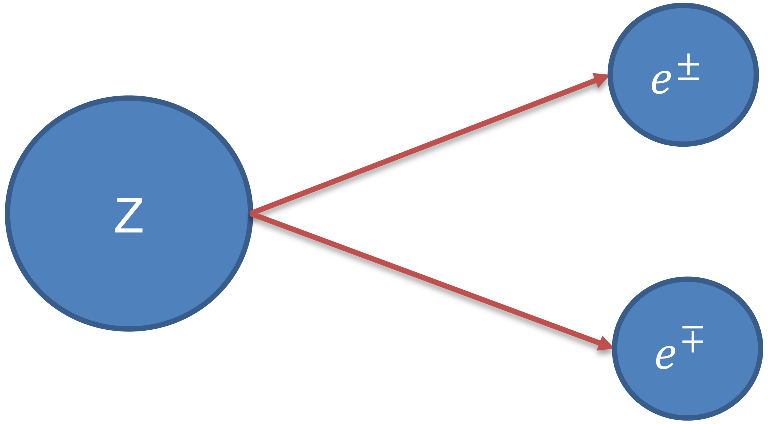
- The way to measure $F_{e\to\gamma}$ is to use:

$$F_{e\to\gamma} = \frac{N_\gamma^{Reco}}{N_e^{Reco}}$$

- We need a control region provides high-purity electron sample. Solution: to use $Z \to ee$ region.

- We can use one electron to tag the event, and probe for another electron/photon. And the photon-electron pair with invariant mass falls around the m_z can be treated as an electron fake photon event (N_γ^{Reco}). And the events with electron pair around m_z will be used as N_e^{Reco}.

Control Region Definition



Leading electron, always treated as tagged

Sub-leading electron / mis-reconstructed leading photon with pT lower than leading electron. Treated as probed.

We have:

$$N_{ee} = \epsilon_e^2 (1-\rho)^2 N_{etag}$$
$$N_{e\gamma} = \epsilon_e \epsilon_\gamma \rho (1-\rho) N_{etag}$$

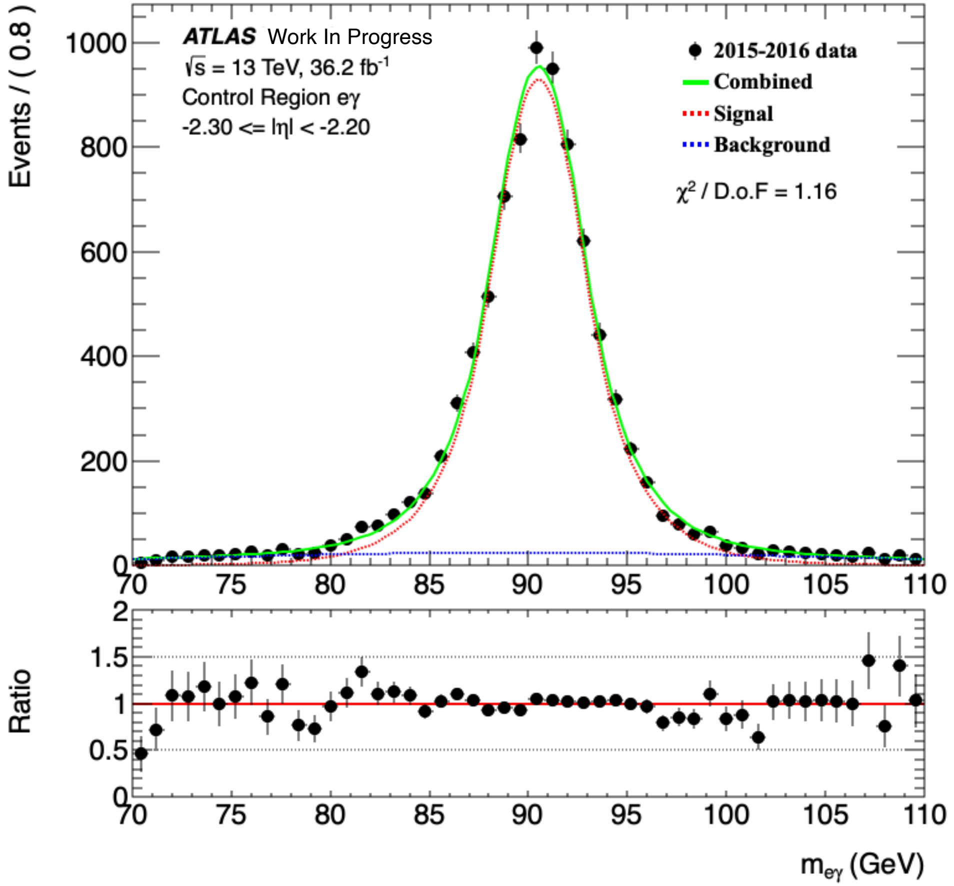
Hence we have:

$$F_{e\to\gamma} = \frac{N_{e\gamma}}{N_{ee}} = \frac{\rho \epsilon_\gamma}{(1-\rho)\epsilon_e}$$

- CR_{ee}: # of electron = 2, # of photon = 0, electron pair has opposite sign, leading one is tagged
- $CR_{e\gamma}$: # of electron = 1, # of photon = 1, $p_{T,e} > p_{T,\gamma}$, electron is tagged

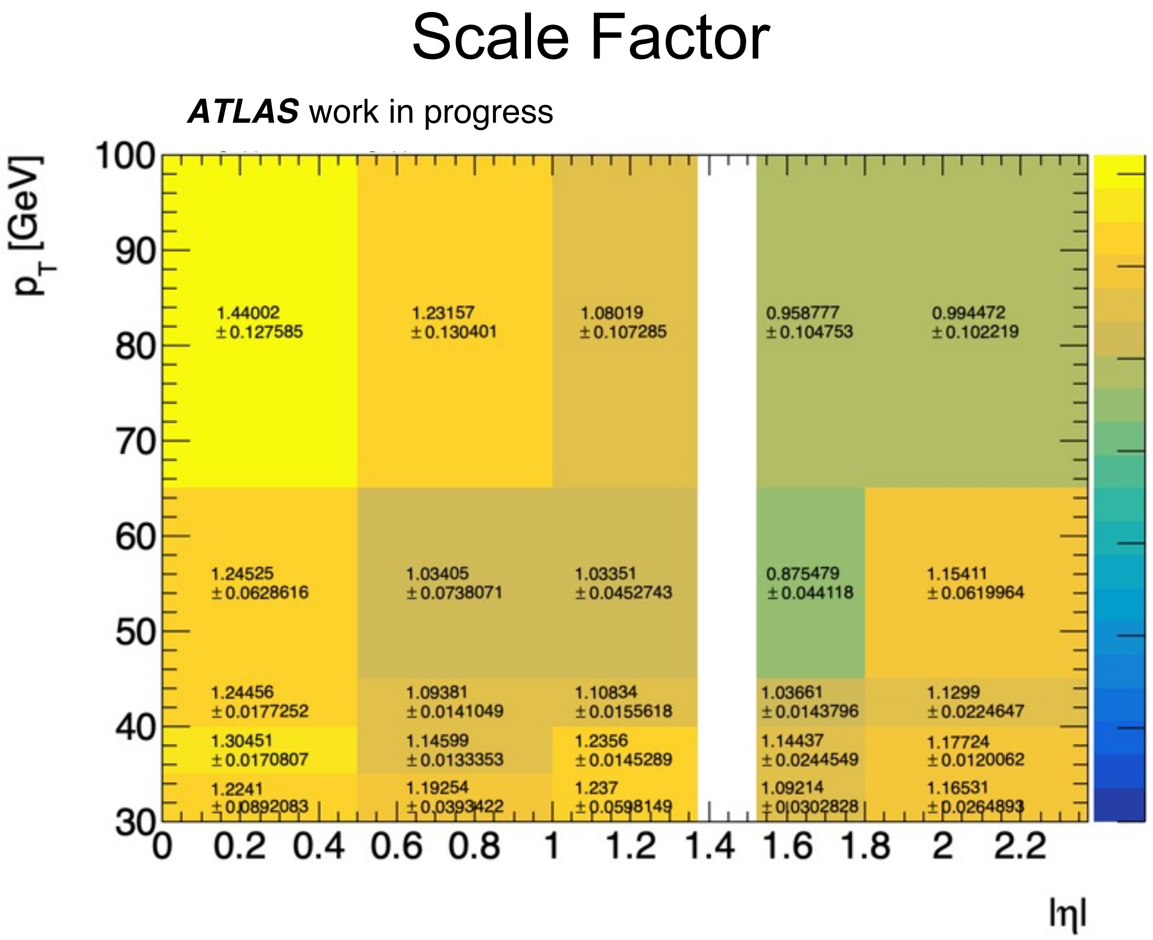
How to get number of ee/eγ events

- Calculate the invariant mass of each ee / eγ pair
- Focus on the region of [70, 110] GeV.
- Model fit to data/MC
    - Use Double Sided Crystal Ball function with symmetric tail as signal PDF.
    - Use Analytical Exponential Function ($f(x) = Ne^{(a_1 x + a_2 x^2)}$) as background PDF.
- Integrate the signal PDF in region [86, 96] GeV t get the number of event.



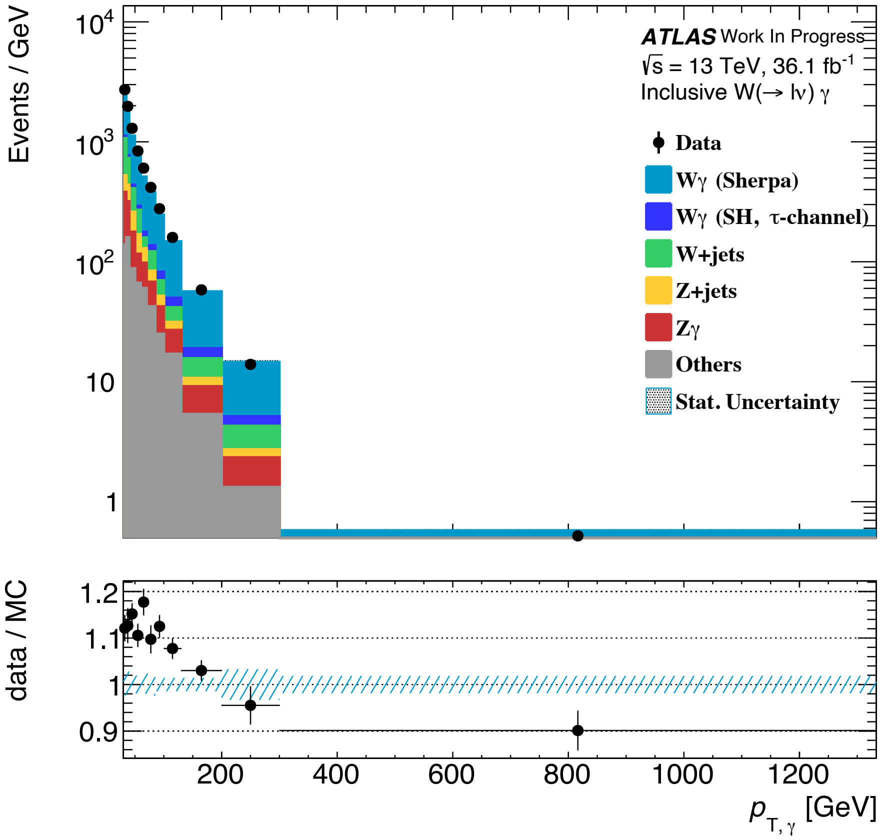
Fake Factor Map

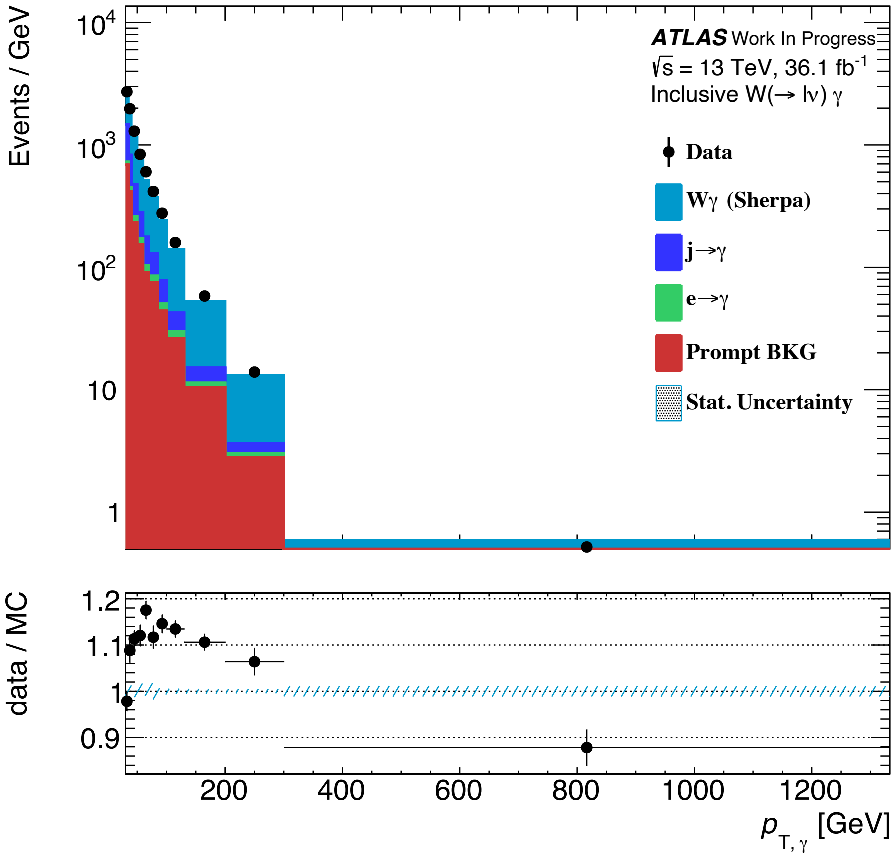
- After getting number of events, we can obtain a map of SF.
- For MC event with an electron-faking-photon, according to the pT and eta of the photon, we can get a related SF.
- The SF will applied to the event weight and we obtain the data-driven electron-faking photon background estimation.



Result & Summary

Result





- What is missing?
  - The data-driven jet-faking lepton estimation (~10%)
  - Pile-up Photon Background

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Summary

- 2015/2016 data and MC16a being used for studies
- Reasonable agreement between data/MC even before data-driven estimates
- Jet faking photon is ready to extend to full Run2
- Electron faking photons is ready to extend to full Run2

Ongoing & Next:

- Jet faking lepton (Two teams working on it: Matrix Method and Fake Factor Method)
- Pile-up photon
- Unfolding our result

Thank You!

Back up

Object Overlap Removal

Object overlap removal (OR) use the ATLAS OR tool, use the standard OR setting:
https://indico.cern.ch/event/631313/contributions/2683959/attachments/1518878/2373377/Farrell_ORTools_ftaghbb.pdf

Reject	Against	Criteria
electron	electron	shared ID track, pt1 < pt2
muon	electron	is calo-muon and shared ID track
electron	muon	shared ID track
jet	photon	dR < 0.4
photon	electron	dR < 0.4
photon	muon	dR < 0.4
jet	electron	dR < 0.2
electron	jet	dR < 0.4
jet	muon	NumTrack < 3 and (ghost-associated or dR < 0.2)
muon	jet	dR < 0.4

Step By Step

Object Overlap Removal (Truth Level)

Truth level overlap removal is mimicking reco overlap removal

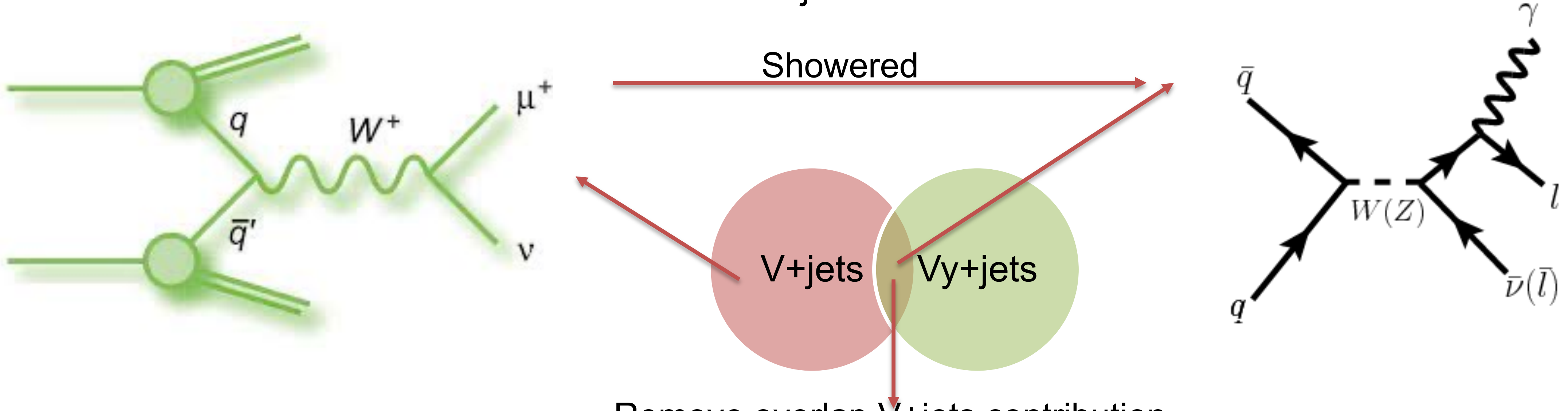
Reject	Against	Criteria
jet	photon	dR < 0.4
photon	electron	dR < 0.4
photon	muon	dR < 0.4
jet	electron	dR < 0.2
electron	jet	dR < 0.4
jet	muon	dR < 0.2
muon	jet	dR < 0.4

Step By Step

Sample Overlap Removal

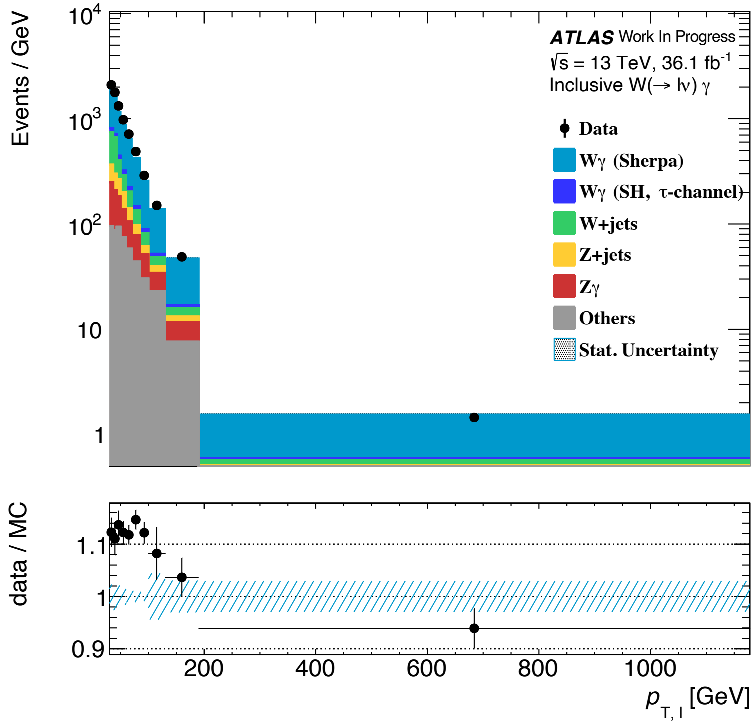
Sample overlap removal uses the ATLAS VGammaORTool:
https://twiki.cern.ch/twiki/bin/viewauth/AtlasProtected/VGammaORTool

- On V+gamma samples parton level cuts are typically applied on pT(gamma), deltaR(gamma,l), and iso(gamma).
- These samples thus need to be combined with V+jets samples, in which no photon cuts are applied, to fill up this part of the phase space.
- The overlap, defined by the V+gamma generation cuts, needs to be removed from the V+jets sample. Accurate simulation of photon emission in V+gamma generation with respect to emission from hadronisation model in V+jets

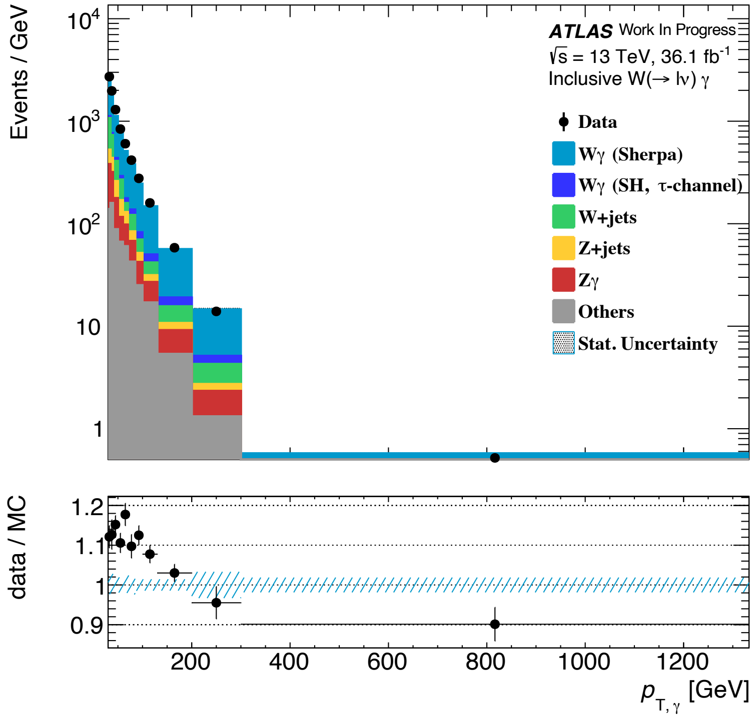


Remove overlap V+jets contribution
(V = W, Z)

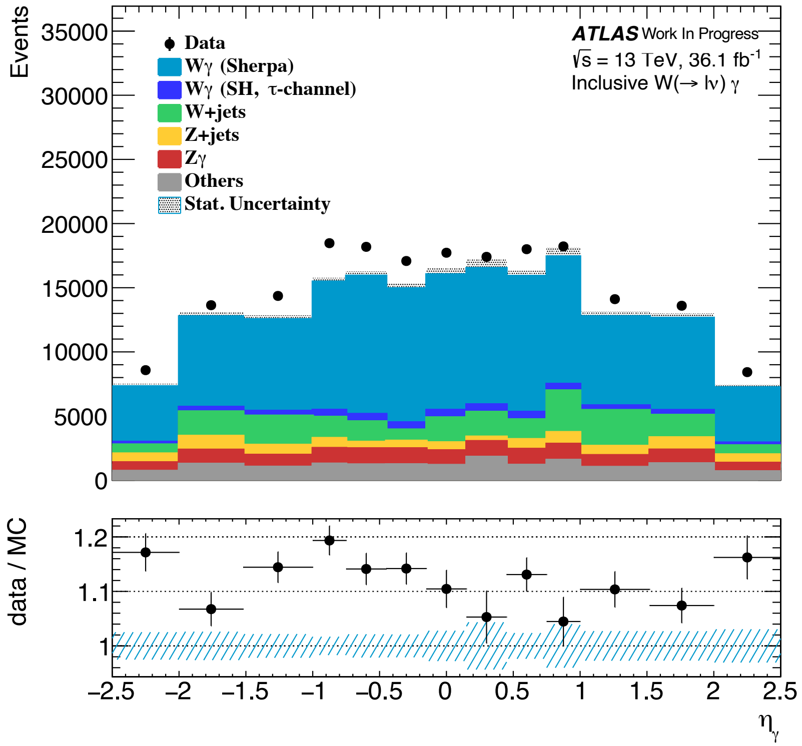
Data/MC comparison and Variable Definition (Sherpa)



lepton transverse momentum $p_{T,\ell}$

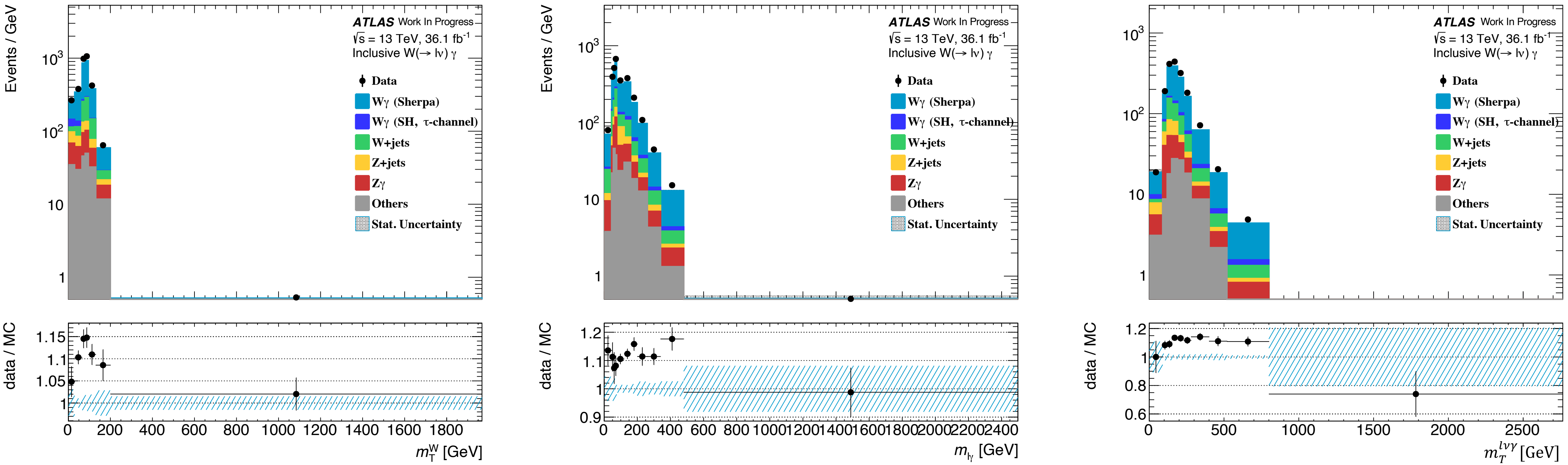


photon transverse momentum $p_{T,\gamma}$



photon pseudo rapidity: η_γ

Data/MC comparison and Variable Definition (Sherpa)



W boson transverse mass:

$$m_T^W = \sqrt{2p_{T,l}p_{T,miss}\cos(\phi_l - \phi_{miss})}$$

- Neutrino taken into account via MET

Mass of lepton-photon system $m_{l\gamma}$

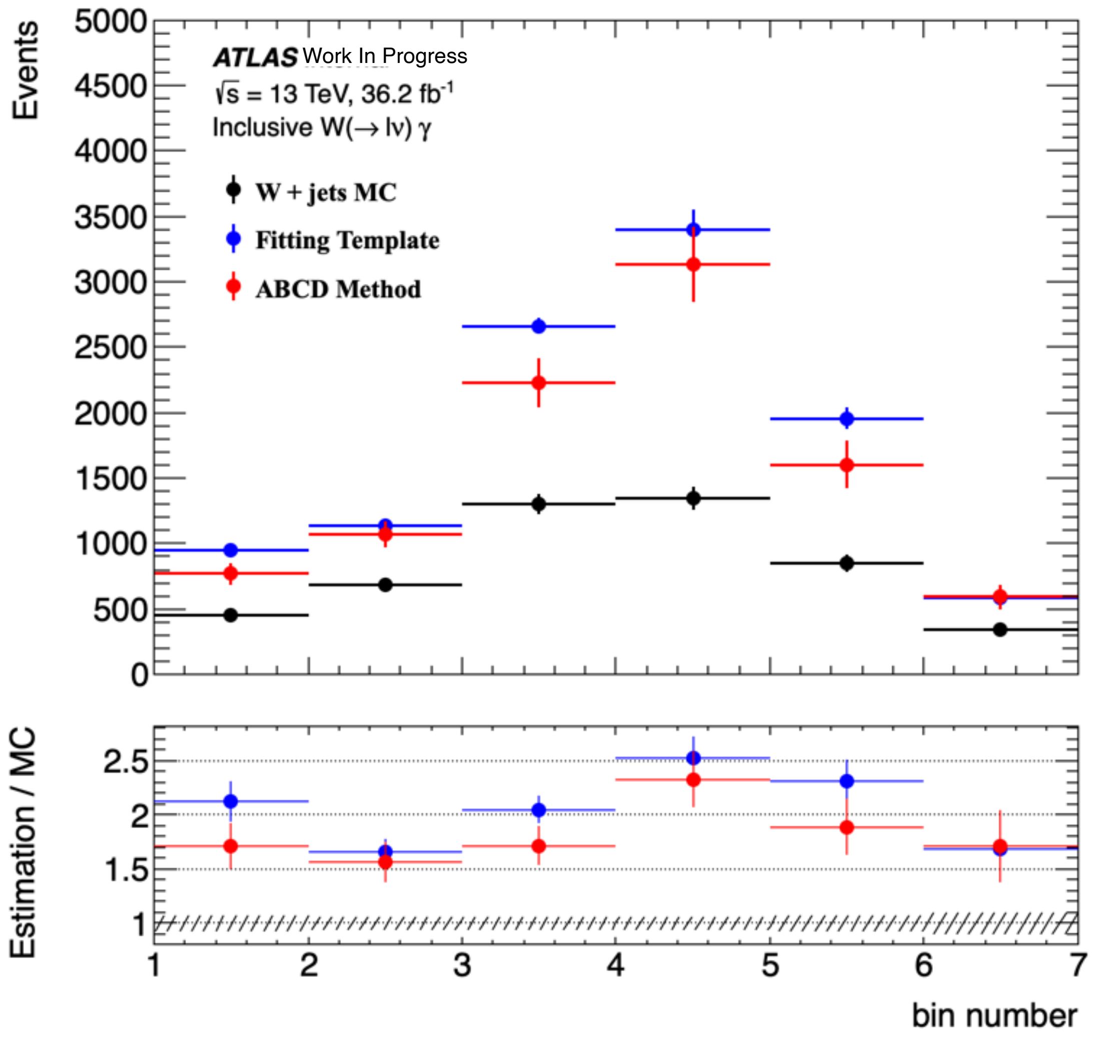
W boson + neutrino system transverse mass:

$$m_T^{l\nu\gamma} = \sqrt{\left(\sqrt{m_{l\gamma}^2 + p_{T,l\gamma}^2} + E_{T,miss}\right)^2 - p_{T,l\nu\gamma}^2}$$

$j \rightarrow \gamma$ Background Cross Check: ABCD Method

In parallel, we use ABCD method (2d side band) to estimate the jet faking photon background, the ABCD region is defined as:

A: Tight ID, Tight ISO
B: Tight ID, Anti-tight ISO
C: Loose'4 but not Tight ID, Tight ISO
D: Loose'4 but not Tight ID, Anti-tight ISO



- The estimated background is generally higher than the MC expectation.
- And the ABCD method is agreeing with the fitting template method.

$j \to \gamma$ Background Cross Check: ABCD Method

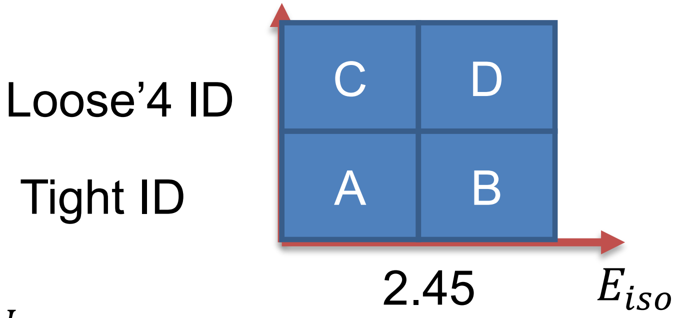
In parallel, we use ABCD method (2d side band) to estimate the jet faking photon background, the ABCD region is defined as:

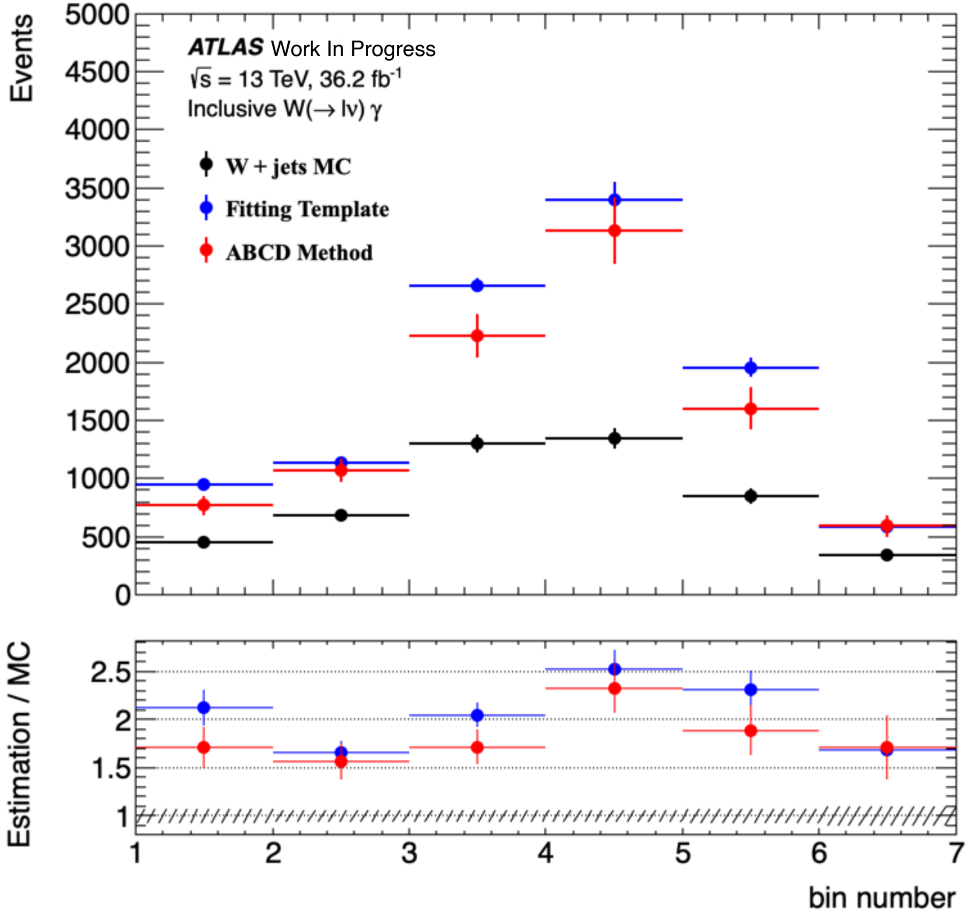
A: Tight ID, Tight ISO
B: Tight ID, Anti-tight ISO
D: Loose'4 but not Tight ID, Tight ISO
D: Loose'4 but not Tight ID, Anti-tight ISO

$$c_{reg} = \frac{N_{reg}^{sig}}{N_{A}^{sig}}$$

$$R = \frac{N_A^{W+jets} \times N_D^{W+jets}}{N_B^{W+jets} \times N_C^{W+jets}}$$

$$N_A^{j\to\gamma} = R * (N_B - N_A * c_B)\frac{N_C - N_A * c_C}{N_D - N_A * c_D}$$

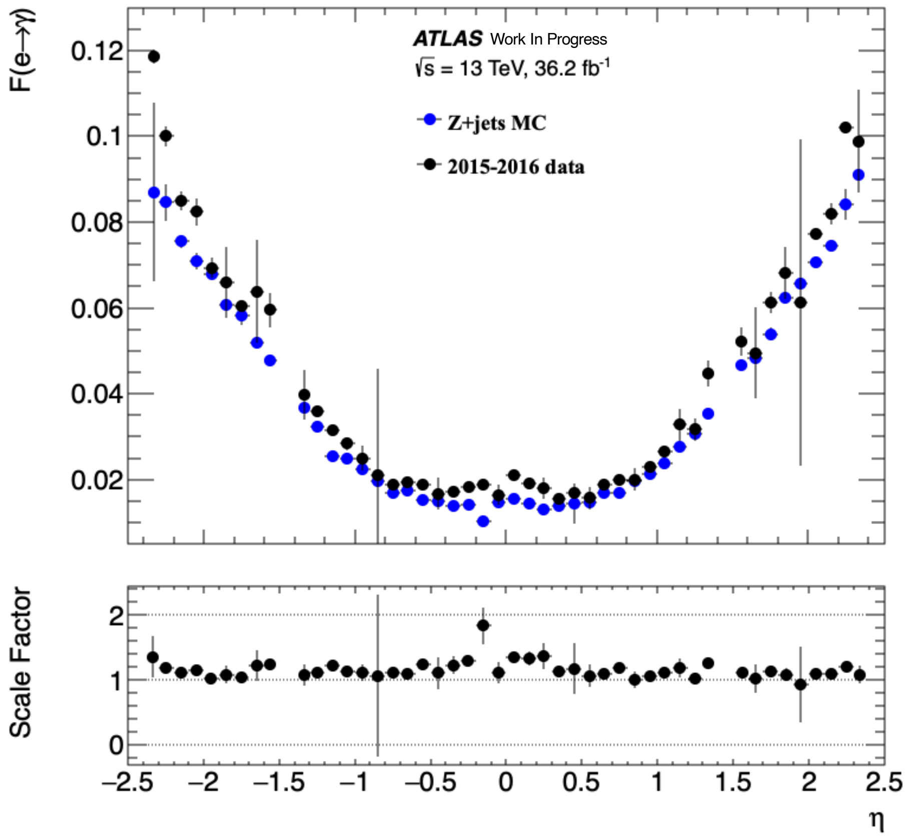




N_{reg}^{sig}: Number of truth matched photon events in reg (A, B, C, D)
N_{reg}: Data yields in reg (A, B, C, D)
N_{reg}^{W+jets}: Number of W+jets events in reg (A, B, C, D)

Kinematic dependency: 1D

- We divide the probe electron / photon according to different eta bins. And calculate the pseudo fake rate and scale factor in different eta bin.



Long Error bar means fitting failed, Error matrix not correct, will deal with that later

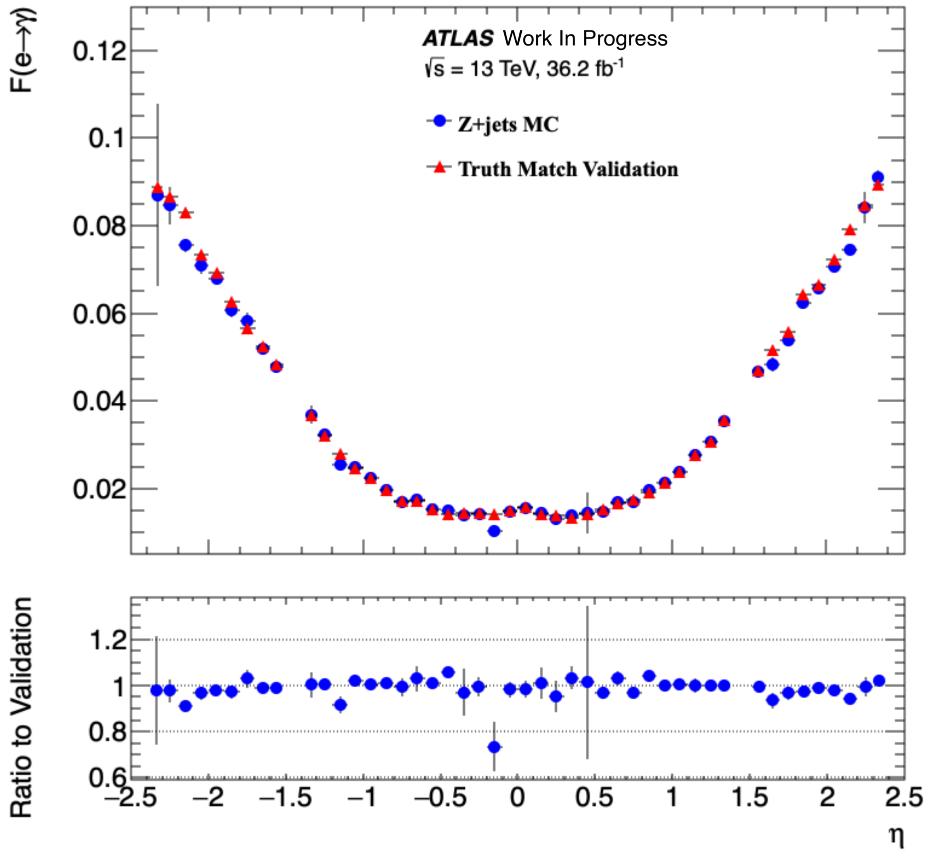
Validation Method

- In stead of doing a fit, we can use truth match to calculate the “pseudo” fake rate by truth match in Z+jets MC.

- All event are passed the control region selection. Besides, we require:
  - $m_{ee}/m_{e\gamma} \in$ [86, 96] GeV
  - For electron, we require the truth match information:
    - Type = IsoElectron, Origin = Zboson
  - For mis-reconstructed photon, we require the truth match:
    - Type = IsoElectron, Origin = Zboson
    - Type = IsoPhoton / NonIsoPhoton / BkgPhoton, Origin = Zboson / FSR

- To calculate the “pseudo” fake rate, N_{ee} and $N_{e\gamma}$ are simply the event numbers passed the requirement.

Validation Method



- Long Error bar means fitting failed, Error matrix not correct, will deal with that later.
- Generally deviation is smaller then 5%.